Physics Beyond the Standard Model

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Beyond the Standard Model

Tantalizing theories:
- Supersymmetry
- Large and warped extra dimensions
- Exotic Higgs models

Tantalizing experiments:
- g-2
- superluminal neutrinos
- top quark forward-backward asymmetry
- Dark matter (its own discussion later)
- Etc.

Tantalizing interpretations:

- No direct or indirect interpretation of experiment supports low-scale X-dimensions
  So let us not discuss....

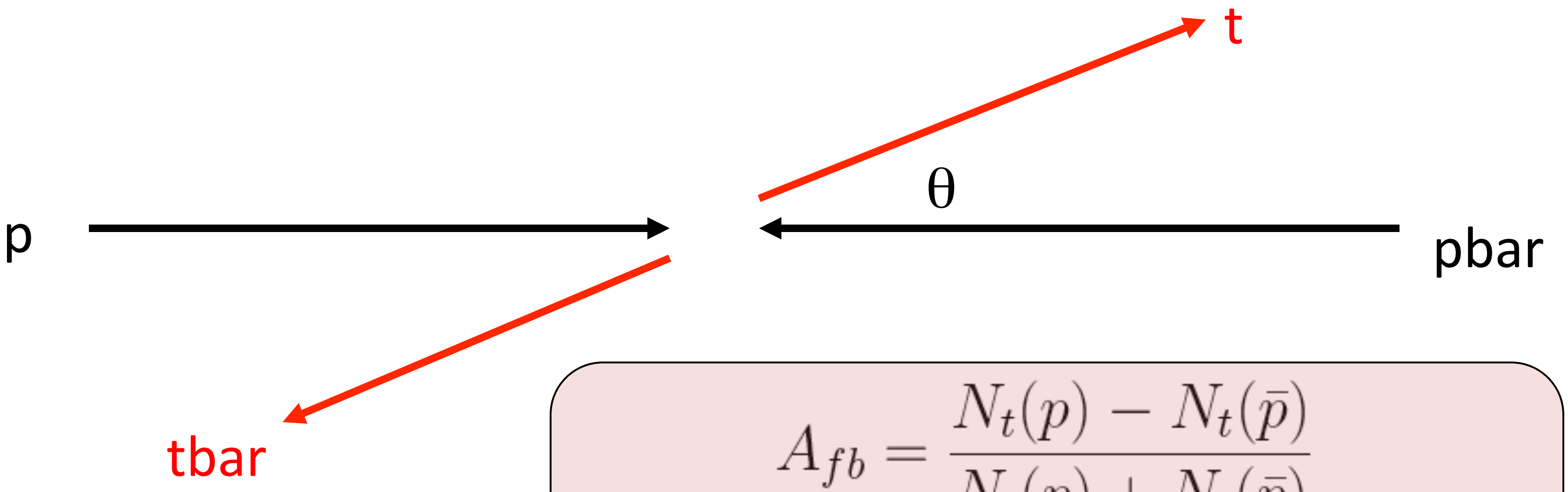
- Supersymmetry good with new Higgs bounds ($m_H < \sim 140$ GeV)
- Supersymmetry good with g-2 and ok with no direct discoveries
  So, let's let Georg Weiglein give his talk on supersymmetry

- Superluminal neutrinos new on the scene – let's postpone implications discussion

- Top quark forward-backward asymmetry persistent and resolvable soon
  So, *let us discuss this*.

- Higgs boson physics is the question of our times: So, *let us discuss this*.

Top Asymmetry at the Tevatron



$$A_{fb} = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})}$$

$N_i(j) = \#$ of particle i in direction of particle j

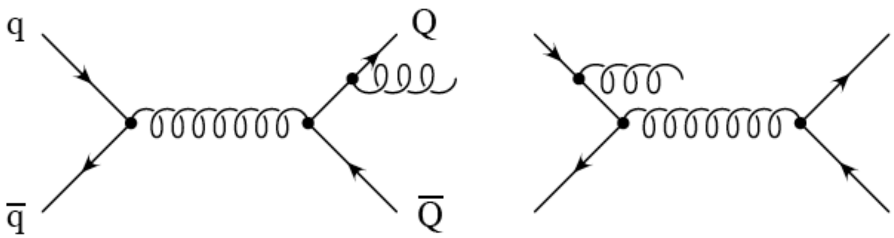
Assuming CP

$N_{\bar{t}}(p) = N_t(\bar{p})$ which implies $A_c = A_{fb}$ where $A_c = \frac{N_t(p) - N_{\bar{t}}(p)}{N_t(p) + N_{\bar{t}}(p)}$

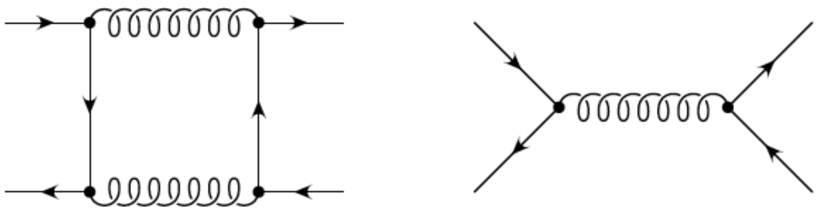
Standard Model Prediction

Asymmetry arises at α_s^3 order.
(Close analogy with QED α^3 asymmetry, Berends et al. 1973)

Interference of ISR with FSR:



Interference of box with tree:



(Antuñano), Kühn, Rodrigo, PRD '99 (0709.1652)

A_{FB}(th) = 3.8 +- 0.6 %

Tevatron Measurement

Measured at the Tevatron : A_{FB} = 16% +/- 6% (l+j)

A_{FB} = 42% +/- 16% (l+l)

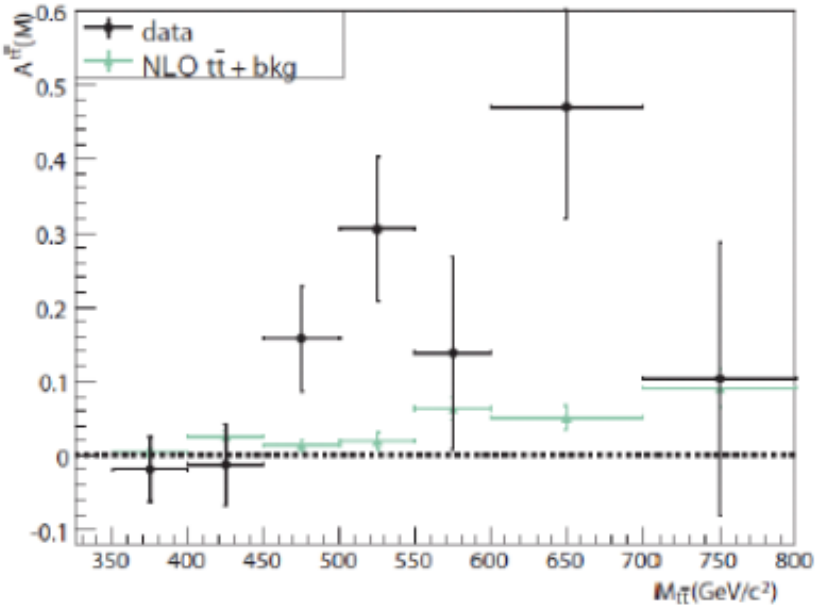
Ref: CDF note 10436, 9724

- Discrepancy actually becomes more significant at high-energy region.

A_{FB} (M_{ttbar}>450GeV) = 48 +/- 11 %

(SM prediction = 9 +/- 1 %)

which is more than 3-sigma away.



Large BSM contribution difficult: Illustrate with Axigluons

So-called chiral color theories of various origins.

$SU(3)_L$ x $SU(3)_R$ breaks to $SU(3)_c$
Leaving 8 massive axigluons.
Coupling is QCD strength but with γ^5

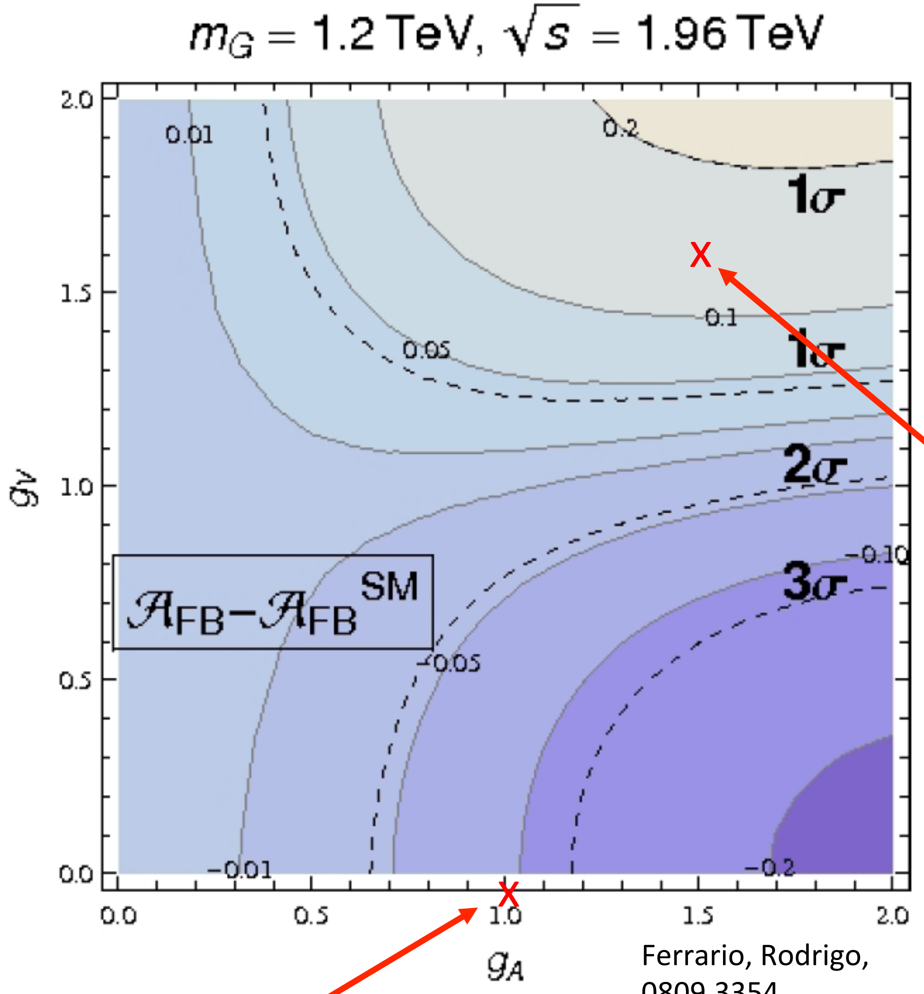
Maximal charge asymmetry as tree-level $\bar{t}\gamma^\mu\gamma^5 t$ is relative C odd to $\bar{t}\gamma^\mu t$.

Problem is the asymmetry goes wrong way!

A_{FB} = - 0.13 for m_A = 1 TeV

Limit on pure axigluon from $A_{FB}(t)$ may be stronger than from direct searches.

Try more general g_V-g_A couplings



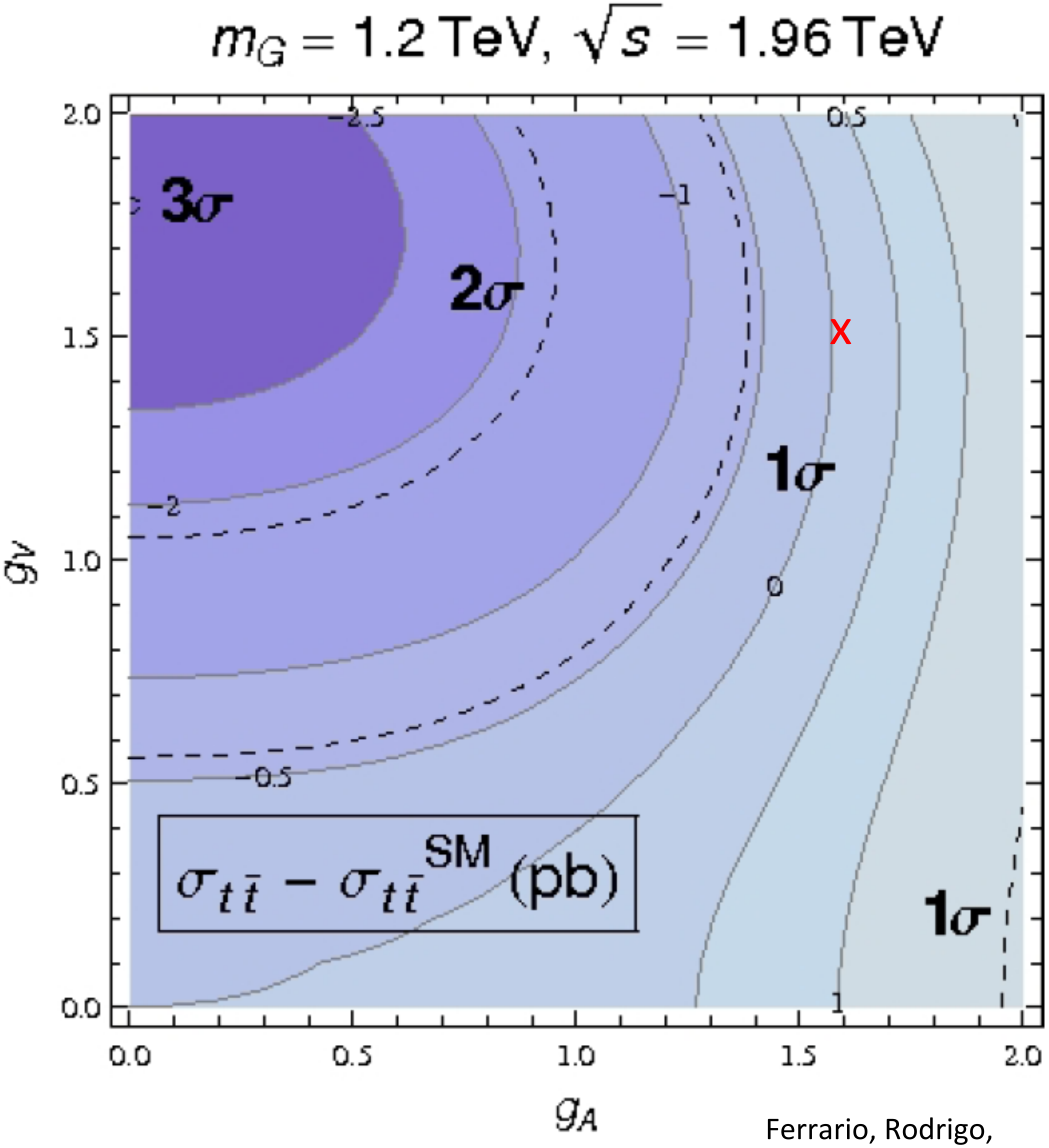
Couplings are with respect to the QCD gauge coupling.

This point looks good!

Ferrario, Rodrigo, 0809.3354

Pure axigluon coupling (large negative contribution to A_{FB})

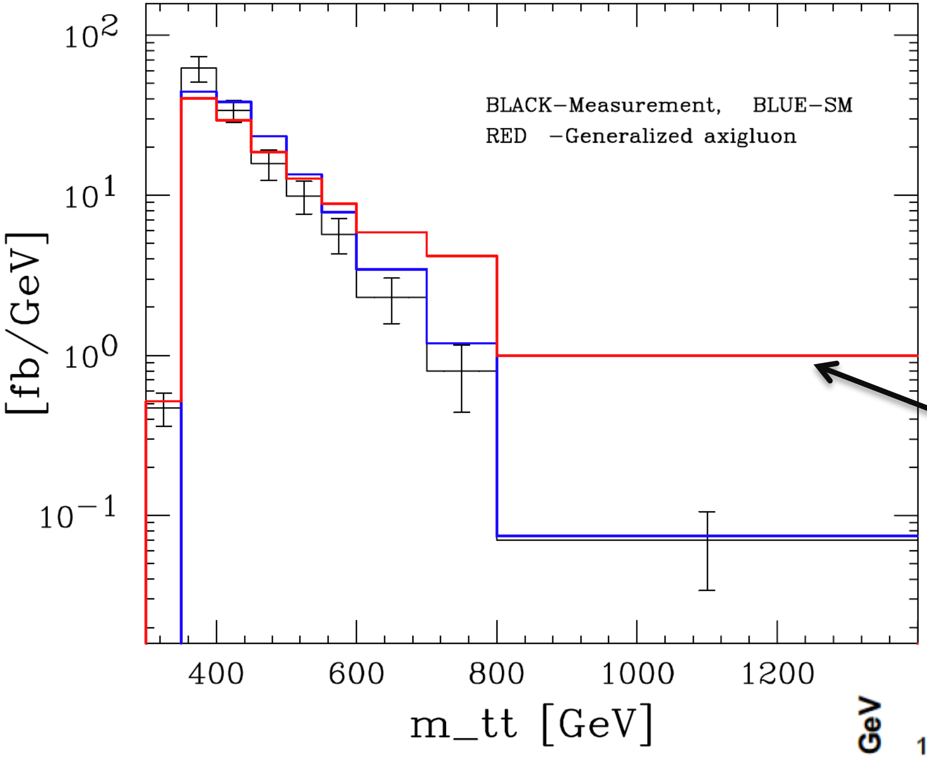
Top cross-section constraint



Consistency with total rate is ok.

Ferrario, Rodrigo, 0809.3354

Generic Problem: Difficulty with differential cross-section

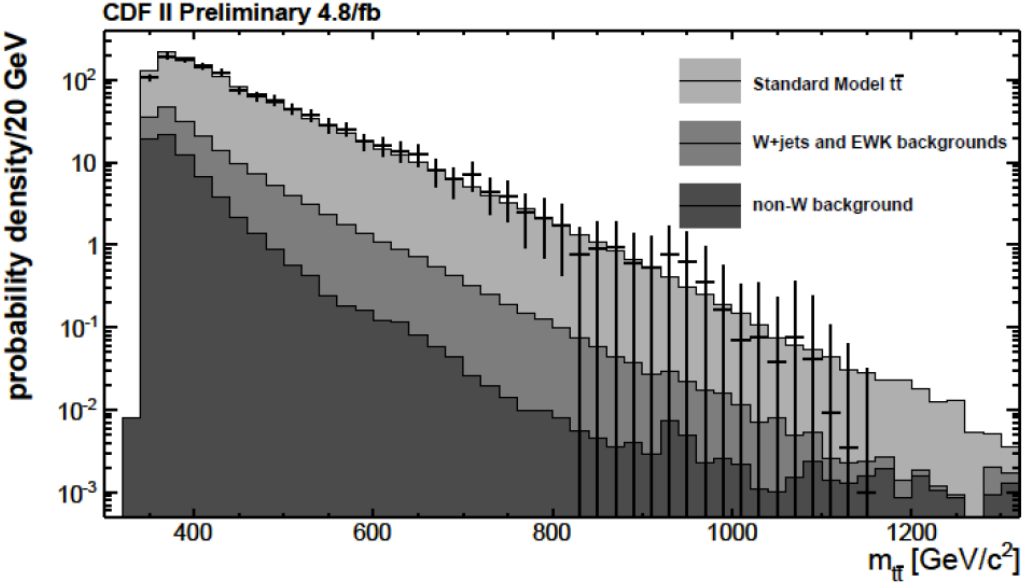


Data from CDF, “Measurement of the ttbar differential cross section … in 2.7 fb^{-1} of CDF II Data”, CDF note 9602 (11 Nov 08).

Invariant mass distribution a problem

Red line: M_X=1.2 TeV g_V=1.65 g_A=1.55

ICHEP 2010



Some things learned…

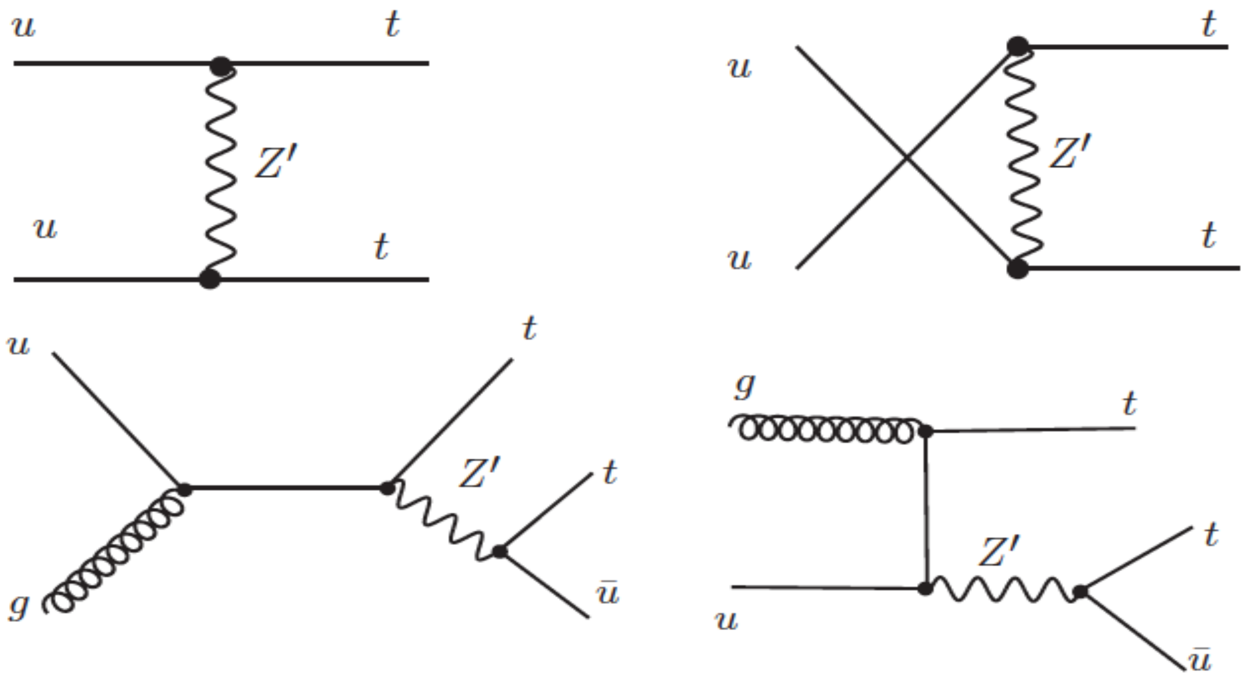
- s-channel solutions do not work so well
- t-channel solutions work better Z'-u-t coupling but challenges/ opportunities remain

  - *challenge*: Model-building (anomalies, flavor, etc.)
  - *challenge*: Experimental constraints (top decays, like-sign tops, etc.)
  - *opportunity*: Experimental signatures (enhanced single top, rich new physics underneath, etc.)

- LHC should find evidence through correlations well before direct A_{FB} measurement.

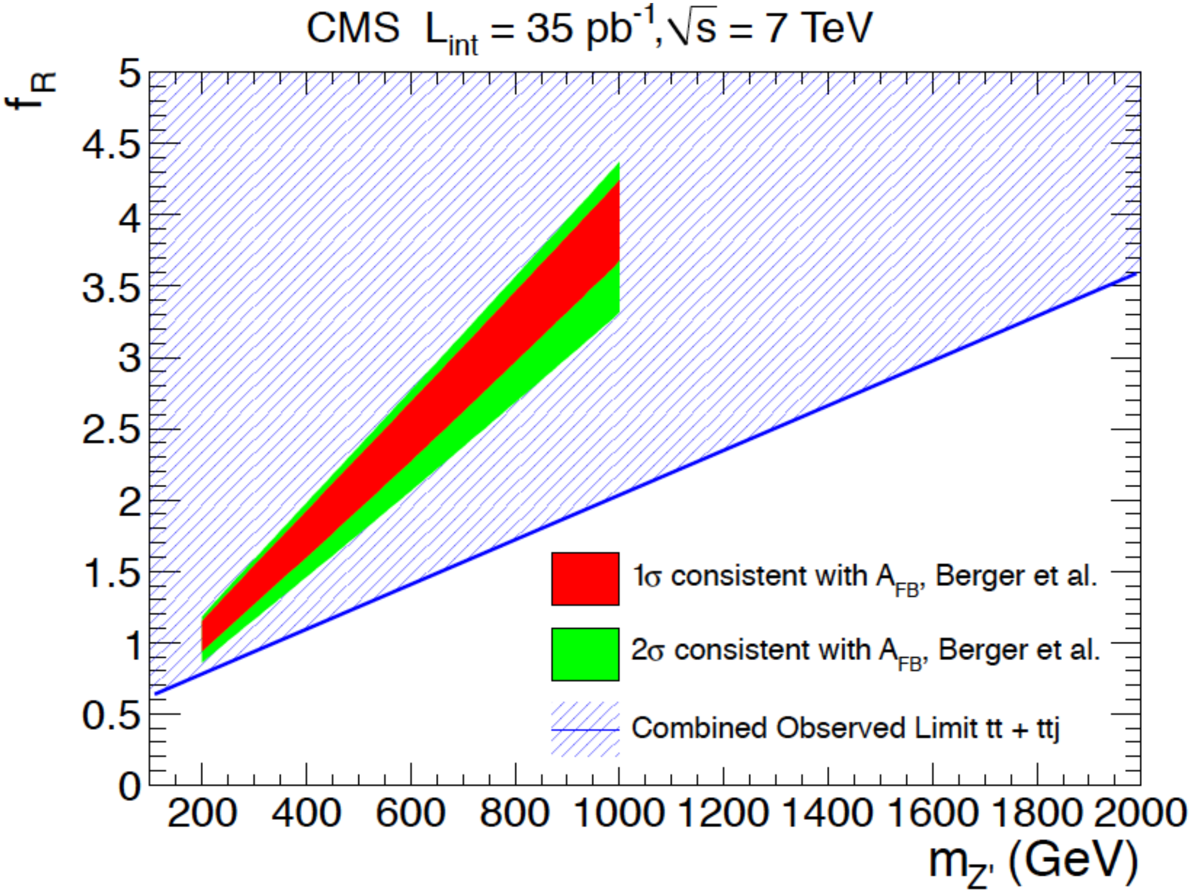
Like-sign top quarks

In most basic V'-u-t or V'-d-t models, there is nothing to prevent the production of like-sign top quarks.



CMS [1106.2142]

Like-sign top quarks (cont.)



$$\mathcal{L} = g_W \bar{\mathrm{u}} \gamma^\mu (f_L P_L + \boxed{f_R P_R}) \mathrm{t} Z'_\mu + \mathrm{h.c.}$$

CMS [1106.2142]

Essentially all *simple* t-channel A_{FB} ideas are ruled out.

More "complicated" t-channel physics

Basic s-channel and basic t-channel explanations of A_{FB} are not working, for different reasons.

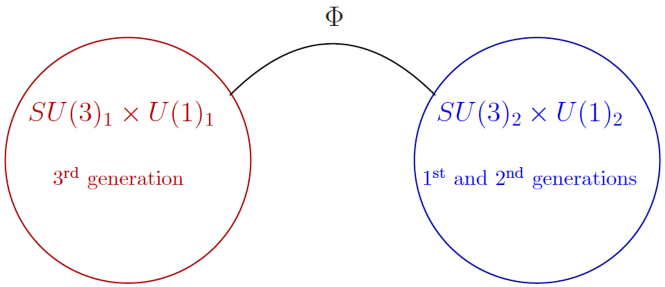
s-channel looks more problematic to salvage than t-channel ideas.

Two more compatible t-channel approaches:

- Non-abelian horizontal symmetry: Jung, Pierce, JW, '11
- Top quark condensate theories: Cui, Han, Schwartz, '11

Top Condensate Theories

If the explanation, lots to study at colliders for years.



$$SU(3)_1 \times SU(3)_2 \times U(1)_1 \times U(1)_2 \overset{\langle\Phi\rangle}{\rightarrow} SU(3)_{\rm QCD} \times U(1)_Y$$

$\langle\Phi\rangle$ is the condensation of $\langle t\bar{t}\rangle = f_\pi$ and $\langle H_{TC}\rangle = f_T$

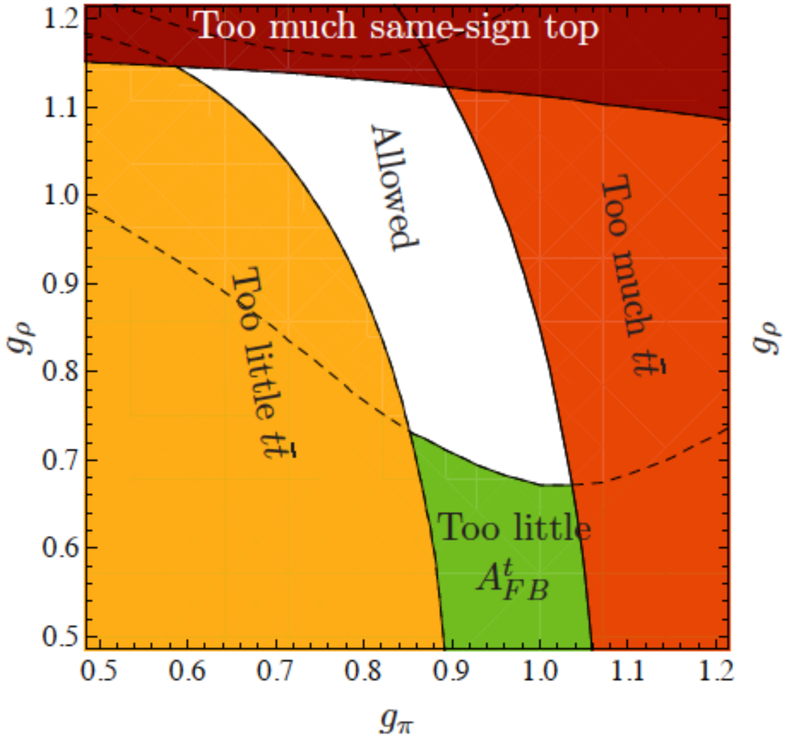
field	$SU(3)_1$	$U(1)_1$	$SU(3)_2$	$U(1)_2$	$SU(2)_L$
T_L	□	$\frac{1}{3}$	-	-	□
t_R	□	$\frac{4}{3}$	-	-	-
b_R	□	$-\frac{2}{3}$	-	-	-
C_L, U_L	-	-	□	$\frac{1}{3}$	□
c_R, u_R	-	-	□	$\frac{4}{3}$	-
s_R, d_R	-	-	□	$-\frac{2}{3}$	-
Φ	□	$\frac{1}{3}$	$\overline{\square}$	$-\frac{1}{3}$	-
det Φ	-	1	-	-1	-

field	$SU(3)_1$	$U(1)_1$	$SU(3)_2$	$U(1)_2$	$SU(2)_L$
$\begin{pmatrix} \tau_L \\ \nu_\tau \end{pmatrix}$	-	-1	-	-	□
τ_R	-	-2	-	-	-
$\begin{pmatrix} \ell_L \\ \nu_\ell \end{pmatrix}$	-	-	-	-1	□
μ_R, e_R	-	-	-	-2	-
H	-	-	-	-1	□
H_t	-	-1	-	-	□

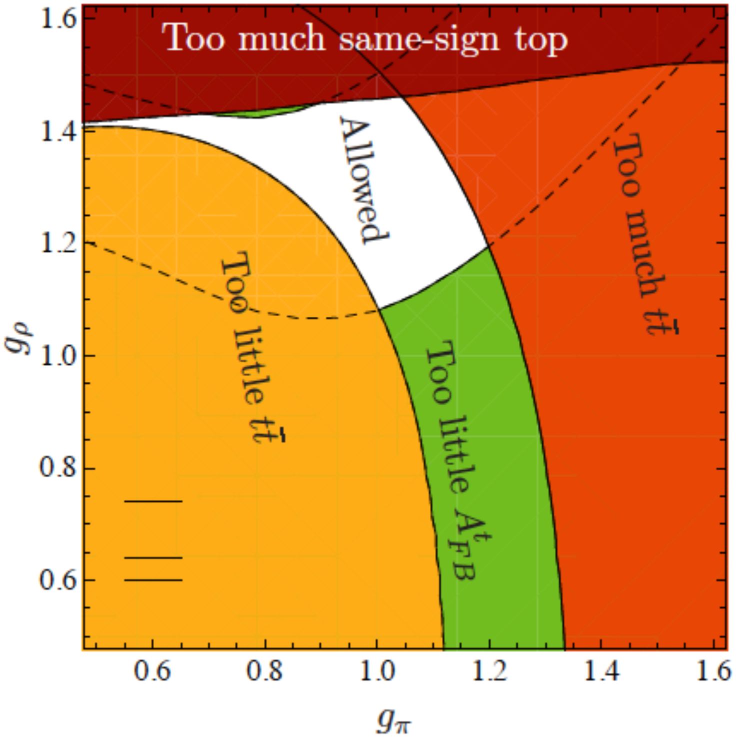
In addition to SM particles have "top pions" $\pi^{\pm,0}$, "top rho" ρ_t, "top Higgs" h_t
Generic to have tu couplings to these extra states!

Top condensate parameter space compatibility

$$\mathcal{L} = g_\pi(i\bar{t}_L u_R \pi^0 + \bar{t}_L u_R h_t) + g_\rho(\bar{t}_R \gamma^\mu u_R \rho_\mu) + \text{h.c.}$$



$m_\pi = 150,\ m_{h_t} = 200,\ m_\rho = 500\,\text{GeV}$



$m_\pi = 350,\ m_{h_t} = 250,\ m_\rho = 600\,\text{GeV}$

Cui, Han, Schwartz, ‘11

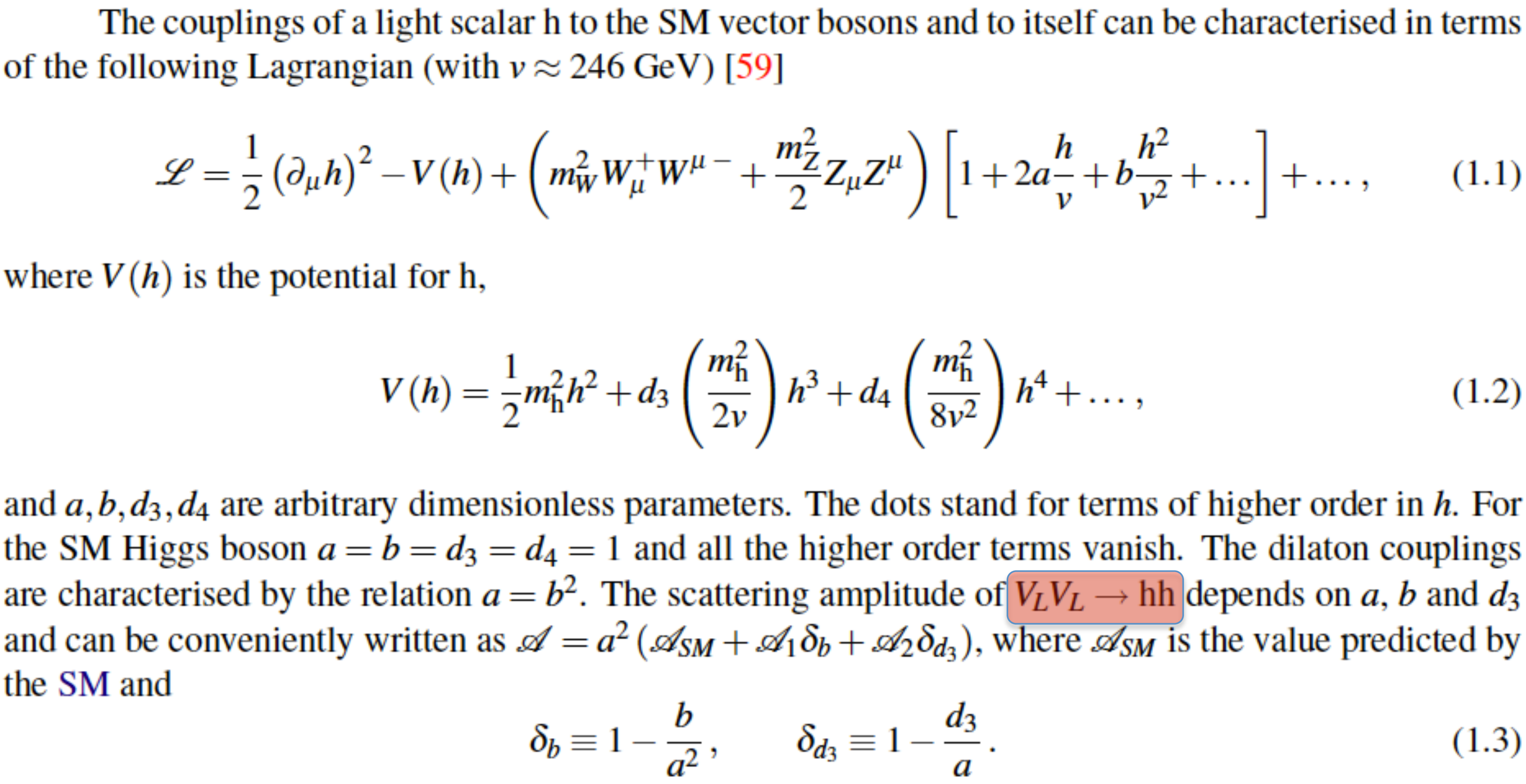
Higgs Boson at the LHC

We expect much more than this. But …

… suppose: After years of LHC running, we find a Standard Model Higgs boson and nothing else.

What benefits regarding Higgs boson physics could there be to LHC upgrades or linear collider?

Is the Higgs boson composite?



The couplings of a light scalar h to the SM vector bosons and to itself can be characterised in terms of the following Lagrangian (with $v \approx 246$ GeV) [59]

$$\mathscr{L} = \frac{1}{2}\left(\partial_\mu h\right)^2 - V(h) + \left(m_W^2 W_\mu^+ W^{\mu -} + \frac{m_Z^2}{2} Z_\mu Z^\mu\right)\left[1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right] + \ldots, \qquad (1.1)$$

where $V(h)$ is the potential for h,

$$V(h) = \frac{1}{2} m_\mathrm{h}^2 h^2 + d_3\left(\frac{m_\mathrm{h}^2}{2v}\right) h^3 + d_4\left(\frac{m_\mathrm{h}^2}{8v^2}\right) h^4 + \ldots, \qquad (1.2)$$

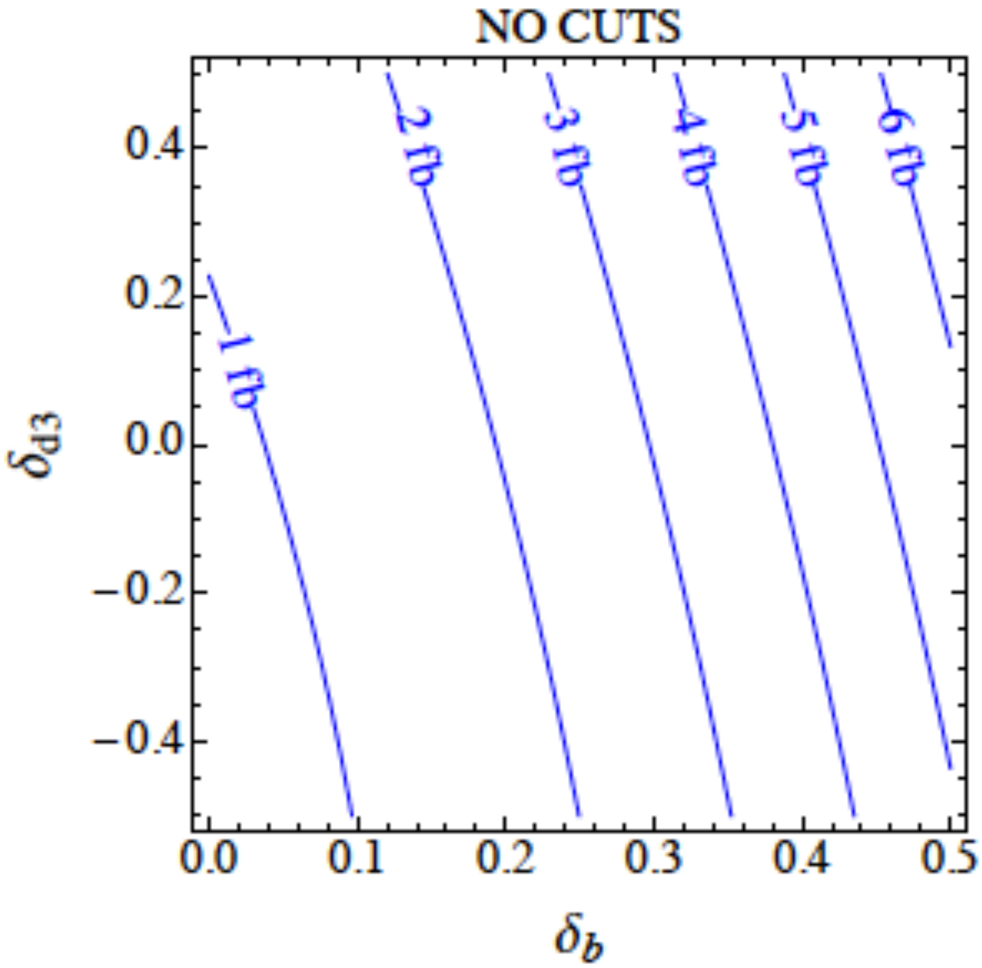
and a, b, d_3, d_4 are arbitrary dimensionless parameters. The dots stand for terms of higher order in h. For the SM Higgs boson $a = b = d_3 = d_4 = 1$ and all the higher order terms vanish. The dilaton couplings are characterised by the relation $a = b^2$. The scattering amplitude of $V_L V_L \rightarrow \mathrm{hh}$ depends on a, b and d_3 and can be conveniently written as $\mathscr{A} = a^2\left(\mathscr{A}_{SM} + \mathscr{A}_1 \delta_b + \mathscr{A}_2 \delta_{d_3}\right)$, where $\mathscr{A}_{SM}$ is the value predicted by the SM and

$$\delta_b \equiv 1 - \frac{b}{a^2}, \qquad \delta_{d_3} \equiv 1 - \frac{d_3}{a}. \qquad (1.3)$$

From CLIC CDR

e^+e^- -> $\nu\nu hh$ at CLIC 3 TeV

Similar precision capability at lower-energy e^+e^- LC.



Contino et al., & CLIC CDR

$\delta \sim (4\pi v/\Lambda)^2$

Measurements of cross-section enable search down to a percent or so on δ and so up to compositeness scale Λ ~ 30 TeV

cf. LHC14 (100 fb^{-1}) is 5-7 TeV and sLHC (1 ab^{-1}) is 10-12 TeV

Hidden world?

"There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy." -Hamlet

The SM is merely a description of the particles that make up our bodies, and copies of those particles, and the forces between those particles.

Copernicus (NASA photo)

Copernicus Monument in Toruń
by Christian Friedrich Tieck (1853)

There is a definite scale in nature whose origin we do not understand: M_Z.

No strong reason to believe that SM is alone at that mass scale. Additional "hidden particles". *How would we see them?*

How can “hidden world” couple to us?

Consider the SM lagrangian plus the following:

$$\begin{aligned}\mathcal{L}_\Phi &= |D_\mu \Phi_{SM}|^2 + |D_\mu \Phi_H|^2 + m^2_{\Phi_H}|\Phi_H|^2 + m^2_{\Phi_{SM}}|\Phi_{SM}|^2 \\ &-\lambda|\Phi_{SM}|^4 - \rho|\Phi_H|^4 - \boxed{\kappa|\Phi_{SM}|^2|\Phi_H|^2}. \qquad (3)\end{aligned}$$

Standard Model Higgs very special:

Gauge invariant and Lorentz invariant all by itself with dim<4.

Higgs boson is the window to new worlds.

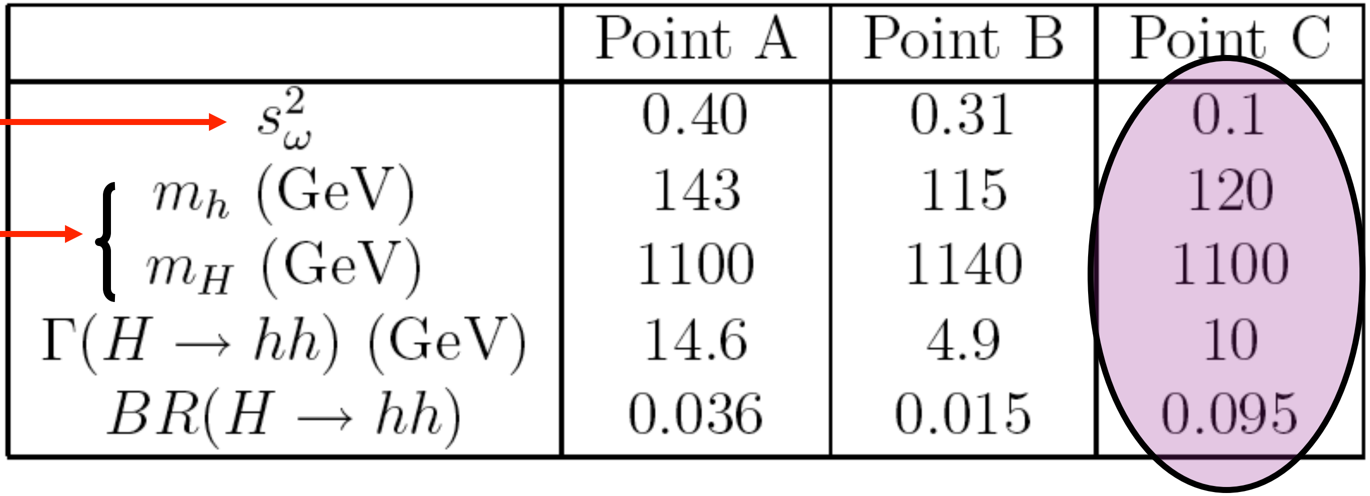
Narrow Trans-TeV Higgs Boson

Within 10% errors, the lighter Higgs boson looks just like the SM Higgs in this example.

When the mixing is small, the heavy Higgs has smaller cross-section (bad), but more narrow (good).

Mixing proportional to κ

Two mass eigenstates

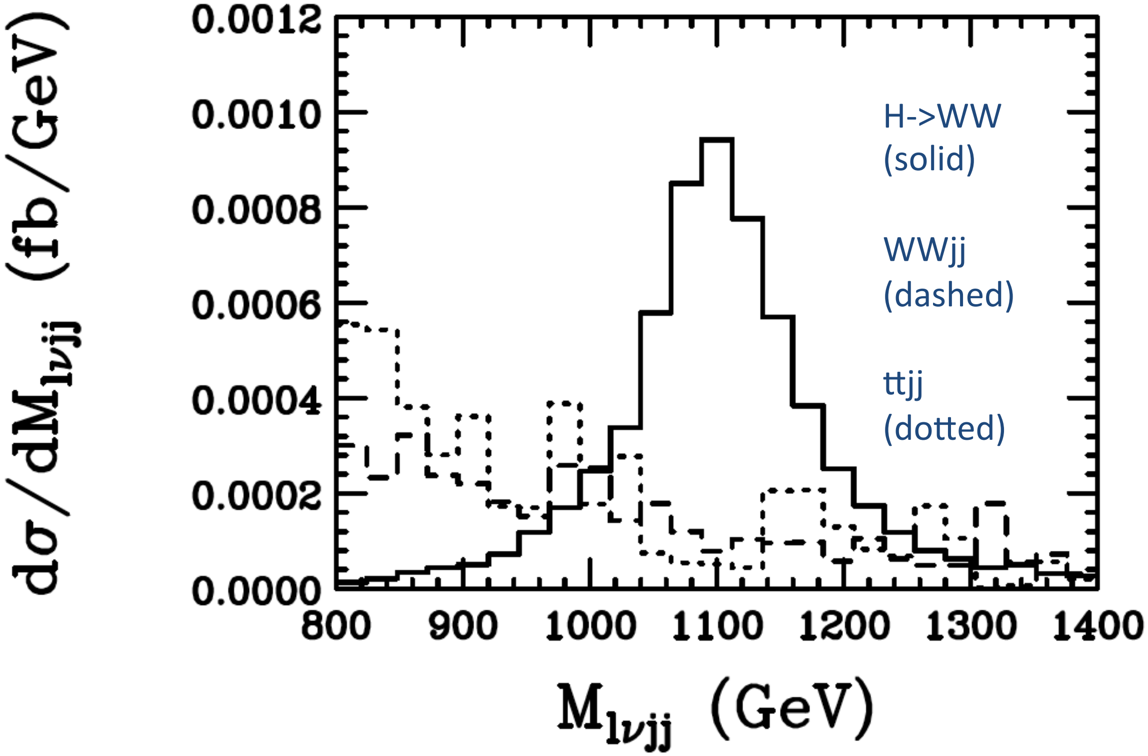


	Point A	Point B	Point C
s_ω^2	0.40	0.31	0.1
m_h (GeV)	143	115	120
m_H (GeV)	1100	1140	1100
$\Gamma(H \to hh)$ (GeV)	14.6	4.9	10
$BR(H \to hh)$	0.036	0.015	0.095

Investigate Point C example

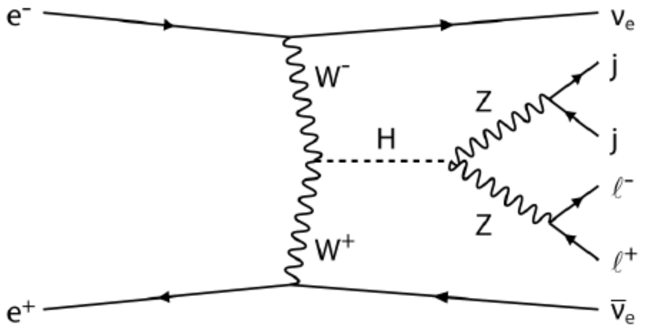
H->WW->jjlν

Techniques: Atlas & CMS TDRs
and Iordanidis, Zeppenfeld, '97



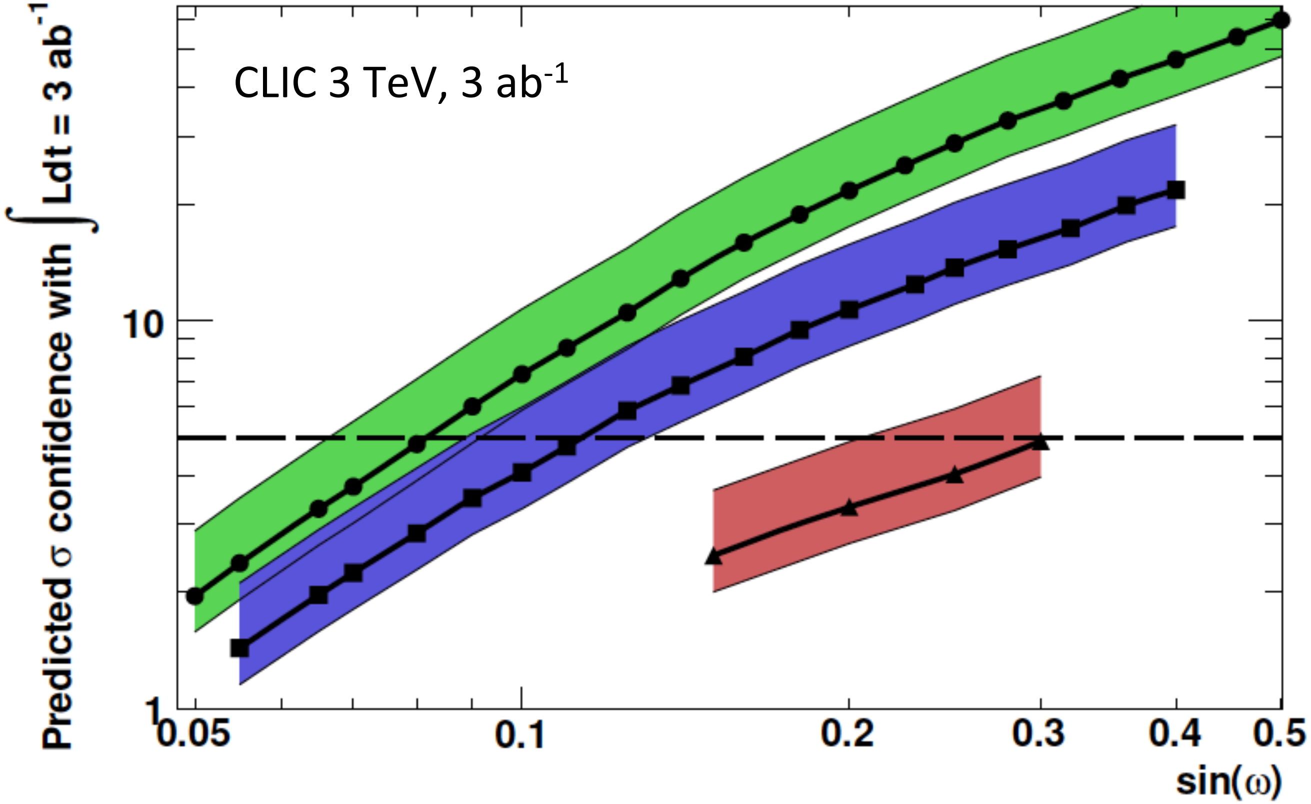
Between 1.0 & 1.3 TeV 13 signal events in 100 fb^{-1} vs. 7.7 bkgd

Similar kind of analysis for H->ZZ->llνν yields even more challenging result:
In 500 fb^{-1} 3.9 signal vs. 1.4 bkgd



Sensitivity at CLIC

Green: 1.0 TeV heavy Higgs
Blue: 1.5 TeV heavy Higgs
Red: 2.0 TeV heavy Higgs

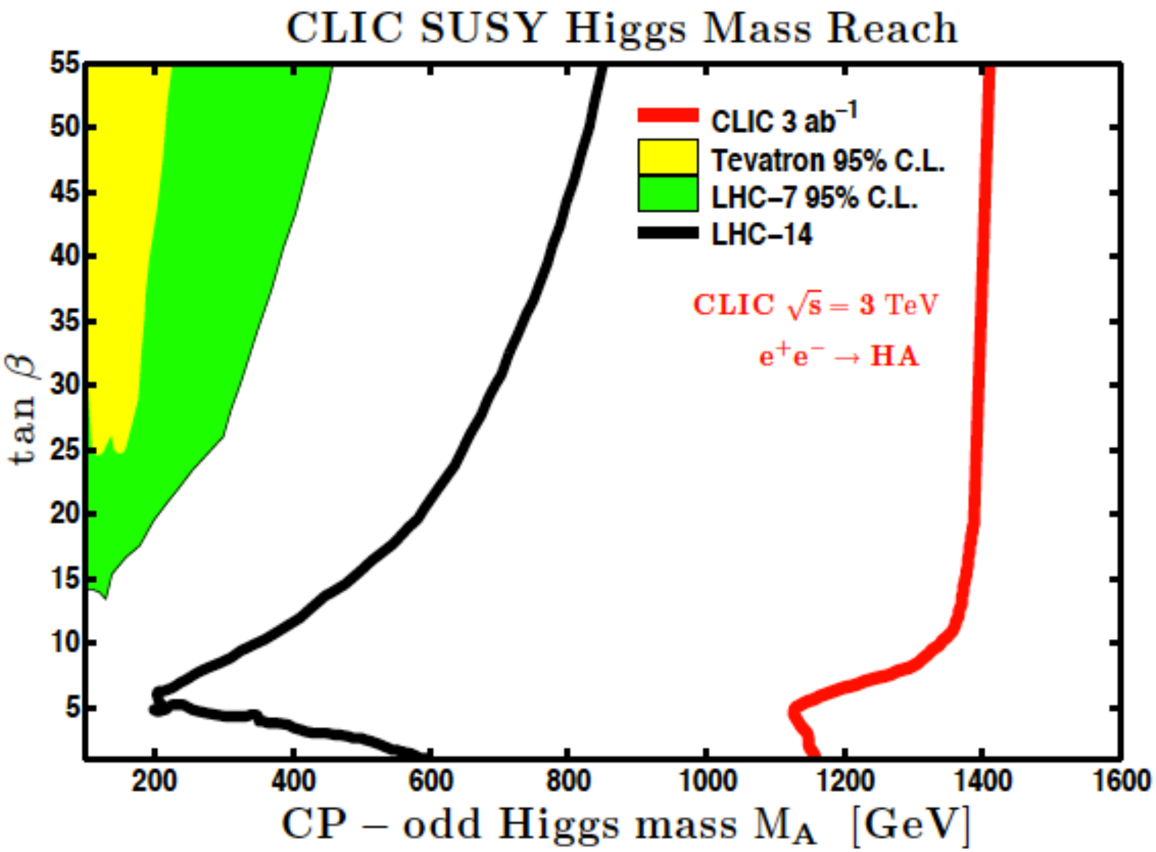


J. Collins (part III), JW

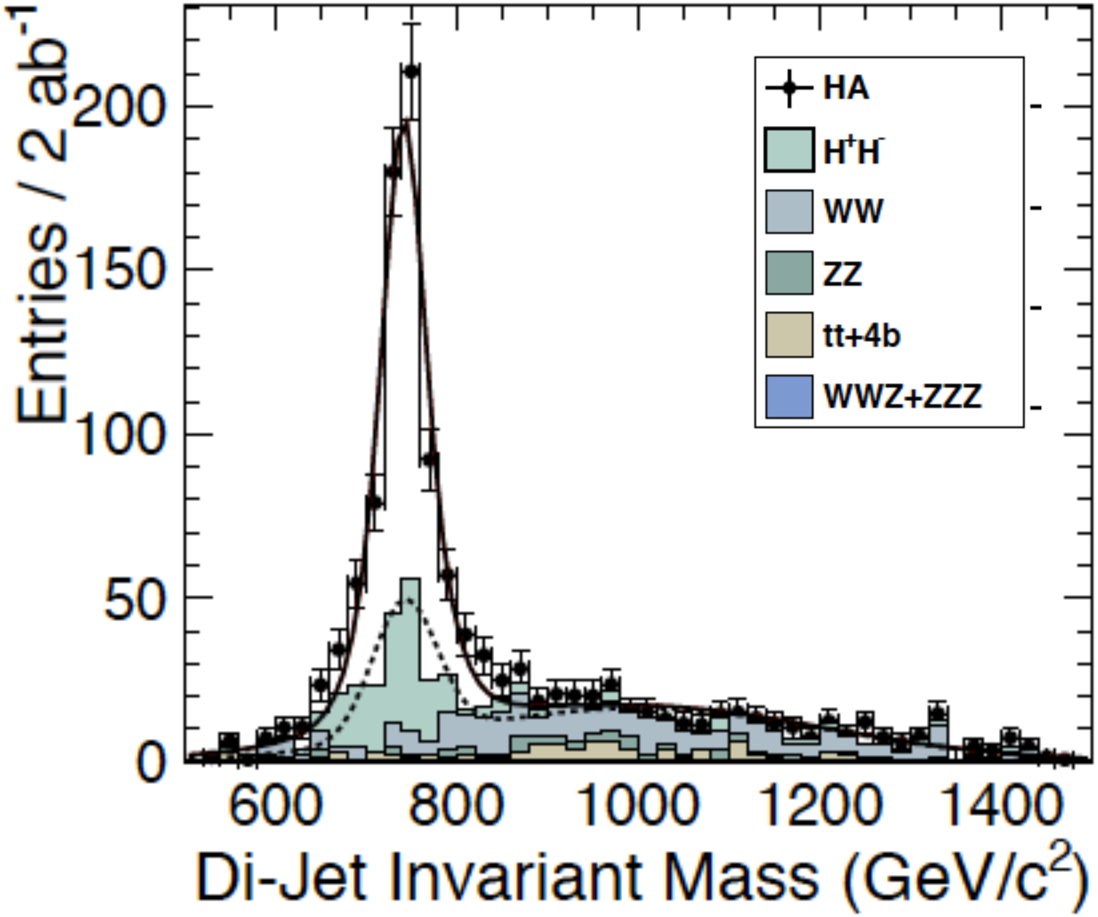
Heavy Higgs Search in Supersymmetry

Finally, let us come back to supersymmetry.

Well known that the heavy Higgs search at LHC is extremely challenging due to low rate and large backgrounds.



SUSY Heavy Higgs at CLIC



CLIC 3 TeV HA study
CLIC CDR

Conclusions

Obvious Fact 1: LHC is a powerful machine moving into prime territory of expected Higgs and BSM physics.

Obvious Fact 2: Our future path is very strongly coupled to results from LHC

Obvious Proposition: The LHC cannot answer all questions posed, nor can it discover all new physics even in the neighborhood of the weak scale

Not So Obvious Conjecture: Every BSM idea addressing key question of EW scale has BSM physics not fully studied or discovered at LHC

Obvious Conclusion: We must prepare new colliders to answer the questions not answered or newly raised by the LHC