Physics at LHC

Lecture 3

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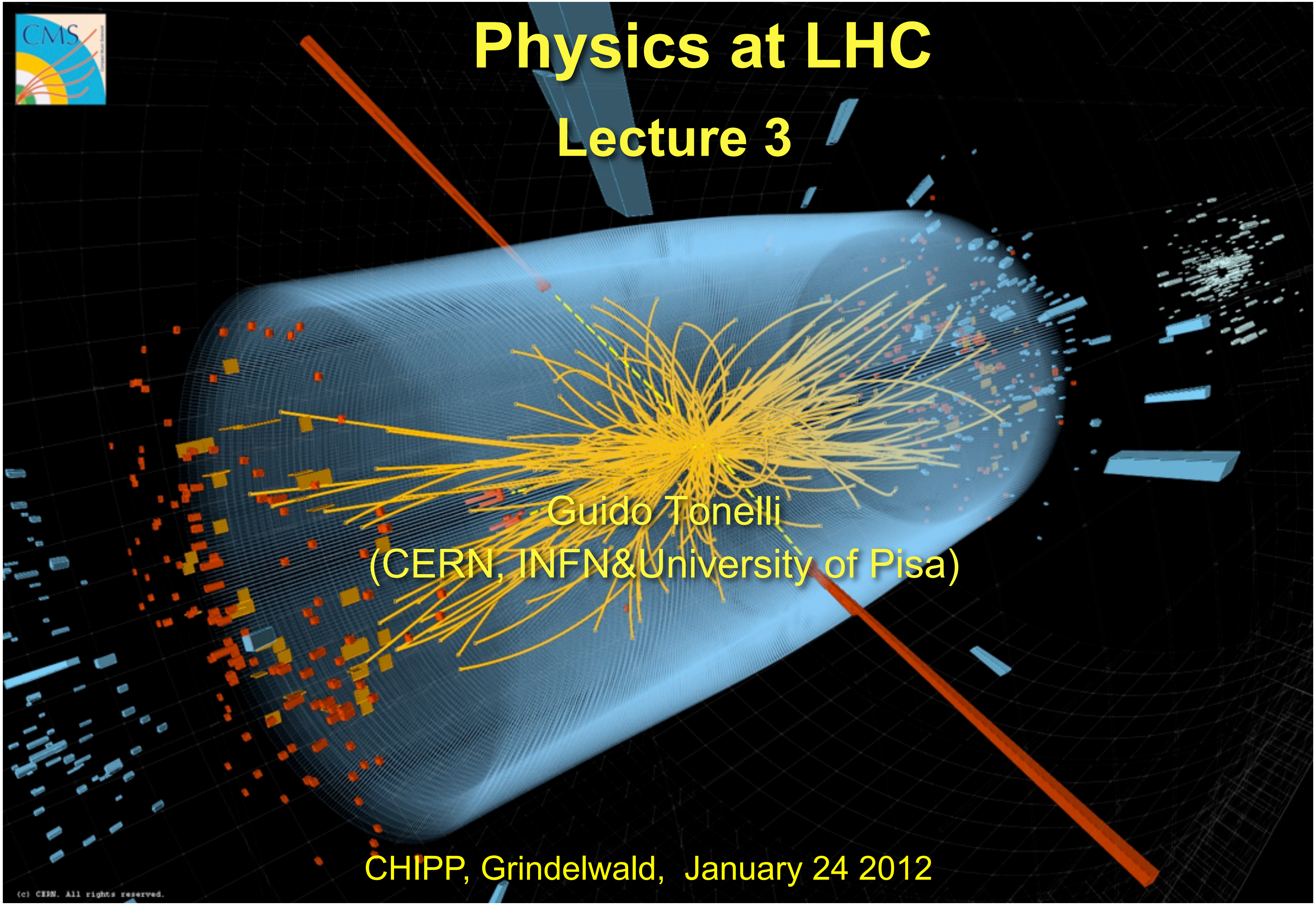
CHIPP, Grindelwald, January 24 2012

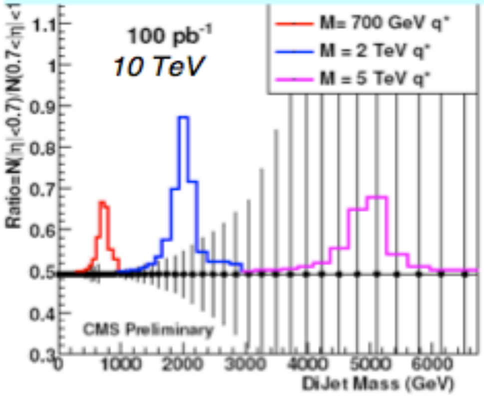


Beyond the SM

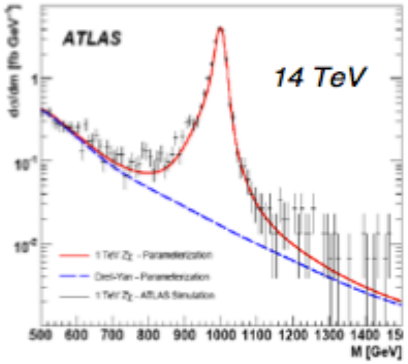
Lecture#3: search for new phyics beyond the standard model: selection of results of exotica and SUSY.

The zoo of new Physics at LHC

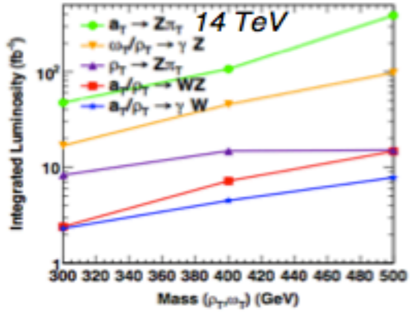
Contact Interaction /Excited Quarks?



New Gauge Bosons?

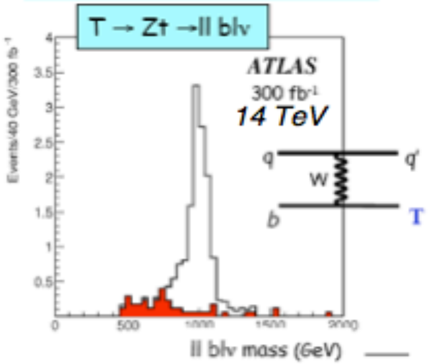


Technicolour?

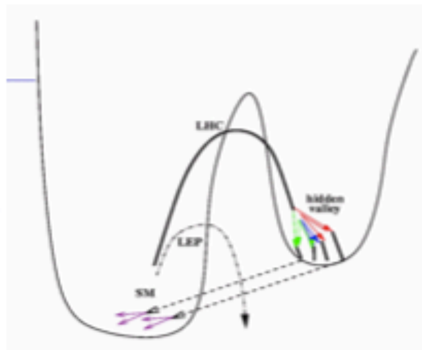


Split Susy?

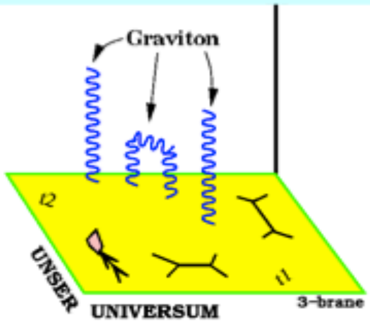
Little Higgs?



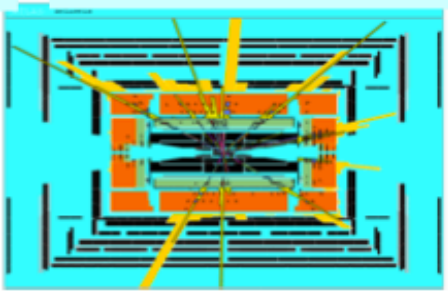
Hidden Valley??



Extra Dimensions?



Black Holes???

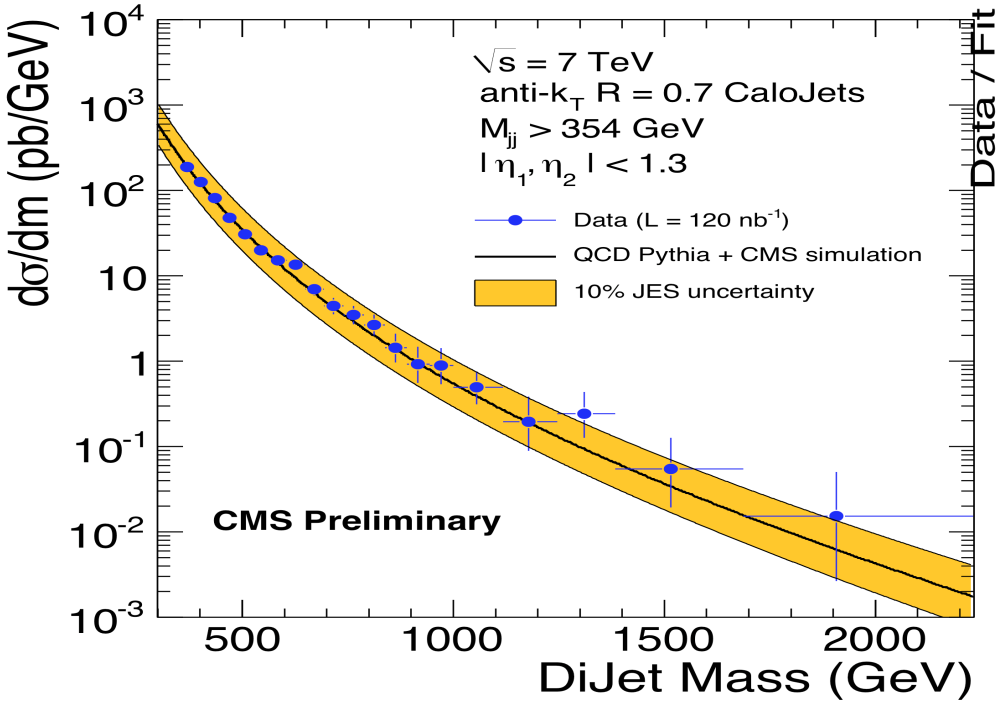


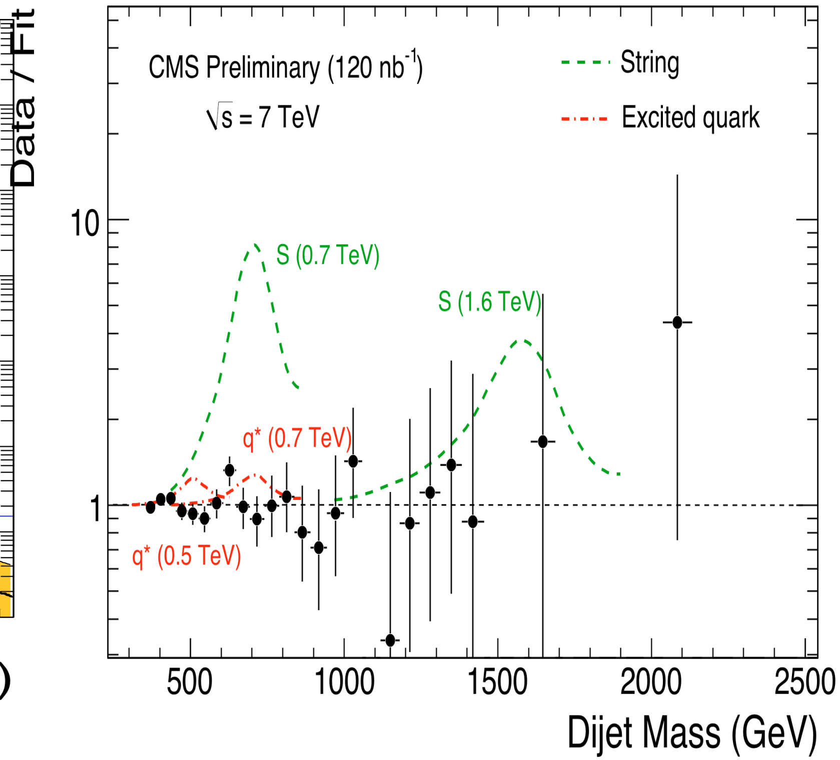
Signatures (not at all complete!!)

Signature	class of model	important backgrounds	issues
Resonances -di-jets -di-leptons/photons	Z', W', excited quarks ED	falling QCD or DY spectrum	- Jet Energy Scale and resolution - leptons : alignment, momentum resolution, calorimeter saturation
Multi-jets + MET	SUSY New heavy quarks, composite models	QCD ttbar V+jets	- data-driven bckg. estimation - MET modeling, jet fluctuations - choice of clever variables (HT, $alpha_T$, Razor, m_{T2}, ...)
leptons + jets + MET	SUSY New heavy quarks, t', b', ...	QCD ttbar V+jets	- like above - jets faking leptons, lepton isolation - lepton charge mis-ID (for same-sign lepton searches)
photons + MET	SUSY Extra Dimensions	QCD	- jets faking photons - MET modeling

Di-jets (early 2010 data)

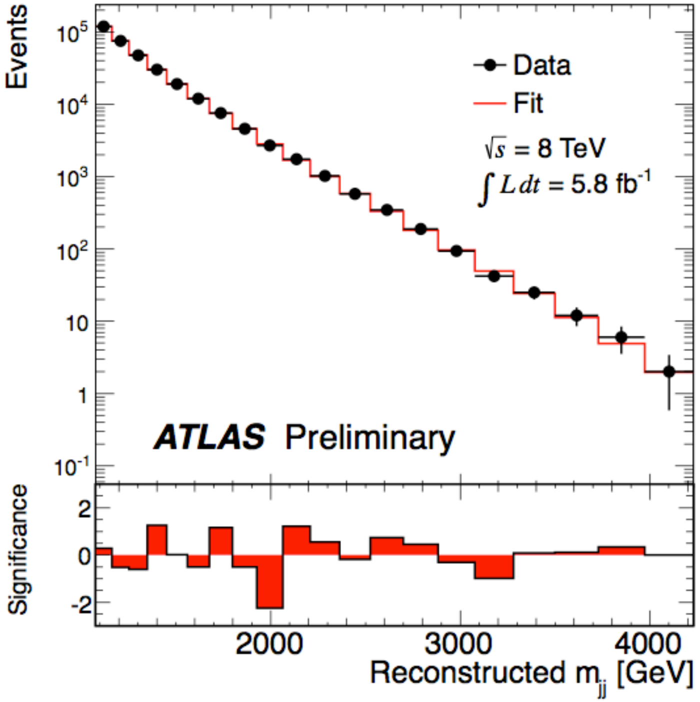
With the very first data ($120 nb^{-1}$) of data you can measure the di-jet mass differential cross section for centrally produced jets $|\eta_1, \eta_2|<1.3$ Since the distribution is very sensitive to the coupling of any new massive object to quarks and gluons you can extract limits on string resonances (1.67TeV), excited quarks (0.59TeV) and axigluons (0.52TeV)



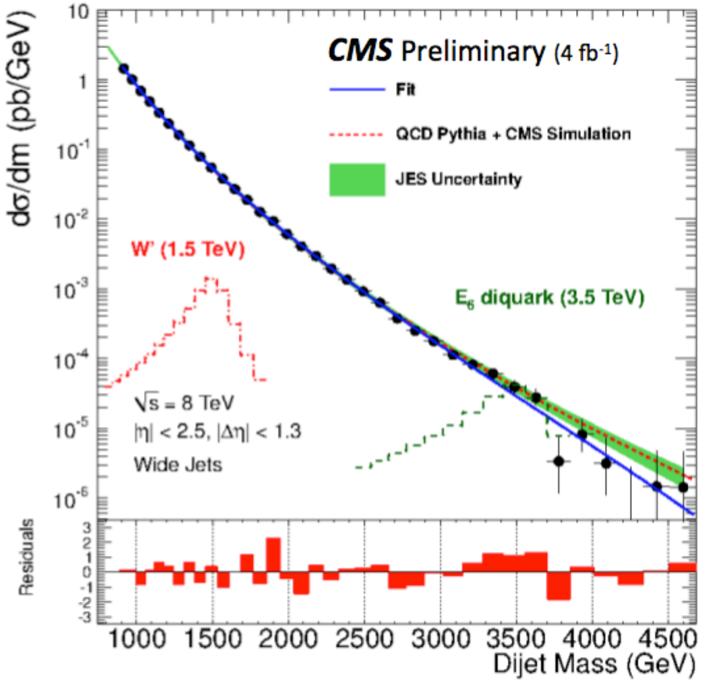


Di-jets today in 8 TeV data

[ATLAS-CONF-2012-110]



[CMS PAS EXO-12-016]

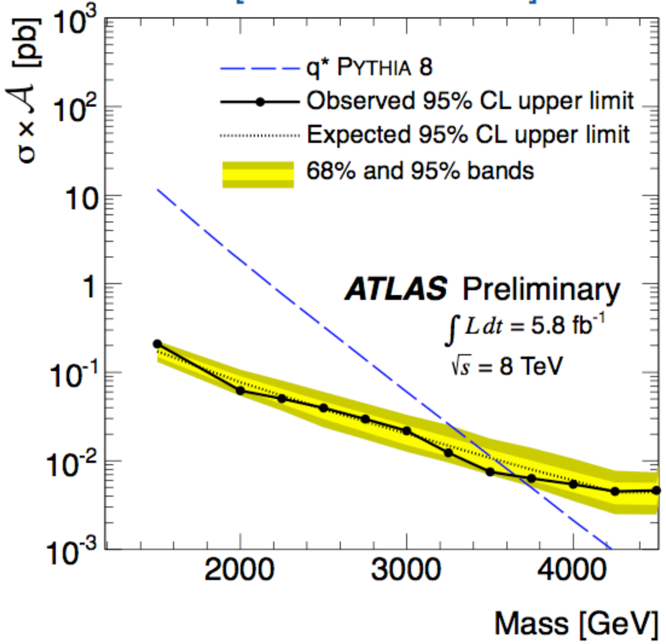


- Search for dijet resonance in smoothly falling mass spectrum
  - leading jet mass $m_{jj} > 0.9$-1 TeV from trigger and other constraints
  - Background estimated from smooth functional fit

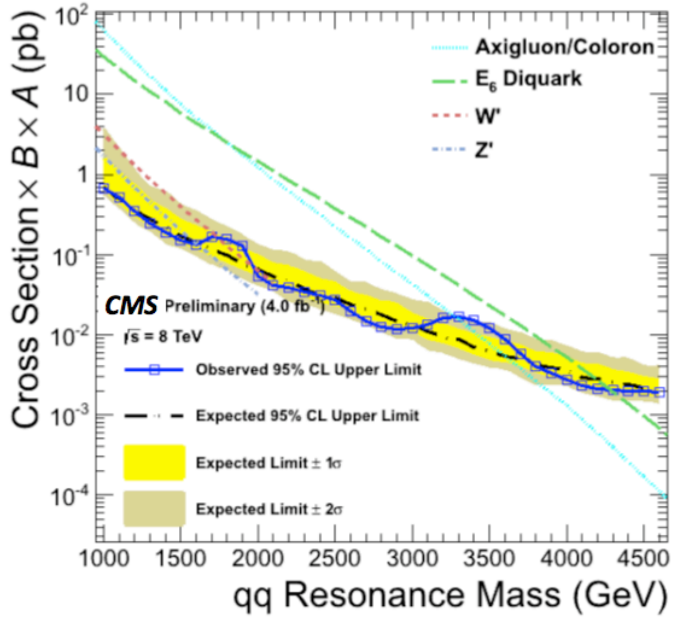
$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$

Di-jets in 8 TeV data

[ATLAS-CONF-2012-110]



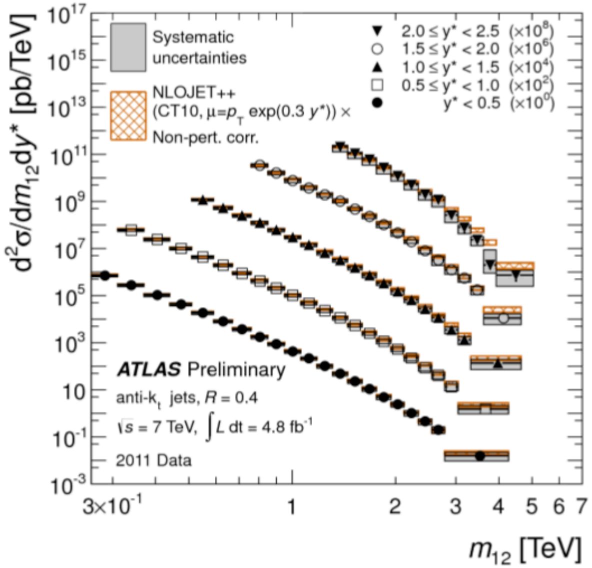
[CMS PAS EXO-12-016]



M(q*) 95% CL	Luminosity	Expected	Observed
ATLAS 2011	4.8	> 3.09 TeV	> 3.55 TeV
CMS 2011	5.0	> 3.27 TeV	> 3.05 TeV
CMS 2012	4.0	> 3.43 TeV	> 3.19 TeV
ATLAS 2012	5.8	> 3.53 TeV	> 3.66 TeV

Jet differential cross sections and di-jet resonance search

Testing predictions over
8 orders of magnitude !



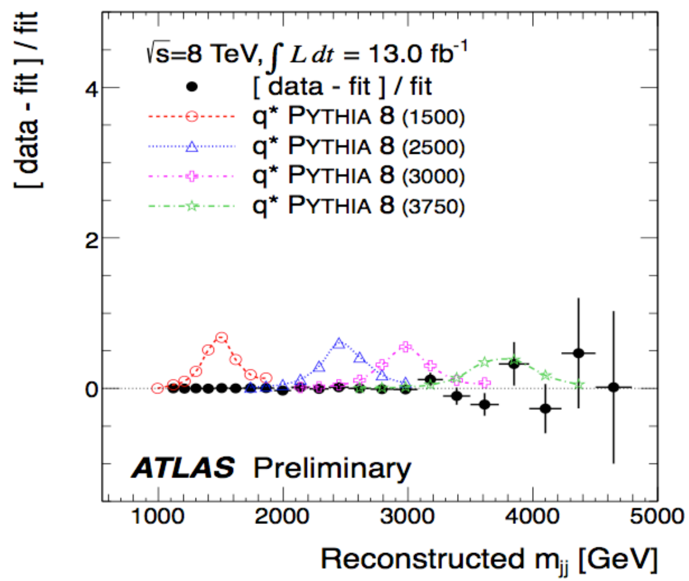
Di-jet mass differential cross section probing :

- Excellent performance and reconstruction
- NLO theory prediction of cross sections and PDFs

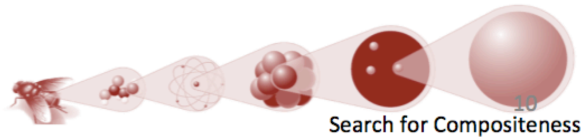
Di-jet Mass Resonance

ATLAS-CONF-2012-148

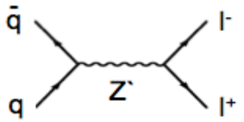
Data / fit ratio, compared to four q* models



$m(q^*)$ > 3.84 TeV (95% CL)

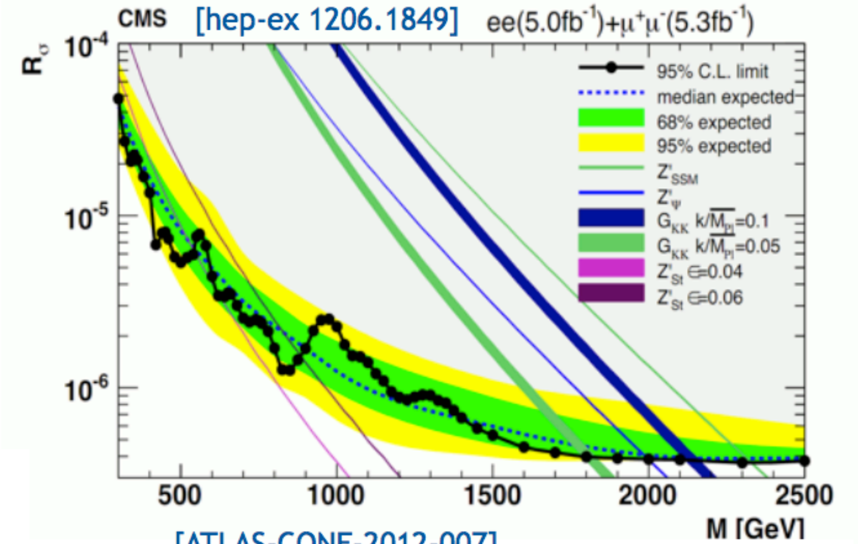


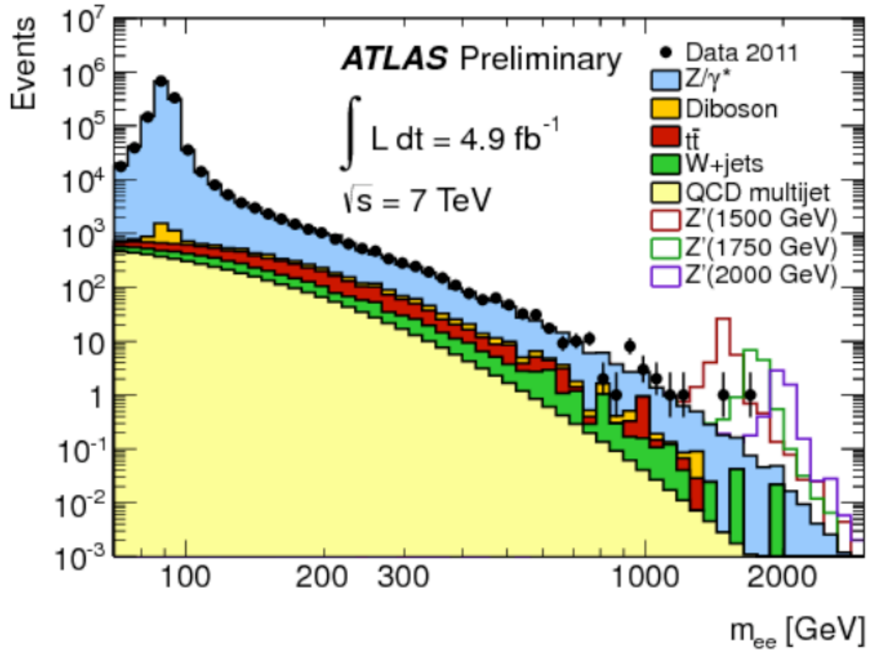
Search for new massive resonances Z'



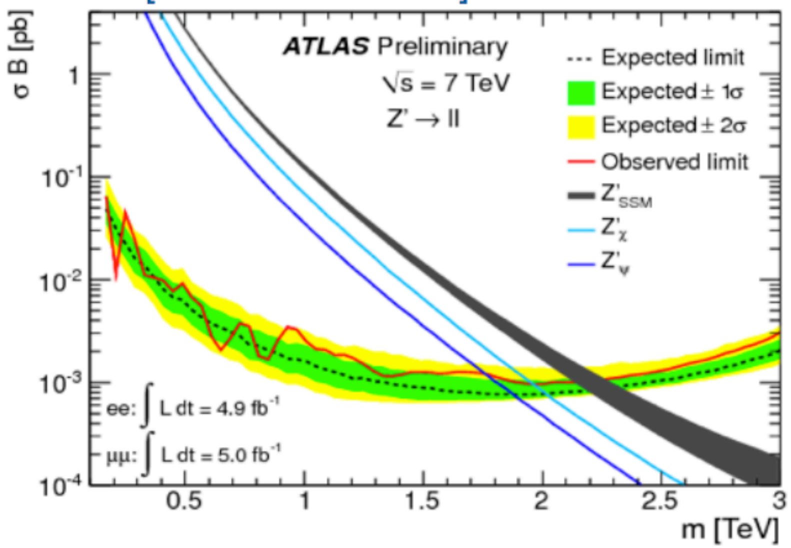
- Many new models have Z-like narrow resonances decaying to dileptons
- Interesting features in dilepton spectra
  - around 2σ each for CMS & ATLAS in e+μ
  - similar in scale to 2011 Higgs excess

Worth watching in 2012's 8 TeV data…





[ATLAS-CONF-2012-007]



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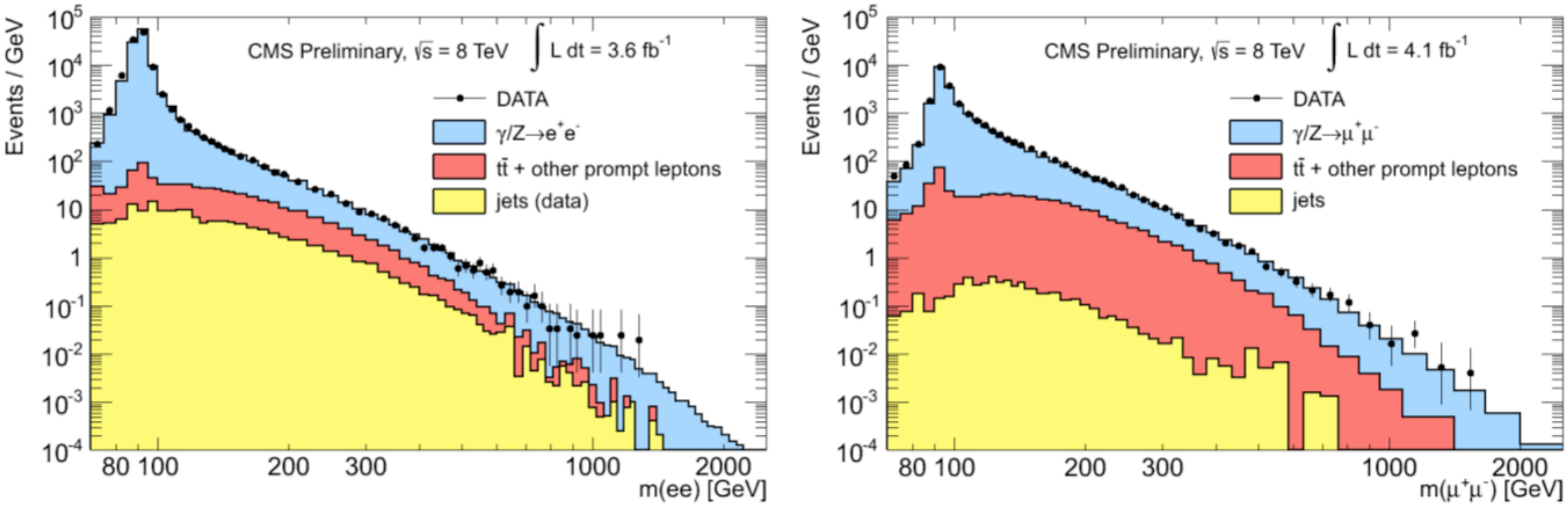
Z' search in 8 TeV data

[CMS EXO-12-015]

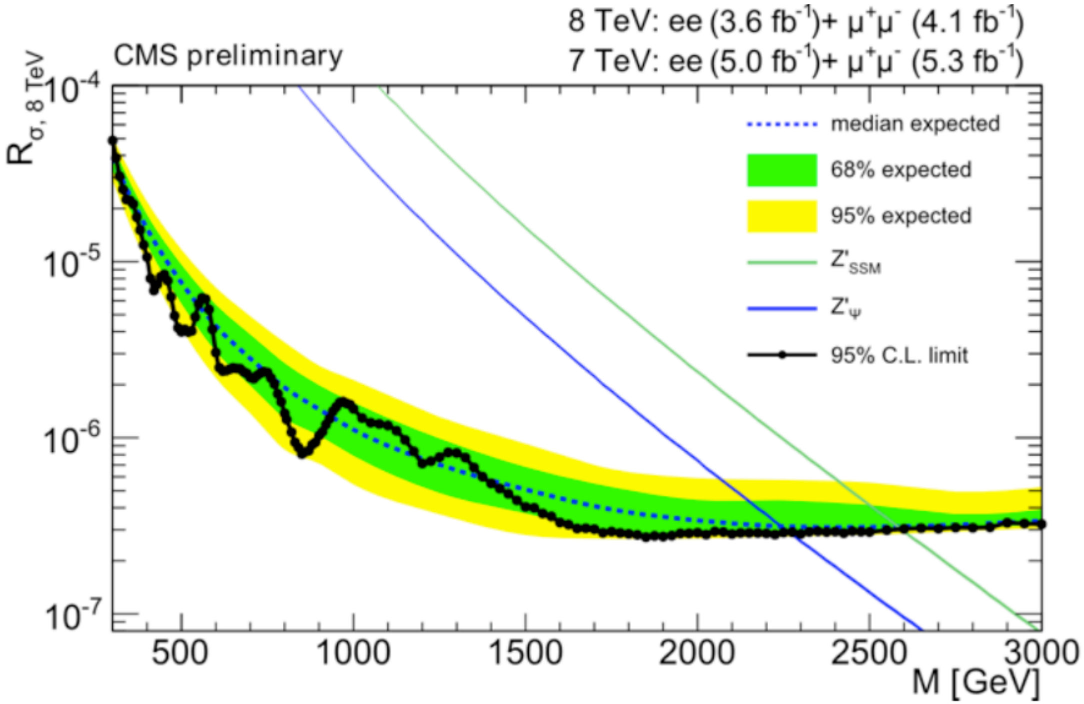
- Event selection
  - E_T (e1,e2) > 35 GeV, p_T (μ1,μ2) > 45 GeV, plus isolation criteria
- Backgrounds
  - Z/γ*, tt, tW, VV, Z → ττ, multijets with ≥1 jet reconstructed as lepton
  - estimated by functional fit to data

No obvious excess observed in 2012 data



Z' search in 8 TeV data

[CMS EXO-12-015]



- Short time between data-taking and result

$$R_\sigma = \frac{\sigma(pp \to Z' + X \to \ell\ell + X)}{\sigma(pp \to Z + X \to \ell\ell + X)}$$

- Limits on the combined 7 TeV and 8 TeV data from 2011+2012
  - $M(Z'_{SSM}) > 2590$ GeV at 95% C.L.
  - $M(Z'_{\psi}) > 2260$ GeV at 95% C.L.

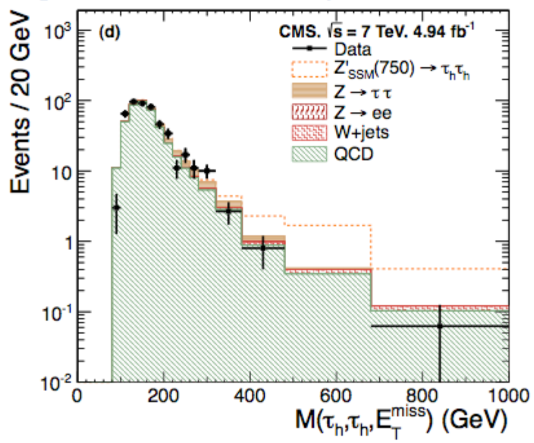
Excess just below 1 TeV all but gone in CMS data

Z' with SM-like couplings **> 2590 GeV**

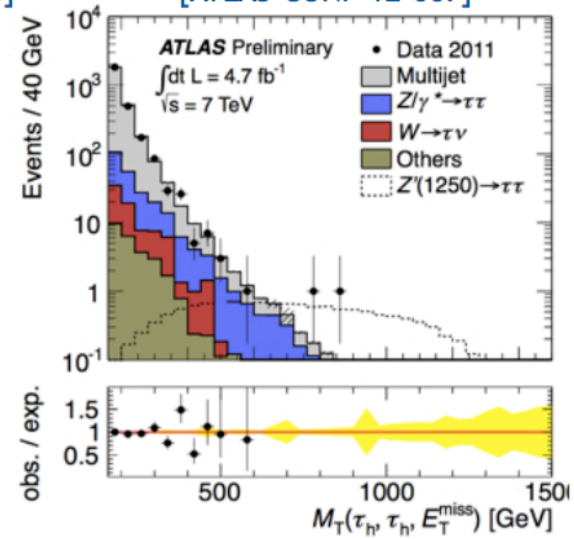
Search for Z' $\rightarrow \tau^+\tau^-$

- Z' might couple preferentially to third-generation fermions
  - 5 fb-1 at √s = 7 TeV
  - Study: $\tau_e\tau_\mu$, $\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_h\tau_h$
  - plot effective (visible) mass
- Backgrounds:
  - DY Z → ττ, W+jets, tt, VV, QCD
  - estimated from data where possible

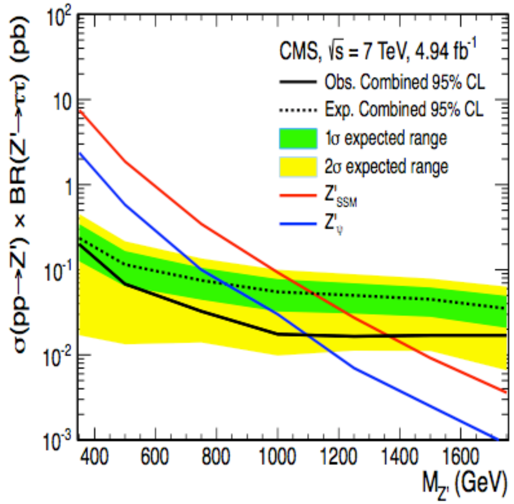
[CMS EXO-11-031, hep-ex 1206.1725]

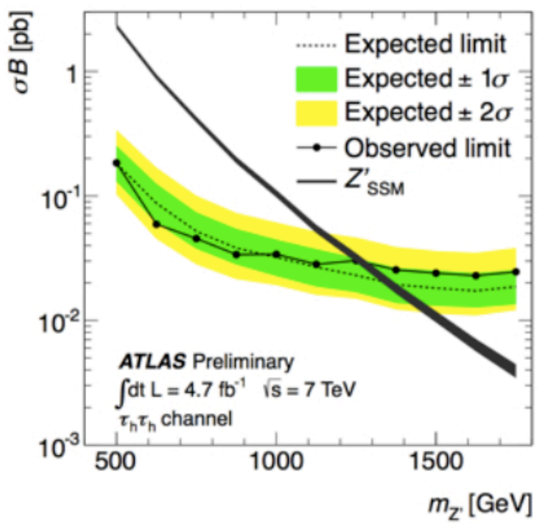


[ATLAS-CONF-12-067]



M(Z'$_{SSM}$)	expected	observed
CMS	> 1.1 TeV	> 1.4 TeV
ATLAS	> 1.4 TeV	> 1.3 TeV





Search for W'→lν

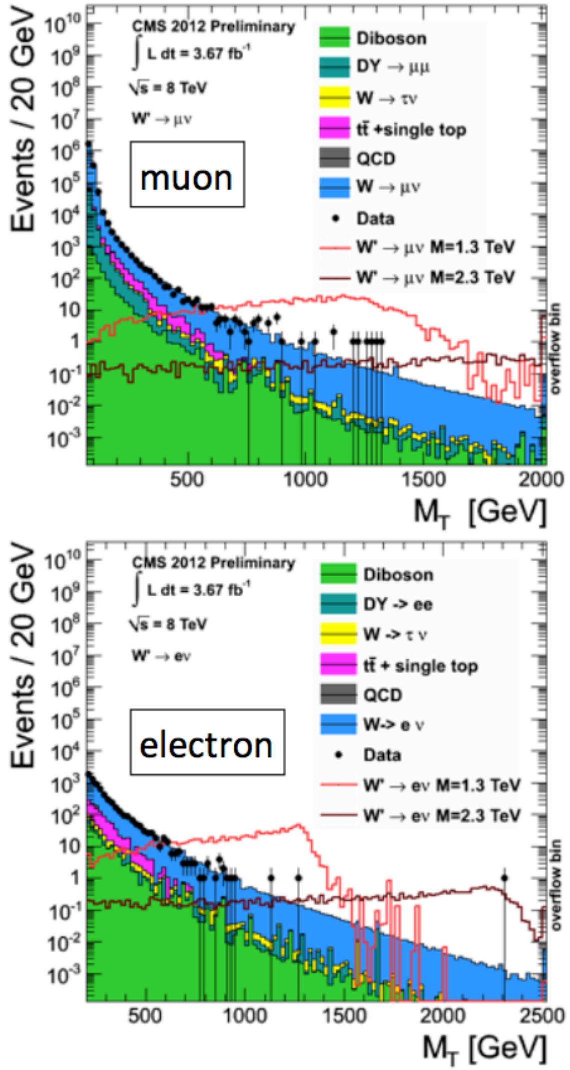
[CMS PAS EXO-12-010]

- Search for a new heavy gauge boson W' decaying to a charged lepton (μ or e) and ν

$$M_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

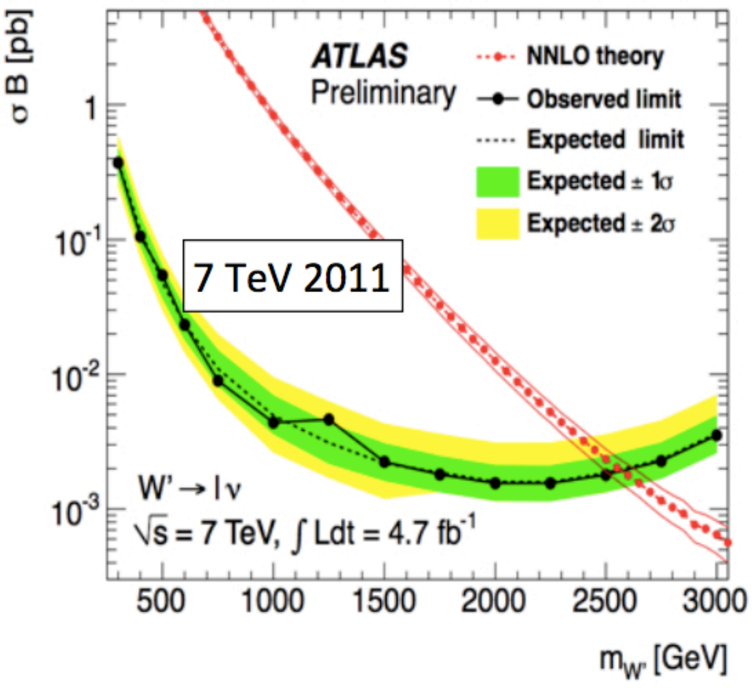
- Many models possible
  - right-handed W' bosons with standard-model couplings
  - left-handed W' bosons including interference
  - Kaluza-Klein W'_{KK}-states in split-UED
  - Excited chiral boson (W*)
- Event Selection and Backgrounds
  - back-to-back isolated lepton and E_T^{miss}
  - Plot transverse mass of lν system
  - backgrounds from W, QCD, tt+single t, DY, VV from data

No significant excess observed

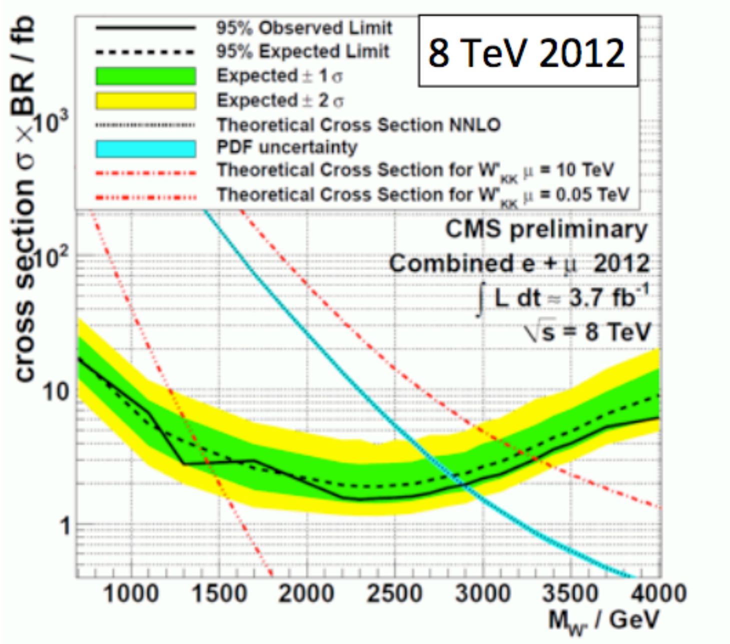


W'→lν (limits)

[ATLAS-CONF-2012-086]



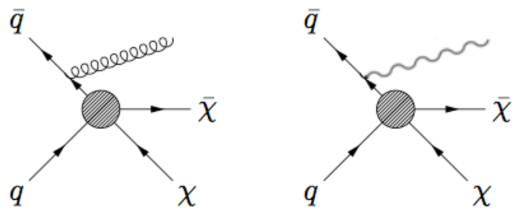
[CMS PAS EXO-12-010]



$M(W'_{SSM})$ 95% CL	Luminosity	Expected	Observed
ATLAS e+μ, 2011	4.7	> 2.55 TeV	> 2.55 TeV
CMS e+μ, 2012	3.7	> 2.80 TeV	> 2.85 TeV
CMS e+μ, 2011+2012	5.0 + 3.7	> 2.85 TeV	> 2.85 TeV

Monophotons and monojets

- Look for missing energy and radiated jet (photon)



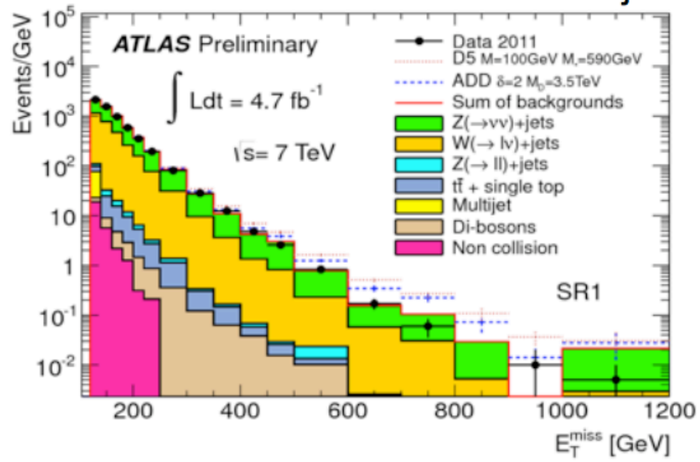
- Monojet Selection:
  - Leading jet p_T > 120 GeV, |η| < 2
  - allow a second jet if not back-to-back
  - veto isolated leptons

- Backgrounds and Uncertainties
  - Z + (jets/γ) --> νν+(jets/γ)
  - W + (jets/γ) --> lν+(jets/γ)
  - smaller backgrounds from top, QCD, non-collision

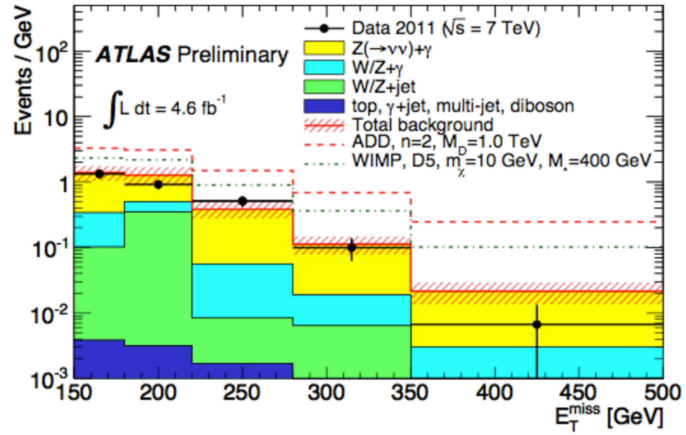
- Missing Energy (E_T^{miss}) to distinguish signal

[ATLAS-CONF-2012-084, ATLAS-CONF-2012-085]

monojet



monophoton



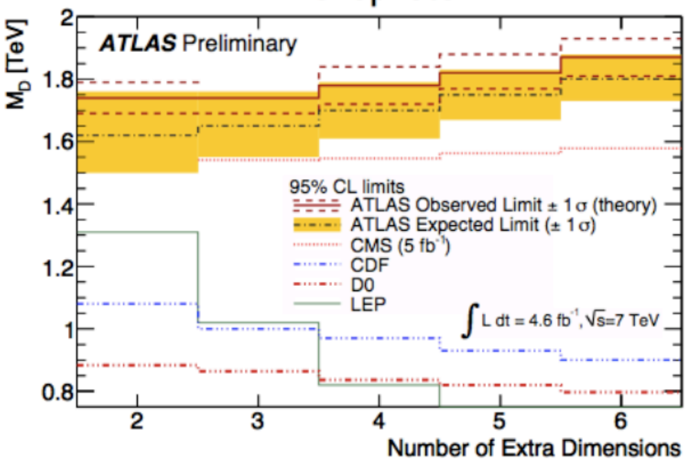
Monophotons, monojets and Large Extra-dimensions

Large Extra Dimensions: Arkani-Hamed, Dimopoulos, Dvali (ADD)

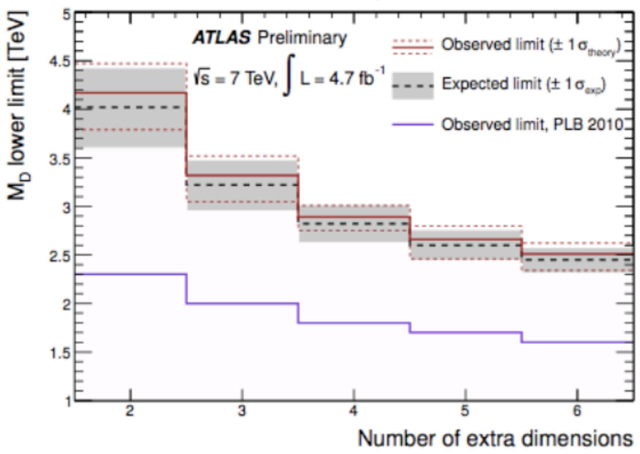
$$M_{Pl}{}^2 \sim M_D{}^{2+n} R^n$$

M_{Pl} = 4-dimensional Planck scale
M_D = fundamental (4+n)-dimensional Planck scale
n = number of the extra dimensions
R = size of the extra dimensions

monophoton



monojet



M_D (ADD) at LO 95% CL limits	Lumi [fb^{-1}]	δ=3 Exp.	δ=3 Obs.	δ=6 Exp.	δ=6 Obs.
CMS Monophoton	5.0	1.5	1.6	1.6	1.6
ATLAS Monophoton	4.6	1.7	1.7	1.8	1.9
CMS Monojet	5.0	3.1	3.2	2.3	2.4
ATLAS Monojet	4.7	3.2	3.3	2.4	2.5

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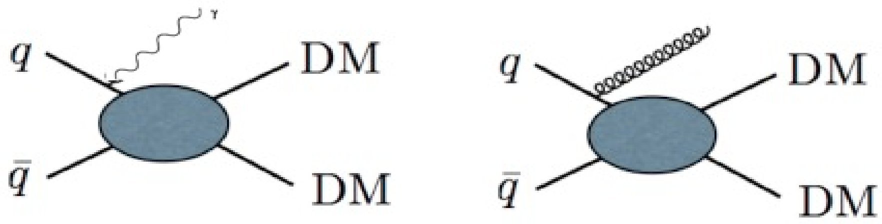
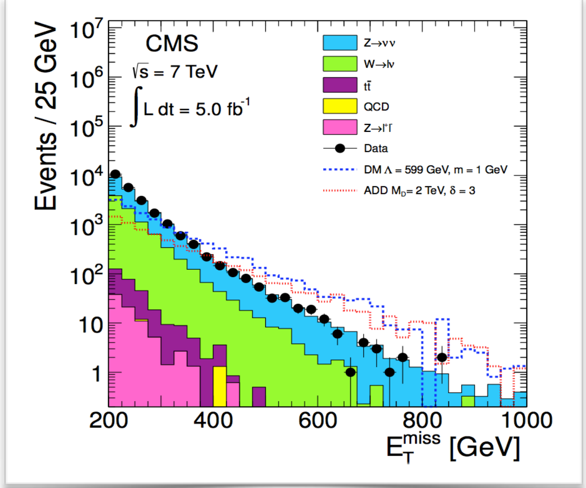
Complementarity between LHC and Dark Matter experiments

- monojets, photons+MET





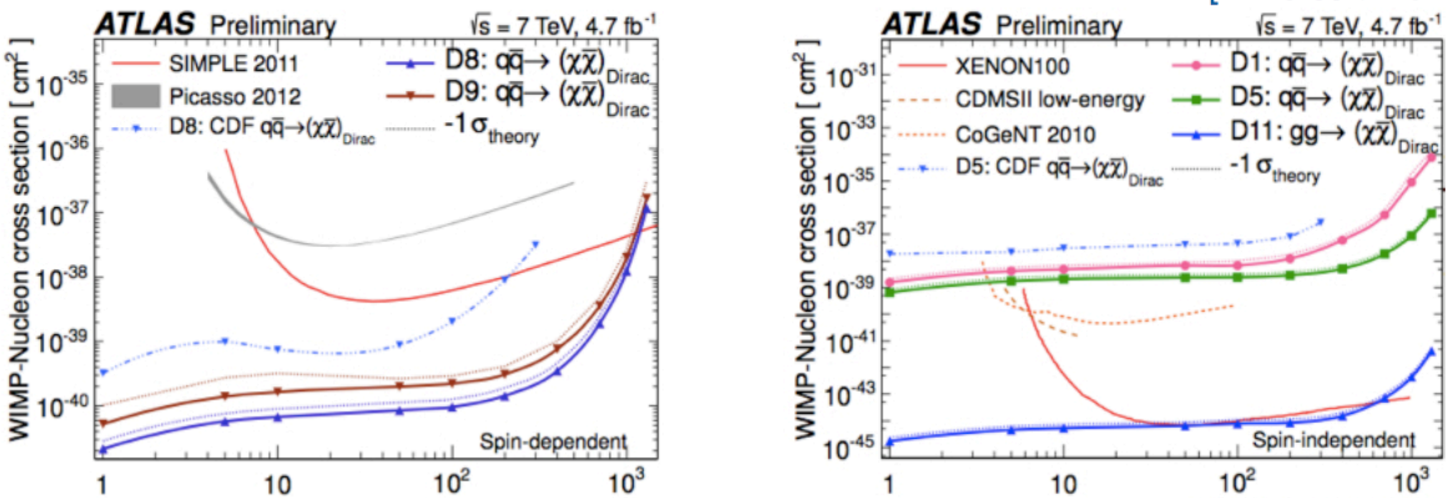
arXiv:1204.0821

At colliders we probe parton-DM couplings, whereas in Direct Dark Matter experiments we look for the coherent nucleon-DM scattering.

Collider exps can cover much lower masses and also very high cross sections not accessible by underground direct DM (DDM) detectors.

Dark matter and monojets

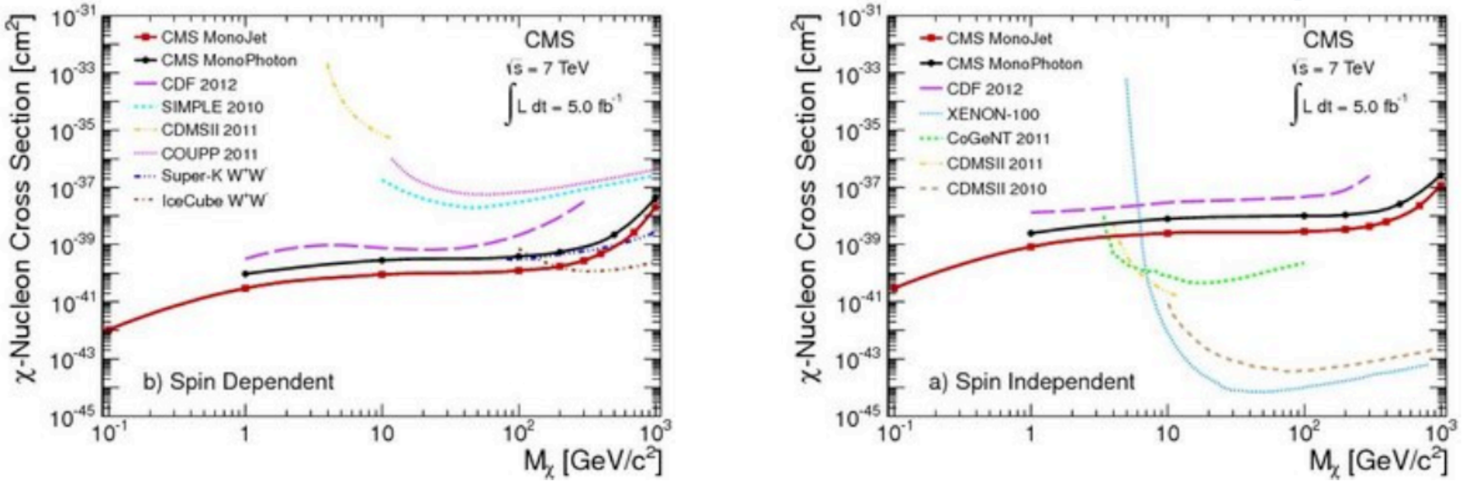
[ATLAS-CONF-2012-084]



Spin-dependent

Spin-independent

[CMS EXO-11-059]



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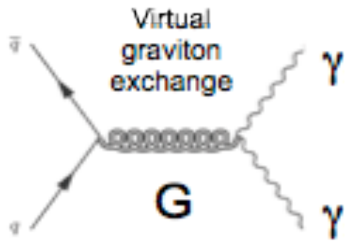
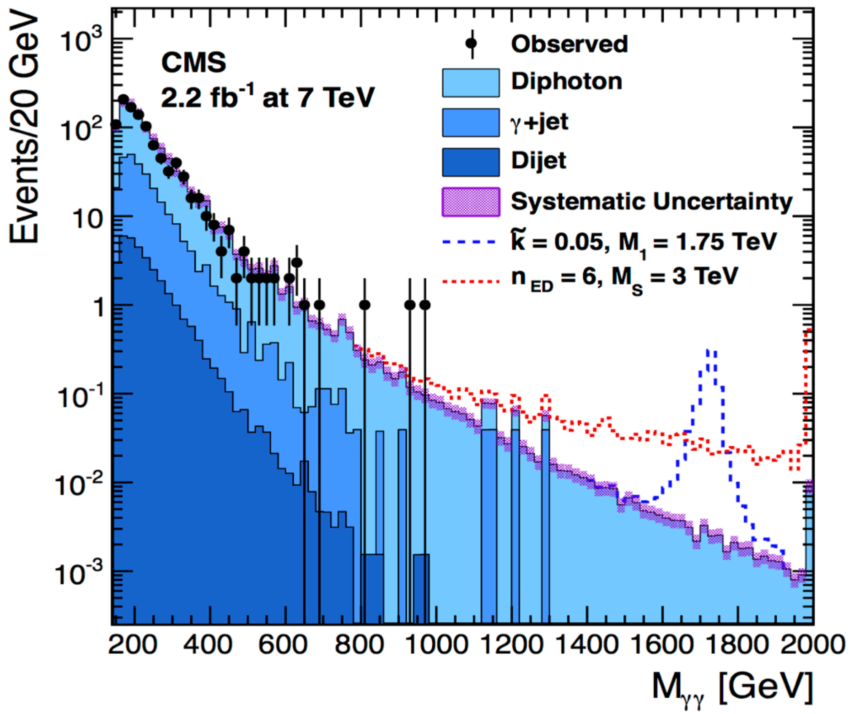
Di-photons or top pairs in the final state

Search for LED via



1112.0688 (hep-ex)

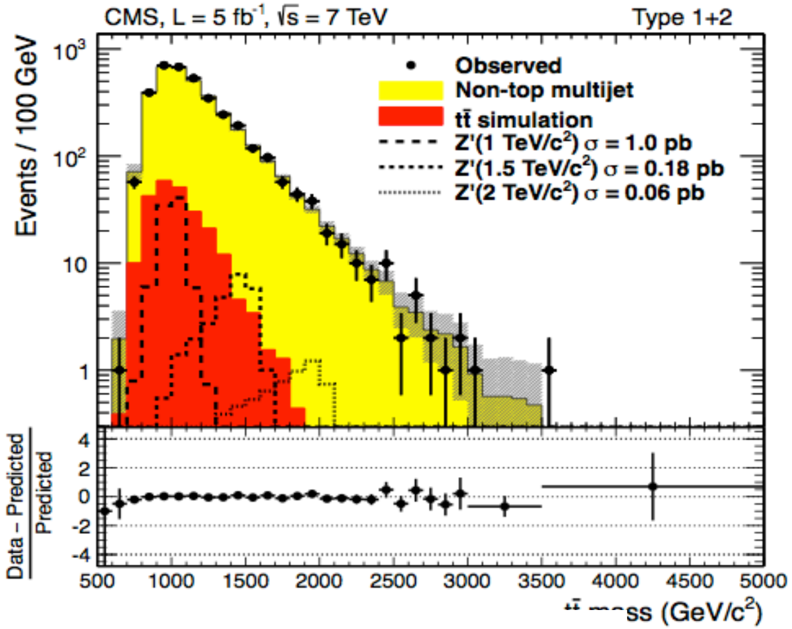


Photons in ECAL barrel, E_T> 70 GeV

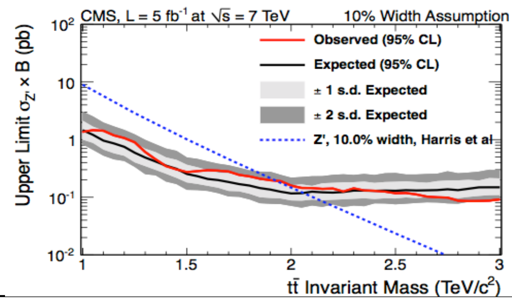
Upper limit on σxBRxA < 3 fb for $M_{\gamma\gamma}$>900 GeV

lower limits on eff. Planck scale of 2.3 - 3.8 TeV !

- **Search for massive neutral bosons**
- Bump hunt in M(ttbar) spectrum
- Reconstructing boosted tops
- No bumps seen so far...



arXiv:1204.2488



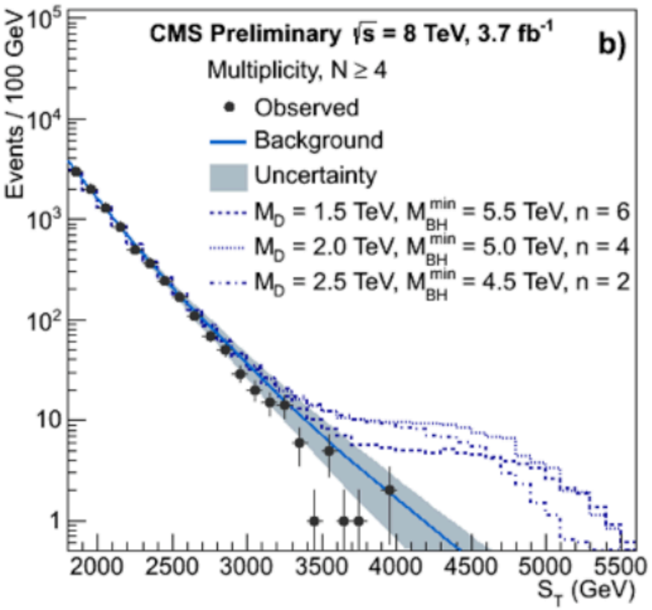
Search for black holes

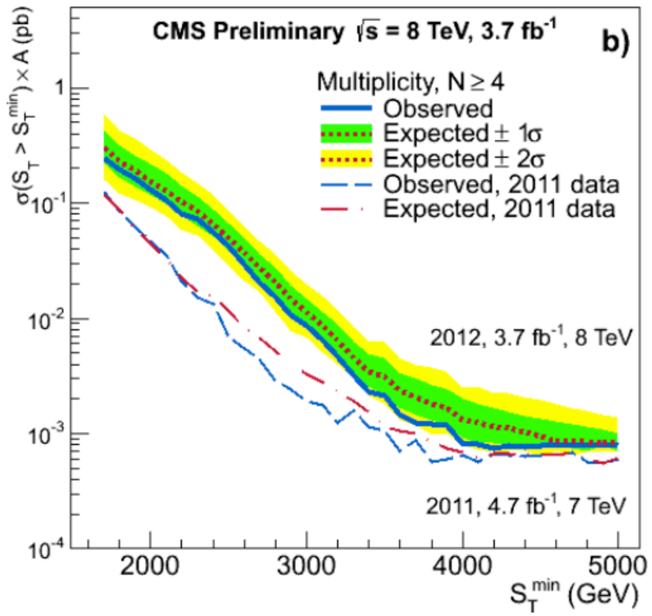
[CMS PAS EXO-12-009

- Hypothetical BH would evaporate into many high-p_T objects
  - Estimate by S_T, the p_T sum of physics objects with p_T > 50 GeV
- Main background of QCD estimated by fit to n=2 distribution
  - Normalised for each multiplicity bin separately at S_T = 1.8–2.2 TeV
  - Model-independent limits vs S_T and multiplicity

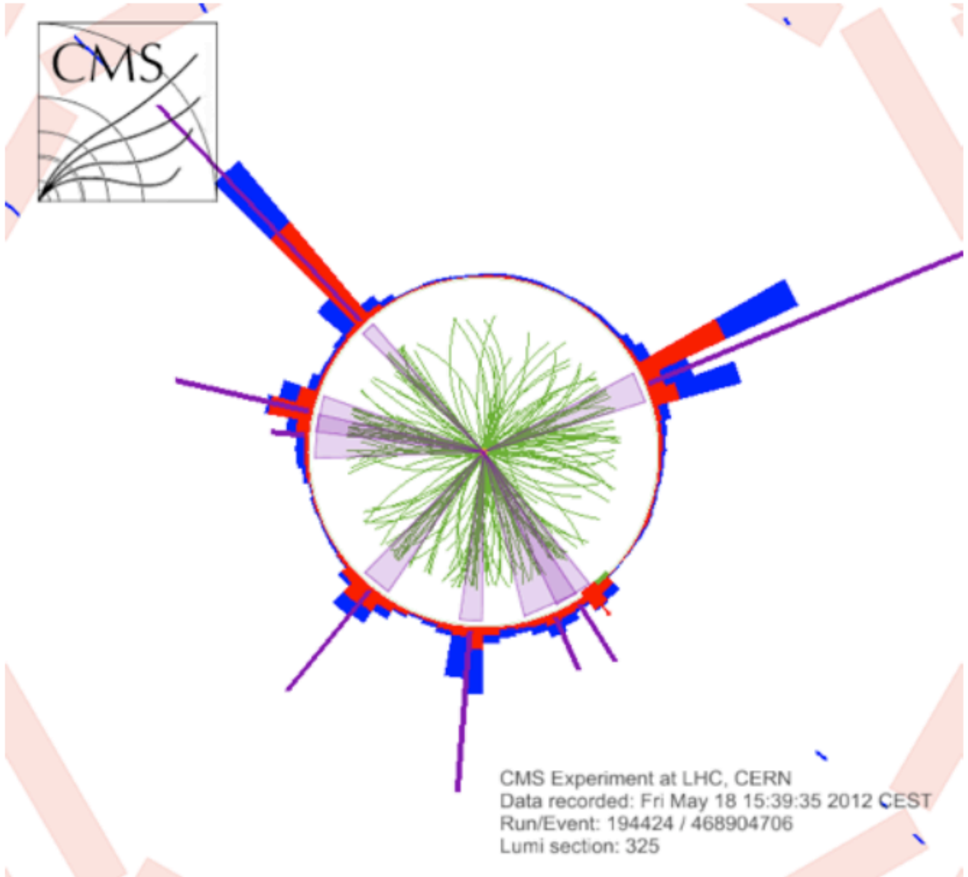
$$S_T = \sum_{j,e,\mu,\gamma,MET}^{N} p_T$$

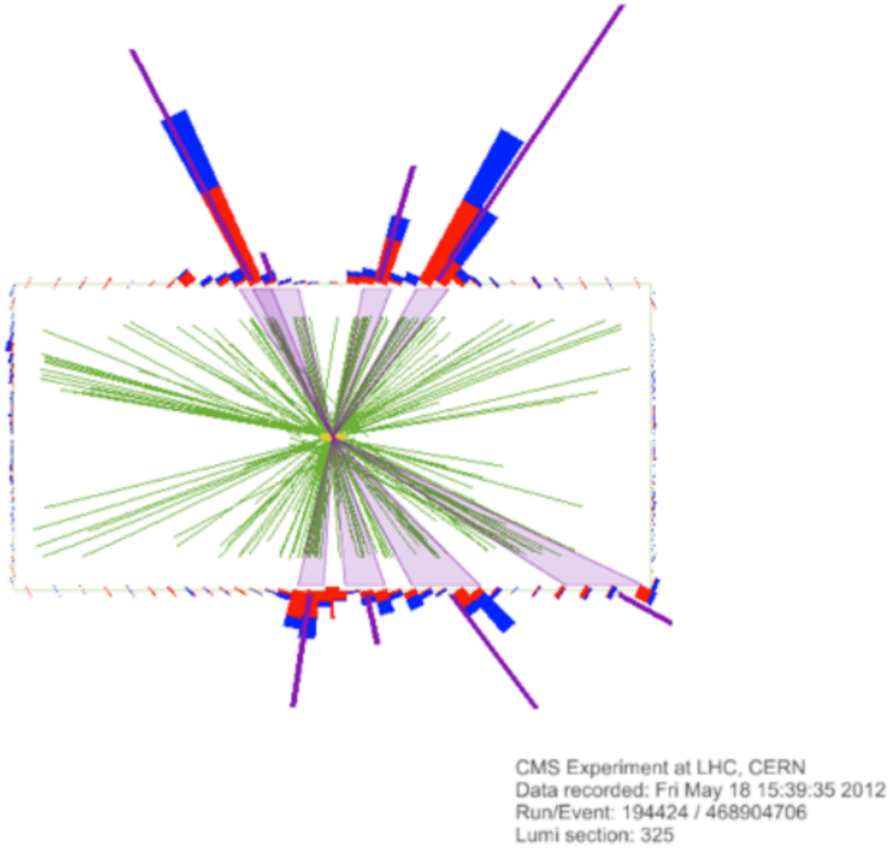
Large improvement in sensitivity (~10-20%) with respect to 2011 analysis



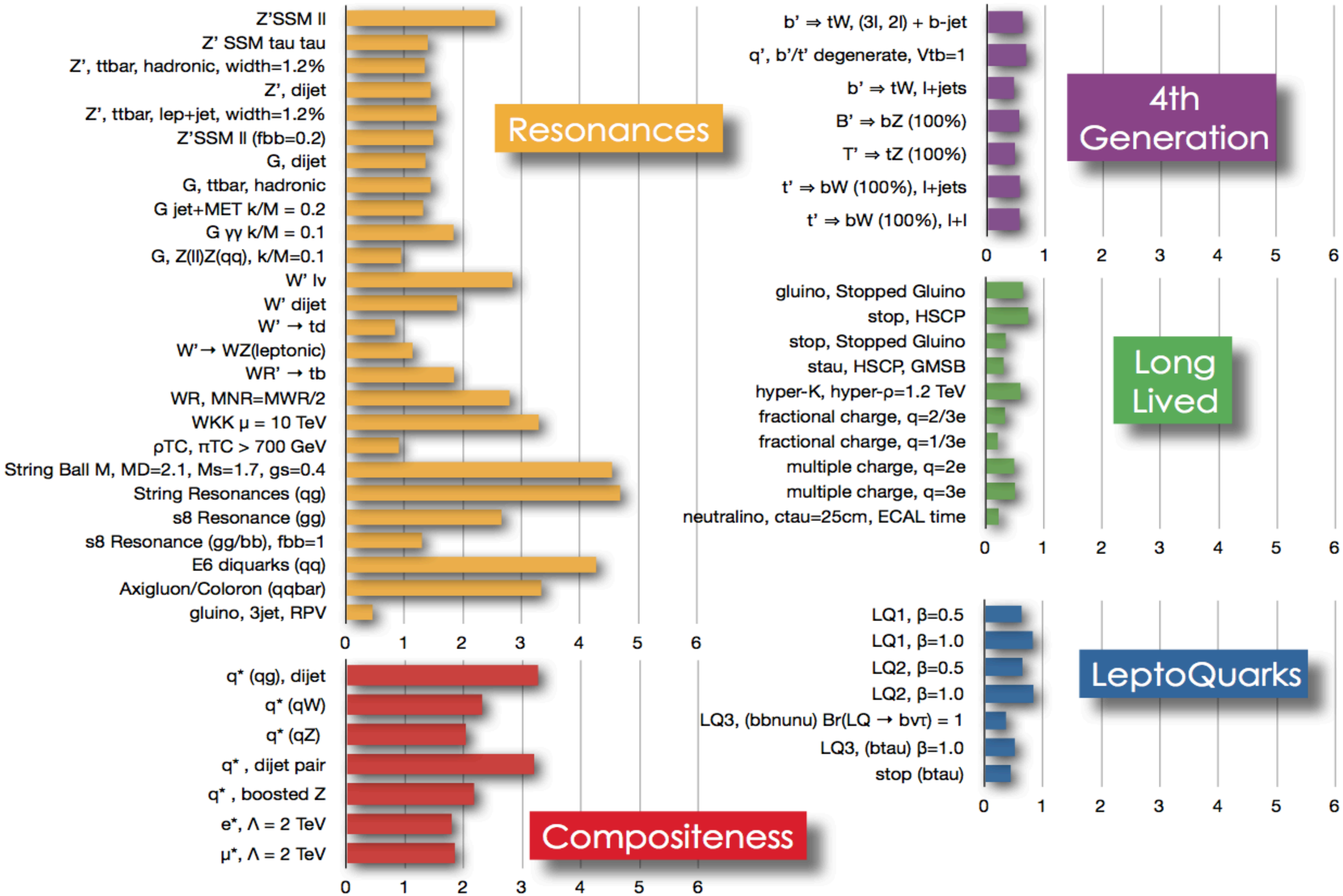


8-jet event, S_T>3TeV



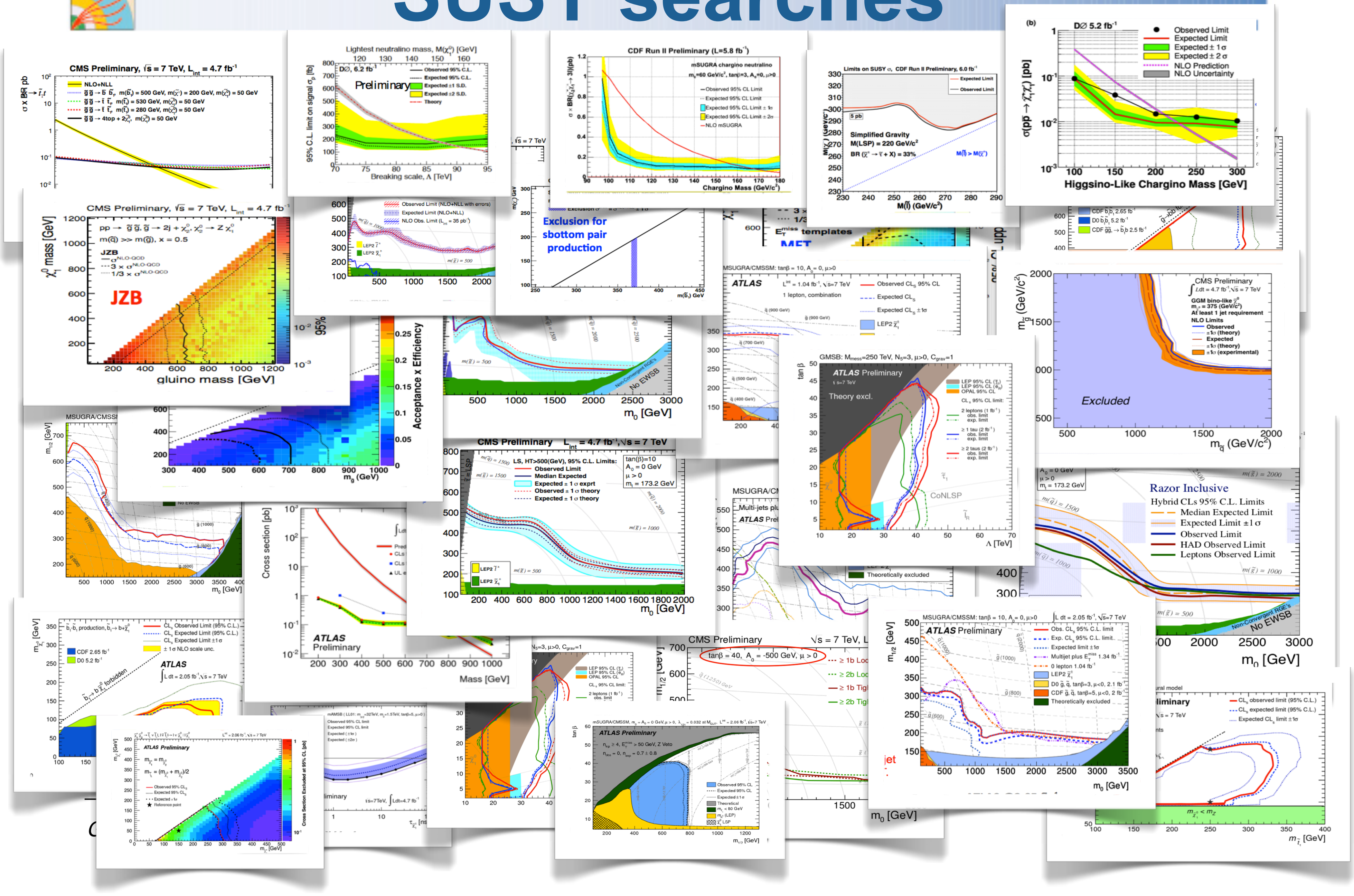


And many, many more...



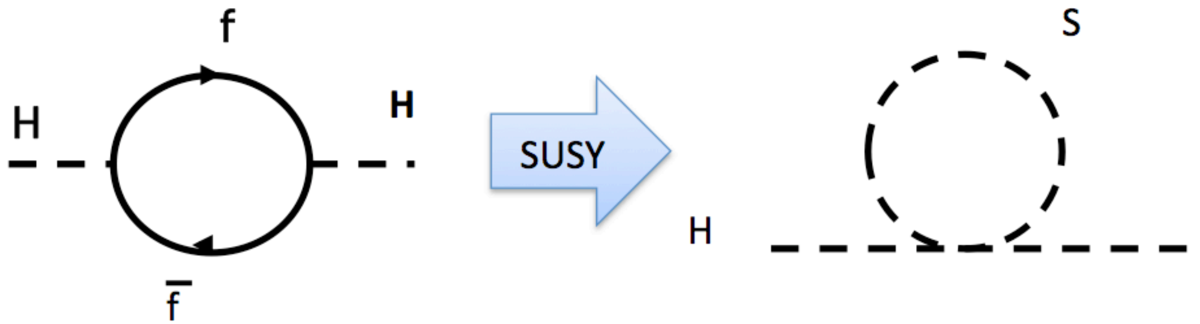
Status of exotic searches

SUSY searches



Why SUSY could still be a real symmetry of nature?

- Two big reasons:
- Dark matter – strong evidence from astrophysics – WIMP miracle fits with SUSY
- Light Higgs – need new physics to stabilise mass



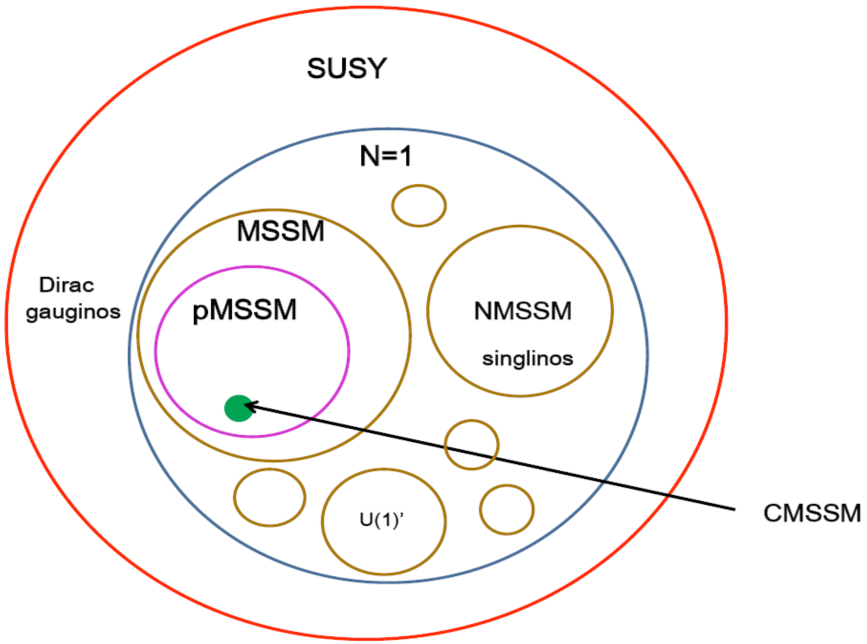
$$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6m_f^2 \ln(\Lambda_{UV}/m_f) + \ldots\right]$$

Need UV cut-off to get finite mass

$$\Delta m_H^2 = \frac{\lambda_s}{16\pi^2}\left[\Lambda_{UV}^2 - 2m_s^2 \ln(\Lambda_{UV}/m_s) + \ldots\right]$$

SUSY provides correct coupling and number of states for cancellations

Minimal Supersymmetric Standard Model

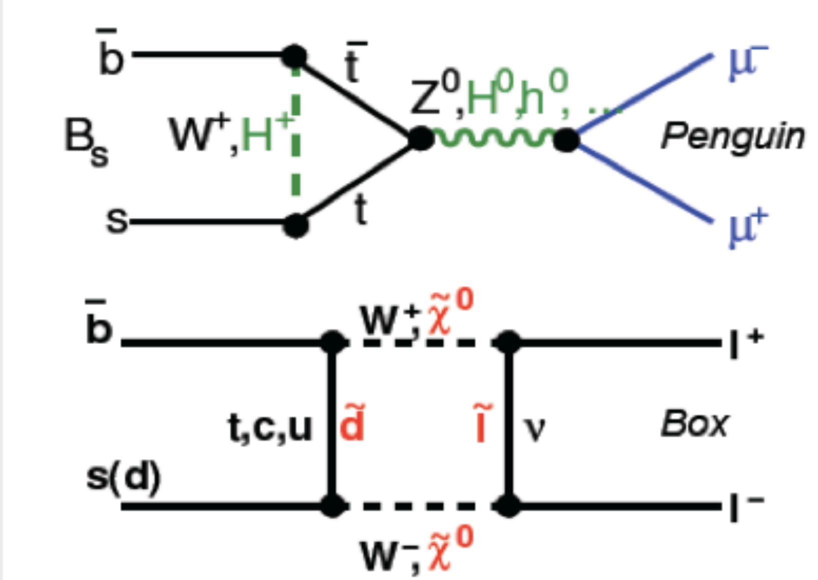


Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

Goal: find hints of (N)MSSM particles in the 100 GeV – 1 TeV range

Probing SUSY with $B_{s,d} \rightarrow \mu^+\mu^-$

- **Decays highly suppressed in SM**
  - Forbidden at tree level
  - b→s(d) FCNC transition only through penguin and box diagrams
  - Helicity suppressed by factors of $(m_\mu/m_B)^2$



- **Standard Model Predictions**
  - $Bs \rightarrow \mu\mu = (3.2\pm0.2)\ 10^{-9}$
  - $Bd \rightarrow \mu\mu = (1.0\pm0.1)\ 10^{-10}$

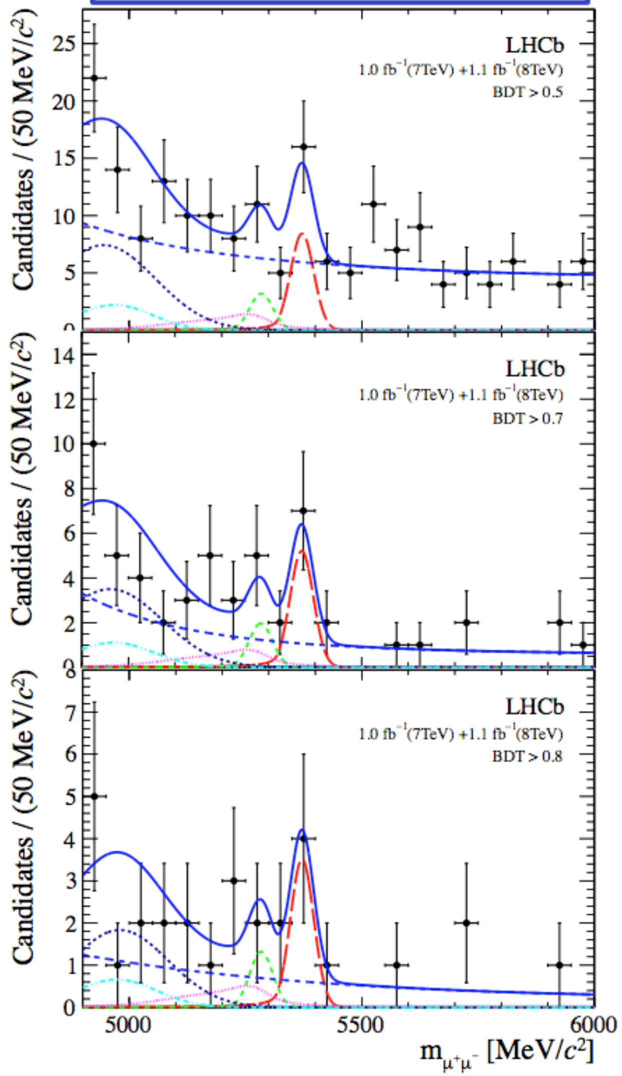
- **Sensitivity to New Physics**
  - BR in MSSM proportional to $\tan\beta^6$

LHCb: measurement of the BR $B_s \rightarrow \mu^+\mu^-$

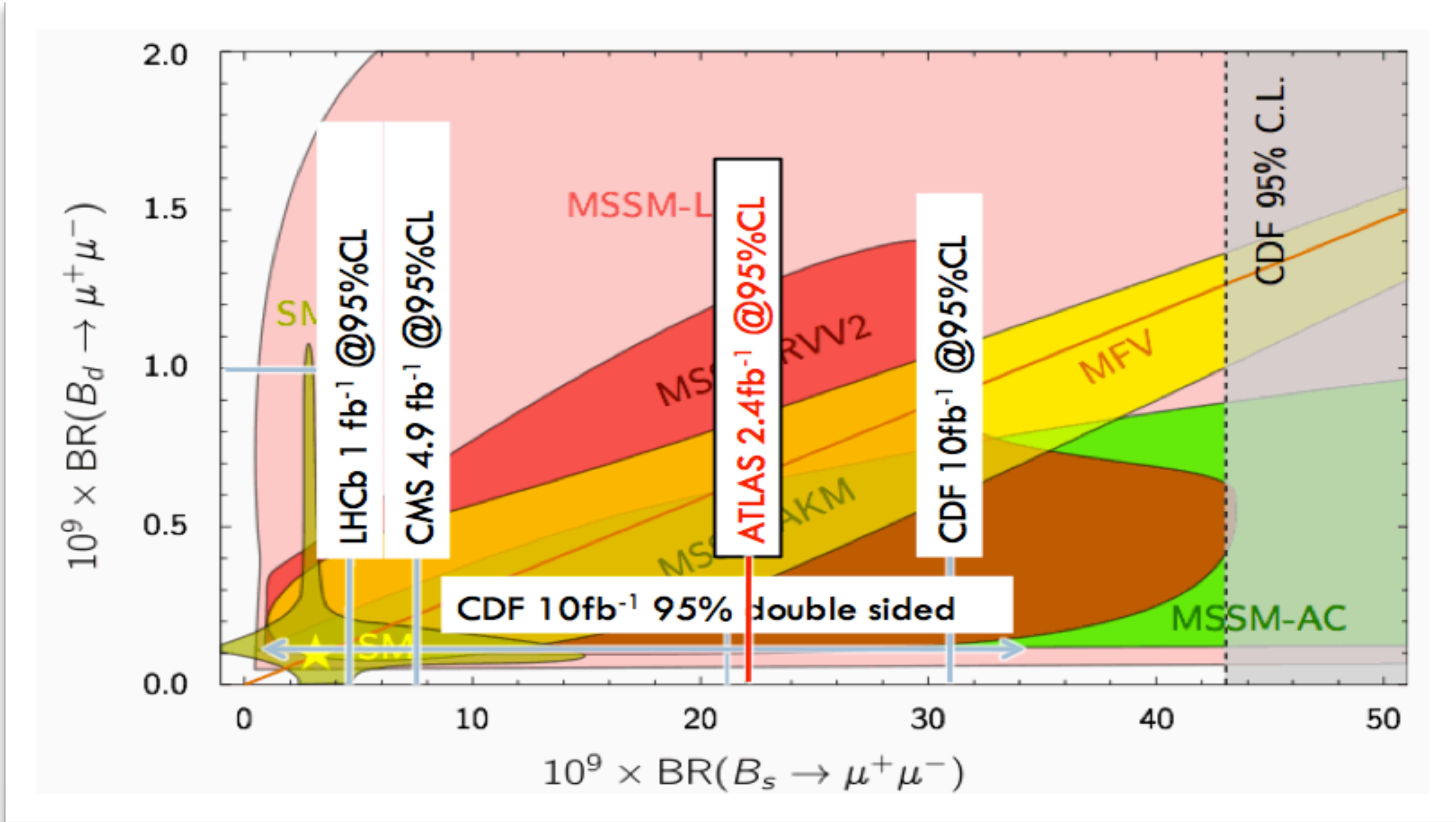
- Combined analysis on $1.0 fb^{-1}$ @ $\sqrt{s}$=7TeV and $1.1 fb^{-1}$ @ $\sqrt{s}$=8TeV
- Upper exclusion limit @ 95% CL
  $BR(B^0 \rightarrow \mu^+\mu^-) < 9.4 \times 10^{-10}$
  worlds best single experiment limit
- **Excess of $B_s \rightarrow \mu^+\mu^-$ candidates with a signal significance of to 3.5 standard deviations**
  (bkg only p-value: 5×10^{-4})
- The branching fraction is measured as

$$BR(B_s \rightarrow \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

$B_s \rightarrow \mu^+\mu^-$ emerging

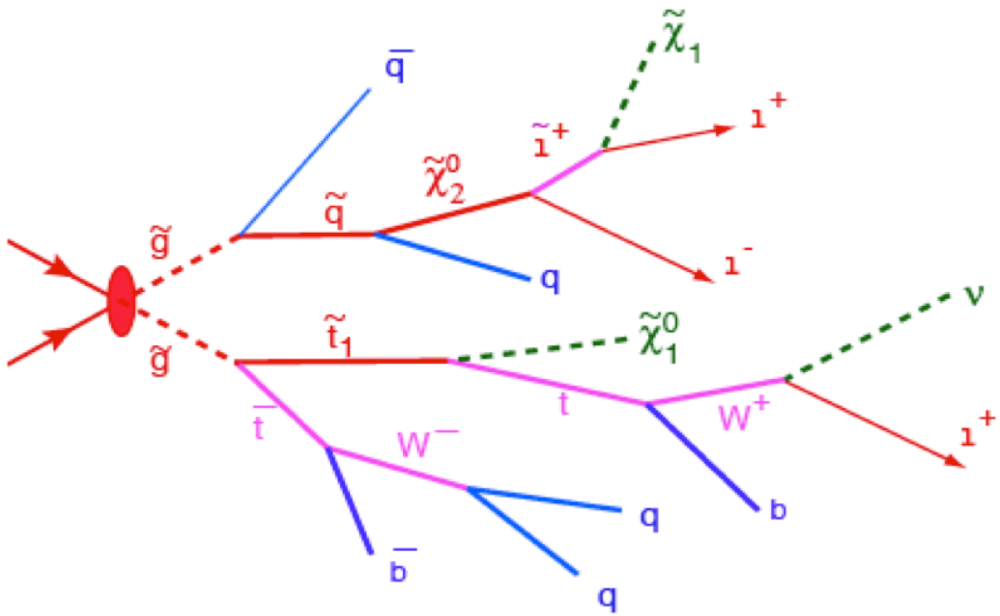


Example of the implications



Topologies

- **A fundamental problem**: most of the models depend on many (!) parameters, which influence production and decay modes. Many topologies to look for!
- To make life a bit easier, people chose some benchmark points/models, and studied those in more detail
- However, some "generic features" very often apply
- Take example of a "typical" SUSY mode (gluino/squark production and decay):
  - Production via strong interactions ie. large cross section
  - decay details depend on model parameters
  - However, once the heavy state is produced, it will decay to jets, leptons/photons and MET
  - Most of the jets and leptons have "relatively large p_T", leptons are isolated, considerable MET and large H_T = sum over p_Ts



Example of the CMS strategy

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

Large SM backgrounds **Low**

sensitivity to strongly produced SUSY

sensitivity to gauge-mediated SUSY

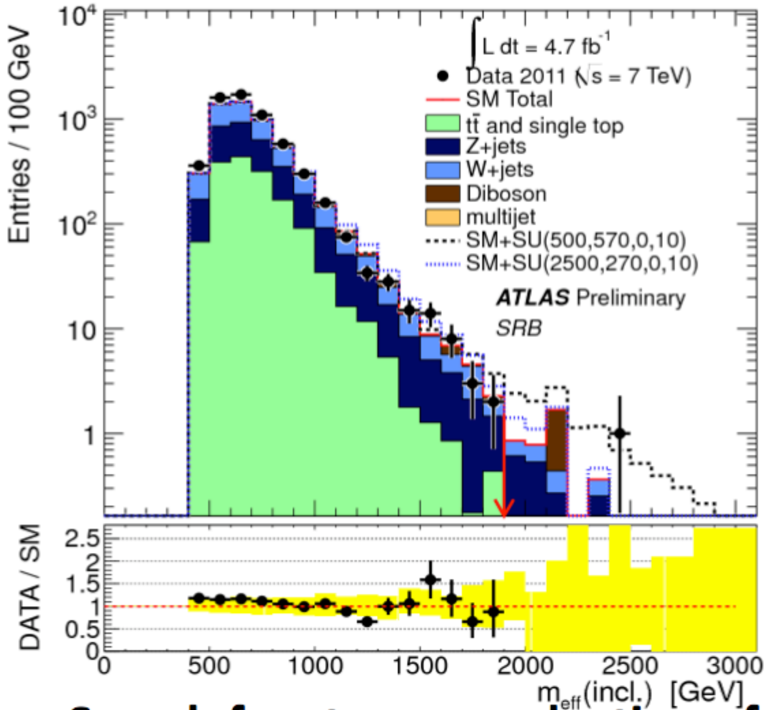
- **Focus on signatures (topologies)**, use different approaches/observables
  - alpha_T, "Razor", MT2, HT, MHT, ...
  - more recently: add b-tags to enhance sensitivity to 3rd gen. squarks, and design dedicated, "high-precision" 3rd gen. searches
- Established many different **data-driven techniques** to derive backgrounds
  - jet smearing and re-balancing, ABCD, fakeable-object technique to estimate fake lepton rates, generic properties of lepton p_T spectra, generic properties of falling SM spectra
- Different trigger paths (all hadronic HT-based, leptonic)
- Not necessarily optimized for best excl. limits, but sharpened tools for discovery!
- **cross check, cross check, cross check....**

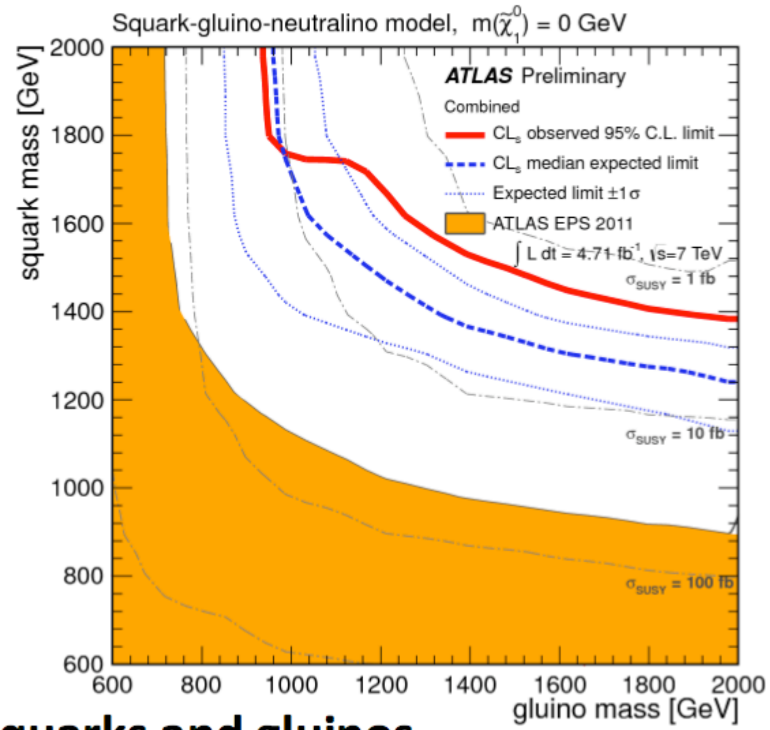
ATLAS 0 lepton search

2-6 jets + E_T^{miss}

M_{eff} defines signal regions

Look for squarks and gluinos with direct decays to SM+LSP





Search for strong production of squarks and gluinos.

Very strong limits from counting experiment.

Dominant background from Z–> νν.

Limits do not apply to stop/sbottom production.

ATLAS-CONF-2012-033

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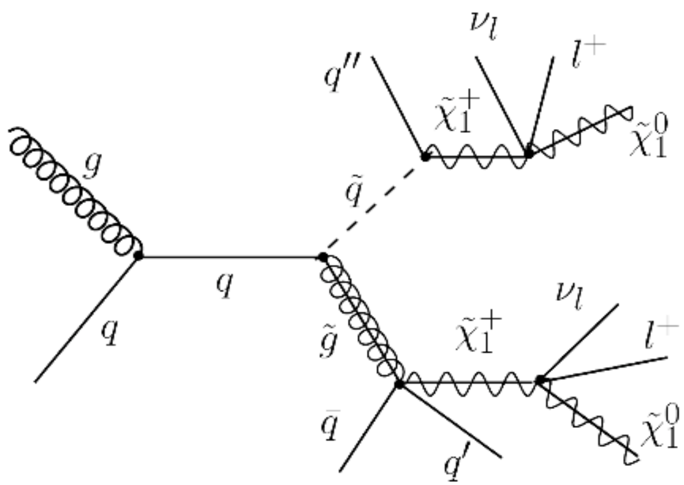
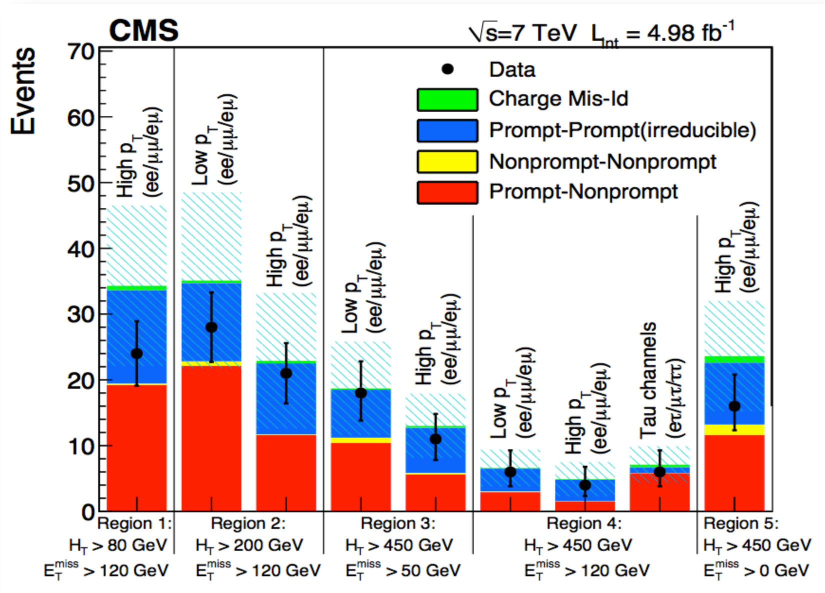
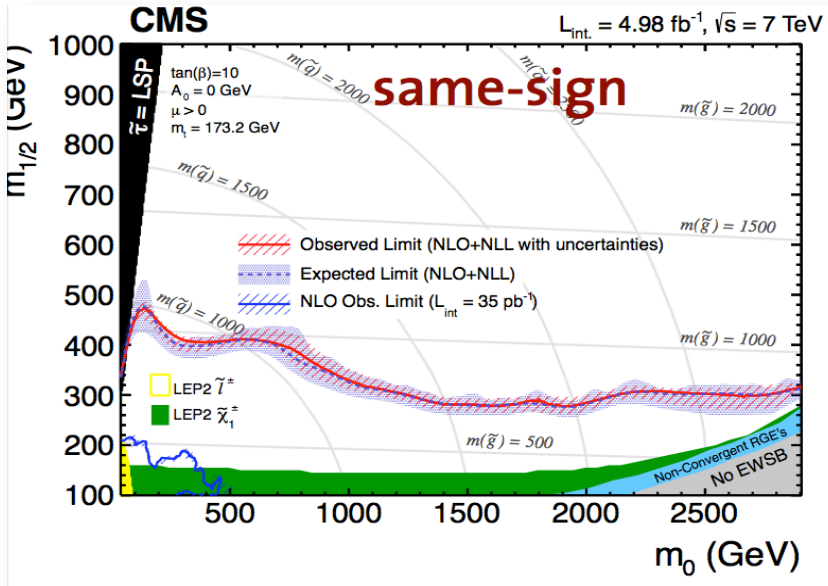
Example: same-sign dileptons +MET

- Very low SM backgrounds
- Name of the game: fake-rate estimates
  - estimated from data
- Baseline selection
  - Define different search regions, based on lepton p_T, H_T, MET





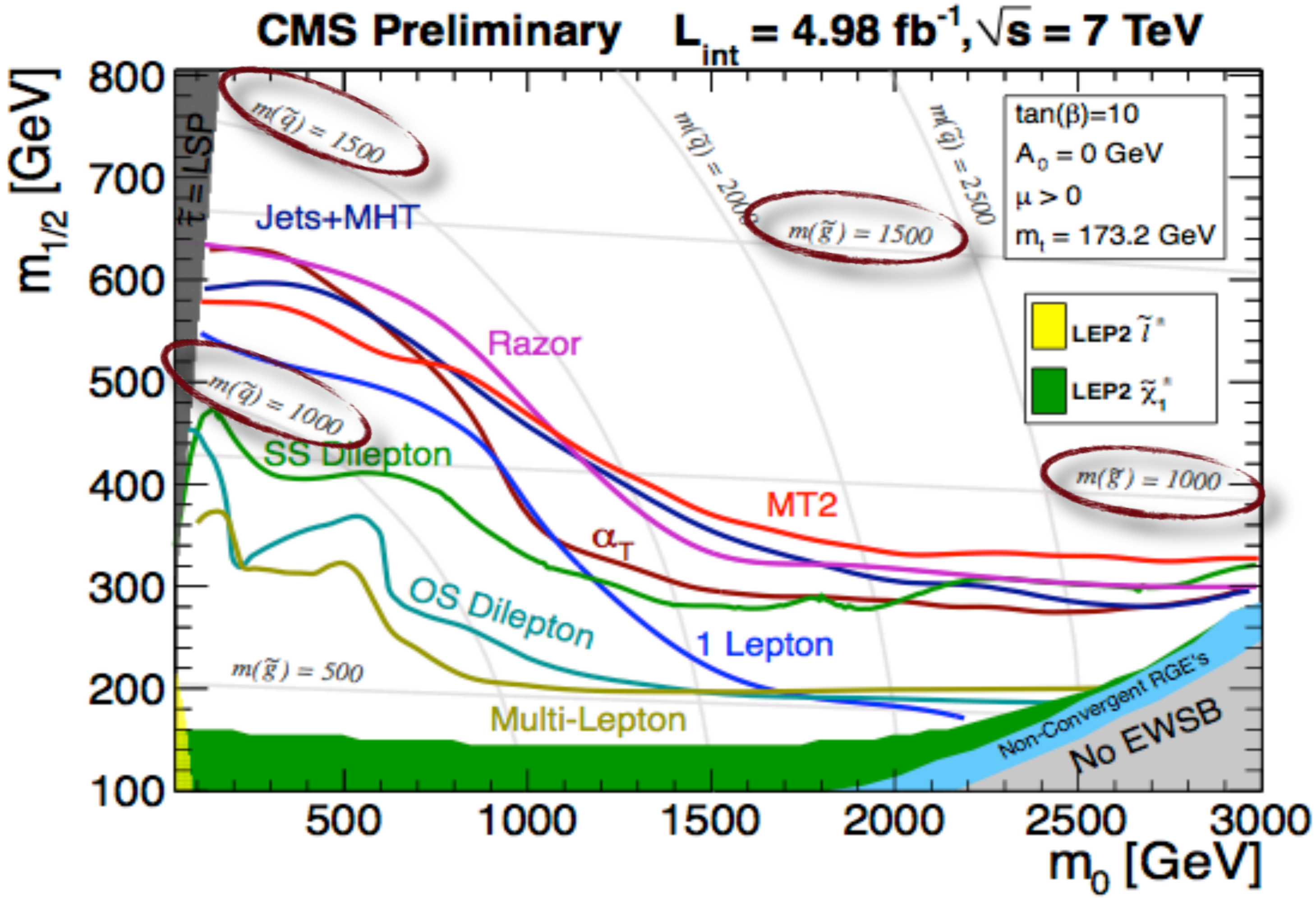


arXiv:1205.6615

cMSSM getting squeezed

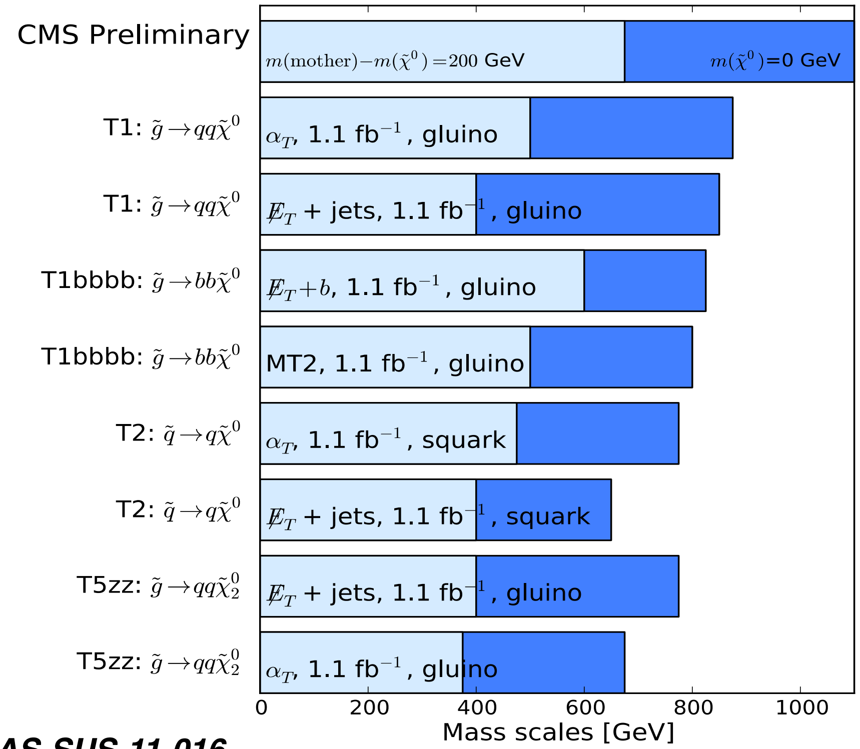
Multiple complementary searches.

Reached cMSSM exclusion of ~1.2 TeV for mass-degenerate gluino and squarks.

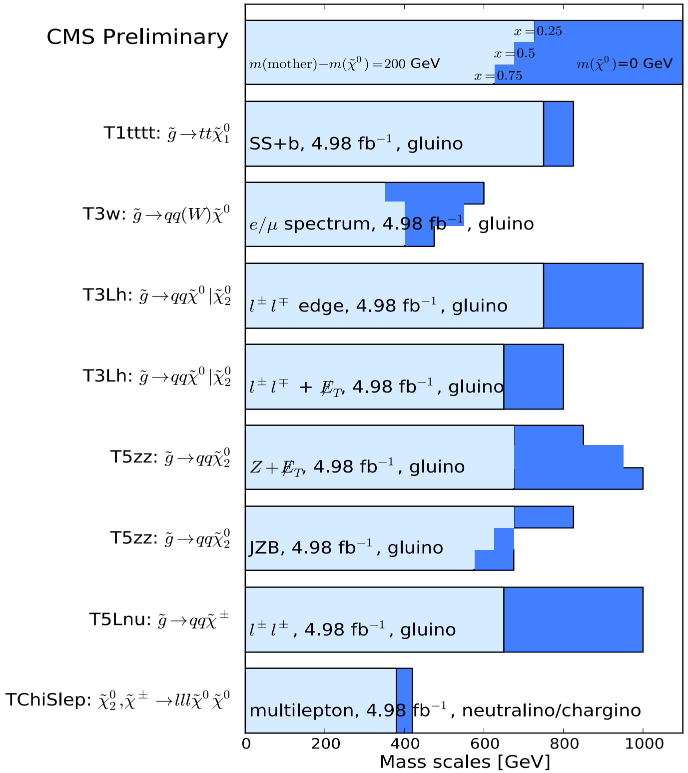


SUSY in simplified models

Hadronic (left) and leptonic (right) SUSY searches in simplified SUSY models. Exclusion limits for gluino and squark masses, for $m_{\chi 0}$ = 0 GeV (dark blue) and $m_{mother} - m_{\chi 0}$= 200 GeV (light blue).

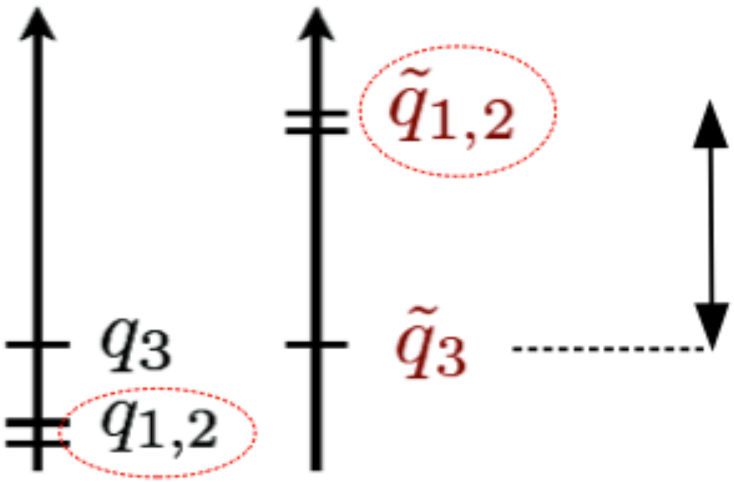


CMS-PAS-SUS-11-016

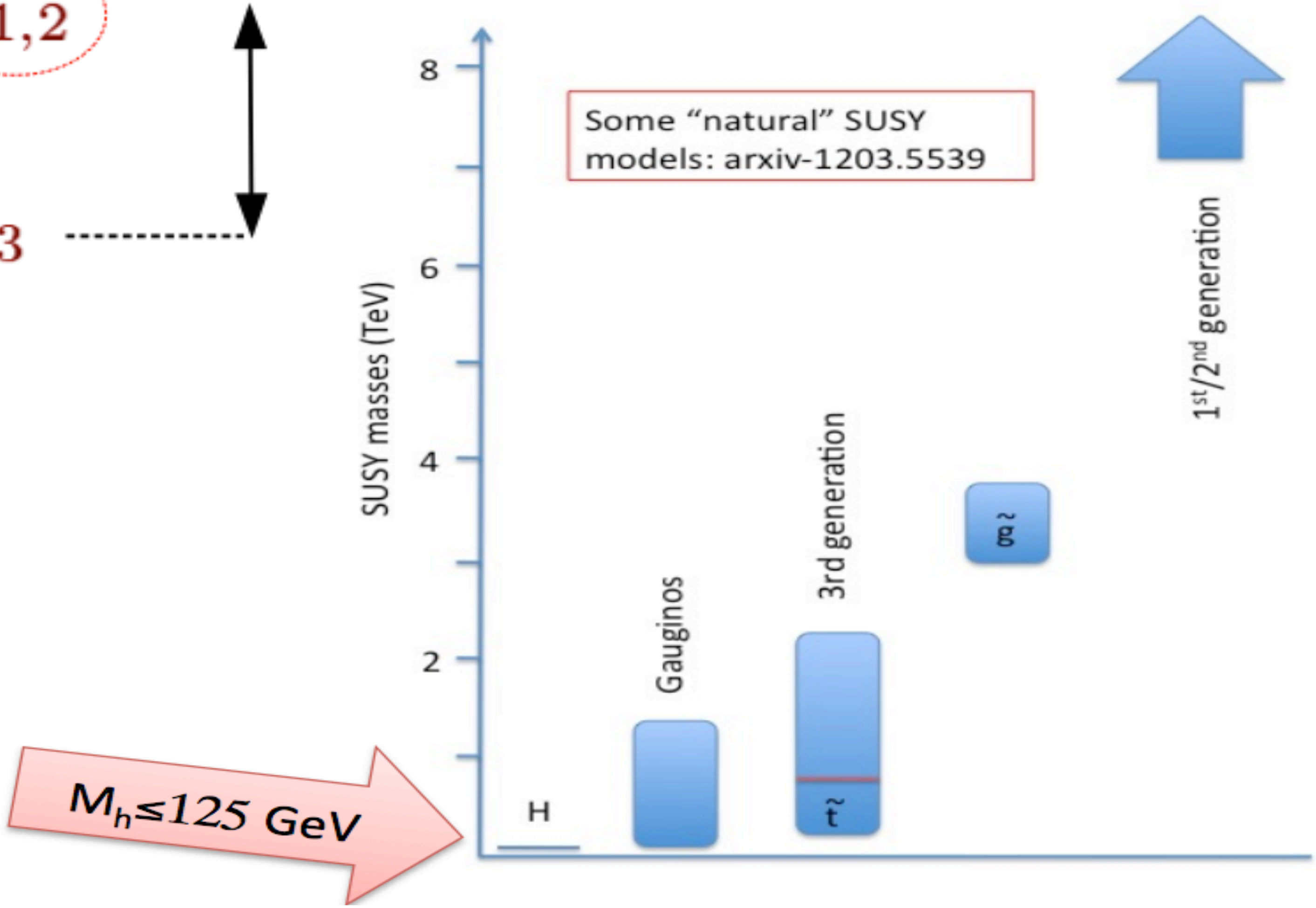


SUSY is not dead (yet). It might still hide in low MET/low HT events. More complicated models are under investigation→ more challenging searches. For some it is hard to even get the data on tape.

Still room for "natural" SUSY



Spectrum is model dependent



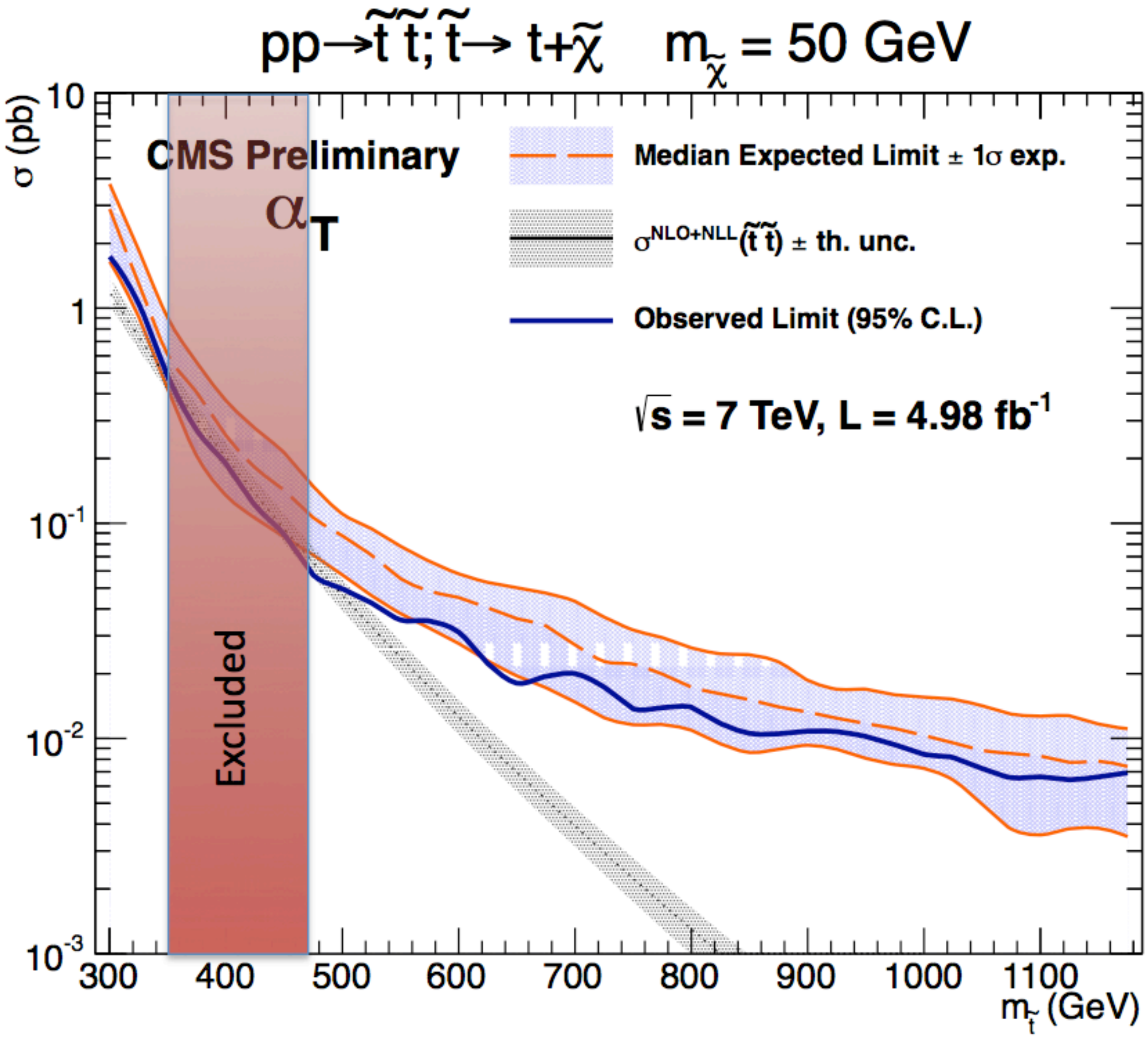
Search for SUSY: the new challenge

- Extend experimental topologies.

- Production: complement gluino/squark “strong” production searches with direct gauginos and stop/sbottom production (expected to be lighter : “naturalness”)
- Decay: complement standard “high-ΔM” topologies (large MET or MHT) with more challenging topologies with small mass differences between produced particles and decay products down to almost degenerate case: soft leptons, long-lived particles, disappearing tracks, ..

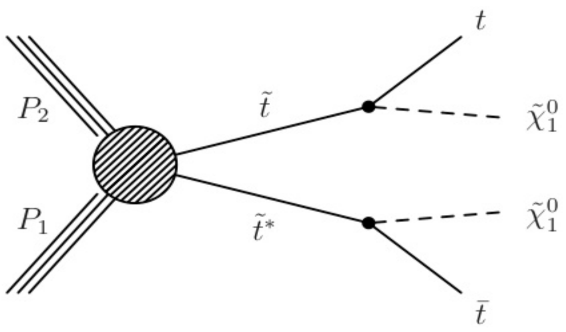
- Two major strategies:
  - Cascade decays with boosted stop and bottom emission (new techniques)
  - Direct production of stop and sbottom: top pair like events with marginal MET (accessible via direct top reconstruction o with high precision measurements of the top-pair cross section if degenerate)

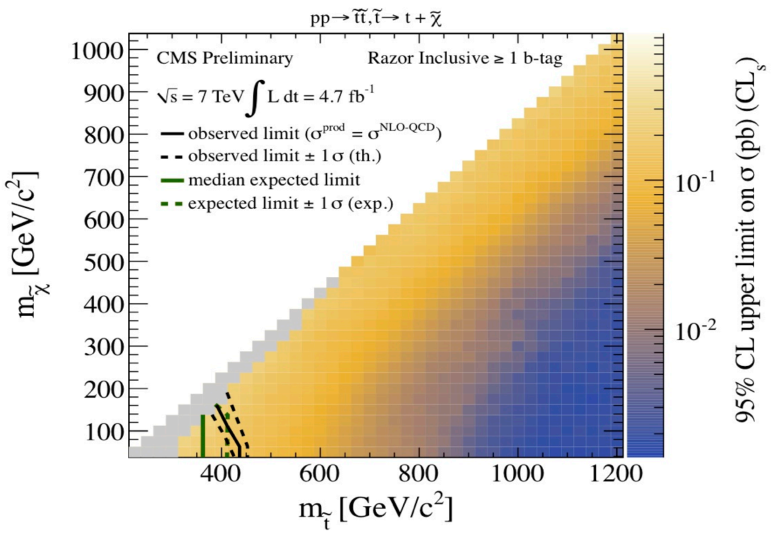
CMS limits on stop production cros section



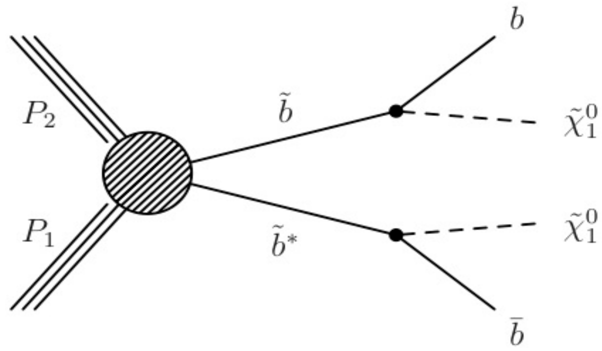
CMS stop and sbottom searches

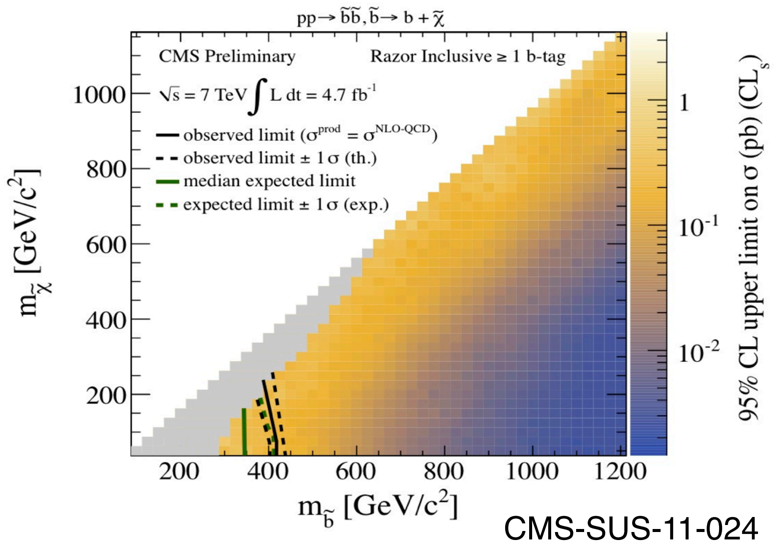
Di-stop production resulting in 2 top quarks +MET final states





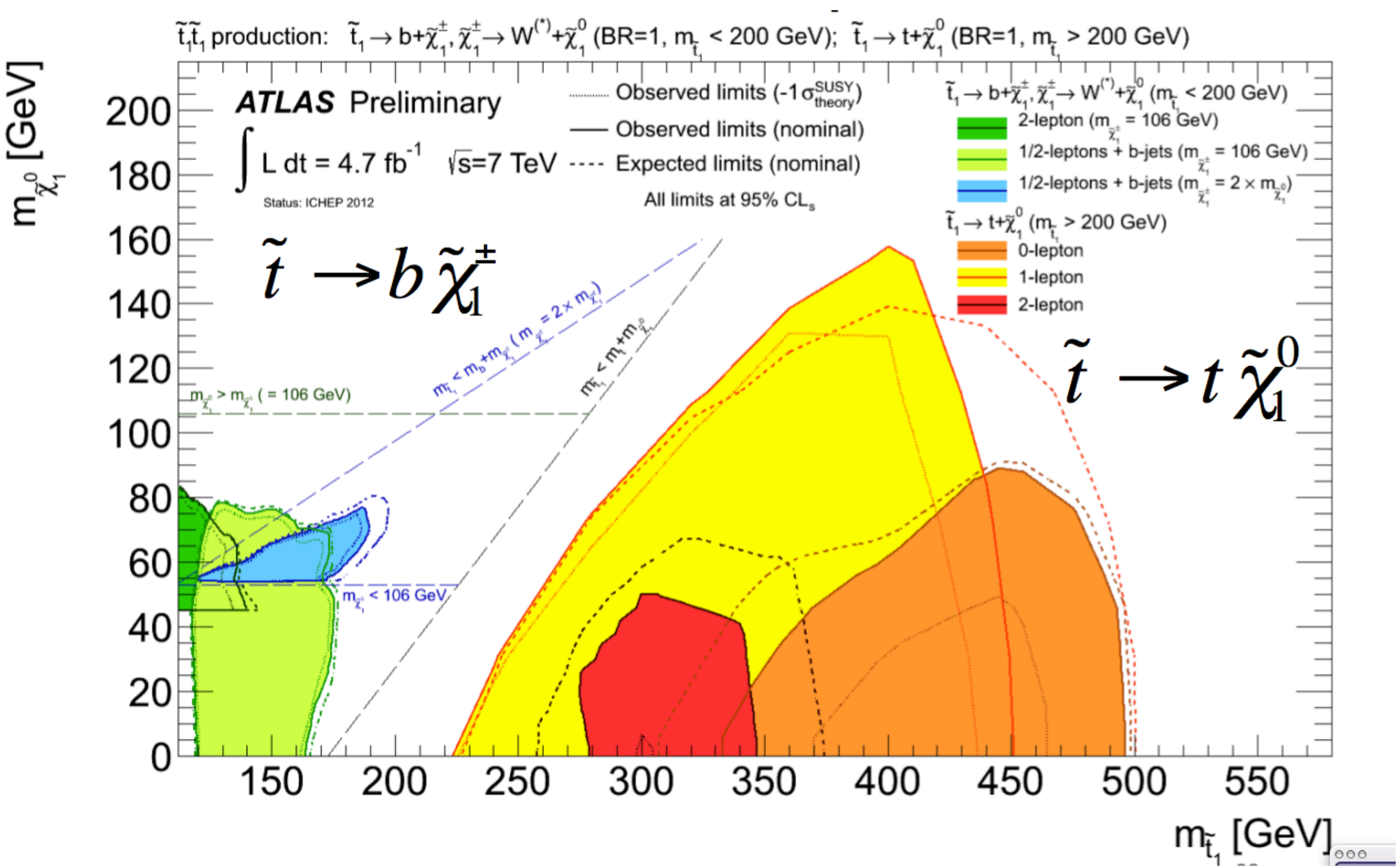
Di-sbottom production resulting in 2 b quarks +MET final states



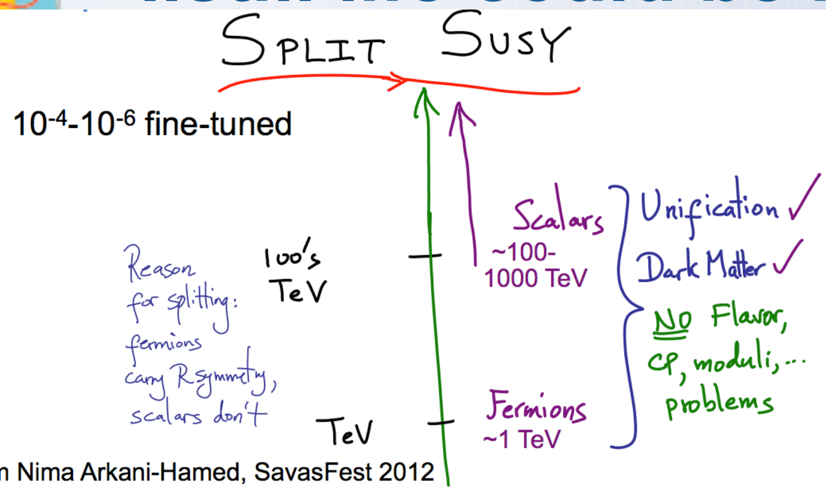


CMS-SUS-11-024

ATLAS stop searches



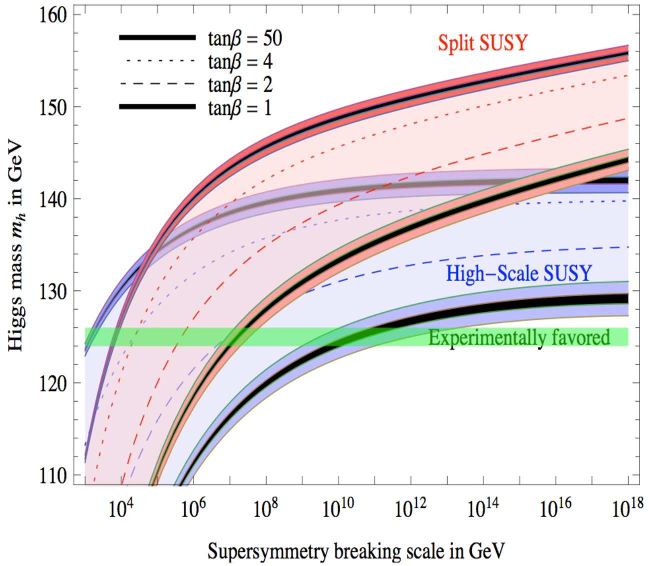
..still life could be much harder: Split SUSY



From Nima Arkani-Hamed, SavasFest 2012

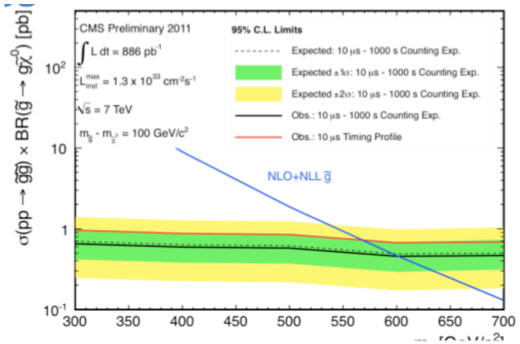
Only gauginos accessible at LHC
Long-lived gluinos
W/Zinos
Non-prompt top decays.
Variety of searches on long-living objects going on from prompt to stopped particles.

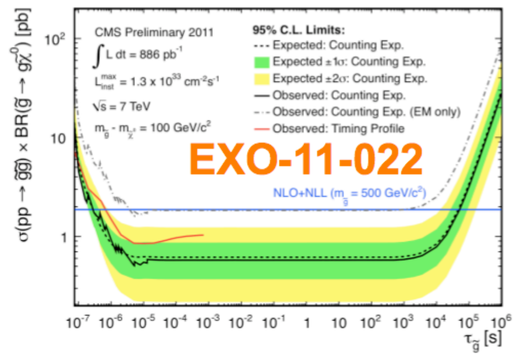
Wells, hep-ph/0306127
Arkani-Hamed, Dimopoulos JHEP **06** (2005) 073
Guidice, Romanino, Nucl.Phys. **B699** (2004) 65



arXiv:1108.6077v2

We have excluded already lifetimes spanning 13 orders of magnitude….but if SUSY breaks at 10^8 GeV we might expect lifetimes in the range 1-100ns. The 25-75ns range has not been exlored so far: too long for "prompt" and too short for "stopped" due to the CMS trigger rule that, after a L1 accept, kills the following two bunch crossings.





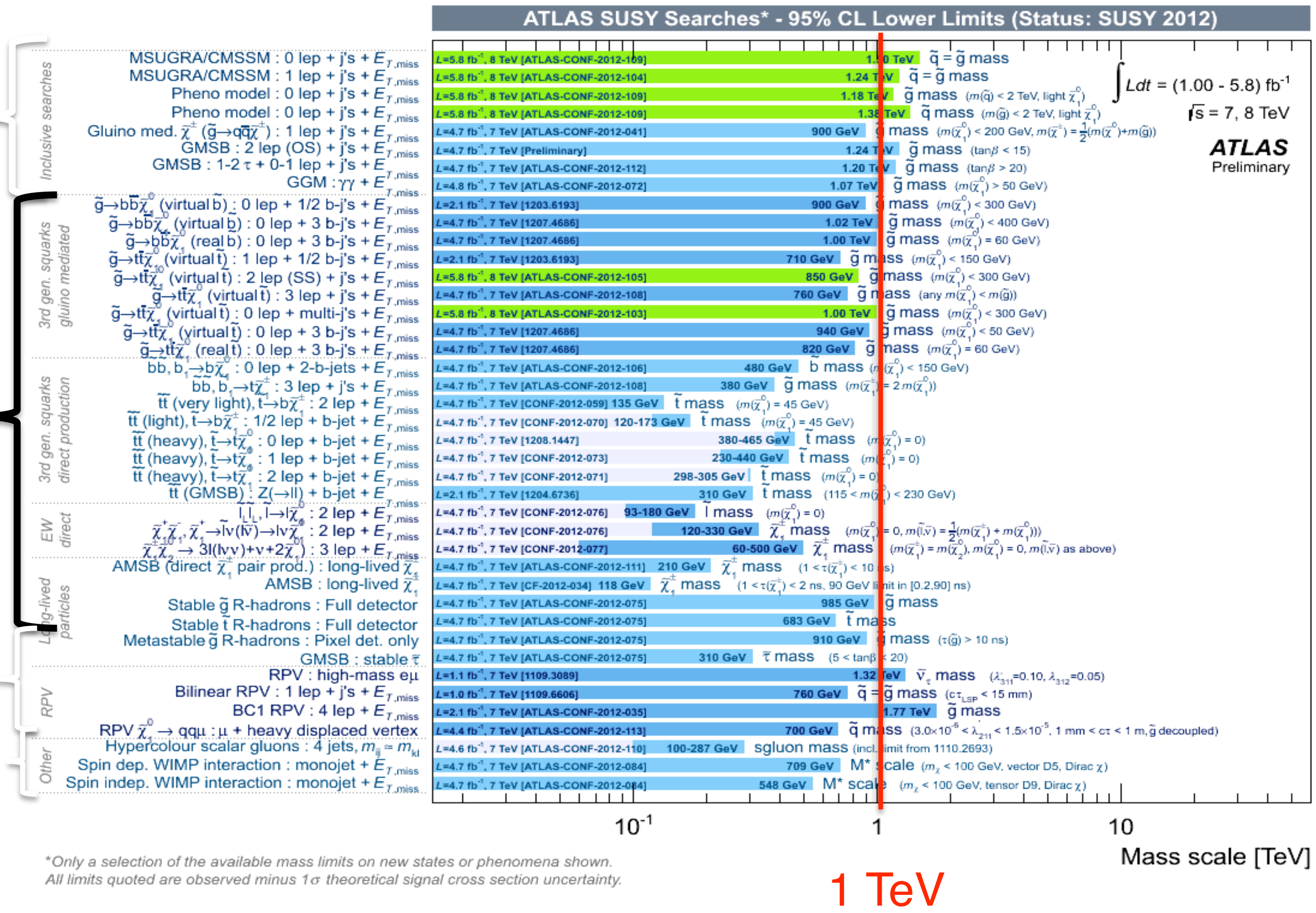
Status of the ATLAS SUSY searches

1. Inclusive searches

2. Natural SUSY

3. Long lived particles

4. RPV



Grand Summary of Searches

- In (too?) simple terms:

SUSY (cMSSM)	1 - 1.2 TeV
Gauge Bosons (SSM)	2 - 3 TeV
Excited quarks	3 TeV