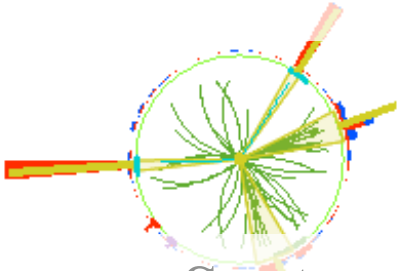
Exotica (non-SUSY) Searches at CMS



Francesco Santanastasio

on behalf of the **CMS Collaboration**

Recontres de Moriond

"EW Interactions and Unified Theories"

March 13th–20th, 2011, LaThuile, Italy

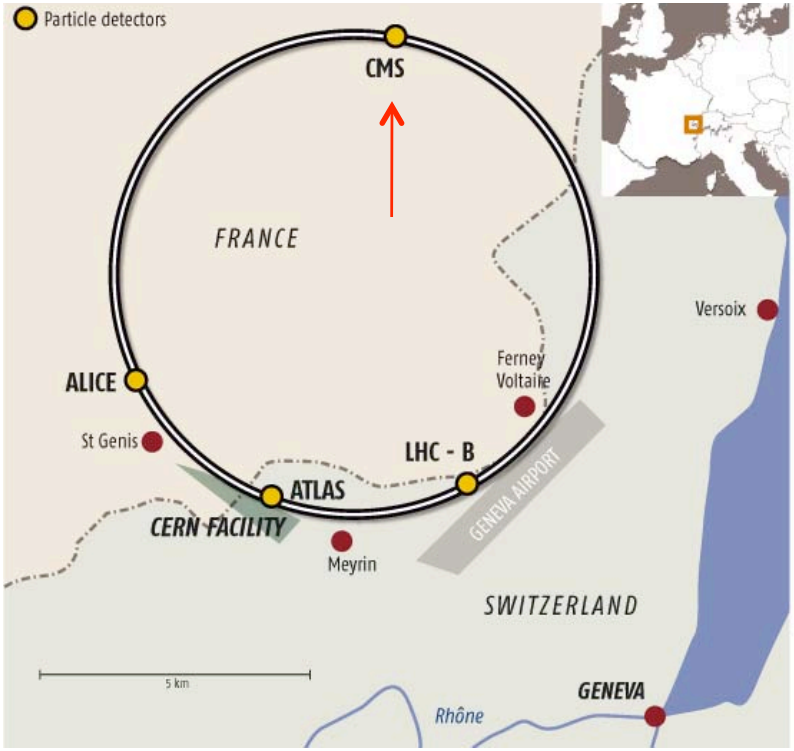
Outline

- Look for exotic signatures of New Physics
  - New Heavy Resonances
  - Quark and Lepton Compositeness
  - Extra Dimensions
  - Other Exotic Signatures
- **>20 searches** with 2010 pp data at $\sqrt{s}$ =7 TeV (LHC)
- Full dataset used in most analyses (~35 pb^{-1})
- Many results published or submitted/accepted for publication
- More focus on the new results

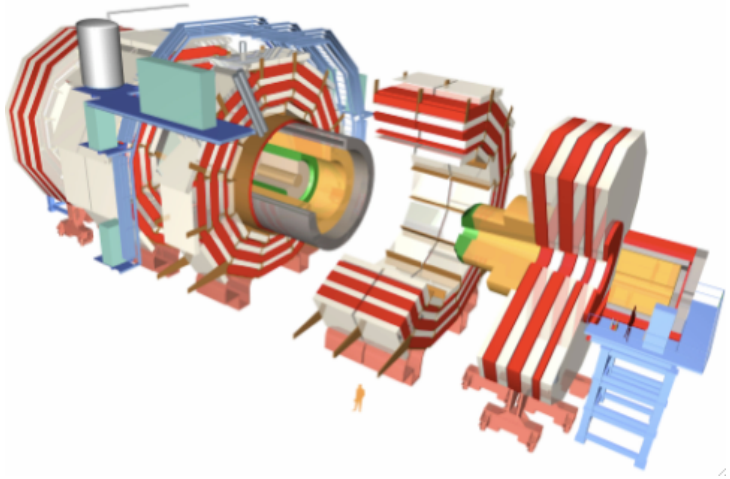
All made possible thanks to…

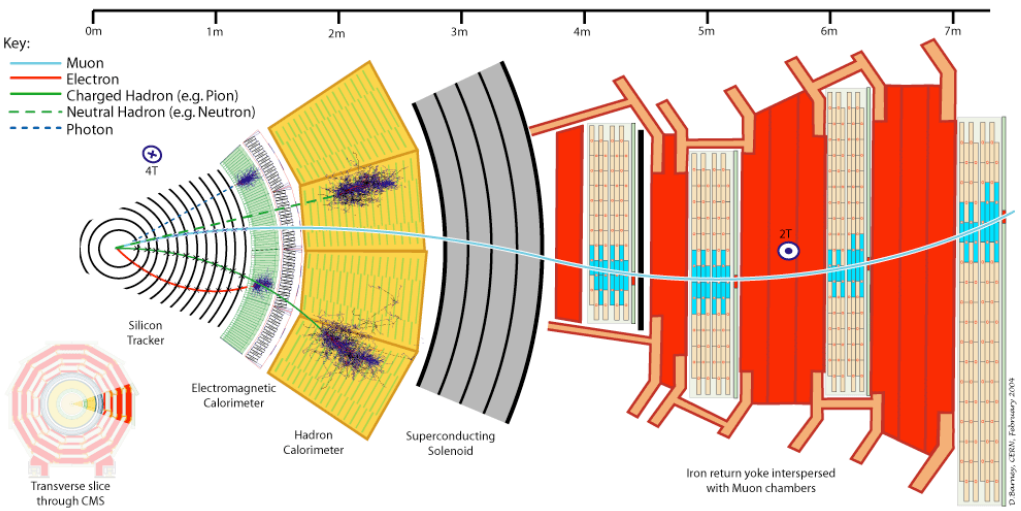
LHC

- First pp collision at 7 TeV on 30 March, 2010
- Almost 50 pb^{-1} of pp collisions delivered at sqrt(s)=7 TeV to both ATLAS and CMS experiments

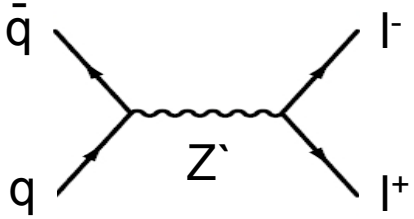


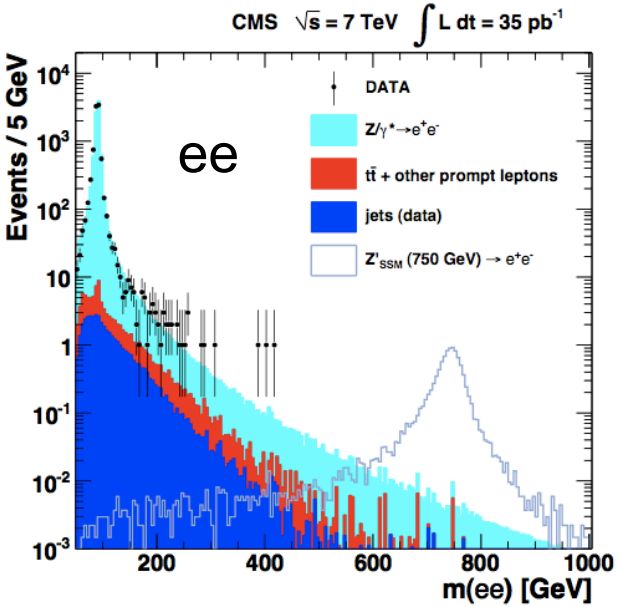
CMS Detector

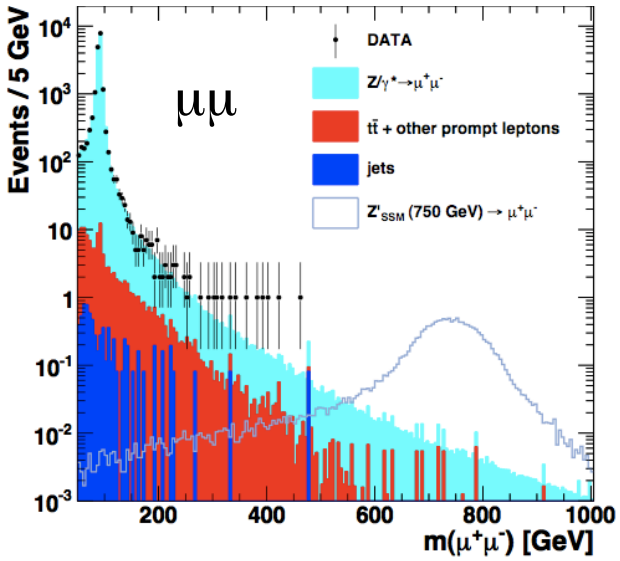




Di-Lepton Resonances







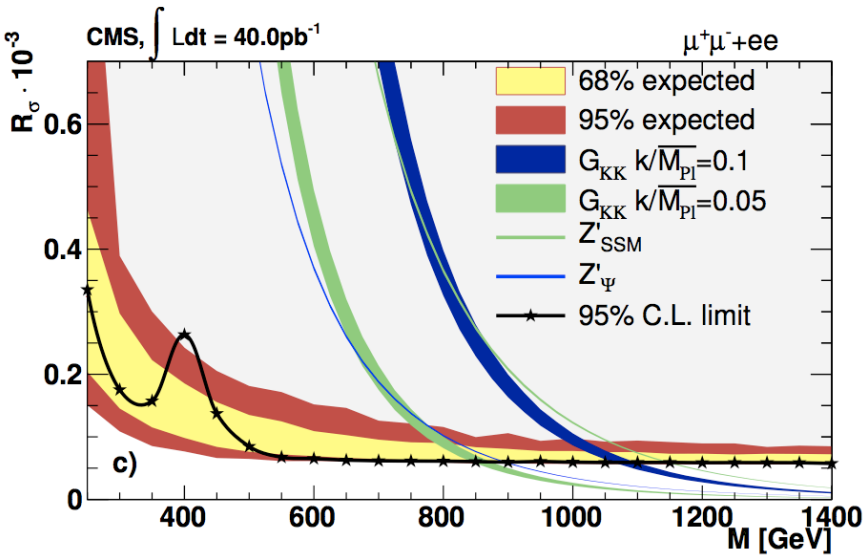
- **Bump hunt in M(ll) spectrum**
- No significant deviation from SM, set limits

arXiv:1103.0981,
Submitted to JHEP

CMS limits (35 – 40 pb^{-1})

Channel	μμ	ee	Combined
Z_{SSM}	1027 GeV	958 GeV	1140 GeV
Z_{ψ}	792 GeV	731 GeV	887 GeV
G_{KK}, k/M_{Pl} = 0.05	778 GeV	729 GeV	855 GeV
G_{KK}, k/M_{Pl} = 0.10	987 GeV	931 GeV	1079 GeV

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



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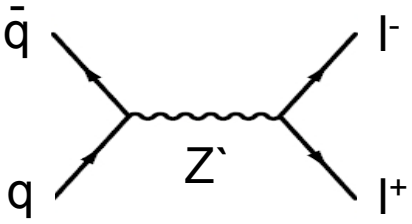

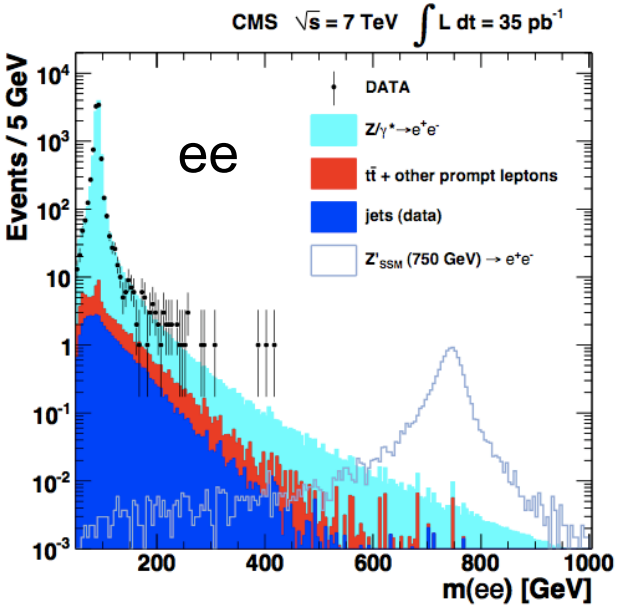

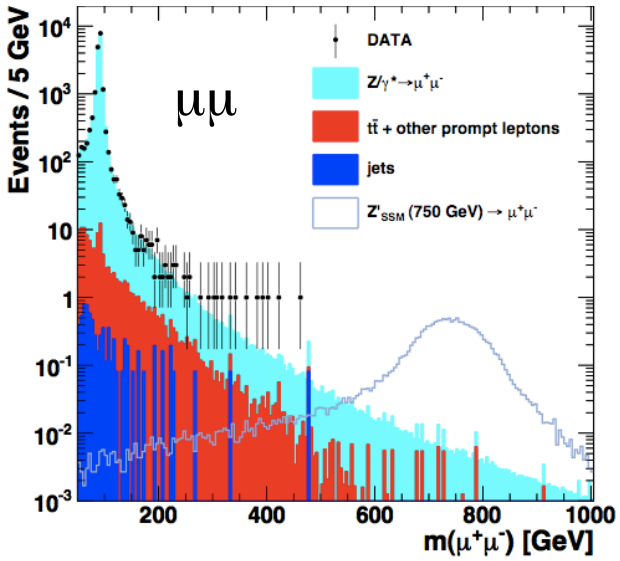

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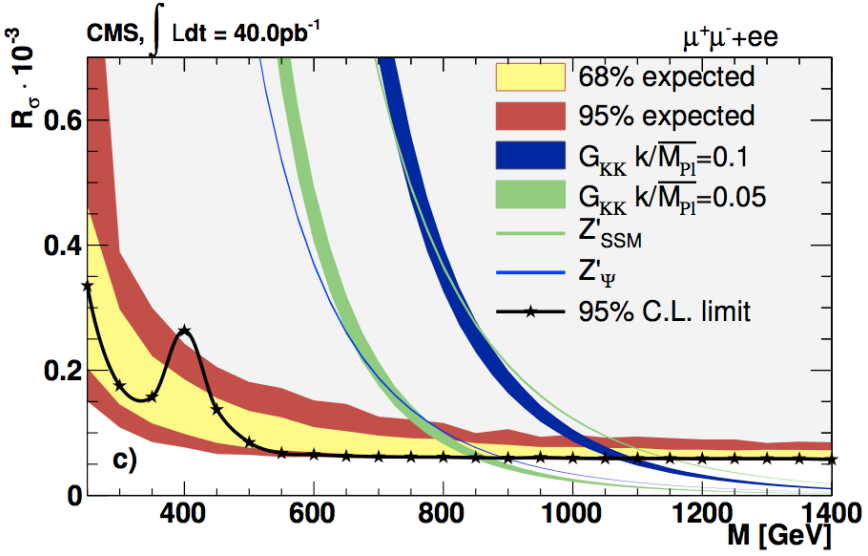

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G_{KK} → γγ channel

M_{GKK}>945 GeV
k/M_{Pl}=0.1

EXO-10-019

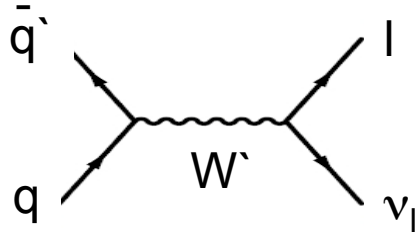
Published CDF/D0 limits

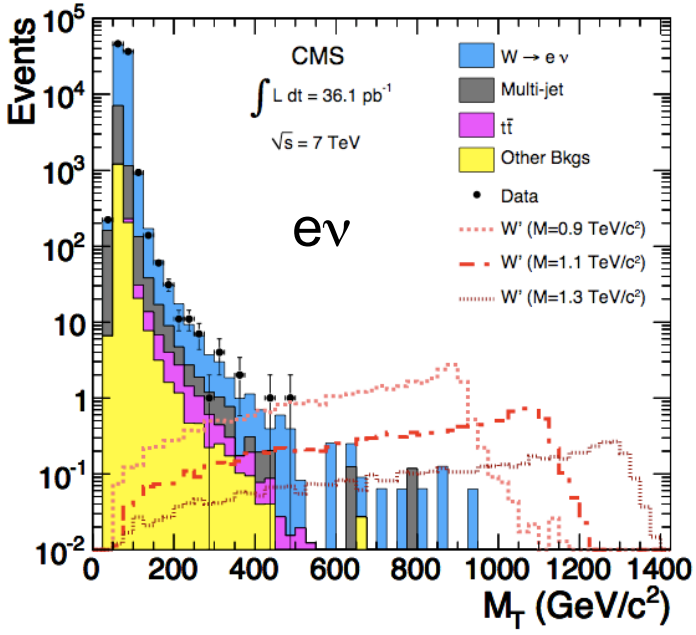
D0, ee,γγ 5.4 fb^{-1}:
$M(Z`_{SSM}) > 1023$ GeV
$M(G_{KK}^{k/M=0.1}) > 1050$ GeV

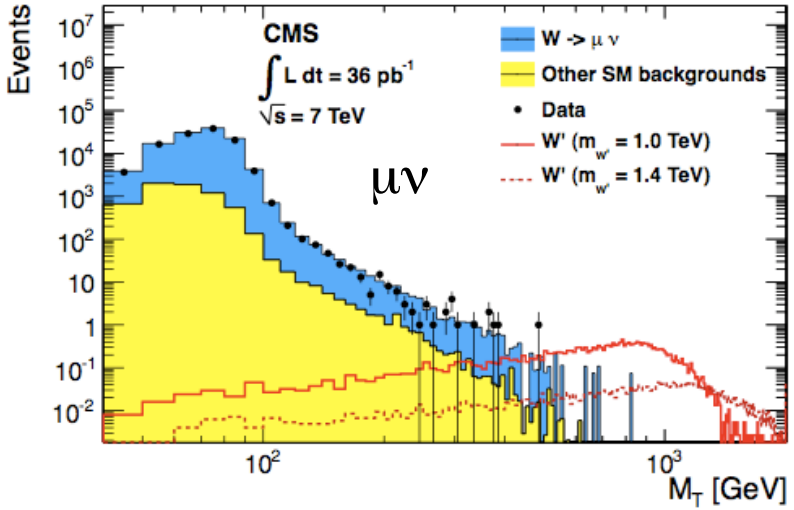
CDF, μμ, 2.3 fb^{-1}:
$M(Z`_{SSM}) > 1030$ GeV
$M(G_{KK}^{k/M=0.1}) > 921$ GeV

CDF, ee , 2.5 fb^{-1}:
$M(Z`_{SSM}) > 963$ GeV
$M(G_{KK}^{k/M=0.1}) > 848$ GeV

W` Searches







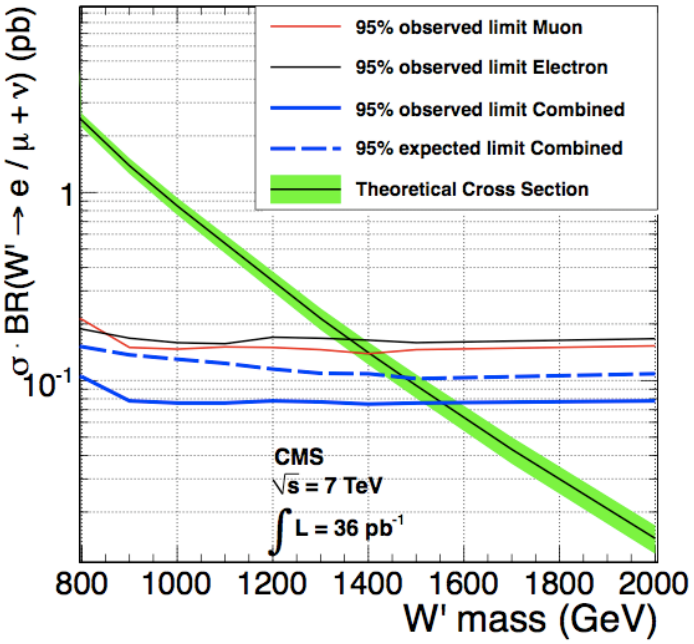
- **Bump hunt in $M_T(l\nu)$ spectrum**

$$M_T = \sqrt{2E_T^{\ell} E_T^{miss}[1 - \cos\Delta\phi(\ell, E_T^{miss})]}$$

- No significant deviation from SM, set limits

eν → arXiv:1012.5945, Accepted by PLB

μν → arXiv:1103.0030, Submitted to PLB



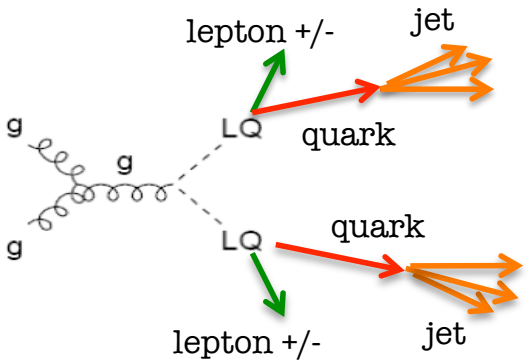
CMS limits (36 pb^{-1})

eν	1.36 TeV
μν	1.4 TeV
eν+μν	1.58 TeV

Published CDF/D0 limits
CDF, eν, 5.3 fb^{-1}:
M(W`) > 1.12 TeV
D0, eν, 1 fb^{-1}:
M(W`) > 1 TeV

Scalar Leptoquarks (1)

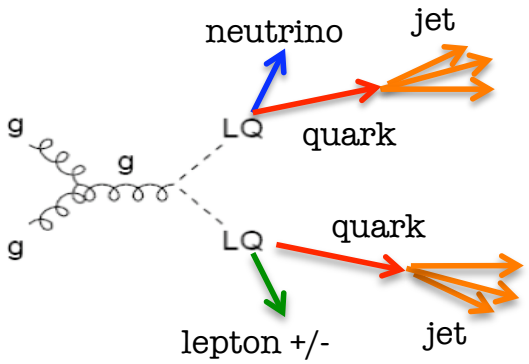
lljj channel – β^2



$$S_T = p_T^{\ell 1} + p_T^{\ell 2} + p_T^{j1} + p_T^{j2}$$

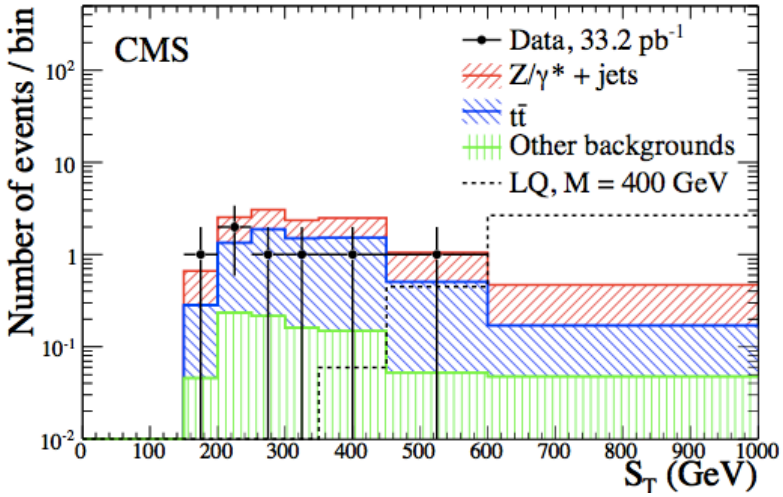
- **LQs decay to lepton and quark**
  - β=BR(LQ→lq)
  - 1-β=BR(LQ→νq)
- Search for 1st (e) and 2nd (μ) generation LQs
- No excess at high S_T

lνjj channel – $2\beta(1-\beta)$



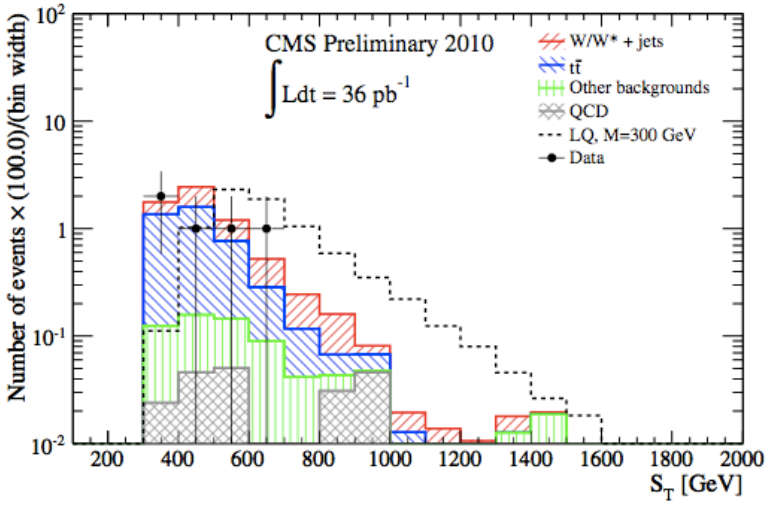
$$S_T = p_T^{\ell 1} + MET + p_T^{j1} + p_T^{j2}$$

eejj channel



First Public Presentation of this Result

eνjj channel

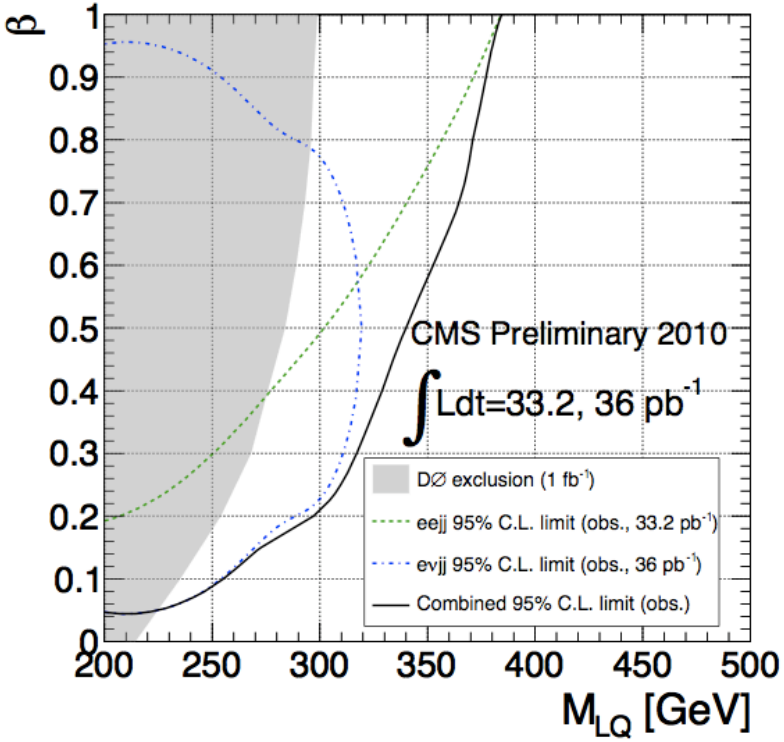


Scalar Leptoquark (2)

eejj : arXiv:1012.4031, accepted by PRL
eνjj + comb. : EXO-10-006

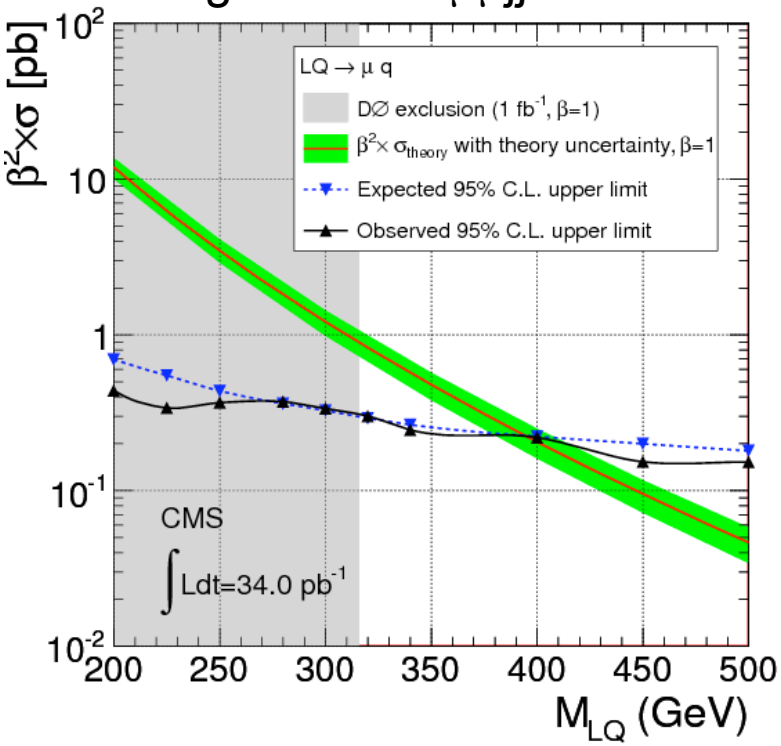
μμjj : arXiv:1012.4033, accepted by PRL
μνjj + comb. : coming soon…

1st gen LQs – eejj+eνjj channels



First Public Presentation of this Combined Result

2nd gen LQs – μμjj channel



M_{LQ}> 340, 384 GeV for β=0.5, 1

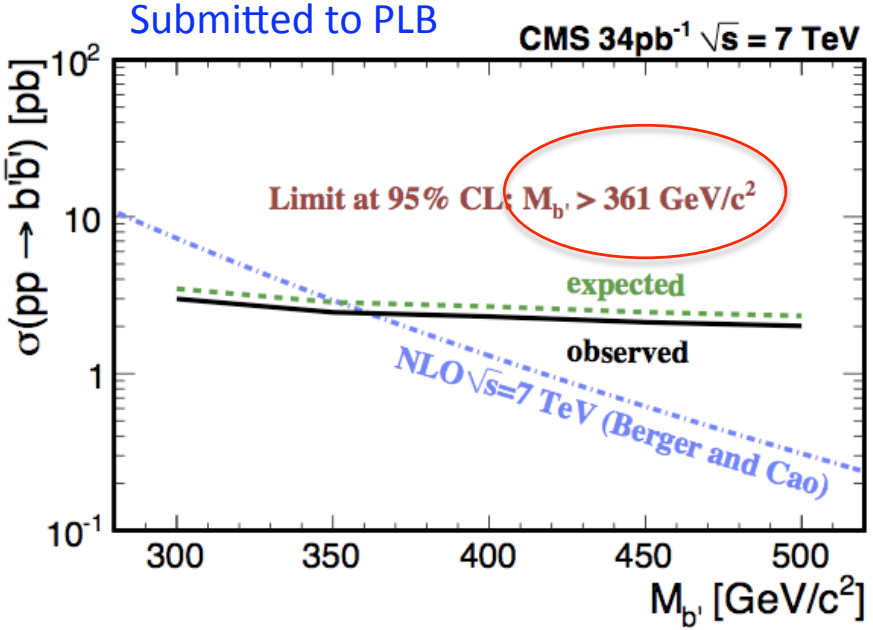
M_{LQ}> 394 GeV for β=1

Exceed Tevatron limits for almost the entire β range

b'→tW and ttbar Resonances

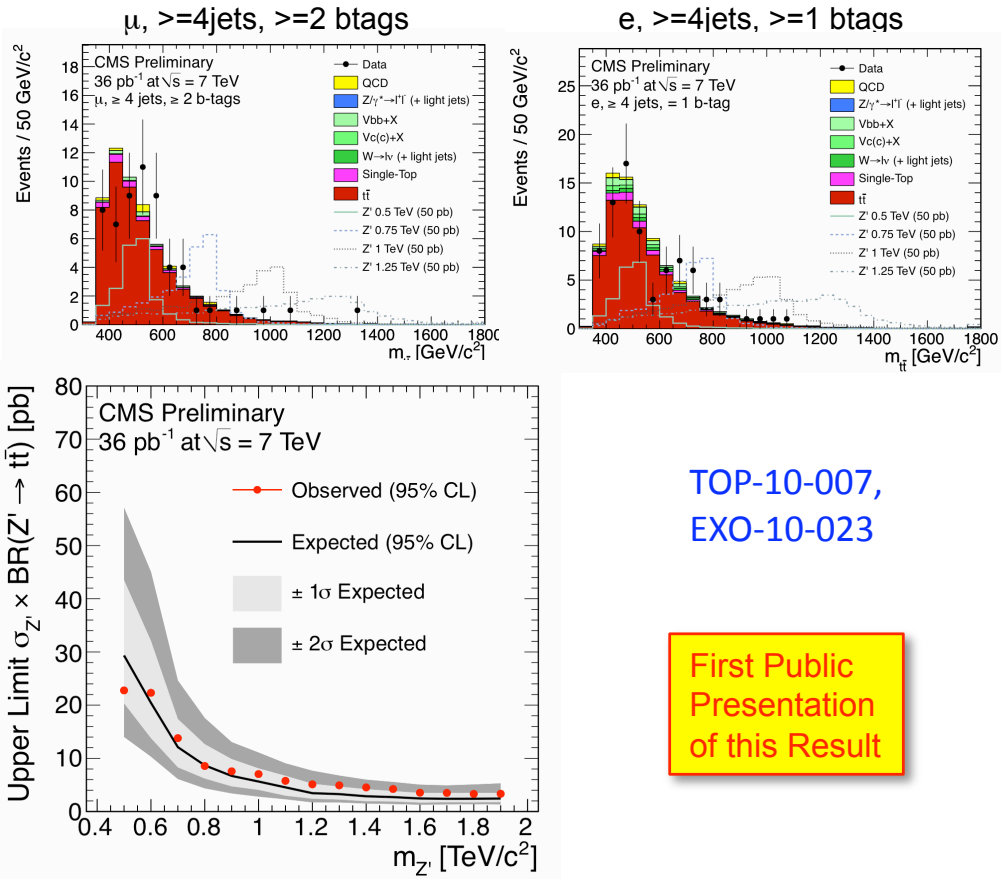
- **Pair produced b'→tW→WWb**
- Like-sign dilepton and trilepton (e,μ) decays + jets (BR=7.3%)
- $N_{background}$ = 0.3 +/- 0.2 events (tt+jets)
- 0 events observed

arXiv:1102.4746,
Submitted to PLB



Similar to a new CDF limit
of 372 GeV, arXiv:1101.5728 (4.8 fb^{-1})

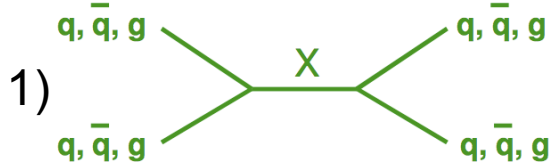
- **Bump hunt in M(ttbar) spectrum**
- Lepton+jets channels (e and μ)
- No bump seen in data
- Set limits, competitive with Tevatron

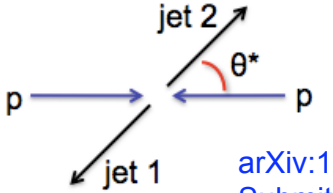


TOP-10-007,
EXO-10-023

First Public Presentation of this Result

Searches with di-jets



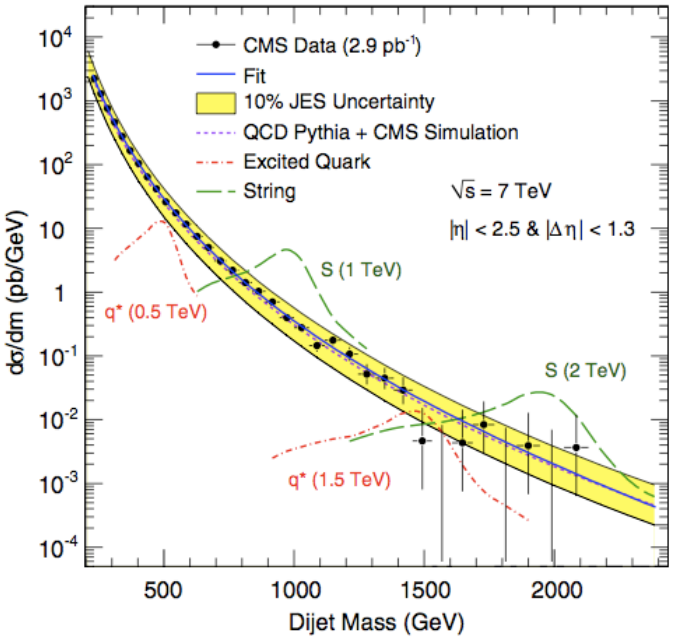


$$\chi = e^{2y^*} = \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$

1) **Di-jet mass spectrum** (→ narrow resonances)

2) **Di-jet angular distributions** (→ contact interactions)

PRL **105**, 211801 (2010)



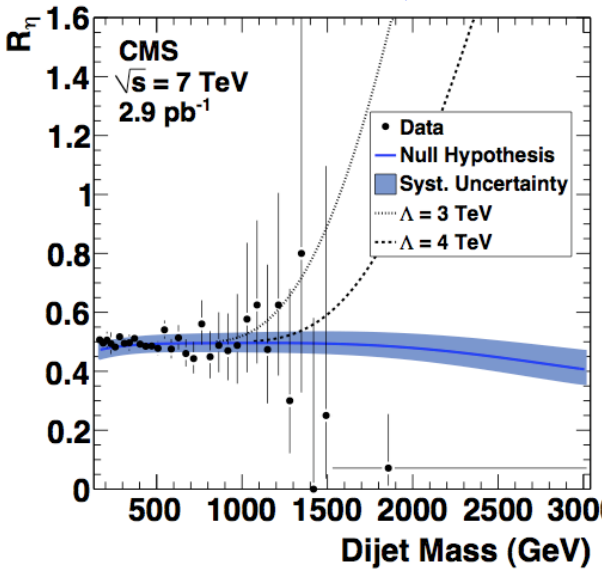
M_{String}>2.5 TeV

M_{q^*}>1.58 TeV

$M_{q^*} = \Lambda,\ f = f' = f_S = 1$

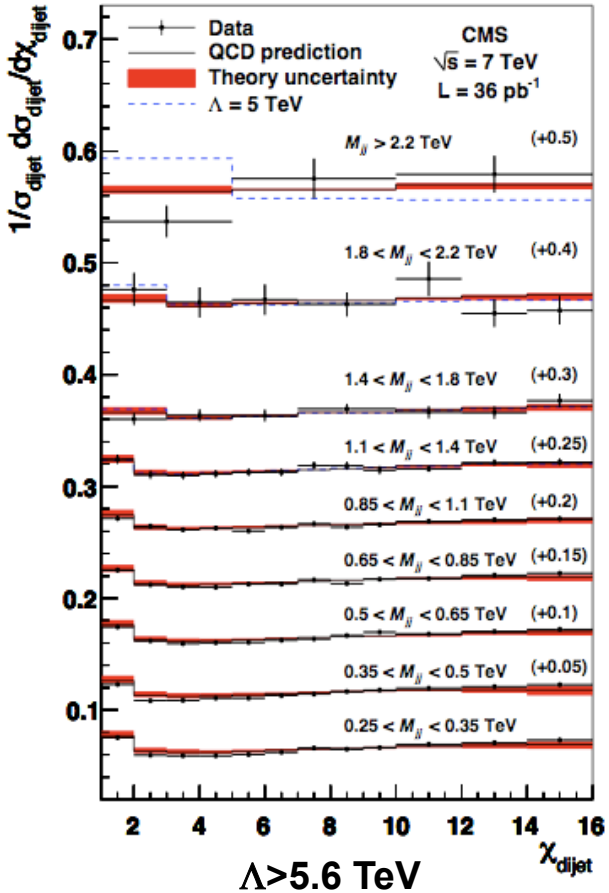
$$R_\eta \equiv \frac{N_{2j}(|\eta| < 0.7)}{N_{2j}(0.7 < |\eta| < 1.3)}$$

PRL 105:262001,2010



Λ>4 TeV
(expected Λ>2.9 TeV)

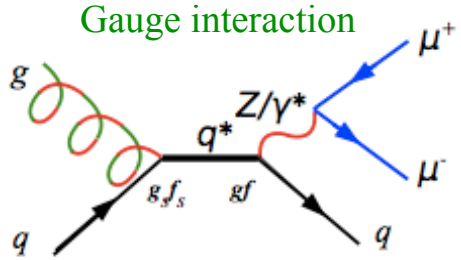
arXiv:1102.2020,
Submitted to PRL



Λ>5.6 TeV
(expected Λ>5 TeV)

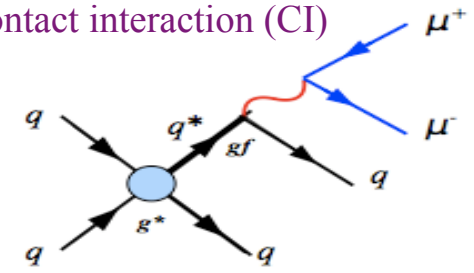
Quark Compositeness (q*→qZ)

Gauge interaction



$$\mathcal{L}_{\text{trans}} = \frac{1}{2\Lambda} f_R^* \sigma^{\mu\nu} \left(g_s f_s \frac{\lambda^a}{2} G^a_{\mu\nu} + g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right) f_L$$

Contact interaction (CI)

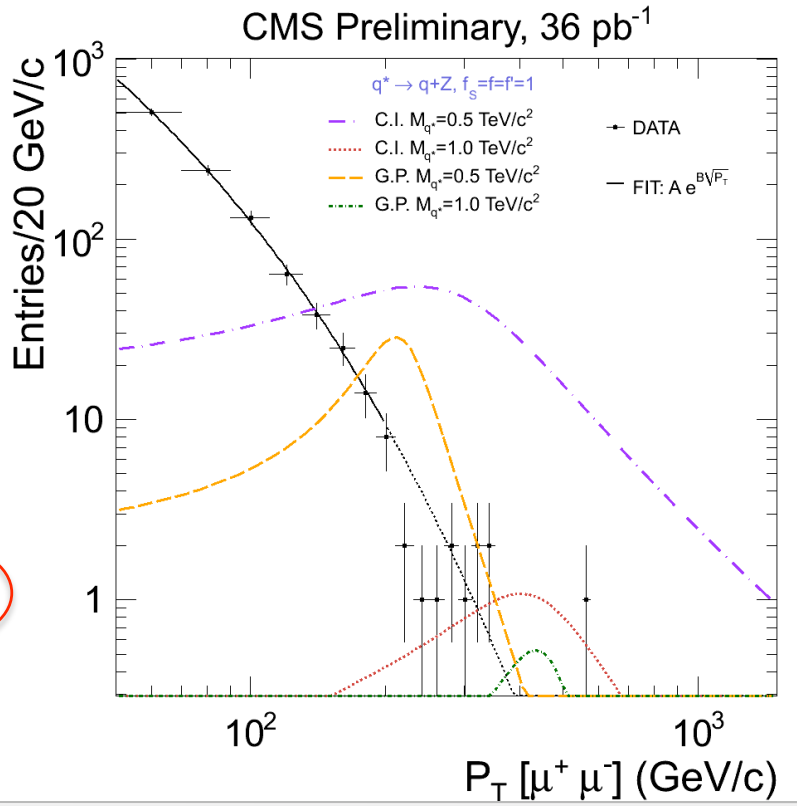


$$L_{eff} = \frac{g^2}{2\Lambda} (\bar{q}\gamma^\mu q)(\overline{q^*}\gamma_\mu q)$$

First Public Presentation of this Result

EXO-10-025

- Complementary to q*→jj decay channel
- **Search for bump/deviations in Z p_T spectrum**
- No deviation from SM prediction, set limits



Gauge Interactions

$M_{q^*} = \Lambda,\ f = f' = f_S = 1$

$M_{q^*} > 0.91$ TeV

Contact Interactions

$M_{q^*} = \Lambda,\ f = f' = 1, f_S = 0$

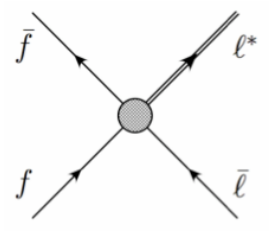
$M_{q^*} > 1.17$ TeV

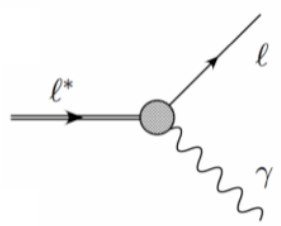
(H1 limit, 475 pb^{-1}, gauge int., f_S=0, M_{q^*}>252 GeV)

Lepton compositeness

First Public Presentation of these Results

Production via new contact interaction → Decay

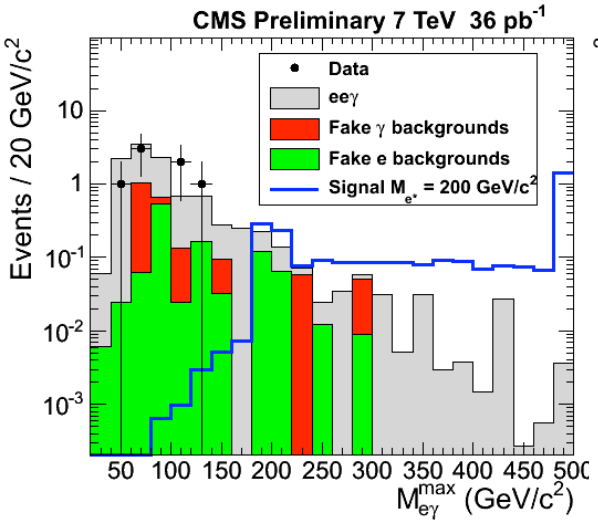


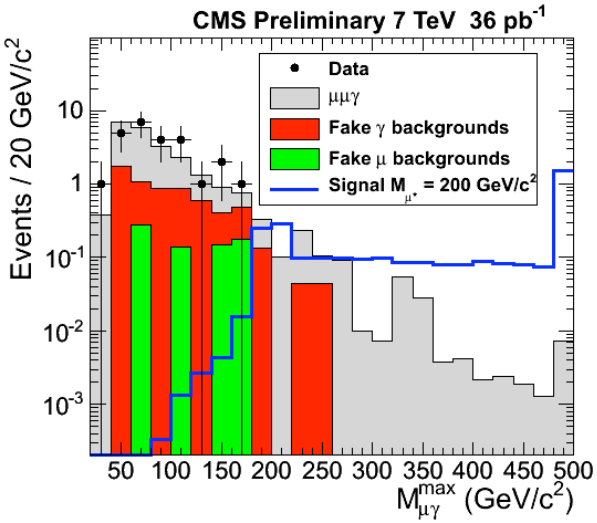


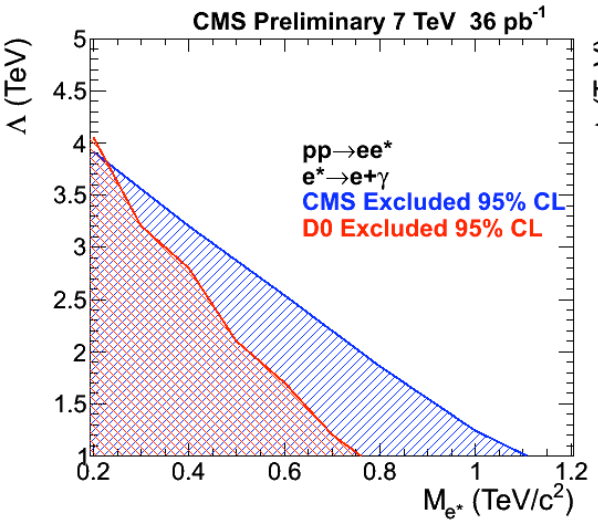
$$\mathcal{L}_{CI} = \frac{g^2}{2\Lambda^2} j^\mu j_\mu$$

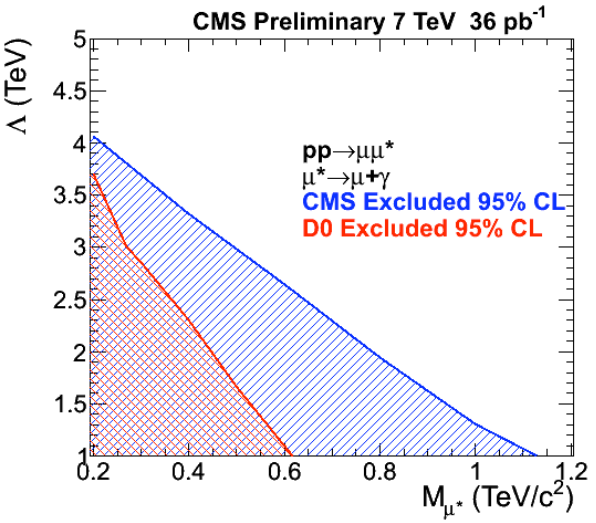
- **Search for excess in data at high M(eγ) or M(μγ)**
- Reducible backgrounds from data
  - Fake γ : Z+jets (l^+l^- + fake γ)
  - Fake l : Wγ+jets (l + fake l + γ)
- 0 events observed at high M(lγ)
- Set limits, exceed Tevatron

qq→ee*→eeγ EXO-10-016 qq→μμ*→μμγ

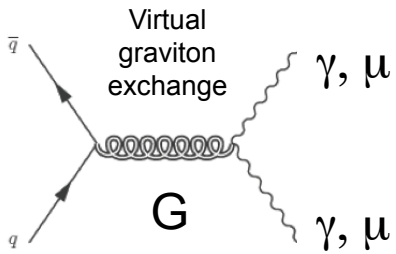




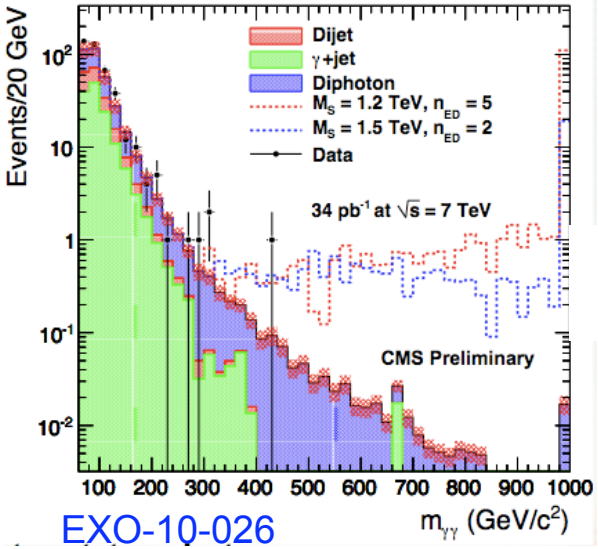




Large Extra Dimensions ($\gamma\gamma$ and $\mu\mu$)



Theory Parameters:
M_S = UV cutoff in σ
n = number of ED



EXO-10-026

- **Look for excess at high mass in $\gamma\gamma$ or $\mu\mu$ spectrum**
- No event observed with $M_{\gamma\gamma}$ ($M_{\mu\mu}$) >500 (600) GeV
- Set lower limits on M_S (TeV) vs n

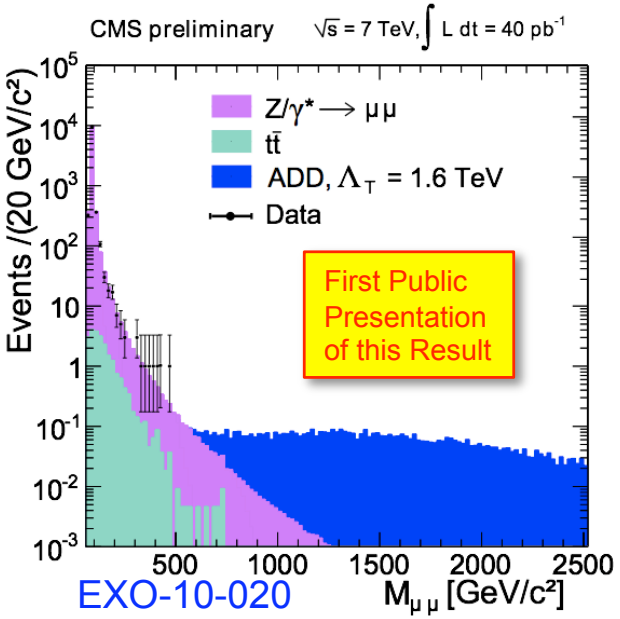
$\gamma\gamma$

	GRW	Hewett		HLZ					
		Pos.	Neg.	$n_{ED}=2$	$n_{ED}=3$	$n_{ED}=4$	$n_{ED}=5$	$n_{ED}=6$	$n_{ED}=7$
Full	1.94	1.74	1.71	1.89	2.31	1.94	1.76	1.63	1.55
Trunc.	1.84	1.60	1.50	1.80	2.23	1.84	1.63	1.46	1.31

$\mu\mu$

	Λ_T [TeV] (GRW)	M_s [TeV/c^2] (HLZ)					
		$n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
Full	1.80	1.75	2.15	1.80	1.63	1.52	1.43
Truncated	1.68	1.67	2.09	1.68	1.49	1.34	1.24

Extend Tevatron limits in all but the n_{ED}=2 case



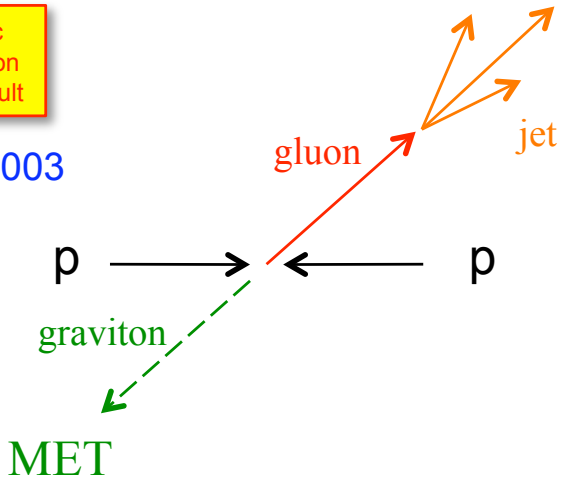
EXO-10-020

Large Extra Dimensions (mono-jet + MET)

- **One high p_T jet + large MET + no leptons**
- Suppress cosmic/beam halo/instrumental backgrounds
- Data-driven estimate for Z→νν + jets background
- Data consistent with SM, set limits on M_D vs δ

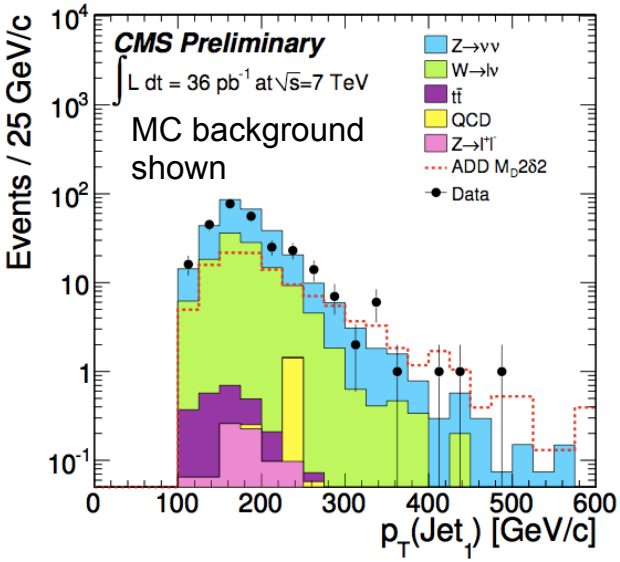
First Public Presentation of this Result

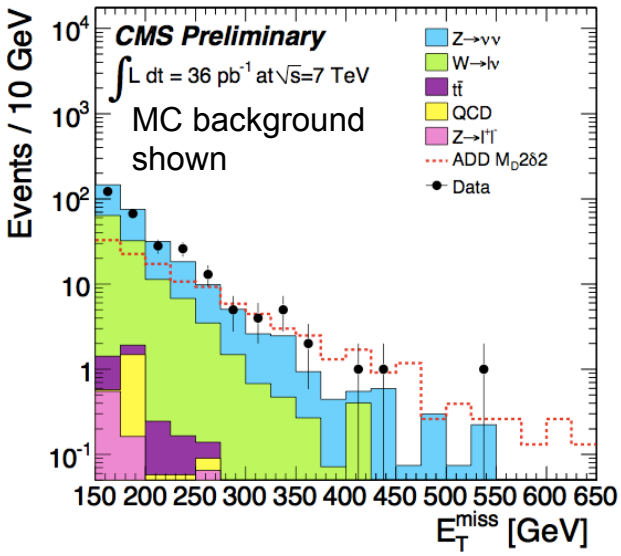
EXO-11-003



N_{DATA}	275
N_{BKG} (data-driven)	297 +/- 45
$N_{SIGNAL}(M_D=2,\delta=2)$	115.2

M_D= "True" Planck scale
δ = number of extra dimensions





CMS limits on M_D (36 pb^{-1})

δ	With K-Factor**	No K-Factor
2	2.37 TeV	2.16 TeV
3	1.98 TeV	1.83 TeV
4	1.77 TeV	1.67 TeV

** = 1.5 (1.4) for δ=2,3 (4)

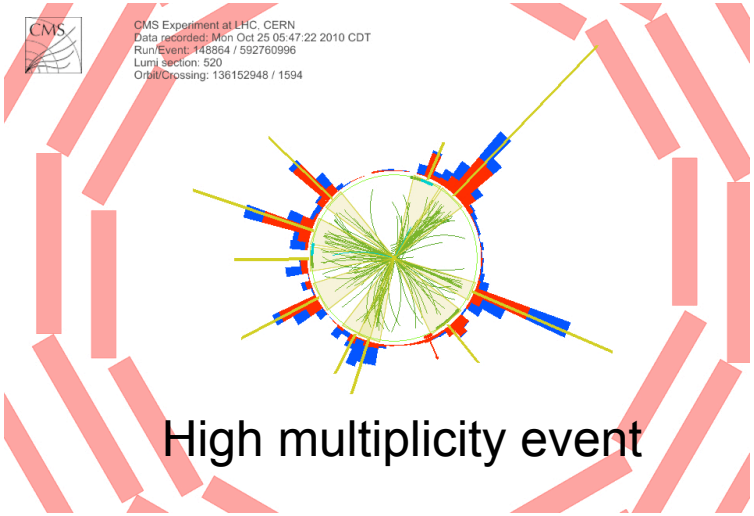
δ	CDF	LEP
2	1.4 TeV	1.6 TeV
3	1.15 TeV	1.2 TeV
4	1.04 TeV	0.94 TeV

Searches for Black Holes

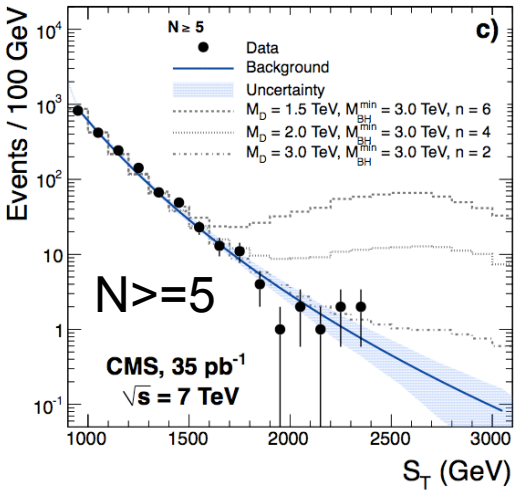
- Smoking gun signature of TeV scale gravity
- Democratic BH decay via Hawking radiation to all SM degrees of freedom (mostly quarks and gluons)
- **Search for deviation in S_T distribution in bins of "object multiplicity" (N)**

$$S_T = \sum_N E_T \quad \text{for jets,e,}\gamma\text{,}\mu \text{ with } E_T\text{>50 GeV} + \text{MET}$$

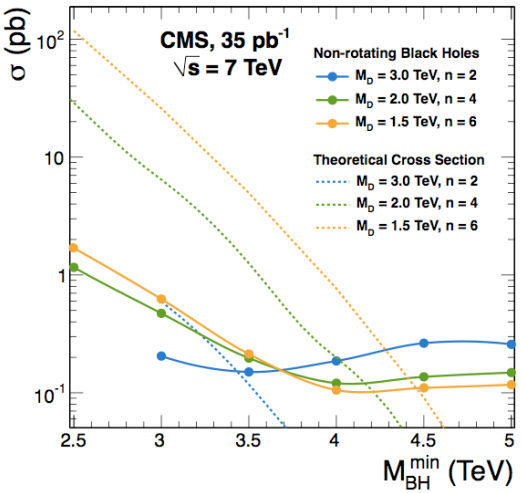
- Use S_T spectrum from N=2 to predict N>=3,4,5, where signal would be present
- No excess observed, set limits (semi -classical approximation)



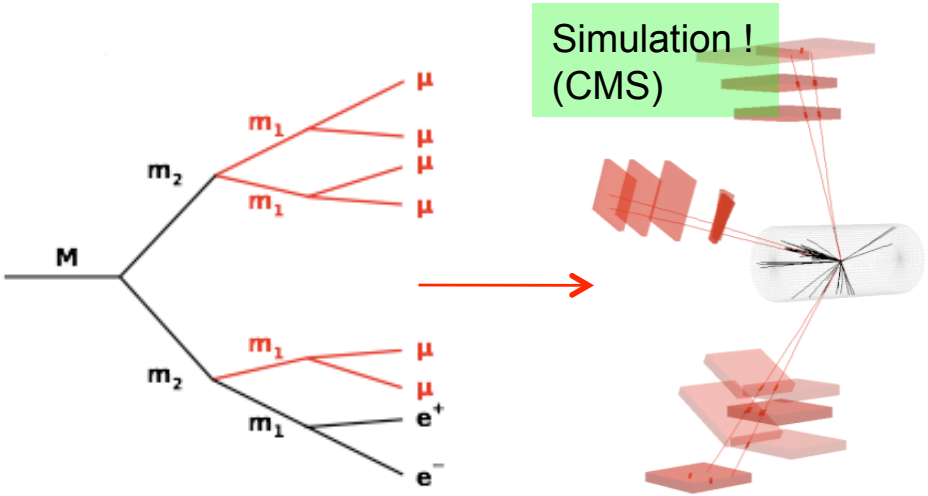
PLB **697**:434-453 (2011)



$M_{BH}^{min} > 3.5 - 4.5$ TeV

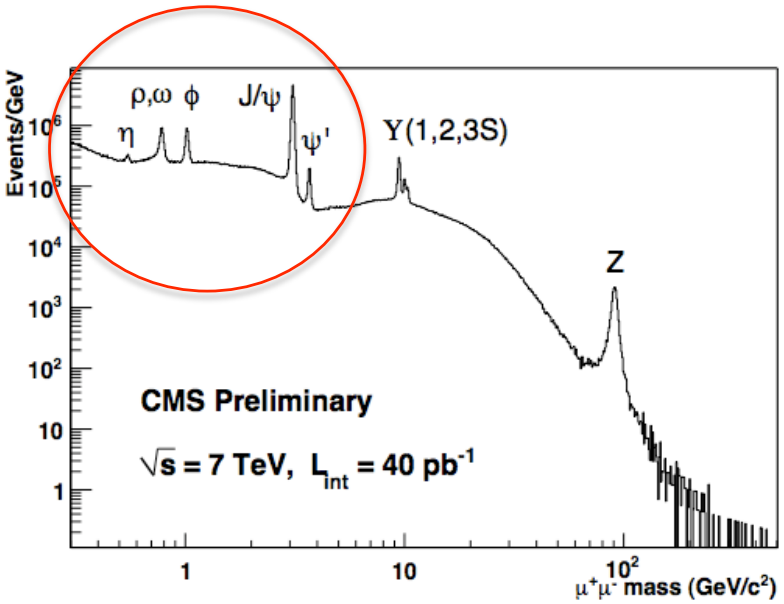


Lepton jets (Hidden Valley)

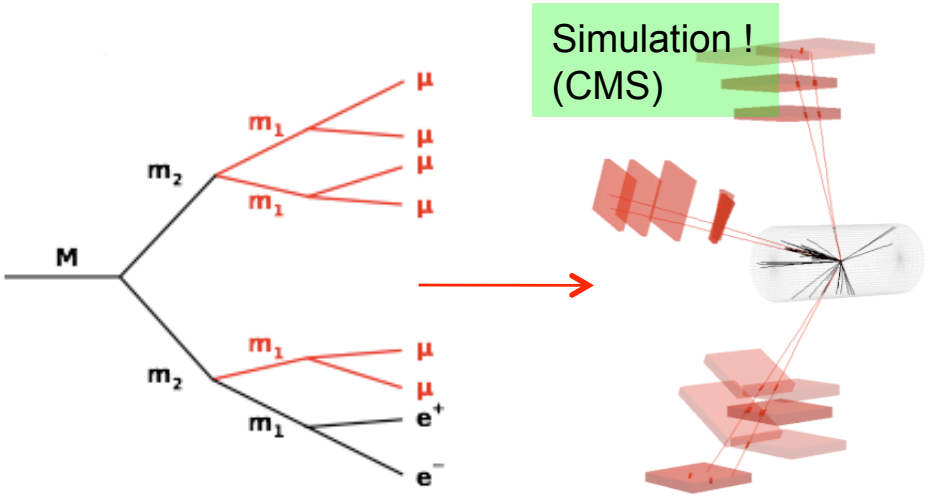


- Hidden sector contains a new low mass particle (m_1 ~ few GeV)
- It decays into SM pairs (i.e. μμ)
- **Collimated groups of di-muons [μμ]**
  - opposite charge, $m_{\mu\mu}$<9 GeV, consistent vertex
- Search for new μμ resonances in various event topologies: [μμ], [μμ][μμ], etc.

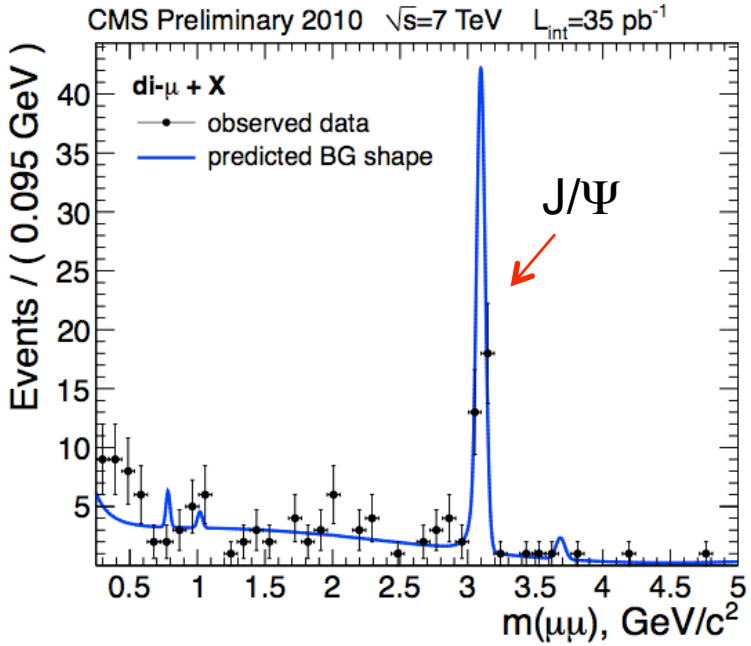
- These are the backgrounds
- M(μμ) background shape from control sample of data at low P_T
- Then look at high P_T …



Lepton jets (Hidden Valley)

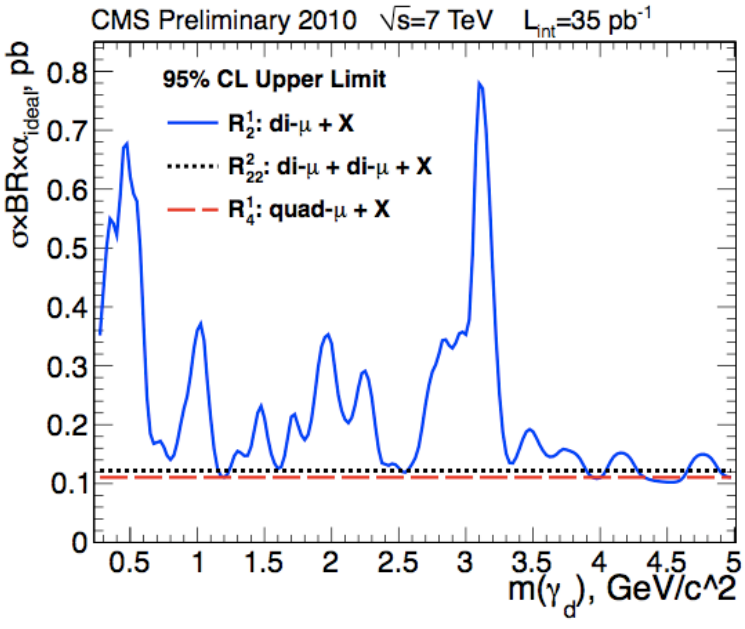


- **No new μμ resonance seen**
- Set model independent upper limits on σ x BR x α (~0.1−0.5 pb)
- Verified sensitivity in various benchmark models (ex. NMSSM Higgs, MSSM + γ_{DARK})



First Public Presentation of this Result

EXO-11-013



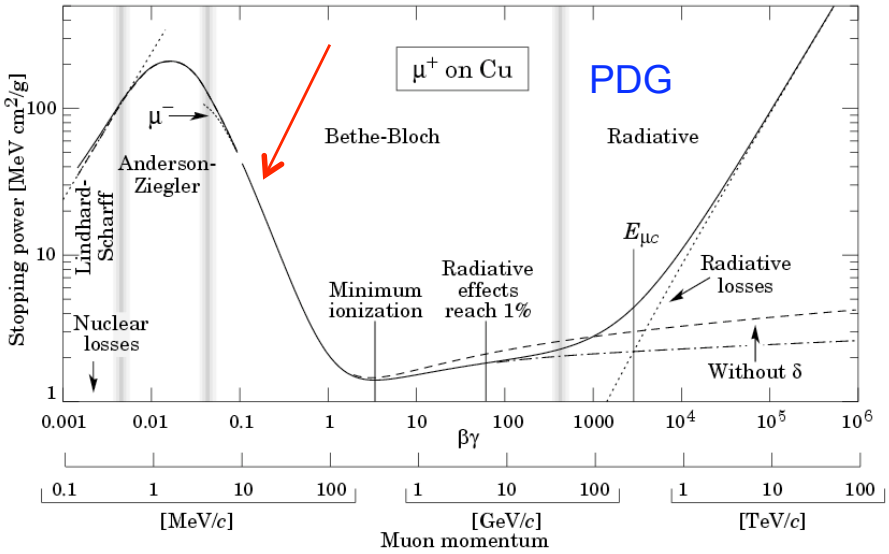
Massive Long-lived Particles (1)

- Benchmark model: "split SUSY"
- Gluinos hadronize forming R-Hadrons
  - bound state of SUSY particle + quarks/gluons

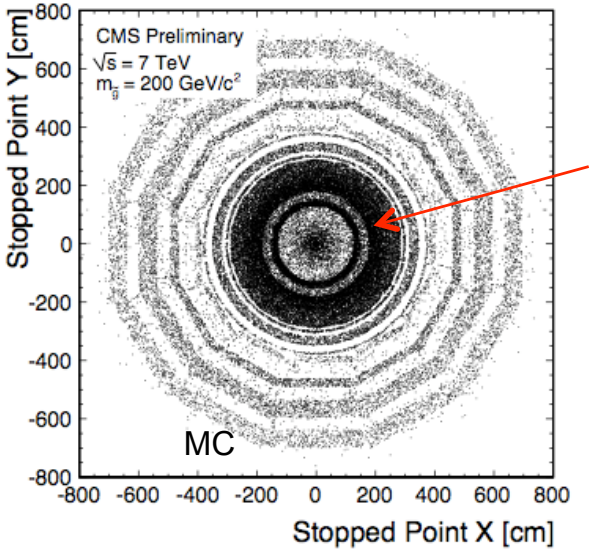
→ Since massive they have **low velocity**

$$\beta\gamma = \frac{p}{m}$$

1) Massive charged particles with large dE/dX in silicon tracker



2) Stopped particles stopped in the detector due to energy loss, decaying out-of-time w.r.t. to collisions



HCAL (hadronic calorimeter of CMS)

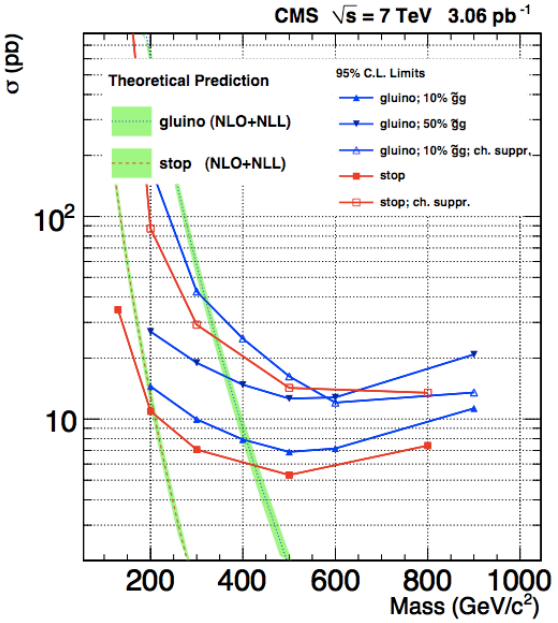
Massive Long-lived Particles (2)

- Benchmark model: "split SUSY"
- Gluinos hadronize forming R-Hadrons
  - bound state of SUSY particle + quarks/gluons

→ Since massive they have **low velocity**

$$\beta\gamma = \frac{p}{m}$$

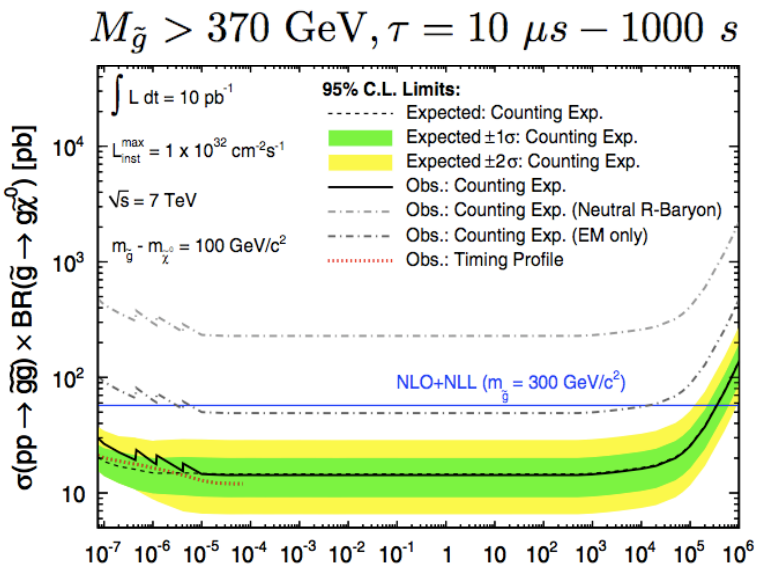
1) Massive charged particles with large dE/dX in silicon tracker



arXiv:1101.1645, submitted to JHEP

M_{gluino}>311-398 GeV

2) Stopped particles stopped in the detector due to energy loss, decaying out-of-time w.r.t. to collisions



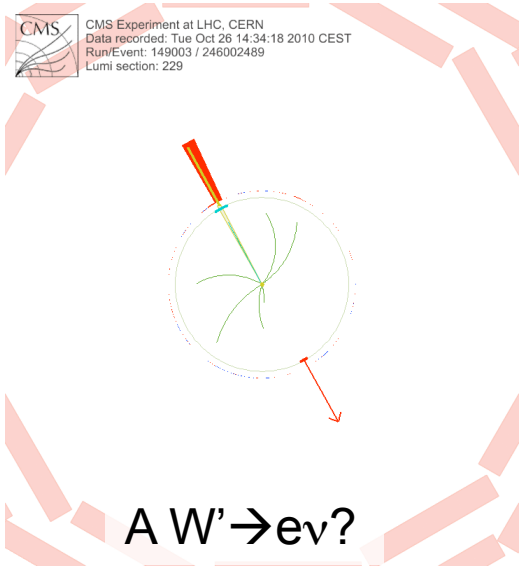
PRL **106**, 011801 (2011)

Summary

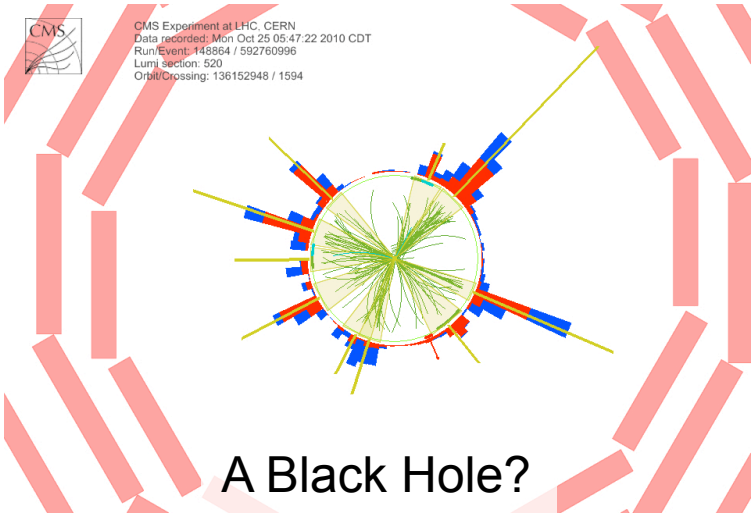
- **>20 searches** for various new physics phenomena
- **No significant excess found in data**
- In many cases, we exceed the limits previously set by Tevatron experiments
- Good understanding of the detector and backgrounds in a variety of channels
  - data-driven background estimation in most cases
- Fundamental component of **successful searches with much larger dataset expected in 2011 and beyond…**

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

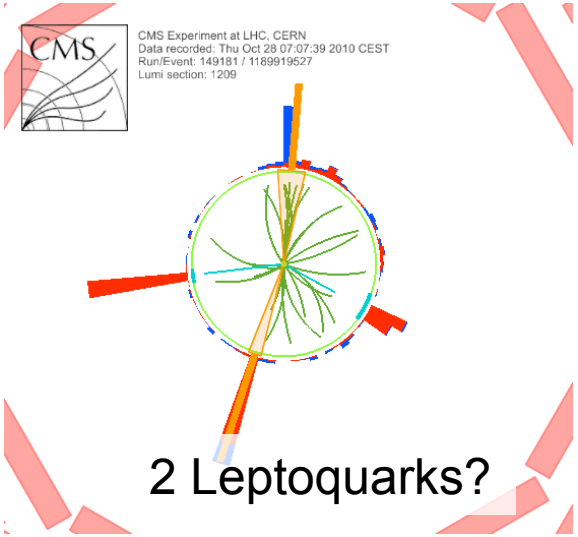
Looking forward to see more of these events…



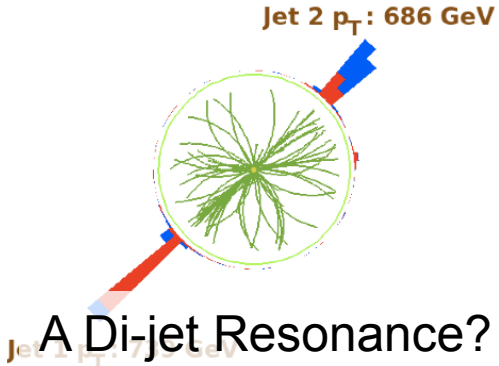
A W'→eν?



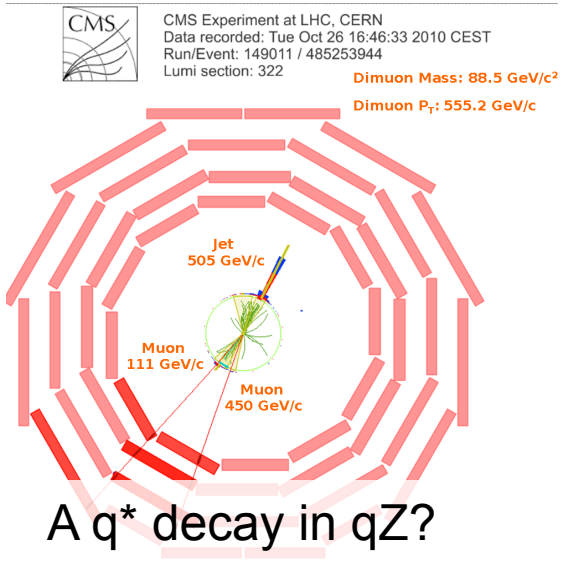
A Black Hole?



2 Leptoquarks?



A Di-jet Resonance?



A q* decay in qZ?

Thank you!

BACKUP SLIDES

Searches with 2010 data (1)

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

❖ New heavy resonances (Z', W', Leptoquarks, q*, etc.)

1) Search for Dijet Resonances in 7 TeV pp Collisions at CMS	PRL 105:211801,2010 arXiv:1010.0203	Mass limits on various new particles (ex. excited quarks M_S>2.5 TeV, M_{q^*}>1.58 TeV)	2.9/pb
2) Search for for a heavy gauge boson W' in the final state with an electron and large missing transverse energy in pp collisions at sqrt(s) = 7 TeV	Accepted by PLB arXiv:1012.5945	Limit on M(W')>1.36 TeV, assuming SM-like coupling and BRs	36/pb
3) Search for a W' boson decaying to a muon and a neutrino in pp collisions at sqrt(s) = 7 TeV	Submitted to PLB arXiv:1103.0030	eν+μν combined limit on M(W')>1.58 TeV, assuming SM-like coupling and BRs	36/pb
4) Search for Resonances in the Dilepton Mass Distribution in pp Collisions at sqrt(s) = 7 TeV	Submitted to JHEP arXiv:1103.0981	ee+μμ combined limit on M(Z')>1.14 TeV, (SM-like coupling) + others models	36-40/ pb
5) Search for Pair Production of First-Generation Scalar Leptoquarks in pp Collisions at sqrt(s) = 7 TeV	Submitted to PRL arXiv:1012.4031	Limit on scalar leptoquark mass > 384 GeV for BR(LQ→eq)=100 %	33/pb
6) Search for Pair Production of Second-Generation Scalar Leptoquarks in pp Collisions at sqrt(s) = 7 TeV	Submitted to PRL arXiv:1012.4033	Limit on scalar leptoquark mass > 394 GeV for BR(LQ→μq)=100 %	34/pb
7) Search for First Generation Scalar Leptoquarks in the channel pp→e+jets +MET at sqrt(s)=7 TeV	Preliminary result EXO-10-006	eejj+evjj combined limit on scalar LQ mass > 255,340,384 GeV, for BR(LQ→eq)=10,50,100%	36/pb
8) Search for a Heavy Bottom-like Quark in pp Collisions at sqrt(s) = 7 TeV	Submitted to PLB arXiv:1102.4746	Limit on mass of b' > 361 GeV	34/pb
9) Search for Resonances in Semi-leptonic Top-pair Decays Close to Production Threshold	Preliminary result TOP-10-007,EXO-10-023	Limit on σ(Z') X BR(Z'→tt) ~< 30 (3) pb for M(Z') ~ 500 (1500) GeV	36/pb

❖ Compositeness and contact interactions

10) Search for Excited Leptons in pp Collisions at sqrt(s)=7 TeV	Preliminary result EXO-10-016	Limit on mass of excited muons (electrons) > 745 (720) GeV for contact int. scale Λ=2 TeV	36/pb
11) Search for New Physics in Highly Boosted Z0 Decays to Dimuons in pp Collisions at sqrt(s)=7 TeV	Preliminary result EXO-10-025	Limit on mass of q* > 911 (1116) GeV for gauge (contact int.) prod. with M_{q^*}=L and f=f'=f_s=1	36/pb

Searches with 2010 data (2)

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

❖ Compositeness and contact interactions

12) Search for Quark Compositeness with the Dijet Centrality Ratio in pp Collisions at sqrt(s) = 7 TeV	PRL 105:262001,2010 arXiv:1010.4439	Limit on energy scale of quark contact interactions Λ>4 TeV	2.9/pb
13) Measurement of Dijet Angular Distributions and Search for Quark Compositeness in pp Collisions at sqrt(s) = 7 TeV	Submitted to PRL arXiv:1102.2020	Limit on contact interaction scale for left-handed quarks Λ>5.6 TeV	36/pb

❖ Extra dimensions

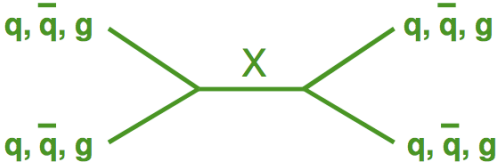
14) Search for Large Extra Dimensions in the Diphoton Final State at the Large Hadron Collider	Preliminary result EXO-10-026	Lower limits on fundamental scale M_D depending on num. of extra dim.	34/pb
15) Search for Large Extra Dimension in Dimuon Events in pp Collisions at sqrt(s)=7 TeV	Preliminary result EXO-10-020	Lower limits on fundamental scale M_D depending on num. of extra dim.	40/pb
16) Search for Large Extra Dimensions with a Mono-jet and Missing Transverse Energy in pp collisions at sqrt(s)=7 TeV	Preliminary result EXO-11-003	Lower limits on fundamental scale M_D depending on num. of extra dim.	36/pb
17) Search for Randall-Sundrum Gravitons Decaying into Two Photons in 7 TeV pp Collisions with the CMS Detector	Preliminary result EXO-10-019	Limit on graviton mass > 371-945 GeV for coupling parameter from 0.01 to 0.1	36/pb
18) Search for Microscopic Black Hole Signatures at the Large Hadron Collider	PLB697:434-453,2011 arXiv:1012.3375	Limits on the min. M_{BH} >3.5-4.5 TeV for various parameters M_D and n in ADD model	35/pb

❖ Other exotic signatures (long-lived particles, lepton-jets)

19) Search for Heavy Stable Charged Particles in pp collisions at sqrt(s) = 7 TeV	Submitted to JHEP arXiv:1101.1645	Limit on mass of stable gluino > 398 GeV using convention model of nucl. int. for R-Hadrons	3.1/pb
20) Search for Stopped Gluinos in pp Collisions at sqrt(s) = 7 TeV	PRL 106:011801,2011 arXiv:1011.5861	Limit on mass of gluino > 370 GeV with 10μs < τ < 1000s	10/pb
21) Search for Resonant Production of Lepton Jets	Preliminary result EXO-11-013	Upper limit on σ x BR x a_{gen} in the range 0.1-0.5 pb for various event topologies	35/pb

Search for dijet resonances (2.9/pb)

- Strong s-channel production of colored objects has huge advantage at the LHC w.r.t. Tevatron, particularly for gg-fusion

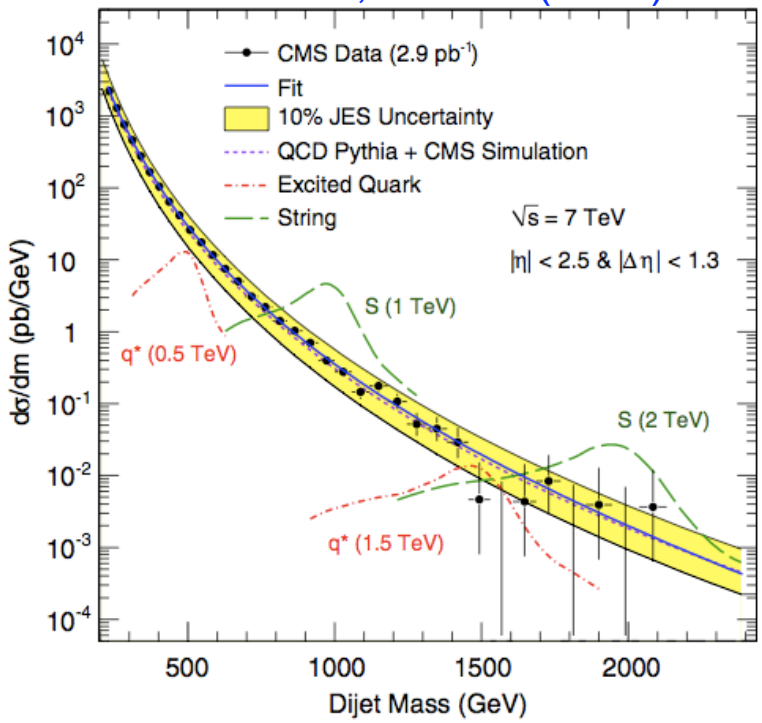


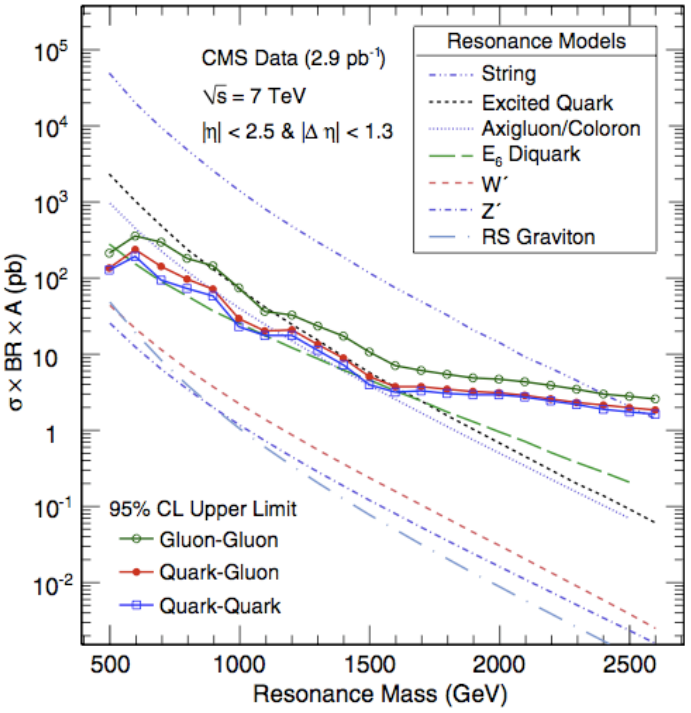
- Parametrize dijet mass spectrum with smooth 4-parameter fit function:

$$\frac{d\sigma}{dm} = \frac{P_0(1-m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2+P_3\ln(m/\sqrt{s})}}$$

- **Look for bumps**
- None observed in 2.9/pb, set limits

PRL **105**, 211801 (2010)





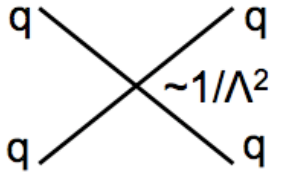
M_S>2.5 TeV

M_{q^*}>1.58 TeV

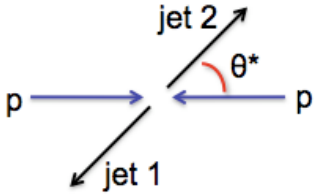
$M_{q^*} = \Lambda,\ f = f' = f_S = 1$

Contact interactions with dijets

$$\mathcal{L}_{qq} = +\frac{2\pi}{\Lambda^2}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L)$$



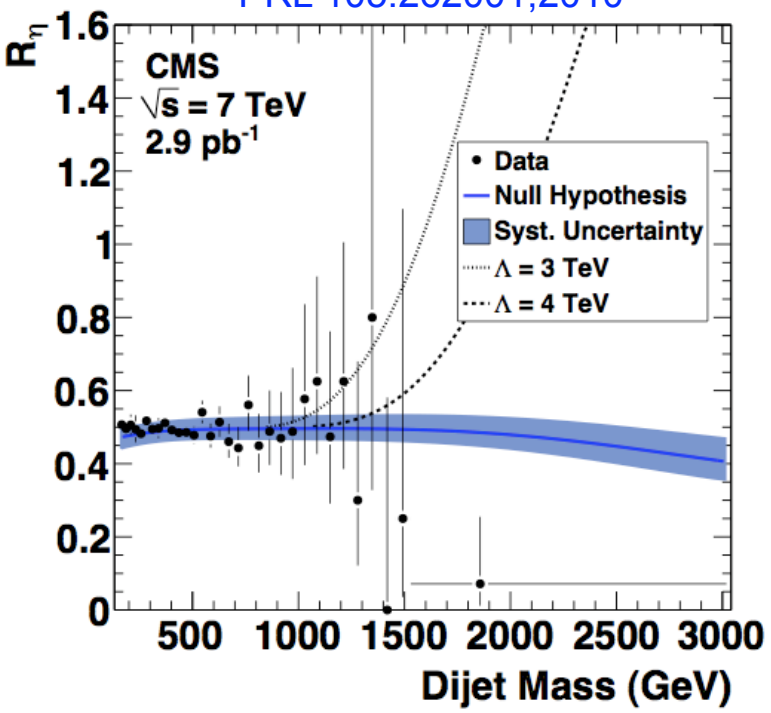
- **Quark compositeness** at energy scale Λ would appear at lower energies as a contact interaction yielding **jet η/θ* distributions different from that predicted by QCD**



$$\chi = e^{2y^*} = \frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$

$$R_\eta \equiv \frac{N_{2j}(|\eta|<0.7)}{N_{2j}(0.7<|\eta|<1.3)}$$

PRL 105:262001,2010

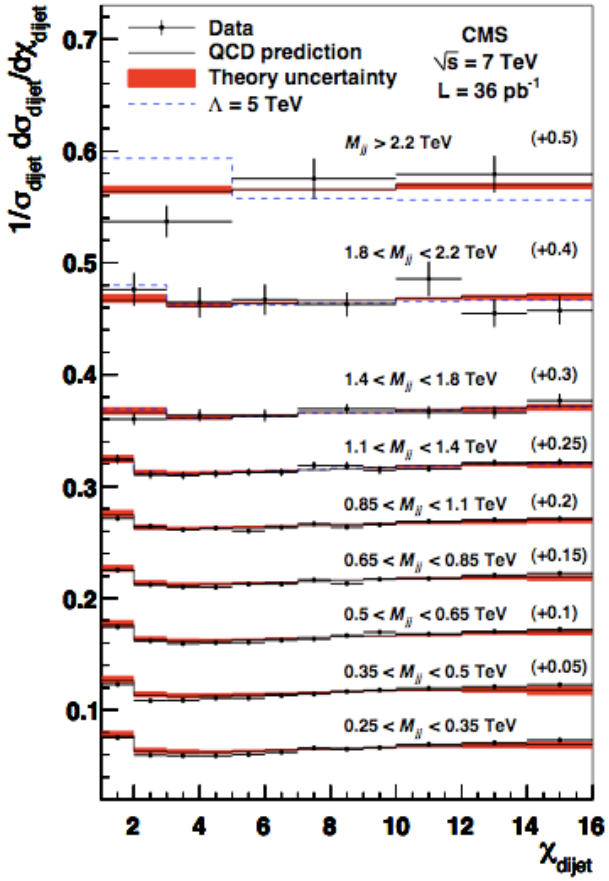


Λ>4 TeV (expected Λ>2.9 TeV)

arXiv:1102.2020,
Submitted to PRL

Complementary analyses:

- R_η has finer bins in M_{jj}, but only two bins in η
- R_η has sensitivity to dijet resonances as well
- χ has finer angular info, but coarser M_{jj} binning
- χ has wider rapidity range |y|<2.5 → samples differ at ~60%



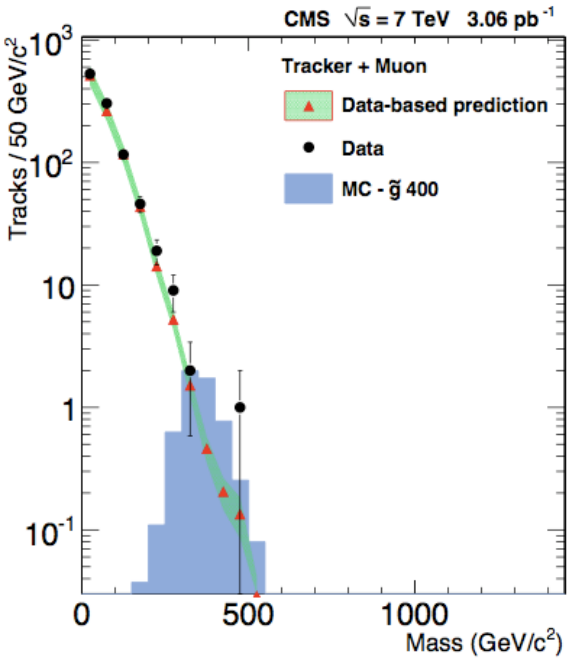
Λ>5.6 TeV (expected Λ>5 TeV)

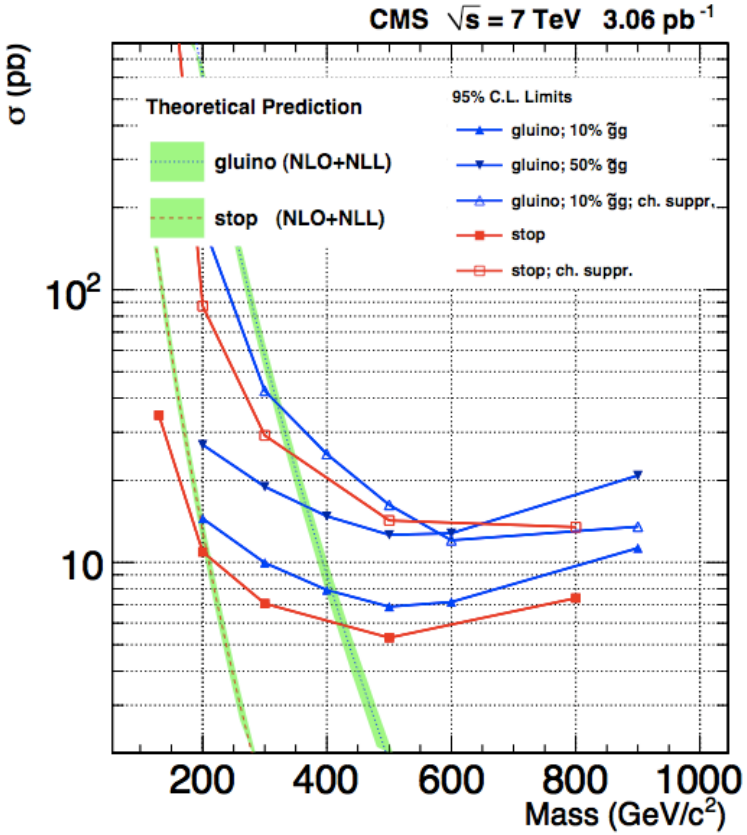
Heavy Stable Charged Particles

- **Select tracks or muons with high pT and dE/dX**
- Reconstruct mass with approx. "Bethe-Bloch formula"
- Data-driven background estimation exploit absence of correlation between pT and dE/dX
- Final selection optimized by requiring total expected background ~0.05
- 0 events observed, set limits

$$\frac{dE}{dX} = K\frac{m^2}{p^2} + C$$

K,C determined from data using a control sample of low-momentum protons





arXiv:1101.1645, submitted to JHEP

Limits on SUSY gluino and stop masses for various fractions of neutral $\tilde{g}g$ states in "R-Hadronization"

In "charge suppr. scenario" R-Hadrons become neutral before reaching muon system →Trk-only analysis still sensitive

M_{gluino}>311-398 GeV

Search for Stopped Gluinos
(10/pb, 63 hours, peak $L_{int}=10^{32}cm^{-2}s^{-1}$)

- **Slow-moving R-Hadrons (β<0.4) can loose enough energy to stop**, by interacting with the dense material of CMS detector (mostly in HCAL)
- **Look for subsequent decay during times where there is no beam** (in between LHC bunches) using dedicated jet trigger

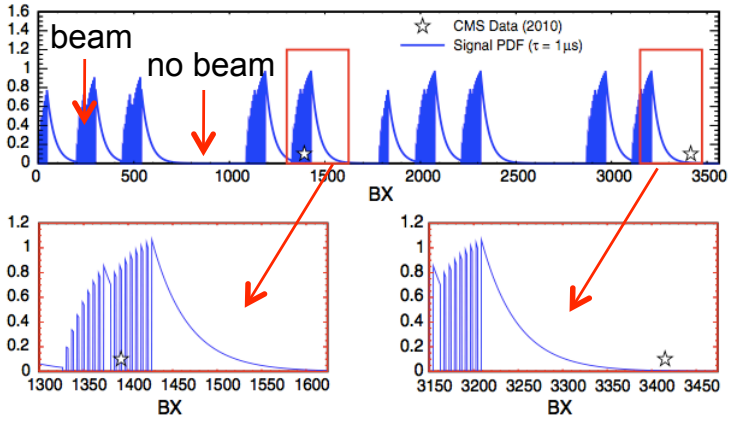
$$BR(\tilde{g} \rightarrow g\tilde{\chi}_1^0) = 100\%$$ (Single-jet-like signature)

- Cosmic/instrumental background derived from data control sample at low L_{int}
- Both counting experiment and time-profile analysis consistent with background only hypothesis, set limits

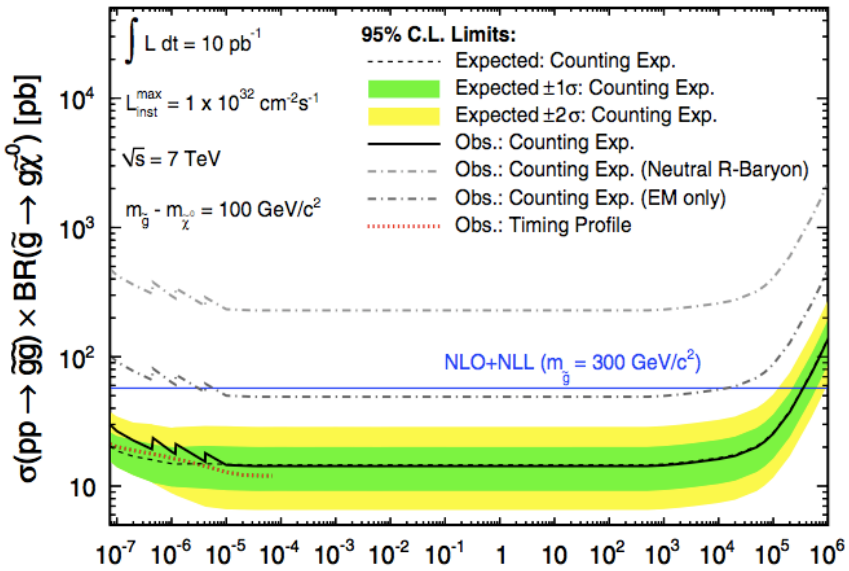
Counting experiment for $10^{-7} < \tau_{gluino} < 10^6$ s

Lifetime [s]	Expected Background (± stat ± syst)	Observed
1×10^{-7}	$0.8 \pm 0.2 \pm 0.2$	2
1×10^{-6}	$1.9 \pm 0.4 \pm 0.5$	3
1×10^{-5}	$4.9 \pm 1.0 \pm 1.3$	5
1×10^{6}	$4.9 \pm 1.0 \pm 1.3$	5

Time-profile analysis for τ_{gluino} < 100μs (~LHC orbit)



$M_{\tilde{g}} > 370$ GeV, $\tau = 10\ \mu s - 1000\ s$



PRL **106**, 011801 (2011)

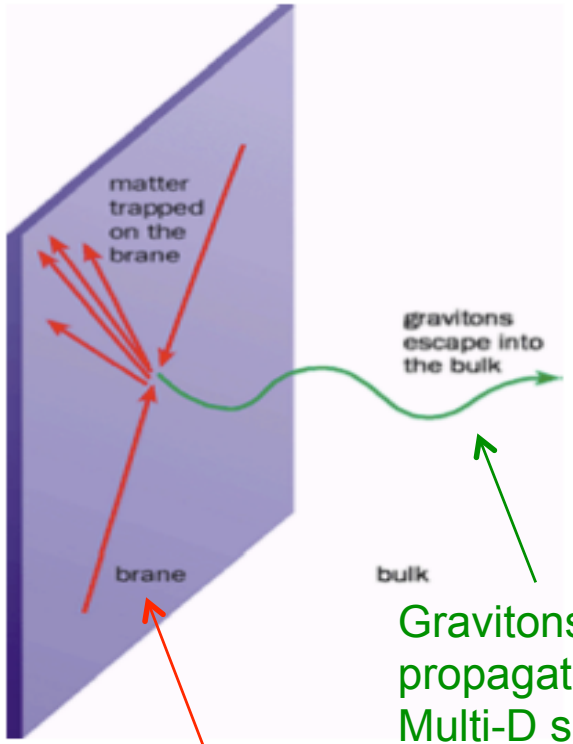
Large Extra Dimensions (ADD model)

PLB 429 (1998) 263

- Hierarchy problem: $M_{Pl} \sim 10^{19}$ GeV, $M_{EW} \sim 10^{2}$ GeV
- The ADD model solves it
  - "n" extra dimensions in space of size "r"
  - Gravity only propagates through multi-D space
- **True Planck scale (M_D) lowered to TeV scale**

  → graviton production possible at LHC

$$M_D^{n+2} \propto M_{Pl}^2 / r^n$$



Gravitons can propagate in Multi-D space

- We have searched for LED in:

  1) Di-photon (γγ)

  2) Di-muon (μμ)

  3) Mono-jet + MET

  4) Microscopic Black Holes

Standard Model lives in 3+1 D space-time

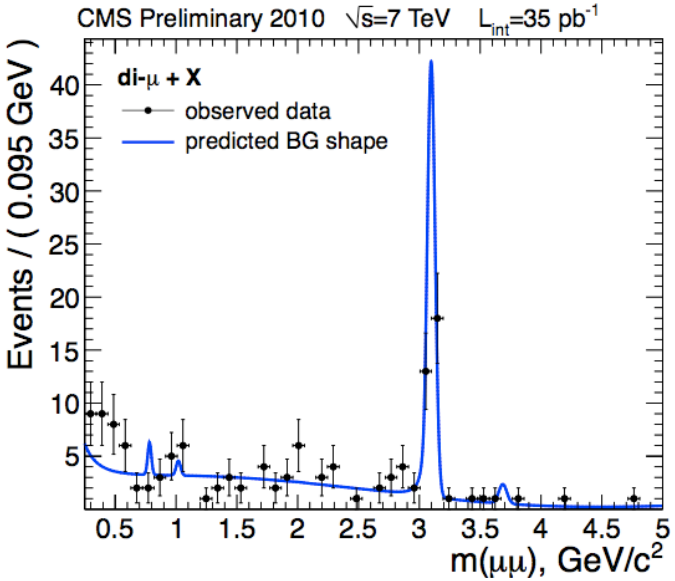
Lepton jets (1)

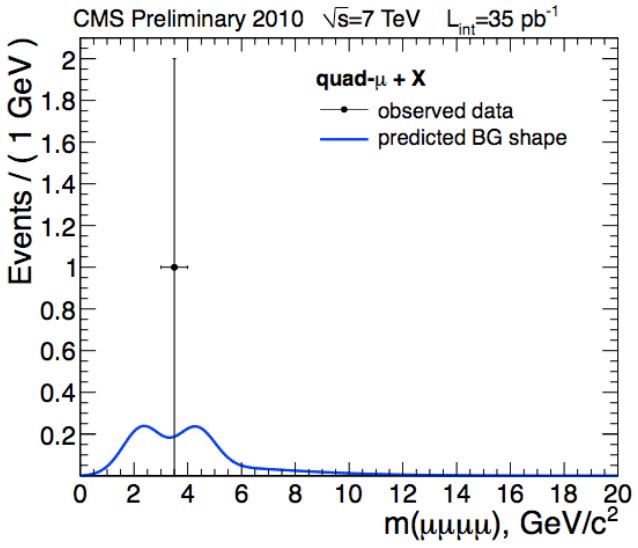
First Public Presentation of this Result

EXO-11-013

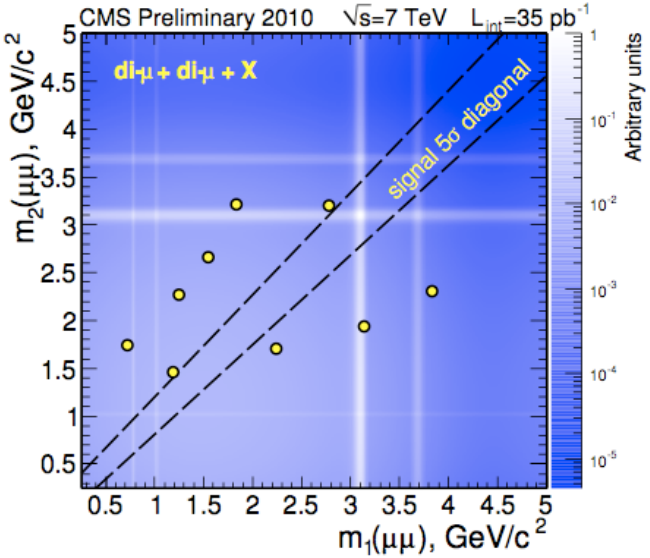
di-μ jet

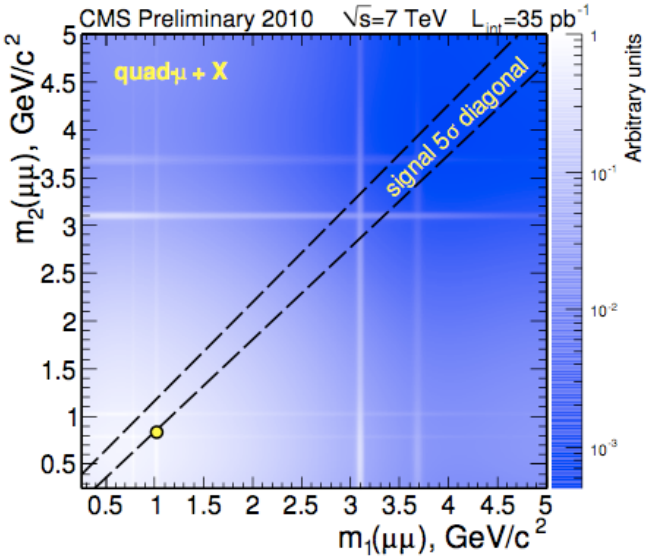
(a) they are opposite-sign, (b) their invariant mass < 9 GeV/c^2, and (c) they have a consistent vertex





$m_2 \rightarrow m_1 m_1$
$m_1 \rightarrow \mu\mu$





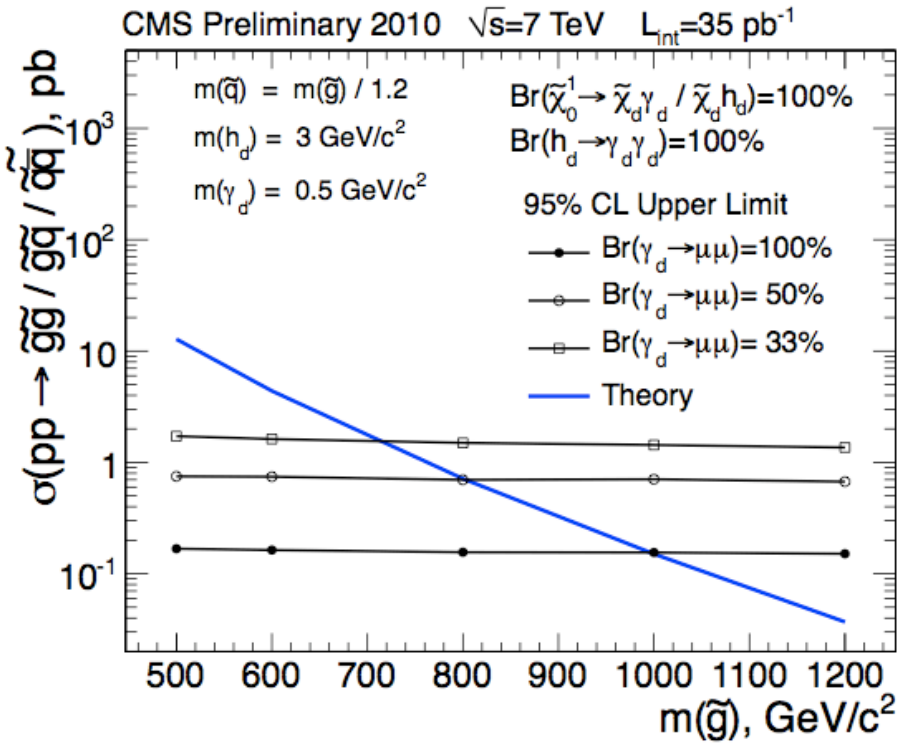
Lepton jets (2)

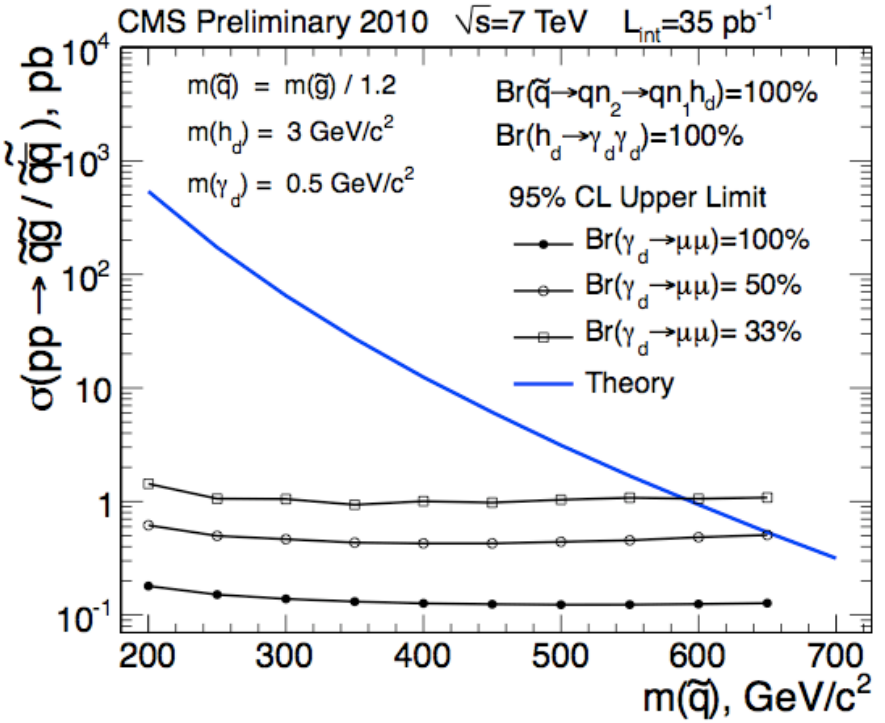
First Public Presentation of this Result

EXO-11-013

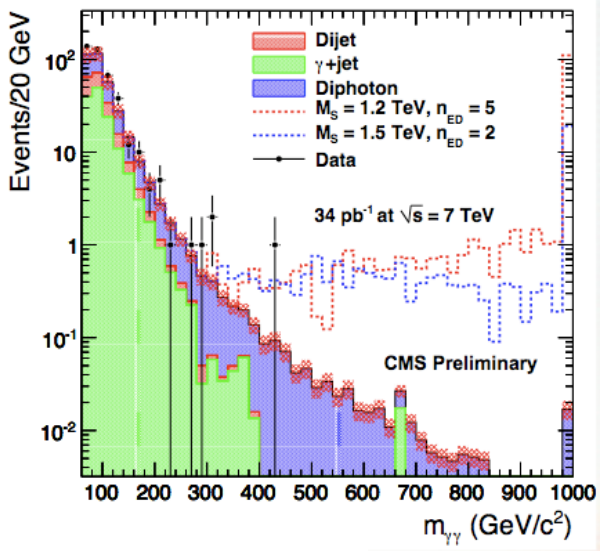
• Model of SUSY dark matter with a ~1 GeV/c^2 dark photon, inspired by the PAMELA interstellar positron excess (PRL 103 (2009) 051801)

• Another dark SUSY model with a ~1 GeV/c^2 dark photon, always produced in pairs from dark higgs to 2 dark photons (to four muons). (JHEP 04 (2009) 014)

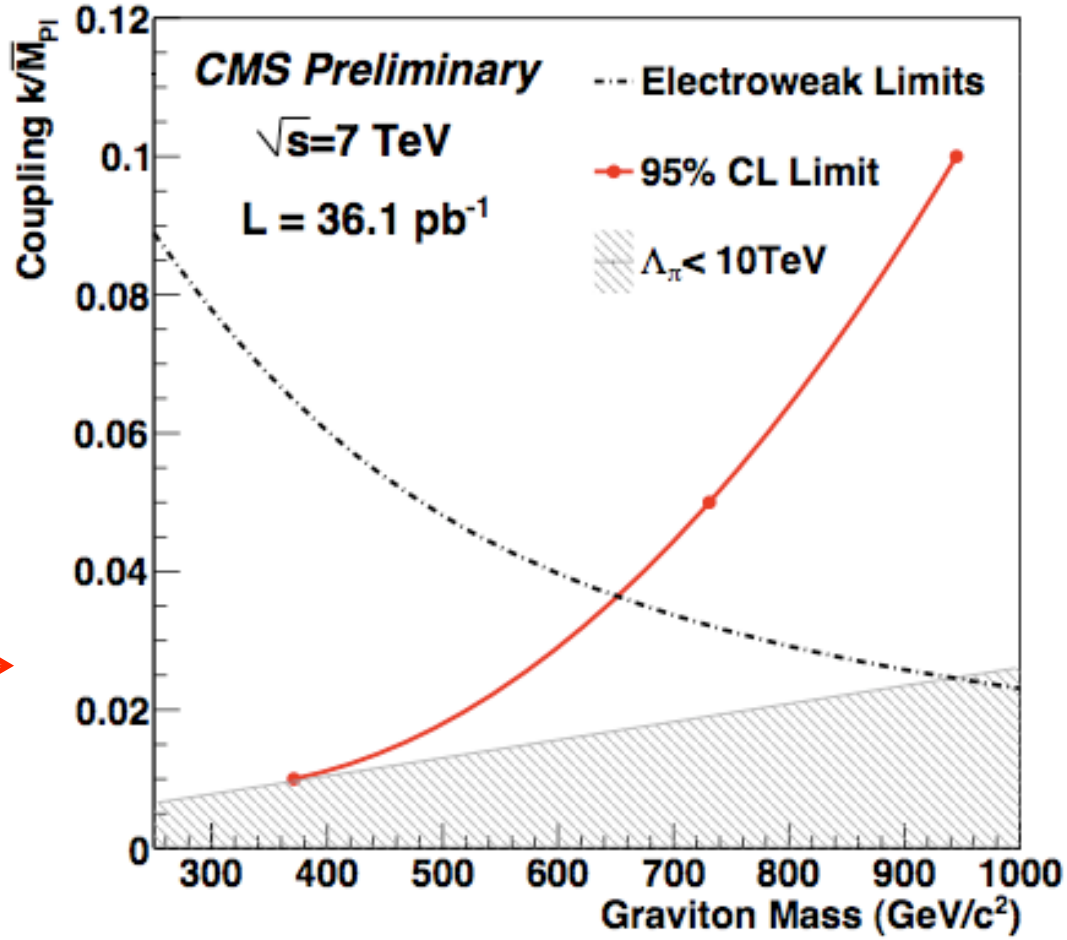




RS Graviton → γγ



Same γγ spectrum
of LED analysis
used to set limits on mass
on RS graviton resonances



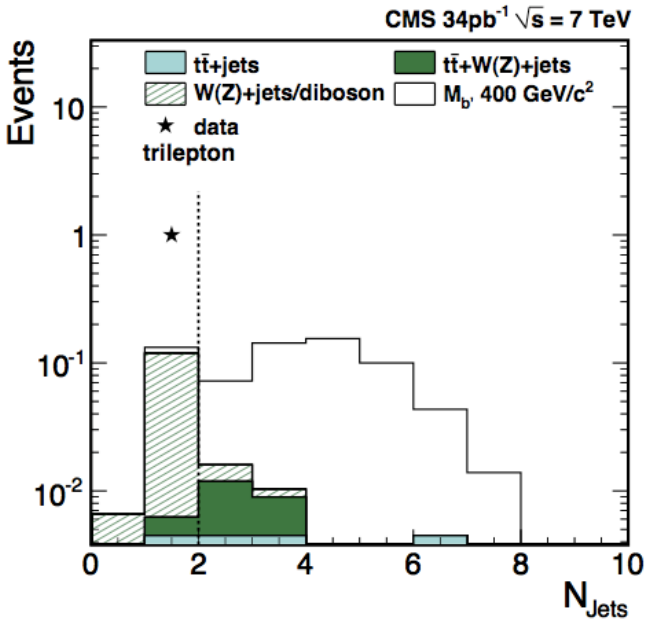
EXO-10-019

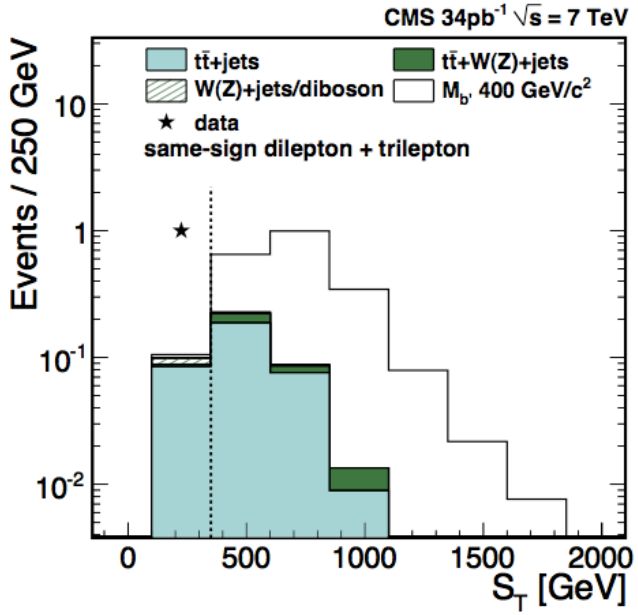
M_{GKK}>945 GeV
k/M_{Pl}=0.1

b'→tW

- Pair produced b': tWtW→bWWbWW
  - same-sign di-lepton, tri-lepton decays (BR~7.3%)
  - lepton (e/μ) PT>20 GeV
  - at least 2 (4) jets PT>25GeV for tri-lepton (same sign di-lepton)
  - Z veto: | M(ll) – M(Z) |<10 GeV
  - ST = Sum PT(jets)+PT(leptons)+MET >350 GeV
- Data-driven background estimate
  - same-sign di-lepton: from fake rate + charge mis-ID
- Expectd bkg = 0.3 +/- 0.2
- 0 events observed

arXiv:1102.4746, Submitted to PLB



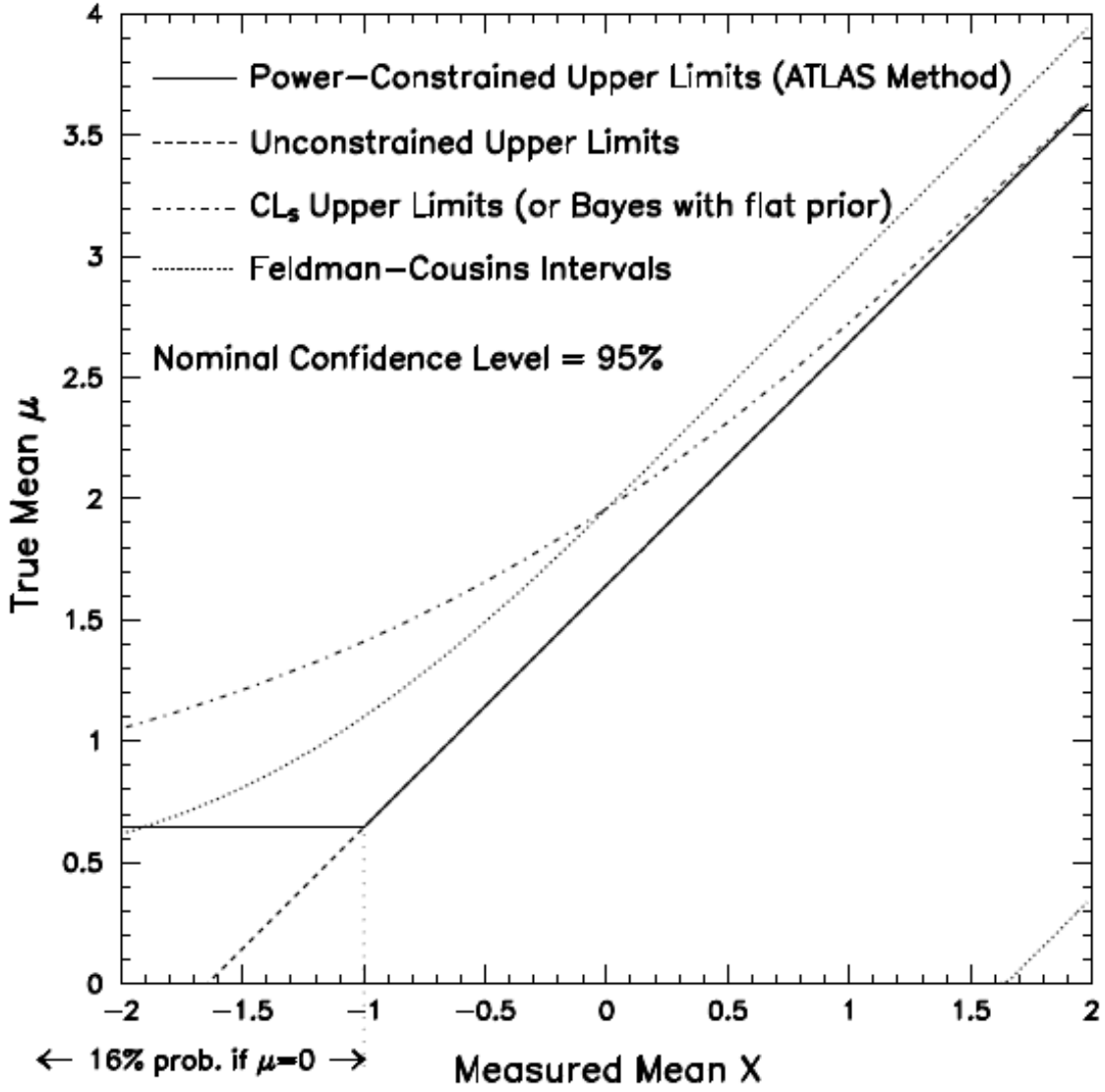


All selections are applied except the one corresponding to the plotted variable

Intervals and Limits for a Physically Bounded μ

- Prototype: measurement x is unbiased Gaussian estimate of μ. (Let σ=1.) What is 95% C.L. Upper Limit (UL)?
- 1986: Six methods for UL surveyed by V. Highland (VH) include U.L. = max(0, x + 1.64) and U.L. = max(0,x) + 1.64.
- RPP 1986: Bayesian: uniform prior on the mean μ for μ≥0, prior prob = 0 for μ<0. (VH's other five not mentioned.)
- 1994,96: 3 ad-hoc frequentist recipes, one using max(x,0).
- 1998: Feldman & Cousins (FC) "Unified Approach" in (Kendall and Stuart) replaces ad hoc frequentist
- 2002: CL_S from LEP added to Bayesian and FC.
- CMS Statistics Committee recommends using (at least) one of the three (red) methods in 2002-present PDG RPP.
- ATLAS SC method implies U.L. = max(0, x + 1.64) before power constraint (PC), U.L. = max(-1,x) + 1.64 after PC.

Comparison of ATLAS PCL with the three methods in PDG



(Atlas unconstrained U.L. is zero, not null, for x < -1.64)

ATLAS PCL re-opens discussion on use of diagonal line along with ad hoc constraint, out of favor for many years, not recommended by CMS SC.

CMS and ATLAS SC's are reviewing arguments and what has been learned in 25+ years. Academic statisticians have commented as well.

Just tip of iceberg: Poisson example brings in other issues. Nuisance parameters yet more. Choice of test statistic varies.