Overall CMS SUSY search strategy

Filip Moortgat (ETH Zurich)

Florence, October 22, 2012

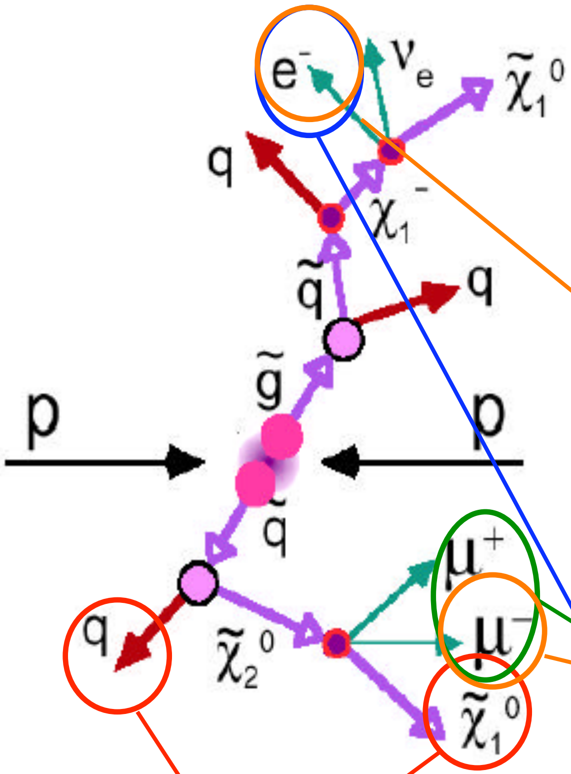
Outline

- Strategy for the first data
  - Assume pair production of colored sparticles (squark/gluino)
  - Wide range of topological searches
  - Develop data-driven background prediction methods

- Current focus
  - Focussed searches for 3rd generation
  - Focussed searches for charginos/neutralinos/sleptons

- Near Future
  - Natural SUSY
  - Compressed spectra

Topological SUSY searches



- Assume pair production of colored sparticles
- All inclusive searches require jets and MET

$$H_T = \sum_{j}^{\text{all jets}} \left| p_T^j \right|$$

- Further categorized by number of leptons or photons
- Different searches have different dominant backgrounds

All hadronic	1-lepton	OS 2-lepton	SS 2-lepton	≥ 3-lepton
Jets + MET Lepton veto	Single lepton + jets + MET	Opposite-sign di-lepton + MET	Same sign di-lepton + jets + MET	Multi-lepton + MET

All topological boxes

All hadronic	1-lepton	OS 2-lepton	SS 2-lepton	≥ 3-lepton
4 separate analyses	5 different analyses	2 analysis inside Z. 3 analyses outside Z.	4 analyses	2/3 analyses

1-photon	2-photon	RPV	Long-lived
1 analysis	1 analysis	(previously exotica, now SUSY)	(Exotica group)

Hadronic searches for SUSY

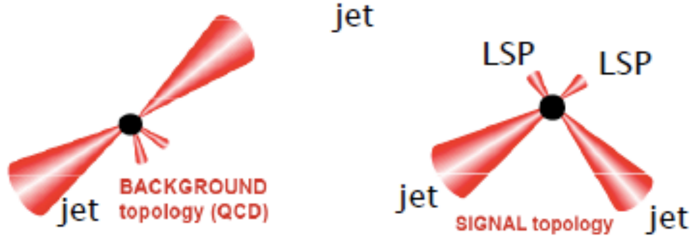
All hadronic	1-lepton	OS 2-lepton	SS 2-lepton	≥ 3-lepton
Jets + MET Lepton veto	Single lepton + jets + MET	Opposite-sign di-lepton + MET	Same sign di-lepton + jets + MET	Multi-lepton

- Only relies on strong production and existence of a LSP
- But most challenging due to large backgrounds:
  - QCD (→ use clever kinematic variables?)
  - Z + jets with Z → neutrinos
  - leptonic ttbar and W + jets where the lepton was lost (or a tau)

- Multiple analyses exist:
  - either based on classical MET and H_T
  - or more recent kinematical variables: α_T, Razor, M_{T2}, …
  - also different trigger and bckg prediction strategies

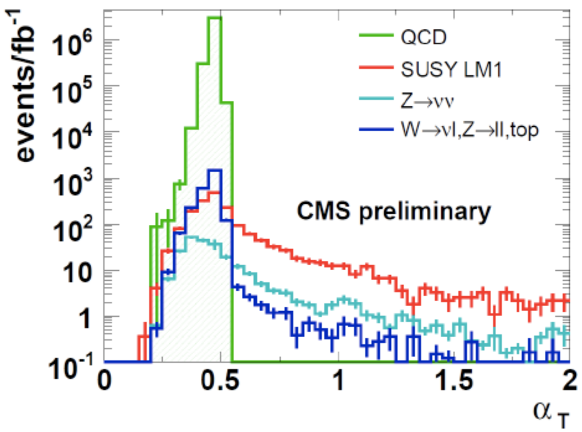
Kinematic variables

CMS hadronic searches make use of dedicated kinematic variables in order to suppress QCD



α_T

$$\alpha_T \equiv E_T^{j_2} / M_T(j_1 j_2) = \frac{\sqrt{E_T^{j_2} / E_T^{j_1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$



M_{T2}

$$M_{T2} = \min_{p_T^{c1}+p_T^{c2}=\not p_T} \left[\max\left(m_T^{(1)}, m_T^{(2)}\right)\right] \approx \sqrt{2 p_T^{vis(1)} p_T^{vis(2)} (1+\cos\phi_{12})}$$

Razor R

$$R \equiv \frac{M_T^R}{M_R}.$$

$$M_R \equiv \sqrt{(E_{j_1}+E_{j_2})^2 - (p_z^{j_1}+p_z^{j_2})^2},$$

$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j1}+p_T^{j2}) - \vec{E}_T^{miss}\cdot(\vec{p}_T^{\,j1}+\vec{p}_T^{\,j2})}{2}}$$

Background predictions

- Pre-data: strong focus on data-driven background prediction methods
  - Not rely on whether the simulation (both MC generators and detector simulation) would describe the data (cfr. Tevatron)
  - So be ready with data-driven background prediction methods
    - To be able to convince ourselves and the world that our prediction of the SM background is reliable
  - Lead to the development of many, redundant data-driven background prediction methods
    - Hopefully methods with orthogonal weaknesses, so they complement each other

- Currently: MC describes the SM processes well!
  - Still beware of extreme tails and other delicate predictions
    - e.g. fake lepton rate (in high PU environment)

Data-driven background prediction methods

Examples of data-driven methods:

- Z → neutrinos (irreducible bckg.):

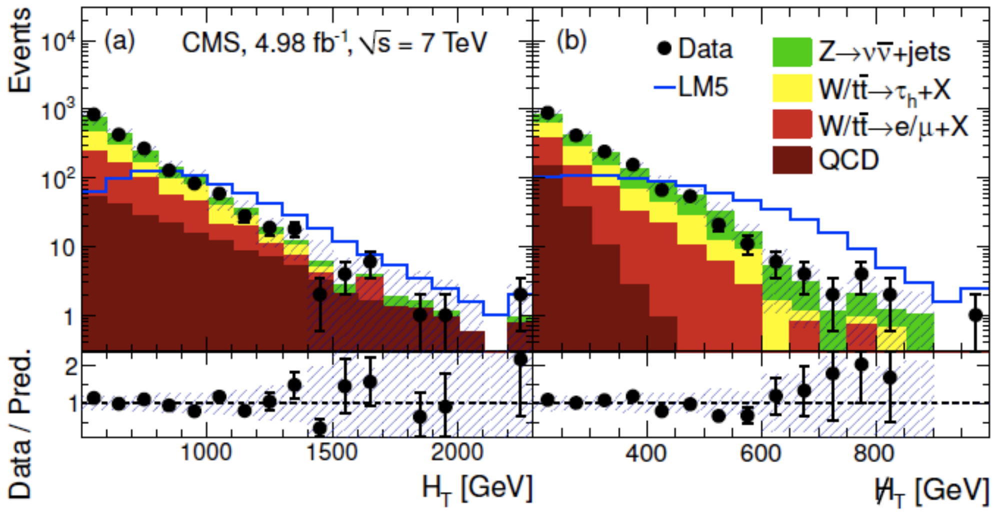
use replacement techniques:

1) Z → l^+l^- + jets: clean (+) but low statistics (-)
2) W → l ν + jets: larger stats (+) but selection is not pure (-)
3) Gamma + jets: very high stats (+) but significant theoretical uncertainties (-)

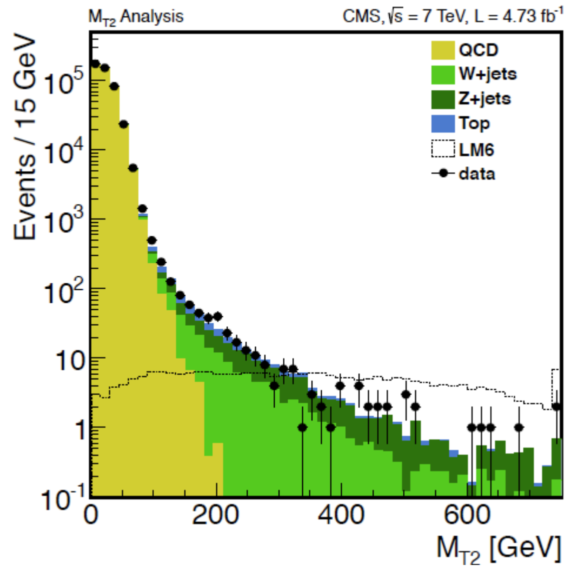
- Top-antitop and W+jets: “lost lepton” method
  - estimate lost leptons using lepton efficiencies from tag/probe; for taus: replace μ by simulated tay decaying hadronically

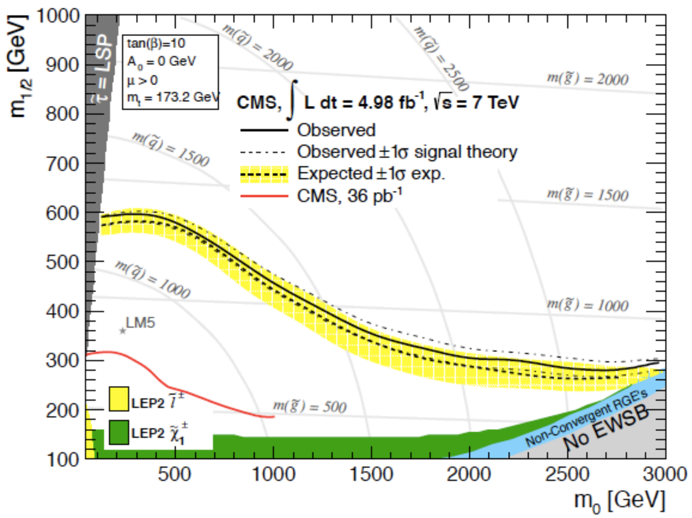
Hadronic search results

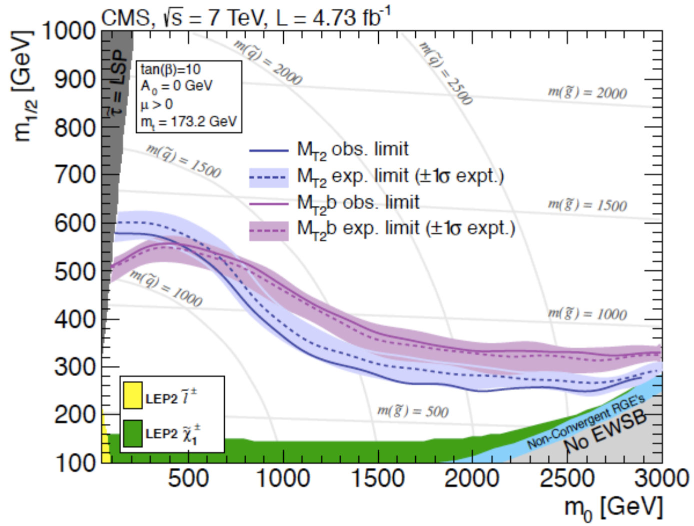
→ Search using MHT at 7 TeV



→ Search using MT2 at 7 TeV







Single lepton searches

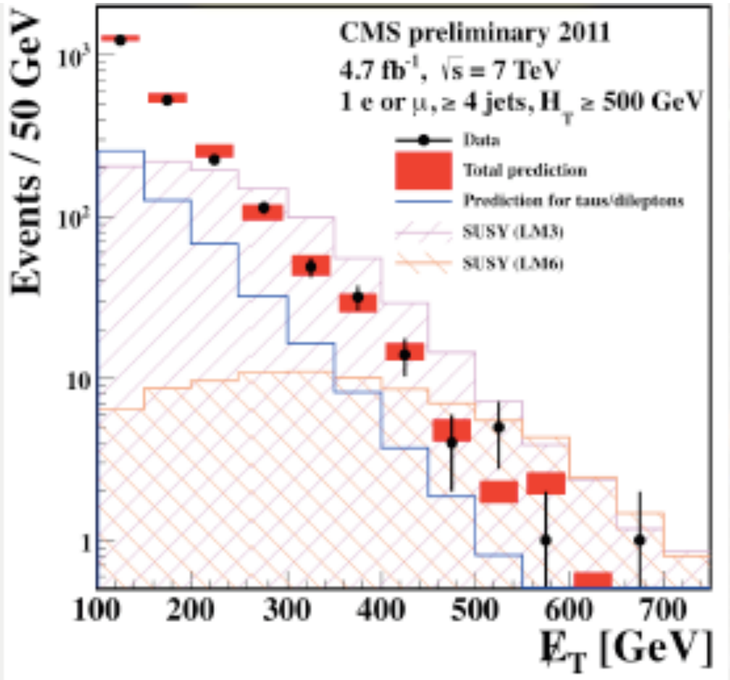
All hadronic	1-lepton	OS 2-lepton	SS 2-lepton	≥ 3-lepton
Jets + MET	Single lepton + jets + MET	Opposite-sign di-lepton + MET	Same sign di-lepton + jets + MET	Multi-lepton

- Lepton requirement reduces backgrounds considerably
- Allows using leptonic triggers (i.e. potentially low cuts on HT and MET)
- Mainly W+jets and top backgrounds left
- Again: multiple analyses exist, differing mainly in their data-driven background prediction method:
  - Lepton Spectrum method (LS)
  - Lepton Projection method (LP)
  - MET template method
  - Factorisation method (ABCD)
  - Neural Network (ANN)

Two examples

→ Lept. Spectr. method at 7 TeV

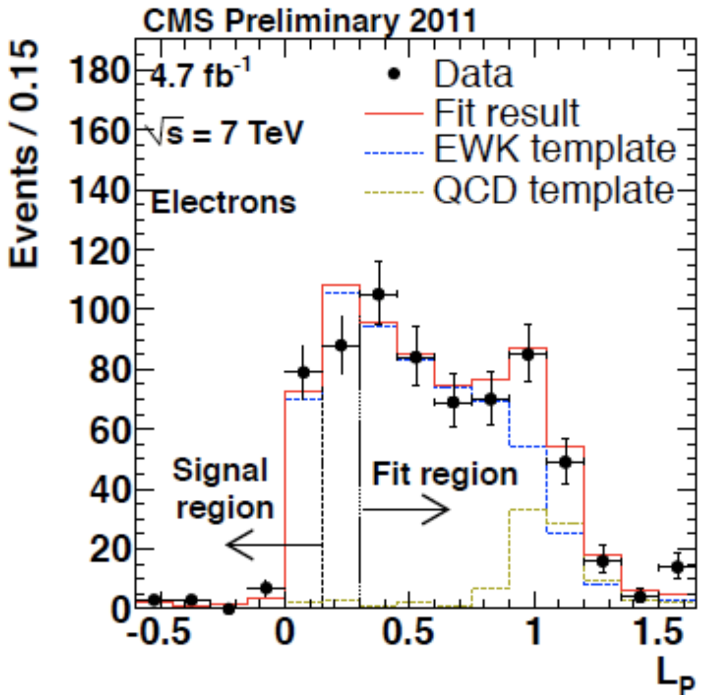
- In W decay, charged lepton and neutrino pT spectra are on average approx. the same
- corrected for acceptance and polarization effects



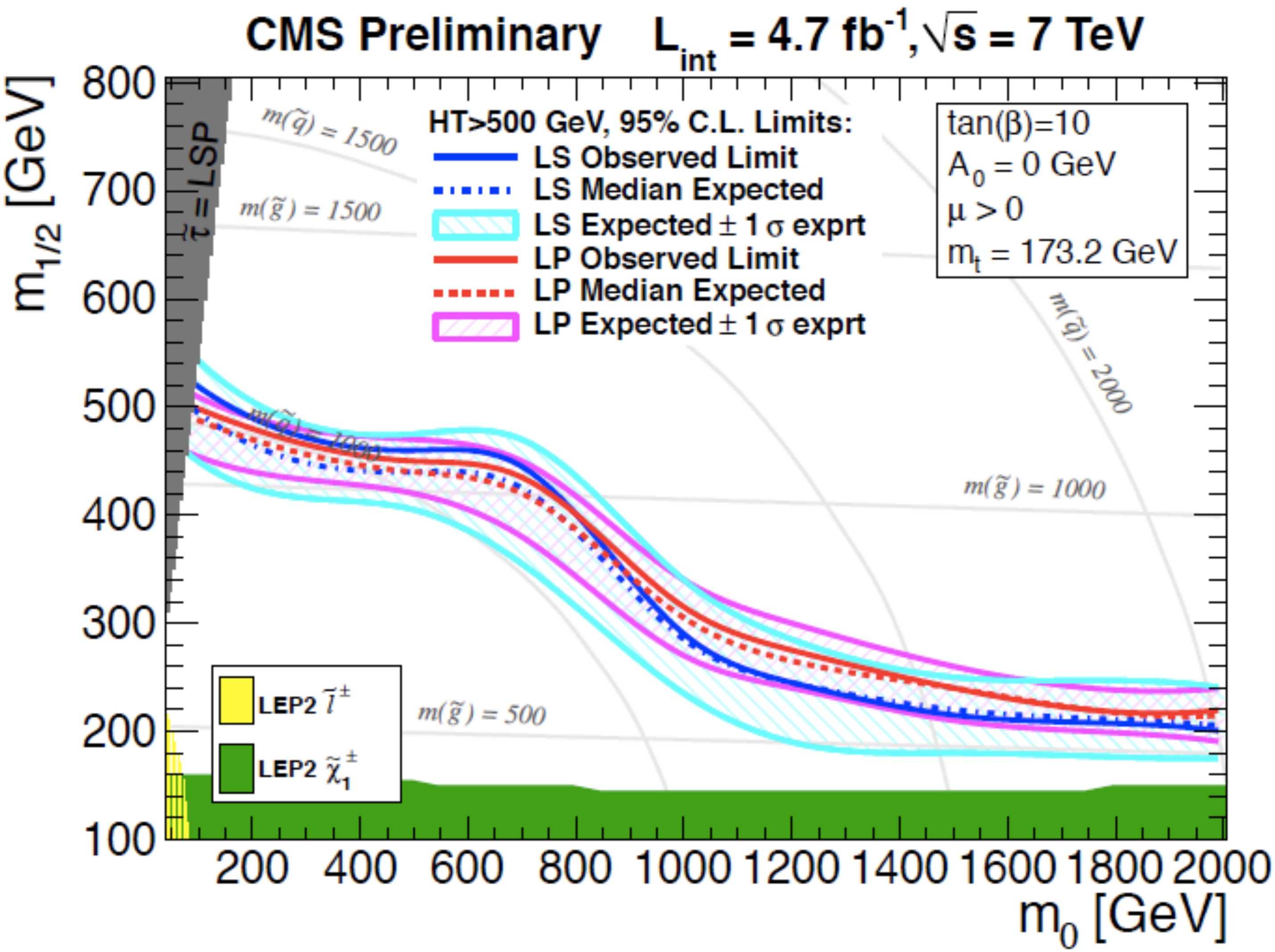
→ Lept. Pol. method at 7 TeV

$$L_P = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$

- In SM: V-A nature of coupling of W to fermions; little correlation in large part of SUSY parameter space



Result @ 7 TeV



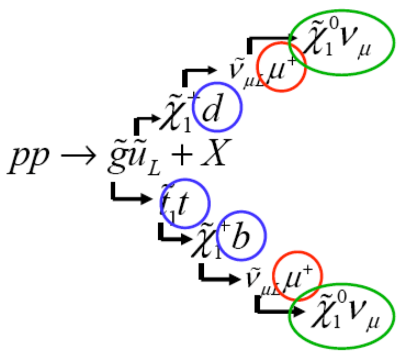
CMS Preliminary L_int = 4.7 fb^-1, √s = 7 TeV
HT>500 GeV, 95% C.L. Limits:
LS Observed Limit
LS Median Expected
LS Expected ± 1 σ exprt
LP Observed Limit
LP Median Expected
LP Expected ± 1 σ exprt
tan(β)=10
A0 = 0 GeV
μ > 0
mt = 173.2 GeV
m(q̃) = 1500
m(g̃) = 1500
m(q̃) = 1000
m(g̃) = 1000
m(q̃) = 2000
m(g̃) = 500
τ̃ = LSP
LEP2 l̃±
LEP2 χ̃±1
m1/2 [GeV]
m0 [GeV]
800
700
600
500
400
300
200
100
200
400
600
800
1000
1200
1400
1600
1800
2000

Same-sign di-leptons

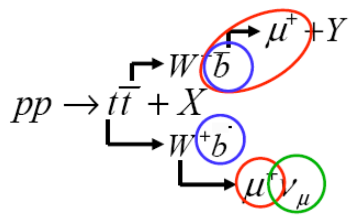
All hadronic	1-lepton	OS 2-lepton	**SS 2-lepton**	≥ 3-lepton
Jets + MET	Single lepton + jets + MET	Opposite-sign di-lepton + MET	Same sign di-lepton + jets + MET	Multi-lepton

- Almost SM background free
- In SUSY, expect significant production through charginos in gluino cascades

Signal:



Background:



Main backgrounds:
- non-prompt leptons
- charge misassignment
- rare processes (e.g. ttW/ttZ, DPS, …)

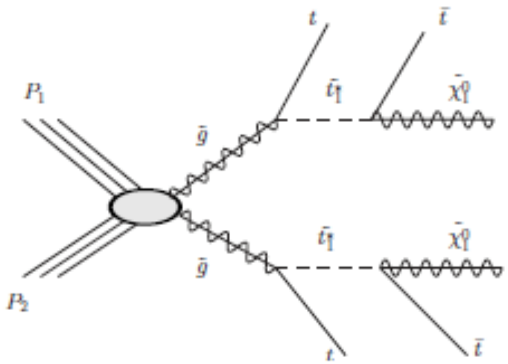
Backgrounds

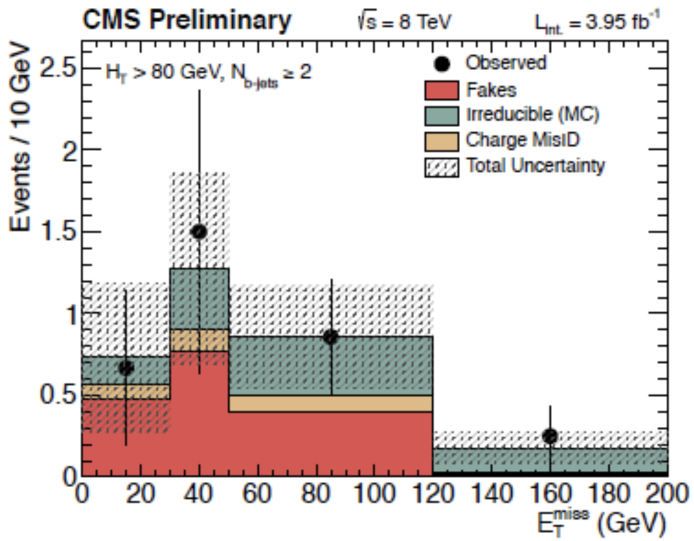
- Backgrounds prediction methods:
  - Non-prompt leptons
    - Do not trust MC
    - Use several methods (tight-to-loose, b-tag & probe), all based on extrapolation in isolation/identification
  - Charge mis-identification
    - Do not trust MC
    - Estimate rate from Z->ee for electrons, from cosmics for muons
  - Rare SM processes
    - Trust MC (with large uncertainty) since these are physics backgrounds

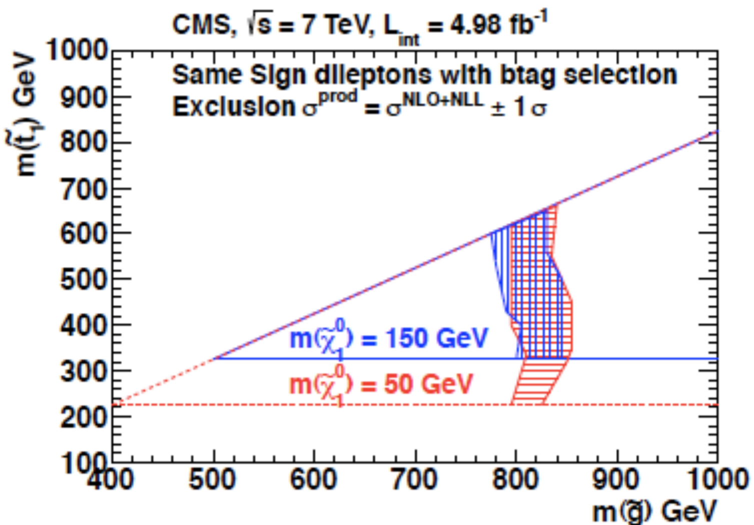
Same-sign dileptons 8 TeV

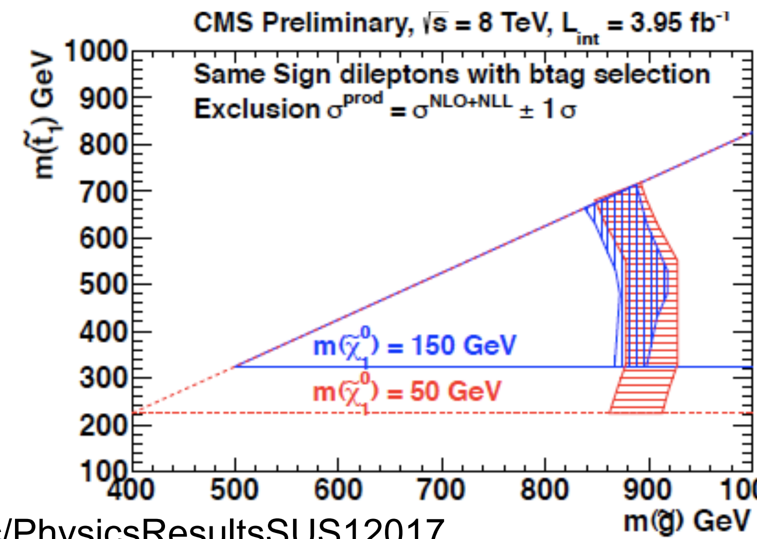
→ 2011 data at 7 TeV

→ 2012 data at 8 TeV









https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS12017

Opposite-sign dileptons

All hadronic	1-lepton	OS 2-lepton	SS 2-lepton	≥ 3-lepton
Jets + MET	Single lepton + jets + MET	Opposite-sign di-lepton + MET	Same sign di-lepton + jets + MET	Multi-lepton

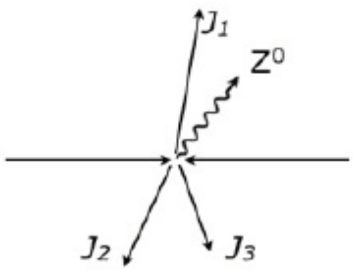
- Second lepton requirement reduces QCD and W background further. Top is now the main background.
- Two separate analysis: inside and outside of the Z peak
- Several background prediction techniques, including opposite-sign opposite flavour subtraction
- Channel very suitable for sparticle mass reconstruction from endpoint measurements

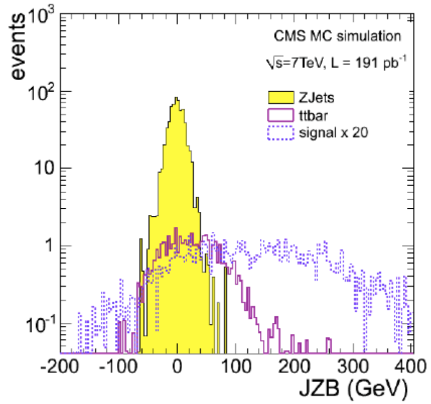
Opposite sign dileptons

- Outside of Z-window:
  - Use OS – SF subtraction to reject ttbar and all other backgrounds containing W pairs

- Inside the Z-window:
  - Two background prediction methods for Z+jet background: "JZB" and MET templates from photon+jets

$$JZB = \left|\sum_{jets} \vec{p}_T\right| - \left|\vec{p}^{\,Z}\right|$$





Multileptons

All hadronic	1-lepton	OS 2-lepton	SS 2-lepton	≥ 3-lepton
Jets + MET	Single lepton + jets + MET	Opposite-sign di-lepton + MET	Same sign di-lepton + jets + MET	Multi-lepton

- Very clean signature with very low Standard Model background
- Allows to require very low MET and HT
- Photon conversions are non-negligible background

Multileptons

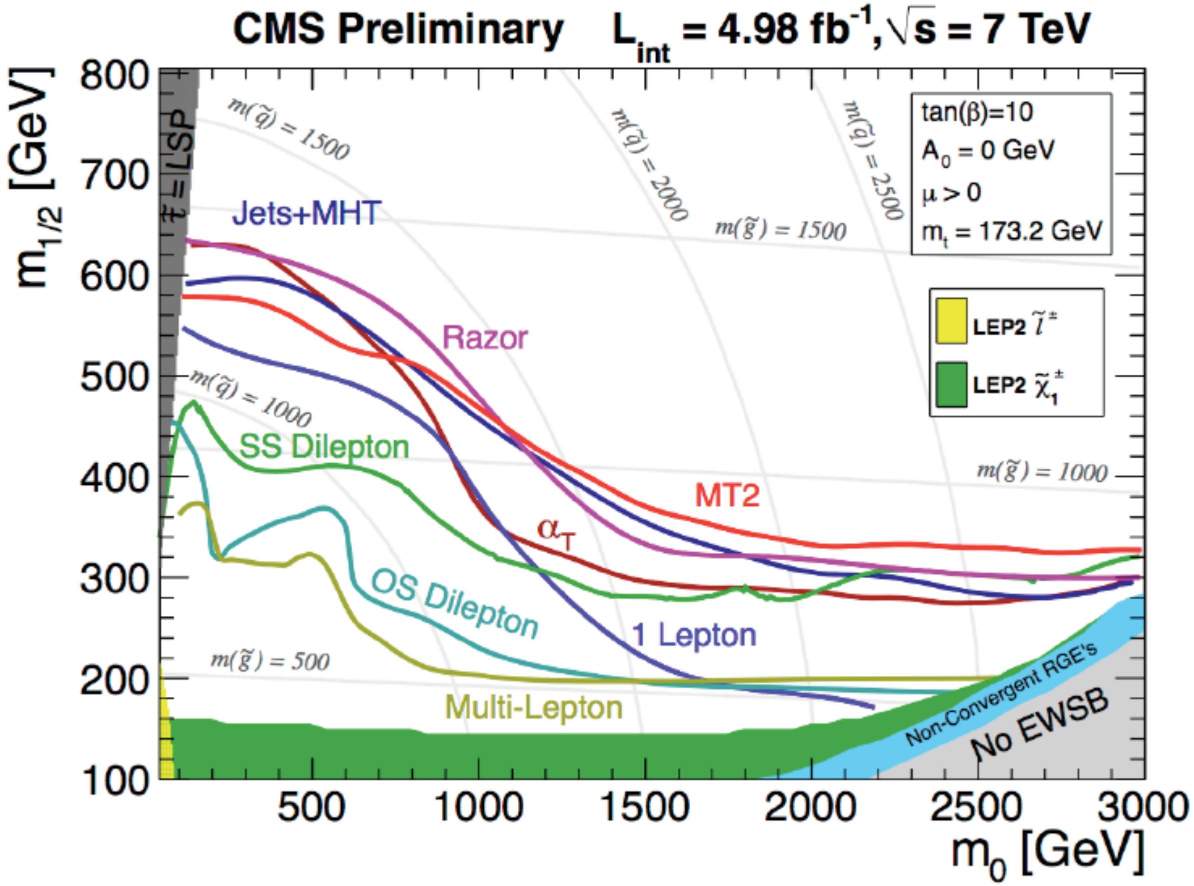
Many signal regions!

Selection	$N(\tau_h)$=0 obs	$N(\tau_h)$=0 expected	$N(\tau_h)$=1 obs	$N(\tau_h)$=1 expected	$N(\tau_h)$=2 obs	$N(\tau_h)$=2 expected
4 Lepton results						
4ℓ E_T^{miss} >50, H_T >200, no Z	0	0.018 ± 0.005	0	0.09 ± 0.06	0	0.7 ± 0.7
4ℓ E_T^{miss} >50, H_T > 200, Z	0	0.22 ± 0.05	0	0.27 ± 0.11	0	0.8 ± 1.2
4ℓ E_T^{miss} >50, H_T <200, no Z	1	0.20 ± 0.07	3	0.59 ± 0.17	1	1.5 ± 0.6
4ℓ E_T^{miss} >50, H_T <200, Z	1	0.79 ± 0.21	4	2.3 ± 0.7	0	1.1 ± 0.7
4ℓ E_T^{miss} <50, H_T >200, no Z	0	0.006 ± 0.001	0	0.14 ± 0.08	0	0.25 ± 0.07
4ℓ E_T^{miss} <50, H_T >200, Z	1	0.83 ± 0.33	0	0.55 ± 0.21	0	1.14 ± 0.42
4ℓ E_T^{miss} <50, H_T <200, no Z	1	2.6 ± 1.1	5	3.9 ± 1.2	17	10.6 ± 3.2
4ℓ E_T^{miss} <50, H_T <200, Z	33	37 ± 15	20	17.0 ± 5.2	62	43 ± 16
3 Lepton results						
3ℓ E_T^{miss} >50, H_T >200, no-OSSF	2	1.5 ± 0.5	33	30.4 ± 9.7	15	13.5 ± 2.6
3ℓ E_T^{miss} >50, H_T <200, no-OSSF	7	6.6 ± 2.3	159	143 ± 37	82	106 ± 16
3ℓ E_T^{miss} <50, H_T >200, no-OSSF	1	1.2 ± 0.7	16	16.9 ± 4.5	18	31.9 ± 4.8
3ℓ E_T^{miss} <50, H_T <200, no-OSSF	14	11.7 ± 3.6	446	356 ± 55	1006	1026 ± 171
3ℓ E_T^{miss} >50, H_T >200, no Z	8	5.0 ± 1.3	16	31.7 ± 9.6	–	–
3ℓ E_T^{miss} >50, H_T >200, Z	20	18.9 ± 6.4	13	24.4 ± 5.1	–	–
3ℓ E_T^{miss} >50, H_T <200, no Z	30	27.0 ± 7.6	114	107 ± 27	–	–
3ℓ E_T^{miss} >50, H_T <200, Z	141	134 ± 50	107	114 ± 16	–	–
3ℓ E_T^{miss} <50, H_T >200, no Z	11	4.5 ± 1.5	45	51.9 ± 6.2	–	–
3ℓ E_T^{miss} <50, H_T >200, Z	15	19.2 ± 4.8	166	244 ± 24	–	–
3ℓ E_T^{miss} <50, H_T <200, no Z	123	144 ± 36	3721	2907 ± 412	–	–
3ℓ E_T^{miss} <50, H_T <200, Z	657	764 ± 183	17857	15519 ± 2421	–	–
Total 4ℓ	37	42 ± 15	32.0	24.9 ± 5.4	80	59 ± 16
Total 3ℓ	1029	1138 ± 193	22693	19545 ± 2457	1121	1177 ± 172
Total	1066	1180 ± 194	22725	19570 ± 2457	1201	1236 ± 173

7 TeV exclusions in CMSSM

ETH Institute for Particle Physics

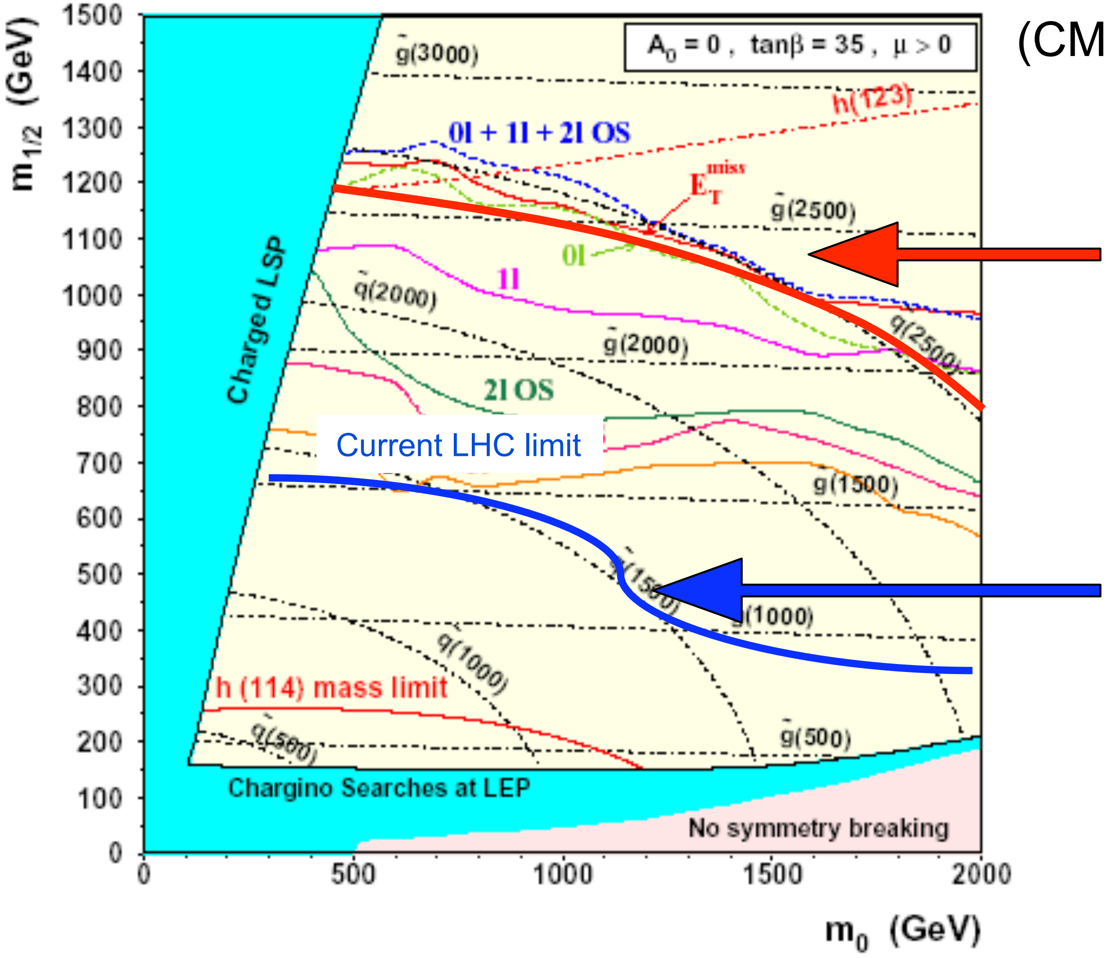
Status after 5 fb^{-1} data 7 TeV:



To put in perspective

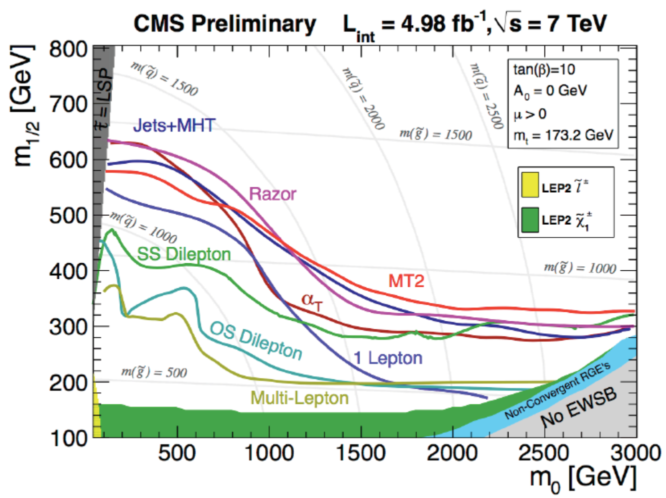
Where we need to go: LHC @ ~14 TeV

mSUGRA reach in various final states for 100 fb^{-1}



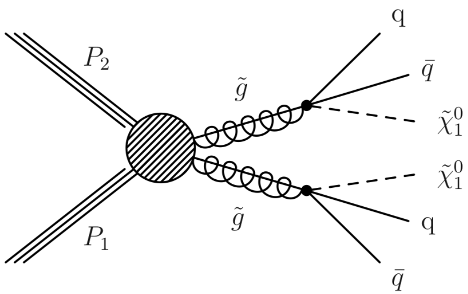
(CMS Physics TDR)

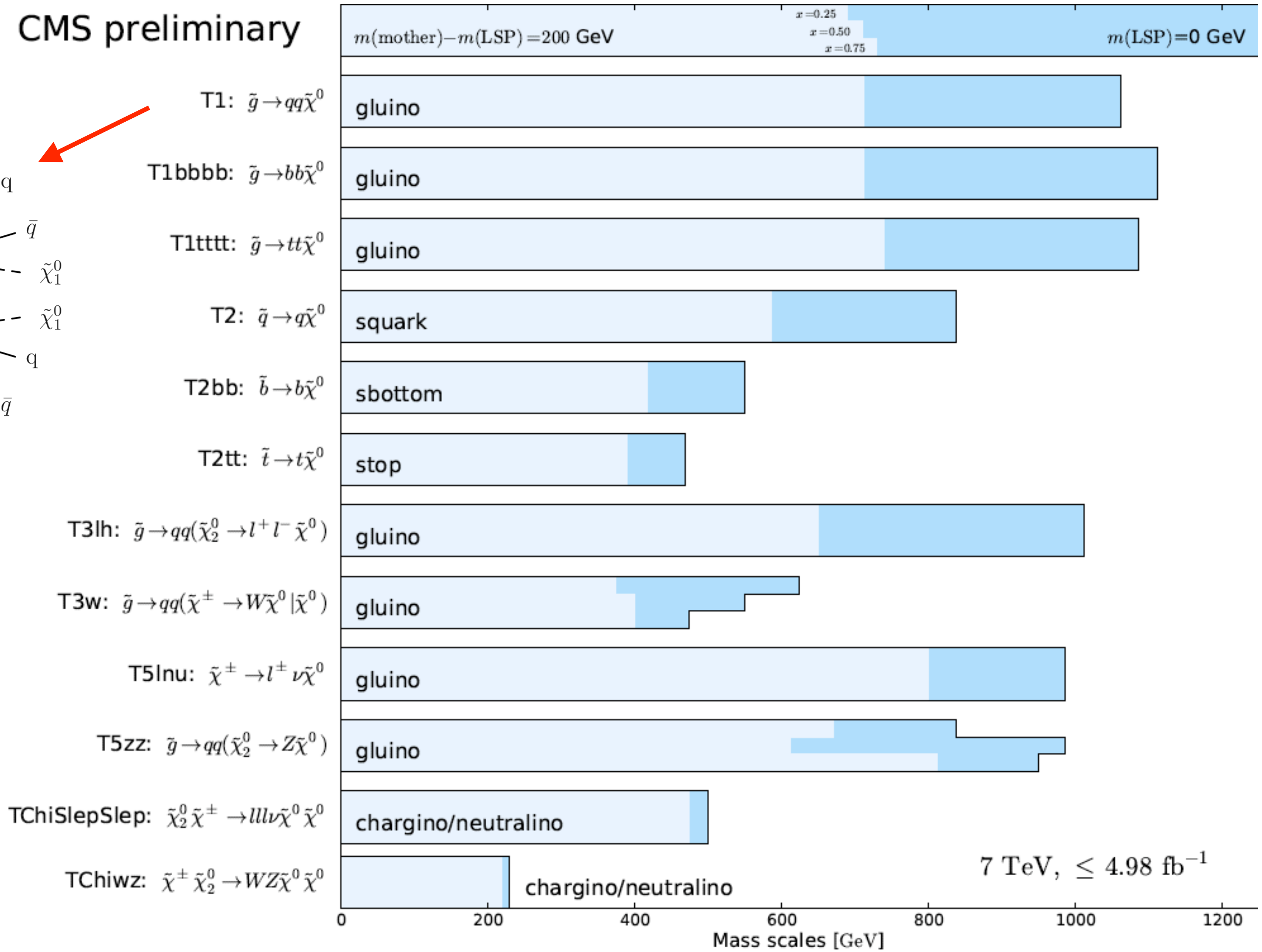
m_H = 125 GeV



7 TeV exclusions in Simplified Model Space (SMS)

e.g.





Warning

The previous plot comes with some fine print:

- Branching ratio's usually assumed to be 100%
  - in particular for the leptonic final states, that's quite a drastic assumption
- Note that these limits typically hold for low LSP masses only and all limits disappear if the mass of the LSP is larger than ~450 GeV
- So be careful when drawing conclusions on physics!

- That was the classic topological strategy
  - Search for generic jet+MET signatures, containing 0/1/2/3+ leptons
  - Generic, but often optimized for specific models (CMSSM, SMS)

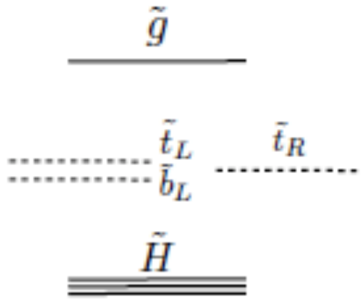
- Recently: also more model-specific approach
  - 3^{rd} generation
  - EWK production of charginos/neutralinos

Natural SUSY

The new (old) paradigm:

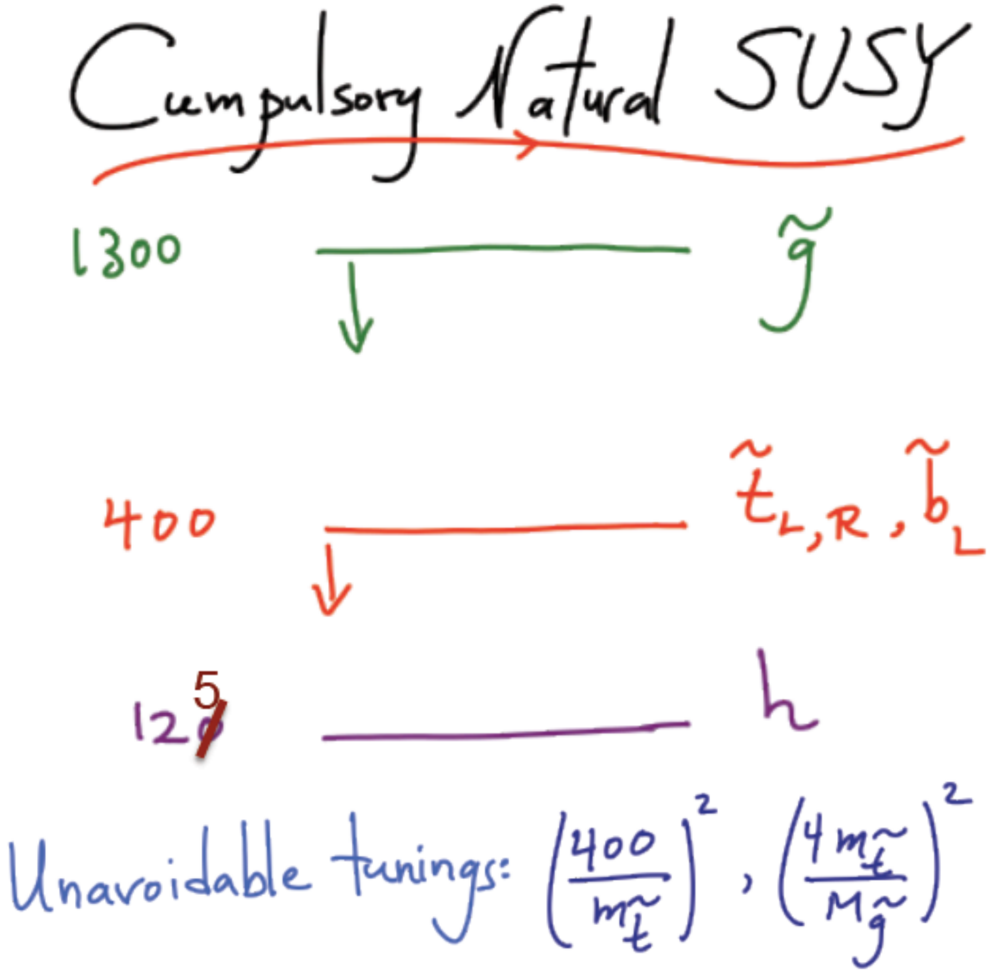
- Light stops/sbottoms
- Light higgsinos
- Not-too-heavy gluinos

are needed for a natural theory of EWSB



natural SUSY

e.g. arXiv:1110.6926



Nima Arkani-Hamed, SavasFest 2012

How to look for natural SUSY

How to look for natural SUSY?

- Existing searches are already sensitive
  (esp. the ones requiring b-tags)
  - Reinterpretation in this context
- Add dedicated searches

Two main directions:

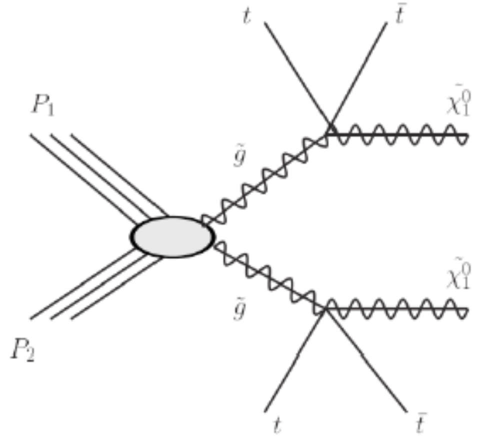
1) Gluino production (+ decay into stop-top or sbottom-bottom)
   ➨ Focus on high jet multiplicity, high #b-jets, …

2) No gluino production, only direct stop/sbottom production
   ➨ Difficult. Needs customized search strategies.

3^{rd} generation in CMS

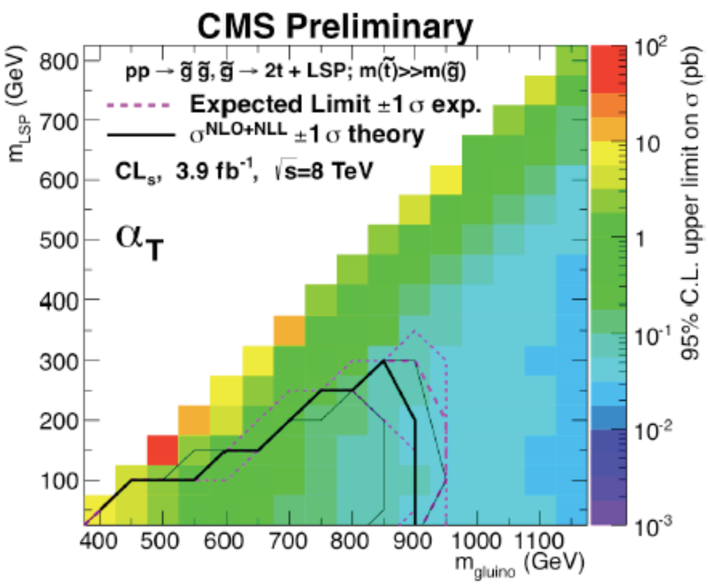
Gluino-mediated stop

- Hadronic with 0/1/2/3+ b-tags
- 2 SS leptons + b-tag

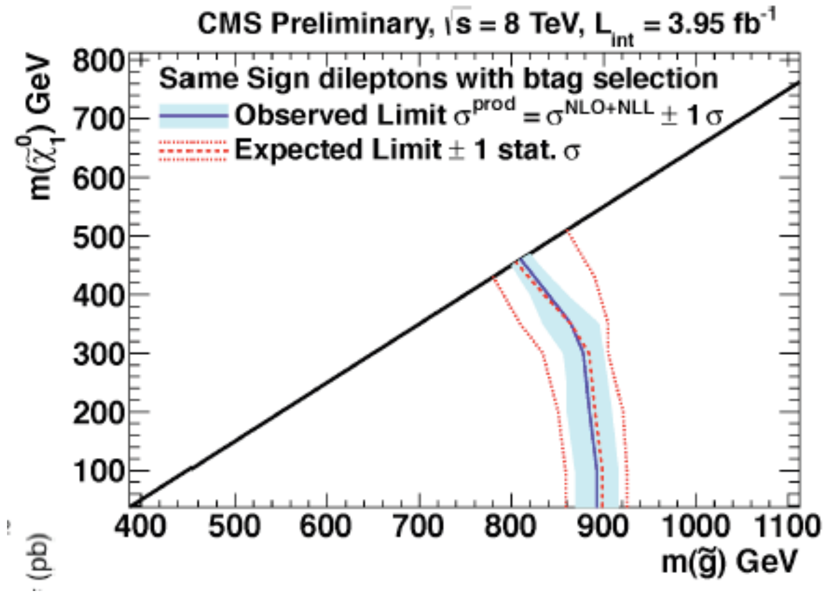


8 TeV

Hadronic search

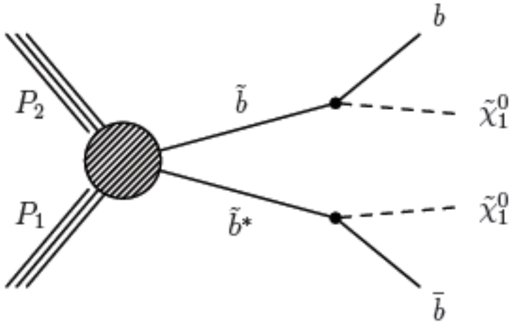


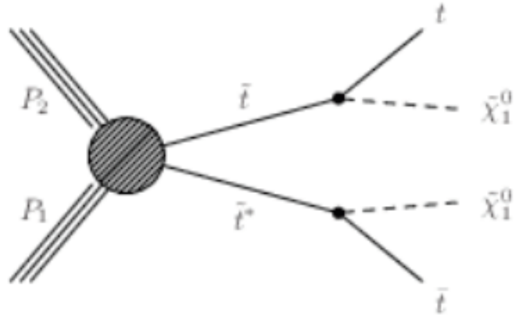
SS 2lepton+b search

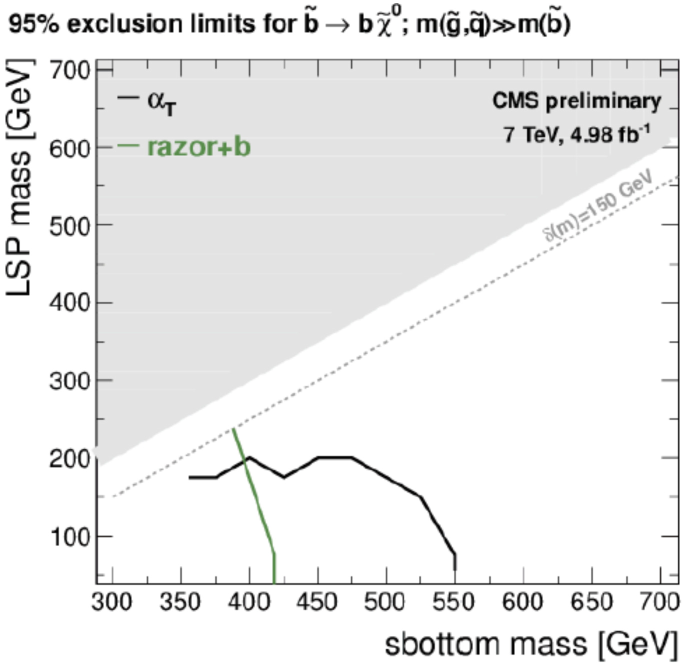


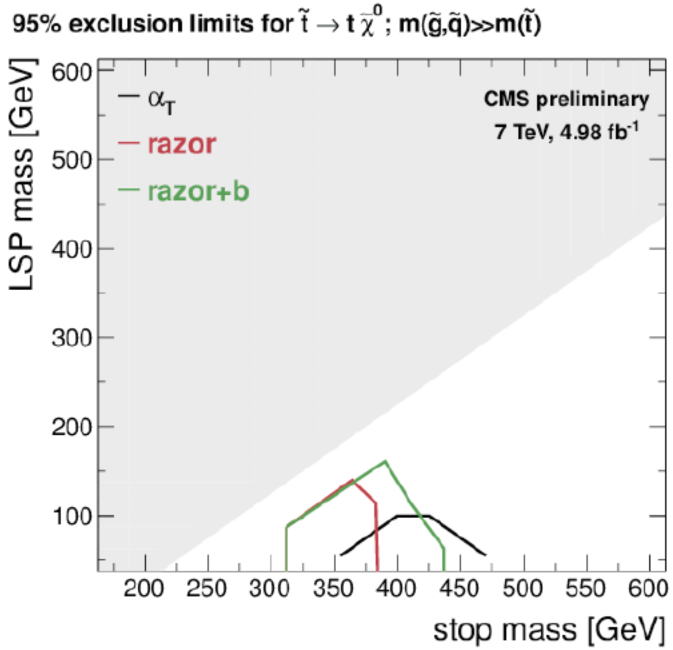
3rd generation in CMS (2)

Direct stop/sbottom production:









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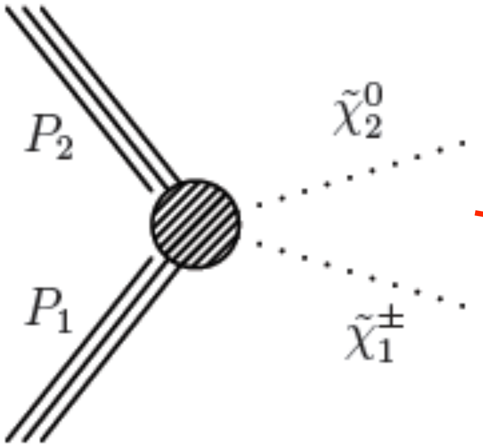
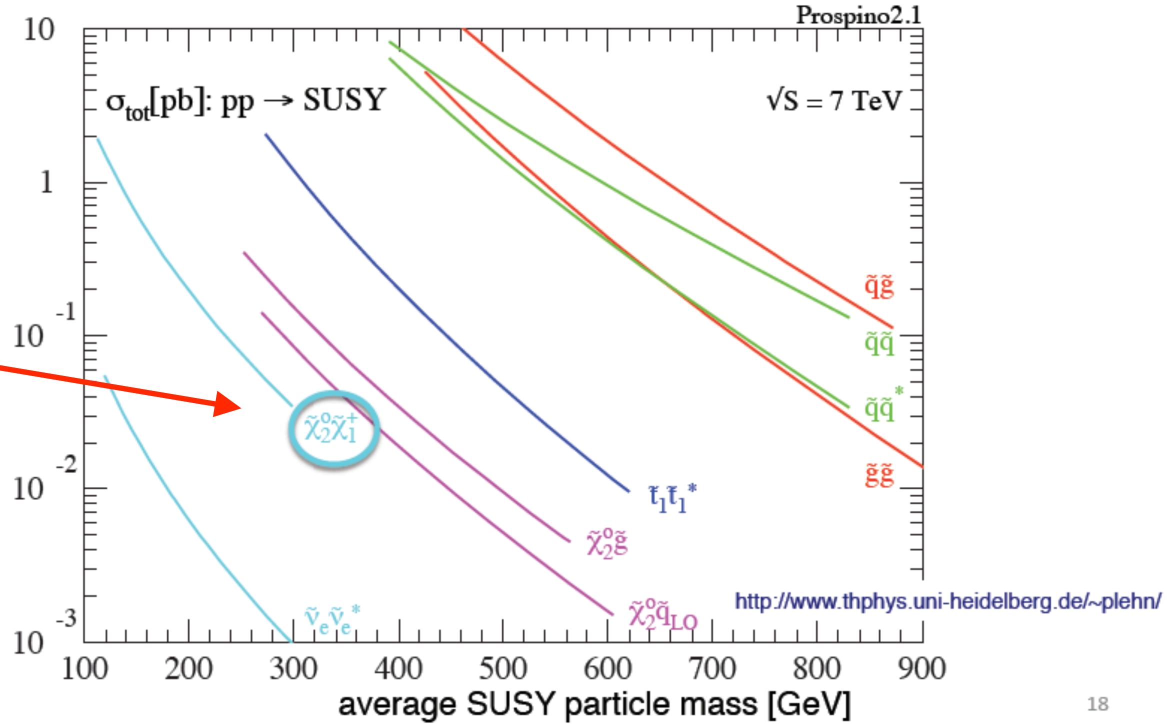
EWK SUSY production

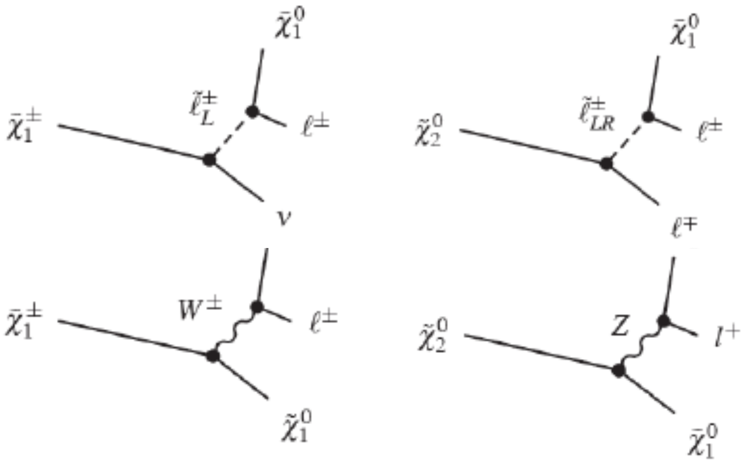
- So far have discussed strong production of colored particles
- But LHC is starting to also get sensitive to EWK production!
  - First one on the list: chargino-neutralino pair production





EWK SUSY decays

Assume decays of chargino/neutralino into leptons



$\tilde{\chi}^\pm \rightarrow \tilde{\ell}\nu(\tilde{\nu}\ell) + \tilde{\chi}_1^0$ $\quad$ $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}\ell(\tilde{\nu}\nu) + \tilde{\chi}_1^0$

$\tilde{\chi}^\pm \rightarrow W^\pm + \tilde{\chi}_1^0$ $\quad$ $\tilde{\chi}_2^0 \rightarrow Z + \tilde{\chi}_1^0$

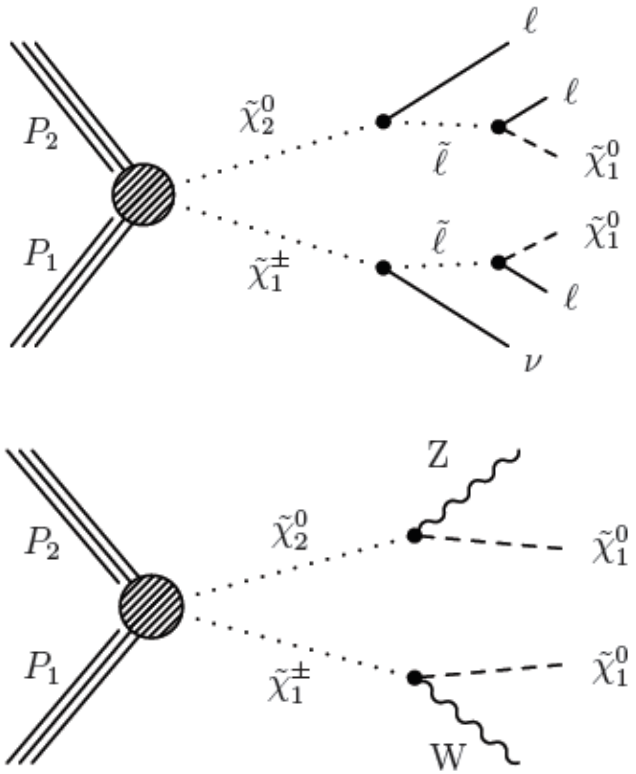
The following searches have been performed:

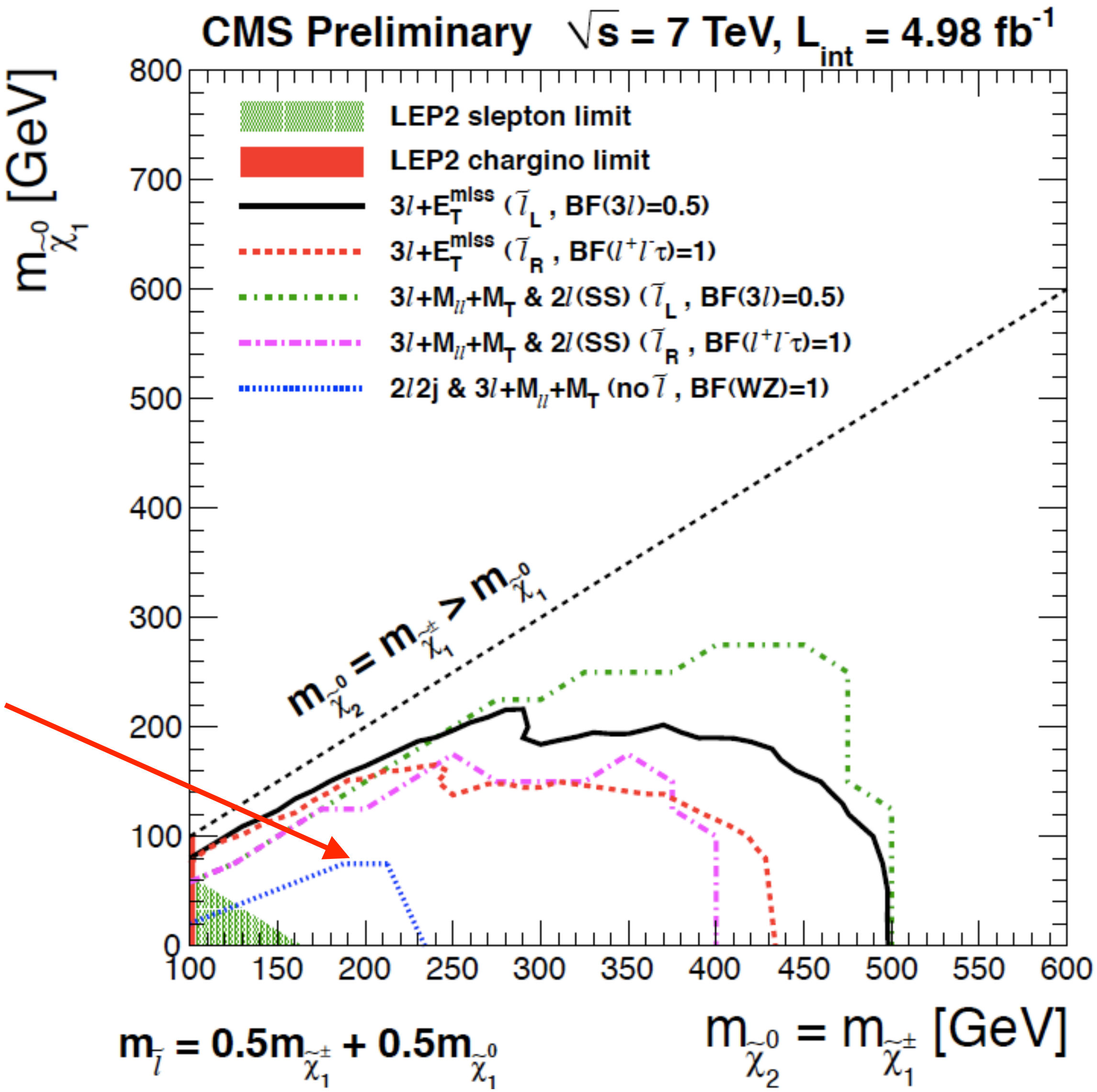
- 3(4) –lepton (incl. taus) + MET
- 3 lepton using M(ll) and M_T(l, v)
- 2 same-sign leptons (incl taus) + MET
- 2 opposite-sign leptons + 2 jets (W/Z) + MET

Sometimes maximal HT cut. Often using a b-jet veto.

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS12006

CMS EWKino search



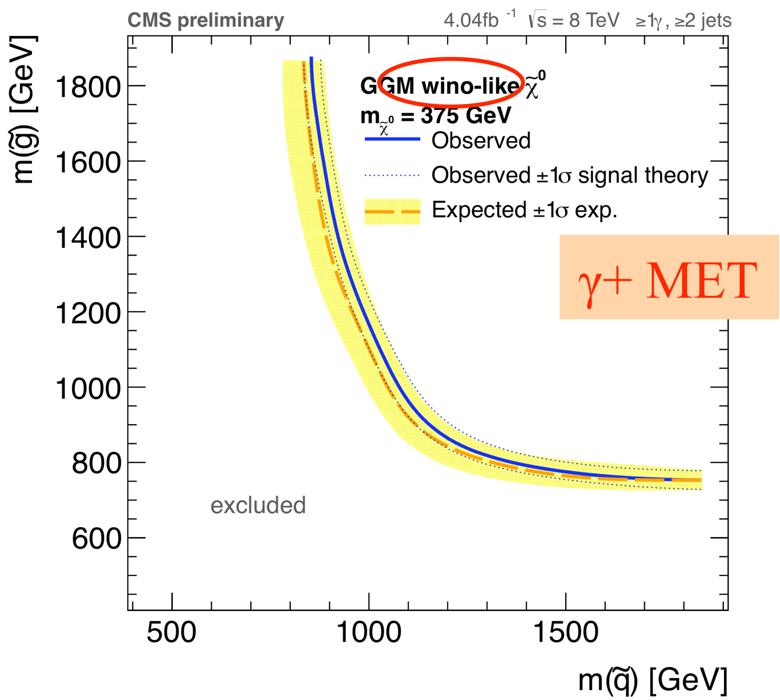


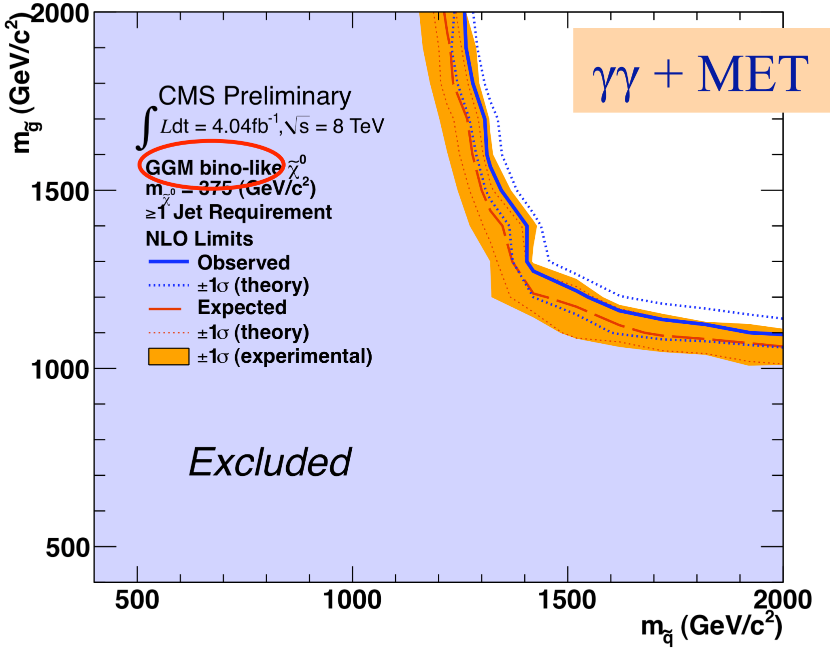
Photons - GMSB

Also gauge mediated scenarios are studied

- Depending on the nature of the LSP, single or double photon final states may dominate:

8 TeV





https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS12018

Summary

- Many topological searches for new physics at the LHC have been performed with the 7/8 TeV data
  - Limits on squarks/gluinos between 800-1200 GeV for light LSP
    - But limits evaporate if LSP is heavier than ~ 450 GeV

- Also some focused search efforts:
  - First limits on direct EWK chargino/neutralino production
  - Dedicated 3rd generation searches ongoing

- Challenges for the future:
  - 3rd generation (direct stop/sbottom searches)
  - Compressed spectra (trigger, analysis strategy, …)

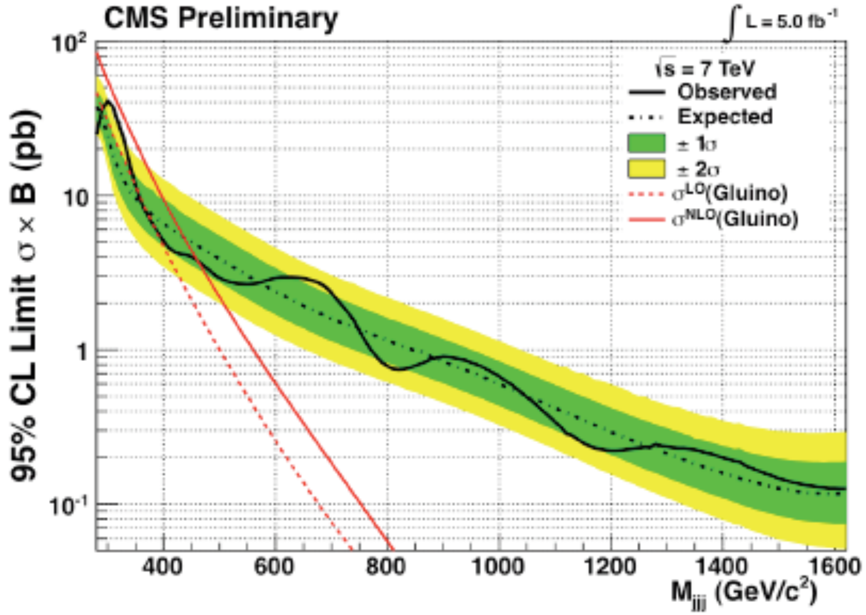

KEEP
CALM
AND
CARRY
ON

Backup

RPV SUSY scenarios

- Many possibilities
- Often can reinterpret Exotica analyses:

Example: gluino to 3 quarks:

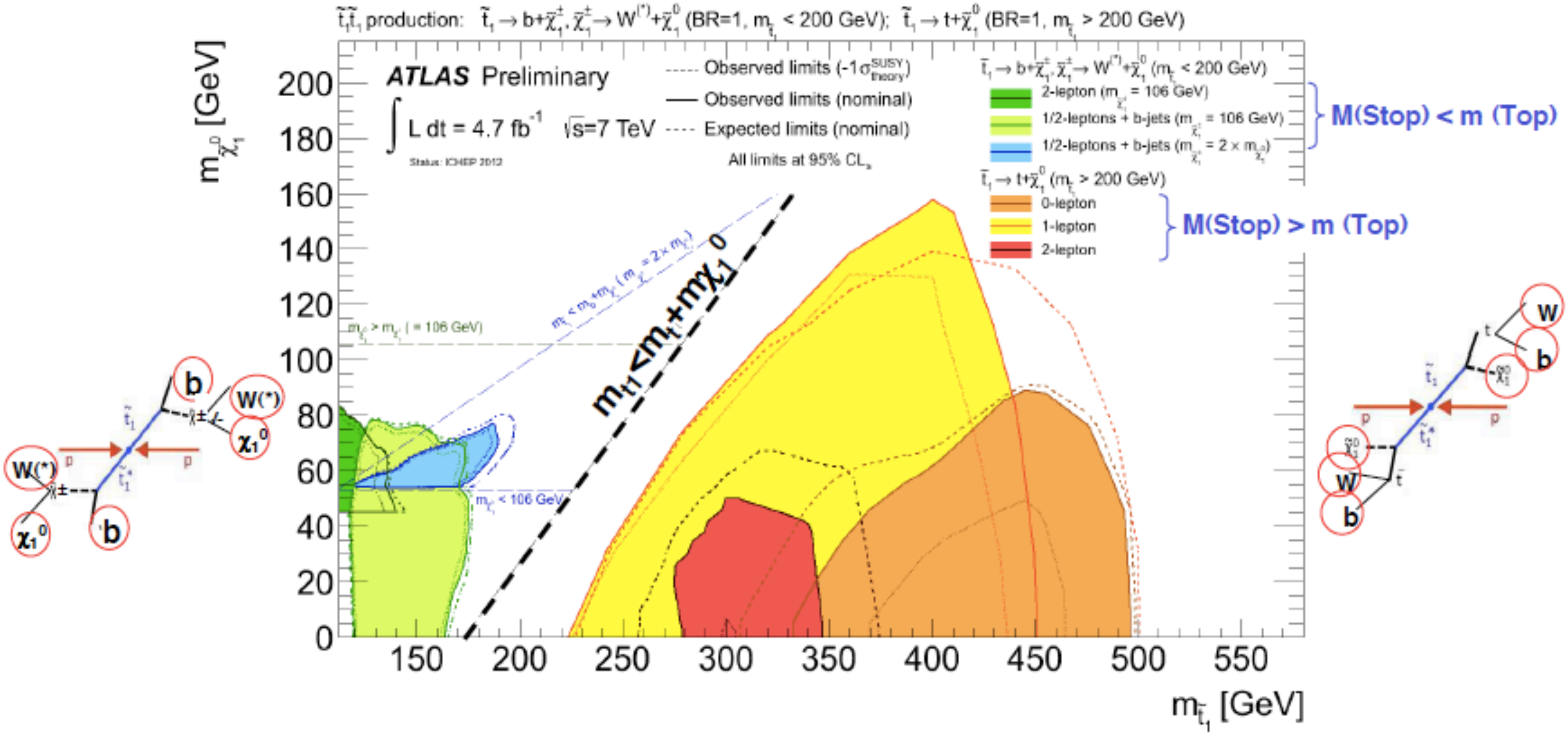


→ exclude gluino masses below 460 GeV

Direct stop in ATLAS

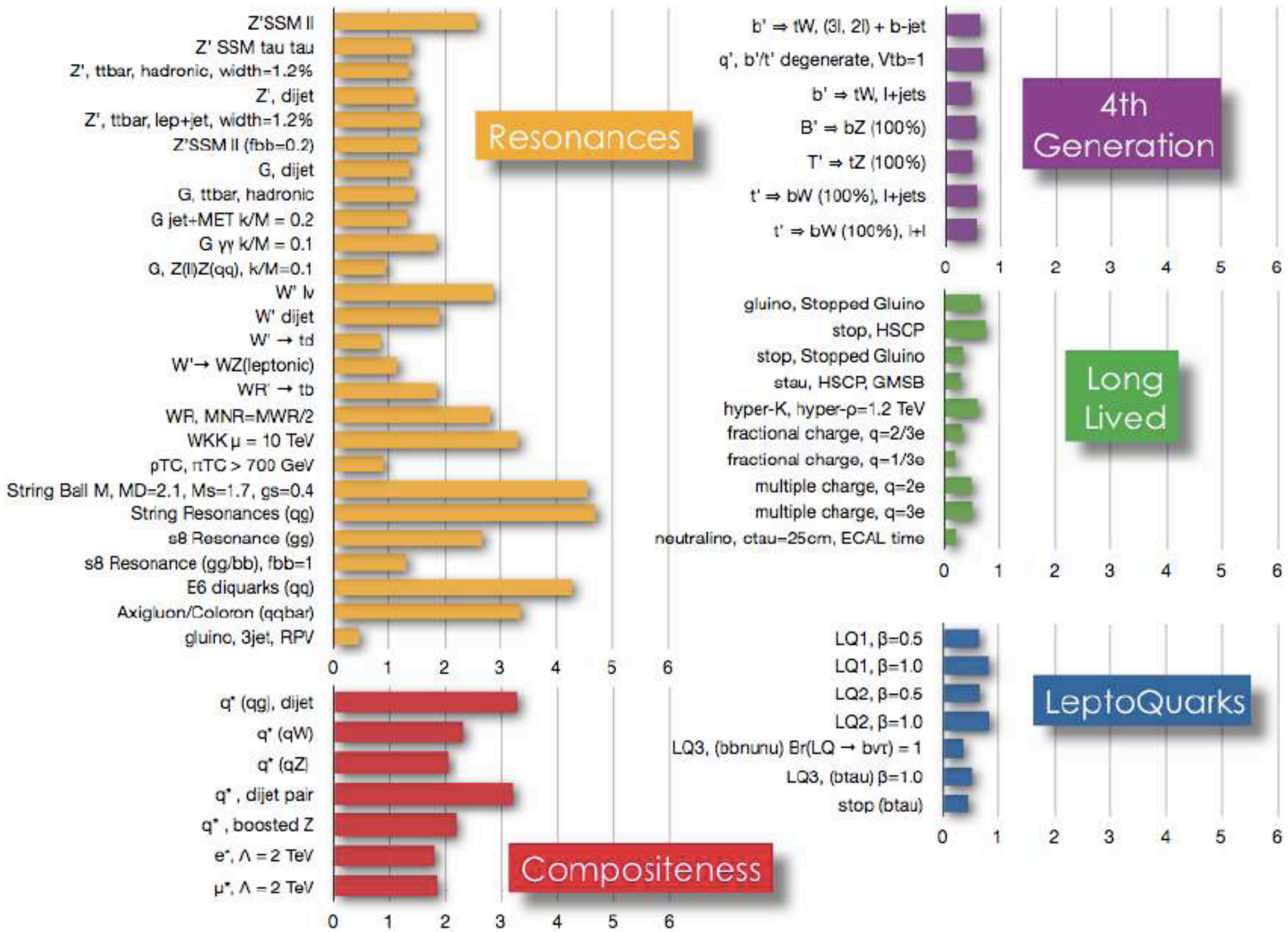
Direct stop production:

- Dedicated analyses with 0/1/2 leptons for m(stop) < m(top) as well as m(stop) > m(top)

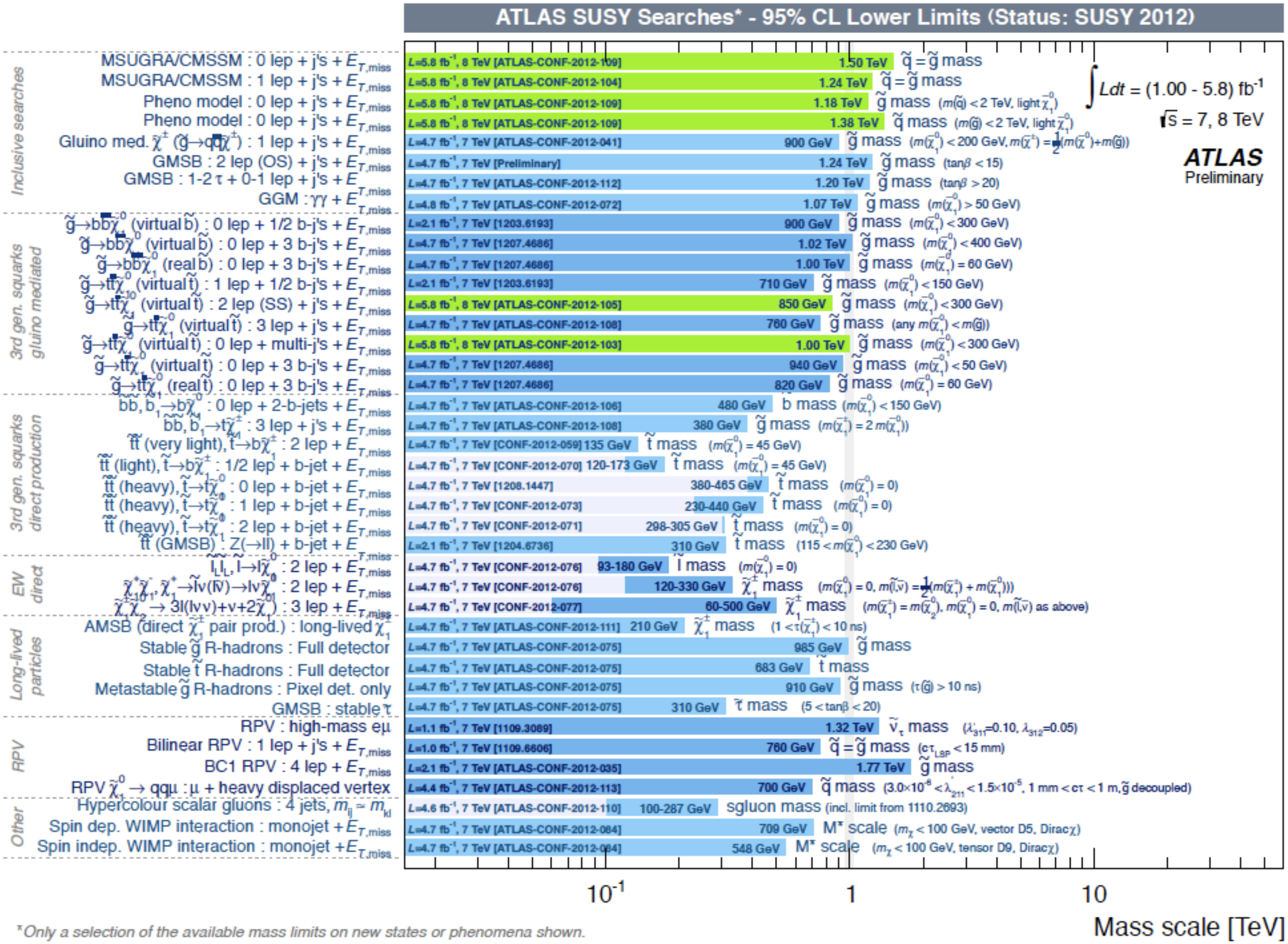


CMS EXO summary

ETH Institute for Particle Physics



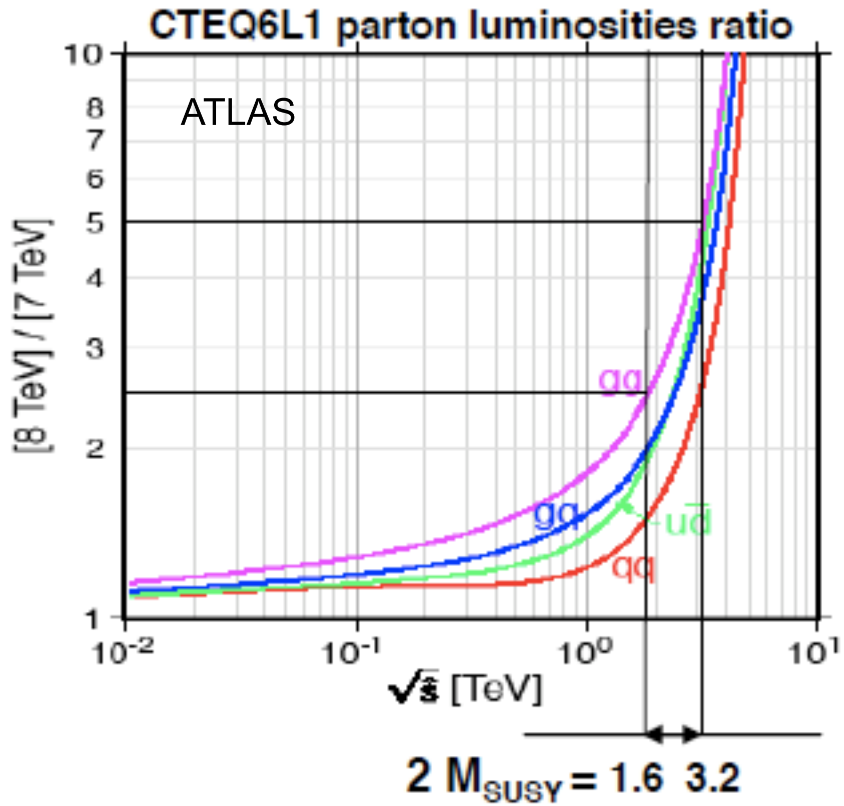
ATLAS SUSY Summary



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

7 TeV to 8 TeV

Can 5 fb^{-1} at 8 TeV add something significant wrt. 5 fb^{-1} at 7 TeV?



Fake ratio method

f = 'fake ratio' tight-to-loose from a background-dominated sample, e.g. Jet events
p = 'prompt ratio' ratio tight-to-loose from a signal-dominated sample, e.g. from a Z boson decays → need to correct for real muon contamination.

Use the definitions of **f** and **p** to write down a **system of equations:**

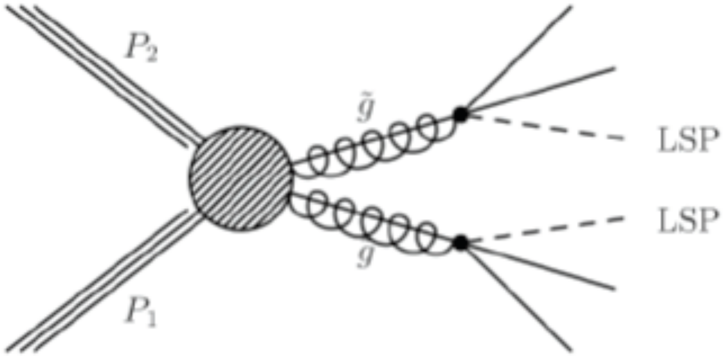
$$N_l = N_{pp} + N_{fp} + N_{ff} = N_{t2} + N_{t1} + N_{t0}$$

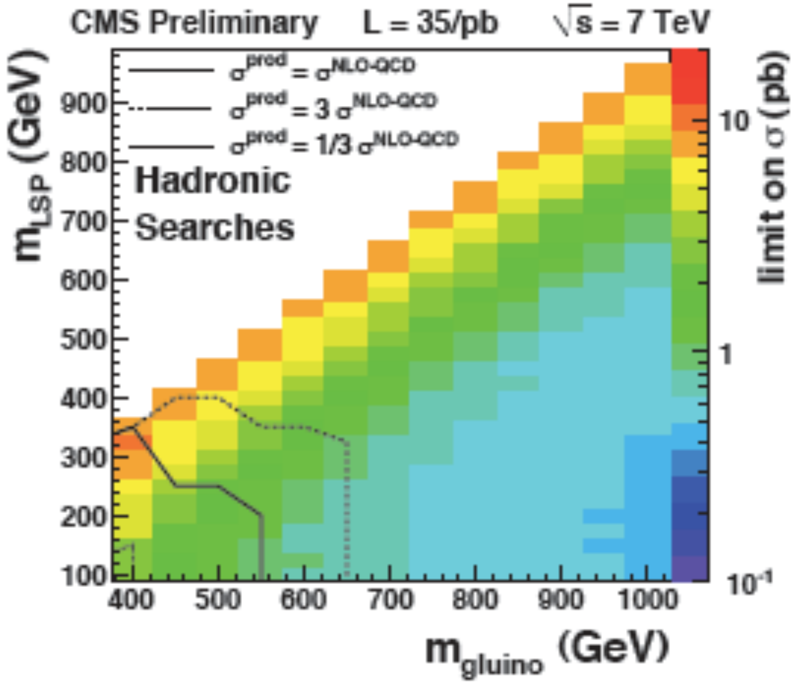
$$\begin{aligned} N_{t0} &= (1-p)^2 N_{pp} + (1-p)(1-f) N_{fp} + (1-f)^2 N_{ff} \\ N_{t1} &= 2p(1-p) N_{pp} + [f(1-p) + p(1-f)]\, N_{fp} + 2f(1-f) N_{ff} \\ N_{t2} &= p^2 N_{pp} + pf N_{fp} + f^2 N_{ff} \end{aligned}$$

N_l = total #events with at least two 'loose' muons
N_{t0}, N_{t1}, N_{t2} = #events with 0,1,2 muons passing 'tight' selection cuts (but not signal cuts)
N_{pp}, N_{fp}, N_{ff} = #events with prompt-prompt, fake-prompt, fake-fake muons (unknown) 5

Model-independent interpretation

More generic interpretation:
Simplified Models





- masses are generic, not model dependent. No cross-section assumed.
- broadens reach of kinematically accessible regions of parameter space
- put 95%CL limits on σ using all existing CMS hadronic searches
- black lines represent QCD-like cross sections