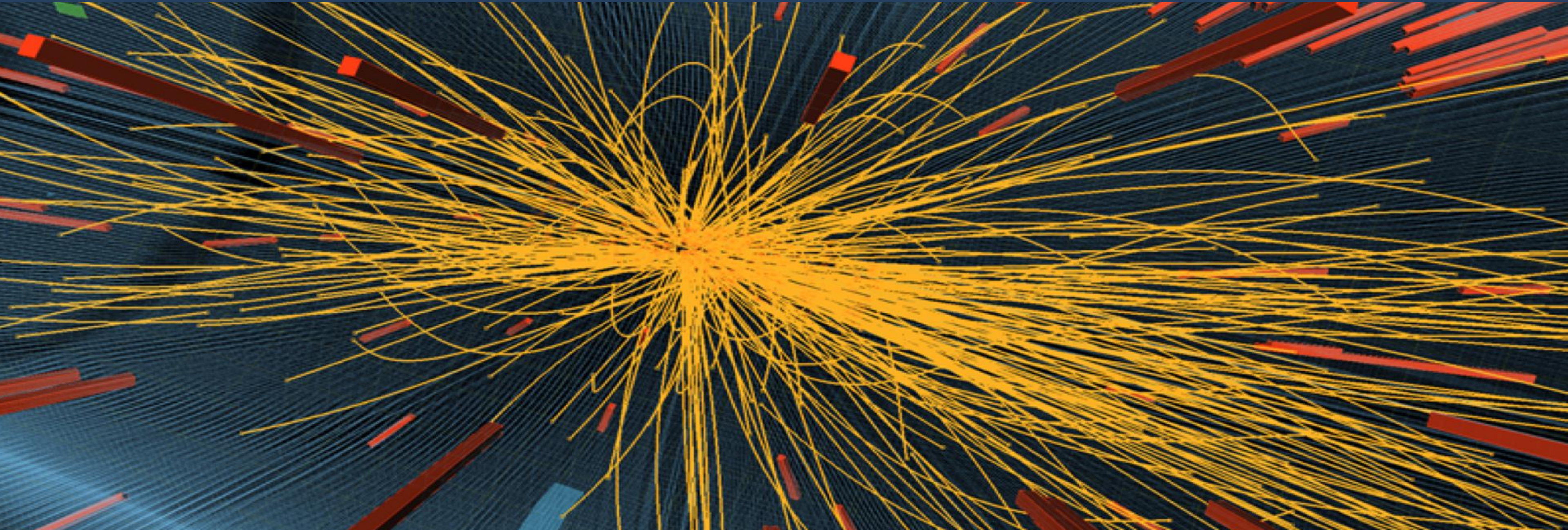
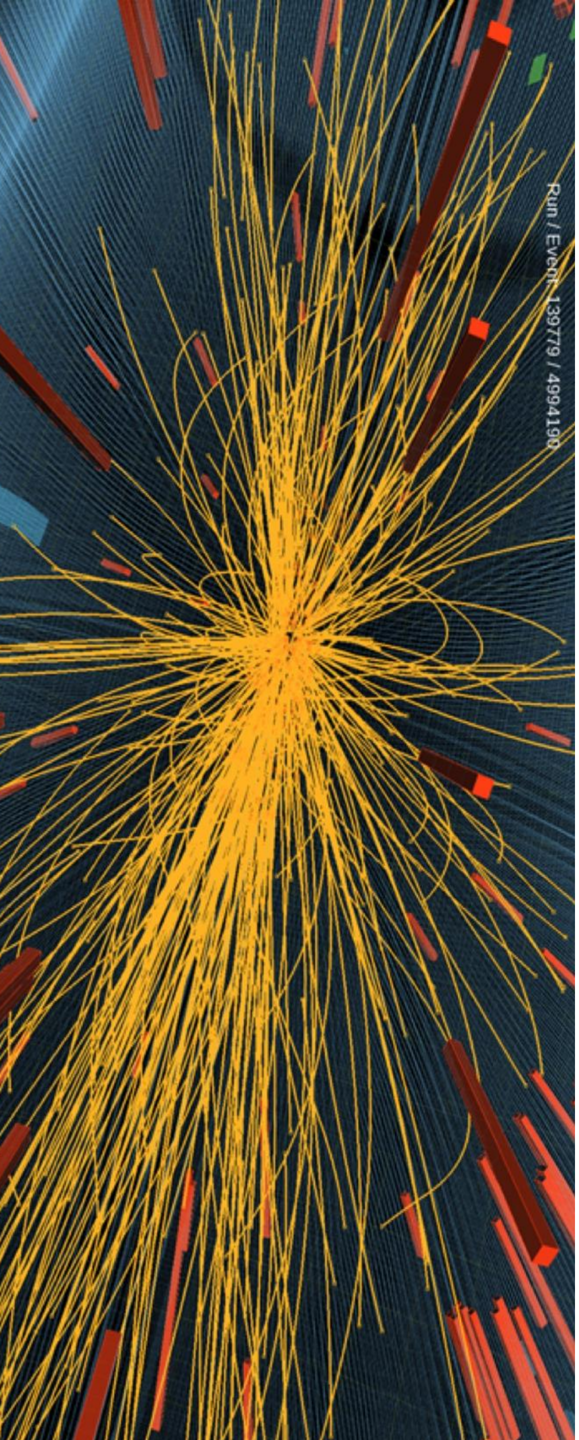
Search for Heavy Resonances with CMS

Kerstin Hoepfner, RWTH Aachen, III. Phys. Inst. A

On behalf of the CMS collaboration

SEARCH2012: Workshop on Characteristics of New Physcis,
University of Maryland, College Park, MD, March 17-19





OUTLINE

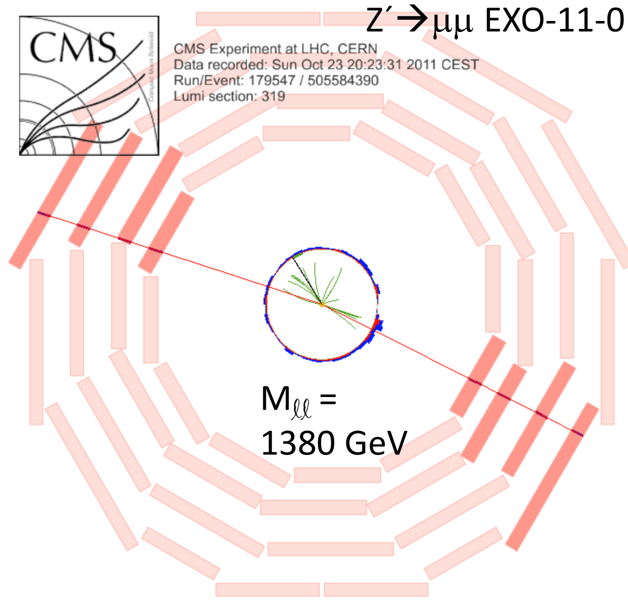
Searches for:

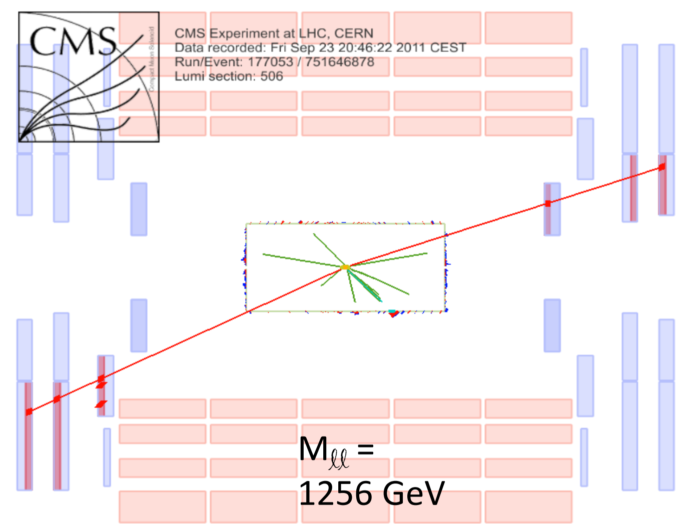
1. **Narrow, new resonances (Z´, RS)**
   EXO-11-009 with 4.7 fb^{-1} (dileptons)
   EXO-11-061 with 4.7 fb^{-1} (jet + MET)
2. **Heavy, charged bosons W´**
   EXO-11-024 with 4.7 fb^{-1} (lν)
   EXO-11-041 with 4.7 fb^{-1} (WZ)
3. **2^{nd} generation Leptoquarks**
   EXO-11-028 with 2 fb^{-1}
4. **3^{rd} generation Leptoquarks**
   EXO-11-030 with 1.8 fb^{-1}
5. **Summary**

High p_T Muon Selection

High redundancy of mu system, 4 stations along track
Iron between stations may cause **bremsstrahlung** for O(TeV) muons
p_T<200 GeV tracker in B=3.8T, p_T>200 GeV mu+tracker

Event displays from Z´→μμ EXO-11-019

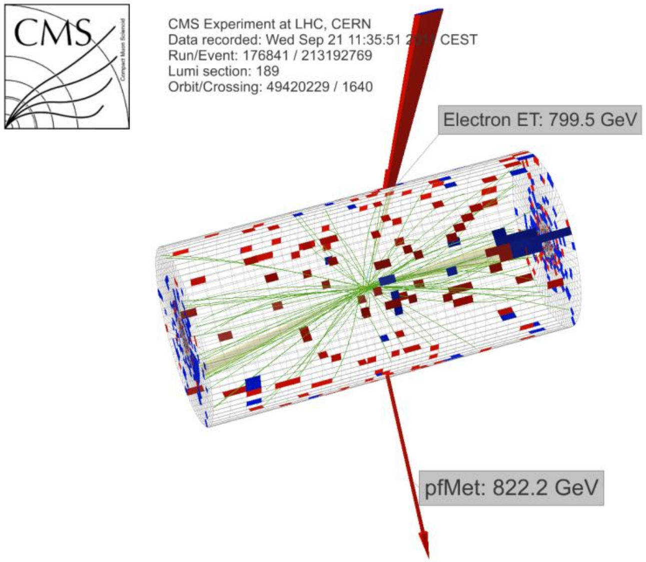


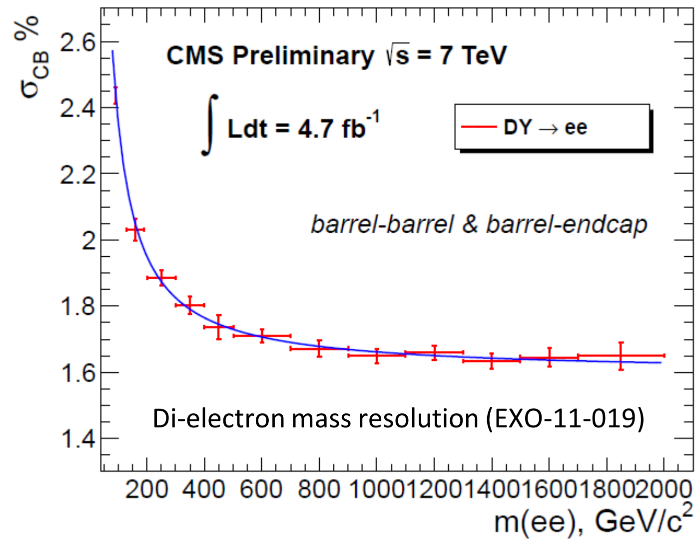


Dedicated muon selection:

- Special algorithm to consider showering
- At least 1 pixel hit
- Number of measured tracker layers > 8
- Transverse impact parameter d0 < =0.2cm (Z´), 0.02cm (W´) reject cosmics, value for W´ tighter than other analyses, Z´ rejects in addition back-to-back muons
- >= 2 matched muon segments
- Relative track isolation <0.10 in $\Delta R < 0.3$
- No cut on chi2 cut introduces a 4-6% inefficiency for muons >500 GeV

High Energy Electron Selection

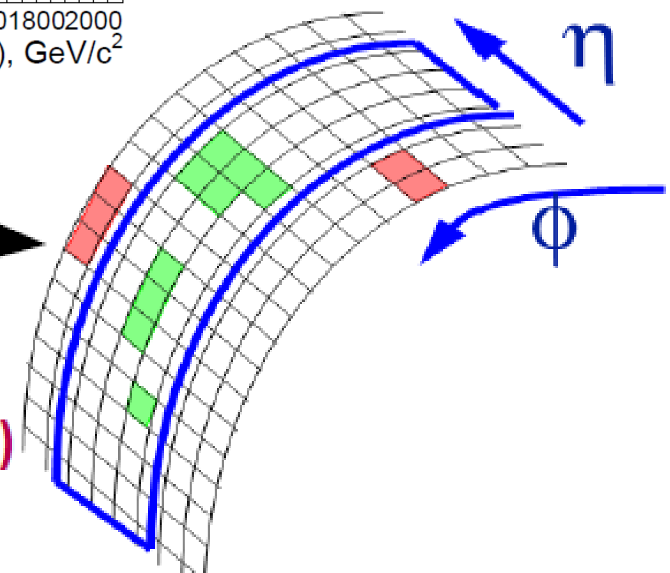




ECAL made of matrix of fully active crystals. Measured energy resolution ~2%

Electrons are reconstructed from energy clusters
In the ECAL and tracks from the silicon tracker
Electron ID optimized for high E_T requires:

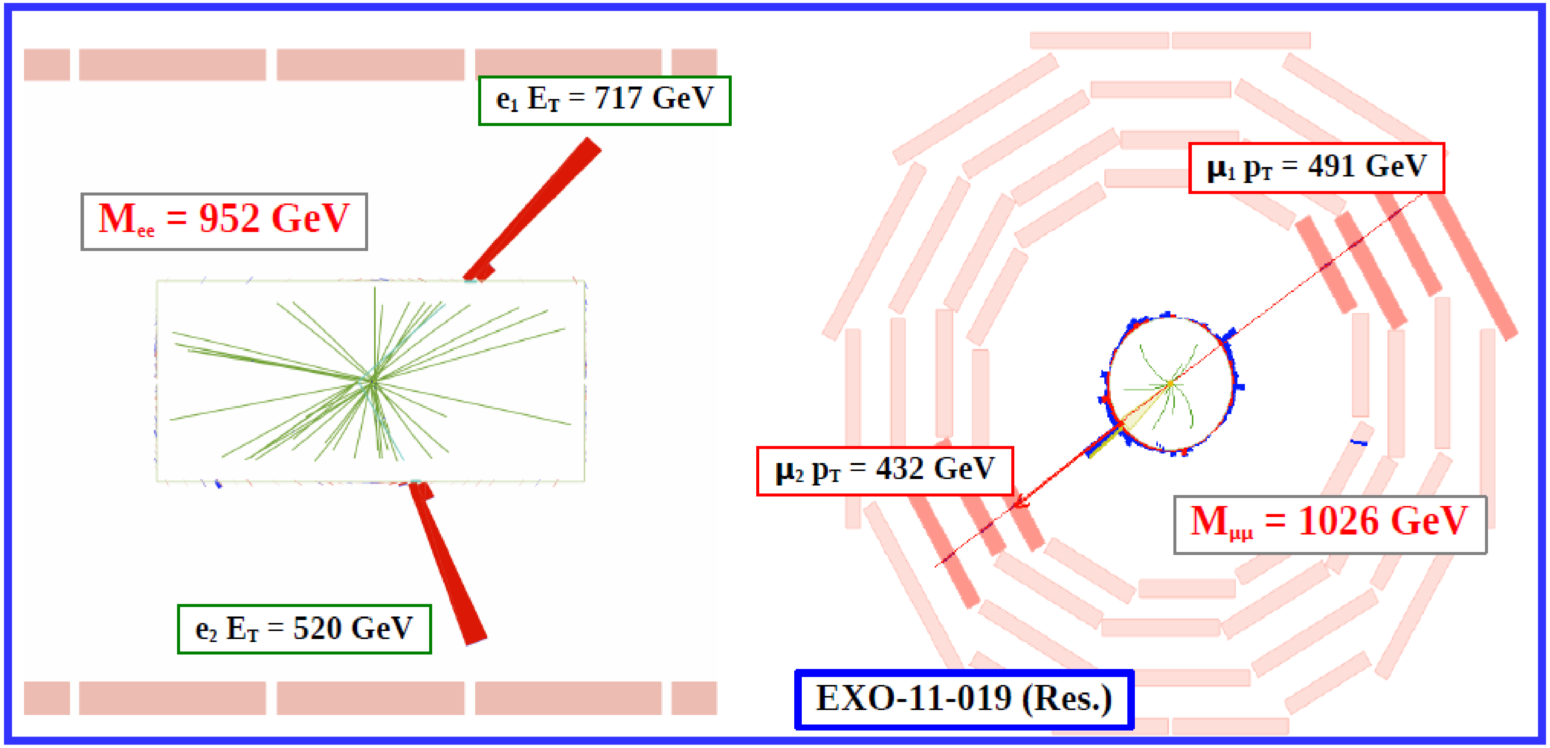
- $E_T > 85$ GeV
- $|\eta| < 1.442$ (barrel) or $1.56 < |\eta| < 2.5$ (endcap)
- Good quality of track and cluster
- Matching between the two
- Isolation



$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

Z´/RS→ℓℓ

Signature: two isolated high energy electrons or two isolated, opposite-sign muons; forming a resonance



Also searches with dijets and boosted top-pairs, see other CMS talks

Z′/RS Assumptions & Channels

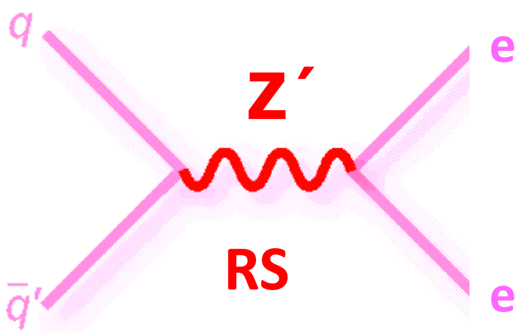
CMS PAS EXO-11-019

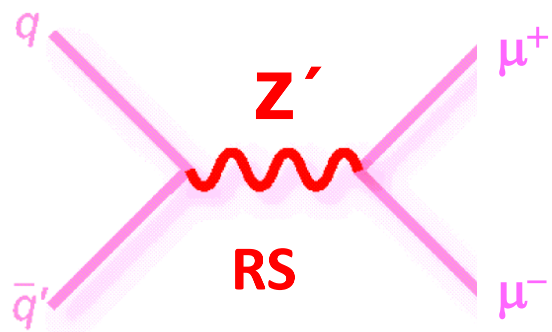
Assume **similar decays as for Standard Model** (plus decay into top quarks)

Generic search for new physics: extra high-mass **resonances** in dilepton spectrum: e.g. new gauge bosons Z′, Randall-Sundrum gravitons (RSG)

Channels **Z′ → ee** **Z′ → μμ**

BR ~8% per channel





Signature

two isolated high energy electrons two isolated, opposite-sign muons

Forming a resonance

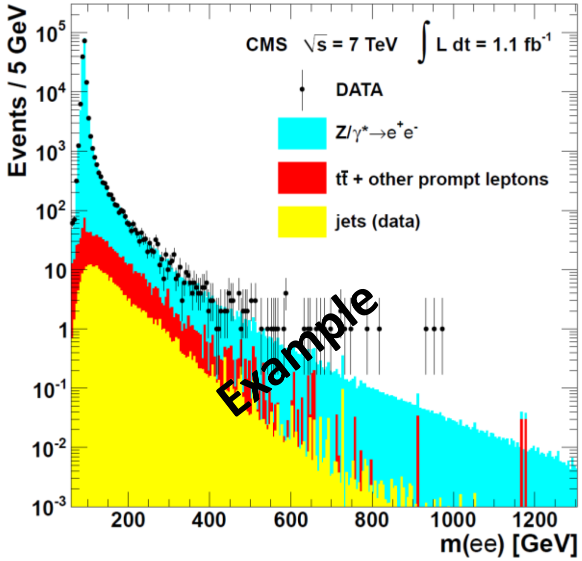
Triggered by **single lepton** trigger with increasing threshold

One common offline p_T cut, above highest trigger threshold

Method of Analysis

CMS PAS EXO-11-019

- Use **dedicated high p_T lepton ID** to avoid mis-reconstruction
- Reconstruct **invariant mass $M_{\ell\ell}$**
- Search for **generic excess** in invariant dielectron and dimuon mass spectra
- Many studies concerning efficiencies etc. at such high invariant masses



Generic shape-based search: no assumptions on absolute background rate, with **results normalized to the Z^0 peak**

Differences $\rightarrow$ small extra systematic uncertainties.

$$\frac{\sigma \times BR(Z')}{\sigma \times BR(Z^0)} = \frac{N(Z')}{N(Z^0)} \times \frac{A(Z^0)}{A(Z')} \times \frac{\epsilon(Z^0)}{\epsilon(Z')}$$

Sources of Background

CMS PAS EXO-11-019

Dominant irreducible SM DY

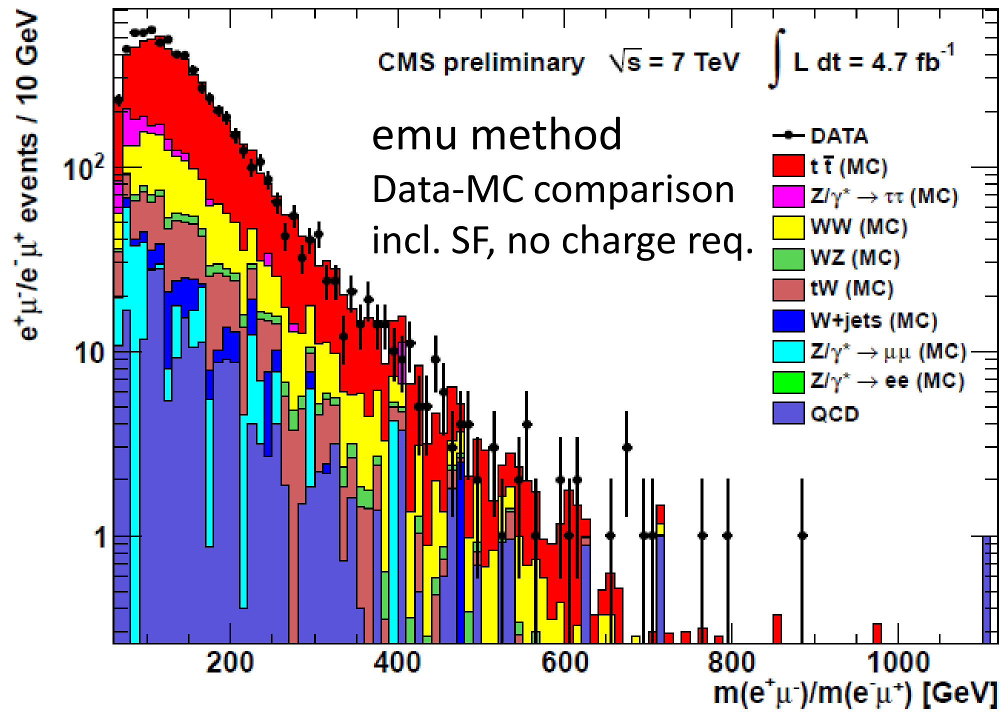
- From POWHEG MC, normalized to data at Z-peak
- PDF uncertainties 5-20%

Jets faking electrons (ee)

- From γ-triggered events. Subtract W/γ+jets using MC.
- Ratio GSF/HEEP
- Max. fake rate ~2% (barrel), 3% (EC). Decreasing with E_T

Cosmics ($\mu\mu$)

- Largely reduced by back-to-back cut



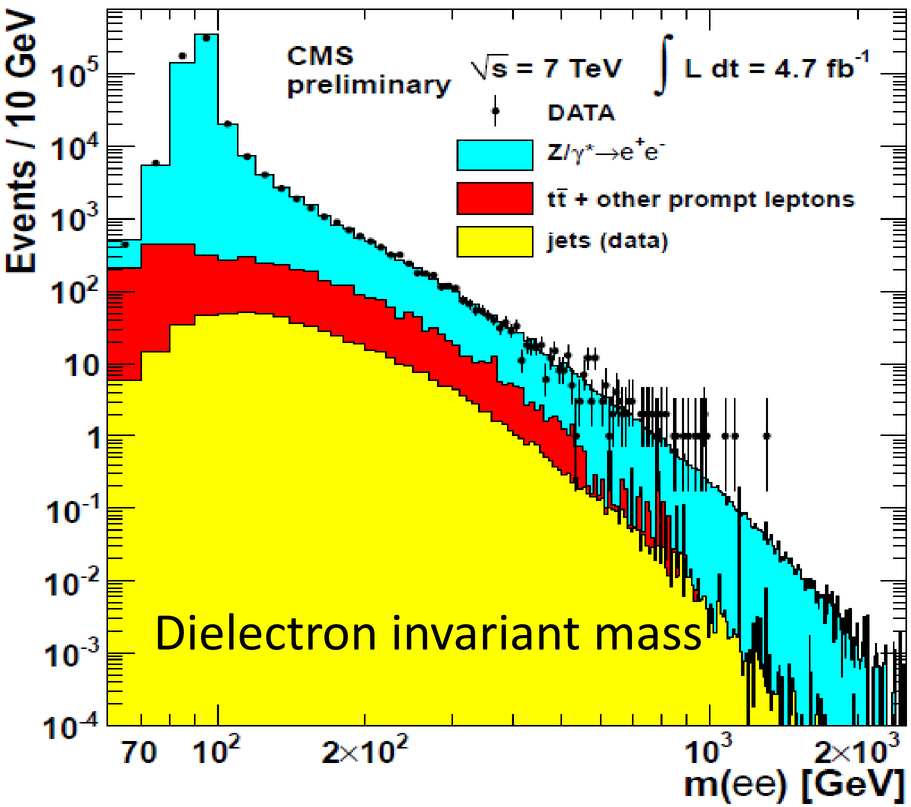
tt and tt-like background

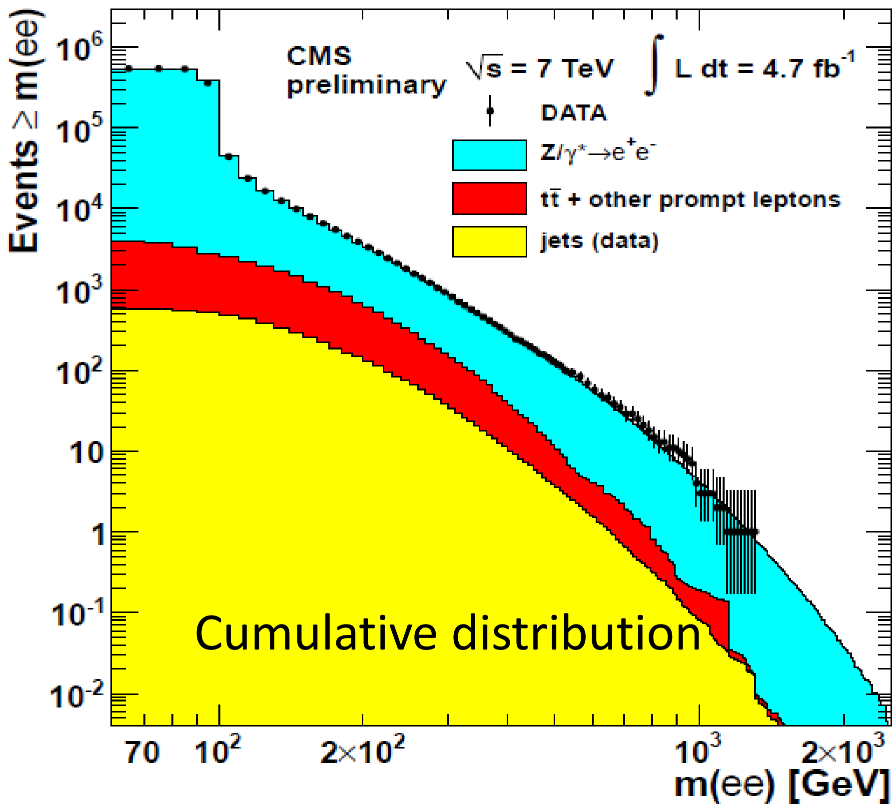
- main bkgr in $M_{\ell\ell}$ tail
- With emu method from MC
- Shape and normalization checked in data

4.7/fb Dielectron mass spectrum

CMS PAS EXO-11-019

- At least one electron has to be in the barrel
- 70% acceptance * efficiency
- Main background due to DY, NLO uncertainties ~6%, PDF uncertainties <20%
- Some contribution from tt and jets faking electrons



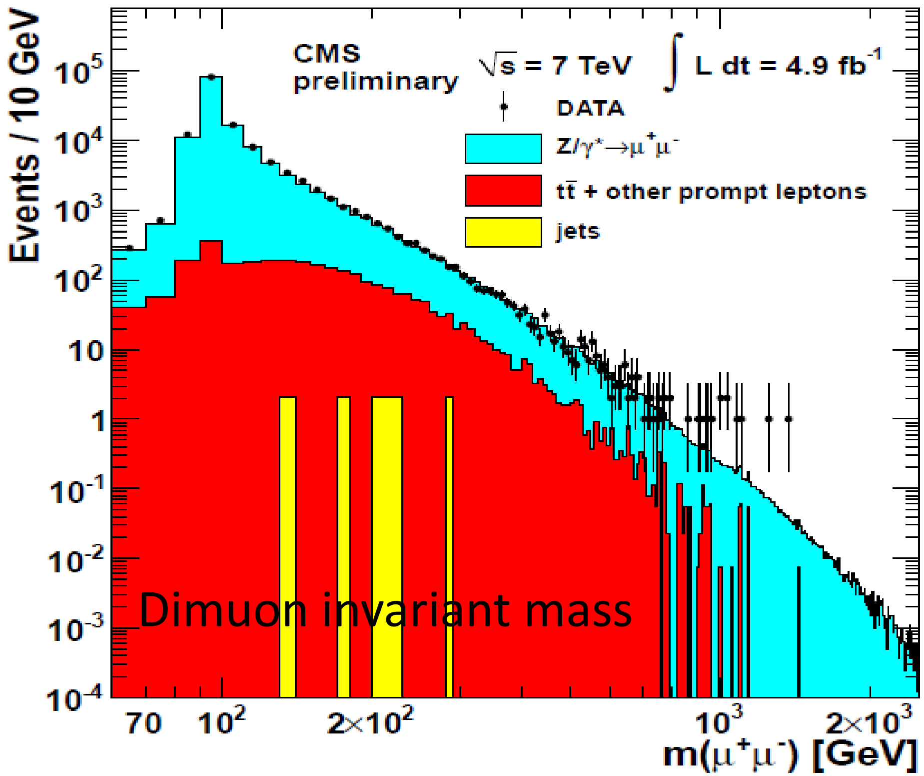


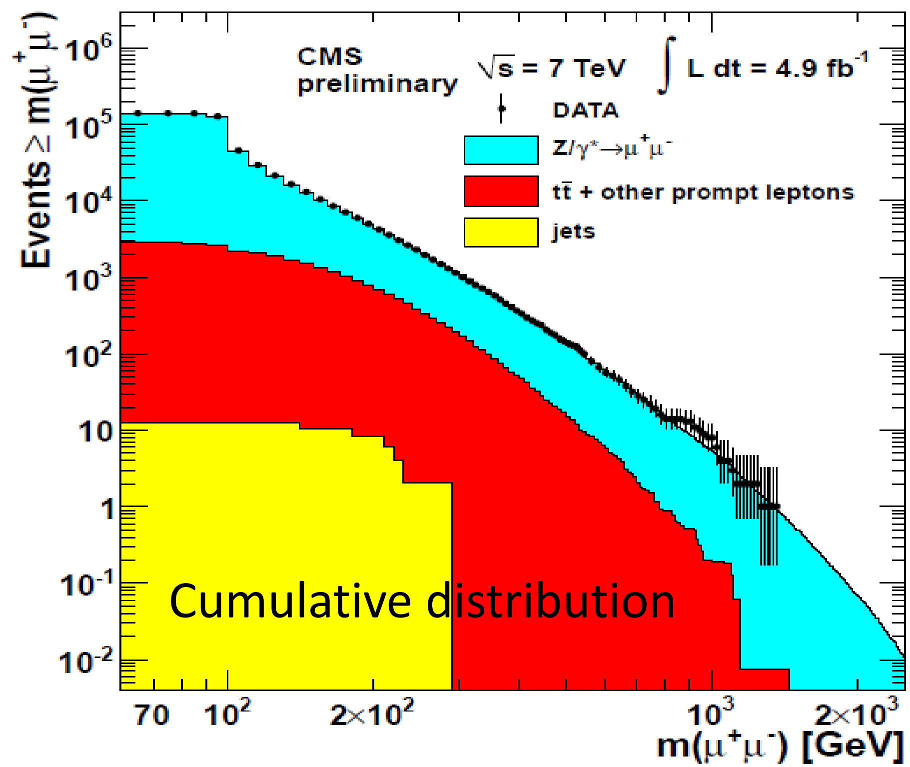
The uncertainties on the data points (statistical only) represent 68% confidence intervals for the Poisson means

4.9/fb Dimuon mass spectrum

CMS PAS EXO-11-019

- Taking full acceptance, up to η<2.4
- 85% acceptance * efficiency
- Main background due to DY, NLO uncertainties like electron channel





The uncertainties on the data points (statistical only) represent 68% confidence intervals for the Poisson means

Exclusion Limit – Dielectrons

CMS PAS EXO-11-019

Exclusion limit on ratio of cross sections using **Bayesian** method.

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

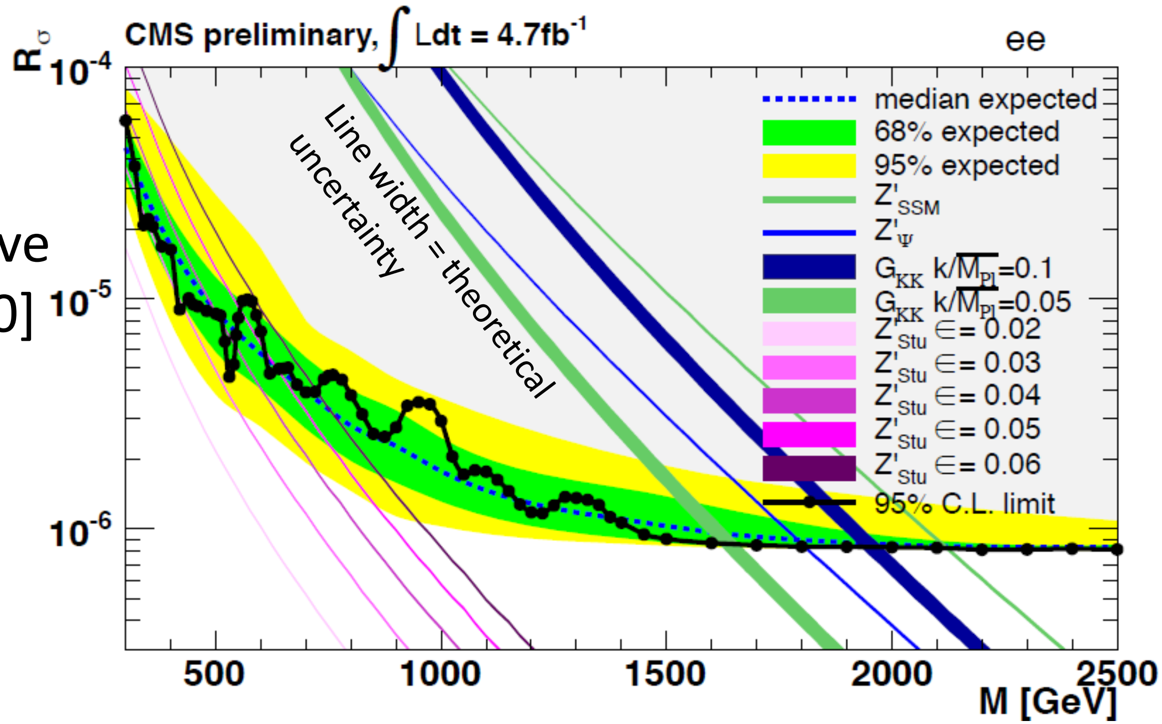
- Cross check with simple cut-and-count method

Limit input:

- Bkgr shape (exponential above Z-peak), 15% error [200-2000]
- Z peak [60-120] ~0.5 mill events, 10% acc x eff
- ΔM as function of mass

Also search for **excess.** LEE by bkgr-only pseudoexperiments

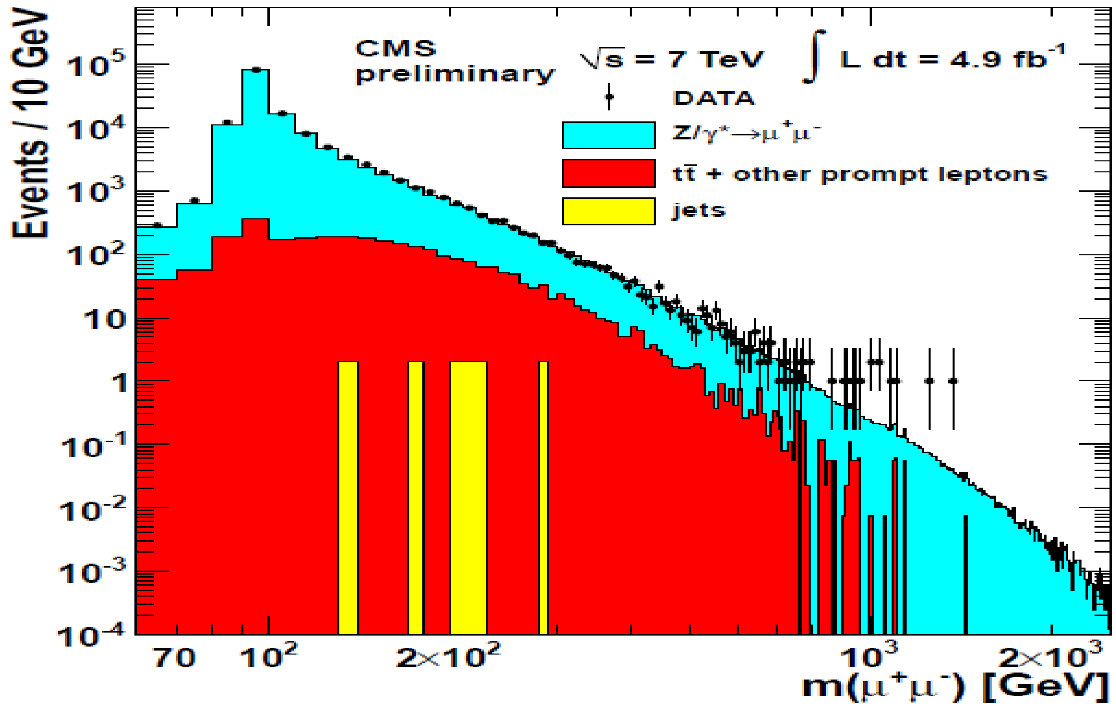
- Highest local significance at M=963 GeV is 2.4 going down to 0.3 when including LEE



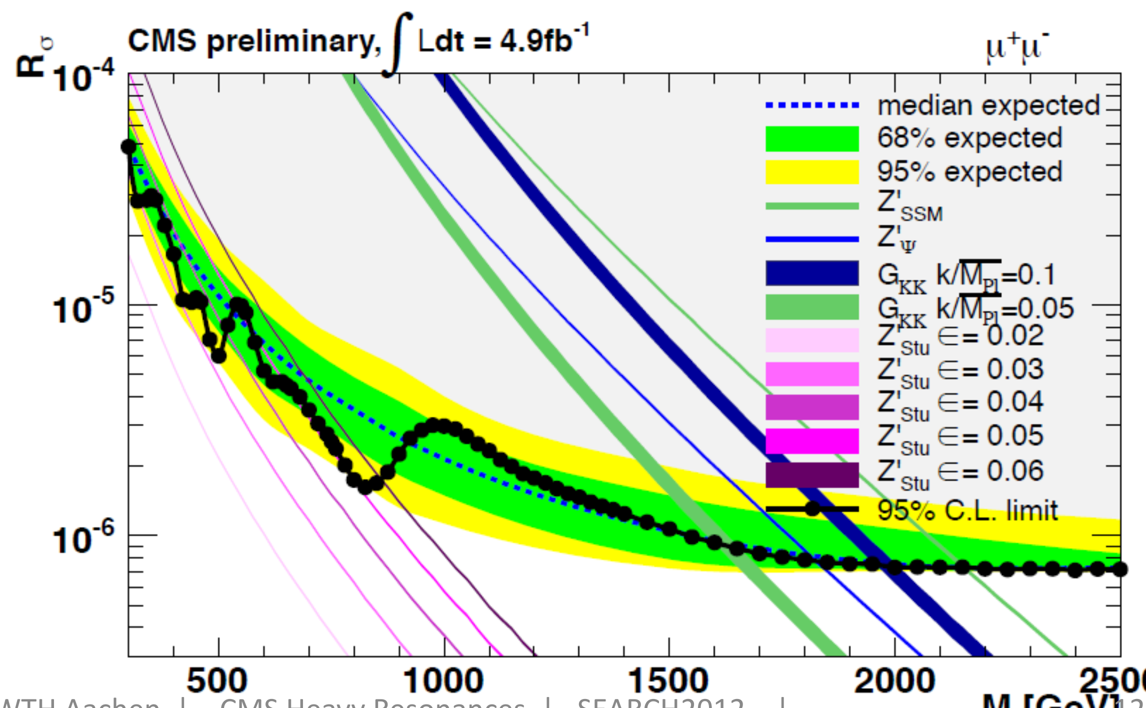
model	exclude mass (GeV/c^2)
SSM Z'	2120
Z'_Ψ	1805
RS Grav ($k/M_{pl} = 0.1$)	1950
RS Grav ($k/M_{pl} = 0.05$)	1630

Exclusion limits μμ

CMS PAS EXO-11-019



Same strategy as electrons adapted to muon channel.
R_σ = ratio of xsec Z′ / Z



Limit input:

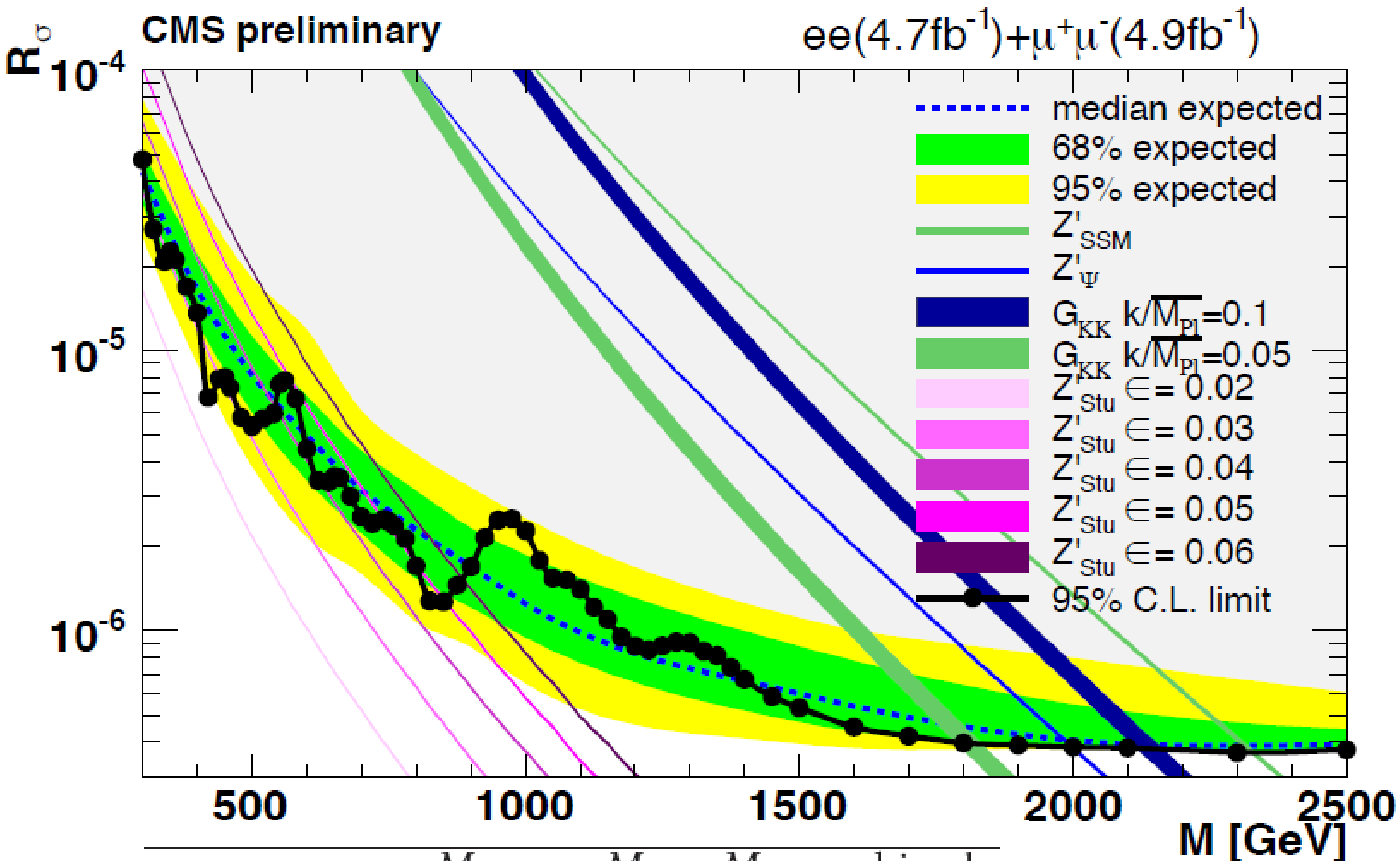
- Exponential bkgr shape
- #Z from pre-scaled trigger ~700, 27% acc x eff
- ΔM as function of mass, lower for muons

Excess search:

Highest local significance at M=1004 GeV at 1.2 which reduces to -0.7 when incl. LEE

Combined Exclusion Limit 95% C.L.

CMS PAS EXO-11-019



	$M_{\mu^+\mu^-}$	M_{ee}	M_{ll}, combined
Z'_{SSM}	2150	2120	2320
Z'_{ψ}	1830	1810	1990
G_{KK}, $c = 0.1$	1980	1940	2140
G_{KK}, $c = 0.05$	1620	1630	1810

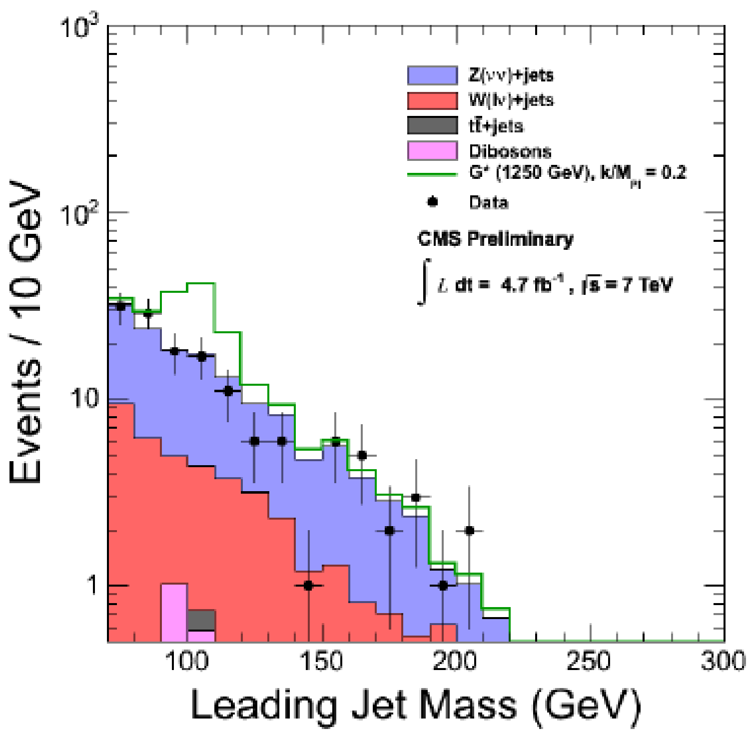
RS graviton → Jet + MET

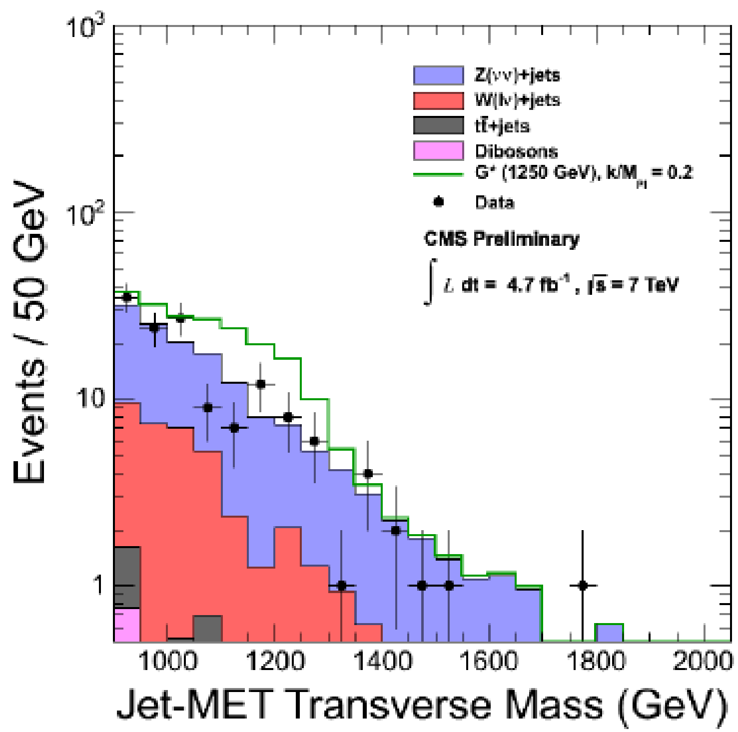
CMS PAS EXO-11-061

RS graviton $G^* \to ZZ \to q\bar{q}\nu\bar{\nu}$ with **boosted Z** yielding signal of **jet + MET**

Search is **signature oriented**, RS model serves as a benchmark model

- Trigger: jet + MET (fully efficient for p_T>200 GeV, MET>300 GeV)
- Signal: single jet (particle flow jet, M_{inv} ~ Z) and MET





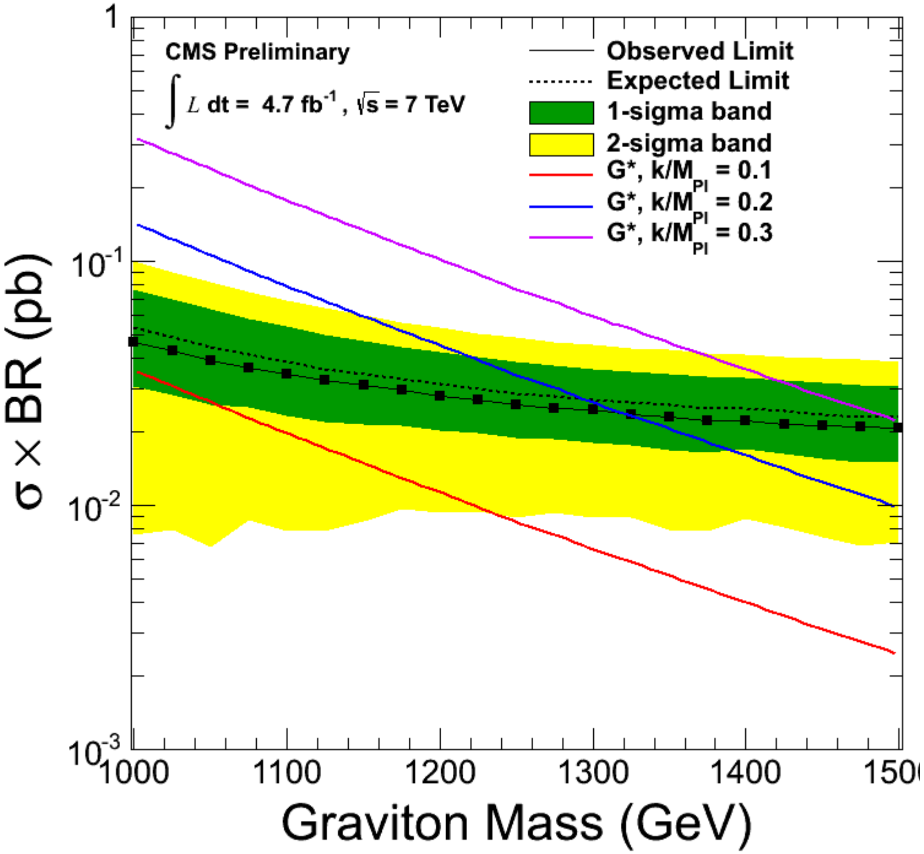
Use correlation $m_J - M_T$(j-MET) to suppress SM background

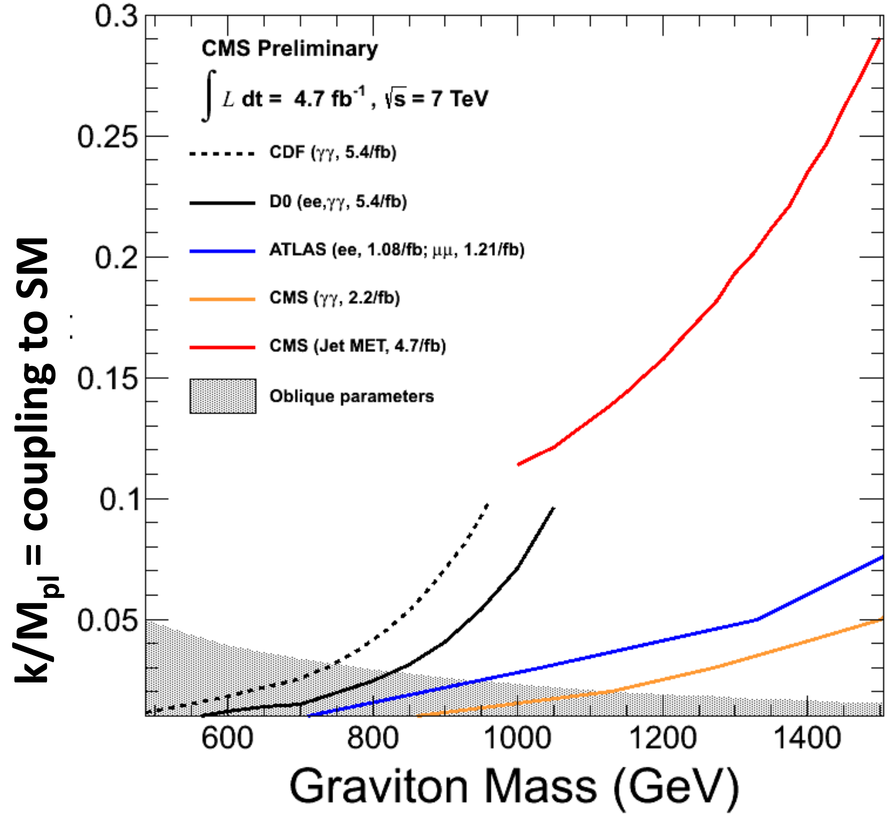
RS graviton → Jet + MET

CMS PAS EXO-11-061

95% C.L. exclusion limits

Systematic uncertainties ~5% (4% PDF, 1% JES, 3% MET)

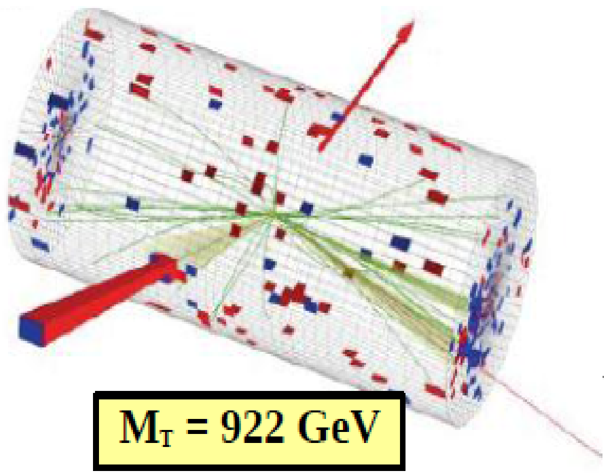




m_G = Mass of lightest Graviton excitation

$W' \rightarrow \ell\nu$

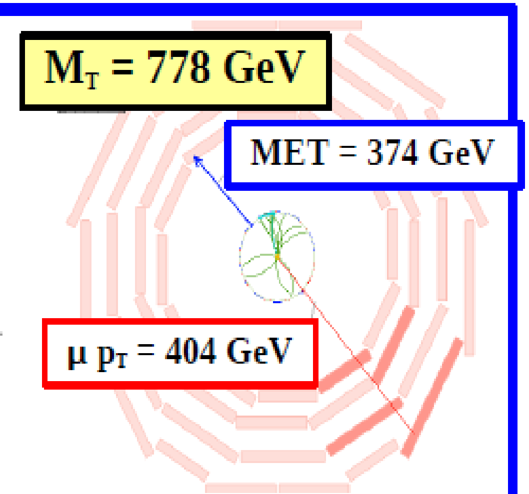
Signature: high energy lepton and "nothing else"



$W' \rightarrow \ell\nu$ (EXO-11-024):

High energy lepton and "nothing else"

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



Analysis 1) **no interference with SM W** (right-handed W′). Signal samples generated individually with PYTHIA6. Limit = f($m_{W'}$)

Analysis 2) including W-W′ **interference**. Signal samples are generated with Madgraph as W+W′ → requires M_T threshold. Cross section limit as function of MT threshold.

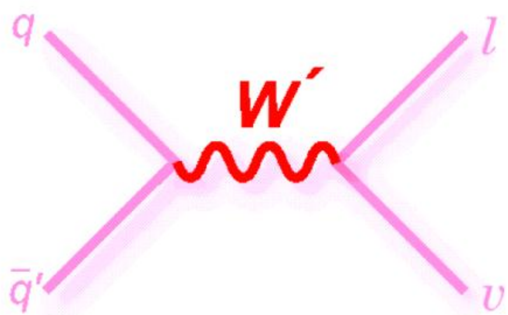
W´→lν Signal (Pythia)

Strategy for all previous searches in lν channel

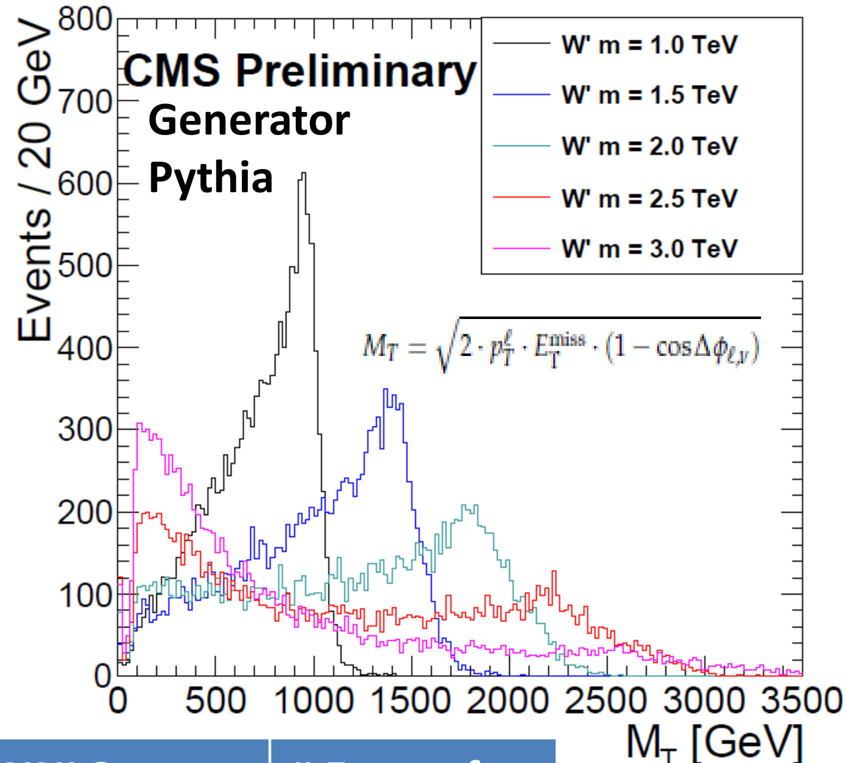
For experimental search:

- Assume **SM-like couplings** (+ tb-channel), ~8% per channel
- SM-like coupling strength $g'/g_{SM} \sim 1$
- Impact of detector resolution.

Channels: W´ → eν and W´ →μν



W´→dijets see hadronic talk



M(W´) [TeV]	NNLO xsec x BR W´→lν	# Events for 4/fb full MT
1.0	0.88 pb	3520
1.5	0.095 pb	380
2.0	0.0135 pb	54
3.0	0.00071 pb	2.8

Analysis Cuts

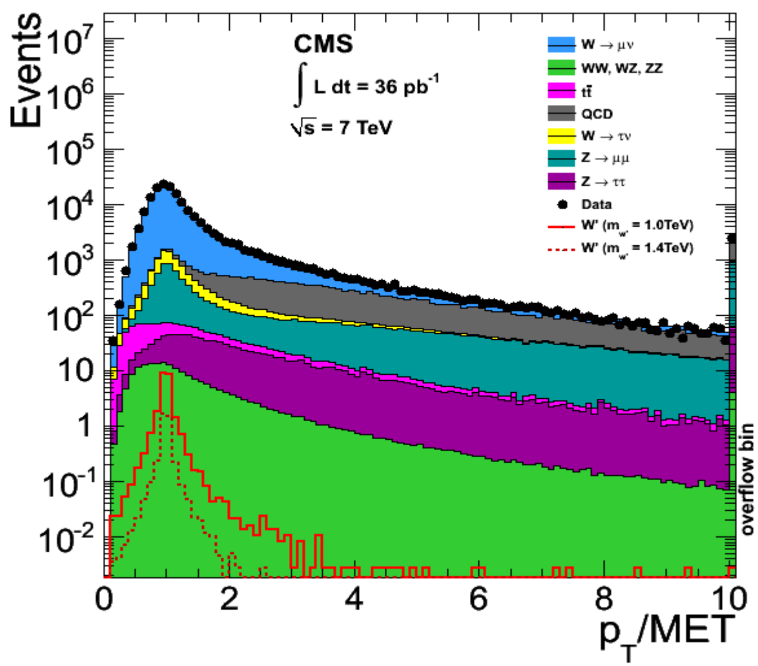
CMS PAS EXO-11-024

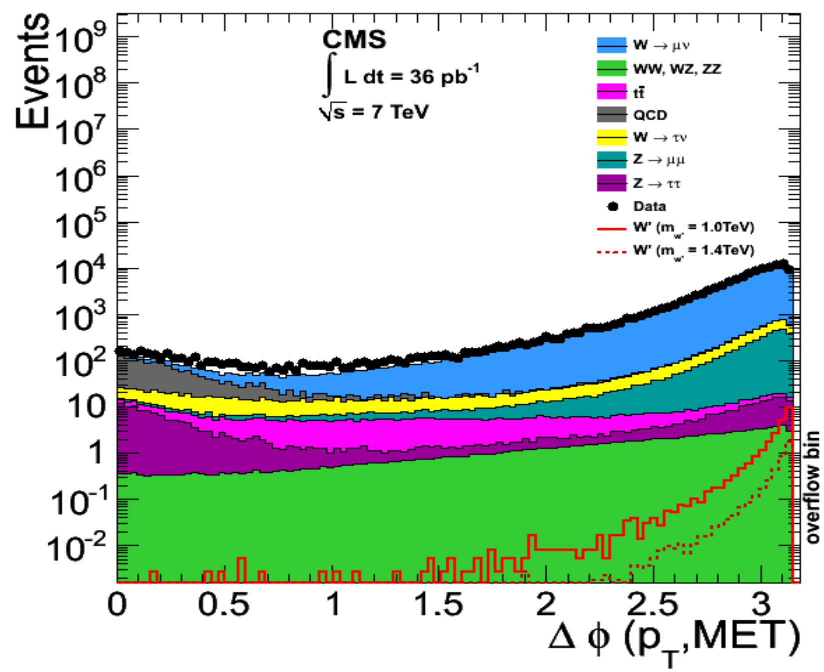
Single lepton trigger with increasing p_T threshold. Common offline p_T cut.

Kinematic cuts in addition to e/mu selection:

- Only 1 lepton with p_T>45 GeV or high quality electron with E_T>85 GeV.
- $0.4 < p_T/\mathrm{MET} < 1.5$
- $\Delta\phi(p_T,\mathrm{MET}) > 2.5$

Analysis also possible with only the lepton signal, ~10% less sensitivity





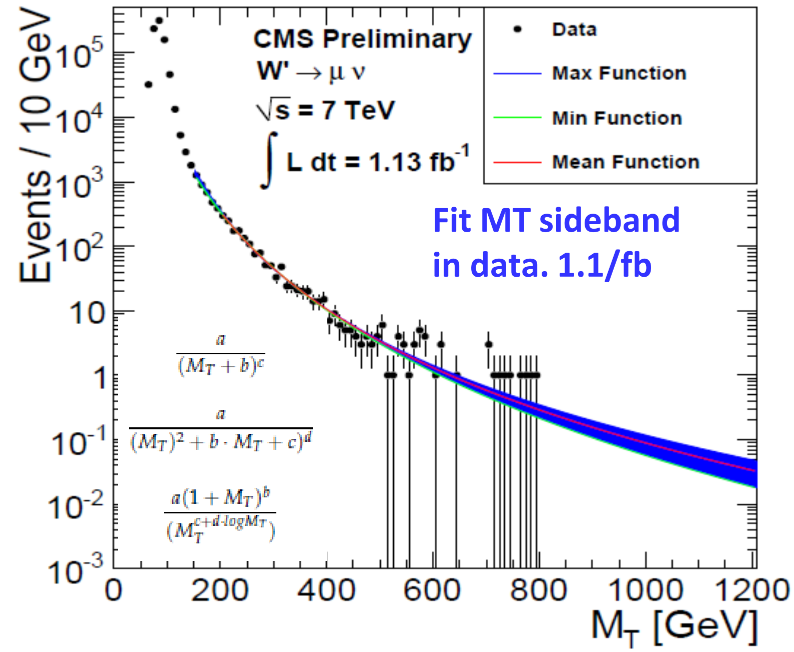
Backgrounds

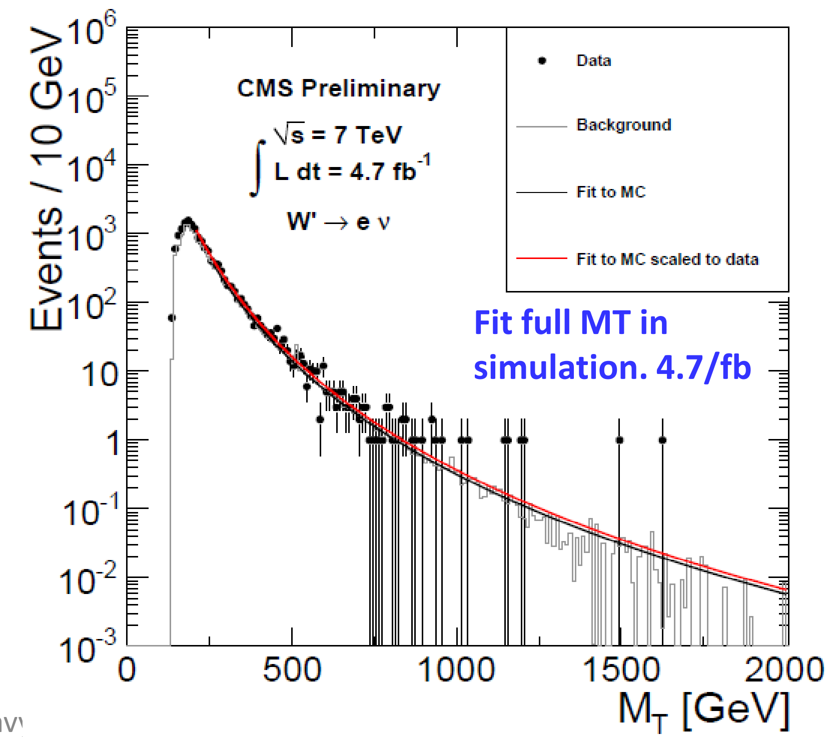
CMS PAS EXO-11-024

Methods:

- **Fit to data**. Fit lower M_T **sideband** (M_T ~200 – 650 GeV) with different functions and varying sideband width. Uncertainties: from variations + extrapolation uncertainty + fit errors.

- Fit **full** M_T distribution (up to 2500 GeV) with **simulation**. Normalization from data. Uncertainties from fit.

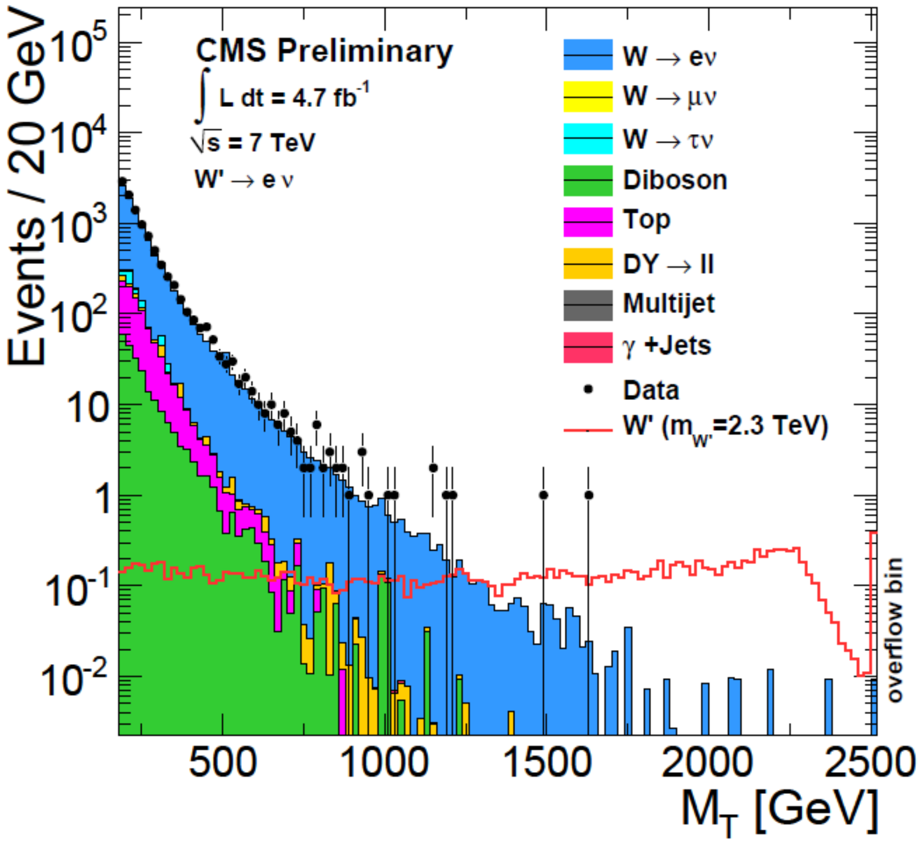


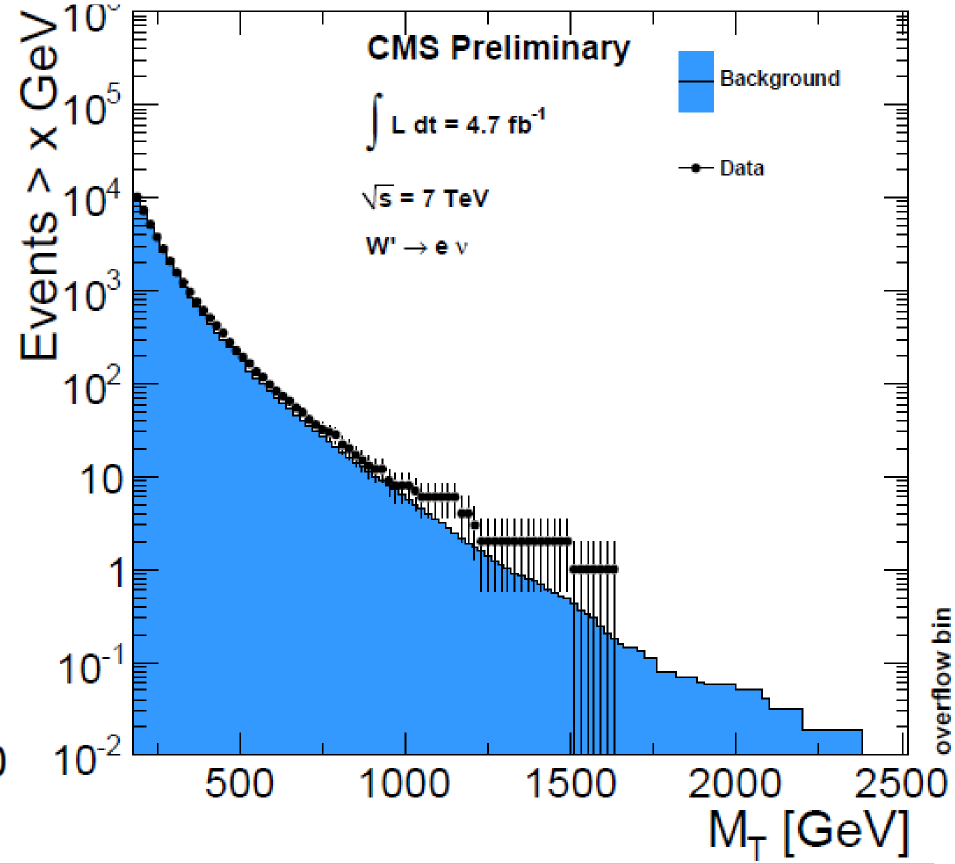


W′ →eν with full 2011 dataset 4.7/fb

CMS PAS EXO-11-024

Average signal efficiency ~80% including ~90% geometrical acceptance



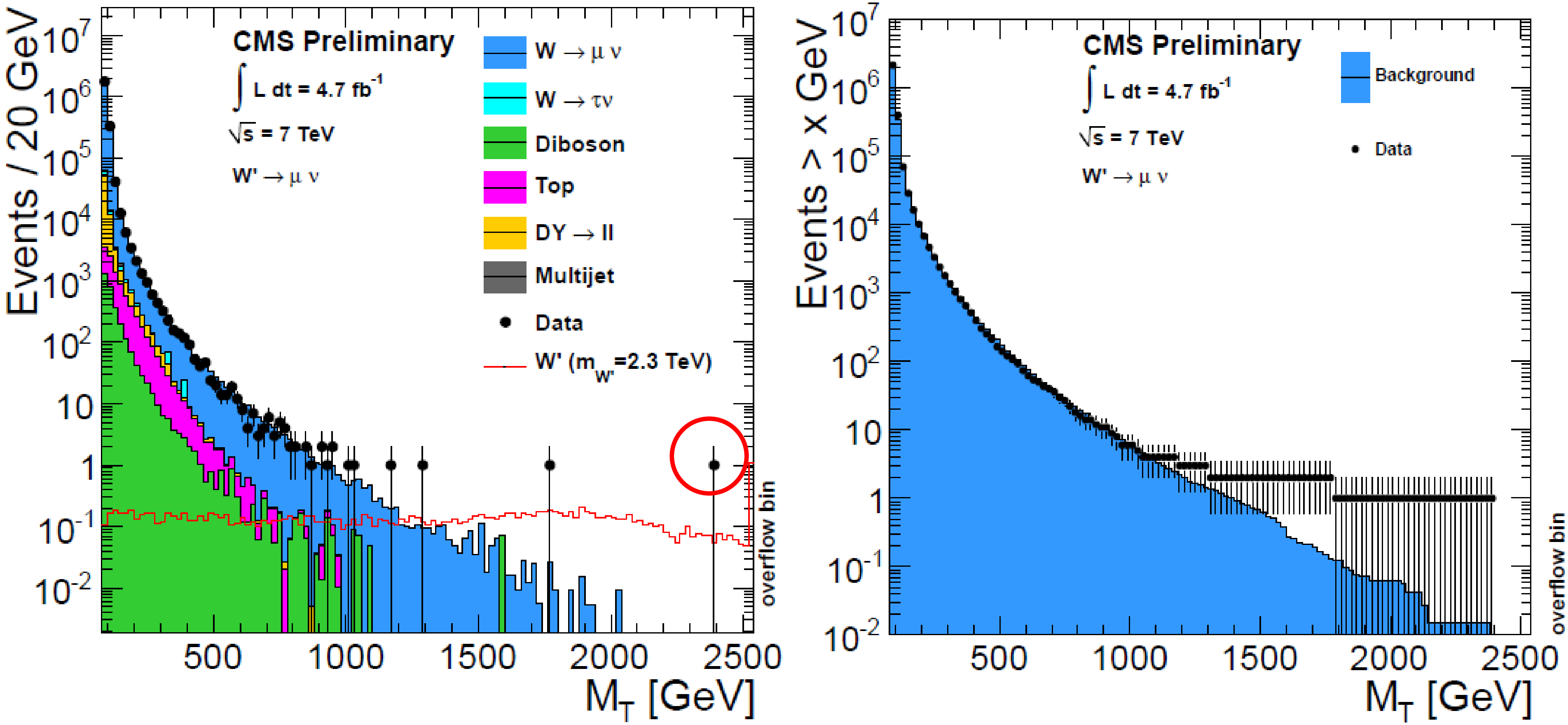


M_T > [GeV]	600	700	800	900	1000	1100	1200
Data	83	41	22	12	8	6	3
SM expected from bkgr fit	76.7 +/- 10.5	37.51 +/- 4.9	20.0 +/- 2.7	11.4 +/- 1.6	6.8 +/- 1.1	4.3 +/- 0.8	2.8 +/- 0.6

W′ →μν with full 2011 dataset 4.7/fb

CMS PAS EXO-11-024

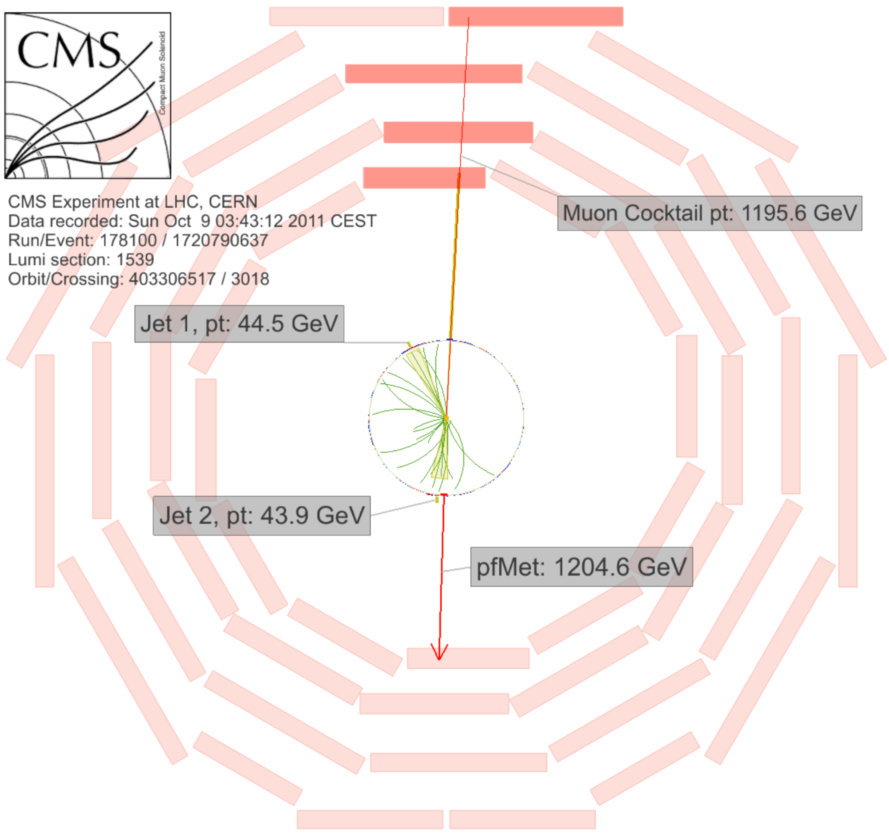
Acceptance * efficiency ~80%, comparable to electron channel

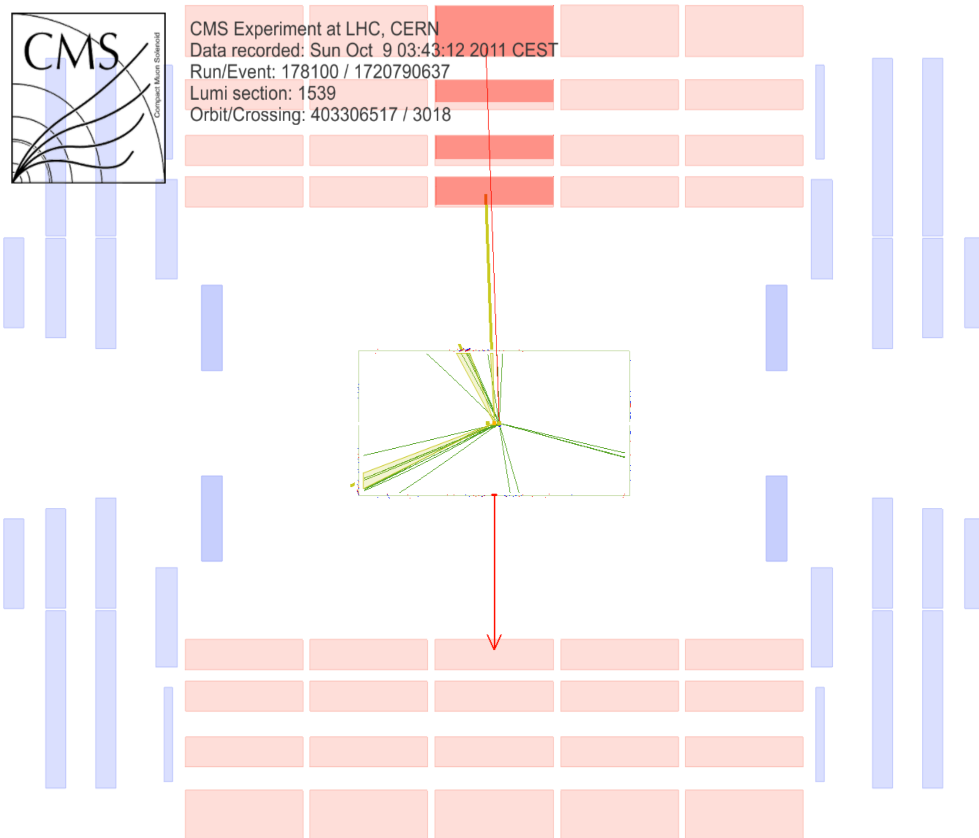


Mt > [GeV]	600	700	800	900	1000	1100	1200	1300
Data	62	36	16	11	6	4	3	2
SM expected from bkgr fit	67.9+/- 7.6	32.6+/- 5.0	17.0+/- 3.3	9.5+/- 2.3	5.6+/- 1.6	3.4+/- 1.1	2.2+/- 0.8	1.5+/- 0.6

Max. M_T Event (M_T~2.4 TeV, $\mu\nu$)

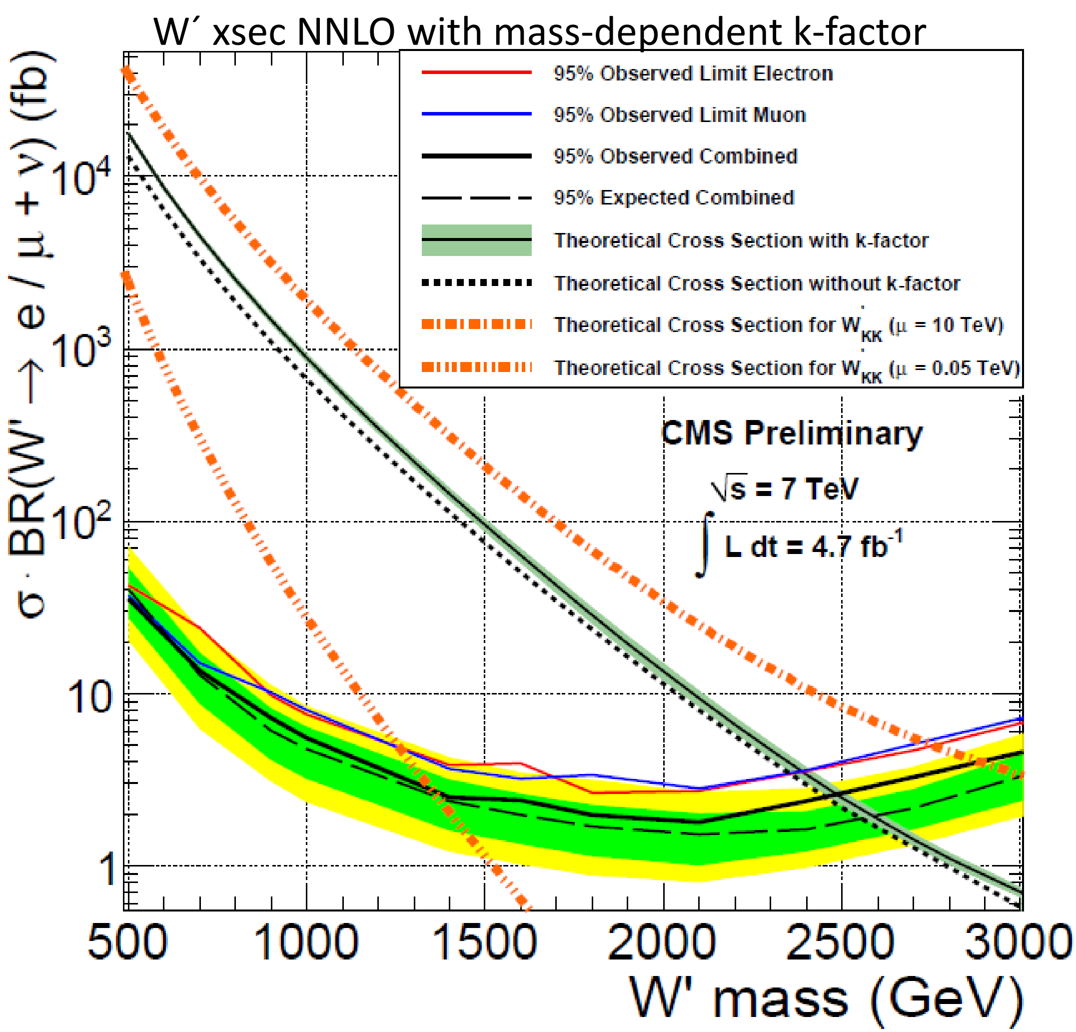
Uncertainty on muon p_T~70 GeV, on M_T~130 GeV





Exclusion Limits 95% C.L.

CMS PAS EXO-11-024



In orange: Interpretation in terms of UED

Single bin counting experiment

- Search window optimized for **best expected limit** for each mass point
- Optimization independently in each channel

Limits per channel ~2.4 TeV

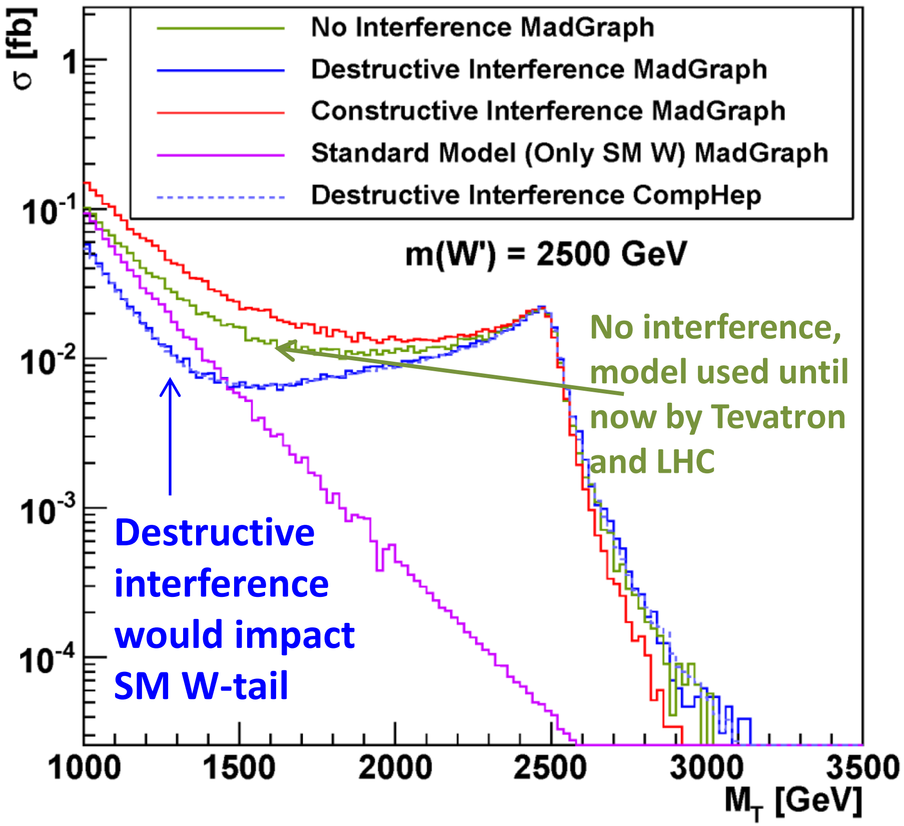
Combining LLH of both channels (W´->ev and $\mu\nu$) ~2.5 TeV

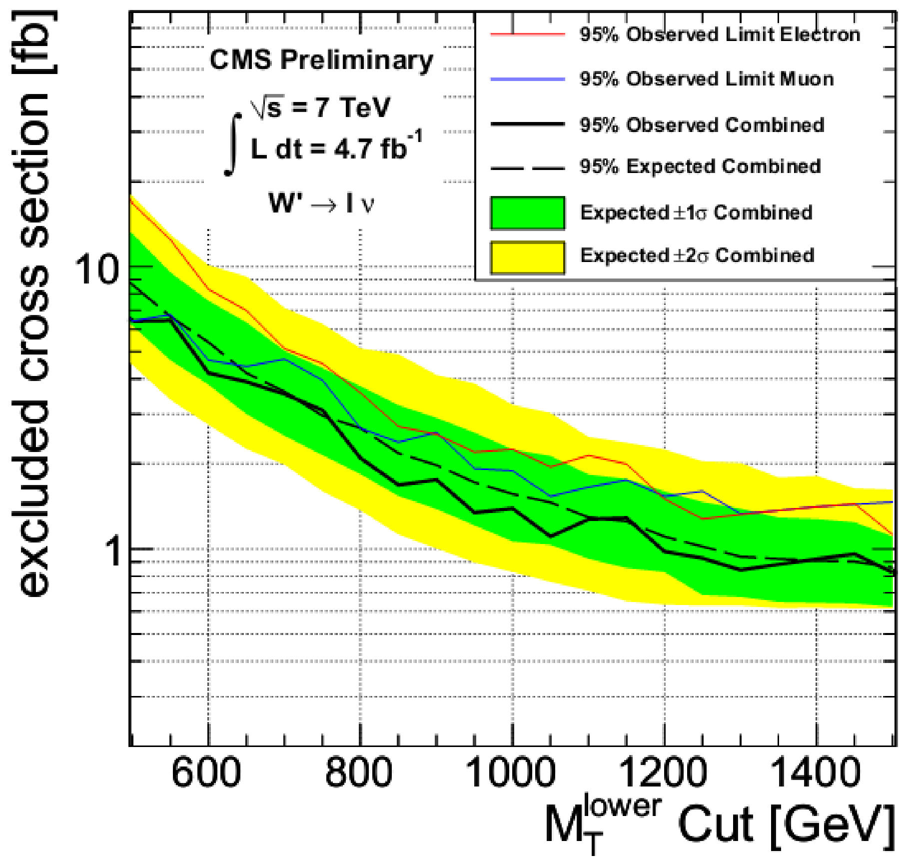
Systematic uncertainties on signal mainly related to detector performance. Largest contributions from mu and MET resolution (10% each, impact on signal <0.5%)

Including W-W´ Interference

CMS PAS EXO-11-024

- If W´ is left-handed, expect interference with SM W → modulation of transverse mass spectrum and impact on mass limits (~10%)
- First time simulated and considered in leptonic W' channels (Madgraph)





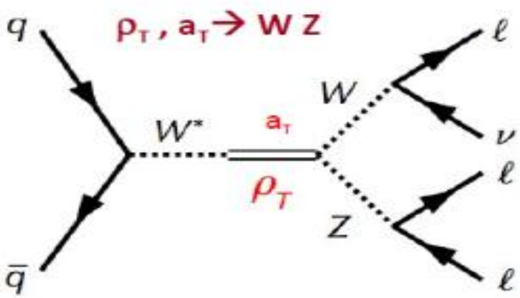
$W'/\rho_{TC} \rightarrow WZ \rightarrow$ 3 leptons + MET

CMS PAS EXO-11-041

Clear signature of three high momentum leptons (e,μ)

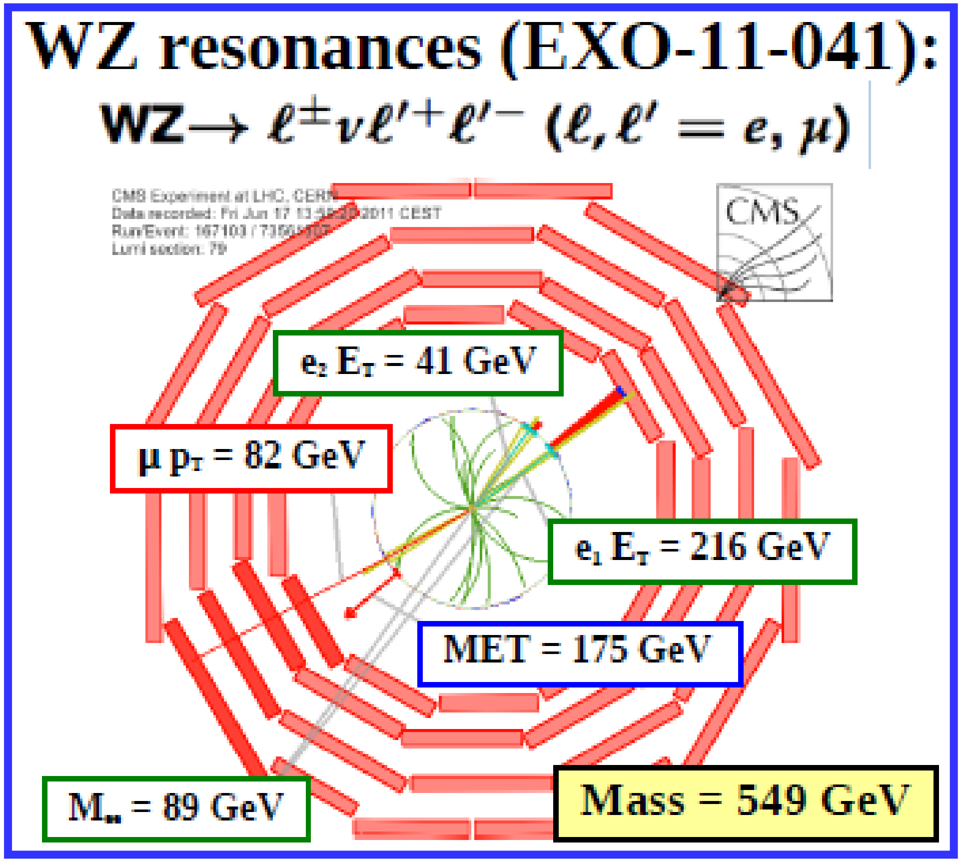
Channel (with public result):

$\mathbf{WZ} \rightarrow \ell^{\pm}\nu\ell'^{+}\ell'^{-}\ (\ell,\ell' = e,\ \mu)$



Recently added channels:

WZ→ lljj, Wγ→e$\nu\gamma$



$W'/\rho_{TC} \rightarrow WZ \rightarrow$ 3 leptons + MET

CMS PAS EXO-11-041

RWTH AACHEN UNIVERSITY

For experimental search

- **For W´ complementary** to lepton channels (e.g. fermiophobic models). Assume WZ as an additional channel.
- BR ~2x less than $W' \rightarrow l\nu$. Further reduced by requiring leptonic decay of W,Z
- Signal generated individually in PYTHIA, no interference
- Same k-factors as $W' \rightarrow l\nu$

- **"Technicolor Strawman Model" (TCSM)**
- $M(\rho_{TC}) < 1$ TeV
- $M(\rho_{TC}) \sim M(\pi_{TC}) \rightarrow BR(\rho_{TC} \rightarrow WZ) \sim 100\%$
- $\Gamma < 5$ GeV, ρ_{TC} much narrower than W´

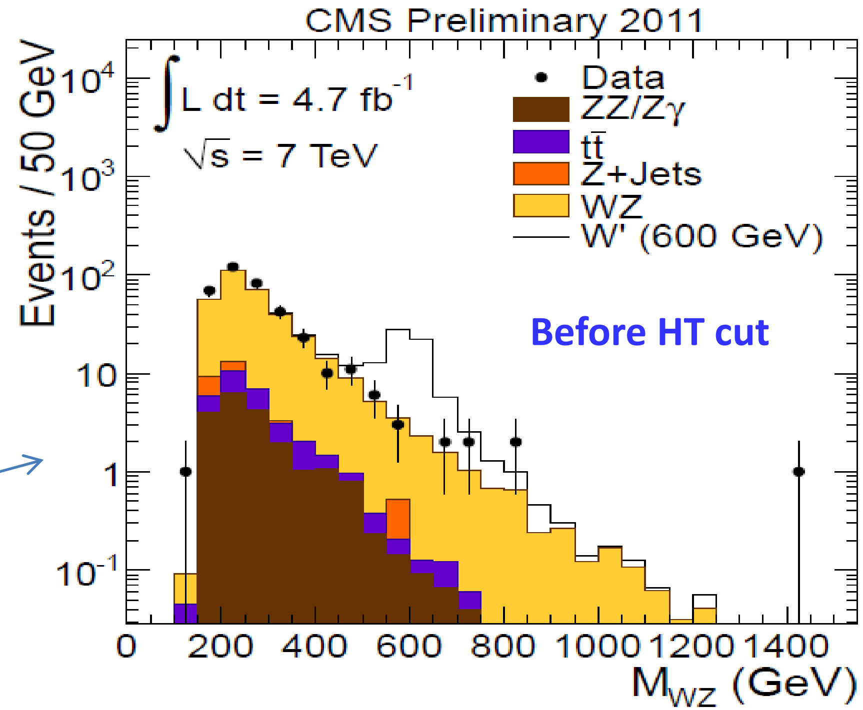
Main background is SM diboson production. CMS diboson xsec measurement used for background prediction (spin-off).

Analysis Steps

CMS PAS EXO-11-041

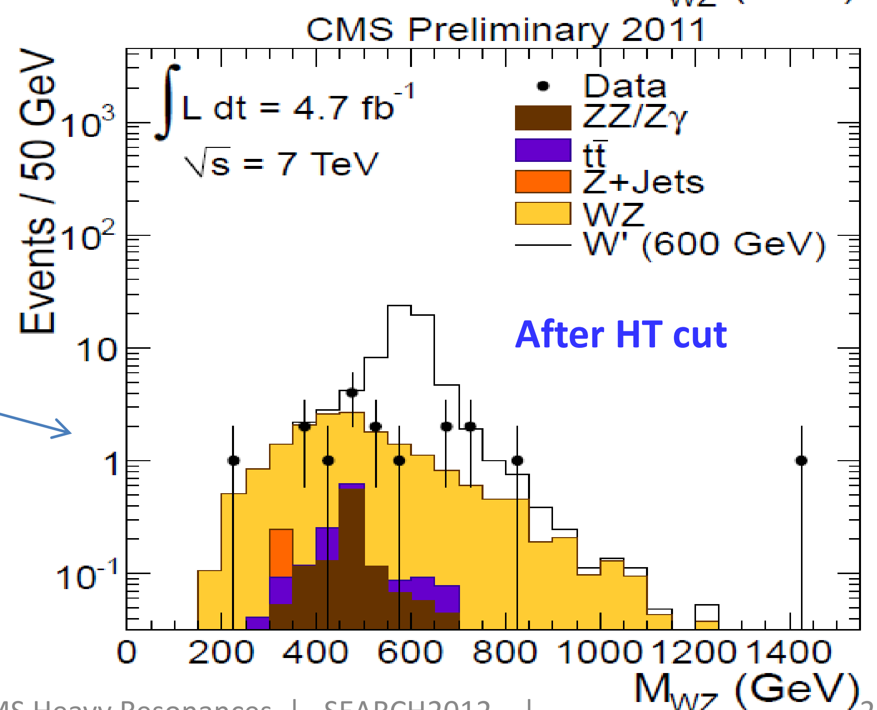
Remove everything but SM WZ. Then add further cuts to suppress SM WZ.

- Reconstruct Z mass [60-120] for 1 Z
- Reconstruct W M_T
- Reconstruct M_{WZ} . WZ accounts for 90% of bkgr. Good agreement data-MC



- To discriminate signal from bkgr:

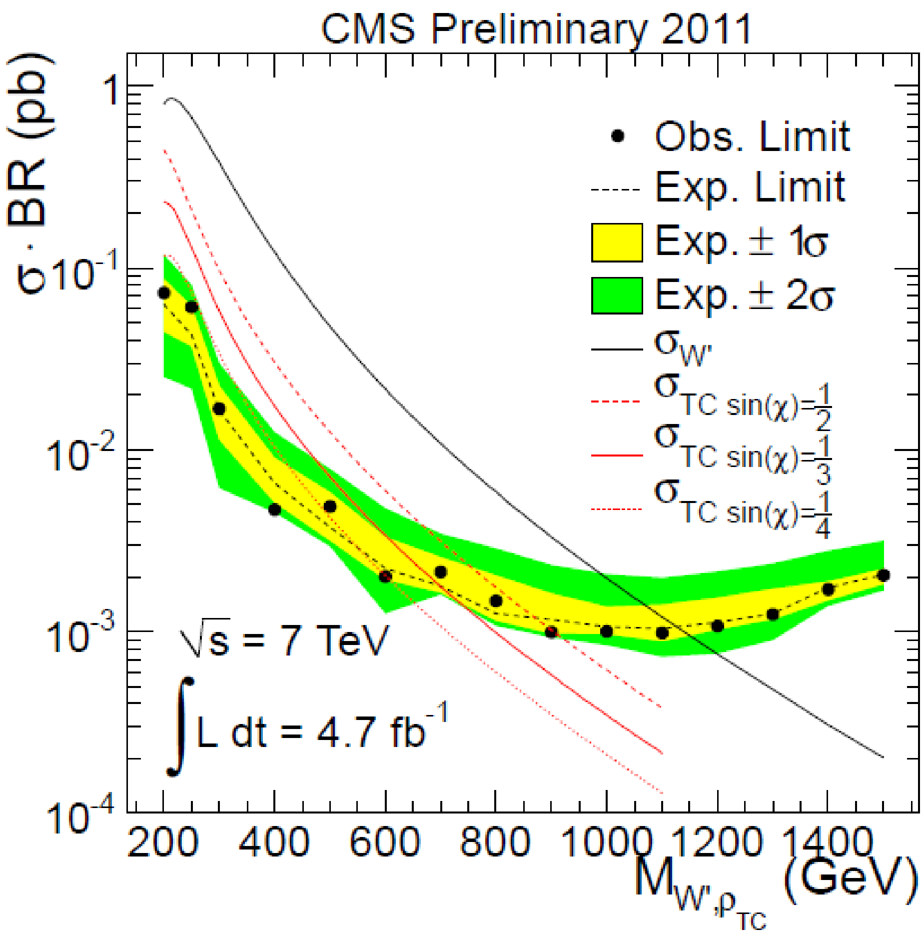
$$H_T \equiv \sum p_T^{\ell}$$



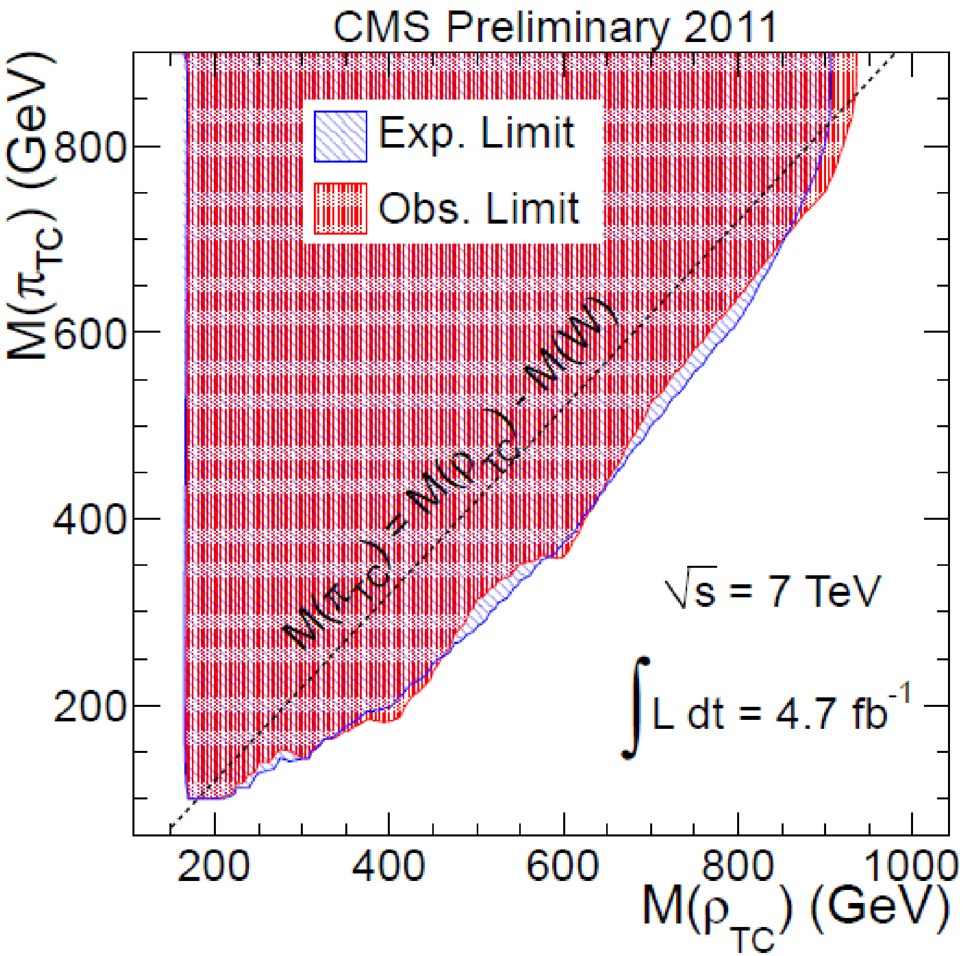
- Search for bump in WZ mass distr.
- Optimize search window for W´ masses

Exclusion Limits 95% C.L.

CMS PAS EXO-11-041

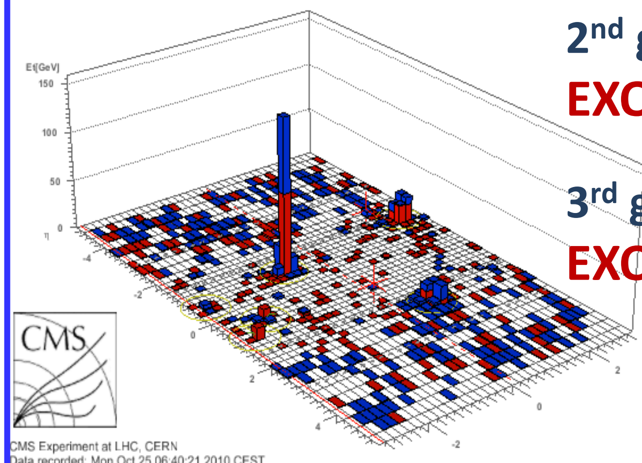


Mass of W´ or Technicolor rho



Technicolor parameter space

LQ

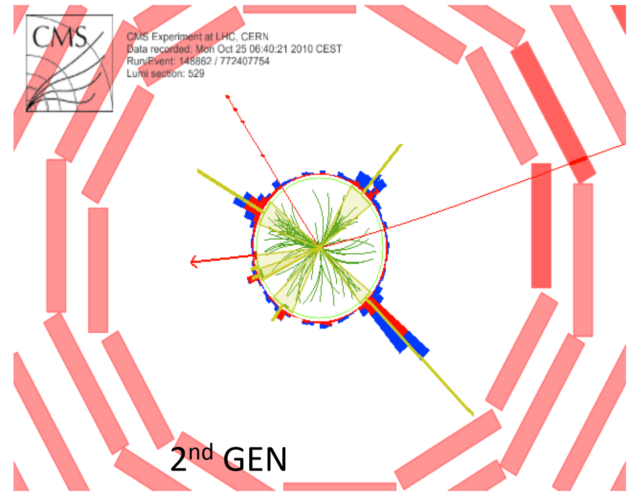


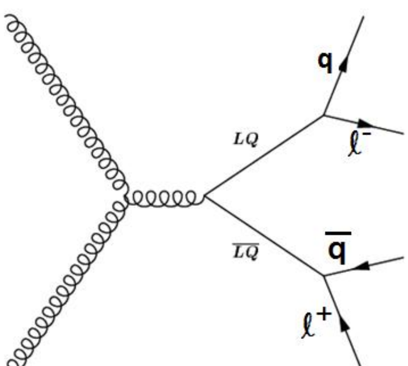
2nd generation Leptoquarks

EXO-11-028 with 2 fb^{-1}

3rd generation Leptoquarks

EXO-11-030 with 1.8 fb^{-1}





Signatures:

2nd generation: **$\mu^+\mu^-$ + jets, $\mu\,\nu$ + jets**

3rd generation: **$\nu_\tau\,\nu_\tau$ + b-jets,** using Razor variable

1st generation: e^+e^- + jets, e ν + jets (released soon for 2011)

2^{nd} Generation LQ, Strategy

CMS EXO-11-028

Object reconstruction and event selection μμjj channel:

- **Muons** as before, with p_T>40 GeV, separated by ΔR>0.3
- **Particle flow jets** (see hadronic talk) with anti-kT algorithm R=0.5, pT>30 GeV
- Scalar sum S_T (μμjj) >250 GeV
- Optimize for each LQ mass:

Table 1: Optimization thresholds for different mass hypothesis of the $\mu\mu jj$ signal.

M_{LQ2} (GeV)	250	350	400	450	500	550	600	650	750	850
$S_T^{\mu\mu} >$ (GeV)	320	450	520	610	640	740	770	850	850	850
$M_{\mu\mu} >$ (GeV)	100	110	140	140	140	140	140	140	110	110
$min M(\mu,\text{jet}) >$ (GeV)	70	130	150	170	260	350	350	350	510	510

Event selection μνjj channel where different from above:

- **MET**>45 GeV. Veto events with 2^{nd} muon or electron.
- MET separated from leading jet by Δϕ>0.5 and from muon by Δϕ>0.8

Table 2: Optimization thresholds for different mass hypothesis of the $\mu\nu jj$ signal.

M_{LQ2} (GeV)	250	350	400	450	500	550	600	650	750	850
$S_T^{\mu\nu} >$ (GeV)	440	540	600	730	740	870	960	910	930	960
$E_T^{\text{miss}} >$ (GeV)	90	125	135	145	190	195	185	160	175	175
$M(\mu,\text{jet}) >$ (GeV)	120	280	310	310	380	380	350	510	510	510

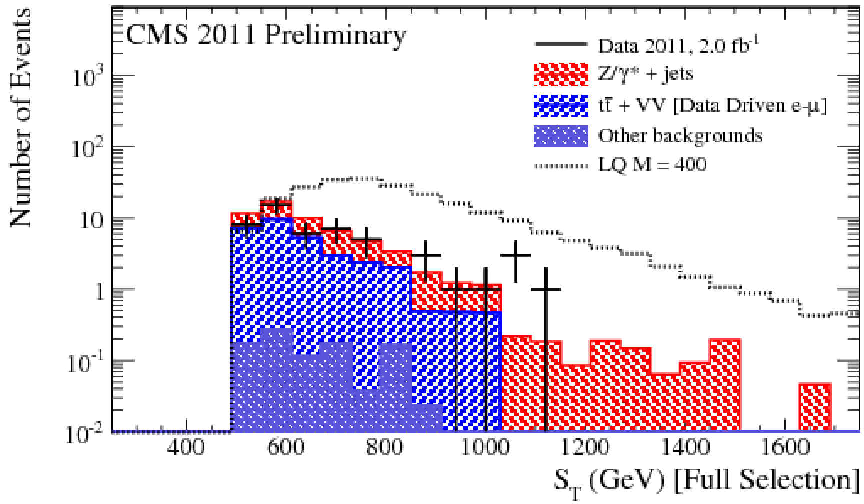
eμjj for ttbar background (emu method see Z´)

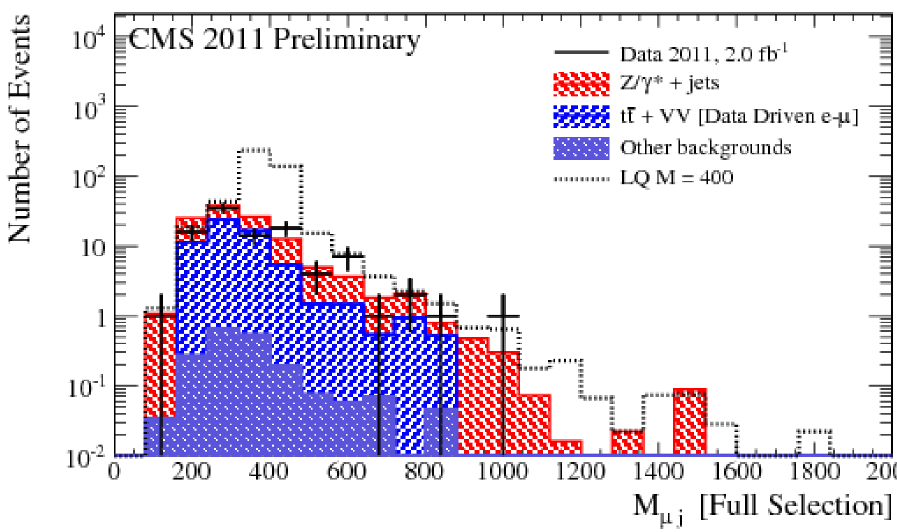
After Final Selection 2/fb

CMS EXO-11-028

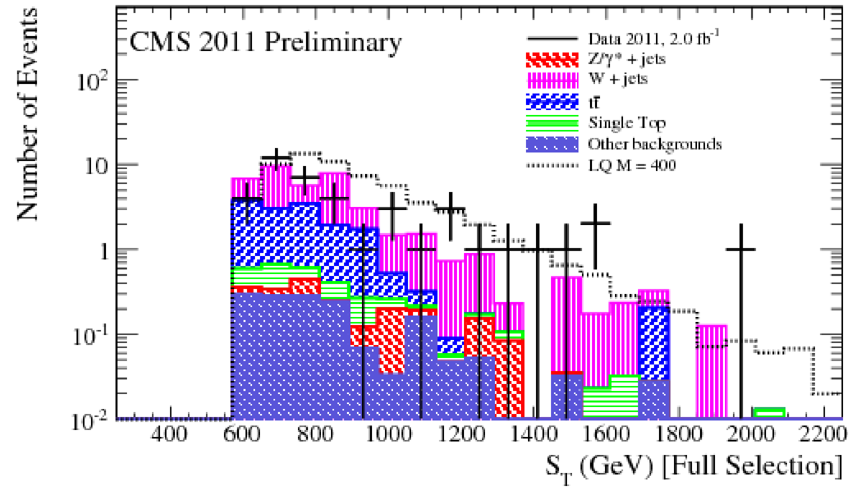
$S_T^{\mu\mu} = p_T(\mu_1) + p_T(\mu_2) + p_T(jet_1) + p_T(jet_2)$

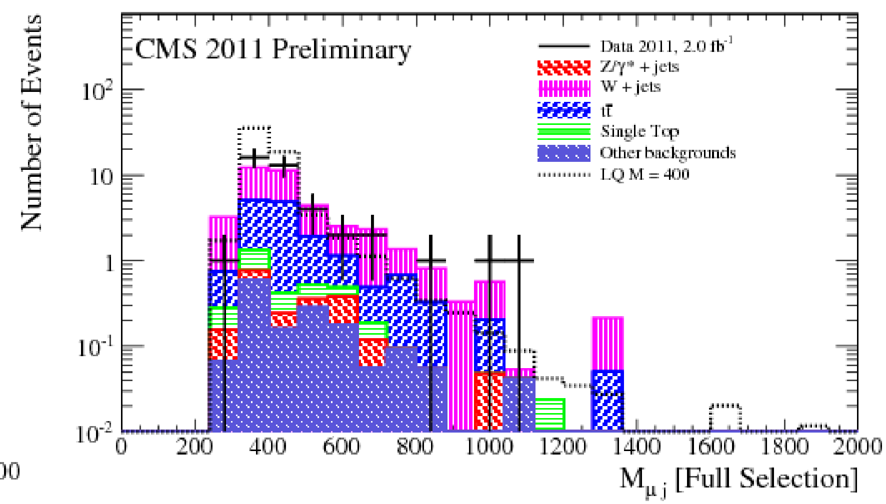
μμjj channel





μνjj channel



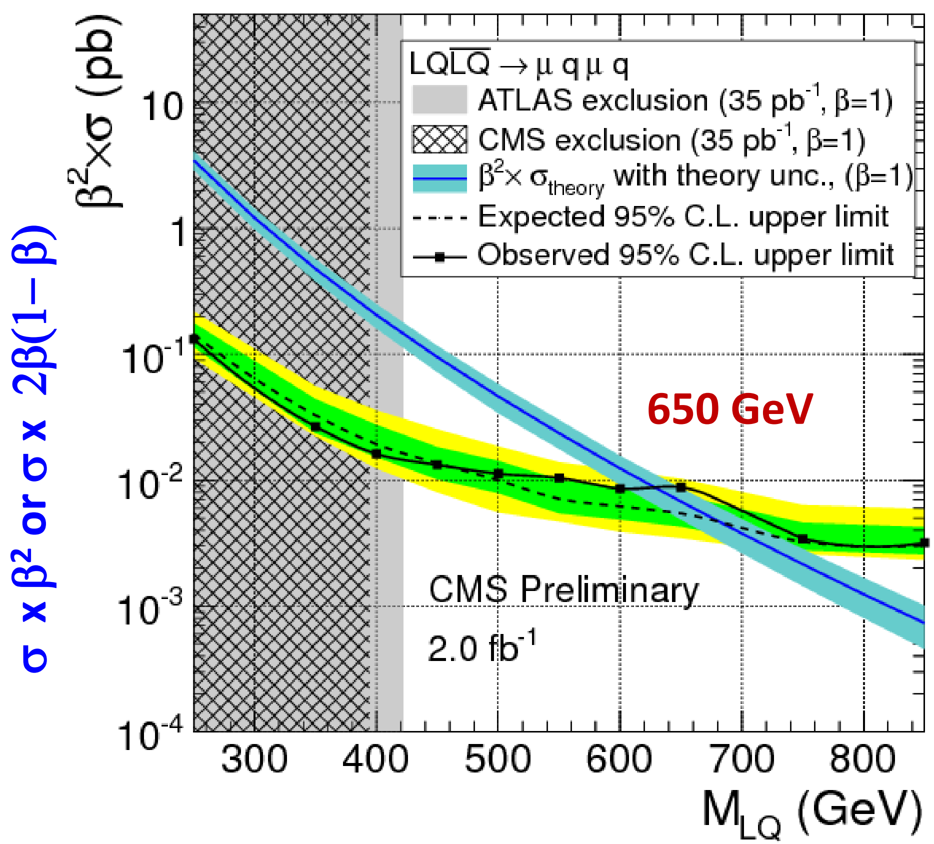


Main background after selection Z+jets and ttbar

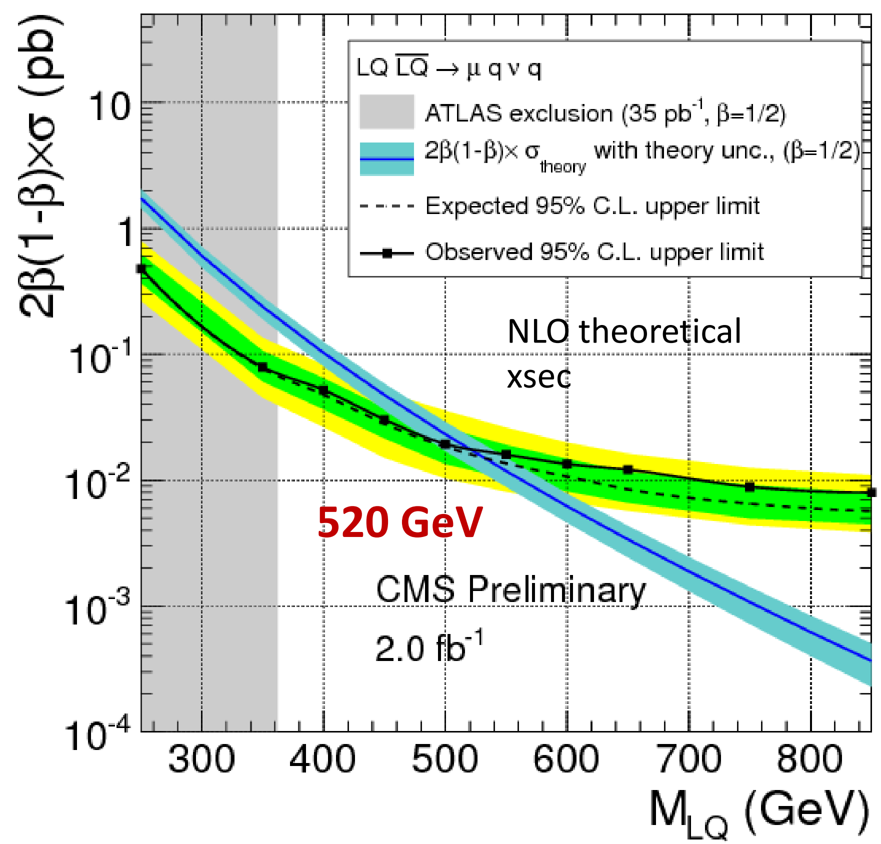
Exclusion Limits 95% C.L. 2/fb

CMS EXO-11-028

μμjj channel



μνjj channel



Statistical analysis using CLs modified frequentist approach

Syst. Uncertainties on μμjj ~28% (dominated by bkgr modelling).

In μνjj channel ~30% (mainly JES)

3^{rd} Generation LQ

CMS EXO-11-030

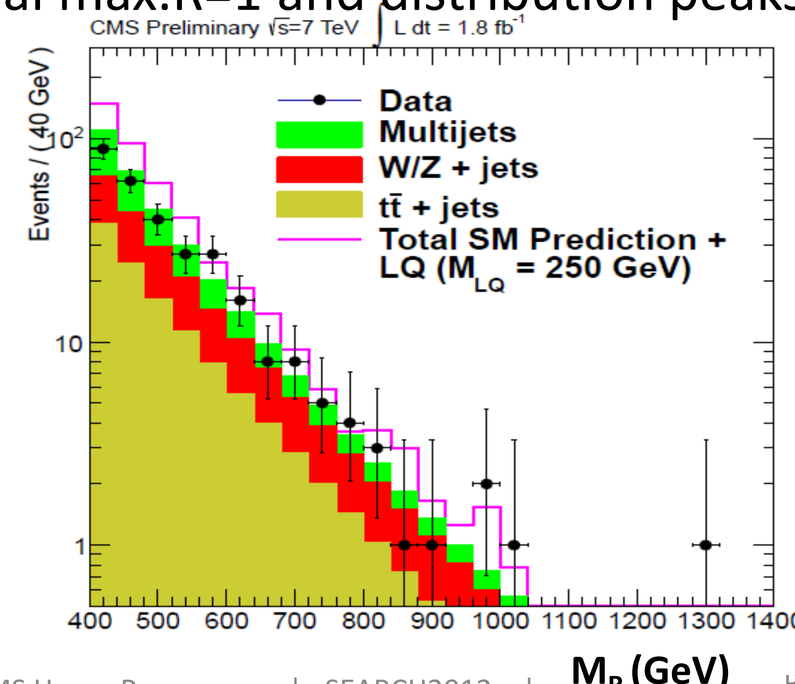
Signal: LQ LQ → ν ν b b = 2 b-jets and MET

- Jets reconstructed with anti-kT (R=0.5). Forcing them into two "mega-jets" with E_{j1} and E_{j2} taking the combination where M_{inv} is minimal.
- Include b-tagging ("track counting high efficiency")
- Define dimensionless **Razor kinematic variable M_R** incl. MET (PF MET) without assumptions on MET shape or details of decay chain.
- Reduce QCD by R>threshold. For signal max.R=1 and distribution peaks ~0.5, while QCD peaks ~0.

Razor dimensionless ratio

$$R = \frac{M_T^R \equiv \sqrt{\dfrac{\not{E}_T(p_T^{j1}+p_T^{j2}) - \vec{\not{E}}_T\cdot(\vec{p}_T^{\,j1}+\vec{p}_T^{\,j2})}{2}}}{M_R \equiv \sqrt{(E_{j1}+E_{j2})^2-(p_z^{j1}+p_z^{j2})^2}}$$

→Set threshold on $R^2>0.25$ (and higher) and $M_R>400$ GeV



Search Strategy

CMS EXO-11-030

Define **“boxes”** of

- MU or ELE: with one loose lepton with p_T>20 GeV, M_R>400 GeV and R^2>0.14 plus 2 jets with p_T>60 GeV
- HADRONIC: without leptons, M_R>400 GeV and R^2>0.2
- Use **lepton boxes for background determination** and control regions
- Shapes for R, M_R for main backgrounds (heavy flavor QCD, tt) from data

Search **signal in Hadronic** with R^2>0.25 (and increasing for larger LQ masses) and at least 2 b-tagged jets and no leptons

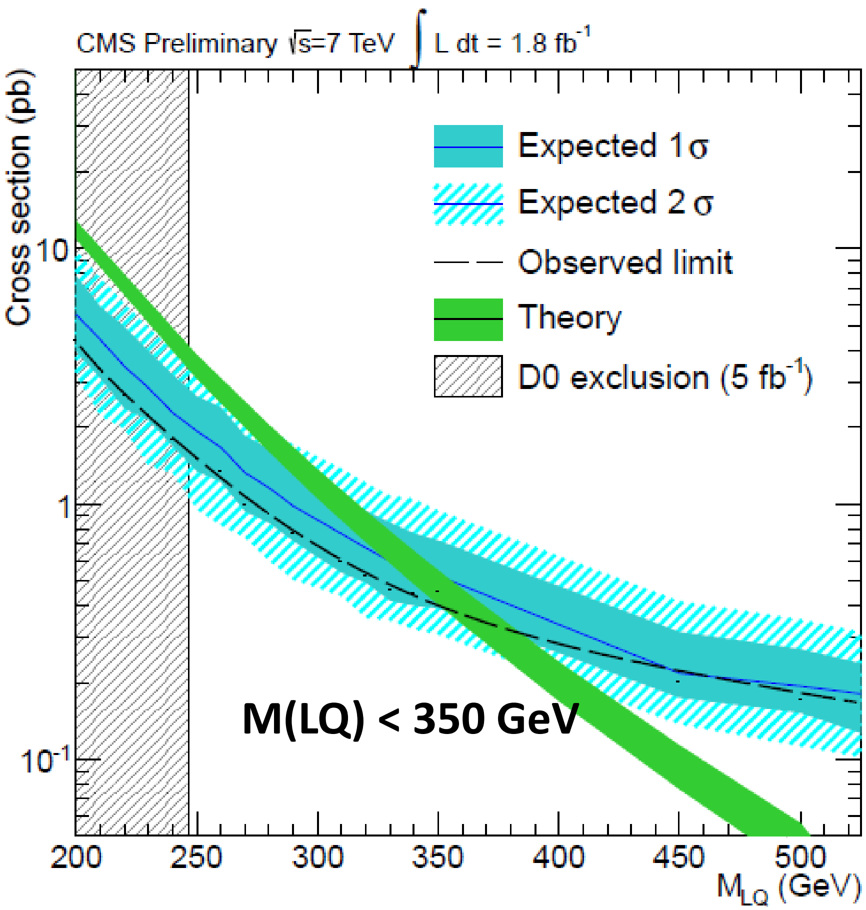
LQ3 mass	R/M_R	Expected Number of Events	Observed Number of Events
>200	$M_R > 400,\ R^2 > 0.25$	326.98 ±30.98	295
>330	$M_R > 400,\ R^2 > 0.30$	195.49 ±25.58	172
>340	$M_R > 400,\ R^2 > 0.35$	121.88 ±21.51	107

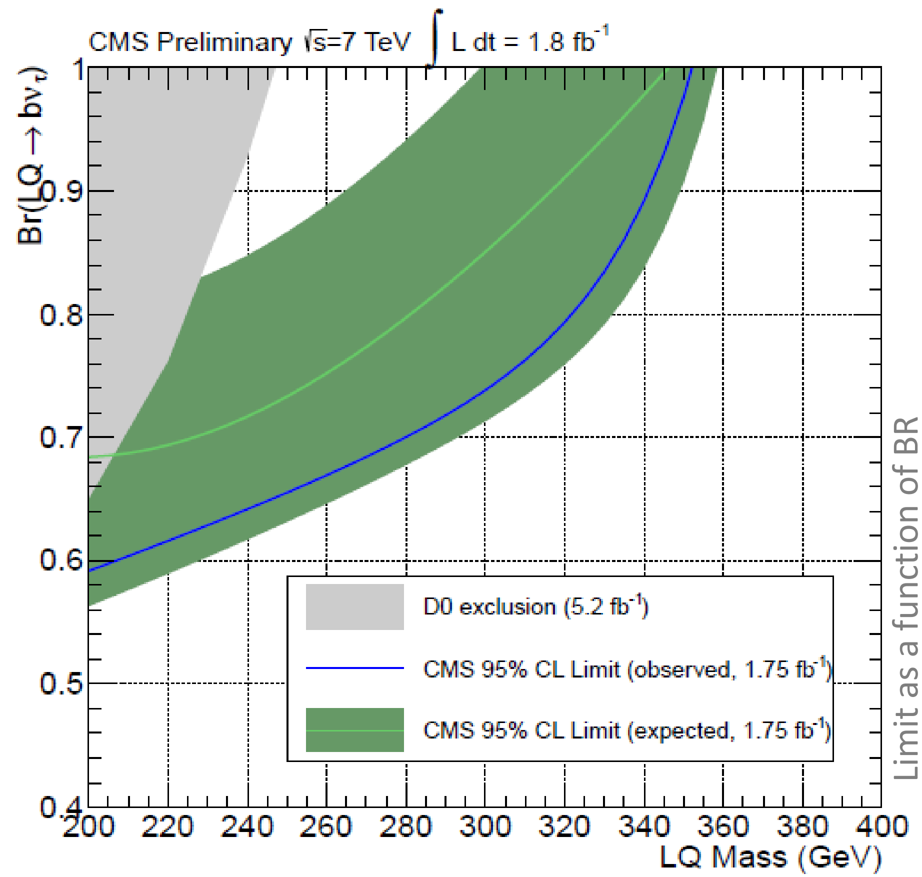
$M_{LQ}[GeV]$	Signal Efficiency
200	0.64 ±0.08
250	1.85 ±0.22
280	3.04 ±0.36
320	5.29 ±0.62
340	4.96 ±0.58
450	9.64 ±1.11
600	11.38 ±1.32

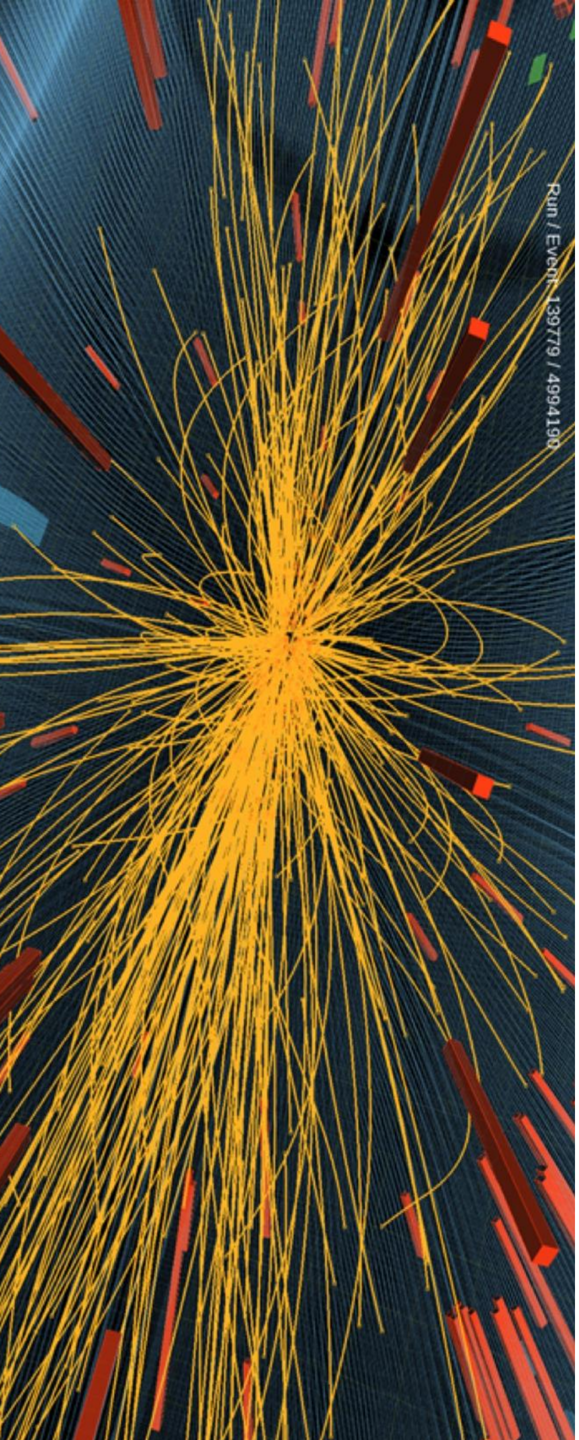
Exclusion Limits 95% C.L.

CMS EXO-11-030

Largest uncertainties from b-tagging (~10%).
Signal PDF 3.5% to 26% (depending on LQ mass)







SUMMARY

Many searches for new heavy resonances beyond SM (Z´, RS, W´, LQ) ongoing in CMS.

No indications for new physics yet…

	95% C.L. exclusion	Channel
Z'_{SSM}	2.3 TeV	$ee + \mu\mu$
Z'_{ϕ}	2.0 TeV	$ee + \mu\mu$
W´	2.5 TeV 1.2 TeV	$e\nu + \mu\nu$, WZ→leptons
G_{KK}	2.1 TeV (c=0.1)	$ee + \mu\mu$
ρ_{TC} TCSM	0.7 TeV	WZ
LQ 2nd GEN	0.6 TeV(β=1), 0.5(β=0.5)	$\mu\mu jj$, $\mu\nu jj$
LQ 3rd GEN	0.35 TeV (β=0)	$\nu\nu jj$

Projections for 2012: increase to 8 TeV and roughly tripling the statistics.