Searches for supersymmetry at the LHC

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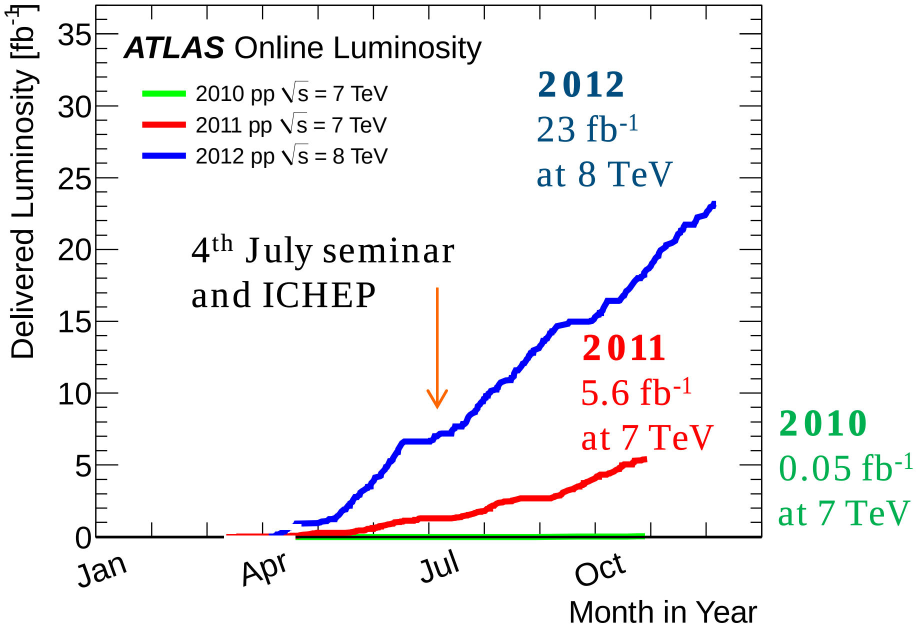
LABORATOIRE
DE L'ACCÉLÉRATEUR
LINÉAIRE

Known biases

Exotics
RPV
Long Lived
Non miminal SUSY
Gravitino LSP
Indirect searches
CMS

SUSY
RPC
Prompt decays
MSSM
Neutralino LSP
Direct searches
ATLAS

Three Years of LHC operations



2010

O(2) Pile-up events

150 ns inter-bunch spacing

2011

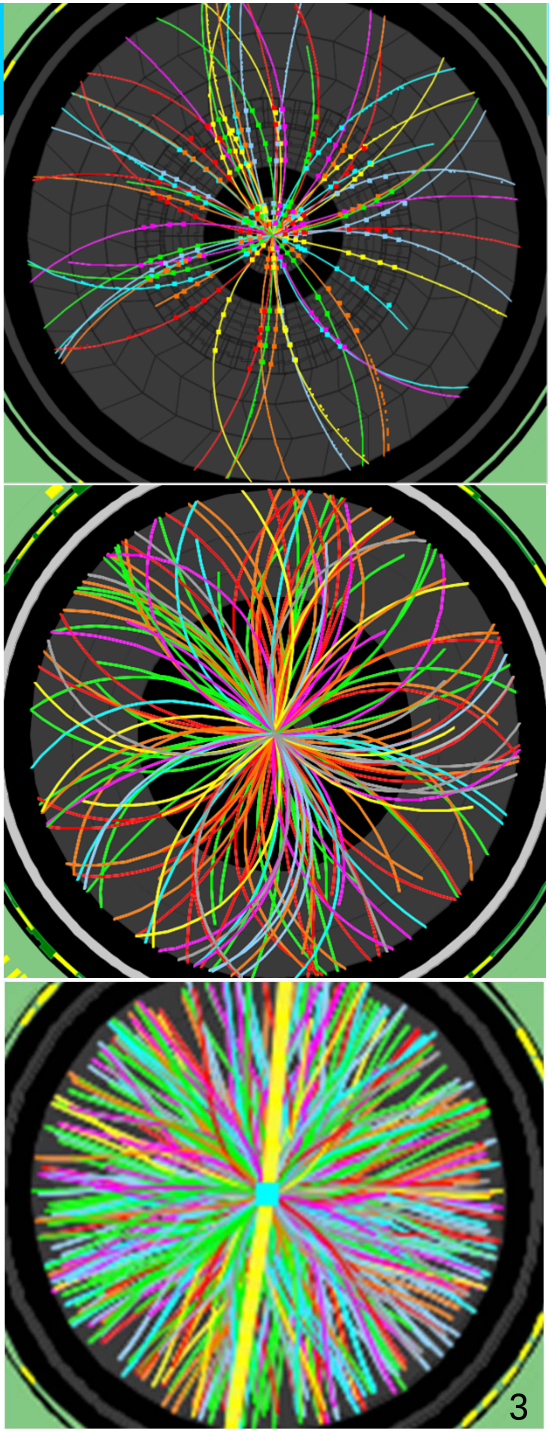
O(10) Pile-up events

50 ns inter-bunch spacing

2012

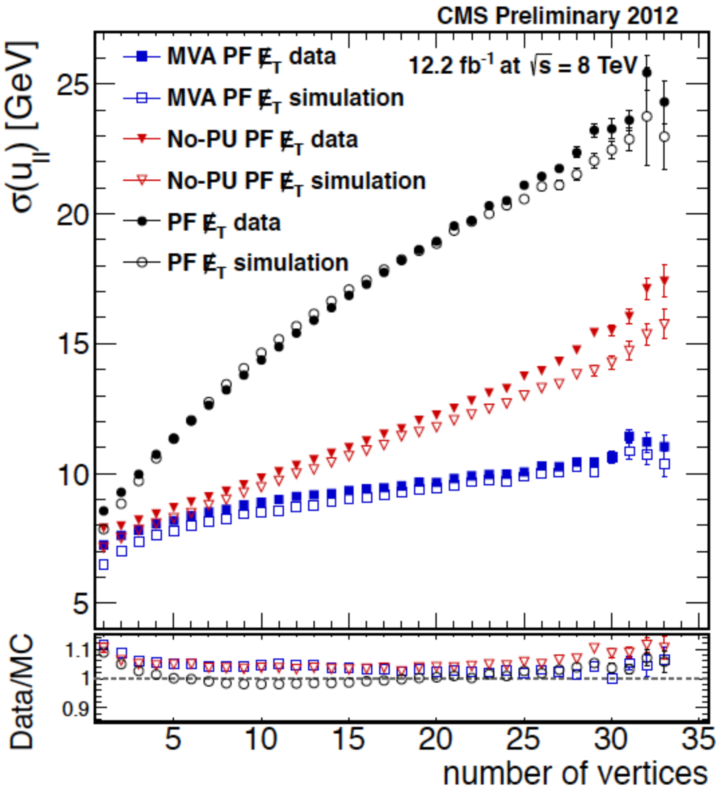
O(20) Pile-up events

50 ns inter-bunch spacing



- In general, the pile-up do not significantly impact tracking, nor muons, nor even electrons and photons
- However, sizable impact on jets, MET and tau reconstruction as well as on trigger rates and computing

Jet and missing transverse energy

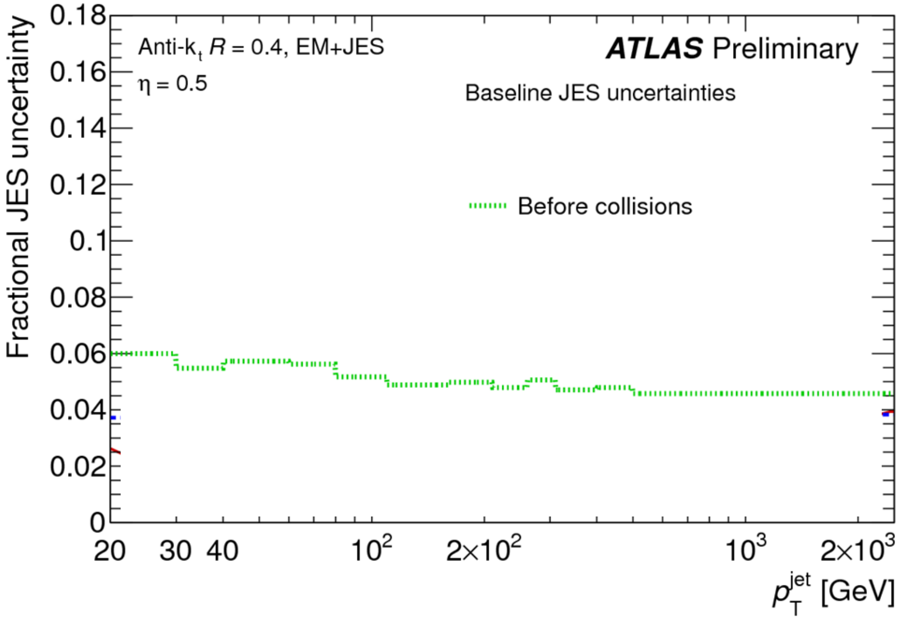


Missing transverse energy (MET) can indicate the presence of neutrinos or other (new?) non-interacting particles.

It is calculated as the negative of the vectorial sum of all of the objects reconstructed in the events

Impressive improvements on the baseline JES determination using in-situ techniques!

But still the main experimental systematic uncertainty in SUSY searches



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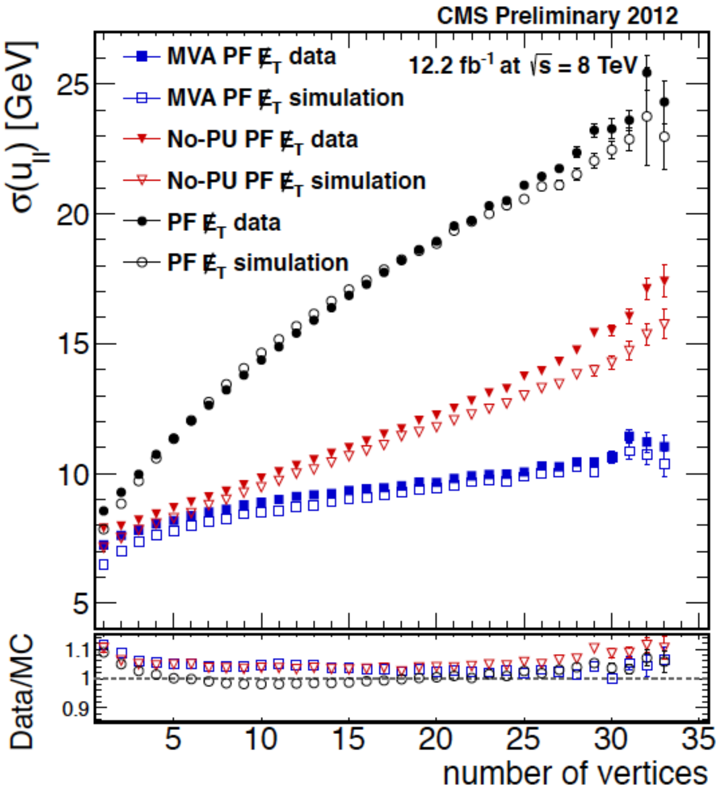

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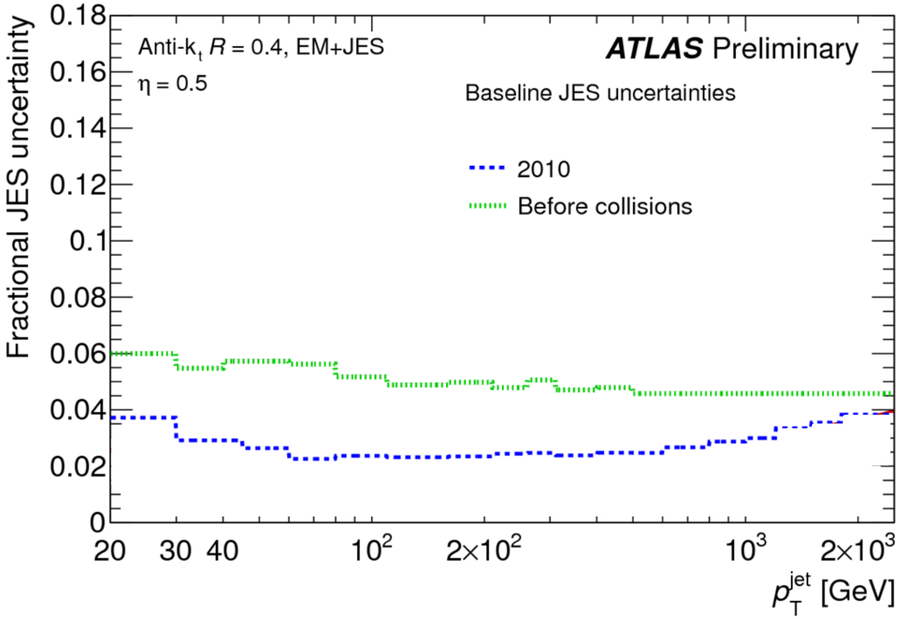

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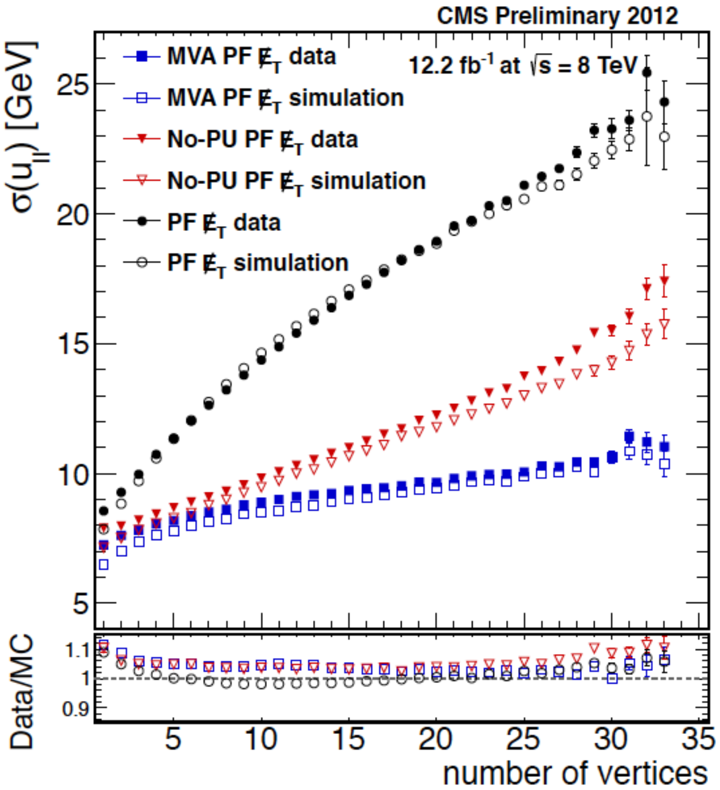

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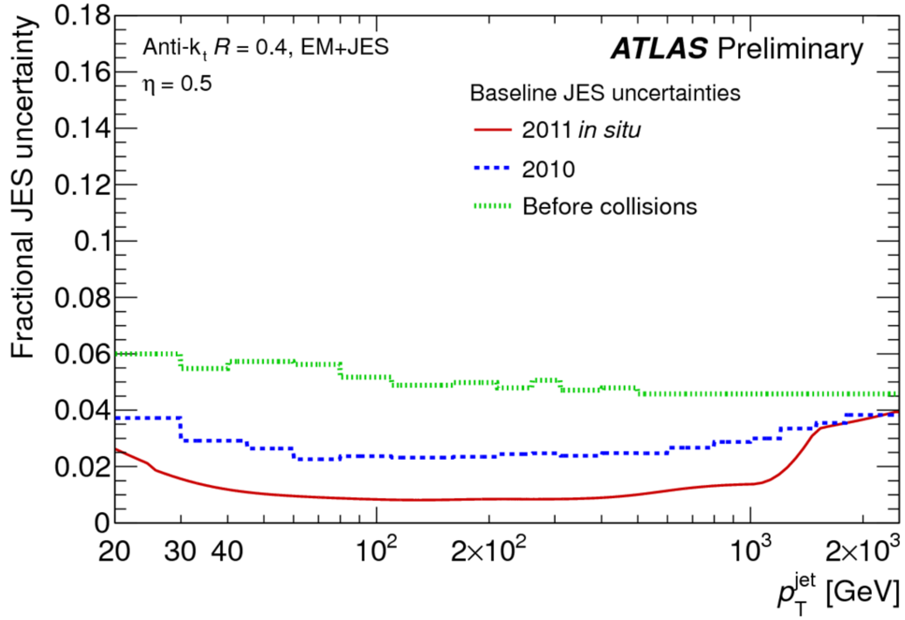
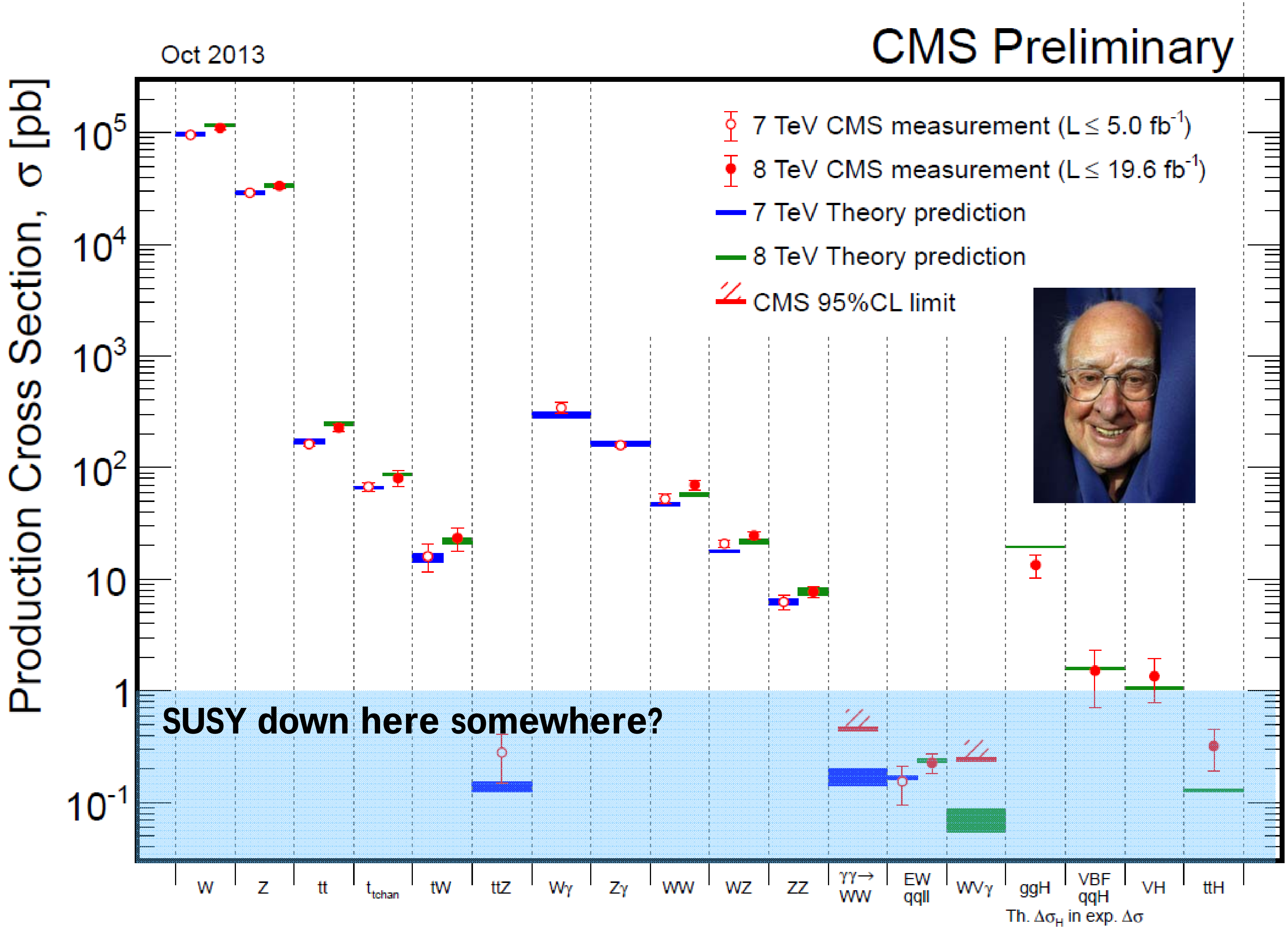
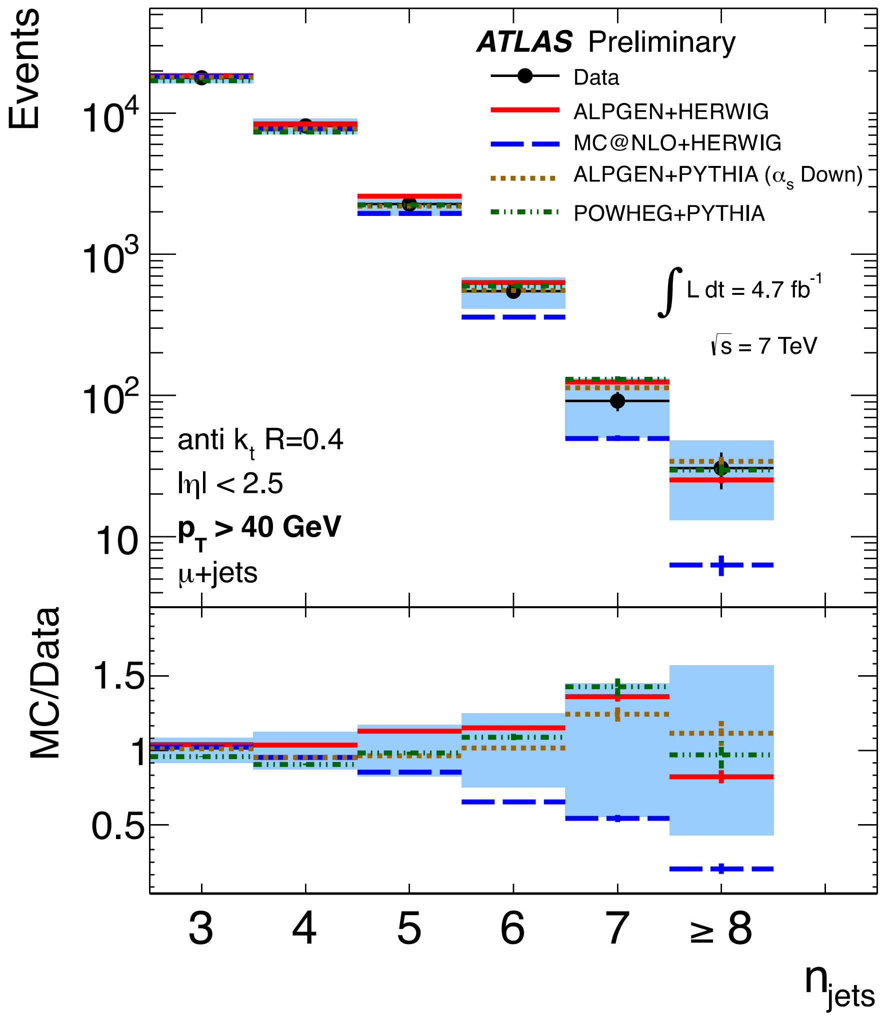


Standard Model measurements at the LHC

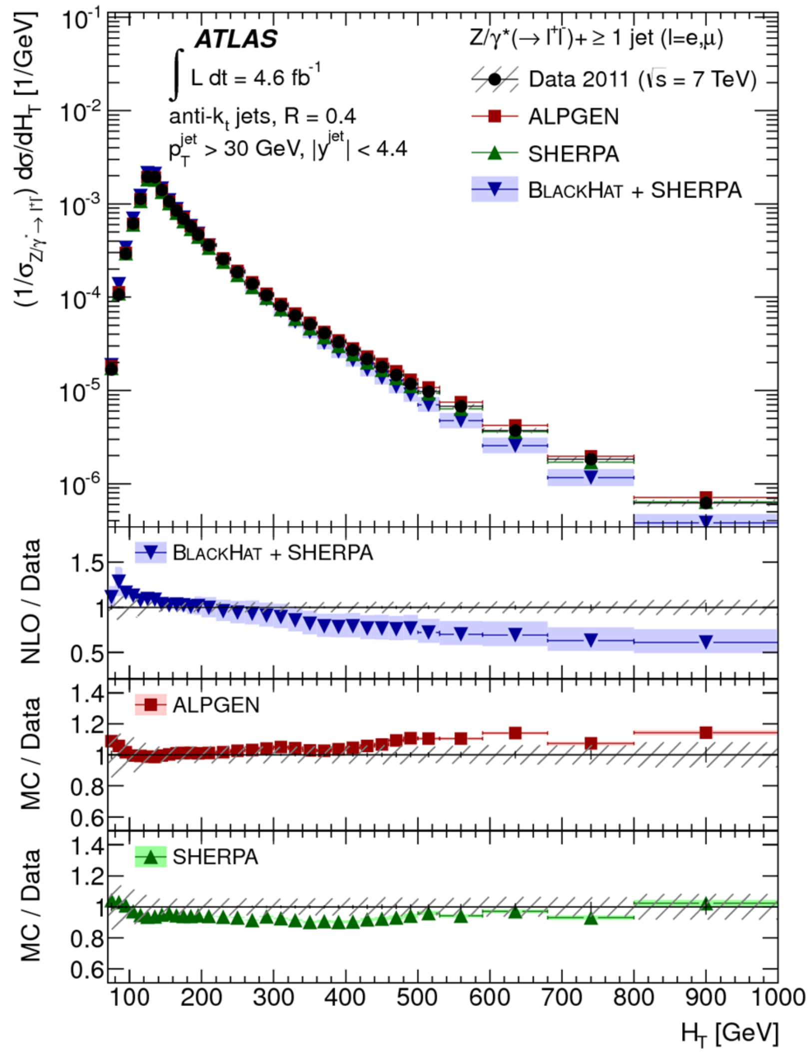


Standard Model measurements at the LHC

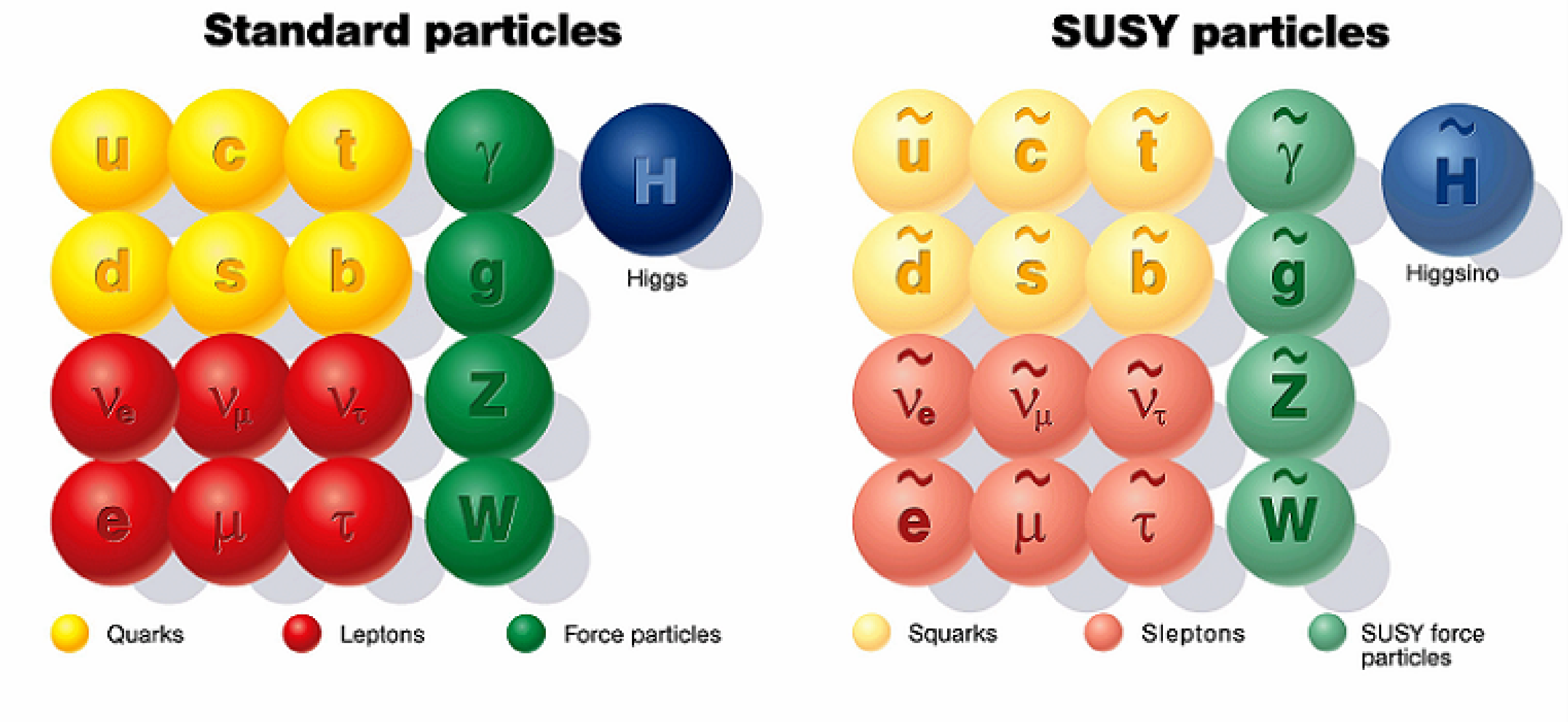
Measurement of fiducial jet multiplicity in $t\bar{t}$ production (lepton+jets)



Measurement of Z + jets production

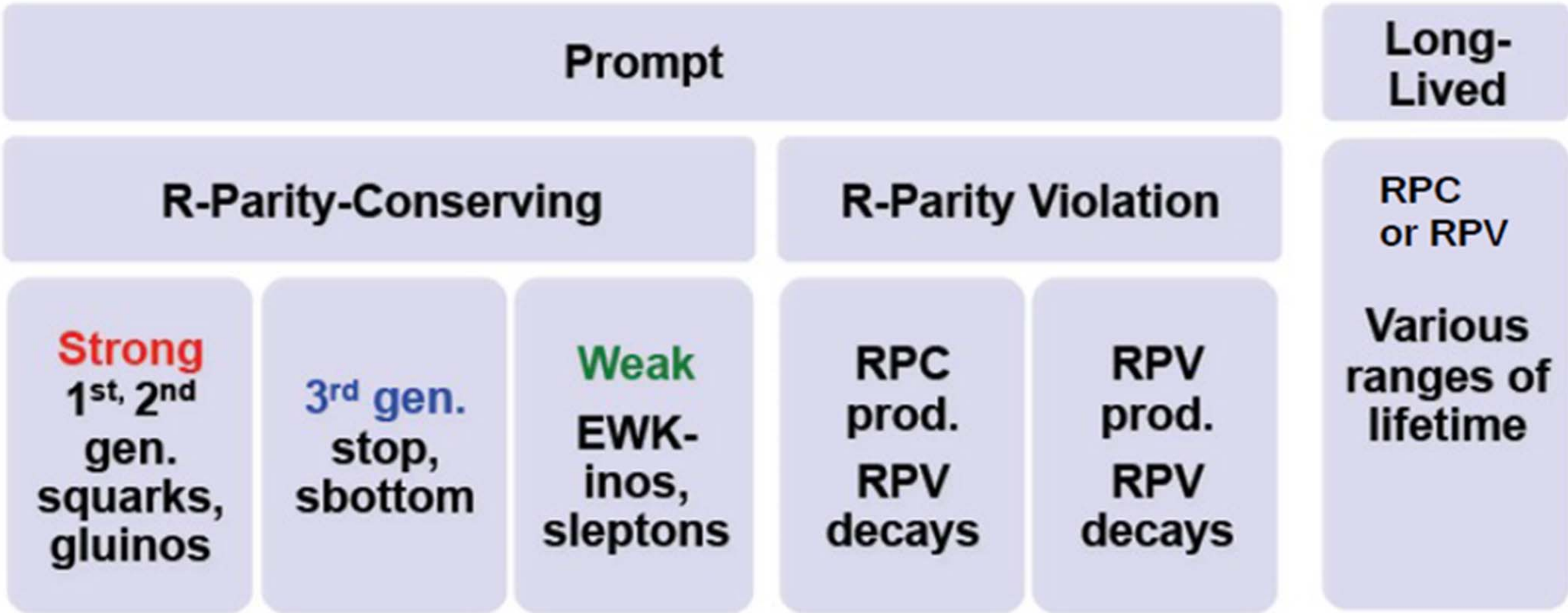


Search strategy



Many new particles, huge parameter space (>100 new parameters), wide range of possible signatures but they are guiding principles….

Search strategy



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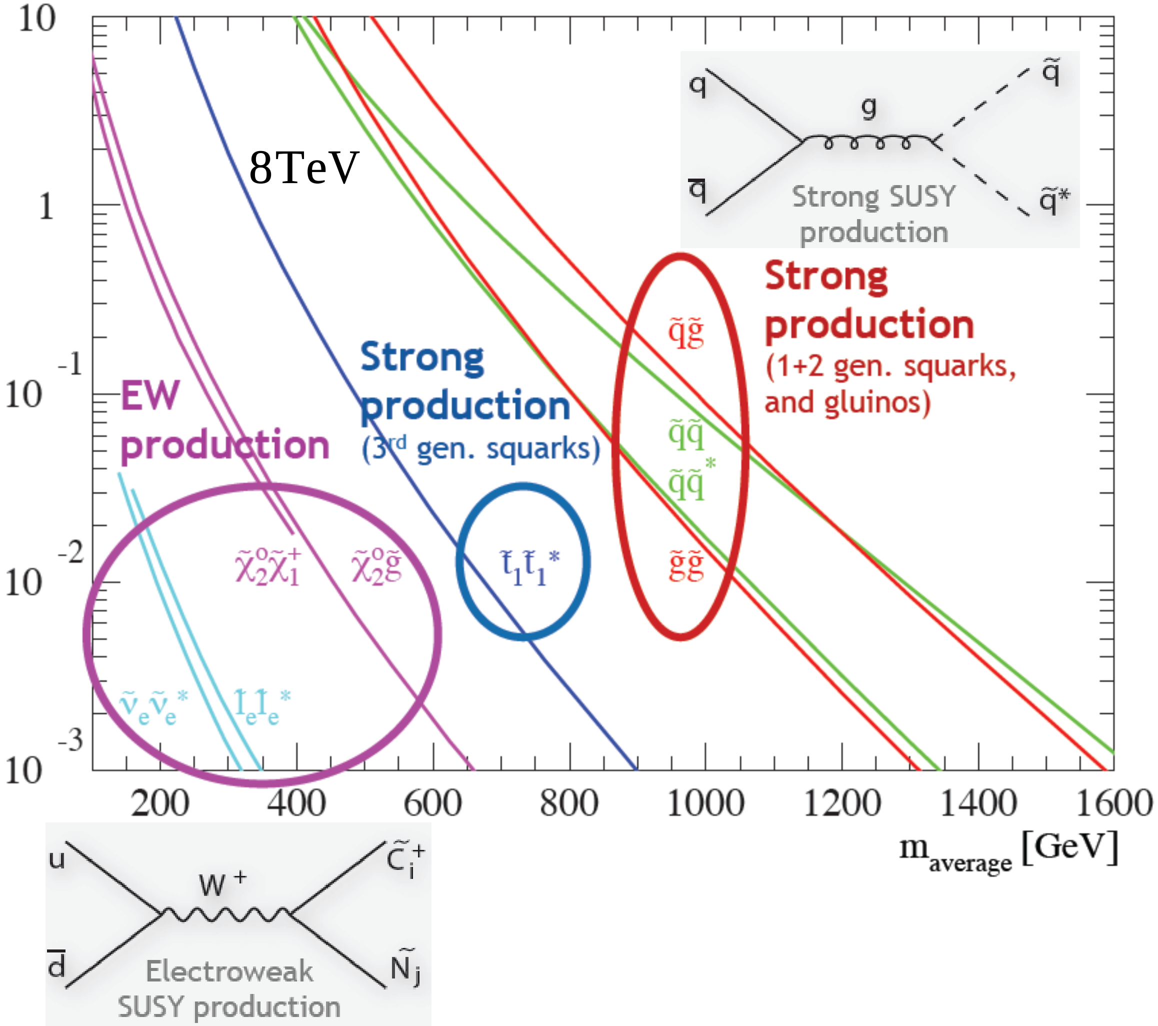
Search strategy

- SUSY searches strategy driven by cross section and luminosity



Early analyses dominated by broad and inclusive searches for gluino and squark production, but right from the start also attacked experimentally challenging searches such as for long-lived particles and RPV

Increasing luminosity gave access to rarer production channels. Additional motivation from *Natural SUSY* paradigm

It was quickly realised that dedicated searches had to be developed to adequately cover the rich decay spectrum

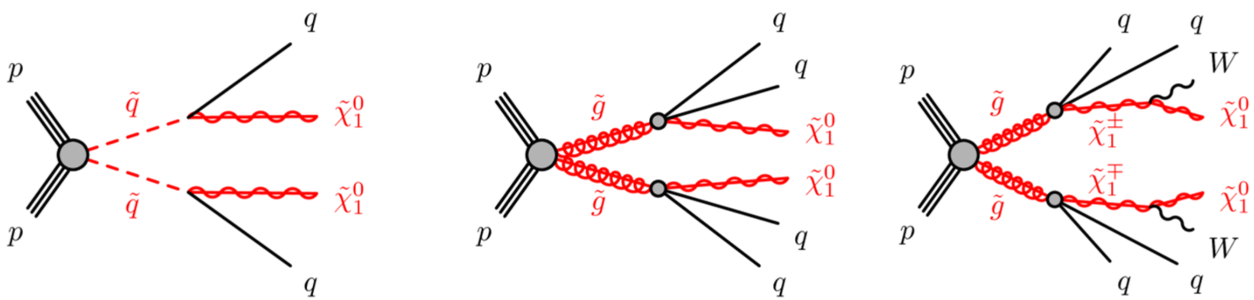
ATLAS 0lepton analysis

- Jet+Met trigger $\Rightarrow$ Leading jet pt>130GeV and MET>160GeV
- Veto events with electrons and muons with pT>10GeV

$$M_{eff} = H_T + E_T^{miss} \qquad H_T = \sum_{jets\ pT>40GeV} p_T^{jets}$$

Requirement	Channel									
	A (2-jets)		B (3-jets)		C (4-jets)		D (5-jets)	E (6-jets)		
	L	M	M	T	M	T	–	L	M	T
$\Delta\phi(\text{jet}_i, \mathrm{E}_\mathrm{T}^{\text{miss}})_{\text{min}} >$	0.4 ($i = \{1, 2, (3 \text{ if } p_\mathrm{T}(j_3) > 40\text{ GeV})\}$)				0.4 ($i = \{1, 2, 3\}$), 0.2 ($p_\mathrm{T} > 40$ GeV jets)					
$E_\mathrm{T}^{\text{miss}}/m_{\text{eff}}(Nj) >$	0.2	–[a]	0.3	0.4	0.25	0.25	0.2	0.15	0.2	0.25
$m_{\text{eff}}(\text{incl.})$ [GeV] >	1000	1600	1800	2200	1200	2200	1600	1000	1200	1500

(a) For SR A-medium the cut on $E_\mathrm{T}^{\text{miss}}/m_{\text{eff}}(Nj)$ is replaced by a requirement $E_\mathrm{T}^{\text{miss}}/\sqrt{H_\mathrm{T}} > 15\ \text{GeV}^{1/2}$.



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- Main background:
  - $Z \rightarrow \nu\nu$+jets: irreducible background, dominant at low jet multiplicity
  - W+jets: mainly coming from $W \rightarrow \tau\nu$ decay
  - Top: mainly coming from $W \rightarrow \tau\nu$ decay, dominant at high jet multiplicity
  - Diboson: small (<10%)
  - Multijets: negligible thanks to harsh cuts to reject it

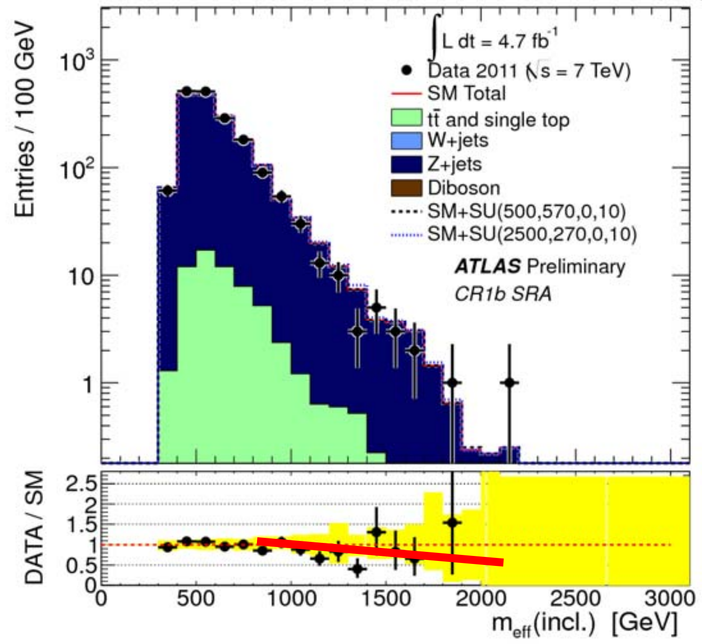
ATLAS 0lepton analysis

$$N_{Z\nu\nu}^{pred} = N_{Z\nu\nu}^{MC}$$

ATLAS 0lepton analysis

$$N^{pred}_{Z\nu\nu} = N^{MC}_{Z\nu\nu}$$

Zll+2jets

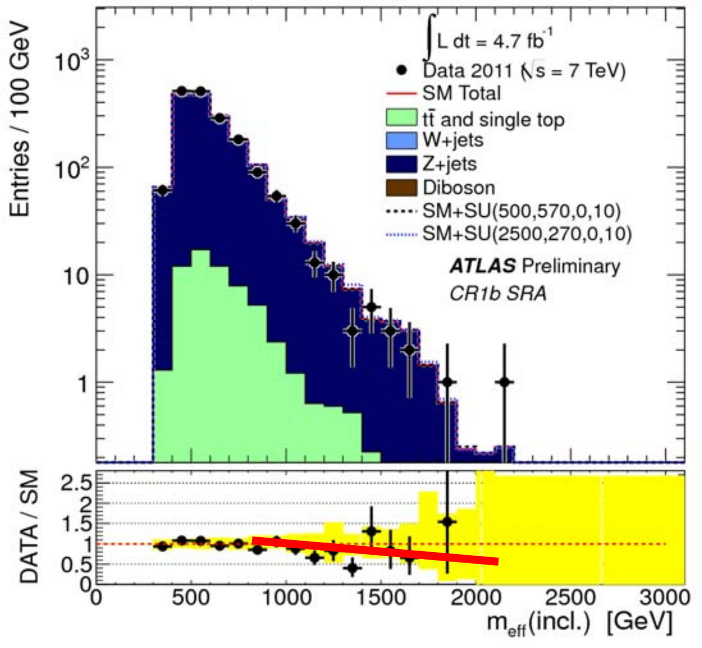


$$meff' = met' + H_T = met + p_T^{Zll} + H_T$$

ATLAS 0lepton analysis

$$N_{Z\nu\nu}^{pred} = N_{Z\nu\nu}^{MC} \times \frac{N_{Zll}^{data}}{N_{Zll}^{MC}}$$

Zll+2jets



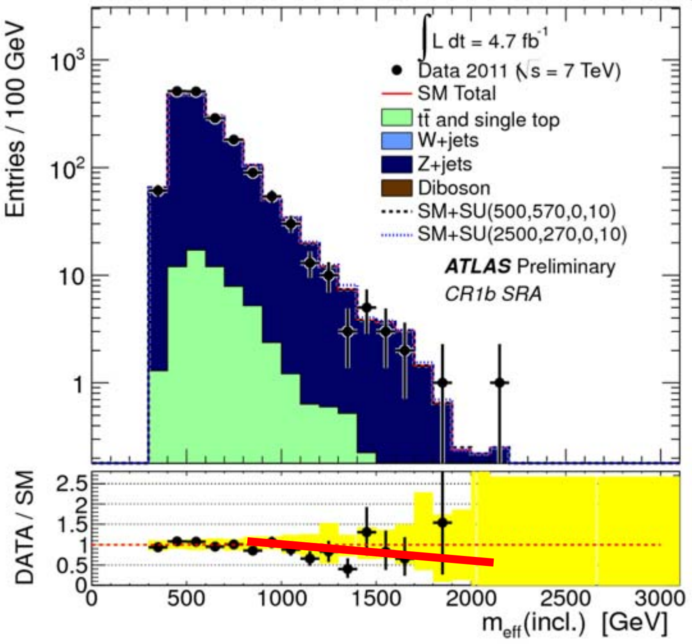
$$meff' = met' + H_T = met + p_T^{Zll} + H_T$$

- Renormalize the MC to data in dedicated control regions
- Control regions are orthogonal to the SR (by inverting cuts) but have kinematical cuts close to SR
- Systematic uncertainties which are correlated between CR and SR largely cancel out in the transfer factor.

ATLAS 0lepton analysis

$$N_{Z\nu\nu}^{pred} = \frac{N_{Z\nu\nu}^{MC}}{N_{Zll}^{MC}} \times N_{Zll}^{data}$$

Zll+2jets



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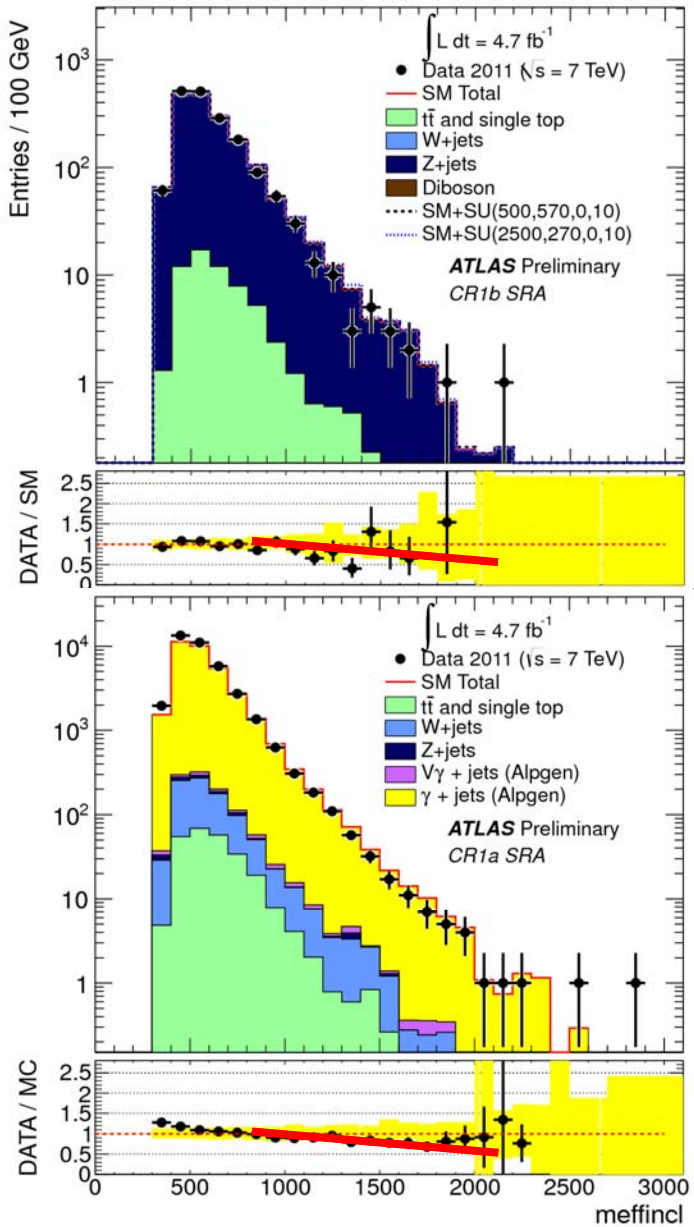
γ+2jets

$$N_{Z\nu\nu}^{pred} = N_{Z\nu\nu}^{MC} \times \frac{N_{\gamma+jets}^{data}}{N_{\gamma+jets}^{MC}}$$

- Zll are statistically limited to estimate accurately the Zνν
- The process γ+jets is used instead
- Larger statistics but massless boson and different couplings
- Transfer factors theoretically understood at the 10% level



ATLAS 0lepton analysis

CR	SR background	CR process	CR selection
CRY	$Z(\rightarrow \nu\nu)$+jets	γ+jets	Isolated photon
CRQ	multi-jets	multi-jets	Reversed $\Delta\phi(\text{jet}, \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}}$ and $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}(Nj)$ requirements[a]
CRW	$W(\rightarrow \ell\nu)$+jets	$W(\rightarrow \ell\nu)$+jets	30 GeV $< m_T(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) <$ 100 GeV, b-veto
CRT	$t\bar{t}$ and single-t	$t\bar{t} \rightarrow bbqq'\ell\nu$	30 GeV $< m_T(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) <$ 100 GeV, b-tag

- A global likelihood fit for the normalization of each background from the 4 control regions is simultaneously performed separately for each signal region.
  - Background cross contamination in control regions automatically taken into account

- Validation regions:
  - VRZ, CRWT with lepton treated as invisible, VRTau, VRQ

- Systematics:
  - Cancellation of the main systematics thanks to semi data driven technics
  - JES, JER: few %
  - Theory: 10 to 20%

ATLAS 0lepton analysis

$$N_{Z\nu\nu}^{pred} = N_{Z\nu\nu}^{MC} \times \frac{N_{\gamma+jets}^{data} - N_{other\ bkg}}{N_{\gamma+jets}^{MC}}$$

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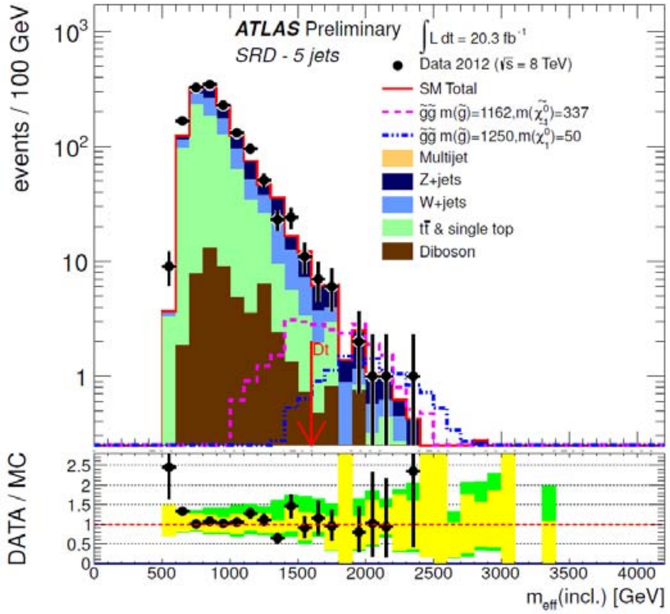
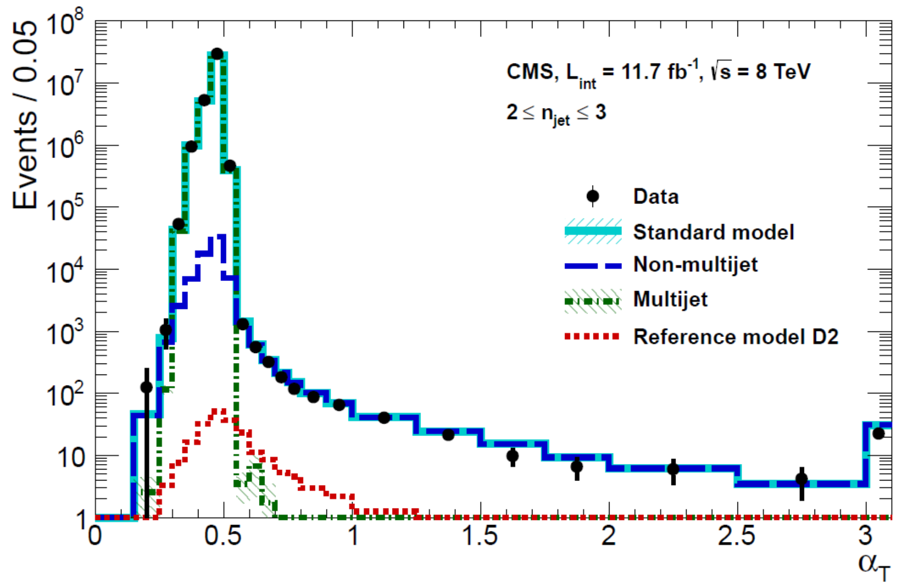


α_T (11.7fb^{-1})

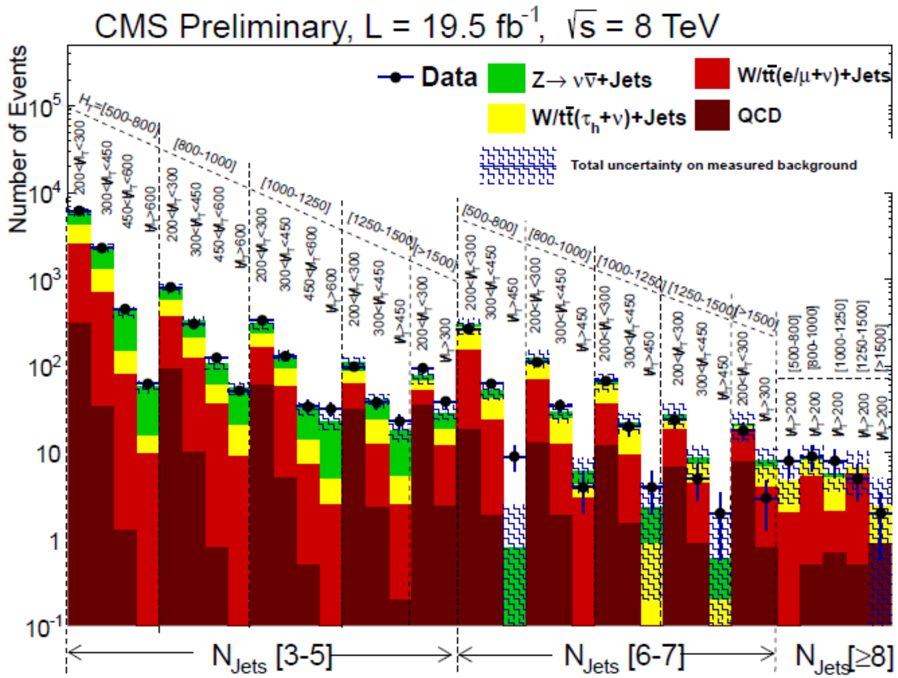
Shape analysis using the 59 bins based on:

- Jet multiplicity ([2,3],≥4)
- bJet multiplicity
- HT

α_T : reject multijet background



$$\alpha_T \equiv \frac{E_T^{J_2}}{M_T(J_1J_2)} = \frac{\sqrt{E_T^{J_2}/E_T^{J_1}}}{\sqrt{2(1-\cos\Delta\varphi_{J_1J_2})}}$$



MHT+HT (19.5fb^{-1})

Shape analysis using the 36bins based on:

- Jet multiplicity ([3,5],[6,7], ≥ 8)
- MHT
- HT

Interpretation

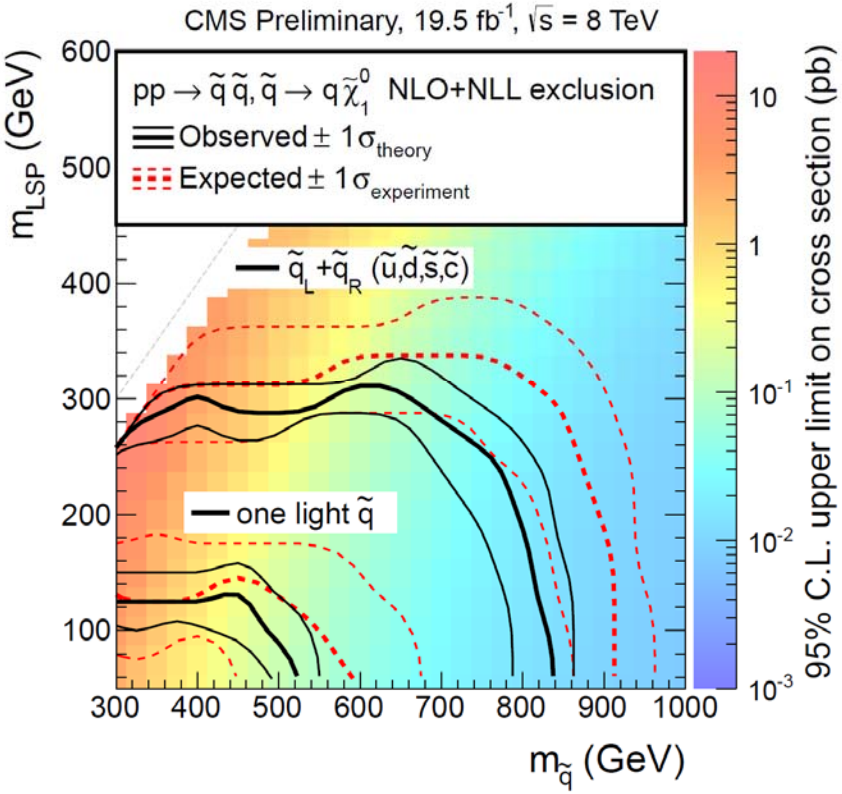
- If we consider general MSSM, there are too many parameters to scan. So we have to reduce the number of parameters.

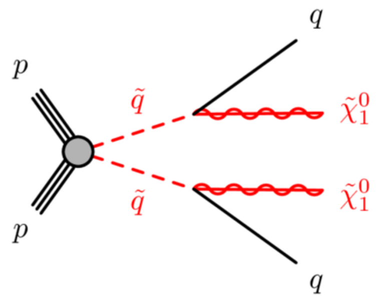
- One approach followed to reduce the number of free parameters is to assume specific breaking models at the GUT scale, i.e.:
  - mSUGRA/CMSSM (Higgs-aware)
  - GMSB
  - mAMSB

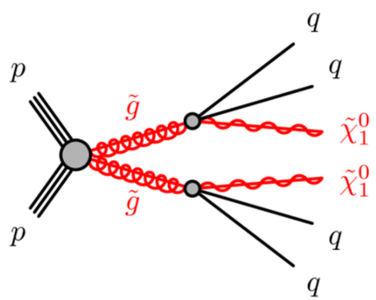
- The alternative approach is to focus on one or few production processes and decay chains (with fixed branching ratio (BR)), extracting only the 'essence' of a certain model:
  - This is what we call simplified model
  - Reasonably well suited to natural SUSY spectra

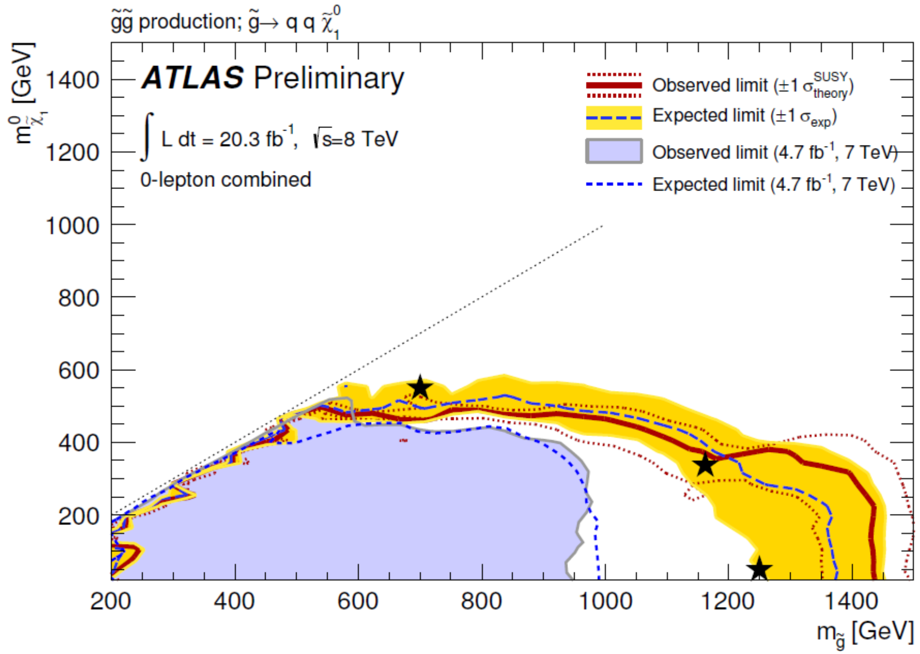
- The third approach is the phenomenological MSSM one, with choices of weak scale parameters agnostic of what happens at GUT scale
  - Understand LHC results in a broader framework
  - Interplay with other constraints (ex: DM)
  - Discover signatures that LHC analyses may not be covering.
  - Tom Rizzo et al., arXiv:1206:5800, arXiv:1206.4321

Simplified models

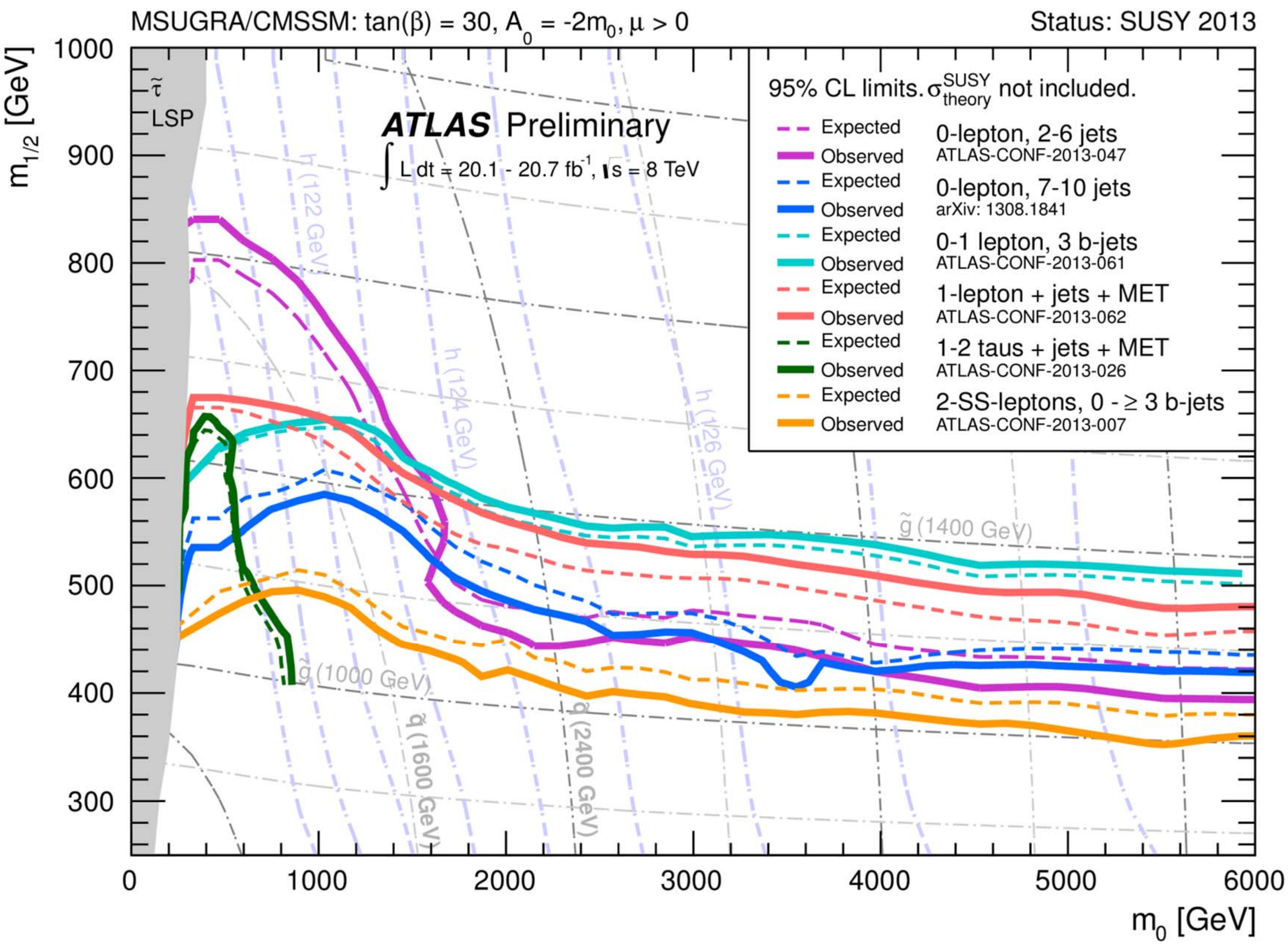






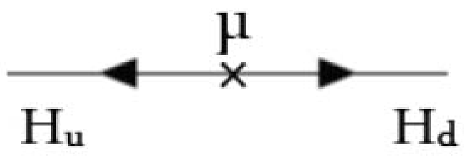


Higgs-aware mSugra

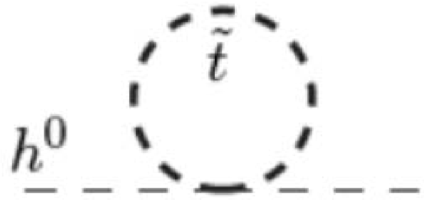


Natural SUSY

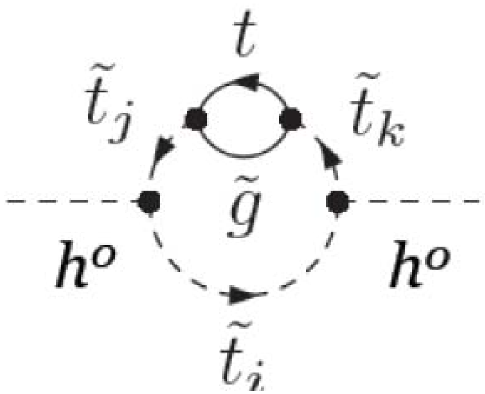
Tree-level: Higgsino < ~350 GeV



One loop: stop < ~1 TeV

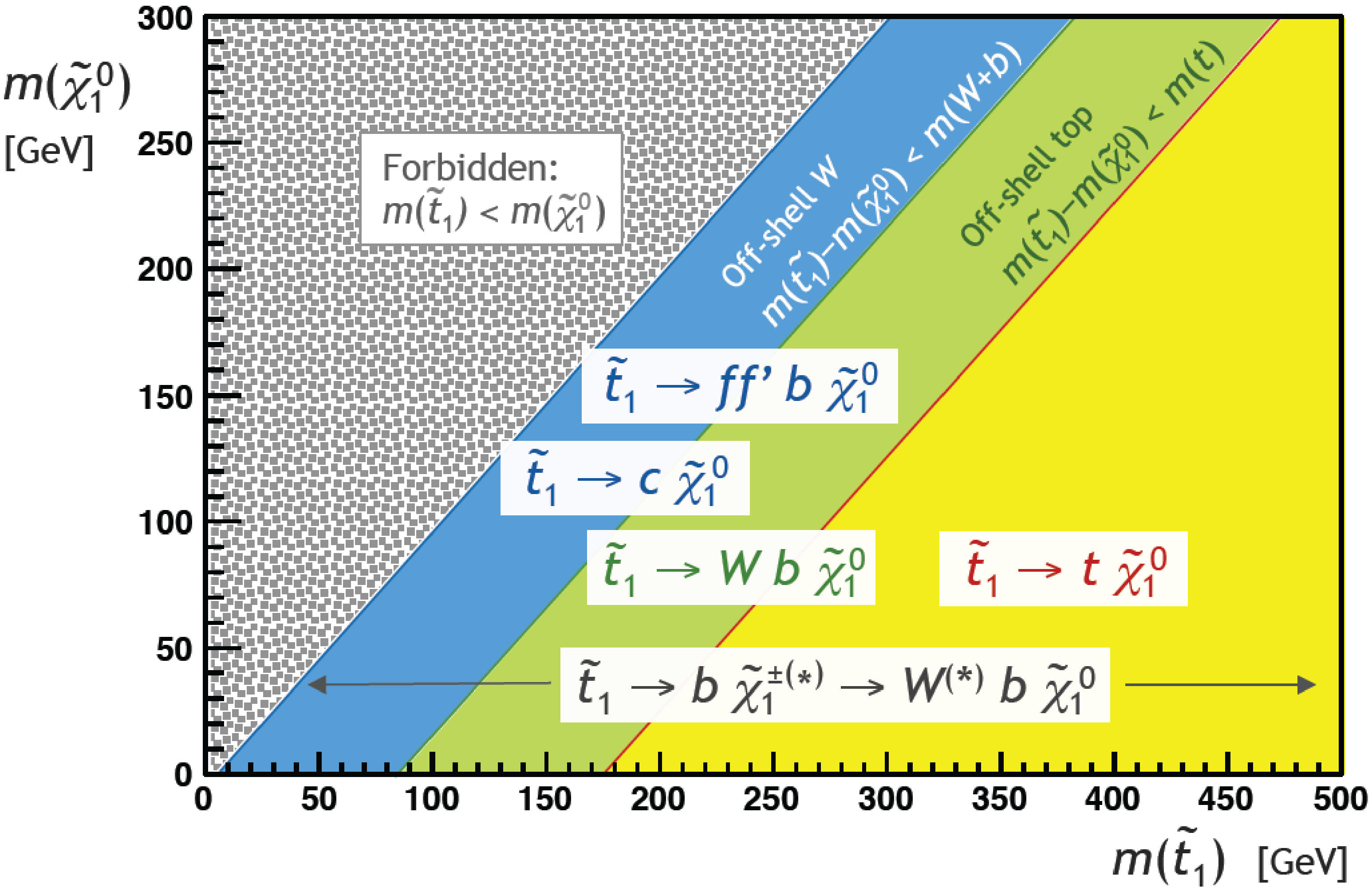


Two loops: gluino < ~2 TeV



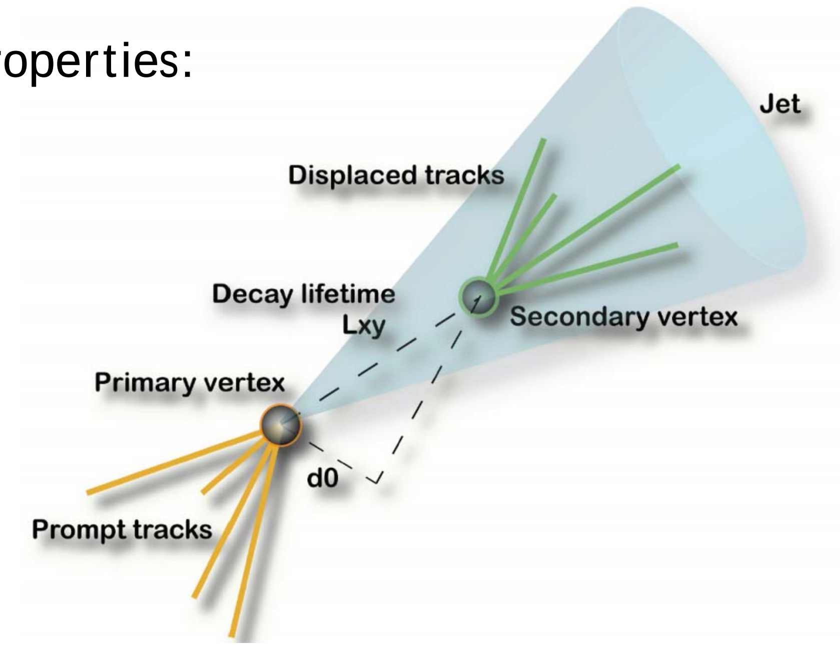
Direct stop pair production

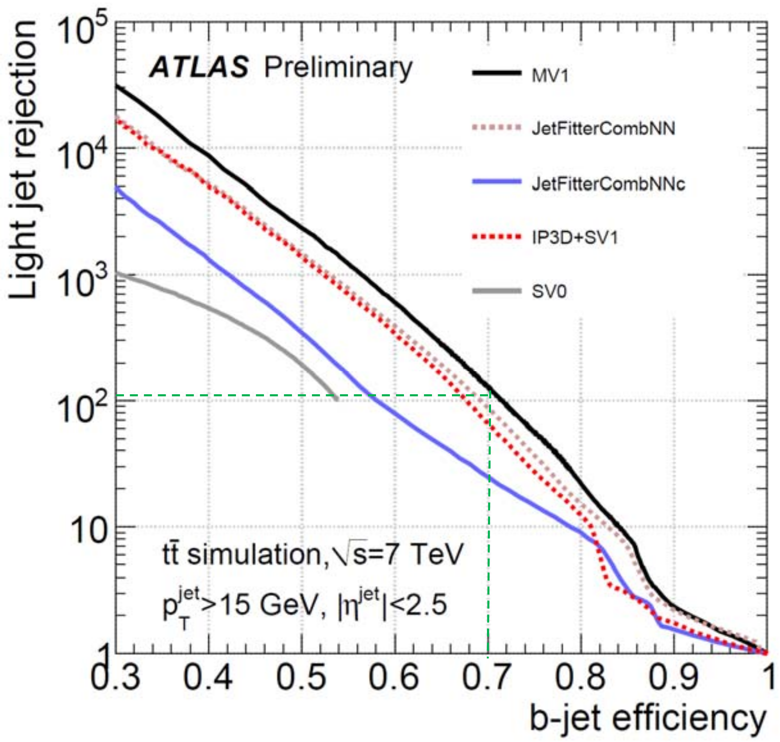
Large spectrum of possible stop decays.
Effort so far concentrated on simplified models with 100% BRs to chosen final state.



b-tagging algorithms exploit the b-hadron properties:

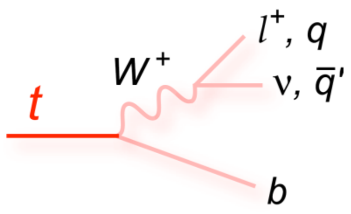
- relative long life time
- displaced tracks/decay vertices
- relatively large B-hadron masses
- semileptonic decays





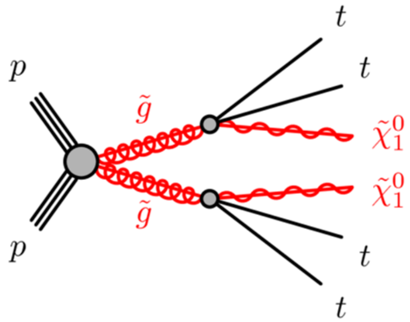
Advanced Neural Net based algorithms (MV1), combine several information to improve the performance.

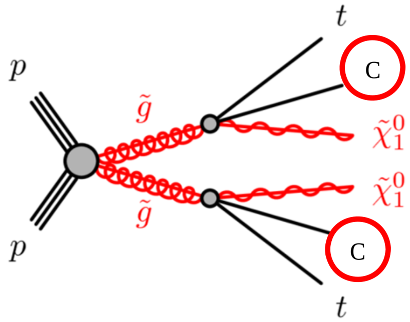
Performance in-situ using in particular top pair events

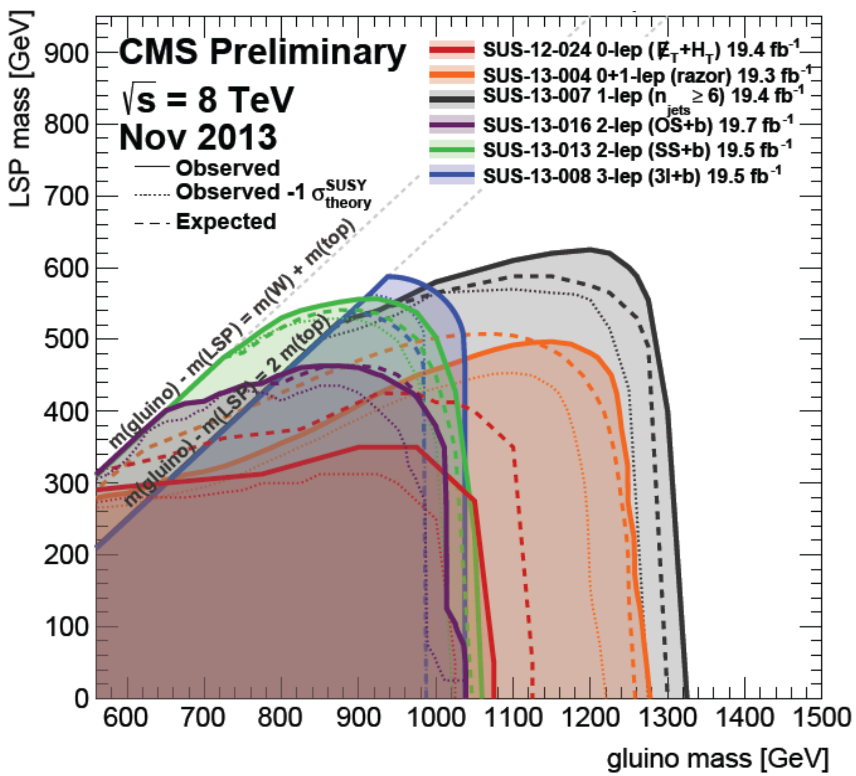


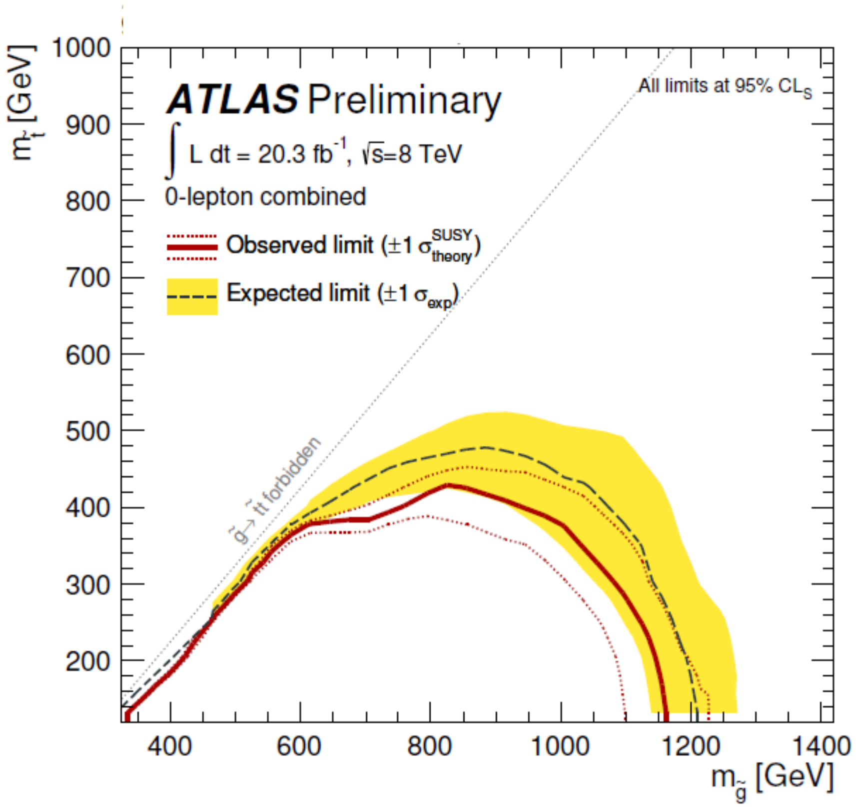
Gluino-mediated stop

If gluinos are light, they are produced in pairs and decay through stops

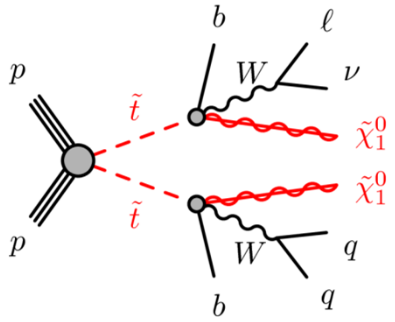


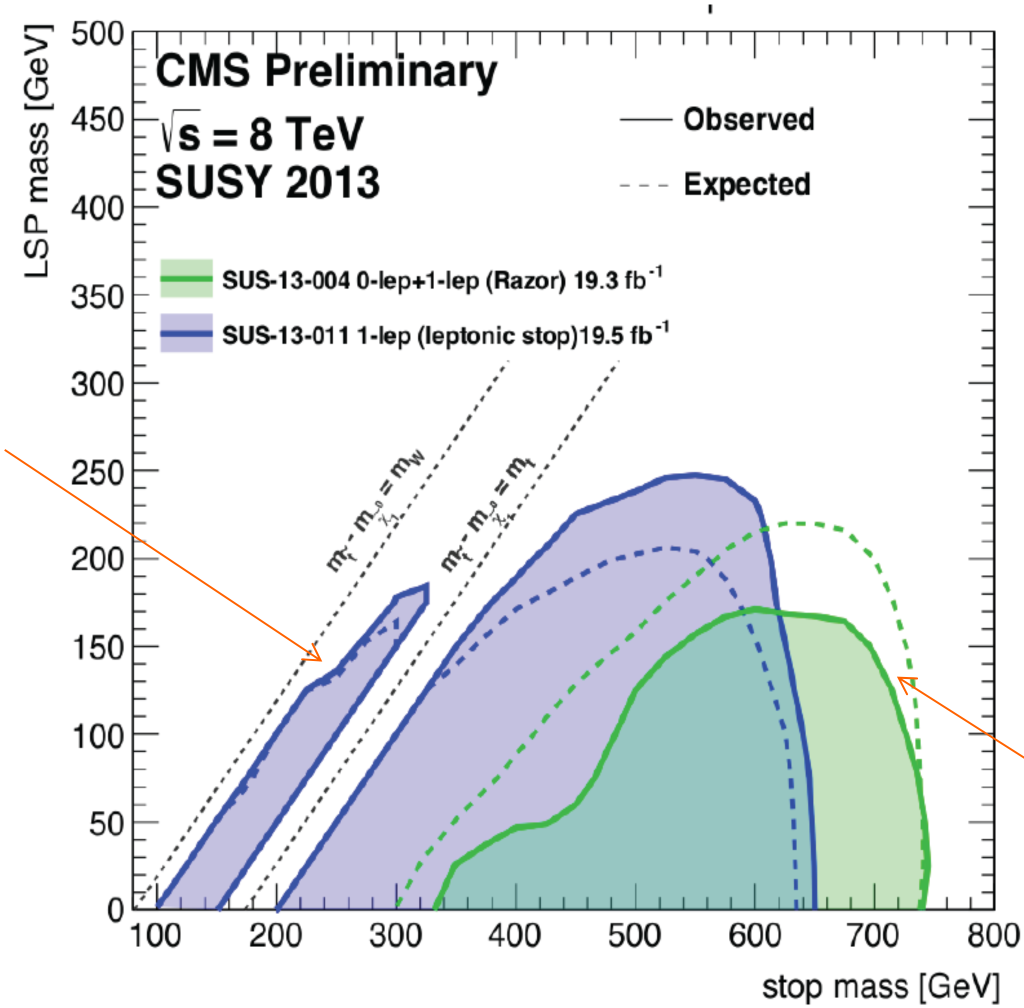


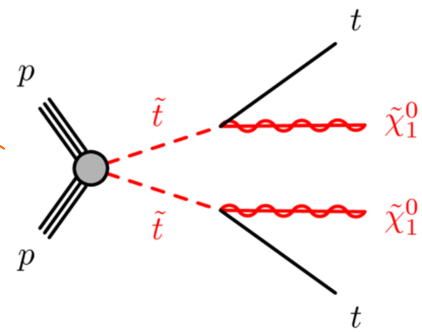




Direct stop pair production







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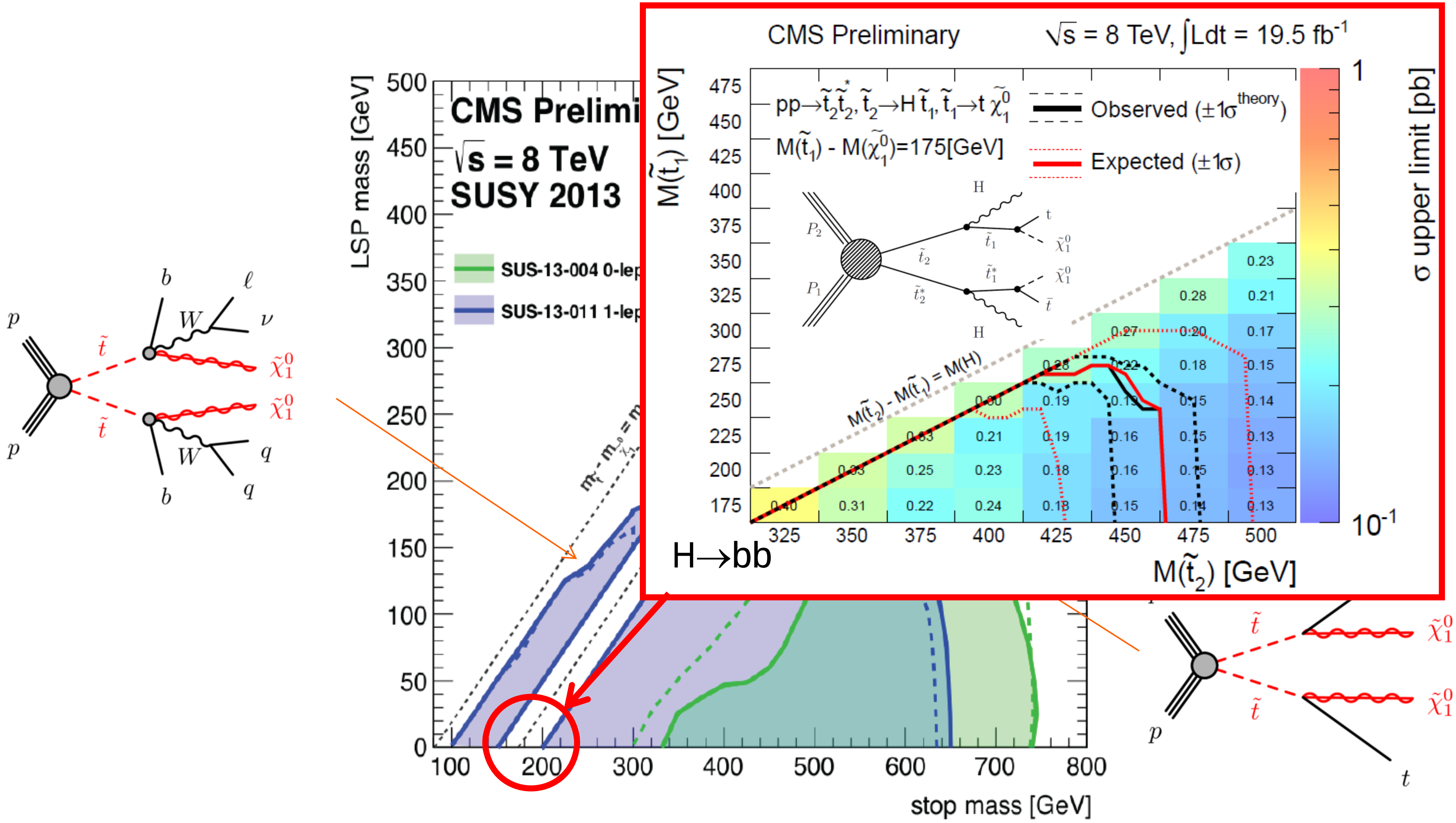
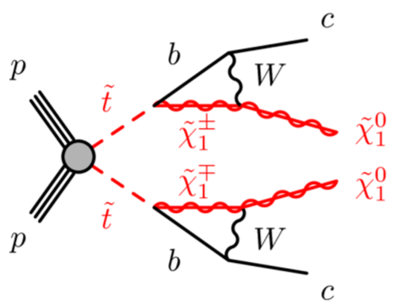
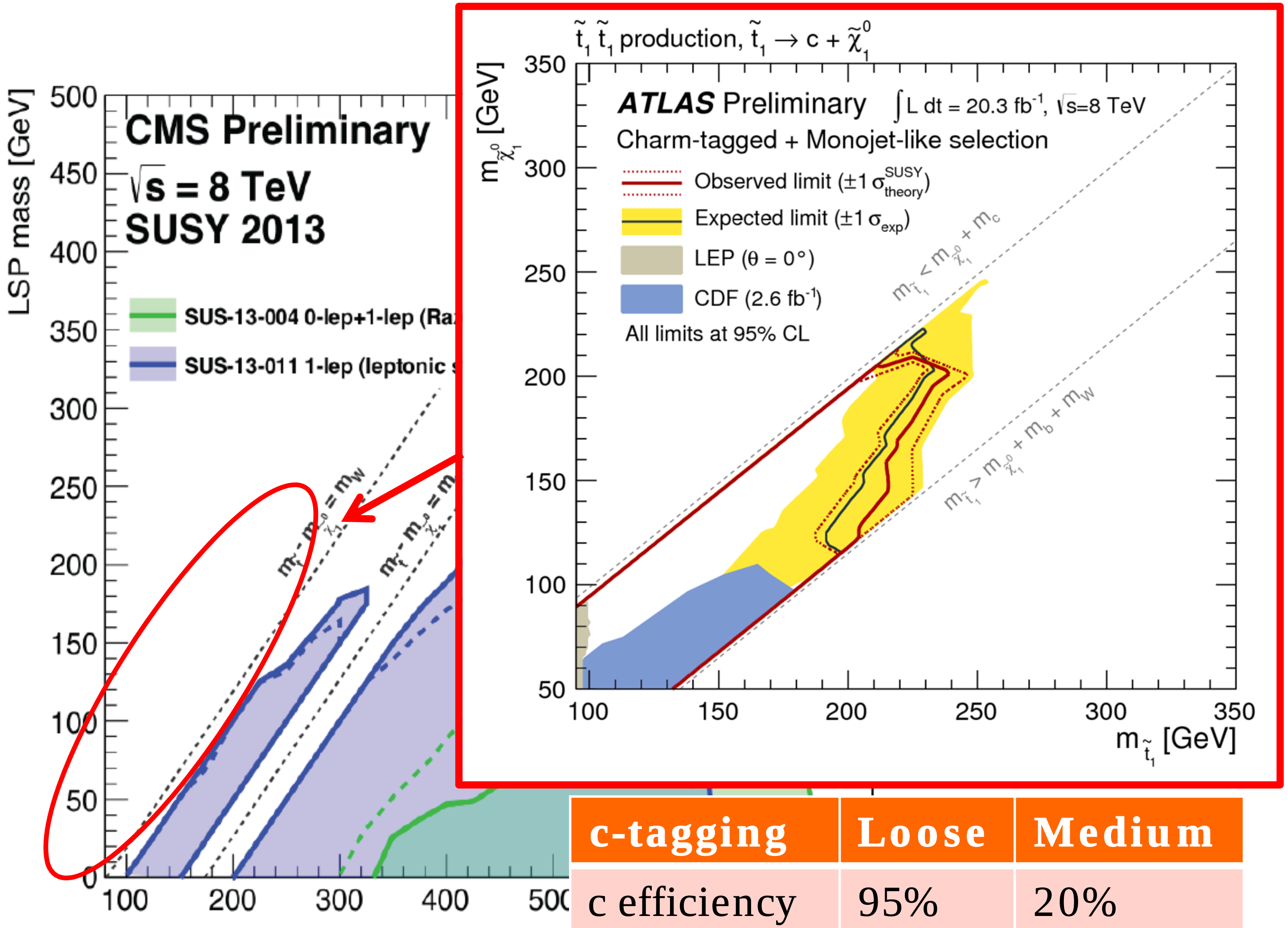


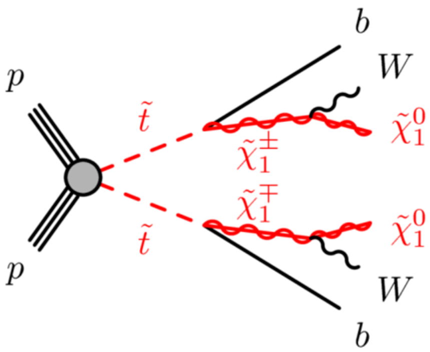
Direct stop pair production

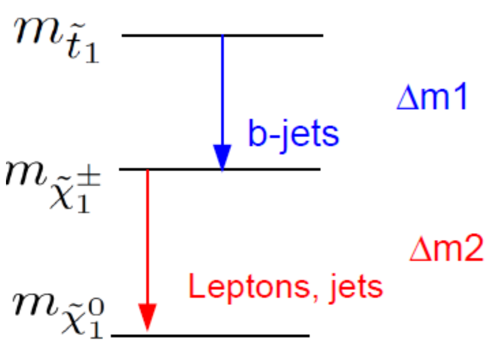


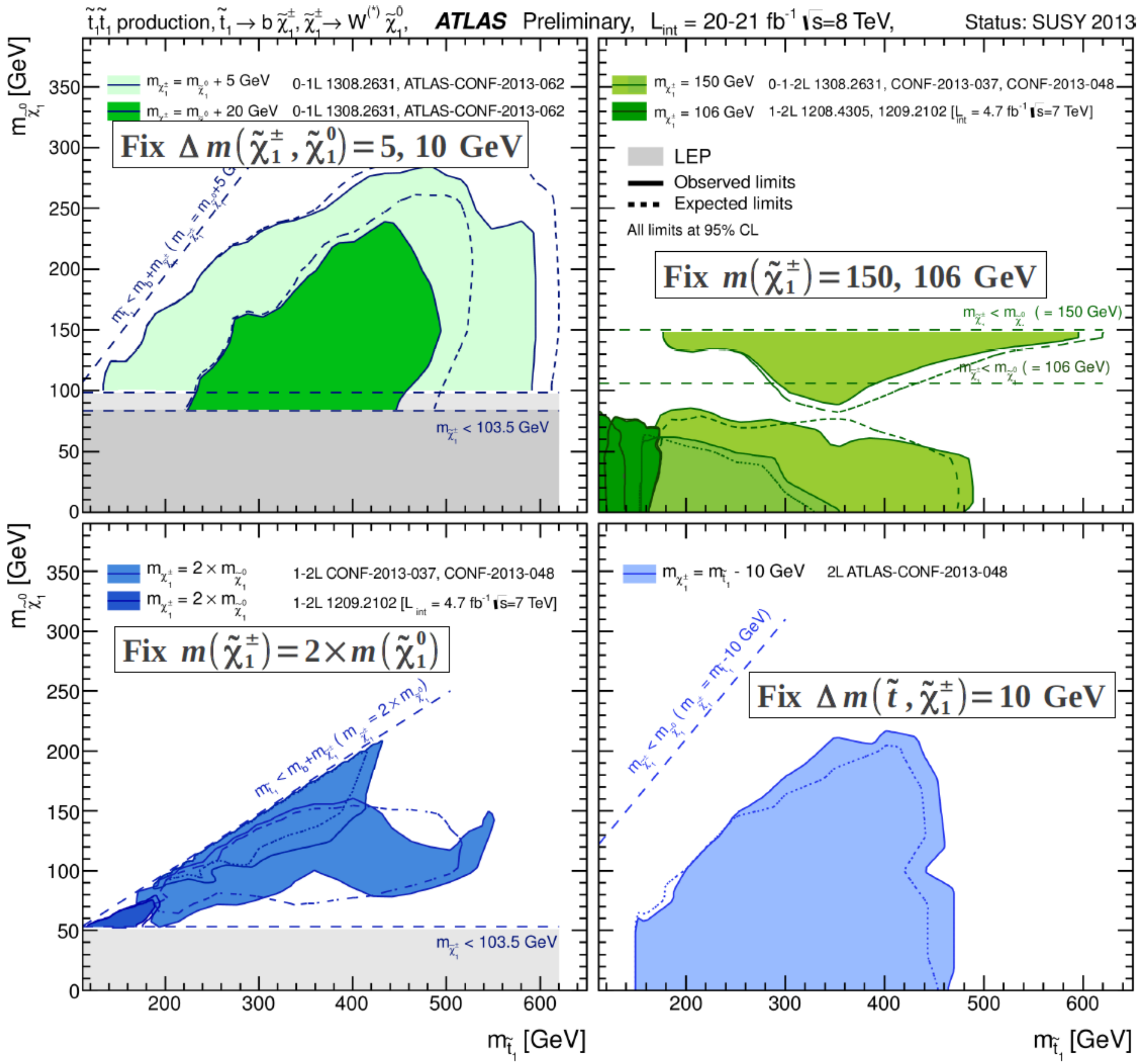


c-tagging	Loose	Medium
c efficiency	95%	20%
b rejection	2	5
l rejection	-	140

Direct stop pair production

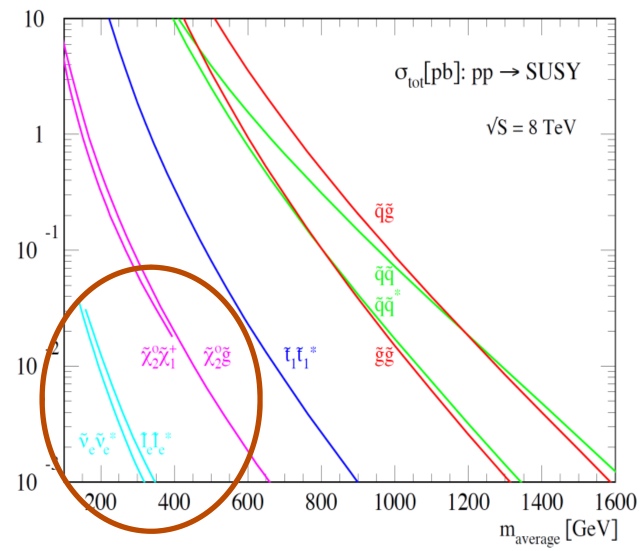






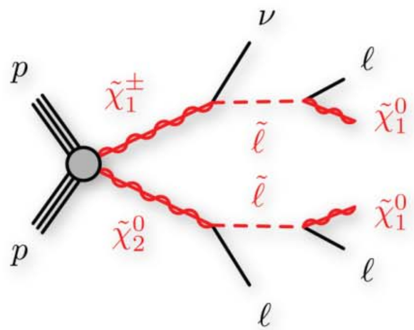
Electroweak production

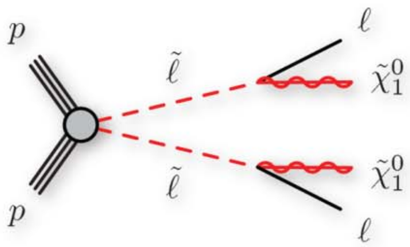
- Low cross-section processes but if squark/gluinos too heavy may be only discovery window at the LHC
- Concentrate on multilepton decays without jet activity
- Low SM backgrounds, dominated by multiple gauge bosons production: WW, WZ, ZZ



Largest cross section for wino-like $\tilde{\chi}$'s. Smaller if higgsino (then also mass-degenerate with LSP)

3-lepton final state if light sleptons



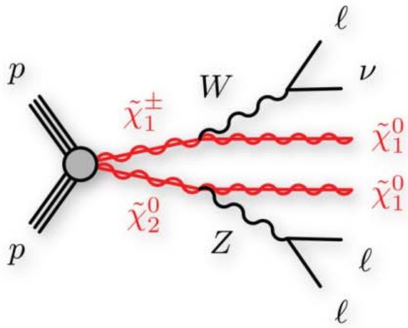


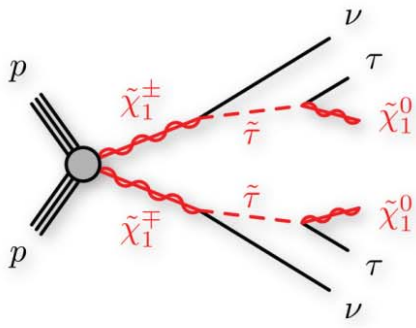
Larger cross section for slepton-left

2L + MET final state

If sleptons heavy, reduced branching ratio to leptons

Equivalent picture for chargino pair production: no-slepton case produces *WW* + MET final state

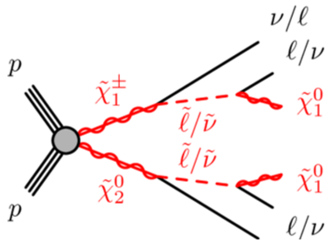


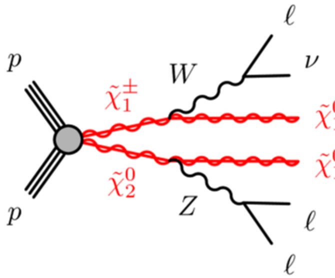


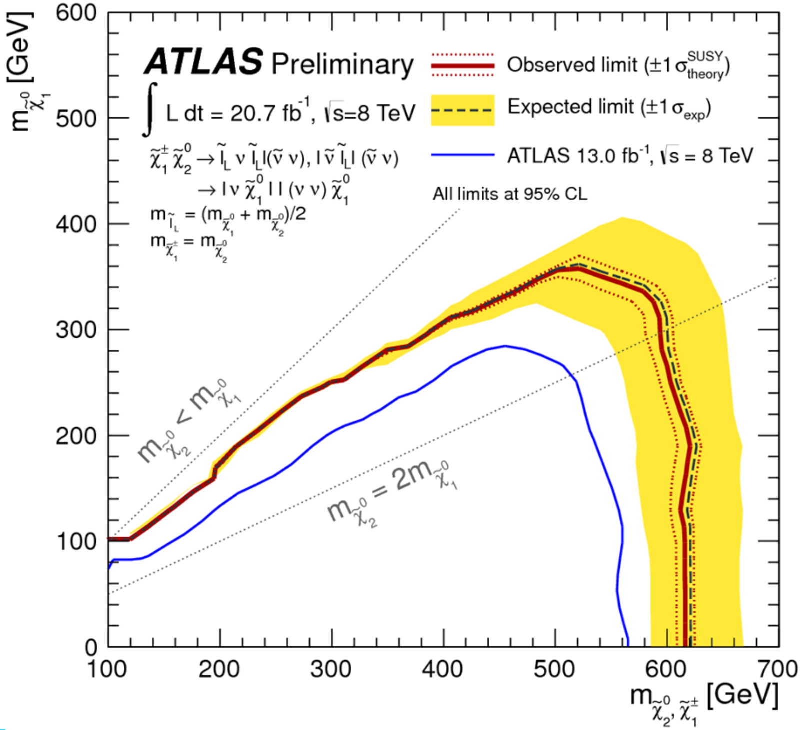
Plausible possibility for light $\tilde{\tau}_1$, while other sleptons heavy

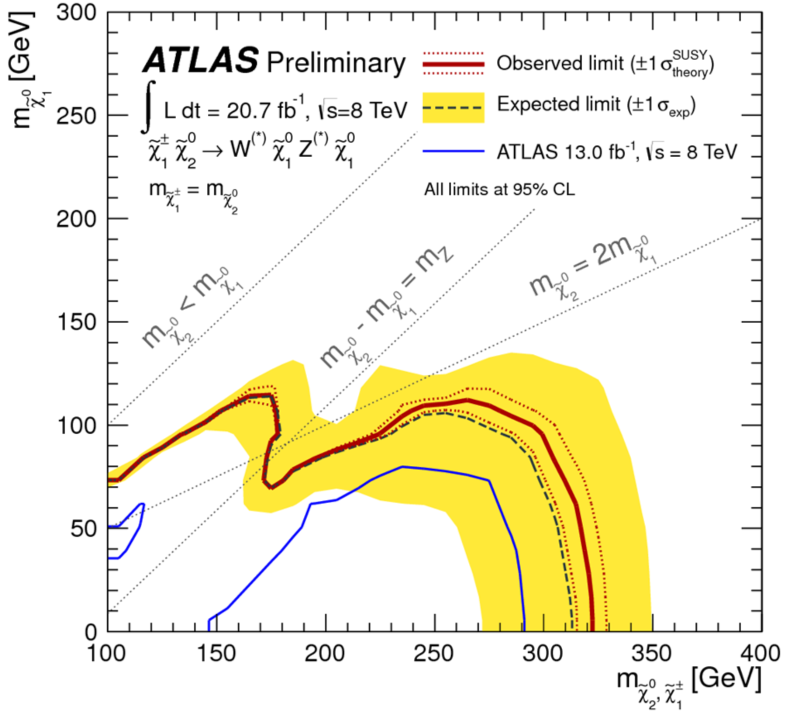
ATLAS 3 leptons (e/μ) + 0 b-jets + MET

- 6 SRs targeting C1N2 production (including Z enriched/depleted)
- b-jet veto to reject top, main background WZ
- Signal interpretation assumes wino-like N2 and C1, bino-like N1

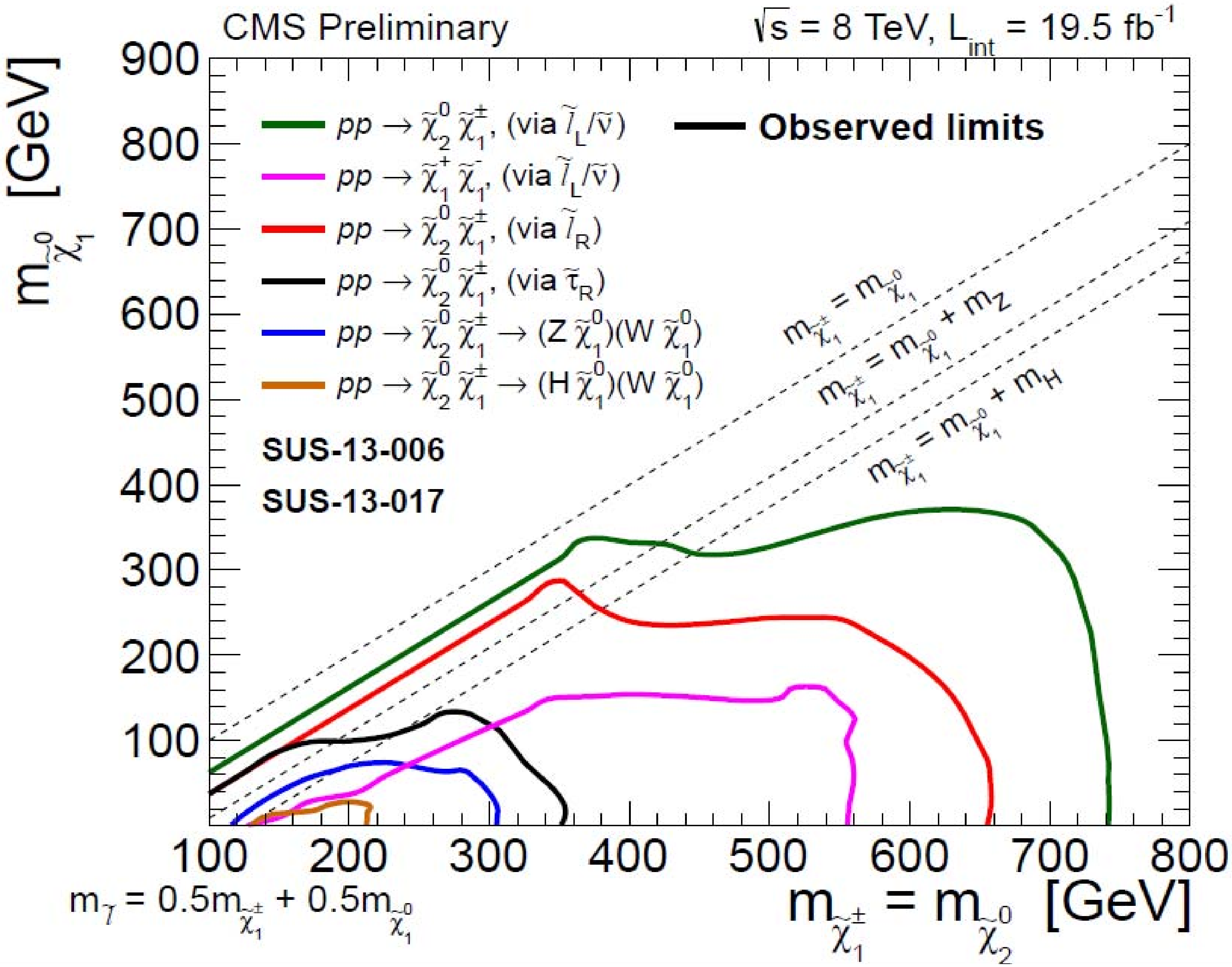




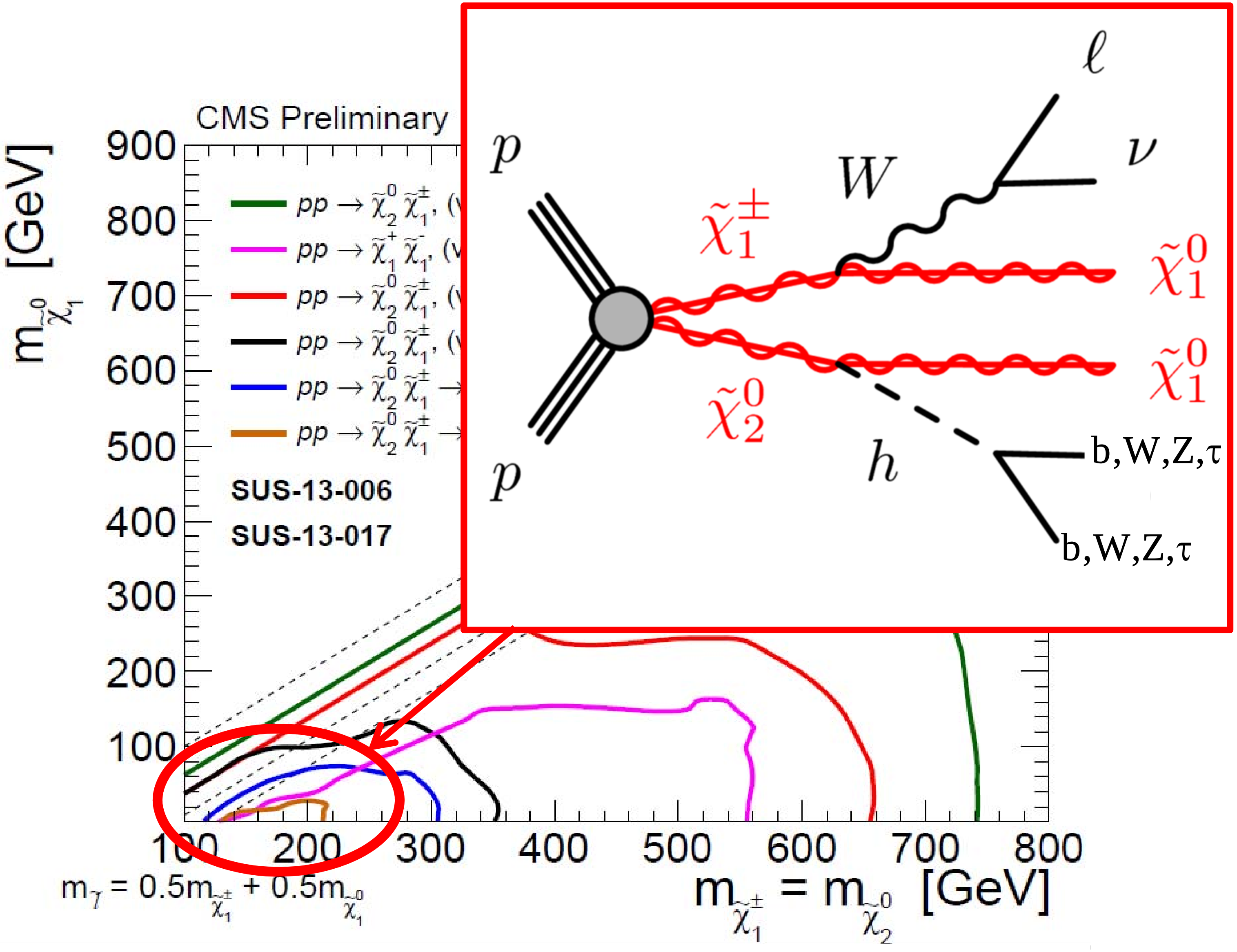


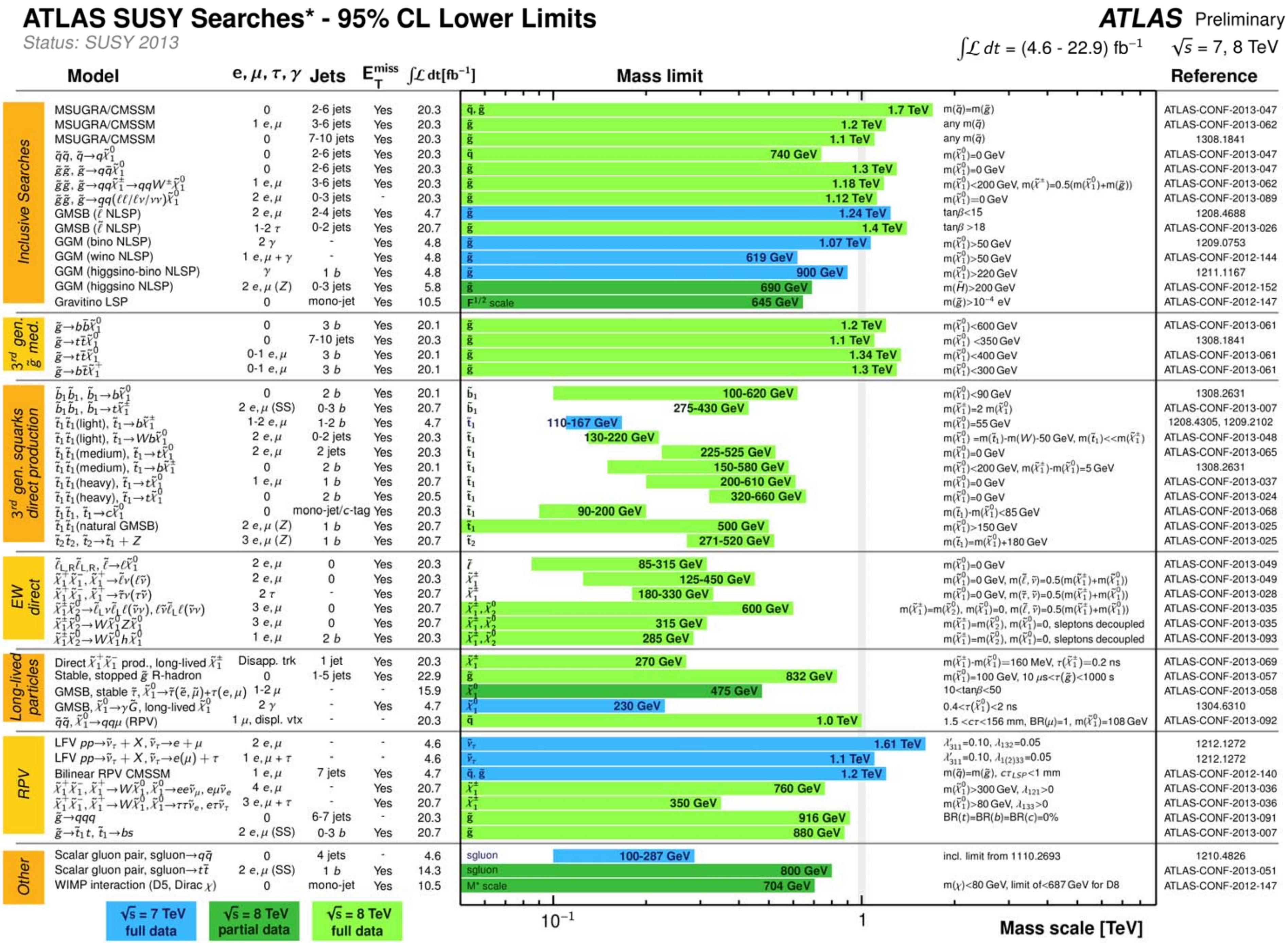


Electroweak production: summary

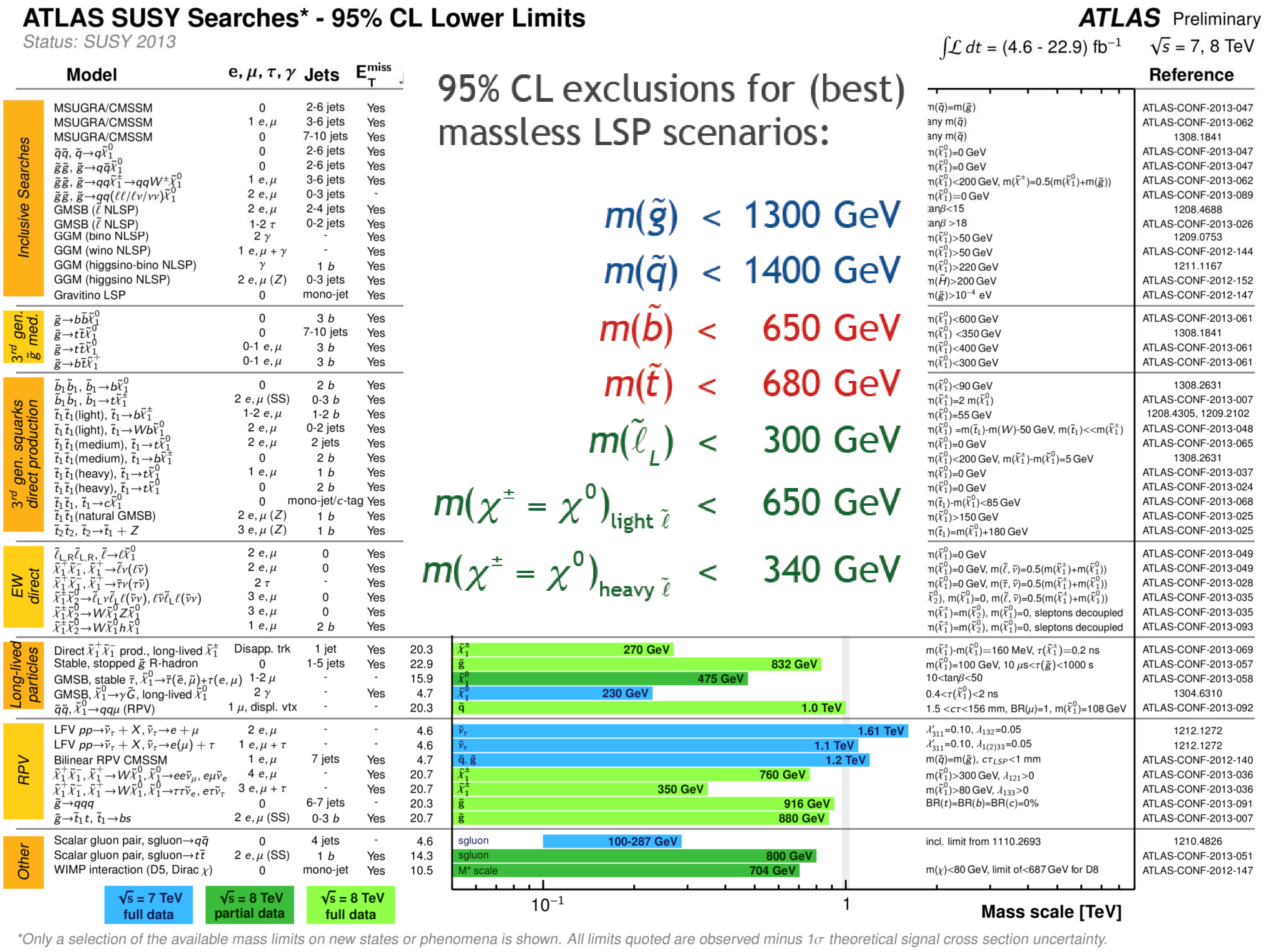


Electroweak production: summary





*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.



95% CL exclusions for (best) massless LSP scenarios:

$m(\tilde{g}) < 1300$ GeV

$m(\tilde{q}) < 1400$ GeV

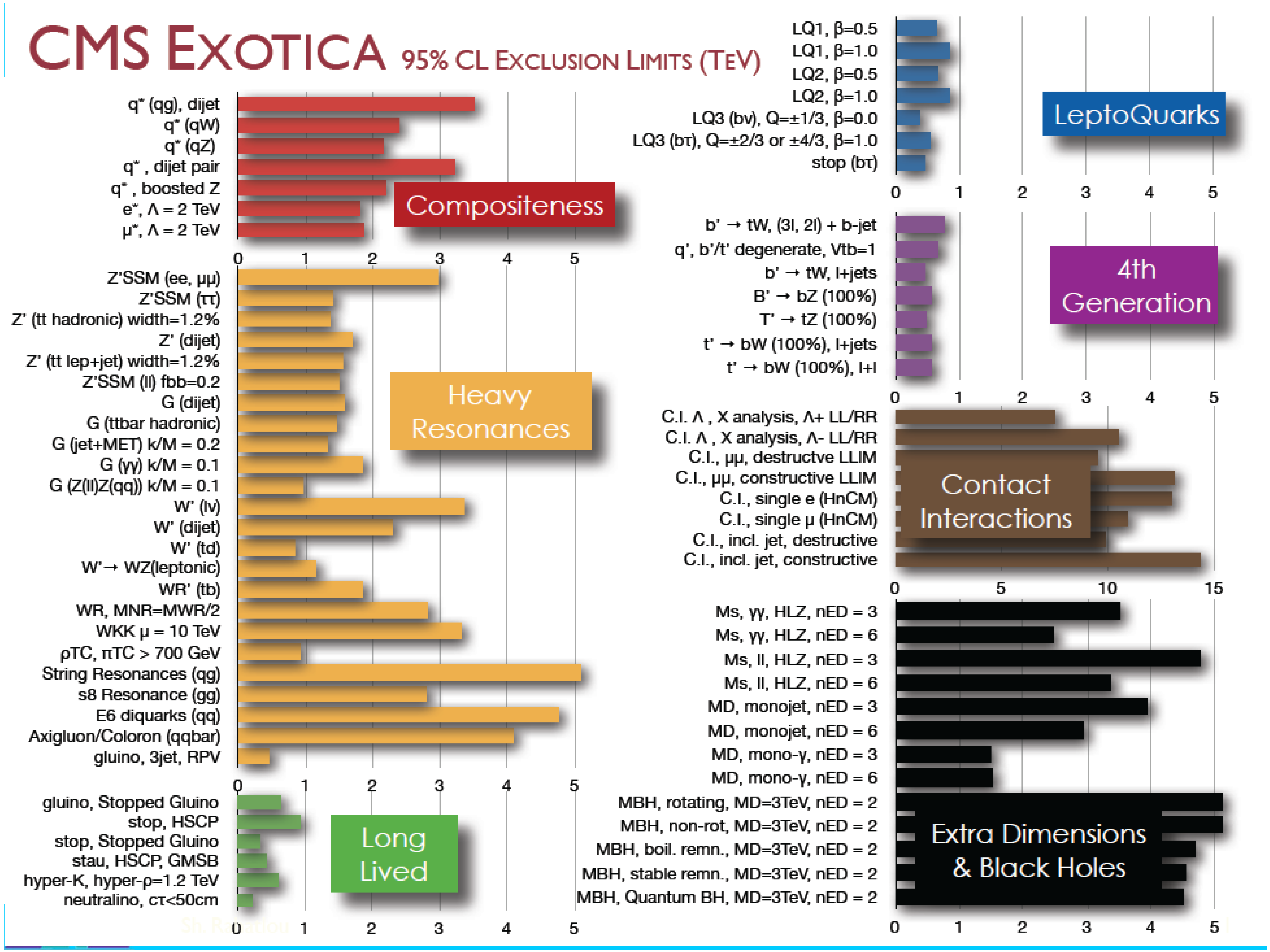
$m(\tilde{b}) < 650$ GeV

$m(\tilde{t}) < 680$ GeV

$m(\tilde{\ell}_L) < 300$ GeV

$m(\chi^{\pm} = \chi^0)_{\text{light } \tilde{\ell}} < 650$ GeV

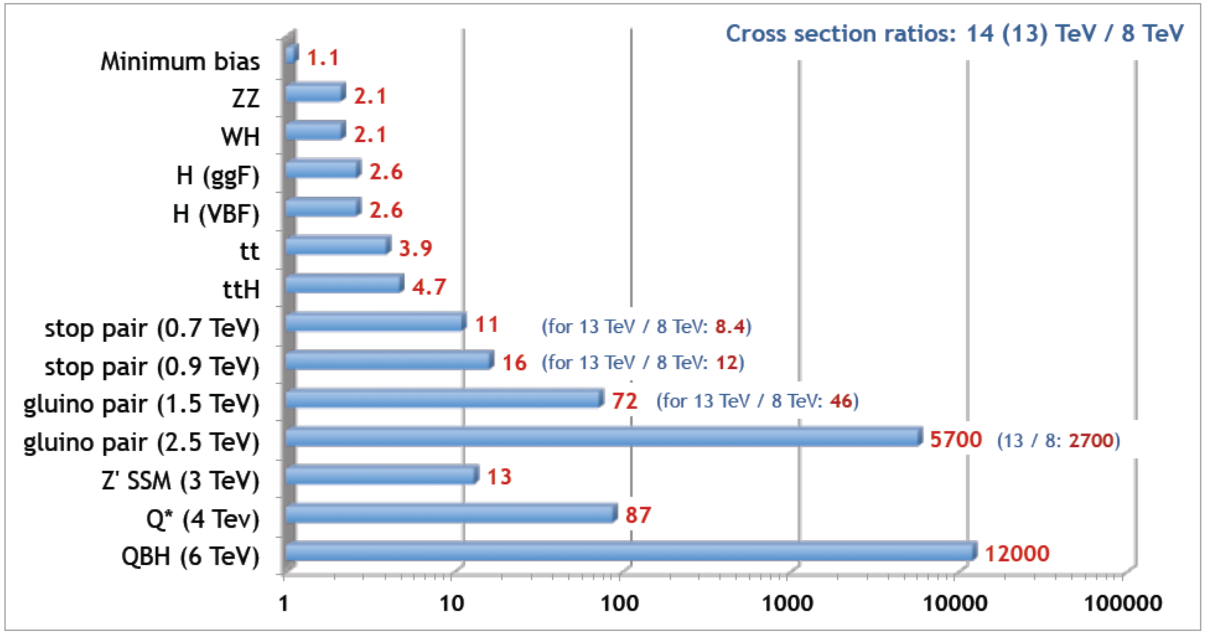
$m(\chi^{\pm} = \chi^0)_{\text{heavy } \tilde{\ell}} < 340$ GeV



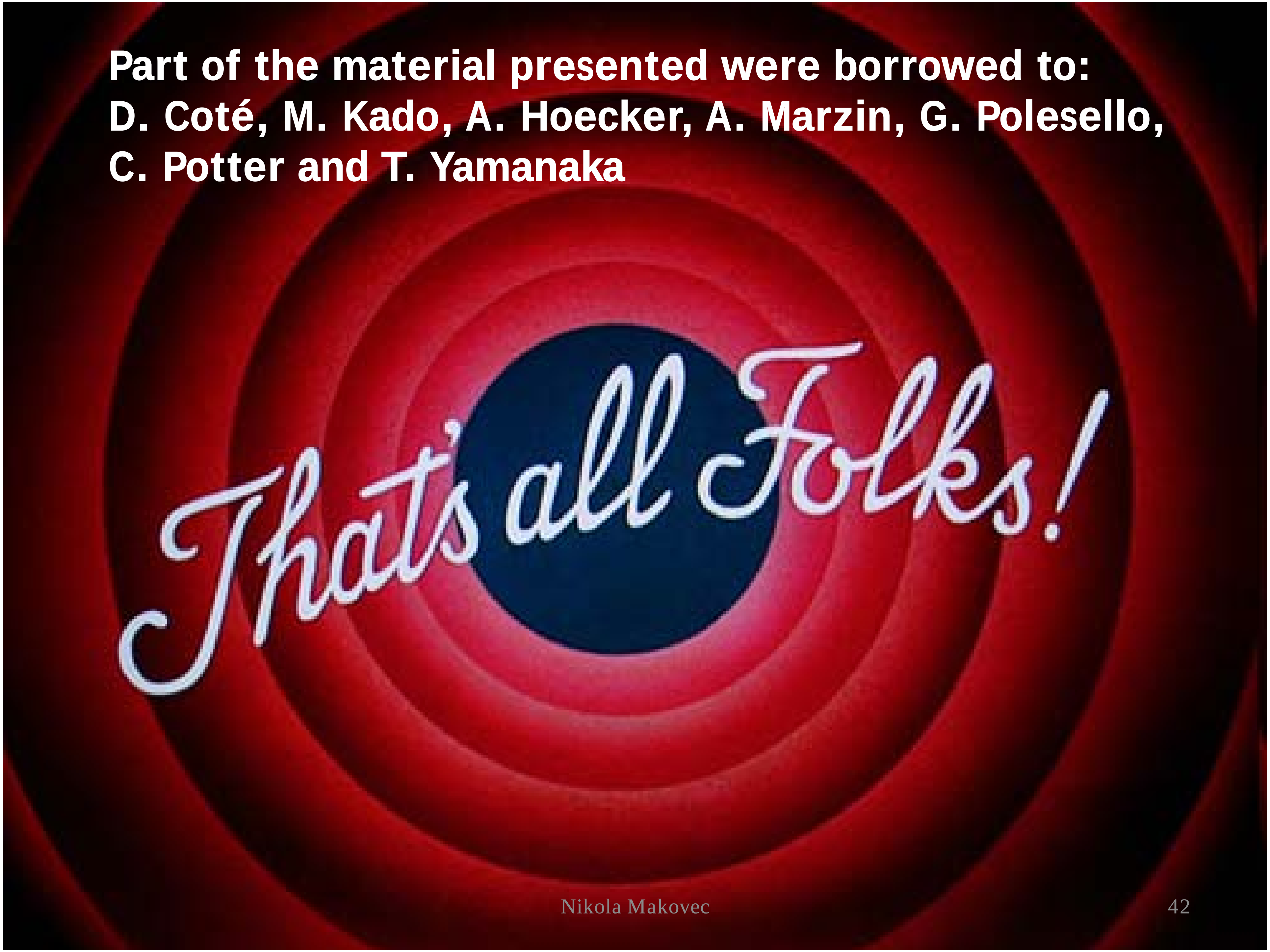
CMS Exotica 95% CL Exclusion Limits (TeV)
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Heavy Resonances
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt lep+jet) width=1.2%
Z'SSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
G (jet+MET) k/M = 0.2
G (γγ) k/M = 0.1
G (Z(ll)Z(qq)) k/M = 0.1
W' (lv)
W' (dijet)
W' (td)
W'→ WZ(leptonic)
WR' (tb)
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
Long Lived
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
neutralino, cτ<50cm
LeptoQuarks
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bν), Q=±1/3, β=0.0
LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0
stop (bτ)
4th Generation
b' → tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' → tW, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l
Contact Interactions
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
Extra Dimensions & Black Holes
Ms, γγ, HLZ, nED = 3
Ms, γγ, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-γ, nED = 3
MD, mono-γ, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2
0
1
2
3
4
5
10
15

Conclusion

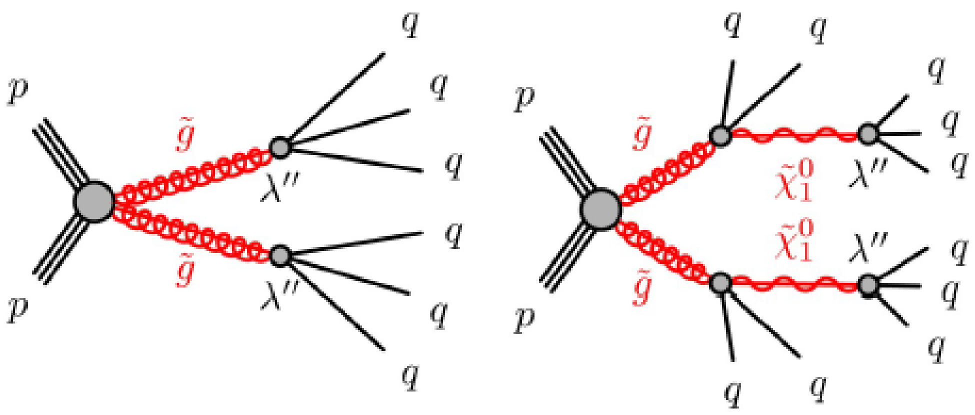
- ATLAS and CMS have searched for supersymmetry in a large variety of final states but nothing exciting so far!
- We are finalizing our search with 7/8 TeV datasets
- We are also preparing our searches for the harsher conditions of the 2015 LHC run: more pileup, larger PDF uncertainties, but also ... higher collision energy !



Part of the material presented were borrowed to:
D. Coté, M. Kado, A. Hoecker, A. Marzin, G. Polesello, C. Potter and T. Yamanaka



RPV multijets



Consider gluino or neutralino LSP decaying to jets
Searching for resonances is difficult due to combinatorics

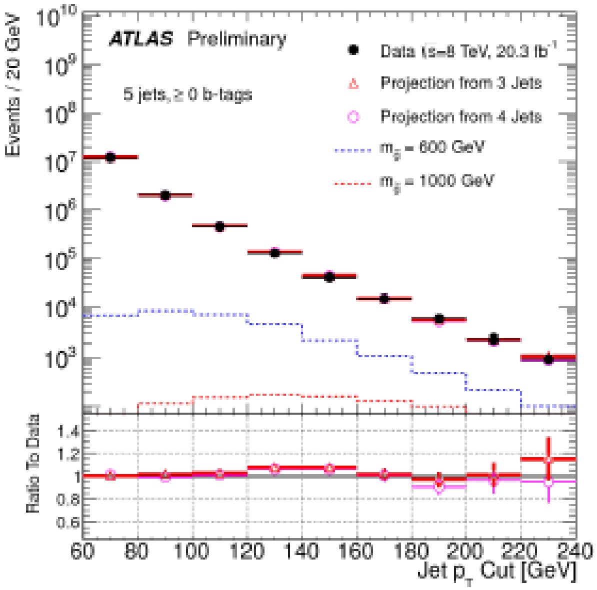
Search for events with ≥ 6 or 7 high p_T jets

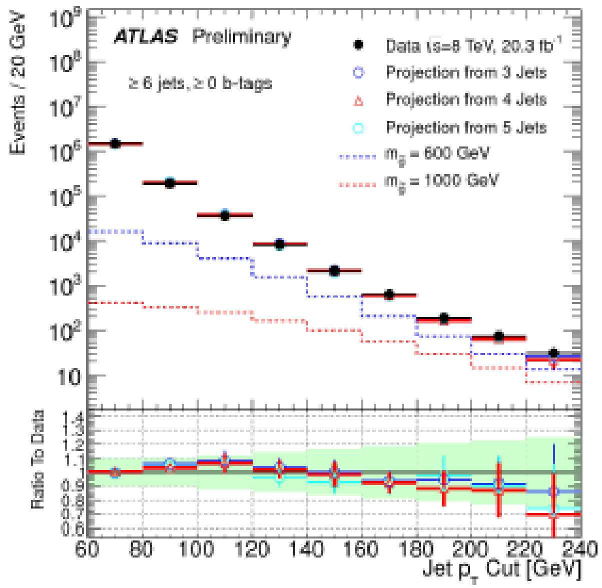
0–2 b-tagged jets to estimate BR to heavy flavour quarks

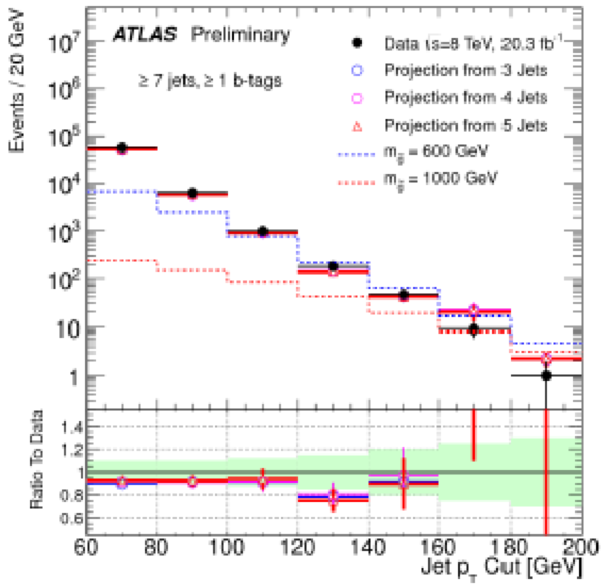
SM multijet background normalised to data in lower jet multiplicity regions

Signal regions optimised for many different models
Jet $p_T \geq$ 80–220 GeV, Njet ≥ 6–7, Nbjet 0–2

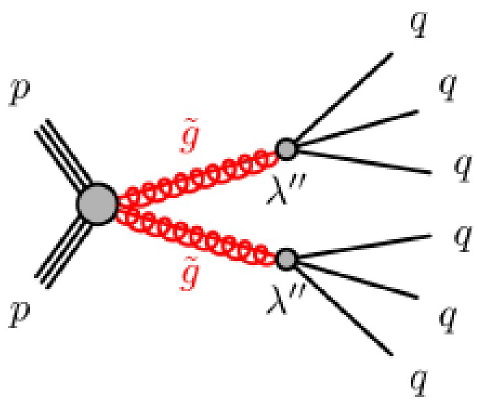
No significant excess seen

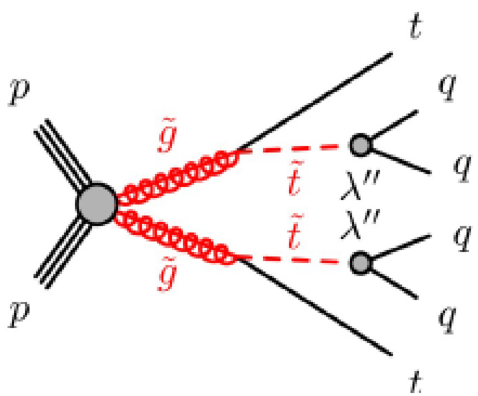


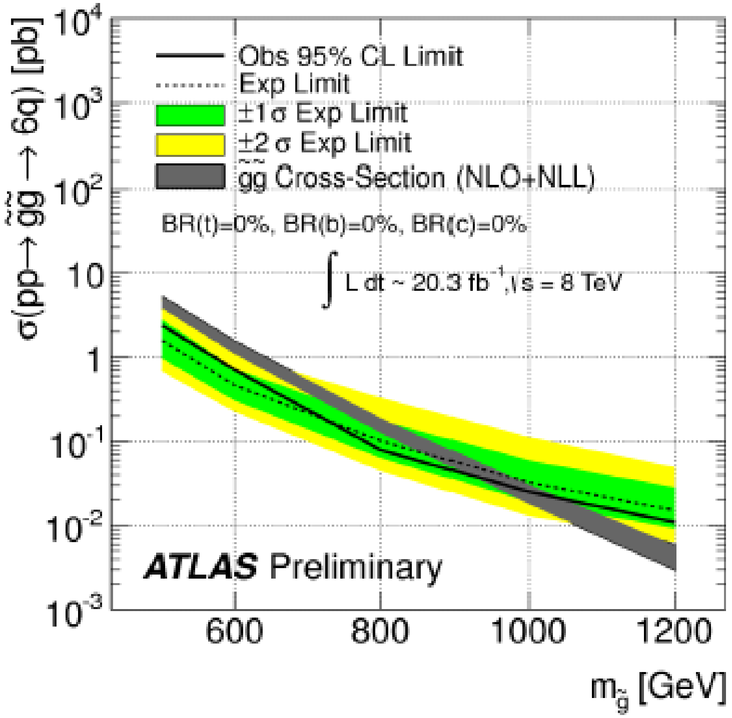




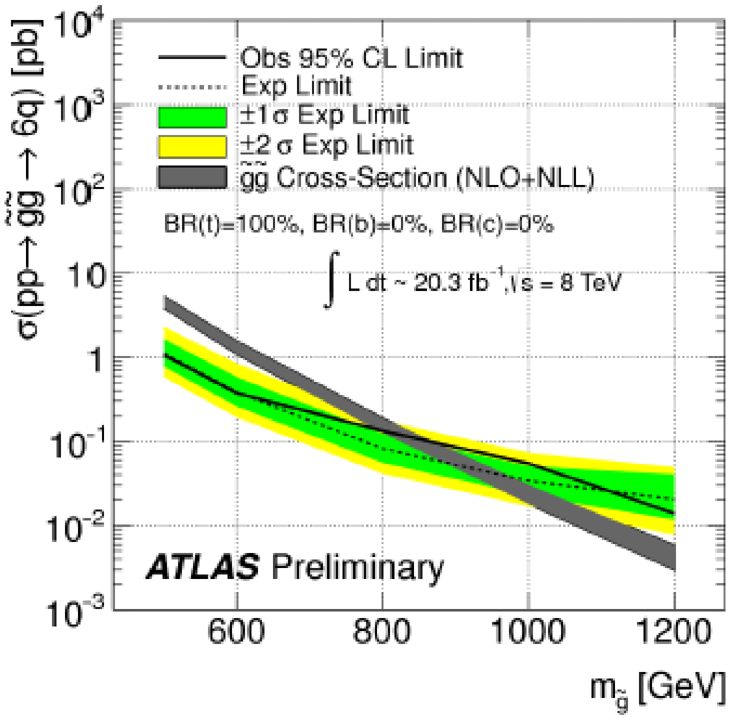
RPV multijets





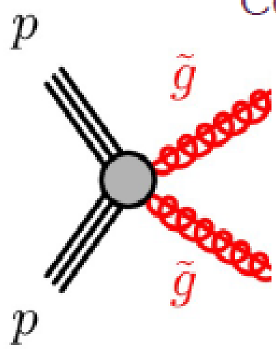


Gluinos excluded up to ~900 GeV for BR(heavy quarks) = 0%



Gluinos excluded up to ~800 GeV for BR(top) = 100%

Long-lived gluino R-hadrons

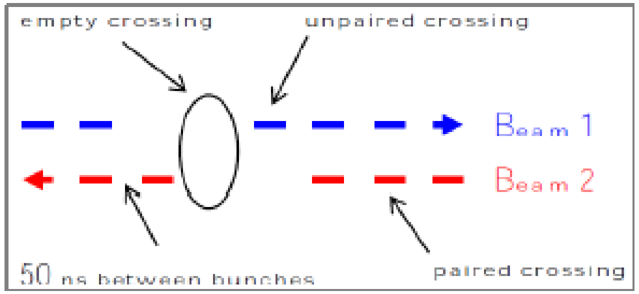


Consider gluino with long lifetime that forms R-hadrons with SM vacuum quarks

R-hadron travels through detector
Gets stuck in detector via dE/dx energy loss and nuclear scattering
Can decay at a much later time!

Also relevent for Split SUSY with a high mass intermediate squark

Use empty bunches in LHC beams to look for hadronic activity

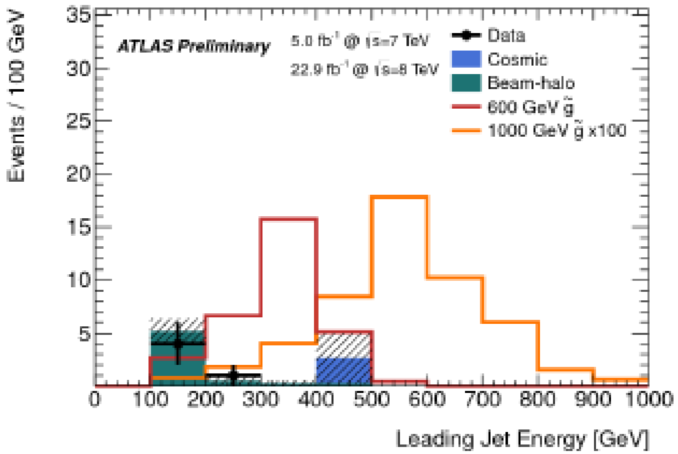


Detection efficiency depends on - stopping fraction
- probability to decay in empty bunch
- reconstruction efficiency

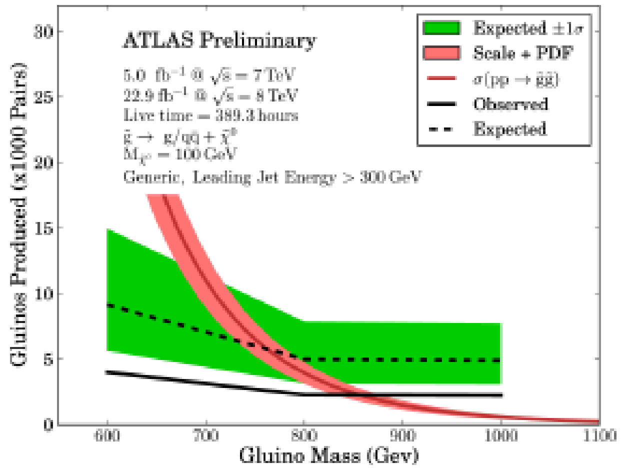
Signal region
Jet + E_T^{miss} empty bunch trigger
Jet E > 100 or 300 GeV
Veto muon activity

Cosmic muon background from low-luminosity run period

Beam halo background from unpaired crossings



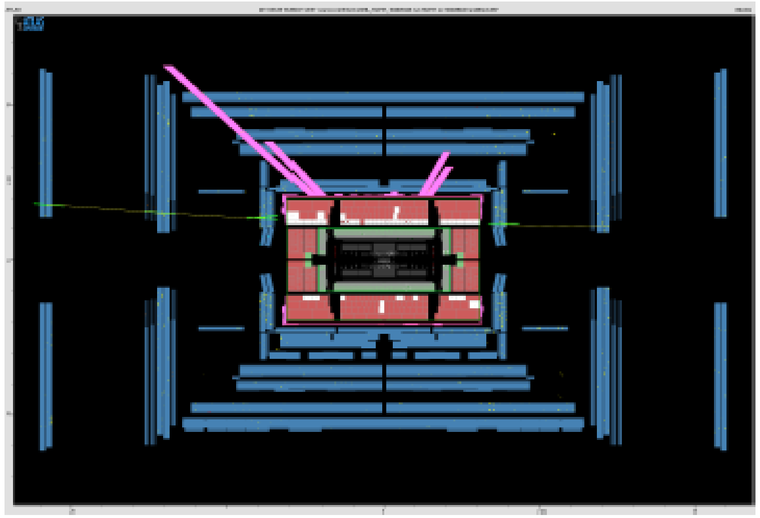
No significant excess seen



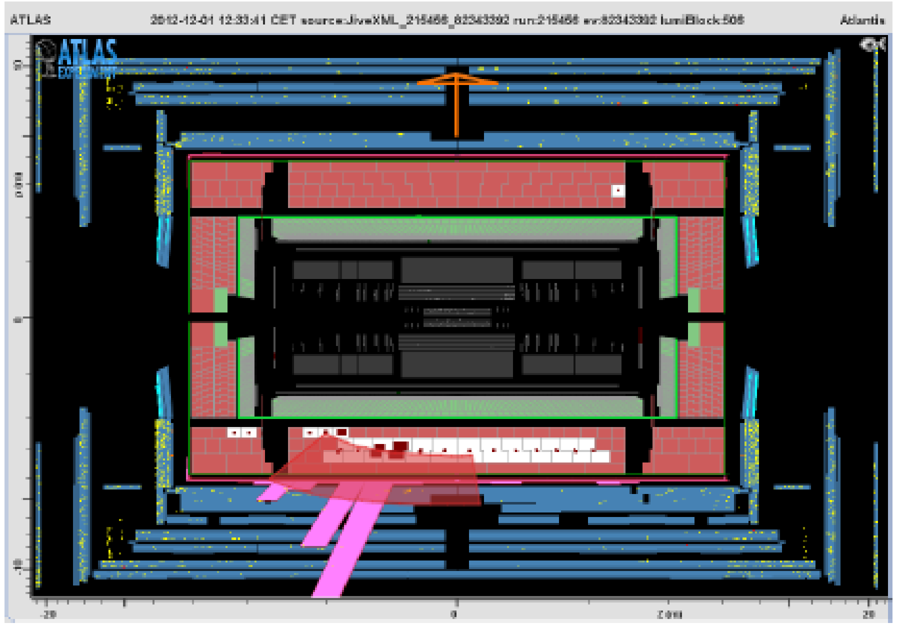
Stopped gluino R-hadrons excluded up to 832 GeV
for 10 μs < τ(gl~) < 1000 s and 100 GeV LSP
Longest lifetime excluded: 2 years!

Long-lived gluino R-hadrons

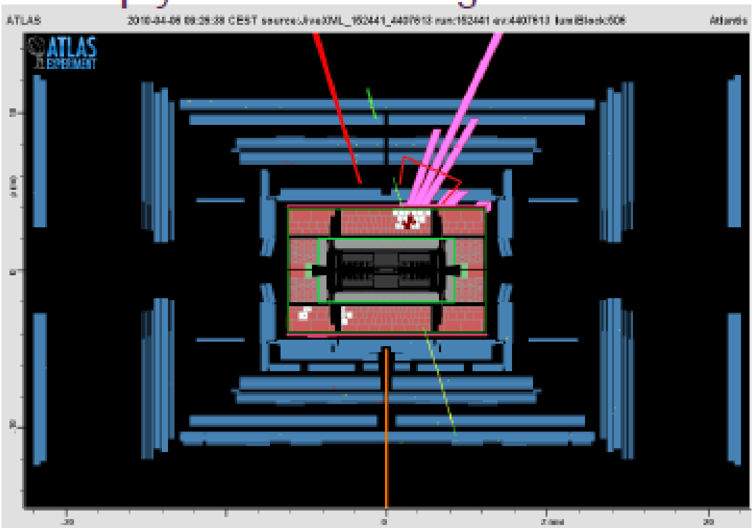
A beam-halo candidate event during an unpaired bunch crossing in data.



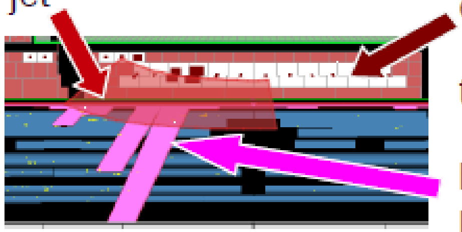
A candidate event display from 2011 data passing all selections



A cosmic ray muon candidate event during an empty bunch crossing in data



jet



energy deposits in TileCal cells fraction of red area indicates the amount of energy in the cell

histogram of total energy in projective TileCal towers

Muon segments are drawn but not reconstructed

The bigger picture — more involved (realistic?) models

CMS reinterpreted 7 TeV and 8 TeV searches within 19-parameter pMSSM

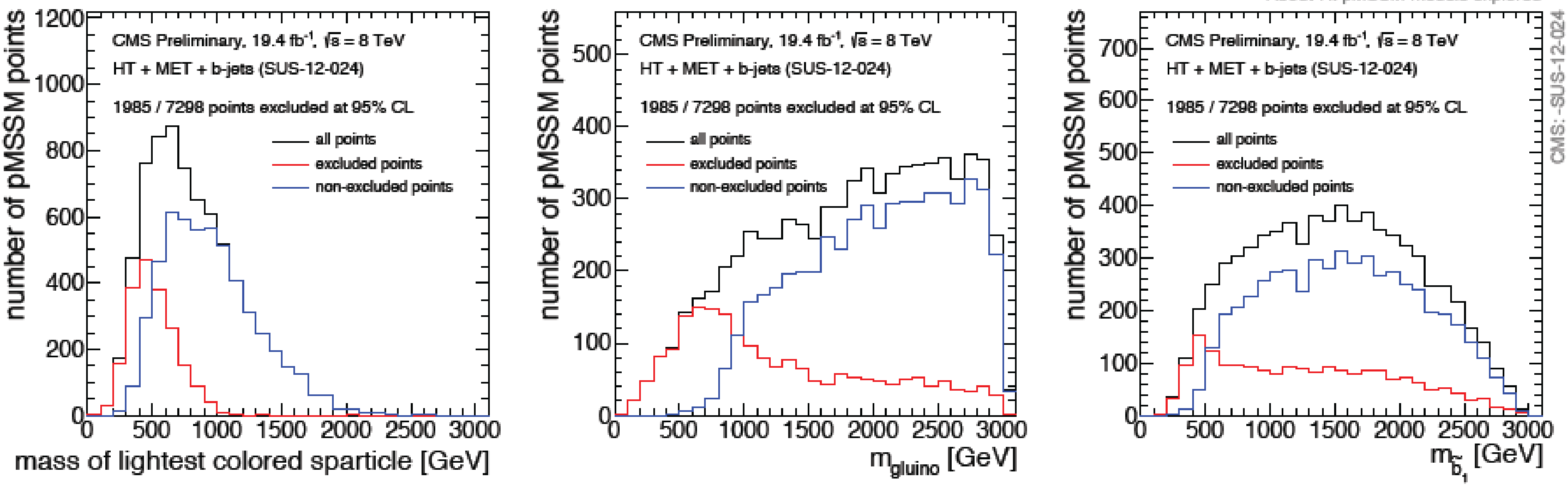
CMS references (8 / 7 TeV): PAS-SUS-12-024 (1305.2390), PAS-SUS-12-030

pMSSM points selected to be compatible with LEP exclusions and flavour physics results

Bayesian sampling of parameter ensembles (sparticle masses < 3 TeV); **constrained by H_T + MET + *b*-jets search**

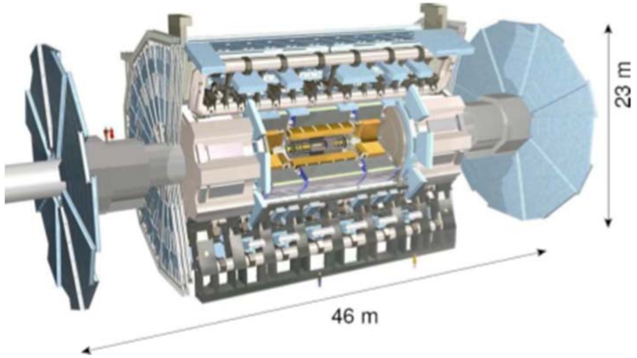
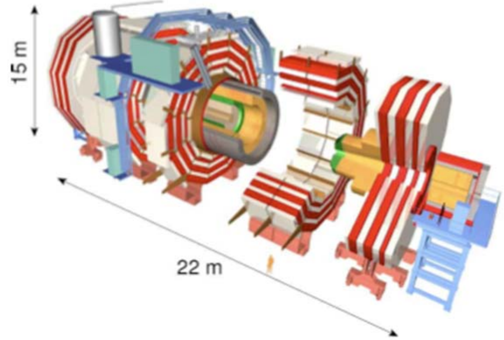
Posterior distributions: each entry corresponds to a particular pMSSM point; the black histogram represents all the pMSSM points considered in the analysis, the red (blue) displays the points (not) excluded at 95% CL by CMS

About 7k pMSSM models explored



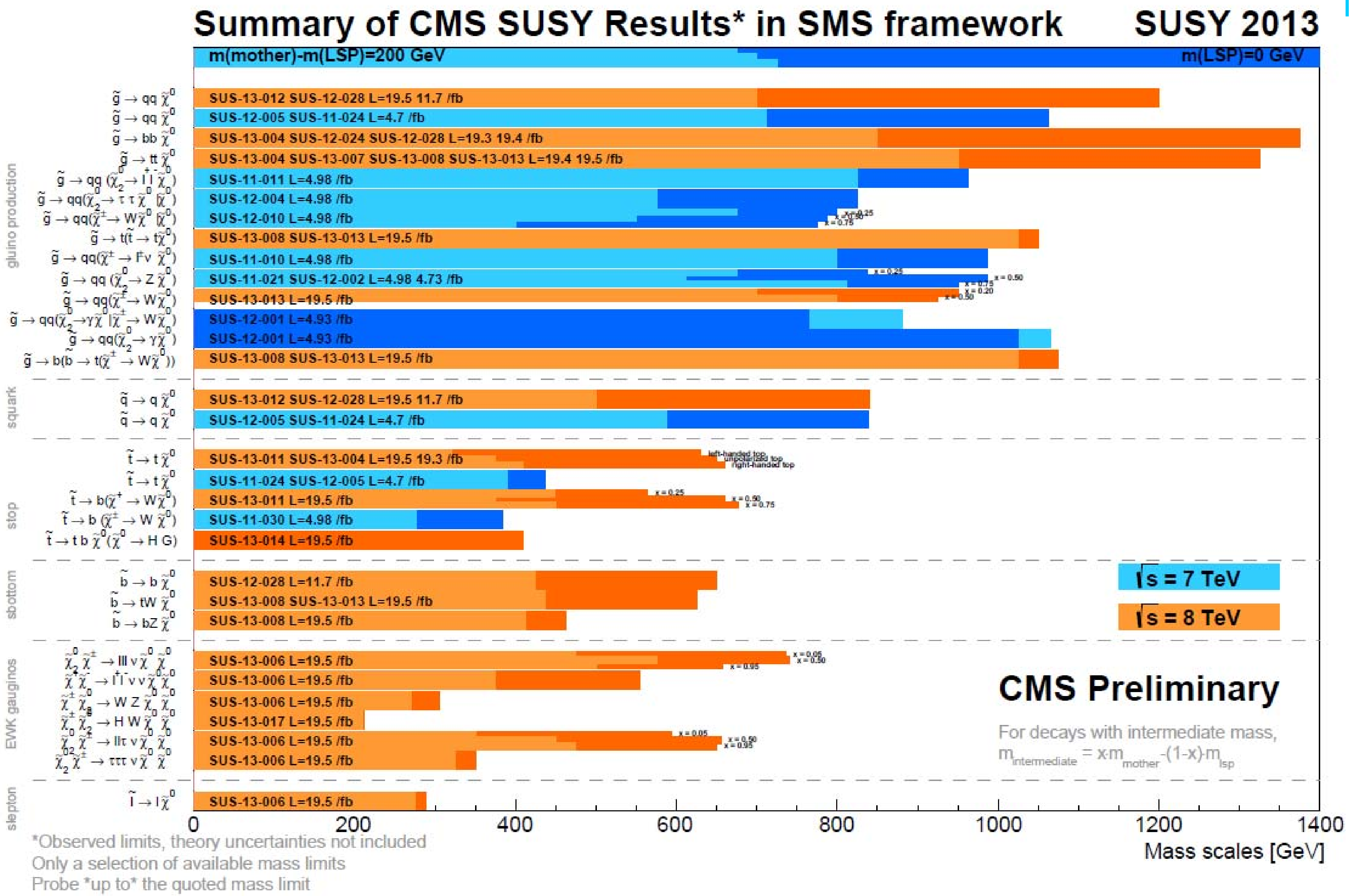
Similar analyses regularly performed by various phenomenological groups using approximate detector simulations

ATLAS and CMS in a nutshell

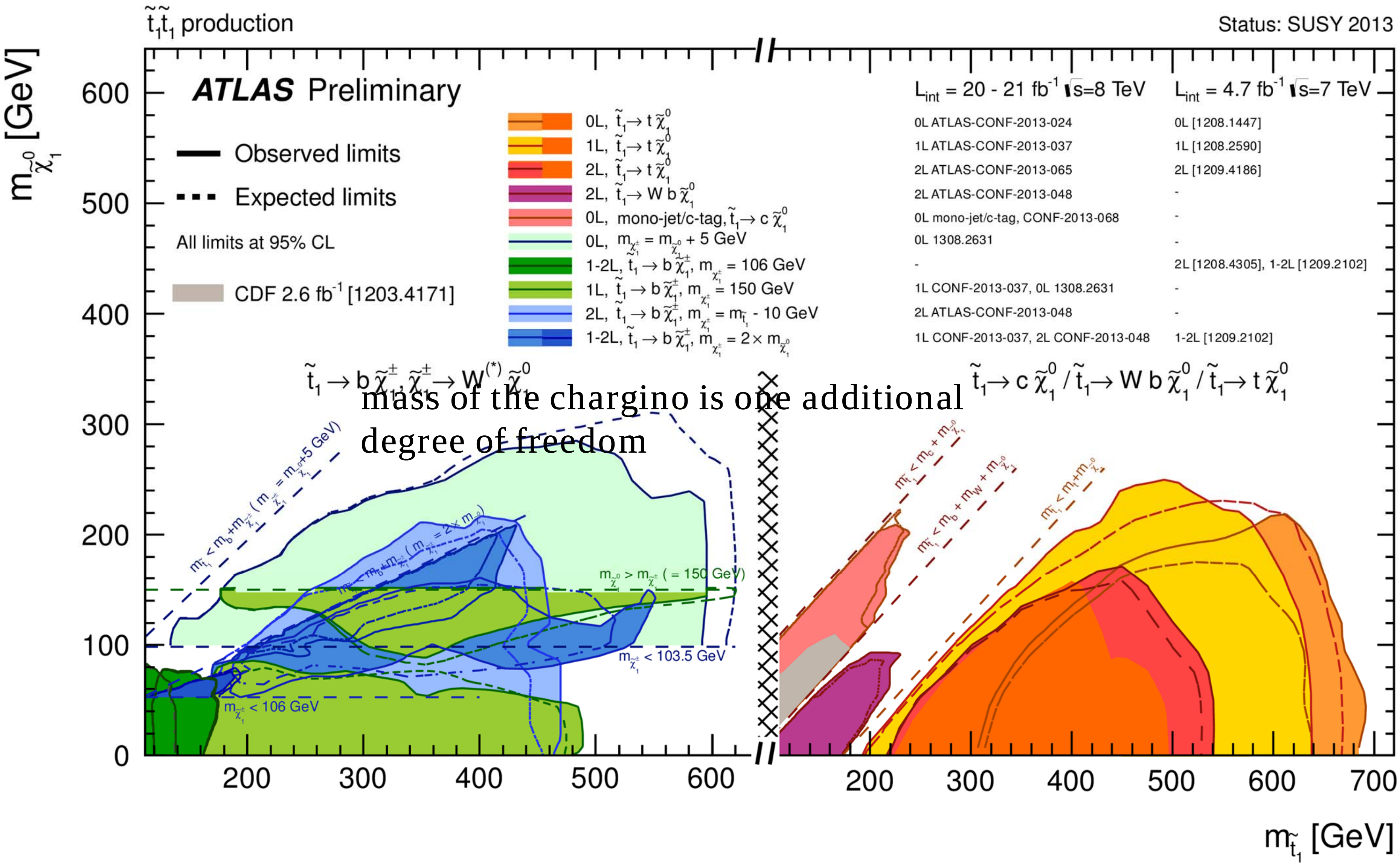
Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\,\%$ (at 50 GeV) $\sim 11\,\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

Motivation for supersymmetry

- SUSY has many theoretical virtues:
  - Non trivial extension of the poincarré group in QFT which relates fermions to bosons
  - Incorpore gravity is SUSY is made local
  - Appears naturally in superstrings theories
- Phenomenological and most compelling arguments for weak scale SUSY:
  - unification of gauge coupling constant
  - provide a dark matter candidate
    - Consequence of the R-parity conservation to preserve the stability of the proton in SUSY models
  - Solve the naturalness issue
- Other
  - Could fix discrepancy in $g_\mu - 2$


Summary of CMS SUSY Results* in SMS framework
SUSY 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-004 SUS-12-024 SUS-12-028 L=19.3 19.4 /fb
SUS-13-004 SUS-13-007 SUS-13-008 SUS-13-013 L=19.4 19.5 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
SUS-13-013 L=19.5 /fb
SUS-12-001 L=4.93 /fb
SUS-12-001 L=4.93 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-011 SUS-13-004 L=19.5 19.3 /fb
SUS-11-024 SUS-12-005 L=4.7 /fb
SUS-13-011 L=19.5 /fb
SUS-11-030 L=4.98 /fb
SUS-13-014 L=19.5 /fb
SUS-12-028 L=11.7 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-017 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
√s = 7 TeV
√s = 8 TeV
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother + (1-x)·m_lsp
0
200
400
600
800
1000
1200
1400
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

Direct stop pair production



mass of the chargino is one additional degree of freedom

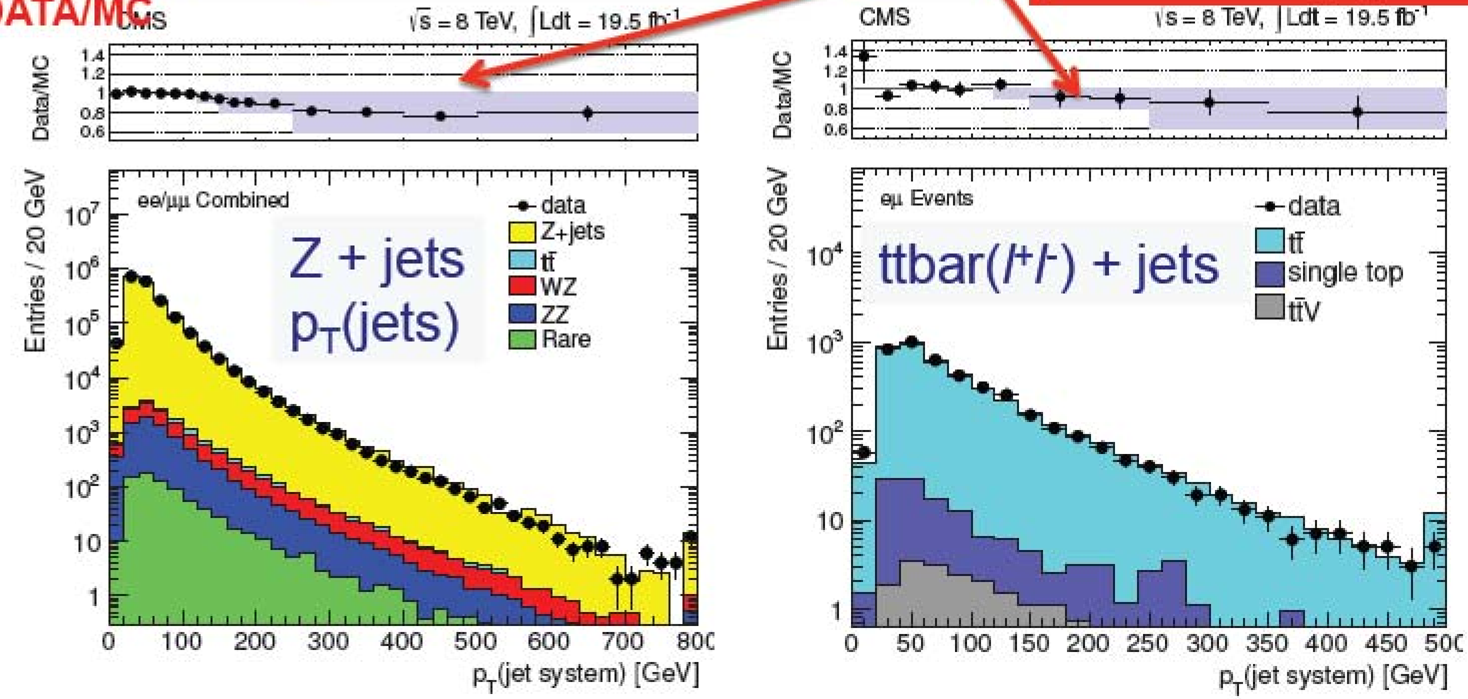
Search for direct stop: initial state radiation

SUS-13-011

- The effects of initial-state radiation are important for the signal efficiency in the region where MET is small.
- Does the simulation get this right (MADGRAPH) ?
- Study in Z+jets and ttbar.

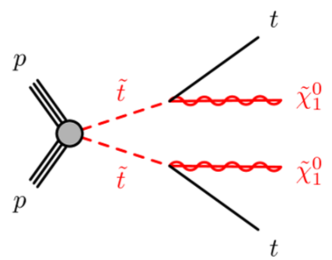
MC predicts up to 20% too much ISR at high pT

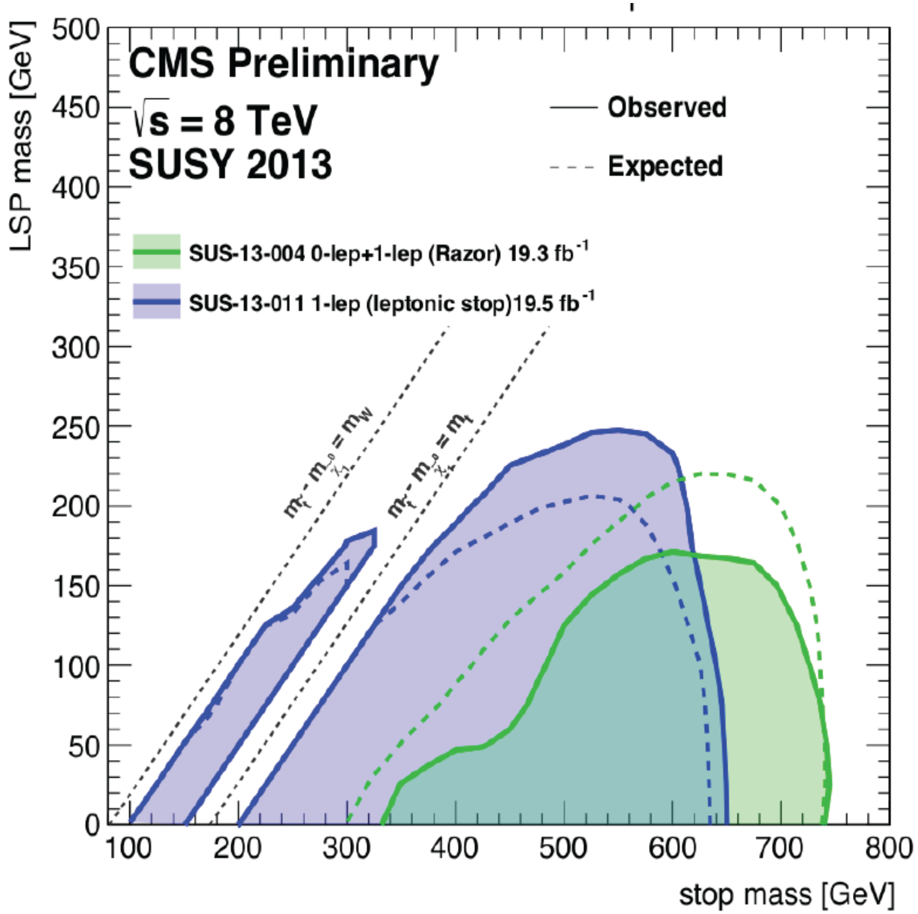
DATA/MC

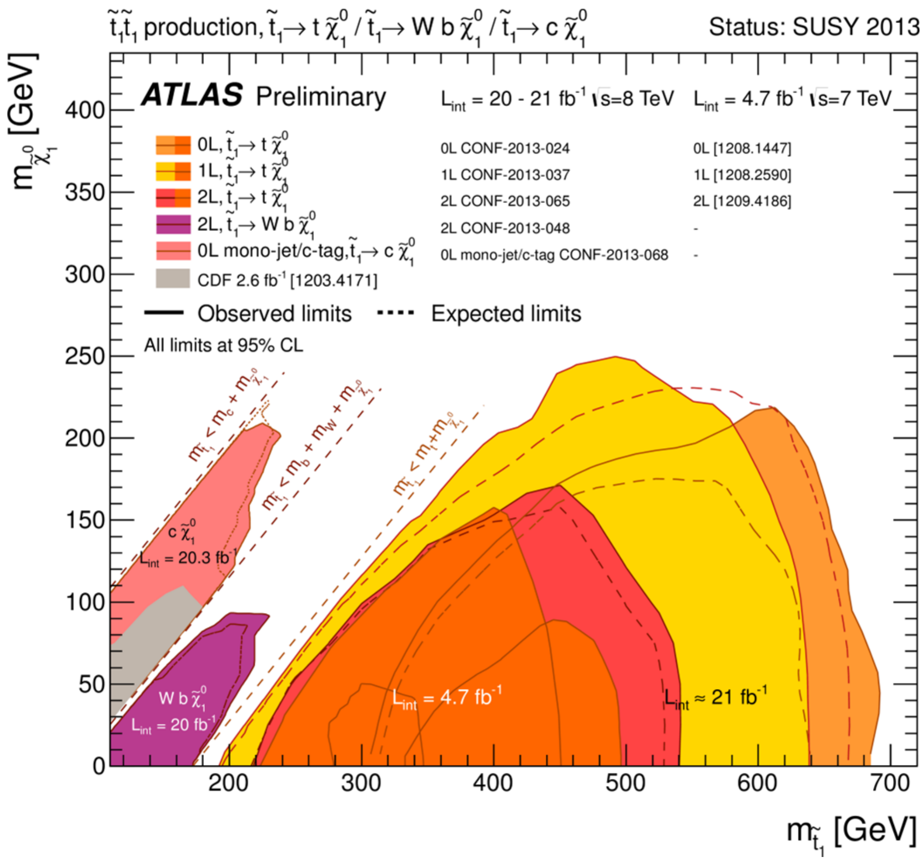


35

Direct stop pair production







Electroweak production: summary