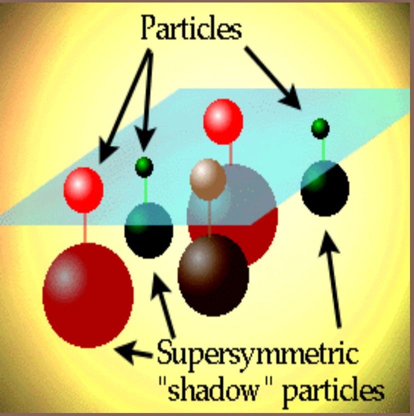
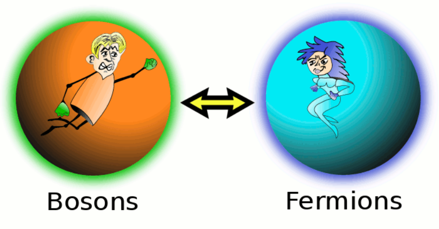
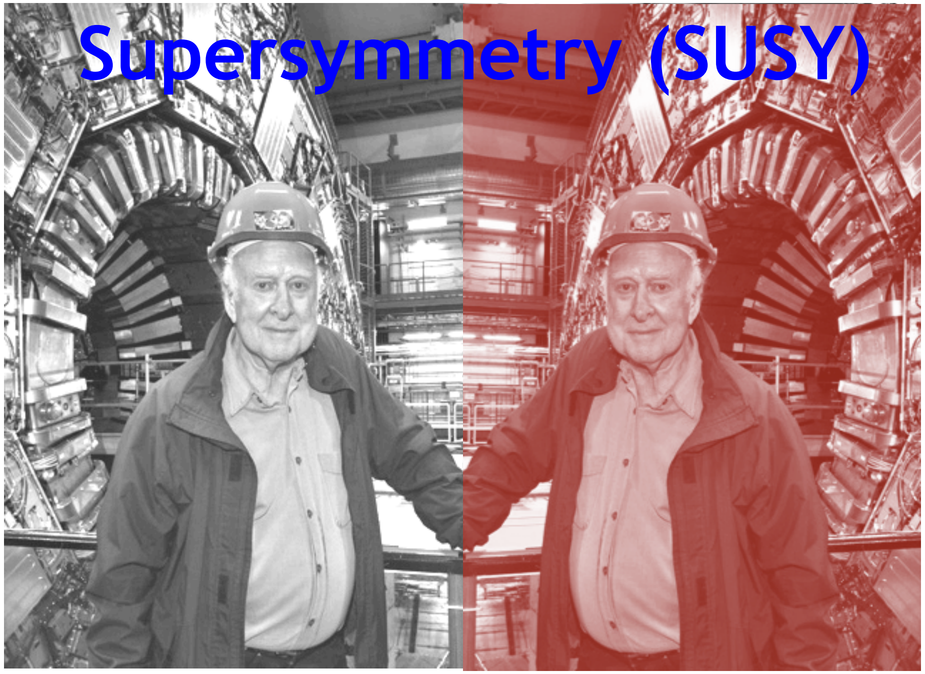




Supersymmetry (SUSY)



BSM SEARCHES — SUSY

Xuai Zhuang (庄胥爱)
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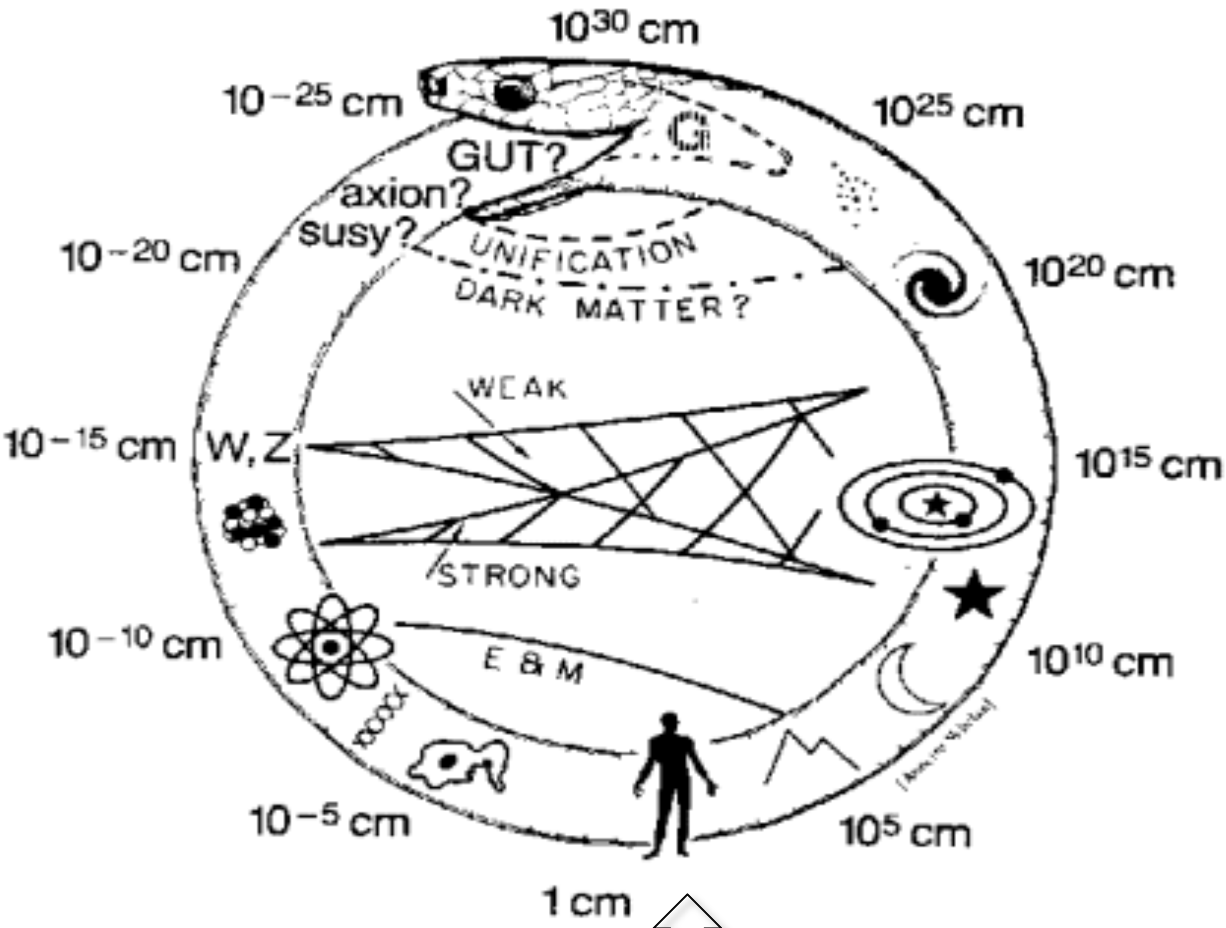
IHEP, Beijing, China

Jul. 10-20 iSTEP2016

中國科學院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Everyday life (and particle physics) are described by the Standard Model

希腊神话中的怪物“Uroboros”与格拉肖的“宇宙圈”



引力和电磁力占主导地位

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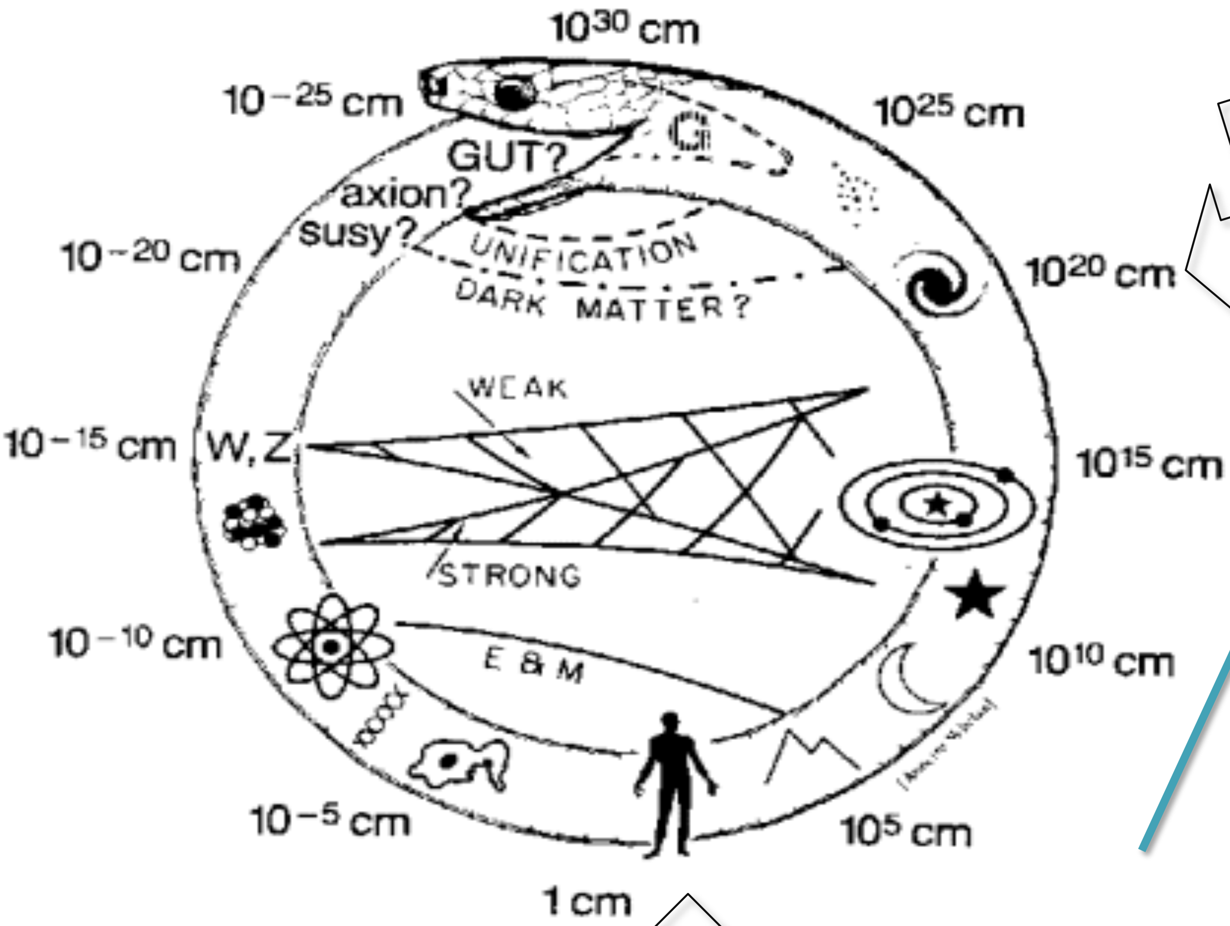

引力主导，
爱因斯坦
的广义相
对论

引力和电磁力占主导地位

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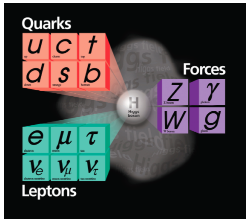
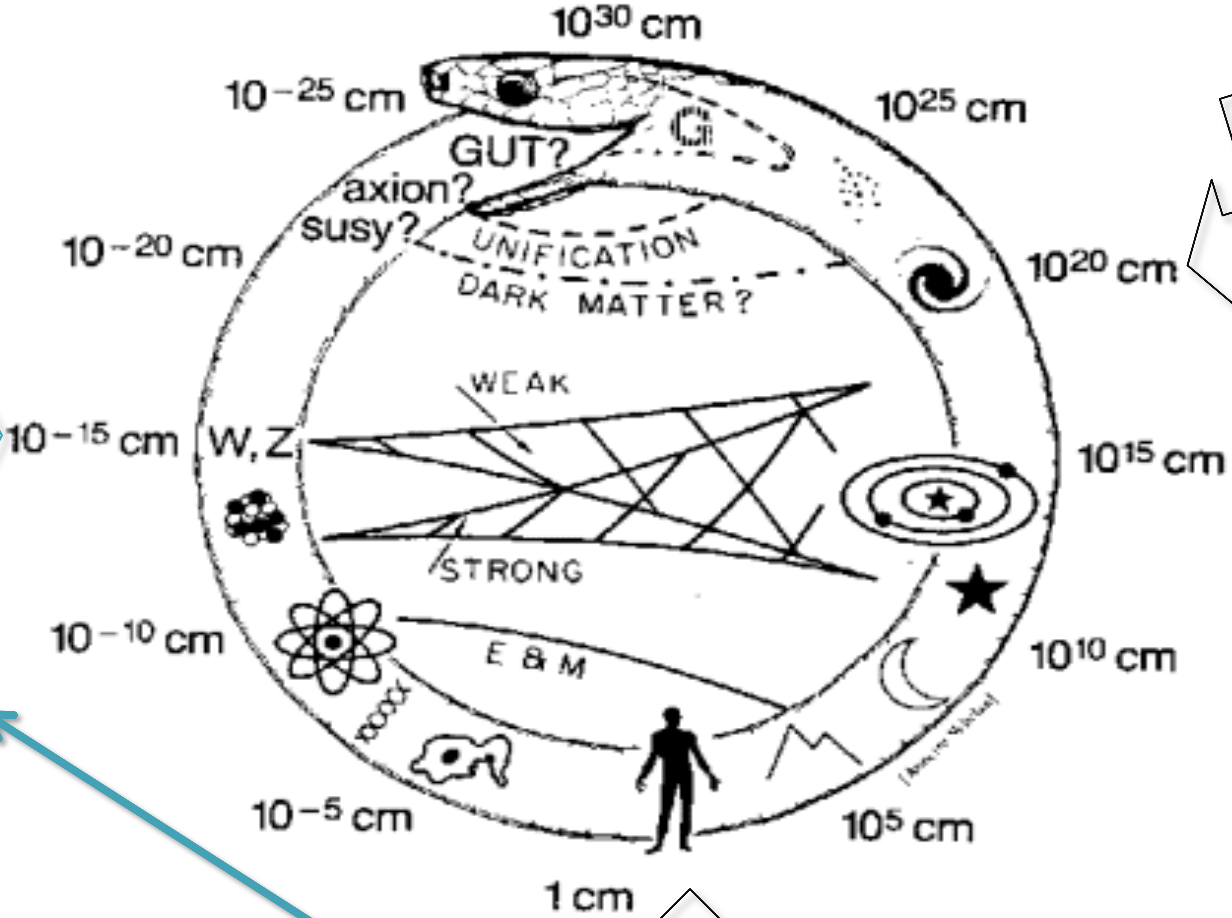
粒子“微观世界”，**强弱相互作用**主导，理论模型是**标准模型**





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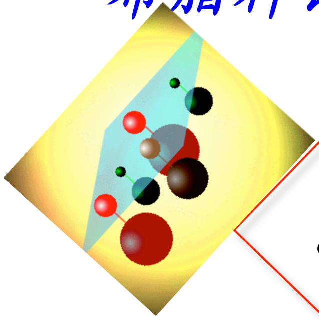
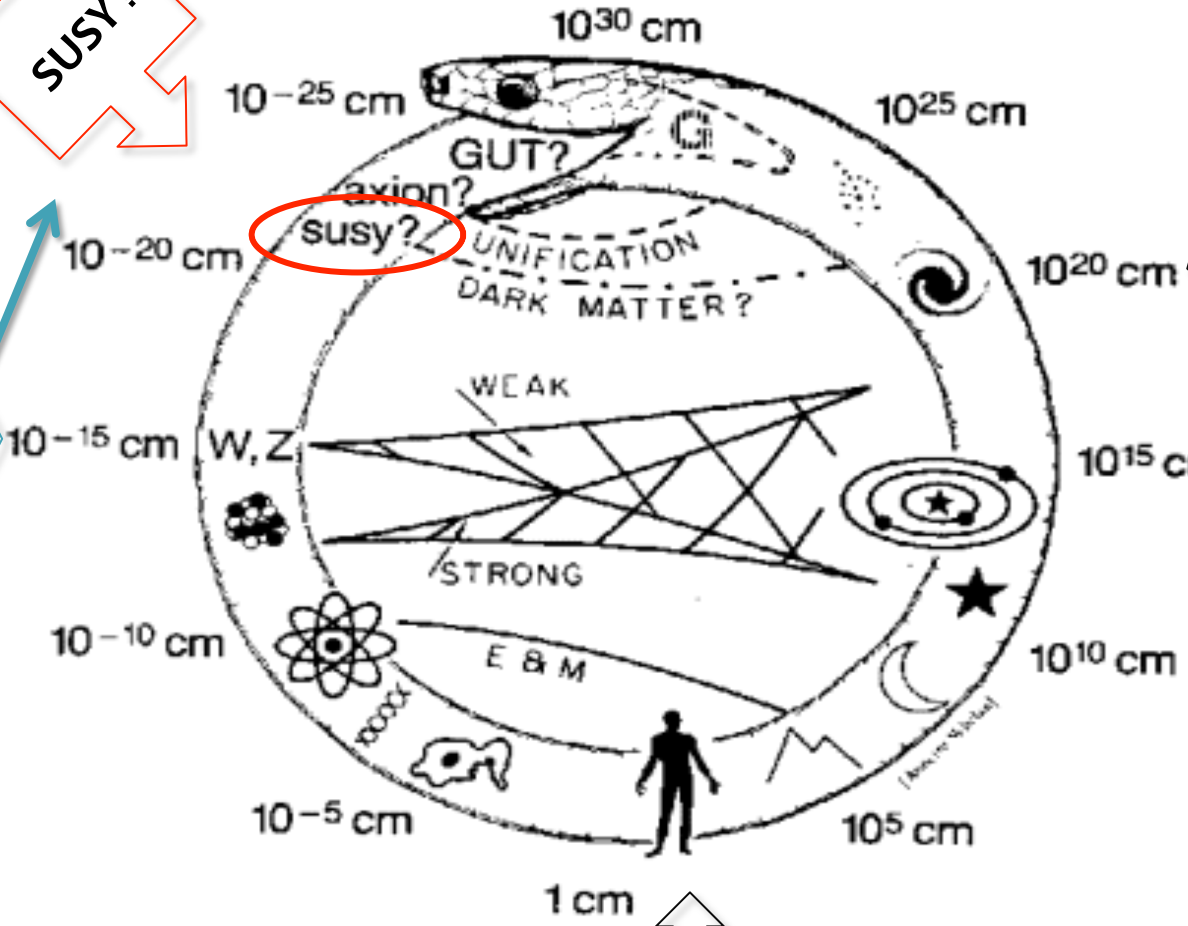


SUSY?



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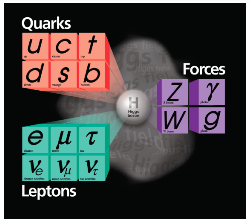

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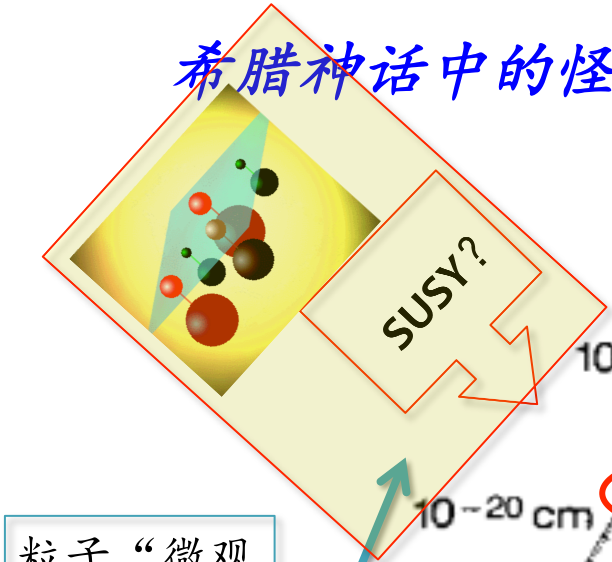

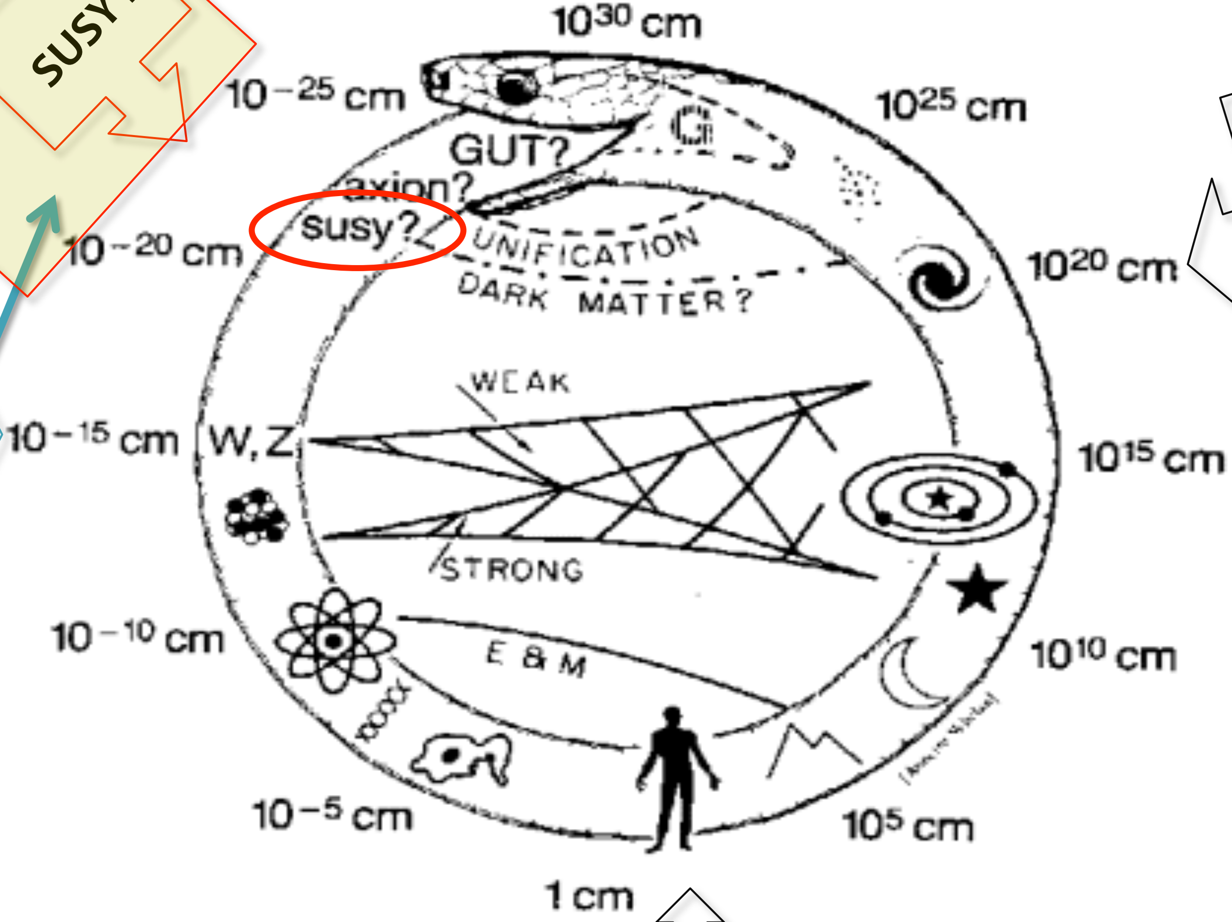

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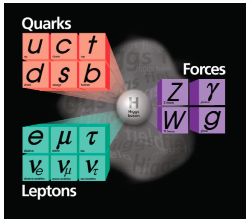

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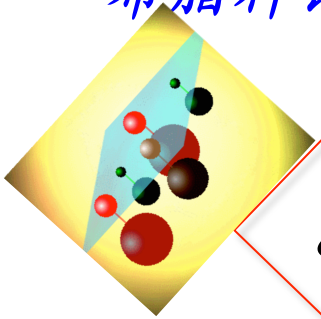

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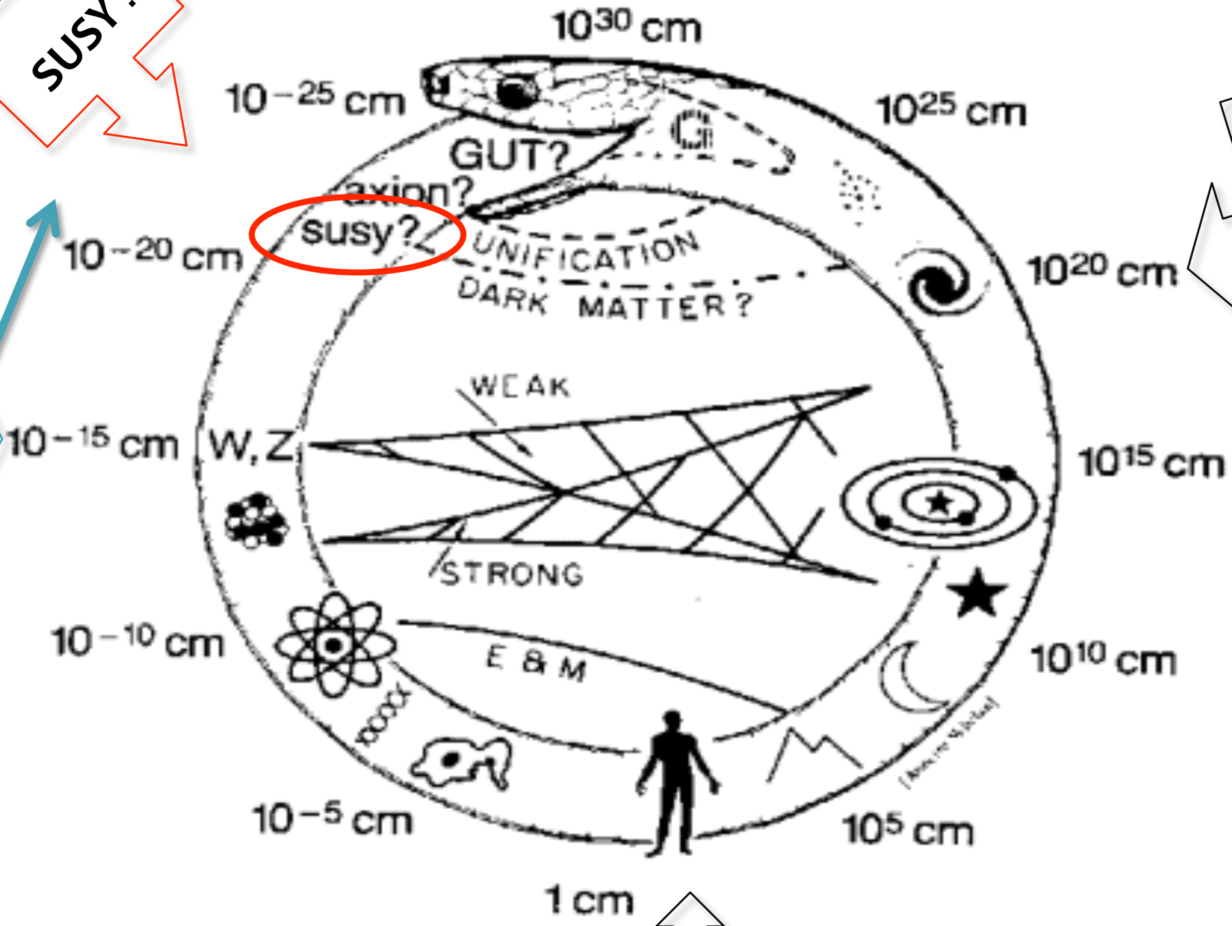

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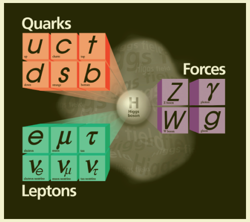

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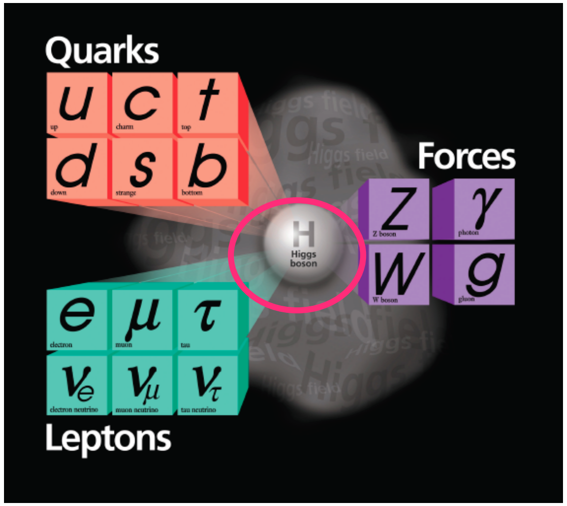
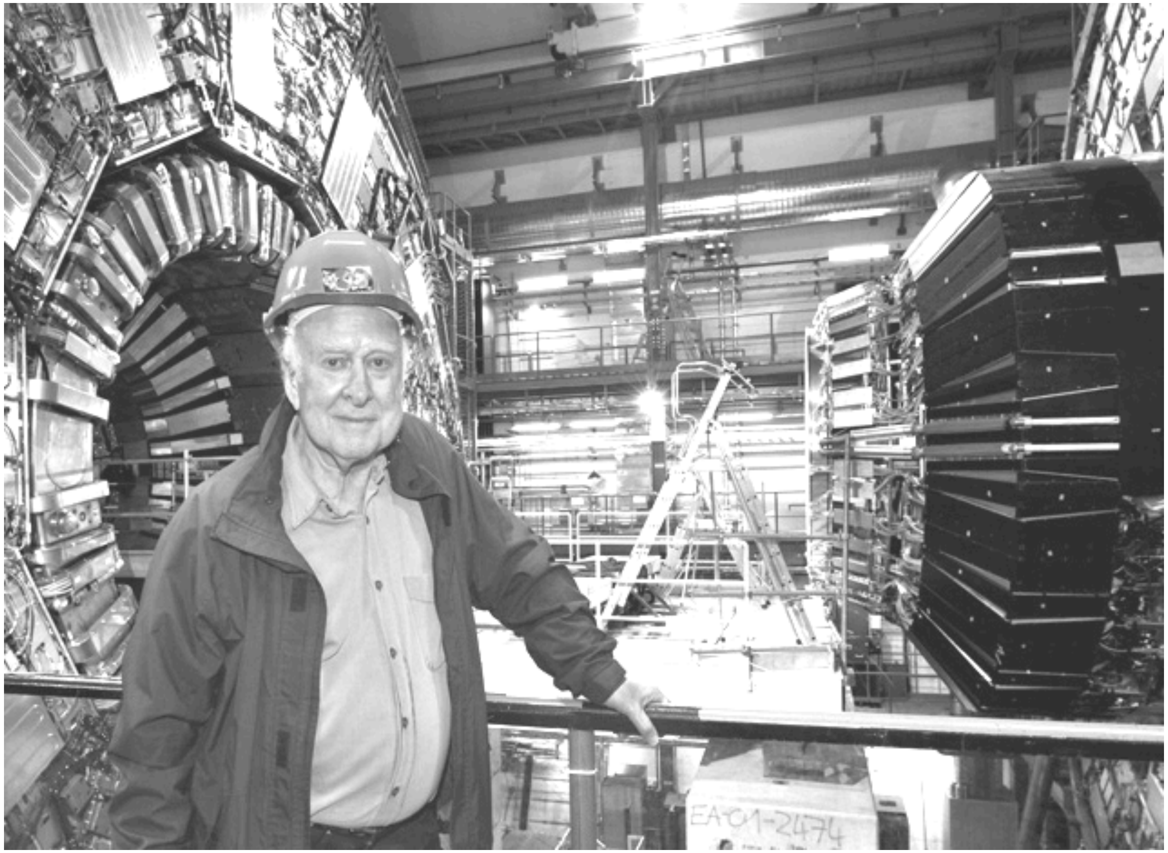


- Higgs boson observed, SM is complete. SM fits the experimental data very well
  ➔ big success in EW scale

The Nobel Prize in Physics 2013

François Englert, Peter Higgs

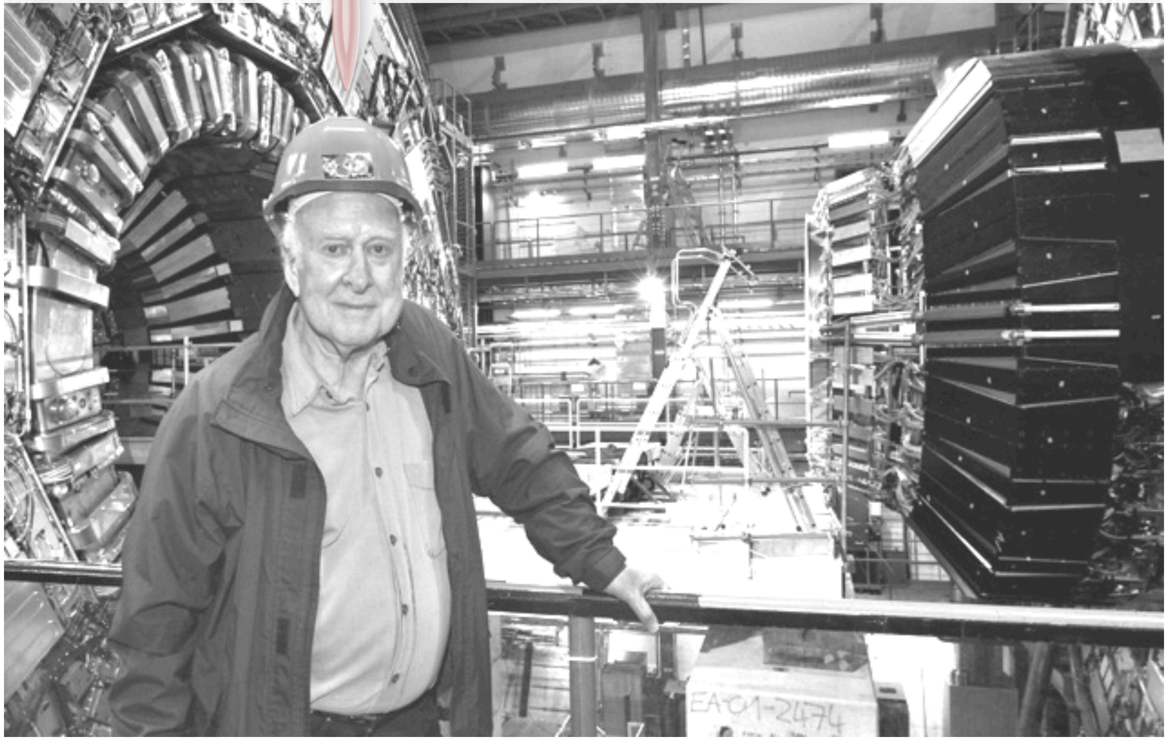

P. Higgs at CMS

Unfortunately, there is a problem with the Higgs!

P. Higgs at CMS

- **While has problem in Planck scale:**
  - Naturalness and “hierarchy” problem
  - Unification of gauge coupling
  - Dark Matter
  - ……

Unfortunately, there is a problem with the Higgs!

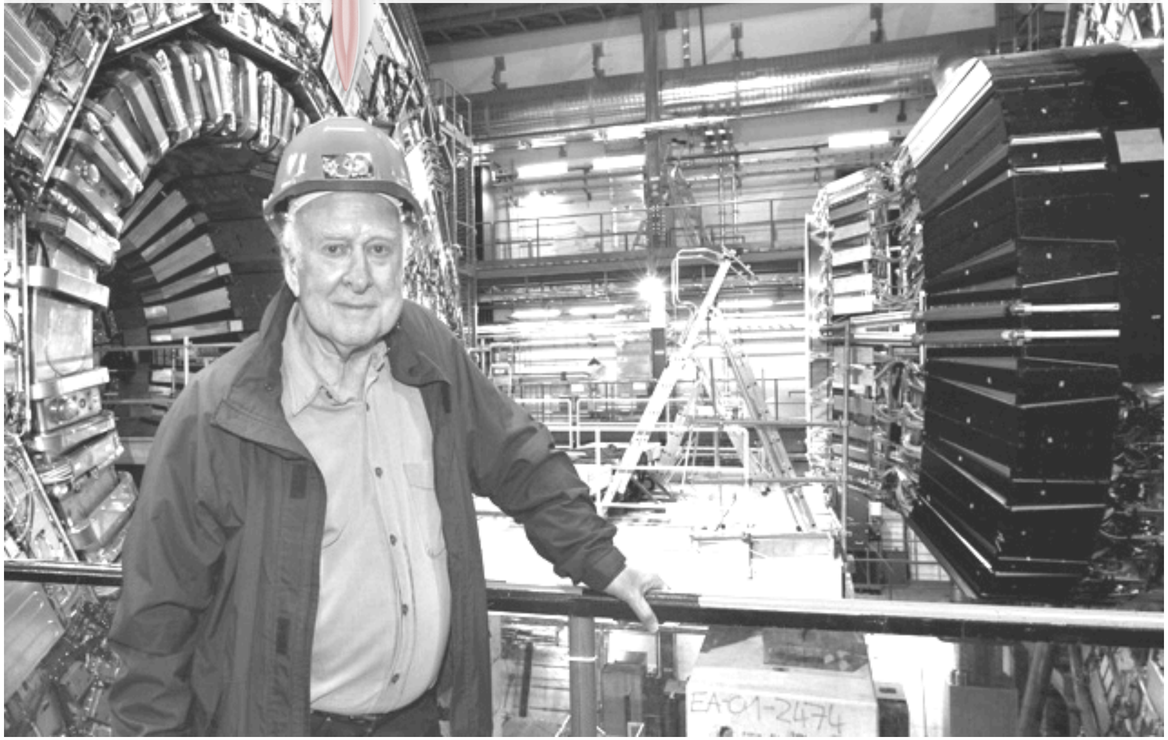


P. Higgs at CMS

- Need a more fundamental theory of which SM is only a low-energy approximation ➔ **New Physics**

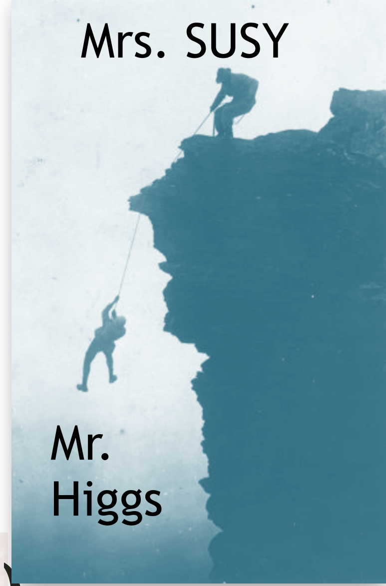
- **While has problem in Planck scale:**
  - Naturalness and “hierarchy” problem
  - Unification of gauge coupling
  - Dark Matter
  - ……

Unfortunately, there is a problem with the Higgs!

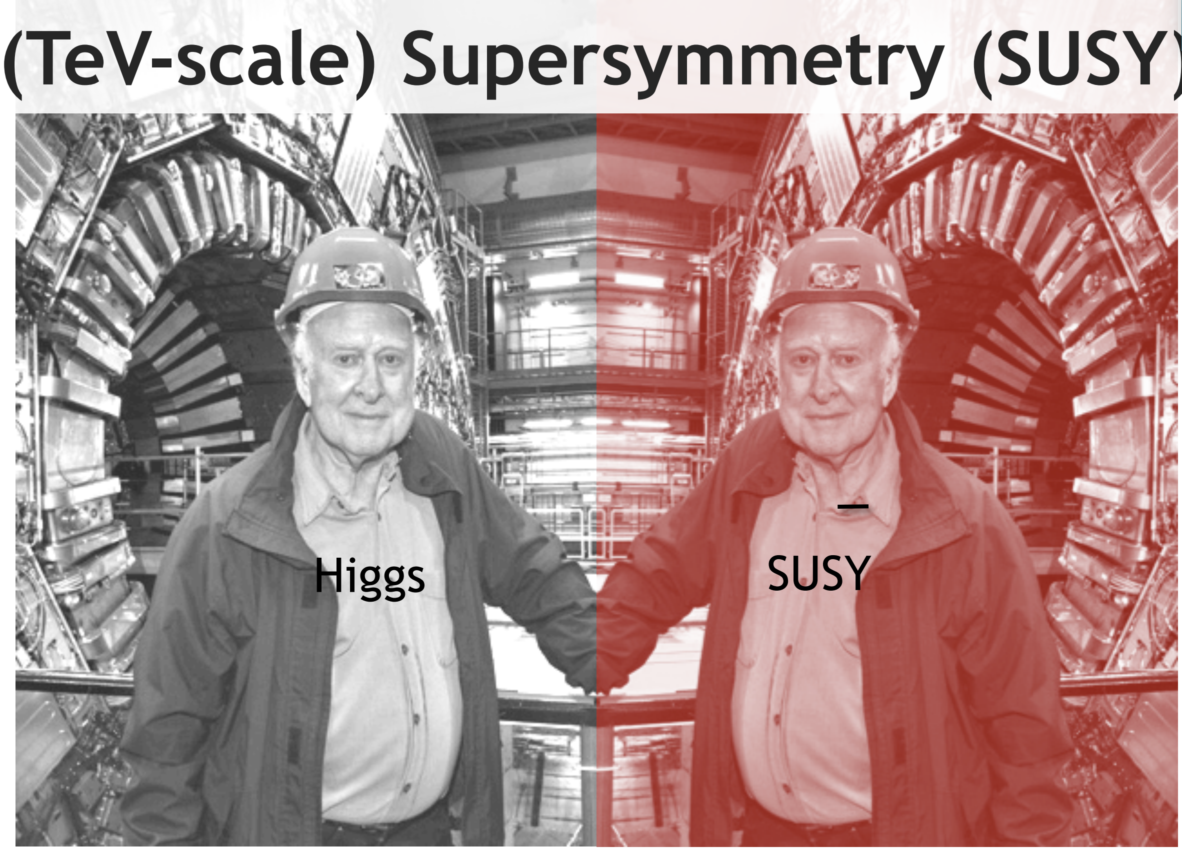


P. Higgs at CMS

SUSY can do help ?

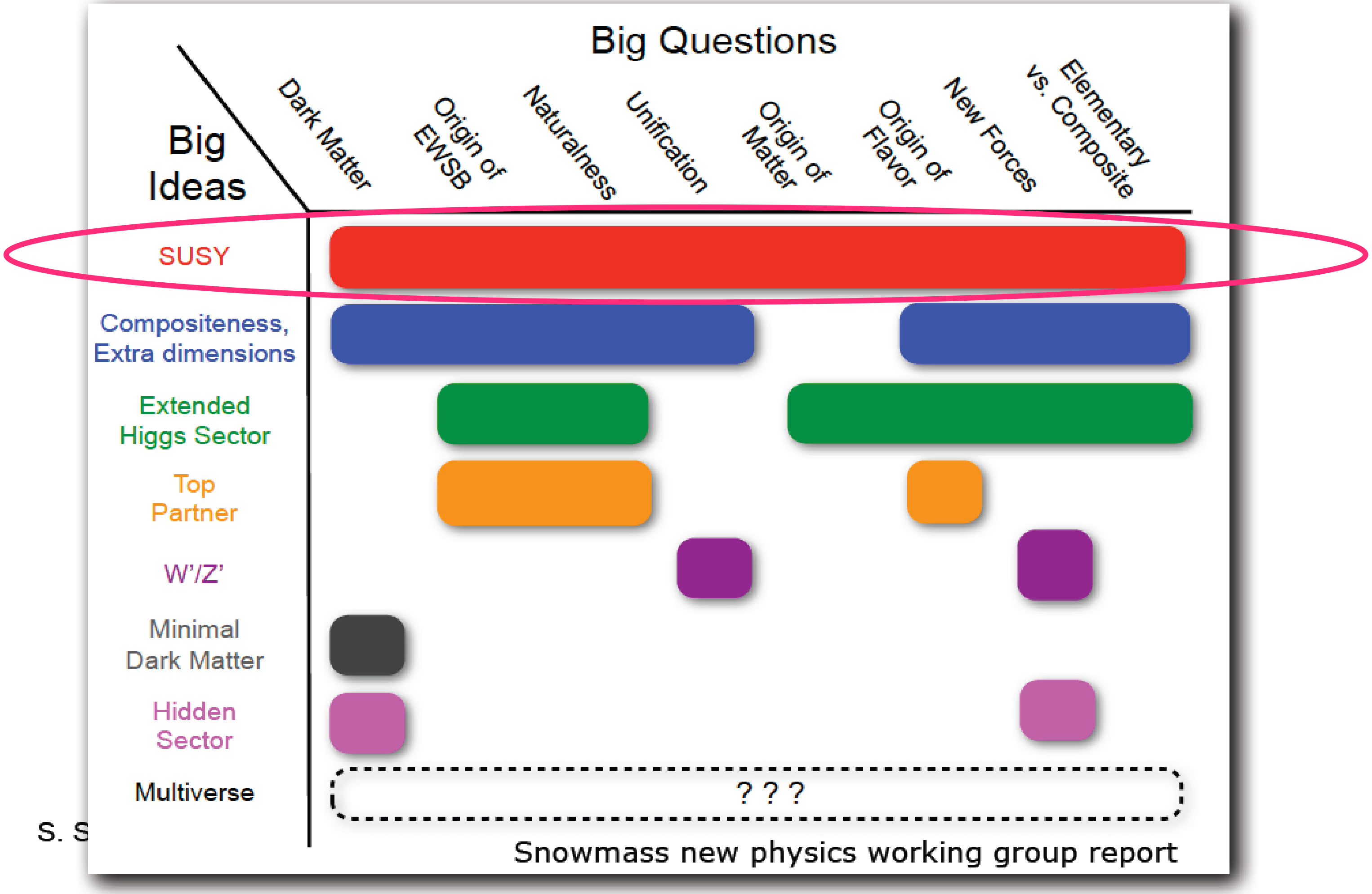


(TeV-scale) Supersymmetry (SUSY)



P. Higgs at CMS

New Physics beyond the SM



Snowmass new physics working group report

→ Higgs 发现后，寻找超对称粒子将是LHC实验下一个最主要的物理目标 ！

Outline

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- The LHC and ATLAS
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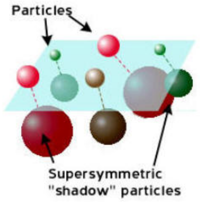
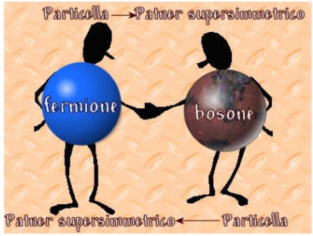
- Outlook and Summary





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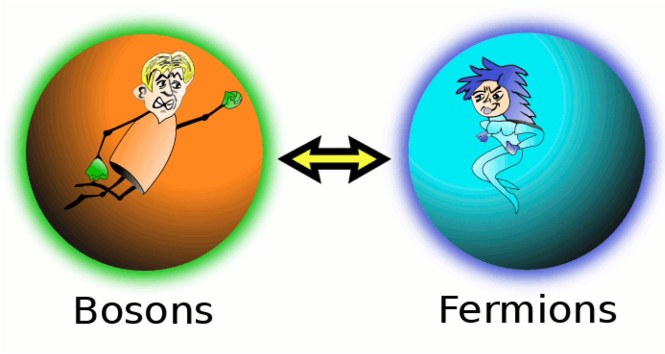
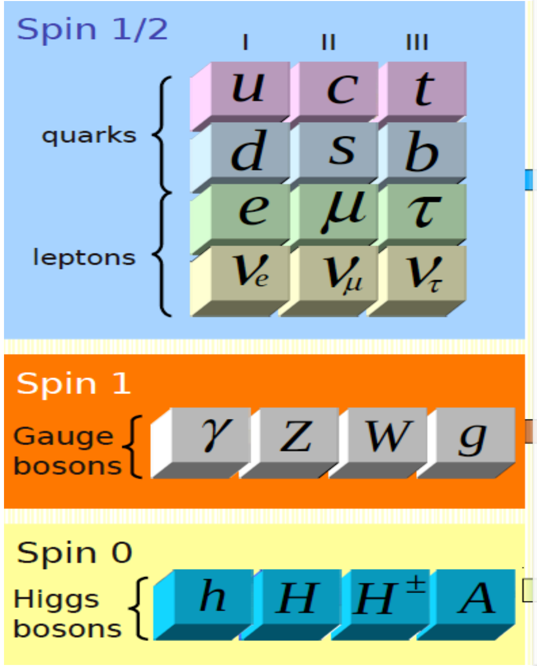
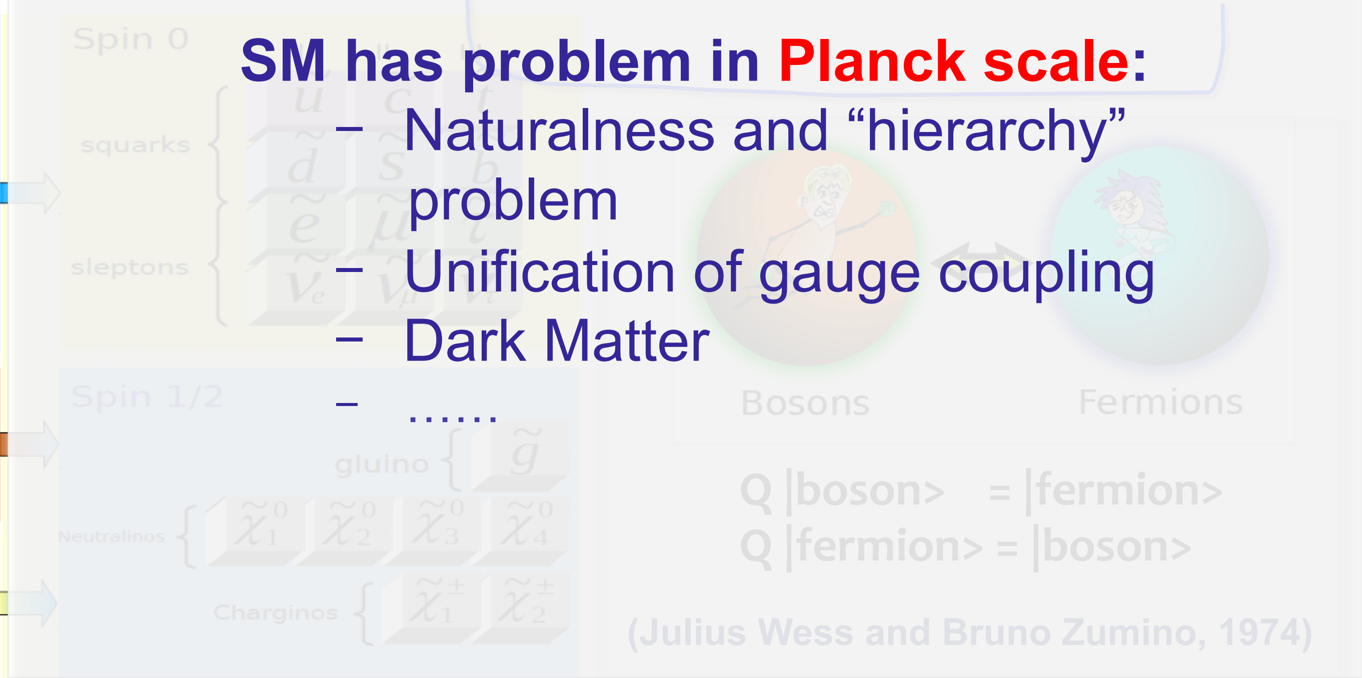


SUSY Introduction - SM

OUR WORLD…



NEW WORLD?



SM has problem in Planck scale:

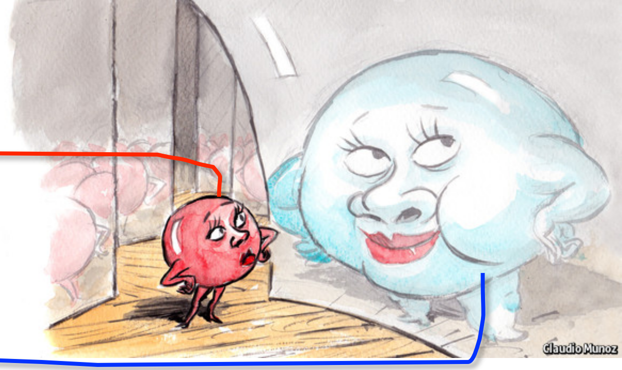
- Naturalness and "hierarchy" problem
- Unification of gauge coupling
- Dark Matter
- ……

Q |boson> = |fermion>
Q |fermion> = |boson>

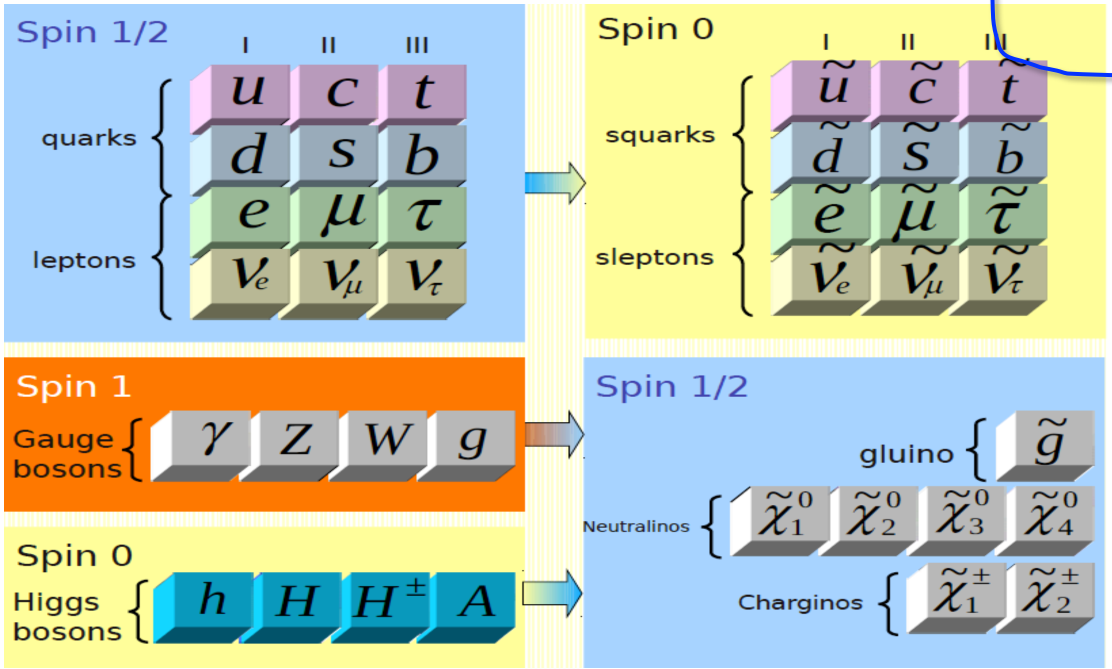
(Julius Wess and Bruno Zumino, 1974)

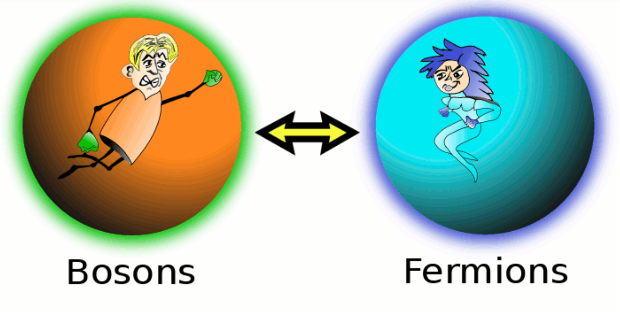
- **A symmetry which unified fermions (mater) and bosons (forces)**
  - Each particle has a super-partner
  - Number of elementary particles doubled
  - Spin differs by ½ between SUSY and SM particles
  - Identical gauge numbers and couplings
- **A more fundamental theory: compatible with SM in EW scale, solve most problems in Planck scale**

SUSY Introduction



OUR WORLD… **NEW WORLD?**





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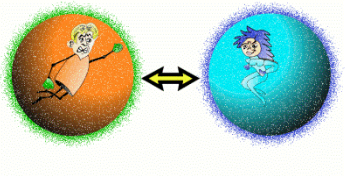
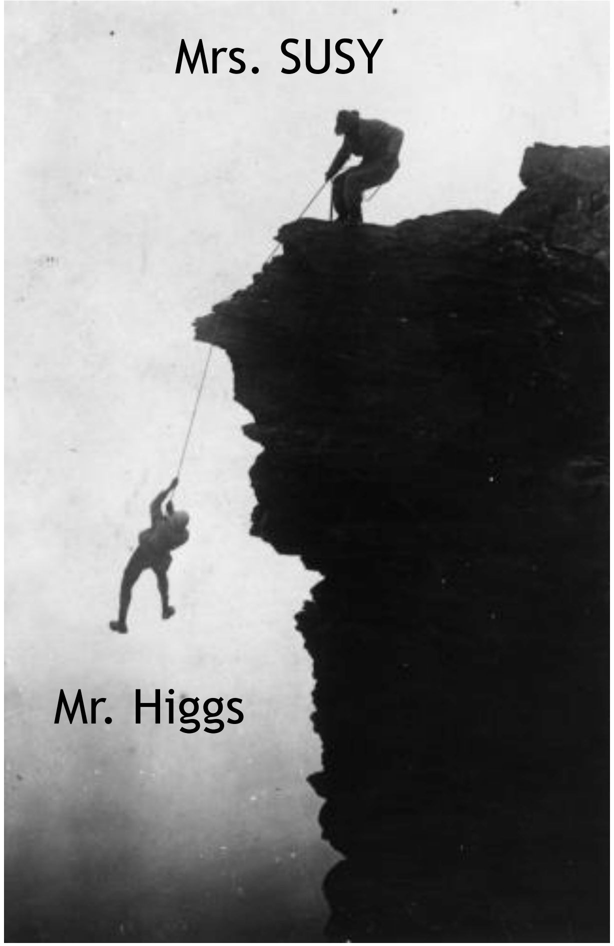
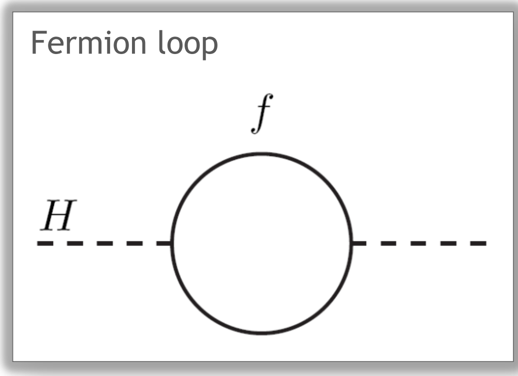
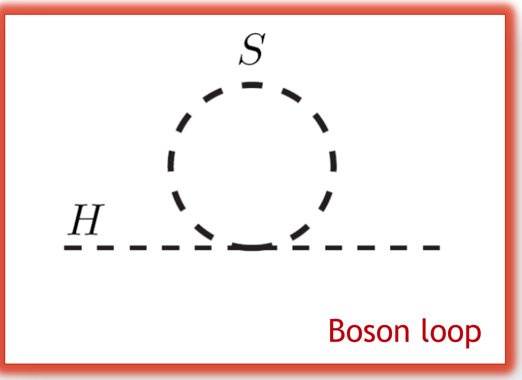
SUSY Introduction



- **Solve hierarchy problem** without "fine tuning"
  - Fermion and boson loops contribute with **different signs** to the Higgs radiative corrections
  - Supersymmetric partner contributions to Higgs mass **cancel** SM contributions





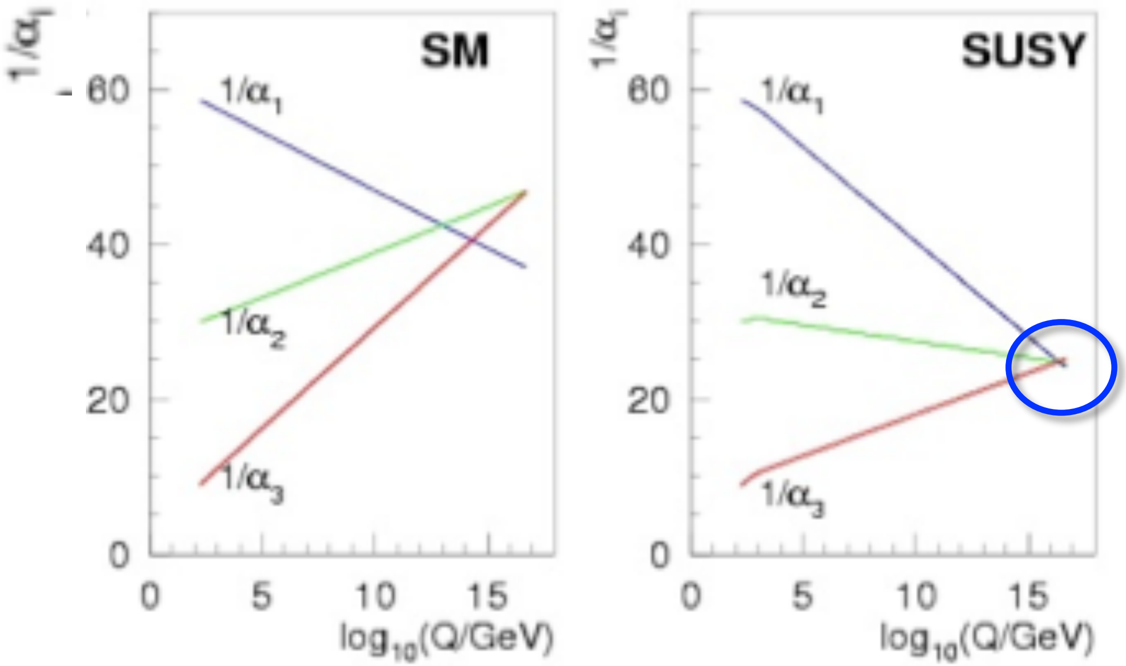


$$M_h^2 = M_{h,tree}^2 + \Delta M_h; \qquad SM : \Delta M_h \sim \Lambda^2; \qquad SUSY : \Delta M_h \sim m_{soft}^2 \log(\Lambda / m_{soft})$$

SUSY Introduction

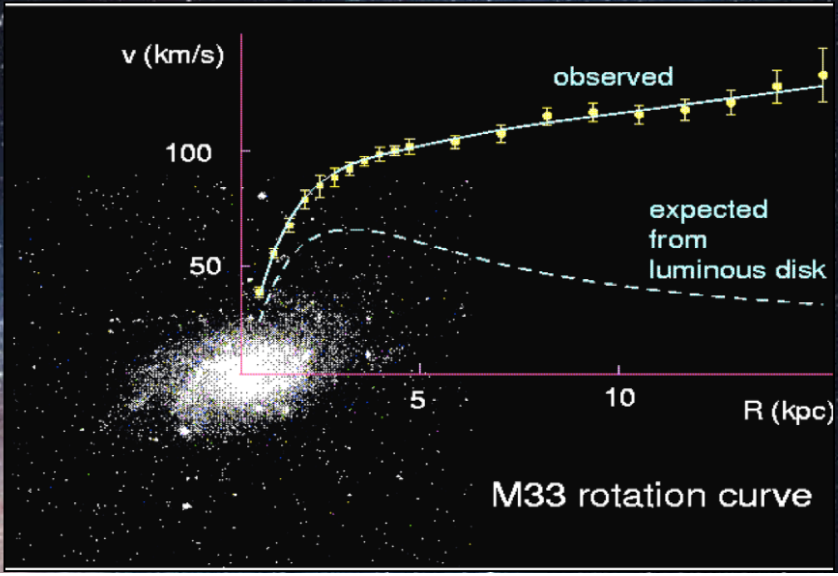
☐ **Unification of gauge couplings**

- New particle content changes running of couplings
- requires SUSY masses below few TeV



Provide Dark Matter candidate

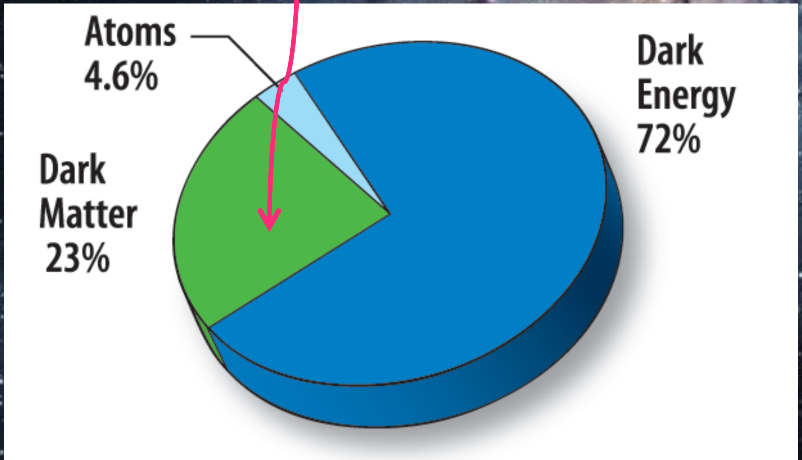
天文学家发现宇宙中很大一部分是我们看不见的 暗物质 （明物质只占4.6%）



- **Provide perfect dark mater candidate - WIMP**(lightest neutralino in R-parity conserving models)
    - ❑ stable
    - ❑ electrically neutron
    - ❑ same density as DM

$0.094 < \Omega_{CDM}h^2 < 0.136$ (95% CL)

‘Supersymmetric’ particles ?



→ 通过寻找SUSY，可以为暗物质寻找提供实验证据！

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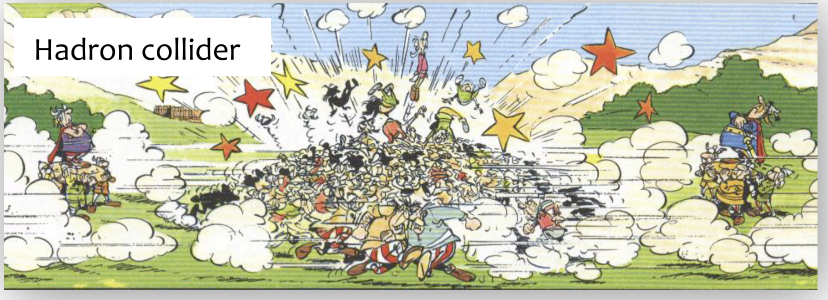
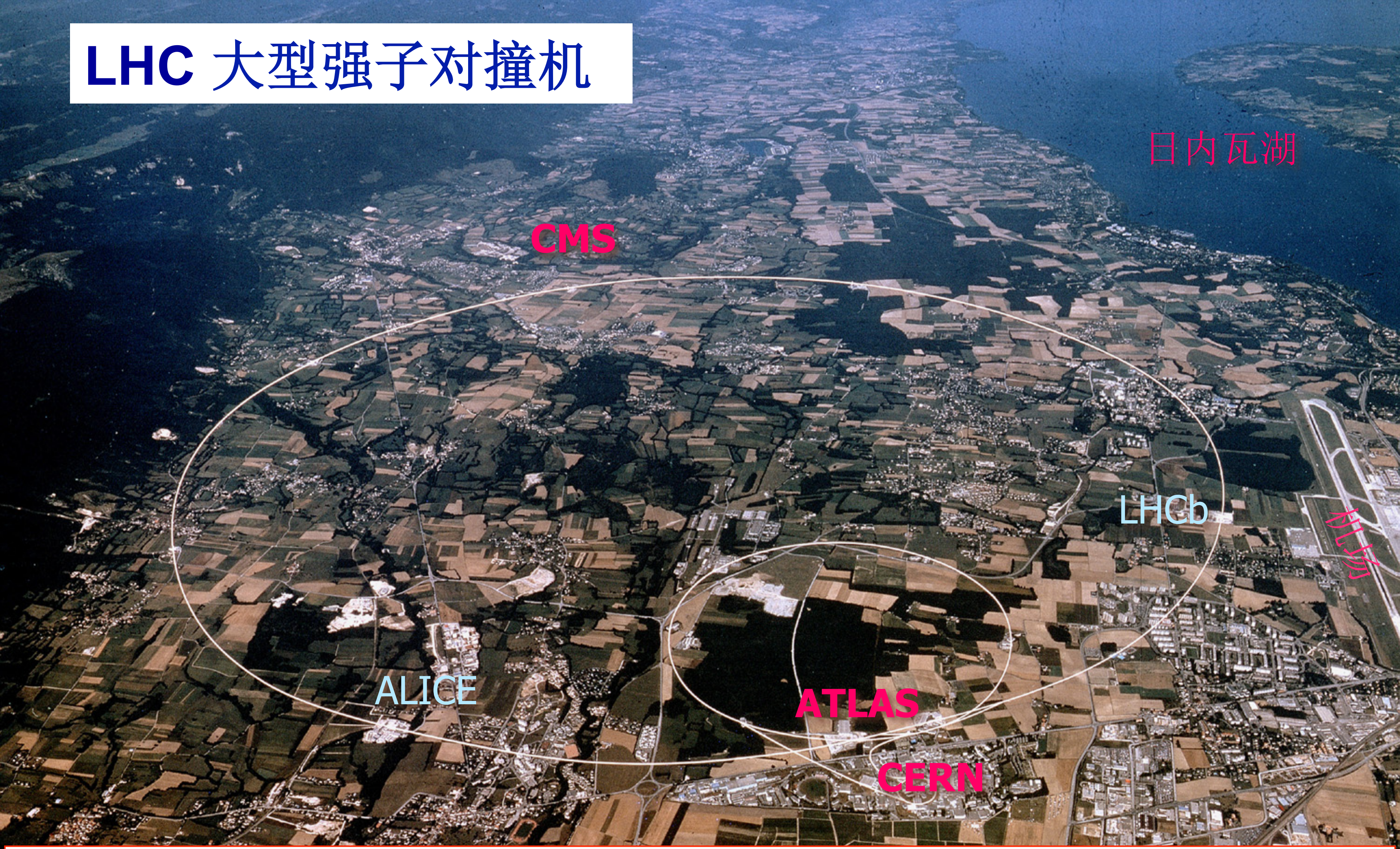
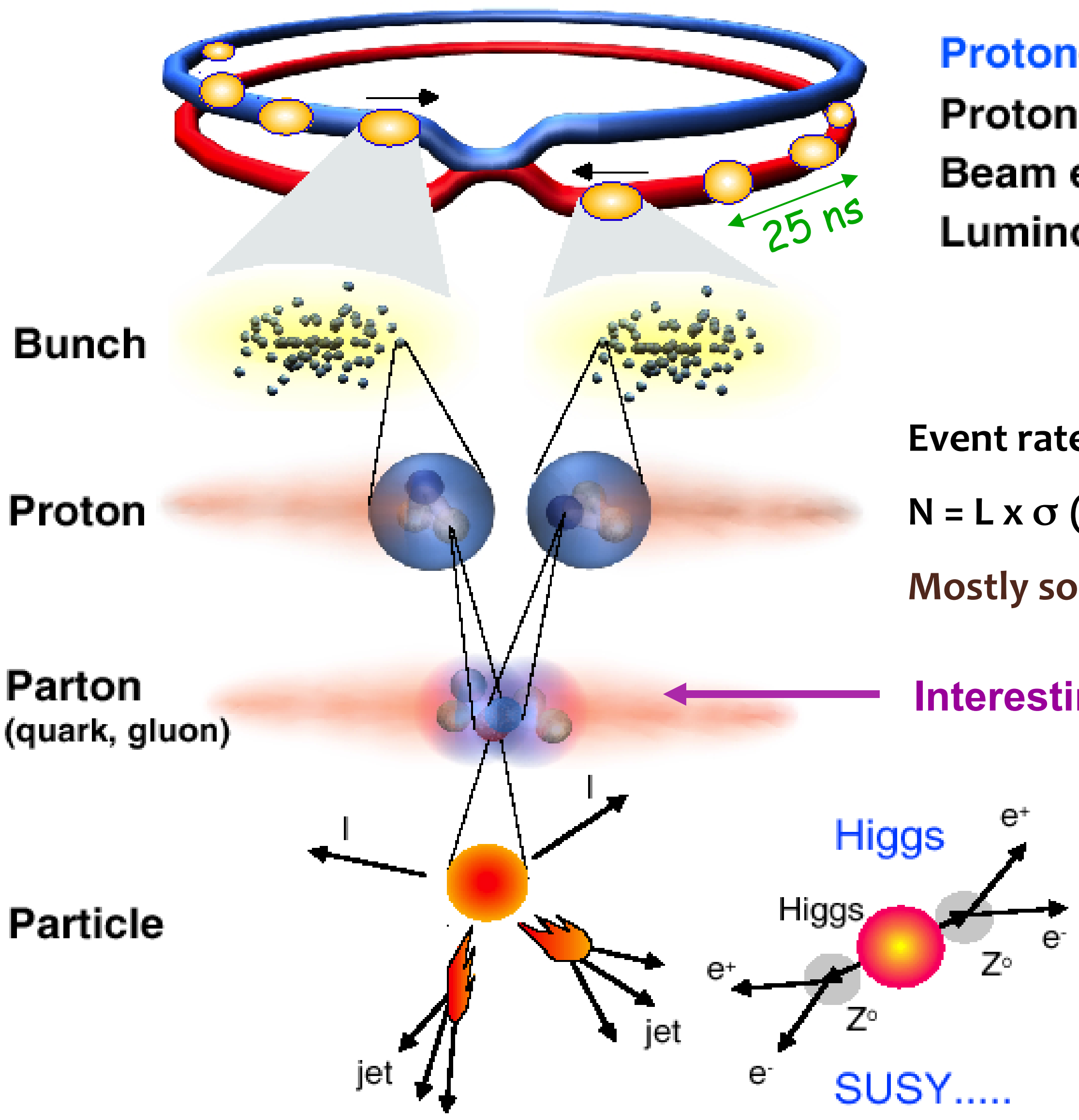


LHC 大型强子对撞机



- 周长 27 公里，隧道深100米，跨越瑞士法国国境
- 世界最大，能量最高的加速器，进行最前沿的粒子物理研究
- **质心系能量14TeV** (Tevatron的7倍)，可以发现**5TeV**以下的**较重的新粒子**
- **积分亮度10^{34} cm^{-2} s^{-1}** (Tevatron 的100倍)，可以发现微小衰变截面的**稀有事例**

Collisions at LHC



Proton-Proton

Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate:

$N = L \times \sigma(pp) \approx$ 10^9 interactions/s

Mostly soft (low p_T) events

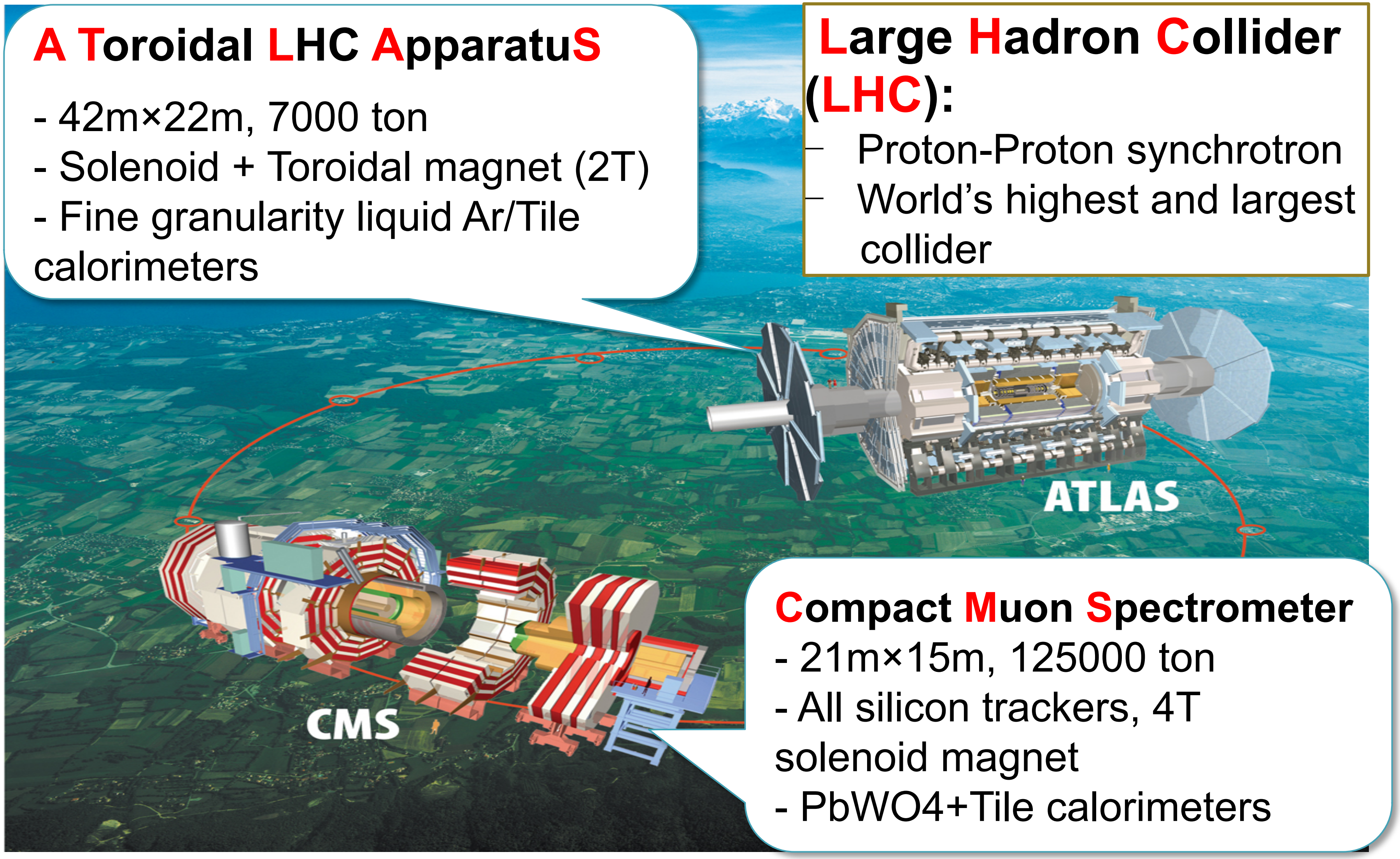
Interesting hard (high-p_T) events are rare

Selection of 1 in 10,000,000,000,000

→ **very powerful detectors needed**

ATLAS and CMS detector @ LHC

ATLAS and CMS: two multi-purpose detectors @LHC



A Toroidal LHC ApparatuS

- 42m×22m, 7000 ton
- Solenoid + Toroidal magnet (2T)
- Fine granularity liquid Ar/Tile calorimeters

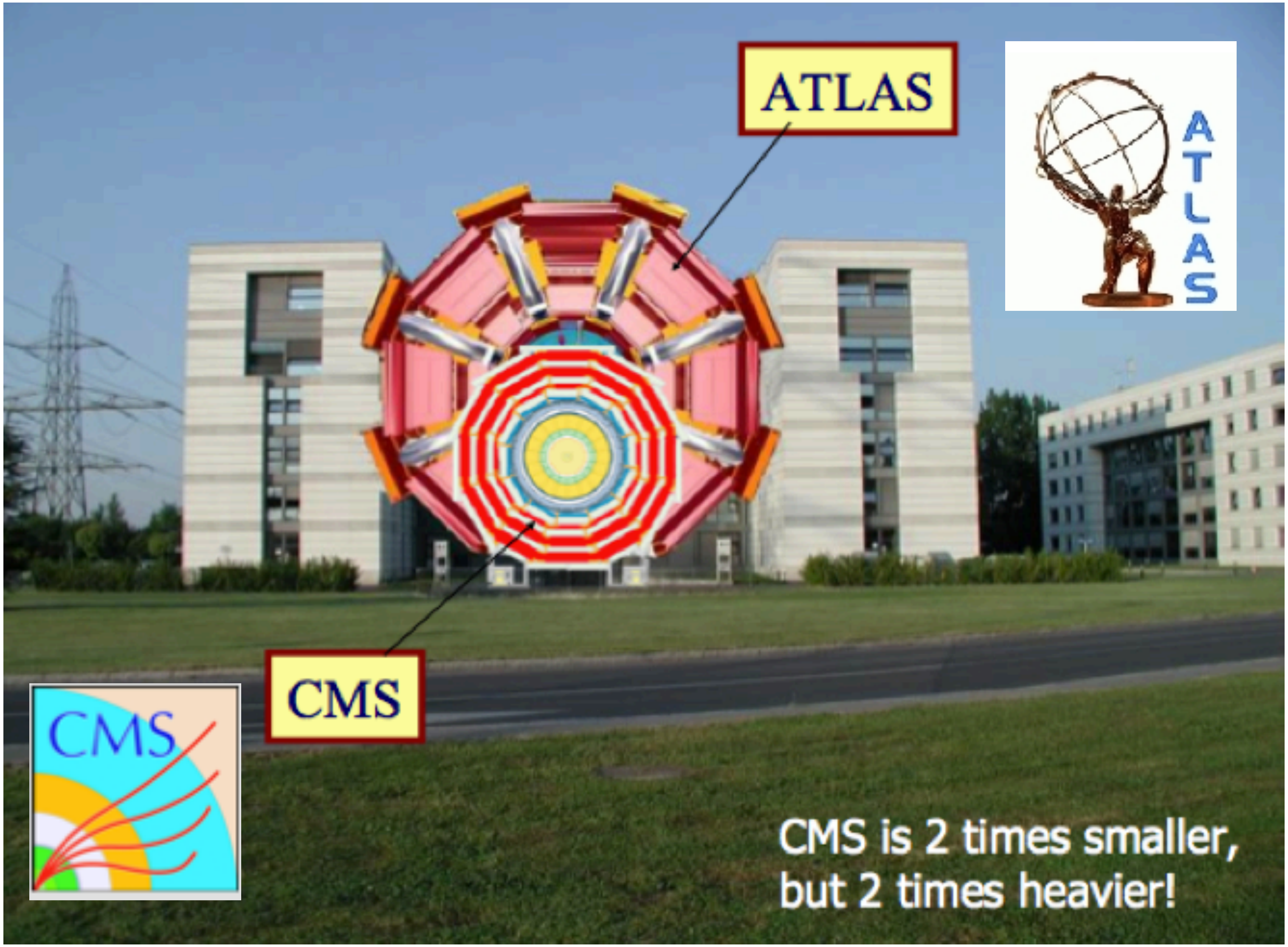
Large Hadron Collider (LHC):

- Proton-Proton synchrotron
- World’s highest and largest collider

Compact Muon Spectrometer

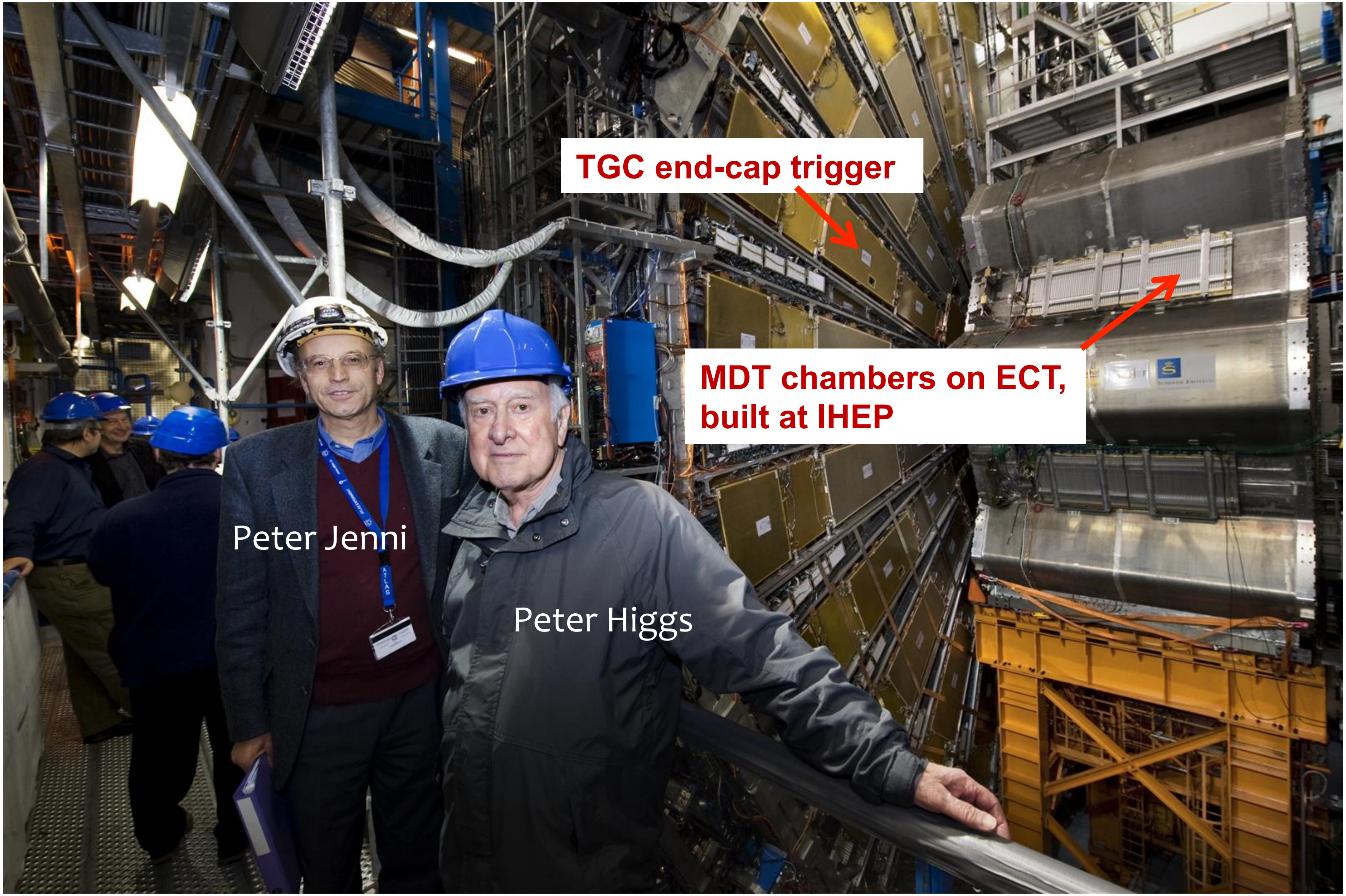
- 21m×15m, 125000 ton
- All silicon trackers, 4T solenoid magnet
- PbWO4+Tile calorimeters

ATLAS and CMS



CMS is 2 times smaller, but 2 times heavier!

Chinese muon chambers installed in the ATLAS detector



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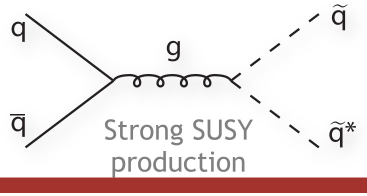
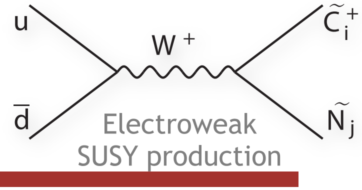
Where do we start?

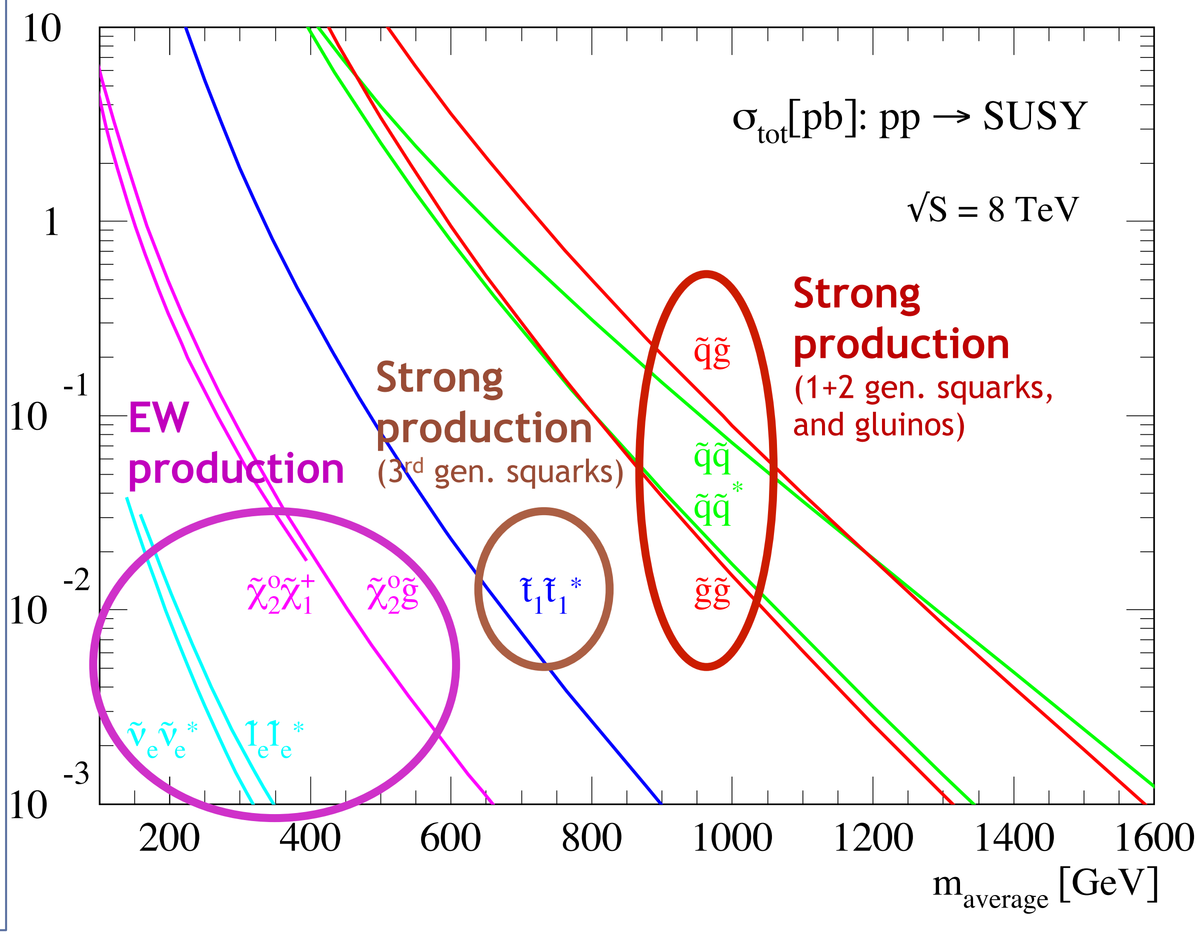
Huge parameter space, but guiding principles





- **Early analyses** dominated by broad and inclusive searches for gluino and squark production
- **Increasing luminosity** gave access to rare production channels. Additional motivation from *Natural SUSY* paradigm
- If 1st and 2nd squark and gluino is too heavy, EWK SUSY production may dominant in LHC

SUSY searches strategy driven by cross section and luminosity



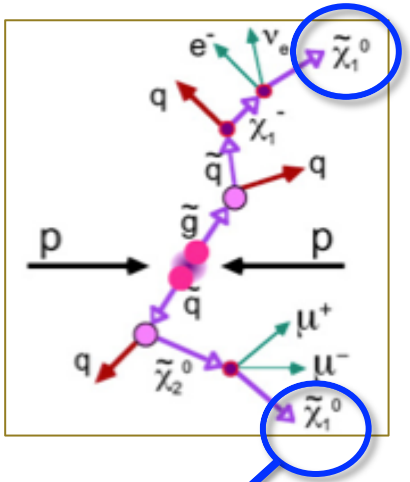
How do we start? - SUSY Signature

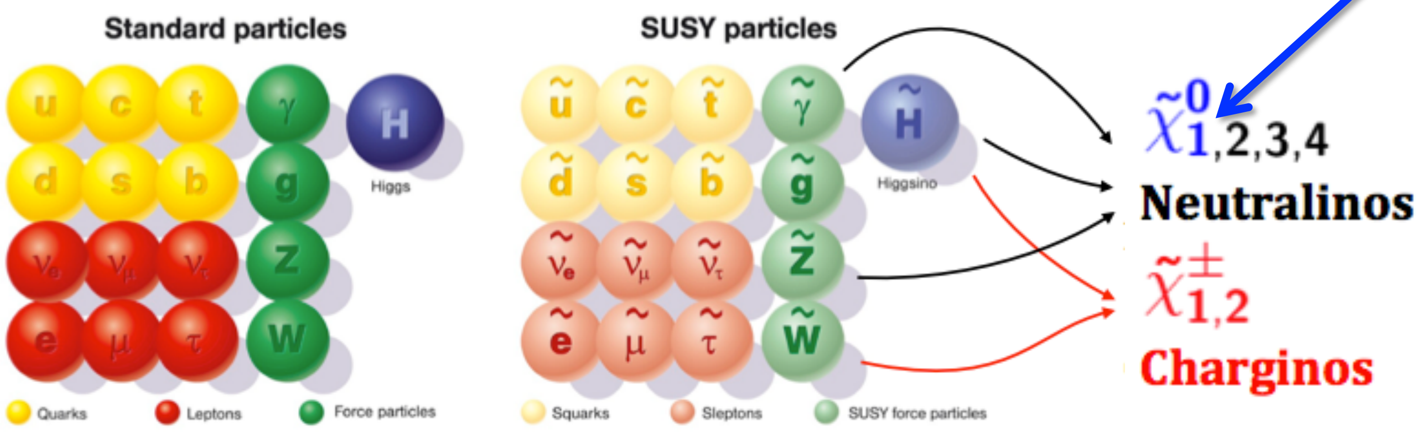
- **<u>Conserved R parity</u>** (originally introduced for stability of proton)

$$R = (-1)^{3(B-L)+2S}$$

R=+1 (SM)
R=-1 (SUSY)

  - SUSY particles produced/annihilated in pairs
  - Lightest SUSY particle (LSP) stable (DM candidate)
  - Typical signature: <u>jets/leptons/photons + **MET**</u> **(key signature: large MET)**

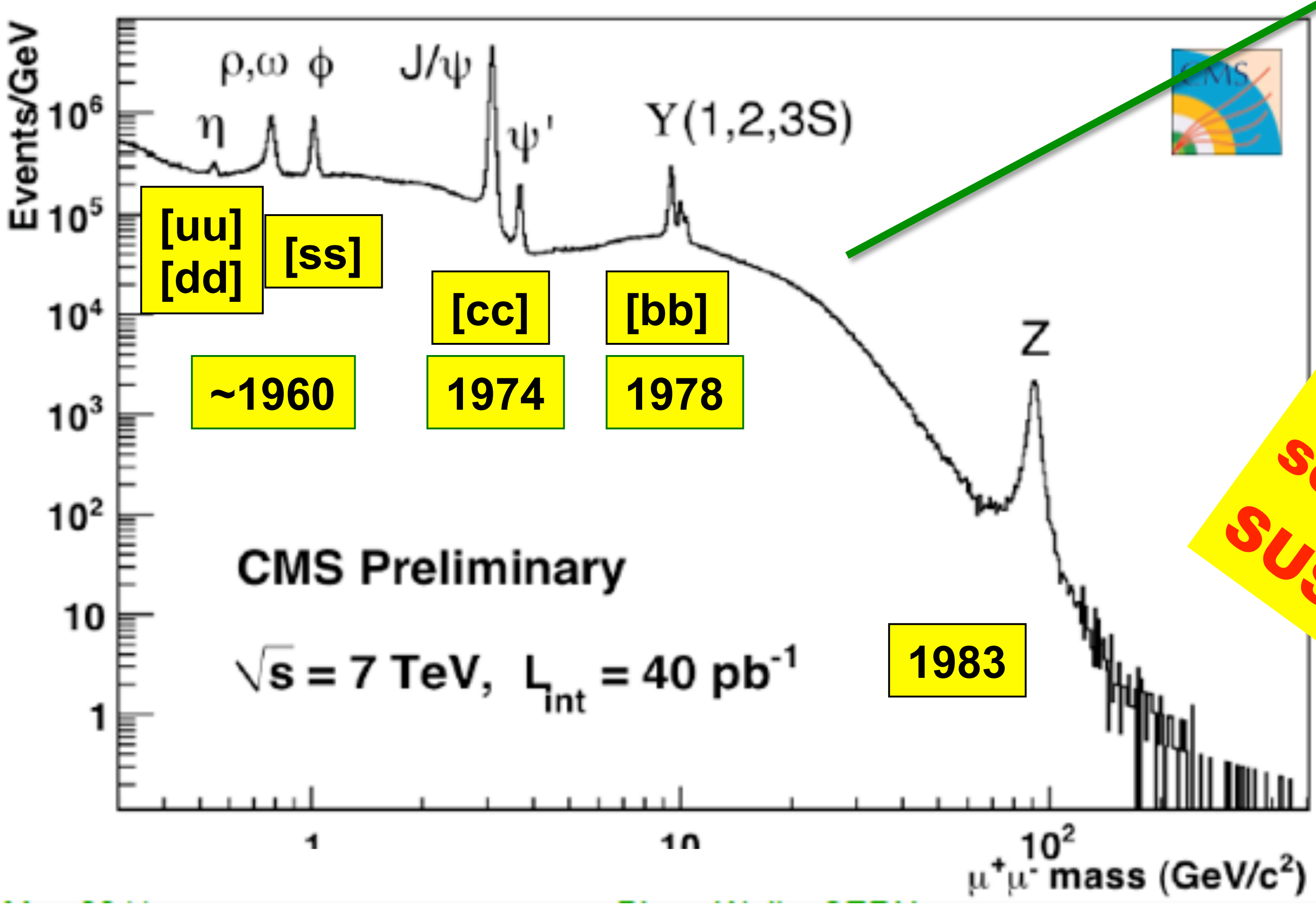


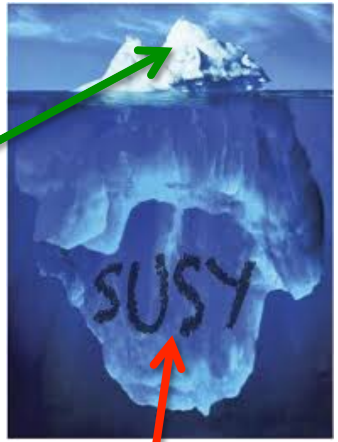


How do we search for SUSY?

2010

- Not like general particles with peak in mass spectrum ☹

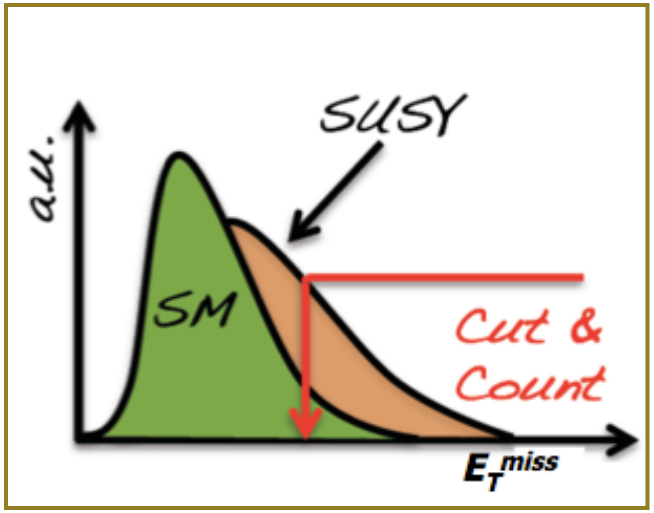




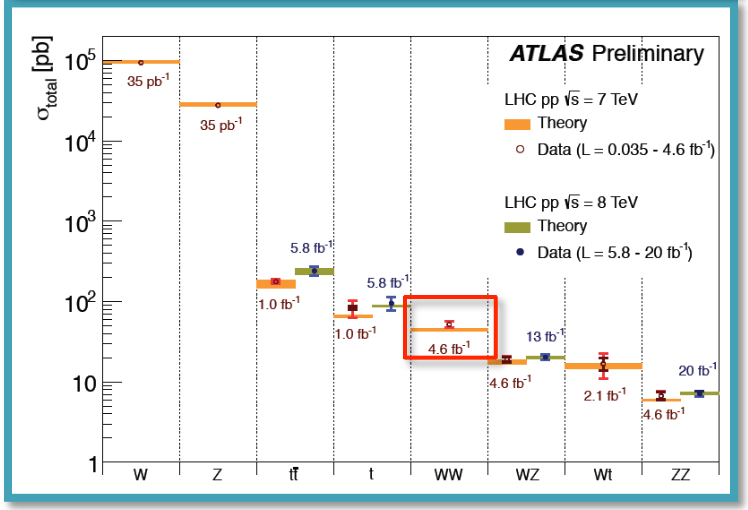
How do we search for SUSY?

How do we search for SUSY?

- **SUSY search strategy:** search for **deviation from SM** from the tails
- **SUSY sensitive variables:** Try to establish excess of events in some sensitive kinematic distribution
- **SM background:** the discovery of new physics can only be claimed when SM backgrounds are understood well or under control
  - SM bgs understood very well ☺
  - No hints for new physics ☹
  - Slightly overshoot in WW cross section, but consistent with NNLO xsec.

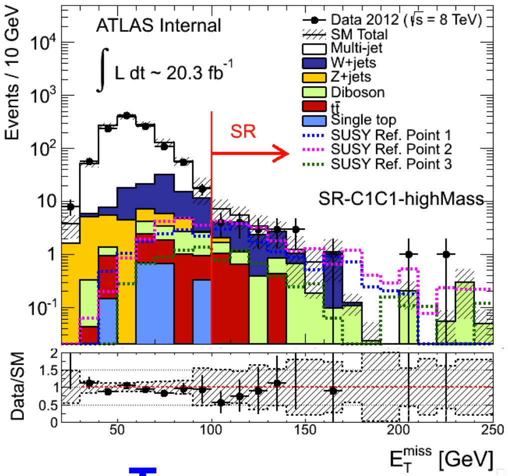


SM "backgrounds"– the big picture

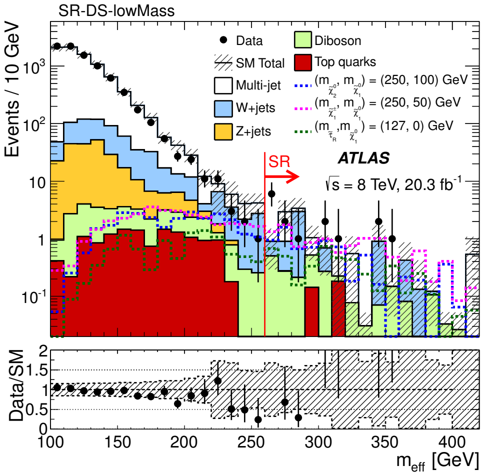


SUSY Sensitive Variables

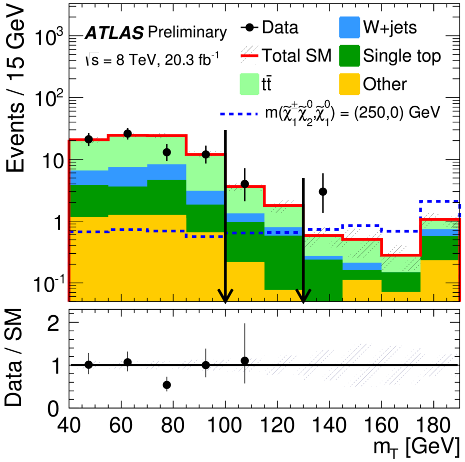
E_T^{miss}



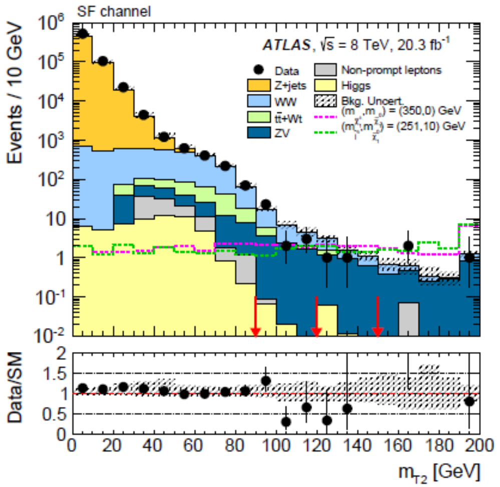
M_{eff}



mT



mT2



- **E_T^{miss}** from escaping LSP, to suppress bg from mis-measured jets and oth. SM BG
- Related to the sparticle mass scale, like effective mass (**M_{eff}**)

$$M_{\rm eff} \equiv \sum_{i=1}^{N_{\rm jets}} p_{\rm T}^{{\rm jet},i} + \sum_{j=1}^{N_{\rm lep}} p_{\rm T}^{{\rm lep},j} + E_{\rm T}^{\rm miss}$$

- **mT, mT2** (stransverse mass): suppress BG with Ws

$$m_{\rm T2} = \min_{\mathbf{q}_{\rm T}}\left[\max\left(m_{\rm T}(\mathbf{p}_{\rm T}^{\ell 1}, \mathbf{q}_{\rm T}), m_{\rm T}(\mathbf{p}_{\rm T}^{\ell 2}, \mathbf{p}_{\rm T}^{\rm miss} - \mathbf{q}_{\rm T})\right)\right]$$

- Many others …

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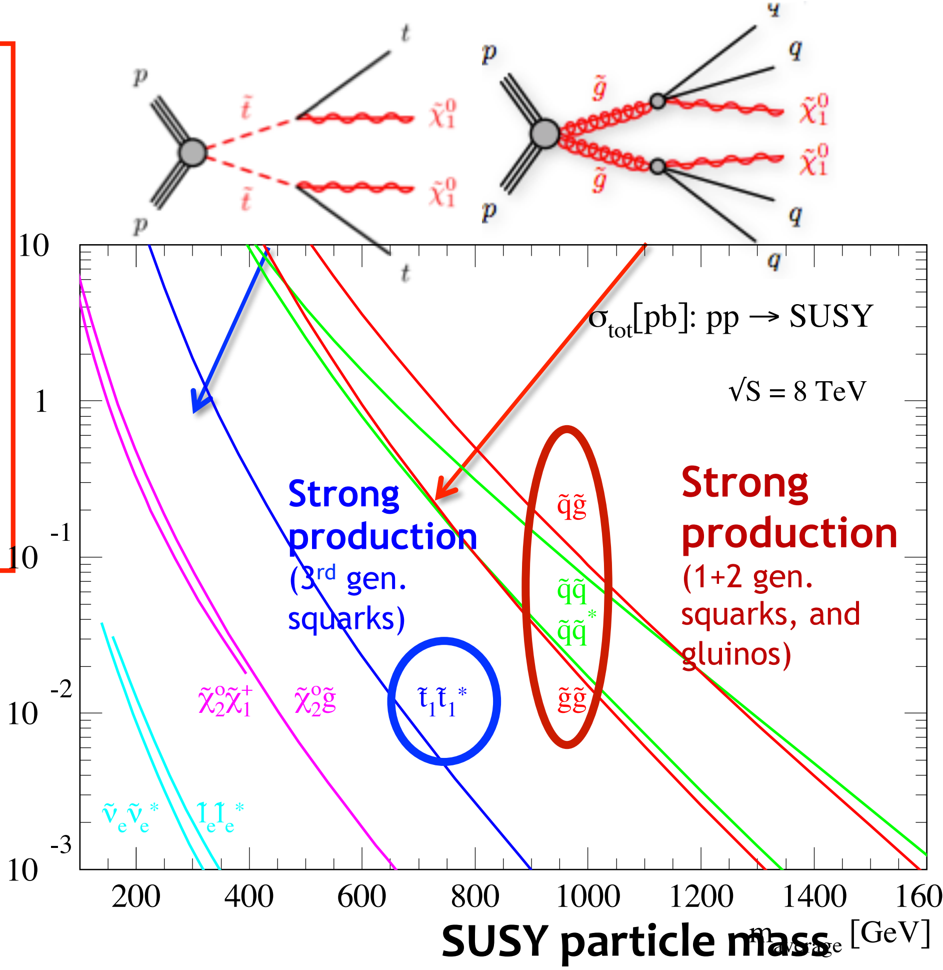
Wide SUSY Signatures

Strong production: gluino pair, gluino-squark and squark pair (include **3rd generation**) production

1）Generic signatures :

Multi -jets + n_lepton/n_photon(n=0,1, ≥2) + large E_T^{miss} **(0L,1 L, >=2L)**

2）large xs, but heavy SUSY mass scale



Wide SUSY Signatures

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Multi -jets + n_lepton/n_photon(n=0,1, ≥2) + large E_T^{miss} **(0L,1 L, >=2L)**

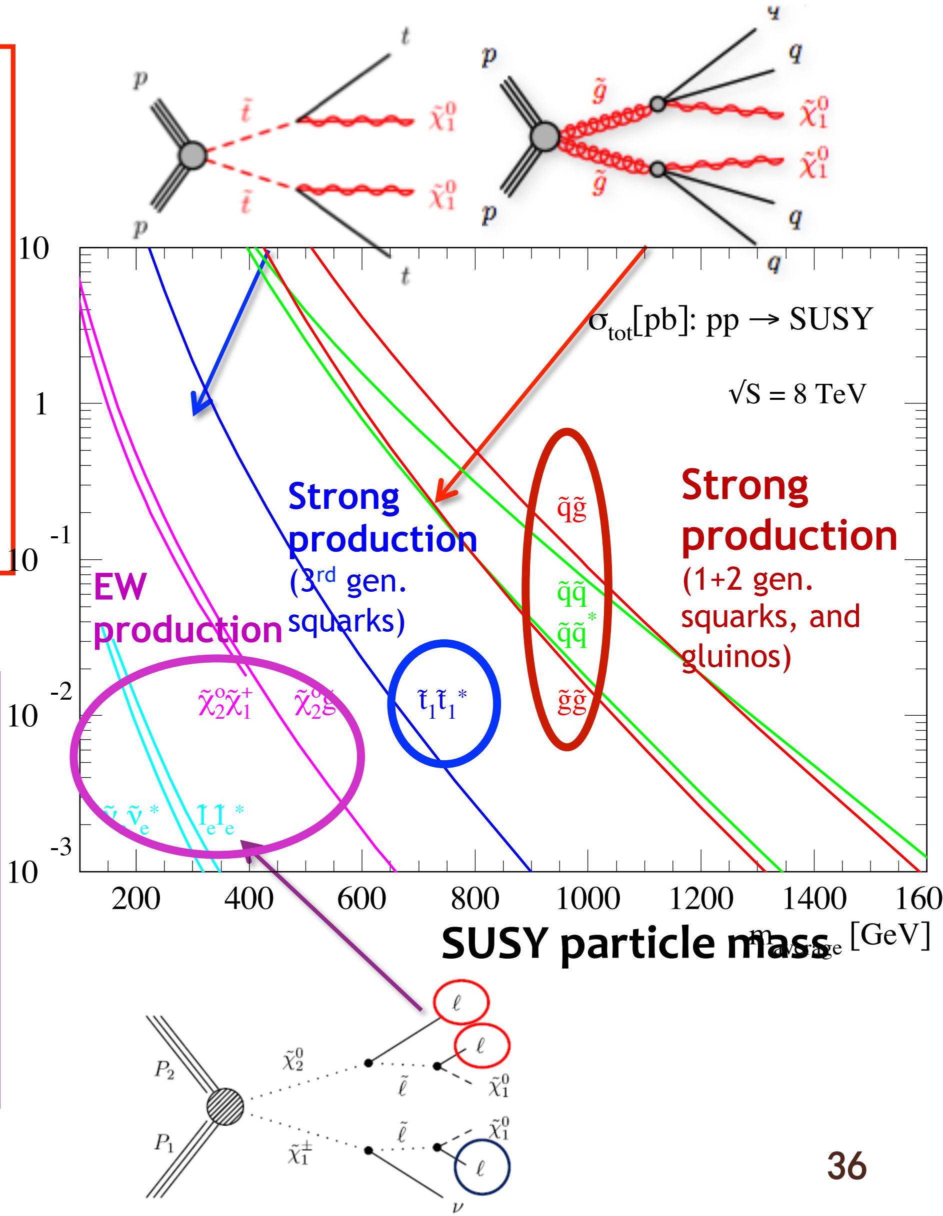
2）large xs, but heavy SUSY mass scale

Weak production: direct gaugino/slepton production

1）Generic signatures:

low–jet multiplicity + ≥ 1 leptons + large E_T^{miss} (1/2/3/4L, **>=2tau**)

2）low xs, but small SUSY mass scale

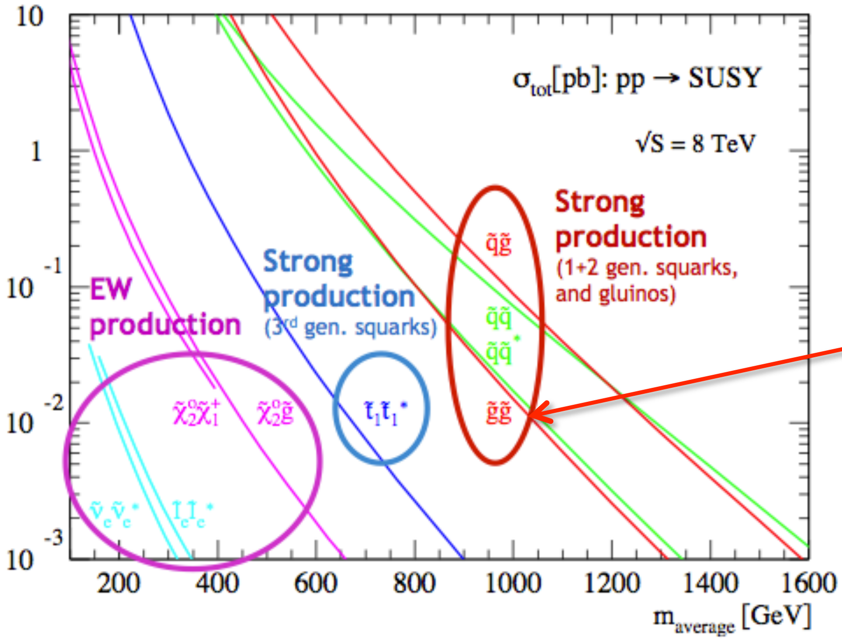


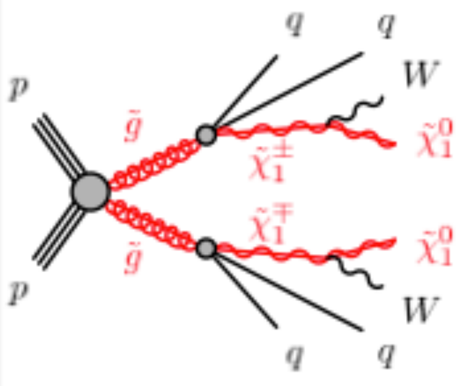
SUSY models: good sale in market

- **Simplified Models:**
  - Not really a model (Br~100%, most masses fixed at high scales)
  - Important tool for signal region optimization & interpretation
- **Phenomenological models:**
  - ☐ pMSSM: captures "most" of phenomenologic features of R-parity conserving MSSM
    - 19 free parameters: M1,M2,M3 ; tan β, μ and $m_{A;}$ 10 sfermion mass parameters; A_t, A_b and A_T
    - Comprehensive and computationally realistic approximation of the MSSM with neutralino LSP
  - ☐ GGM (gravitino)
- **Complete SUSY models**: mSUGRA, GMSB …

One example

arXiv:1605.04285





gluinos decaying via charginos

W → l nu
→ qq

Final states:

≥ 1 lepton + multi-jets + large E_T^{miss}

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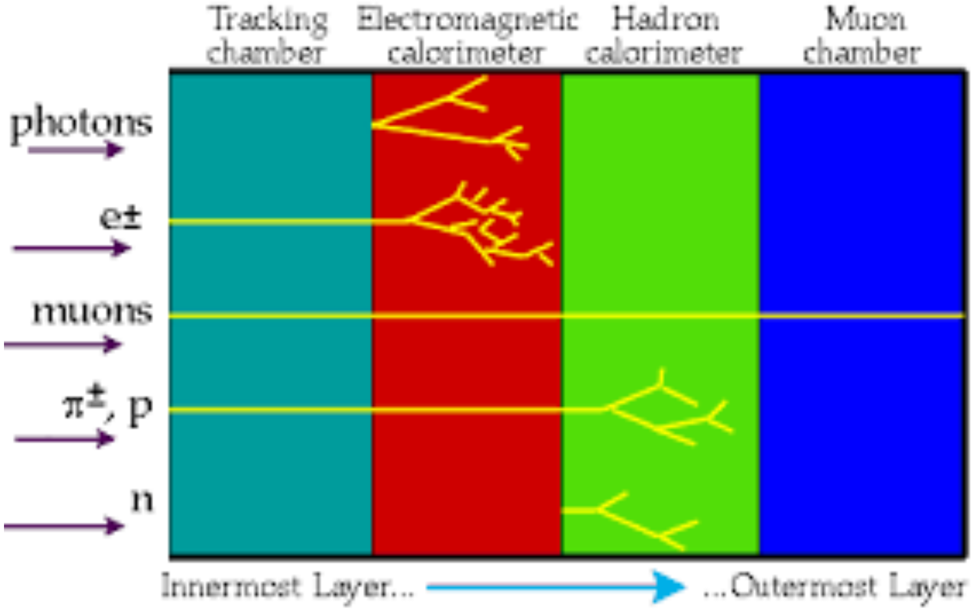
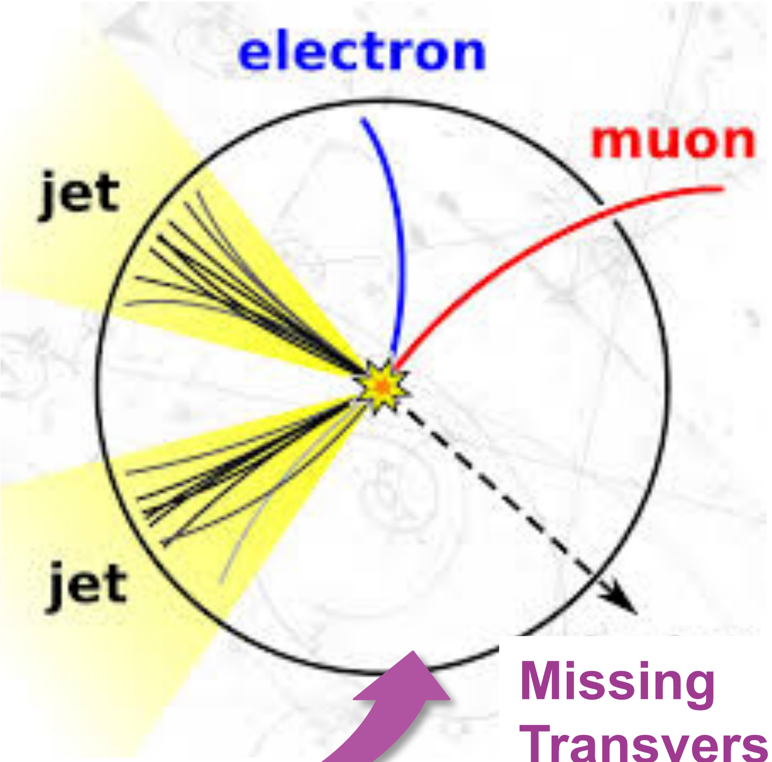
Reconstructed Objects

- Photons: no track but energy in el-m (and not in the hadronic) calorimeter
- Electrons: track and energy in el-m (and not in the hadronic) calorimeter
- Muons: track in inner tracker and muon chamber
- Jets: cluster in hadronic calorimeter



MET: Missing Transverse Energy

- At the LHC an unknown proportion of the energy of the colliding protons escapes down the beam-pipe
- Invisible particles (neutrinos, neutralinos?) are created their momentum can be constrained in **the plane transverse to the beam direction**



Missing Transverse Energy

$$E_T^{\text{miss}} = -\sum_i p_T(i)$$

How do we search for SUSY?

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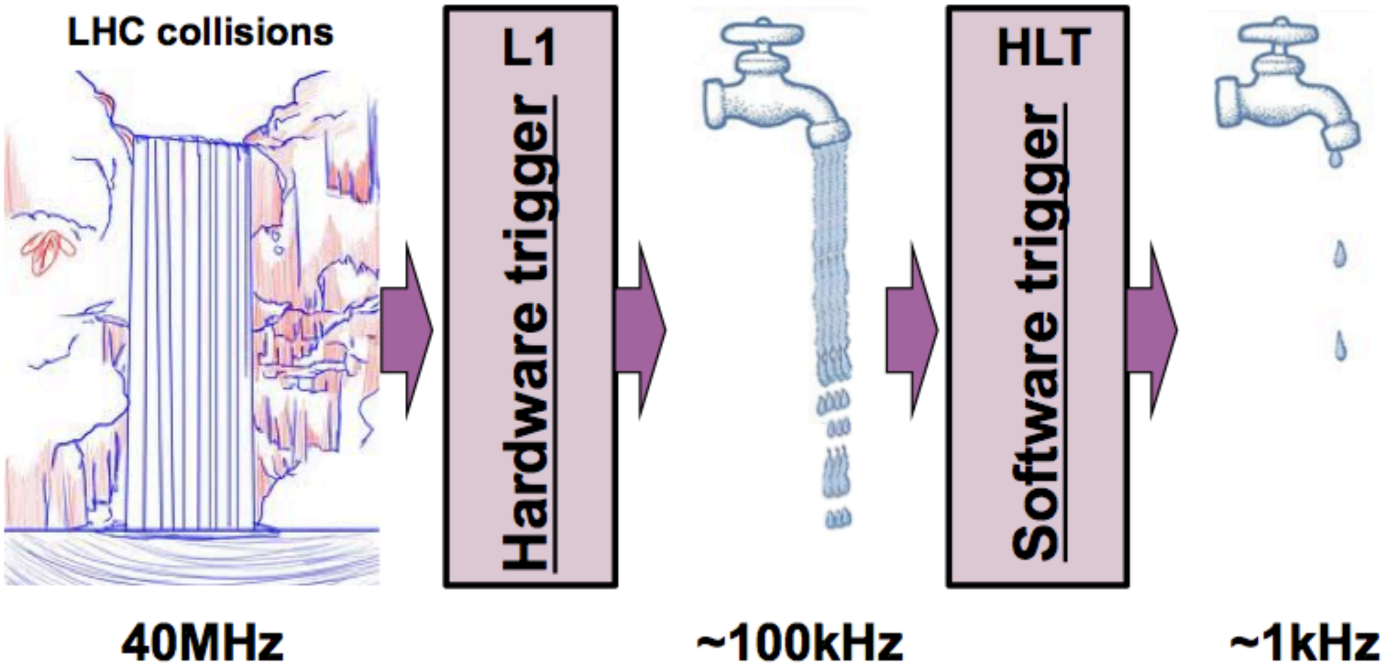
Triggering on Physics



- Apply trigger depending on analysis
- Only pick up what we are interested events
- MissingET trigger used here

Final states:

≥ 1 lepton + multi-jets + large E_T^{miss}

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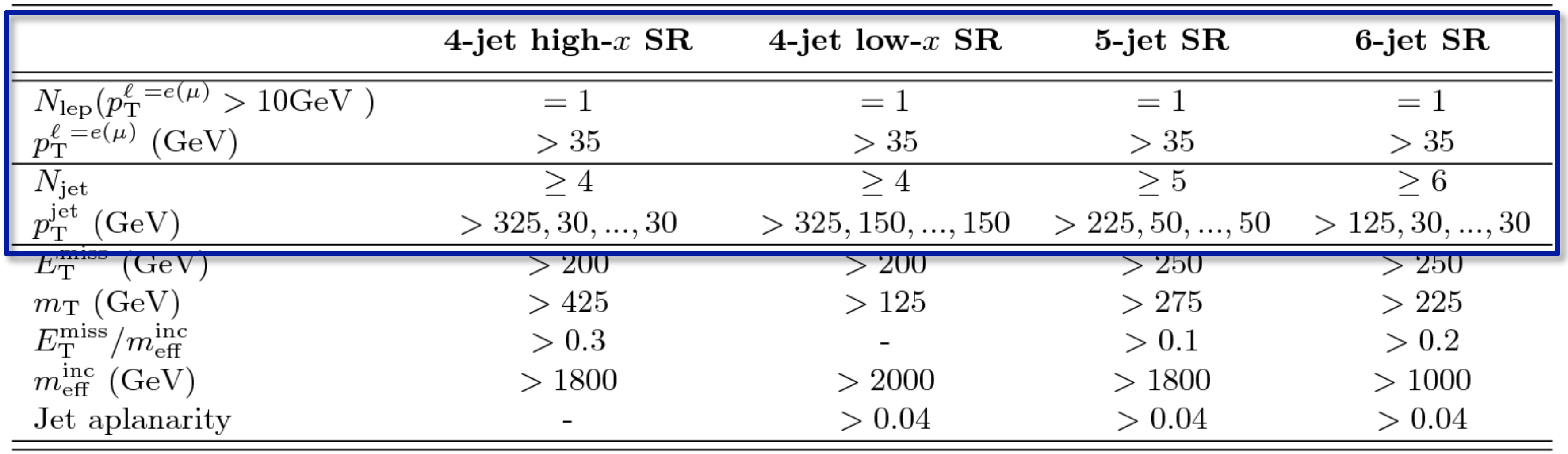
SR definition and optimization

arXiv:1605.04285



	4-jet high-x SR	4-jet low-x SR	5-jet SR	6-jet SR
$N_{\text{lep}}(p_{\text{T}}^{\ell=e(\mu)} > 10\text{GeV})$	$= 1$	$= 1$	$= 1$	$= 1$
$p_{\text{T}}^{\ell=e(\mu)}$ (GeV)	> 35	> 35	> 35	> 35
N_{jet}	≥ 4	≥ 4	≥ 5	≥ 6
$p_{\text{T}}^{\text{jet}}$ (GeV)	$> 325, 30, ..., 30$	$> 325, 150, ..., 150$	$> 225, 50, ..., 50$	$> 125, 30, ..., 30$
$E_{\text{T}}^{\text{miss}}$ (GeV)	> 200	> 200	> 250	> 250
m_{T} (GeV)	> 425	> 125	> 275	> 225
$E_{\text{T}}^{\text{miss}}/m_{\text{eff}}^{\text{inc}}$	> 0.3	-	> 0.1	> 0.2
$m_{\text{eff}}^{\text{inc}}$ (GeV)	> 1800	> 2000	> 1800	> 1000
Jet aplanarity	-	> 0.04	> 0.04	> 0.04

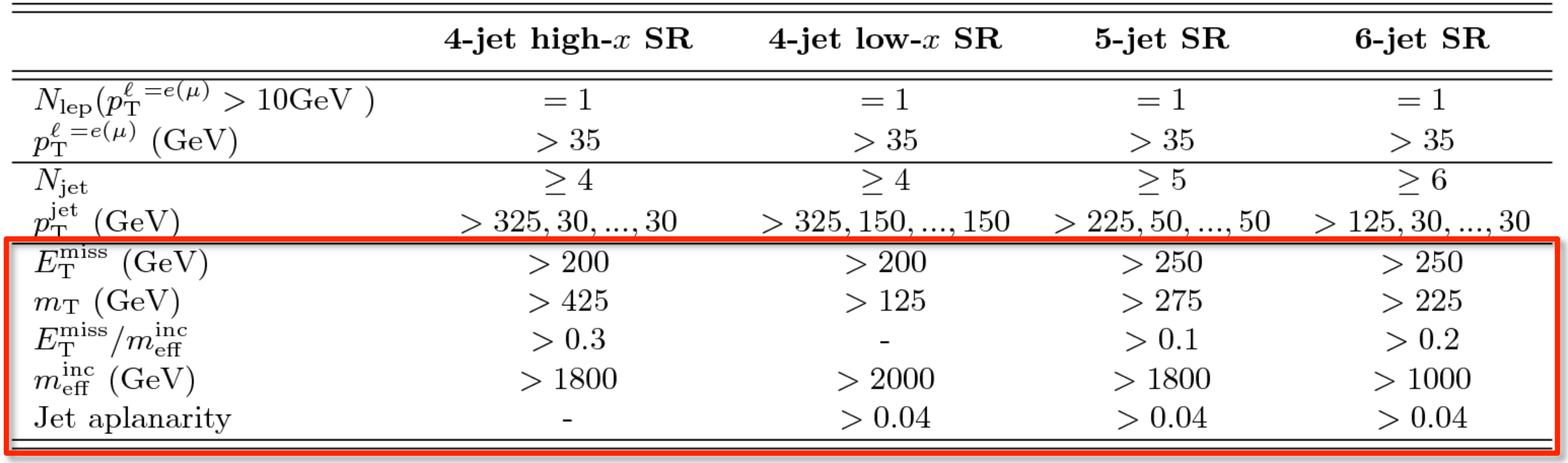
- According to signal signature, select interested final states objects: number of jets, leptons requirement

Final states:

$\geq$ 1 lepton + multi-jets + large $E_{\text{T}}^{\text{miss}}$

SR definition and optimization

arXiv:1605.04285



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Jet aplanarity	-	> 0.04	> 0.04	> 0.04

- Suppress background using SUSY discriminating variables
- The cuts are from optimization with signal significance

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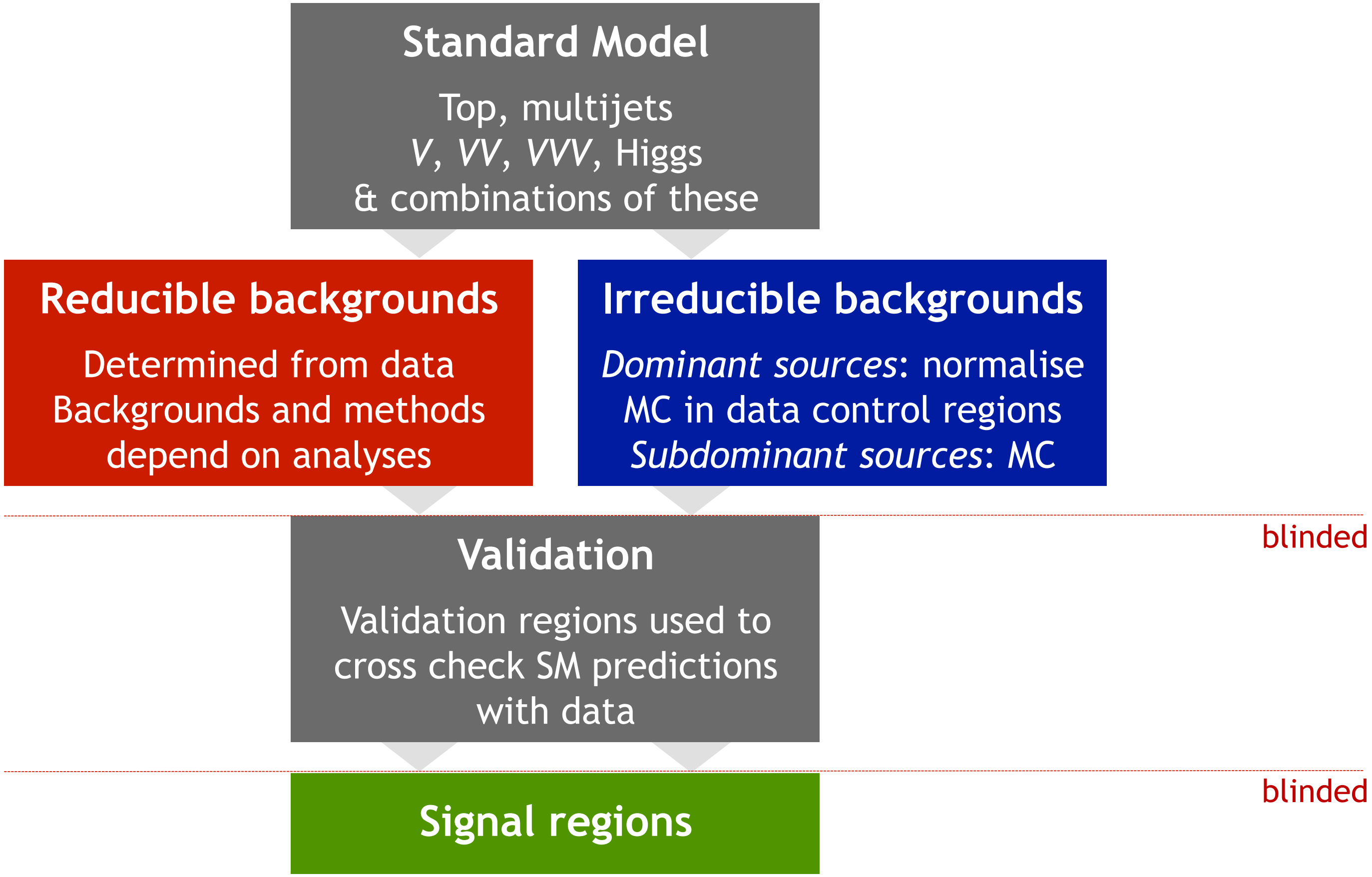
SM Background Estimation

SUSY searches rely primarily on the understanding of the SM BG



Standard Model

Top, multijets
V, *VV*, *VVV*, Higgs
& combinations of these

Reducible backgrounds

Determined from data
Backgrounds and methods depend on analyses

Irreducible backgrounds

Dominant sources: normalise MC in data control regions
Subdominant sources: MC

blinded

Validation

Validation regions used to cross check SM predictions with data

blinded

Signal regions

SM Background Estimation

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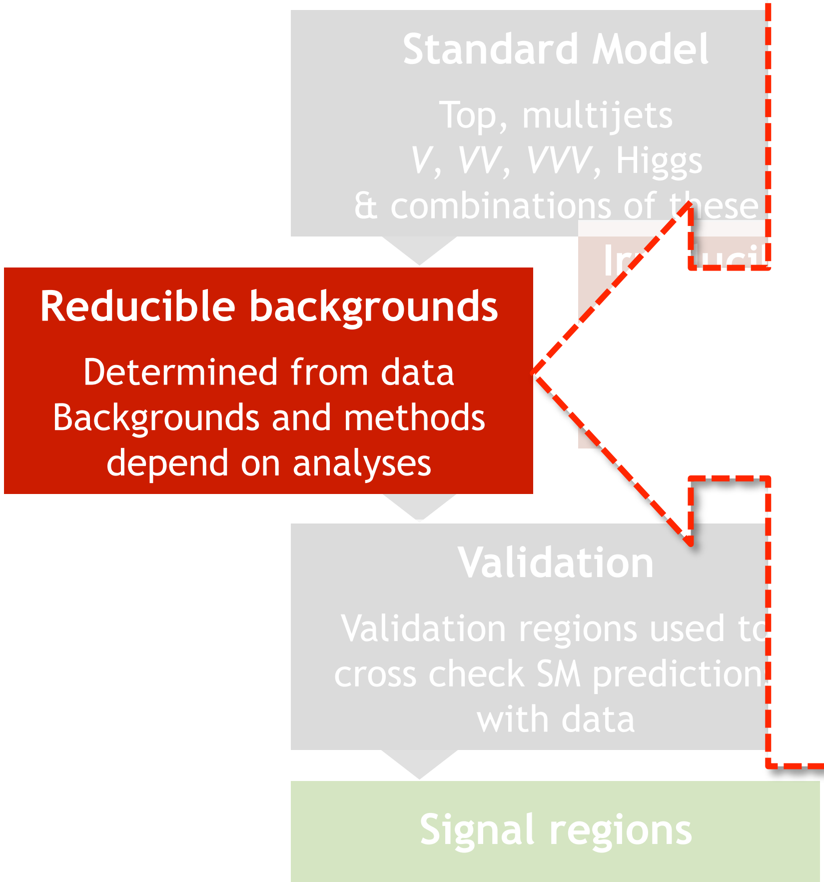

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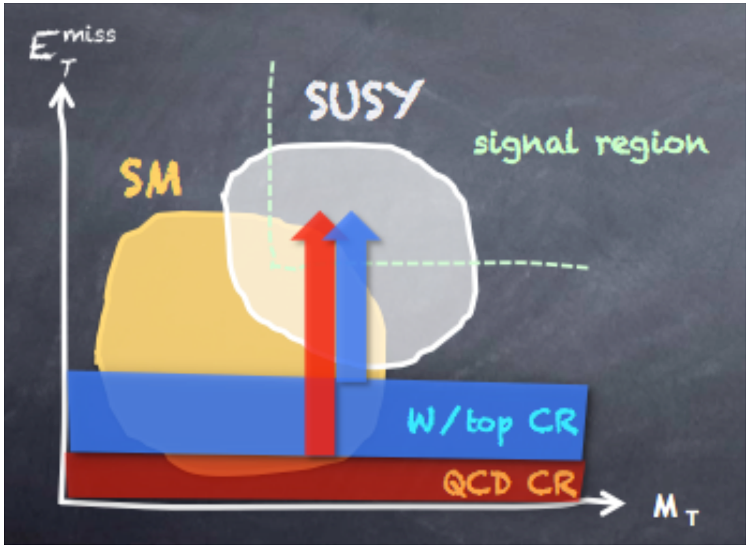
Signal regions

- **Multijet background**: "ABCD method" or jet smearing method
- **Fake leptons or heavy-flavour jets** determined with "matrix method" in different-purity samples using "real" and "fake" probabilities measured in data.
- **Charge flip rate** measured in *Z* events

SM Background Estimation

SUSY searches rely primarily on the understanding of the SM BG

Normalise MC prediction in SRs using dedicated CRs → transfer factor: T



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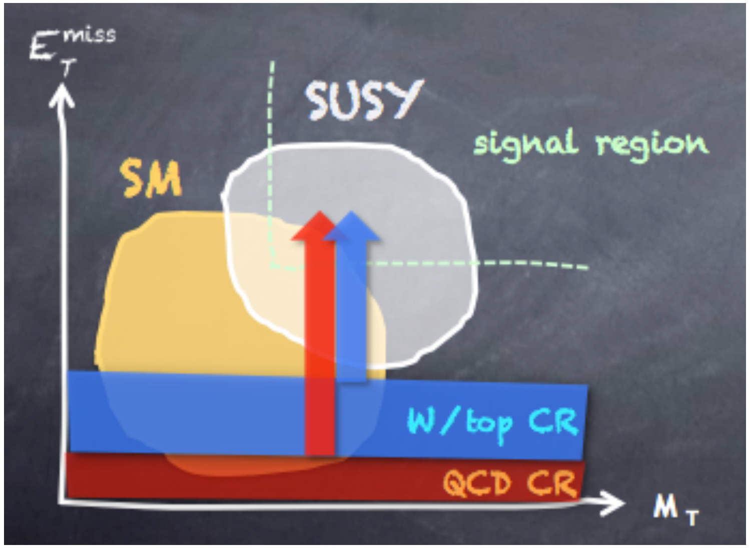

Standar

Top, mu
V, *VV*, *VV*
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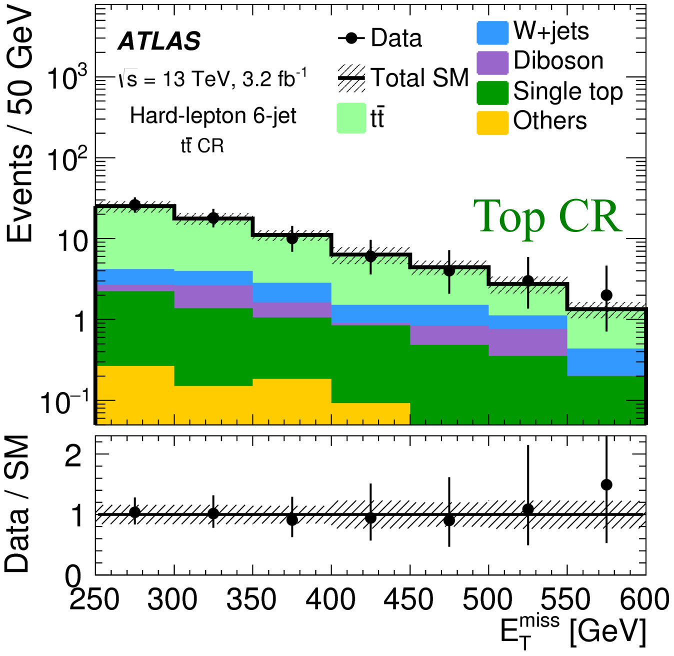
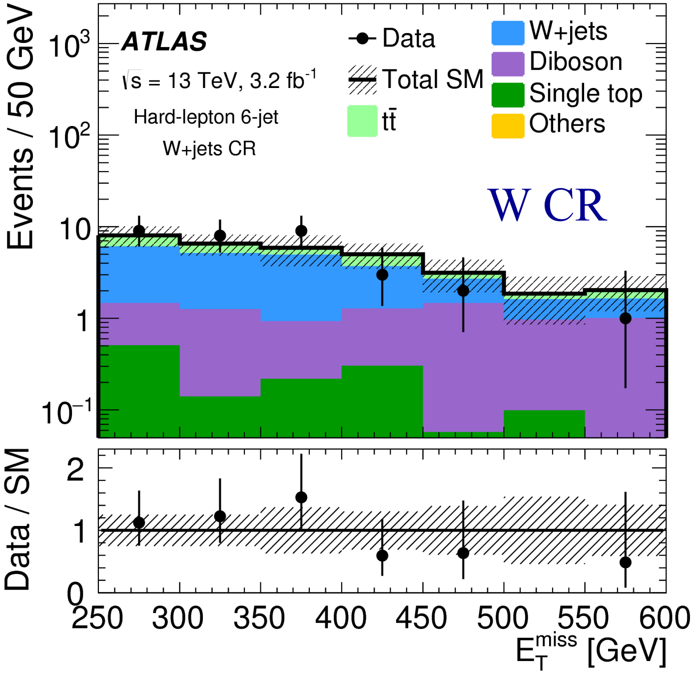
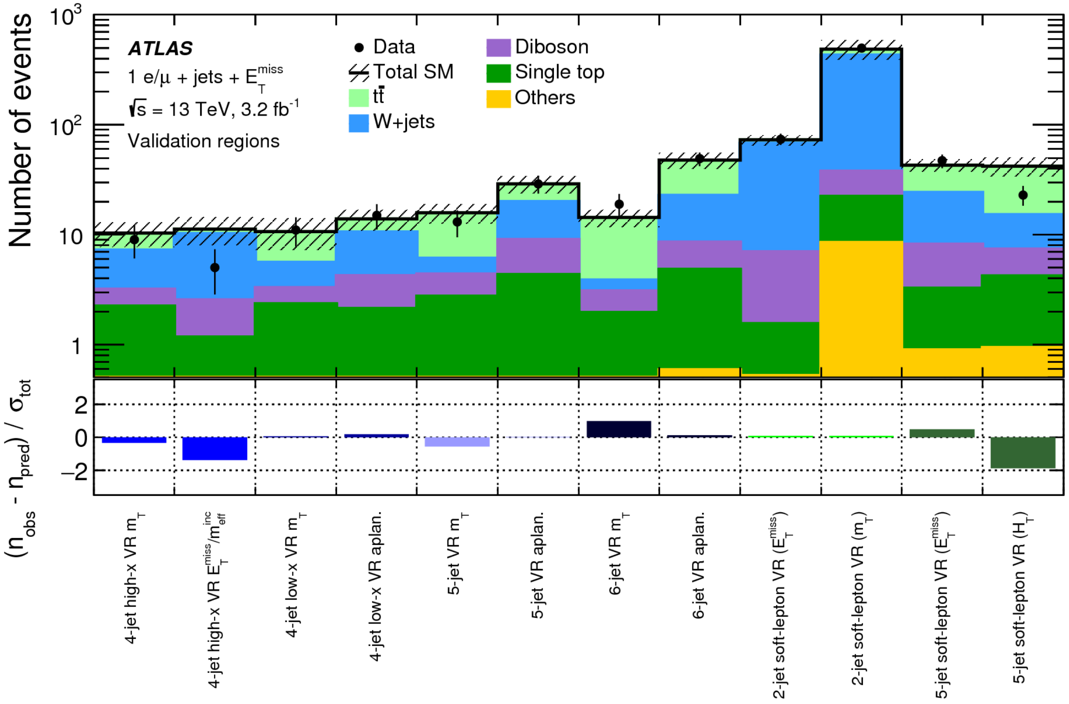




SU … e SM

BG



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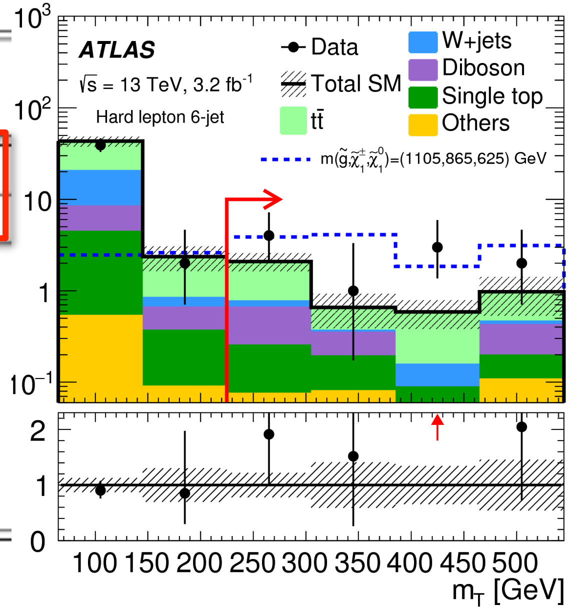
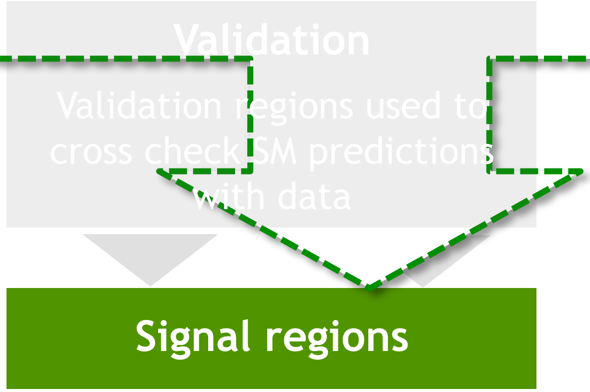
	Hard-lepton			
	4-jet low x	4-jet high x	5-jet	6-jet
Observed events	1	0	0	10
Fitted background events	1.3 ± 0.5	0.9 ± 0.5	1.3 ± 0.6	4.4 ± 1.0
$t\bar{t}$	0.40 ± 0.31	0.08 ± 0.07	0.40 ± 0.24	2.5 ± 0.9
W+jets	0.19 ± 0.12	0.8 ± 0.5	0.16 ± 0.12	0.23 ± 0.16
Z+jets	0.045 ± 0.023	0.028 ± 0.027	0.073 ± 0.035	0.08 ± 0.08
Single-top	0.5 ± 0.5	$0.04^{+0.10}_{-0.04}$	$0.21^{+0.22}_{-0.21}$	0.4 ± 0.4
Diboson	$0.06^{+0.20}_{-0.06}$	$0.002^{+0.014}_{-0.002}$	0.37 ± 0.23	0.9 ± 0.5
$t\bar{t}$+V	0.048 ± 0.021	0.024 ± 0.012	0.059 ± 0.029	0.23 ± 0.08



arXiv:1605.04285

- No significant excess except for 6jet-SR



Data/SM comparisons

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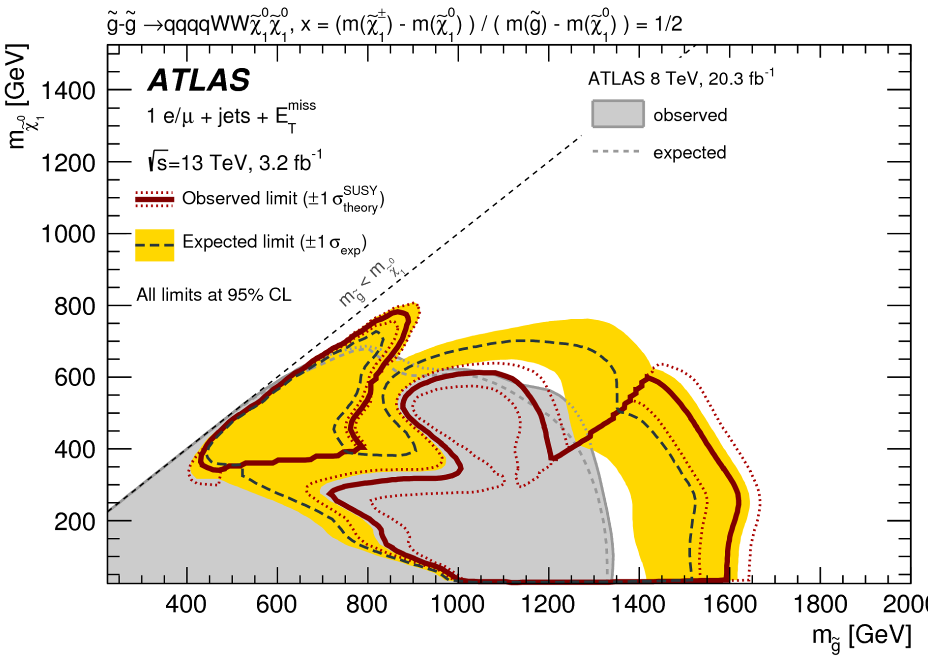
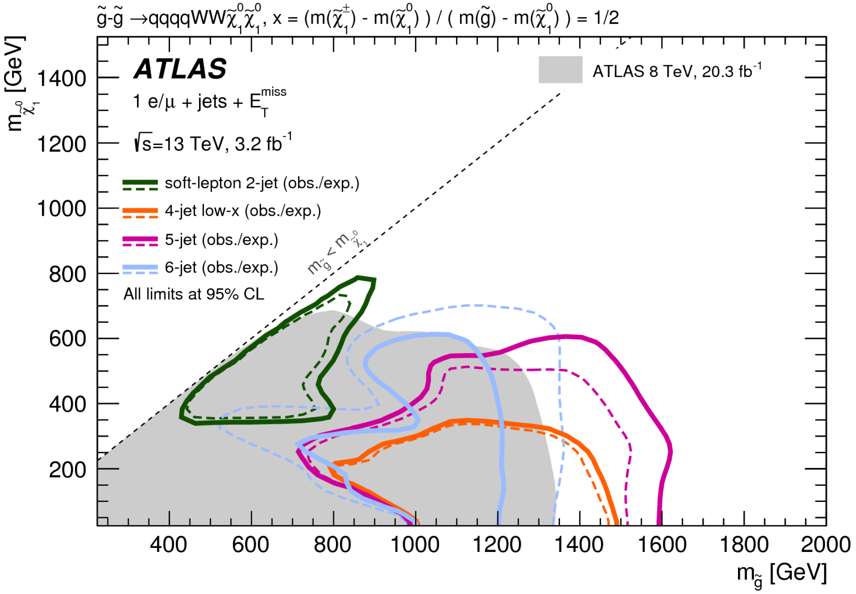
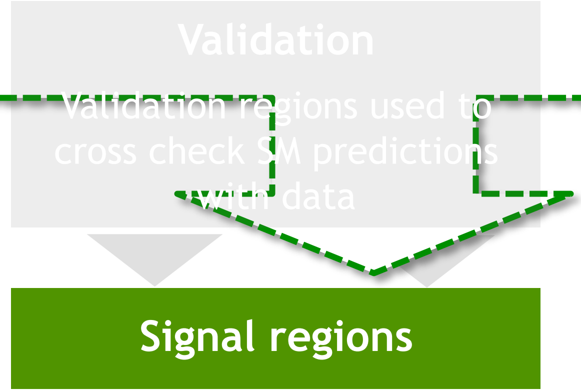




arXiv:1605.04285

- excludes **gluino masses** up to **1.6 TeV**



Validation

Validation regions used to cross check SM predictions with data

Signal regions

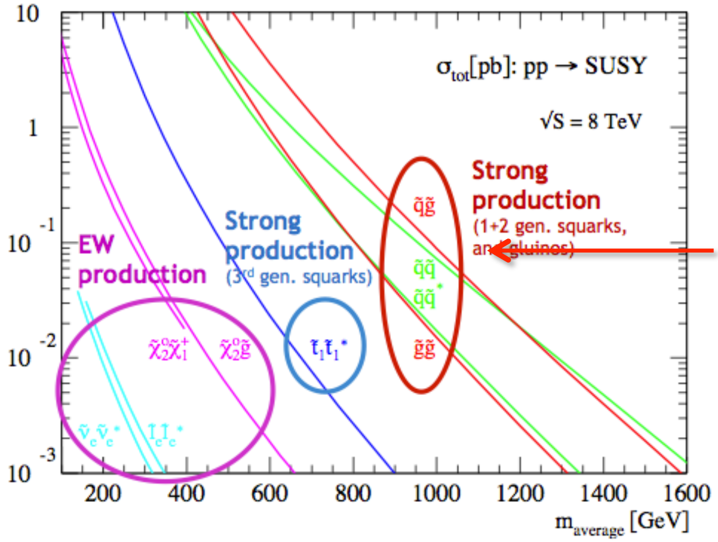
Interpretations

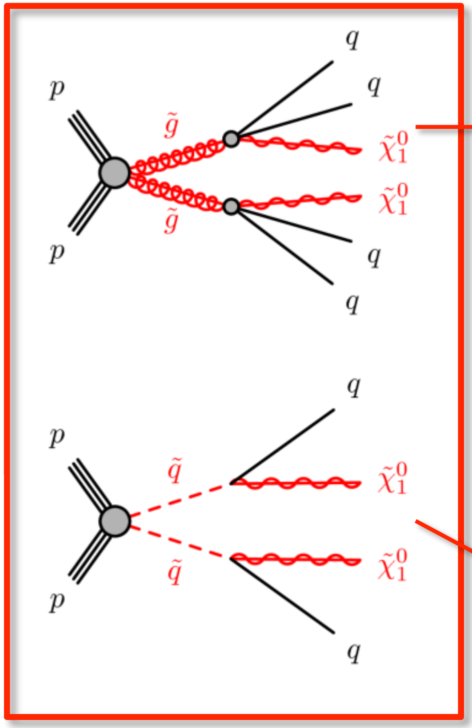
Outline

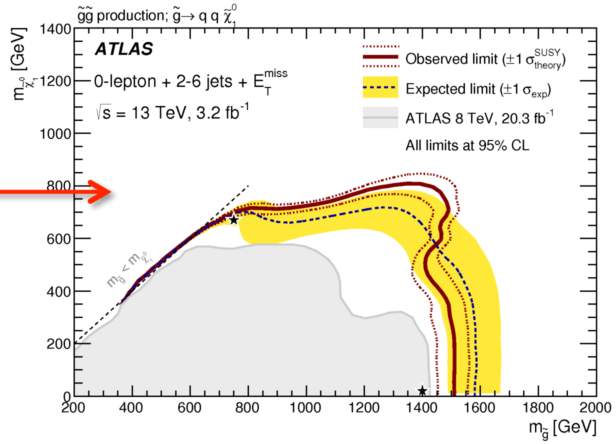
- SUSY Introduction
- The LHC and ATLAS
- SUSY search strategy
- Overview of SUSY search results
- Outlook and Summary

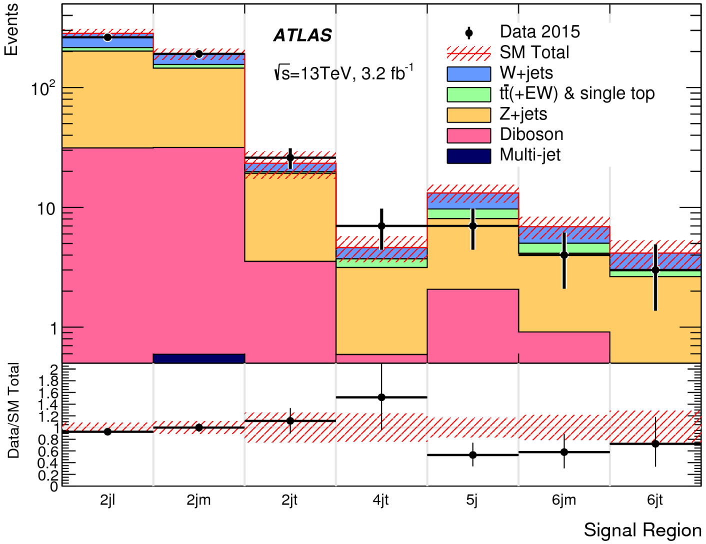
squarks/gluinos via full hadronic decay : 0L+2-6 jets + MET (3.2 fb^{-1}@ 13 TeV)

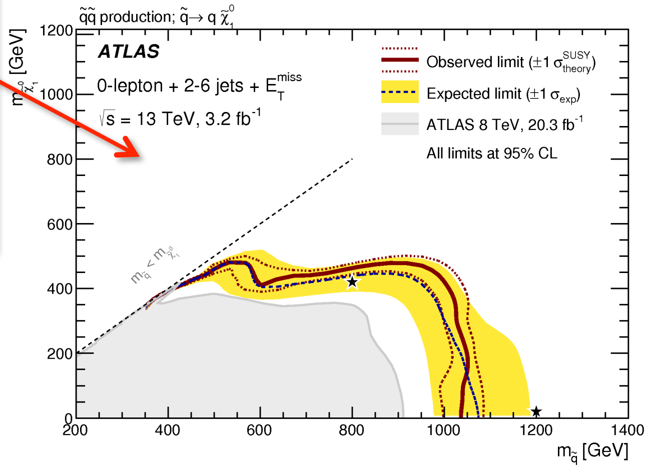
arXiv:1605.03814





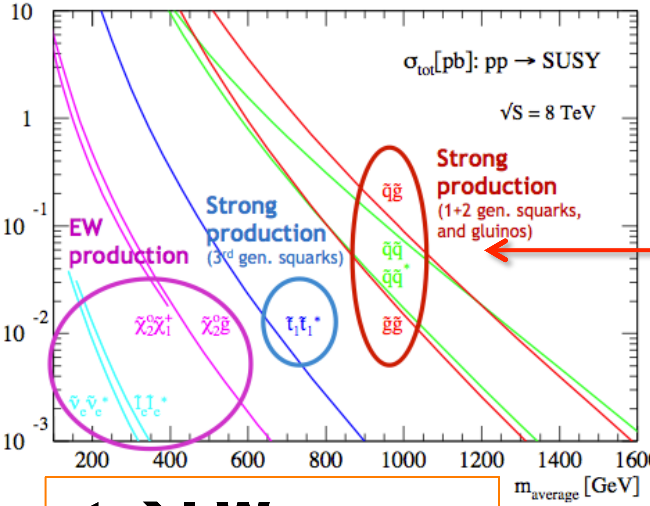


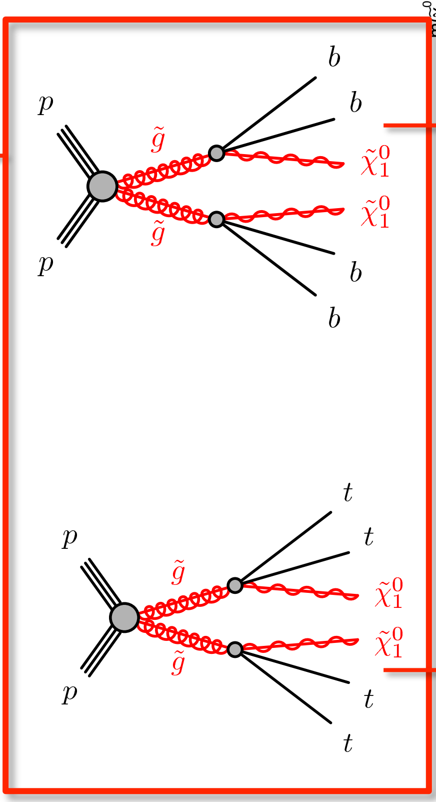


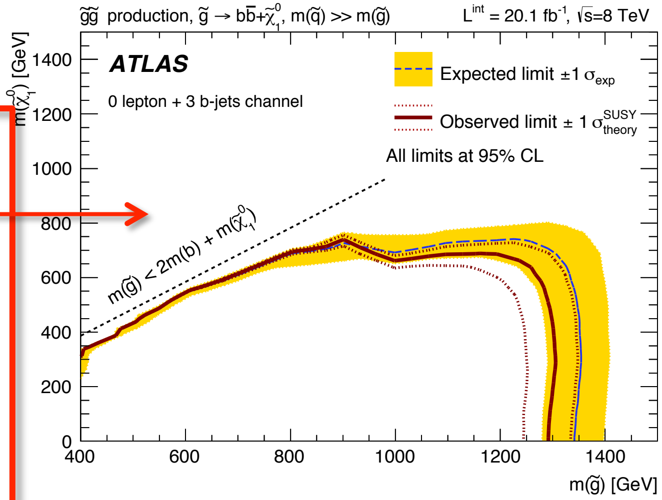


squarks/gluinos via **stop/sbottom decay**:
0-1l + 3 b-jets +MET ($20\ fb^{-1}$@ 8 TeV)

JHEP 10 (2014) 024



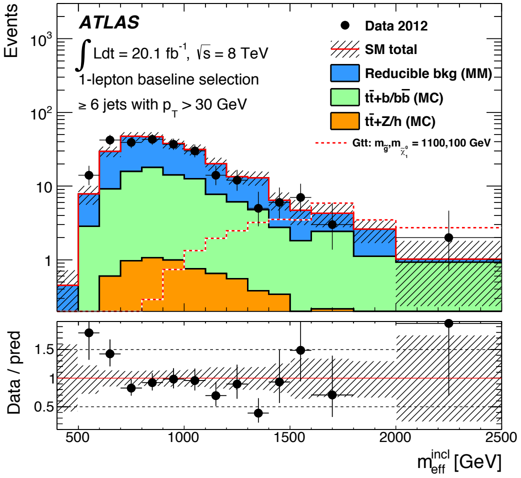


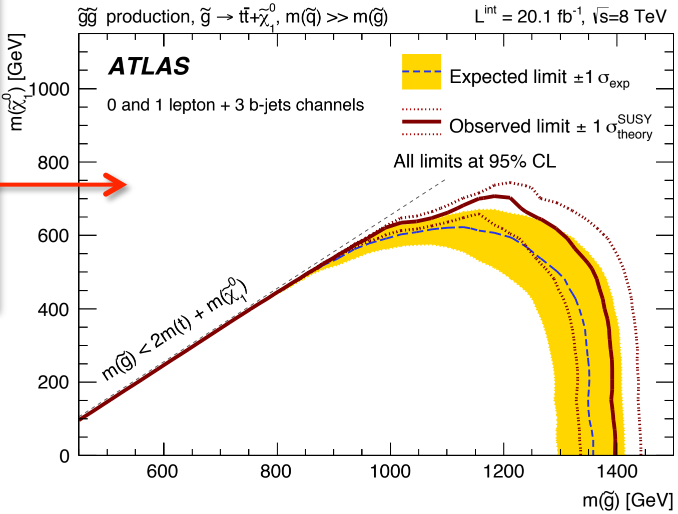


t → bW

W → l nu

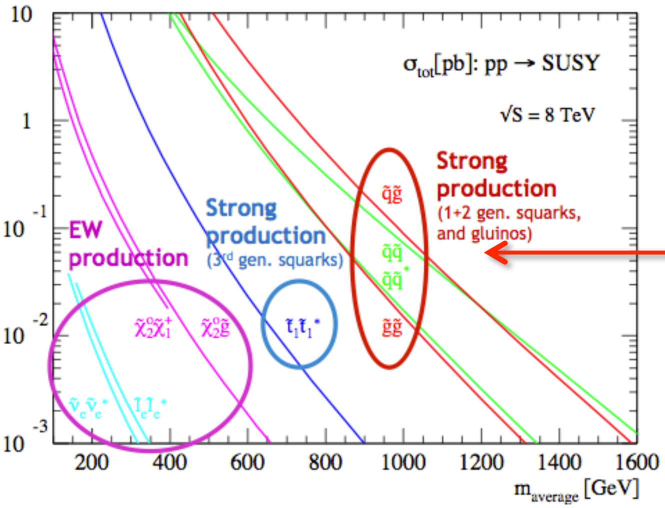
→ qq

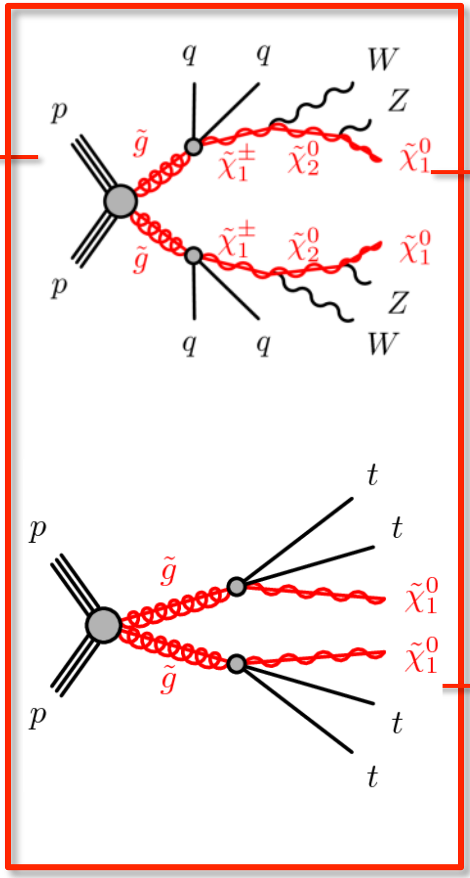


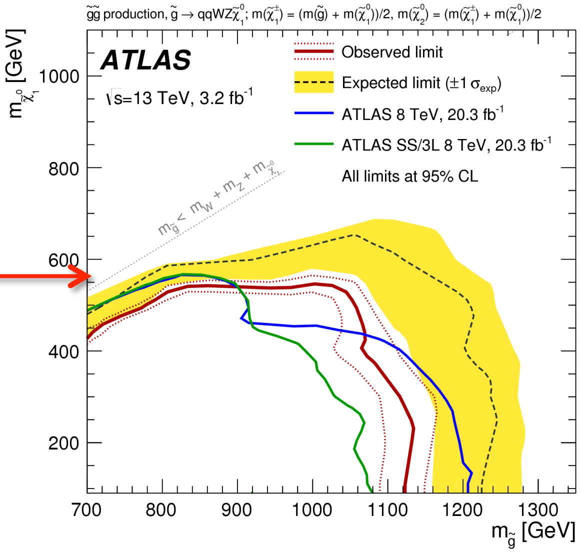


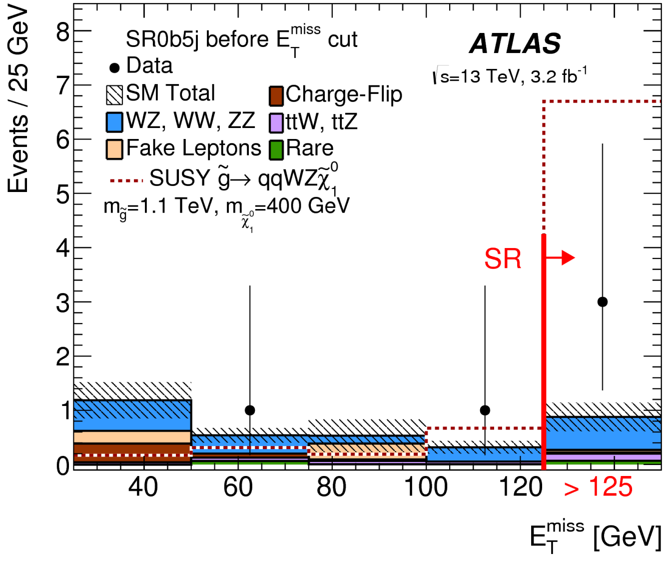
squarks/gluinos via long decay chain: SS2L/3L+jets+MET (3.2 fb^{-1}@ 13 TeV)

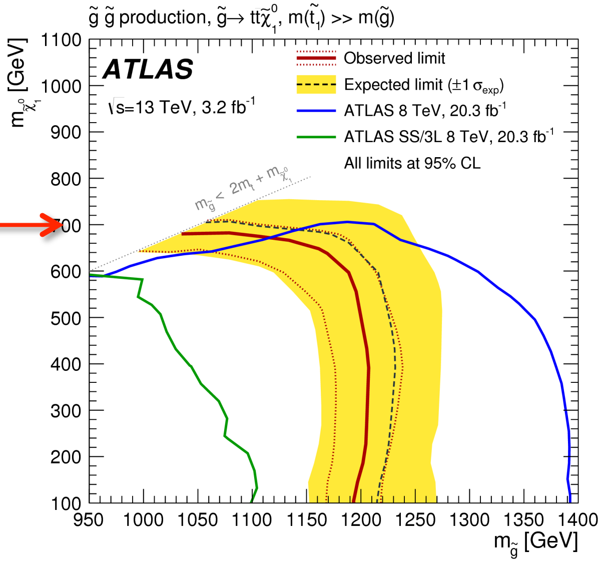
EPJC (2016), 76(5), 1-26





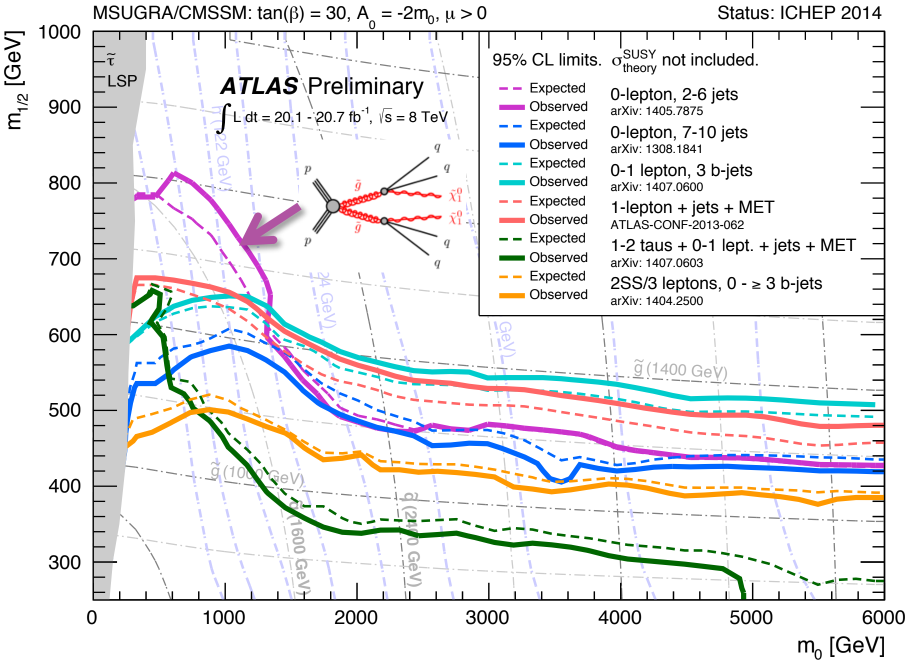




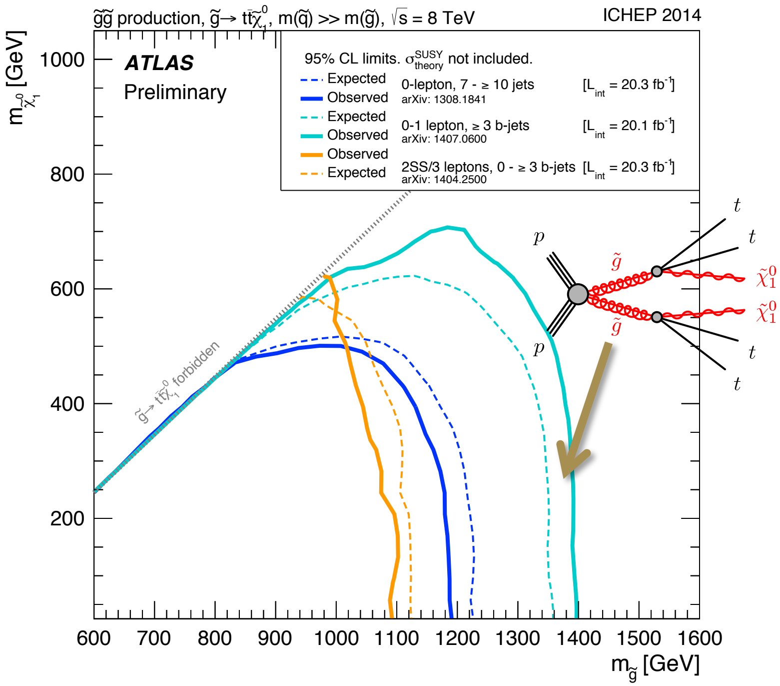


Inclusive search for squark and gluino production Summary (20 fb^{-1}@ 8 TeV)

m_0 .vs. $m_{1/2}$ (mSUGRA/cMSSM)



M(~g) .vs. m(LSP)

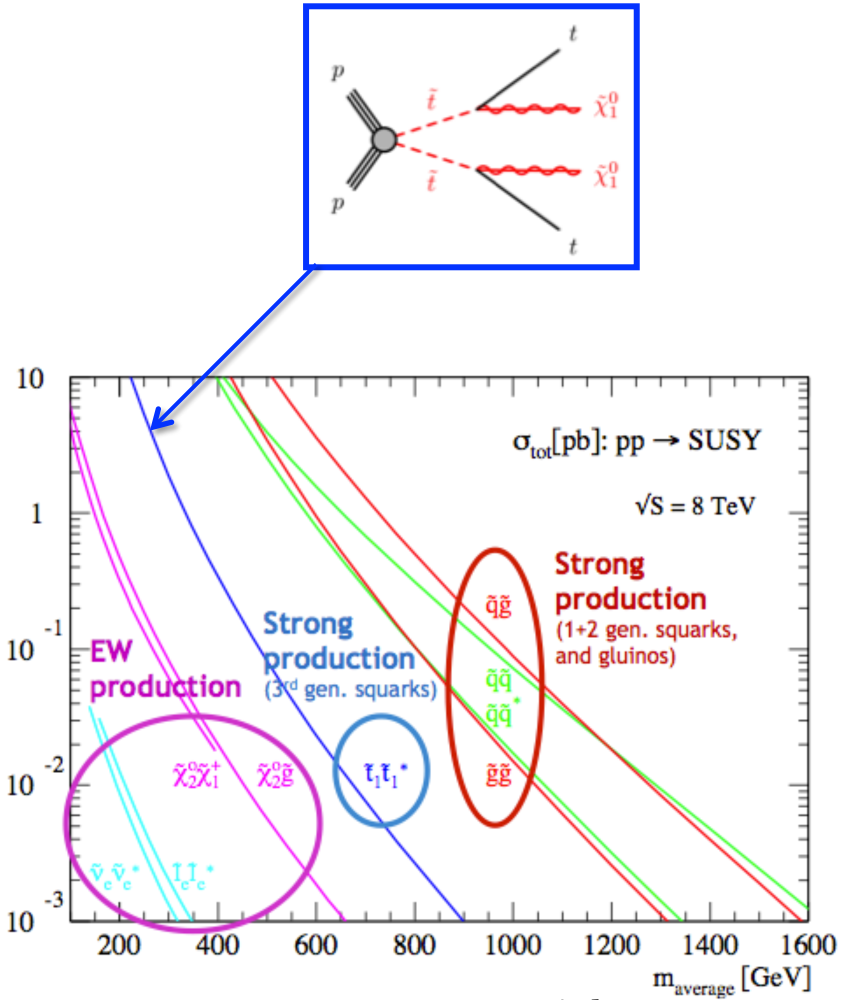


- m(~q) ~m(~g): m(~g) > 1.7 TeV
- M(~q) >> m(~g): m(~g)>1.35 TeV
- Conditional/indirect limit on LSP: m> 200-300 GeV

- No exclusion for M(LSP) ≥ 700 GeV
- Strongest limit: m(~g) ≥ 1400 GeV

Direct stop/sbottom search

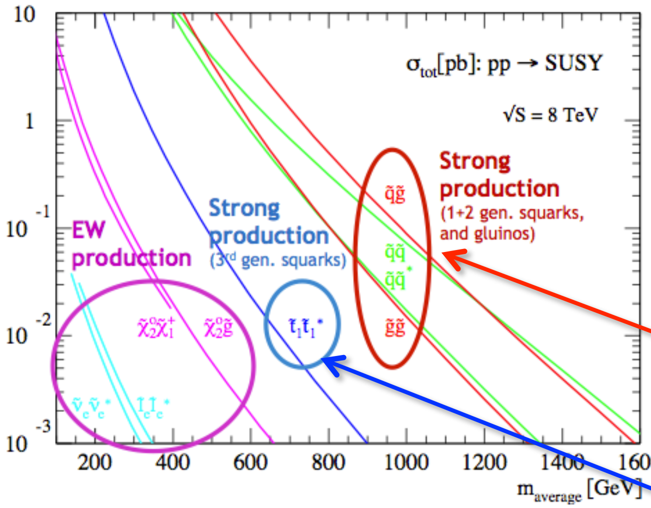
- **Light stop and sbottom is motivated by nature SUSY**
  - strong physics case for third generation squarks.
- **Generic signatures:**
  - n_lepton(n=0,1, ≥2) + multi-jets **(≥ 1 b-jets)** + large MET

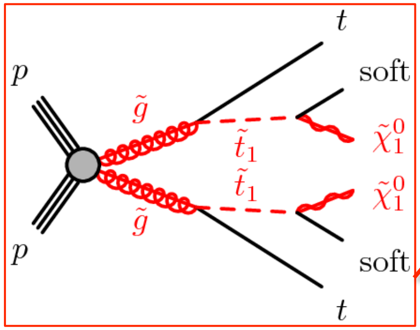


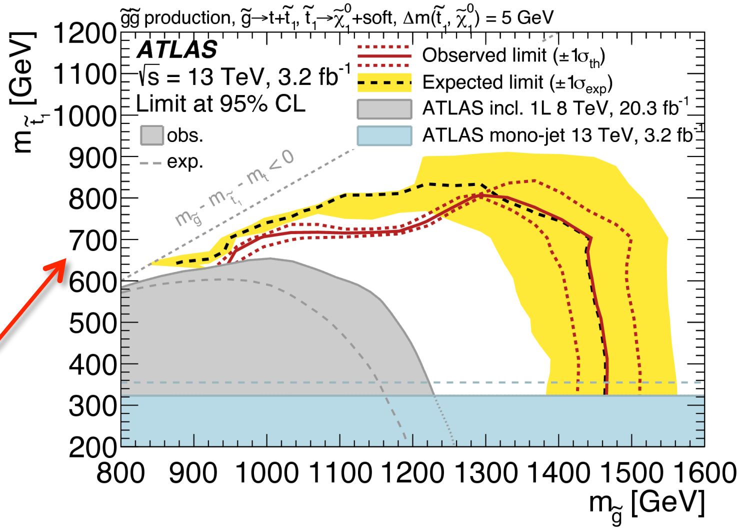
SUSY particle mass

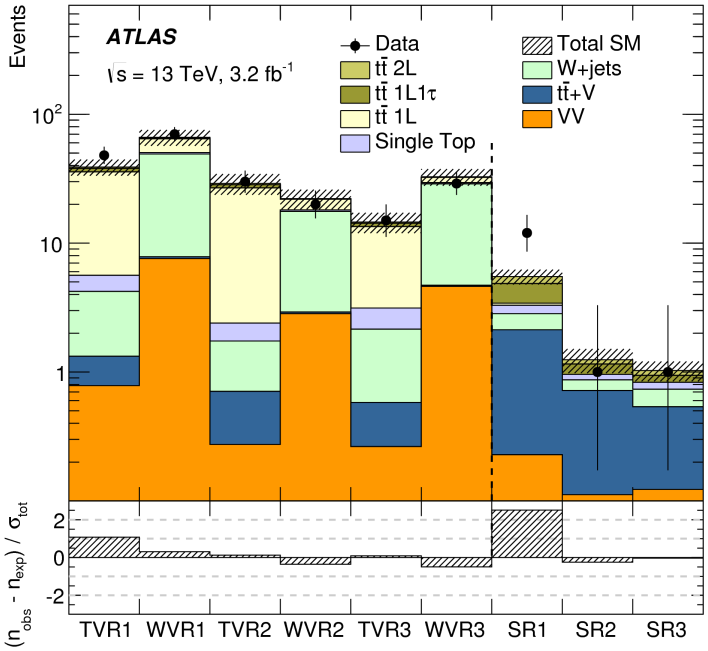
Stop search: 1L+(b-)jets+MET

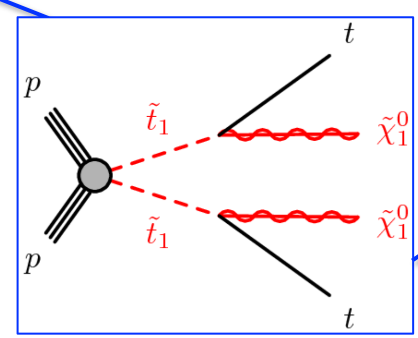
3.2 fb^{-1}@ 13 TeV
arXiv:1606.03903

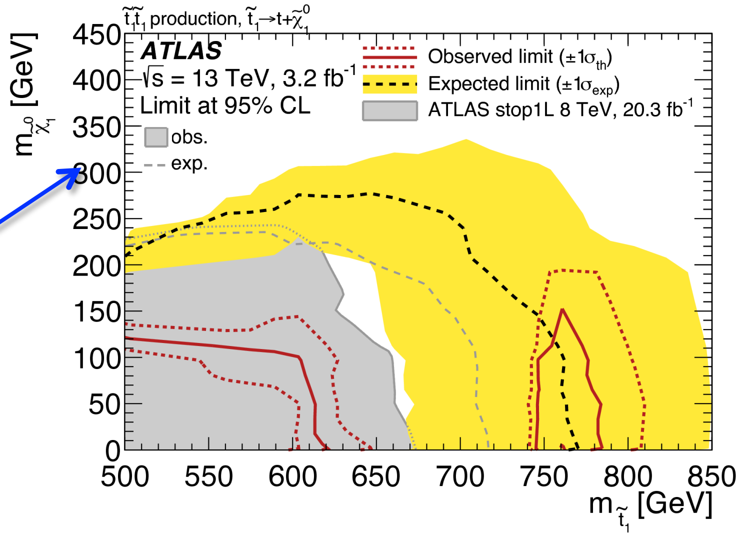








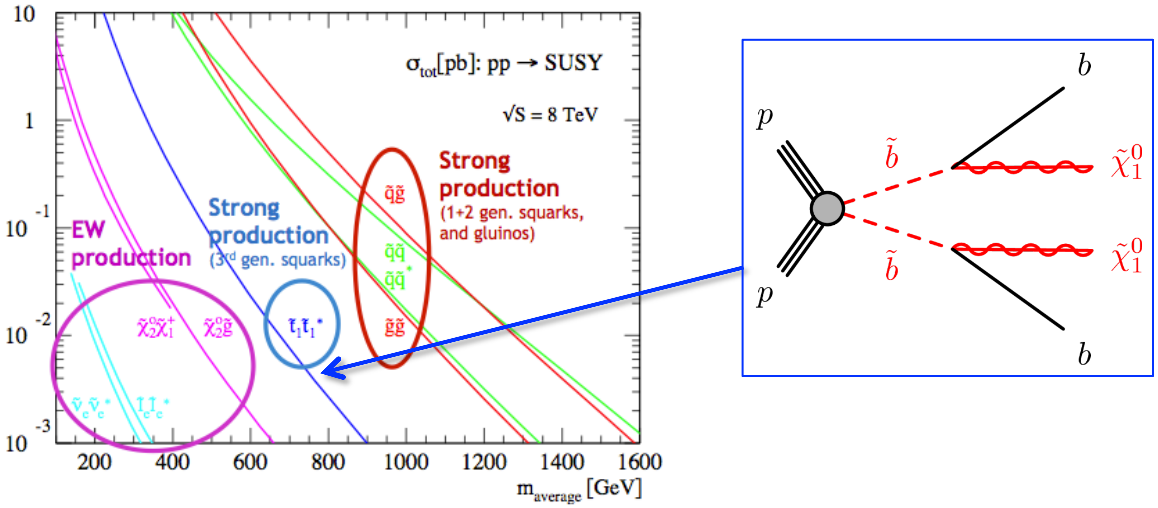


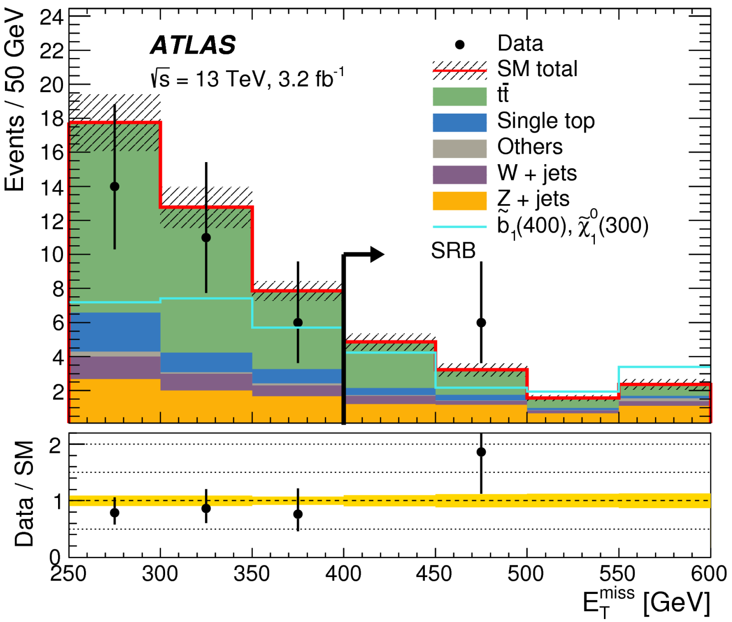


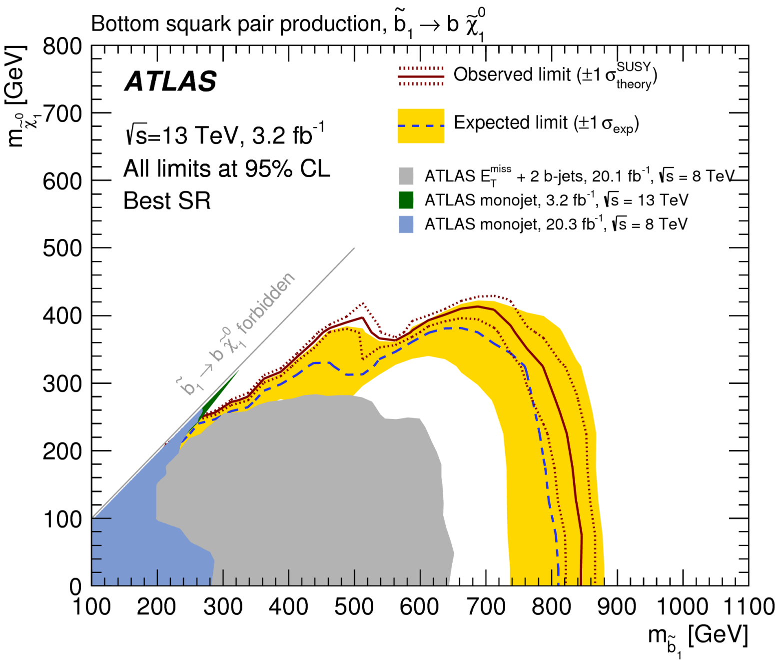
Sbottom search: 2b-jets+MET

$3.2\ \mathrm{fb}^{-1}$@ 13 TeV

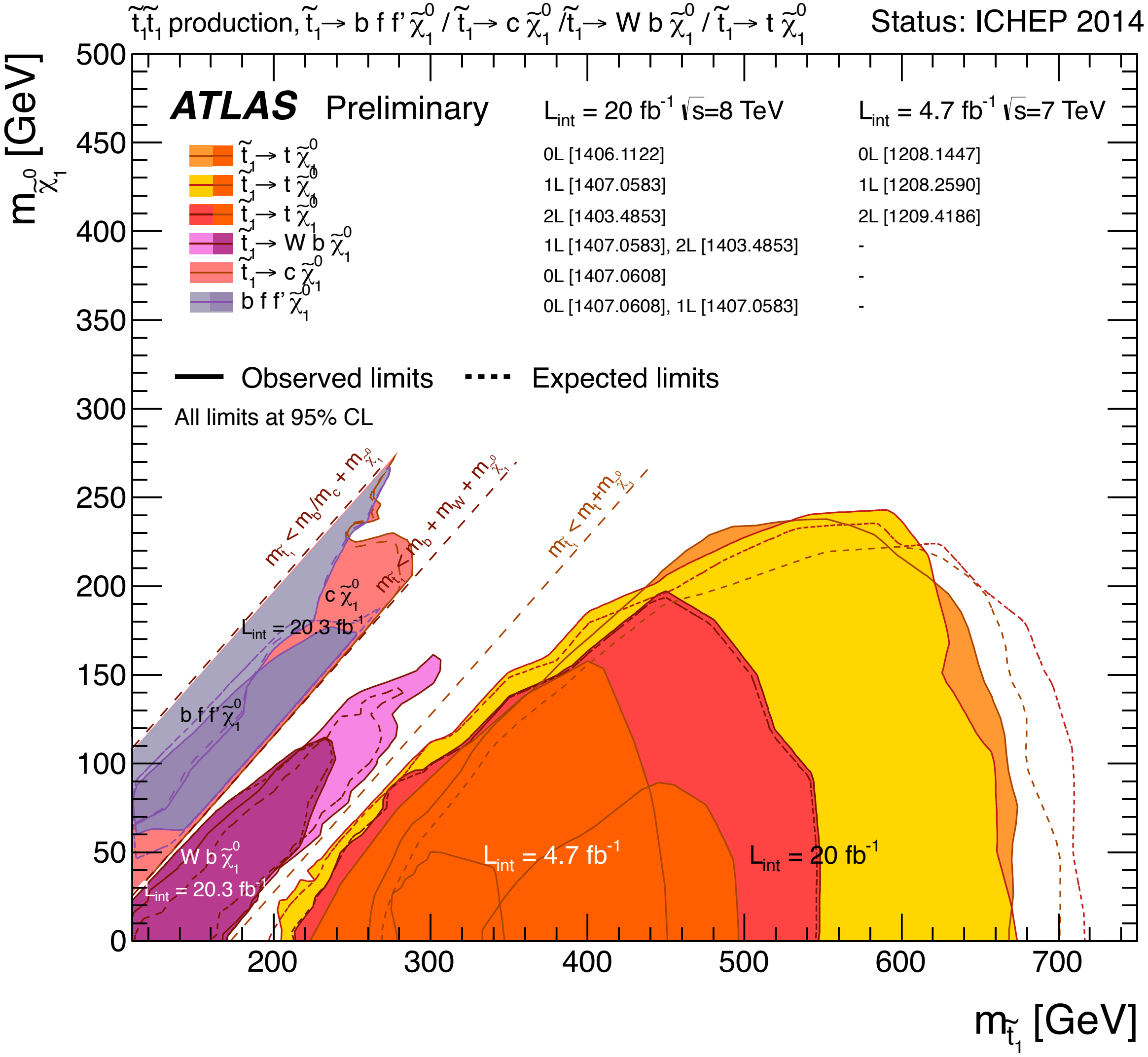
arXiv:1606.08772







Direct stop pair production Summary



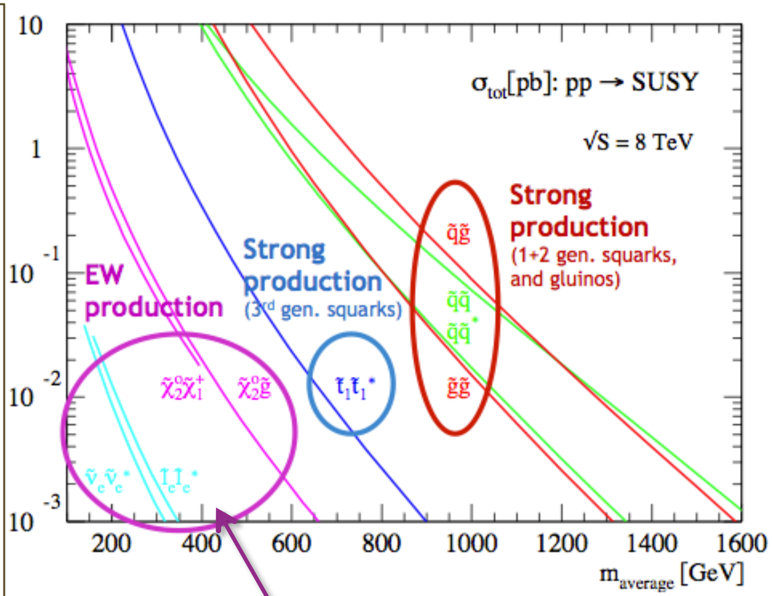
$(20\ fb^{-1}@\ 8\ TeV)$

- **Strong search program on stop, covering range from low to heavy stop mass, various decay modes.**
- **Exclusion for m(~t1) < ~660GeV for massless LSP, exclusion up to m(LSP) ~250 GeV**

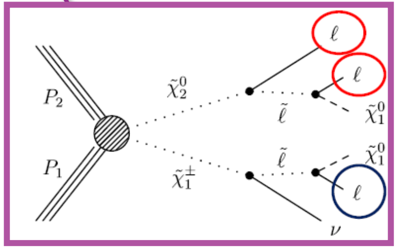
Direct EWK-ino Search

(20 fb^{-1}@ 8 TeV)

- Search for electroweak (EWK) SUSY below the TeV scale is motivated by naturalness arguments.
- EWK production has a low cross-section compared to strong production
  - Very challenging searches
  - But leads to multi-lepton signatures with very low SM background.
- If strong production is suppressed, EWK processes could be the dominant SUSY production at the LHC. (EWKino < 1 TeV)



SUSY particle mass



Generic signature: >=1 lepton(s) in the final state arising from the decay of charginos/neutralinos via sleptons/sneutrinos, gauge bosons or Higgs.

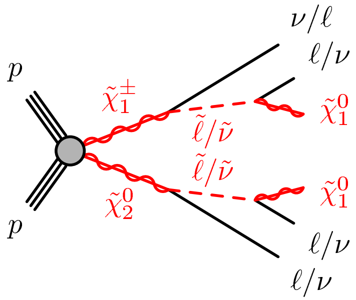
C1N2 production – 2-3L(tau)

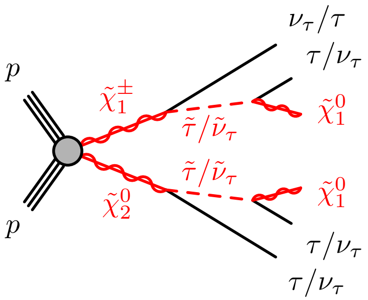
JHEP 04 (2014) 169
JHEP 05 (2014) 071
JHEP 10 (2014) 096

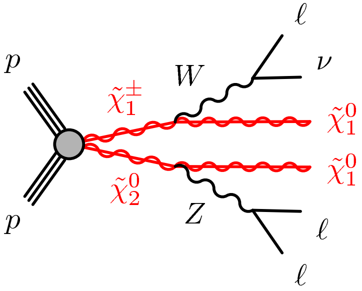
C1N2 via stlepton/sneutrino

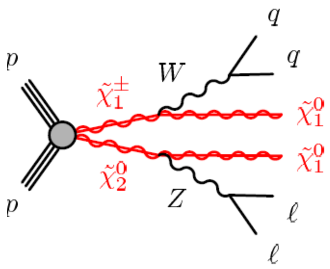
C1N2 via stau/sneutrino

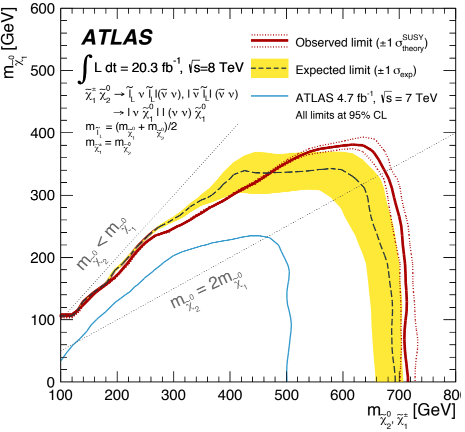
C1N2 via WZ

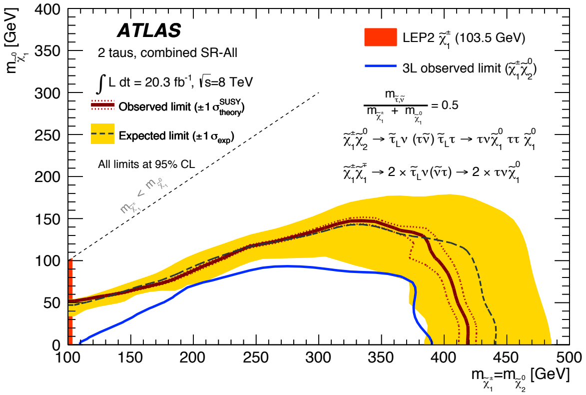


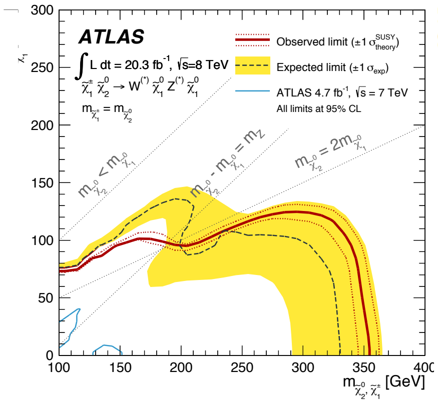


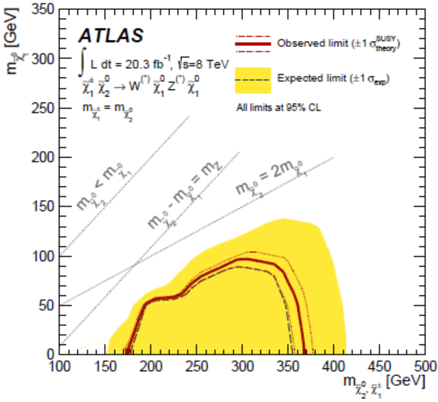








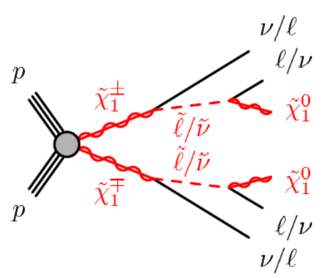


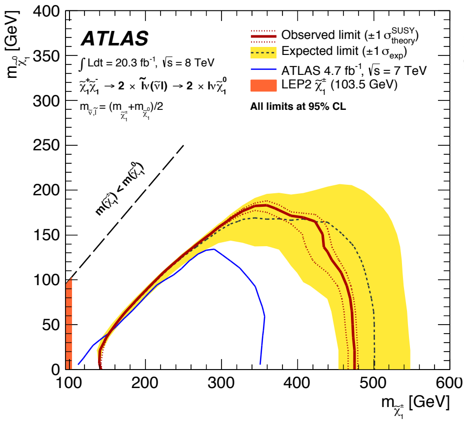


C1C1 production – 2L(tau)

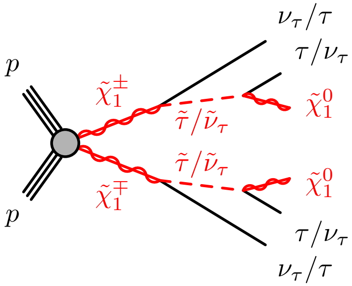
JHEP 05（2014）071
JHEP 10（2014）096

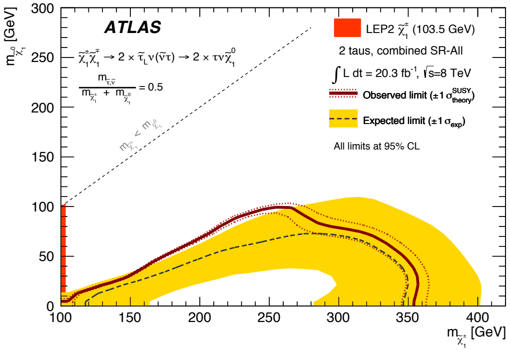
C1C1 via slepton/ sneutrino



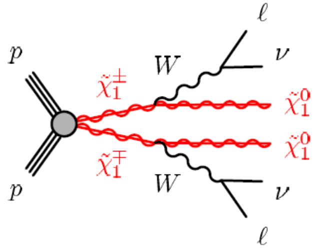


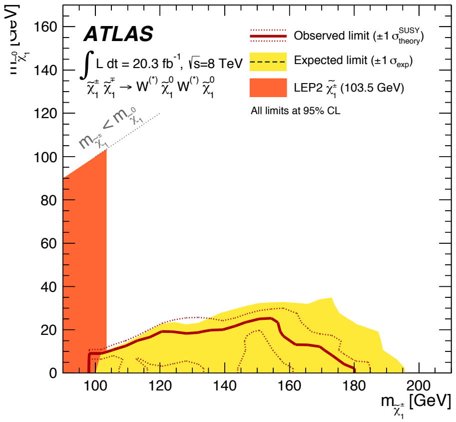
C1C1 via Stau/sneutrino



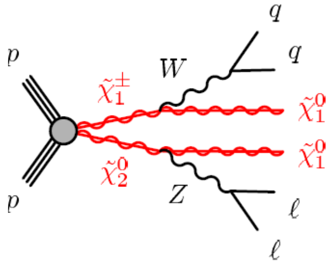


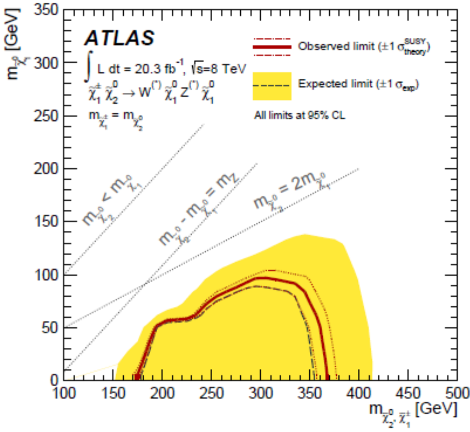
C1C1 via WW





C1N2 via WZ

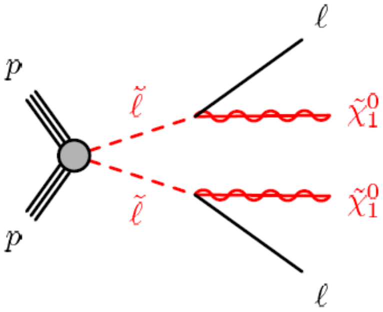


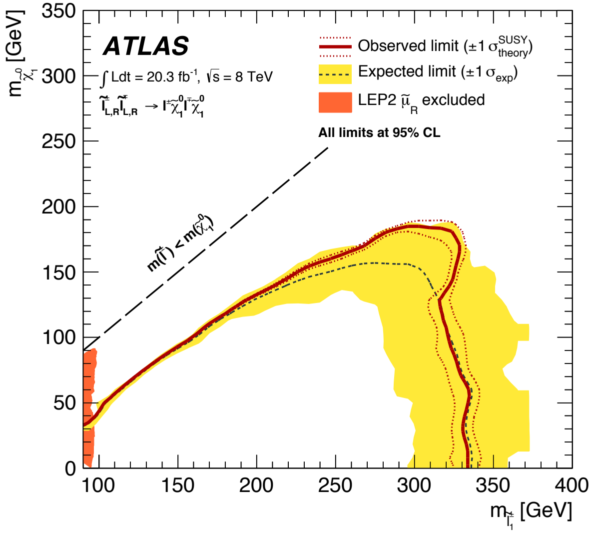


~l~l production – 2L(tau)

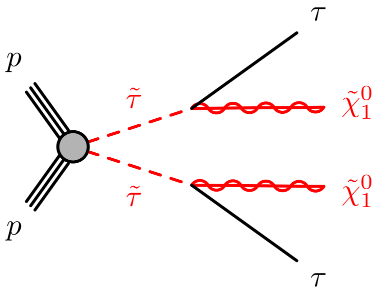
JHEP 05（2014）071
JHEP 10（2014）096

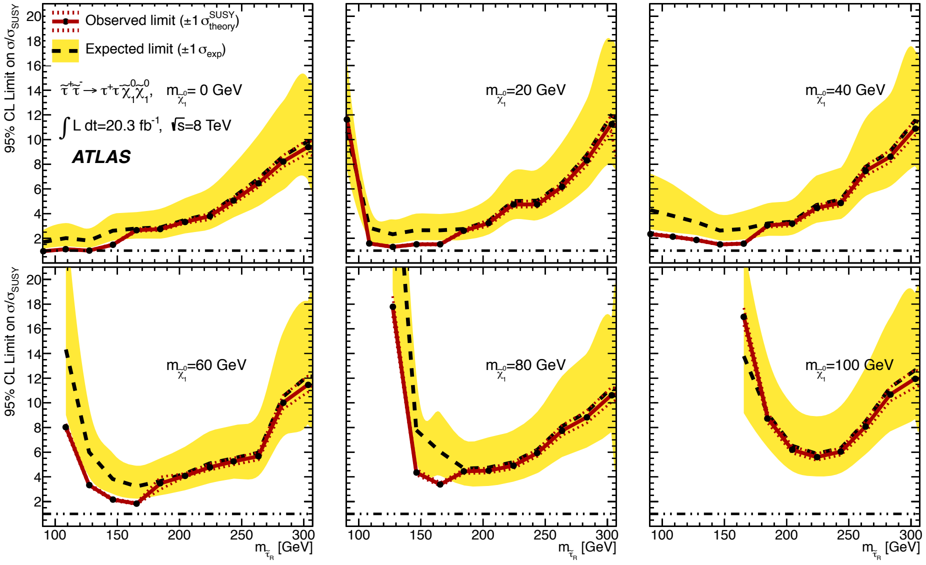
Direct slepton pair





Direct stau pair

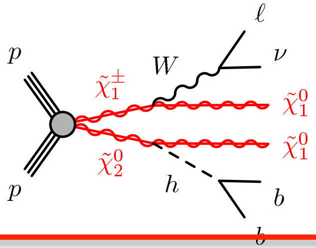




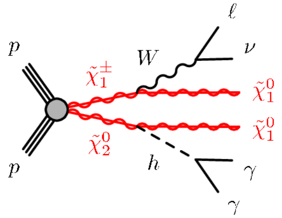
Electroweak production – Wh

[direct C1N2 production via higgs]

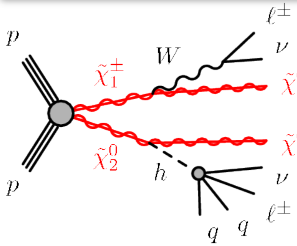
C1N2 via Wh, 1Lbb



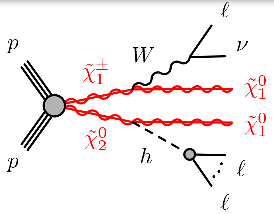
C1N2 via Wh, 1Lγγ



C1N2 via Wh, SS2L

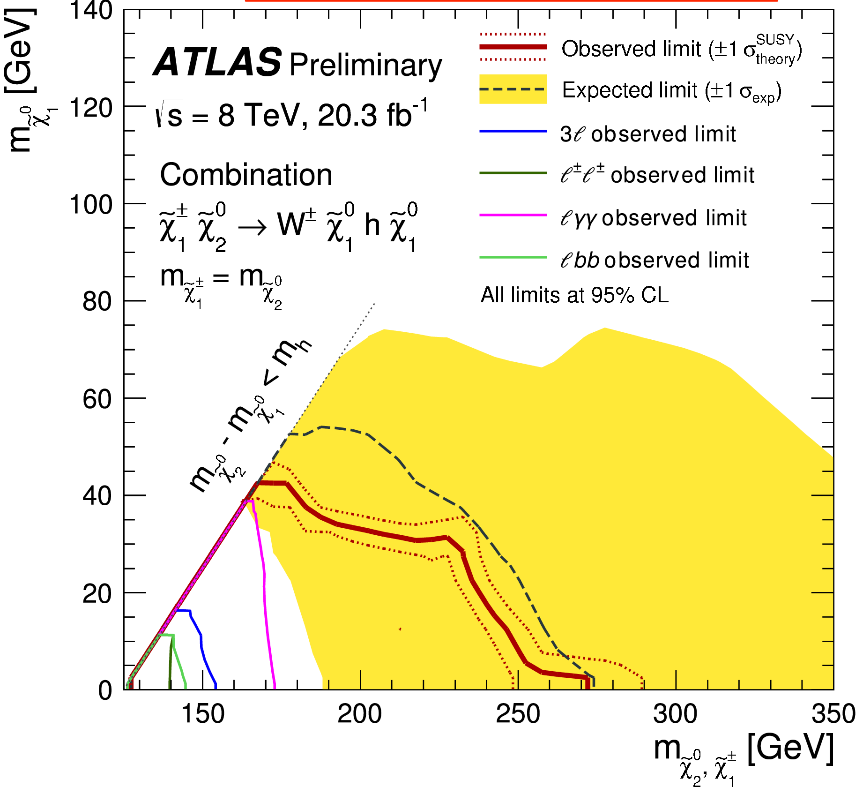


C1N2 via Wh,3L



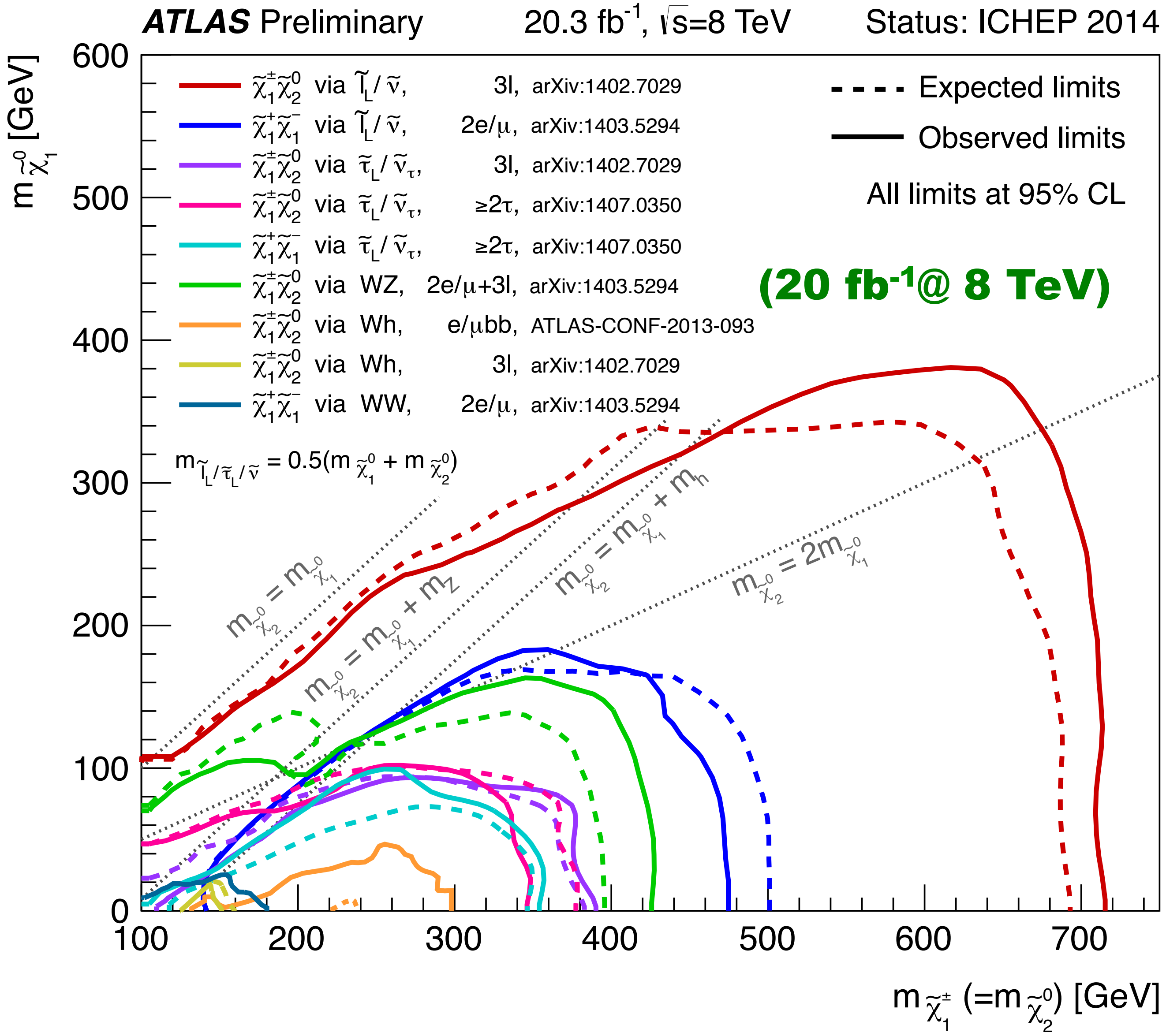
ATLAS−CONF−2014−062

JHEP 04（2014）169



- Electroweakino mass > 250 GeV for massless LSP in models with higgs in decay
- For chargino mass < 170 GeV all channels contribute
- For chargino mass > 170 1L +bb channel dominates
- 1L+bb sensitivity varies slowly due to decreasing XS

ElectroWeak Production Summary



(20 fb^{-1}@ 8 TeV)

Outline

- SUSY Introduction
- The LHC and ATLAS
- Overview of SUSY search results on run-1 data
- *Outlook and Summary*

Outlook and Summary

- **ATLAS developed a vast program to search for SUSY**
  - No significant excess seen so far
  - All public results:

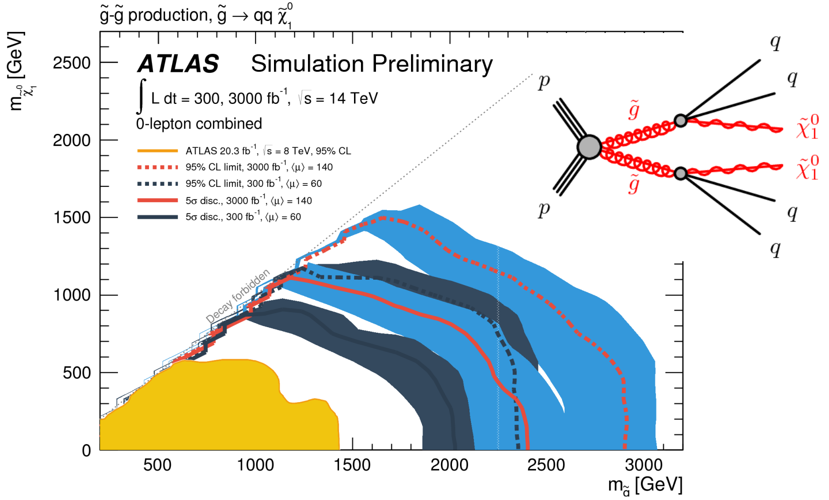
    https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

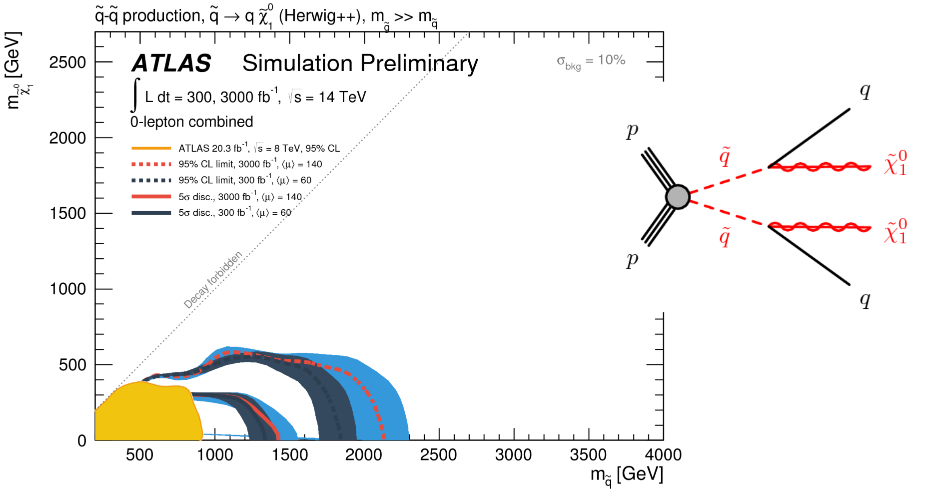
- **The reach with SUSY is expected to increase significantly at run2 and run3 ☺**

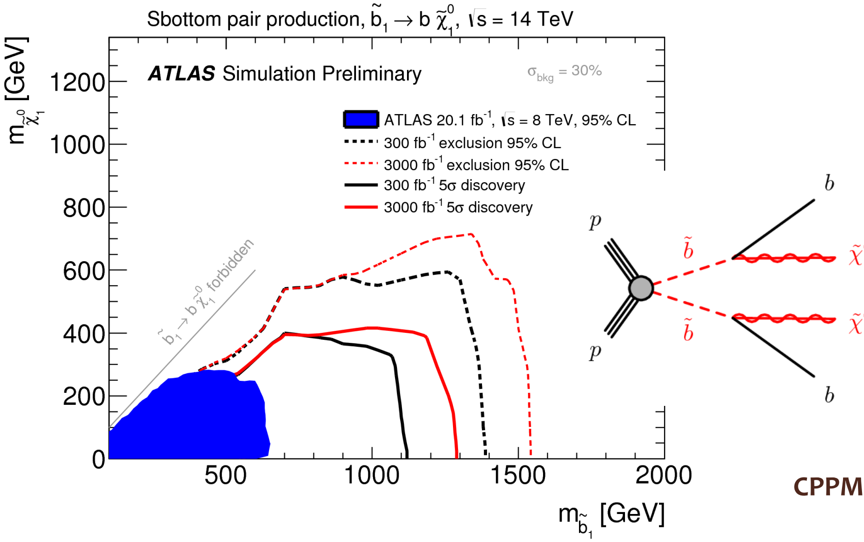
Long term prospects

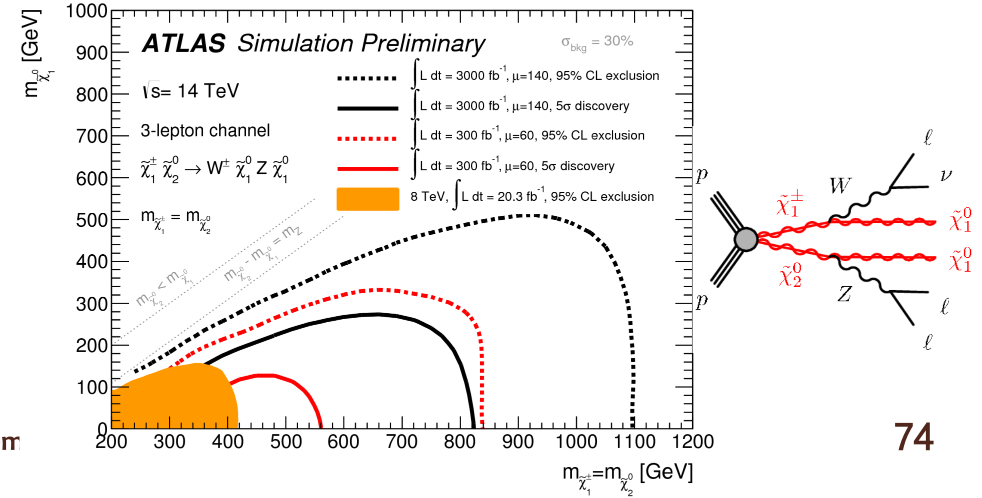
ATL-PHYS-PUB-2014-010

- ATLAS studied long term prospects for the (HL-)LHC with 300, 3000 fb^{-1}@14 TeV
- Discovery potential up **to 2.5 TeV gluinos, 1.3 TeV squarks/sbottom and 800 GeV Electroweakinos**









Exciting times are ahead of us !

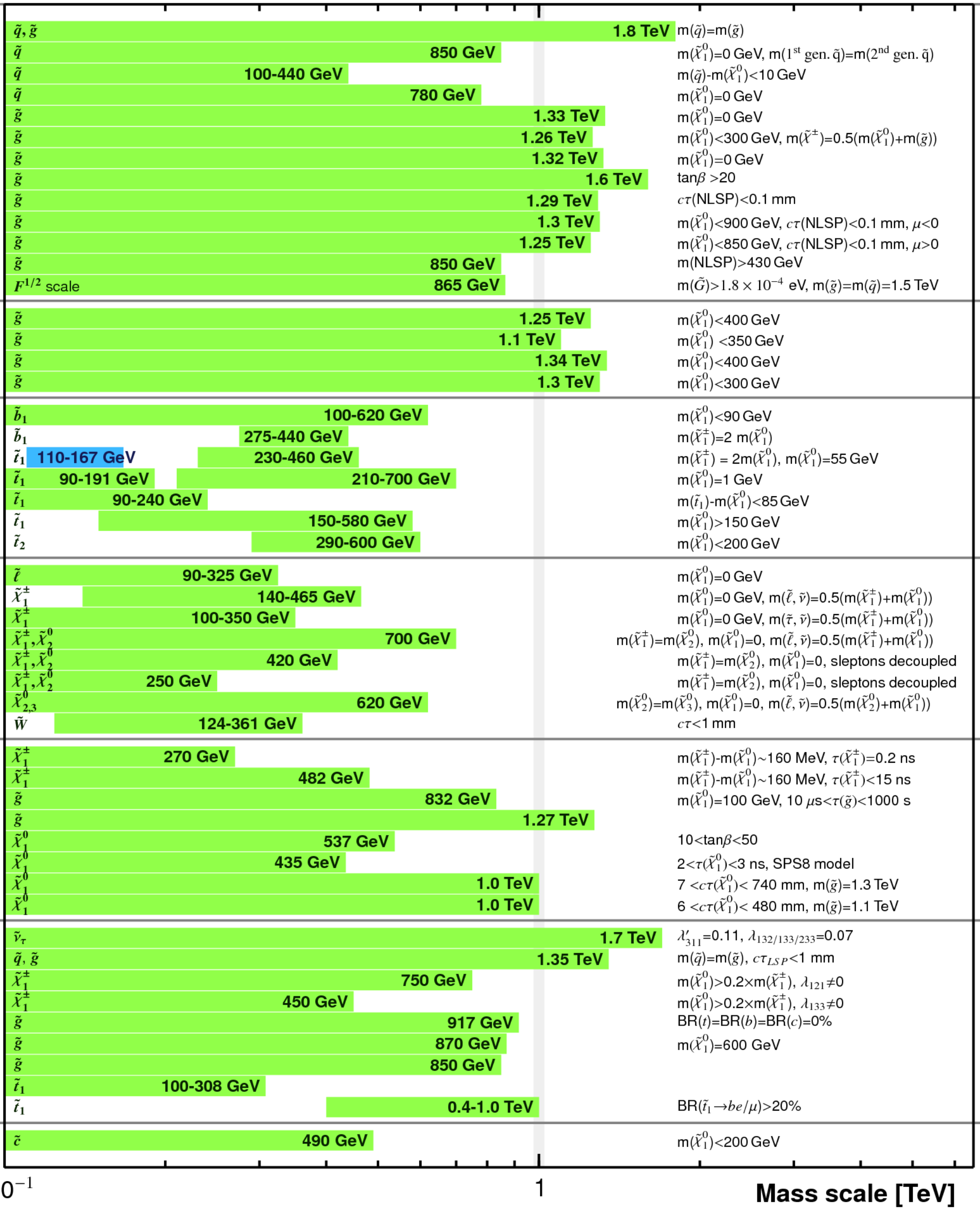
ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

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

🟦 $\sqrt{s}$ = 7 TeV   🟩 $\sqrt{s}$ = 8 TeV

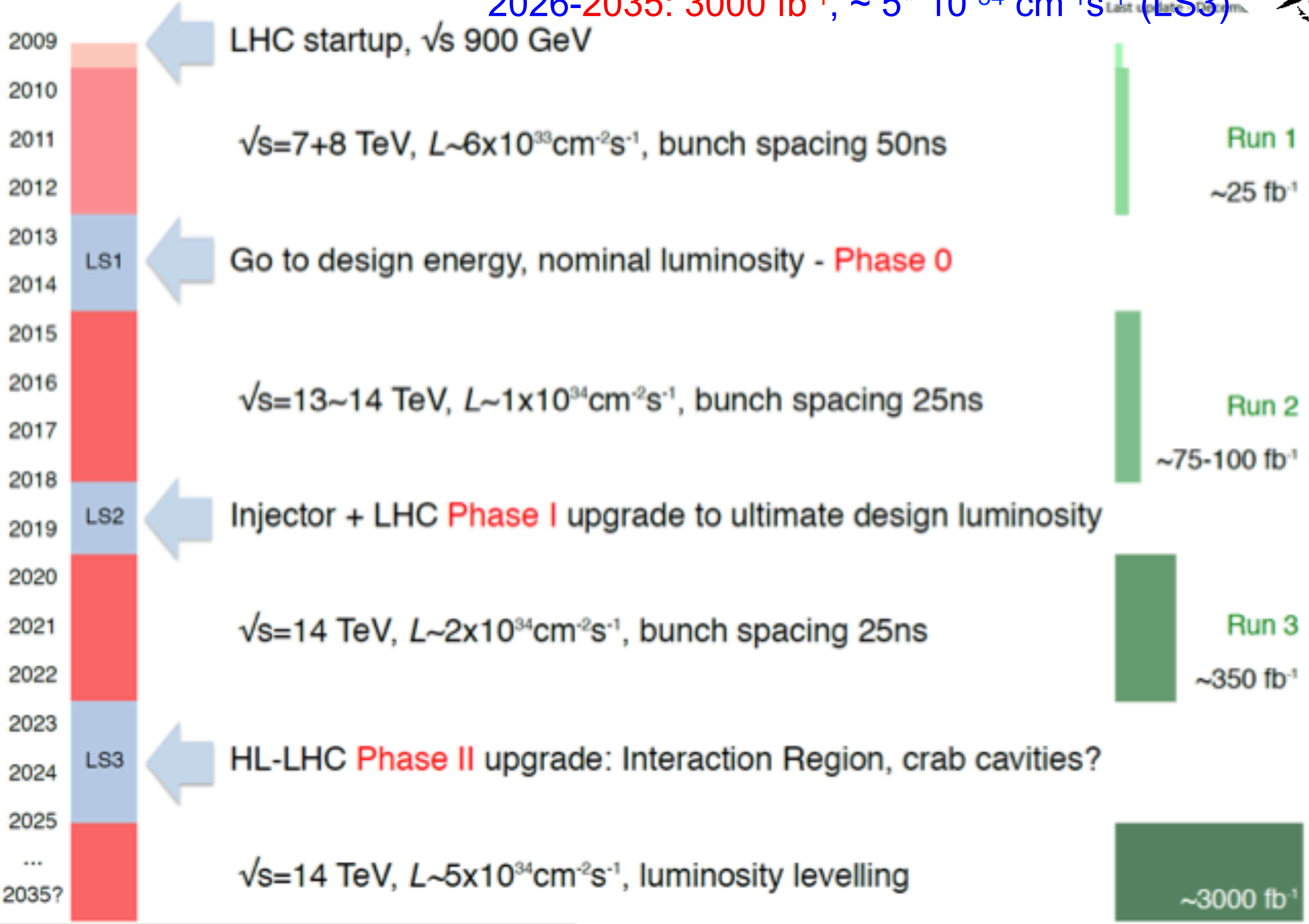


	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.8 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	20.3	$\tilde{q}$ 100-440 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<10 GeV	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ (off-Z)	2 jets	Yes	20.3	$\tilde{q}$ 780 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1503.03290
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0-1 e,μ	2-6 jets	Yes	20	$\tilde{g}$ 1.26 TeV	m($\tilde{\chi}_1^0$)<300 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	1507.05525
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.29 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 1.3 TeV	m($\tilde{\chi}_1^0$)<900 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	$\tilde{g}$ 1.25 TeV	m($\tilde{\chi}_1^0$)<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 850 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	m($\tilde{G}$)>1.8×10^{-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	20.1	$\tilde{g}$ 1.25 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 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	20.1	$\tilde{b}_1$ 100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	m($\tilde{\chi}_1^{\pm}$)=2 m($\tilde{\chi}_1^0$)	1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7/20.3	$\tilde{t}_1$ 🟦 110-167 GeV 🟩 230-460 GeV	m($\tilde{\chi}_1^{\pm}$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$ 90-191 GeV, 210-700 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 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	20.3	$\tilde{t}_2$ 290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 700 GeV	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($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 420 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 250 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons 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	$\tilde{\chi}_{2,3}^0$ 620 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.	1 $e,\mu+\gamma$	-	Yes	20.3	$\tilde{W}$ 124-361 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	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$ 482 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795
	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	$\tilde{\chi}_1^0$ 435 GeV	2<τ($\tilde{\chi}_1^0$)<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 $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$ 1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu$, $e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e$, $e\tau\tilde{\nu}_\tau$	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	6-7 jets	-	20.3	$\tilde{g}$ 917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 870 GeV	m($\tilde{\chi}_1^0$)=600 GeV	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	20.3	$\tilde{t}_1$ 100-308 GeV		ATLAS-CONF-2015-026
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 490 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

LHC roadmap

2015-2017: 100 fb^{-1}, ~ 1* 10 ^{34} $cm^{-1}s^{-1}$ (LS1)
2020-2022: 300 fb^{-1}, ~ 2* 10 ^{34} $cm^{-1}s^{-1}$ (LS2)
2026-2035: 3000 fb^{-1}, ~ 5* 10 ^{34} $cm^{-1}s^{-1}$ (LS3)



LHC startup, √s 900 GeV

√s=7+8 TeV, L~6x10^{33}cm^{-2}s^{-1}, bunch spacing 50ns

Go to design energy, nominal luminosity - Phase 0

√s=13~14 TeV, L~1x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns

Injector + LHC Phase I upgrade to ultimate design luminosity

√s=14 TeV, L~2x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns

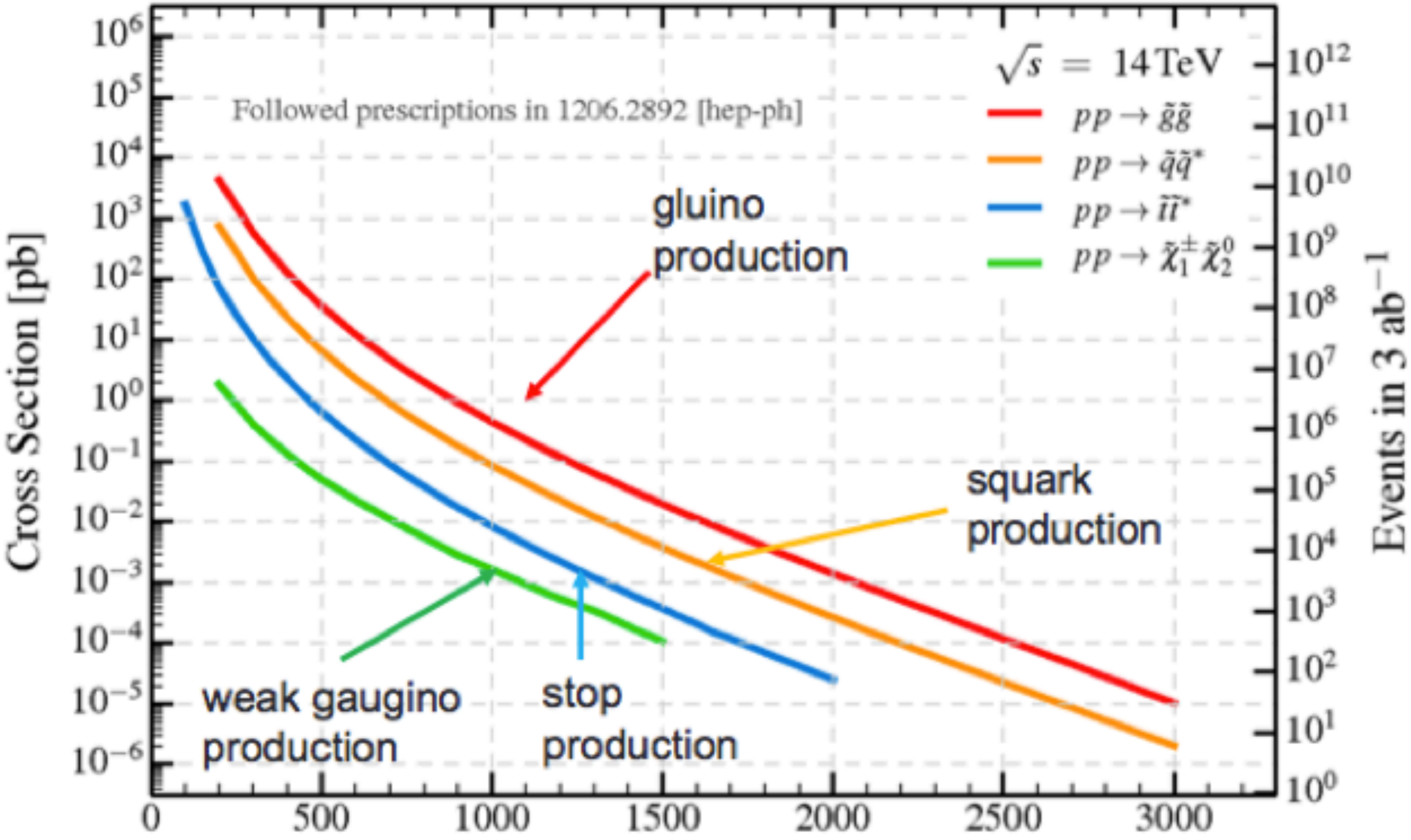
HL-LHC Phase II upgrade: Interaction Region, crab cavities?

√s=14 TeV, L~5x10^{34}cm^{-2}s^{-1}, luminosity levelling

From LHCC Open meeting, 03.12.2013

SUSY Search at HL-LHC

- Limits set by Run-1 LHC: $m_{\tilde{q}} < 0.7$ TeV, $m_{\tilde{g}} < 1.3$ TeV
- Less stringent limits on sleptons, 3rd generation squark, weak gauginos
  - → Accessible at HL-LHC



1-lepton stop search: 2/3/4-body decay to LSP

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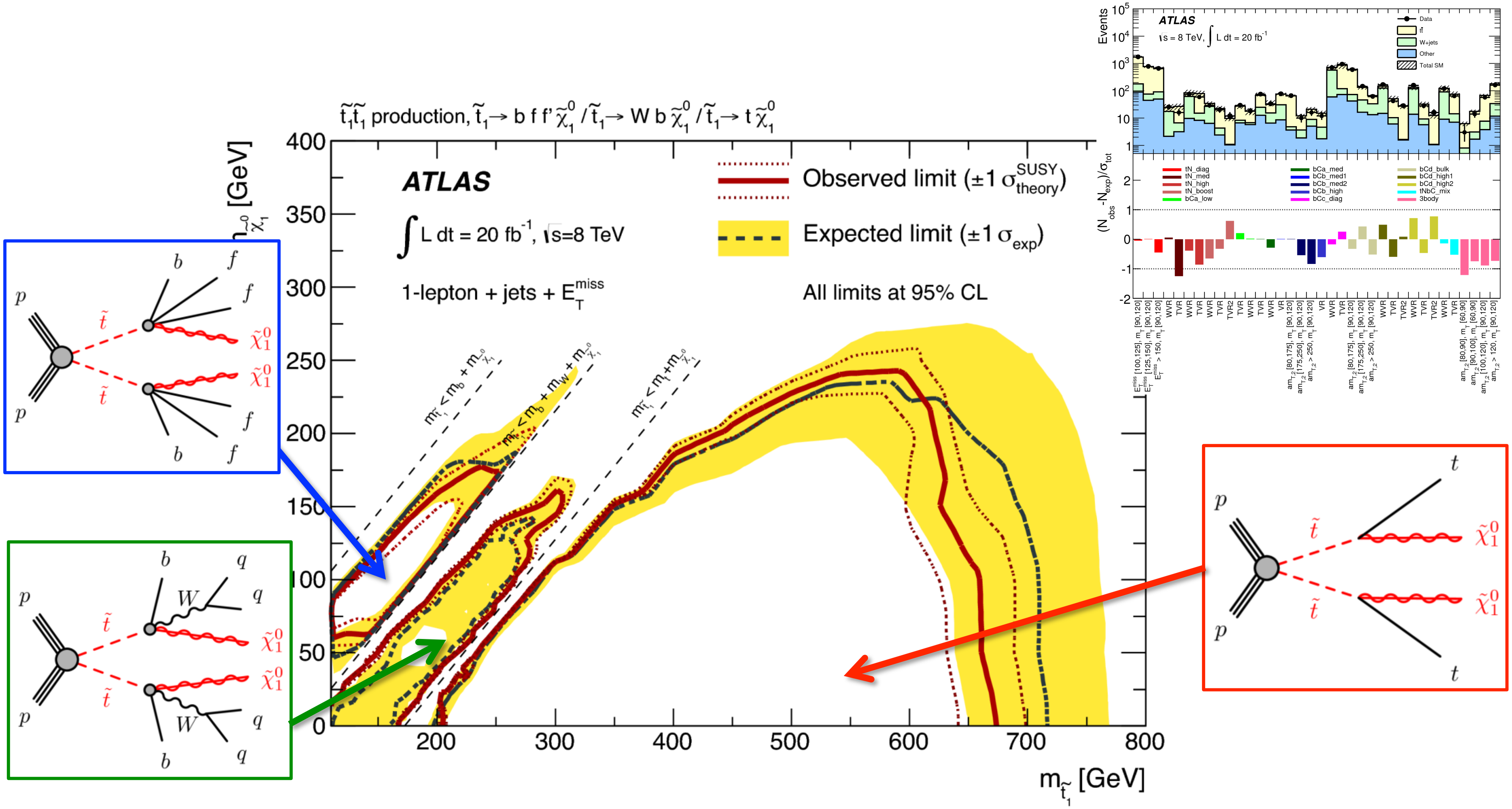


Minimal Supersymmetric Standard Model

Standard Model Particles and Fields		Supersymmetric Partners			
		Interaction Eigenstates		Mass Eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = u, d, c, s, t, b$	quark	$\tilde{q}_L, \tilde{q}_R$	**squark**	$\tilde{q}_1, \tilde{q}_2$	**squark**
$l = e, \mu, \tau$	lepton	$\tilde{l}_R, \tilde{l}_L$	**slepton**	$\tilde{l}_1, \tilde{l}_2$	**slepton**
$l = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	**sneutrino**	$\tilde{\nu}$	**sneutrino**
g	gluon	$\tilde{g}$	**gluino**	$\tilde{g}$	**gluino**
$W^\pm$	W-boson	$\tilde{W}^\pm$	**wino**	$\tilde{\chi}^\pm_{1,2}$	**chargino**
H_u^+, H_d^-	charged Higgs boson	$\tilde{H}_u^+, \tilde{H}_d^-$	**charged higgsino**		
B	B-field	$\tilde{B}$	**bino**	$\tilde{\chi}^0_{1,2,3,4}$	**neutralino**
W^0	W^0-field	$\tilde{W}^0$	**wino**		
H_u^0, H_d^0	neutral Higgs boson	$\tilde{H}_u^0, \tilde{H}_d^0$	**neutral higgsino**		

LHC

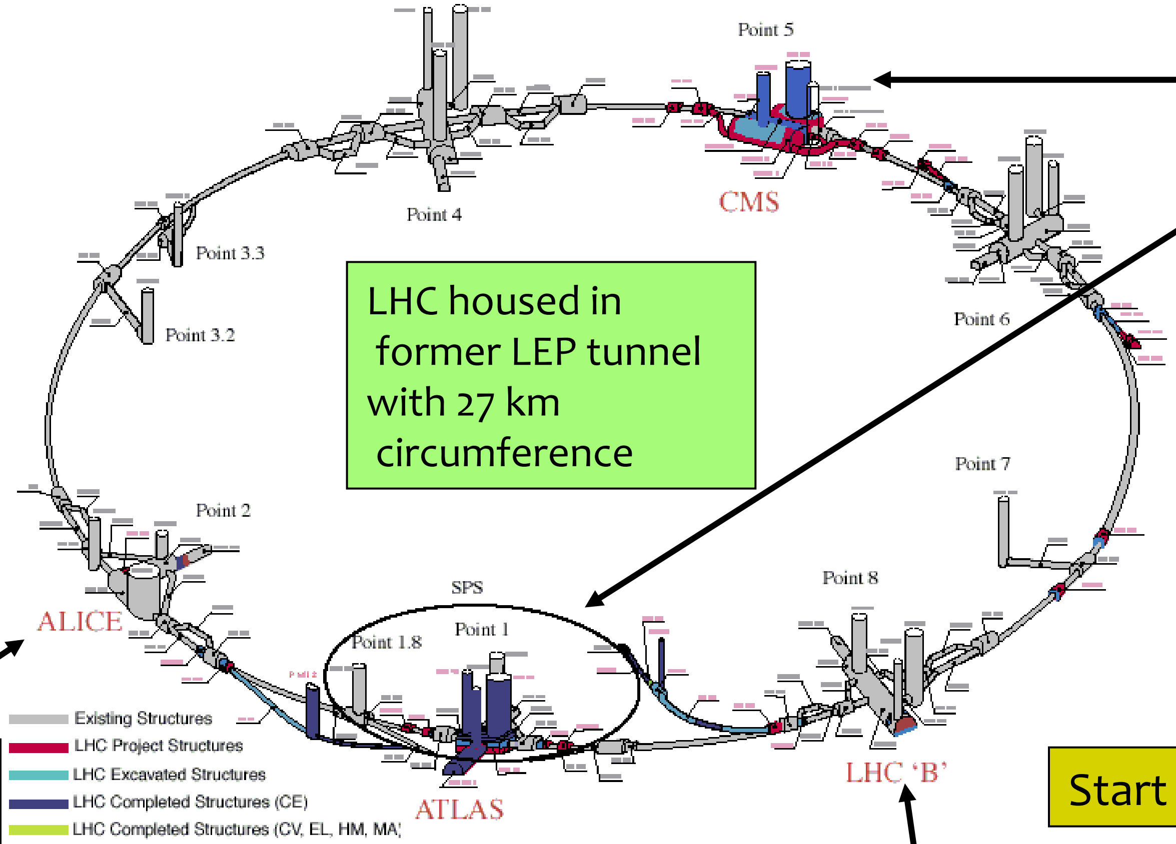
pp

- $\sqrt{s}$ = 14 TeV (7 times higher than Tevatron/Fermilab)

  → search for new massive particles up to m ~ 5 TeV

- L_{design} = 10^{34} cm^{-2} s^{-1} (>10^2 higher than Tevatron/Fermilab)

  → search for rare processes with small σ ($N = L\sigma$)



LHC housed in former LEP tunnel with 27 km circumference

ATLAS and CMS : pp, general purpose

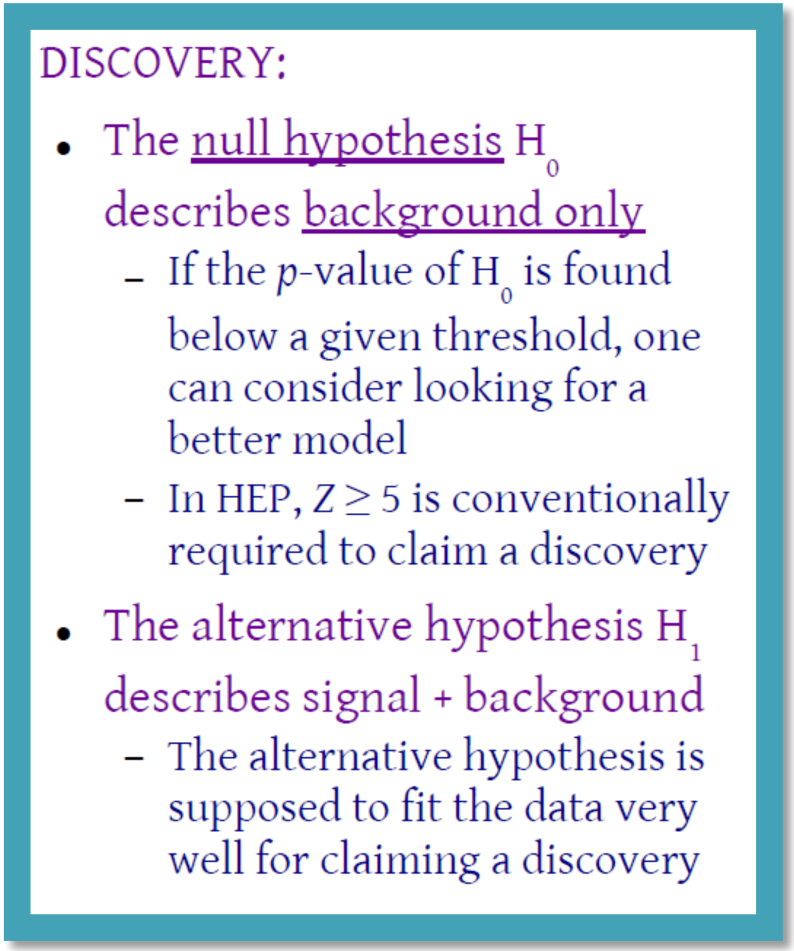
ALICE : heavy ions

LHCb : pp, B-physics

Start : Winter 2009

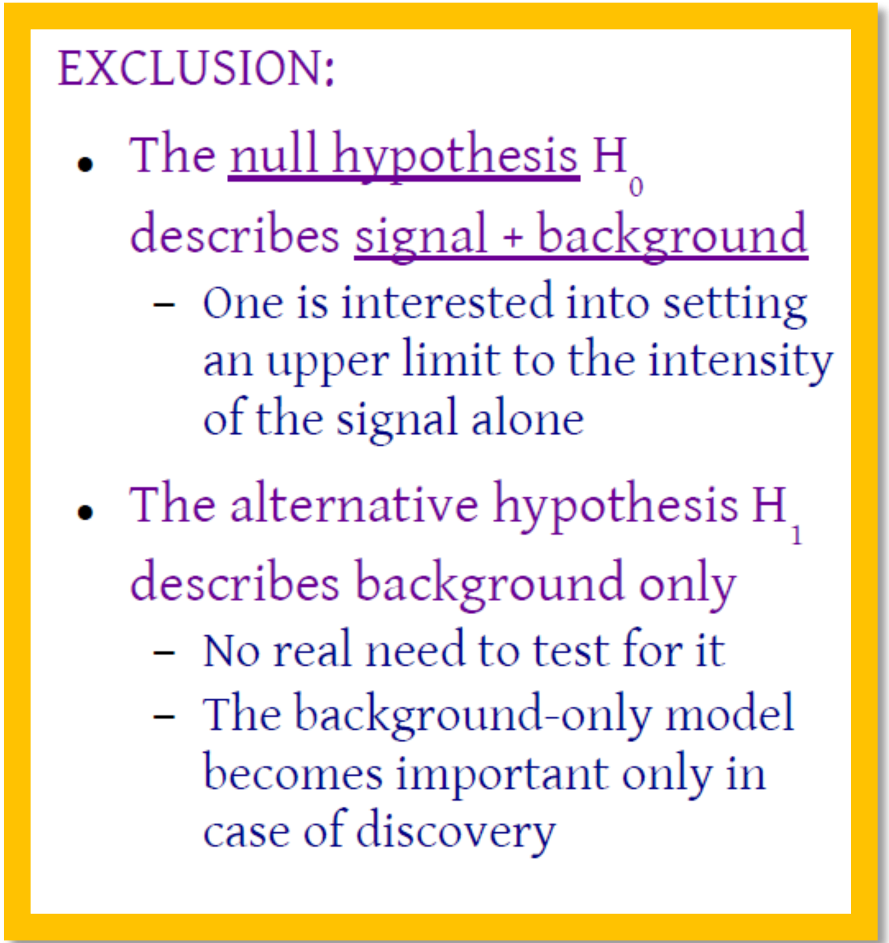
Discovery and exclusion

- P-value=probability that result is as/less compatible with the hypothesis



DISCOVERY:

- The null hypothesis H_0 describes background only
  - If the p-value of H_0 is found below a given threshold, one can consider looking for a better model
  - In HEP, $Z \geq 5$ is conventionally required to claim a discovery
- The alternative hypothesis H_1 describes signal + background
  - The alternative hypothesis is supposed to fit the data very well for claiming a discovery



EXCLUSION:

- The null hypothesis H_0 describes signal + background
  - One is interested into setting an upper limit to the intensity of the signal alone
- The alternative hypothesis H_1 describes background only
  - No real need to test for it
  - The background-only model becomes important only in case of discovery

Interpretation strategy

Based on the number of observed, expected events in all regions with all uncertainties: Probability density function (PDF)

Likelihood function: L(μ,θ)

μ: signal strength (POI);

θ: nuisance parameters(NP)

Profile Likelihood: constrain uncertainty (NP) as part of a likelihood fit

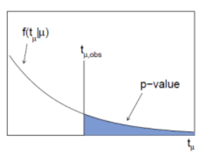
Construct test statistics t_μ based on likelihood ratio λ:

$$\tilde{\lambda}(\mu) = \begin{cases} \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} & \hat{\mu} \geq 0, \\ \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(0,\hat{\hat{\theta}}(0))} & \hat{\mu} < 0 \end{cases}$$

$$t_\mu = -2\ln\lambda(\mu)$$

Find the observed test statistic for tested μ: $t_{\mu,obs}$

Construct the PDF of test statistic t_μ: generate toy Monte Carlo or using asymptotic formula



From the constructed distribution of test statistic for s+b, find the p-value of the observation

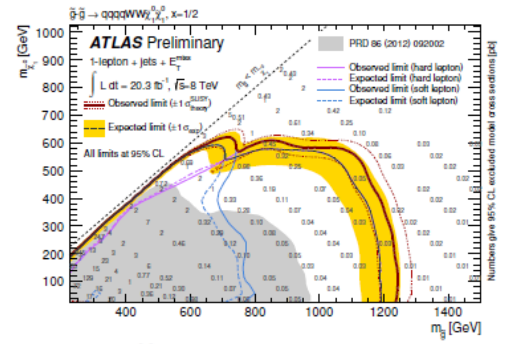
$$p_\mu = \int_{t_{\mu,obs}}^{\infty} f(t_\mu|\mu)\, dt_\mu$$

If CLs<0.05: the value of signal is excluded at 95% CL……….

$$\mathrm{CL_s} = \frac{\mathrm{CL_{s+b}}}{\mathrm{CL_b}} = \frac{p_{s+b}}{1-p_b}$$

The above check has been done for each signal grid points on the SUSY model.

The line can be drawn for the area where points are excluded



Simultaneous fit

- Background estimates in SRs are obtained by a *simultaneous fit* in each channel based on the profile likelihood method. Three dedicated fit for different purpose…
  - **Background-only fit**
    - Fit for all CRs, excluding SRs.
      - Get background-only estimates.
      - Also extrapolate to VRs (non used in fit, only for cross-check) and SRs.
  - **Discovery fit**
    - Fit for all CRs and SRs.
    - Signal contamination is turned off in CRs and set as a dummy number 1 in SR (so, the fitted non-SM signal strength = the excess in Nevents of SR)
      - Get model-independent upper limit on signal in SR.
  - **Exclusion fit**
    - Fit for all CRs and SRs.
    - Signal is turned on in all regions, according to model-dependent prediction.
      - Got signal model-dependent exclusion from all CRs+SRs →final exclusion contours for SUSY model
- The basic strategy is to share background information in all regions (CR,SR,VR). The background parameters are predominantly constrained by CRs with large statistics, which in turn reduces the impact of uncerts in SR.

Data-driven background estimation

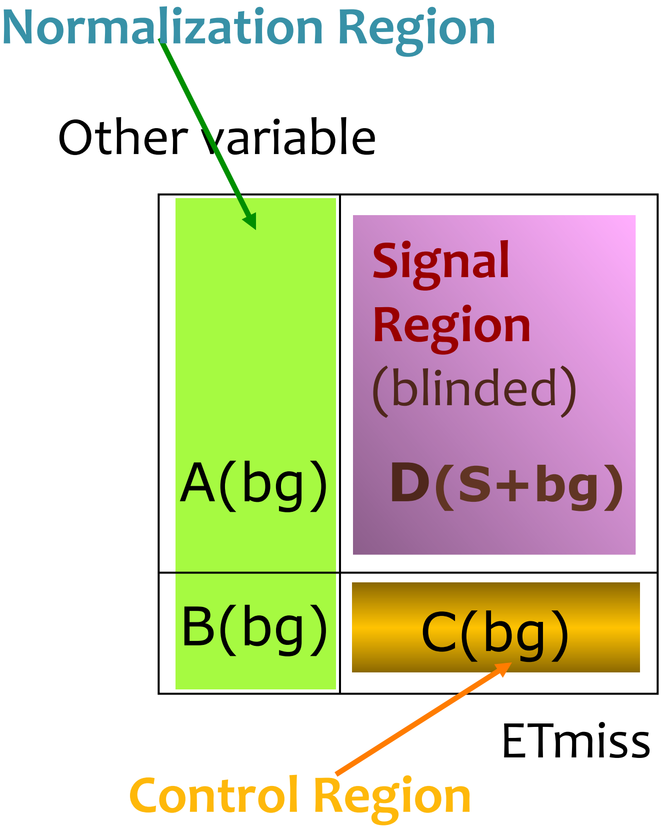
"ABCD" Method

One approach to data-driven bg ***estimation*** is to use uncorrelated model-independent variables to *extrapolate* the background from a background-dominated control region to the signal region.

Nbg in signal region D = (A/B)*C

Normalize Factor

Control Sample



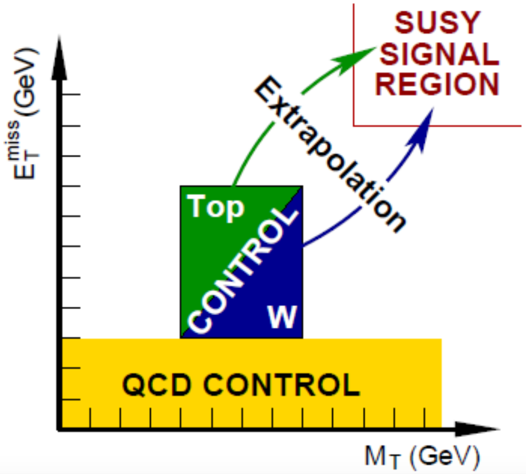
Key points:

- The two variables should have good discrepancy and uncorrelated
- Control Sample selection: enough statistics;lower susy contamination; unbiased estimation of SM background
- Normalization region selection: enough statistics;lower susy contamination; flat ratio(A/B) distribution with ETmiss

Background Estimation Strategy

ATLAS-CONF-2013-062

- **W/Z/ttbar background (dominant)**
- Semi-data driven approach
- Normalize MC to Data in W/T-CR
- Extrapolate to SR using MC: assuming shape is described correctly
- Extrapolation done in simultaneous fit.



$$N^{SR}_{pred_j} = (N^{CR_j}_{data} - N^{CR_j}_{other\ bkg}) \times \frac{N_{pred}(MC^j, SR)}{N_{pred}(MC^j, CR_j)}$$

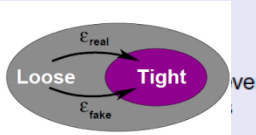
$$= (N^{CR_j}_{data} - N^{CR_j}_{other\ bkg}) \times C^j_{CR_j \to SR}$$

- **QCD background (small bg)**
- Fullly-data driven approach
- Measure real and fake efficiencies in QCD-CRs
- Apply Matrix Method to get contribution in SR

$$\text{QCD BG} = \frac{1}{1/\epsilon_{fake} - 1/\epsilon_{real}} \cdot N_{fail} - \frac{1/\epsilon_{real} - 1}{1/\epsilon_{fake} - 1/\epsilon_{real}} \cdot N_{pass}$$

N_{pass}: Events passing the signal selection cuts (*tight*)

N_{fail}: Events satisfying relaxed lepton isolation criteria but not passing the signal selection cuts (*loose-but-not-tight*)



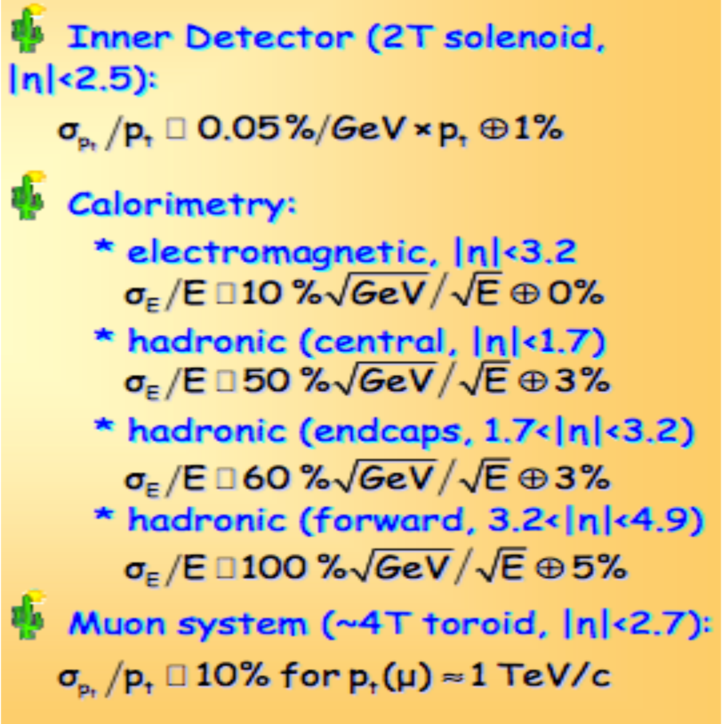
ϵ_{real}: Probability t vent passes also

ϵ_{fake}: Probability that a loose QCD event passes also the tight selection cuts

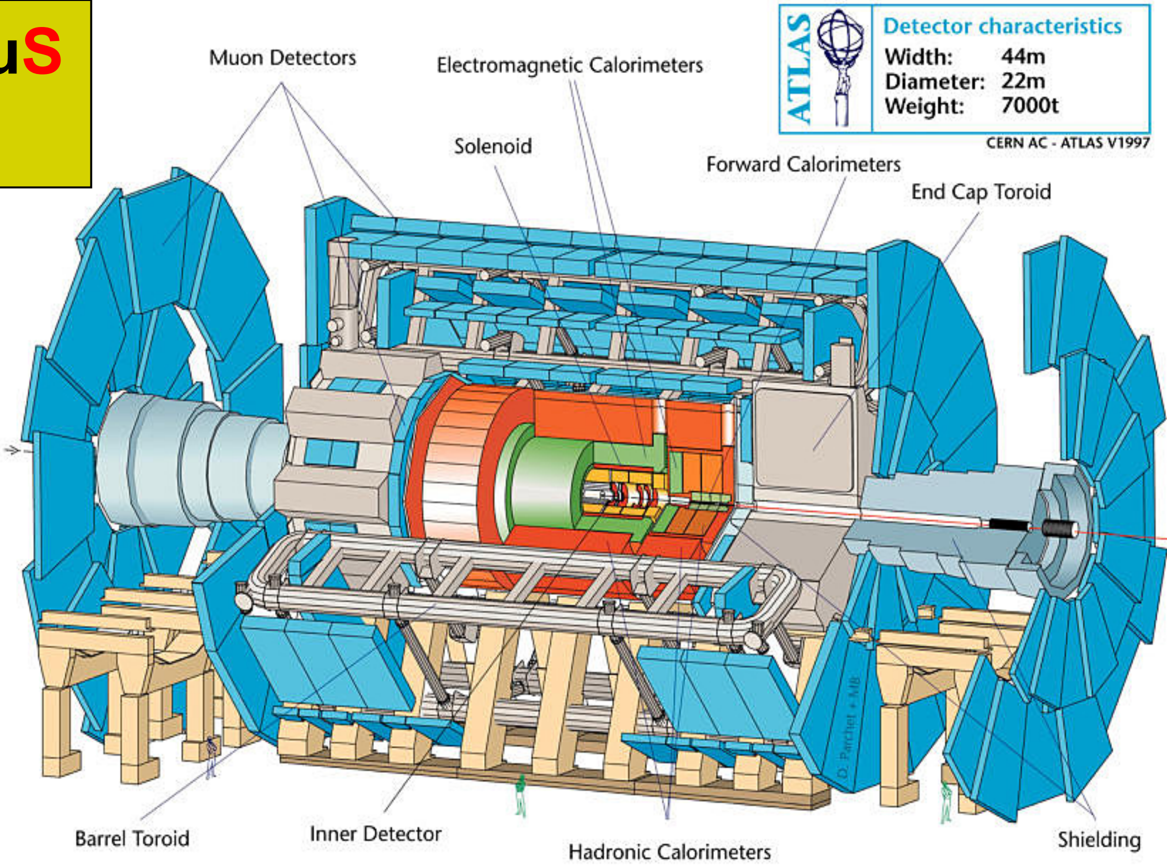
Other small BGs (diboson, single top etc) are directly estimated from MC.

A Toroidal LHC ApparatuS

- 42m×22m, 7000 ton



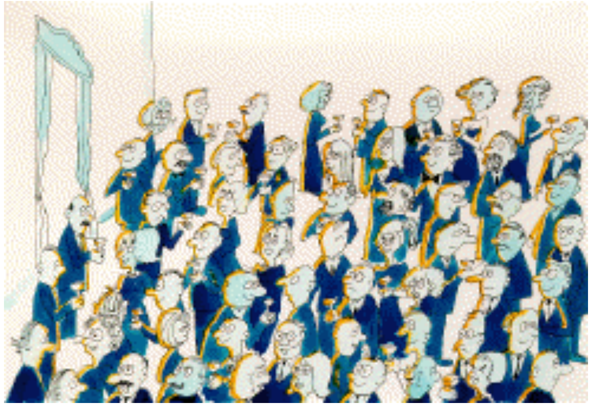
- **Inner Detector (2T solenoid, |η|<2.5):**
  - σ_{p_t}/p_t □ 0.05%/GeV × p_t ⊕ 1%
- **Calorimetry:**
  - * electromagnetic, |η|<3.2
    - σ_E/E □ 10 %$\sqrt{GeV}/\sqrt{E}$ ⊕ 0%
  - * hadronic (central, |η|<1.7)
    - σ_E/E □ 50 %$\sqrt{GeV}/\sqrt{E}$ ⊕ 3%
  - * hadronic (endcaps, 1.7<|η|<3.2)
    - σ_E/E □ 60 %$\sqrt{GeV}/\sqrt{E}$ ⊕ 3%
  - * hadronic (forward, 3.2<|η|<4.9)
    - σ_E/E □ 100 %$\sqrt{GeV}/\sqrt{E}$ ⊕ 5%
- **Muon system (~4T toroid, |η|<2.7):**
  - σ_{p_t}/p_t □ 10% for $p_t(\mu) \approx 1$ TeV/c



- **Inner Detector:** Highly segmented silicon strips, determine very accurately charged particles trajectories
- **Solenoid Magnet:** Solenoid coil that generates a 2T magnetic field in the region of the Inner Detector
- **Electromagnetic Calorimeter:** Electron and photon energies are measured through electromagnetic showers
- **Hadronic Calorimeter:** Hadrons interact with dense material and produce a shower of charged particles
- **Toroid Magnets:** 8 toroidal coils that create a 0,4T magnetic field in the area of the Muon Spectrometer
- **Muon Spectrometer:** Muons traverse the rest of the detector and are measured in its outer layers

The Higgs mechanism, an analogy...

D. Miller
(UC London)



The Higgs field fills all space

A ‘particle’ that moves in the Higgs field ...

... moves slower the more it attract attention (interacts with the Higgs field, generating its mass, the larger, the stronger its interactions...)

The Higgs particle, an analogy...

Somebody whispers a rumour into the room...

... and the field starts to get excited and interact with itself giving birth to a massive particle