Searches for Physics Beyond the Standard Model at CMS

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(for the CMS Collaboration)

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Fermilab
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Experimentalist's Checklist

- ☑ Discover new boson consistent with Higgs.
  - ☐ Confirm it is the Higgs (2–3σ on J^P, 3–5σ on couplings with 30fb^{-1}).

- ☐ **Why is the electroweak scale so small in units of the assumed UV cutoff of the SM, i.e. the Planck mass?**
  - ☐ Natural solutions: Large extra dimensions, supersymmetry (SUSY),
  - ☐ Unnatural solutions: multiverse (anthropic principle).

- ☐ **How do the gauge interactions unify at higher energy?**
  - ☐ Georgi–Glashow+SUSY, Pati–Salam+SUSY.

- ☐ **What is dark matter?**
  - ☐ Stable, neutral, lightest SUSY particle; other fermionic WIMP.

- ☐ **Why do neutrinos have such small mass?**
- ☐ **Why does the electroweak interaction violate parity symmetry?**

Experimental Considerations

Many non-SUSY BSM models predict accessible topologies and large cross sections.

Sensitivity vs. Generality.

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Don't stop there!

- Use **categories** of b-tags, vector boson tags, particle multiplicity, etc.
- Explore more **challenging regions of phase space**: lower thresholds
- Cover as many topologies as possible.

Sensitivity vs. Generality.

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Sensitivity vs. Generality.

Biggest issue!

- We are working to safely **generalize optimized analyses** & **optimize general searches**.
- Advertise our model-independent results.
- Interpret searches in context of more models. For instance, leptoquarks ⇔ RPV SUSY.

Outline

Basic "Resonances"

- Z' → ee, μμ, ττ
- X → dijet, bb, dijet+W/Z-tag
- X → invisible

S_T scaling

- Black holes → jets+X
- Stealth SUSY → photons+jets

Leptons + Jets

- LQ, RPV $\tilde{q} \rightarrow \ell j + \ell j$
- $W_R \rightarrow \ell\ell jj$

Long-lived particles

- Stopped particle
- Heavy stable charge particle
- Fractionally charged HSCP
- Displaced photons

Results from both 7TeV and 8TeV data.
All 7TeV results with full 5/fb dataset.
Publications in progress for most results.

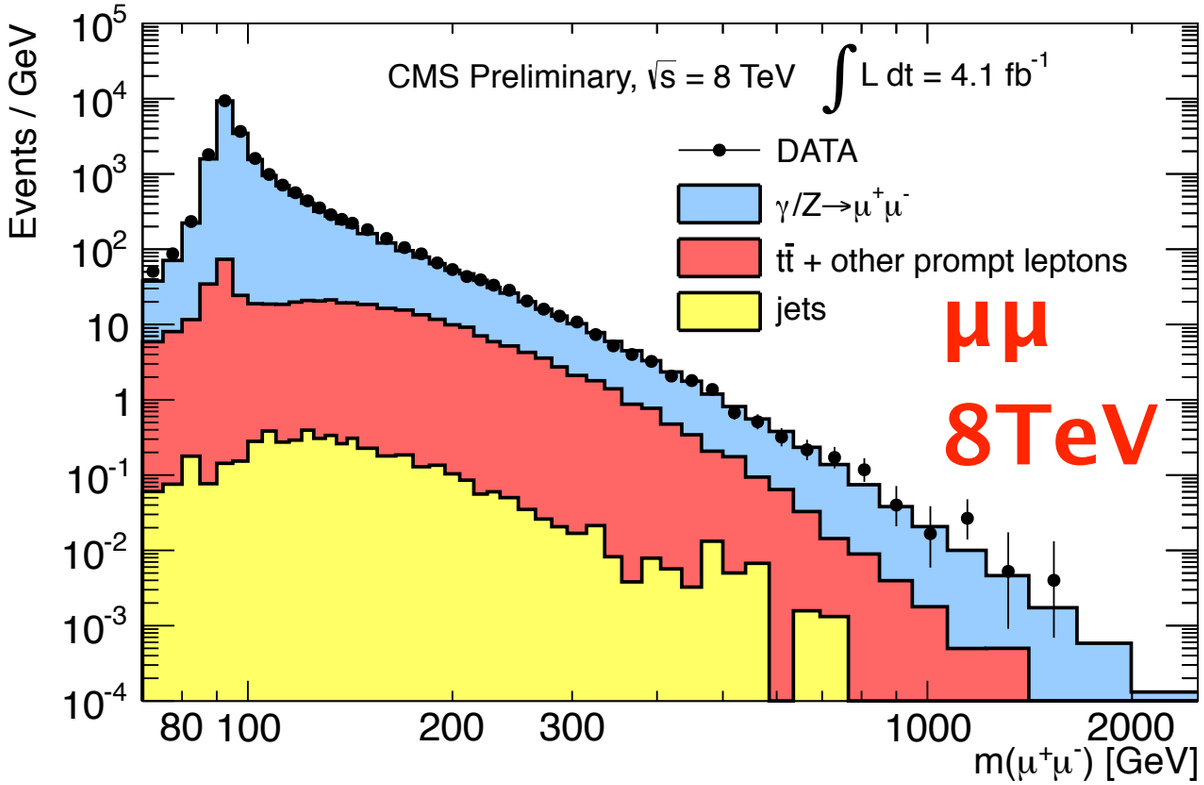
I will not discuss 4th generation searches or general boosted topologies.

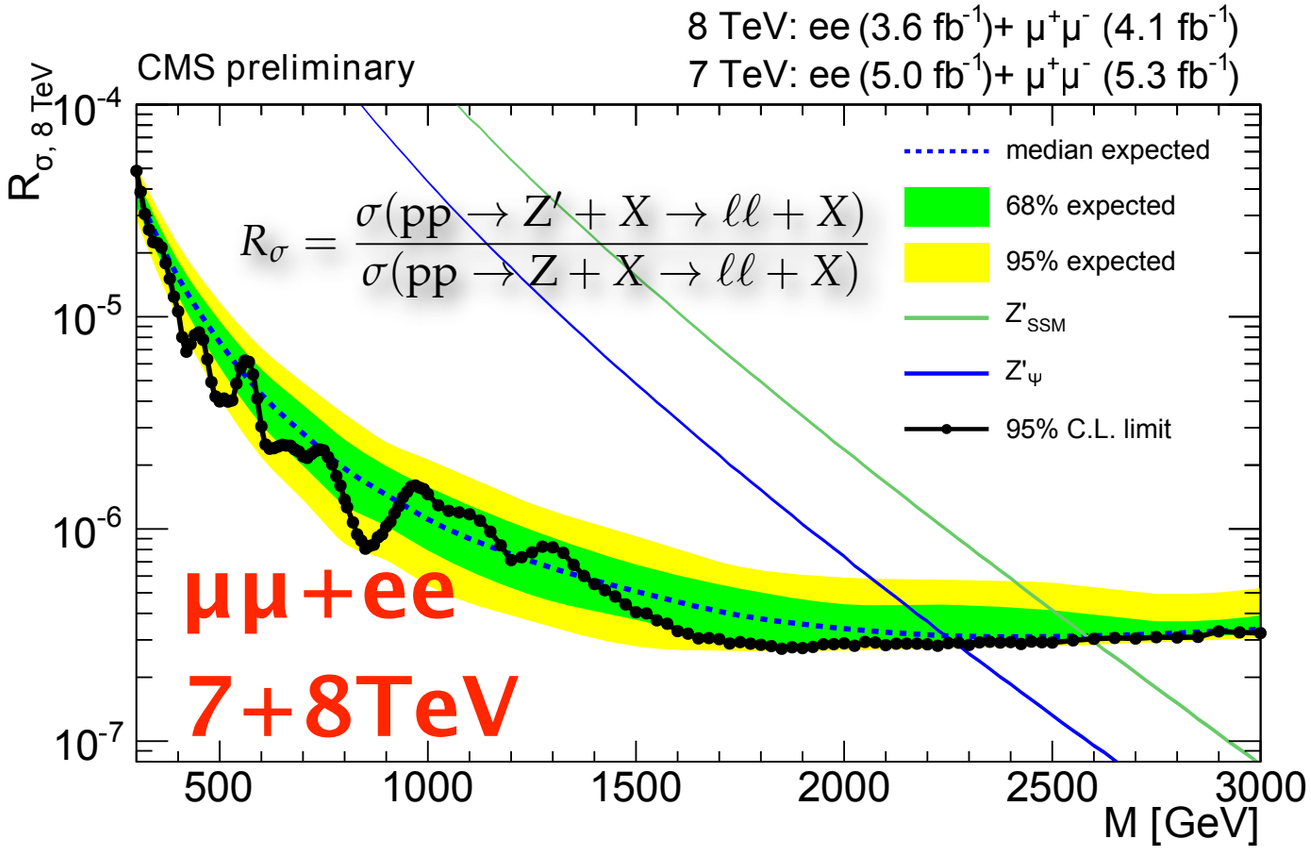
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO

$Z' \rightarrow e^+e^-, \mu^+\mu^-$

EXO-12-015
EXO-11-019

- Search for narrow [4–14% σ(M)/M] resonance predicted in many models.
- Background from Drell-Yan, $t\bar{t}$, and QCD (non-prompt ℓ) estimated with fit of spectrum.





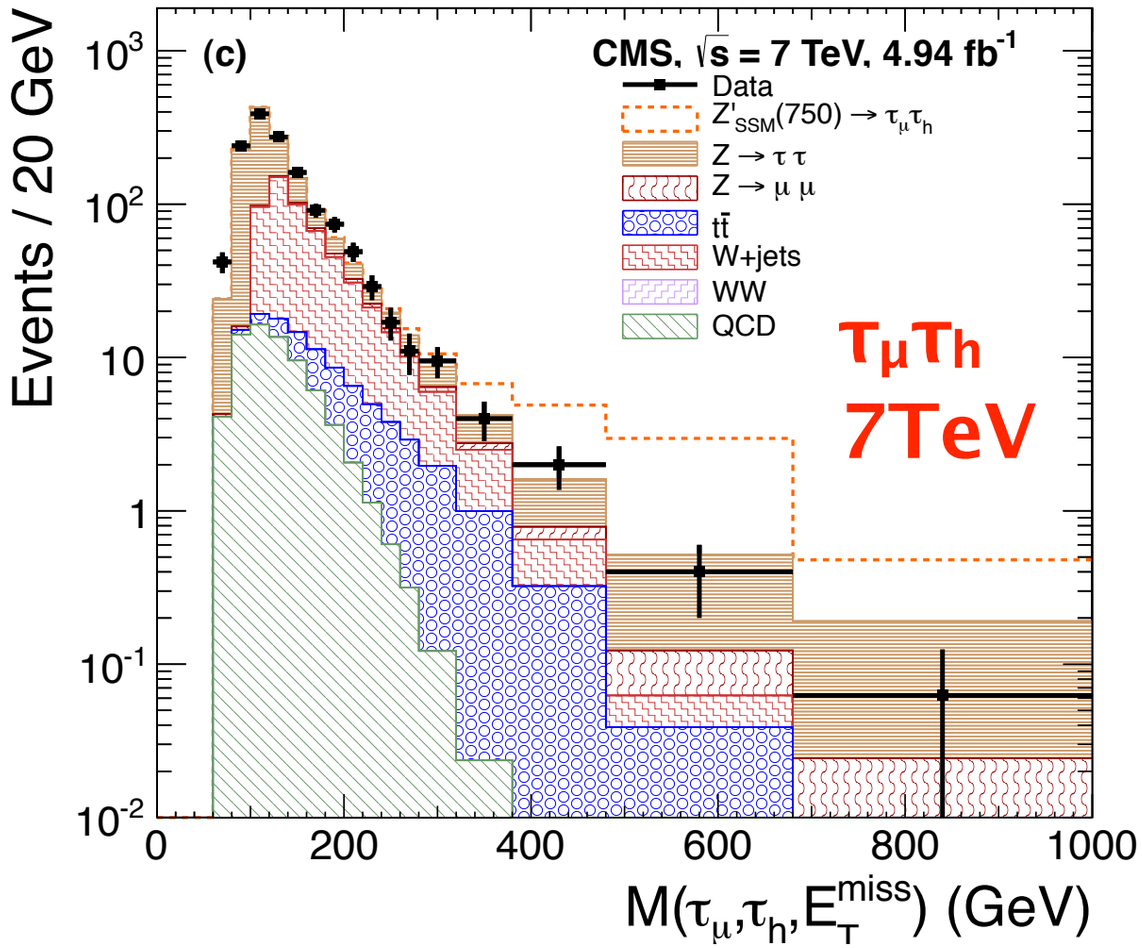
- Interpretations for Z'_{SSM} of sequential standard model and Z'_ψ of SU(5) GUTs.
- No hint of excess just below ~1TeV that visible in 7TeV data.

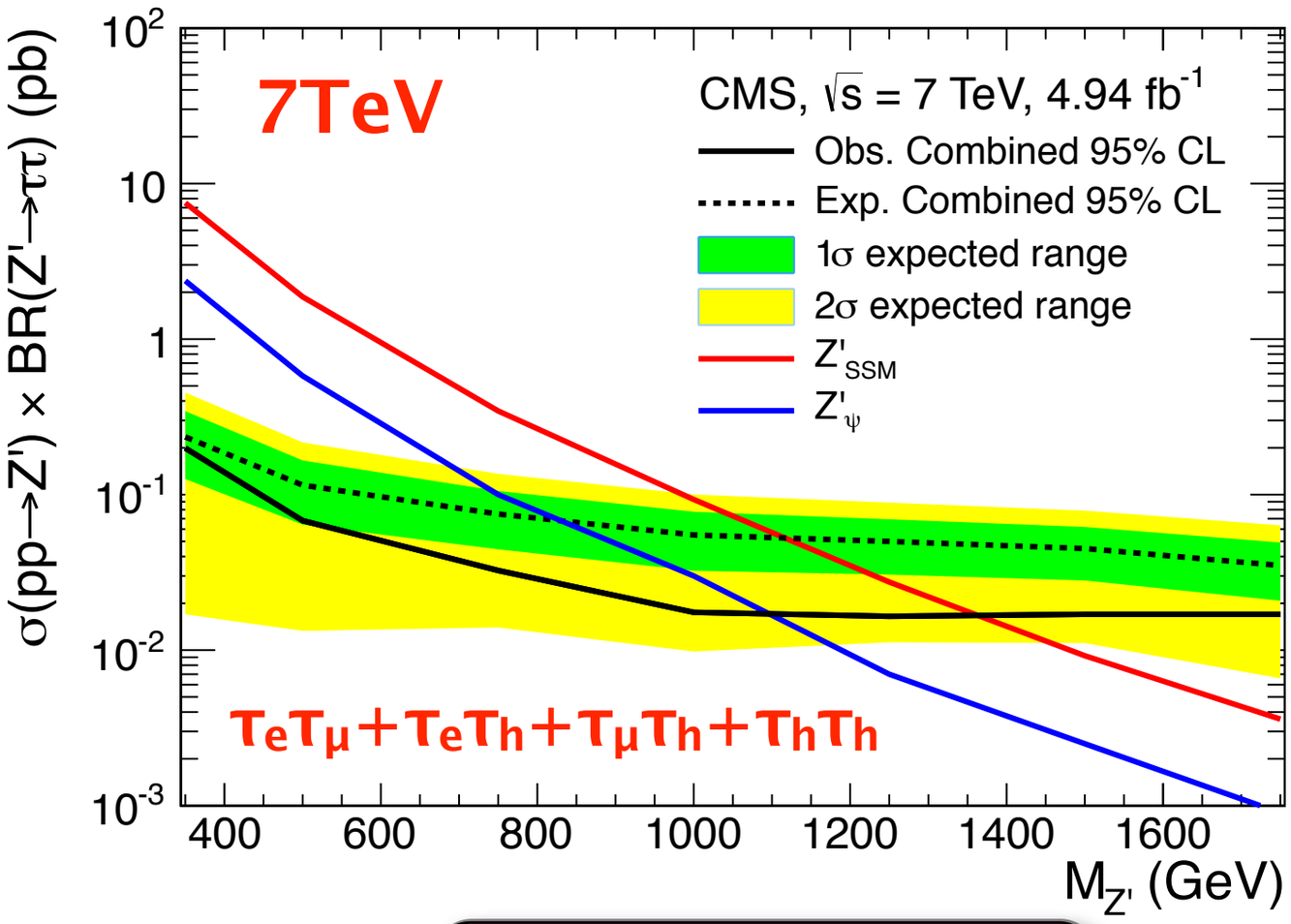
$M(Z'_{SSM}) > 2.59$ TeV
$M(Z'_\psi) > 2.26$ TeV

$Z' \rightarrow \tau\tau$

EXO-11-031

- Search for resonance **coupling to 3rd generation** in $\tau_e\tau_\mu$, $\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_h\tau_h$.
- Background from Drell-Yan, $t\bar{t}$, W+jets, QCD estimated from data samples with like-sign leptons, relaxed isolation, extra MET, extra b-jets, etc.





Effective visible mass:

$$M(\tau_1, \tau_2, \not{E}_{\mathrm{T}}) = \sqrt{(E_{\tau_1} + E_{\tau_2} + \not{E}_{\mathrm{T}})^2 - (\vec{p}_{\tau_1} + \vec{p}_{\tau_2} + \vec{\not{E}}_{\mathrm{T}})^2}$$

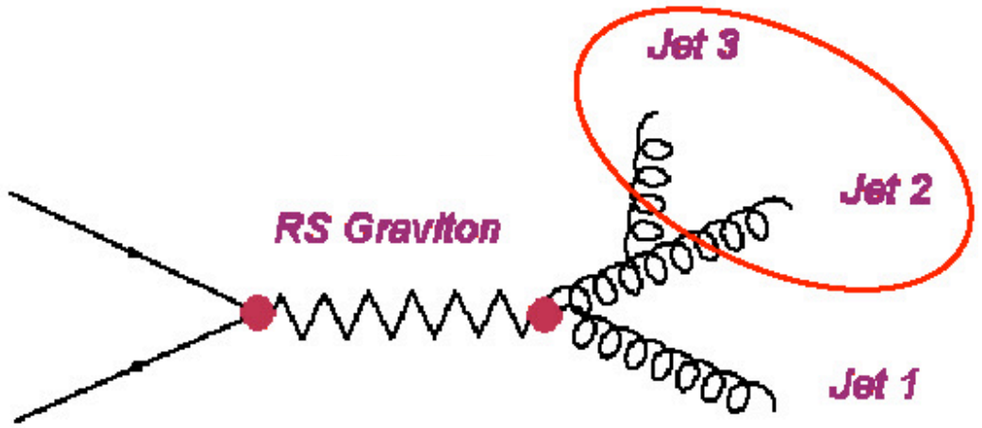
$M(Z'_{SSM}) > 1.4$ TeV

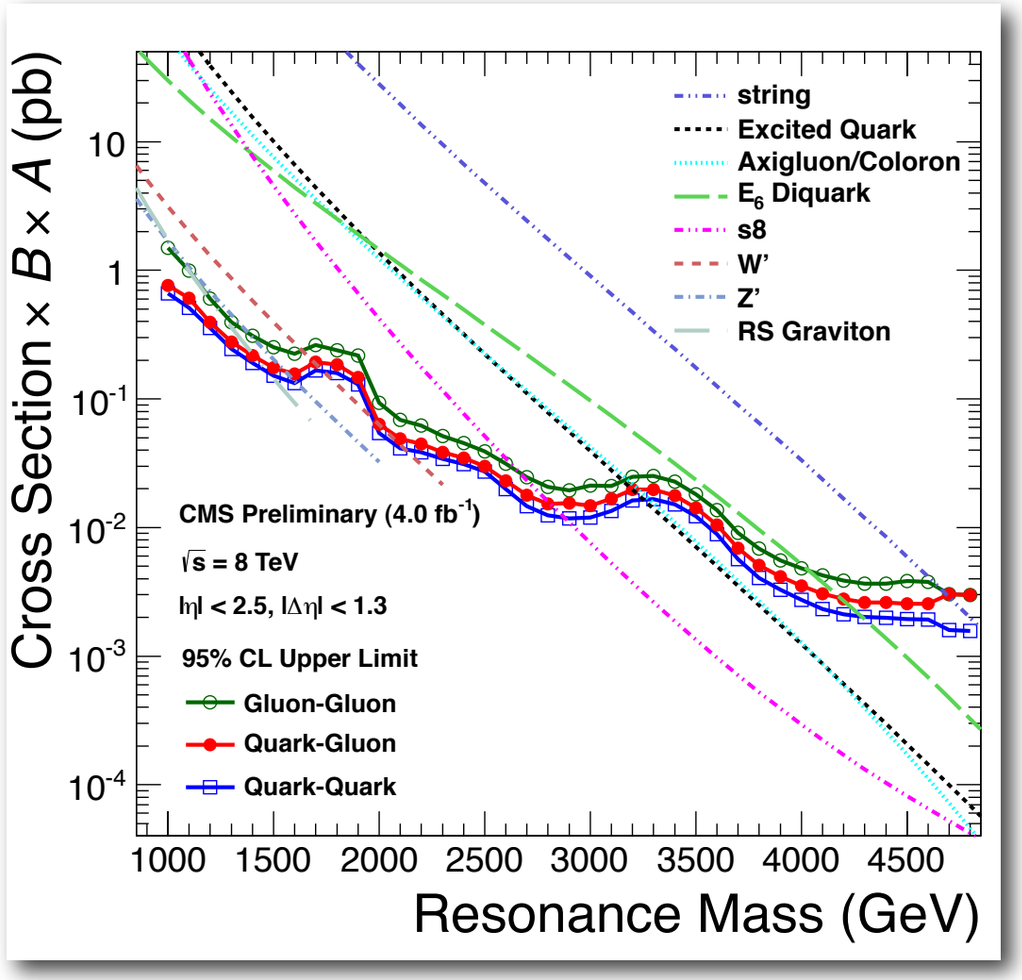
$M(Z'_{\psi}) > 1.1$ TeV

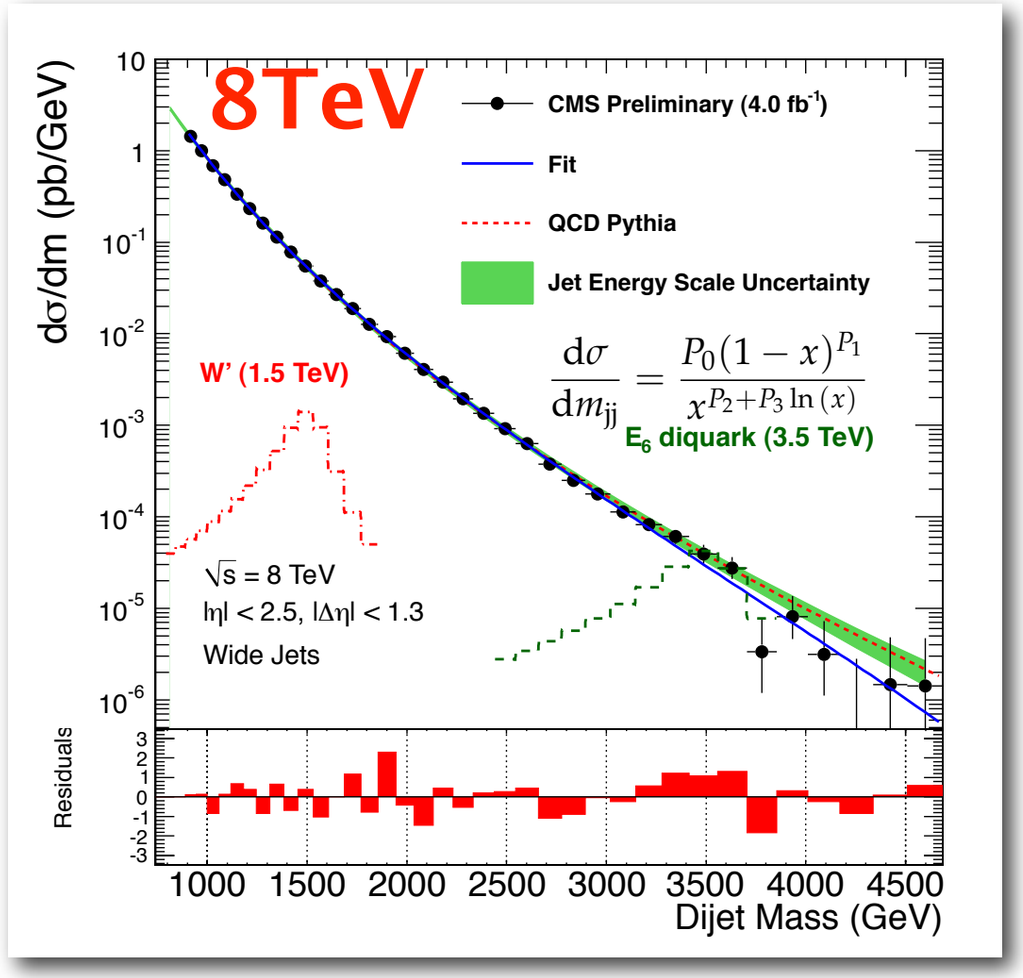
Dijets

EXO-12-016

- Search for narrow resonance in dijets.
- "**WideJet**" reconstruction improves mass resolution by few-50% depending on parton content.
- Background from fit of smooth spectrum.



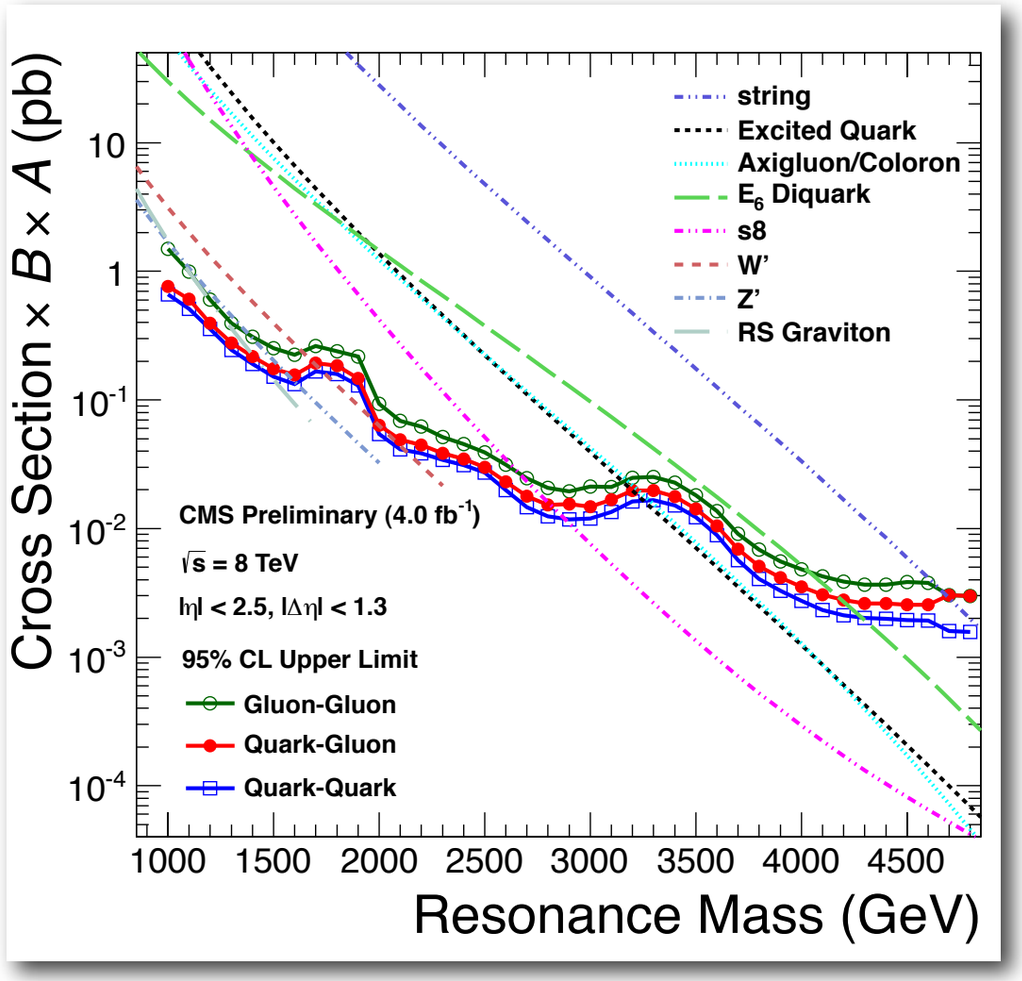




Low Mass Dijets

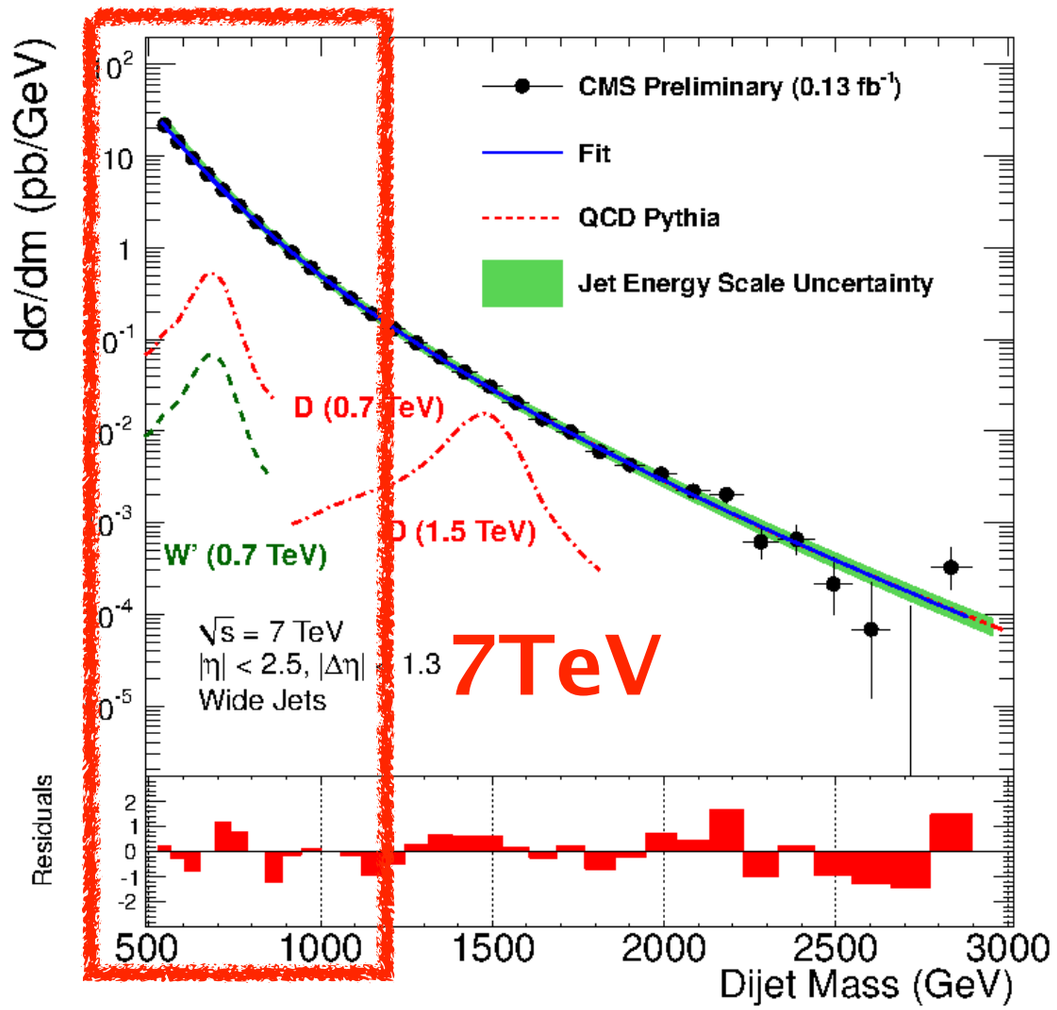
EXO-12-016

- Search for narrow resonance in dijets.
- "**WideJet**" reconstruction improves m
  resolution by few-50% depending on
  parton content.
- Background from fit of smooth spect



Jet 3

CMS-PAS-EXO-11-094

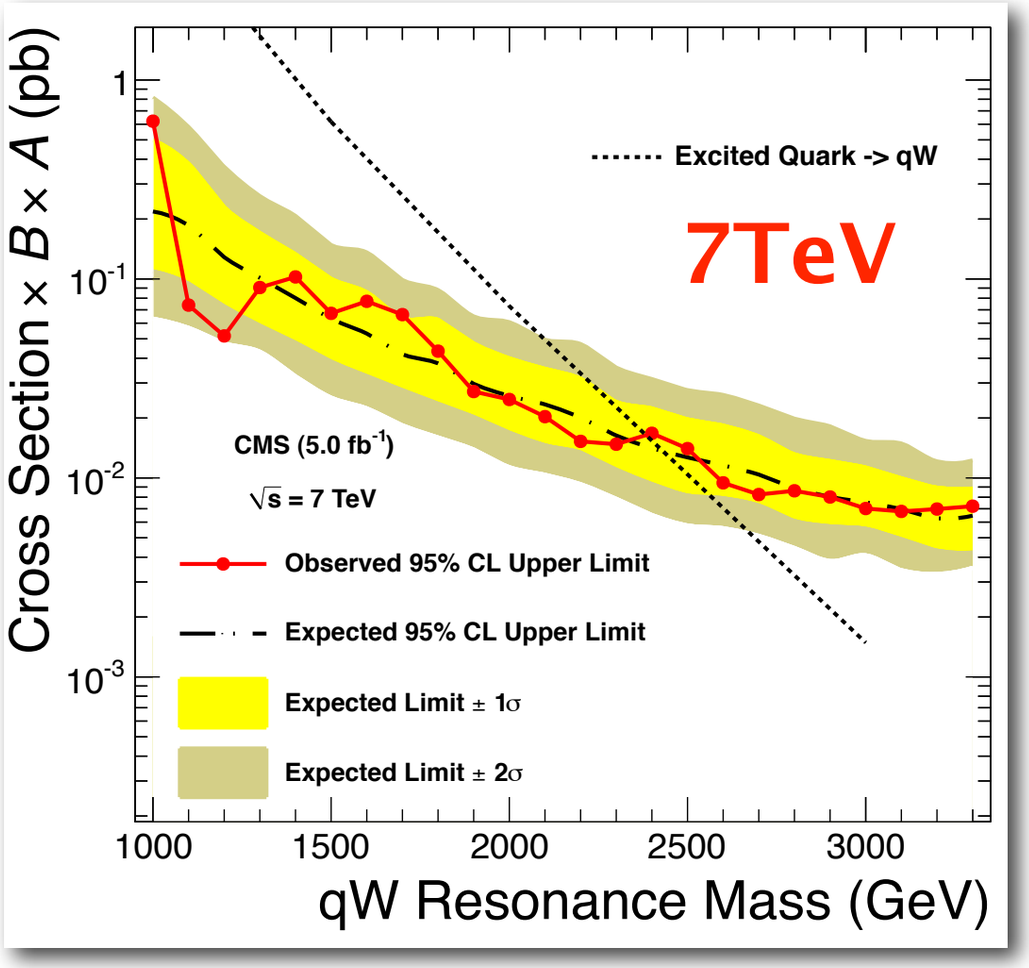


Data scouting: Low mass (0.5-1TeV) probed with special trigger and reduced data format.

Dijets with b- and W/Z-tags

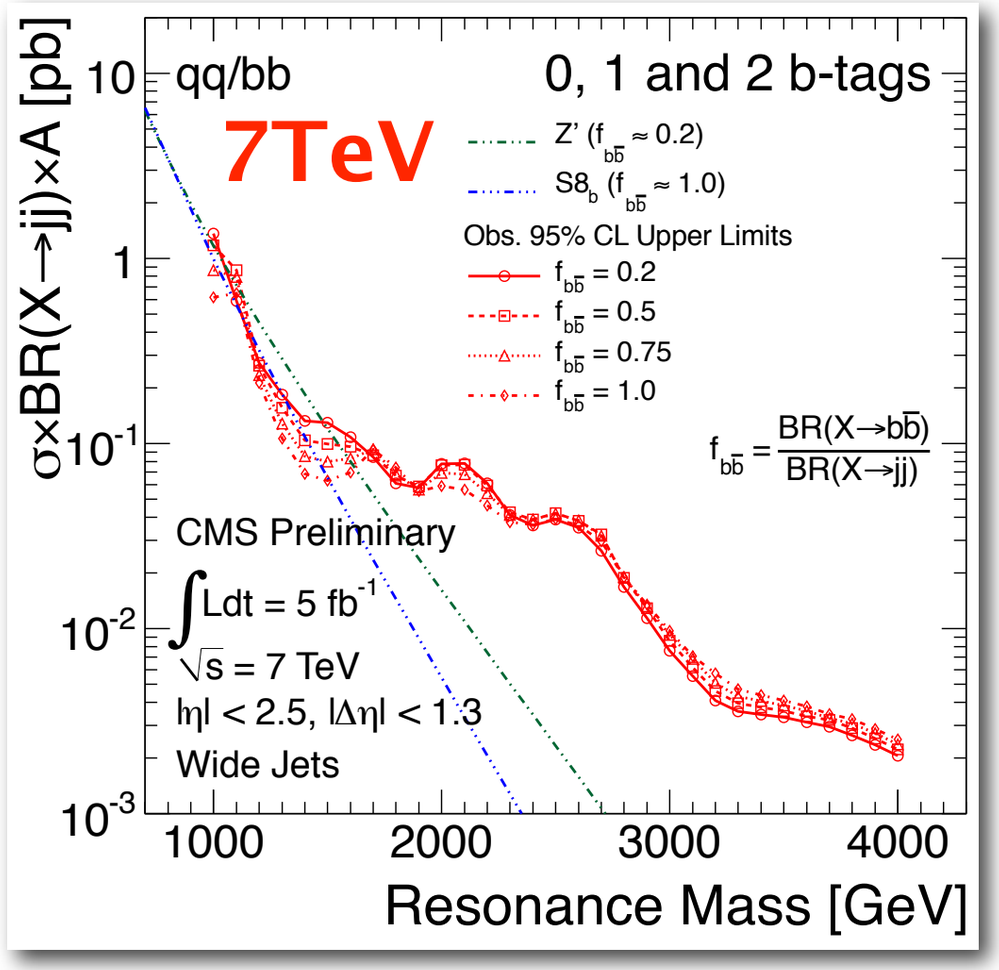
EXO-11-095

- Merged W/Z → jj tagged according to jet substructure.
- Models : q* in qW/qZ, RSG in WW/ZZ, and W' in WZ.

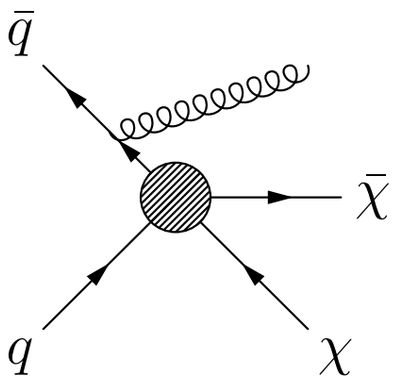


EXO-11-008

- Categories for 0,1,2 b-tags and BR(gg), BR(qq) for range of $f_{b\bar{b}} = \frac{BR(X \to b\bar{b})}{BR(X \to jj)}$

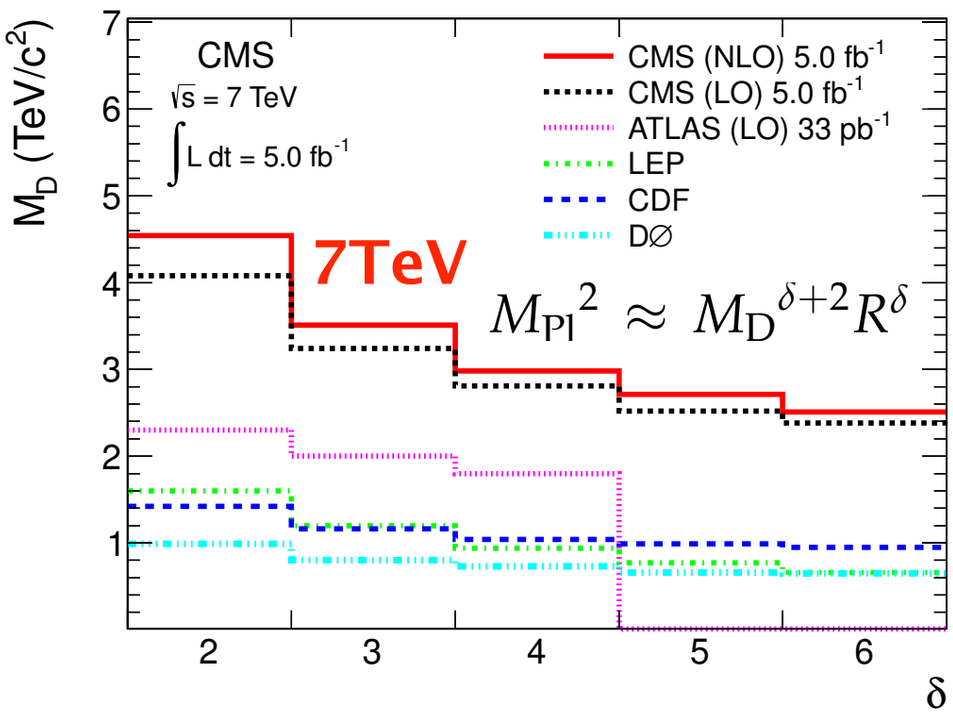


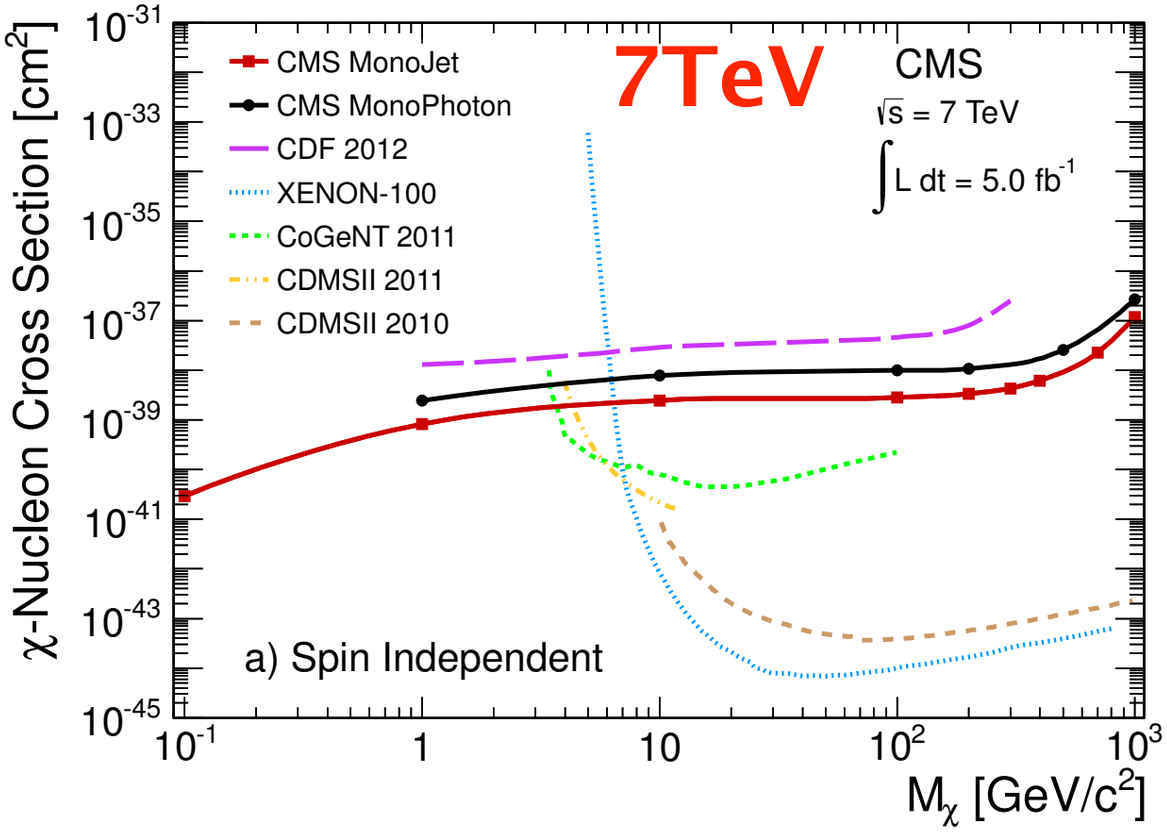
MonoJet & MonoPhoton

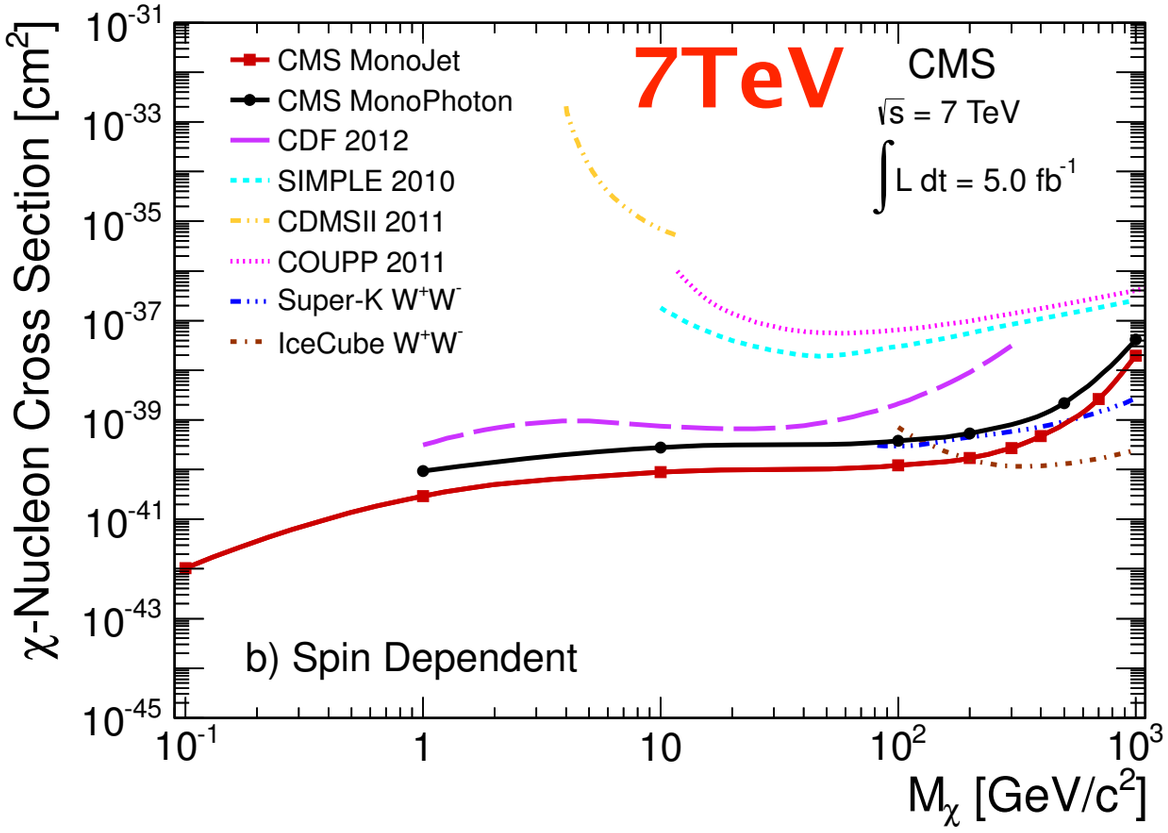


EXO-11-059
EXO-11-096

- Search for **non-interacting particles** (dark matter, ADD graviton) **tagged by ISR jet/γ** in MET distribution.
- Background: Z+jets/γ, W+jets/γ from Z(μμ) and W(μν).



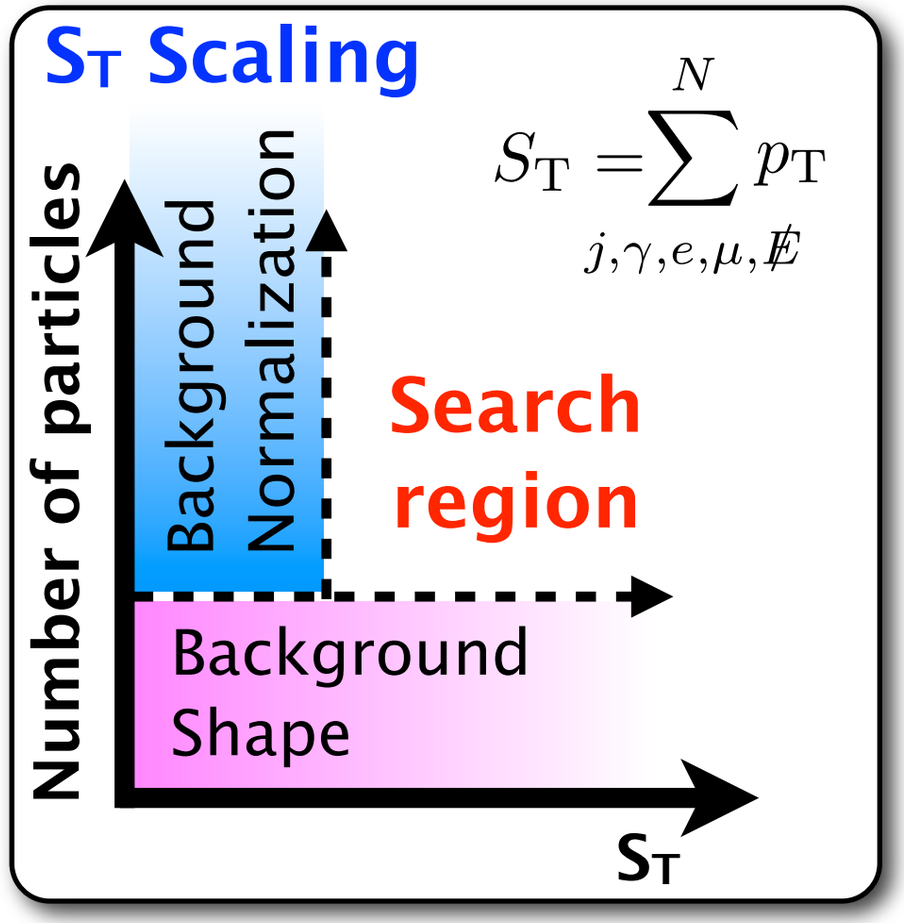


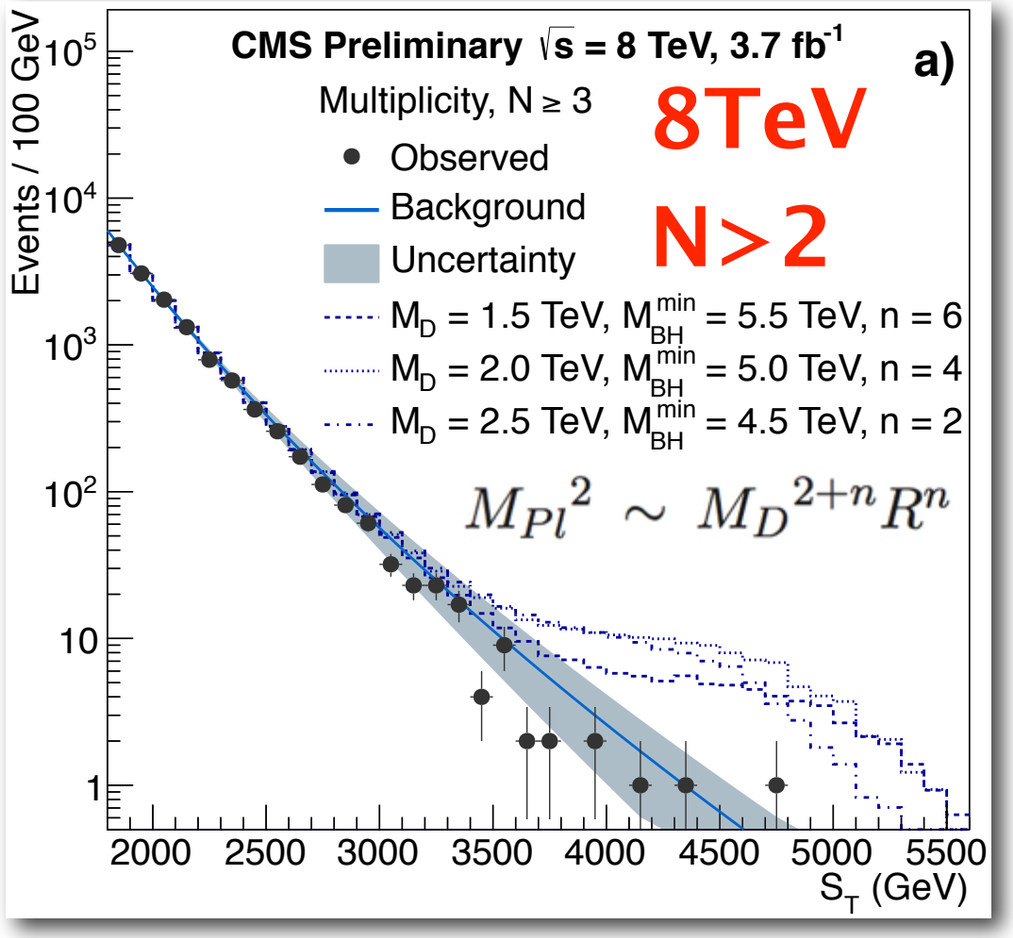


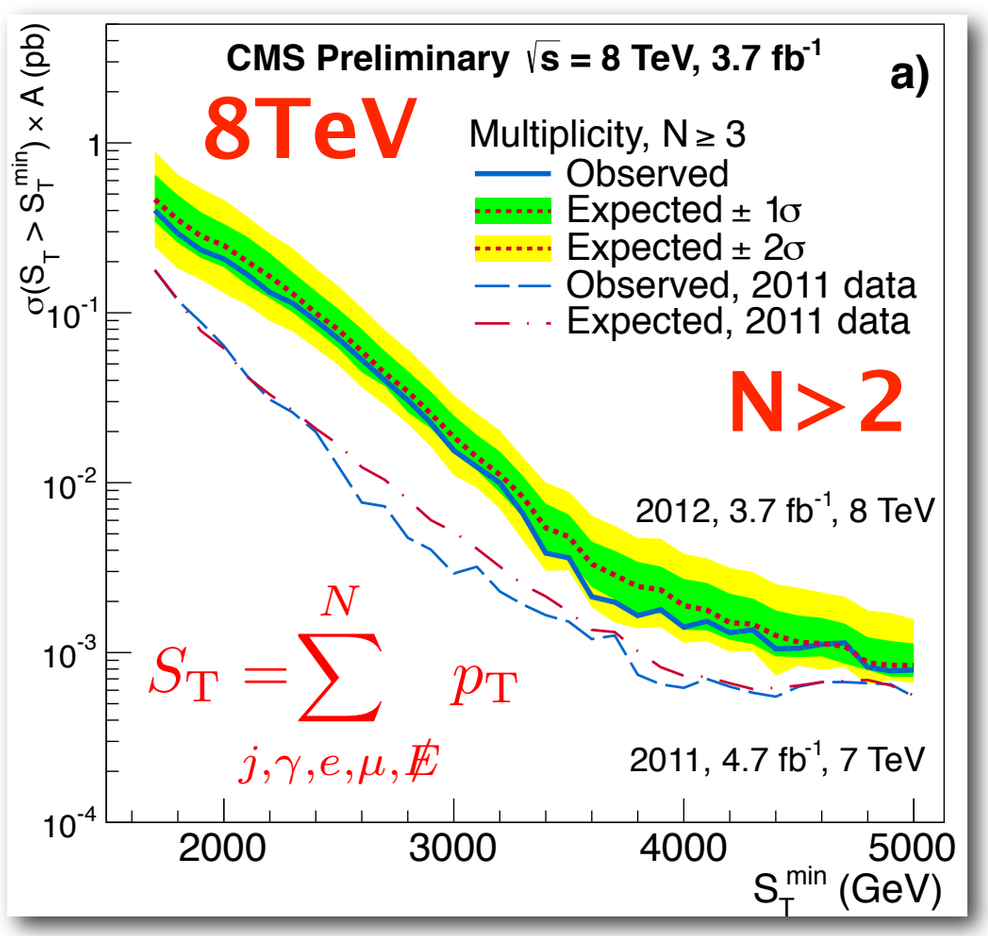
Black Holes

EXO-12-009

- Search for particle decaying into **many high p_T particles** (BH ~ 75% jets).
- Background prediction from **S_T scaling**.
- Limits on BH vs. M_D and n ED.
- Model-independent limits vs. S_T and # final state particles.





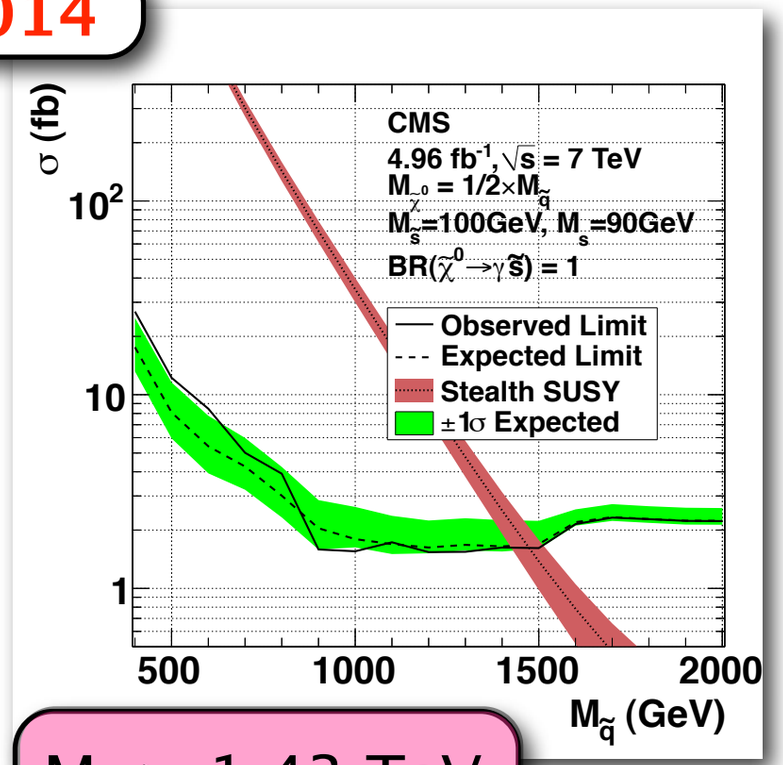


Diphotons+Jets

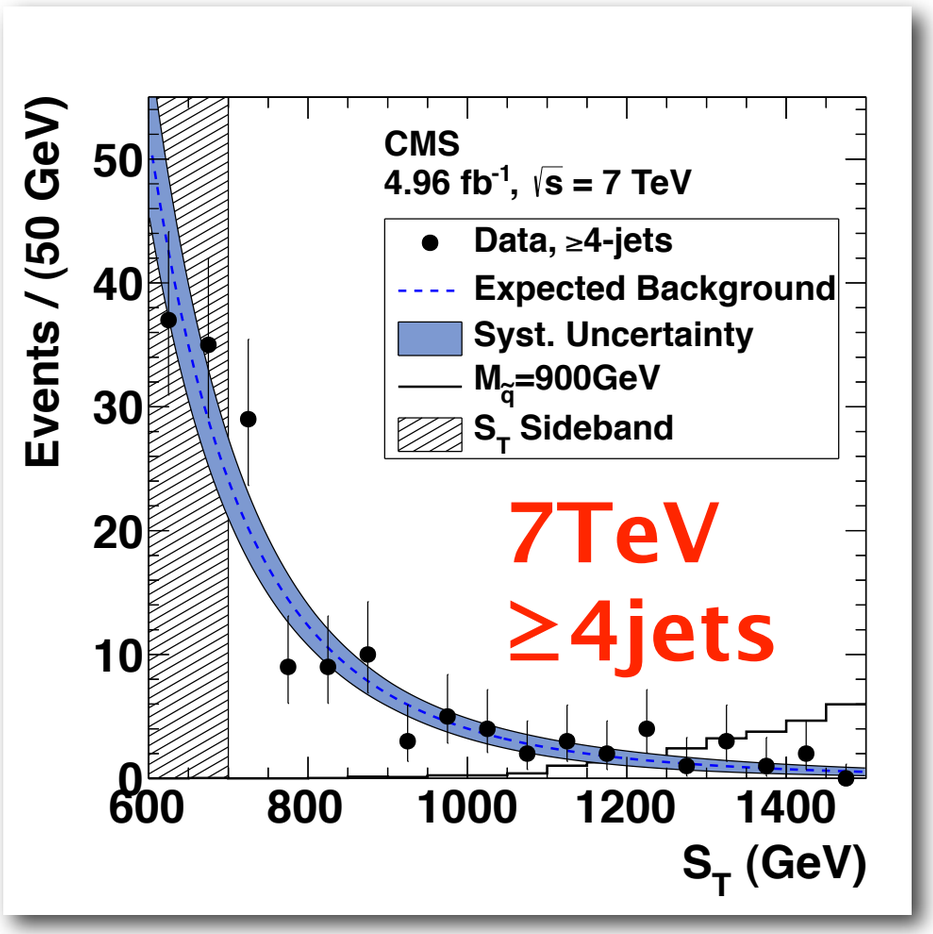
SUS-12-014

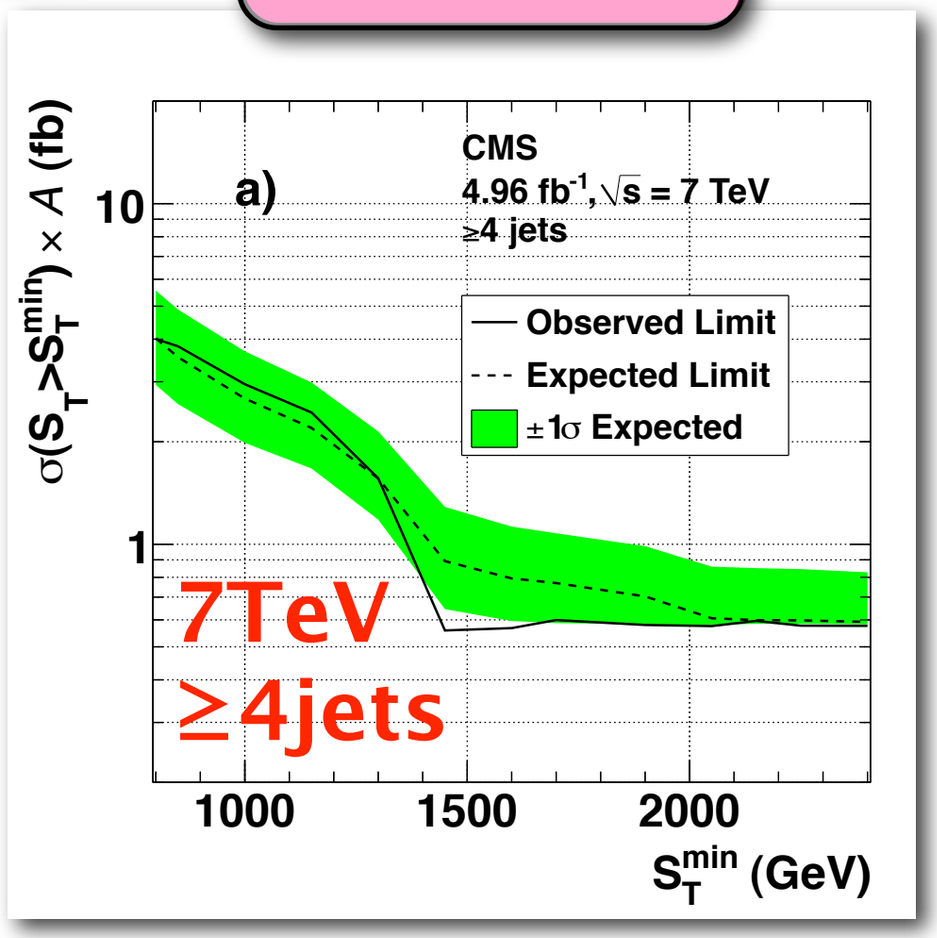
- Search for excess in events with 2 photons, jets, and **NO MET requirement**.
- Background prediction from **S_T scaling**.
- Limits on "**stealth SUSY**" cross section and squark mass.
- Model-independent limits vs. S_T and jet multiplicity.

$$S_{\mathrm{T}} = \sum_{j,\gamma,\not{E}}^{N} p_{\mathrm{T}}$$



$M_{\tilde{q}} > 1.43$ TeV

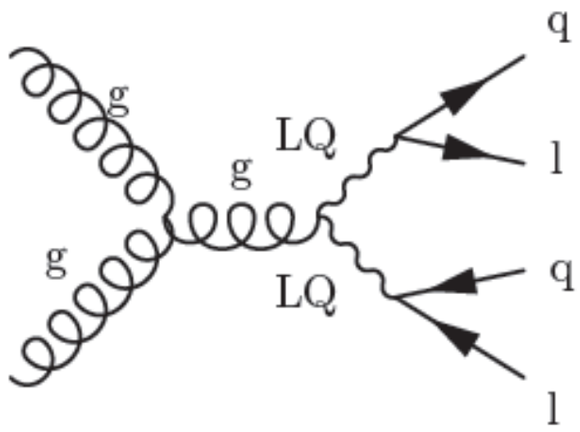


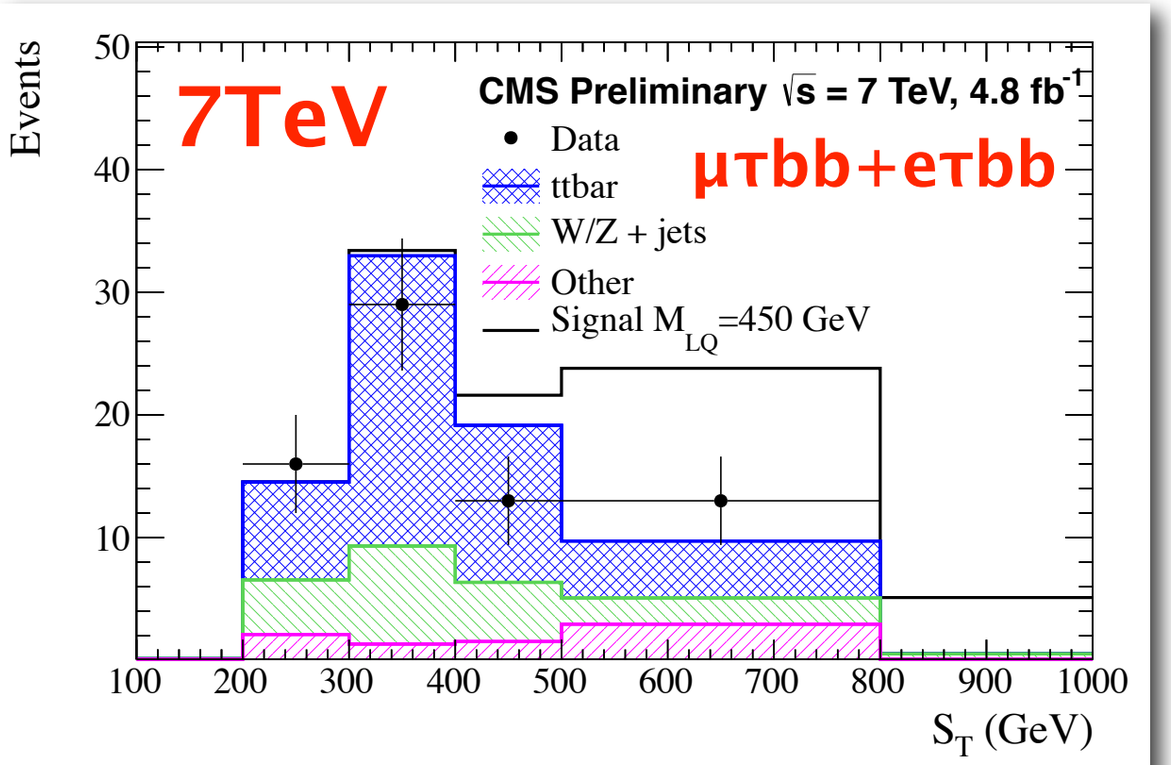


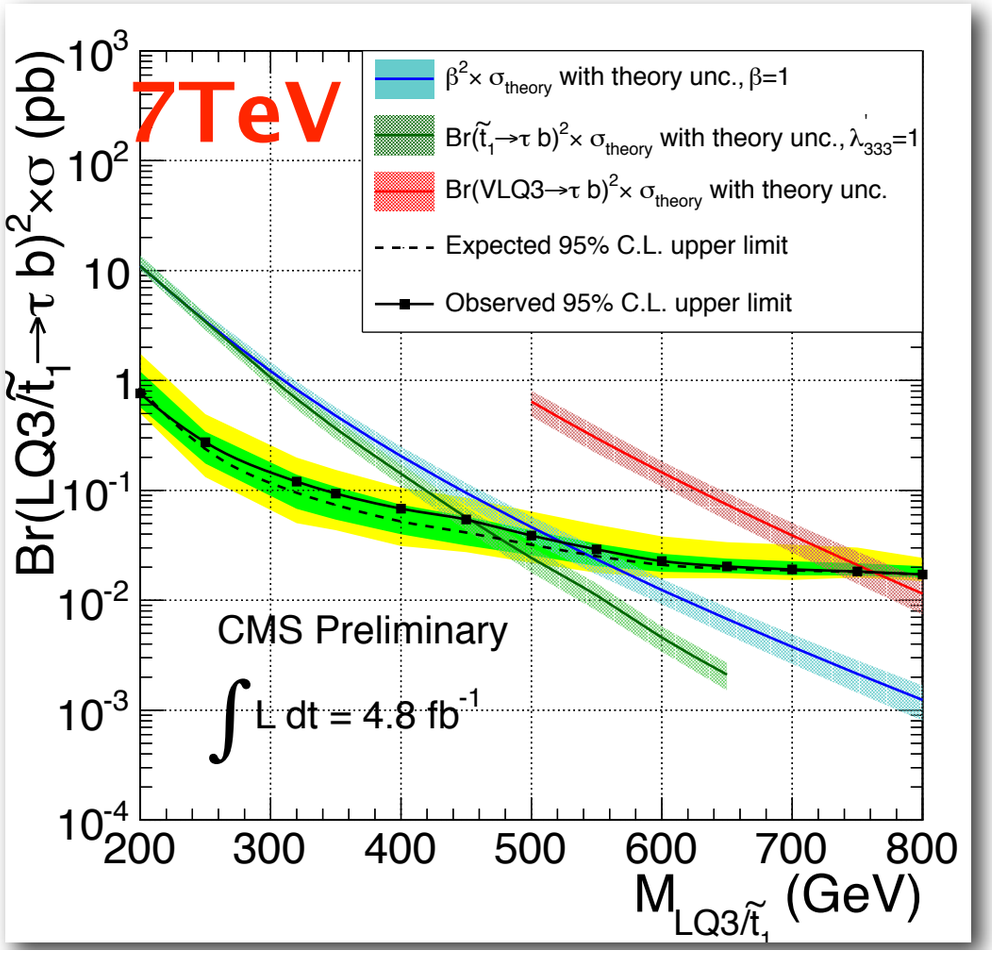
3rd Generation LQ + light RPV $\tilde{t}$

EXO-12-002

Search for **LQ3**, **vector LQ3**, and **light RPV stop** in $\tau_\ell b + \tau_{had} b$ (ℓ=e,μ).







Background estimation:

top: MC validated in $M_{\tau b}$ sideband,

V+jets: Rate of jet misID as τ_{had} measured in data,

Z→ℓℓ/ττ and diboson: From MC

$M_{LQ3} > 525$ (370) GeV for $\beta = 1.0$ (0.5).

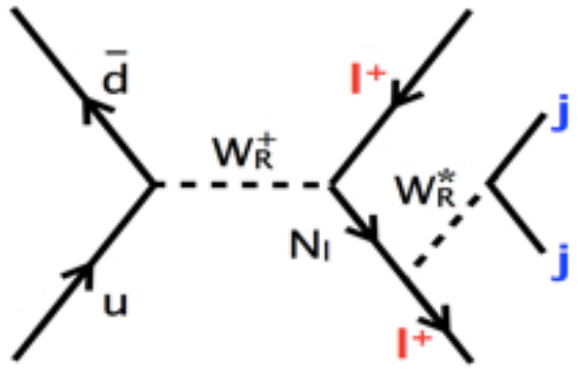
$M_{VLQ3} > 763$ GeV for $\beta = 1.0$.

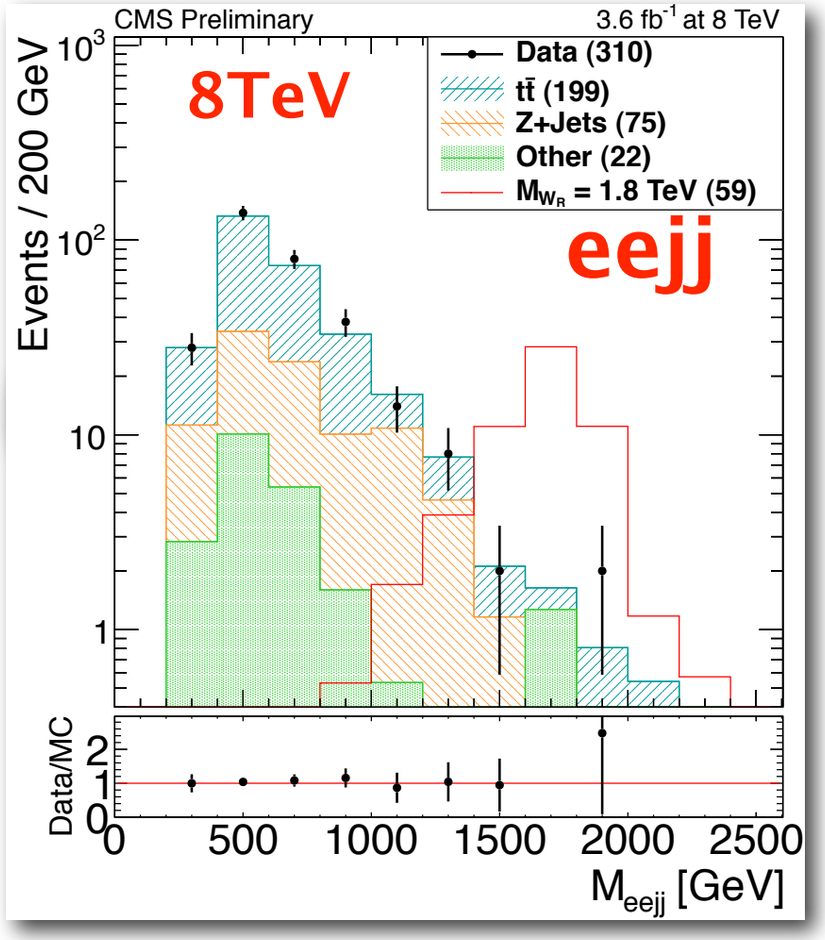
$M_{stop} > 453$ (240) GeV for $\lambda_{333}=1$ (→0).

Heavy Neutrino & W_R
of Left-Right Symmetric Model

P-violation from LR breaking at intermediate scale.

Heavy LRSM neutrino + seesaw mechanism → **small M_ν in SM**.





Assume: small W_R/W_L, $N_\ell/N_{\ell'}$ mixing; **one lepton channel** kinematically accessible.

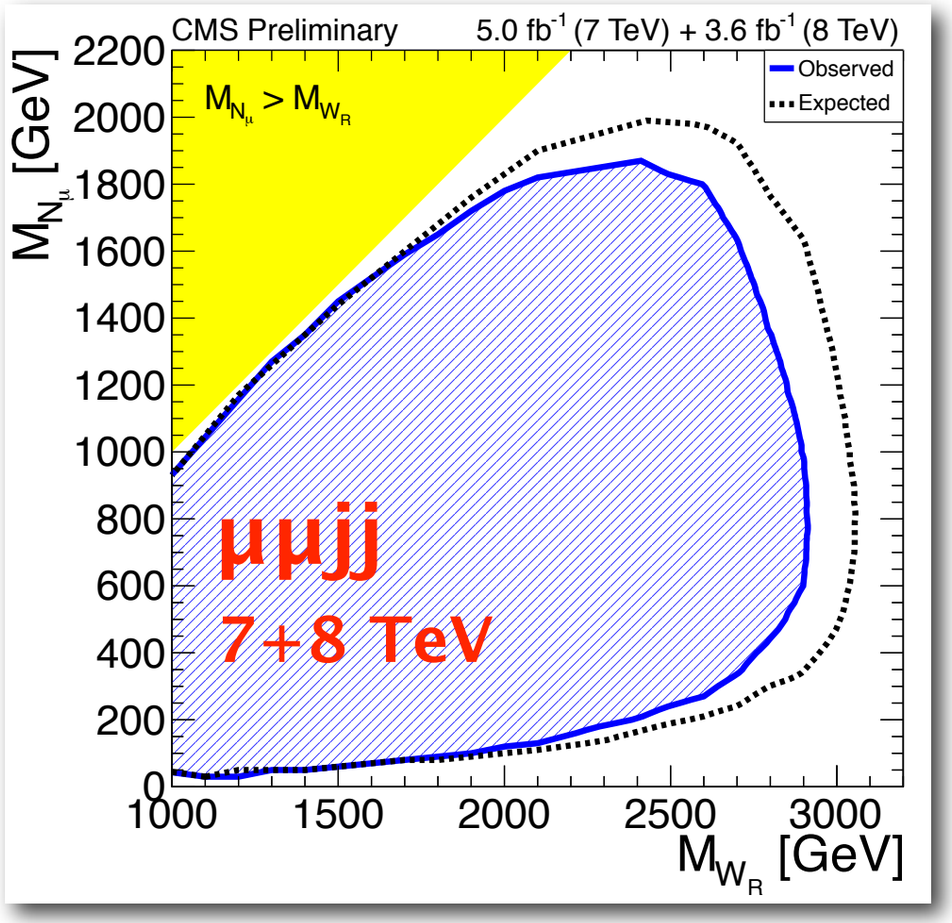
Background Estimation

Top: shape/norm from eμjj data.

DY+jets: normalize MC shape in Z-peak.

QCD: fake rate from data

M_{WR} > 2.8 TeV for $M_N=M_{WR}/2$ from 2011+2012 combination of μμjj.



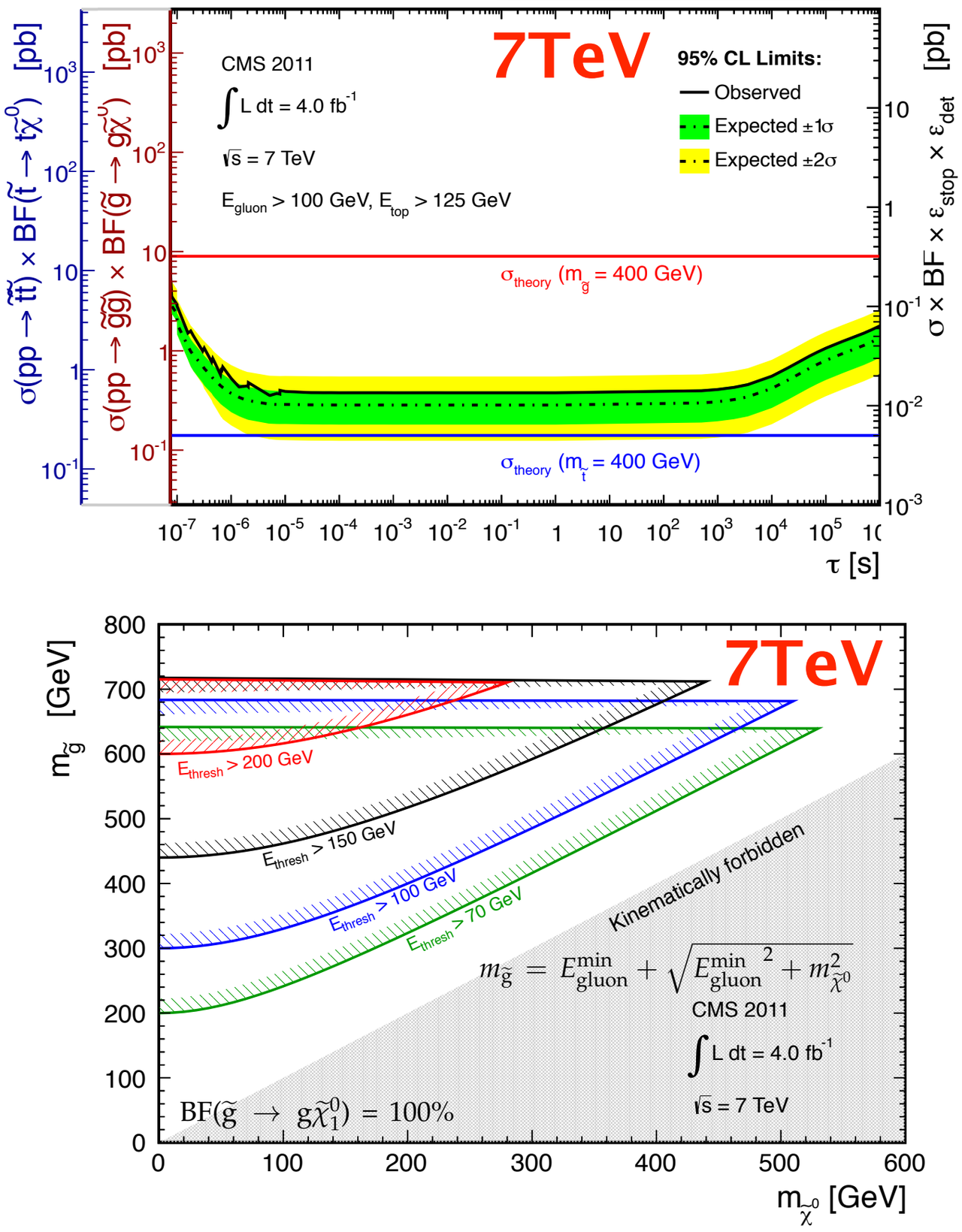
Stopped Long Lived Particle (LLP)

EXO-11-020

Search for **gluino/stop decays at rest in calorimeter** (with cloud model of R-hadron interactions).

Trigger: 50 GeV jet trigger with beam veto in triggered bunch crossing ±1BX. 246 hrs live time.

Background rate measured in 2010 data (3.6 pb^{-1}) = 5.6±2.5e-6 Hz from beam-related, cosmic rays, and detector noise.



Heavy Stable Charged Particle

EXO-11-022

Search for LLP via dE/dx in tracker

- Gluino, stop with **cloud** and conservative **charge suppression** models.
- **Lepton-like:** stau, Hyper-kaon

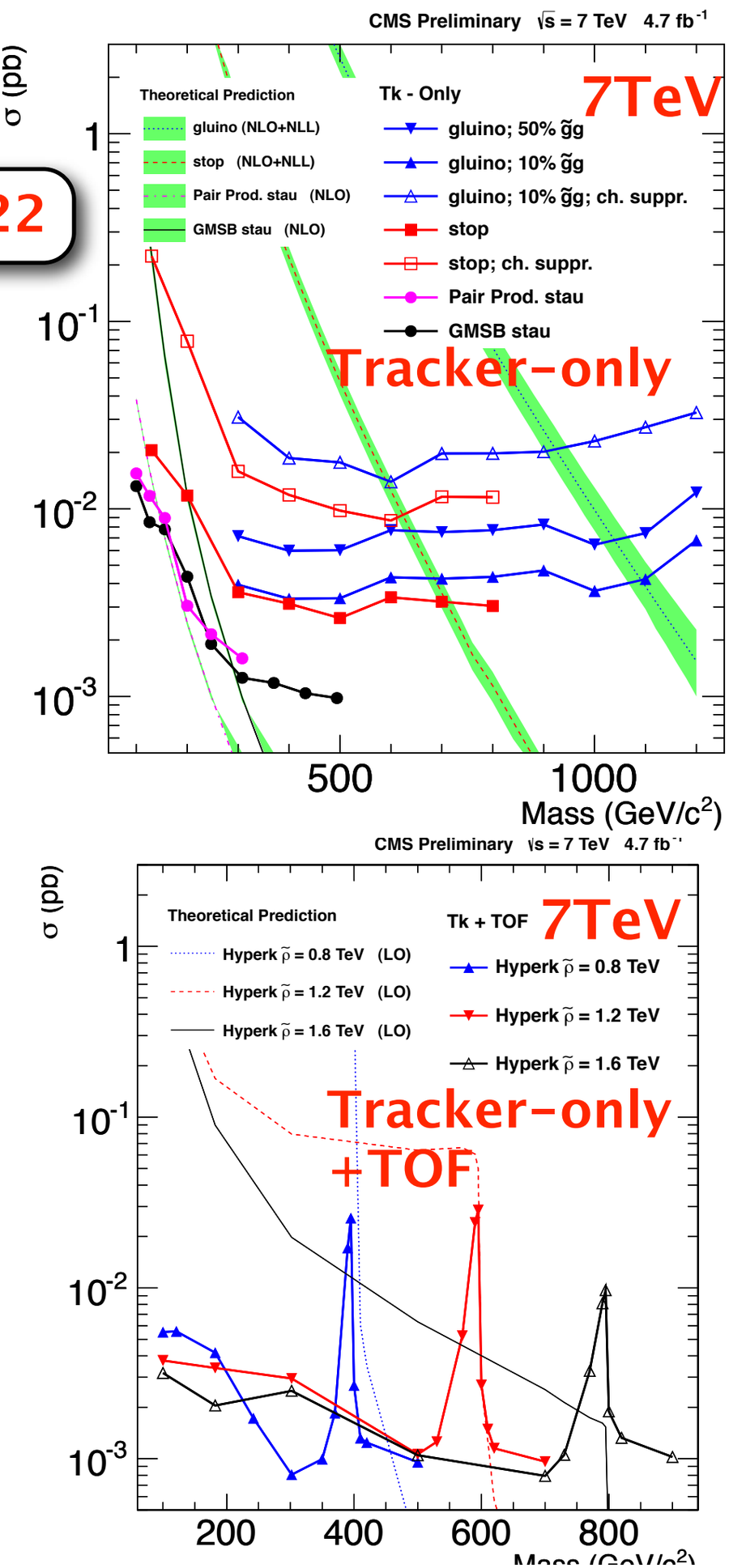
Triggers:

- Single μ, MET (for charge suppression models)
- Sensitivity for $\beta>0.3$.

Identification strategies:

- **Tracker-only** : large dE/dx + large p_T
- **Tracker+TOF**: Tracker-only + μ-like + long time-of-flight (β^{-1} from μ system)

Background estimation from sidebands in β^{-1}, dE/dx MIP-compatibility (I_{as}), and p_T.

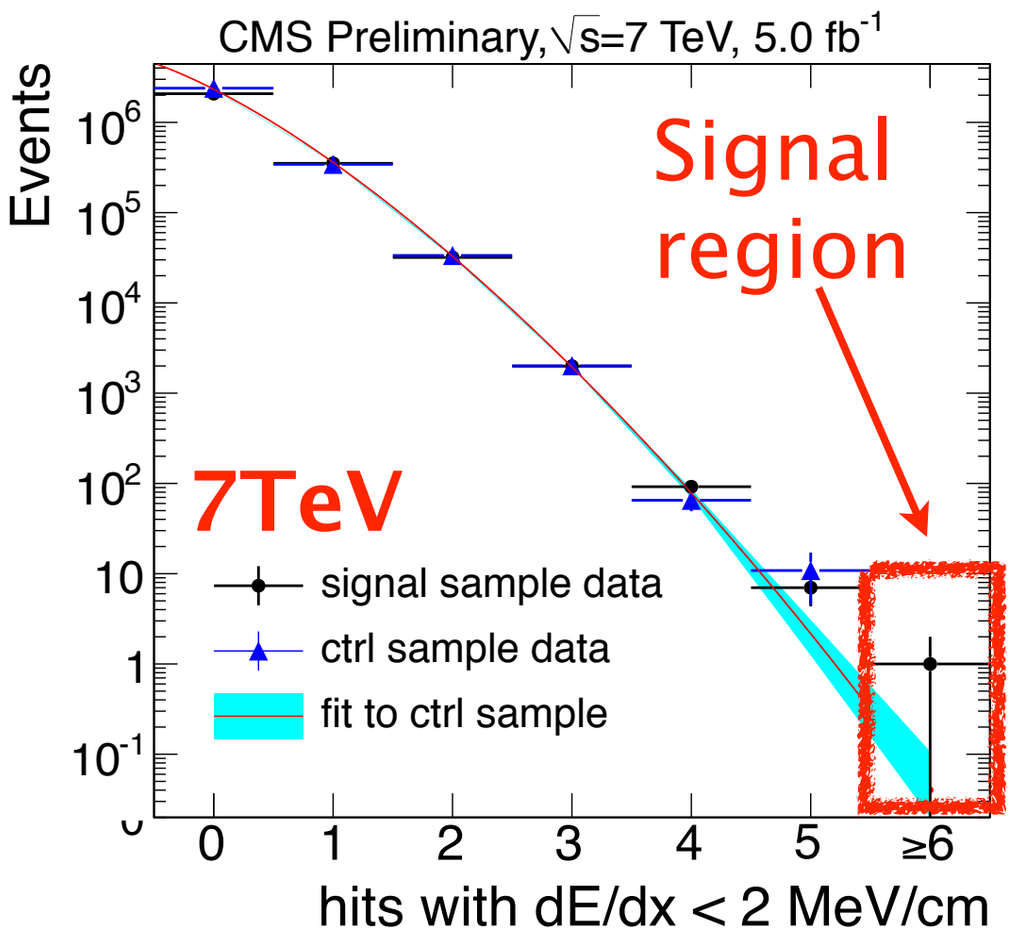


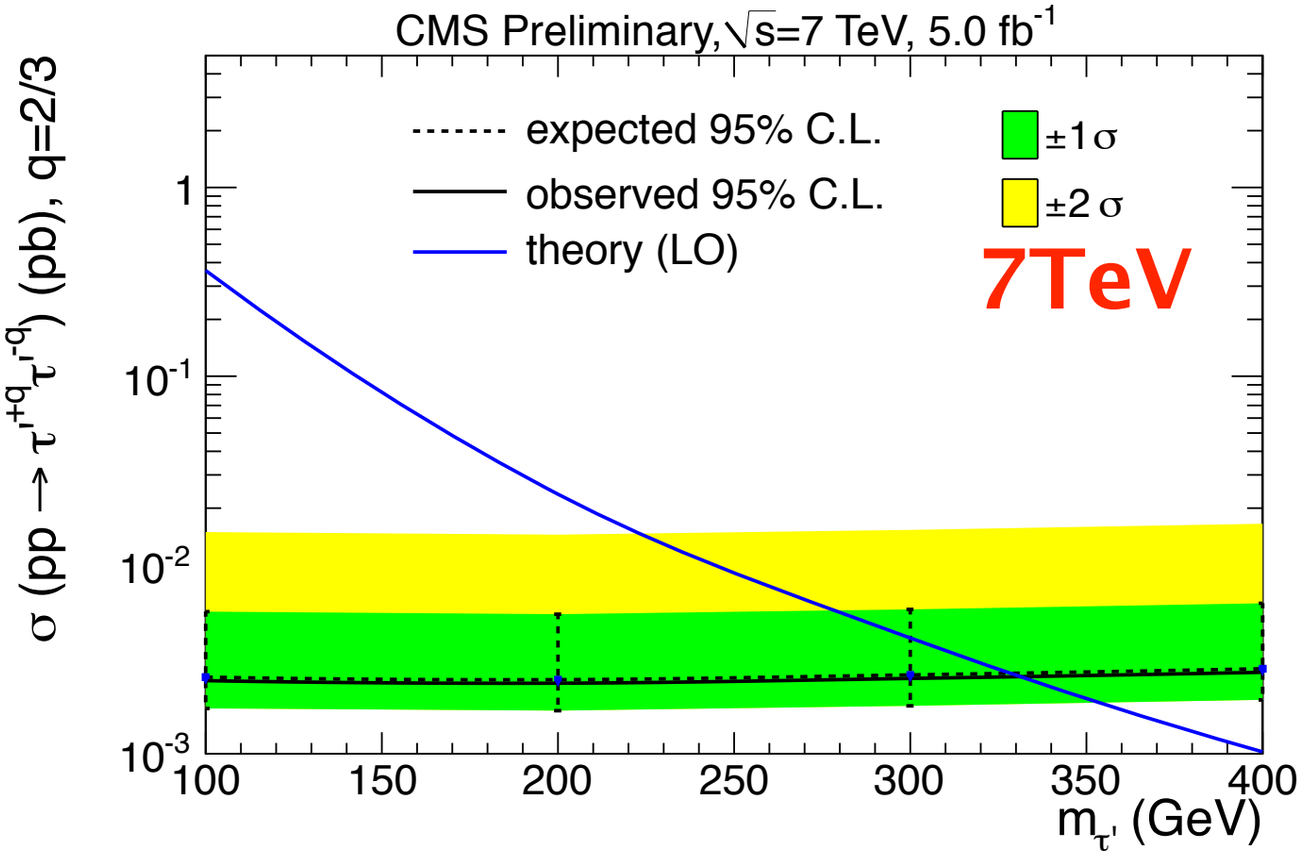
Heavy Stable Fractionally Charged Particle

EXO-11-074

- Search for fractionally charged long-lived lepton-like particle.
- Signature = 6 or more low-dE/dx hits in tracker.
- Backgrounds:
  - **Cosmics** from impact parameter sideband.
  - **Collisions** measure "hits with dE/dx<2 MeV/cm" in Z → μμ.

M > 210 GeV for Q = e/3
M > 330 GeV for Q = 2e/3





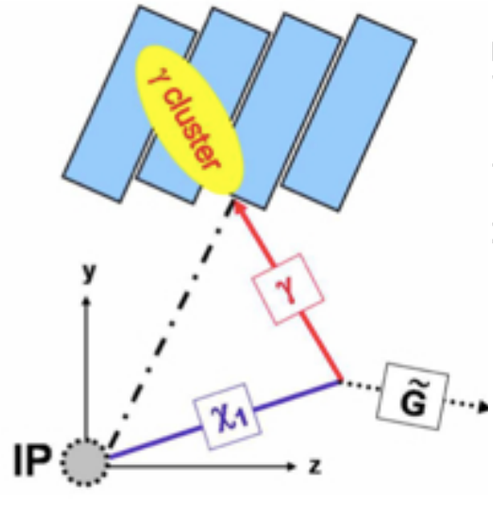
HSCP : EXO-11-022
Multiply charged HSCP : EXO-11-090

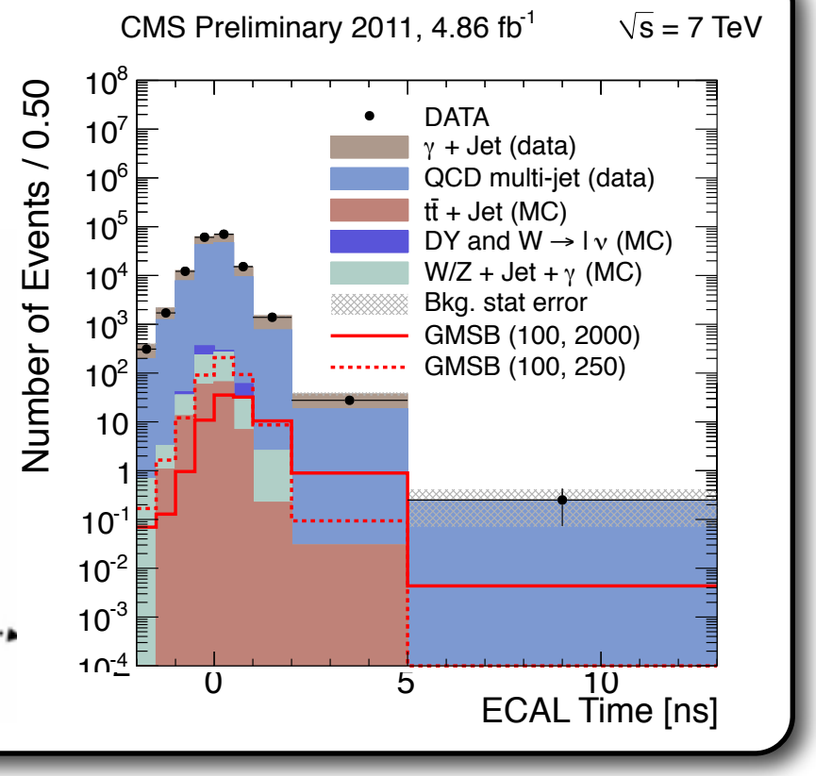
Displaced Photons

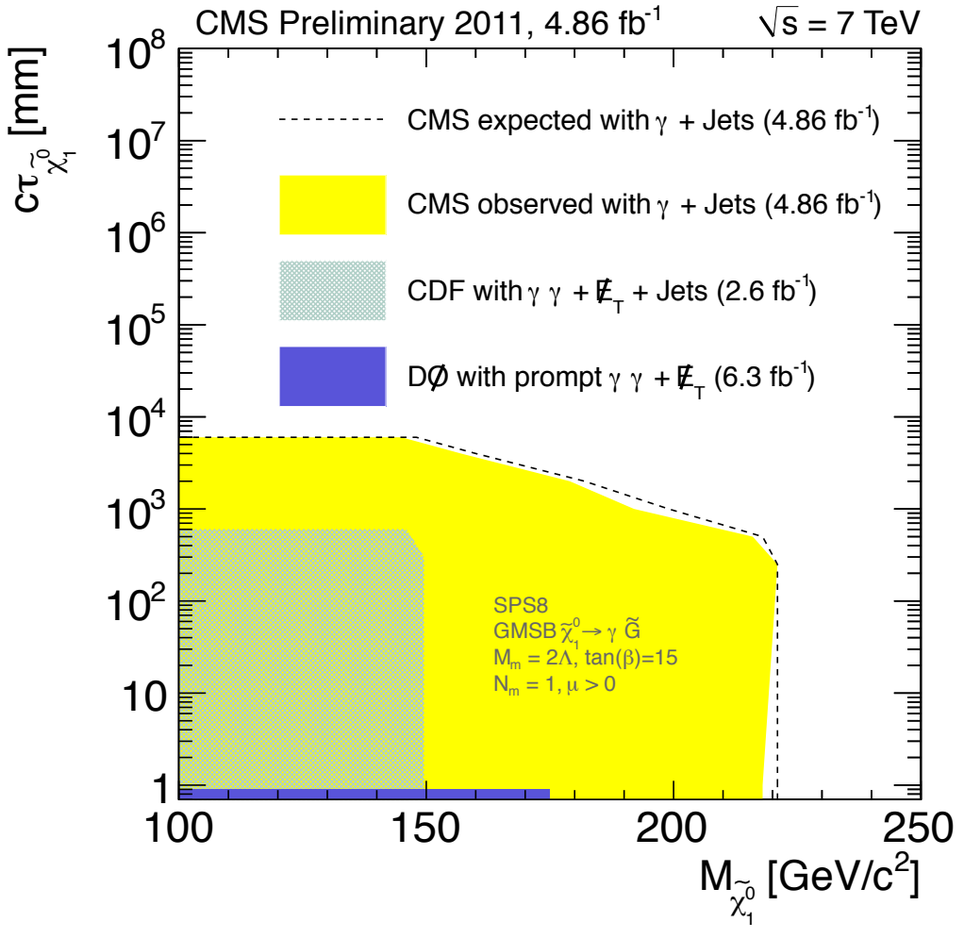
EXO-11-035

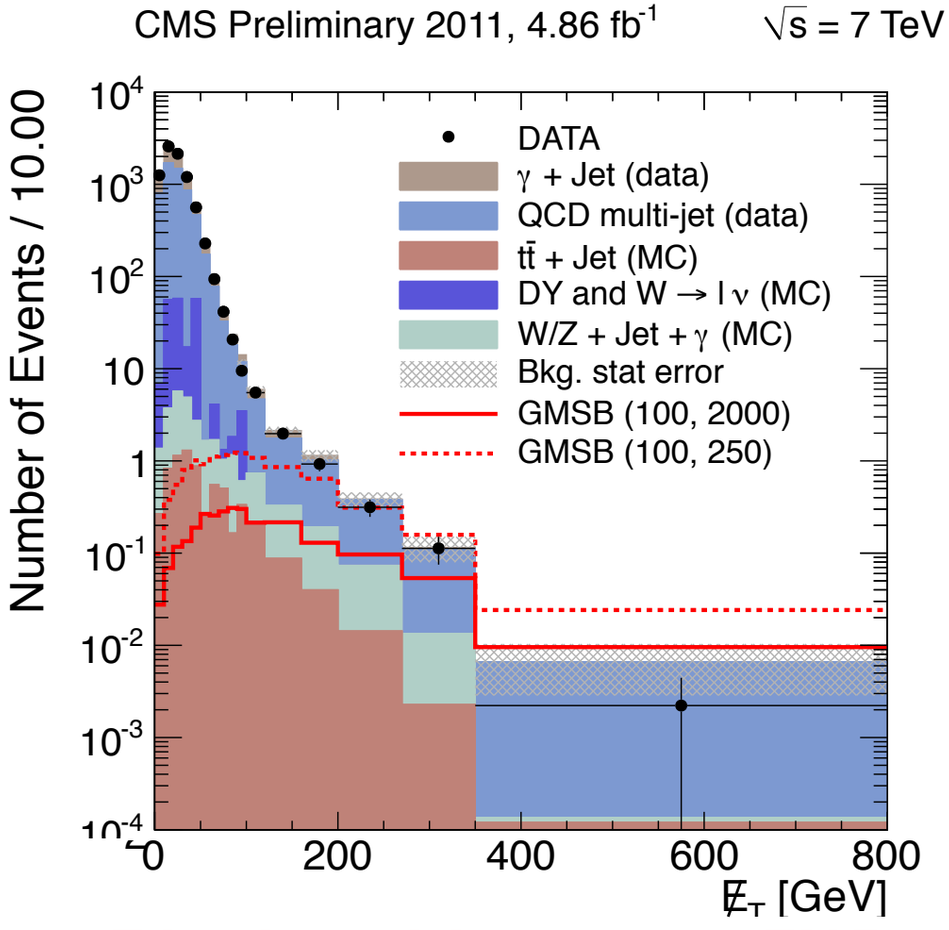
Search for displaced photons with special ECAL timing and shower shape.

$M_{\chi} > 220$ GeV for $c\tau < 10$cm





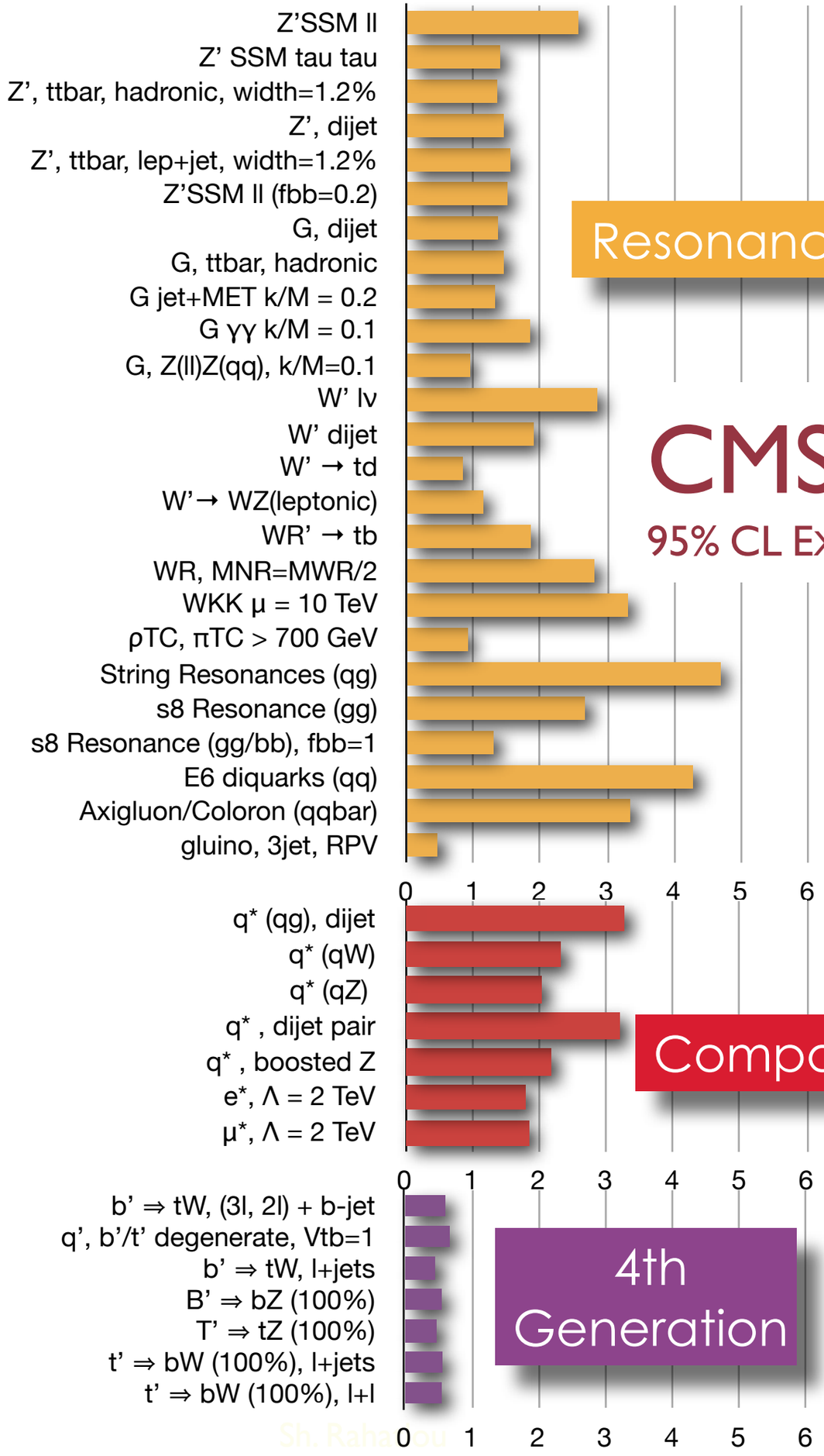


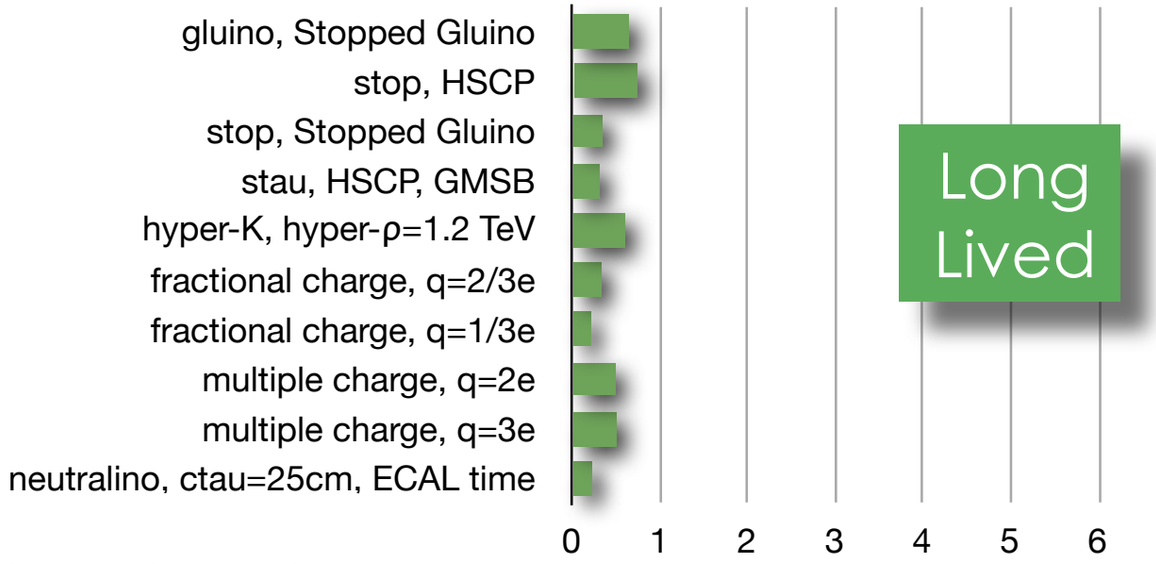


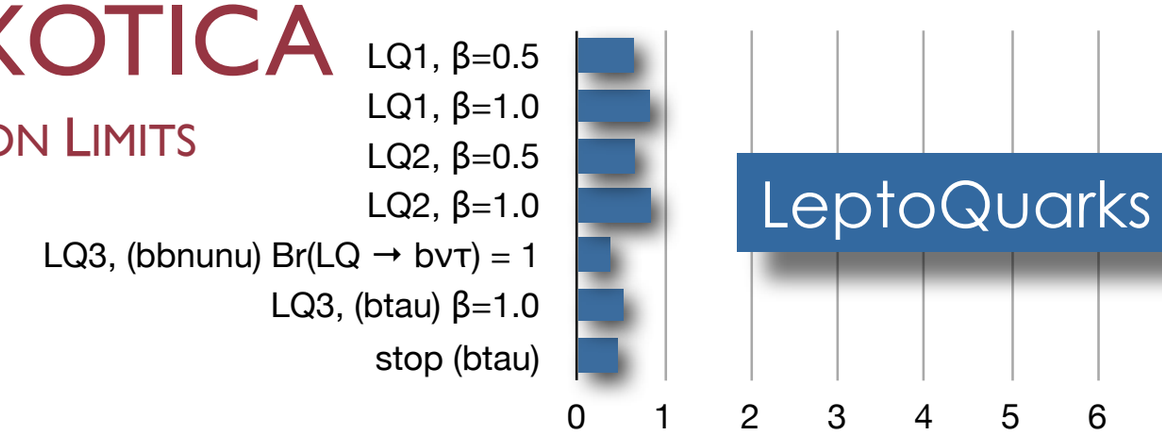
Displaced Leptons : EXO-11-101

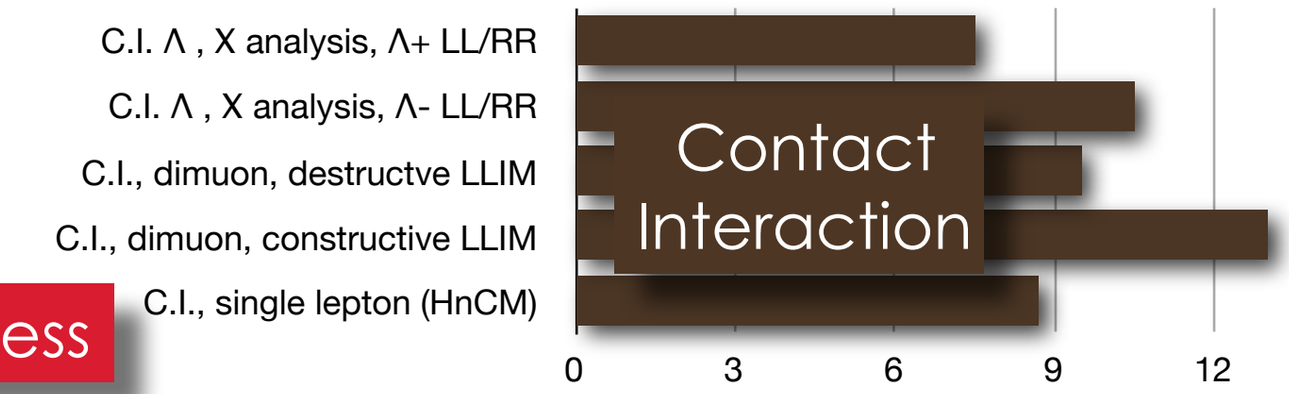
CMS EXOTICA

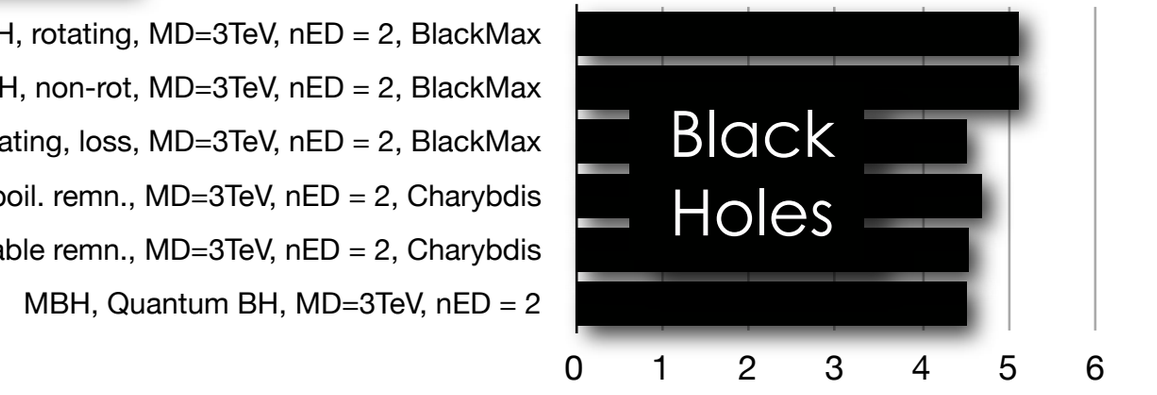
95% CL EXCLUSION LIMITS







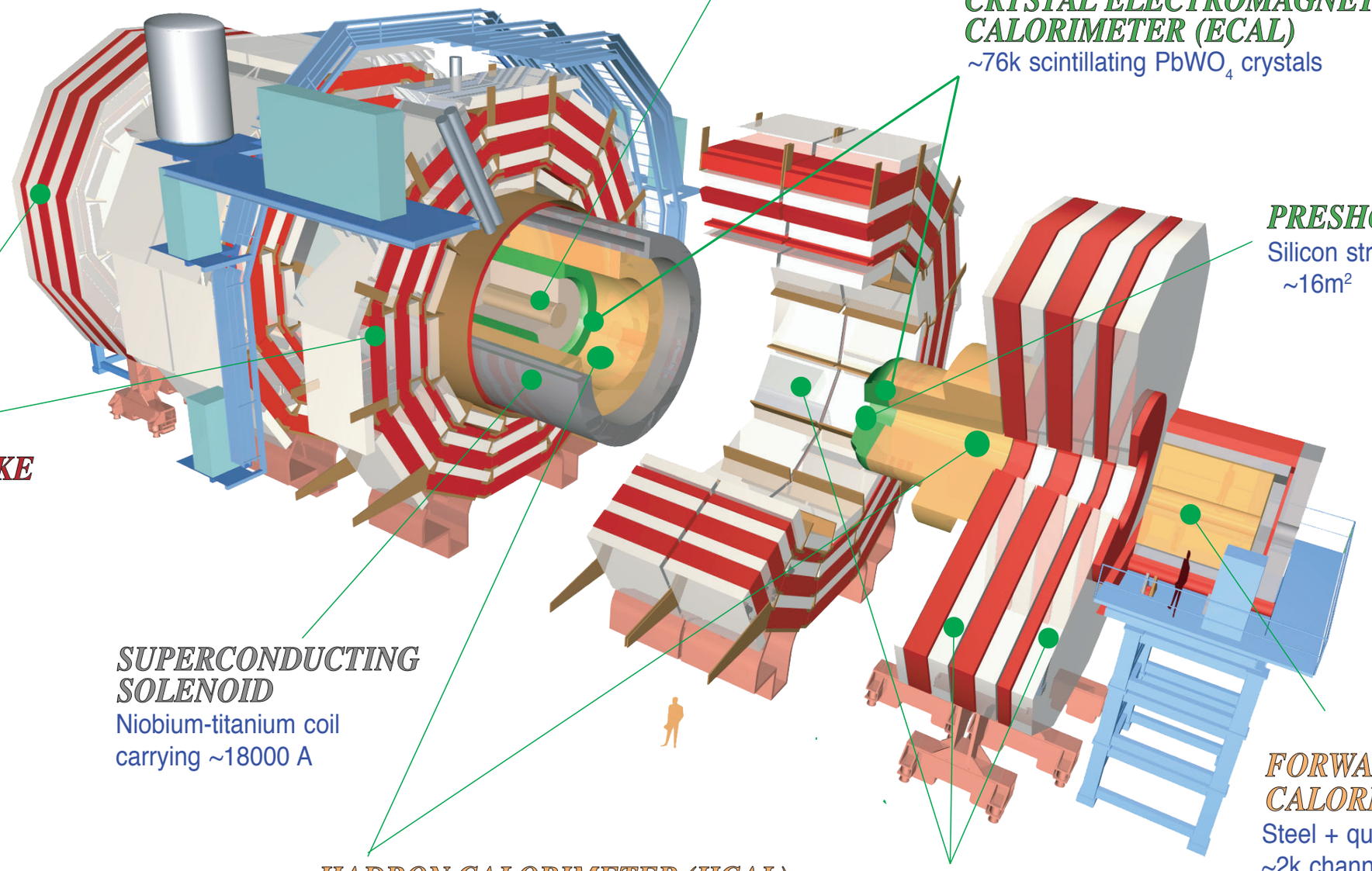




Additional Material

CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating $PbWO_4$ crystals

PRESHOWER
Silicon strips
~16m² ~137k channels

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

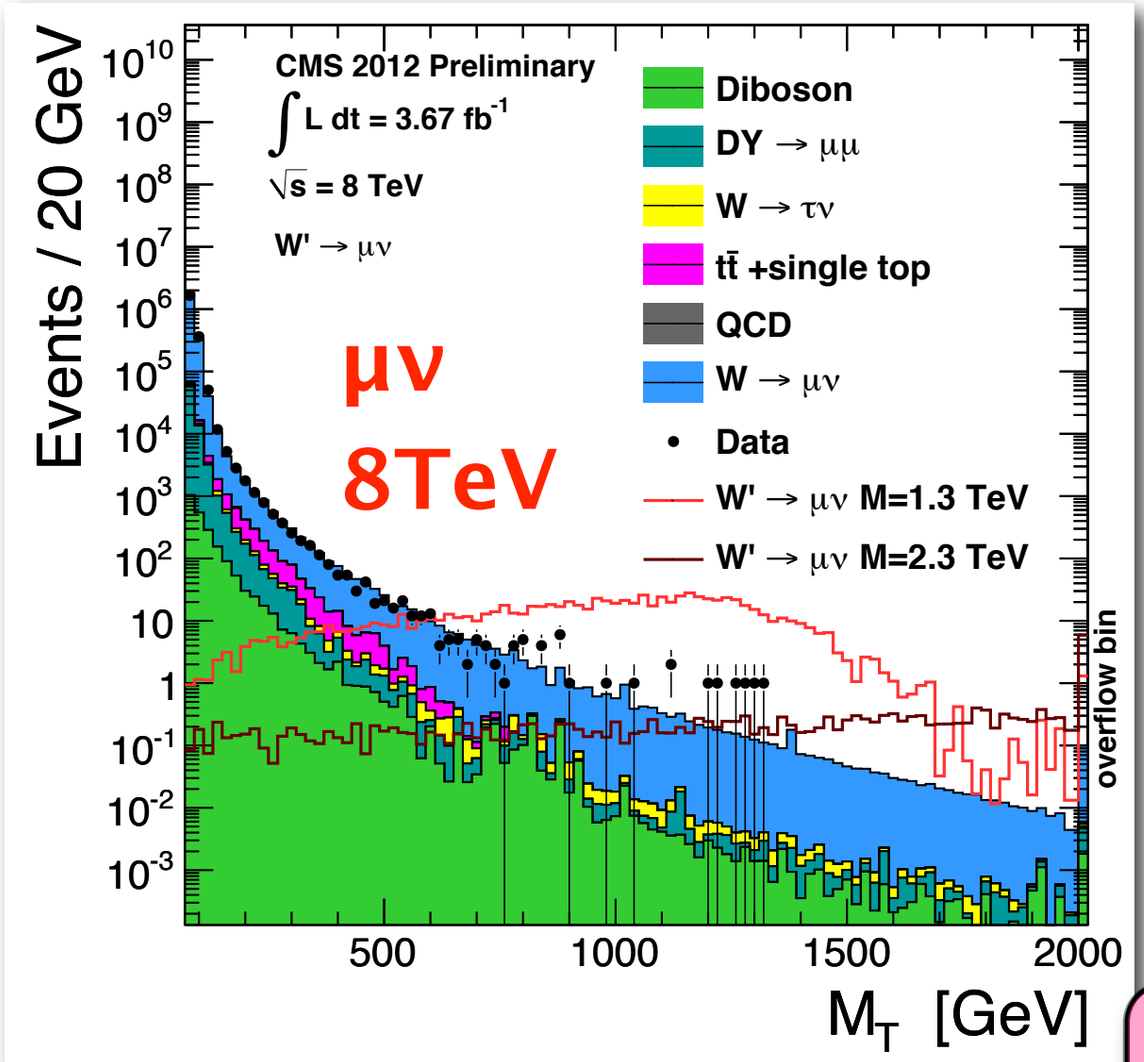
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

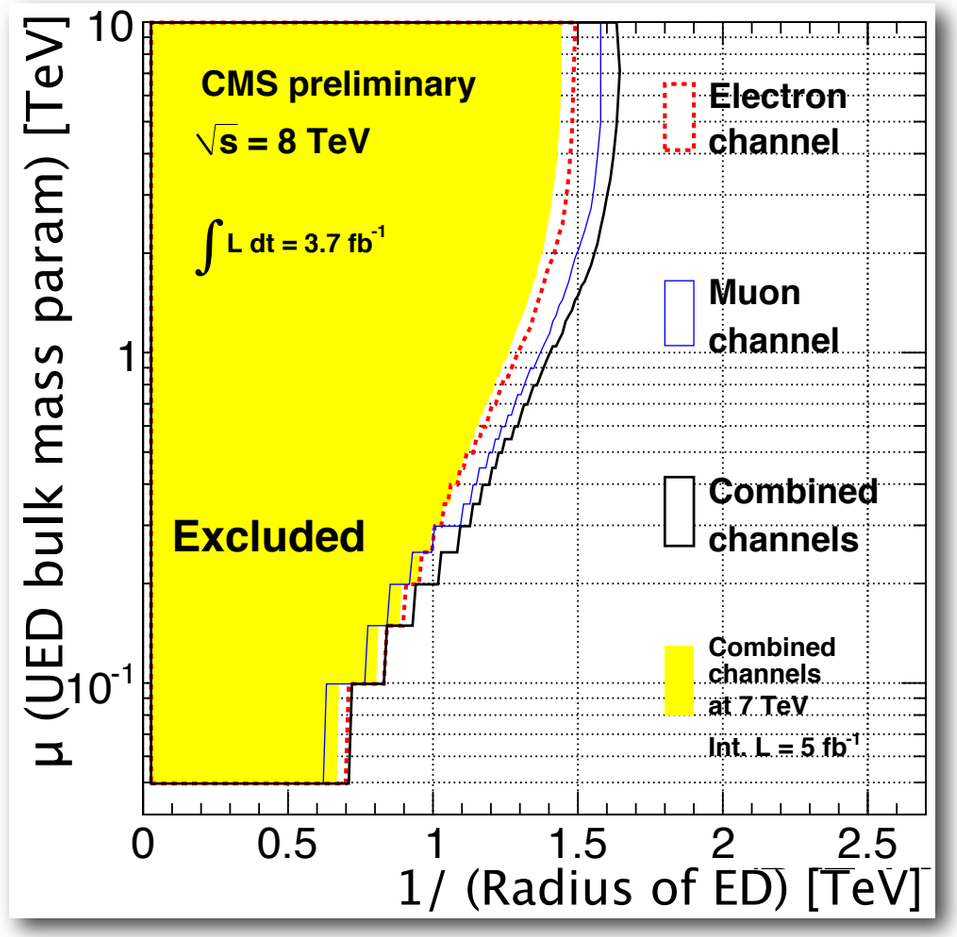
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

$W' \to \ell\nu$

EXO-12-010

- Search for W'_{SSM}, W'_{KK} in split-UED, $qq\ell\nu$ contact interaction (CI).
- Background shape from MC, normalized in M_T sideband. Crosscheck with extrapolation of fit to M_T sideband.





$$M_T = \sqrt{2p_{\mathrm{T}}^{l}\not{E}_{\mathrm{T}}(1-\cos\Delta\phi_{l,\nu})}$$

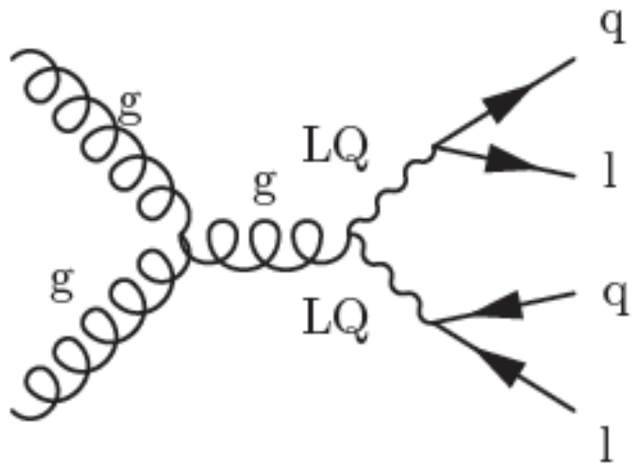
$M(W'_{SSM}) > 2.85$ TeV

$M(W'_{KK}) > 1.4\text{–}3.3$ TeV (μ=0.05–10TeV)

$qq\ell\nu$ CI energy scale >8.7 TeV

1st/2nd Generation Leptoquarks EXO-11-027/8

- Search in μμjj, eejj, μνjj, evjj

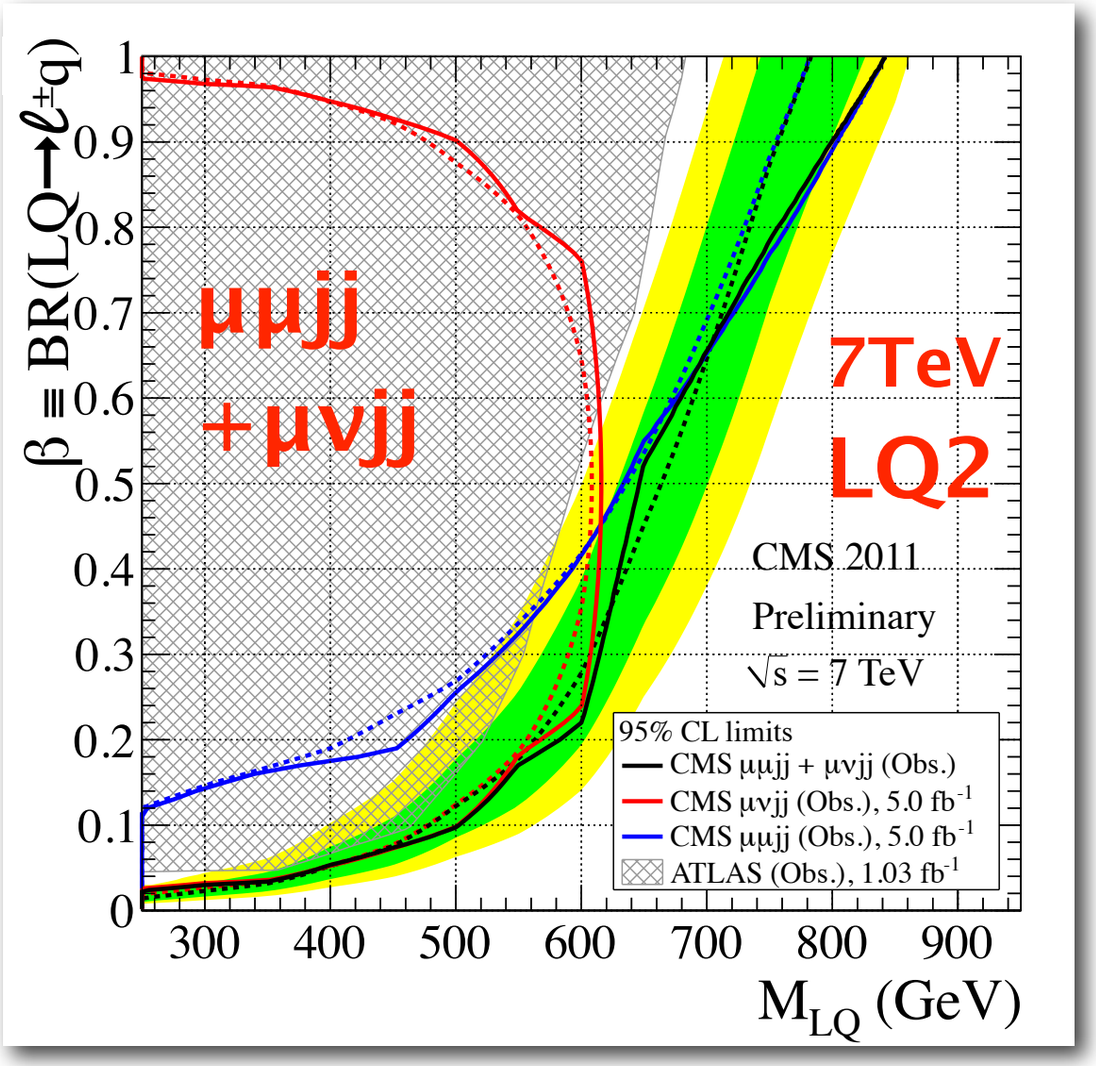


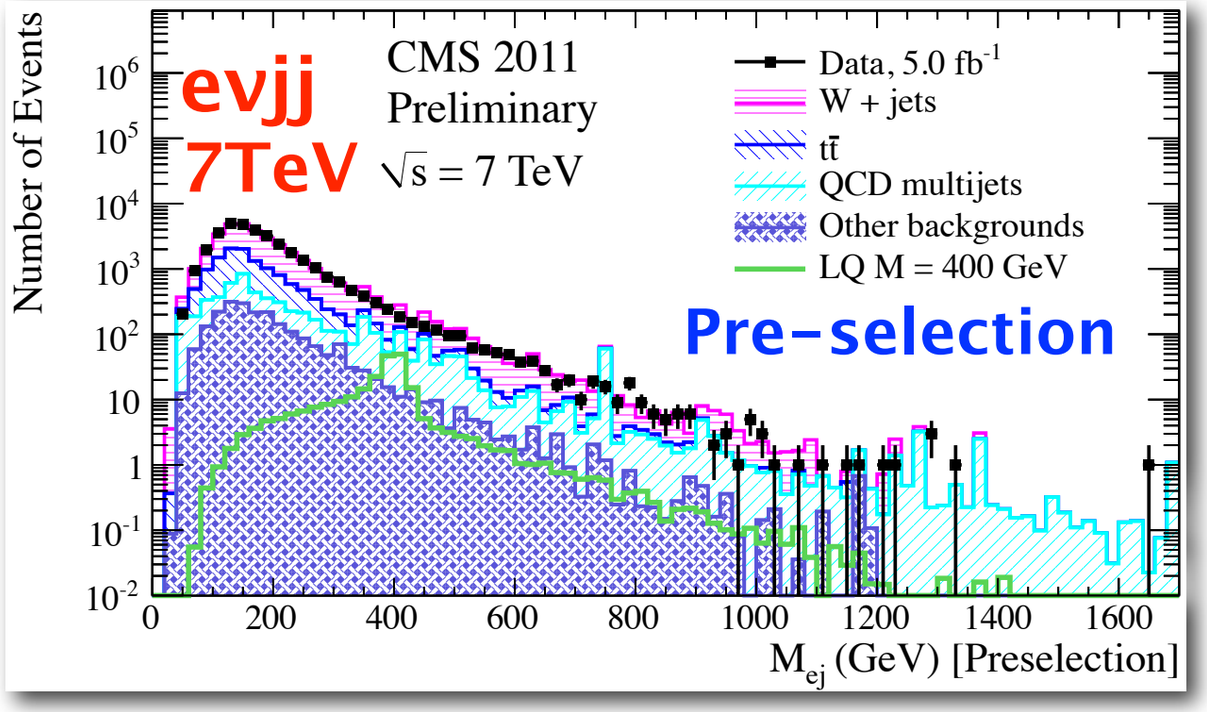
Background estimation

Z+jets: MC shape normalized in Z-peak.

top: Shape and norm from eμjj for ℓℓjj

W+jets, top (for ℓνjj): MC shape normalized in M_T(ℓ,MET) sideband.





$M_{LQ1} > 830\ (640)$ GeV for $\beta = 1.0\ (0.5)$

$M_{LQ2} > 840\ (650)$ GeV for $\beta = 1.0\ (0.5)$