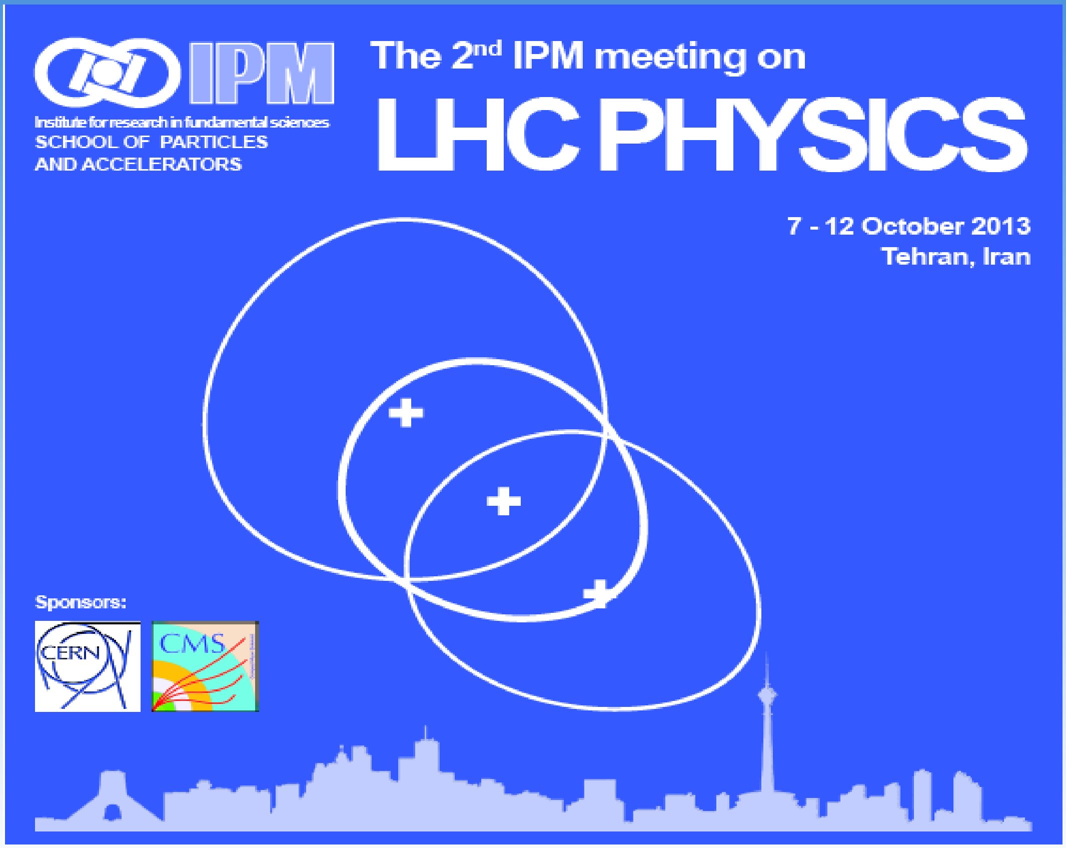
Search for exotica at

- Introduction

- A topical review of Exotica @ CMS

- Outlook and Conclusions



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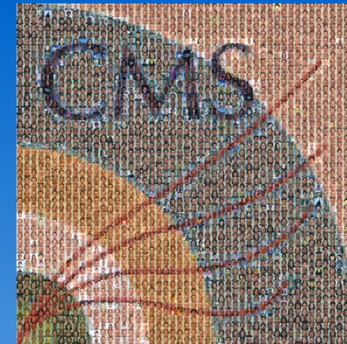

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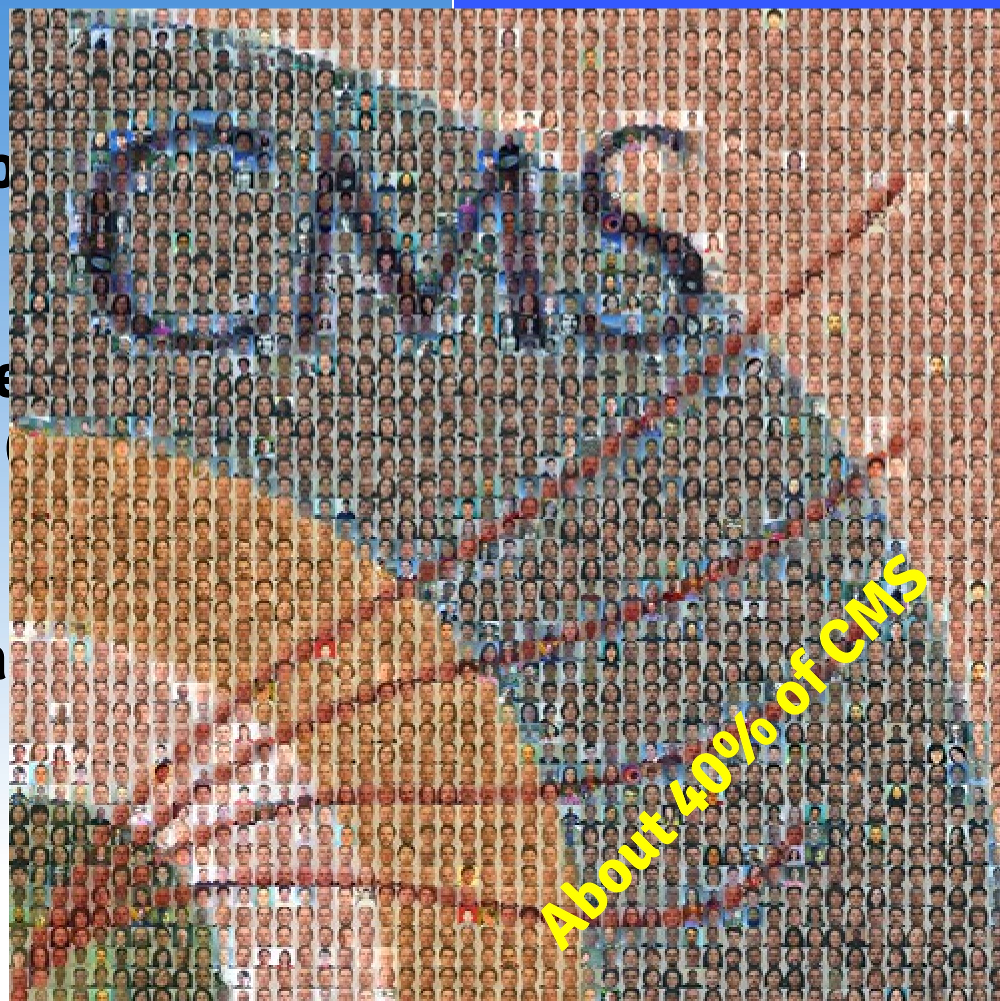

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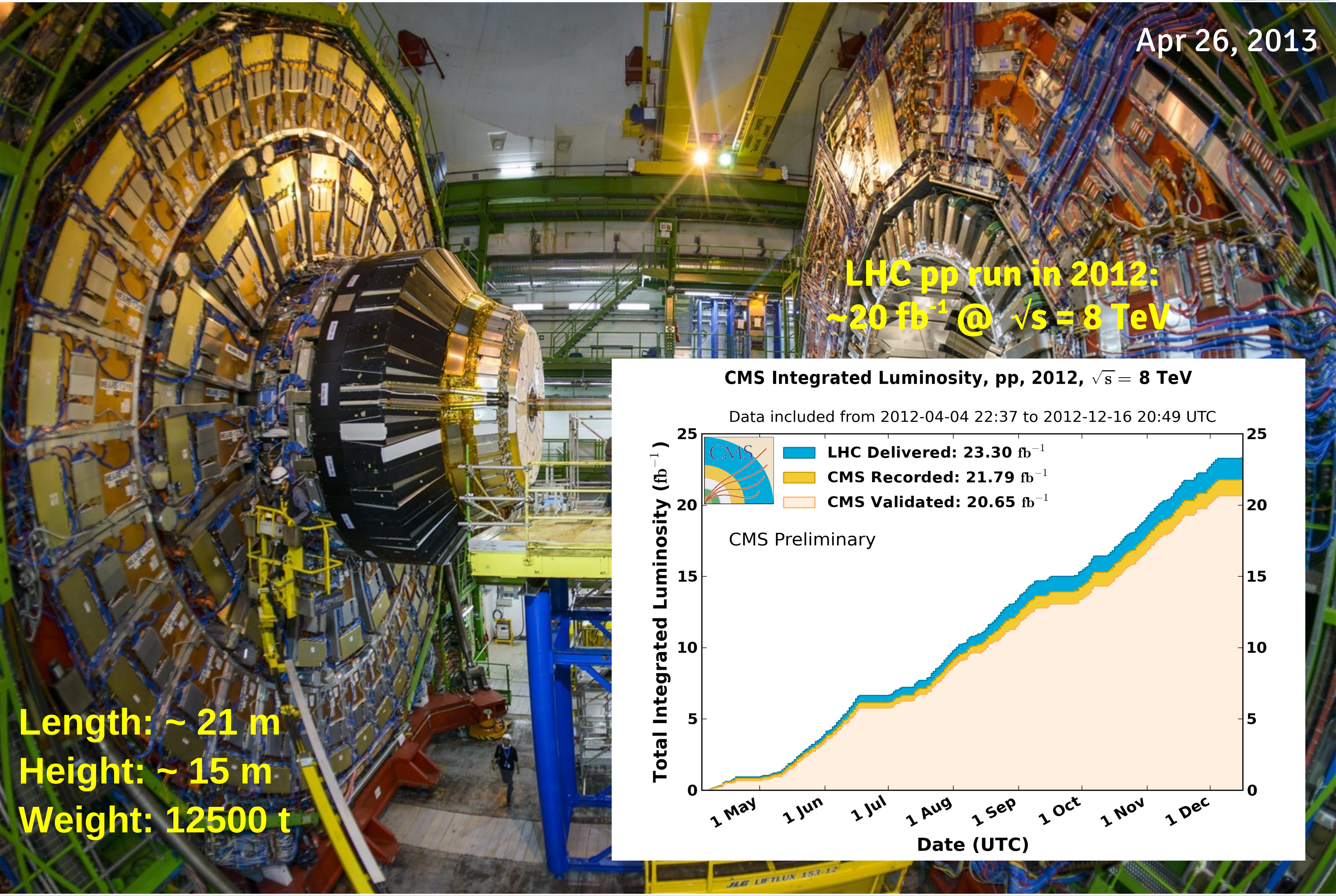
The Compact Muon Solenoid



Apr 26, 2013

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

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

Searches for BSM (what are Exotica?)

- … are a key part of the CMS physics program (and substantial)
- Supersymmetry, ...
- Technicolor, ...
- Extra dimensions, ...
- Extended gauge sector, 4th gen.
- Substructure, Leptoquarks
- Dark matter
- Black holes, unparticles
- (Non-)resonant structures
- Rare decays
- Metastable, long-lived particles
- Signature-based ↔ model-inspired
- Already more than 100 BSM physics papers!

Theories

Concepts

Signatures

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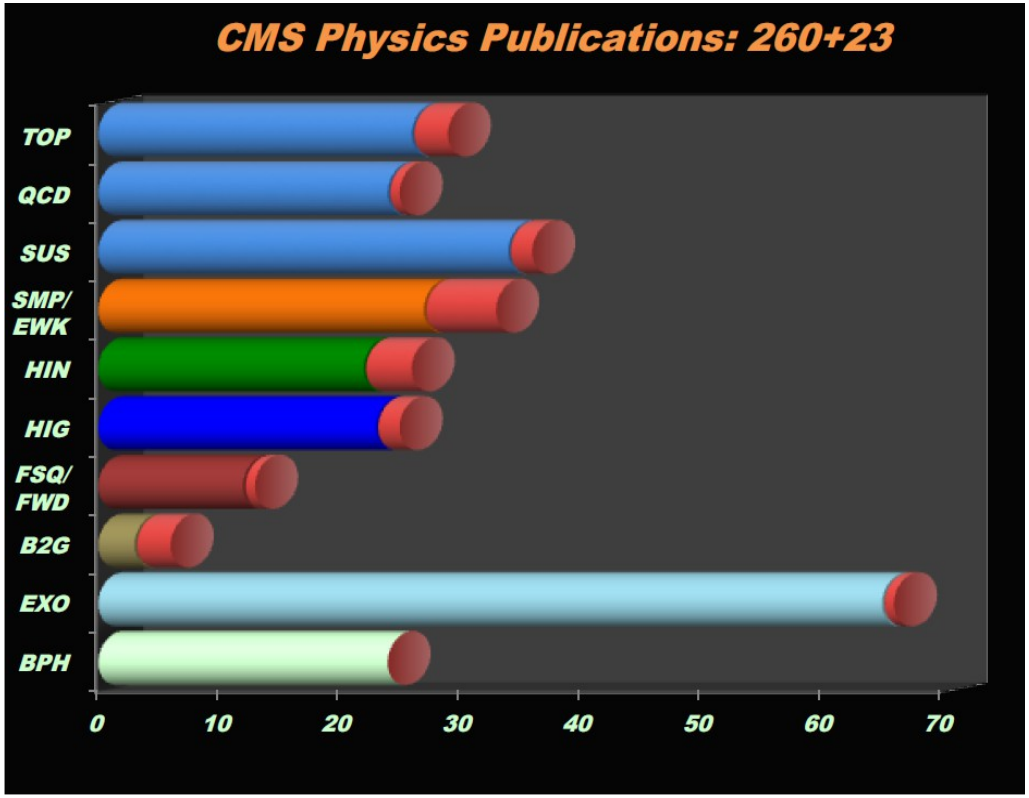
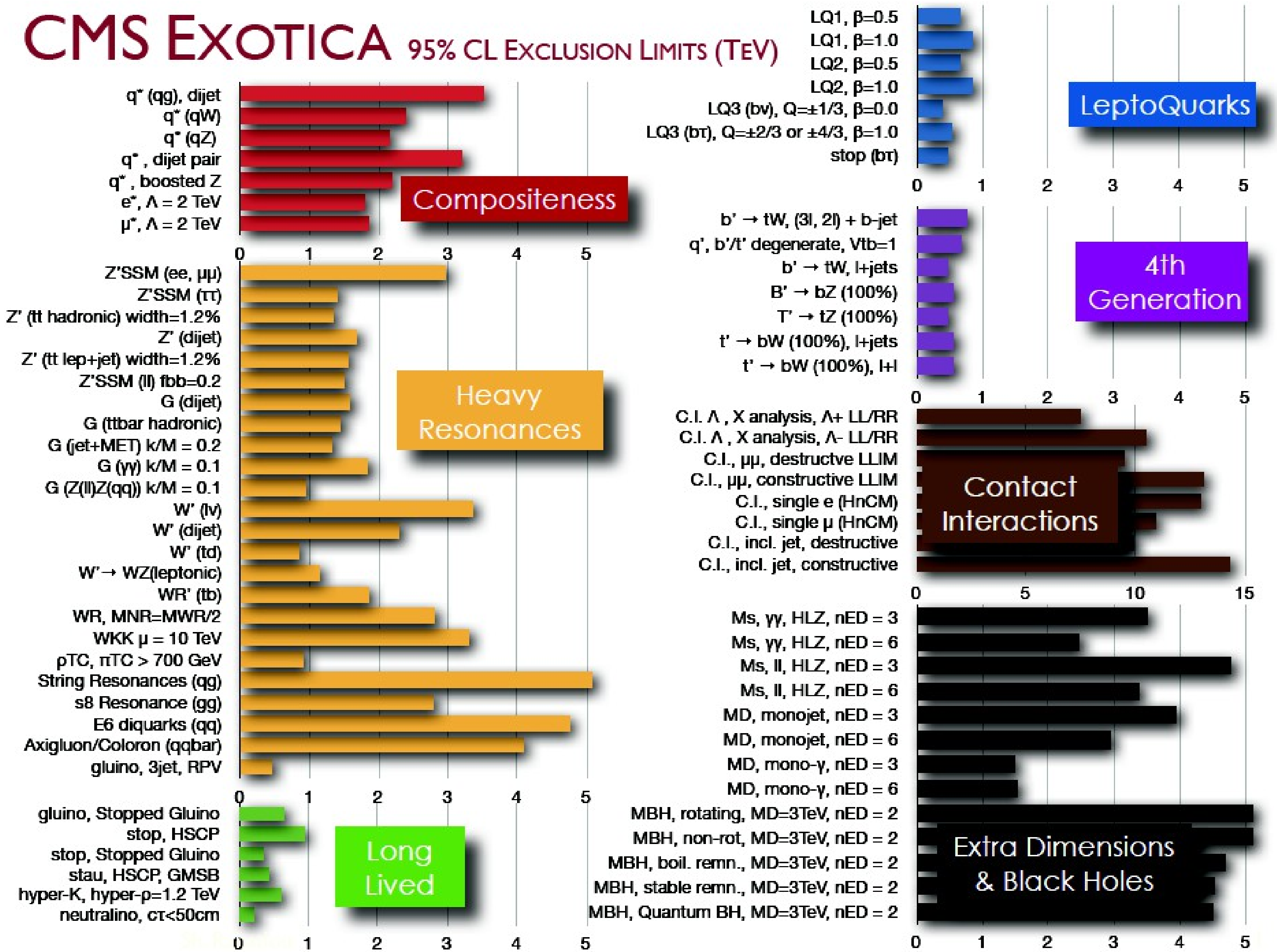


Summary of Exotica at CMS



Overview

- Monojets
  - Large extra dim., dark matter, ...
- Di-jet resonances (w, w/o b-tag)
  - Many interpretations
- 3-jet resonances (RPV SUSY)
- Di-lepton resonances
- Di-lepton large extra dimensions
- Single lepton + MET
  - W', Universal ED, CI, DM
- W' → tb
- 2^{nd} generation leptoquarks (l+jets)
- Z' → ttbar searches
  - Semi-leptonic, all-hadronic

- Vector-like T' → tZ, tH, bW
- Vector-like B' → tW, bH, bZ
- Q = 5/3 top partners
- High mass di-boson resonances
  - W', extra dimensions, ...
- Microscopic black holes
- Jet extinction
  - Black holes, ...
- Displaced jets
  - Split/RPV SUSY, hidden valley, ...
- Heavy stable charged particles

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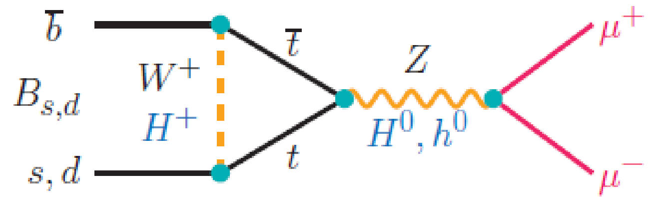
■ : Next talk

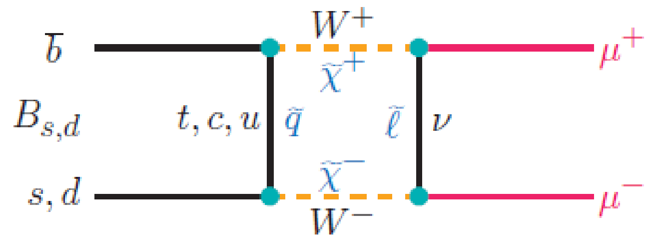
■ : Next-to-next talk

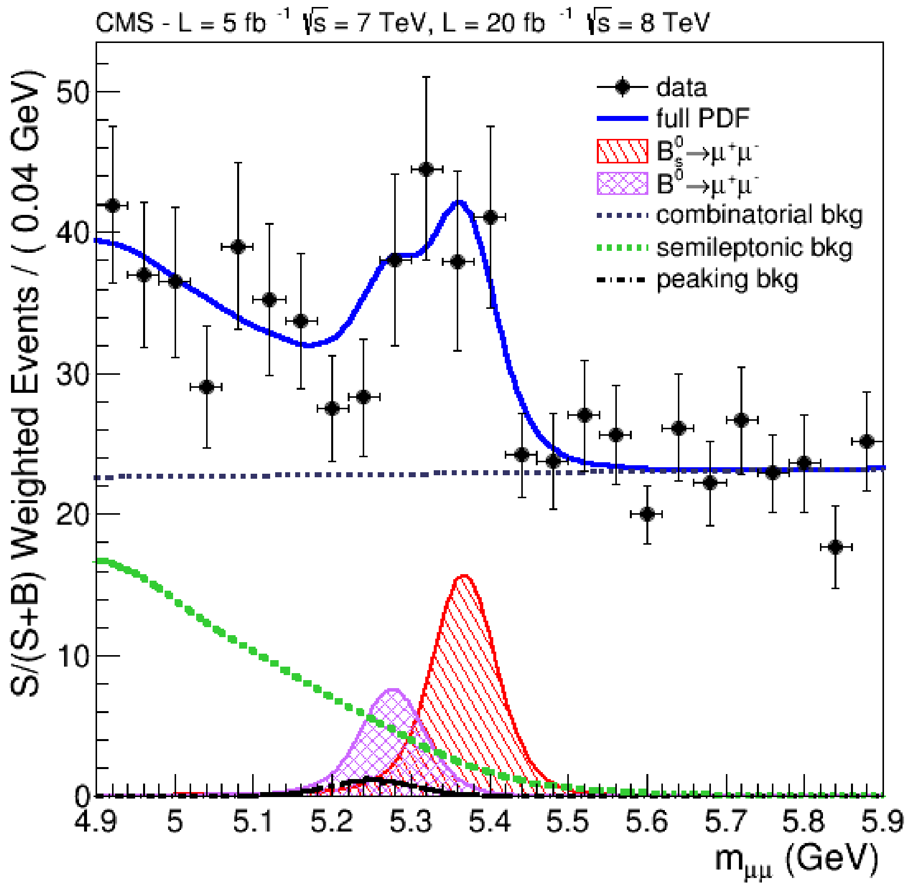
Aside: $B_s \to \mu\mu$

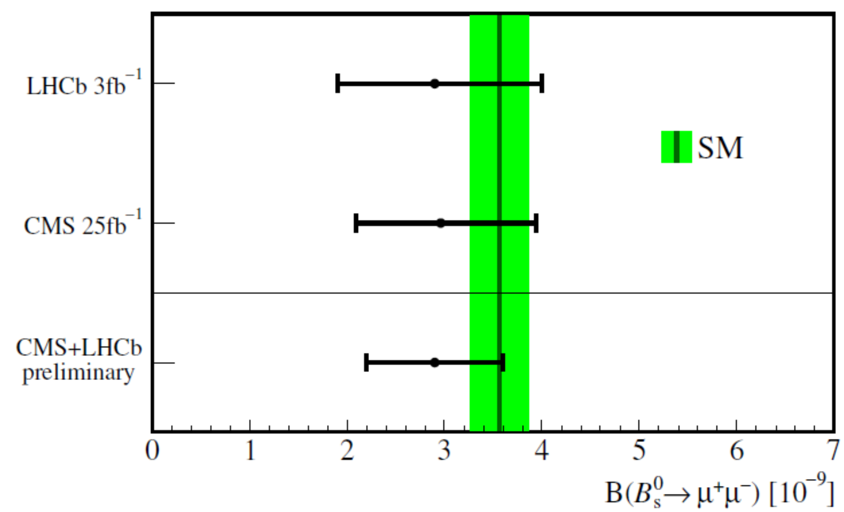
BPH-13-007

- Highly suppressed in standard model (FCNC)
- Very sensitive to new physics in loops
- Finally observed by CMS and LHCb
- Result compatible with SM expectation









$$\mathcal{B}\left(B^0_s \to \mu^+\mu^-\right) = (2.9 \pm 0.7) \times 10^{-9}$$

Aside: $B_s \to \mu\mu$

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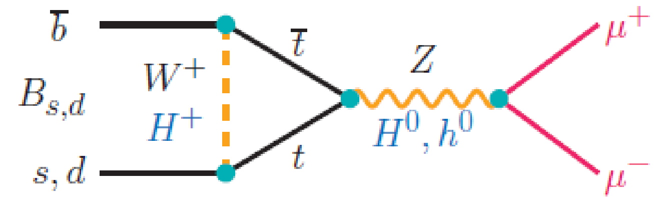

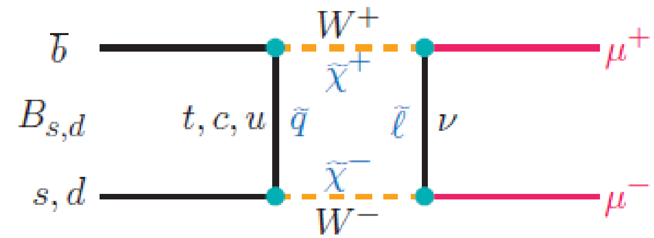

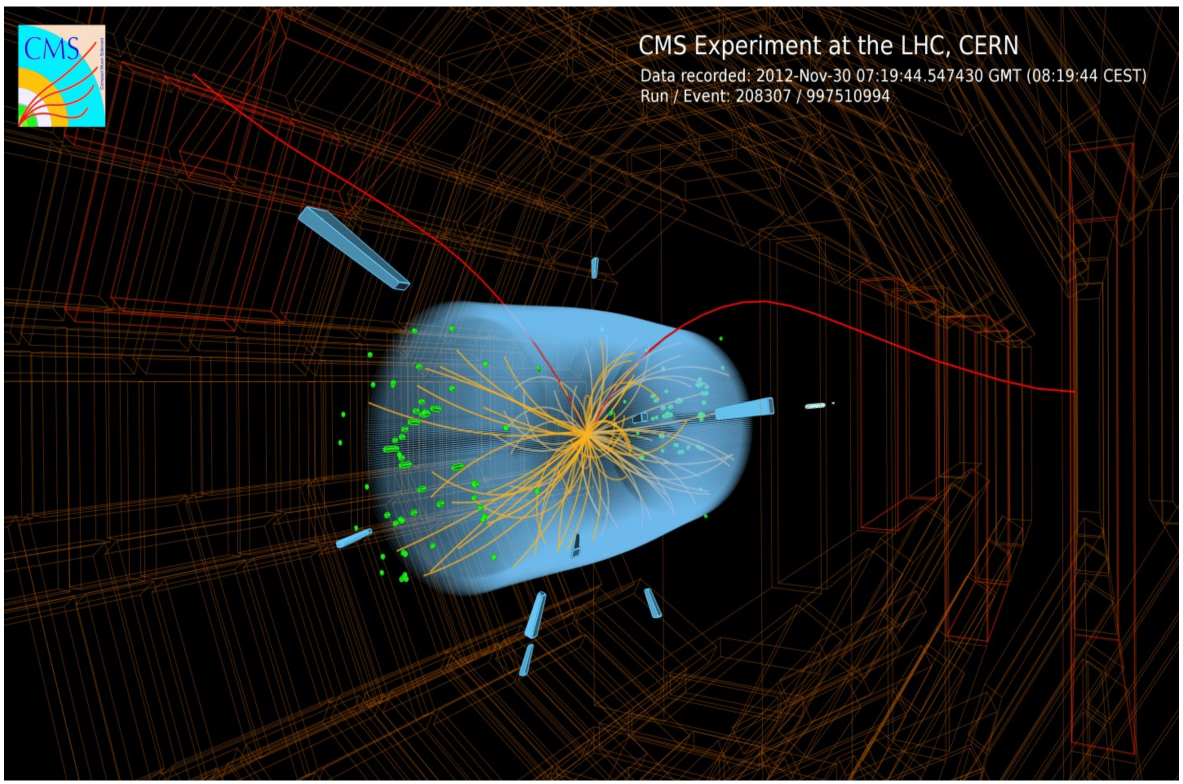

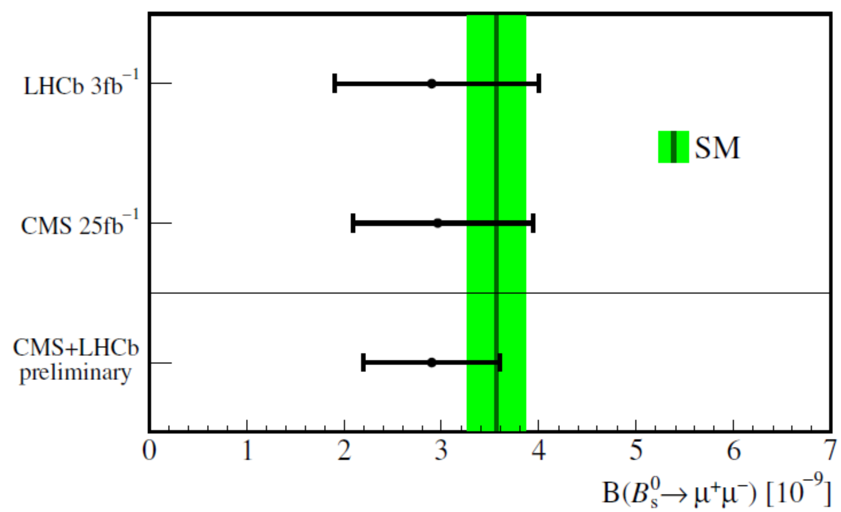

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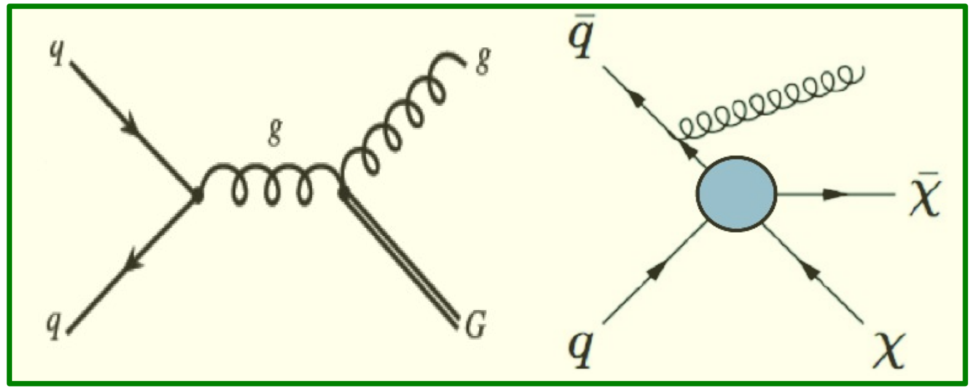
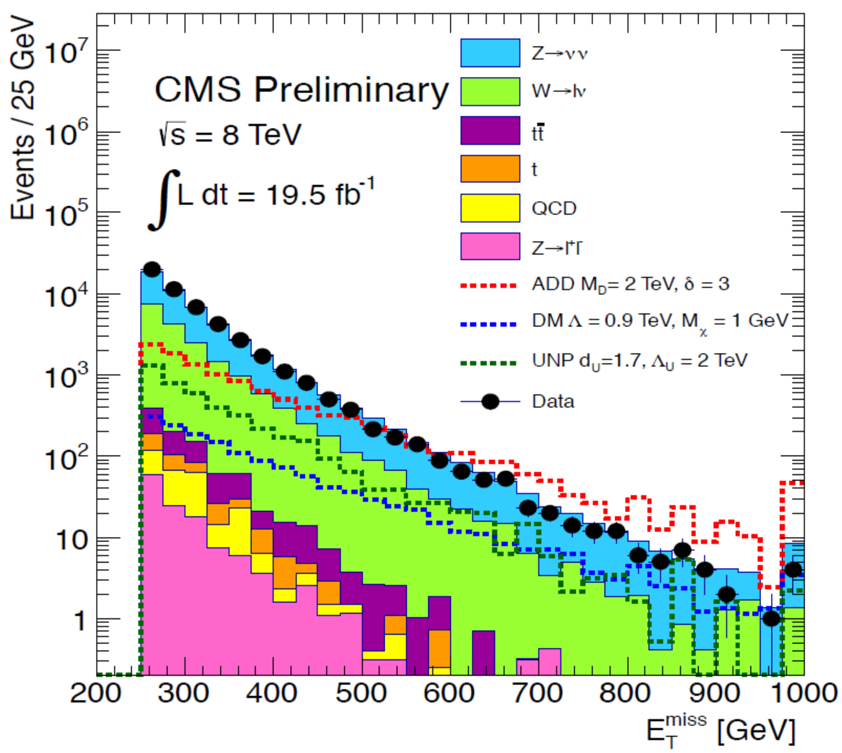
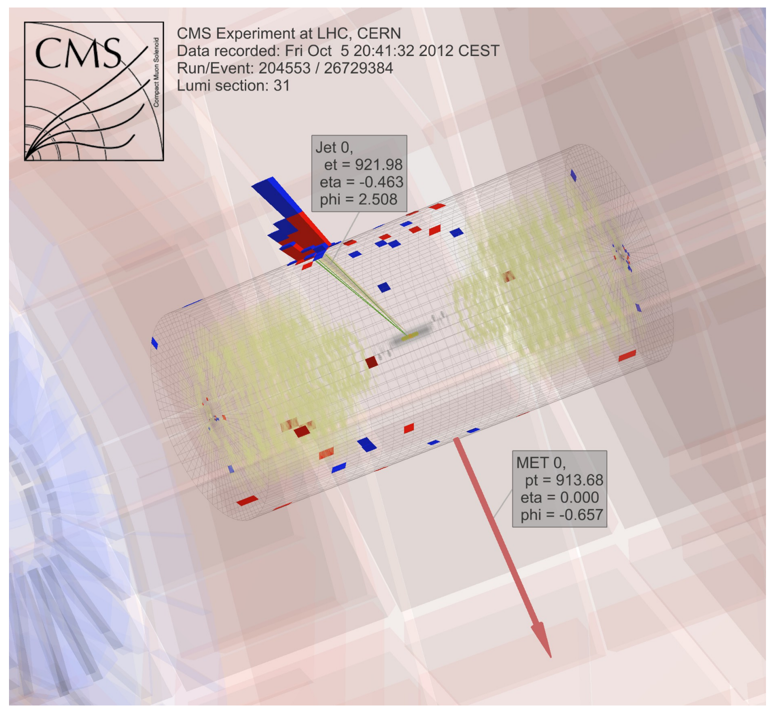
“Mono”-jets

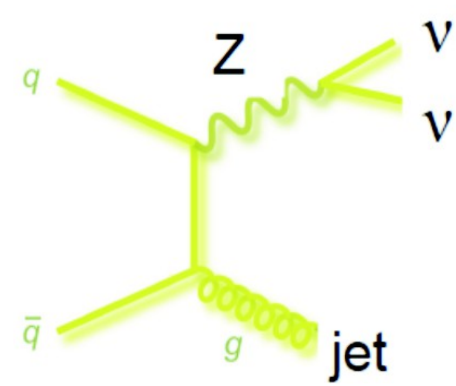
EXO-12-048

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



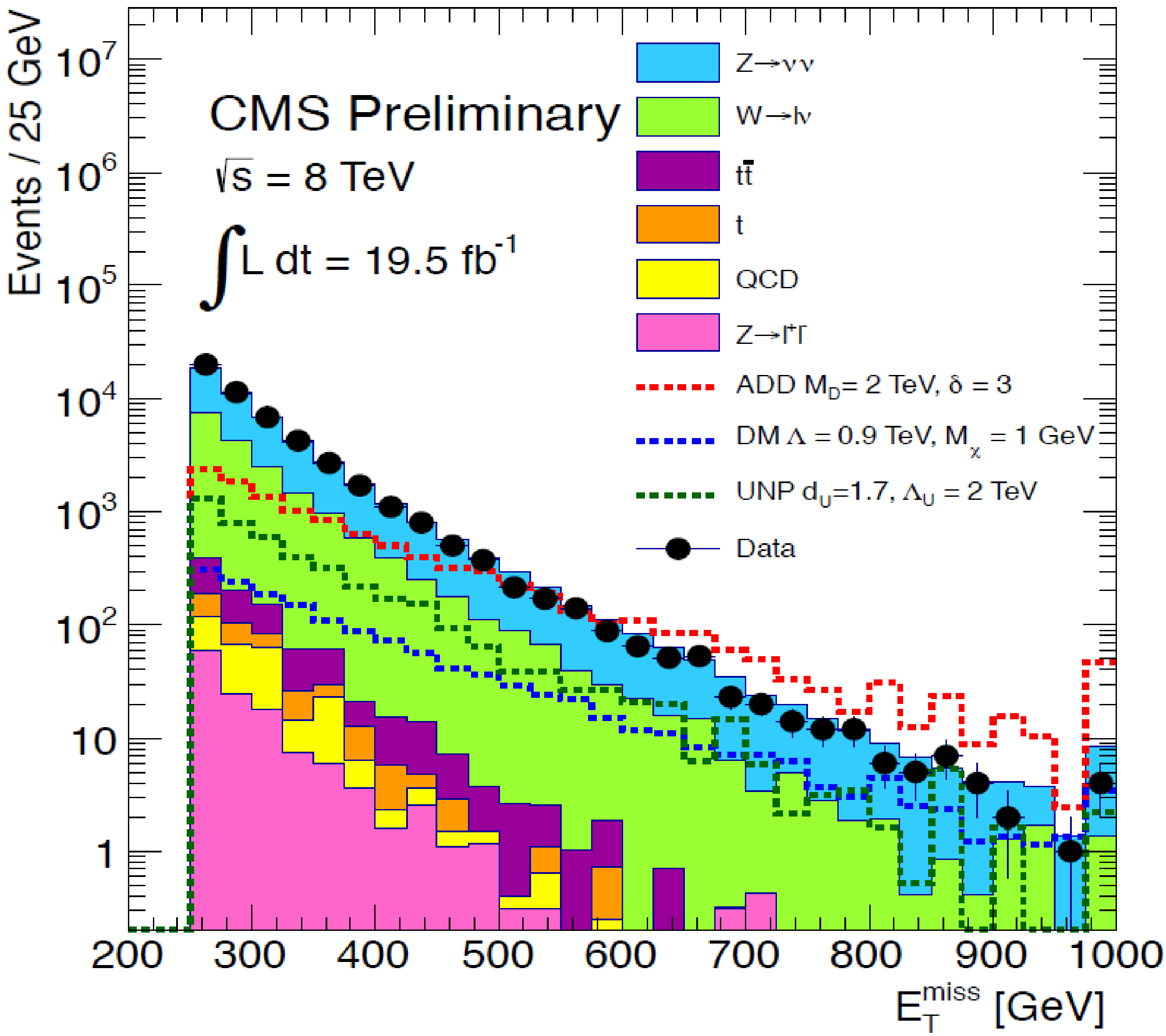






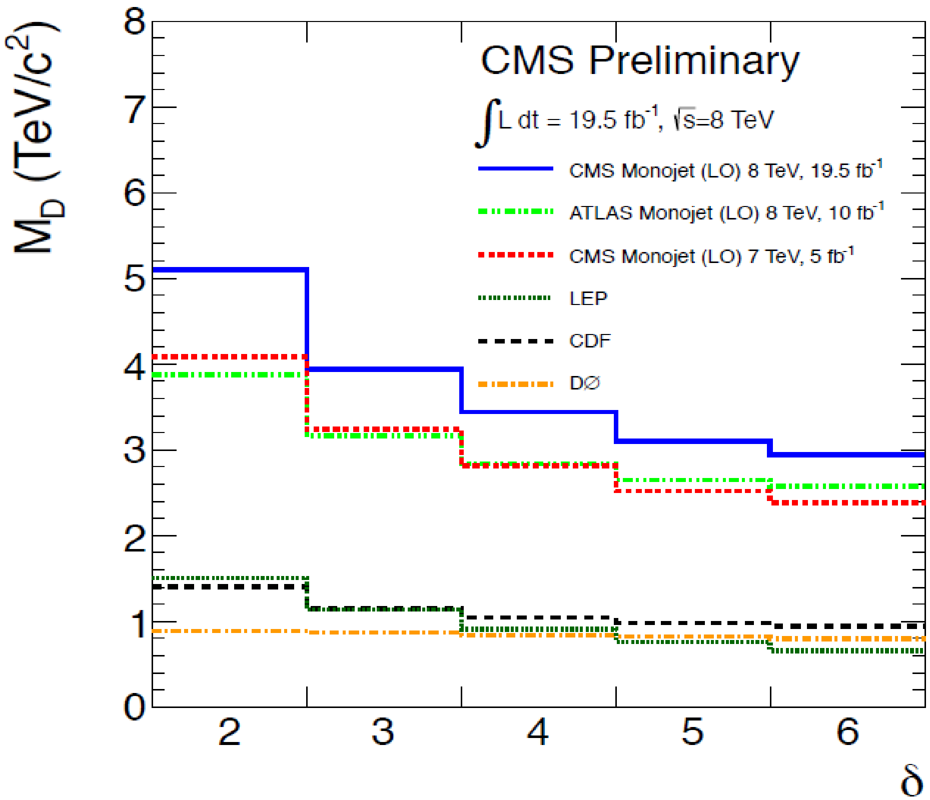
"Mono"-jets

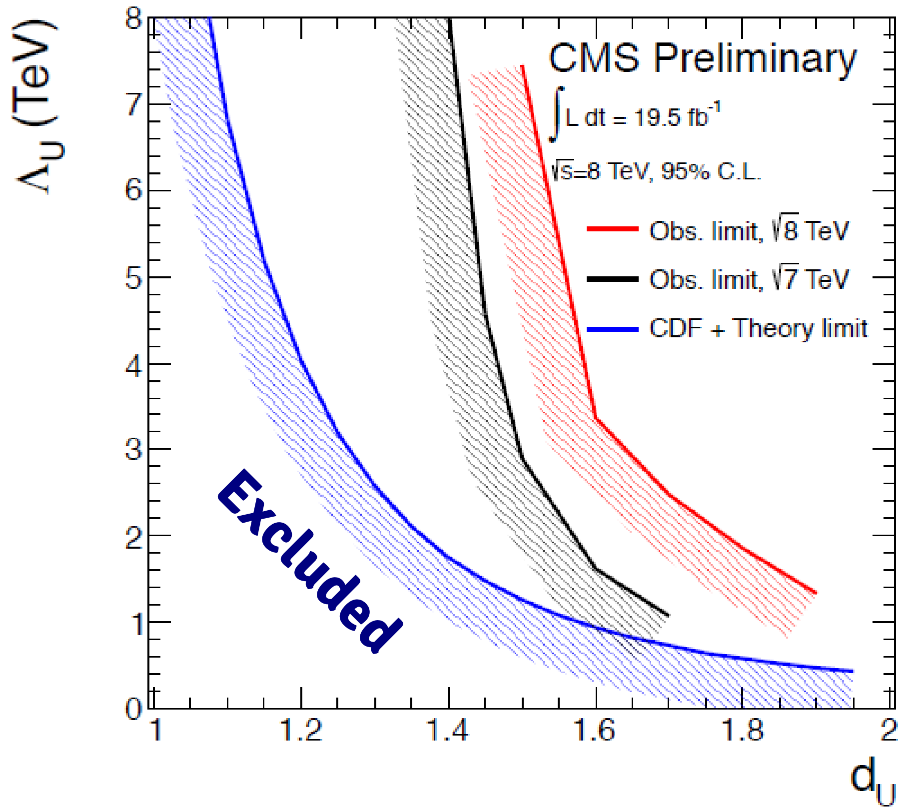
EXO-12-048



“Mono”-jets

EXO-12-048





Large extra dimensions:

Fundamental Planck scale M_D > 3... 5 TeV

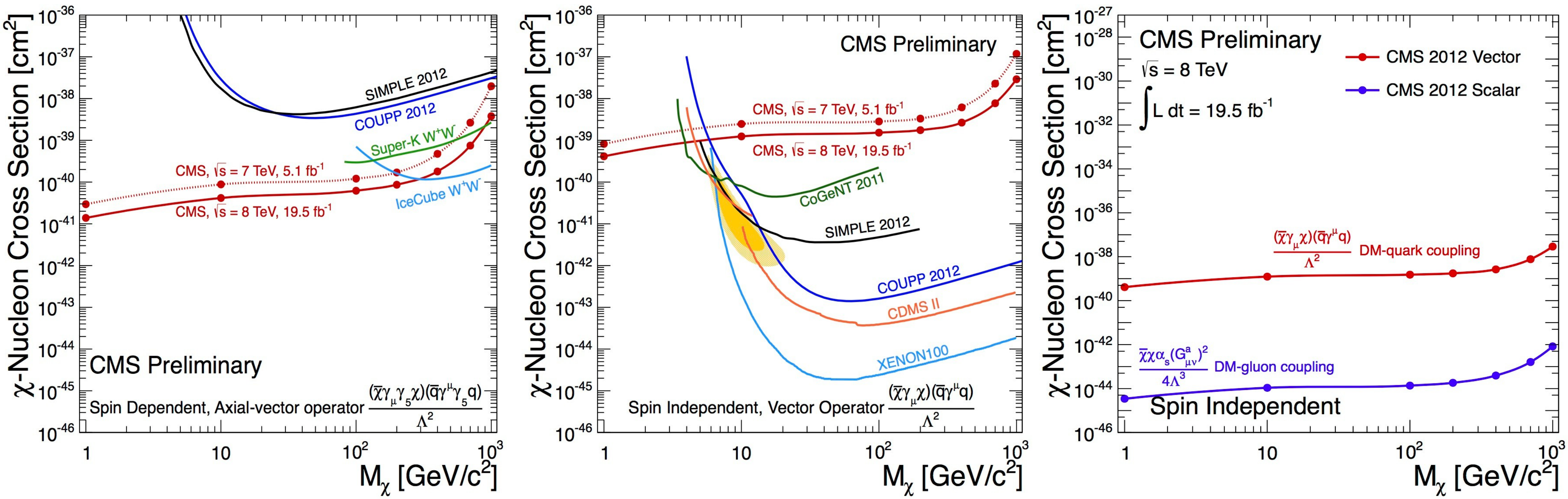
(up to 5.7 TeV @ NLO)

(Stable, scalar) unparticles

“Mono”-jets

EXO-12-048

- Pair production of dark matter characterized by a contact interaction effective theory
- Limits translated to DM-nucleon cross sections in order to compare with direct detection experiments

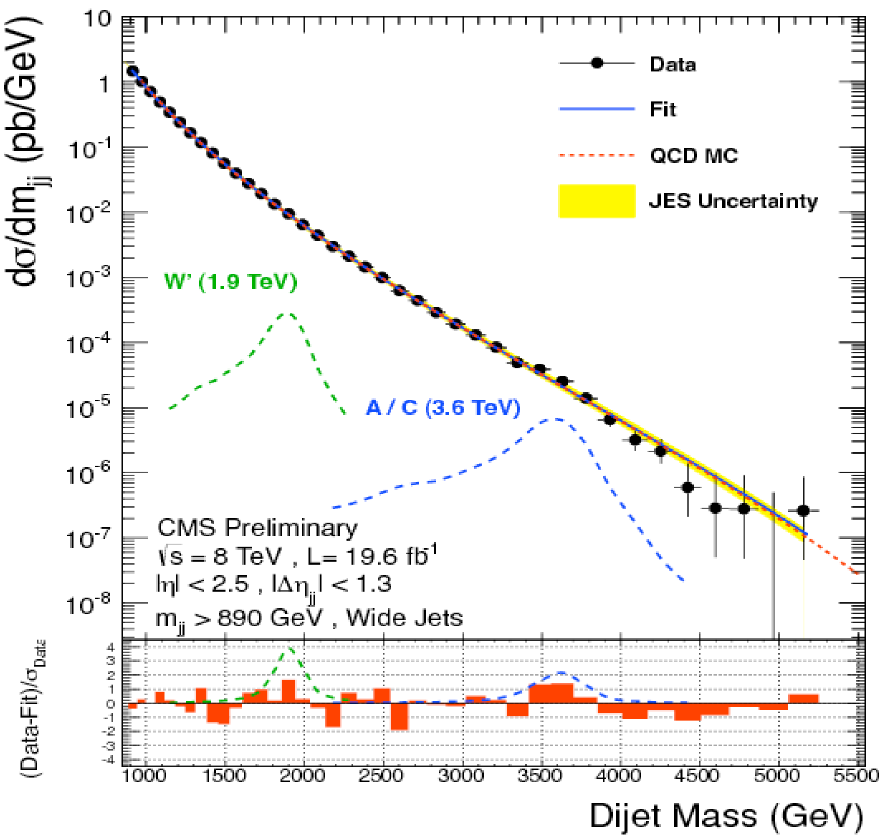


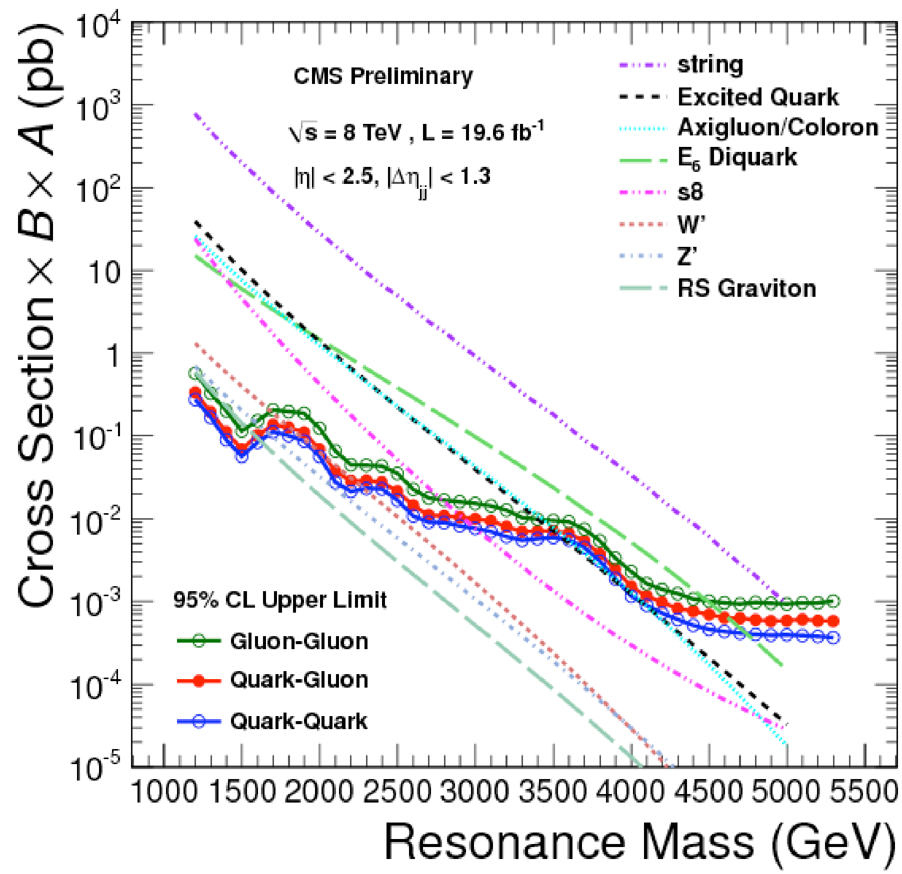
- Many operators, validity range of effective theory, new models, ...

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', ...





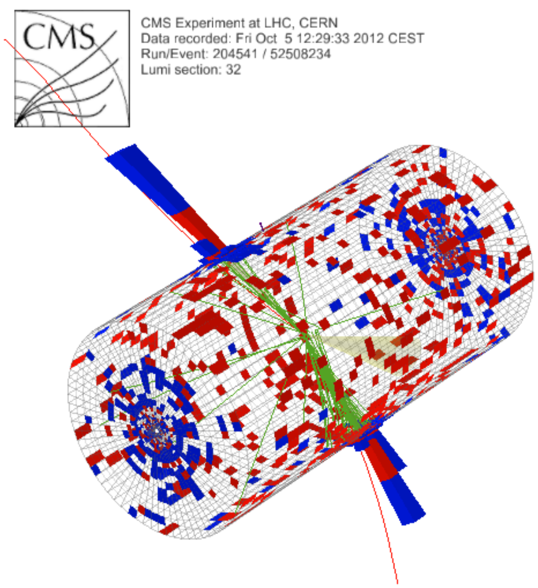
- Present results in a way to allow straightforward application to new models

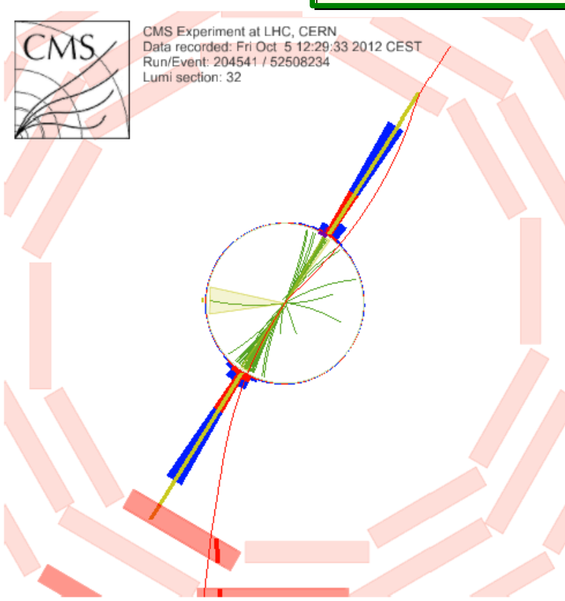
Di-jet searches

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]



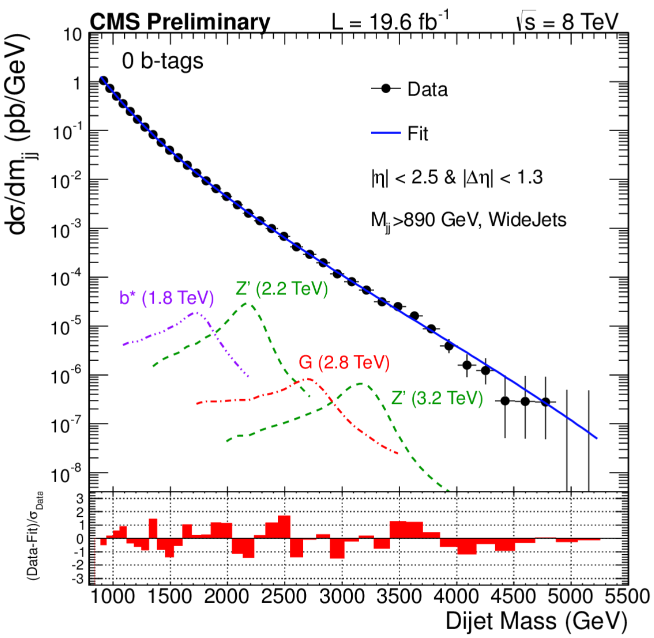


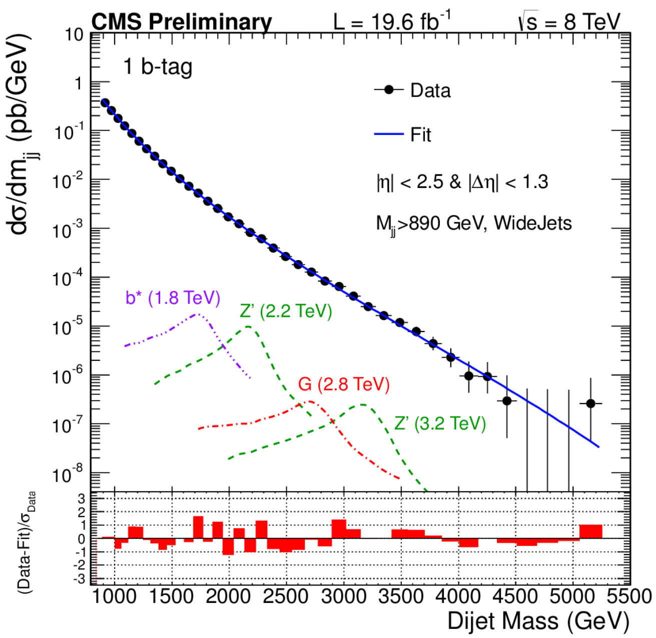
Di-jet mass = 5.15 TeV

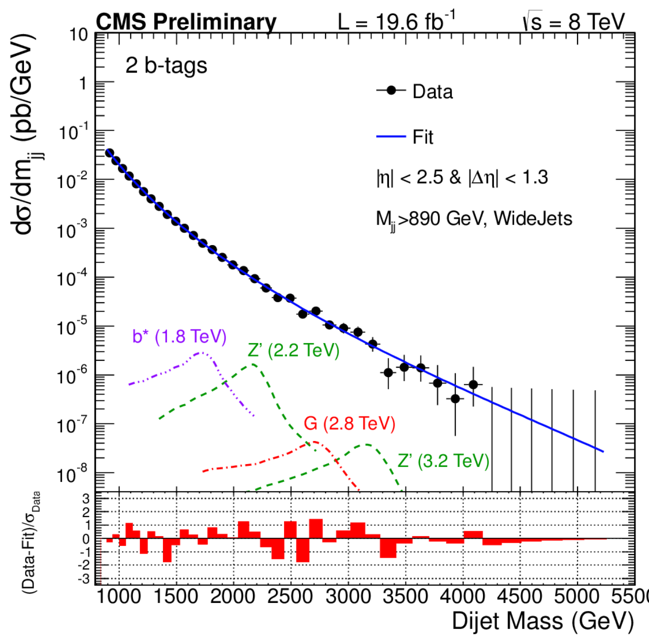
- Present results in a way to allow straightforward application to new models

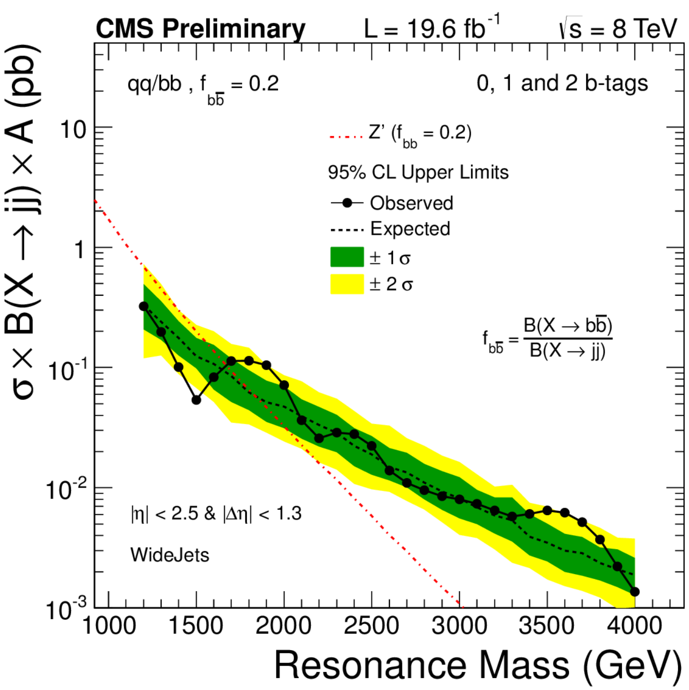
Di-jet searches (b$\bar{b}$, bg)

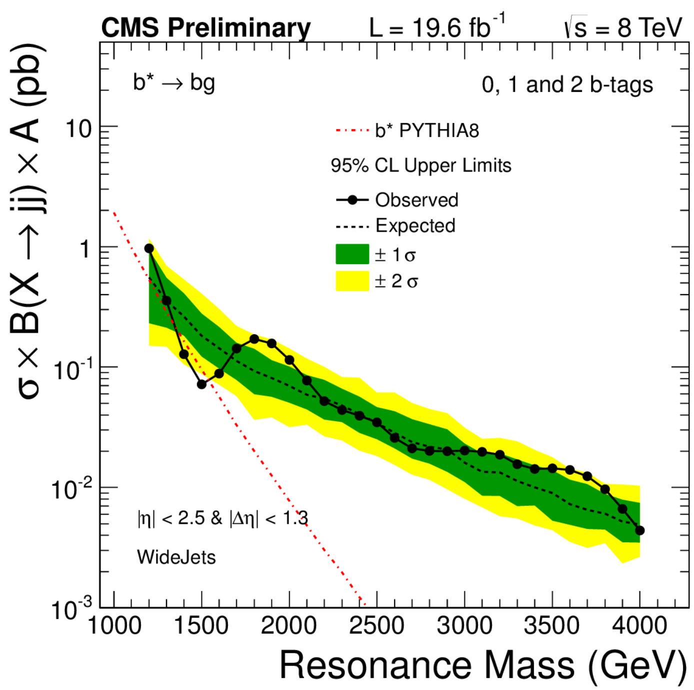
EXO-12-023











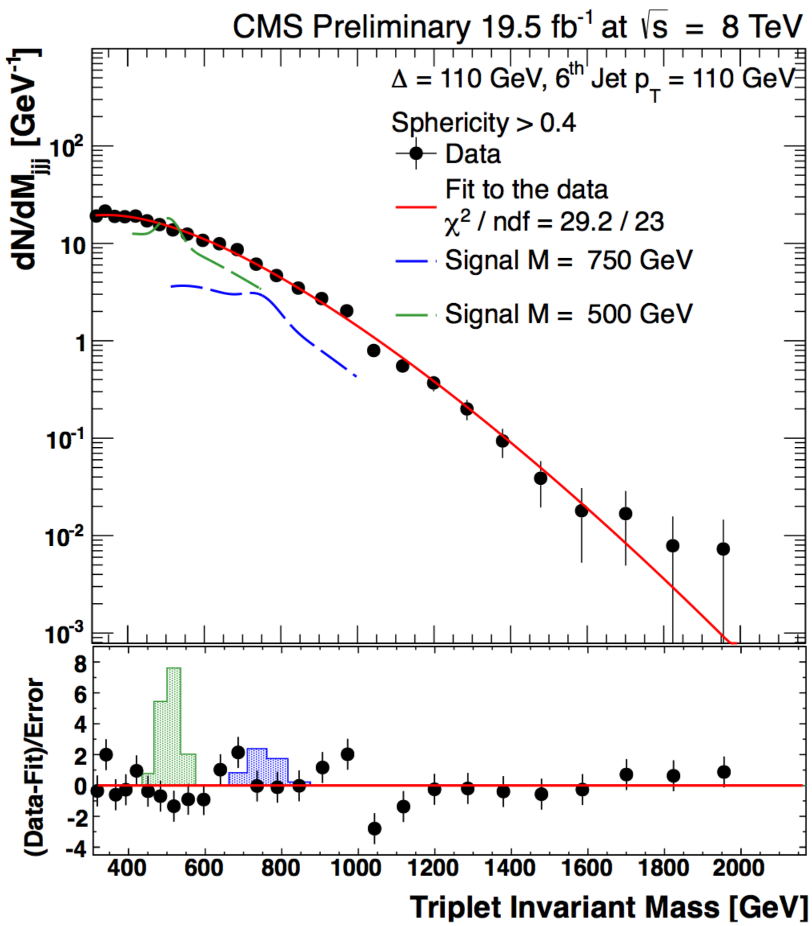
Extend to (0,) 1, 2 b-tags

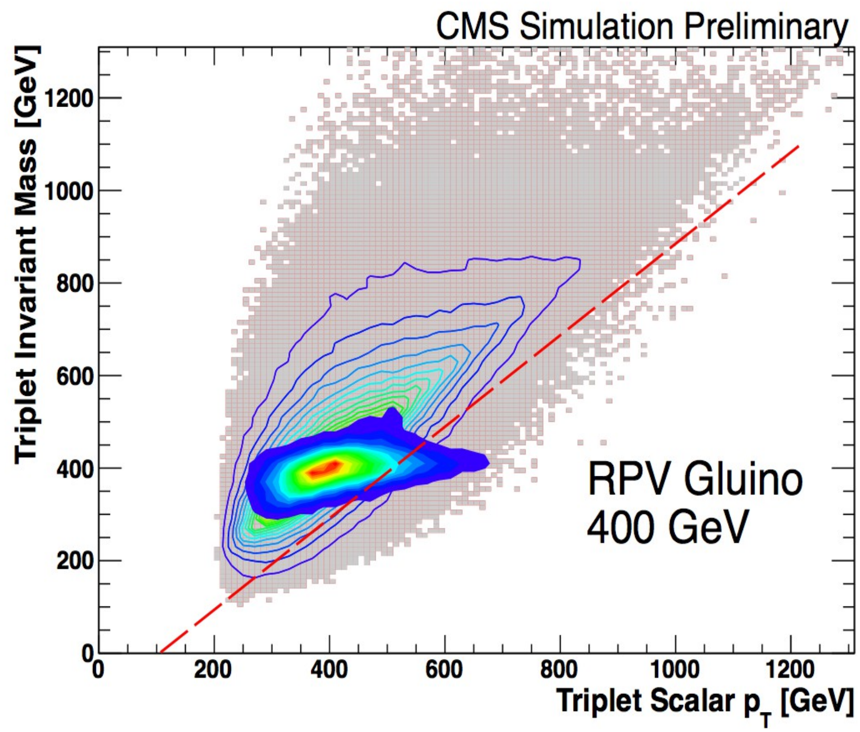
Pair-produced 3-jet resonances

EXO-12-049

- Benchmark: pair-produced gluinos decaying to 3 jets in RPV SUSY
- Combine 6 highest p_T jets into 20 unique triplet combinations
- To suppress wrong combinations and QCD, only accept triplets that satisfy
- Look for bump in falling spectrum

$$M_{jjj} < \sum_{i=1}^{3} |p_{\mathrm{T}}|_i - \Delta$$

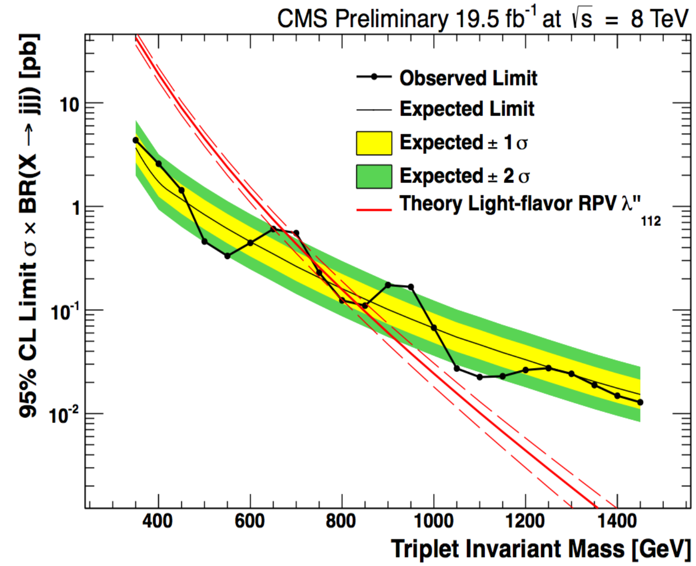


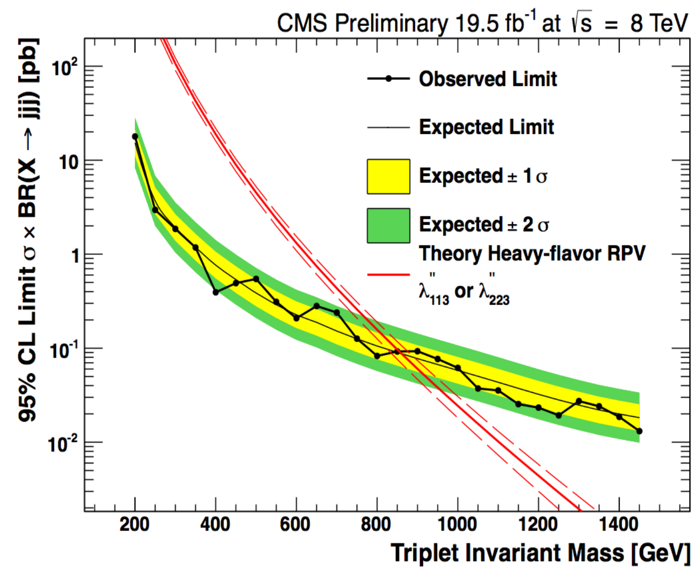


Pair-produced 3-jet resonances

EXO-12-049

- In addition to inclusive search, apply b-tagging for enhanced sensitivity to decays with b quarks (gluino → udb, csb)
- Inclusive search: exclude RPV decaying gluinos with **M < 650 GeV**
- b-tagged: exclude **200 < M < 835 GeV**

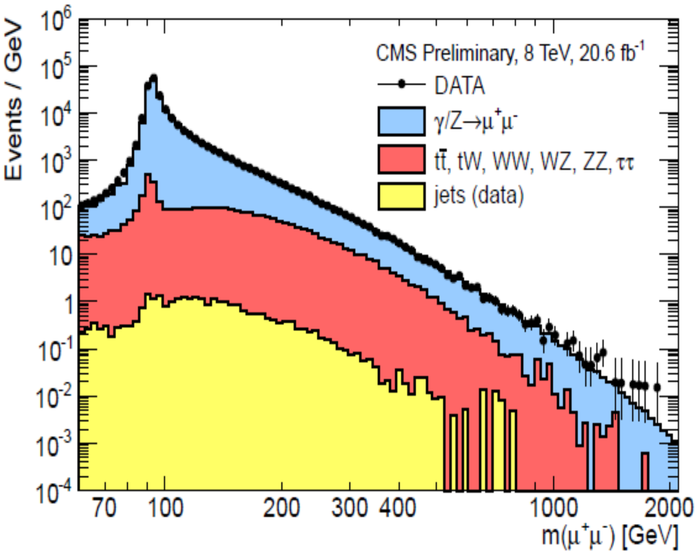


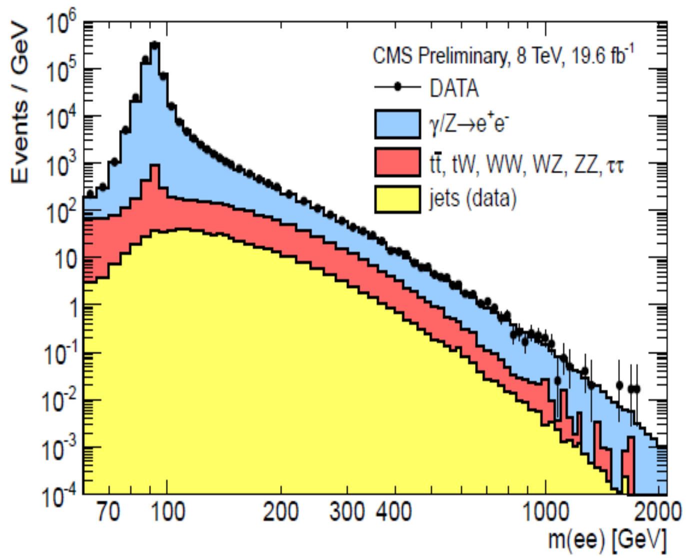


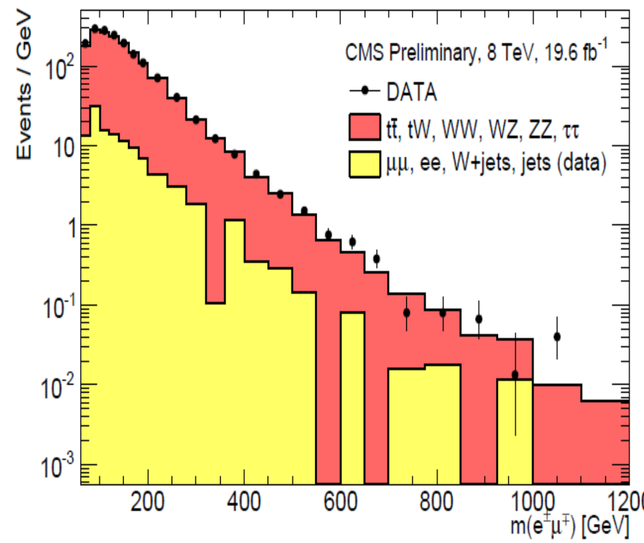
Di-lepton resonances

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

EXO-12-061

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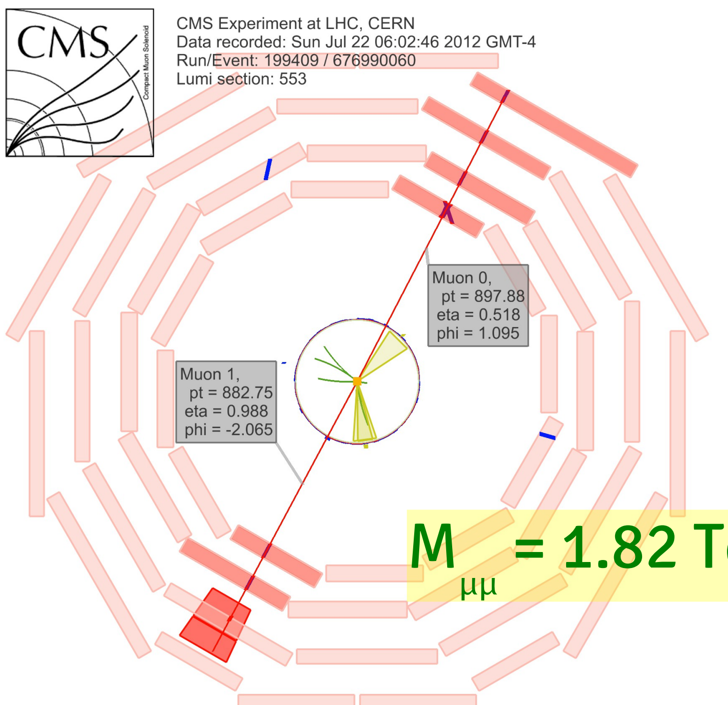
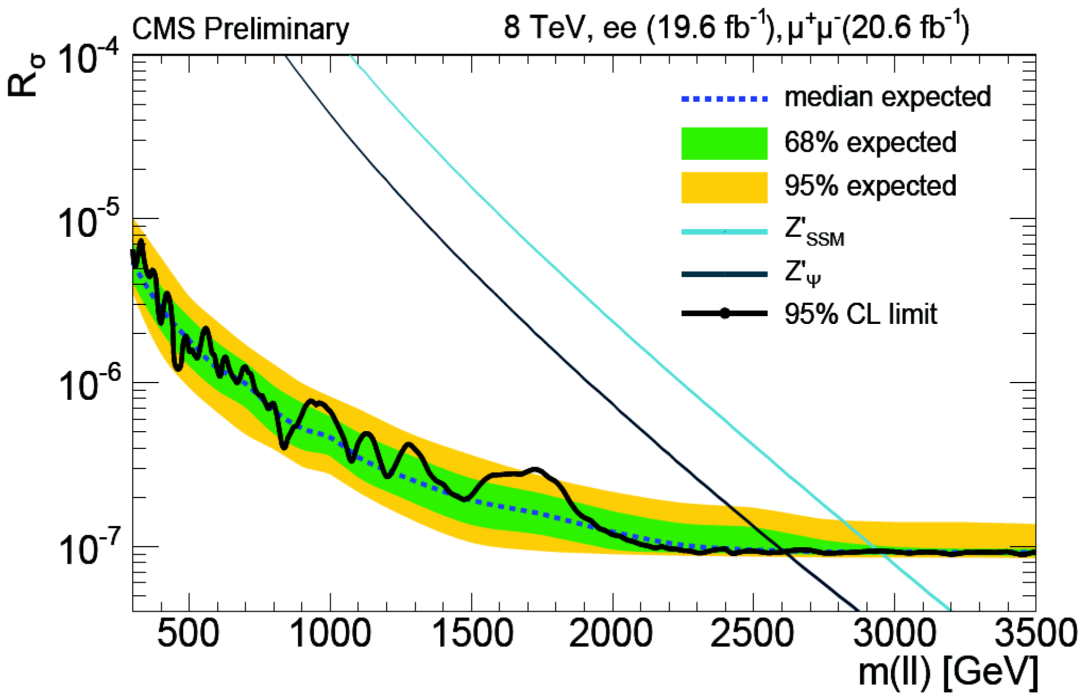


$M_{\mu\mu} = 1.82$ TeV



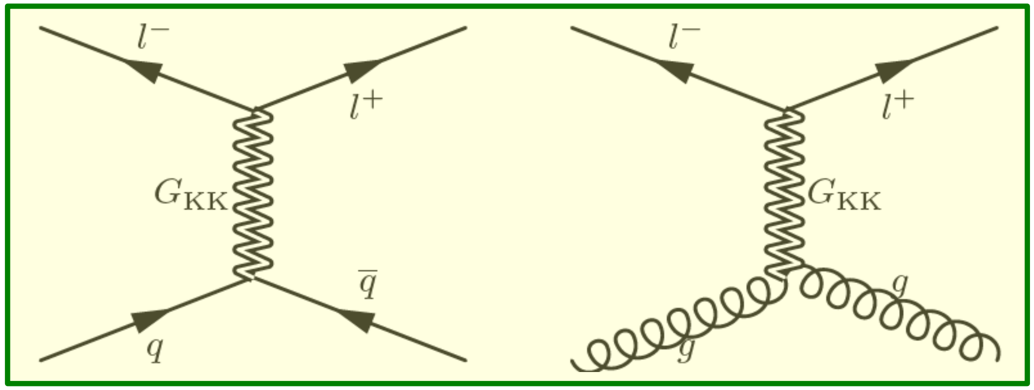
95% CL mass limits:

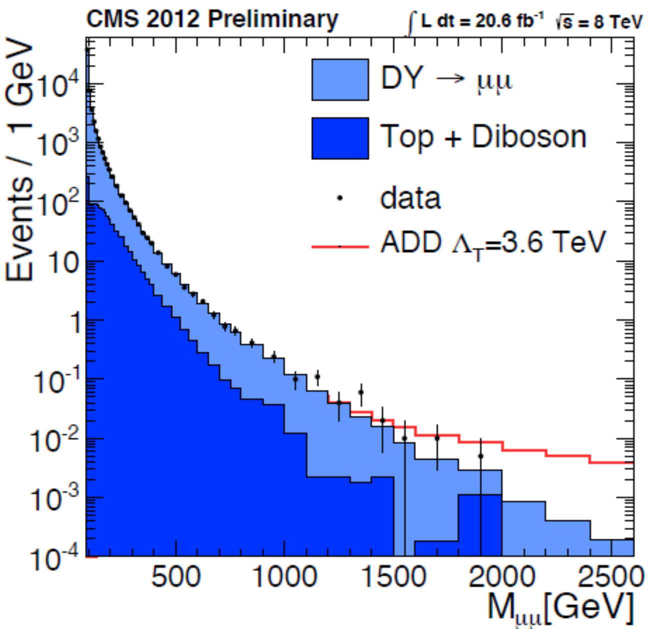
Z' SSM	Z' Psi
2.96 TeV	2.60 TeV

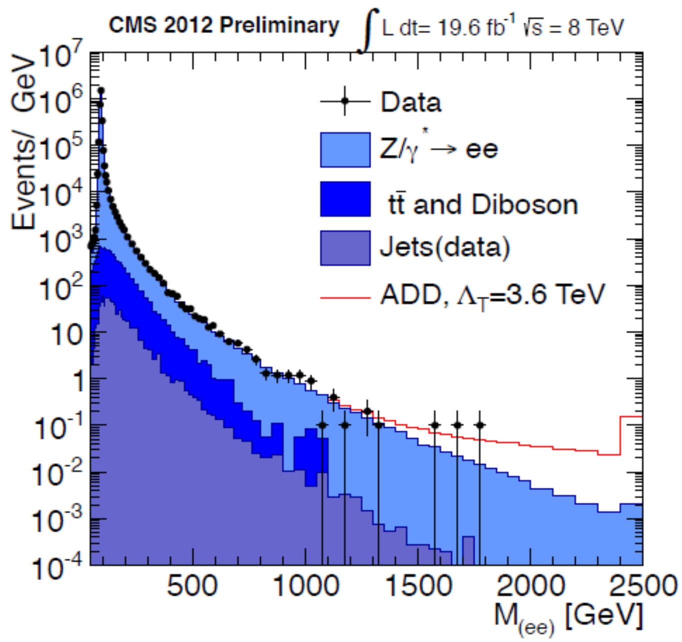
Large extra dimensions (ADD) in ee, μμ

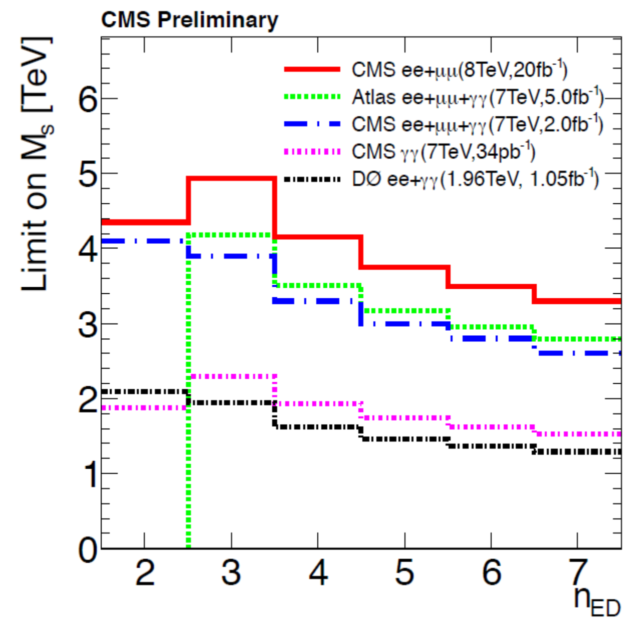
EXO-12-027/031

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



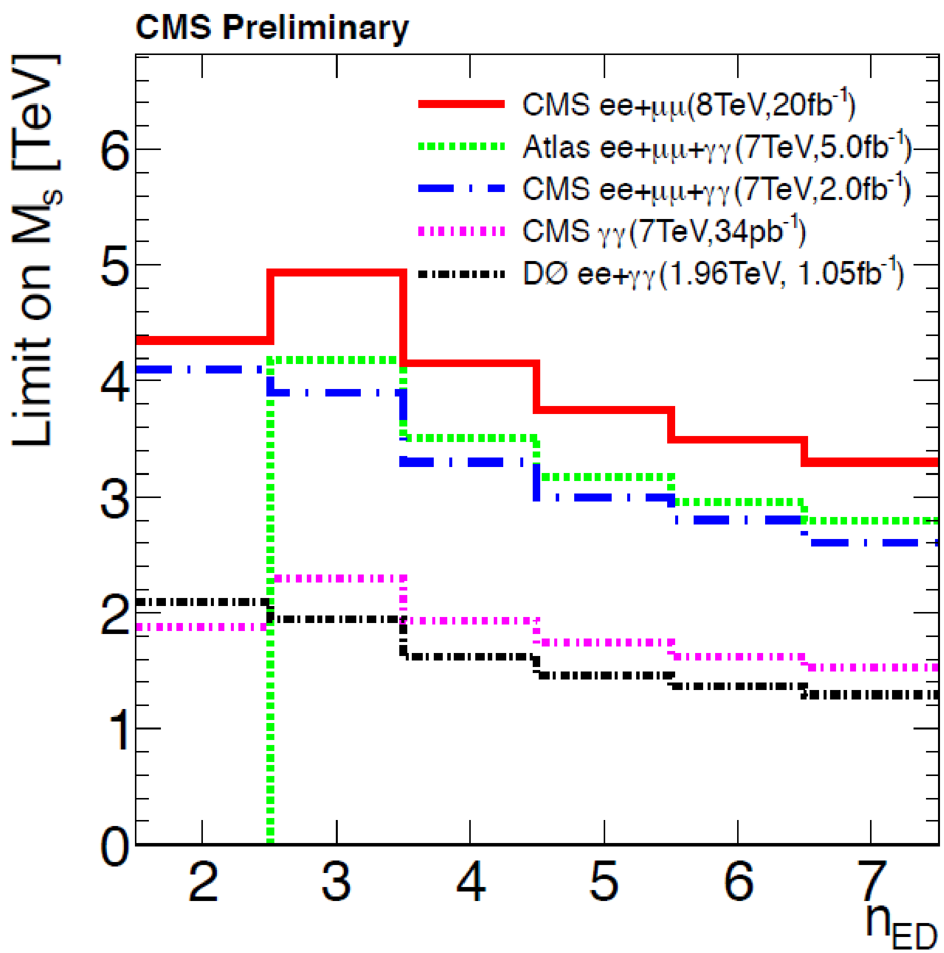






M_S (ADD) at LO 95% CL limits	Lumi. [fb^{-1}]	δ=3 Exp.	δ=3 Obs.	δ=6 Exp.	δ=6 Obs.	Λ_T (GRW) [TeV]
CMS dimuon	20.6	4.34	4.33	3.07	3.06	3.64
CMS dielectron	19.6	4.62	4.64	3.27	3.28	3.90
Combined:	20.6+19.6	4.76	4.77	3.37	3.37	4.01

Large extra dimensions (ADD) in ee, μμ



- UV cut-off parameter M_s, not directly comparable to fundamental Planck scale M_D
- Complementary to mono-jets and mono-photons
- Large part of interesting parameter space excluded

Ms (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]
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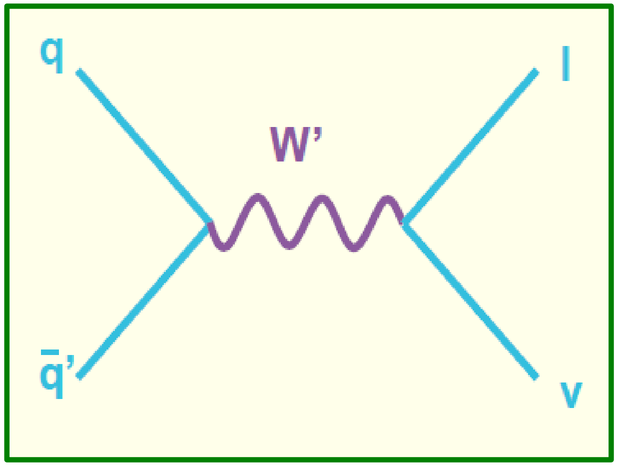
Combined:	20.6+19.6	4.76	4.77	3.37	3.37	4.01

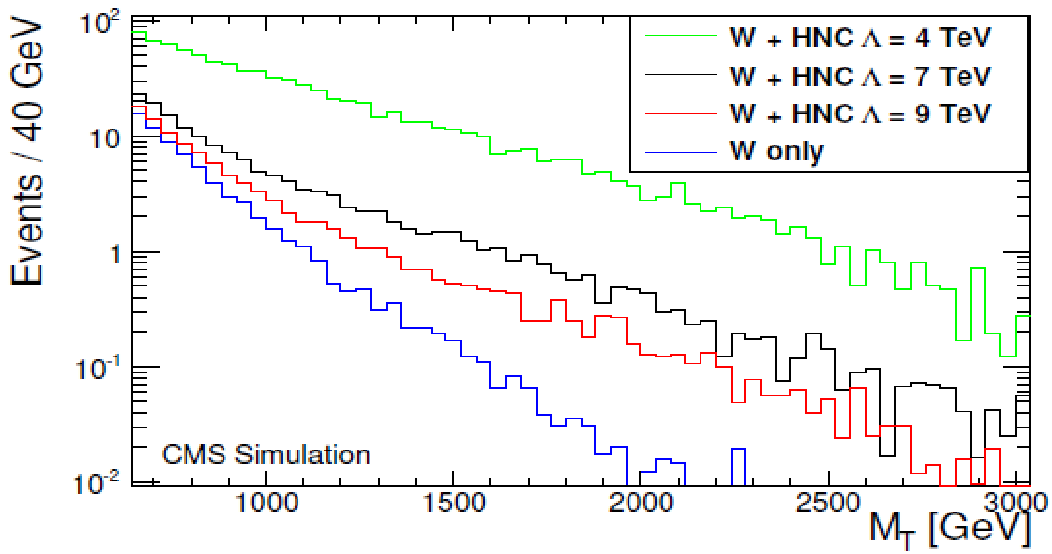
Single lepton + MET (eν, μν)

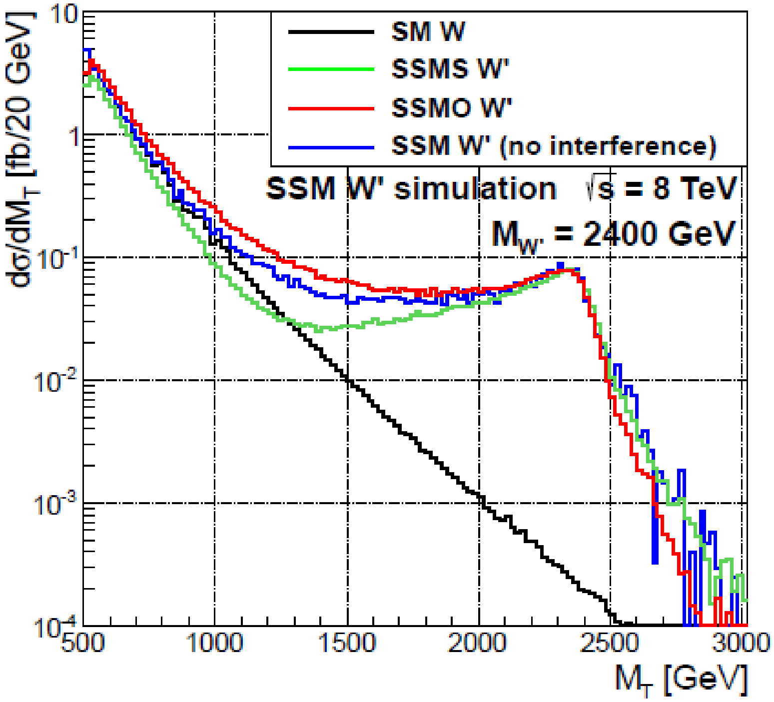
EXO-12-060

- Many models, e.g.:
  - sequential SM with and w/o interference, no decays to WZ
  - Universal extra dimensions
  - Four fermion contact interactions
- In events with isolated e or μ plus MET, use binned likelihood in M_T



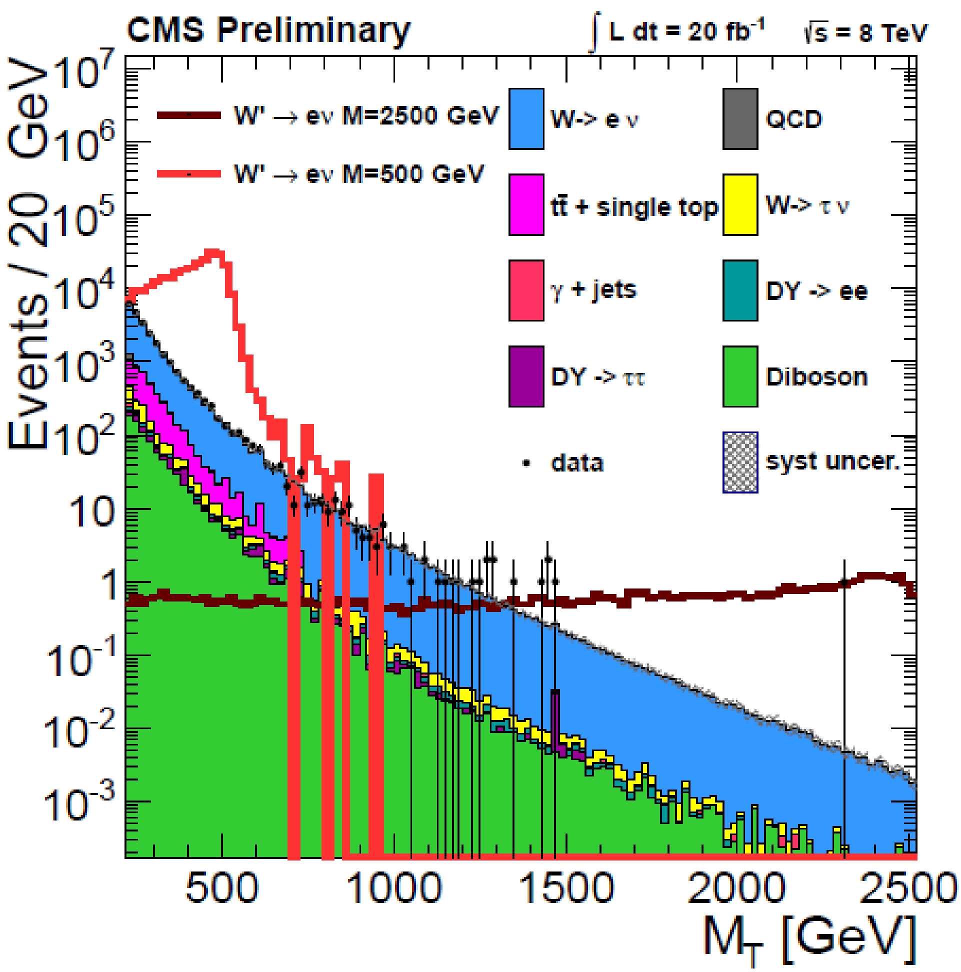
$$M_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

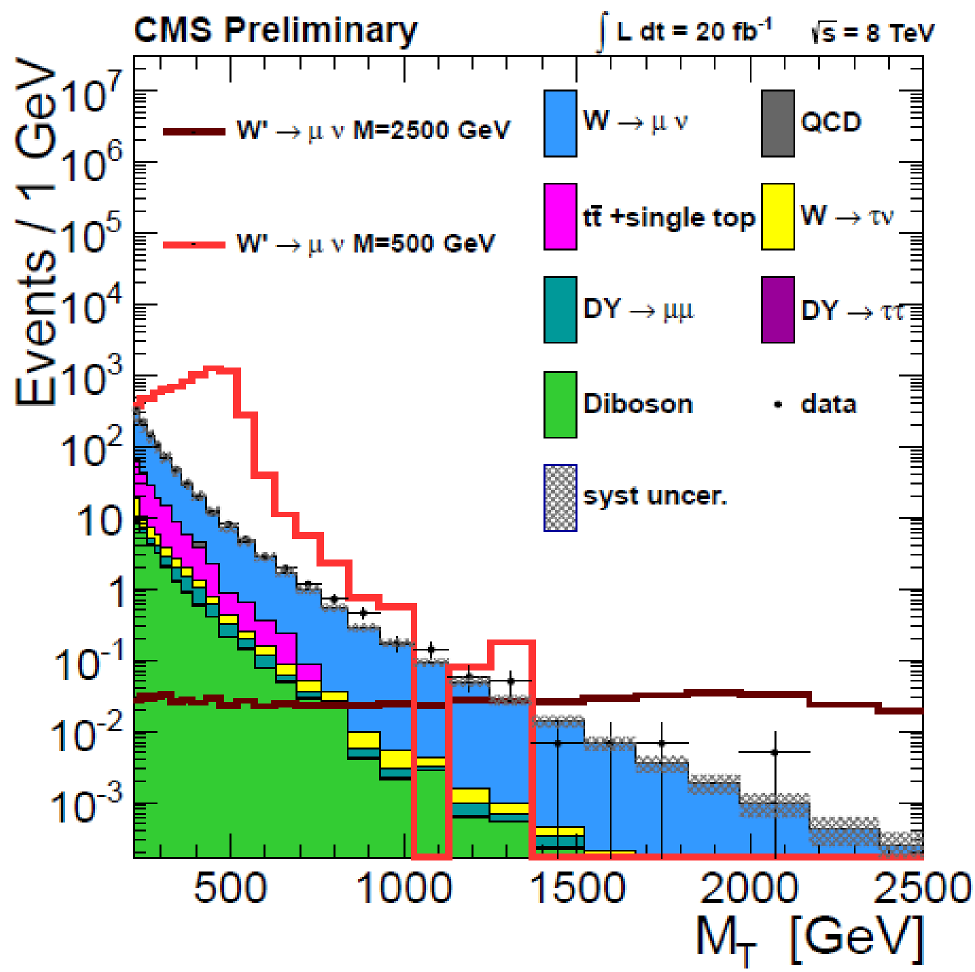




Single lepton + MET (eν, μν)

EXO-12-060



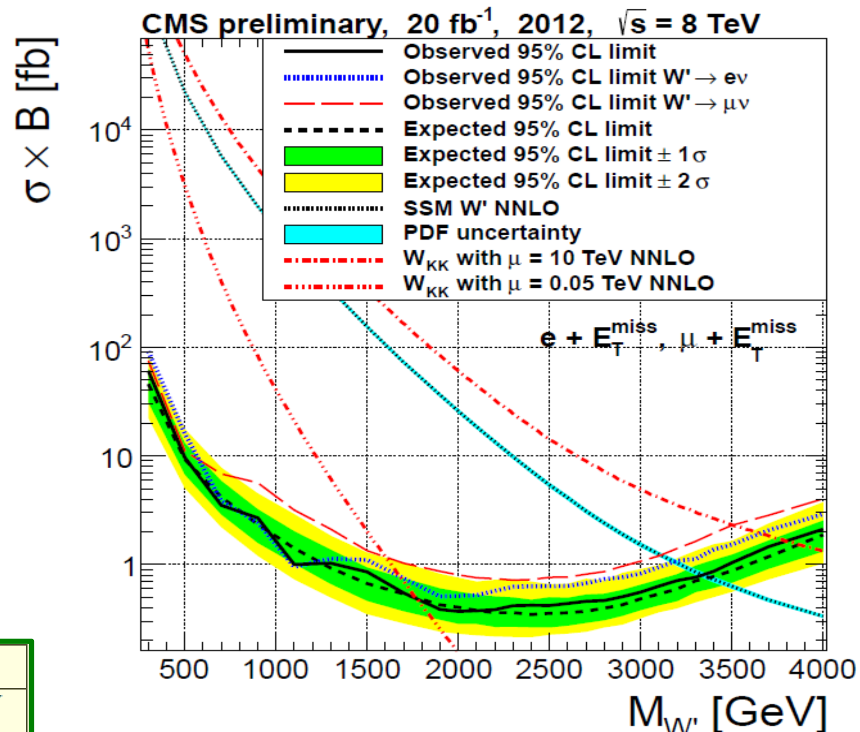


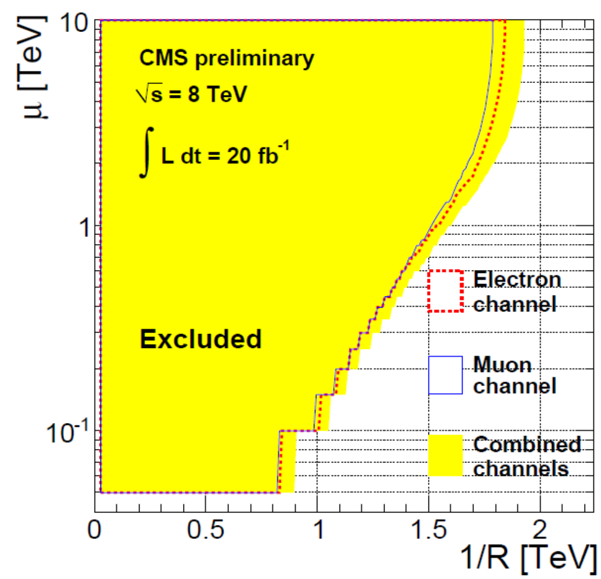
Single lepton + MET (eν, $\mu\nu$)

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

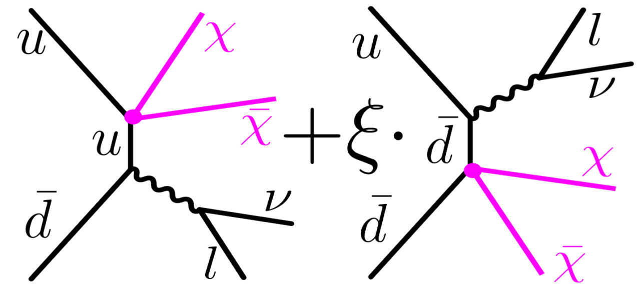


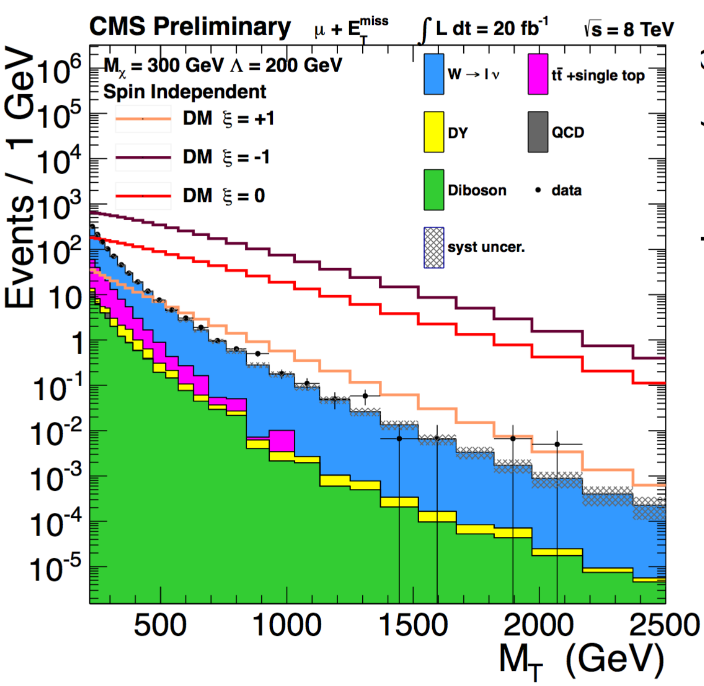


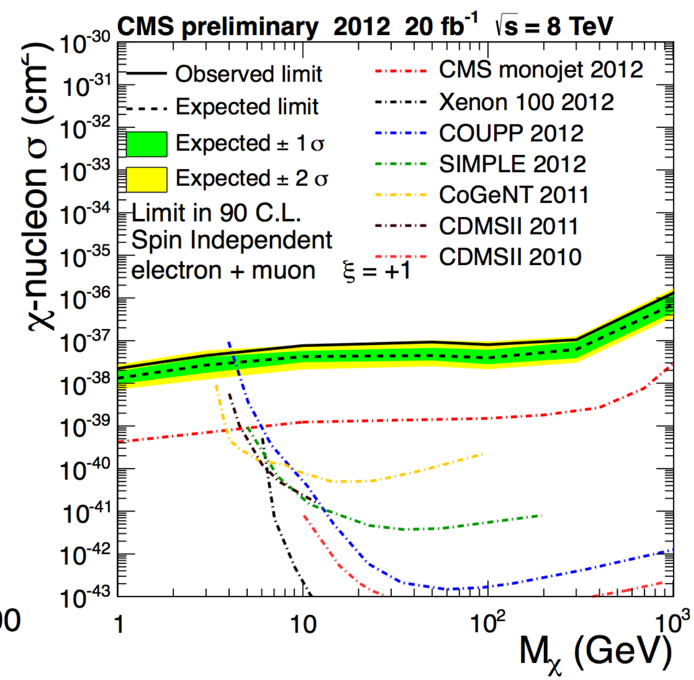
Single lepton + MET ($e\nu$, $\mu\nu$)

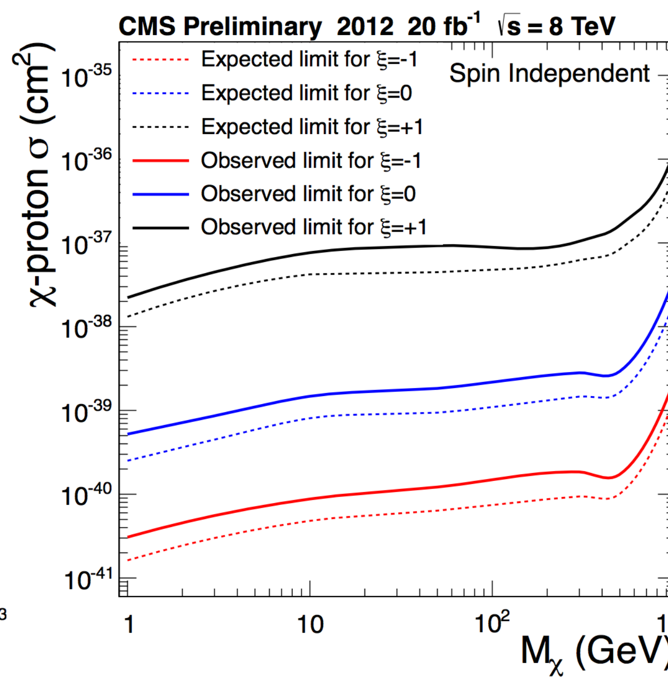
EXO-13-004

- Dark matter production: W recoiling against pair-produced dark matter
- Reinterpretation of leptonic W' search
- Consider vector and axial-vector like couplings
- Possible interference effects
- First limits on "monolepton" DM





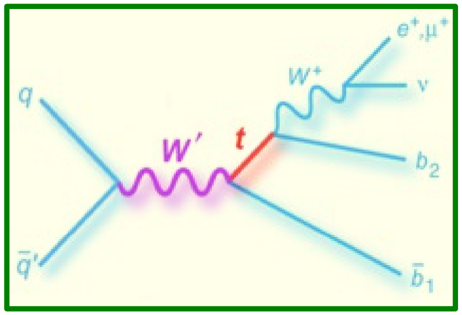


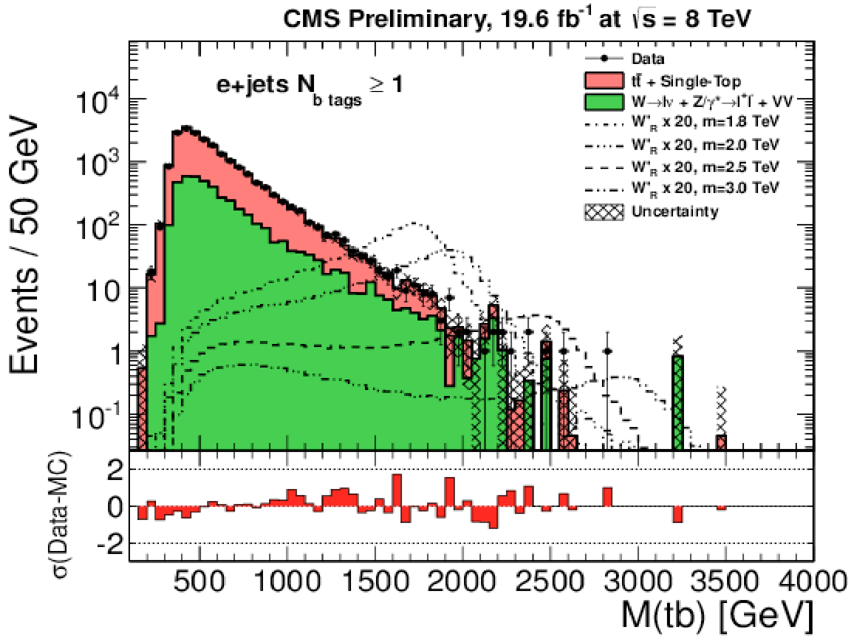


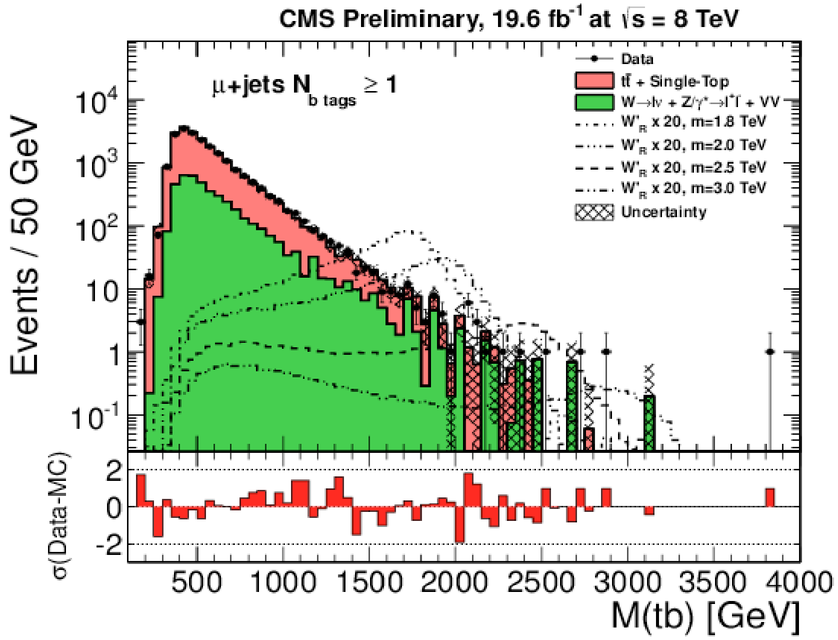
$W' \to t\,b$

B2G-12-010

- Searches in W' → quark final states important to complement leptonic searches, in case decays into leptons are suppressed
  - Also, can reconstruct mass (modulo ambiguities)
- Enhanced couplings to 3rd generation possible (and easier!)
- 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
- Limits for arbitrary combinations of LH or RH couplings



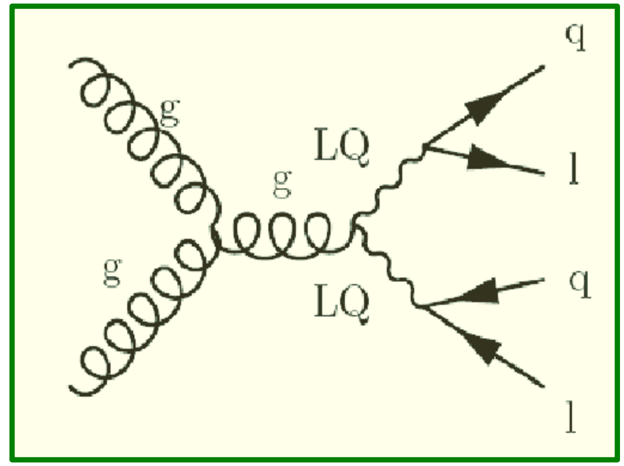


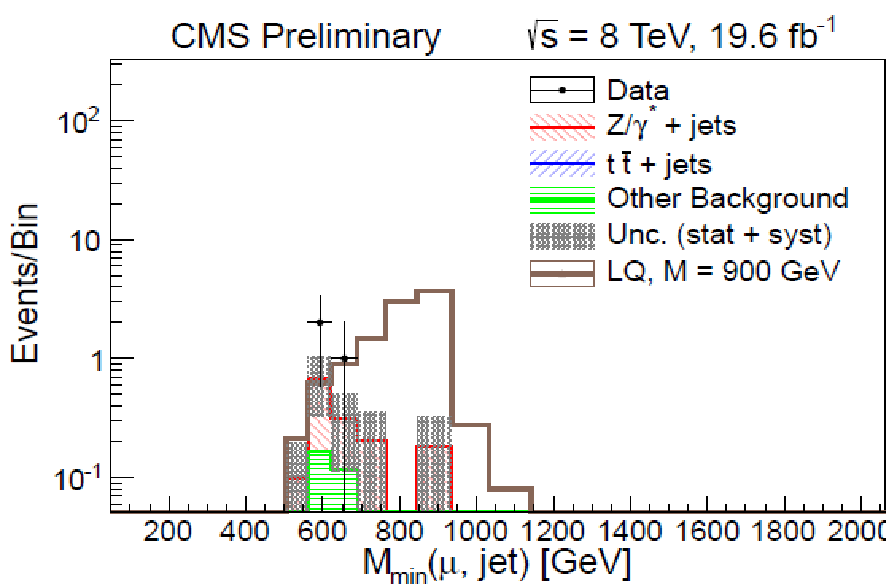


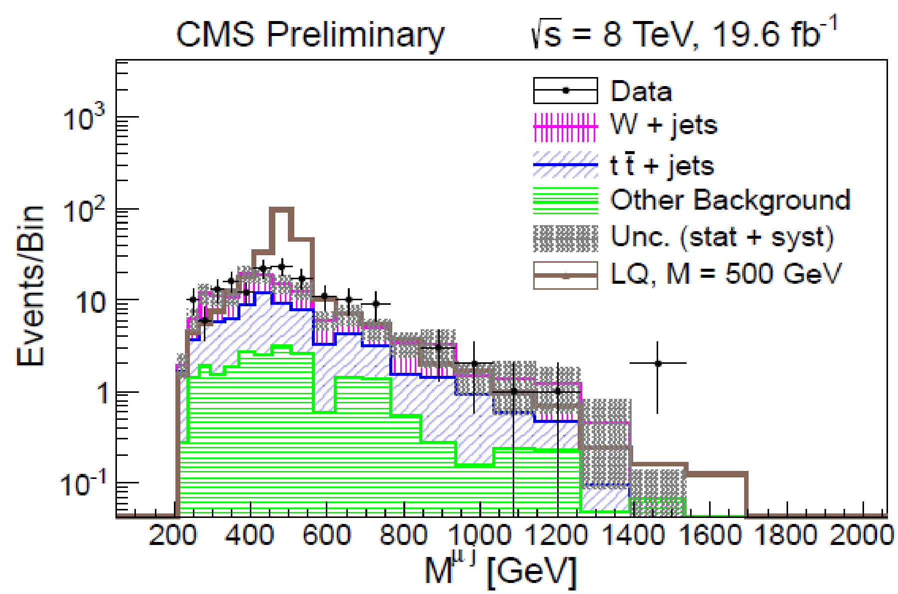
LQ2 ($\mu\nu$+jj, $\mu\mu$+jj)

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)
- Optimize cuts for each hypothetical M(LQ)
  - S_T ; $M(\mu\mu)$, $M_T(\mu\nu)$; $M(\mu,\text{jet})$
  - S_T = scalar p_T sum of μ, μ (ν), j1, j2

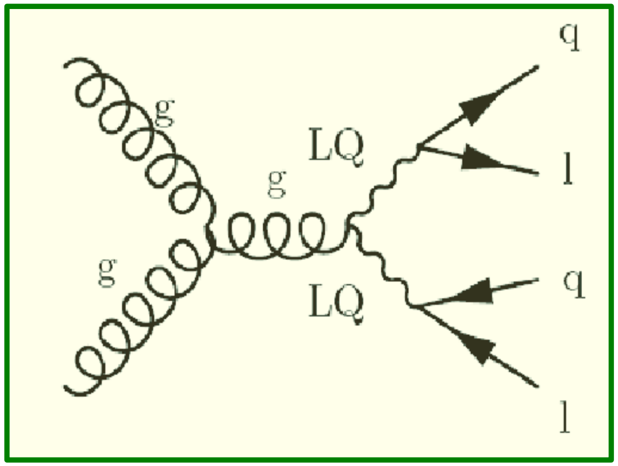


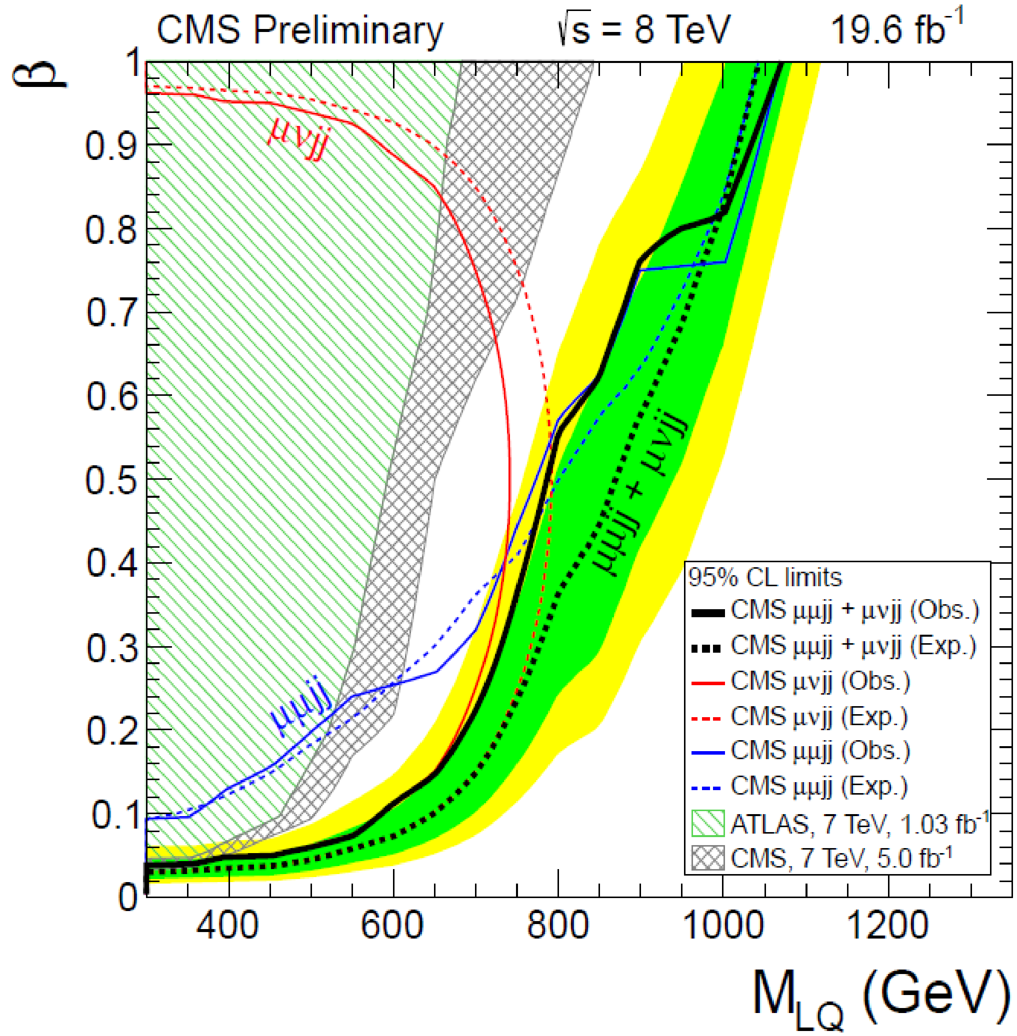




LQ2 ($\mu\nu$+jj, $\mu\mu$+jj)

EXO-12-042



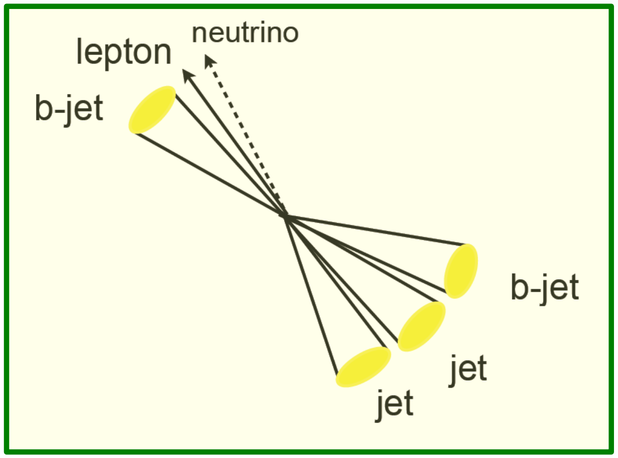


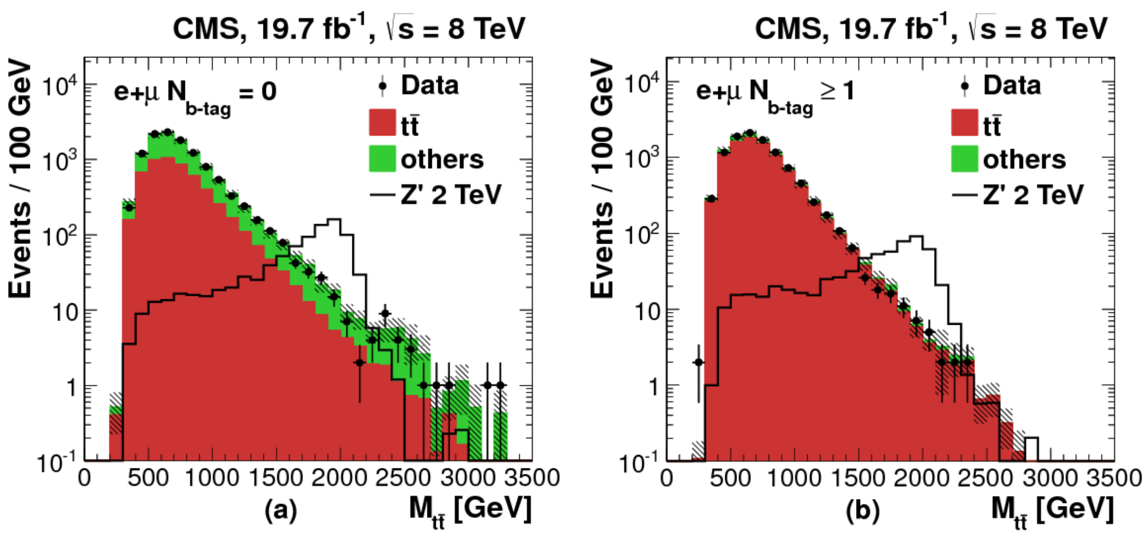
M > 1070 (785) GeV
for B(LQ→μq) = 1 (0.5)

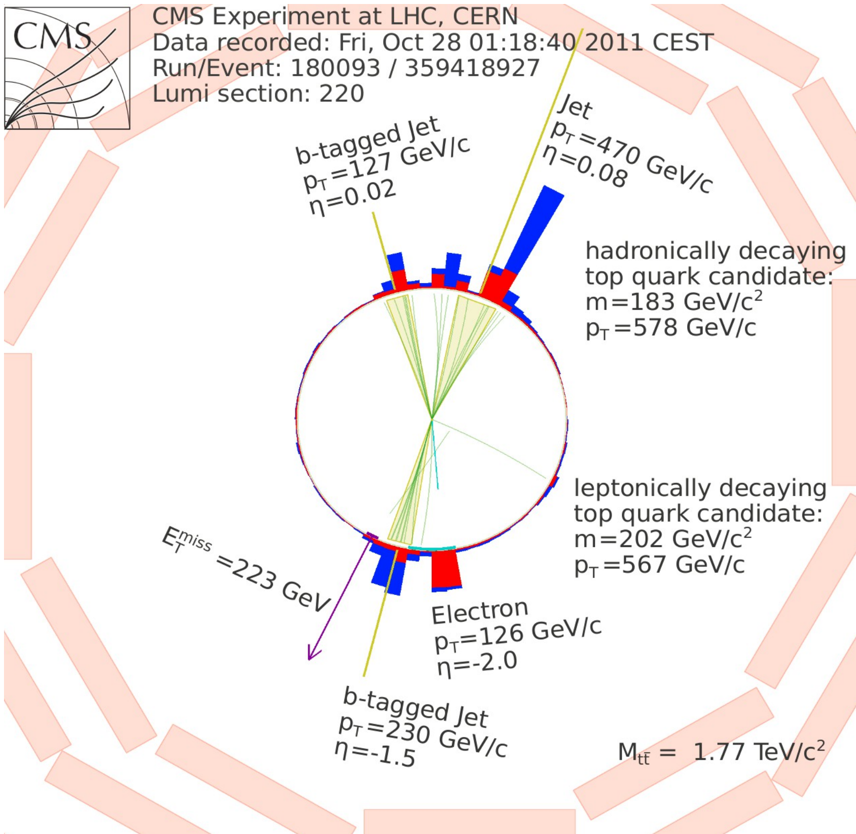
$Z' \to t\bar{t} \to e/\mu$ + jets

B2G-12-006
B2G-13-001

- 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



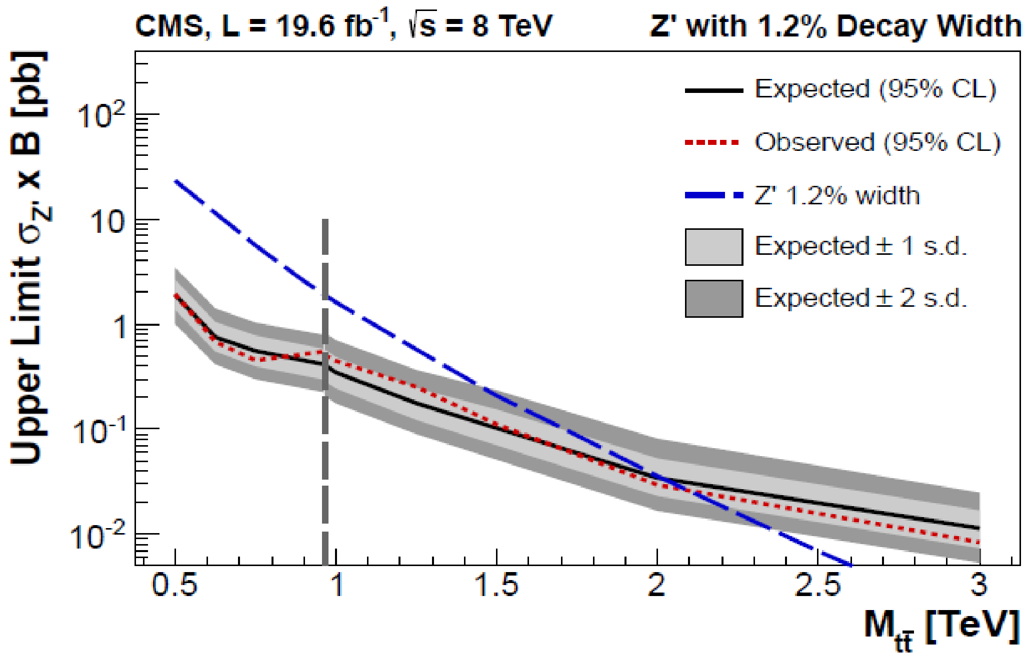


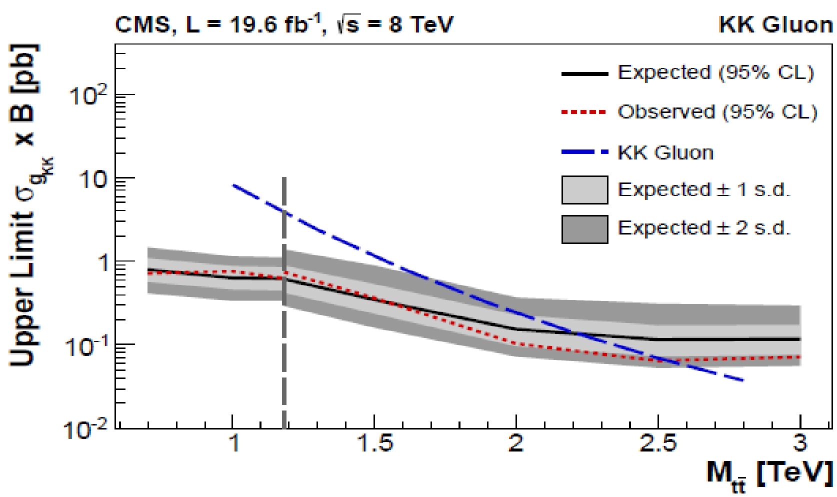


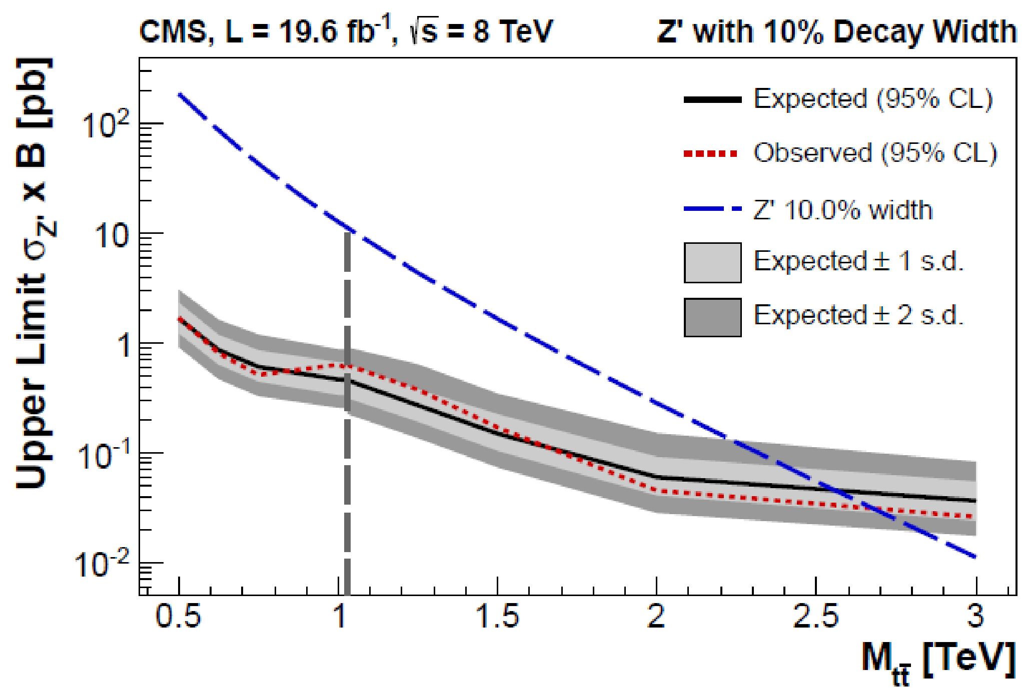
$Z' \rightarrow t\bar{t} \rightarrow e/\mu$ + jets

B2G-12-006
B2G-13-001

- **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**



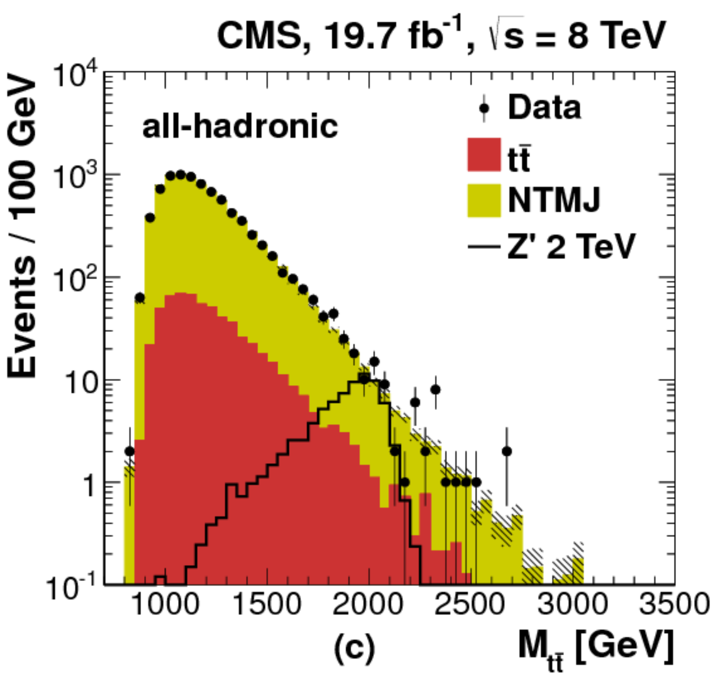




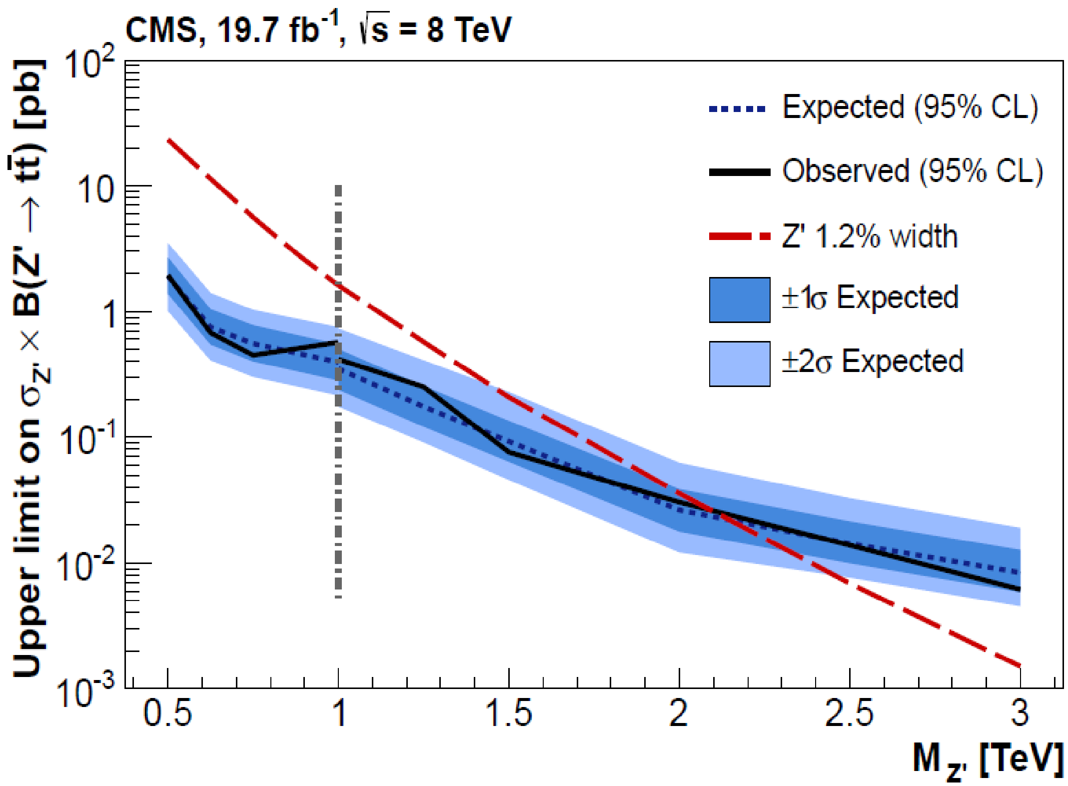
$Z' \rightarrow t\bar{t}$ all hadronic

B2G-12-005
B2G-13-001

- 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**



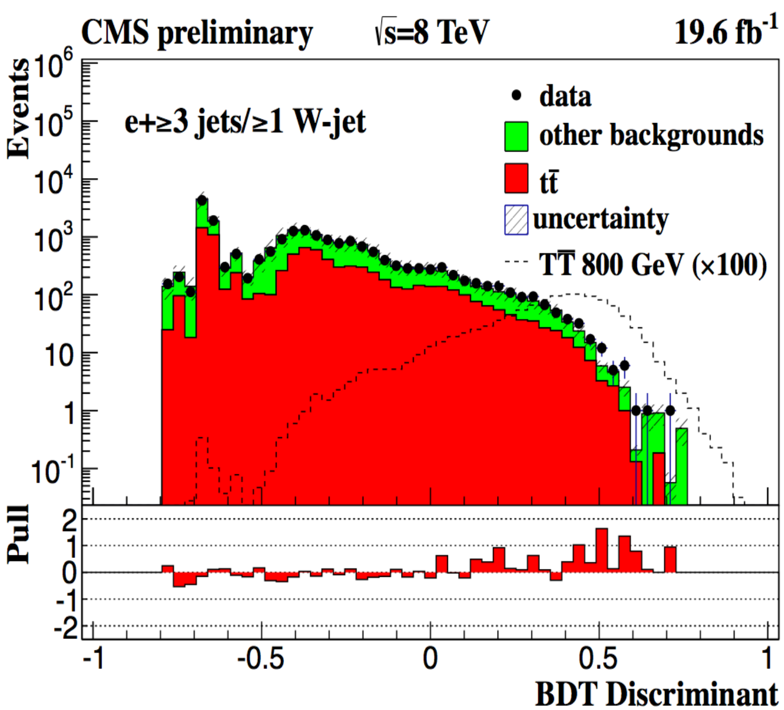
Combination

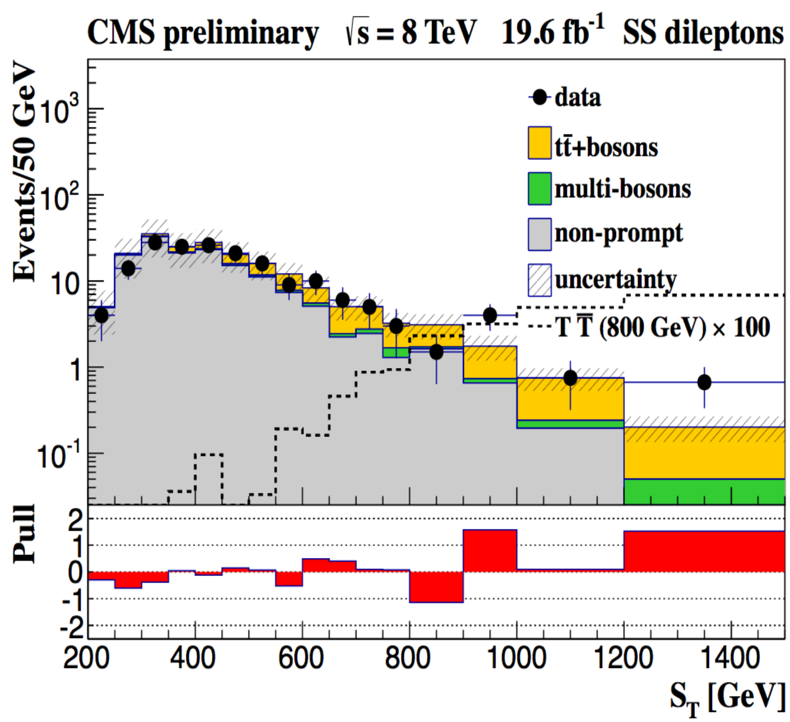


Vector-like T' → tZ/tH/bW

B2G-12-015

- Combined information from single lepton, SS and OS di-lepton, tri-lepton
- Bin by W-tags, N(jets), N(b-jets), H_T, MET, lepton p_T, 3rd / 4th jet p_T
  - OS targeting tZtZ: on-Z, >=5 jets, >=2 b-jets, H_T > 500 GeV, S_T > 1000 GeV
  - OS targeting bWbW: off-Z, 2-3 jets, H_T > 300 GeV, S_T > 900 GeV
  - SS targeting tZ or tH: >=3 jets, H_T > 500 GeV, S_T > 700 GeV, lepton flavor categs.
  - Tri-lepton targeting tZ or tH: >=3 jets, H_T > 500 GeV, S_T > 700 GeV, lepton flavor categories

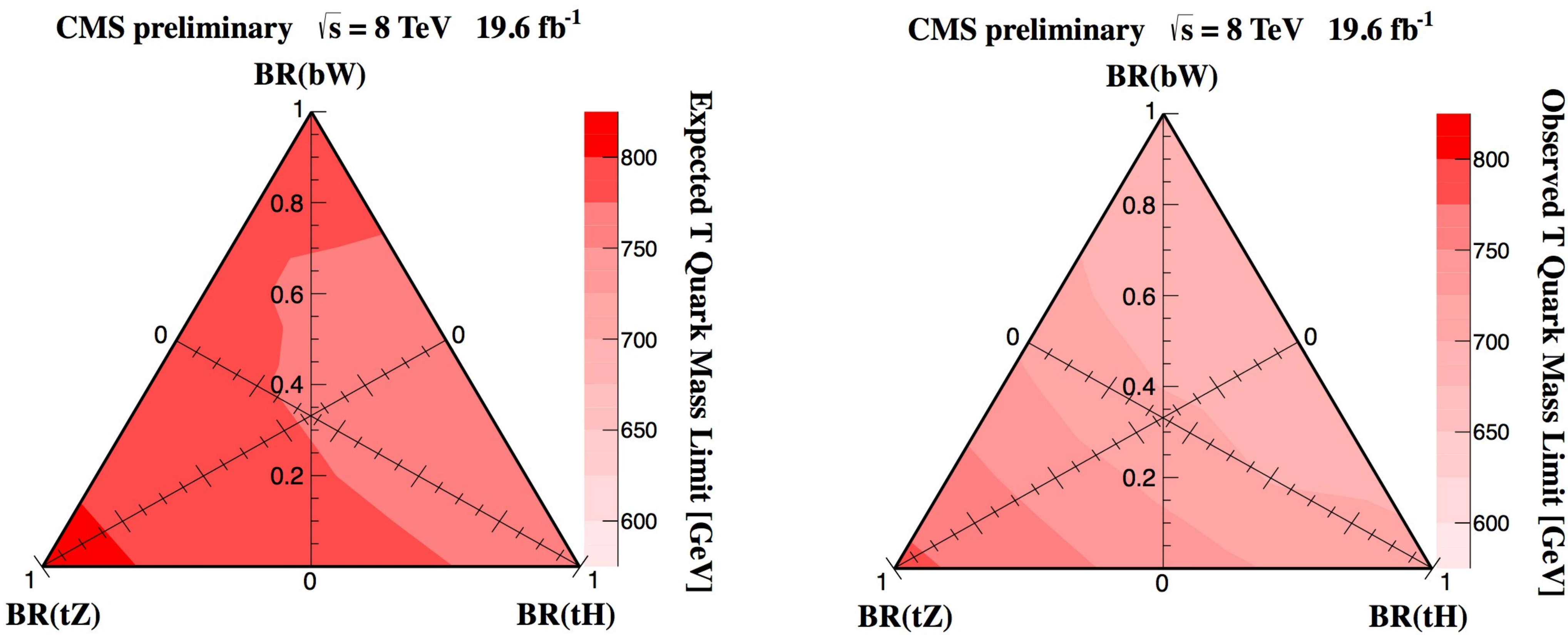




Vector-like T' → tZ/tH/bW

B2G-12-015

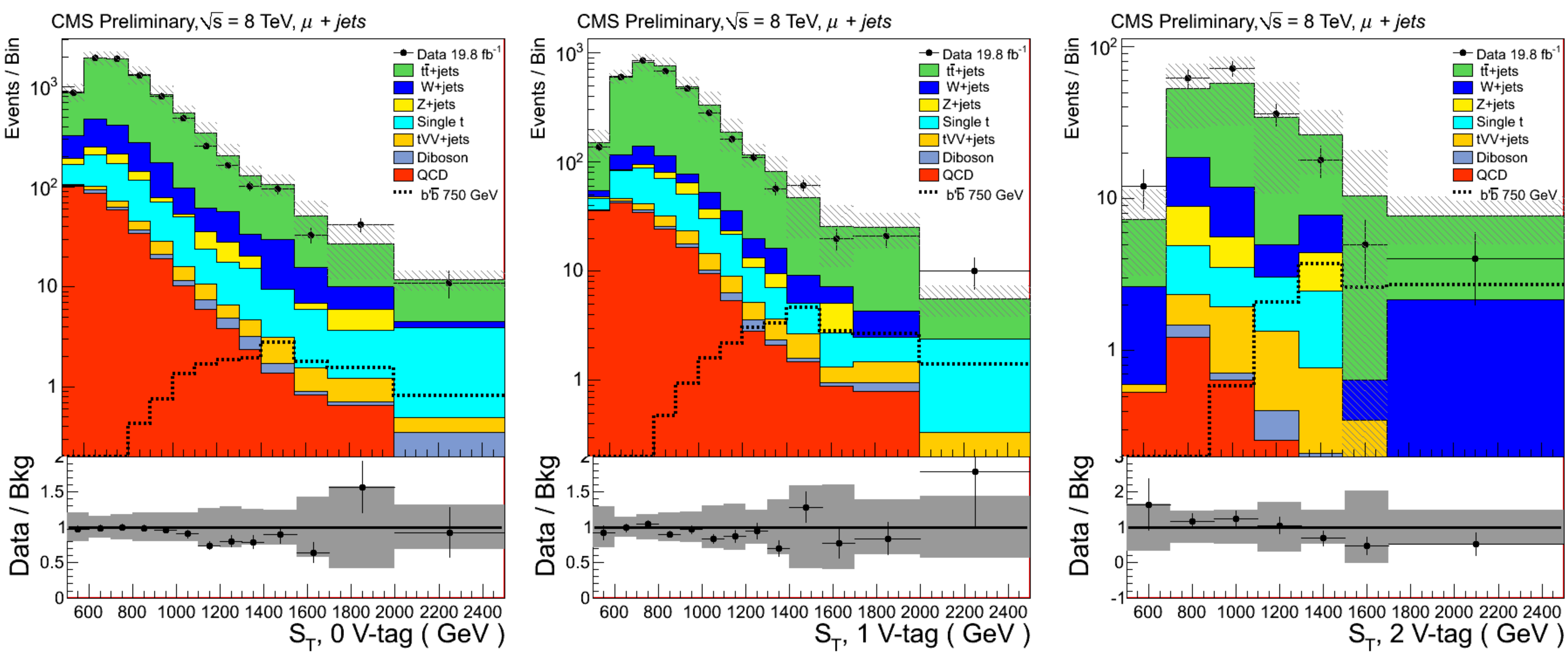
- Combine all channels to get limits
- As function of branching fractions, exclude masses between 687 and 782 GeV



Vector-like b' → tW/bH/bZ (lepton+jets)

B2G-12-019

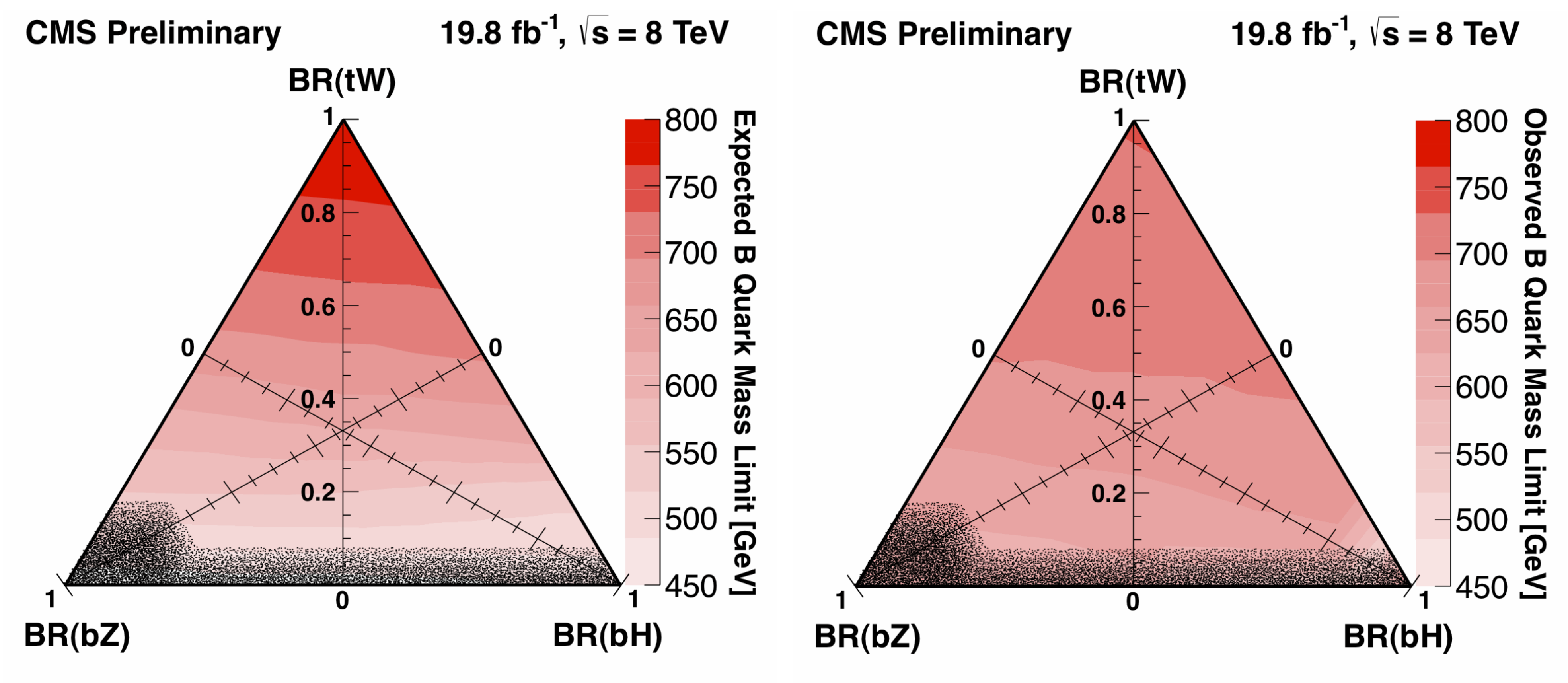
- One electron/muon, MET, >=4 jets including 1 with b-tag
- Classify events based on "V-tags" = number of jets consistent with boosted W, Z, or H boson
- Search for excess in S_T = scalar sum of jet p_T, lepton p_T, MET
  - Fit to background and signal templates in different categories



Vector-like b' → tW/bH/bZ (lepton+jets)

B2G-12-019

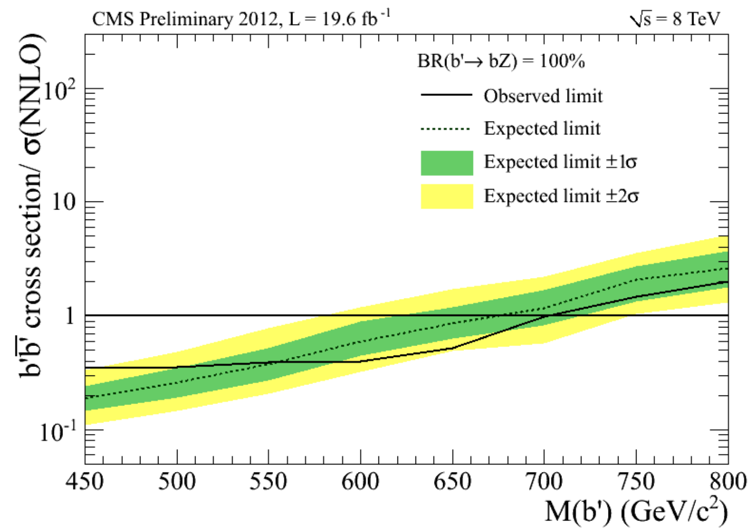
- As a function of b' → tW, bH, bZ branching fractions, exclude up to **M(b') < 732 GeV**
- Highest sensitivity for b' → tW

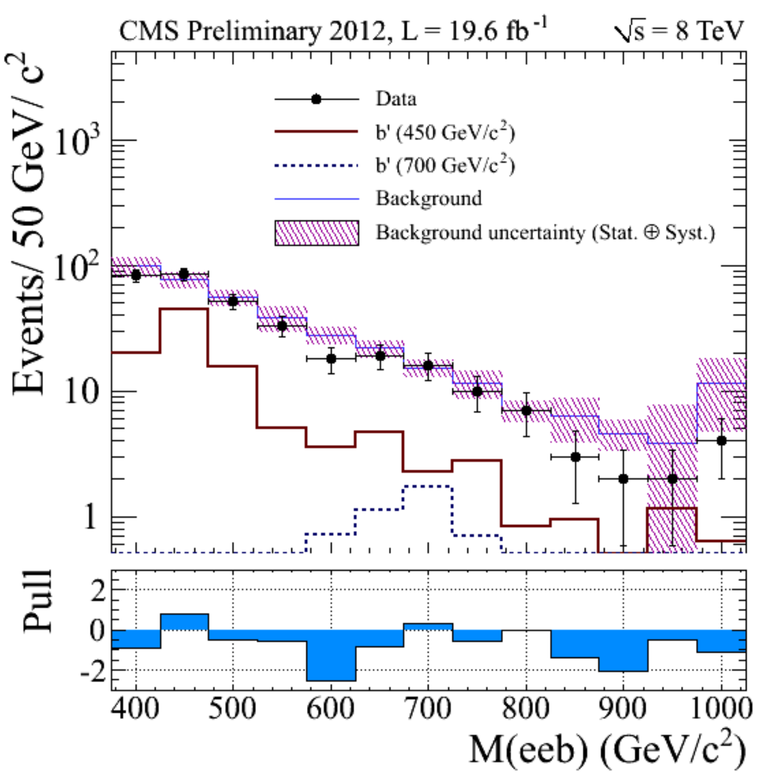


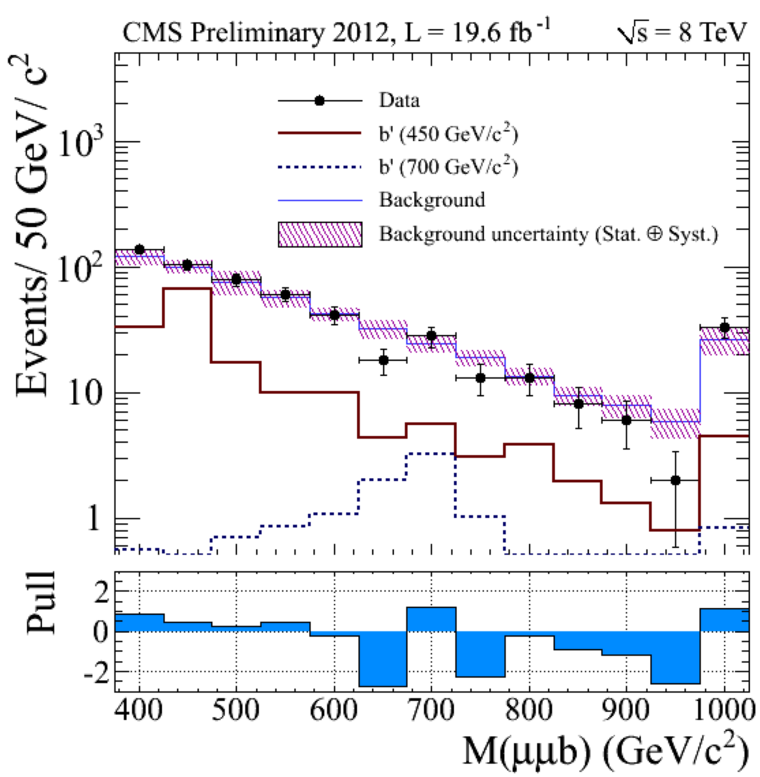
Vector-like b' → bZ (di-lepton + jets)

B2G-12-021

- Consider decay to bZ and tW
- Reconstruct resonance of e^+e^- and $\mu^+\mu^-$ pairs compatible with Z, plus b-jet
- Assuming B(b' → bZ) = 100%, exclude **M(b') < 700 GeV**
- … plus limits on B(b' → bZ) vs. M(b')



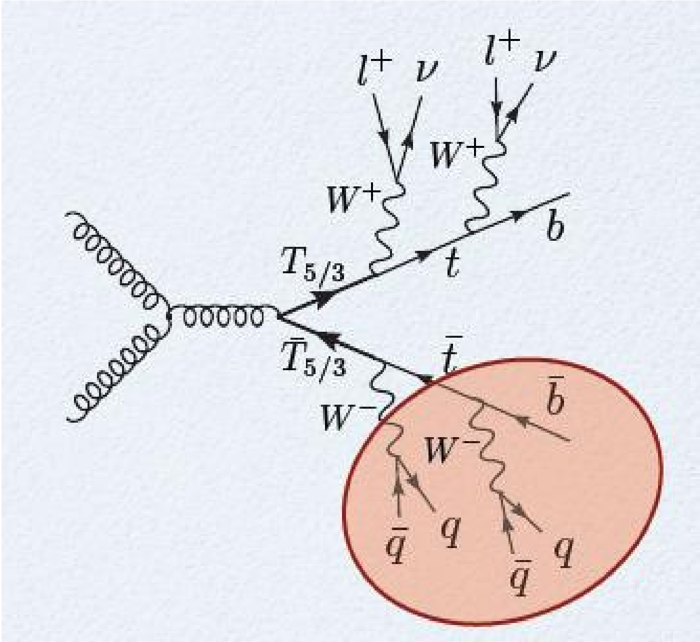


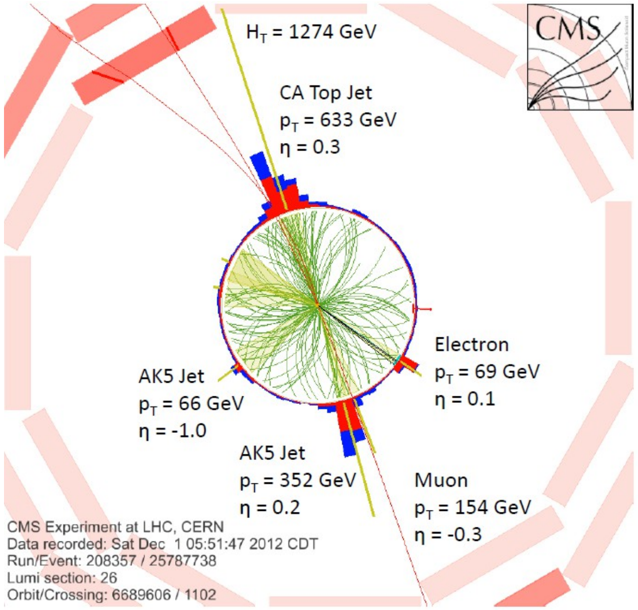


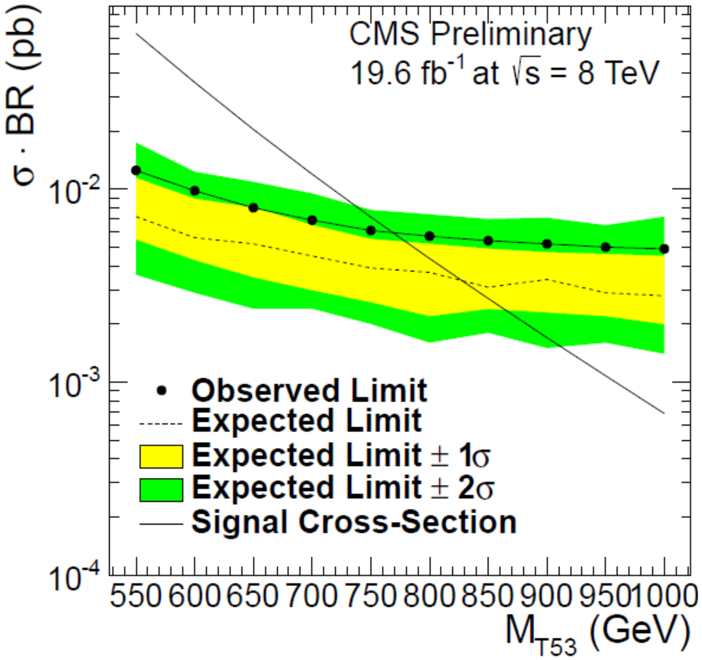
$T_{5/3} \rightarrow t\,W$

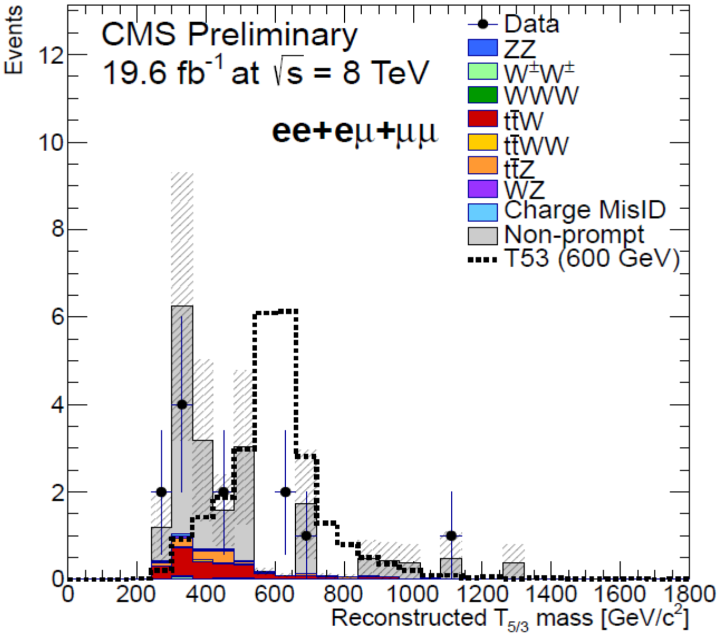
B2G-12-012

- Composite Higgs or models with extra dimensions
- Same-sign di-leptons (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 → data: 11 events; bgrd: 6.6 ± 2.0
- Exclude **M($T_{5/3}$) < 770 GeV** at 95% CL





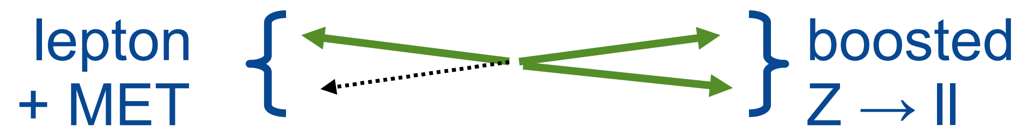




High mass di-boson resonance searches

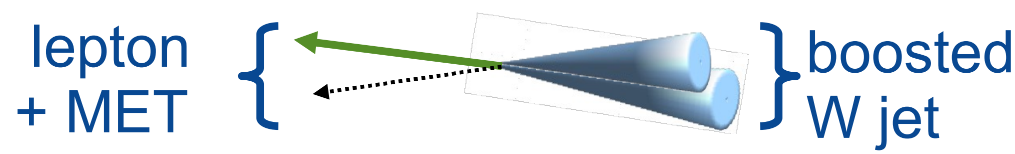
EXO-12-025:

$W'/\rho_{TC} \longrightarrow WZ \longrightarrow 3l + MET$



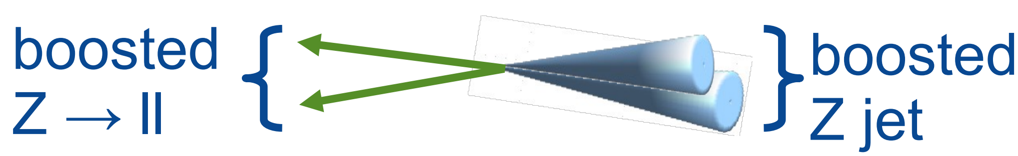
EXO-12-021:

$G_{bulk} \longrightarrow WW \longrightarrow l + jet + MET$



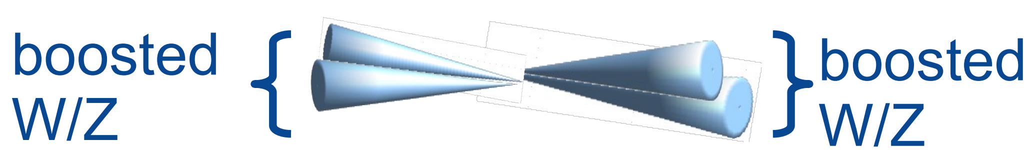
EXO-12-022:

$G_{bulk} \longrightarrow ZZ \longrightarrow 2l + 2jets$



EXO-12-024:

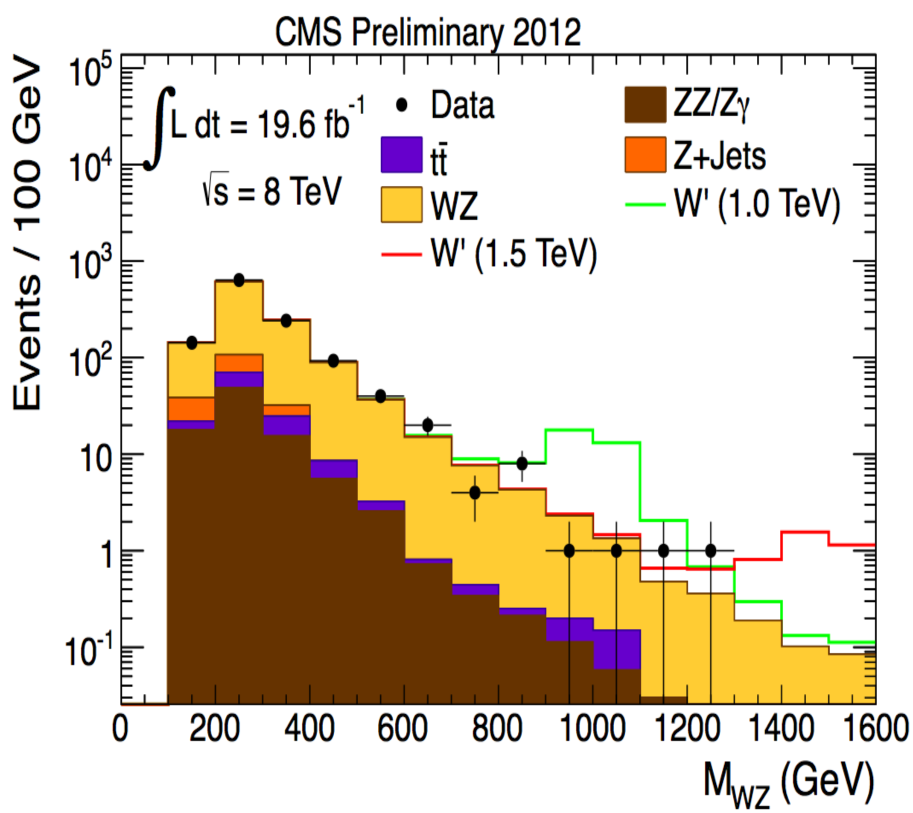
$G_{RS} \longrightarrow WW/ZZ, W' \longrightarrow WZ$

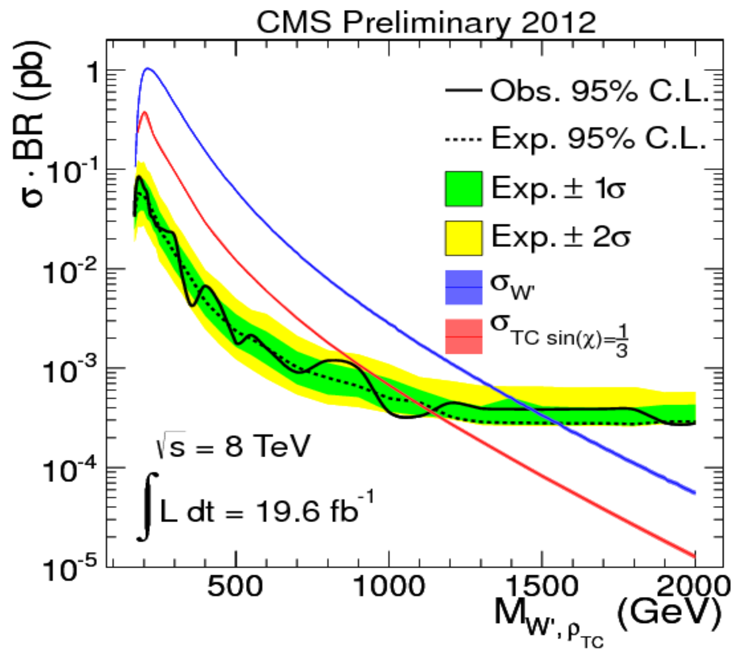


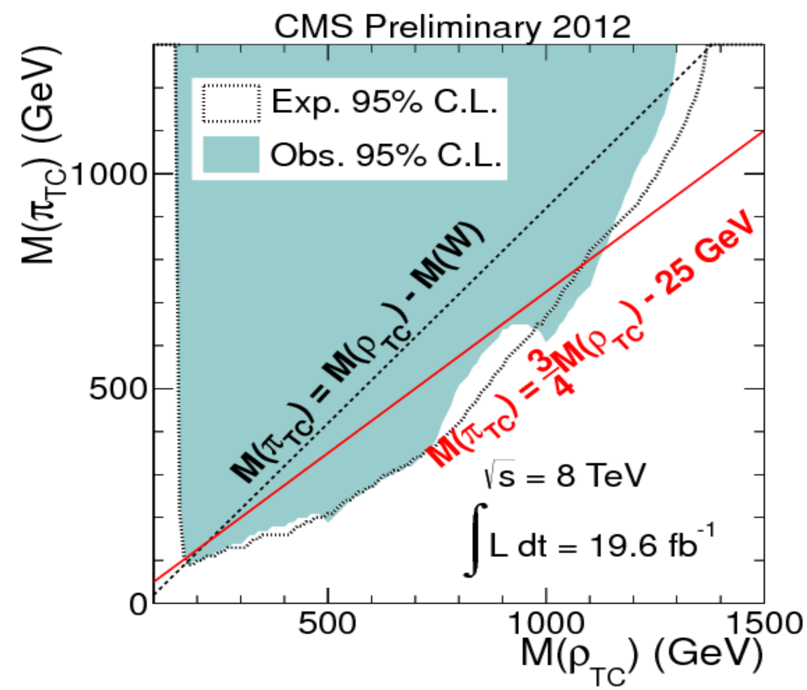
W' / $\rho_{TC} \to WZ \to 3l$ + MET

EXO-12-025

- Use M_{WZ} (taking MET into account) and $\Sigma\, p_T(l)$
- Modified ID and isolation for muons (from boosted Z)
- W' → WZ excluded for **0.17 < M < 1.45 TeV**



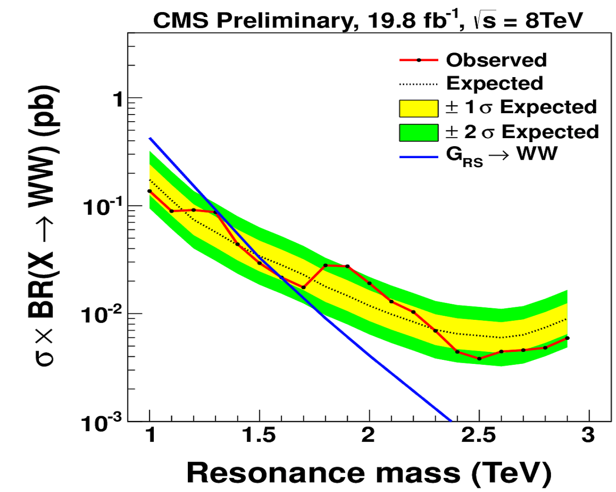


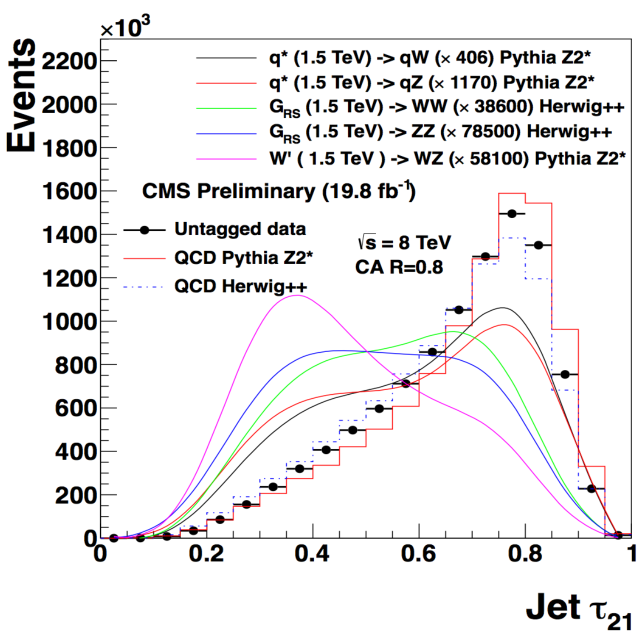


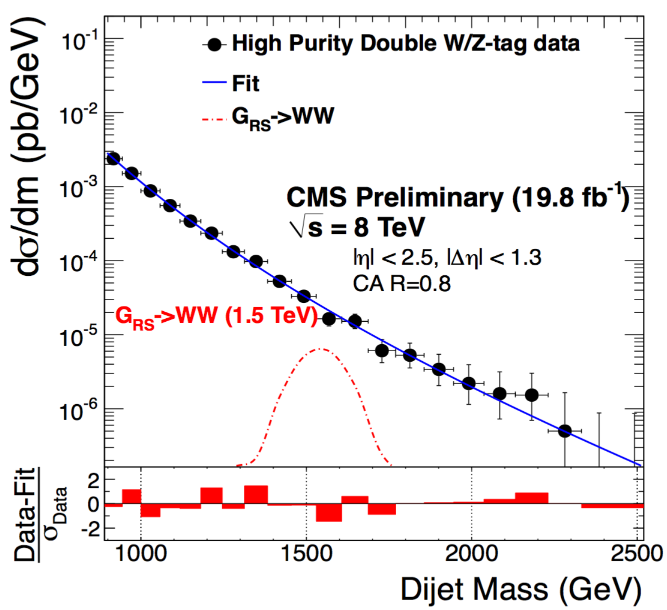
WW / ZZ / WZ in di-jets

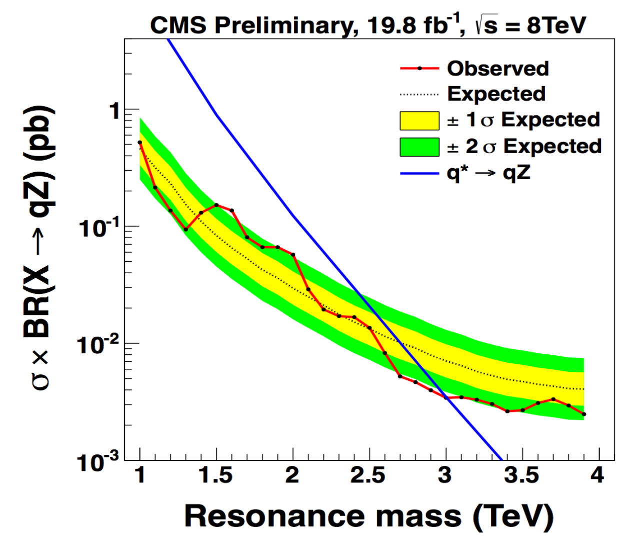
EXO-12-024

- $G_{RS} \rightarrow$ WW, WZ and W' $\rightarrow$ WZ in di-jets, with W and Z $\rightarrow$ jj
  - Jets from W/Z decays boosted and merged into single jets
  - Each jet required to pass "W/Z-tagger": pruned jet mass, N-subjettiness
- Exclude
  - G_{RS} (k/M_{PL}=0.1) $\rightarrow$ WW(ZZ) for 1.0 < M < 1.59 (1.17) TeV
  - W' $\rightarrow$ WZ for 1.0 < M < 1.73 TeV
  - q* $\rightarrow$ qW (qZ) for 1.0 < M < 3.23 (3.00) TeV

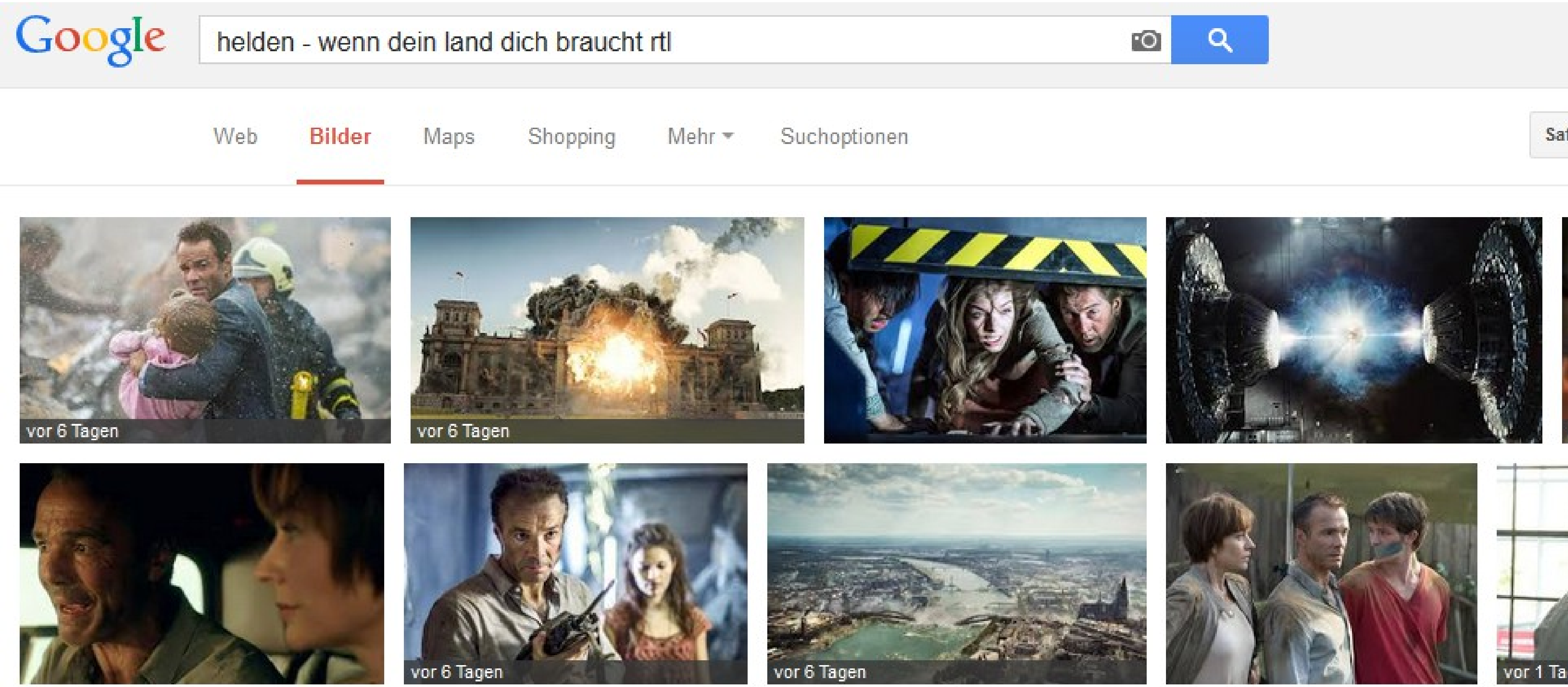








Black holes

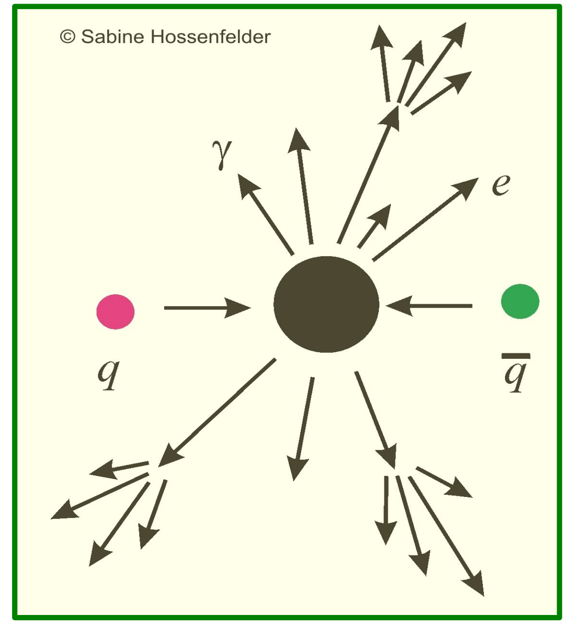


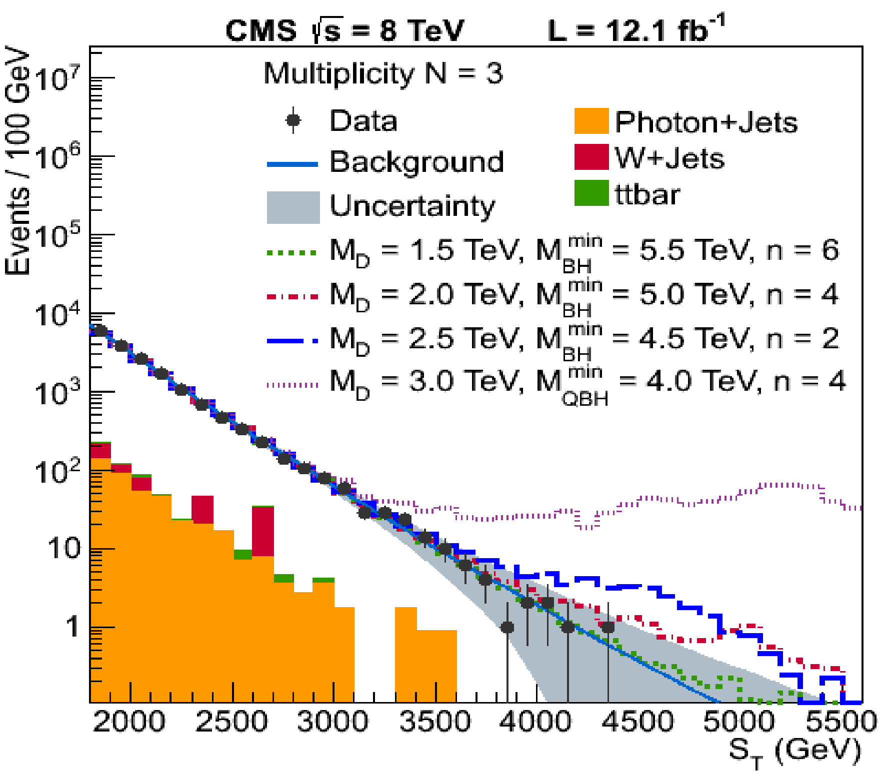
"Helden" (Heroes) last week on German television (RTL)

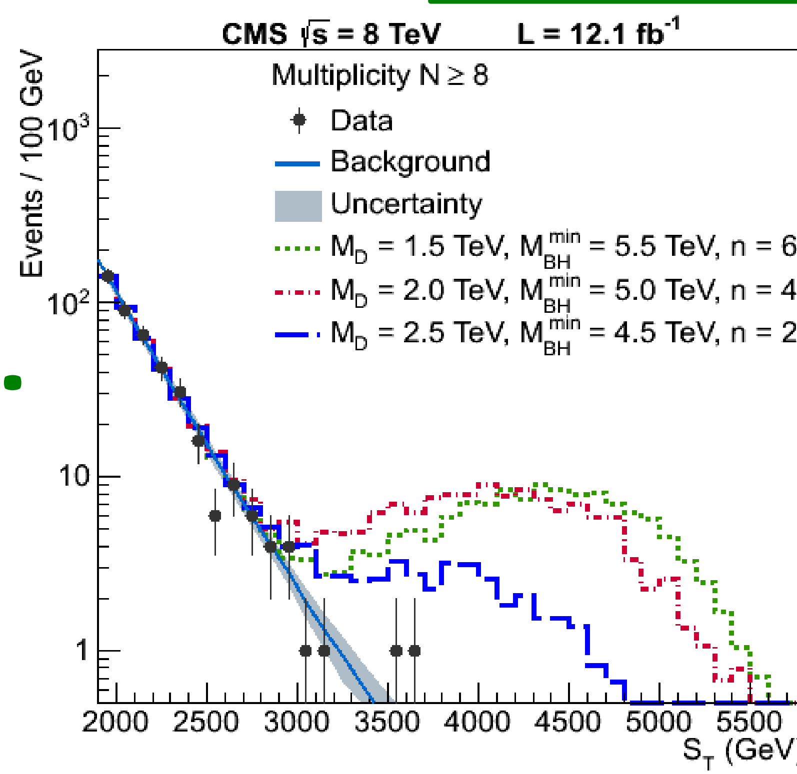
Microscopic black holes

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

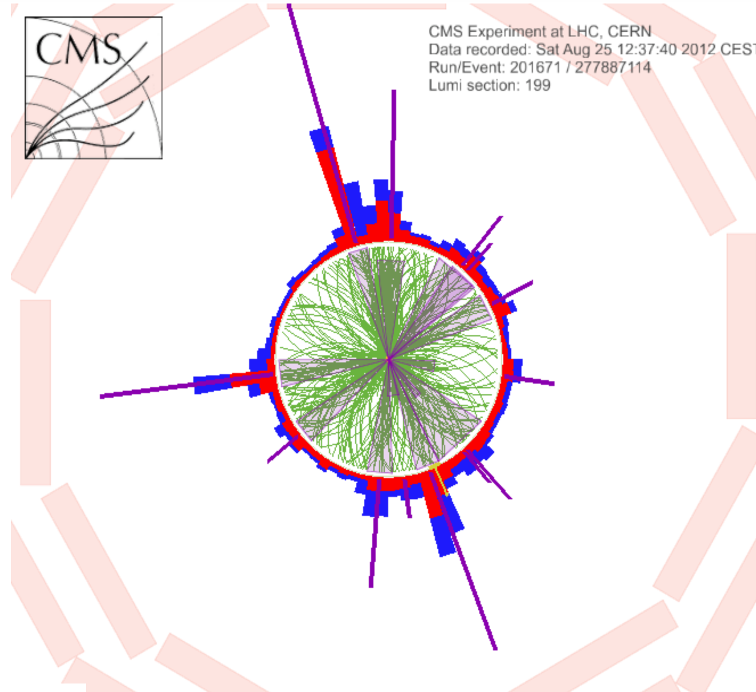






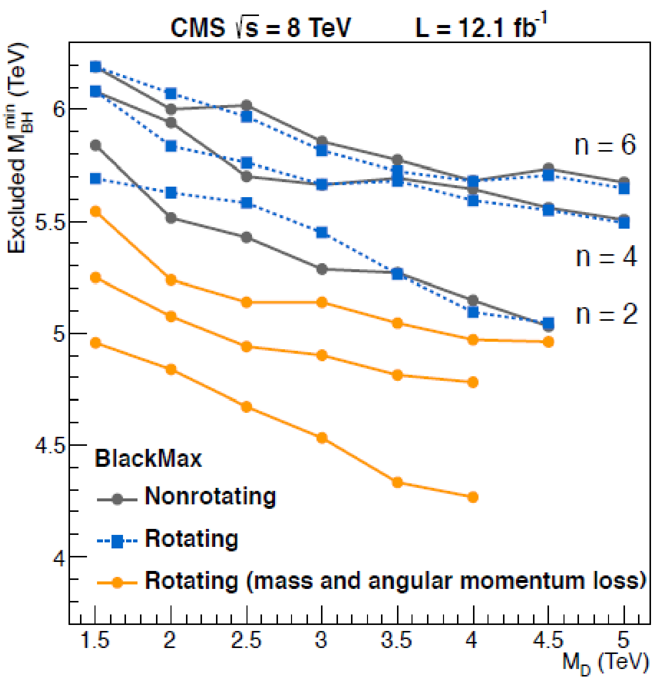
Microscopic black holes

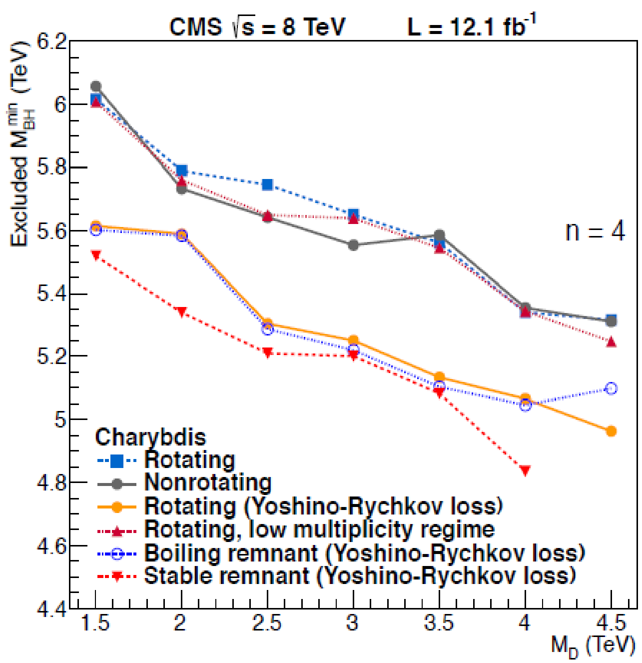
EXO-12-009



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

13 jets, S_T = 4.5 TeV

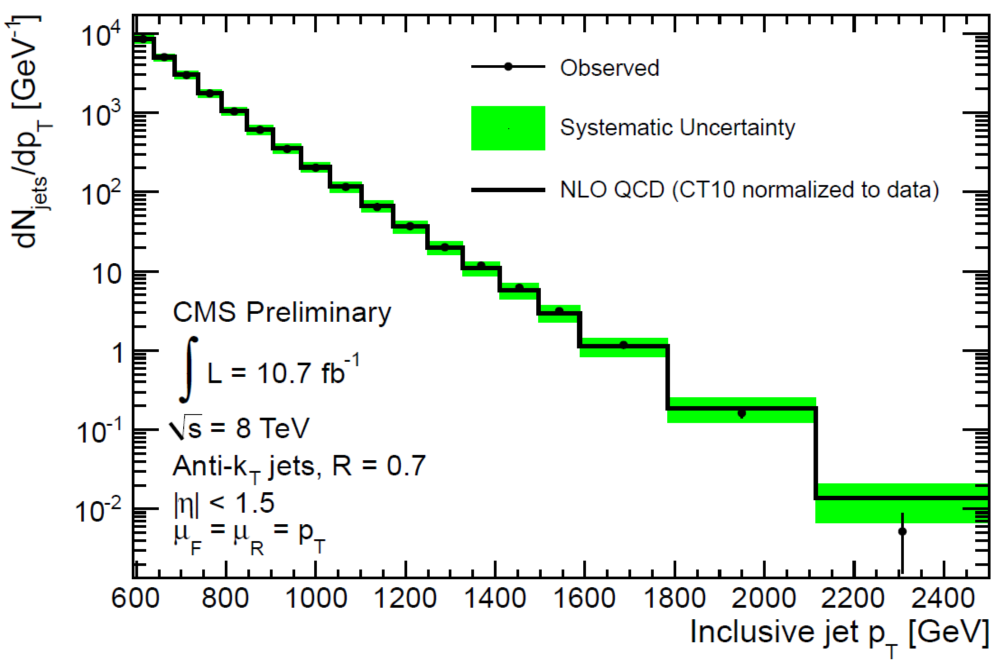


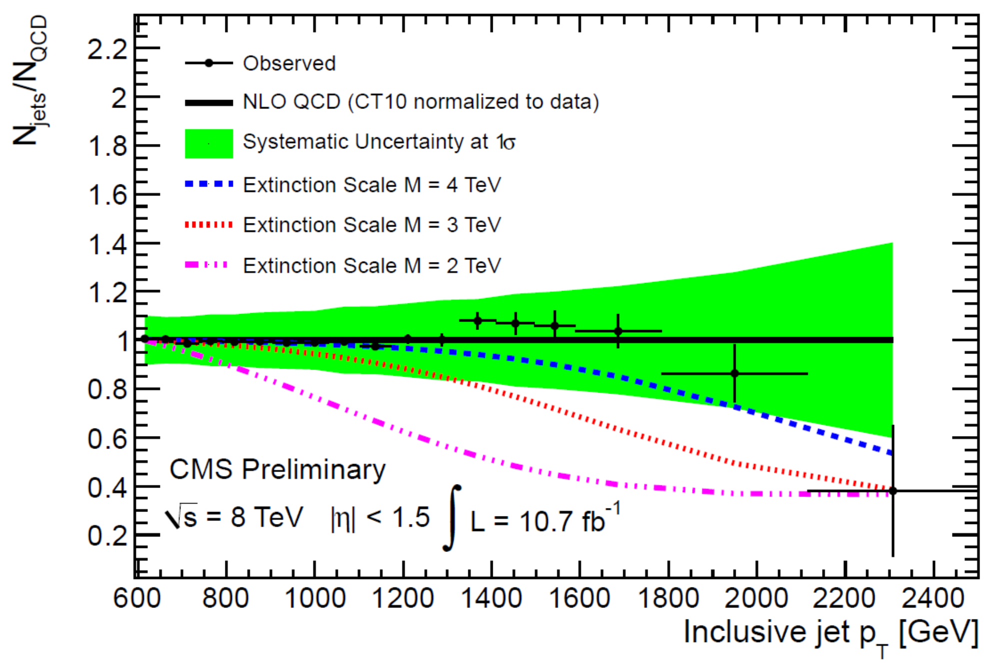


Jet extinction

EXO-12-051

- Even if black holes (or similar phenomena) are produced, we may miss them (trigger, no decay to our "objects", not yet significant, …)
- However, above production threshold, SM processes are highly suppressed
  - Good place to check are inclusive jets
  - PDF and jet energy scale uncertainty are important



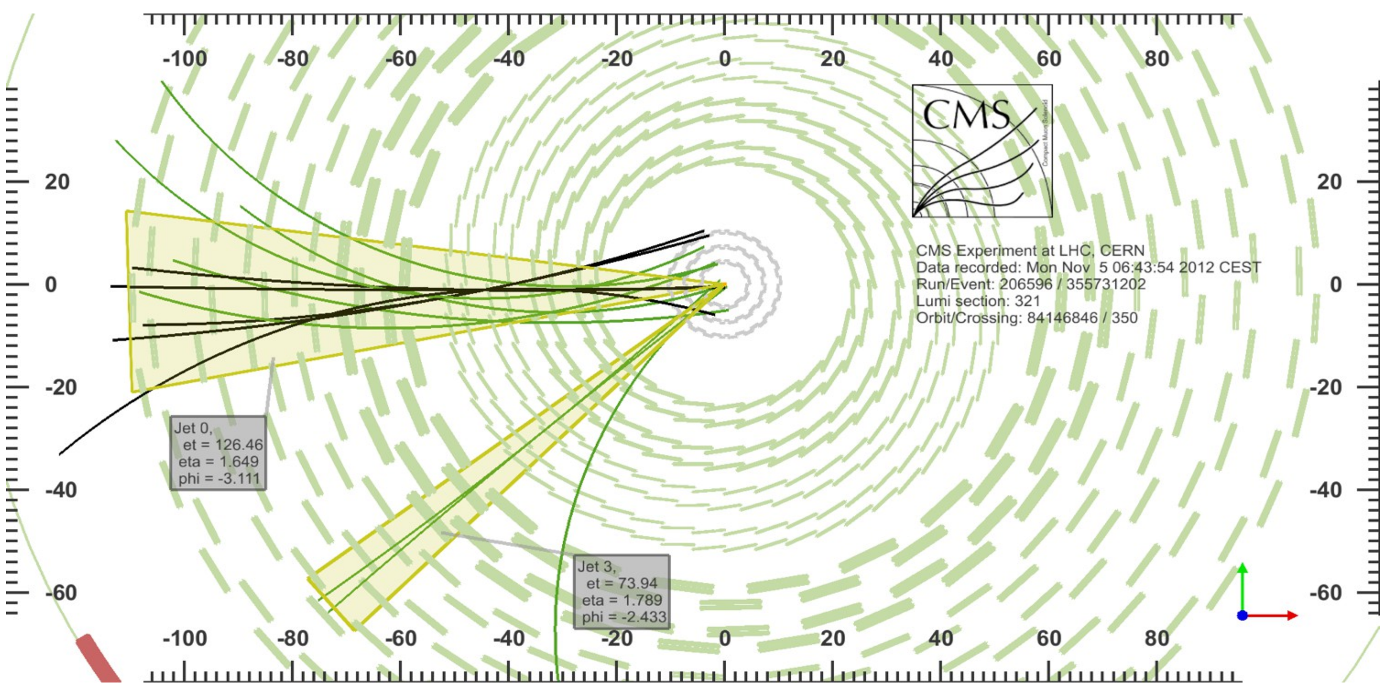


- Limit on the extinction energy scale (fundamental Planck scale) **M > 3.3 TeV**

Displaced jets

EXO-12-038

- Massive long-lived particles decaying to displaced jets can occur in many models: split SUSY, RPV SUSY, hidden valley models etc.
- Benchmark here is a heavy scalar: gg → H^0 → X^0X^0 → qq qq
  - Mean decay length of X^0: 3... 300cm
- Search for di-jets from a common, displaced vertex
- Background suppression based on vertex track multiplicity, fraction of tracks with positive d0, likelihood discriminant



2 candidate events, compatible with background expectation

Displaced jets

EXO-12-038

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- Benchmark here is a heavy scalar: $gg \rightarrow H^0 \rightarrow X^0X^0 \rightarrow qq\ qq$
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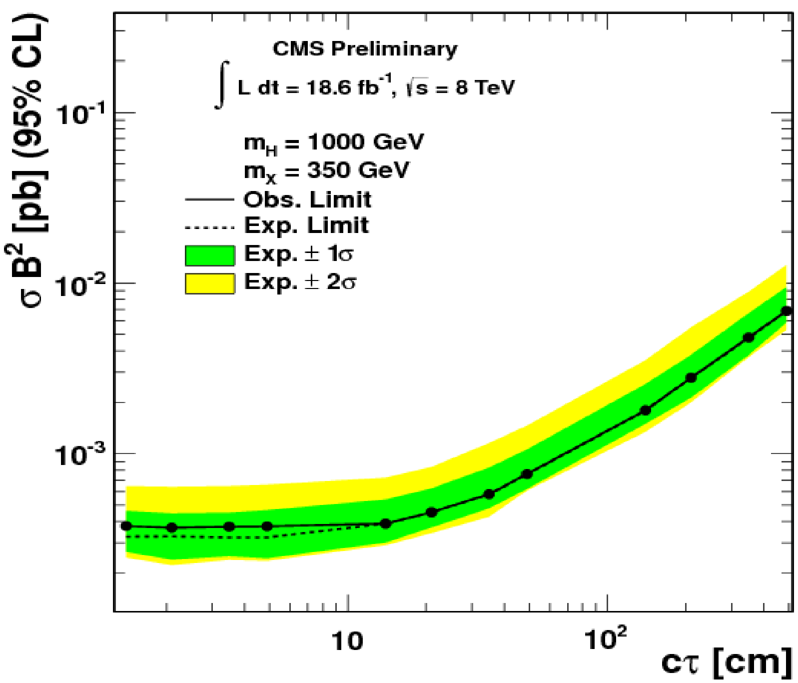
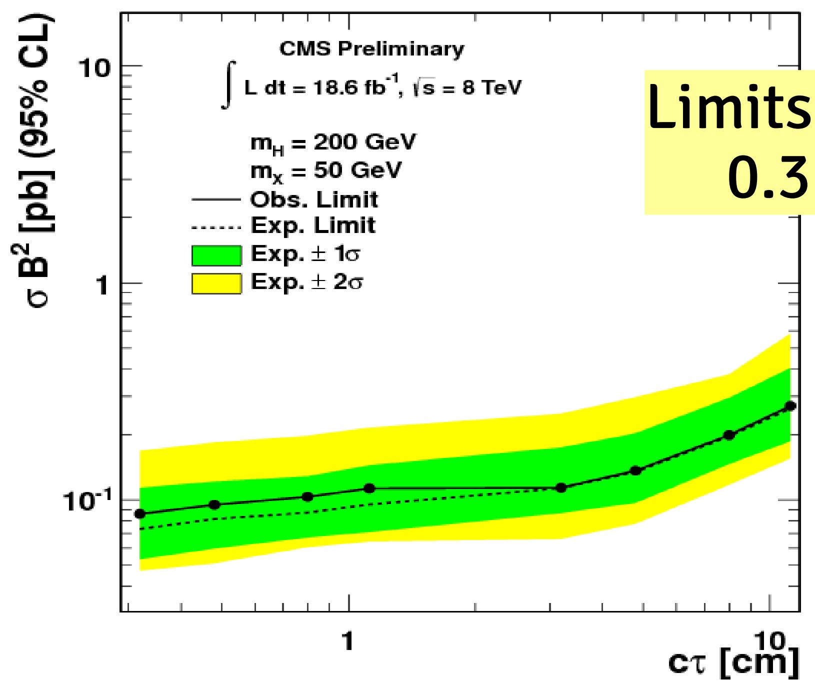


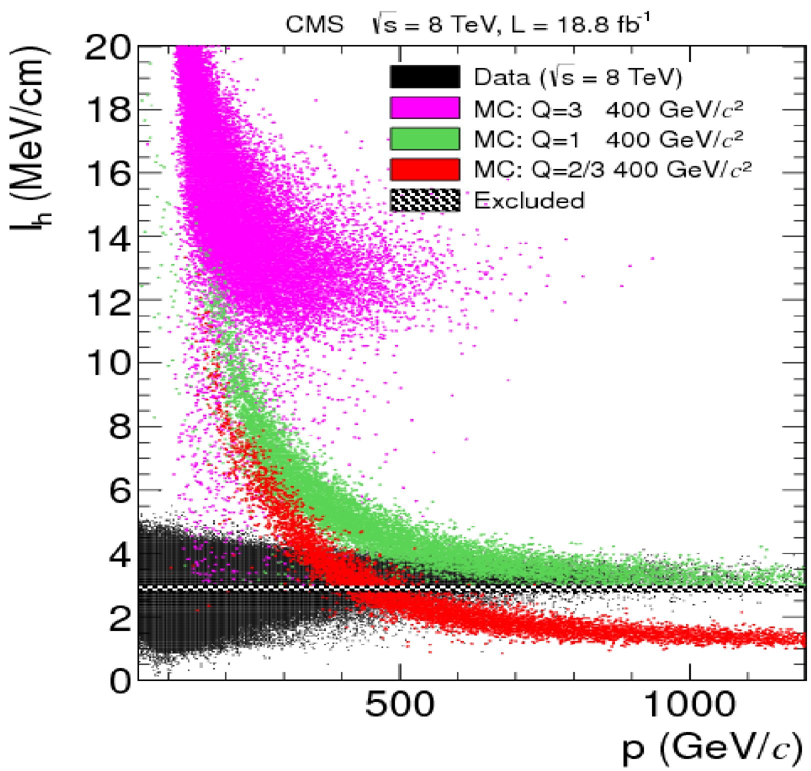


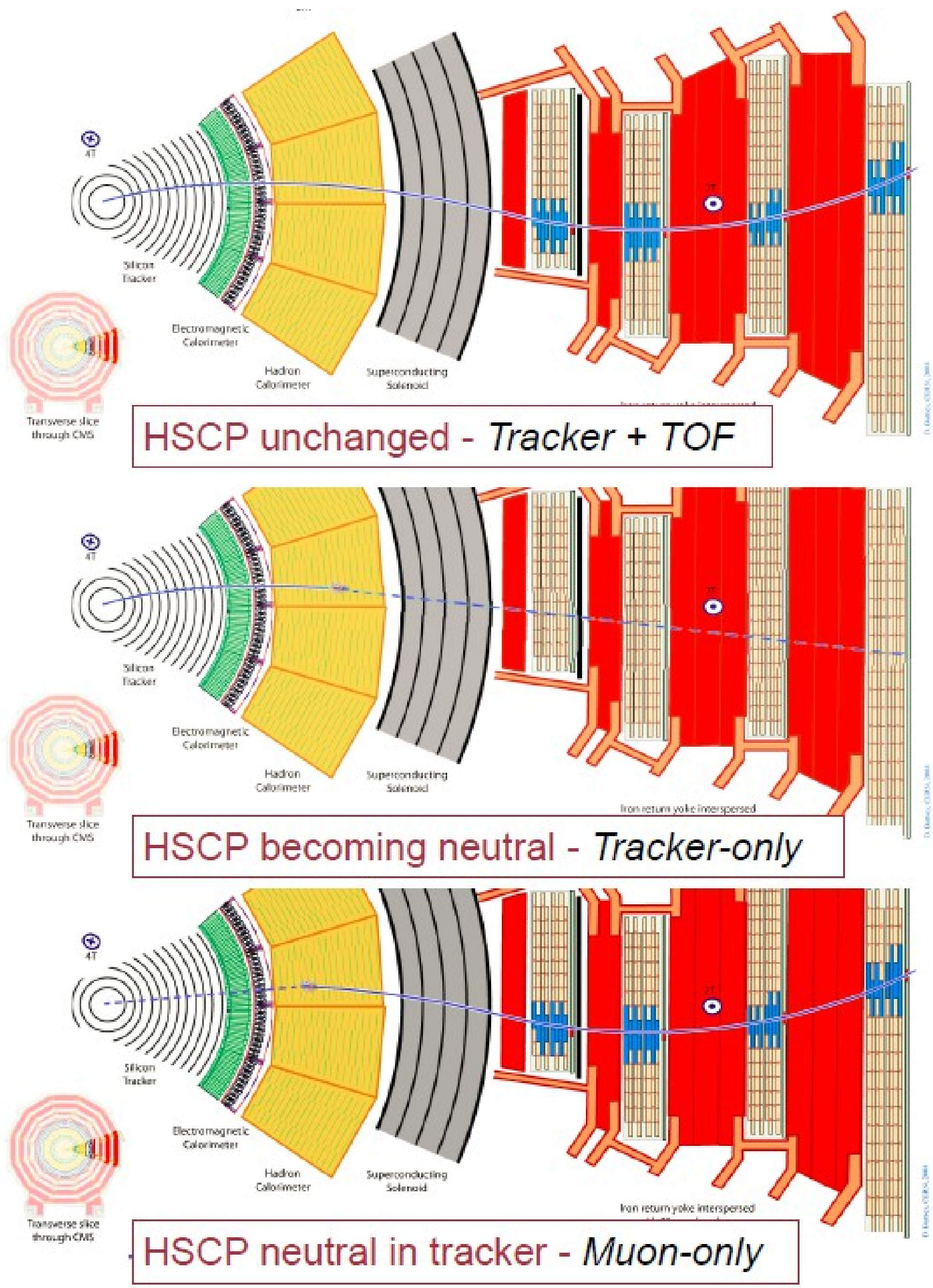
Limits in the range 0.3 … 300 fb

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
- Make use of
  - Track p_T: inner tracker
  - Muon $1/\beta$: muon system
  - Track I_{as}: dE/dx MIP incompatibility

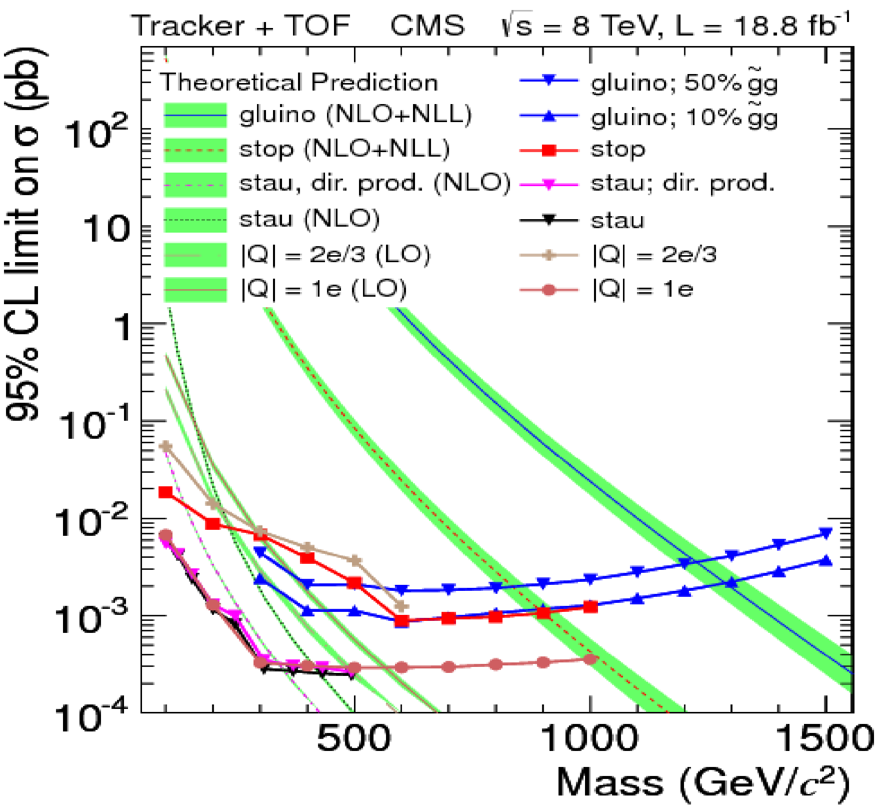


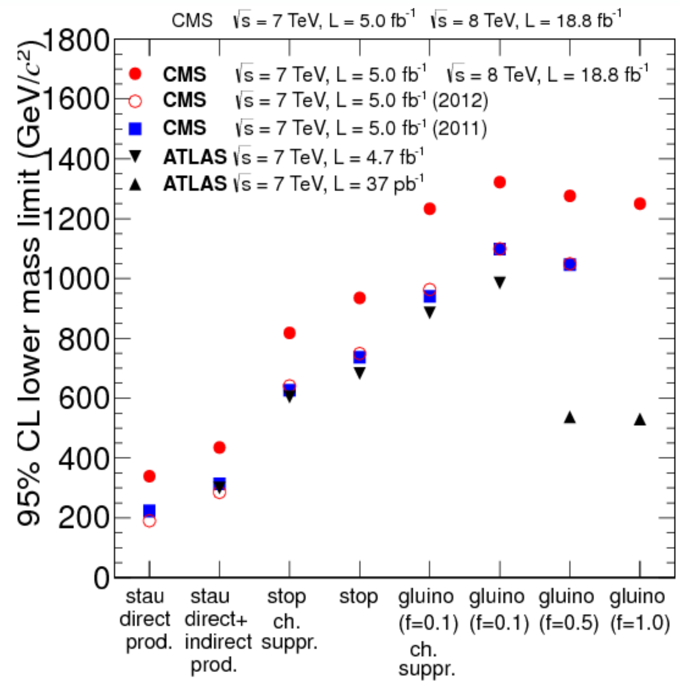


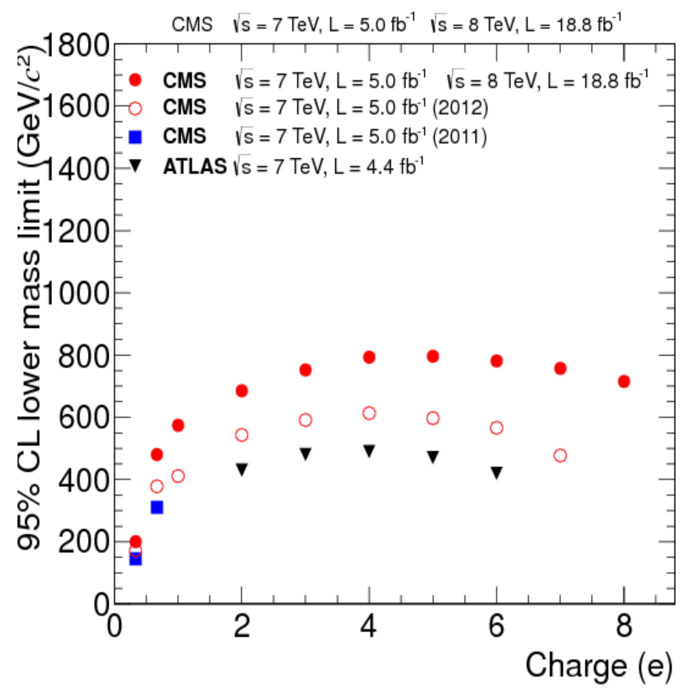
Heavy stable charged particles

EXO-12-026

- Results for long-lived gluinos, scalar top quarks, scalar tau leptons, fractionally/multiply charged leptons
- Mass limits up to > 1300 GeV (gluinos)



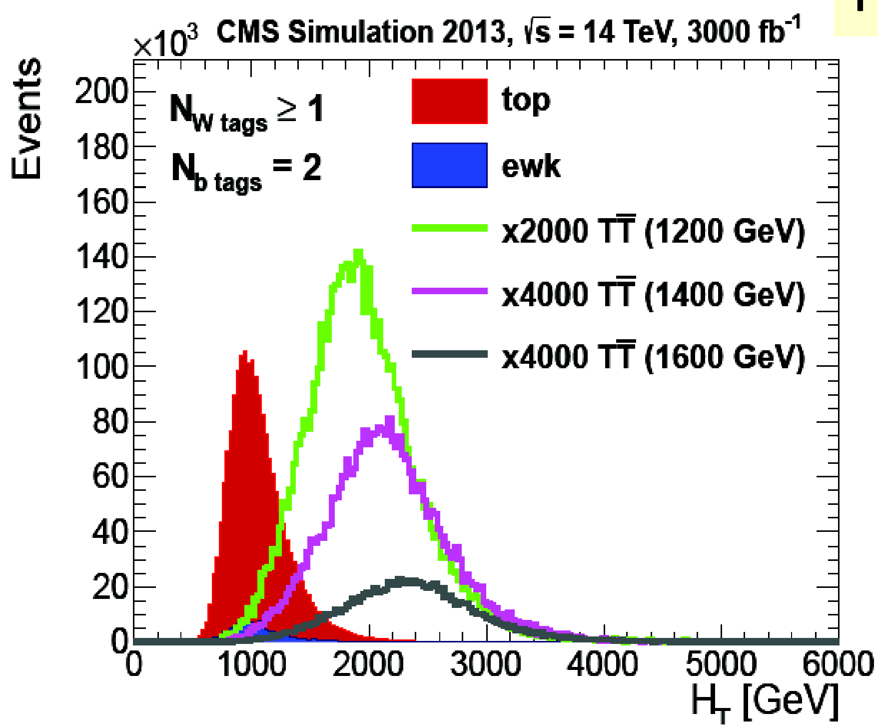


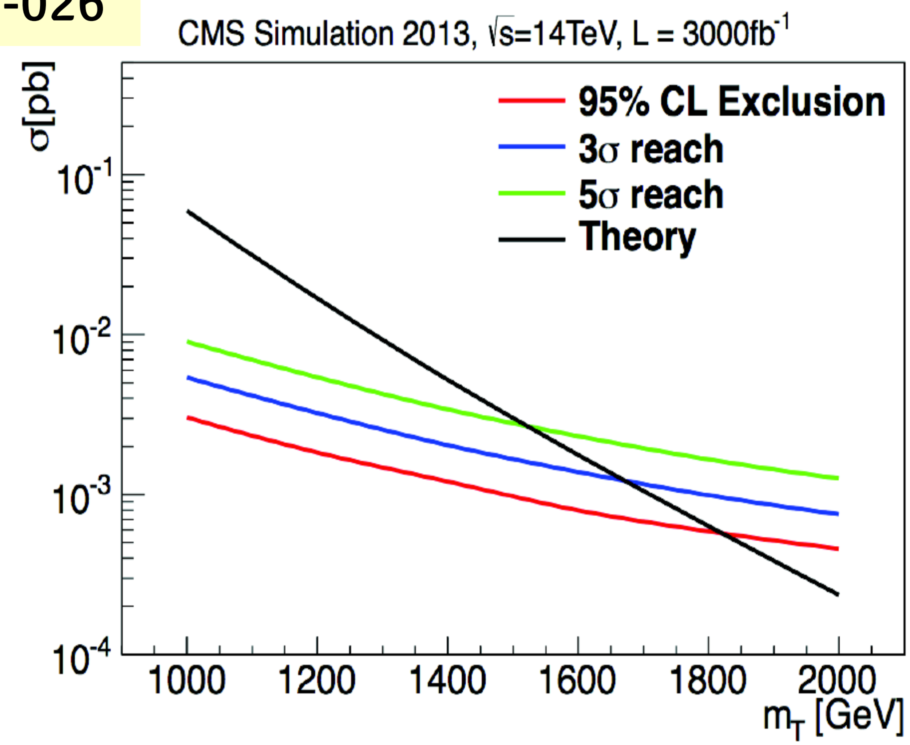


Outlook

- Run 2 from 2015 to 2017: $\sqrt{s}$ = 13 – 14 TeV, $\int L\,dt$ ~ 40 – 45 fb^{-1}/a
- Longterm HL-LHC from ~2023, $\int L\,dt$ ~ 300 fb^{-1}/a, 3000 fb^{-1} total, ~ 140 PU
- Example: vector-like T' → tZ, tH, bW (as B2G-12-015)

FTR-13-026





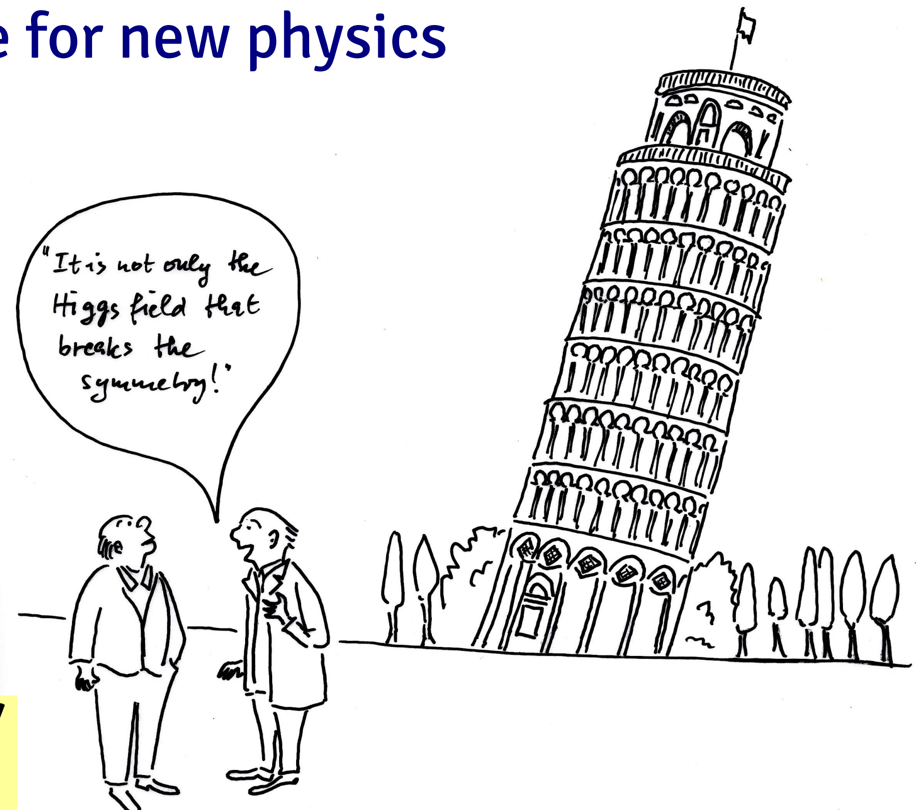
5σ discovery reach up to M(T') of 1500 GeV (compared to ~700 GeV exclusion @8 TeV)

- ECFA workshop last week: https://indico.cern.ch/conferenceDisplay.py?confId=252045

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
- This and more at

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO and PhysicsResultsB2G



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

Backup

Summary