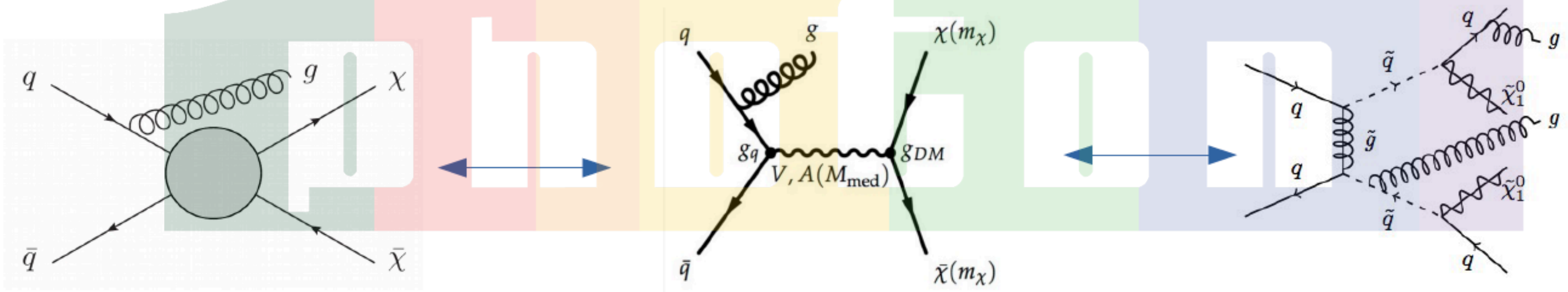
CHARACTERIZATION OF SEARCHES FOR DARK MATTER PRODUCTION AT COLLIDERS

Oliver Buchmueller, Imperial College London

XXVIII INTERNATIONAL SYMPOSIUM ON LEPTON PHOTON INTERACTIONS AT HIGH ENERGIES AT YAT-SEN UNIVERSITY (SYSU), GUANGZHOU, CHINA



EFTs — Simplified Models — UV-complete Models

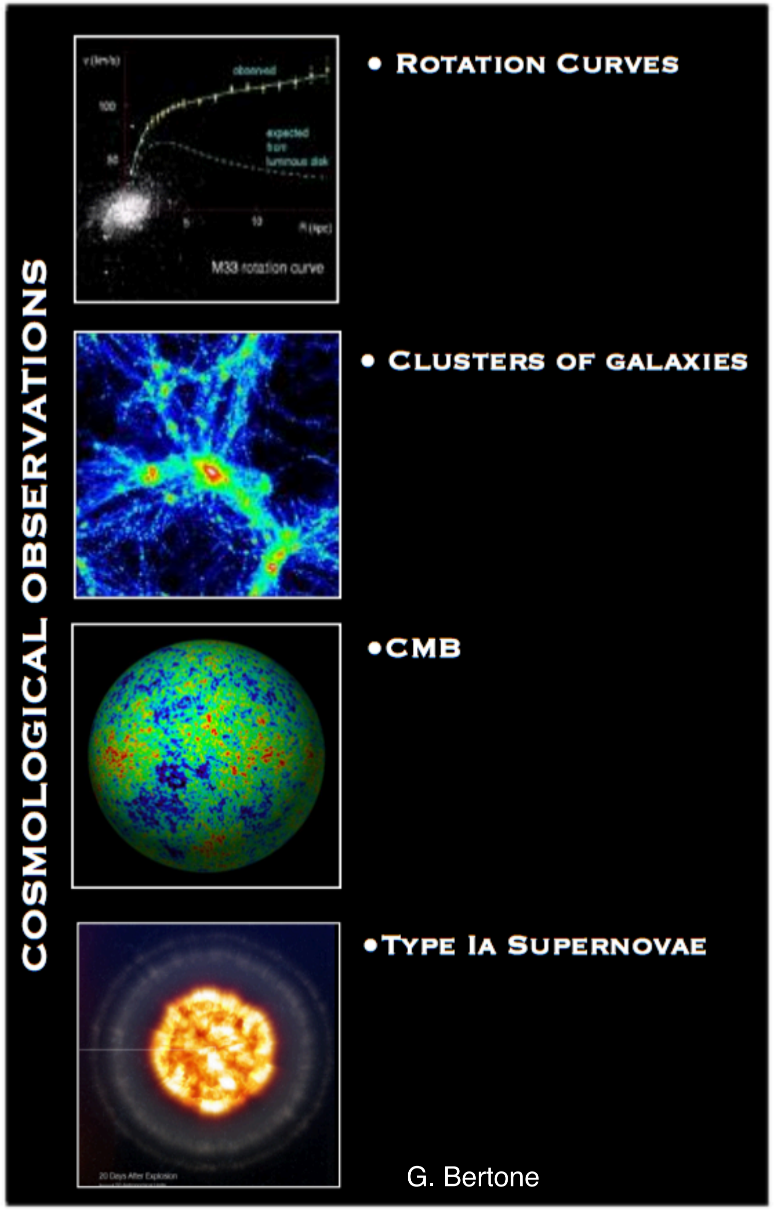
Preface

I will mainly revert to material/searches shown in:

- **Searches for Beyond SM Higgs Bosons**, ***Soshi TSUNO***
- **Searches for SUSY at LHC**, ***Iacopo VIVARELLI***
- **Exotics searches at LHC**, ***Sunil SOMALWAR***

and outline how these results can be (hands-on) interpreted in the context of Dark Matter and in turn be compared with other experiments like Direct Detection or Indirect Detection experiments.

(Very Strong) Evidence for Dark Matter



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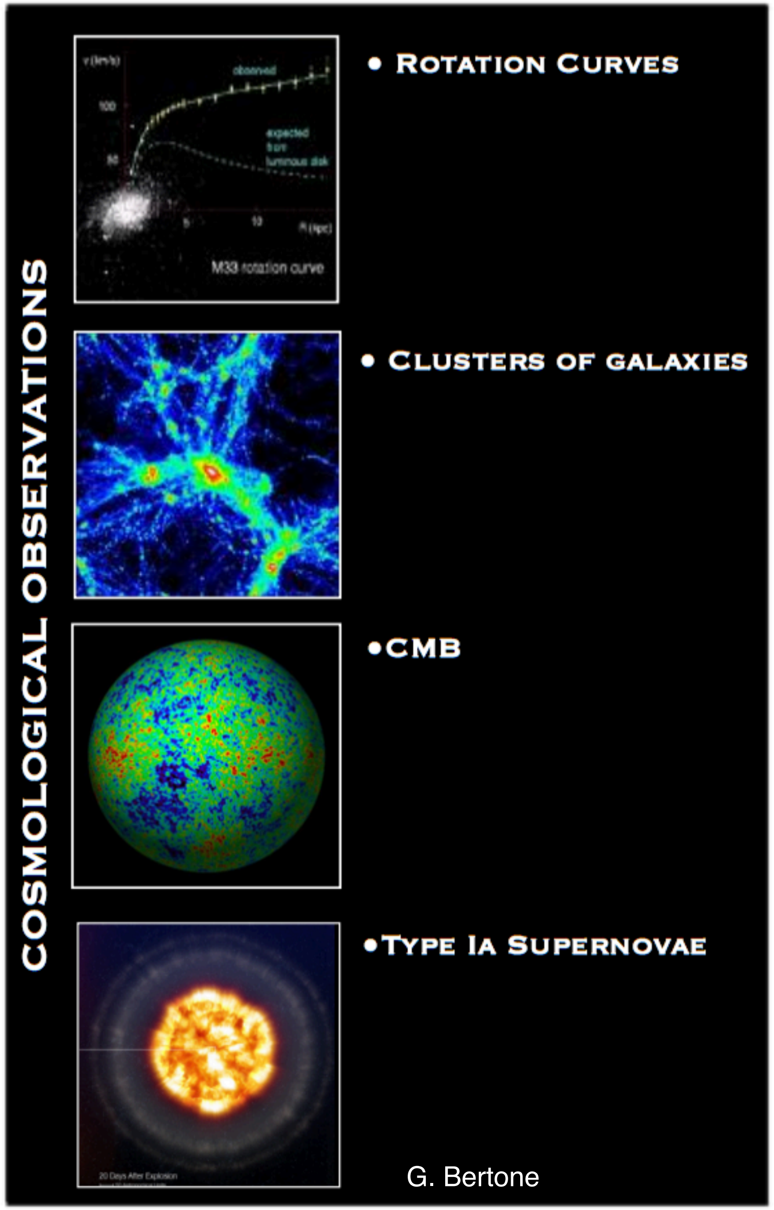
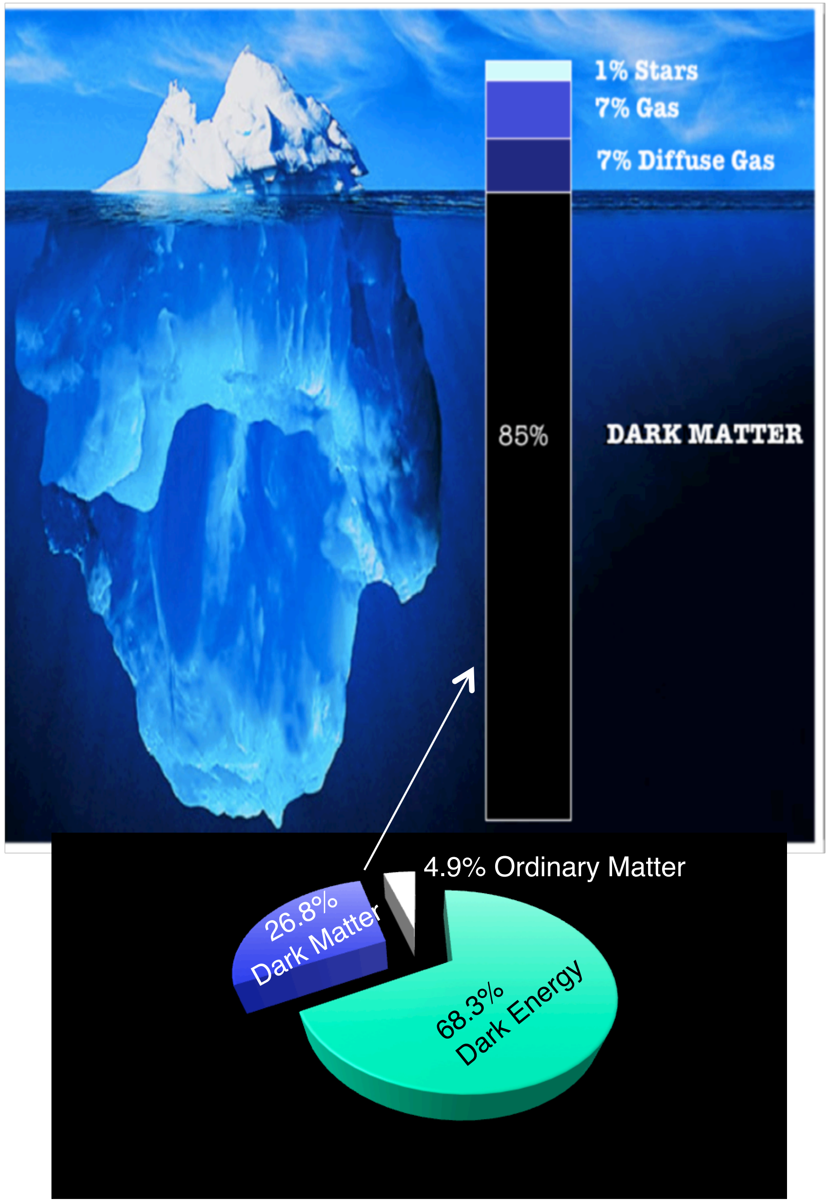
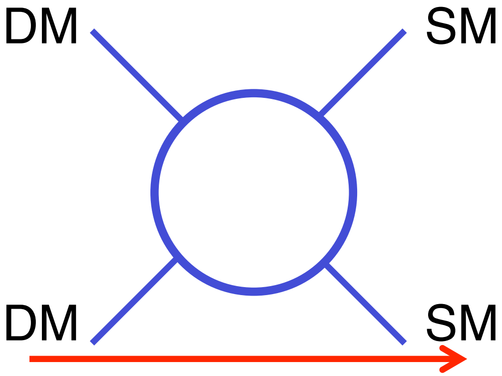
(Very Strong) Evidence for Dark Matter

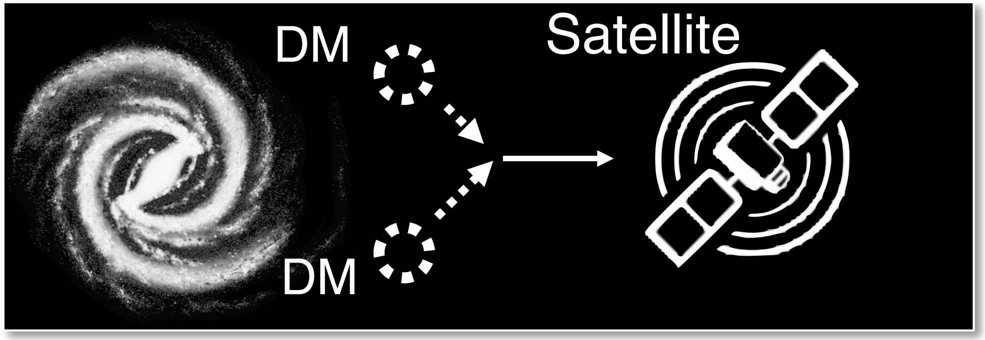




Hunting for Particle DM



Indirect Detection Experiments



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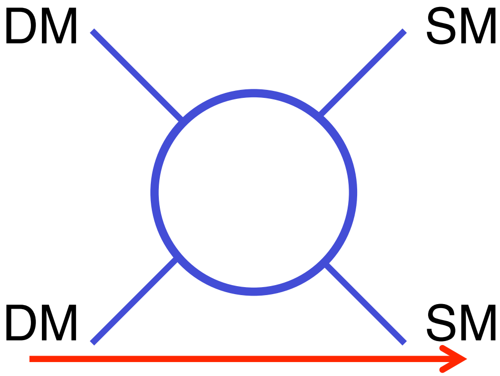

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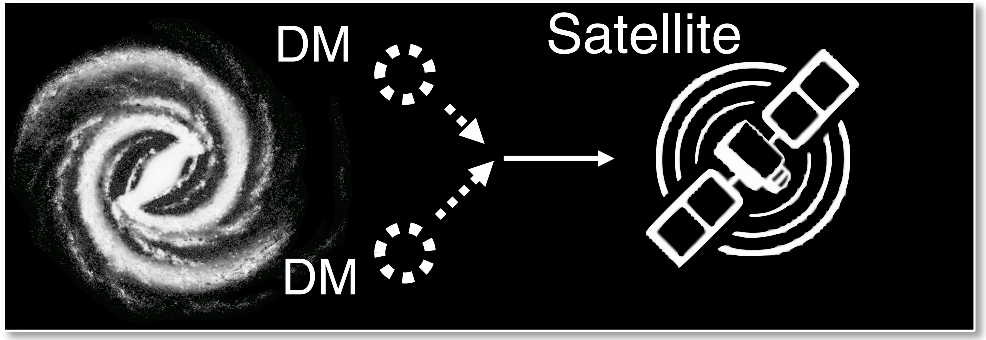

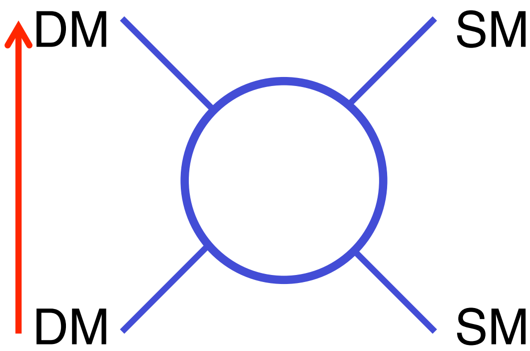

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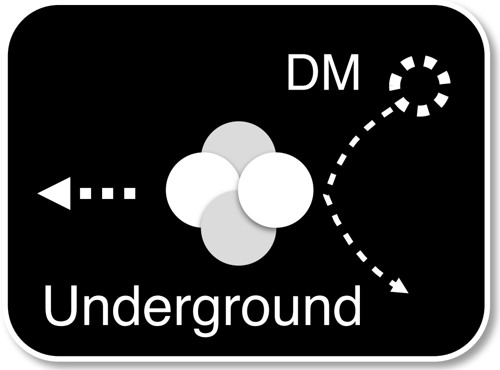

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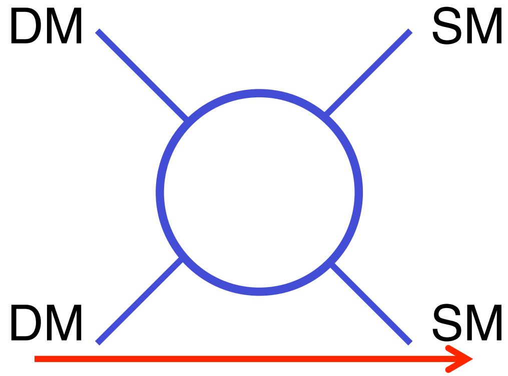

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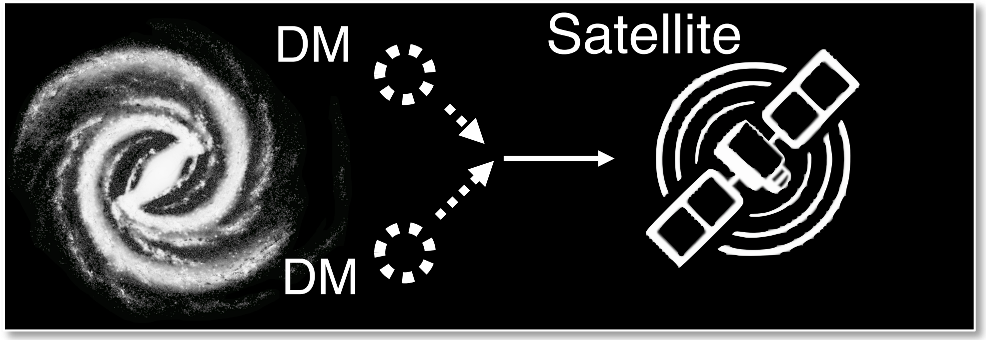

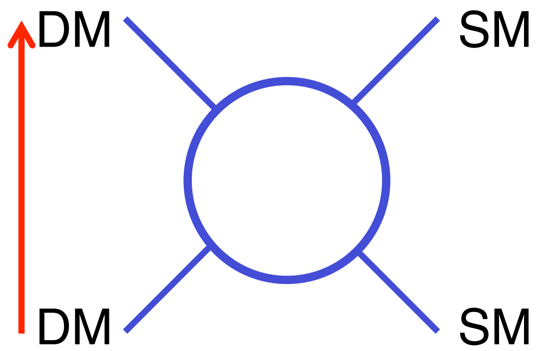

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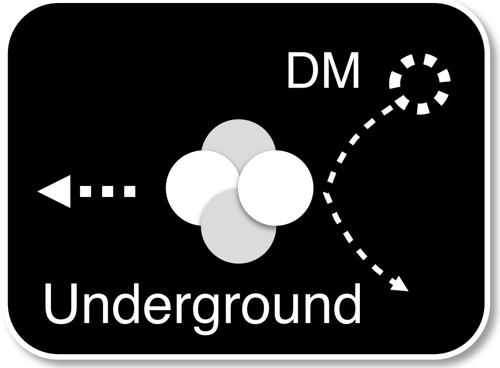
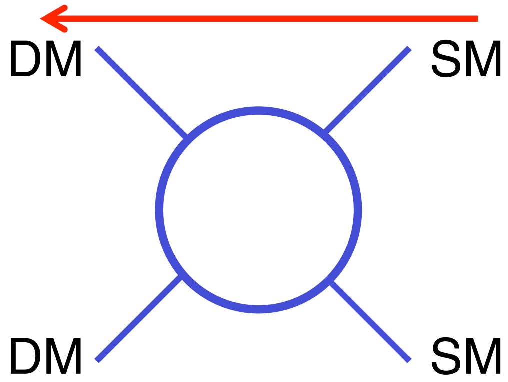
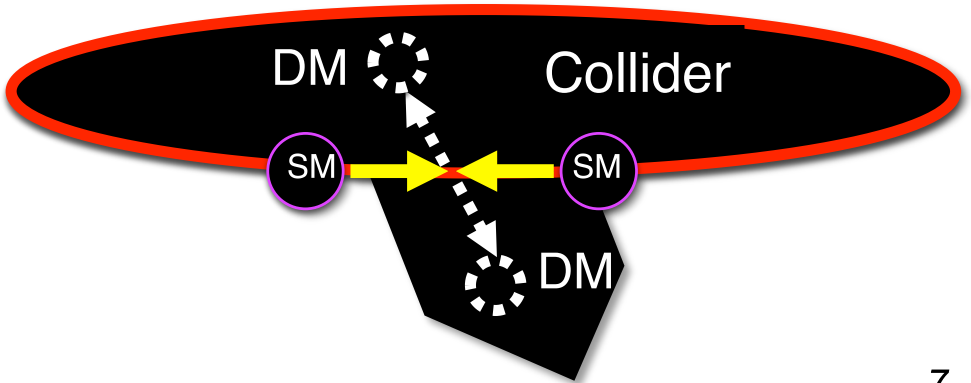
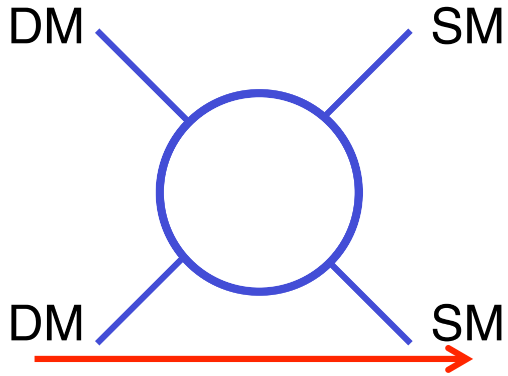




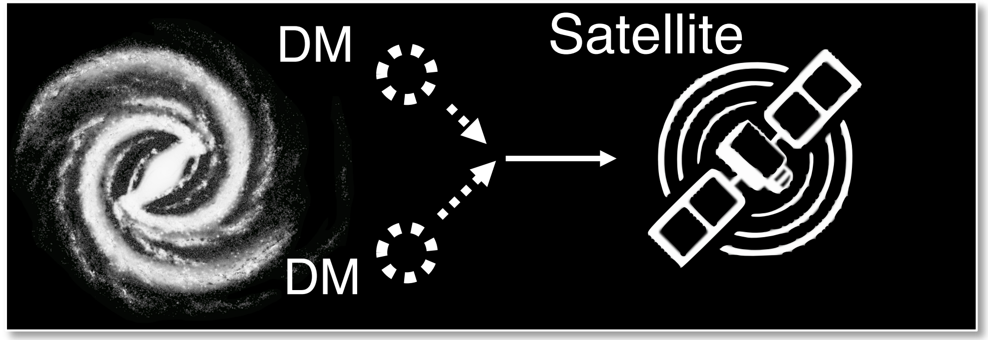
Collider
Experiments

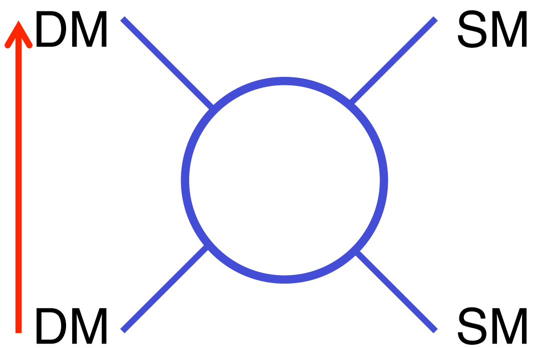


Hunting for Particle DM



Indirect Detection Experiments





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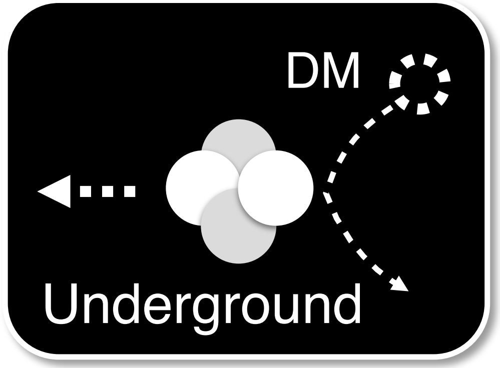
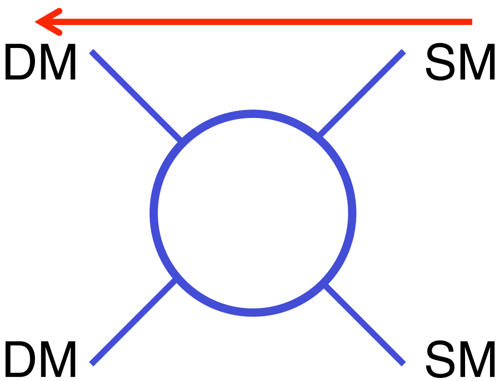
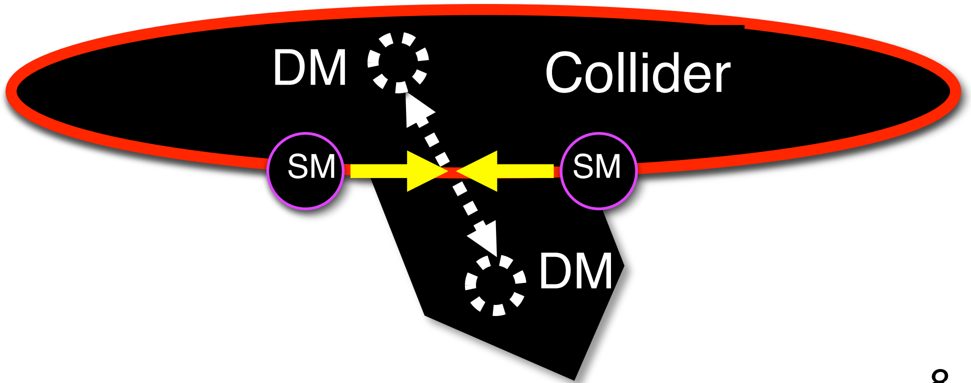




Collider Experiments



Characterisation of Dark Matter searches at colliders

Simplicity vs. Complexity

Finding the right balance is a challenge!

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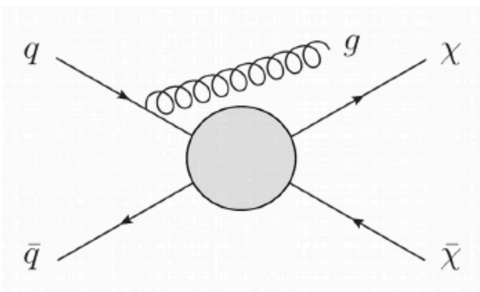
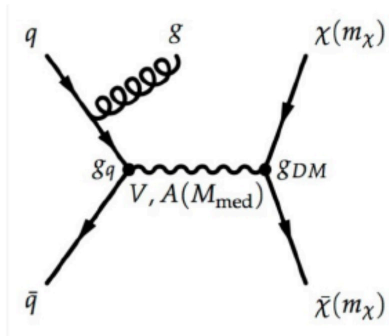
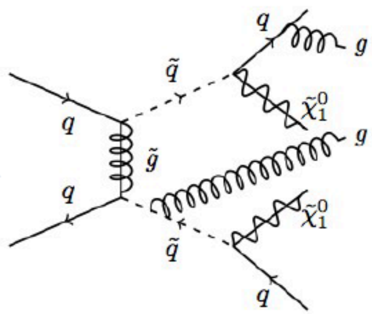


EFTs



Simplified Models



UV-complete Models

Characterisation of Dark Matter searches at colliders

Simplicity vs. Complexity

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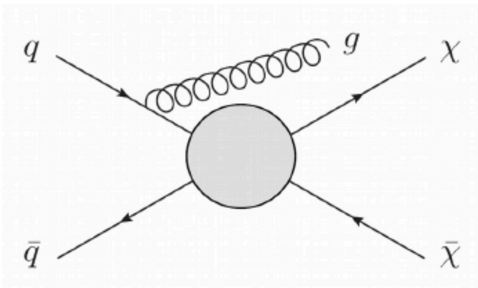

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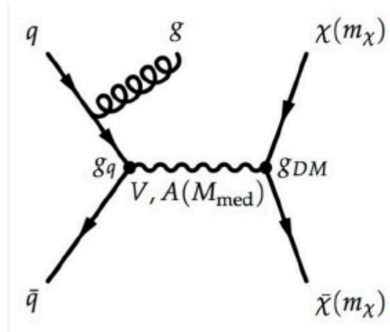

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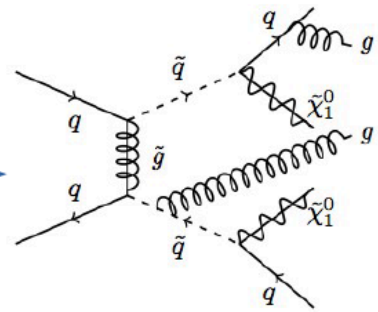
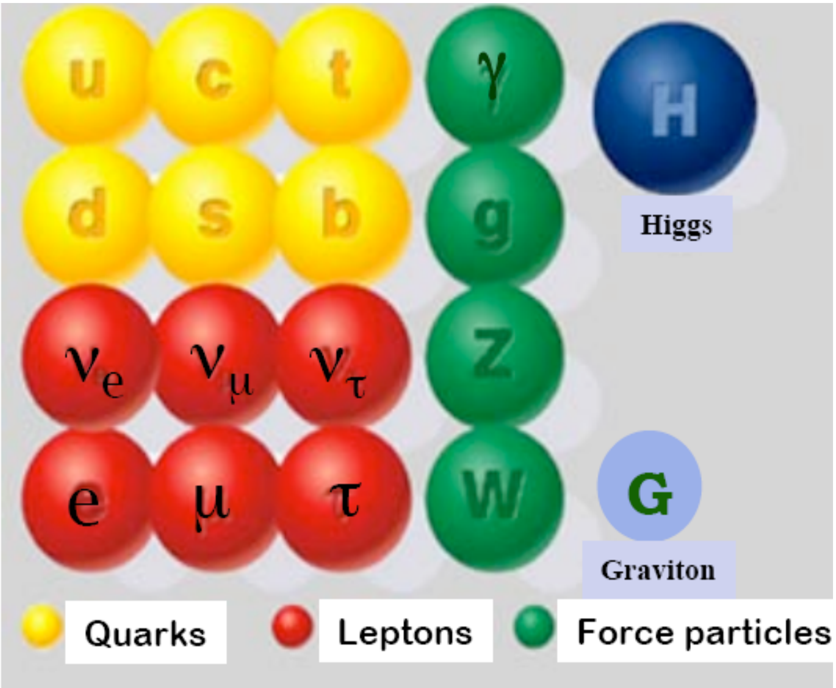


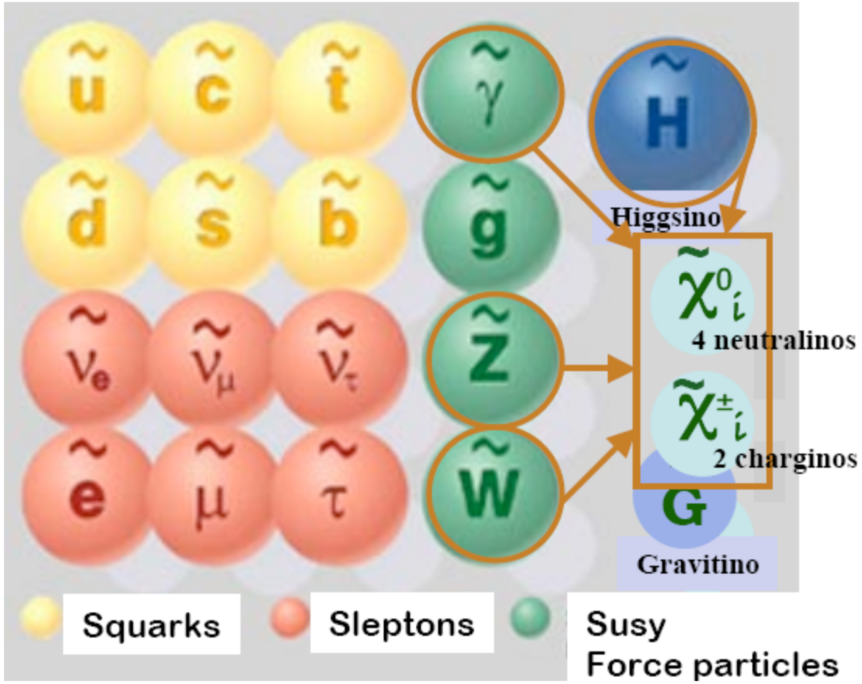
UV-complete Models

Supersymmetry

Extension of the Standard Model: Introduce a new symmetry
Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

Standard Model particles **SUSY particles**



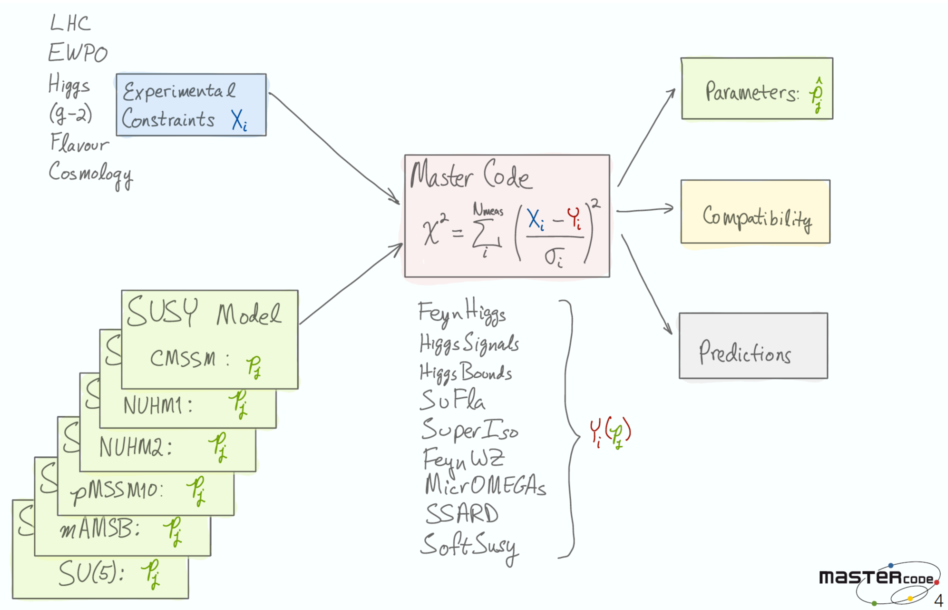


New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ = +1 SM particles
- 1 SUSY particles

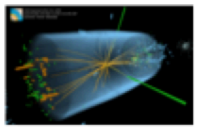
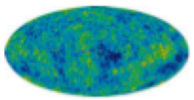
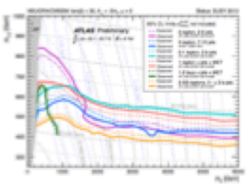
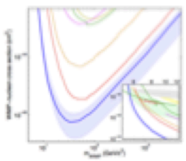
<u>R-parity conservation</u>:
- SUSY particles are produced in pairs
- The lightest SUSY particle (LSP) is stable

Dark Matter in Supersymmetry with MasterCode

Global Fit to indirect and direct constraints on SUSY!



Source:
http://mastercode.web.cern.ch/mastercode/

Direct Constraints	Indirect Constraints	Dark Matter Constraints
 Lightest Higgs	Mw, Z-pole (g-2)$_\mu$ Electroweak observables	 CMB
 SUSY particles	Flavour observables	 Direct Detection

Observable	Source Th./Ex.	Constraint	$\Delta\chi^2$ (CMSSM)	$\Delta\chi^2$ (NUHM1)	$\Delta\chi^2$ ("SM")
m_t [GeV]	[43]	173.2 ± 0.90	0.05	0.06	-
$\Delta\alpha^{(5)}_{had}(M_Z)$	[42]	0.02749 ± 0.00010	0.009	0.004	-
M_Z [GeV]	[44]	91.1875 ± 0.0021	2.7×10^{-5}	0.26	-
Γ_Z [GeV]	[26] / [44]	$2.4952 \pm 0.0023 \pm 0.001_{SUSY}$	0.078	0.047	0.14
σ^0_{had} [nb]	[26] / [44]	41.540 ± 0.037	2.50	2.57	2.54
R_l	[26] / [44]	20.767 ± 0.025	1.05	1.08	1.08
$A_{fb}(\ell)$	[26] / [44]	0.01714 ± 0.00095	0.72	0.69	0.81
$A_\ell(P_\tau)$	[26] / [44]	0.1465 ± 0.0032	0.11	0.13	0.07
R_b	[26] / [44]	0.21629 ± 0.00066	0.26	0.29	0.27
R_c	[26] / [44]	0.1721 ± 0.0030	0.002	0.002	0.002
$A_{fb}(b)$	[26] / [44]	0.0992 ± 0.0016	7.17	7.37	6.63
$A_{fb}(c)$	[26] / [44]	0.0707 ± 0.0035	0.86	0.88	0.80
A_b	[26] / [44]	0.923 ± 0.020	0.36	0.36	0.35
A_c	[26] / [44]	0.670 ± 0.027	0.005	0.005	0.005
A_ℓ(SLD)	[26] / [44]	0.1513 ± 0.0021	3.16	3.03	3.51
$\sin^2\theta^\ell_w(Q_{fb})$	[26] / [44]	0.2324 ± 0.0012	0.63	0.64	0.59
M_W [GeV]	[26] / [44]	$80.399 \pm 0.023 \pm 0.010_{SUSY}$	1.77	1.39	2.08
$a_\mu^{EXP} - a_\mu^{SM}$	[53] / [42,54]	$(30.2 \pm 8.8 \pm 2.0_{SUSY}) \times 10^{-10}$	4.35	1.82	11.19 (N/A)
M_h [GeV]	[28] / [55,56]	$> 114.4[\pm 1.5_{SUSY}]$	0.0	0.0	0.0
$BR^{EXP/SM}_{b\to s\gamma}$	[45] / [46]	$1.117 \pm 0.076_{EXP}$ $\pm 0.082_{SM} \pm 0.050_{SUSY}$	1.83	1.09	0.94
$BR(B_s \to \mu^+\mu^-)$	[29] / [41]	CMS & LHCb	0.04	0.44	0.01
$BR^{EXP/SM}_{B\to\tau\nu}$	[29] / [46]	$1.43 \pm 0.43_{EXP+TH}$	1.43	1.59	1.00
$BR(B_d \to \mu^+\mu^-)$	[29] / [46]	$< 4.6[\pm 0.01_{SUSY}] \times 10^{-9}$	0.0	0.0	0.0
$BR^{EXP/SM}_{B\to X_s\ell\ell}$	[47] / [46]	0.99 ± 0.32	0.02	$\ll 0.01$	$\ll 0.01$
$BR^{EXP/SM}_{K\to\mu\nu}$	[29] / [48]	$1.008 \pm 0.014_{EXP+TH}$	0.39	0.42	0.33
$BR^{EXP/SM}_{K\to\pi\nu\bar{\nu}}$	[49] / [50]	< 4.5	0.0	0.0	0.0
$\Delta M^{EXP/SM}_{B_s}$	[49] / [51,52]	$0.97 \pm 0.01_{EXP} \pm 0.27_{SM}$	0.02	0.02	0.01
$\frac{\Delta M^{EXP/SM}_{B_s}}{\Delta M^{EXP/SM}_{B_d}}$	[29] / [46,51,52]	$1.00 \pm 0.01_{EXP} \pm 0.13_{SM}$	$\ll 0.01$	0.33	$\ll 0.01$
$\Delta\epsilon^{EXP/SM}_K$	[49] / [51,52]	$1.08 \pm 0.14_{EXP+TH}$	0.27	0.37	0.33
$\Omega_{CDM}h^2$	[31] / [13]	$0.1120 \pm 0.0056 \pm 0.012_{SUSY}$	8.4×10^{-4}	0.1	N/A
σ^{SI}_p	[25]	$(m_{\chi^0_1}, \sigma^{SI}_p)$ plane	0.13	0.13	N/A
jets + $\not{E}_T$	[18,20]	$(m_0, m_{1/2})$ plane	1.55	2.20	N/A
$H/A, H^\pm$	[21]	$(M_A, \tan\beta)$ plane	0.0	0.0	N/A
Total χ^2/d.o.f. p-values	All	All	28.8/22 15%	27.3/21 16%	32.7/23 (21.5/22) 9% (49%)

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Dark Matter in Supersymmetry with MasterCode

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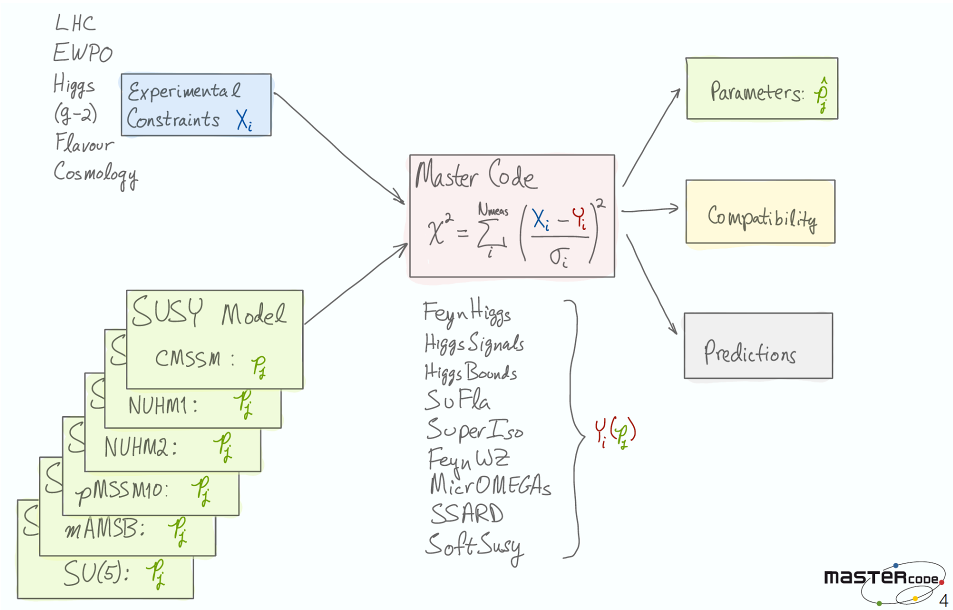

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Direct Constraints | Indirect Constraints | Dark Matter Constraints

Other "global Fitters" with similar studies are:

Fittino group: [see e.g. arXiv:1508.05951]
http://flcwiki.desy.de/Fittino

Gambit group: [see e.g. arXiv:1705.07917]
https://gambit.hepforge.org

SuperBayeS: [see e.g. arXiv:1507.07008]

SUSY particles | Flavour observables | Direct Detection

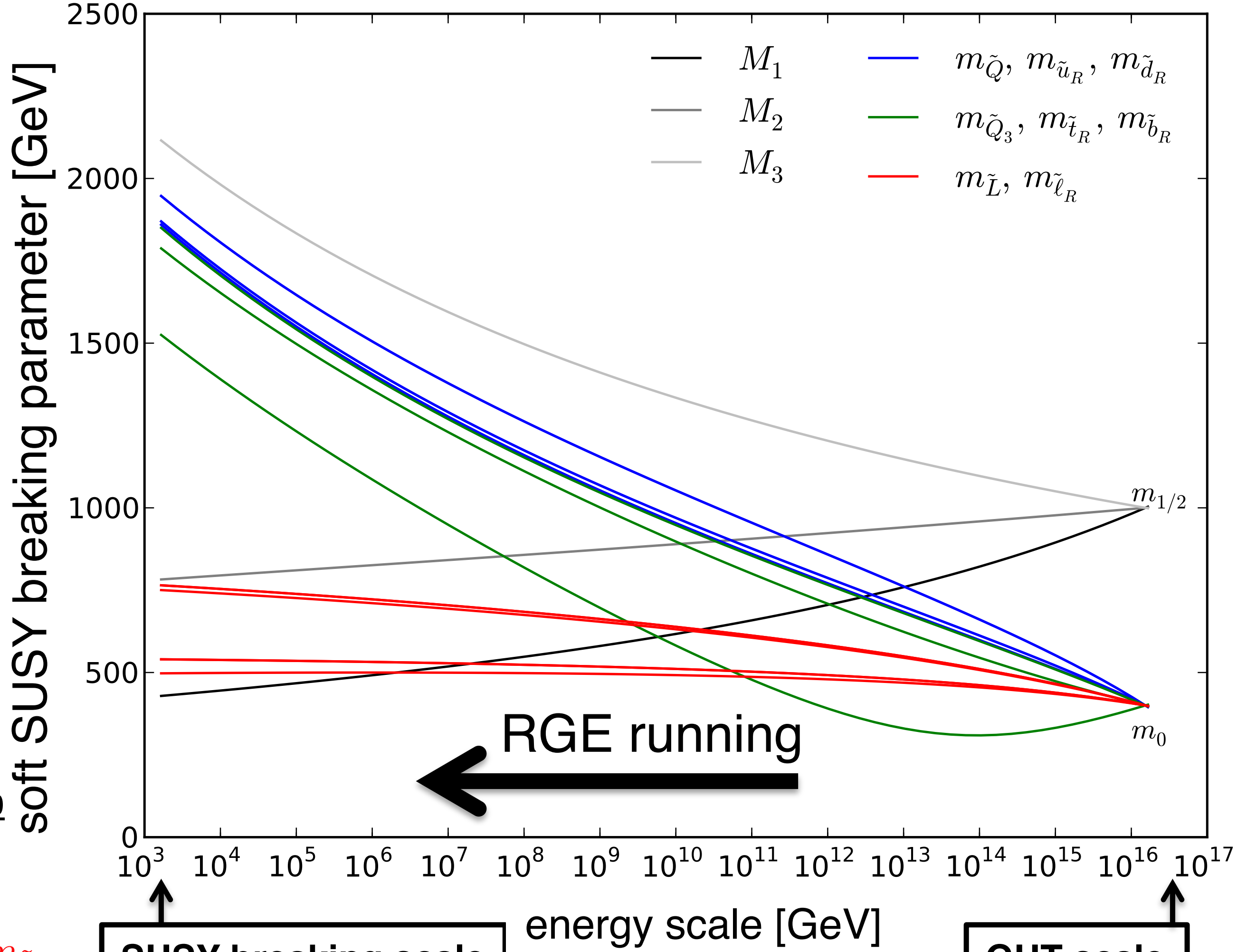
MasterCode: The two worlds of SUSY models

"Soft scale" ⟷ "GUT scale"

pMSSM10

$M_1,$ $M_2,$ $M_3,$ $m_{\tilde{q}12},$ $m_{\tilde{q}3},$ $m_{\tilde{\ell}},$ $A,$ $M_A,$ $\tan\beta$ μ

arXiv:1504.03260



SUSY breaking scale **GUT scale**

pMSSM11

$m_{\tilde{l}} \rightarrow m_{\tilde{l}_{12}}, m_{\tilde{l}_3}$

in preparation

CMSSM

$m_0, \ m_{1/2},$

$A_0, \ \tan\beta$

arXiv:1312.5250

NUHM1

$m^2_{H_u} = m^2_{H_d}$

arXiv:1312.5250

NUHM2

$m^2_{H_u} \neq m^2_{H_d}$

arXiv:1408.4060

SU5

$m_0 \rightarrow m_5, m_{10}$

arXiv:1610.10084

AMSB

$m_0, m_{3/2}, tan\beta$

arXiv:1612.05210

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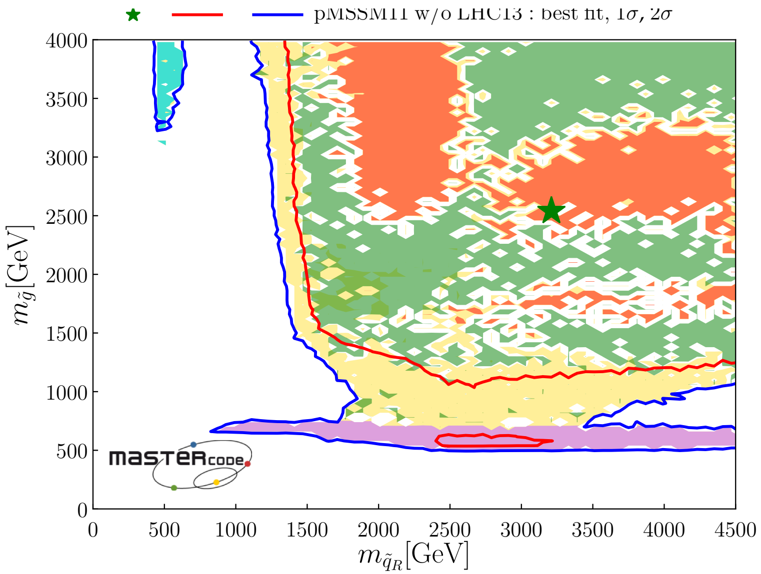
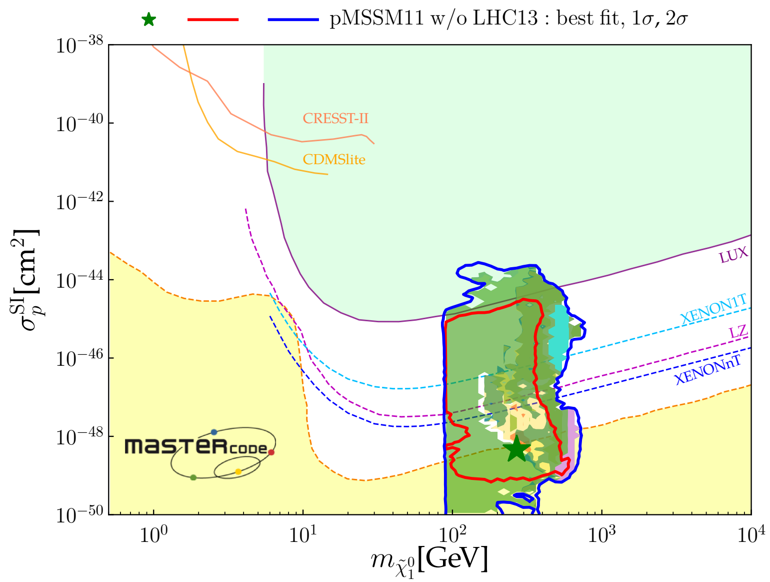
pMSSM11: Status LHC RUN 1 (pre-LHC 13 TeV)

stau coann. | $\tilde{\chi}_1^{\pm}$ coann. | slep coann | gluino coann. | squark coann.





DM mechanisms:

To satisfy cosmological DM density constraint requires, in general, specific relations between sparticle masses that suppress the relic density via coannihilation effects and/or rapid annihilations through direct channel resonances.

Define indicative measures to highlight different DM mechanisms in the preferred regions of the fit:

$\left(\frac{M_{\tilde{\tau}}}{m_{\chi_1^0}} - 1\right) < 0.15$ **Stau coannihilation**

$\left(\frac{M_{\tilde{l}}}{m_{\chi_1^0}} - 1\right) < 0.15$ **Slepton Co-annihilation**

$\left(\frac{M_{\chi_1^{\pm}}}{m_{\chi_1^0}} - 1\right) < 0.25$ **Chargino Co-annihilation**

$\left(\frac{M_{\tilde{g}}}{m_{\chi_1^0}} - 1\right) < 0.25$ **Gluino Co-annihilation**

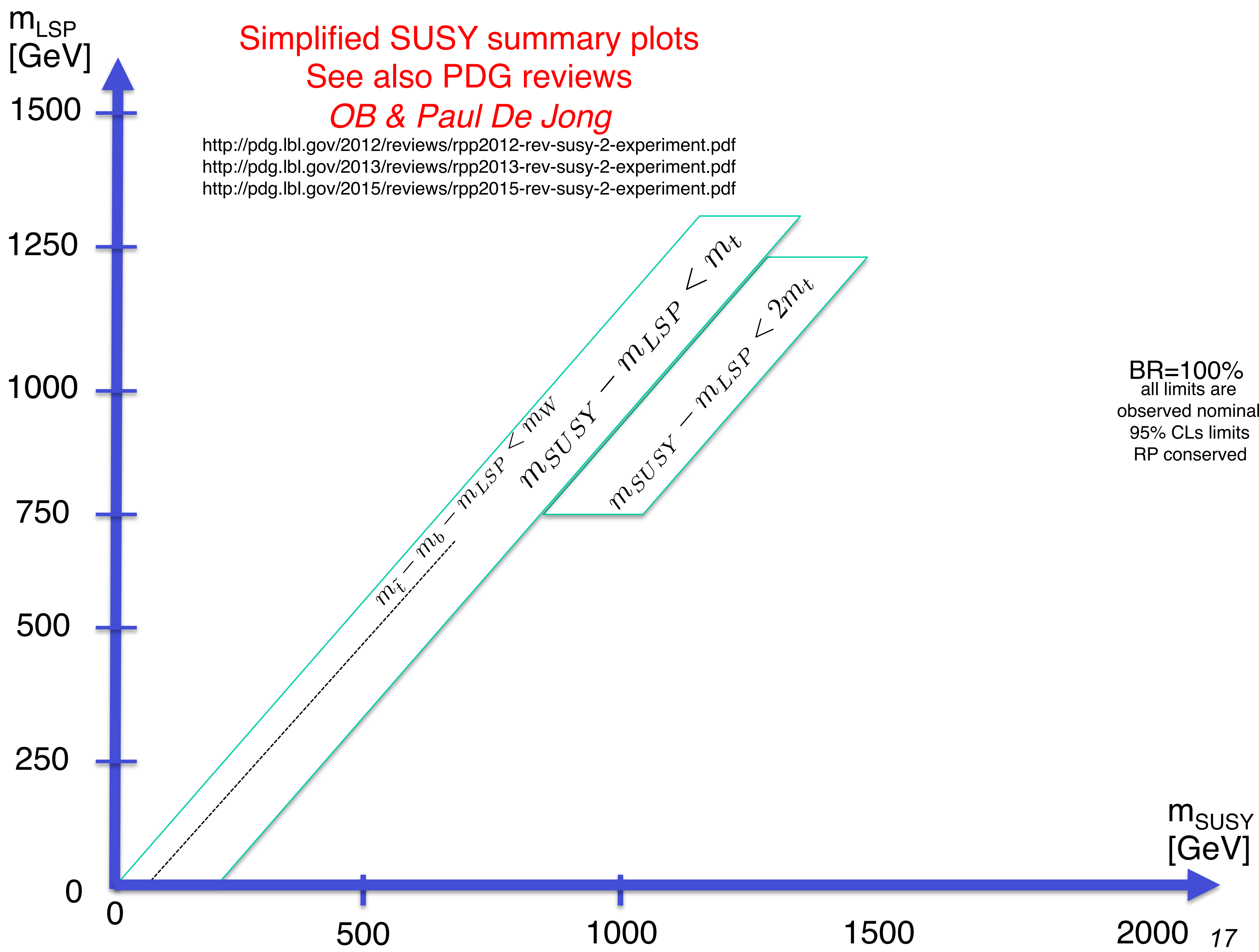
$\left(\frac{M_{\tilde{q}}}{m_{\chi_1^0}} - 1\right) < 0.20$ **Squark Co-annihilation**

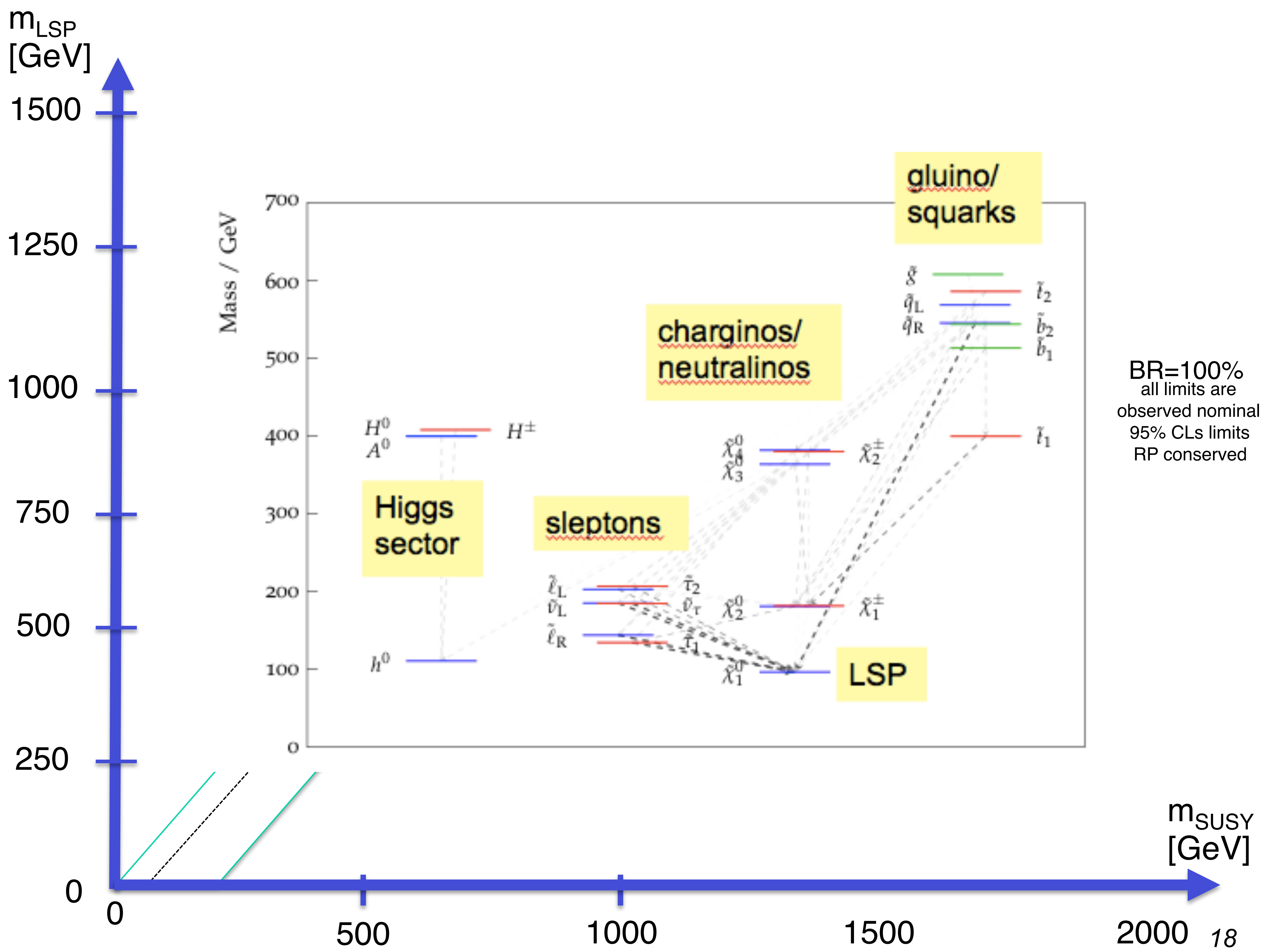
$\left|\frac{M_B}{m_{\chi_1^0}} - 2\right| < 0.4$ **B = h, Z or H/A funnel**

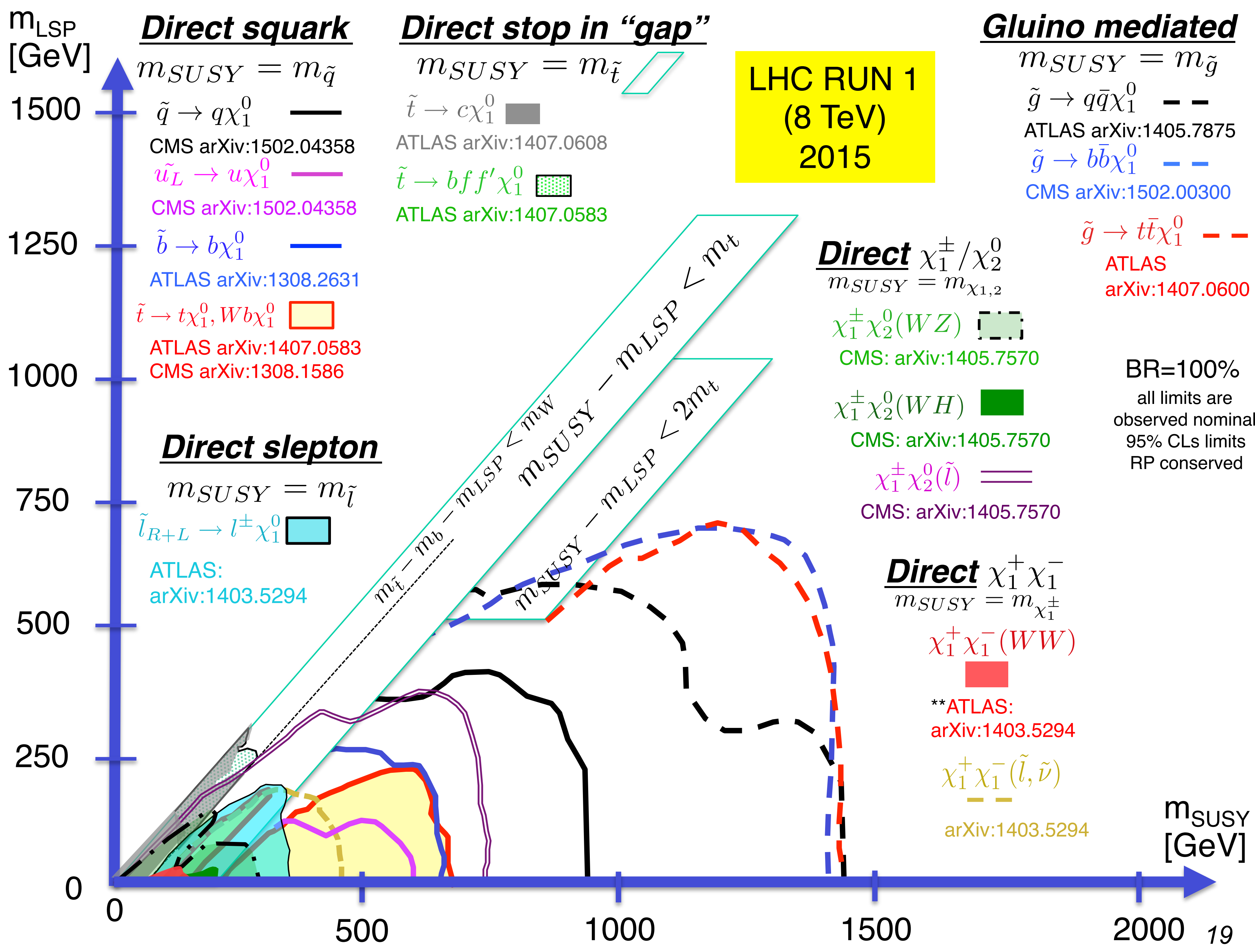
$\left|\frac{\mu}{m_{\chi_1^0}} - 1\right| < 0.30$ **Higgsino enriched "focus-point" like**

Hybrid regions:
In addition to the `primary' regions where only one of the conditions is satisfied, there can also be `hybrid' regions where more than one condition is satisfied. If present, these are indicated using combined colours.

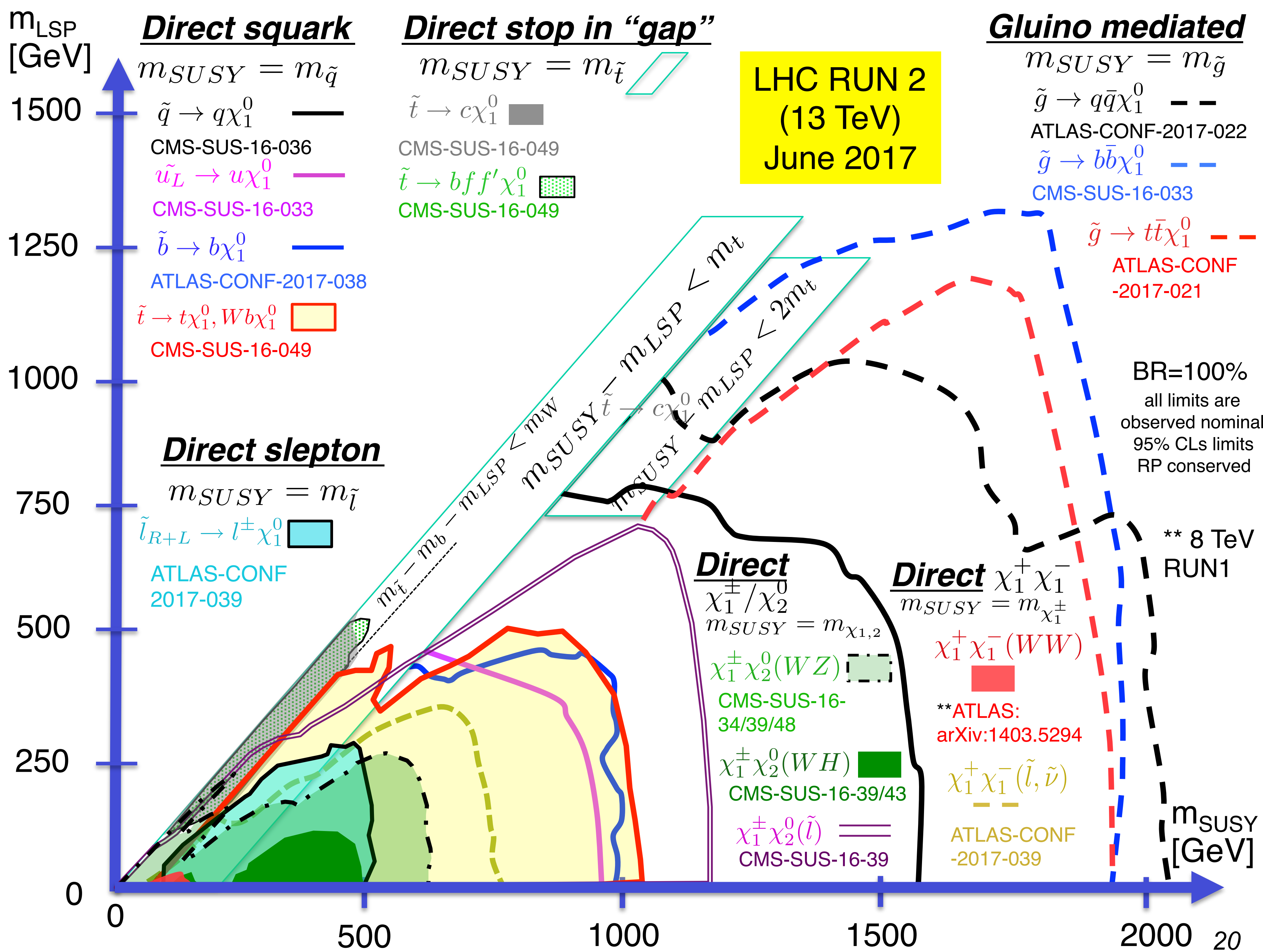
See also arXiv:1508.01173 for further details


Simplified SUSY summary plots
See also PDG reviews
OB & Paul De Jong
http://pdg.lbl.gov/2012/reviews/rpp2012-rev-susy-2-experiment.pdf
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf
http://pdg.lbl.gov/2015/reviews/rpp2015-rev-susy-2-experiment.pdf
m_{LSP} [GeV]
1500
1250
1000
750
500
250
0
m_{SUSY} [GeV]
0
500
1000
1500
2000
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved


m_LSP [GeV]
1500
1250
1000
750
500
250
0
m_SUSY [GeV]
0
500
1000
1500
2000
Mass / GeV
gluino/ squarks
charginos/ neutralinos
Higgs sector
sleptons
LSP
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved

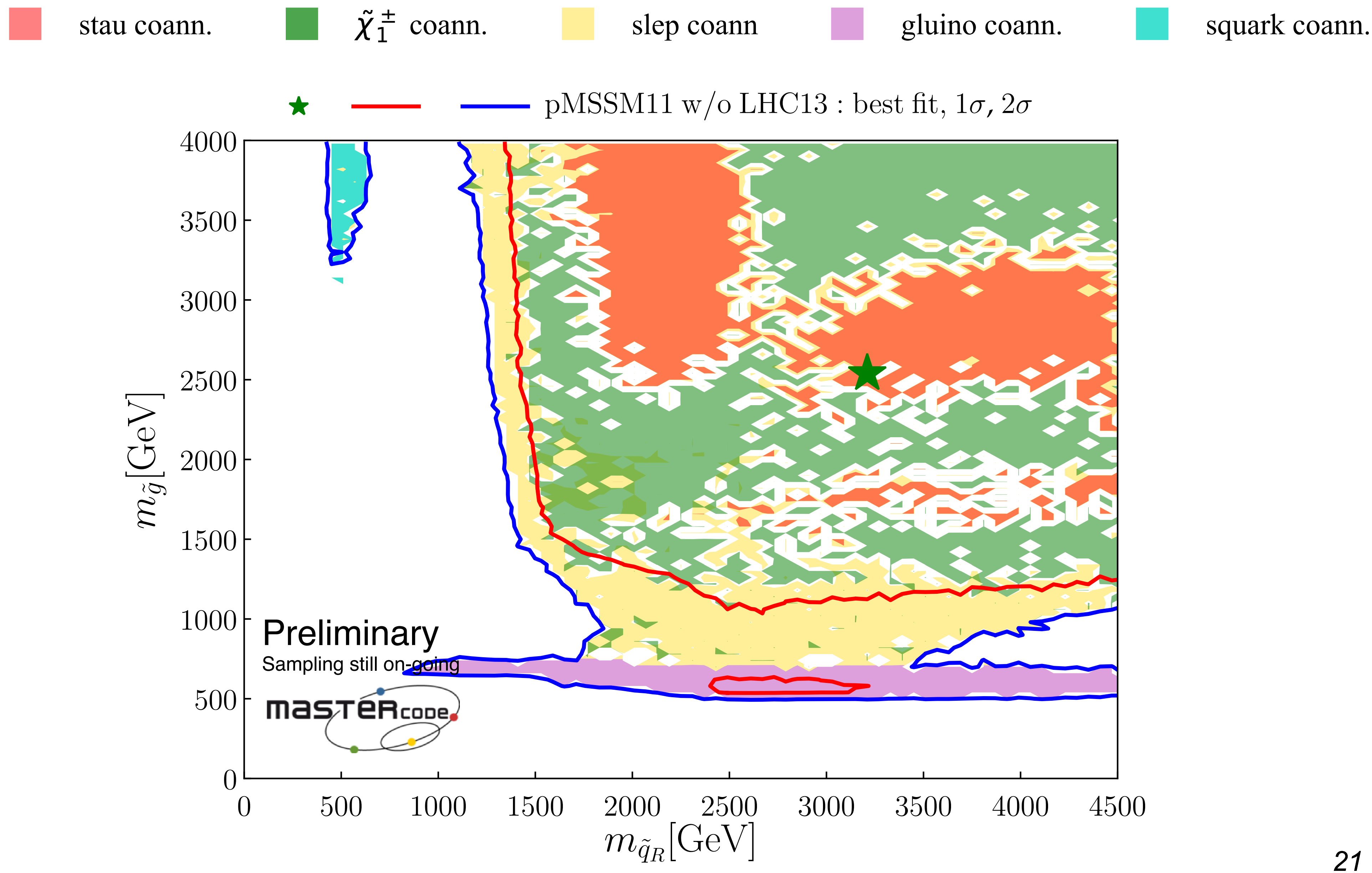


m_LSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u_L} \rightarrow u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \rightarrow b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \rightarrow t\chi_1^0, Wb\chi_1^0$
ATLAS arXiv:1407.0583
CMS arXiv:1308.1586
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \rightarrow c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde{t} \rightarrow bff'\chi_1^0$
ATLAS arXiv:1407.0583
LHC RUN 1
(8 TeV)
2015
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \rightarrow q\bar{q}\chi_1^0$
ATLAS arXiv:1405.7875
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$
CMS arXiv:1502.00300
$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
ATLAS
arXiv:1407.0600
Direct $\chi_1^{\pm}/\chi_2^0$
$m_{SUSY} = m_{\chi_{1,2}}$
$\chi_1^{\pm}\chi_2^0(WZ)$
CMS: arXiv:1405.7570
$\chi_1^{\pm}\chi_2^0(WH)$
CMS: arXiv:1405.7570
$\chi_1^{\pm}\chi_2^0(\tilde{l})$
CMS: arXiv:1405.7570
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_{R+L} \rightarrow l^{\pm}\chi_1^0$
ATLAS:
arXiv:1403.5294
Direct $\chi_1^+\chi_1^-$
$m_{SUSY} = m_{\chi_1^{\pm}}$
$\chi_1^+\chi_1^-(WW)$
**ATLAS:
arXiv:1403.5294
$\chi_1^+\chi_1^-(\tilde{l},\tilde{\nu})$
arXiv:1403.5294
m_SUSY [GeV]
0
250
500
750
1000
1250
1500
0
500
1000
1500
2000



m_LSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS-SUS-16-036
$\tilde{u}_L \to u\chi_1^0$
CMS-SUS-16-033
$\tilde{b} \to b\chi_1^0$
ATLAS-CONF-2017-038
$\tilde{t} \to t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-049
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$
CMS-SUS-16-049
$\tilde{t} \to bff'\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF
-2017-021
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$\tilde{t} \to c\chi_1^0$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_{R+L} \to l^{\pm}\chi_1^0$
ATLAS-CONF
2017-039
Direct $\chi_1^{\pm}/\chi_2^0$
$m_{SUSY} = m_{\chi_{1,2}}$
$\chi_1^{\pm}\chi_2^0(WZ)$
CMS-SUS-16-
34/39/48
$\chi_1^{\pm}\chi_2^0(WH)$
CMS-SUS-16-39/43
$\chi_1^{\pm}\chi_2^0(\tilde{l})$
CMS-SUS-16-39
Direct $\chi_1^+\chi_1^-$
$m_{SUSY} = m_{\chi_1^{\pm}}$
$\chi_1^+\chi_1^-(WW)$
**ATLAS:
arXiv:1403.5294
$\chi_1^+\chi_1^-(\tilde{l},\tilde{\nu})$
ATLAS-CONF
-2017-039
** 8 TeV
RUN1
m_SUSY [GeV]
0
250
500
750
1000
1250
1500
0
500
1000
1500
2000

Gluino vs Squark: LHC RUN 1



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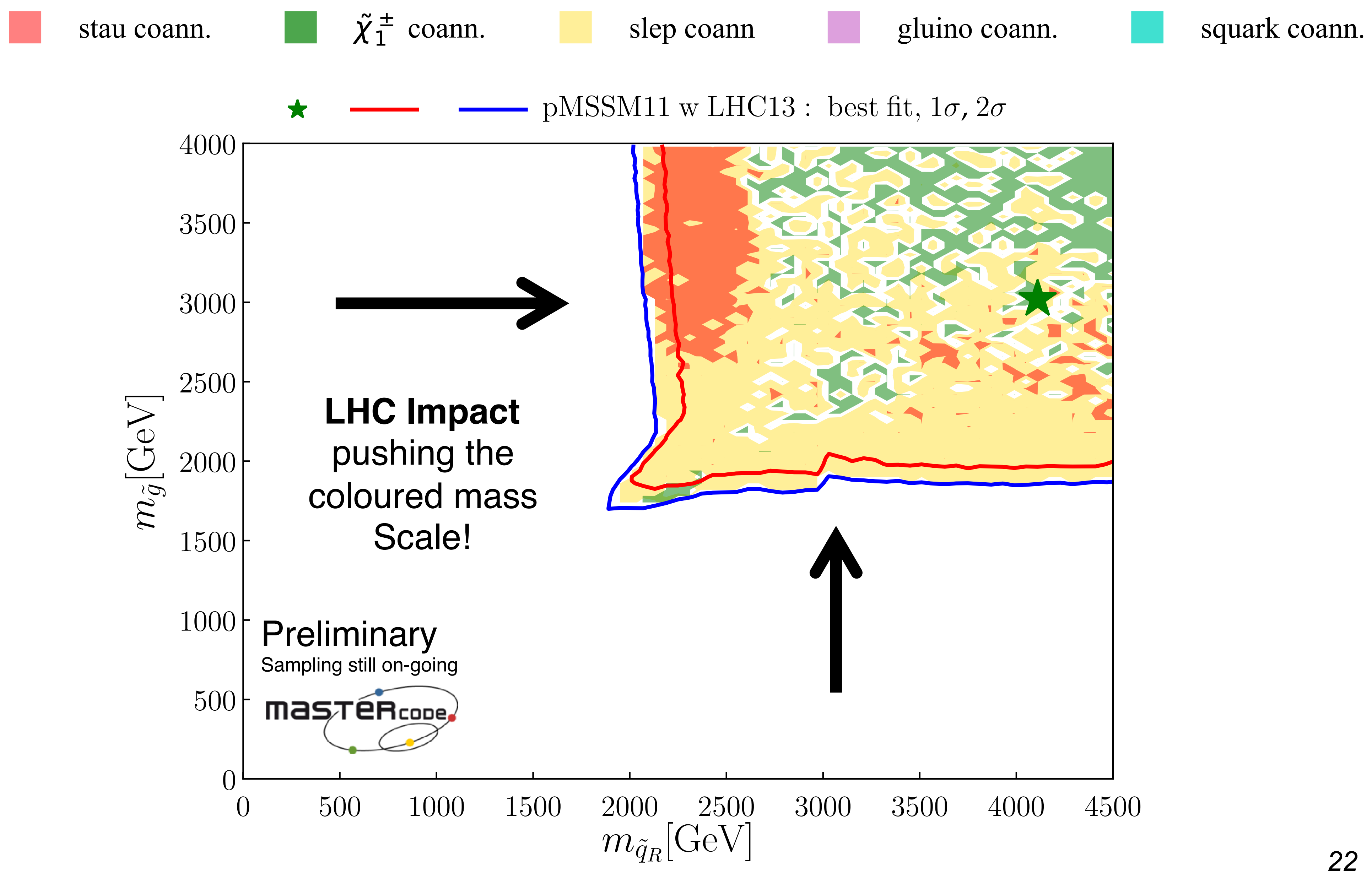
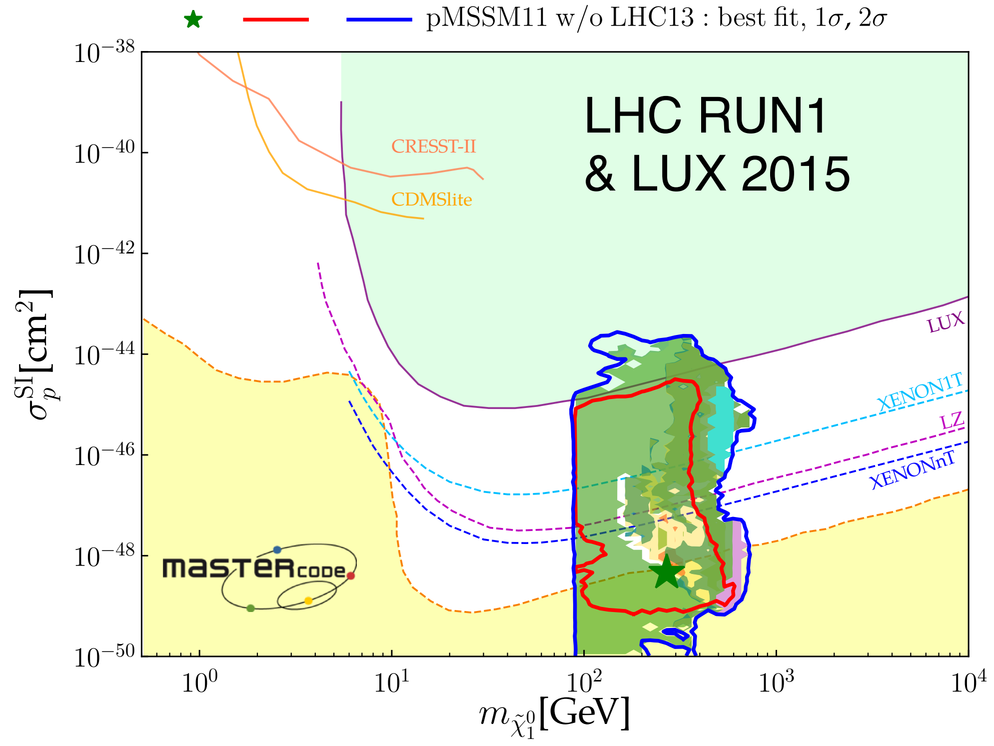
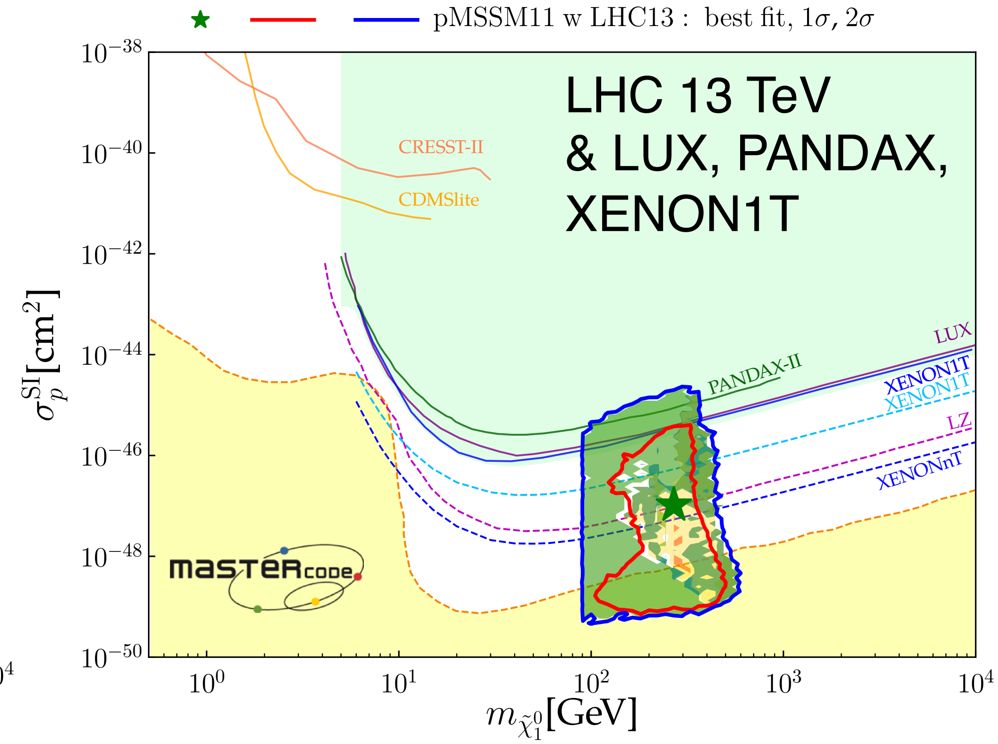
Gluino vs Squark: LHC RUN 2 (2015 + 2016 data)



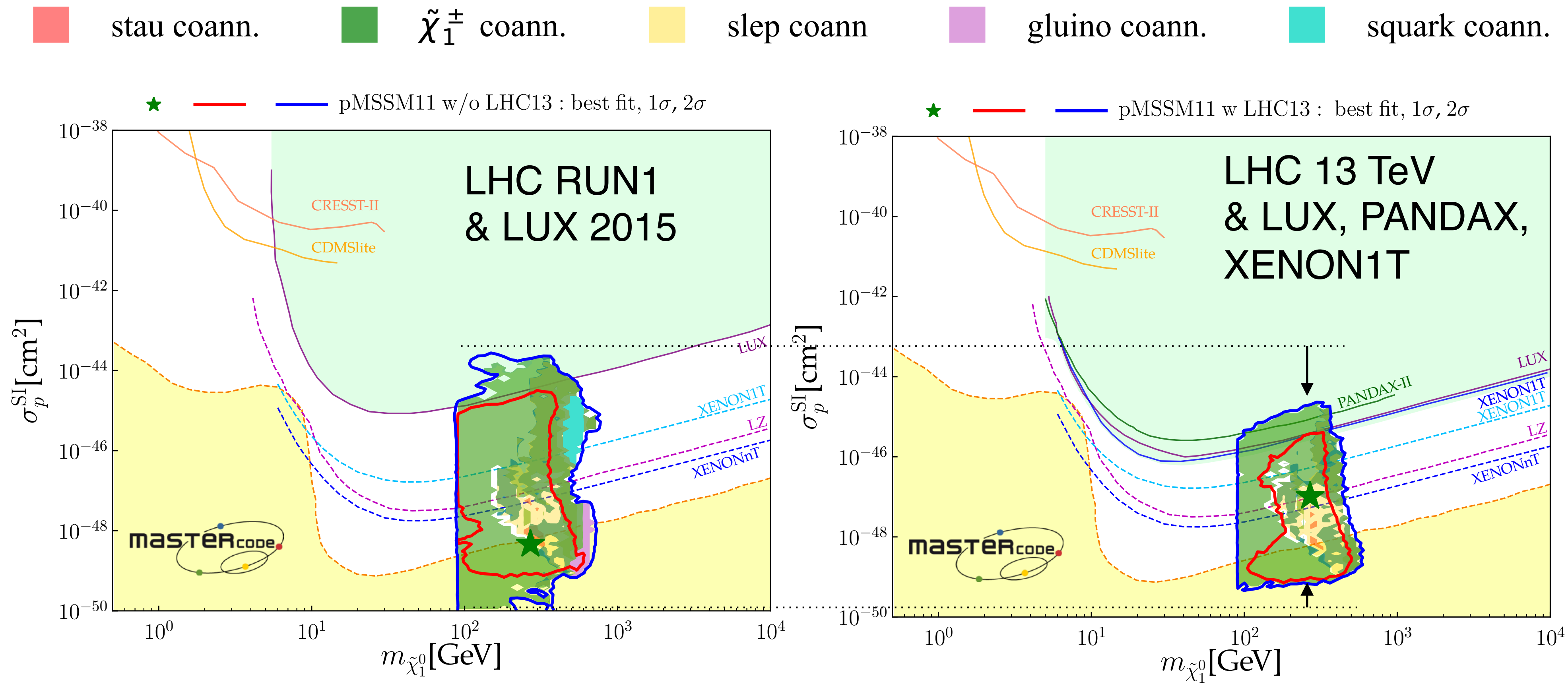
pMSSM11: σ_{SI} vs m_{DM}

stau coann. | $\tilde{\chi}_1^{\pm}$ coann. | slep coann | gluino coann. | squark coann.





pMSSM11: σ_{SI} vs m_{DM}



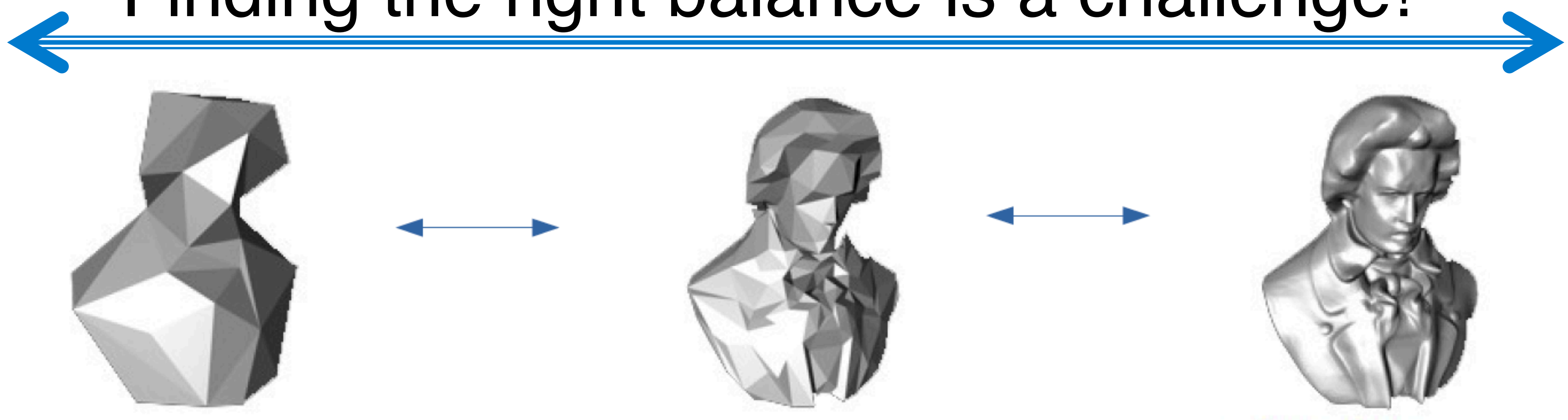
Clear complementarity of collider and DD constraints:

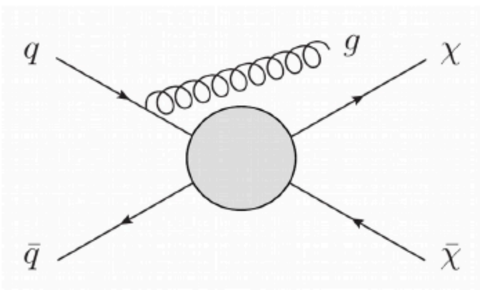
- Collider covers regions not easily or not at all accessible to DD experiments (i.e. low m_{DM} and also very small σ_{SI})
- On the other hand, DD experiments push strongly the preferred region to lower σ_{SI} (and will continue to do so in the future)

Characterisation of Dark Matter searches at colliders

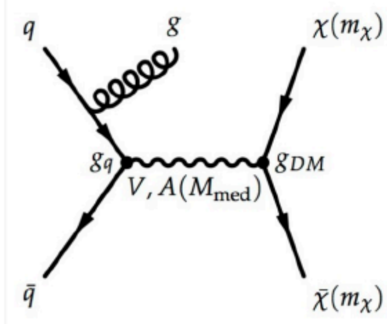
Simplicity vs. Complexity

Finding the right balance is a challenge!

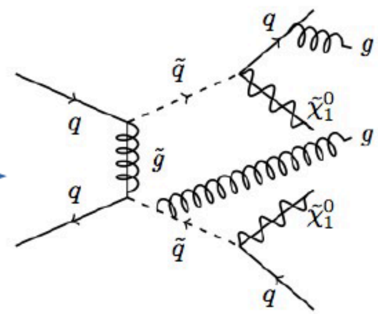




EFTs

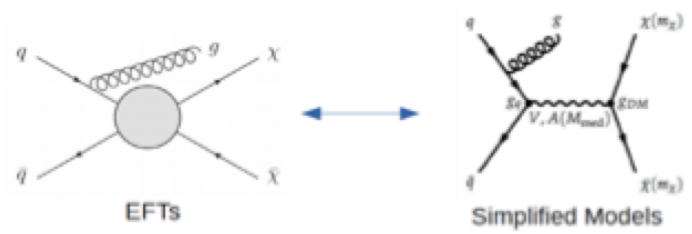


Simplified Models

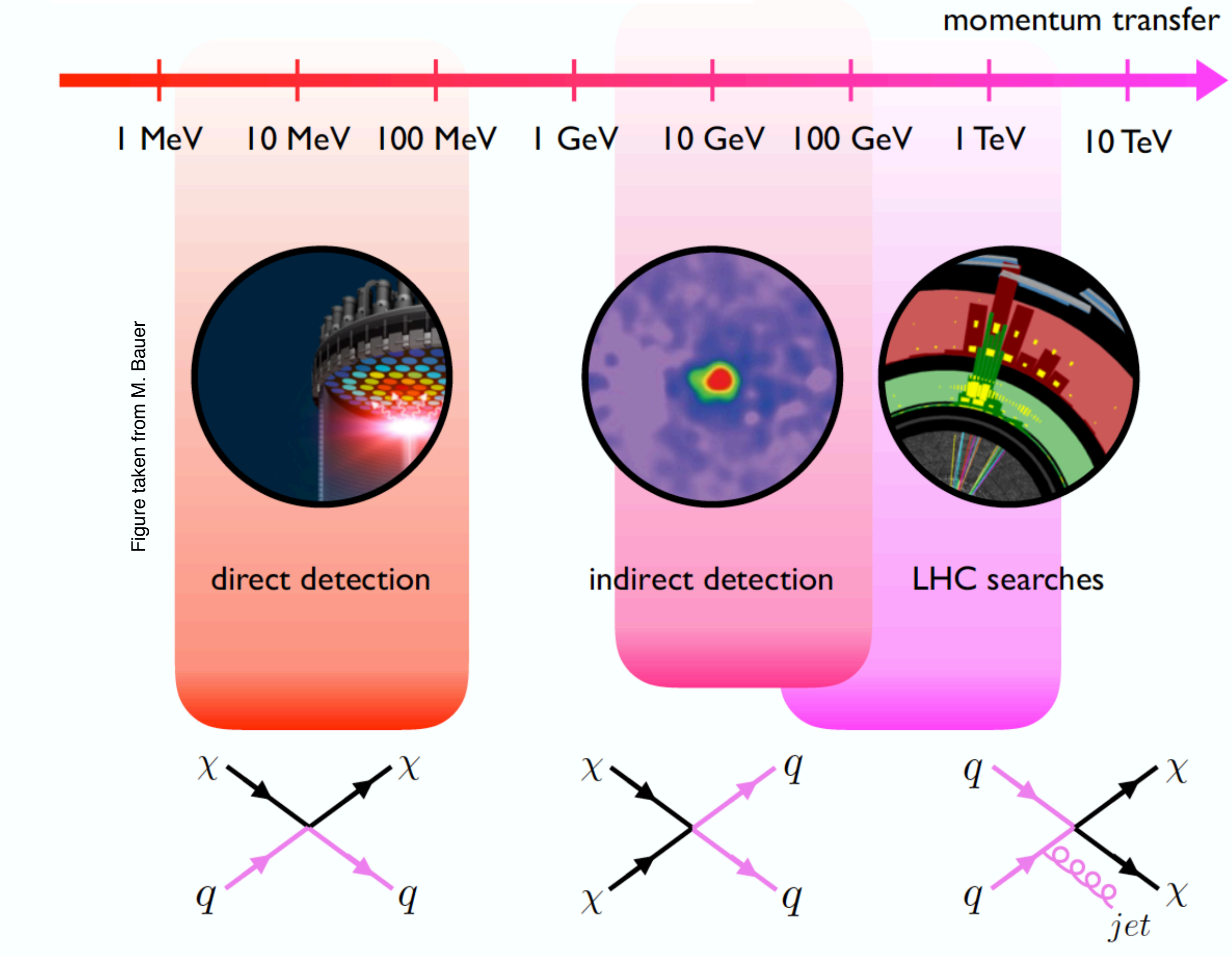


UV-complete Models

EFT vs Simplified Model



EFT validity in a nutshell:
For a valid Effective Field Theory application the momentum transfer Q must be much smaller than the mediator mass M_{med} probed:
$Q \ll M_{med}$



Therefore, validity requires typically:

<u>DD Experiments:</u>
M_{med} > few hundred **MeV**

<u>ID Experiments:</u>
M_{med} > few hundred **GeV**

<u>Collider (LHC):</u>
M_{med} > few **TeV**

As the LHC probes the TeV scale, a comprehensive application of the EFT for DM searches is not possible.

Therefore, adopt simplified DM models as main vehicle to interpret DM searches for LHC!

For more info about EFT validity for DM collider searches see e.g.:
arXiv:1307.2253
arXiv:1308.6799
arXiv:1405.3101
arXiv:1402.1275

LHC Dark Matter Working Group

End of Run-1: Discussion on how to present the Dark Matter search data in the experiments for Run-2, in a DM forum and now DM working group

First collection on DM models (simplified an look-alike) for LHC

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

arXiv:1507.00966

Guidelines how to compare data from LHC and non-LHC search results

Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter

arXiv:1603.04156

Guidelines for direct DM production searches with constraints on the heavy mediators

Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels

arXiv:1703.05703

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LHC Dark Matter Working Group

End of Run-1: Discussion on how to present the Dark Matter search data in the experiments for Run-2, in a DM forum and now DM working group

First collection on

Dark Matter Benchmark Models for Early LHC Run-2 Searches:

This Working Group brings together theorists and experimentalists to define guidelines and recommendations for the benchmark models, interpretation, and characterisation necessary for broad and systematic searches for dark matter at the LHC.

More details can be found at this page:

http://lpcc.web.cern.ch/LPCC/index.php?page=dm_wg

and the mailing list is lhc-dmwg@cern.ch**.

**To join the WG mailing list, go to

http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg

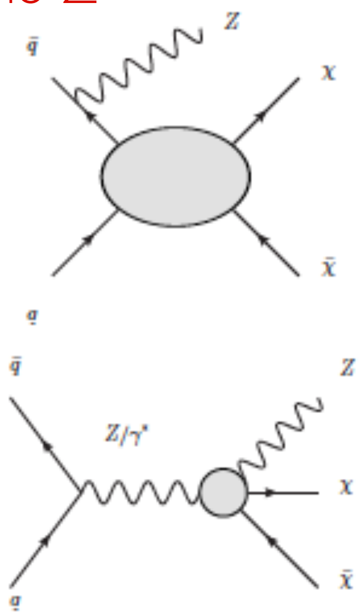
Guidelines for direct DM production searches with constraints on the heavy mediators

Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels

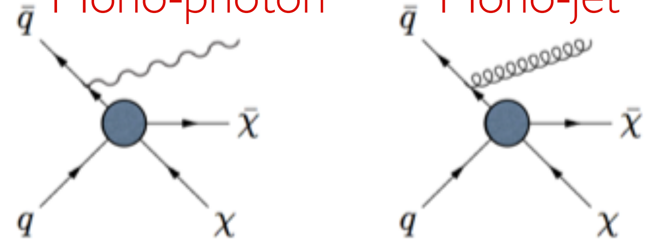
arXiv:1703.05703

Mono-Mania (at the LHC)

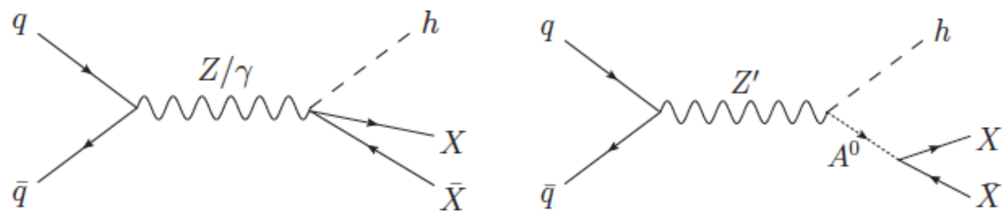
Mono-Z



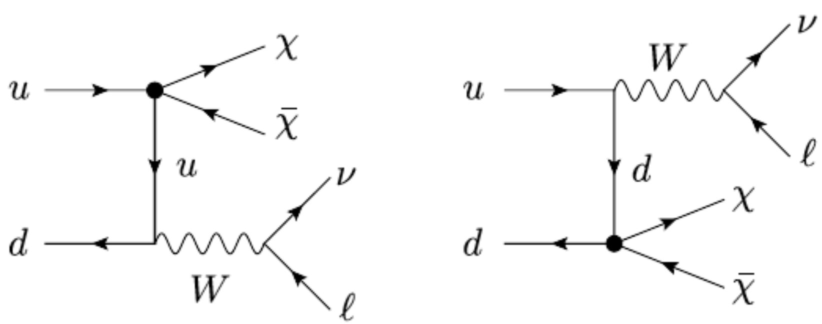
Mono-photon / Mono-jet



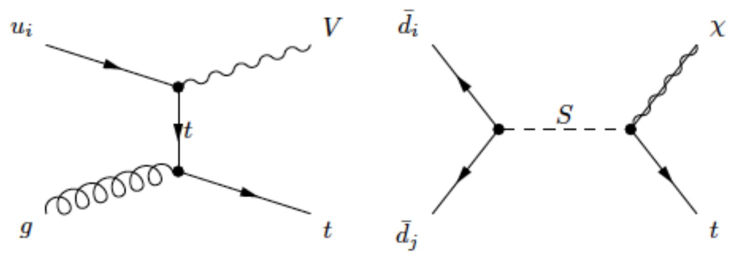
Mono-Higgs



Mono-W



Mono-top



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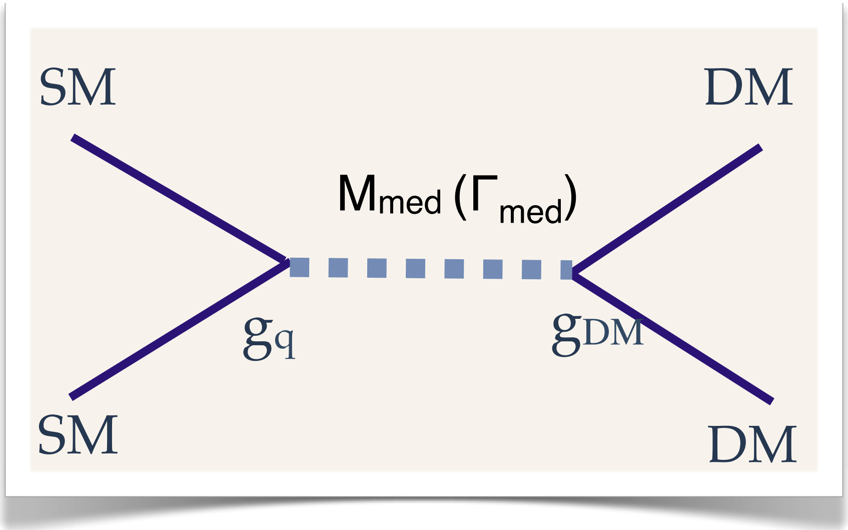
Minimal Simplified Dark Matter Model

See e.g.
arXiv:1407.8257
arXiv:1507.00966
arXiv:1603.04156



s-channel

Define simplified model with (minimum) 4 parameters	
Mediator mass (M_{med})	DM mass (M_{DM})
g_q	g_{DM}

DM	
Dirac fermion	Scalar - real
Majorana fermion	Scalar - complex

Consider comprehensive set of diagrams for mediator	
Vector	Axial-vector
Scalar	Pseudoscalar

(Γ_{med} can also be free as long
As $\Gamma_{med}<M_{med}$)

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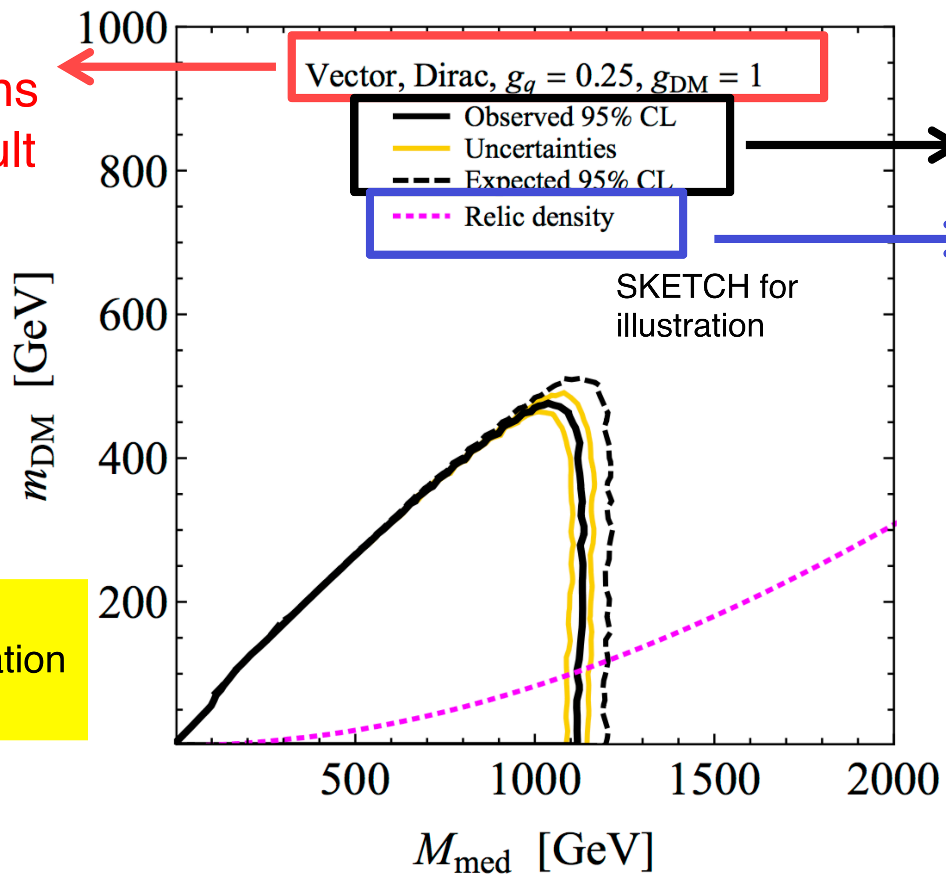
Mass-Mass plane [M_{med} – M_{DM}]

Main result of the interpretation of collider search in simplified model

Clearly state Main assumptions entering the result
- Mediator
- DM type
- Couplings



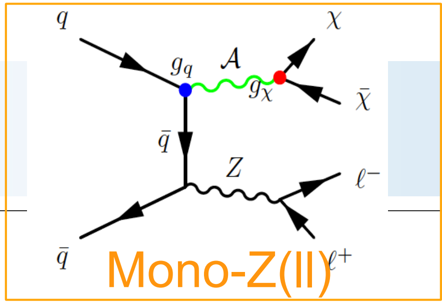
Usual "LHC limits" For 95% CL [not 90%]

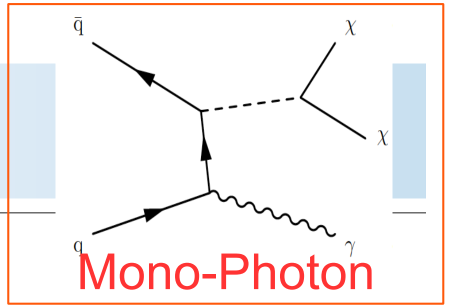
Indicate Relic density line but do not use it as "validity" requirement. Its FI only. [more caveats and discussion are provided in the report]

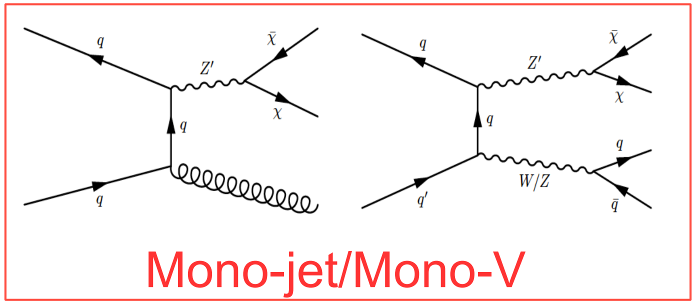
All based on LHC DM WG recommendation 1603.04156

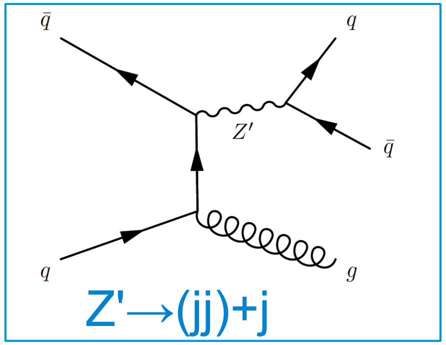
MET + X

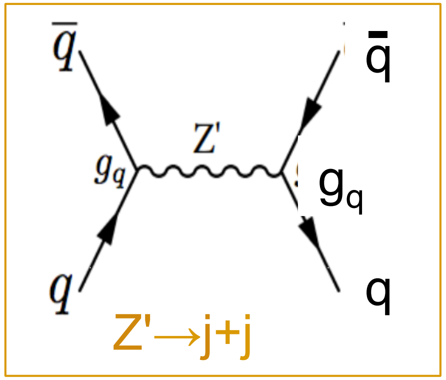
Bump hunt

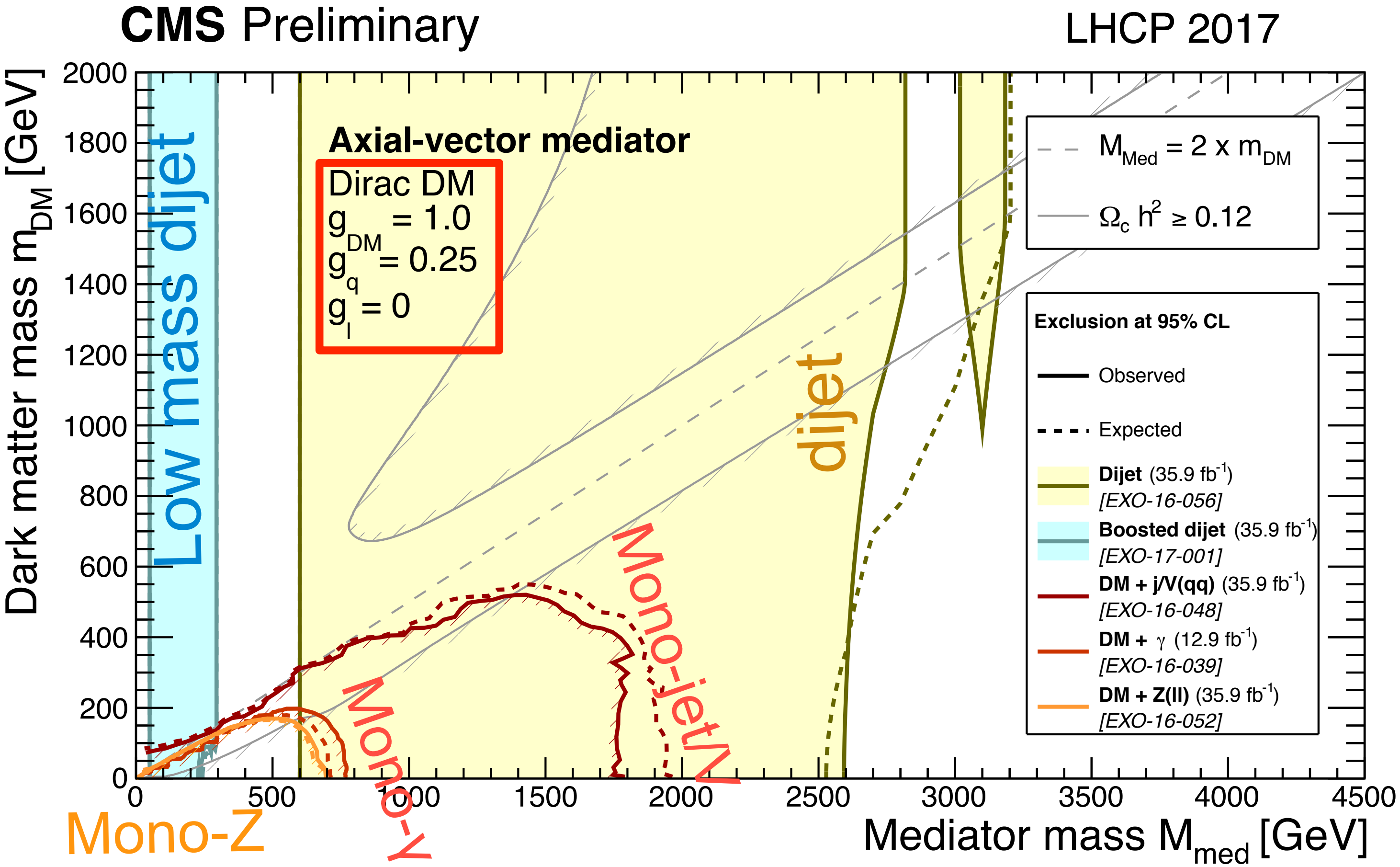








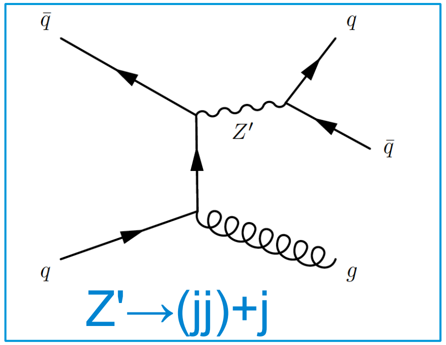


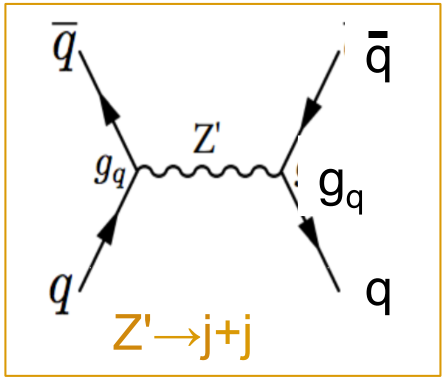


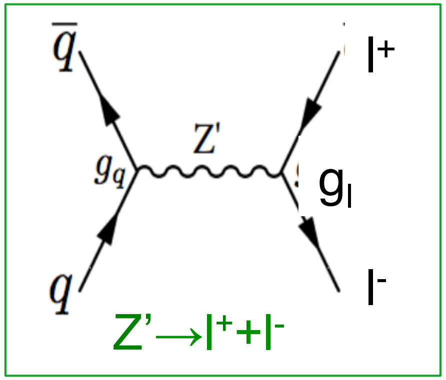
ATLAS very similar

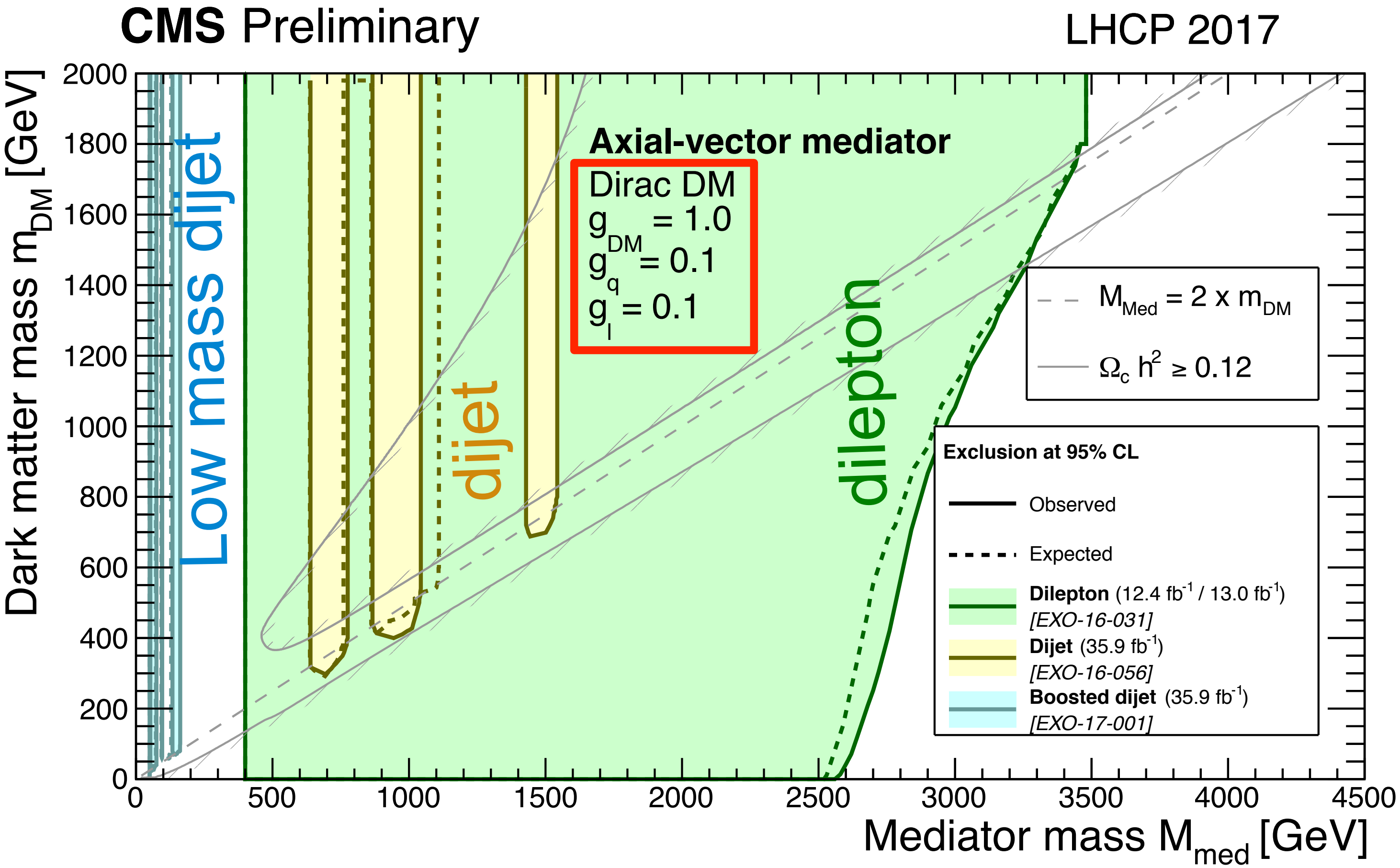
MET + X

Bump hunt





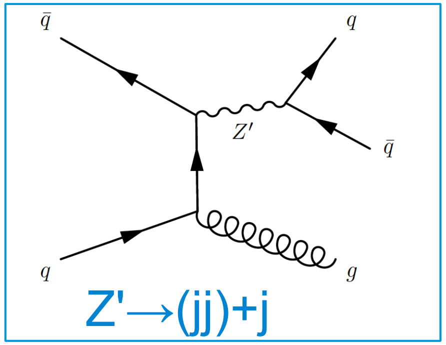


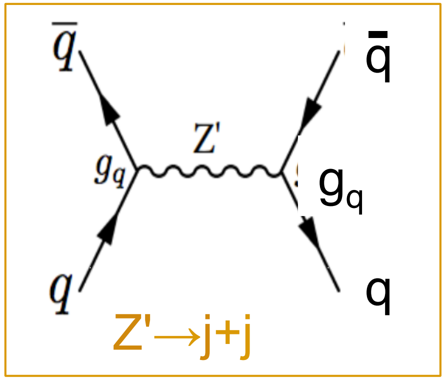


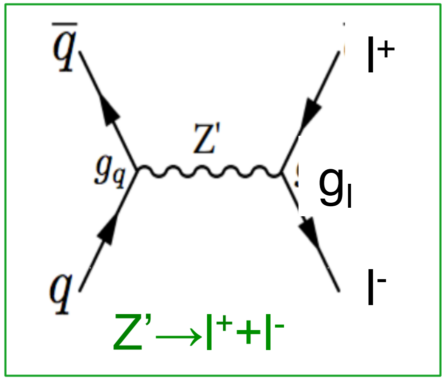
ATLAS very similar

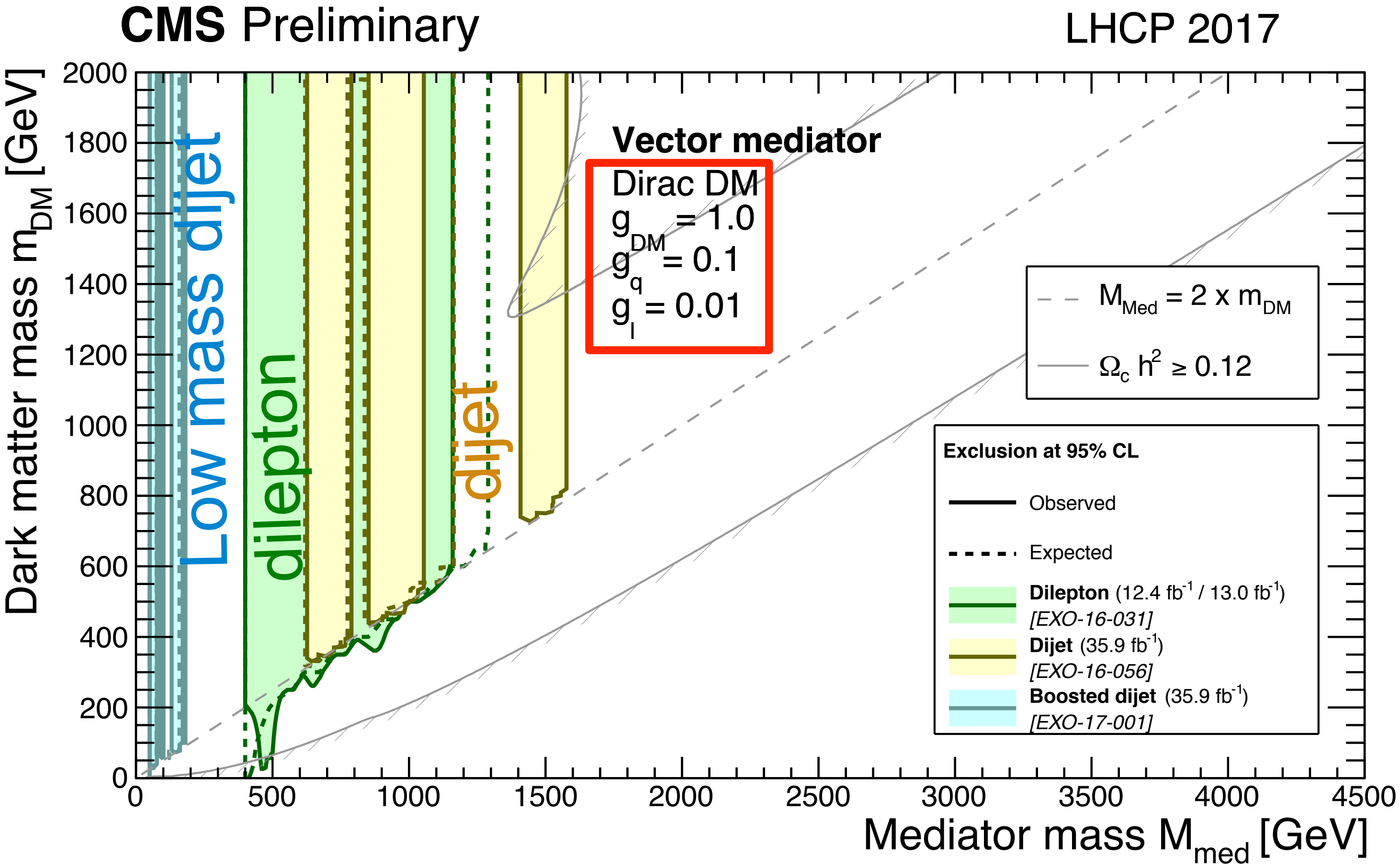
MET + X

Bump hunt





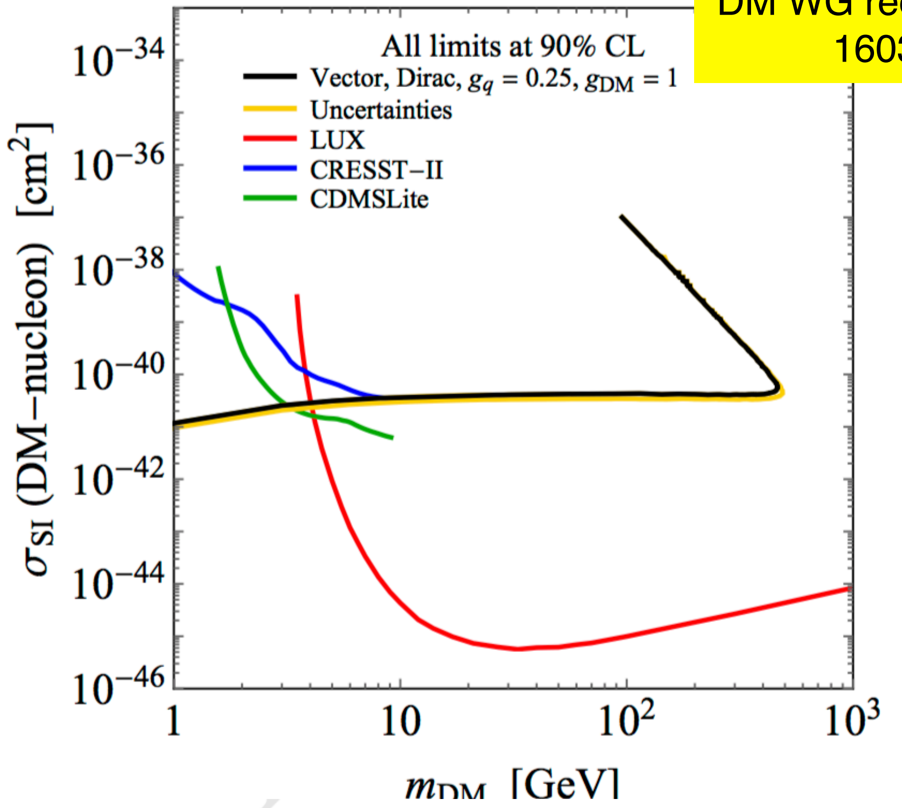


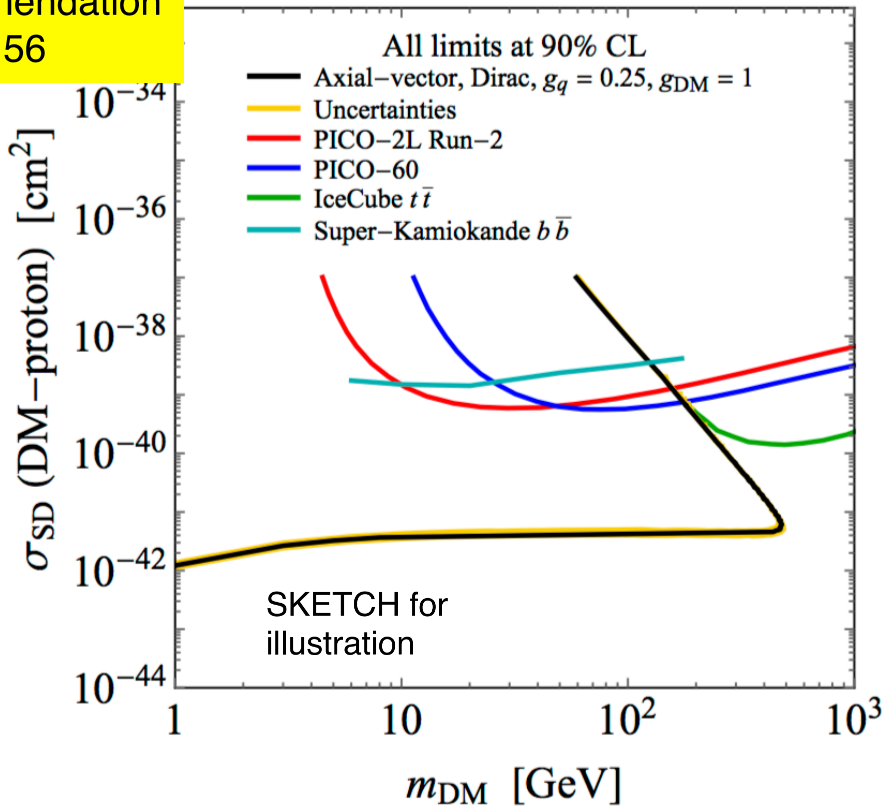


ATLAS very similar

Comparison with Direct Detection

All based on LHC DM WG recommendation 1603.04156





Vector:

$$\sigma_{SI} = \frac{9\, g_q^2\, g_{DM}^2\, \mu_{n\chi}^2}{\pi M_{med}^4}$$

$$\approx 1.1 \times 10^{-39}\ \mathrm{cm}^2 \cdot \left(\frac{g_{DM}\, g_q}{1}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$$

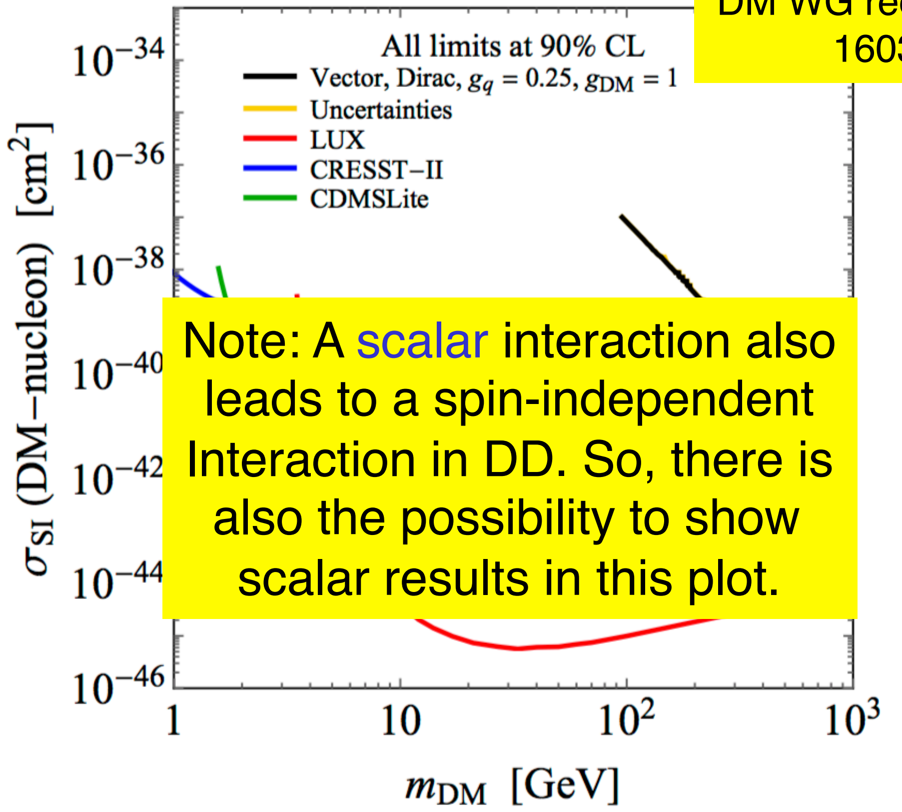
Axial-Vector:

$$\sigma^{SD} \simeq 2.4 \times 10^{-42}\ \mathrm{cm}^2 \cdot \left(\frac{g_q\, g_{DM}}{0.25}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$$

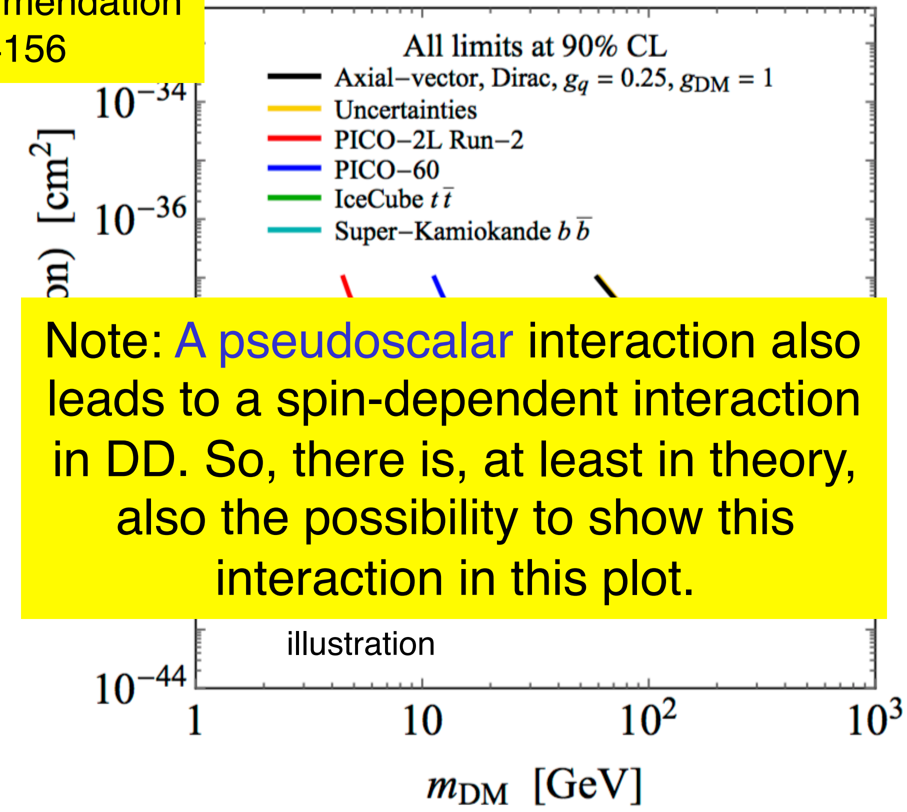
Provide simple formulas to perform the translation of the Mass-mass plane results into these planes. A full derivation of these formulas along with assumptions/caveat discussions is provided in the report.

Comparison with Direct Detection

All based on LHC DM WG recommendation 1603.04156



Note: A scalar interaction also leads to a spin-independent Interaction in DD. So, there is also the possibility to show scalar results in this plot.



Note: A pseudoscalar interaction also leads to a spin-dependent interaction in DD. So, there is, at least in theory, also the possibility to show this interaction in this plot.

Scalar:

$$\sigma_{SI} \approx 6.9 \times 10^{-43}\ \text{cm}^2 \cdot \left(\frac{g_{DM}\, g_q}{1}\right)^2 \left(\frac{125\ \text{GeV}}{M_{med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \text{GeV}}\right)^2$$

Pesudoscalar
see next slides

Provide simple formulas to perform the translation of the Mass-mass plane results into these planes. A full derivation of these formulas along with assumptions/caveat discussions is provided in the report.

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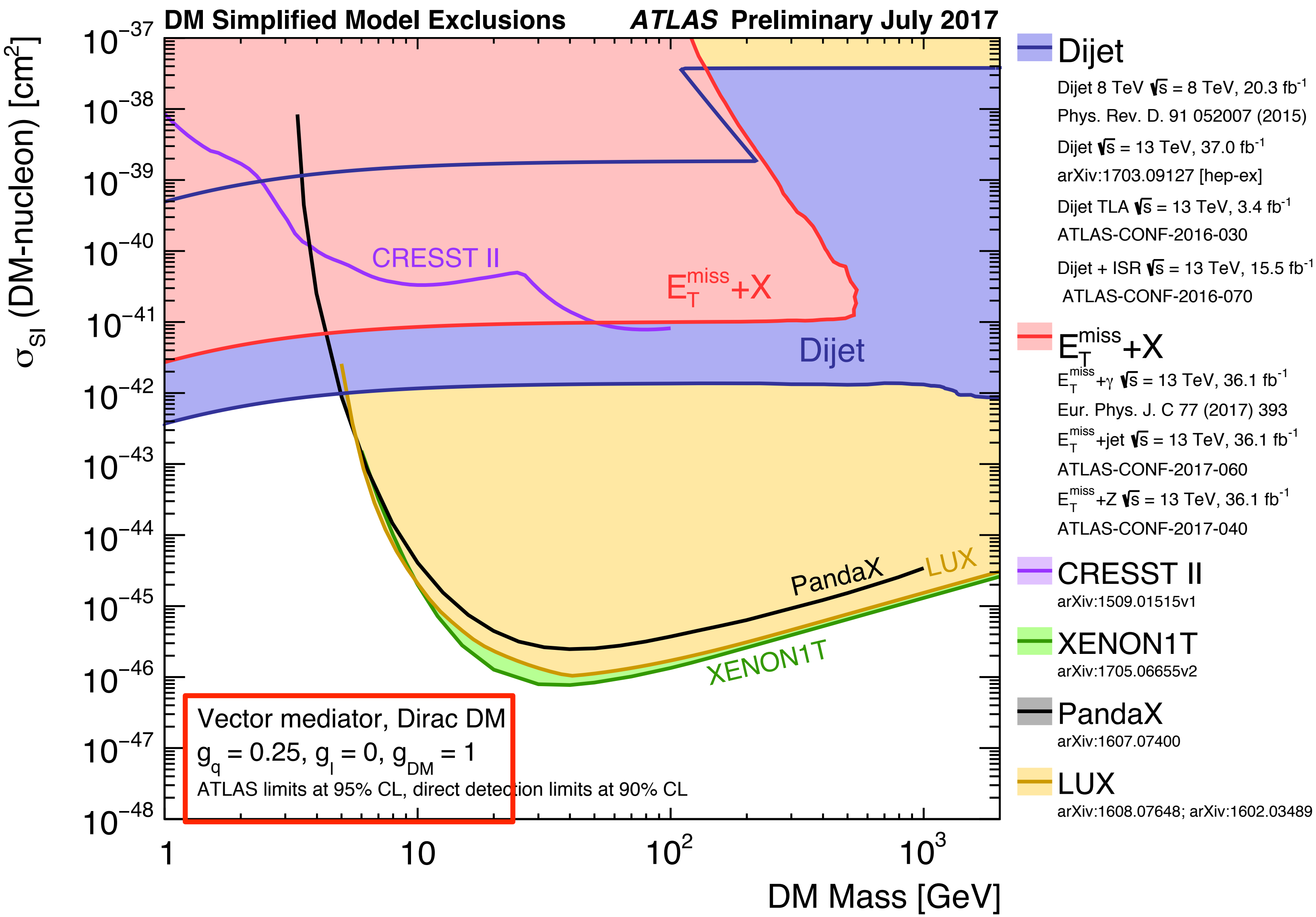
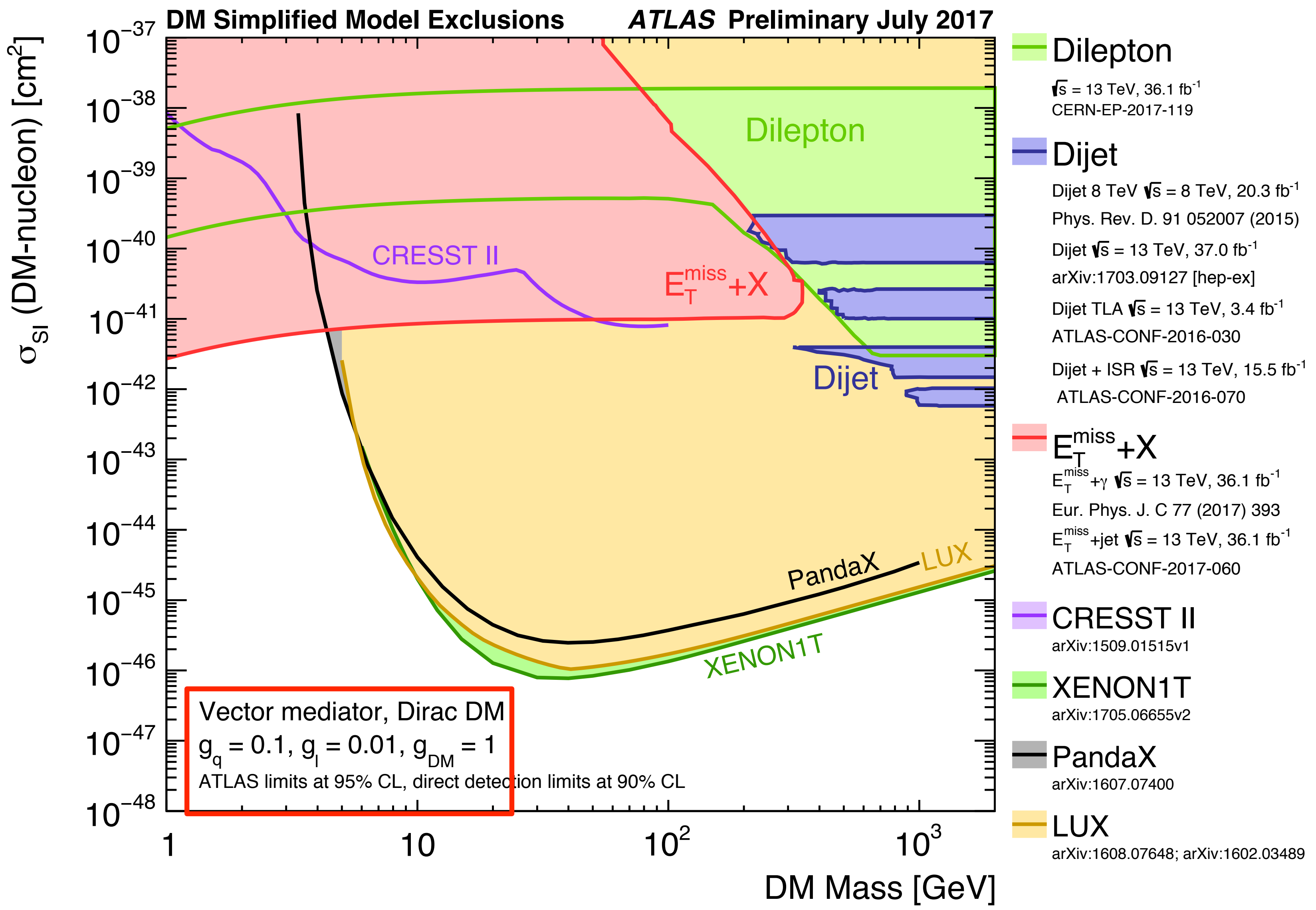
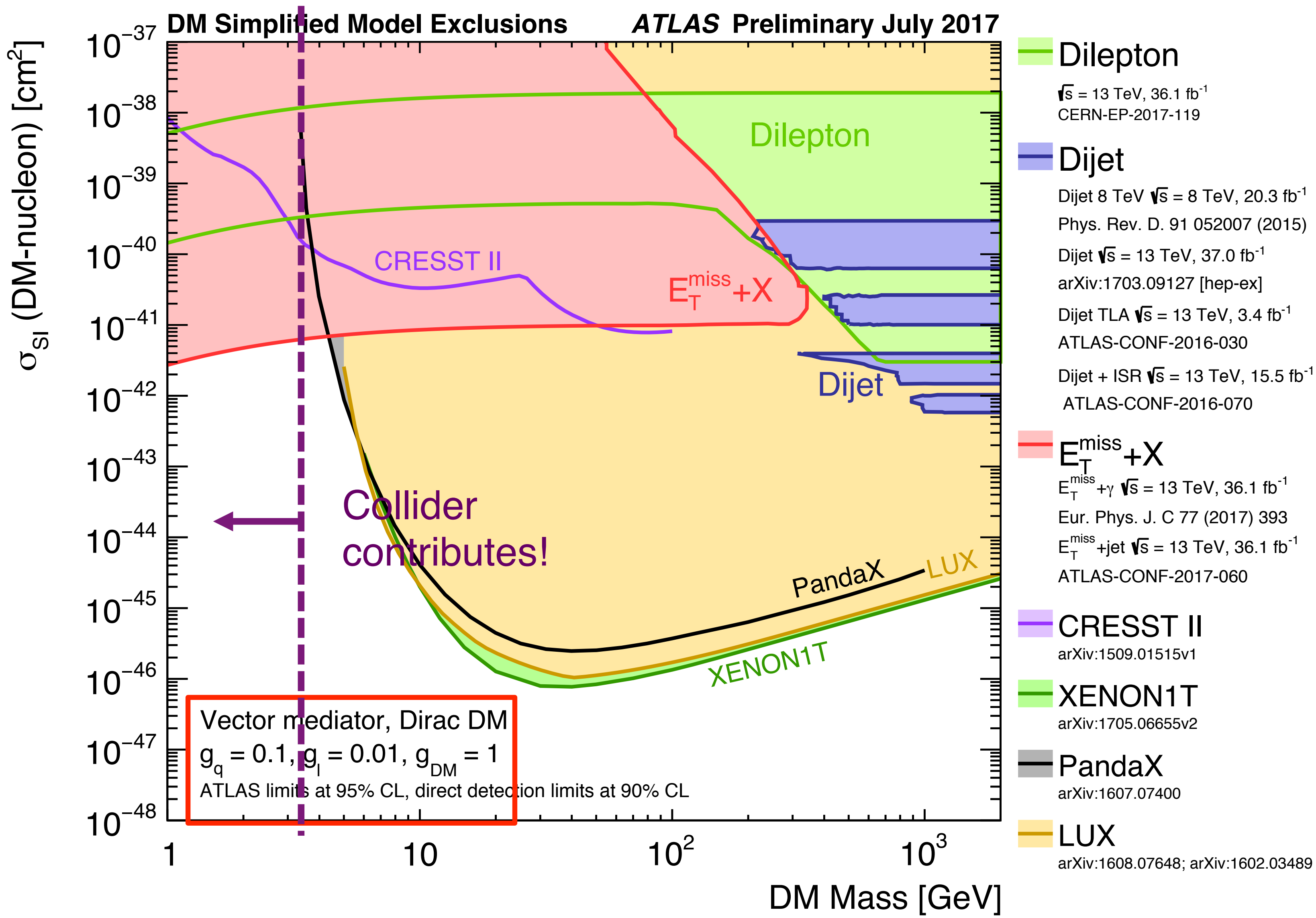
Comparison with Direct Detection: Vector case



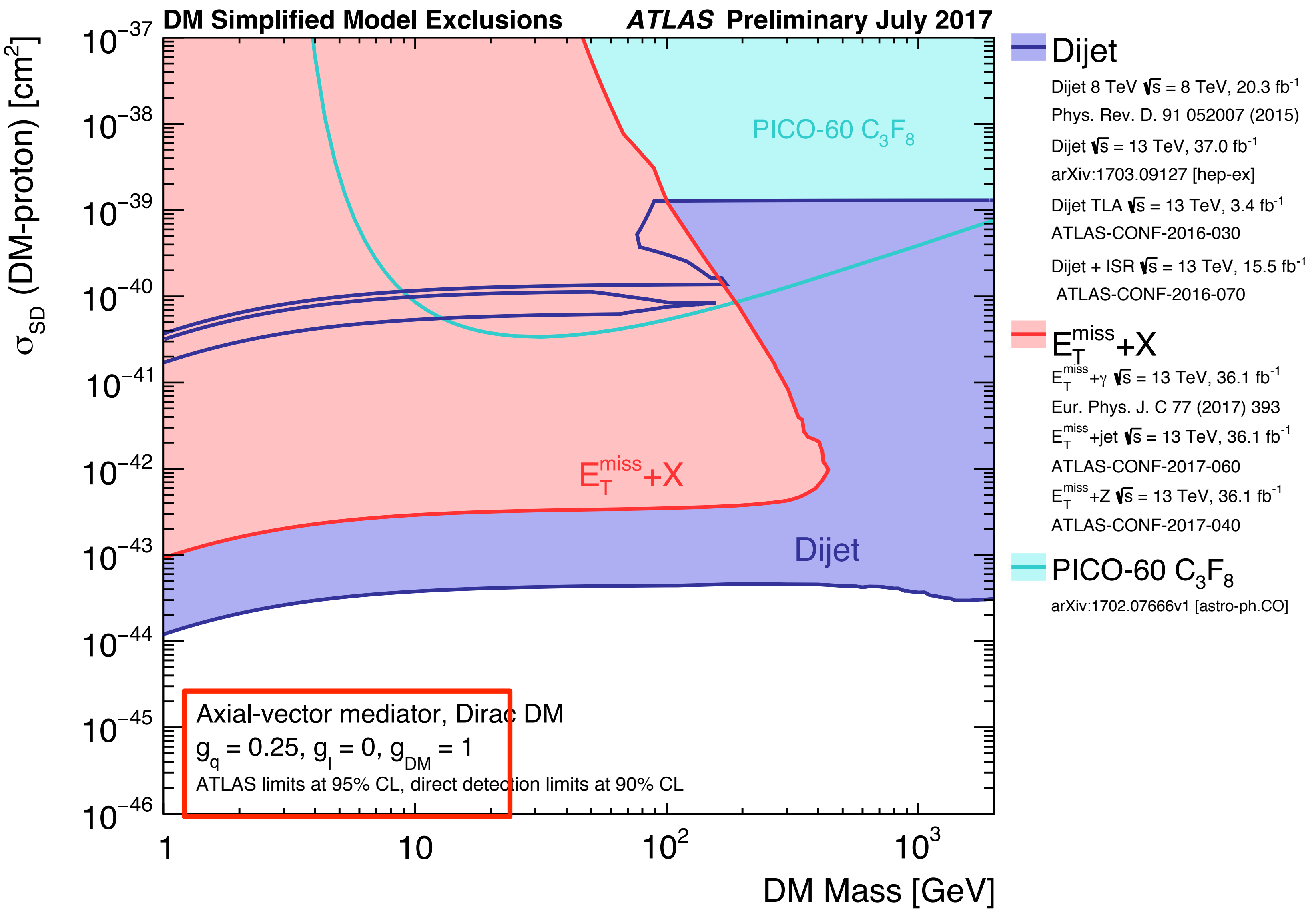
Comparison with Direct Detection: Vector Case



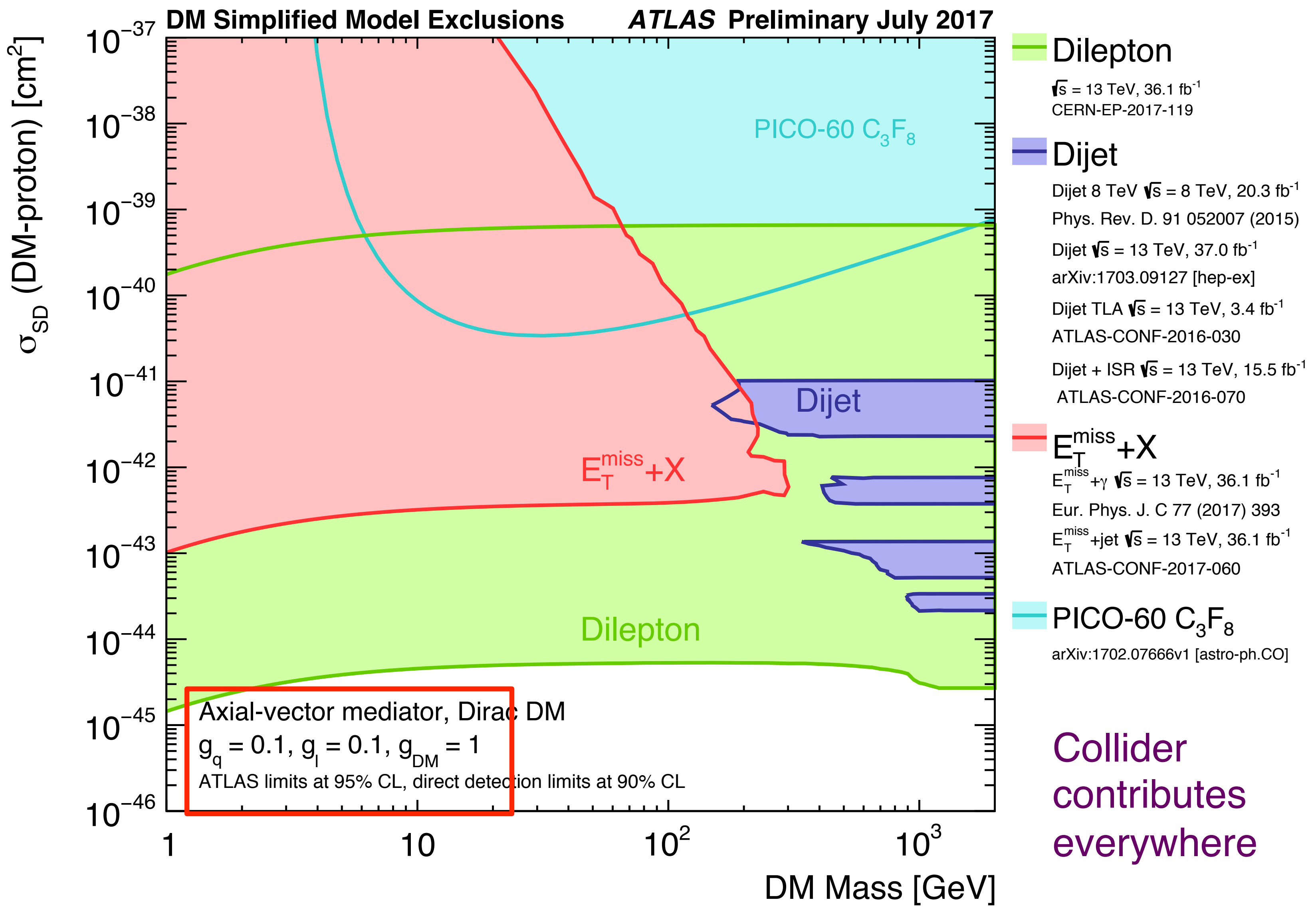
Comparison with Direct Detection: Vector Case



Comparison with Direct Detection: Axial-Vector



Comparison with Direct Detection: Axial-Vector



Collider contributes everywhere

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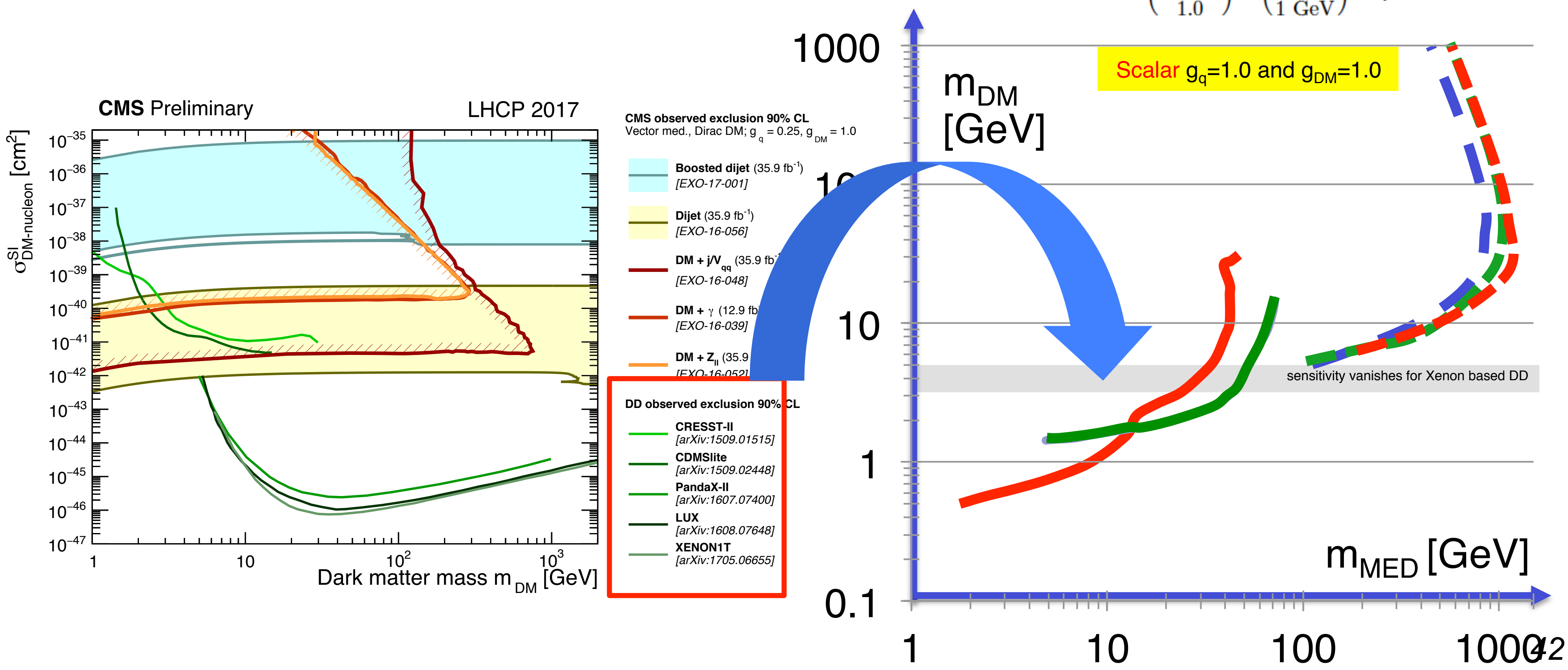
Scalar and Pseudoscalar

Of course, there is also a well-defined way to compare DD limits with collider results in the collider language: mass-mass plane:

Based on arXiV:1407.8257 Numerical calculation provide by. C. McCabe

Scalar simplified model: g_q=1.0 and g_{DM}=1.0

$$M_\phi = 125\ \text{GeV} \left(\frac{6.9\times10^{-43}\ \text{cm}^2}{\sigma^{\text{SI}}}\right)^{0.25} \cdot \left(\frac{g_{\text{DM}}g_q}{1.0}\right)^{0.5}\left(\frac{\mu_n}{1\ \text{GeV}}\right)^{0.5}.$$



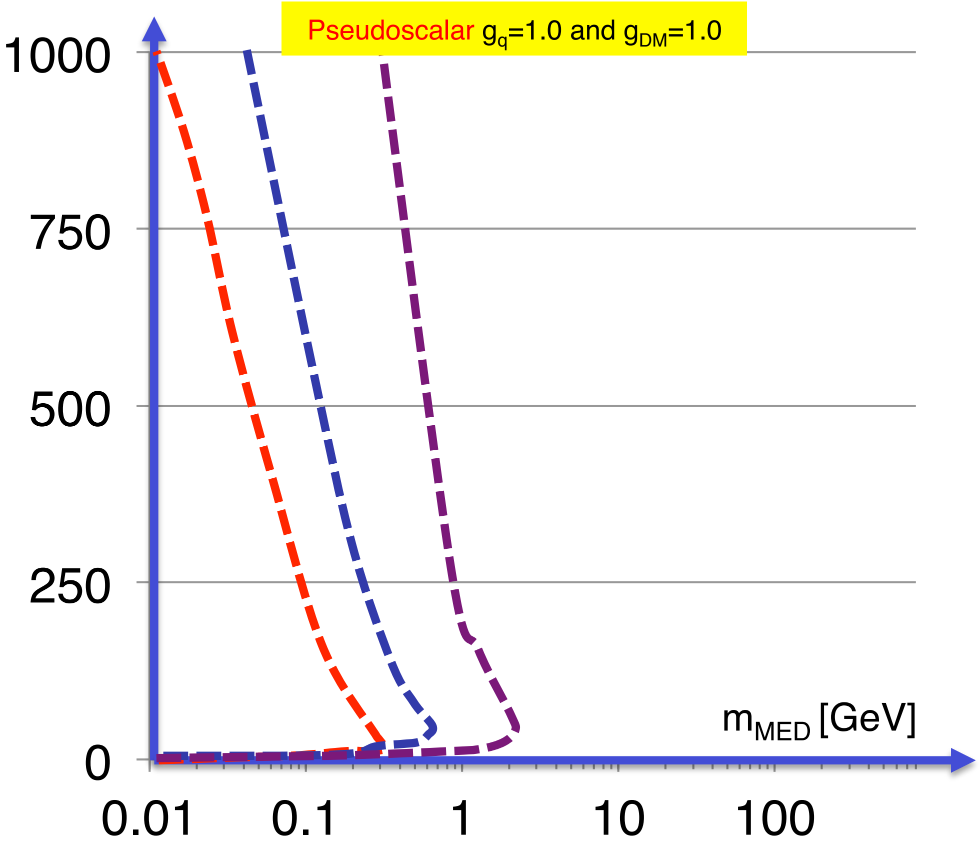
Scalar and Pseudoscalar

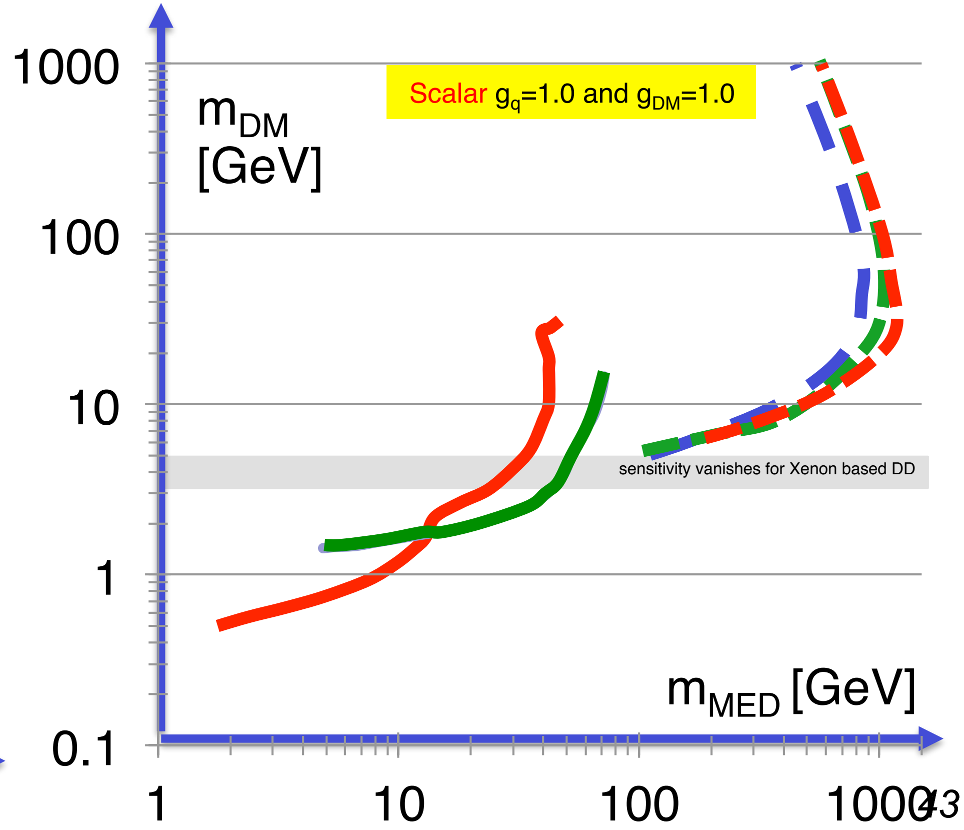
Of course, there is also a well-defined way to compare DD limits with collider results in the collider language: mass-mass plane:

Pseudoscalar (PS) simplified model: g_q=1.0 and g_{DM}=1.0

Based on arXiV:1407.8257 Numerical calculation provide by. C. McCabe

Scalar simplified model: g_q=1.0 and g_{DM}=1.0





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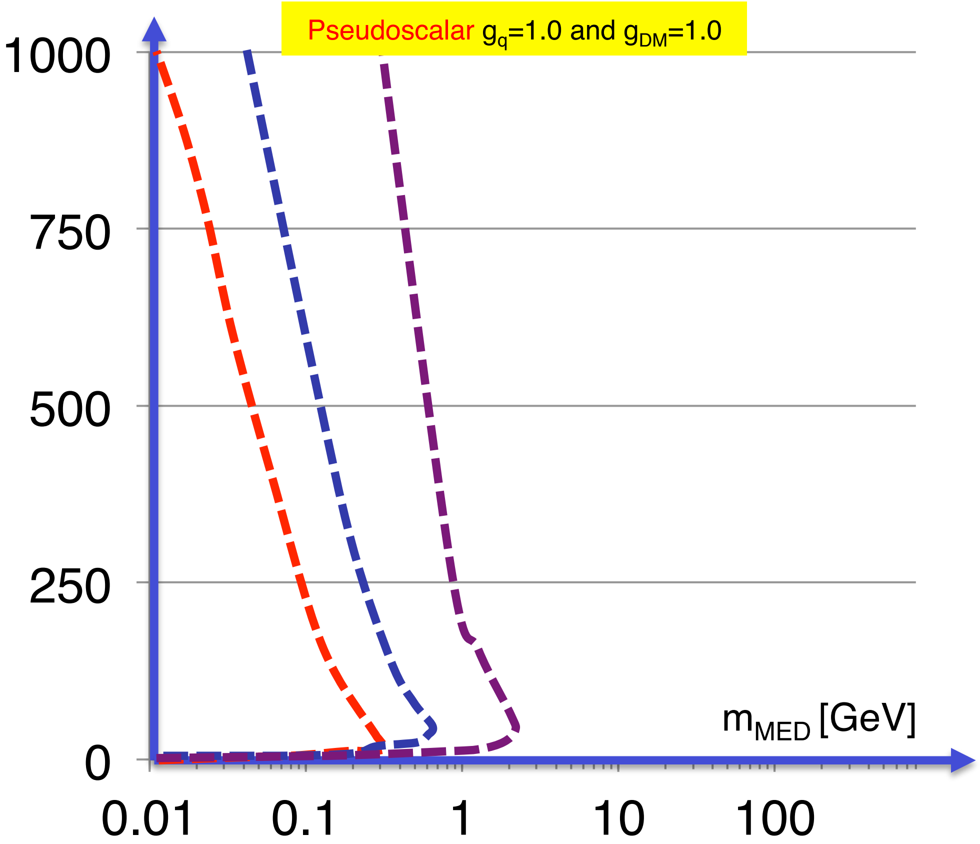
DD limits in collider plane: σ_{SI}

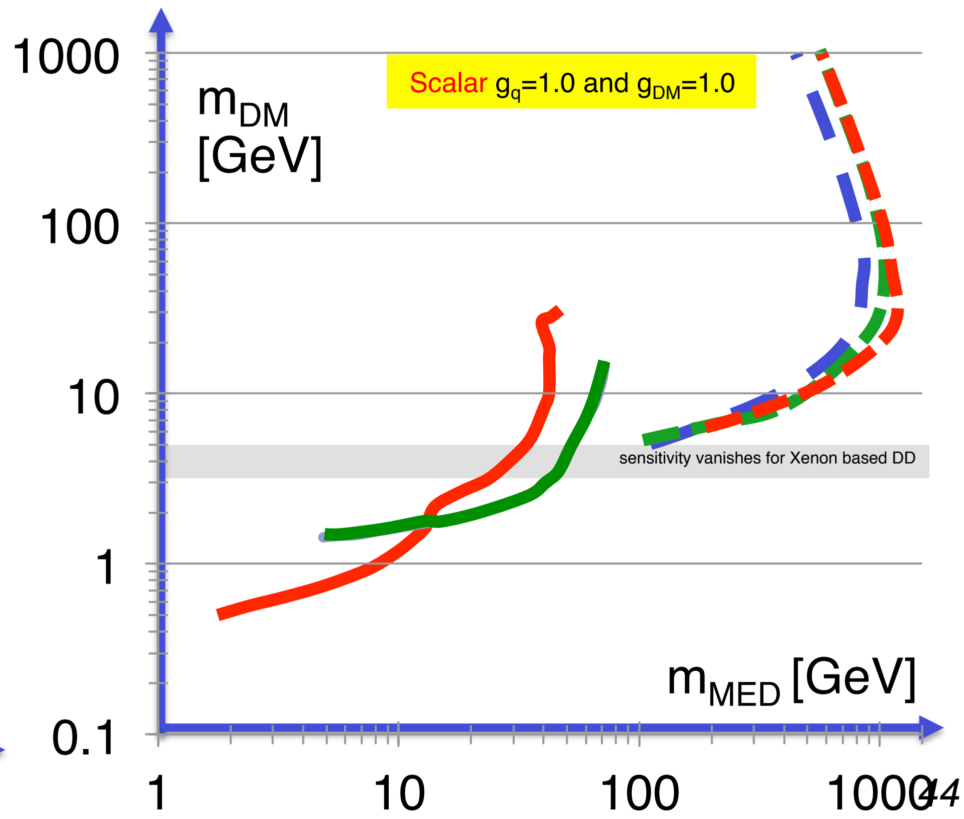
Pseudoscalar case

PICO60 [arXiv:1702.07666]
XENON1T [arXiv:1705.06655]
LZ/XENONnT 15 t-yr projection



Scalar case

CRESST-II [arXiv:1509.01515]
CDMSlite [arXiv:1509.02448]
PandaX-II [arXiv:1607.07400]
LUX [arXiv:1608.07648]
XENON1T [arXiv:1705.06655]

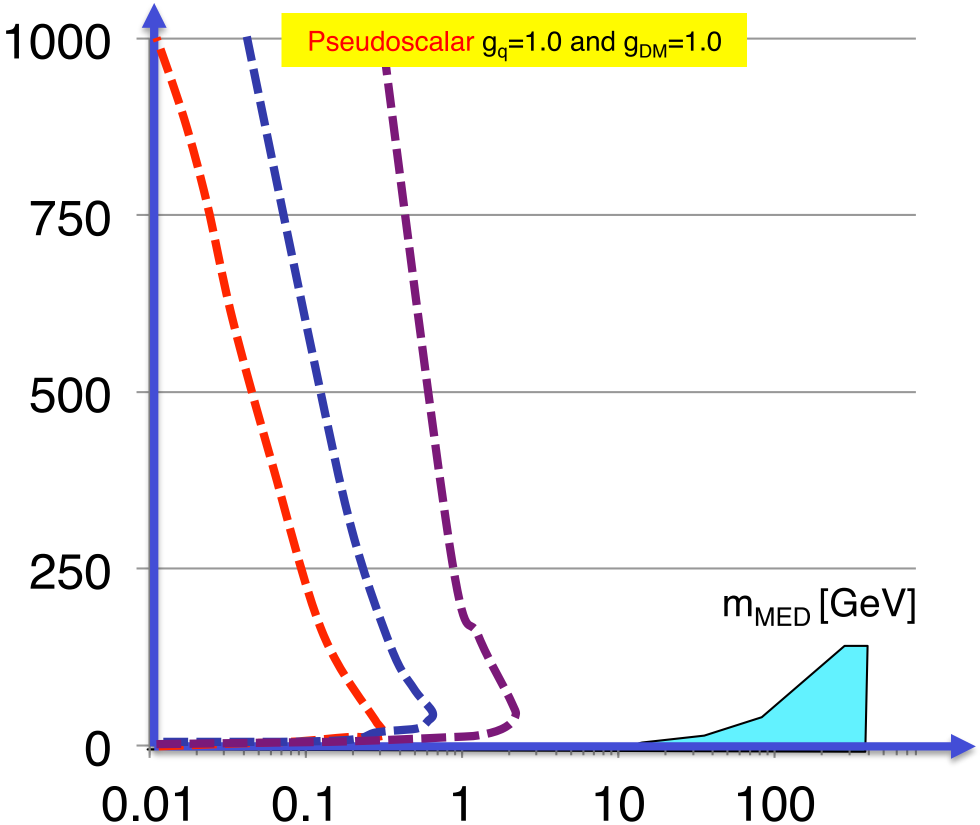


DD limits in collider plane: σ_{SI}

Pseudoscalar case

PICO60 [arXiv:1702.07666]
XENON1T [arXiv:1705.06655]
LZ/XENONnT 15 t-yr projection

Mono-jet [EXO-16-048]

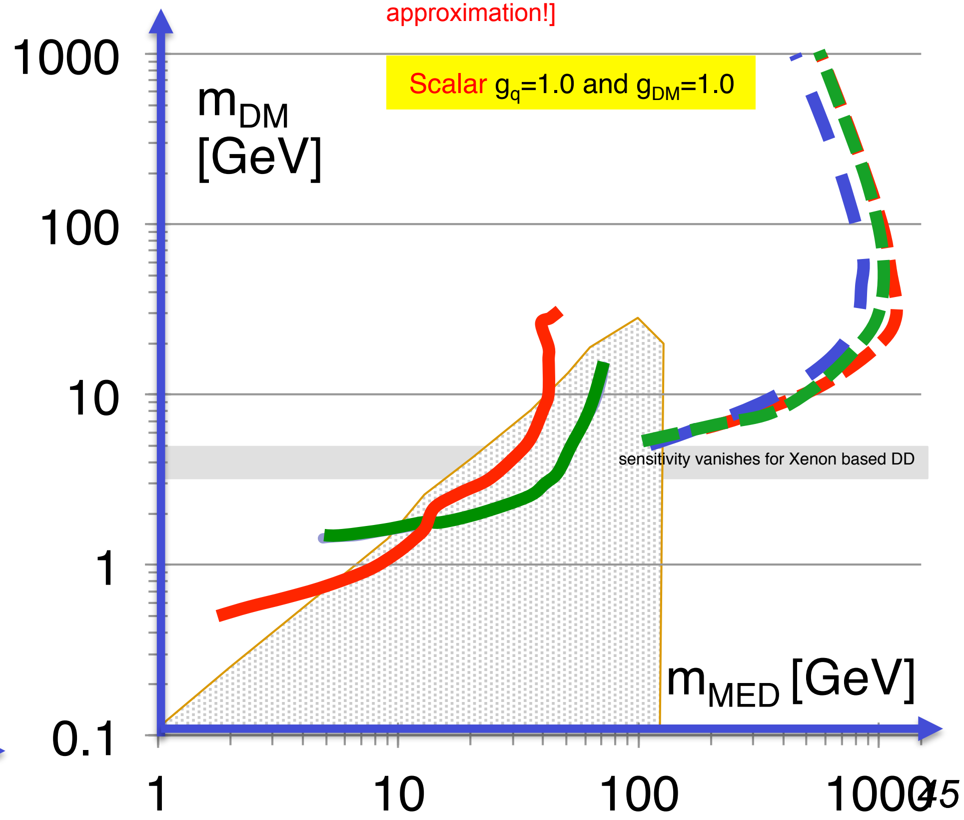


Scalar case

CRESST-II [arXiv:1509.01515]
CDMSlite [arXiv:1509.02448]
PandaX-II [arXiv:1607.07400]
LUX [arXiv:1608.07648]
XENON1T [arXiv:1705.06655]

2L + MET [SUS-17-001]

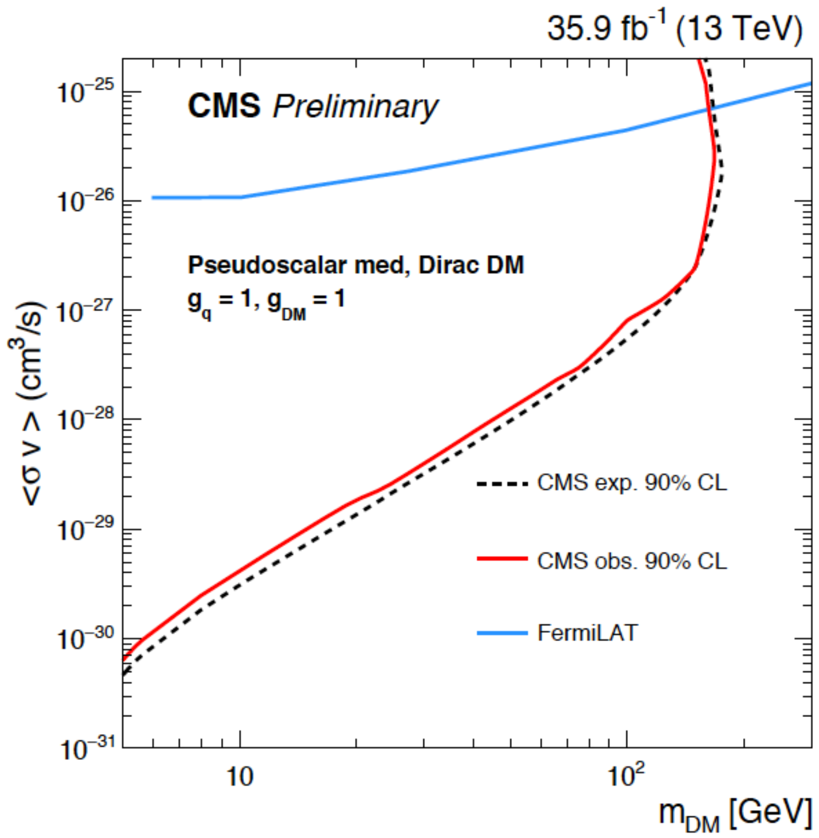
[Note: private estimate of 2D exclusion – only rough approximation!]



Comparing with Indirect Detection

$$\langle \sigma v_{\rm rel} \rangle_q = \frac{3 m_q^2}{2\pi v^2} \frac{g_q^2 g_{\rm DM}^2 m_{\rm DM}^2}{(M_{\rm med}^2 - 4 m_{\rm DM}^2)^2 + M_{\rm med}^2 \Gamma_{\rm med}^2} \sqrt{1 - \frac{m_q^2}{m_{\rm DM}^2}}$$

All based on LHC
DM WG recommendation
1603.04156



Due to additional velocity suppression DD experiments, have sensitivity for Mmed > few GeV, but indirect detection can provide further constrains on pseudoscalar (PS) interactions.

Hence, compare collider also with ID

Mono-jet [EXO-16-048]
FermiLAT arXiv:1503.02641

DD and Collider Complementarity in nutshell ...

<table>
<tr><td colspan="2">Wimp – Nucleon Interaction</td></tr>
<tr><td>Spin-Independent (SI)</td><td>Spin-Dependent (SD)</td></tr>
<tr><td colspan="2">Basic Mediators</td></tr>
<tr><td>Vector
Besides low DM masses DD provides best sensitivity.
Complementarity at low DM masses (<5 GeV)!</td><td>Axial-vector
DD and collider are equal in overall sensitivity but probe different regions of parameter space!
Complementarity in full parameter space!</td></tr>
<tr><td>Scalar
Besides low DM masses DD provides best sensitivity.
Complementarity at low DM masses (<5 GeV)!</td><td>Pseudoscalar
Effectively no limits from DD above a few GeV in M_{med}, Collider and ID probe region at larger M_{med}.
Complementarity in M_{med}!</td></tr>
</table>

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Summary

- The LHC experiments have established an impressive variety of very powerful direct searches that can be linked to DM production!
  - The traditional SUSY searches are complemented by mono-X analyses.
- The challenge is now to find a good balance between simplicity and complexity for the DM interpretations of theses searches.
  - We have started to outline an interpretation programme that uses simplified DM models.
  - Today, the used simplified models are still very basic and therefore interpretations come along with several assumptions and some caveats – this will evolve with time!
  - Our goal is to establish the "big picture" in order to understand if/where our search strategy might have weak spots or even holes and this also requires appropriate interpretations of the searches and a MEANIGFUL comparison with other experiments.
- We have still almost two decades of data taking in front of us, with a factor 100 increase of statistic still to come!

The story continues …

BACKUP

DD limits in collider plane: σ_{SI}

Of course, there is also a well-defined way to compare DD limits with collider results in the collider language: mass-mass plane:

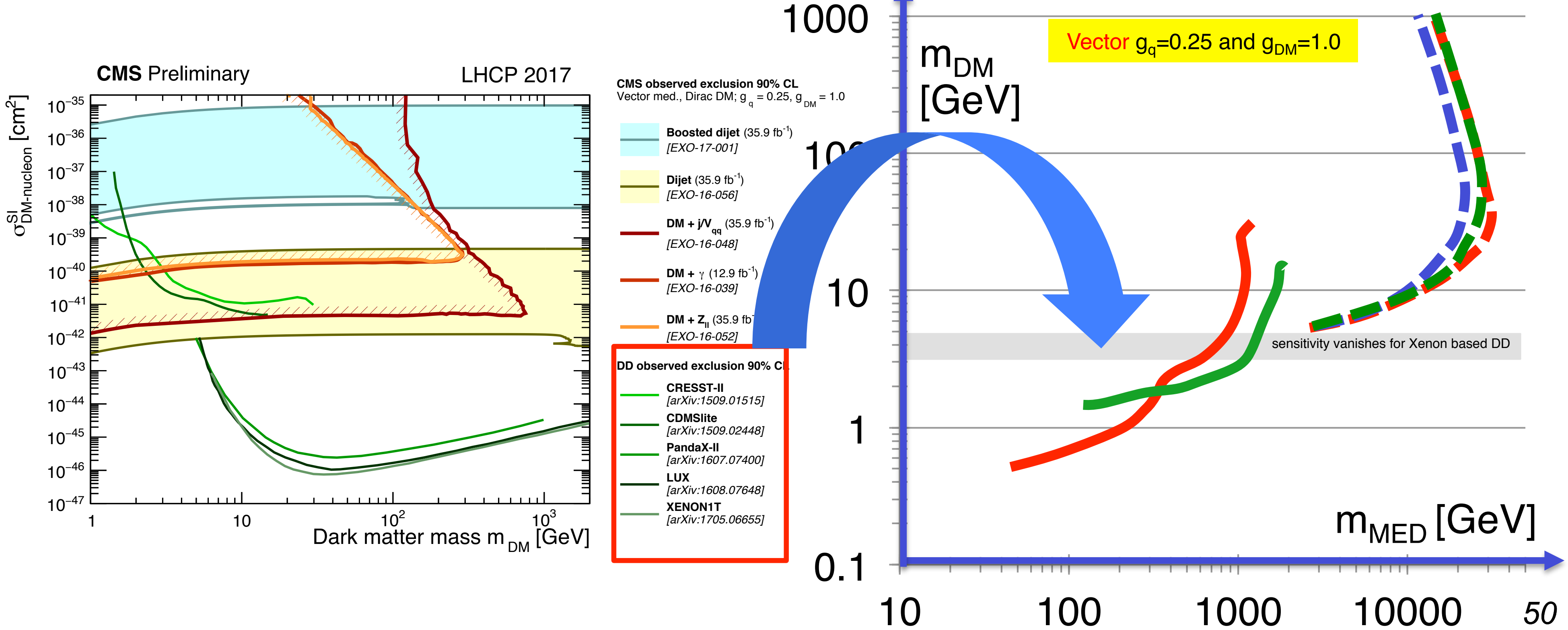
Scalar simplified model: g_q=1.0 and g_{DM}=1.0

$$M_\phi = 125\ \mathrm{GeV} \left(\frac{6.9\times10^{-43}\ \mathrm{cm}^2}{\sigma^{\mathrm{SI}}}\right)^{0.25} \cdot \left(\frac{g_{\mathrm{DM}}g_q}{1.0}\right)^{0.5}\left(\frac{\mu_n}{1\ \mathrm{GeV}}\right)^{0.5}.$$

Based on arXiV:1407.8257
Numerical calculation provide by. C. McCabe

Vector simplified model: g_q=0.25 and g_{DM}=1.0

$$M_A = 1\ \mathrm{TeV} \left(\frac{6.971\times10^{-41}\ \mathrm{cm}^2}{\sigma_n^{\mathrm{SI}}}\right)^{0.25} \cdot \left(\frac{g_{\mathrm{DM}}g_q}{0.25}\right)^{0.5}\left(\frac{\mu_n}{1\ \mathrm{GeV}}\right)^{0.5}.$$



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DD limits in collider plane: σ_{SI}

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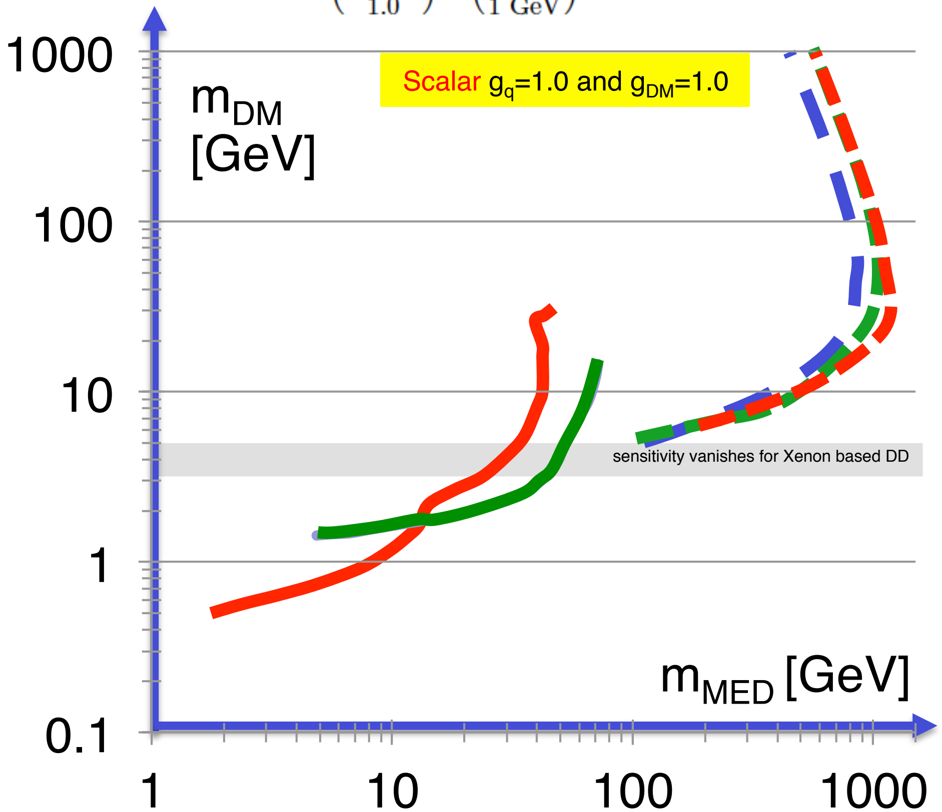

Based on arXiV:1407.8257
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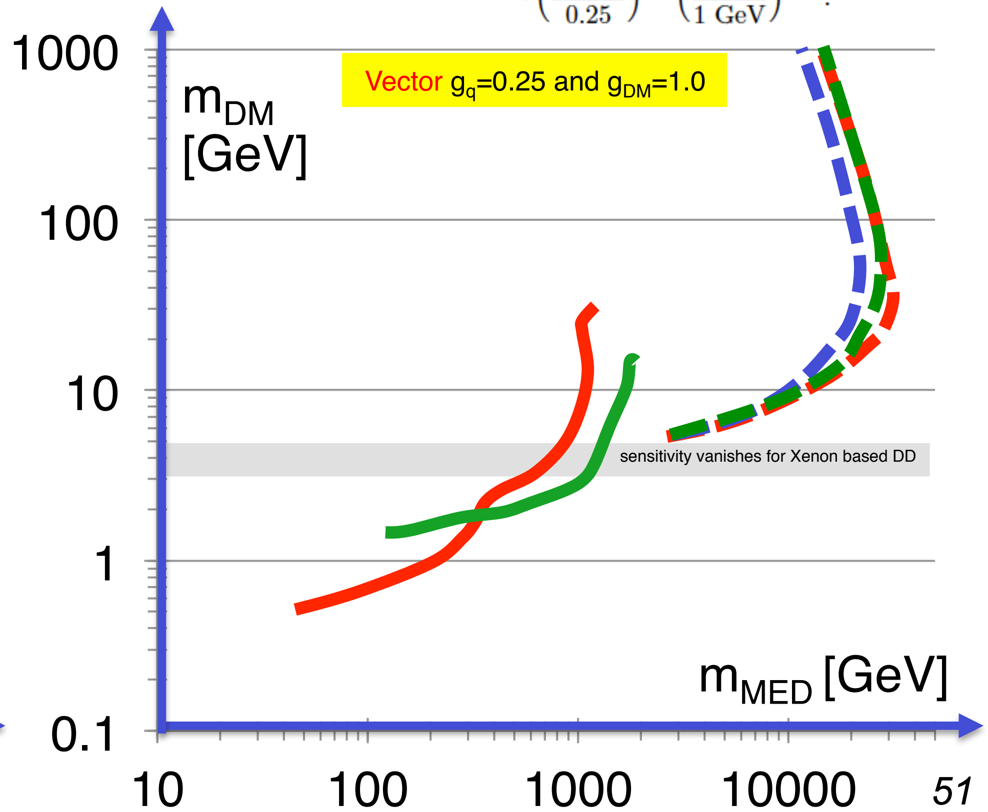
Vector simplified model: g_q=0.25 and g_{DM}=1.0

$$M_A = 1\ \text{TeV} \left(\frac{6.971\times 10^{-41}\ \text{cm}^2}{\sigma_n^{\text{SI}}}\right)^{0.25} \cdot \left(\frac{g_{\text{DM}} g_q}{0.25}\right)^{0.5} \left(\frac{\mu_n}{1\ \text{GeV}}\right)^{0.5} .$$



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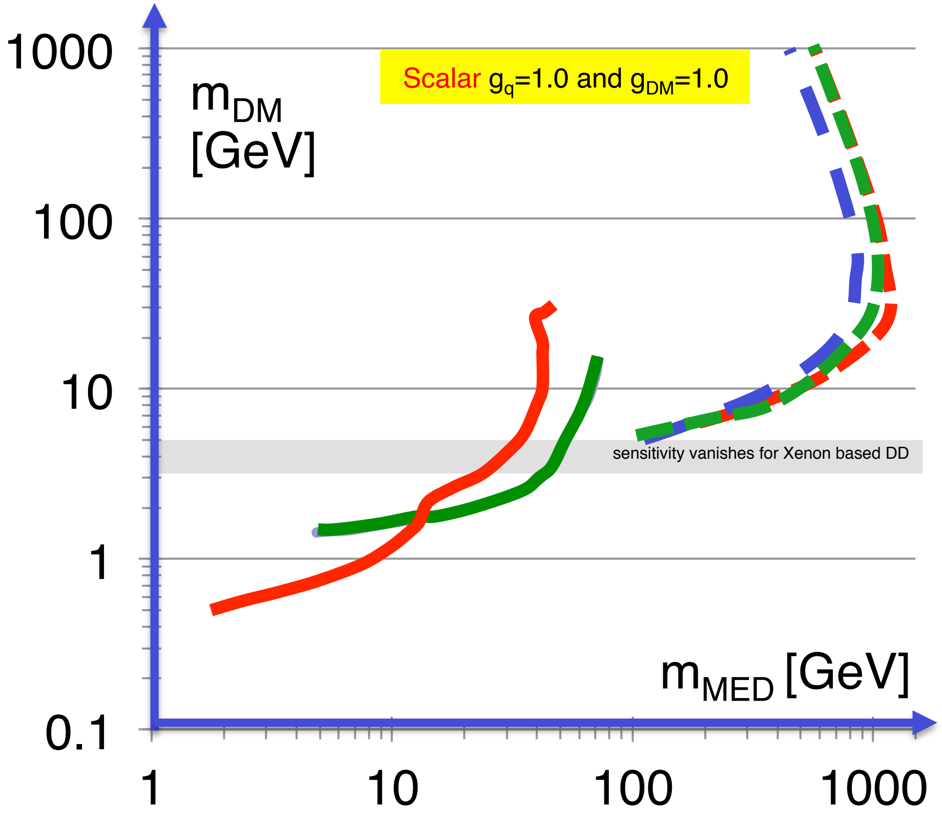
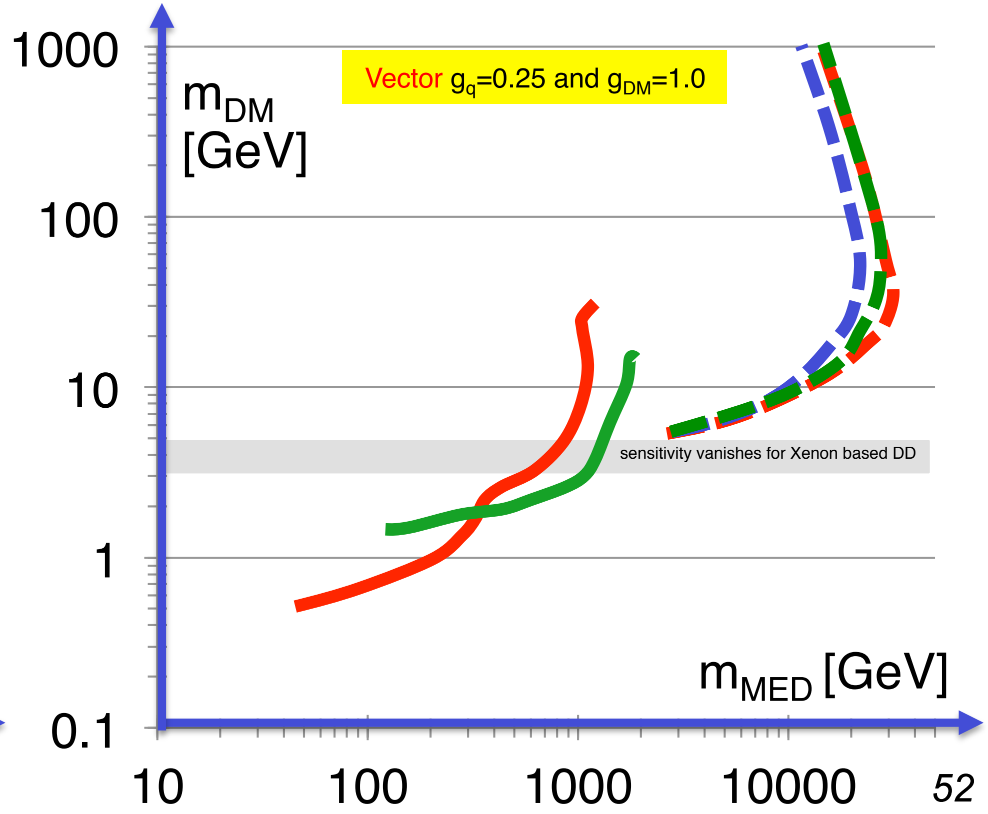
DD limits in collider plane: σ_{SI}

DD Experiments

CRESST-II [arXiv:1509.01515]
CDMSlite [arXiv:1509.02448]
PandaX-II [arXiv:1607.07400]
LUX [arXiv:1608.07648]
XENON1T [arXiv:1705.06655]





DD limits in collider plane: σ_{SI}

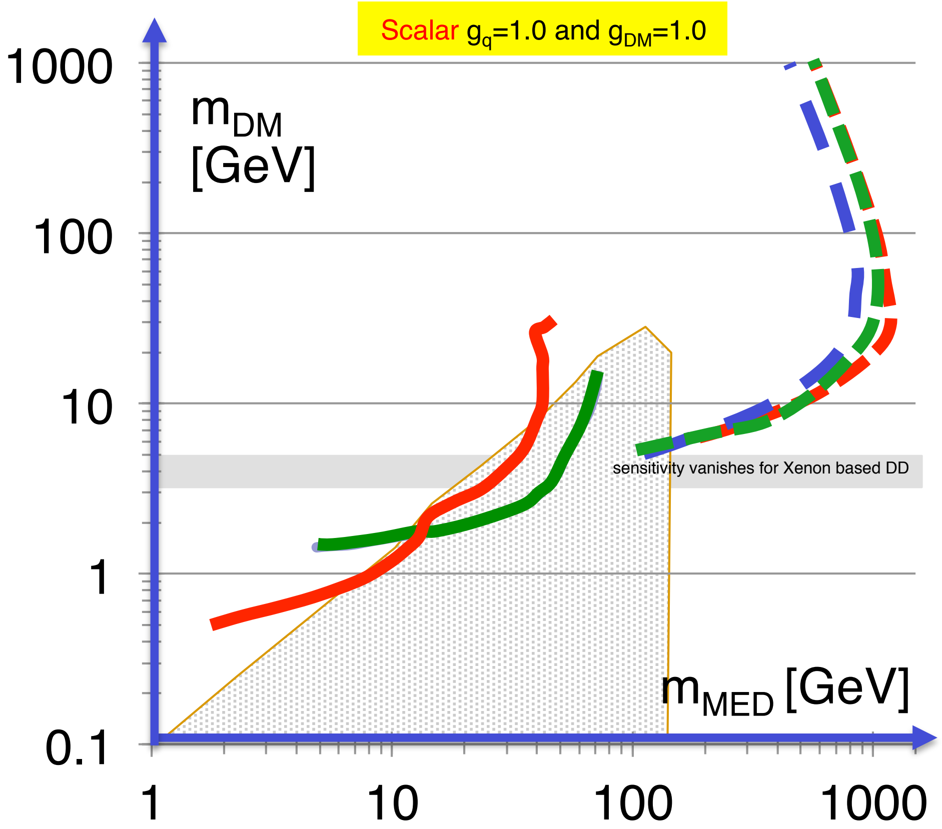
DD Experiments

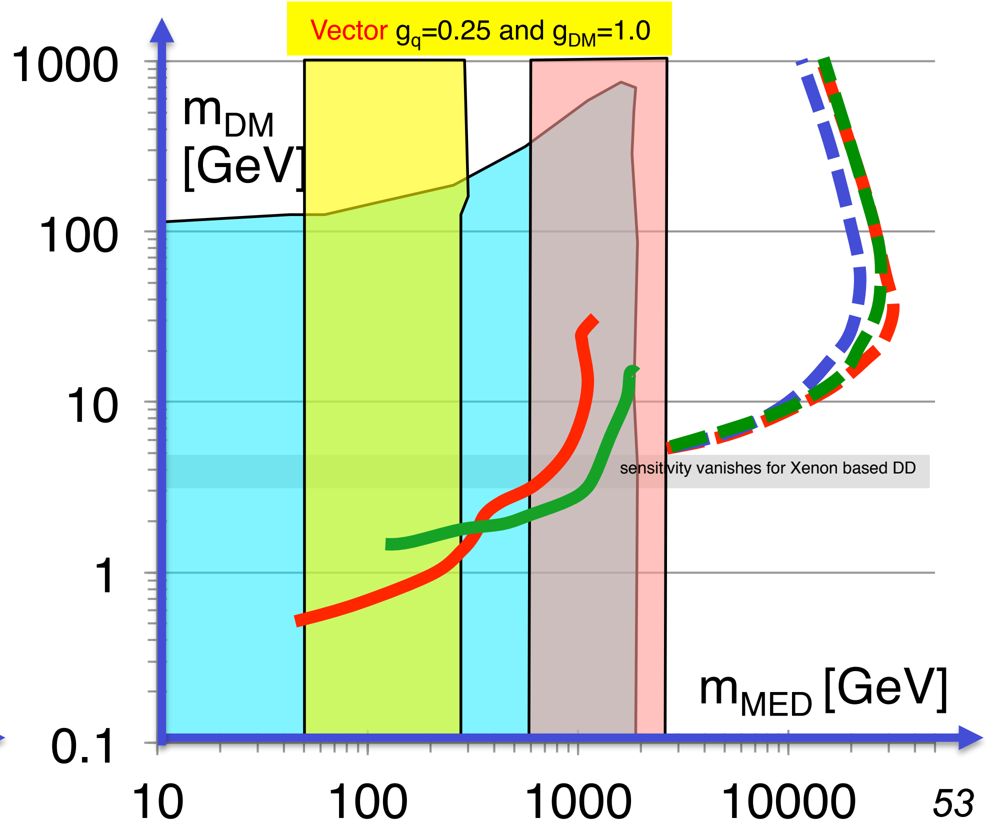
CRESST-II
[arXiv:1509.01515]
CDMSlite
[arXiv:1509.02448]
PandaX-II
[arXiv:1607.07400]
LUX
[arXiv:1608.07648]
XENON1T
[arXiv:1705.06655]

Collider

2L + MET
[SUS-17-001]
[Note: private estimate of 2D exclusion – only rough approximation!]

Boosted dijet
[EXO-17-001]
Dijet
[EXO-16-056]
Mono-jet
[EXO-16-048]





DD limits in collider plane: σ_{SI}

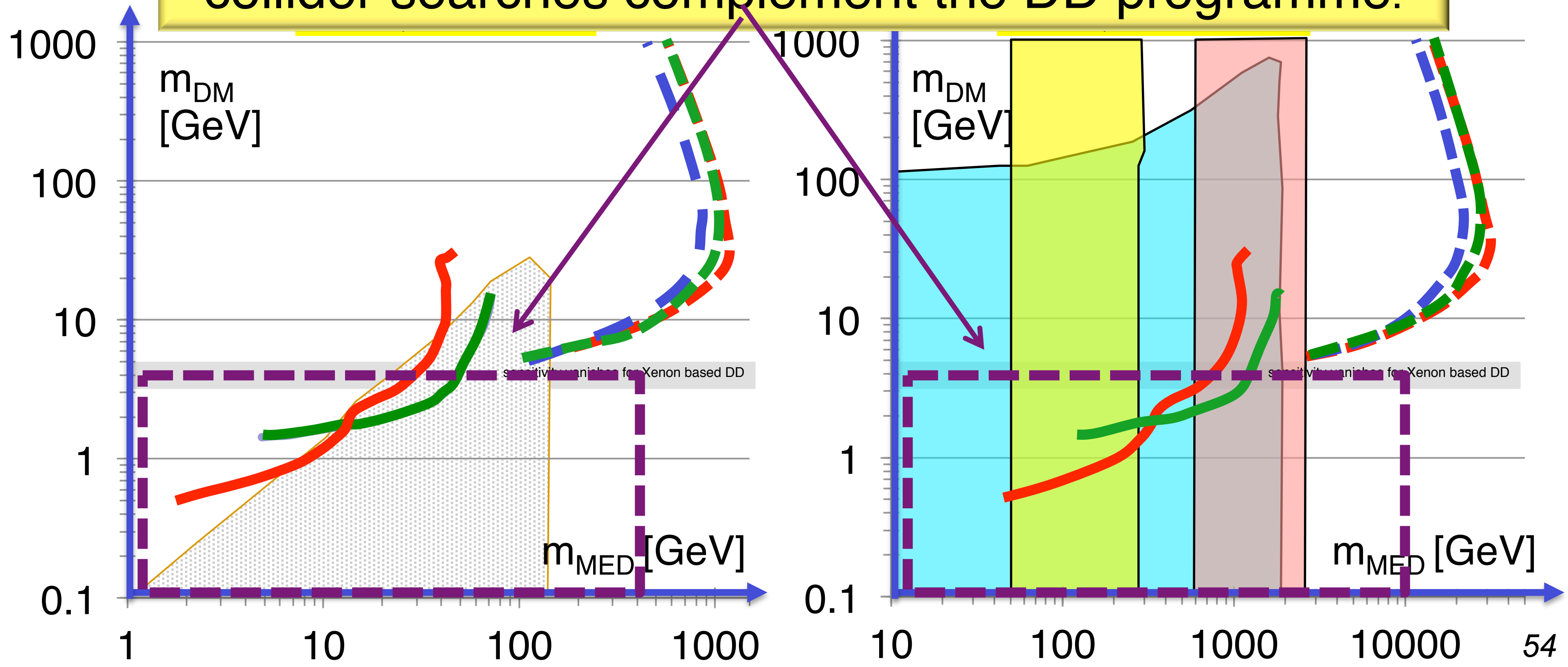
DD Experiments | **Collider**

PandaX-II ---- [arXiv:1607.07400]

Boosted dijet [EXO-17-001]

CRE[...] [arXi[...]
CDM[...] [arXi[...]

Broad brush bottom line:
For Vector and Scalar interactions, xenon based DD experiments rule, while for low m_{DM} (<~5 GeV) collider searches complement the DD programme.



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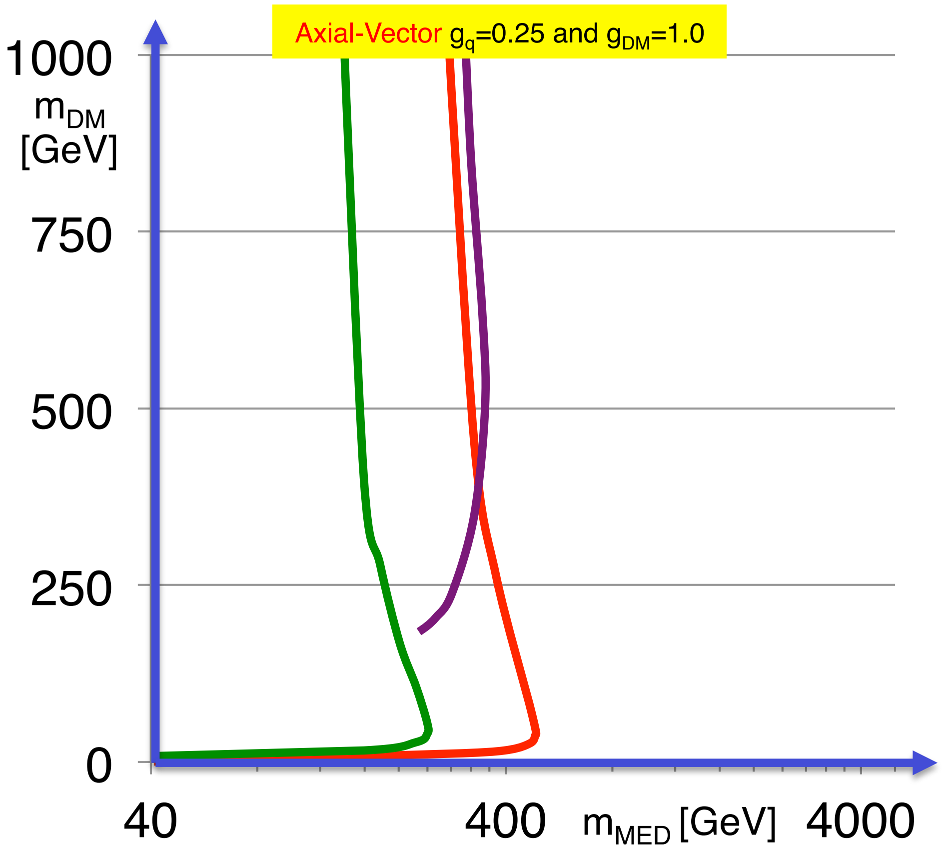
DD limits in collider plane: $\sigma_{SD(p,n)}$

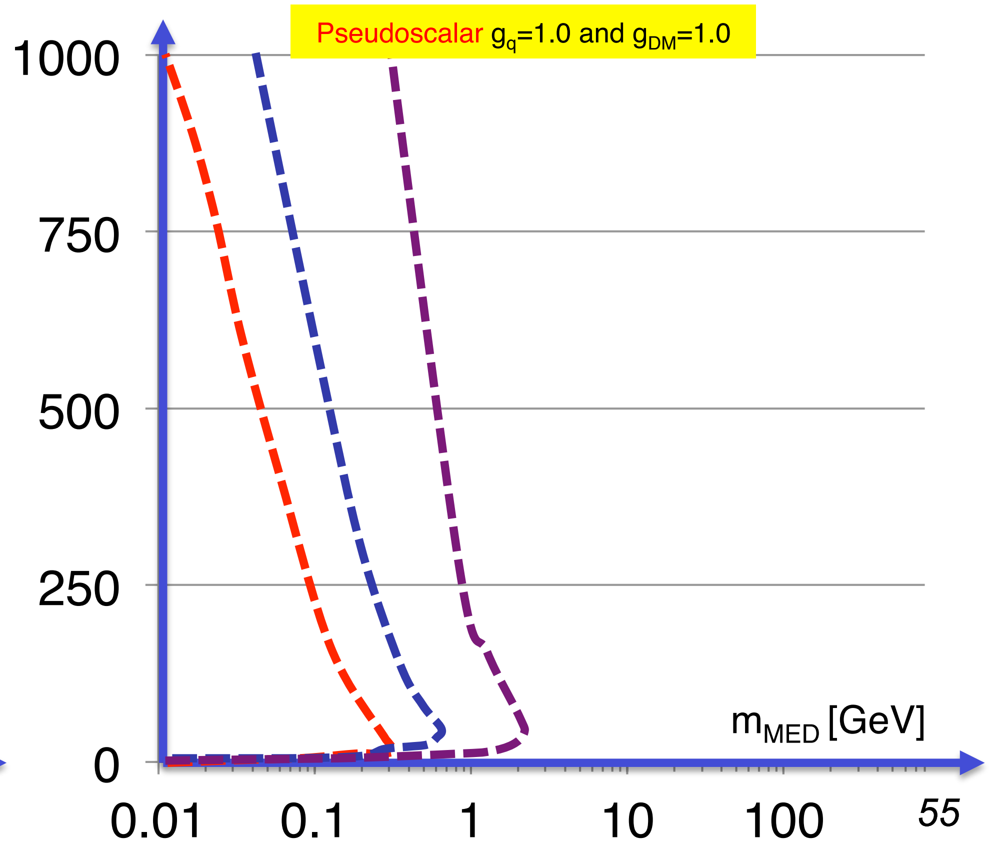
Axial-Vector simplified model: g_q=0.25 and g_{DM}=1.0

$$M_A = 1\ \mathrm{TeV} \left(\frac{2.38 \times 10^{-42}\ \mathrm{cm}^2}{\sigma^{SD}_{p,n}}\right)^{0.25} \cdot \left(\frac{g_{DM} g_q}{0.25}\right)^{0.5} \left(\frac{\mu_n}{1\ \mathrm{GeV}}\right)^{0.5} .$$

Based on arXiV:1407.8257
Numerical calculation provide by. C. McCabe

Pseudoscalar (PS) simplified model: g_q=1.0 and g_{DM}=1.0





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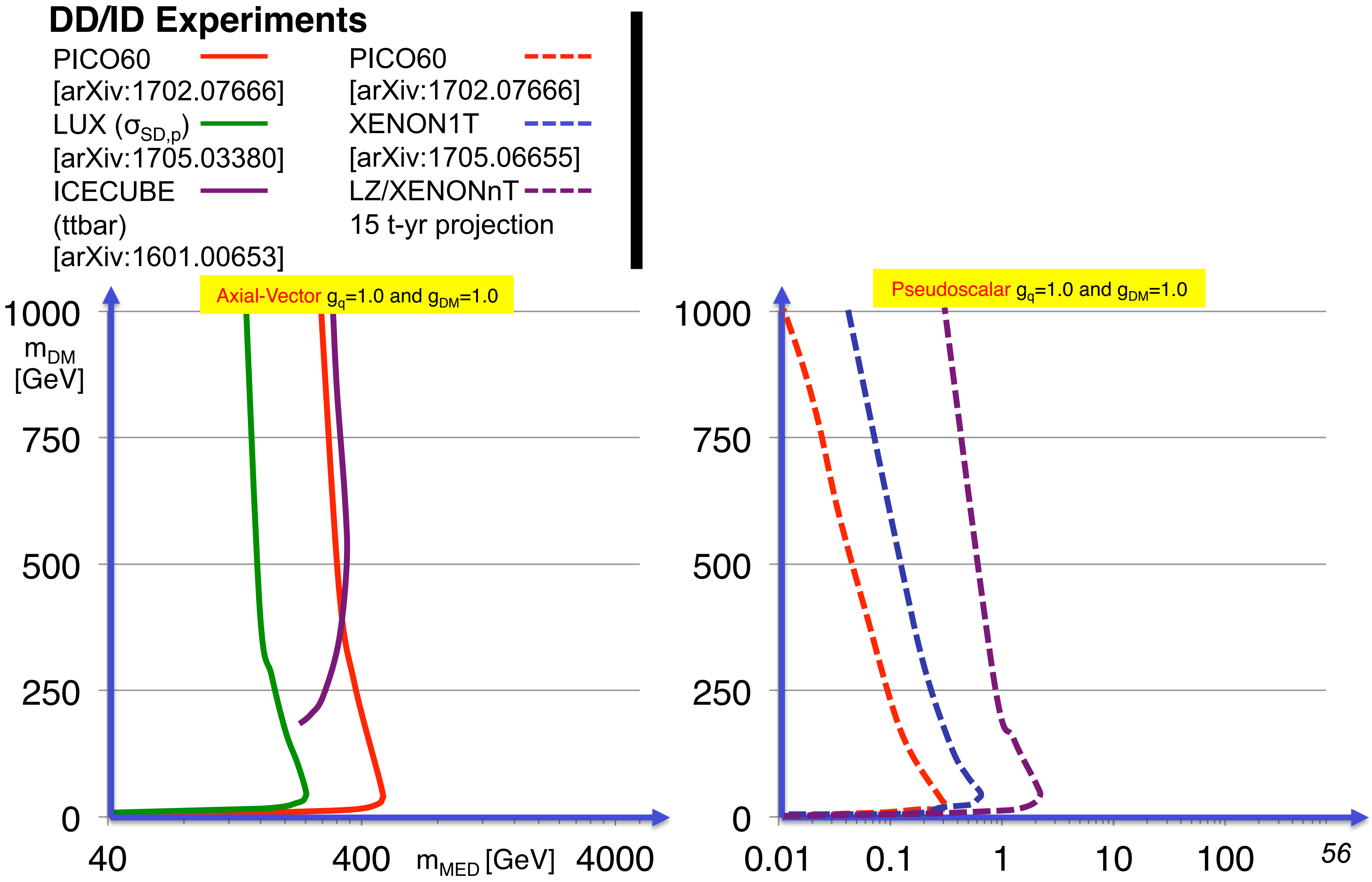
DD limits in collider plane: $\sigma_{SD(p,n)}$



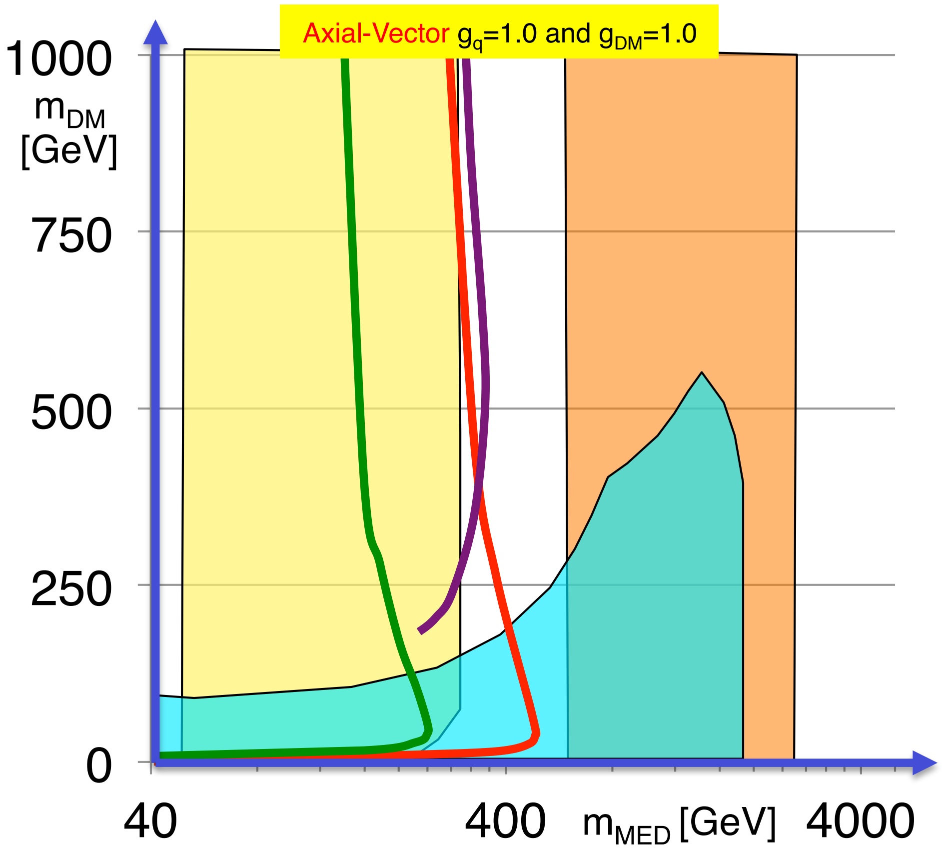
DD limits in collider plane: $\sigma_{SD(p,n)}$

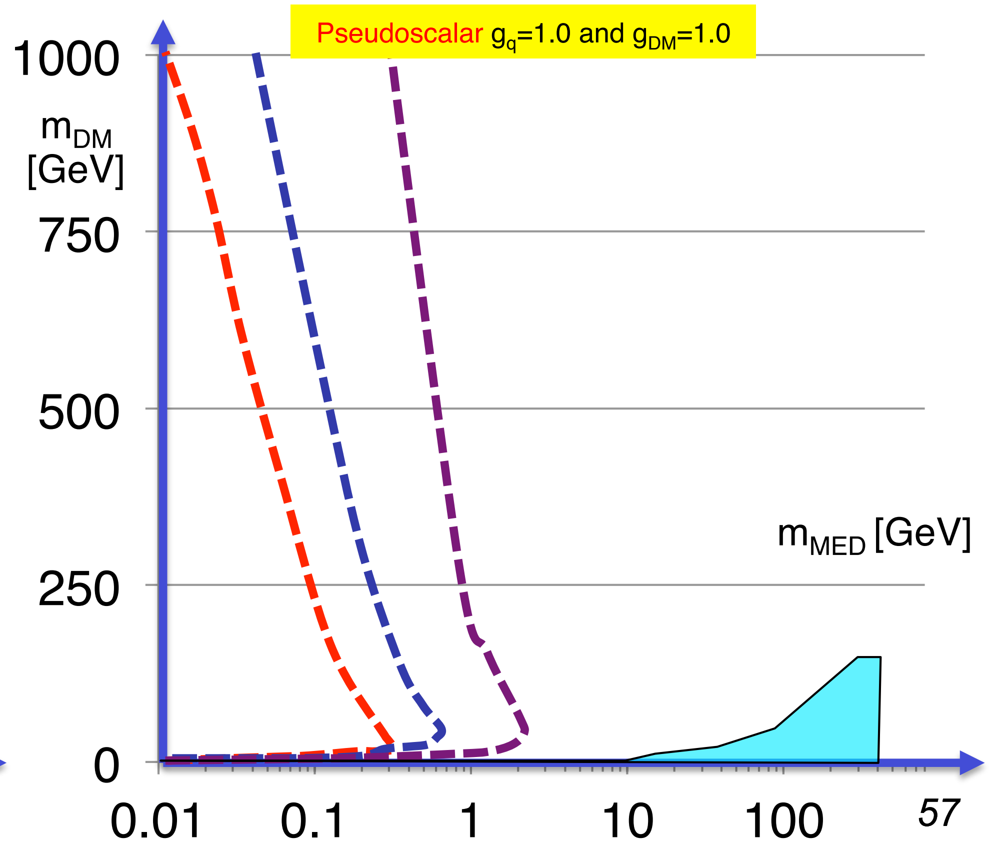
DD/ID Experiments

- PICO60 [arXiv:1702.07666] (solid red line)
- LUX ($\sigma_{SD,p}$) [arXiv:1705.03380] (solid green line)
- ICECUBE (ttbar) [arXiv:1601.00653] (solid purple line)
- PICO60 [arXiv:1702.07666] (dashed red line)
- XENON1T [arXiv:1705.06655] (dashed blue line)
- LZ/XENONnT 15 t-yr projection (dashed purple line)

Collider

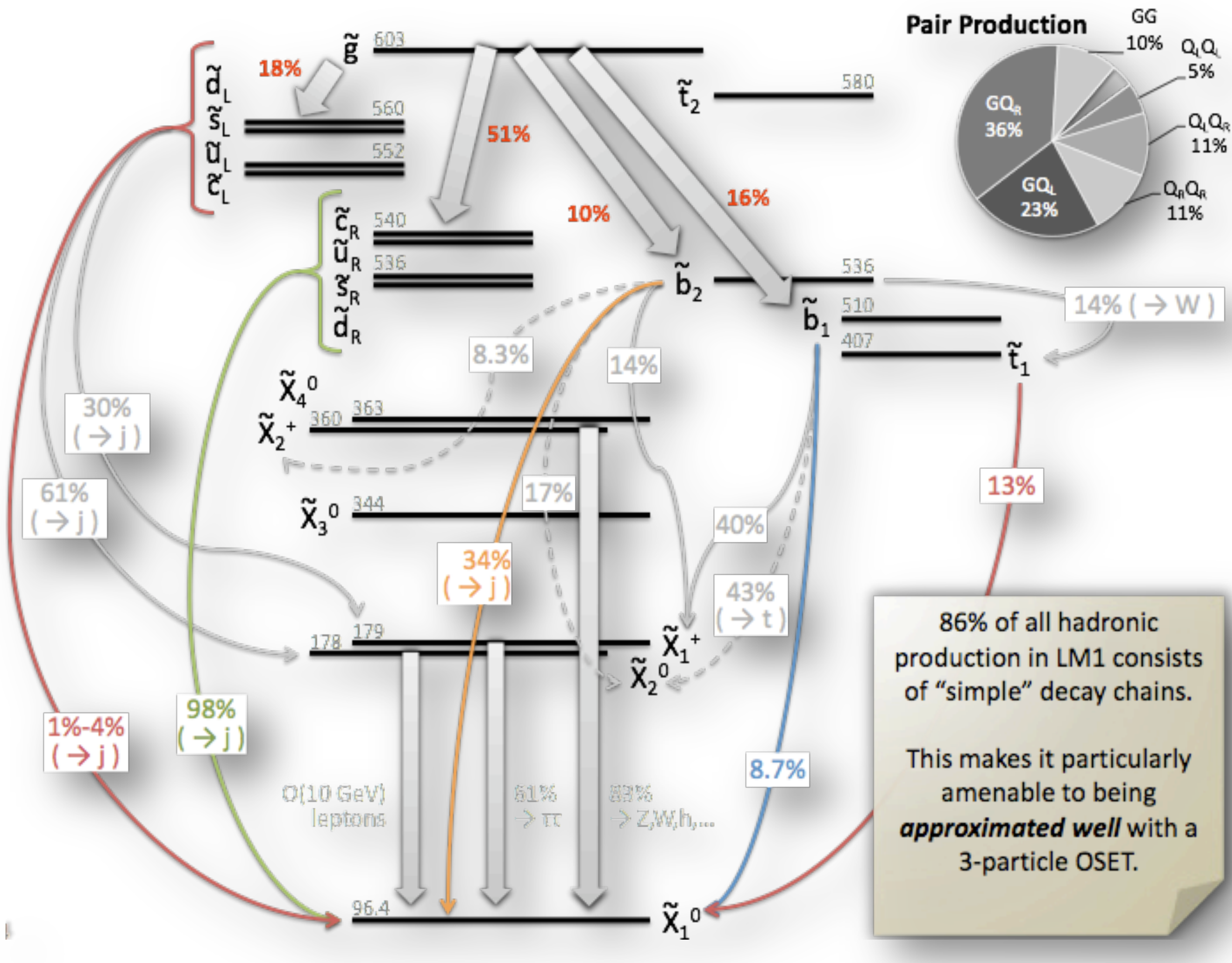
- Boosted dijet [EXO-17-001] (yellow)
- Dijet [EXO-16-056] (pink)
- Mono-jet [EXO-16-048] (cyan)



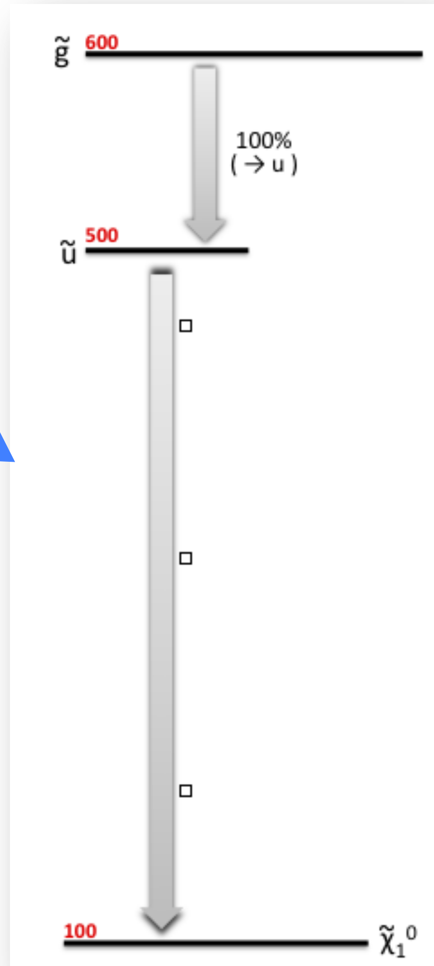


Interpretation od SUSY Searches in Simplified Models

CMSSM



What the individual searches are sensitive to is much more simple…



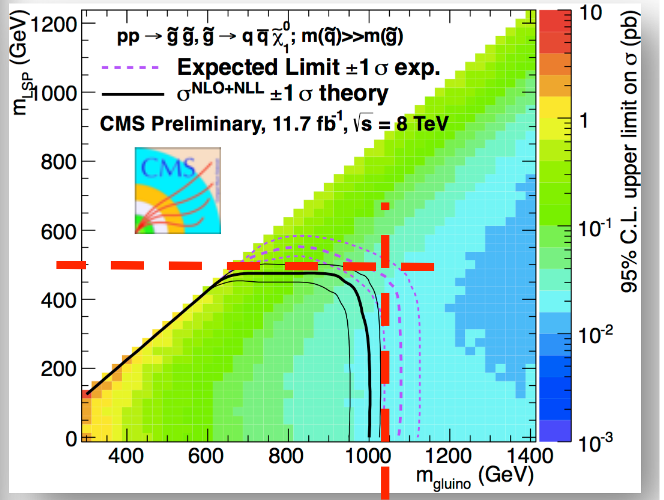
Simplified model spectrum (SMS)
with 3 particles, 2 decay modes

How to summarize SMS limits?

Approach taken in the 2012 and 2013 Experimental SUSY PDG reviews [OB & Paul De Jong]:

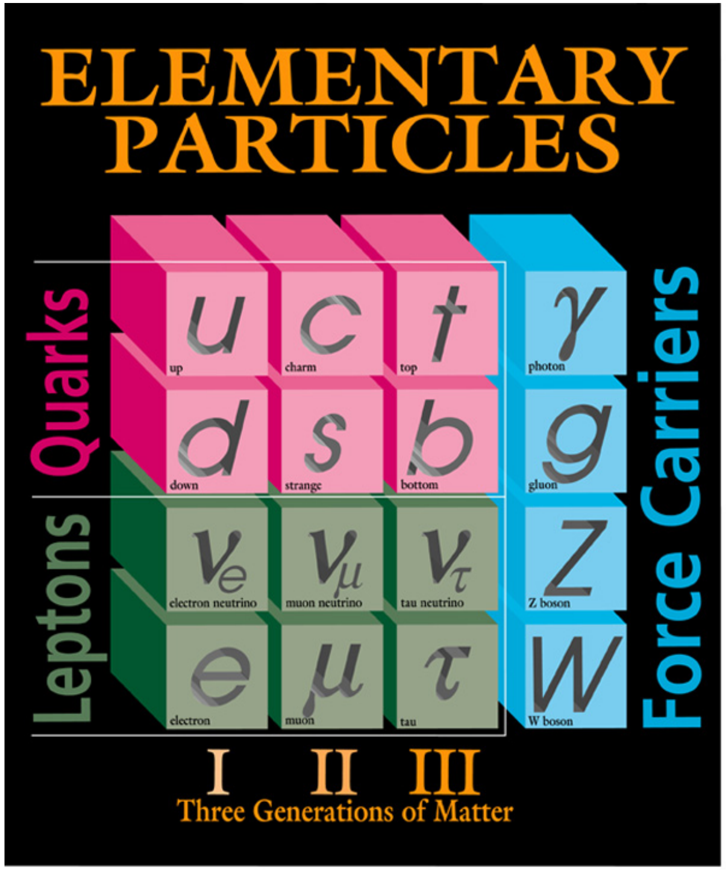
http://pdg.lbl.gov/2012/reviews/rpp2012-rev-susy-2-experiment.pdf
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf

Model	Assumption	$m_{\tilde{q}}$	$m_{\tilde{g}}$
CMSSM	$m_{\tilde{q}} \approx m_{\tilde{g}}$	1400	1400
	all $m_{\tilde{q}}$	-	800
	all $m_{\tilde{g}}$	1300	-
Simplified model $\tilde{g}\tilde{g}$	$m_{\tilde{\chi}_1^0} = 0$	-	900
	$m_{\tilde{\chi}_1^0} > 300$	-	no limit
Simplified model $\tilde{q}\tilde{q}$	$m_{\tilde{\chi}_1^0} = 0$	750	-
	$m_{\tilde{\chi}_1^0} > 250$	no limit	-
Simplified model $\tilde{g}\tilde{q}, \tilde{g}\bar{\tilde{q}}$	$m_{\tilde{\chi}_1^0} = 0$, $m_{\tilde{q}} \approx m_{\tilde{g}}$	1500	1500
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{g}}$	1400	-
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{q}}$	-	900



This was an appropriate approach for the rather limited amount of inclusive searches and corresponding SMS interpretations available in 2011 (7 TeV).

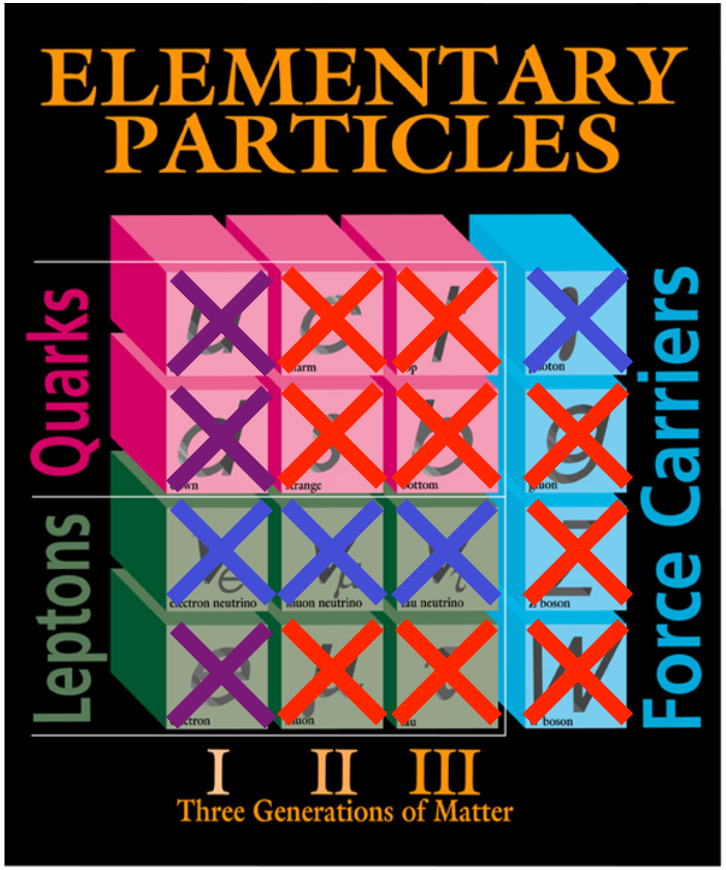
Dark Matter: Particle Hypothesis



Fermilab 95-759

Known DM properties

Dark Matter: Particle Hypothesis

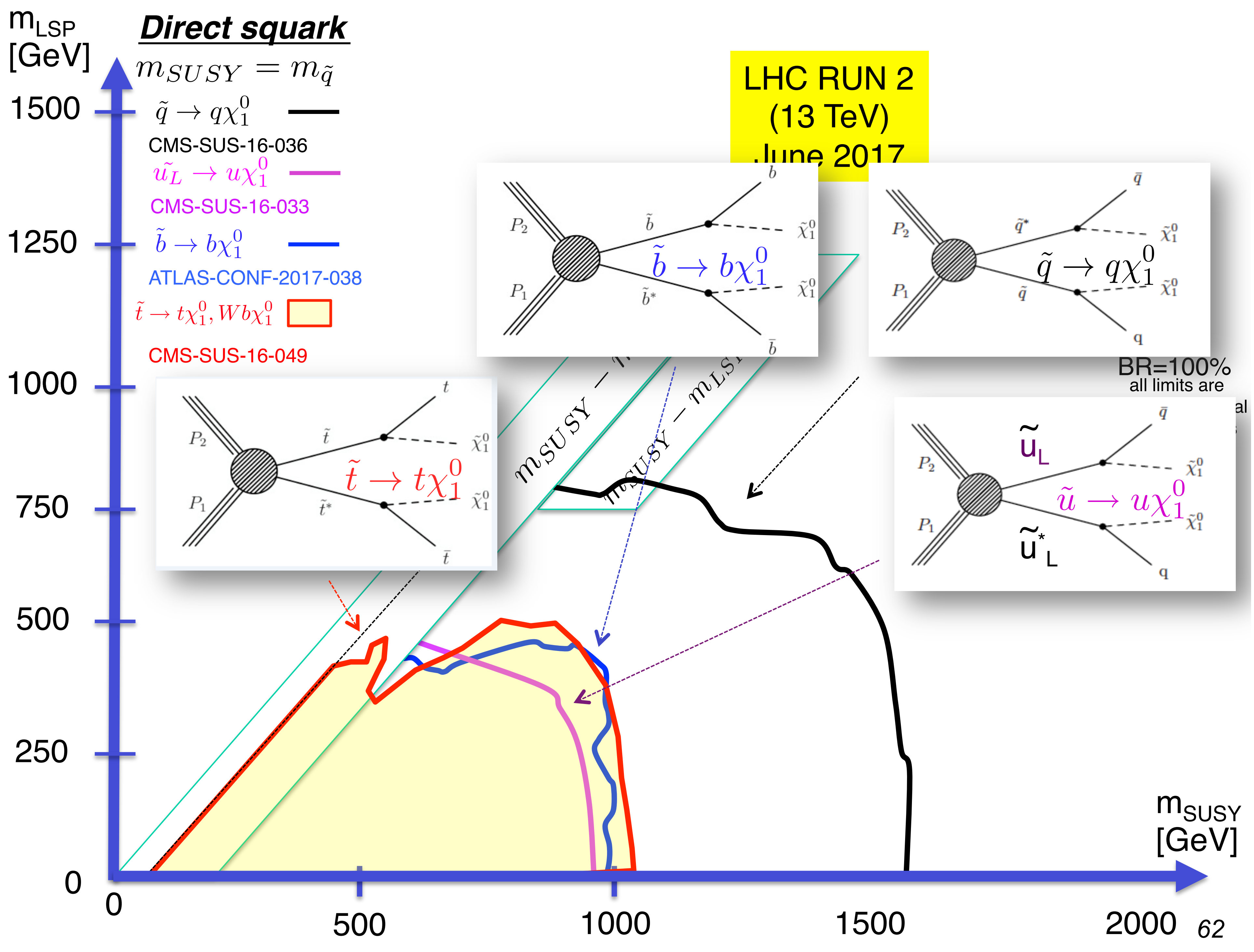


Fermilab 95-759

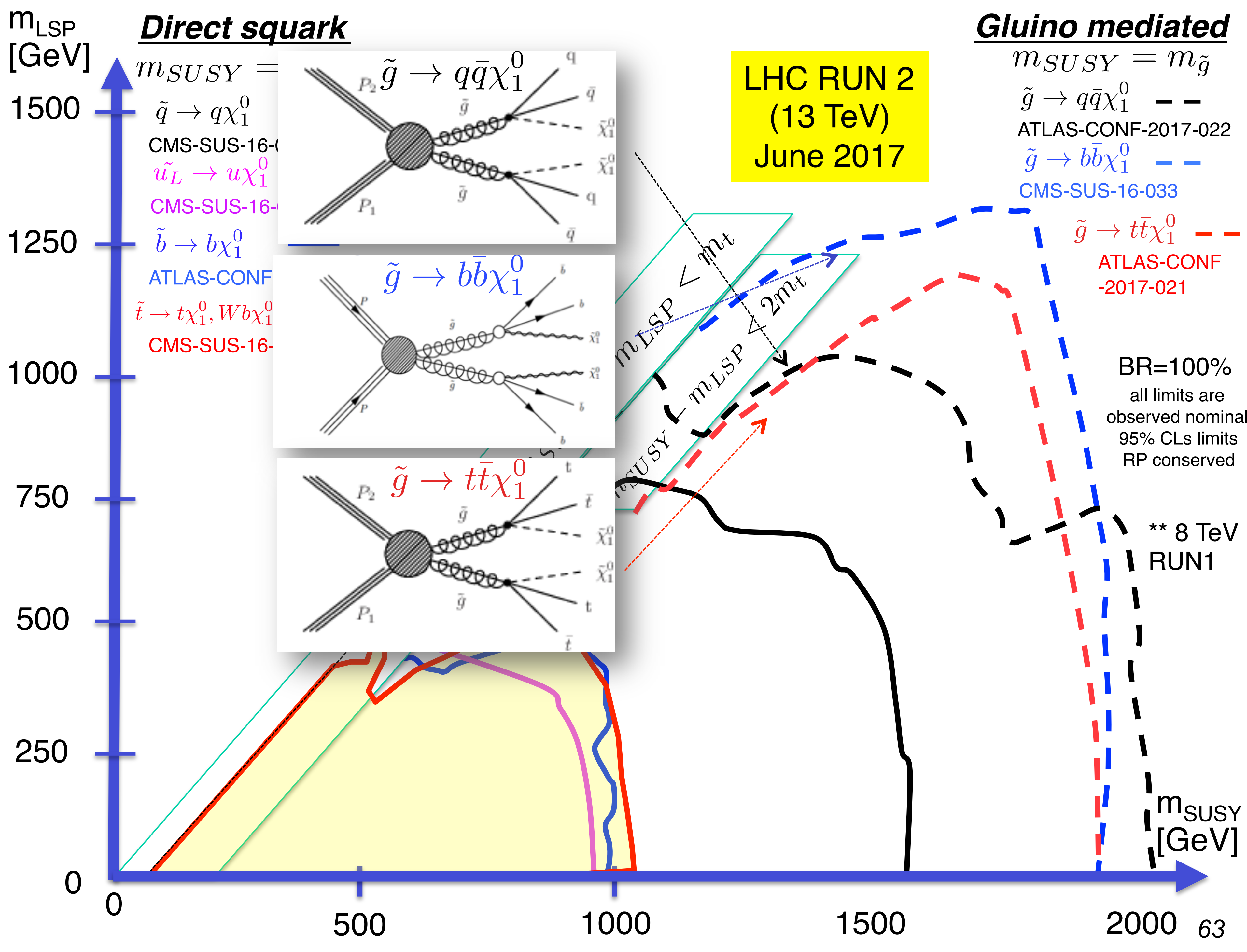
Known DM properties:

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

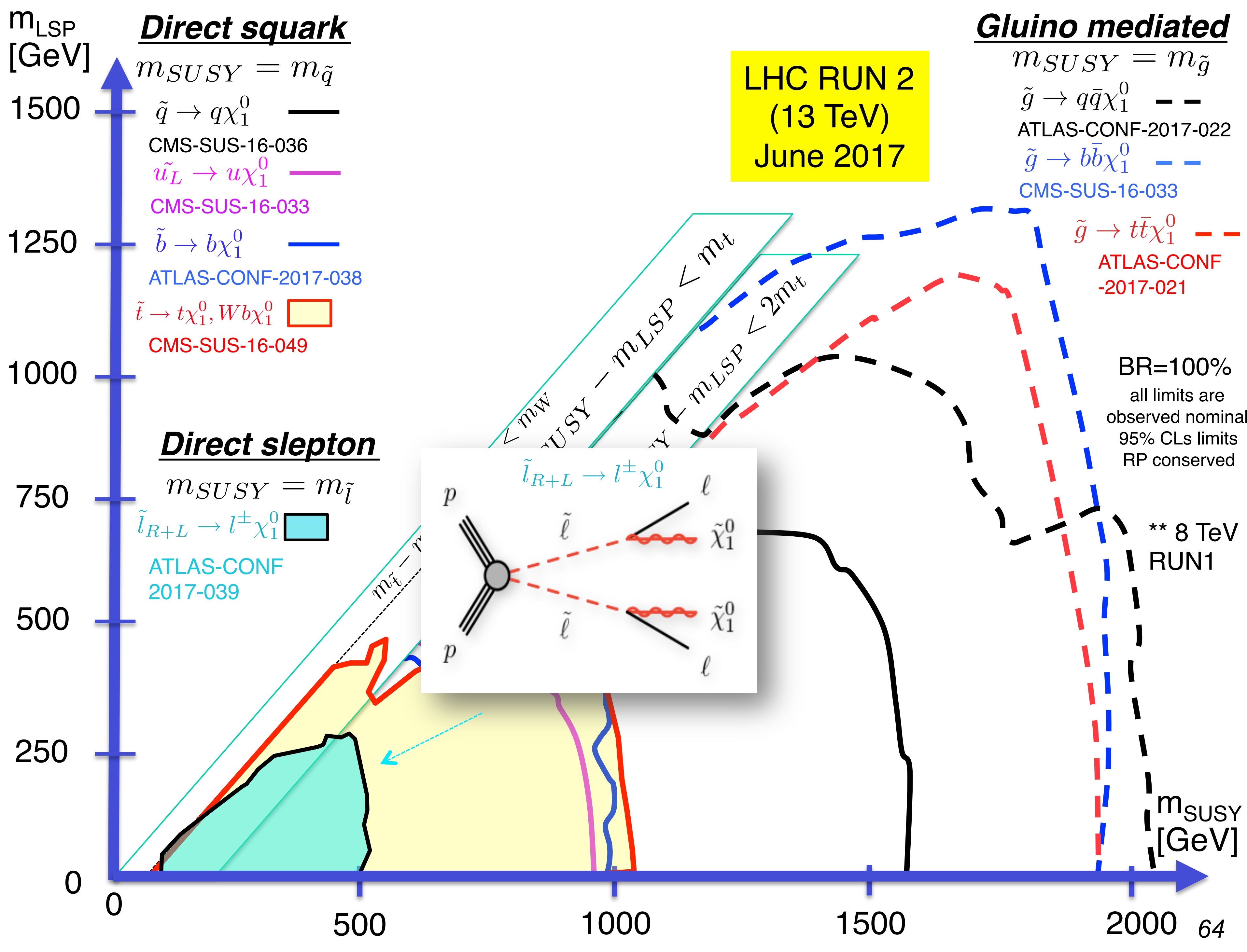
Hypothesis: Dark Matter is a new particle (or particles)



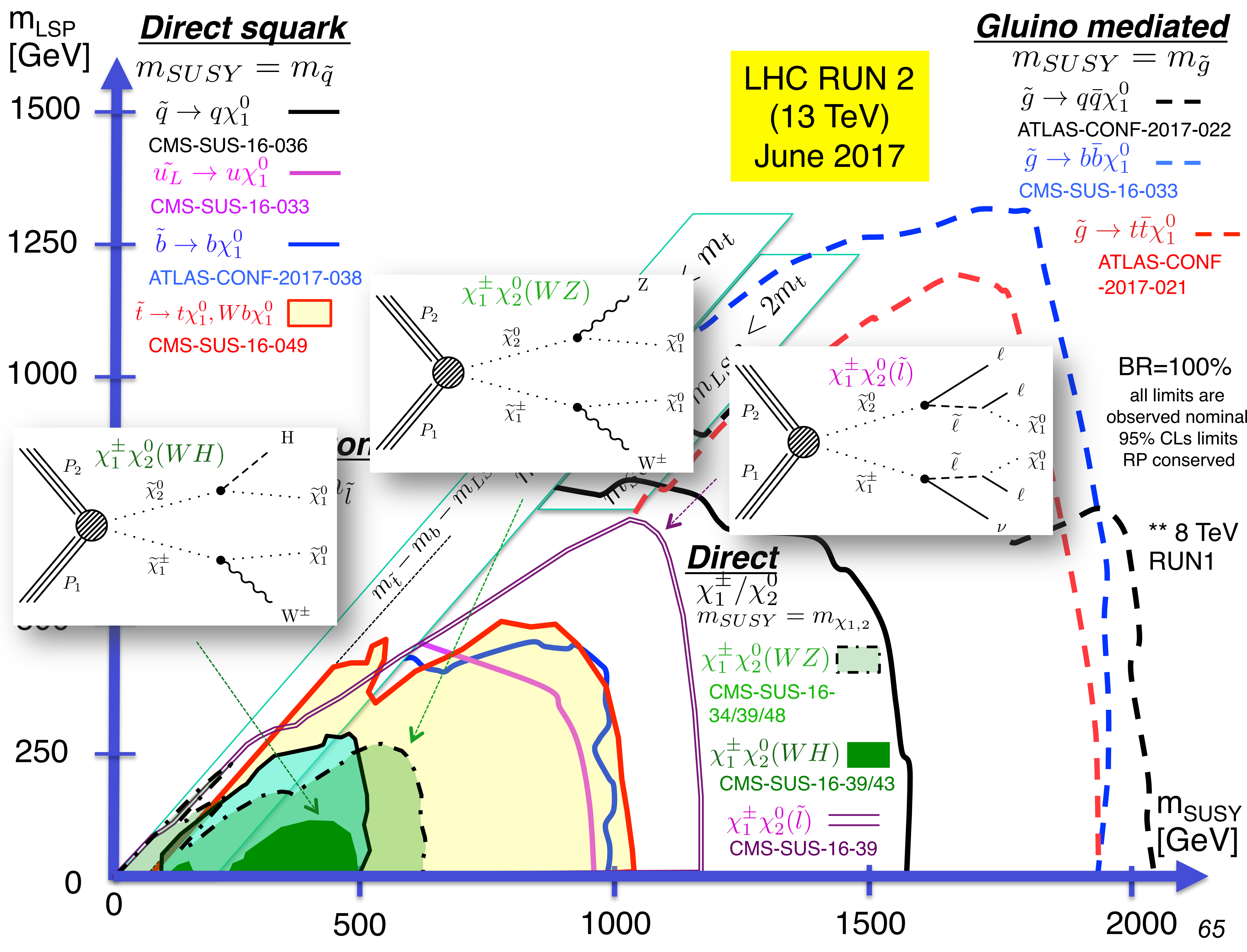
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
m_{LSP} [GeV]
1500
1250
1000
750
500
250
0
$\tilde{q} \rightarrow q\chi_1^0$
CMS-SUS-16-036
$\tilde{u}_L \rightarrow u\chi_1^0$
CMS-SUS-16-033
$\tilde{b} \rightarrow b\chi_1^0$
ATLAS-CONF-2017-038
$\tilde{t} \rightarrow t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
BR=100%
all limits are
$\tilde{b} \rightarrow b\chi_1^0$
$\tilde{q} \rightarrow q\chi_1^0$
$\tilde{t} \rightarrow t\chi_1^0$
$\tilde{u}_L$
$\tilde{u} \rightarrow u\chi_1^0$
$\tilde{u}^*_L$
m_{SUSY} [GeV]
0
500
1000
1500
2000



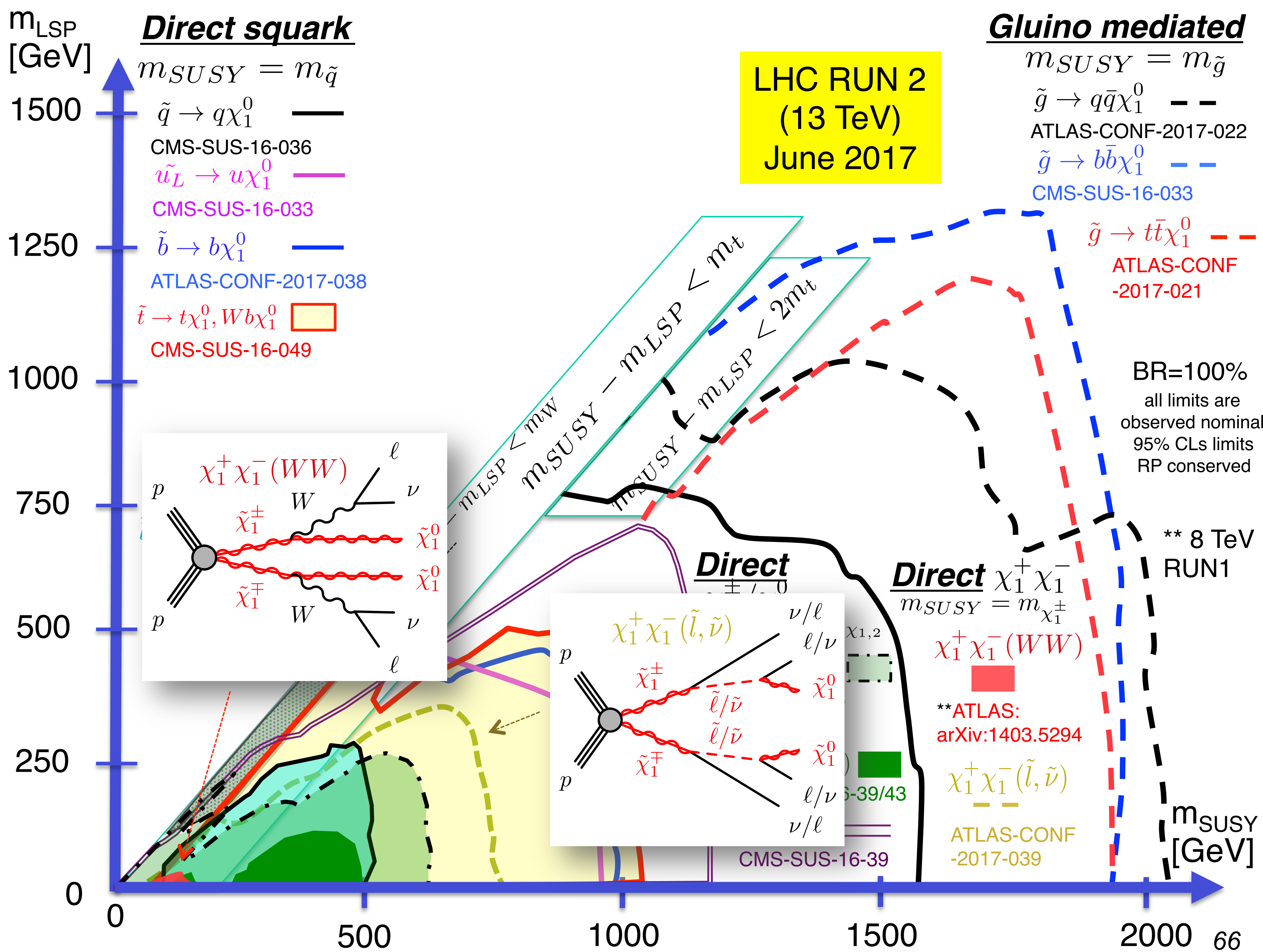
m_LSP [GeV]
Direct squark
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{q} \to q\chi_1^0$
CMS-SUS-16-0
$\tilde{u_L} \to u\chi_1^0$
CMS-SUS-16-0
$\tilde{b} \to b\chi_1^0$
ATLAS-CONF
$\tilde{t} \to t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-
$\tilde{g} \to q\bar{q}\chi_1^0$
$\tilde{g} \to b\bar{b}\chi_1^0$
$\tilde{g} \to t\bar{t}\chi_1^0$
LHC RUN 2
(13 TeV)
June 2017
ATLAS-CONF-2017-022
CMS-SUS-16-033
ATLAS-CONF
-2017-021
$m_{LSP} < m_t$
$m_{LSP} < 2m_t$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
** 8 TeV
RUN1
m_SUSY [GeV]
1500
1250
1000
750
500
250
0
0
500
1000
1500
2000



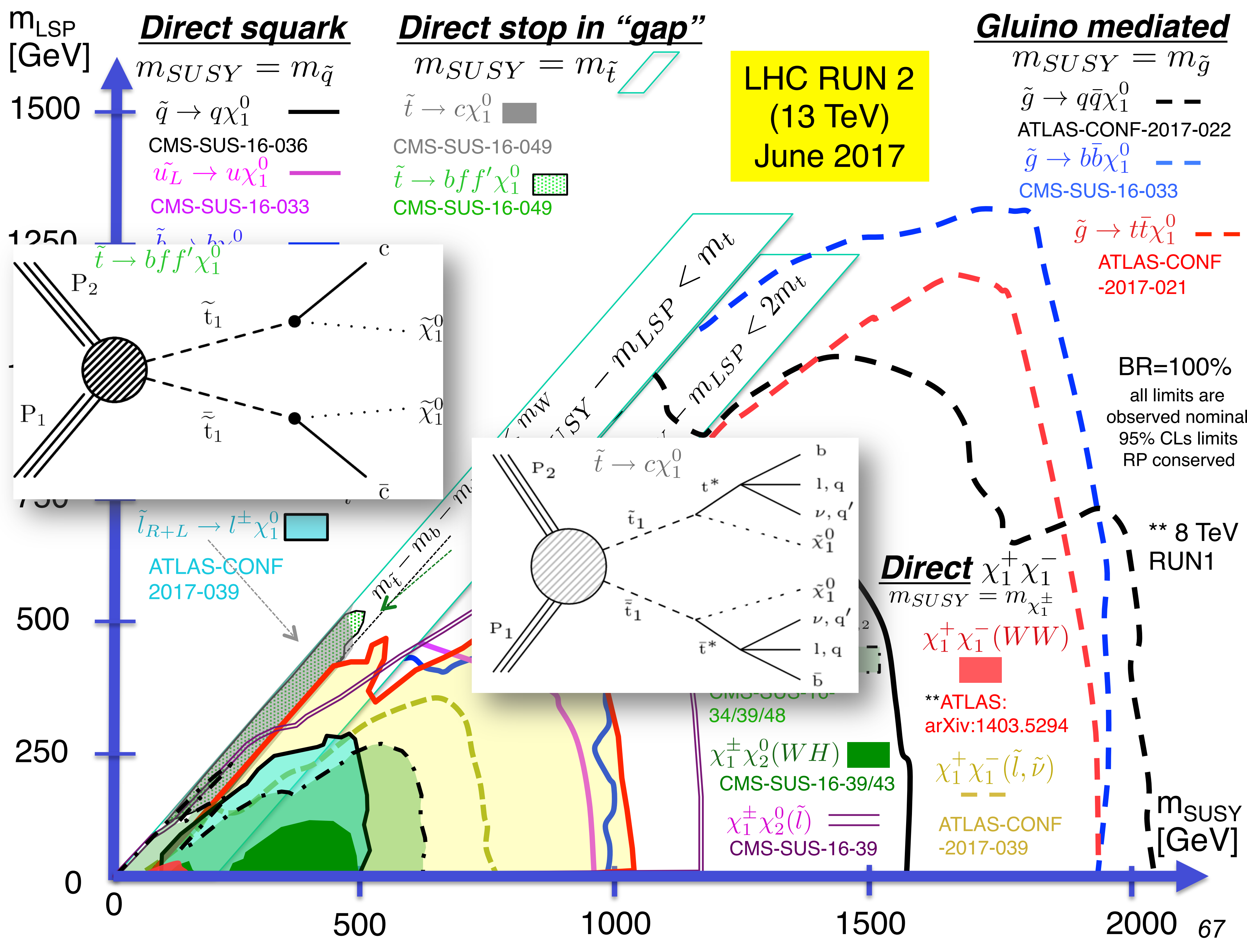
m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS-SUS-16-036
$\tilde{u}_L \to u\chi_1^0$
CMS-SUS-16-033
$\tilde{b} \to b\chi_1^0$
ATLAS-CONF-2017-038
$\tilde{t} \to t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF
-2017-021
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
** 8 TeV
RUN1
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_{R+L} \to l^{\pm}\chi_1^0$
ATLAS-CONF
2017-039
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$< m_W$
p
$\tilde{\ell}$
$\tilde{\chi}_1^0$
ℓ
1500
1250
1000
750
500
250
0
0
500
1000
1500
2000
m_{SUSY} [GeV]



m_LSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS-SUS-16-036
$\tilde{u}_L \to u\chi_1^0$
CMS-SUS-16-033
$\tilde{b} \to b\chi_1^0$
ATLAS-CONF-2017-038
$\tilde{t} \to t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF
-2017-021
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
** 8 TeV
RUN1
$\chi_1^\pm\chi_2^0(WH)$
$\chi_1^\pm\chi_2^0(WZ)$
$\chi_1^\pm\chi_2^0(\tilde{l})$
$m_{\tilde{t}} - m_b - m_{LSP}$
Direct
$\chi_1^\pm/\chi_2^0$
$m_{SUSY} = m_{\chi_{1,2}}$
$\chi_1^\pm\chi_2^0(WZ)$
CMS-SUS-16-
34/39/48
$\chi_1^\pm\chi_2^0(WH)$
CMS-SUS-16-39/43
$\chi_1^\pm\chi_2^0(\tilde{l})$
CMS-SUS-16-39
m_SUSY [GeV]
1500
1250
1000
250
0
0
500
1000
1500
2000



m_LSP [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$
CMS-SUS-16-036
$\tilde{u}_L \rightarrow u\chi_1^0$
CMS-SUS-16-033
$\tilde{b} \rightarrow b\chi_1^0$
ATLAS-CONF-2017-038
$\tilde{t} \rightarrow t\chi_1^0, Wb\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \rightarrow q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
ATLAS-CONF
-2017-021
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
** 8 TeV
RUN1
$m_{SUSY} - m_{LSP} < m_W$
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$\chi_1^+\chi_1^-(WW)$
Direct
Direct $\chi_1^+\chi_1^-$
$m_{SUSY} = m_{\chi_1^\pm}$
$\chi_1^+\chi_1^-(WW)$
**ATLAS:
arXiv:1403.5294
$\chi_1^+\chi_1^-(\tilde{l},\tilde{\nu})$
ATLAS-CONF
-2017-039
$\chi_1^+\chi_1^-(\tilde{l},\tilde{\nu})$
-39/43
CMS-SUS-16-39
m_SUSY [GeV]
0
250
500
750
1000
1250
1500
0
500
1000
1500
2000



m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS-SUS-16-036
$\tilde{u}_L \to u\chi_1^0$
CMS-SUS-16-033
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$
CMS-SUS-16-049
$\tilde{t} \to bff'\chi_1^0$
CMS-SUS-16-049
LHC RUN 2
(13 TeV)
June 2017
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS-CONF-2017-022
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS-SUS-16-033
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS-CONF
-2017-021
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
** 8 TeV
RUN1
$m_{SUSY} - m_{LSP} < m_t$
$m_{LSP} < 2m_t$
$\tilde{l}_{R+L} \to l^{\pm}\chi_1^0$
ATLAS-CONF
2017-039
Direct $\chi_1^+\chi_1^-$
$m_{SUSY} = m_{\chi_1^{\pm}}$
$\chi_1^+\chi_1^-(WW)$
**ATLAS:
arXiv:1403.5294
34/39/48
$\chi_1^{\pm}\chi_2^0(WH)$
CMS-SUS-16-39/43
$\chi_1^+\chi_1^-(\tilde{l},\tilde{\nu})$
ATLAS-CONF
-2017-039
$\chi_1^{\pm}\chi_2^0(\tilde{l})$
CMS-SUS-16-39
m_{SUSY} [GeV]
0
250
500
750
1250
1500
0
500
1000
1500
2000

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DM Mechanisms

stau coann. | $\tilde{\chi}_1^{\pm}$ coann. | slep coann | gluino coann. | squark coann.

$$\left(\frac{M_{\tilde{\tau}}}{m_{\chi_1^0}} - 1\right) < 0.15$$

Stau coannihilation

$$\left|\frac{M_B}{m_{\chi_1^0}} - 2\right| < 0.4$$

B = h, Z or H/A funnel

$$\left(\frac{M_{\chi_1^{\pm}}}{m_{\chi_1^0}} - 1\right) < 0.25$$

Chargino Co-annihilation

$$\left|\frac{\mu}{m_{\chi_1^0}} - 1\right| < 0.30$$

Higgsino enriched "focus-point" like

$$\left(\frac{M_{\tilde{l}}}{m_{\chi_1^0}} - 1\right) < 0.15$$

Slepton Co-annihilation

$$\left(\frac{M_{\tilde{g}}}{m_{\chi_1^0}} - 1\right) < 0.25$$

Gluino Co-annihilation

$$\left(\frac{M_{\tilde{q}}}{m_{\chi_1^0}} - 1\right) < 0.20$$

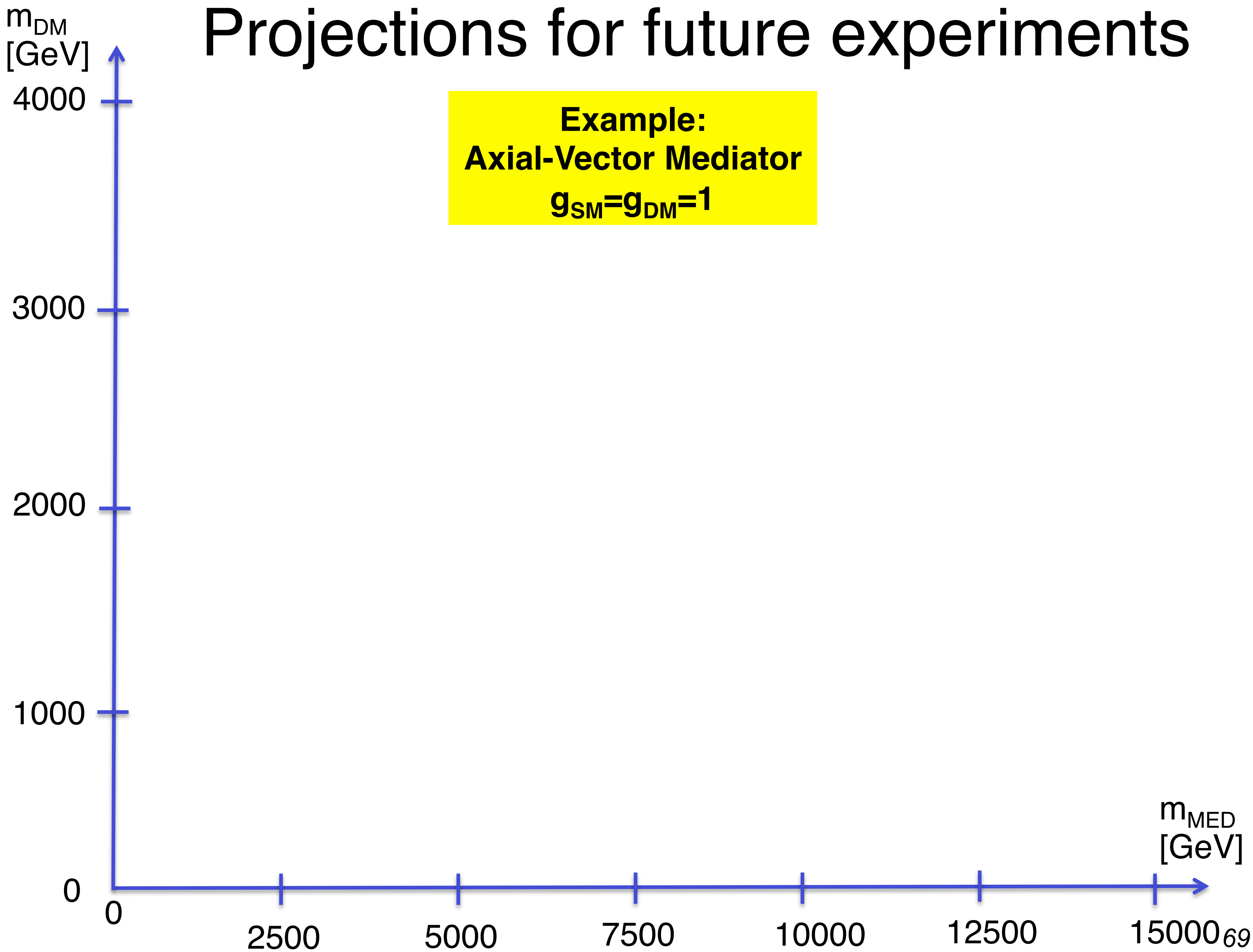
Squark Co-annihilation

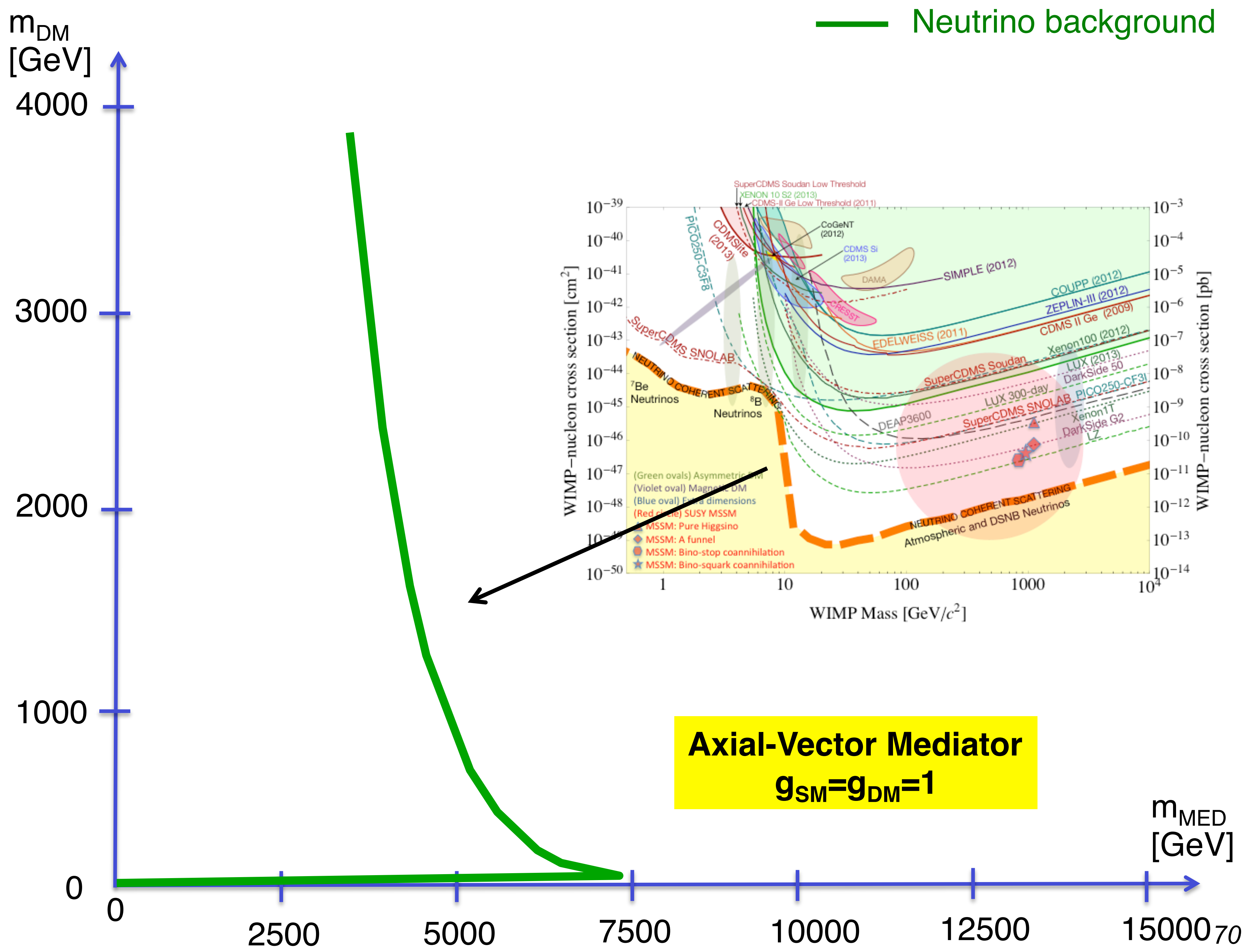
Hybrid regions:
In addition to the `primary' regions where only one of the conditions is satisfied, there are also `hybrid' regions where more than one condition is satisfied. These are indicated using combined colours.

See also arXiv:1508.01173 for further details

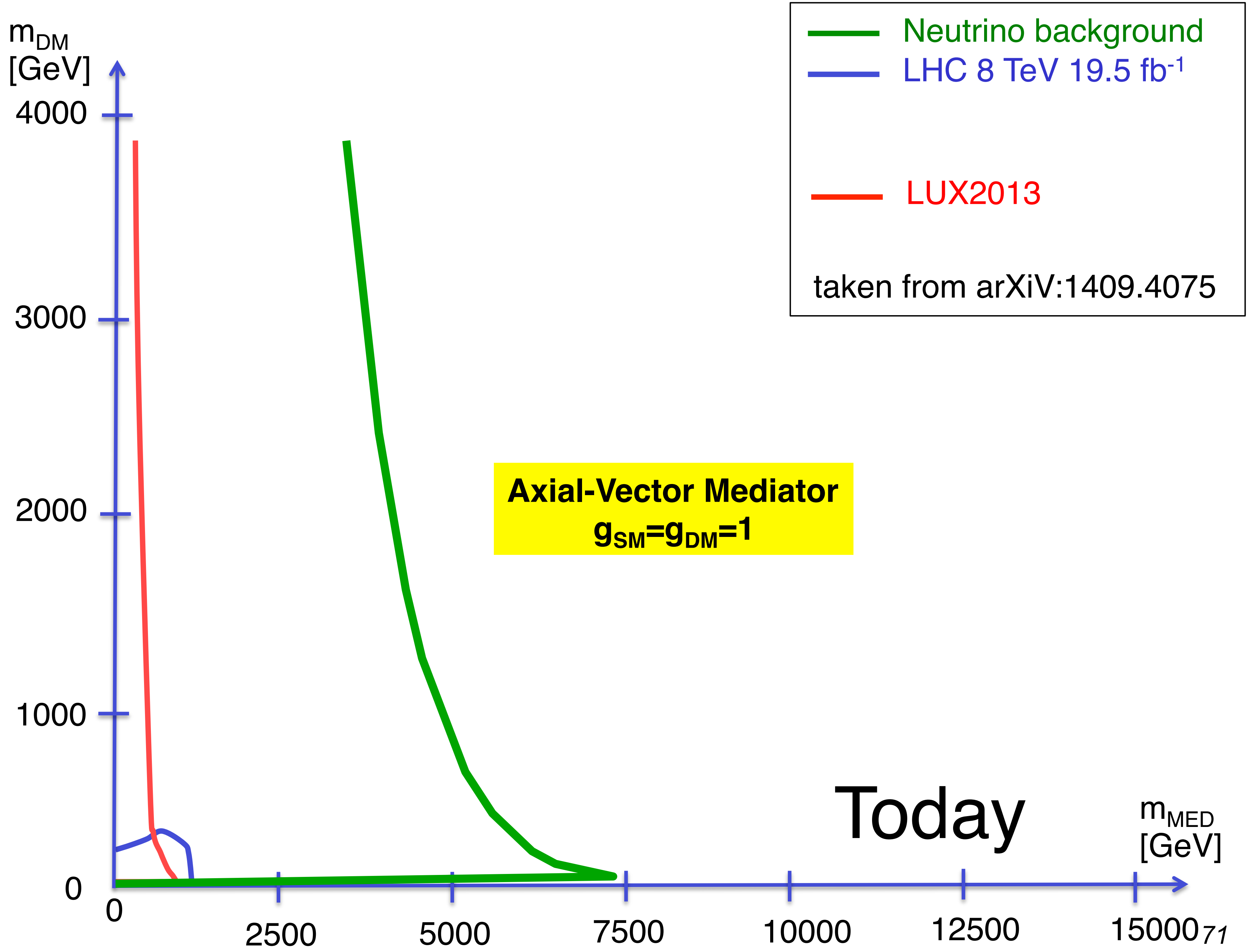
Projections for future experiments

Example:
Axial-Vector Mediator
$g_{SM}=g_{DM}=1$

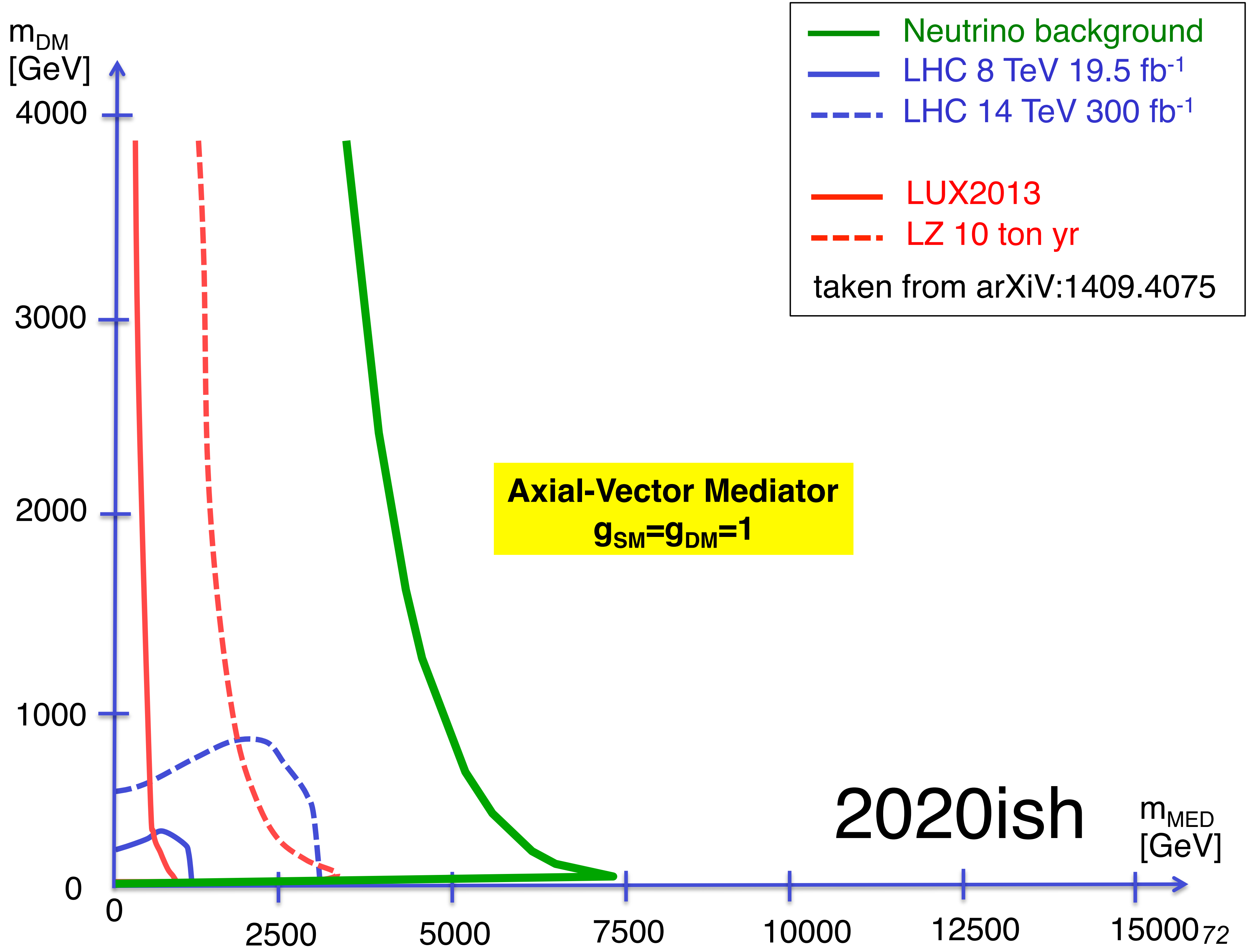




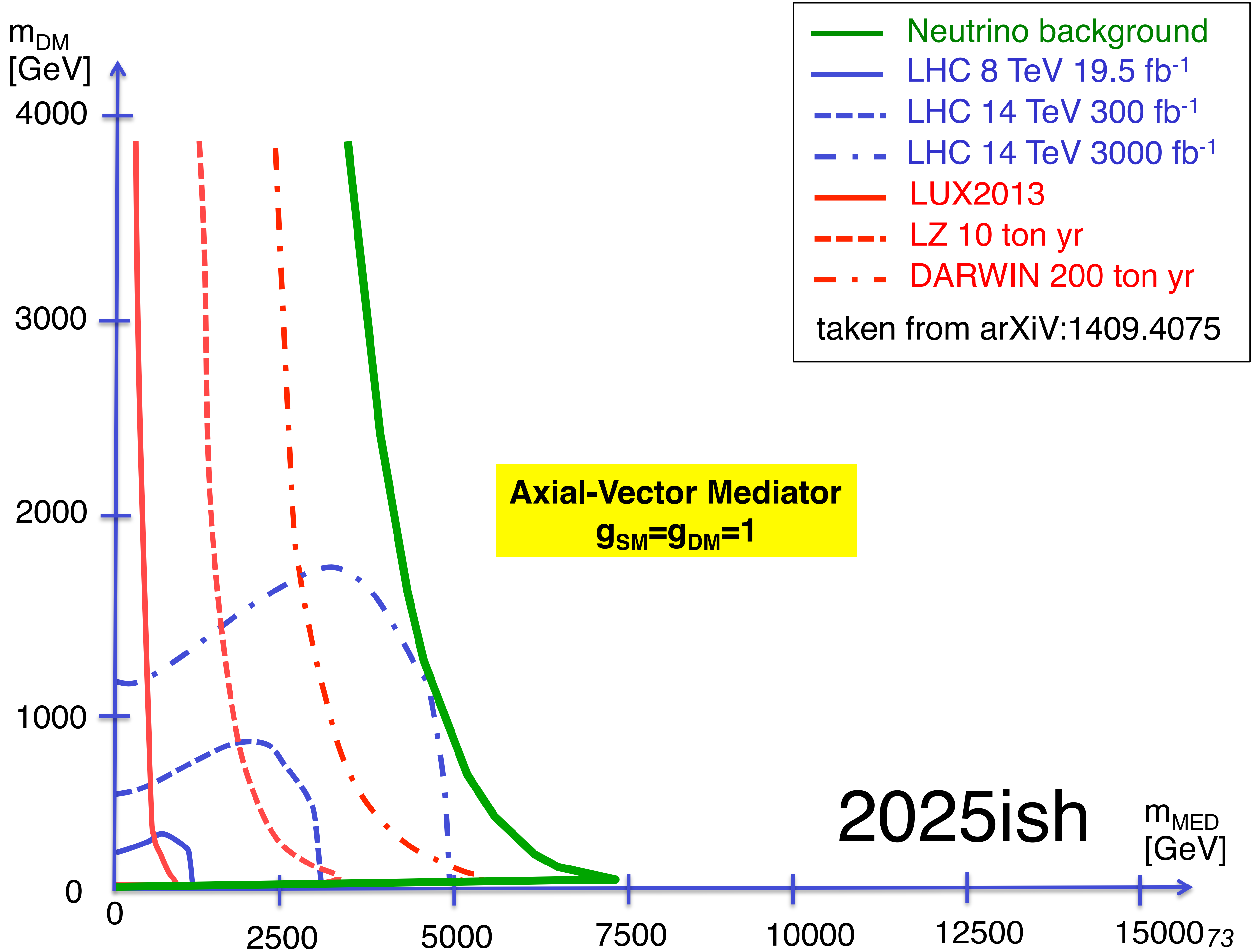
Neutrino background
m_{DM} [GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000
m_{MED} [GeV]
Axial-Vector Mediator
$g_{SM}=g_{DM}=1$
WIMP–nucleon cross section [cm²]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c²]
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
CRESST
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
DarkSide 50
SuperCDMS Soudan
LUX 300-day
PICO250-CF3I
SuperCDMS SNOLAB
Xenon1T
DarkSide G2
LZ
DEAP3600
CDMSlite (2013)
PICO250-C3F8
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
⁷Be Neutrinos
⁸B Neutrinos
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation



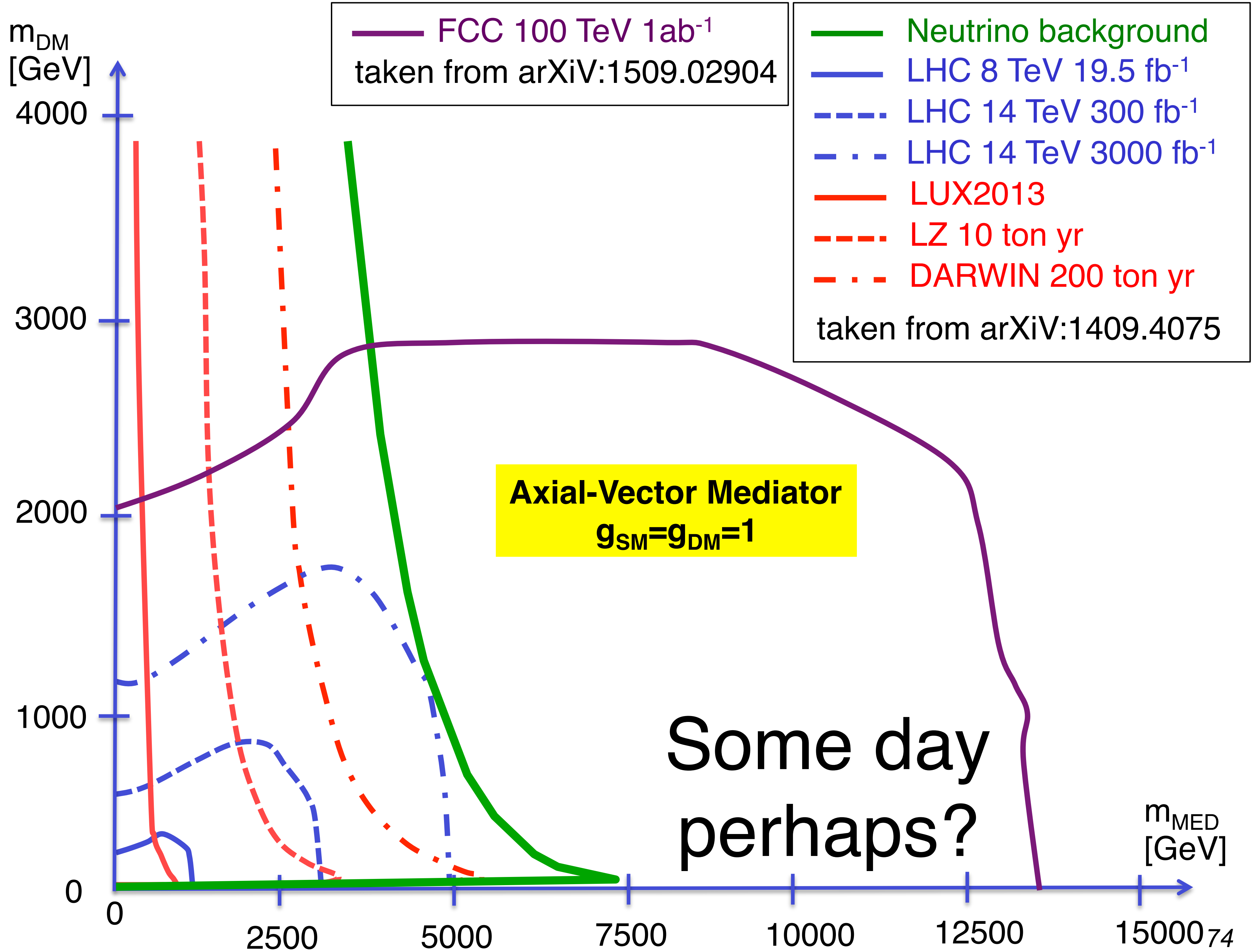
m_DM [GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000
m_MED [GeV]
Neutrino background
LHC 8 TeV 19.5 fb-1
LUX2013
taken from arXiV:1409.4075
Axial-Vector Mediator
gSM=gDM=1
Today



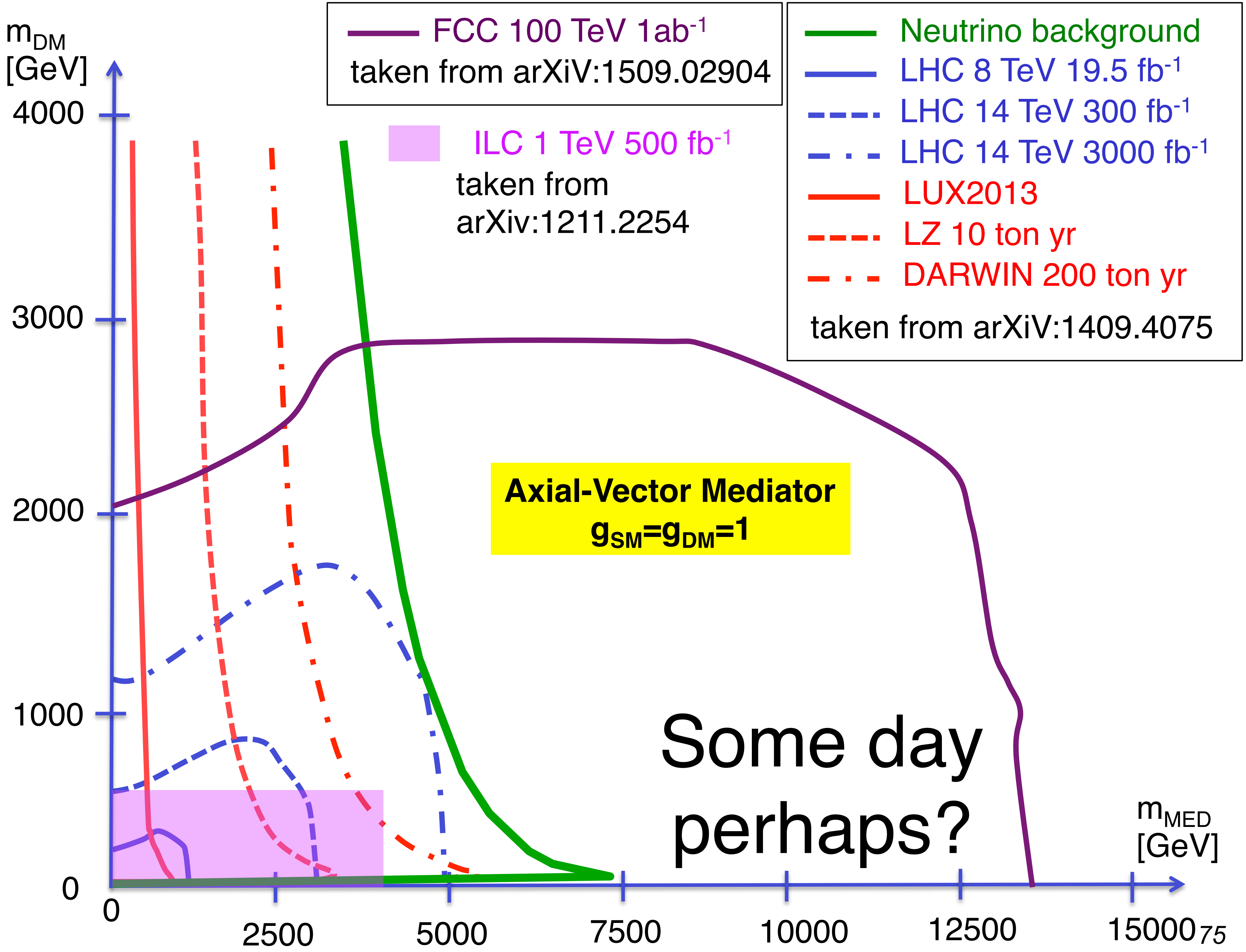
m_{DM} [GeV]
4000
3000
2000
1000
0
Neutrino background
LHC 8 TeV 19.5 fb^{-1}
LHC 14 TeV 300 fb^{-1}
LUX2013
LZ 10 ton yr
taken from arXiV:1409.4075
Axial-Vector Mediator
$g_{SM}=g_{DM}=1$
2020ish
m_{MED} [GeV]
0
2500
5000
7500
10000
12500
15000



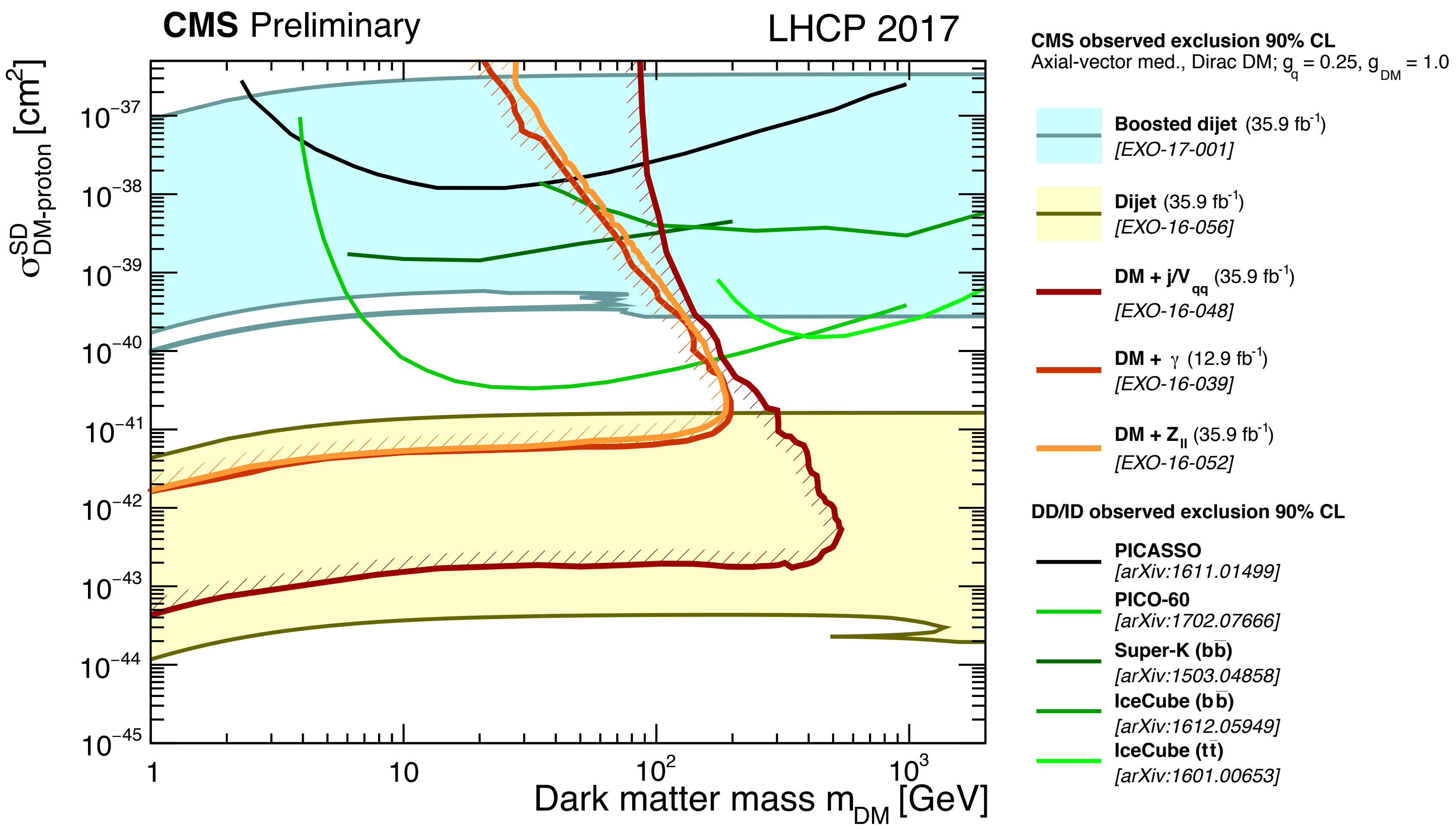
m_DM [GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000
m_MED [GeV]
Neutrino background
LHC 8 TeV 19.5 fb-1
LHC 14 TeV 300 fb-1
LHC 14 TeV 3000 fb-1
LUX2013
LZ 10 ton yr
DARWIN 200 ton yr
taken from arXiV:1409.4075
Axial-Vector Mediator
gSM=gDM=1
2025ish



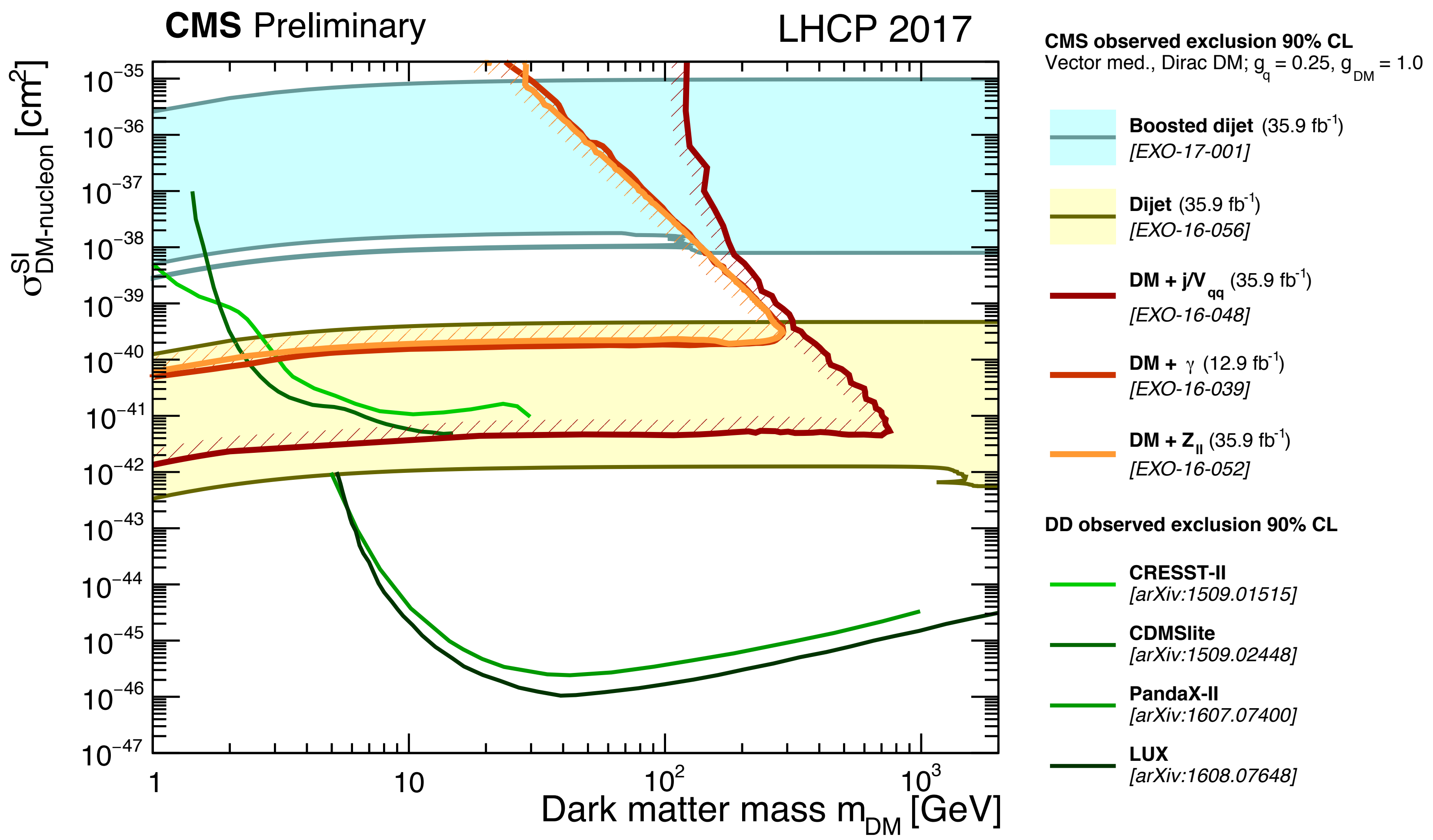
FCC 100 TeV 1ab-1
taken from arXiV:1509.02904
Neutrino background
LHC 8 TeV 19.5 fb-1
LHC 14 TeV 300 fb-1
LHC 14 TeV 3000 fb-1
LUX2013
LZ 10 ton yr
DARWIN 200 ton yr
taken from arXiV:1409.4075
mDM [GeV]
4000
3000
2000
1000
0
0
2500
5000
7500
10000
12500
15000
mMED [GeV]
Axial-Vector Mediator
gSM=gDM=1
Some day perhaps?


m_{DM} [GeV]
4000
3000
2000
1000
0
FCC 100 TeV 1ab^{-1}
taken from arXiV:1509.02904
ILC 1 TeV 500 fb^{-1}
taken from arXiv:1211.2254
Neutrino background
LHC 8 TeV 19.5 fb^{-1}
LHC 14 TeV 300 fb^{-1}
LHC 14 TeV 3000 fb^{-1}
LUX2013
LZ 10 ton yr
DARWIN 200 ton yr
taken from arXiV:1409.4075
Axial-Vector Mediator
$g_{SM}=g_{DM}=1$
Some day perhaps?
m_{MED} [GeV]
0
2500
5000
7500
10000
12500
15000

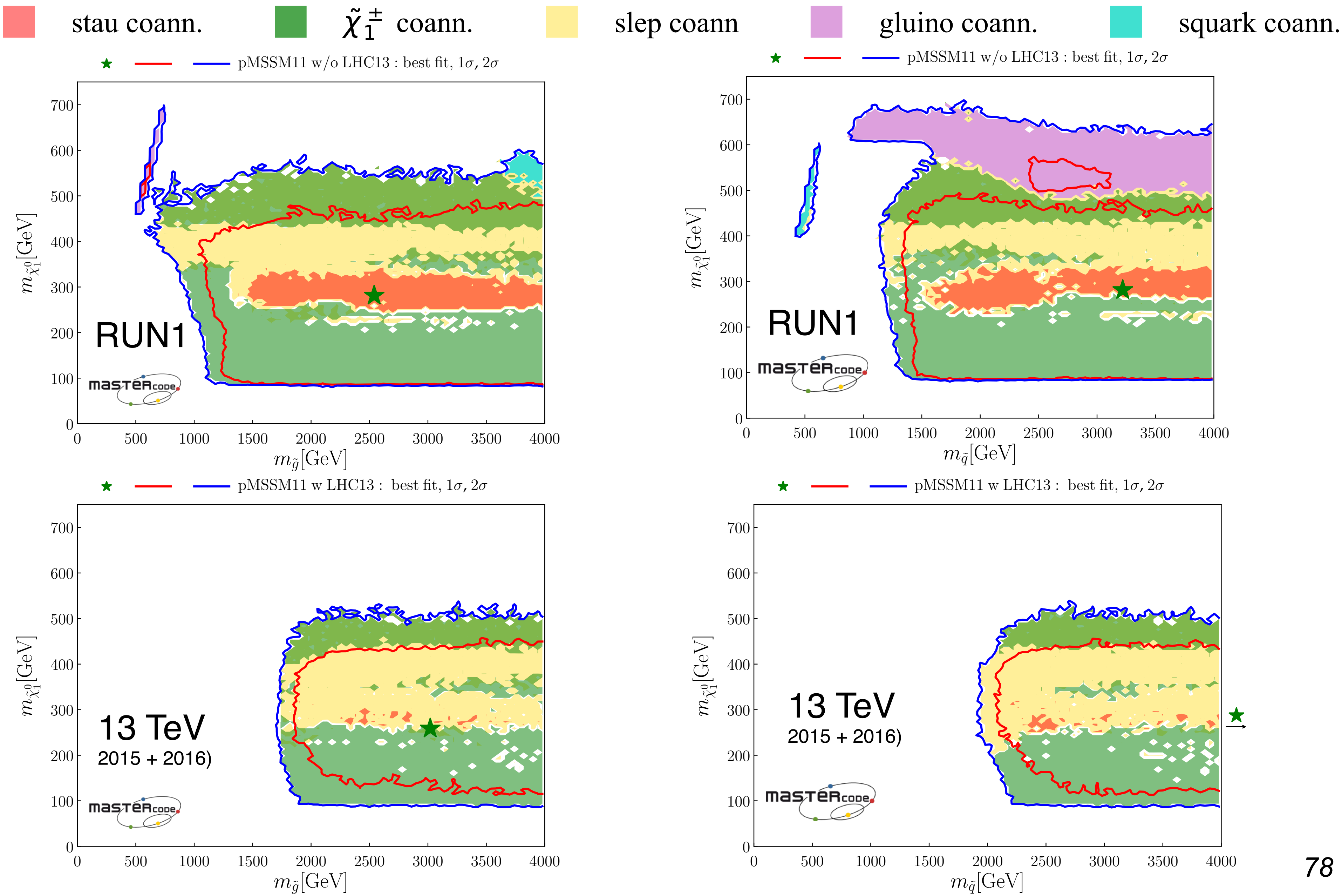
Comparison with Direct Detection Experiments



Comparison with Direct Detection Experiments

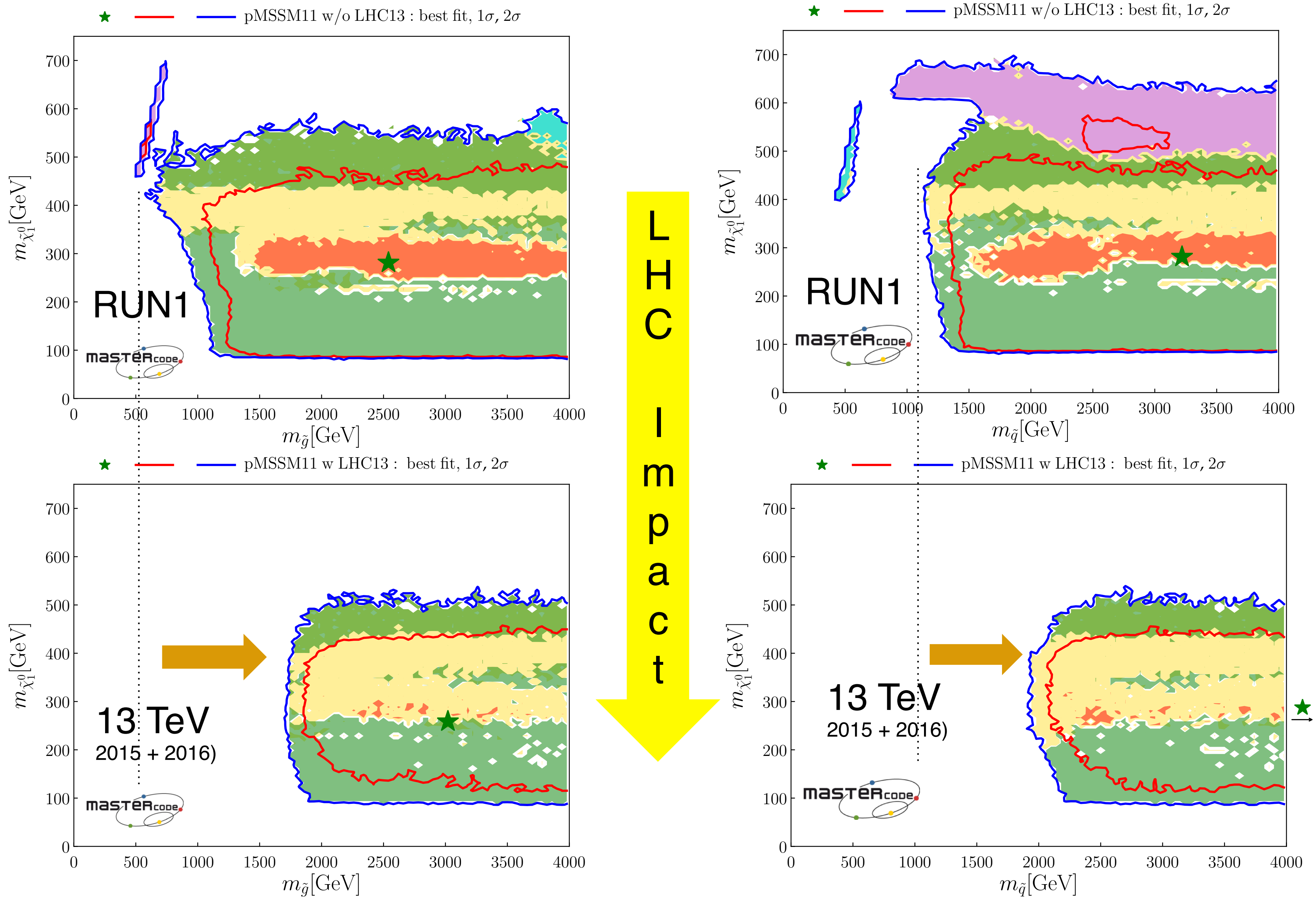


pMSSM11: RUN1 vs 13 TeV (2015 + 2016)



pMSSM11: RUN1 vs 13 TeV (2015 + 2016)

stau coann. | $\tilde{\chi}_1^\pm$ coann. | slep coann | gluino coann. | squark coann.



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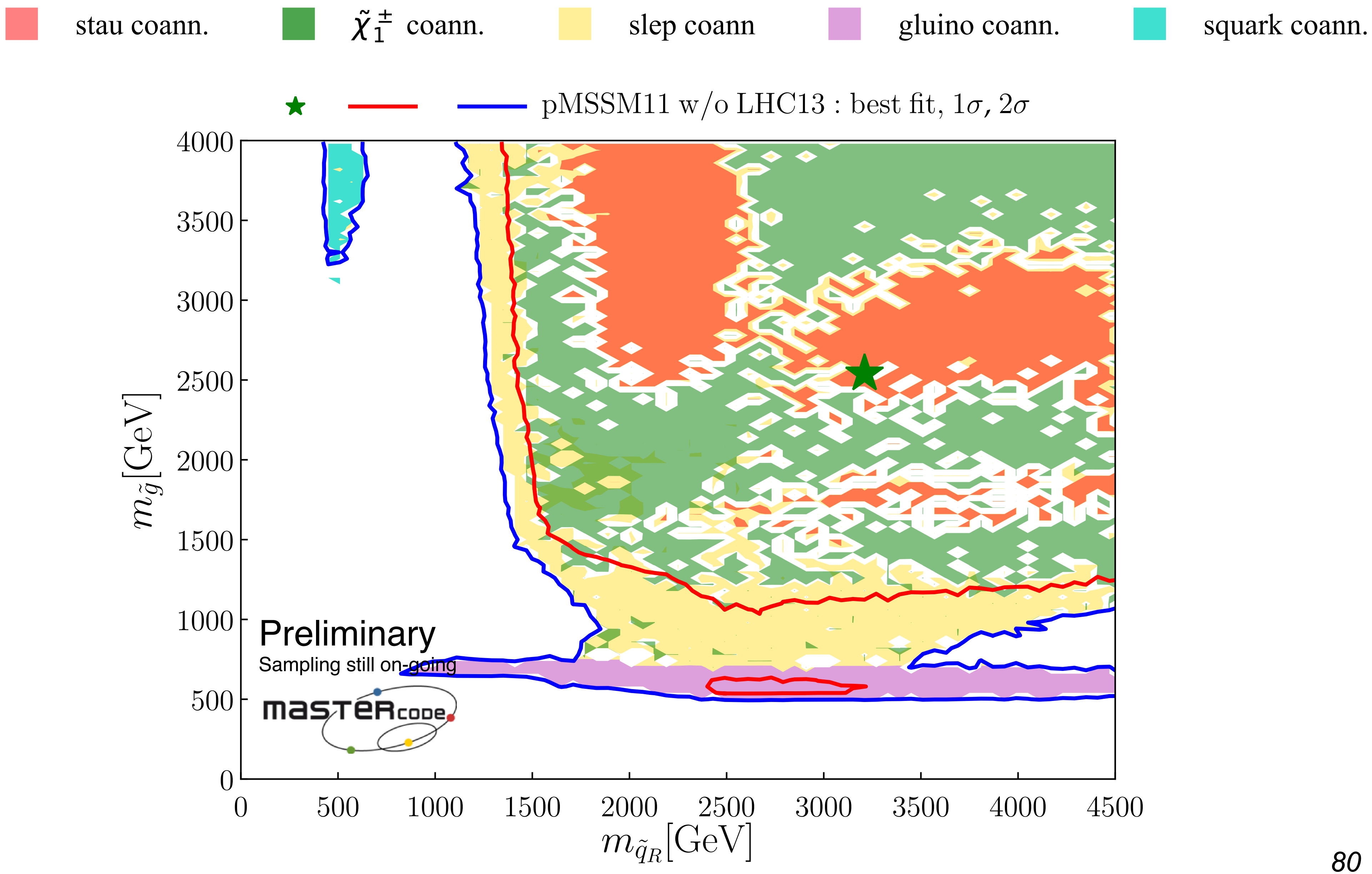
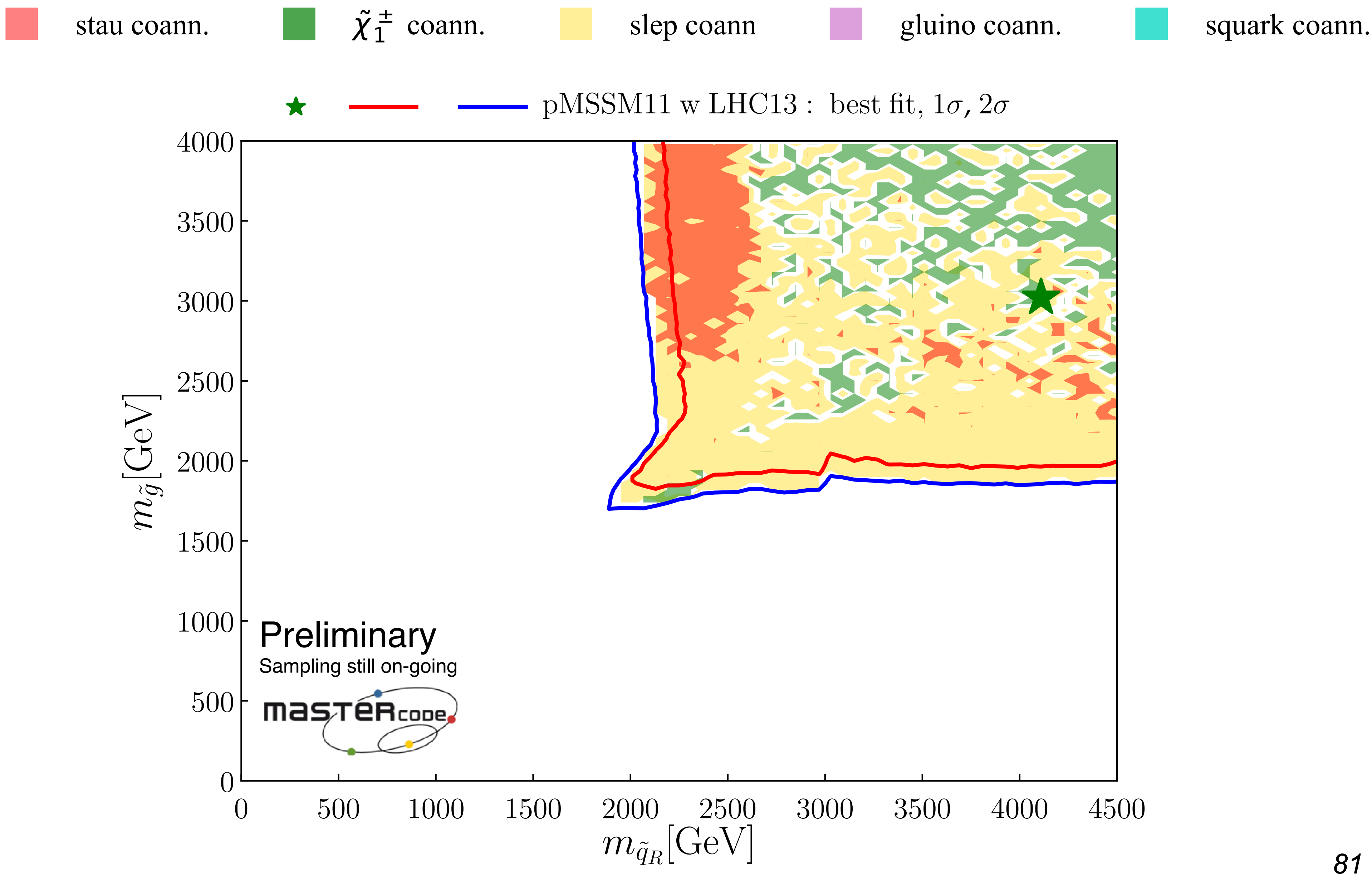
Gluino vs Squark: LHC RUN 1

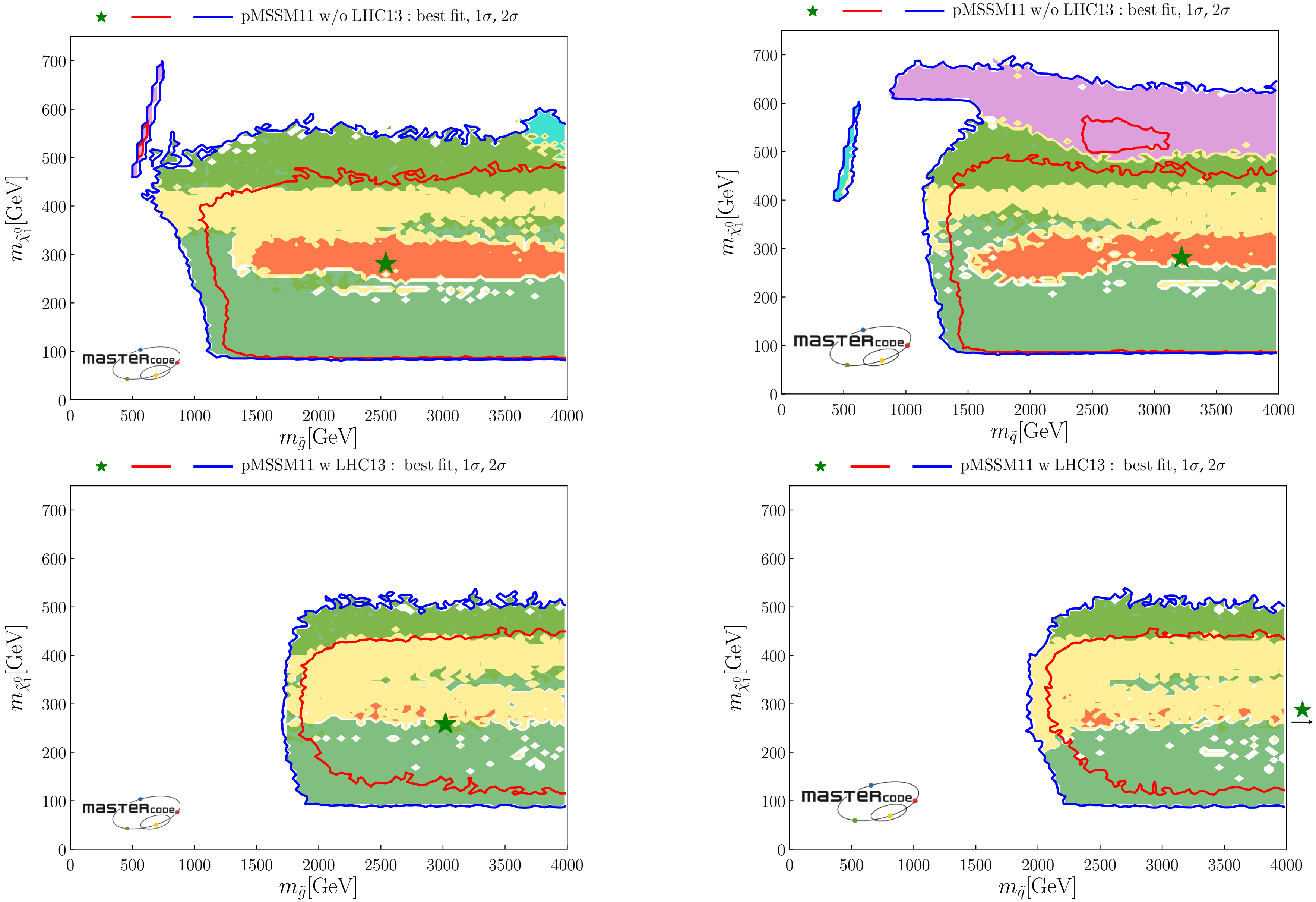


Gluino vs Squark: LHC RUN 2 (2015 + 2016 data)



Gluino: LHC RUN 1

stau coann. | $\tilde{\chi}_1^{\pm}$ coann. | slep coann | gluino coann. | squark coann.



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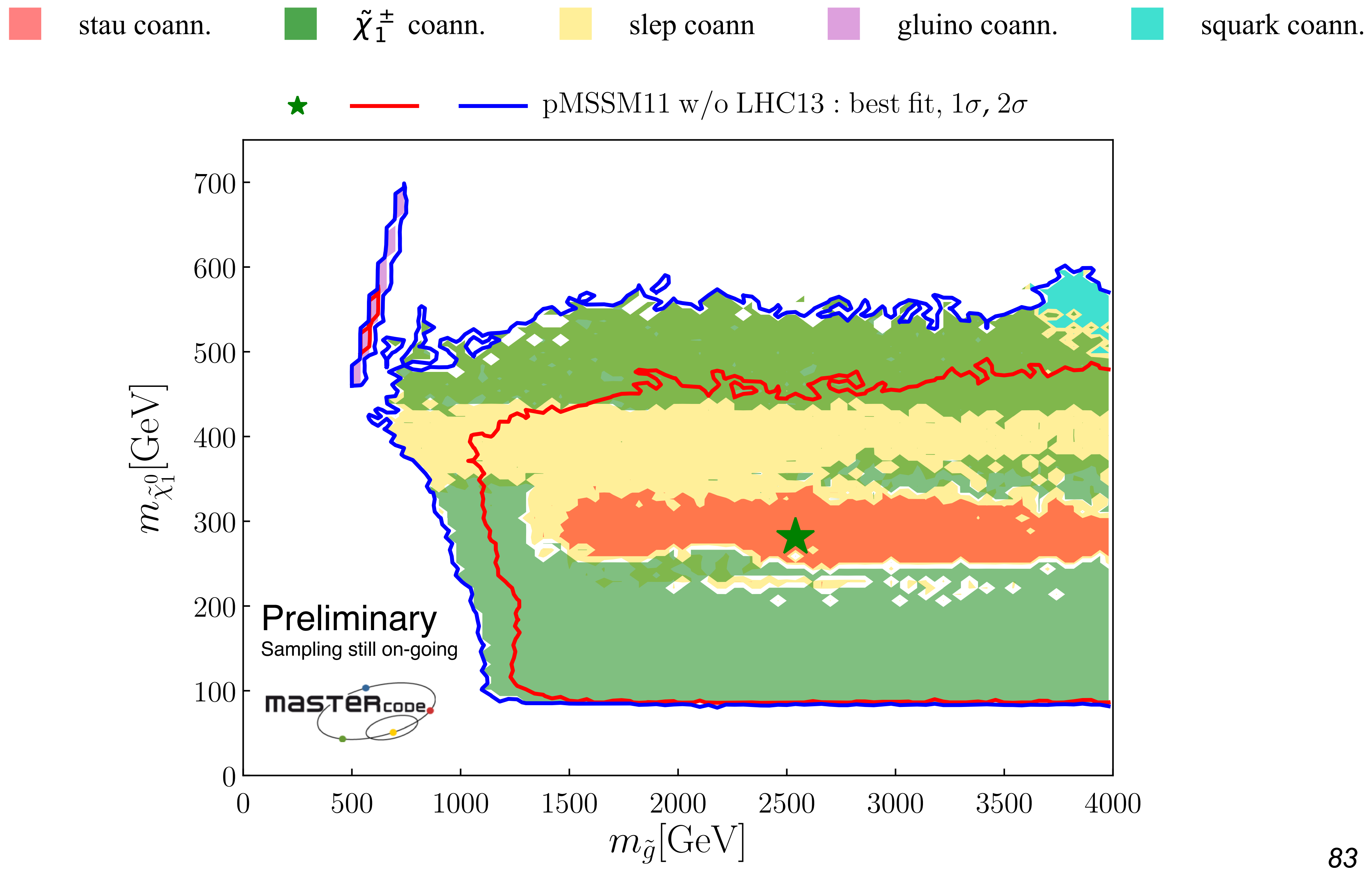
Gluino: LHC RUN 1



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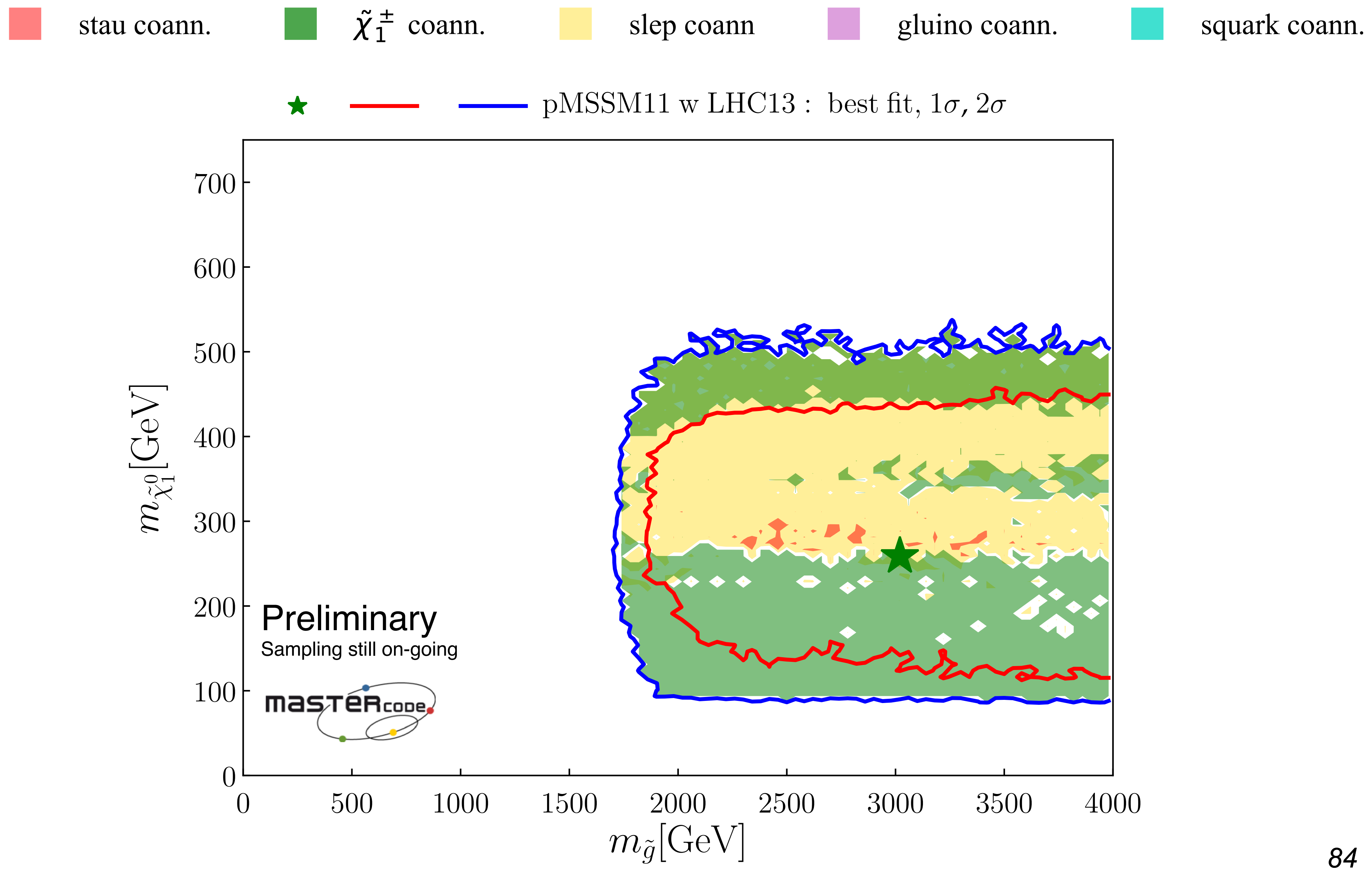
Gluino: LHC RUN 2 (2015 + 2016 data)



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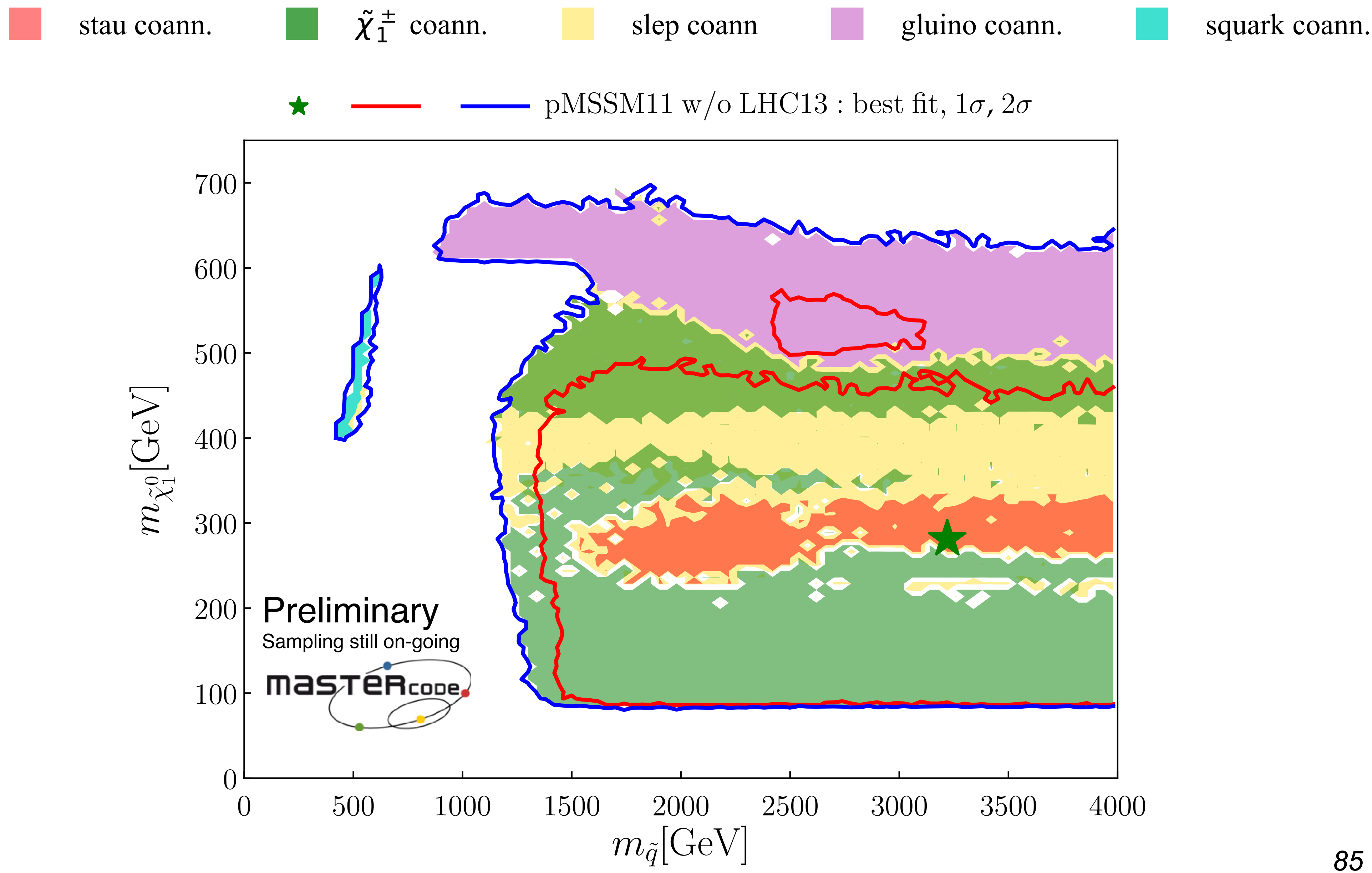
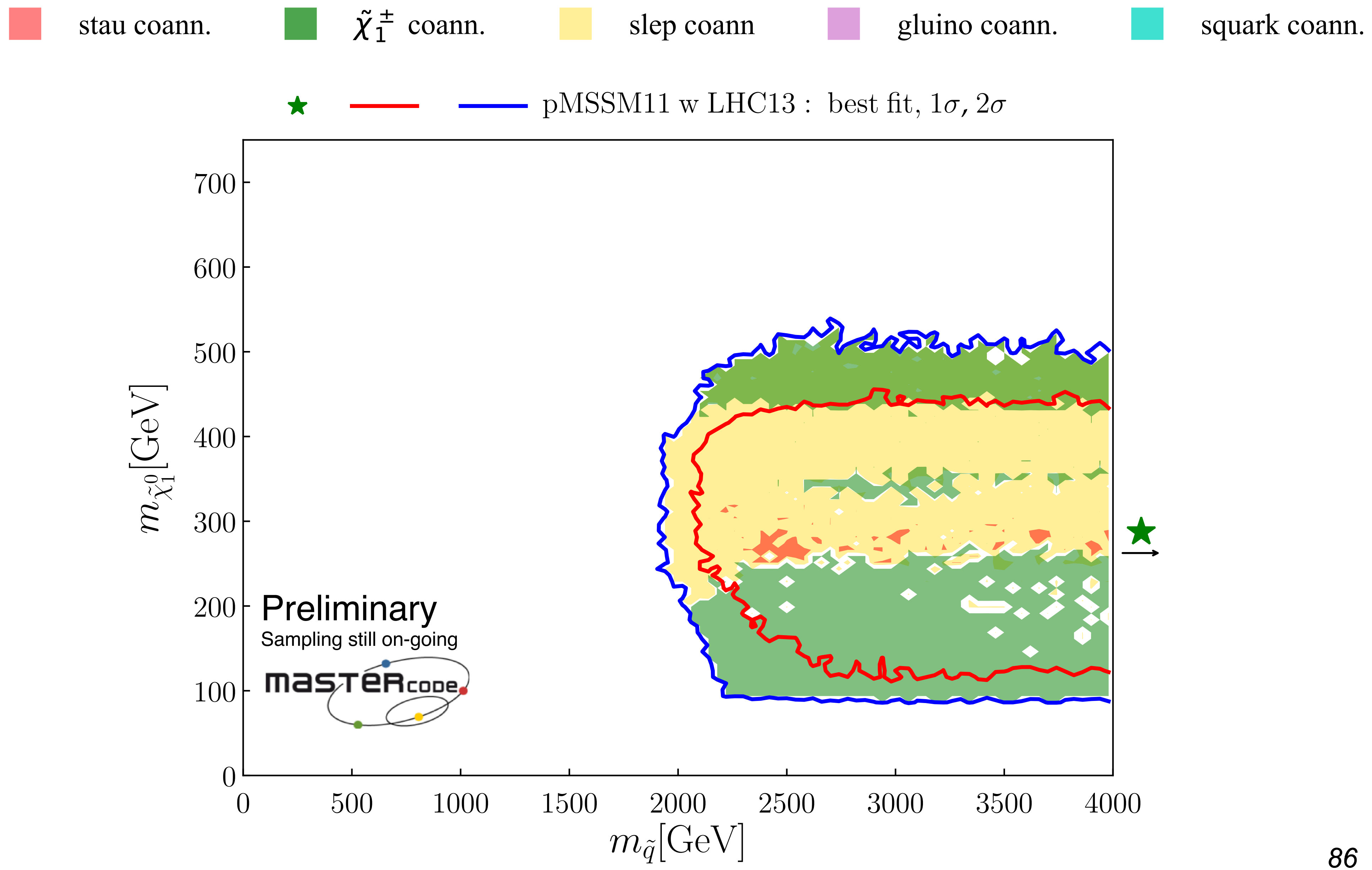
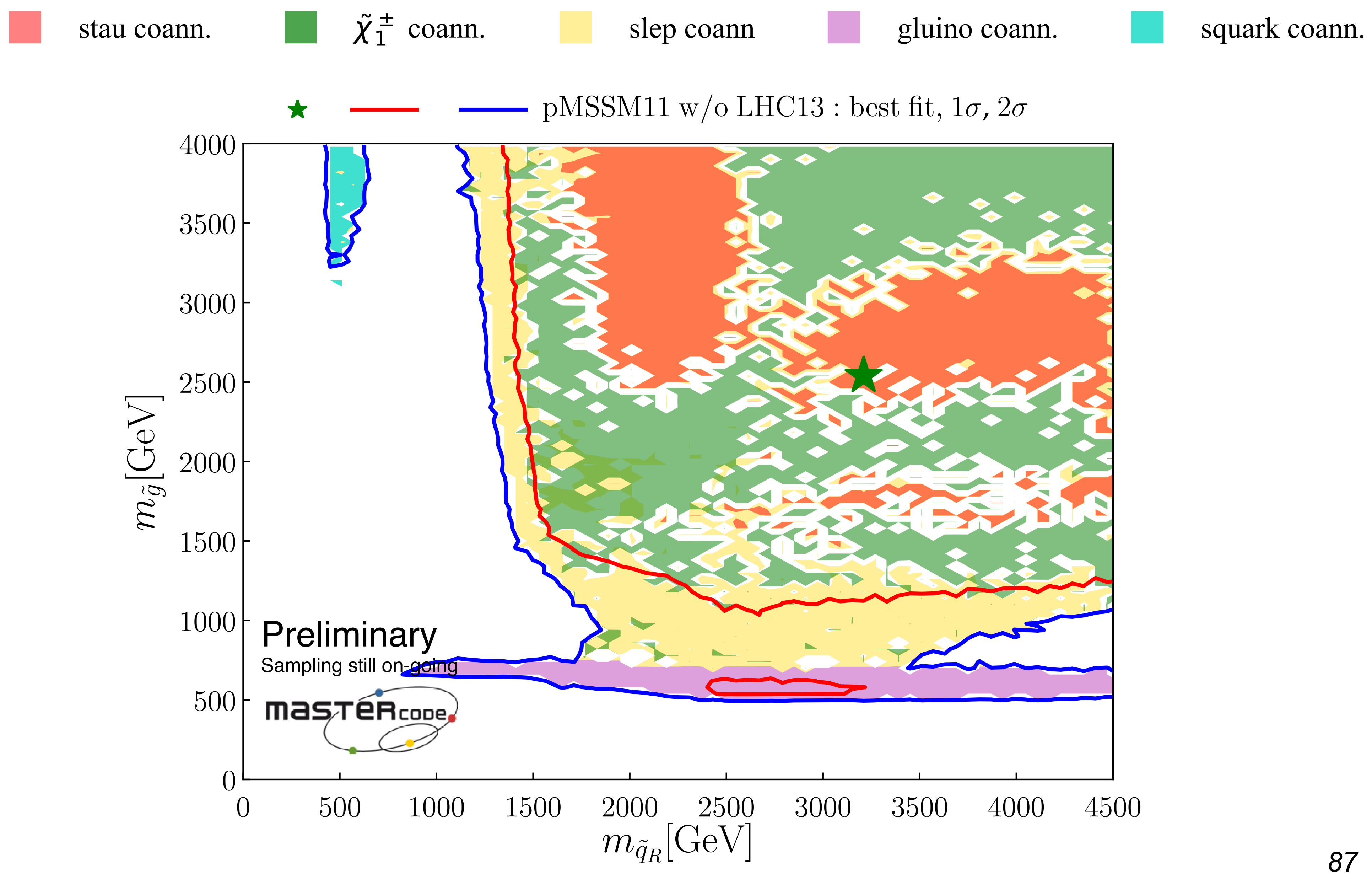
Squark: LHC RUN 1



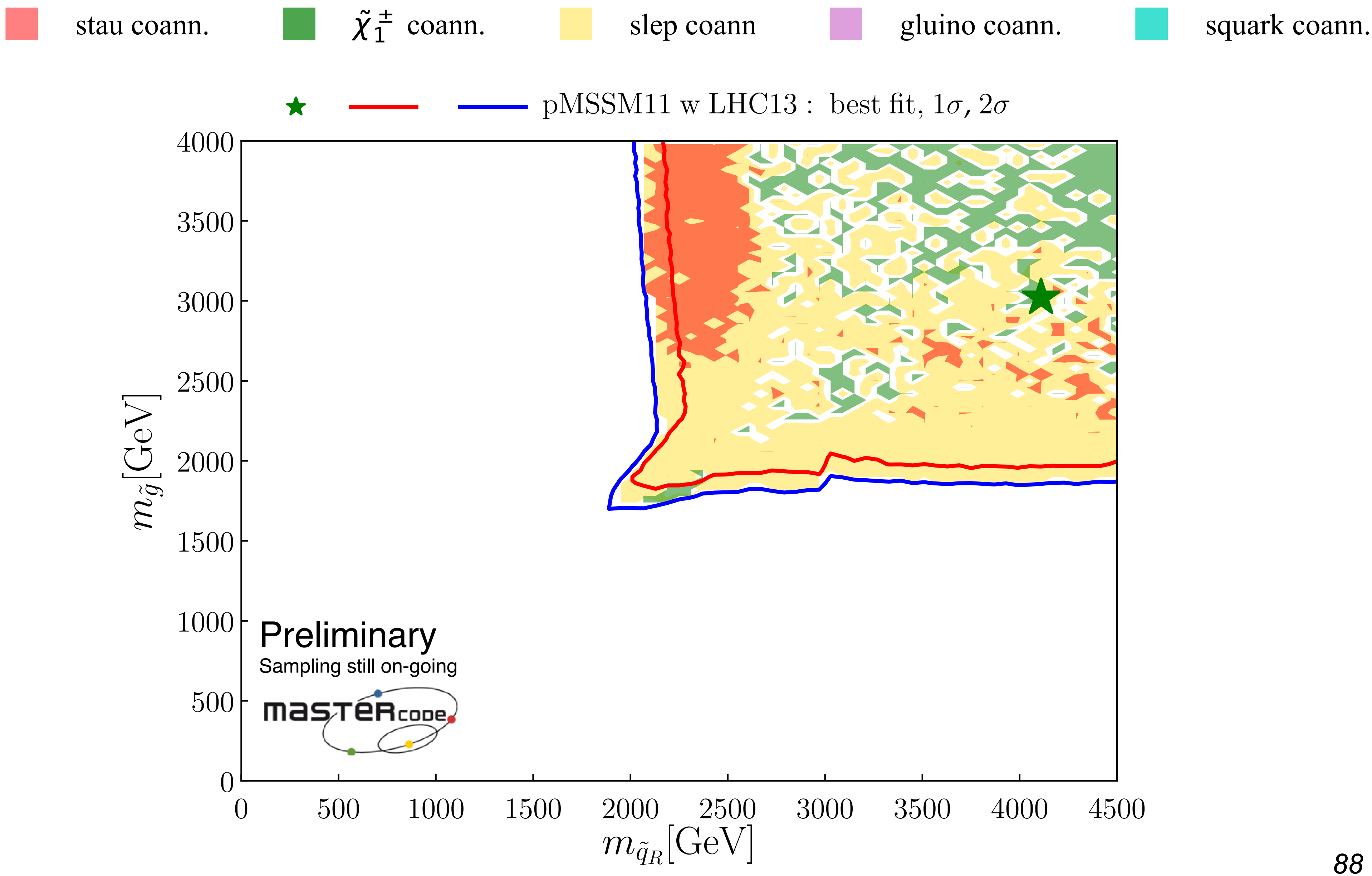
Squark: LHC RUN 2 (2015 + 2016 data)



Gluino vs Squark: LHC RUN 1



Gluino vs Squark: LHC RUN 2 (2015 + 2016 data)



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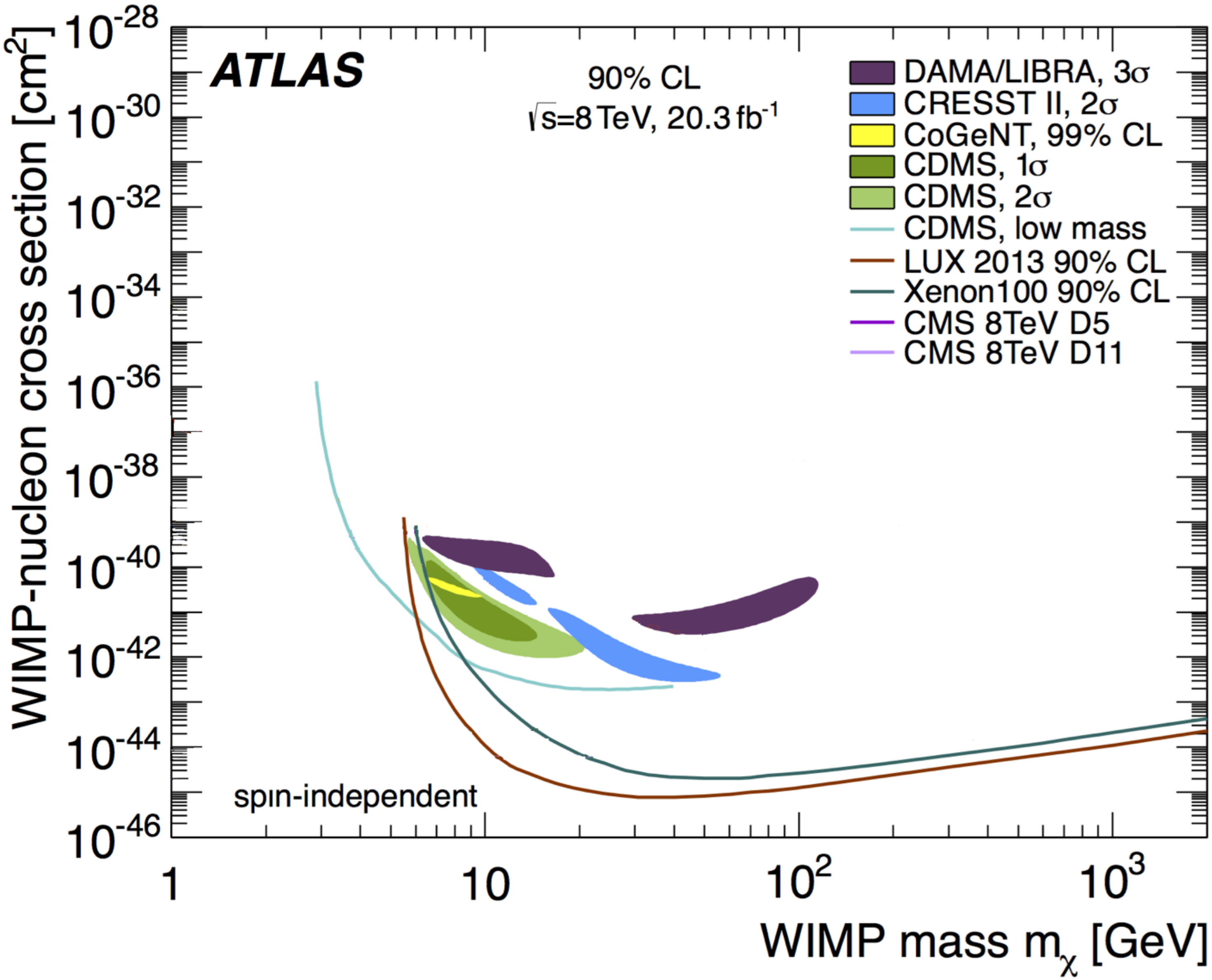
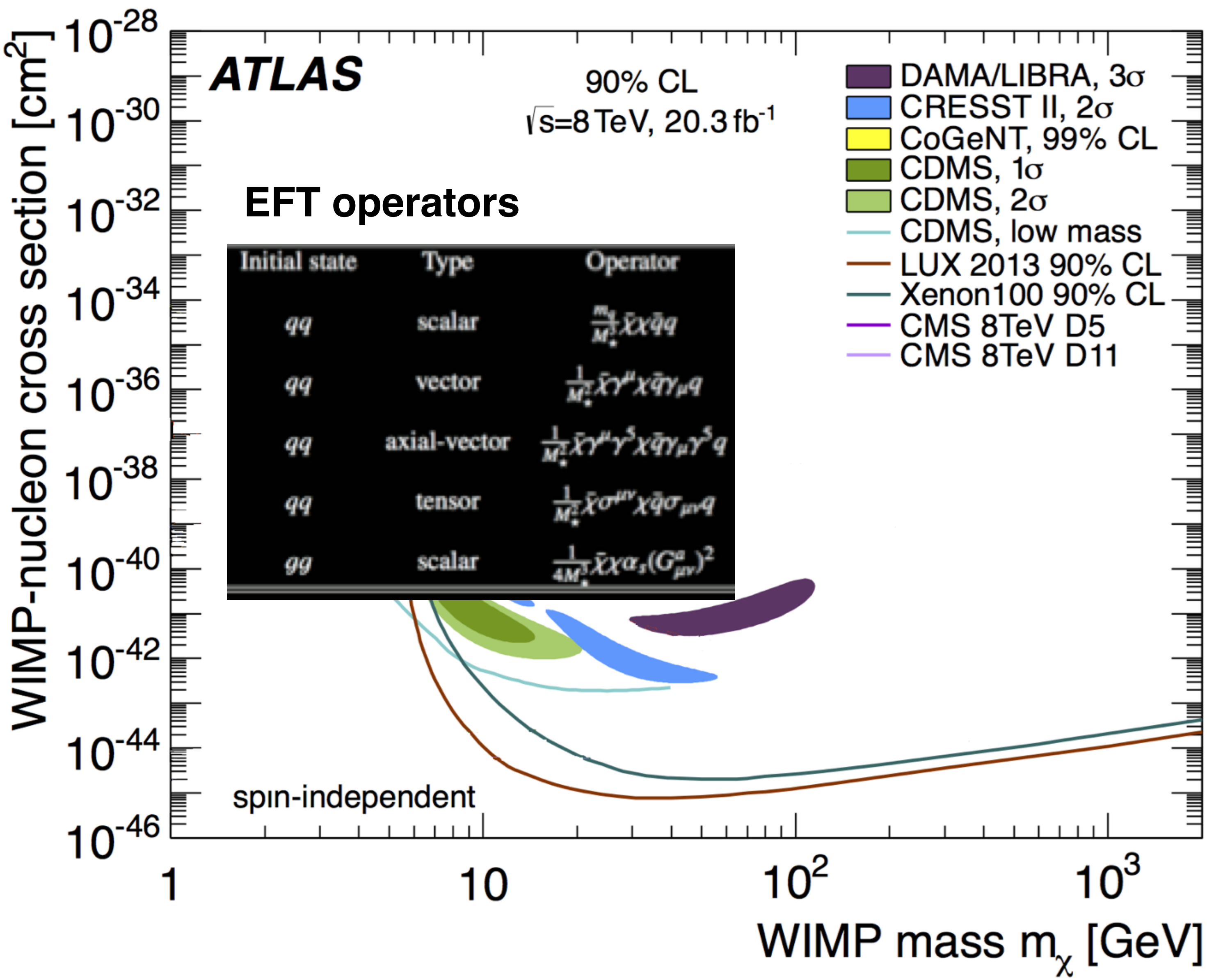
FROM EFT TO SIMPLIFIED MODELS

ATLAS Mono-Jet: Comparison with Direct Detection

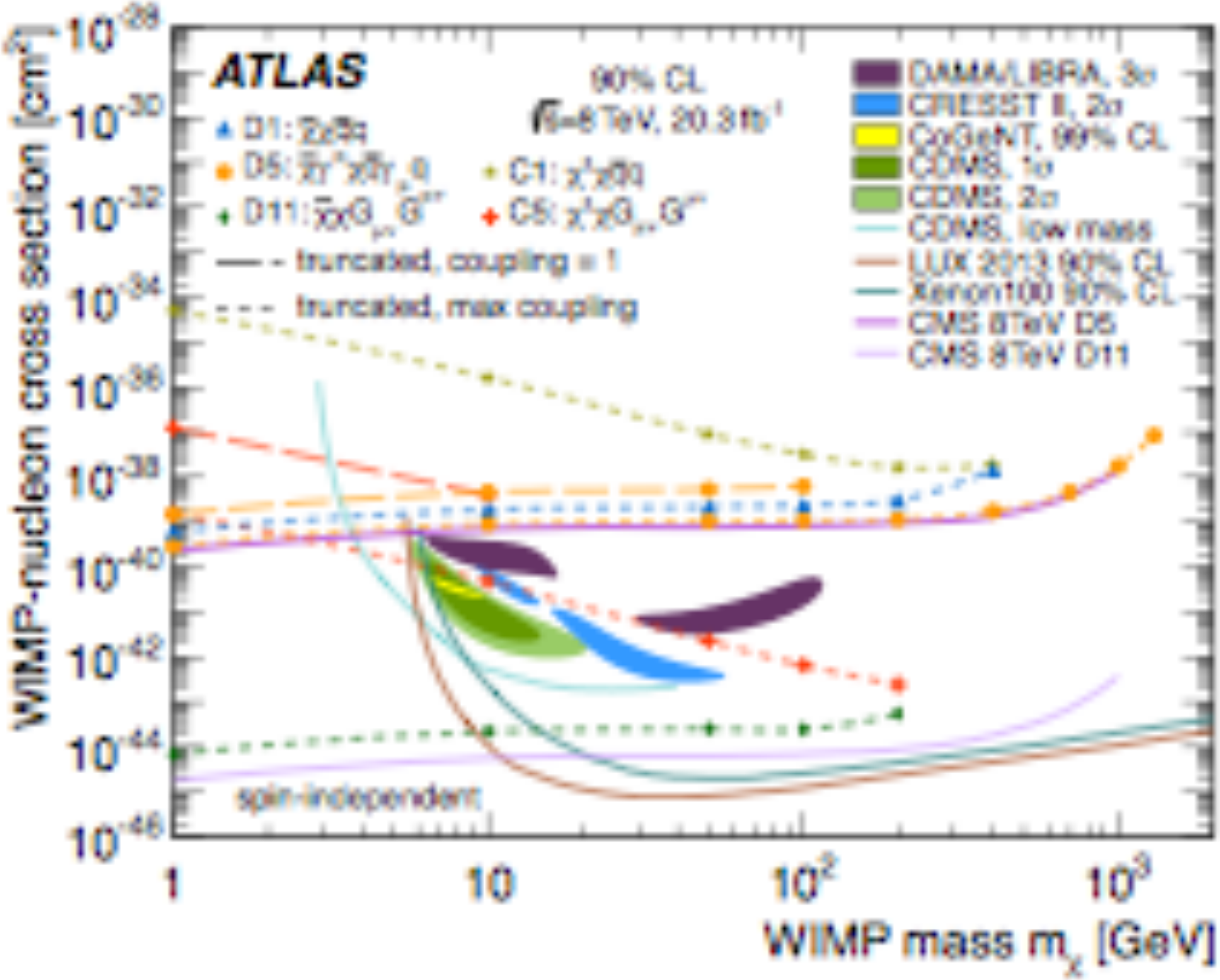


ATLAS Mono-Jet: Comparison with Direct Detection

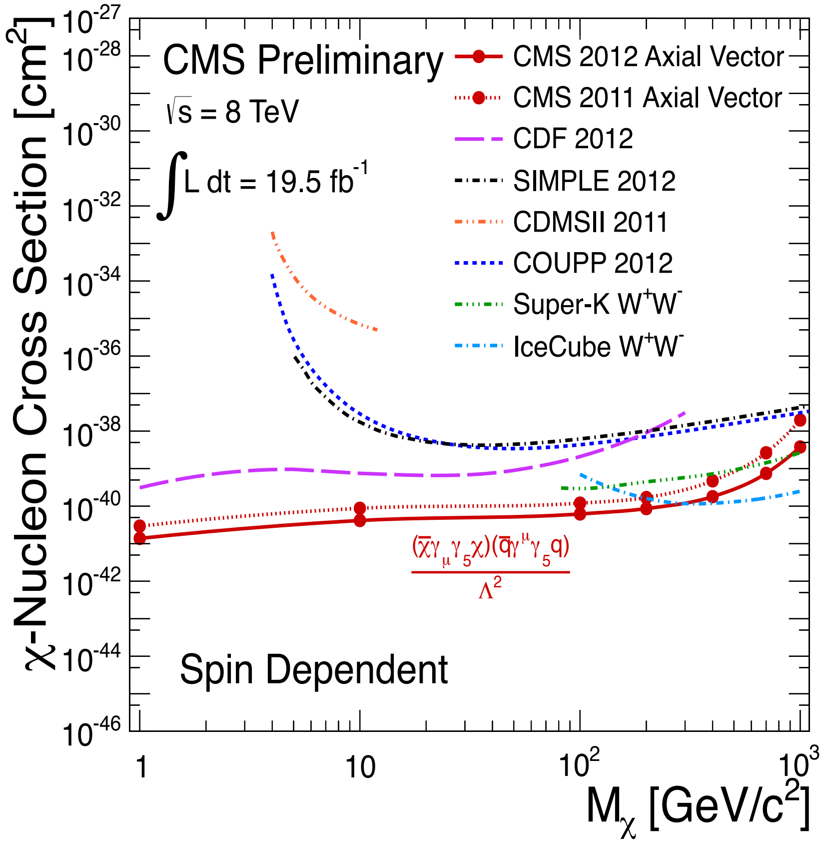


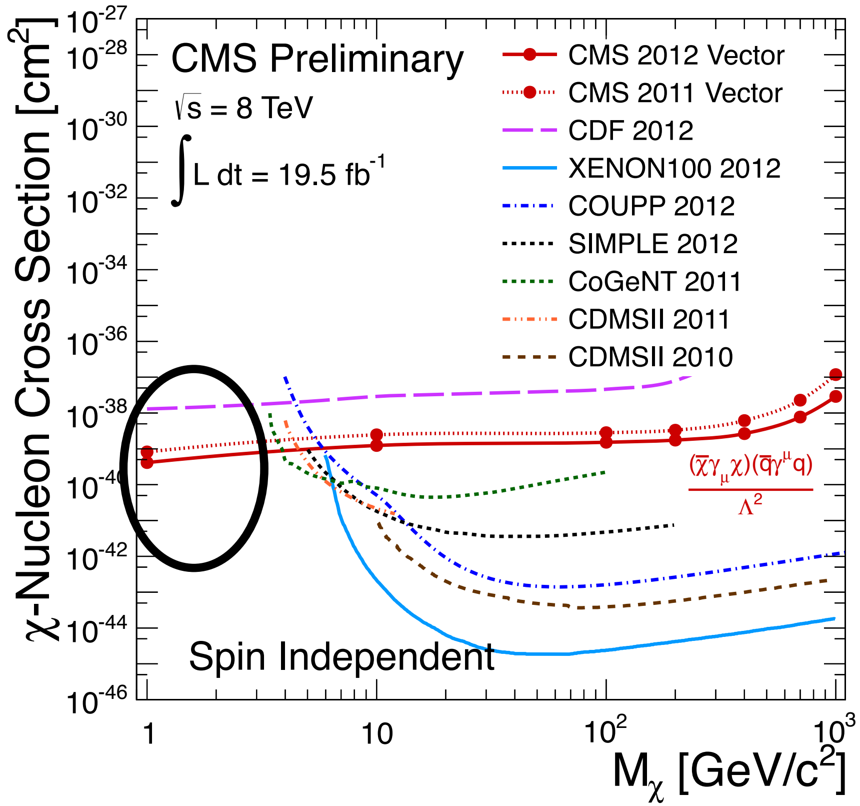
Initial state	Type	Operator
qq	scalar	$\frac{m_q}{M_*^3}\bar{\chi}\chi\bar{q}q$
qq	vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
qq	axial-vector	$\frac{1}{M_*^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
qq	tensor	$\frac{1}{M_*^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
gg	scalar	$\frac{1}{4M_*^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

ATLAS Mono-Jet: Comparison with Direct Detection



Mono-Jet analyses better than direct detection?!



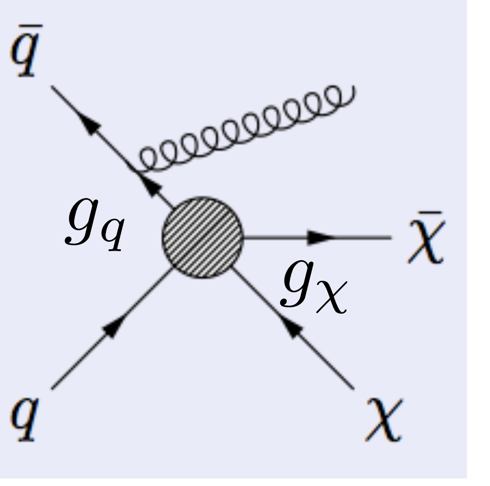


Claim [often made]:
For low mass and the entire spin-dependent case monojet limits are stronger than direct detection limits!

Effective Field Theory (EFT) Interpretation

Example of considered operators:

$$O_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma_\mu q)}{\Lambda^2}$$ Vector operator, s-channel



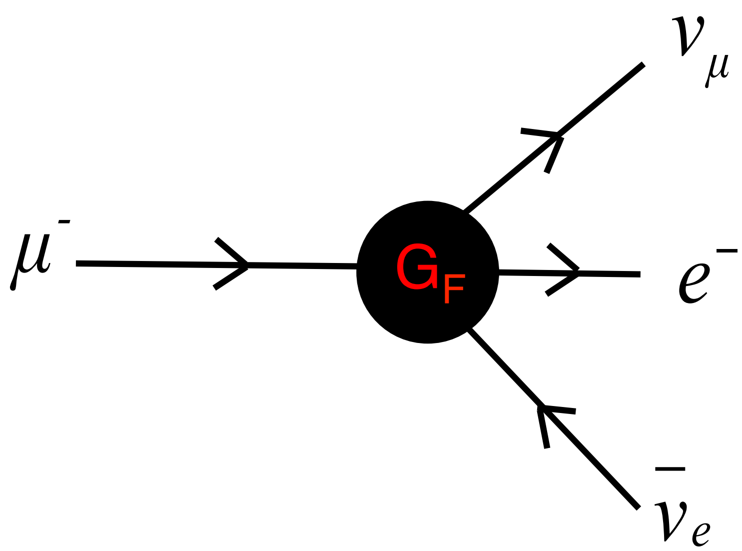
$$O_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)}{\Lambda^2}$$ Axial vector operator, s-channel

Assumption of EFT

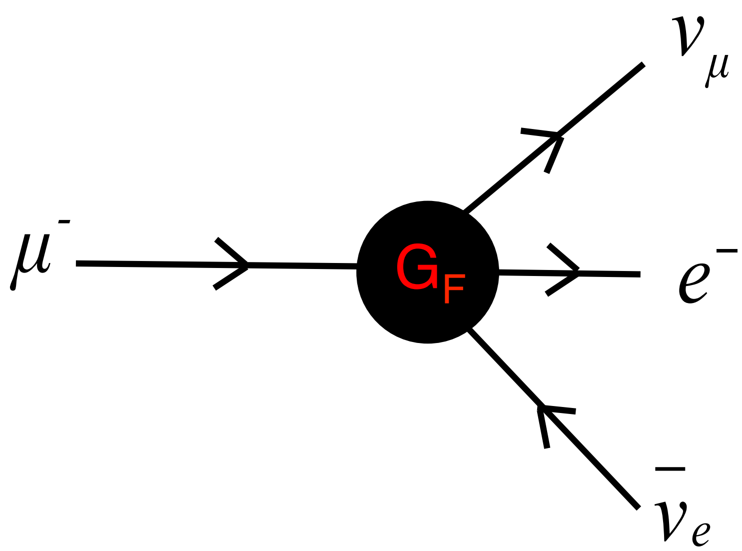
If the operator (e.g. V or AV) mediator is suitably(!!) heavy it can be integrated out to obtain the effective V or AV contact operator. In this case (and only this case), the contact interaction scale Λ is related to the parameters entering the Lagrangian:

$$\Lambda = \frac{M_{mediator}}{\sqrt{g_q g_\chi}}$$ (relation in the full theory)

Fermi Interaction & Muon Decay



Fermi Interaction & Muon Decay



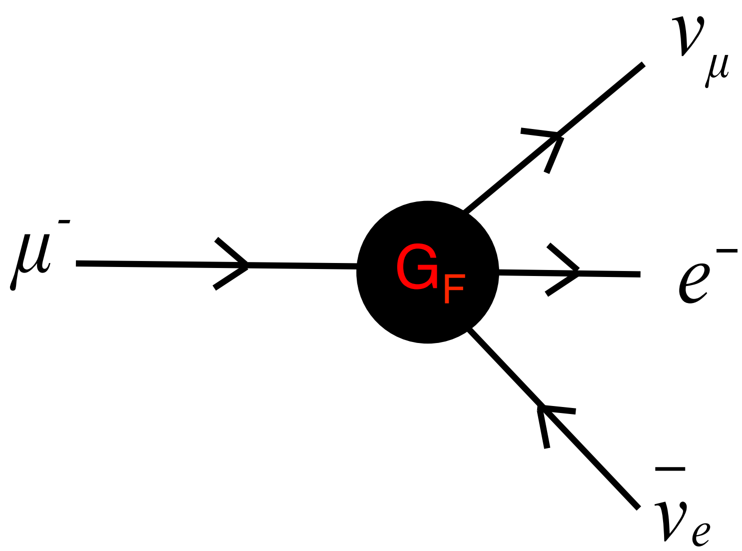
The Fermi 4-point interaction was able to explain well the beta-decay as well as the muon decay with one single interact strengths G_F (Fermi constant)

However, the cross-section grows as the square of the energy:

$$\sigma \propto G_F^2 E^2$$

making it invalid for higher energies!

Fermi Interaction & Muon Decay

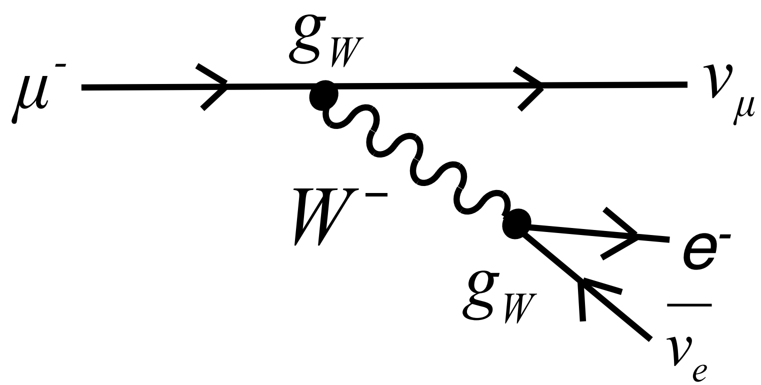


The Fermi 4-point interaction was able to explain well the beta-decay as well as the muon decay with one single interact strengths G_F (Fermi constant)

However, the cross-section grows as the square of the energy:

$$\sigma \propto G_F^2 E^2$$

making it invalid for higher energies!



Solution:

Resolve the “blob” and replace the 4-point interaction with an ultraviolet complete theory!

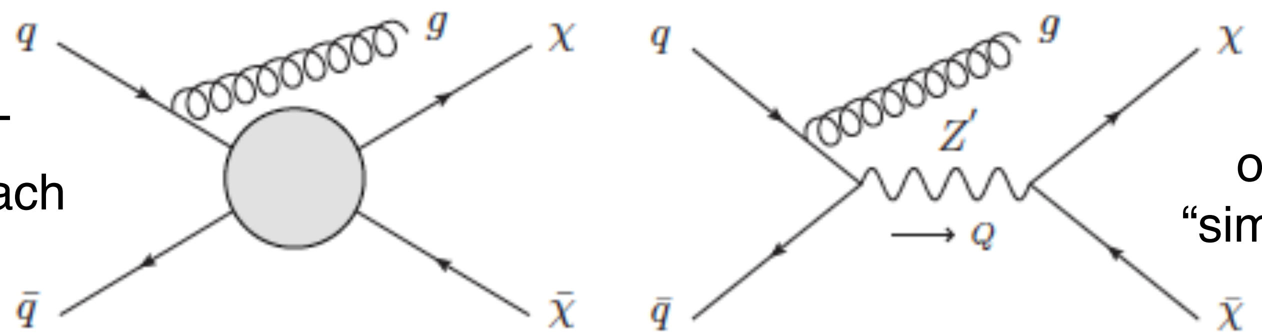
$$\sigma \propto G_F^2 M_W^2$$

Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

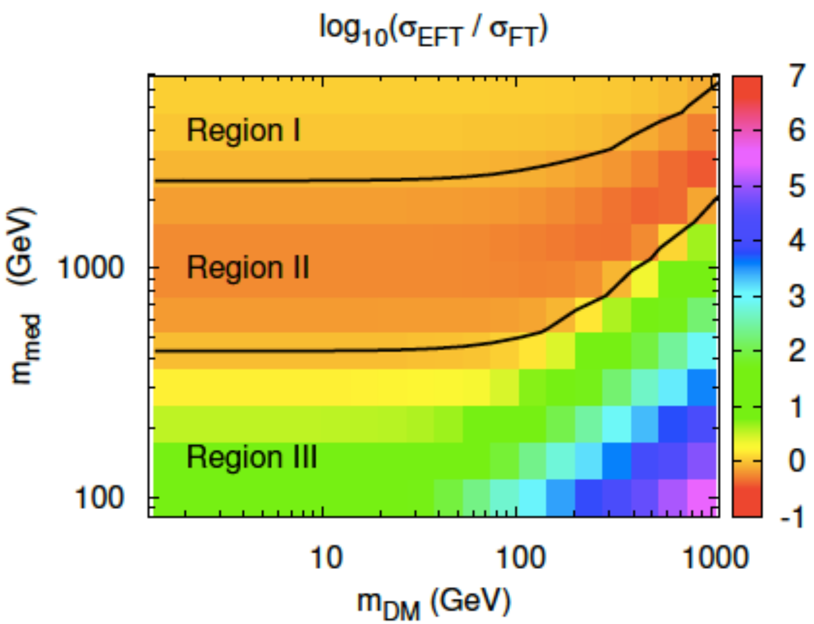
➢ Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT
approach



FT
one diagram
"simplified model"

Use vector and axial-vector mediators (e.g. Z') as example - scalar are similar in conclusion!



Compare prediction of FT with EFT in $m_{med} - m_{DM}$ plane. Three regions become visible:

Region I: EFT and FT agree better then 20%

➢ EFT is valid!

Region II: EFT yields significant weaker limits then FT

➢ EFT limits are too conservative!

Region III: EFT yields significant stronger limits then FT

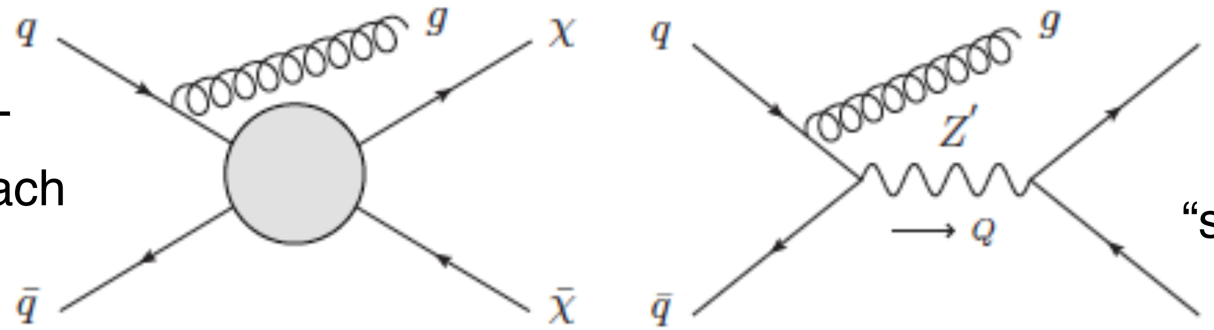
➢ EFT limits are too aggressive!

Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

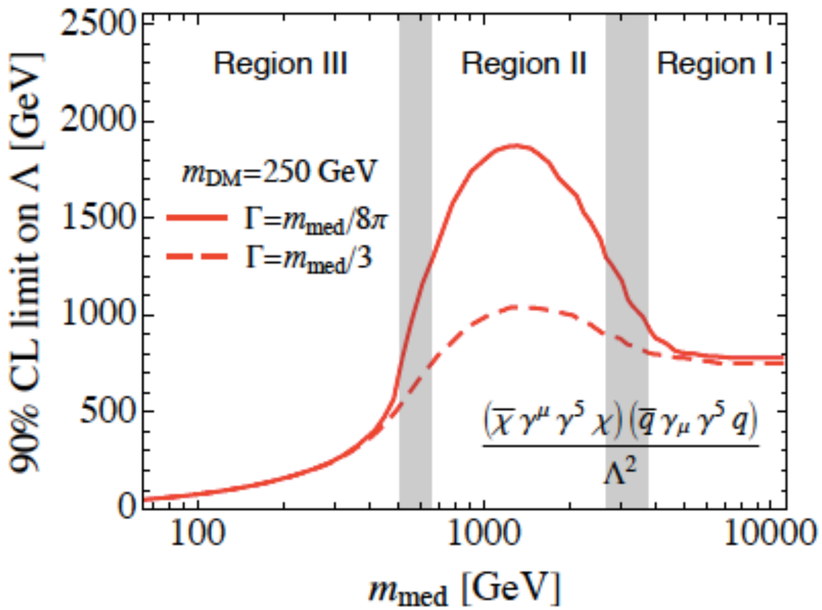
- Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT approach



FT
one diagram
“simplified model”

Use vector and axial-vector mediators (e.g. Z’) as example - scalar are similar in conclusion!



Three Regions as function of mediator mass:

Region I: Heavy m_{med}

- EFT is valid!

Region II: Medium m_{med} – Resonant enhancement

- EFT limits are too conservative!

Region III: Low m_{med}

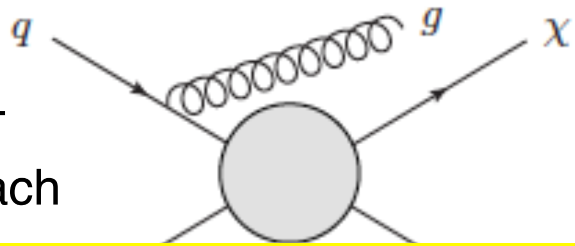
- EFT limits are too aggressive!

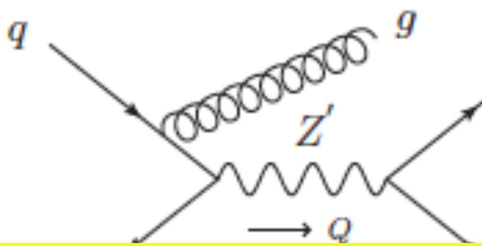
Validity of Effective Field Theory Limits

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

- Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT
approach

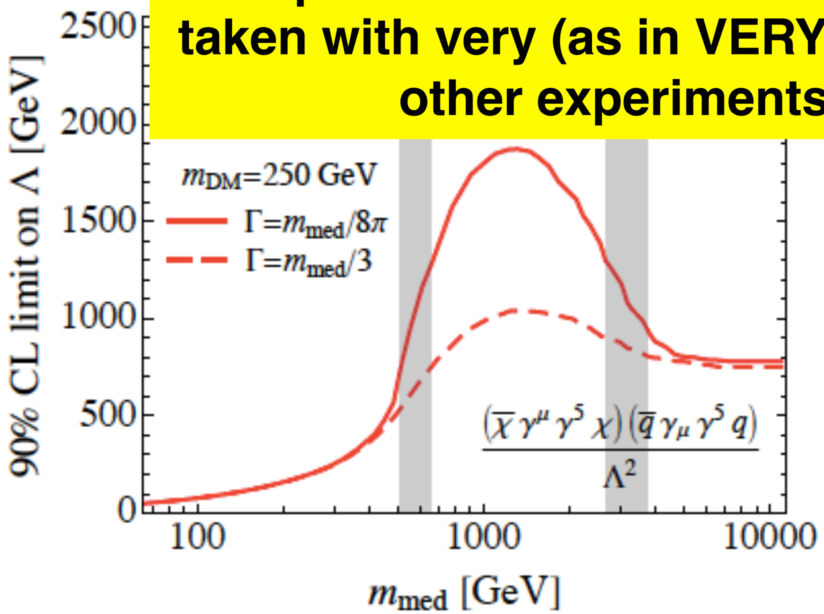




FT
one diagram
“simplified model”

Conclusion:
The EFT is not an appropriate framework for a comprehensive Interpretation of DM searches at colliders and especially must taken with very (as in VERY) special care when comparing with other experiments such as Direct Detection!

Use v … clusion!



Region I: Heavy m_{med}
- EFT is valid!

Region II: Medium m_{med} – Resonant enhancement
- EFT limits are too conservative!

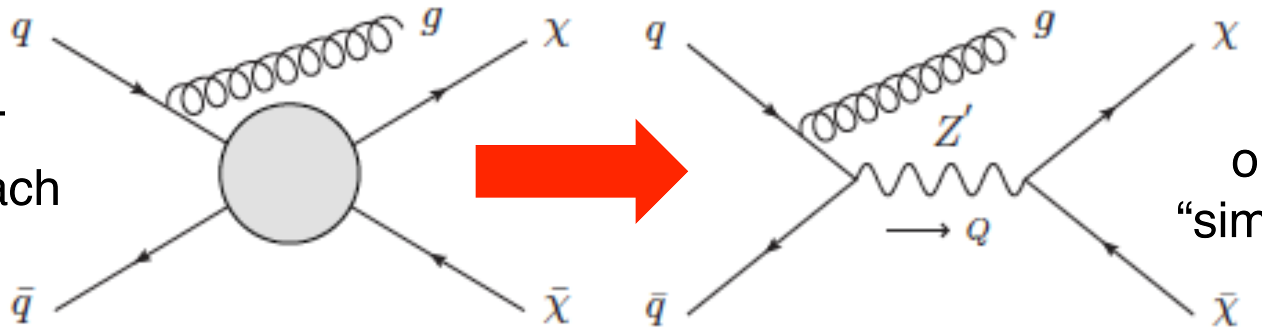
Region III: Low m_{med}
- EFT limits are too aggressive!

Alternative Interpretation Ansatz: Simplified models

Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

- Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT
approach



FT
one diagram
“simplified model”

After three years of operation at the LHC the landscape for interpretation of searches has changed dramatically – new superior & modern approaches have replaced in many areas longstanding traditional ones
(e.g. SUSY searches)

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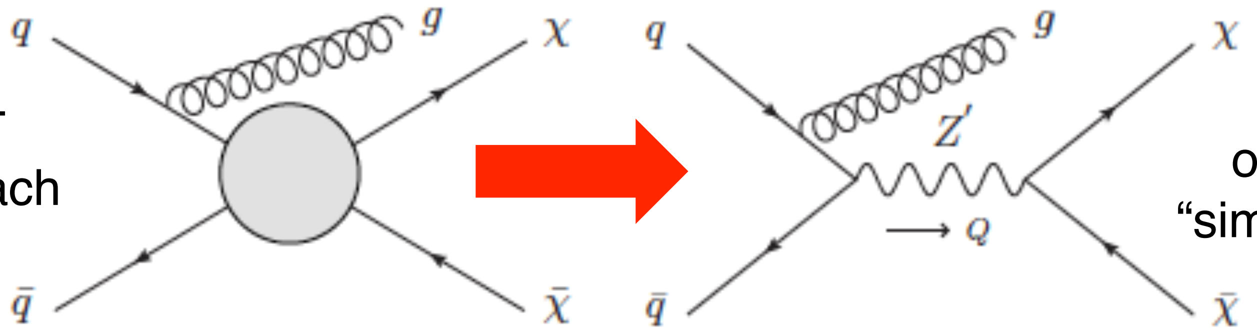
Alternative Interpretation Ansatz: Simplified models

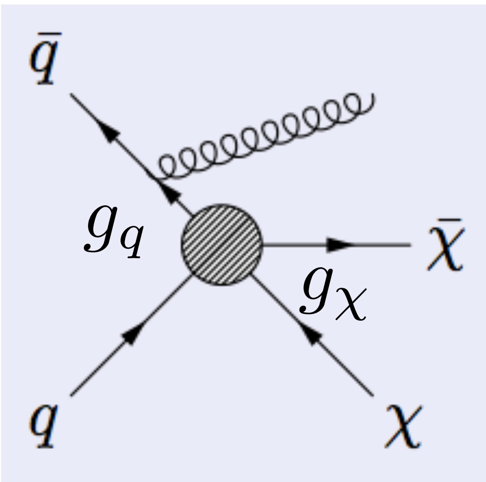
Recent work from OB, M.Dolan,C.McCabe: arXiv:1308.6799

- Compare Effective Field Theory (EFT) with Full Theory (FT)

EFT approach



FT
one diagram
"simplified model"



<u>The problem is governed by five variables:</u>

- Couplings g_q and g_χ
- Mediator mass m_{med} and mediator width Γ_{med}
- Dark matter candidate mass m_{DM}

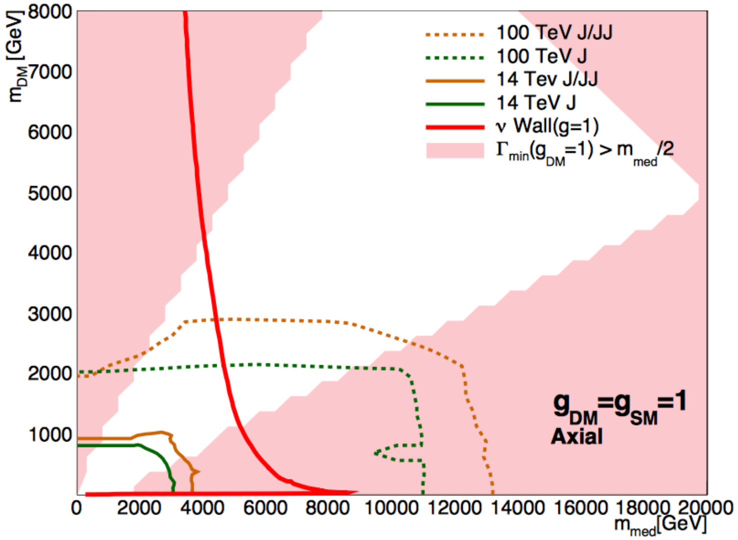
ATLAS & CMS public results

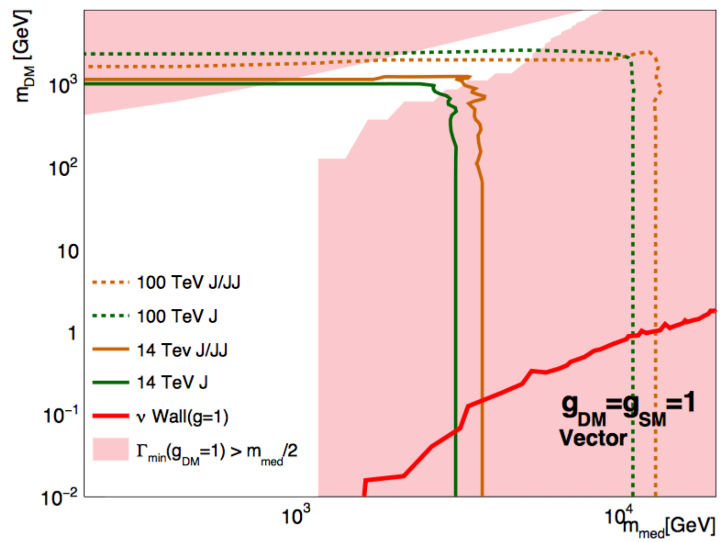
Most results presented in this talk (and many more) can be accessed via the public page of the ATLAS and CMS experiments:

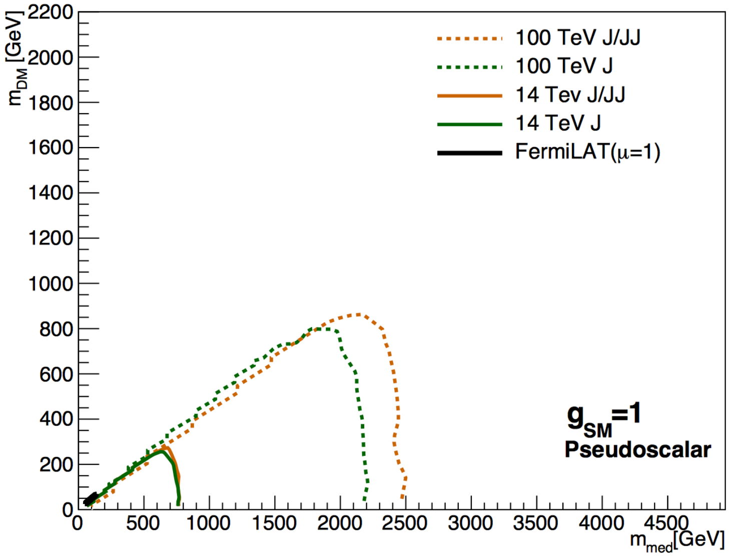
ATLAS SUSY: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

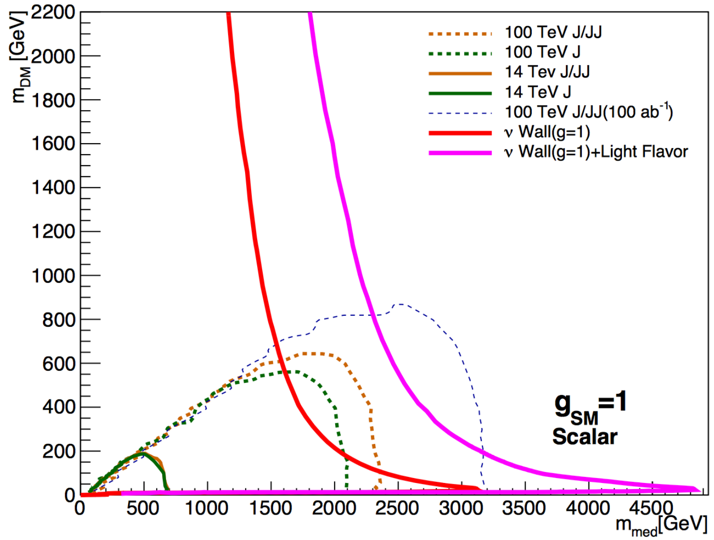
CMS SUSY :https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

100 TeV Prediction from arXiv:1509.02904



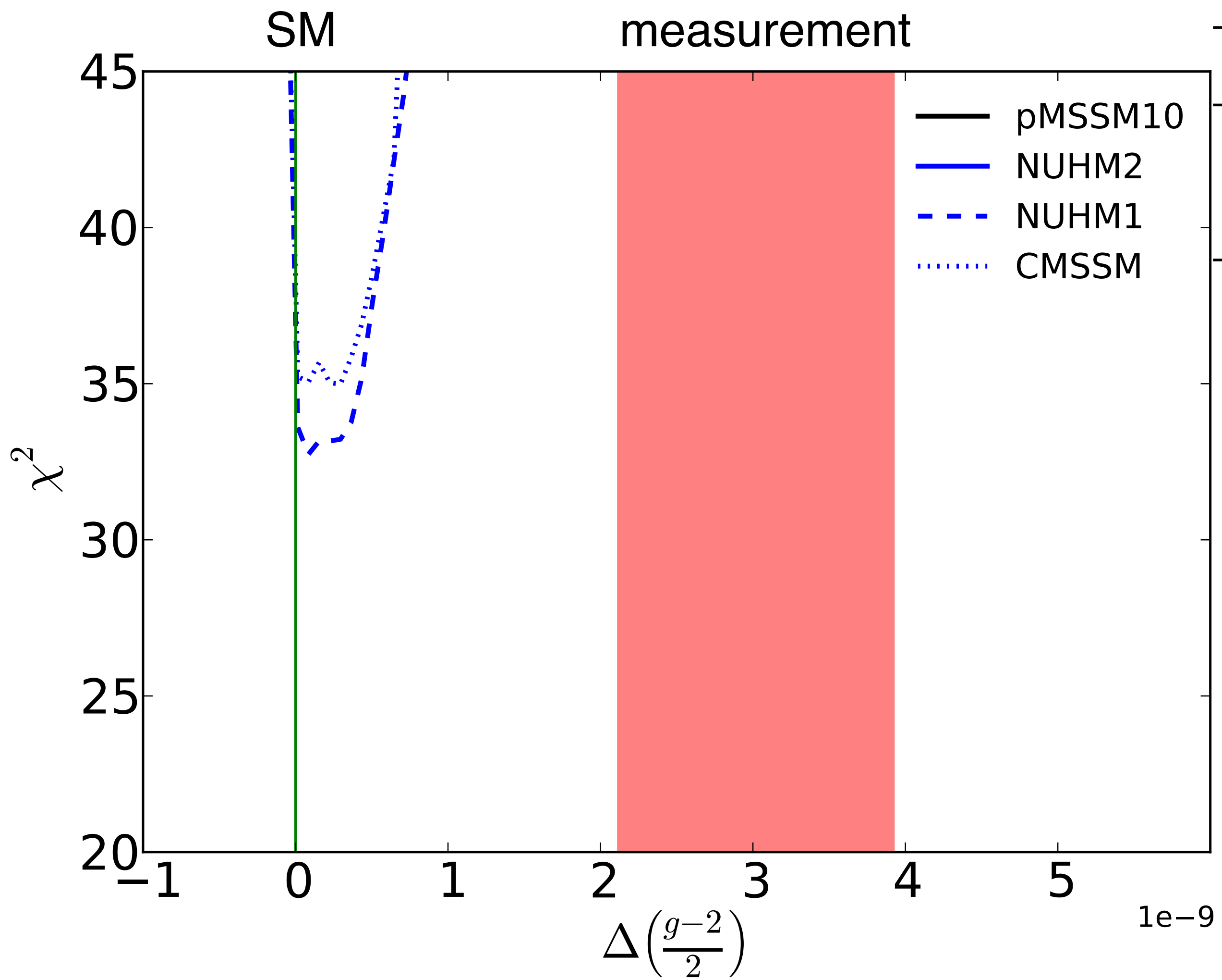






MASTERCODE

Resolving tension (g-2) and LHC



	X^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %

Can adding extra parameters resolve the tension between (g-2) and jets+MET constraints?

From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

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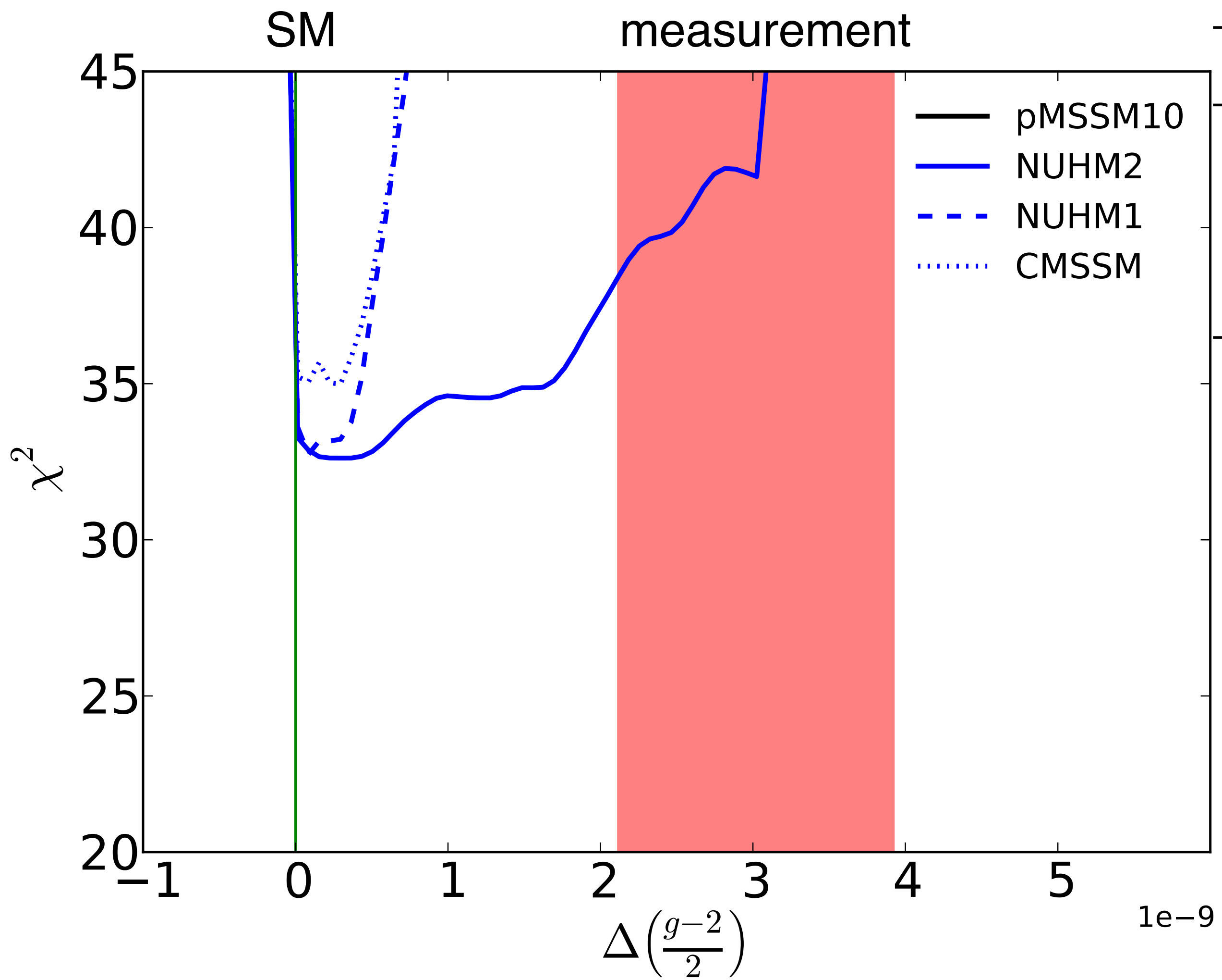
Resolving tension (g-2) and LHC



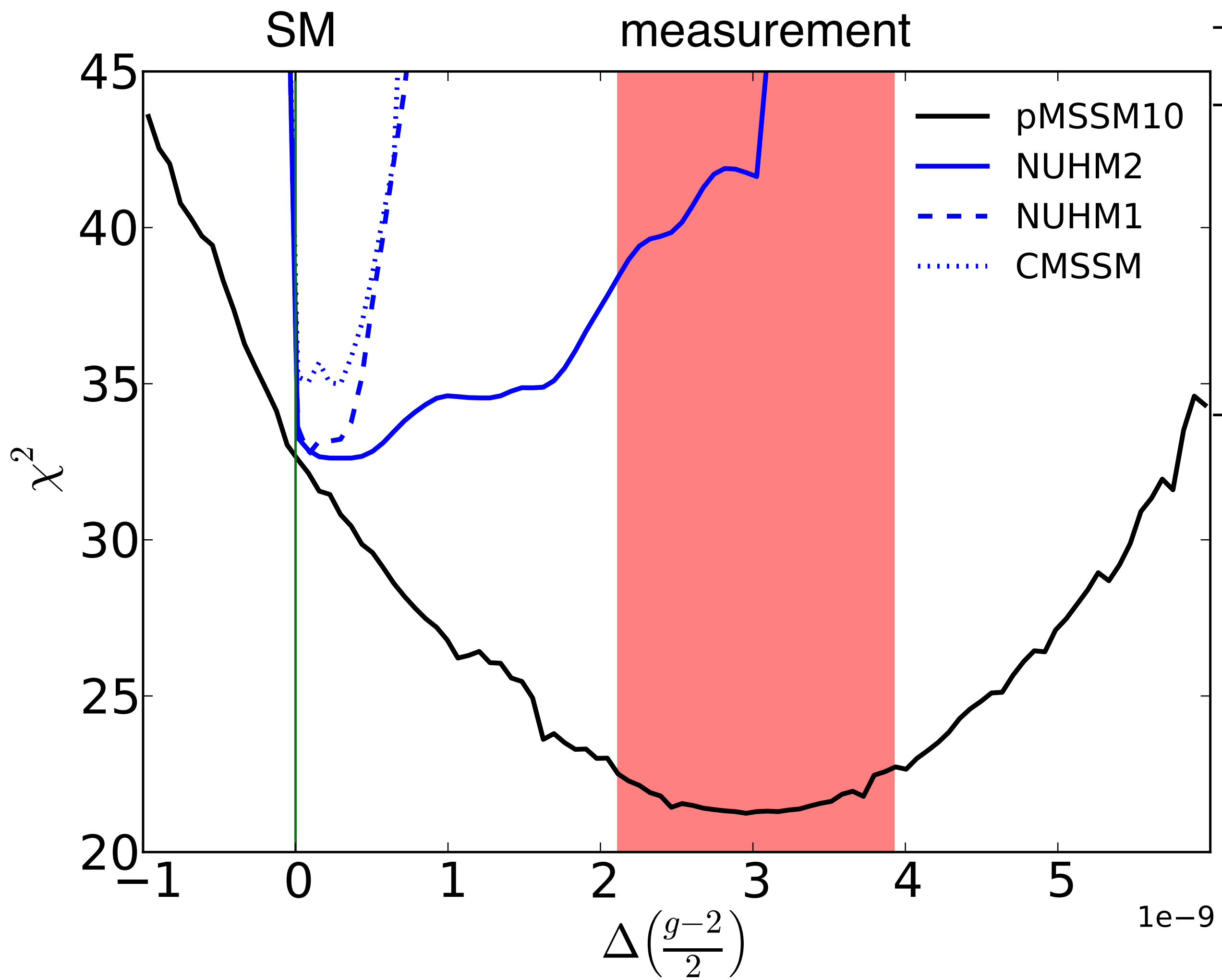
	X^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %

NUHM2 can get (g-2) right but only at the expense of M_h and jets + MET constraints.

masterCODE

From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

Resolving tension (g-2) and LHC

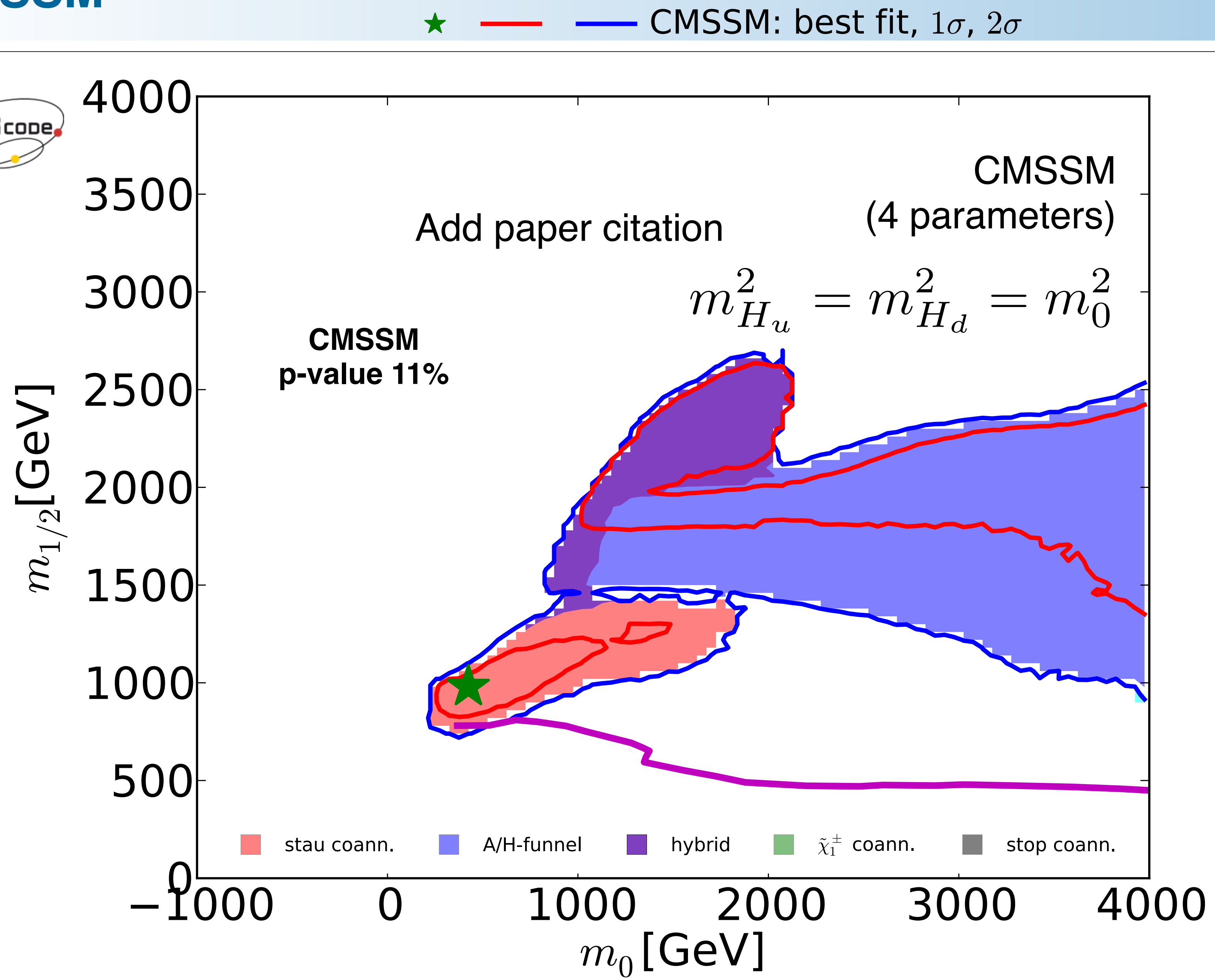


	X^2/n_{dof}	p-value
CMSSM	32.8/24	11 %
NUHM1	31.1/23	12 %
NUHM2	30.3/22	11 %
pMSSM10	**20.5/18**	**31 %**

pMSSM10 resolves the tension between (g-2) and LHC constraints. This significantly improves the fit.

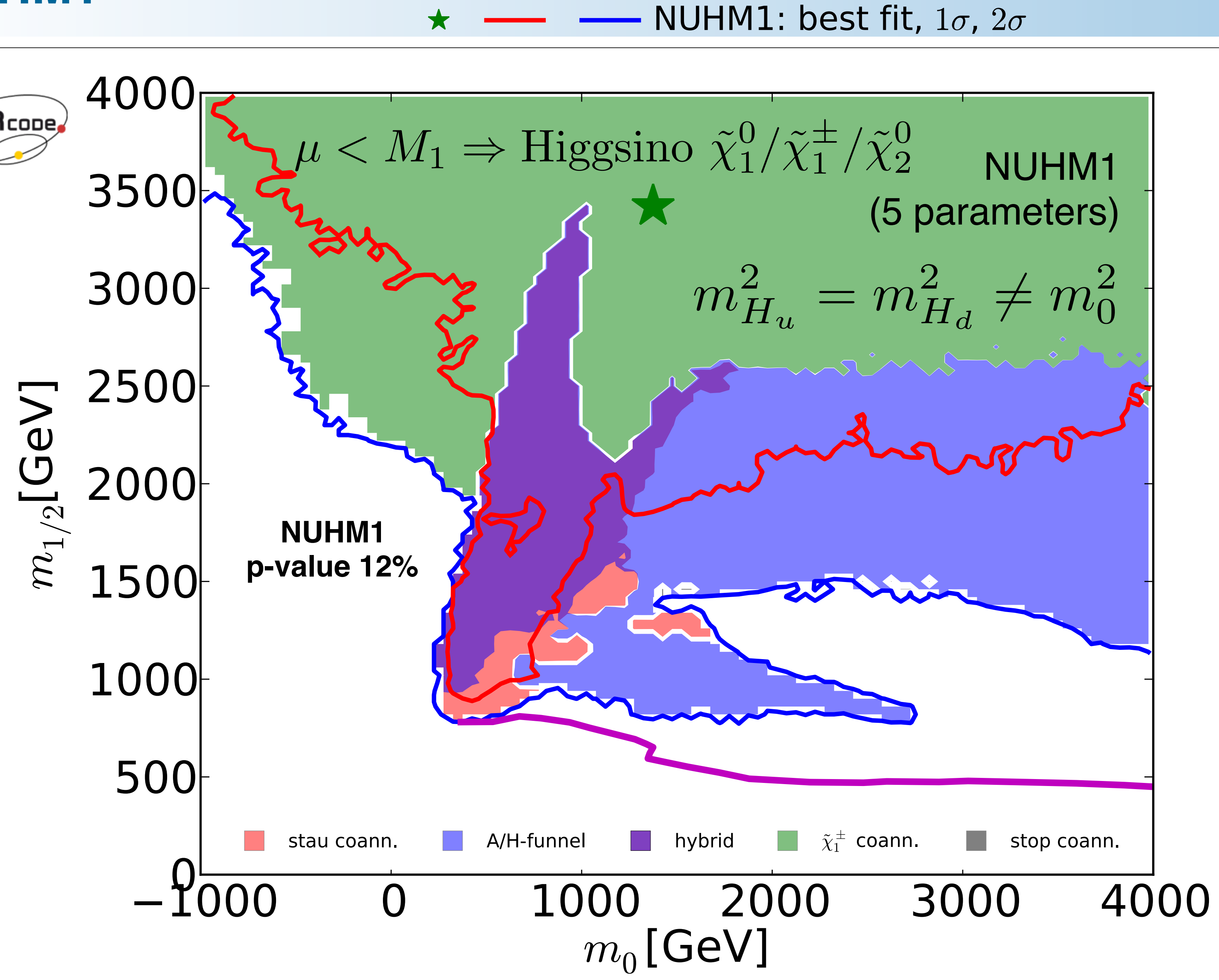
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

CMSSM



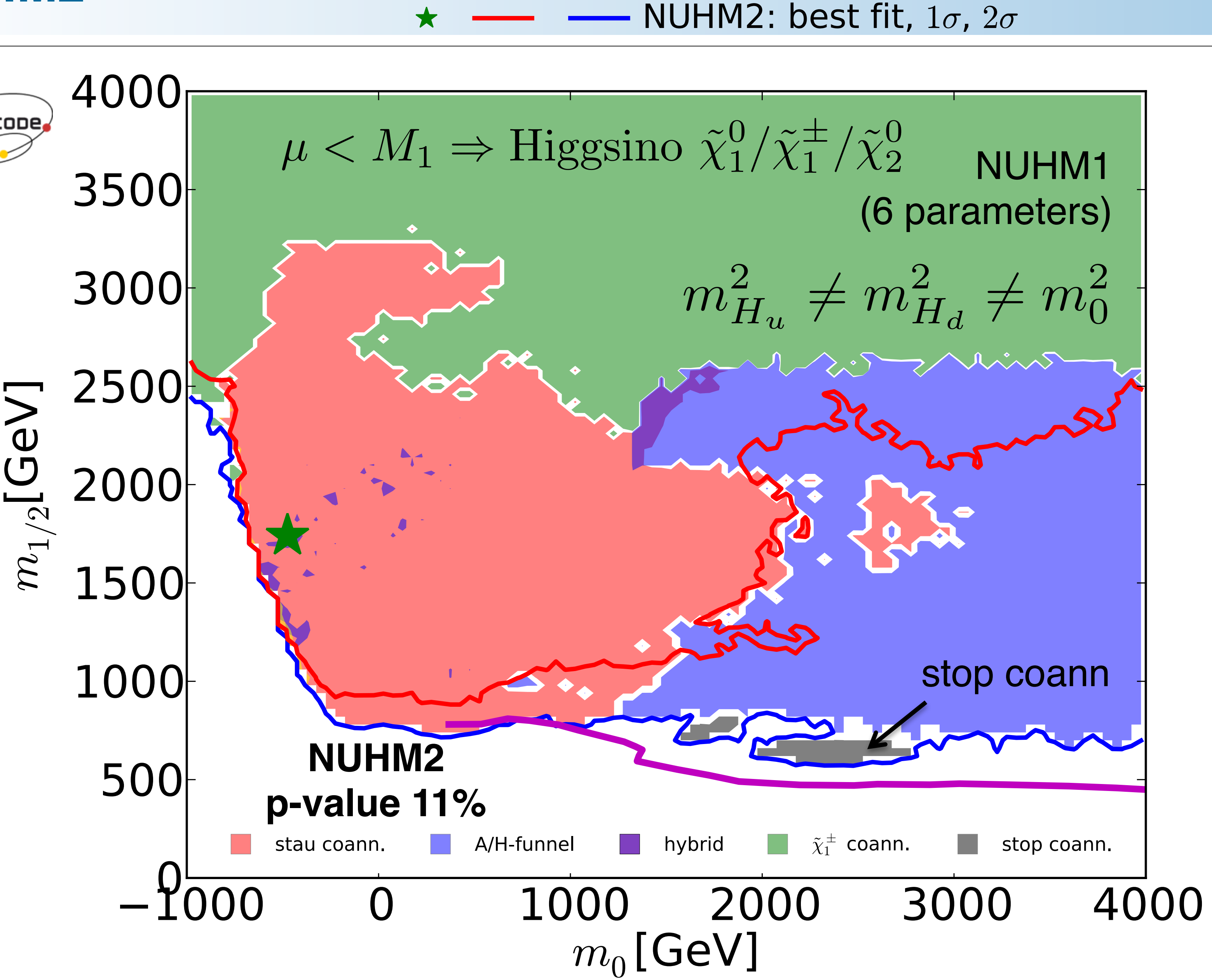
From MasterCode papers: 1312.5250, 1408.4060 and 1504.03260

NUHM1



From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

NUHM2



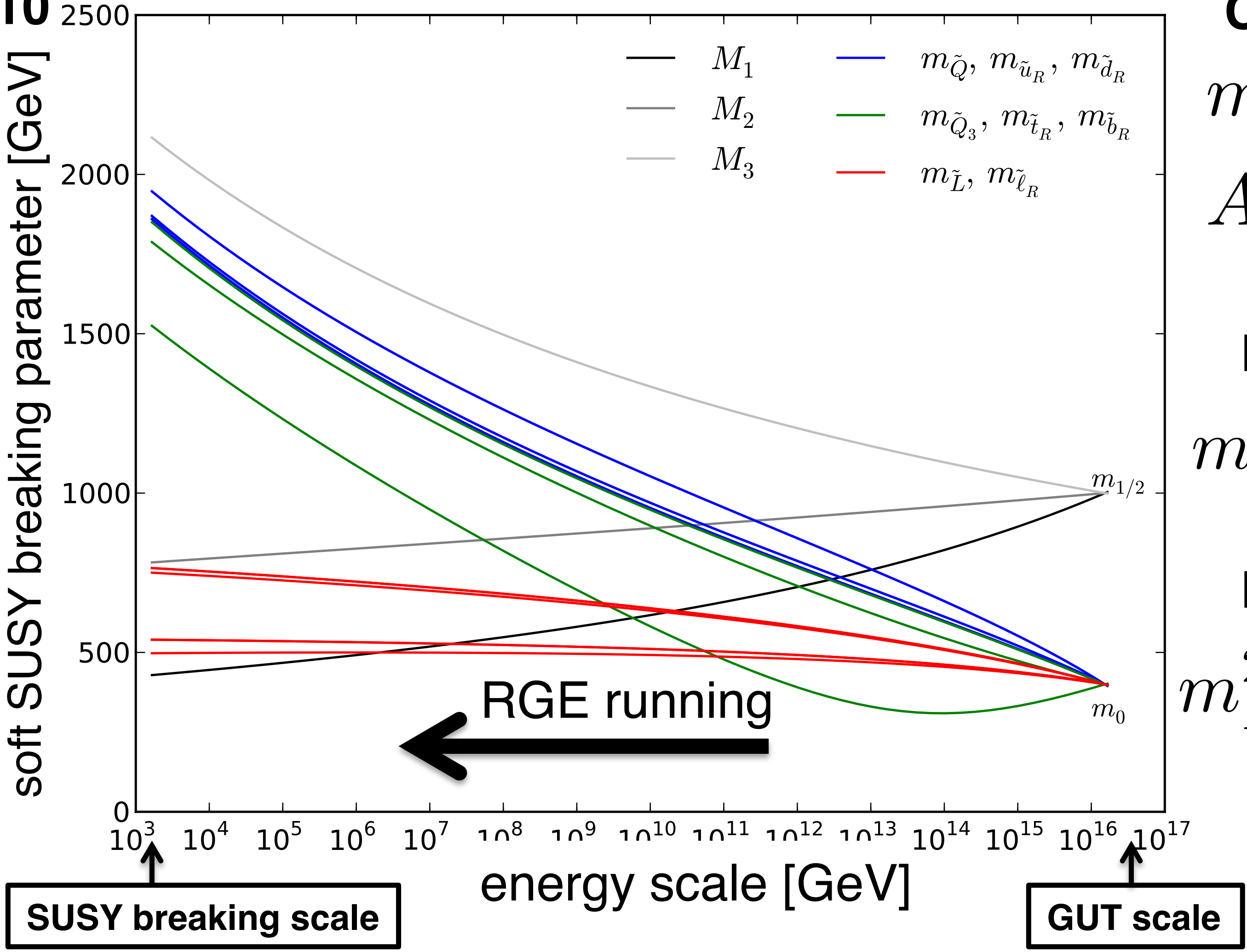
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

MasterCode: The two worlds of SUSY models

"Soft scale" ⟷ "GUT scale"

pMSSM10

M_1, M_2, M_3, $m_{\tilde{q}_{12}}$, $m_{\tilde{q}_3}$, $m_{\tilde{\ell}}$, A, M_A, $\tan\beta$, μ



CMSSM

m_0, $m_{1/2}$, A_0, $\tan\beta$

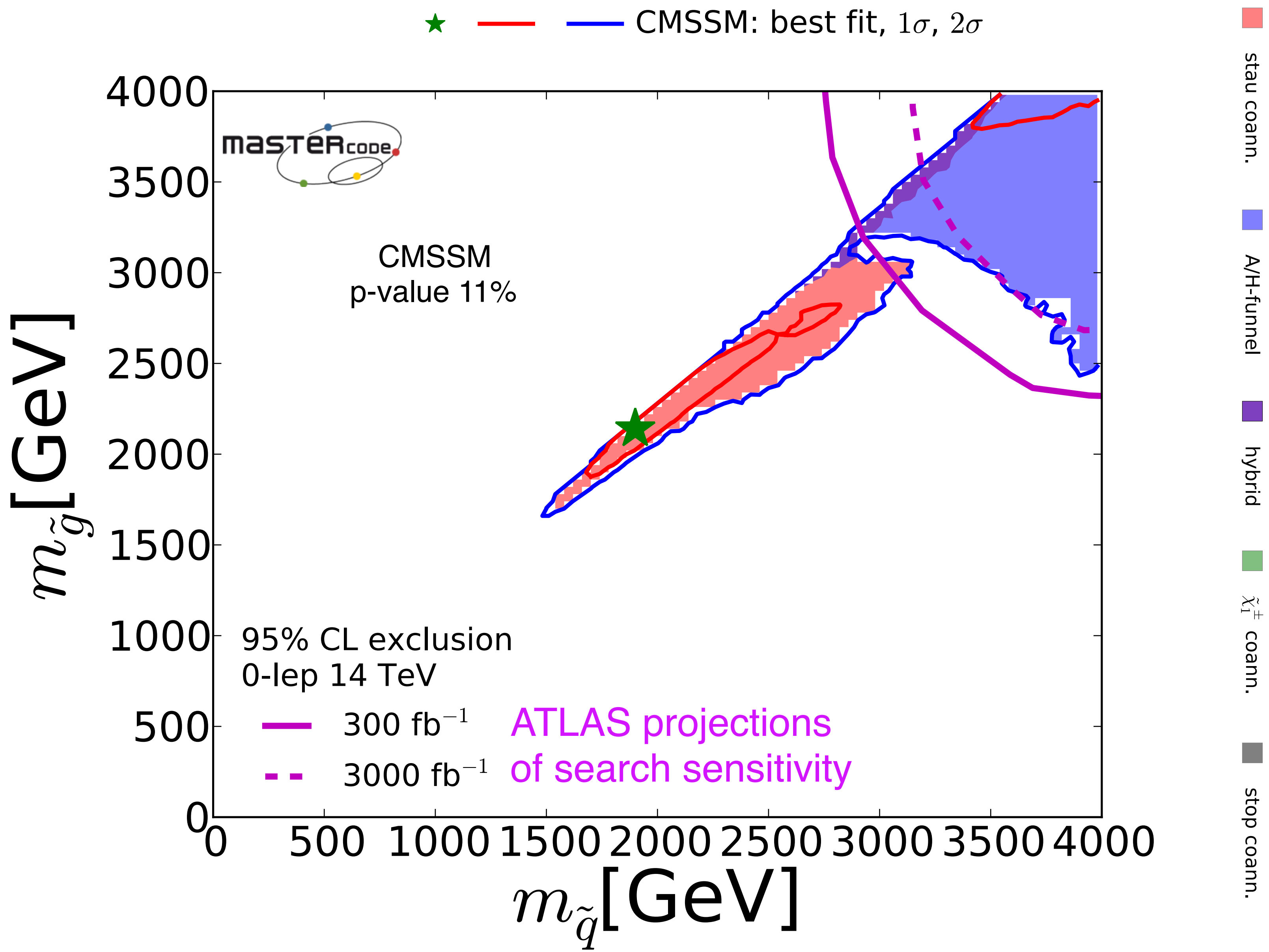
NUHM1

$$m^2_{H_u} = m^2_{H_d}$$

NUHM2

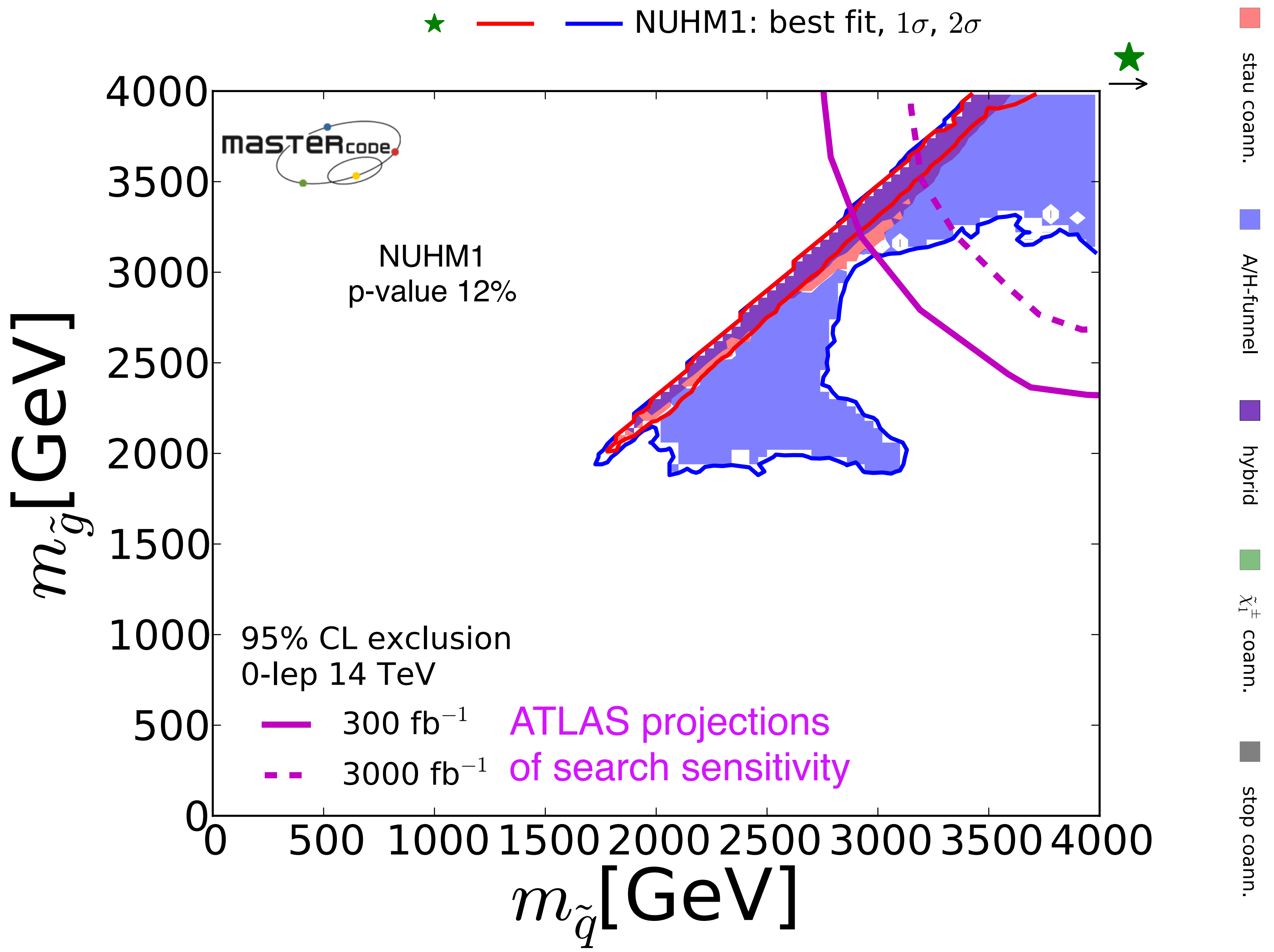
$$m^2_{H_u} \neq m^2_{H_d}$$

CMSSM Today: Mq-Mg Search plane



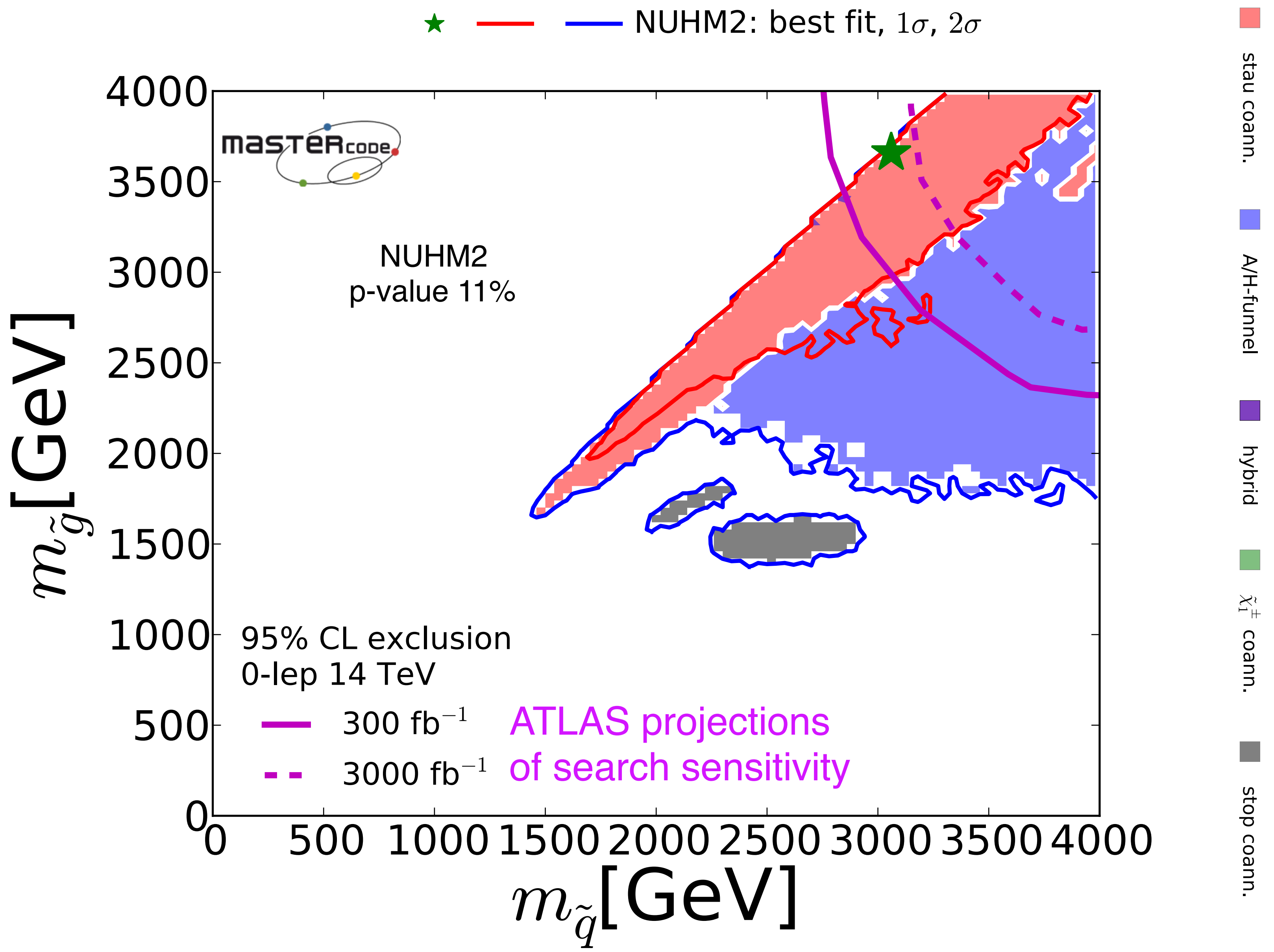
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

CMSSM Today: Mq-Mg Search plane



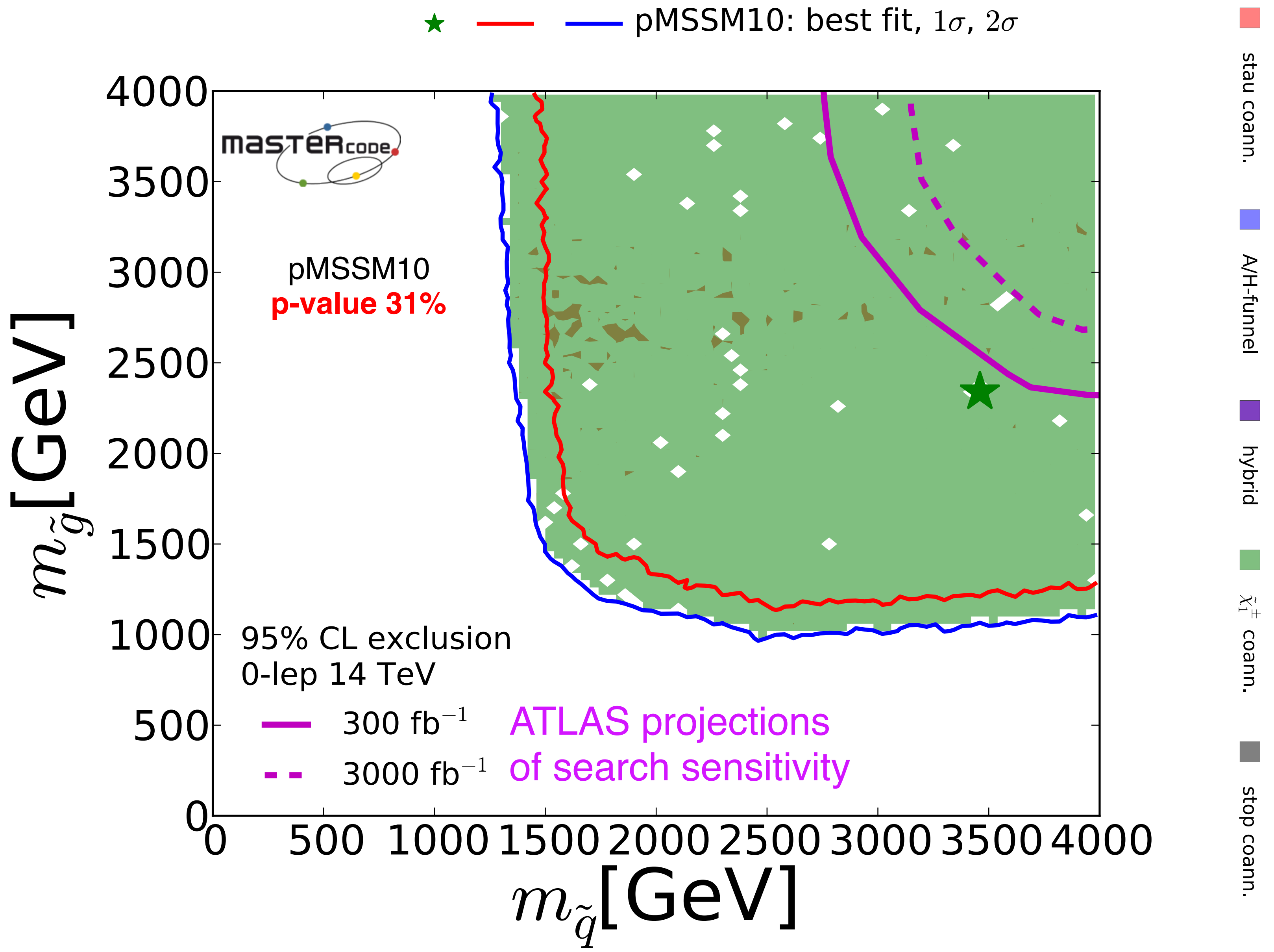
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

CMSSM Today: Mq-Mg Search plane



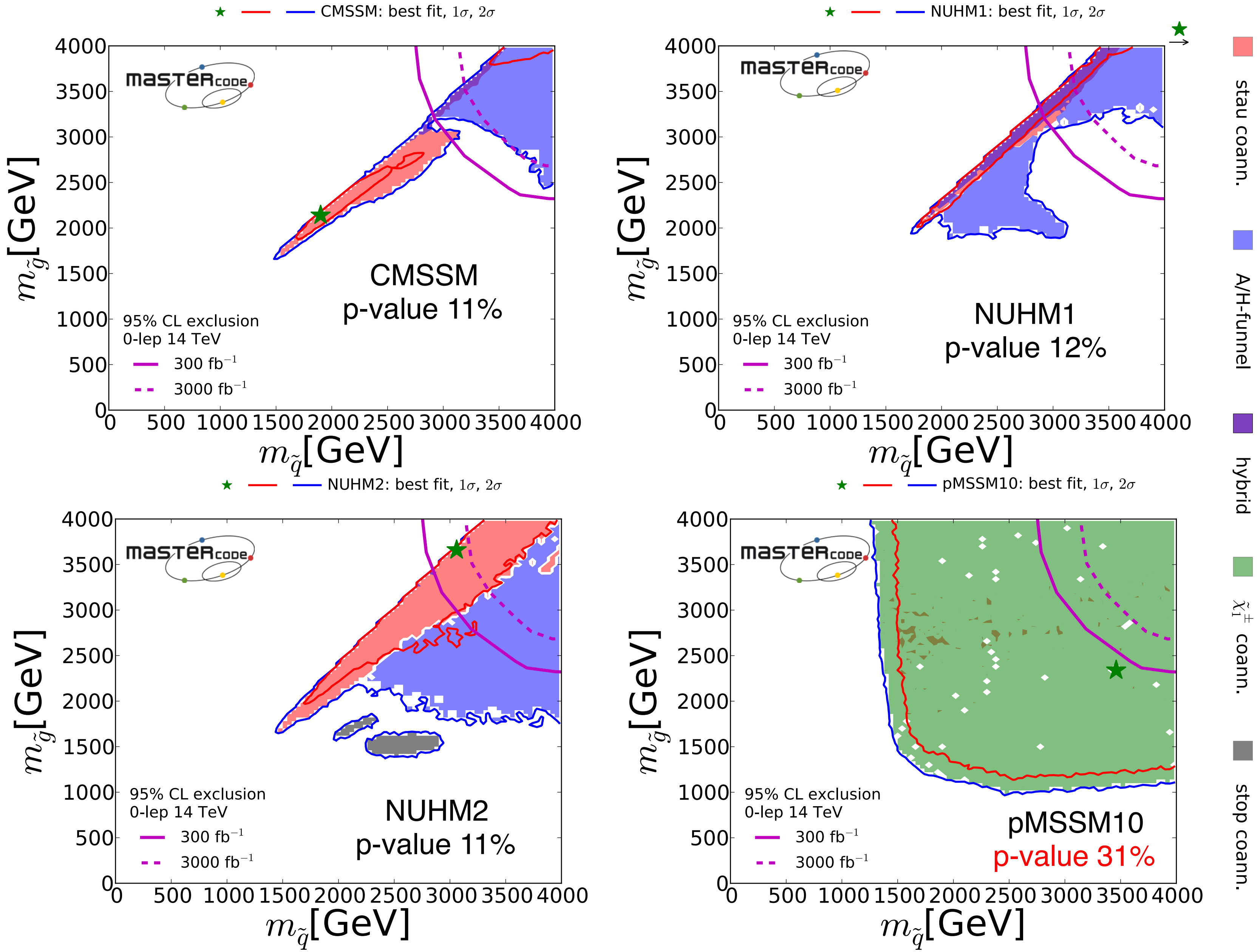
From MasterCode papers: 1312.5250, 1408.4060 and 1504.03260

CMSSM Today: Mq-Mg Search plane



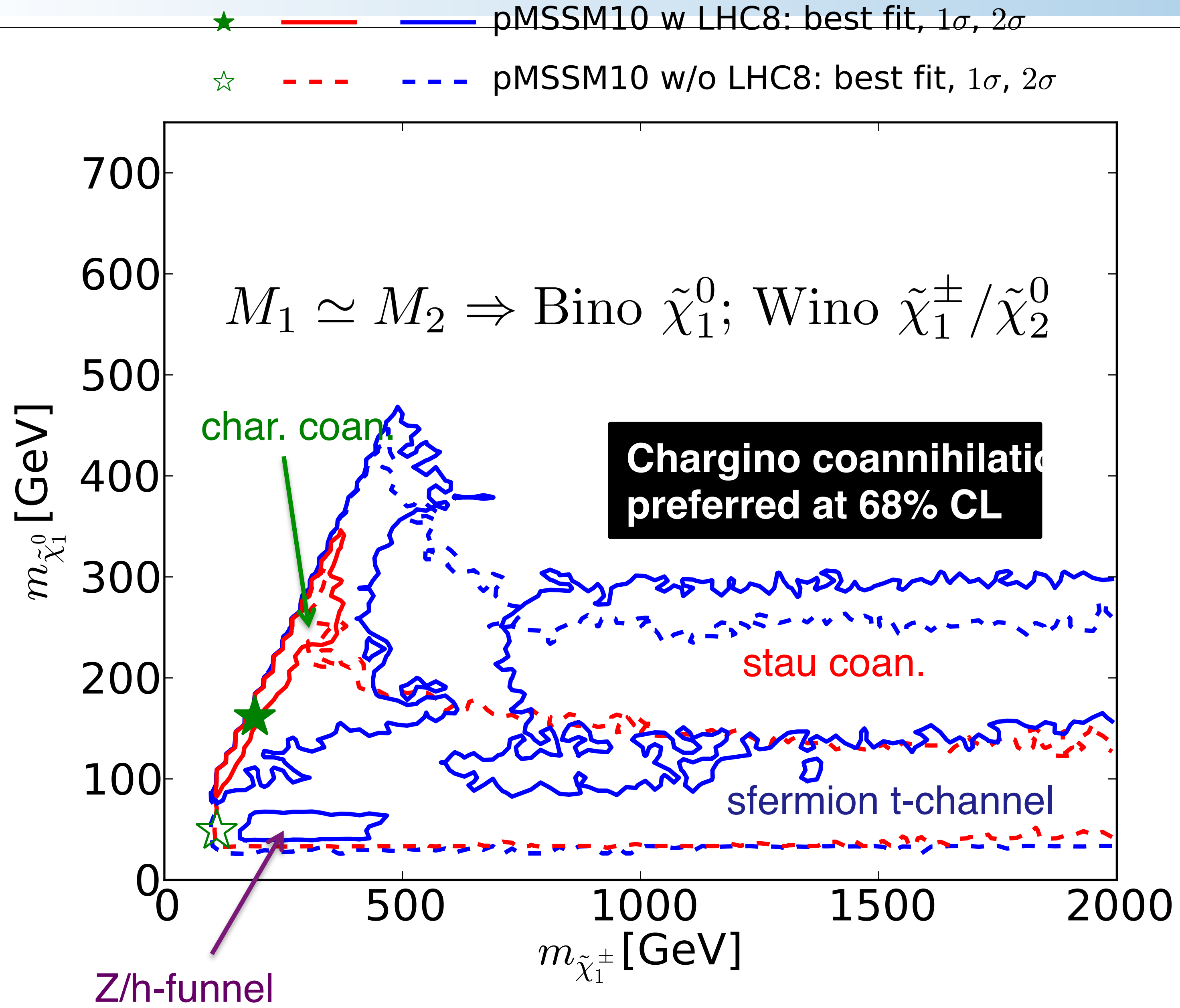
From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

Models in Comparison in “Mq-Mg Search plane”



From MasterCode papers:
1312.5250, 1408.4060 and 1504.03260

pMSSM10: parameter space



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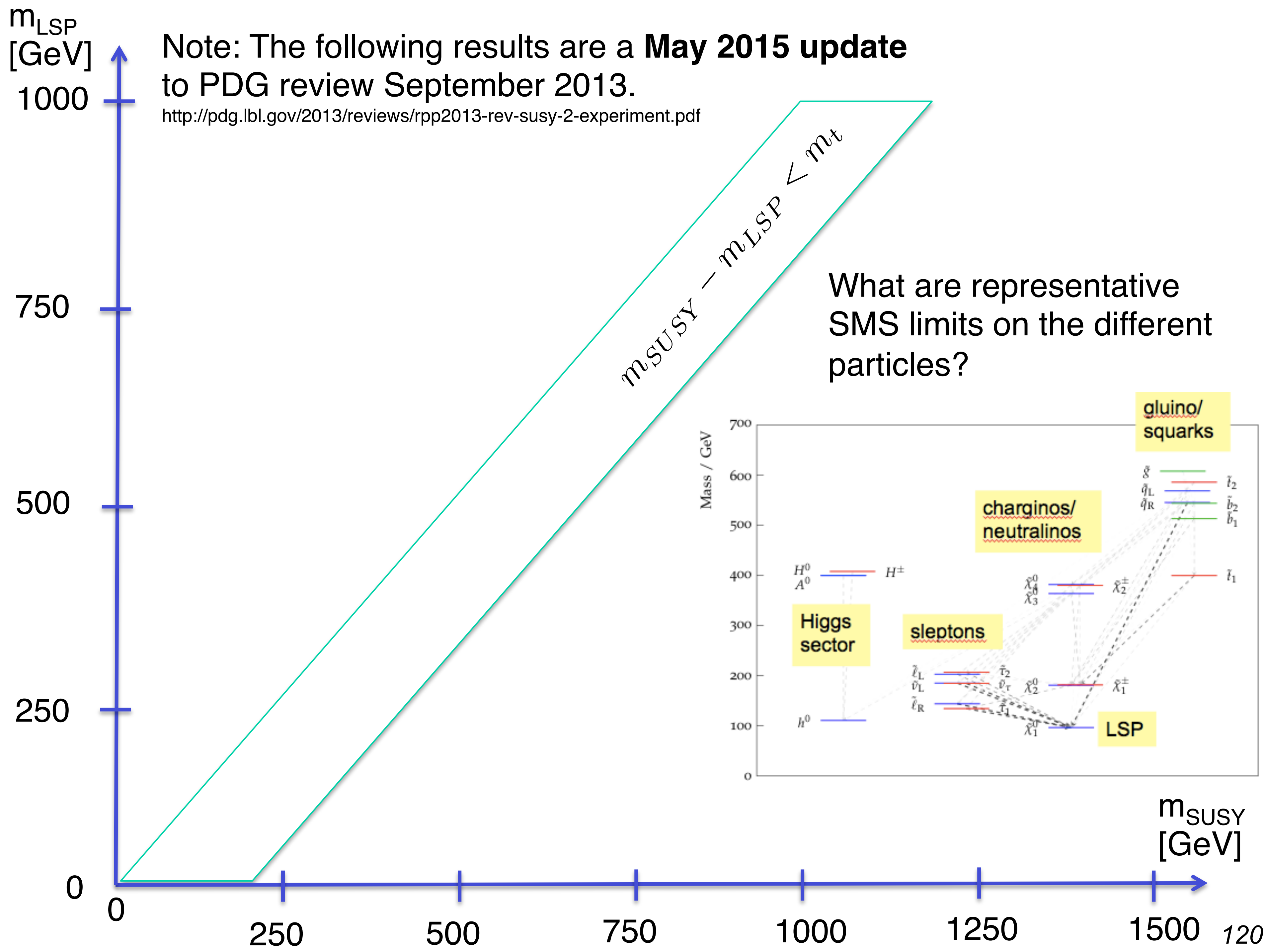
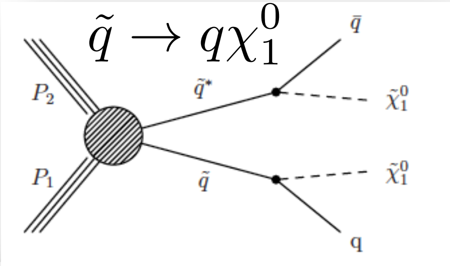
The full story

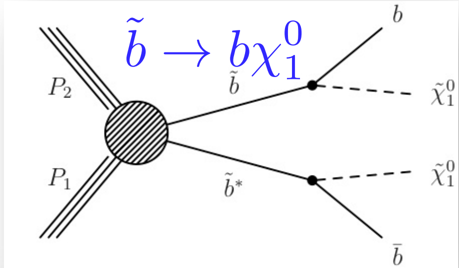
SUSY SUMMARY PLOT

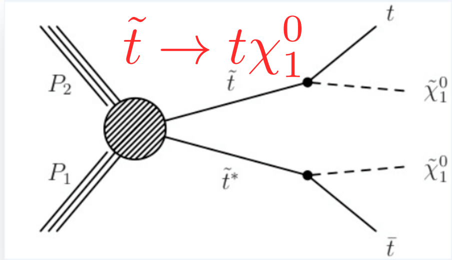


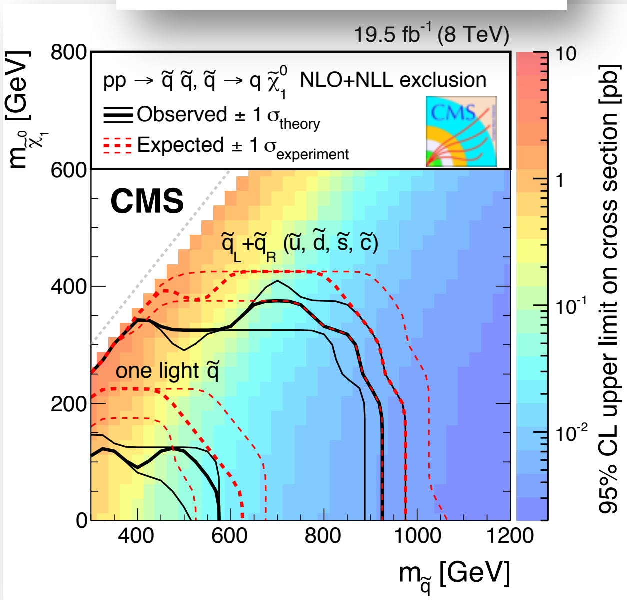
m_{LSP} [GeV]
1000
750
500
250
0
Note: The following results are a **May 2015 update** to PDG review September 2013.
http://pdg.lbl.gov/2013/reviews/rpp2013-rev-susy-2-experiment.pdf
$m_{SUSY} - m_{LSP} < m_t$
What are representative SMS limits on the different particles?
Mass / GeV
gluino/ squarks
charginos/ neutralinos
Higgs sector
sleptons
LSP
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500

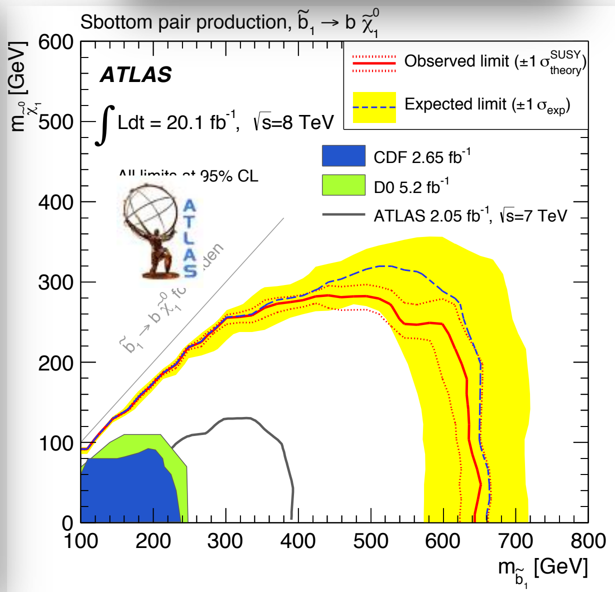
Direct squark production – chosen limits

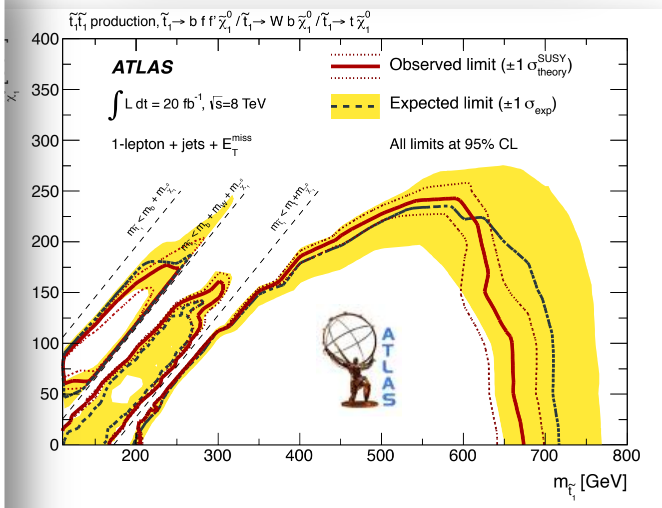








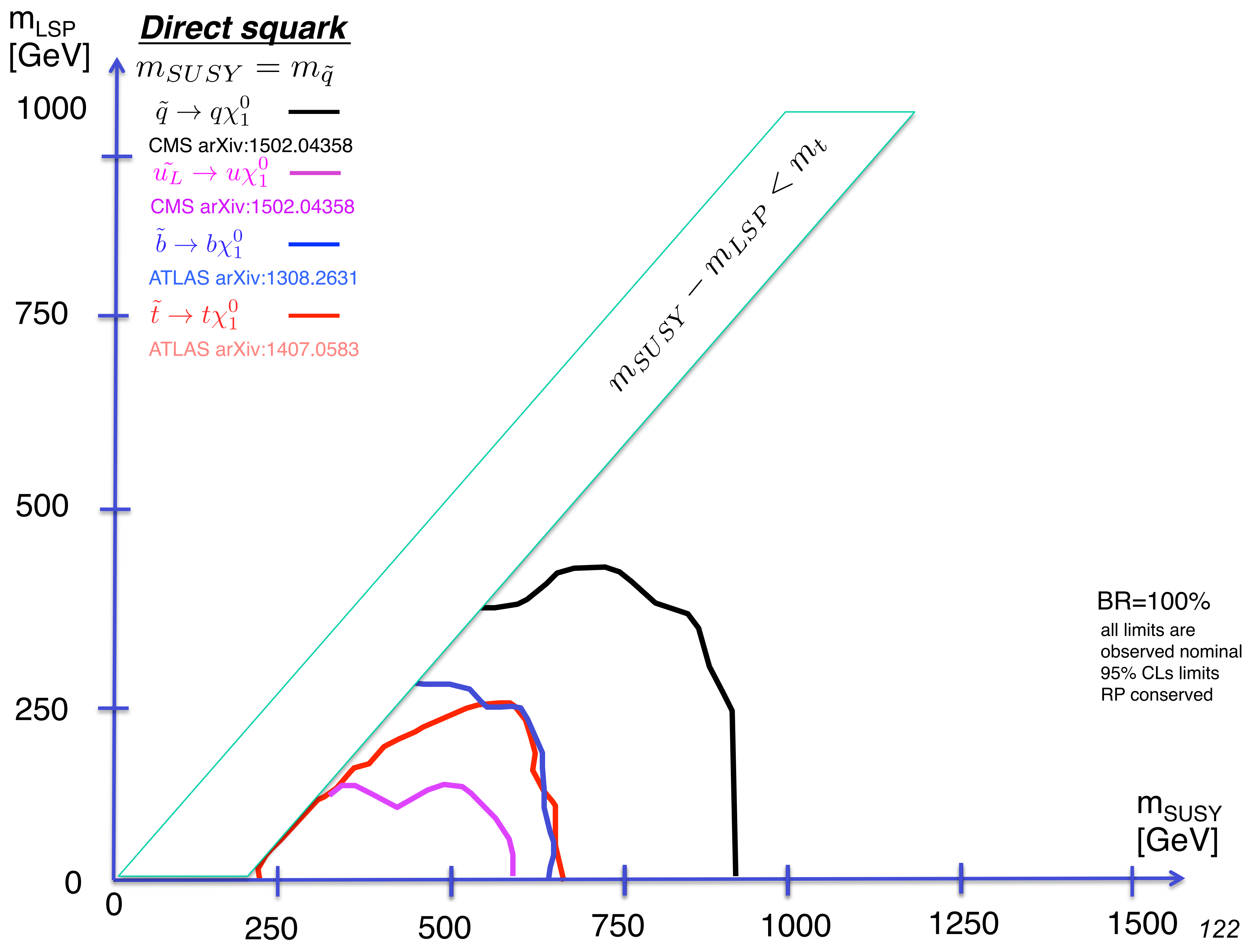




CMS arXiv:1502.04358
Signature: Jets + E_t^{miss} with M_{T2}
Limit assumes all 1st & 2nd gen squarks to be mass degenerate [or only one light squark]!

ATLAS arXiv:1308.2631
Signature: 2 b-jets + E_T^{mis}

ATLAS arXiv:1407.0583
Signature: 1Lepton + jets + E_T^{mis}



m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u}_L \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
$m_{SUSY} - m_{LSP} < m_t$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
m_{SUSY} [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500

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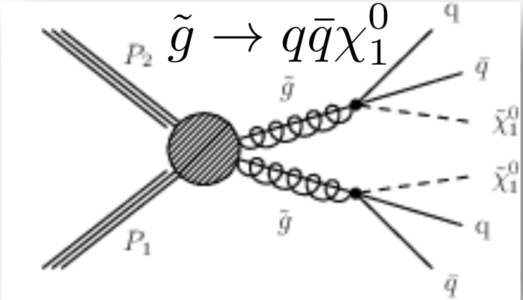
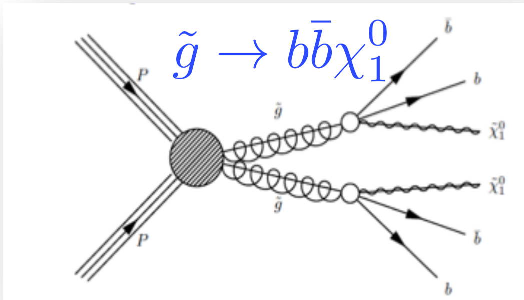
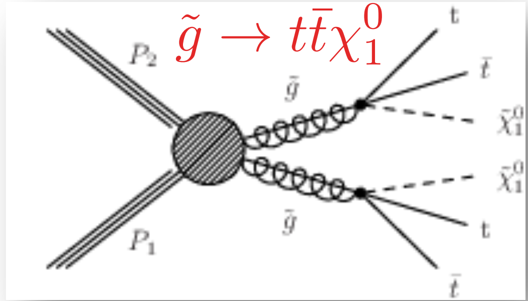
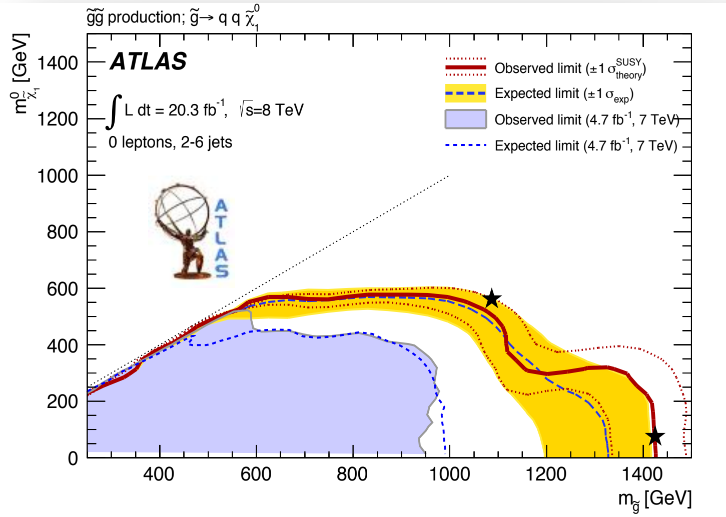
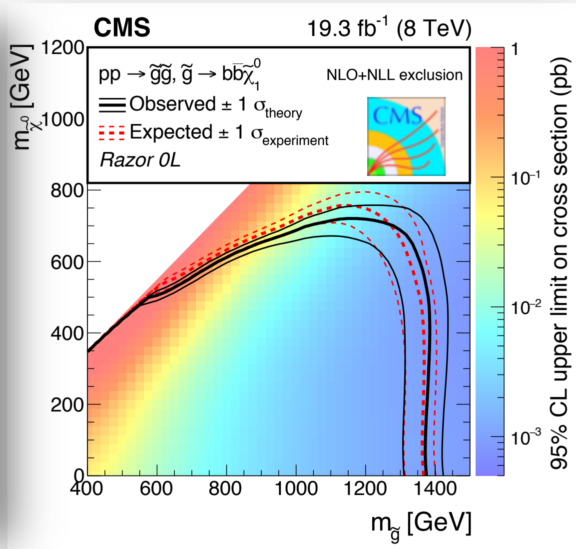
Gluino mediated squark production – limits chosen

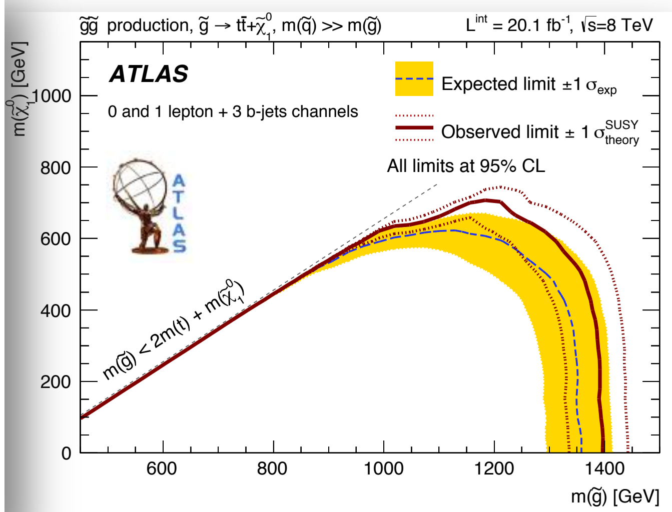








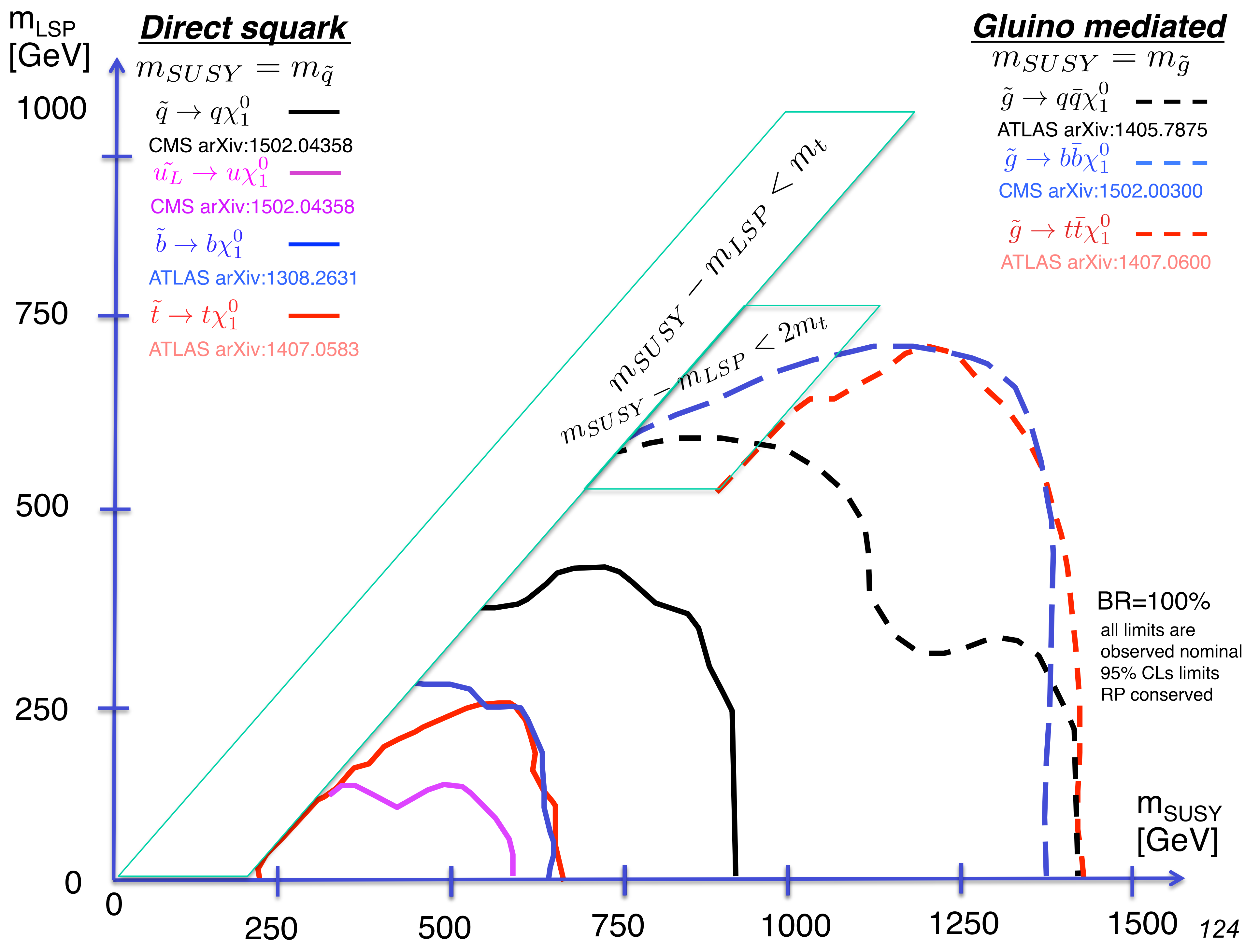




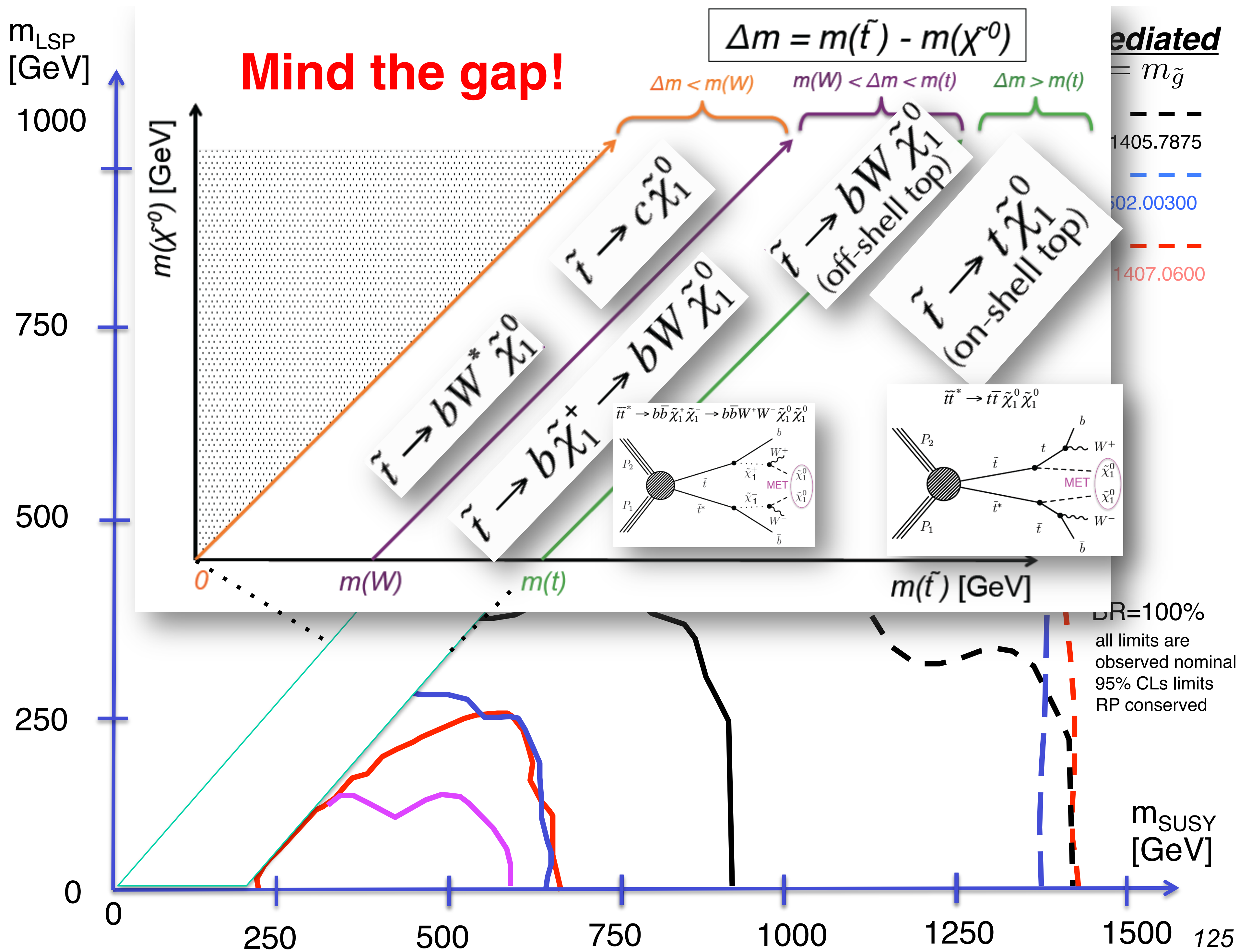
ATLAS arXiv:1405.7875
Signature: 0L + 2-6 Jets + E_t^{miss}

CMS arXiv:1502.00300
Signature: : 0L + Razor + b-tag

Signature: 0/1 Leptons + 3 b-tag + E_t^{mis}

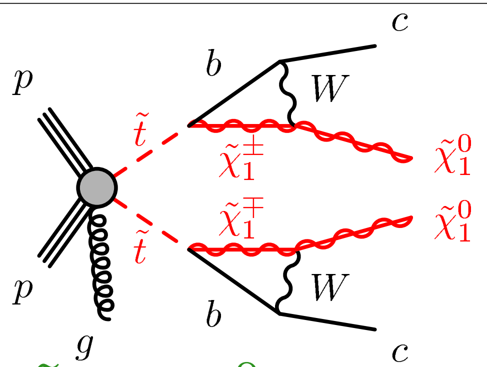


m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u_L} \rightarrow u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \rightarrow b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \rightarrow t\chi_1^0$
ATLAS arXiv:1407.0583
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \rightarrow q\bar{q}\chi_1^0$
ATLAS arXiv:1405.7875
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$
CMS arXiv:1502.00300
$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
ATLAS arXiv:1407.0600
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_{SUSY} [GeV]
1000
750
500
250
0
0
250
500
750
1000
1250
1500

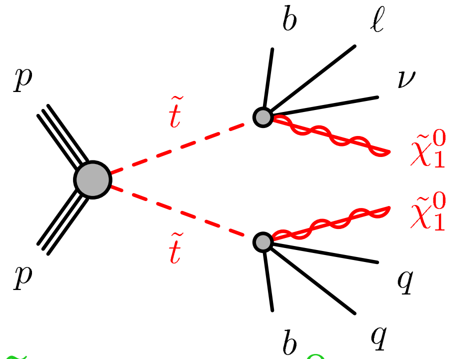


m_LSP [GeV]
1000
750
500
250
0
Mind the gap!
Δm = m(t̃) - m(χ̃⁰)
Δm < m(W)
m(W) < Δm < m(t)
Δm > m(t)
m(χ̃⁰) [GeV]
t̃ → bW* χ̃₁⁰
t̃ → c χ̃₁⁰
t̃ → b χ̃₁⁺ → bW χ̃₁⁰
t̃ → bW χ̃₁⁰ (off-shell top)
t̃ → t χ̃₁⁰ (on-shell top)
MET
0
m(W)
m(t)
m(t̃) [GeV]
ediated
1405.7875
502.00300
1407.0600
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
m_SUSY [GeV]
0
250
500
750
1000
1250
1500

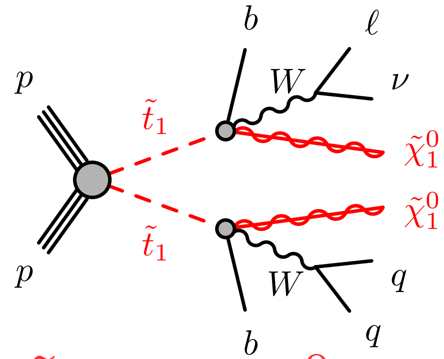
Compressed stop – mind the gap!



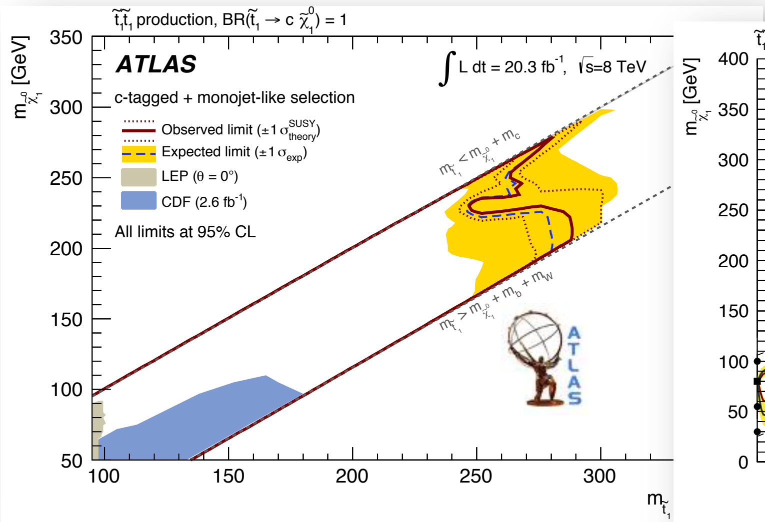
$\tilde{t} \to c\chi_1^0$

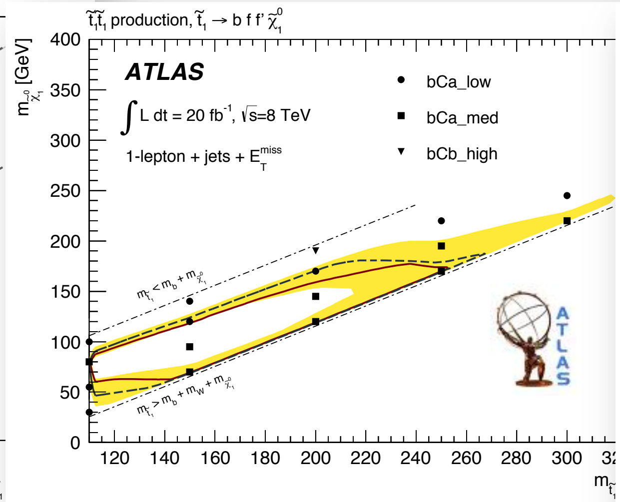


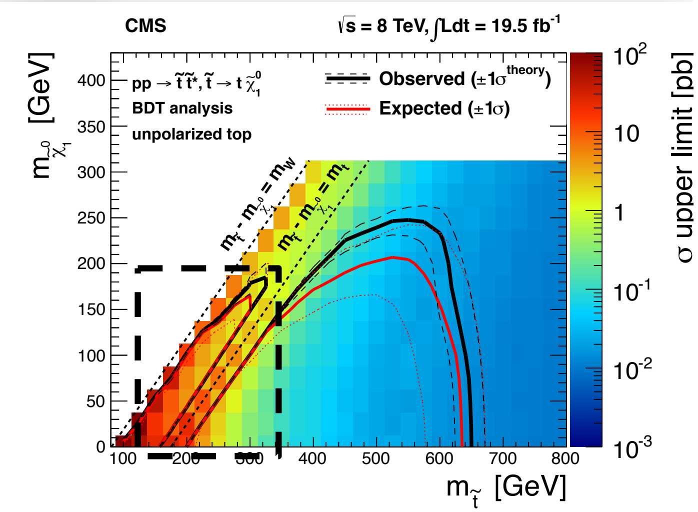
$\tilde{t} \to bff'\chi_1^0$



$\tilde{t} \to Wb\chi_1^0$



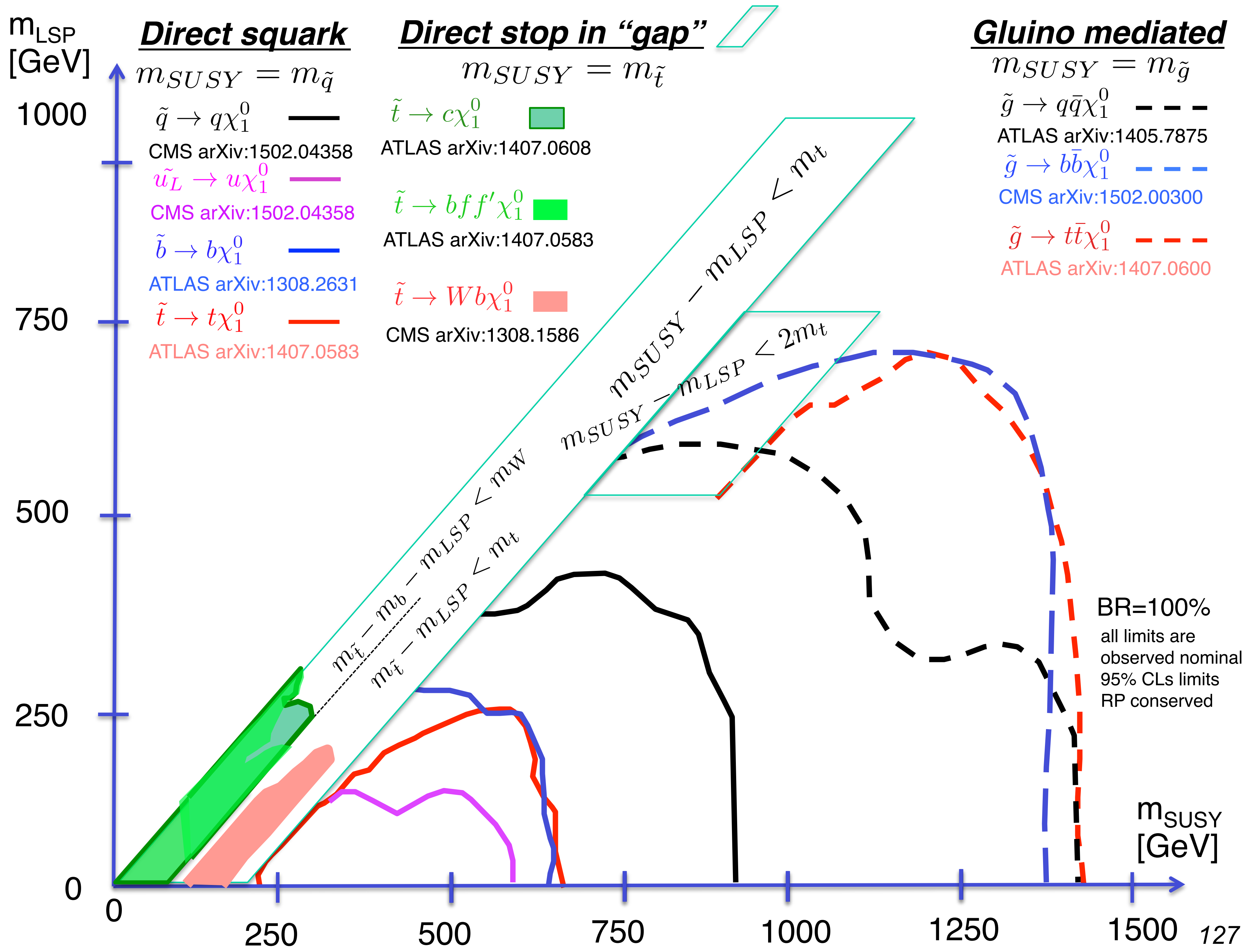




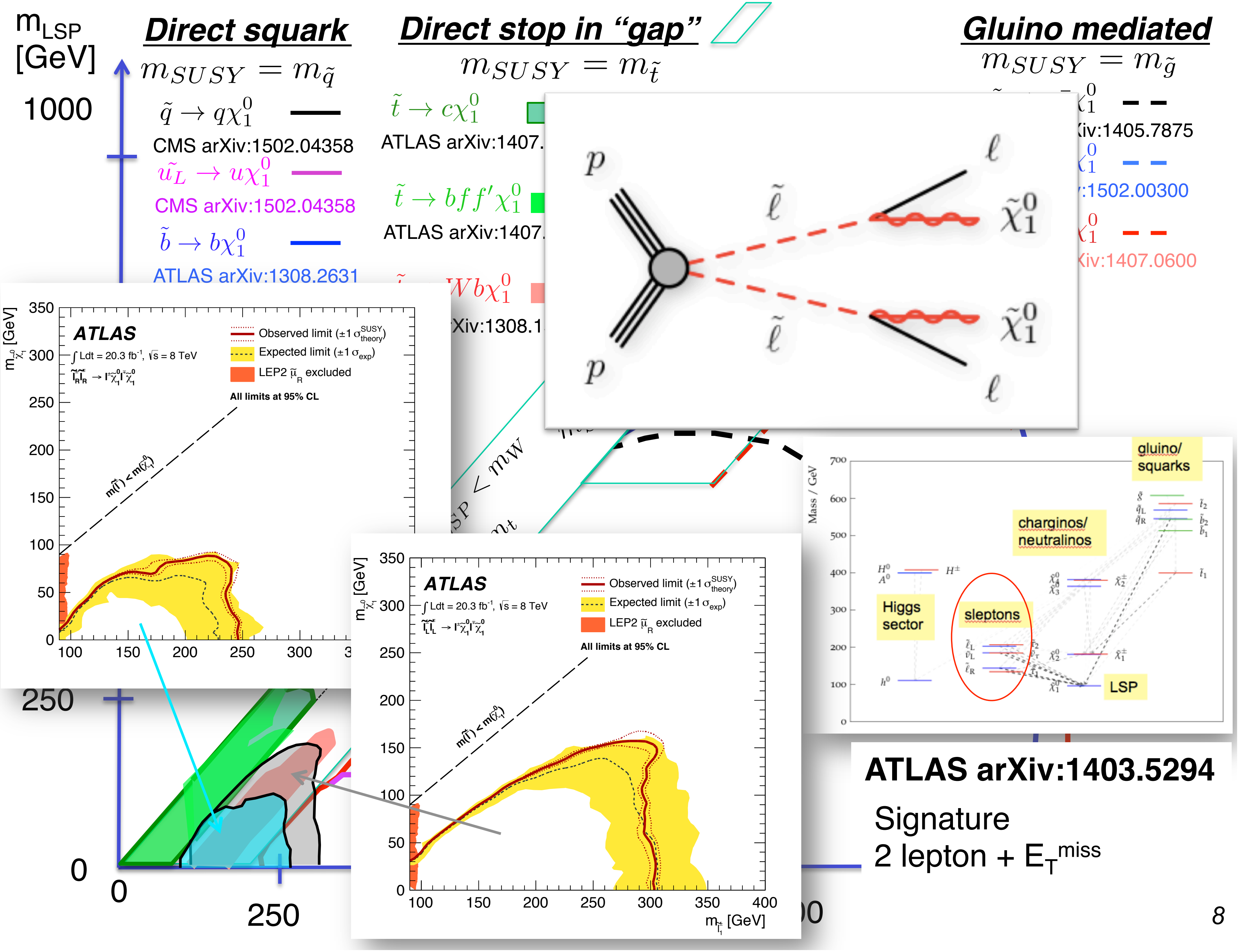
ATLAS arXiv:1407.0608
Mono-jet & c-tag combined

ATLAS: arXiv:1407.0583
$1L + E_t^{mis}$ & b-tag

CMS arXiv:1308.1586
$1L + E_t^{mis}$ and BDT & b-tag



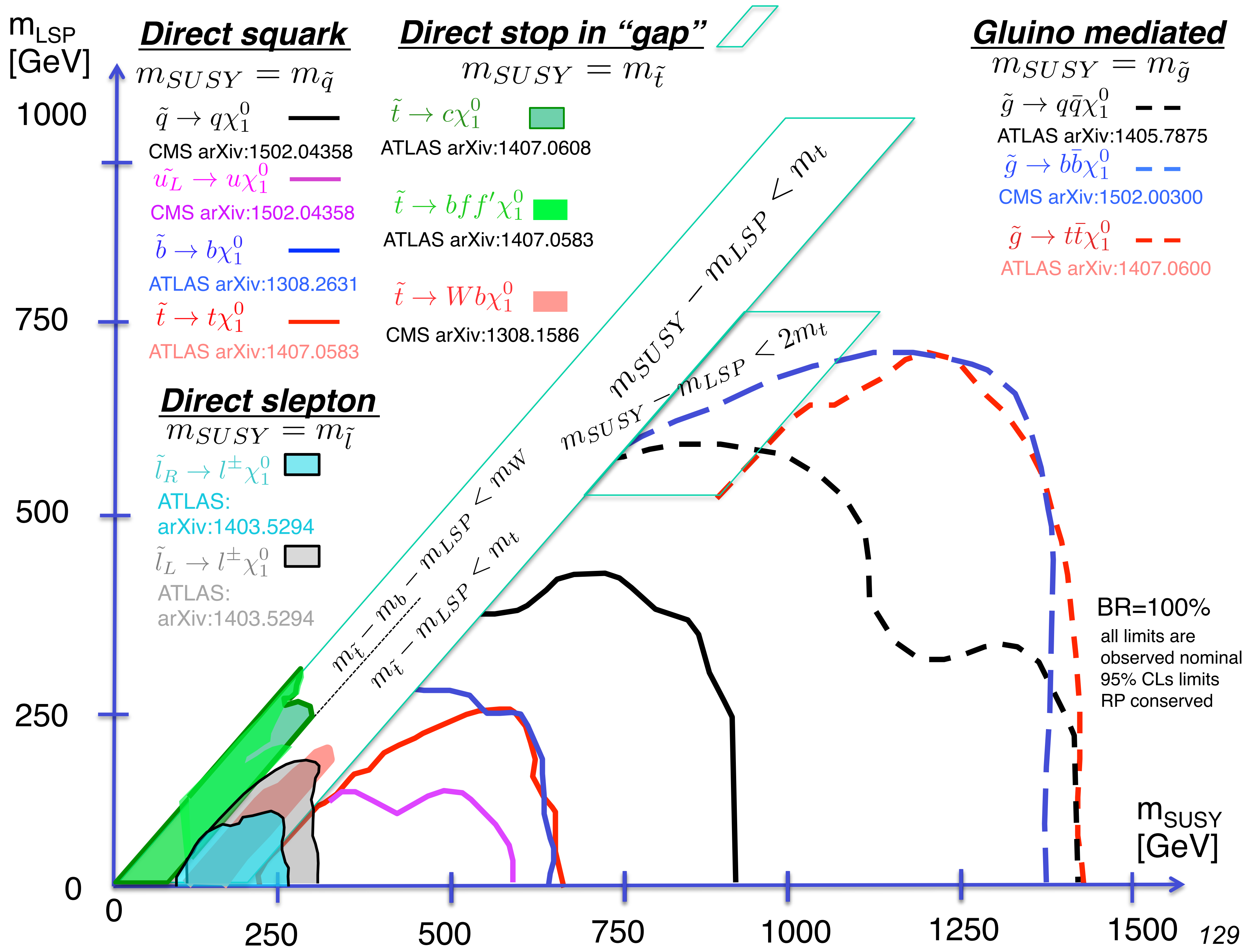
m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \rightarrow q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u_L} \rightarrow u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \rightarrow b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \rightarrow t\chi_1^0$
ATLAS arXiv:1407.0583
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \rightarrow c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde{t} \rightarrow bff'\chi_1^0$
ATLAS arXiv:1407.0583
$\tilde{t} \rightarrow Wb\chi_1^0$
CMS arXiv:1308.1586
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \rightarrow q\bar{q}\chi_1^0$
ATLAS arXiv:1405.7875
$\tilde{g} \rightarrow b\bar{b}\chi_1^0$
CMS arXiv:1502.00300
$\tilde{g} \rightarrow t\bar{t}\chi_1^0$
ATLAS arXiv:1407.0600
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500



ATLAS arXiv:1403.5294

Signature

2 lepton + E_T^{miss}

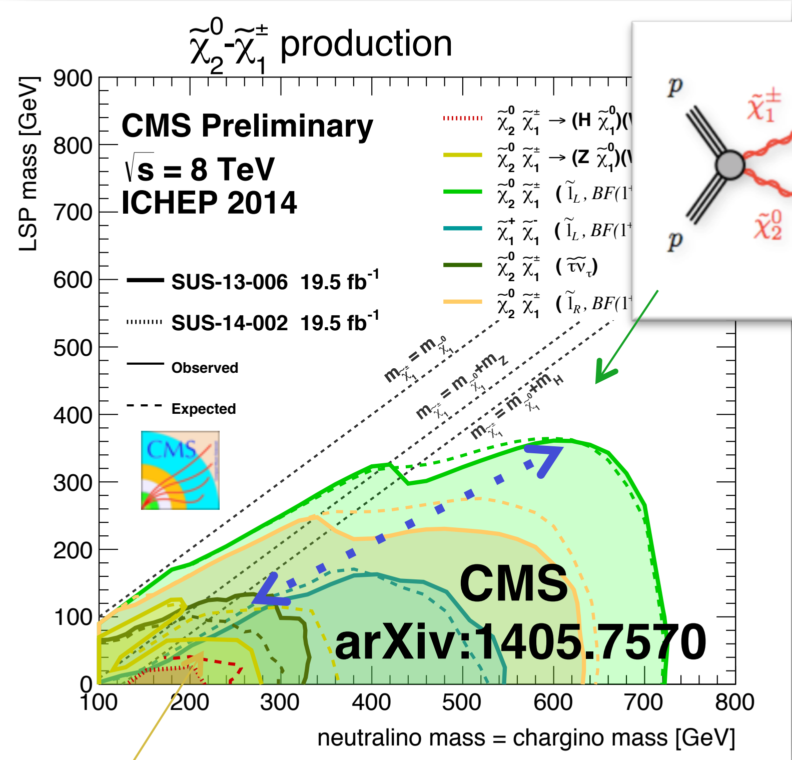


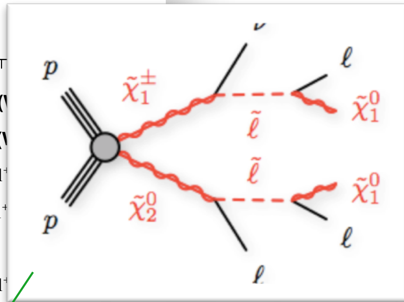
m_{LSP} [GeV]
1000
750
500
250
0
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u_L} \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde{t} \to bff'\chi_1^0$
ATLAS arXiv:1407.0583
$\tilde{t} \to Wb\chi_1^0$
CMS arXiv:1308.1586
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS arXiv:1405.7875
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS arXiv:1502.00300
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS arXiv:1407.0600
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_R \to l^{\pm}\chi_1^0$
ATLAS:
arXiv:1403.5294
$\tilde{l}_L \to l^{\pm}\chi_1^0$
ATLAS:
arXiv:1403.5294
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500

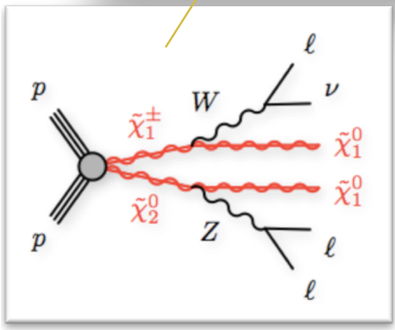
Imperial College London

Direct chargino/neutralino production

$\chi_2^0\,\chi_1^{+-}$ production

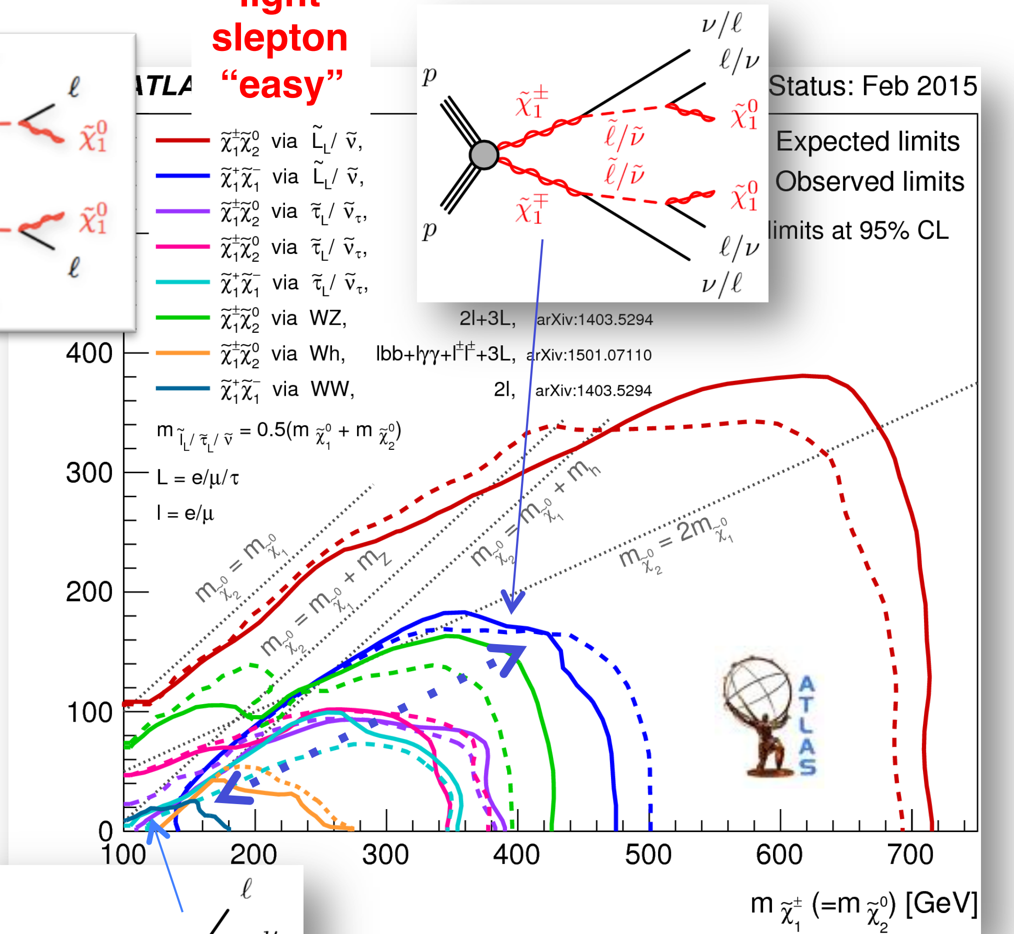


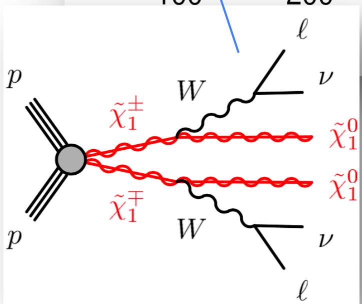




$X_1^+\,X_1^-$ production

light slepton "easy"

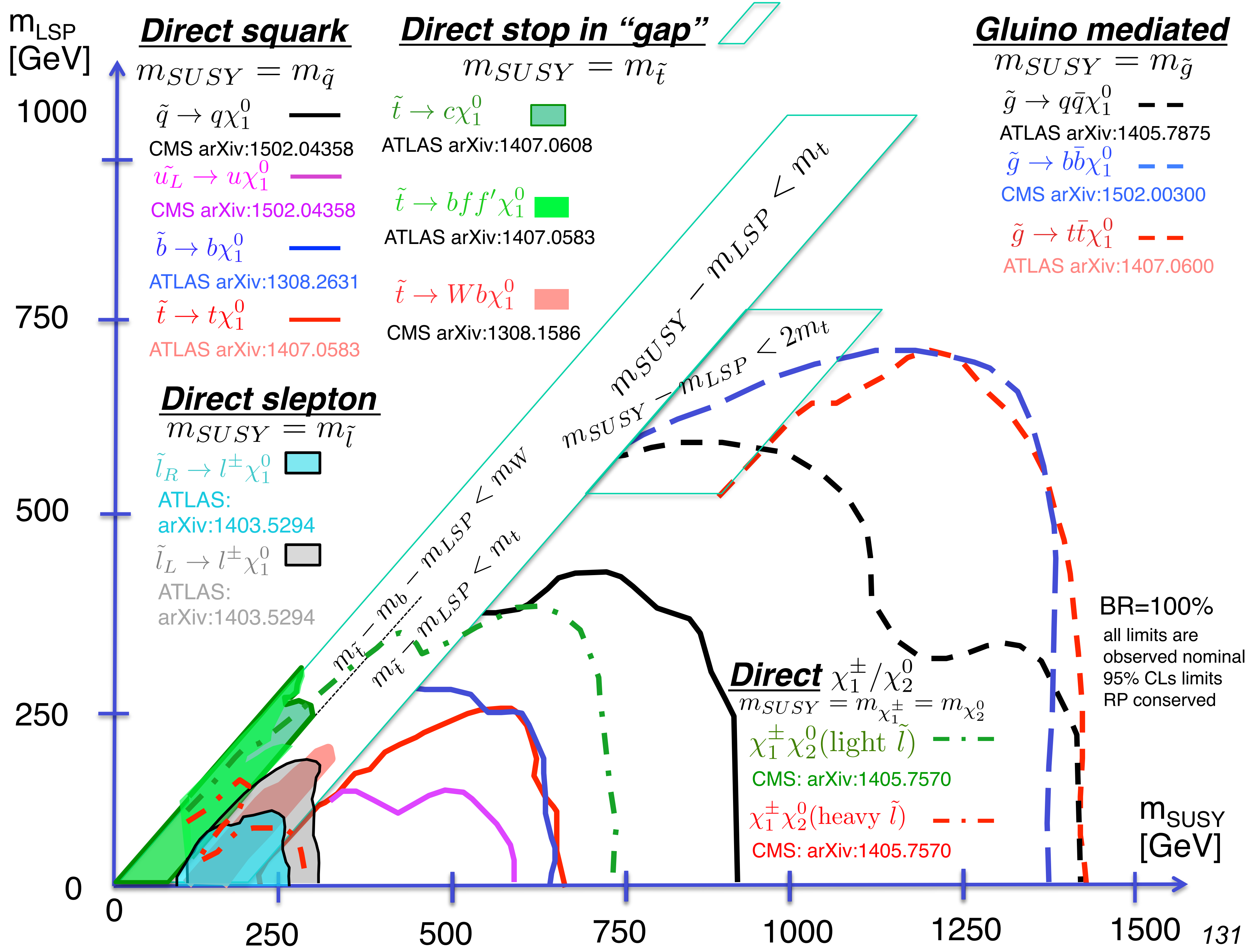




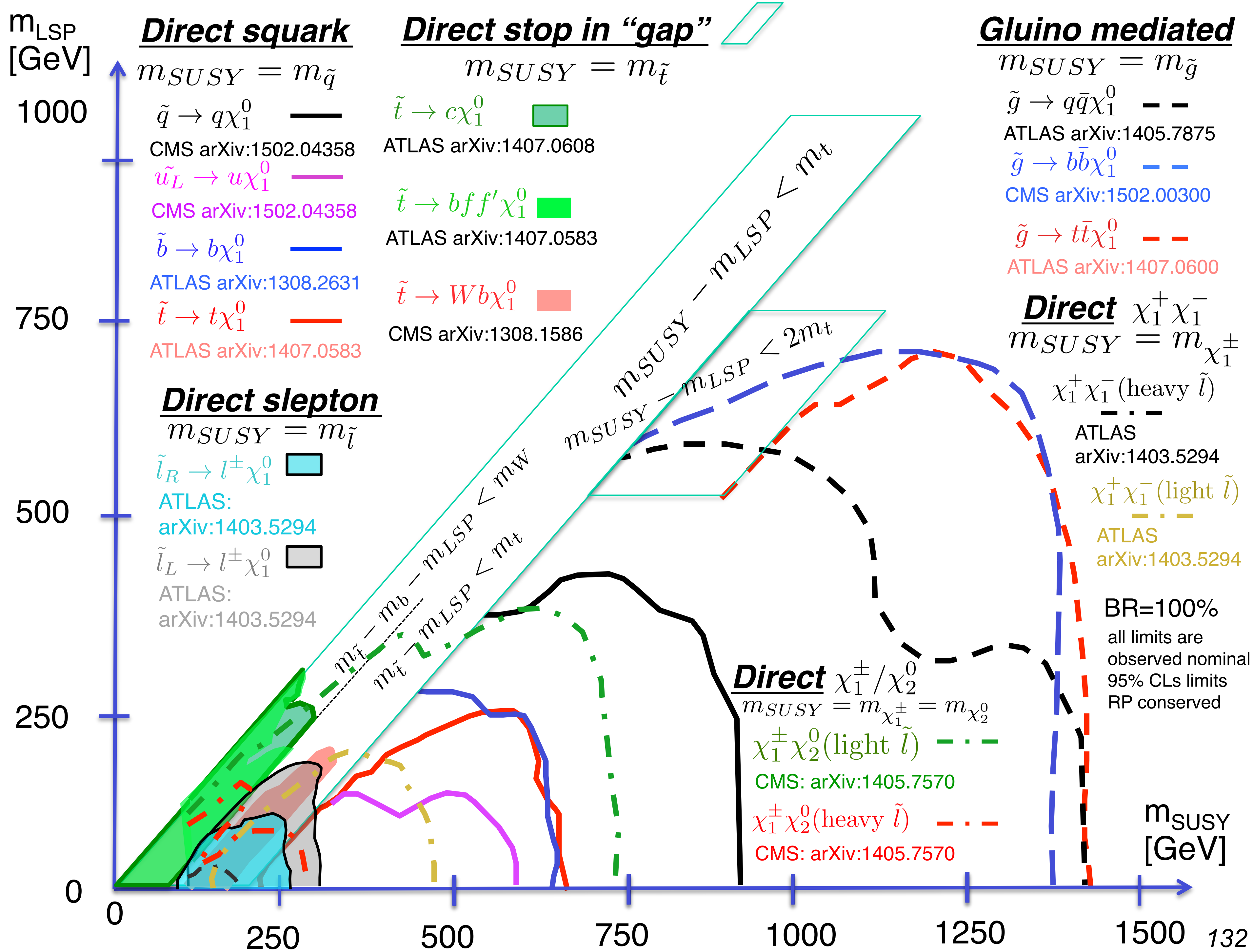
heavy slepton "hard(er)"

Add Z(l$^+$l$^-$)+2jets topology in bins of E_t^{miss} to increase sensitivity for "heavy" slepton case

ATLAS arXiv:1403.5294

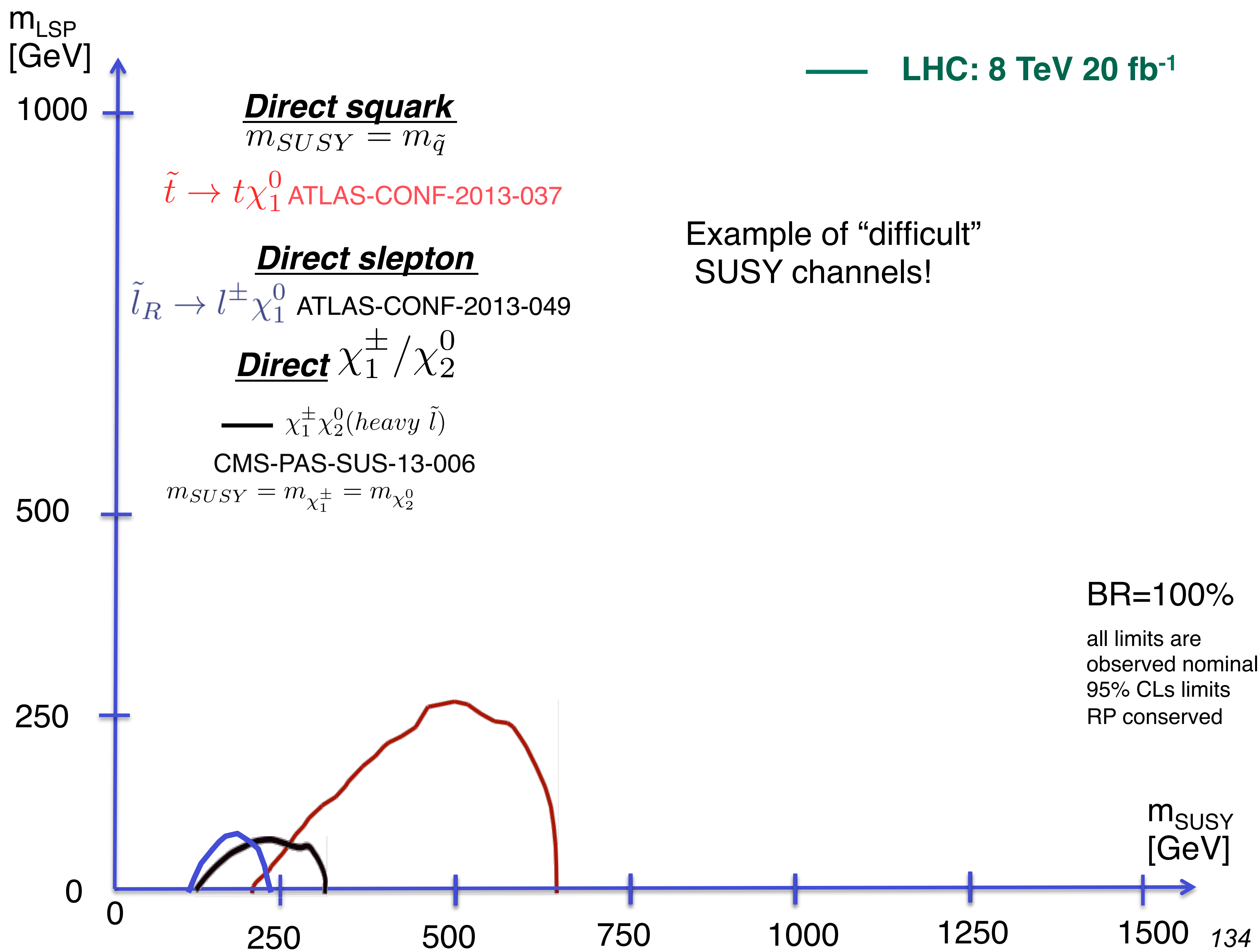


m_{LSP} [GeV]
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u}_L \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde{t} \to bff'\chi_1^0$
ATLAS arXiv:1407.0583
$\tilde{t} \to Wb\chi_1^0$
CMS arXiv:1308.1586
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS arXiv:1405.7875
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS arXiv:1502.00300
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS arXiv:1407.0600
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_R \to l^{\pm}\chi_1^0$
ATLAS:
arXiv:1403.5294
$\tilde{l}_L \to l^{\pm}\chi_1^0$
ATLAS:
arXiv:1403.5294
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
Direct $\chi_1^{\pm}/\chi_2^0$
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
$\chi_1^{\pm}\chi_2^0$(light $\tilde{l}$)
CMS: arXiv:1405.7570
$\chi_1^{\pm}\chi_2^0$(heavy $\tilde{l}$)
CMS: arXiv:1405.7570
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500

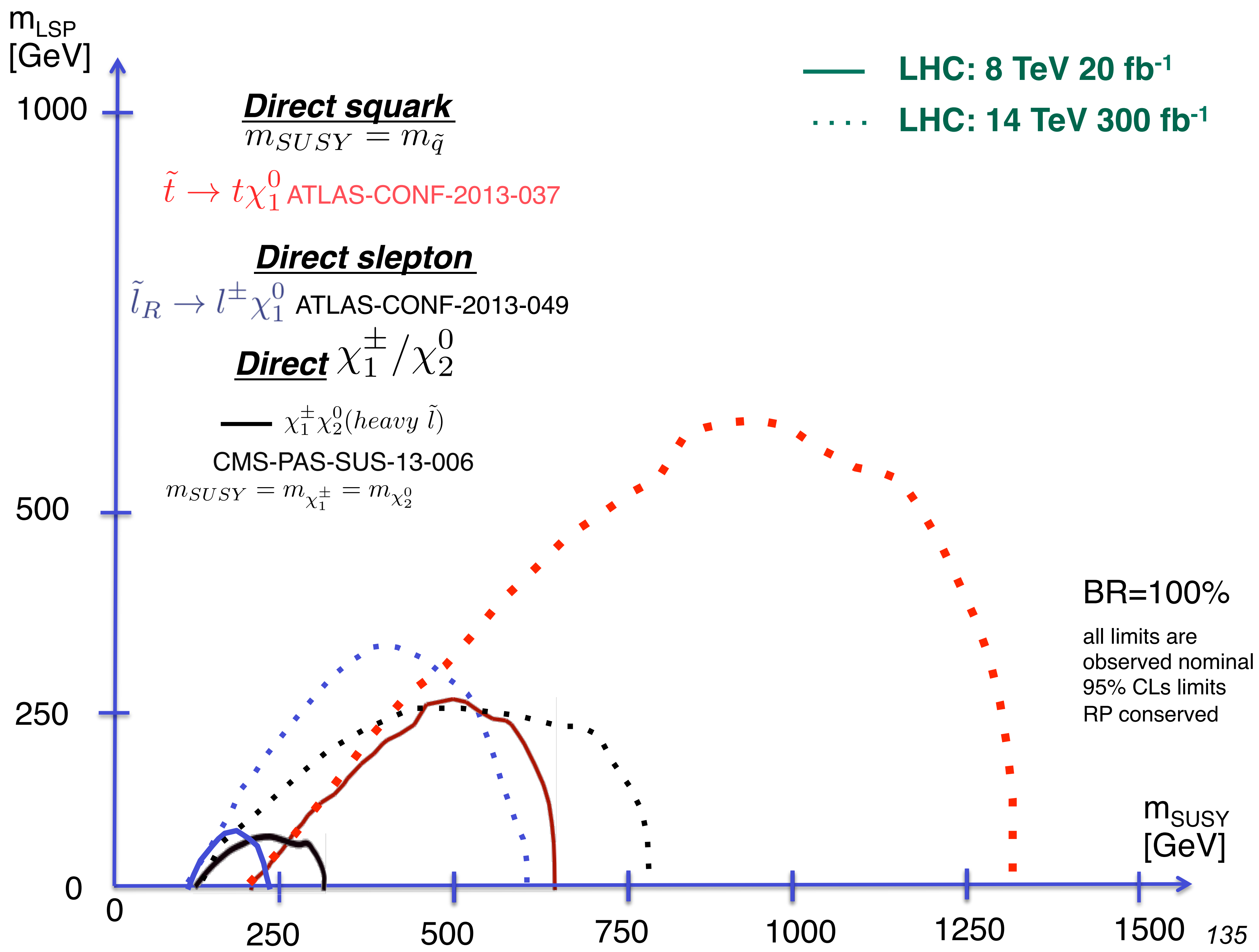


m_LSP [GeV]
1000
750
500
250
0
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{q} \to q\chi_1^0$
CMS arXiv:1502.04358
$\tilde{u}_L \to u\chi_1^0$
CMS arXiv:1502.04358
$\tilde{b} \to b\chi_1^0$
ATLAS arXiv:1308.2631
$\tilde{t} \to t\chi_1^0$
ATLAS arXiv:1407.0583
Direct stop in "gap"
$m_{SUSY} = m_{\tilde{t}}$
$\tilde{t} \to c\chi_1^0$
ATLAS arXiv:1407.0608
$\tilde{t} \to bff'\chi_1^0$
ATLAS arXiv:1407.0583
$\tilde{t} \to Wb\chi_1^0$
CMS arXiv:1308.1586
Gluino mediated
$m_{SUSY} = m_{\tilde{g}}$
$\tilde{g} \to q\bar{q}\chi_1^0$
ATLAS arXiv:1405.7875
$\tilde{g} \to b\bar{b}\chi_1^0$
CMS arXiv:1502.00300
$\tilde{g} \to t\bar{t}\chi_1^0$
ATLAS arXiv:1407.0600
Direct slepton
$m_{SUSY} = m_{\tilde{l}}$
$\tilde{l}_R \to l^{\pm}\chi_1^0$
ATLAS: arXiv:1403.5294
$\tilde{l}_L \to l^{\pm}\chi_1^0$
ATLAS: arXiv:1403.5294
$m_{SUSY} - m_{LSP} < m_t$
$m_{SUSY} - m_{LSP} < 2m_t$
$m_{\tilde{t}} - m_b - m_{LSP} < m_W$
$m_{\tilde{t}} - m_{LSP} < m_t$
Direct $\chi_1^+\chi_1^-$
$m_{SUSY} = m_{\chi_1^{\pm}}$
$\chi_1^+\chi_1^-(\text{heavy } \tilde{l})$
ATLAS arXiv:1403.5294
$\chi_1^+\chi_1^-(\text{light } \tilde{l})$
ATLAS arXiv:1403.5294
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
Direct $\chi_1^{\pm}/\chi_2^0$
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
$\chi_1^{\pm}\chi_2^0(\text{light } \tilde{l})$
CMS: arXiv:1405.7570
$\chi_1^{\pm}\chi_2^0(\text{heavy } \tilde{l})$
CMS: arXiv:1405.7570
m_SUSY [GeV]
0
250
500
750
1000
1250
1500

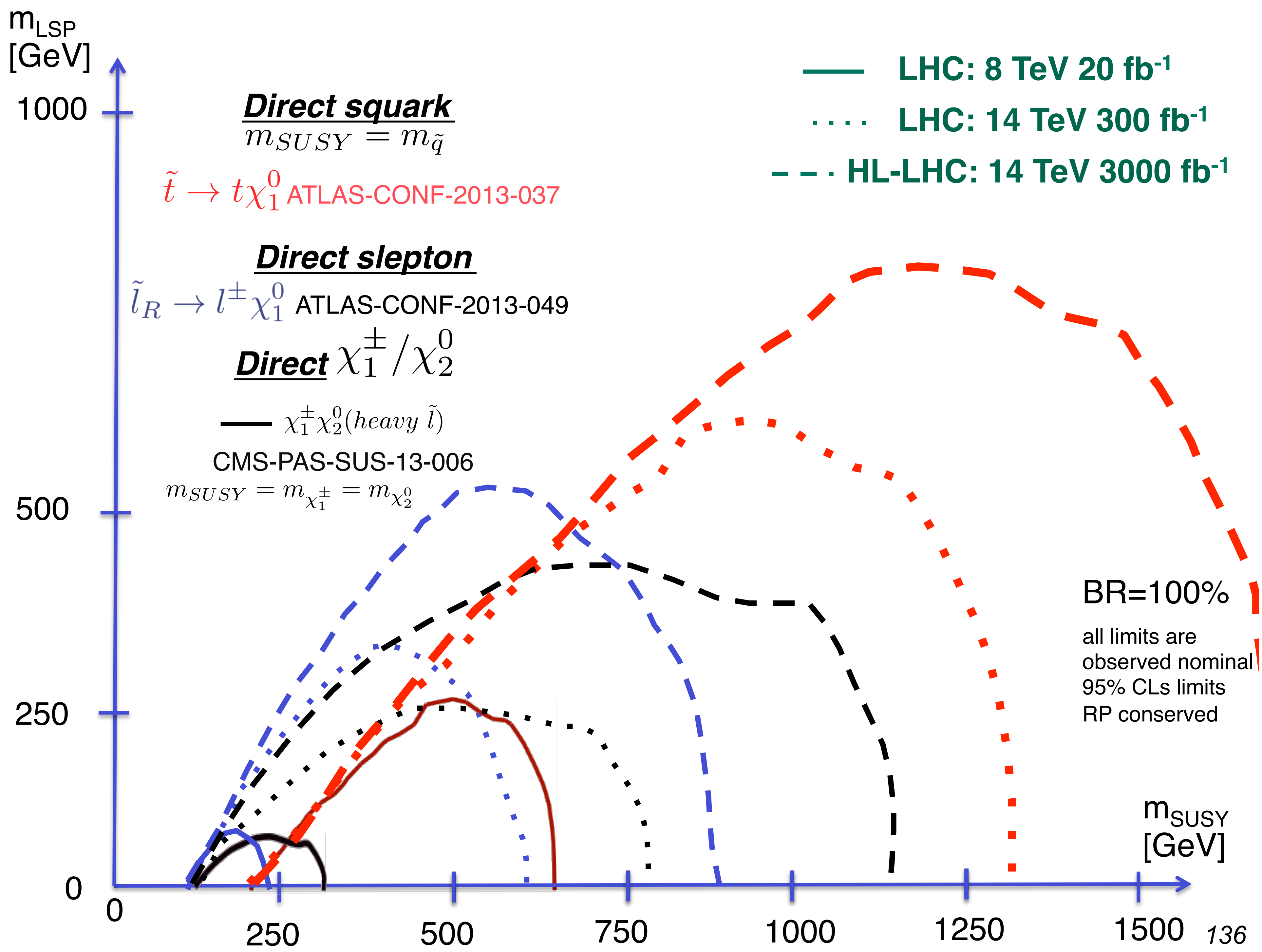
SUSY PROJECTION OF DIFFICULT CHANNELS



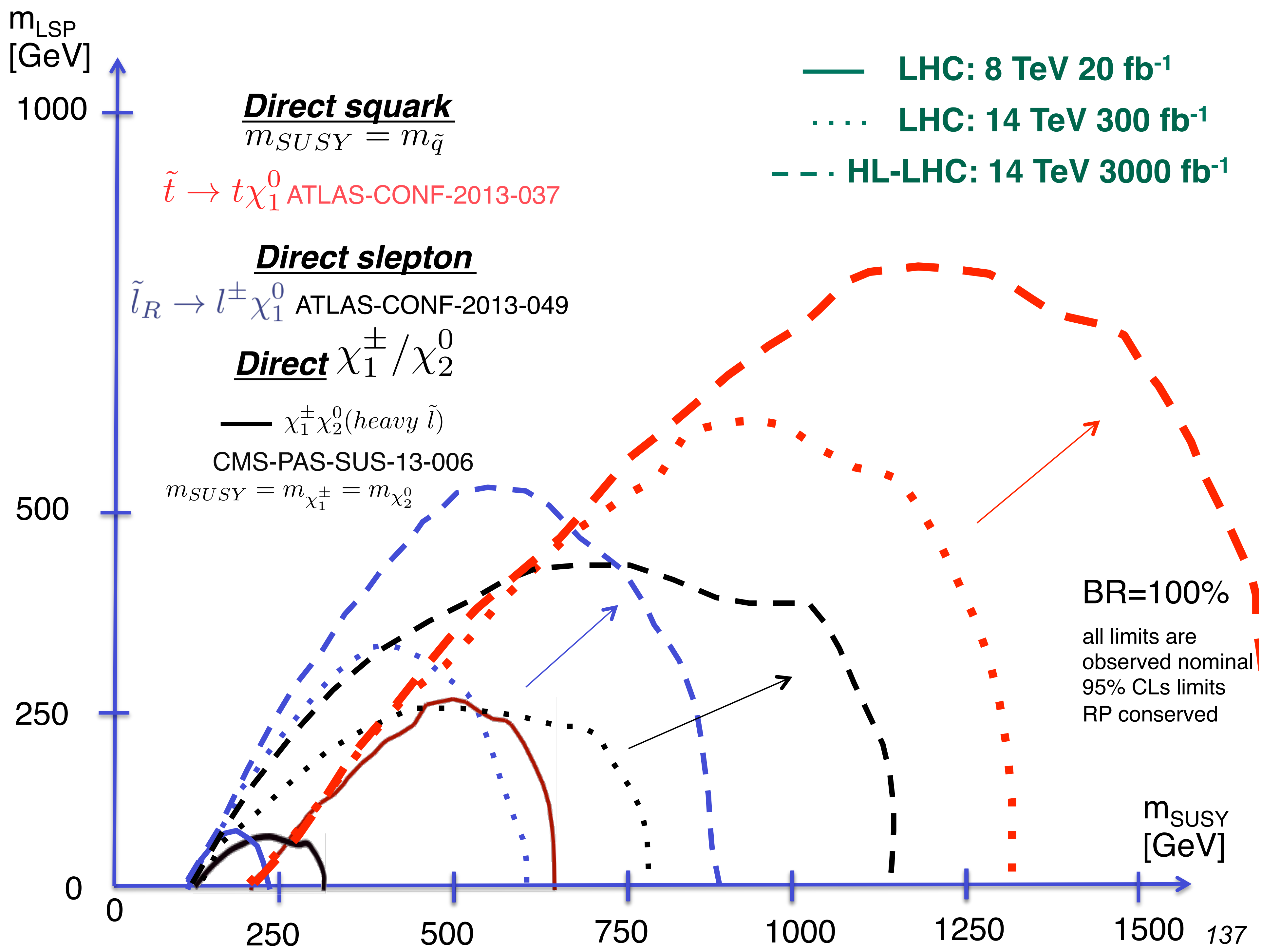
m_{LSP} [GeV]
1000
500
250
0
LHC: 8 TeV 20 fb^{-1}
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \rightarrow t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \rightarrow l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
Example of "difficult" SUSY channels!
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500



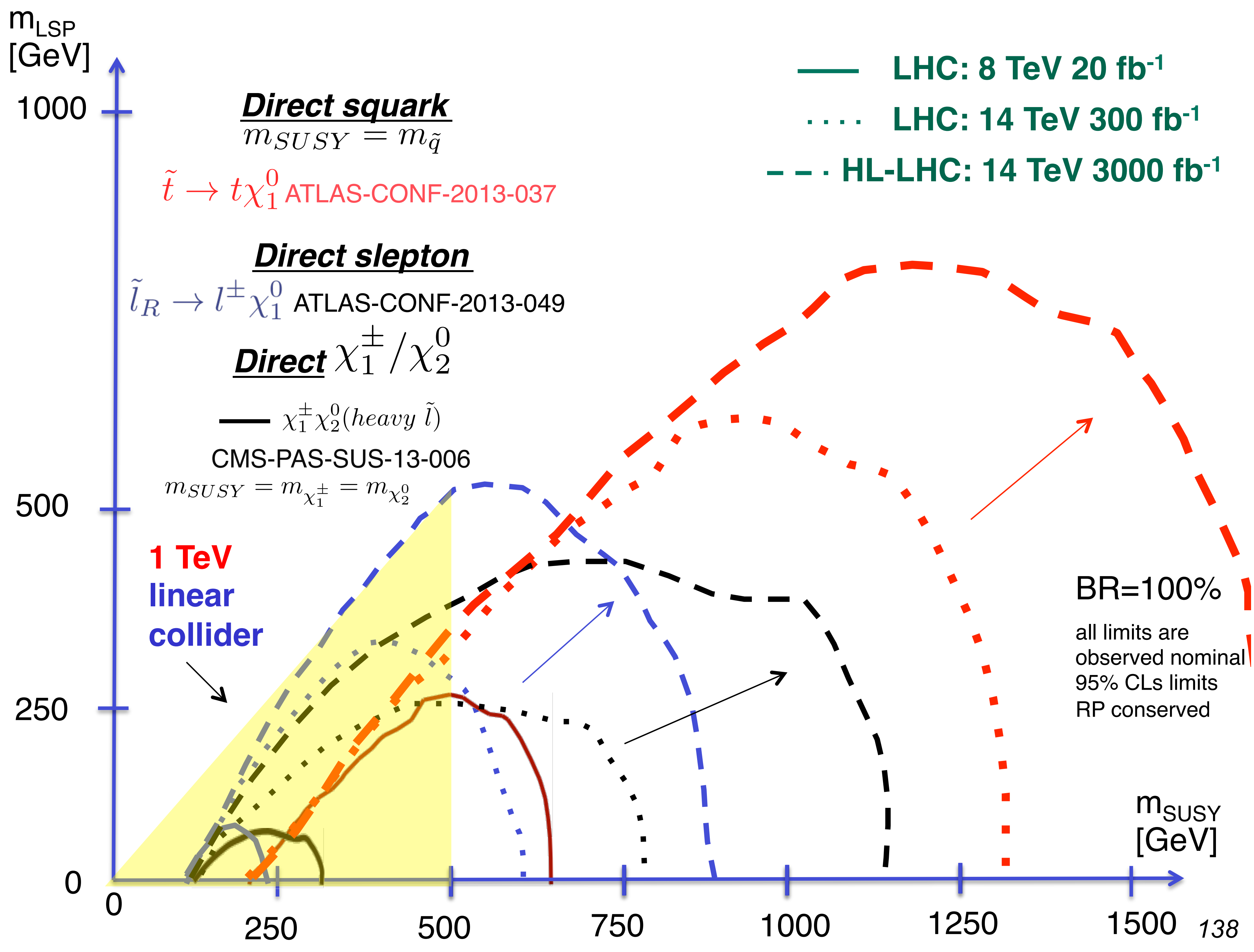
m_{LSP} [GeV]
1000
500
250
0
LHC: 8 TeV 20 fb^{-1}
LHC: 14 TeV 300 fb^{-1}
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \rightarrow t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \rightarrow l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500



m_{LSP} [GeV]
1000
500
250
0
LHC: 8 TeV 20 fb^{-1}
LHC: 14 TeV 300 fb^{-1}
HL-LHC: 14 TeV 3000 fb^{-1}
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \to l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500



m_{LSP} [GeV]
1000
500
250
0
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \to l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
LHC: 8 TeV 20 fb^{-1}
LHC: 14 TeV 300 fb^{-1}
HL-LHC: 14 TeV 3000 fb^{-1}
BR=100%
all limits are
observed nominal
95% CLs limits
RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500

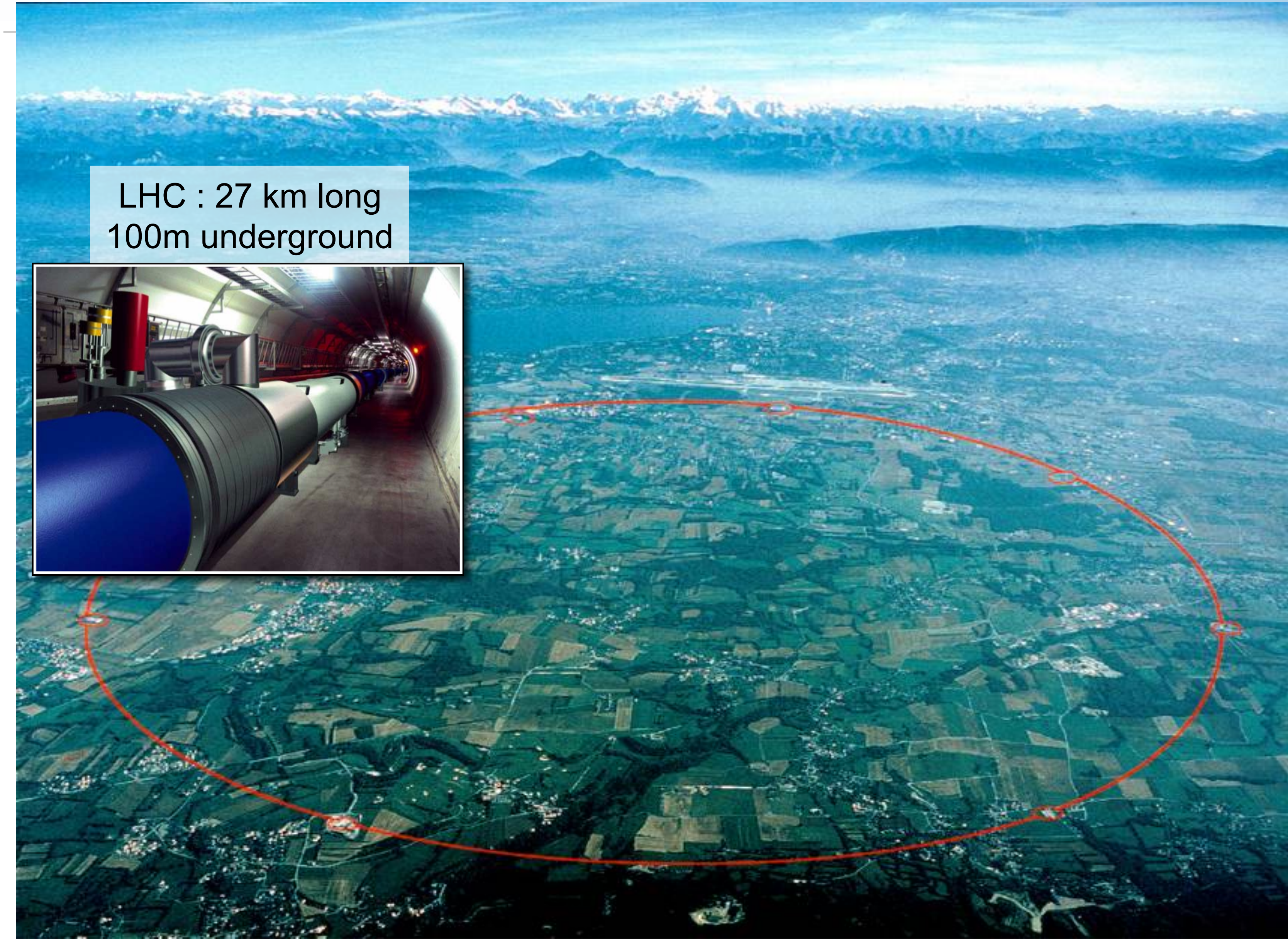


m_{LSP} [GeV]
1000
500
250
0
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \to t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \to l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
LHC: 8 TeV 20 fb^{-1}
LHC: 14 TeV 300 fb^{-1}
HL-LHC: 14 TeV 3000 fb^{-1}
1 TeV linear collider
BR=100%
all limits are observed nominal 95% CLs limits RP conserved
m_{SUSY} [GeV]
0
250
500
750
1000
1250
1500

LHC

The Large Hadron Collider at CERN

The Large Hadron Collider at CERN



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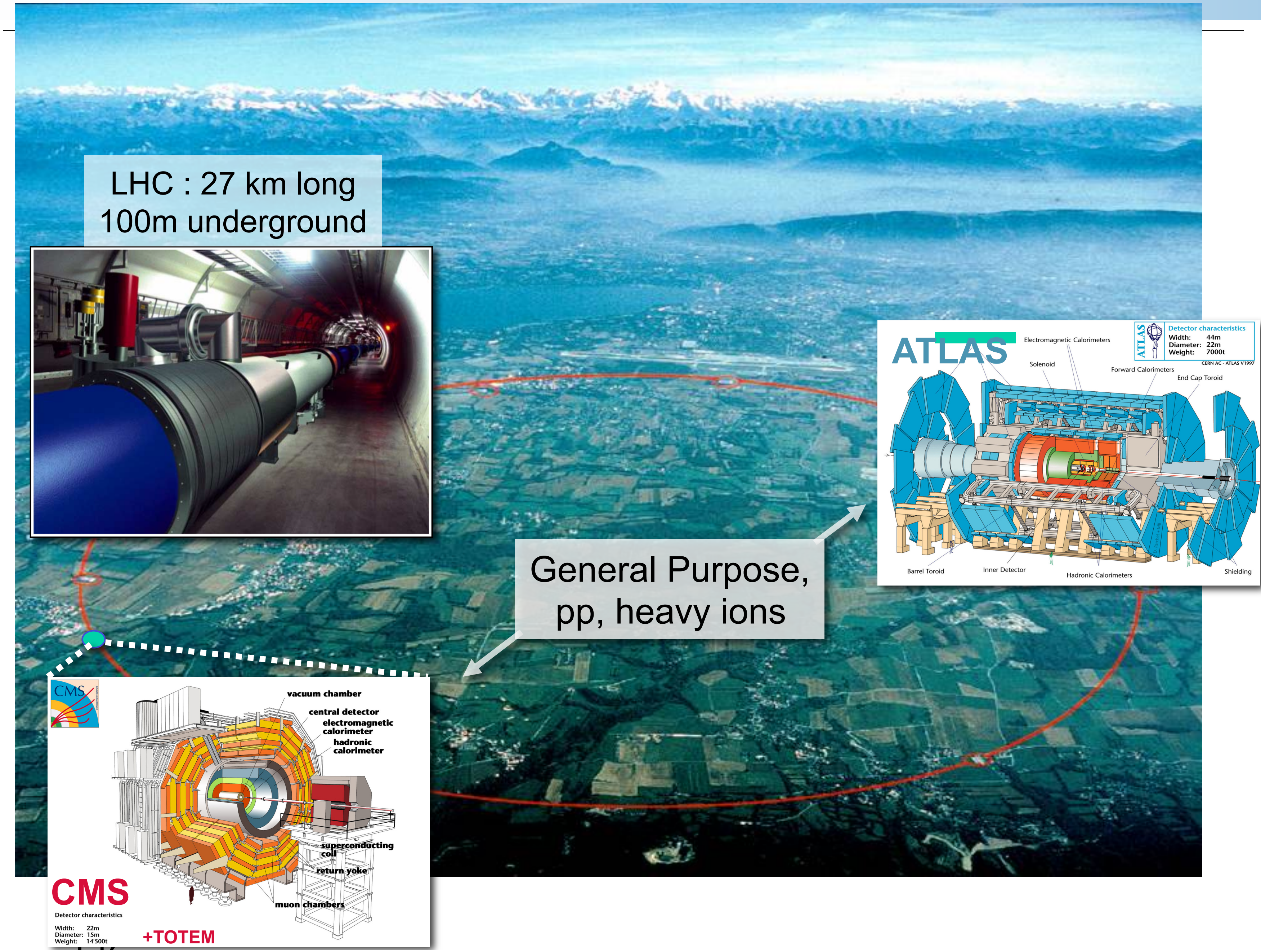
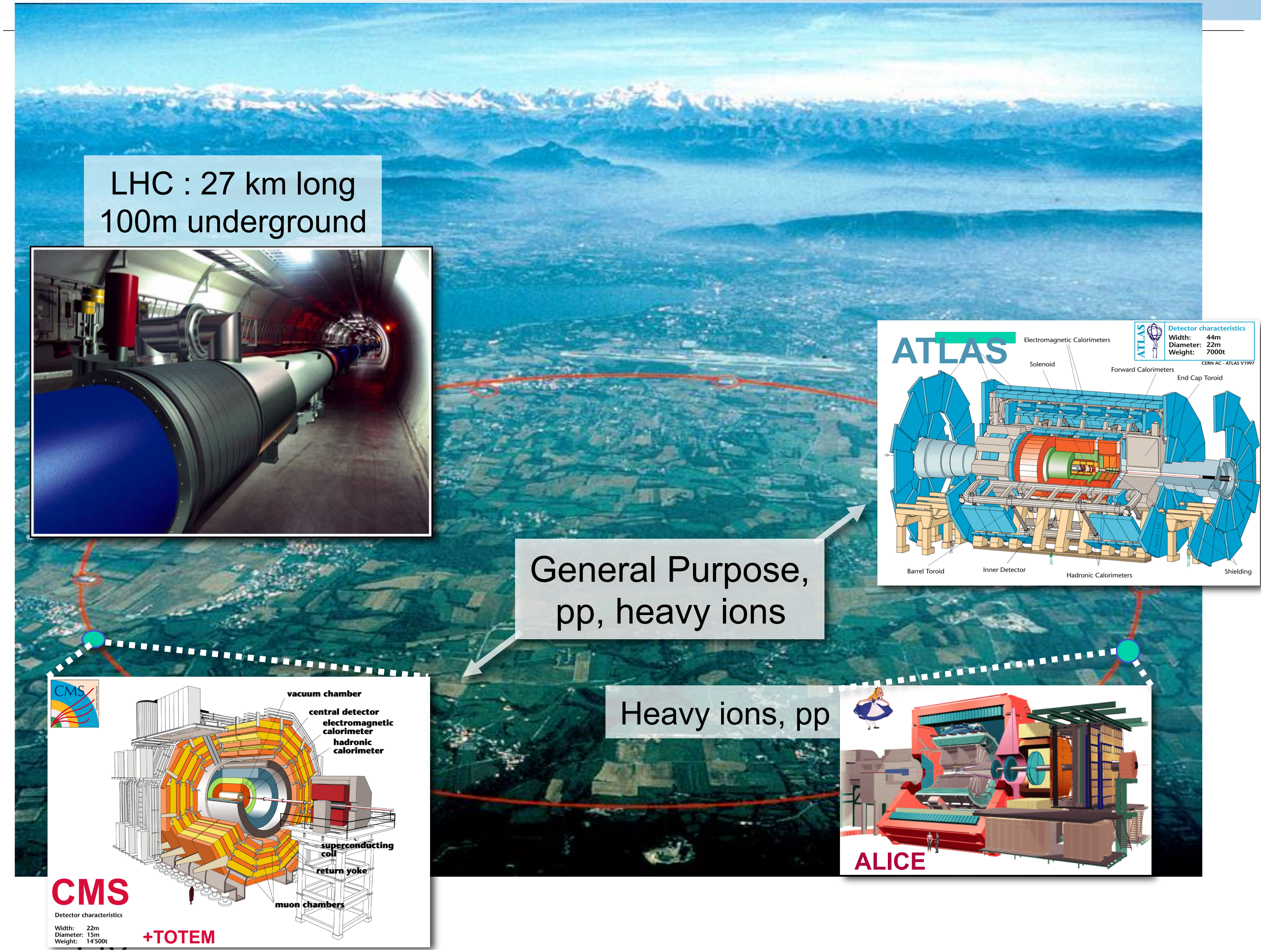
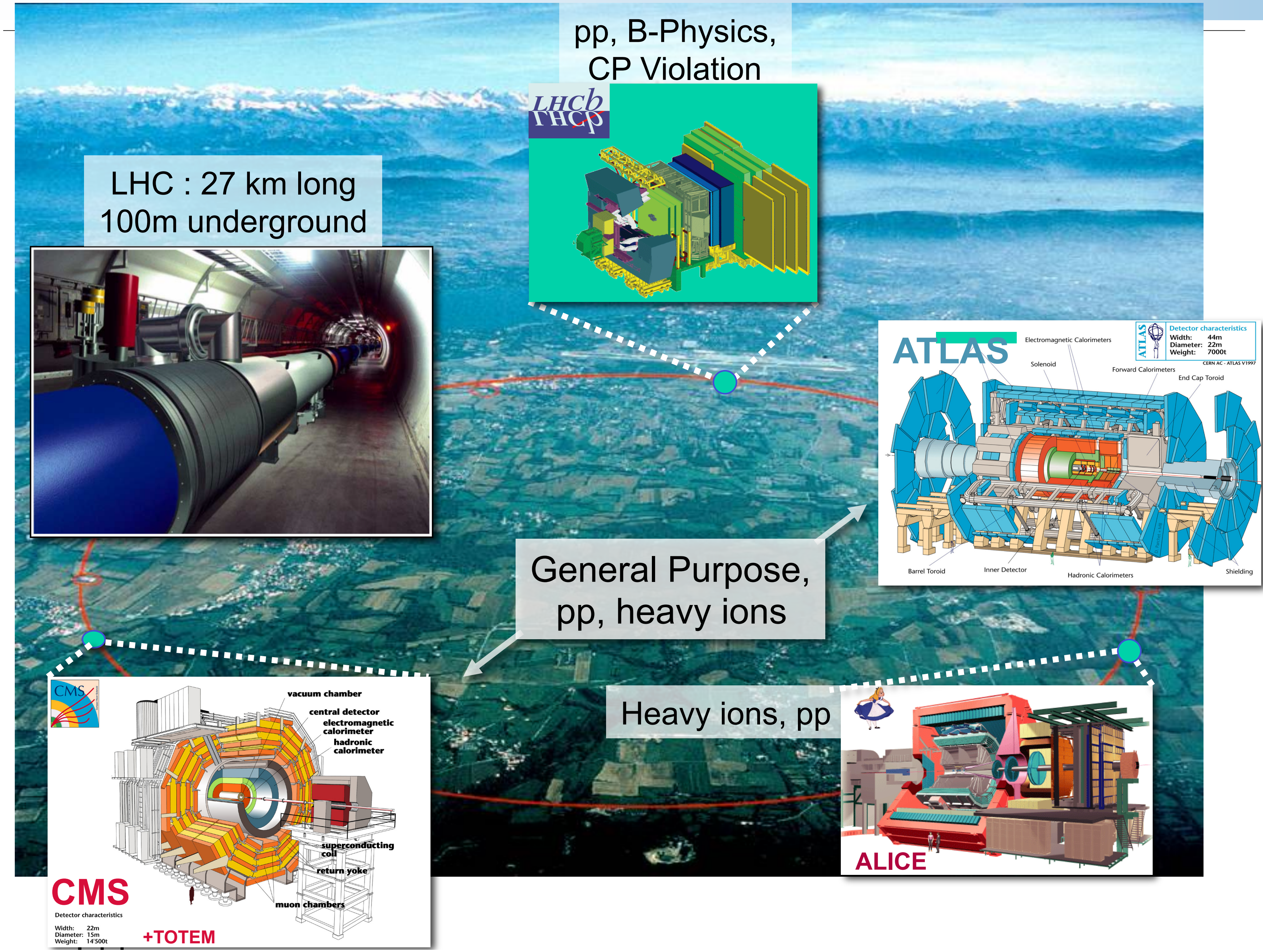
The Large Hadron Collider at CERN

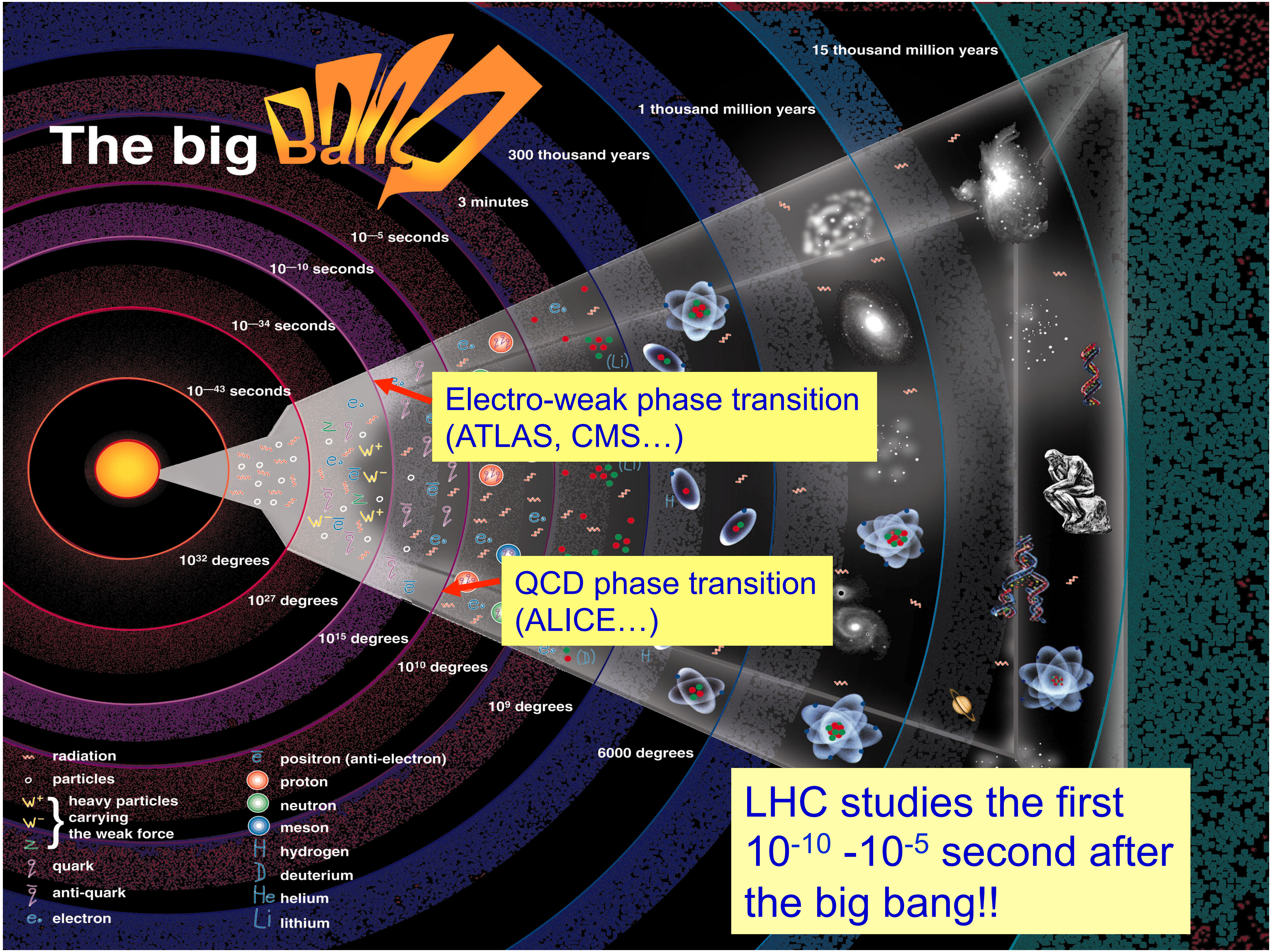


The Large Hadron Collider at CERN



The Large Hadron Collider at CERN





Electro-weak phase transition (ATLAS, CMS…)

QCD phase transition (ALICE…)

LHC studies the first 10^{-10} - 10^{-5} second after the big bang!!

Comparison with Direct Detection: Vector Case