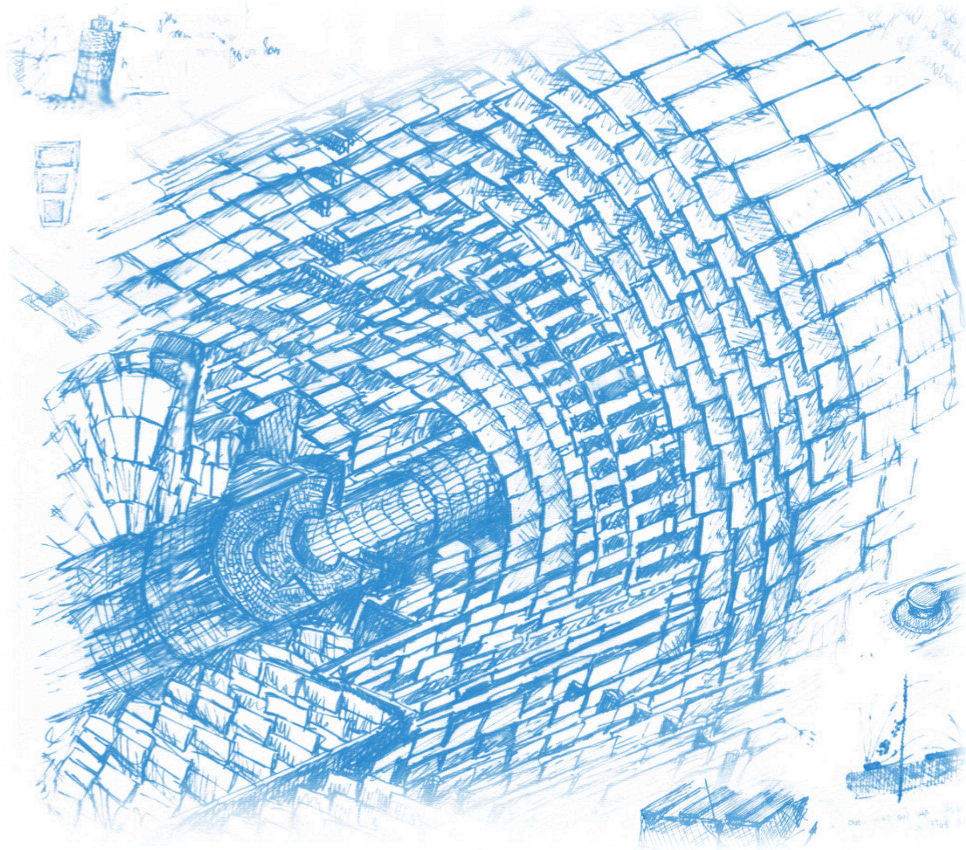
Beyond the Standard Model

Supersymmetry and Exotica – Lecture II



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DESY, 13.08.2013
Hamburg, Germany.

HELMHOLTZ ASSOCIATION

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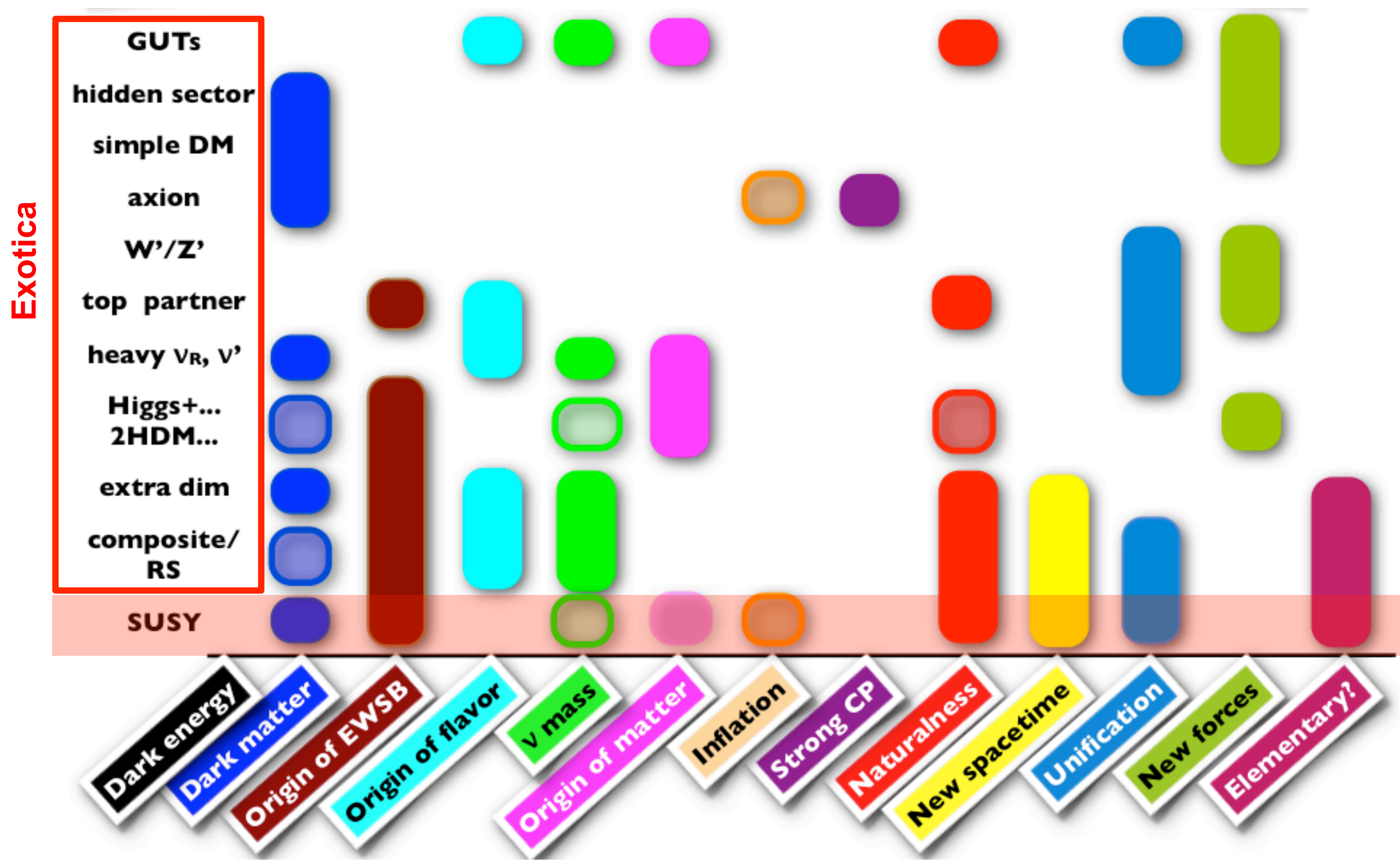
Questions from the first lecture?

① It is a profound phenomenon in nature that the gauge symmetry SU(2)xU(1) is spontaneously broken.
→ **Why does this happen?**

② What does explanation look like for hierarchy problem? → **Are there any new particles, forces or dimensions in nature?**

③ Anomalies: we face significant experimental issues which guaranteed to be beyond the Standard Model.

Searches for new physics phenomenology and questions



Where are we?

- All these questions → the weak/Higgs mass scale and "naturalness"
  - New physics appears near electro-weak scale (fix divergences)
  - New physics modifies couplings: GUT at the electro-weak scale
  - Gravity is strong in ND, weak in 4D; e.g. MPl (5D) ~ TeV ?
  - Extra groups: Occur naturally in GUT scale theories
  - Natural combination for the quark and lepton sector
  - More generations? New/excited fermions

Where are we?

- All these questions → the weak/Higgs mass scale and "naturalness"
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Supersymmetry

  - Gravity is strong in ND, weak in 4D; e.g. MPl (5D) ~ TeV ?

Extra Dimensions

  - Extra groups: Occur naturally in GUT scale theories

Extra Gauge groups: Z`, W`

  - Natural combination for the quark and lepton sector

Leptoquarks

  - More generations? New/excited fermions

Compositeness

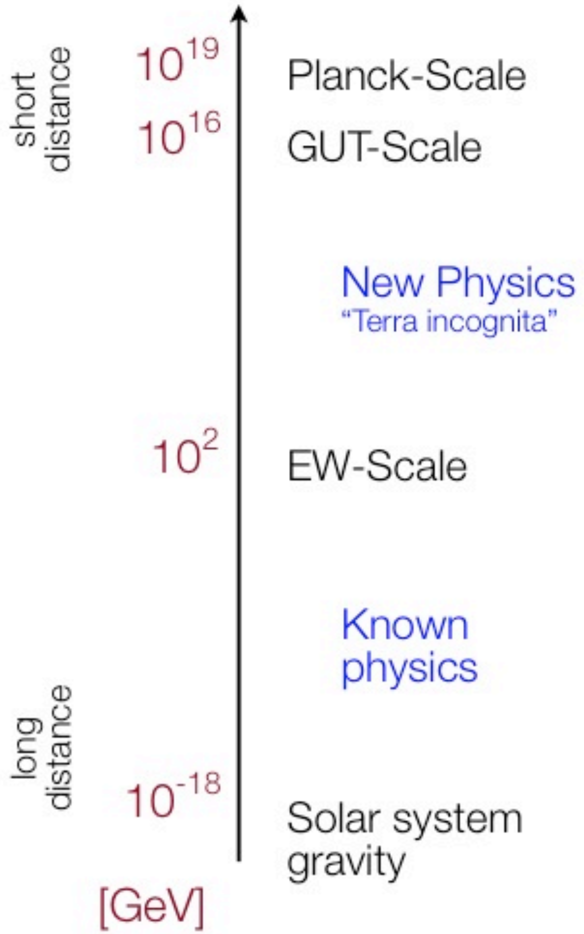
Topological signals vs BSM models?

- Many extensions of the SM have been developed over the past decades:
- Supersymmetry
- Extra-Dimensions
- Technicolor(s)
- Little Higgs
- ~~No Higgs~~
- GUT
- Hidden Valley
- Leptoquarks
- Compositeness
- 4^{th} generation (t', b')
- LRSM, heavy neutrino
- etc...

- 1 jet + MET
- jets + MET
- 1 lepton + MET
- Same-sign di-lepton
- Dilepton resonance
- Diphoton resonance
- Diphoton + MET
- Multileptons
- Lepton-jet resonance
- Lepton-photon resonance
- Gamma-jet resonance
- Diboson resonance
- Z+MET
- W/Z+Gamma resonance
- Top-antitop resonance
- Slow-moving particles
- Long-lived particles
- Top-antitop production
- Lepton-Jets
- Microscopic blackholes
- Dijet resonance
- etc...

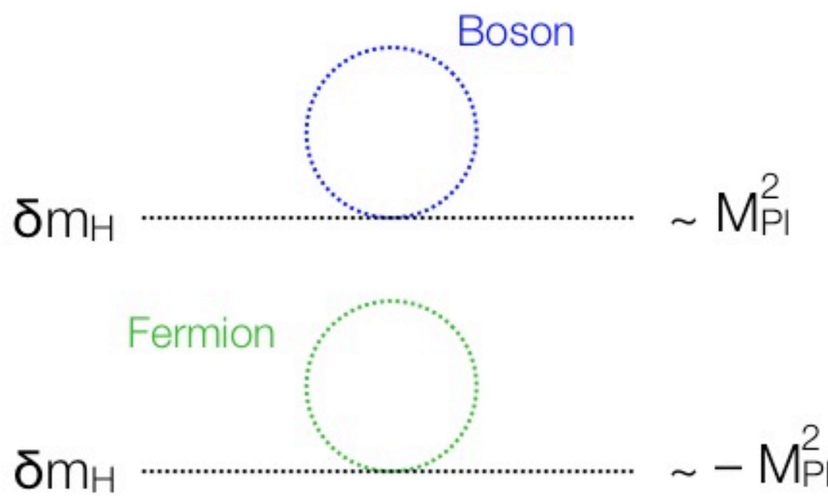
Topological presentation requires jumping between very different models

Remember!



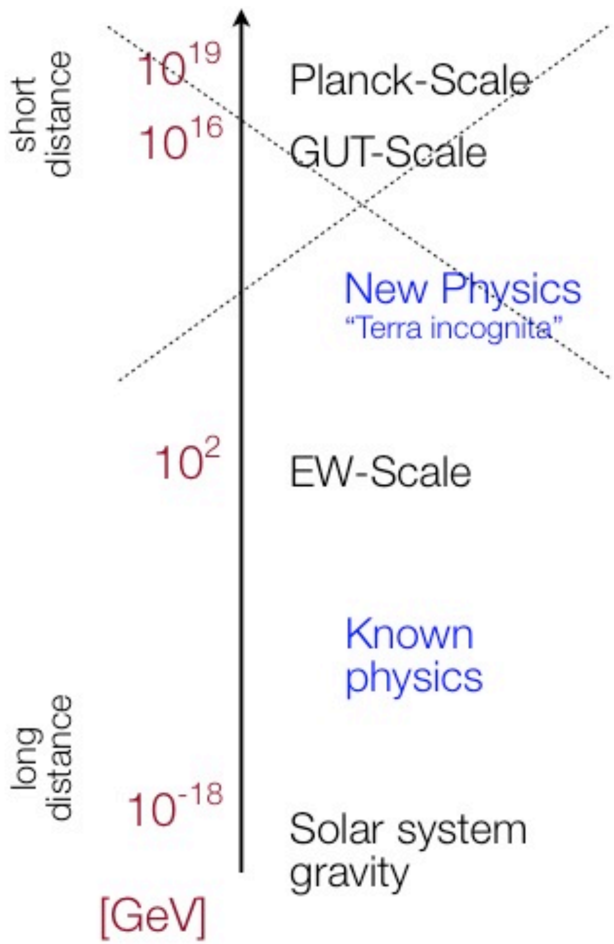
Solution "Supersymmetry"

Symmetry between Bosons and Fermions



The Standard Model of elementary particle physics gives no explanation for this hierarchy

Extra Dimensions



Solution "Extra Dimensions"

Existence of large, extra, compactified space-dimensions ...

Fundamental scale in 4+δ dimensions: M_D

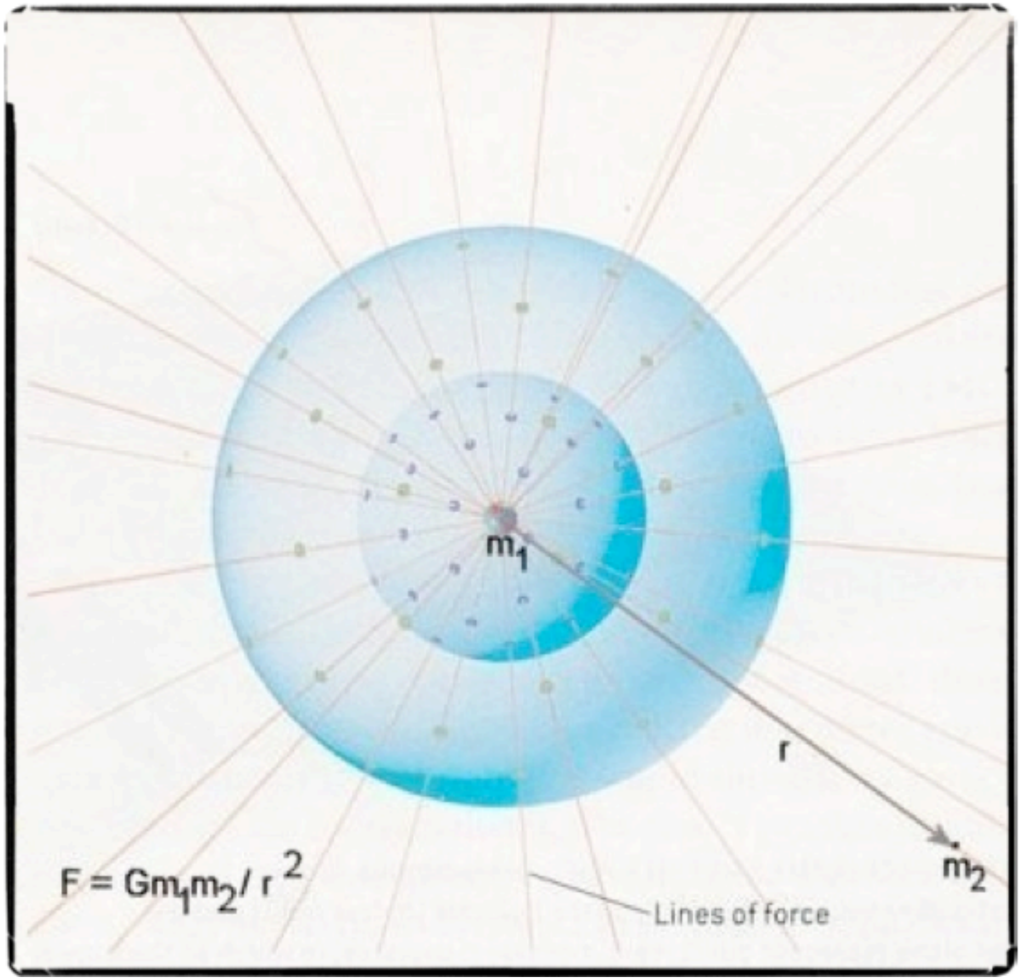
Then:

$$M_{Pl}^2 = (\mathrm{Volume})_\delta \, M_D^{2+\delta}$$

Gravitation exists in all D=1+3+δ dimensions.

The Standard Model of elementary particle physics gives no explanation for this hierarchy

Extra Dimensions



Gauß' Law:

$$\oint \vec{F}_G d\vec{S} \sim M$$

$$\Rightarrow F_G \cdot S \sim M$$

$$F_G \sim M/S$$

S: n-dim. Surface
[2-dim.: $S=4\pi r^2$]

3-dim.

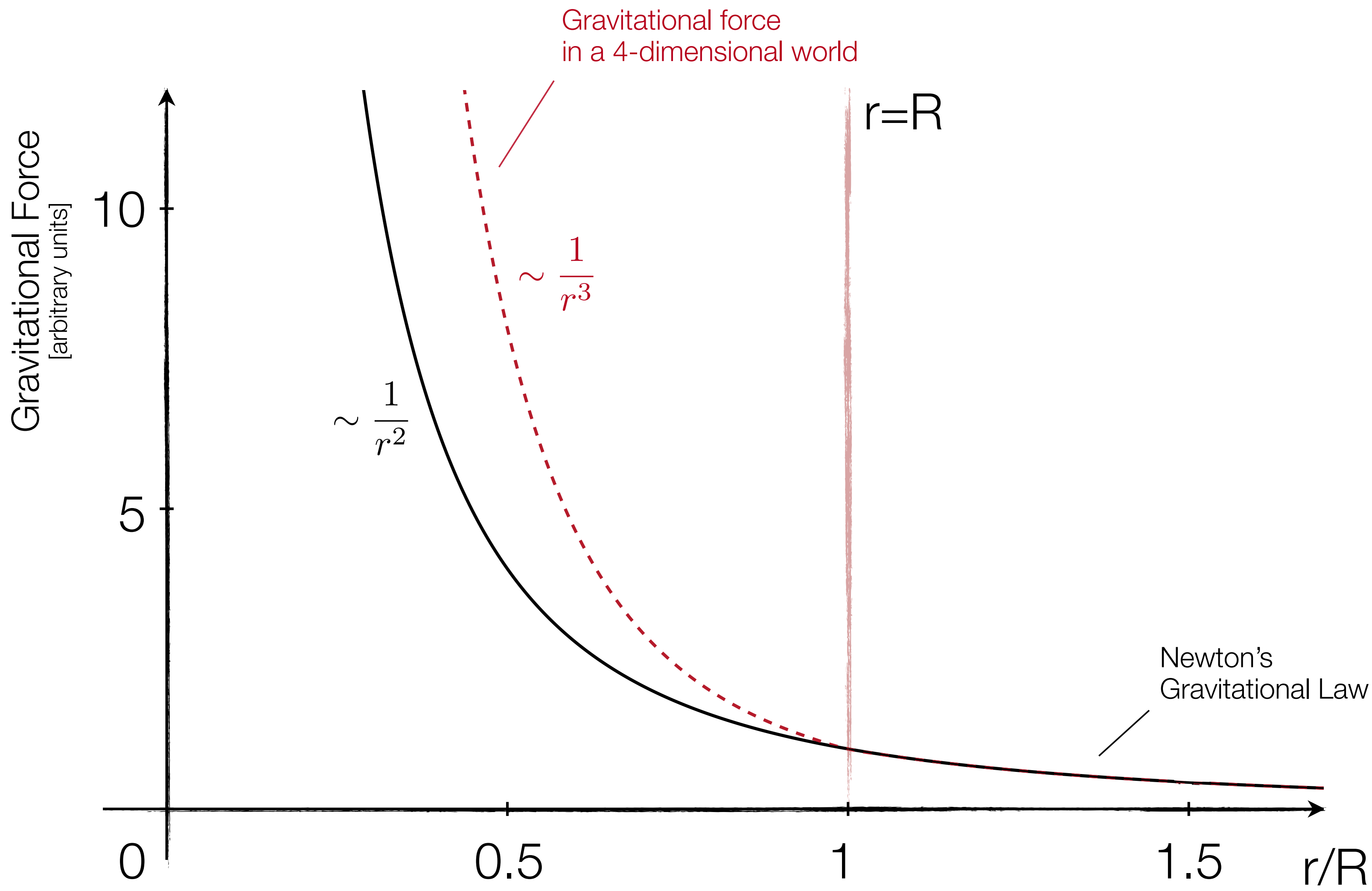
$$F(r) = G_{(3)} \frac{mM}{r^2} \propto \frac{1}{r^2}$$

(n+3)-dim.

$$F(r) = G_{(3+n)} \frac{mM}{r^{2+n}} \propto \frac{1}{r^{2+n}}$$

This theory requires that the fields of the Standard Model are confined to a four-dimensional membrane, while gravity propagates in several additional spatial dimensions that are large compared to the Planck scale.

Gravitational Force 4D



Extra Dimensions

r » R:

$$\oint \vec{F}_G d\vec{S} = \int_0^R \oint \vec{F}_G d\vec{r} dL \sim mM$$

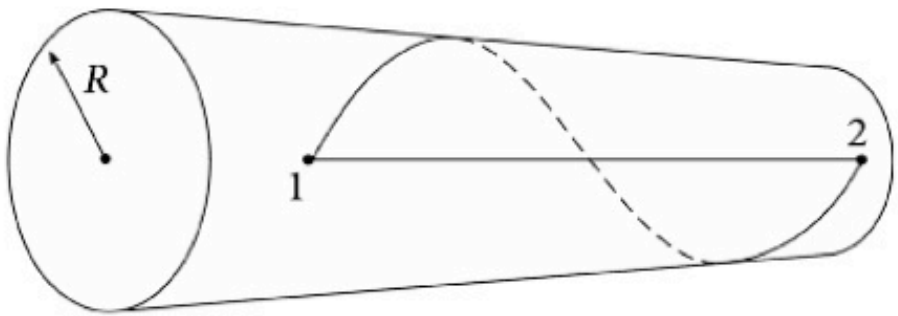
$$\Rightarrow \quad F_G \sim \frac{mM}{r^2 R}$$

4-dim.

$$F(r) = \frac{G_{(3+n)}}{R^n}\frac{mM}{r^2} \propto \frac{1}{r^2}$$

3+n-dim.

$G_{(3)}$



R: size of the dimension

SM interactions tested up to r ~ 10^{-18} m

But gravity ...
only tested down to about 0.1 mm ...

r « R:

$$F(r) = G_{(3+n)}\frac{mM}{r^{2+n}} \propto \frac{1}{r^{2+n}}$$

3+n-dim.

No conflict ...

if only gravity 'lives' in extra dimensions

Hierarchy Problem?

The real Planck Scale:

i.e. energy scale at which gravity gets ‘strong’

Schwarzschild Radius

Compton Wavelength

$$r_s = \frac{G_{(3)} M_{\rm Pl}}{c^2} = \frac{\hbar}{M_{\rm Pl} c}$$

$$M_{\rm Pl} = \sqrt{\frac{\hbar c}{G_{(3)}}} \sim 10^{19} \mathrm{GeV} \Leftrightarrow G_{(3)} = \frac{\hbar c}{M_{\rm Pl}^2}$$

Planck Mass

Gravitational constant

$$M_{\rm S} = \sqrt[n+2]{\frac{(\hbar c)^{n+1}}{c^{2n} G_{(3+n)}}} \Leftrightarrow G_{(3+n)} = \frac{(\hbar c)^{n+1}}{c^{2n} M_{\rm S}^{n+2}}$$

“True” Planck Scale: M_S

$$M_{\rm Pl}^2 \sim G_{(3)}^{-1} \sim G_{(3+n)}^{-1} R^n \sim M_{\rm S}^{2+n} R^n$$

R,n large → M_S small

$$G_{(3)} = \frac{G_{(3+n)}}{R^n}$$

s.o.

Hierarchy Problem

Extra Dimensions may solve Hierarchy problem

if size of the compactified dimensions is large enough

$$M_{\mathrm{Pl}}^2 \approx M_{\mathrm{S}}^{2+n} R^n \quad \Rightarrow \quad R \approx \frac{1}{M_{\mathrm{S}}} \left(\frac{M_{\mathrm{Pl}}}{M_{\mathrm{S}}} \right)^{\frac{2}{n}}$$

Size

Observed Planck scale

True Planck scale

Size of Extra Dimensions

Gravity becomes strong at small distances

i.e. for distances of the order of the size of the extra dimensions

But: Only gravity should live inside the Extra Dimensions

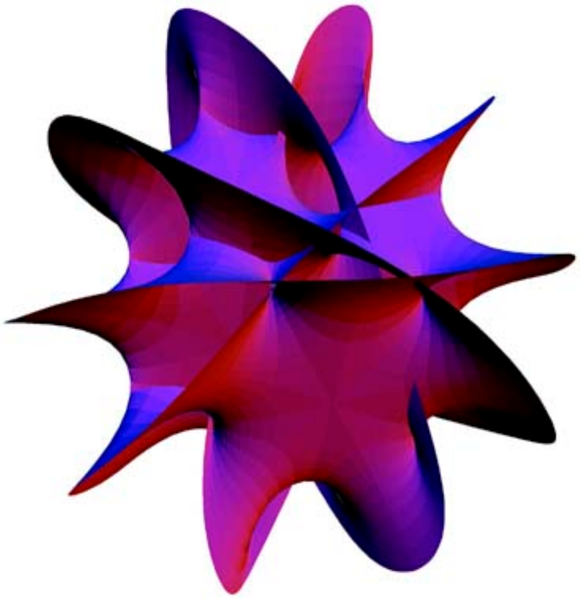
as distance laws for other SM interactions are much better known

New Dimensions

☞ Removes the hierarchy problem

☞ Consider 4+n dimensional space time

- Gravity propagates in all dimensions
- Appears weak in 4D space-time
- Gravity becomes strong at short distances



✓ expect

- Effects of virtual graviton interactions
- Kaluza-Klein excitations of graviton

ADD Arkani-Hamed, Dimopoulos, Dvali, PL **B429** (1998)

– n dimensions, compactified over multidim torus of radius R

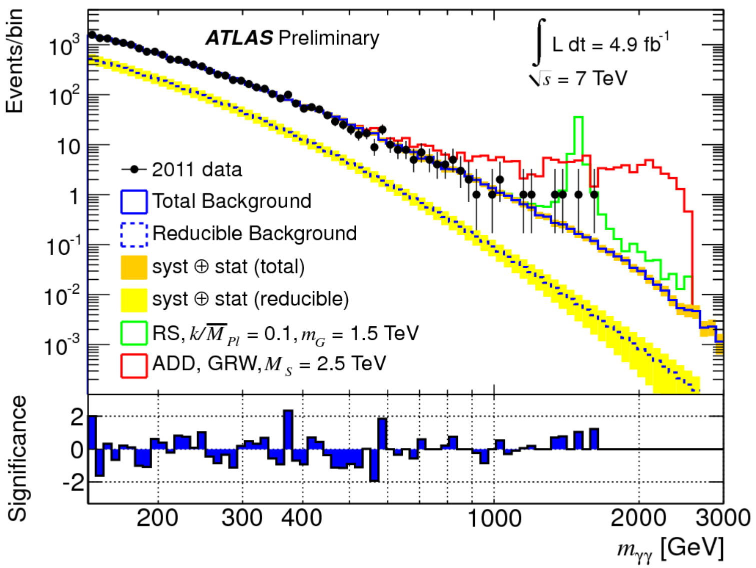
– $M_{\mathrm{Pl}}^2 \approx M_{\mathrm{S}}^{2+n} R^n$

RS Randall and Sundrum, PRL 83, 3370 (1999)

– one warped dimension

Extra Dimensions → ADD and RS

- virtual gravitons modify production of sm particles
  - enhanced production at high mass
- graviton production
  - KK excitations → resonances
  - graviton unobserved → missing momentum
- example: $\gamma\gamma$ mass spectrum
  - ADD $M_D > 2.6 \ldots 3.9\ \text{TeV}$
    - for $n = 7 \ldots 3$
  - RS $m(g_{RS}) > 1.0\ \ldots 2.1\ TeV$
    - for $k/\overline{M}_{Pl} = 0.01\ \ldots 0.1$



Black Holes

- Black Holes are a direct prediction of Einstein's general theory on relativity
- If Planck scale ~TeV region, expect Quantum Black Hole production

- Using Gauss's law with n extra dimensions $V(r) \sim \frac{M}{M_p^{n+2}} \frac{1}{r^{n+1}}$
- For small extra dimension of size R $V(r) \sim \frac{M}{M_p^{n+2} R^n} \frac{1}{r}$
- Relation between planck scale in 4D and 4+nD $M_{p(4)}^2 \sim M_p^{n+2} R^n$

- Schwarzschild radius is the radius in which a confined mass would become a black hole

$$r_h = \frac{1}{\sqrt{\pi} M_p} \left(\frac{M_{BH}}{M_p} \right)^{\frac{1}{n+1}} \left(\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2} \right)^{\frac{1}{n+1}}$$

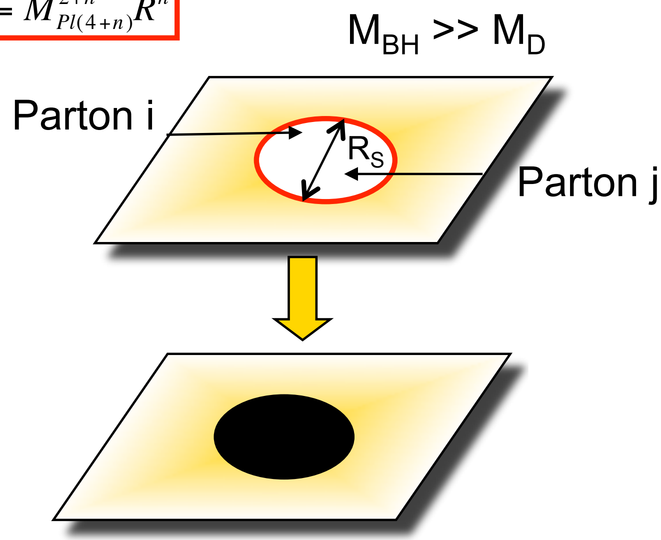
  - $M_{pl} = 10^{19}$ GeV in 4D implies $r_h << 10^{-35}$ m
  - M_{pl} = TeV in 4+n D implies $r_h \sim 10^{-17}$ m

- Occasionally protons with parton center of mass energy $M_{BH} = \sqrt{\hat{s}}$ could collide at a distance smaller than r_h
- such collisions satisfy the black hole definition but with tiny mass

Production and Decay of Black Holes

- Formation: semi-classical argument
  - Partons with impact parameter less than Schwarzchild radius $R_s(\sqrt{s})$

$$M_D^2 = M_{Pl(4+n)}^{2+n} R^n$$



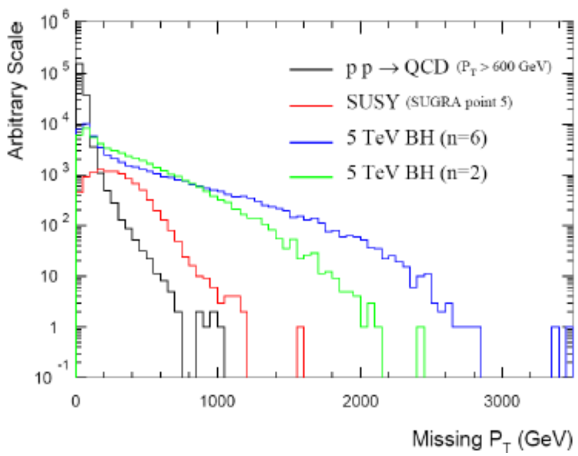
area ~ πR_S^2 ~ 1 TeV $^{-2}$ ~ 10^{-38} m^2 ~ 100 pb
Production rate of ~0.1 Hz at L = $10^{34} cm^{-2} s^{-1}$

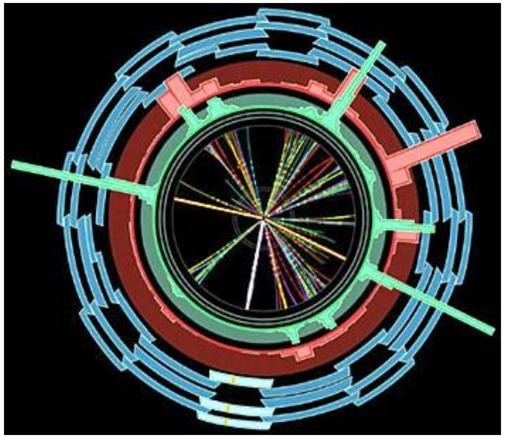
- Hawking evaporation with lifetime $\tau \sim 10^{-27}$ sec

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

- Experimental signatures
  - High multiplicity events
  - Hadrons:Leptons ~ 5:1
  - Spherical events
  - Large missing PT

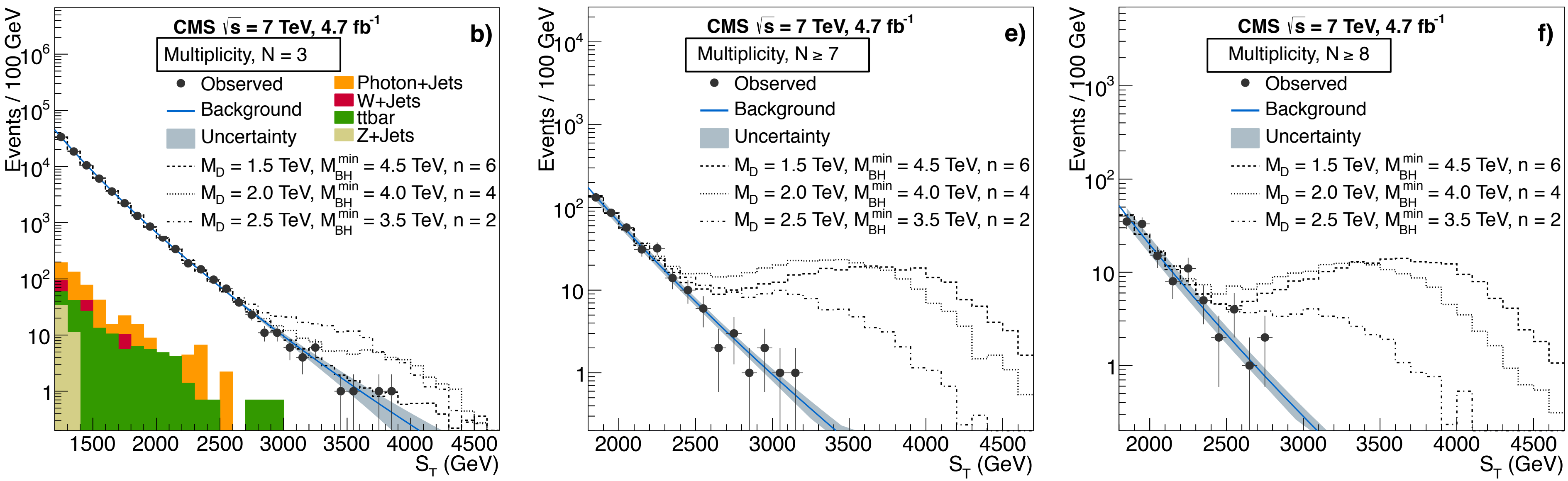
- Could be discovered with 1 fb^{-1} if M_{Pl} < 5 TeV!



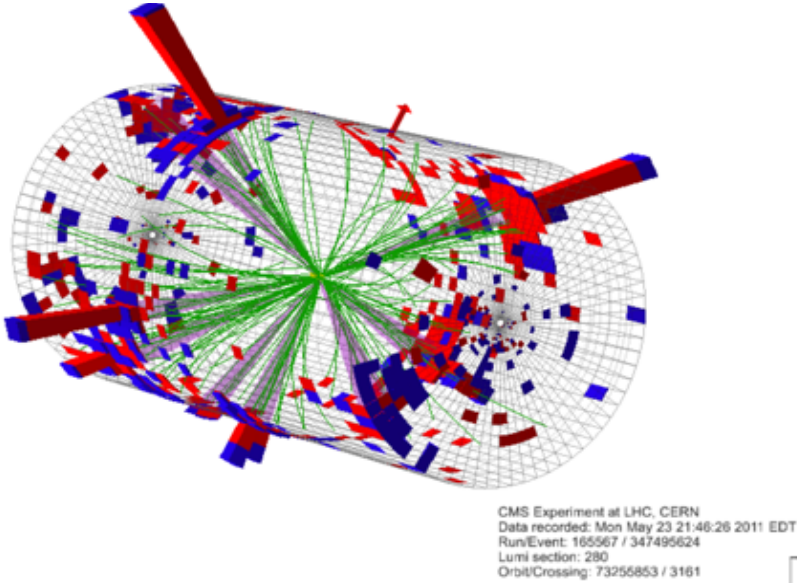


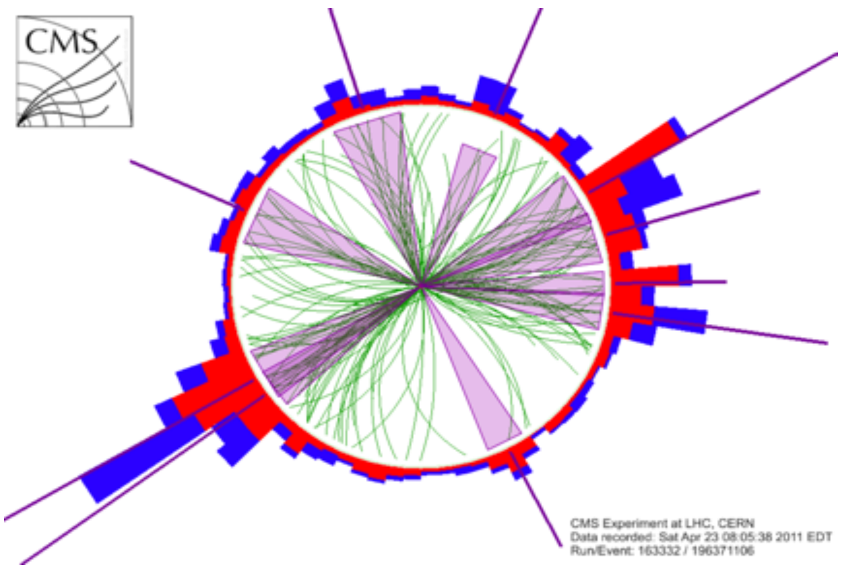
Searches for Black Holes at the LHC

- Analysis strategy: events with large transverse energy, multiple high- energy jets, leptons, and photons
- Main Standard Model background: QCD multijet production
- Discrimination variable: visible transverse energy
  - scalar sum of ET for identified physics objects and MET
- Estimate background shape from low multiplicity events



Multijet events as Black Holes



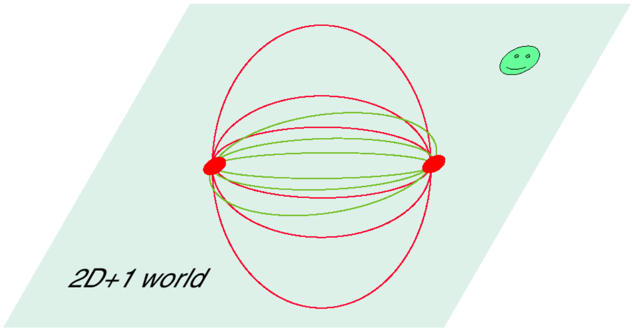


Searches for new resonances at the LHC

- New gauge bosons predicted by many extensions of the Standard Model with extended gauge symmetries
  - Z_{SSM} in Sequential Standard Model with same Z0 coupling as in Standard Model
  - Z' models from E6 and SO(10) GUT groups
  - The Kaluza-Klein model from Extra Dimension
  - Little, Littlest Higgs model
- No precise prediction for mass scale of gauge bosons
- Technicolor also predicts variety of narrow heavy particles
- Backgrounds
  - relatively clean with good S/B
  - mostly tails of SM processes
- Experimental challenges
  - detector resolution can be a key player
    - 1.3% - 2.4% for electrons and 7% for muons at 1 TeV mass
  - extra care for energy/momentum reconstruction above 1 TeV

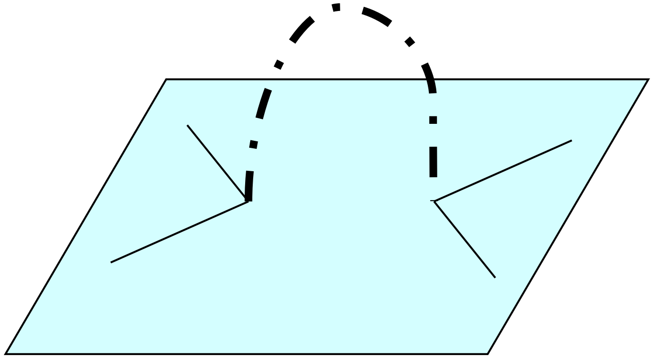
New Resonances

- **Number (D) of space-time dimensions → form of force observed**

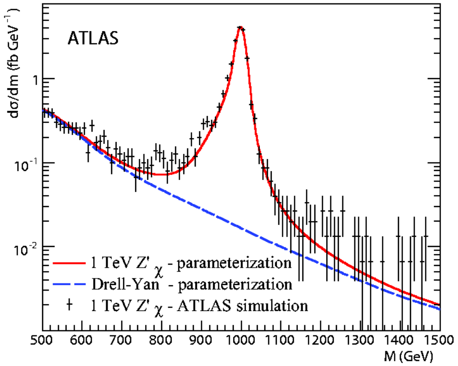


- **Tabletop experiments: look for deviations from $1/r^2$ law**

- **Propagation into the other dimensions:**
  - **Resonances!**

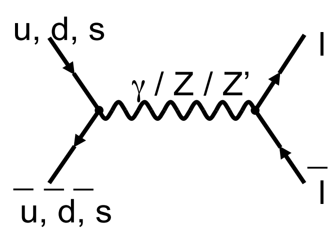


- **What we will see:**

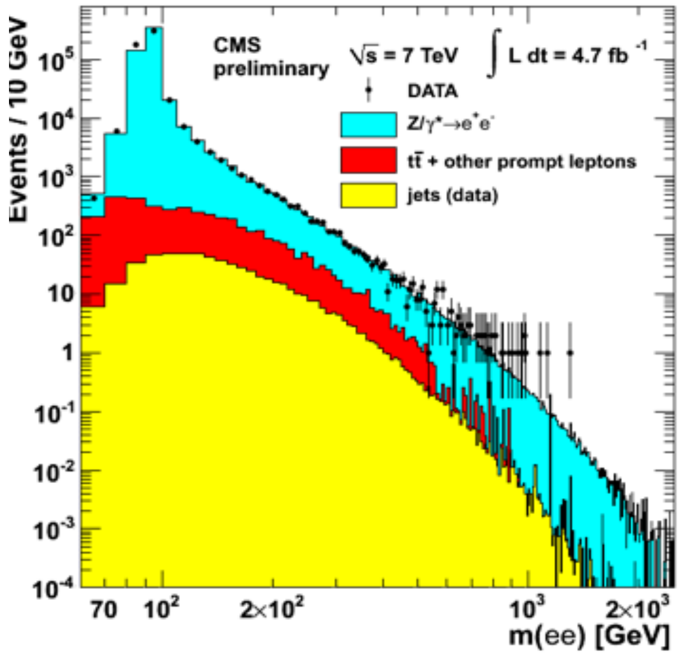


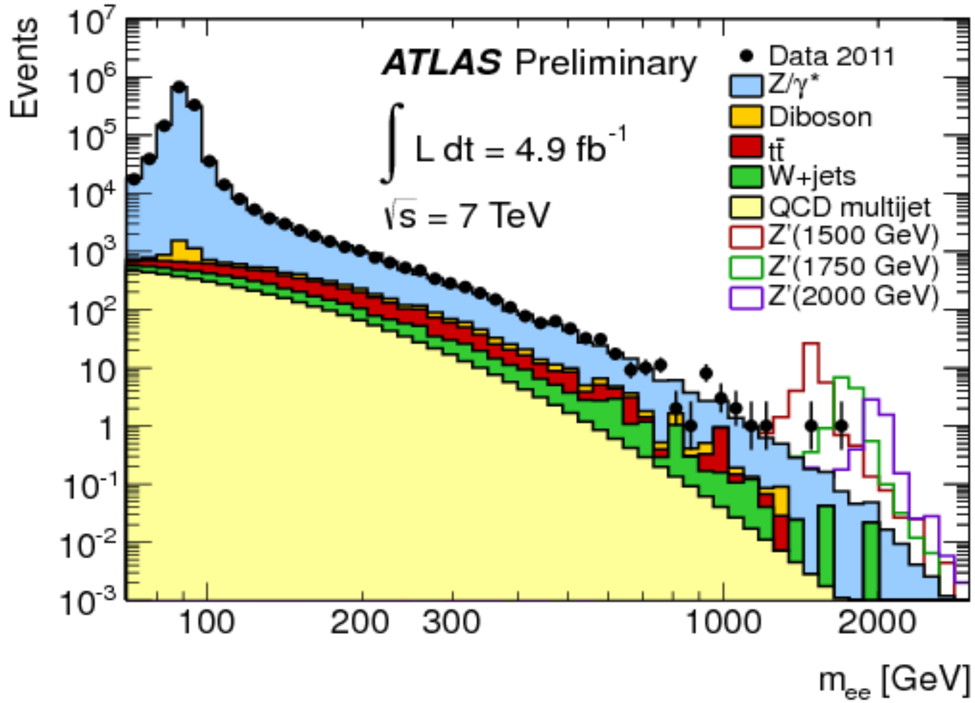
Di-Electron Searches for Z` Model

- Additional U(1) gauge symmetries and associated *Z* gauge bosons are one of the best motivated extensions of the Standard Model (SM).



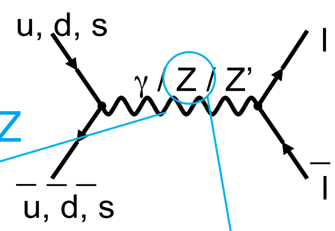
- Also E6 Grand Unified Theory (GUT), broken in U(5) and two U(1) groups, giving raise to two new U(1) fields. Their mixing can give rise to *Z'* candidates



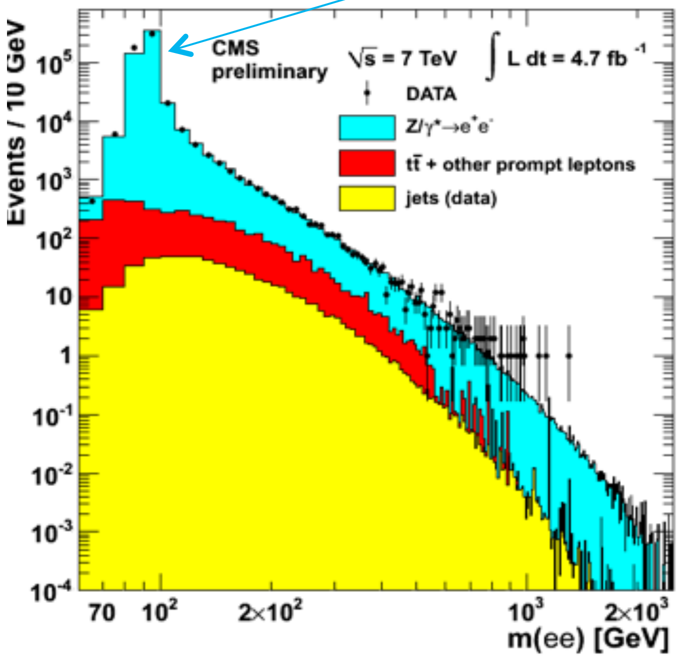


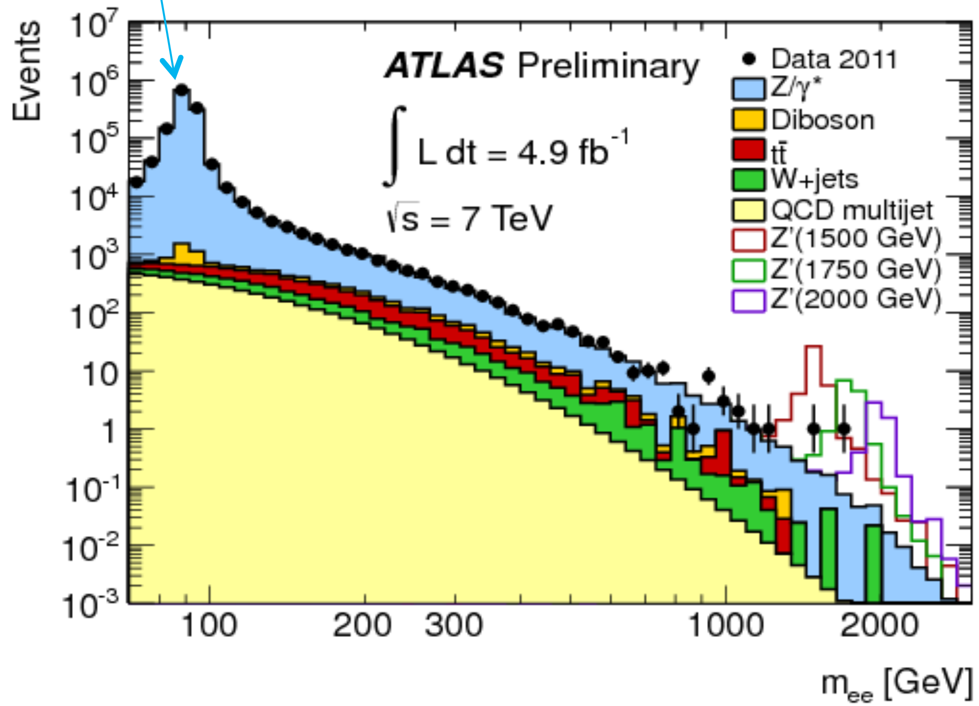
- Background estimation: QCD and ttbar from data, DY from MC

Di-Electron Searches for Z` Model



background from Z





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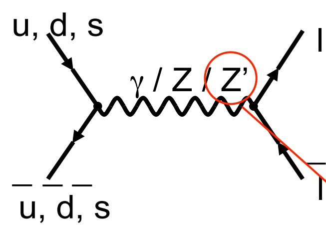
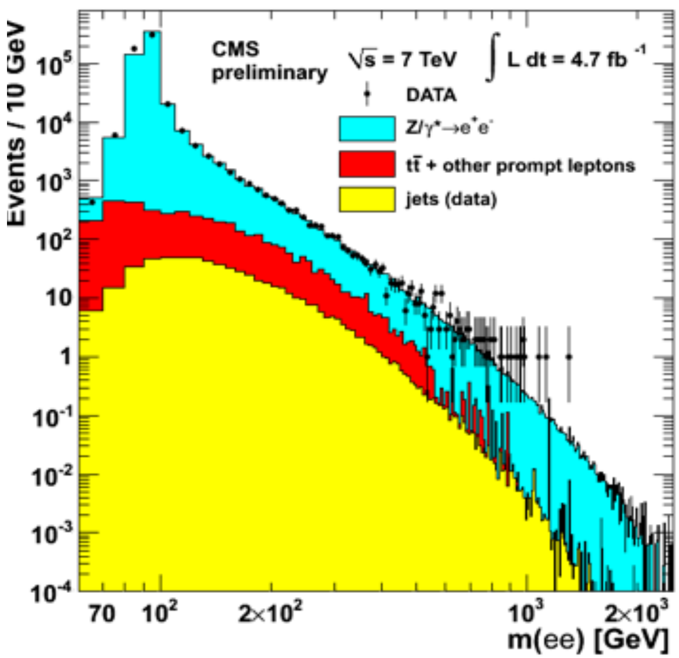
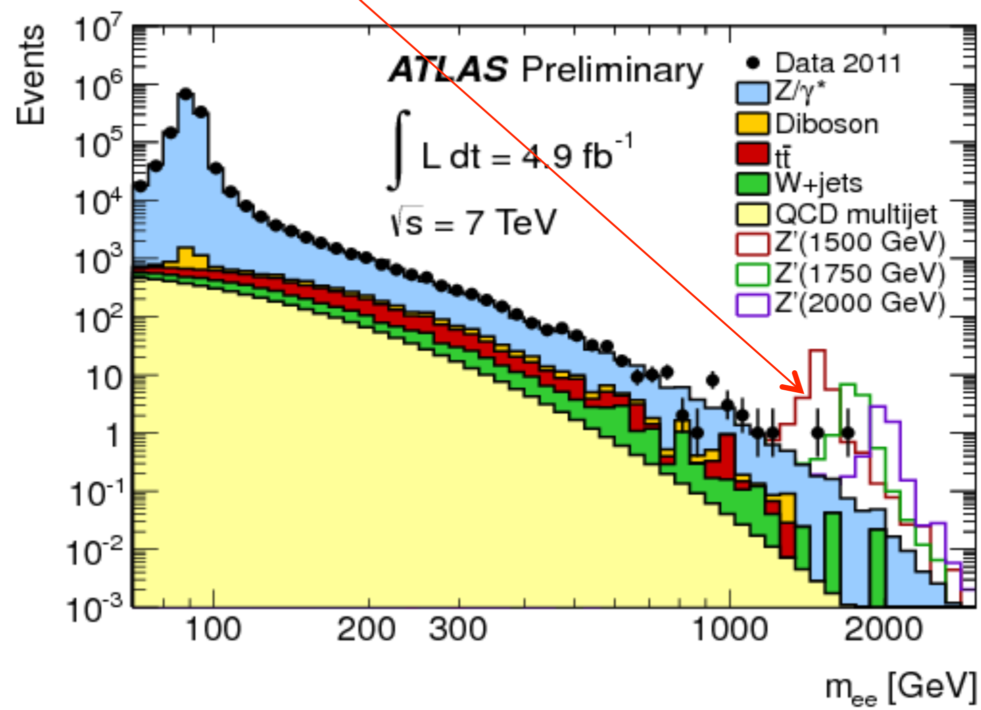
Di-Electron Searches for Z` Model



signals





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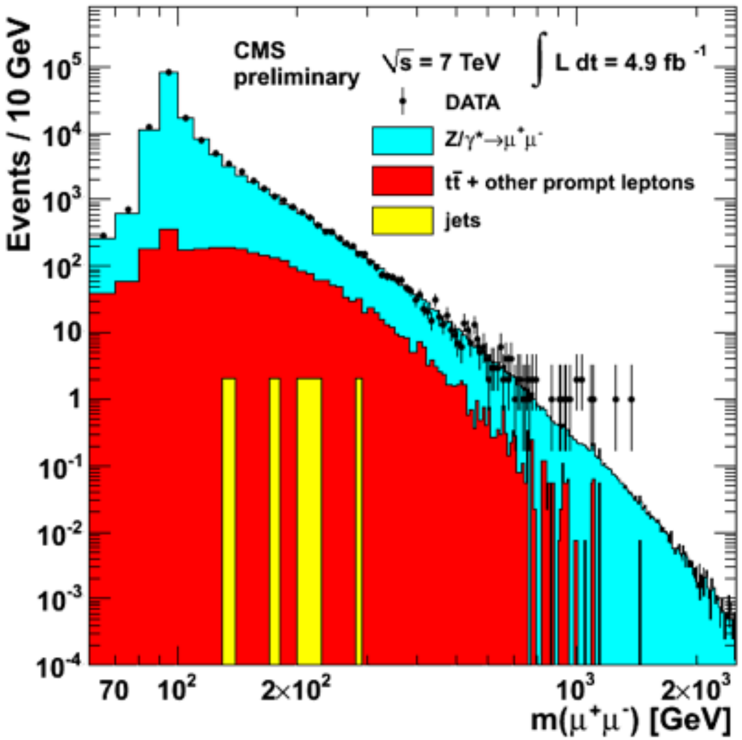
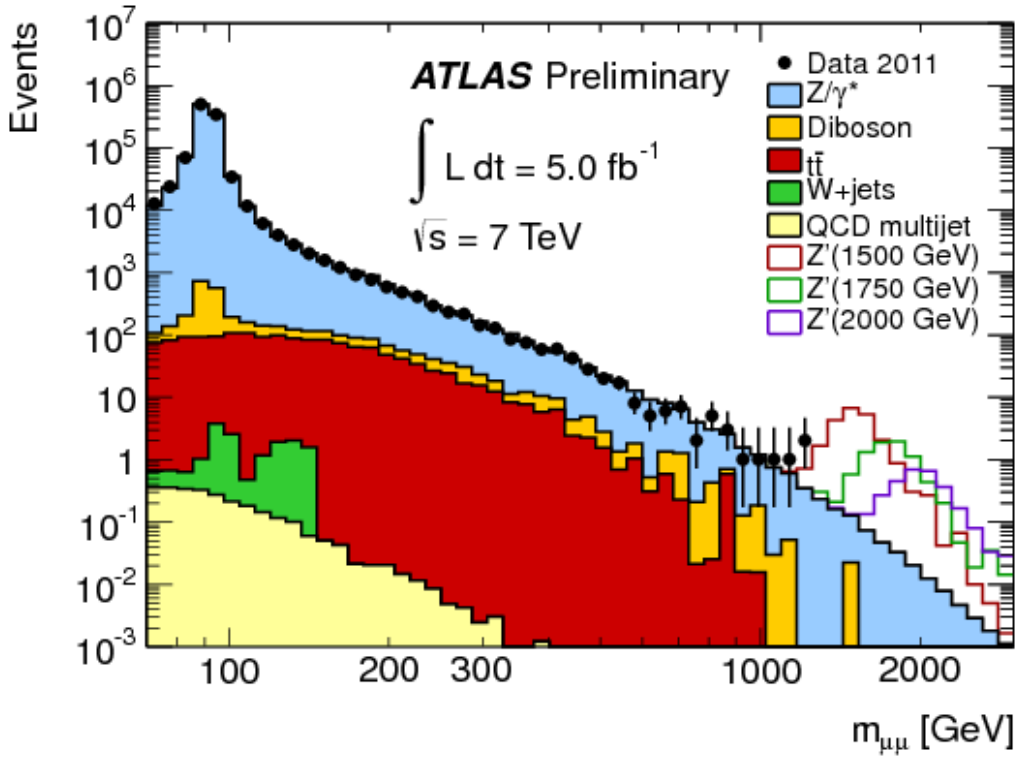
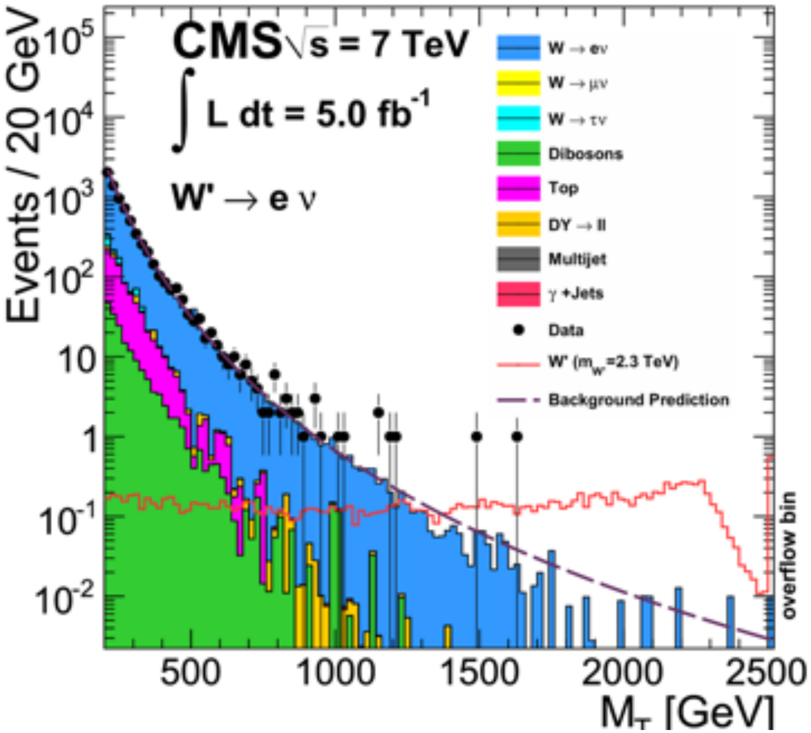
Di-Muon

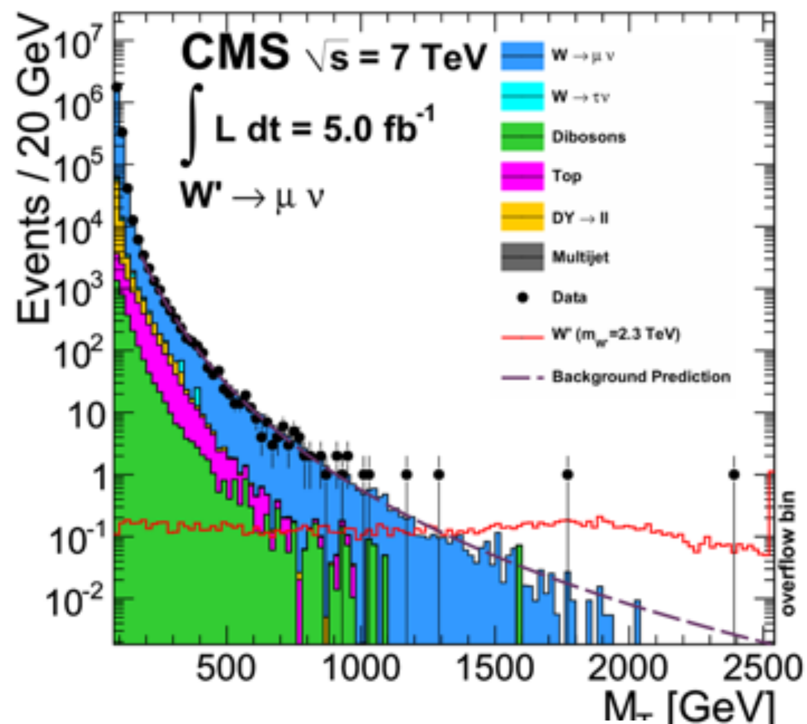




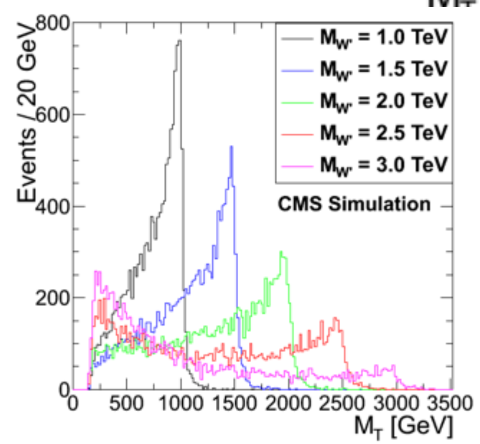
- Several events with mass of 1 TeV
- But much larger resolution with muons spreads out a possible signal a lot compared to electrons

W` → Lepton + MET Search





- **Heavy analog of SM W; assume same couplings to fermions. Cleanest signature: high-p_T lepton (e or μ)**
- **Search for peak/enhancement in transverse mass spectrum (e/μ + MET)**



- Look for heavy W-like Jacobian peak in transverse mass

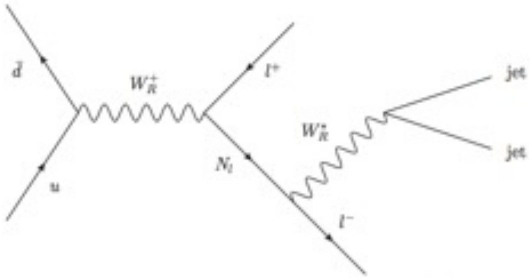
$$m_T = \sqrt{2 p_T \not{E}_T (1 - cos\Delta\phi_{\ell,\not{E}_T})}$$

- Dominant background: W production in Standard Model
- Now also take into account interference with SM

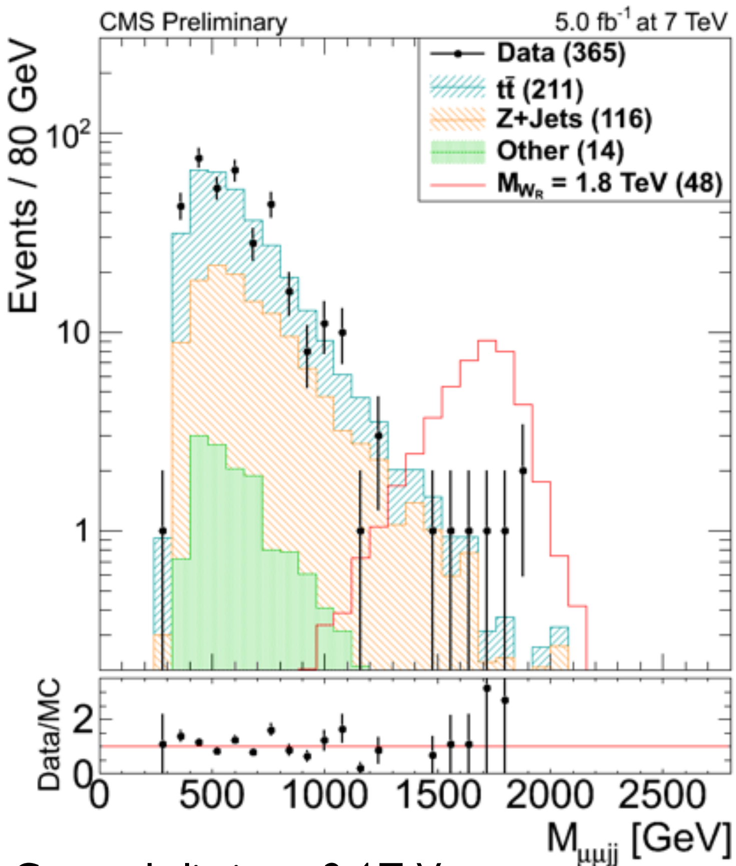
Heavy Neutrinos and LR Symmetry

	Standard Model	Left-Right-Symmetric Extension (LRSM)
Gauge group	$SU(2)_L$ X $U(1)_Y$	$SU(2)_L$ **X $SU(2)_R$** X $U(1)_{B-L}$
Fermions	LH doublets: $Q_L = (u^i, d^i)_L$, $L_L = (l^i, \nu^i)_L$ RH singlets: $Q_R = u^i_R$, d^i_R, $L_R = l^i_R$	LH doublets: $Q_L = (u^i, d^i)_L$, $L_L = (l^i, \nu^i)_L$ RH doublets: $Q_R = (u^i, d^i)_R$, $L_R = (l^i, N^i)_R$
Neutrinos	ν^i_R do not exist ν^i_L are massless & pure chiral	N^i_R are heavy partners to the ν^i_L N^i_R Majorana in the Minimal LRSM
Gauge bosons	$W^\pm_L$, Z^0, γ	$W^\pm_L$, **$W^\pm_R$**, Z^0, **Z'**, γ

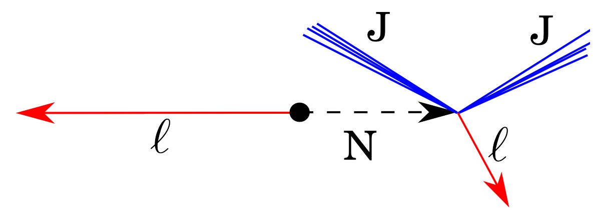
- Parity violation built-in for the Standard Model
  - Parity violation in LRSM via symmetry breaking at intermediate mass scale
- Neutrino oscillations require massive neutrinos
  - but neutrinos mass forbidden in SM
  - "See saw" mechanism in LRSM can explain small mass of neutrinos via heavy partners

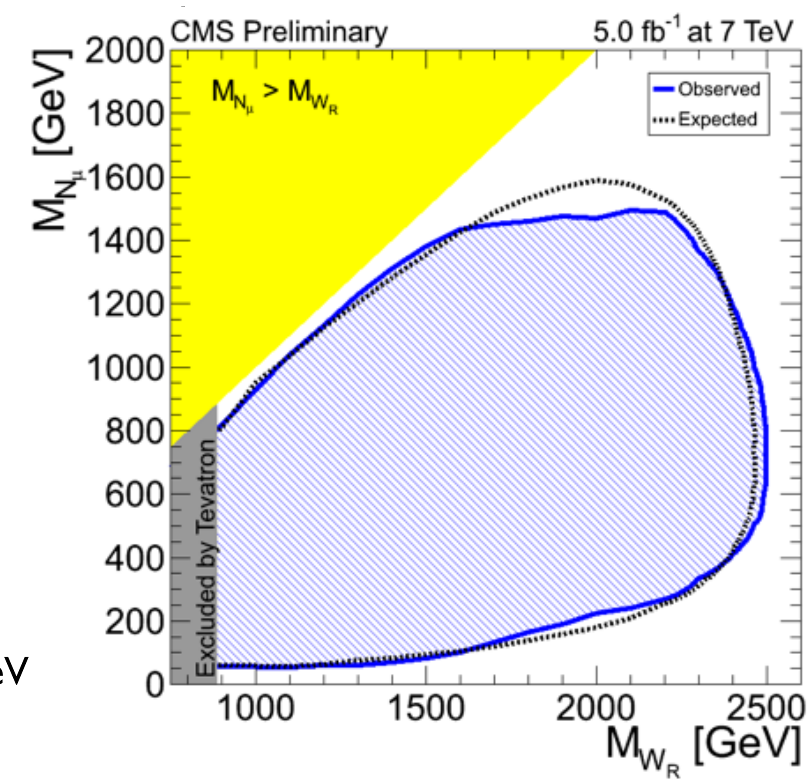


Heavy Neutrino and W_R Symmetry



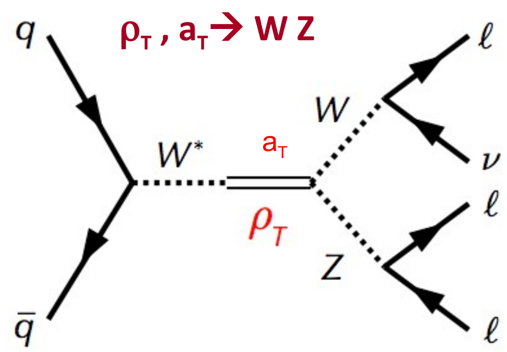
$$W_R \rightarrow \mu_1 N_\mu \rightarrow \mu_1 \mu_2 W_R^* \rightarrow \mu_1 \mu_2 jj$$





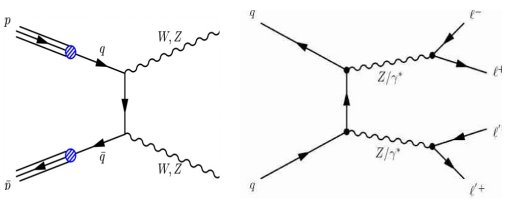
- Currently limits at 2.4 TeV
  - Most stringent limits today!
- Gets very interesting for theory once limits at 2.5 TeV
- Enhanced cross section at 8 TeV with

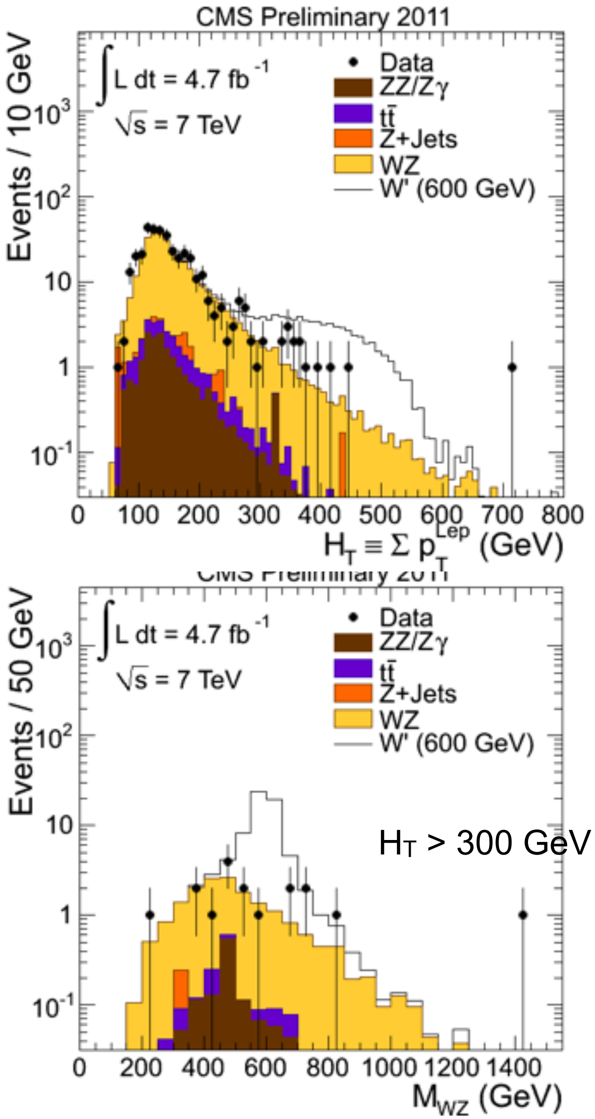
WZ Resonances



- Sensitive to sequential SM and techni-hadrons
- 3 leptons + missing energy
  - Sum of lepton Pt
  - WZ invariant mass with W mass constraint

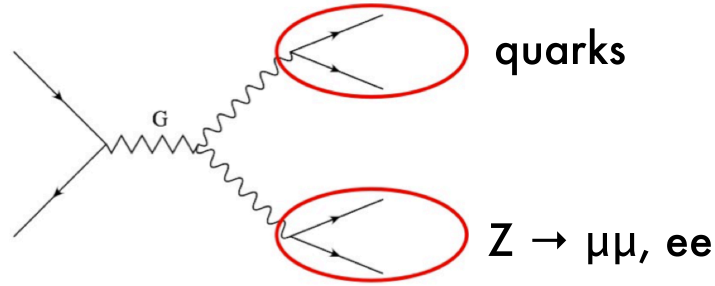
- Scalar sum of transverse momenta a key discriminator to reject SM background

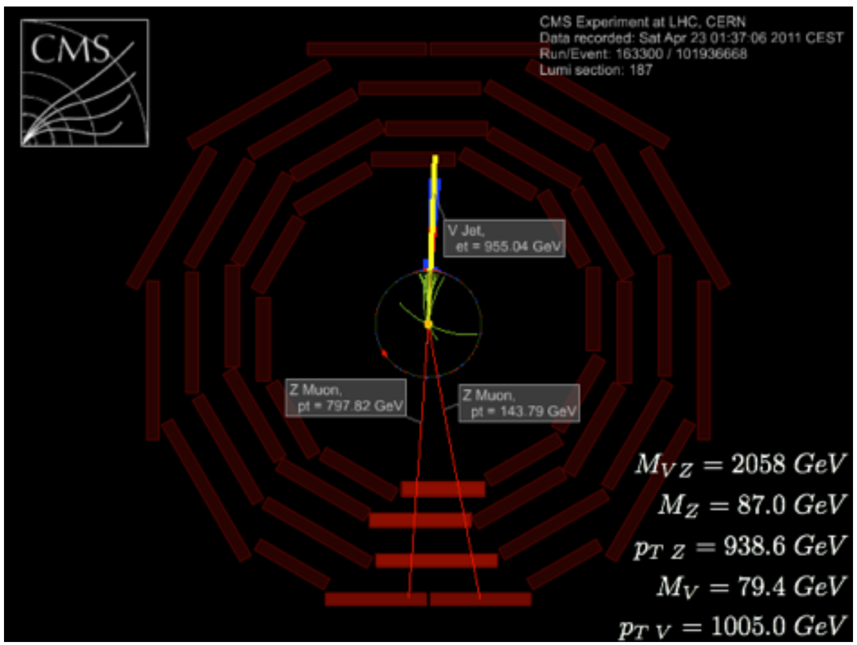


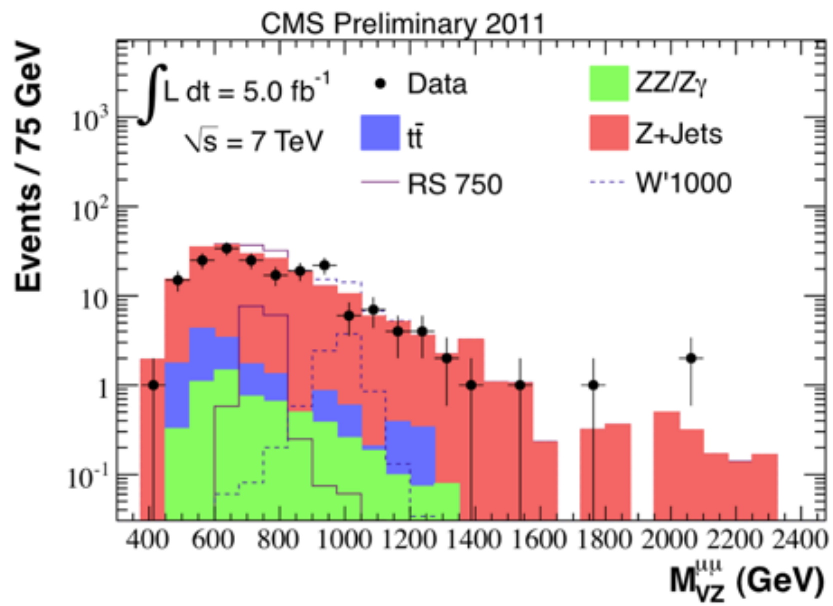


WZ and ZZ Resonances

$$pp \to G^* \to ZZ \to q\bar{q}\, l^+ l^-$$
$$pp \to W' \to WZ \to q\bar{q}\, l^+ l^-$$



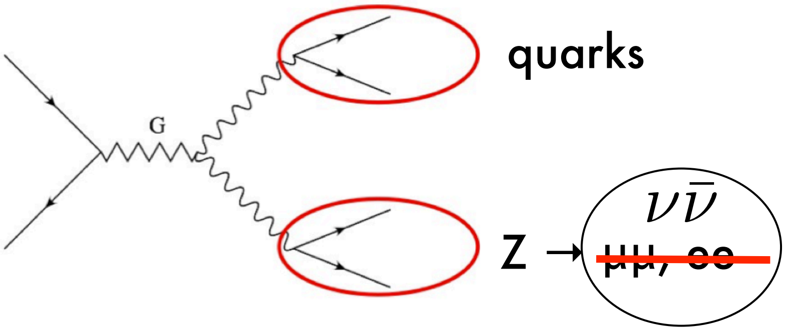




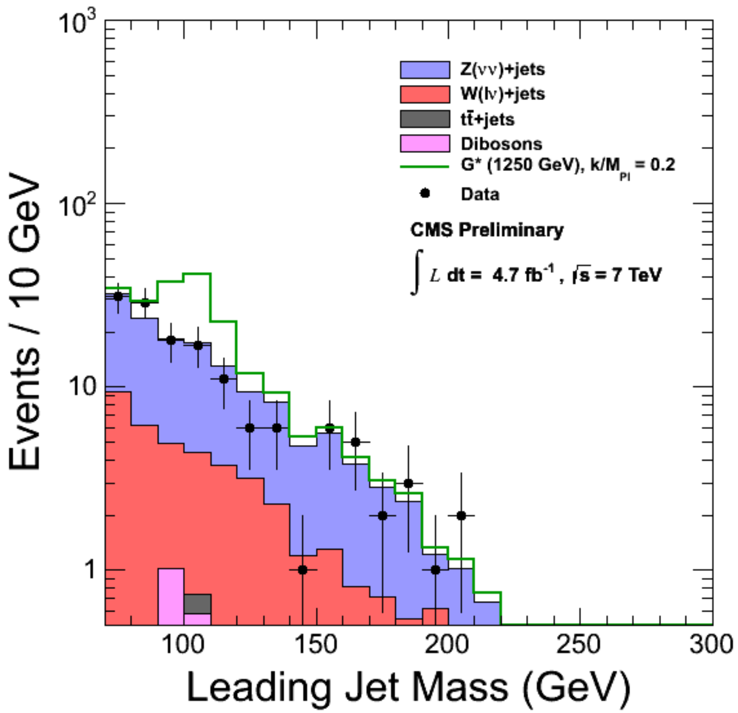
- For very heavy resonances hadronic W and Z merge into one fat jet
  - jet energy resolution

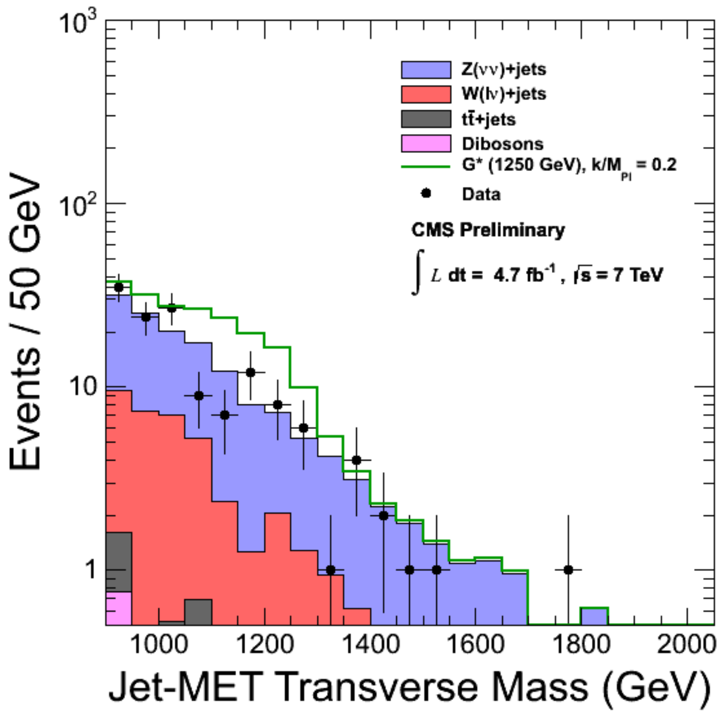
ZZ Resonance

$$pp \to G^* \to ZZ \to q\bar{q}\,\nu\bar{\nu}$$



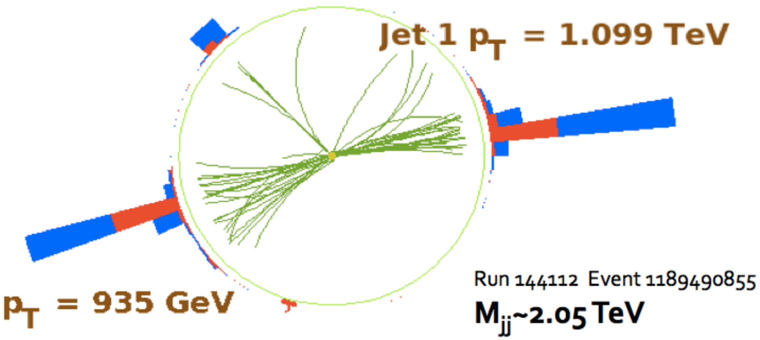
Remember the trick!

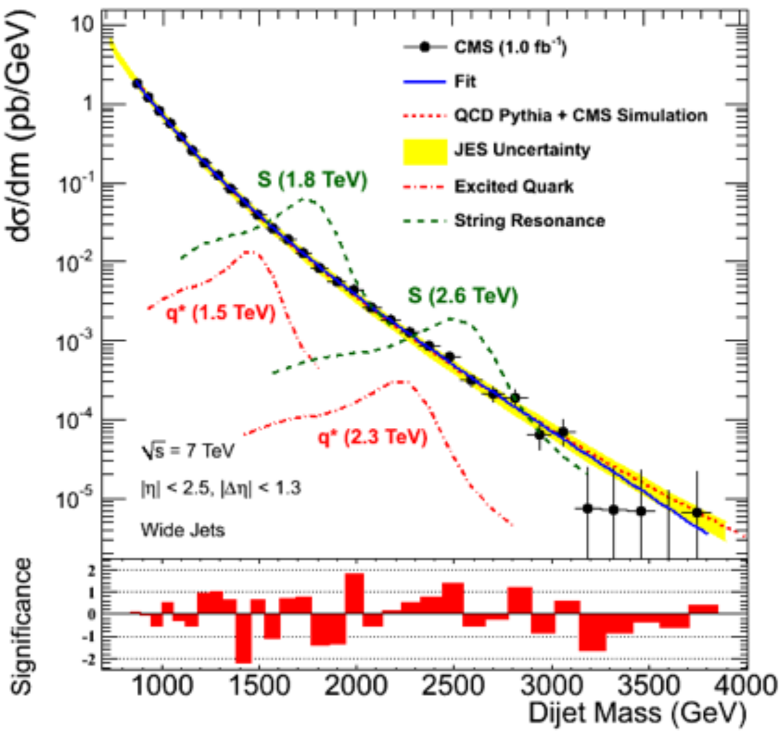




Di-Jet Resonance

- **Very early search for numerous resonances BSM: string resonance, excited quarks, axi-gluons, colorons, E6 diquarks, W' & Z', RS gravitons**

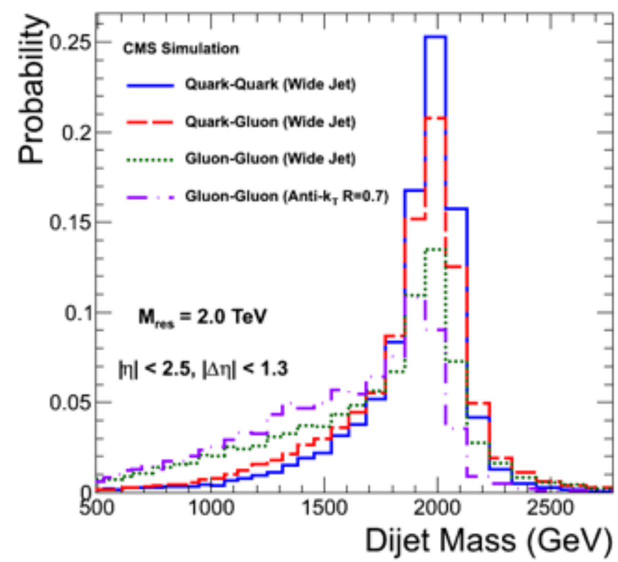


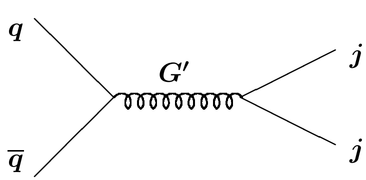


Four-parameter fit to describe QCD shape

$$\frac{d\sigma}{dm} = p_0 \frac{\left(1 - \frac{m}{\sqrt{s}}\right)^{p_1}}{\left(\frac{m}{\sqrt{s}}\right)^{B}};$$

$$B = p_2 + p_3 \left(m / \sqrt{s}\right)$$

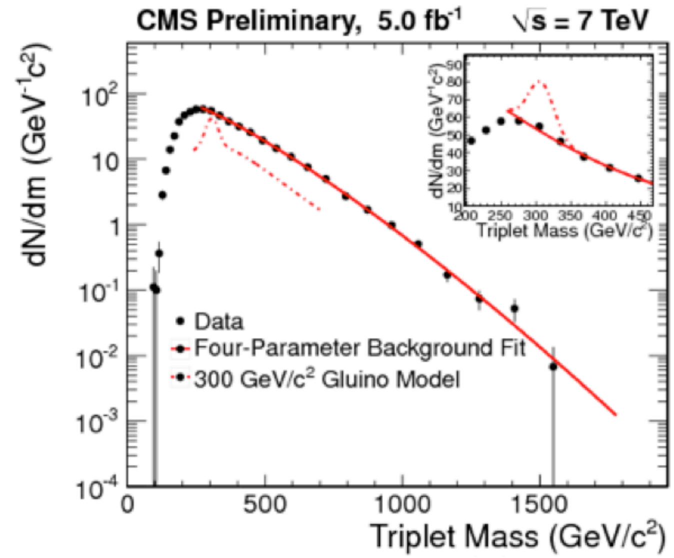


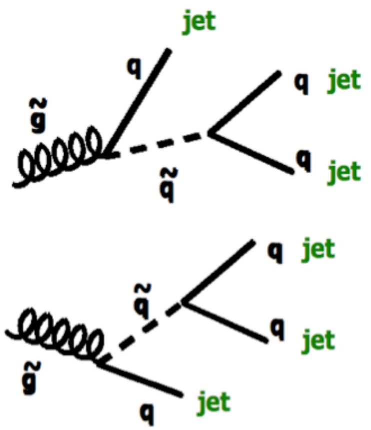


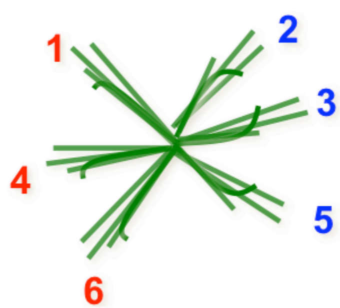
Tri-Jet Resonance

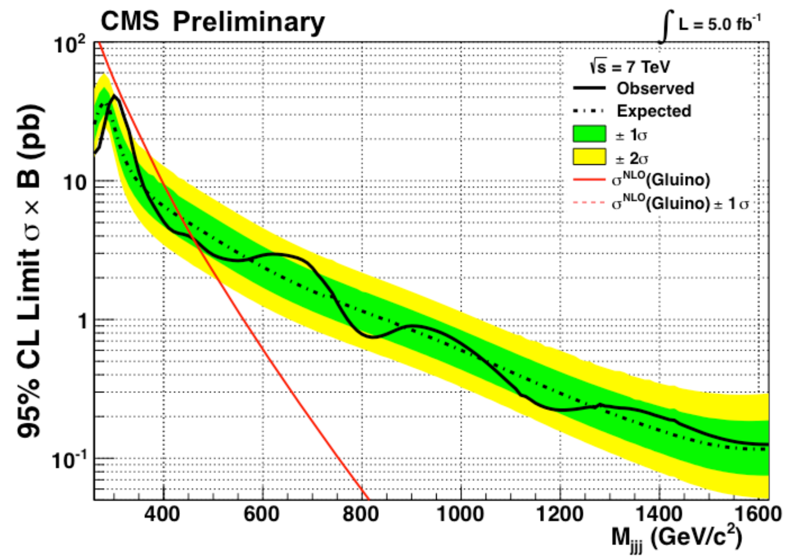
- 6 jets in several theoretical models
  - Q = g = SU(3)C Adjoint Majorana Fermion
  - R-Parity violating (No Missing ET)
- Modeled as R-parity violating gluino (negligible intrinsic width)

$$pp \rightarrow QQ \rightarrow 3j + 3j$$

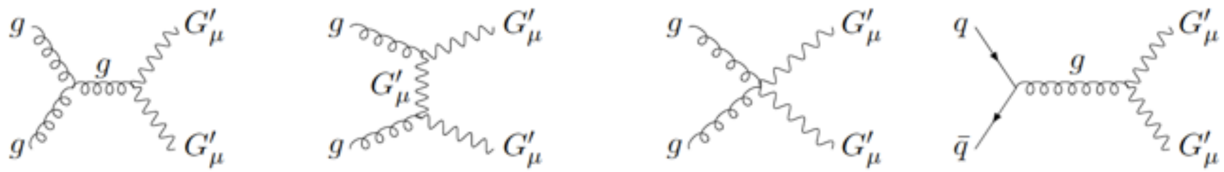




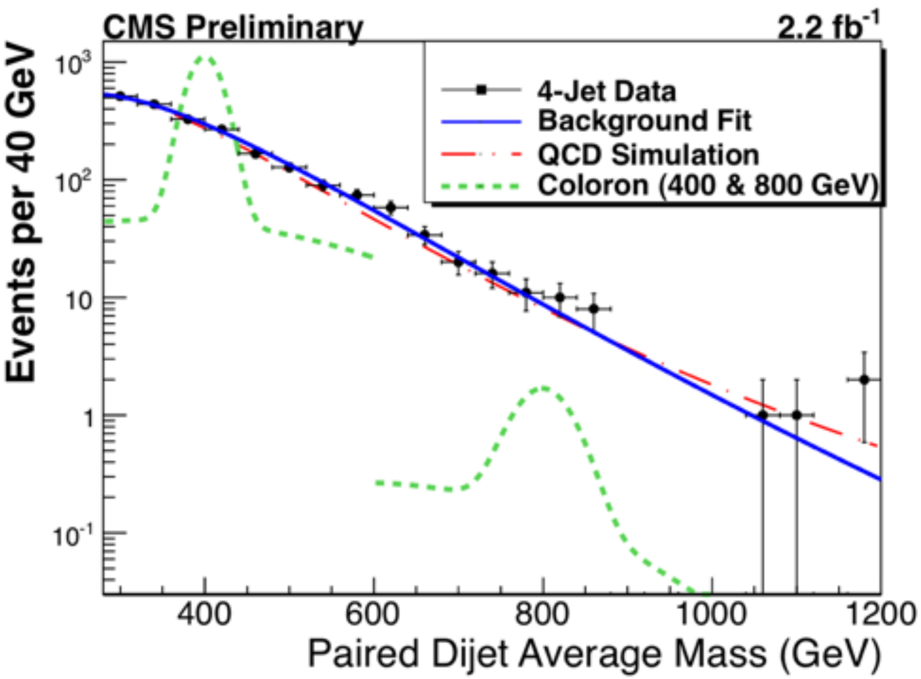




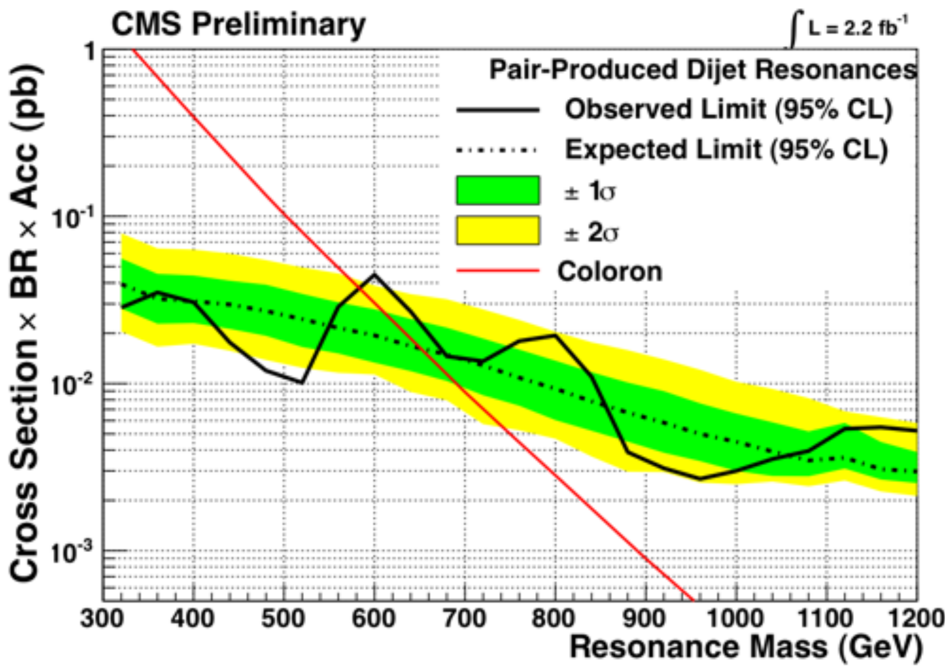
Di-Jet Pair



g
g
g
G'_μ
G'_μ
g
g
G'_μ
G'_μ
G'_μ
g
g
G'_μ
G'_μ
q
$\bar{q}$
g
G'_μ
G'_μ

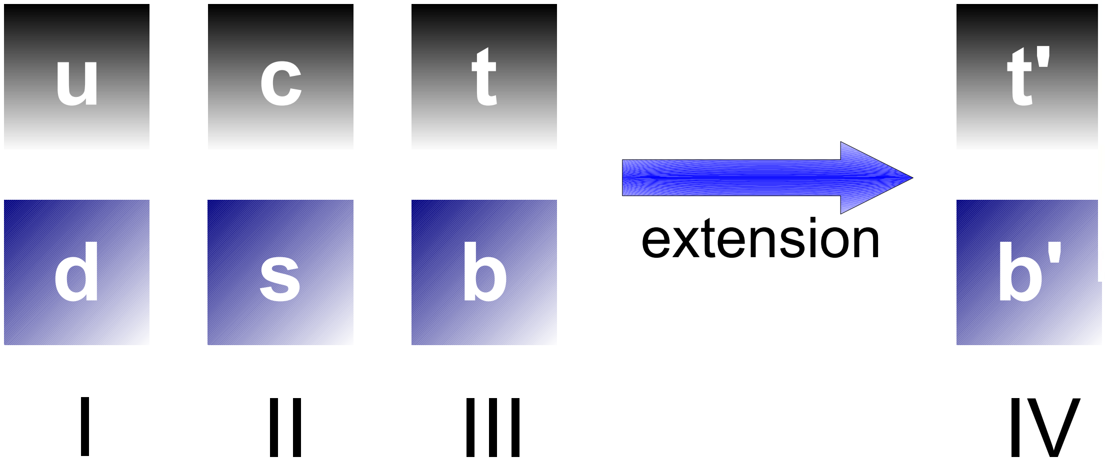


CMS Preliminary
2.2 fb^{-1}
4-Jet Data
Background Fit
QCD Simulation
Coloron (400 & 800 GeV)
Events per 40 GeV
Paired Dijet Average Mass (GeV)

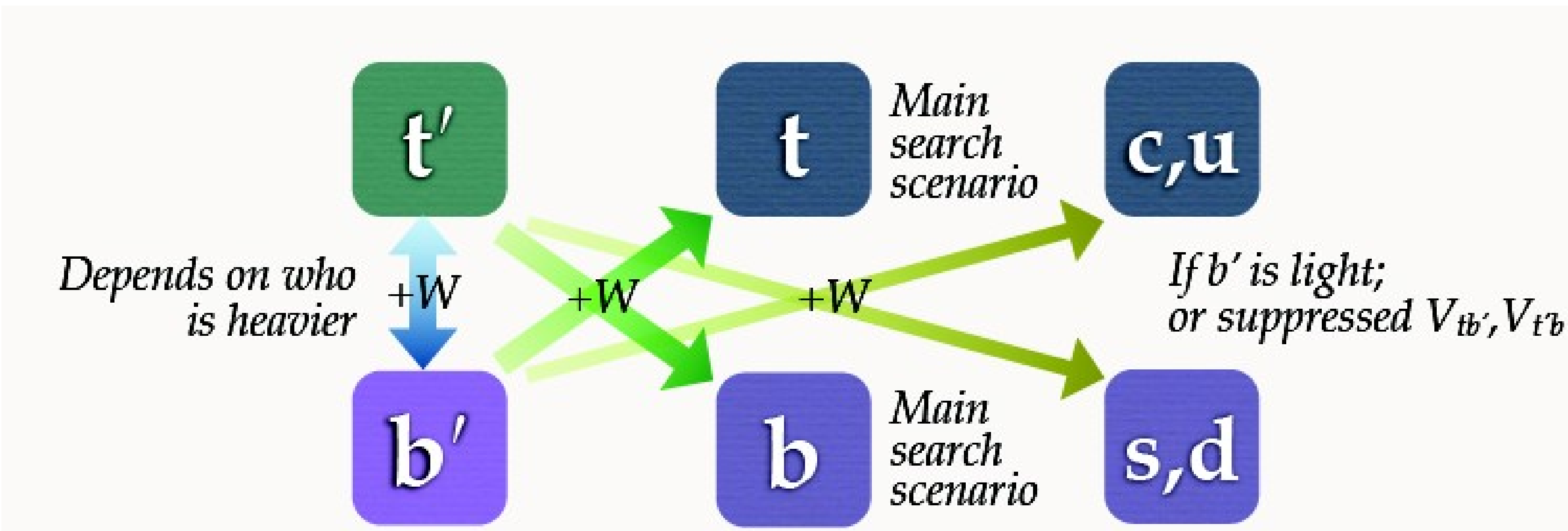


CMS Preliminary
$\int$ L = 2.2 fb^{-1}
Pair-Produced Dijet Resonances
Observed Limit (95% CL)
Expected Limit (95% CL)
± 1σ
± 2σ
Coloron
Cross Section × BR × Acc (pb)
Resonance Mass (GeV)

Fourth Generation

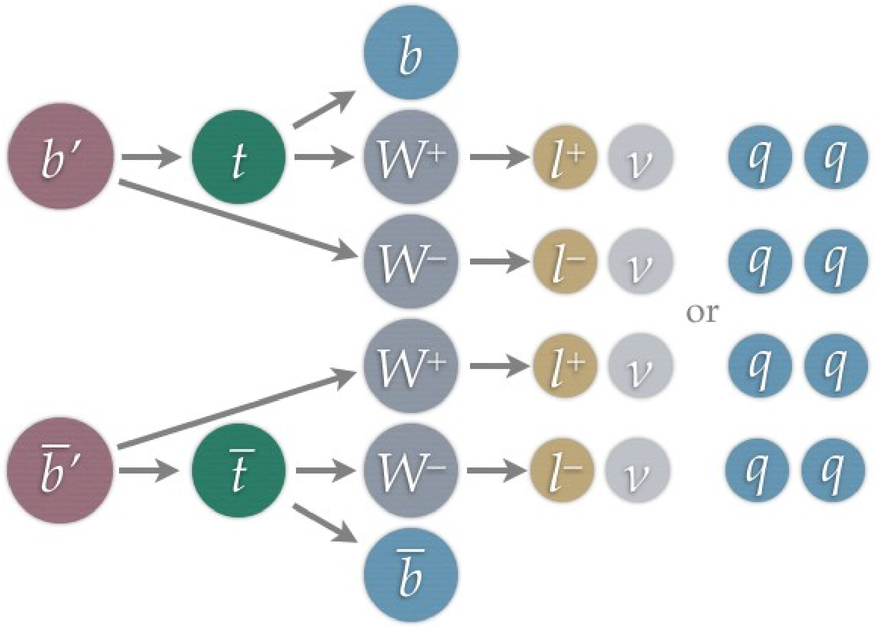


- Search for b'
  - ➔ b'→tW @1.14fb^{-1}
- Search for t'
  - ➔ t'→bW (l+j channel) @0.8fb^{-1}
  - ➔ t'→bW (dilepton channel) @1.14fb^{-1}
  - ➔ T→tZ @0.2fb^{-1}



Fourth Generation

- $b'\bar{b}'$ pair production
- $BR(b' \rightarrow tW) = 100\%$
- Decay Chain: $b'b' \rightarrow tWtW \rightarrow$ **$bbW^+W^-W^+W^-$**
- Complex signature
  - Final States: 4L+2J, **3L+4J**, **2L+6J**, 1L+8J, 0L+10J
    (clean/large modes)



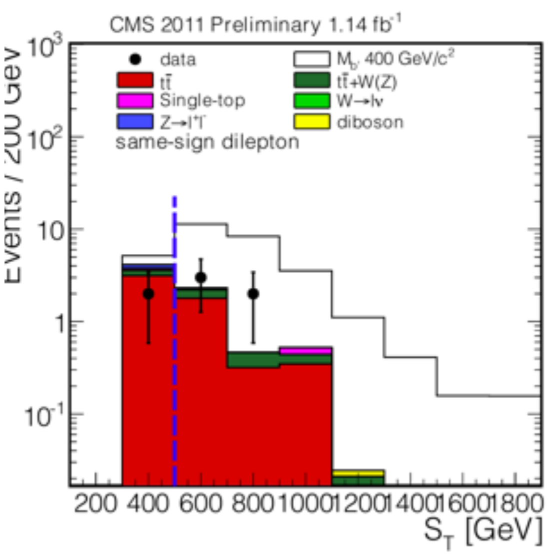
How to see *l*, *ν*, q, b?

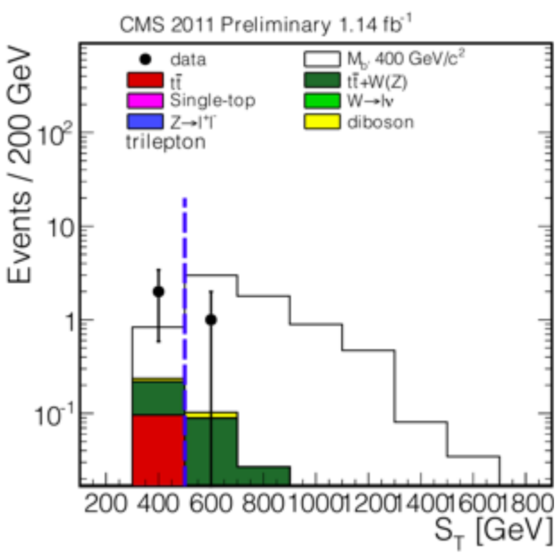
- Counting experiment
- same-sign lepton(e/μ) pair or trilepton
- at least 1 b-jet
- higher mass then top quark & more Jets then top pair

Fourth Generation

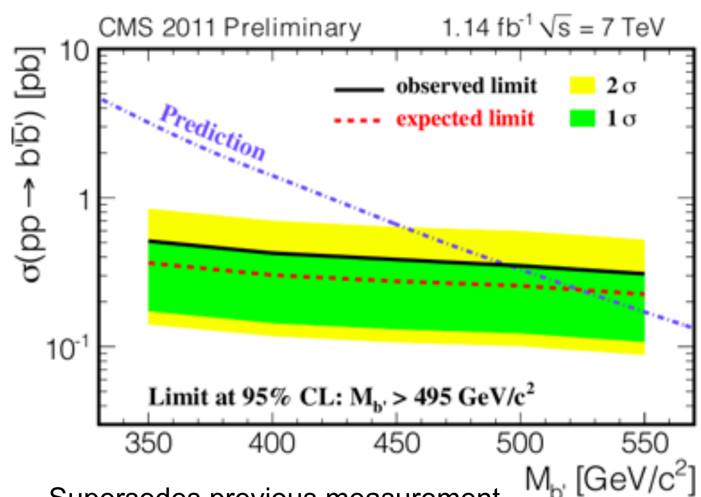
$$b'\bar{b}' \to tW^-\bar{t}W^+ \to bW^+W^-\bar{b}W^-W^+$$

- At least 1 b-jet, 2 or 3 leptons
- Main backgrounds determined from lepton fake rate in data
- Dominant systematic uncertainty: b-tagging and lepton efficiency
- Main background discrimination from total transverse energy $\sum p_{\mathrm{T}}(\mathrm{jets}) + \sum p_{\mathrm{T}}(\mathrm{leptons}) + \not{E}_{\mathrm{T}}$





CMS EXO-11-036

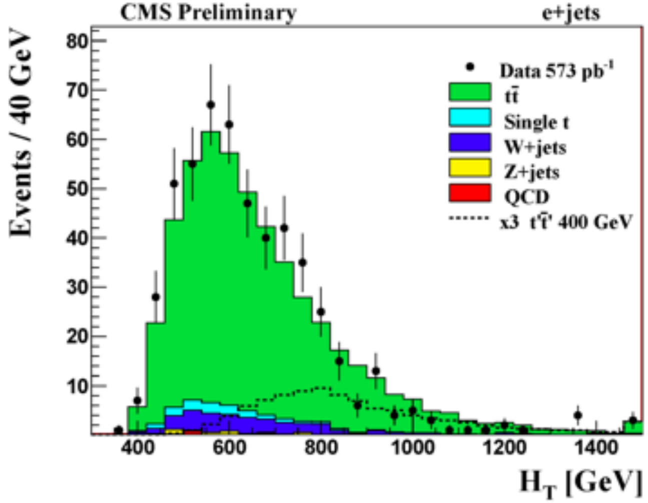


Supersedes previous measurement by CDF at 372 GeV

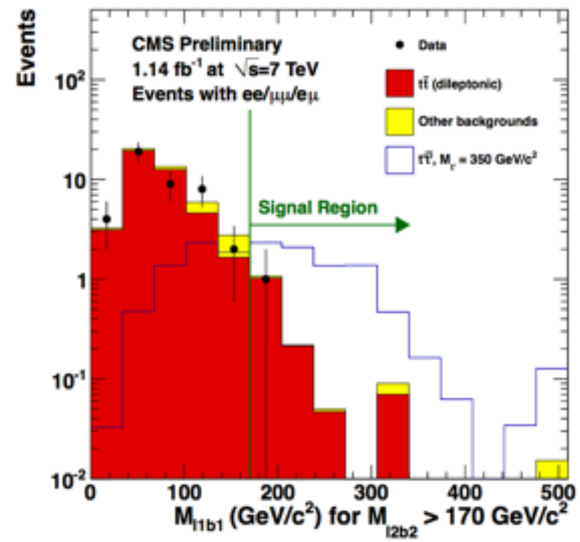
CDF: PRL106.141803 (2011)

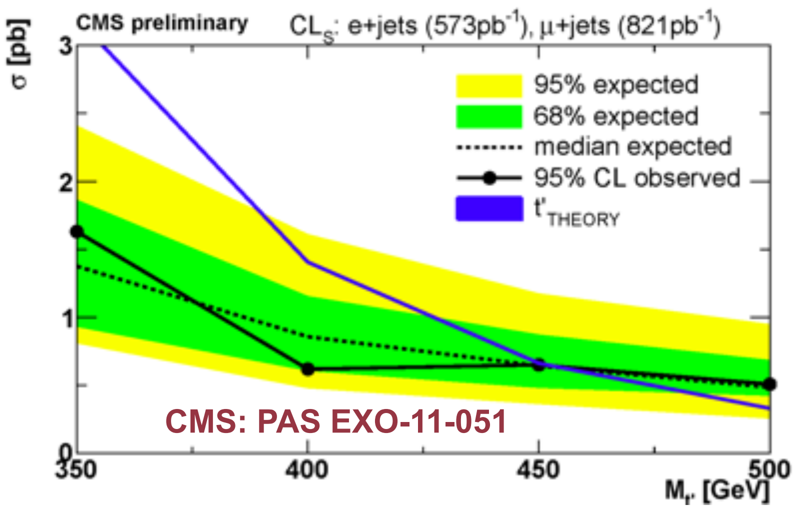
Fourth Generation

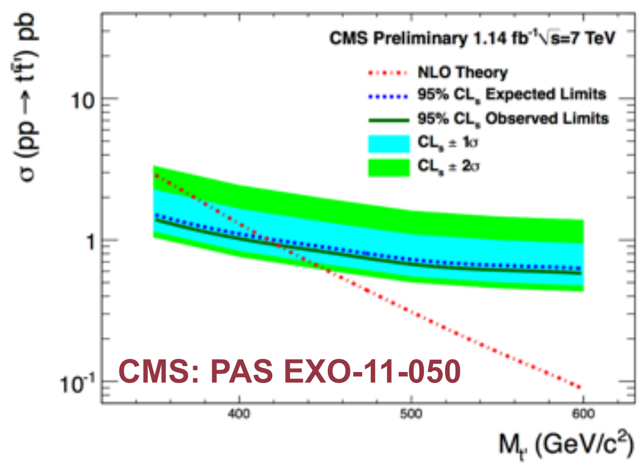
$t'\bar{t}' \rightarrow WbW\bar{b} \rightarrow \ell\nu bq\bar{q}\bar{b}$



$t'\bar{t}' \rightarrow bW\bar{b}W \rightarrow bl\nu\bar{b}l\nu$

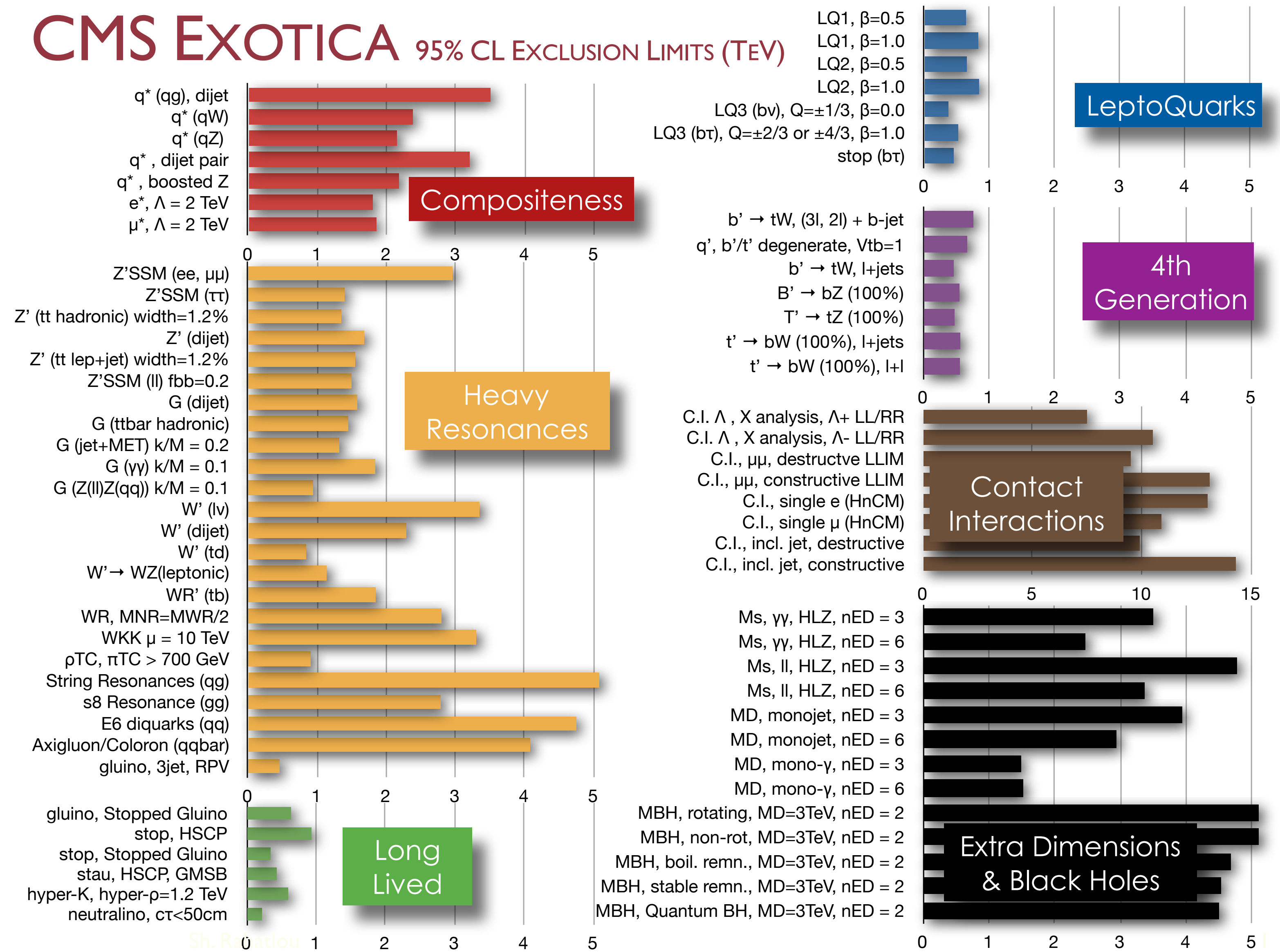






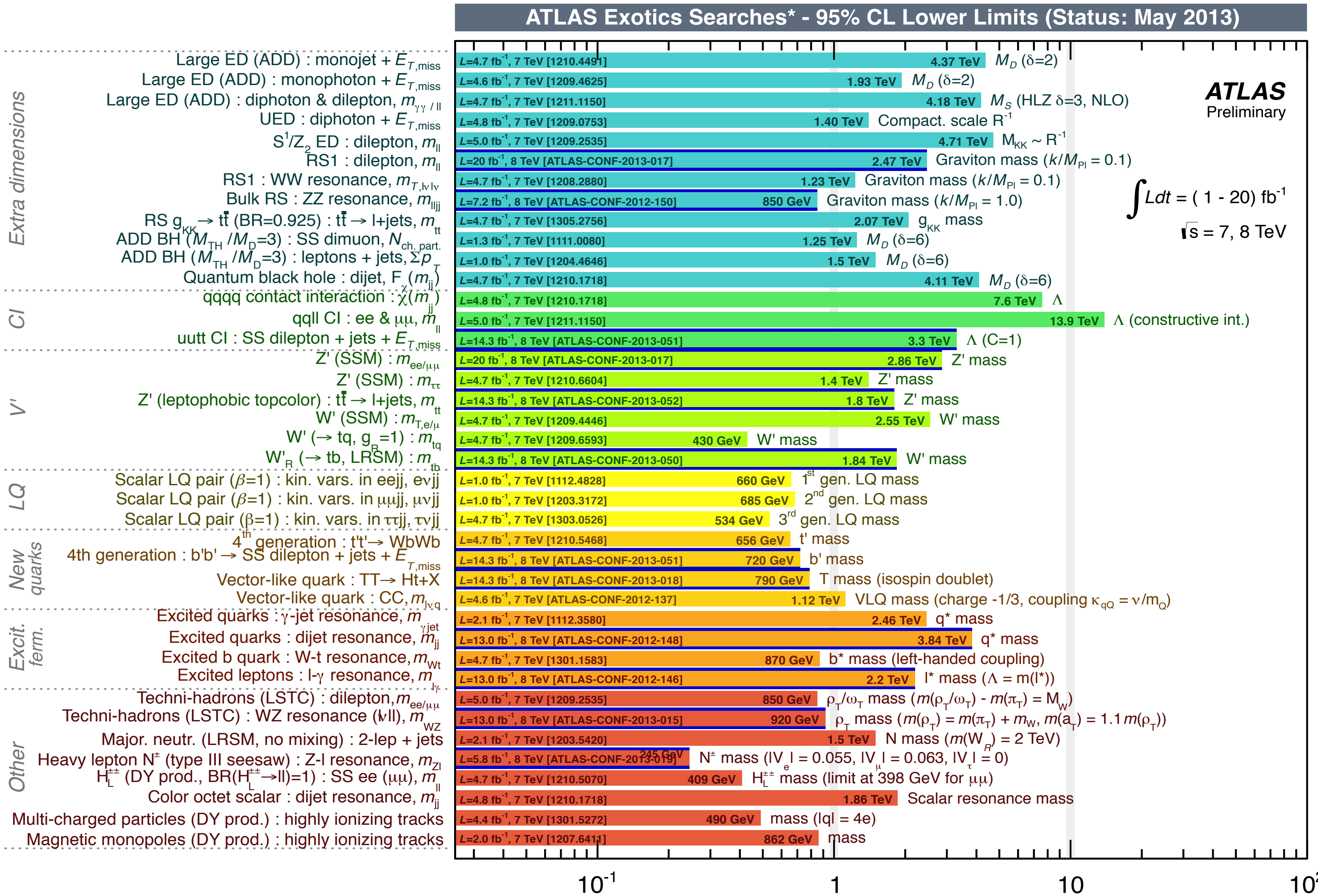
m_{Q4} > 270 GeV with 35 pb^{-1}

Exotica Searches in the CMS Collaboration



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

Exotica Searches in the ATLAS Collaboration



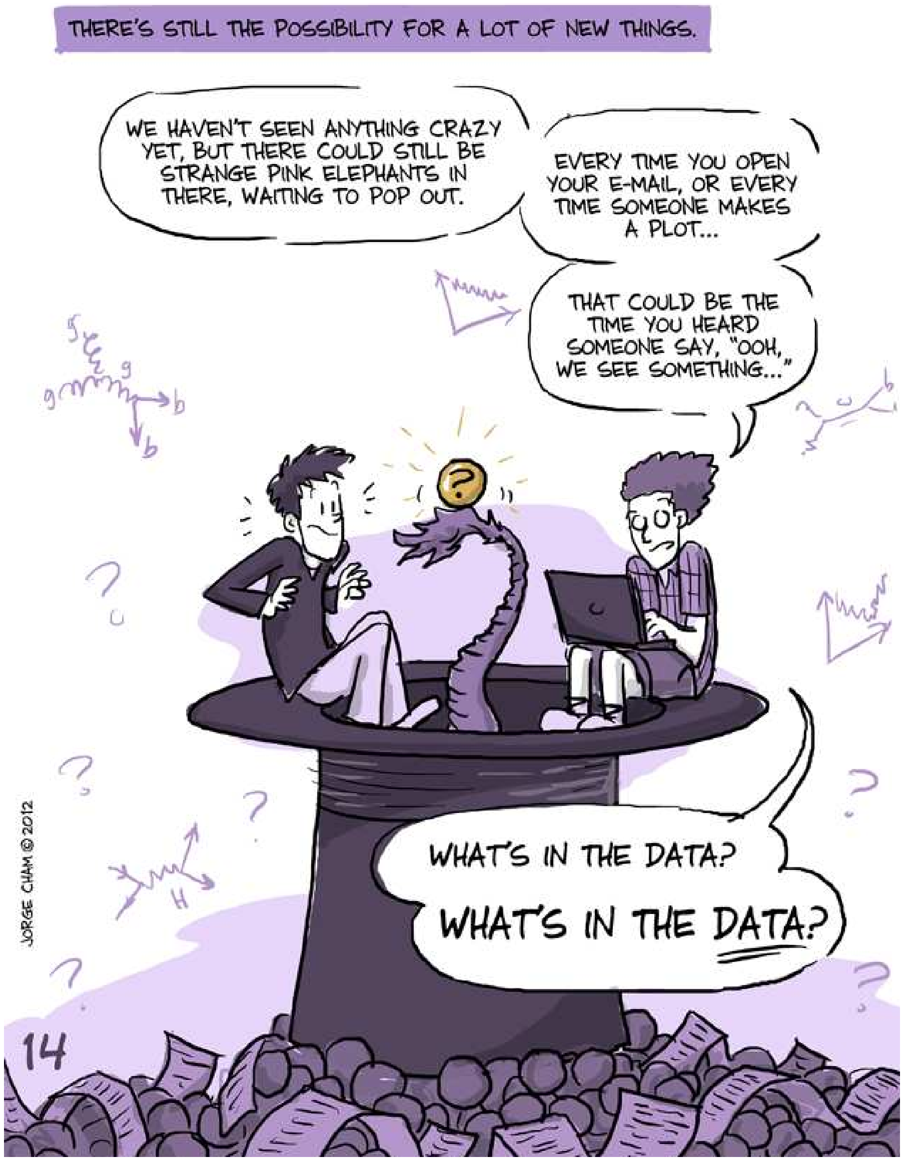
*Only a selection of the available mass limits on new states or phenomena shown

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Summary

- ✓ There is a very rich and exciting the physics beyond the SM program at LHC (beyond?) probing many fundamental aspects of the nature.
- ✓ Past 3 years of data taking at the LHC have been very intense and productive!
- ✓ Many different signatures of new physics (SUSY & Exotica) are being studied in both collaborations (also many other experiments).
- ✓ Many searches of new Physics in complementary final states have been performed, and many analyses are ready to process with full dataset in 2012.
- ✓ **Unfortunately, no significant excess observed over SM.**

Outlook



Understand electroweak symmetry breaking
Observe the Higgs boson ☑ → Observation of the new boson!
Measure neutrino masses and mixings
Establish Majorana neutrinos ($\beta\beta_{0\nu}$)
Thoroughly explore CP violation in B decays
Exploit rare decays (K, D, ...)
Observe neutron EDM, pursue electron EDM
Use top as a tool
Observe new phases of matter
Understand hadron structure quantitatively
Uncover QCD's full implications
Observe proton decay
Understand the baryon excess
Catalogue matter and energy of the universe
Measure dark energy equation of state
Search for new macroscopic forces
Determine GUT symmetry
Detect neutrinos from the universe
Learn how to quantize gravity
Learn why empty space is nearly weightless
Test the inflation hypothesis
Understand discrete symmetry violation
Resolve the hierarchy problem
Discover new gauge forces
Directly detect dark-matter particles
Explore extra spatial dimensions
Understand the origin of large-scale structure
Observe gravitational radiation
Solve the strong CP problem
Learn whether supersymmetry is TeV-scale
Seek TeV-scale dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate problem of identity