Susy 2011

$$U(3)_C \times Sp(1)_L \times U(1)_L \times U(1)_R$$

Luis Anchordoqui

Outline

- String theory and all that...
- Extra U(1)'s in D-brane constructions
- CDF anomaly
- Z' harbingers of low mass strings
- Regge recurrences ☛ dijet signals
- Photons and gluons as quiver neighbors
- LHC discovery reach of low mass strings
- Conclusions

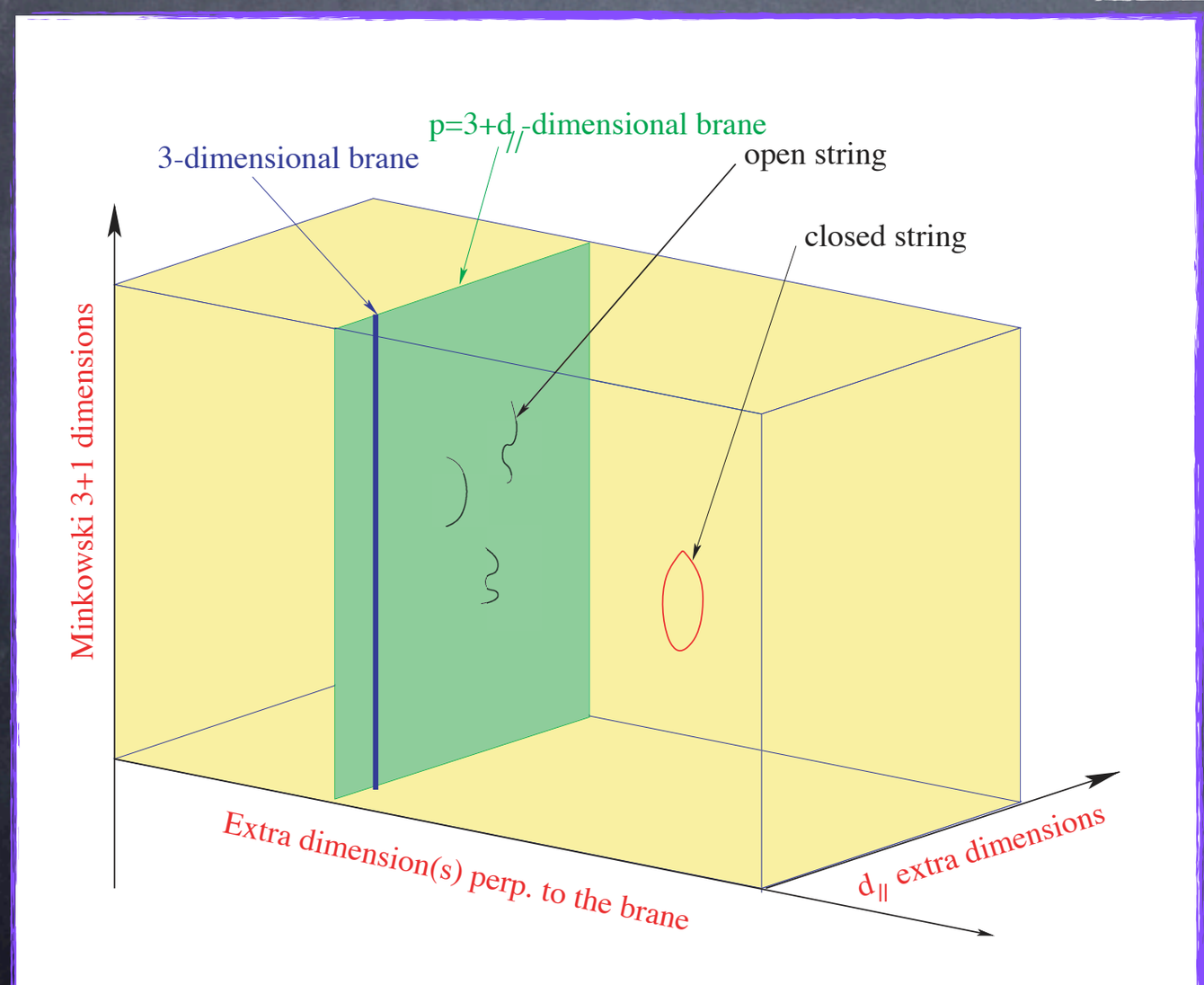
This talk is based on

- LAA, I. Antoniadis, H. Goldberg, X. Huang, D. Lüst, & T. Taylor
  arXiv:1107.4309
- LAA, H. Goldberg, S. Nawata & T. Taylor
  PRL 100, 171603 (2008) arXiv:0712.0386
  PRD 78, 016005 (2008) arXiv:0804.2013
- LAA, H. Goldberg, & T. Taylor
  PLB 668, 373 (2008) arXiv:0806.3420
- LAA, H. Goldberg, D. Lüst, S. Nawata, S. Stieberger & T. Taylor
  PRL 101, 241803 (2008) arXiv:0808.0497
  NPB 821, 181 (2009) arXiv:0904.3547
- LAA, H. Goldberg, D. Lüst, S. Stieberger & T. Taylor
  MPLA, 2481 (2009) arXiv:0909.2216
- LAA, W.-Z. Feng, H. Goldberg, X. Huang, & T. Taylor
  PRD 83, 106006 (2011) arXiv:1012.3446

TeV Scale Superstrings

- Superstring theory was born as a theory of Planck scale or just below the Planck scale
- Large scale compactification and D-brane constructs decouple the Planck scale from the string scale by introducing another parameter in the theory ➡ $M_{\rm Pl}^2 \sim M_s^2 \, (M_s R^{\perp})^n$

A²D² PLB 436 (1998) 257



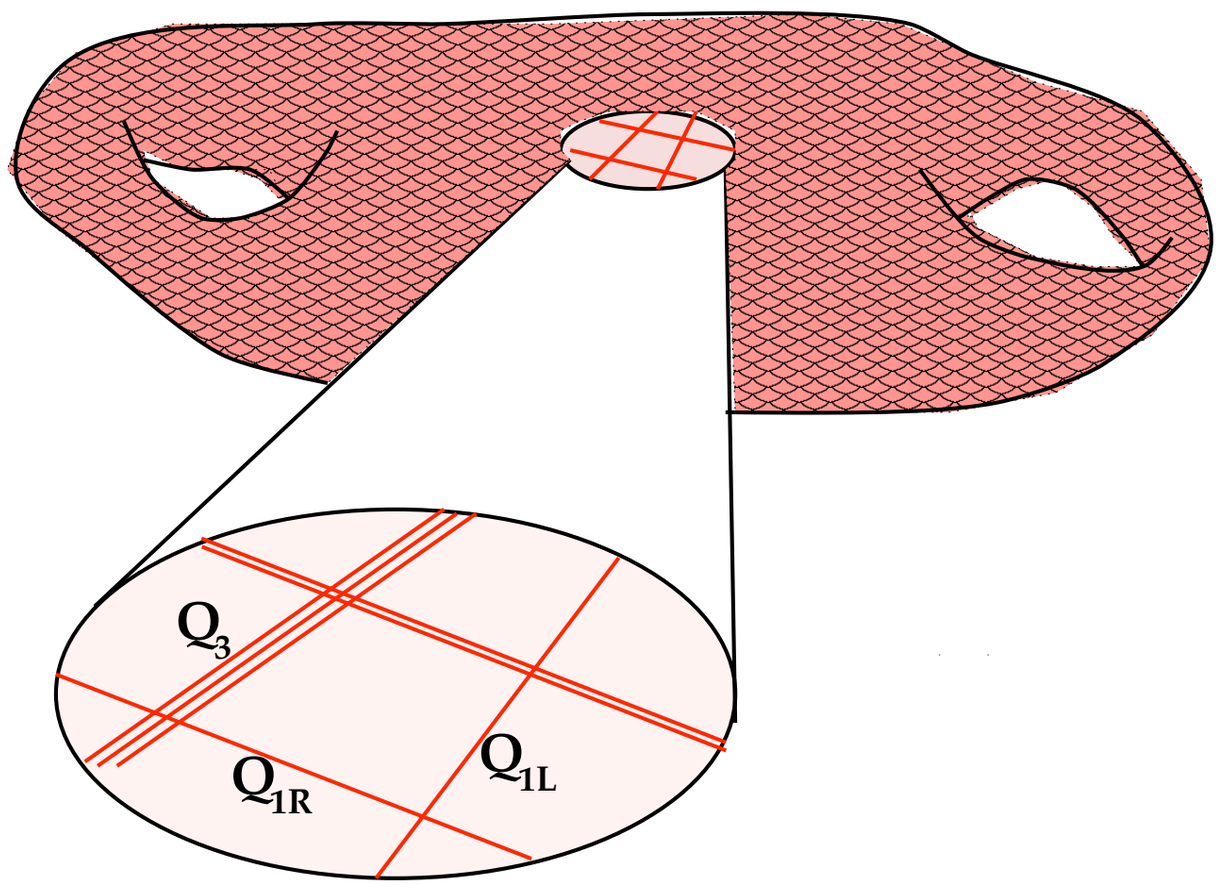
☛ Courtesy of Ignatios Antoniadis

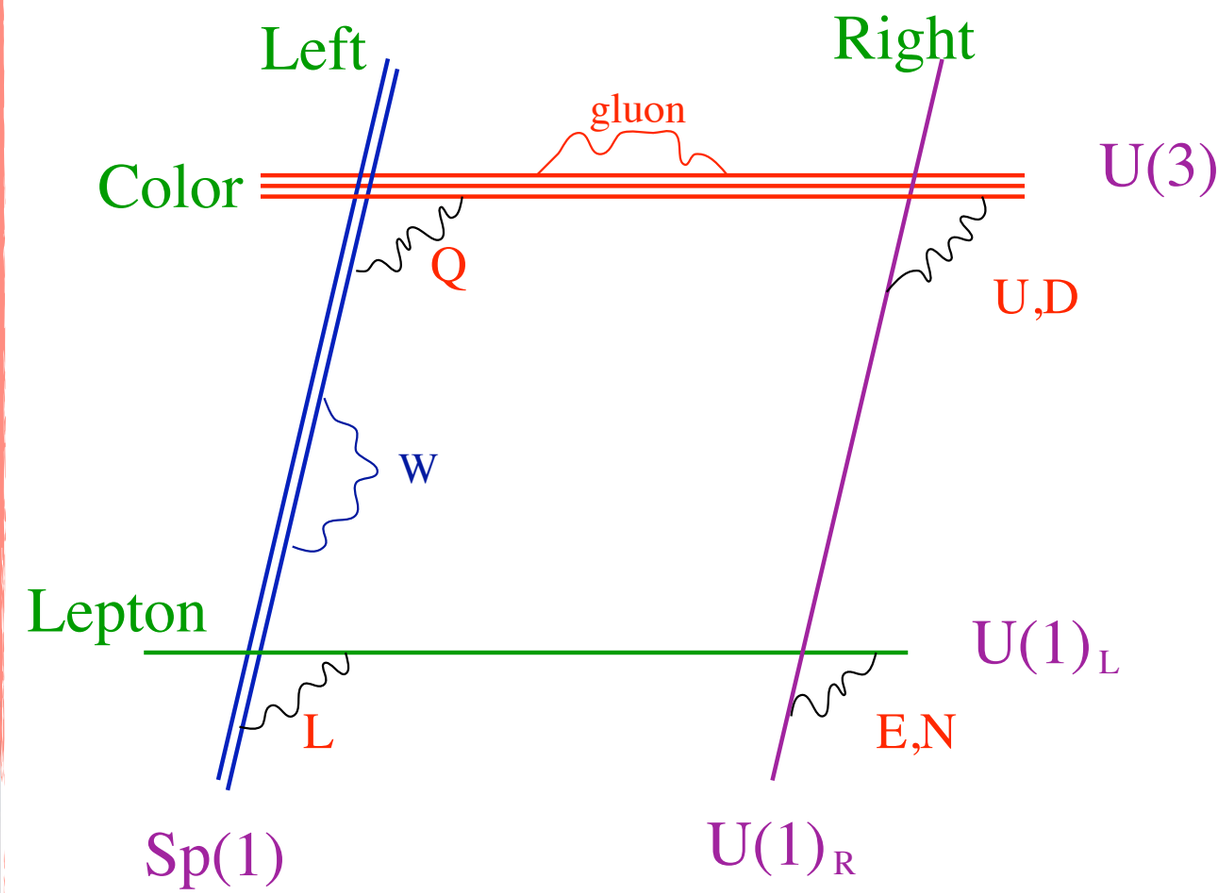
Intersecting D-brane Models

- Basic unit of gauge invariance for oriented string constructions is a $U(1)$ field ⇨ one can stack up N identical D-branes to generate a $U(N)$ theory with associated $U(N)$ gauge group
- In presence of orientifolds ☛ open strings become (in general) non oriented allowing for $SO(N)$ and $Sp(1)$ gauge group factors
- Gauge bosons (and associated gauginos in a SUSY model) arise from strings terminating on one stack of D-branes
- Chiral matter fields are due to strings stretching between intersecting D-branes (from different stacks)
- Consider scattering processes which take place on color $U(3)_C$ stack of D-branes which is intersected by $Sp(1)_L$ (weak doublet) stack of D-branes and $U(1)_R$ stack of D-brane
- Lepton $U(1)_L$ stack completes our minimal model

Blumenhagen, Kors, Lüst, & Ott, Nucl. Phys. B 616 (2001) 3
Blumenhagen, Kors, Lüst & Stieberger, Phys. Repts. 445 (2007) 1

Pictorial Representation





Fundamental principles similar to $U(3)_B \times U(2)_L \times U(1)_L \times U(1)_R$

Ibanez, Marchesano, Rabadan, JHEP 0111 (2001) 002

Cremades, Ibanez, Marchesano, JHEP 0307 (2003) 0388

Quantum Numbers

chiral fermions and Higgs doublet

Name	Representation	Q_3	Q_{1L}	Q_{1R}	Q_Y
Q_i	$(3,2)$	1	0	0	$\frac{1}{6}$
$\bar{U}_i$	$(\bar{3},1)$	-1	0	-1	$-\frac{2}{3}$
$\bar{D}_i$	$(\bar{3},1)$	-1	0	1	$\frac{1}{3}$
L_i	$(1,2)$	0	1	0	$-\frac{1}{2}$
$\bar{E}_i$	$(1,1)$	0	-1	1	1
$\bar{N}_i$	$(1,1)$	0	-1	-1	0
H	$(1,2)$	0	0	1	$\frac{1}{2}$

B-L anomaly free ➡ right-handed nus must exist

Bonus ➡ in 'flavor' space charges are orthogonal

Running of abelian gauge couplings

Covariant derivative for $U(1)$ fields X^i_μ canonically normalized

$$\mathcal{D}_\mu = \partial_\mu - i \sum g'_i \, Q_i \, X^i_\mu$$

Relations between
- $U(1)$ couplings g'_i
- non-abelian g_i counterparts

are left open for now

Carry out an orthogonal transformation of fields $X^i_\mu = \sum_j O_{ij} \, Y^j_\mu$

$$\begin{aligned} \mathcal{D}_\mu &= \partial_\mu - i \sum_i \sum_j g'_i \, Q_i \, O_{ij} \, Y^j_\mu \\ &= \partial_\mu - i \sum_j \bar{g}_j \, \bar{Q}_j \, Y^j_\mu \end{aligned}$$

for each j ☛

$$\bar{g}_j \bar{Q}_j = \sum_i g'_i \, Q_i \, O_{ij}$$

$$Q_Y = \sum_i c_i \, Q_i$$

Normalization for hypercharge (say $j = 1$)

$$g_Y \, Q_Y = \sum_i g'_i \, Q_i \, O_{i1}$$

$$g_Y \sum_i Q_i \, c_i = \sum_i g'_i \, O_{i1} \, Q_i$$

Running of abelian gauge couplings (cont'd)

Take charges as vectors with components labeled by particles

Should charges be orthogonal ☛ $\sum_p Q_{i,p} Q_{k,p} = 0$ for $i \neq k$

$$\sum_p Q_{k,p}\, g_Y \sum_i Q_{i,p}\, c_i = \sum_p Q_{k,p} \sum_i g_i'\, O_{i1}\, Q_{i,p}$$

$$g_Y\ c_i = g_i'\, O_{i1}$$

☛

$$O_{i1} = \frac{g_Y\ c_i}{g_i'}$$

Orthogonality of rotation matrix ☛ $\sum_i O_{i1}^2 = 1$

$$g_Y^2 \sum_i \left(\frac{c_i}{g_i'}\right)^2 = 1$$

$$P \equiv \frac{1}{g_Y^2} - \sum_i \left(\frac{c_i}{g_i'}\right)^2 = 0$$

needs to stay intact

Running of abelian gauge couplings (cont'd)

One loop corrections to various couplings are

$$\frac{1}{\alpha_Y(Q)} = \frac{1}{\alpha_Y(\Lambda)} - \frac{b_Y}{2\pi}\ln(Q/\Lambda)$$

$$\frac{1}{\alpha_i(Q)} = \frac{1}{\alpha_i(\Lambda)} - \frac{b_i}{2\pi}\ln(Q/\Lambda)$$

with

$$b_Y = \frac{2}{3}\,\mathrm{Tr}\,Q^2_{Y,f} + \frac{1}{3}\,\mathrm{Tr}\,Q^2_{Y,s}$$

$$b_i = \frac{2}{3}\,\mathrm{Tr}\,Q^2_{i,f} + \frac{1}{3}\,\mathrm{Tr}\,Q^2_{i,s}$$

Recall charges are orthogonal ☛ Y normalization implies

$$\sum_s Q^2_{Y,s} = \sum_i c_i^2 \sum_s Q^2_{i,s}$$

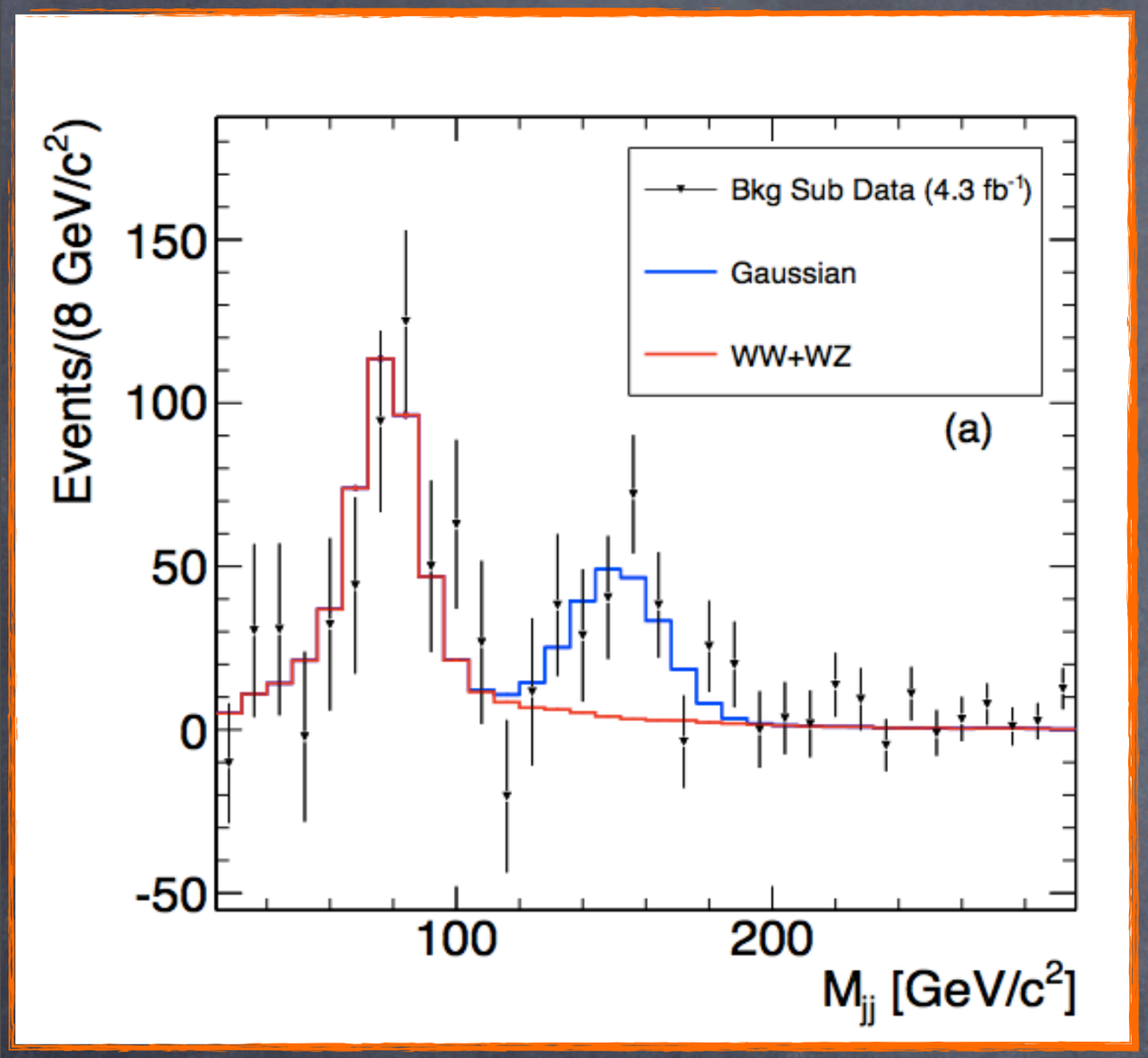
$$\sum_f Q^2_{Y,f} = \sum_i c_i^2 \sum_f Q^2_{i,f}$$

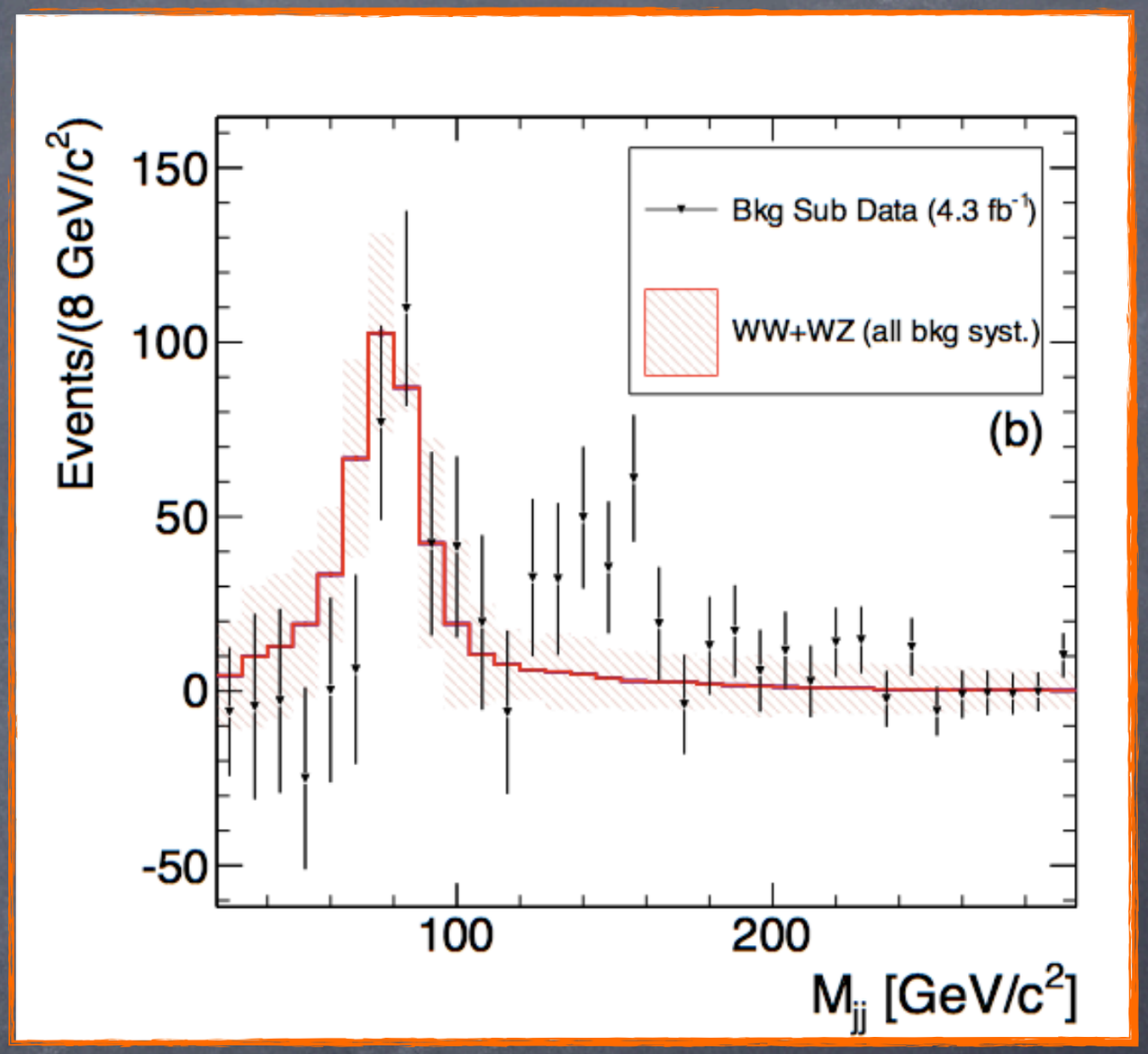
$$b_Y = \sum_i c_i^2 b_i$$

RG-induced change on P

$$\begin{aligned}\Delta P &= \Delta\left(\frac{1}{\alpha_Y}\right) - \sum_i c_i^2\,\Delta\left(\frac{1}{\alpha_i}\right)\\ &= \frac{1}{2\pi}\left(b_Y - \sum_i c_i^2\, b_i\right)\ln(Q/\Lambda)\end{aligned}$$

Has CDF data pierced SM's resistant armor?

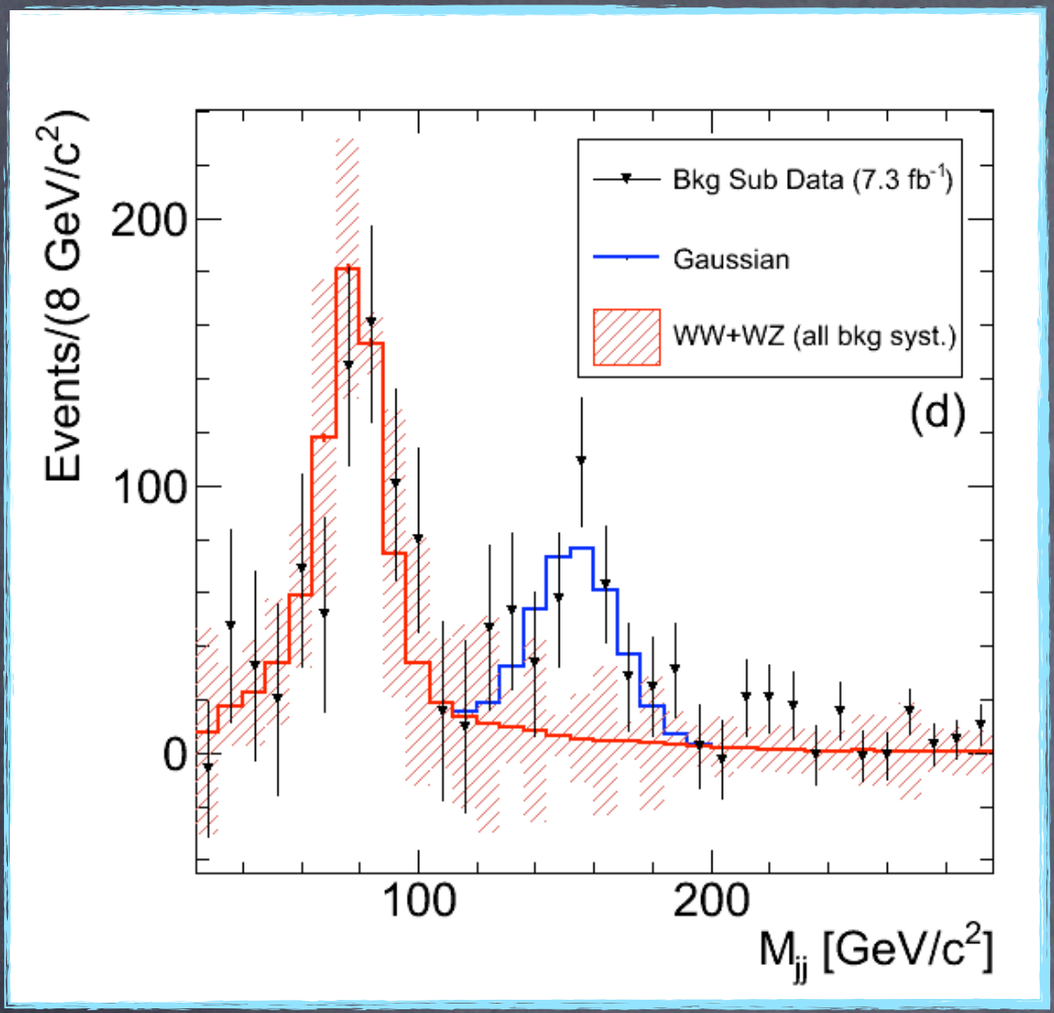


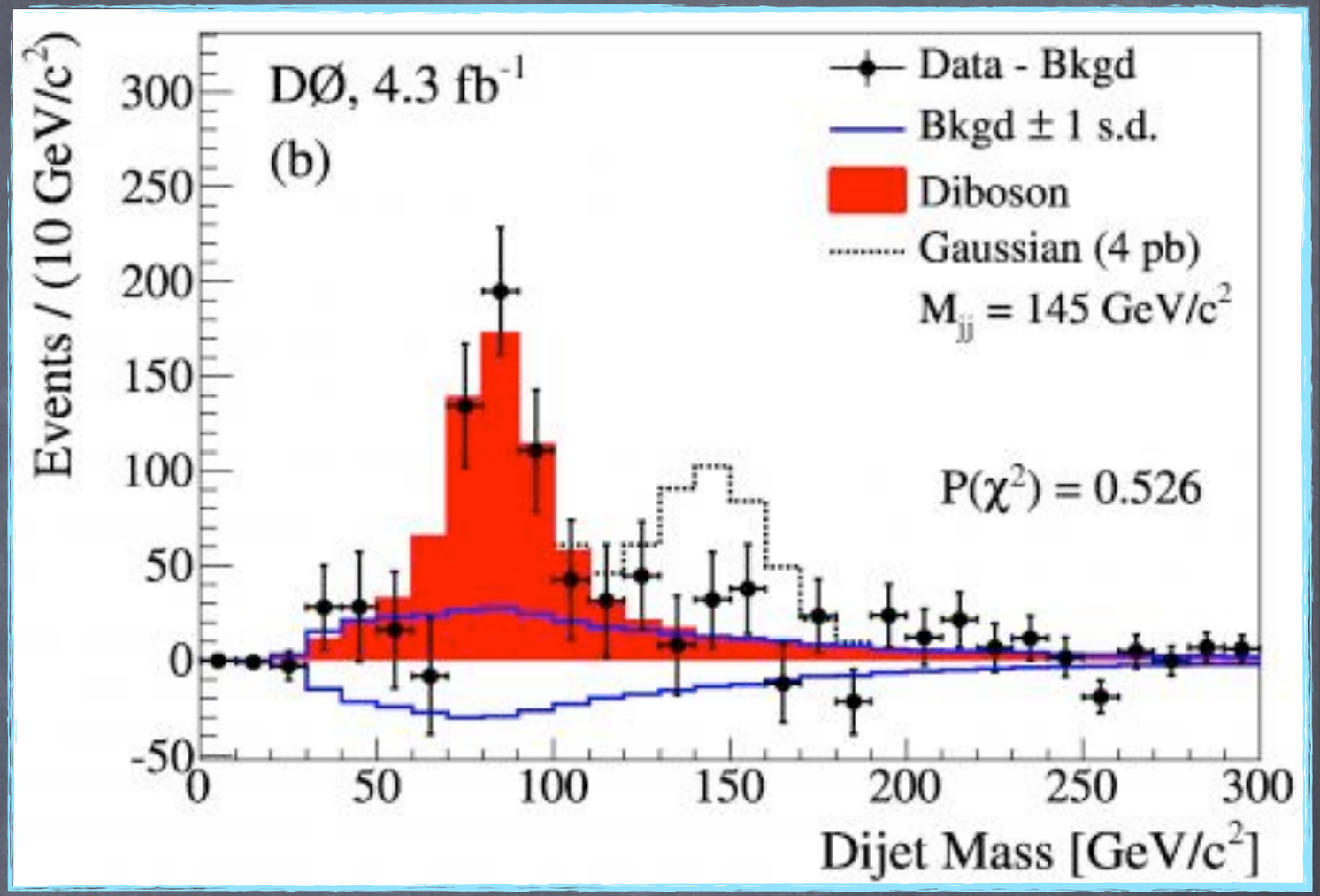


- Excess in Wjj production
- For search window ☛ $120\ \mathrm{GeV} < M_{jj} < 200\ \mathrm{GeV}$ excess significance above SM background 3.2σ (including systematic uncertainties)

CDF Collaboration, Phys. Rev. Lett. 106 (2011) 171801

More data





http://www-cdf.fnal.gov/physics/ewk/2011/wjj/7_3.html

DO Collaboration, Phys. Rev. Lett. 107 (2011) 011804

LHC will eventually weigh in on this issue:

If new physics is responsible for CDF anomaly ☛ Wjj signal should become statistically significant by end of this year

Buckley, Hooper, Kopp, Martin, Neil, arXiv:1107.5799

U(1) gauge interactions

Covariant derivative reads

$$\mathcal{D}_\mu = \partial_\mu - i g_3' \, C_\mu \, Q_3 - i g_4' \, \tilde{B}_\mu \, Q_{1L} - i g_1' \, B_\mu \, Q_{1R}$$

fields $C_\mu \;\; \tilde{B}_\mu \; B_\mu$ are related to $Y_\mu, Y_\mu{}', Y_\mu{}''$ by Euler matrix

$$\mathbb{O} = \begin{pmatrix} C_\theta C_\psi & -C_\phi S_\psi + S_\phi S_\theta C_\psi & S_\phi S_\psi + C_\phi S_\theta C_\psi \\ C_\theta S_\psi & C_\phi C_\psi + S_\phi S_\theta S_\psi & -S_\phi C_\psi + C_\phi S_\theta S_\psi \\ -S_\theta & S_\phi C_\theta & C_\phi C_\theta \end{pmatrix}$$

$$\begin{aligned} \mathcal{D}_\mu &= \partial_\mu - i Y_\mu \left(-S_\theta g_1' Q_{1R} + C_\theta S_\psi g_4' Q_{1L} + C_\theta C_\psi g_3' Q_3 \right) \\ &- i Y_\mu' \left[C_\theta S_\phi g_1' Q_{1R} + \left(C_\phi C_\psi + S_\theta S_\phi S_\psi \right) g_4' Q_{1L} + \left(C_\psi S_\theta S_\phi - C_\phi S_\psi \right) g_3' Q_3 \right] \\ &- i Y_\mu'' \left[C_\theta C_\phi g_1' Q_{1R} + \left(-C_\psi S_\phi + C_\phi S_\theta S_\psi \right) g_4' Q_{1L} + \left(C_\phi C_\psi S_\theta + S_\phi S_\psi \right) g_3' Q_3 \right] \end{aligned}$$

Orthogonal Transformation

- Demanding that Y_μ is anomaly free

$$Q_Y = c_1 Q_{1R} + c_3 Q_3 + c_4 Q_{1L}$$

we set $c_1 = 1/2 \quad c_3 = 1/6 \quad c_4 = -1/2$

- First column of rotation matrix $\mathbb{O}$ is fixed

$$\begin{matrix} C_\mu \\ \tilde{B}_\mu \\ B_\mu \end{matrix} = \begin{pmatrix} Y_\mu\, c_3 g_Y / g_3' & \dots \\ Y_\mu\, c_4 g_Y / g_4' & \dots \\ Y_\mu\, c_1 g_Y / g_1' & \dots \end{pmatrix}$$

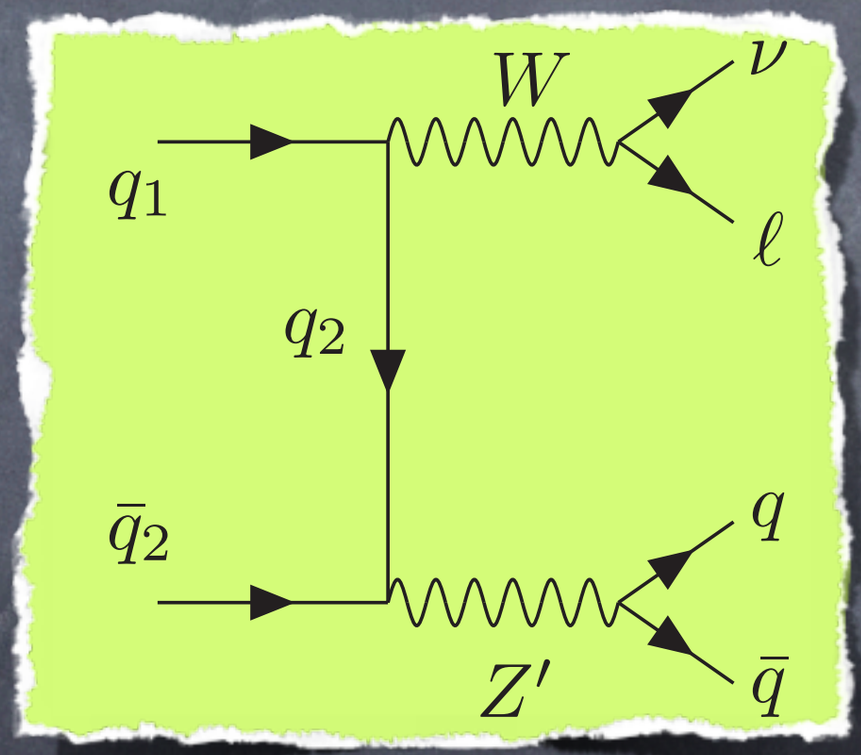
determine value of two associated Euler angles

$$\theta = -\arcsin[c_1 g_Y / g_1'] \quad \& \quad \psi = \arcsin[c_4 g_Y / (g_4'\, C_\theta)]$$

Wjj production rate

$$\mathcal{L} = \frac{1}{2}\sqrt{g_Y^2 + g_2^2}\sum_f \left(\epsilon_{f_L}\bar{\psi}_{f_L}\gamma^\mu\psi_{f_L} + \epsilon_{f_R}\bar{\psi}_{f_R}\gamma^\mu\psi_{f_R}\right) Z'_\mu$$

$$= \sum_f \left((g_{Y'}Q_{Y'})_{f_L}\,\bar{\psi}_{f_L}\gamma^\mu\psi_{f_L} + (g_{Y'}Q_{Y'})_{f_R}\bar{\psi}_{f_R}\gamma^\mu\psi_{f_R}\right) Z'_\mu$$

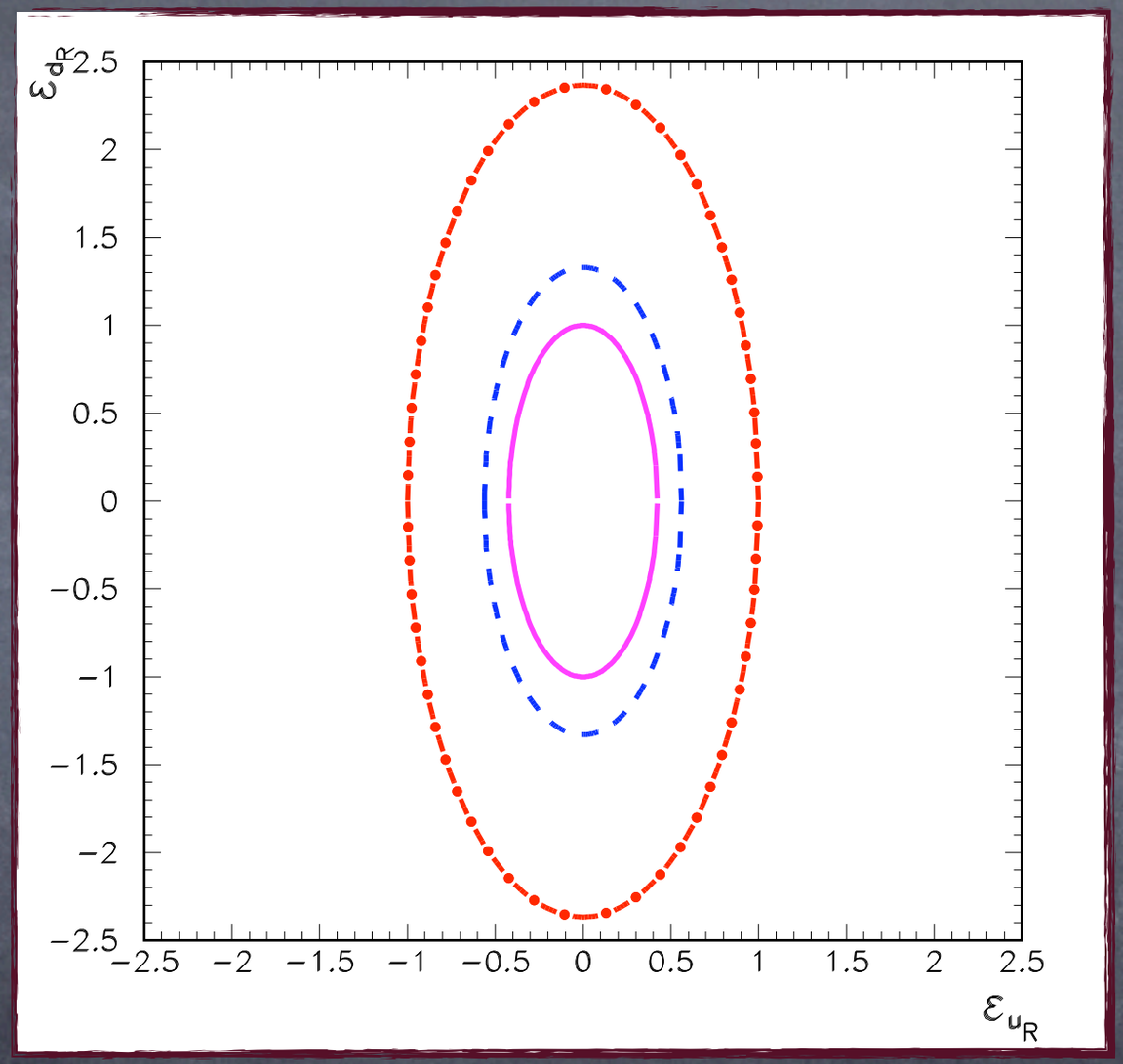


$$\sigma(p\bar{p} \to WZ') \times \mathrm{BR}(Z' \to jj) \simeq \left[0.719\left(\epsilon_{u_L}^2 + \epsilon_{d_L}^2\right) + 5.083\,\epsilon_{u_L}\,\epsilon_{d_L}\right] \times \Gamma(\phi, g_1')_{Z'\to q\bar{q}}\ \mathrm{pb}$$

Hewett & Rizzo arXiv:1106.0294

UA2 upper limit

$$\sigma(p\bar{p} \to Z') \times \mathrm{BR}(Z' \to jj) \simeq \frac{1}{2}\left[773(\epsilon^2_{u_L} + \epsilon^2_{u_R}) + 138(\epsilon^2_{d_L} + \epsilon^2_{d_R})\right] \times \Gamma(\phi, g_1')_{Z' \to q\bar{q}} \text{ pb}$$



dilepton searches

$$\sigma(p\bar{p} \to Z') \times \mathrm{BR}(Z' \to \ell\bar{\ell}) \simeq \frac{1}{2}\left[773(\epsilon^2_{u_L} + \epsilon^2_{u_R}) + 138(\epsilon^2_{d_L} + \epsilon^2_{d_R})\right] \times \Gamma(\phi, g_1')_{Z' \to \ell\bar{\ell}} \text{ pb}$$

requires $\Gamma(\phi, g_1')_{Z' \to \ell\bar{\ell}}$ to be negligible

Counting degrees of freedom upper limit

orthogonality condition

$$\left(\frac{c_4}{g_4'}\right)^2 = \frac{1}{g_Y^2} - \left(\frac{c_3}{g_3'}\right)^2 - \left(\frac{c_1}{g_1'}\right)^2$$

$$\begin{aligned}
\epsilon_{u_L} = \epsilon_{d_L} &= \frac{2}{\sqrt{g_Y^2 + g_2^2}} (C_\psi S_\theta S_\psi - C_\phi S_\psi) g_3' \,, \\
\epsilon_{u_R} &= -\frac{2}{\sqrt{g_Y^2 + g_2^2}} [C_\theta S_\phi g_1' + (C_\psi S_\theta S_\psi - C_\phi S_\psi) g_3'] \,, \\
\epsilon_{d_R} &= \frac{2}{\sqrt{g_Y^2 + g_2^2}} [C_\theta S_\phi g_1' - (C_\psi S_\theta S_\psi - C_\phi S_\psi) g_3']
\end{aligned}$$

g_3' fixed by $U(N)$ unification relation $g_3 = g_3'/\sqrt{6}$

$g_3' \simeq 0.383$ for $5 \text{ TeV} < M_s < 10 \text{ TeV}$

Precision Electroweak Limits

- Additional mixing of Z and Y' through their coupling to two Higgs doublets

$$\langle H_u \rangle = \begin{pmatrix} 0 \\ v_u \end{pmatrix} \qquad Q_3 = Q_{1L} = 0, Q_{1R} = 1, Q_Y = 1/2$$

$$\langle H_d \rangle = \begin{pmatrix} v_d \\ 0 \end{pmatrix} \qquad Q_3 = Q_{1L} = 0, Q_{1R} = -1, Q_Y = -1/2$$

$$v = \sqrt{v_u^2 + v_d^2} = 172 \text{ GeV} \quad \& \quad \tan\beta \equiv v_u / v_d$$

- Covariant derivative $\mathcal{D}_\mu = \partial_\mu ... - i g_{Y'} Y_\mu{}' Q_{Y'} - i g_{Y''} Y_\mu{}'' Q_{Y''}$

is conveniently written as $-i \frac{x_{H_i}}{v_i} \overline{M}_Z Y'_\mu - i \frac{y_{H_i}}{v_i} \overline{M}_Z Y''_\mu$

for each H_i

$$x_{H_u} = -x_{H_d} = 1.9 \sqrt{g_1'^2 - 0.032}\, S_\phi$$

&

$$y_{H_u} = -y_{H_d} = 1.9 \sqrt{g_1'^2 - 0.032}\, C_\phi$$

Precision Electroweak Limits (cont'd)

- Higgs field kinetic term together with Green-Schwarz mass terms $\Rightarrow$ $-\frac{1}{2}M'^2 Y'_\mu Y'^\mu - \frac{1}{2}M''^2 Y''_\mu Y''^\mu$

yield following mass square matrix $\Downarrow$

$$\begin{pmatrix} \overline{M}_Z^2 & \overline{M}_Z^2(x_{H_u}C_\beta^2 - x_{H_d}S_\beta^2) & \overline{M}_Z^2(y_{H_u}C_\beta^2 - y_{H_d}S_\beta^2) \\ \overline{M}_Z^2(x_{H_u}C_\beta^2 - x_{H_d}S_\beta^2) & \overline{M}_Z^2(C_\beta^2 x_{H_u}^2 + S_\beta^2 x_{H_d}^2) + M'^2 & \overline{M}_Z^2(C_\beta^2 x_{H_u} y_{H_u} + S_\beta^2 x_{H_d} y_{H_d}) \\ \overline{M}_Z^2(y_{H_u}C_\beta^2 - y_{H_d}S_\beta^2) & \overline{M}_Z^2(C_\beta^2 x_{H_u} y_{H_u} + S_\beta^2 x_{H_d} y_{H_d}) & \overline{M}_Z^2(y_{H_u}^2 C_\beta^2 + y_{H_d}^2 S_\beta^2) + M''^2 \end{pmatrix}$$

with

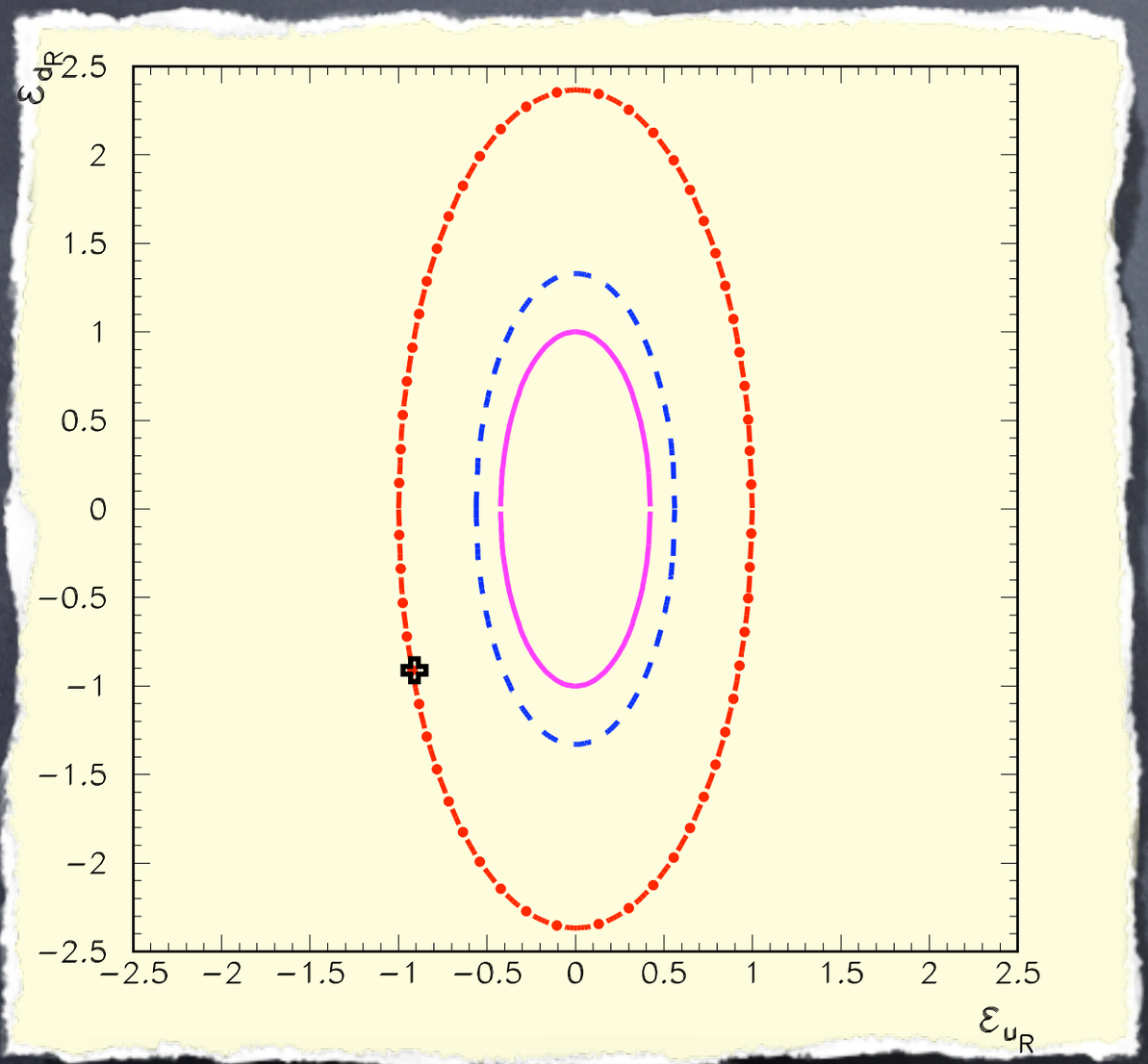
$$x_{H_u} = -x_{H_d} = -0.351$$

$$y_{H_u} = -y_{H_d} = 0.151$$

mass^2 matrix independent of $\tan\beta$

Best Eyeball Fit

Free parameters are fixed by requiring shift of Z mass to lies within 1σ of experimental value $+\Gamma_{Z''\to e^+e^-}/\Gamma_{Z''\to q\bar{q}} \lesssim 1\%$



Name	$g_{Y'}Q_{Y'}$	$g_{Y''}Q_{Y''}$
Q_i	0.368	−0.119
U_i	−0.368	0.028
D_i	−0.368	0.209
L_i	0.143	0.143
E_i	−0.142	−0.262
N_i	−0.143	−0.443

$M_{Z'} = 150 \pm 2\text{GeV}$ $\quad g_1' = 0.2$ $\quad \phi = 0.0028$ $\quad M_{Z''} > 5\text{TeV}$

Leptophobic Z' at the LHC

If CDF anomaly does not survive additional scrutiny

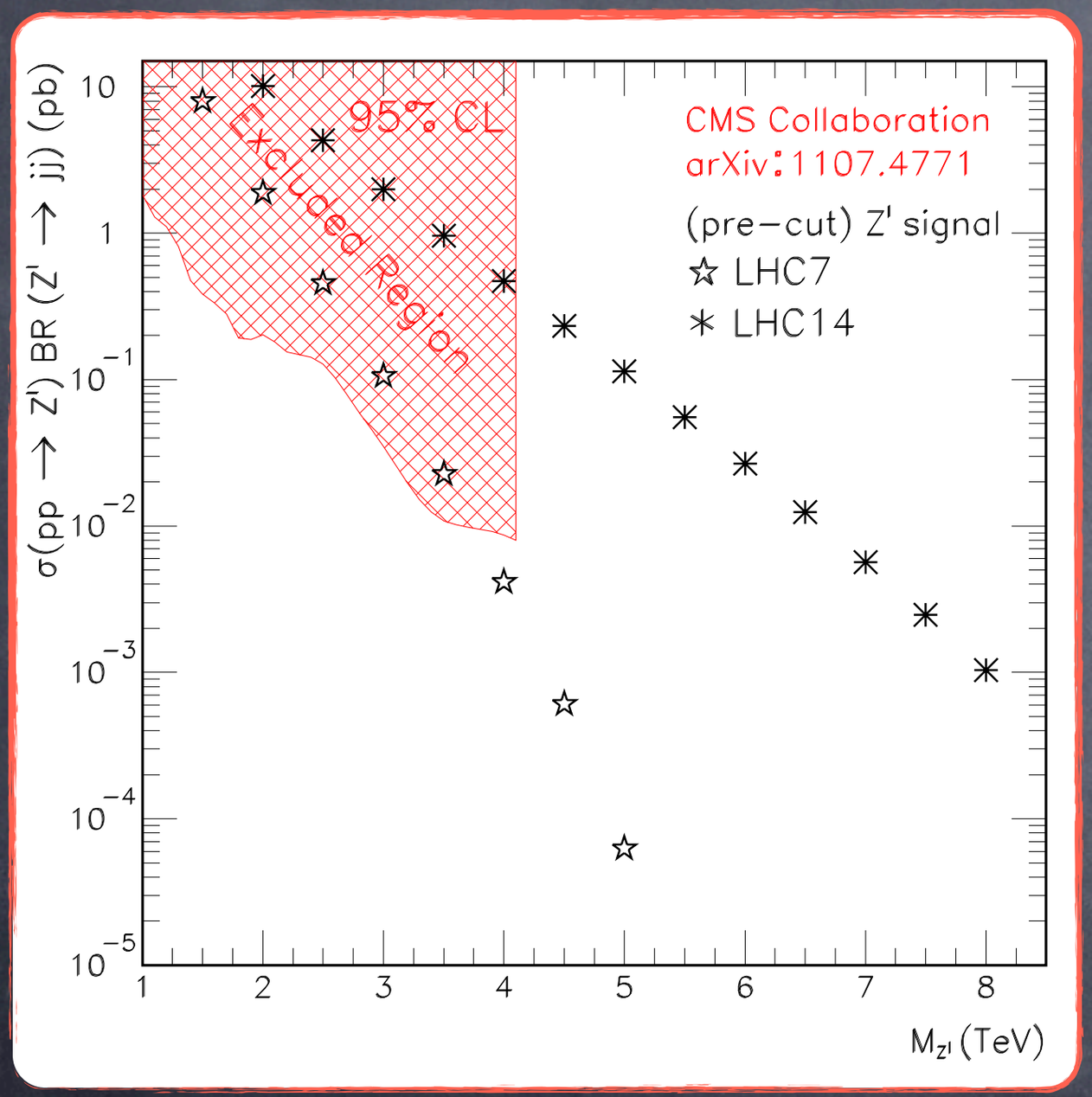
previous analysis can be directly applied to high energy realm

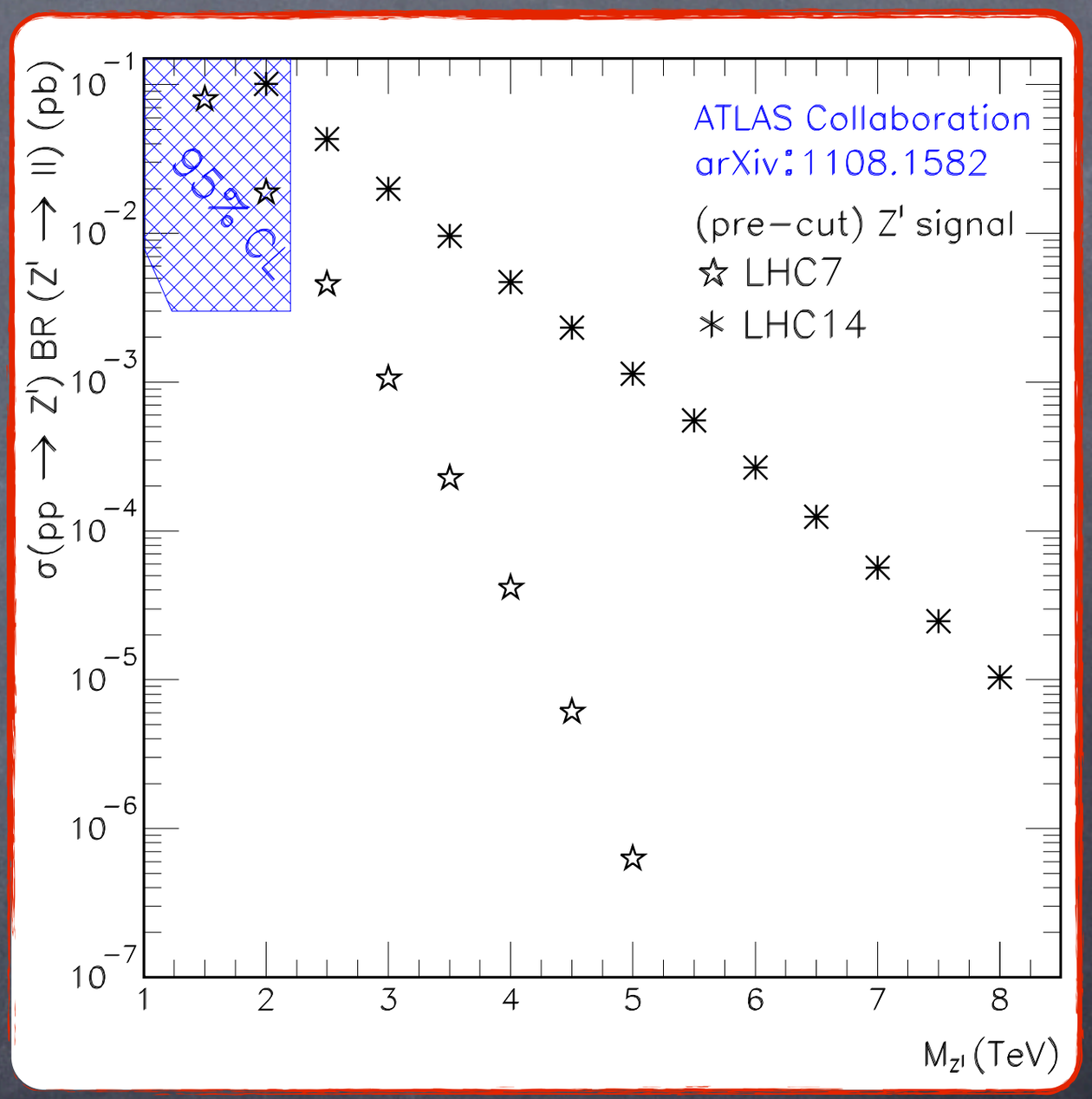
Duplicating calculation for LHC energies

$M_{Z'} \geq 1\mathrm{TeV}$ $\quad \mathrm{M}_{Z''} > 2\mathrm{M}_{Z'}$ $\quad \mathrm{g}_1' = 0.195$ $\quad \phi = 0.0638$

Name	$g_{Y'}Q_{Y'}$	$g_{Y''}Q_{Y''}$
Q_i	0.370	−0.112
U_i	−0.365	0.033
D_i	−0.375	0.190
L_i	0.154	0.154
E_i	−0.159	−0.338
N_i	−0.149	−0.495

Dijet & Dilepton Mass Spectra





LHC provides generous discovery potential for Z'

Model independence on color stack

- Particles created by vibrations of relativistic strings populate Regge trajectories relating their spins and masses

$$J = J_0 + \alpha' M^2 \quad \Rightarrow \quad \alpha' = M_s^{-2}$$

- Scattering on U(3) brane: involves quarks and gluons
  4-point functions $gg \to gg,\ q\bar{q} \to gg,\ qg \to qg$
  do not excite KK or winding modes only Regge recurrences
  independent of compactification
- Not so for $qq \to qq$ (KK/winding modes involved)

  Lüst, Stieberger, Taylor, NPB 808 (2009) 1

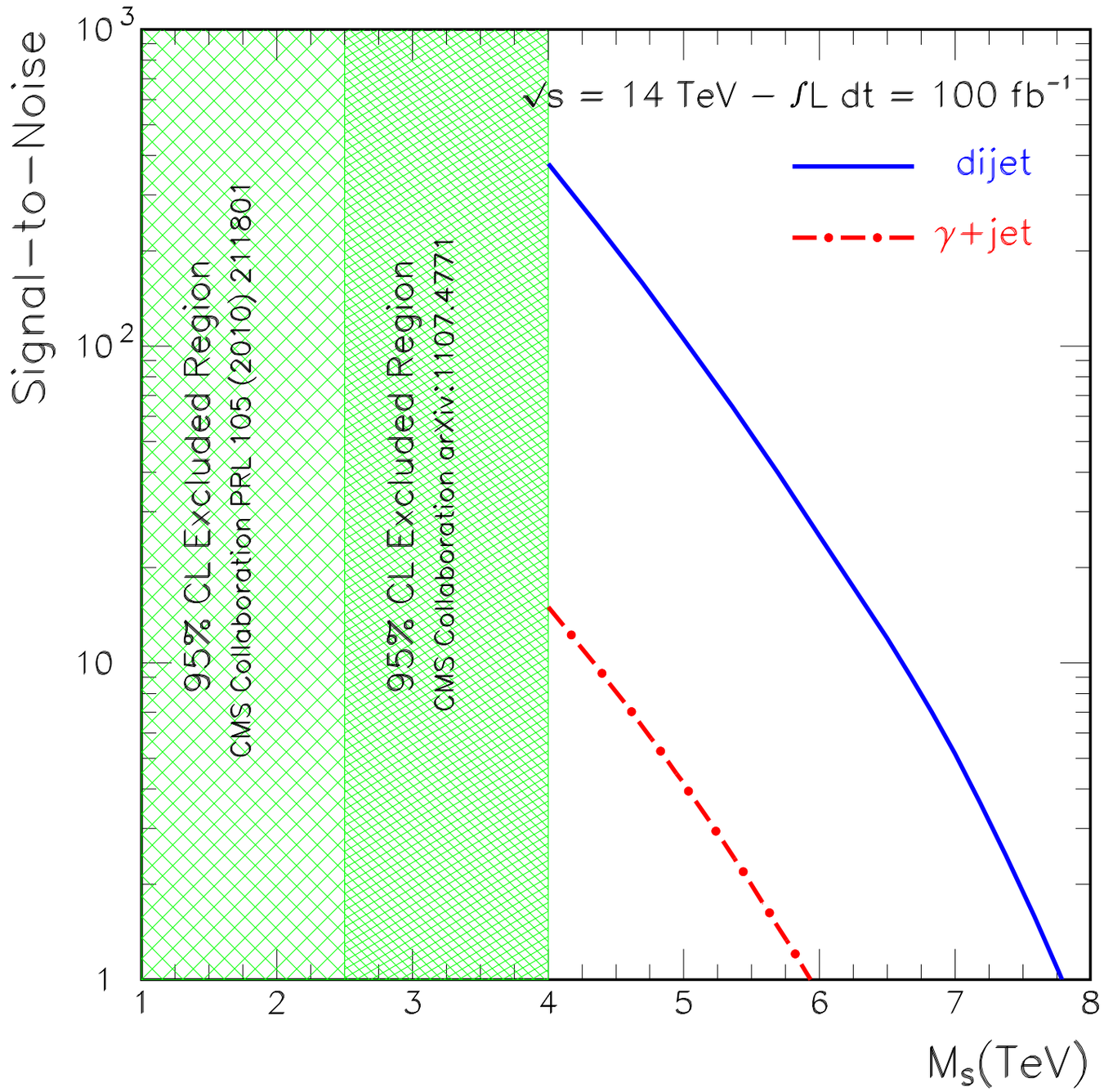
- Go to lowest massive resonant poles at $s = M_s^2$

  bosonic $g^*,\ C^*,\ J = 0,\ 2$

  fermionic $q^*,\ J = 1/2,\ 3/2$

- Soften to Breit-Wigner
  obtaining widths by factorizing amplitudes at the pole

Signal-to-Noise



summary of string-signal & QCD-background calculations

[arXiv:1108... tonight on hep-ph]

Conclusions

- We have considered a low-mass string compactification in which SM gauge multiplets originate in open strings ending on D-branes
- Model contains three $U(1)$ gauge bosons
- One linear combination is identified as hypercharge Y field
  ☛ coupled to anomaly free hypercharge current
- Two remaining linear combinations (Y', Y'') grow masses
- After electroweak breaking ➡ mixing with third isospin component results in three observable gauge bosons
  ☛ where with small mixing $Z' \simeq Y', Z'' \simeq Y''$
- For a fixed $M_{Z'}$ ☛ model contains two free parameters -a single mixing angle and a gauge coupling constant unconstrained by data- which are chosen to explain CDF excess
- Sizeable cross sections for lowest massive Regge recurrences allow LHC14 discovery at 5σ for string scales as high as $M_s = 6.8\,\mathrm{TeV}$ with $100\,\mathrm{fb}^{-1}$ -- dijet topology --
- γ + jet can provide corroboration for TeV-scale string physics