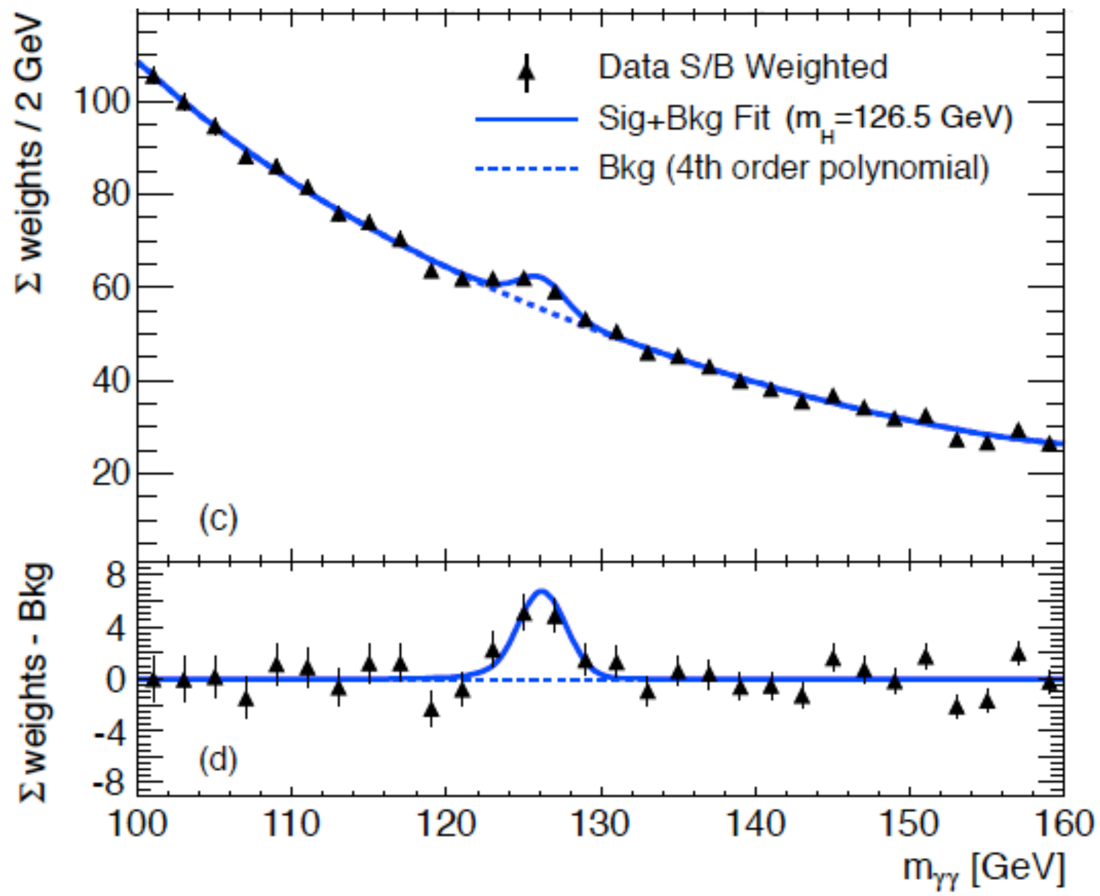
Vector Boson Signals of Electroweak Symmetry Breaking

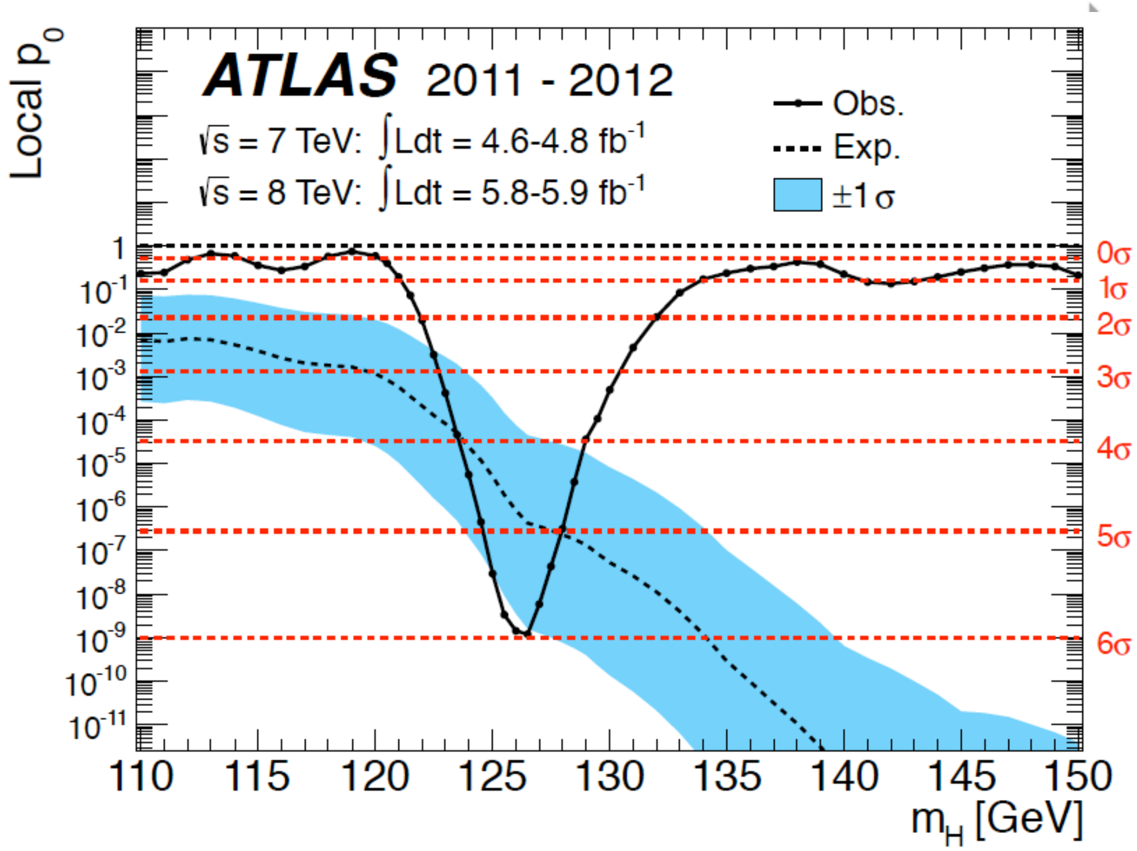
R. Sekhar Chivukula
Michigan State University
December 5, 2012

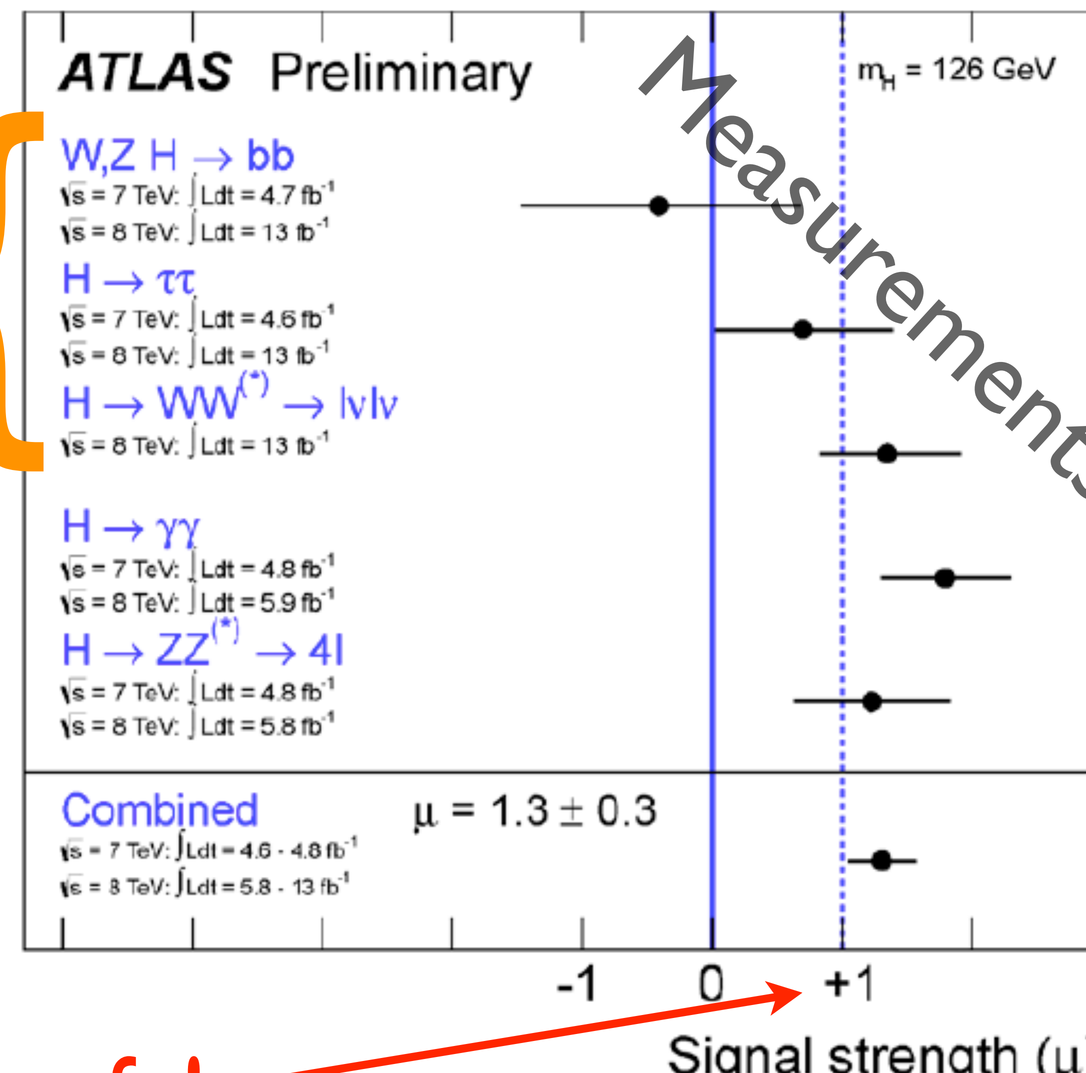
SCGT 12
KMI-GCOE Workshop on Strong Coupling Gauge Theories in the LHC Perspective

A New Boson

ATLAS







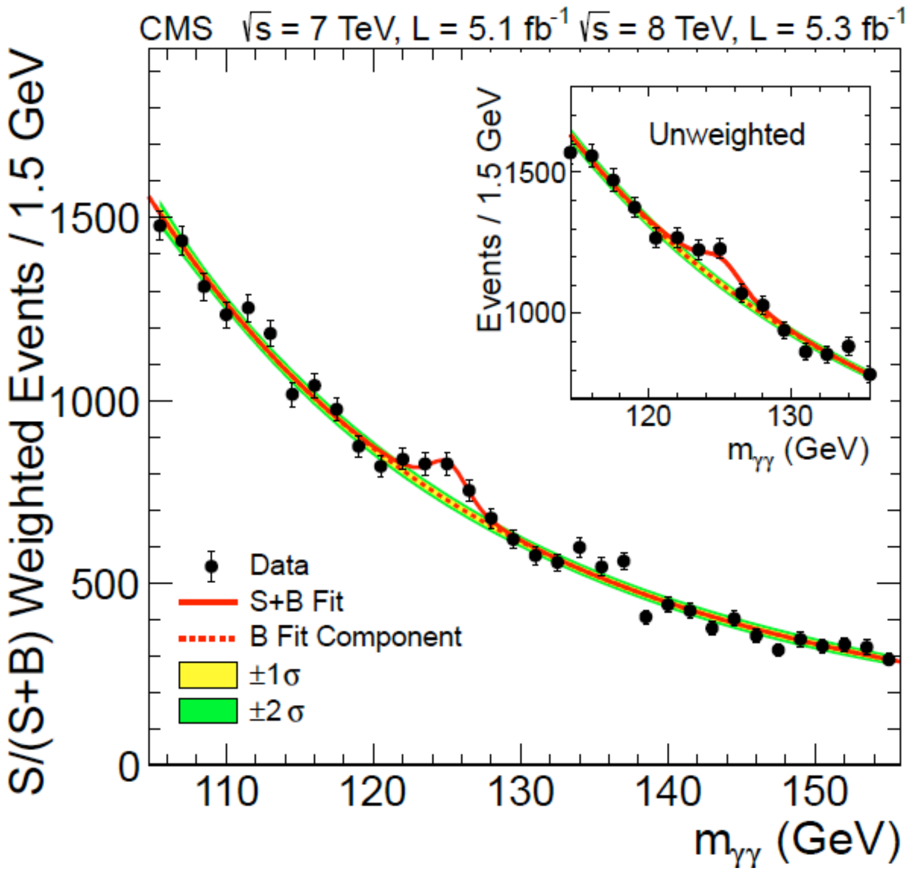
Measurements of f_σ

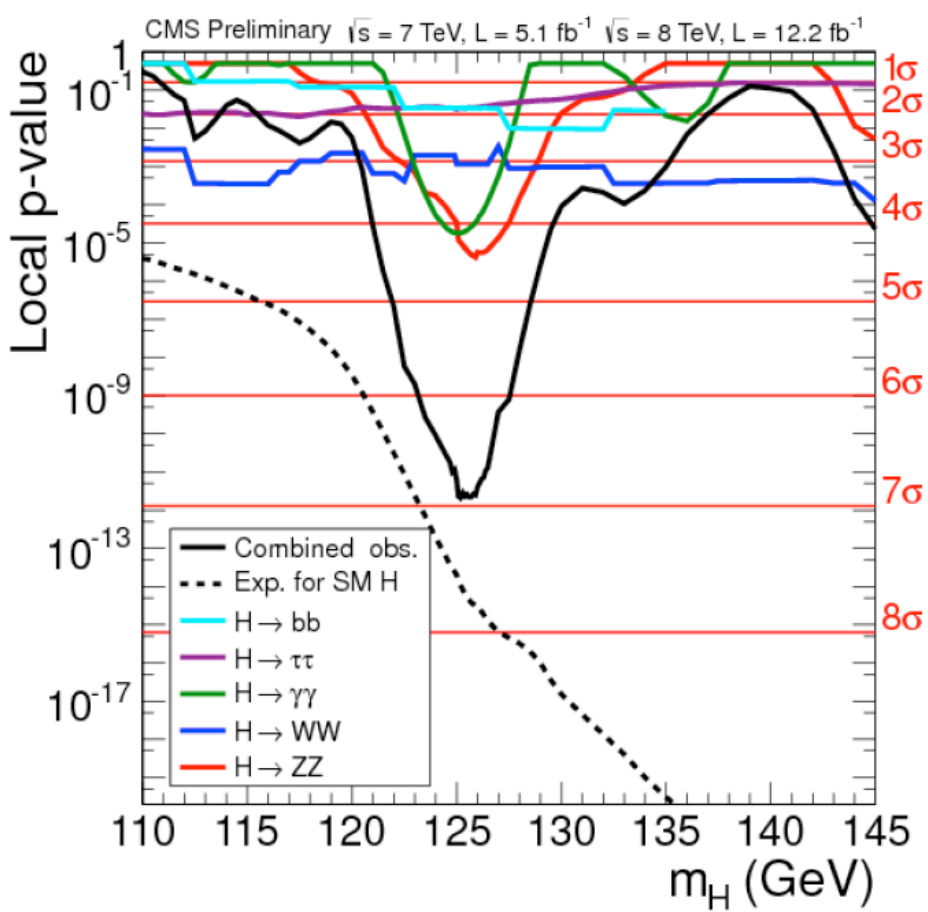
$f_\pi = f_\sigma$!

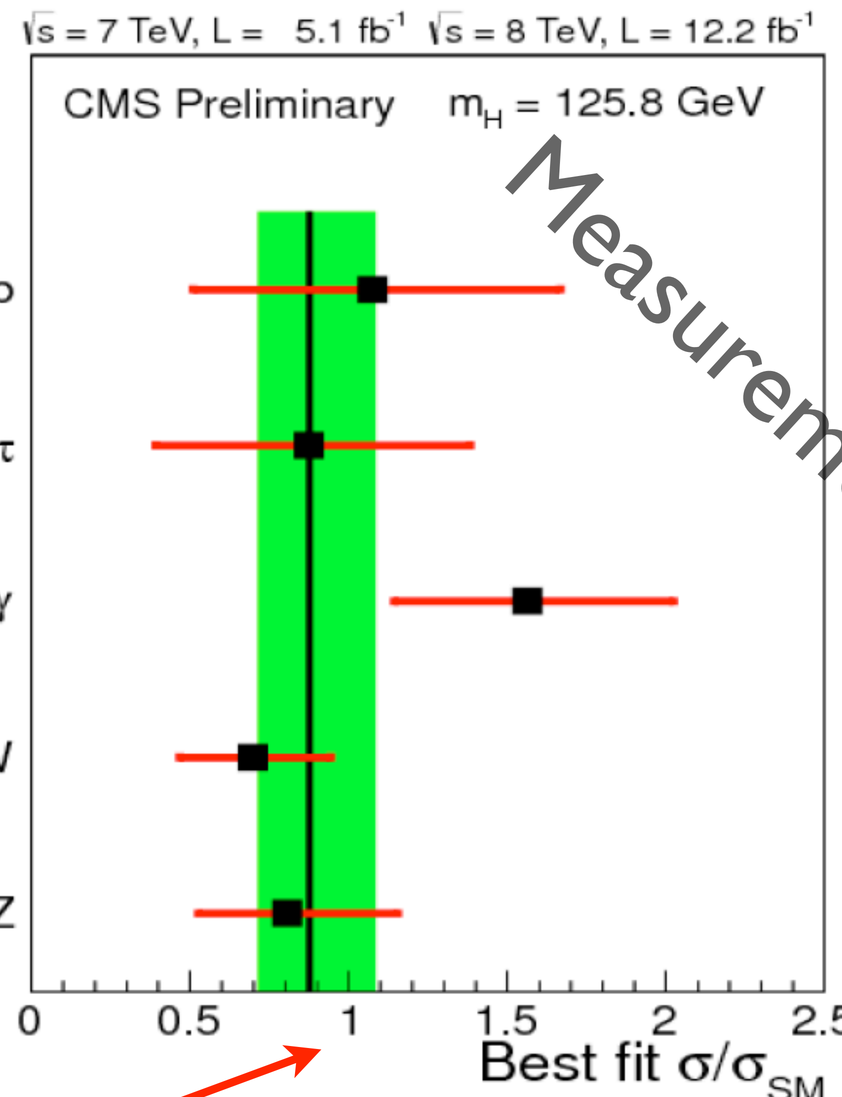
$M_W \rightarrow f_\pi$

HCP2012
ATLAS-CONF-2012-162

CMS







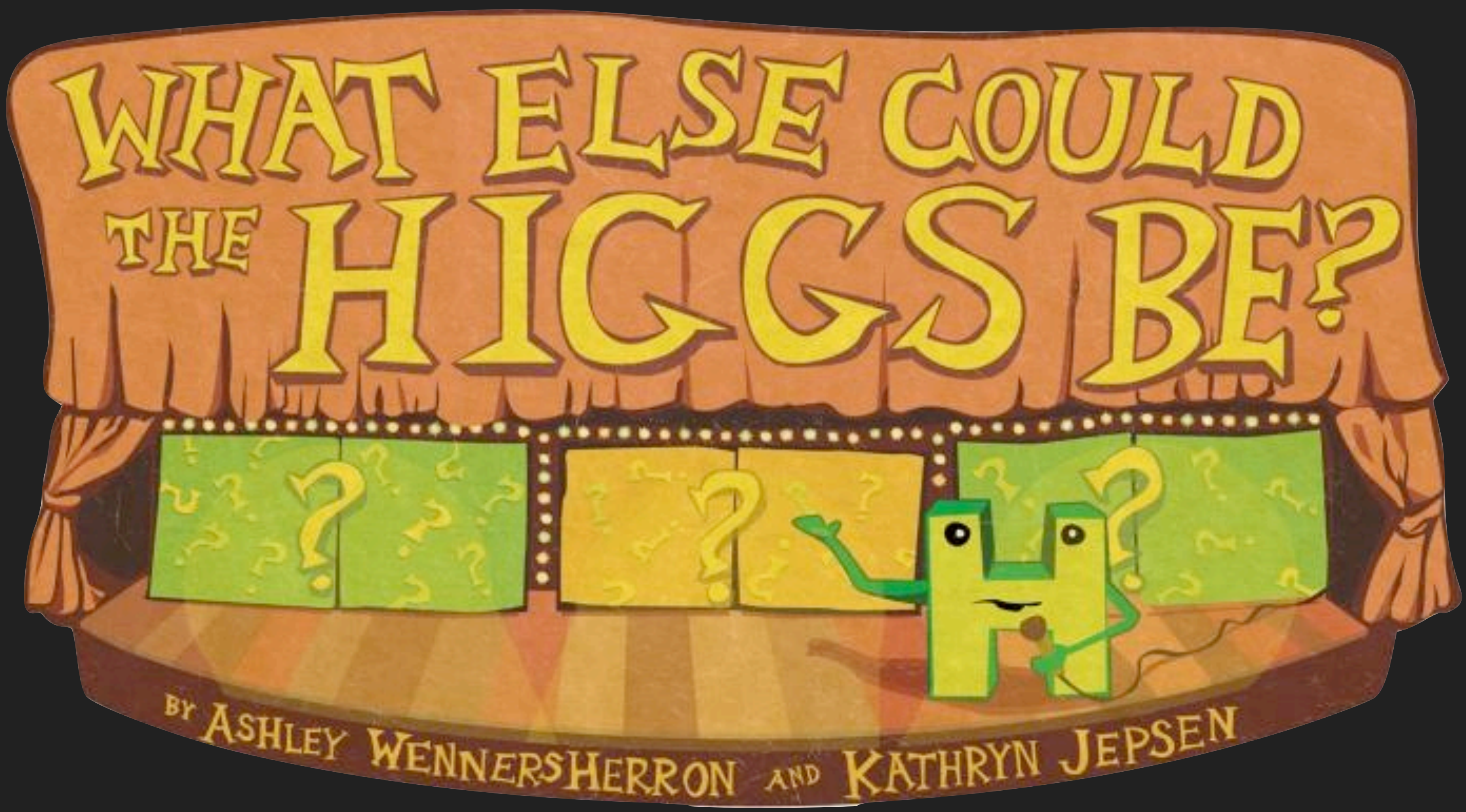
Measurements of f_σ

$f_\pi = f_\sigma$!

$M_W \rightarrow f_\pi$

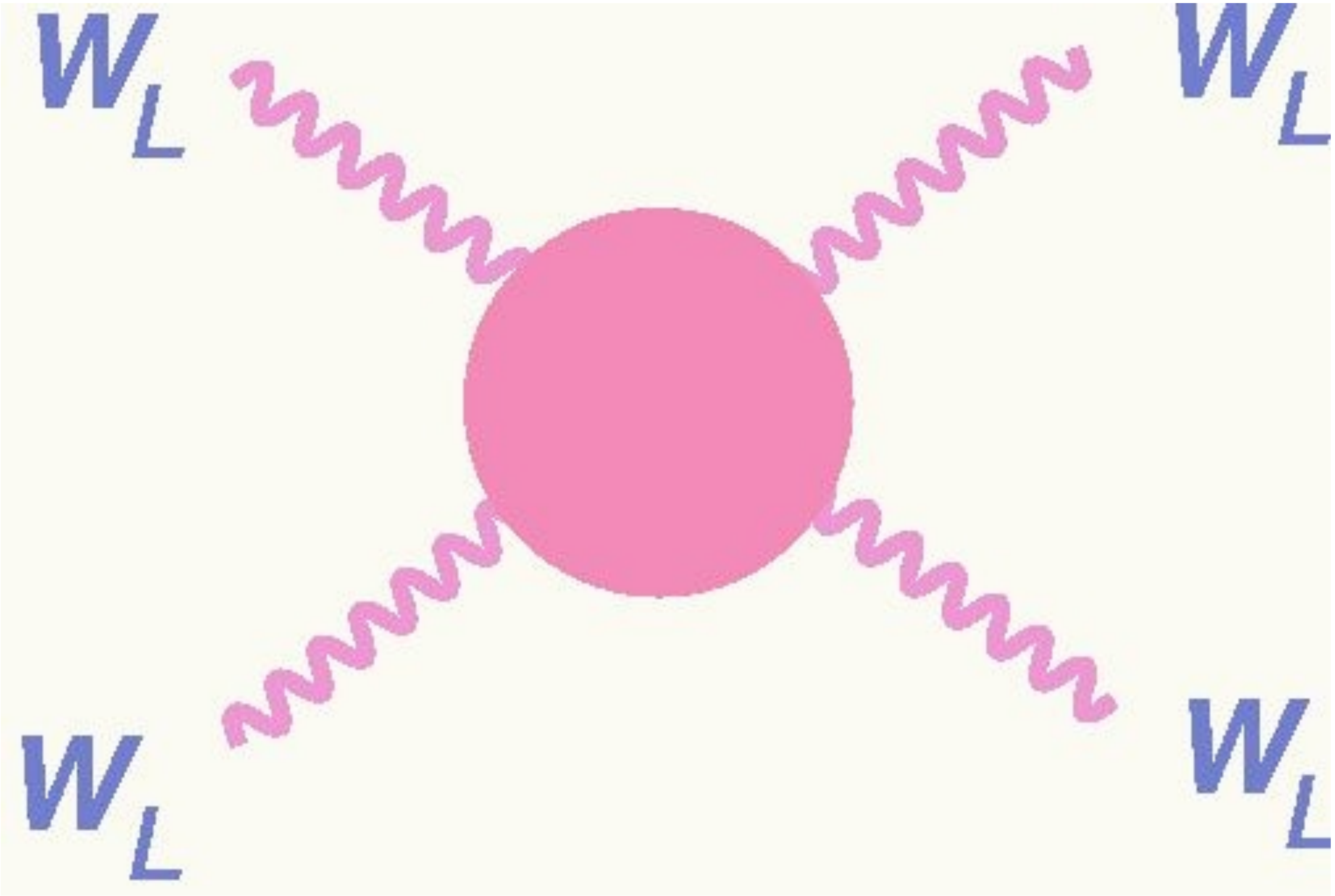
Paus, HCP2012

Is the New Boson THE HIGGS Boson?

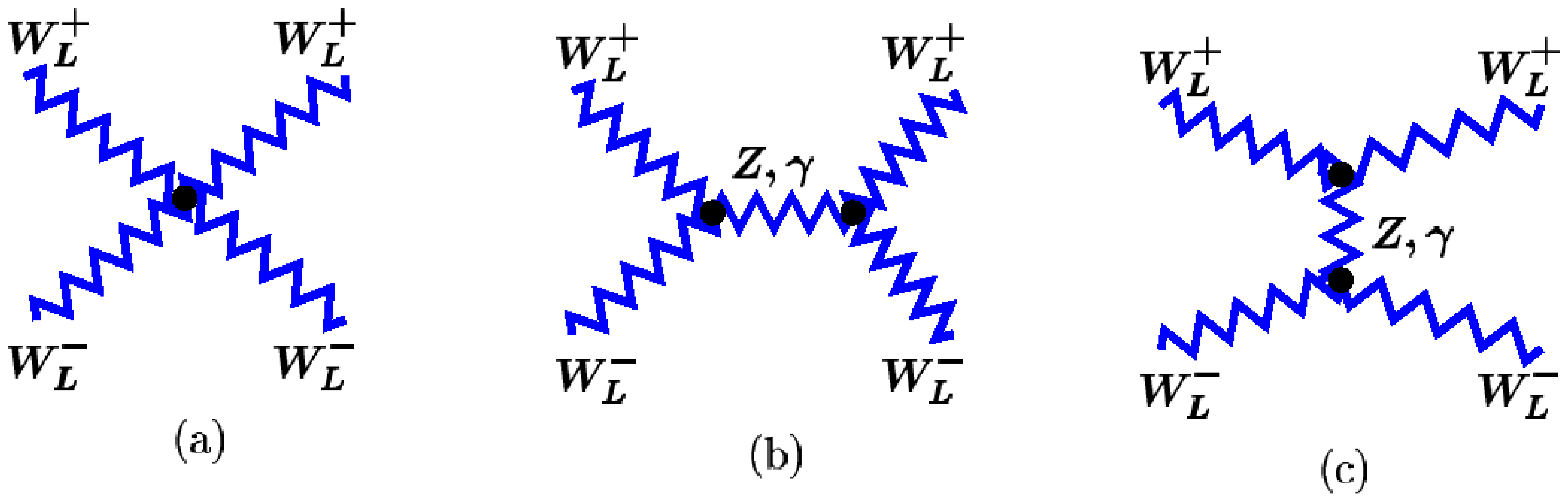


Symmetry Magazine, Oct 30, 2012

Loss of Unitarity in



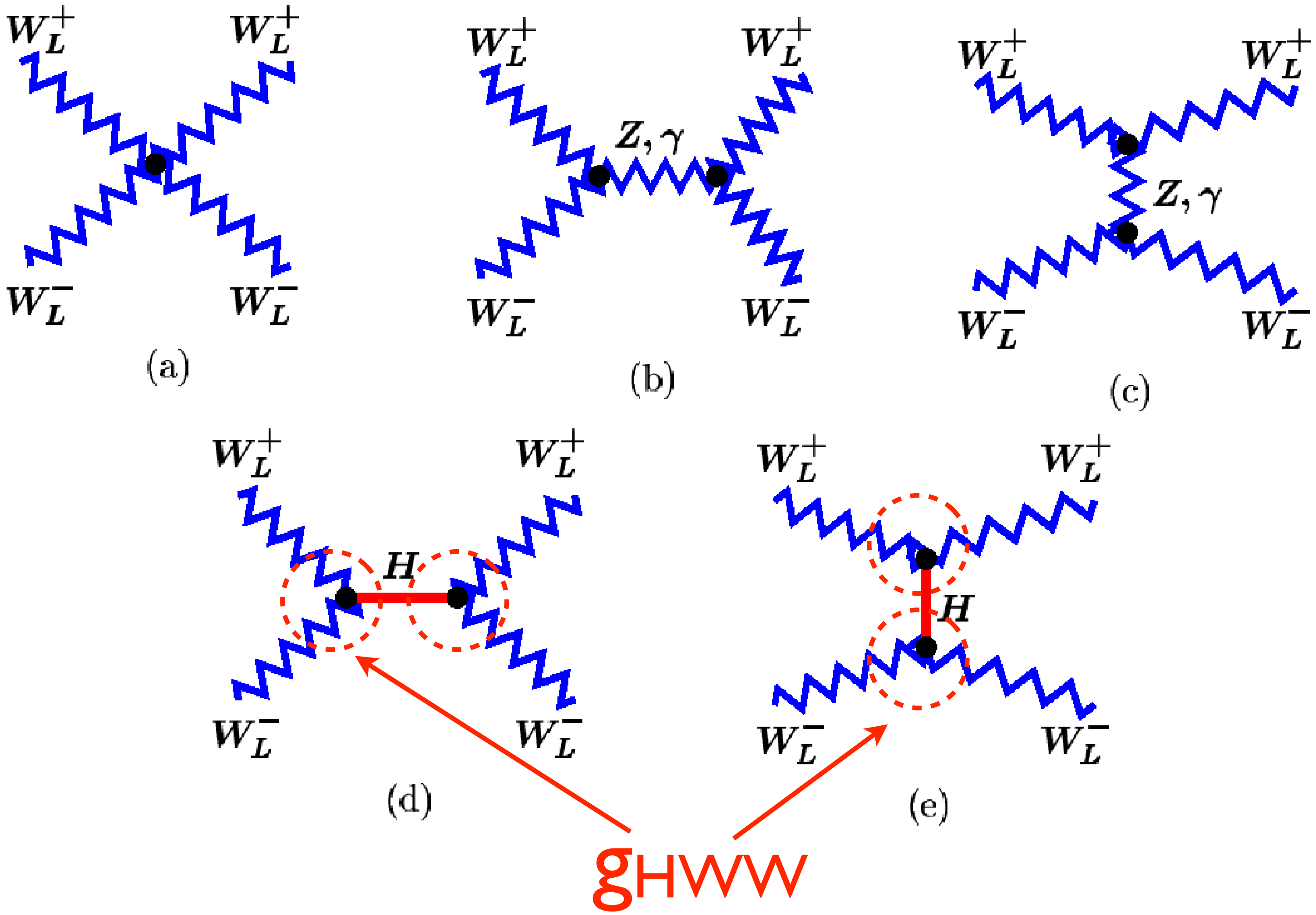
SU(2) x U(1) @ E^4



Graphs	$g^2\frac{E^4}{m_w^4}$
(a)	$-3+6\cos\theta+\cos^2\theta$
(b)	$-4\cos\theta$
(c)	$+3-2\cos\theta-\cos^2\theta$
Sum	0

$$\epsilon_L^\mu(k) = \frac{k^\mu}{m_w} + \mathcal{O}\left(\frac{m_w}{E}\right)$$

SU(2) x U(1) @ E² & The Higgs



Graphs	$g^2 \frac{E^2}{m_w^2}$
(a)	$+2 - 6\cos\theta$
(b)	$-\cos\theta$
(c)	$-\frac{3}{2} + \frac{15}{2}\cos\theta$
(d + e)	$-\frac{1}{2} - \frac{1}{2}\cos\theta$
Sum including (d+e)	**0**

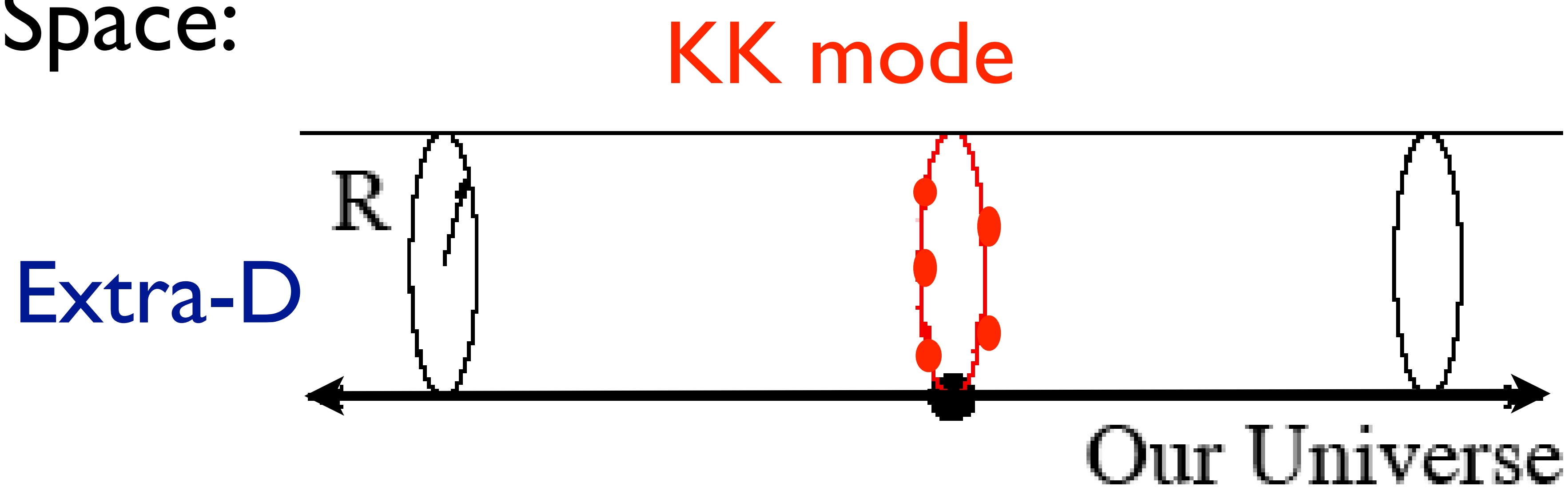
- $\mathcal{O}(E^0) \Rightarrow$ 4d m_H bound: $m_H < \sqrt{16\pi/3}\, v \simeq 1.0$ TeV
- If no Higgs $\Rightarrow \mathcal{O}(E^2) \Rightarrow \; E < \sqrt{4\pi}\, v \simeq 0.9$ TeV

Lee, Quigg, Thacker

Alternatives?
“Higgsless” Models

Massive Vector Bosons from 5-D

Flat Space:



Expand 5-D gauge bosons in eigenmodes: e.g. for S^1/Z_2:

$$\hat{A}^a_\mu = \frac{1}{\sqrt{\pi R}}\left[A^{a0}_\mu(x_\nu) + \sqrt{2}\sum_{n=1}^{\infty} A^{an}_\mu(x_\nu)\cos\left(\frac{n x_5}{R}\right)\right]$$

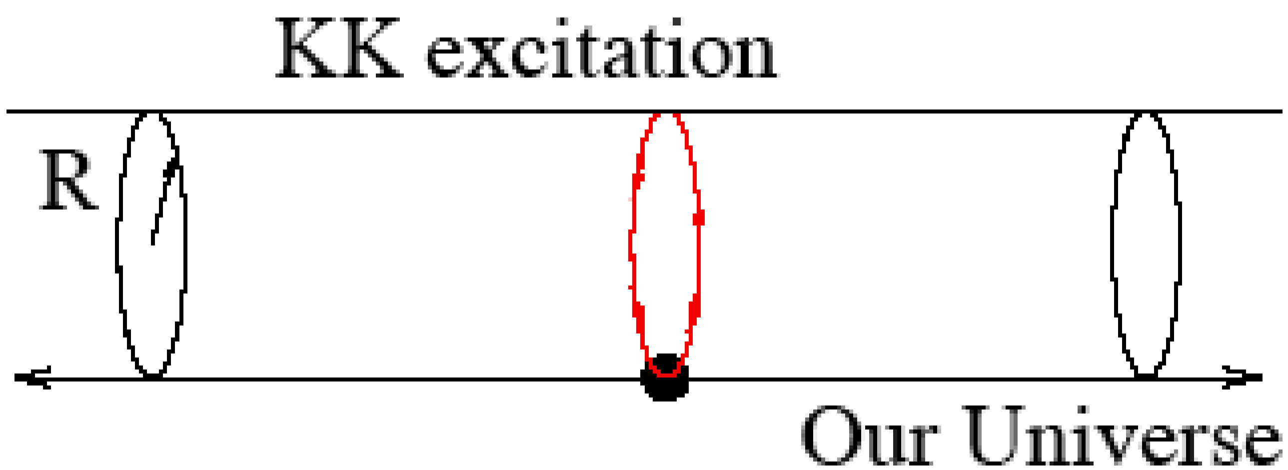
$$\hat{A}^a_5 = \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty} A^{an}_5(x_\nu)\sin\left(\frac{n x_5}{R}\right)$$

4-D gauge kinetic term contains $\quad M_n = \frac{n}{R}$

$$\frac{1}{2}\sum_{n=1}^{\infty}\left[M_n^2 (A^{an}_\mu)^2 - 2 M_n A^{an}_\mu \partial^\mu A^{an}_5 + (\partial_\mu A^{an}_5)^2\right]$$

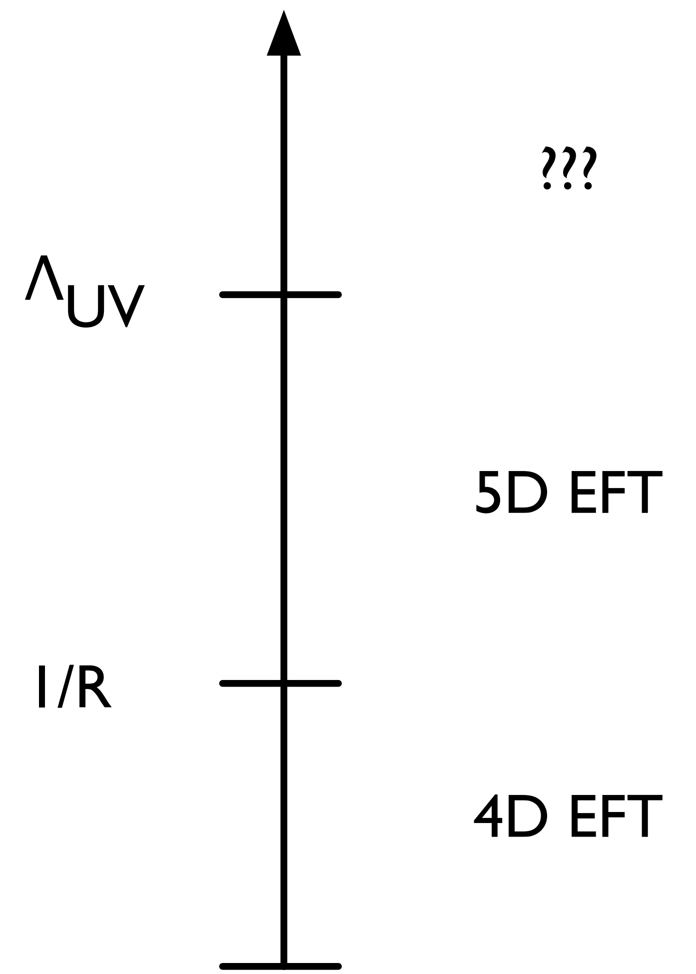
i.e., $A^{an}_L \leftrightarrow A^{an}_5$

Energy Scales and Couplings



$$\hat{A}^a_\mu = \frac{1}{\sqrt{\pi R}}\left[A^{a0}_\mu(x_\nu) + \sqrt{2}\sum_{n=1}^{\infty} A^{an}_\mu(x_\nu)\cos\left(\frac{n x_5}{R}\right)\right]$$

$$\hat{A}^a_5 = \sqrt{\frac{2}{\pi R}}\sum_{n=1}^{\infty} A^{an}_5(x_\nu)\sin\left(\frac{n x_5}{R}\right)$$

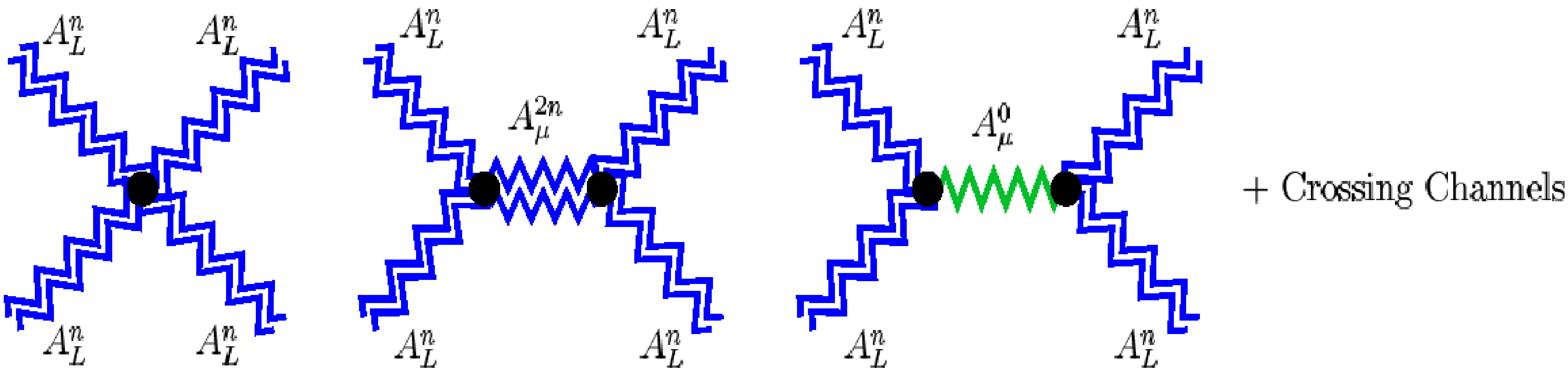


$$g_4 = \frac{g_5}{\sqrt{\pi R}}$$

$$M_n = \frac{n}{R}$$

$$\Lambda_{UV} \propto \frac{1}{g_5^2}$$

4-D KK Mode Scattering



(a) $(b1)$ $(c1)$ $(b2, b3)+(c2, c3)$

graph	$g^2 C^{eab} C^{ecd}$	$g^2 C^{eac} C^{edb}$	$g^2 C^{ead} C^{ebc}$
(a)	$6c(x^4-x^2)$	$\frac{3}{2}(3-2c-c^2)x^4$ $-3(1-c)x^2$	$\frac{-3}{2}(3+2c-c^2)x^4$ $+3(1+c)x^2$
$(b1)$	$-2c(x^4+x^2)$		
$(c1)$	$-4cx^4$		
$(b2,3)$		$\frac{-1}{2}(3-2c+c^2)x^4$ $+3(1-c)x^2$	$\frac{1}{2}(3+2c-c^2)x^4$ $-3(1+c)x^2$
$(c2,3)$		$(-3+2c+c^2)x^4$ $-8cx^2$	$(3+2c-c^2)x^4$ $-8cx^2$
Sum	$-8cx^2$	$-8cx^2$	$-8cx^2 \Rightarrow \mathbf{0}$

Cancellation of bad high-energy behavior through exchange of massive vector particles

RSC, H.J. He, D. Dicus (2002)
Csaki, Grojean, Murayama, Pilo, Terning (2004)

General Principles

Higgsless models are low-energy effective theories of Dynamical Electroweak Symmetry Breaking with. They include:

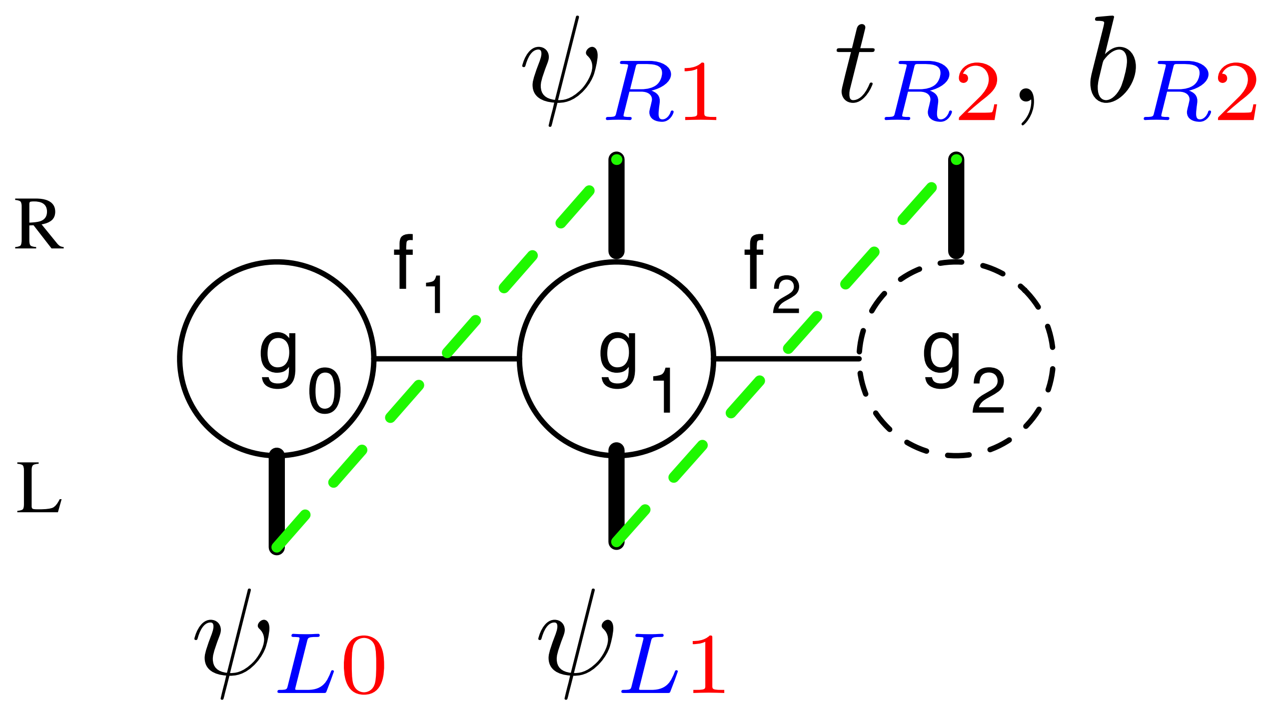
- massive 4-d gauge bosons arise in the context of a 5-d gauge theory with appropriate boundary conditions
- WW scattering is unitarized through exchange of KK modes (instead of scalar bosons)
- the language of Deconstruction allows a 4-d "Moose" representation of the model

Chivukula & He hep-ph/0201164
Csaki, Grojean, Murayama, Pilo, Terning hep-ph/0305237

A Simple Realizaton:
The Three-Site Model

3-Site Model: Basic Structure

$SU(2) \times SU(2) \times U(1)$ $\qquad$ $g_0,\ g_2 \ll g_1$



Gauge boson spectrum: photon, Z, Z', W, W' (as in BESS)

Fermion spectrum: t, T, b, B (ψ is an SU(2) doublet)

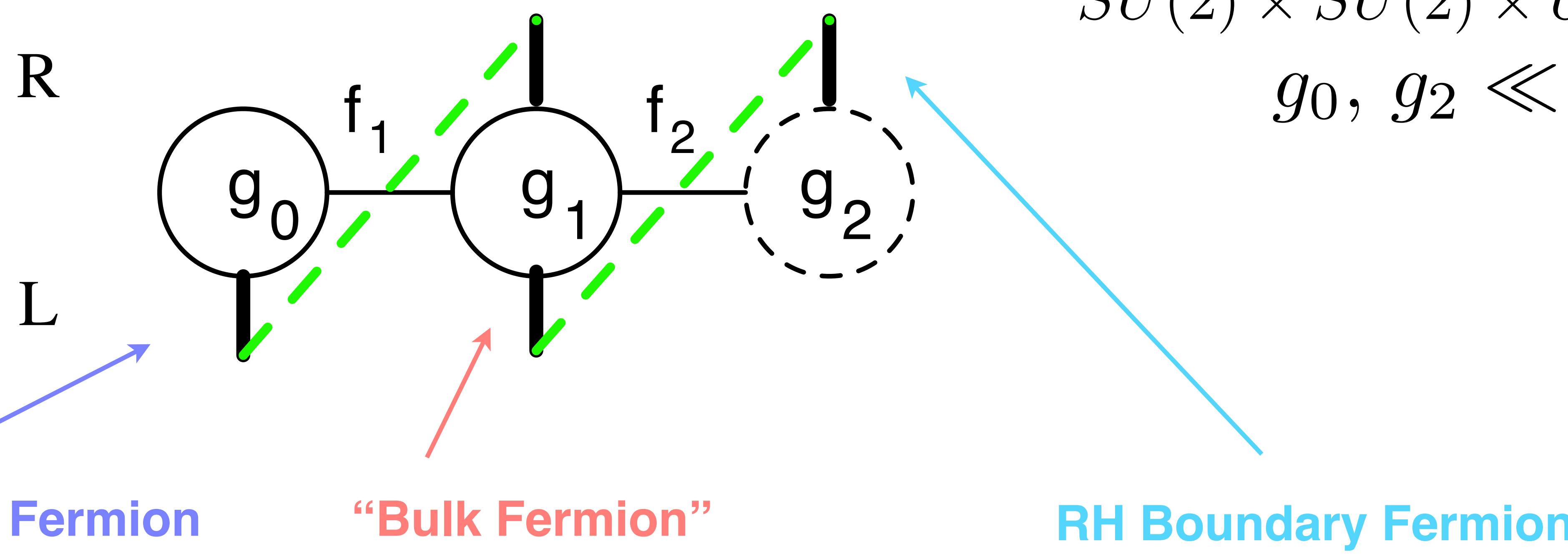
and also c,C, s,S, u,U, d,D plus the leptons

RSC, Coleppa, DiChiara, He, Kurachi, EHS, Tanabashi hep-ph/0607124

3-Site Fermion masses

$SU(2) \times SU(2) \times U(1)$

$g_0,\ g_2 \ll g_1$



$$M \left[\epsilon_L \bar{\psi}_{L0} \Sigma_{01} \psi_{R1} + \bar{\psi}_{R1}\psi_{L1} + \bar{\psi}_{L1}\Sigma_{12} \begin{pmatrix} \epsilon_{uR} & 0 \\ 0 & \epsilon_{dR} \end{pmatrix} \begin{pmatrix} u_{R2} \\ d_{R2} \end{pmatrix} \right]$$

degree of delocalization

<u>ordinary fermion masses</u> are of the form $m_f \approx M \epsilon_L \epsilon_{fR}$

each ordinary fermion mass value is tied to ϵ_{fR}

flavor structure same as in standard model

<u>heavy "KK" fermion masses</u> are ~ M

3-Site Ideal Delocalization

General ideal delocalization condition $g_i(\psi_i^f)^2 = g_W v_i^w$

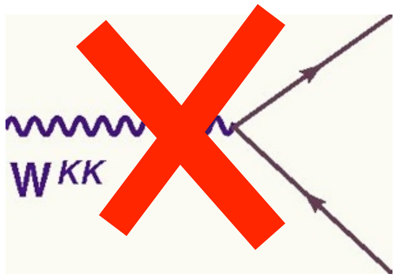
is realized as $\frac{g_0(\psi_{L0}^f)^2}{g_1(\psi_{L1}^f)^2} = \frac{v_W^0}{v_W^1}$ in 3-site model

From the W, fermion eigenvectors, one solves for

$$\epsilon_L^2 \to (1+\epsilon_{fR}^2)^2 \left[\frac{x^2}{2} + \left(\frac{1}{8} - \frac{\epsilon_{fR}^2}{2}\right)x^4 + \cdots\right] \qquad x^2 \equiv \left(\frac{g_0}{g_1}\right)^2 \approx 4\left(\frac{M_W}{M'_W}\right)^2$$

For all but top quark, $\epsilon_{fR} \ll 1$ so the choice $\epsilon_L^2 \approx 2\left(\frac{M_W^2}{M_{W'}^2}\right)$

makes W' fermiophobic and Z' nearly so



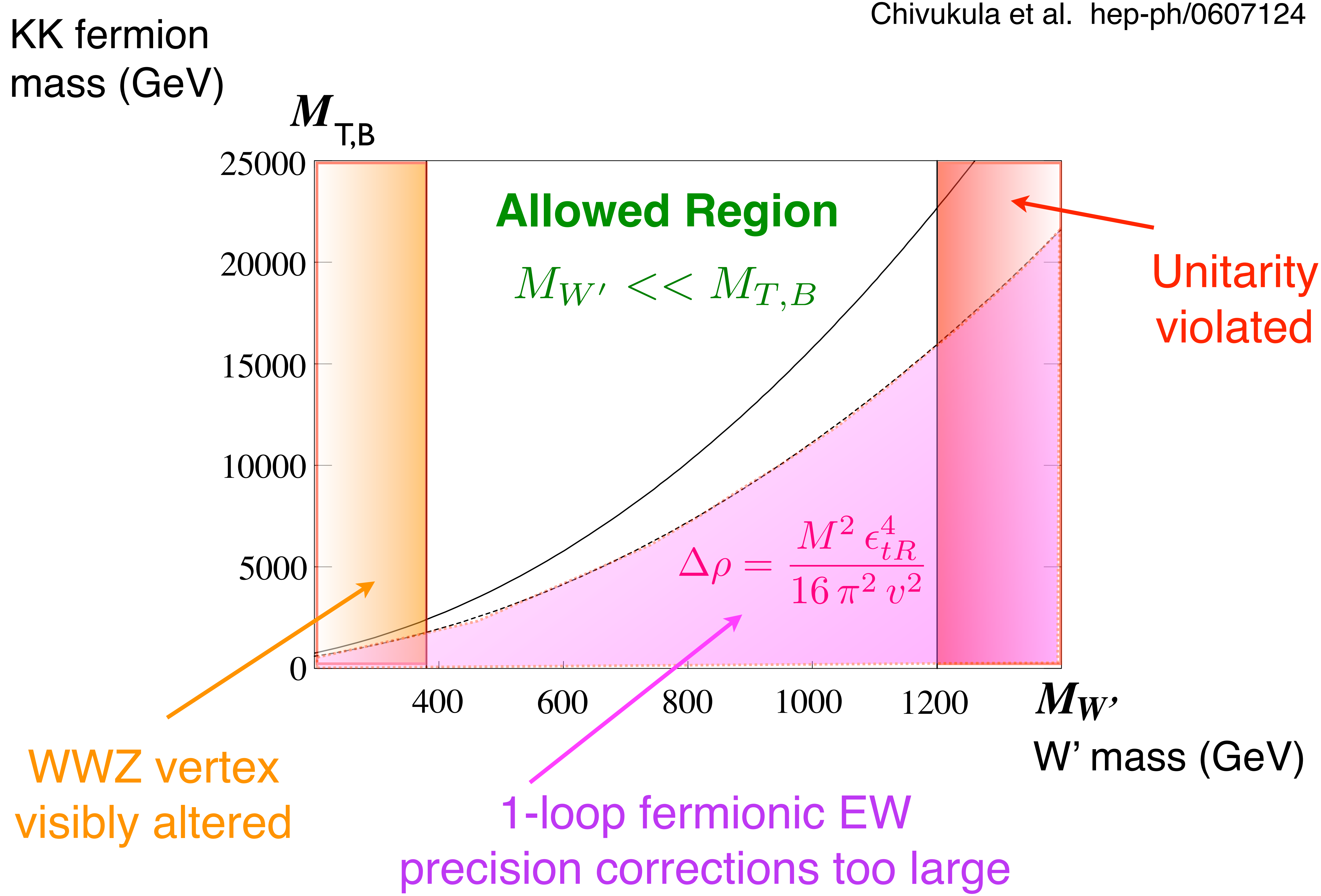
$$\hat{S} = \hat{T} = W = 0$$

$$Y = M_W^2(\Sigma_W - \Sigma_Z)$$

Use WW scattering to see W': Birkedal, Matchev, Perelstein hep-ph/0412278

3-Site Parameter Space

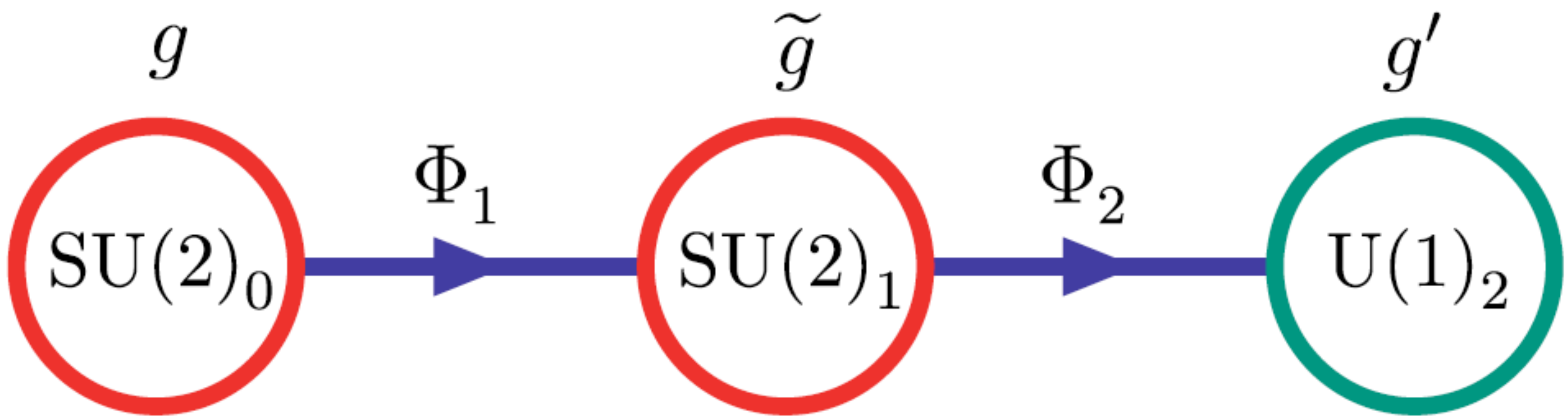
Chivukula et al. hep-ph/0607124



But What About the New Boson?

Hong-Jian He, Ning Chen, Tomohiro Abe: Arxiv 1207.4103

Linear 3-Site Model

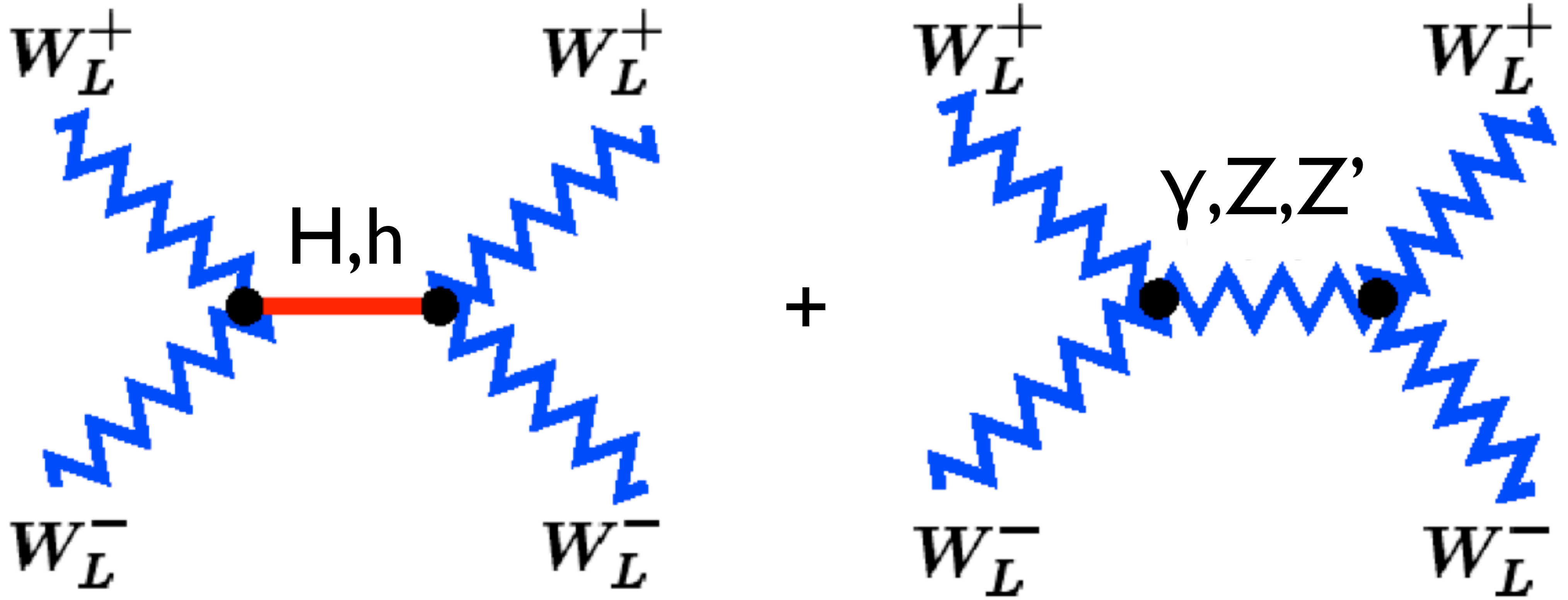


Linear Scalar Link Fields: ϕ_1 & ϕ_2

Leads to two-Higgs particles: h, H

He, Chen, Abe: arxiv 1207.4103

WW Unitarization



Unitarize *jointly* by scalar and vector exchange!
Leads to sum rule:

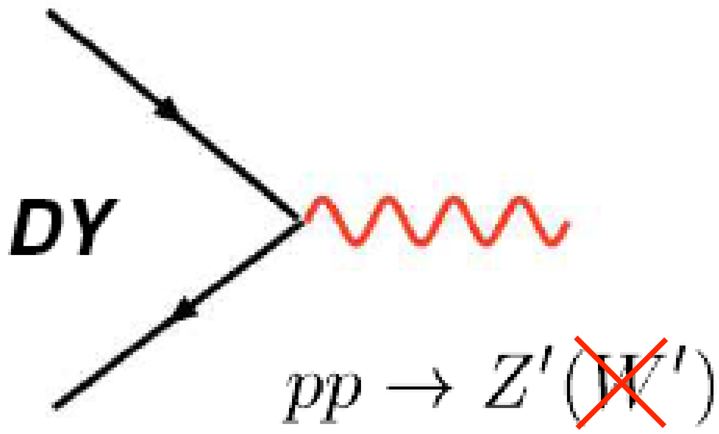
$$G_{4W_0} - \frac{3M_{Z_0}^2}{4M_{W_0}^2} G_{W_0W_0Z_0}^2 = \sum_k \frac{3M_{Z_k}^2}{4M_{W_0}^2} G_{W_0W_0Z_k}^2 + \sum_k \frac{G_{W_0W_0h_k}^2}{4M_{W_0}^2}$$

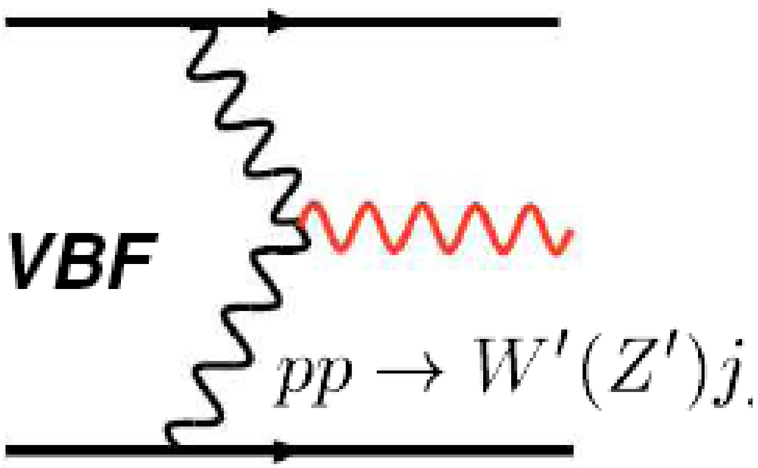
See next talk...

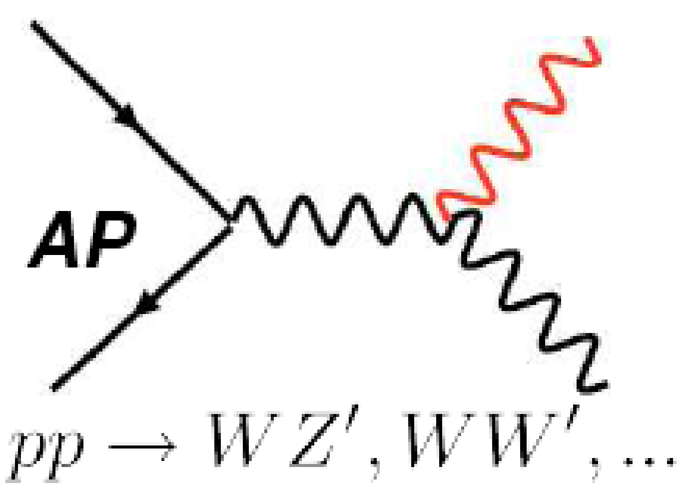
LHC Phenomenology of Vector Bosons

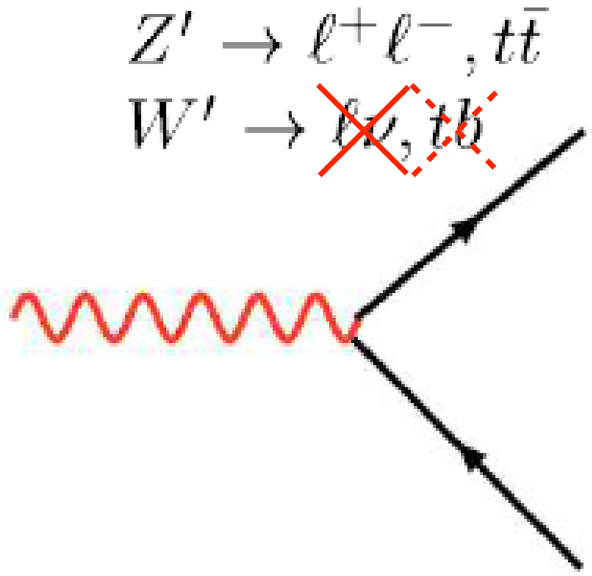
RSC, EHS, H.-J. He, Y.-P. Kuang, et. al., Phys. Rev. D78 (2008) 031701
& arxiv:1206.6022 and PRD in press

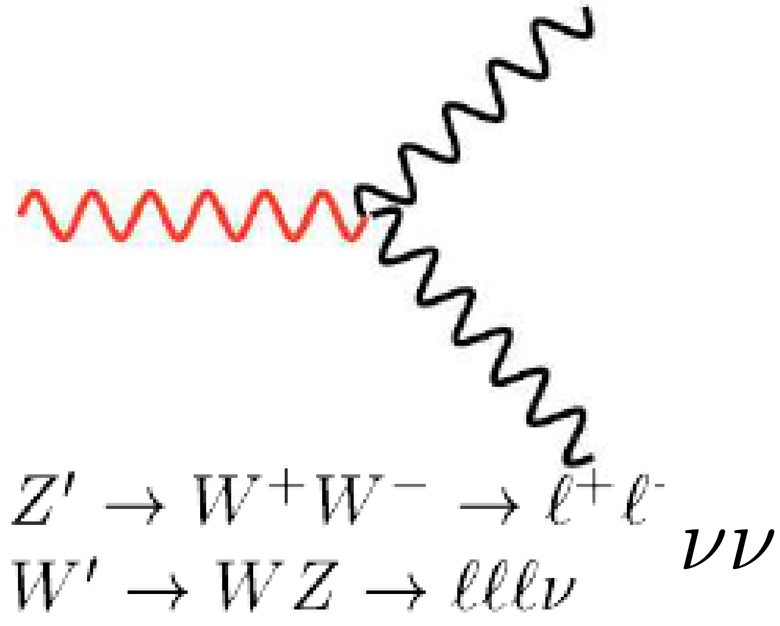
W',Z' Production and Decay at LHC







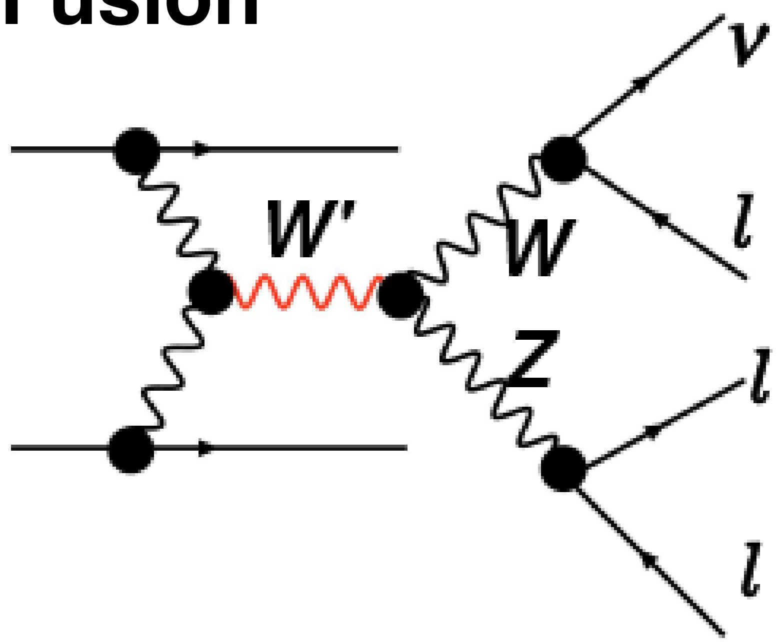




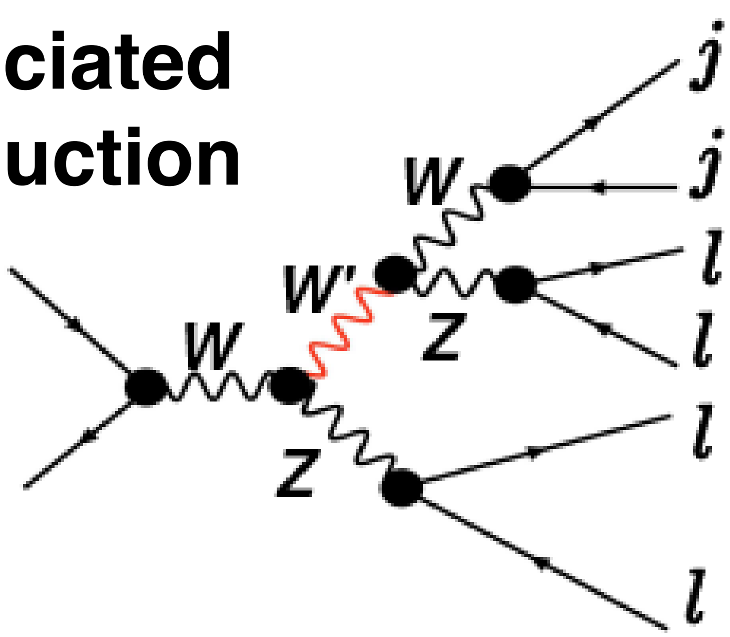
W' production at LHC

Two processes with large rates and clear signatures!

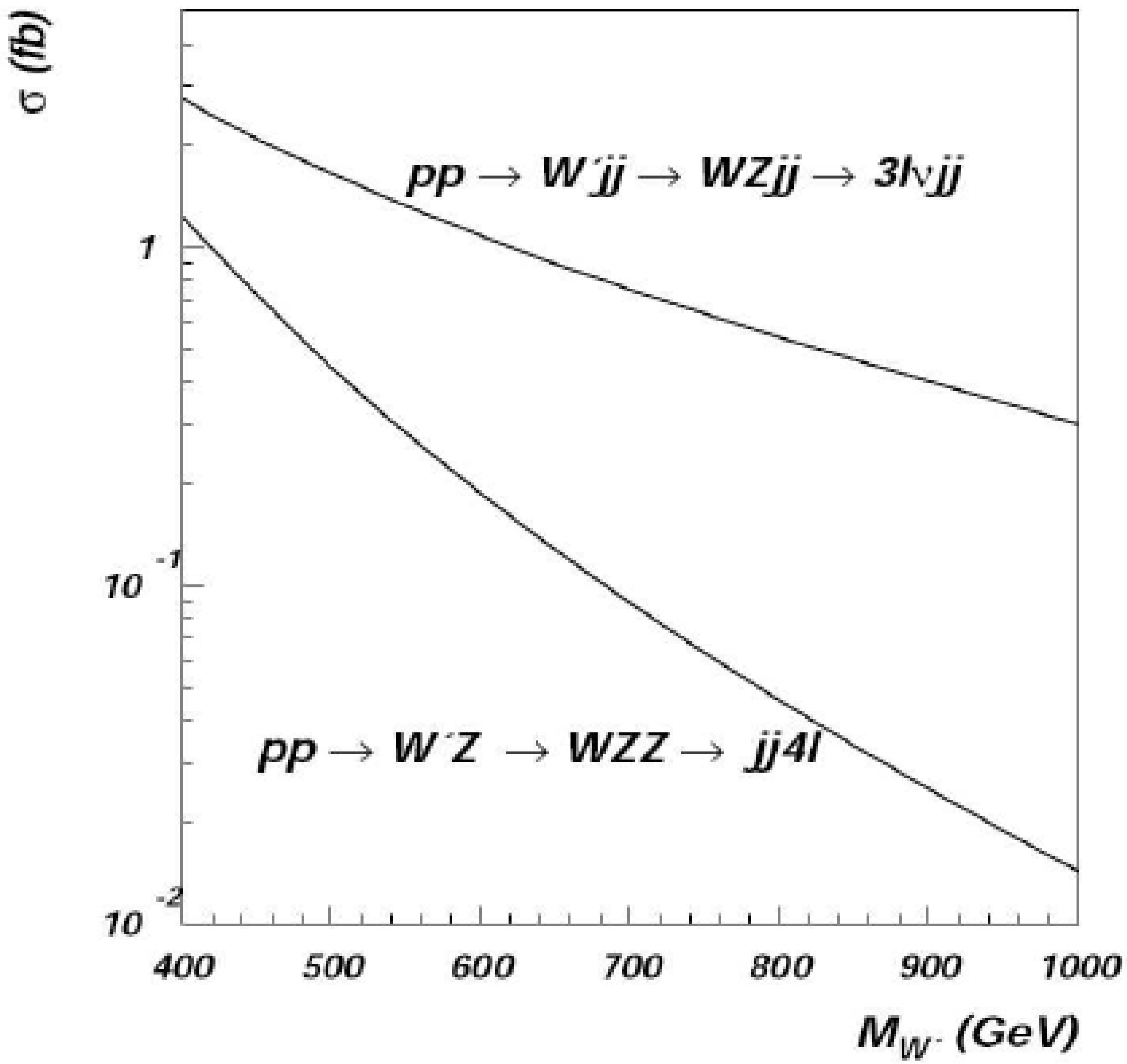
Vector Boson Fusion



Associated Production

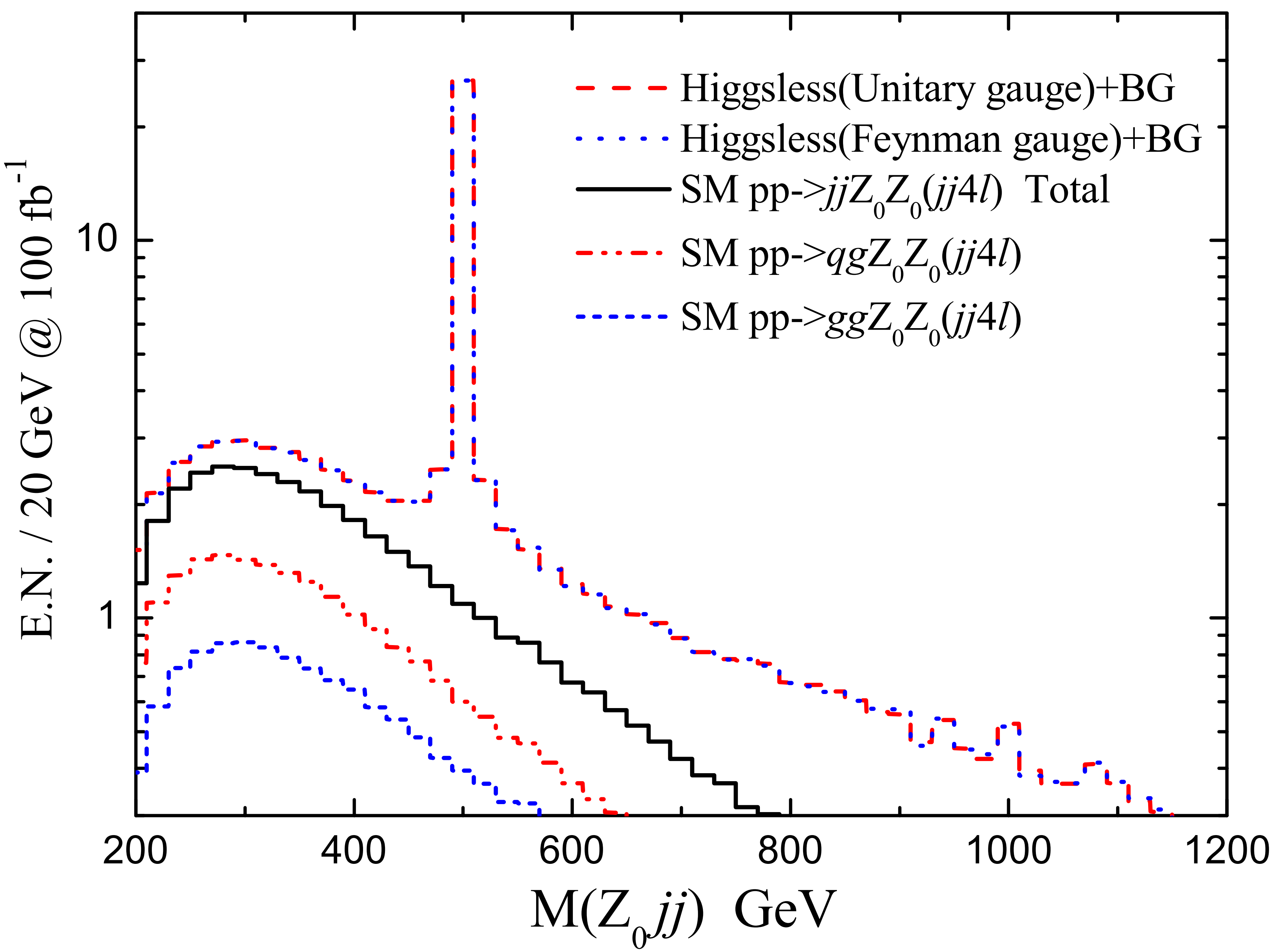


LHC @14 TeV



Associated Production (WZZ channel)

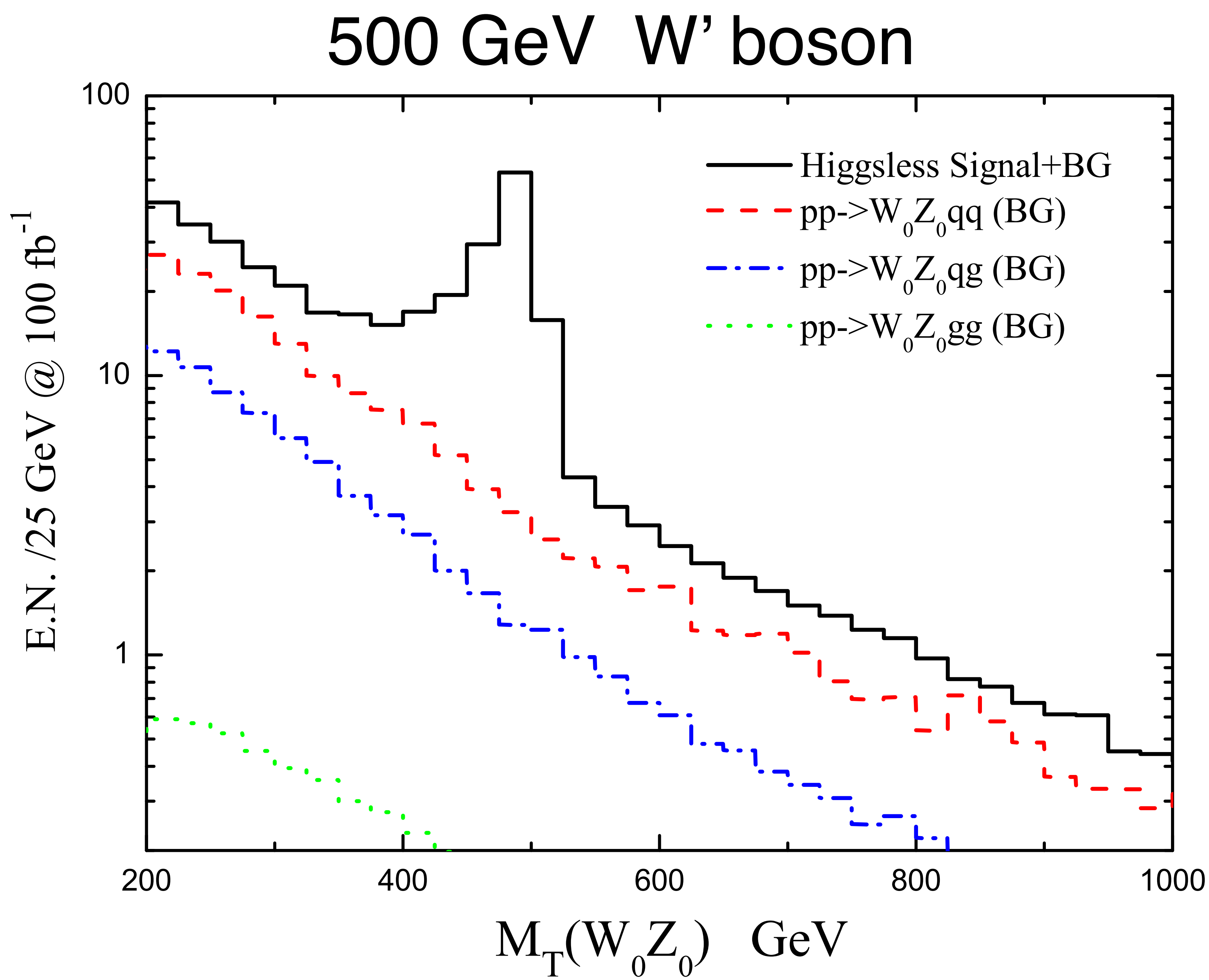
500 GeV W' boson



$$M_{jj} = 80 \pm 15\,\mathrm{GeV}, \qquad \Delta R(jj) < 1.5\,, \qquad \sum_Z p_T(Z) + \sum_j p_T(j) = \pm 15\ \mathrm{GeV}.$$

$$p_{T\ell} > 10\,\mathrm{GeV}, \qquad |\eta_\ell| < 2.5\,, \qquad p_{Tj} > 15\,\mathrm{GeV}, \qquad |\eta_j| < 4.5\,.$$

Vector Boson Fusion (WZjj channel)



Background is 10x larger than estimated in Birkedal, Matchev & Perelstein (2005)

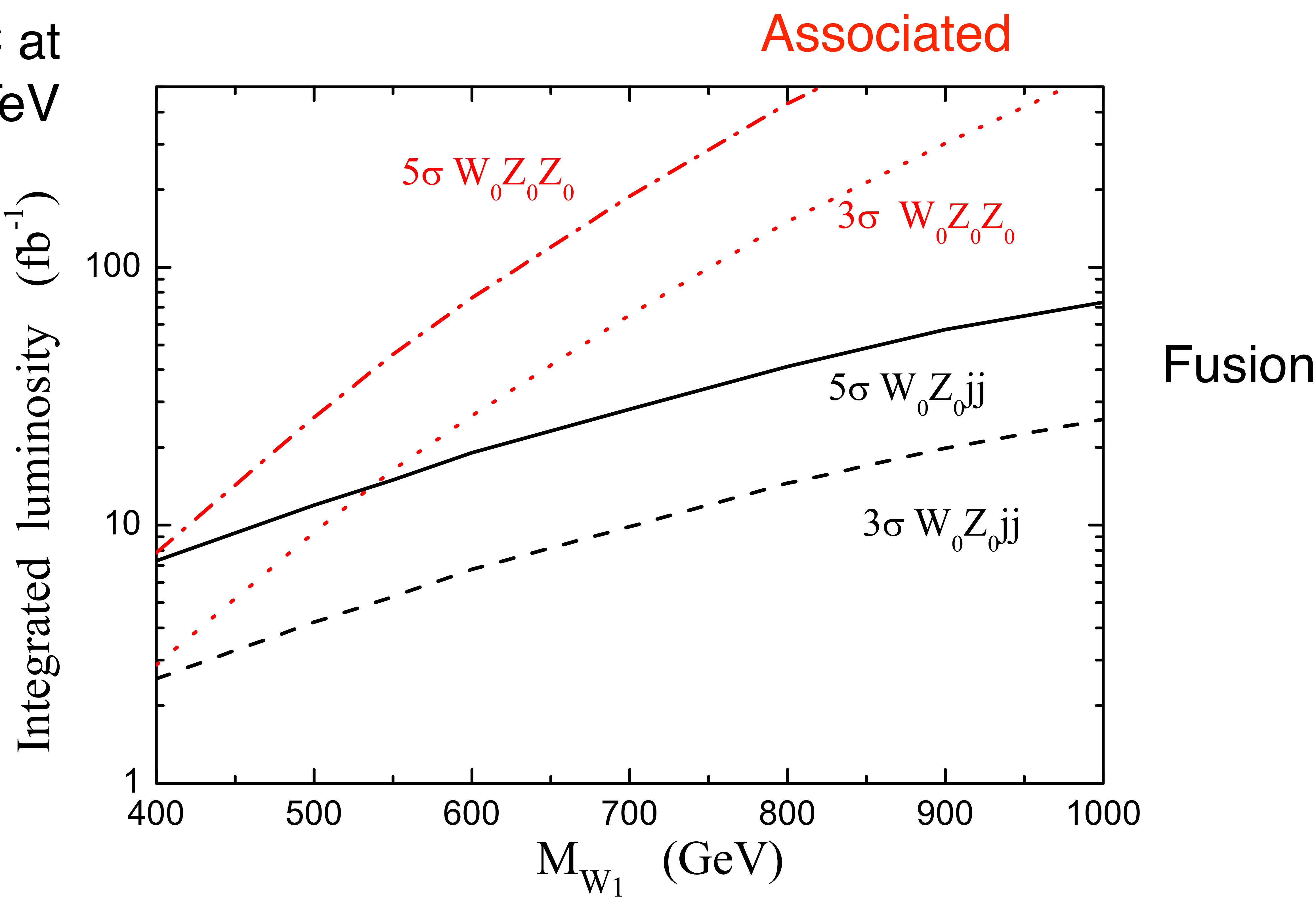
forward jet tag removes WZ background

$$E_j > 300\,\text{GeV}\,, \qquad p_{Tj} > 30\,\text{GeV}\,, \qquad |\eta_j| < 4.5\,, \qquad |\Delta\eta_{jj}| > 4$$

$$p_{T\ell} > 10\,\text{GeV}\,, \qquad |\eta_\ell| < 2.5$$

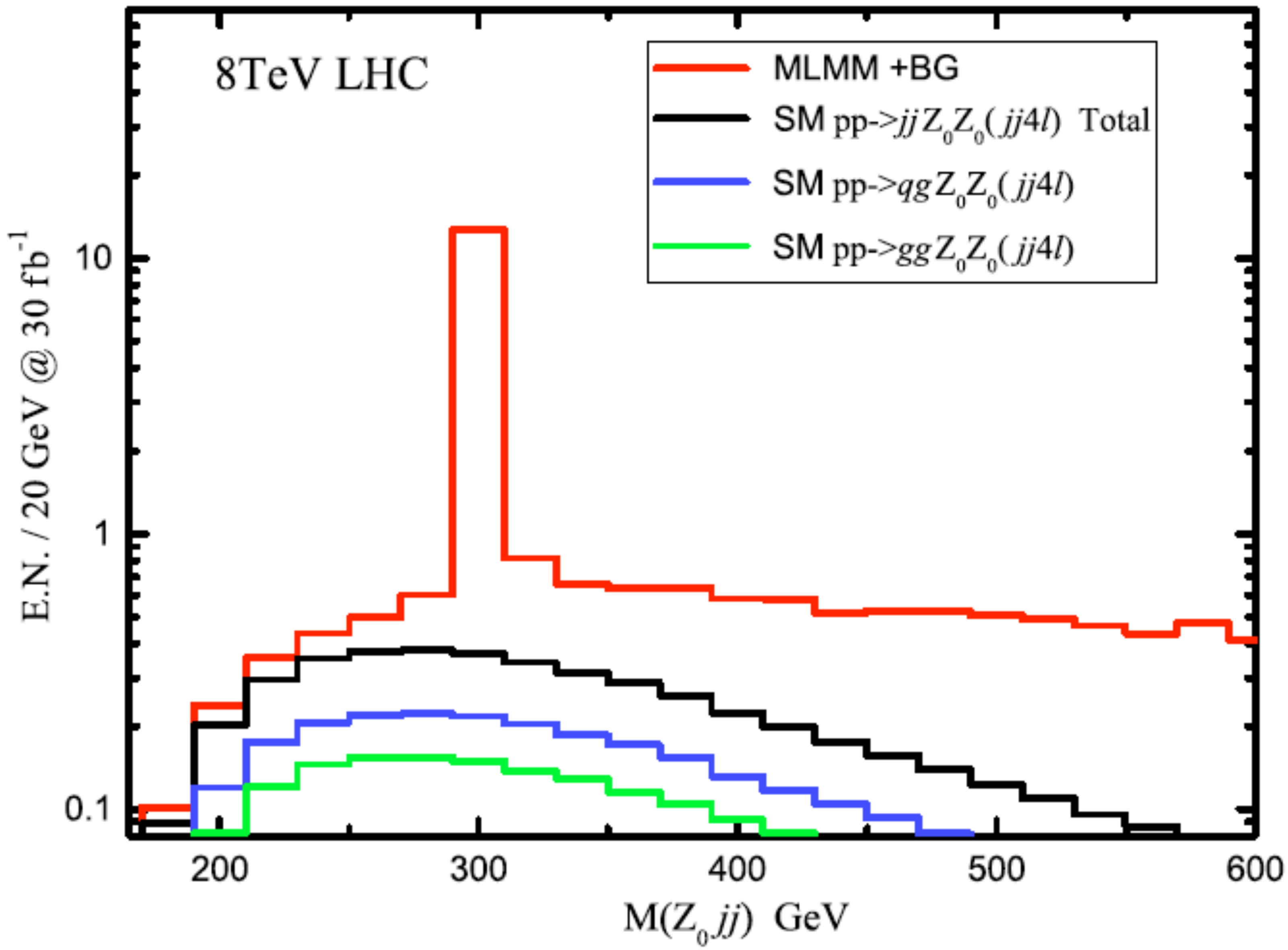
Integrated Luminosity for W' Discovery

LHC at
14 TeV



W' Discovery at 8 TeV

Associated Production



$$p_{T\ell} > 10 \text{ GeV}, \quad |\eta_\ell| < 2.5, \quad M_{jj} = 80 \pm 15 \text{ GeV}.$$

$$p_{Tj} > 15 \text{ GeV}, \quad |\eta_j| < 4.5, \quad \Delta R(jj) < 1.6.$$

W' Production at 8 TeV

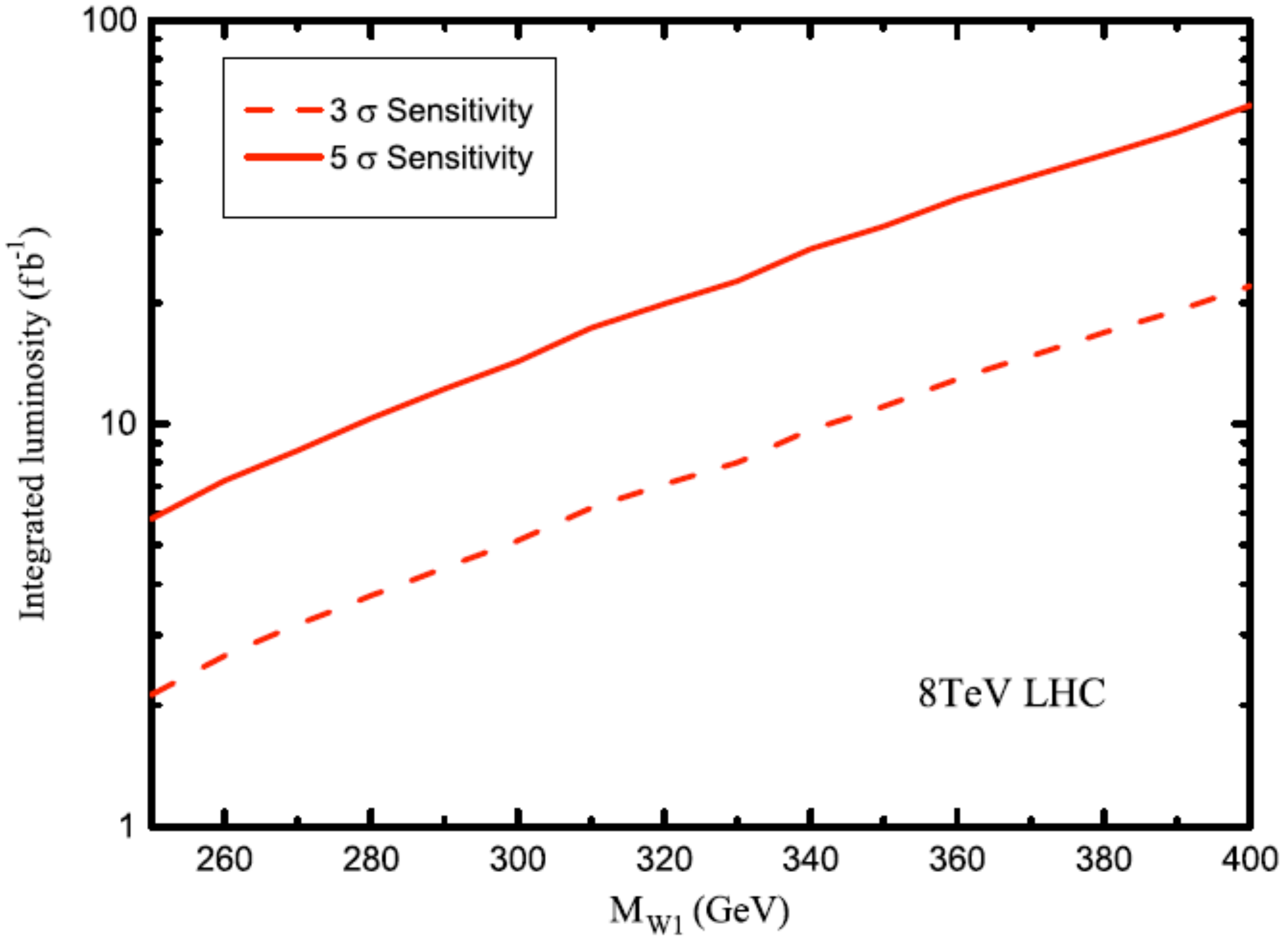


TABLE II. The 5σ discovery reaches of the $W_1^\pm$ bosons at the LHC-8, with the integrated luminosities $\int \mathcal{L} = 10, 15, 20, 25, 30, 35, 40, 50, 60$ fb^{-1}, respectively.

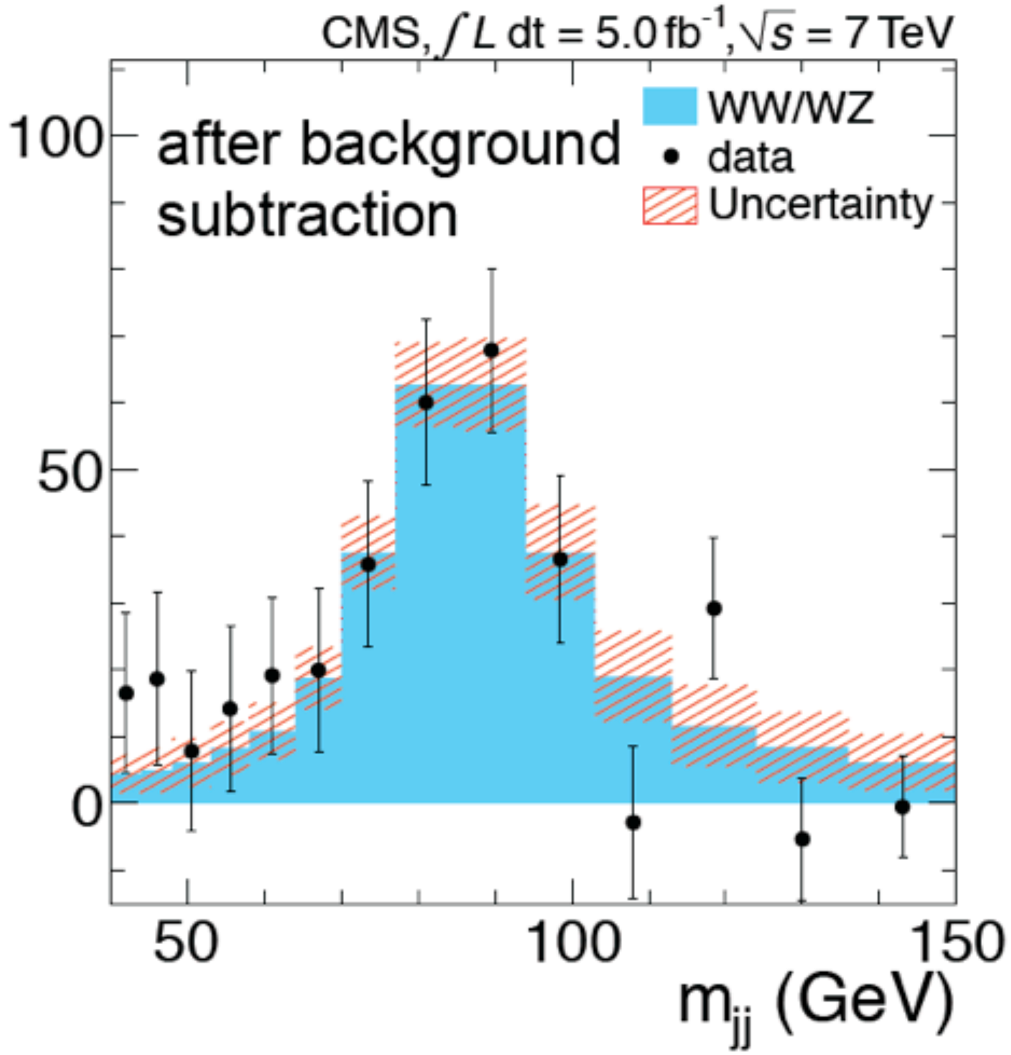
$\int \mathcal{L}$ (fb^{-1})	M_{W_1} (GeV)
10	277
15	302
20	320
25	335
30	346
35	357
40	367
50	385
60	397

arxiv:1206.6022, PRD in press

LHC Searches Have Begun

Semi-Leptonic WW at 7 TeV

WW+WZ→ℓνqq cross section at 7 TeV



arXiv:1210.7544 (*Eup. J. Phy. C*)

#diboson = 2682 ± 339(stat) ± 357(syst), NLO prediction = 2564

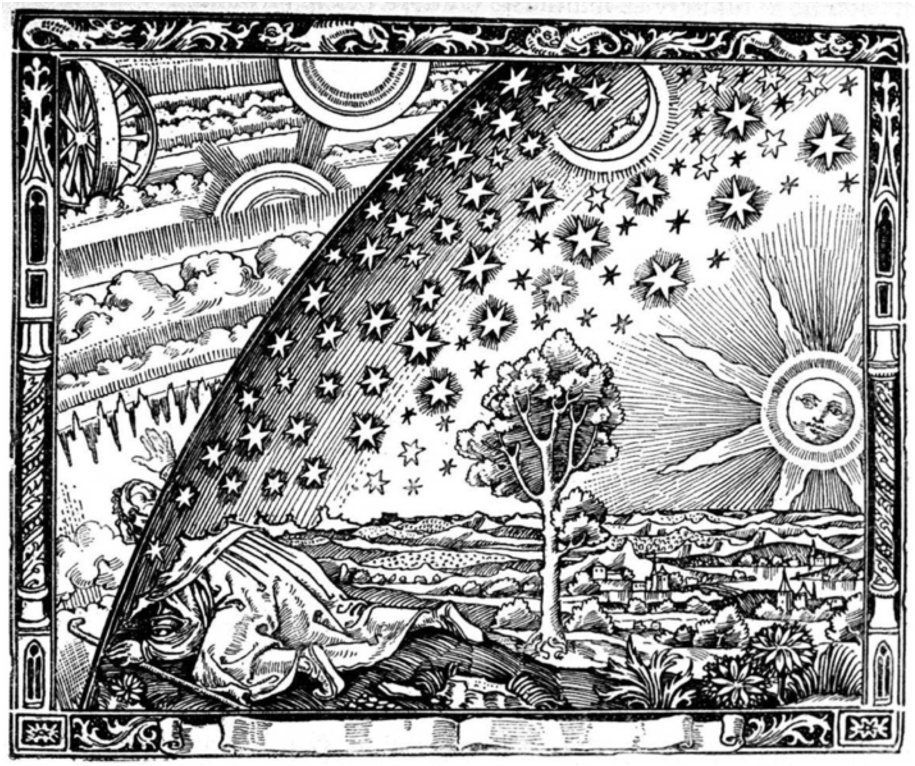
- The first observation of diboson in semi-leptonic channel at LHC.

σ = 68.9 ± 8.7 (stat) ± 9.7 (sys) ± 1.5 (lum) pb
NLO prediction (MCFM): 65.6 ± 2.2 pb

☑ Consistent with NLO

Conclusion

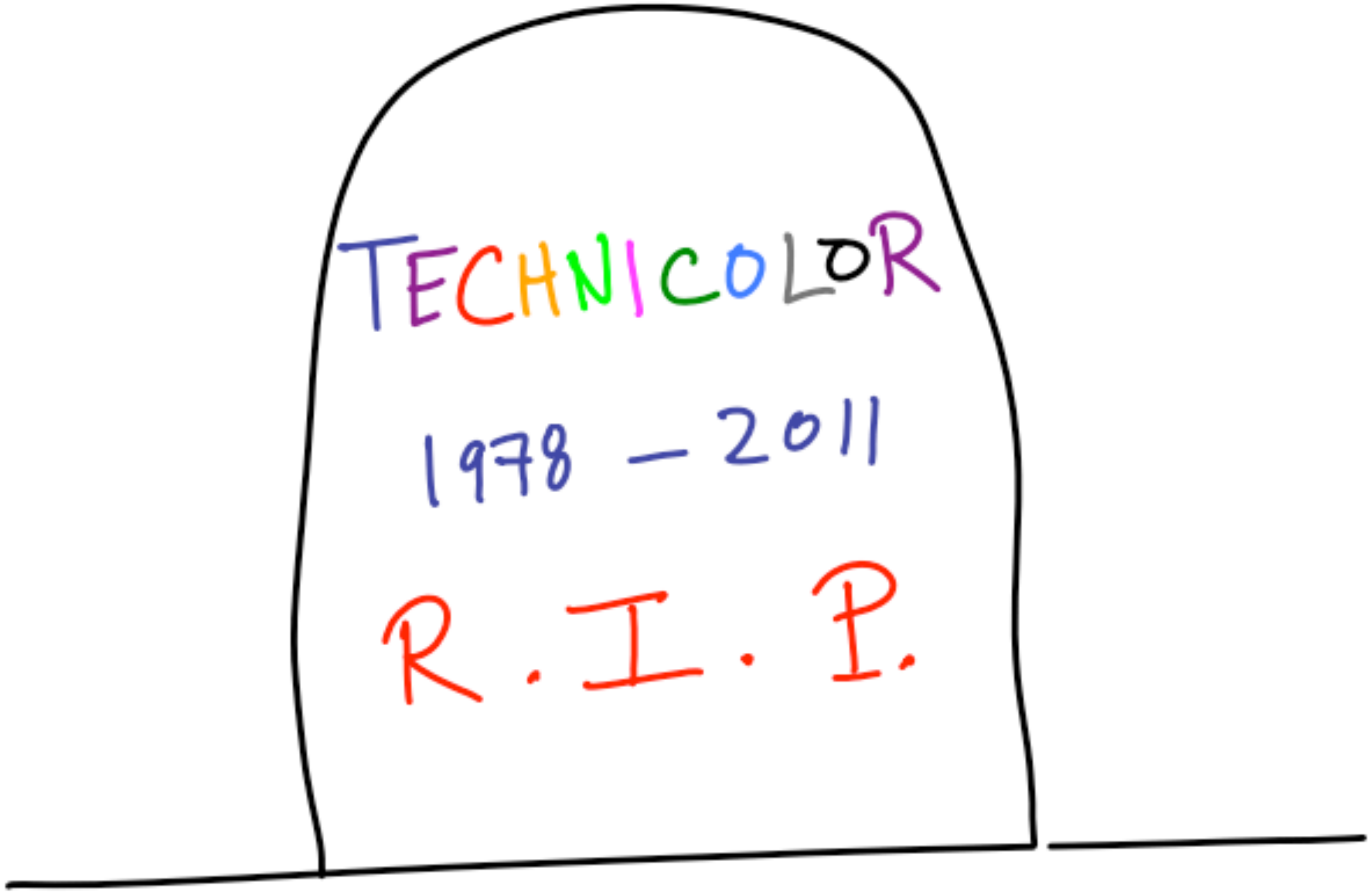
- ATLAS/CMS has discovered a new boson.
- Measure properties: is it the Higgs?
  - Must check in multiple channels!
- If it isn't, there are potential new signatures in multi-gauge boson signals.



Backup Slides

Discussion Question

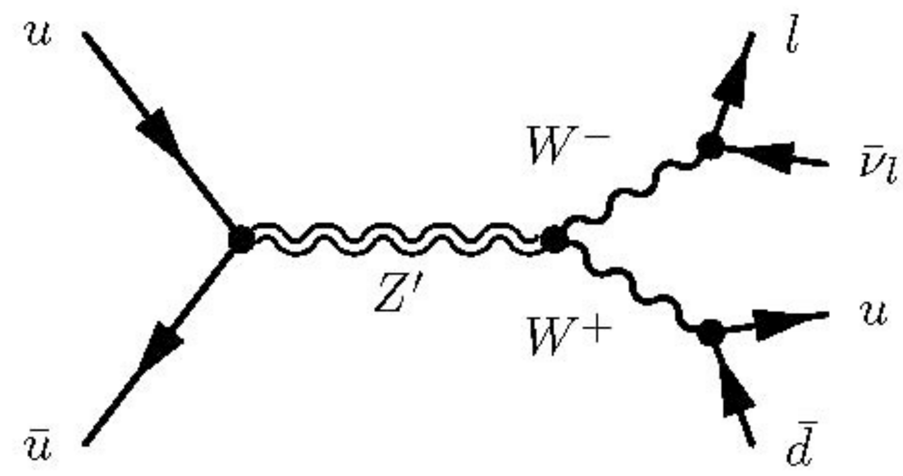
Obvious Implications of $m_H \sim 125\,\text{GeV}$?

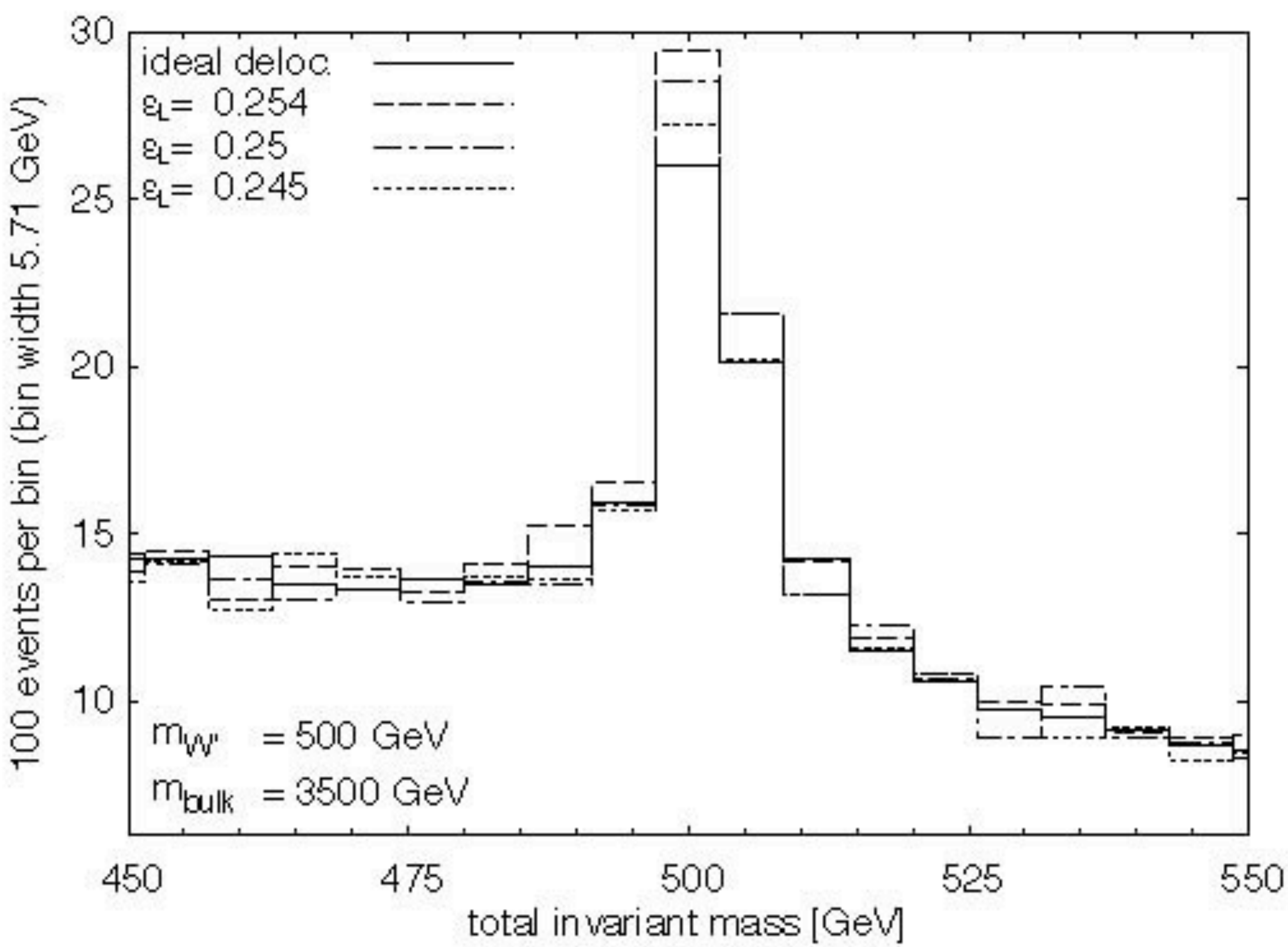


N.Arkani-Hamed, SavasFest 2012

Z' Search at LHC

Ohl & Speckner predict that the 3-site Z' boson (at or near ideal delocalization) should be visible in 100 fb^{-1} of LHC data





$$p_T \geq 50 \text{ GeV}$$

$$|\cos\theta| \leq 0.95$$

$$75 \text{ GeV} \leq m_{jj} \leq 85 \text{ GeV}$$

$$M_{W'} = 500 \text{ GeV}$$

Ohl & Speckner arXiv:0809.0023