The first few fb^{-1}; potential for observation of physics beyond the Standard Model

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CERN

on behalf of **ATLAS** and **CMS** collaborations

XLIII Rencontres de Moriond

Electroweak interactions and unified theories

Outline

At LHC many models can be tested

Signatures are very similar: isolated high-p_T leptons, large missing E_T, very energetics photons and jets, high invariant mass of the final state...

→ combination of the above signatures

→ early data may not be enough to identify which is the model which the new signal belongs to

...But we can see if there is new physics!

Discovery potential for

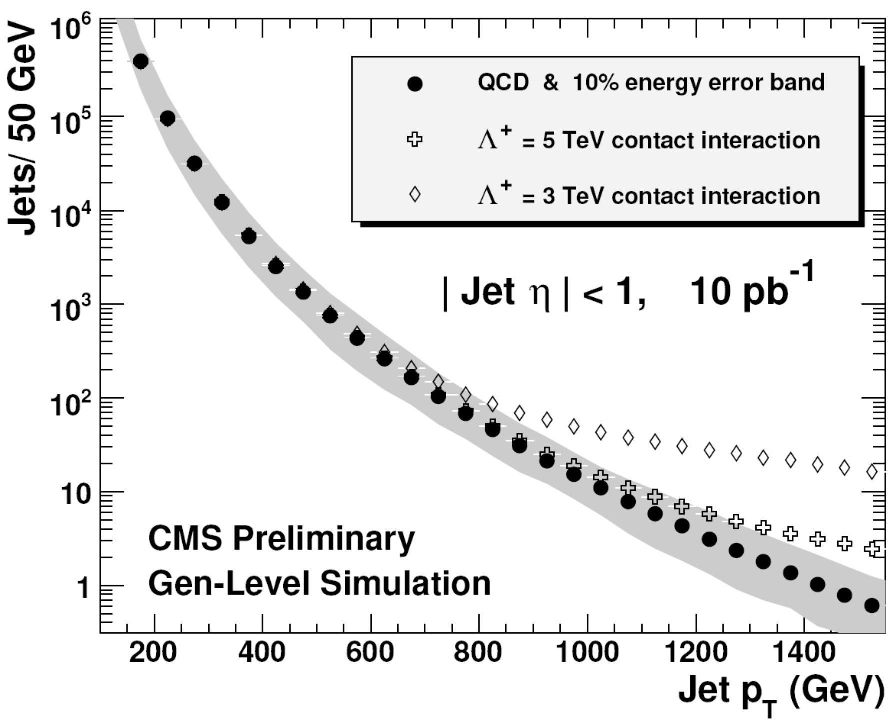
- Contact interactions
- New vector bosons
- Extra dimensions
- Dynamical electroweak symmetry breaking

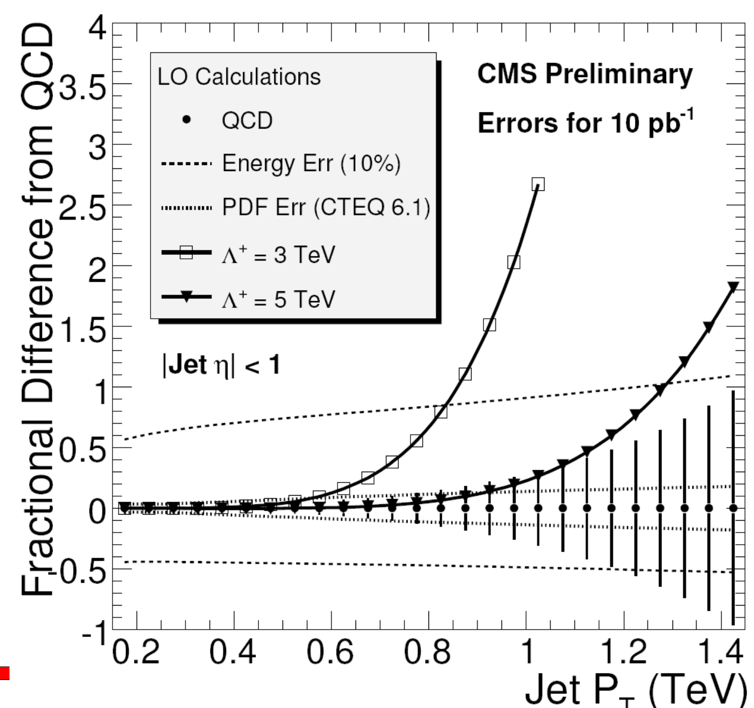
Quick scan of the jet final states

- Contact interaction
- Resonances in di-jet invariant mass

Modification to Inclusive Jet p_T Continuum

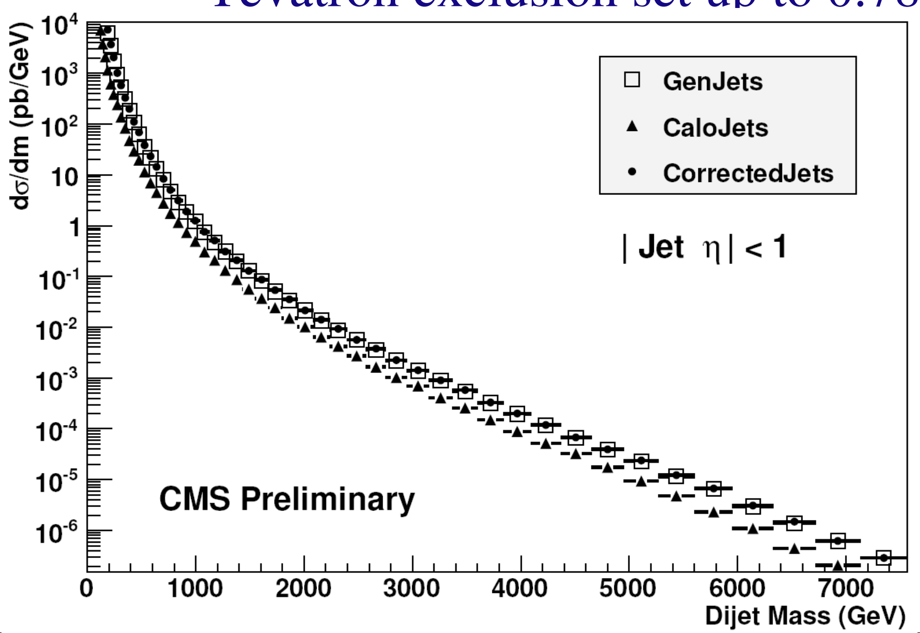
- Contact interactions create large rate at high p_T and **immediate discovery is possible**
  - error dominated by jet energy scale (~10%) in early running (**<u>10 pb^{-1}</u>**)
    - ΔE ~ 10% not as big an effect as $\boldsymbol{\Lambda^{+}}$ **= 3 TeV** for p_T > 1 TeV
  - Uncertainties in the PDF and statistical errors at 10 pb^{-1} are smaller than E scale error
- With 10 pb^{-1}, LHC can see new physics beyond the Tevatron exclusion of **Λ^{+} < 2.7 TeV**

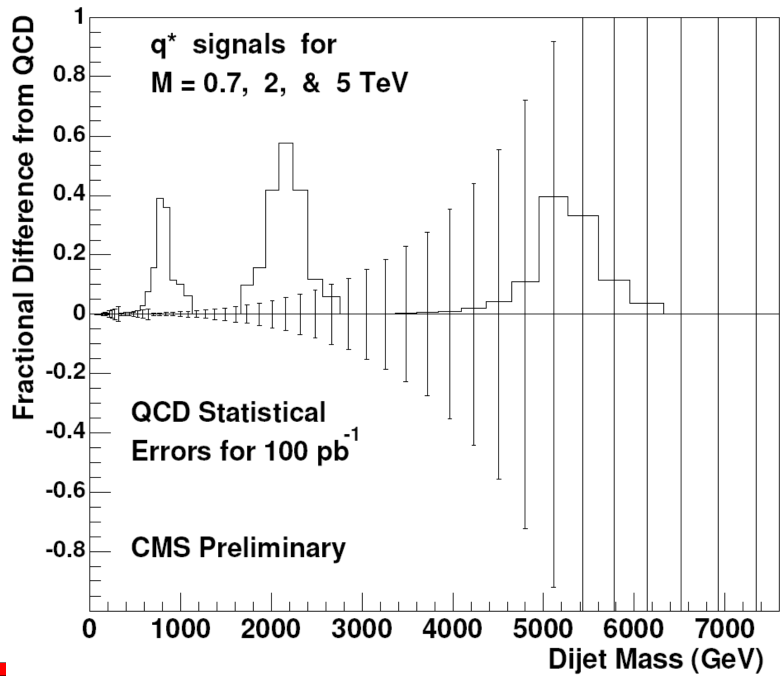




High Mass Di-jet Resonances

- Measure rate as a function of the correct di-jet mass and **search for resonances**
  - Use a smooth parametrised fit or QCD prediction to model the background
- Strongly produced resonances can be seen
  - e.g. signal for a **2 TeV** excited quark (in E6 model) in **100 pb^{-1}**
    - Tevatron exclusion set up to 0.78 TeV

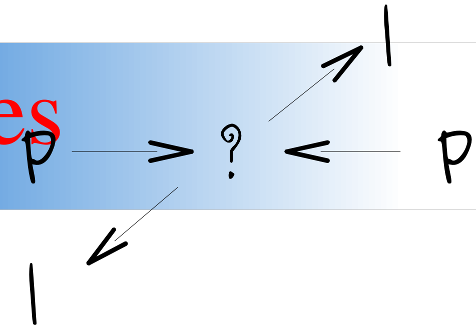




High mass di-lepton final states

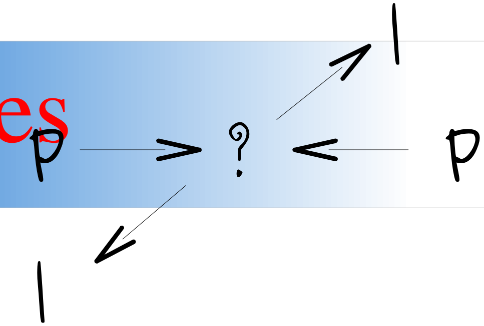
- Z'
- Randall-Sundrum Graviton
- ADD ED Graviton

Di-lepton final states



- Signature
  - pair of isolated **high momentum** leptons with large invariant mass
- Main background
  - **Drell-Yan**
- Experimental Issues
  - *electronics saturation* for high energetic electrons
  - *muon bremsstrahlung* (no isolation at calo level)
  - *alignment*

Di-lepton final states



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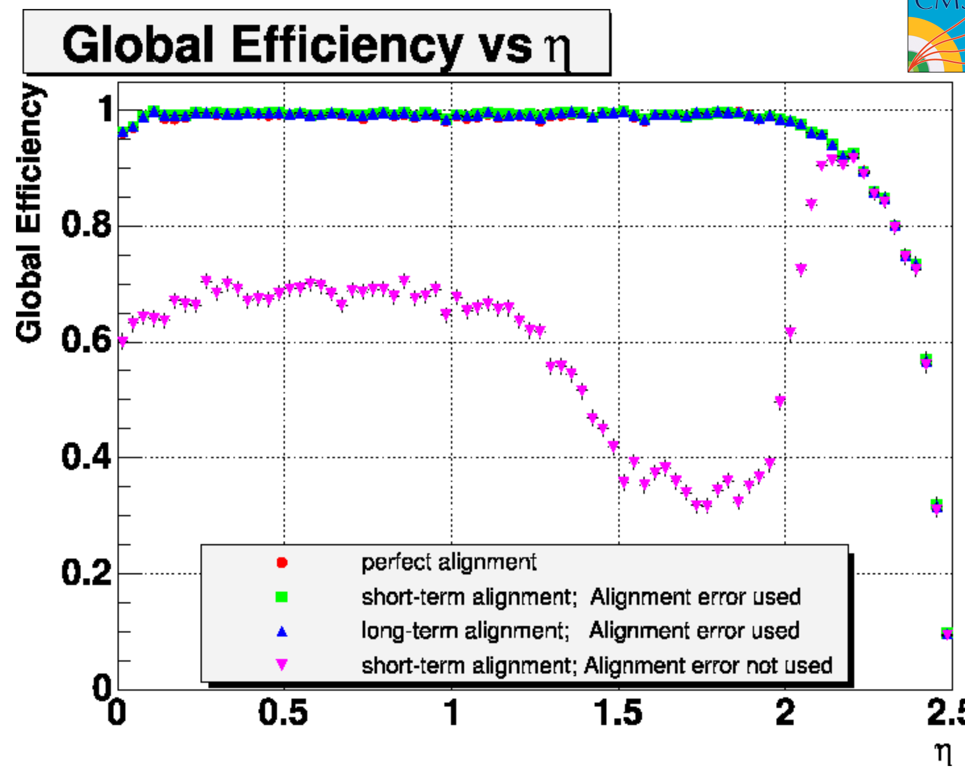

Di-lepton final states

l

p → ? ← p

l

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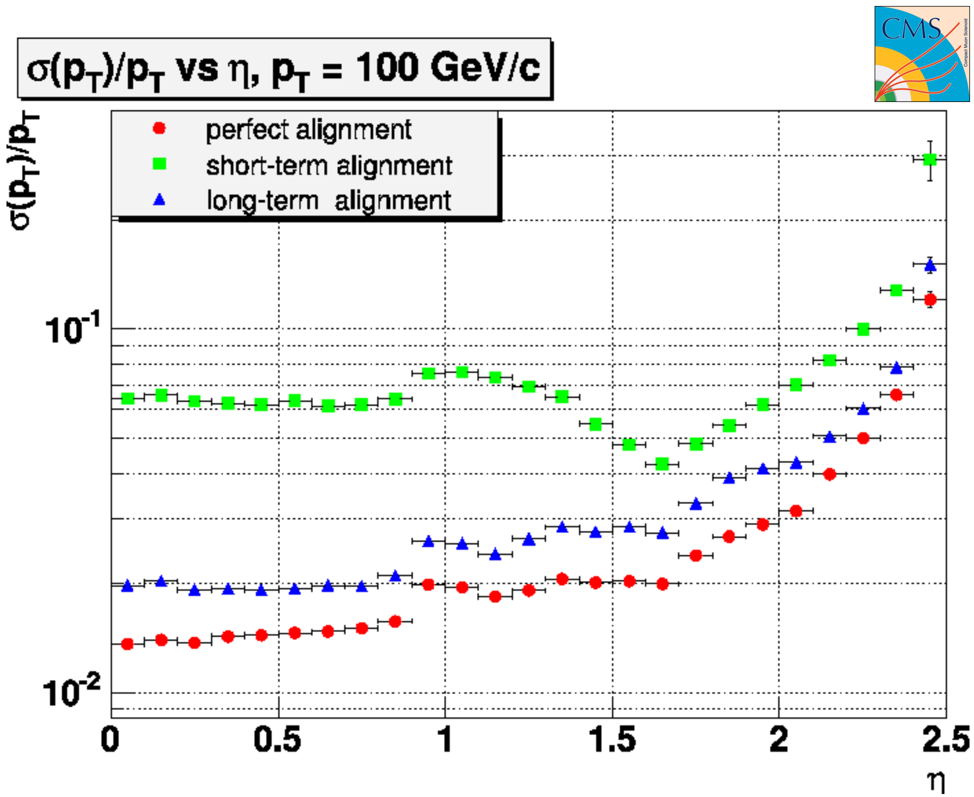
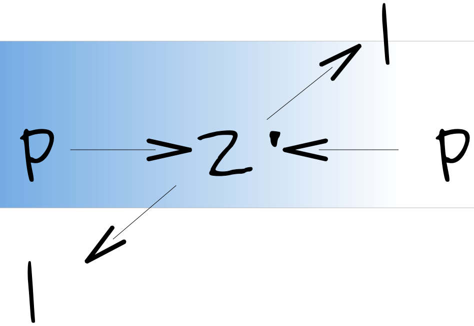
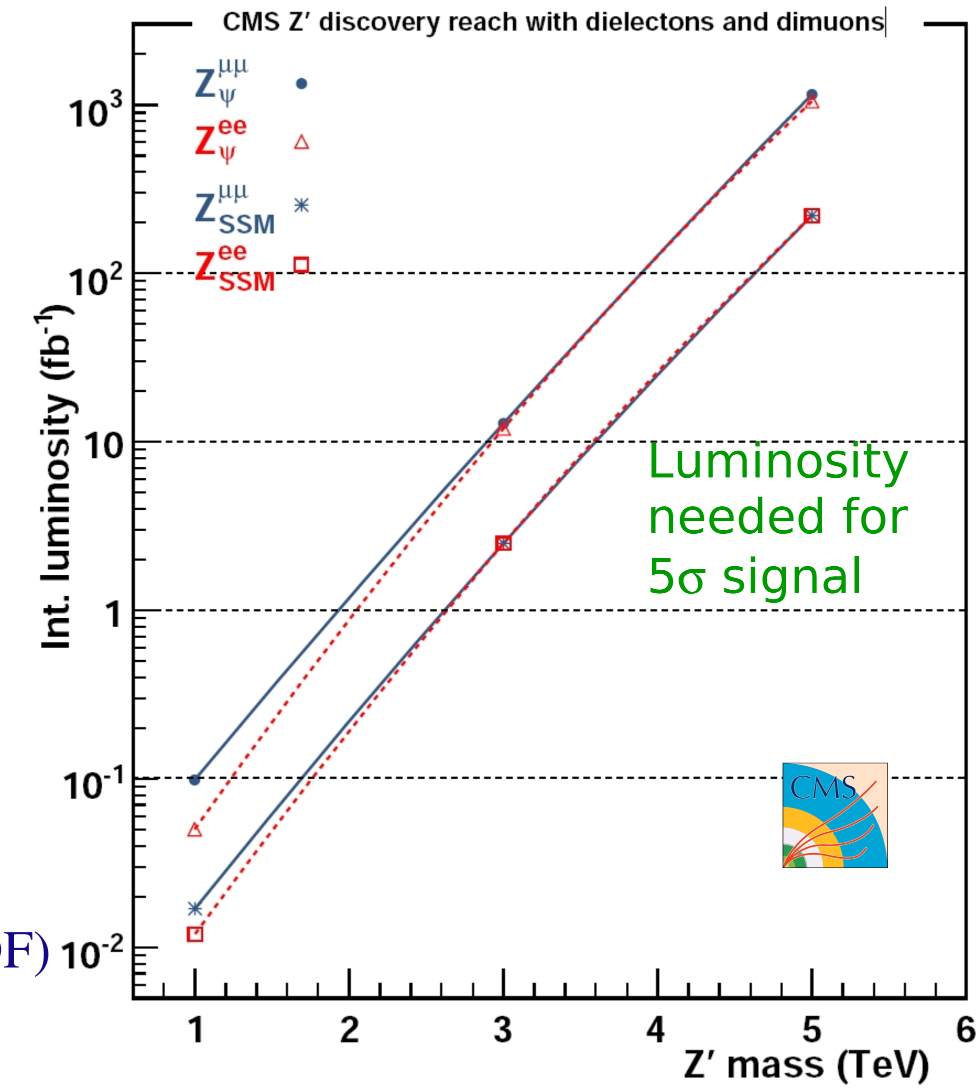


Z'



- Z_ψ , Z_χ , Z_η models from E_6 and SO(10) GUT groups
- Z_{LR} in Left-Right symmetry models
- **KK excitation** of SM Z



<u>Limits from experiments</u>:

- Z_{SSM}: **850 GeV** (CDF), **1.5 TeV** (EW fit), both @ 95% C.L.
- Z_{LR}: **630 GeV** (CDF), **860 GeV** (EW fit), both @ 95% C.L.
- Z_χ: **740 GeV**, Z_ψ: **725 GeV**, Z_η: **745 GeV** (CDF)

Randall - Sundrum

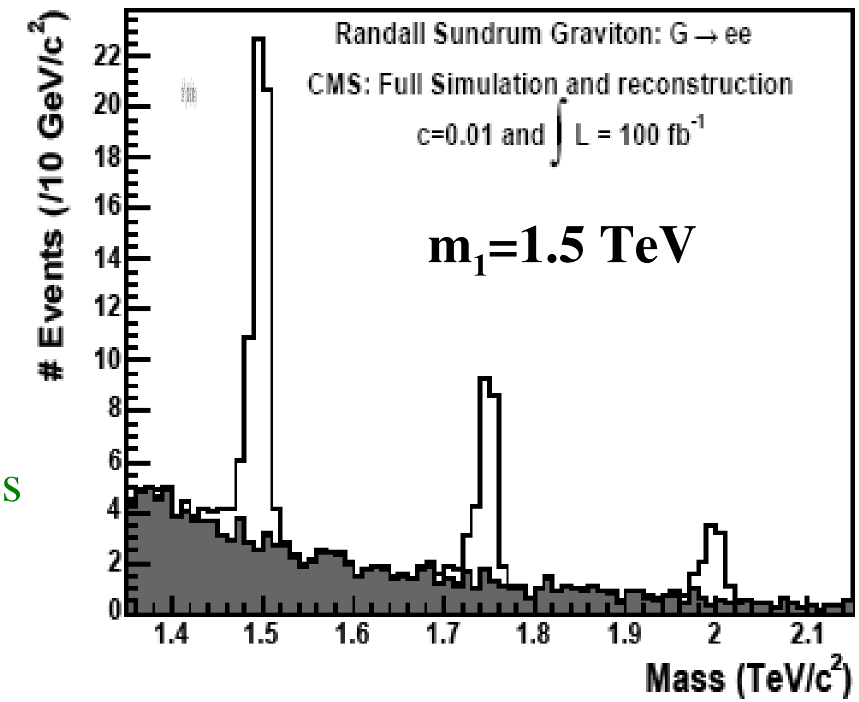
2 4D-branes (TeV and Planck) connected by a warped ED

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2, with\, y = r_c\phi$$

$$\Lambda_\pi = M_{pl}e^{-kr_c\pi} \qquad kr_c\pi \sim 35 \;\Rightarrow\; \Lambda_\pi \sim \text{TeV}$$

k = curvature

r_c = compactification radius



- Only graviton can propagate in the bulk
  - resonances predicted with well separated masses

$$m_n = kx_n e^{-kr_c\pi}, with\;\; J_1(x_n) = 0$$

$$m_1 = 3.83\, c\,\Lambda_\pi, with\;\; c = k/M_{pl}$$

  - width is sensitive to the coupling $(\Gamma \propto c^2)$

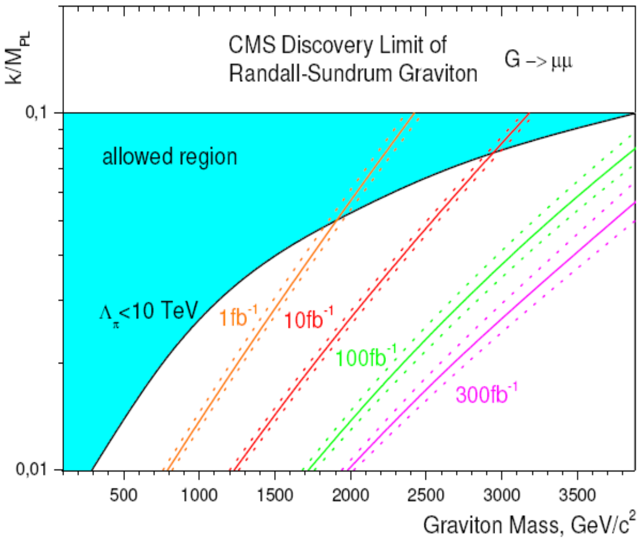
- Graviton discovery in different channels will help to distinguish it with respect to other particles (e.g. Z')

Randall - Sundrum

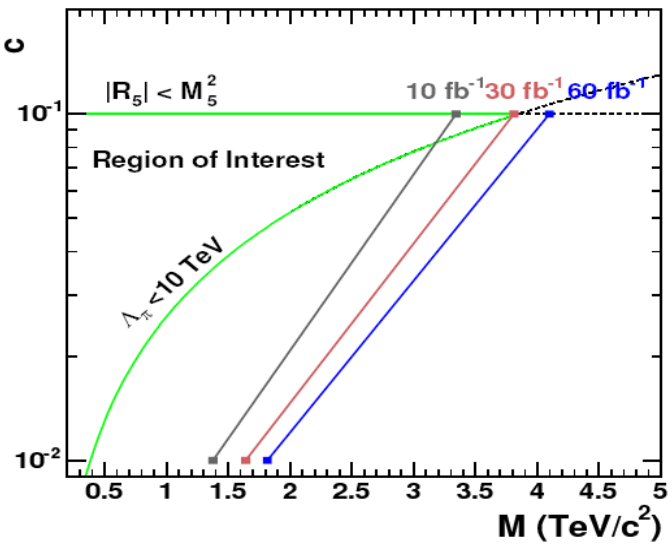
$p \rightarrow G_{RS} \leftarrow p$

l l

$G_1 \rightarrow \mu^+\mu^-$



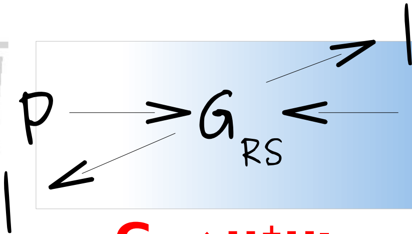
$G_1 \rightarrow e^+e^-$



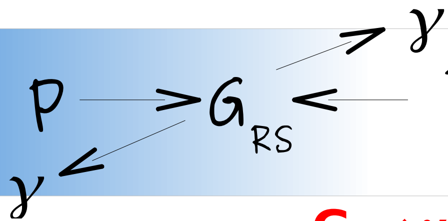
c > 0.1 disfavoured as bulk curvature becomes to large (larger than the 5-dim Planck scale)

Systematic effects included: misalignment, EW corrections, PDF

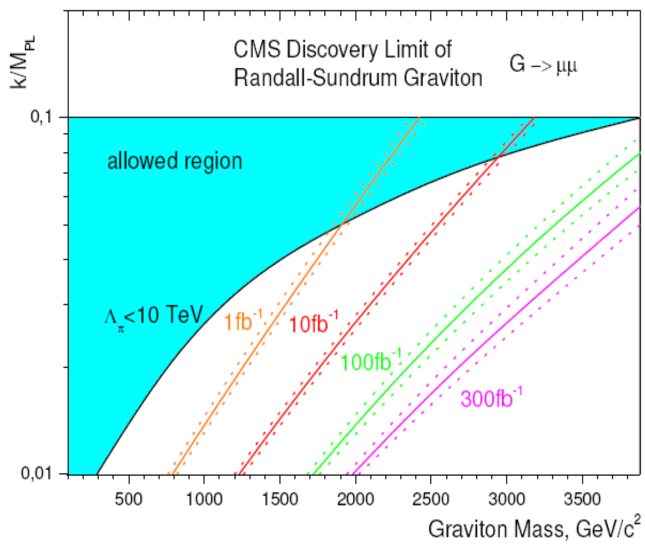
L ~ 30 fb^{-1} <u>is enough</u> to cover the whole mass region



Randall - Sundrum



$G_1 \to \mu^+\mu^-$



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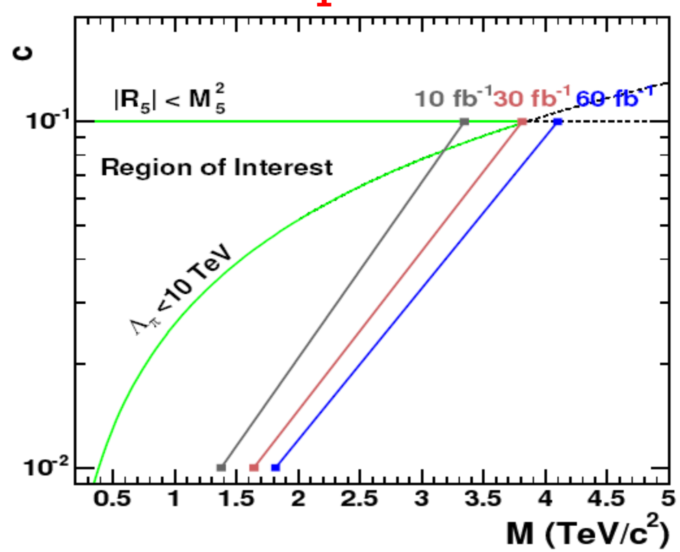
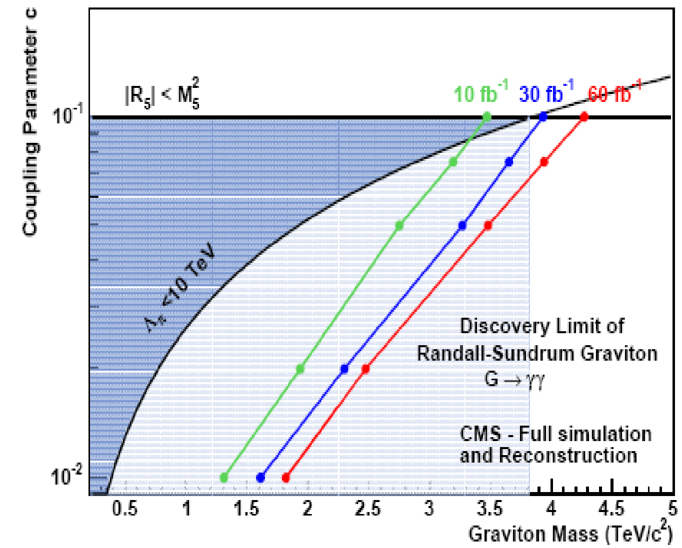


$G_1 \to \gamma\gamma$



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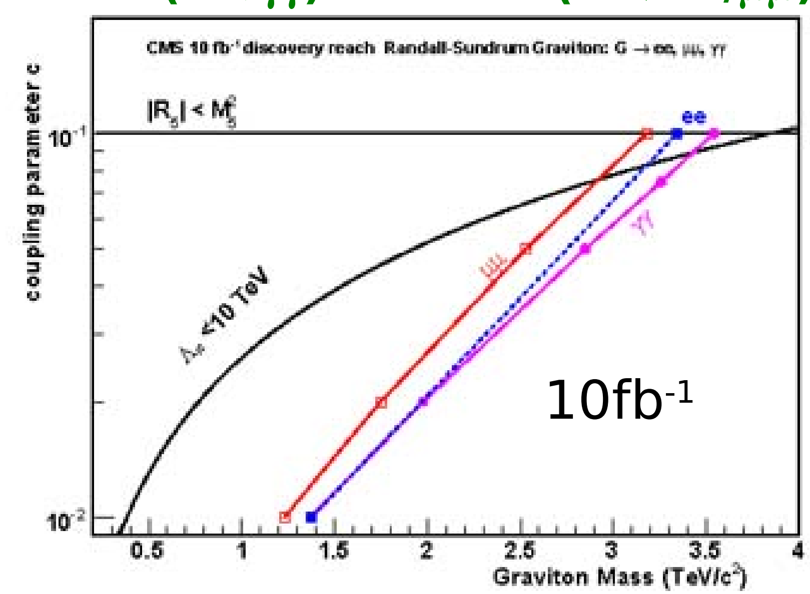
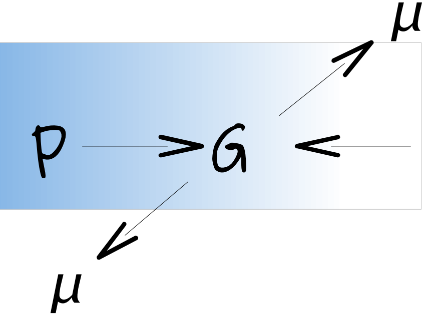
$G \to \gamma\gamma$ allows to cross check the model

BR($G \to \gamma\gamma$) = 2 x BR($G \to ee/\mu\mu$)



ADD

Arkani-Hamed, Dimopoulos, Dvali



- Additional Large Extra Dimensions (**LED**)

$$M_{pl}^2 \sim R^n M_D^{2+n} \qquad \text{if } M_D \sim 1 \text{ TeV} \rightarrow R \sim 10^{32/n} \cdot 10^{-4} \text{ fm}$$

$n = 2 \rightarrow R \sim 1$ mm
$n = 4 \rightarrow R \sim 100$ fm
$n = 6 \rightarrow R \sim 0.02$ fm

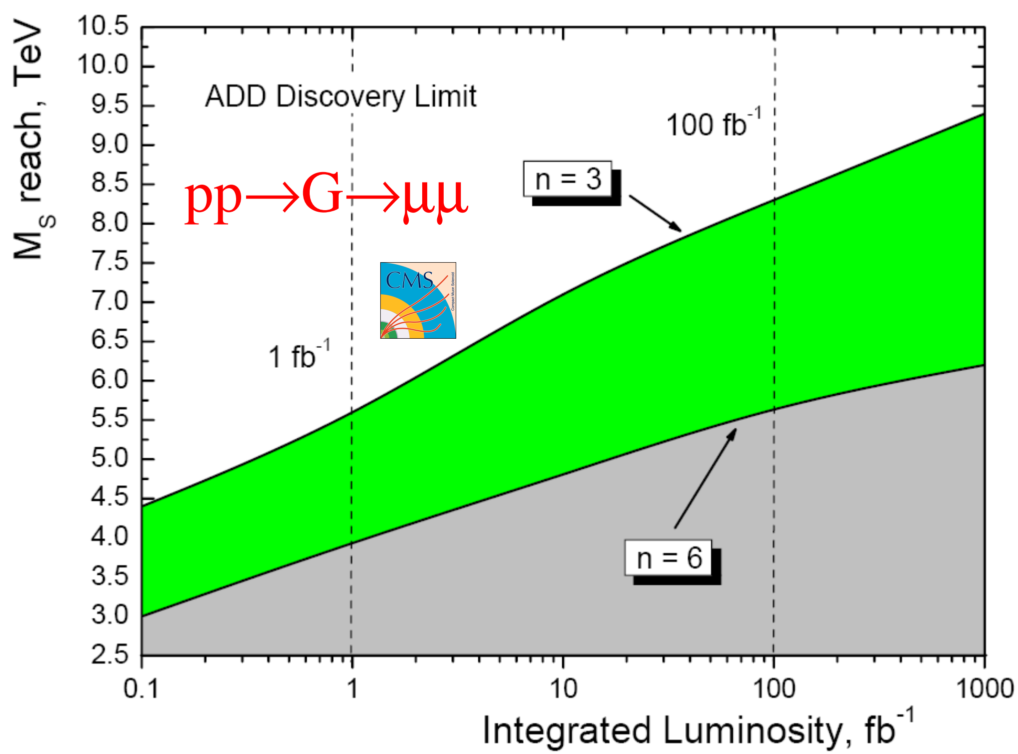
n = number of ED, M_D = Planck mass in the 4+n dimensions

– SM particles cannot propagate in ED

- Experimental limits:

– **M_D > 1 TeV** from Tevatron+Lep

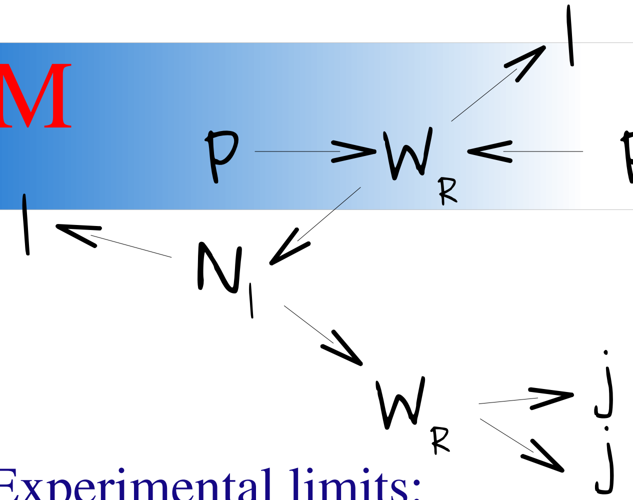
and **$n \geq 2$**



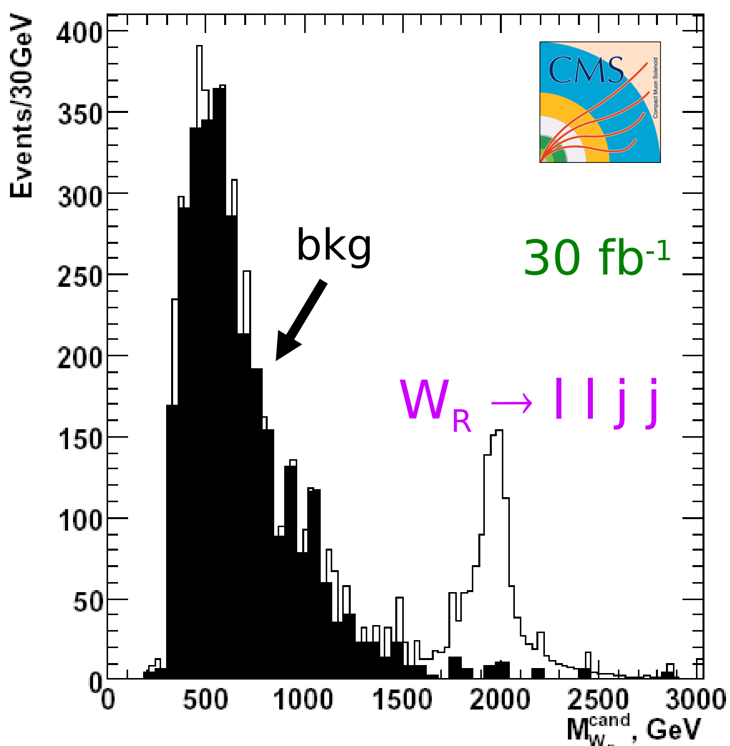
2 leptons and 2 jets final states

- Left-Right symmetry models

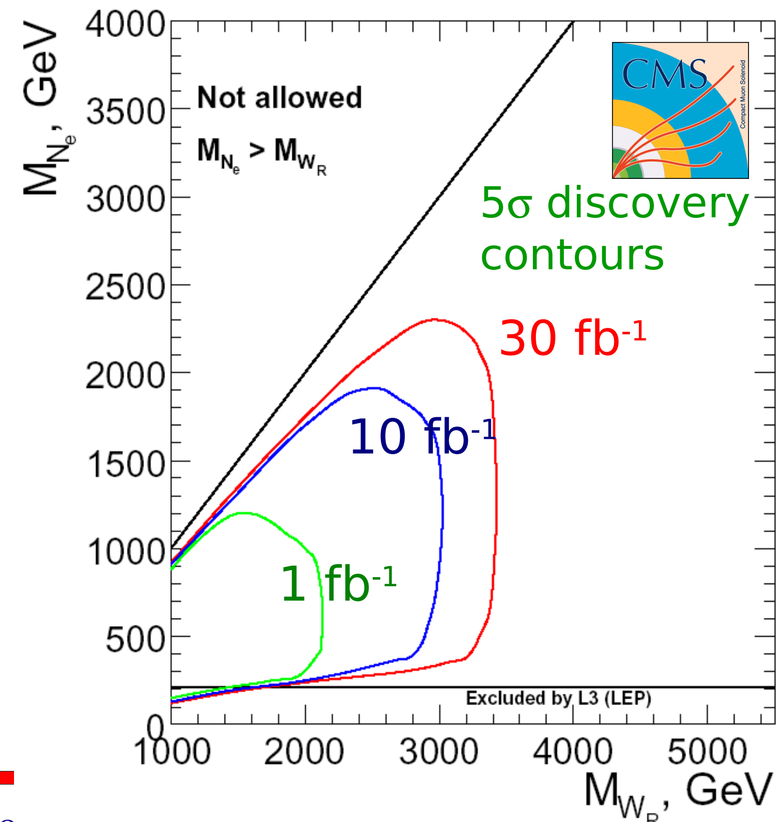
W_R in LRM



- Symmetry between **Left and Right**
  - $SU_C(3)\otimes SU_R(2)\otimes SU_L(2)\otimes U_Y(1)$
- Signature:
  - di-lepton + 2 jets for W_R
  - 1 lepton + 2 jets for heavy neutrino N_l



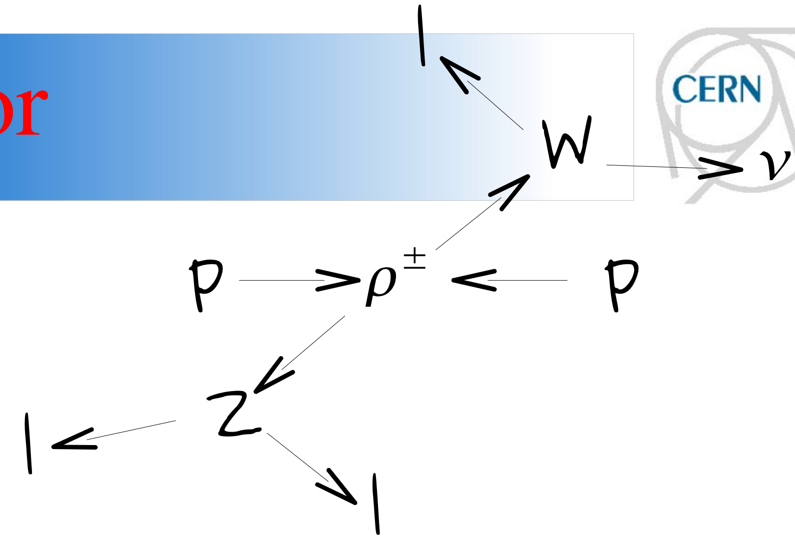
- Experimental limits:
  - **$m_{W'}$ > 715 GeV @ 90% C.L.** (Electroweak fit)



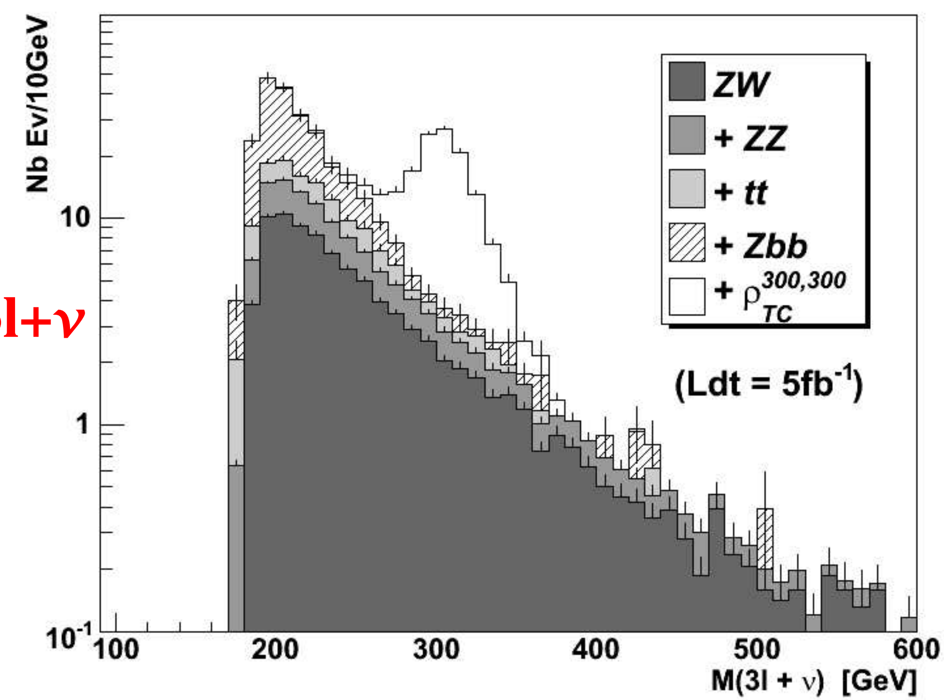
Leptons and missing E_T final states

- Technicolor
- W' (Sequential Standard Model)

Technicolor



- **Dynamical Electroweak Symmetry Breaking**
  - QCD-like force which acts on **technifermions** at a scale of ~ 250 GeV
  - Mediated by **technimesons**
    - π_{TC} (s = 0), ρ_{TC} and ω_{TC} (S = 1)
  - *No need* for the Higgs boson
- Most promising channel is $\rho_{TC} \rightarrow W+Z \rightarrow 3l+\nu$
  - isolated high-p_T leptons + missing E_T
  - W and Z kinematics as signature
  - Background from VV (V=Z,W), Z bb, tt



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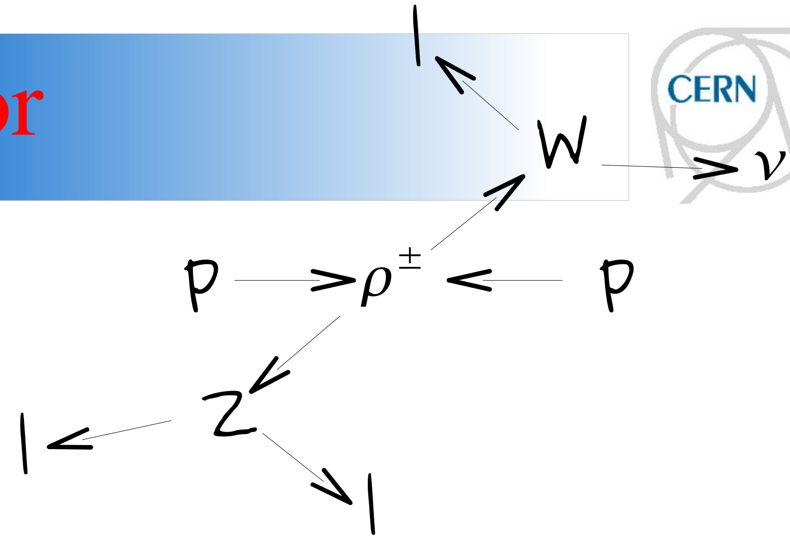

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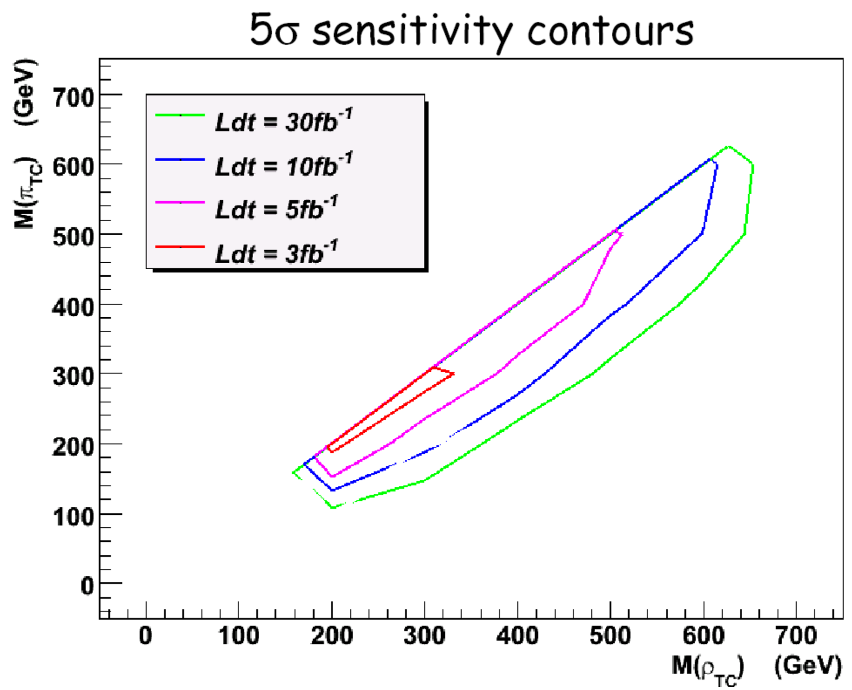
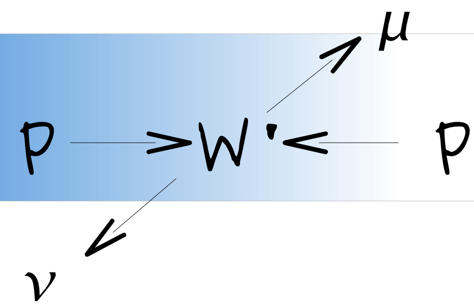
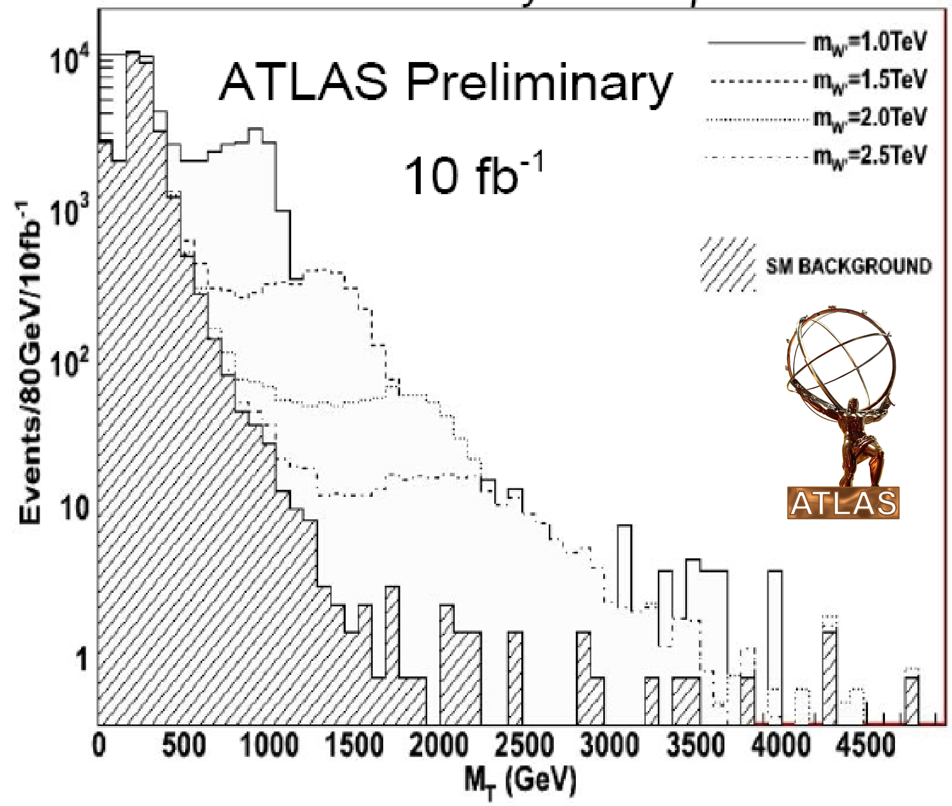


W' in SSM



- W' with **same properties** as W in SM
- Signature:
  - single isolated mu, with high p_T,
  - large missing E_T
- Main Background:
  - $W \to \mu\nu$ / $Z \to \mu\mu$ + jets,
  - WW/Z inclusive, ttbar inclusive
- Instantaneous luminosity considered:
  - $2 \cdot 10^{33}$ cm^{-2}s^{-1}
    - $\to$ pile-up ~ 3.5 event per bunch crossing

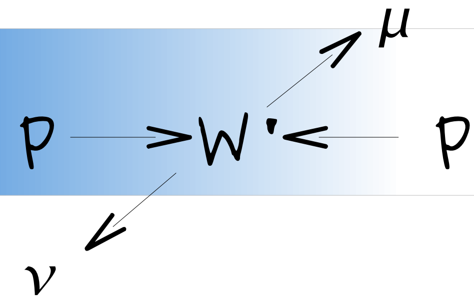
"Recent results on W' observability" Z. Ropas



Experimental limits:

$m_{W'}$ > 800 GeV @ 95%C.L. from D0

W' in SSM



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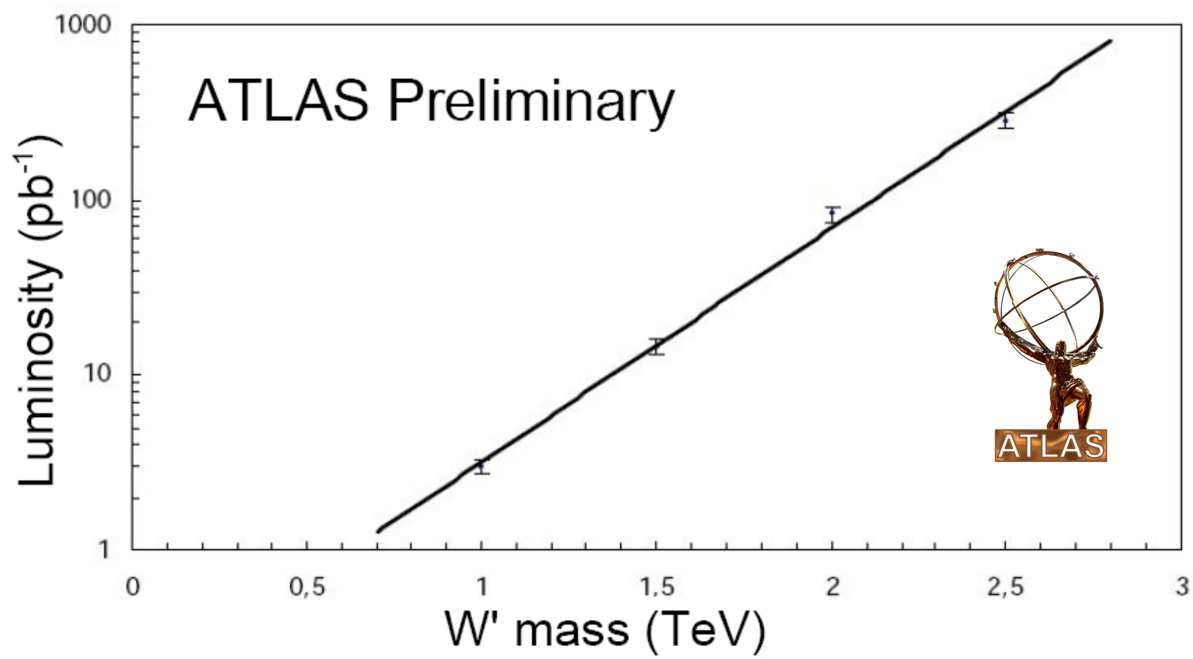

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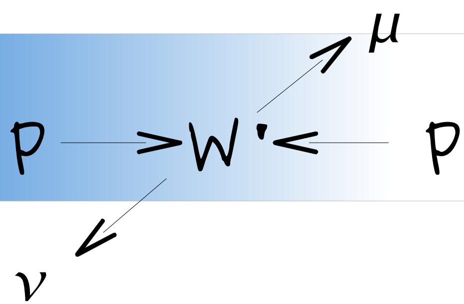

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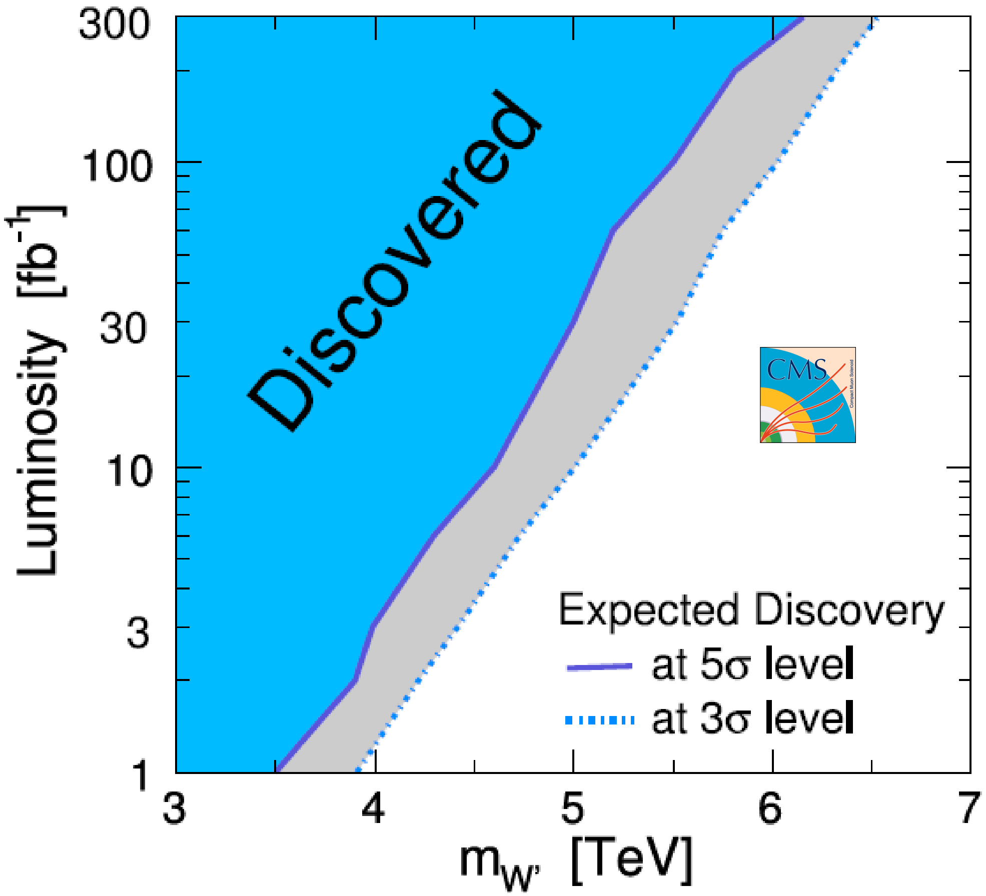

Experimental limits:

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M-jets, M-leptons, Large MET

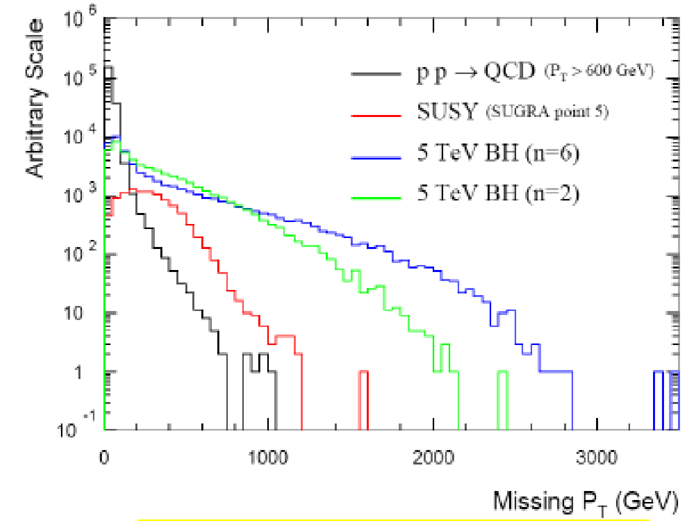
- Black Holes

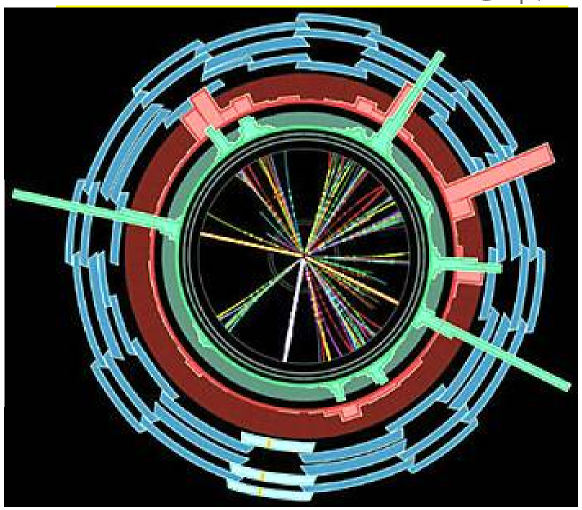
Black Hole at LHC

CERN

- In case of LED micro Black Holes (BH) could be produced at LHC energy scale, *in (4+n)-dimensional space-time*
  - Schwarzschild radius $r_{s(4+n)}$
- BH is formed is the p-p impact parameter is less than $r_{s(4+n)}$
  - from semi-classical approach $\sigma(M_{BH}) = \pi r^2_{s(4+\delta)}$
  - $M_{BH} > M_D$ and in case of **M_D ~ TeV then σ_{BH} ~ pb**
- BH would have a very short life time, of the order of 10^{-12}fs
- BH is expected to evaporate by emission of all particle types
  - source of new particles
  - possibility to probe quantum gravity in lab
- Signature
  - High track multiplicity, hadrons:leptons = 5:1
  - spherical event

Could be discovered with $1\ fb^{-1}$ if $M_D < 5$ TeV





BH → (q and g : leptons : Z and W : ν and G : H : γ)
= (72% : 11% : 8% : 6% : 2% : 1%)

Discovery Potential with Early Data

Model	Mass reach (TeV)	L (pb^{-1})	Early systematic
Contact Interaction	$\Lambda \sim 2.8$	10	Jet Eff., E scale
Z' ALRM SSM LRM E6, SO(10)	 M ~ 1 M ~ 1 M ~ 1 M ~ 1	 10 20 30 300-100	Alignment
Excited quark	M ~ [0.7, 3.6]	100	Jet energy scale
Axigluon or Colouron	M ~ [0.7, 3.5]	100	Jet energy scale
E6 diquarks	M ~ [0.7, 4]	100	Jet energy scale
Technirho	M ~ [0.3]	100	Jet energy scale
ADD virtual G_{KK}	$M_D \sim 4.3$ (n = 3), ~ 3 (n = 6) $M_D \sim 5$ (n = 3), ~ 4 (n = 6)	100 1000	Alignment
ADD real G_{KK}	$M_D \sim 1.5$ (n = 3), ~ 1 (n = 6)	100	MET, Jet/γ scale
mUED	M ~ 0.3 M ~ 0.6	10 1000	MET, Jet/γ scale
TeV^{-1} (Z_{KK})	$M_{z1} < 5$	1000	
RS1 di-jets di-muons	 $M_G \sim [0.7,0.8]$, c = 0.1 $M_G \sim [0.8,2.3]$, c = [0.01,0.1	 100 1000	 Jet energy scale Alignment

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mUED	M ~ 0.3 M ~ 0.6	10 1000	MET, Jet/γ scale
TeV^{-1} (Z_{KK})	$M_{z1} < 5$	1000	
RS1 di-jets	 M_G ~ [0.7,0.8], c = 0.1	 100	 Jet energy scale
di-muons	M_G ~ [0.8,2.3], c = [0.01,0.1	1000	Alignment

Conclusion

- Many models can be investigated with the first data, looking at **simplest signatures**
  - **10 pb^{-1}** can be enough to see new physics
- Some questions will finally get an answer
- An exciting period for the particle physics is starting in the next **few months**

This talk next year:

The first few fb^{-1}; observation of new physics beyond the Standard Model

???

on behalf of the ? and ? collaborations

XLIV Rencontres de Moriond
Electroweak interactions and unified theories

...or at least...

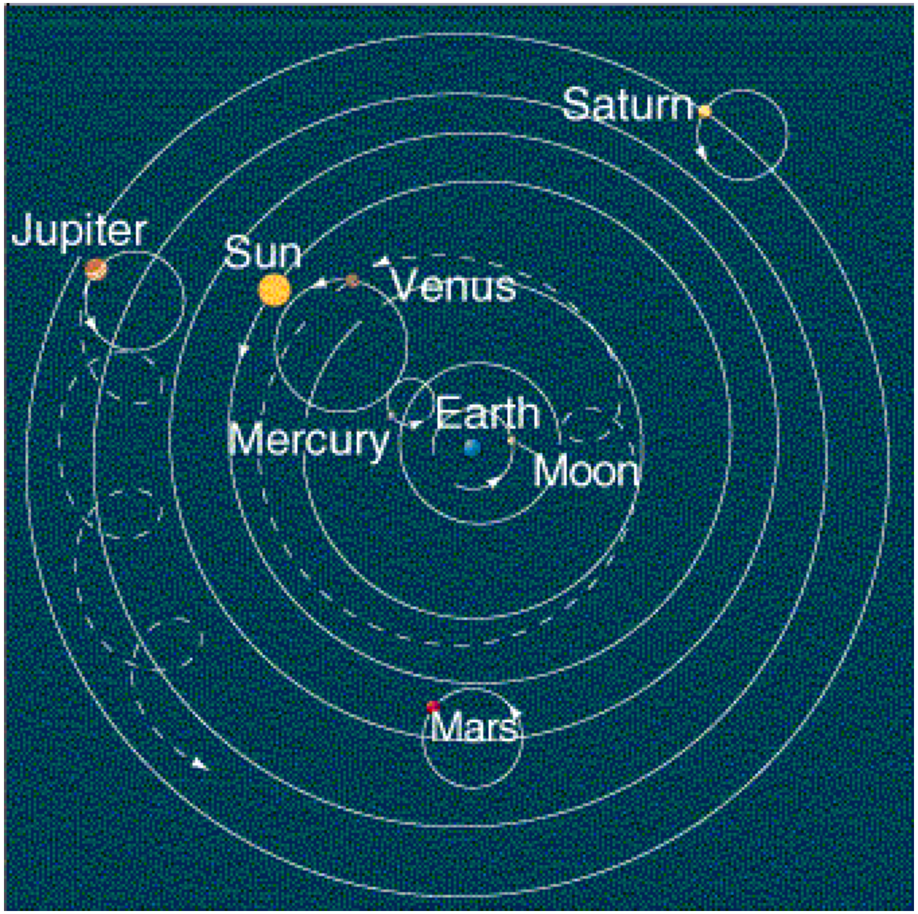
The first few fb^{-1}; limits on new physics beyond the Standard Model

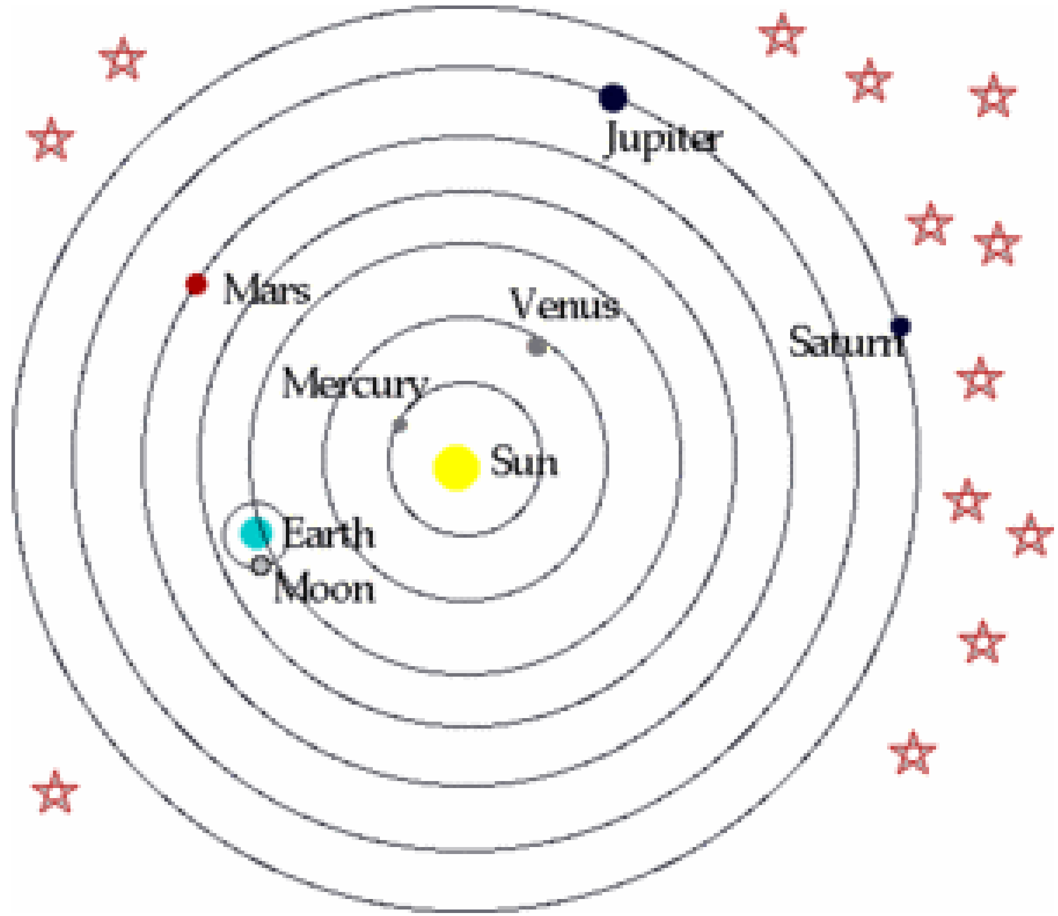
???

on behalf of the ? and ? collaborations

XLIV Rencontres de Moriond
Electroweak interactions and unified theories

hope we are not in this situation...





...and the data were always there...

Back-Up

New Gauge Bosons

- Predicted by *many models*
  - Z_{SSM} and W_{SSM} in Sequential Standard Model with same Z^0 / W couplings as in Standard Model
  - Z_R and W_R in Left-Right symmetry model (LRM) and Alternative LRM (ALRM)
  - Z_ψ , Z_χ , Z_η models from E_6 and SO(10) GUT groups
  - The Kaluza-Klein model (KK) from Extra Dimension
  - Little, Littlest Higgs model
- **No prediction for mass scale** of gauge bosons
- Measurement of mass, width, backward-forward asymmetry and cross section needed to *discriminate between models*
  - **not possible with first data**

Extra Dimension Models

- Try to solve the hierarchy problem $M_{Pl}/EW \sim 10^{17}$
  - gravity force is much weaker than other gauge fields
- Several models available with signatures reachable at LHC

Discussed here:

- Randall-Sundrum (**RS**)
- Arkani-Hamed, Dimopoulos, Dvali Extra Dimension (**ADD-ED**)
- Minimal Universal Extra Dimensions (**mUED**)

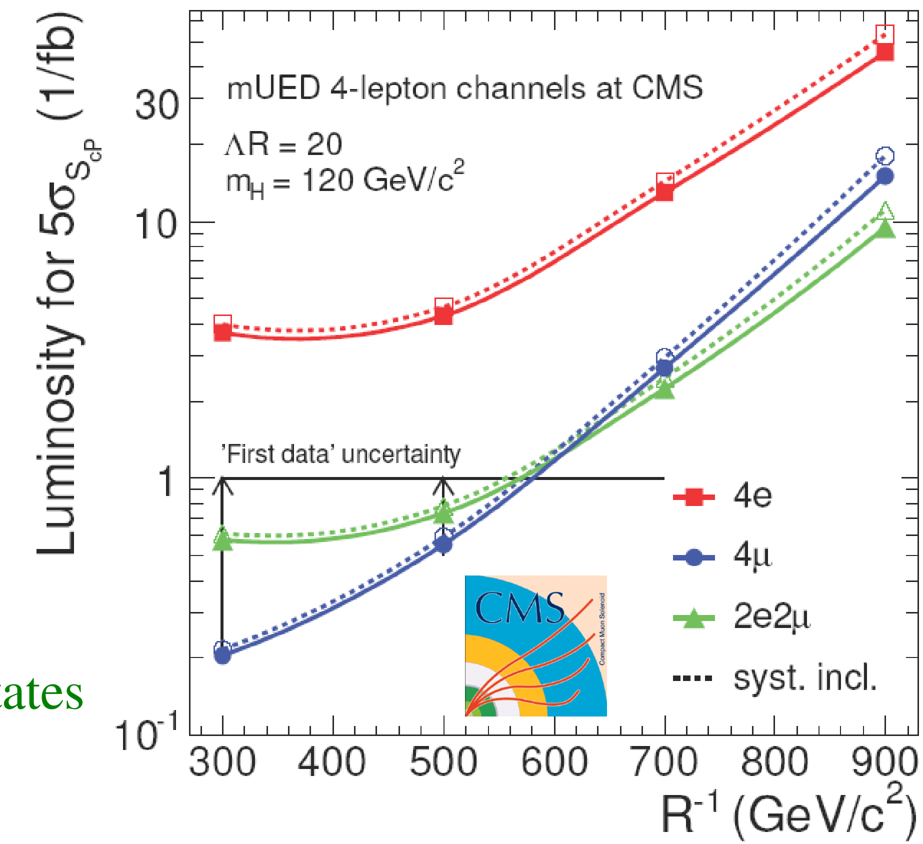
Minimal Universal Extra Dimensions

Extension of ADD model

- **Only 1 ED**
- SM particles can propagate in the ED

  → KK excitations
- 1° excitation below TeV scale
- The KK parity is conserved

  → **pair production** of 1° excited level of KK states



Decay cascades with lightest KK particles being KK photon

Signature studied:

4 leptons + jets + missing E_T

Main background:

ZZ/W + jets

ADD
Arkani-Hamed, Dimopoulos, Dvali

- Additional Large Extra Dimensions (**LED**)

$M_{pl}^2 \sim R^\delta M_D^{2+\delta}$ if $M_D \sim 1$ TeV $\rightarrow R \sim 10^{32/\delta} \cdot 10^{-4}$ fm

$\delta = 2 \rightarrow$ R~1 mm
$\delta = 4 \rightarrow$ R~100 fm
$\delta = 6 \rightarrow$ R~0.02 fm

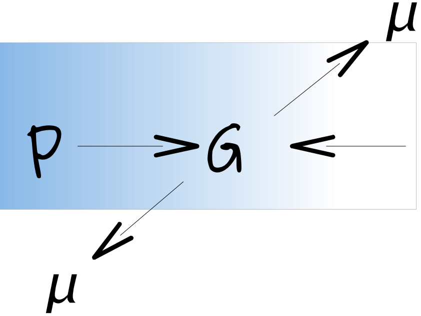
δ = number of ED, M_D = Planck mass in the 4+δ dimensions

  – SM particles cannot propagate in ED

- Experimental limits:
  – **M_D > 1 TeV** from Tevatron+Lep and **$\delta \geq 2$** (direct test of Newton's law + astrophysics limits)

- Experimental signatures:
  – **Deviation from SM cross sections** (e.g. di-lepton invariant mass continuum) + asymmetries in SM processes → *Virtual graviton exchange*
  – **Missing E_T** associated with jets or vector bosons → *Real graviton emission*

ADD
Arkani-Hamed, Dimopoulos, Dvali



- Additional Large Extra Dimensions (**LED**)

$$M_{pl}^2 \sim R^n M_D^{2+n} \qquad \text{if } M_D \sim 1\text{ TeV} \rightarrow R \sim 10^{32/n} \cdot 10^{-4}\text{ fm} \quad \begin{cases} n = 2 \rightarrow R \sim 1\text{ mm} \\ n = 4 \rightarrow R \sim 100\text{ fm} \\ n = 6 \rightarrow R \sim 0.02\text{ fm} \end{cases}$$

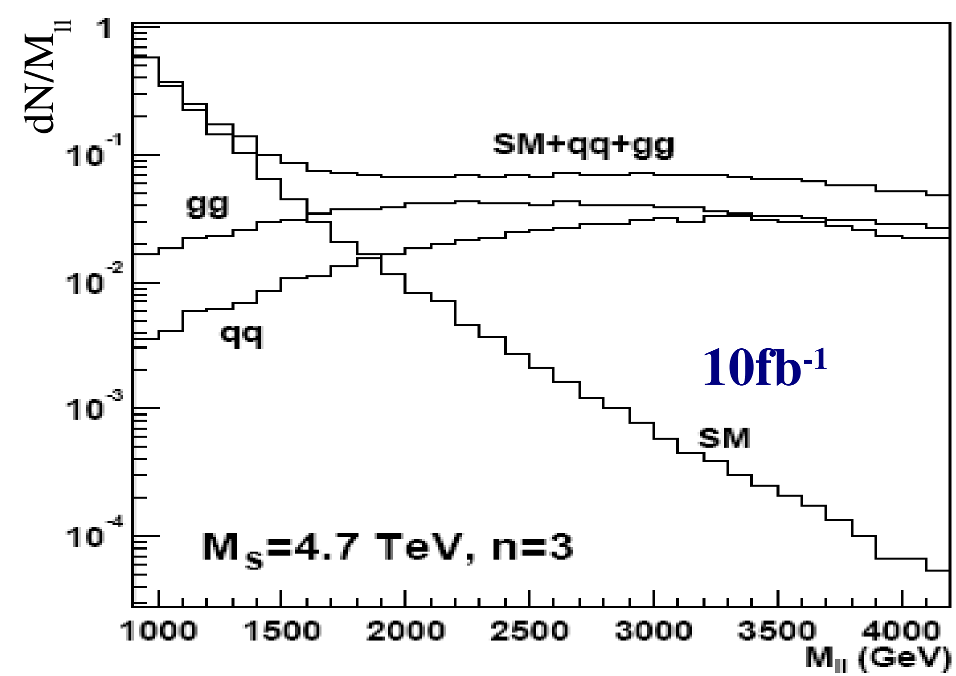
n = number of ED, M_D = Planck mass in the 4+n dimensions

– SM particles cannot propagate in ED

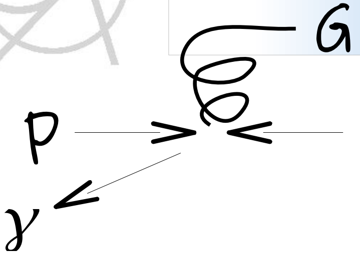
- Experimental limits:

– **M_D > 1 TeV** from Tevatron+Lep

and **n ≥ 2**



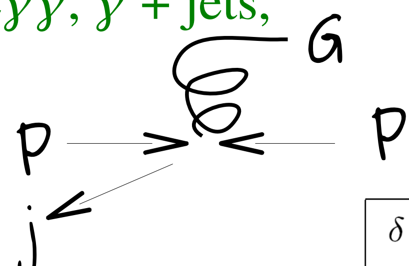
ADD: Real Graviton Emission



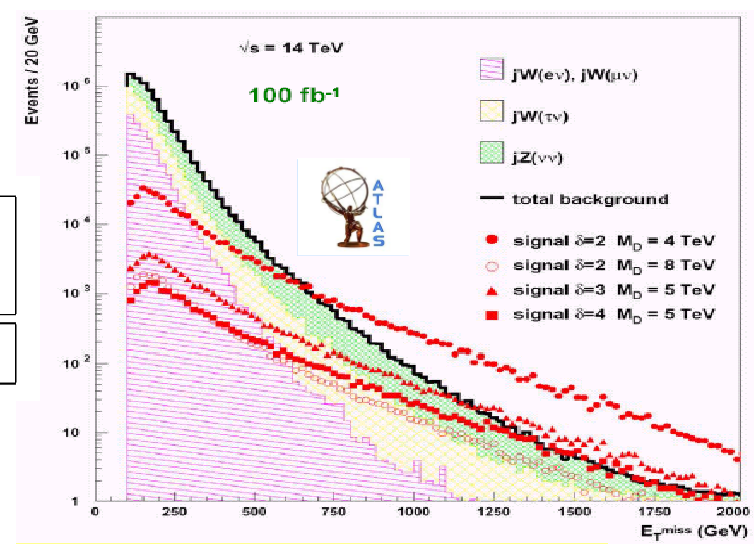
δ	M_D^{max} (TeV) LL, 30 fb^{-1}	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	7.7	9.1	~ 4
3	6.2	7.0	~ 4.5
4	5.2	6.0	~ 5

- Signature
  - high-p_T photon + high missing E_T
- Main Background
  - $Z\gamma \rightarrow \nu\nu\gamma$, di-photon production, Z + jets
  - $W \rightarrow l\nu$, $W\gamma \rightarrow e\gamma\gamma$, γ + jets,

M_D/n	$n=2$	$n=3$	$n=4$	$n=5$	$n=6$
$M_D = 1.0$ TeV	0.21 fb^{-1}	0.16 fb^{-1}	0.14 fb^{-1}	0.15 fb^{-1}	0.15 fb^{-1}
$M_D = 1.5$ TeV	0.83 fb^{-1}	0.59 fb^{-1}	0.56 fb^{-1}	0.61 fb^{-1}	0.59 fb^{-1}
$M_D = 2.0$ TeV	2.8 fb^{-1}	2.1 fb^{-1}	1.9 fb^{-1}	2.1 fb^{-1}	2.3 fb^{-1}
$M_D = 2.5$ TeV	9.9 fb^{-1}	8.2 fb^{-1}	8.7 fb^{-1}	9.4 fb^{-1}	10.9 fb^{-1}
$M_D = 3.0$ TeV	47.8 fb^{-1}	46.4 fb^{-1}	64.4 fb^{-1}	100.8 fb^{-1}	261.2 fb^{-1}
$M_D = 3.5$ TeV	5 σ discovery not possible anymore				



δ	M_D^{max} (TeV) HL, 100 fb^{-1}	M_D^{min} (TeV)
2	4	~ 3.5

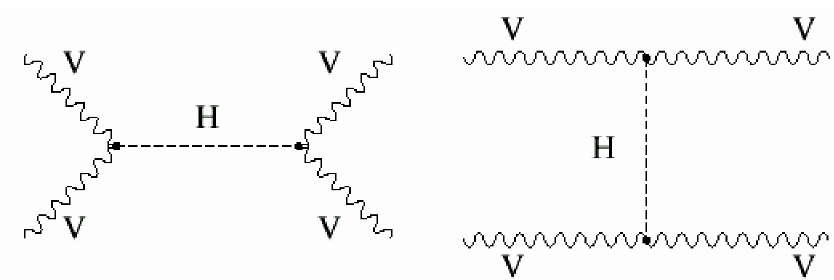


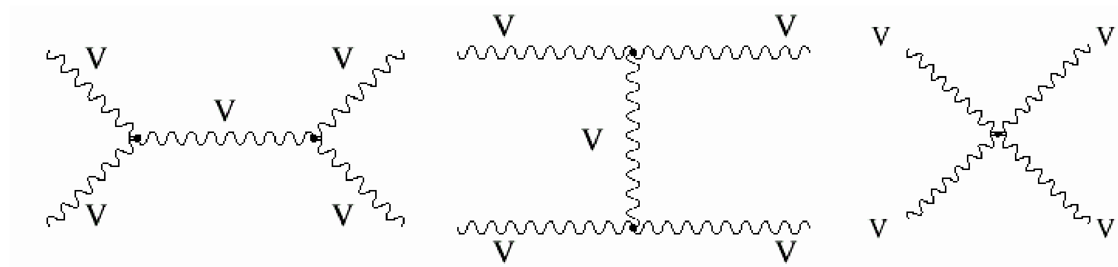
- Signature
  - high-E_T jet + large missing E_T
- Main Background
  - Z/W + jets $\rightarrow$ jets + missing E_T

Vector Boson Fusion

The processes which involve the **fusion** of **longitudinally** polarized **vector bosons** (V=W,Z) are very <u>promising</u> channels to study the EWSB...

...with





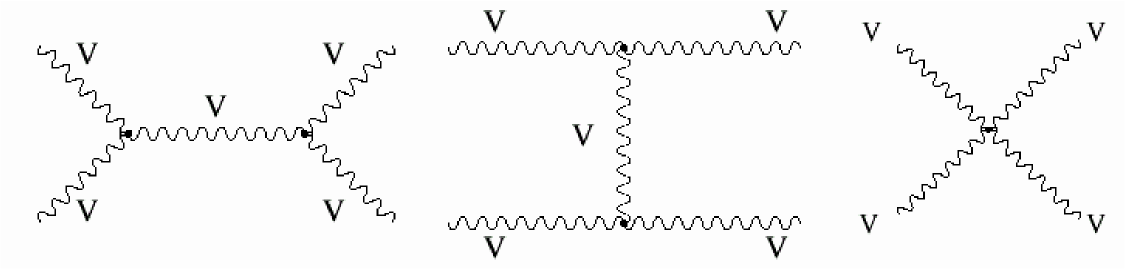
In the case of a Higgs, it will be possible to observe in the cross section a **<u>resonance</u>** in correspondence to m_H

Vector Boson Fusion

The processes which involve the **fusion** of **longitudinally** polarized **vector bosons** (V=W,Z) are very promising channels to study the EWSB…

…or without

$$M \sim \frac{G_F s}{\sqrt{2}} (1 + \cos\theta_{cm})$$



Without the Higgs

the amplitude of

longitudinally polarized

vector boson fusion

violates unitarity

A deviation from the Standard Model cross section (as a function of VV invariant mass) will be observed in the **range 1-2 TeV**

Accessible at LHC!