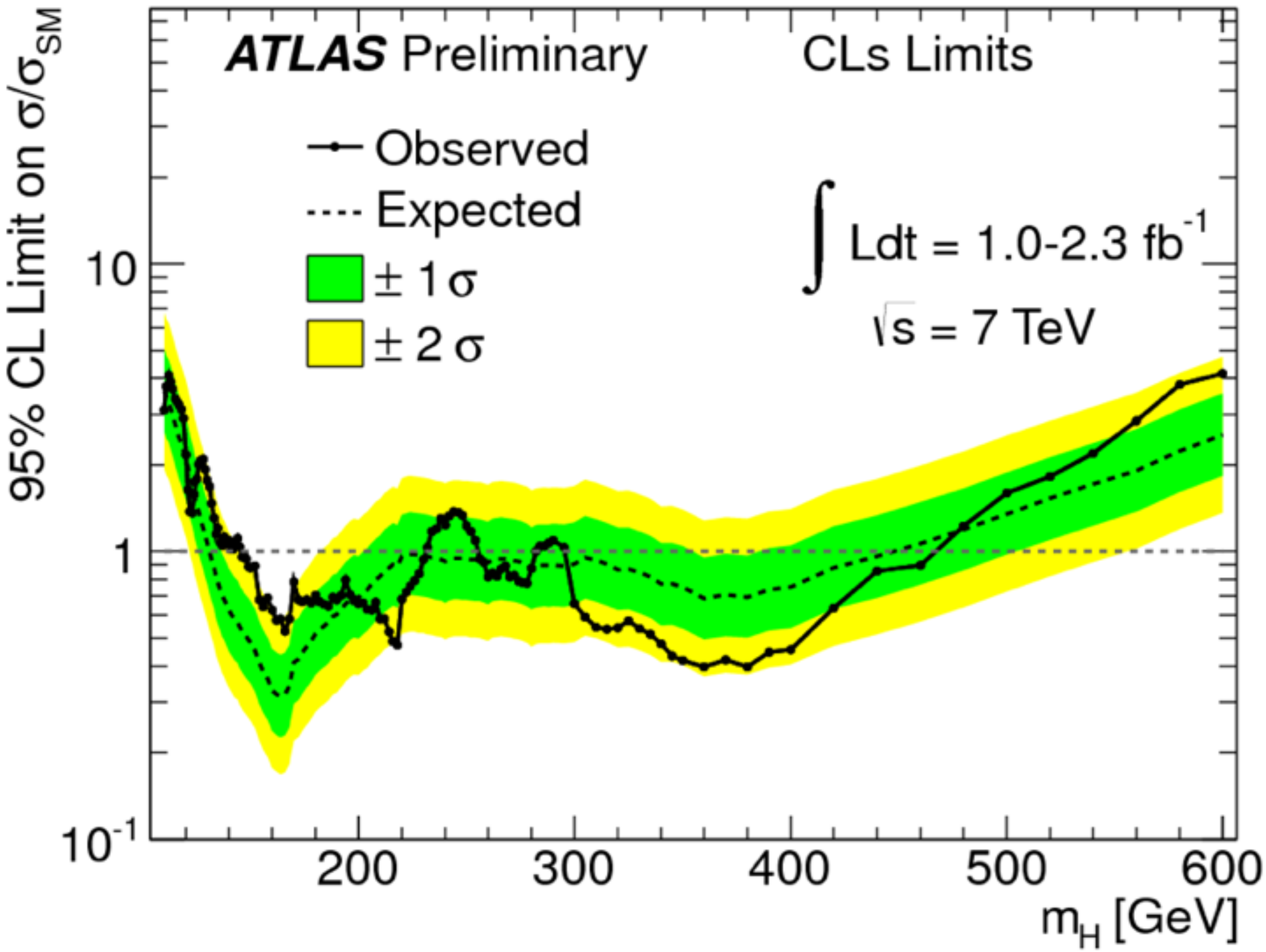
Technicolor in the LHC Era

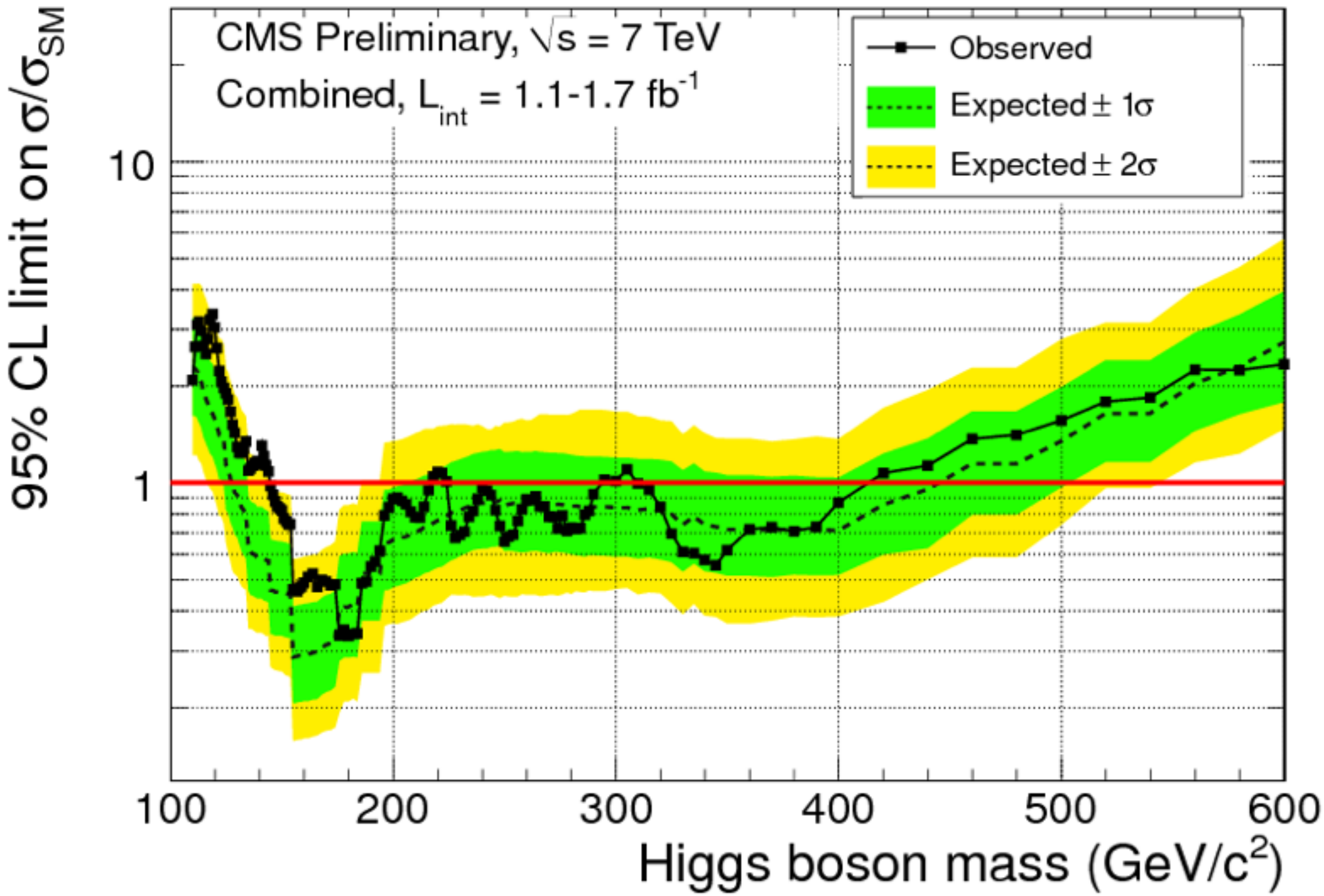
R. Sekhar Chivukula
Michigan State University

ATLAS Higgs Results



Lepton-Photon 2011

CMS Higgs Results



Lepton-Photon 2011

Salt Lake City
Clear
59°
Weather | Traffic

Deseret News

Creation theory may be wrong; collider hasn't found 'God particle'

By Michael De Groote, Deseret News

Published: Thursday, Sept. 1, 2011 10:17 a.m. MDT

88 comments

PRINT | F

Page: 1 2 Next >

GENEVA — Creation is at the center of religion, and it is also at the center of a search, not particle."

NewScientist Physics & Math

Don't panic about the missing Higgs – for now

› 18:00 28 August 2011 by Lisa Grossman
› For similar stories, visit the The Large Hadron Collider Topic Guide

Online quiz: "Will the LHC discover the Higgs boson?"

The world's most-wanted particle continues to elude the world's most powerful particle accelerator. A sign that the elusive Higgs boson doesn't exist? Not so fast. For now, there are good reasons to assume the Higgs is just hiding.

"It's never too early to think about it, but it is too early to worry," says Nobel prize-winner Frank Wilczek of the Massachusetts Institute of Technology.

DISCOVER® MAGAZINE

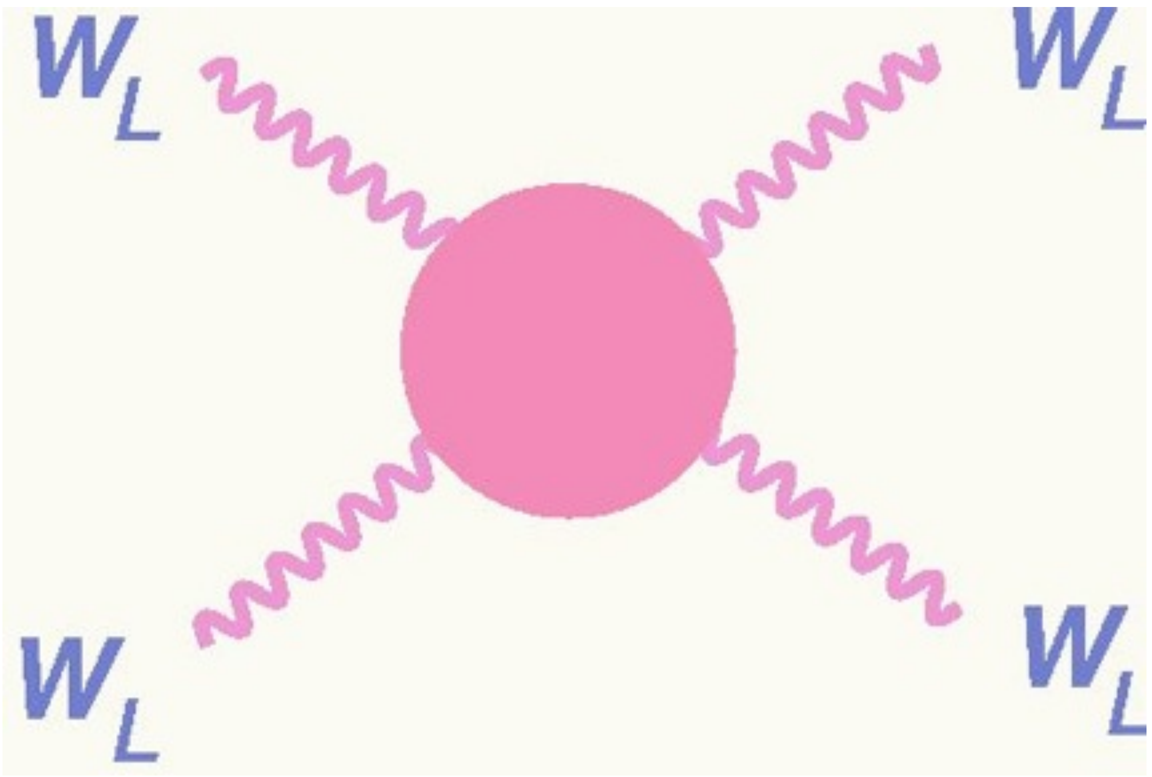
At the LHC, the "God Particle" is Running Out of Places to Hide

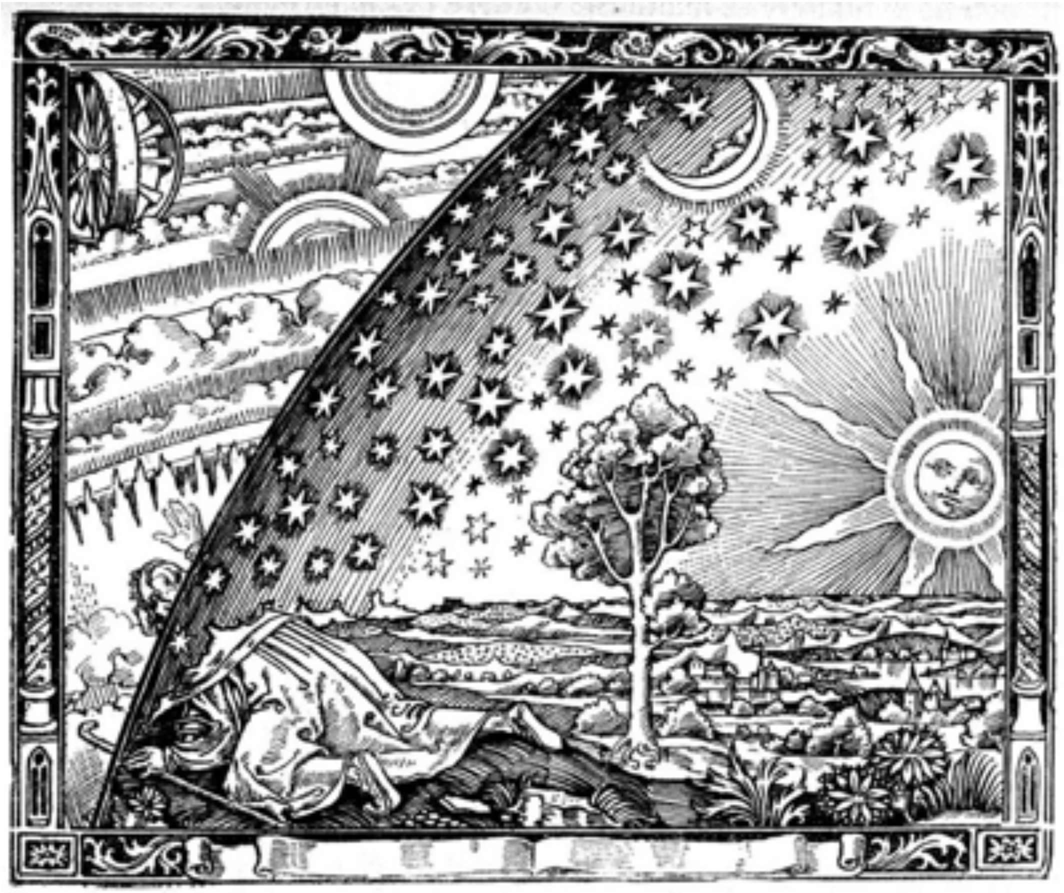
SCIENTIFIC AMERICAN™

A Higgs Setback: Did Stephen Hawking Just Win the Most Outrageous Bet in Physics History?

By Amir Aczel | August 23, 2011 | 37

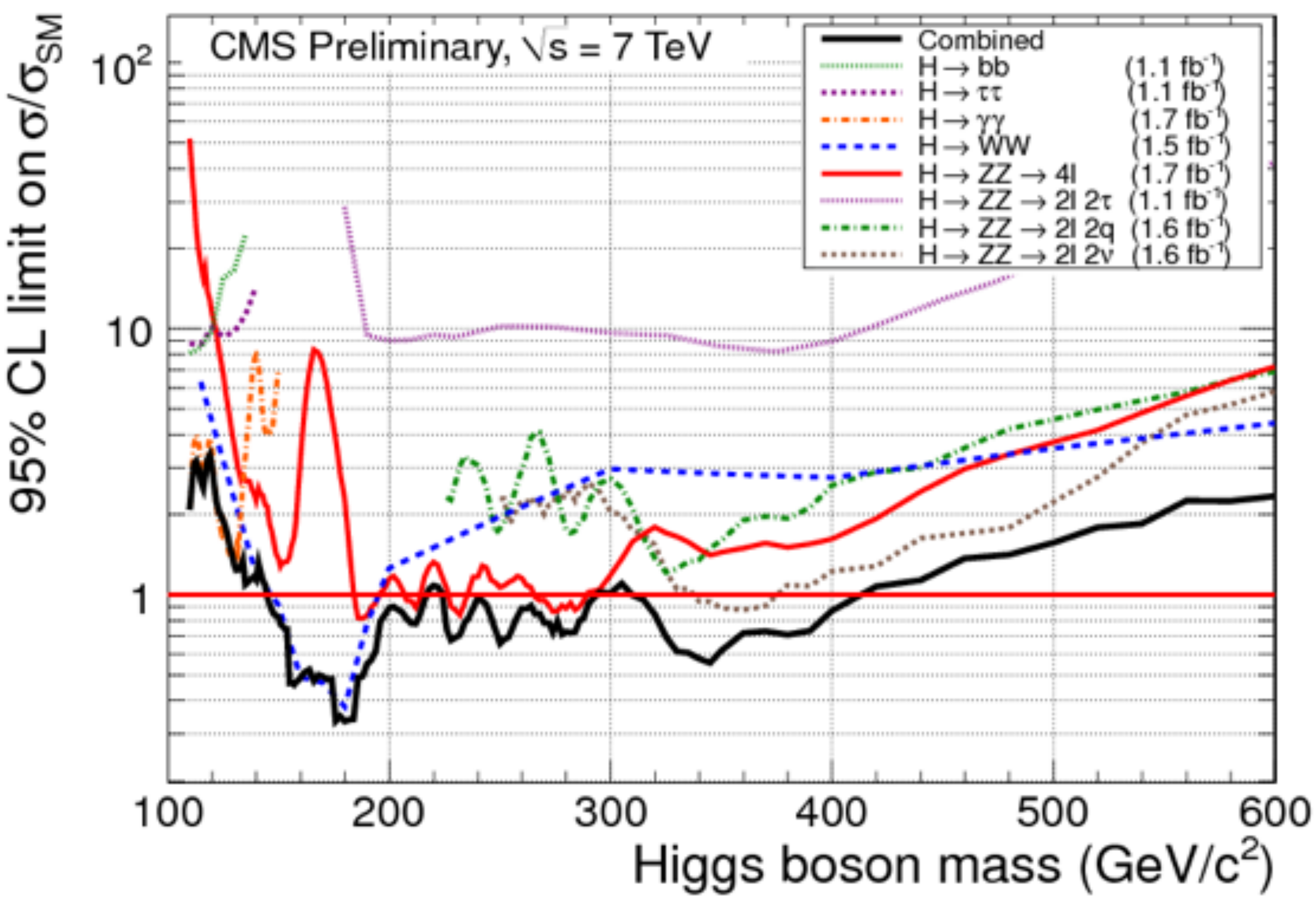
These headlines are missing the point...



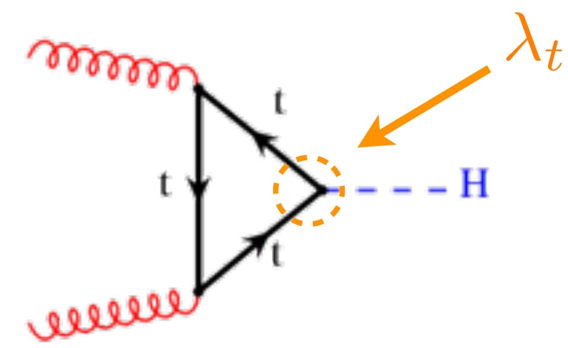


ATLAS/CMS are exploring a whole new world!

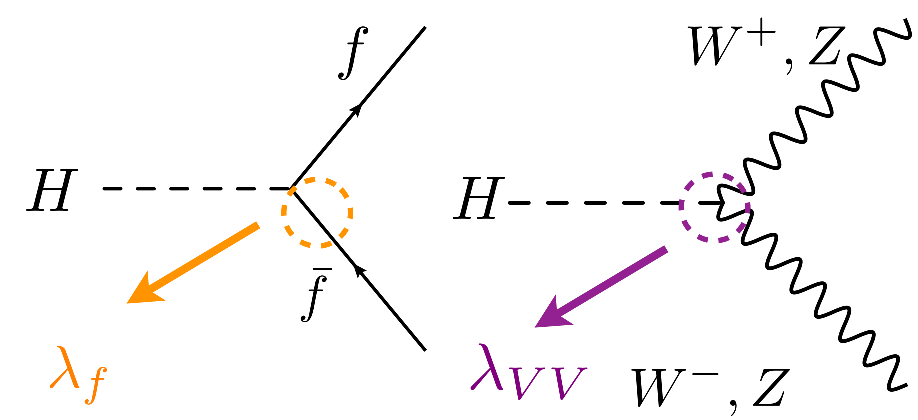
LHC Higgs Sensitivity

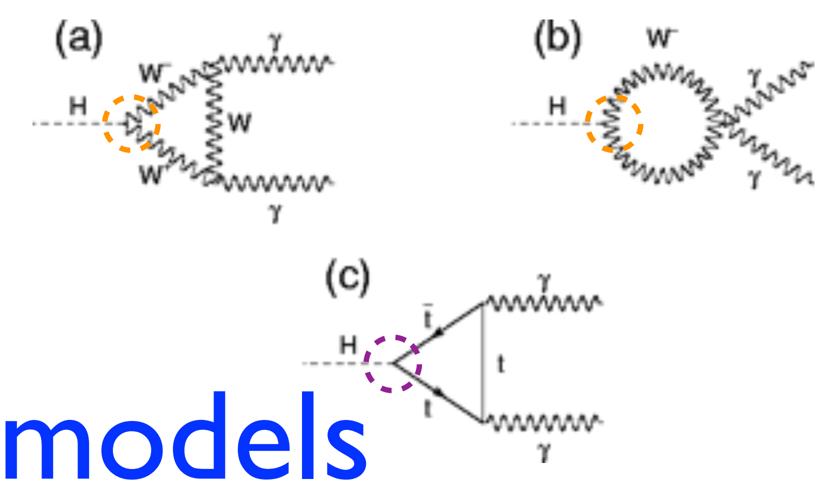


$\sigma(pp \to H)$



$BR(H \to X)$





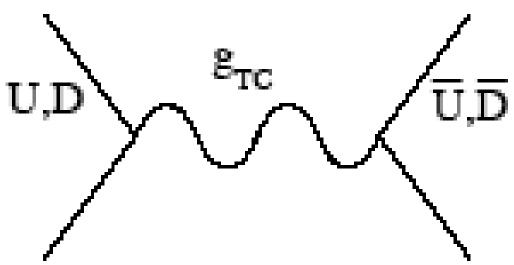
Reach Extends to non-standard models including models of DEWSB!

Dynamical Electroweak Symmetry BReaking

Technicolor

- Use scaled-up QCD to break electroweak symmetry

$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$$



$$\rightarrow \langle \bar{U}_L U_R \rangle = \langle \bar{D}_L D_R \rangle \neq 0$$

No hierarchy problem!

S?

$$\pi^{\pm},\ \pi^0 \rightarrow W_L^{\pm},\ Z_L$$

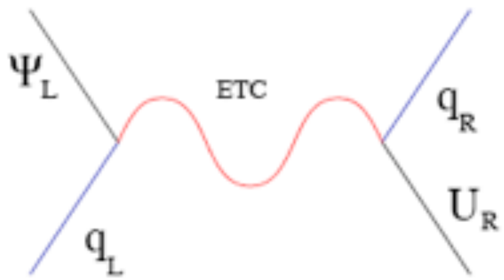
$$M_W = \frac{gF_{TC}}{2} \rightarrow F_{TC} \approx 250\text{GeV}$$

Gauge Symmetry + SSB = Higgs Mechanism

But: difficult to accommodate top-quark!

Walking Technicolor

Extended Technicolor Interactions — Connect chiral-symmetries of TFs to quarks & leptons.



$$\Rightarrow \frac{g^2_{ETC}}{M^2_{ETC}} (\overline{\Psi}_L U_R)(\overline{q}_R q_L)$$

$$m_q \approx \frac{g^2_{ETC}}{M^2_{ETC}} \langle \overline{U} U \rangle_{ETC}$$

$$\langle \overline{U} U \rangle_{ETC} = \langle \overline{U} U \rangle_{TC} \exp\left(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu} \gamma_m(\mu) \right)$$

If $\beta_{TC} \sim 0$, we expect $\gamma_m \sim 1$, enhancing fermion masses.

A realistic (E)TC model will not be like QCD!

Holdom, Yamawaki et. al., Appelquist and Wijewardana

Low/Multi-Scale technicolor

How can $\beta(\alpha_{TC}) \simeq 0$?

Or, minimal SU(2) theory... Sannino, et. al.

Eliminated by Lattice Calculations!

- Many fermions
- Fermions in different TC representations.

Extended/Multiple Symmetry-Breaking Sector(s):

- Large Chiral Symmetry
- Many π_T
- $F << v \Rightarrow$ potentially light ρ_T, ω_T, & π_T

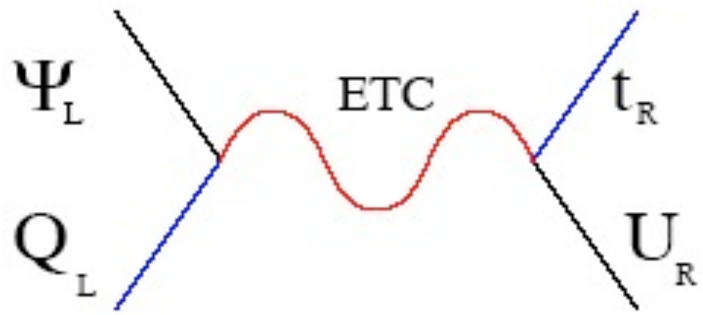
Our interest: π^0_{TC}

e.g.The "Technicolor" Straw Man

Lane and Mrenna, Phys. Rev. D67:115011,2003

Eichten, Lane, Womersley

Top Quark Mass Generation



$$\Rightarrow \frac{g_{ETC}^2}{M_{ETC}^2}(\overline{\Psi}_L U_R)(\bar{t}_R Q_L)$$

$$m_t \approx \frac{g_{ETC}^2}{M_{ETC}^2}\langle \overline{U}U\rangle_{ETC}$$

$$\frac{M_{ETC}}{g_{ETC}} \approx 1\,\mathrm{TeV}\left(\frac{F_{TC}}{250\,\mathrm{GeV}}\right)^{\frac{3}{2}}\left(\frac{175\,\mathrm{GeV}}{m_t}\right)^{\frac{1}{2}}$$

Challenge: ETC must violate custodial symmetry to make $m_t >> m_b$. But how to keep this from causing additional large contributions to $\Delta\rho$?

Are new interactions required to explain top-quark mass?

TopColor Assisted Technicolor

- Strong Technicolor dynamics at 1 TeV dynamically generates most of EWSB.
- Extended Technicolor dynamics at scales much higher than 1 TeV generate the light quark and lepton masses.
- Strong Topcolor dynamics also at a scale of 1 TeV generates $\langle \bar{t}t \rangle \neq 0$, $m_t \sim 170$ GeV.

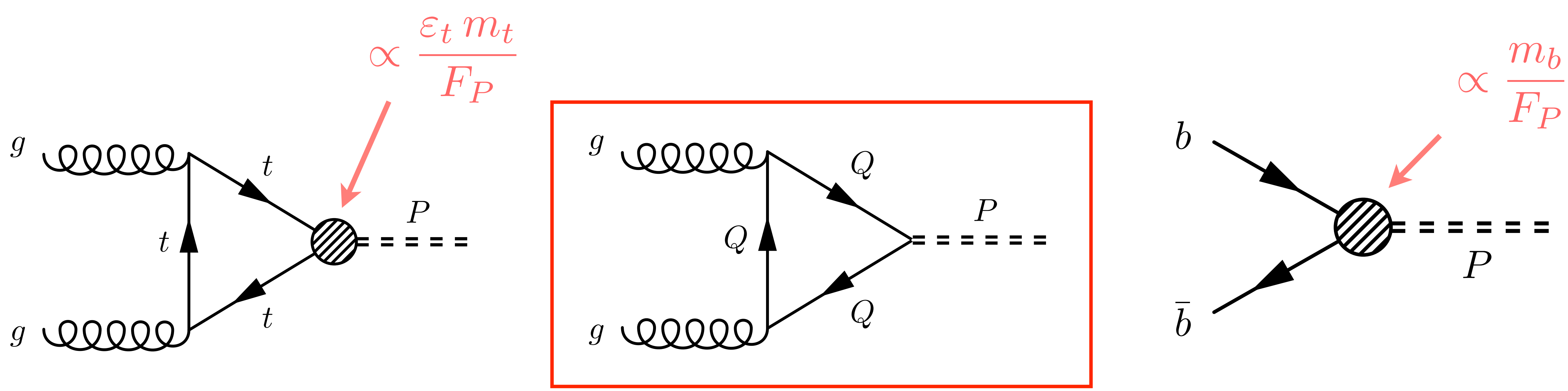
$$v^2 = \frac{1}{\sqrt{2}G_F} = f_t^2 + F_{TC}^2 \approx (246\,\mathrm{GeV})^2, \quad f_t = \mathcal{O}(60\,\mathrm{GeV}) \ll v$$

Hill, hep-ph/9411426

Technicolor in the LHC Era

RSC, EHS, P. Ittisamai, J. Ren, arxiv:1110.3688

LHC Technipion Sensitivity



$$\mathbb{A}(P \to V_1 V_2) = N_{TC} \mathcal{A}_{V_1 V_2} \frac{g_1 g_2}{8\pi^2 F_P} \epsilon_{\mu\nu\lambda\sigma} k_1^\mu k_2^\nu \epsilon_1^\lambda \epsilon_2^\sigma$$

Models with Colored Technifermions

TC models	PNGB and content		v/F_P	A_{gg}	$A_{\gamma\gamma}$	λ_l	λ_f
FS one family (Farhi:1980)	P^1	$\frac{1}{4\sqrt{3}}(3\bar{L}\gamma_5 L - \bar{Q}\gamma_5 Q)$	2	$-\frac{1}{\sqrt{3}}$	$\frac{4}{3\sqrt{3}}$	1	1
Variant one family (Casalbuoni:1998)	P^0	$\frac{1}{2\sqrt{6}}(3\bar{E}\gamma_5 E - \bar{D}\gamma_5 D)$	1	$-\frac{1}{\sqrt{6}}$	$\frac{16}{3\sqrt{6}}$	$\sqrt{6}$	$\sqrt{\frac{2}{3}}$
LR multiscale (Lane:1991)	P^0	$\frac{1}{6\sqrt{2}}(\bar{L}_\ell\gamma_5 L_\ell - 2\bar{Q}\gamma_5 Q)$	4	$-\frac{2\sqrt{2}}{3}$	$\frac{8\sqrt{2}}{9}$	1	1
TCSM low scale (Lane:1999)	$\pi_T^{0'}$	$\frac{1}{4\sqrt{3}}(3\bar{L}\gamma_5 L - \bar{Q}\gamma_5 Q)$	$\sqrt{N_D}$	$-\frac{1}{\sqrt{3}}$	$\frac{100}{27\sqrt{3}}$	1	1
MR Isotriplet (Manohar:1990)	P^1	$\frac{1}{6\sqrt{2}}(3\bar{L}\gamma_5 L - \bar{Q}\gamma_5 Q)$	4	$-\frac{1}{\sqrt{2}}$	$24\sqrt{2}y^2$	1	1

Technipion Properties

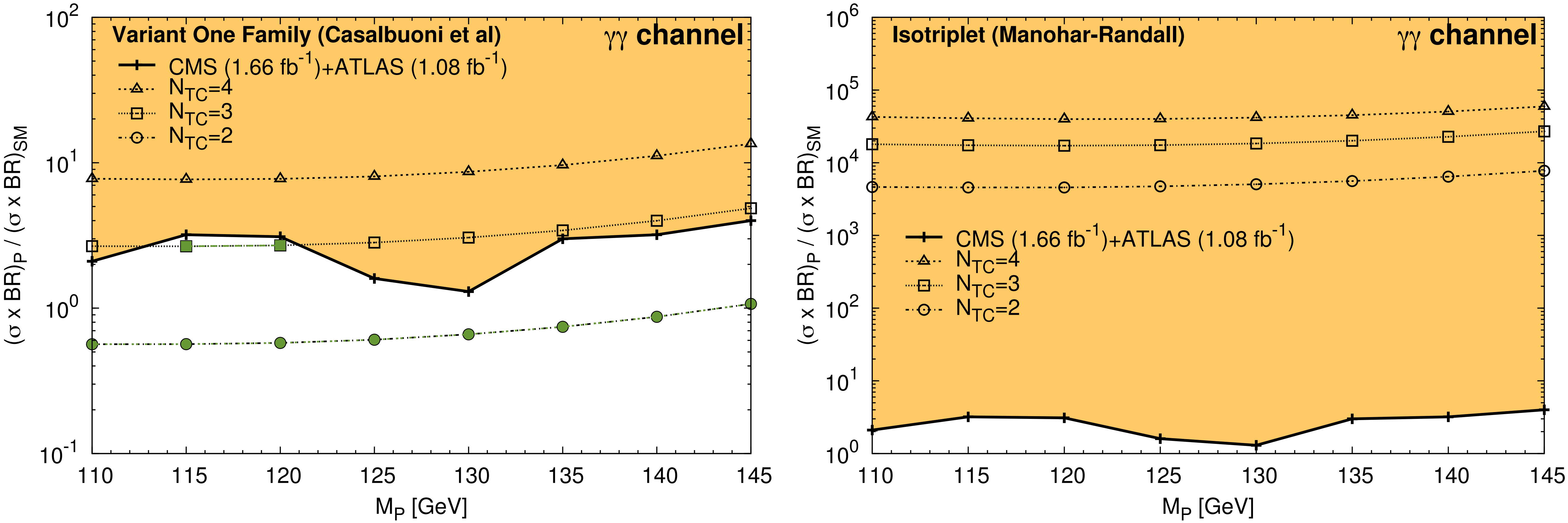
130 GeV

Decay Channel	One Family		Variant one family		Multiscale		TCSM low-scale		Isotriplet		SM Higgs
	N_{TC} =2	N_{TC} =4	N_{TC} =2	N_{TC} =4	N_{TC} =2	N_{TC} =4	N_{TC} =2	N_{TC} =4	N_{TC} =2	N_{TC} =4	
$b\bar{b}$	77	56	61	50	64	36	77	56	60	31	49
$c\bar{c}$	7	5.1	0	0	5.8	3.2	7	5.1	5.4	2.8	2.3
$\tau^+\tau^-$	4.5	3.3	32	26	3.8	2.1	4.5	3.3	3.5	1.8	5.5
gg	12	35	7	23	26	59	12	35	14	29	7.9
$\gamma\gamma$	0.011	0.033	0.11	0.35	0.025	0.056	0.088	0.26	17	36	0.23
W^+W^-	0	0	0	0	0	0	0	0	0	0	31

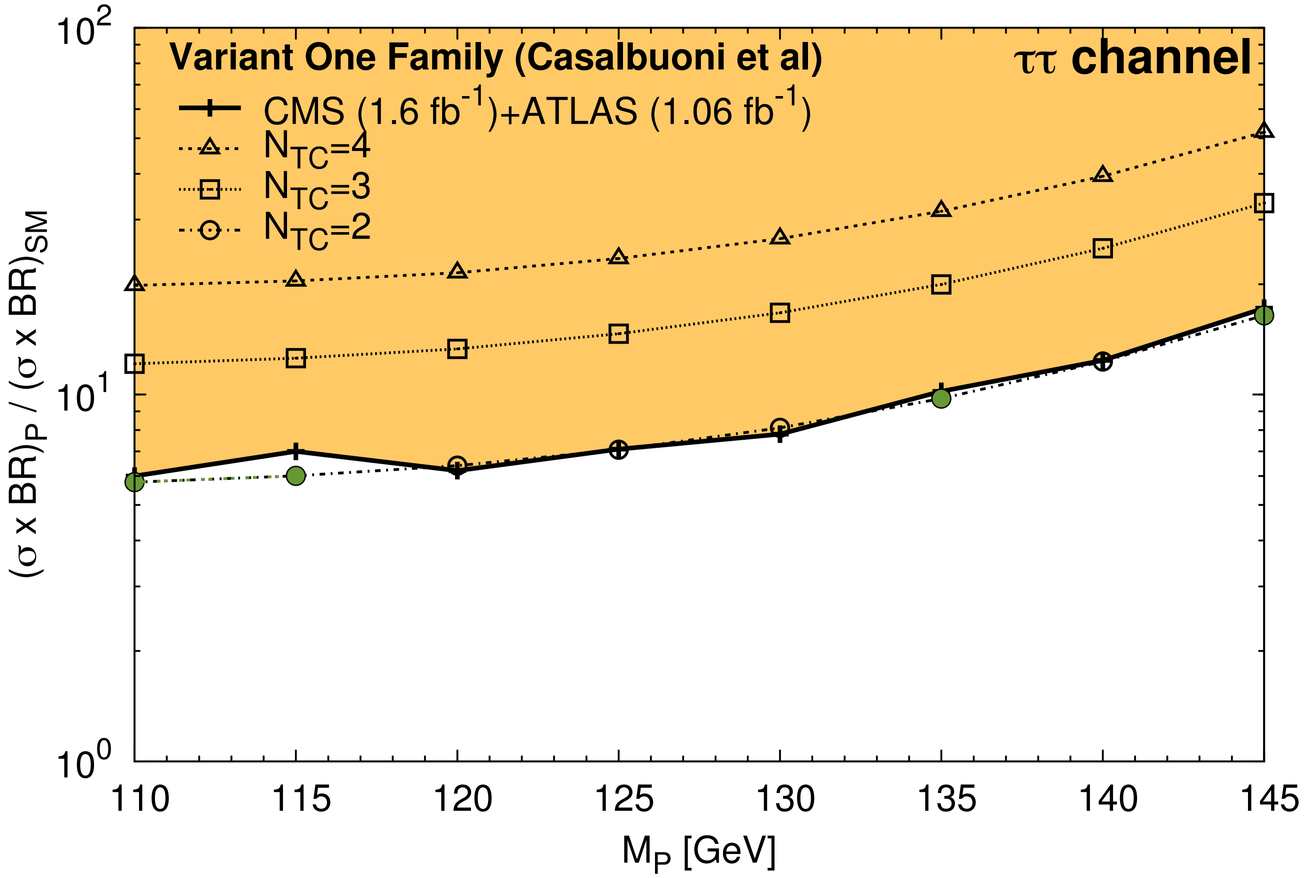
350 GeV

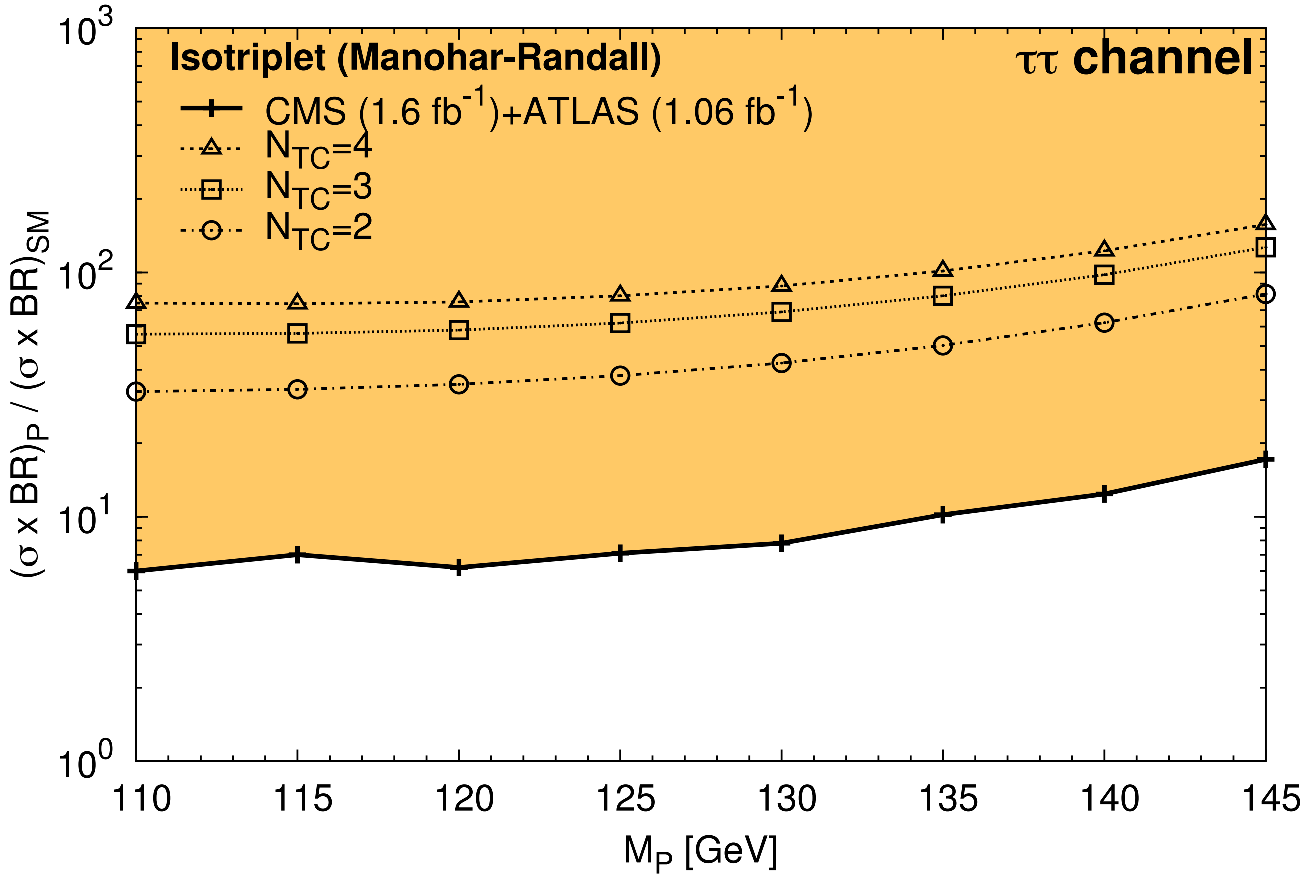
Decay Channel	One Family		Variant one family		Multiscale		TCSM low-scale		Isotriplet		SM Higgs
	N_{TC} =2	N_{TC} =4	N_{TC} =2	N_{TC} =4	N_{TC} =2	N_{TC} =4	N_{TC} =2	N_{TC} =4	N_{TC} =2	N_{TC} =4	
$b\bar{b}$	44	18	42	20	24	7.7	44	18	20	6.2	0.036
$c\bar{c}$	4	1.6	0	0	2.2	0.69	4	1.6	1.8	0.56	0.0017
$\tau^+\tau^-$	2.6	1	22	11	1.4	0.45	2.6	1	1.2	0.36	0.0048
gg	49	79	35	68	72	91	49	79	34	41	0.085
$\gamma\gamma$	0.047	0.076	0.54	1	0.069	0.087	0.36	0.58	42	51	~ 0
W^+W^-	0	0	0	0	0	0	0	0	0	0	68

Light Technipion Limits: γγ

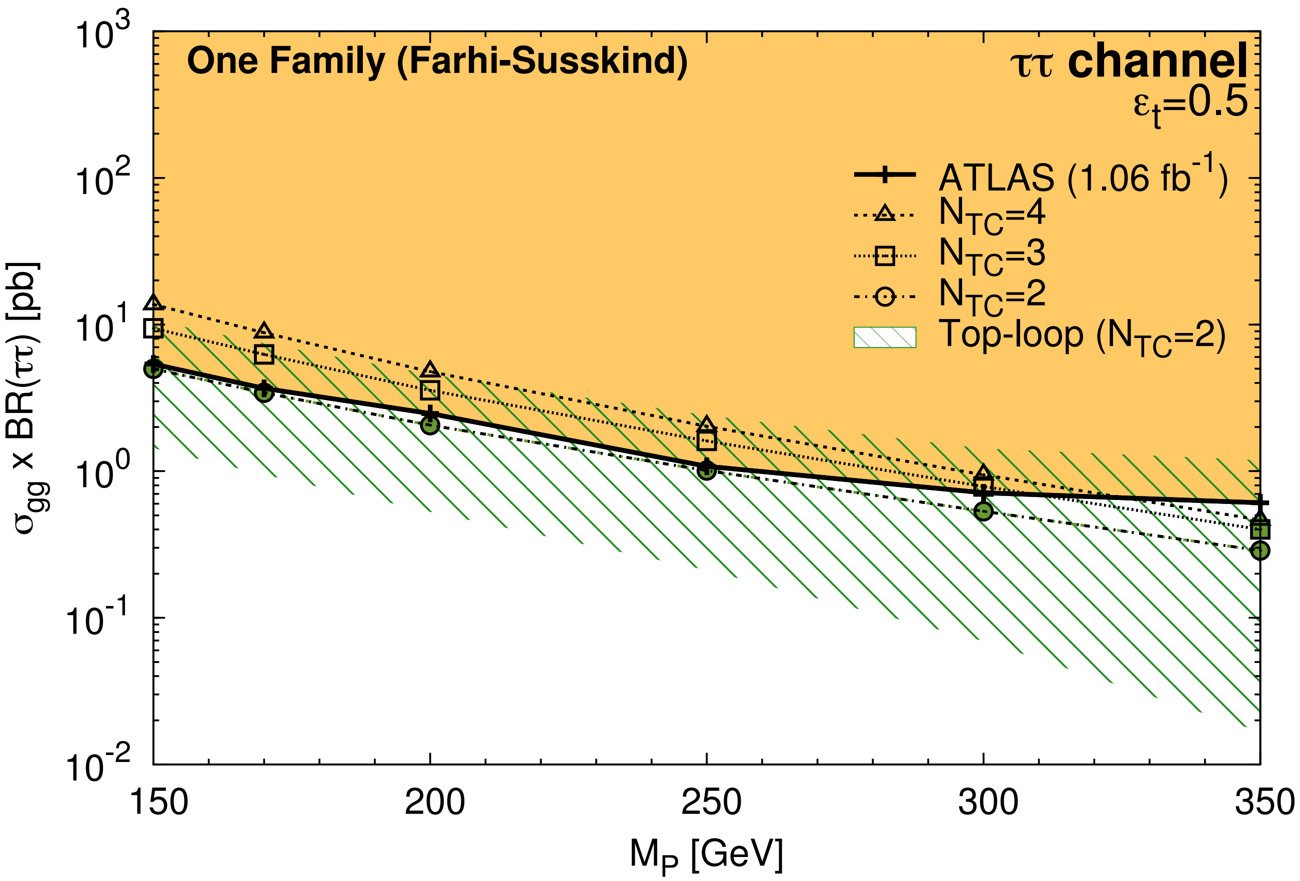


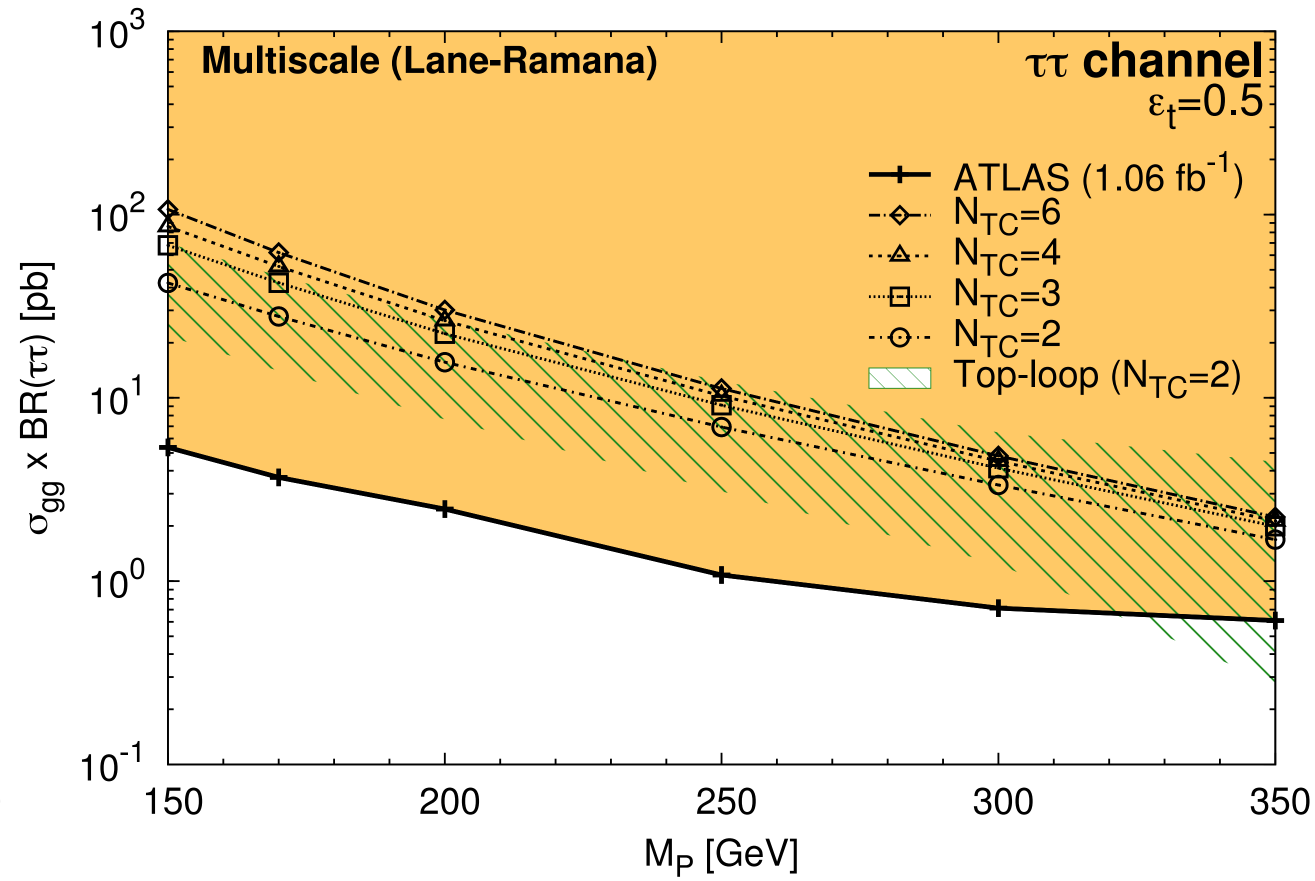
Light Technipion Limits: ττ

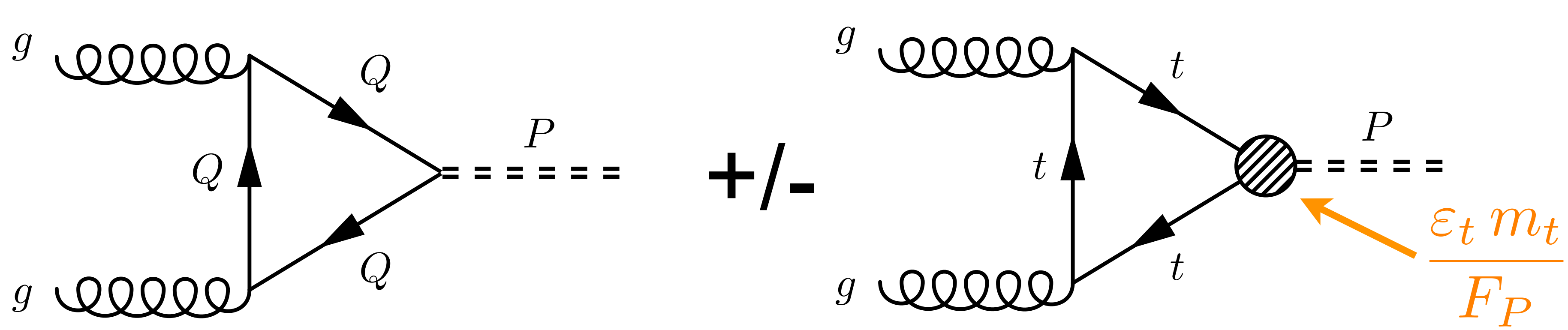




Heavy Technipion Limits: ττ

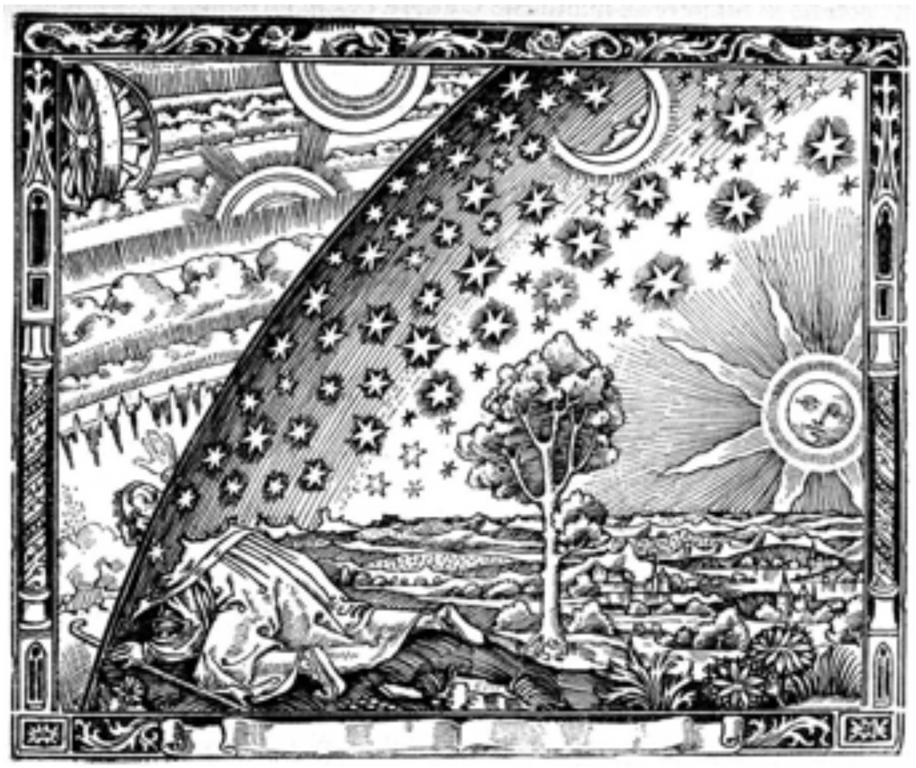






Conclusions: Part I

- ATLAS/CMS results are strongly constraining technipions in models with colored technifermions.
- We are (finally!) at the TeV frontier.



Conclusions: Part I

Report on the question from Council to the SPC

CERN/SPC/978/Rev.2
CERN/2986/Rev.2
Original: English
3 October 2011

The scientific significance of the possible exclusion of the SM Higgs boson in the mass range 114-600 GeV and how it should be best communicated

Looking further into the future, if a light Standard Model Higgs boson were eventually excluded at the 5 standard deviation level, direct searches should continue, looking for Higgs particles or other signals foreseen in models alternative to the Standard Model. For example, many models with an extended Higgs sector and/or additional particles with respect to the Standard Model, such as supersymmetry or extra dimensions, predict the existence of one or more particles that would look like a Standard Model Higgs boson, but produce a lower rate of experimentally detectable signals at the Tevatron and LHC. This would call for extending the search to larger samples of LHC data, in which these more subtle signals could be detectable. In addition, it would be crucial to study the scattering of pairs of massive vector bosons (WW, WZ, ZZ) emitted by the colliding protons.

Higgsless Models

General Principles

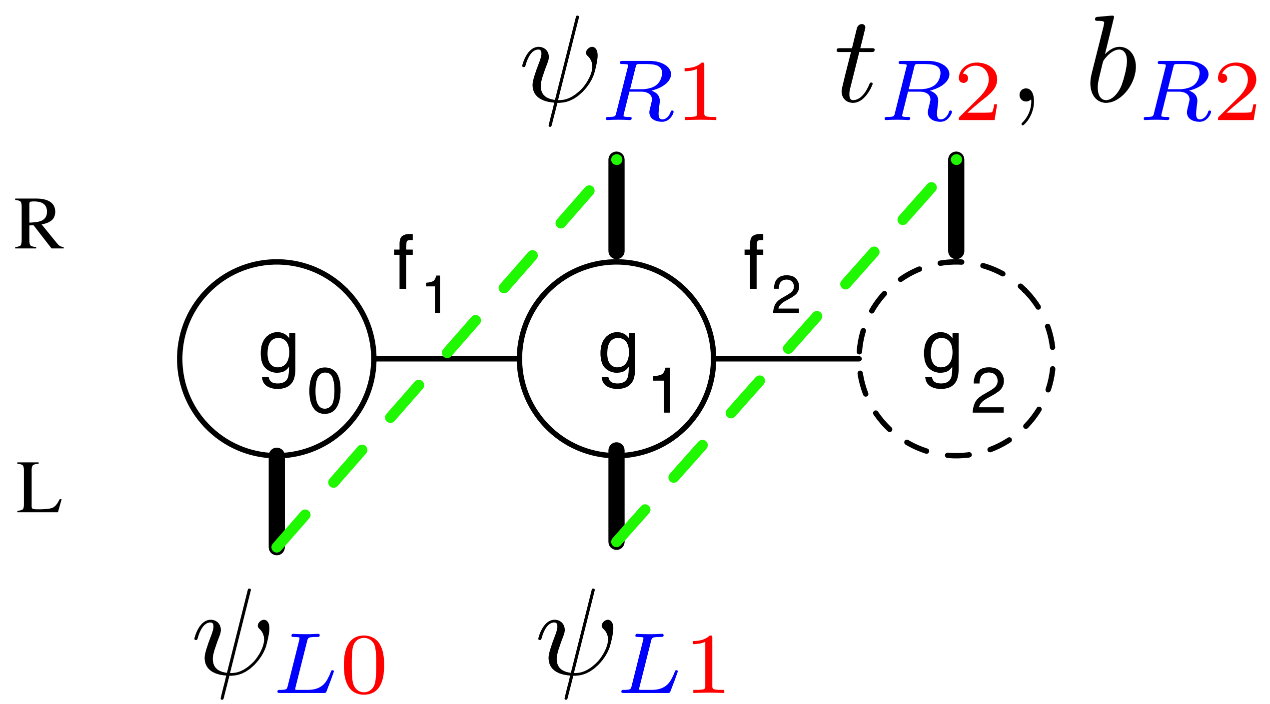
Higgsless models are low-energy effective theories of Dynamical Electroweak Symmetry Breaking with. They include:

- 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

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

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)

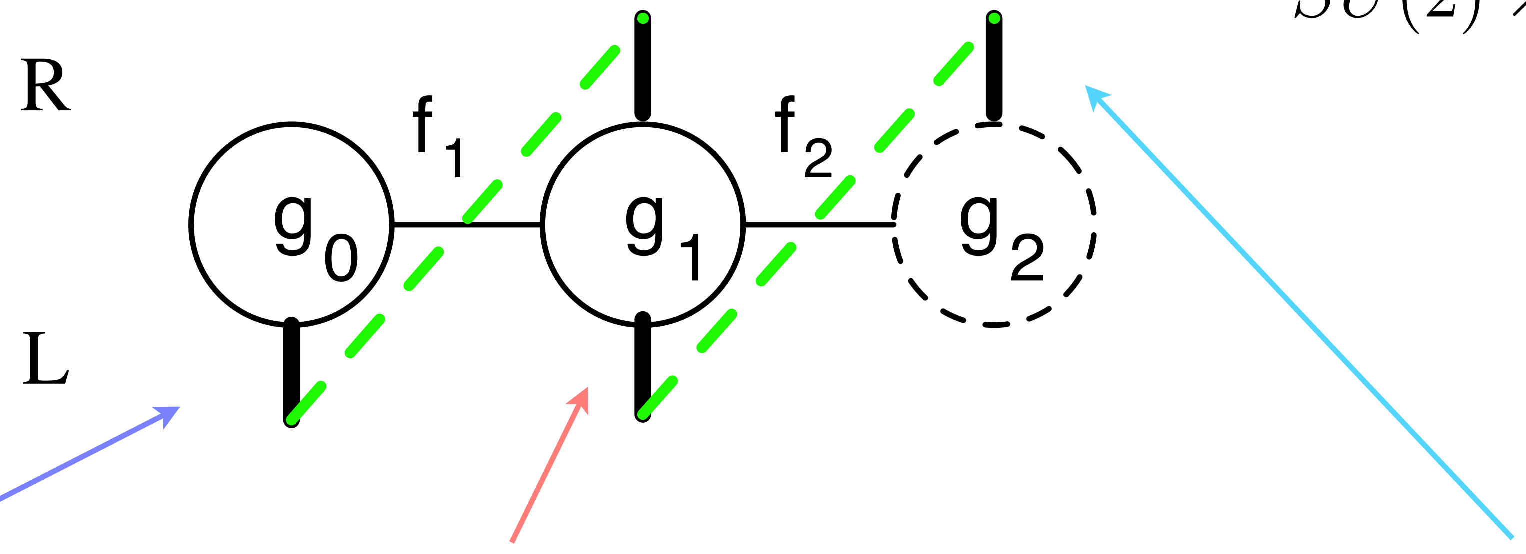
and also c,C, s,S, u,U, d,D plus the leptons

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

3-Site Fermion masses

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

$g_0,\ g_2 \ll g_1$



LH Boundary Fermion

"Bulk Fermion"

RH Boundary Fermion

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

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 $\sim$ 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

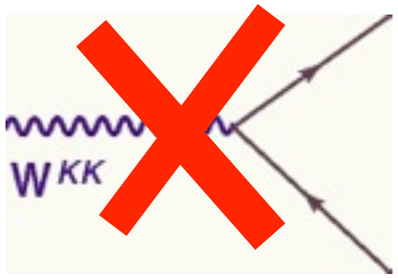
From the W, fermion eigenvectors, one solves for

$$\epsilon_L^2 \to (1+\epsilon_{fR}^2)^2 \left[\frac{x^2}{2} + \left(\frac{1}{8} - \frac{\epsilon_{fR}^2}{2} \right) x^4 + \cdots \right]$$

$$x^2 \equiv \left(\frac{g_0}{g_1}\right)^2 \approx 4 \left(\frac{M_W}{M'_W}\right)^2$$

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



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

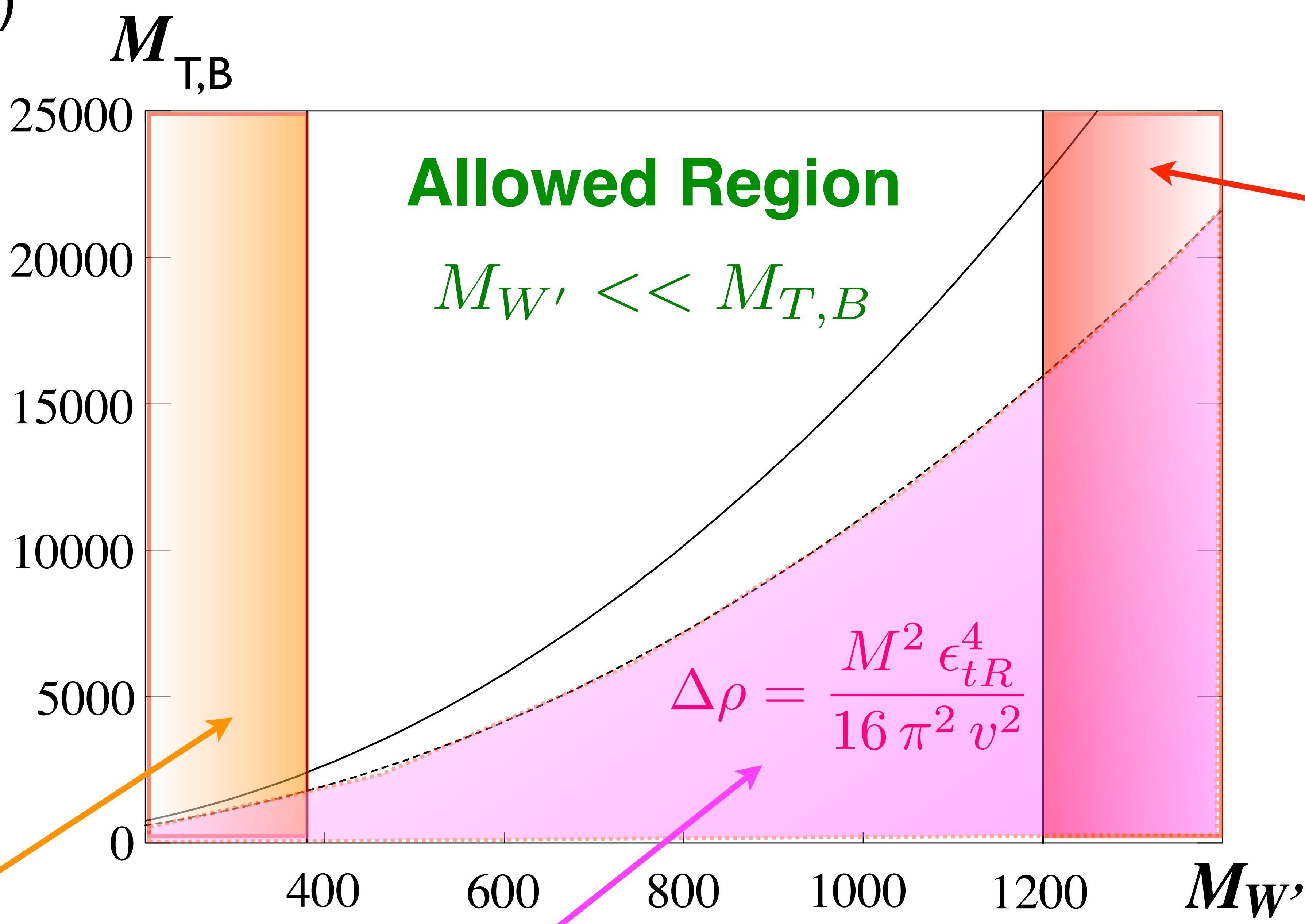
$$Y = M_W^2(\Sigma_W - \Sigma_Z)$$

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

3-Site Parameter Space

Chivukula et al. hep-ph/0607124

KK fermion mass (GeV)



Unitarity violated

W' mass (GeV)

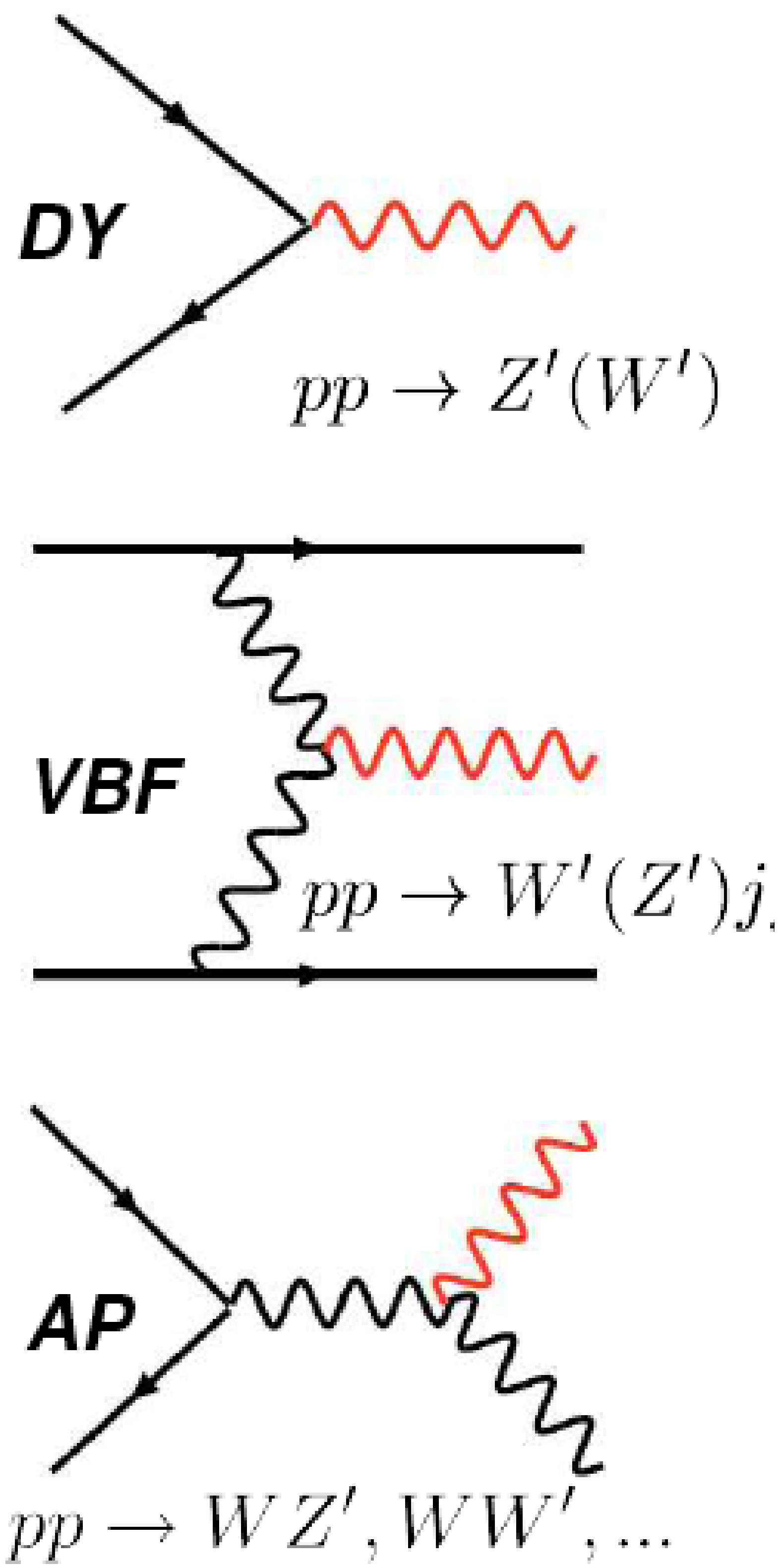
WWZ vertex visibly altered

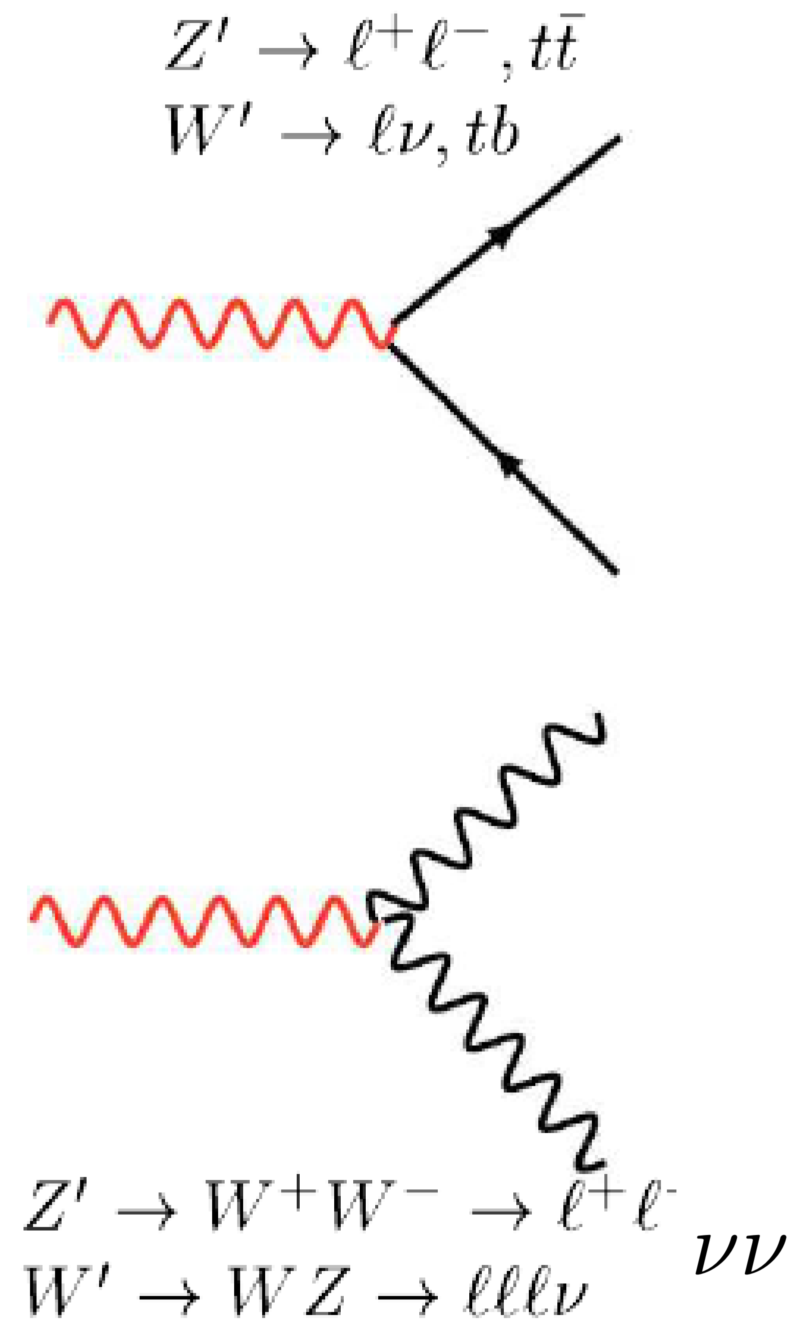
1-loop fermionic EW precision corrections too large

LHC Phenomenology

RSC, EHS, H.-J. He, Y.-P. Kuang, et. al. arxiv: 0708.2588

W',Z' Production and Decay at LHC

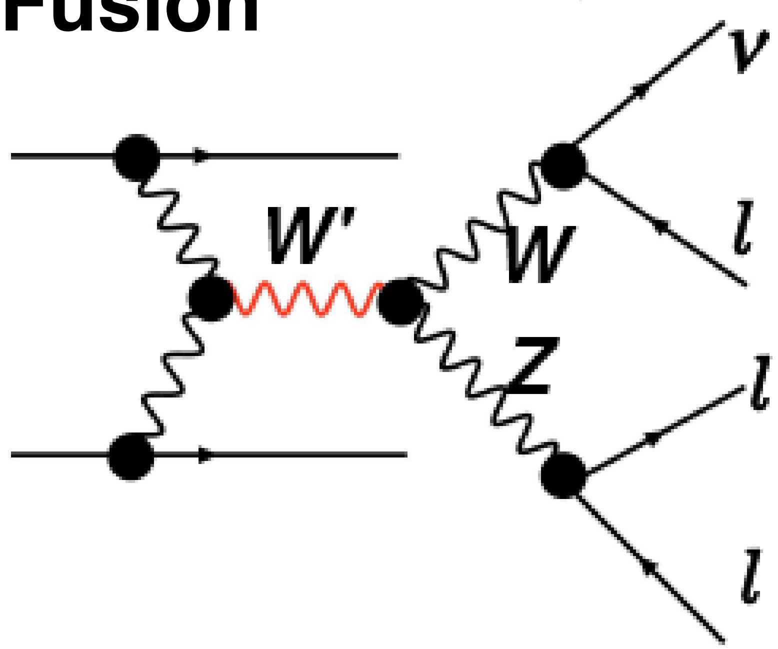




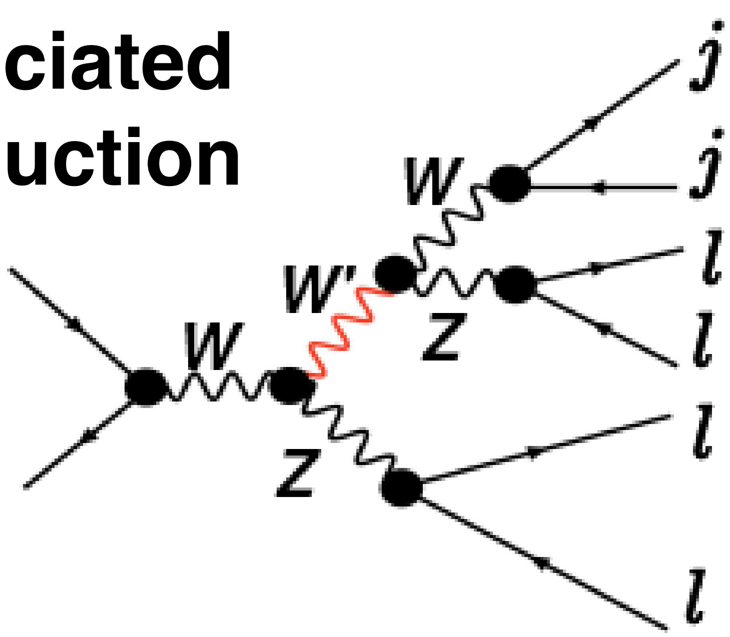
W' production at LHC

Two processes with large rates and clear signatures!

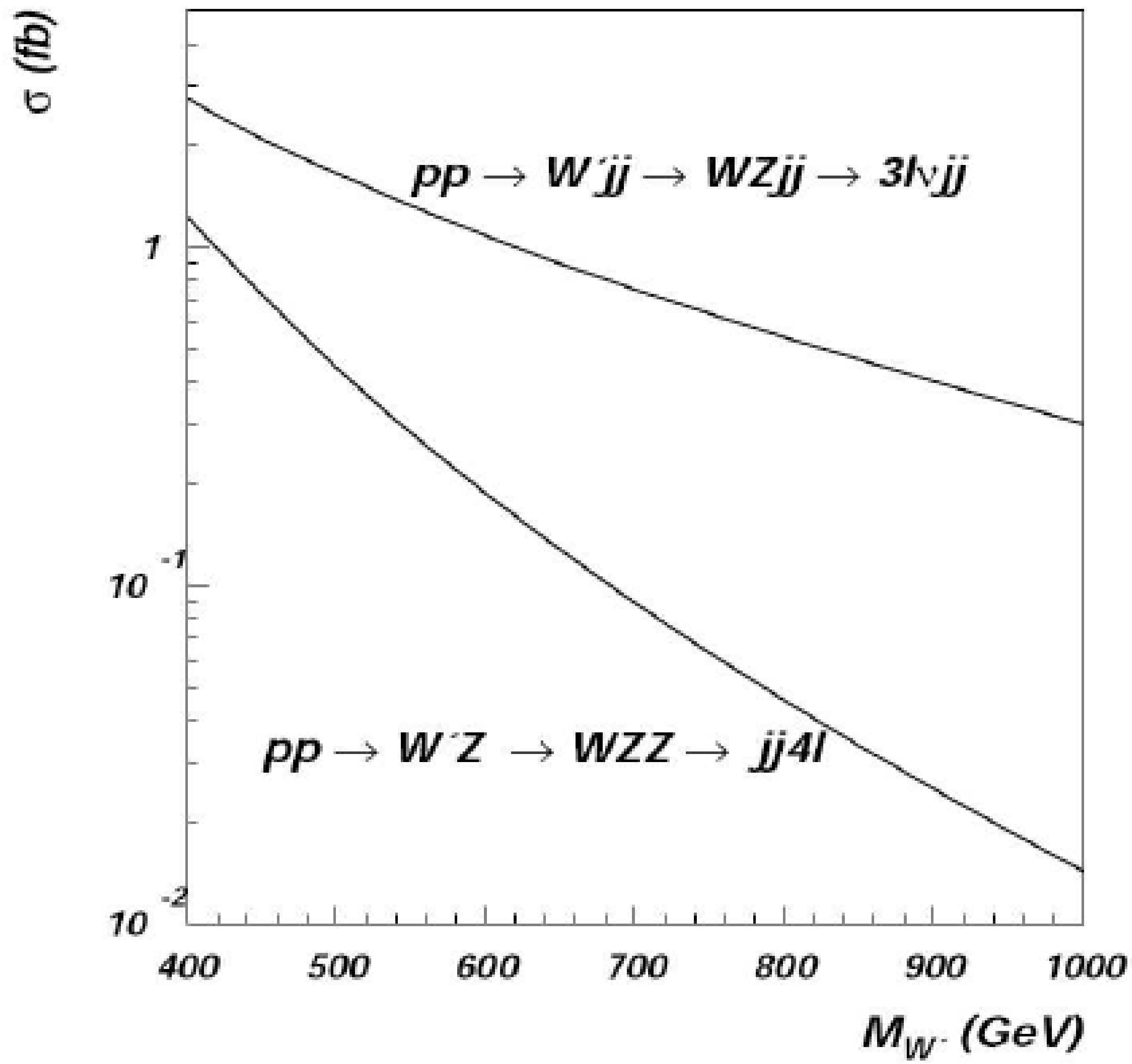
Vector Boson Fusion



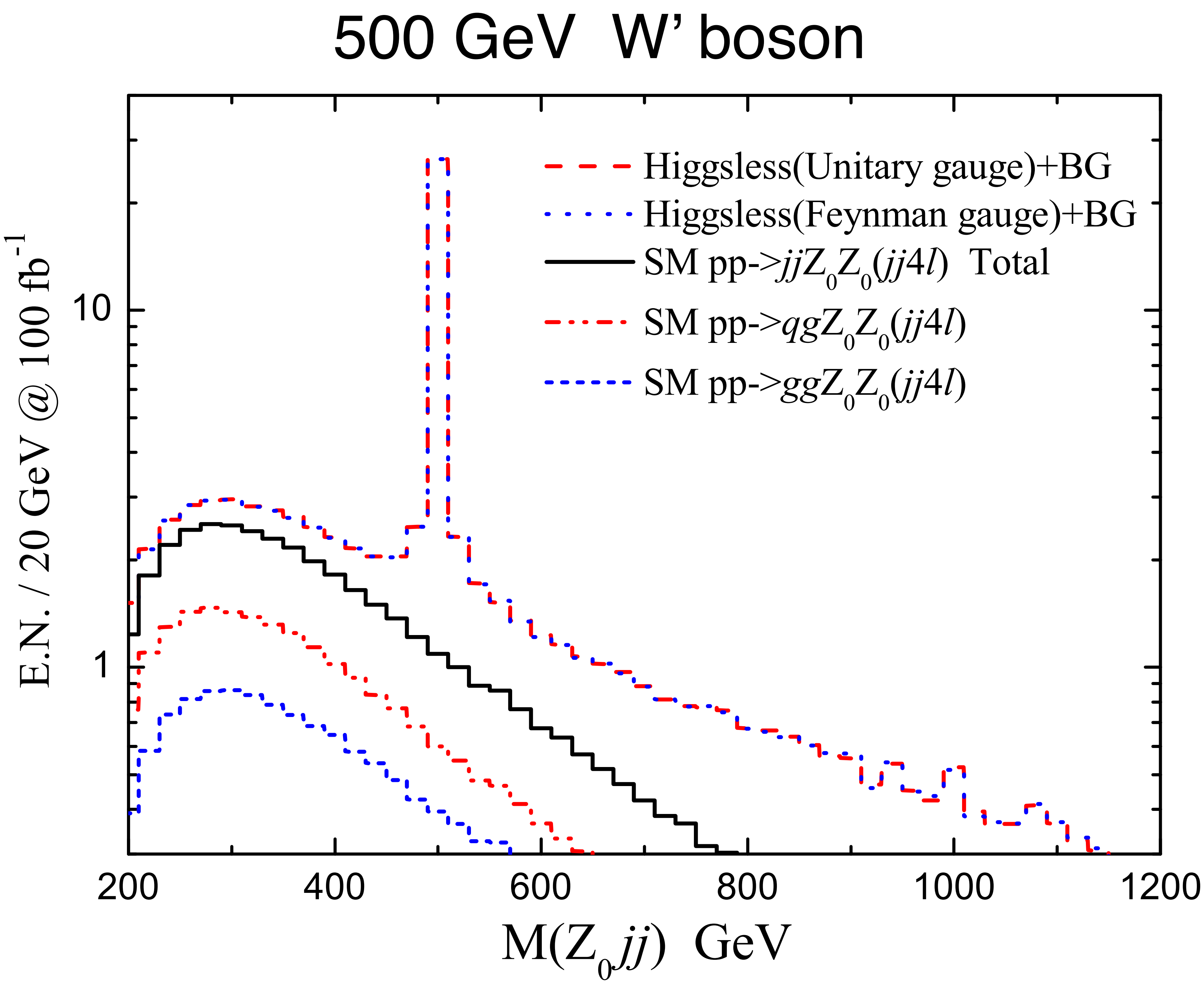
Associated Production



LHC @14 TeV



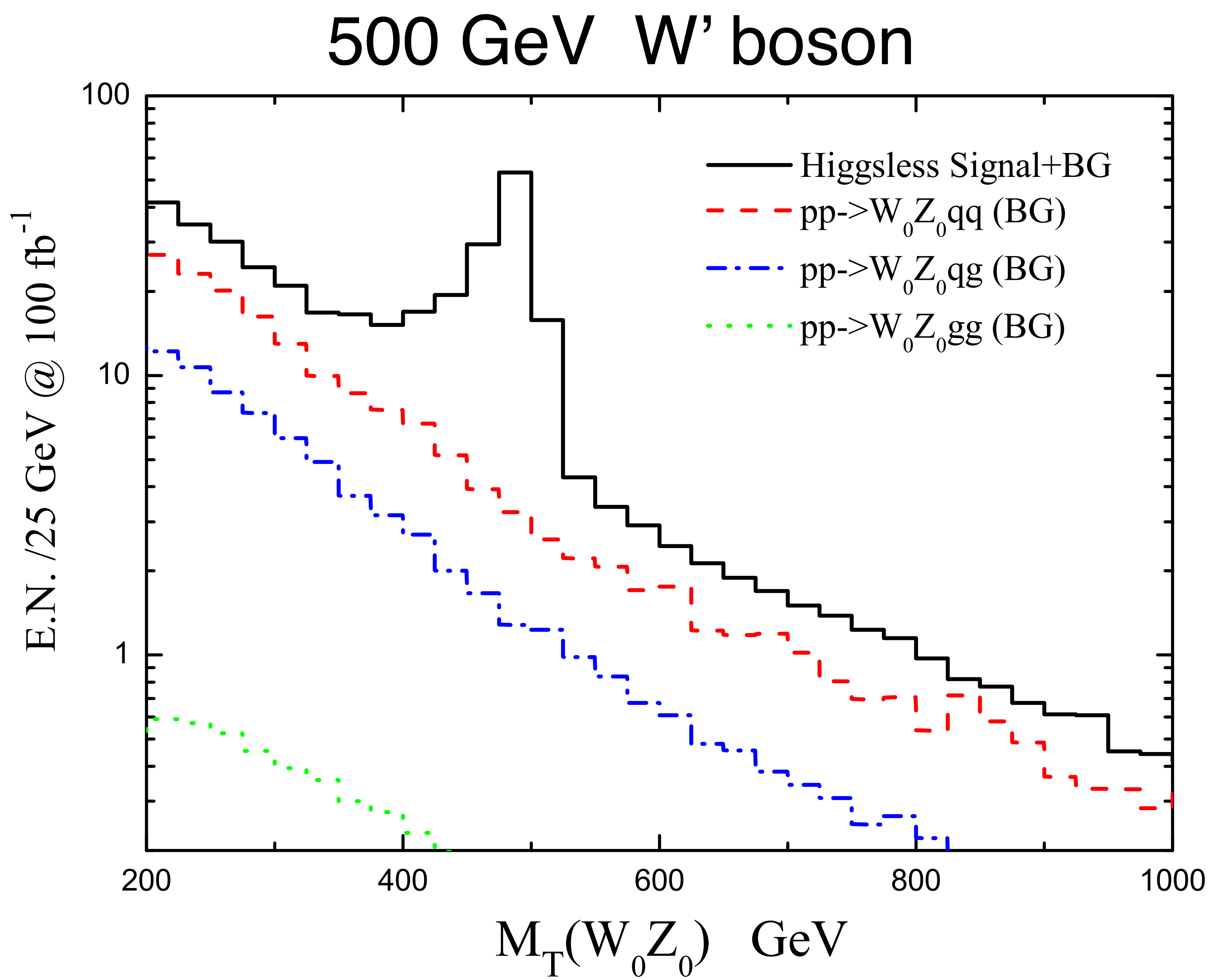
Associated Production (WZZ channel)



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

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

Vector Boson Fusion (WZjj channel)



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

forward jet tag removes WZ background

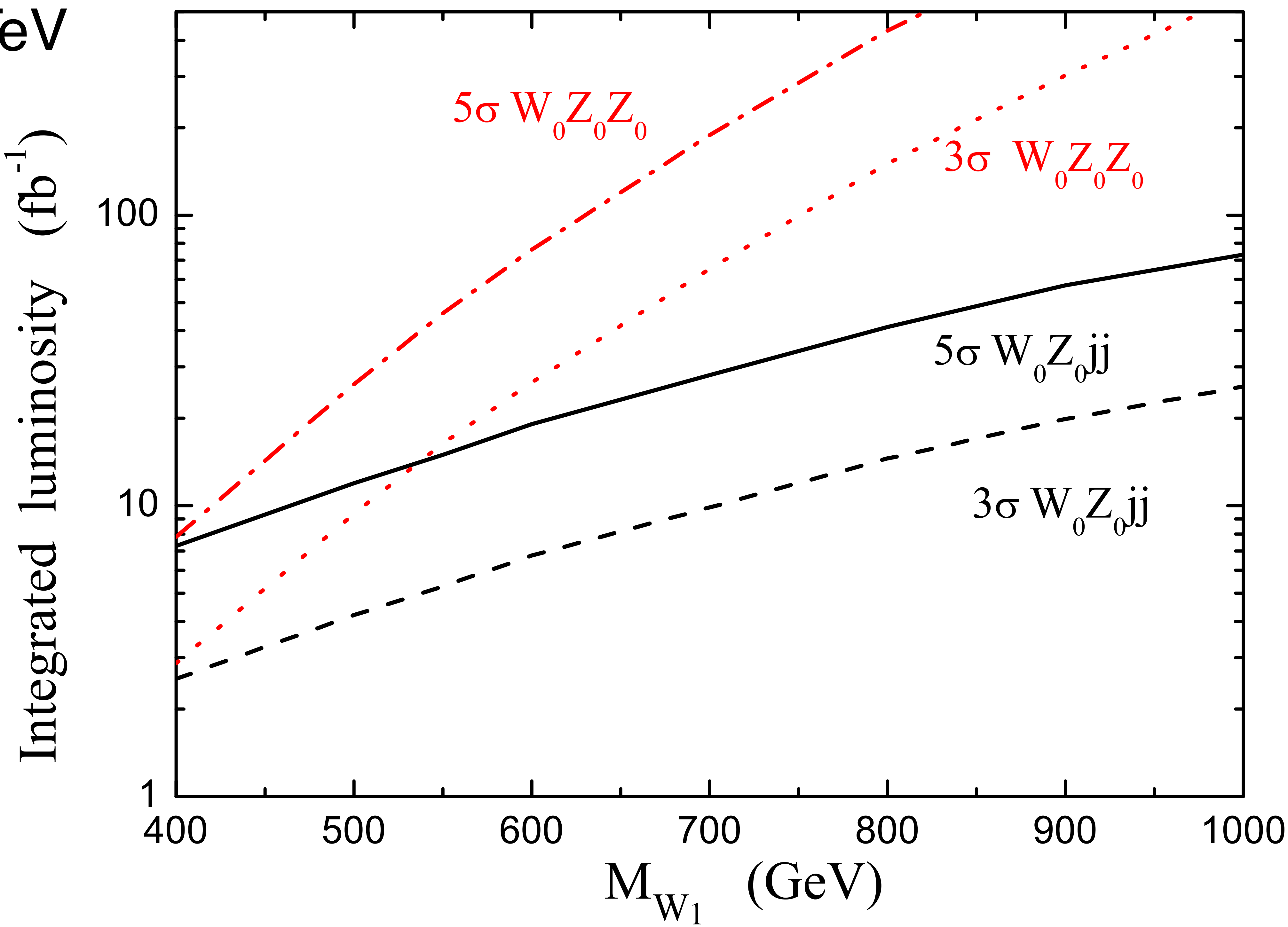
$$E_j > 300\,\text{GeV}\,, \qquad p_{Tj} > 30\,\text{GeV}\,, \qquad |\eta_j| < 4.5\,, \qquad |\Delta\eta_{jj}| > 4\,,$$

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

Integrated Luminosity for W' Discovery

LHC at
14 TeV

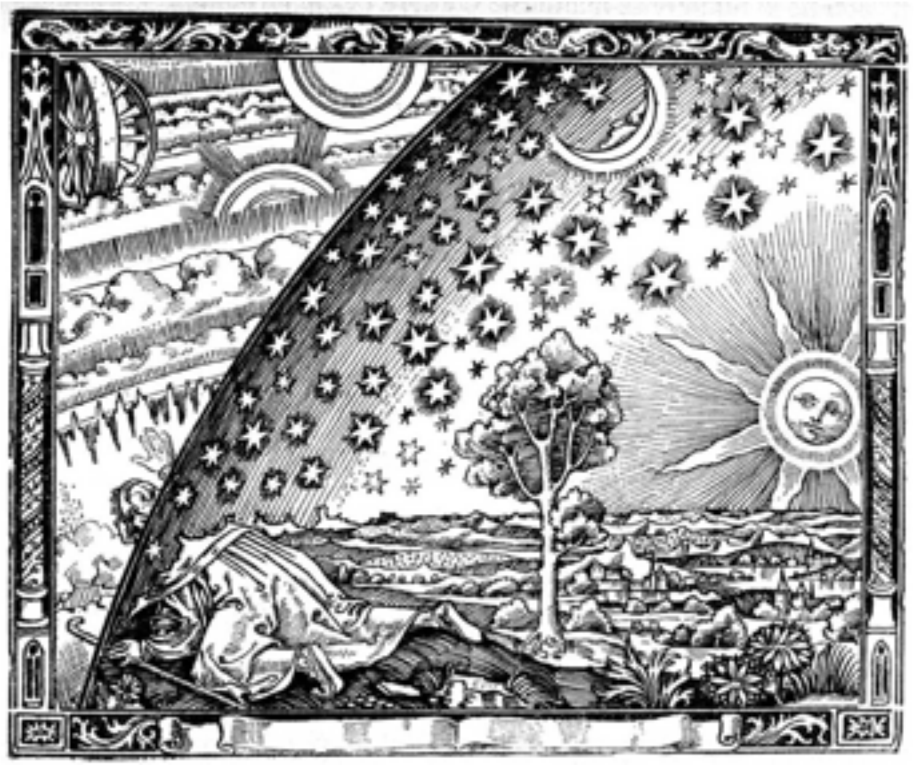
Associated



Fusion

Conclusions: Part II

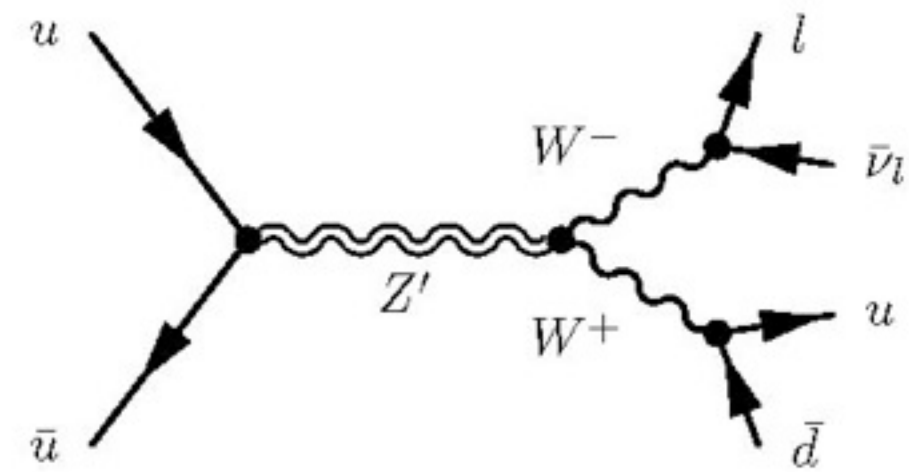
- ATLAS/CMS will have substantial reach in Higgsless models as well, at 14 TeV.
- Investigations at 7 TeV are underway.

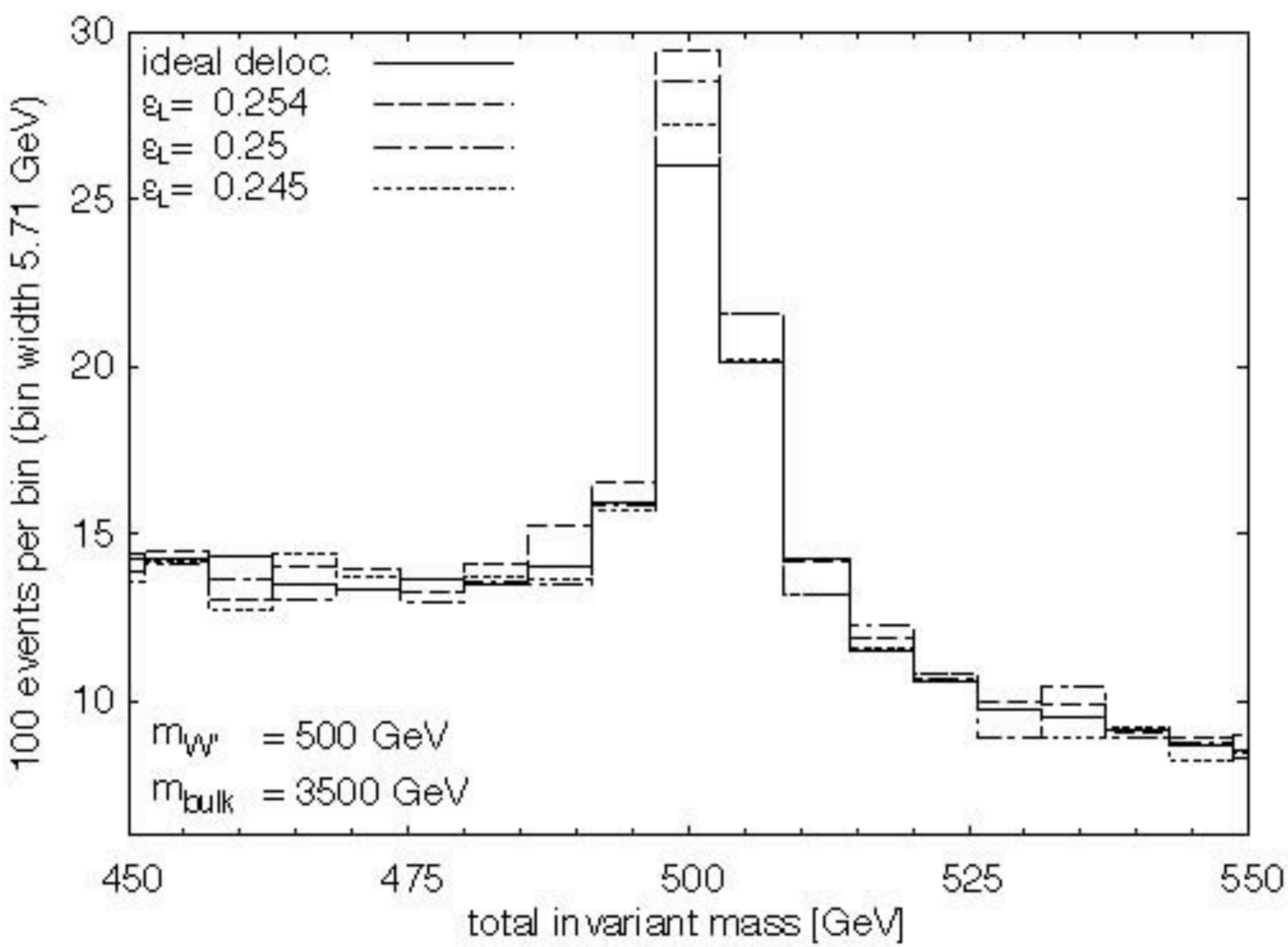


Backup Slides

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