TeV-scale strong dynamics and the lattice

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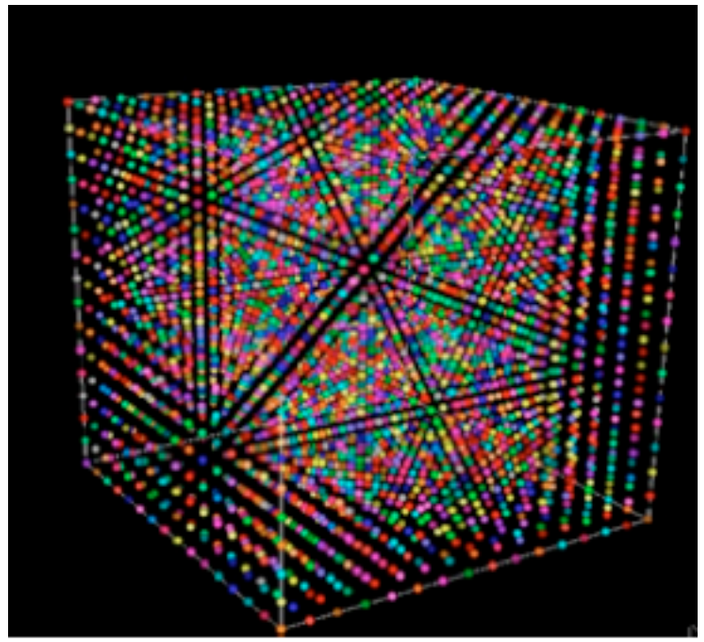

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Fermilab

Fermilab

Lattice meets Experiment, Oct 15th 2011

Punchline

Q: why is TeV-strong dynamics interesting now, in 2011?

after the explosion of results this summer, we have seen:

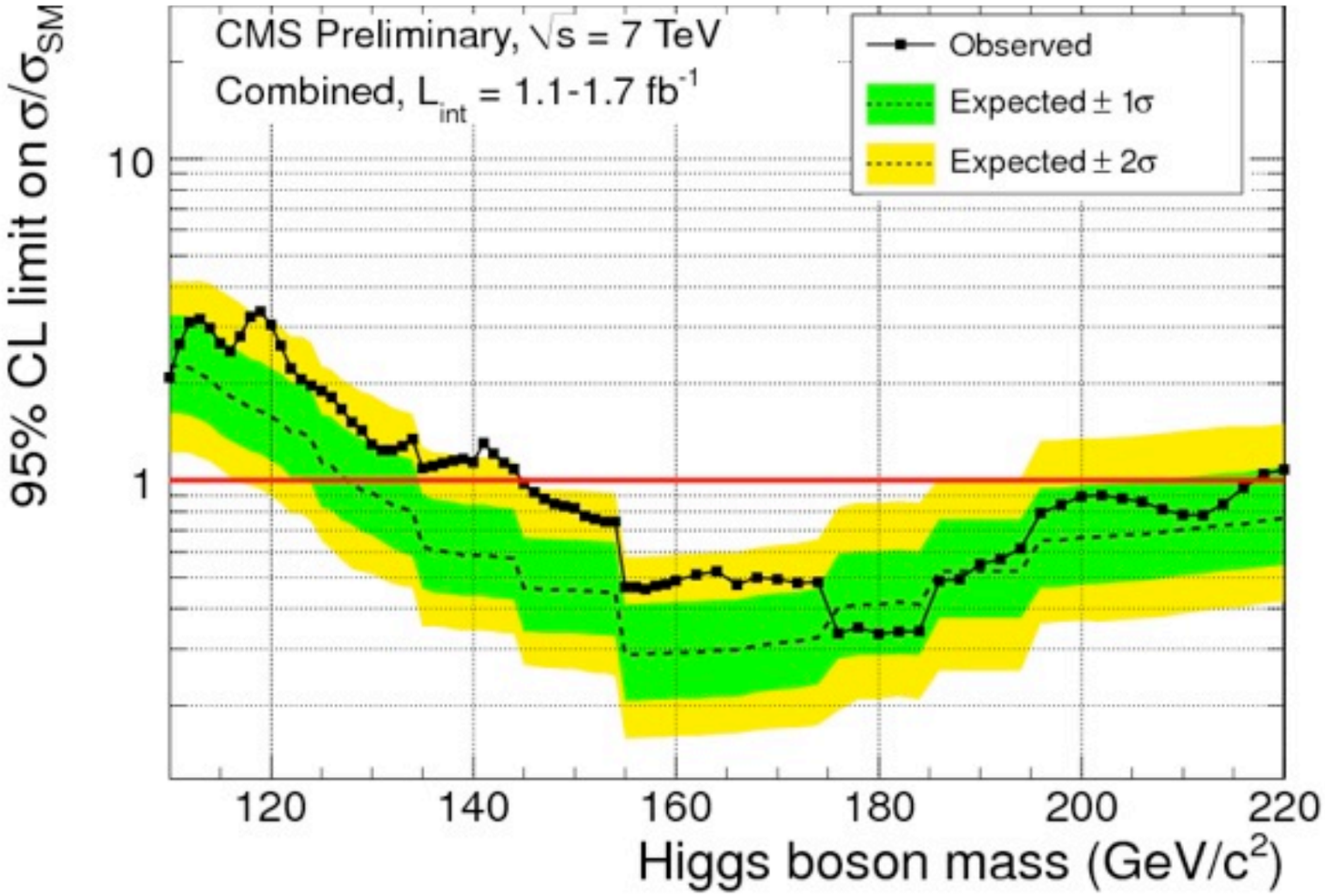
- no light (< TeV), colored states
- no large missing energy signals
- no resonances with O(SM) couplings to SM fermions
- so far, no light Higgs

doesn't mean these possibilities are ruled out...

BUT these are all characteristics of models with
TeV-scale strong interactions (technicolor)

- lattice input can greatly help us understand viable versions of these theories

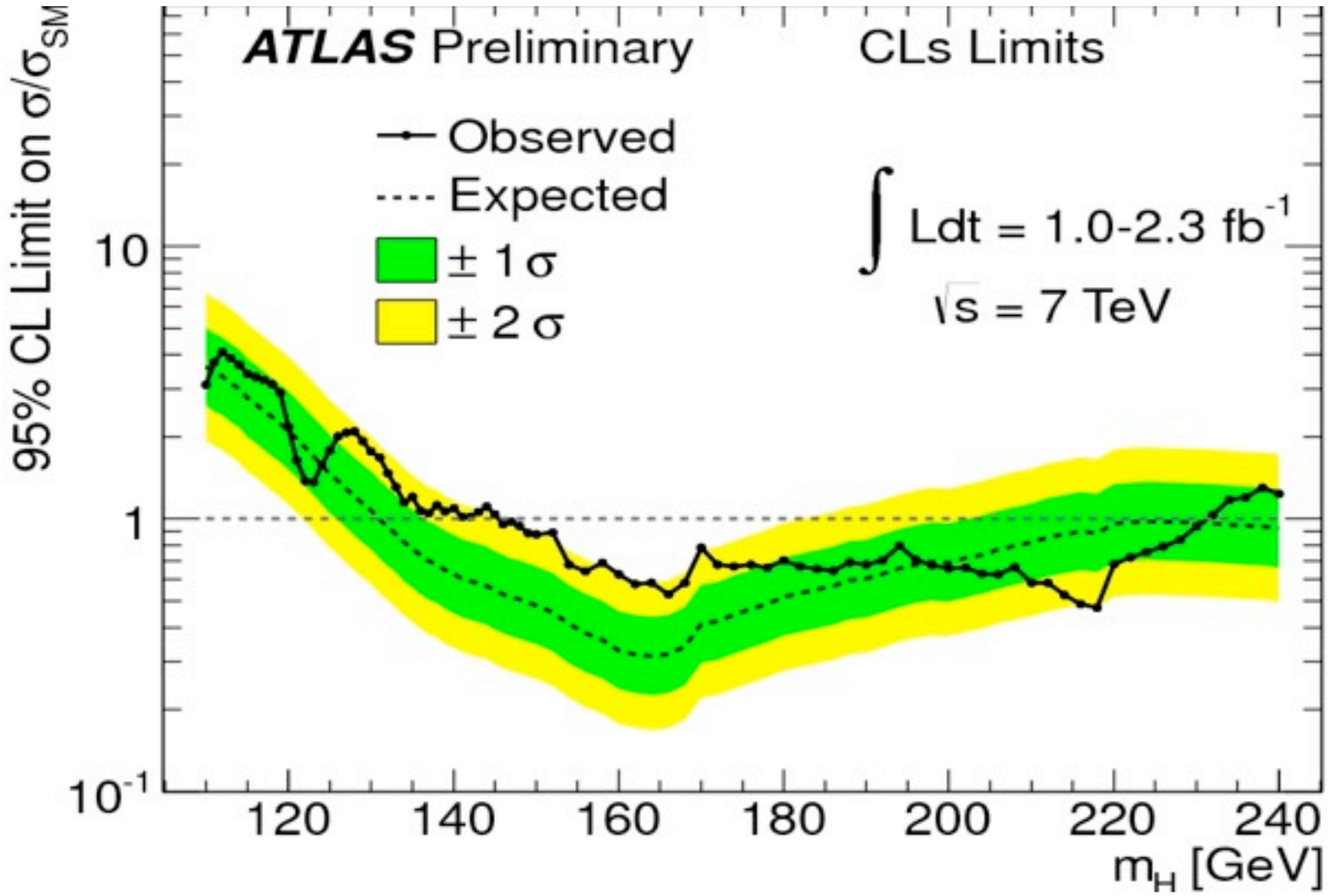
No Higgs?



CMS obs. exclusion (95% CL):

$m_H \subset$ 145–216 GeV, 226–288 GeV, 310–400 GeV

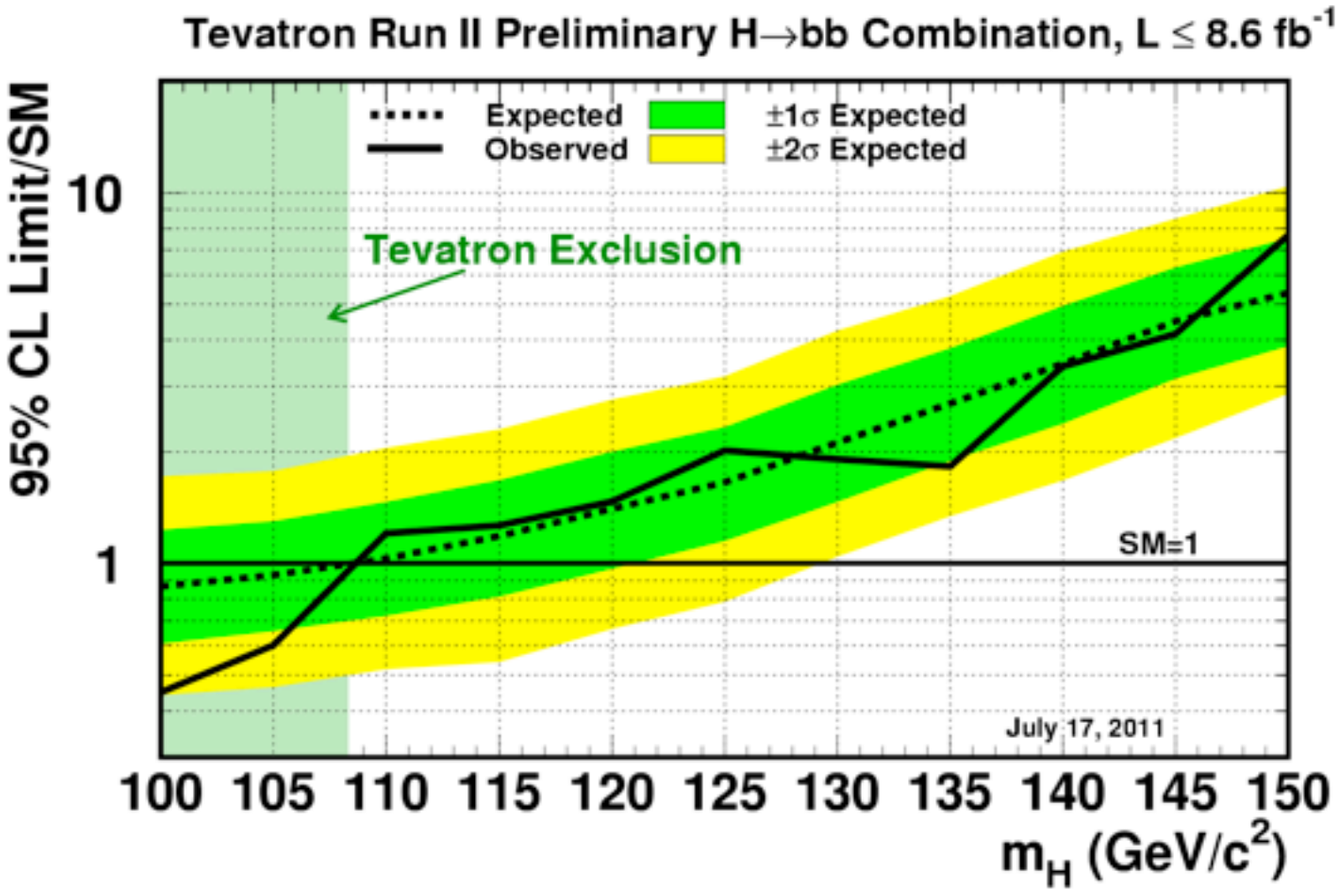
No Higgs?



ATLAS obs. exclusion (95% CL):

$m_H \subset$ 146-232 GeV, 256-282 GeV, 296-466 GeV

No Higgs?



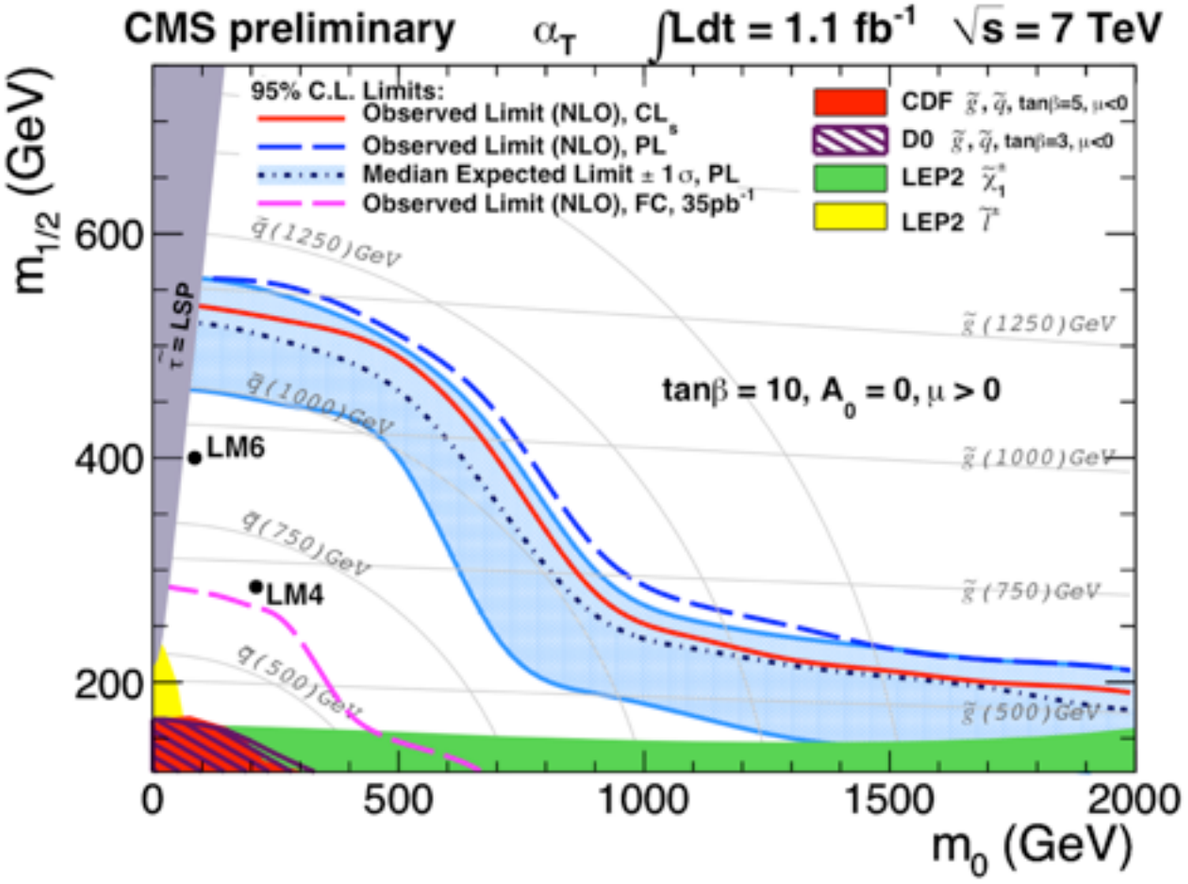
For low-mass Higgses, the Tevatron is more sensitive...

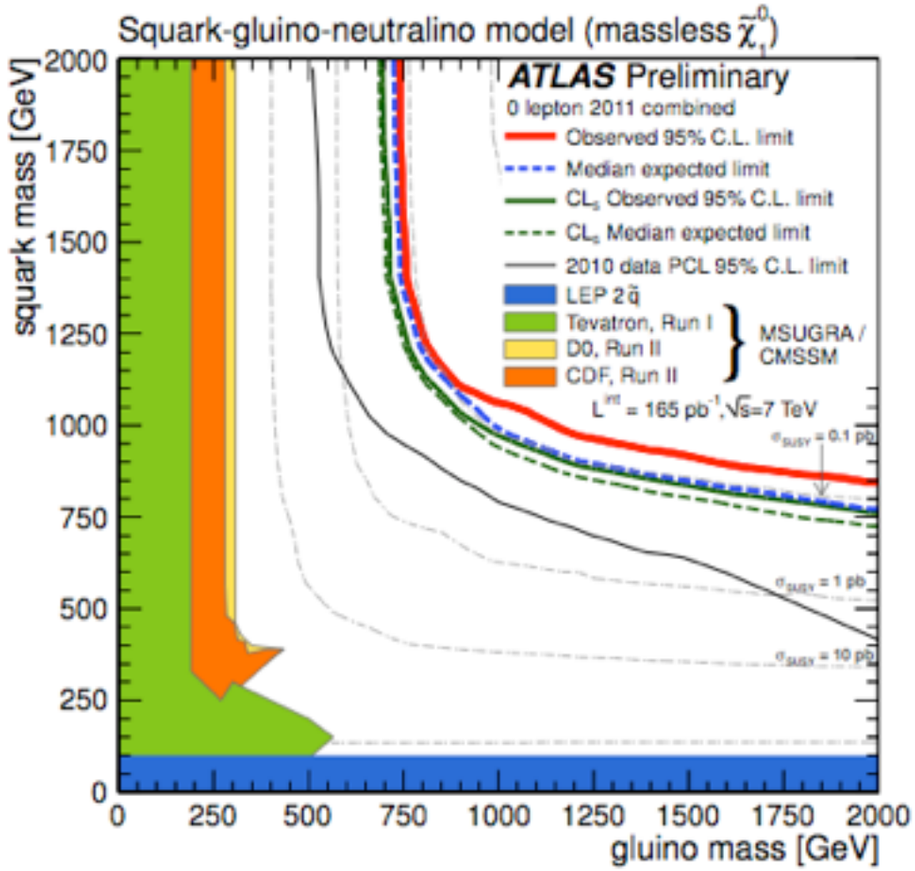
- At 115-120 GeV
  - Almost at 1*SM sensitivity
  - No excess seen

MC studies injecting signal 115-130 GeV: Not consistent with signal

(see talk by Kilminster 8/29/11 'Implications of LHC')

No SUSY?



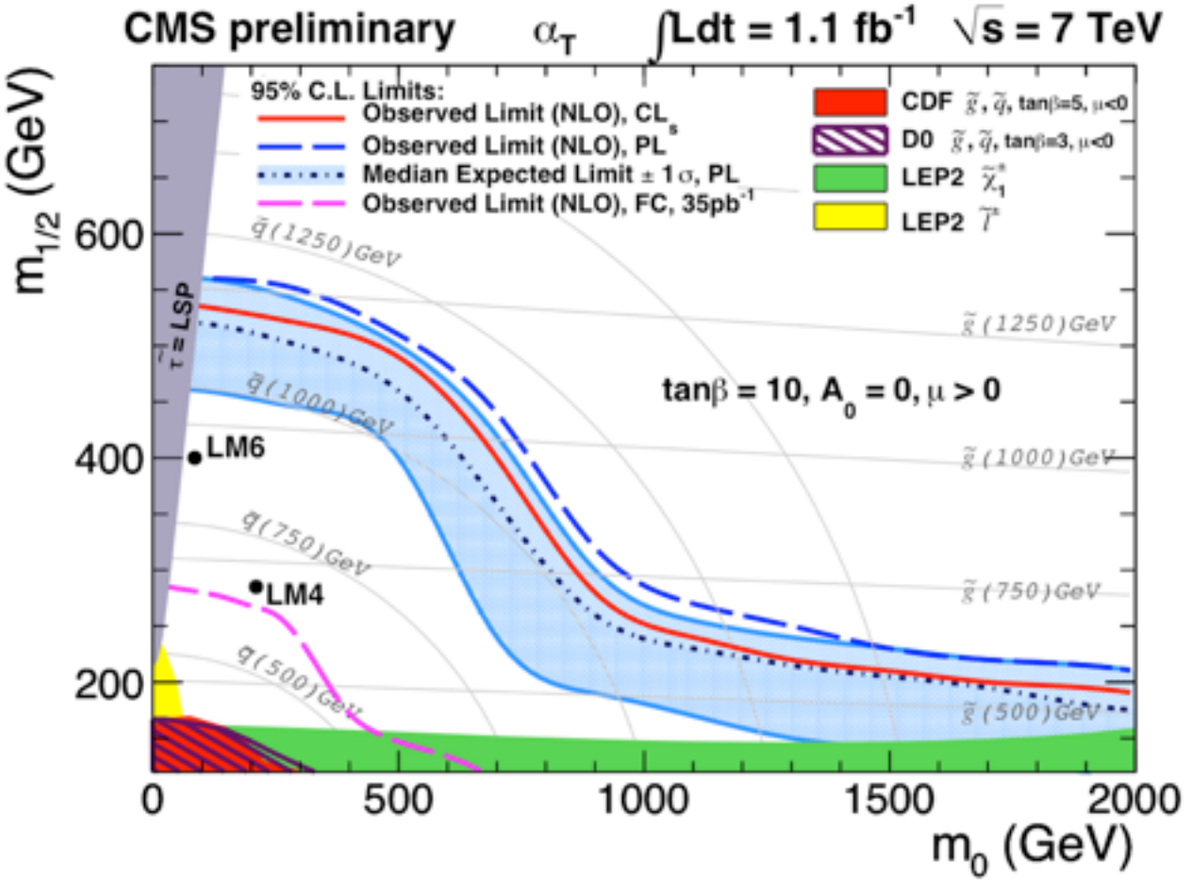


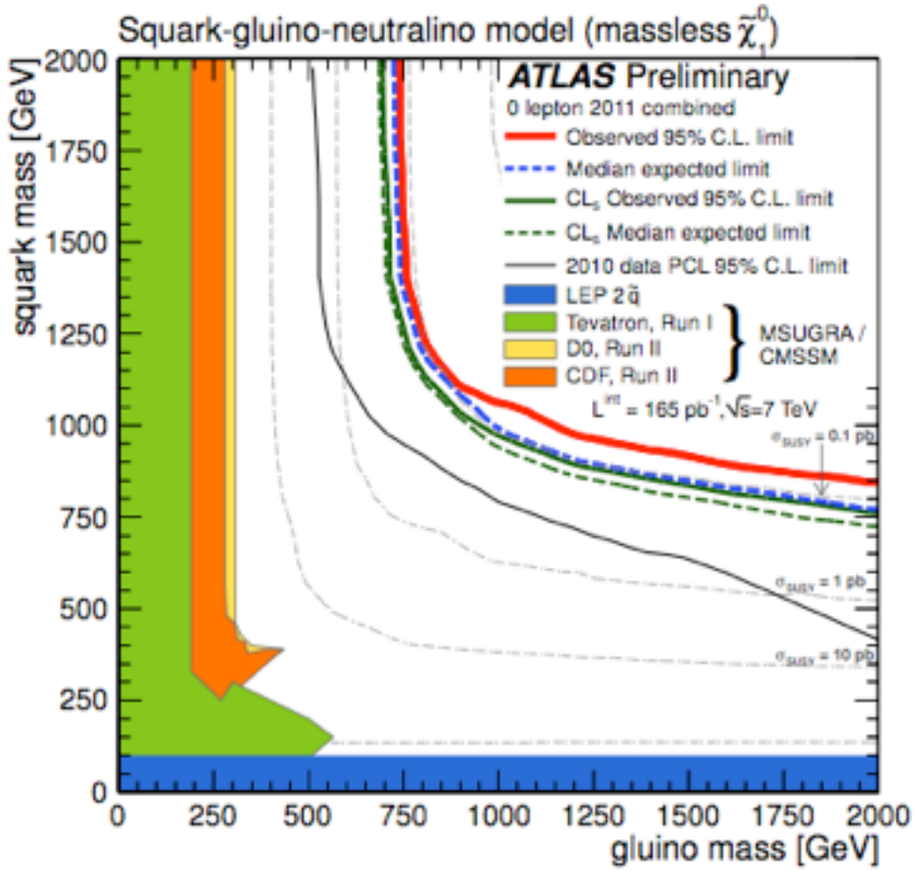
- MSSM scenarios* already pushed to ~TeV squarks and gluinos, mainly by jets + MET searches

- moved beyond MSUGRA: limits now presented in 'simplified models', i.e.) $m_{\tilde{Q}}$ vs. $m_{\tilde{g}}$

*compressed spectra can still avoid limits, as can lighter 3rd generation smatter

No SUSY?





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FINALLY!

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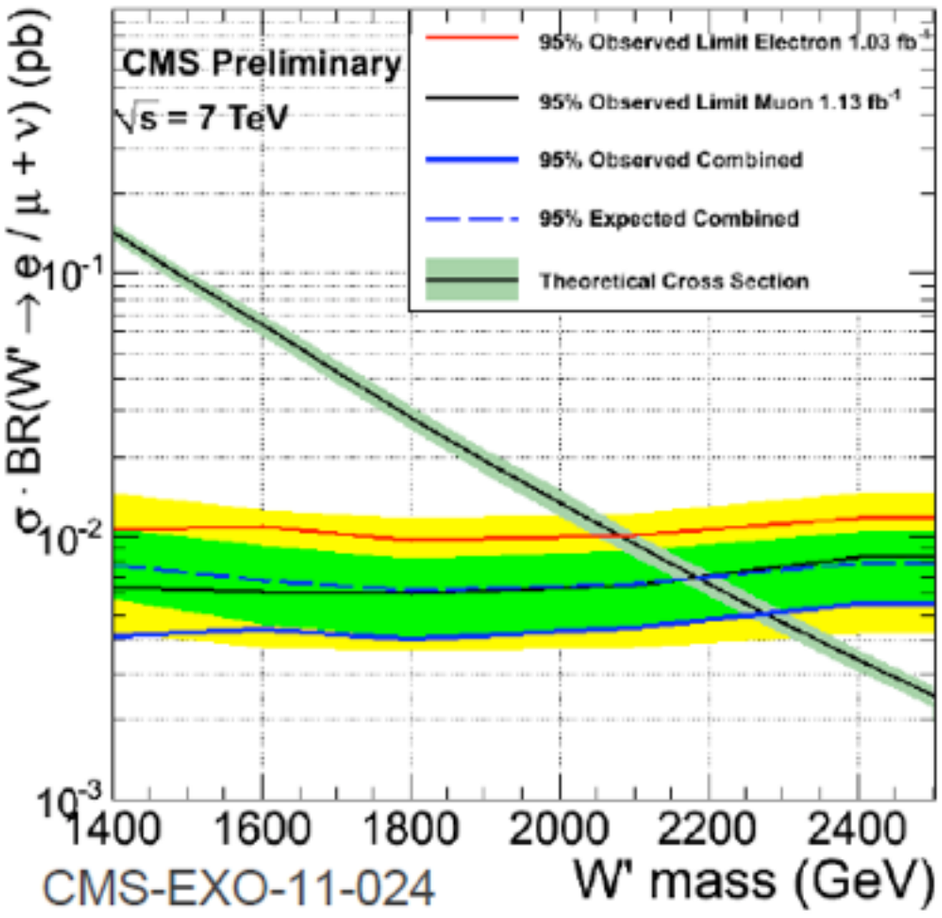
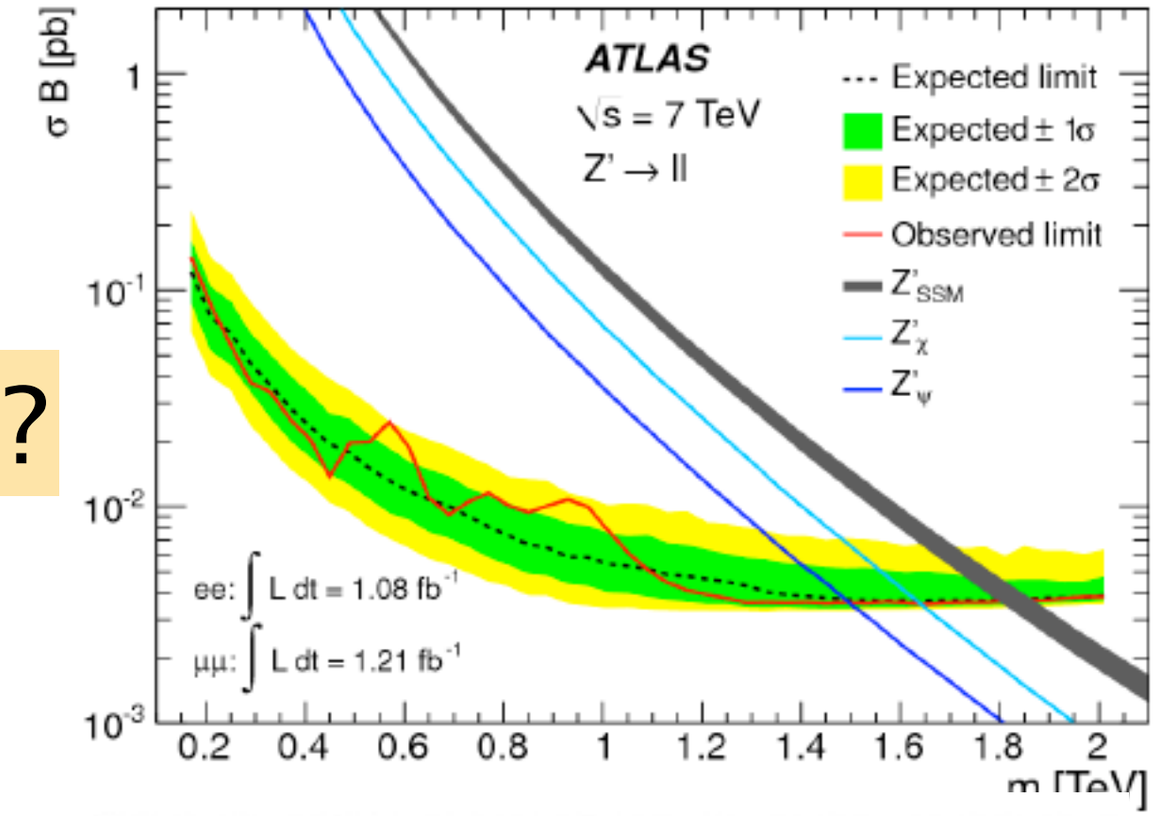
Nothing?

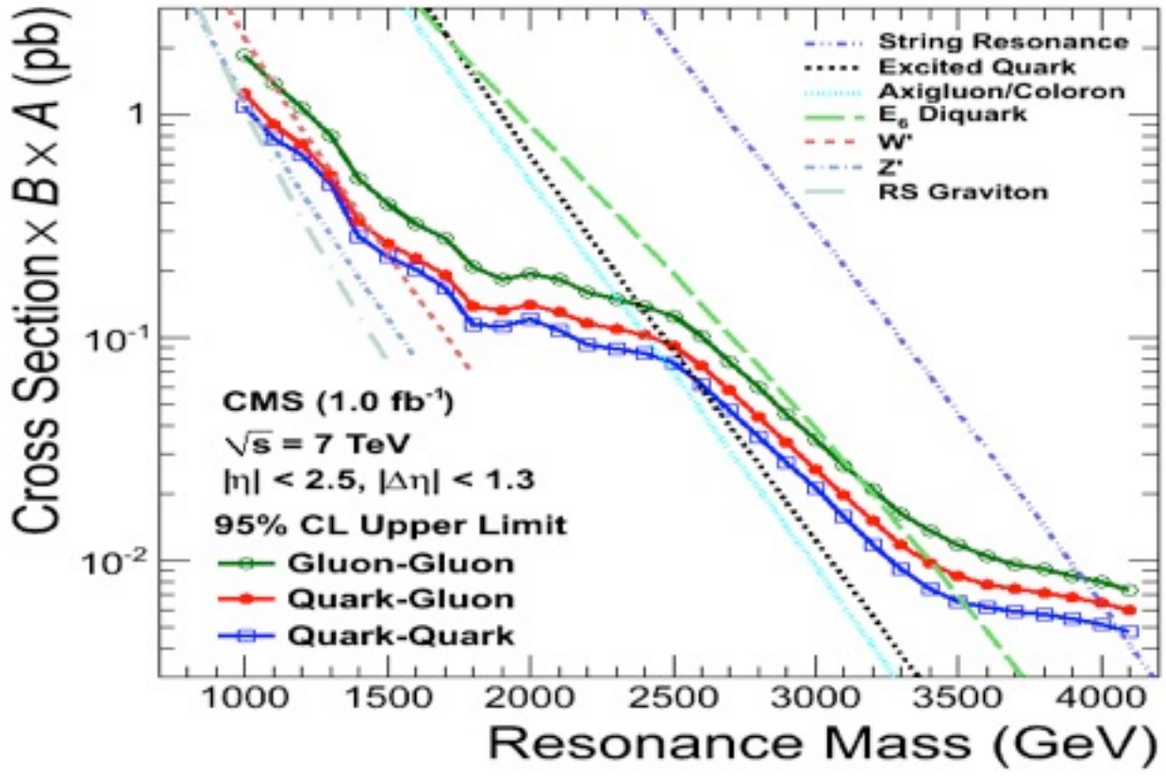
W'?



Z'?



dijets?



Why new Tev-scale strong dynamics?

- dynamical symmetry breaking has precedents in nature (**QCD**, superconductivity)

  ... but requires strong interactions

- we don't need a Higgs boson for EWSB

add in some new fermions:

"techni-fermions"

chiral EW charges

$$T_{iL} = (N_{TC}, 2)_0$$
$$T_{iR} = (N_{TC}, 1)_{\pm 1/2}$$

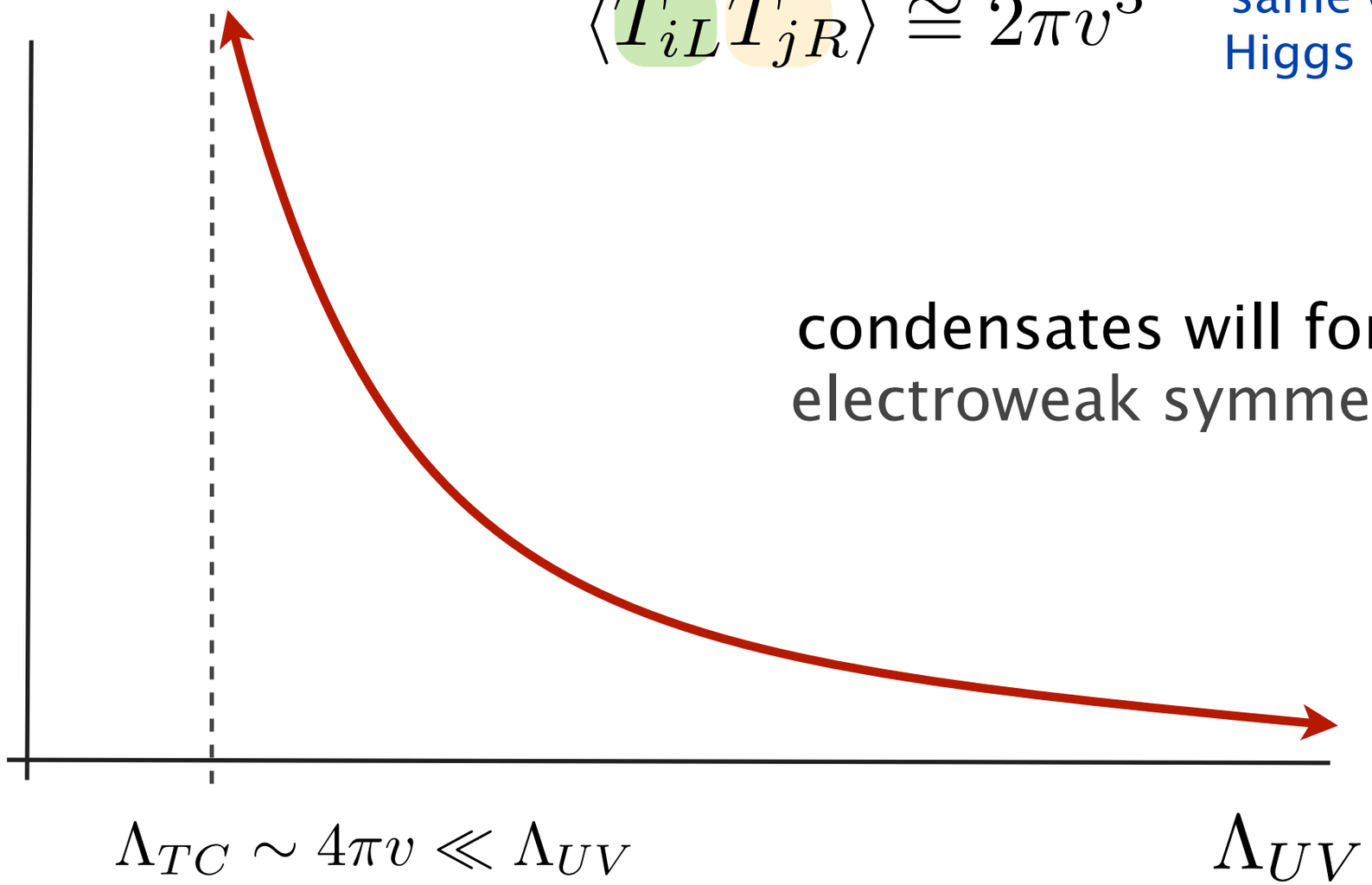
new strong gauge interaction = "technicolor"

Why new Tev-scale strong dynamics?

if technicolor becomes confining at ~ TeV ...

$$\langle \bar{T}_{iL} T_{jR} \rangle \cong 2\pi v^3$$

same Q# as a Higgs doublet



condensates will form, causing electroweak symmetry to break

ONLY natural way to generate exponentially large hierarchies

new Tev-scale strong dynamics

many different names & slightly different mechanisms

multi-scale technicolor

topcolor-assisted technicolor

topcolor

Technicolor

minimal walking technicolor

top-seesaw

composite Higgs

Extended Technicolor

warped extra dimensions/RS

Bosonic technicolor

deconstructed models/(D)BESS

strong coupling means there is a lot we don't know

what we know:

for N_D doublets, we have

$(2\,N_D)^2 - 1$	goldstones
-3	eaten by W/Z
$(2\,N_D)^2 - 4$	uneaten, "techni-pions"

what we don't know:

what else is around?.. expect spin-1 resonances in analogy to QCD

$$\rho_T, a_T, \omega_T, \ldots$$

but mass ($\sim\Lambda_{TC}$?) , coupling, hierarchy not calculable, must be modeled

some intuition from QCD... but no reason TC should have QCD-like dynamics (different N_C, N_F, etc.)

LATTICE INPUT CAN HELP

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for N_D doublets, we have

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EW-resonances!

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LATTICE INPUT CAN HELP

Technicolor formalism

EW chiral lagrangian: lets take the simplest example, one technidoublet. Start with chiral lagrangian, adjust for the heavier scale, and $SU(2)_W$, $U(1)_Y$ gauge interactions

(Appelquist, Bernard, Longhitano)

$$\mathcal{L}_{EW\chi} = \frac{F_T^2}{4}\mathrm{tr}(D_\mu \Sigma D^\mu \Sigma^\dagger) + \cdots \qquad \Sigma = e^{2i\vec{\pi}_T / F_T}$$

$$\vec{\pi}_T = \pi_{T,a}\tau^a$$

$$D_\mu \Sigma = \partial_\mu \Sigma - ig\vec{W}_\mu \Sigma + i\frac{g'}{2}\Sigma B_\mu$$

use gauge invariance to remove π_T --> go to unitary gauge $\Sigma = \mathbf{1}$

$$\mathcal{L}_{EW\chi} = \frac{F_T^2}{4} g^2 W_\mu^+ W^{-\mu} + \frac{F_T^2}{8\cos^2\theta_W} Z_\mu^2 + \cdots$$

for more than two techniflavors ($N_D > 1$), there will be extra π_T

what else?

Cast of Characters:

exactly which states are lurking at the TeV scale depends somewhat from model to model

present in **all** models (wide range of masses)

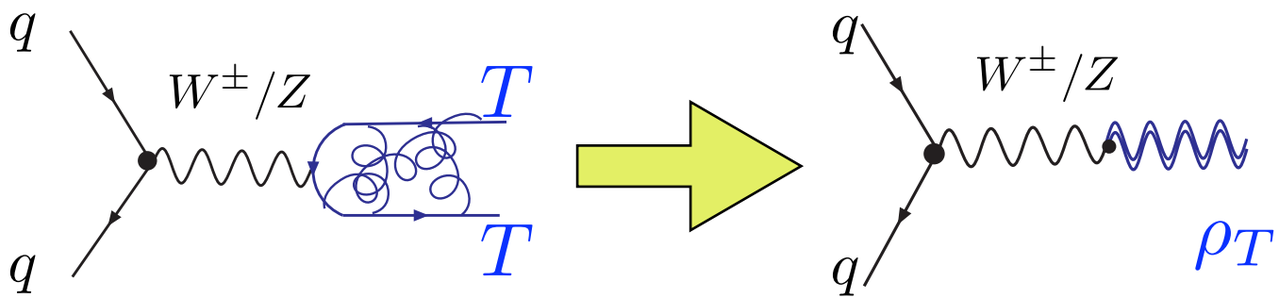
- spin-1, EW resonances: ρ_T, Z', W_{KK}

model dependent

- spin-0, pseudoscalars: “technipions”, “top-pions”
- spin-0, scalars: “top-Higgs”
- spin-1, colored resonances: “colorons”, “axigluons”
- heavy fermions: ψ_{KK}, ”techni-baryons”
- more.. (spin-2, spin-3/2..)?

all with interesting phenomenology

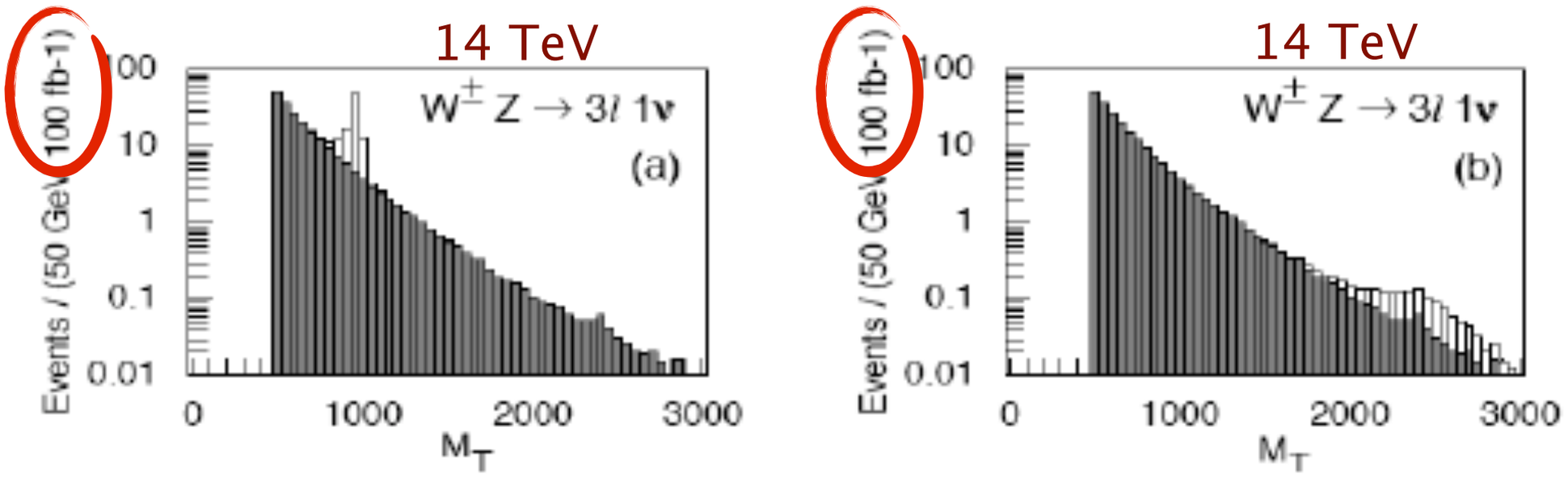
Technicolor phenomenology



Vector meson dominance

analogous to how
$e^+e^- \to \rho$
is described in QCD

decays to W^+W^- or $W^{\pm}Z^0$: 3 lepton + neutrino is cleanest



can also decay to fermion pairs, but tiny branching fraction

BR(WW/WZ) enhanced by: M^4_ρ/M^4_W

for early studies, Bagger et al hep-ph/9306256, 9504426, Golden 9511206

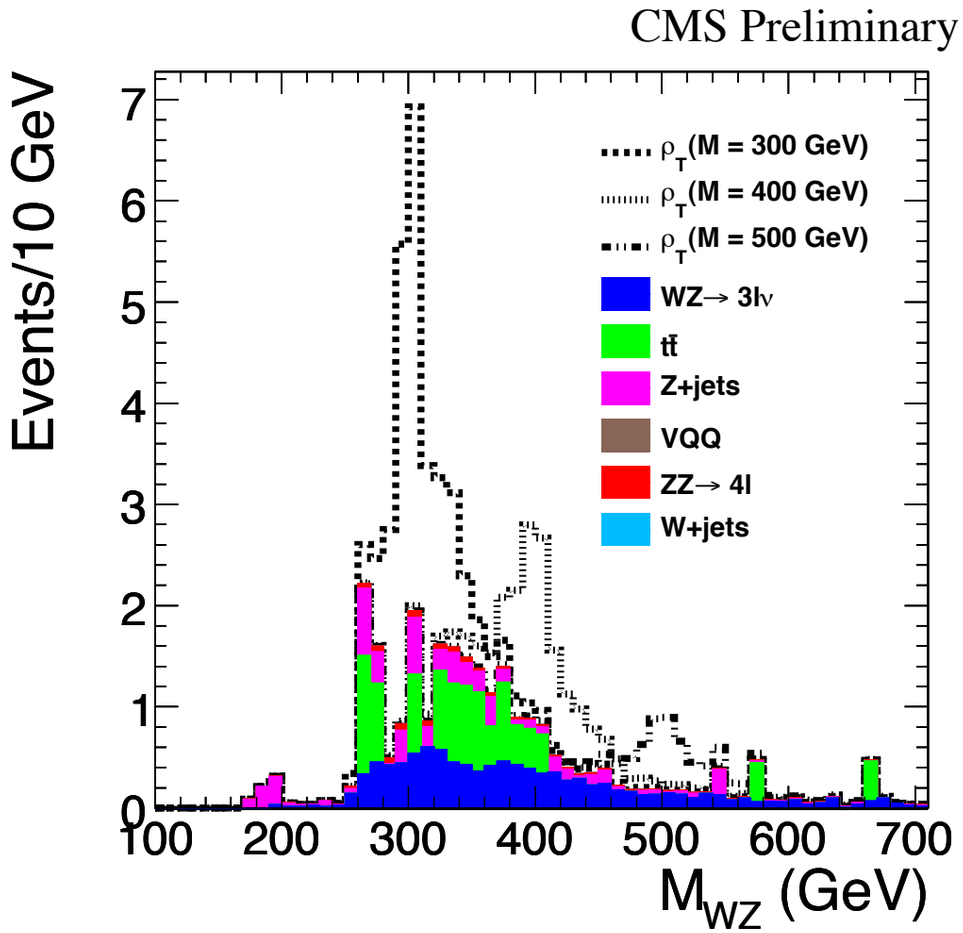
Technicolor phenomenology

lighter resonances have better detection prospects

for example: multi-scale technicolor (Eichten, Lane)

two-different condensates, ~motivated by 'walking'

$v_1^2 + v_2^2 = v^2$, $v_1/v_2 = \tan\beta$



assuming 1 fb^{-1}, 10 TeV LHC

resonances from light scale: $M_{\rho 1} \sim 4\pi v_1$

can be ~300 GeV and still safe from current limits

$$g_{ff\rho_{T1}} \sim g \frac{M_W}{M_{\rho_{T1}}} \left(\frac{v_1}{v}\right)$$

parity/isospin partners of ρ_T: a_T, ω_T can be seen in pp -> W+γ, pp -> Z+γ

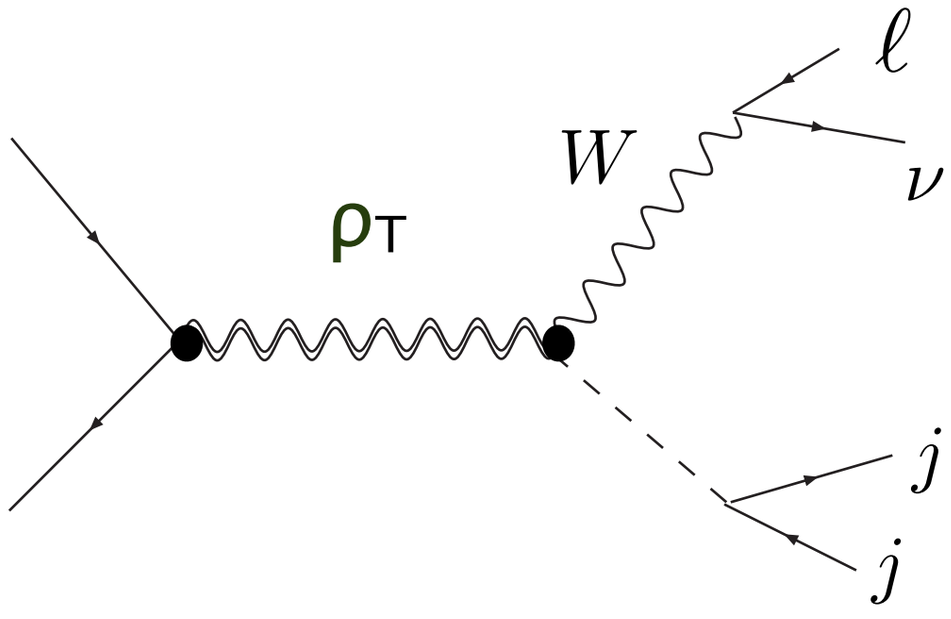
similar signals in MWT (Sanino), SCT (Luty)

Technicolor phenomenology

if there are π_T around, usually light (pNGB) and couple according to mass*:

$$\frac{1}{\Lambda^2}\langle \bar{T}_{1L} T_{1R}\rangle \bar{f}_L f_R \longrightarrow m_f\left(+i\frac{\pi_T}{v}+\cdots\right)\bar{f}_L f_R$$

small fermion masses make π_T difficult to produce directly, so dominantly produced by $\rho_T/a_T/\omega_T$ decay:



W/Z + jets signature...

*up to mixing angles

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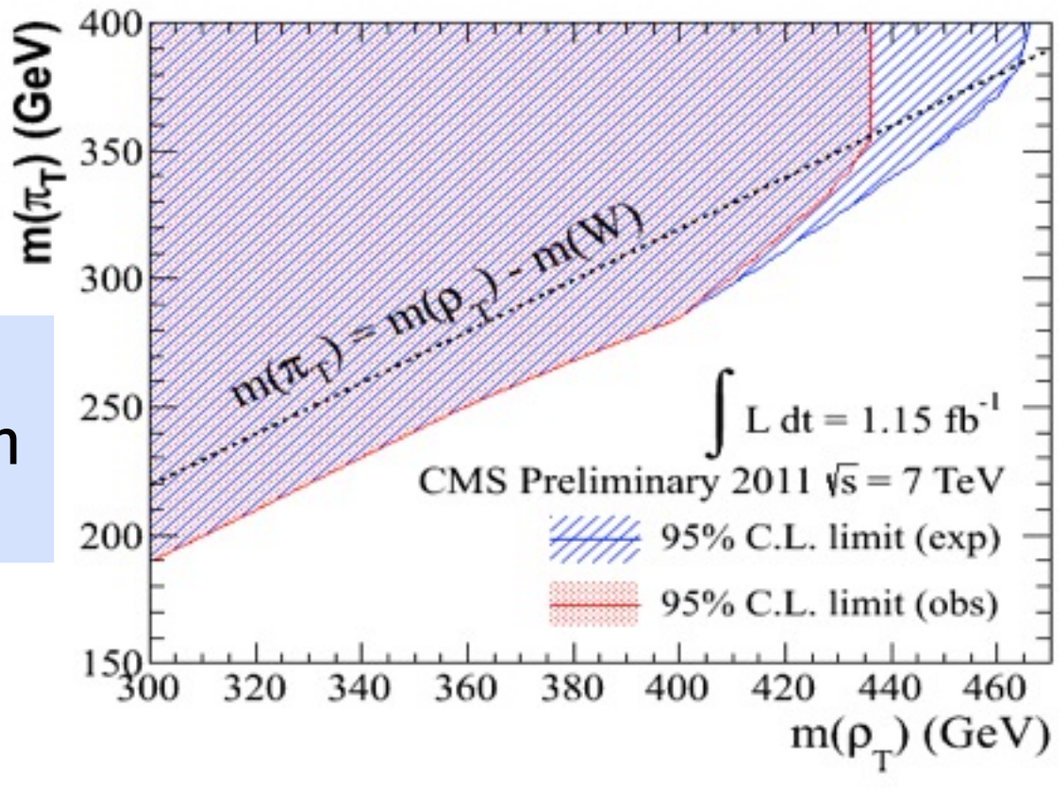
in
3 lepton
+ MET



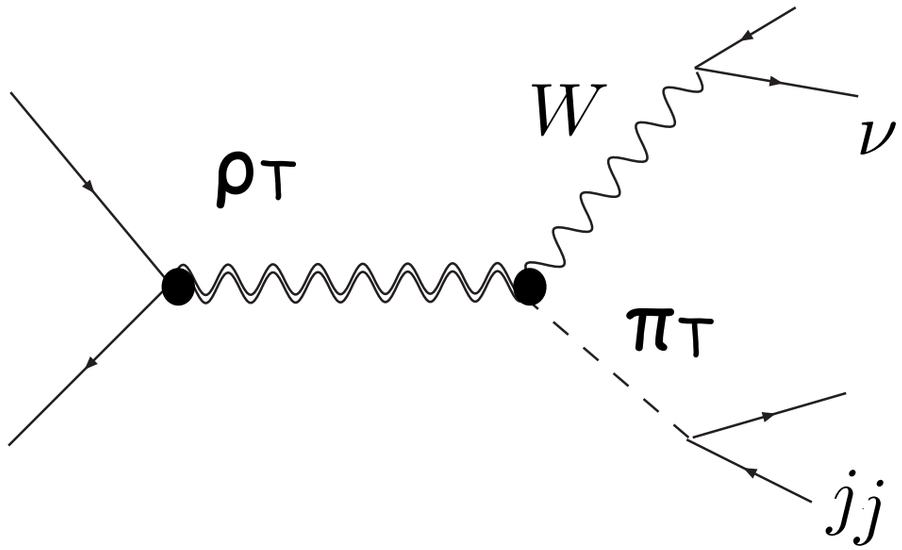
W/Z + jets signature...

*up to mixing angles

wait a minute...

maybe we're already seeing something in W+jj ...

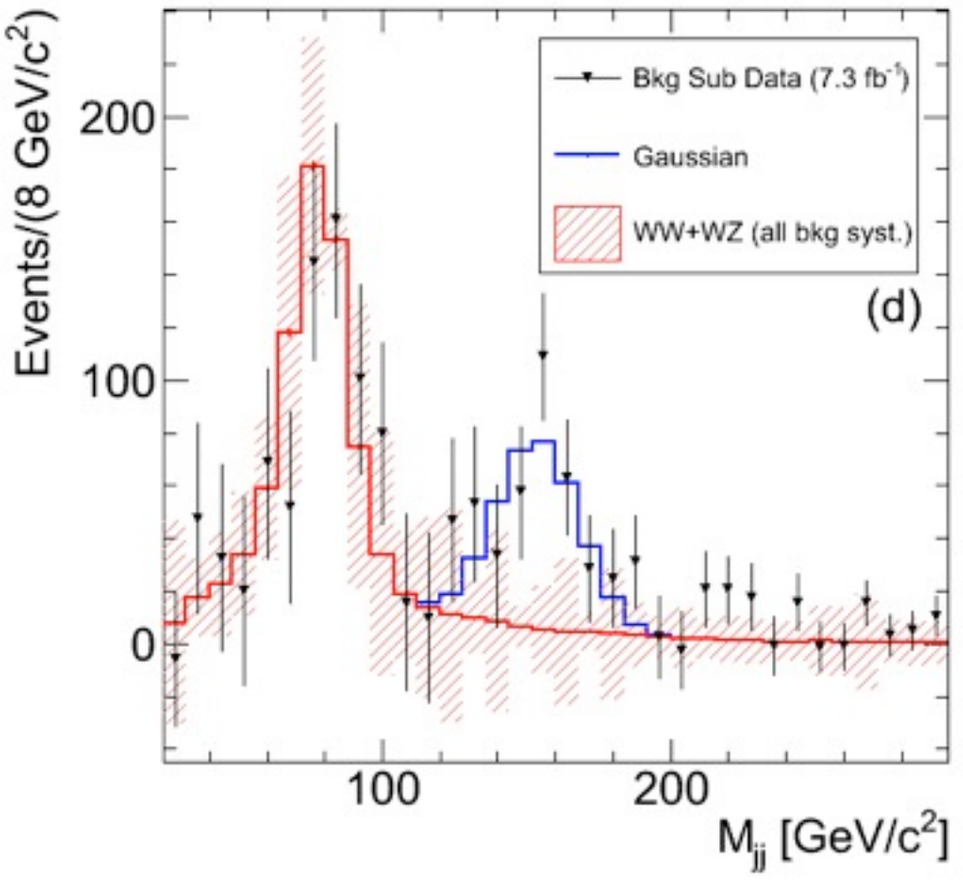
CDF W+jets 'bump' fit well by low-scale technicolor



M_π ~ 150–160 GeV, M_ρ ~ 300 GeV

(ELM '11)

L = 7.3 fb-1 4.1 sigma



not observed by D0, though analyses differ in small, but important ways ... **NOT** settled yet

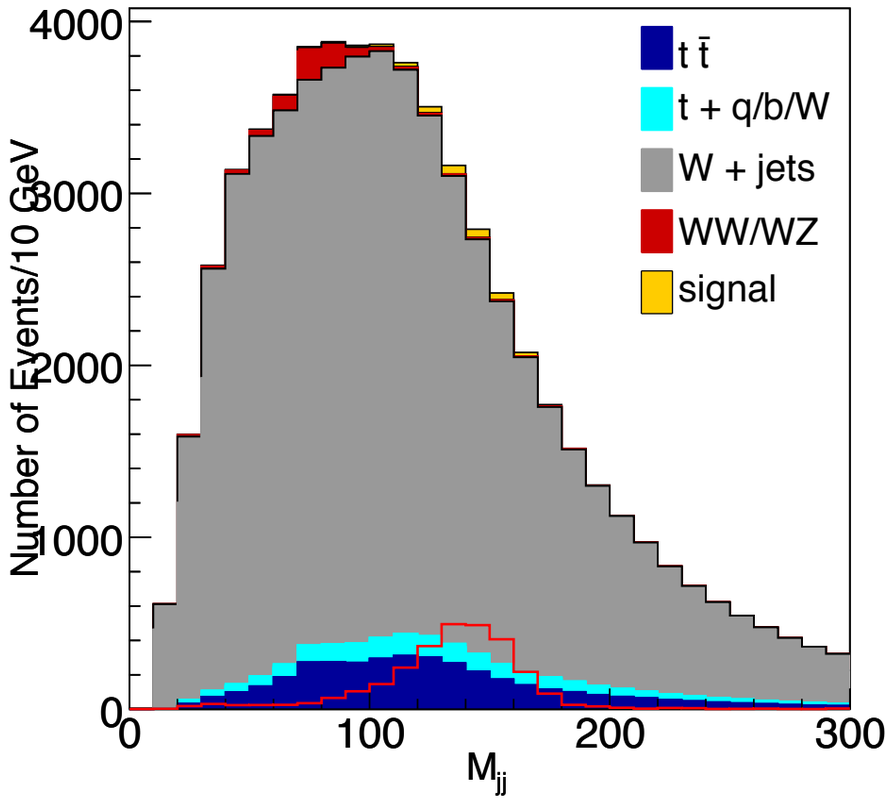
wait a minute...

- kinematics favor technicolor over other W+jj explanations, though limited discriminating power

(Buckley et al, 1107.5799)

At the LHC:

1 fb^{-1} CDF cuts



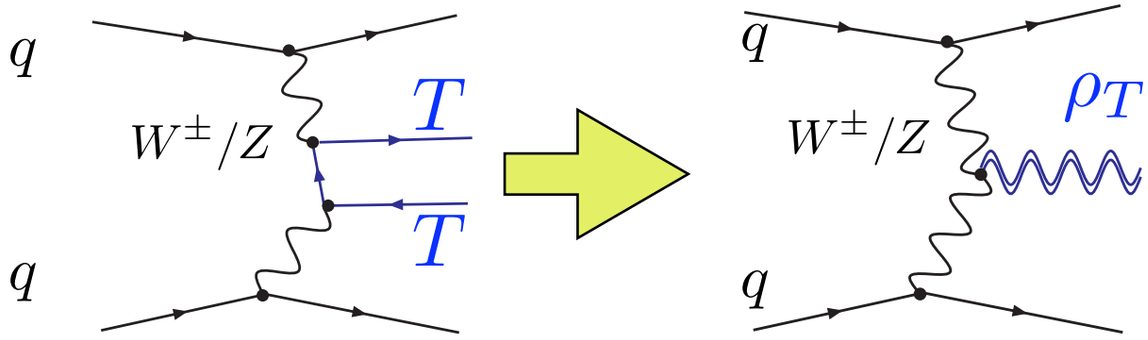
(ELM 1107.4075)

with cuts similar to CDF, $q\bar{q}$ induced sources of Wjj (like TC) are barely visible... W+jets is just too big (10 x Tevatron)

better cuts can help, but still require >5 fb^{-1}, good control of systematics for discovery

Technicolor phenomenology

Vector Boson Fusion

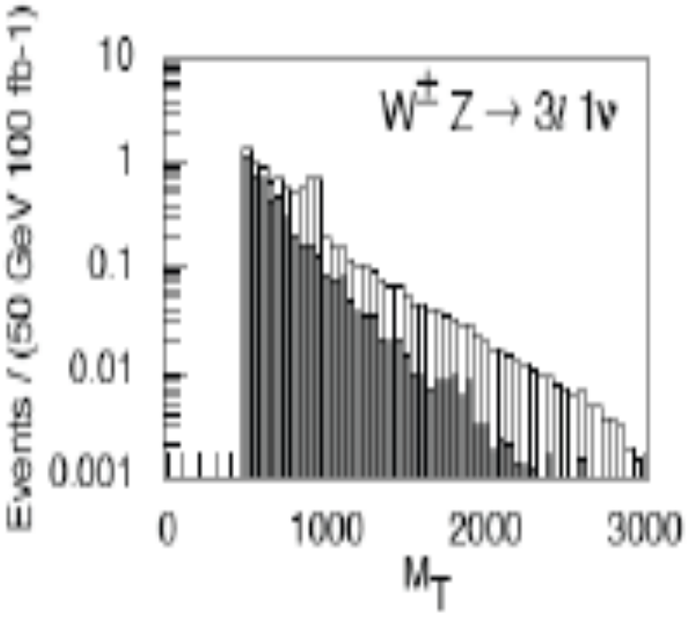


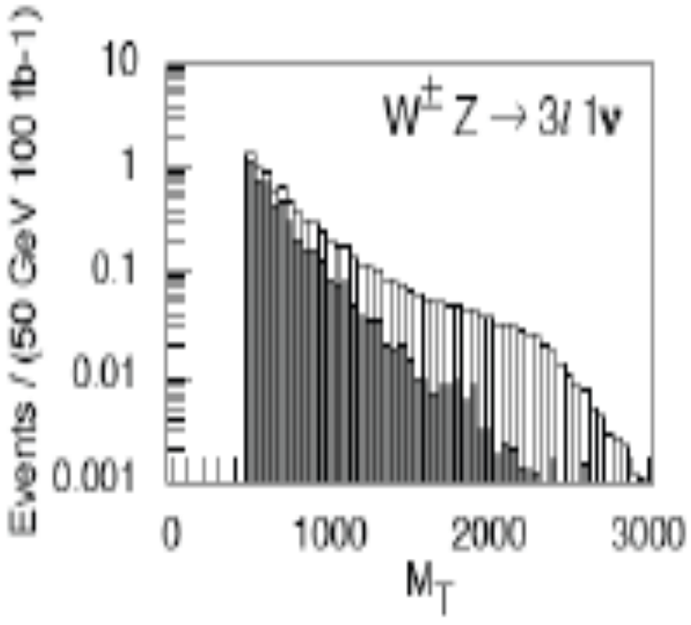
most direct probe of EWSB via

$W_L W_L \rightarrow W_L W_L$

scattering

For $M_{\rho_{TC}} = 1.0$ TeV, 2.5 TeV:



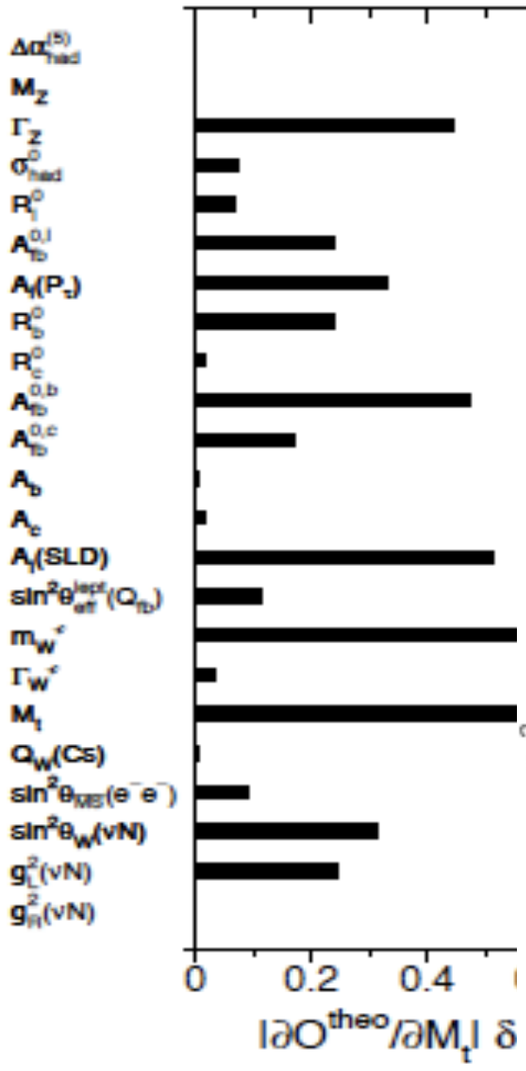


but incredibly difficult experimentally, even for lighter resonances

should be revisited

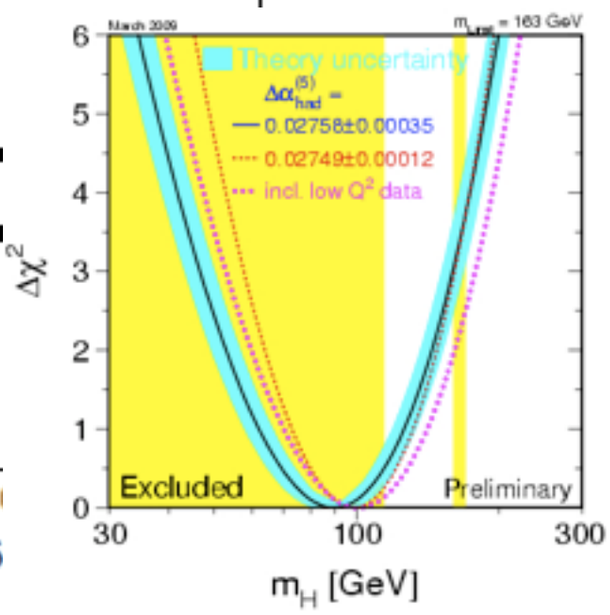
Why not Tev-scale strong dynamics?

- Precision electroweak:



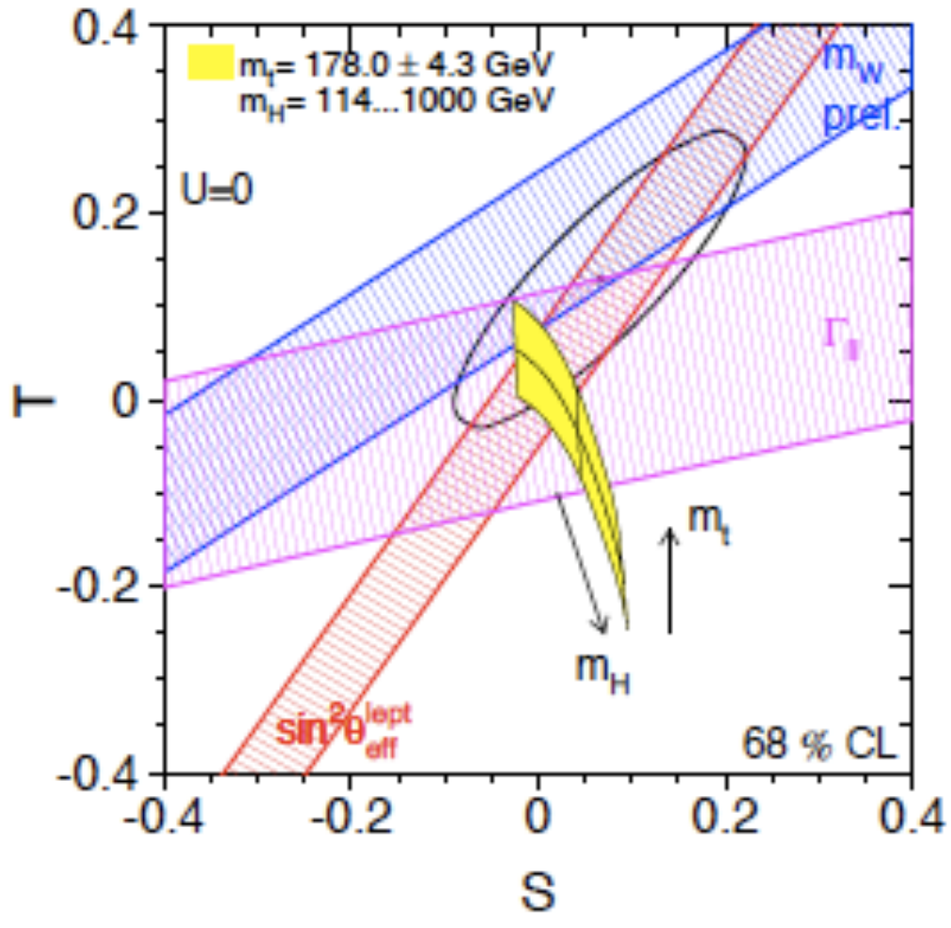
Parameter	Average
$g_{A\nu} \equiv g_{V\nu}$	$+0.5003 \pm 0.0012$
g_{Ae}	-0.50111 ± 0.00035
$g_{A\mu}$	-0.50120 ± 0.00054
$g_{A\tau}$	-0.50204 ± 0.00064
g_{Ve}	-0.03816 ± 0.00047
$g_{V\mu}$	-0.0367 ± 0.0023
$g_{V\tau}$	-0.0366 ± 0.0010

Parameter	Average



S, T, U: parameterized deviation of EW params from SM values

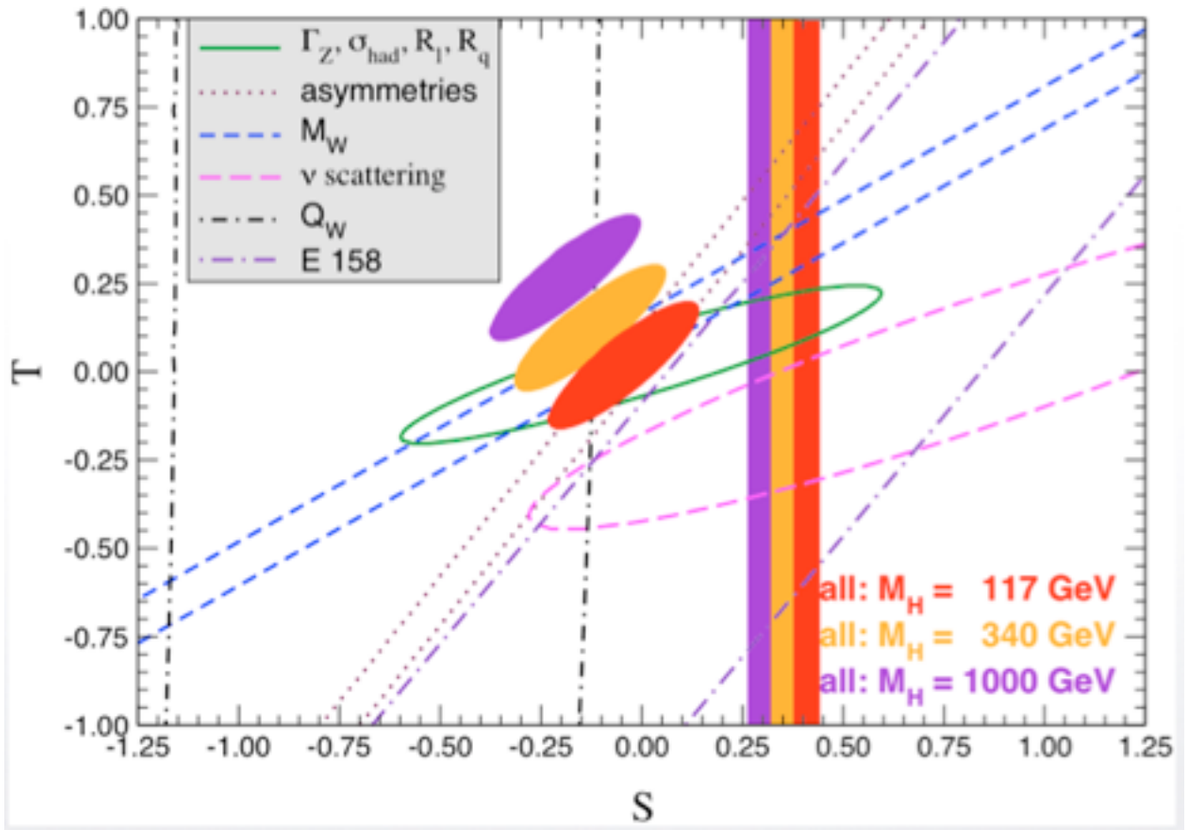
constrains new EW physics



- A light, Standard Model Higgs boson is preferred by these indirect measurements

Why not Tev-scale strong dynamics?

S is too big (Peskin & Takeuchi)



BUT:

this assumes a particular model:
TeV-scale dynamics = rescaled QCD

should not exclude other models based on this

New dynamics could easily be very different (i.e. 'walking coupling')

Also: $\sin^2\theta_W$ not totally settled: 3 sig variation among 'best' measurements: S = 0.45 preferred by LEP alone

(Chanowitz, Marciano)

What about fermion masses

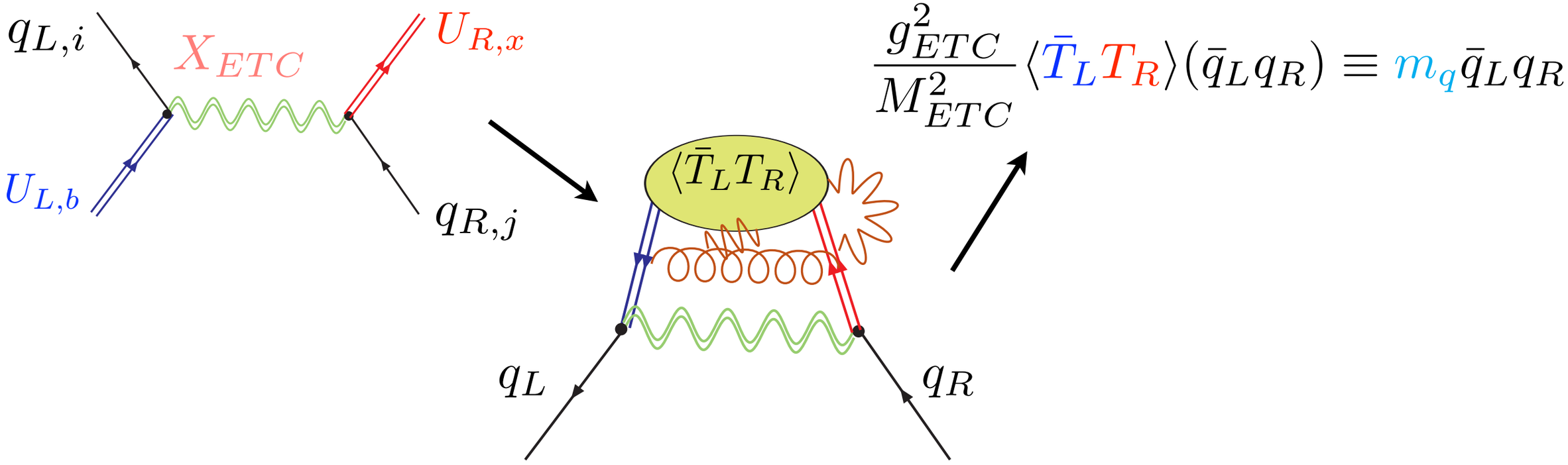
new strong dynamics nicely generates W/Z masses, but what about fermions?

have to attach SM fermions to strong dynamics in a way that allows sizable masses, CKM, etc. but avoids flavor constraints

couple of different ideas, with different implications at colliders

Extended Technicolor

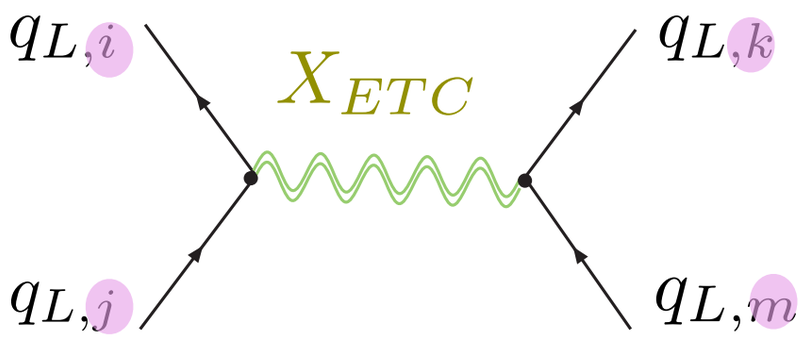
attach SM matter to techni-sector with a new, broken gauge interaction:



$$\frac{g_{ETC}^2}{M_{ETC}^2}\langle \bar{T}_L T_R \rangle (\bar{q}_L q_R) \equiv m_q \bar{q}_L q_R$$

straight forward to set up, but we cannot avoid

four SM-fermion operators



$$\sim \gamma_{ab}\frac{g_{ETC}^2(\bar{q}\gamma_\mu t^a q)(\bar{q}'\gamma^\mu t^b q')}{M_{ETC}^2}$$

Extended Technicolor

to avoid problems from flavor physics, need to take M_{ETC} large, 100's to 1000's of TeV --> far too big to generate reasonable SM fermion masses

a way out?

mass formula knows about TC condensate at ETC scale, EWSB cares about condensate at TC scale, RGE connects them

$$\langle \bar{T}_L T_R \rangle|_{ETC} = \boxed{\langle \bar{T}_L T_R \rangle|_{TC} = 4\pi F_T^3} \times exp\left(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu} \gamma_{(\bar{T}_L T_R)}(\mu) \right)$$

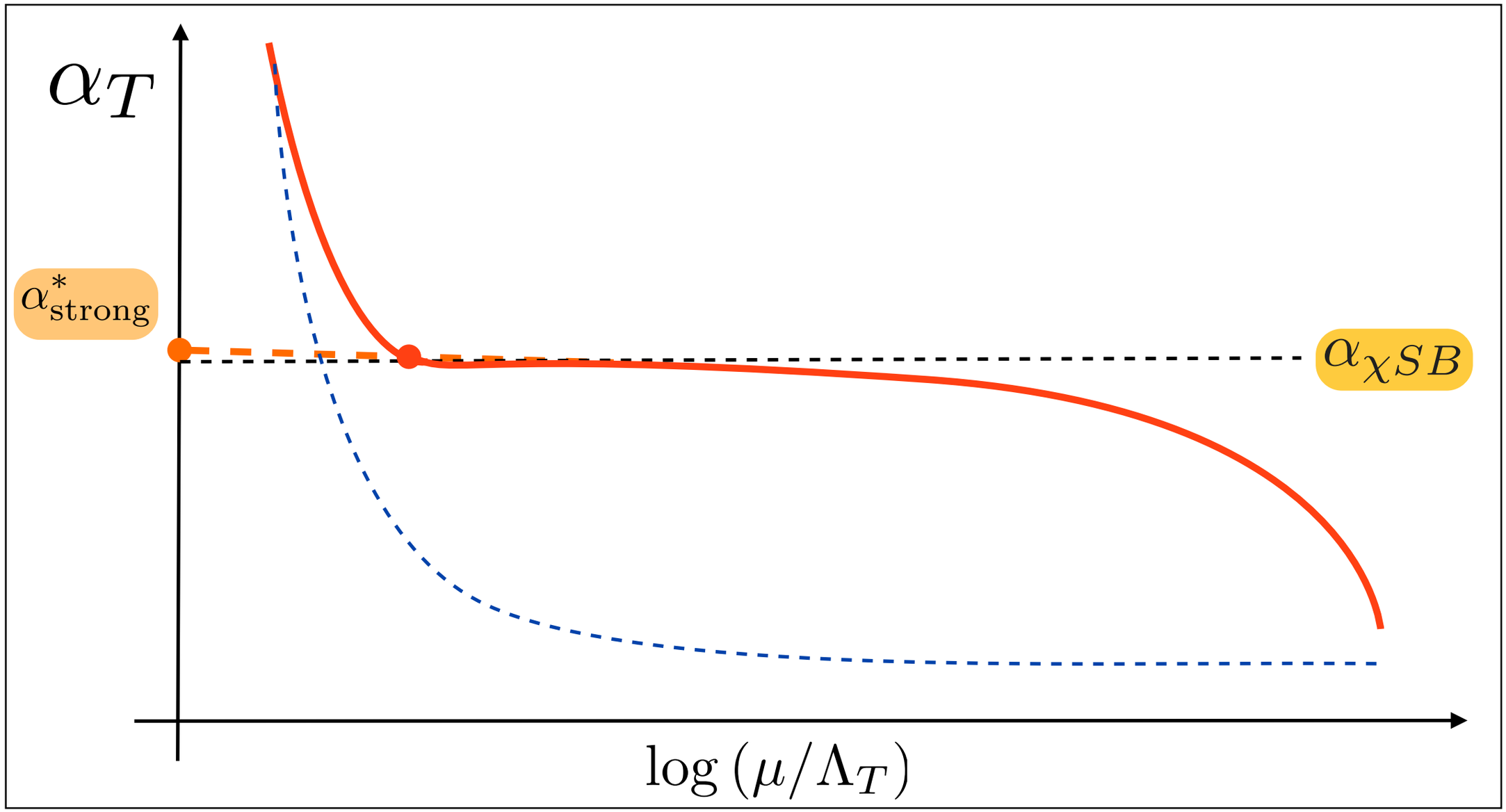
if $\gamma_{\bar{T}T}$ is large, O(1), can get huge enhancement in fermion mass term even when M_{ETC} is safely large

O(1) anomalous dim. expected in conformal or near conformal theories

$$m_q, m_l \sim \frac{g_{ETC}^2}{M_{ETC}^2} (4\pi F_T^3) \left(\frac{\Lambda_{ETC}}{\Lambda_{TC}} \right)$$

Walking Technicolor

need to have chiral symmetry breaking



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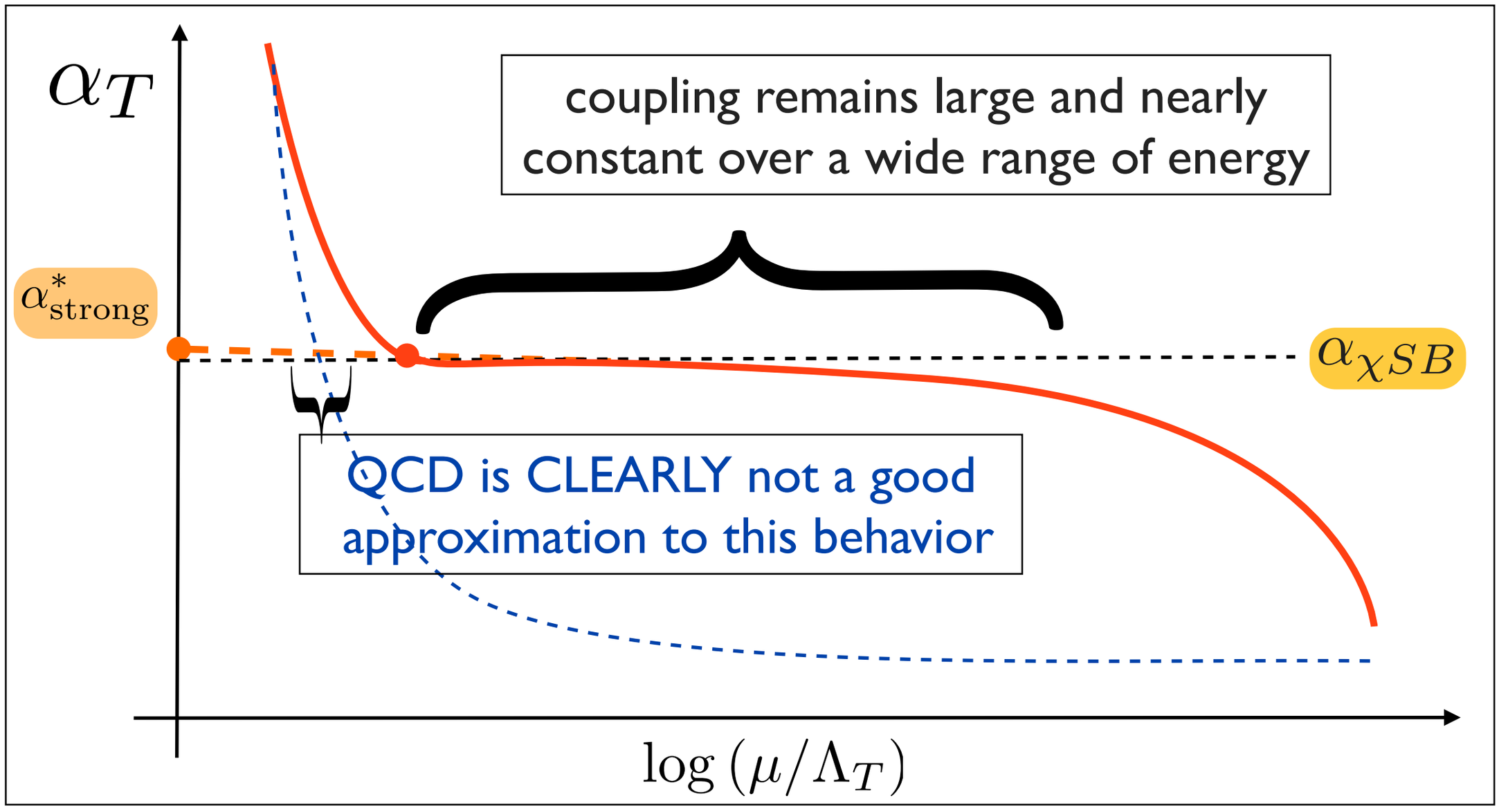


(Lane, Appelquist & Sannino)

Different phases of gauge theories

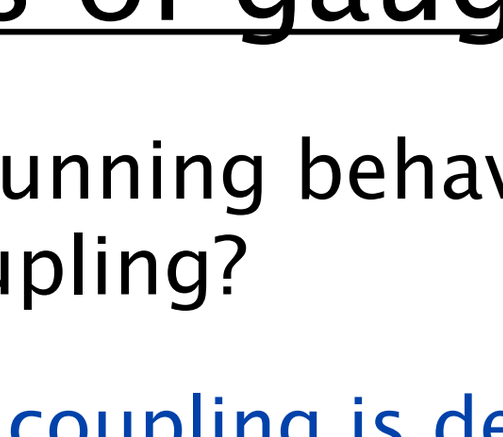
How do we change the running behavior of a gauge coupling?

the running of the gauge coupling is described by:

$$\beta(\alpha) = \frac{-2b_0}{4\pi}\alpha^2 - \frac{2b_1}{(4\pi)^2}\alpha^3 + \cdots$$

gauge group:
SU(N), SO(N), Sp(N), etc

matter representations:
fundamental, Adj, (anti)-symmetric, etc.

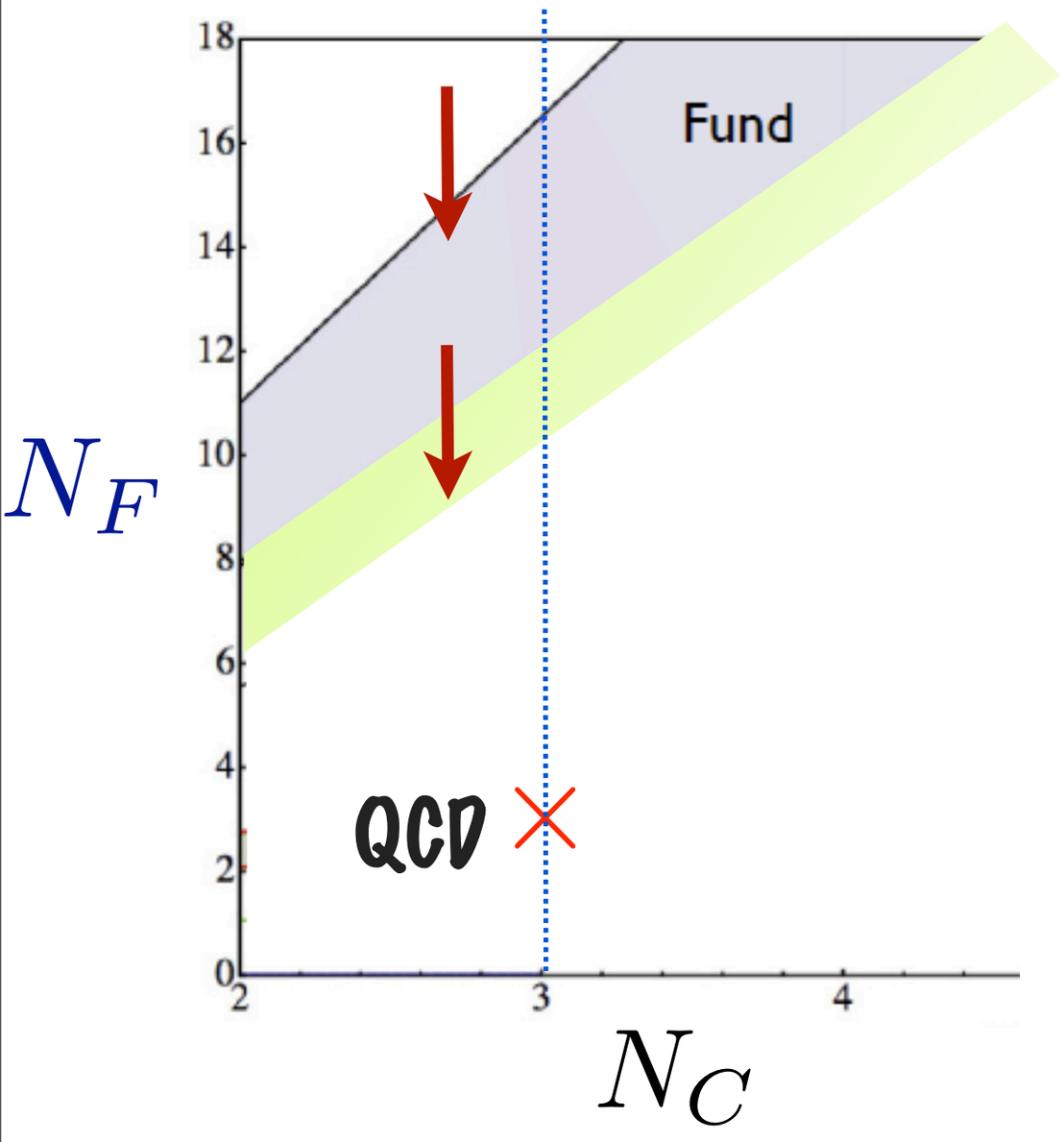


amount of matter: $N_{F,r}$

confinement scale Λ

changing dials alters running. In pert. theory, one can get get $\beta(\alpha^*) \sim 0$, but we need strong coupling

Walking Technicolor & Lattice



lots of studies based on perturbation theory, but need non-perturbative input

LATTICE

the more info we can get about the conformal window, the better:

- phase diagram as a fn. of (N_F, N_C)
- anomalous dimension: $\gamma_{\bar{T}T}(N_F, N_C)$
- spectrum scaling: M_ρ/F_π, M_π/M_ρ
- how stable is a 'walking theory' in the presence of ETC-like interactions? how does it change?

- $S(N_F, N_C)$
- is there a pNGB (dilaton) associated with walking?

Interesting directions:

Partial compositeness: linear coupling of SM fermions to strong sector (Kaplan)

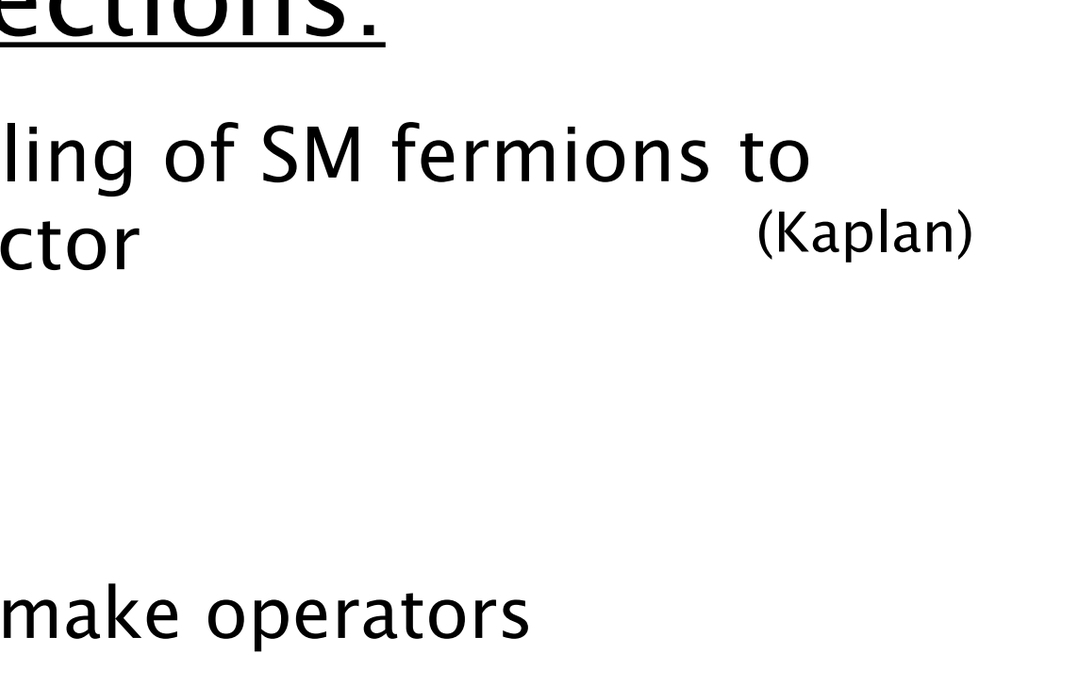
$$\lambda_L f_L \mathcal{O}_L + \lambda_R f_R \mathcal{O}_R$$

- by dialing dimension of $\mathcal{O}_L$, $\mathcal{O}_R$, can make operators relevant -> irrelevant
- easy to get fermion mass hierarchy (even TOP!), while flavor can still be controlled

4D modeling hard, often done in 5D (AdS) (Agashe, Contino, Pomarol)

profile of fermion <-> anomalous dimension

benefits from lattice understanding techni-baryon properties in non-QCD theories



Interesting directions:

Partial compositeness: linear coupling of SM fermions to strong sector (Kaplan)

$$\lambda_L f_L \mathcal{O}_L + \lambda_R f_R \mathcal{O}_R \quad \sim \text{fermion–technibaryon mixing}$$

- by dialing dimension of $\mathcal{O}_L$, $\mathcal{O}_R$, can make operators relevant -> irrelevant
- easy to get fermion mass hierarchy (even TOP!), while flavor can still be controlled

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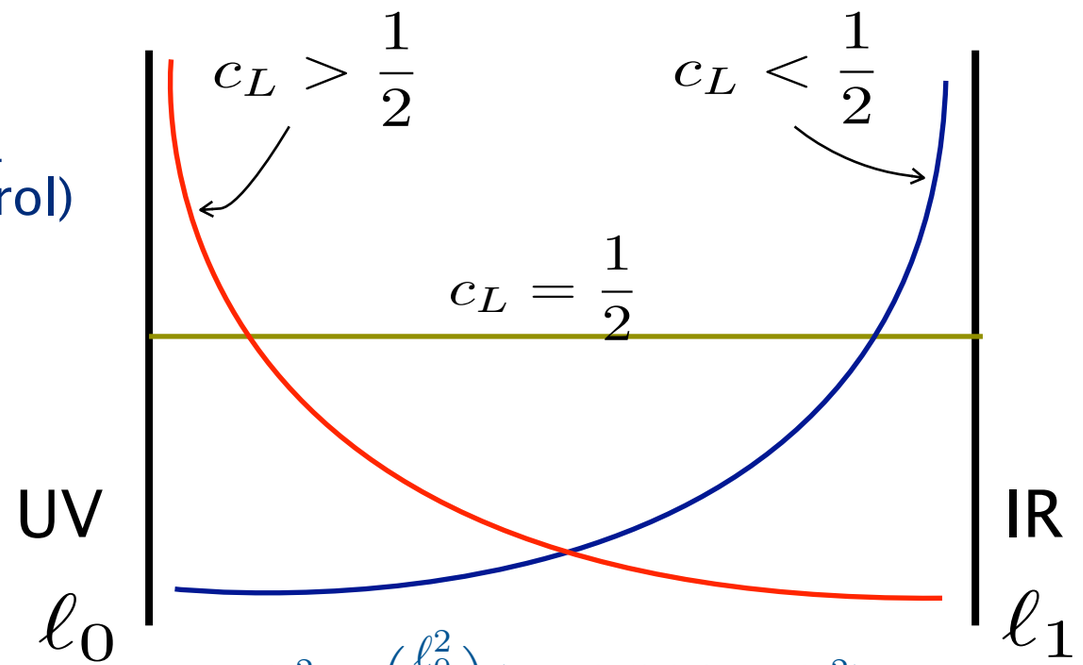


Interesting directions:

'Vector-like' technifermions: in old technicolor models, all techni-matter is chirally charged under $SU(2)_W$. This does not have to be the case

(see recent work by Luty et al)

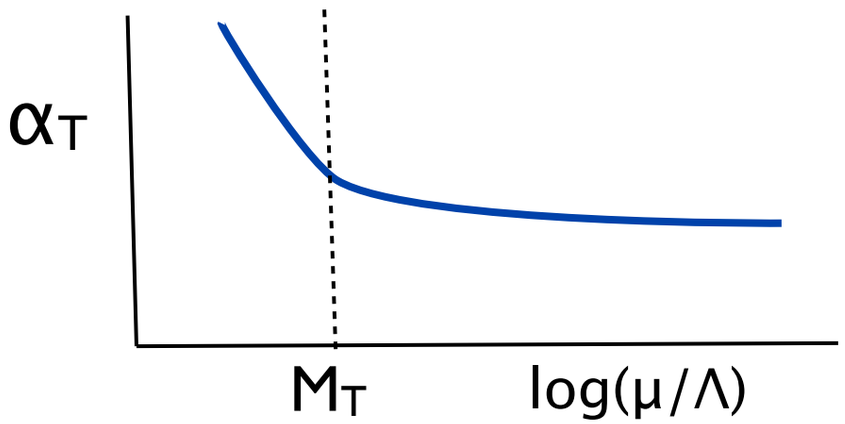
consider:

1 chiral flavor + N vector-like flavors

$$\mathcal{L} = \ldots + M_T \, \overline{T}_{Li} \, T_{Ri}$$

allowed, technically natural

both contribute to α_T running above M_T, only chiral flavors below M_T

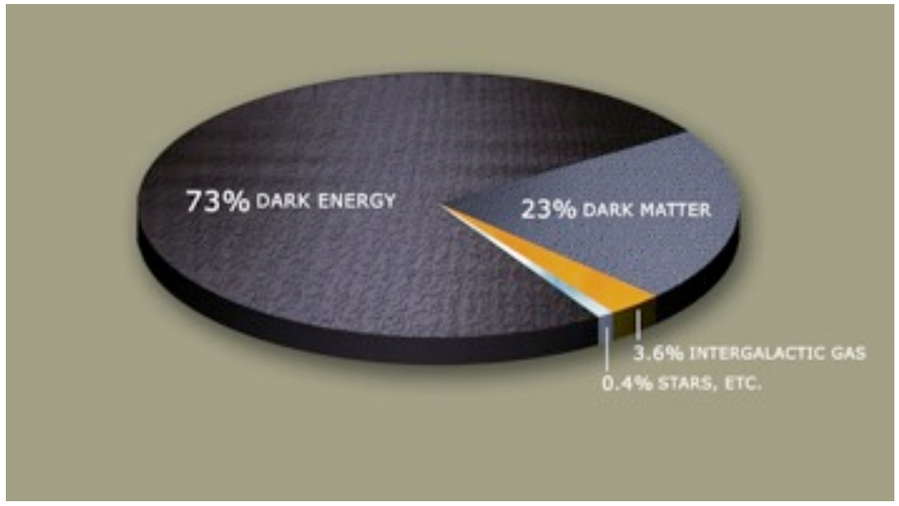


... but looks like $N_D = 1$ from EWSB point of view & electroweak corrections

introduces 'techni-Kaons' into the spectrum...

Interesting directions:

technicolor & Dark Matter:



- lightest technibaryon can be stable by analog of $U(1)_B$
- an initial matter/anti-matter asymmetry gets shared among baryons, leptons, technibaryons via sphalerons

(Chivukula, Barr, Fahri, Nussinov)

- can get observed $\Omega_{DM}/\ \Omega_B$ easily for ~ TeV scale DM

must be electrically neutral, EW singlets to avoid direct detection

Then leading operators are charge radius and polarizability:

ex.) $$\frac{B^* B\, v_\mu\, \partial_\nu F^{\mu\nu}}{\Lambda_{TC}^2}\ ,\ \frac{B^* B\, F_{\mu\nu} F^{\mu\nu}}{\Lambda_{TC}^3}$$

(scalar B, NREFT power counting, Kribs et al, Sannino et al)

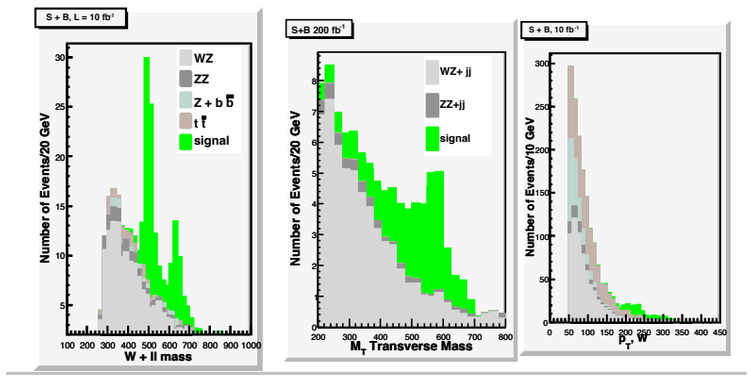
lattice input?

Lattice–Phenomenology connection

technicolor model building:
ETC/flavor, dark matter...

Lattice data for some non-QCD theory:
(spectra, S, γ, etc.)

LHC phenomenology:



Conclusions

Technicolor remains a viable, interesting possibility for TeV-scale physics

- classic signals are pp -> W/Z/γ + X and $f\bar{f}$, though many other possibilities
- relatively free of collider constraints (for now...)
- depending on spectrum, can be extremely difficult to find

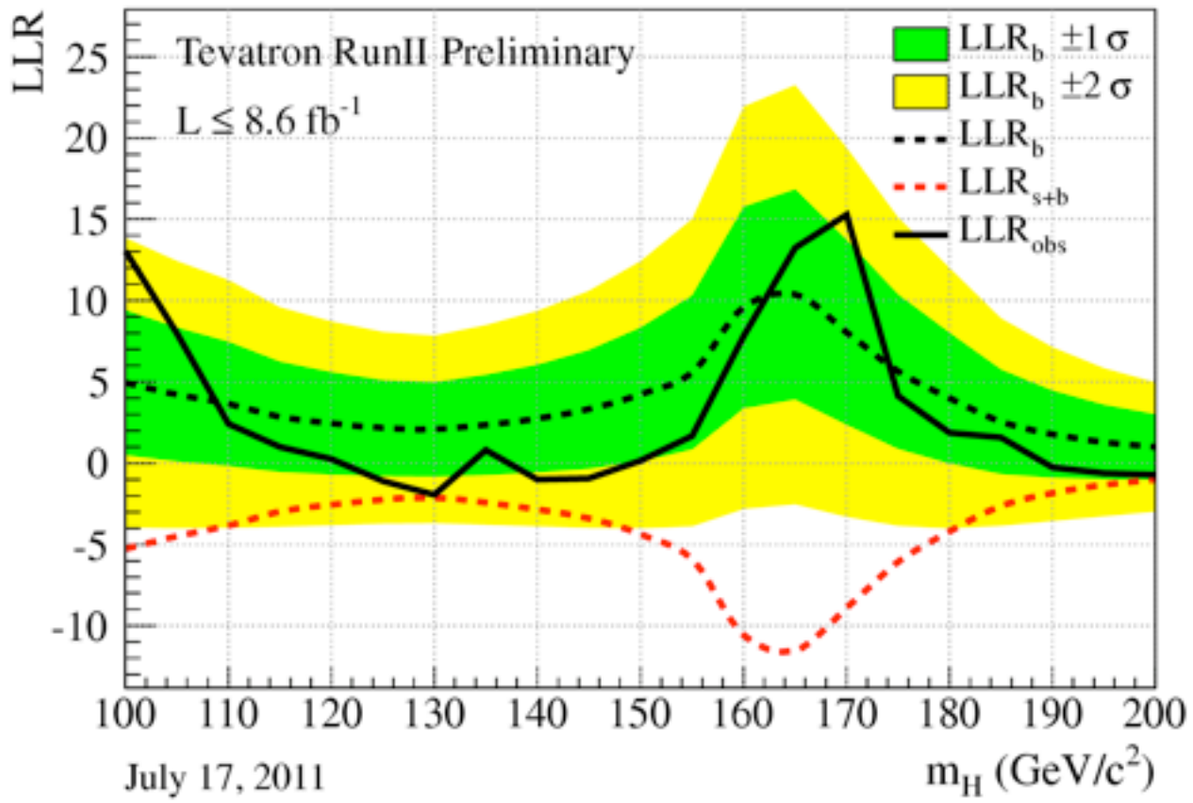
viable models involve non QCD-like dynamics
to mitigate S, flavor problems

Need lattice input to improve model building/phenomenology

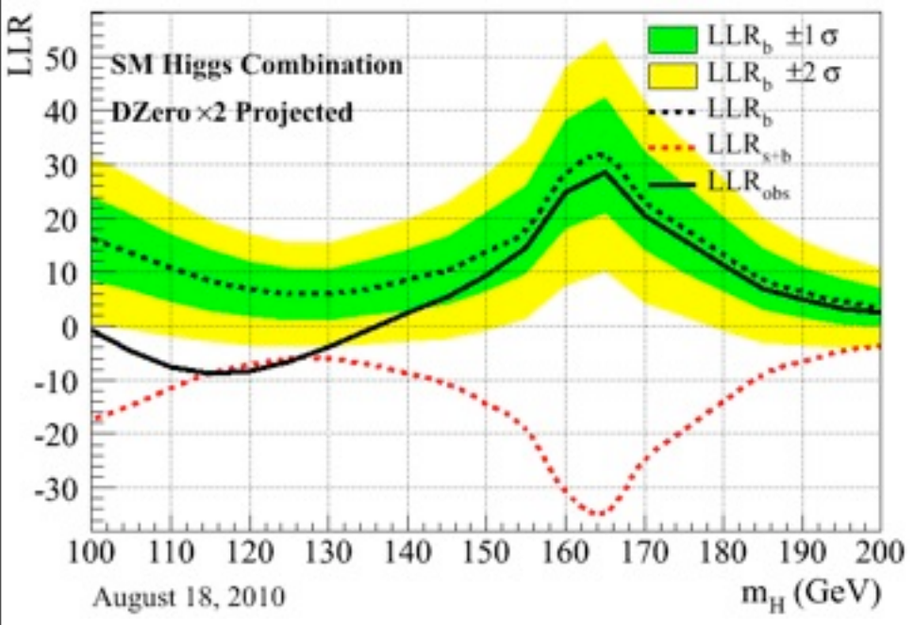
newer directions: vector-like matter, Dark Matter also benefit from lattice input

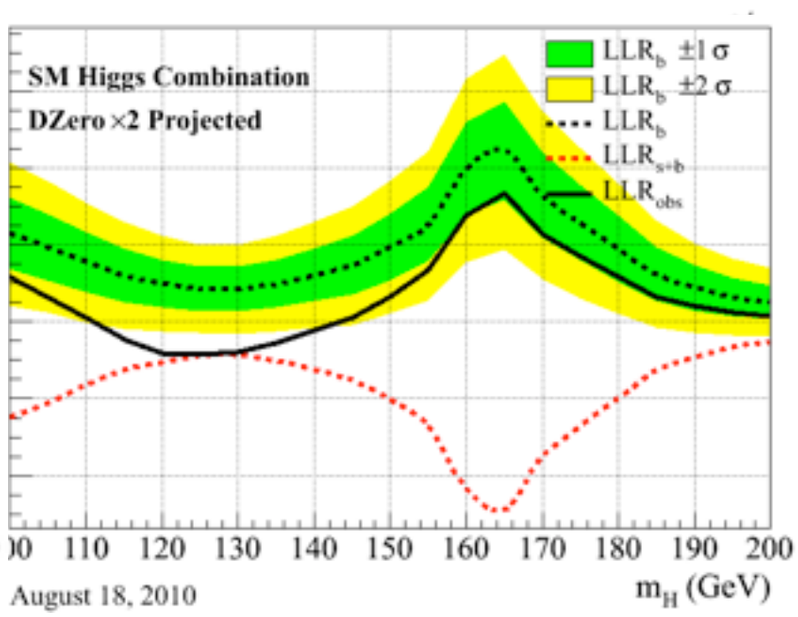
THANK YOU!

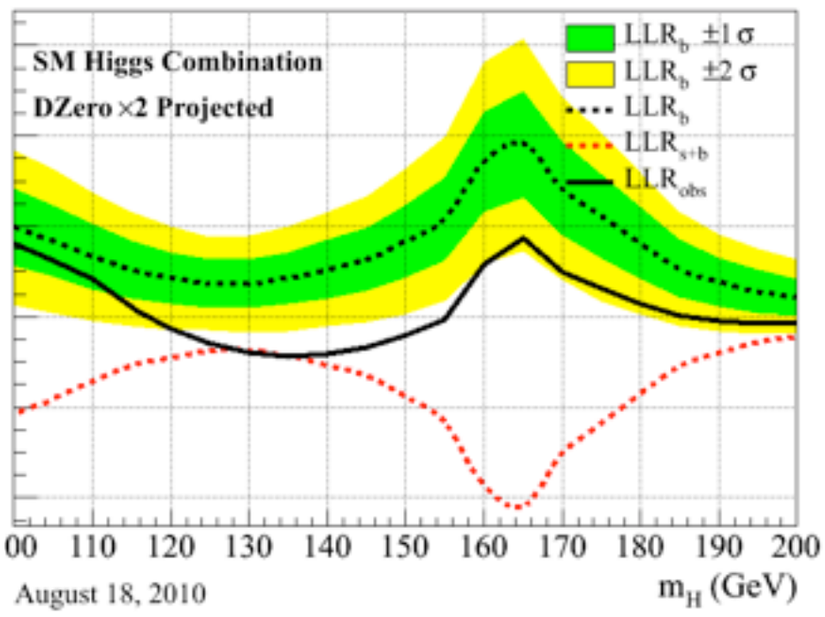
from Kilminster



Actual Tevatron data







Signal injected at 115 GeV Signal injected at 125 GeV Signal injected at 135 GeV

Not consistent with 130 GeV injection at either end