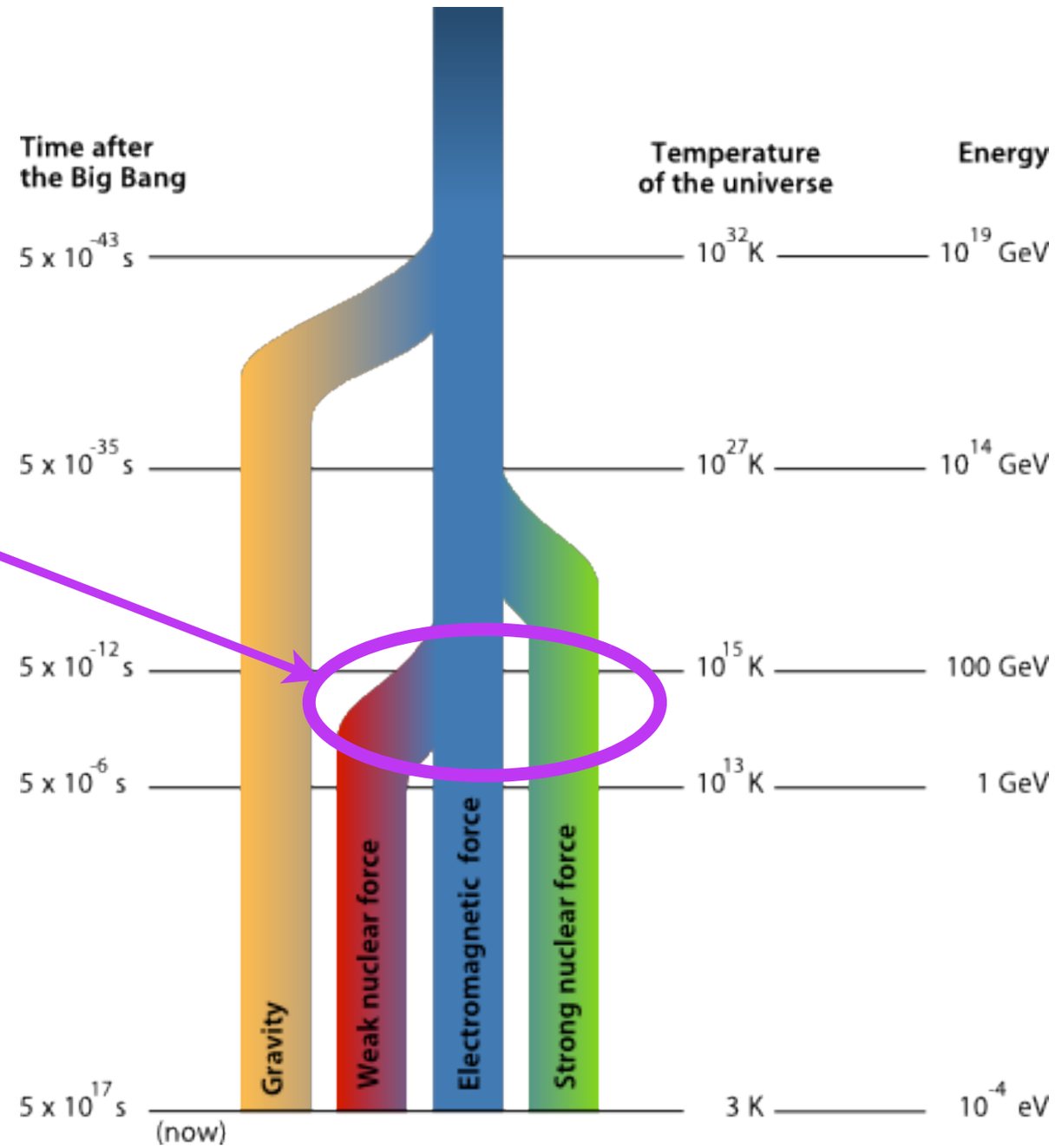
Recent Beyond the SM Results from ATLAS and CMS

Yuri Gershtein

LHC is exploring Electroweak Scale

We are here



Yuri Gershtein

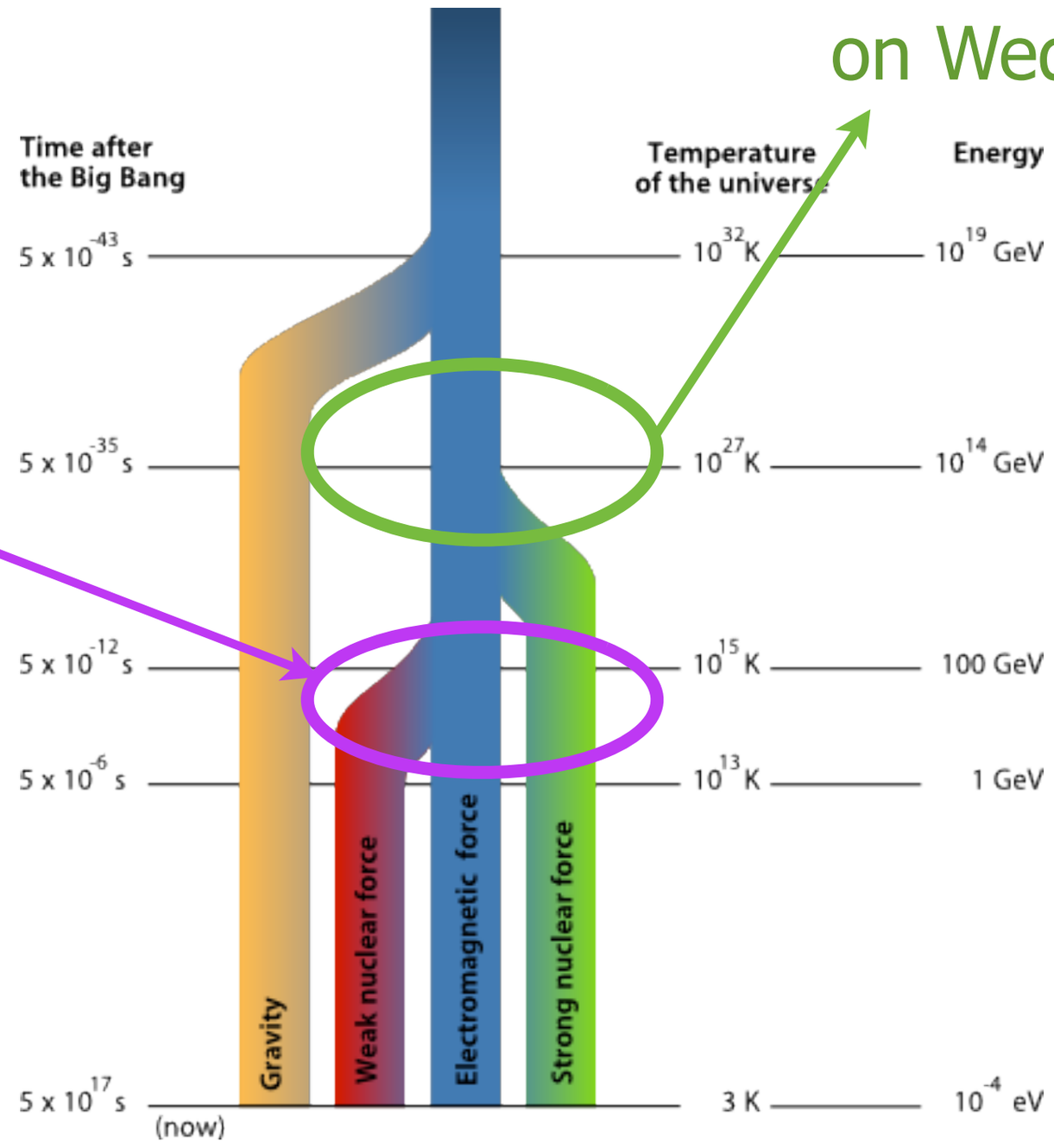
What's so Exciting

- Exploring Electroweak Symmetry Breaking Scale
  - had to find something - and already have
    - something that looks a lot like a **fundamental scalar** - *more in Halladjian and Bortoletto talks*
  - is the small Higgs mass anthropic or a consequence of some new symmetry? The answer is likely to lie at O(EWSB scale)
  - every time we produce a Higgs (or a W, or a Z at large $\sqrt{s}$) at the LHC we learn more about EWSB
- Are there more fundamental scalars?
  - *SUSY never looked more attractive*
- Can we produce Dark Matter at the LHC?
  - *especially given hints of indirect detection of DM with preferential coupling to the third generation*
- LHC probes Unknown territory - have to watch out for new things: **Occama razor has a terrible record in our field**

LHC is exploring Electroweak Scale

More on 10^{16} scale on Wednesday

We are here

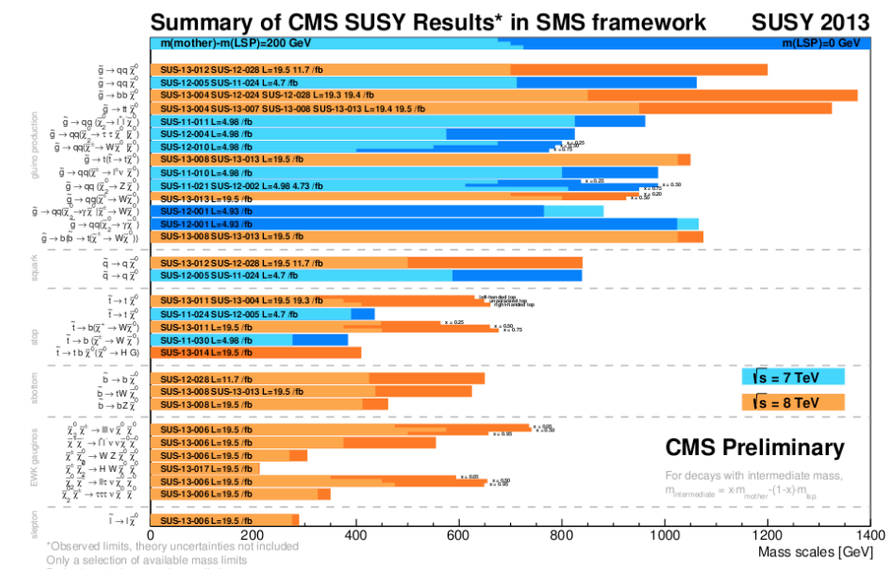


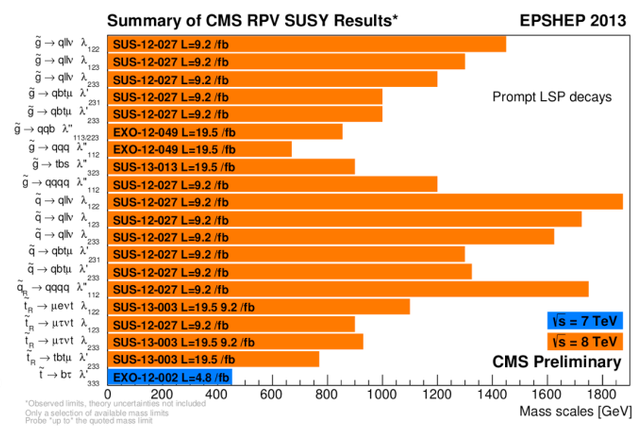
Yuri Gershtein

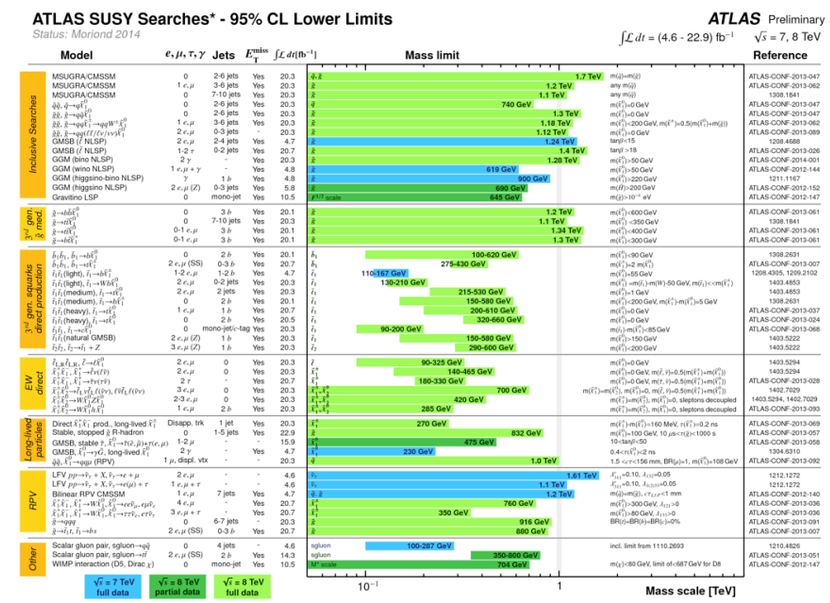
In Torrential Detail

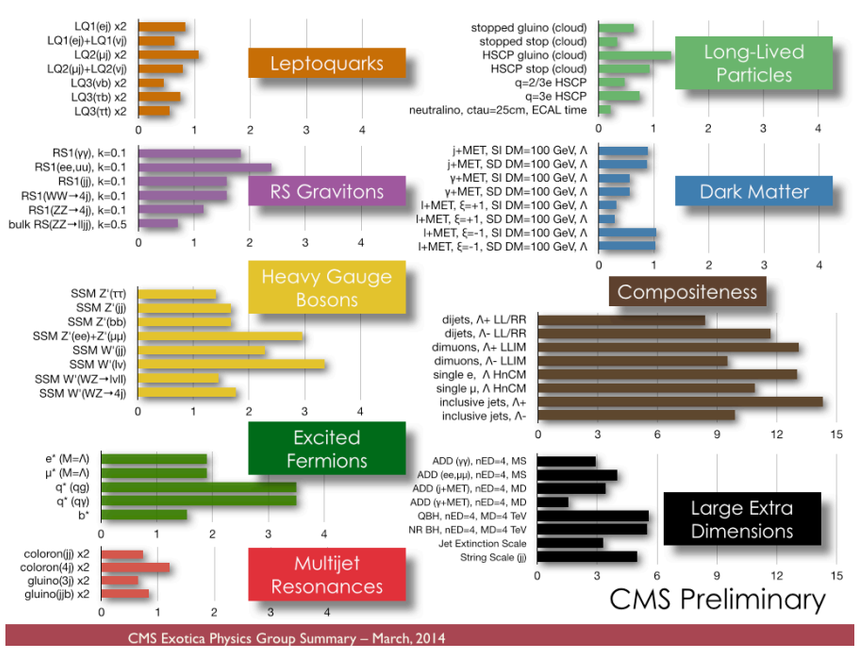
For the full picture see

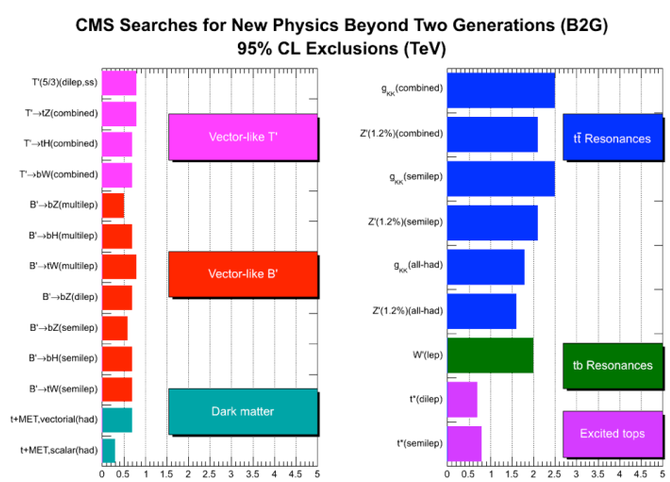
- SUSY and Exotics at https://twiki.cern.ch/twiki/bin/view/AtlasPublic/
- SUS, EXO and B2G at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

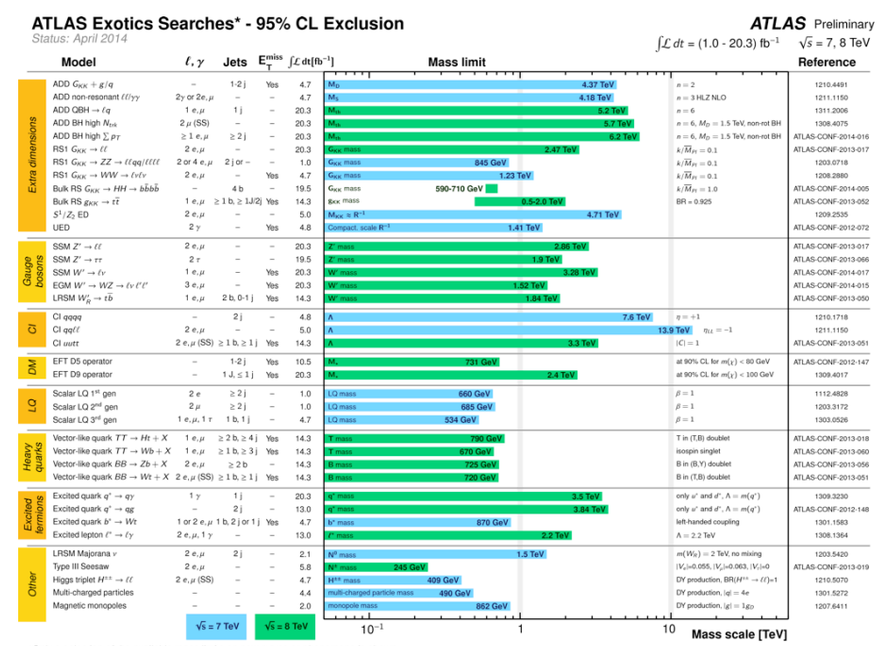












Yuri Gershtein

In this talk

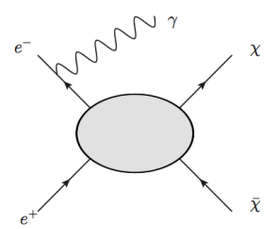
My personal pick of “most interesting” and links to a more complete set of results

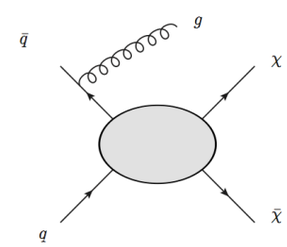
- Dark Matter searches
- Exotica
  - extra dimensions, extra gauge bosons, vector quarks
- Supersymmetry
  - “Classic”, “Natural”, RPV violating
- Higgs as a new physics tag
  - Higgsino searches
- Summary / Outlook

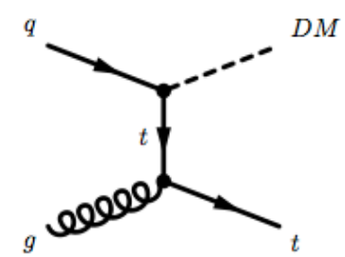
Most searches are carried out at both ATLAS and CMS and have ~same sensitivity

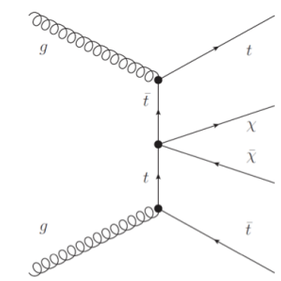
Dark Matter Searches

- If DM interacts more then gravitationally, it could be made in perceptible numbers at the LHC
- To be observable at the LHC, it has to be associated production with SM particles (that would also tell us about the DM couplings)
  - mono-jet / mono-photor
  - mono W/Z
  - mono top / top pairs
  - ...

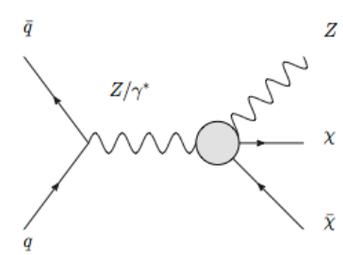


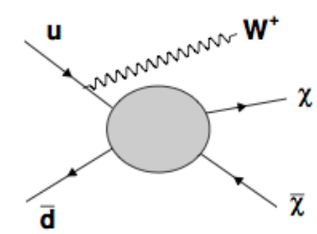






- Interpretation
  - model independent cross section times acceptance measurement / limits
  - Effective Field Theory approach for heavy DM force mediator
  - Specific model (i.e. Higgs portal, etc)





for comprehensive details see

ATLAS-EXOT-2012-26
ATLAS-EXOT-2012-27
ATLAS-CONF-2013-073
ATLAS-EXOT-2011-20
ATLAS-EXOT-2012-05
ATLAS-CONF-2012-085
ATLAS-CONF-2012-084

CMS-EXO-13-004
CMS-B2G-13-004
CMS-B2G-12-022
CMS-EXO-11-059
CMS-EXO-11-096

EFT Operators

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu arXiv:1008.1783

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

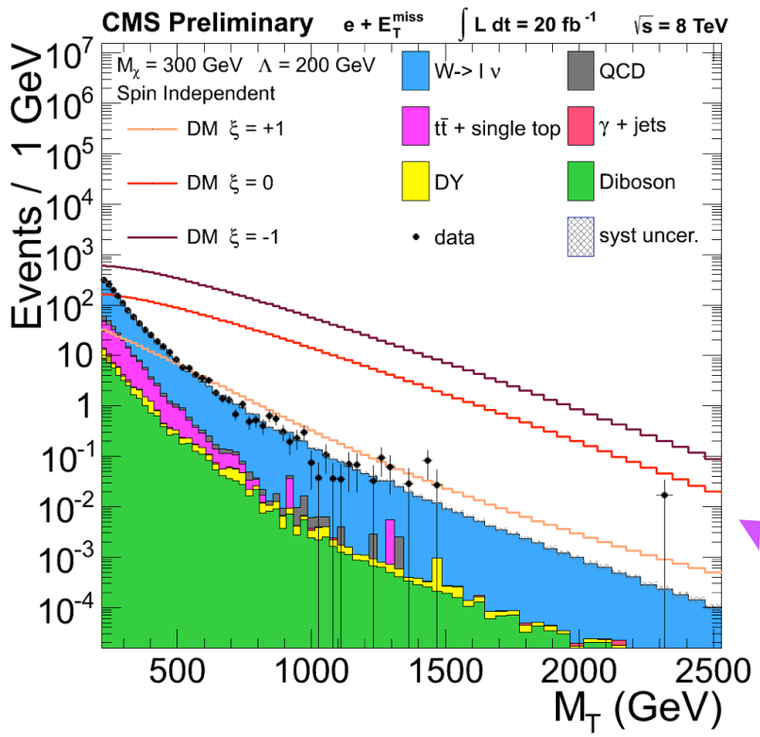
Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

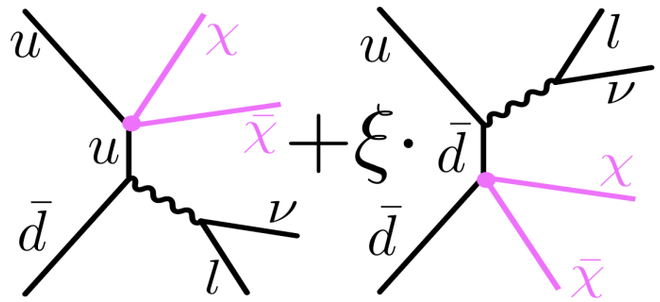
TABLE I: Operators coupling WIMPs to SM particles. The operator names beginning with D, C, R apply to WIMPS that are Dirac fermions, complex scalars or real scalars respectively.

Mono W/Z

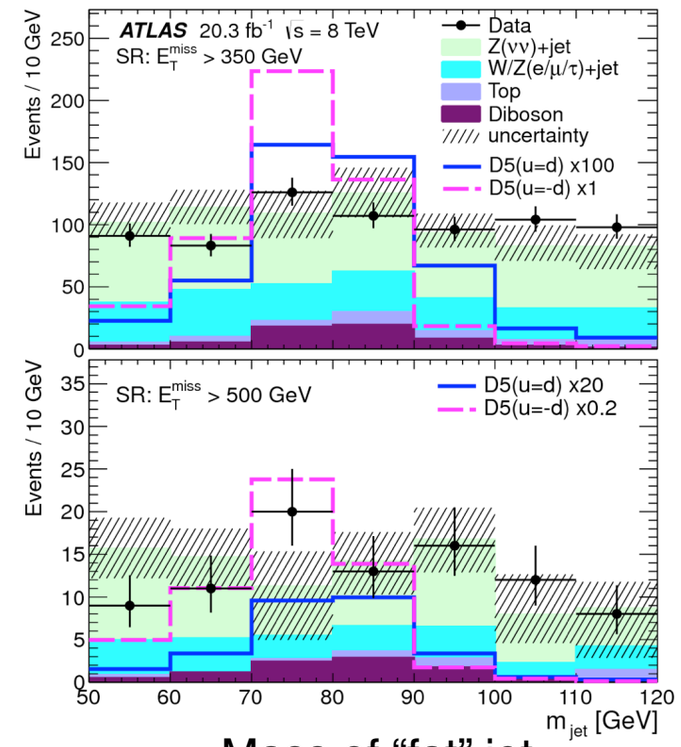
CMS-EXO-13-004
leptonic W decay

ATLAS-EXOT-2012-27
hadronic W/Z decay



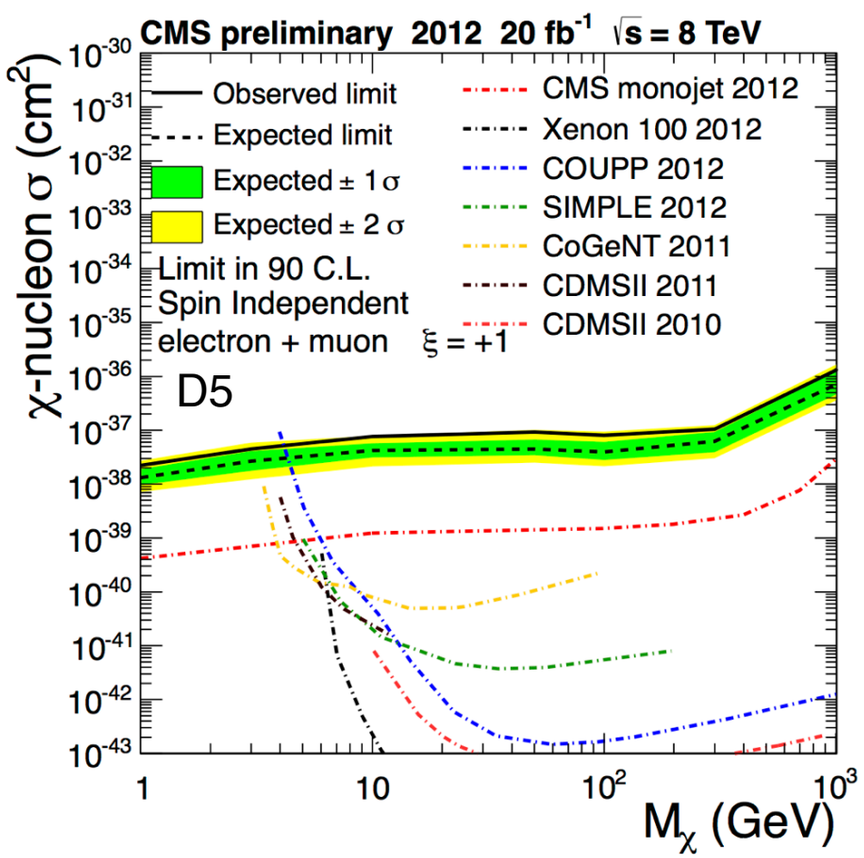


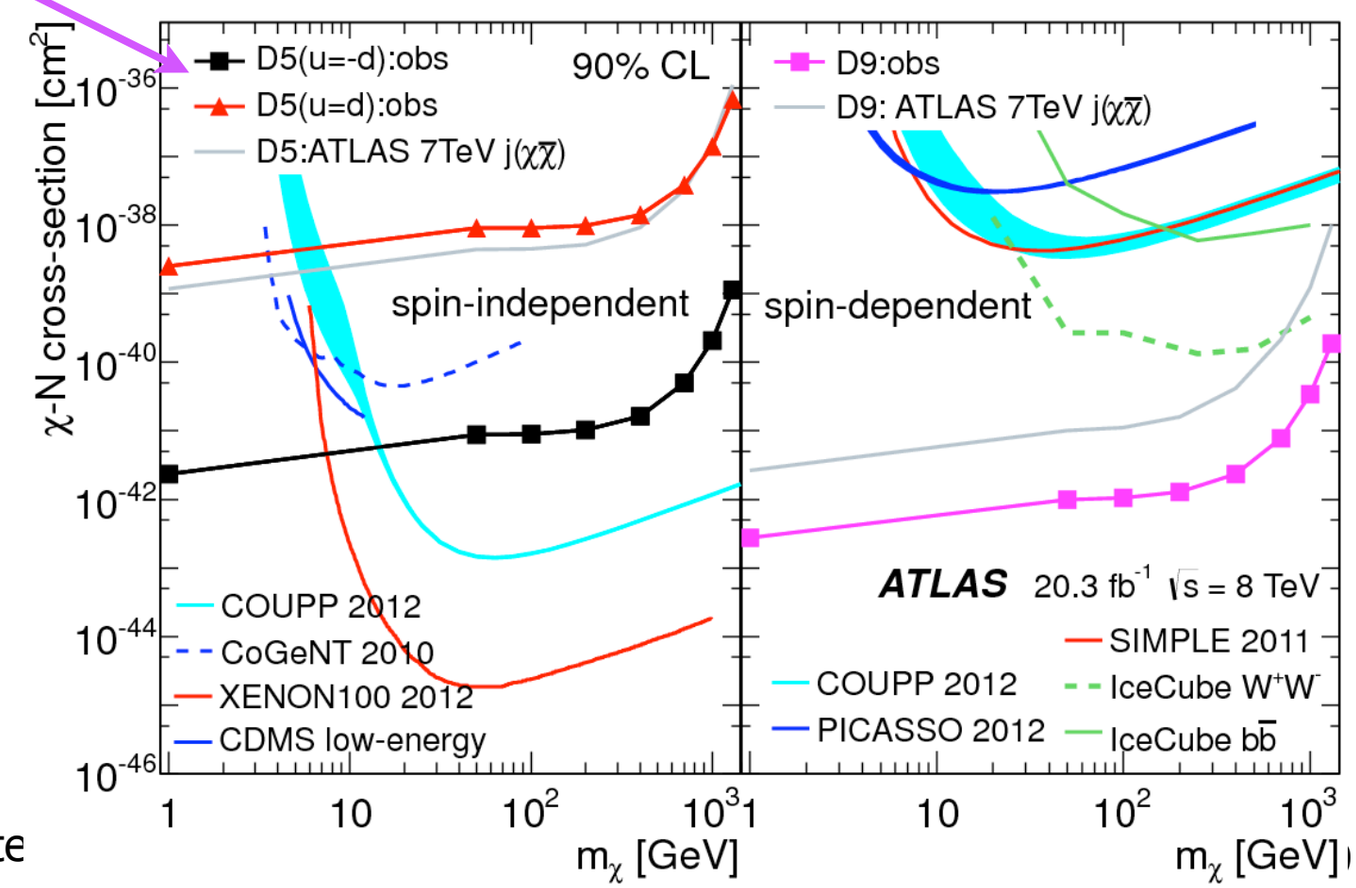
D5 (SI): $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi \quad \xi_i\bar{q}_i\gamma_\mu q_i$



Mass of "fat" jet

Interference effects



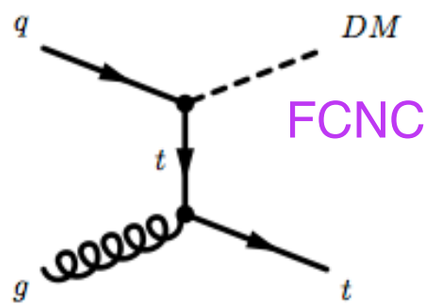


Yuri Gershte

Associated top

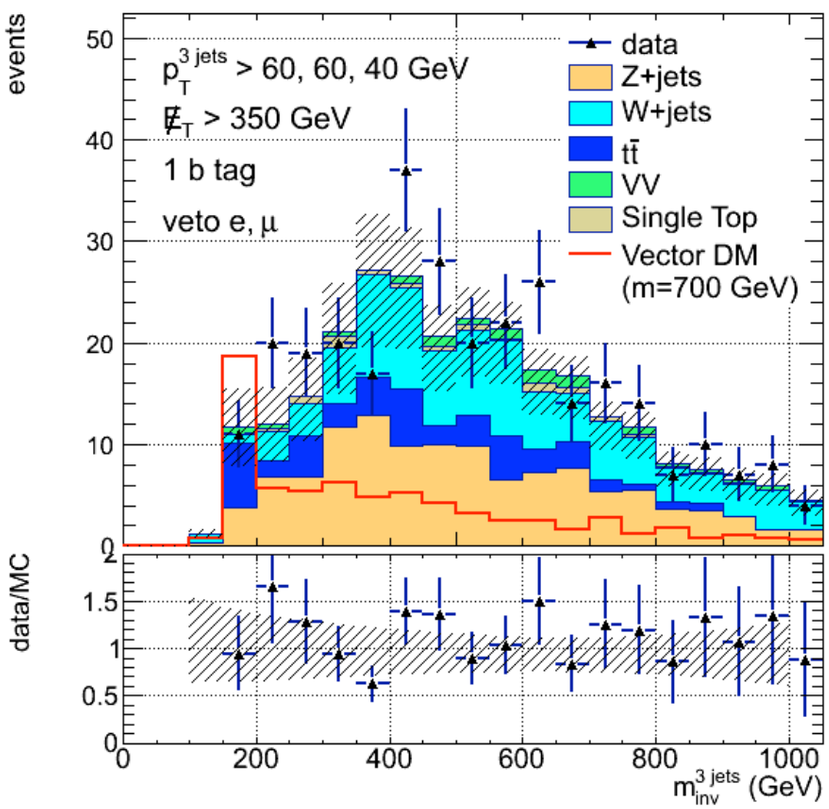
CMS-B2G-12-022

http://feynrules.irmp.ucl.ac.be/wiki/Monotops

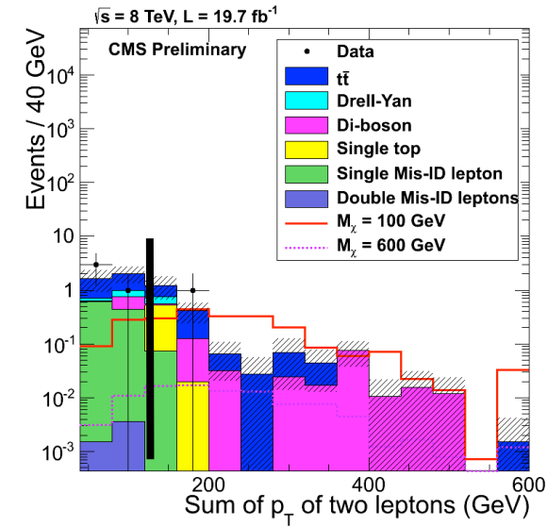


FCNC

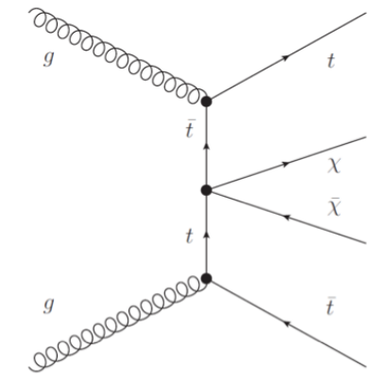
Lepton + 3 jets
Veto events with fourth jet above 25 GeV
Veto events with extra leptons



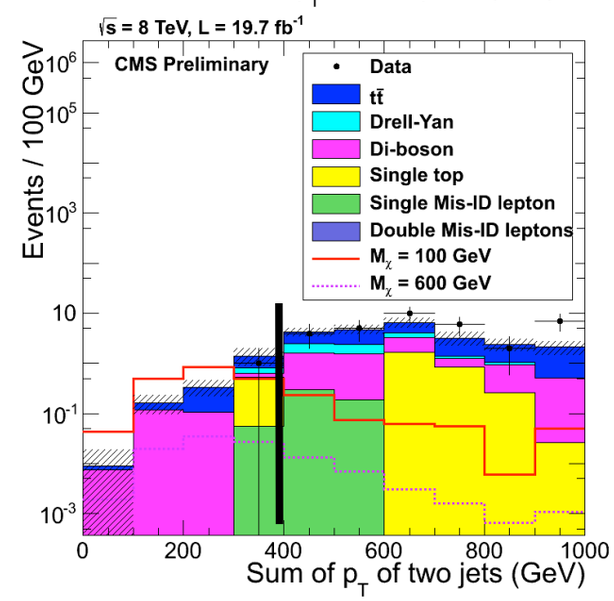
Exclude vector (scalar) DM masses below 655 (327) GeV

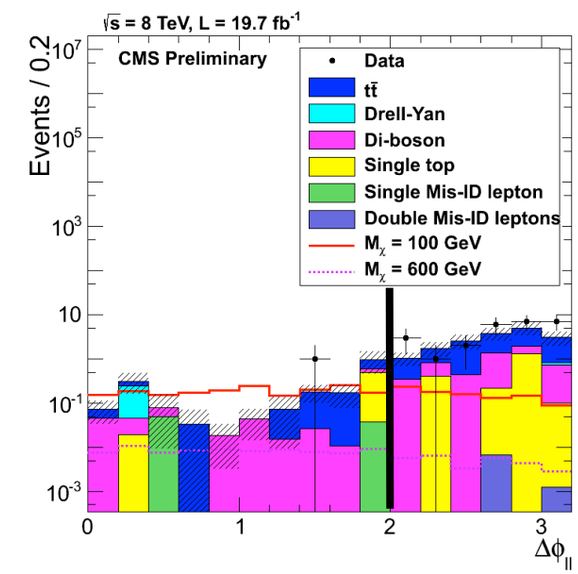


CMS-B2G-13-004



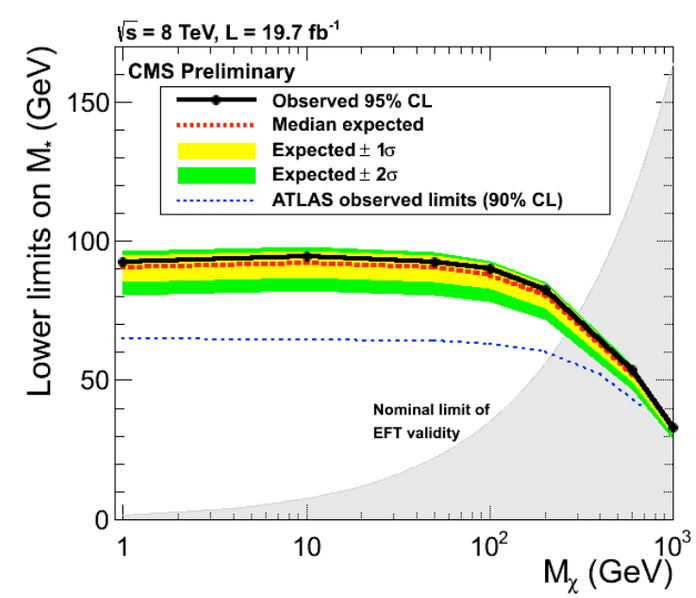
Dilepton channel
MET > 320 GeV





For scalar interaction (D1)

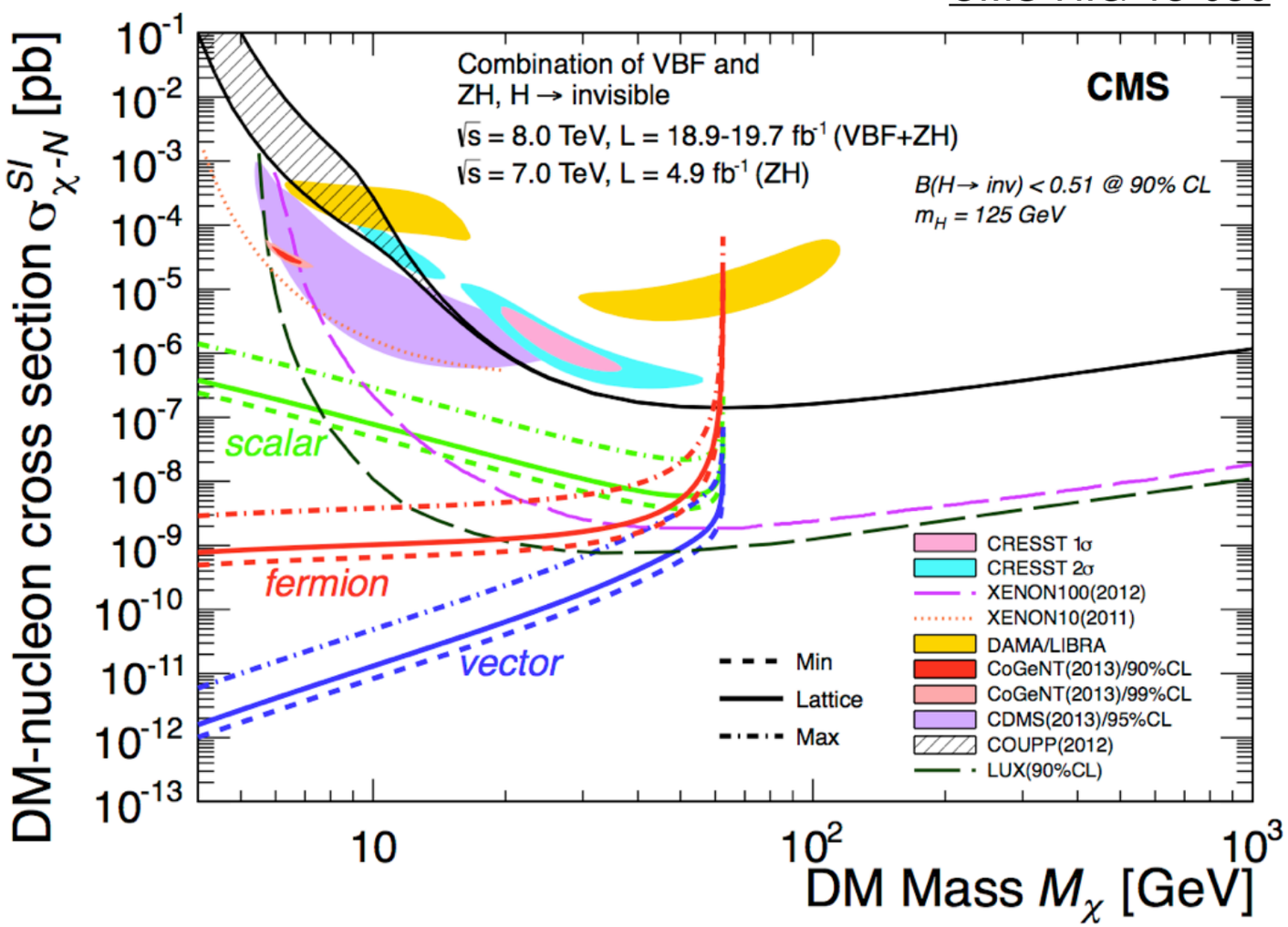
$$L_{int} = \frac{m_q}{M_*^3}\bar{q}q\bar{\chi}\chi$$



Higgs Portal

- If the DM couples to Higgs and is lighter them 125/2, then Higgs would have increased rate of invisible decays

CMS-HIG-13-030



See also ATLAS Z(ll)+H(inv)
ATLAS-HIGG-2013-03

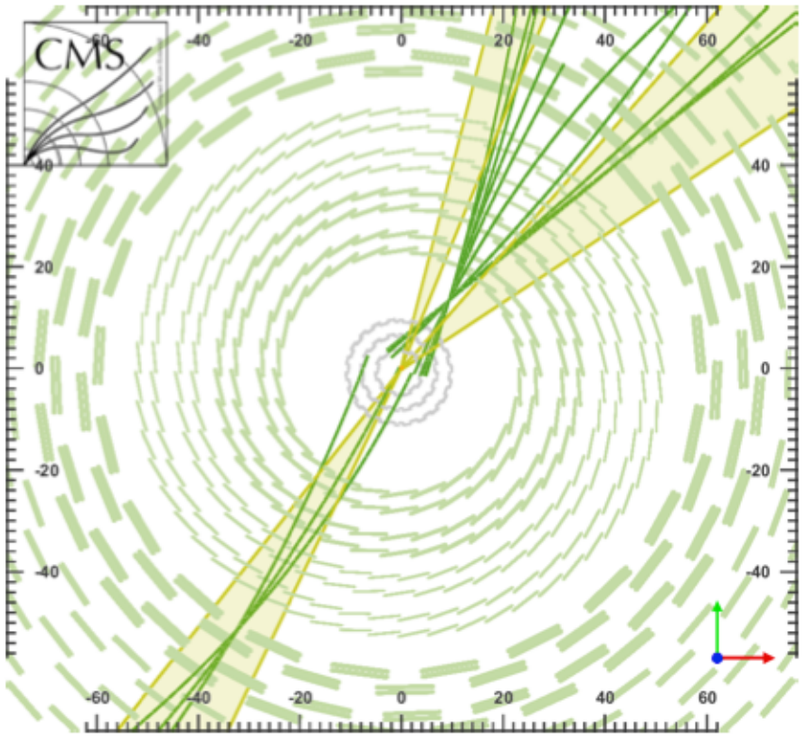
S. Kanemura, S. Matsumoto, T. Nabeshima, N. Okada, Phys. Rev. D82 (2010) 055026.

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2 \,,$$
$$\Delta\mathcal{L}_V = \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu,$$
$$\Delta\mathcal{L}_f = -\frac{1}{2}m_f \bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H \bar{\chi}\chi \,. \qquad (1)$$

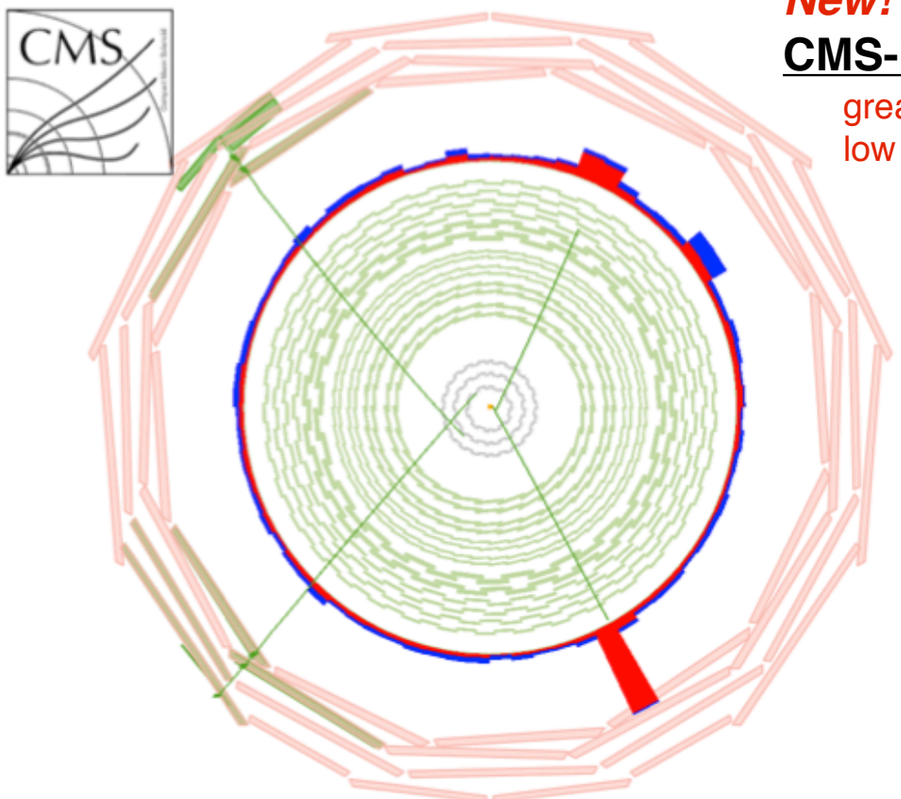
If the Dark Sector is complex, some of the dark cascade can “come back”: long-lived neutral particles

Long-lived particles

- Large number of well-motivated scenarios predict long-lived particles
  - hidden valley models
  - rare Higgs decays (the one at 125 GeV or a new one) - if there are HVs, Higgs may the particle that senses them most: $H \to XX, \quad X \to f\bar{f}$
  - GMSB SUSY $\tilde{\chi}_1^0 \to \tilde{G}Z(\to jj)$
  - RPV SUSY $\tilde{q} \to q\chi^0(\to \ell^+\ell^-\nu)$ (or H cascade) $\tilde{t} \to jb$



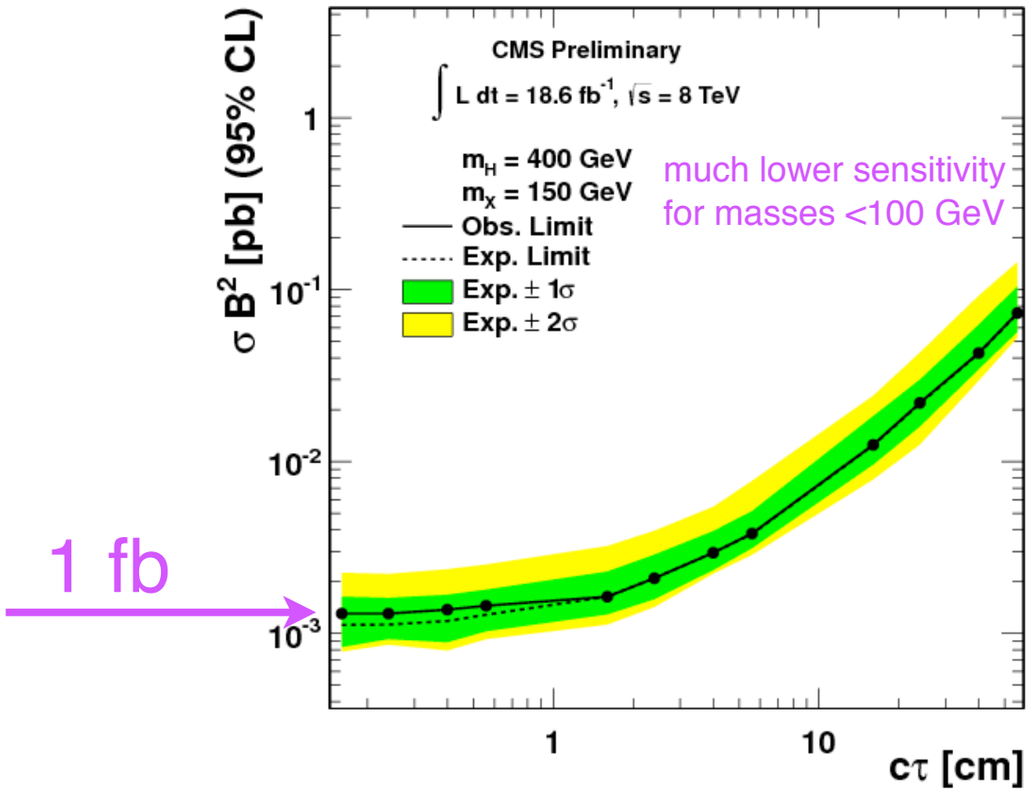
CMS-EXO-12-038



New!

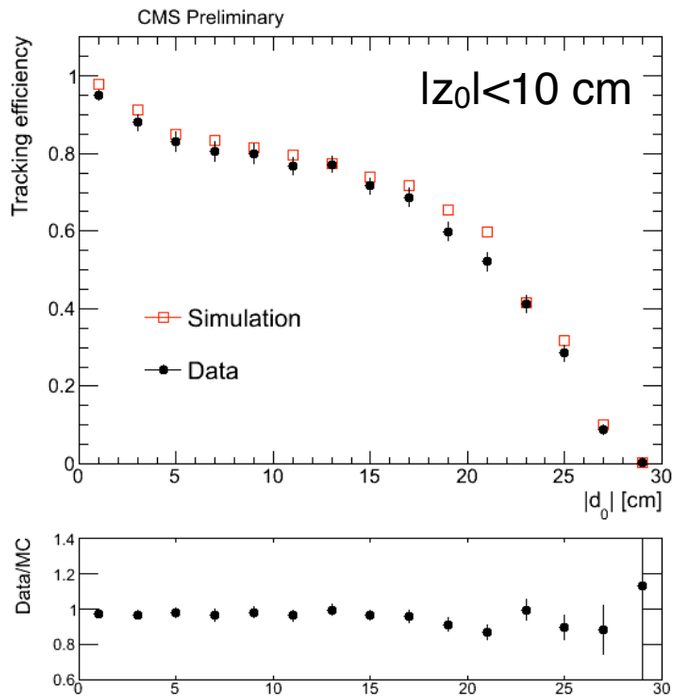
CMS-EXO-12-037

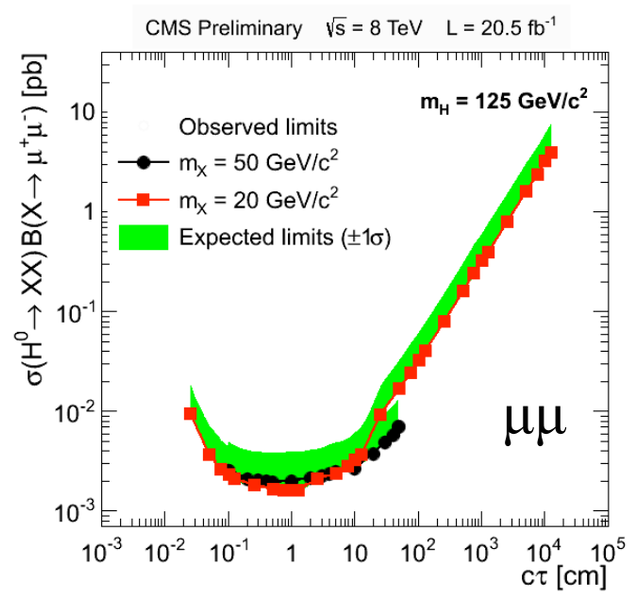
great reach at low masses!

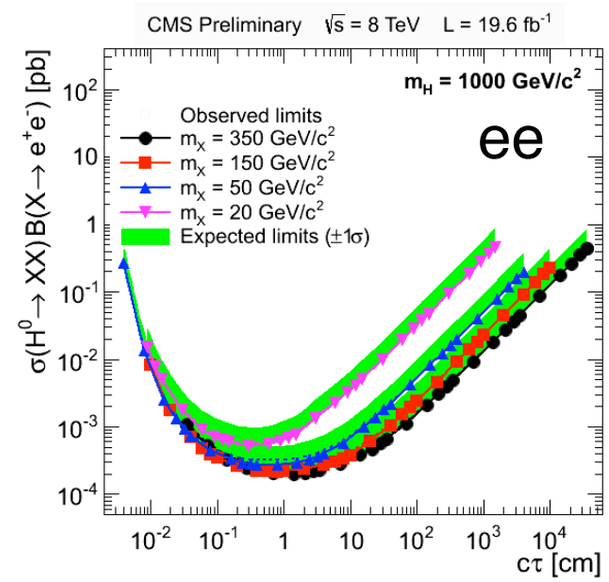


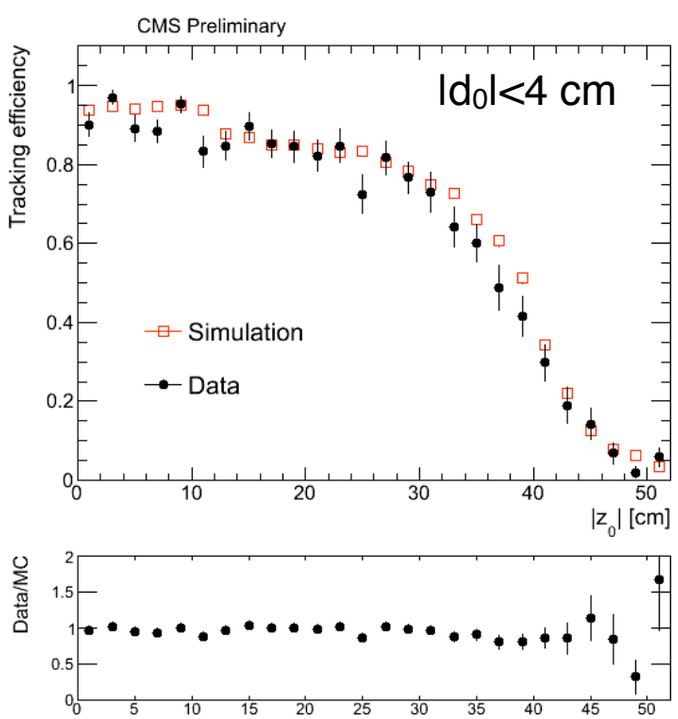
Long-Lived Particles decaying into leptons

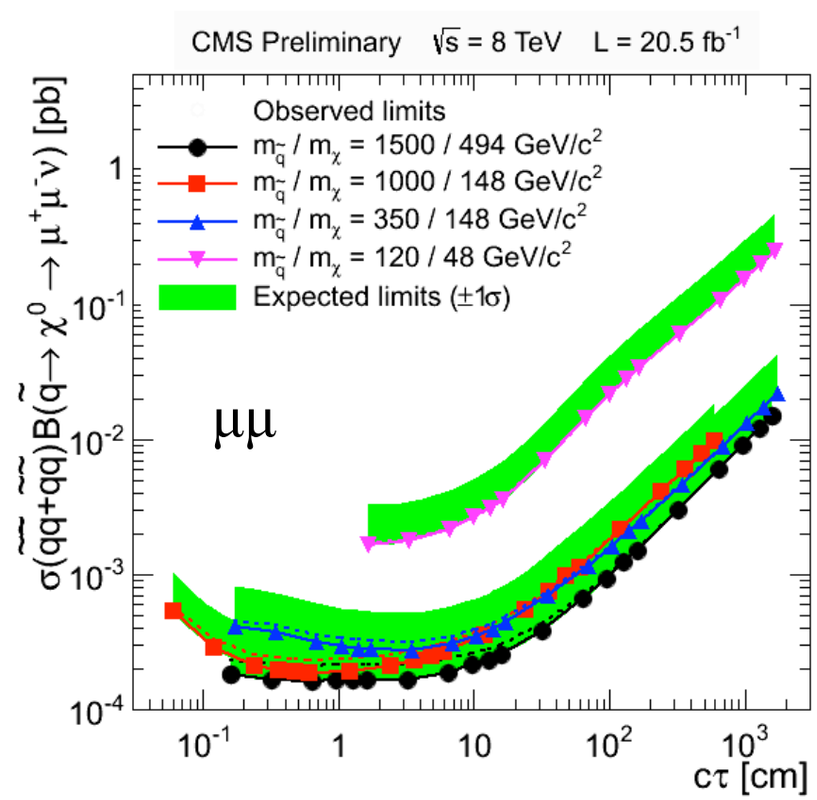
- observe no events for IP significance > 12σ





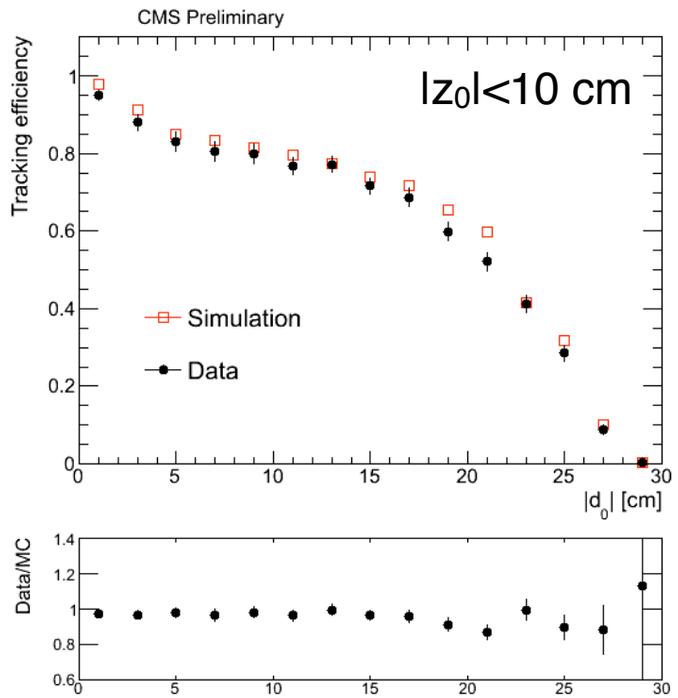


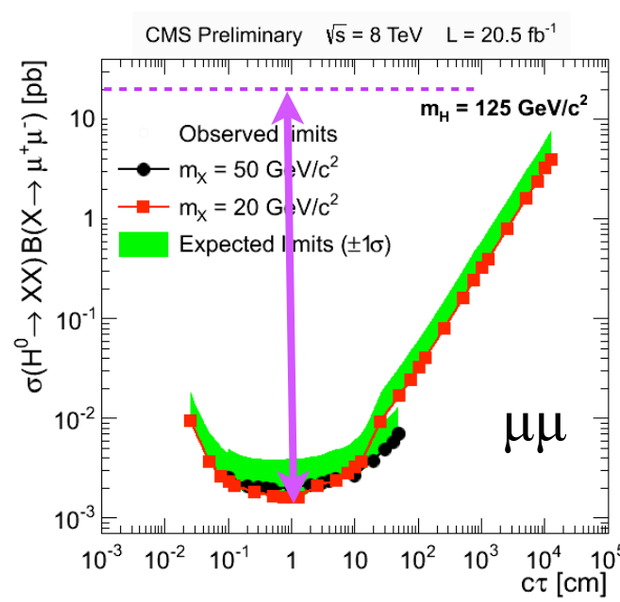




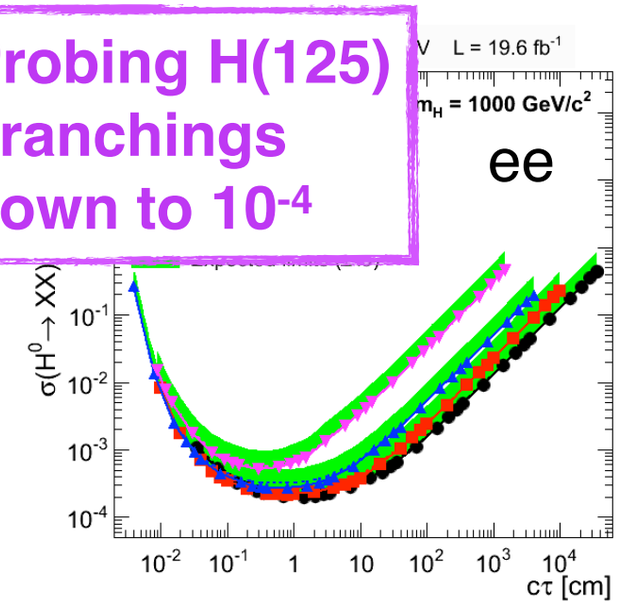
Long-Lived Particles decaying into leptons

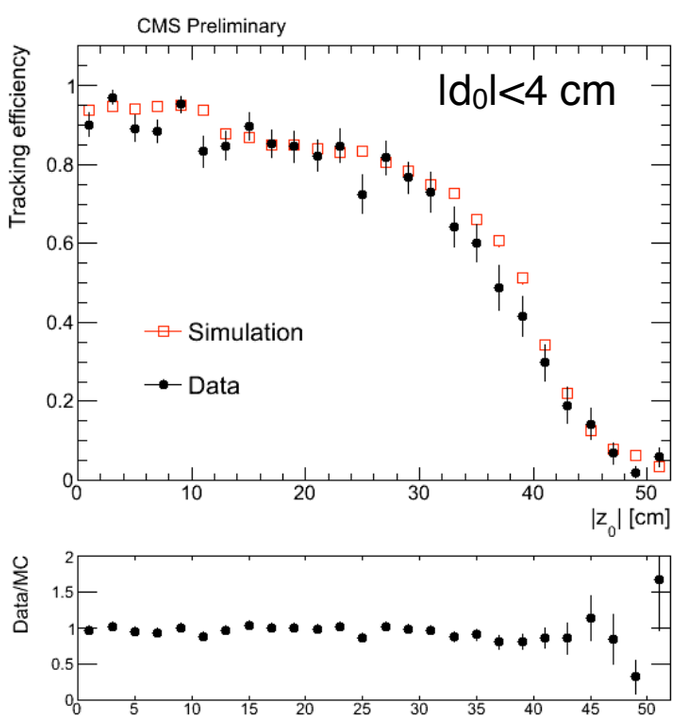
- observe no events for IP significance > 12σ

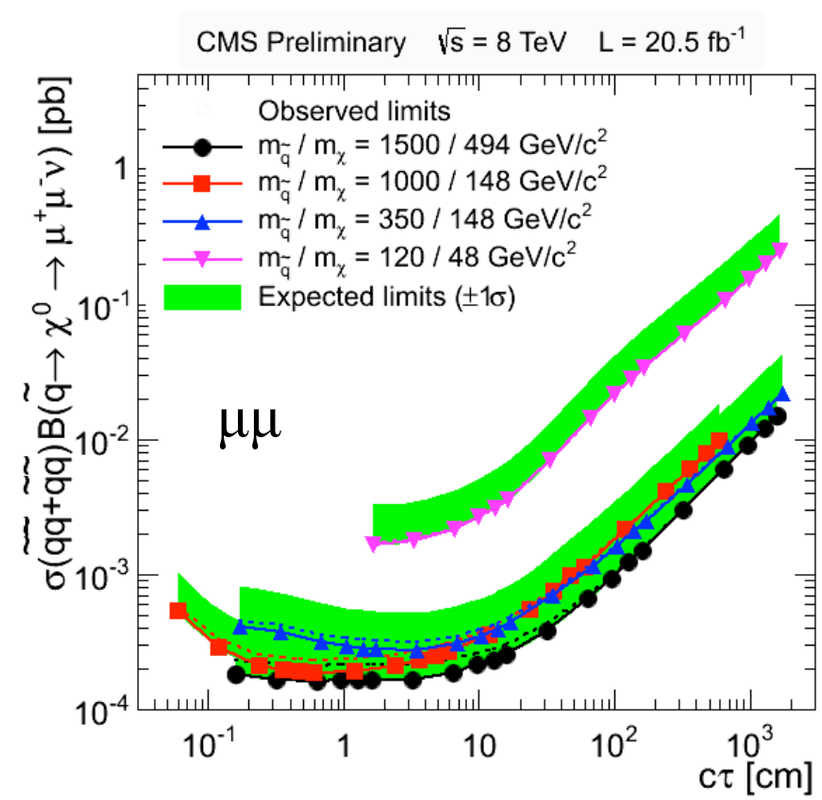




Probing H(125) branchings down to 10^{-4}

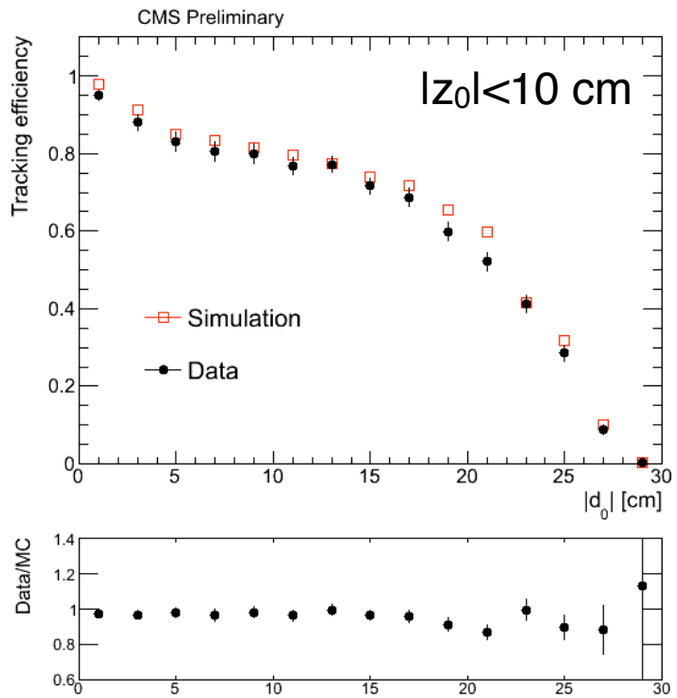


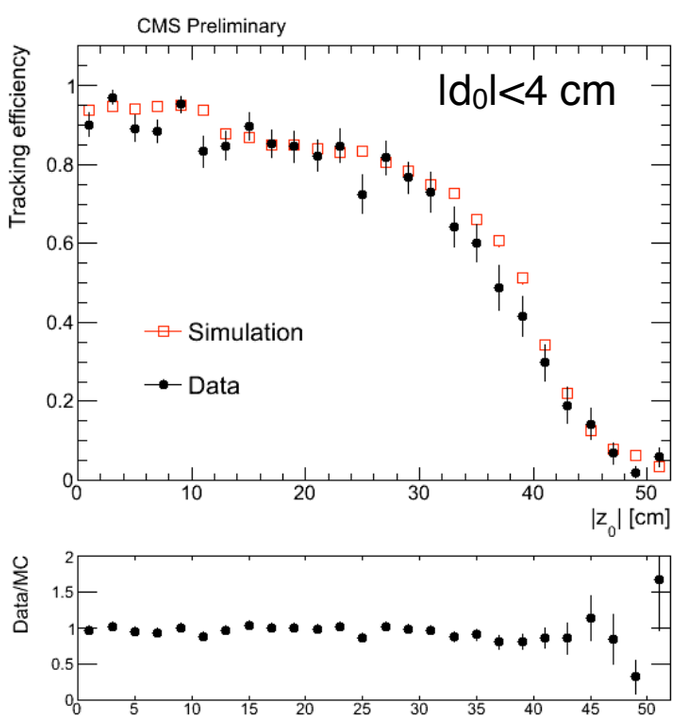


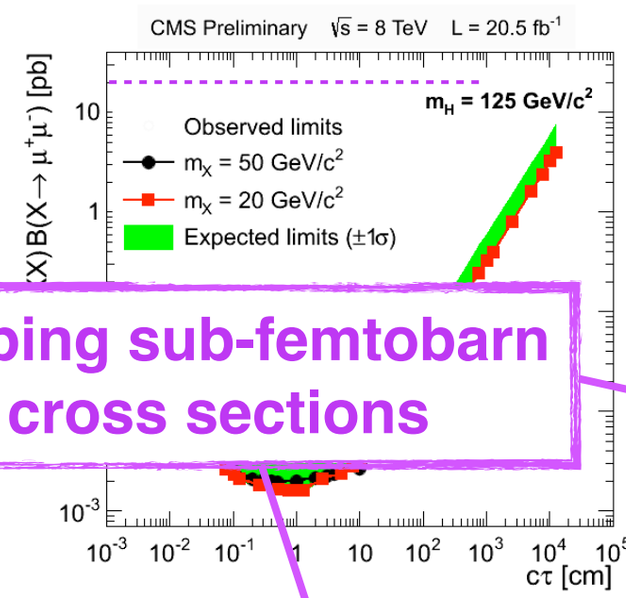


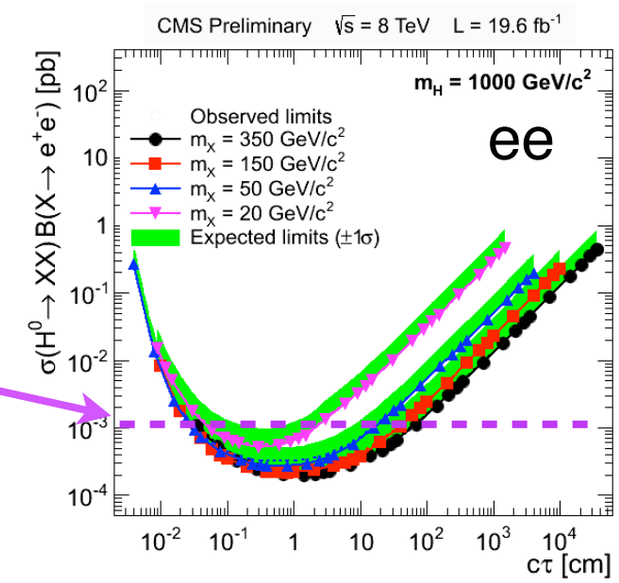
Long-Lived Particles decaying into leptons

- observe no events for IP significance > 12σ

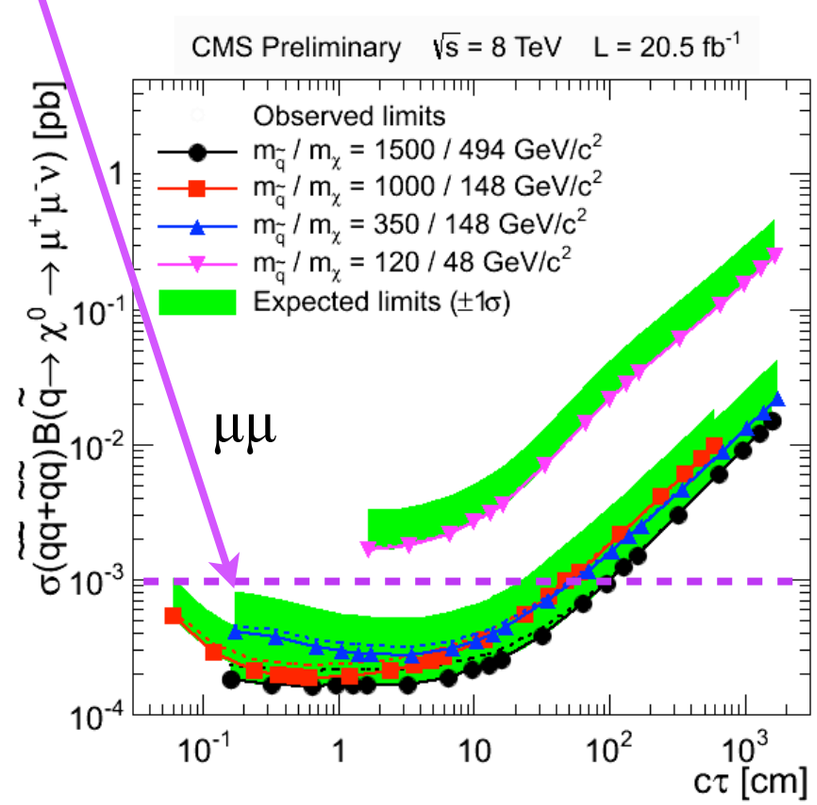






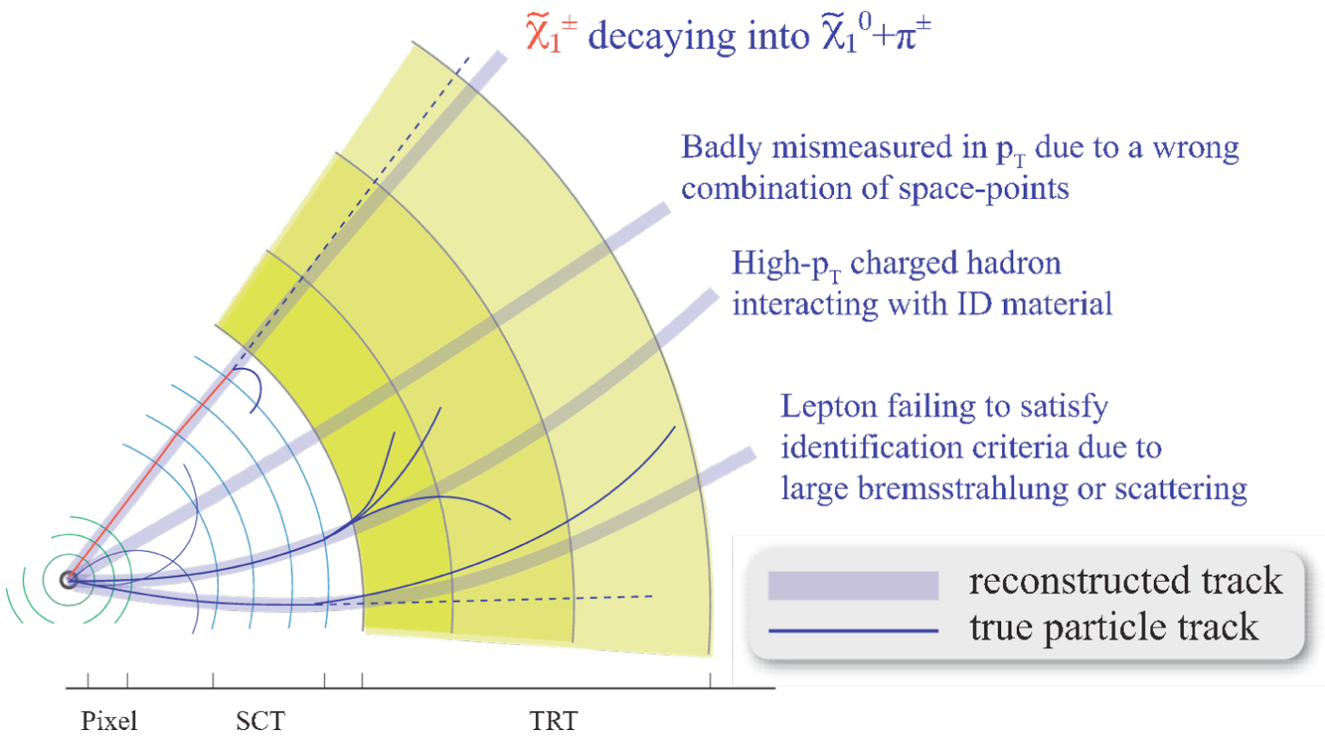


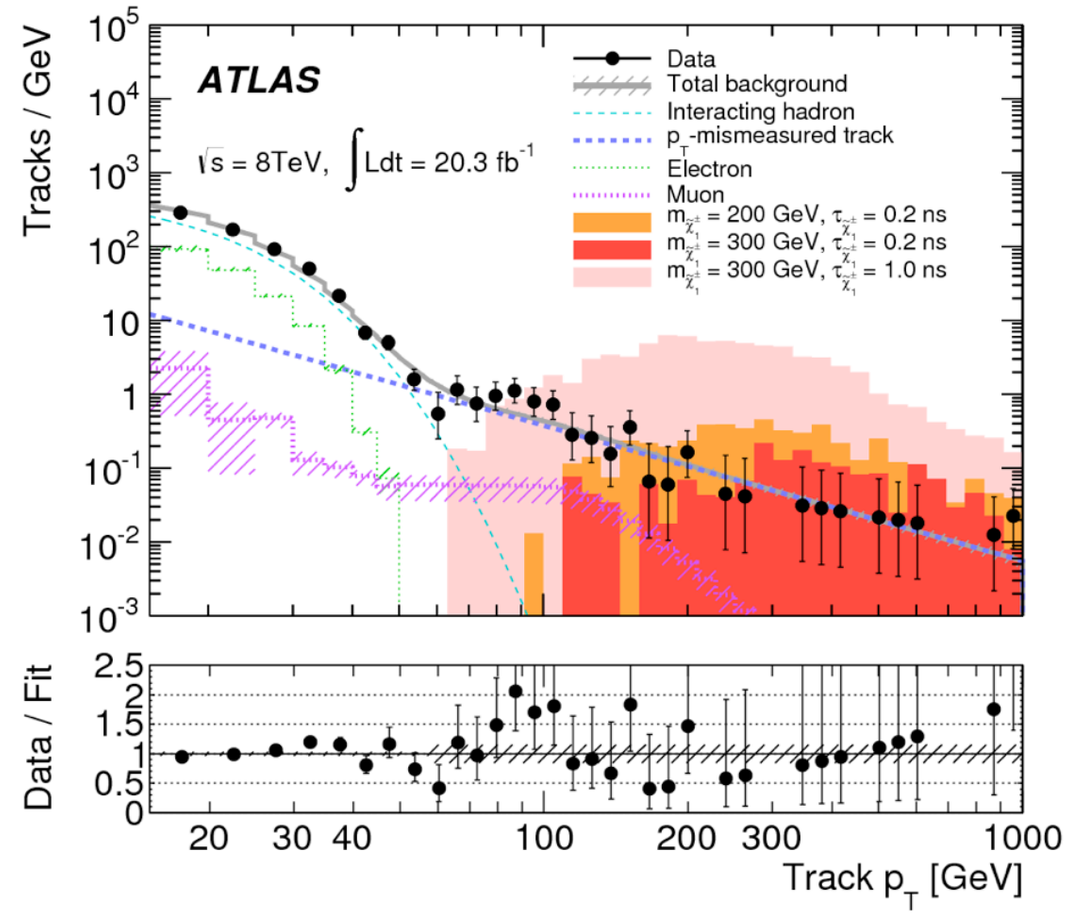
Probing sub-femtobarn cross sections

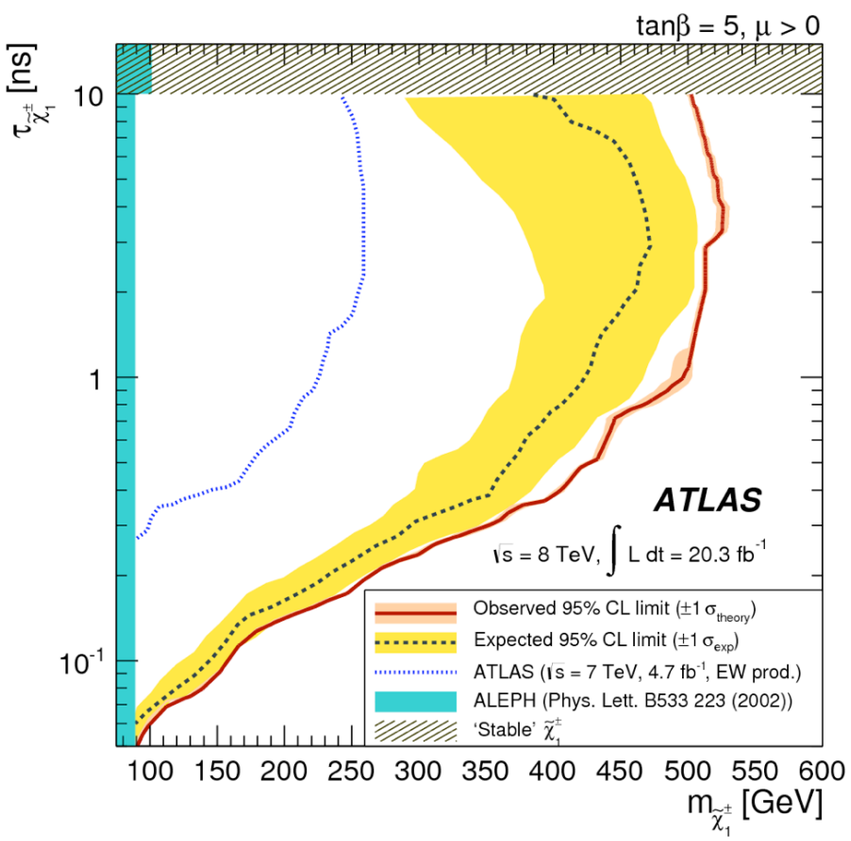


Long-Lived Particles

ATLAS-SUSY-2013-01







for ~recent results also see

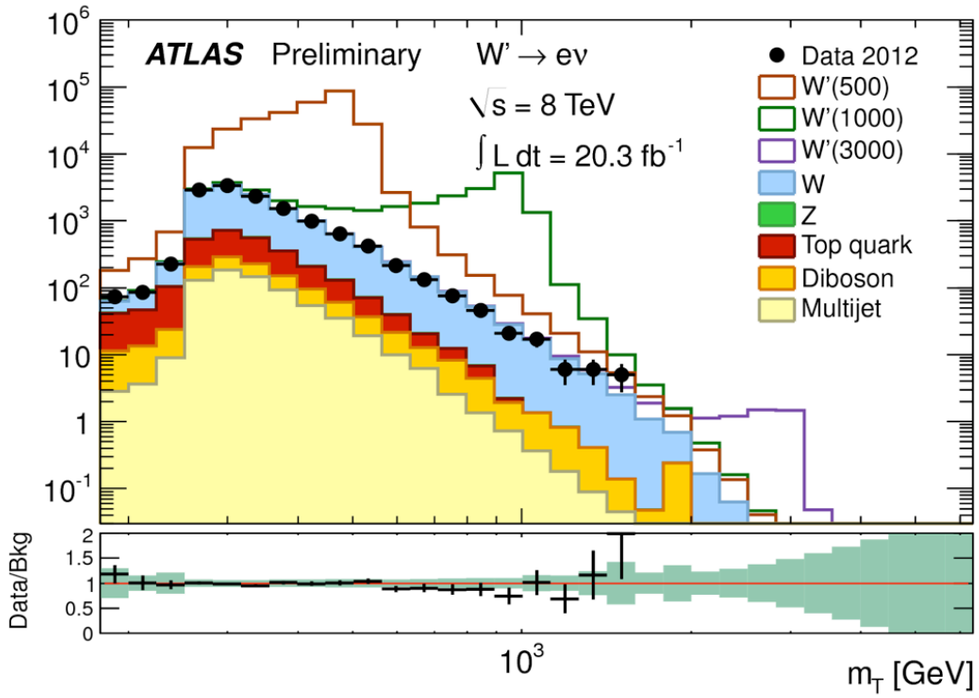
Stopped particles: ATLAS-SUSY-2013-03 CMS-EXO-11-020

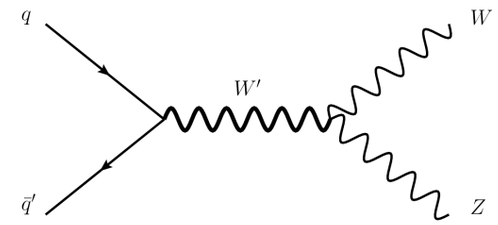
"slow" charged particles: ATLAS-CONF-2013-058; ATLAS-EXOT-2012-10; ATLAS-EXOT-2011-11; CMS-EXO-12-026

displaced photons: ATLAS-SUSY-2012-15; CMS-EXO-2011-035; CMS-EXO-2011-067

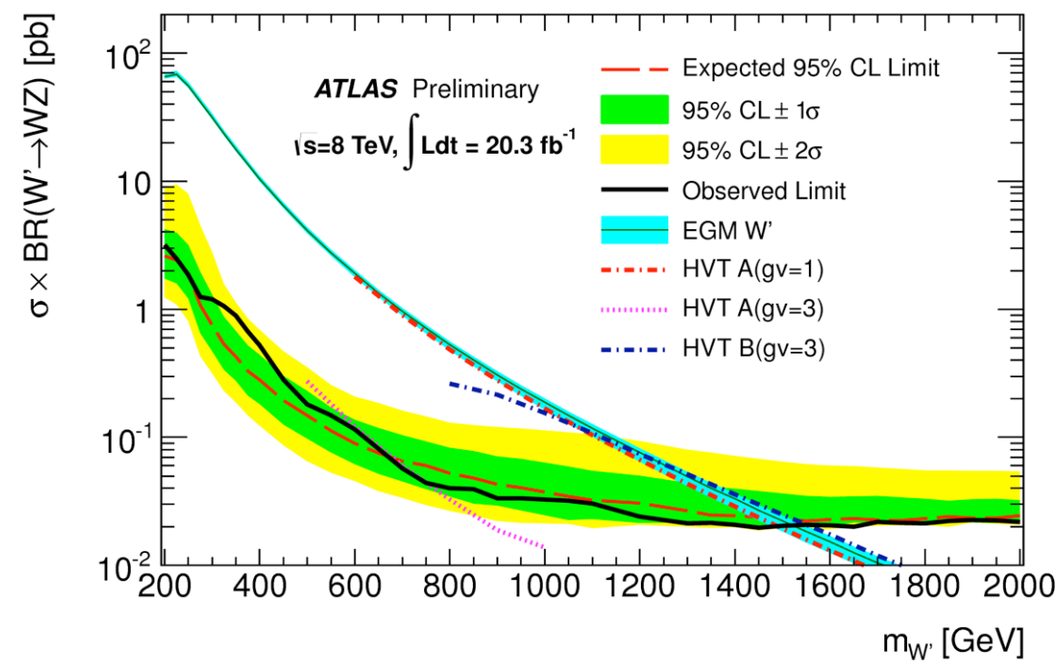
Extra Gauge bosons

ATLAS-CONF-2014-017: qq→W'→lν

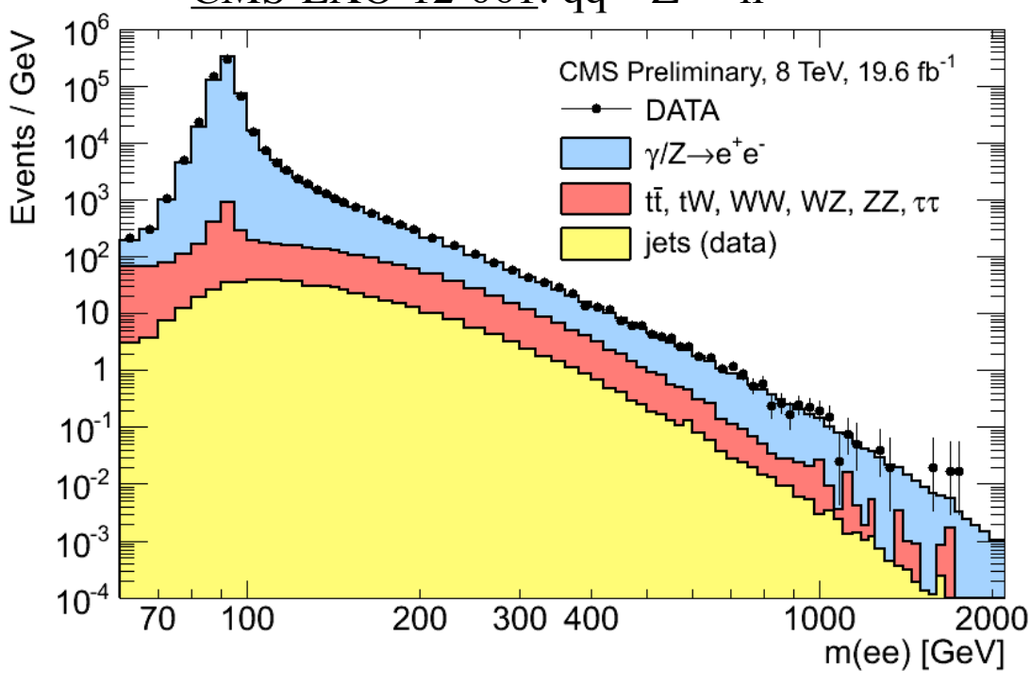


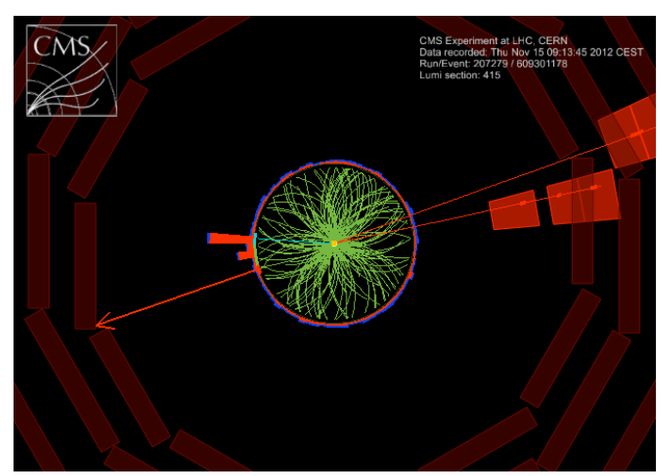


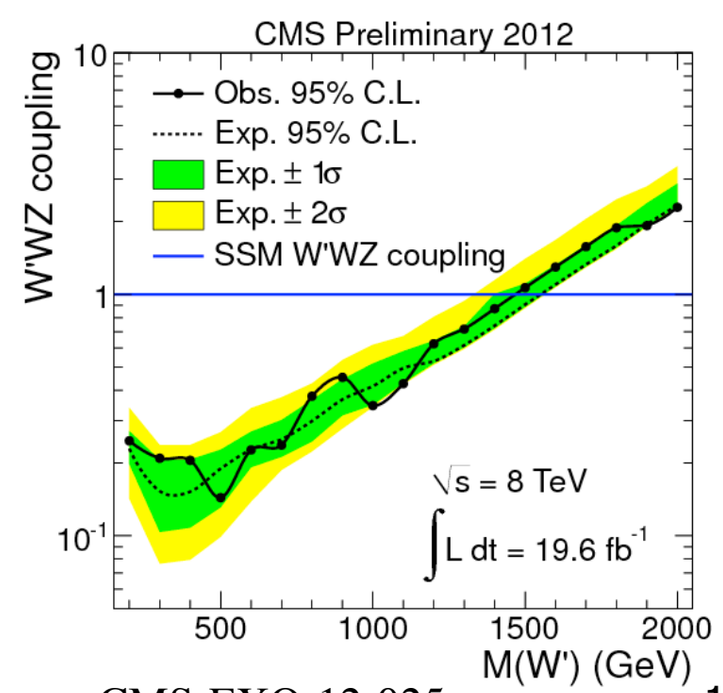
ATLAS-CONF-2014-015



CMS-EXO-12-061: qq→Z'→ll







CMS-EXO-12-025

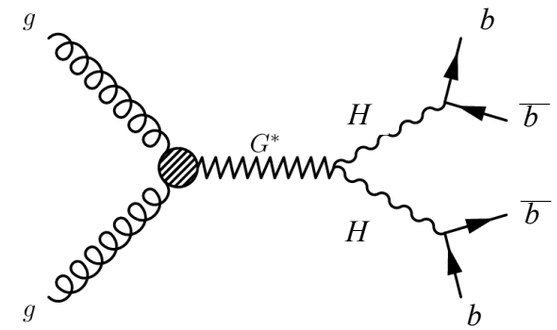
W', Z' limits ~3 TeV assuming SSM

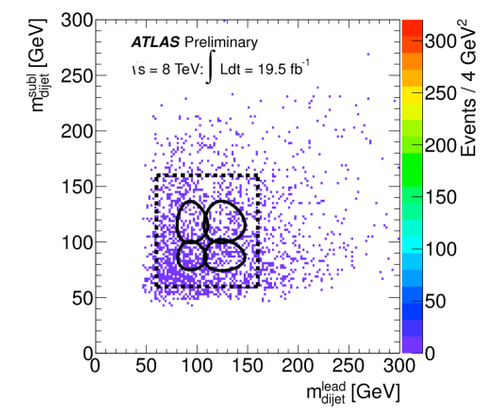
Yuri Gershtein

Extra Dimensions

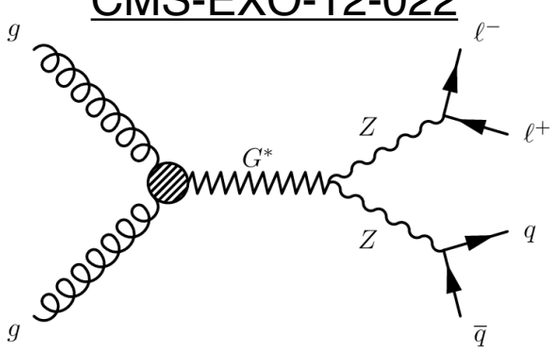
- Randall-Sundrum model with a wrapped extra dimension
  - geometric way out of the Naturalness problem
- G*: first KK excitation of a graviton
  - decays into $t\bar{t}$, WW, **ZZ**, **hh**, $\gamma\gamma$, l^+l^-, ...

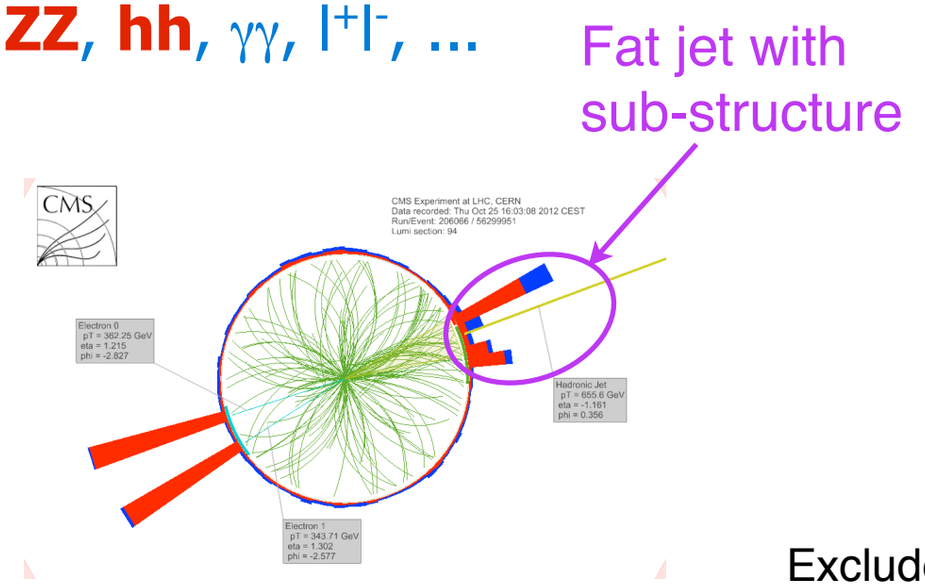
ATLAS-CONF-2014-005

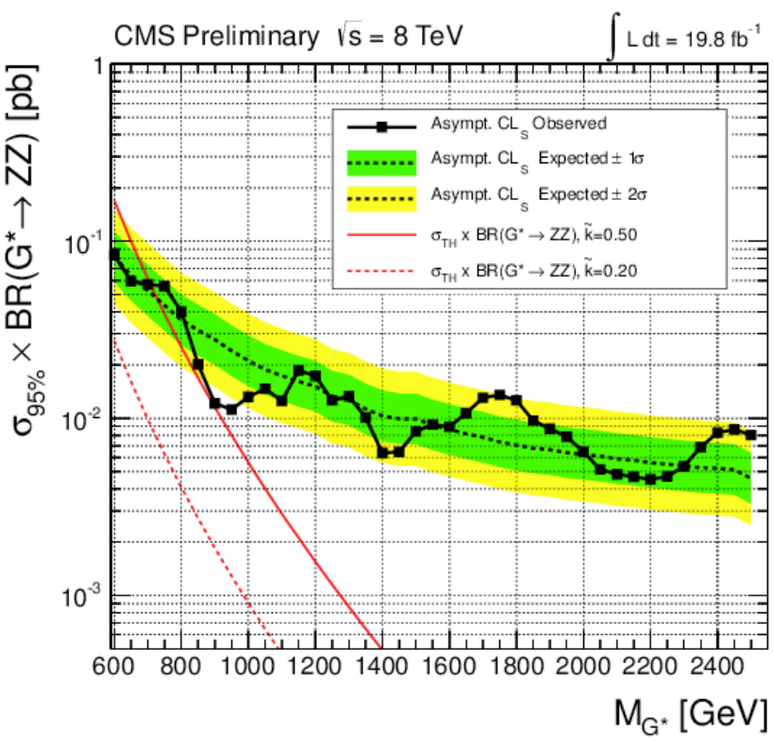




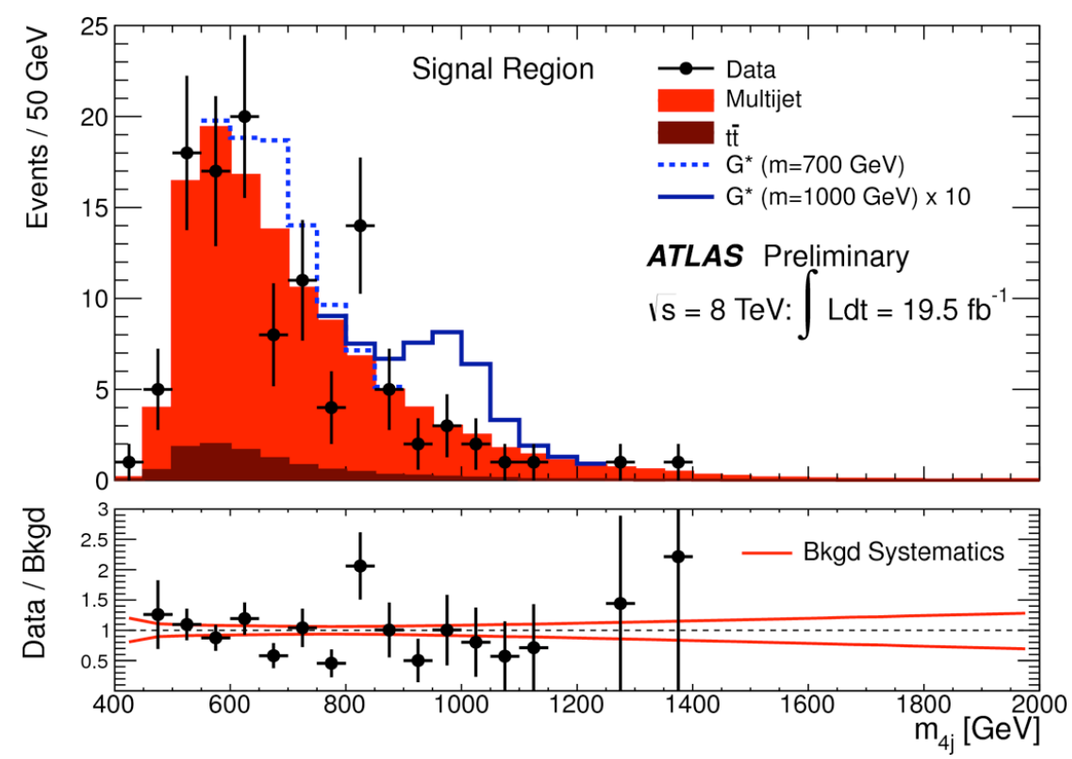
CMS-EXO-12-022







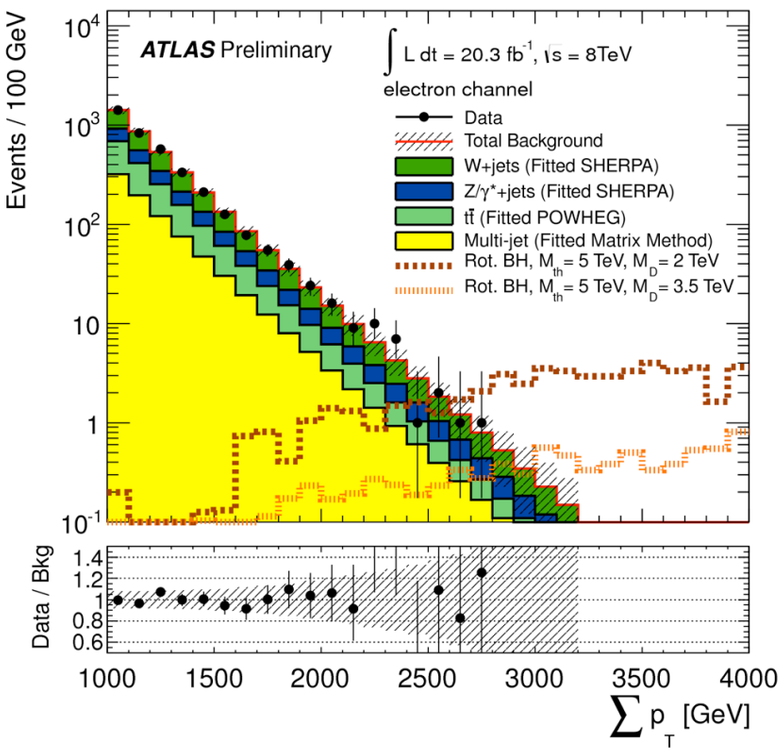
Excludes G* below 700 GeV for k/M_{Pl}=1

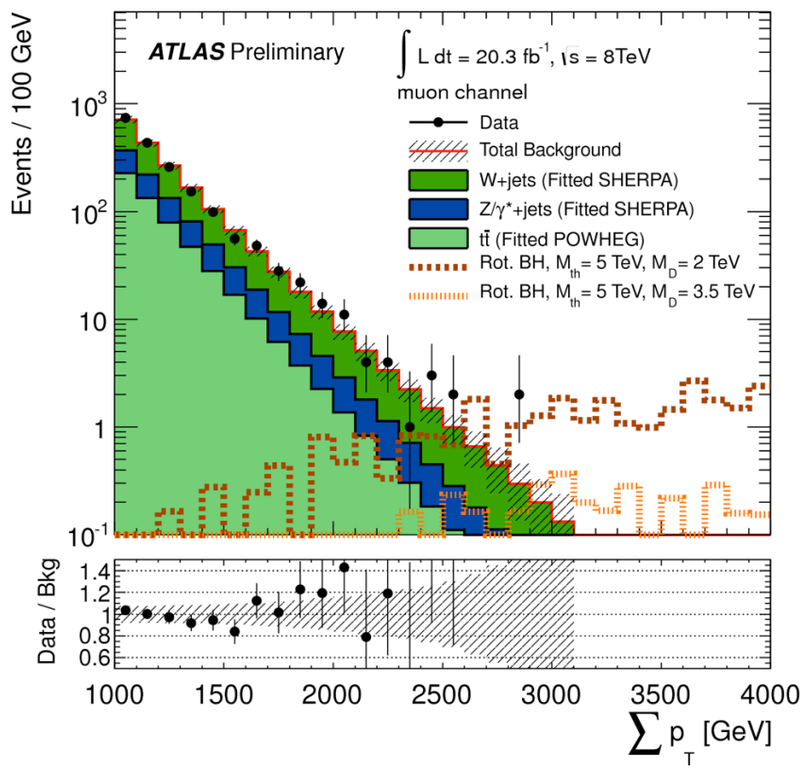


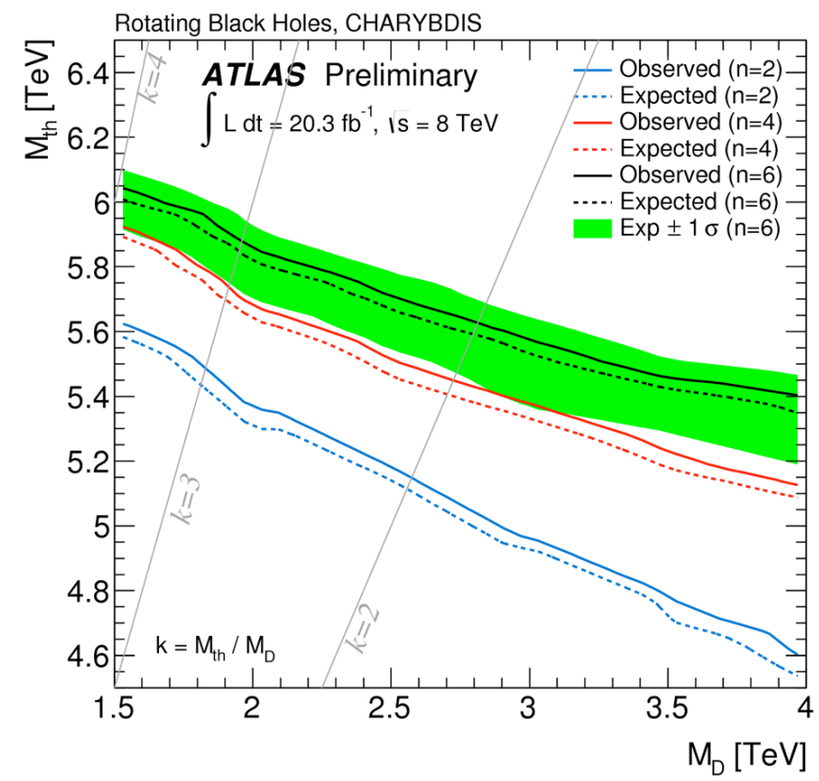
mini black holes

ATLAS-CONF-2014-016

- One of most striking consequences of ~TeV Planck scale
  - require at least three high E_T objects, one of them - an electron or a muon







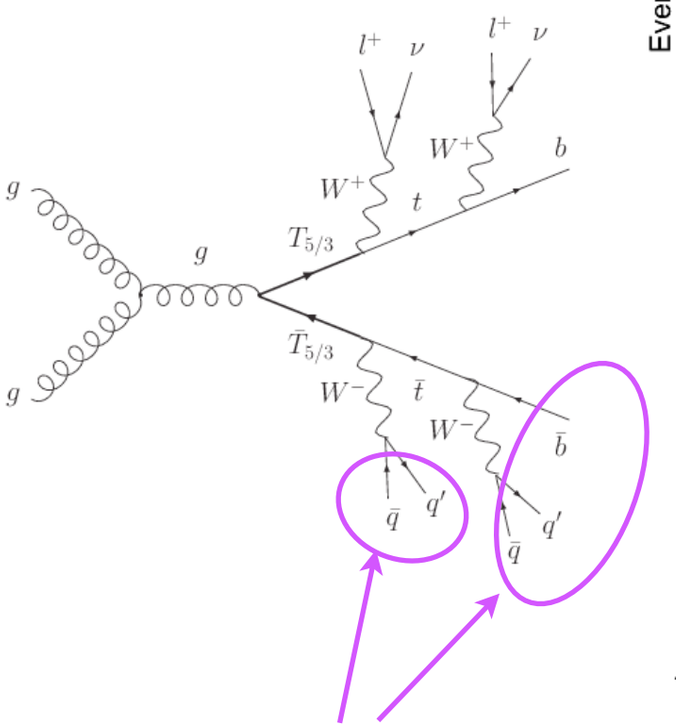
Limits on M_{th} of 5-6 TeV depending on assumptions

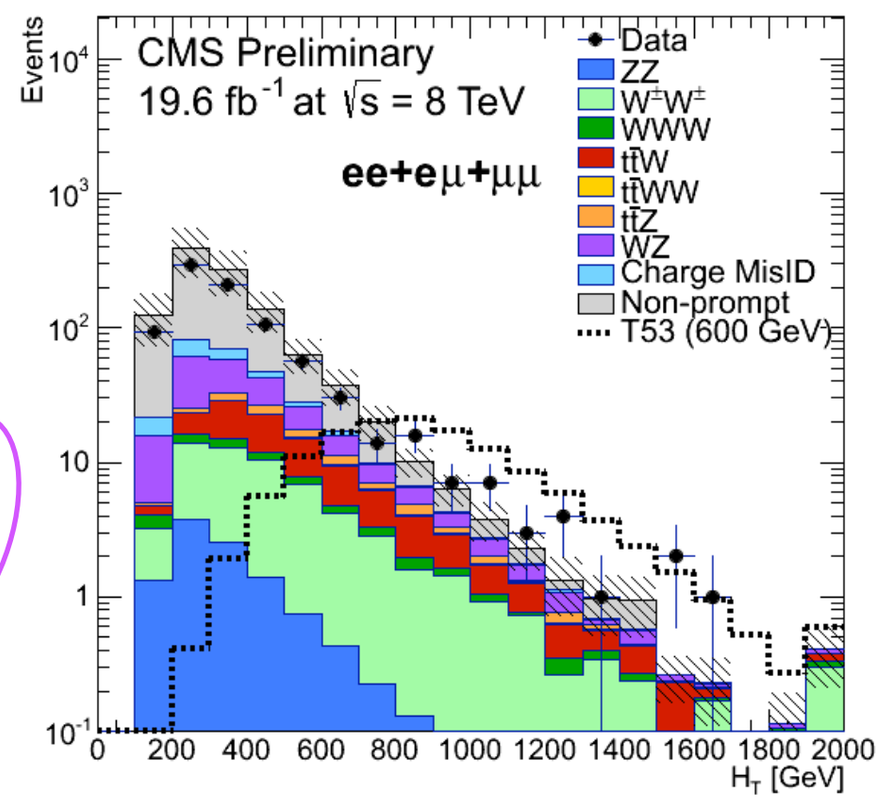
See Also: ATLAS-EXOT-2013-003
CMS-EXO-12-009

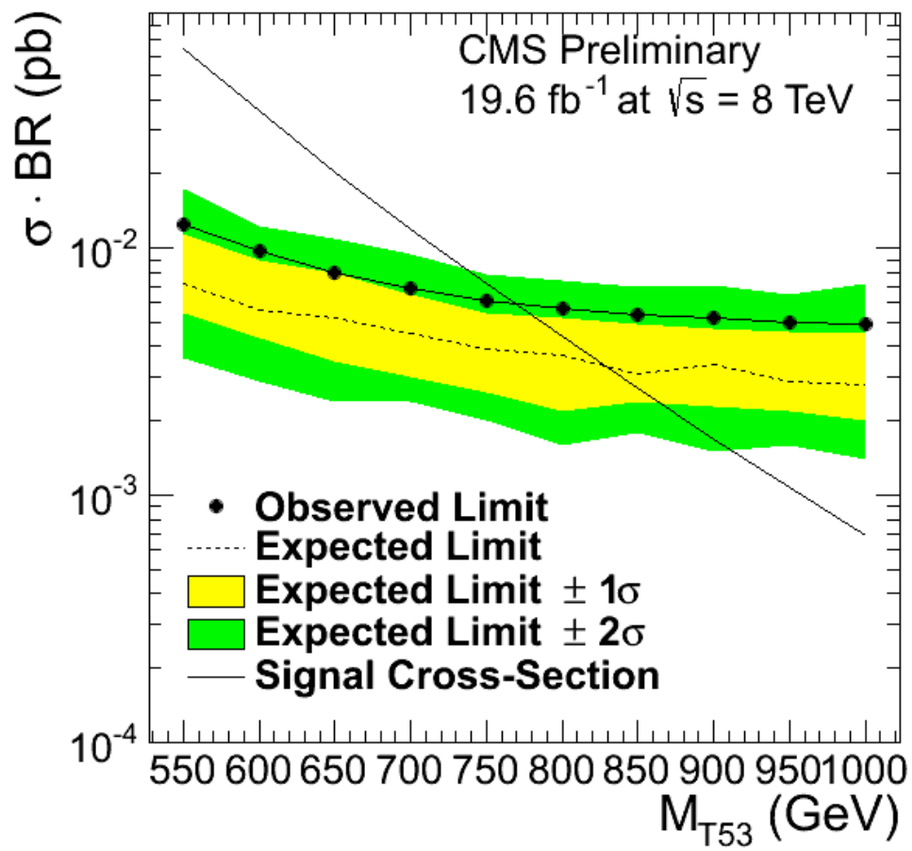
Vector-like quarks

- Supersymmetry is not the only symmetry that can protect the Higgs mass
  - the 125 GeV boson could be a pseudo-Goldstone boson from a spontaneous breaking of a global symmetry
  - several attractive models exist with new strong dynamics and vector-like quarks. Exotic charges (i.e. can be a 5/3)

CMS-B2G-12-012







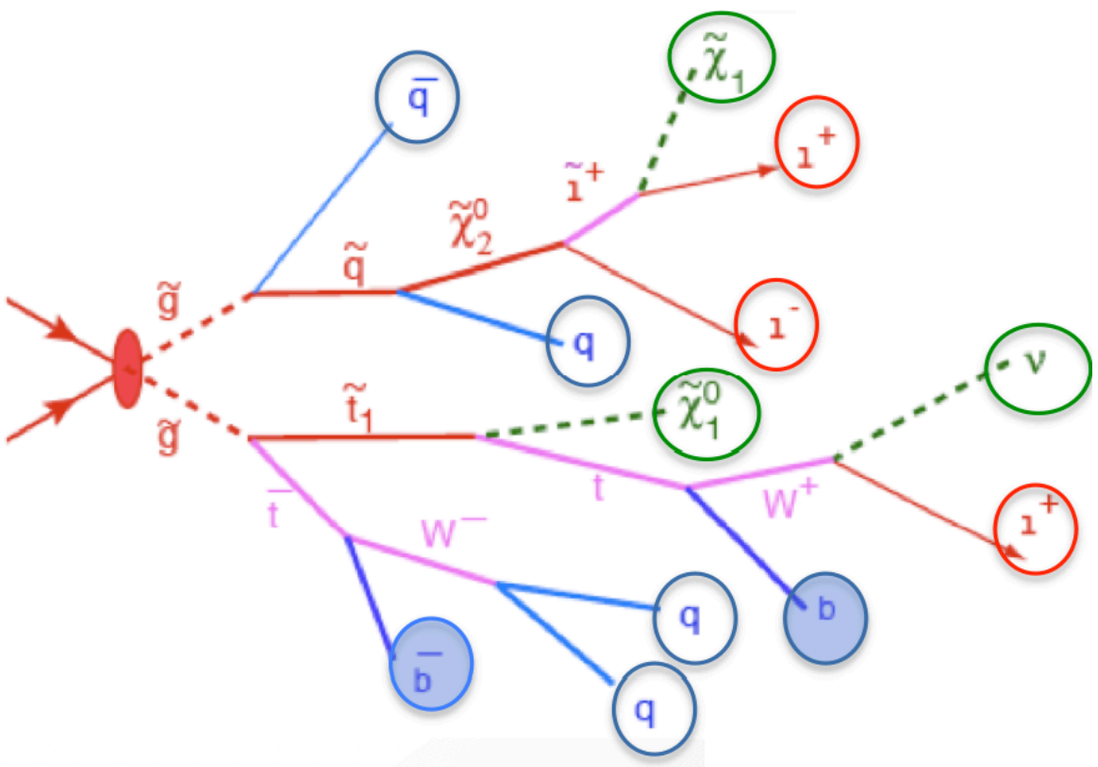
boosted jet substructure methods are used

See Also: CMS-B2G-12-015
ATLAS-CONF-2013-018
ATLAS-CONF-2013-018

Supersymmetry

- Complexity of the final state can be staggering

Cascade from strong production



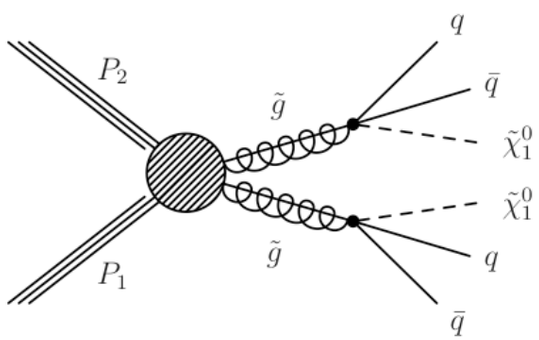
If colored partners are inaccessible, can produce EWKly interacting partners (lower cross sections and more SM-like events)

What happens to the neutralino χ_1^0 ?

- R-parity conserved and SUSY broken at high scale:
  - Dark Matter candidate!
- R-parity conserved and SUSY broken at low scale:
  - gravitino is LSP (DM component)
  - χ_1^0 decays to gravitino plus a
    - photon, Z, or Higgs
  - long lived decays are possible
- R-parity is not conserved:
  - decay chains with little or no MET
  - 3-rd generation if MFV
  - long lived decays are possible
  - Can make ~any final state (great for signature generation)

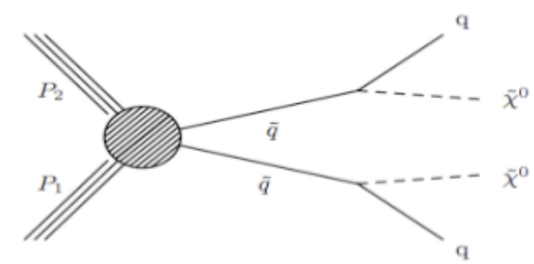
Supersymmetry

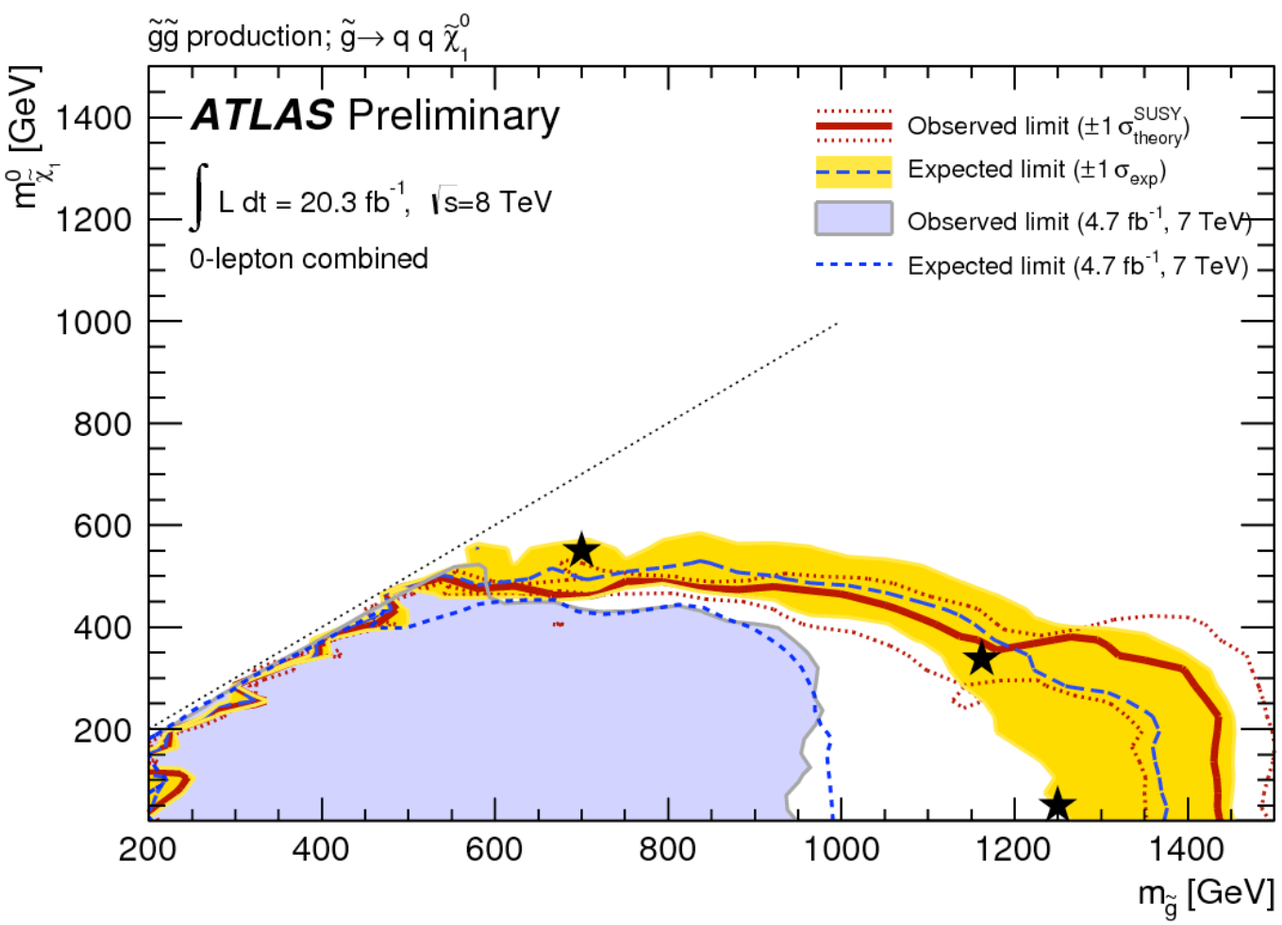
- In the "expected" version of SUSY with R-parity conservation at the LHC, squarks and gluinos were strongly produced, resulting in light flavor jets + MET signature

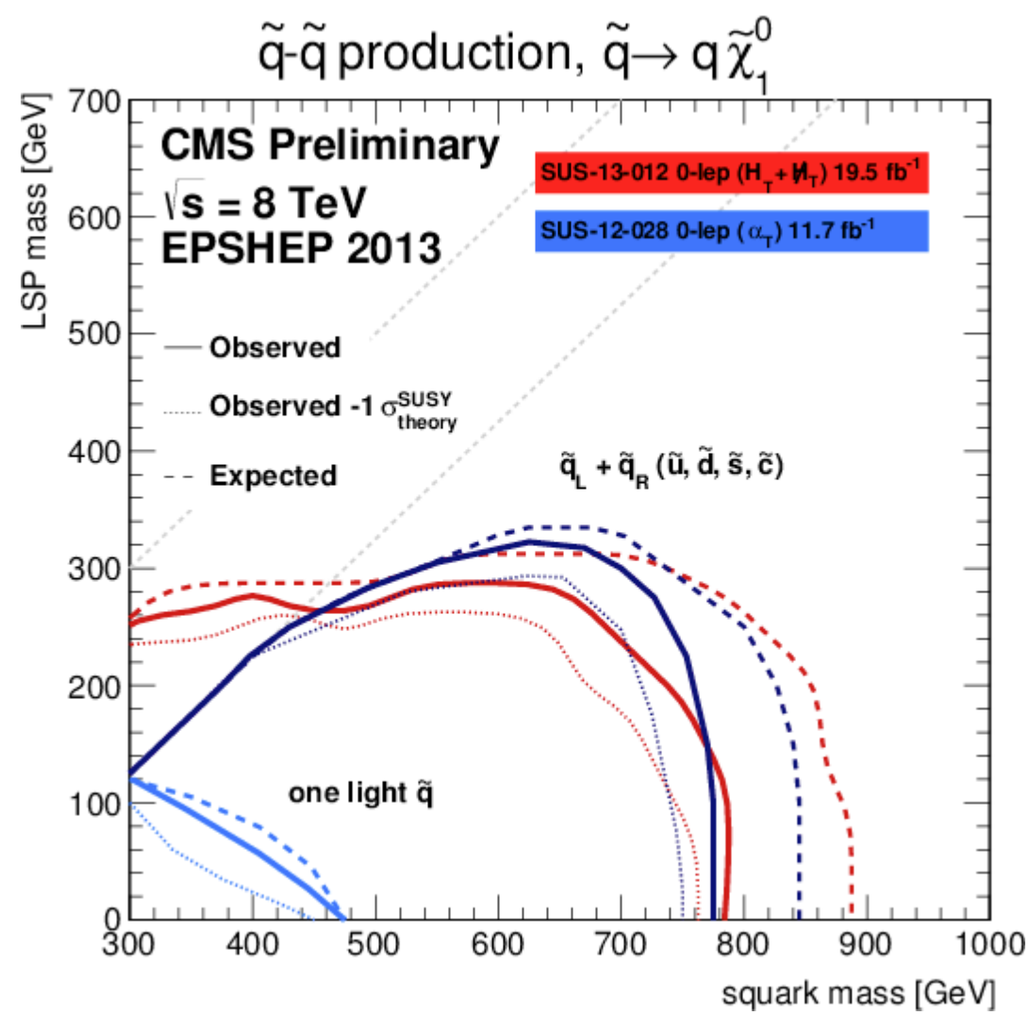


Z/W + jets dominant background
MET tails under control

constrained models ~dead



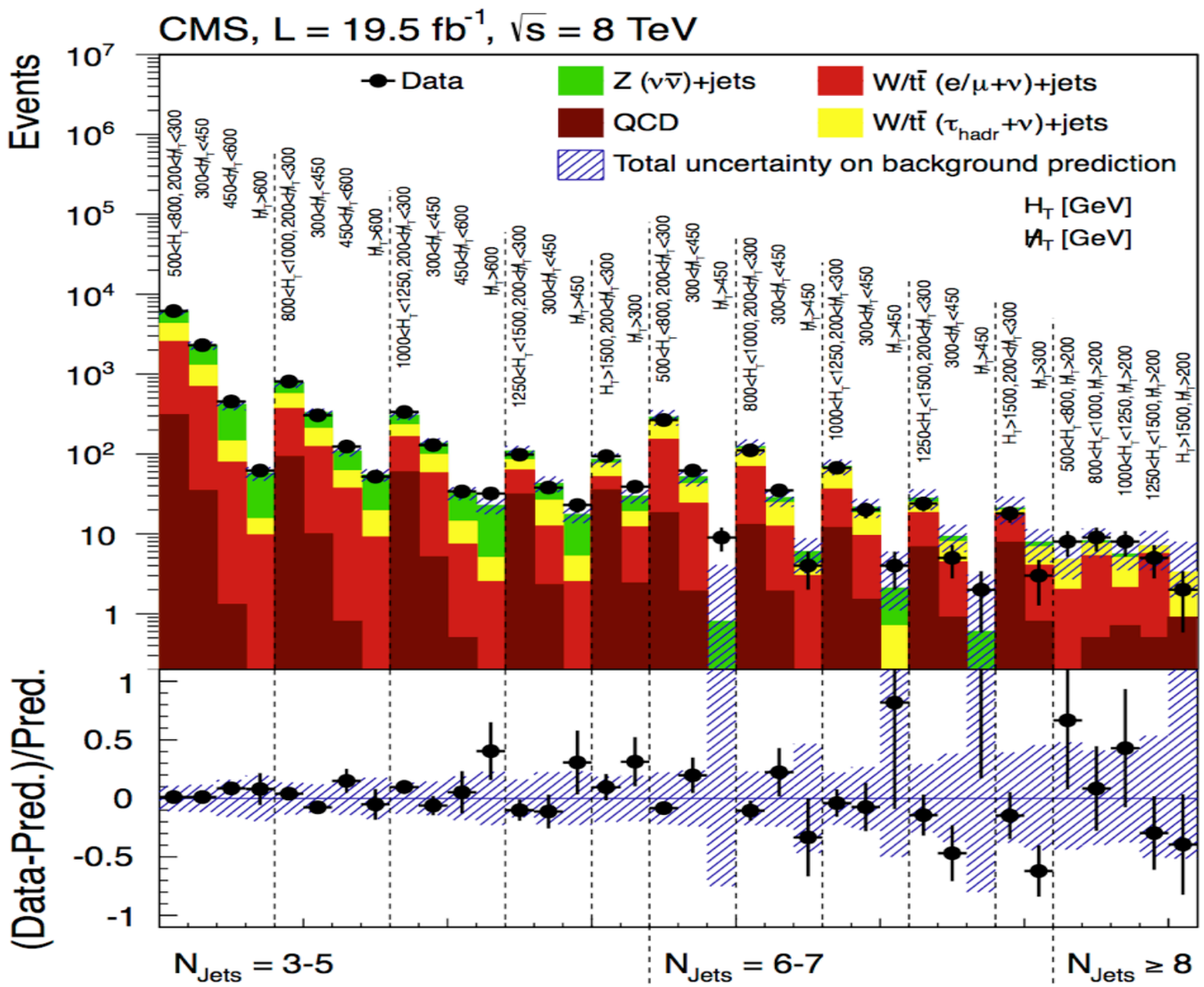




Yuri Gershtein

Search methodology

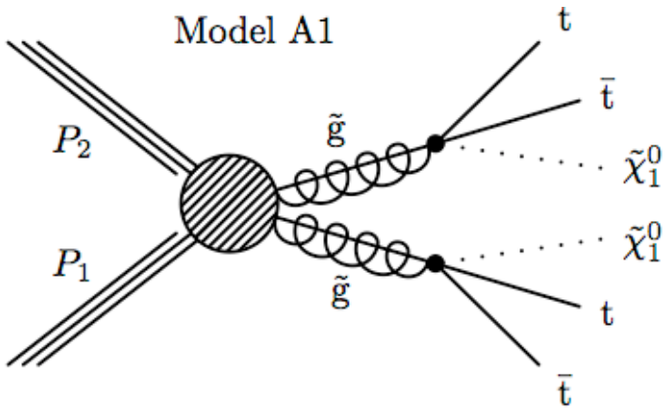
- The phenomenology is very rich even in simple and simplified models
- Need to make results re-castable into many models
- Move away from making kinematic cuts beyond base selection
  - instead make multiple kinematic regions - some dominated by specific SM backgrounds, some - with potentially clean BSM signals

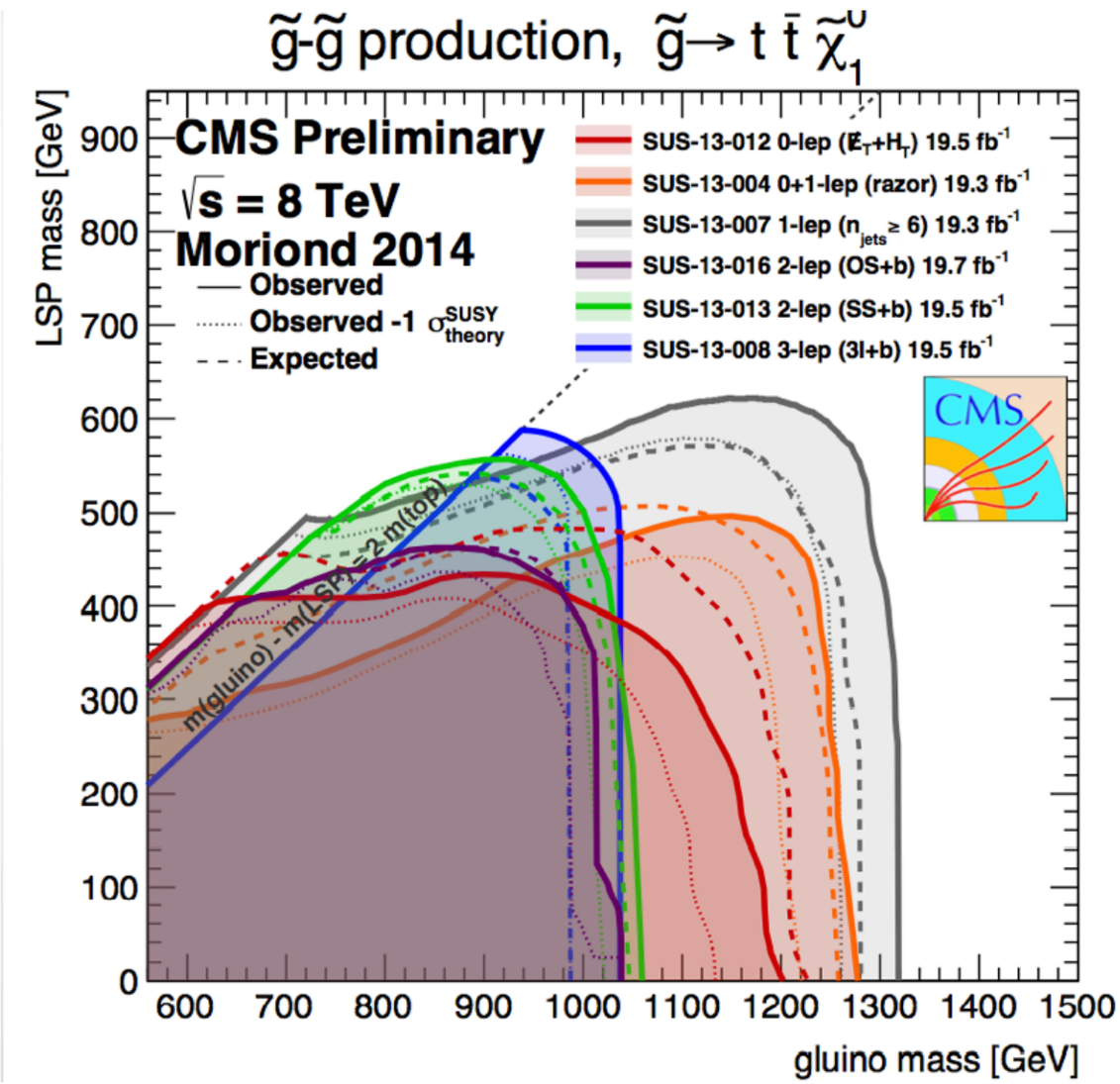


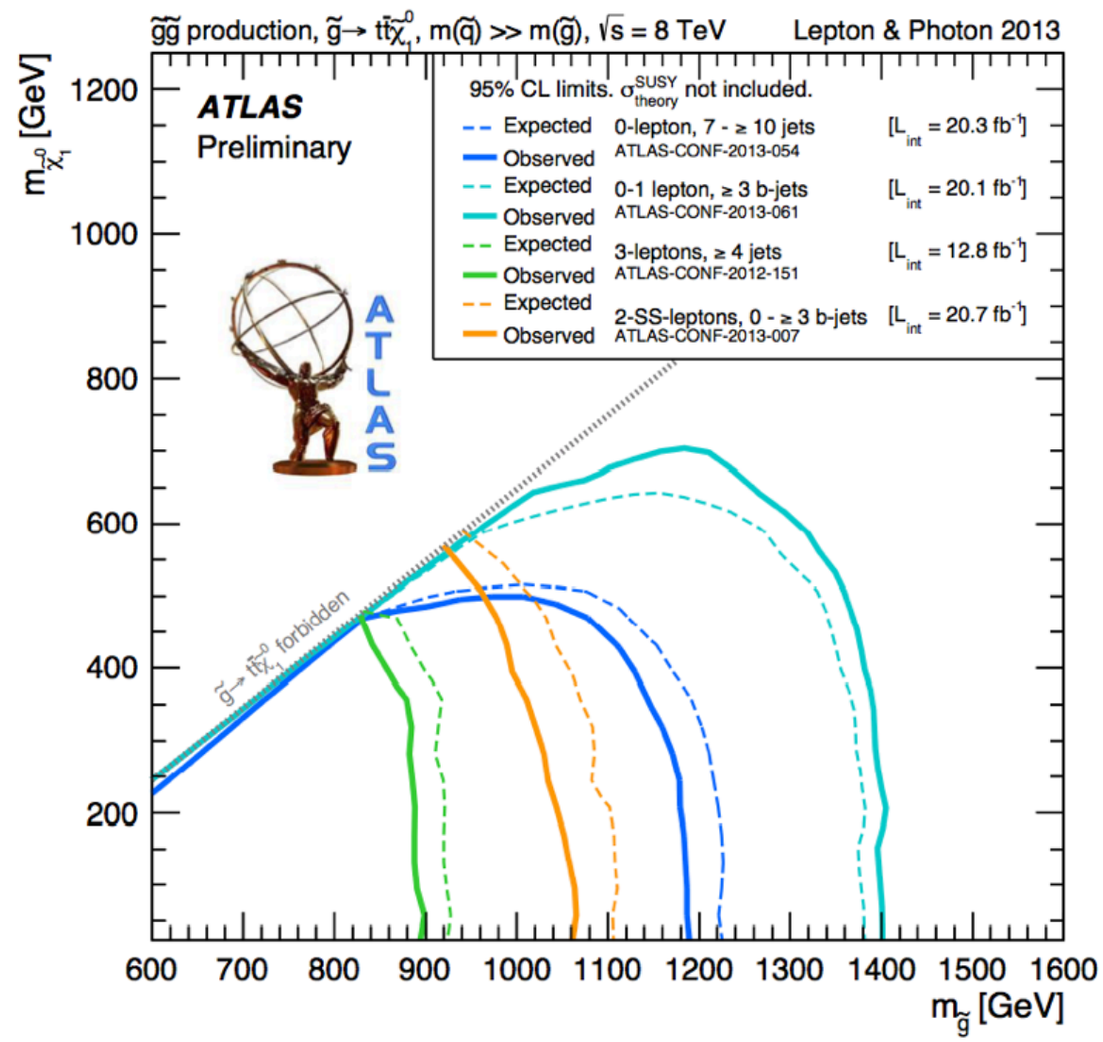
36 kinematic regions of the SUS-13-012 jets+MET search

Tops in SUSY cascades

- Even if SUSY "hides" in a complex long decay chains, it should have lots of tops in them - gives extra handles for searches
  - with all Run 1 data, it's almost impossible to miss a gluino below a TeV

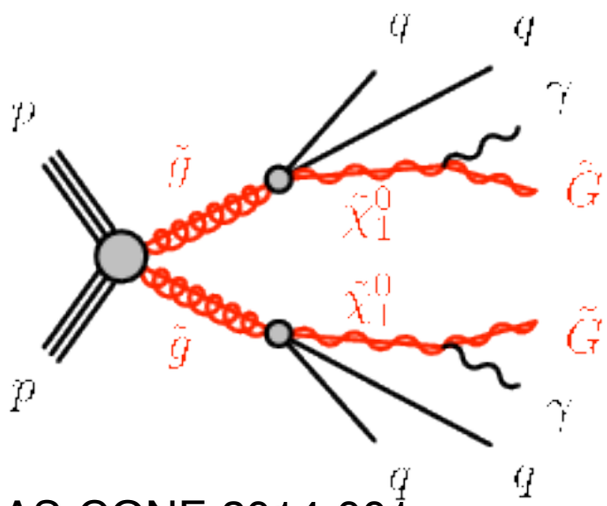


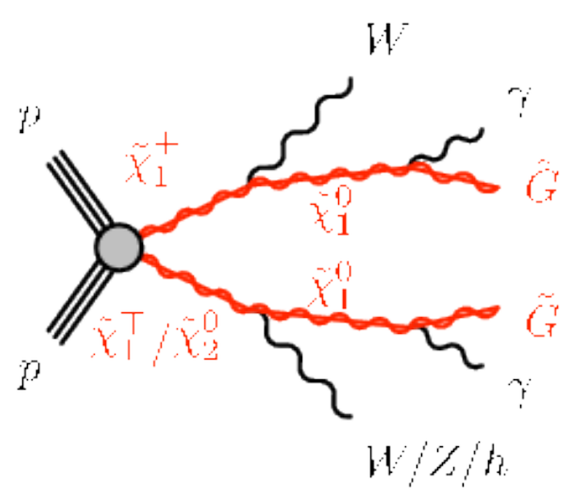


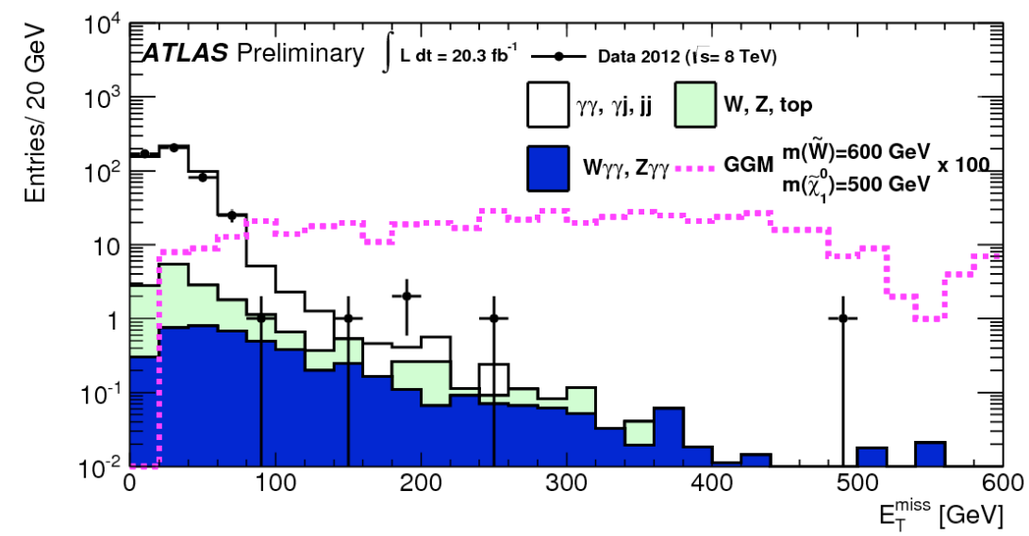


Gauge Mediated SUSY

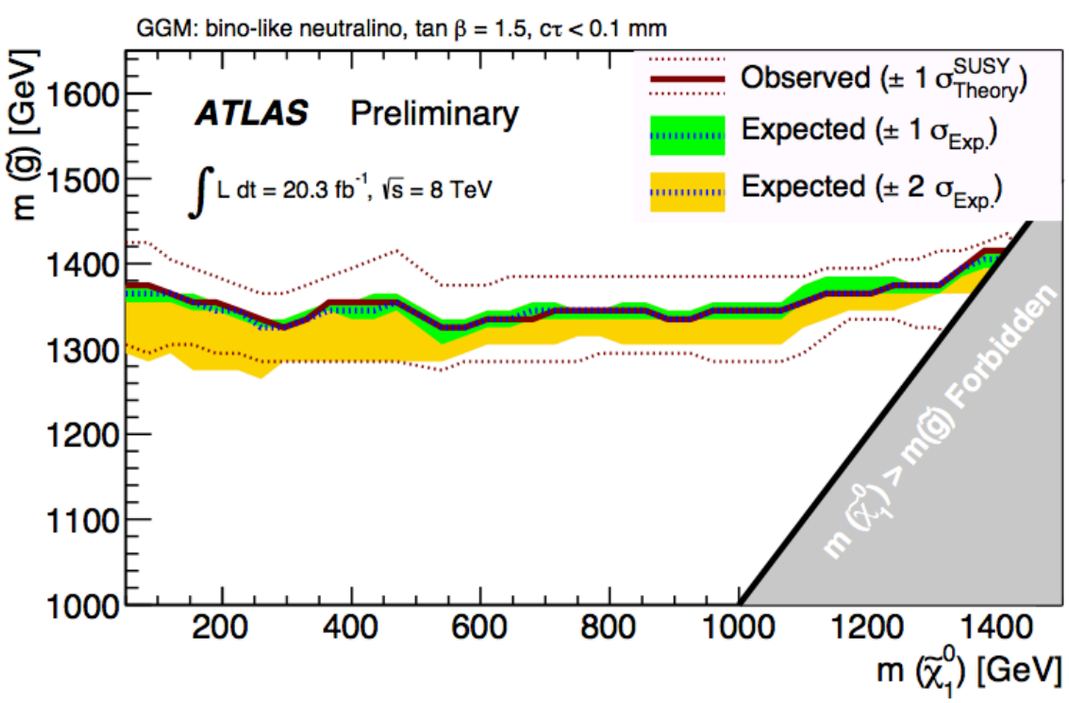
- Diphotons + MET: "classic" GMSB Bino
  - strong and EWK production

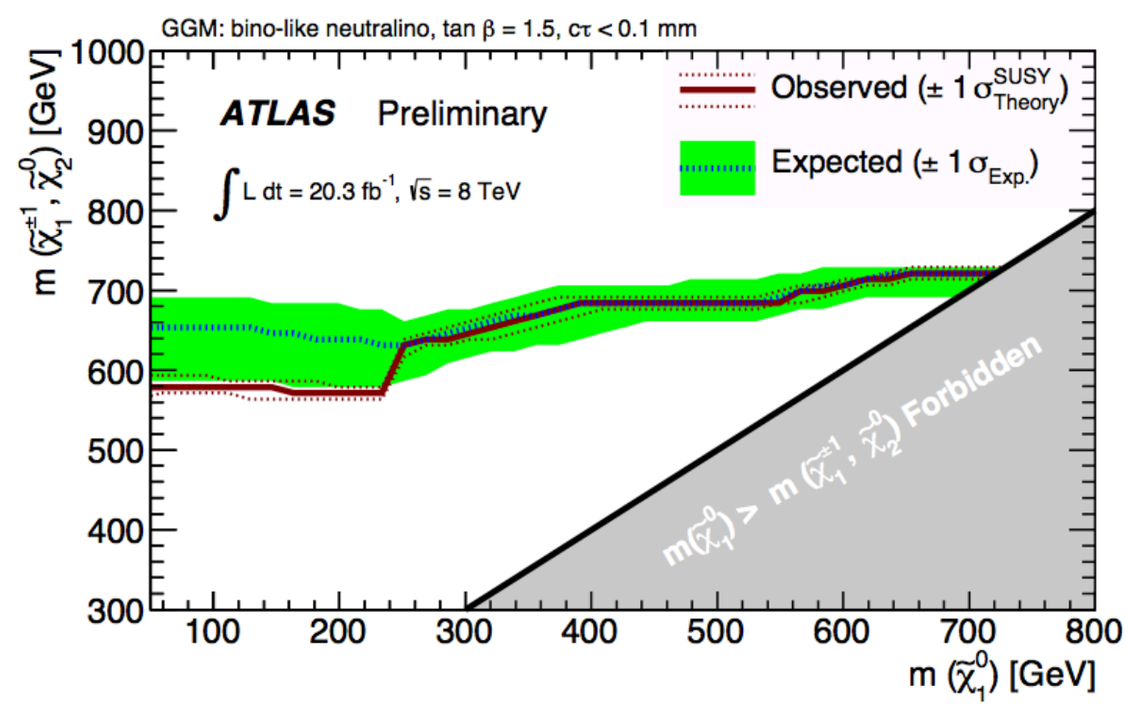






ATLAS-CONF-2014-001

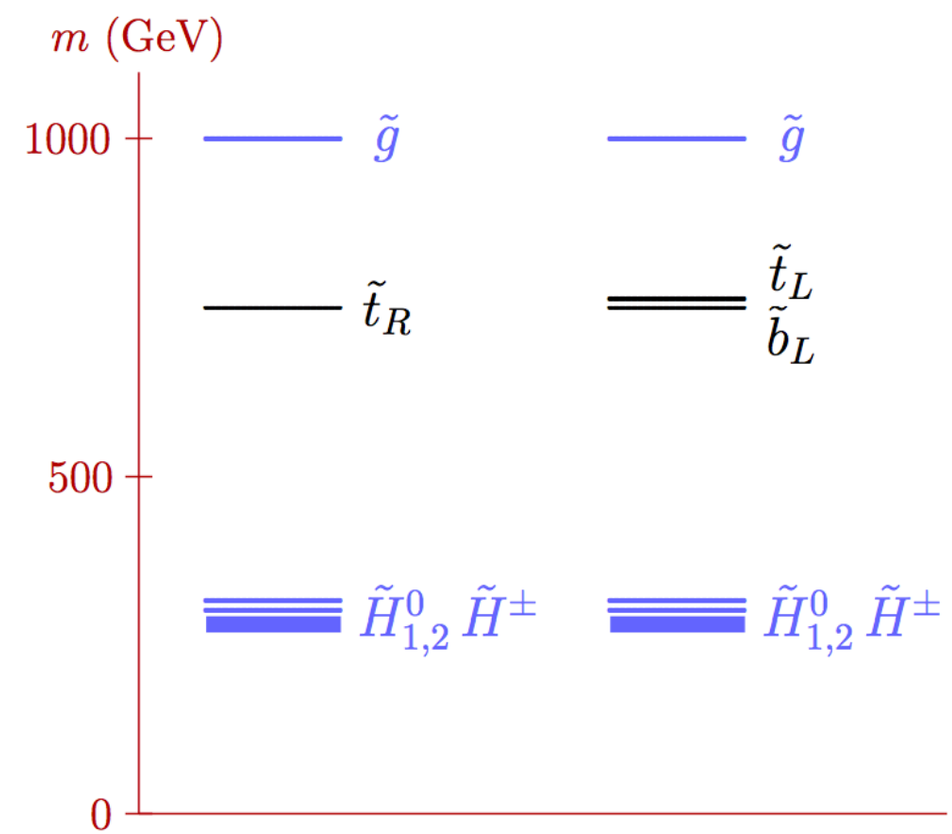




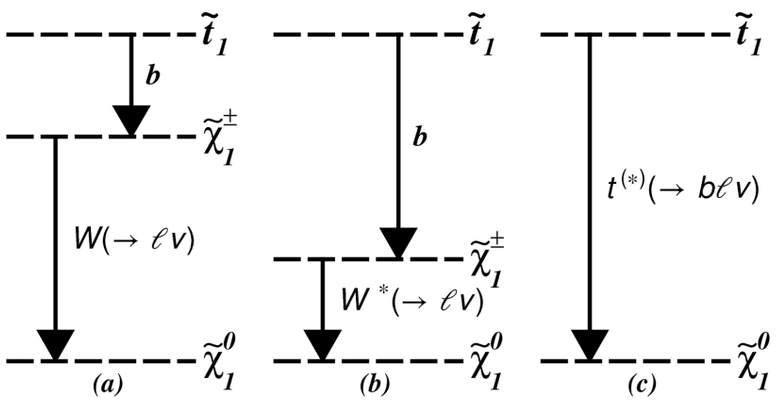
"Natural" SUSY

- How heavy can SUSY be without making fine tuning too large?
  - recall the Sun and the Moon have same size: 10^{-2} tuning
- The criteria of Naturalness are squishy, but wholistically:
  - higgsino should not be too heavy (200-500 GeV)
  - at least one stop should be not too heavy (500-1000 GeV)
  - gluino should not be much heavier then 1.5 TeV

- Some requirements are "easy" to relax
  - i.e. if gluino is a Dirac fermion, then a 3 TeV mass can be perfectly natural
- light higgsino is the least squishy attribute of Naturalness
  - if bino/wino are much heavier they decouple, and the three higgsinos are almost mass degenerate (~GeV splitting)



“Natural” SUSY: Stop



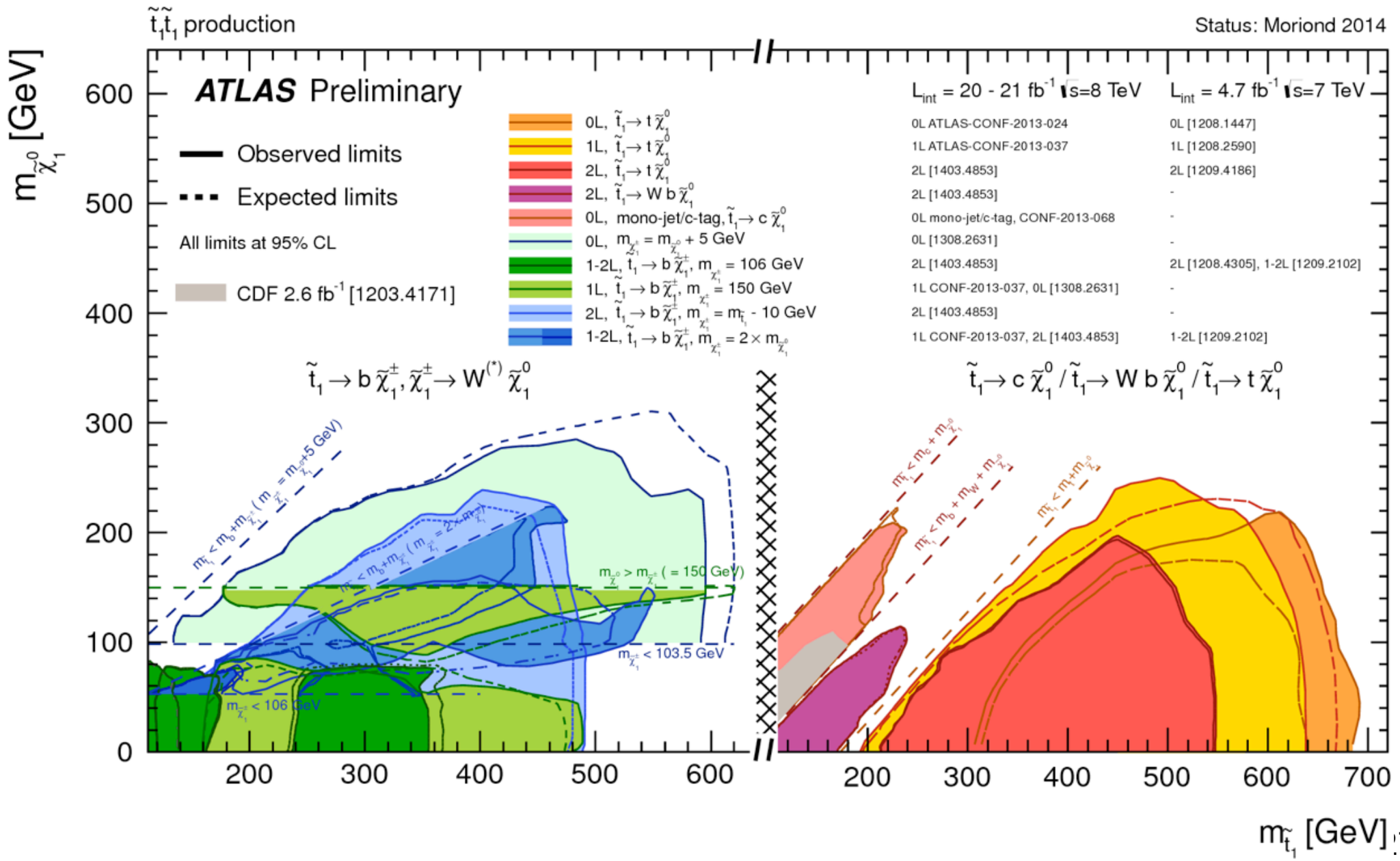
Limits ~ 600-700 GeV

Notable hole:

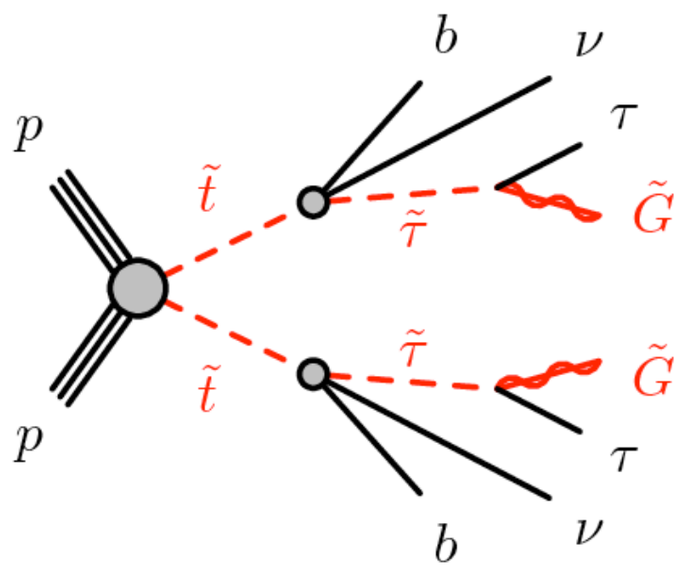
- m(stop)-m(neutralino)~m(top)

see also

CMS-SUS-13-004
CMS-SUS-13-011
CMS-SUS-13-009

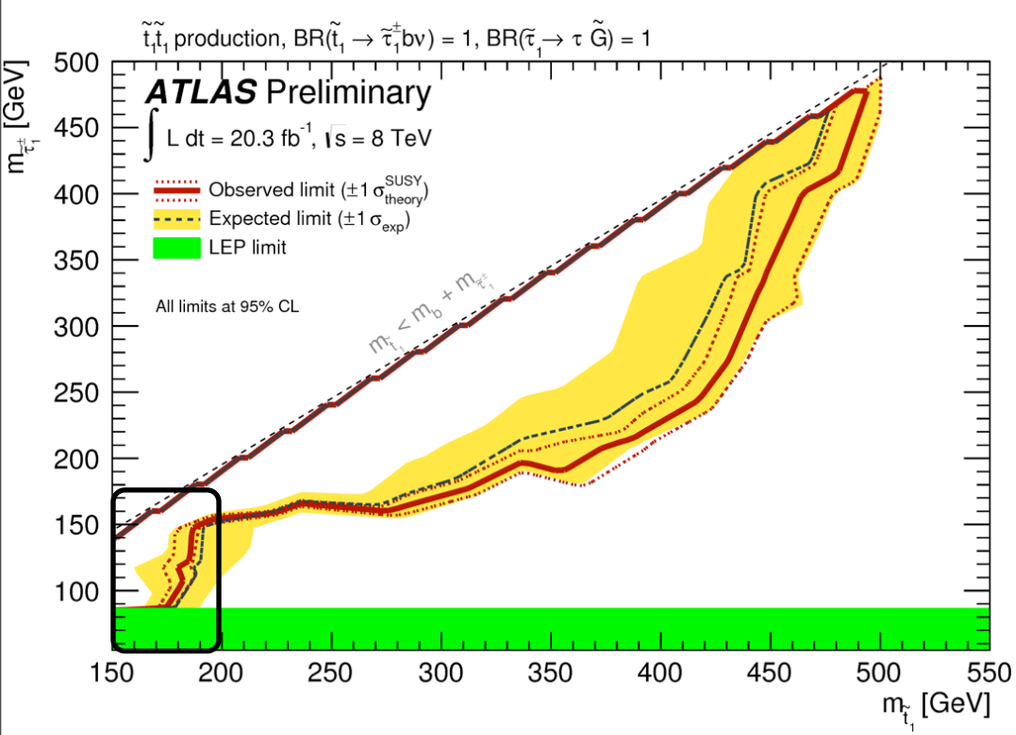


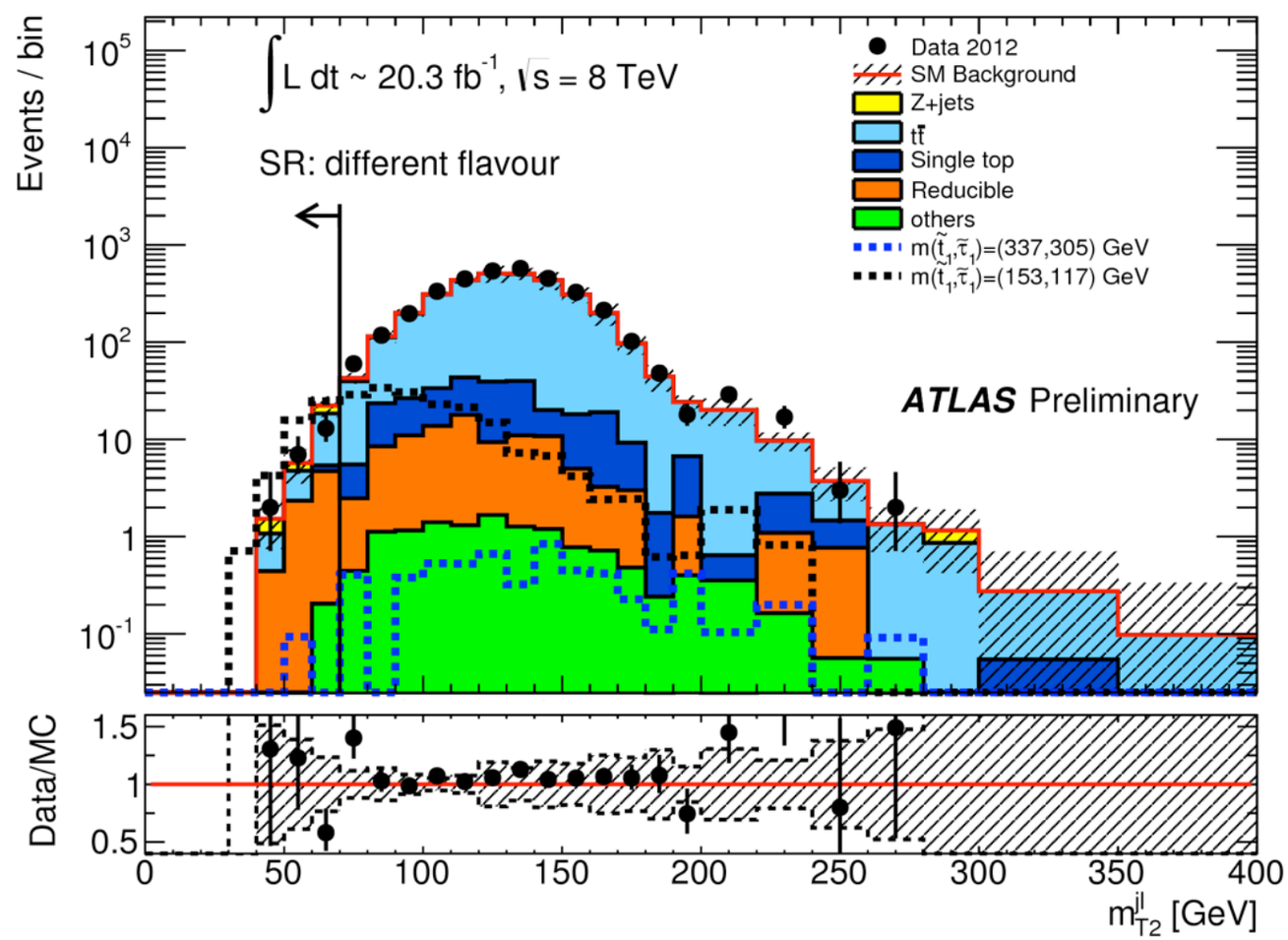
Stop + Stau in GMSB



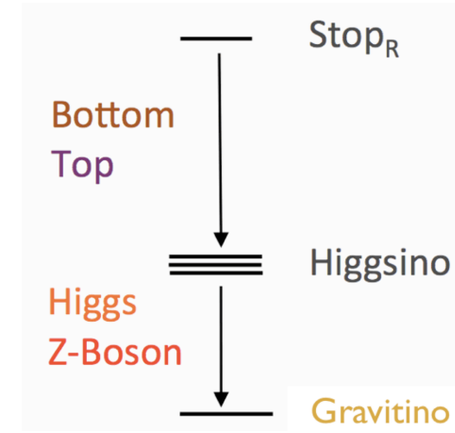
- Expansion of the di-lepton + b + MET stop analysis (MT2)
  - add low mass region sensitivity by constructing MT2 variable for (jet-l) pairs

ATLAS-CONF-2014-014

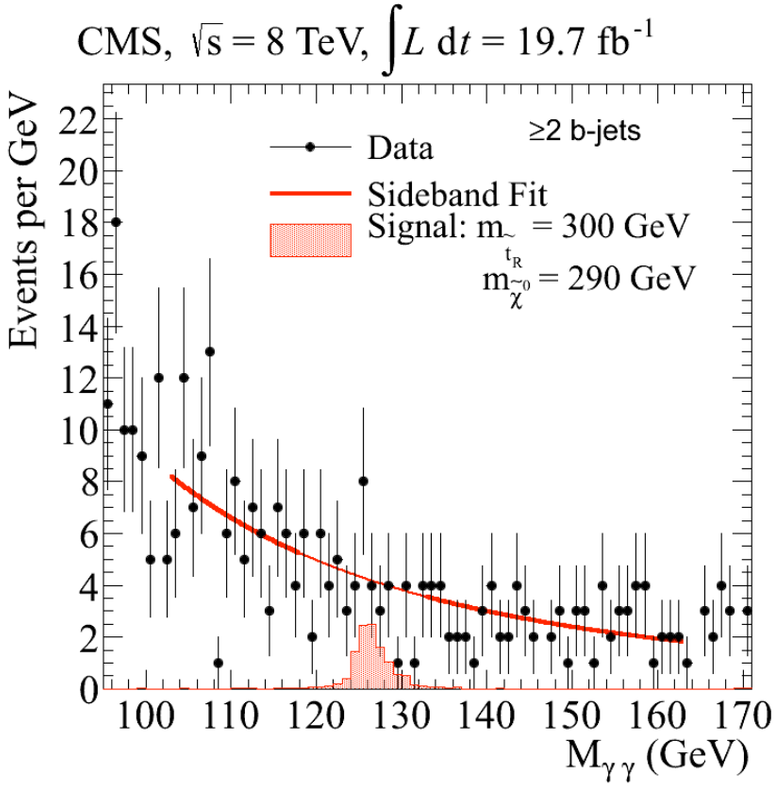


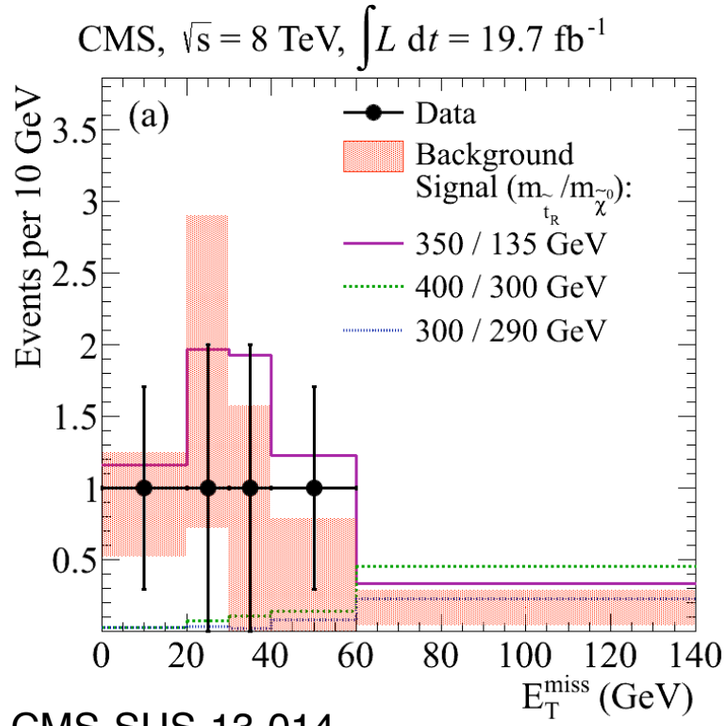


Stop + Higgsino in GMSB

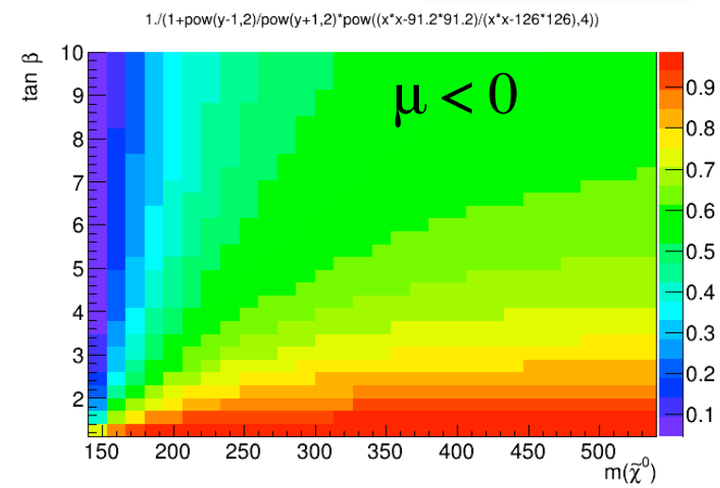


- Events with two higgses and at jets from stop cascades
- use di-photon higgs decay mode: low Br but very clean

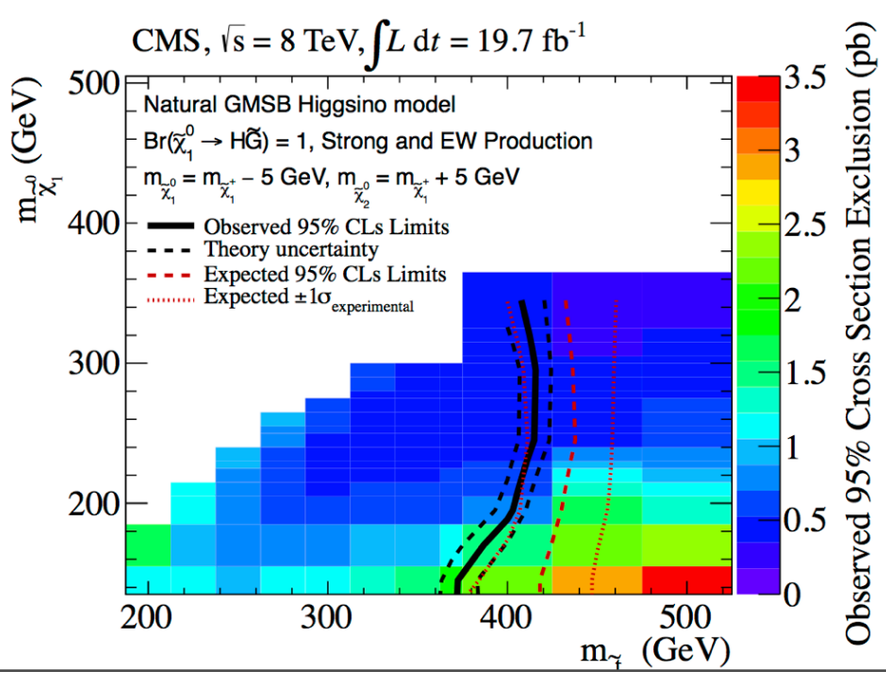




CMS-SUS-13-014

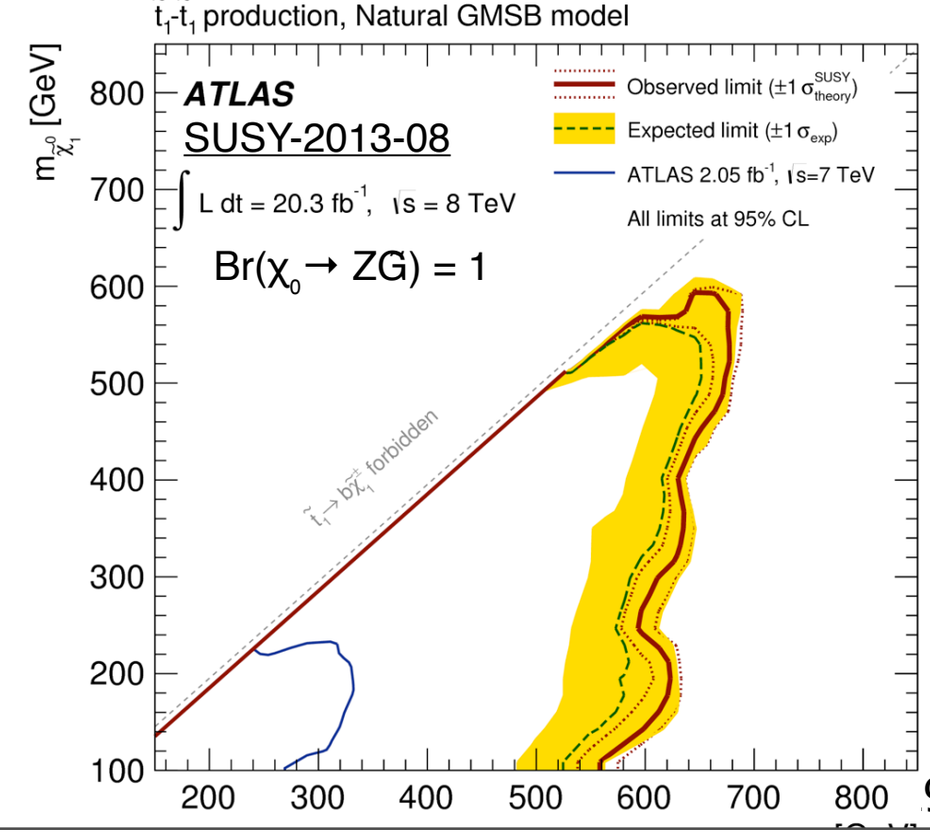


For Z final states use lepton channel



see also SUS-13-022, SUS-13-021 for different stop-higgs topologies

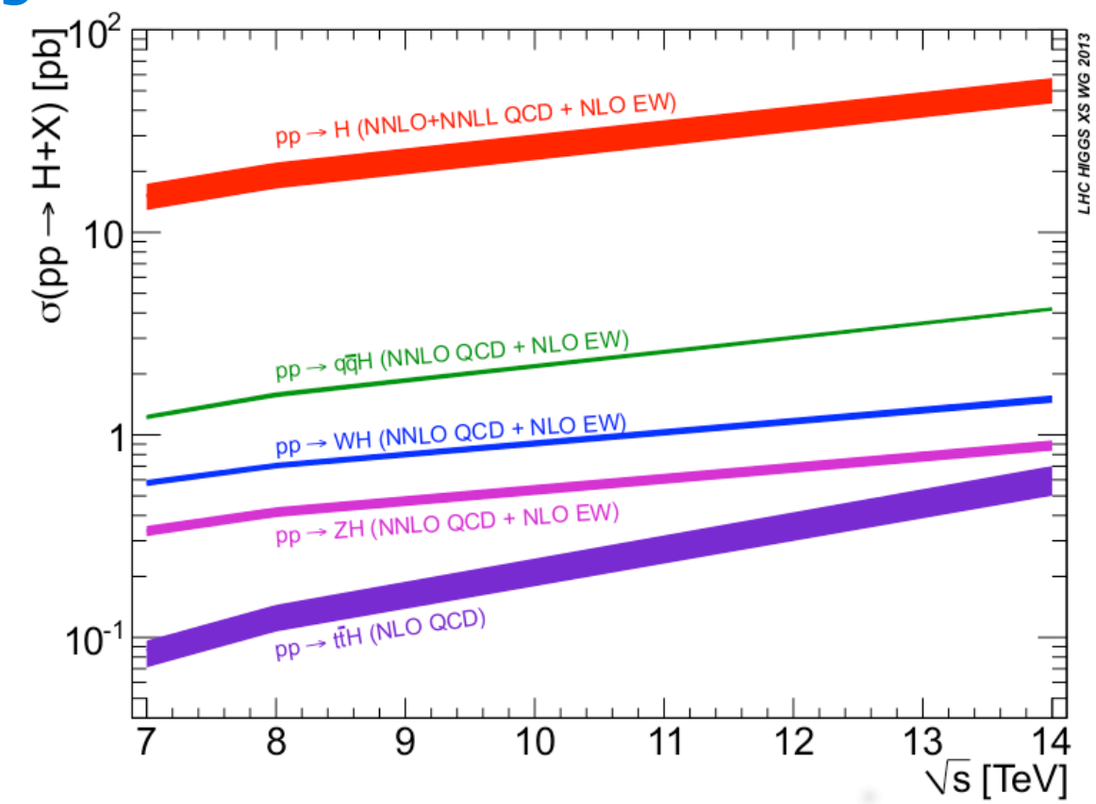
$\tilde{t}_1$-$\tilde{t}_1$ production, Natural GMSB model



Yuri Gershtein

Higgs as New Physics Tag

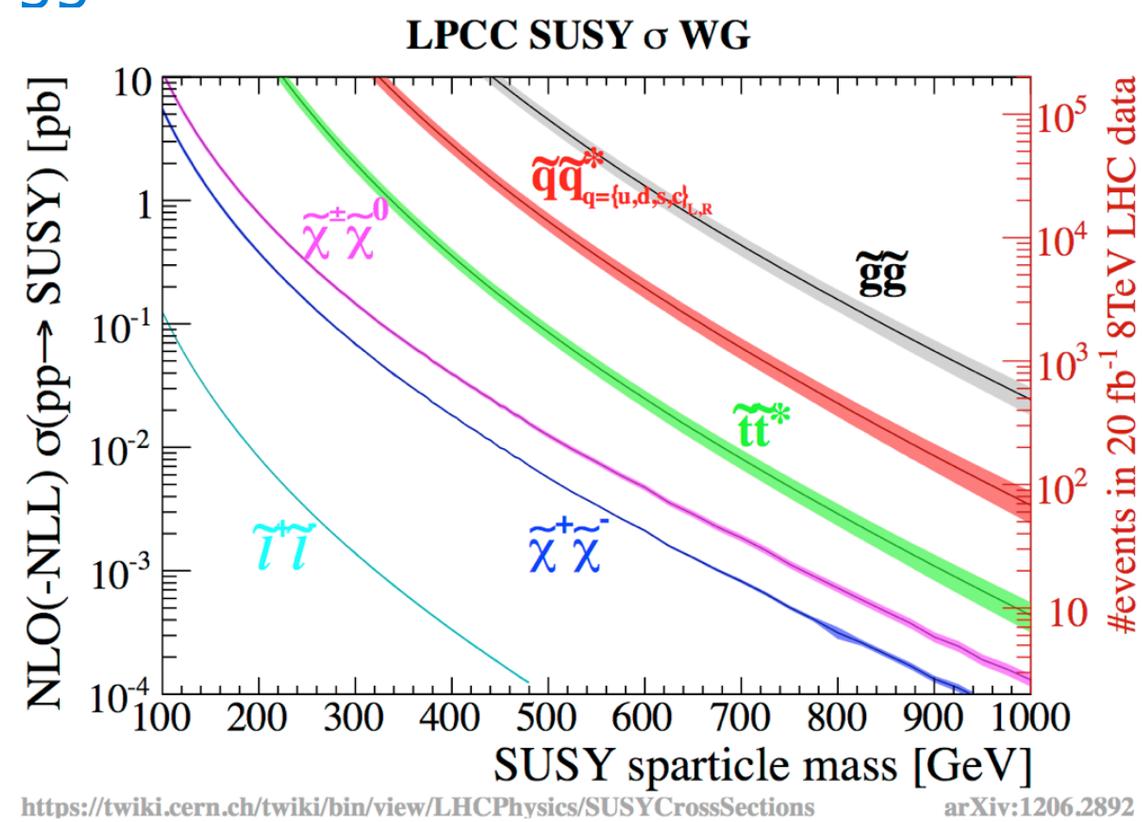
- New physics (SUSY?) cascades may produce higgses as copiously as W's and Z's - but the SM Higgs cross section is tiny compared to W/Z
  - single W: 10^5 pb
    - W+lots of jets (aka top): 10^3 pb
  - single h: 20 (50) pb
    - h + lots of jets (tth): 0.1 (0.6) pb
  - ***requiring higgs production is a New Physics booster***
  - even paying $2 \cdot 10^{-3}$ penalty for $\gamma\gamma$ branching one gets ~reasonable number of events
    - $5/\text{fb} \cdot 1\text{pb} \cdot 2 \cdot 10^{-3} =$ 10 events



- Impact way beyond just SUSY - every time you produce a Higgs you explore EWSB: SUSY here is just a great way to "generate signatures" with Higgs + stuff.

Higgs as New Physics Tag

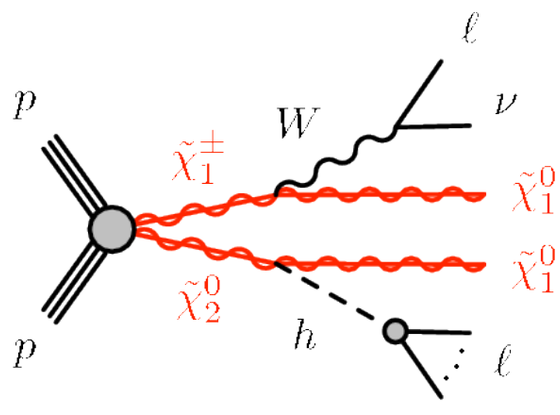
- New physics (SUSY?) cascades may produce higgses as copiously as W's and Z's - but the SM Higgs cross section is tiny compared to W/Z
  - single W: 10^5 pb
    - W+lots of jets (aka top): 10^3 pb
  - single h: 20 (50) pb
    - h + lots of jets (tth): 0.1 (0.6) pb
  - ***requiring higgs production is a New Physics booster***
  - even paying $2 \cdot 10^{-3}$ penalty for $\gamma\gamma$ branching one gets ~reasonable number of events
    - $5/\text{fb} \cdot 1\text{pb} \cdot 2 \cdot 10^{-3} = 10$ events

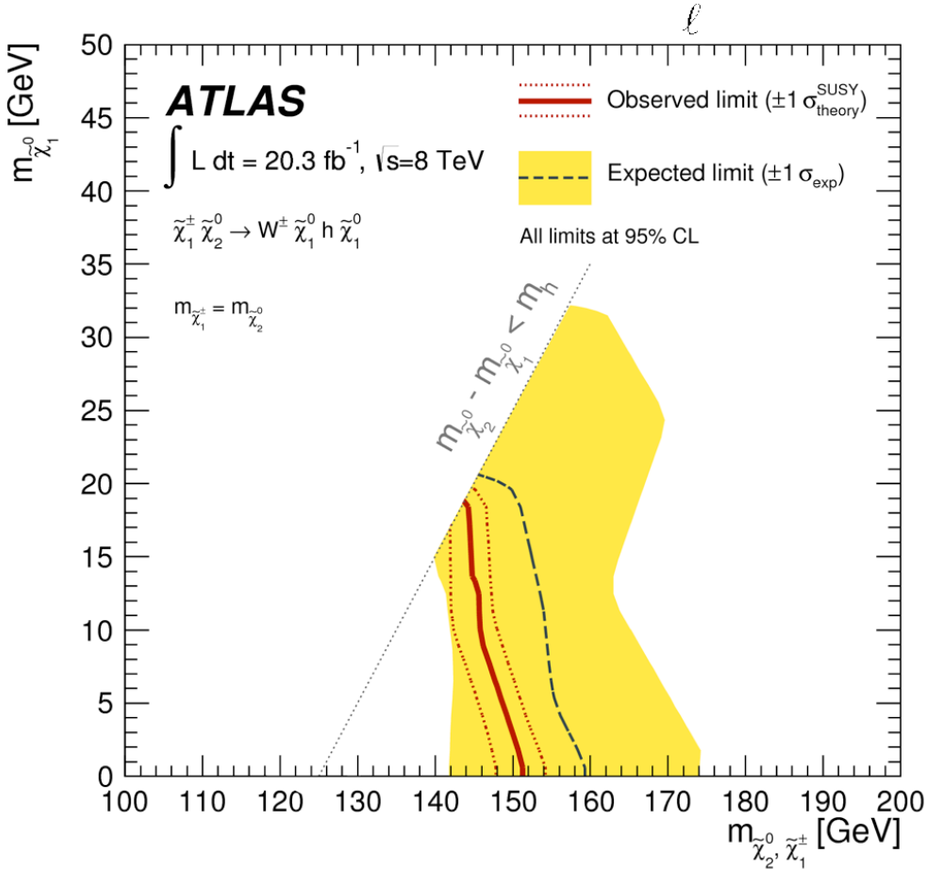


- Impact way beyond just SUSY - every time you produce a Higgs you explore EWSB: SUSY here is just a great way to "generate signatures" with Higgs + stuff.

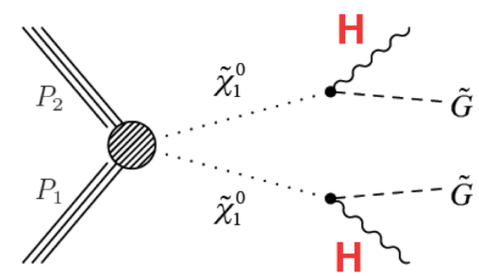
Electroweak production

- Quiet events, small cross sections
- Even combining a lot of channels does not exclude a lot of parameter space

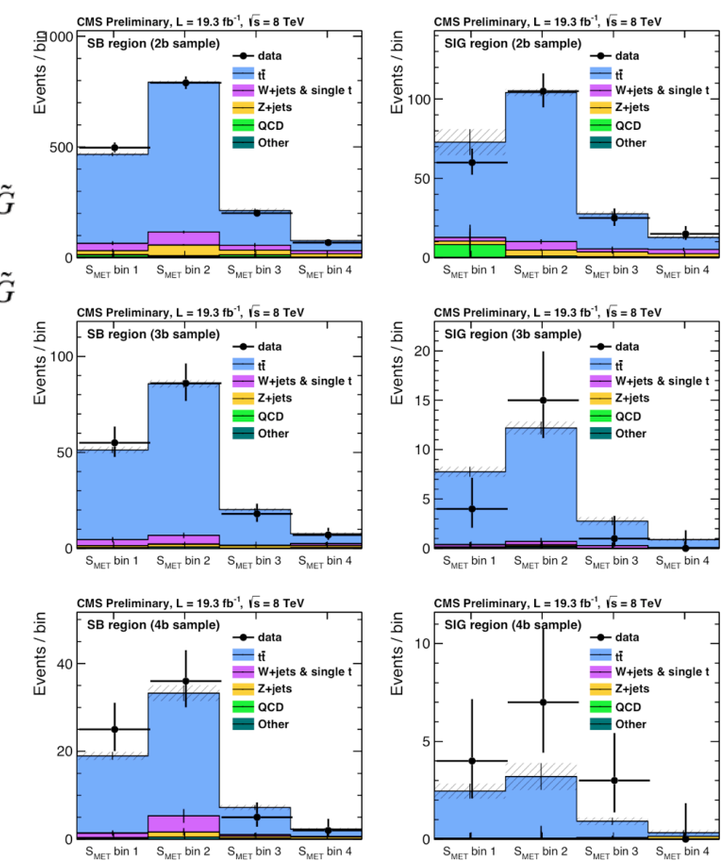




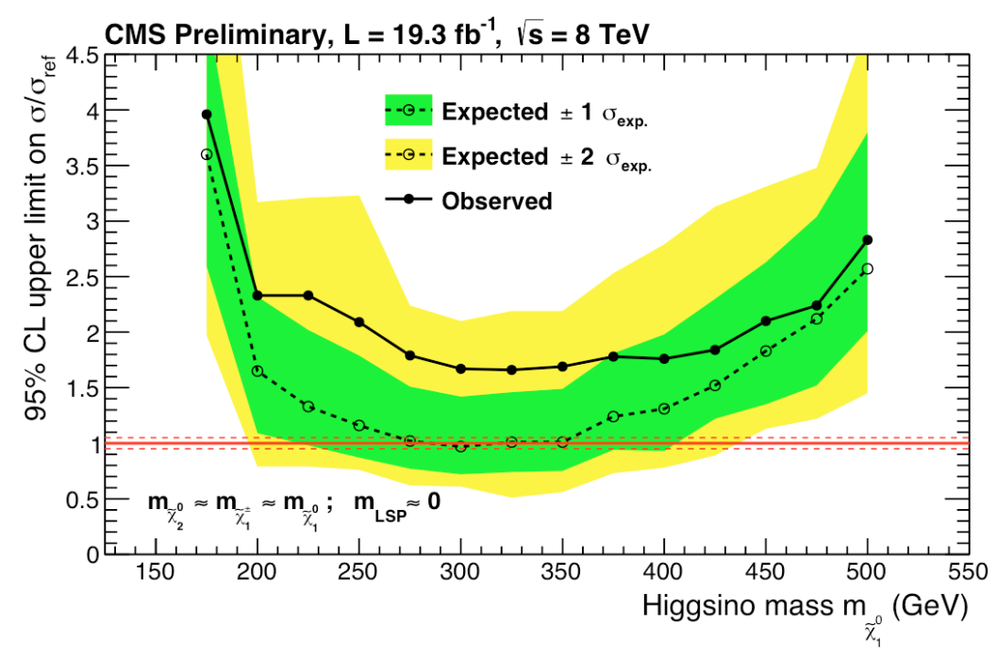
CMS-SUS-13-022



control region signal region



Complementary to diphotons and multileptons: sensitive to higher masses



Summary

- Extensive program of searches for BSM
  - now getting results from really tough final states
  - exclude huge portions of BSM models' parameter space - and we have not run at nominal energy yet
- Although no new sign of BSM yet, we barely started exploring the TeV scale
  - i.e. Natural SUSY is still perfectly viable
- Stay tuned for more Run 1 results and 13 TeV data next year!

Comparison with multileptons

- Higgs decays into leptons
  - mostly though WW and $\tau\tau$
  - Br[h→1 e/μ]≈11%, Br[h→2 e/μ]≈1.8%
  - Br[hh→3 e/μ]≈0.4% - comparable to $\gamma\gamma$
    - in reality, a little less sensitive - soft leptons from τ, W^* and larger background (no mass peak!)