Non-standard EWSB scenarios

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Outline

Spontaneous Symmetry Breaking

Beyond the SM: New Physics at the Terascale

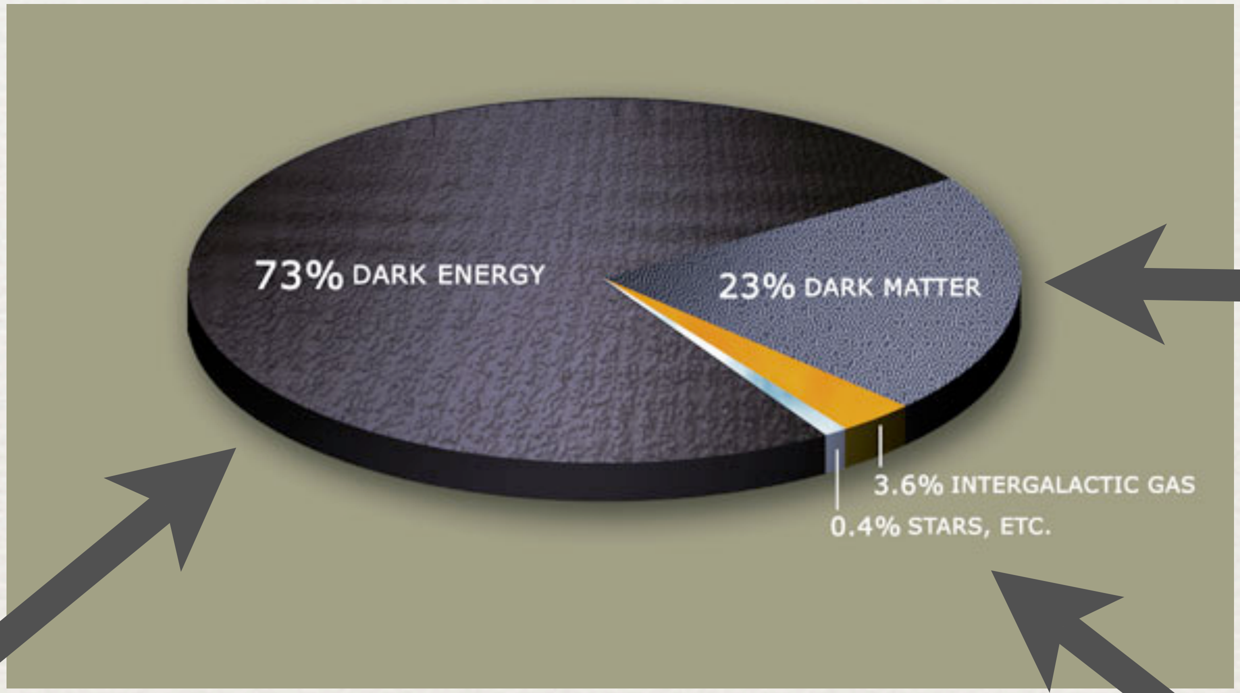
Non-Standard EWSB scenarios

Composite Higgs

Higgsless

Spontaneous Symmetry Breaking

FACT: We don't understand most of the Universe



Some new form of matter

Particle Physics?

Us

The origin of mass in the SM

good story, unknown ending

SM is based on gauge symmetries

The origin of mass in the SM

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SM is based on gauge symmetries

$$\phi(x) \rightarrow e^{i\alpha(x)}\,\phi(x)$$

physical degrees of freedom

GAUGE BOSONS

Force carriers

Gauge symmetry conserved $\rightarrow$ Force carriers are massless

$\downarrow$

Force is long range

This picture works extremely well with EM

QED

$$\frac{1}{\alpha} = 137{,}035\ 999\ 084\ (33)(39)$$

theory

BUT

SM also theory of weak interactions

Weak interactions are short range

$$\frac{1}{r^2} \rightarrow \frac{e^{-r/r_0}}{r^2}$$

$$r_0 \sim 10^{-18}\ \mathrm{m} \longrightarrow m \sim 100\ \mathrm{GeV}$$

Force carrier

massive $\longrightarrow$ Symmetry is broken

So, we have to break the symmetry

So what!? That's a no-no

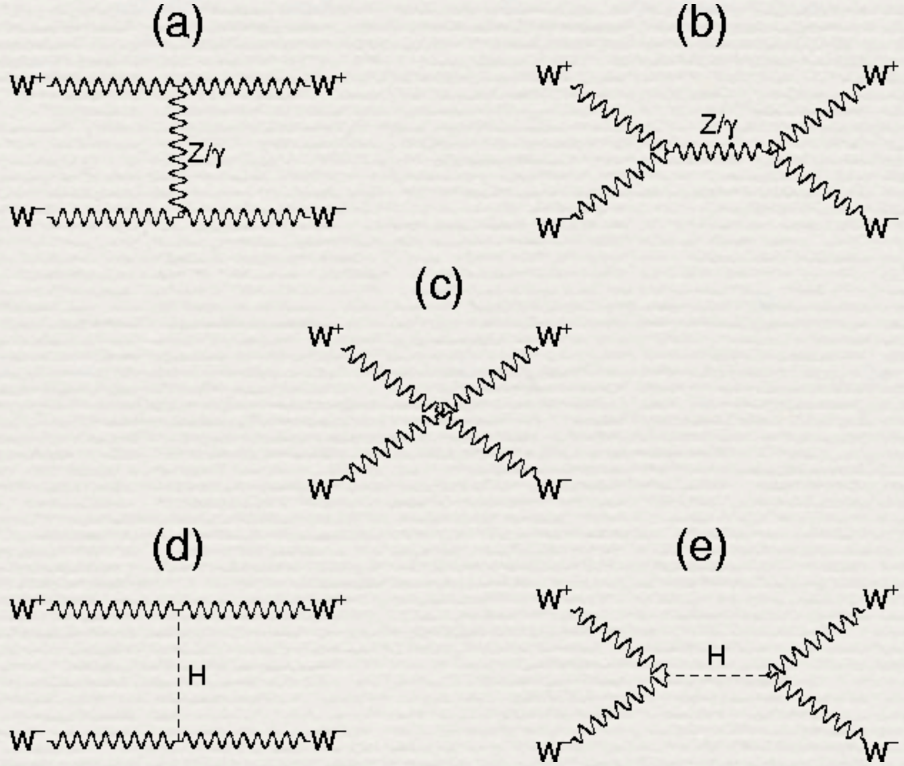
So, we have to break the symmetry

So what!? That's a no-no

How do we compute in Particle Physics?

$$\mathcal{L}_{\rm physical} = \mathcal{L}_{\rm clas} + \mathcal{L}_{\rm qua} + \mathcal{L}_{\rm reg}$$

Physical quantities



If we just add a mass term to the classical theory

$$\mathcal{L}_{\text{weak}} + m_Z^2\, Z^2$$

We can't regularize the theory!

Conclusion

massive force carrier=no predictions?

divergences cancelled if precise adjustment of constants?

Feinberg, 1958

→ Fine-tuning

The solution

Spontaneous Symmetry Breaking

The solution

Spontaneous Symmetry Breaking

Lagrangian preserves the symmetry

BUT

the vacuum of the theory doesn't

The solution

Spontaneous Symmetry Breaking

Lagrangian preserves the symmetry
BUT
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SM way: the Higgs mechanism

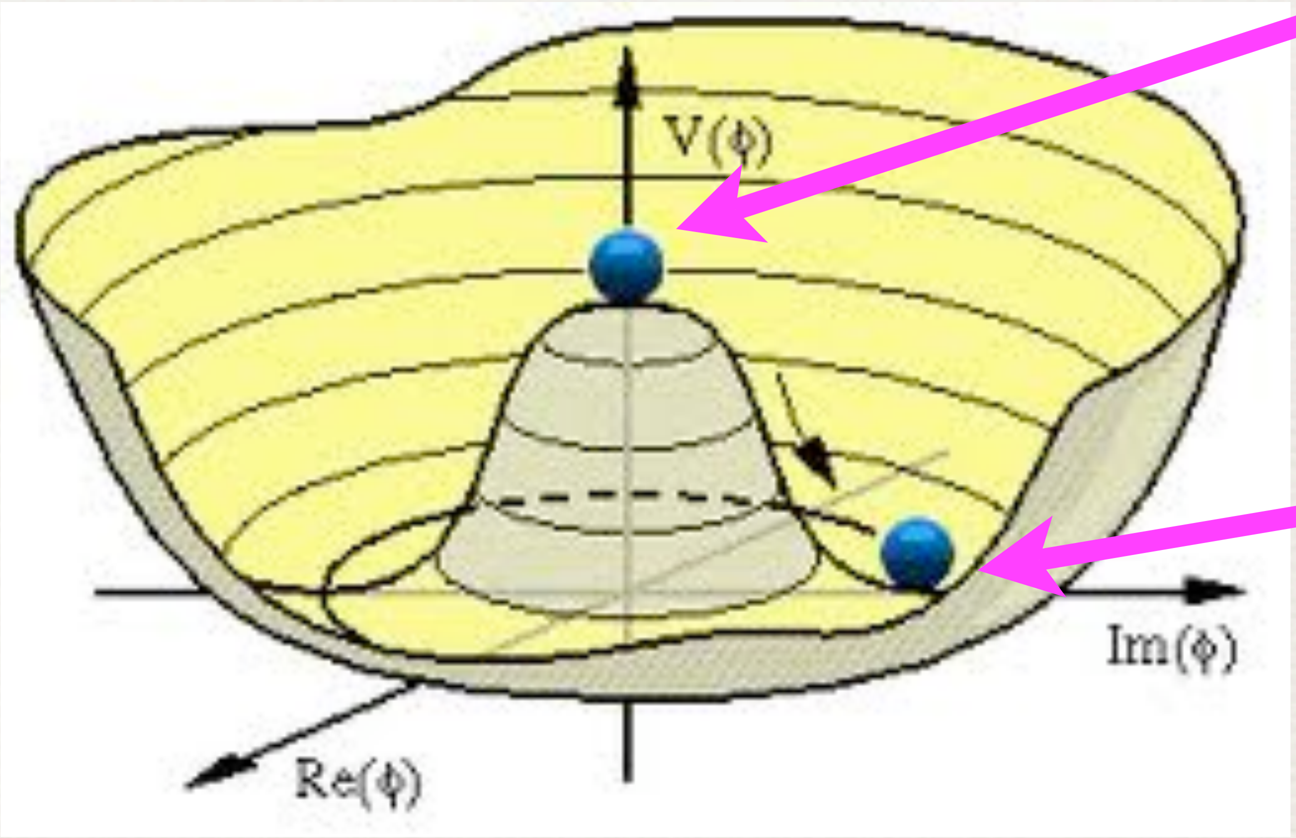
$$(D\,H)\,(D\,H)^{\dagger} - V(H)$$

$$D\,H \equiv \partial\,H - ig\,A_{ew}\,H$$

Higgs = Scalar charged under EW interactions

Scalar=no Lorentz structure

Higgs potential



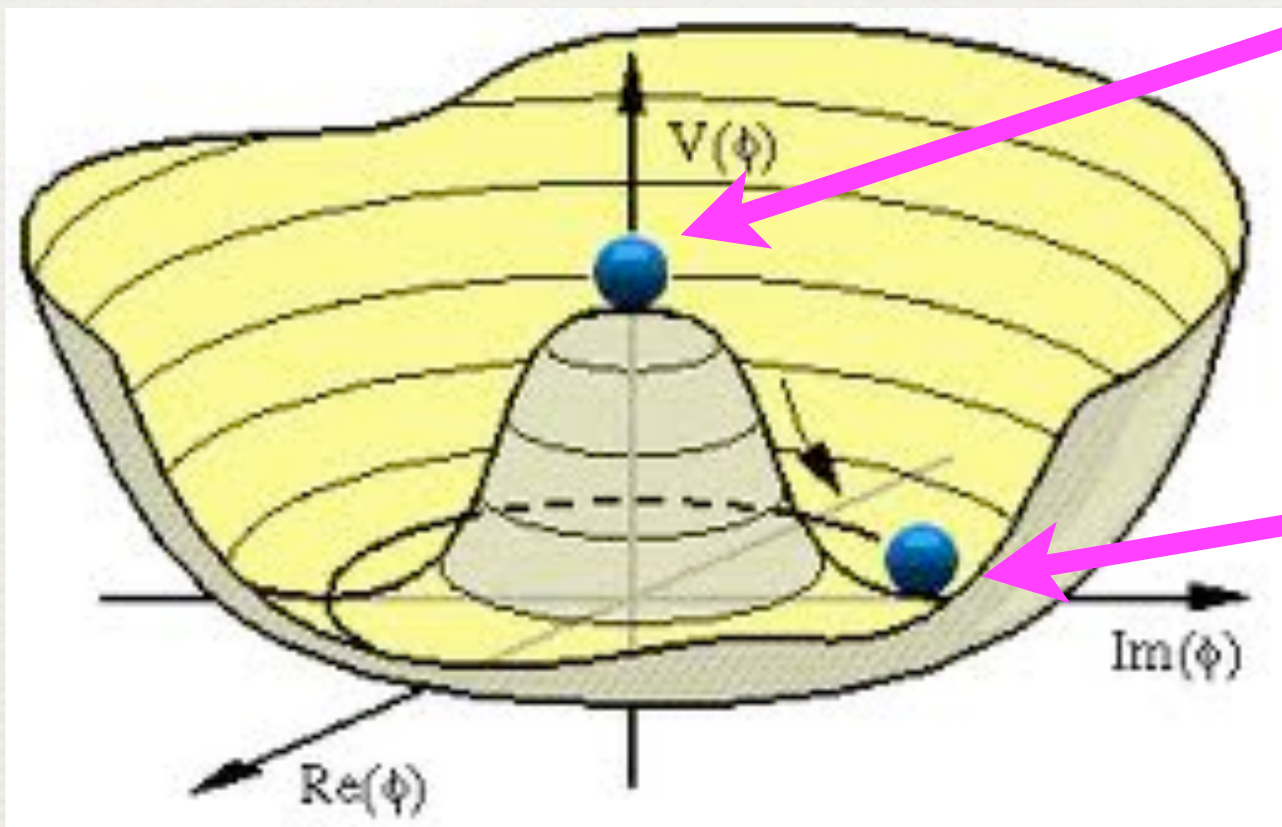
False vacuum

True vacuum

Scalar=no Lorentz structure

Higgs potential

False vacuum



True vacuum

Physics=expand around true vacuum

$H \to H - \langle H \rangle$ Breaks EW symmetry

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Shift = masses for EW force carriers

$$(D\,H)\,(D\,H)^\dagger \to g^2 \langle H \rangle^2 A_{ew}^2 = m_{ew}^2 A_{ew}^2$$

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no new infinities to deal with

shift doesn't change the UV structure of the theory

secret renormalizability

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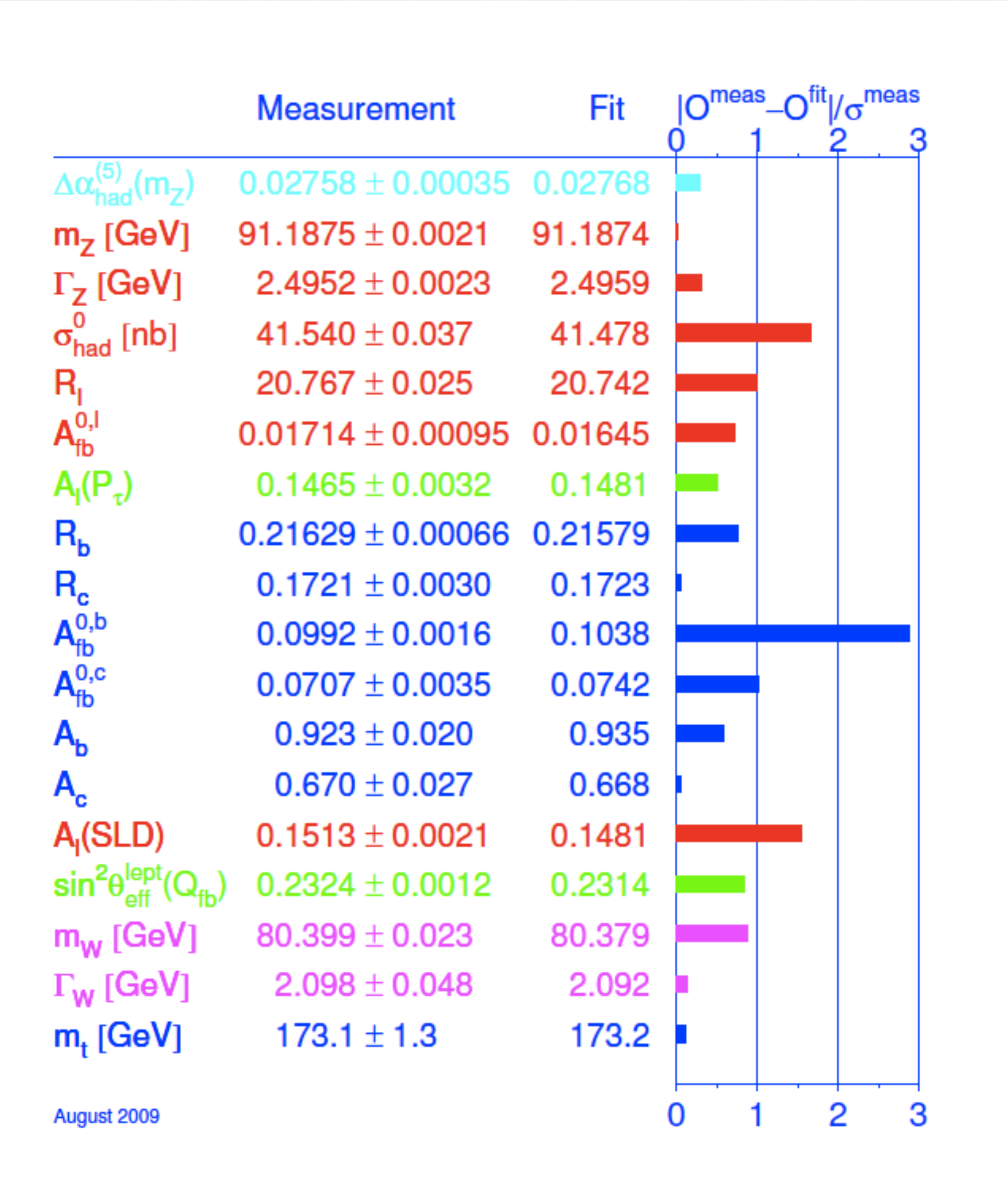
Conclusion

Spontaneous Symmetry Breaking=

predictive theory of massive force carriers

EWPTs



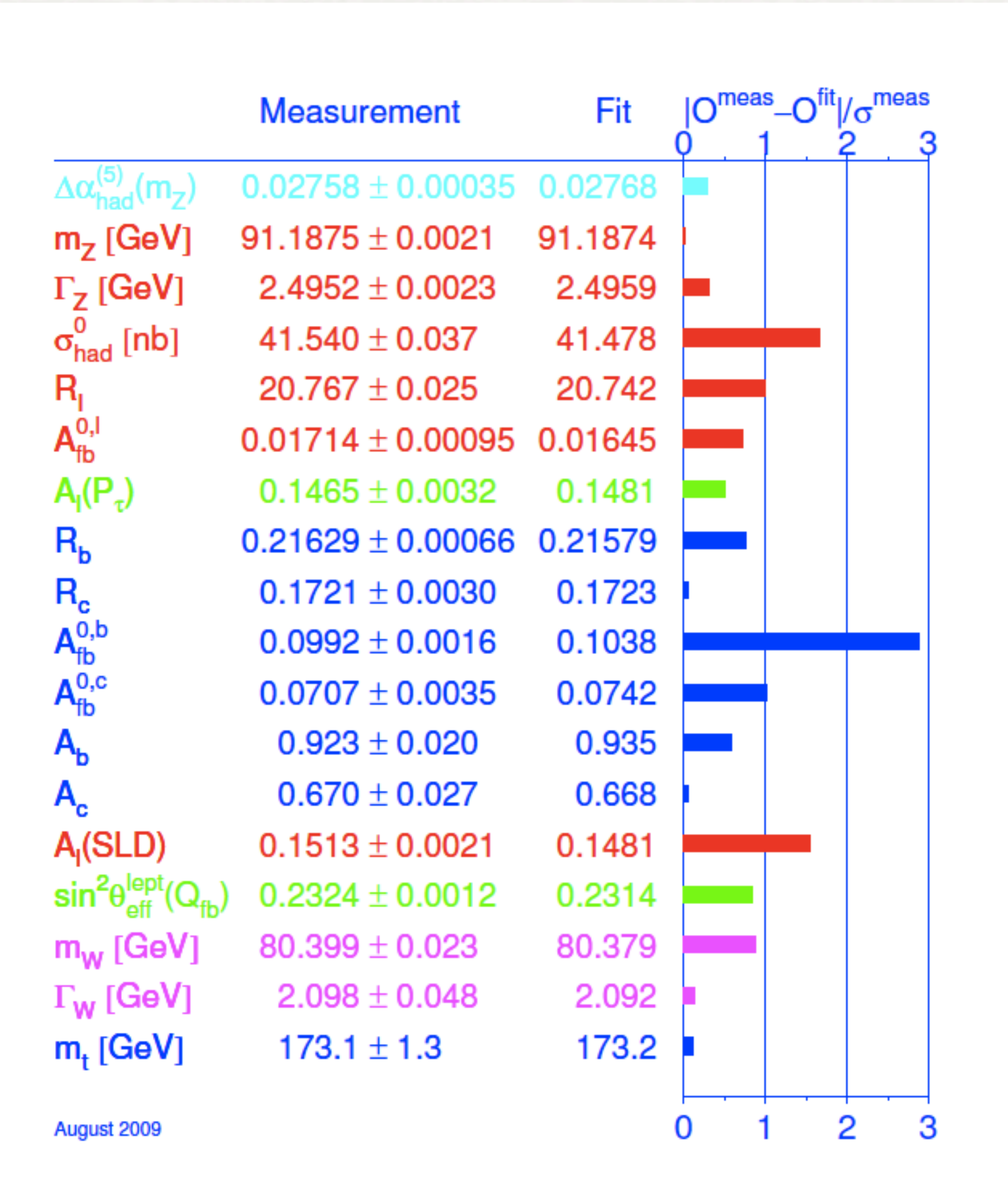
SM way:

forces are local symmetries

EW symmetry is spontaneously broken

outstanding success

EWPTs



SM way:

forces are local symmetries

EW symmetry is spontaneously broken

outstanding success

W,Z discovery just the beginning

EWTPs characterization

principle: EWSB

TOKEN: masses for everybody!

Yukawa interactions preserve EW

$$y_\Psi H \bar{\Psi}\Psi \to y_\Psi \langle H \rangle \bar{\Psi}\Psi$$

EWSB is the origin of mass:

short range forces AND massive fermions

TOKEN: masses for everybody!

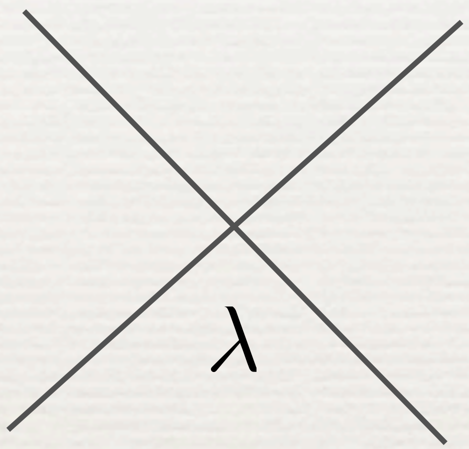
Yukawa interactions
preserve EW

$$y_\Psi H \bar{\Psi}\Psi \to y_\Psi \langle H \rangle \bar{\Psi}\Psi$$

$$\boxed{\begin{array}{c}\text{Conclusion}\\ \text{Higgs, and only Higgs=}\\ \text{origin of SM masses?}\end{array}}$$

Nice story, unknown ending

1.) Higgs sector is incomplete



$$\langle H \rangle^2 \sim m_h^2/\lambda$$

Interacting Higgs
after LEP, quartic order 1

Nice story, unknown ending

1.) Higgs sector is incomplete

$$\langle H\rangle^2 \sim m_h^2/\lambda$$

Interacting Higgs
after LEP, quartic order 1

Triviality & stability= need new physics @ high scale
or theory is trivial or unstable(=no SSB)

Nice story, unknown ending

1.) Higgs sector is incomplete

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Interacting Higgs
after LEP, quartic order 1

Triviality & stability= need new physics @ high scale
or theory is trivial or unstable (=no SSB)

2.) New Physics talking to the Higgs=disaster

Why New Physics+Higgs = disaster?

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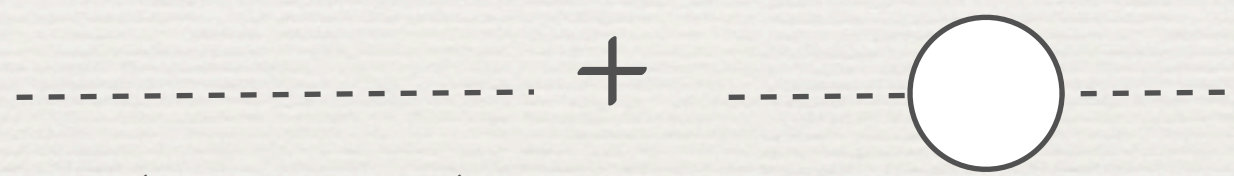
Higgs is a new type of particle: scalar

Any new states coupled to the Higgs: threshold correction



classical quantum

$$m_{tree}^2 \quad + \quad \delta m_H^2$$

$$\delta m_H^2 \sim M_{new}^2$$

$$m_{phys} \sim M_{new}$$

or cancellations

1. Triviality, stability $\rightarrow$ New States

2. Quantum corrections $\rightarrow$ Higgs mass ~ largest scale

$\boxed{\text{Conclusion: Higgs mass is at least TeV, possibly Planck}}$

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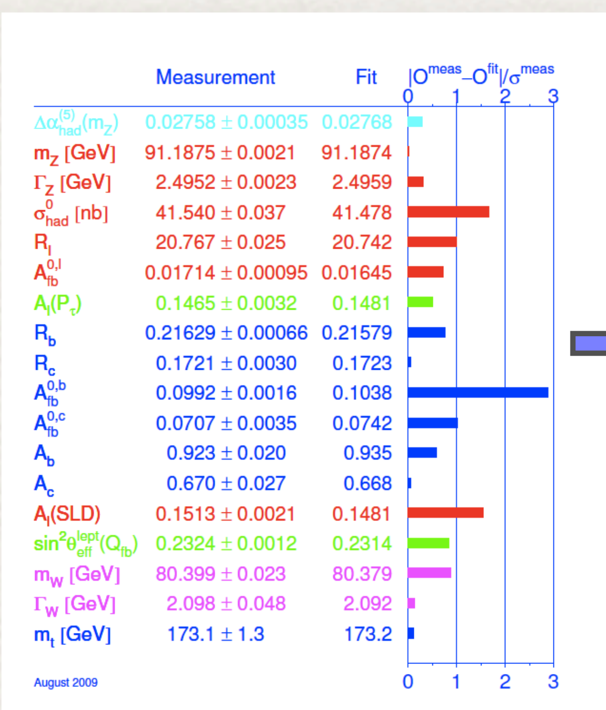
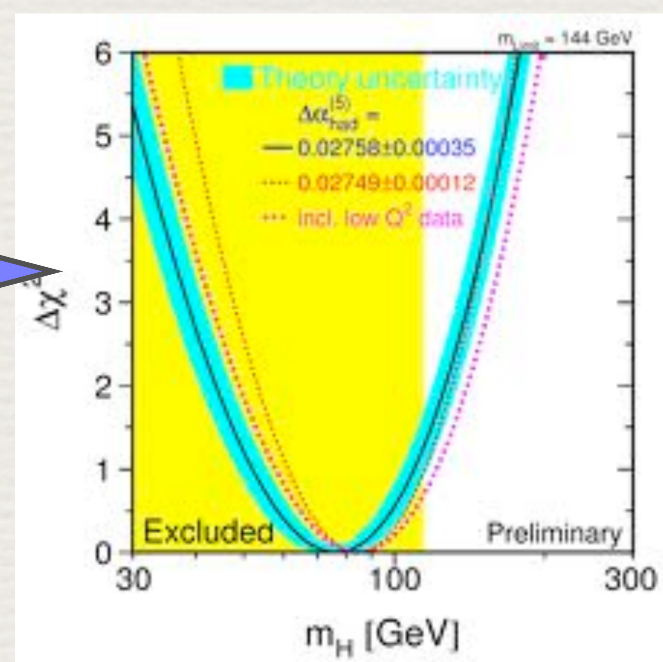
2. Quantum corrections → Higgs mass ~ largest scale

Conclusion: Higgs mass is at least TeV, possibly Planck

BUT





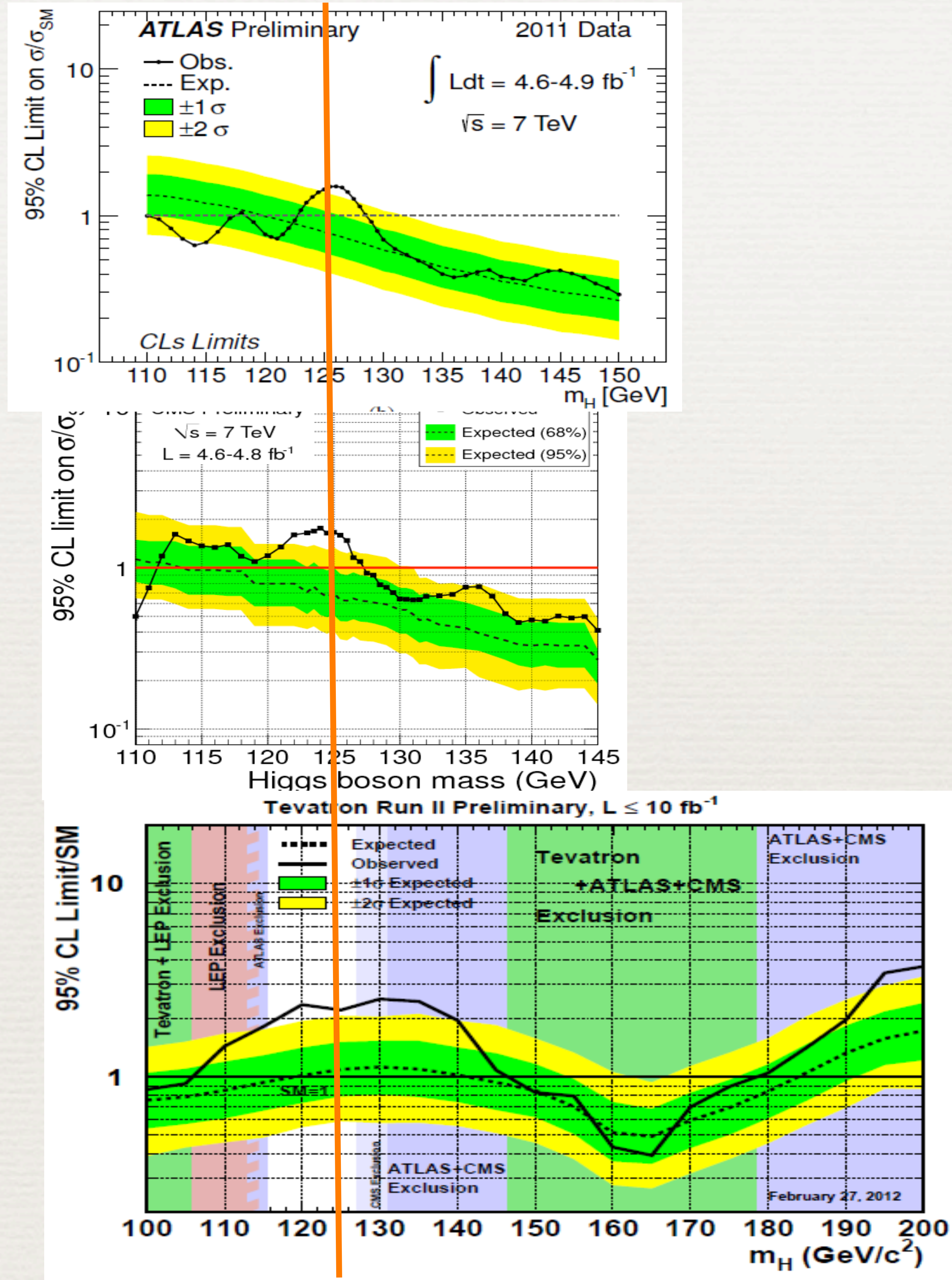
EWPTs

Higgs below ~200 GeV

Indeed

Exciting news
from Moriond

ATLAS, CMS and
TeVatron
hints of a Higgs
around 125 GeV



Option#1 No Higgs

something else breaks EW symm

unitarization WW scattering =

something else MUST be @TeV

Option#1 No Higgs

something else breaks EW symm

unitarization WW scattering ⇒

something else MUST be @TeV

Option#2 Higgs

Need (very special) new physics

Option#1 No Higgs

something else breaks EW symm

unitarization WW scattering ⇒

something else MUST be @TeV

Option#2 Higgs

Need (very special) new physics

TeV physics is the origin of SM masses

Beyond the SM: New Physics at the Terascale

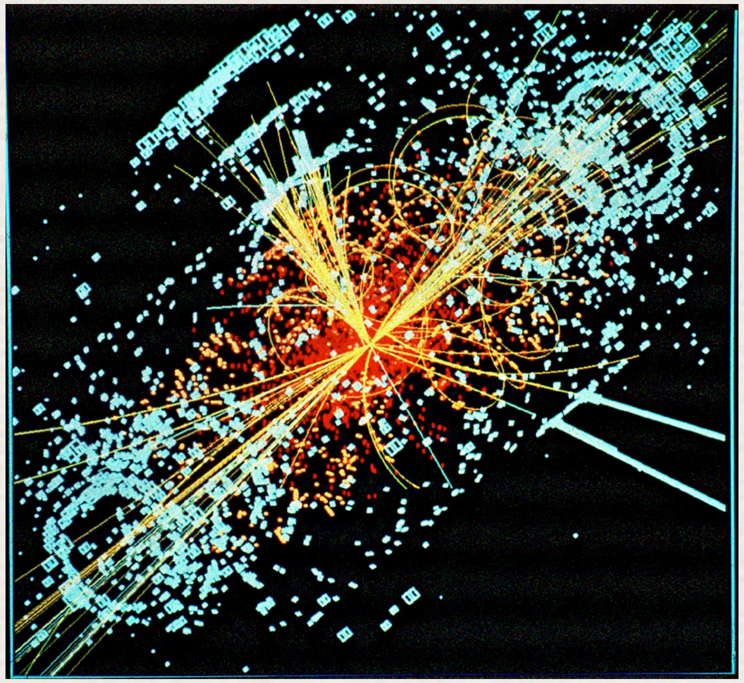
Principle: Spontaneous symmetry breaking

Realization?

Principle: Spontaneous symmetry breaking

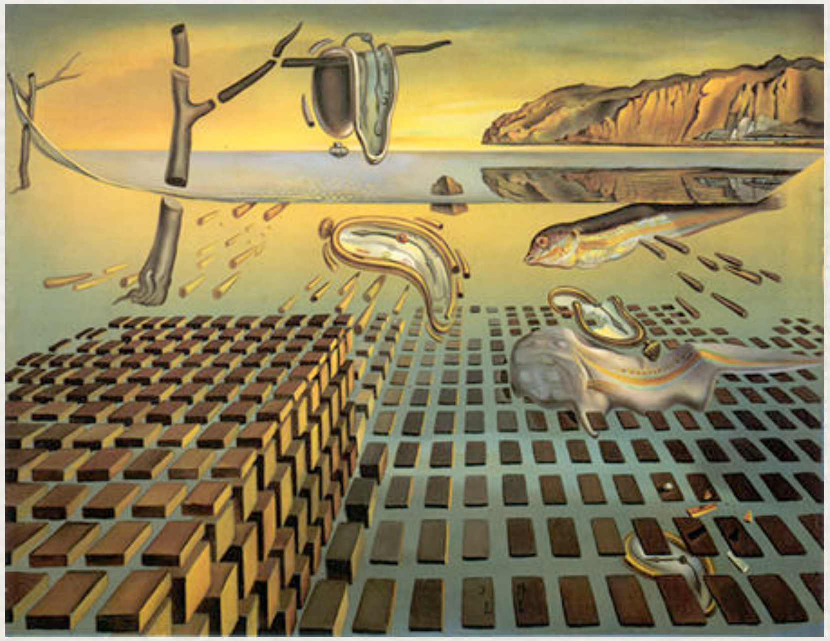
Realization?

Higgs particle



Superconductivity

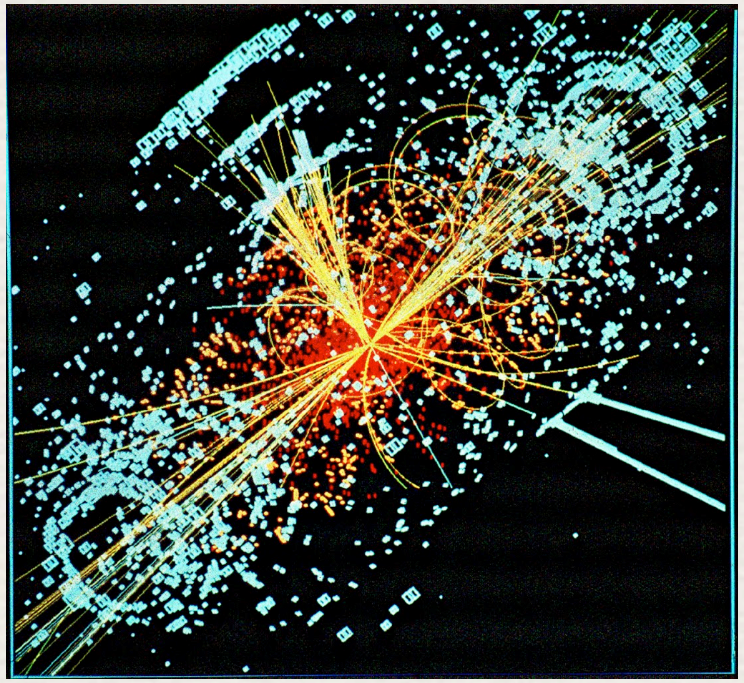
Compactification



Principle: Spontaneous symmetry breaking

Realization?

Higgs particle



A scalar particle ad hoc properties
needs fine-tuning

as in the massive force carriers:
new principle? Supersymmetry?

Principle: Spontaneous symmetry breaking

Realization?

Superconductivity

Known and natural (no fine-tuning)

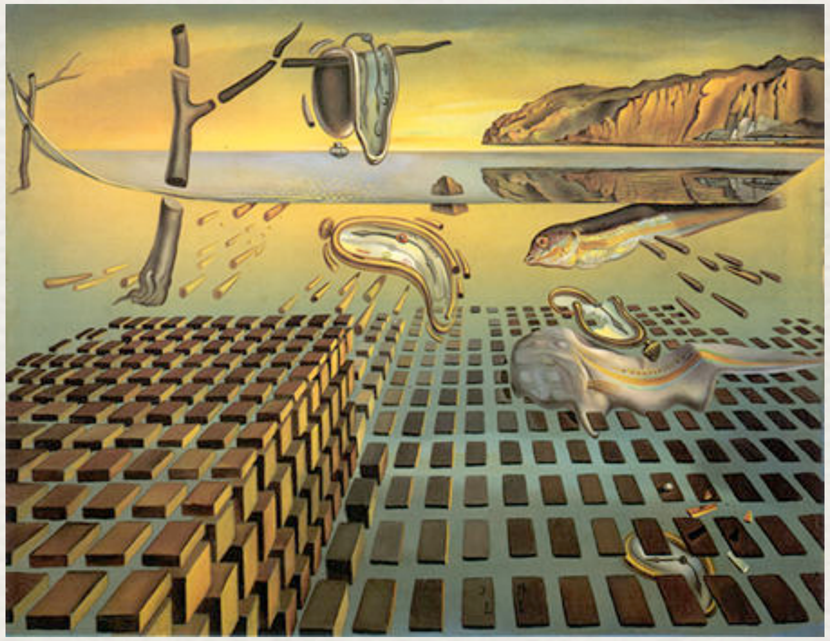
fermions/vectors tightly bound to each other condense

aka Technicolor

Principle: Spontaneous symmetry breaking

Realization?

Compactification



Particles live in more than 4D

some dimensions are boxes

zero-point energy=mass

aka Extra-Dimensions:

UED, RS...

Ideas on mechanisms for EWSB abound

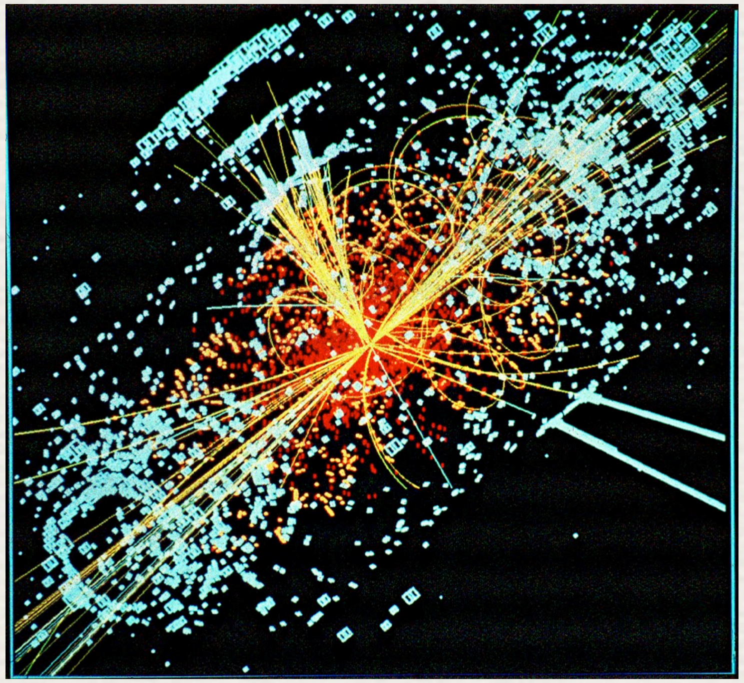
LHC= window to TeV scale

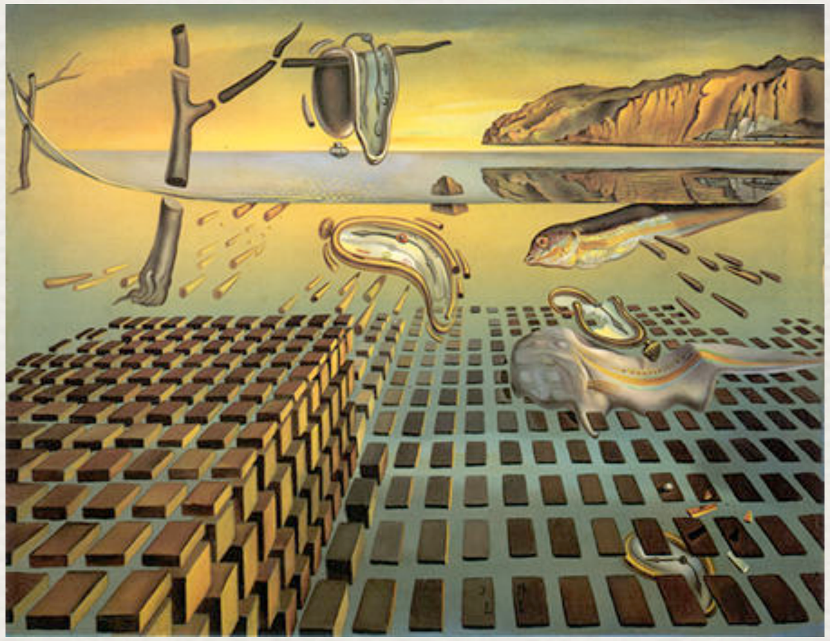
Exciting times for New Physics

Higgs particle

Superconductivity

Compactification





Non-Standard EWSB scenarios

In this talk

What is standard?

EWSB by elementary Higgs(es)

includes SM and SUSY

What is non-standard?

EWSB by

-composite Higgs

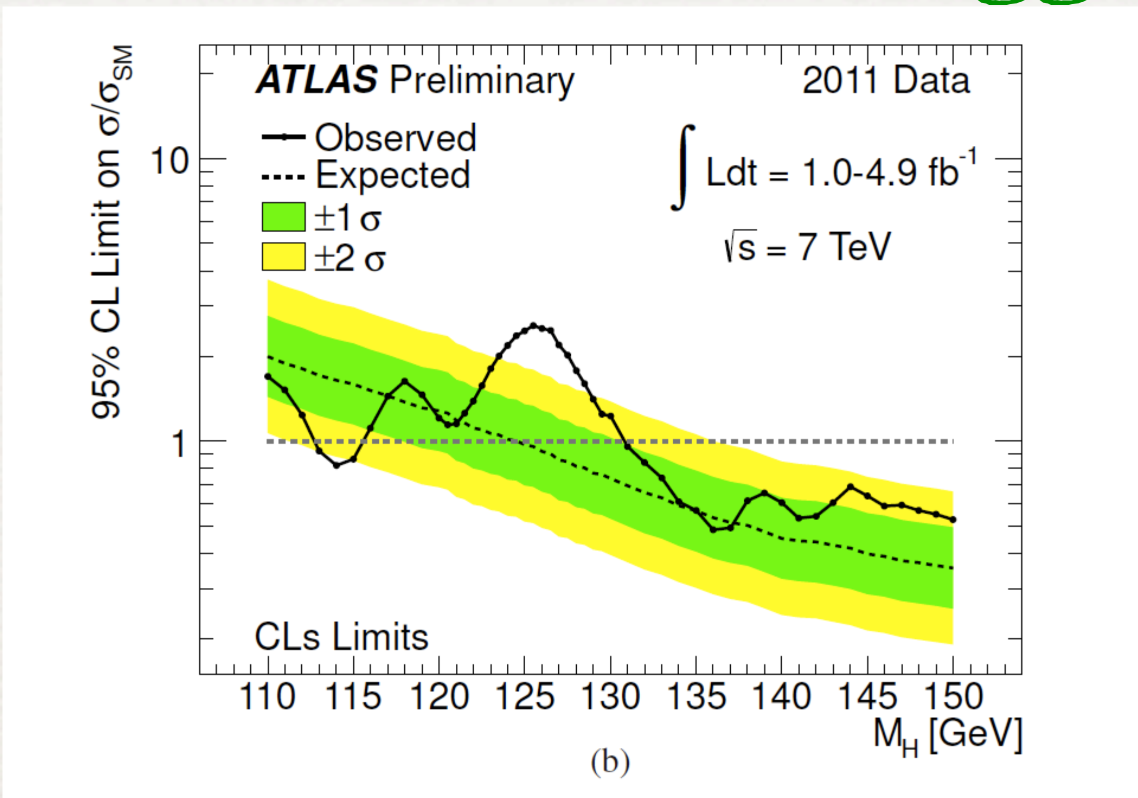
- no scalar at all

includes Little Higgs, Extra-Dimensions and Technicolor

Composite Higgs

Composite Higgs - Motivation

What if there is a Higgs?



(b)

Light scalar

Need stabilization mechanism

(or we have no clue about QFT)

Symmetries

Fermionic SUSY

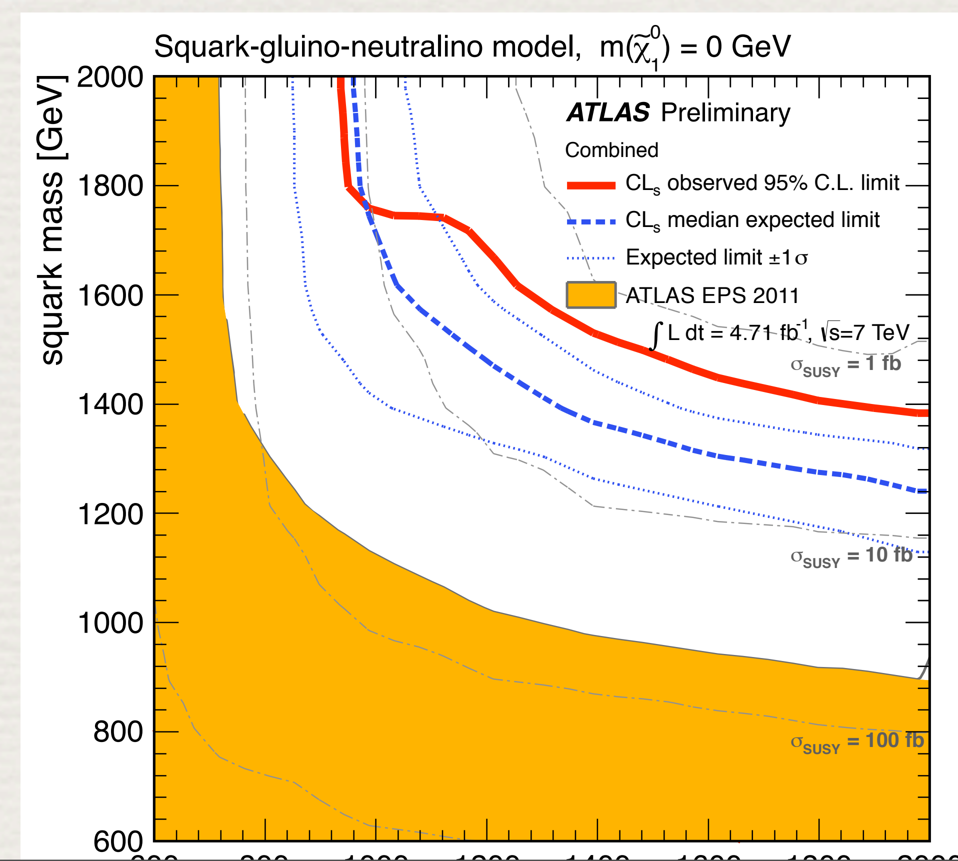
Bosonic Goldstone

since SUSY may not be there to save the day

Higgs as a PGB

like the pion of QCD

composite Higgs



Composite Higgs - Realizations

Composite Higgs is realized in

Little Higgs, Extra-Dimensions and Technicolor

symmetry PGB

-Little Higgs, TC: new 4D symmetry

-Extra-dimensions: SM 5D gauge= 4D gauge+GB

Composite Higgs-Generic features

scalar resonance WW unitarization

non-SM scalar: deviations

$$\xi = \frac{v^2}{f^2}$$ degree of fine-tuning

Giudice, Grojean, Pomarol and Rattazzi '07

Theory study 300 ifb @ 14 TeV for $\xi > 0.2$

$4\pi f$

f

v

composite Higgs already unitarize WW

$\xi \to 0$ SM-like

generic features are too SM-like

Composite Higgs-Generic features

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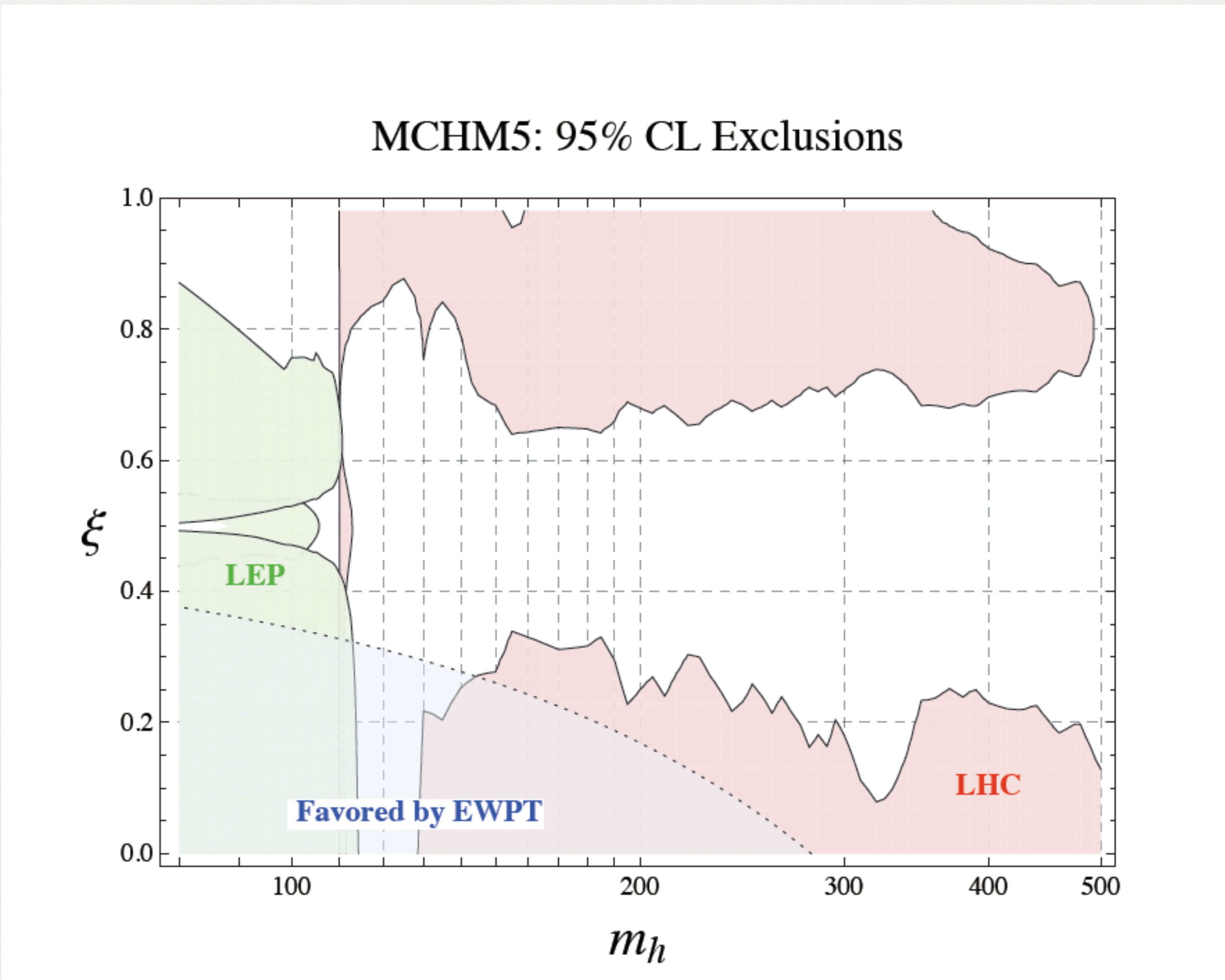

for $\xi > 0.2$

Azatov, Contino and Galloway, 12023415.

4π

f

v

arize WW

M-like

are too SM-like

Composite Higgs-Common

s=1

ex. Z' $,\rho_{TC},Z_{KK}$

not crucial for WW scattering

Composite Higgs-Common

s=1 ex. Z',ρ_{TC},Z_{KK}

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new gauge symms?

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→ new gauge symms?

s=2 ex. G_{KK}, f_2^{TC}

Extra-Dimensions and TC-type $\xrightarrow{\text{see next}}$

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new gauge symms?

s=2 ex. G_{KK}, f_2^{TC}

Extra-Dimensions and TC-type see next

s=1/2 ex. T, Q_{KK}, techni-baryons

New heavy quarks

mix with SM quarks

Composite Higgs-Common

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light quarks

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4th gen?

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see next

How to tell apart a graviton from an impostor?

Fok, Guimaraes, Lewis, VS

arXiV-1203.2917

i.e. massive spin-2 resonance = smoking gun of extra-dimensions?

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G

KK-graviton

$\hat{G}$

TC-type impostor

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propagation | Pauli-Fierz | Pauli-Fierz

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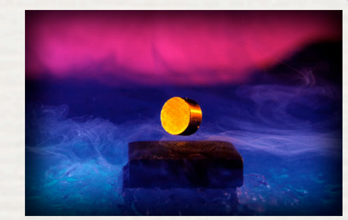
i.e. massive spin-2 resonance = smoking gun of extra-dimensions?

	G  KK-graviton	$\hat{G}$  TC-type impostor
propagation	Pauli-Fierz	Pauli-Fierz
interactions	$\frac{c_i}{M} G_{\mu\nu} T^{\mu\nu}_{i,SM}$	

c_i overlap G with fields i and $M \sim \mathrm{TeV}$

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c_i overlap G with fields i and $M \sim$ TeV

 vs 

$\hat{G}$ couplings?

Lorentz and gauge $\Rightarrow$ no dimension-4

 vs 

$\hat{G}$ couplings?

Lorentz and gauge $\Rightarrow$ no dimension-4

dimension-5

flavor and CP invariant $\Rightarrow$ same as in $T_{\mu\nu}$

$\boxed{\hat{G} \text{ couples like } G}$

same spin determination

vs

$\hat{G}$ couplings?

Lorentz and gauge $\rightarrow$ no dimension-4

dimension-5

flavor and CP invariant $\rightarrow$ same as in $T_{\mu\nu}$

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same spin determination

How do we distinguish them?

vs

$$\boxed{R_{g/\gamma} = \frac{Br(\to gg)}{Br(\to \gamma\gamma)} = \frac{8c_g^2}{c_\gamma^2}}$$

In any extra-dimension of the type

$$ds^2 = w(z)^2\,(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2)$$

example UED,RS

 vs 

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In any extra-dimension of the type

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example UED,RS

G: $\boxed{R_{g/\gamma} = 8}$

$\hat{G}$ can produce any other ratio

First generation compositeness

Martin and VS
JHEP (2010)
Redi, VS, Weiler
in preparation

Composite baryons and elementary quarks mix

$$\mathcal{L}_{mixing} = \lambda^u_{L,R}\, u_{L,R} \bar{U}_L + (u \to d) \qquad\qquad y \propto \lambda_L \lambda_R$$

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1st generation compositeness! Flavor?

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1st generation compositeness! Flavor?

MFV if composite sector flavor invariant

Redi, Weiler '11

- Left-handed compositeness: $\lambda_{Lu} \propto Id\,, \quad \lambda_{Ld} \propto Id$
  $\lambda_{Ru} \propto y_u\,, \quad \lambda_{Rd} \propto y_d$
- Right-handed compositeness: $\lambda_{Lu} \propto y_u\,, \quad \lambda_{Ld} \propto y_d$
  $\lambda_{Ru} \propto Id\,, \quad \lambda_{Rd} \propto Id$

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1st generation compositeness! Flavor?

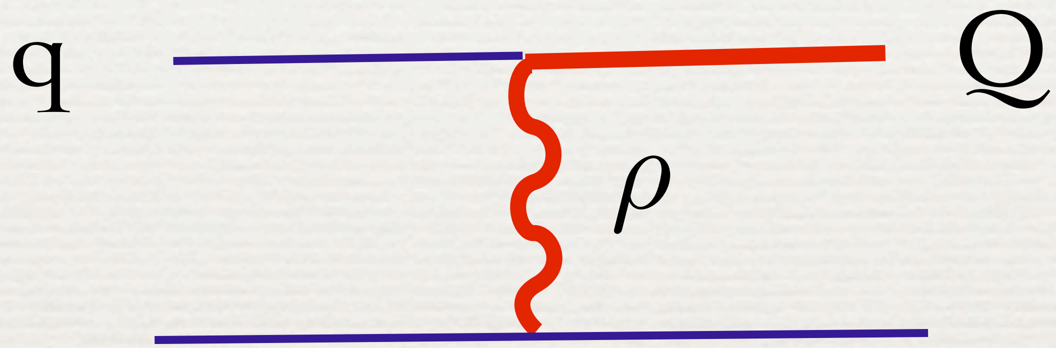
MFV if composite sector flavor invariant

Redi, Weiler '11

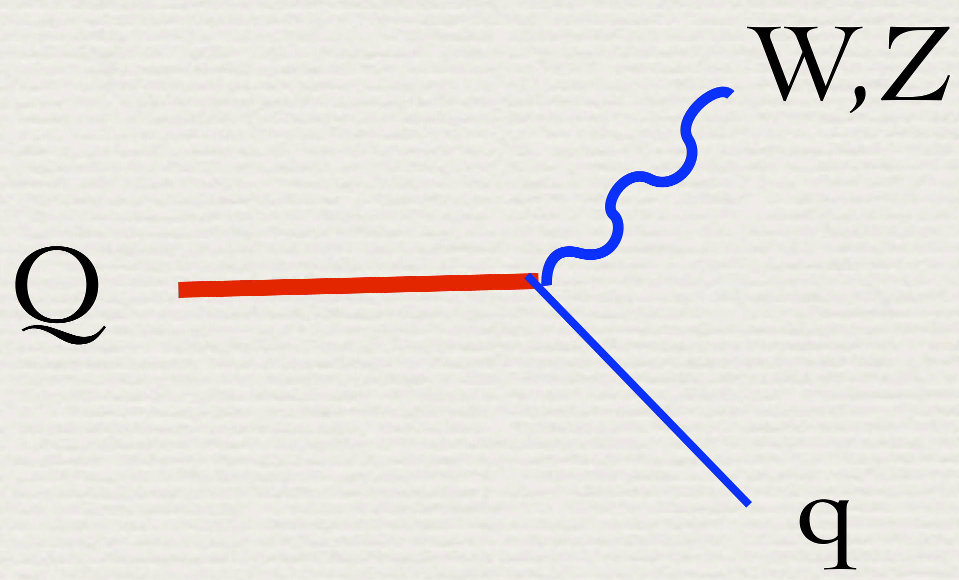
MFV $\longrightarrow$ half of the proton could be composite

How to tell apart 1st generation RH or LH compositeness?

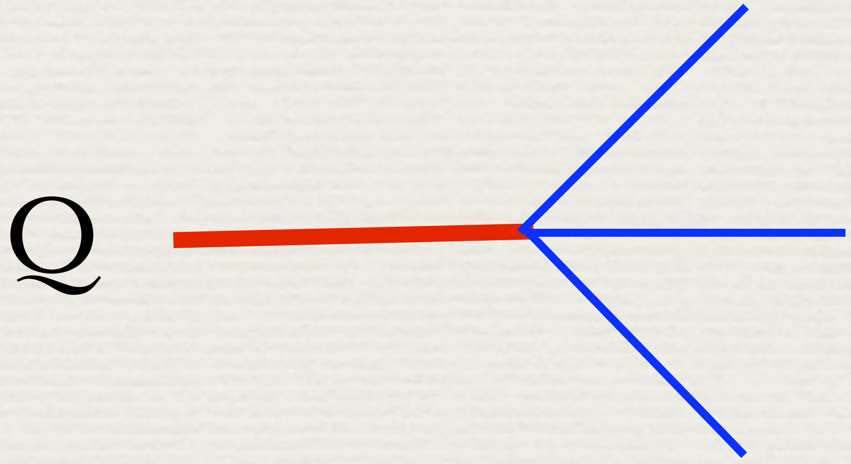
Signature: single production heavy quark



LH compositeness



RH compositeness



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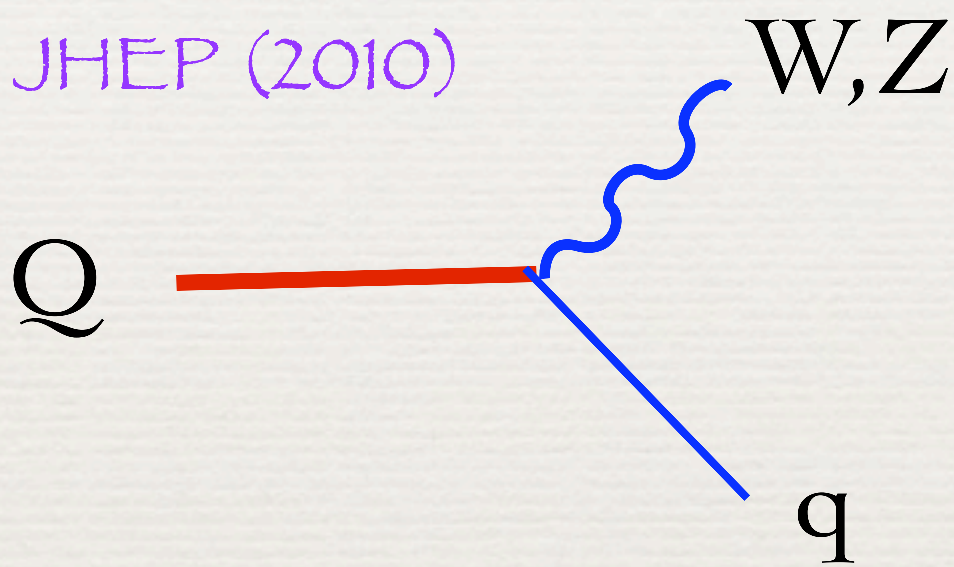
LH compositeness

Martin and VS

JHEP (2010)



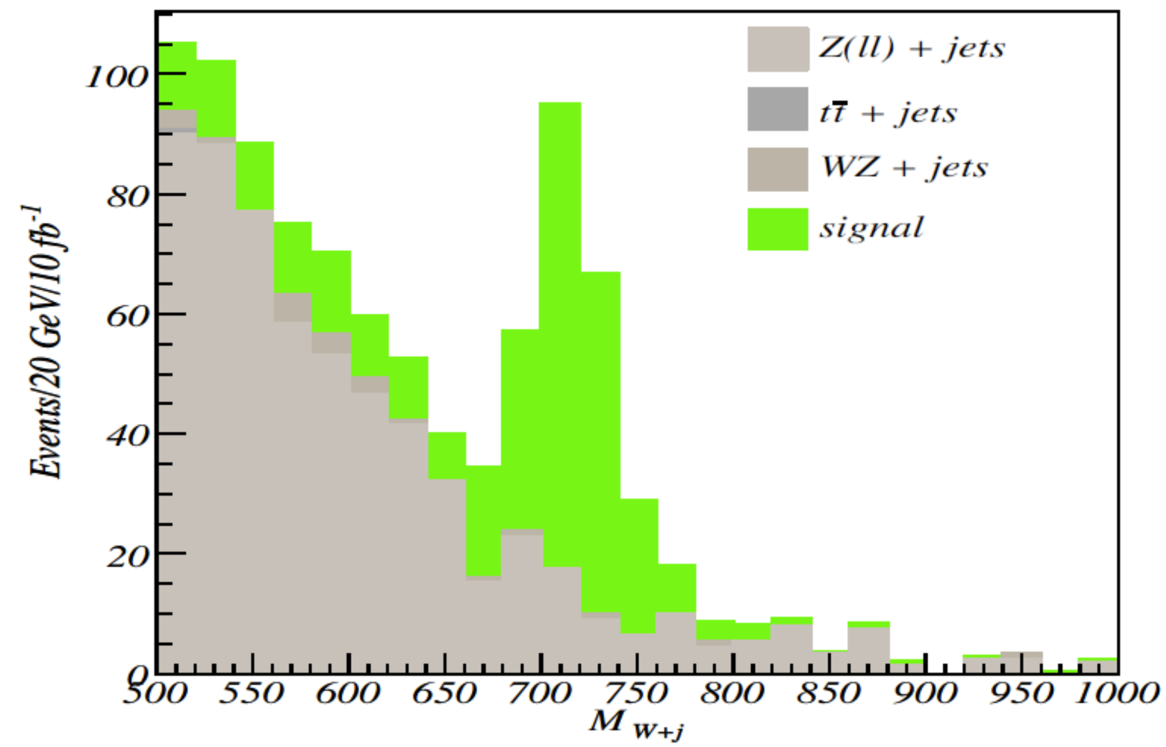


Figure 11: Single production invariant mass reconstruction in the $2\ \ell + 2\ j$ channel.

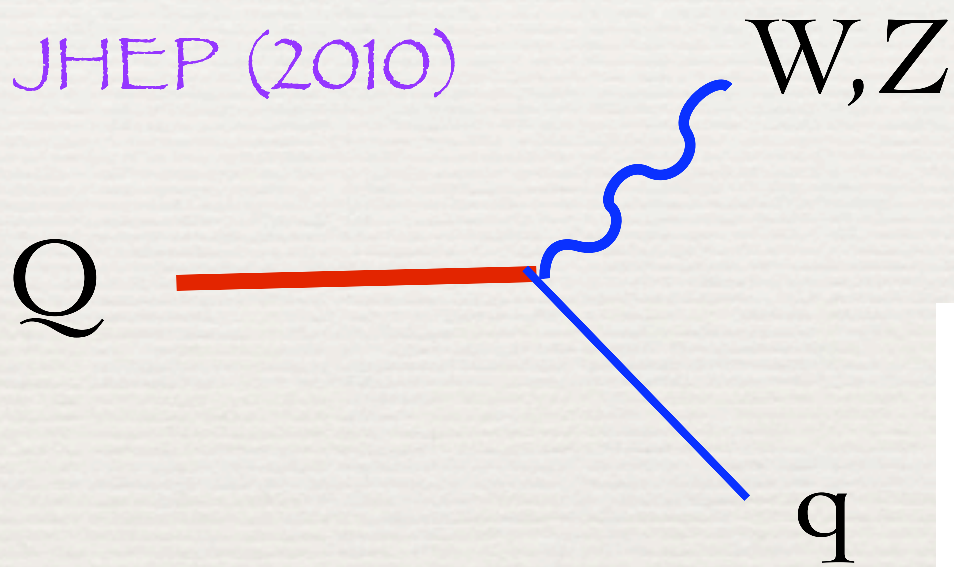
1. $n_\ell = 2$, same-flavor, opposite sign leptons and $m_{\ell\ell} = m_Z \pm 20$ GeV
2. $n_j \geqslant 2$, where $p_{T,2nd\,j} > 100$ GeV, $H_{T,j} > 800$ GeV and $m_{jj} < 45$ GeV or $m_{j,j} >$125 GeV
3. $\Delta R_{Z,j} < 2$ for the nearest jet
4. $\not{E}_T < 150$ GeV
5. $m_{Z,j} > 500$ GeV

How to tell apart 1st generation RH or LH compositeness?

LH compositeness

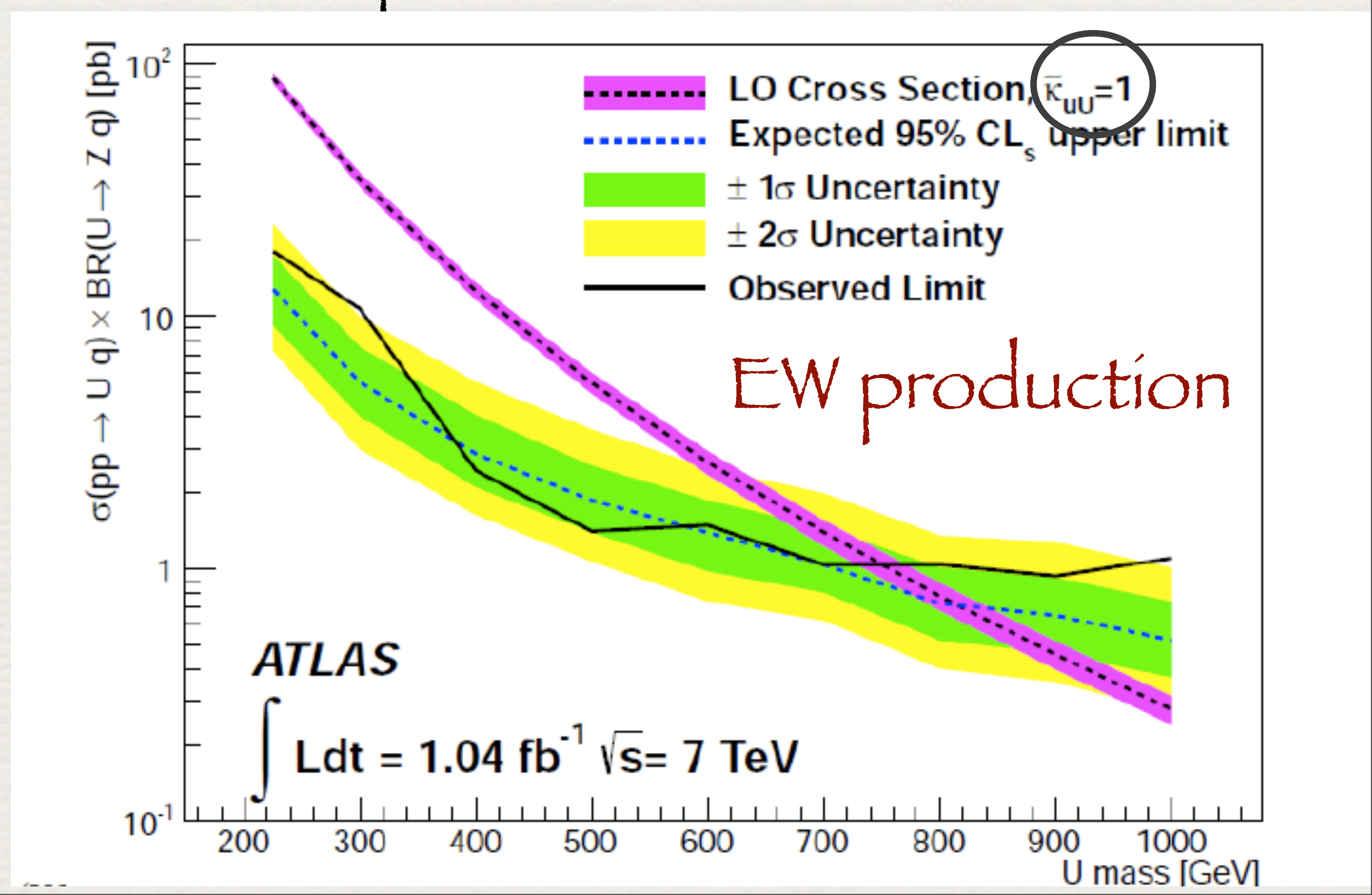
Martin and VS

JHEP (2010)



ATLAS-PH-EP-2011-193.

Lepton channel w/ 1 ifb.

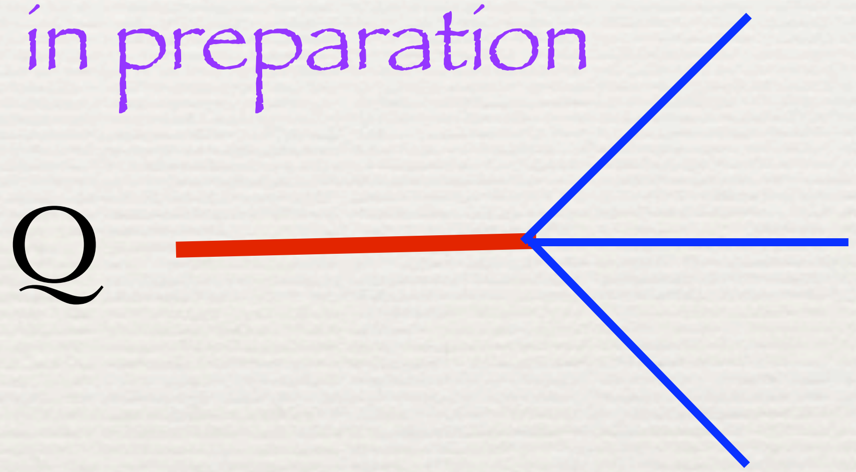


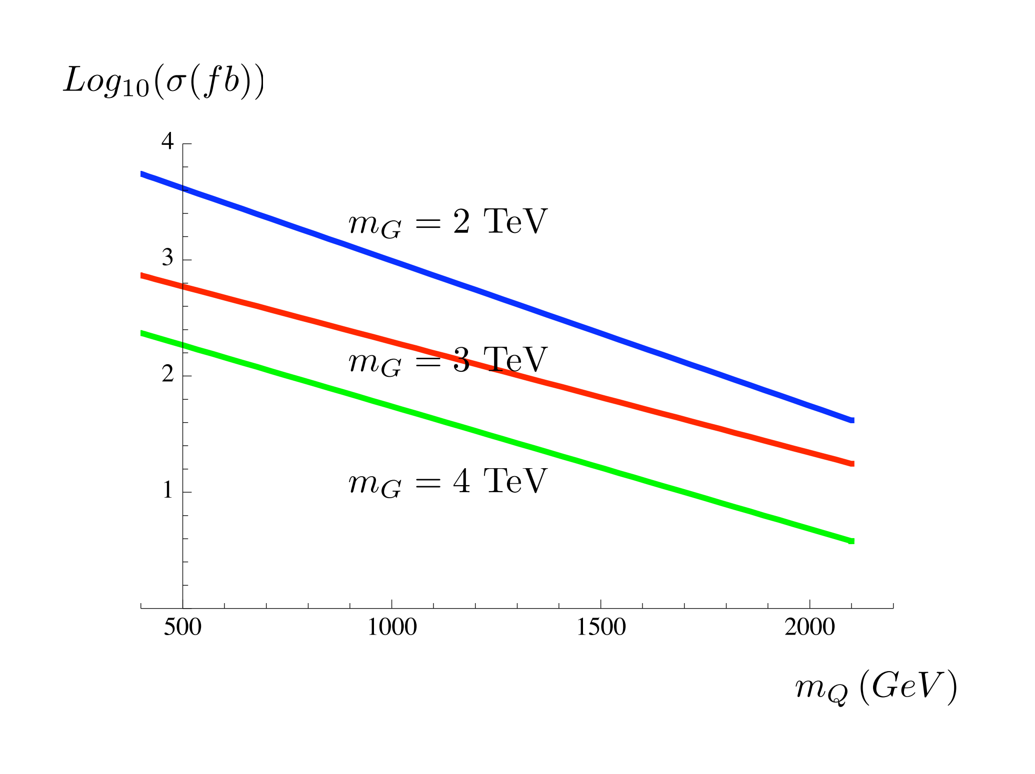
How to tell apart 1st generation RH or LH compositeness?

RH compositeness

Redi, VS, Weiler

in preparation





Looking at current bounds and discovery prospects

BGs: multijet, W+jets, Z+jets, top pair and single top

ATLAS-PH-EP-2011-154

Rejection: exclude dijet near W or Z and veto b-tagging, cut on leading jet

QCD generated with ALPGEN -> PYTHIA

signal xsecs mQ=1 TeV, mG=2 TeV

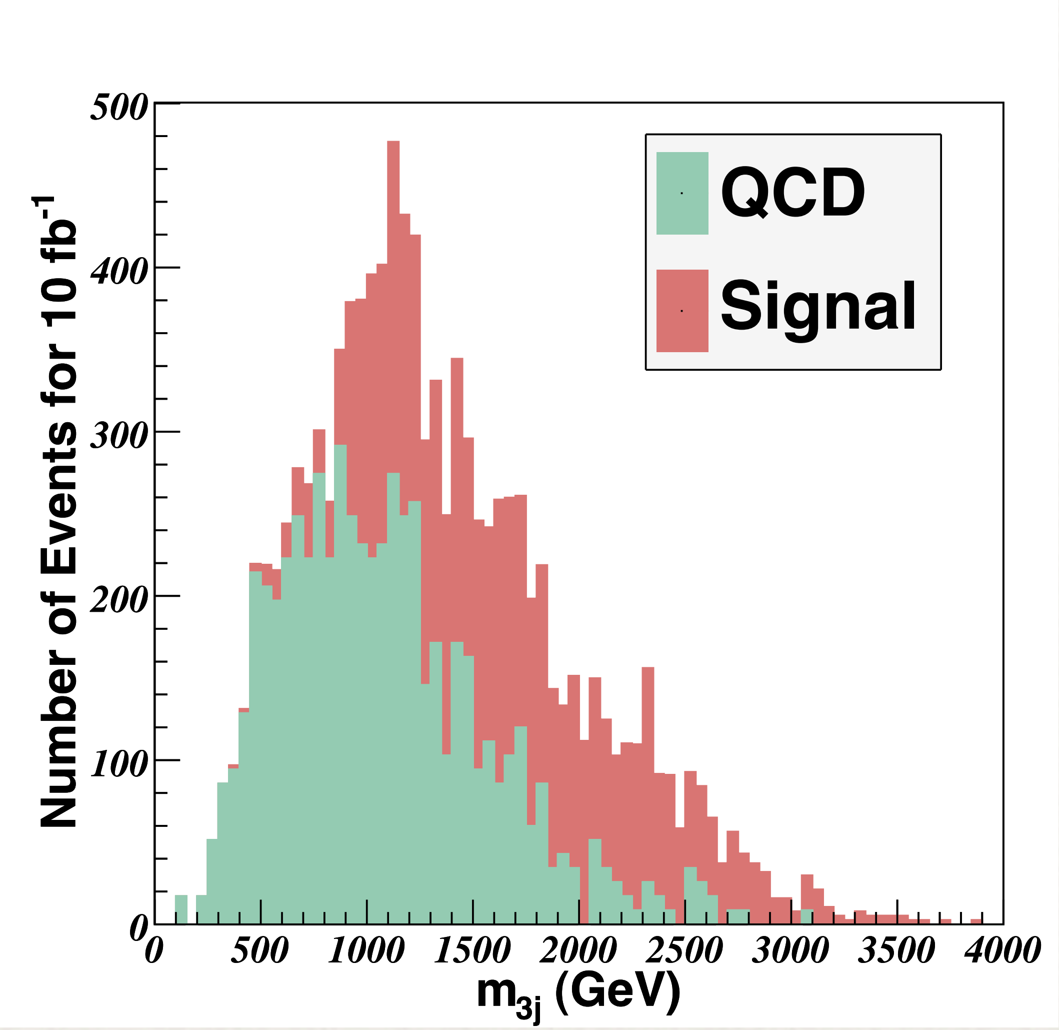
Cuts	QCD 4 jets (fb)	Signal (fb)
basic cuts	2×10^9	1300
$p_T^{lead} > 700, p_T > 200$	100	354
$p_T > 200$	2900	556
$p_T > 100$	3.5×10^5	1040
$p_T^{lead} > 500, p_T > 100$	9000	830
$p_T^{lead} > 500, p_T > 200$	670	495

How to tell apart 1st generation RH or LH compositeness?

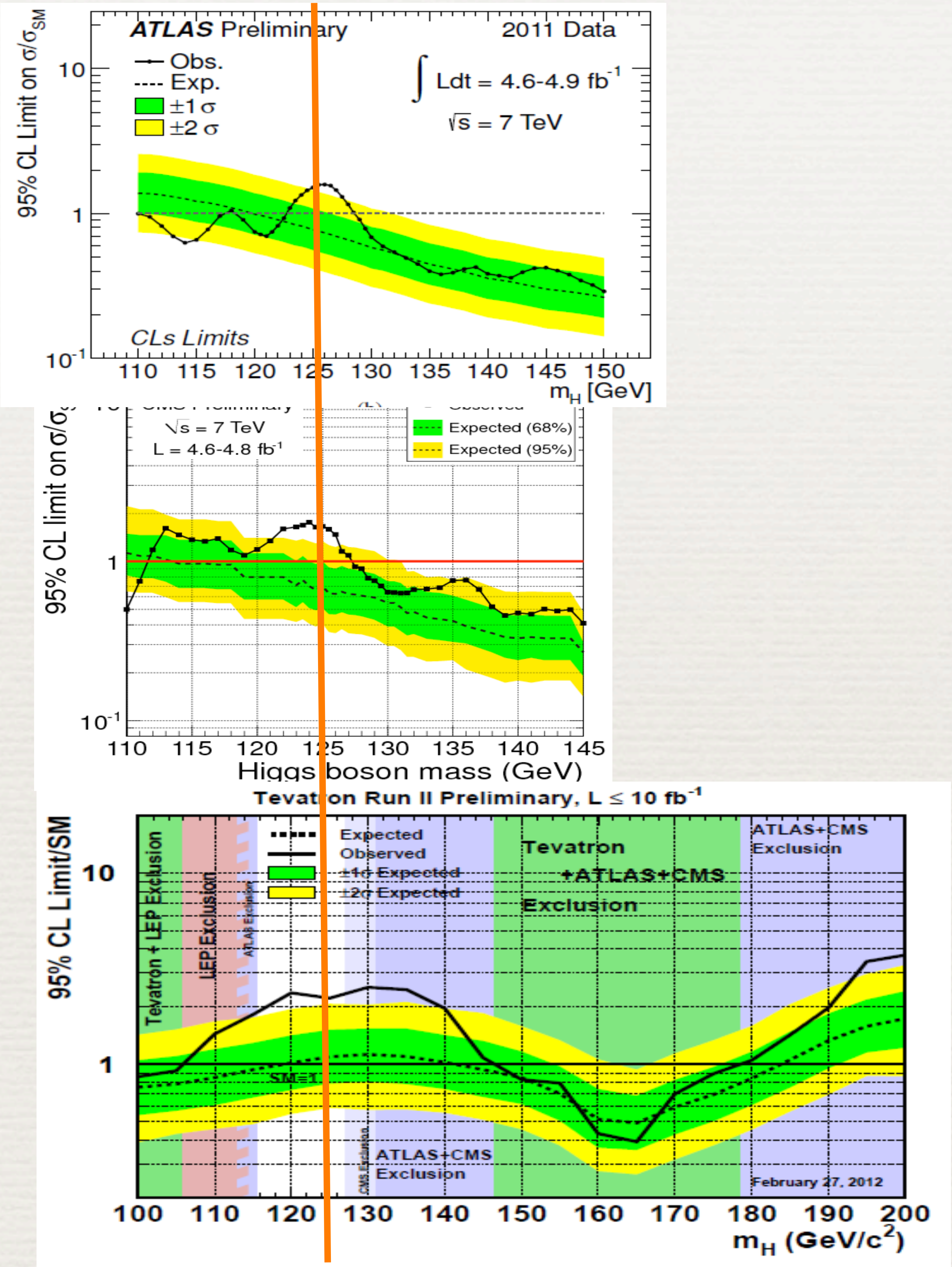
RH compositeness

Redi, VS, Weiler
in preparation

We use two methods: deltaR and leading jet optimized for high-low mQ



Higgsless


ATLAS Preliminary
2011 Data
Obs.
Exp.
±1 σ
±2 σ
∫ Ldt = 4.6-4.9 fb-1
√s = 7 TeV
CLs Limits
95% CL Limit on σ/σSM
mH [GeV]
√s = 7 TeV
L = 4.6-4.8 fb-1
Expected (68%)
Expected (95%)
95% CL limit on σ/σSM
Higgs boson mass (GeV)
Tevatron Run II Preliminary, L ≤ 10 fb-1
Expected
Observed
±1σ Expected
±2σ Expected
Tevatron
+ATLAS+CMS
Exclusion
ATLAS+CMS
Exclusion
Tevatron + LEP Exclusion
LEP Exclusion
SM=1
February 27, 2012
95% CL Limit/SM
mH (GeV/c2)

Higgsless

?

No Scalar-Generic features

Realized in warped extra-dimensions and TC-type s=1 resonances do unitarize WW scattering

No Scalar-Generic features

Realized in warped extra-dimensions and TC-type

s=1 resonances do unitarize WW scattering

THE problem: S parameter

solutions do not abound

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Non-calculable, ignore   TCSM   Eichten, Lane Phys. Lett. B '89

No Scalar-Generic features

Realized in warped extra-dimensions and TC-type

s=1 resonances do unitarize WW scattering

THE problem: S parameter

solutions do not abound

→ Non-calculable, ignore TCSM

Eichten, Lane
Phys. Lett. B '89

→ Mechanisms to cancel, warped models

→ Cured Higgsless

(s=1)-(s=1/2) cancellation

Cacciapaglia et al
Phys. Rev. D '05

→ Holographic TC

s=1 cancellation

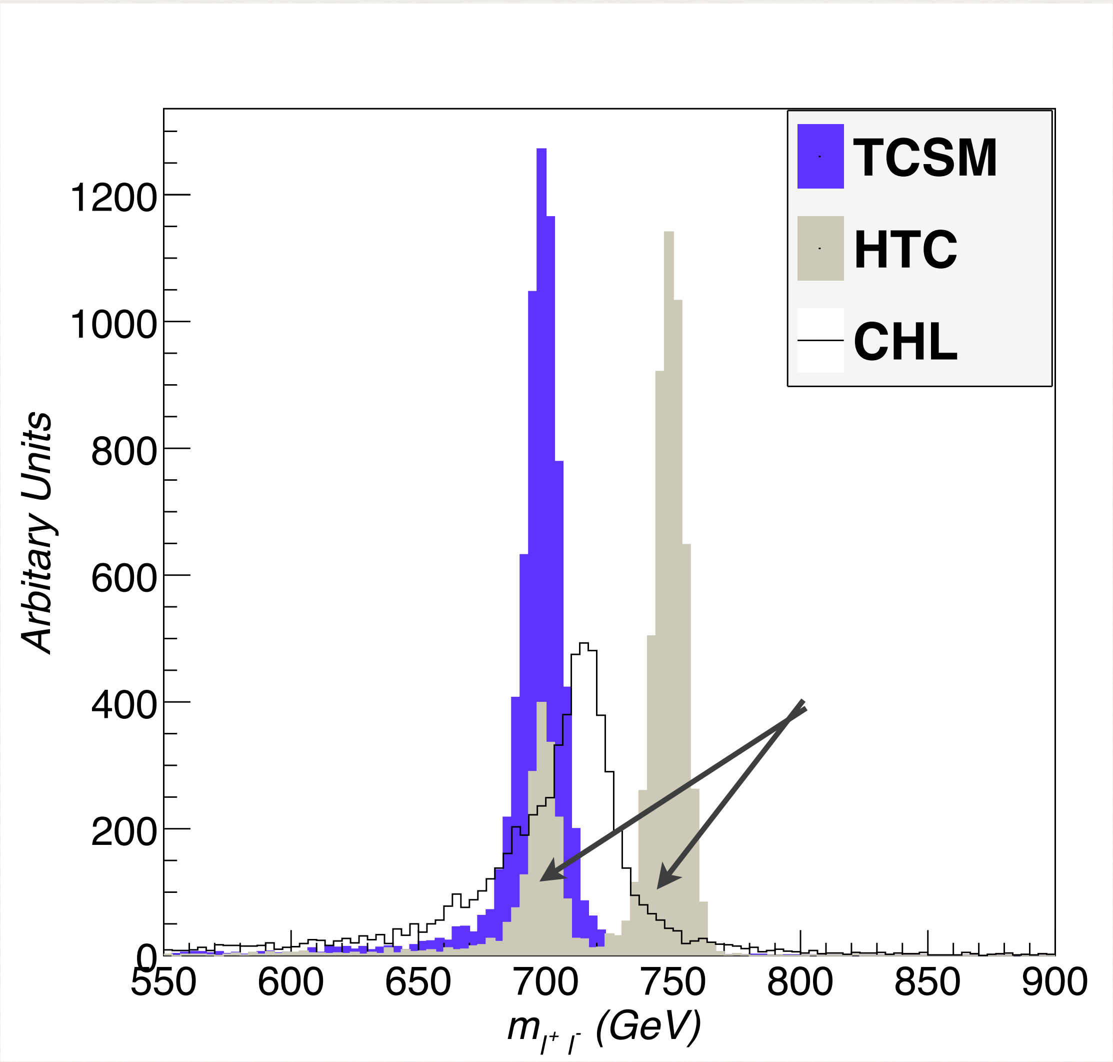
Hirn,VS
Phys. Rev. Lett. '06

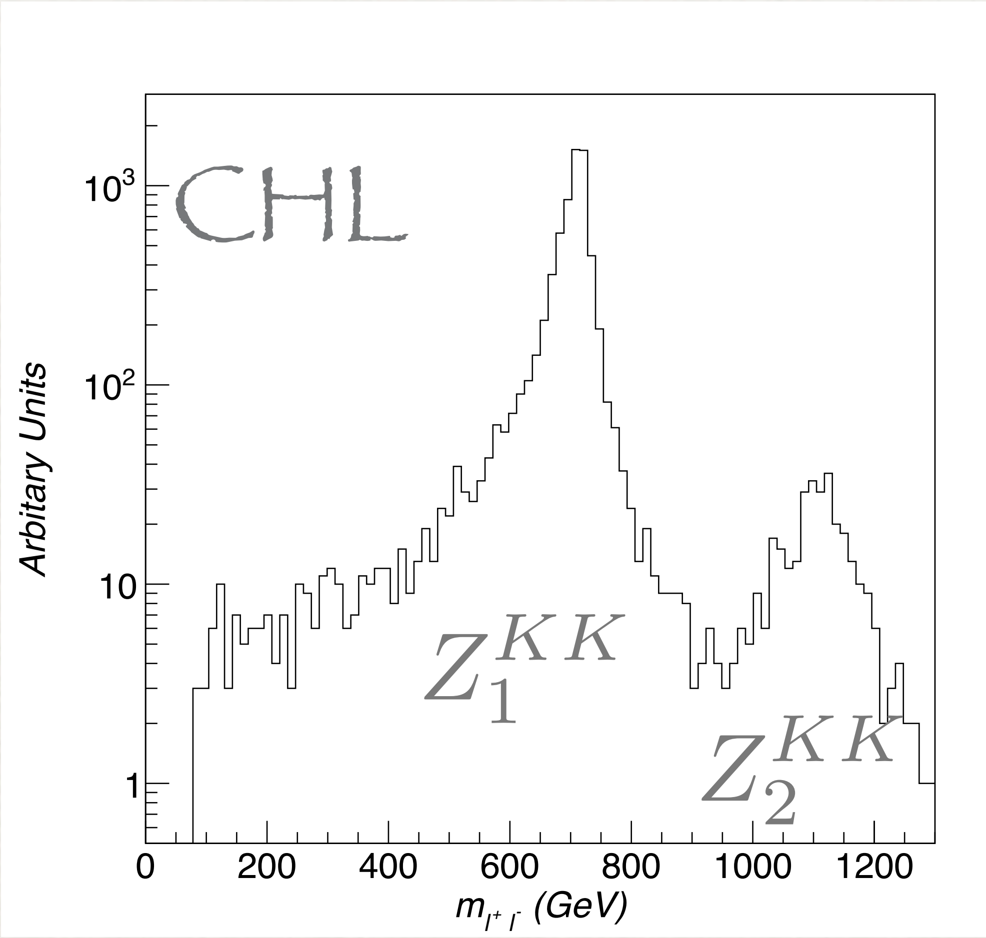
How to tell apart scenarios of dynamical EWSB?

Banerjee, Martin and VS
JHEP (2012)

In dileptons...

1. Invariant mass





MG> PYTHIA> ATLFAST and DELPHES@7 TeV

How to tell apart scenarios of dynamical EWSB?

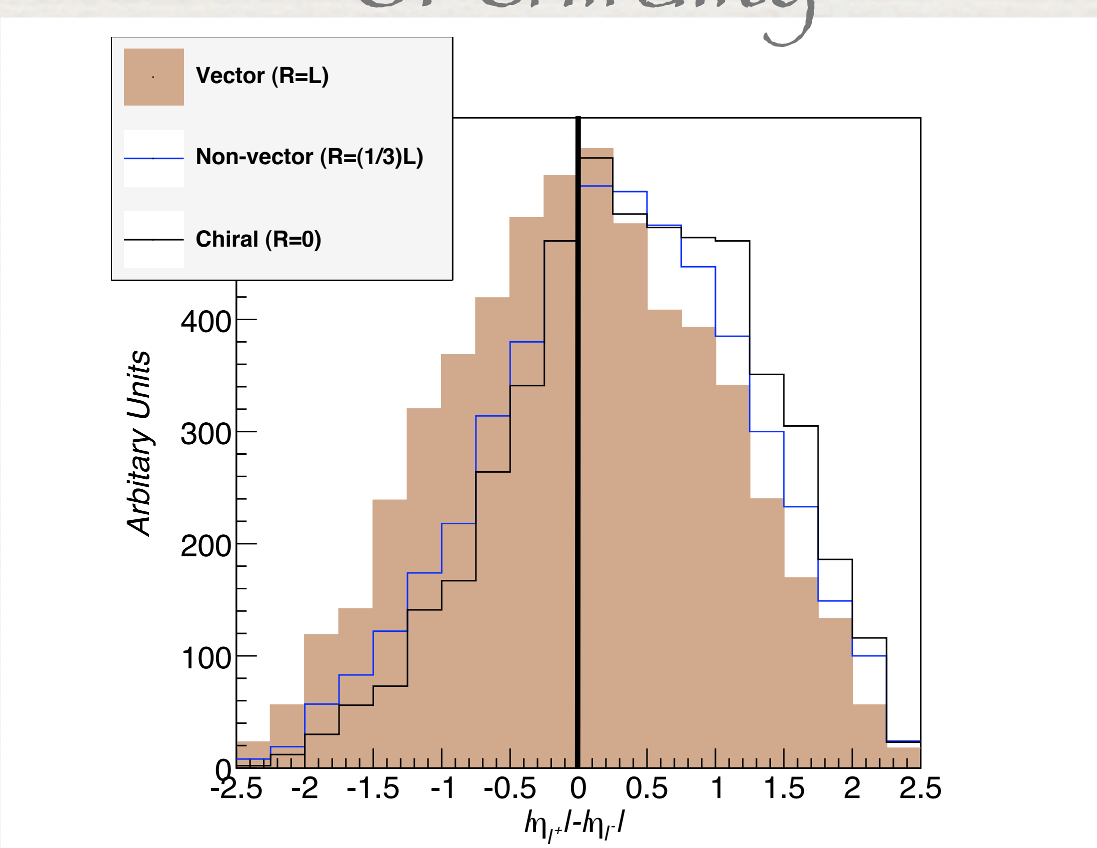
Banerjee, Martin and VS
JHEP (2012)

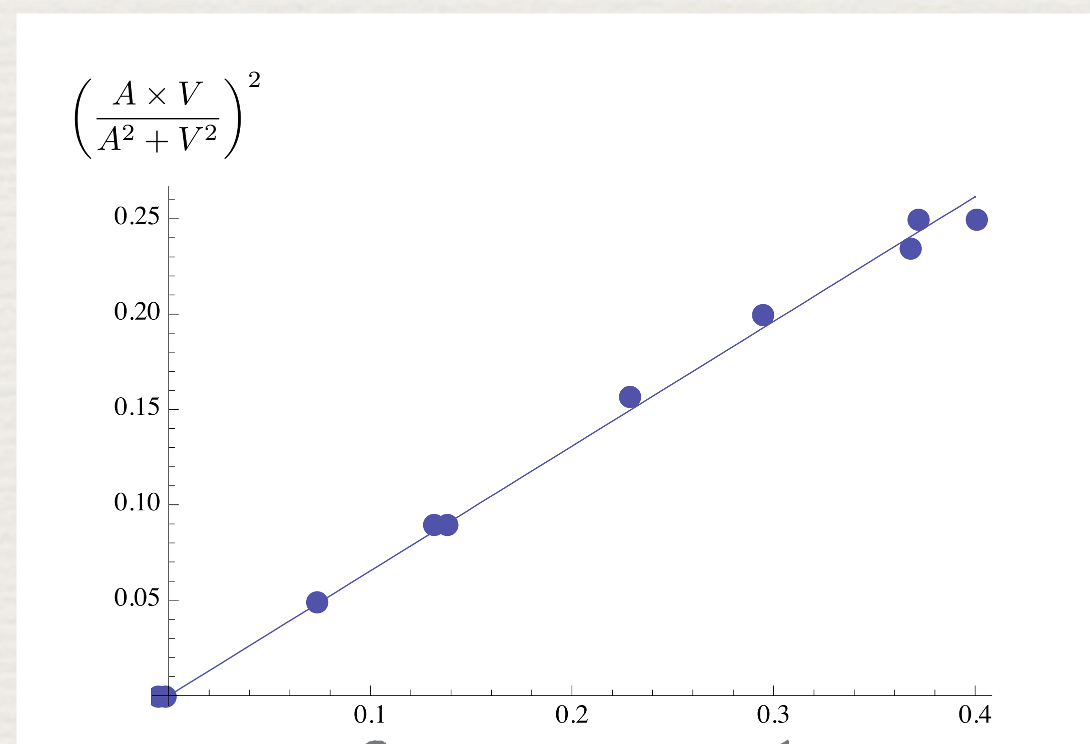
2. Charge asymmetry

$$A_{\text{charge}} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)} \qquad \Delta\eta = |\eta_{\ell+}| - |\eta_{\ell-}|$$

eta asym is a good measure of chirality

can tell V,A admixture





A after simulation

Conclusions

- Non-standard EWSB ideas abound and have a very rich phenomenology.
- May not be easy to discover by just looking at scalar EWSB sector. Need correlations with other signals.
- Tell apart Extra-Dimensions from TC-type: gravitons and its impostor.
- First generation RH or LH compositeness in multijets.
- Tell apart different scenarios of DEWSB in dileptons.

Operators

	$\hat{O}^{decay}_{\mu\nu}$	CP	coefficients
(a)	$\bar{\psi}\sigma_{\mu\nu}\psi$	$-$	$\hat{c}^a_f$
(b)	$\bar{\psi}\gamma_\mu\partial_\nu\psi$	$+$	$\hat{c}^b_f$
(c)	$\bar{\psi}\gamma^5\gamma_\mu\partial_\nu\psi$	$-$	$\hat{c}^c_f$

nionic operators up to dimension 5 that could lead to two-body
ntribute to $\hat{G}$ decay because $\hat{G}^{\mu\nu}\sigma_{\mu\nu} = 0$. As long as we consi
ly, (c) must vanish as they are CP odd. The only remaining oper
elative 4-momenta of the fermions because of the gauge conditio
term in the Lagrangian is $c^b_f \hat{G}^{\mu\nu}\hat{O}^{decay}_{\mu\nu}$. Expressions for the coeff

	$\hat{O}^{decay}_{\mu\nu}$	CP	coefficients
(a)	$F_\mu^{\ \rho}F_{\rho\nu}$	$+$	$\hat{c}^a_A$
(b)	$\epsilon_{\alpha\beta\mu\delta}F_\nu^{\ \delta}F^{\alpha\beta}$	$-$	$\hat{c}^b_A$
(c)	$F_{\mu\nu}$	$+$	$\hat{c}^c_A$
(d)	$\partial_\mu H\,\partial_\nu H$	$+$	$\hat{c}_\phi$

ratio to gluons
gluon-jet from quark-jet?

1. most models: G coupling to light quarks suppressed
2. Angular correlations

$$\frac{d\sigma}{d\cos\theta^*}(q\bar{q} \to G) = 1 + c^2_{\theta*}\left(1 - 4s^2_{\theta*}\right) \text{ to fermions}$$
$$= 1 - c^4_{\theta*} \text{ to gluons },$$

3. Tag light jet using Galliccio-Schwartz techniques