LEPTON PHOTON 2017

University of Sussex

Searches for supersymmetry

Iacopo Vivarelli - University of Sussex

On behalf of the ATLAS, CMS and LHCb collaborations

LP2017 - Sun Yat-Sen University - Guangzhou

ATLAS EXPERIMENT

CMS Compact Muon Solenoid

LHCb

EW-scale supersymmetry

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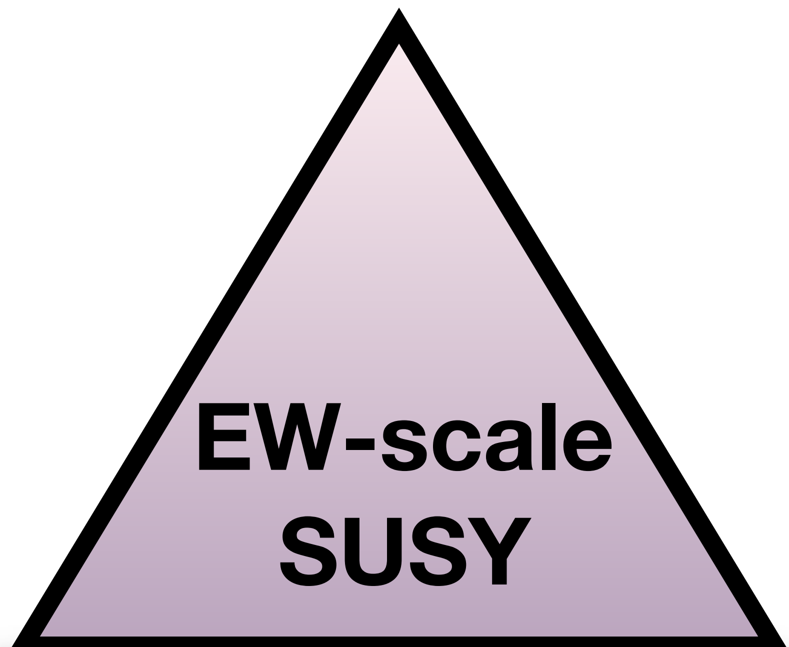
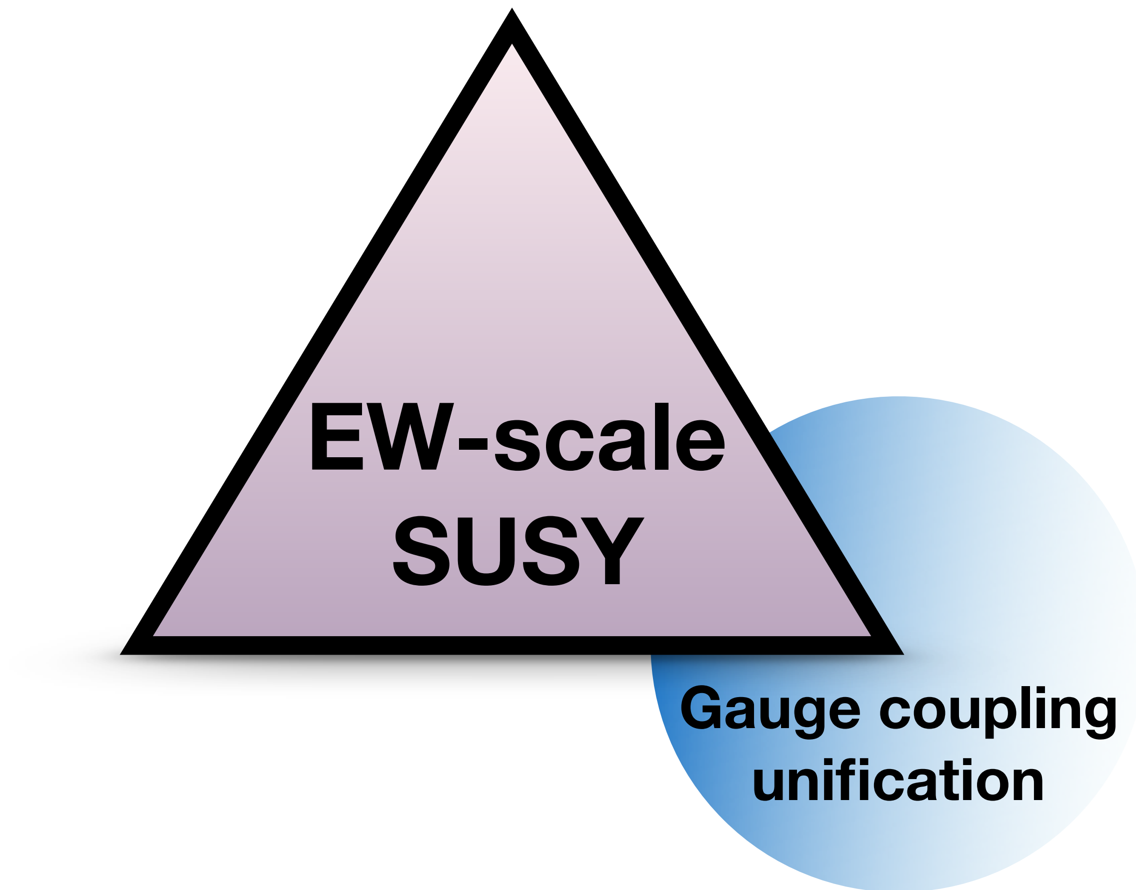


EW-scale supersymmetry

University of Sussex



EW-scale supersymmetry

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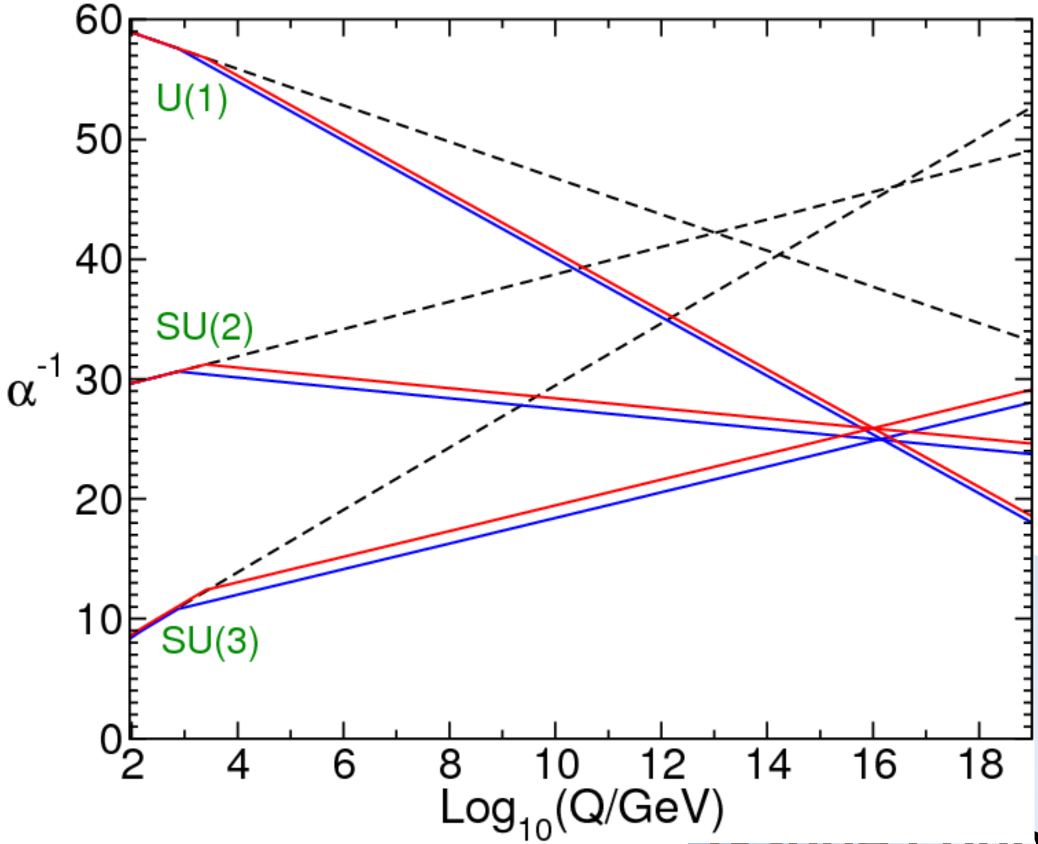

Gauge coupling unification

EW-scale supersymmetry

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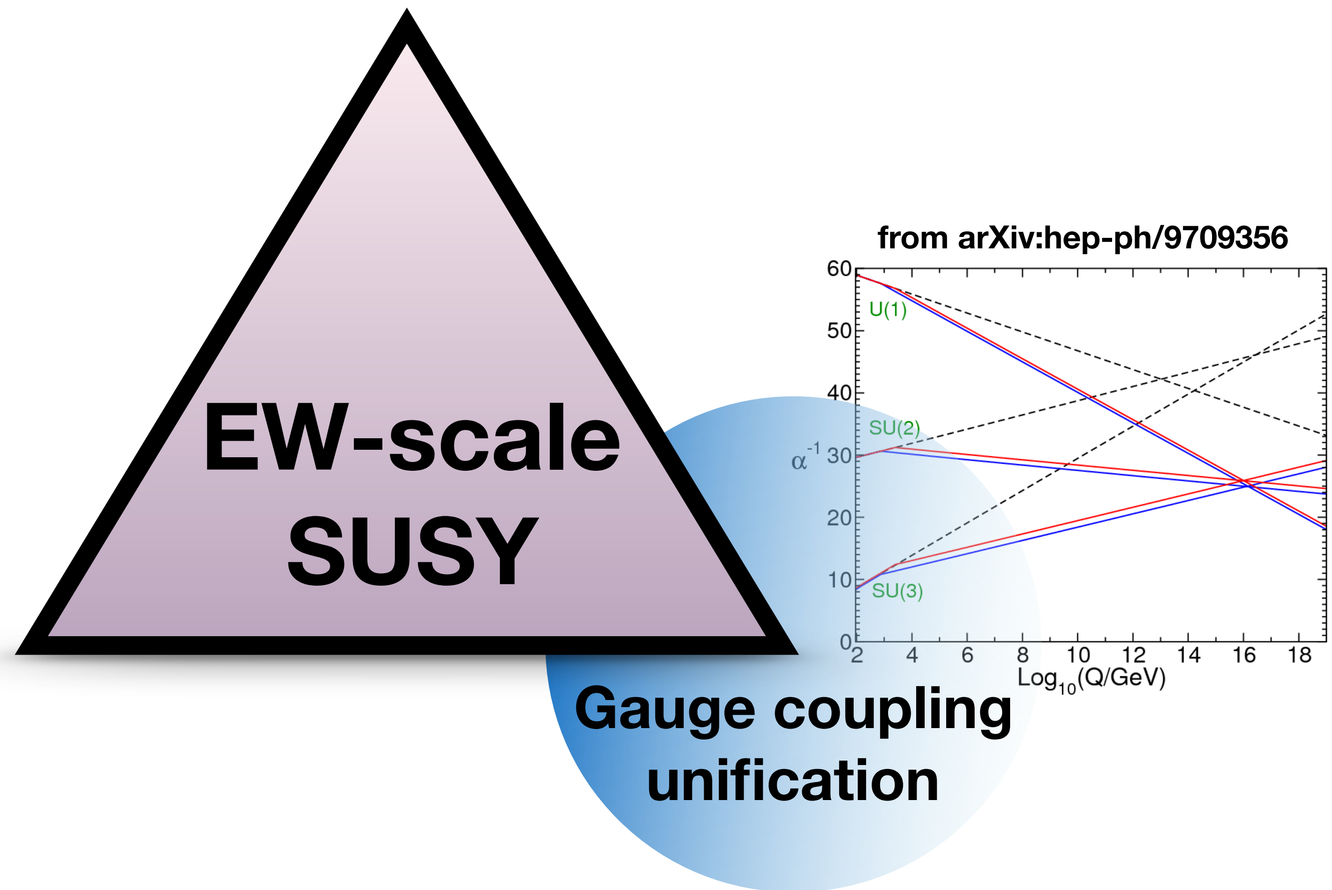
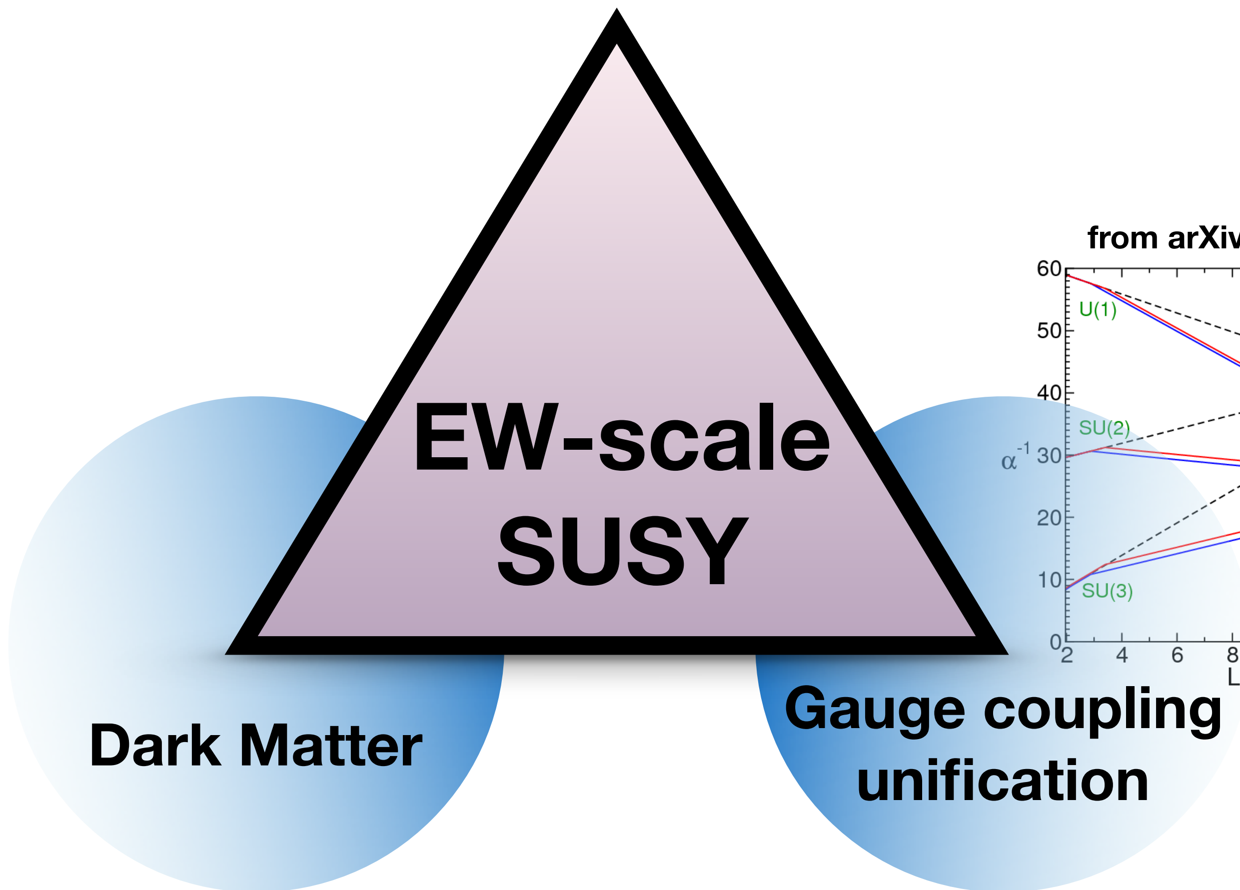
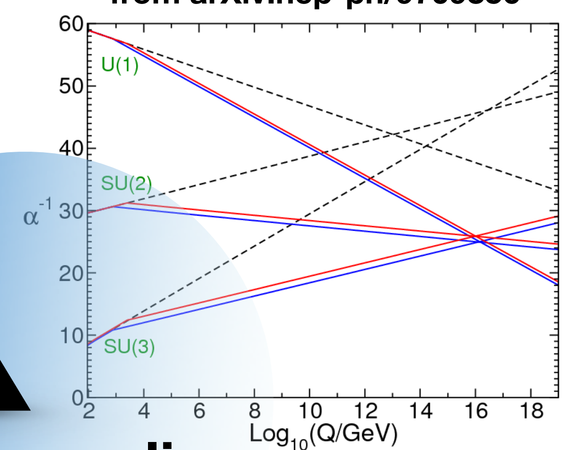


EW-scale supersymmetry



from arXiv:hep-ph/9709356



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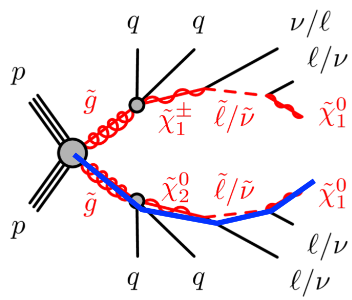
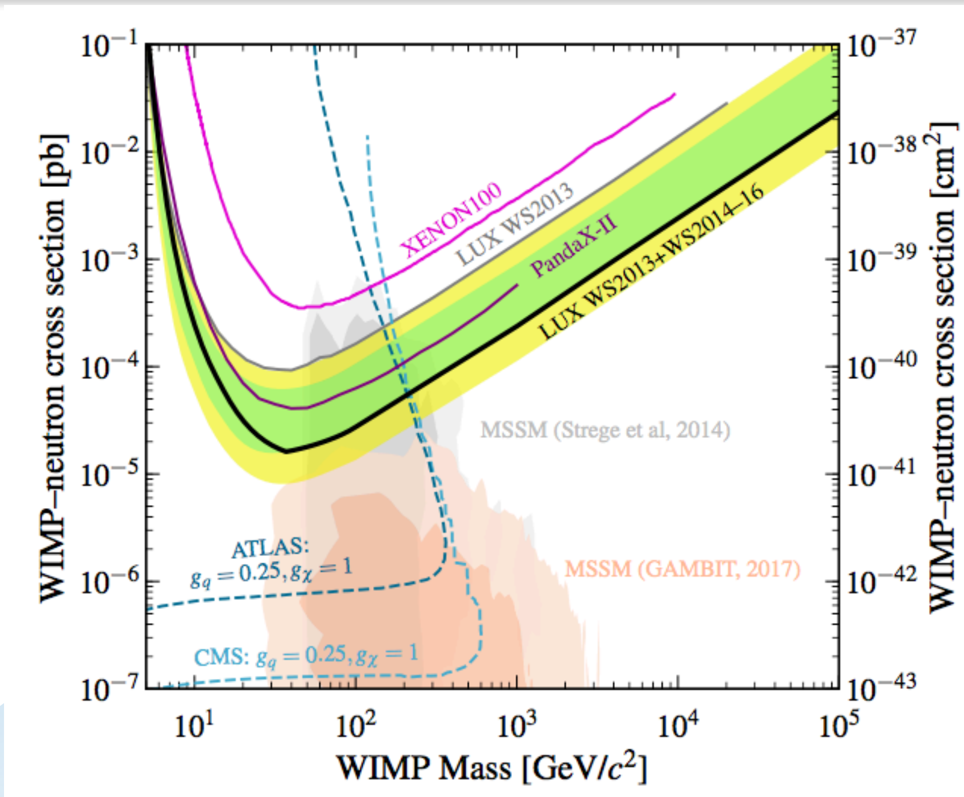
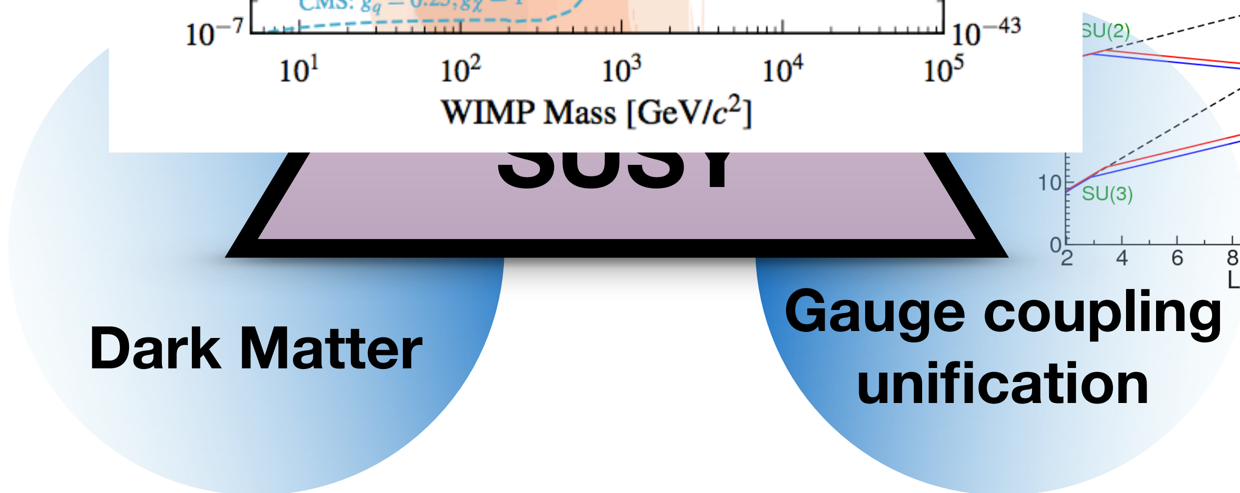


R-parity conservation





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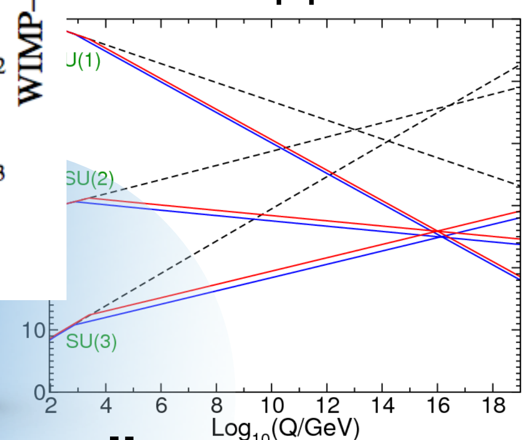

EW-scale supersymmetry

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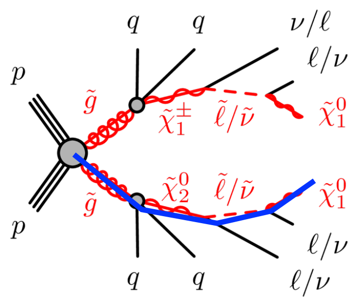

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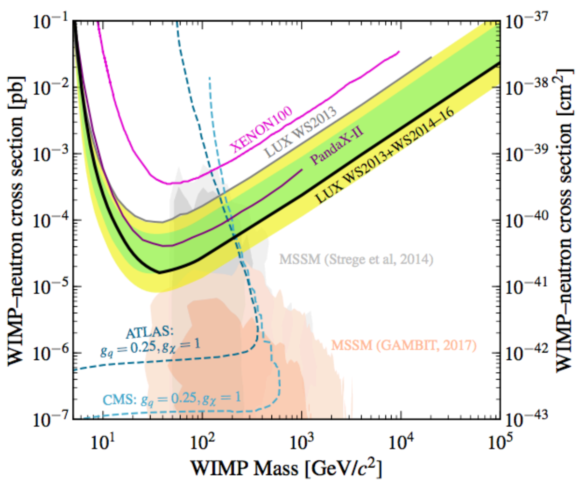

EW-scale SUSY

Dark Matter

Gauge coupling unification

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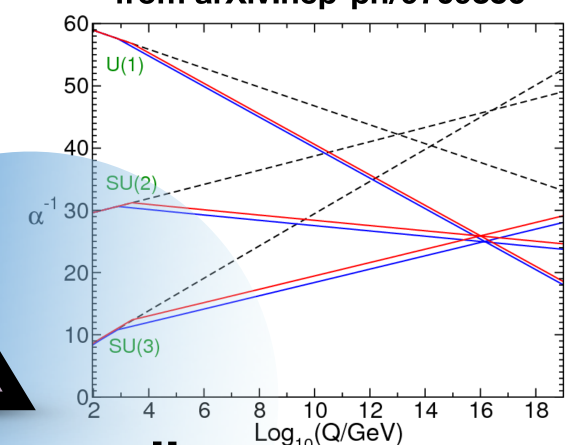
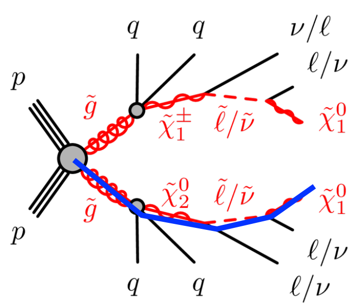


EW-scale supersymmetry



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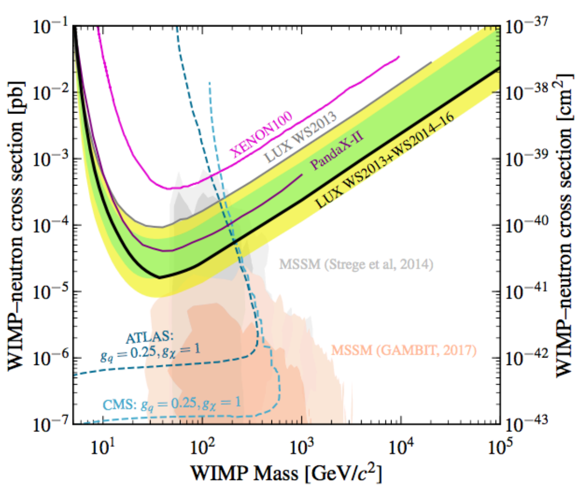

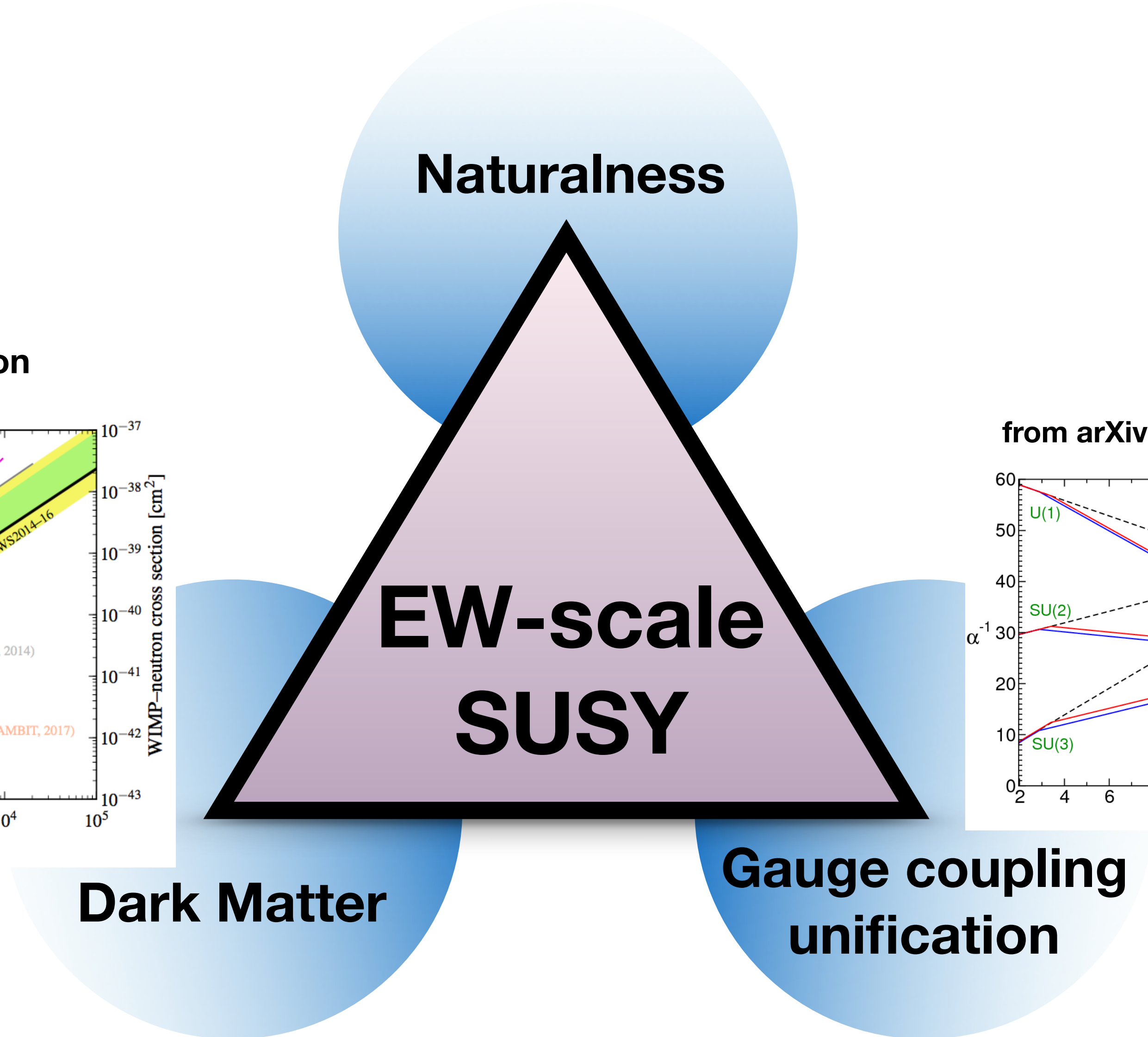

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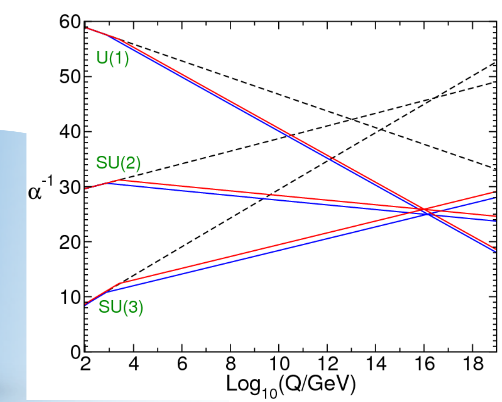

EW-scale supersymmetry

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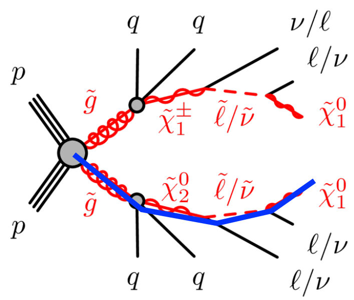

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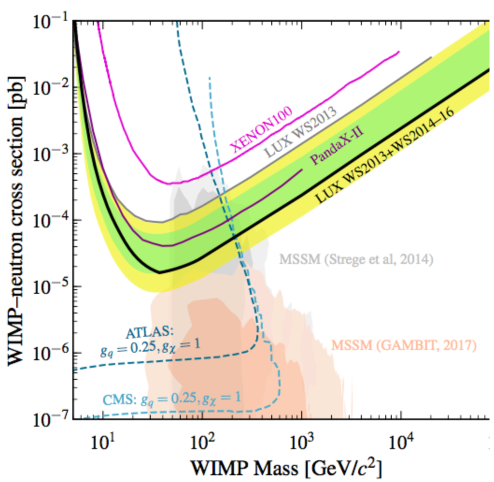
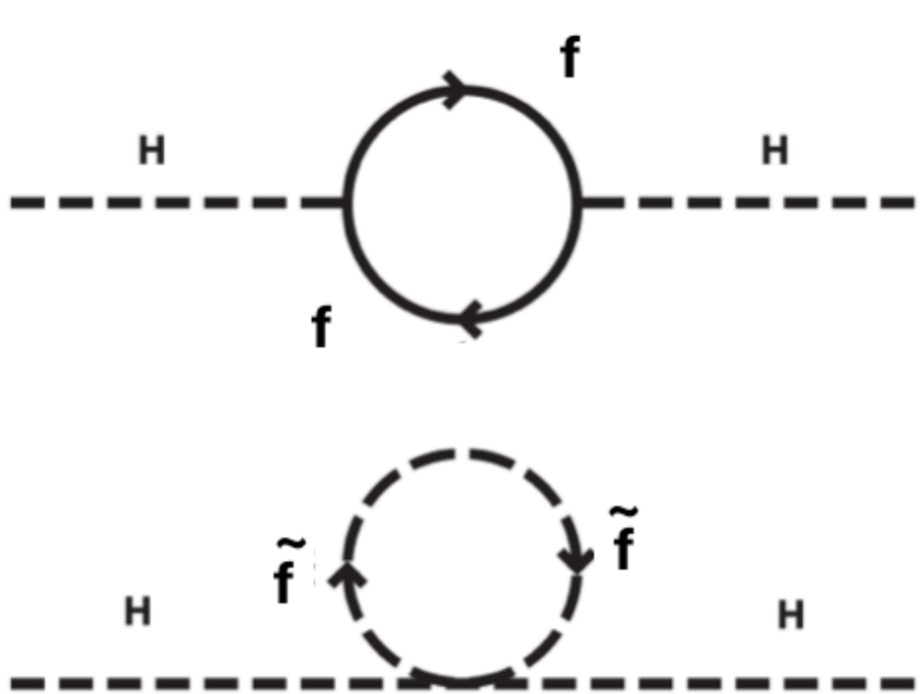
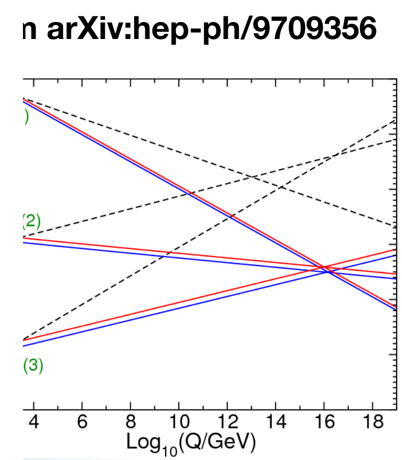


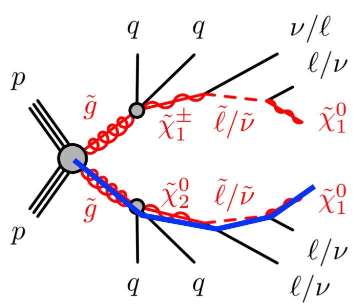




Dark Matter

Gauge coupling unification

EW-scale supersymmetry



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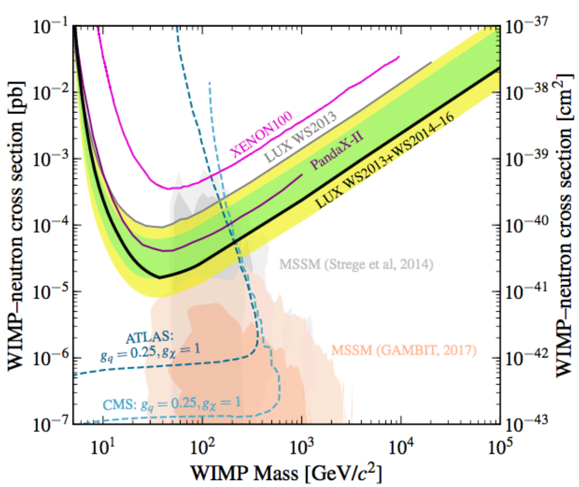
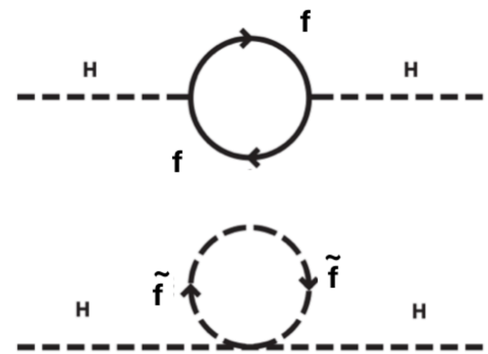


Naturalness



EW-scale SUSY

Dark Matter

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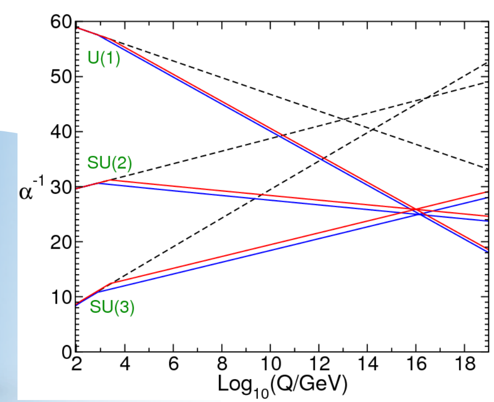
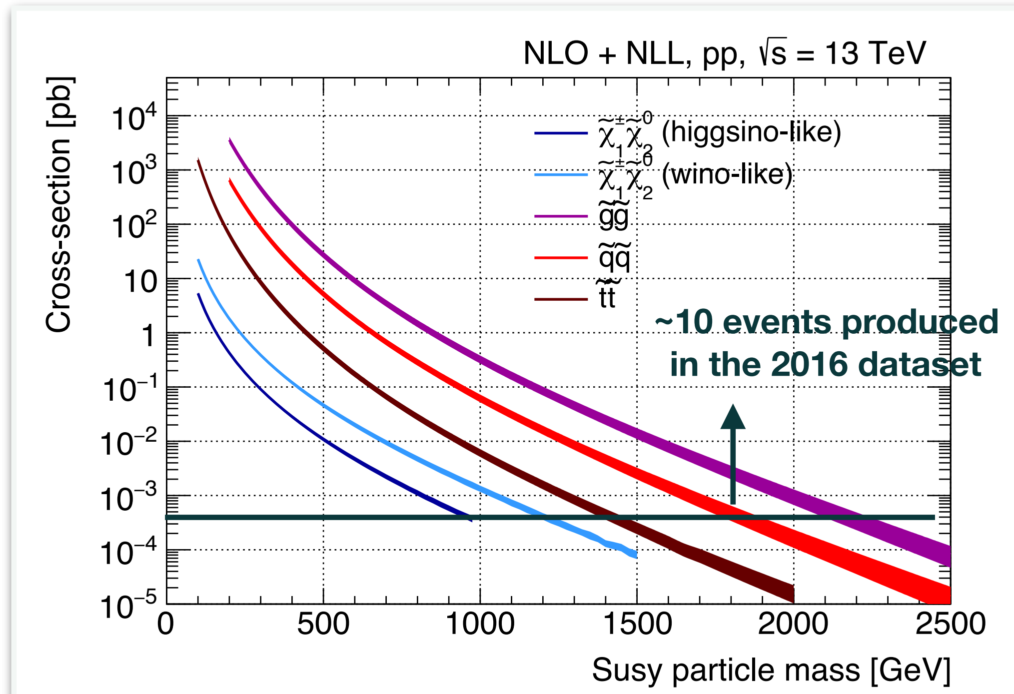
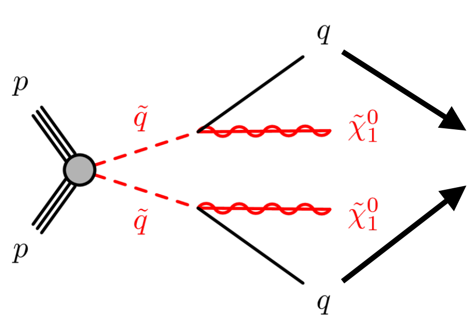


Thanks to N. Craig for the idea

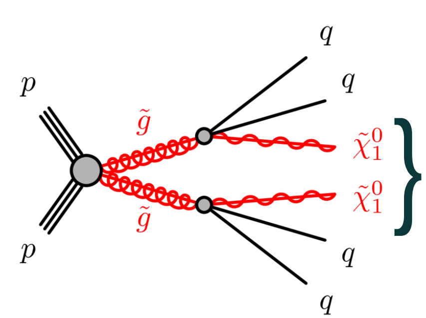
Signatures of EW-scale SUSY

- Generic expectation for **sparticles with ~1 TeV mass**:
  - Production cross section **dominated by strong interactions.**
  - Abundant production of **gluinos and squarks.**



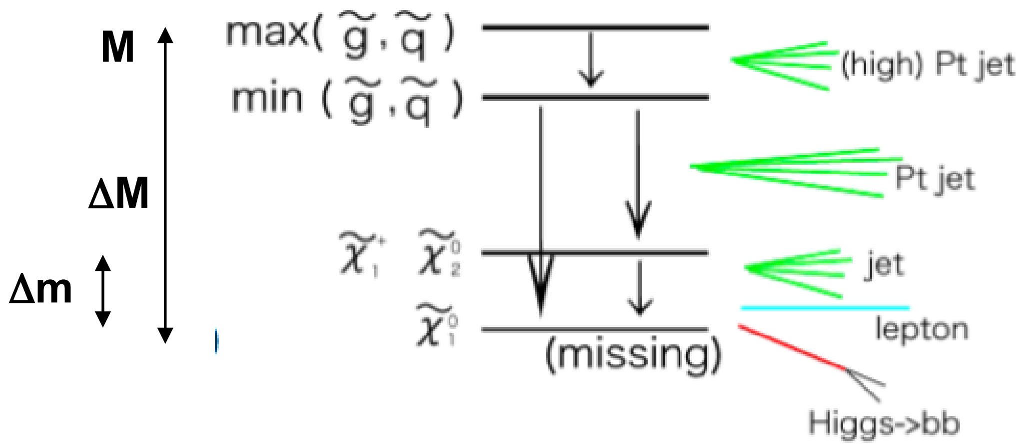


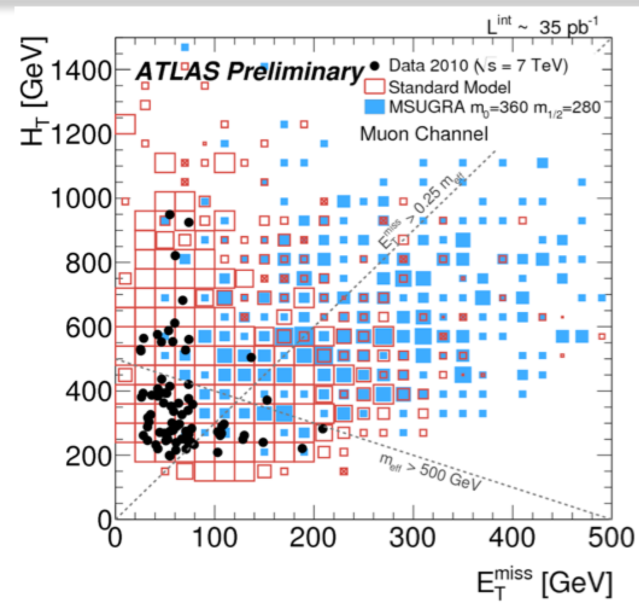
Jets from squark/ gluino decay



Invisible to the detector→ E_T^{miss}

Inclusive searches

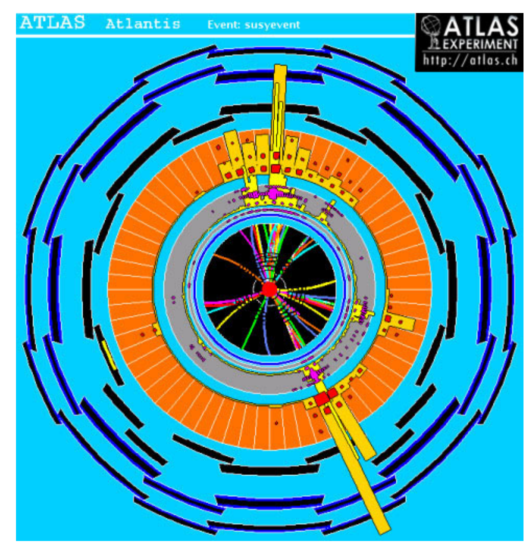




$$H_T = \sum_{jets} p_T^{jets} (+ \sum_{l} p_T^{l} + ...)$$

$$H_T^{\mathrm{miss}} = - \sum_{\mathrm{jets}} \vec{p}_T^{\;\mathrm{jets}}$$

$$E_T^{\mathrm{miss}} = - \sum_{\mathrm{all\ objects}} \vec{p}_T$$



Inclusive searches for EW-scale SUSY

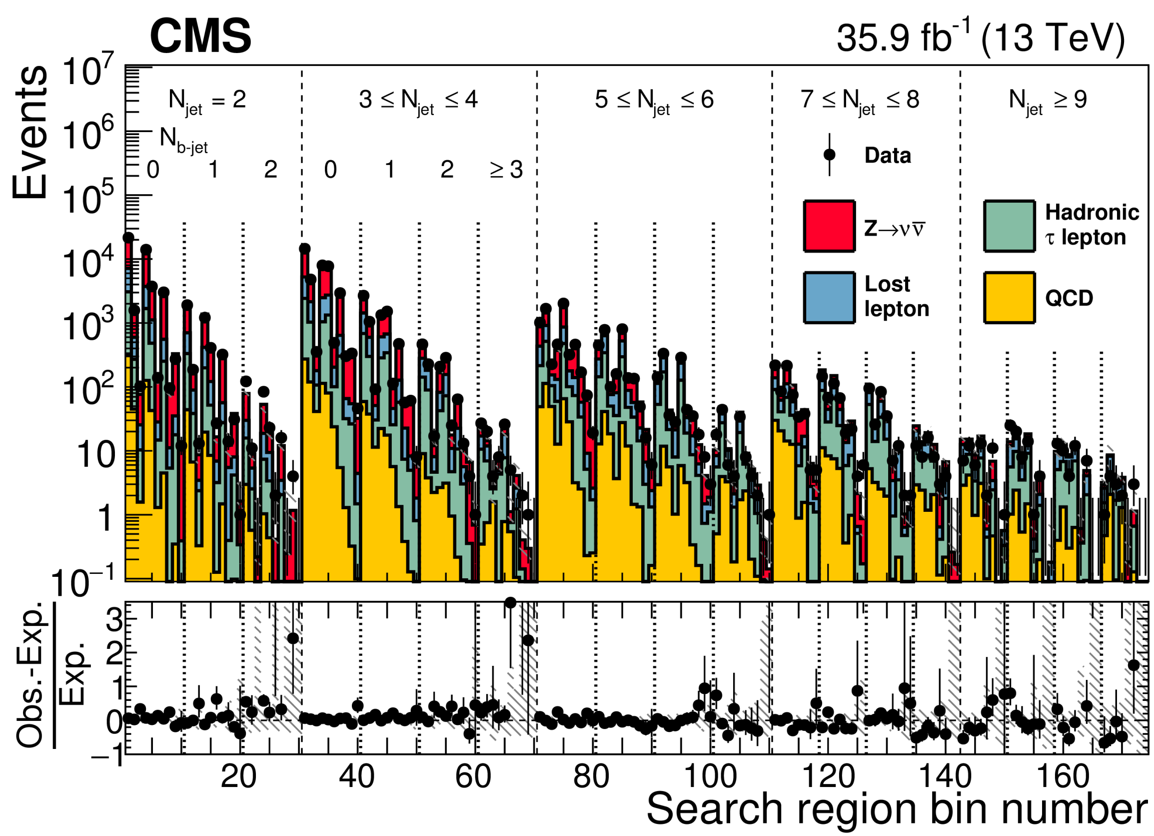
https://arxiv.org/abs/1704.07781

- Thorough search in **signal-like phase space region with no leptons**
  - Standard Model background estimated with a mixture of **MC- and data-driven techniques**.

Example: https://arxiv.org/abs/1704.07781

Phase space binned in N_{jets}, N_{bjets}, H_T, H_T^{miss}

No excess above the Standard Model predictions



Inclusive searches for EW-scale SUSY

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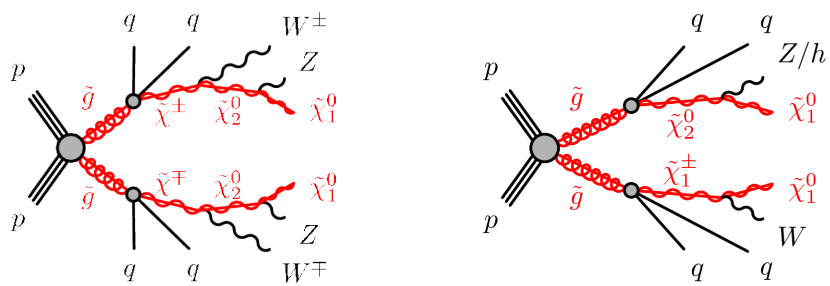
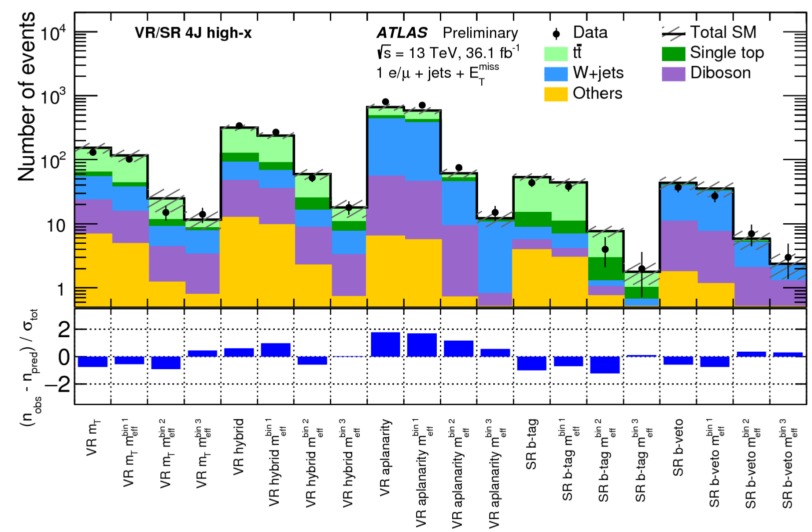
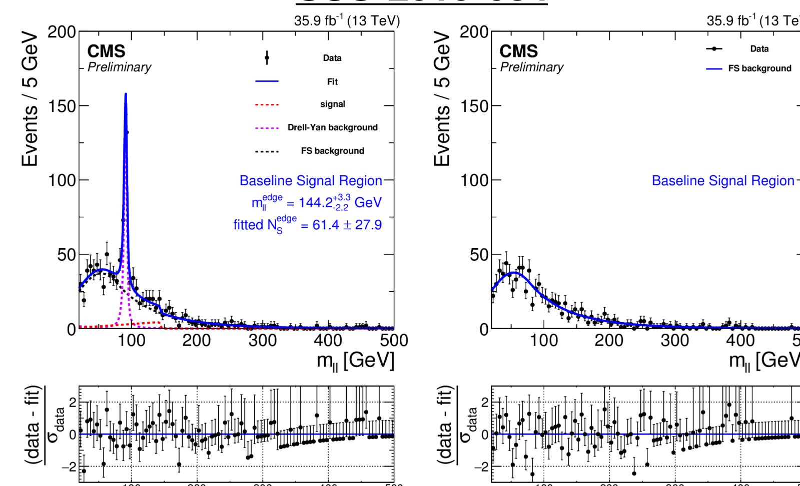


SUSY-2016-12, to appear



- Final states with leptons typically **target longer decay chains**:
  - One-lepton final states looking for **inclusive production of vector bosons.**
  - Two-lepton final states looking for a **Z peak or a shoulder in the m_{ll} distribution.**
  - Searches for final states with **SS leptons** profit from **Majorana nature of gluinos.**
    - Extremely versatile searches, see arXiv:1706.03731 and arXiv:1704.07323.

SUS-2016-034



"Vanilla" SUSY exclusion limits

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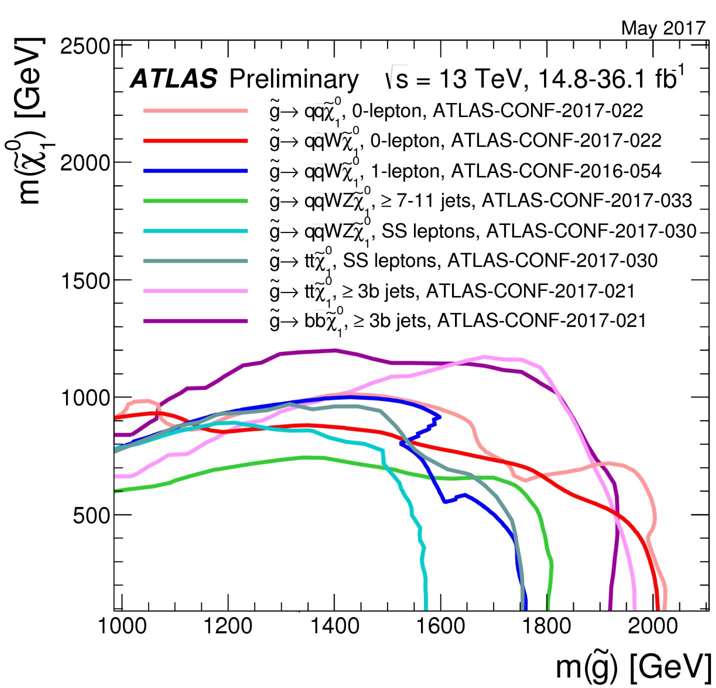
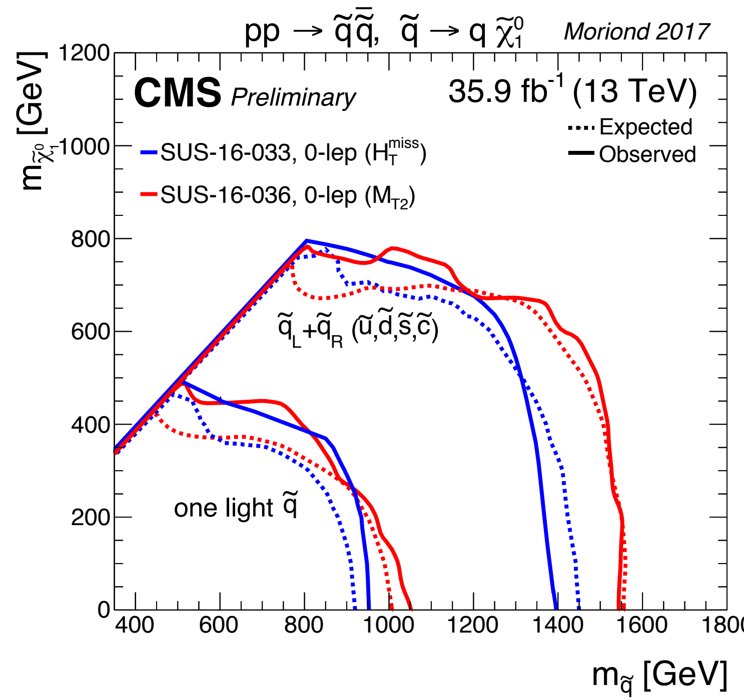
- **2-TeV exclusion on gluinos** starts to be a reality. Eight-fold degenerate squark production excluded **up to ~ 1.5 TeV**
  - One-fold squark degeneracy limit ~ 1 TeV.
  - Limits on **simplified models** - Run 1 experience tells us that **they translate quite reliably** on more generic exclusions.





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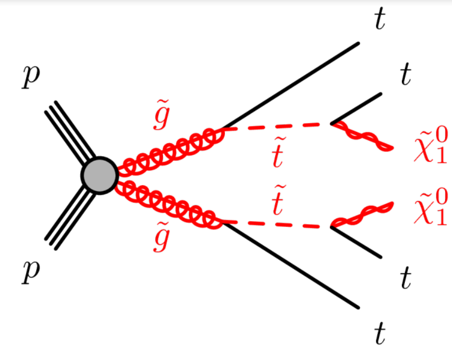
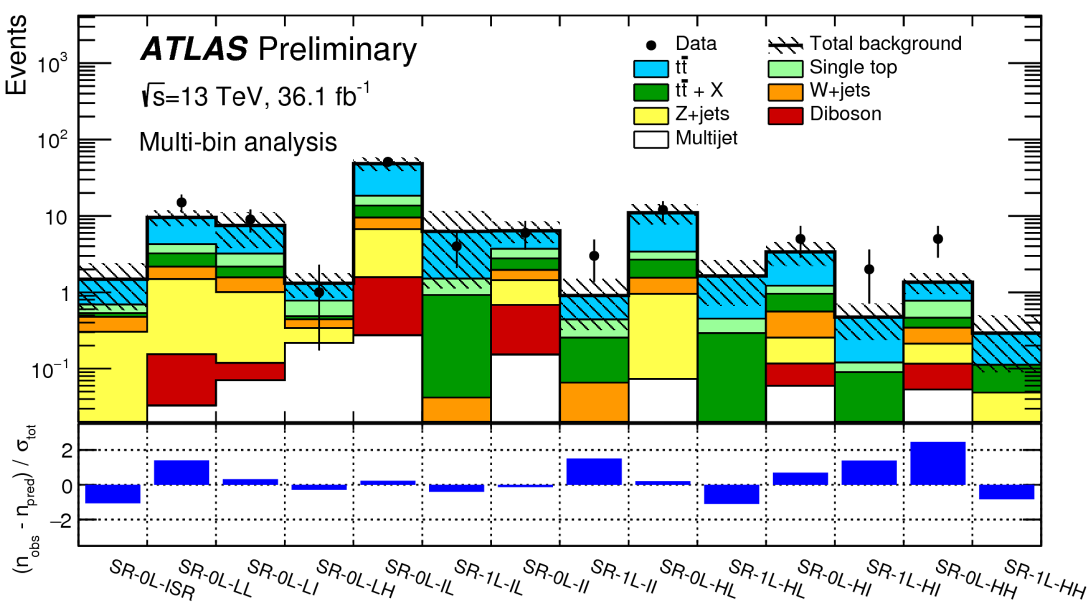
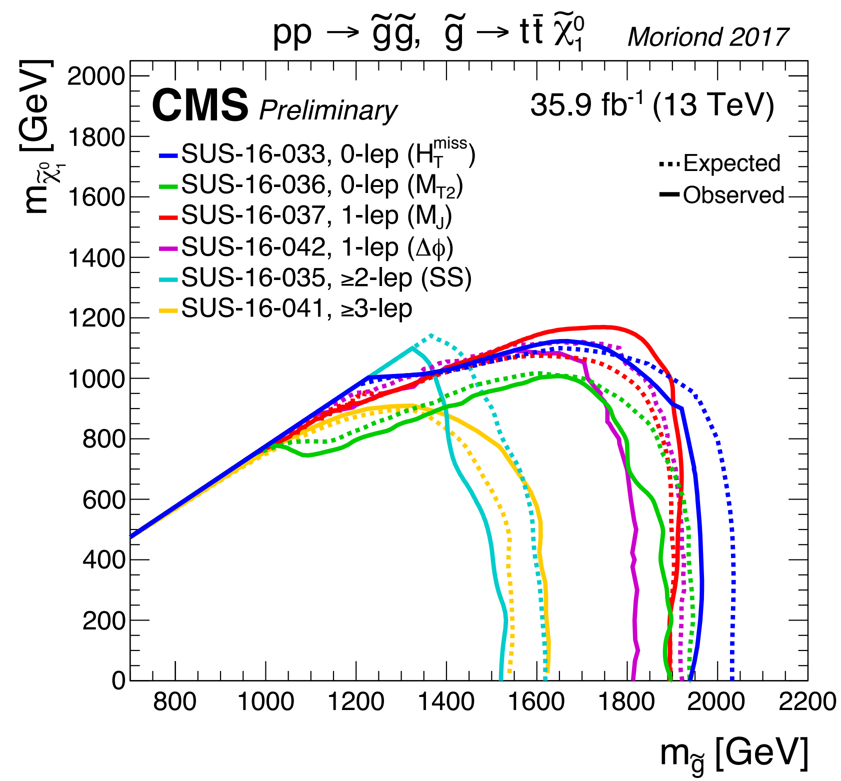
Natural SUSY under test

- Gluino pair productionand decay through (possibly of-shell) stop also **excluded up to a mass of 2 TeV.**



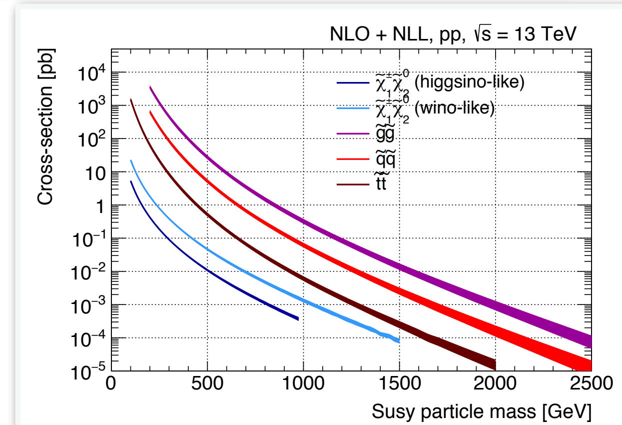


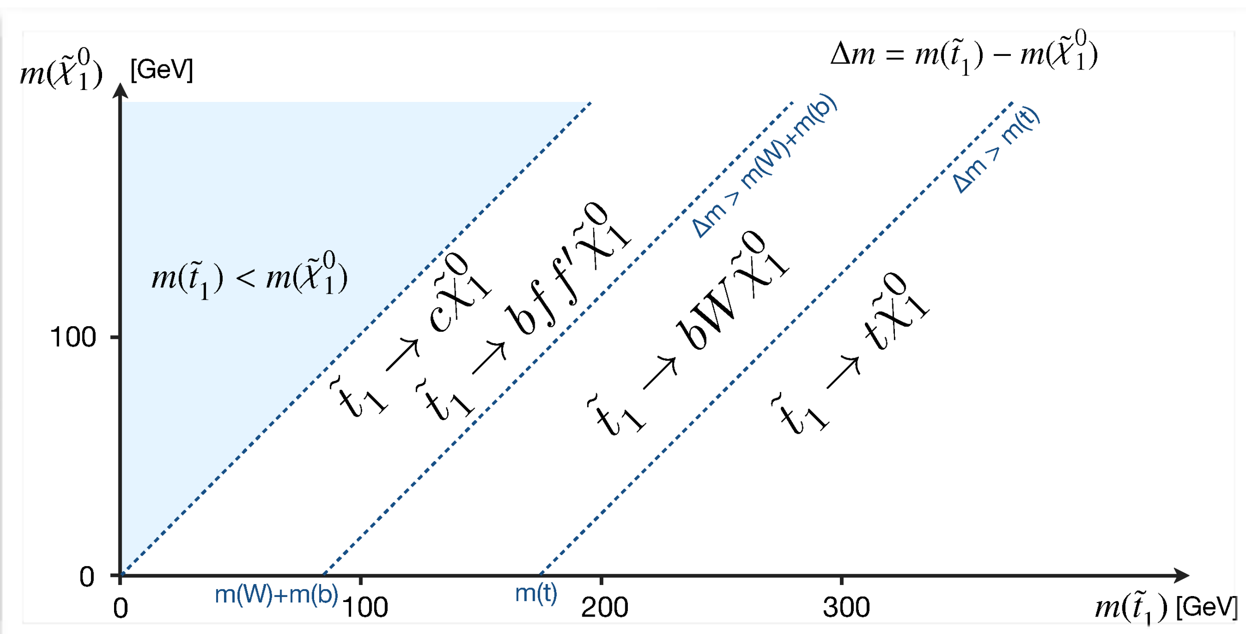
ATLAS-CONF-2017-021

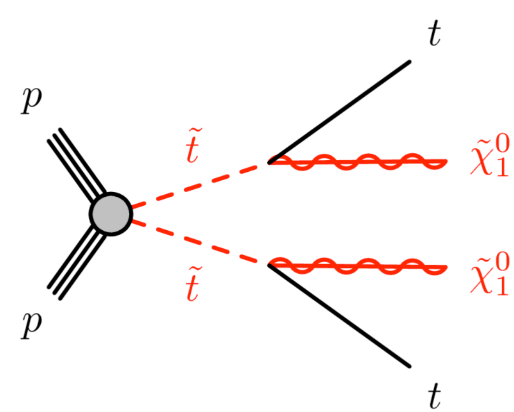


Stop pair production

- Gluino pair production not observed → stop pair production?
  - cross section nearly **two orders of magnitude lower.**
- Large top quark mass makes stop decay topology complex:
  - If **no SUSY particle other than the stop and the neutralino LSP takes part in the process** then the decay is $\tilde{t} \to t^{(*)} \tilde{\chi}_1^0$ with 100% BR.



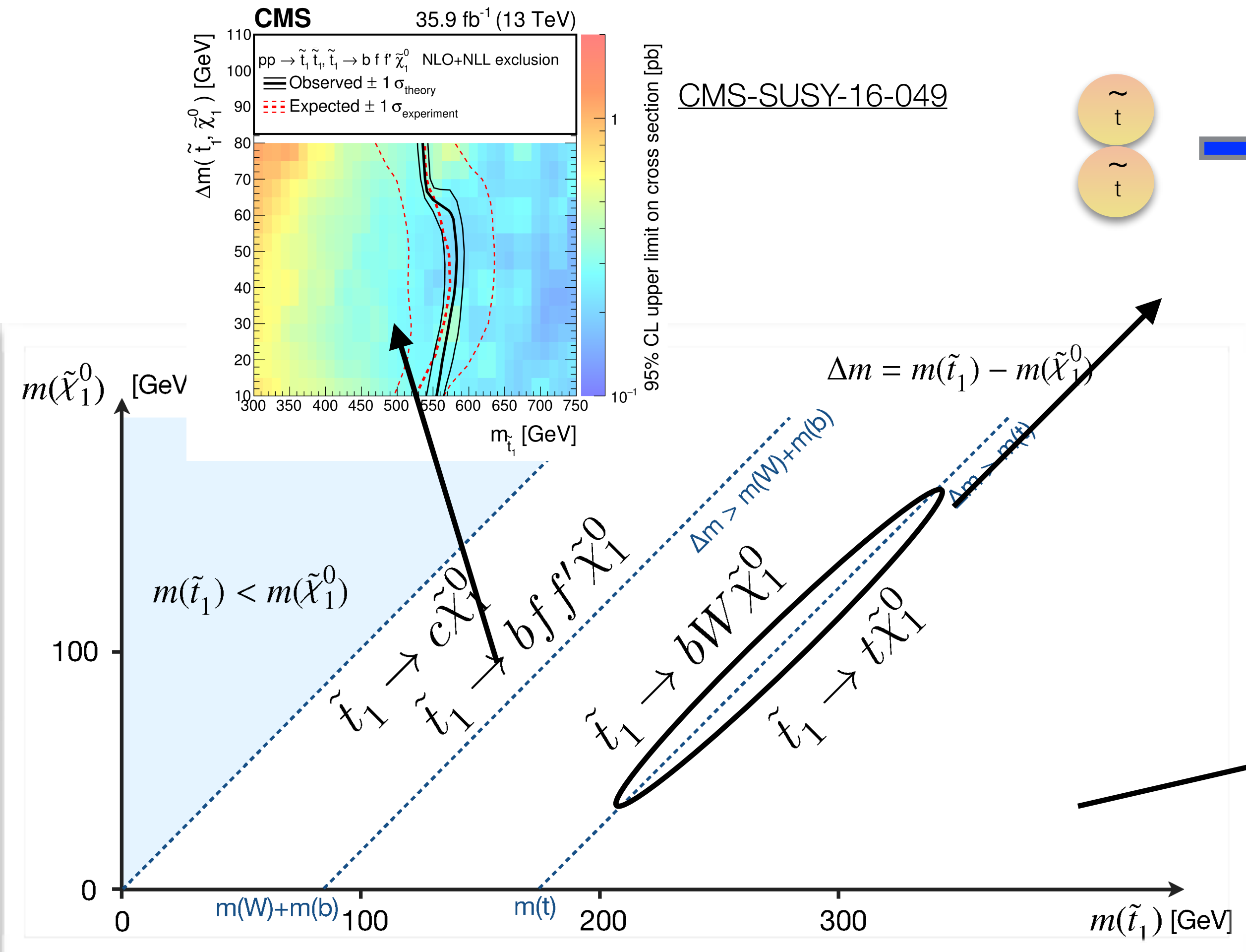




Techniques

- **Secondary vertex counting** enhances sensitivity to low-p_T b-jets.

CMS-SUSY-16-049



- **ISR-like selection** with dedicated variables.

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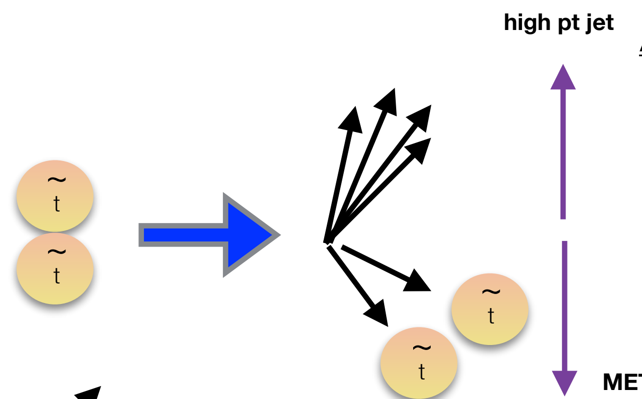
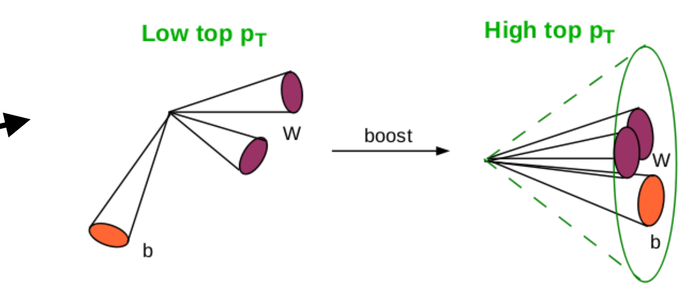
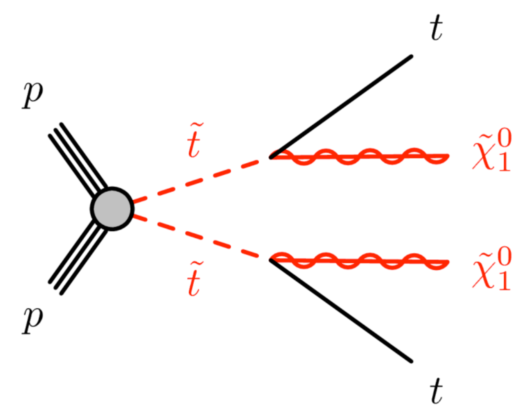


- **Boosted top quark reconstruction** for large stop-neutralino mass gaps.



Stop-neutralino summary

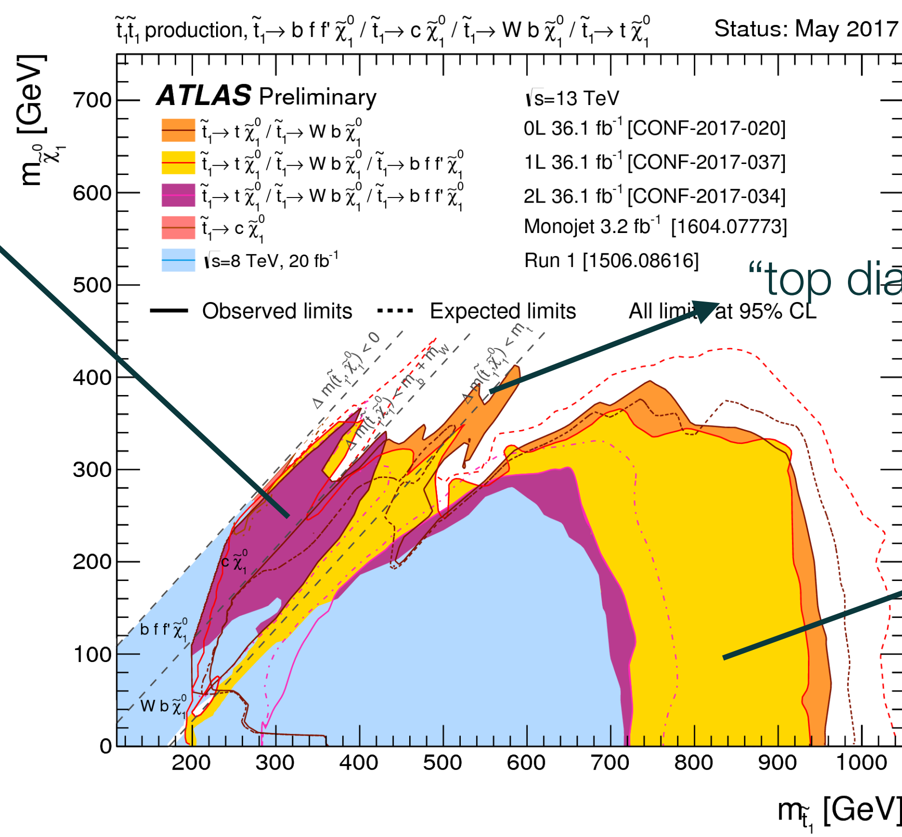
- Sensitivity **exceeds 1 TeV** in favourable scenarios.
- (Almost) no gaps left behind.



Compressed region

“top diagonal” region

“boosted” regime



More realistic models

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- What if the stop-neutralino model is too simple?

Intermezzo - the electroweak sector

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“Standard Model”
(scalars and vectors,
before EW simmetry breaking)

$$B$$
$$\vec{W}$$
$$H_u, H_d$$

Intermezzo - the electroweak sector

"Standard Model"
(scalars and vectors,
before EW simmetry breaking)

$$B$$
$$\vec{W}$$
$$H_u, H_d$$

⇒

SUSY partners (fermions)

$\tilde{B}$ b-ino, 1 neutral state

$\tilde{W}$ w-ino, 1 neutral, 2 charged states

$\tilde{h}$ higgs-ino, 2 neutral, 2 charged states

Intermezzo - the electroweak sector

University of Sussex

"Standard Model"
(scalars and vectors,
before EW simmetry breaking)

B
$\vec{W}$
H_u, H_d

$\Rightarrow$

SUSY partners (fermions)

$\tilde{B}$ b-ino, 1 neutral state

$\tilde{W}$ w-ino, 1 neutral, 2 charged states

$\tilde{h}$ higgs-ino, 2 neutral, 2 charged states

$\Rightarrow$

$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$

Intermezzo - the electroweak sector

University of Sussex

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$$\vec{W}$$
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⇒

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⇒

$$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$
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Let's neglect the mixing

Intermezzo - the electroweak sector

University of Sussex

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B

$\vec{W}$

H_u, H_d

→

SUSY partners (fermions)

$\tilde{B}$ b-ino, 1 neutral state

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$\tilde{h}$ higgs-ino, 2 neutral, 2 charged states

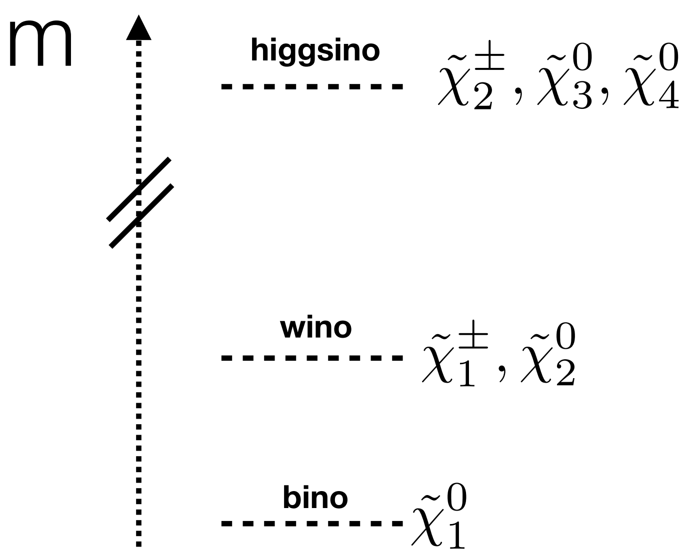
→

$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$

$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$

Let's neglect the mixing

wino-bino



Intermezzo - the electroweak sector

"Standard Model" (scalars and vectors, before EW simmetry breaking)

B

$\vec{W}$

H_u, H_d

→

SUSY partners (fermions)

$\tilde{B}$ b-ino, 1 neutral state

$\tilde{W}$ w-ino, 1 neutral, 2 charged states

$\tilde{h}$ higgs-ino, 2 neutral, 2 charged states

→

$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$

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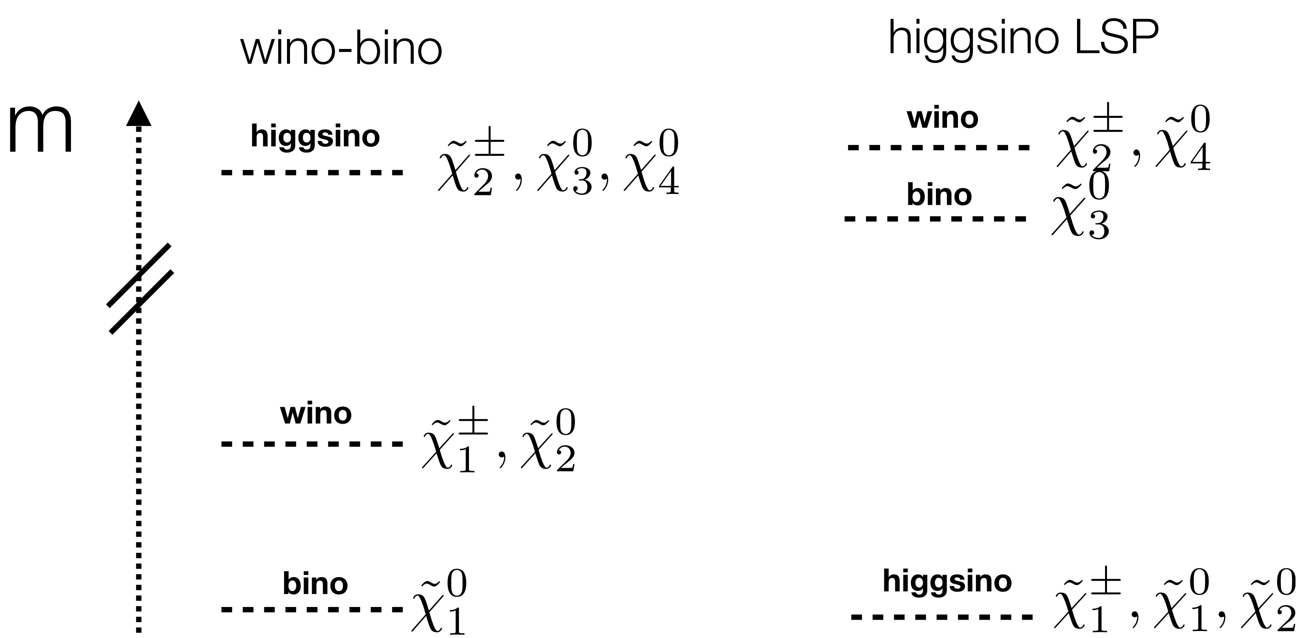
Let's neglect the mixing



Intermezzo - the electroweak sector

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"Standard Model" (scalars and vectors, before EW simmetry breaking)

B

$\vec{W}$

H_u, H_d

⇒

SUSY partners (fermions)

$\tilde{B}$ b-ino, 1 neutral state

$\tilde{W}$ w-ino, 1 neutral, 2 charged states

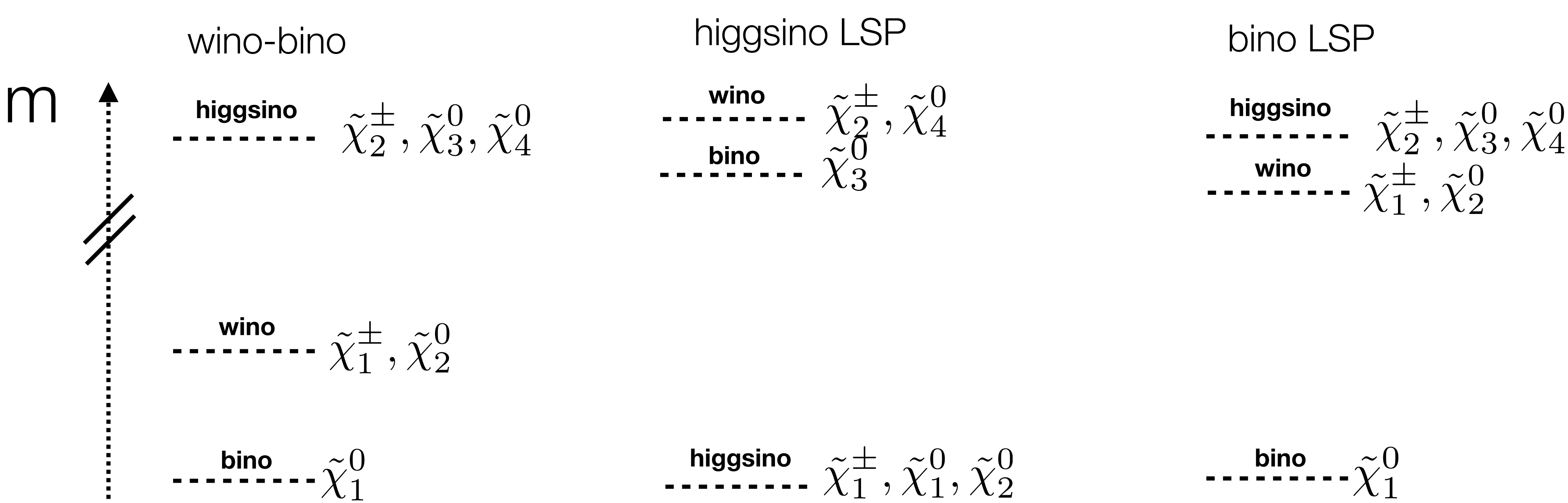
$\tilde{h}$ higgs-ino, 2 neutral, 2 charged states

⇒

$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$

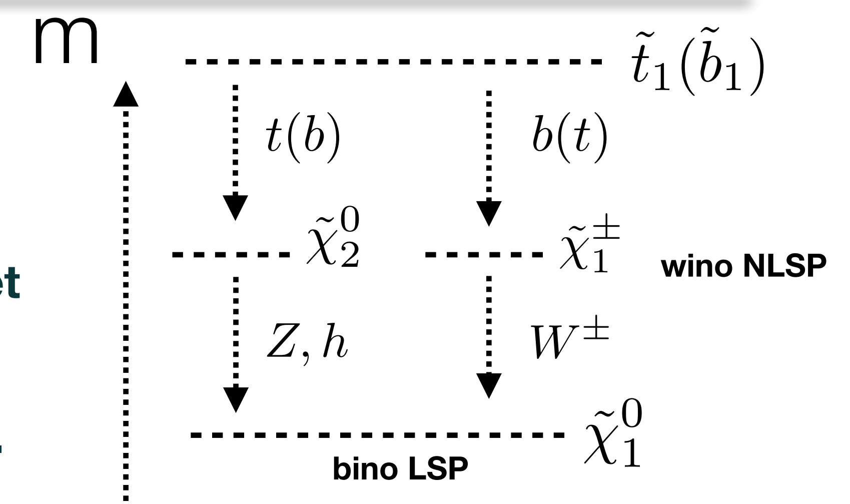
$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$

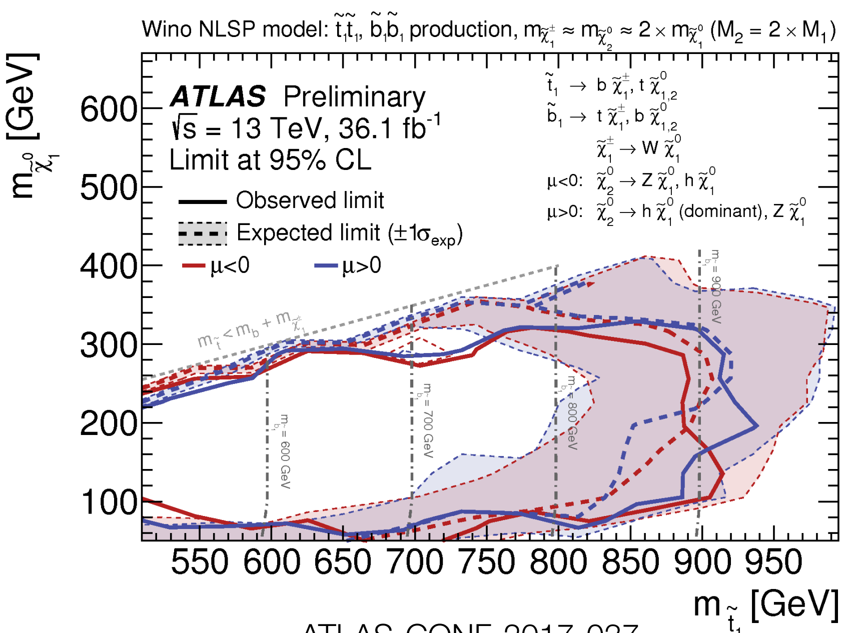
Let's neglect the mixing



More realistic models

- What if the stop-neutralino model is too simple?
  - pMSSM oriented simplified models.
  - For example: assume **bino LSP**, and a **wino doublet** as NSLP.
  - More complex phenomenology, **reduced sensitivity.**





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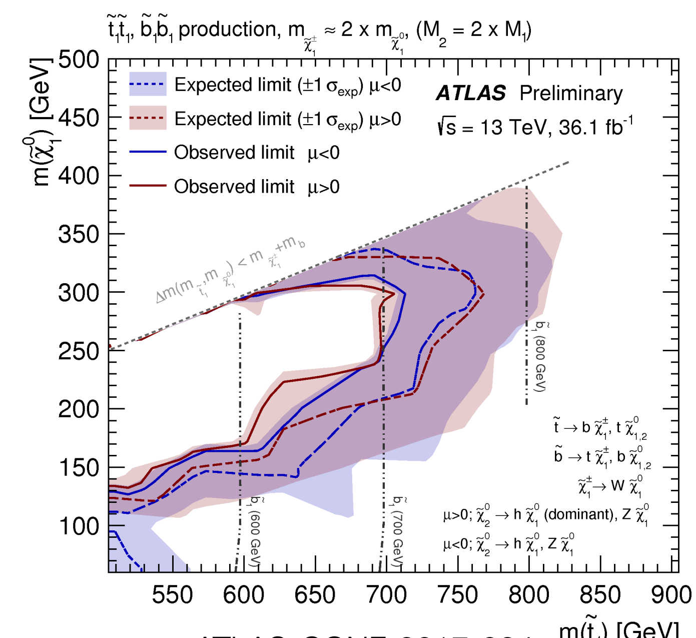
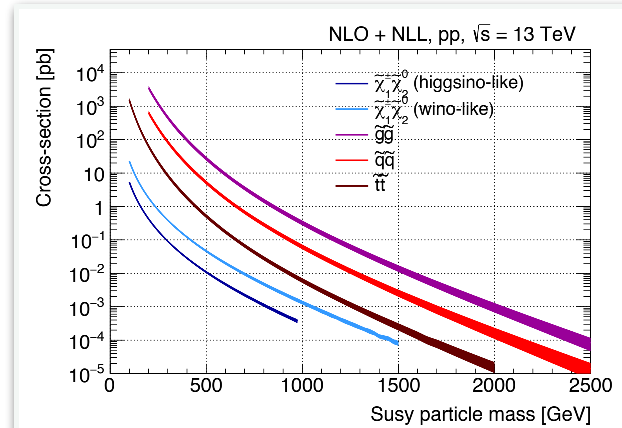


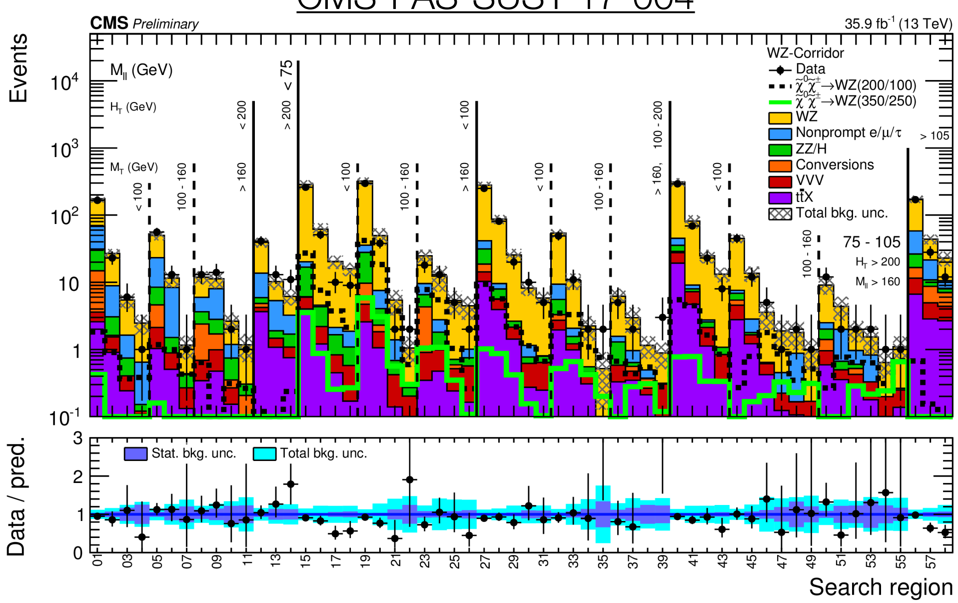
ATLAS-CONF-2017-034

EW production

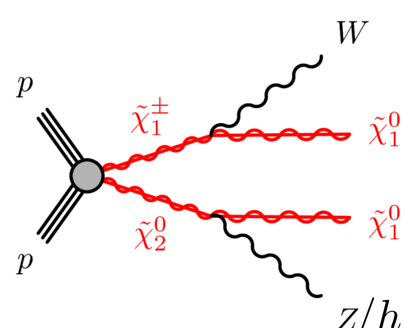
- Maybe SUSY is produced via EW interactions?
  - Direct production of **charginos, neutralinos, sleptons.**
  - Beware: cross sections **depend on the EW state composition** in terms of bino, wino, higgsino, or (for slepton) chirality.
    - **Wino-bino hierarchy.** Several event categories:
      - 3L, SS leptons, 2L2J (transitions with WZ, WH).
      - 1Lbb, 1Lγγ (WH).

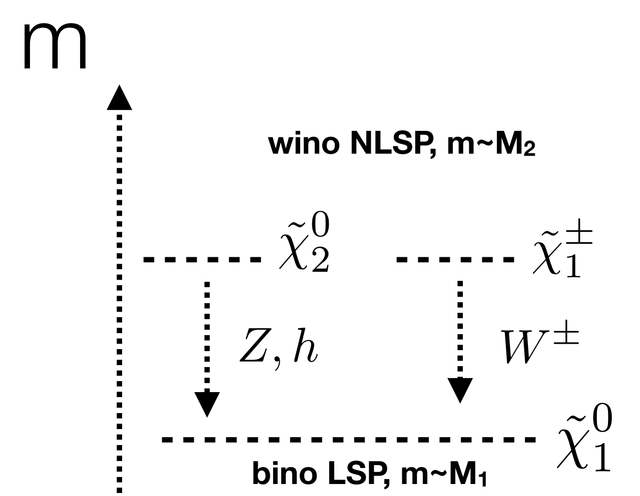


CMS-PAS-SUSY-17-004



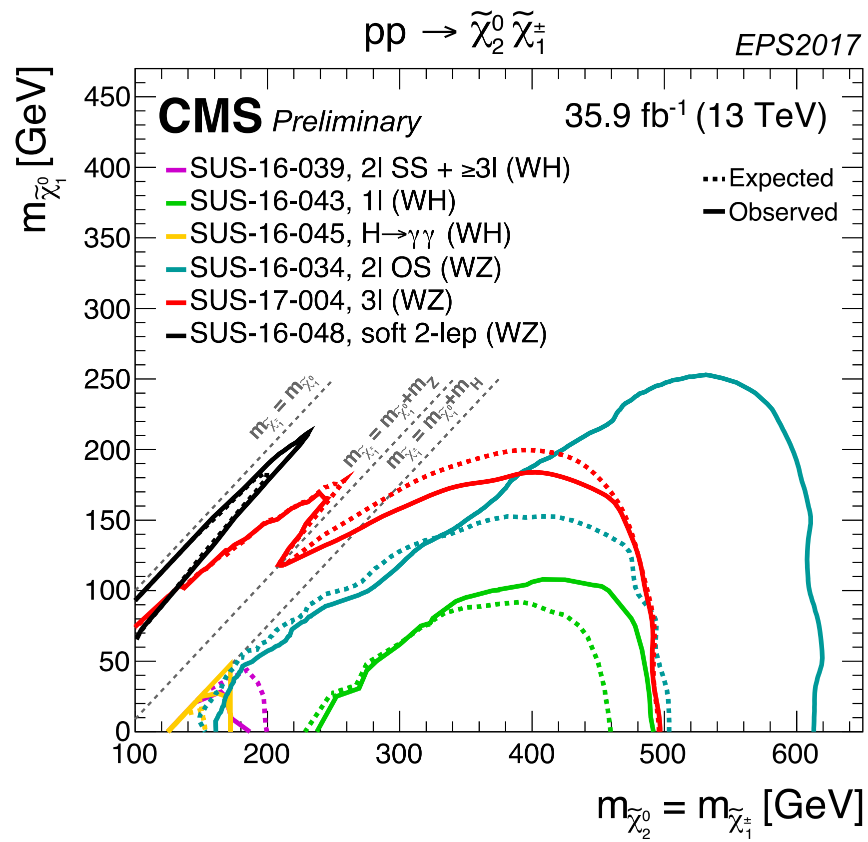
same as in slide 16 (no stop/sbottom)





Wino-bino limit summary

- Common **wino NLSP mass excluded up to ~600 GeV** assuming BR into WZ of 100%
  - Significantly weaker limits with increasing BR into WH.



EW production and naturalness

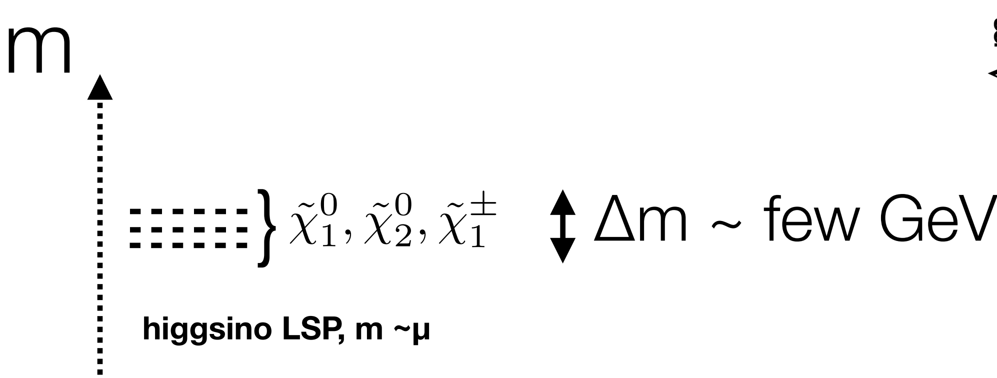
Naturalness wants **light higgsinos.**

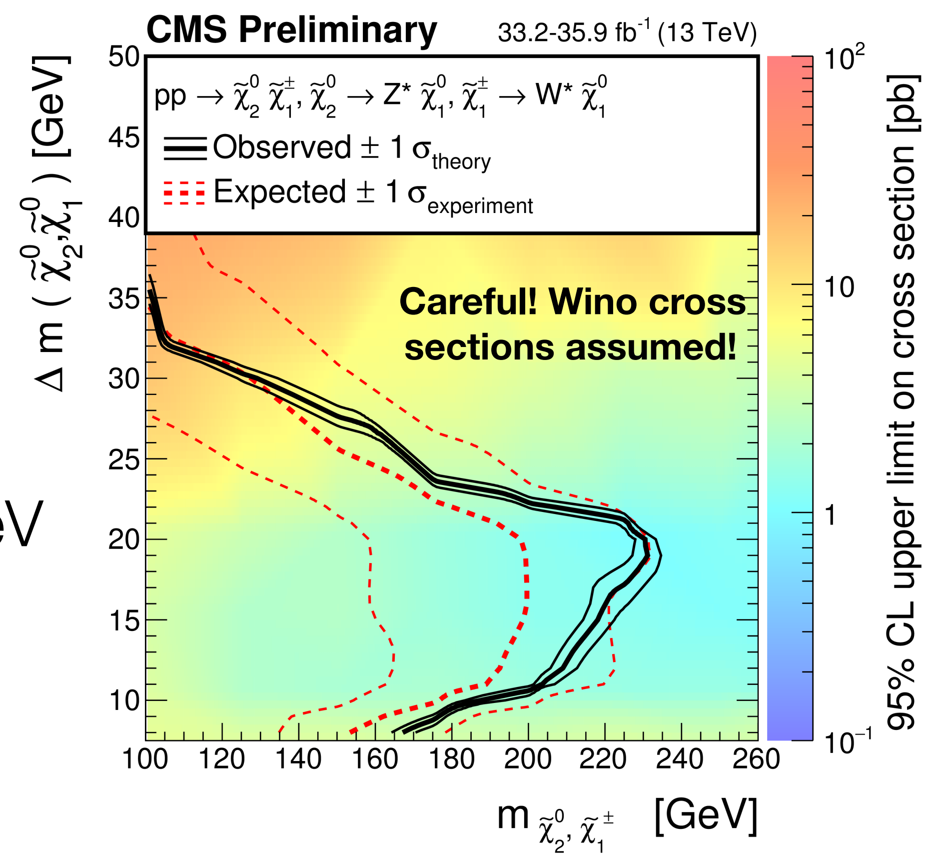
- If higgsinos are **decoupled (heavy bino and wino)**, then Δm is **typically o(GeV)** (but it can be as low as 300 MeV).

- … and the **cross section is small**…

⇒ Extremely challenging!

Selection highlights:
- Two OS leptons with low p_T
- Large E_T^{miss}, $0.6 < E_T^{miss}/H_T < 1$
- $4 \text{ GeV} < m_{ll} < 50 \text{ GeV}$ (and Υ veto)

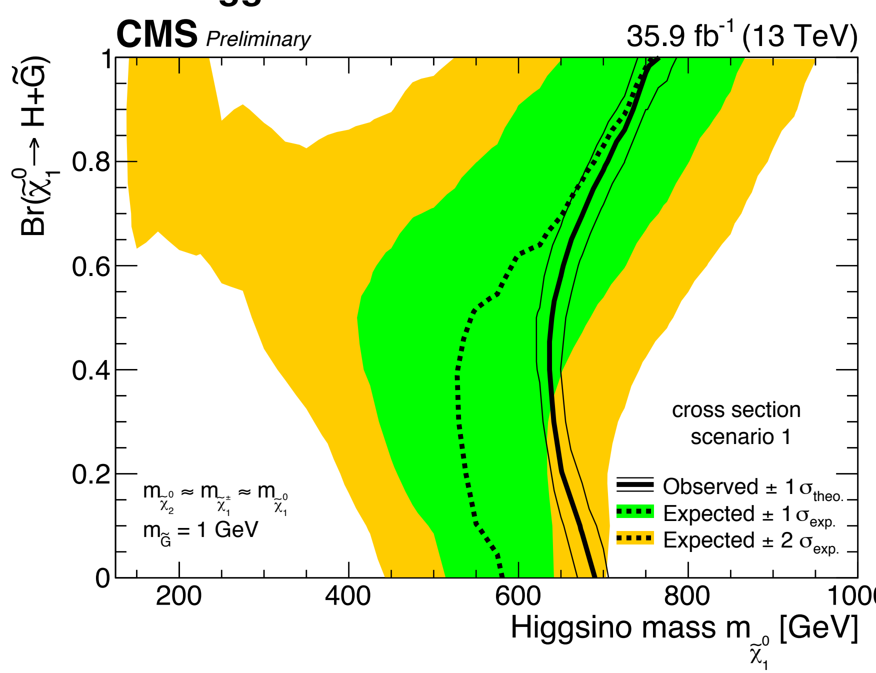




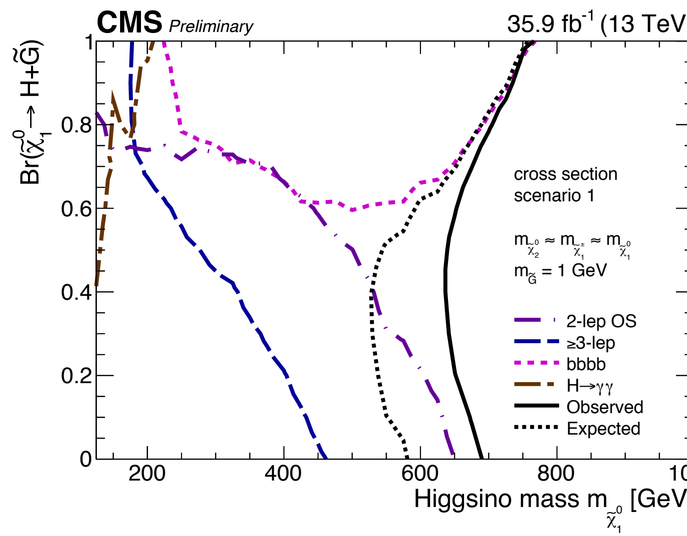
Higgsino NLSP

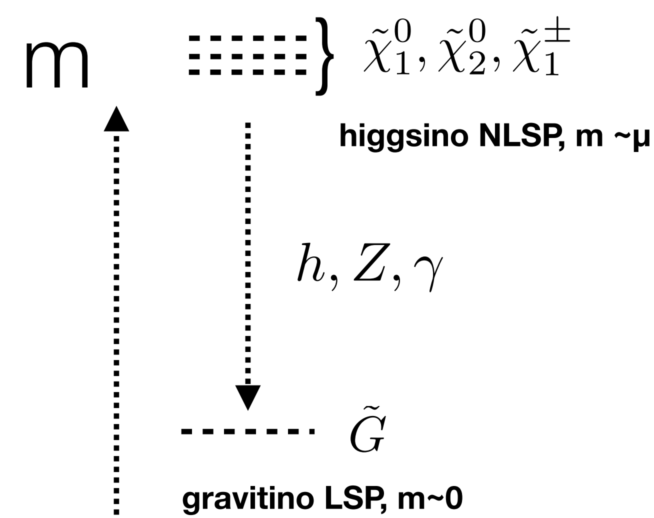
- Naturalness **does not require** a higgsino LSP. GMSB-like higgsino NLSP scenarios are potentially “natural”.
  - Dedicated 1Lbb, 1Lγγ analyses:
    - SUS-16-044, SUS-16-045.

Higgsino cross sections assumed

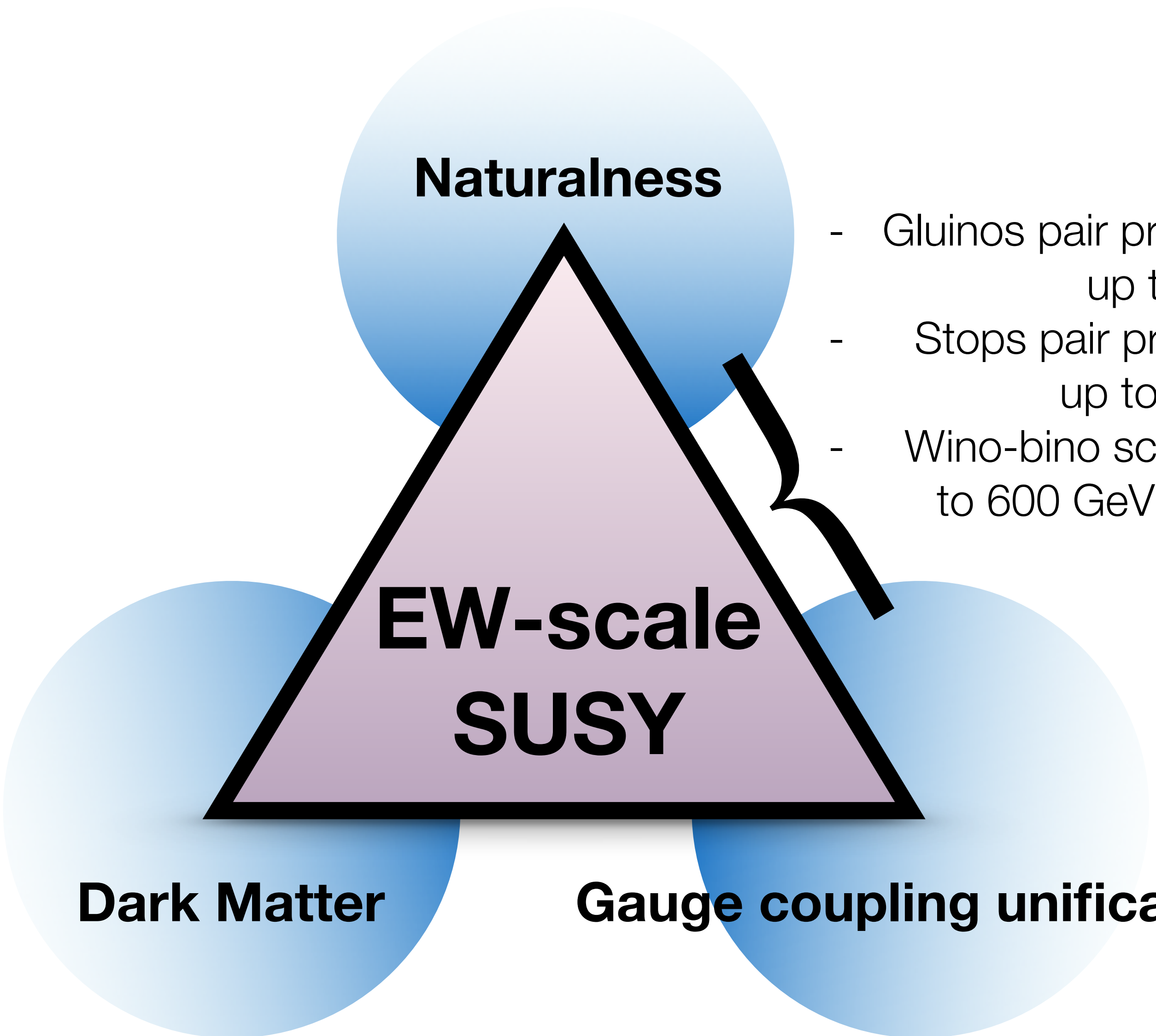


CMS-PAS-SUS-17-004





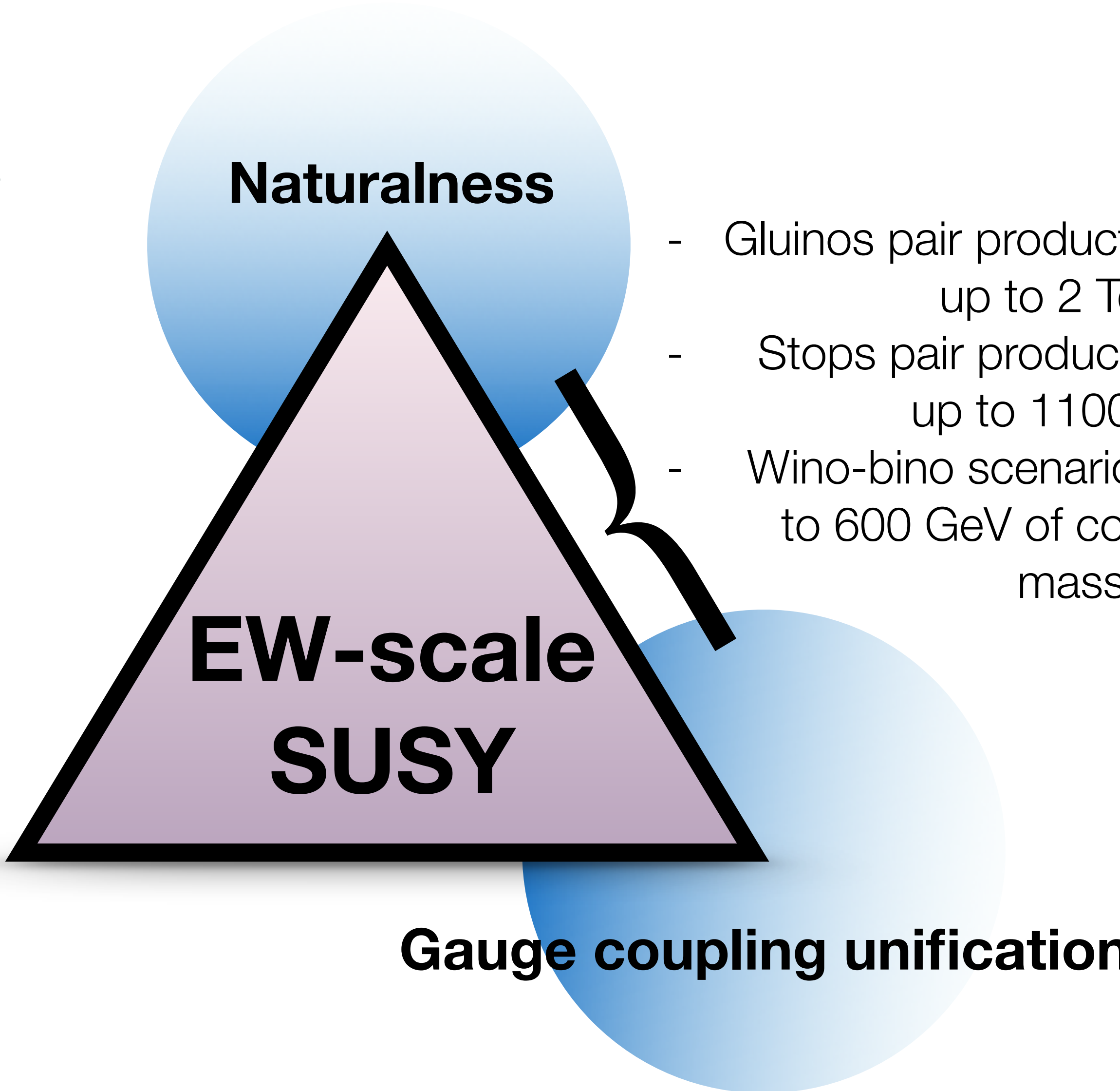
EW-scale supersymmetry



- Gluinos pair production excluded up to 2 TeV
- Stops pair production excluded up to 1100 GeV
- Wino-bino scenario excluded up to 600 GeV of common wino mass

EW-scale supersymmetry

**Let's release some assumptions:
R-Parity violation implies no good SUSY SM counterpart as Dark matter candidate**



- Gluinos pair production excluded up to 2 TeV
- Stops pair production excluded up to 1100 GeV
- Wino-bino scenario excluded up to 600 GeV of common wino mass

R-parity violating scenarios

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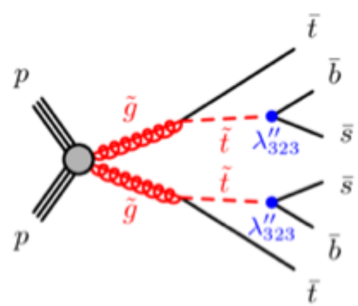
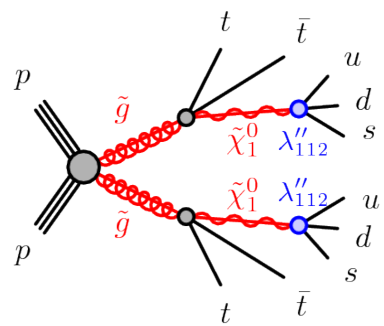
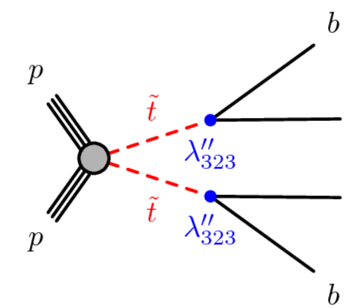
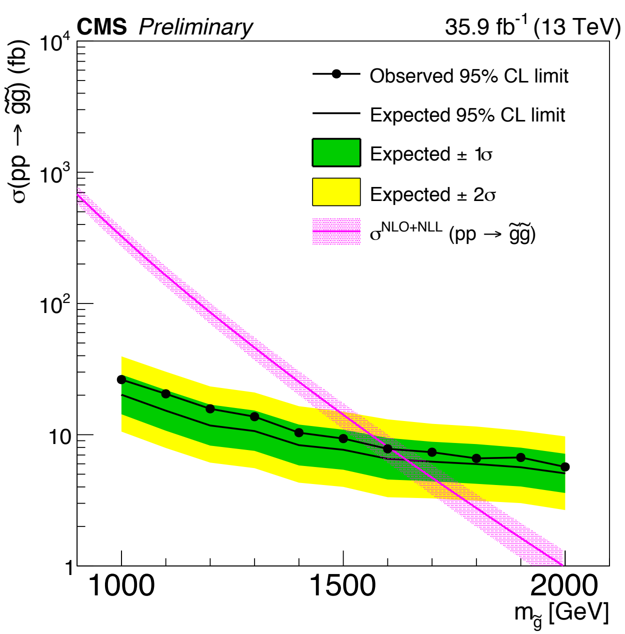
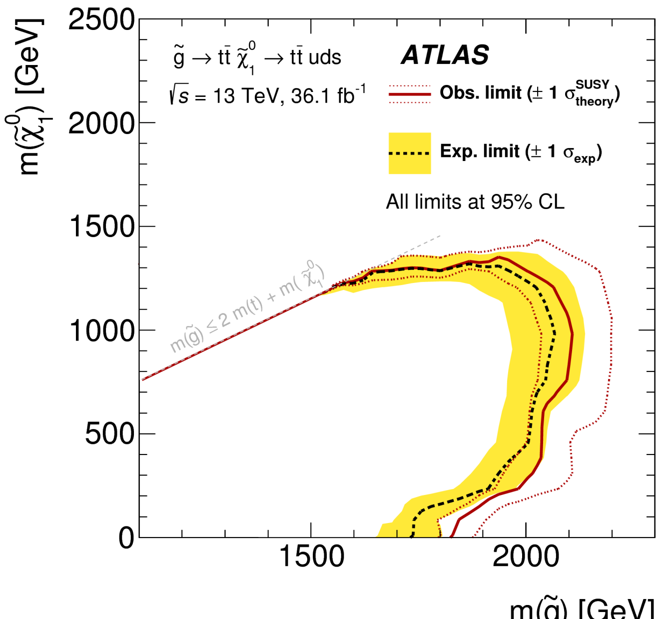
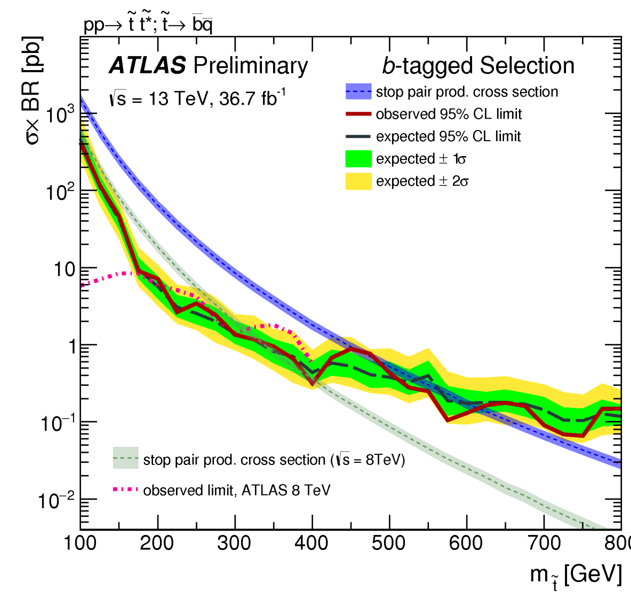
- Limits for R-parity violating natural SUSY are also competitive







CMS-PAS-SUS-16-040, to appear, and arXiv:1704.08493

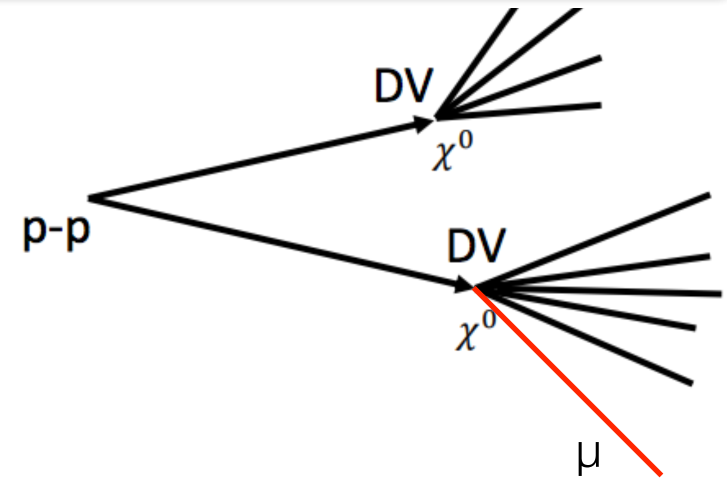
ATLAS-CONF-2017-025

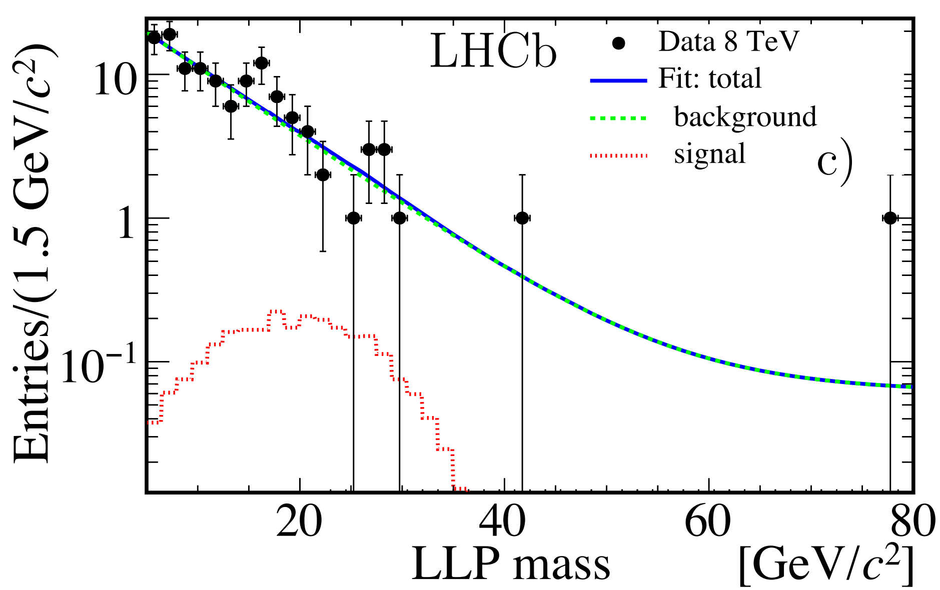
R-parity violating scenarios

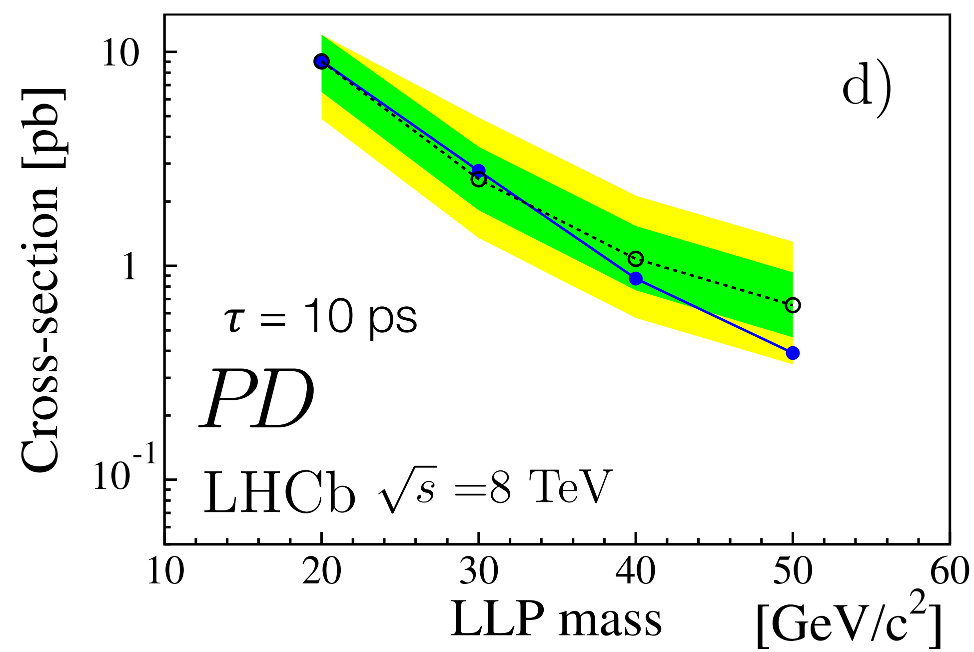
University of Sussex

arxiv:1612.00945

- LHCb results on R-parity violating neutralino decays:
  - For example: look for a **displaced vertex** produced in association with a muon
  - Using 1 (2) fb^{-1} of 7 (8) TeV data



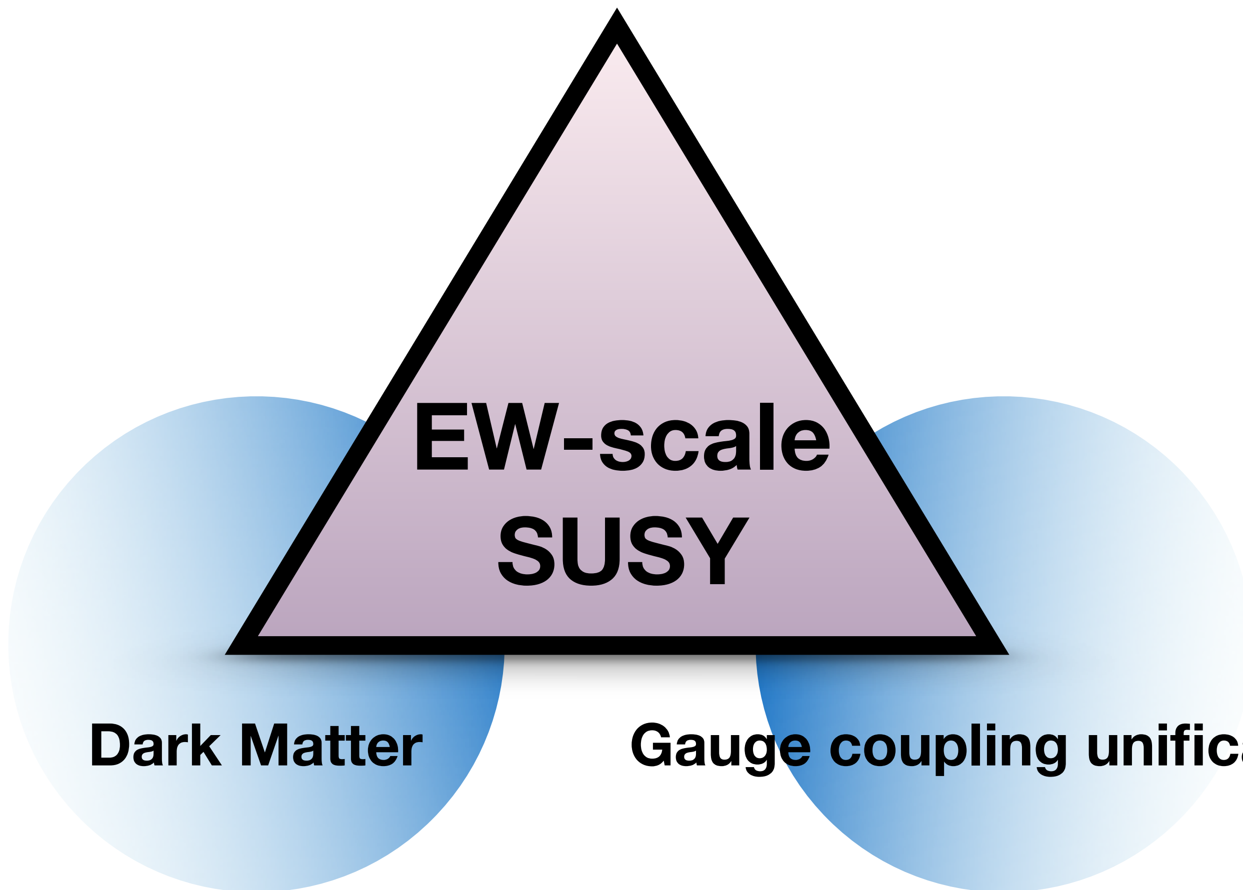




EW-scale supersymmetry

What if we drop the naturalness requirement altogether?

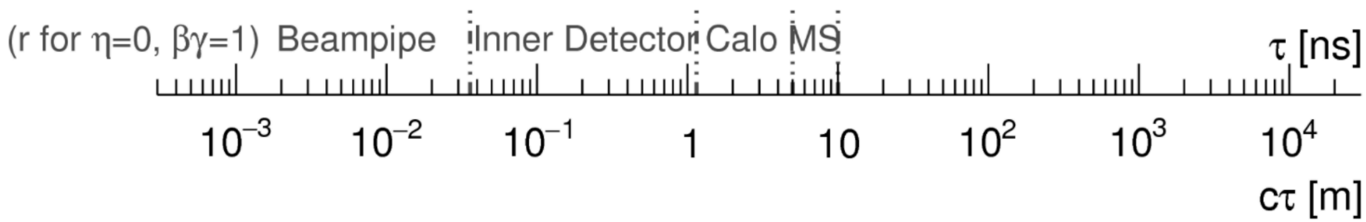
Beware: no “naturalness” criterium implies **no need for “EW-scale” SUSY**

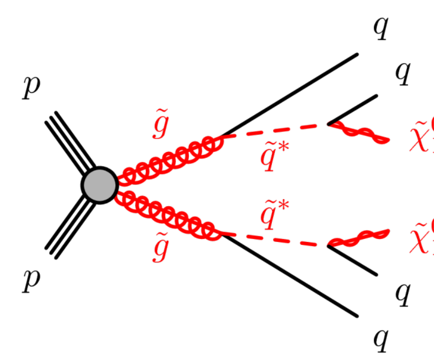


Long-lived gluinos

- Squark-mediated gluino decay: gluino lifetime **becomes measurable** if the squark mass is large (e.g., split SUSY).
- Different techniques probe different gluino lifetimes

$$\Gamma \sim \frac{m_{\mathrm{gluino}}^5}{m_{\mathrm{squark}}^4}$$





Long-lived gluinos

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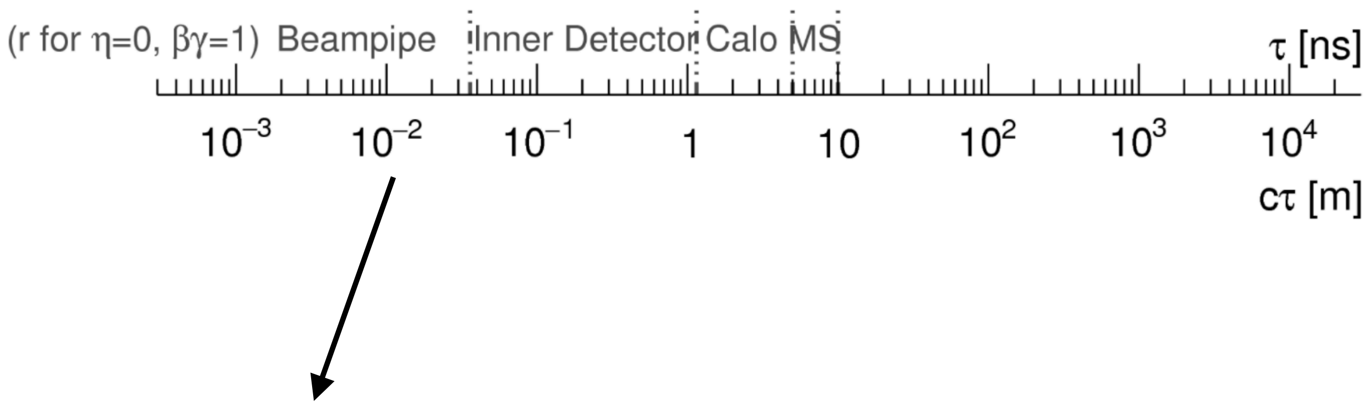
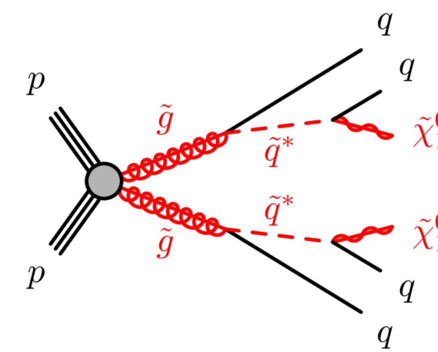
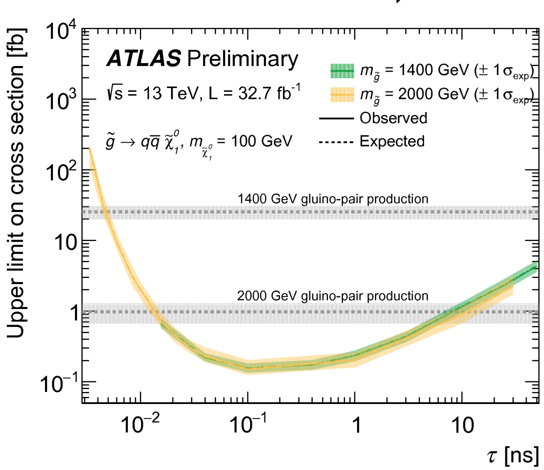
- Squark-mediated gluino decay: gluino lifetime **becomes measurable** if the squark mass is large (e.g., split SUSY).
- Different techniques probe different gluino lifetimes

$$\Gamma \sim \frac{m^5_{\text{gluino}}}{m^4_{\text{squark}}}$$





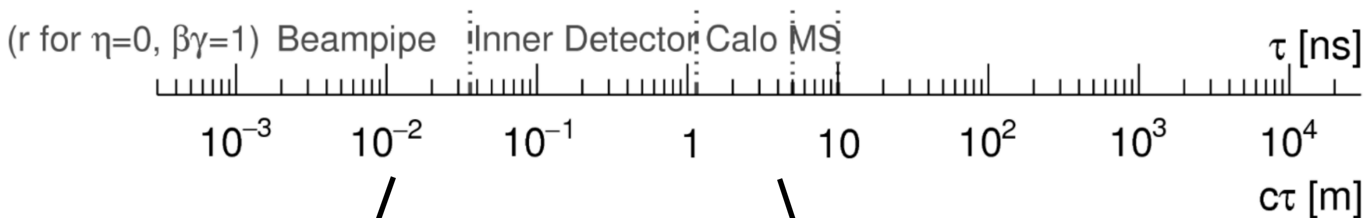


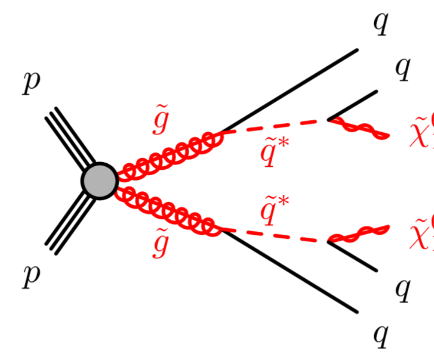
Displaced vertices
ATLAS-CONF-2017-026

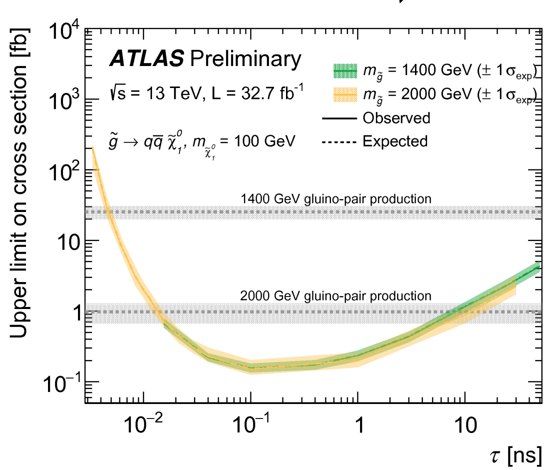
Long-lived gluinos

- Squark-mediated gluino decay: gluino lifetime **becomes measurable** if the squark mass is large (e.g., split SUSY).
- Different techniques probe different gluino lifetimes

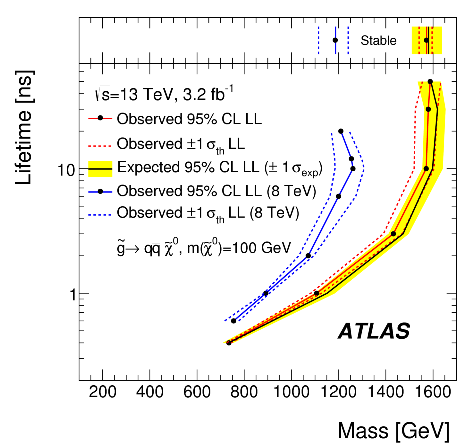
$$\Gamma \sim \frac{m_{\text{gluino}}^5}{m_{\text{squark}}^4}$$







Displaced vertices
ATLAS-CONF-2017-026



Ionisation, time of flight
Phys. Rev. D 93 112015
Phys. Lett. B 760 (2016) 647-665
CMS-PAS-EXO-16-036

Long-lived gluinos

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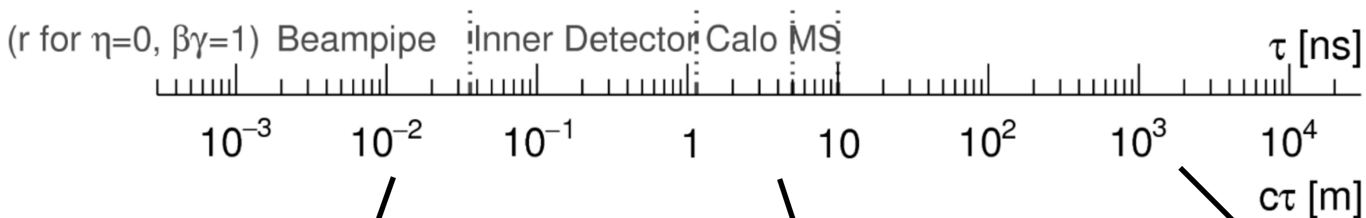
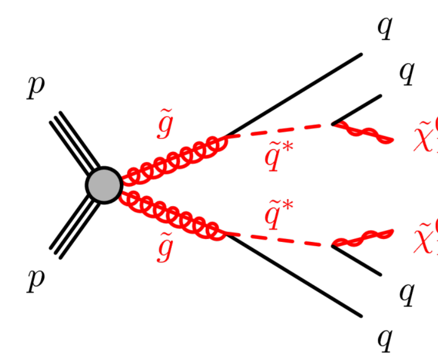
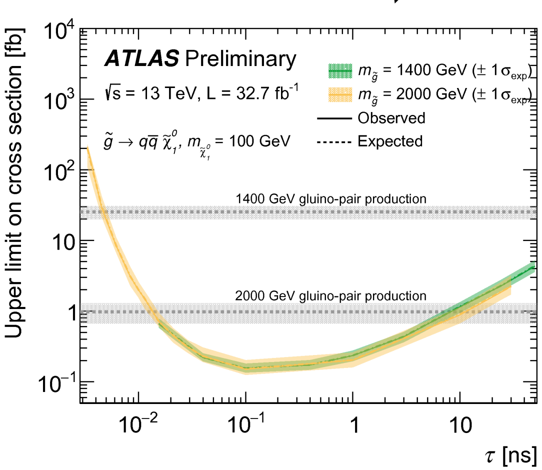
- Squark-mediated gluino decay: gluino lifetime **becomes measurable** if the squark mass is large (e.g., split SUSY).
- Different techniques probe different gluino lifetimes

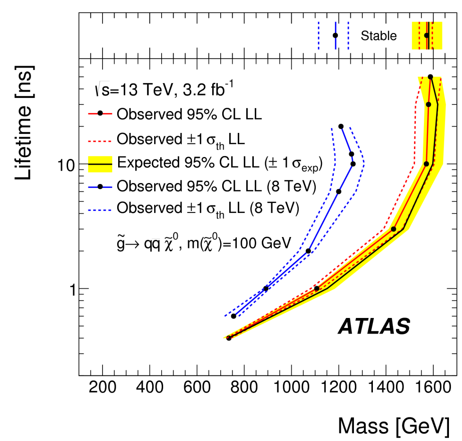
$$\Gamma \sim \frac{m^5_{\mathrm{gluino}}}{m^4_{\mathrm{squark}}}$$



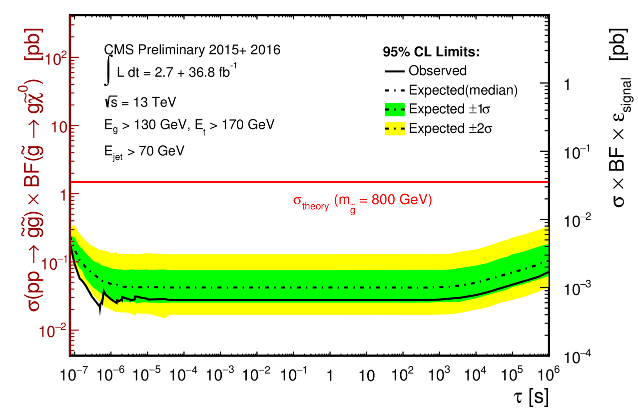




Displaced vertices
ATLAS-CONF-2017-026



Ionisation, time of flight
Phys. Rev. D 93 112015
Phys. Lett. B 760 (2016) 647-665
CMS-PAS-EXO-16-036

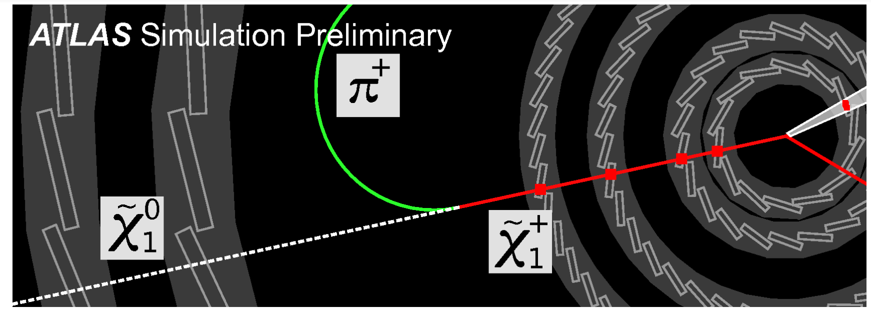


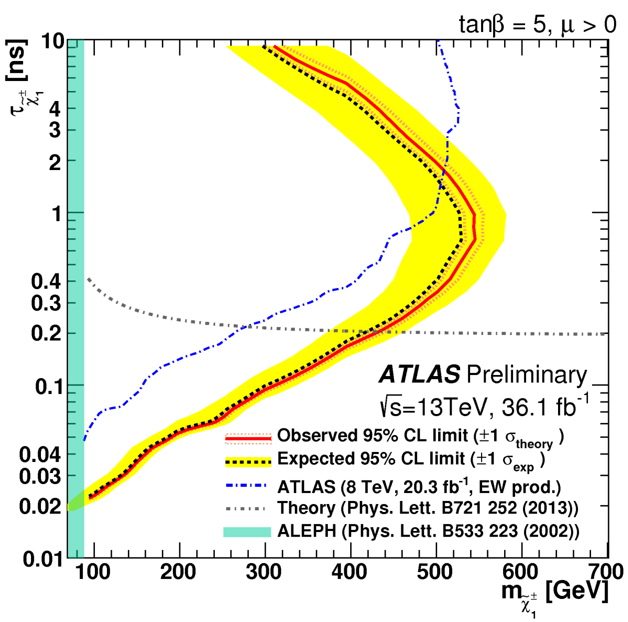
Stopped gluinos
CMS-PAS-EXO-16-004

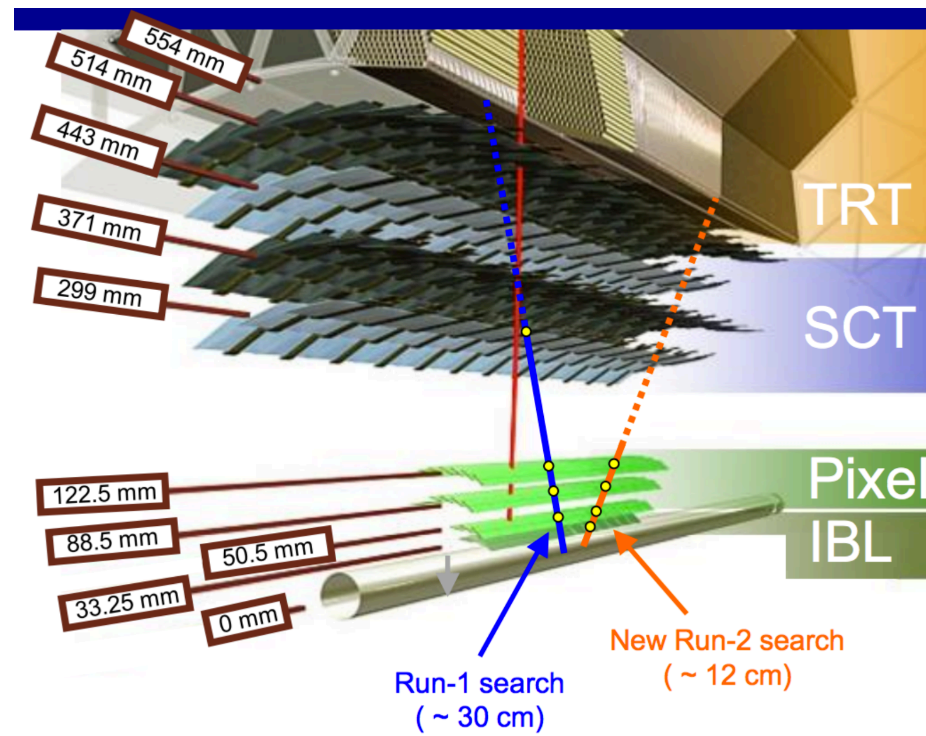
Wino-LSP scenario

ATLAS-CONF-2017-017

- Very common (in MSSM) SUSY scenario:
    - A **chargino nearly degenerate with a neutralino** (wino-like LSP).
    - The chargino **becomes long-lived** (typical τ = 0.2 ns or cτ~6 cm).
    - Effort to increase to **increase sensitivity at low lifetime.**







The big picture

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ATLAS SUSY Searches* - 95% CL Lower Limits

May 2017

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

$\sqrt{s}$ = 7, 8 TeV | $\sqrt{s}$ = 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [fb^{-1}]$		Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.85 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$	1.57 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$	608 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0)$<5 GeV	1604.07773
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.02 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.01 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	36.1	$\tilde{g}$	1.825 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2017-030
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$	1.8 TeV	$m(\tilde{\chi}_1^0)$ <400 GeV	ATLAS-CONF-2017-033
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$	2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$	1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$	1.37 TeV	$m(\tilde{\chi}_1^0)$<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$	1.8 TeV	$m(\tilde{\chi}_1^0)$>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$	900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	$\tilde{g}$	1.92 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$	1.97 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.37 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	$\tilde{b}_1$	950 GeV	$m(\tilde{\chi}_1^0)$<420 GeV	ATLAS-CONF-2017-038
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	1 b	Yes	36.1	$\tilde{b}_1$	275-700 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})= m(\tilde{\chi}_1^0)$+100 GeV	ATLAS-CONF-2017-030
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$	117-170 GeV; 200-720 GeV	$m(\tilde{\chi}_1^{\pm}) = 2m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$	90-198 GeV; 205-950 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, ATLAS-CONF-2017-020
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	$\tilde{t}_1$	90-323 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-600 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ (Z)	1 b	Yes	36.1	$\tilde{t}_2$	290-790 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2017-019
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$	320-880 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2017-019
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$	90-440 GeV	$m(\tilde{\chi}_1^0)$=0	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}$	710 GeV	$m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}$	760 GeV	$m(\tilde{\chi}_1^0)$=0, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	1.16 TeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	36.1	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	580 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	270 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	635 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	1 $e,\mu + \gamma$	-	Yes	20.3	$\tilde{W}$	115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	2 γ	-	Yes	20.3	$\tilde{W}$	590 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^{\pm}$	430 GeV	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	ATLAS-CONF-2017-017
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$	495 GeV	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	850 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$	1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$	1.57 TeV	$m(\tilde{\chi}_1^0)$=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	440 GeV	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$	1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.45 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	$\tilde{\chi}_1^{\pm}$	1.14 TeV	$m(\tilde{\chi}_1^0)$>400GeV, $\lambda_{12k}\neq0$ (k = 1, 2)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 $e,\mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$	1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$	1.55 TeV	$m(\tilde{\chi}_1^0)$=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	2.1 TeV	$m(\tilde{\chi}_1^0)$= 1 TeV, $\lambda_{112}\neq0$	ATLAS-CONF-2017-013
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$	1.65 TeV	$m(\tilde{t}_1)$= 1 TeV, $\lambda_{323}\neq0$	ATLAS-CONF-2017-013
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	$\tilde{t}_1$	410 GeV; 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$	0.4-1.45 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2017-036
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$	510 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

10^{-1} 1 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Summary

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LHC has **radically changed** the way we think about SUSY

- Where are all the sparticles?
  - **7 years of LHC** have given us only a **striking agreement with the Standard Model.** Many pre-LHC SUSY models now **highly disfavoured** by the data.
  - The pillars of **EW scale SUSY** are under severe scrutiny (and a bit of pressure)
- A very rich research programme - if there is **a discovery** to be made, **we do not want to miss it**.

Full list of results can be found at

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- ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
- CMS: http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SUS/index.html
- LHCb: http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_QEE.html

BACKUP

Higgs boson discovery

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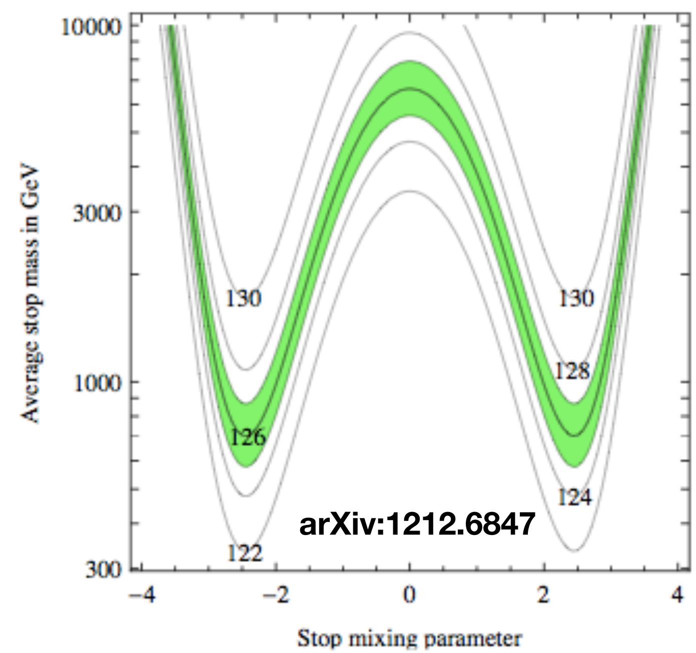
- The **Higgs boson mass** in the MSSM is determined (at 1-loop) by **EW parameters** and by the **stop masses and mixing**

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3y_t^2 m_t^2}{4\pi^2}\left[\log\left(\frac{m_S^2}{m_t^2}\right) + X_t^2\left(1 - \frac{X_t^2}{12}\right)\right] + \cdots$$

- Critical connection of stops and electroweakinos (actually higgsinos) **to the heart of the only argument in favour of EW-scale SUSY**
- However, Higgs at 125 GeV already hinting for heavy-ish stops (Barbieri-Giudice fine tuning measurement requires them to be ~ 500 GeV)



Simplified model approach

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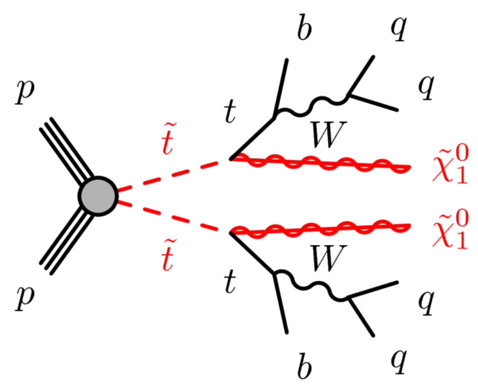
- Simplified model:
  - only one (or few) **SUSY production mode**
  - only one (or few) **decay mode**
  - only few **SUSY particles** involved in the **decay**



The good:
- Optimise for a well defined topology
- Intuitive understanding of sensitivity
- Exclusion limits easily reproducible by theory colleagues

The bad:
- The approach becomes quickly cumbersome at increasing complexity of final state

The ugly:
- Real model complexity hidden: sensitivity claimed on simplified model does not necessarily map to a real model

Disclaimer

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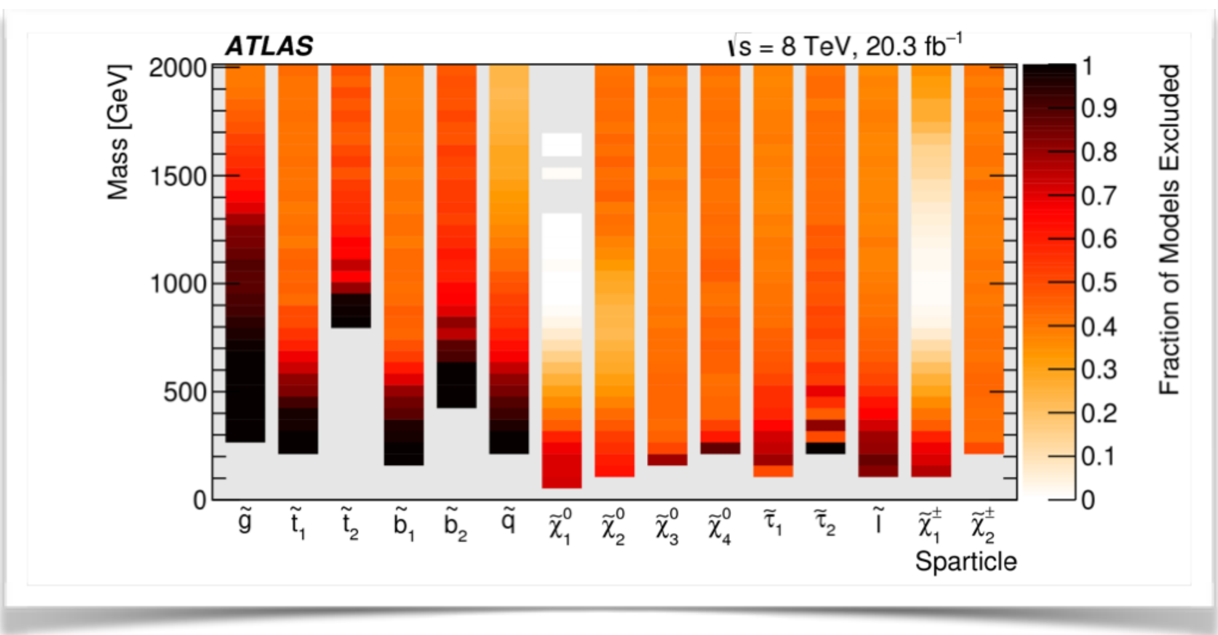
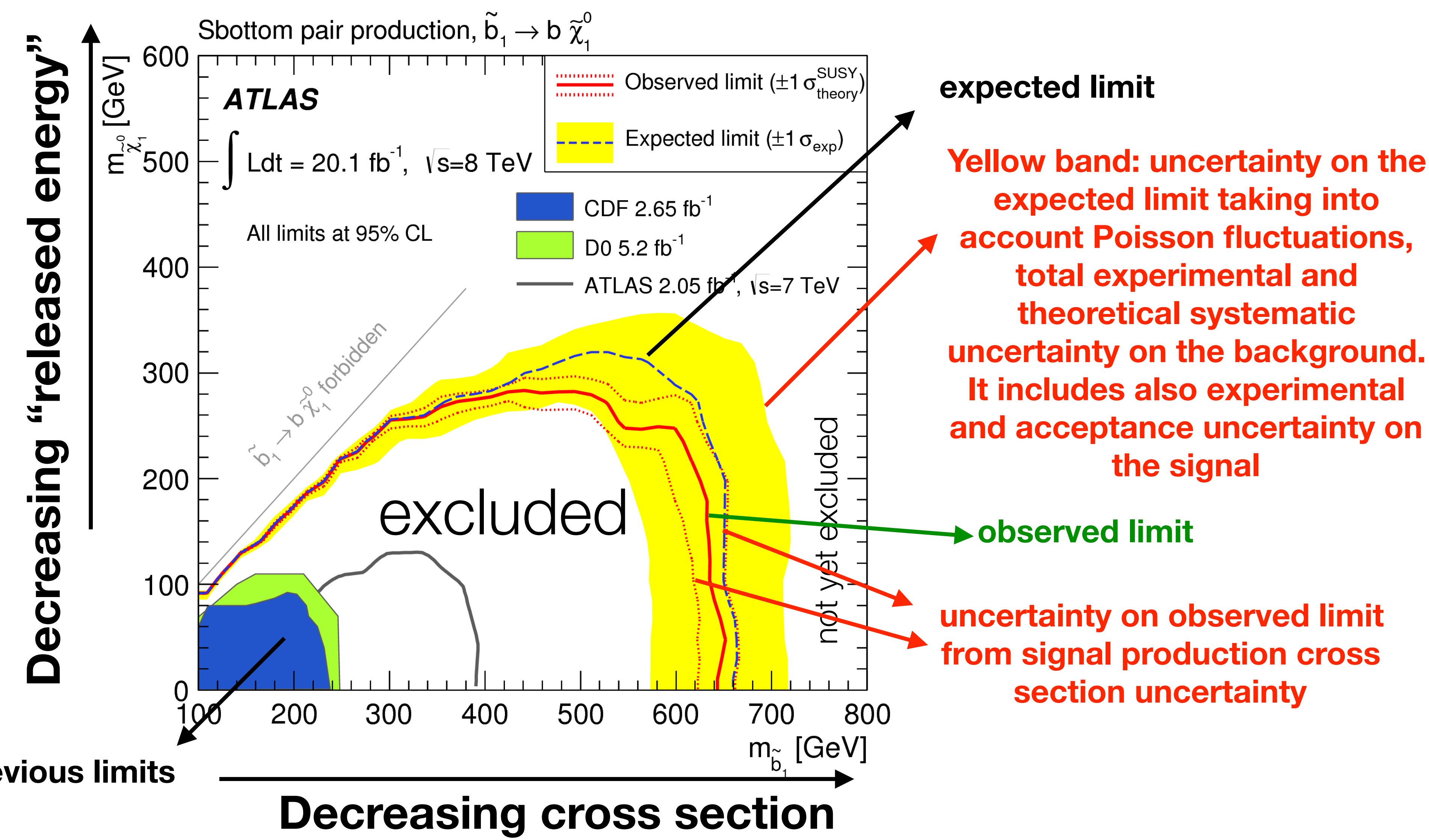
- We use simplified models to **optimise our analyses** and (often) to **interpret the result**
- The translation to actual models **not always straightforward.** "Absolute" exclusion (when they exist) limits **are weaker.**
- Take our limits *cum grano salis*



How to read a limit



Highlights (RPC strong production)

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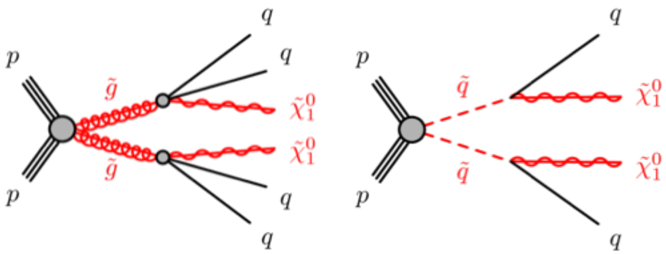
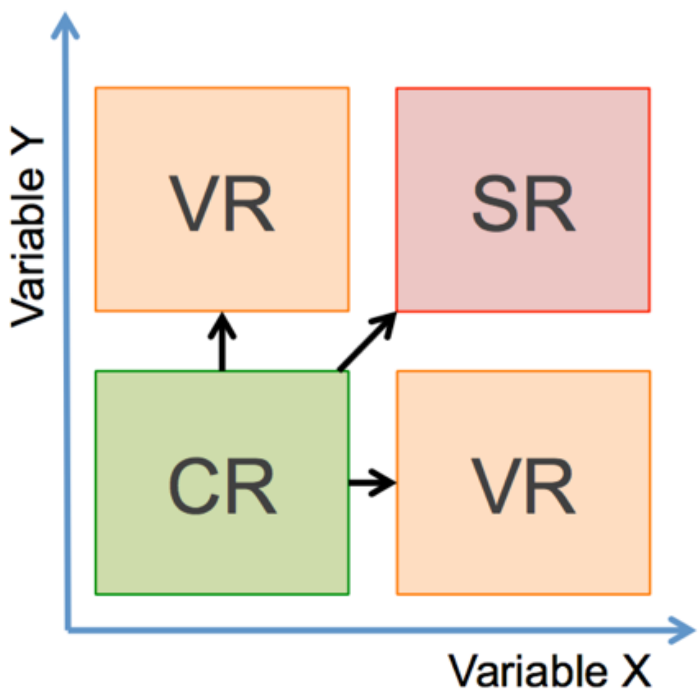
ATLAS-CONF-2016-078





- 0L + jets + E_T^{miss}: traditionally **the flagship** of the ATLAS SUSY
- To **record** these events, require a $\mathbf{E_T^{miss}}$ **trigger**
- Signal regions defined for **different jet multiplicities** and **different $\mathbf{m_{eff}}$** selections
- **Irreducible background** prediction obtained **from MC normalised in dedicated Control Regions**
- **Reducible background** (e.g. multijet) completely **data-driven**

Dark matter connection

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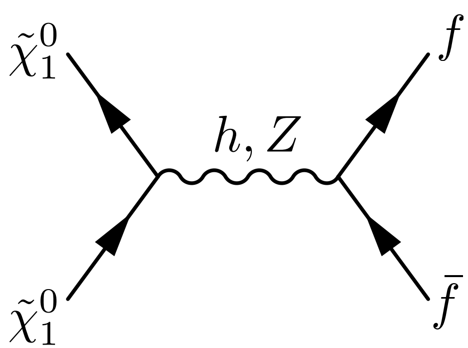
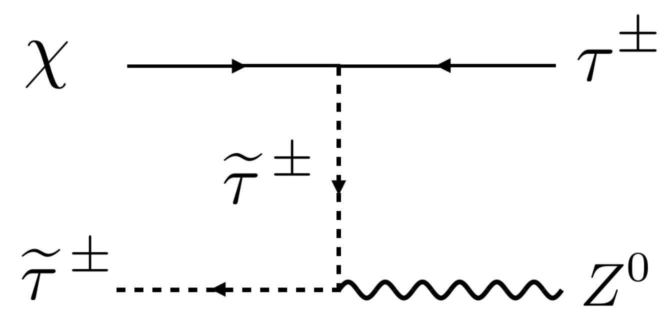
- Relic dark matter WIMP density depends on **assumed velocity spectrum** and on **WIMP self-interaction cross section**

$$\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\rm Pl}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma_A v \rangle}$$

- Bino self-interaction cross-section **usually too low** (predicted density too high). Need mechanism to increase it.



(Or other diagrams requiring low-mass sparticles, for example stau co-annihilation)



- Wino-Higgsino self-interaction cross-section **usually too high**.

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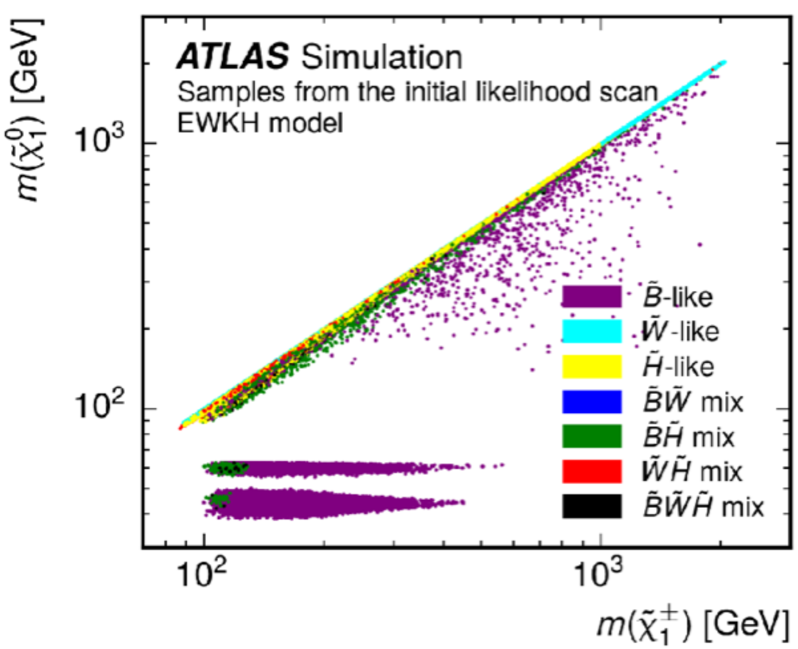
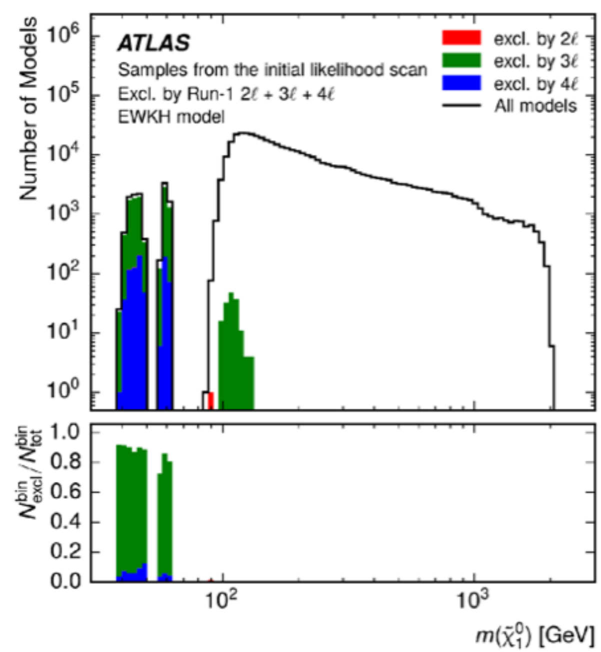
Dark matter connection

- Scan a **5-parameter pMSSM** (EWKH, scanning M_1, M_2, μ, tanβ, M_A)
- Apply **EW constraints** and **relic density abundance as upper limit**
- Finally evaluate the impact of **ATLAS EW run 1 electroweak analyses**
- Very important **impact on the h- and Z-funnel** regions
- **Hardly scratching** the rest of the parameter space…





Long-lived gluinos

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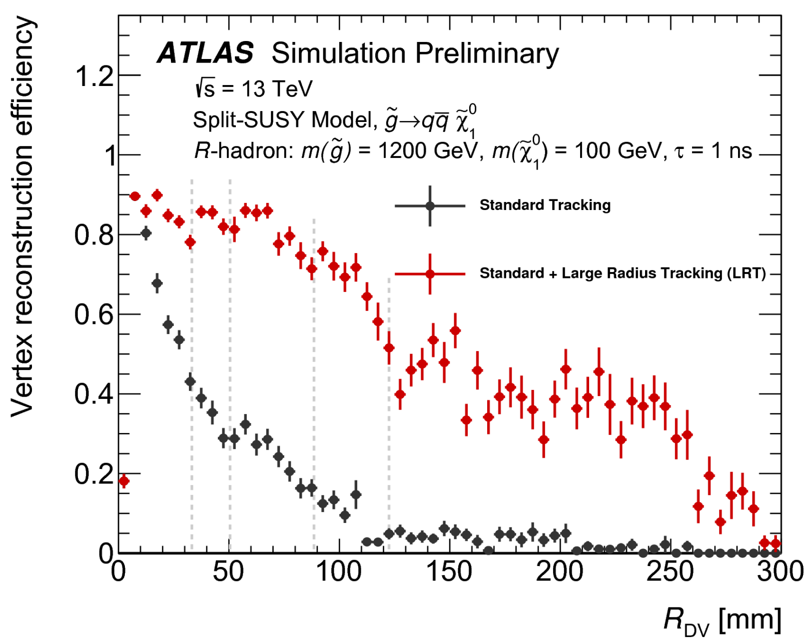
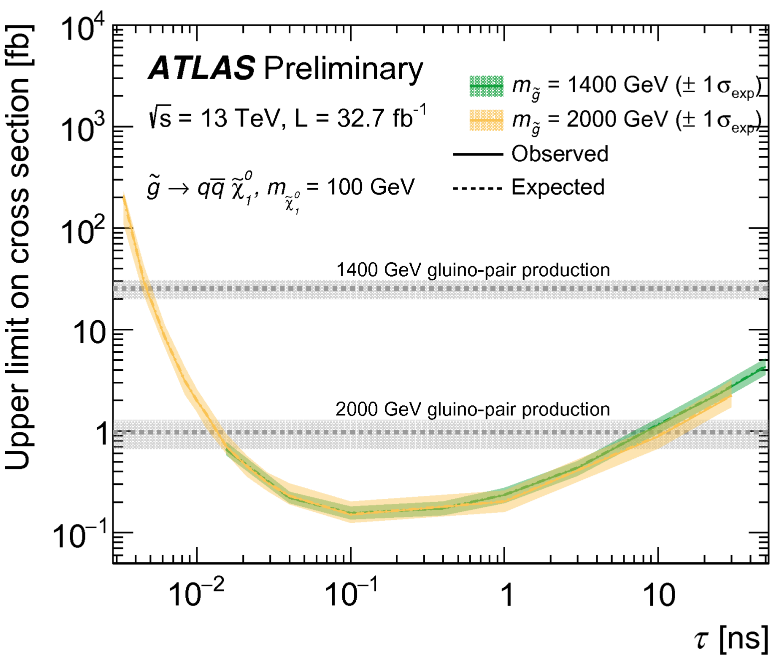
ATLAS-CONF-2017-026

- Squark-mediated gluino decay: gluino lifetime **becomes measurable** if the squark mass is large (e.g., split SUSY).
  - Long-lived SUSY particles can yield a **high-mass displaced vertex** (DV).
- Current search: DV + E_T^{miss} (RPC decay of the gluino).
- Dedicated **large radius tracking** improves tracking efficiency in the sensitive region.





EW-scale supersymmetry

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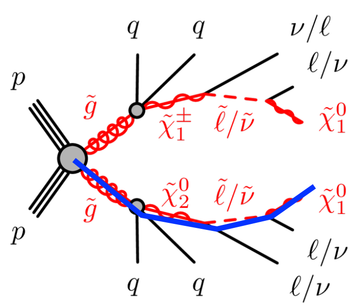
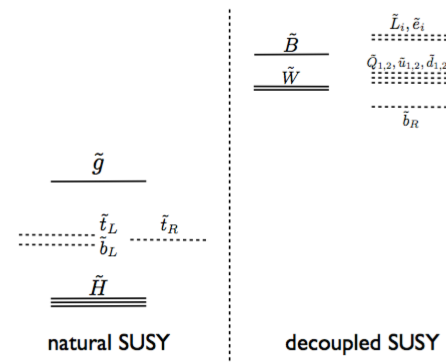
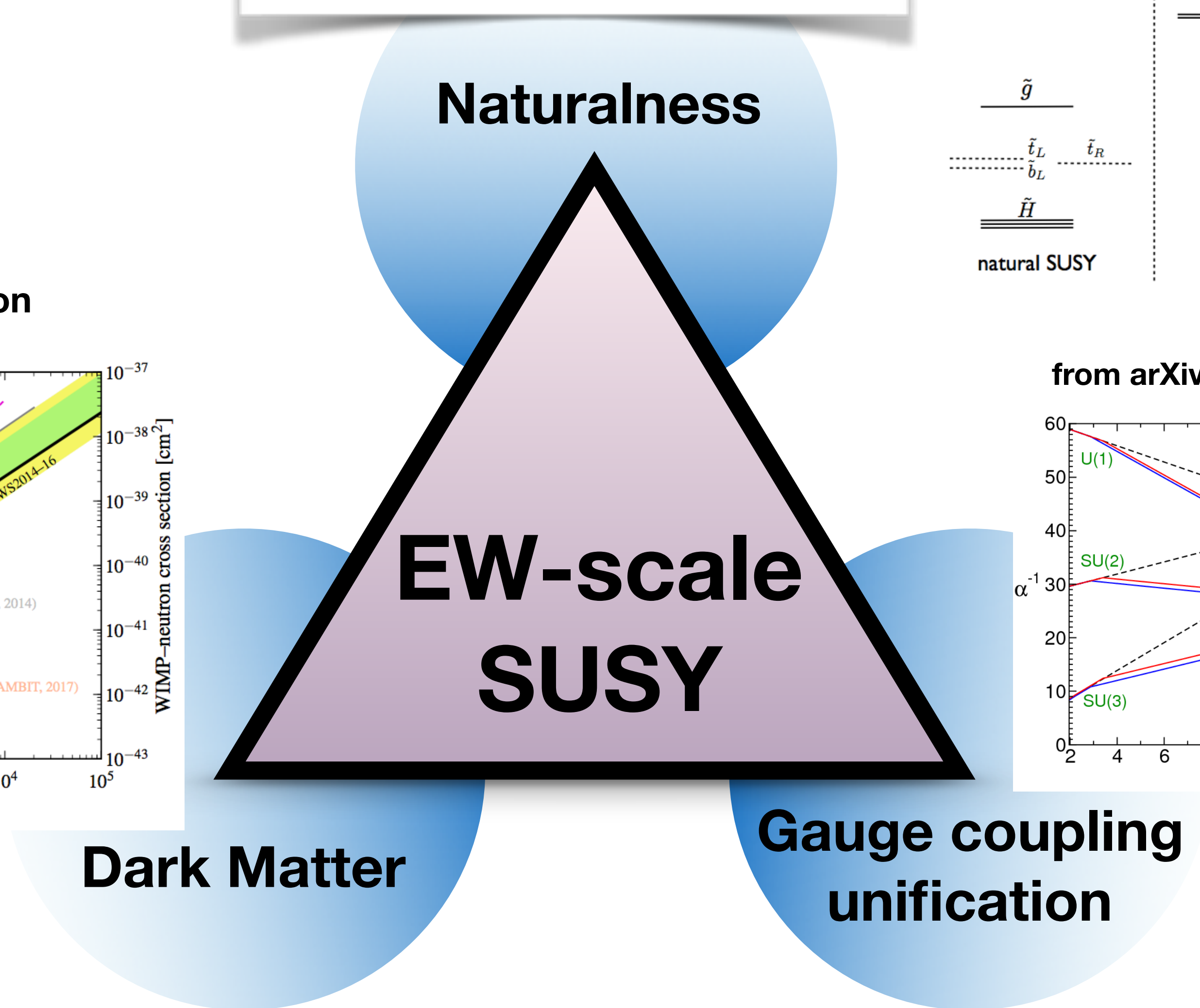
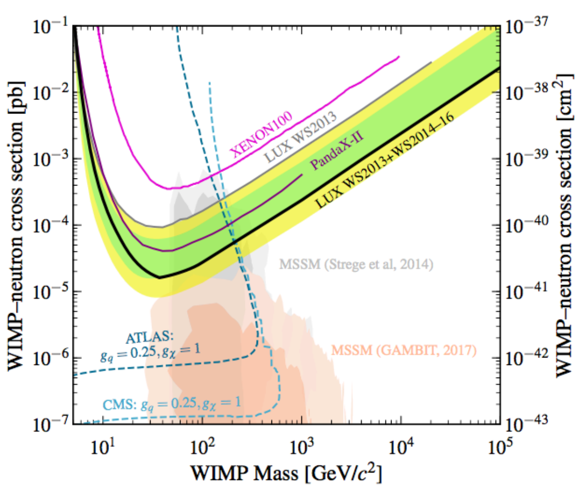
$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3y_t^2 m_t^2}{4\pi^2}\left[\log\left(\frac{m_S^2}{m_t^2}\right) + X_t^2\left(1 - \frac{X_t^2}{12}\right)\right] + \cdots$$



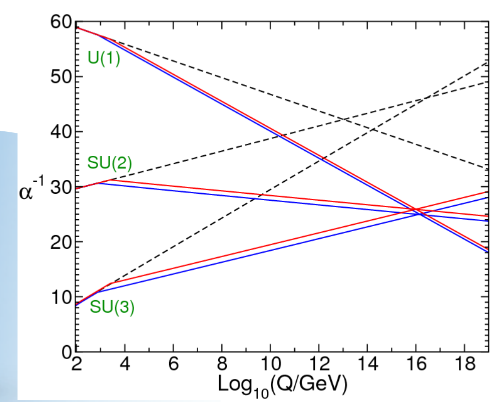
R-parity conservation







from arXiv:hep-ph/9709356



Sbottom pair production

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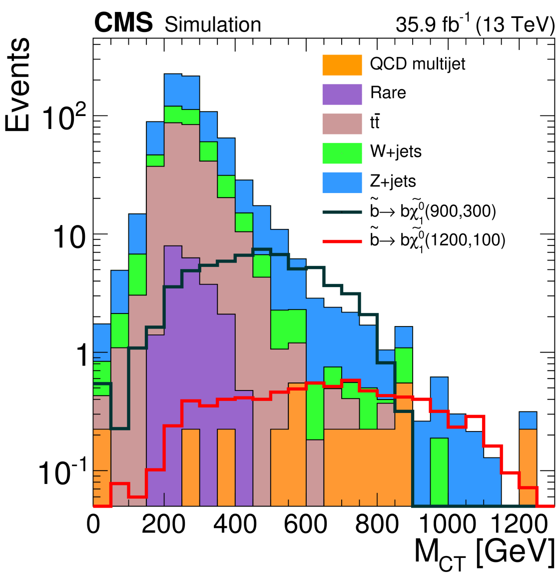
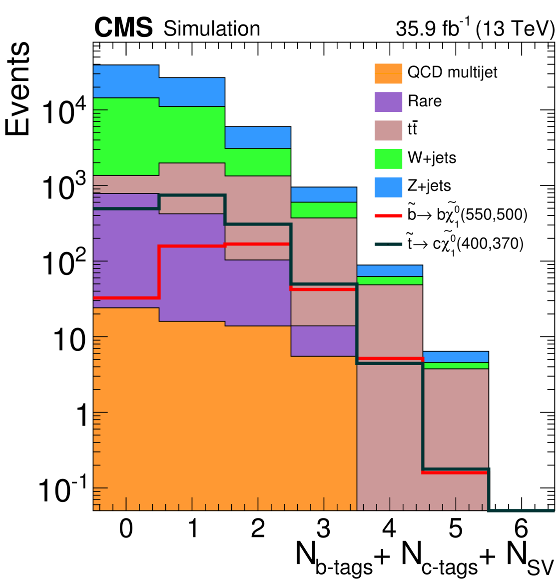
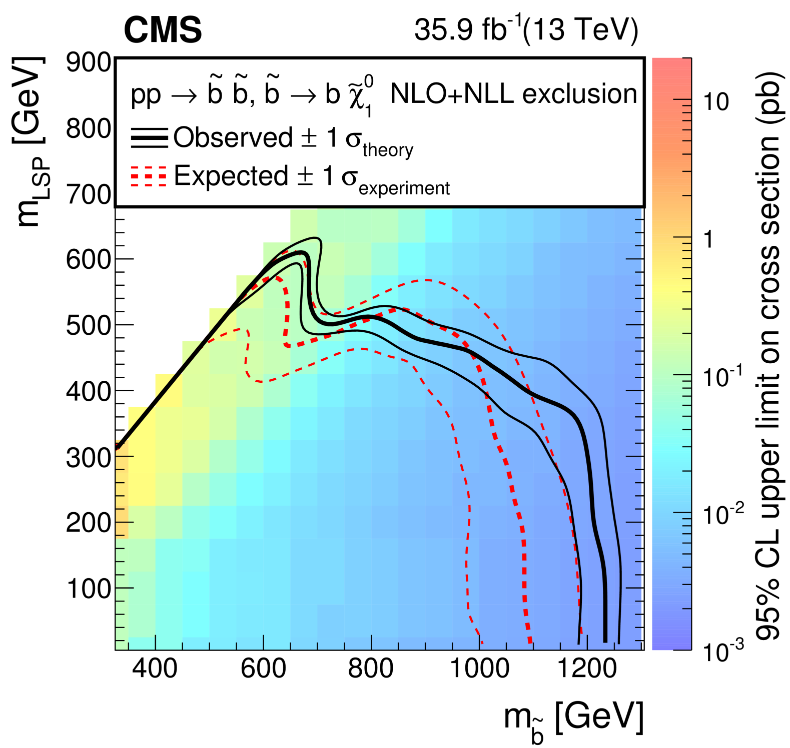
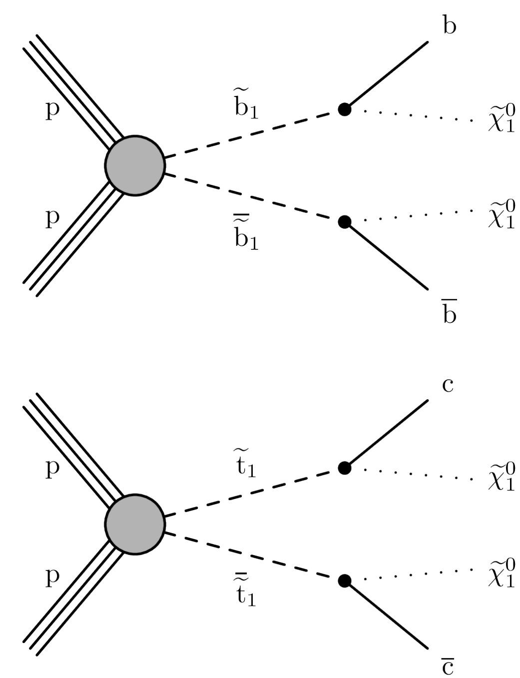




- Common SUSY-breaking mass parameter with stop_L imposes **indirect constraints** on sbottom mass
  - See SUS-2016-32 and ATLAS-CONF-2017-038.
- M_{CT}: contransverse mass, a transverse mass type variable. It shows a kinematical end-point for top pair production.

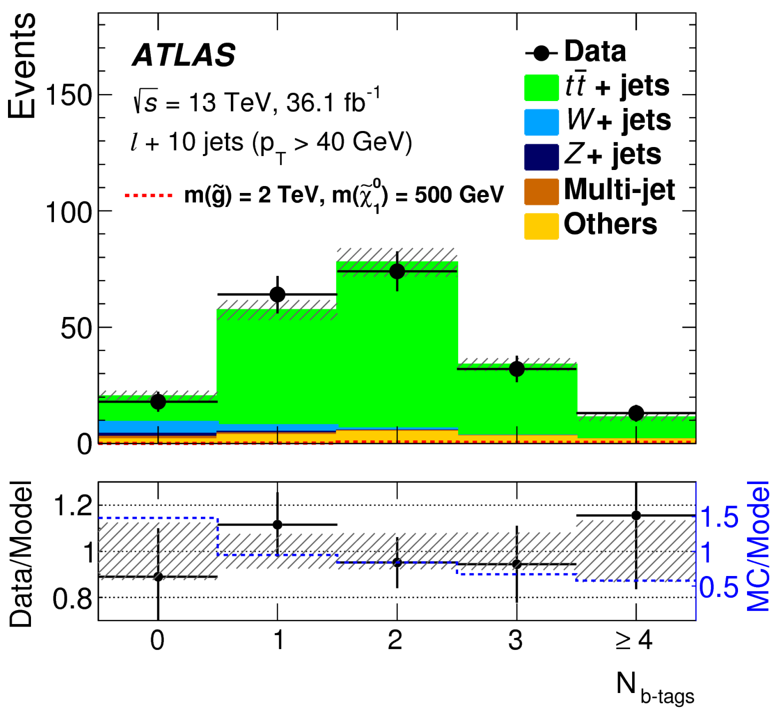


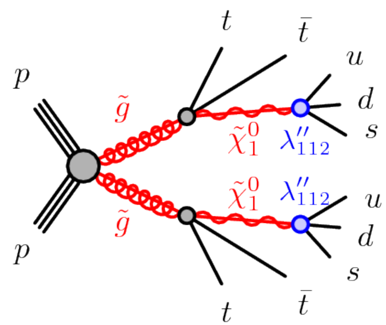


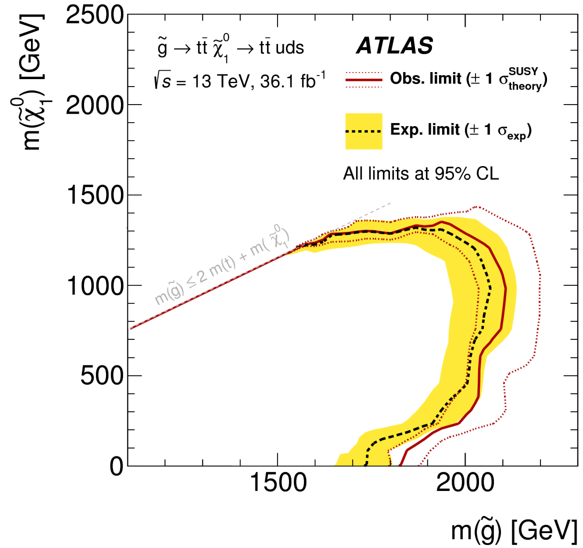
R-parity violating scenarios

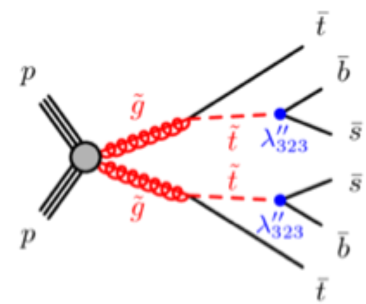
arXiv:1704.08493

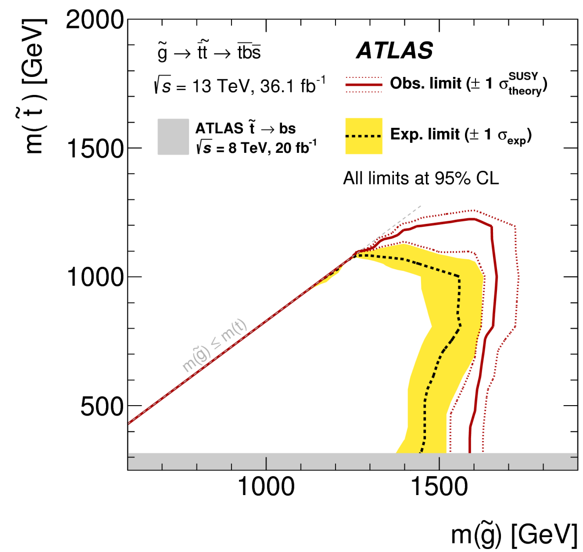
- Final states **with up to 12 jets** and a lepton
- Bin the phase space in **jet and b-jet multiplicity:**
  - (nearly) **fully data-driven** background estimate, with ttbar **scaling in jets multiplicity and number of b-tagged jets.**







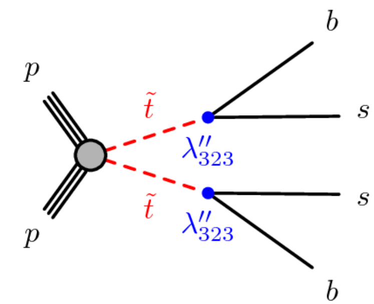


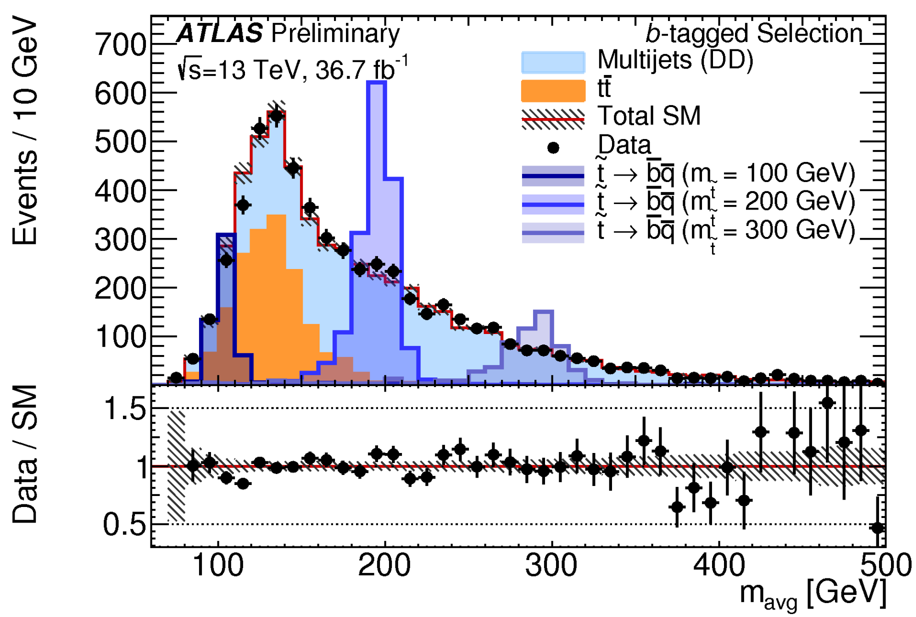


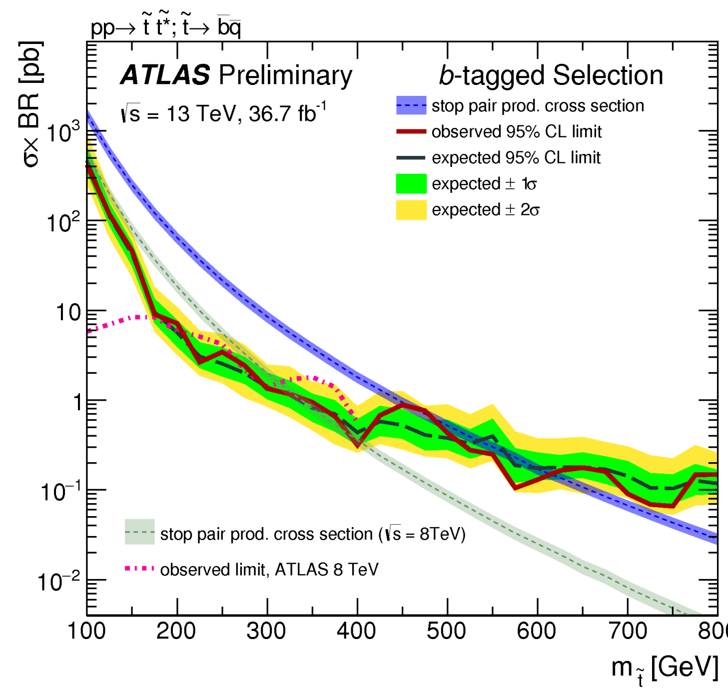
R-parity violating scenarios

ATLAS-CONF-2017-025

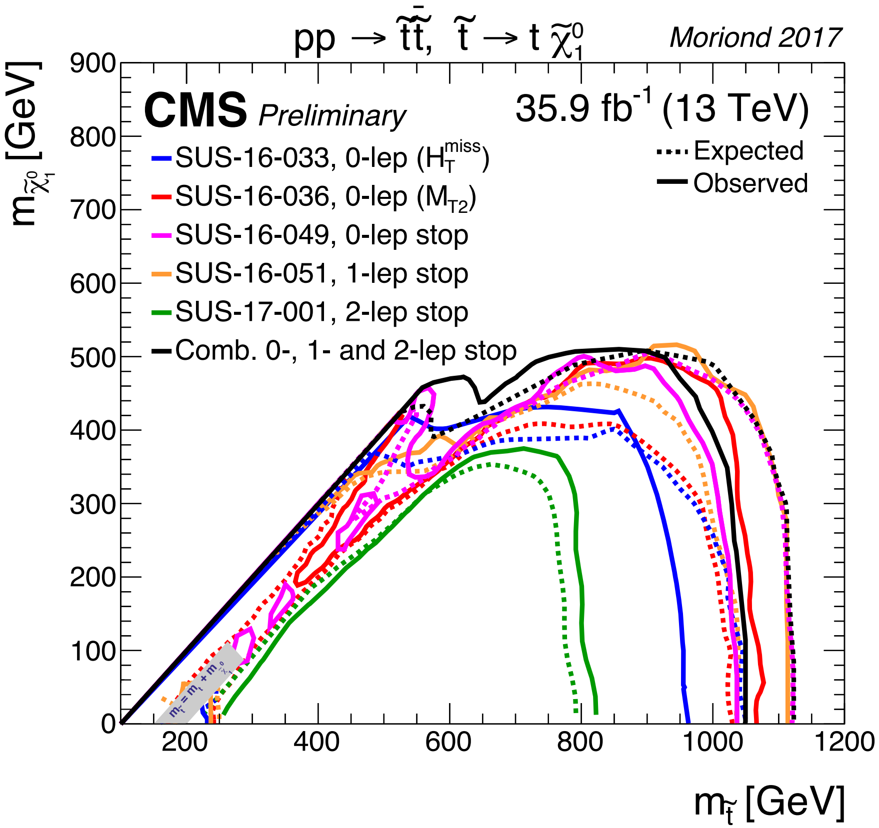
- Stop with **RPV decays**: look for **2x2 jet resonances:**
  - **Two-jet resonances with compatible mass**
  - **Signal regions no b-tags and two b-tags**
- Stops excluded **up to 600 GeV.**

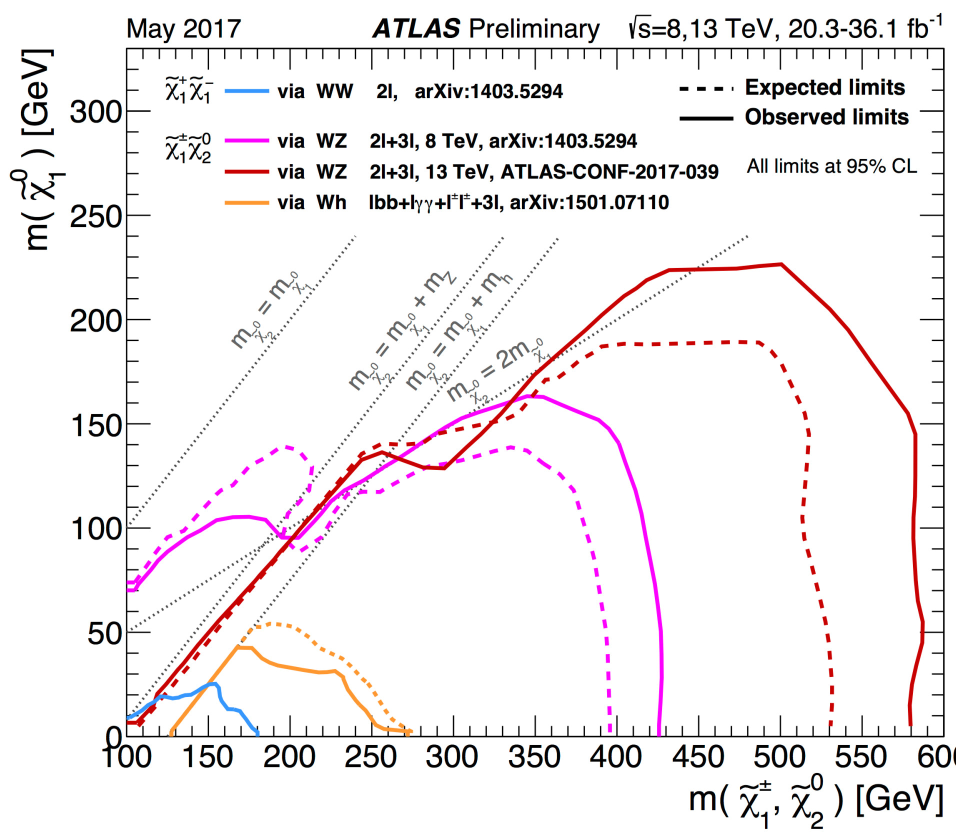






Summary plots





"Natural" SUSY under test

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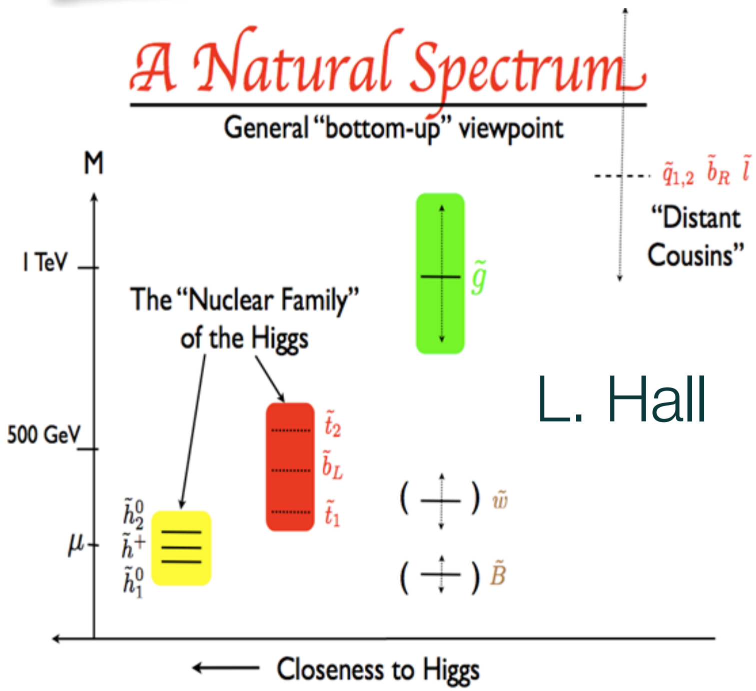
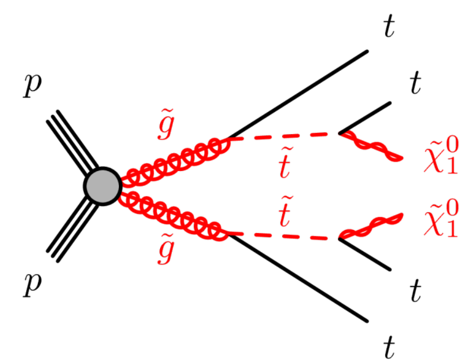
- The **Higgs boson mass** in the MSSM is determined (at 1-loop) by **EW parameters** and by the **stop masses and mixing.**

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3y_t^2 m_t^2}{4\pi^2}\left[\log\left(\frac{m_S^2}{m_t^2}\right) + X_t^2\left(1 - \frac{X_t^2}{12}\right)\right] + \cdots$$



L. Hall



Final state involving **up to 12 jets, up to 4 b-jets, SS leptons**

- Lot of work on understanding the y-scale: stop masses of **few TeV** may **well be natural** (see, for example, H. Baer et al.)