Strong EW Symmetry Breaking

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Why Strong EW Breaking?

- No fundamental scalar = no fine tuning problem.
  Mass of other fields are protected from divergent corrections:
  - Vector fields by gauge invariance
  - Spinors by chiral symmetry

- Small scale (small pure numbers) easily/naturally generated without tuning:

$$\frac{1}{\alpha(M)} - \frac{1}{\alpha(\mu)} = \frac{b}{8\pi} \ln\left(\frac{M}{\mu}\right) \qquad \Rightarrow \qquad \frac{\mu_{\text{strong}}}{M} = \exp\left(-\frac{8\pi/b}{\alpha(M)}\right)$$

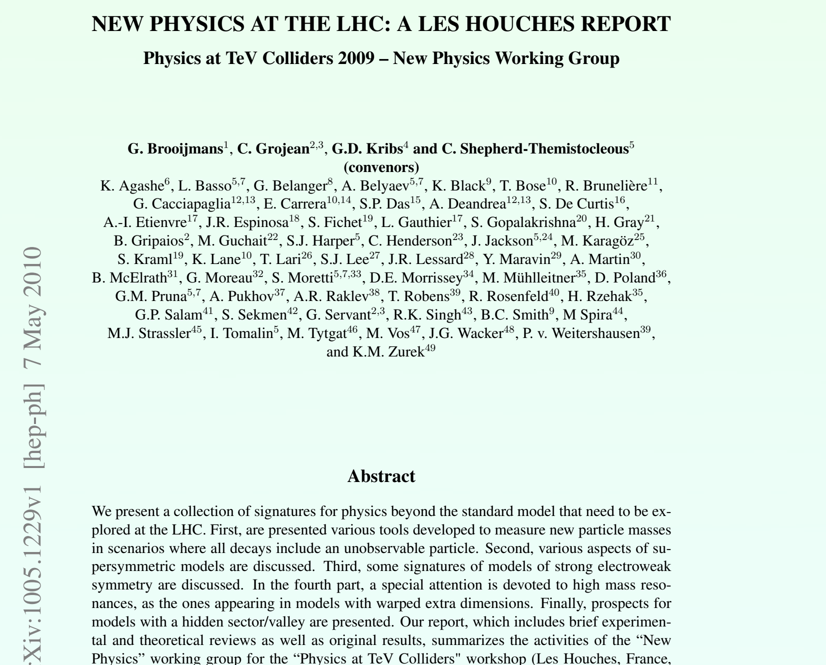
- Nature already uses this:
  - Flavor symmetry spontaneously broken by strong force:
    SU(3) x SU(3) → SU(3)
  - BCS theory: electron condensate breaks $U(1)_{EM}$

- Two cases of strong EW symmetry breaking:
  1. A strong interaction produces a light scalar (eg, a pseudo Godlstone boson) that acts as a higgs field
  2. No light higgs-like particle

- First case was presented by Christophe Grojean

- Here we concentrate on second case

- The two talks parallel the two sections on strong EWSBof the Les Houches report (CG is a coauthor, but not me).



NEW PHYSICS AT THE LHC: A LES HOUCHES REPORT

Physics at TeV Colliders 2009 – New Physics Working Group

G. Brooijmans[1], C. Grojean[2,3], G.D. Kribs[4] and C. Shepherd-Themistocleous[5]
(convenors)
K. Agashe[6], L. Basso[5,7], G. Belanger[8], A. Belyaev[5,7], K. Black[9], T. Bose[10], R. Brunelière[11], G. Cacciapaglia[12,13], E. Carrera[10,14], S.P. Das[15], A. Deandrea[12,13], S. De Curtis[16], A.-I. Etienvre[17], J.R. Espinosa[18], S. Fichet[19], L. Gauthier[17], S. Gopalakrishna[20], H. Gray[21], B. Gripaios[2], M. Guchait[22], S.J. Harper[5], C. Henderson[23], J. Jackson[5,24], M. Karagöz[25], S. Kraml[19], K. Lane[10], T. Lari[26], S.J. Lee[27], J.R. Lessard[28], Y. Maravin[29], A. Martin[30], B. McElrath[31], G. Moreau[32], S. Moretti[5,7,33], D.E. Morrissey[34], M. Mühlleitner[35], D. Poland[36], G.M. Pruna[5,7], A. Pukhov[37], A.R. Raklev[38], T. Robens[39], R. Rosenfeld[40], H. Rzehak[35], G.P. Salam[41], S. Sekmen[42], G. Servant[2,3], R.K. Singh[43], B.C. Smith[9], M Spira[44], M.J. Strassler[45], I. Tomalin[5], M. Tytgat[46], M. Vos[47], J.G. Wacker[48], P. v. Weitershausen[39], and K.M. Zurek[49]

arXiv:1005.1229v1 [hep-ph] 7 May 2010

Abstract

We present a collection of signatures for physics beyond the standard model that need to be explored at the LHC. First, are presented various tools developed to measure new particle masses in scenarios where all decays include an unobservable particle. Second, various aspects of supersymmetric models are discussed. Third, some signatures of models of strong electroweak symmetry are discussed. In the fourth part, a special attention is devoted to high mass resonances, as the ones appearing in models with warped extra dimensions. Finally, prospects for models with a hidden sector/valley are presented. Our report, which includes brief experimental and theoretical reviews as well as original results, summarizes the activities of the "New Physics" working group for the "Physics at TeV Colliders" workshop (Les Houches, France,

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If I had my choice I would tell you
everything you wanted to know (and more)
about indefinite metric quantization,
its applications to SM physics and
its fascinating phenomenology.

There is always coffee break.

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Why not Strong EW Breaking

- Quark/lepton masses
  - and top!
- Light spin-0 particles (pseudo-Goldstone bosons)
- FCNCs
- EW precision data
- No GUTs

. . .

Some frameworks that address some of these problems

- Extended Technicolor
- Walking
- Conformal Technicolor
- Topcolor assisted TC, ...

Minimal Technicolor

A beautiful idea that does not work

Recall: 2-flavor QCD breaks $SU(2)_L \times SU(2)_R \to SU(2)_V$

$$q = \begin{pmatrix} u \\ d \end{pmatrix} \qquad \langle \bar{q}_L^i q_R^j \rangle = \Lambda_\chi^3 \delta^{ij}$$

Pions ($\pi^\pm, \pi^0$) are the associated pseudo-Goldstone Bosons

$$\Lambda_\chi \sim 4\pi f_\pi$$ (or sometimes $\Lambda_\chi^3 \sim 4\pi f_\pi^3$)

Their mass is due to the explicit symmetry breaking from $m_u \neq 0$ and $m_d \neq 0$

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SM: $SU(2)_L$ x $U(1)_R$ is gauged: mass for W/Z

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Minimal Technicolor is a copy of 2-flavor QCD with:

- "QCD" replaced by "TC," "gluons" by "technigluons," "quarks" by "techniquarks"
- The condensate at EW scale: $\Lambda_{\rm TC} \sim 4\pi v = 4\pi(246\ \text{GeV})$
- An $SU(2)_L \times U(1)$ subgroup of $SU(2)_L \times SU(2)_R$ is gauged, giving EW interactions

The would-be Goldstone Bosons become longitudinal components of $W^\pm$ and Z

In $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$, the group $SU(2)_V$ is explicitly broken by the gauging of U(1). Up to hypercharge corrections, the $SU(2)_V$ guarantees ("custodial" symmetry)

$$M_W = M_Z \cos\theta_W \qquad \text{that is} \qquad \rho = \frac{M_W^2}{\cos^2\theta_W M_Z^2} = 1$$

Masses: Extended Technicolor

Dual role of Higgs field in SM:

- break EW symmetry (*W* and *Z* masses)
- quark and lepton masses: $Y_U \tilde{H} \bar{q}_L u_R + Y_D H \bar{q}_L d_R + Y_E H \bar{\ell}_L e_R$

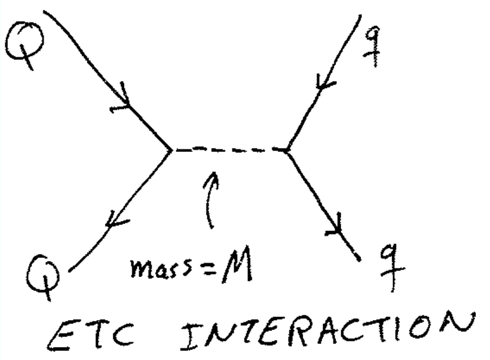
Minimal technicolor: massless quarks and leptons

- need coupling of techniquarks $\bar{Q}Q$ to quarks/leptons $\bar{q}_L u_R,\ \bar{q}_L d_R,\ \bar{\ell}_L e_R$

Extended Technicolor (ETC): assume additional interactions of the form

$$\frac{C}{M^2}\bar{Q}Q\ \bar{q}q$$

- *M* is the ETC scale
- *C* are constants that characterize the quark mass matrices (like Y_Q of the SM)
- Can arise from exchange of a heavier particle of mass M



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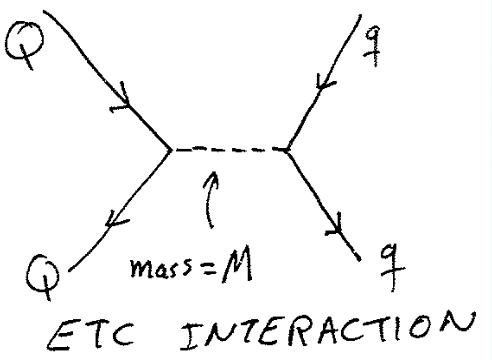
There are alternatives, like Partial Compositeness (Kaplan); Minimal composite Higgs (Contino et al). See CG's talk.



Problem:

- FCNC's: Must similarly have $\frac{C'}{M^2}\bar{q}q\;\bar{q}q$ and in particular, *e.g.*, $\frac{C'}{M^2}\bar{s}d\;\bar{s}d$

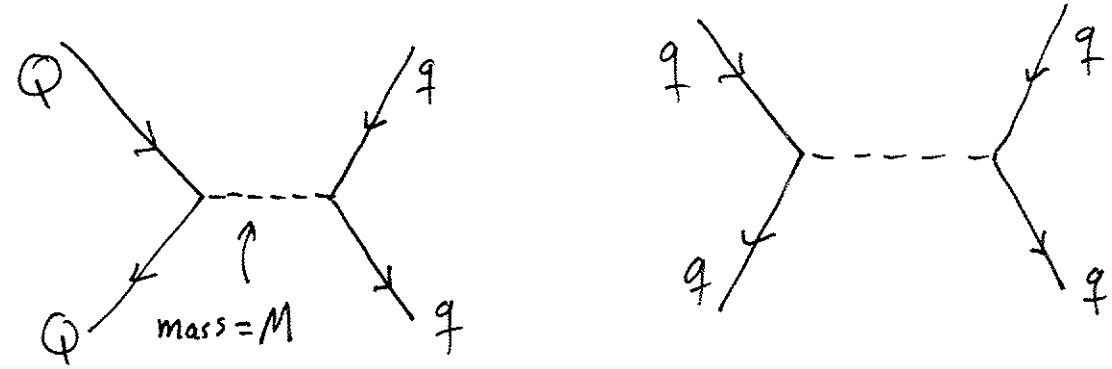
- Neutral K mixing: $M/\sqrt{|C'|} \geq 1000\;TeV$

- Quark masses: $m_q \sim \frac{C}{M^2}\langle\bar{Q}Q\rangle \sim \frac{C}{M^2}\Lambda^3$

Even with extreme assumptions, $\Lambda = 4\pi v$, still only get $(C \sim C')$

$$m_q \lesssim 10\ \mathrm{MeV}$$

... too small except for light ones



- Similar problem with technipions (additional pseudo goldstone bosons)
  ... too light

Walking Technicolor

A fairy tale (but a good one, and an interesting one)

What it is supposed to do:

nota bene: we do not know it does this… will return to this point

Dynamically replace $\frac{\Lambda^2}{M}$ for $\frac{\Lambda^3}{M^2}$ in quark mass formula, so that $m_q \sim \frac{C}{M}\Lambda^2$

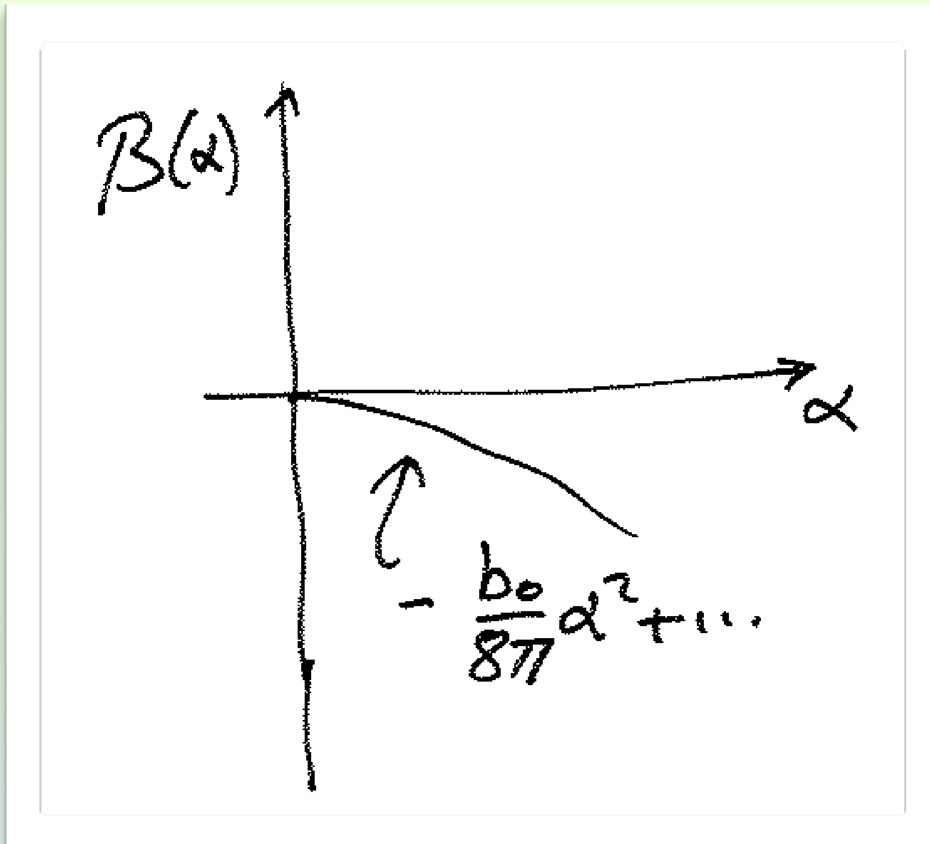
The same extreme assumptions as before now give

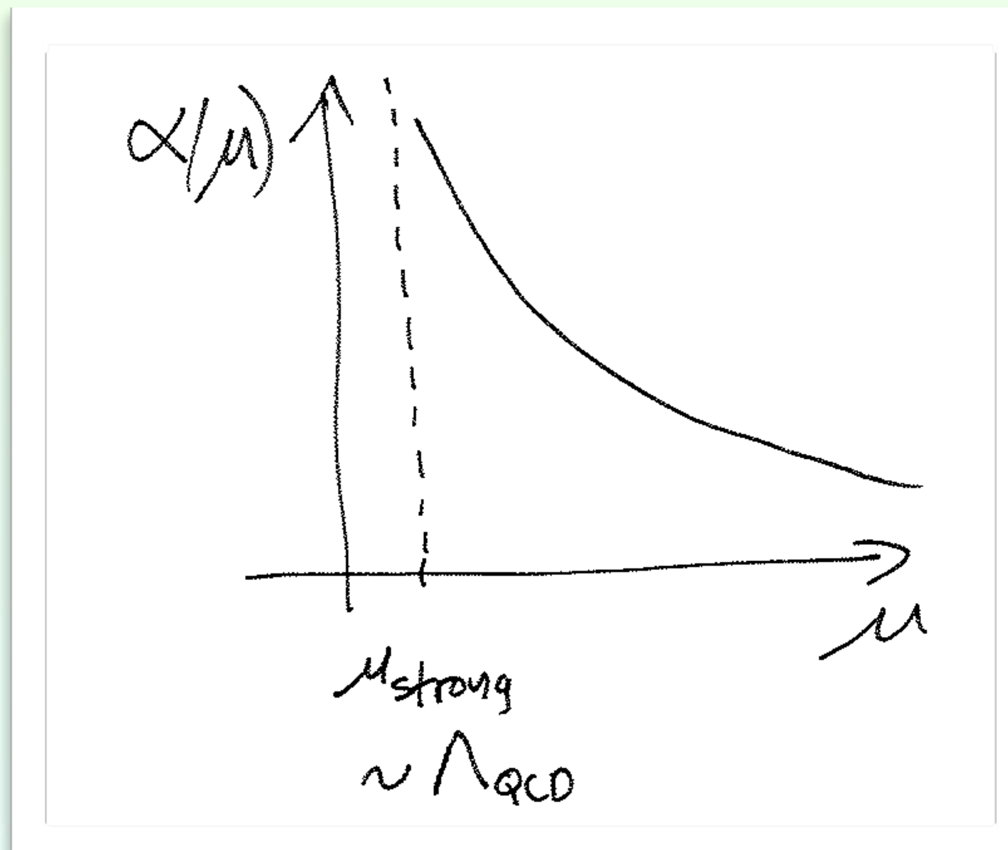
$$m_q \lesssim 10 \text{ GeV}$$

Fine (except for top quark, needs to be dealt with separately, eg, with topcolor models; Won't do so here. Plenty else to discuss!)

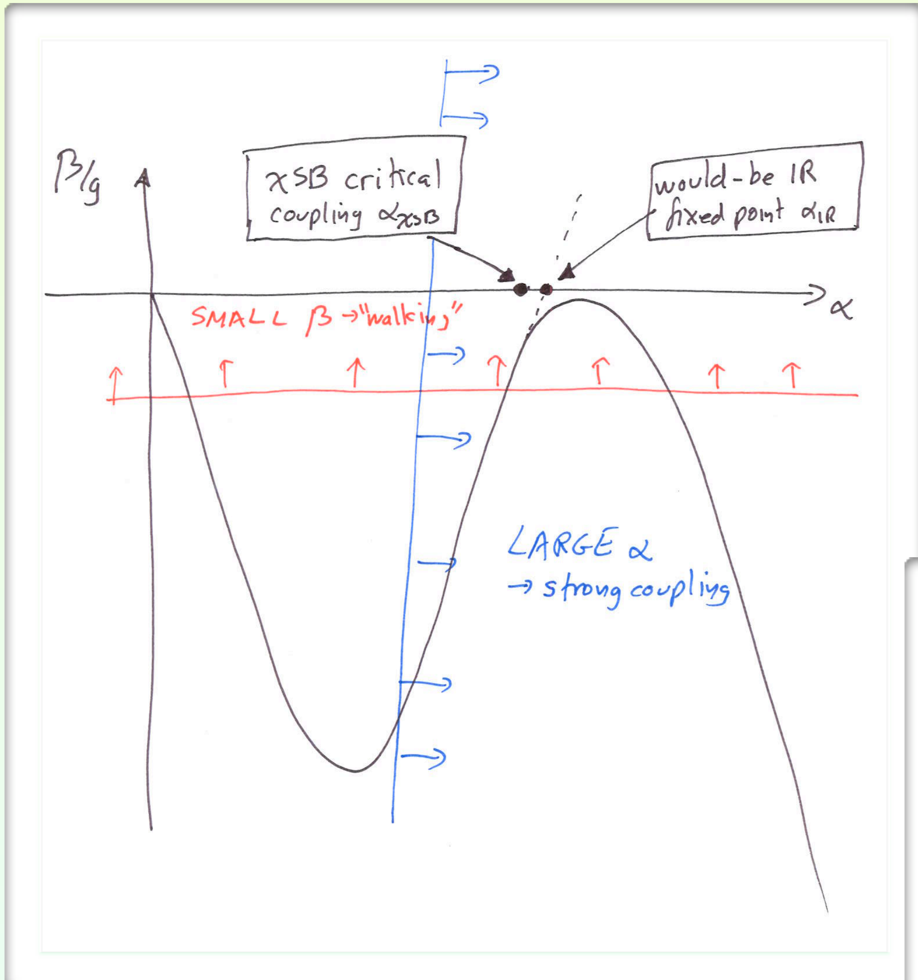
Walking Technicolor in Pictures

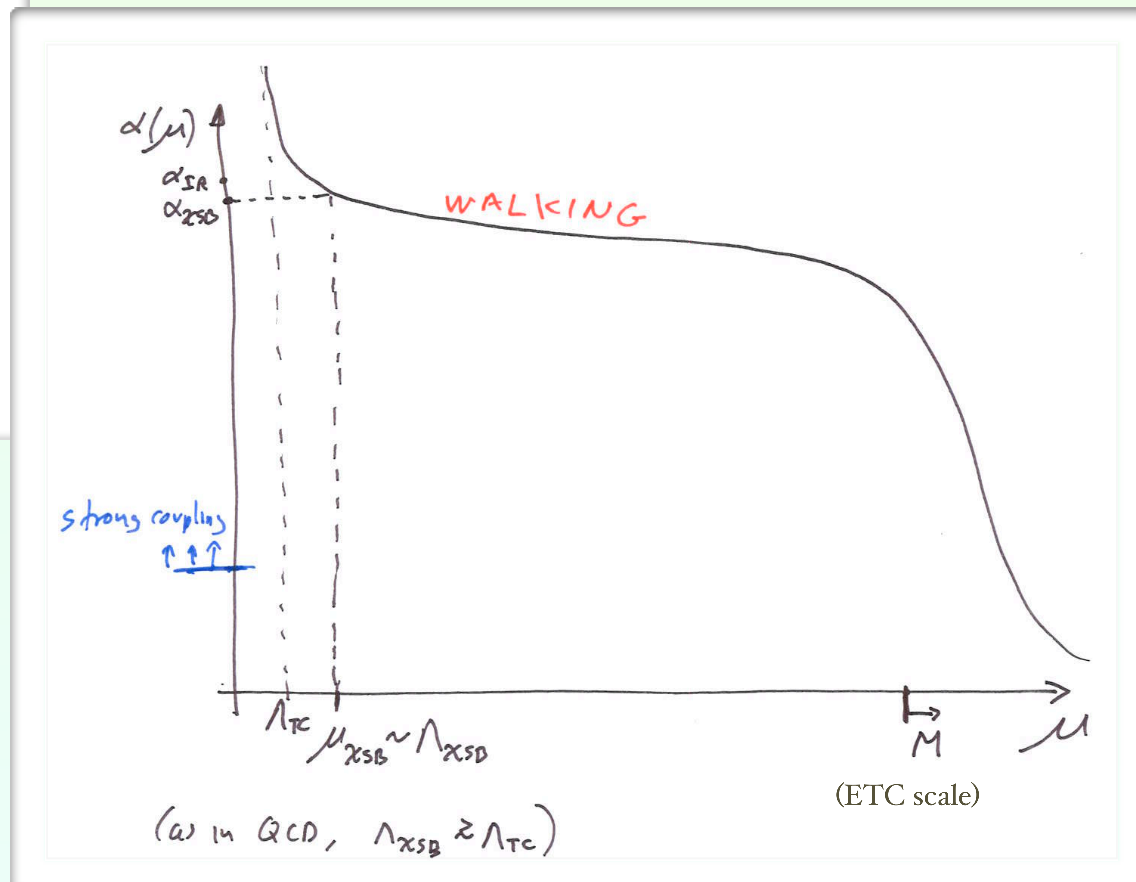
First review QCD:





WTC:


β/g
χSB critical coupling $\alpha_{\chi SB}$
would-be IR fixed point α_{IR}
α
SMALL β → "walking"
LARGE α
→ strong coupling


α(μ)
α_{SR}
$\alpha_{\chi SB}$
WALKING
strong coupling
Λ_{TC}
$\mu_{\chi SB} \sim \Lambda_{\chi SB}$
M
μ
(ETC scale)
(as in QCD, $\Lambda_{\chi SB} \gtrsim \Lambda_{TC}$)

The quark mass:

$$\mathcal{L}_{\text{mass}} = \frac{C(\mu)}{M^2}\langle\bar{Q}Q\rangle(\mu)\ \bar{q}q = \underbrace{\frac{C(M)}{M^2}}_{\text{o(1)}}\underbrace{\langle\bar{Q}Q\rangle(M)}_{\text{hidden dependence on }\Lambda/M}\ \bar{q}q = \underbrace{\frac{C(\Lambda)}{M^2}}_{\text{hidden dependence on }\Lambda/M}\underbrace{\langle\bar{Q}Q\rangle(\Lambda)}_{\text{o}(\Lambda^3)}\ \bar{q}q$$

Renormalization Group: $$C(\Lambda) = \left(\frac{M}{\Lambda}\right)^{\gamma_*}$$

The central observation: large coupling gives large anomalous dimension
It is argued that $\gamma_* \cong 1$

Hence

$$\mathcal{L}_{\text{mass}} = \frac{C(M)}{M\Lambda}\langle\bar{Q}Q\rangle(\Lambda)\ \bar{q}q \qquad \Rightarrow \qquad m_q \sim C(M)\frac{\Lambda^2}{M}$$

Bonus: in non-minimal TC this also raises the mass of pseudo-goldstone bosons:

If $\gamma_{(\bar{Q}Q)(\bar{Q}Q)} \approx 2\gamma_{(\bar{Q}Q)} \approx 2$ then $(\bar{Q}Q)(\bar{Q}Q)$ has dimension 4 (marginal operator).

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Answer may come from QFT on the Lattice

Or from LHC!

Future may be like learning about strong interactions from experiment, all over again!

EW Precision data

- A little experiment (homework for non-hep-th'ers):
  1. Ask your hep-th'er colleague at home whether they work on TC/ETC/WTC
  2. Ask them why

  (Answers: 1. No. 2. Theories are ruled out by EW precision data)

- Since the EW sector is strongly coupled there does not exist a reliable way to calculate radiative corrections (S and T parameters)

- The exception is Minimal TC: since this is scaled up QCD one can scale up measured quantities. Minimal TC is ruled out by EW precision data.

  It is also ruled out by quark masses/FCNCs, light pGBs, etc, so who cares???

- The walking-ETC theory is probably very un-QCD like. There is no guidance form experiment as to how to calculate EW corrections.

QCD-like lamppost

WTC @ LHC

- Two steps:
  - Discovery --- focus on this now
  - Learning --- like strong interactions all over again

- Dynamics not understood
  - Requirements on dynamics roughly known
  - Les Houches Reports 07 & 09: Focus on least dynamics specific & most model independent features

    Spectrum: use $SU(2)_W$ as "isospin" anlogue: $\pi_T, \rho_T, a_T, f_T, \pi'_T, \ldots$
    $(\bar{Q}Q)(\bar{Q}Q)$ gives large π_T mass, likely that (and assume) $m_{\rho_T} < 2m_{\pi_T}$, $m_{\omega_T} < 3m_{\pi_T}$
    Hence *narrow* states!

- Les Houches '09 studies: *pp*, 10 TeV (Drell-Yan production)
  - $\rho_T^\pm \to W^\pm Z^0$ (CMS)
  - $\omega_T \to \gamma Z^0 \to \gamma \ell^+ \ell^-$ (PGS)
  - $\omega_T, \rho_T^0, a_T^0 \to \ell^+ \ell^-$ $Q_U + Q_D = 1$ (CMS)

"Low Scale TC"

"TC Straw Man"

Note: we will present results only. See e-Print: arXiv:1005.1229 for:

(i) Parameters used
(ii) Analysis strategy
(iii) Signal & Event selection
(iv) Background estimation

(so it is more like a picture show)

Cases studied, and gross results:

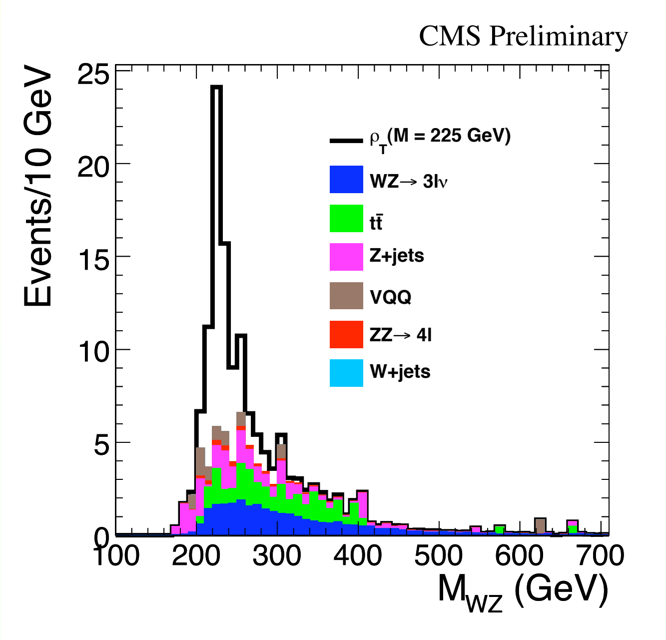
SM background

						$\rho_T \longrightarrow$	$a_T \longrightarrow$	$\omega_T \longrightarrow$	$\rho_T, a_T, \omega_T \longrightarrow$
Case	M_{ρ_T,ω_T}	M_{a_T}	M_{π_T}	$M_{V_1,\ldots,A_2}$		$\sigma(W^\pm Z^0)$	$\sigma(\gamma W^\pm)$	$\sigma(\gamma Z^0)$	$\sigma(e^+e^-)$
1a	225	250	150	225		230	330	60	1655 (980)
1b	225	250	140	225		205	285	45	1485 (980)
2a	300	330	200	300		75	105	11	425 (290)
2b	300	330	180	300		45	85	7	380 (290)
3a	400	440	275	400		22	40	4	130 (90)
3b	400	440	250	400		14	35	3	120 (90)

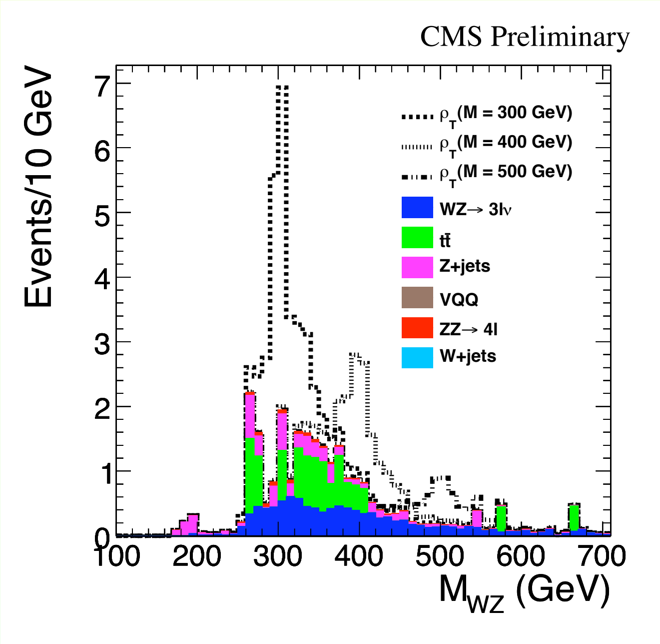
integrated over
25GeV around 3 resonances

$$\boxed{\rho_T^{\pm} \to W^{\pm} Z^0}$$

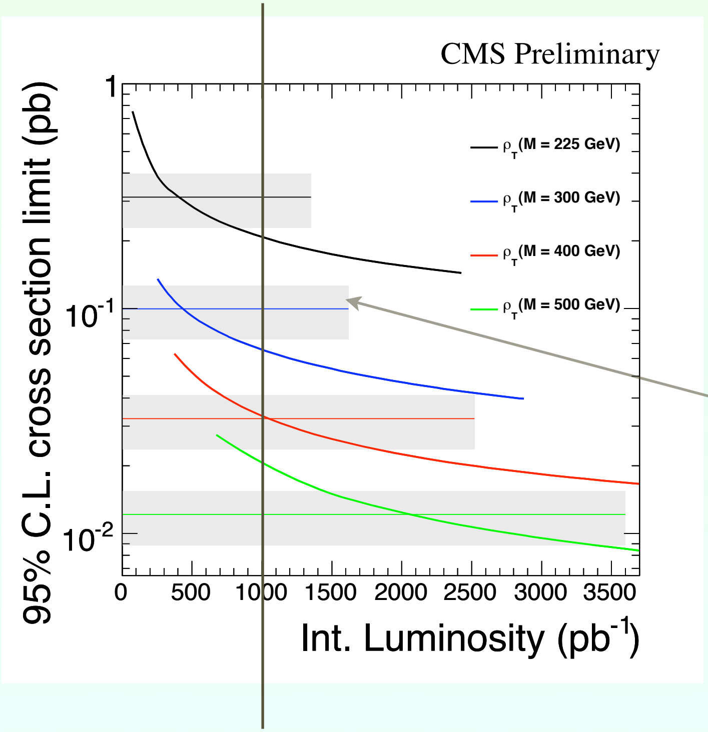
Normalized to 1 fb^{-1}



Optimized for low luminosity (low mass), early running.



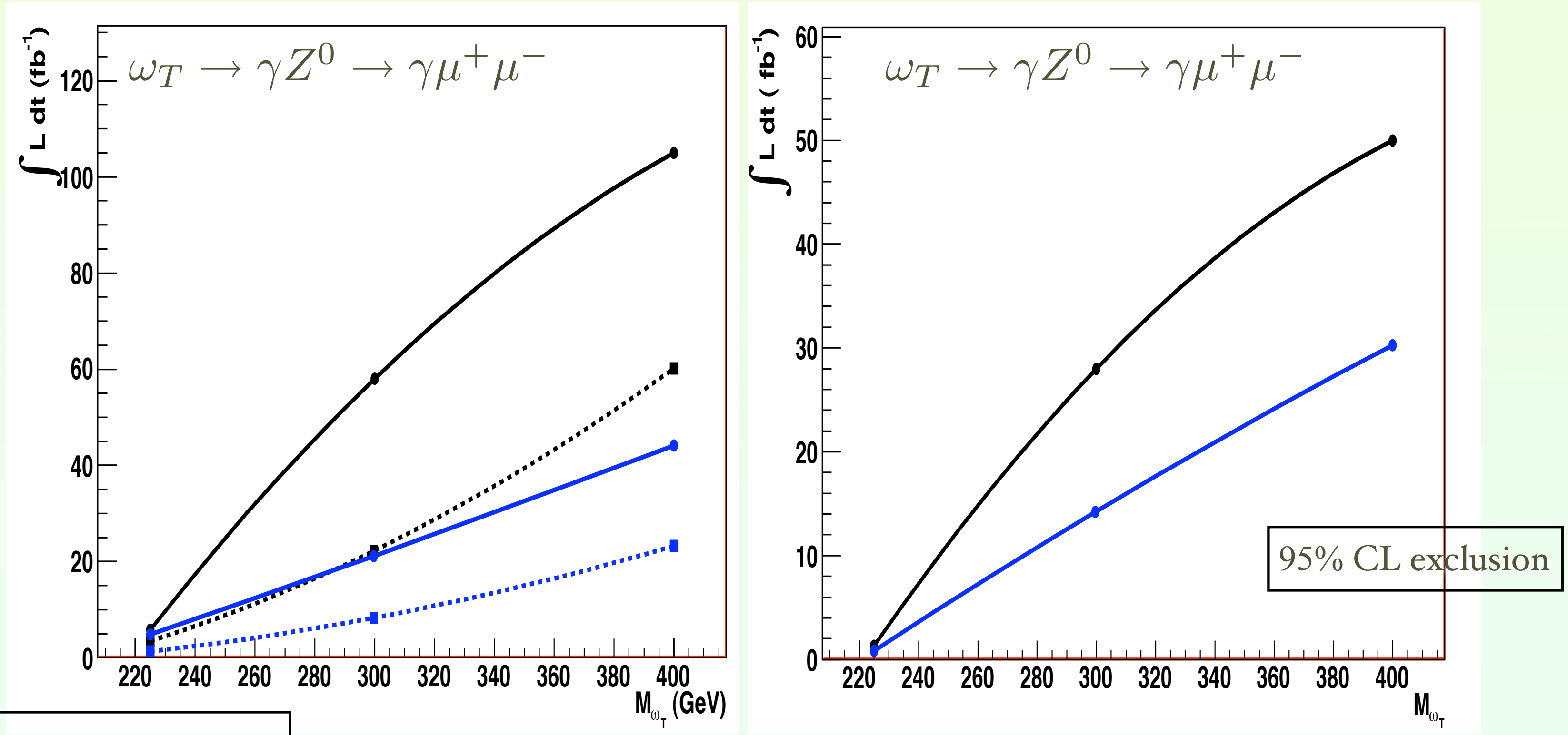
Optimized for high luminosity (higher mass), later running.



Theory cross section with 27% error bands

$\omega_T \to \gamma Z^0 \to \gamma \ell^+ \ell^-$

Note: for $Q_U + Q_D = 1$ $\omega_T \to \ell^+ \ell^-$ is forbidden



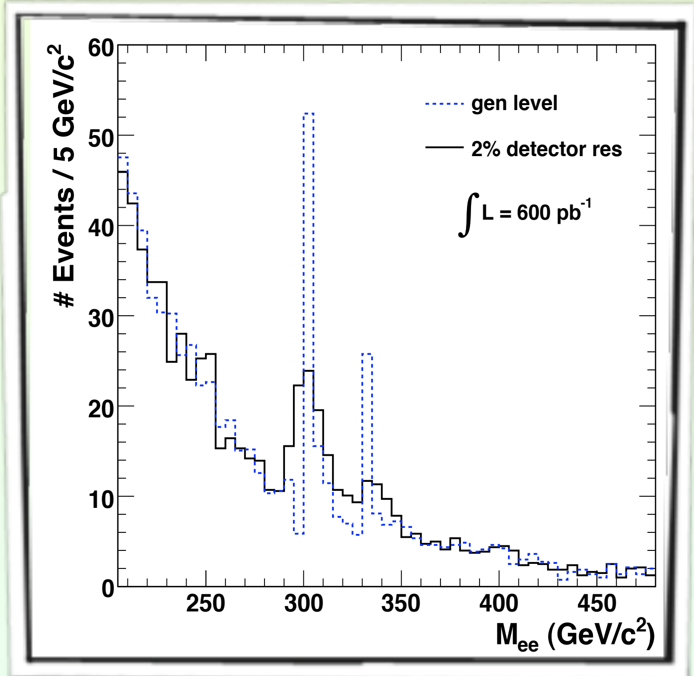
dashed: 3σ evidence
solid: 5σ observation

blue: case "a" (heavier π_T)
black: case "b" (lighter π_T)

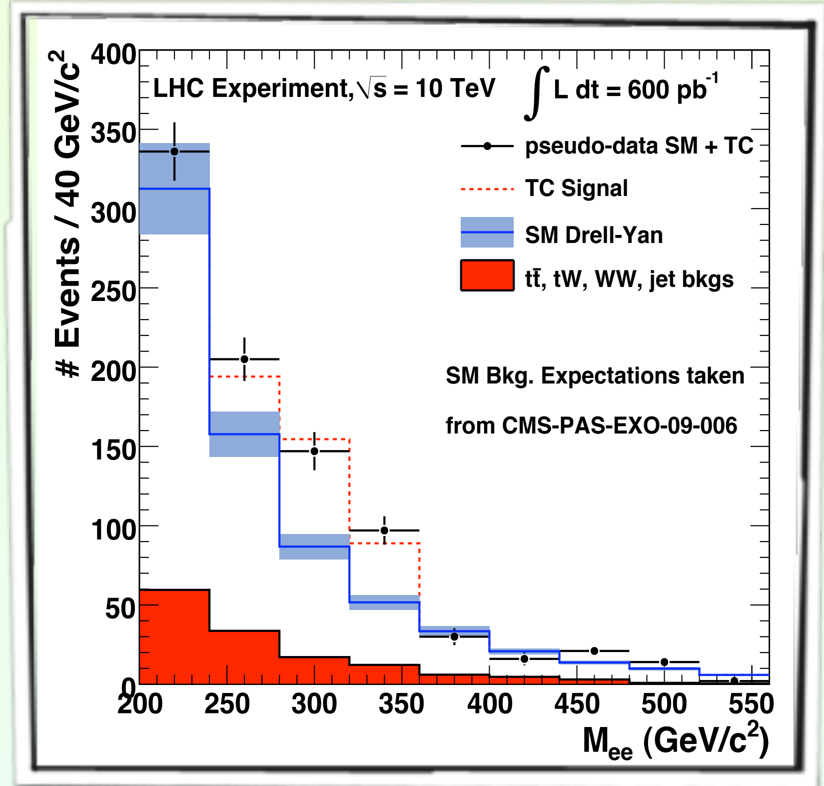
$\rho_T, a_T^0, \omega_T \to e^+e^-$

(assume $Q_U + Q_D = 1$; for $Q_U + Q_D = 0$ rate vanishes for ω_T)

pseudo experiment



signal only
compare generator only vs
with detector resolution



case 2a: $M_{\rho_T,\omega_T} = 300$ GeV, $M_{a_T^0} = 330$ GeV
$E_T(e^{\pm}) > 50$ GeV,
full η kinematic acceptance of CMS

10 TeV luminosities (pb^{-1}) for ω_T exclusion

Model	nominal syst.	improved syst.
1a	20	20
1b	31	31
2a	170	150
2b	360	320
3a	610	560
3b	1120	930

10 TeV, 1 fb^{-1}: discovery in cases 1a-b, strong evidence for 2a-b.

Other stuff

- Organizers: “Strong Dynamics and New Electroweak Models”
- Would like to present other models. But
  - Even WTC/ETC is not a model.
  - Argued: generic features → experiment → theory
  - Out of time

- Conformal TC [Luty & Okui, JHEP 0609:070,2006]
  - Assume $H \sim QQ$ has dimension 1, $H^2 \sim QQQQ$ has dimension 4
  - Both Yukawa (eg Hqu, H^*qd) and mass H^2 are marginal, that is, depend on cutoff only logarithmically → no hierarchy problem!
  - Some evidence against this arrangement of anomalous dimensions [Rattazzi, et al, JHEP 0812:031 (2008)]

- 5D models. For example [Cui et al JHEP 0911:080 (2009)]
  - W/Z localized on IR brane, b.c.'s break gauge symmetry explicitly
  - 4D dual: composite W/Z, no higgs, KK modes (in lieu of techni-resonances)
  - Top, a problem

Rehash

- Strong EW symmetry breaking is very appealing
- News of its demise are premature
- Incalculable and non-QCD like (un-xeroxable):
  - Search & discover (or exclude)
  - Study
  - Build model and learn about strong dynamics
  - In that order!

- Can strog EW be excluded?
  - No (no worse than SUSY)

- Can generic WTC be excluded
  - Yes: to the extent you cannot expect WTC to give heavier than multi-TeV T-stuff
  - No better than specific SUSY, eg, CMSSM

- 200 nb^{-1} down ... 999800 nb^{-1} to go! Looking forward to it!