Collider Phenomenology 2011, Cambridge

CMS
Results from 2010

C. H. Shepherd-Themistocleous

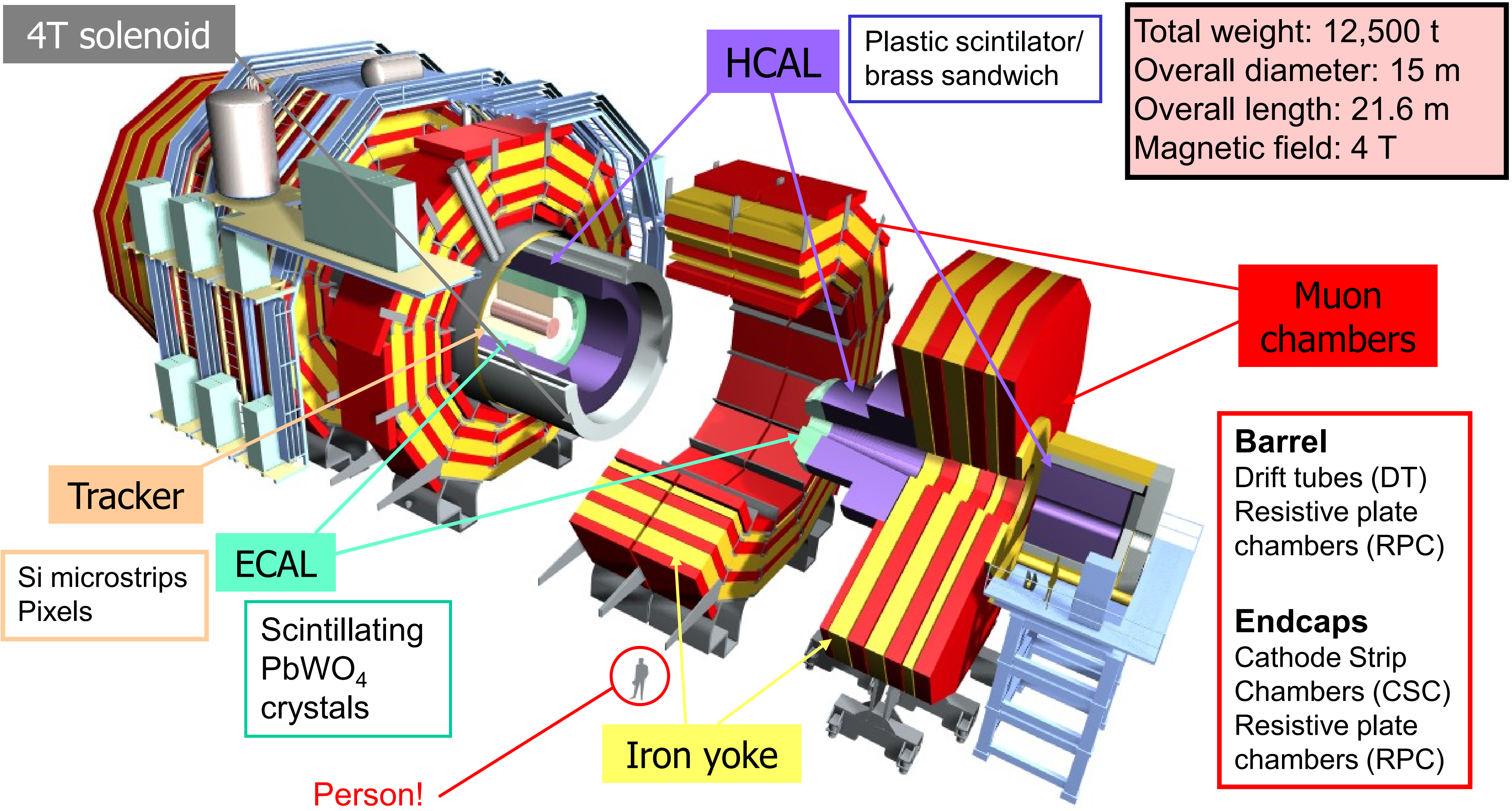
Rutherford Appleton Laboratory

Outline

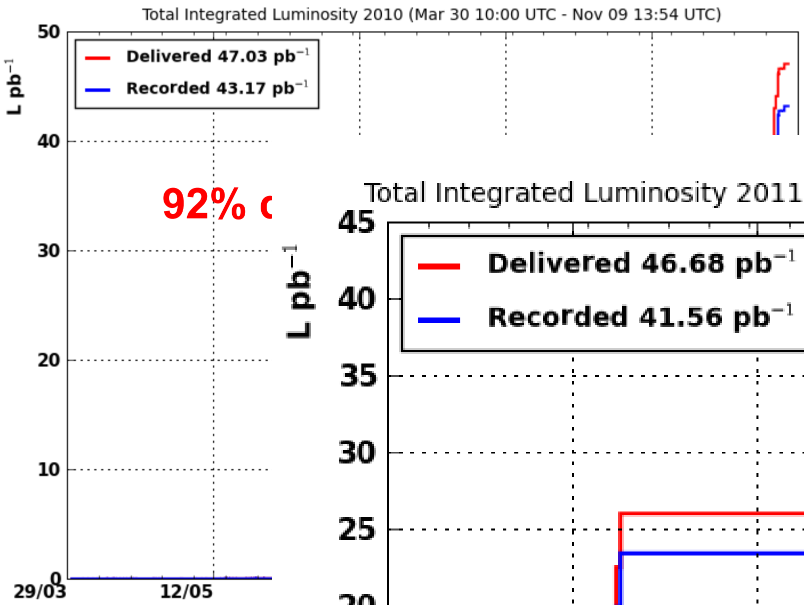
Results from the first year of data taking

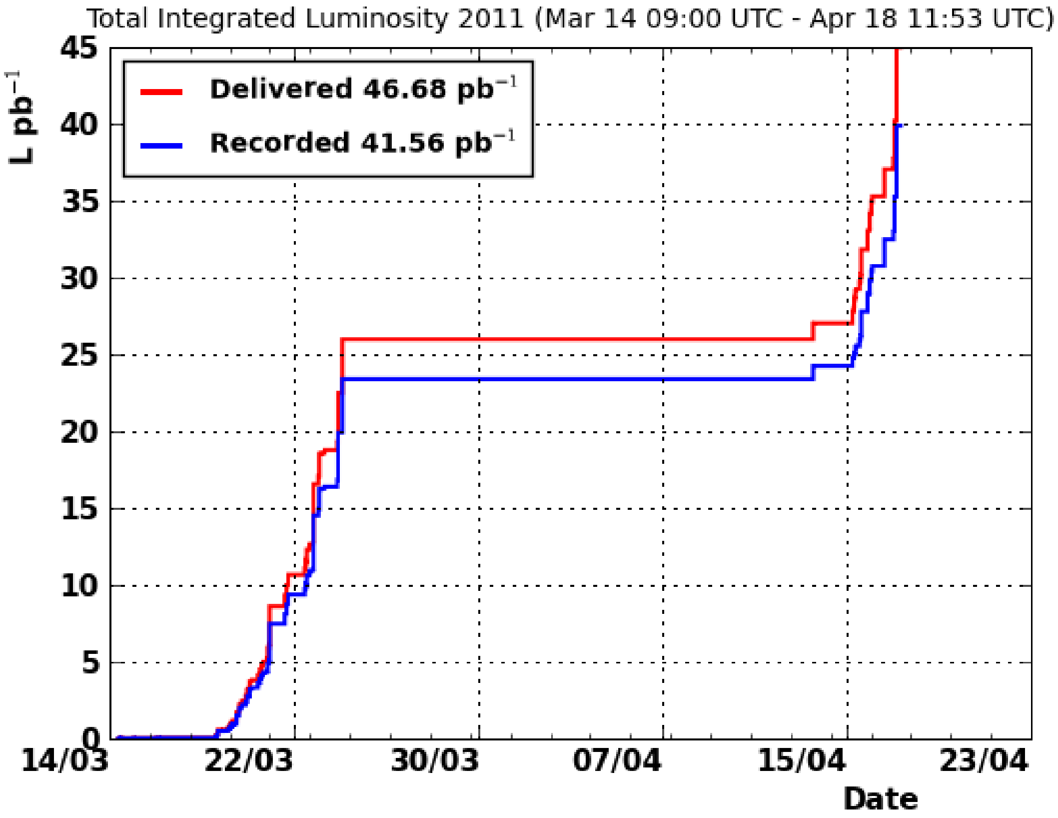
- Performance of the CMS detector
- SUSY and Exotics results using 2010 data
- Conclusions

Compact Muon Solenoid

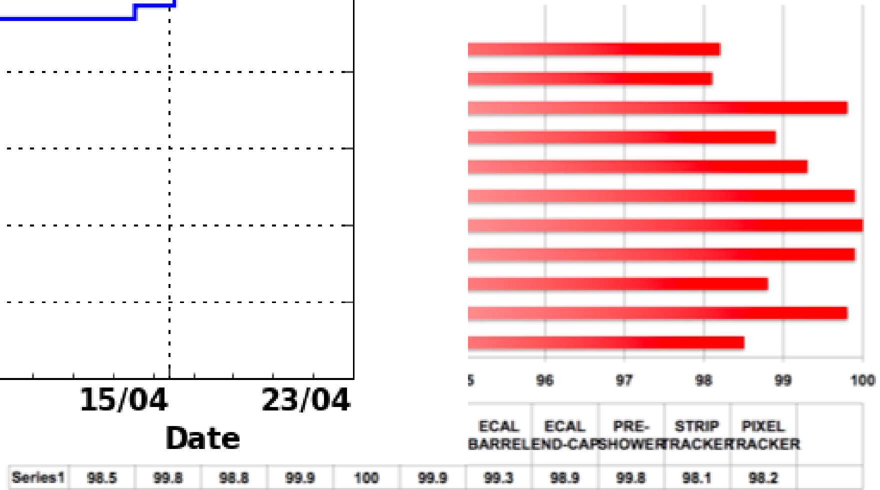


CMS performance



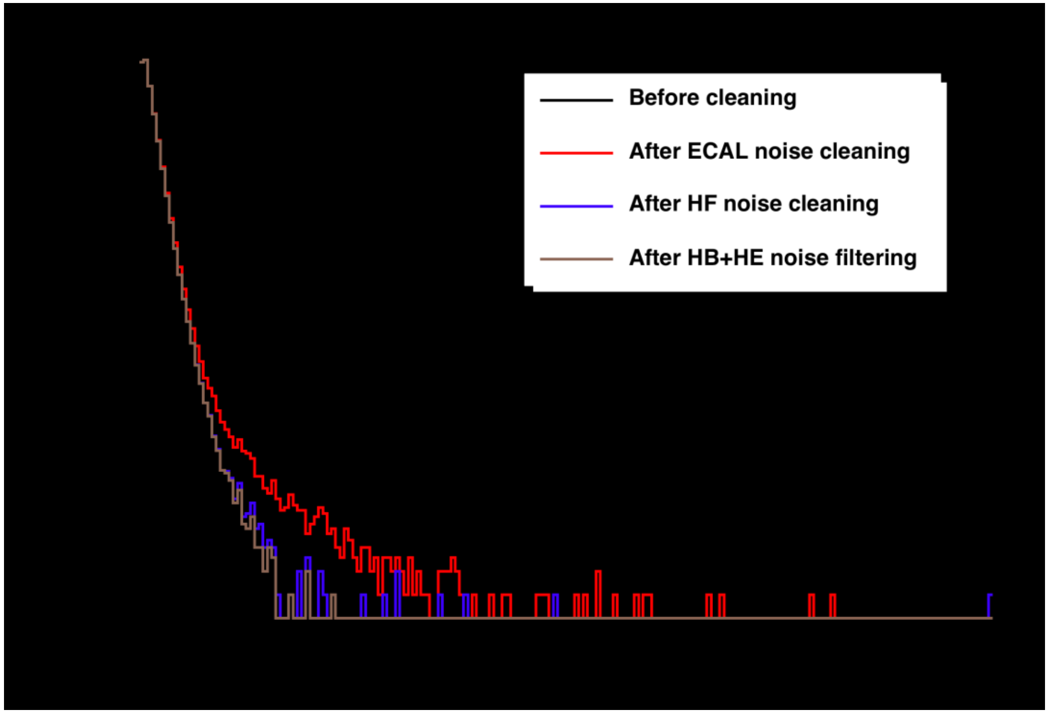


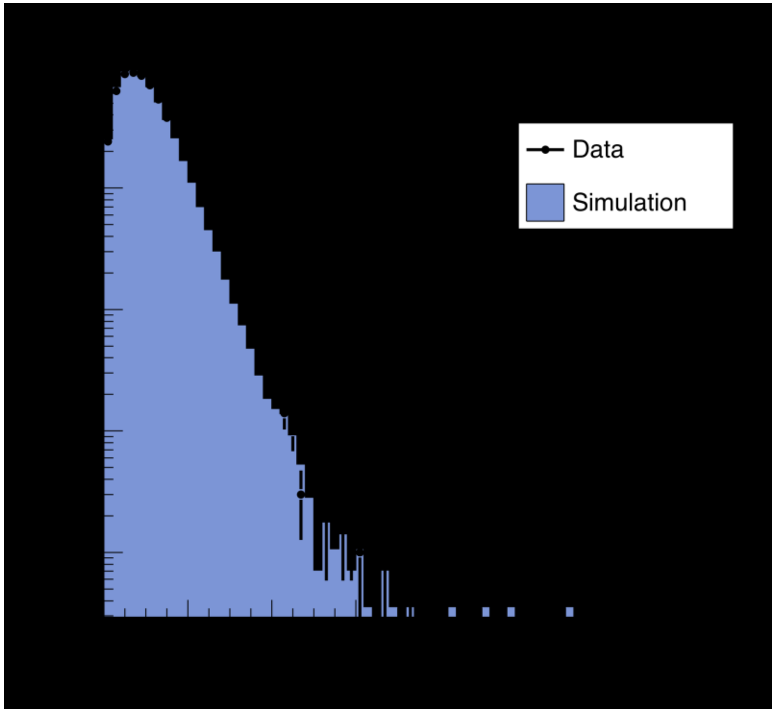
- LHC delivered ~47 pb^{-1}
- 43 pb^{-1} (~92%)
- lers of increase in
- nosity
- n ~35-40 pb^{-1}



Very high fra
Functional, a

Missing energy

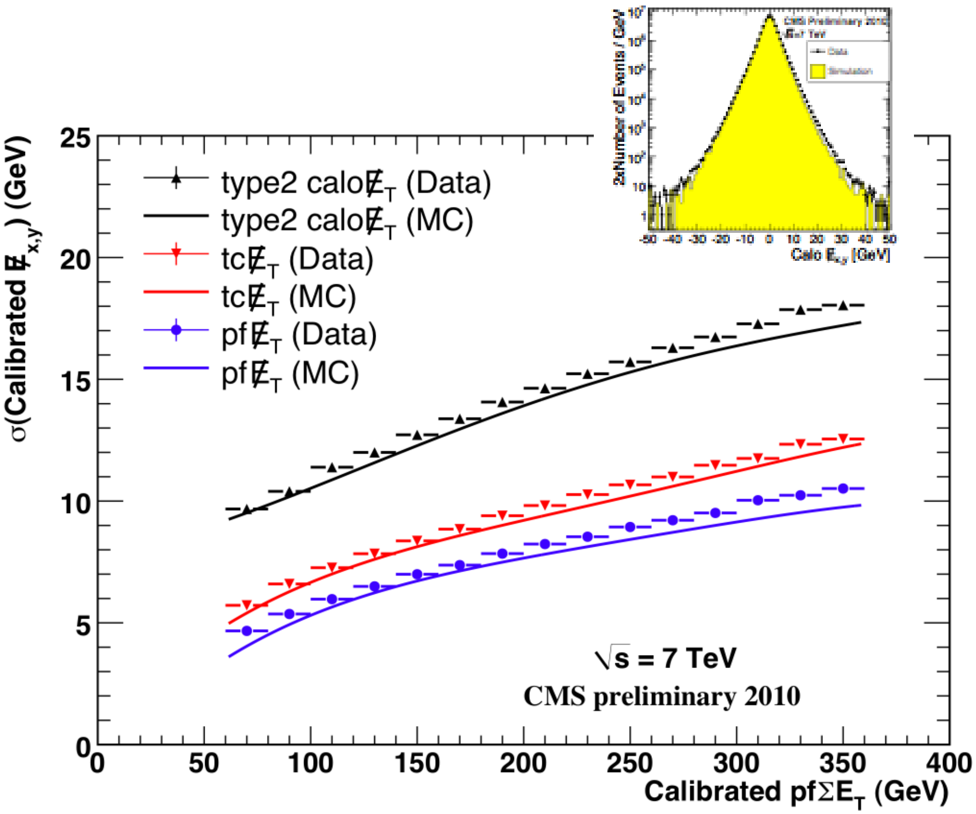


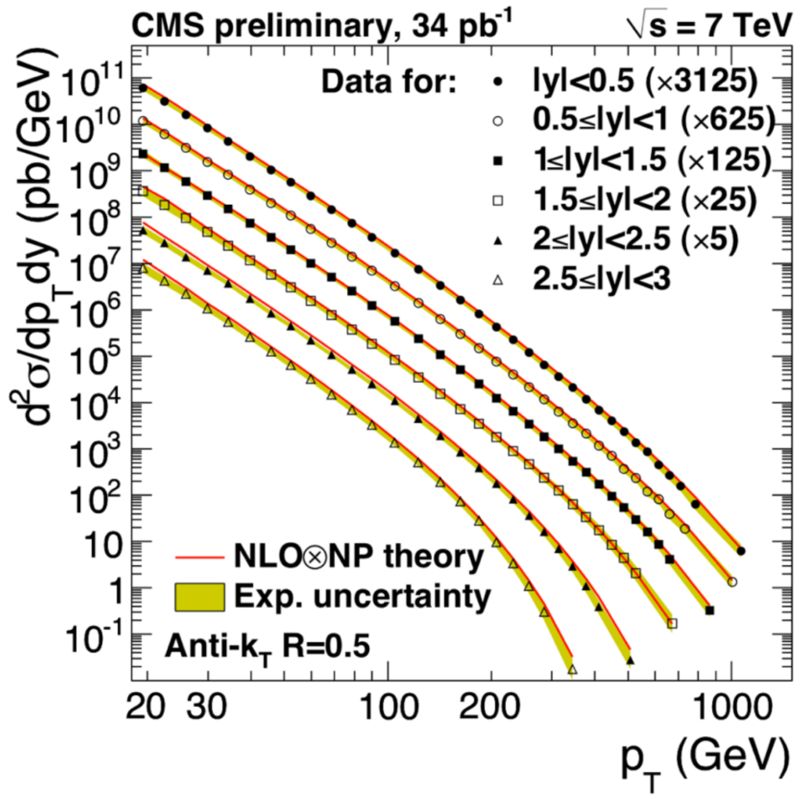


Effect of cleaning noise sources from events. Minimum bias events.

Comparison of data and MC in events with at least 2 jets. Particle Flow algorithm illustrated here.

Missing energy & jets

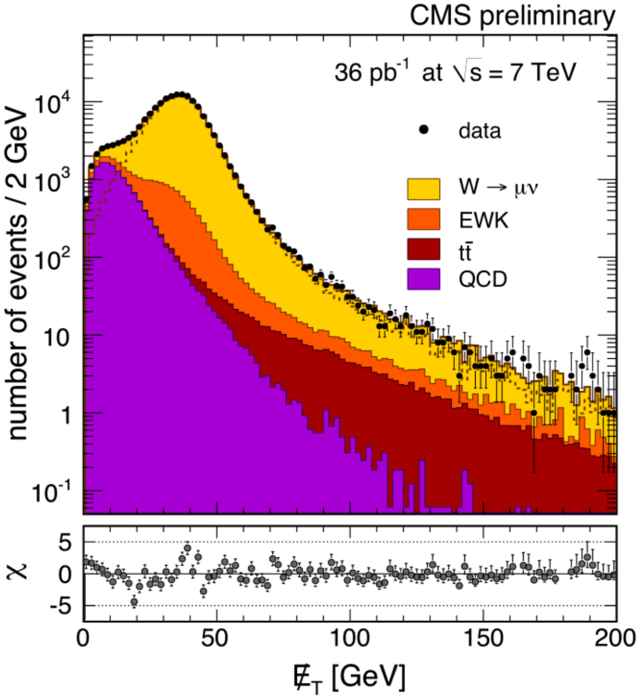


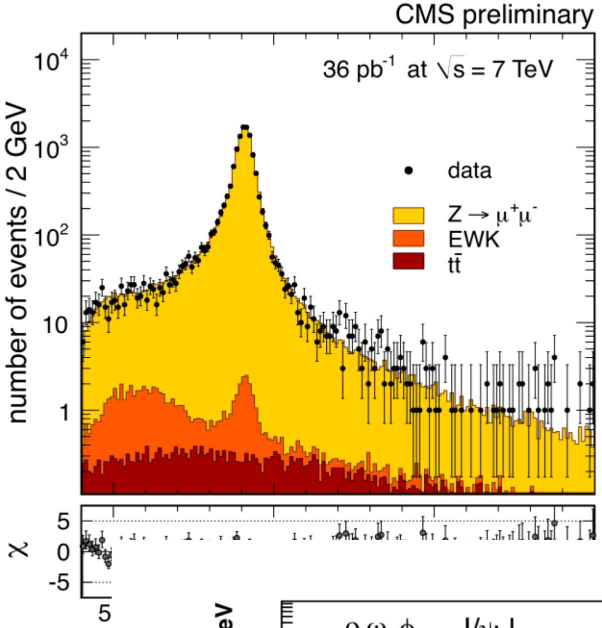


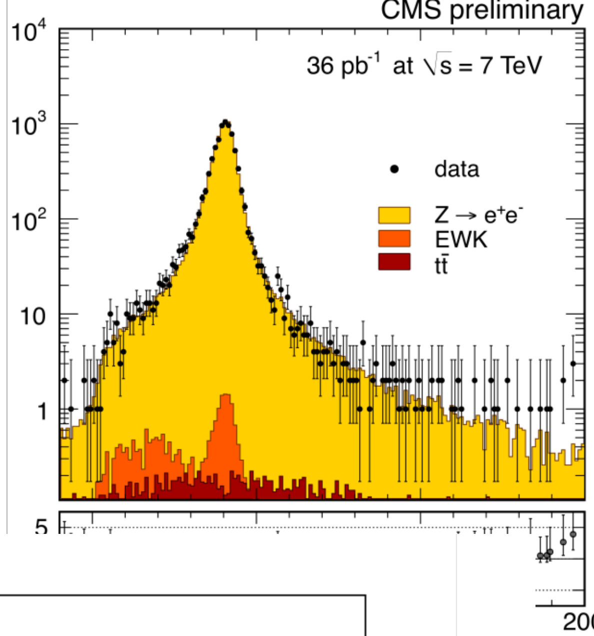
Resolution in various reconstructions of missing energy

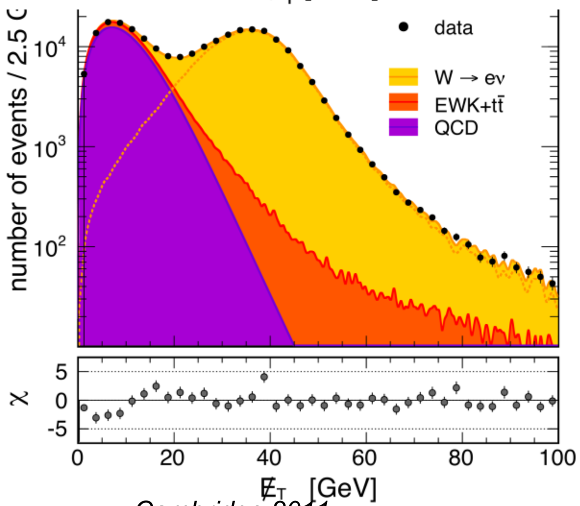
Good agreement with expectations for inclusive jet cross sections. Implies energy scale well measured.

Electrons and Muons



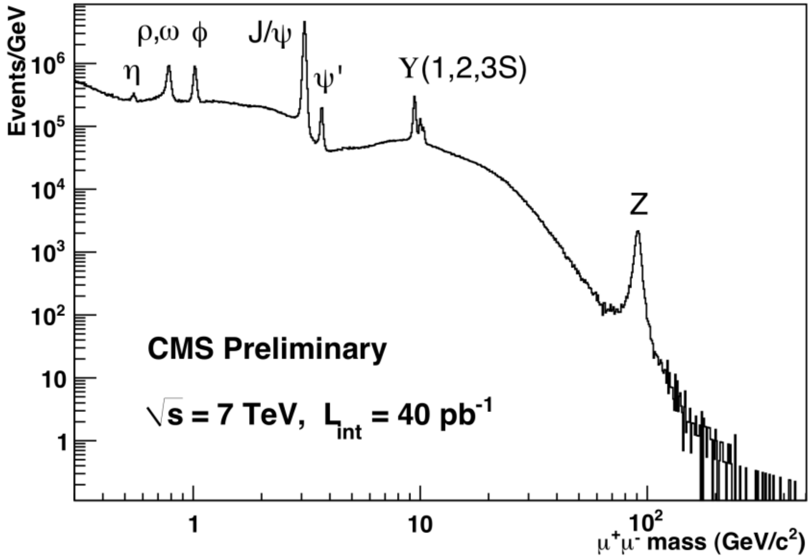




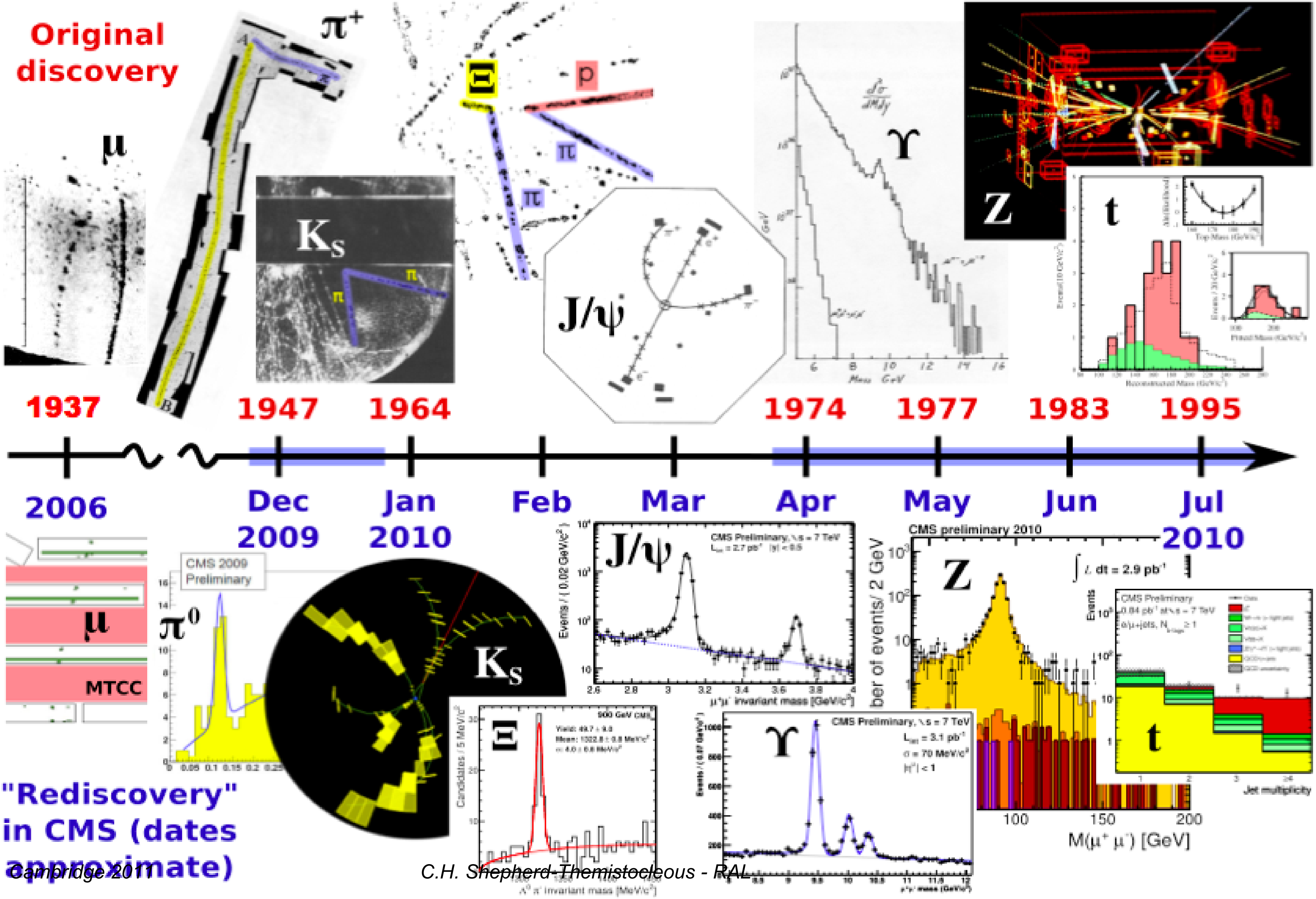


❑ Z … ron

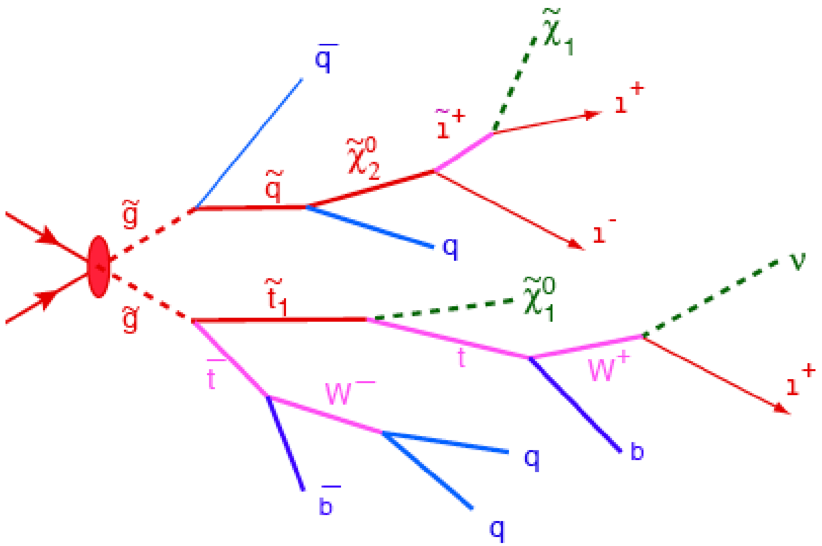
❑ W … per



Re-discovery of the SM



SUSY searches



- ❑ Squark, gluino production dominant
- ❑ Cross section depends on mass
- ❑ Typical decay chain give a signature of missing energy, jets, leptons.
- ❑ Numerous models lead to this type of signature.

CMS strategy

- ❑ Focus on a set of simple signatures not specific physics models
- ❑ Backgrounds measured using the data – do not rely on MC.

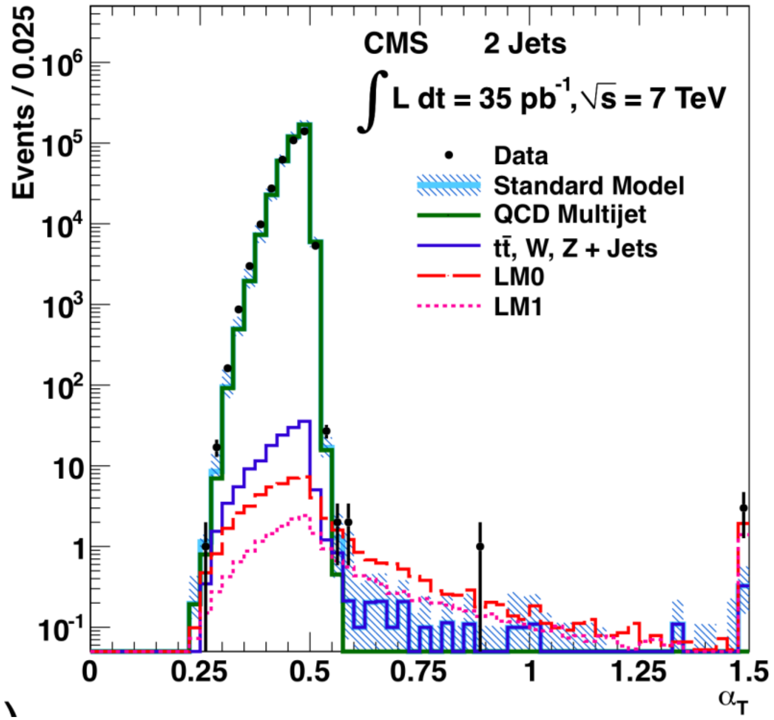
SUSY analyses

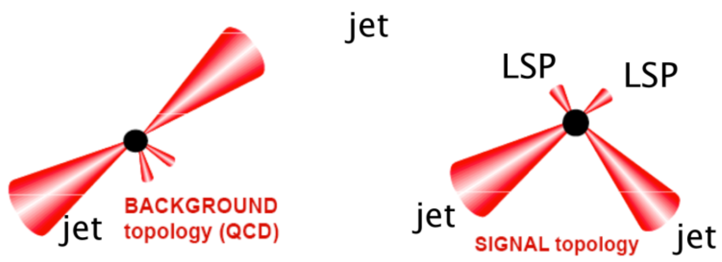
0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

- Jets + MET Largest potential sensitivity but backgrounds hardest to handle
- Add leptons (increasingly) suppresses backgrounds to very clean (≥ 3 leptons)
- Photons useful for gauge mediated models.
- Add lepton reduces background again
- Non MET based searches also possible (e.g. Split-SUSY see later)

Use of variety of data based methods for determining backgrounds key feature

Hadronic SUSY search





$$\alpha_T = \frac{E_{T\,j2}}{M_{T\,j1j2}} = \frac{\sqrt{E_{T\,j2}/E_{T\,j1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$

If back-to-back $\alpha_T = 1/2$

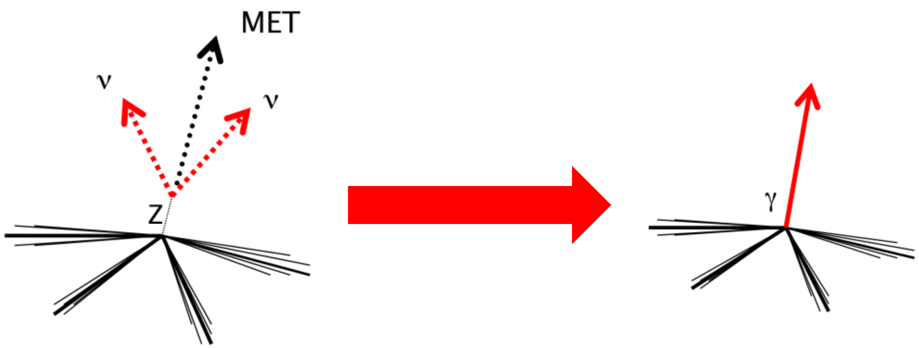
- Two leading jets E_T > 100 GeV, leading | η | < 2.5

  (If > 2 jets E_T > 50 GeV then combined into 2 pseudo-jets)
- Veto events with e,μ,γ
- H_T ($\Sigma E_{T(jets)}$)> 350 GeV and α>0.55

Background Estimates

Background estimated from data using two approaches
(Main backgrounds QCD, W+jets, ttbar, $Z(\nu\nu)$+jets)

- Estimate of total background
  - Use H_T in regions not used for search to extrapolate to search region
- Estimate of SM background with missing energy
  - W+jets, ttbar. Use $W(\mu\nu)$ + jets control sample and MC scaling
  - $Z(\nu\nu)$+jets

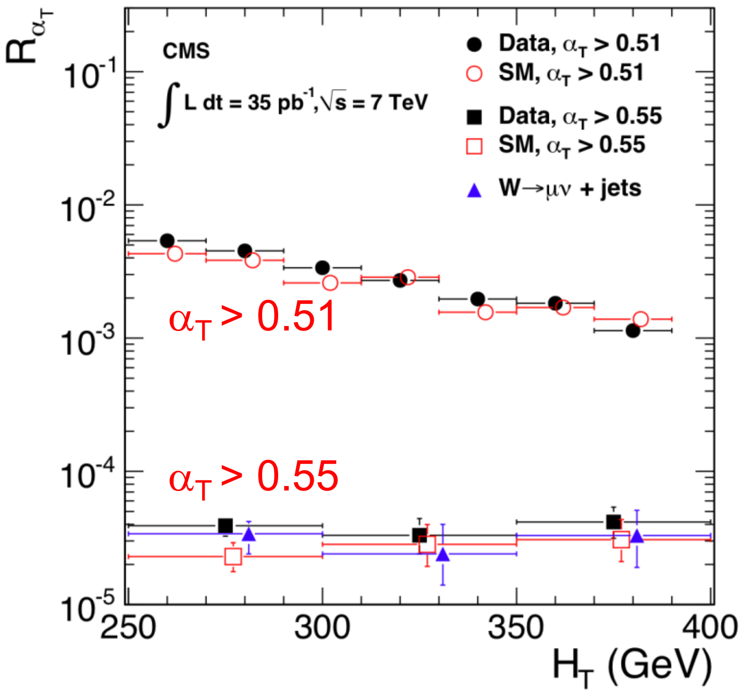


γ + jets

Strength: large statistics and clean at high E_T

Weakness: background at low E_T, theoretical errors

Background estimate



$R_{\alpha T}$ = No. Pass (i.e. $\alpha_T > X$) / No. Fail (i.e. $\alpha_T < X$)

Use low H_T bins (no signal) to extrapolate to high

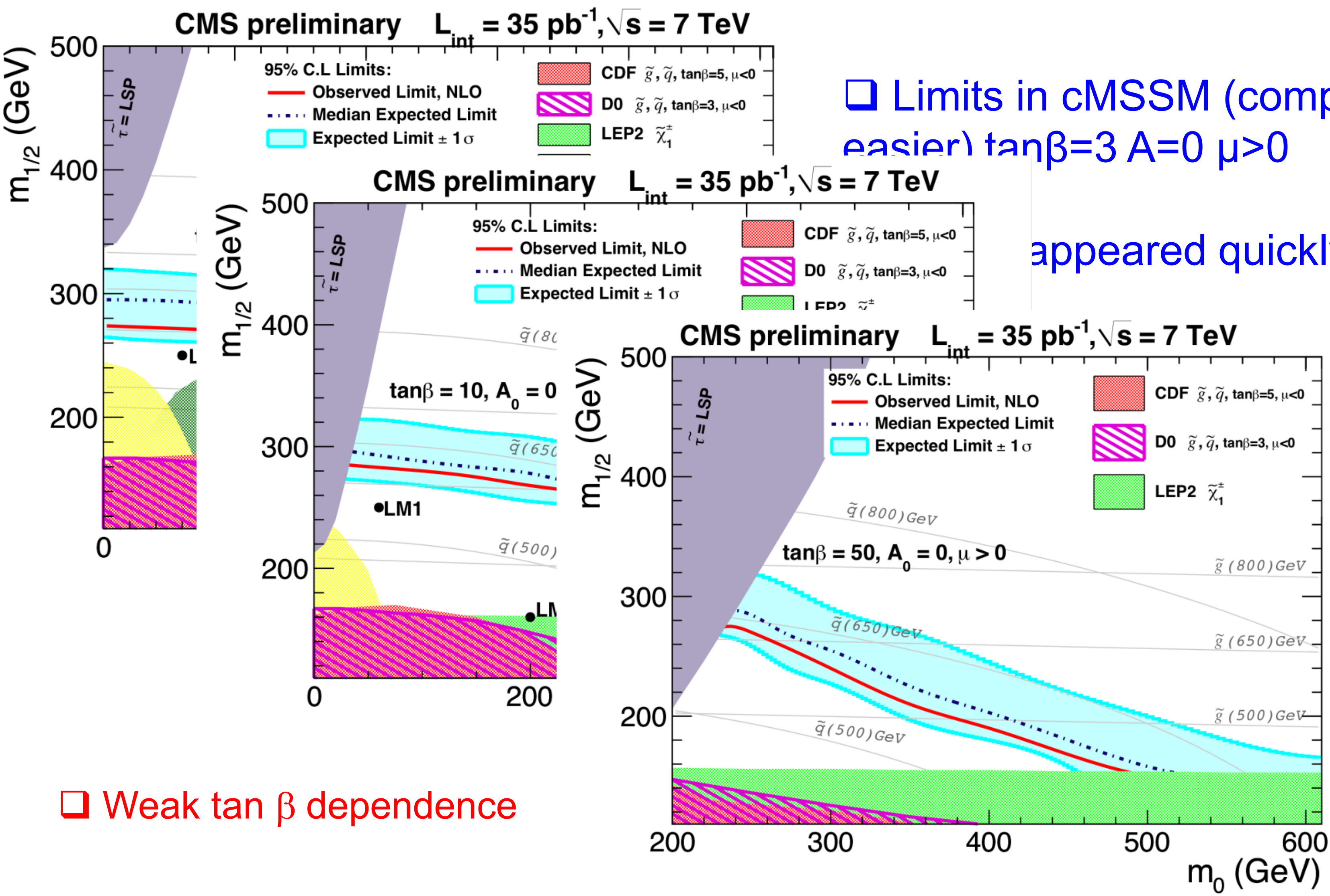
For missmeasured QCD expect $R_{\alpha T}$ to falls with H_T. Resolution improves.

For EWK real MET expect $R_{\alpha T}$ to be flat.

Predicts $9.4\ ^{+4.8}_{-4.0}$(stat.) $\pm$1.0 (syst.)

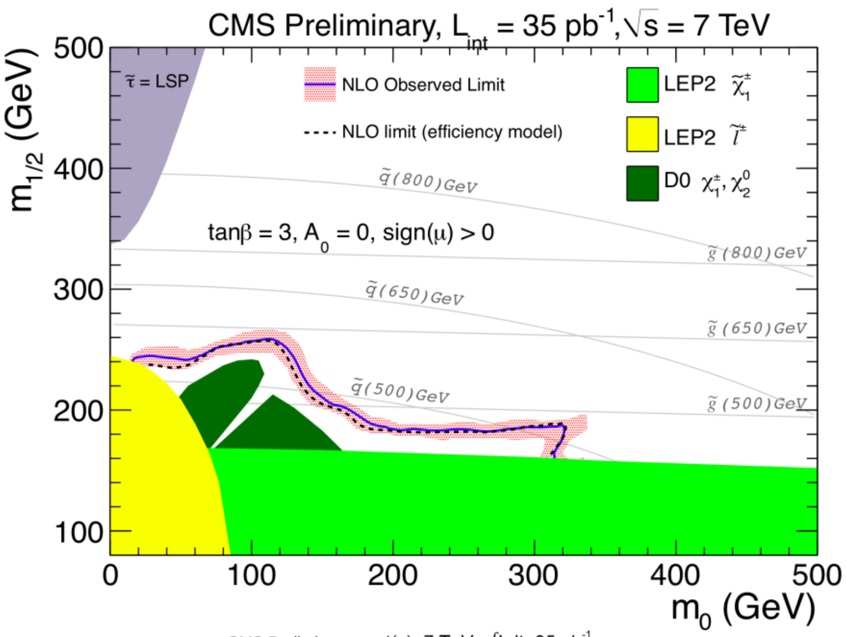
Observe 13 events in data

- Limits in cMSSM (comparison easier) $\tan\beta=3$ $A=0$ $\mu>0$
- appeared quickly



- Weak tan β dependence

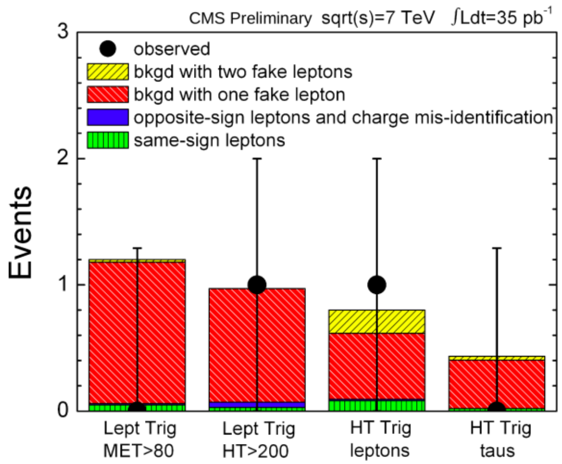
Same sign di-lepton



Performed in all leptonic channels same and diff flavour

Signal very suppressed in SM ttbar (W, b decay), QCD

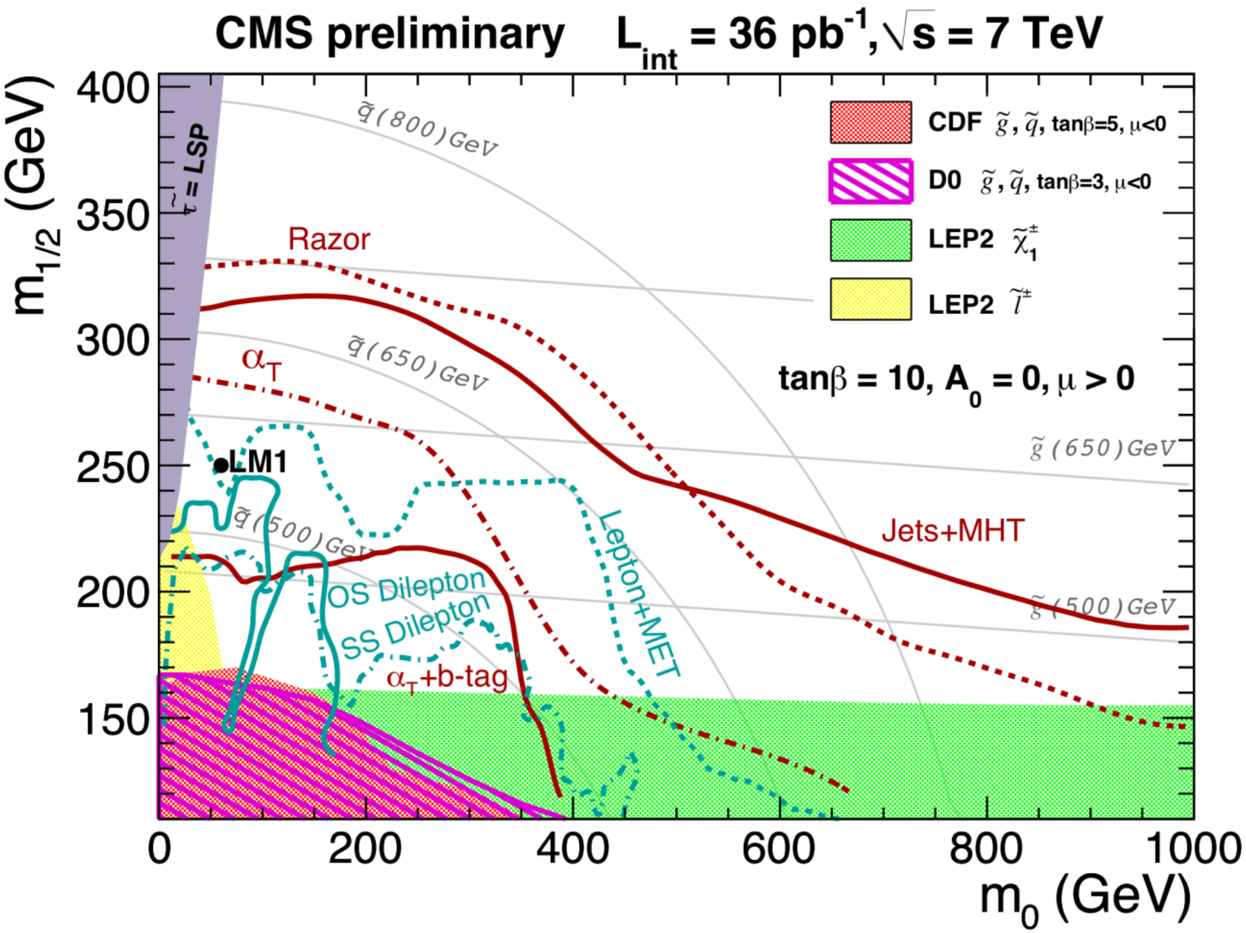
Background estimated using tight vs. loose lepton selection



Limit calculated using fast MC and generator level plus parametrized efficiencies. (dashed vs. solid)

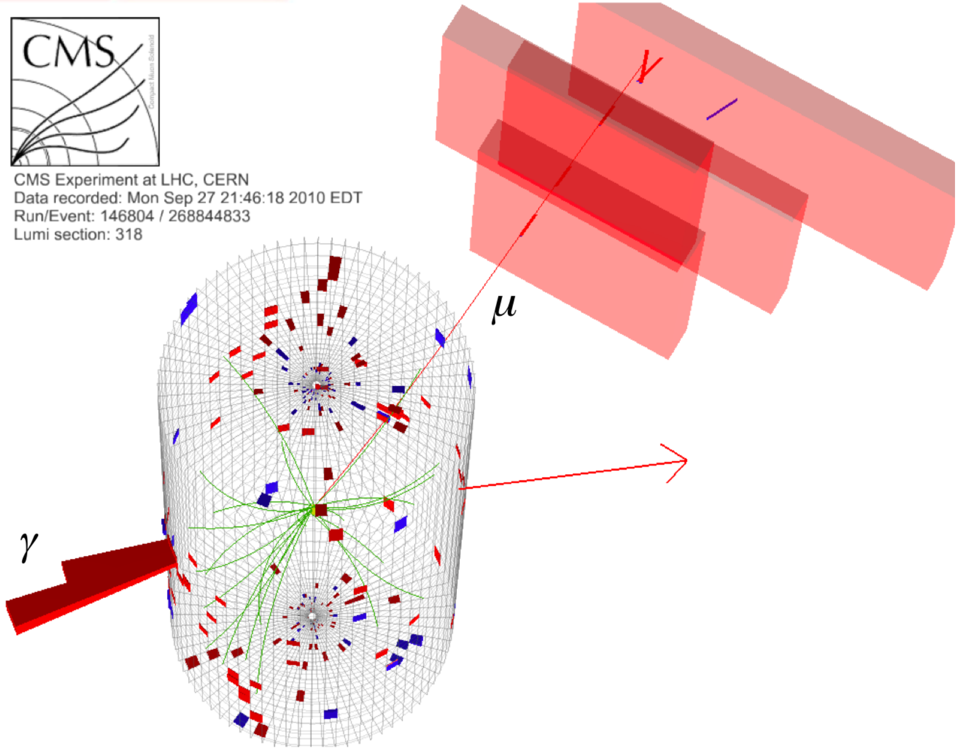
Enables easy extrapolating to other models.

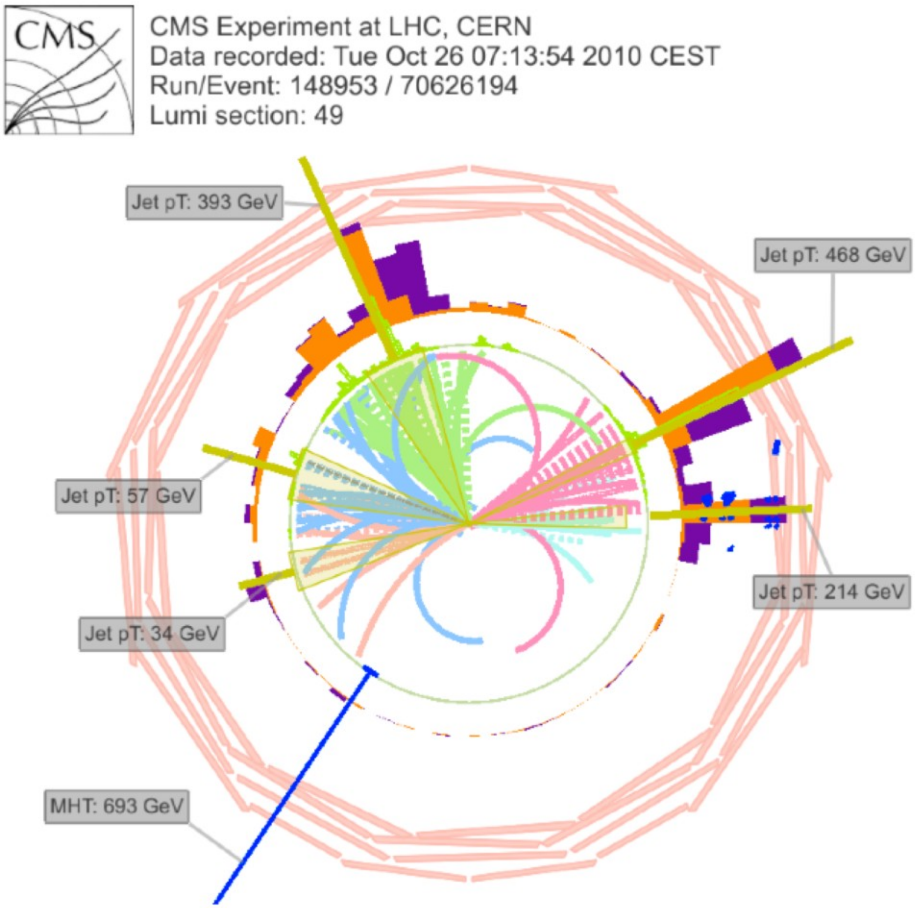
SUSY summary



- ❑ Large number of searches.
- ❑ All use data driven methods for backgrounds
- ❑ No evidence of SUSY (yet).

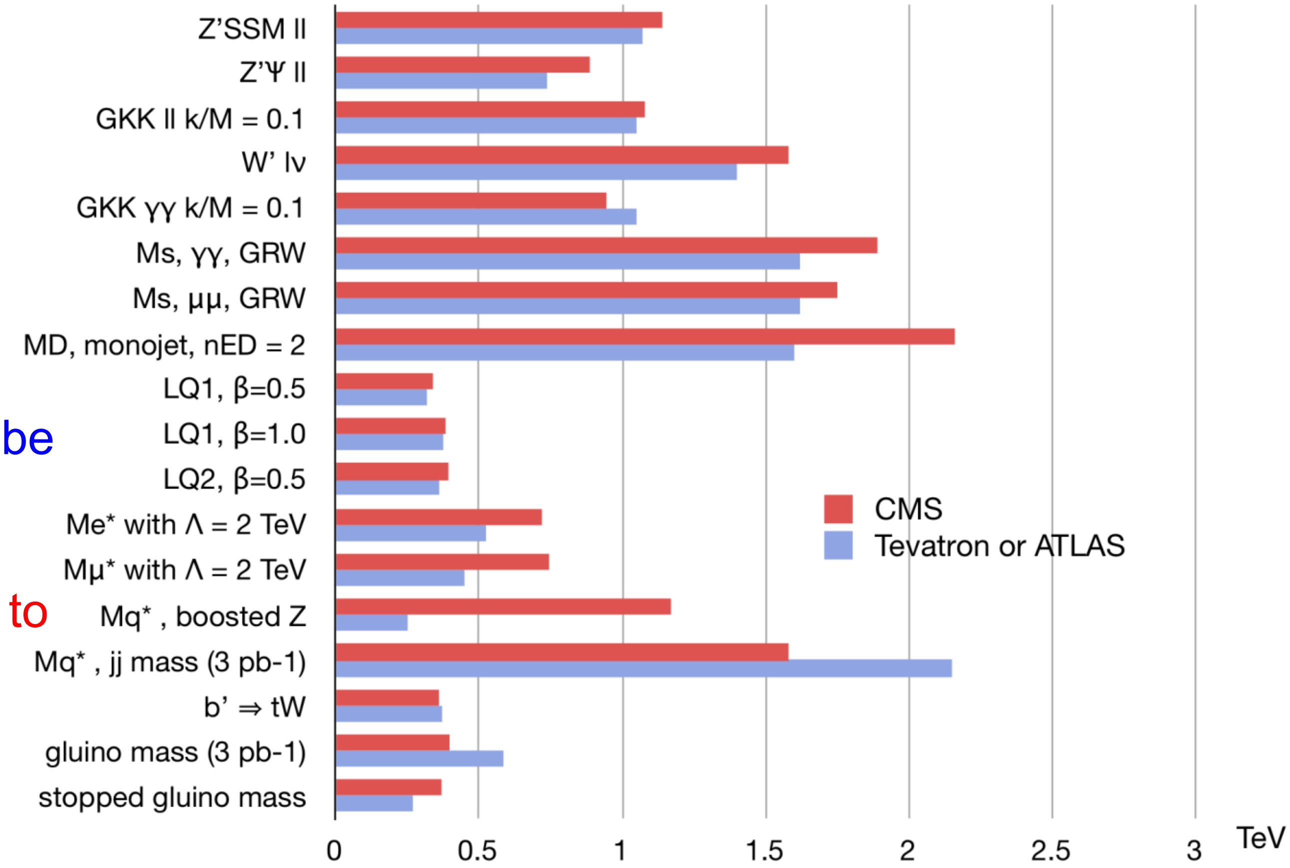
Nice events


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon Sep 27 21:46:18 2010 EDT
Run/Event: 146804 / 268844833
Lumi section: 318
γ
μ
γ


CMS
CMS Experiment at LHC, CERN
Data recorded: Tue Oct 26 07:13:54 2010 CEST
Run/Event: 148953 / 70626194
Lumi section: 49
Jet pT: 393 GeV
Jet pT: 468 GeV
Jet pT: 57 GeV
Jet pT: 214 GeV
Jet pT: 34 GeV
MHT: 693 GeV

Exotics

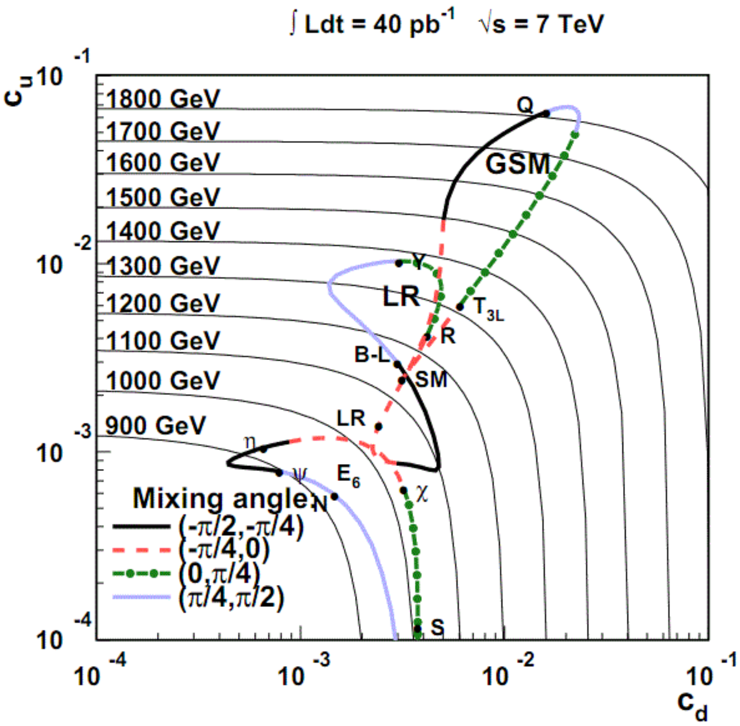
- New physics searches (not standard SUSY)
- Large number of analyses
- Signature often unusual requires something special to be done
- Results better than or close to best other results.

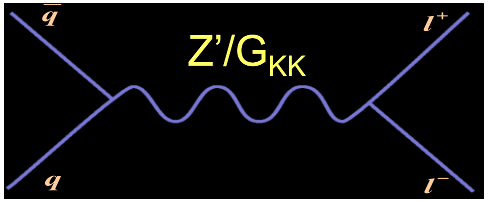


Summary of CMS results vs rest of world

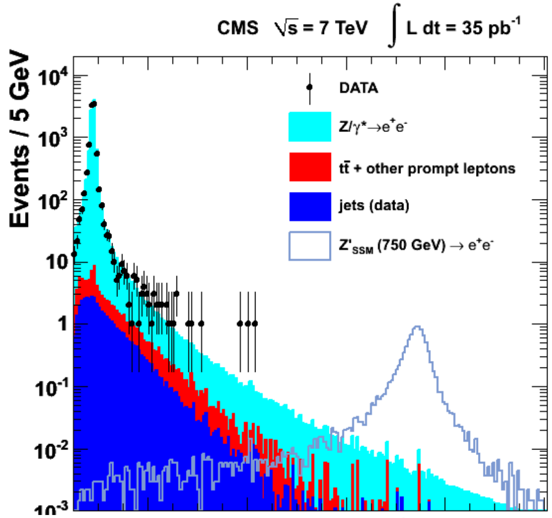
Di-lepton Resonance

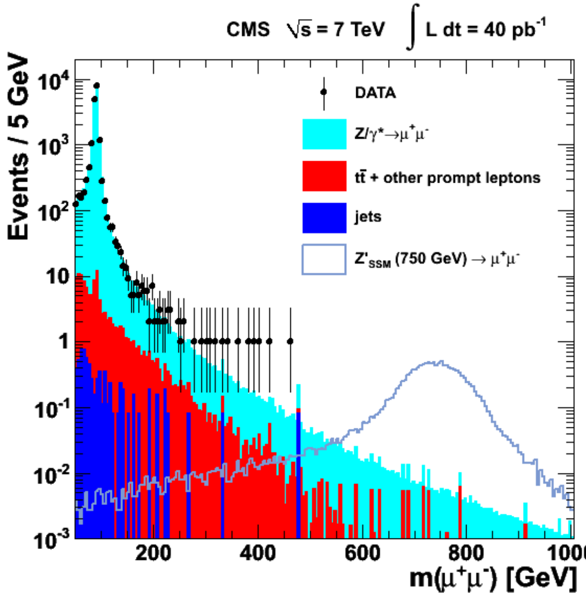
- Search for bump in di-lepton spectra
- Fit distribution in data
- Fakes for electrons from data
- Non-DY leptons checked using e-μ





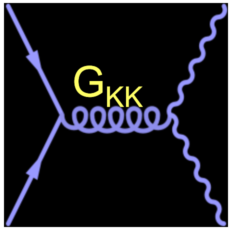
Z'_{SSM}	1140 GeV
$Z□_{\psi}$	887 GeV
$G_{KK}(0.05)$	885 GeV
$G_{KK}(0.1)$	1079 GeV





Di-photon searches

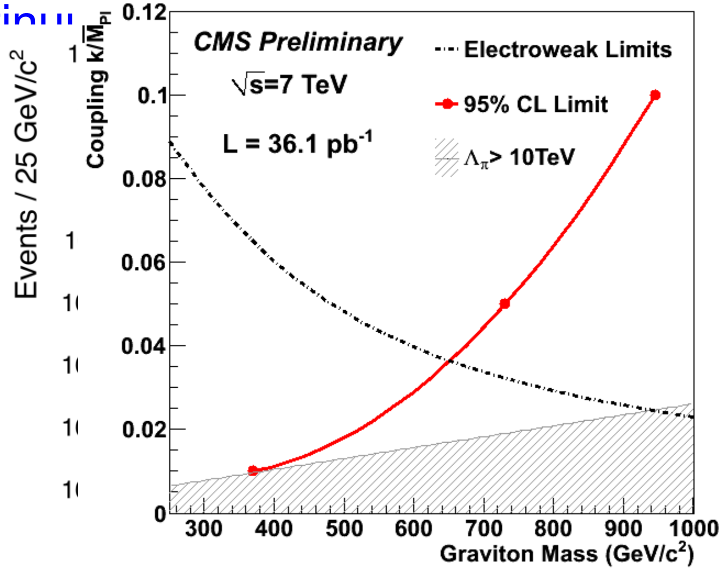
Search for deviation from SM either as a resonance or contin

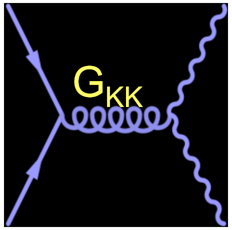


Warped Extra dimensions

RS graviton Spin-2 object. (BR = 2x(Br(ee or

Limits 371 GeV– 945 GeV
(coupling param k/M_{Pl} (0.01-0.1)



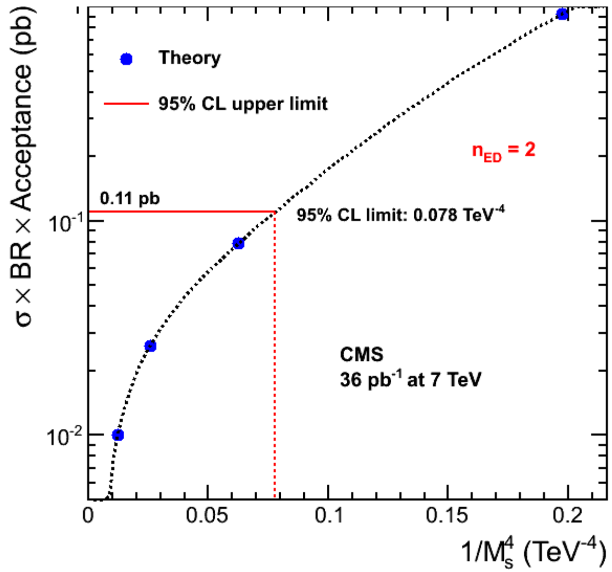


LED (ADD). Close states -> continuum deviation

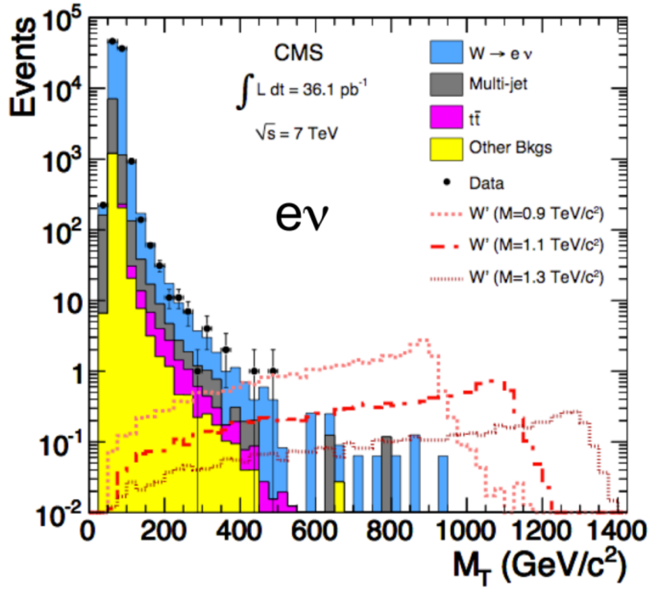
Signal region σ < 0.118 pb@95% C.L.

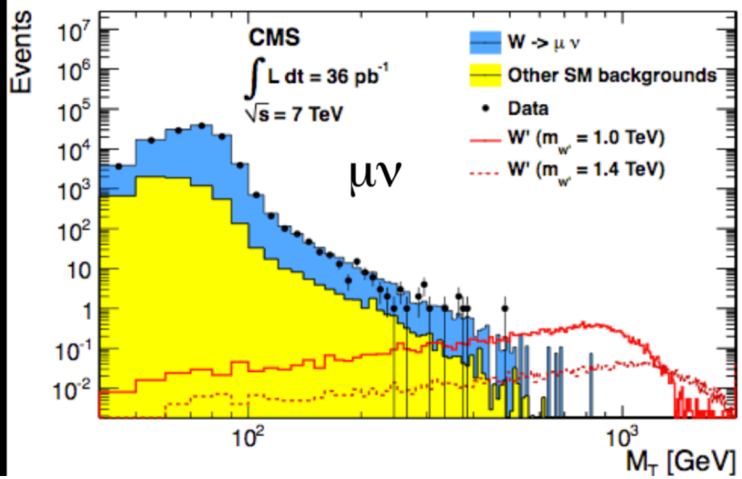
Limits on model parameters M_s (U.V. cut off)
1.6-2.3 TeV

$$\sigma_{total} = \sigma_{SM} + \eta_G \sigma_{int} + \eta_{G2} \sigma_{ED}$$



W' search

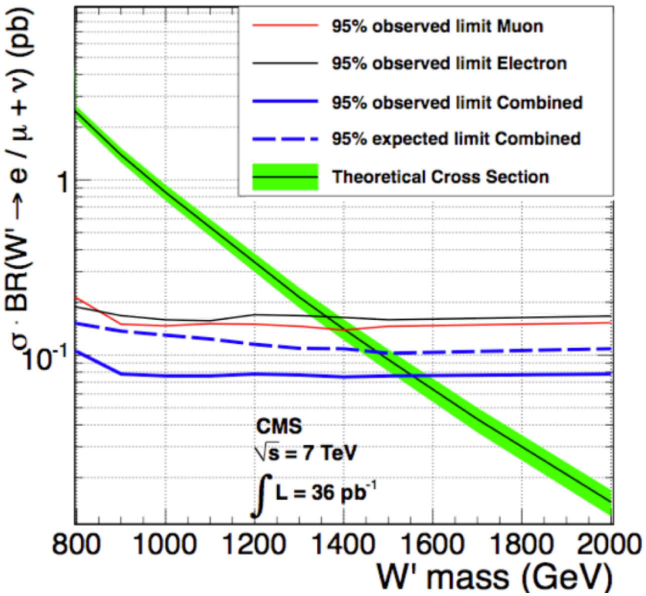




- **Bump hunt in $M_T(l\nu)$ spectrum**

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

- No significant deviation from SM, set limits



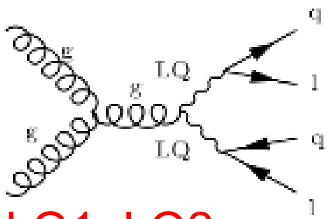
CMS limits (36 pb^{-1})

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

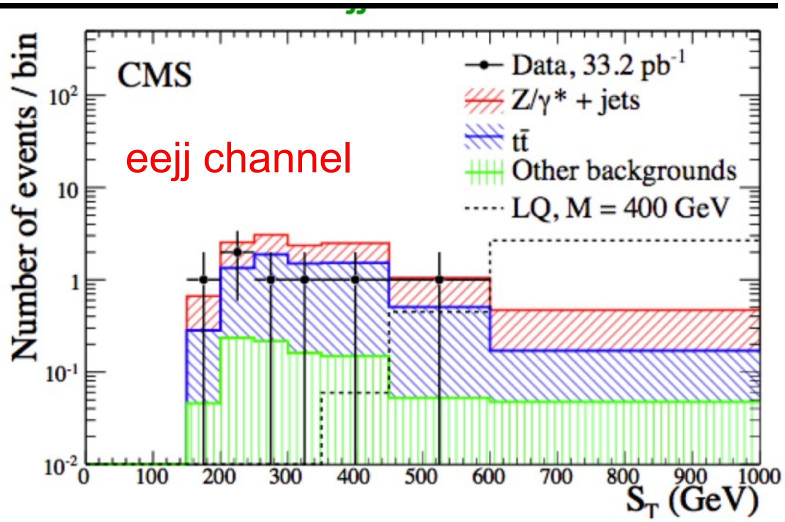
Lepto-quarks

Can decay to $q\ell$ ($q\nu$)

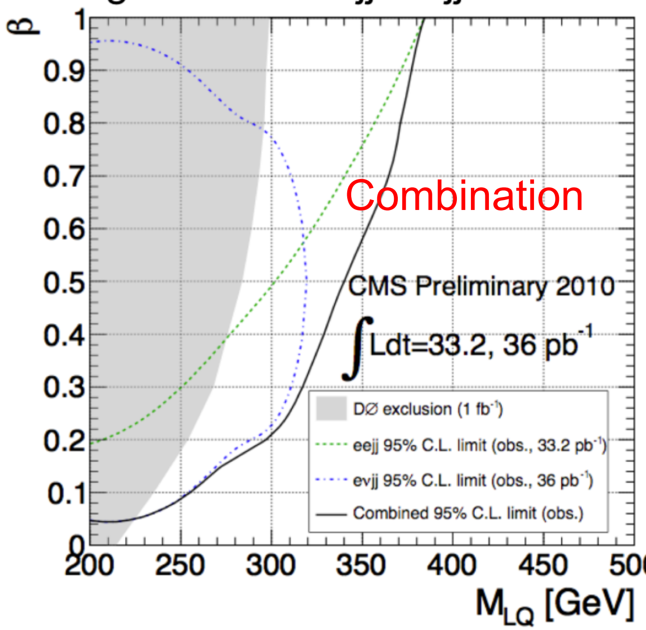


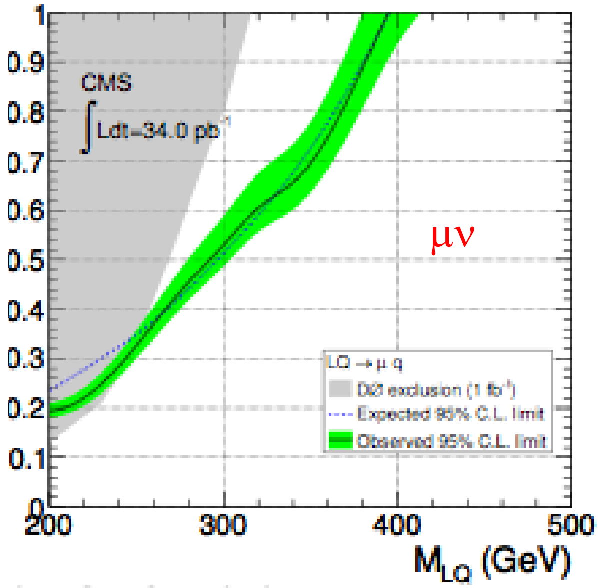
Generations treated separately LQ1, LQ2

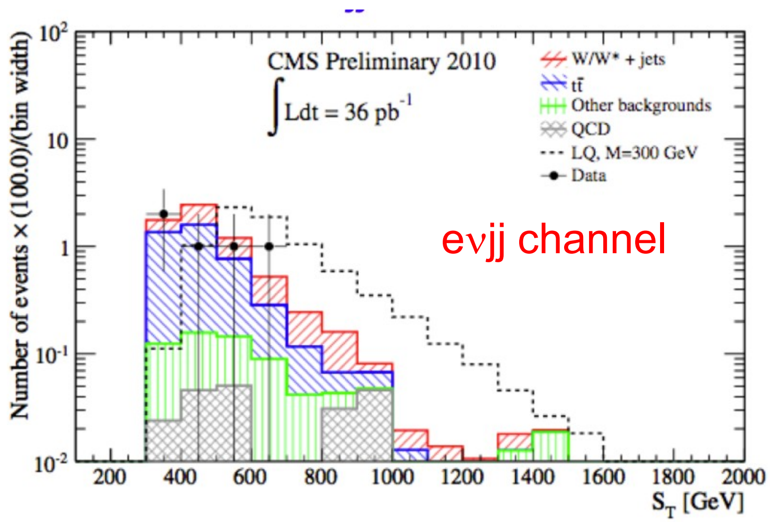
Scalar sum E_T of 2ℓ + 2jet used as discriminant



1st gen LQs – eejj+eνjj channels







M(LQ) > 384 GeV for β = 1 to eν

M(LQ) > 394 GeV for β = 1 to μν

M_{LQ} > 340, 384 GeV for β=0.5, 1

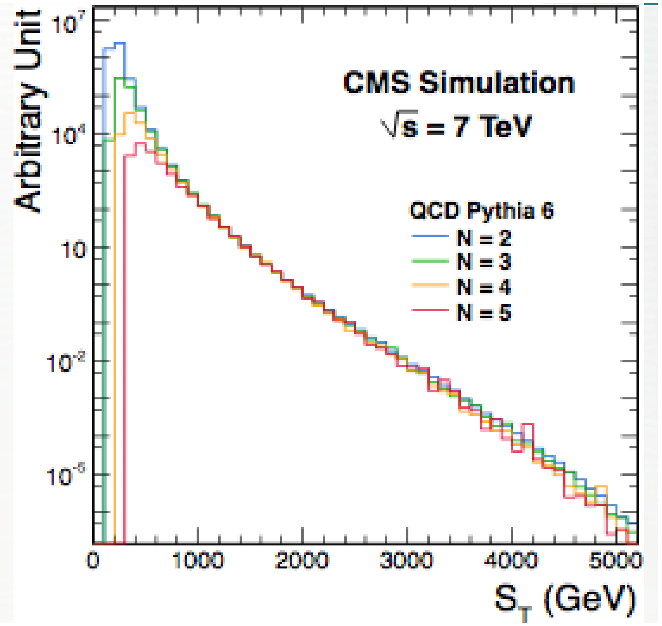
Black Holes

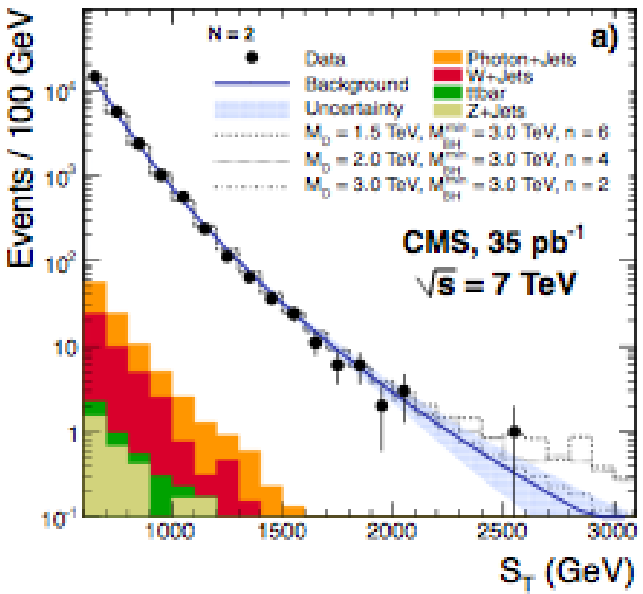
Look for an excess in high multiplicity final states.

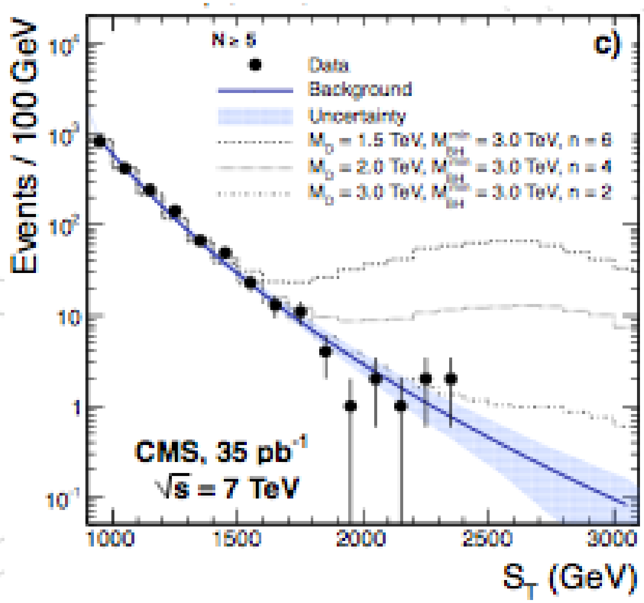
QCD background estimated using S_T variable.
$S_T = \sum E_T$ (inc. E_{Tmiss}) for all objects with $E_T > 50$ GeV

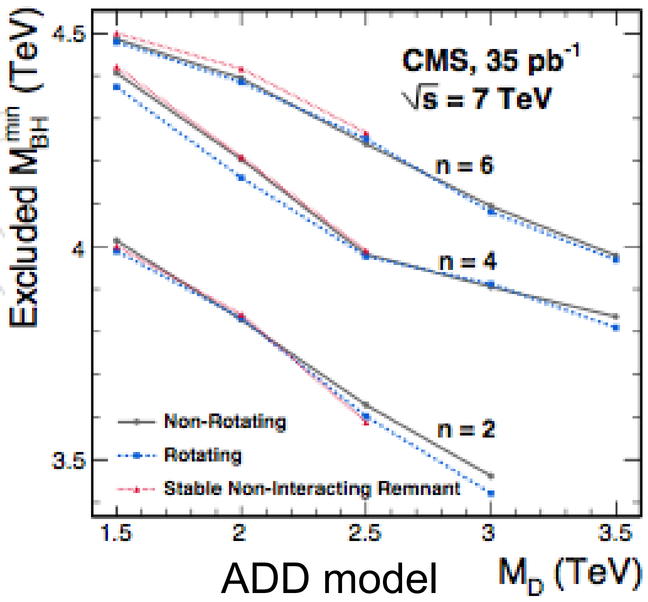
Use low mult samples to predict backgrounds

Limit in ADD model - M_D "true" Planck scale





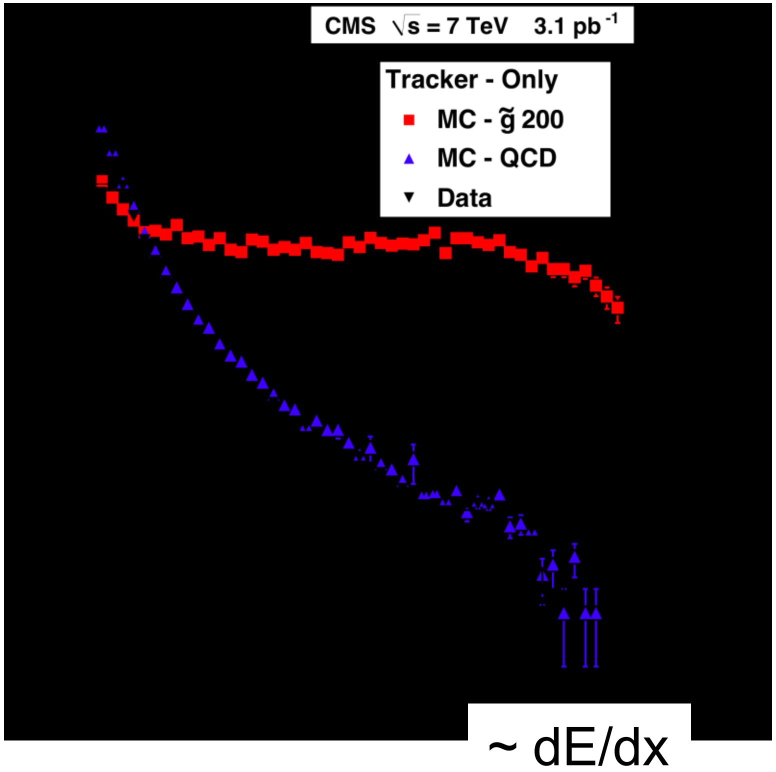




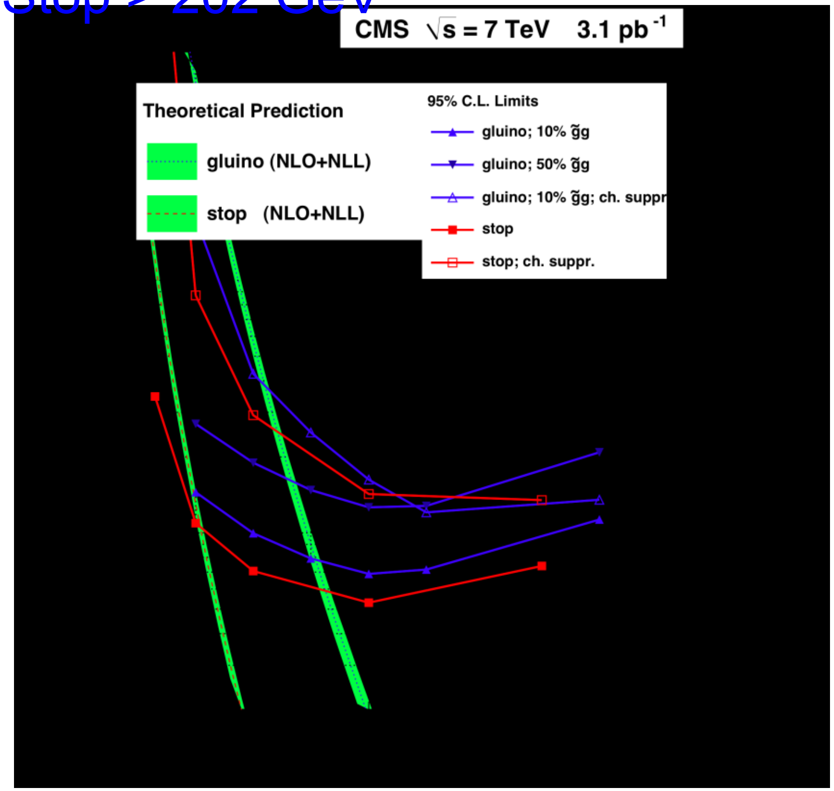
ADD model

Long Lived Particles

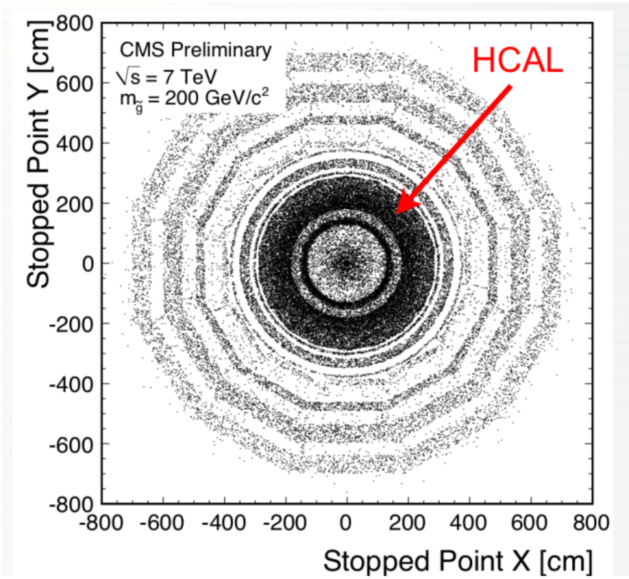
- Massive slow particle.
- dE/dx ~ $1/\beta^2$ from Si tracker
- Use p find mass.



- Split-SUSY model - Search for charged R-hadrons
- No events pass selections
- Gluino (f =0.1 gluon state) > 398 GeV Stop > 202 GeV



Stopping Particles



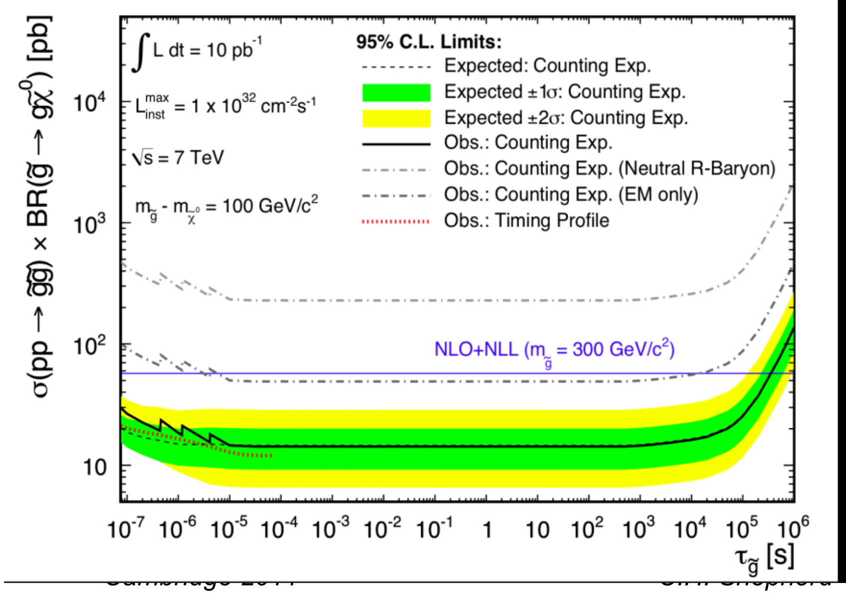
Charged heavy particles can stop in the detector.

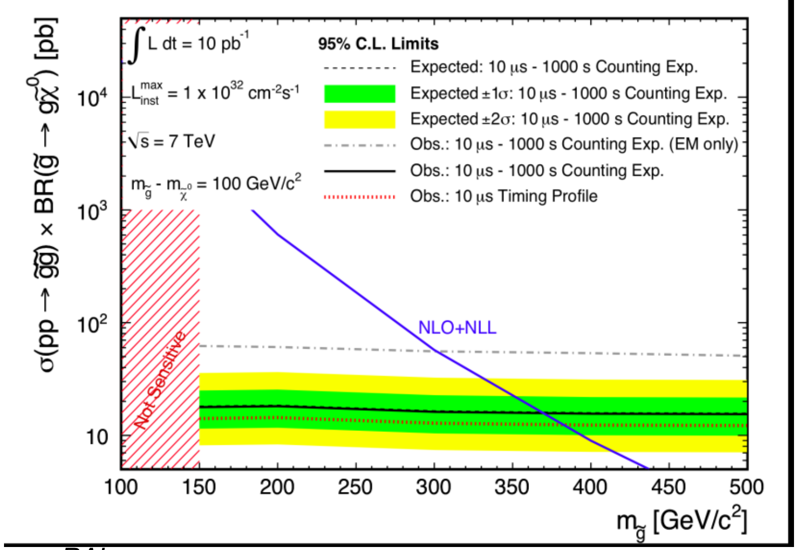
Signals searched for in the beam off periods of detector operation.

Specific trigger beam gaps.

Suppress main background from cosmic rays, beam halo, and HCAL noise

$M_g > 382$ GeV, $\tau = 10\ \mu s$
$M_g > 370$ GeV, $\tau = 10 - 1000\ \mu s$

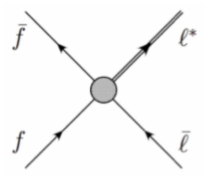




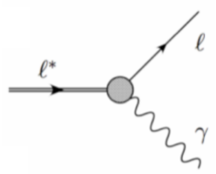
Excited leptons

Production contact interaction

Decay



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

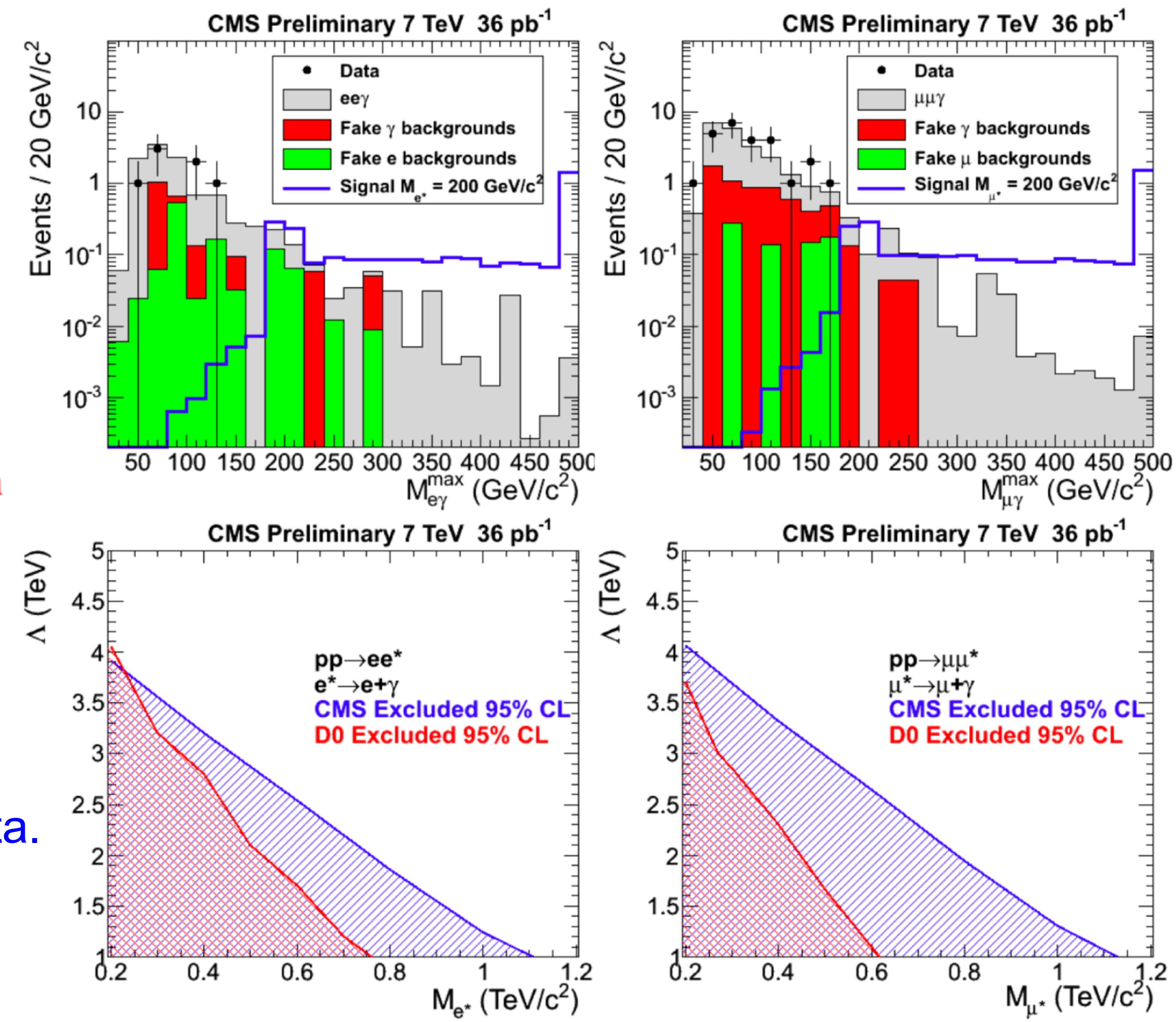


Search for eeγ or μμγ

Counting experiment in signal region

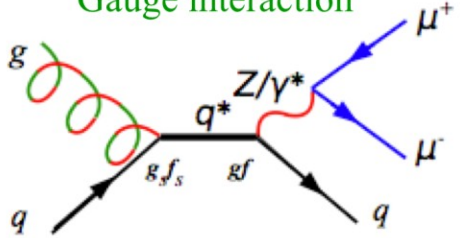
SM background from MC,
Backgrounds from fakes from data.

No events observed, limits set.



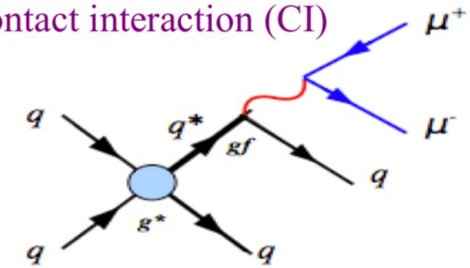
Boosted Z

Gauge interaction



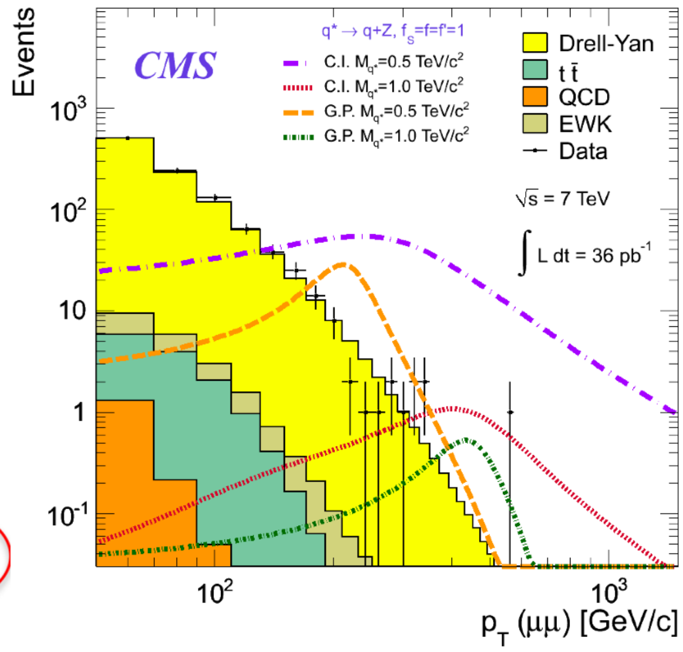
$$\mathcal{L}_{trans} = \frac{1}{2\Lambda} \bar{f}_R^* \sigma^{\mu\nu} \left(g_s f_s \frac{\lambda^a}{2} G^a_{\mu\nu} + g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu} \right) f_L$$

Contact interaction (CI)



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

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



Gauge Interactions

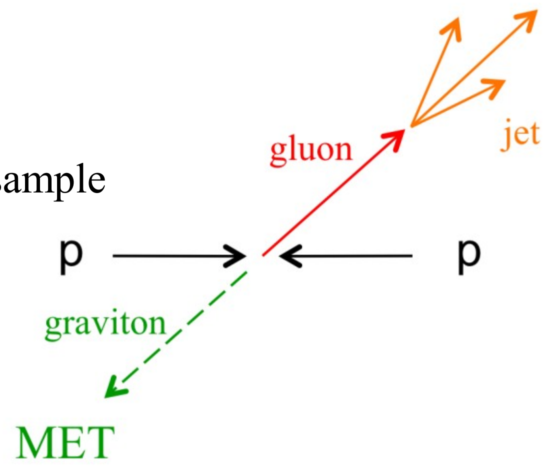
$$M_{q^*} = \Lambda,\ f = f' = f_S = 1$$
$$M_{q^*} > 0.91\ \text{TeV}$$

Contact Interactions

$$M_{q^*} = \Lambda,\ f = f' = 1,\ f_S = 0$$
$$M_{q^*} > 1.17\ \text{TeV}$$

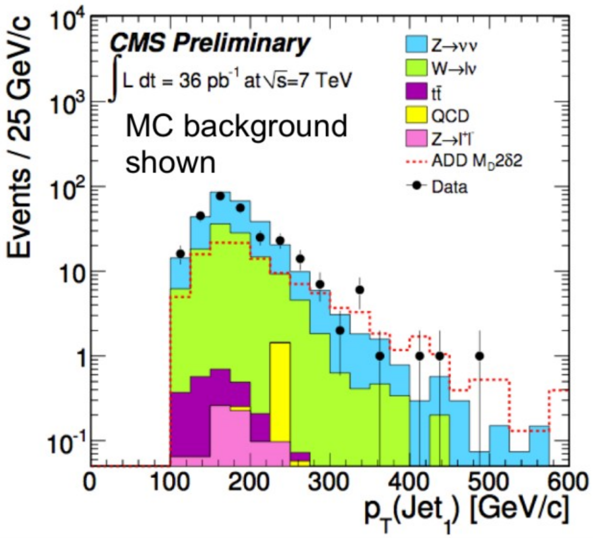
Mono-jets (ADD)

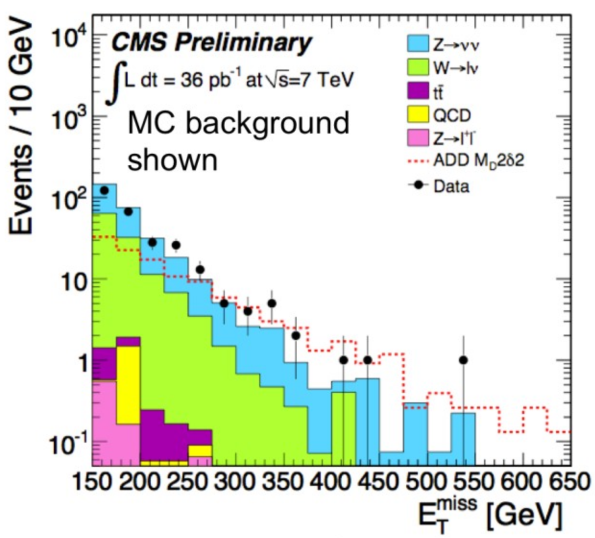
- **One high p_T jet + large MET + no leptons**
- Suppress cosmic/beam halo/instrumental backgrounds
- Backgrounds Z(νν)+jets, W(lν)+jets dominate. Est. from W+jets sample
- Data consistent with SM, set limits on M_D vs δ



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





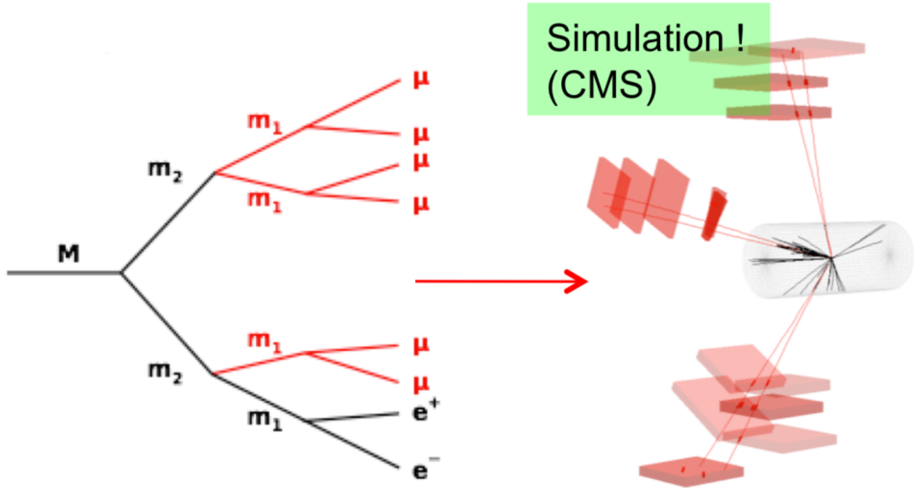
CMS limits on M_D ($36\ pb^{-1}$)

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)

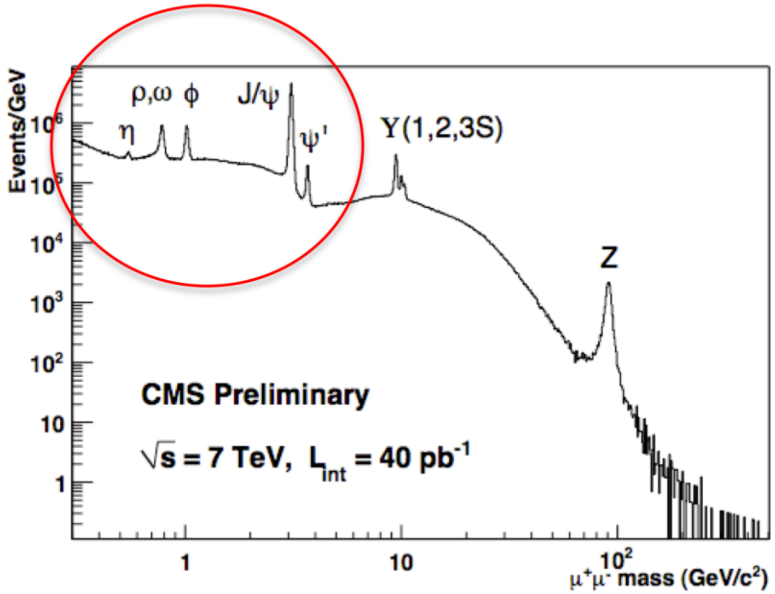
δ	CDF	LEP
2	1.4 TeV	1.6 TeV
3	1.15 TeV	1.2 TeV
4	1.04 TeV	0.94 TeV

Lepton jets

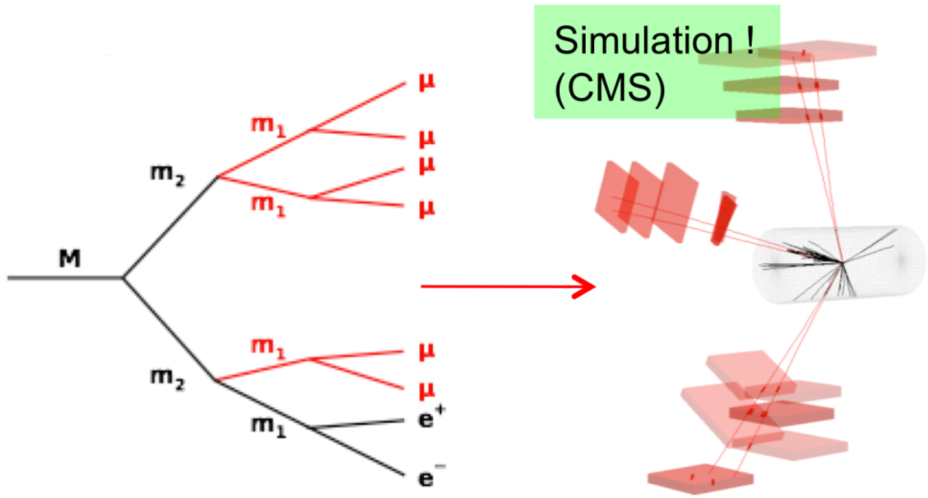


- Hidden sector contains a new low mass particle (m_1 ~ few GeV)
- It decays into SM pairs (i.e. μμ)
- **Collimated groups of di-muons [μμ]**
  - opposite charge, $m_{\mu\mu}$<9 GeV, consistent vertex
- Search for new μμ resonances in various event topologies: [μμ], [μμ][μμ], etc.

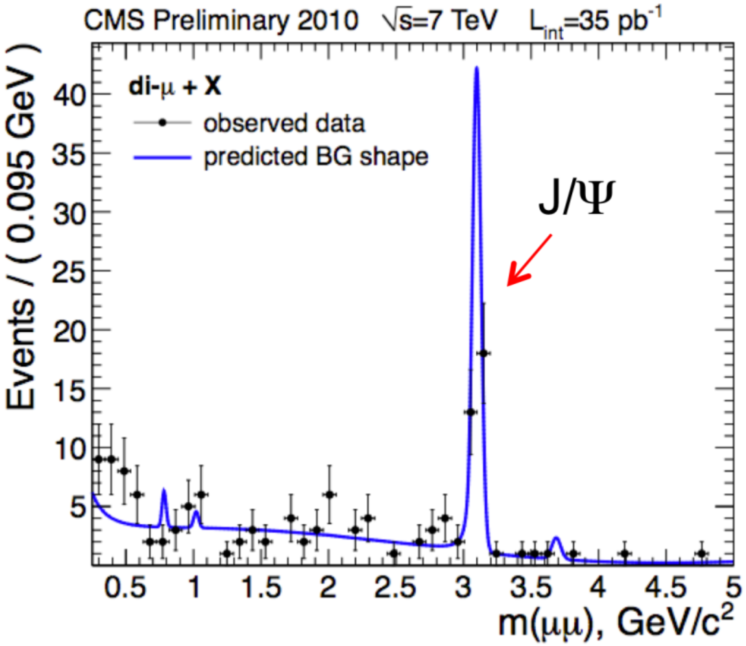
- These are the backgrounds
- M(μμ) background shape from control sample of data at low P_T
- Then look at high P_T …

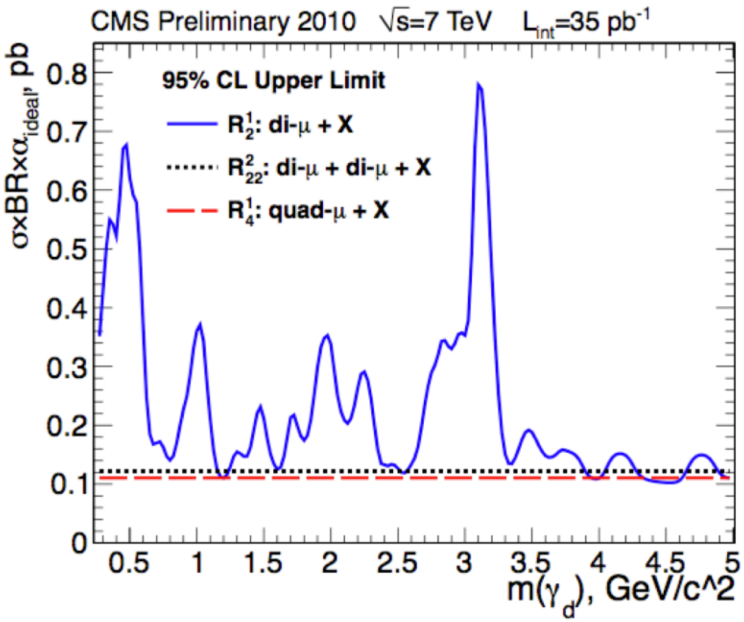


Lepton jets



- **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})

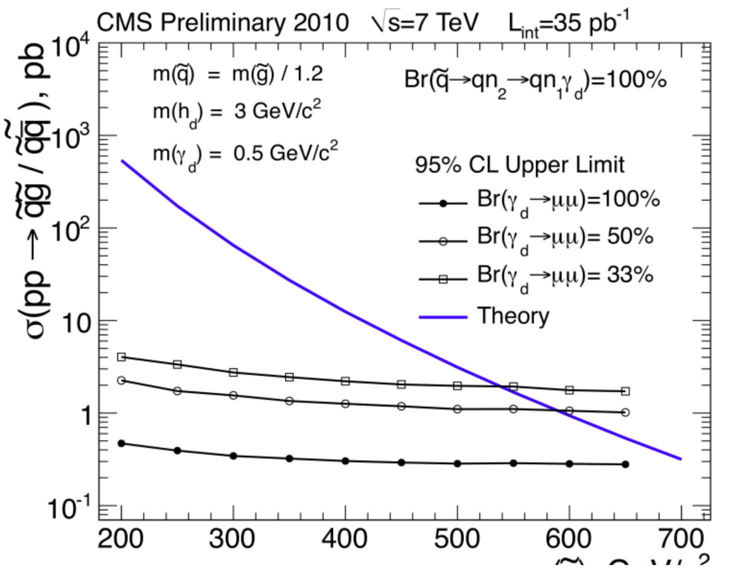


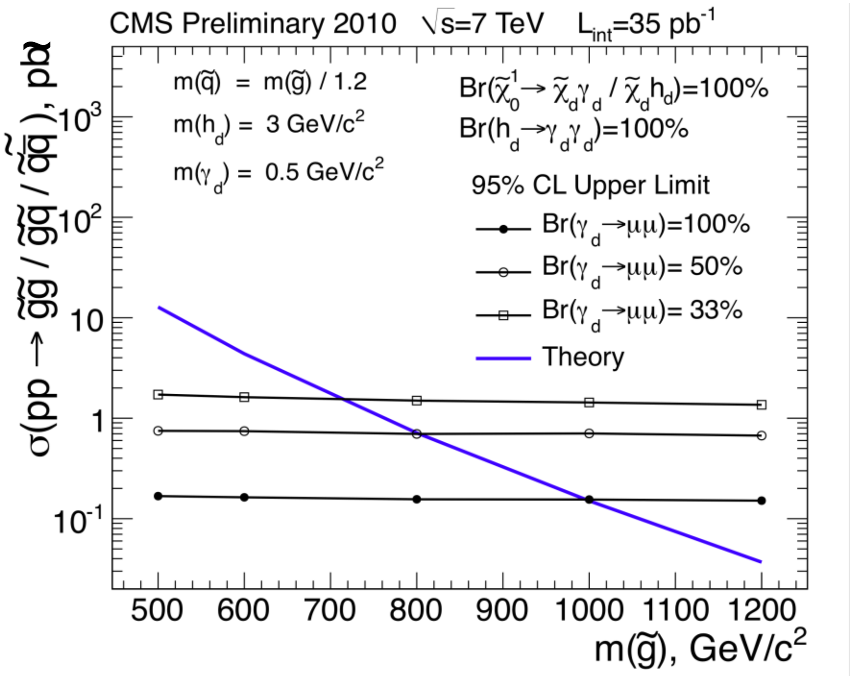


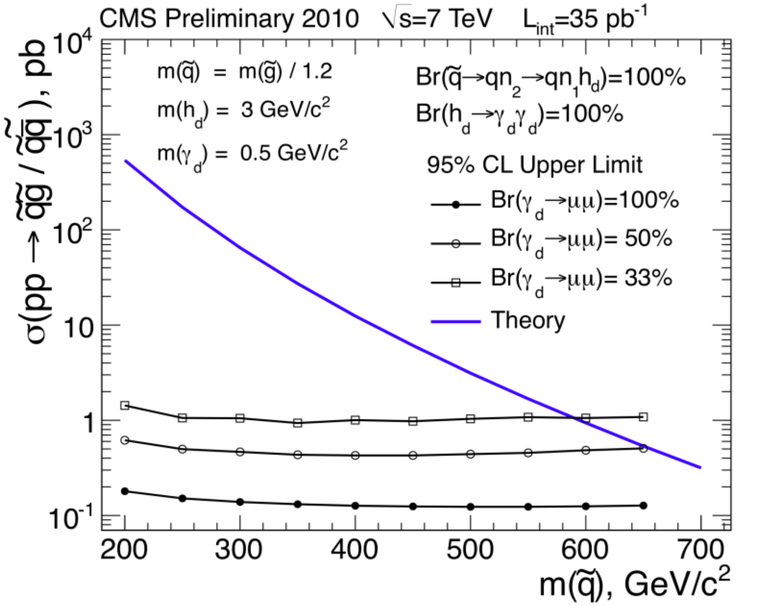
Lepton jets

$\tilde{\chi}^0_1 \rightarrow \tilde{\chi}_{dark}\, \gamma_{dark} + \tilde{\chi}_{dark} + h_{dark}\ (\rightarrow \gamma_{dark}\, \gamma_{dark})$

$\tilde{q} \rightarrow q\, n_2\ ;\ n_2 \rightarrow n_1\, \gamma_{dark} + n_1 h_{dark}\ (\rightarrow \gamma_{dark}\, \gamma_{dark})$







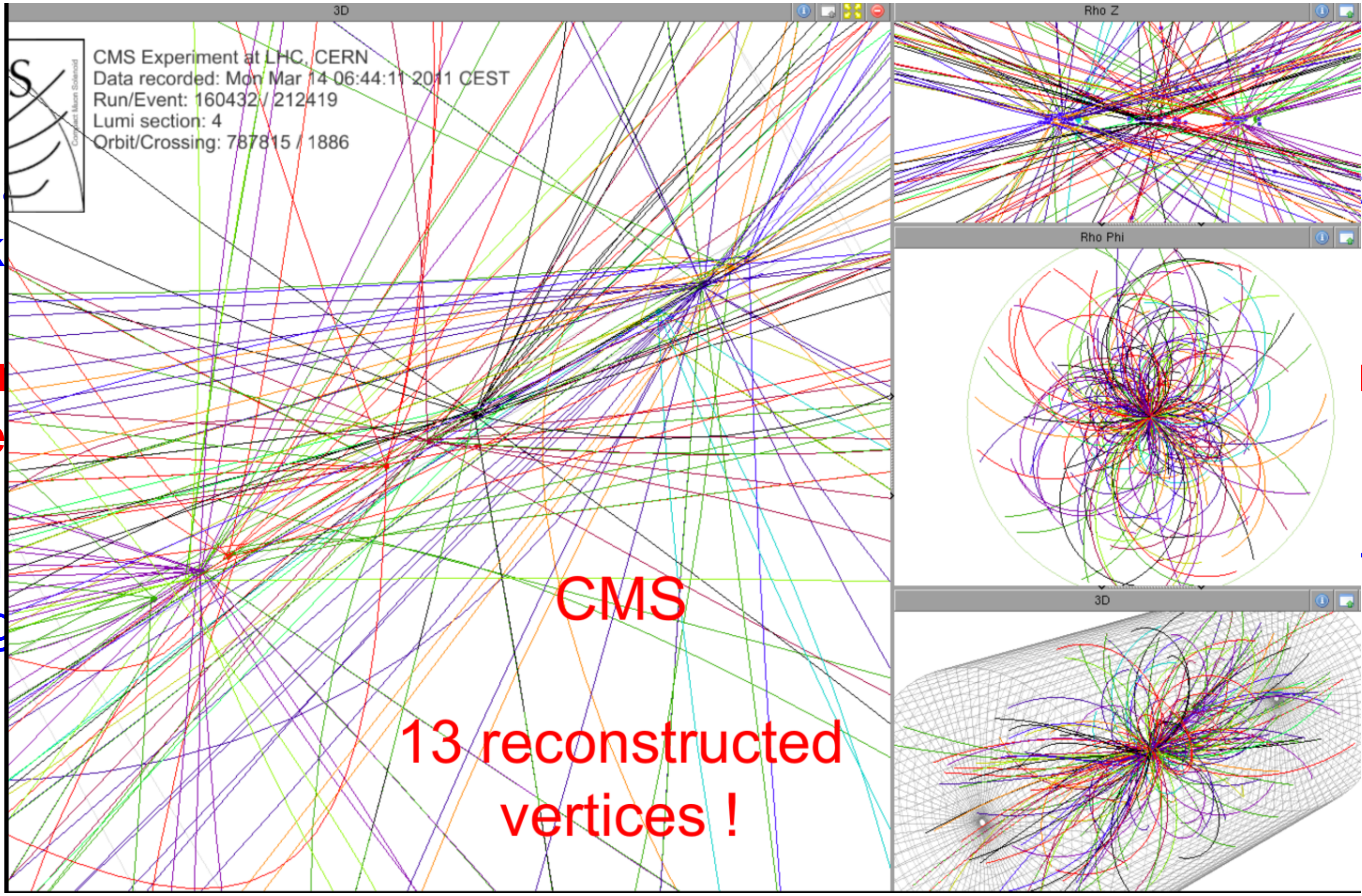
Other analyses…

Analyses not discussed

- Di-jet resonances
- ttbar resonances
- 4th Generation
- …

Conclusions

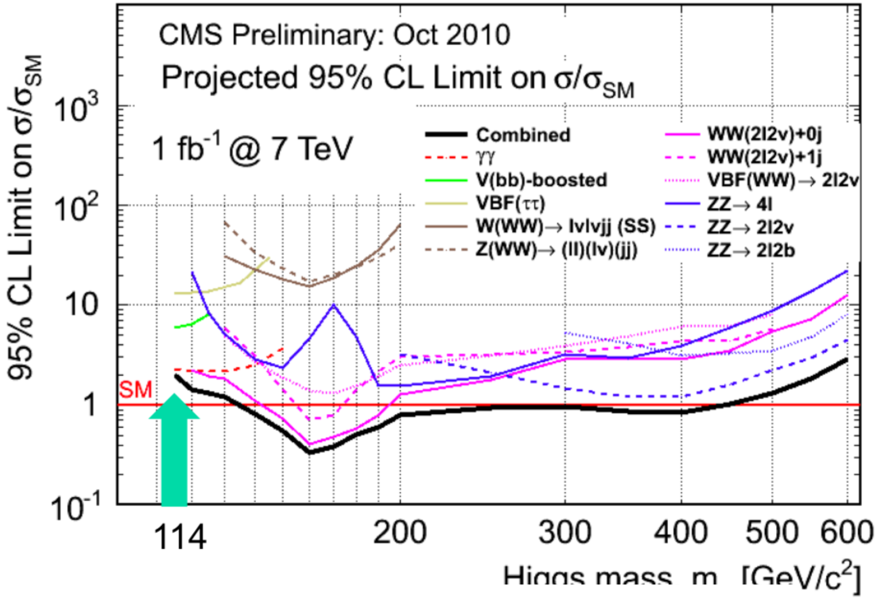
- CMS … year of data tak…
- Obse… …any searche…
- The n… …new challeng…

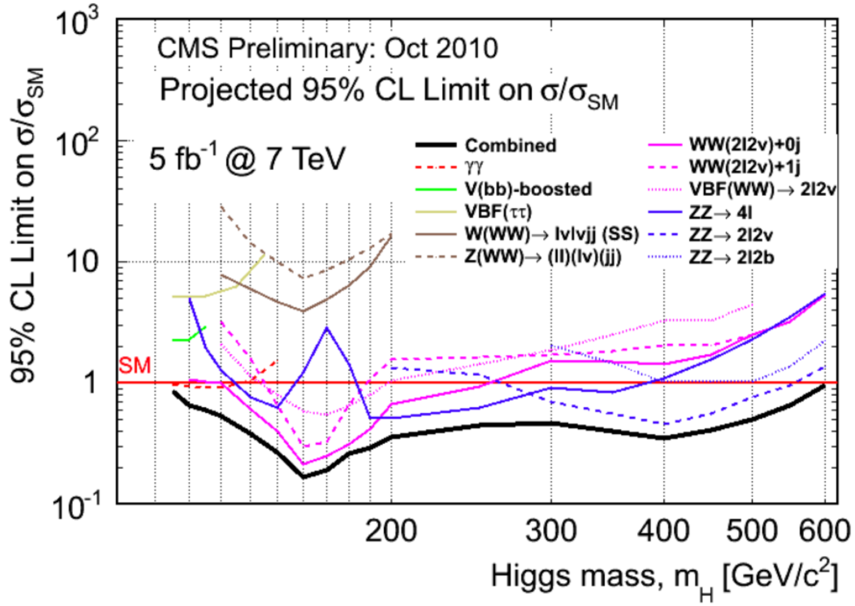


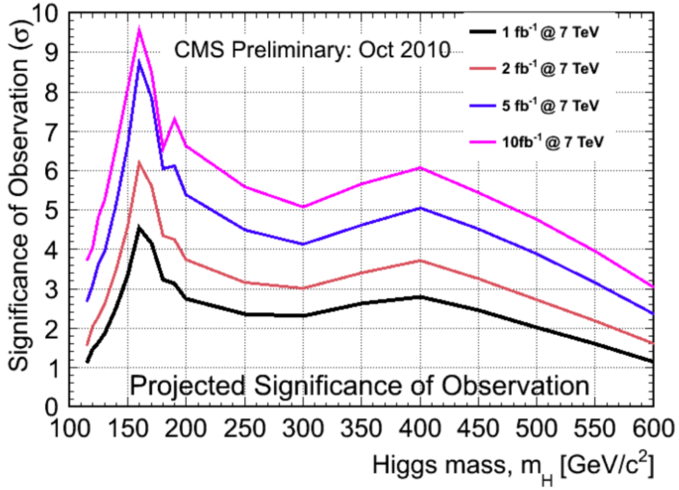
Backup slides

Higgs

Over next two years Higgs searches become interesting







ATLAS + CMS ≈ 2 x CMS	95% CL exclusion	3σ sensitivity	5σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535

$U(1)'$	Parameter	g_V^u	g_A^u	g_V^d	g_A^d	g_V^e	g_A^e	g_V^ν	g_A^ν
E_6 ($g' = 0.462$)	θ								
$U(1)_\chi$	0	0	-0.316	-0.632	0.316	0.632	0.316	0.474	0.474
$U(1)_\psi$	0.5π	0	0.408	0	0.408	0	0.408	0.204	0.204
$U(1)_\eta$	-0.29π	0	-0.516	-0.387	-0.129	0.387	-0.129	0.129	0.129
$U(1)_S$	0.129π	0	-0.129	-0.581	0.452	0.581	0.452	0.516	0.516
$U(1)_I$	0.21π	0	0	0.5	-0.5	-0.5	-0.5	-0.5	-0.5
$U(1)_N$	0.42π	0	0.316	-0.158	0.474	0.158	0.474	0.316	0.316
GLR ($g' = 0.595$)	ϕ								
$U(1)_R$	0	0.5	-0.5	-0.5	0.5	-0.5	0.5	0	0
$U(1)_{B-L}$	0.5π	0.333	0	0.333	0	-1	0	-0.5	-0.5
$U(1)_{LR}$	-0.128π	0.329	-0.46	-0.591	0.46	0.068	0.46	0.196	0.196
$U(1)_Y$	0.25π	0.833	-0.5	-0.167	0.5	-1.5	0.5	-0.5	-0.5
GSM ($g' = 0.760$)	α								
$U(1)_{SM}$	-0.072π	0.193	0.5	-0.347	-0.5	-0.0387	-0.5	0.5	0.5
$U(1)_{T_{3L}}$	0	0.5	0.5	-0.5	-0.5	-0.5	-0.5	0.5	0.5
$U(1)_Q$	0.5π	1.333	0	-0.666	0	-2.0	0	0	0

$$U(1)' = \cos\theta\ U(1)_\chi + \sin\theta\ U(1)_\psi,$$

$$Q_{E_6} = \cos\theta\ T_\chi + \sin\theta\ T_\psi.$$

$$Q_{GLR} = \cos\phi\ T_{3R} + \sin\phi\ T_{B-L},$$

$$Q_{GSM} = \cos\alpha\ T_{3L} + \sin\alpha\ Q,$$

In these models one envisages that at the GUT scale the gauge group is E_6. The gauge group E_6 is broken at the GUT scale to $SO(10)$ and a $U(1)_\psi$ gauge group,

$$E_6 \to SO(10) \times U(1)_\psi. \tag{III.1}$$

The $SO(10)$ is further broken at the GUT scale to $SU(5)$ and a $U(1)_\chi$ gauge group,

$$SO(10) \to SU(5) \times U(1)_\chi. \tag{III.2}$$

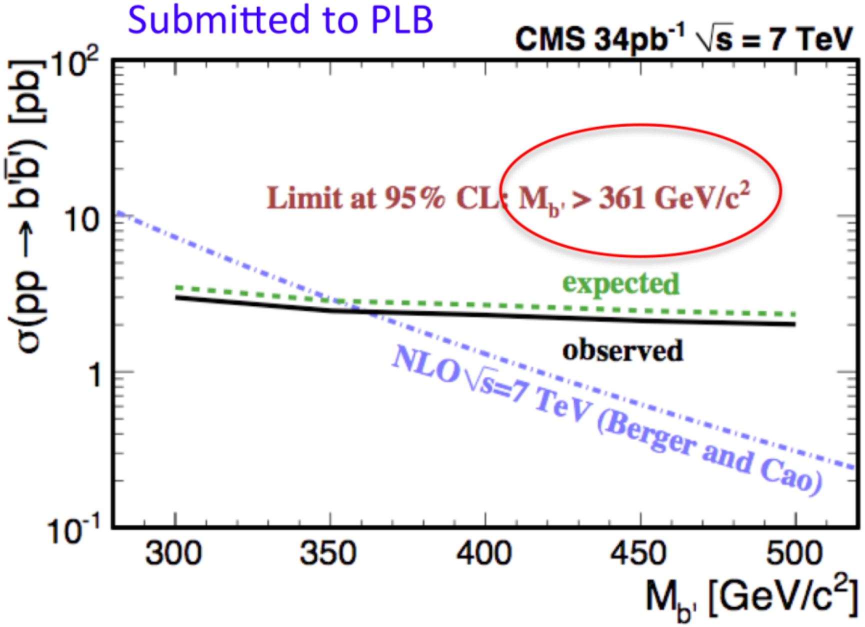
Finally the $SU(5)$ is broken at the GUT scale to the Standard Model (SM) gauge group,

$$SU(5) \to SU(3)_C \times SU(2)_L \times U(1)_Y. \tag{III.3}$$

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

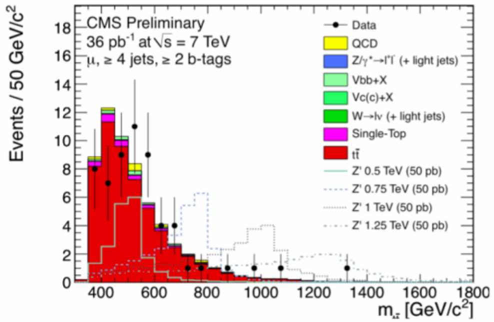
arXiv:1102.4746, Submitted to PLB



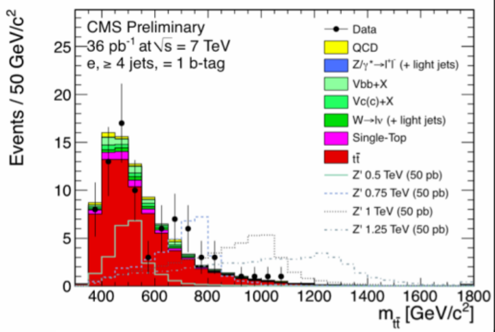
Similar to a new CDF limit of 372 GeV, arXiv:1101.5728 (4.8 fb^{-1})

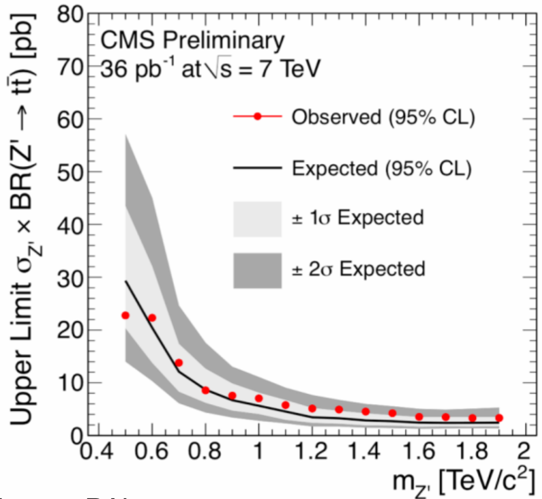
- **Bump hunt in M(ttbar) spectrum**
- Lepton+jets channels (e and μ)
- No bump seen in data
- Set limits, competitive with Tevatron

μ, >=4jets, >=2 btags



e, >=4jets, >=1 btags

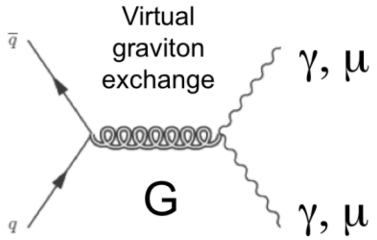




TOP-10-007, EXO-10-023

Cambridge 2011 *C.H. Shepherd-Themistocleous - RAL*

ADD di-μ di-γ



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

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

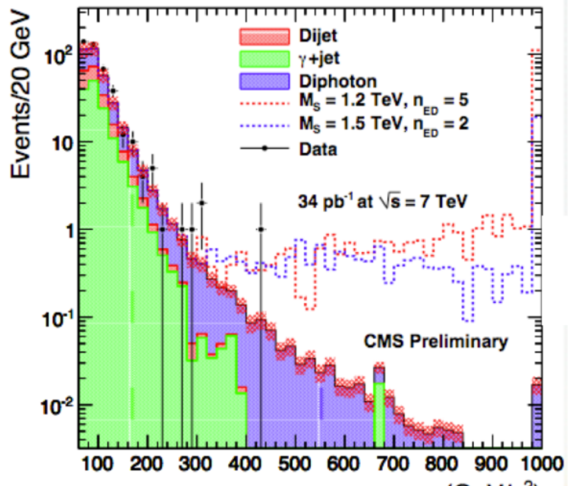
γγ

	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

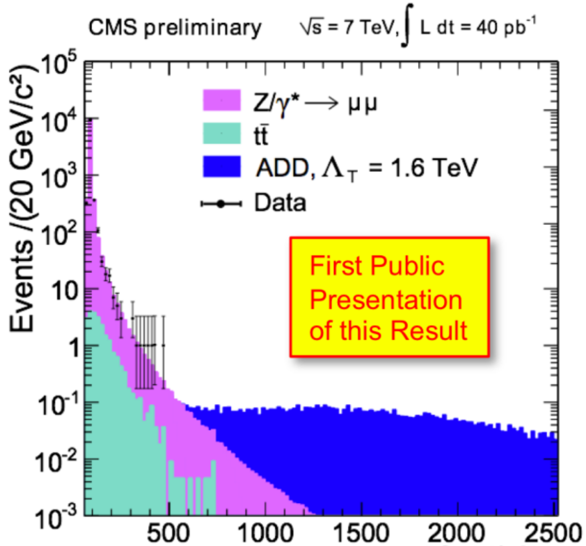
μμ

	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-10-026



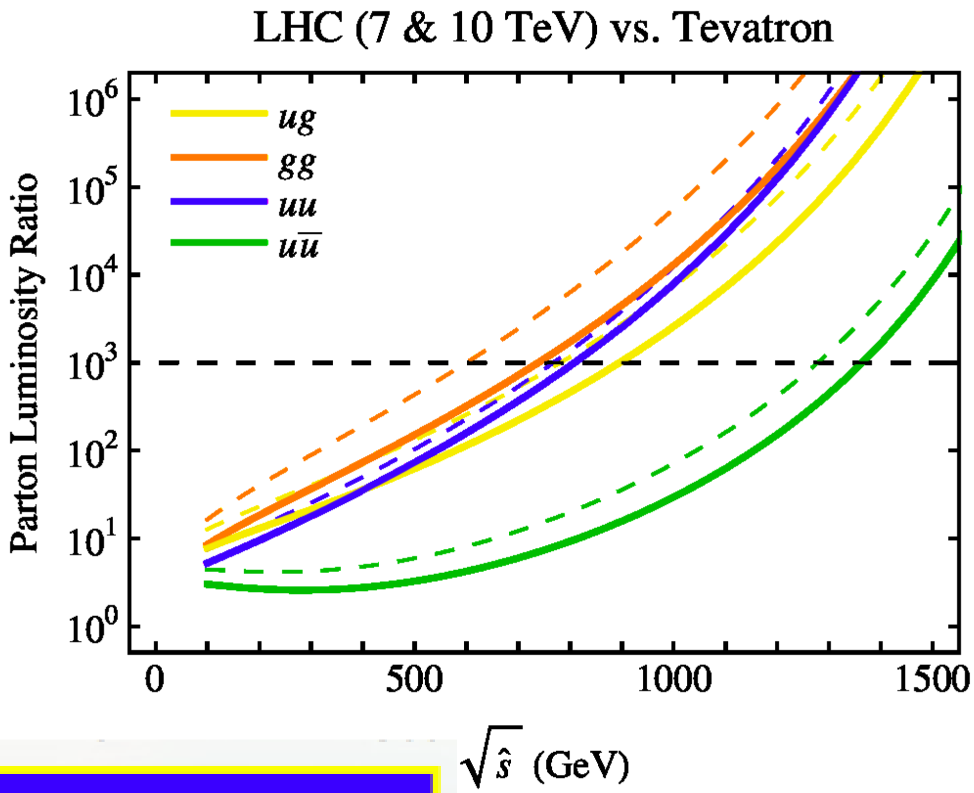
EXO-10-020

Search potential wrt Tevatron

Ratio of int. luminosities LHC (40 pb^{-1}) /TEV (5fb^{-1}) ~ 1/100

For ratios of parton luminosities > 100 LHC wins (F^n of initial state)

Pair production of Intermediate mass particles from gg, qg, qq



Production of massive objects > ~ 1TeV

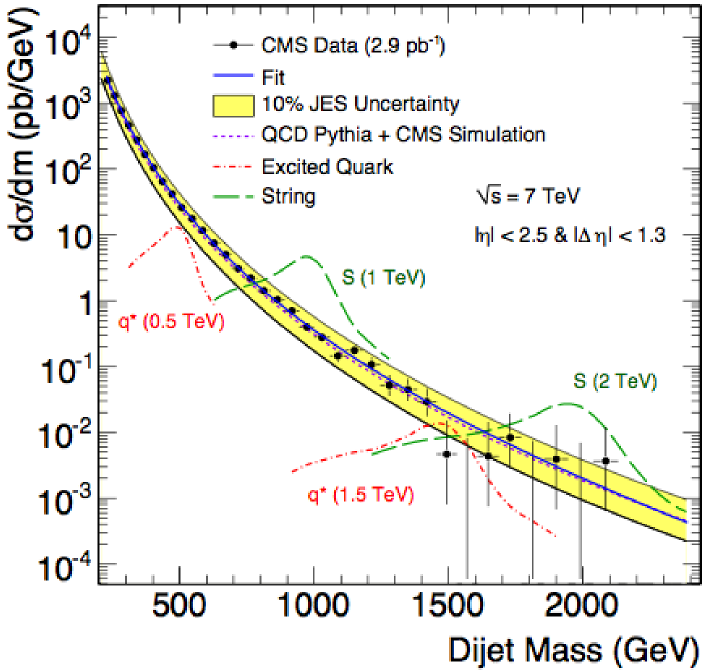
Bauer et al., Phys. Lett. B 690, 280 (2010)

Di-jet

Mass spectrum → resonances

Jet energy scale important

Fit function describing background to data

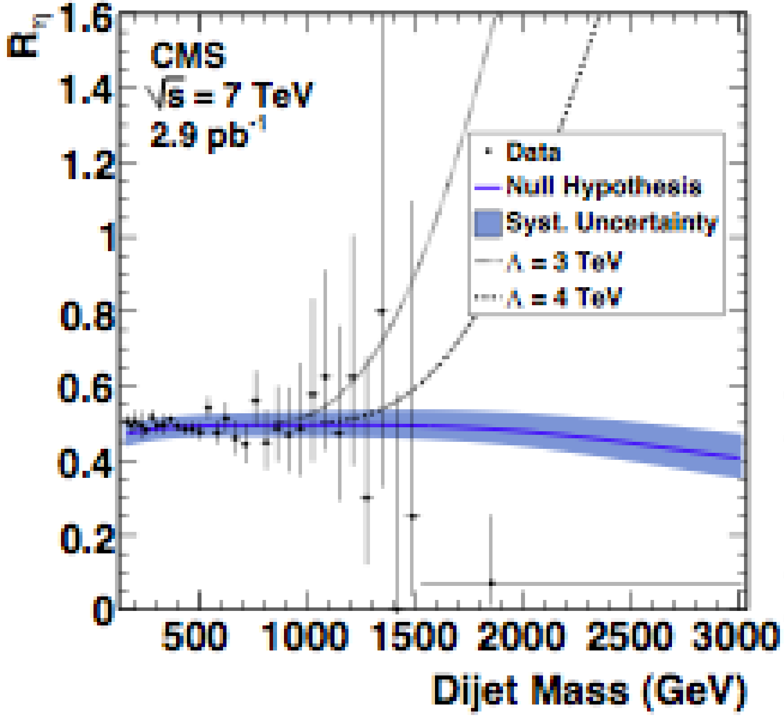


Excited q>1.58 TeV   String res. > 2.5 TeV

Angular distribution → contact interactions

QCD peaked large η. NP different

Centrality Ratio: Ratio central (η < 0.70 to forward (0.7 < η < 1.3) events flat as f^n of mass for QCD.



Compositness Limit
Λ > 4 TeV