2013 Shanghai Particle Physics and Cosmology Symposium

Higgs, New Physics at LHC and Dark Matter Searches

SPCS 2013, June 3-5, 2013, Shanghai, China

New results from the search for new physics at

- Introduction
- Exotica
- Supersymmetry
- Conclusions

2004

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Arnd Meyer

RWTH Aachen University

June 4, 2013

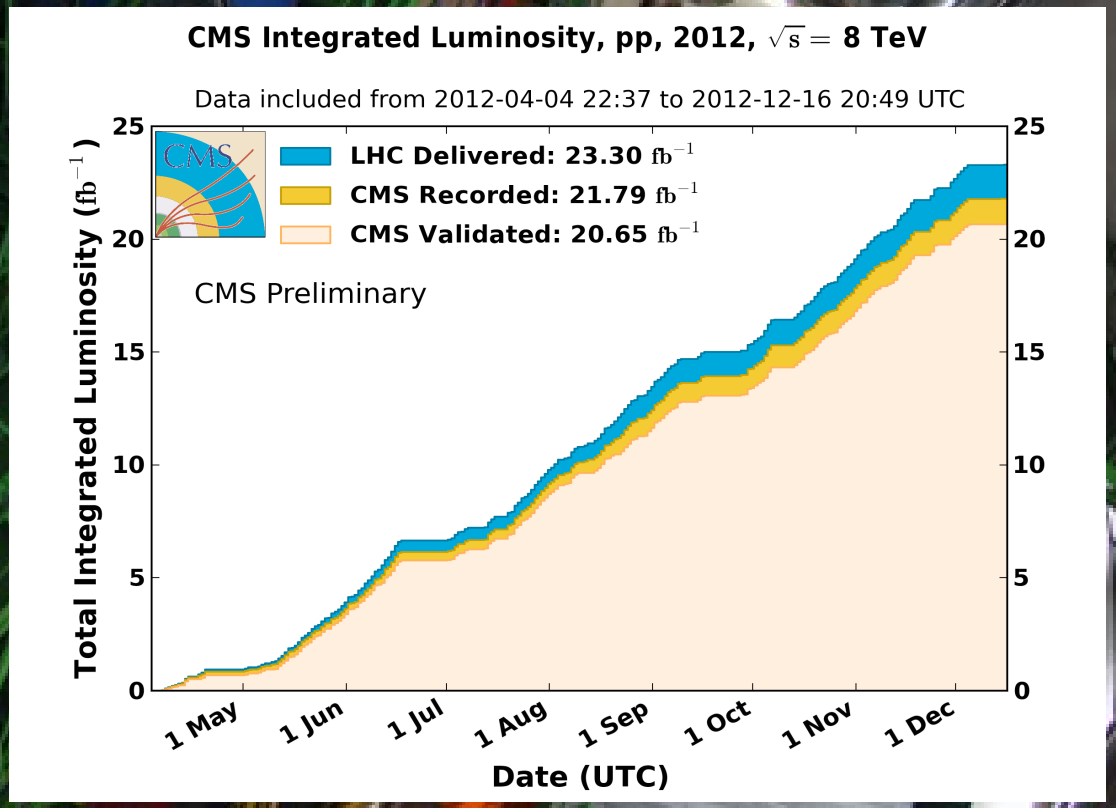
RWTH AACHEN UNIVERSITY

III. Physikalisches Institut A

The Compact Muon Solenoid

Apr 4, 2013

LHC pp run in 2012:
~20 fb^{-1} @ √s = 8 TeV



Length: ~ 21 m
Height: ~ 15 m
Weight: 12500 t

Searches for BSM

- … are a key part of the CMS physics program (and substantial)
- Supersymmetry
- Extra dimensions, black holes, Unparticles
- Extended gauge sector
- Substructure, Leptoquarks
- Technicolor
- 4^{th} generation
- Rare decays
- Metastable, long-lived particles
- …

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- Signature-based, model-inspired
- Already more than 100 BSM physics papers!

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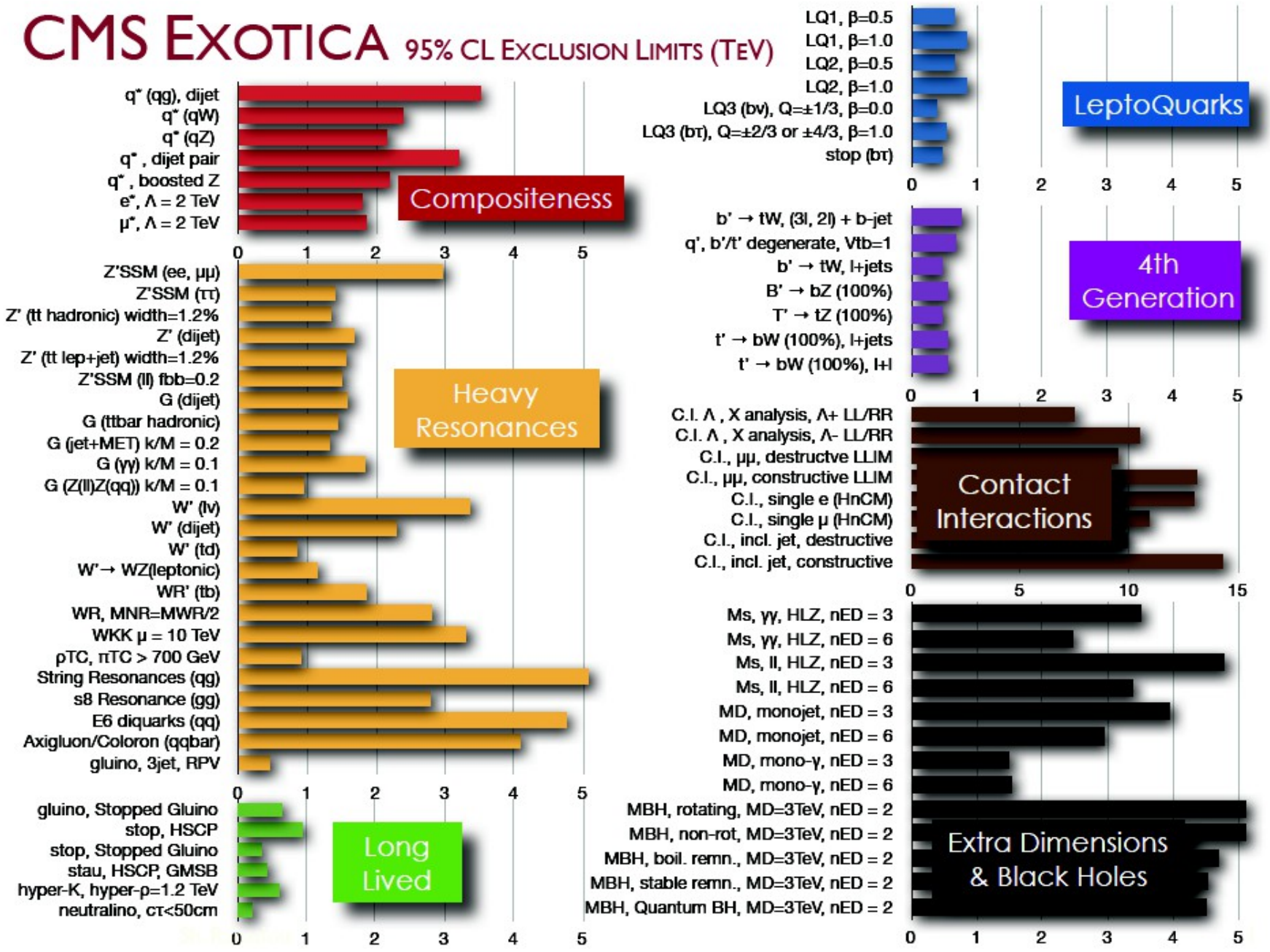
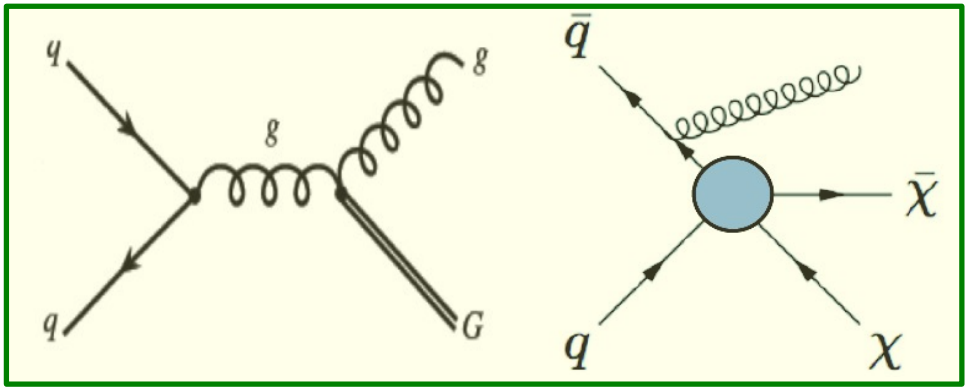
Summary of Exotica at CMS

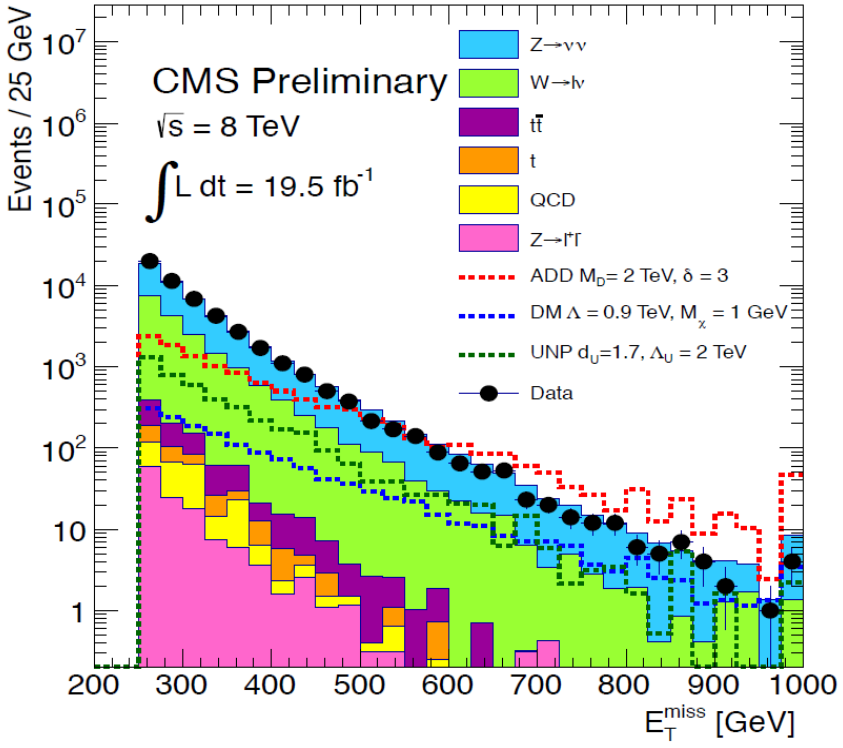


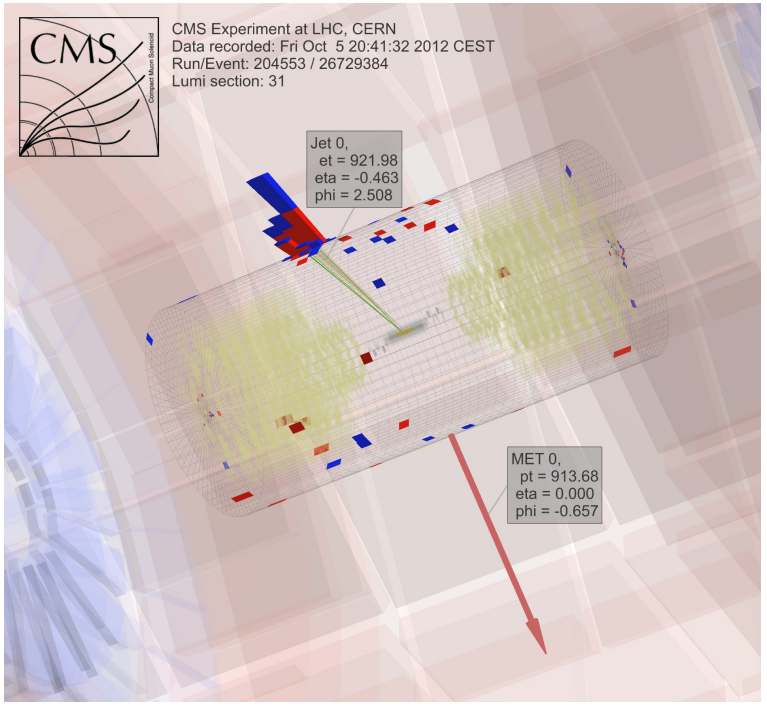
“Mono”-jets

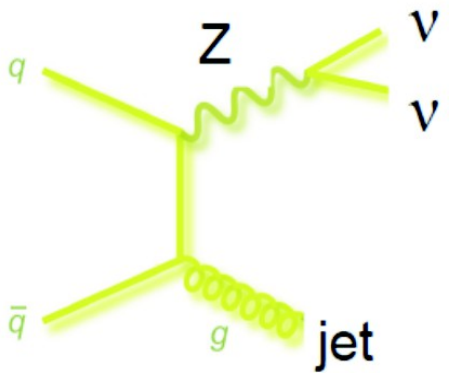
EXO-12-048

- Versatile search channel for many “invisible” new particles
- Highly sensitive for extra dimensions, unparticles, dark matter, …
- Main knobs: jet p_T, missing E_T
  - Allow second jet (not back-to-back)



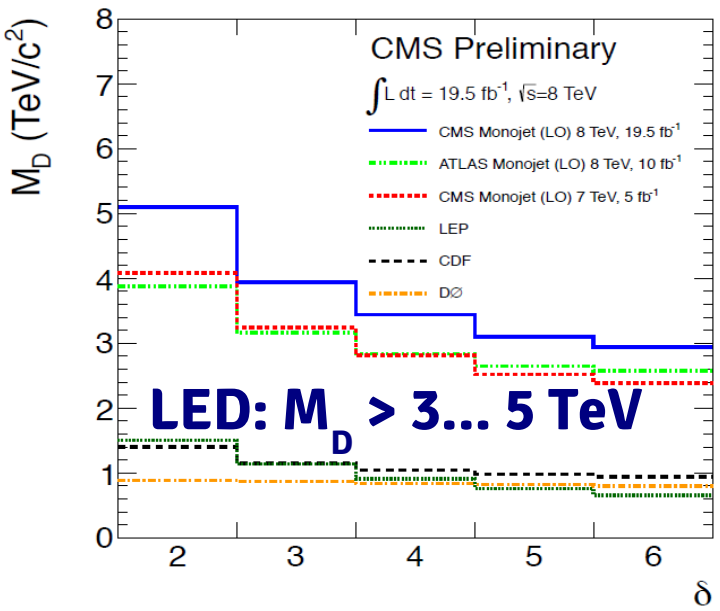


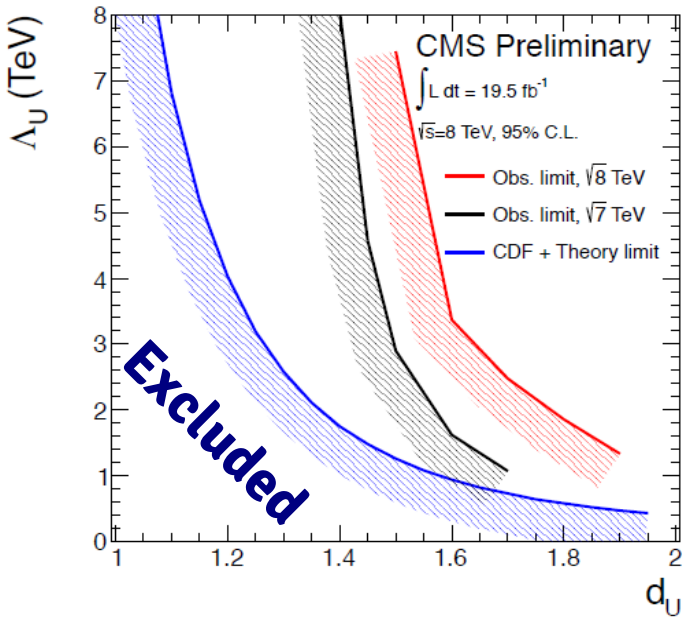


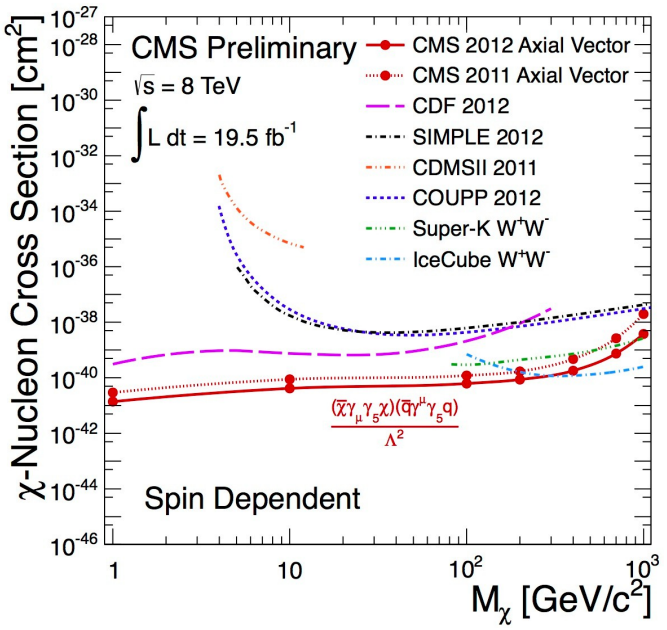


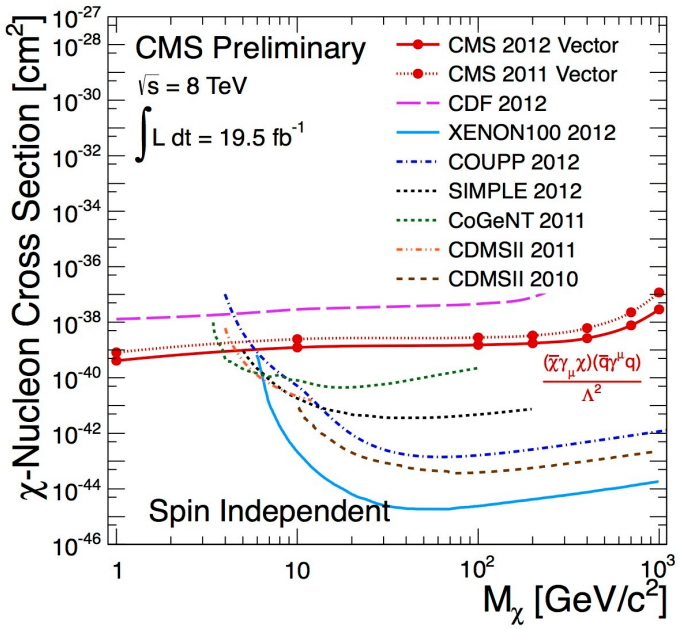
“Mono”-jets

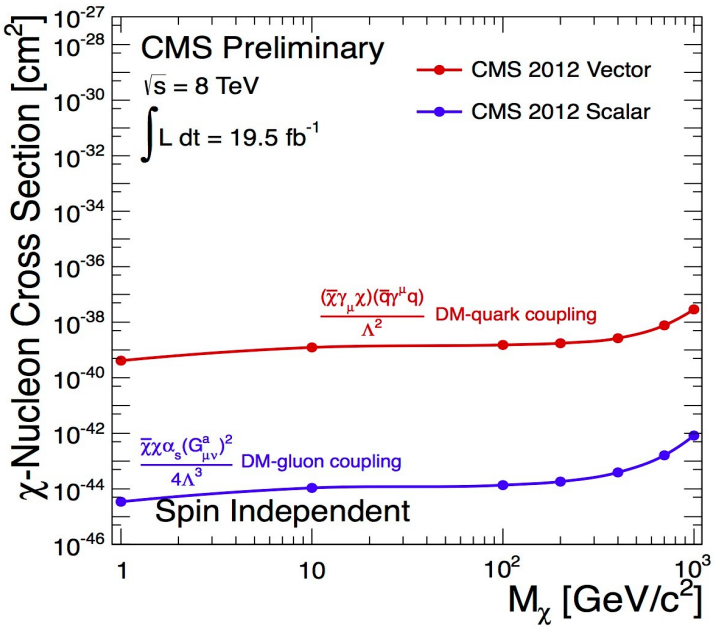
EXO-12-048







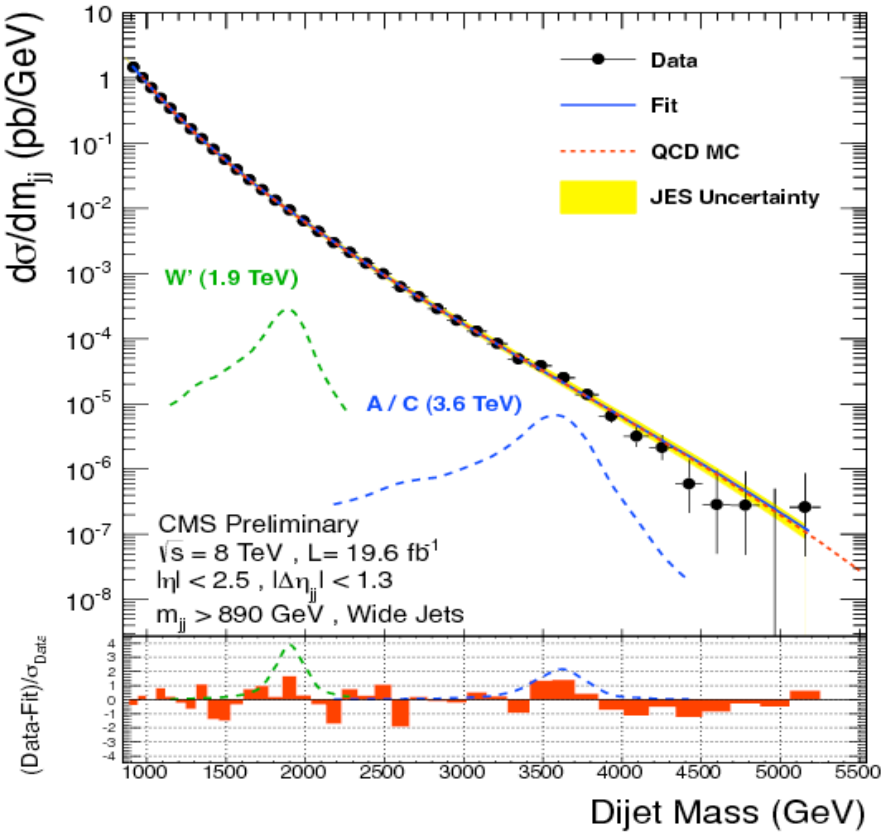


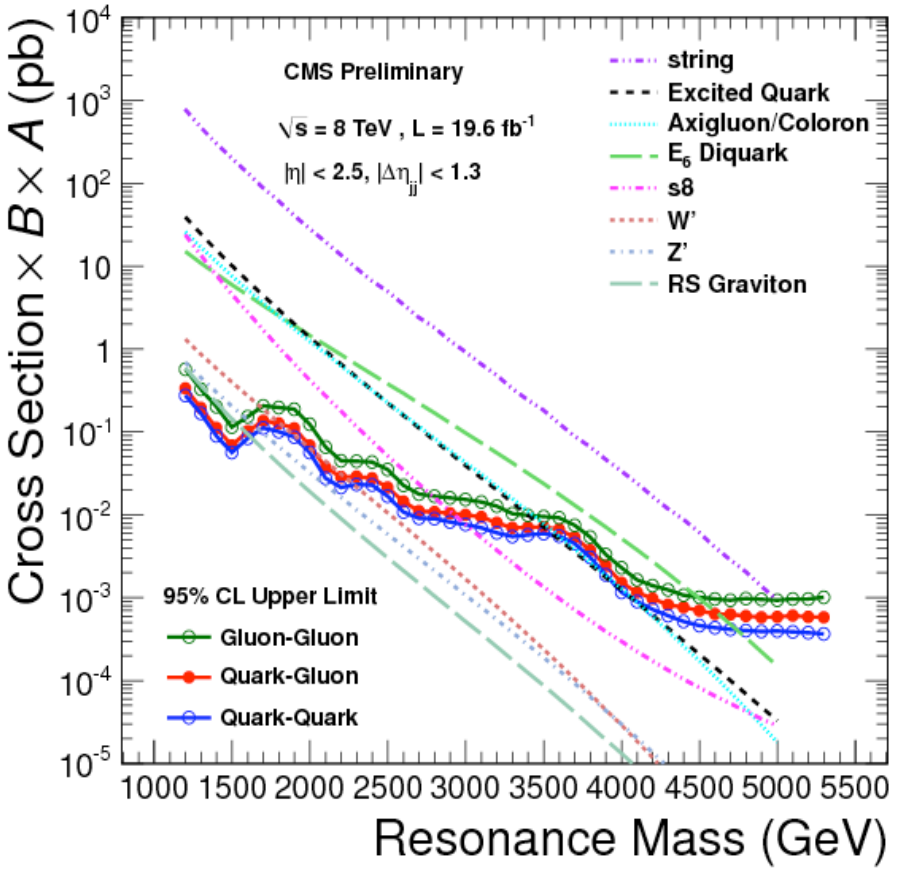


Di-jet searches

EXO-12-059

- Di-jet mass highly sensitive to many new physics models including excited quarks and contact interactions, axigluons, W', Z', ...





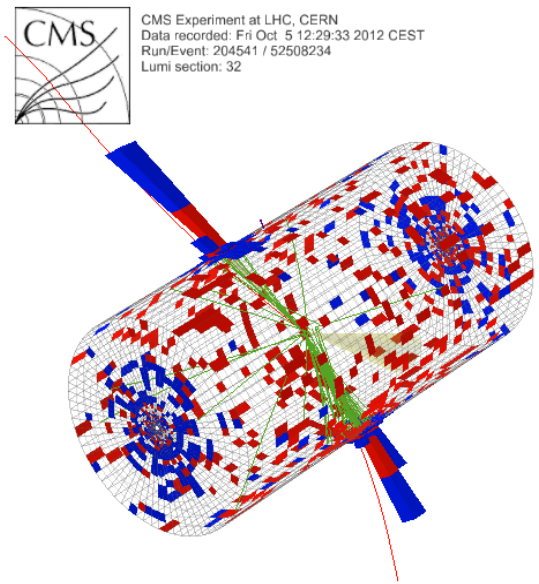
- Present results in a way to allow straightforward application to new models

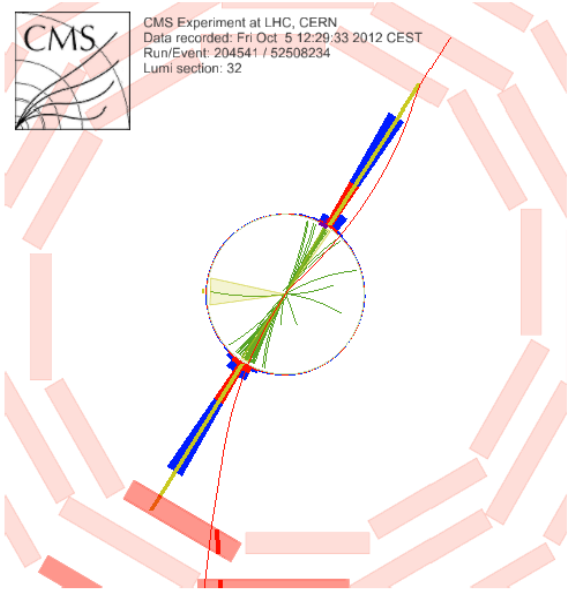
Di-jet searches

EXO-12-059

- Di-jet mass highly sensitive to many new physics models including excited quarks and contact interactions, axigluons, W', Z', ...

Model	Final State	Obs. Mass Excl. [TeV]	Exp. Mass Excl. [TeV]
String Resonance (S)	qg	[1.20,5.08]	[1.20,5.00]
Excited Quark (q^*)	qg	[1.20,3.50]	[1.20,3.75]
E_6 Diquark (D)	qq	[1.20,4.75]	[1.20,4.50]
Axigluon (A)/Coloron (C)	$q\bar{q}$	[1.20,3.60] + [3.90,4.08]	[1.20,3.87]
Color Octet Scalar (s8)	gg	[1.20,2.79]	[1.20,2.74]
W′ Boson (W′)	$q\bar{q}$	[1.20,2.29]	[1.20,2.28]
Z′ Boson (Z′)	$q\bar{q}$	[1.20,1.68]	[1.20,1.87]
RS Graviton (G)	$q\bar{q}$+gg	[1.20,1.58]	[1.20,1.43]



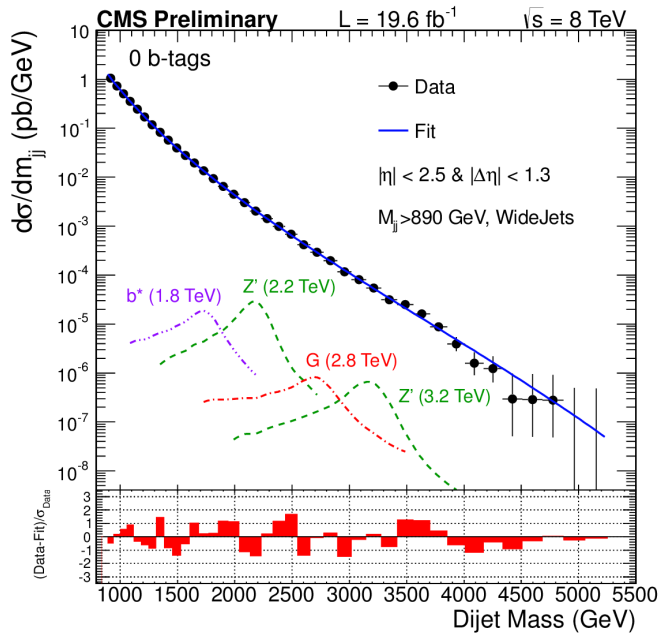


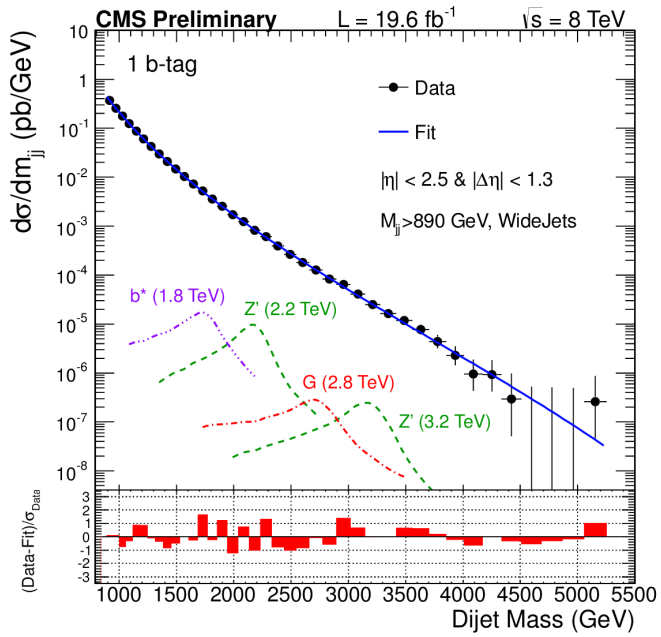
Di-jet mass = 5.15 TeV

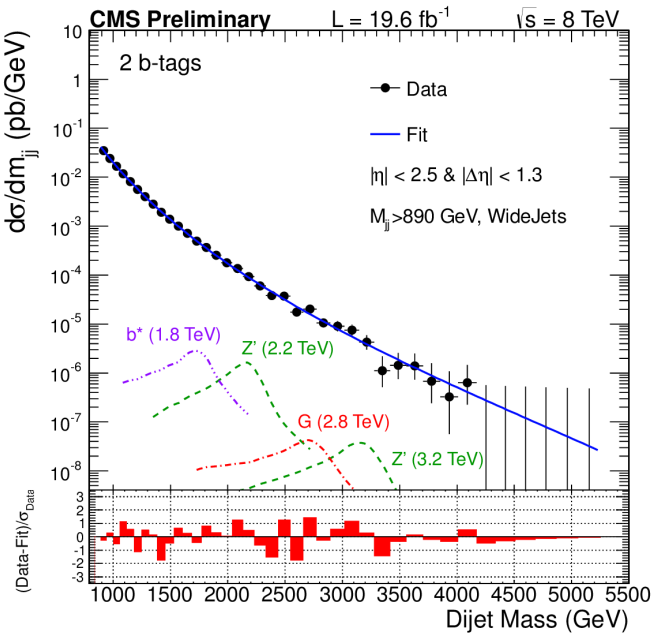
- Present results in a way to allow straightforward application to new models

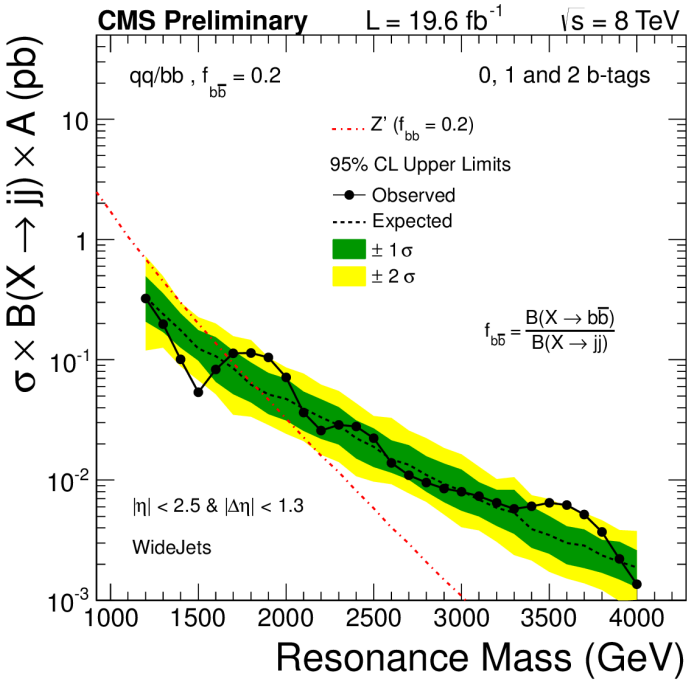
Di-jet searches ($b\bar{b}$, bg)

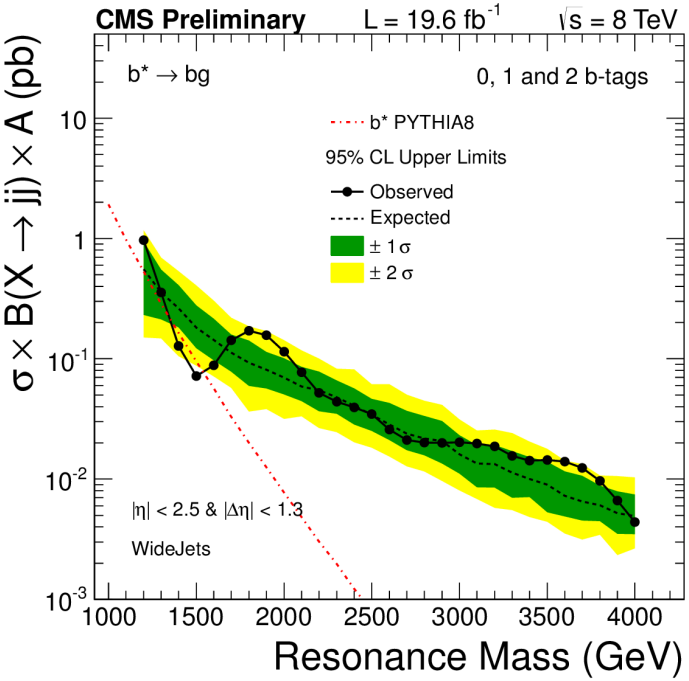
EXO-12-023









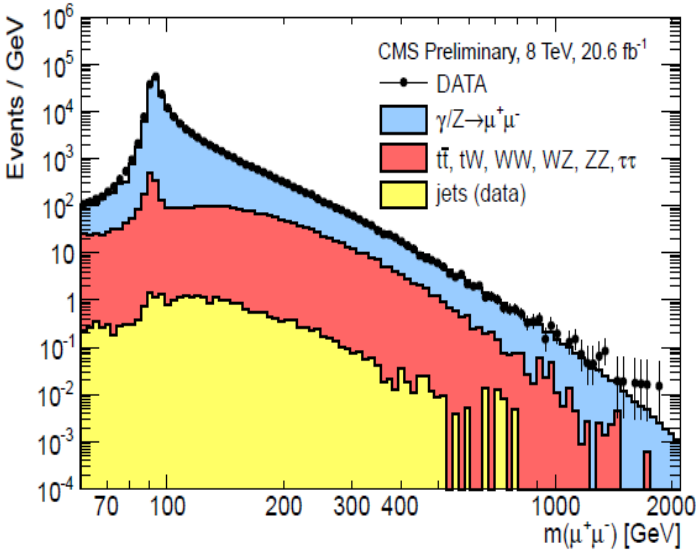


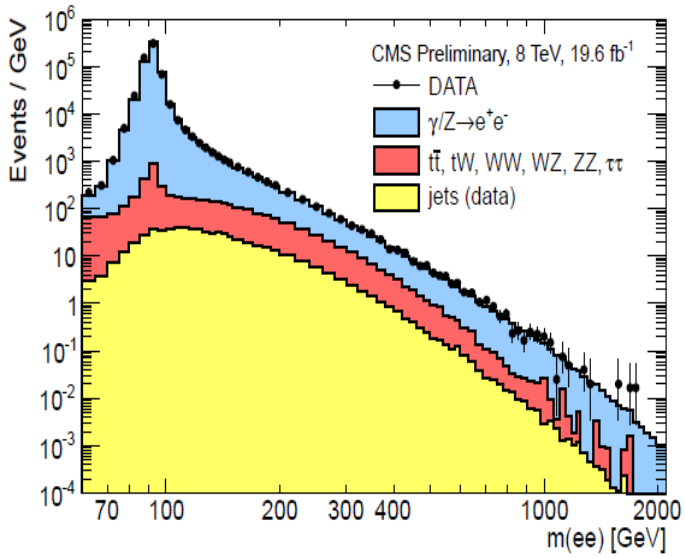
Extend to (0,) 1, 2 b-tags

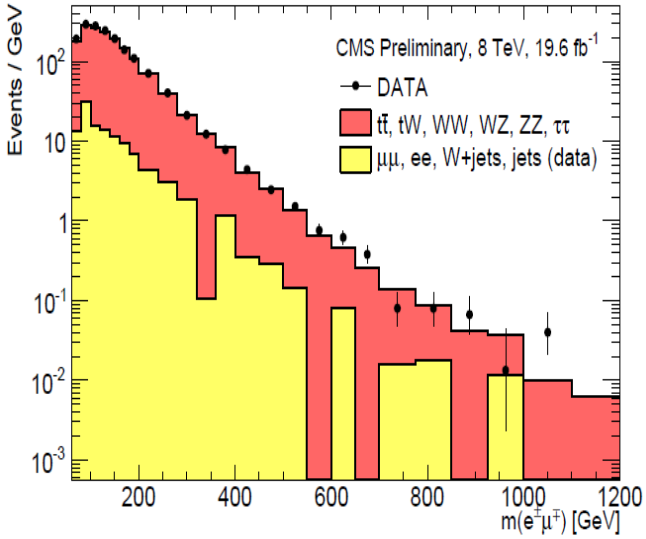
Di-lepton resonances

EXO-12-061

- New heavy gauge bosons → narrow ee,μμ resonances in the TeV region







→ Upper limit on the ratio of Z' (or G_{KK} or …) to SM Z production

95% CL mass limits:

Z' SSM	Z' Psi
2.96 TeV	2.60 TeV

Di-lepton resonances

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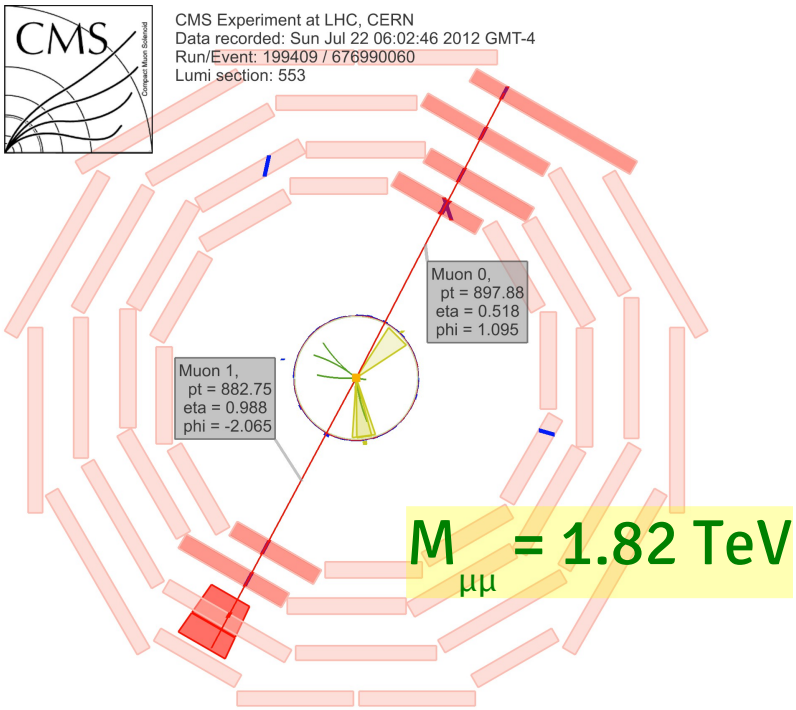
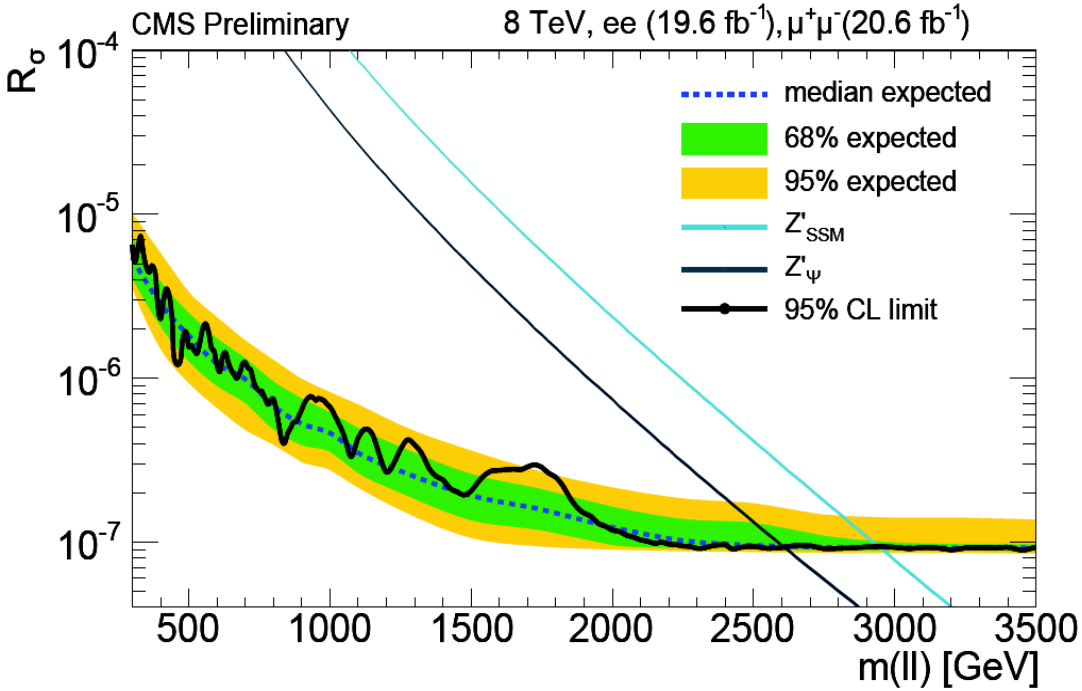




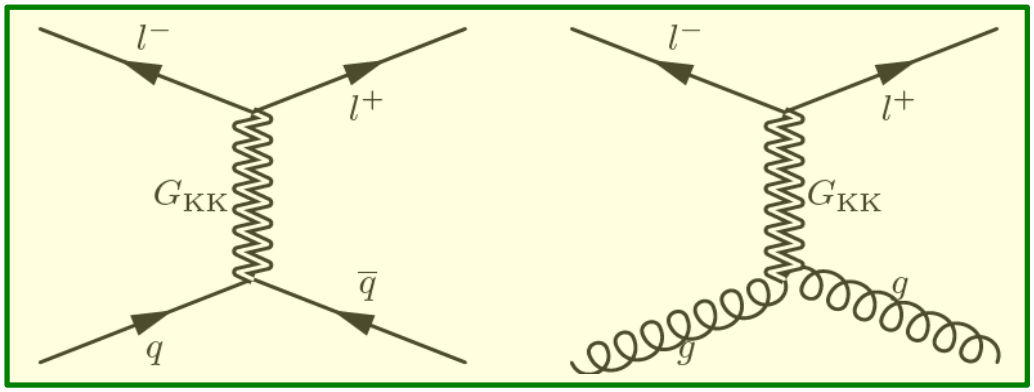
95% CL mass limits:

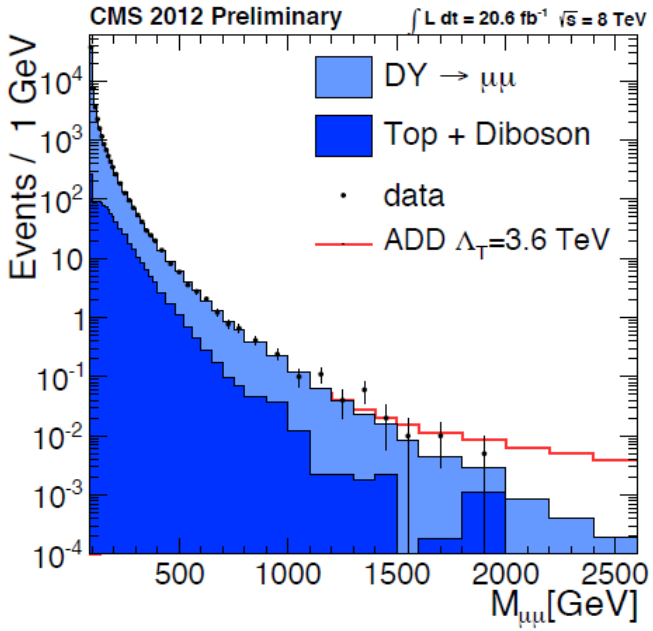
Z' SSM	Z' Psi
2.96 TeV	2.60 TeV

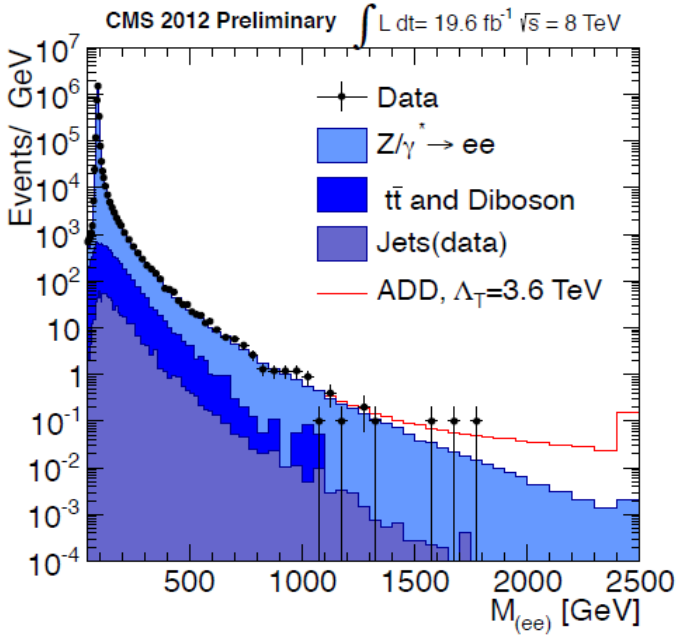
Large extra dimensions (ADD) in ee, μμ

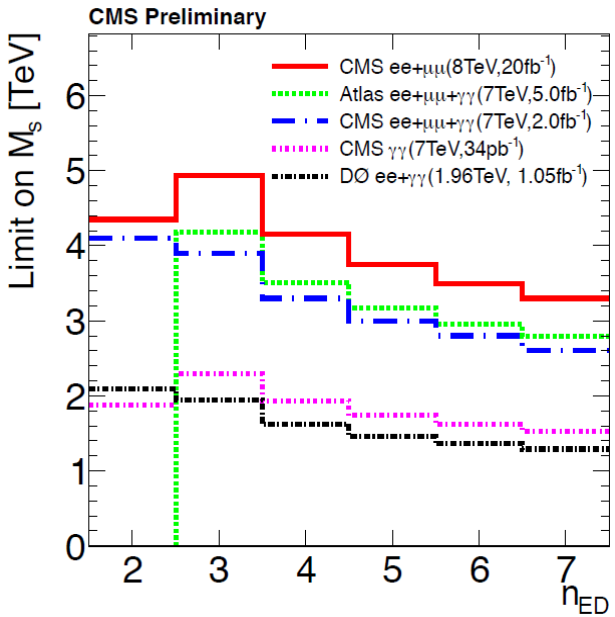
EXO-12-027/031

- Virtual graviton production modifies Drell-Yan spectrum
- Signal region: $M_{ll} > 1.8$ TeV







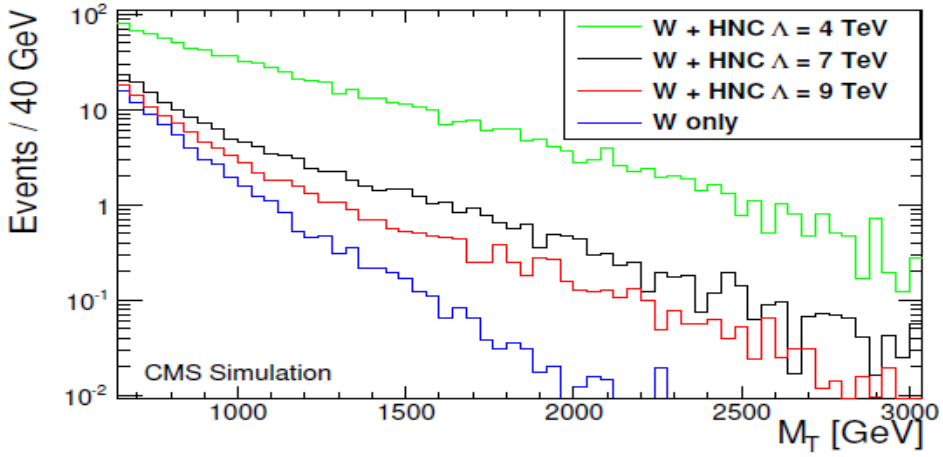


M_S (ADD) at LO 95% CL limits	Lumi. [fb^{-1}]	δ=3 Exp.	δ=3 Obs.	δ=6 Exp.	δ=6 Obs.	Λ_T (GRW) [TeV]
CMS dimuon	20.6	4.34	4.33	3.07	3.06	3.64
CMS dielectron	19.6	4.62	4.64	3.27	3.28	3.90
Combined:	20.6+19.6	4.76	4.77	3.37	3.37	4.01

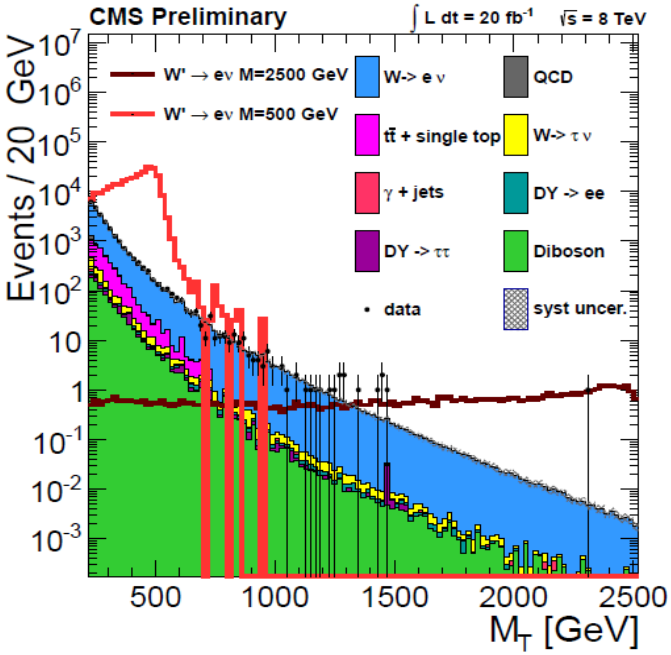
Single lepton + MET (eν, μν)

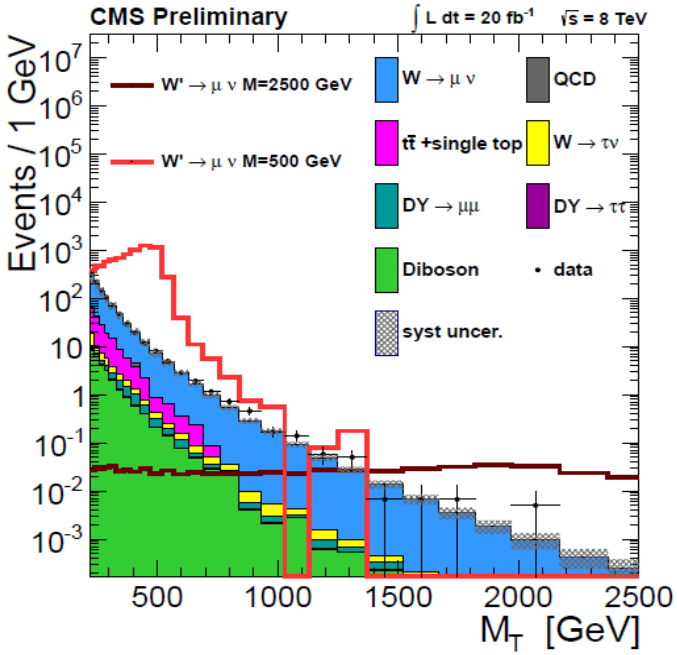
EXO-12-060

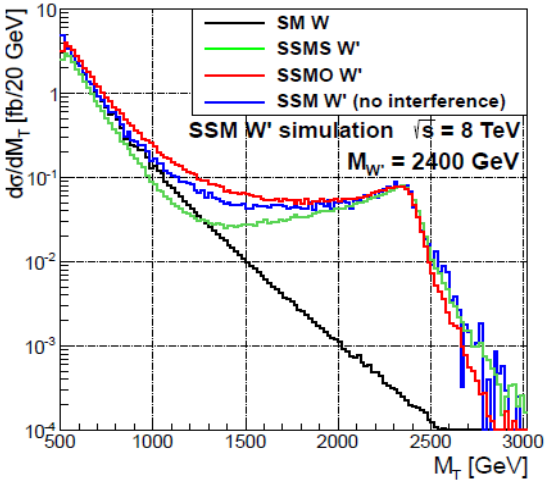
- Many models – considering here:
  - L-R symmetric models
  - sequential SM with and w/o interference
  - UED
  - Contact interaction
- In events with isolated e or μ plus MET, count events above variable M_T threshold

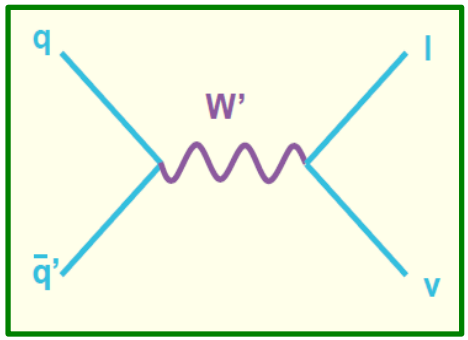


$$M_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{miss} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$







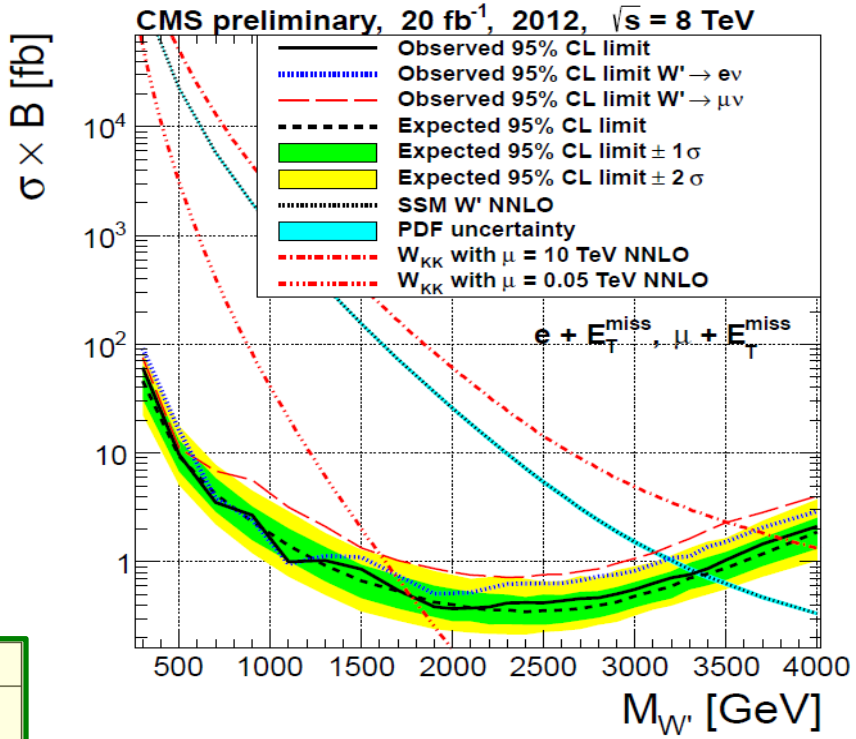


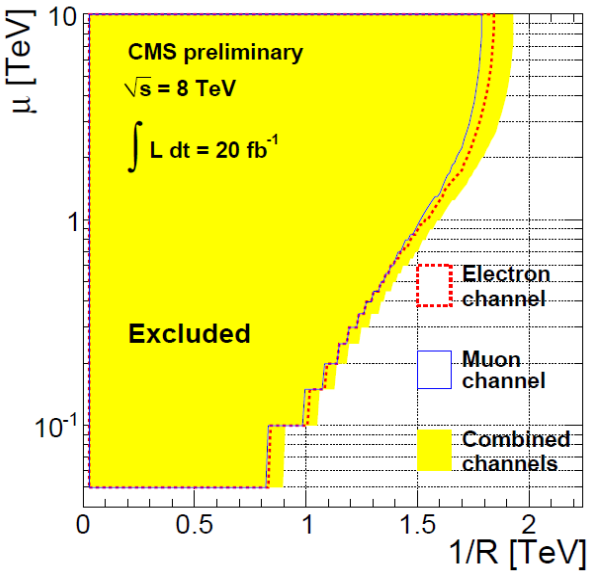
Single lepton + MET (eν, μν)

EXO-12-060

- Limits in SSM:
  - **M > 3.35 TeV (no interference)**
  - **M > 3.10 TeV / 3.60 TeV (destr. / constr.)**
- At high masses, W' mostly off-peak
- Limits on HNC CI:
  - **Λ > 13.0 TeV (e) / 10.9 TeV (μ)**

Model	Channel	Observed limit	Expected limit
SSM	e	$m_{W'} < 3.20$TeV	$m_{W'} < 3.25$TeV
SSM	μ	$m_{W'} < 3.15$TeV	$m_{W'} < 3.10$TeV
SSM	combined	$m_{W'} < 3.35$TeV	$m_{W'} < 3.40$TeV
SSMO	e	$m_{W'} < 3.60$TeV	$m_{W'} < 3.60$TeV
SSMO	μ	$m_{W'} < 3.05$TeV	$m_{W'} < 3.30$TeV
SSMO	combined	$m_{W'} < 3.60$TeV	$m_{W'} < 3.60$TeV
SSMS	e	$m_{W'} < 3.00$TeV	$m_{W'} < 3.10$TeV
SSMS	μ	$m_{W'} < 2.80$TeV	$m_{W'} < 2.90$TeV
SSMS	combined	$m_{W'} < 3.10$TeV	$m_{W'} < 3.20$TeV
W^2_{KK}	μ=0.05 TeV, combined	$m_{W^2_{KK}} < 1.7$TeV	$m_{W^2_{KK}} < 1.7$TeV
W^2_{KK}	μ=10.0 TeV, combined	$m_{W^2_{KK}} < 3.7$TeV	$m_{W^2_{KK}} < 3.6$TeV
HNC CI	e	$\Lambda < 13.0$ TeV	$\Lambda < 13.3$ TeV
HNC CI	μ	$\Lambda < 10.9$ TeV	$\Lambda < 12.2$ TeV

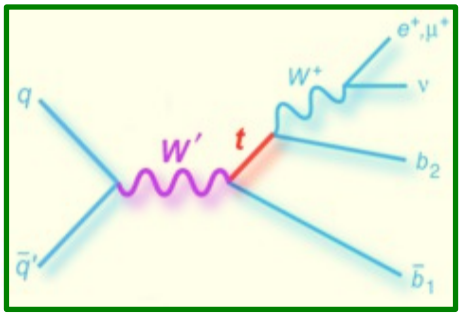


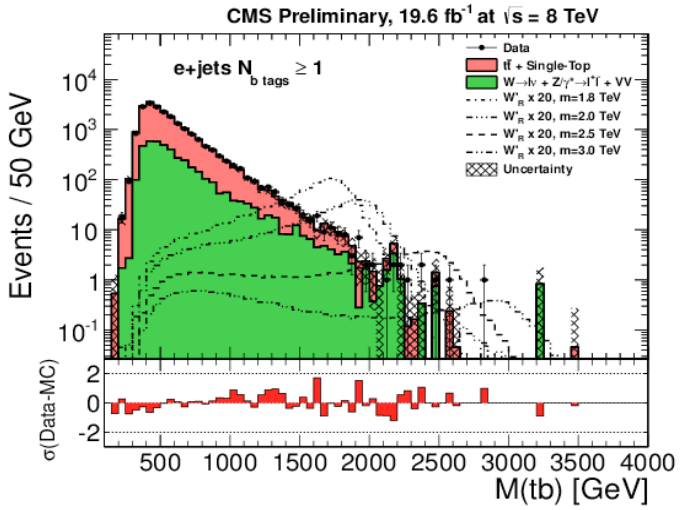


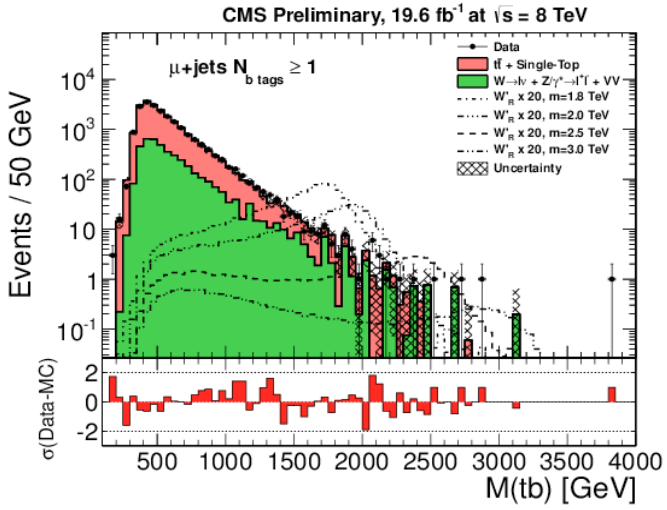
W' → t b

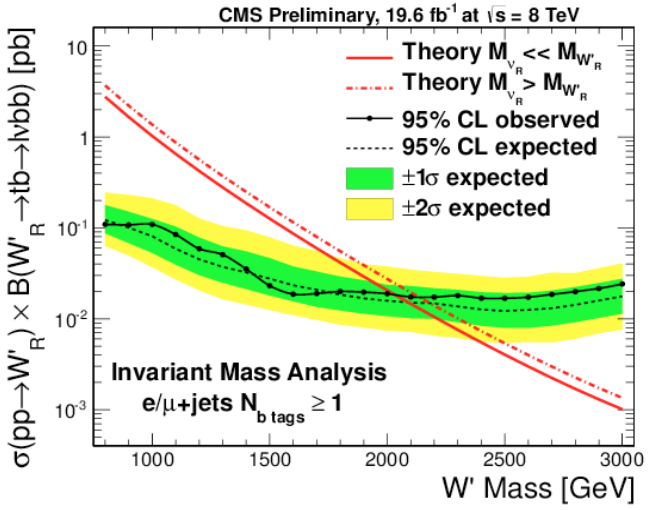
B2G-12-010

- Searches in W' → quark final states important to complement leptonic searches, in case decays into leptons are suppressed
- Enhanced couplings to third generation possible
- Signature is a high p_T isolated lepton, large MET, and 2 b-jets (one b-tag required)
- Exclude **M(W') < 2.03 TeV** at 95% CL for W_R and W_L w/o interference
- Also give limits for arbitrary combinations of left-handed or right-handed couplings





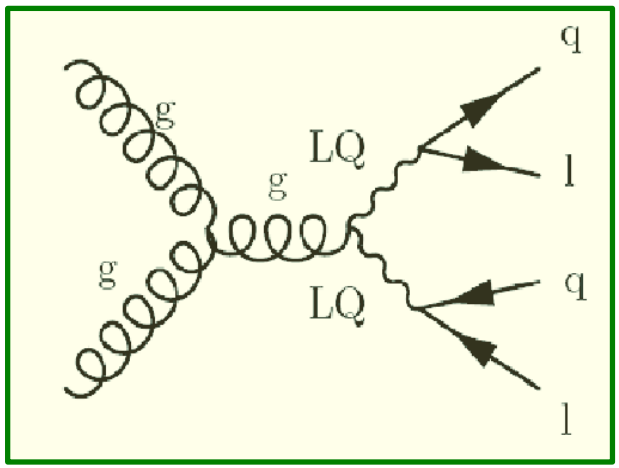


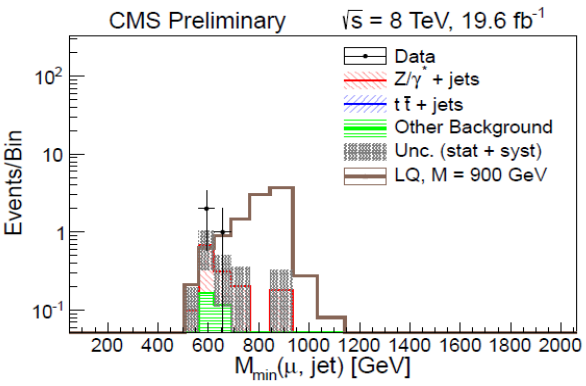


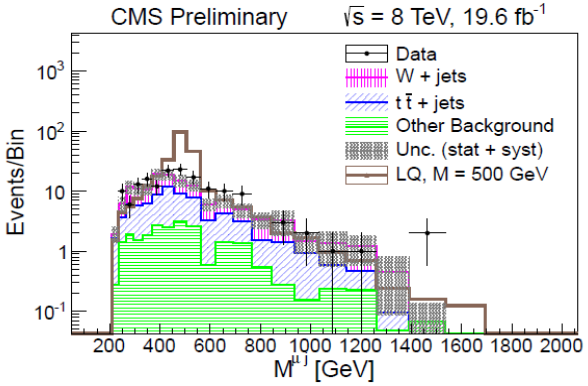
LQ2 (μν+jj, μμ+jj)

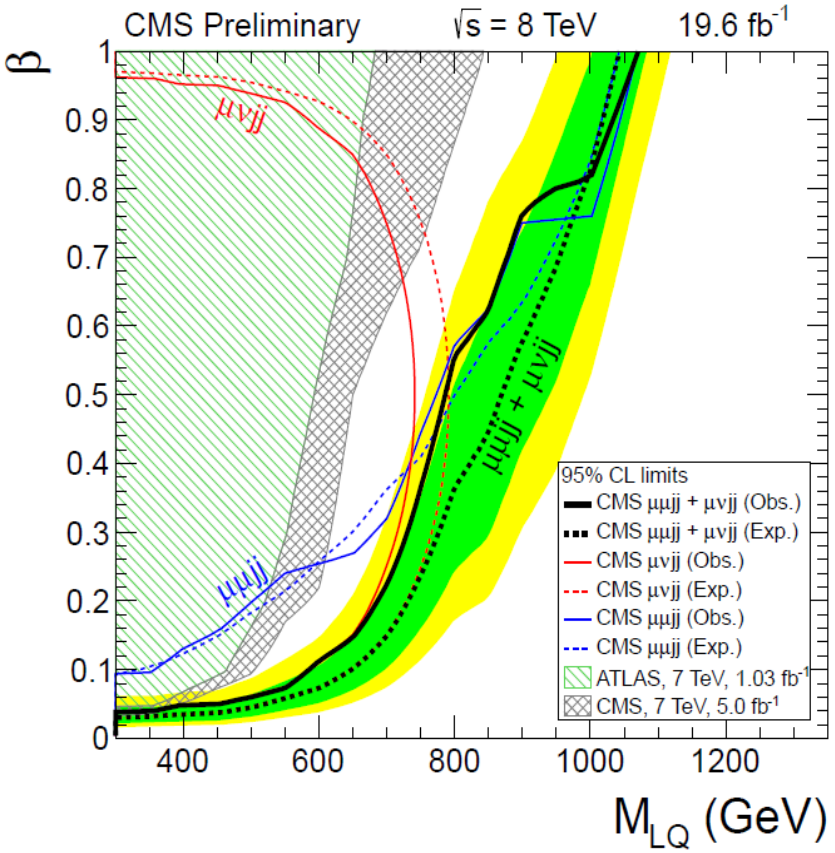
EXO-12-042

- Carrying both lepton and baryon numbers, coupling to lepton-quark pair
- Fractional charge, three generations
- Here: pair production of scalar LQ, coupling to one generation only
- Parameters: LQ mass, BF to lq (β)







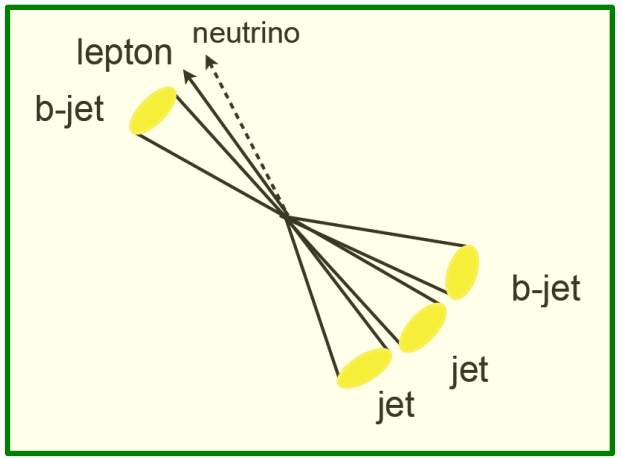


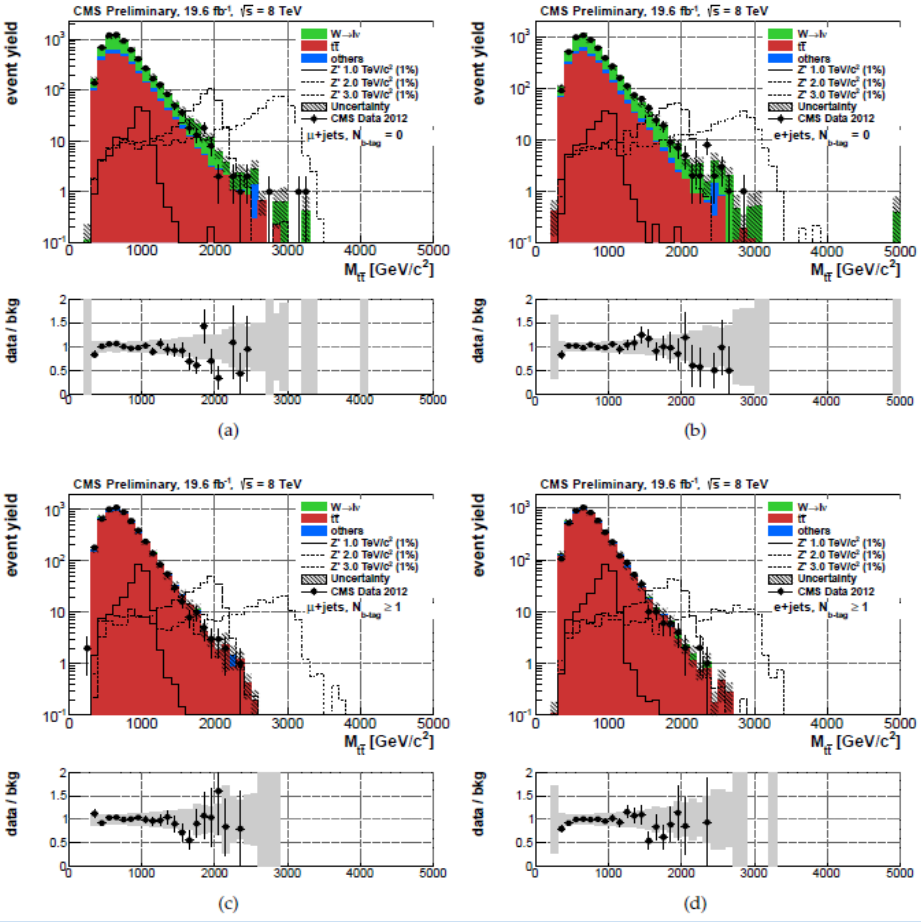
M > 1070 (785) GeV for B(LQ→μq) = 1 (0.5)

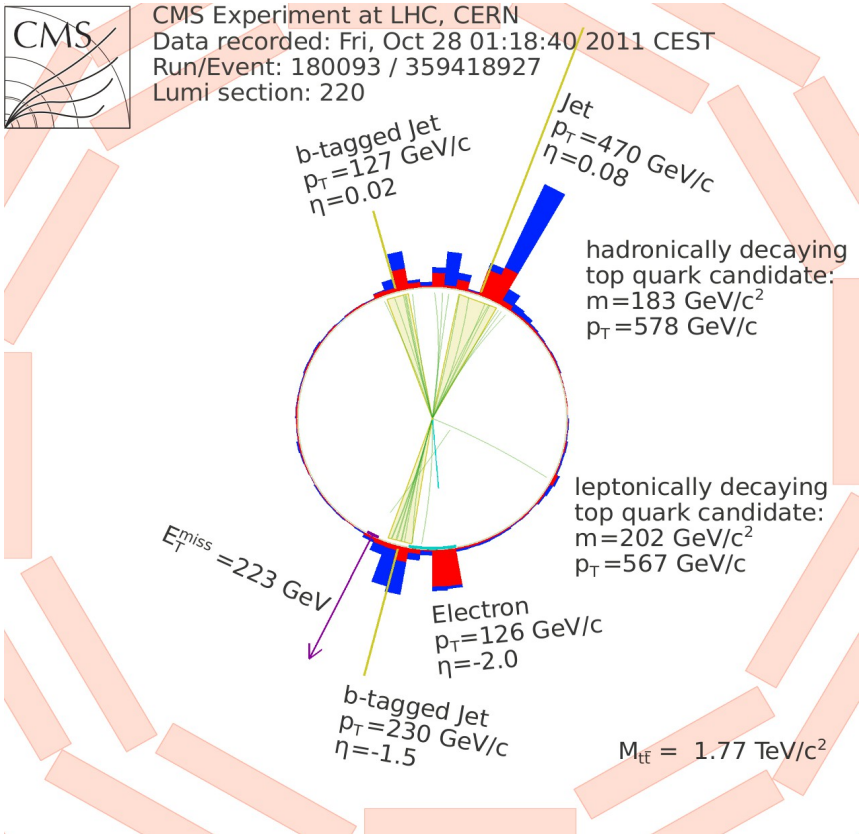
$Z' \rightarrow t\bar{t} \rightarrow e/\mu$ + jets

B2G-12-006

- 1 lepton + MET + >=2 jets
- 0 or 1 b-tag
- Define χ^2 for top hypotheses
  - Separately optimized for low mass ($M_{t\bar{t}}$ <~ 1 TeV, non-boosted) and high mass (boosted) regime



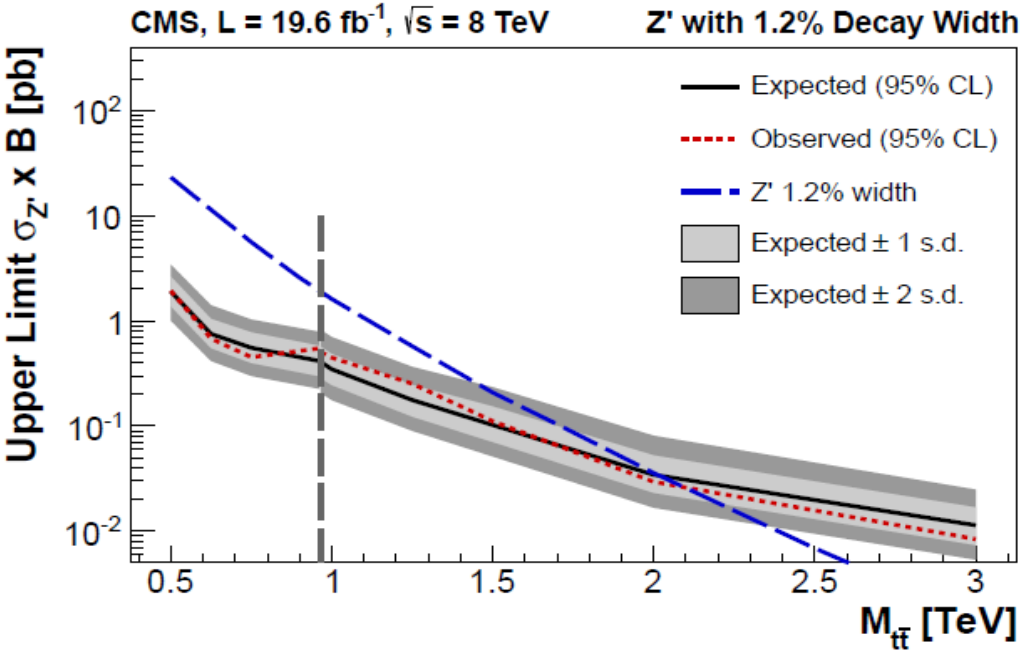


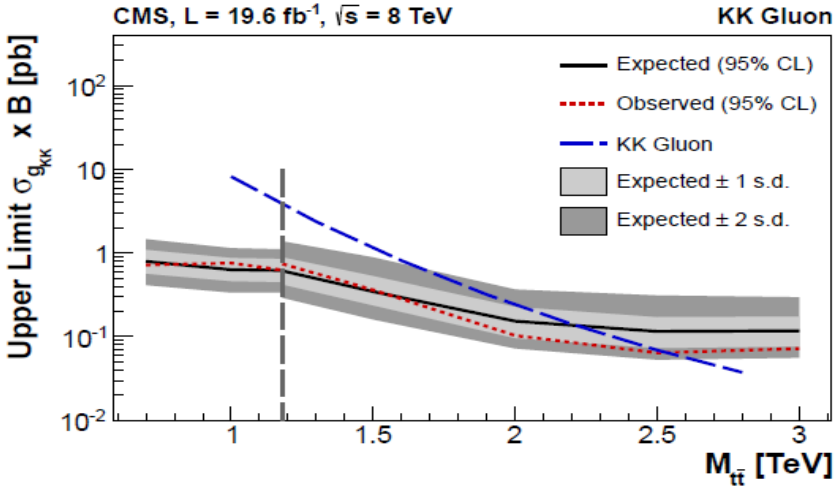


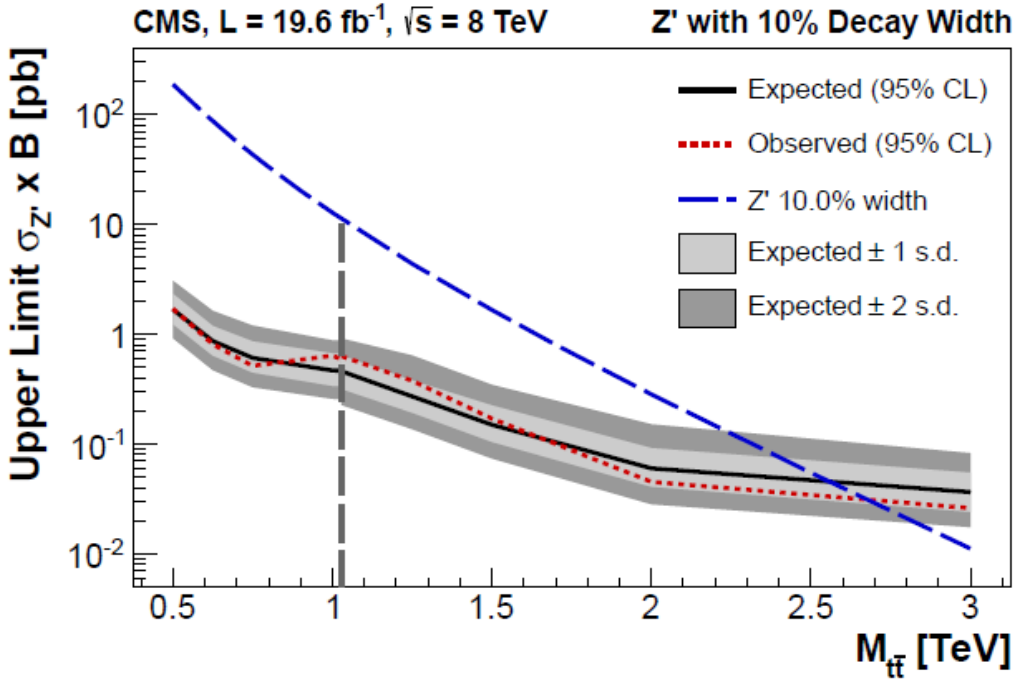
$Z' \rightarrow t\bar{t} \rightarrow e/\mu$ + jets

B2G-12-006

- Topcolor Z' limits with 95% CL:
  - Narrow: **M(Z') > 2.1 TeV**
  - Wide: **M(Z') > 2.7 TeV**
- Randall-Sundrum model:
  - **M(KK gluon) > 2.5 TeV**



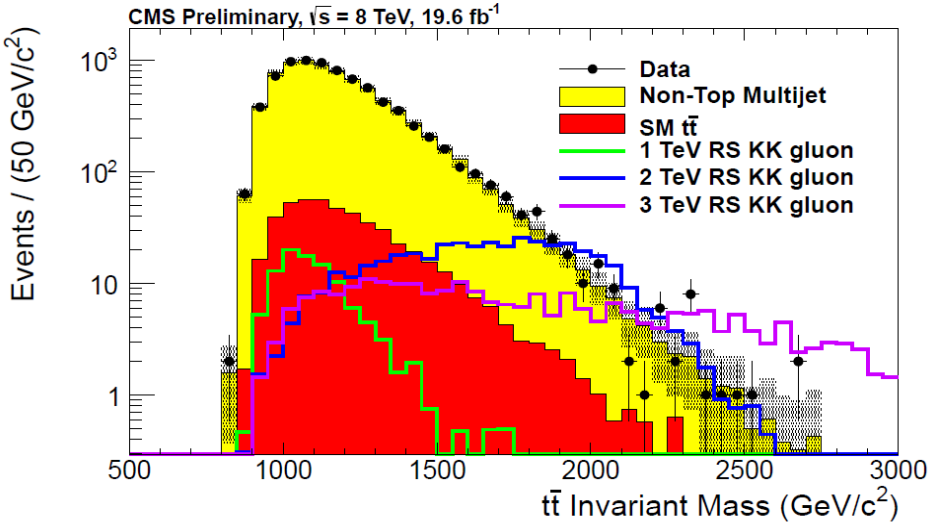


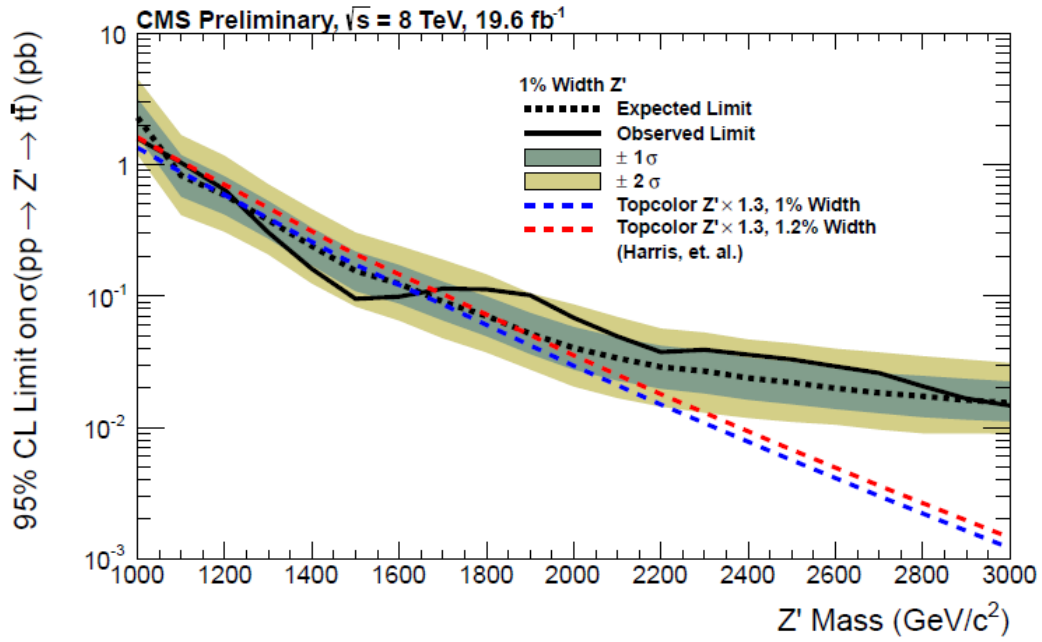


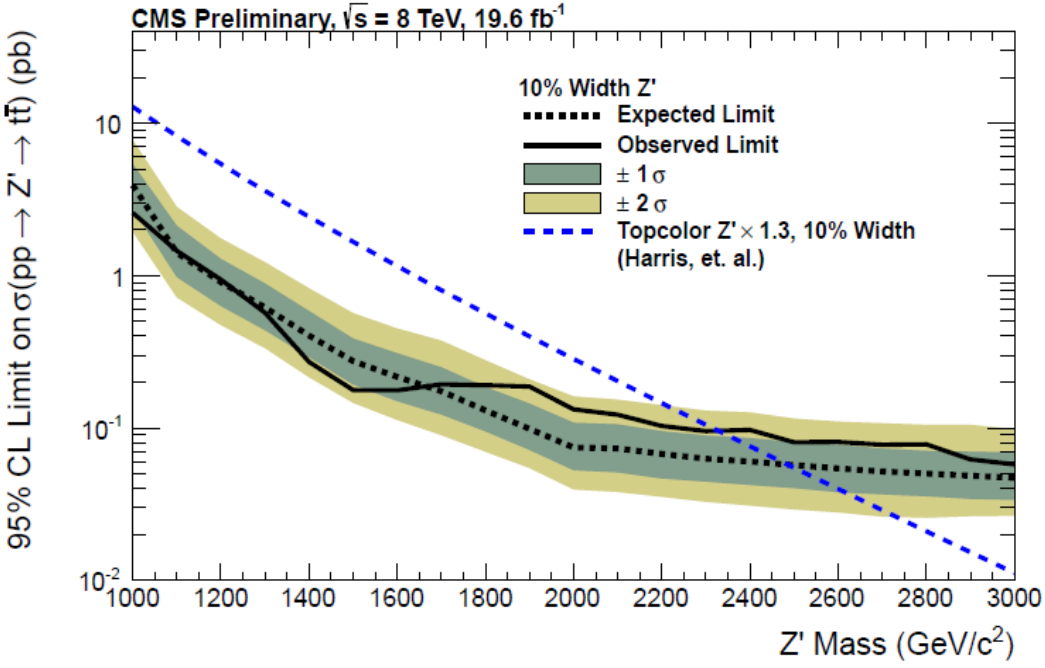
Z' → $t\bar{t}$ all hadronic

B2G-12-005

- Boosted top- and W-tagging
- Topcolor Z' limits with 95% CL:
  - Narrow: **M(Z') > 1.7 TeV**
  - Wide: **M(Z') > 2.35 TeV**
- Randall-Sundrum model:
  - **M(KK gluon) > 1.8 TeV**



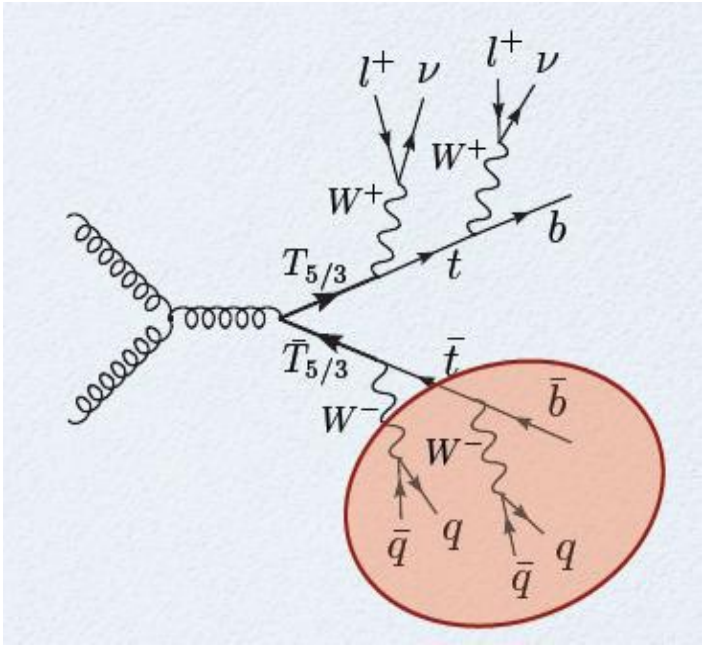


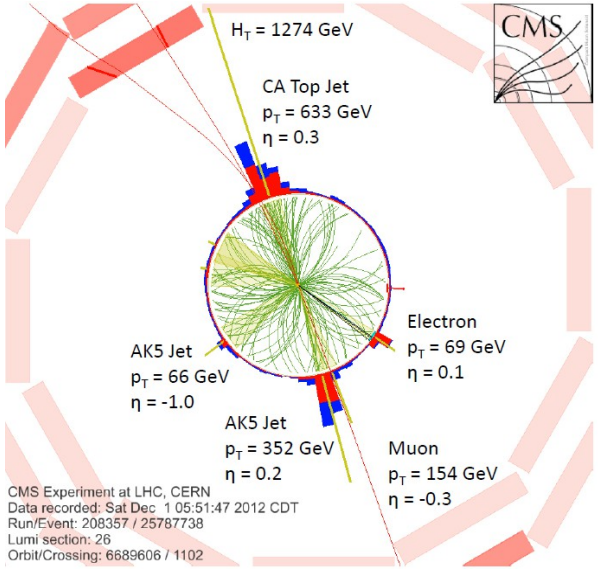


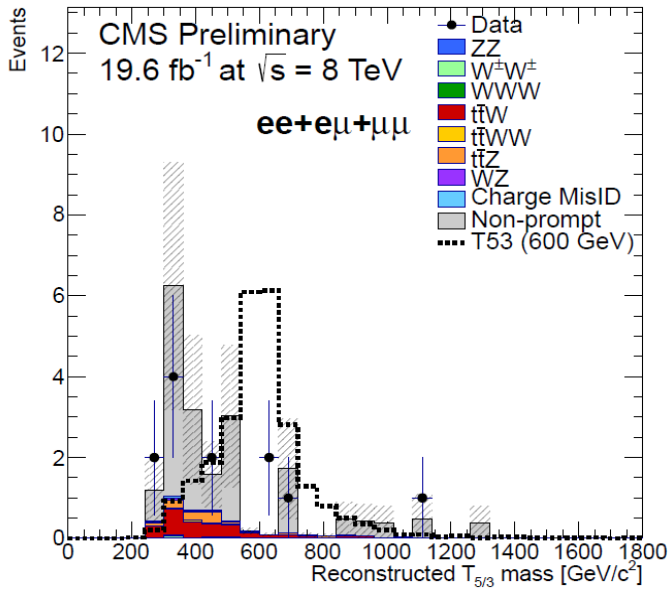
$T_{5/3} \rightarrow t\,W$

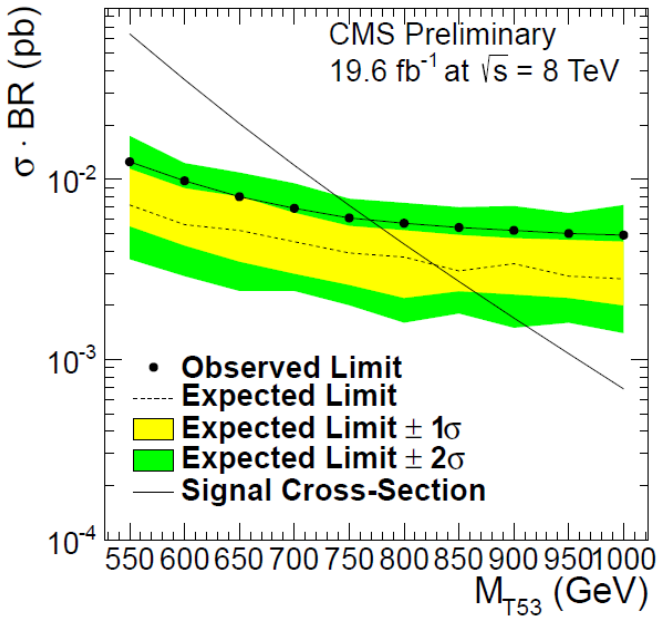
B2G-12-012

- Composite Higgs or models with extra dimensions
- Same-sign dileptons (e or μ)
- Allow for boosted top and W
- 5 or more constituents (top=3, W=2) in addition to the two leptons
- H_T > 900 GeV
- Exclude $M(T_{5/3})$ < 770 GeV at 95% CL





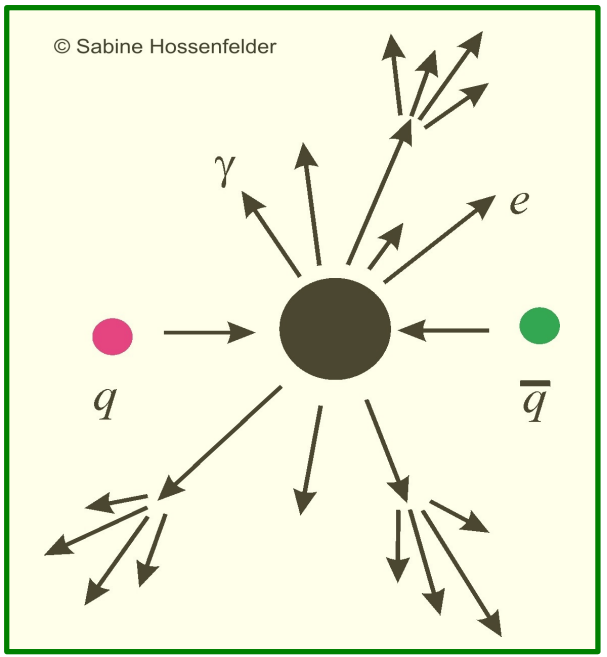


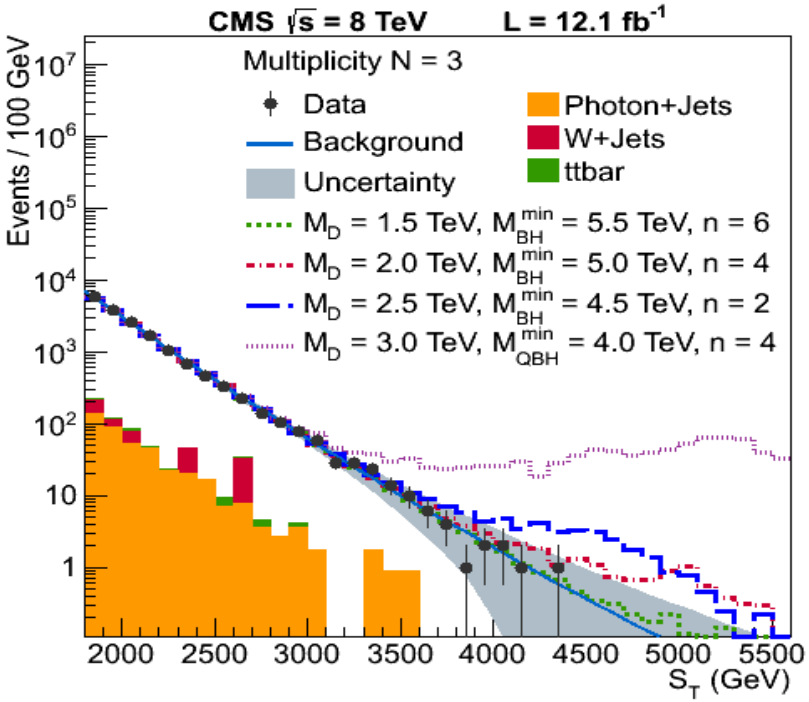


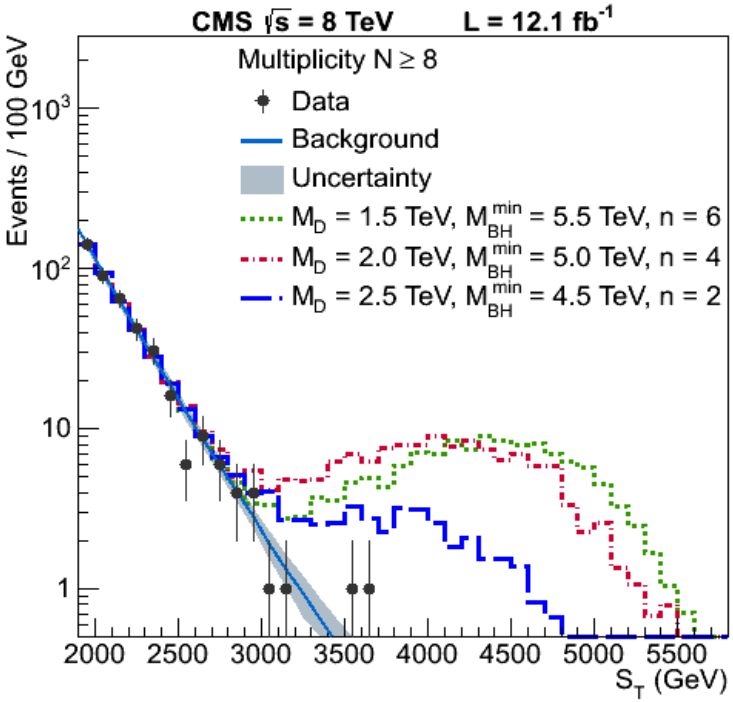
Microscopic black holes

EXO-12-009

- Would decay to multiple objects: jets, leptons, photons, …
- Distribution of interest: scalar p_T sum = S_T
- For backgrounds, extrapolate shape from low (N=2, 1.8 < S_T < 2.8 TeV) to high multiplicity
  - Normalization from low S_T, 1.9 < S_T < 2.3 TeV



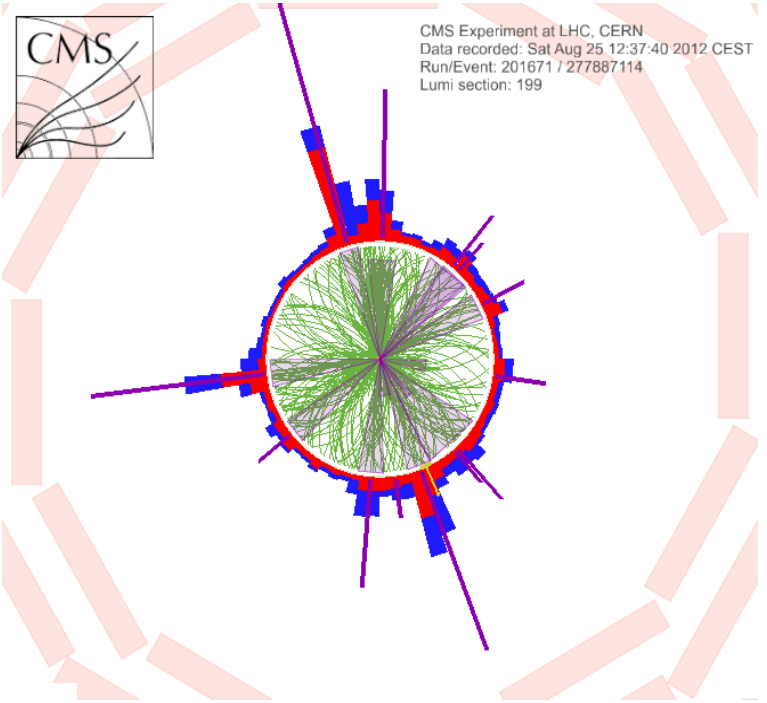




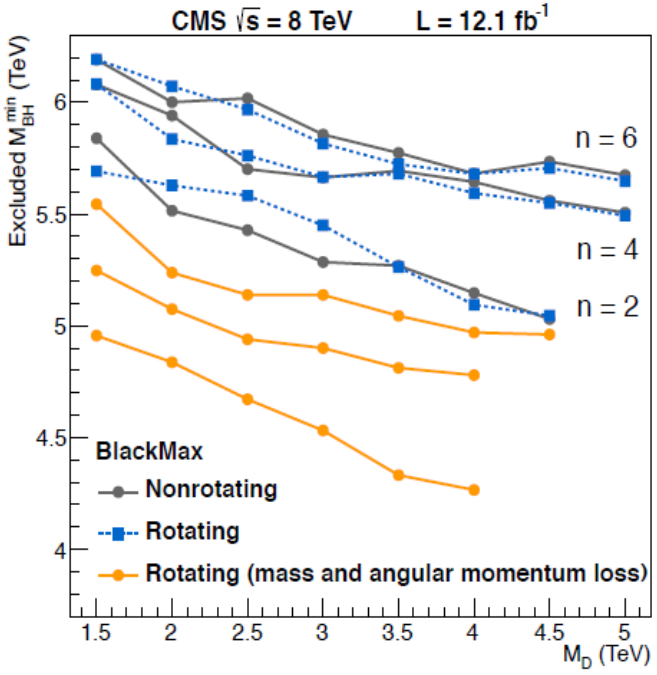
Microscopic black holes

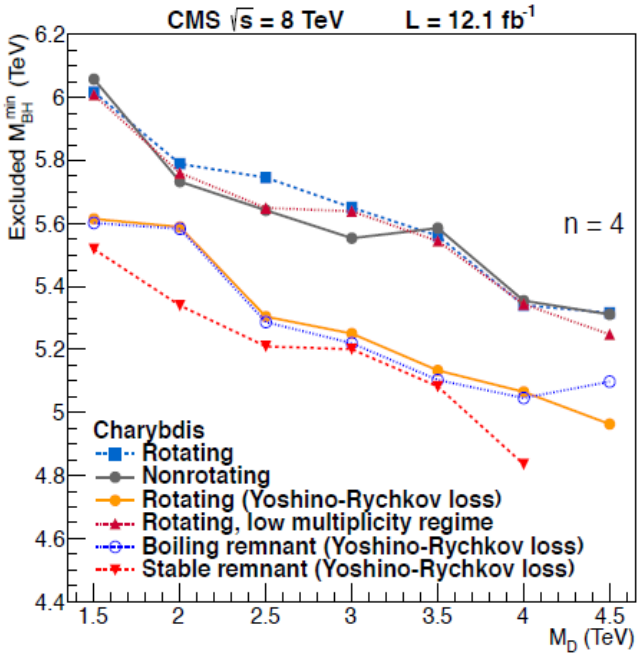
EXO-12-009

- Derive model-dependent limits, as well as limits on excess S_T for different object multiplicities



13 jets, S_T = 4.5 TeV

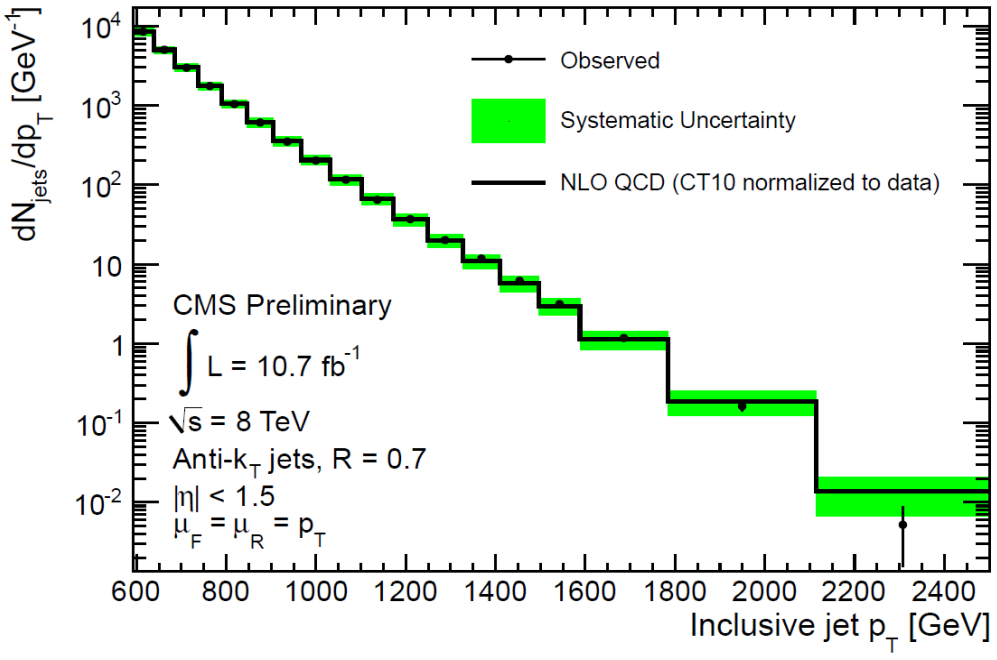


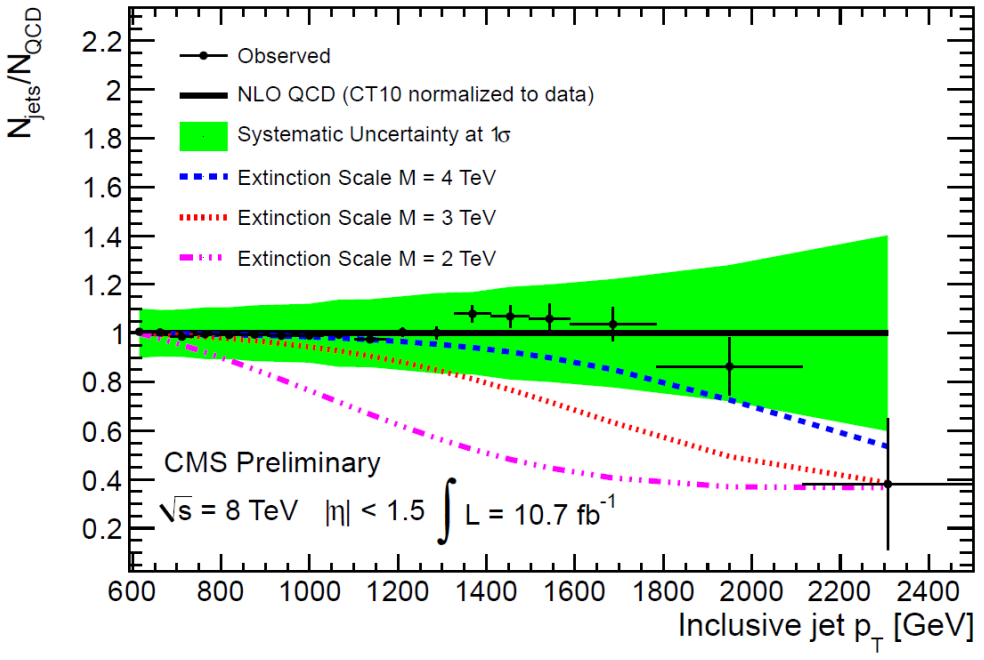


Jet extinction

EXO-12-051

- Even if black holes (or similar phenomena) are produced, we may miss them (trigger, no decay to our “objects”, …)
- However, above production threshold, SM processes are highly suppressed
  - Good place to check are inclusive jets
  - PDF and jet energy scale uncertainty are important



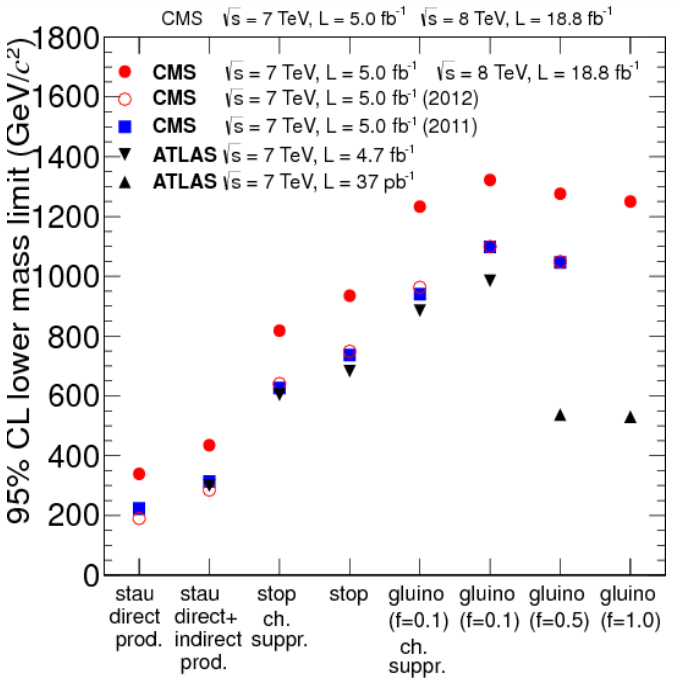


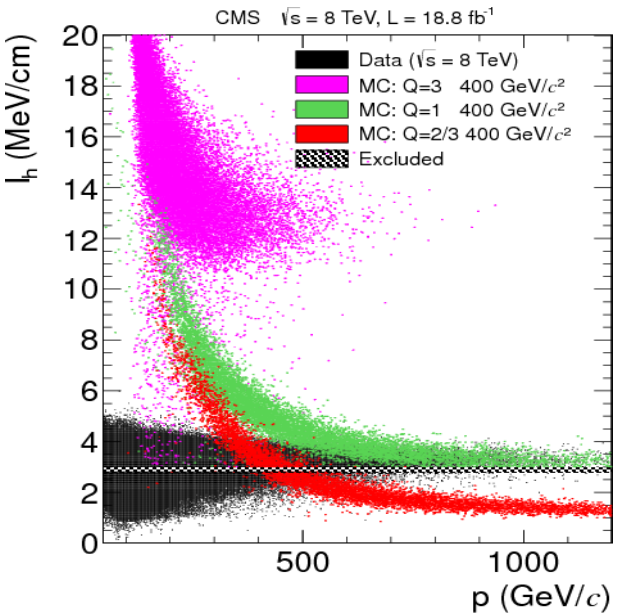
- Limit on the extinction energy scale $M_s > 3.3$ TeV

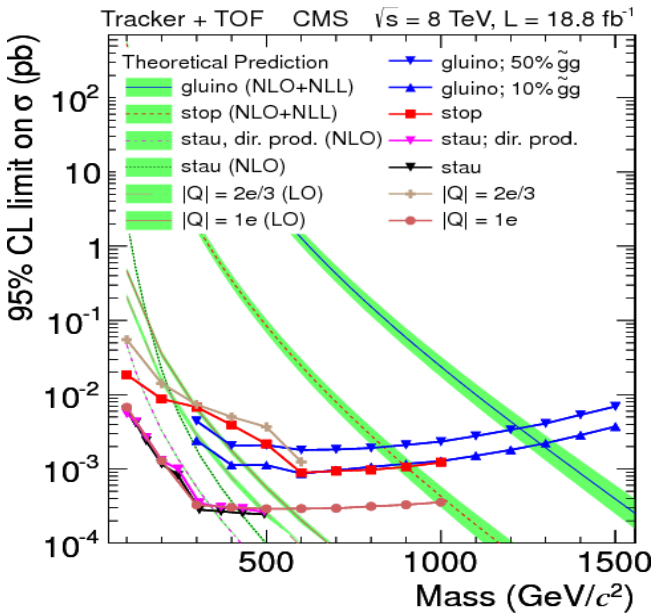
Heavy stable charged particles

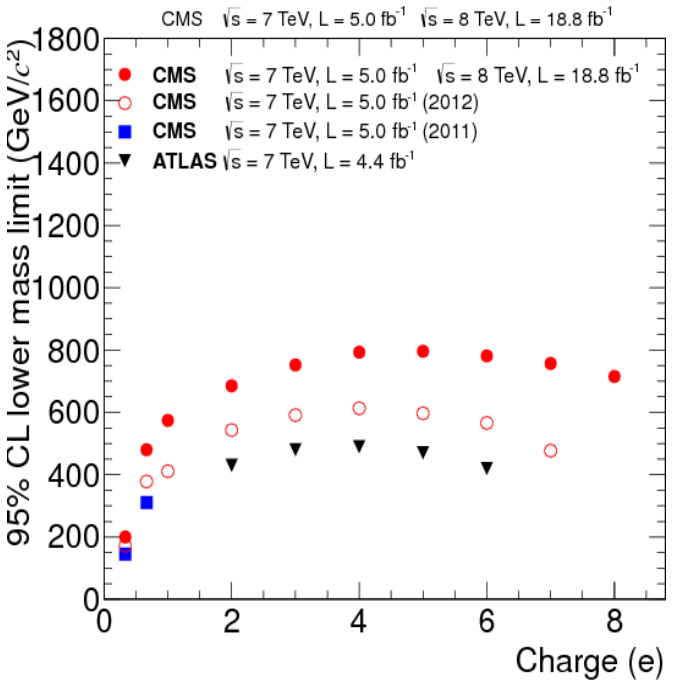
EXO-12-026

- Comprehensive analysis using time-of-flight (muon system) and/or dE/dx (tracker)
  - Lifetime > 1 ns, mass > 100 GeV
- Results for long-lived gluinos, scalar top quarks, scalar tau leptons, fractionally/multiply charged leptons
- Limits up to > 1300 GeV (gluinos)



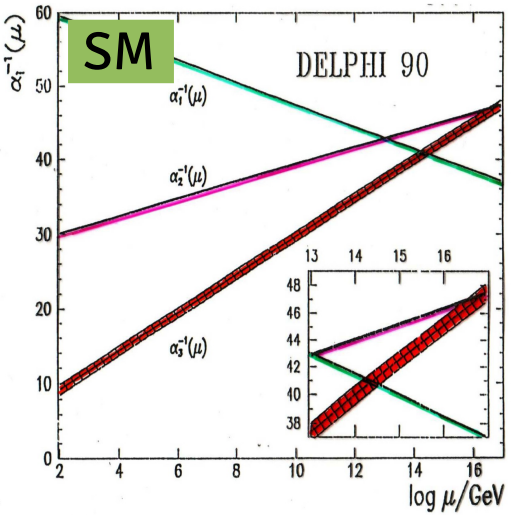


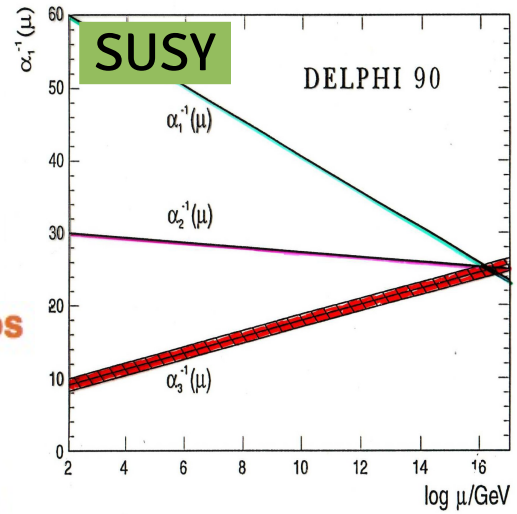


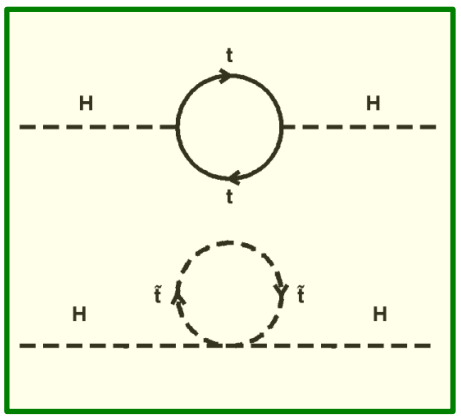


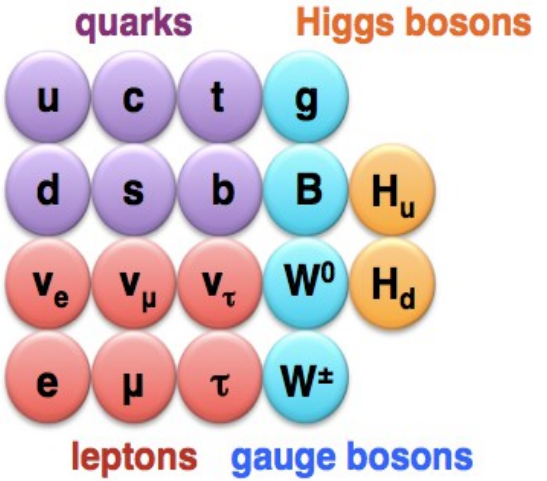
Supersymmetry – textbook wisdom

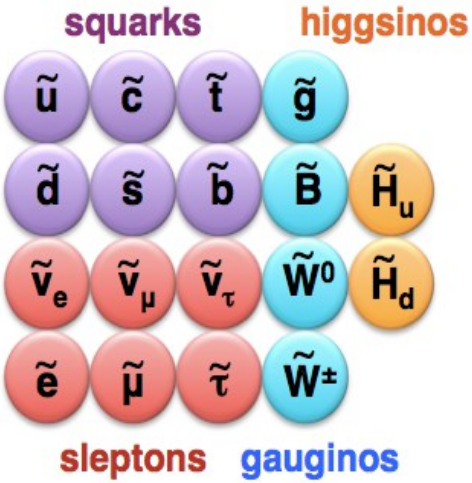
- A fundamental symmetry relating bosons and fermions
- Allowing for unification of couplings at a single scale
- LSP (lightest SUSY particle) is candidate for dark matter (if R parity conserved)
- Stabilizing Higgs mass ("fine-tuning")
  - If the scale for new physics is too high, large **"unnatural"** cancelations in the radiative corrections must occur to get M(Higgs) right









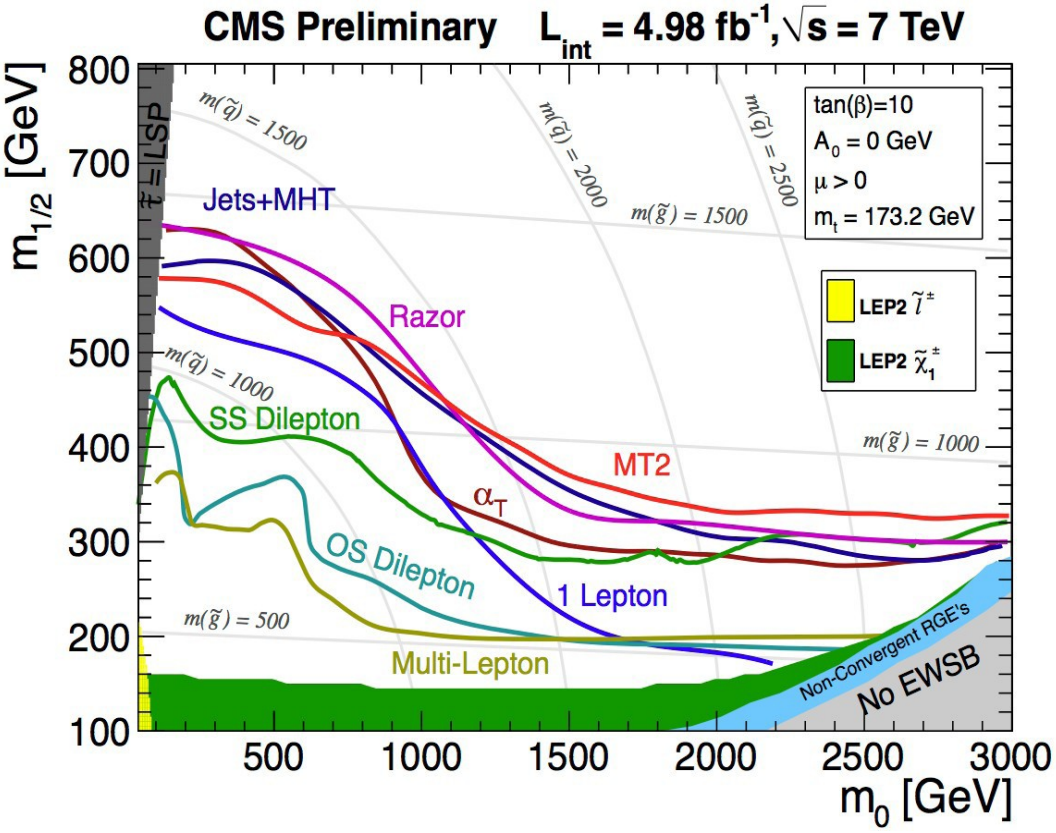


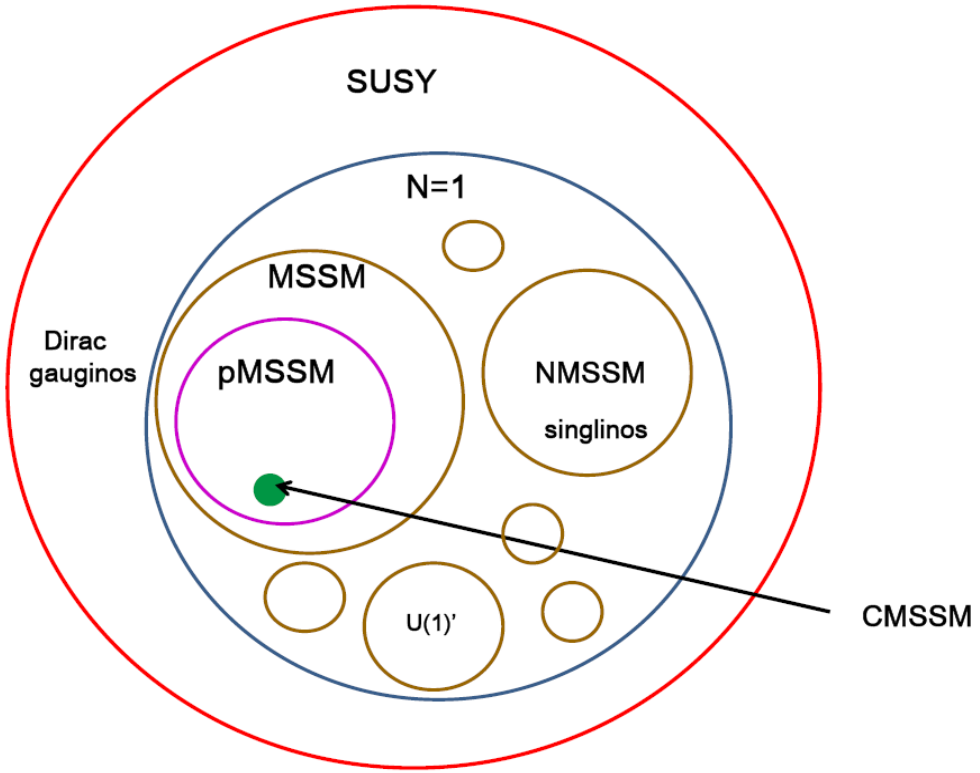
(No) Supersymmetry?

http://cp3-origins.dk/a/4276

(No) Supersymmetry?

- Exclusion regions in constrained minimal supersymmetric standard model (CMSSM) based on 2011 data ($\sqrt{s}$ = 7 TeV)

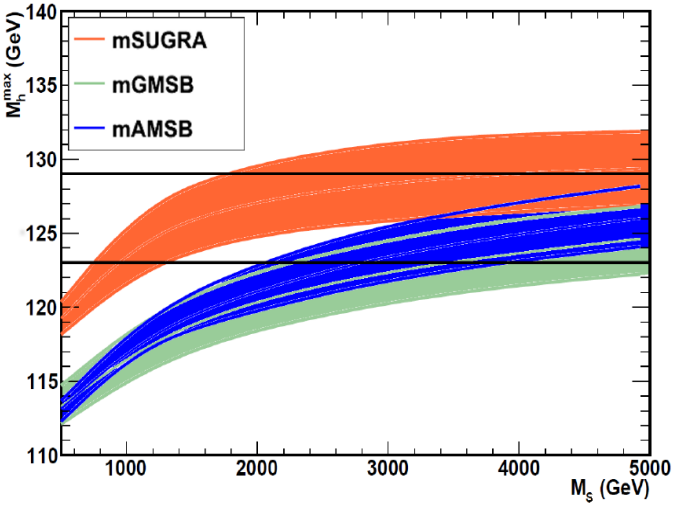




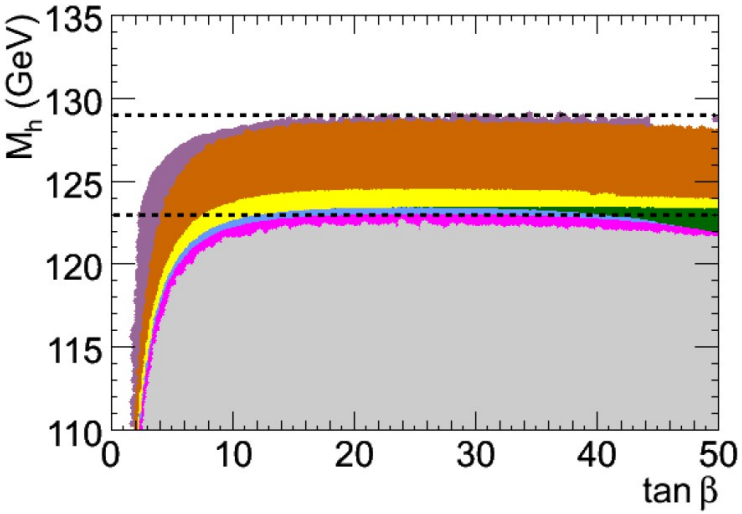
T. Rizzo, SLAC summer school 2012

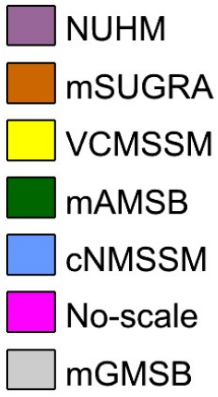
Supersymmetry cornered

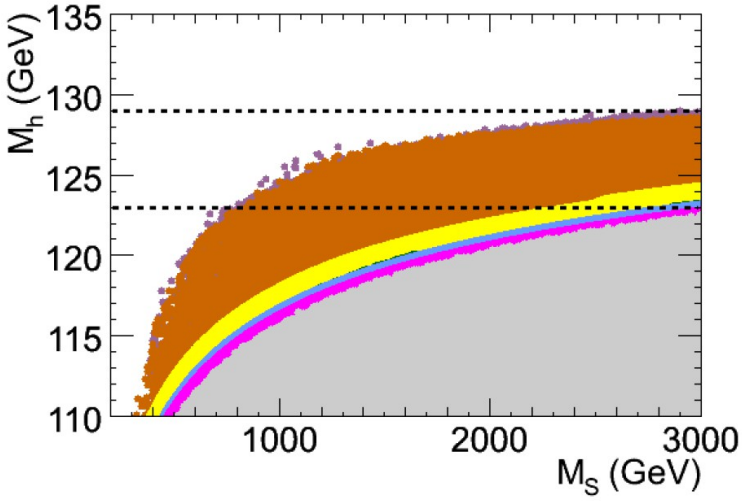
- A 126 GeV Higgs is an essential constraint for any supersymmetric model (numerous studies)
- Add to that "naturalness", and chances for a SUSY discovery at the LHC increase dramatically



Arbey, Battaglia, Djouadi, Mahmoudi, JHEP 1209 (2012) 107

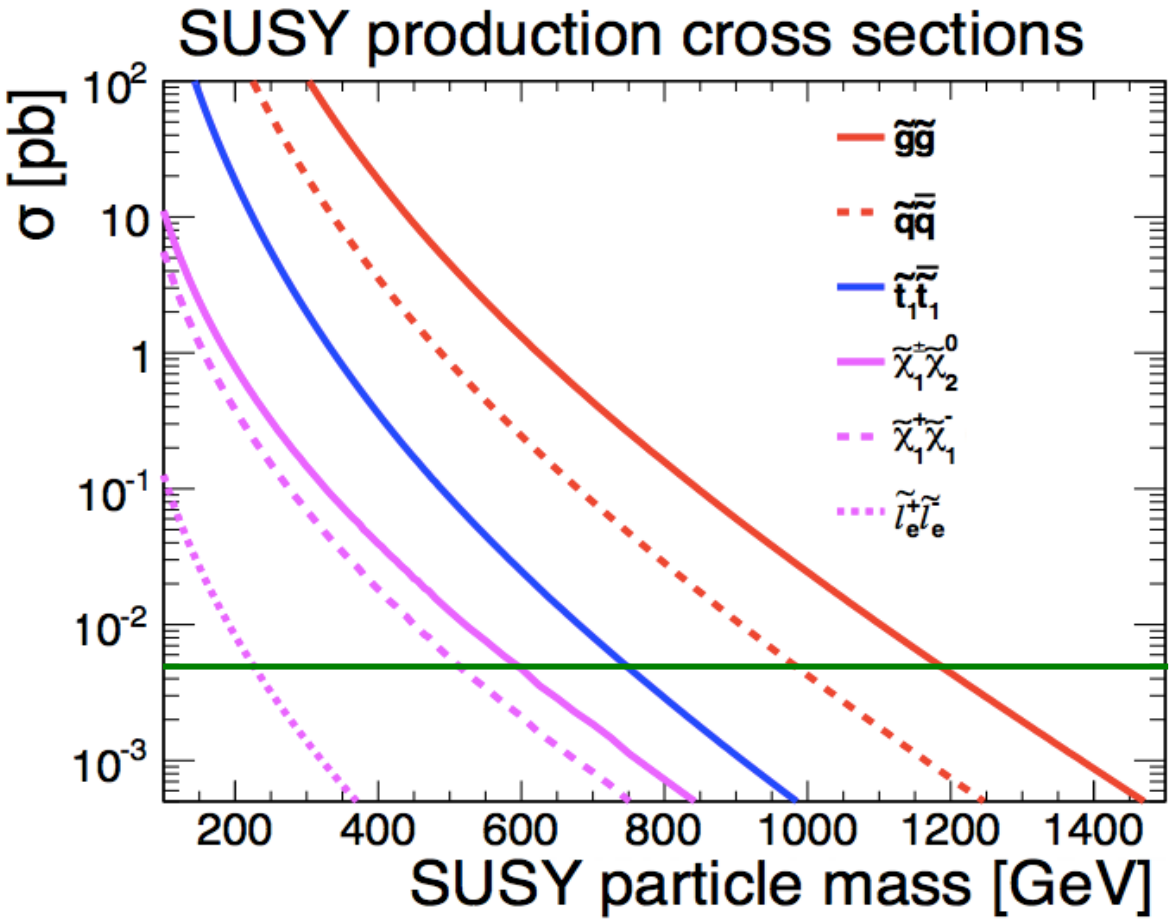






Natural SUSY at CMS

Krämer et al., arXiv:1206.2892



In 20 fb^{-1}, might have produced ~100 events with:

1.2 TeV	gluinos
750 GeV	stops
600 GeV	charginos/ neutralinos

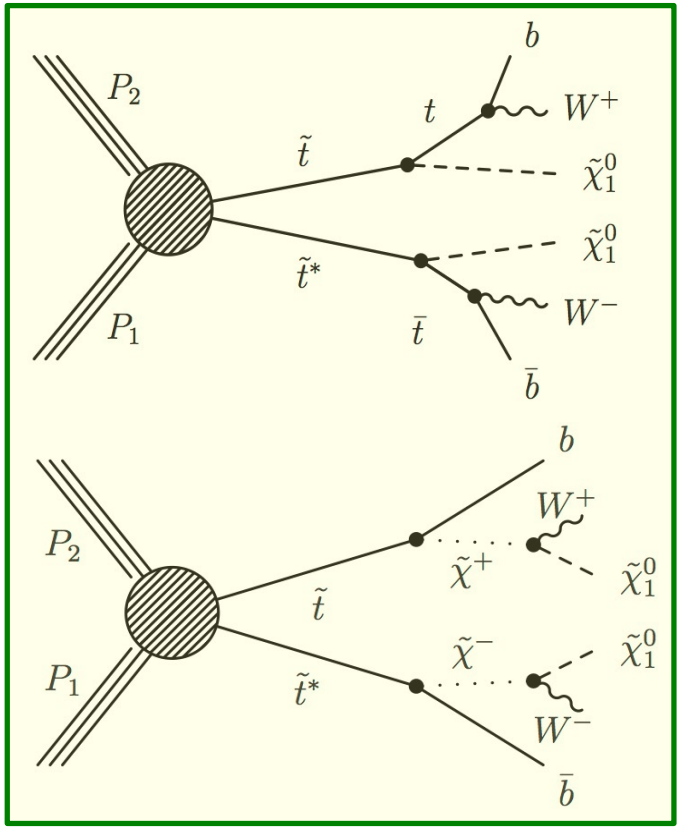
- Direct pair production of 3rd generation squarks
- 3rd generation squarks in gluino pair production
- Direct EW partner pair production

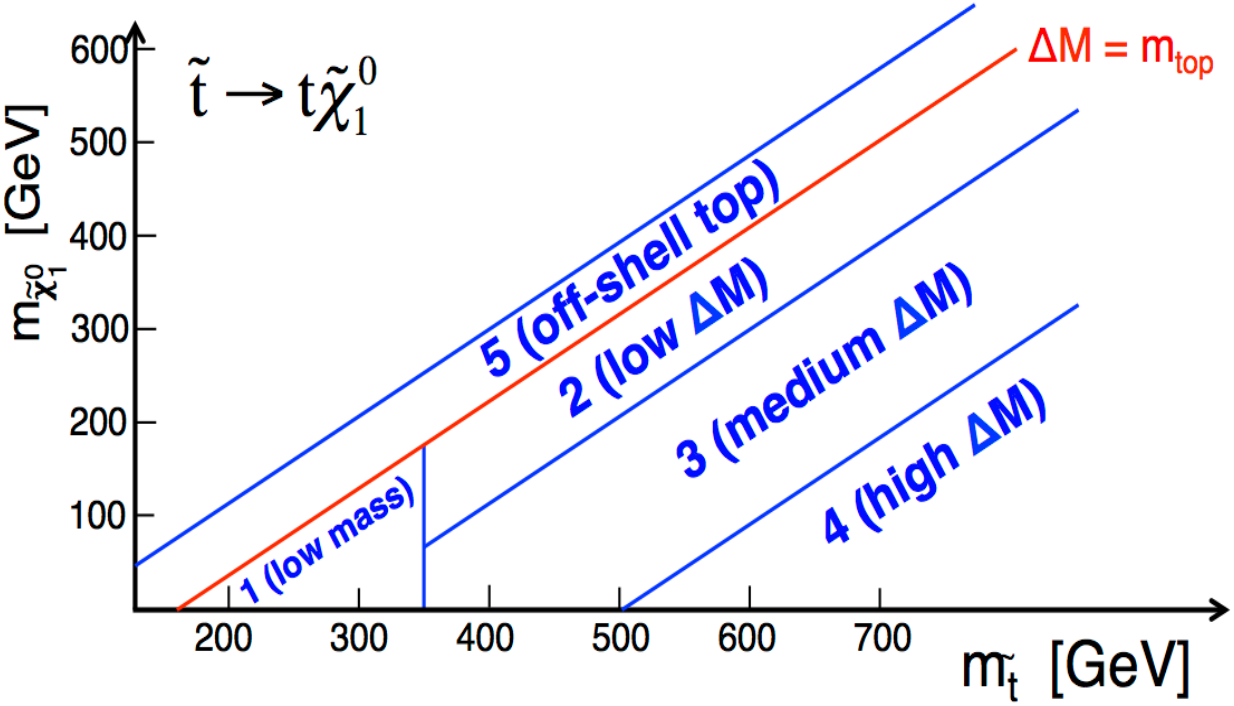
} **Examples here**

Stop production in single leptons

SUS-13-011

- Exactly one lepton, at least 4 jets including 1 b-tag
- Large MET
- Large M_T against $t\bar{t}$ and W+jets
- Train different BDT's for different signal regions





Stop production in single leptons

SUS-13-011

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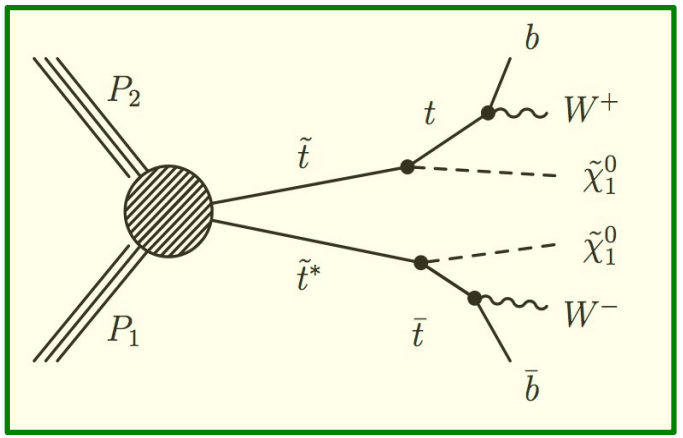
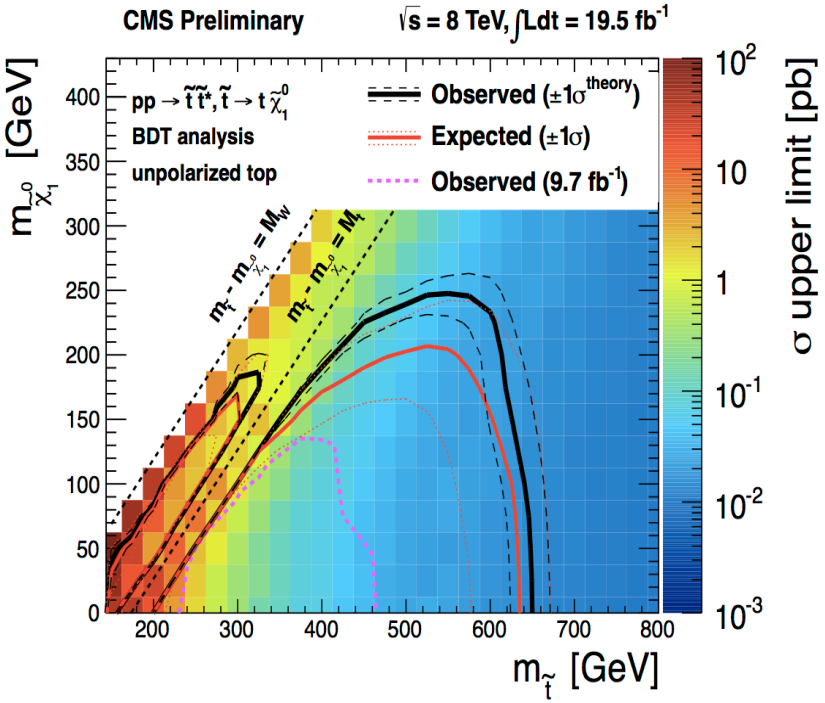
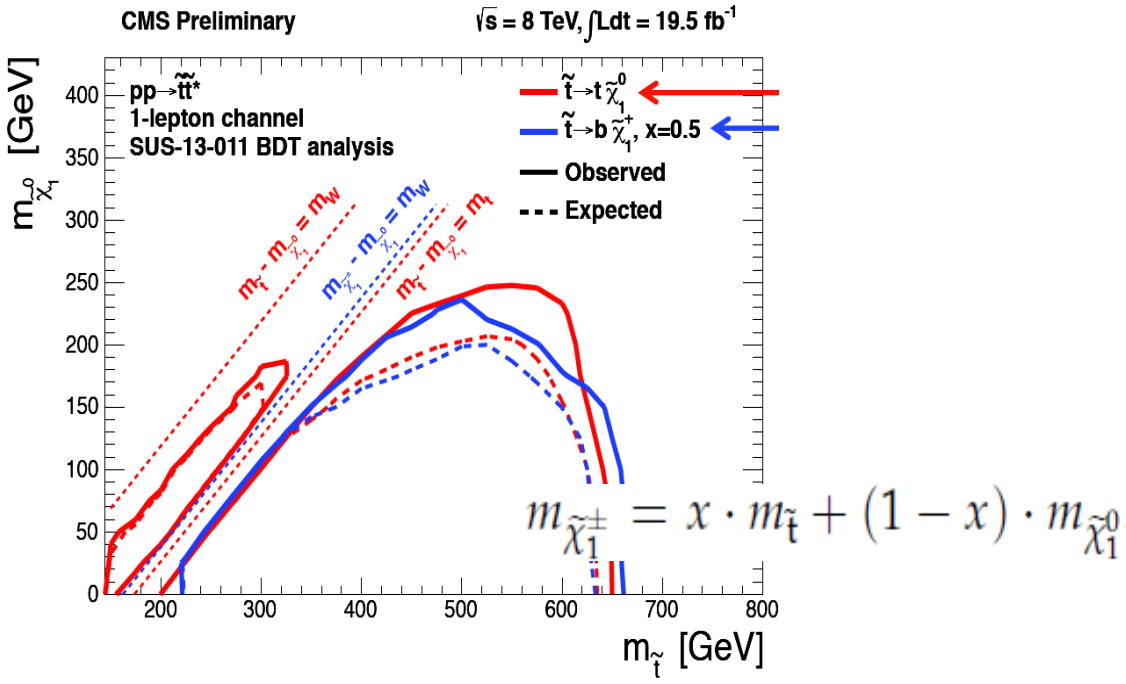


Sample	BDT1 Loose	BDT1 Tight	BDT2	BDT3	BDT4	BDT5
Total	763 ± 102	124 ± 21	85 ± 16	13 ± 4	2.9 ± 1.1	87 ± 18
Data	728	104	56	8	2	76



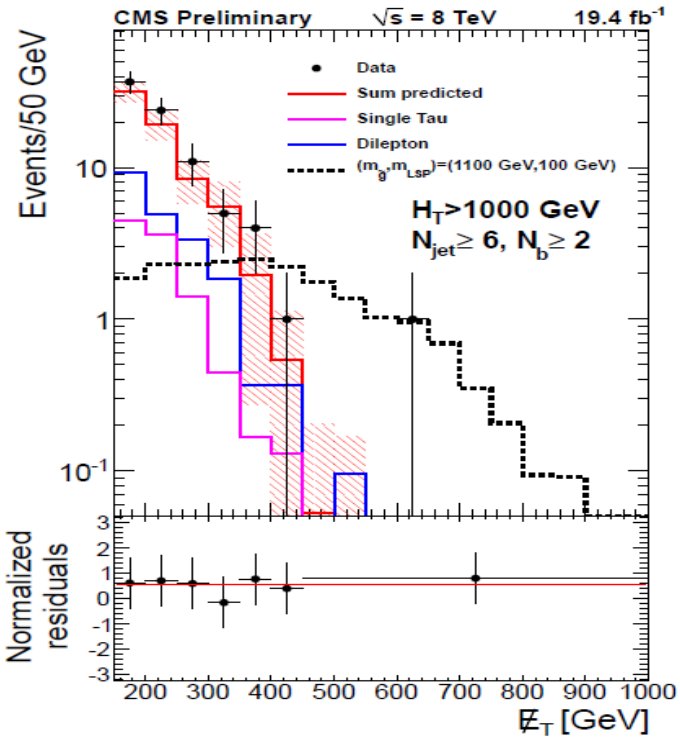


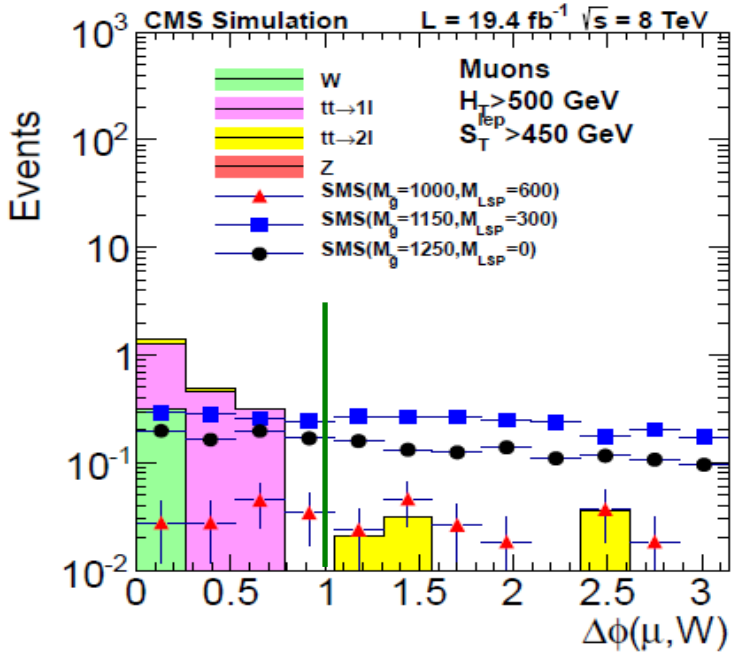
$$m_{\tilde{\chi}_1^\pm} = x \cdot m_{\tilde{t}} + (1-x) \cdot m_{\tilde{\chi}_1^0}$$

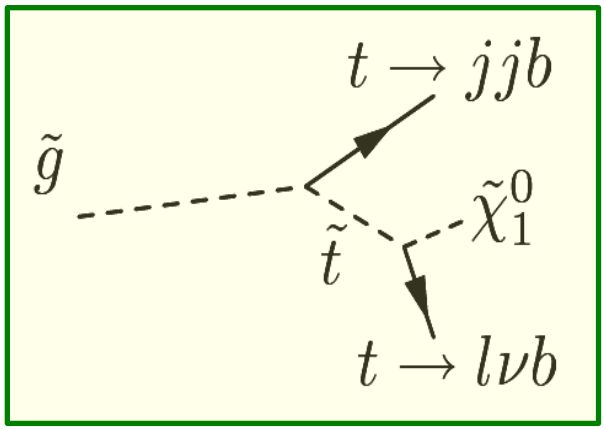
Gluino pair production

SUS-13-007

- Searches in many modes: 0, 1, 2, 3, 4 or more leptons, b-tags, various N_{jets} …
- New results for example in:
  - 1 lepton, at least 6 jets including 2 b-jets, H_T > 500 GeV, with 2 complementary searches:
    - Large MET and H_T
    - Exploit correlation between lepton and W directions to suppress SM $t\bar{t}$



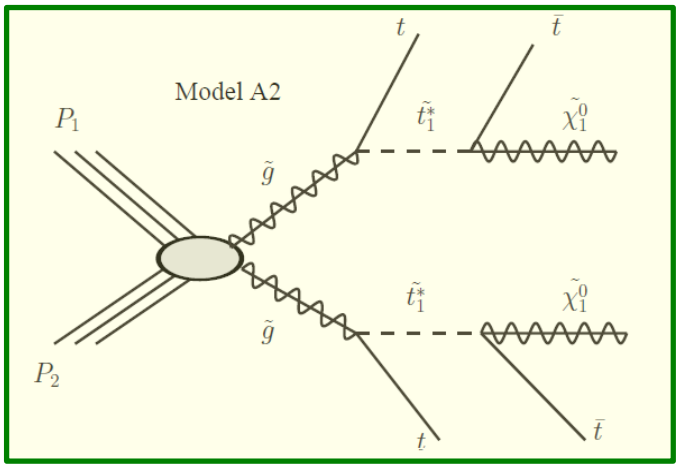


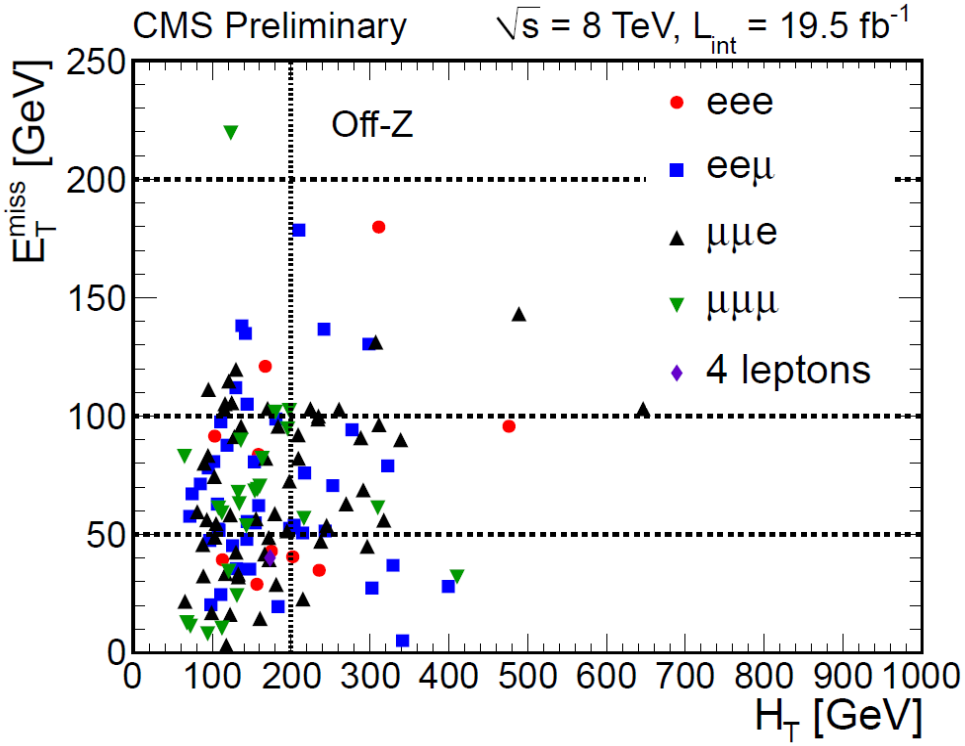


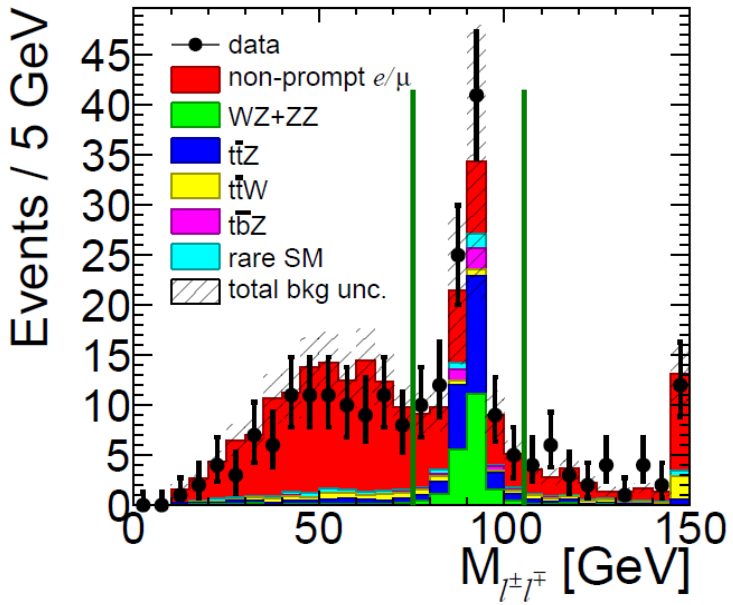
Gluino pair production

SUS-13-008

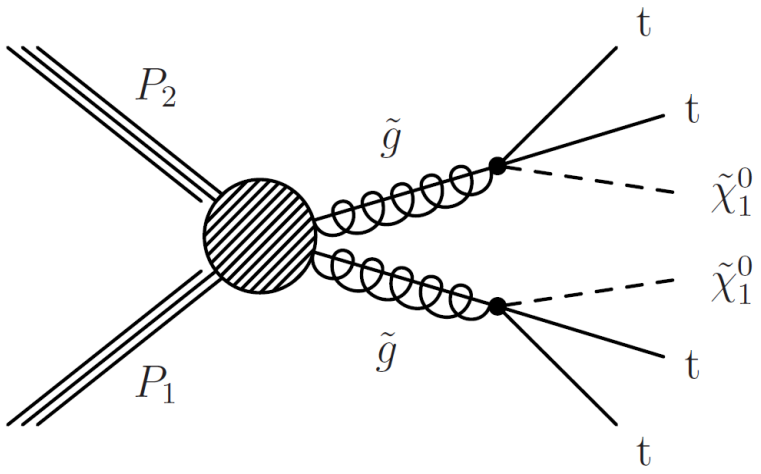
- Searches in many modes: 0, 1, 2, 3, 4 or more leptons, b-tags, various N_{jets} …
- New results for example in:
  - 3 or more leptons, at least 2 jets including 1 b-jet, MET > 50 GeV
  - With / without Z candidate
  - 60 exclusive search regions in n_{jets}, H_T, MET, $n_{b\text{-}tags}$

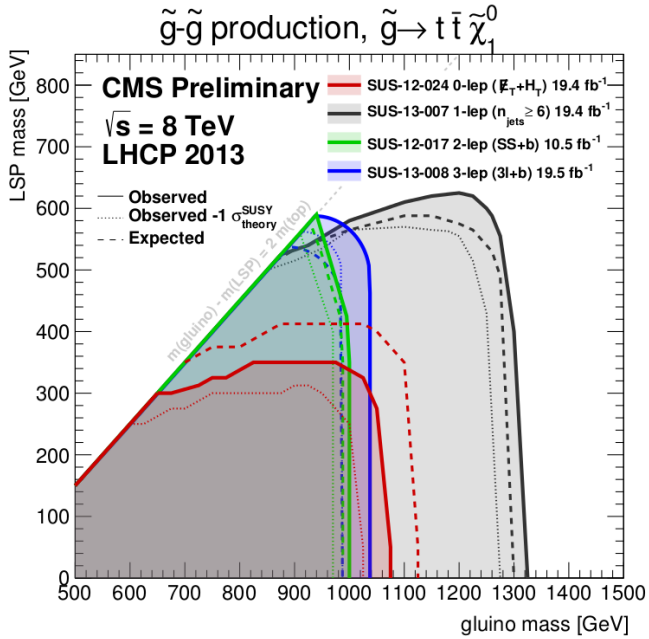




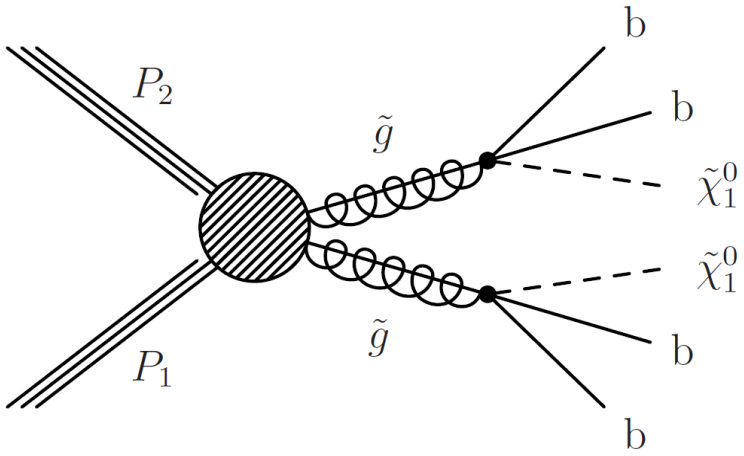


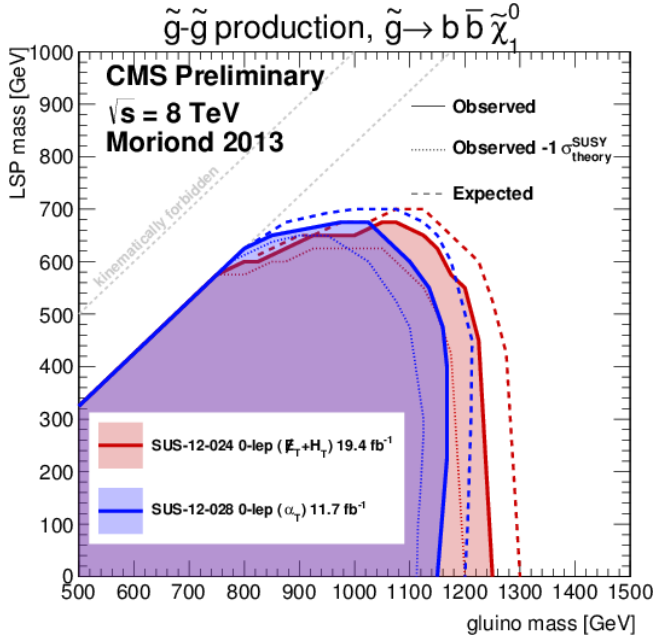
Gluino pair production – summary





Probe gluino masses up to ~ 1.3 TeV

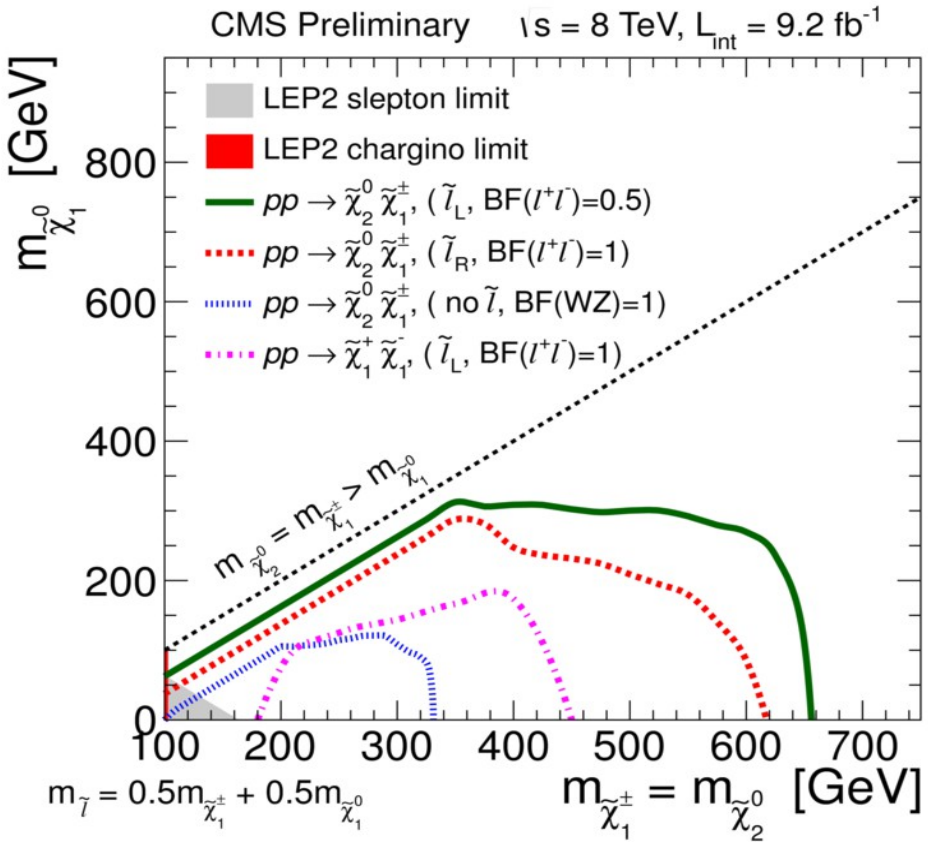


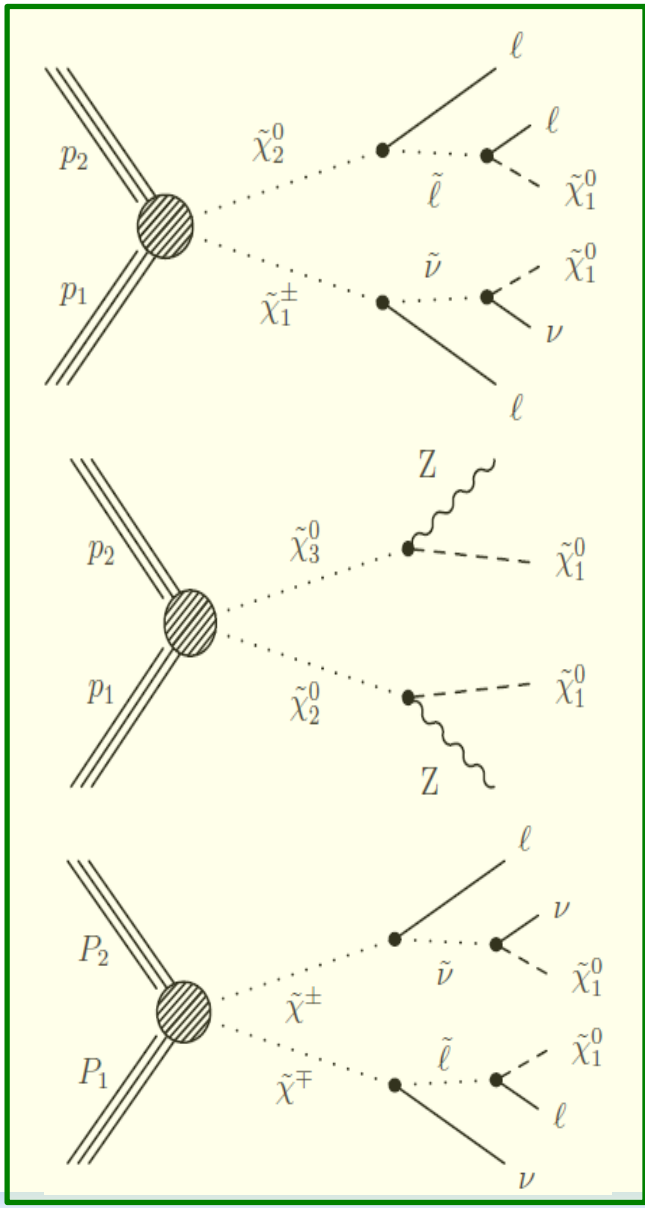


Chargino / neutralino production

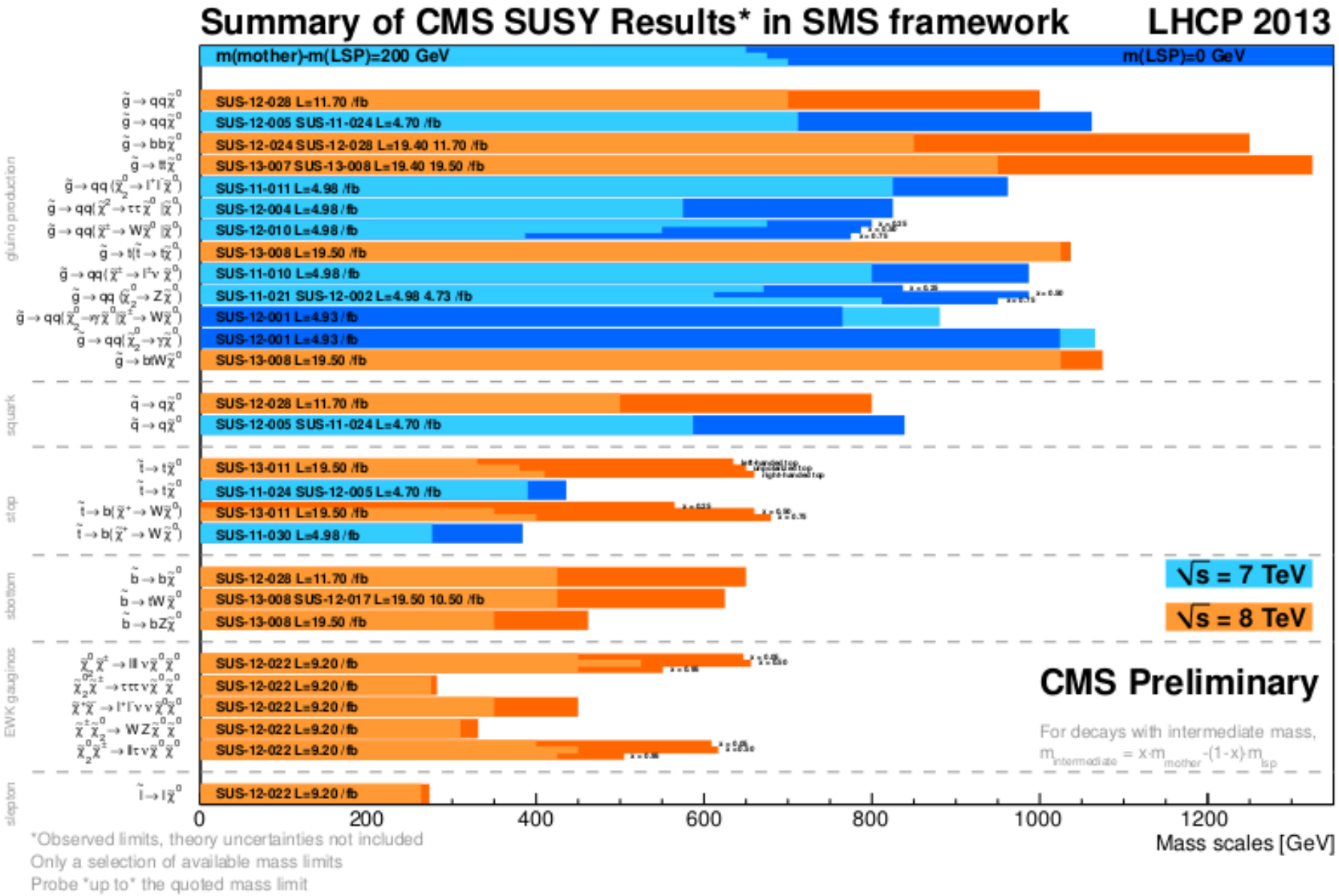
SUS-12-022

- Classify events as exactly 3 leptons, 4 leptons, 2 SS leptons, 2 OSSF leptons + 2 jets, or 2 OS leptons inconsistent with Z boson decay

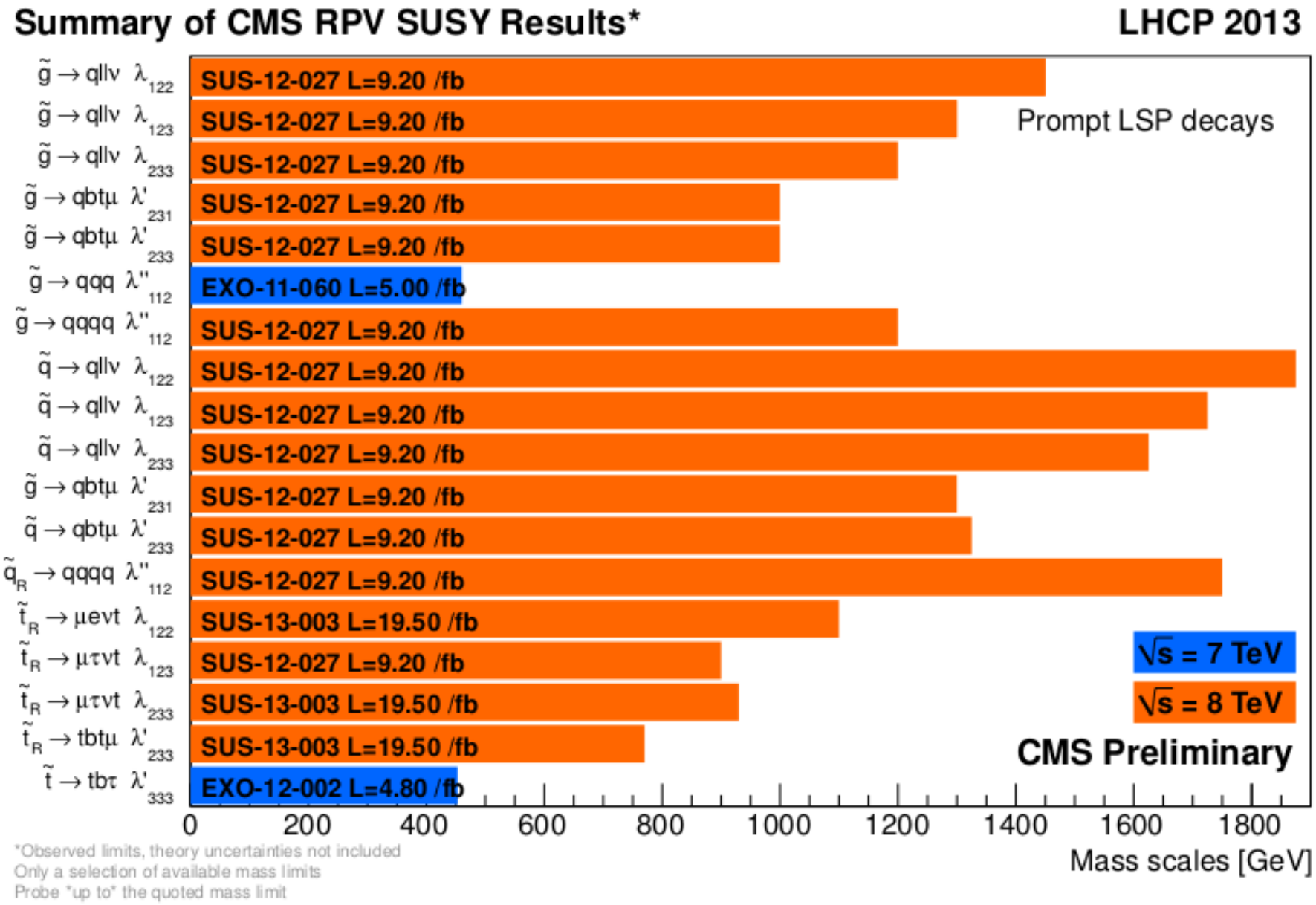




Summary of SUSY at CMS (R conserved)

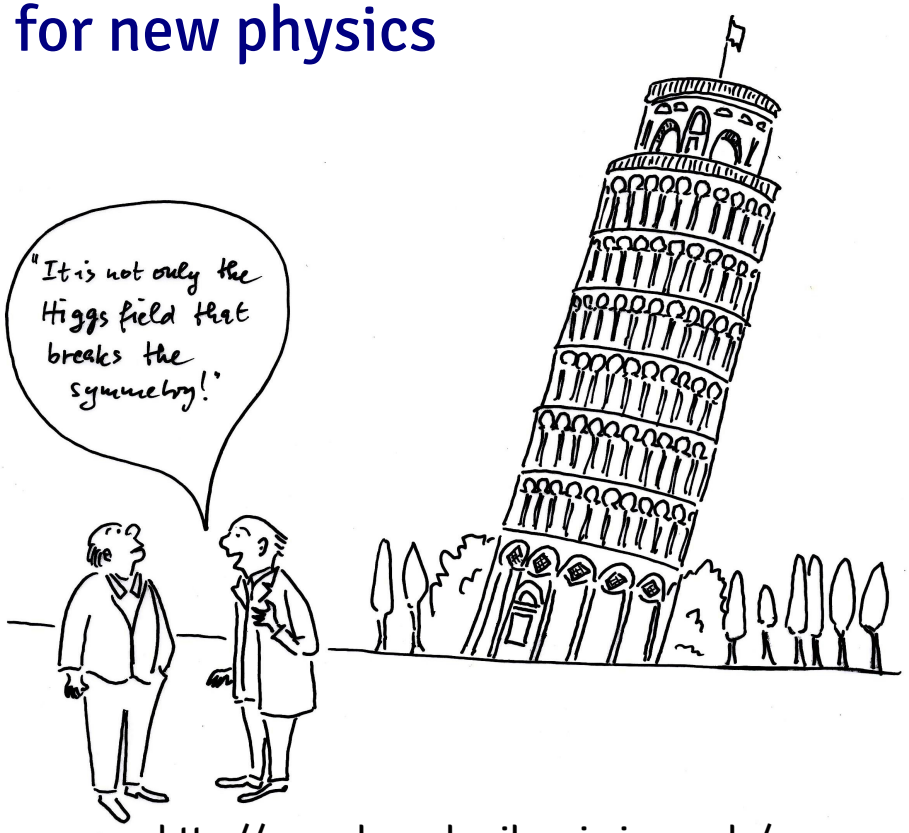


Summary of SUSY at CMS (R violated)



Conclusions

- No stone left unturned in BSM searches at the LHC and CMS
- While there's an overwhelming output of results, many signatures are not yet fully exploited
  - New physics may still be hiding in the data already collected
  - Important guidance from the “new boson”
- Unfortunately no compelling evidence for new physics
  - But many results exploring new territory
- Many publications with full 2012 data set close to publication
- Preparing for next run in 2015



http://www.hep.physik.uni-siegen.de/~grupen

Backup

Summary