Top Quark Theory

&

The New Physics Searches Frontier

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Large Hadron Collider

NOBEL SYMPOSIA

Outline (3 parts, speculative order)

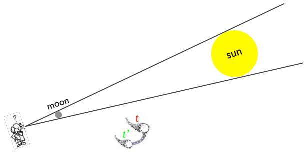
- Why is top phys. interesting, regardless of electroweak (EW) phys.?

Large mass + small width => unique info'; new data & theory precision;

anomalous asymmetries (Tevatron); (clean flavor source).

- Why is the top quark so interesting given EW & Higgs phys.?

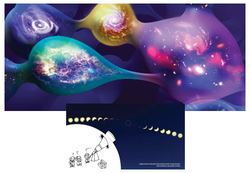
Quantum top deforms EW scale:



Standard model (SM): top induces vacuum instability;

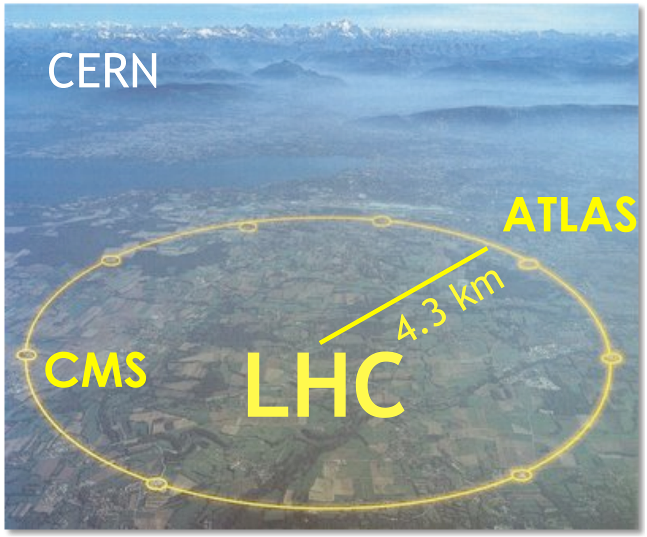
Battle for naturalness: *t*-partner searches => robust test of naturalness.

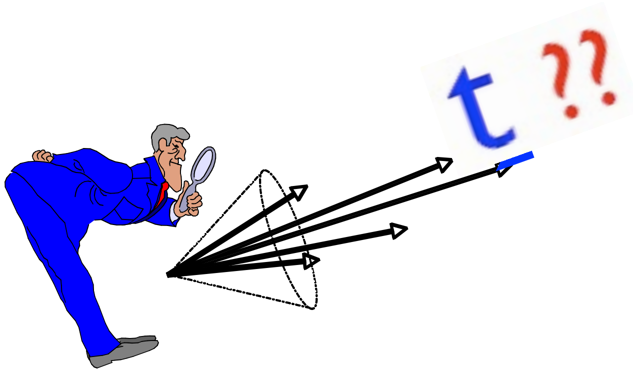
- [Why are the top (& light Higgs) living dangerously?]

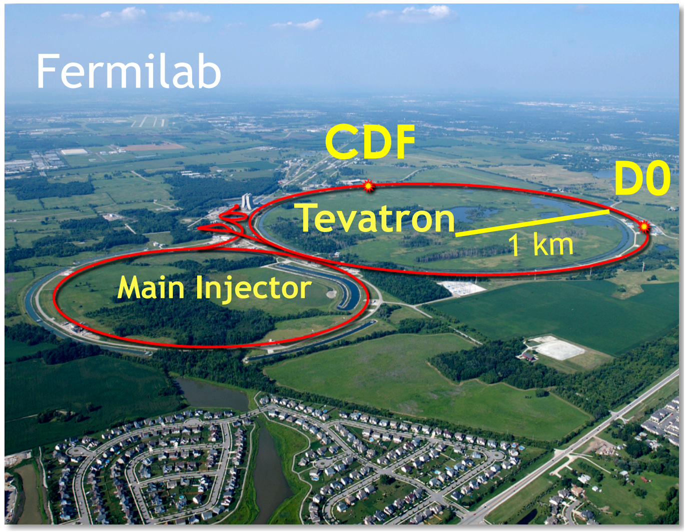


- Top questions.

Why is the top quark interesting (just because)?







Top (exp') uniqueness, mass

- The heaviest point like particle known to exist.

$$m_t \approx 10^5 \times m_u \approx 180 \times m_{\rm pr} \approx 10^{-22}\,{\rm gr}$$

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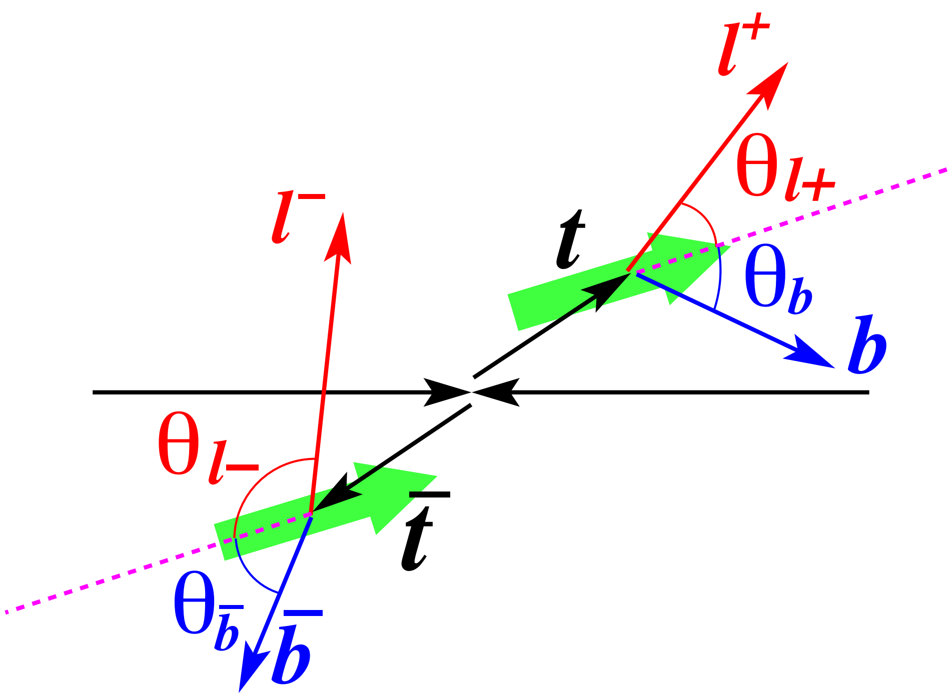
Top (exp') uniqueness, spin

- t -> only quark to decay before hadronizes, yet narrow.

- Direct access to its spin, charge & flavor.



Few relevant pheno' facts, the quantum top

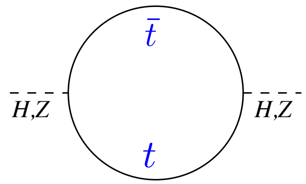
See previous talk by Chierici ...

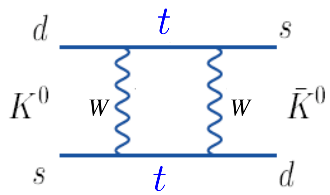
- Tevatron: top mass now known to 0.5%, m_t = 173.2 ± 0.9 GeV

Tevatron combination (11).

Standard Model (SM): top coupling to Higgs is perturbative but LARGE: $y_t \simeq 1$

Quantum effects (virtual tops) => dramatic impact on EW & flavor phys.: $\frac{2N_c\, {y_t}^2}{16\pi^2} \simeq 5\%$





- Theory: t-Xsection (Tevatron, LHC) now known to NNLO (+NNLL resum')

Bärnreuther, Czakon & Mitov; Czakon & Mitov x2 (12); Czakon, Fiedler & Mitov (13).

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) −0.200(2.8%)	+0.169(2.4%) −0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) −5.8(3.4%)	+4.7(2.7%) −4.8(2.8%)
LHC 8 TeV	245.8	+6.2(2.5%) −8.4(3.4%)	+6.2(2.5%) −6.4(2.6%)
LHC 14 TeV	953.6	+22.7(2.4%) −33.9(3.6%)	+16.2(1.7%) −17.8(1.9%)

Mitov, CERN, 4/13

Few interesting pheno'facts, the quantum top

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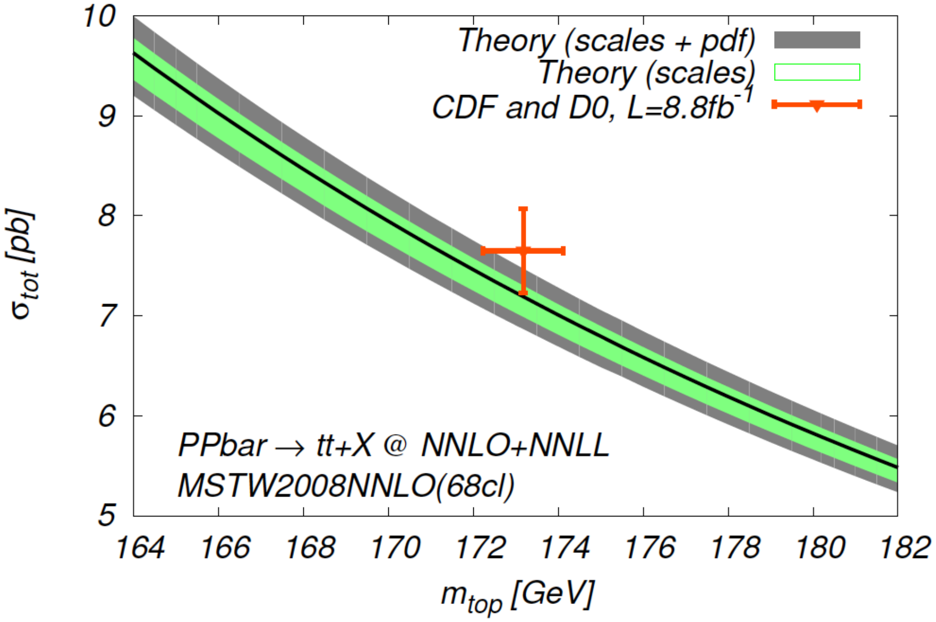
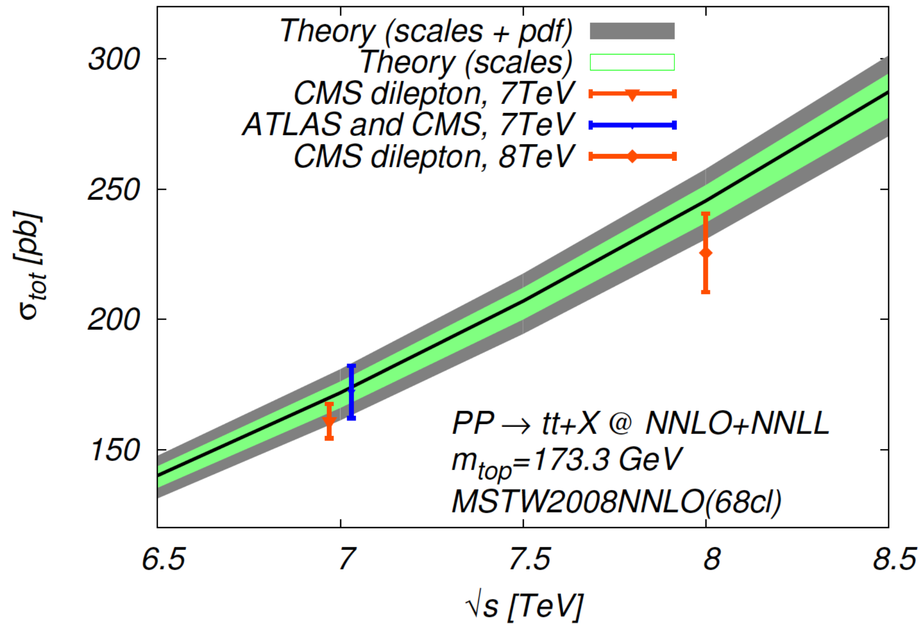
Nice agreement with SM





1

$\simeq 5\%$

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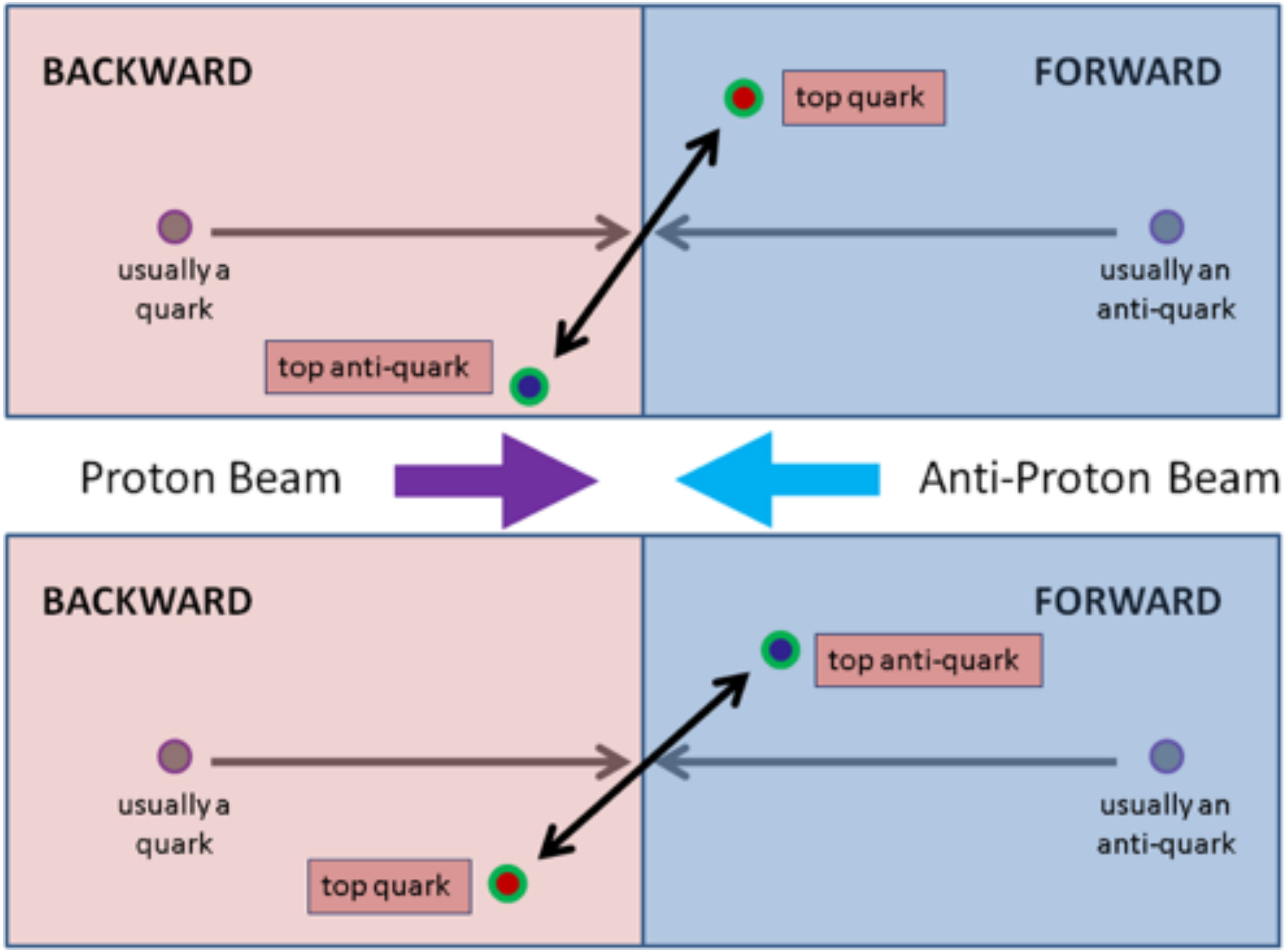
Tevatron's Top Forward-Backward Asymmetry Anomaly

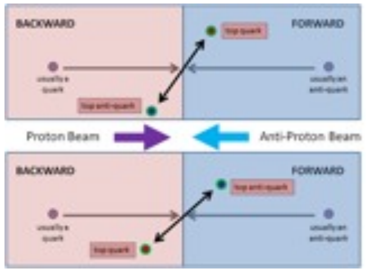


The $t\bar{t}$ forward backward asymmetry (AFB) theory & 2x3 measurements

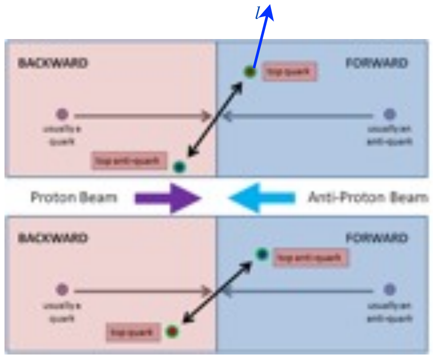
2 kind of independent anomalous asymmetries (***3*** observables):

(i) Partonic top-pair AFB -

$a.$ inclusive; $b.$ differential, $m_{t\bar{t}} > 450\,\mathrm{GeV}$.



(ii) Lepton asymmetry (A_l).

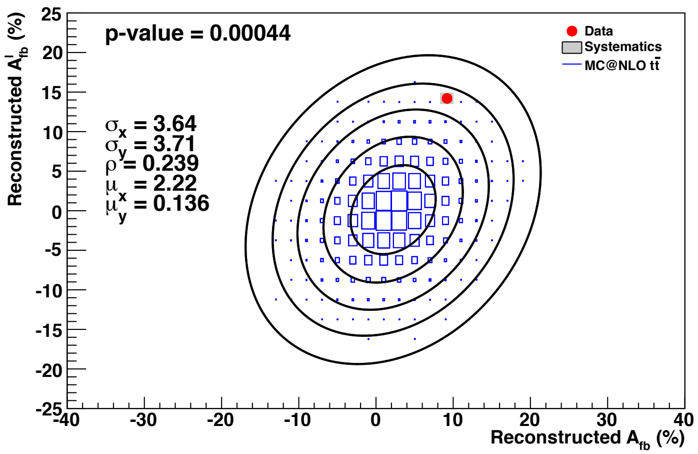


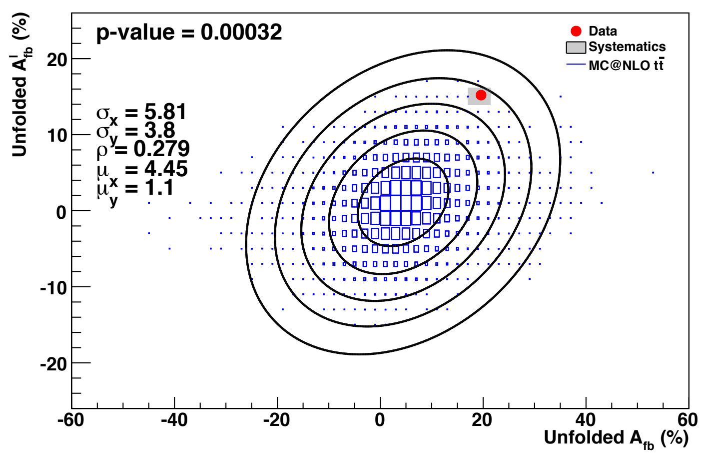
The $t\bar{t}$ forward backward asymmetry (AFB) theory & 2x3 measurements

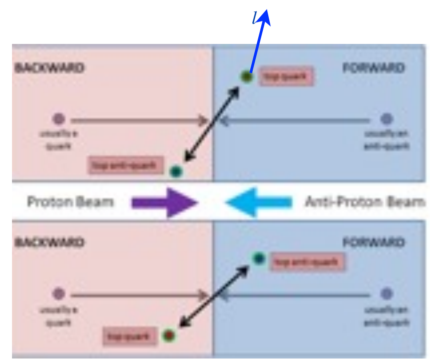
2 kind of independent anomalous asymmetries (*3* observable):

Top & lepton asymmetries are independent

A_l vs. AFB "uncorrelation" plots (D0, CERN Top Phys. workshop, 5/12)







- 100,000 pseudo experiments made from signal and background simulation

Th.: Near threshold the lepton asymmetry not even related to top physics! Falkowski, GP & Schmaltz (11)

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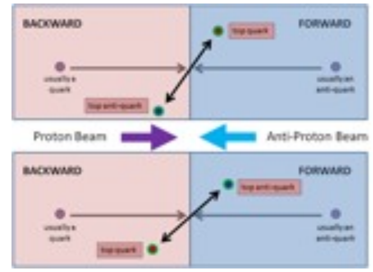

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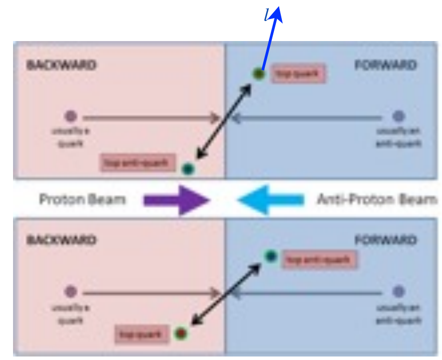

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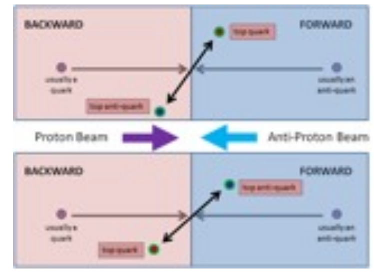

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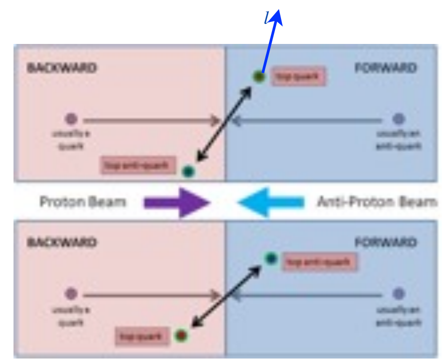
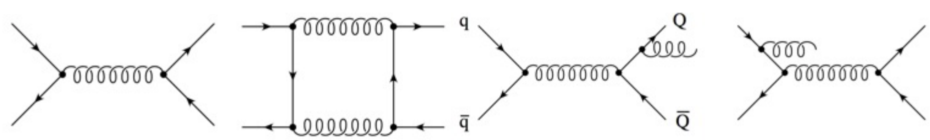


SM: Contributions start at NLO QCD, i.e. ~$(\alpha_S)^3$.



Higher order soft effects probed. No essential new effects (beyond Kuhn & Rodrigo).
Awaiting for real EW calculation & most importantly the NNLO answer!

AFB: Kuhn, Moch, Penin & Smirnov (01); Almeida, Sterman, Wogelsang (08); Melnikov, Schultze (09); Ahrens, Ferroglia, Neubert, Pecjak, Yang; Kuhn, Rodrigo; Hollik, Pagani (11); Manohar, Trott; Skands, Webber, Winter (12).
Lepton based asym': Bernreuther & Si(10,12);Campbell & Ellis (12).

Tevatron's $t\bar{t}$ forward backward anomaly

Data vs. theory, 6 x 2-3 sigma effects:

(i) Top forward backward asymmetry (*AFB*).

- Combined CDF+DO results: $A_{FB}^{inclusive} \approx (18 \pm 4)\%$

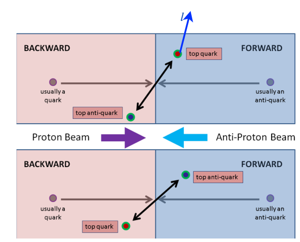
  post-Moriond 2012 $A_{FB}^{>450GeV} \approx (28 \pm 6)\%$

  in ttbar rest frame

QCD+EW state of the art: $A_{FB}^{[inclusive|>450GeV]} \approx [6.6|10]\% \pm ??$ (NLOx30%?)

Delaunay, Beauty talk (13)

(ii) Lepton asymmetry (A_l).



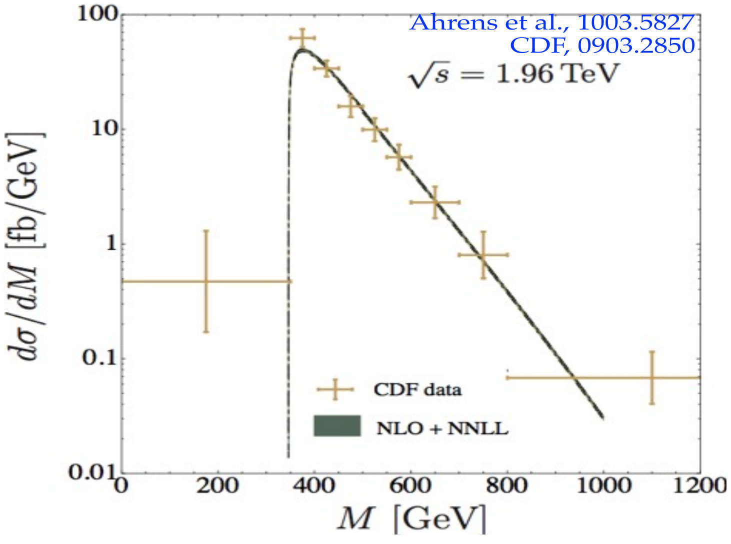
CDF with 9.4 fb^{-1}	**D0** with 5.4 fb^{-1}	**SM**
$A_\ell = (9.4 \pm 3.1)\%$	$A_\ell = (11.8 \pm 3.2)\%$	$A_\ell \simeq 4\%$

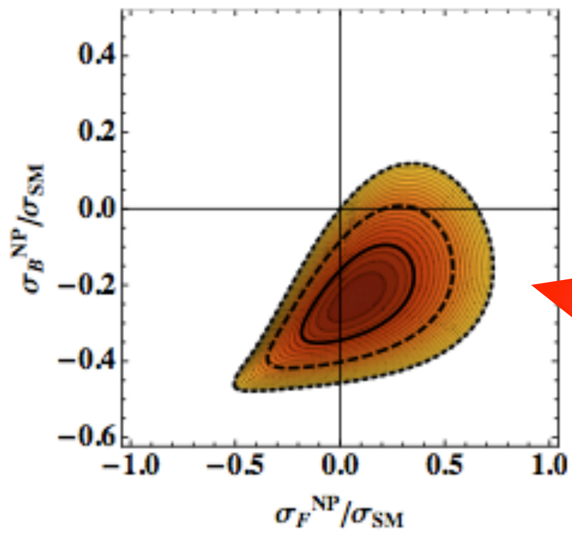
Some features of new physics (NP) interpretations*

- Top asymmetry is special, not only top sector is probed:

  Large asymmetry (PDFs) => new dynamics couple to both $u\bar{u}$ & $t\bar{t}$.
  (furthermore the lepton asymmetry need not be related to top physics)

- Challenged by agreement \w SM Xsec' => SM-NP interference.





Grinstein, Kagan, Trott, Zupan (11)

negative Xsec' favors, new physics interference.

- Two broad classes of models: *(i)* hard physics; *(ii)* on shell physics.

* Hundreds of papers, just give brief subjective impression.

Relevant observables (constraints) @ the LHC

- Charged asymm' A_c, large errors, consistent \w SM, $A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$

ATLAS

A_C(l+jets) = -0.018 ± 0.028 ± 0.023

A_C(dilept.) = 0.057 ± 0.024 ± 0.015

A_C(comb.) = 0.029 ± 0.018 ± 0.014

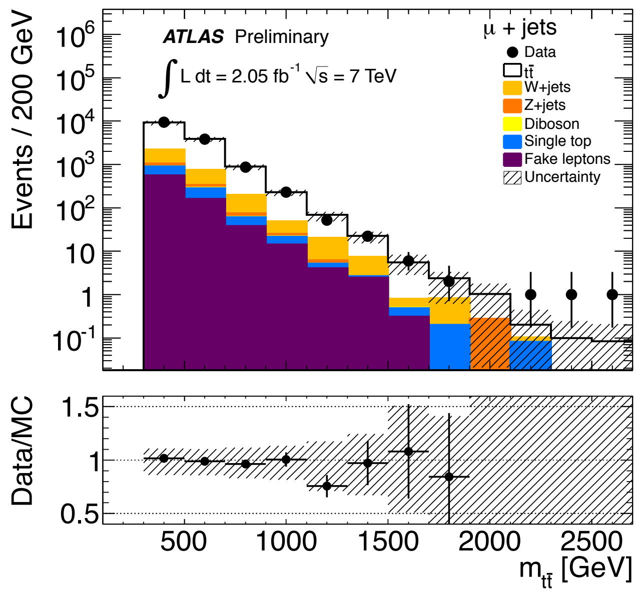
MC@NLO: 0.006 ± 0.002

CMS

A_C(l+jets) = 0.004 ± 0.010 ± 0.012

MC@NLO: 0.0115 ± 0.0006

- $t\bar{t}$ spectrum finally approaching the 2TeV barrier, both differential & cumulative distributions consistent \w SM (more below):

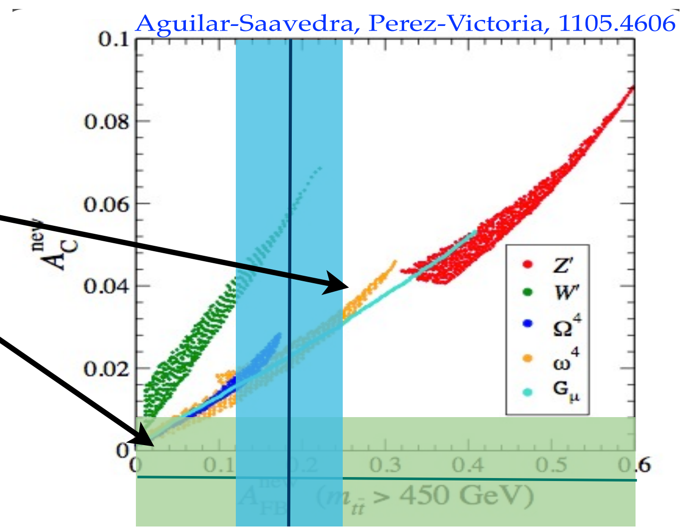


$$\mathcal{S} = \frac{\int_{m_{t\bar{t}}>1\,\mathrm{TeV}/c^2} \frac{d\sigma_{SM+NP}}{dm_{t\bar{t}}} dm_{t\bar{t}}}{\int_{m_{t\bar{t}}>1\,\mathrm{TeV}/c^2} \frac{d\sigma_{SM}}{dm_{t\bar{t}}} dm_{t\bar{t}}}$$ **< 2.6 at 95% CL**

CMS:1204.2488.

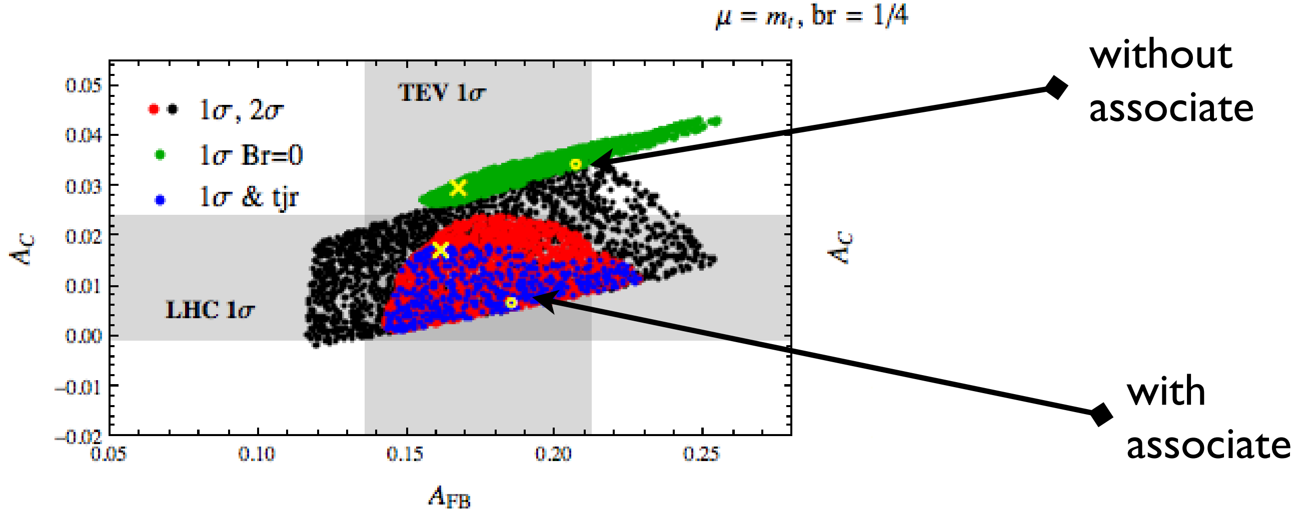
Forward Tevatron Tops & Backward LHC Tops

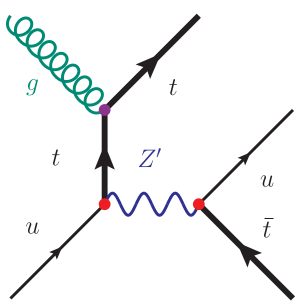
- Apparent serious tension with A_C.



- However, A_{FB} & A_C indep' observables, associate production => natural venue for negative A_C.

Aguilar-Saavedra & Juste; Drobnak, Kamenik & Zupan; Alvarez & Leskow; Drobnak, Kagan, Kamenik, GP, Zupan (12).





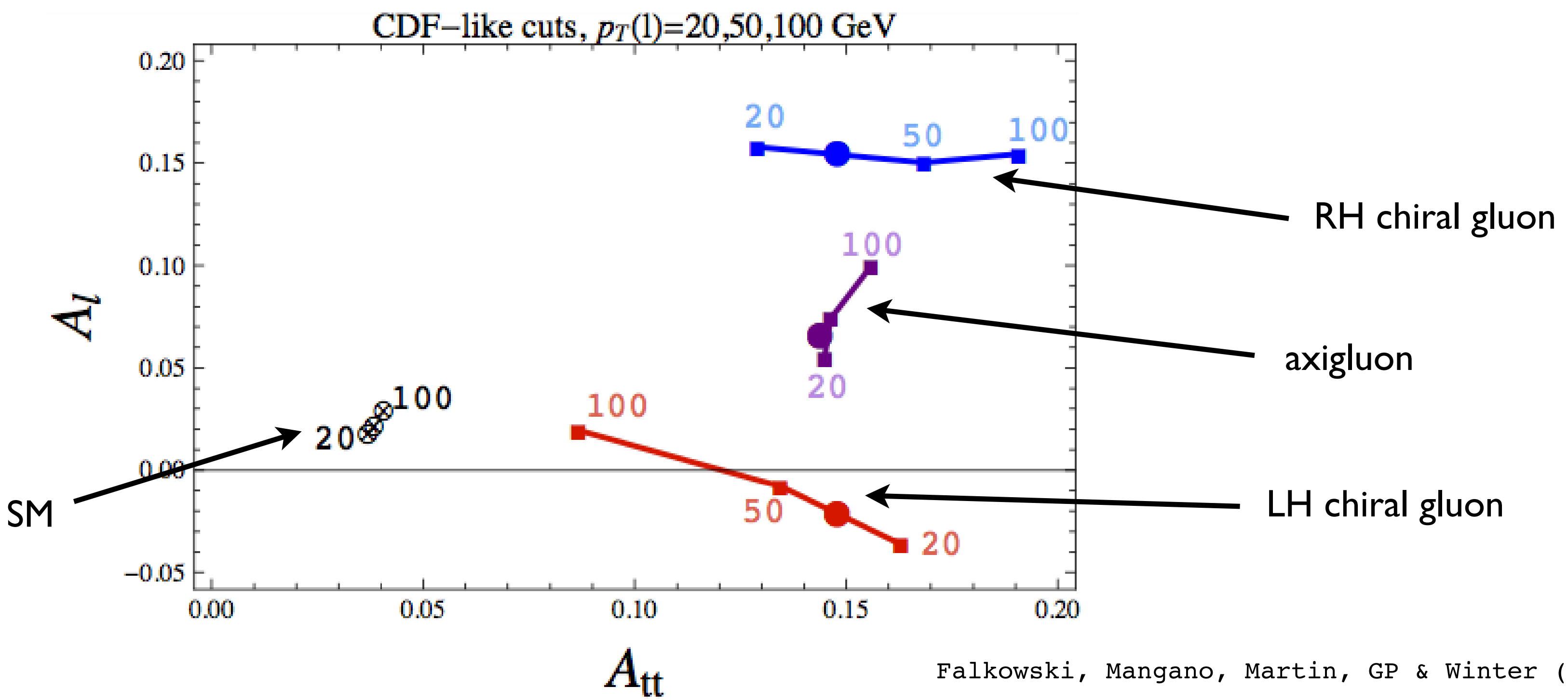
Drobnak, Kagan, Kamenik, GP, Zupan

Towards robust test via data

- Tevatron: looking at A_{FB} vs. A_l as a function of the lepton p_T (since are correlated within the SM)

Falkowski, Mangano, Martin, GP & Winter (12).
See also: Godbole et al. (10) ; Krohn, et al.; Jung, et al.; Cao et al.; Berger, et al. x2 (11); Fajfer, et al.; Berger, et al.; Aguilar-Saavedra & Herrero-Hahn (12).

"Trade" A_{FB} curve for A_l or look at slope => cleaner extraction:

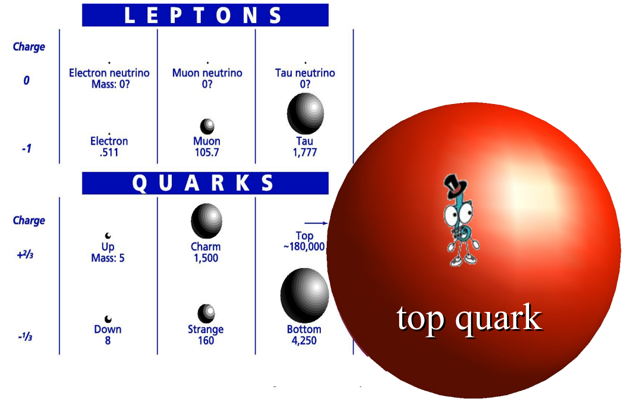


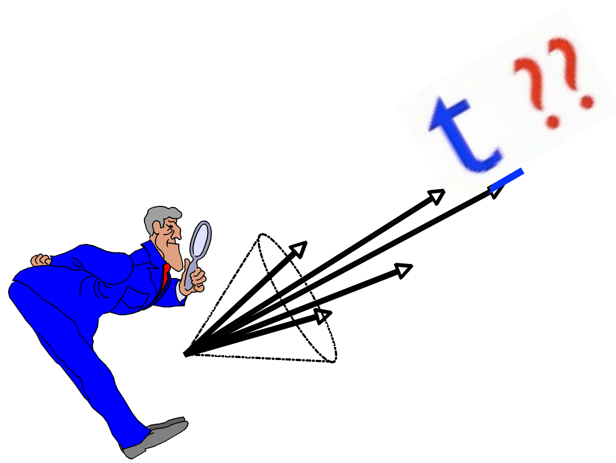
Falkowski, Mangano, Martin, GP & Winter (12).

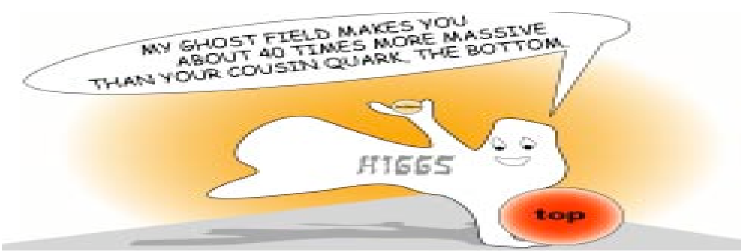
Why is the top quark interesting theoretically?

(*i*) Electroweak symmetry breaking.

(*ii*) The fine tuning problem.

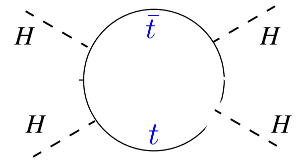




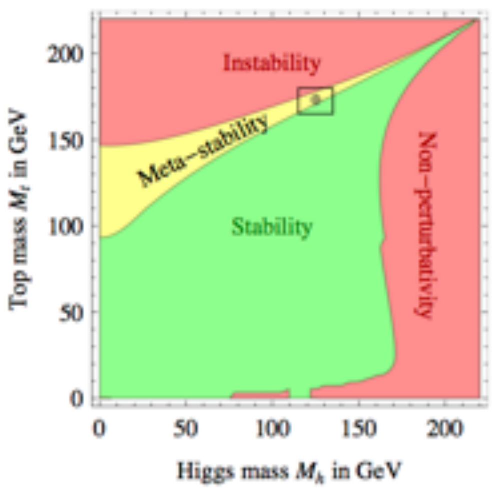


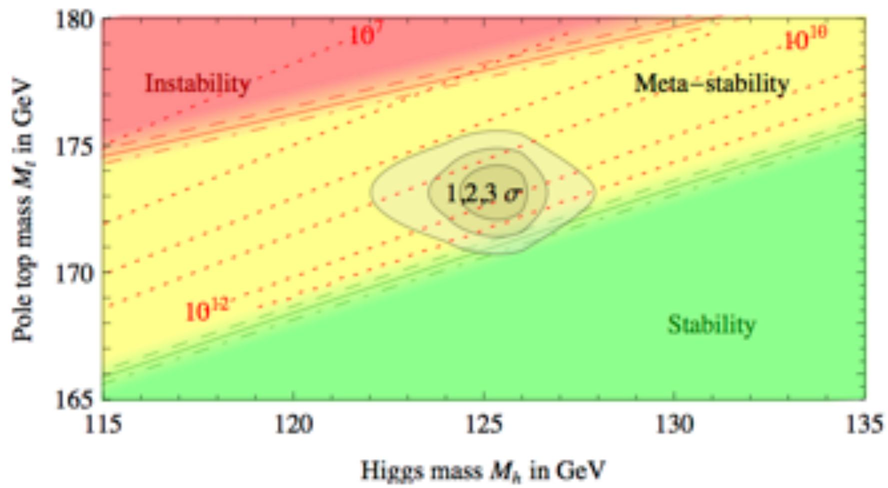
125 GeV Higgs -> top is ~ saturating metastability

$$m_h > 111\,\text{GeV} + 2.8\,\text{GeV}\left(\frac{m_t - 173.2\,\text{GeV}}{0.9\,\text{GeV}}\right) - 0.9\,\text{GeV}\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 3\,\text{GeV}\ .$$



See e.g.: Cabibbo, et al.; Hung (79); Elias-Miro, et al. (11); Degrassi et al.; Alekhin et al.; Bezrukov et al. (12)



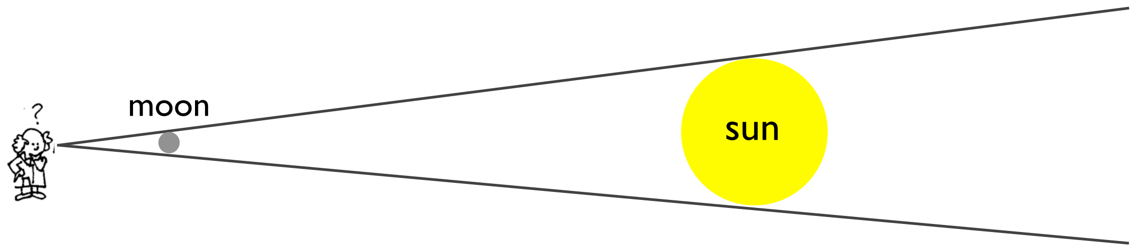


Degrassi, Vita, Elias-Miro, Espinosa, Giudice, Isidori & Strumia (12)

A raise of < 3% in top Yukawa => weakless universe!

The fine tuning problem & its remedies

- Extending top sector adding top partners states that due to sym' contribute to Higgs mass in opposite way => reduce sensitivity.



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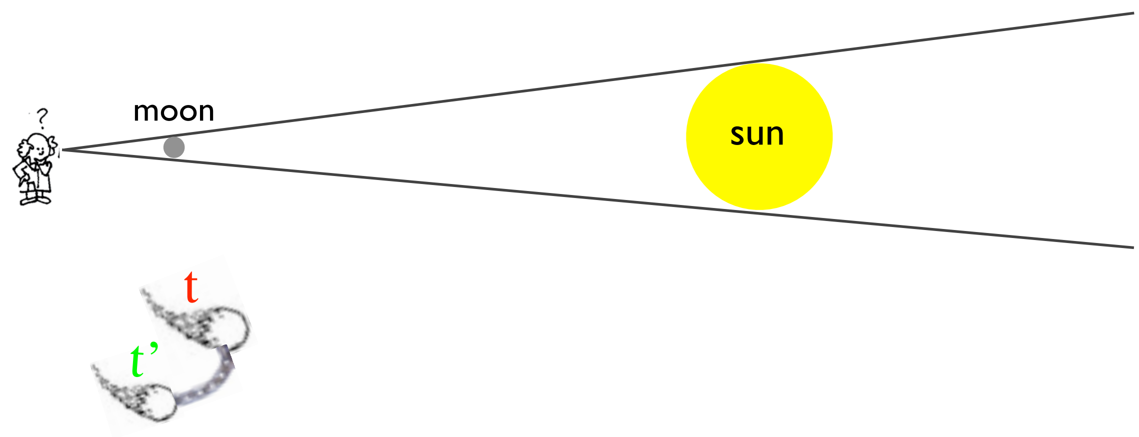

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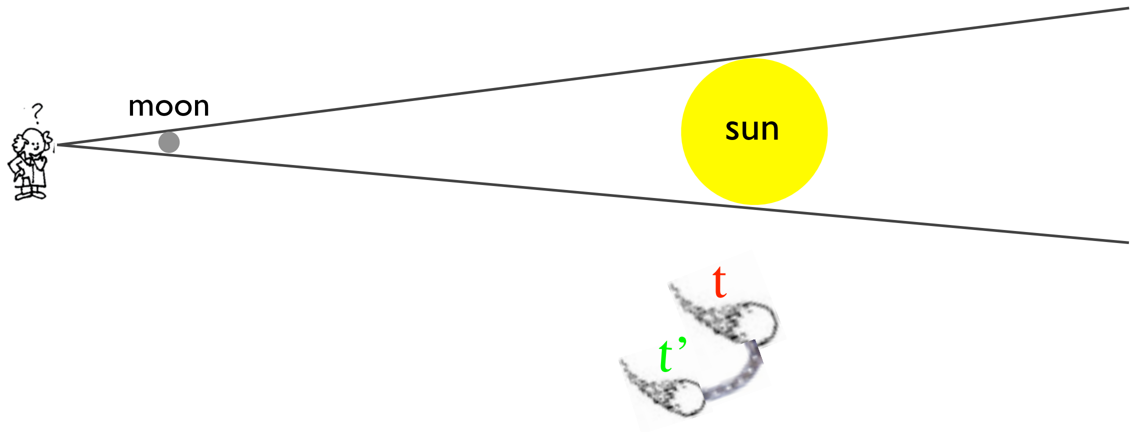

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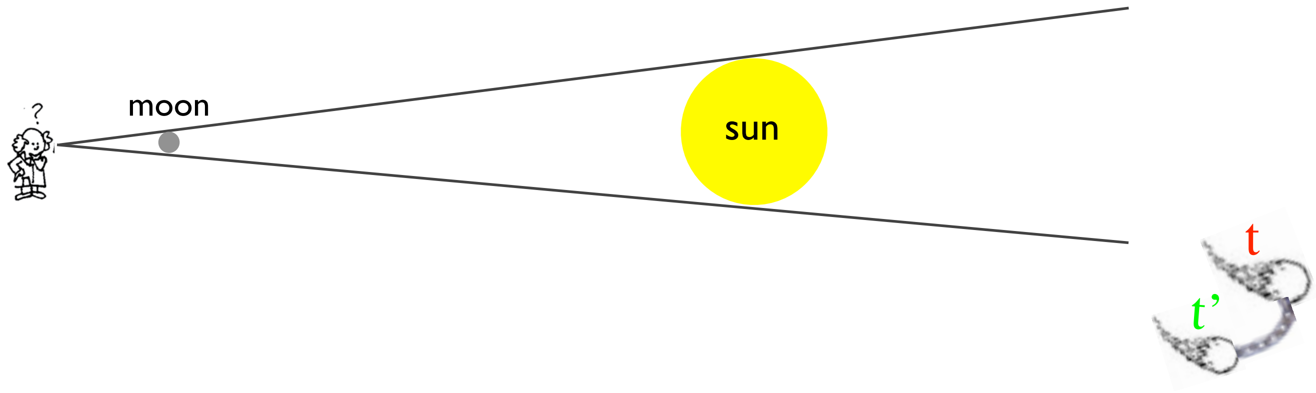

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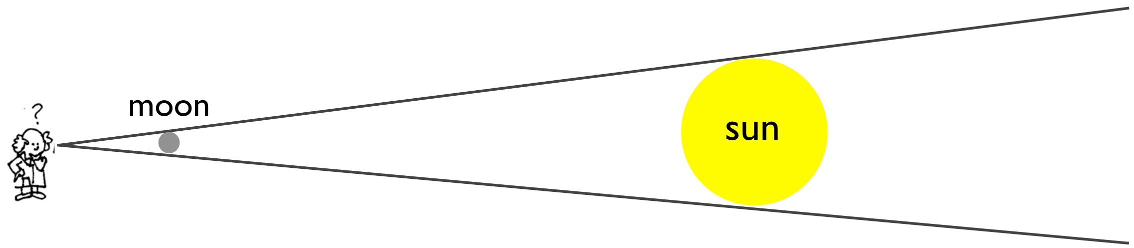

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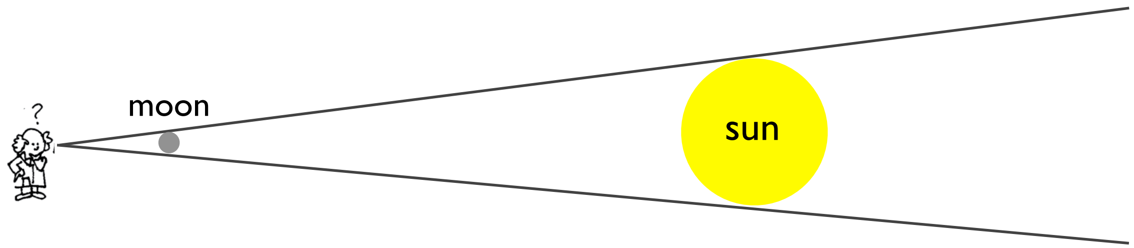
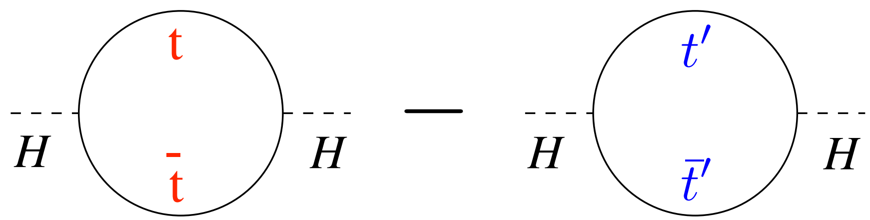


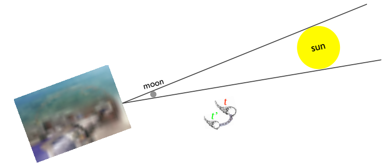
$$\left(m_W^2/m_{\rm Pl}^2\right)_{\rm obs} \sim \left(m_H^2+\delta m_H^2\right)/m_{\rm Pl}^2 \sim \; m_W^2 +$$

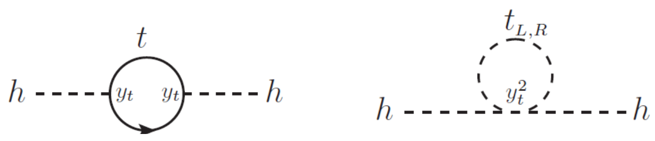


Top physics expected to yield insight on how the fine tuning problem is solved.

Top partners & LHC Searches

Naturalness => new colored partners, potentially within the LHC reach.





$$\frac{\delta m_h^2}{m_h^2} \sim \left(\frac{\tilde{m}_t}{400\,\mathrm{GeV}} \right)^2$$

2 leading frameworks
of naturalness

Supersymmetry,
top partners=stops

Composite Higgs
top partners = "T"

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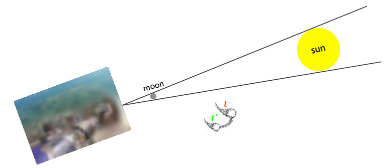
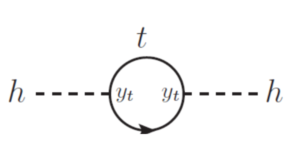
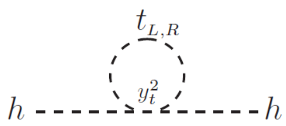
Naturalness => new colored partners, potentially within the LHC reach.





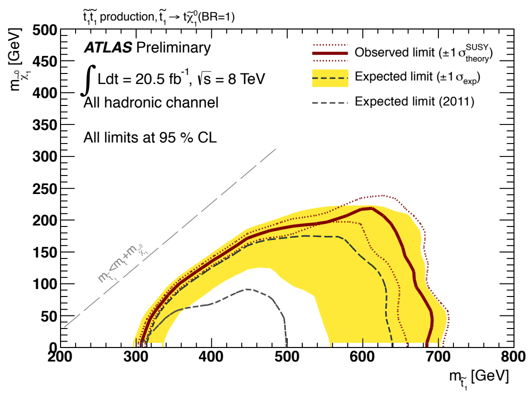


$$\frac{\delta m_h^2}{m_h^2} \sim \left(\frac{\tilde{m}_t}{400\ \mathrm{GeV}} \right)^2$$

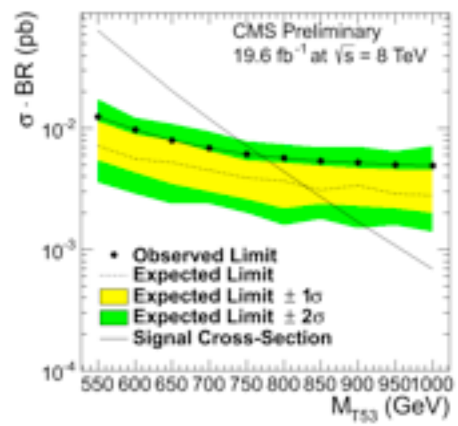
2 leading frameworks of naturalness

SUSY

composite Higgs



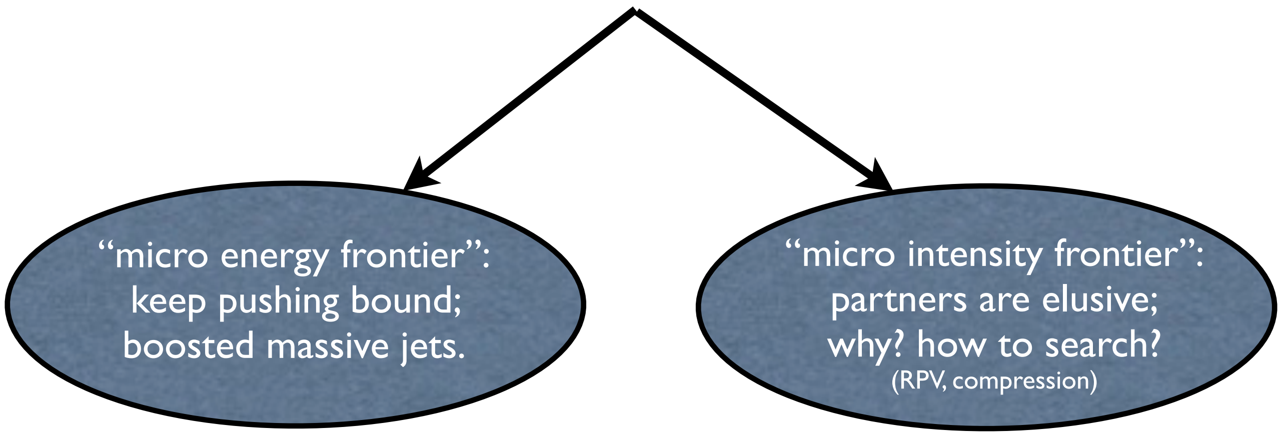
$m_{\mathrm{stop}} \gtrsim 700\ \mathrm{GeV}$



$m_{\mathrm{T}^{5/3}} \gtrsim 800\ \mathrm{GeV}$

The LHC Battle for Naturalness

LHC8: where are the partners ⁇



“the micro intensity frontier”:
partners are elusive;
why? how to search?

Case study: partners are elusive because of non-trivial flavor physics effects that were ignored!

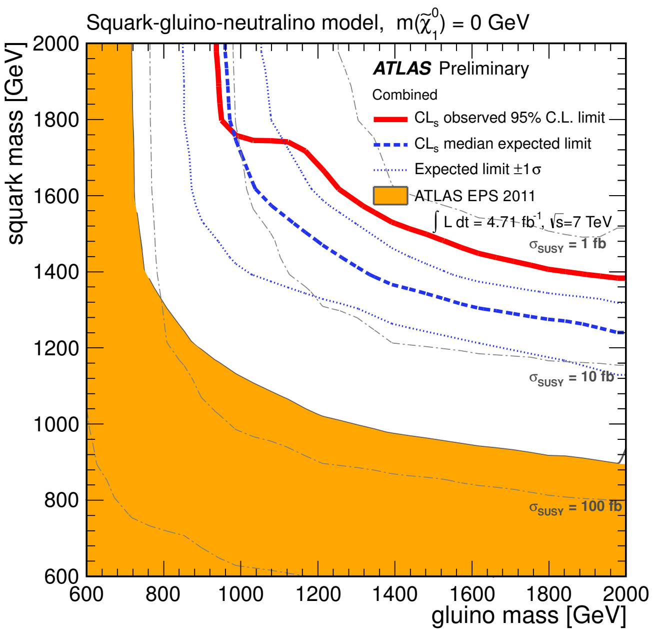
(“first 2 gen’ are completely irrelevant to naturalness & Higgs physics, LHC physics”)

Supersymmetric Flavorful Naturalness

Current status of Supersymmetry

Putting stops aside, what are the bounds on first 2-generation “light” squarks?

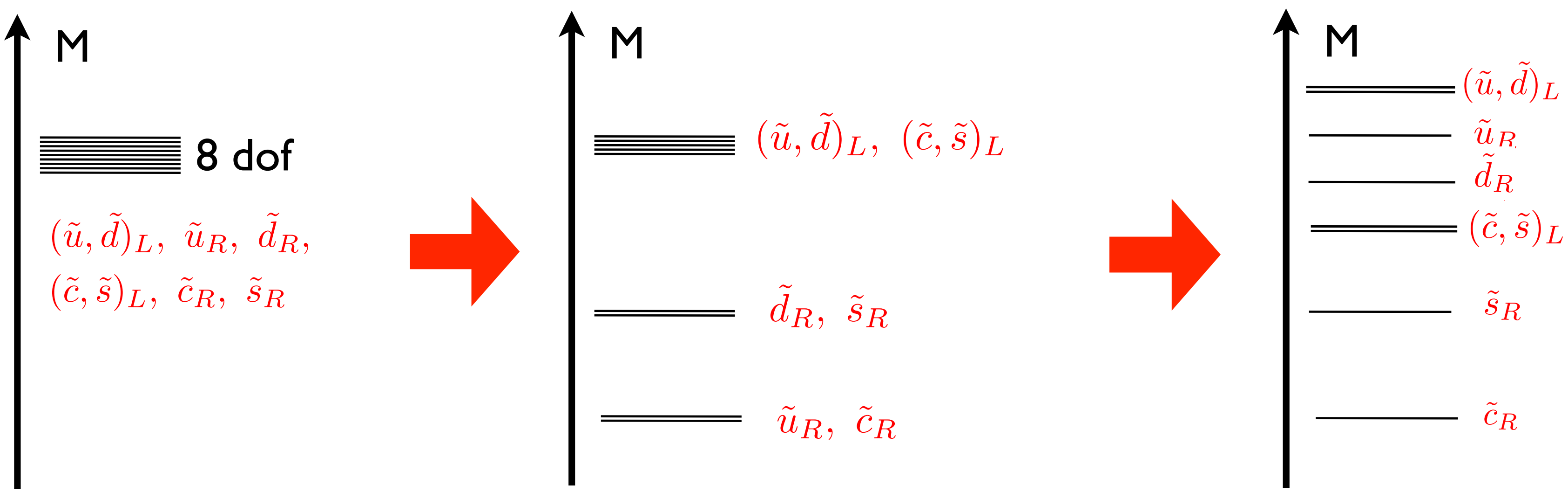
Summer bounds from ATLAS & CMS (*parker;* recent data tomorrow):



Light squarks > 1.4 TeV?

What if first 2 generation squark not degenerate?

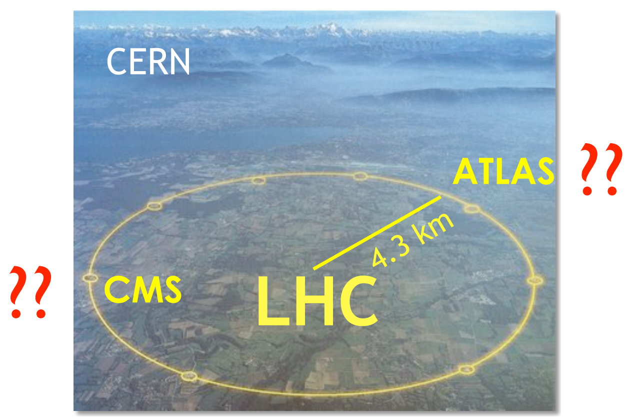
Mahbubani, Papucci, GP, Ruderman & Weiler (12).



Everything degenerate

Split, but MFV

Anarchy!



What drives the experimental limits?

- Squark multiplicity;
- Signal efficiencies;
- Production rate, PDFs.

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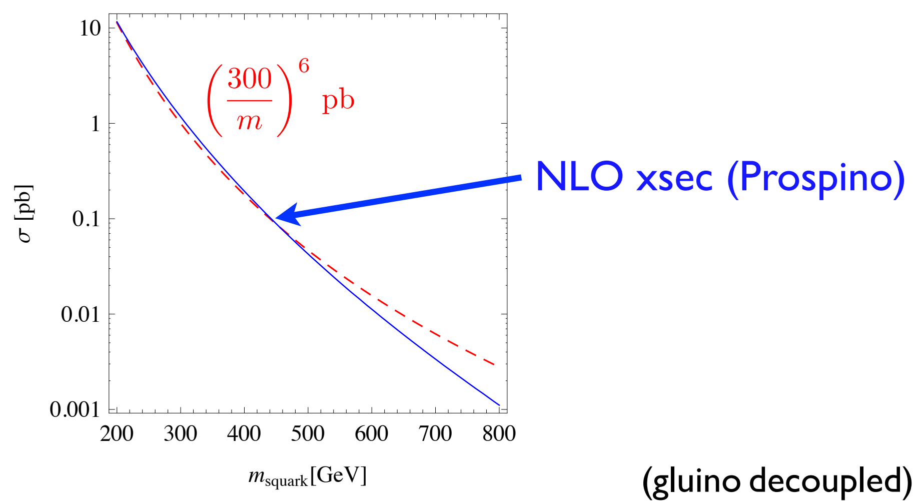
Multiplicity: how bound changes when one doublet is made lighter ?

Cross-sections vs. mass

$\sigma(pp \to \tilde{u}_R \tilde{u}_R^*) \propto \frac{1}{m^6}$ (roughly)



(gluino decoupled)

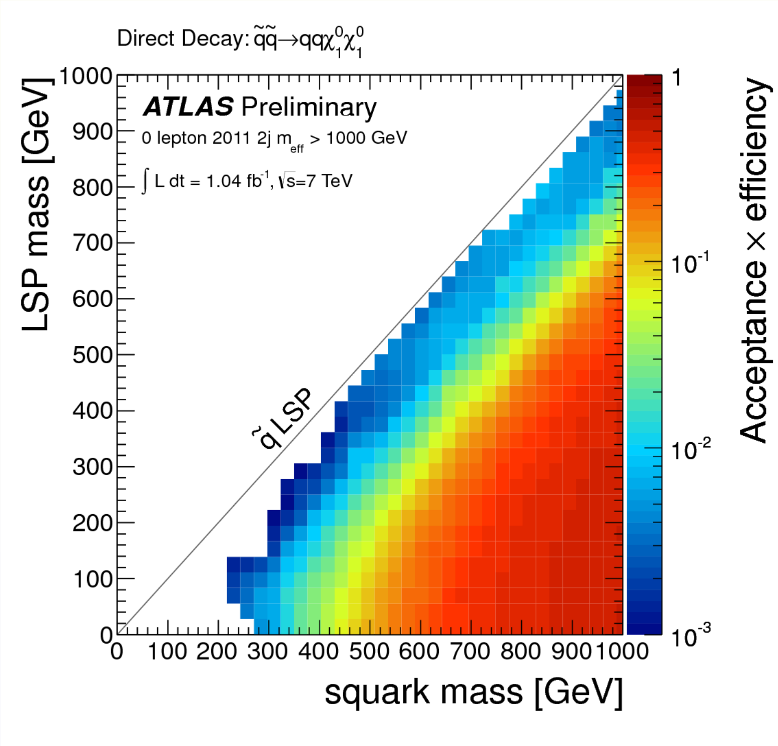
$$8/m^6 = 6/m_H^6 + 2/m_L^6$$

$$(m_L/m_H) = (1/4)^{1/6} \sim 0.8$$

gain is marginal

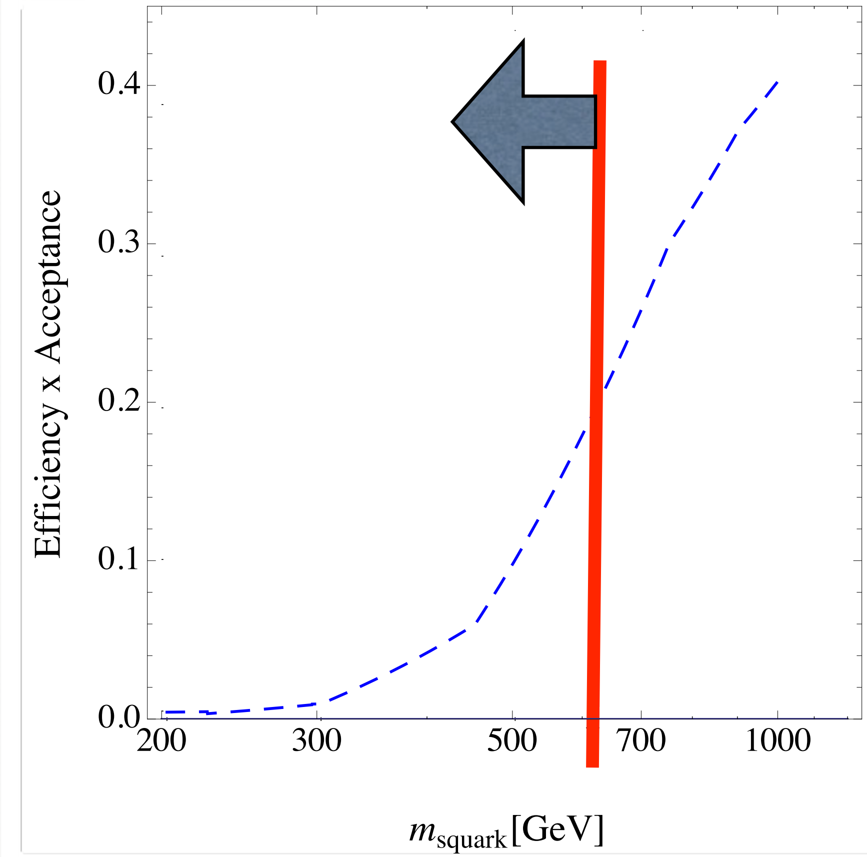
Efficiencies, strong mass dependence!

Signal efficiency falls very rapidly with decreasing squark mass



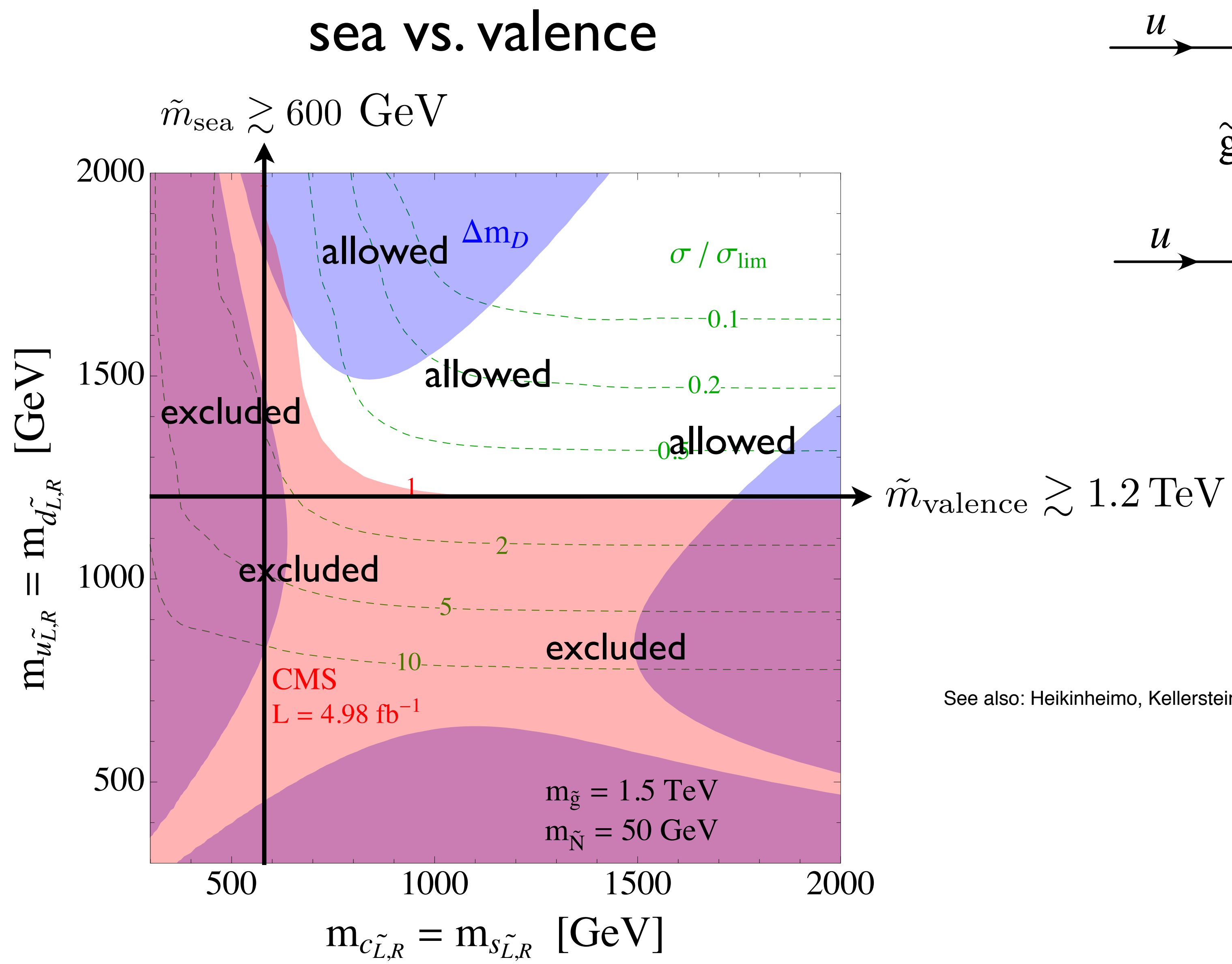
Below $\sim$ 600 GeV $\epsilon\sigma = 1$

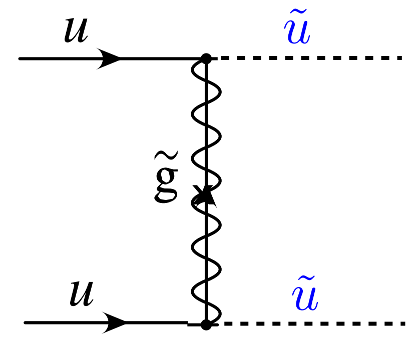
ATLAS 1/fb,
2jet M_{eff}>1TeV



meff is the scalar sum of transverse momenta of the leading N jets with E^{miss}.

PDFs: all 4 flavor "sea" squarks can be rather light!



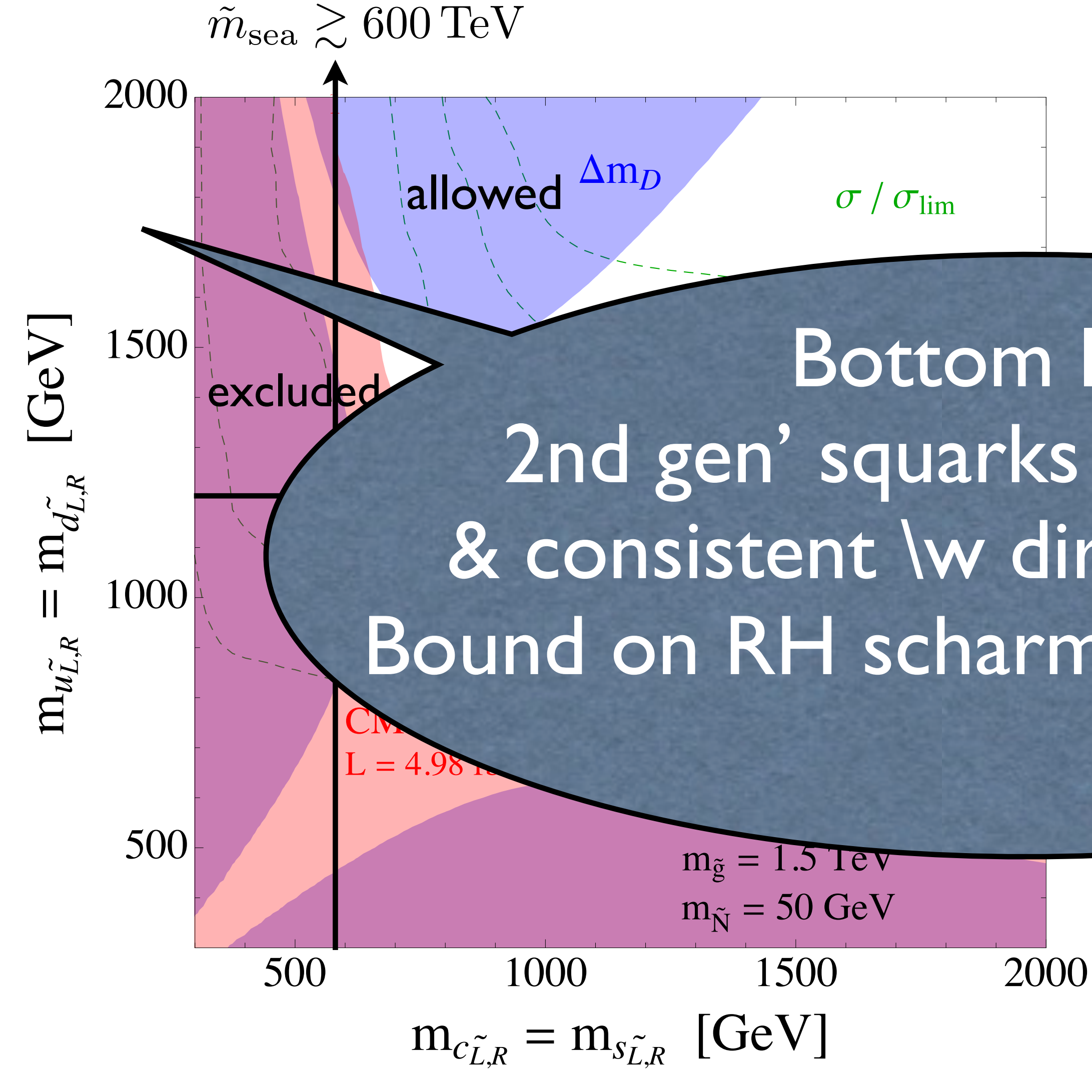


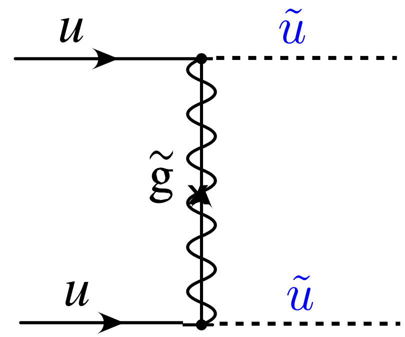
See also: Heikinheimo, Kellerstein & Sanz (11); Kribs & Martin (12),

Mahbubani, Papucci, GP, Ruderman & Weiler (12);
Kadosh, Paradisi & GP, to appear.

PDFs: all 4 flavor "sea" squarks can be rather light!

sea vs. valence





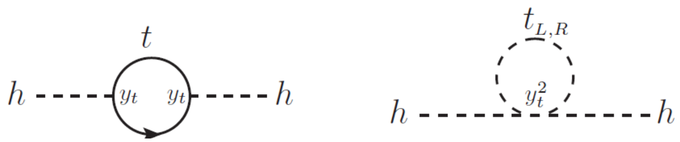
Bottom line:
2nd gen' squarks can be light
& consistent \w direct searches!
Bound on RH scharm only ~400GeV

What is the impact of adding flavor violation on stop searches ? (flavored naturalness)

- Flavor: only $\tilde{t}_R - \tilde{u}_R$ or $\tilde{t}_R - \tilde{c}_R$ sizable mixing is allowed.

- Naively sounds crazy ...

Dine, Leigh & Kagan (93); Dimopoulos & Giudice (95).



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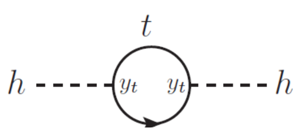

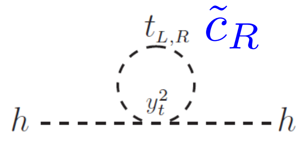

$$\delta m^2_{Hu} = -\frac{3y_t^2}{8\pi^2}\left(m^2_{\tilde{t}_L} + \cos^2\theta_{23}^{RR} m_1^2 + \sin^2\theta_{23}^{RR} m_2^2\right)$$

- However, just established the scharm can be light.

- The $"\tilde{t}_R\,\tilde{t}_R^*" \to t_R\, t_R^*$ production is suppressed by $\left(\cos\theta_{23}^R\right)^4$.

Potentially: new hole in searches, possibly improve naturalness

Constraining flavorful naturalness

- RH stops dominates naturalness, $m_{\tilde{t}_R} \gtrsim m_0 = 570\,\mathrm{GeV}$

ATLAS (12), now new bound.

- To constrain, look for: tt, cc & tc + MET (very qualitative).

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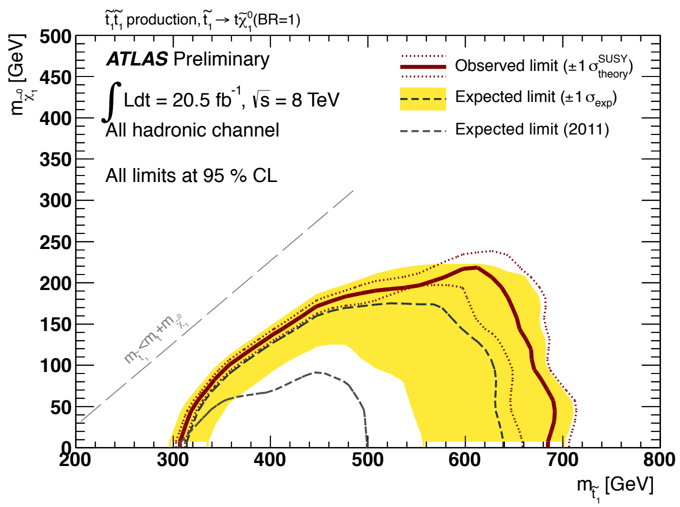

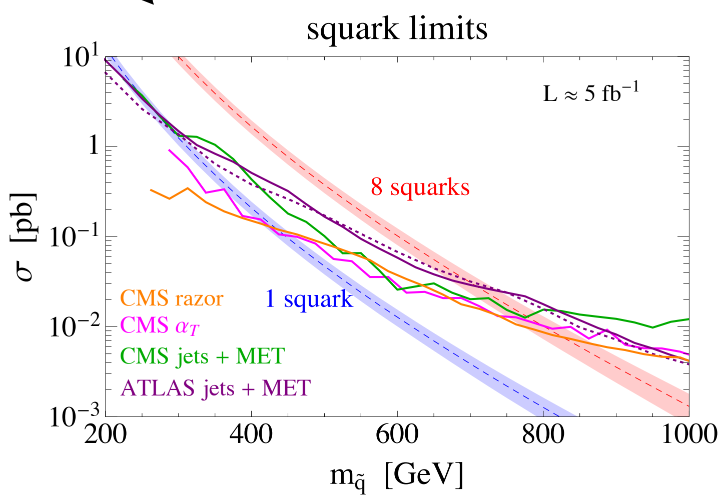

Mahbubani, Papucci, GP, Ruderman & Weiler (12).

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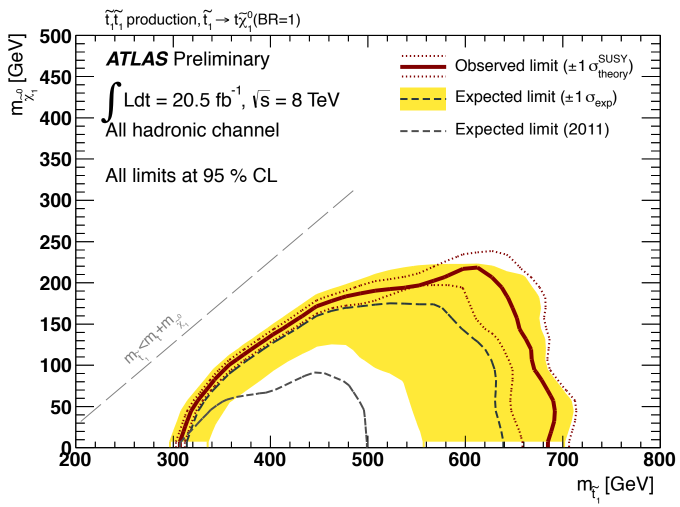

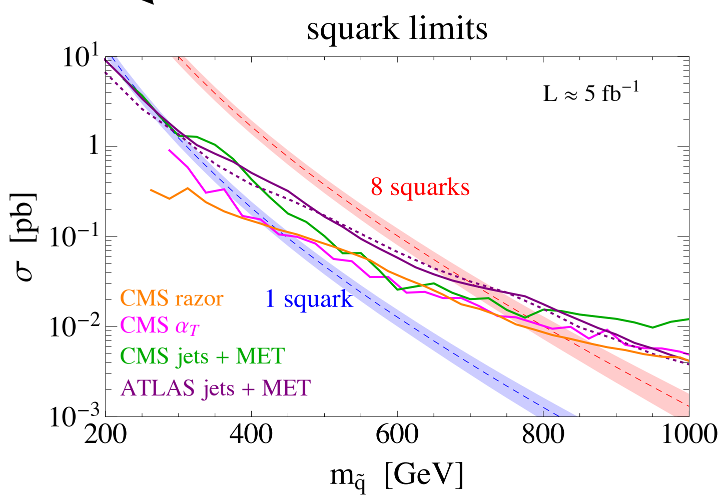

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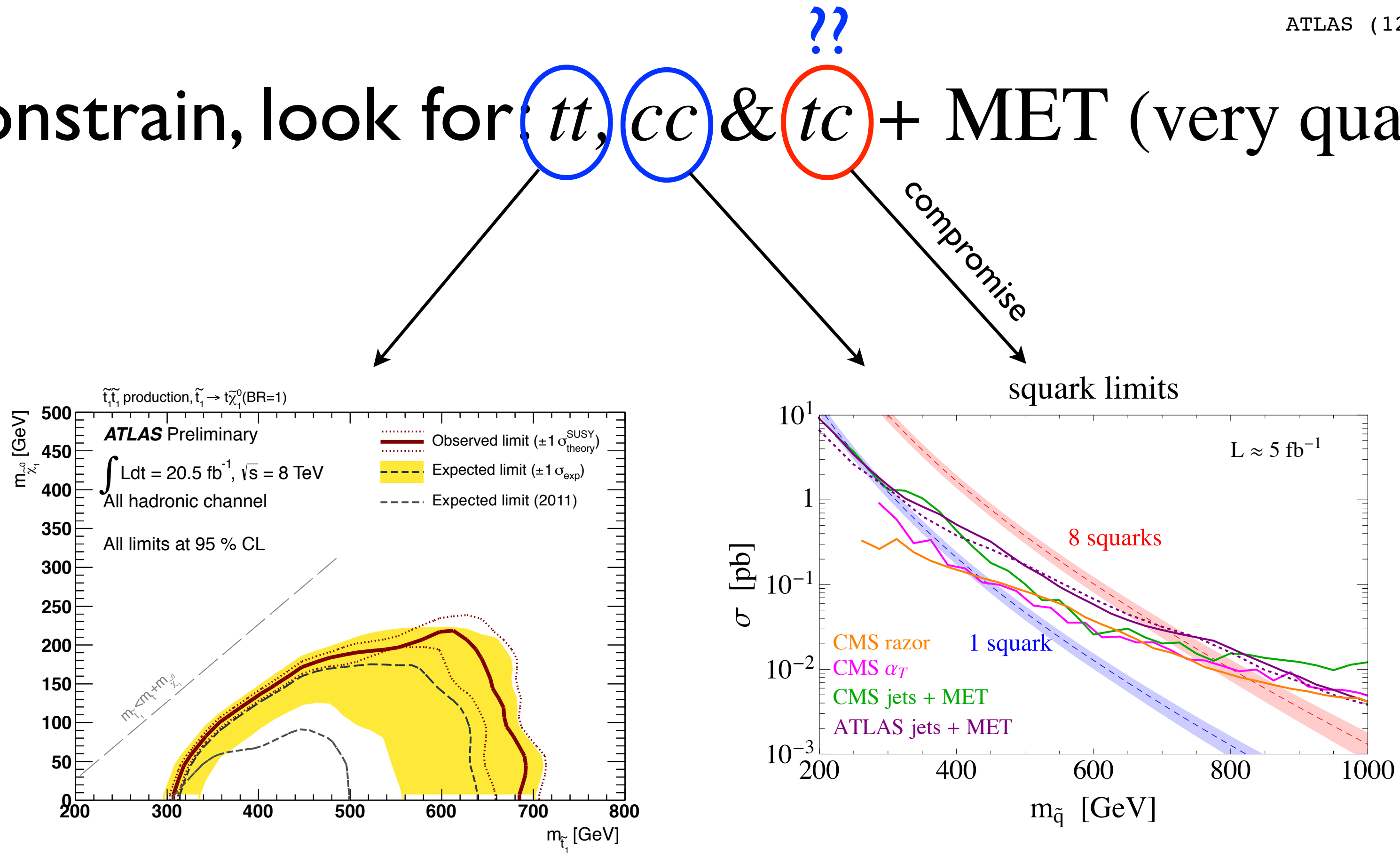

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Flavored naturalness, *preliminary* results

Blanke, Giudice, Paride, GP & Zupan (13)

- The relevant parameters to constrain are:

Define relative tuning measure: $\xi = \frac{\tilde{m}_1^2 c^2 + \tilde{m}_2^2 s^2}{m_0^2}$, $\quad (m_0 = 570\,\mathrm{GeV})$

stop,scharm like squark mass, $m_{1,2}$ & $C \equiv \cos\theta_{23}^{RR}$

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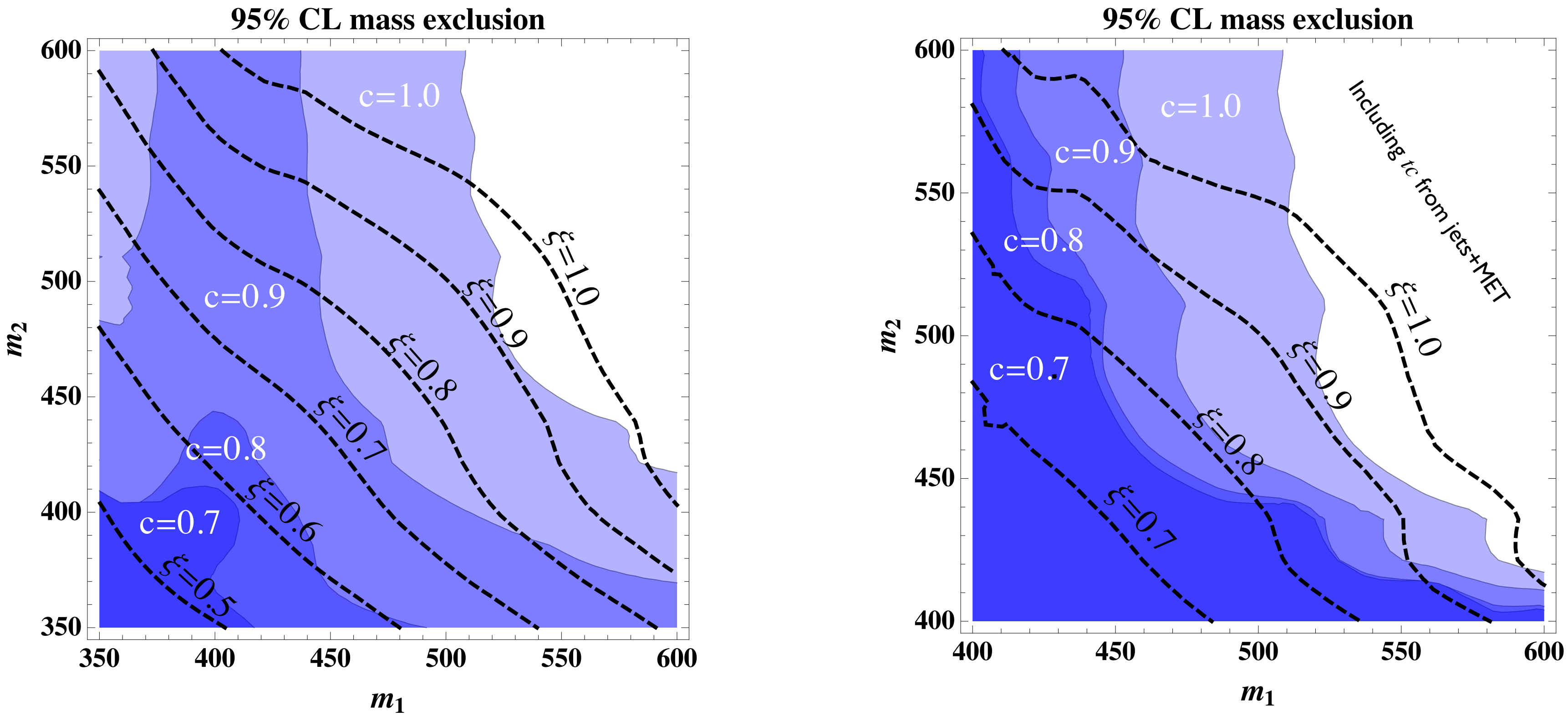
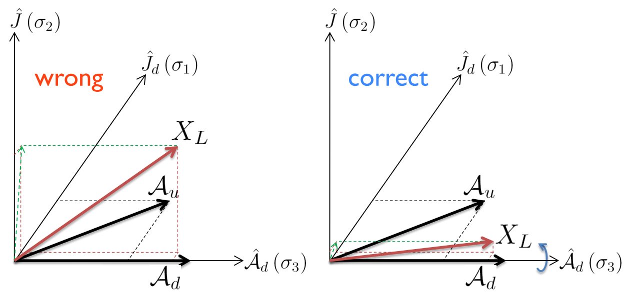


Can get $\xi \sim 0.5 - 0.8$ for $\theta_{23}^{RR} \sim 45^o$!

Word about: microscopic & macroscopic of alignment models

♦ Macro: successful alignment models are consistent with flavor constraints, due to smallness of physical CP violating phases.



Gedalia, Kamenik, Ligeti & GP (12);

Formalism: Gedalia, Mannelli & GP (10) x2

♦ Micro: Nir & Seiberg (93) showed existing proof; however, with ultra high mediation => induce universality & fine tuning.

Progress: flavor gauge mediation (Shadmi-Sabo (11)+5 more recent) => non-trivial (MFV) flavor structure & naturally obtain light scharm.

Galon, GP & Shadmi, to appear.

“the micro energy frontier”:
Physics of boosted top &
their partners

Resonances searches & emergence of top jets

(i) Strong dynamics inspired models (composite Higgs, Randall-Sundrum ...) => heavy Kaluza-Klein (KK) resonances, $m_{\rm KK} \gtrsim 1\,{\rm TeV}$.

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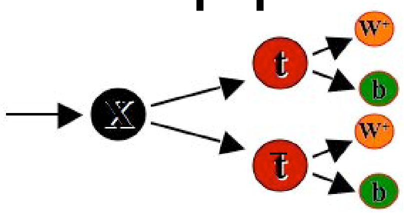

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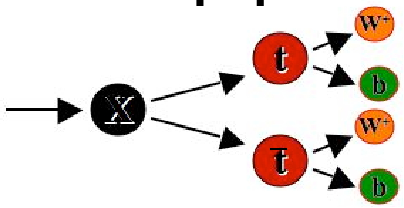

(iii) Since $m_t \ll m_{\rm KK}$ the outgoing tops are ultra-relativistic,

their products collimate => top jets.

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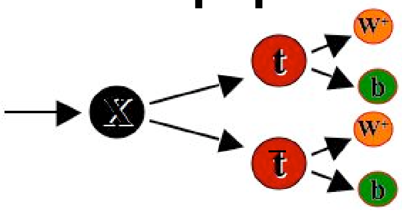

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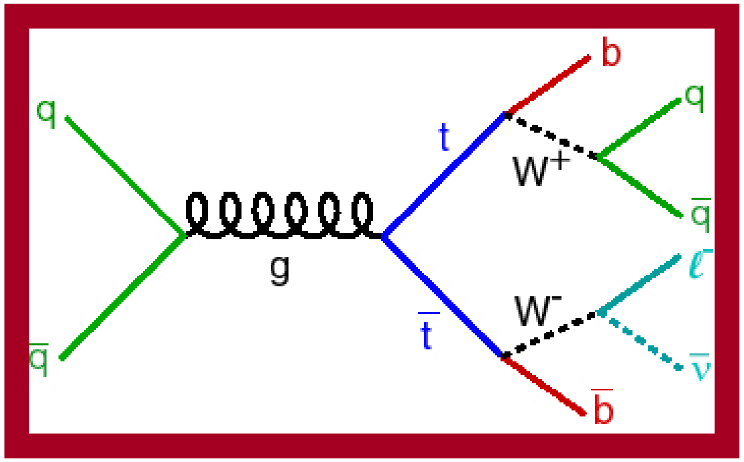

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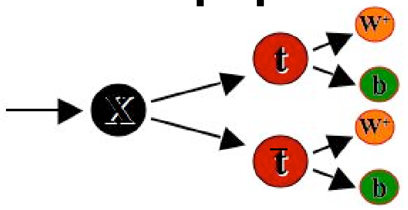

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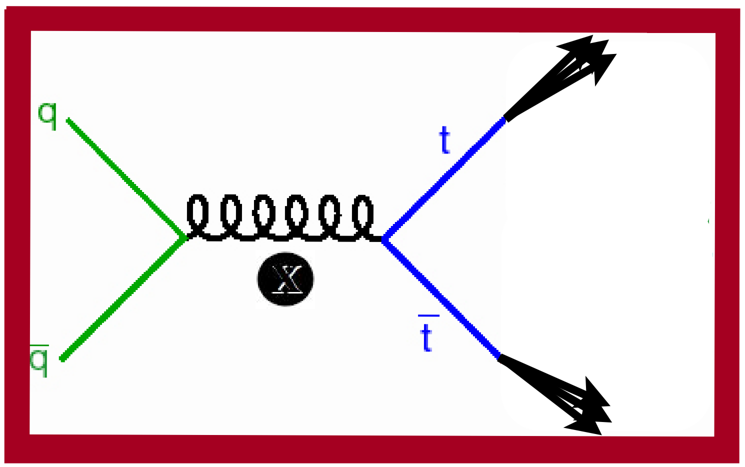

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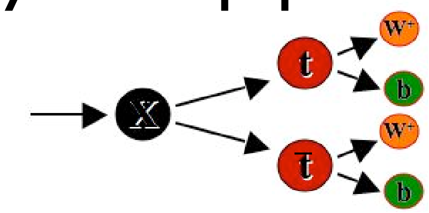

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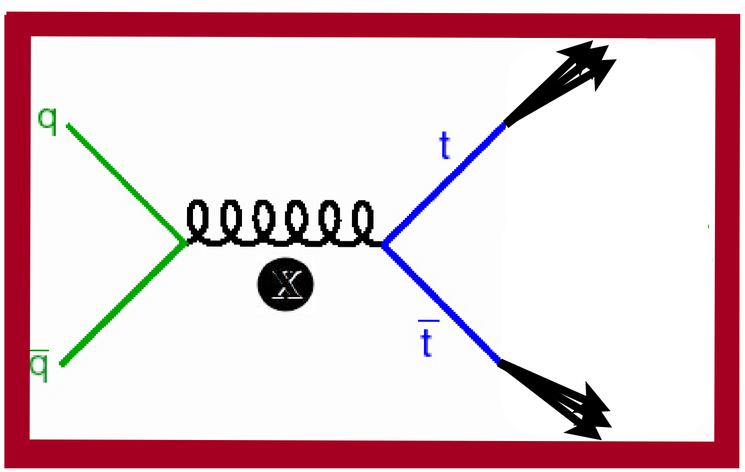
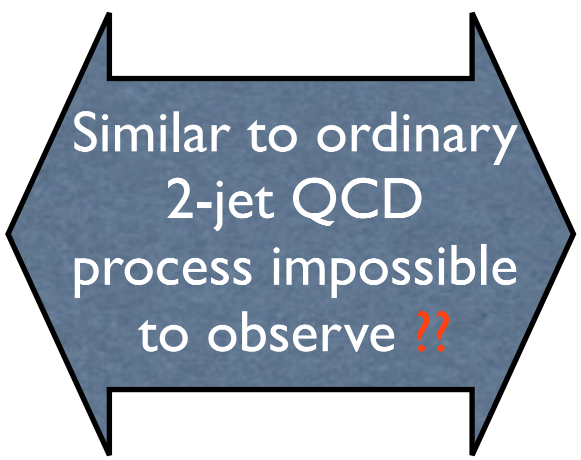
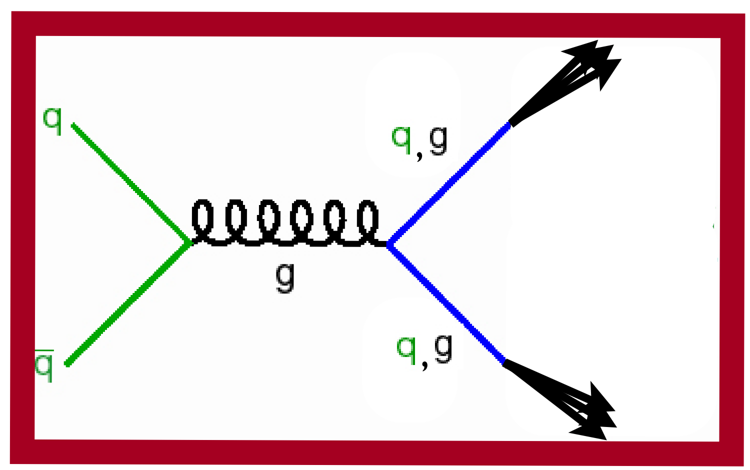
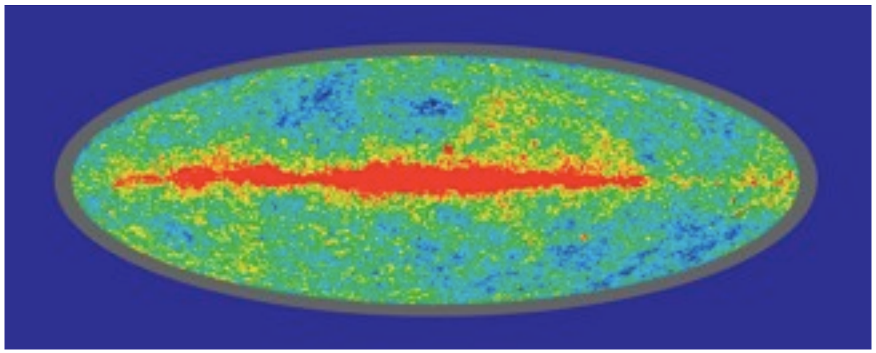
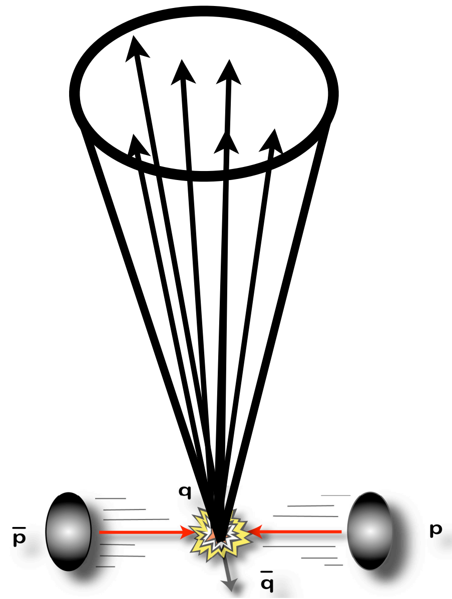




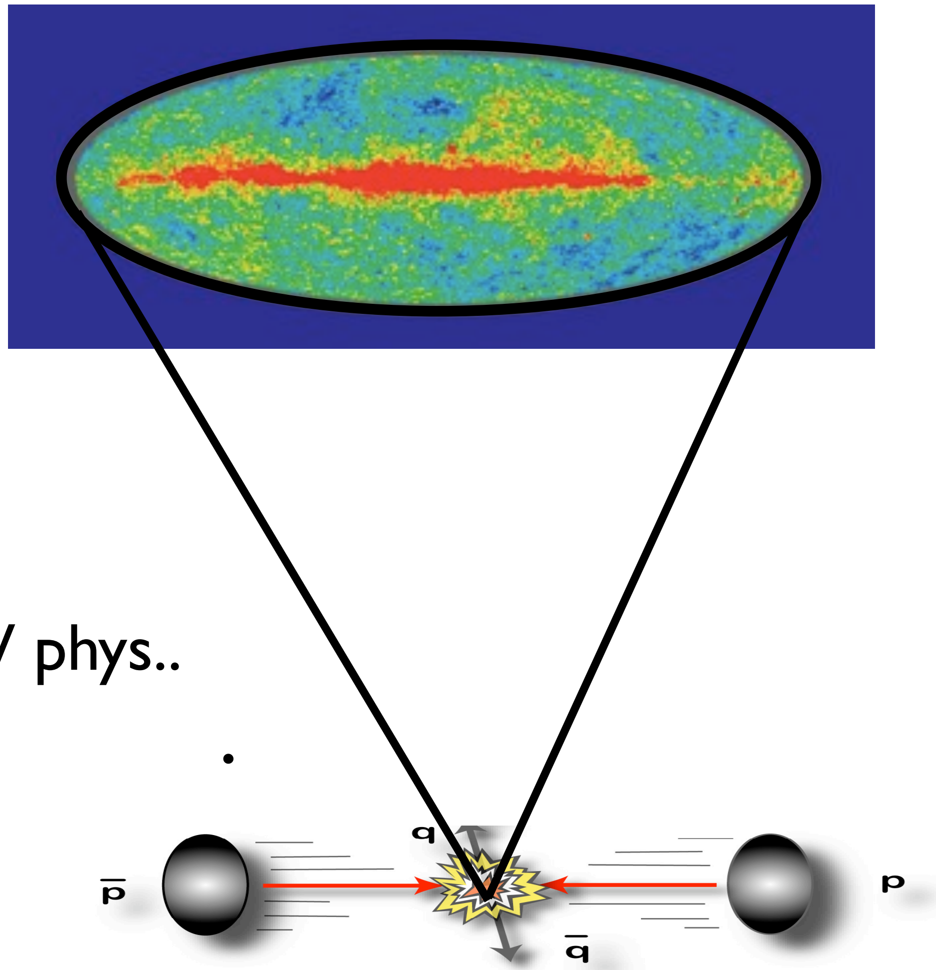


Need to distinguish between top & ordinary QCD jet





Need to understand the energy flow inside jet
jet shapes or jet substructure



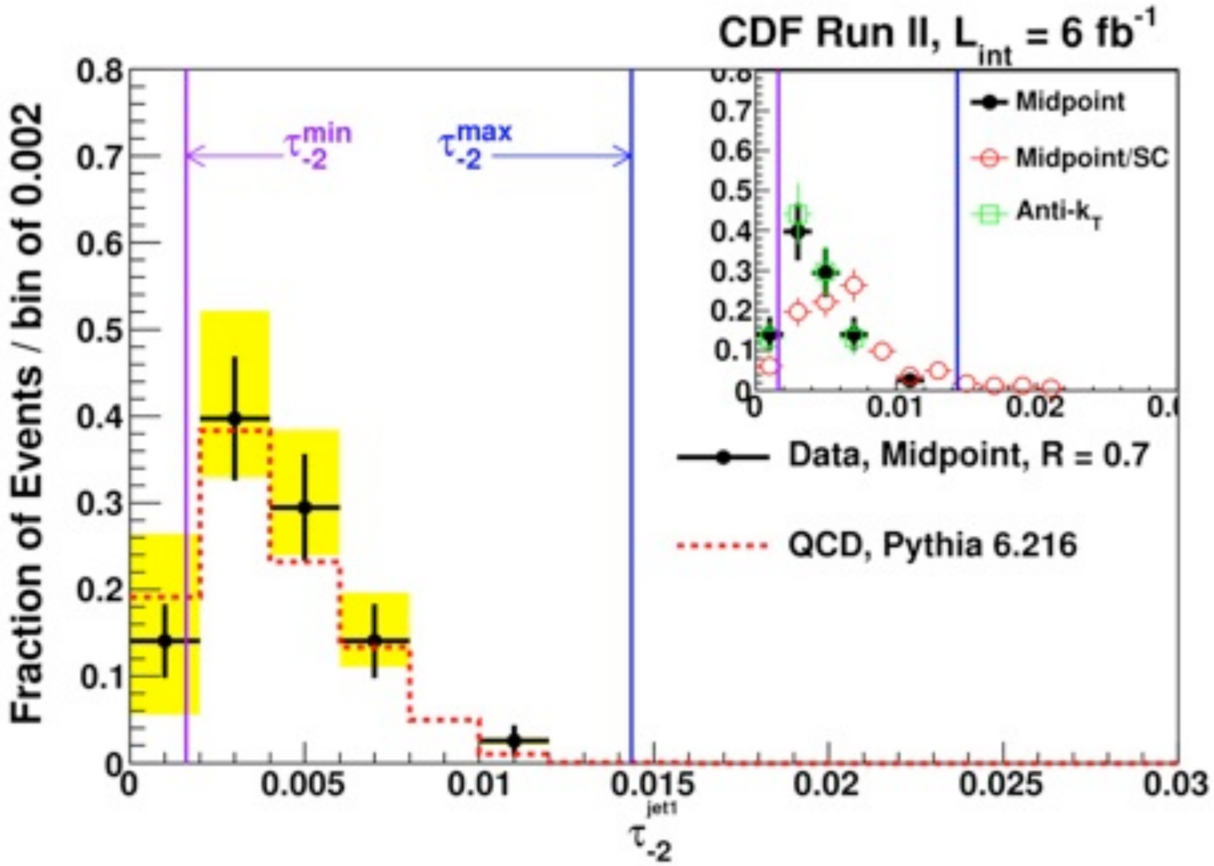
Still learning ...
Important in other direction, e.g. EW phys..

[Butterworth, Davison, Rubin & Salam (08)]

Boosted jets' angular distribution, angularity τ_{-2}

$$\frac{d\sigma}{d\theta} \to \frac{d\sigma}{d\tau_{-2}} \approx 1/\tau_{-2}\,,\ \tau_{-2}^{\min} = \left(\frac{m_J}{2E_J}\right)^3 \quad \left(\tau_{-2} \sim \sum_{i \in J} E_i \theta_i^4\right)$$

Almeida, et al. (10)



jets with mass ∈ (90, 120) GeV/c², p_T > 400 GeV/c

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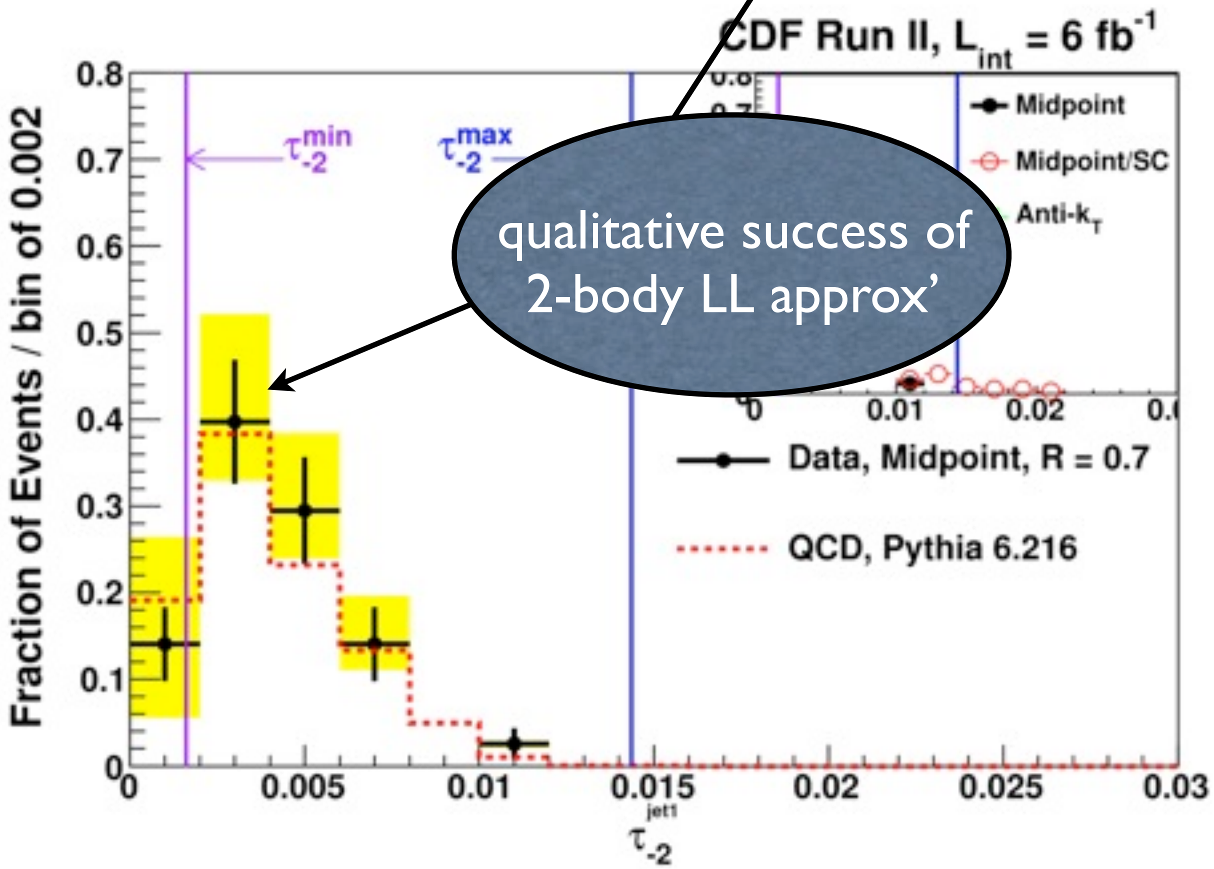

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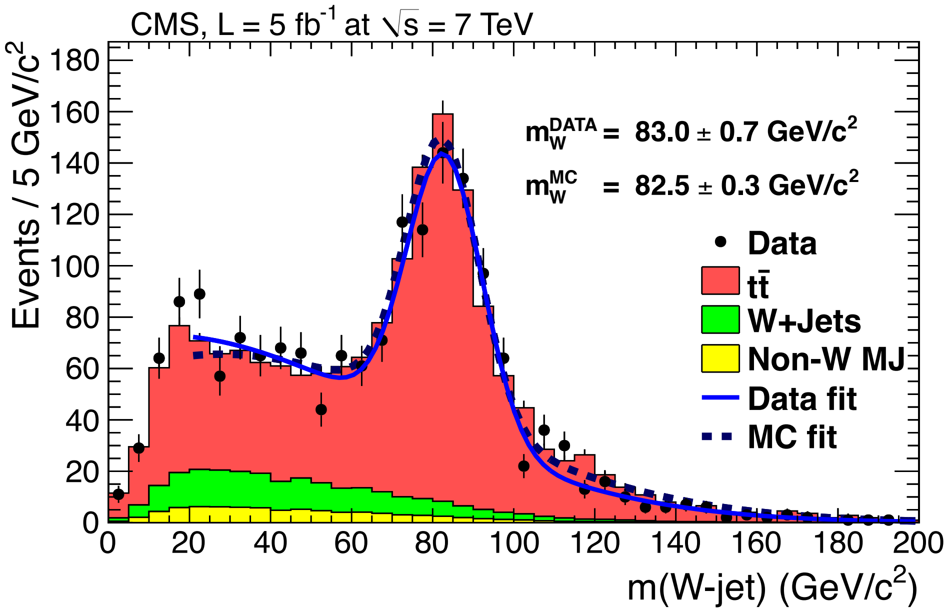
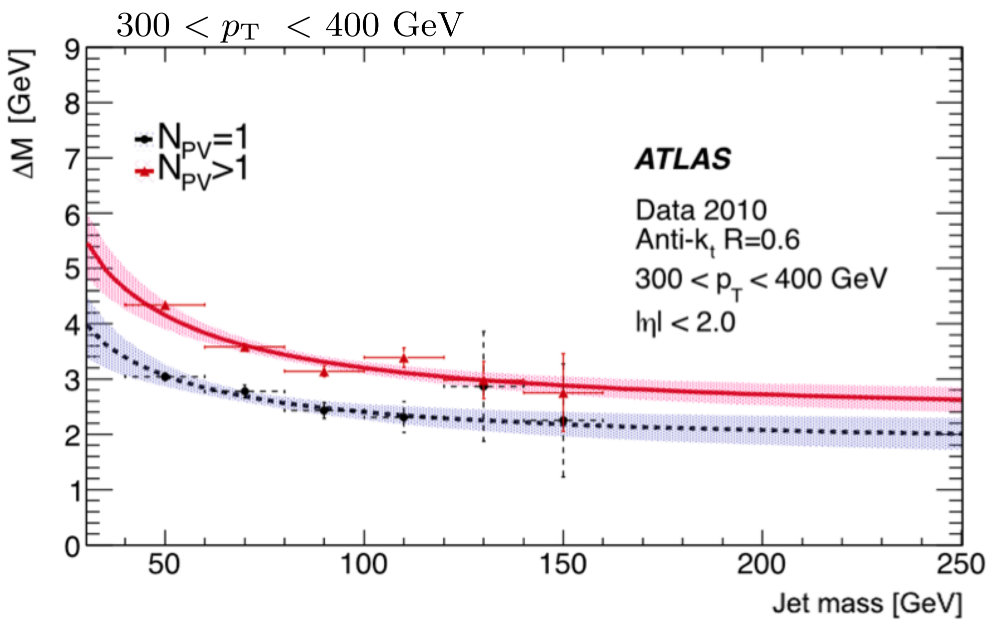
ATLAS & CMS

CMS, 1204.2488

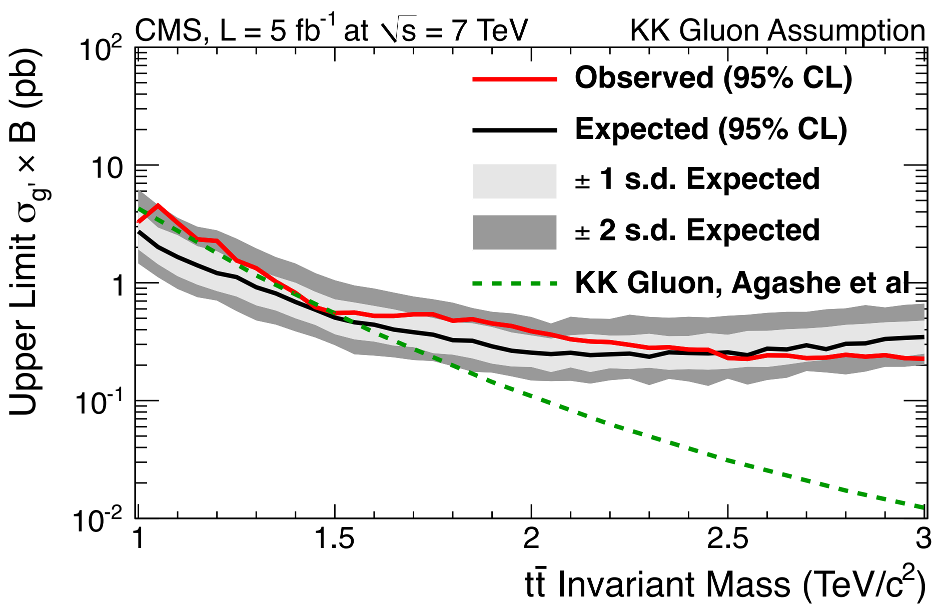


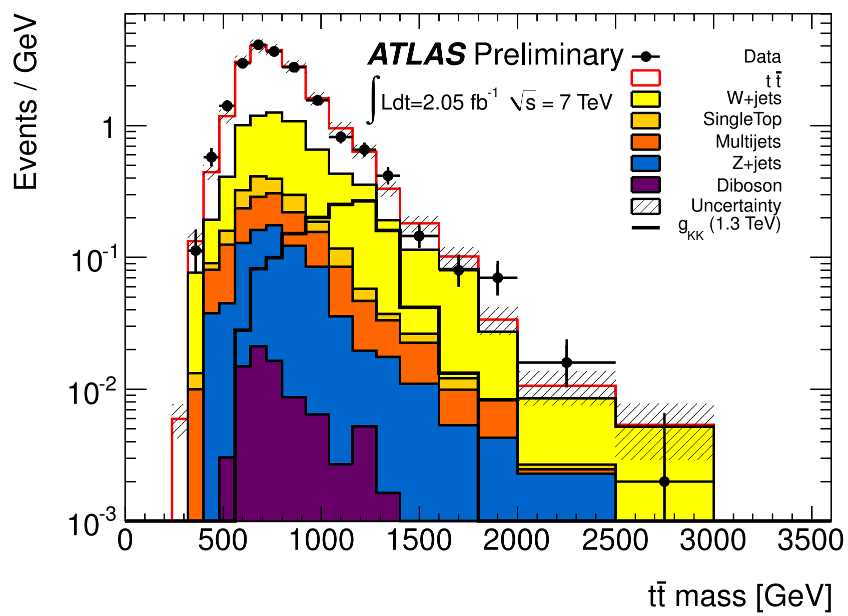
ATLAS,1206.5369



Left: The W tagging algorithm uses a jet “pruning” technique. Right: the size of the mass shift in anti-kt R = 0.6 jets \w & \wo pileup. For rev. see: Boost 2011 writeup,1201.0008.

$t\bar{t}$ resonance searches

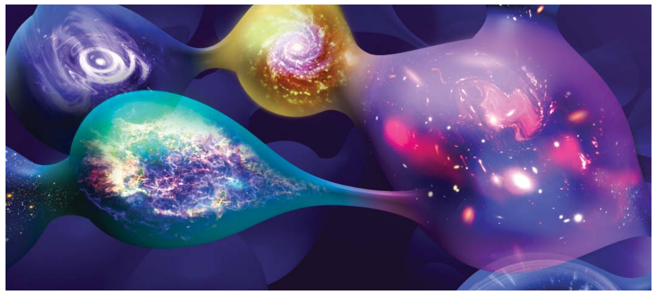


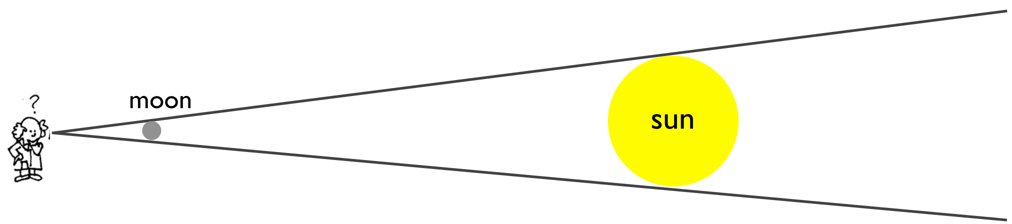


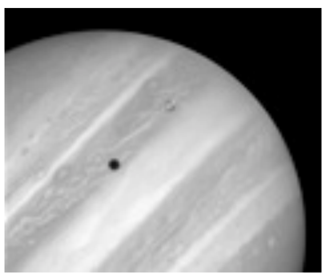
Bottom line: $m_X \gtrsim 2\,\mathrm{TeV}$ (still long way to go ...)

So far crazily reasonable, is there alternative paradigm?

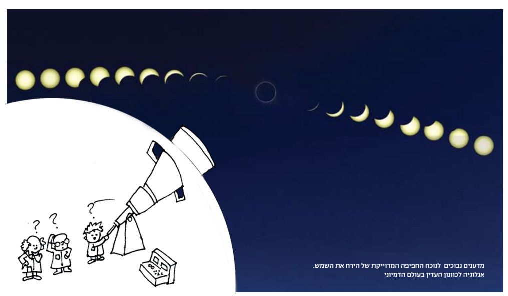
Potential implications for a 125GeV Higgs on flavor physics







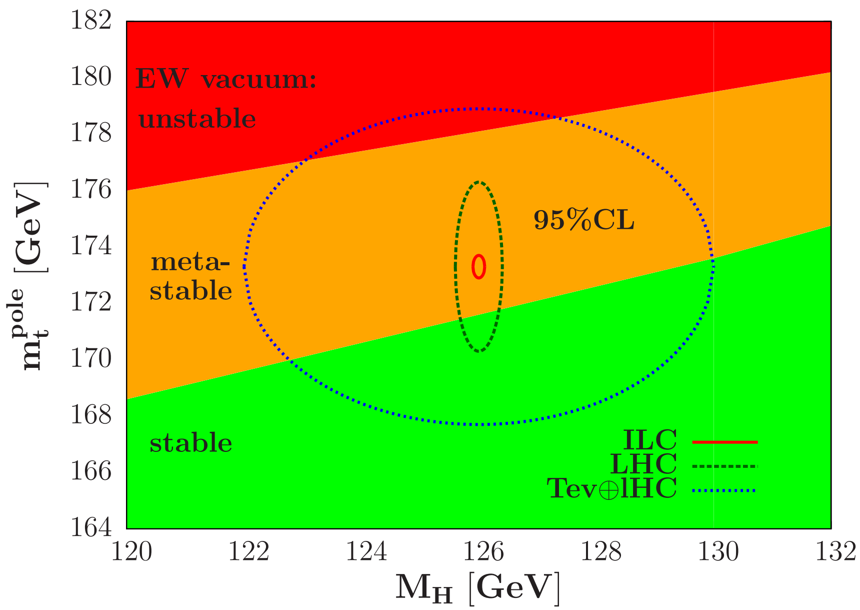
Jupiter's volcanic moon



Earth & our moon

125 GeV Higgs -> top is ~saturating metastability

$$y_t \lesssim 1.03 + 1.8 \cdot 10^{-3}\ (m_H - 125.5\,\mathrm{GeV})$$



Alekhin, Djouadi & Moch (12)

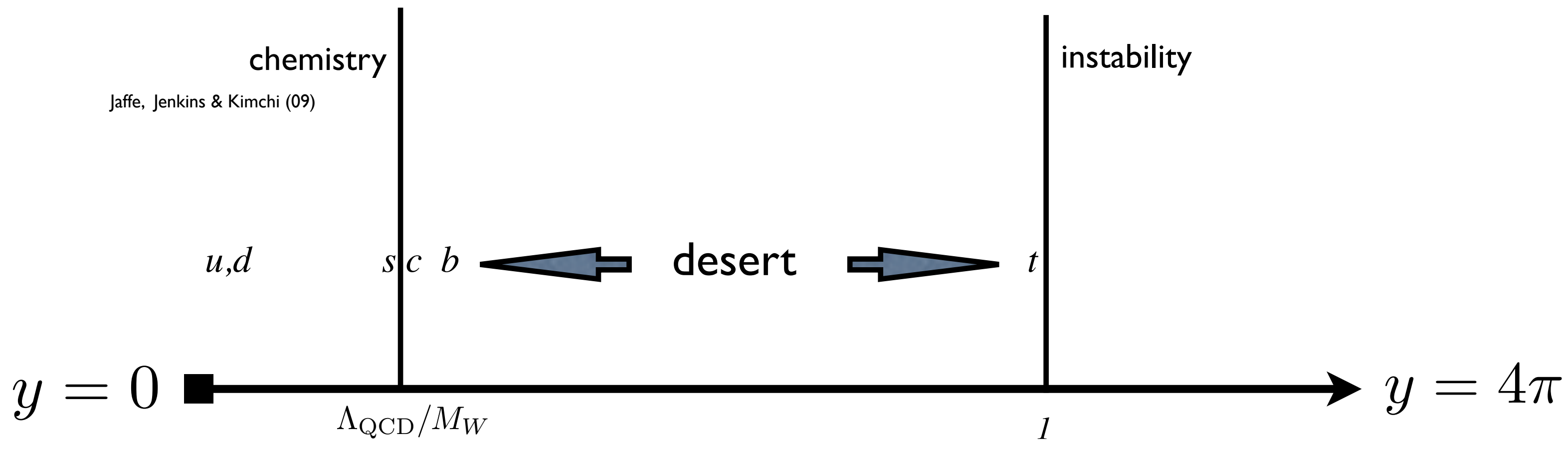
A raise of < 3% in top Yukawa => weakless universe!

A new coincidence, top *(H)* flavor puzzle?

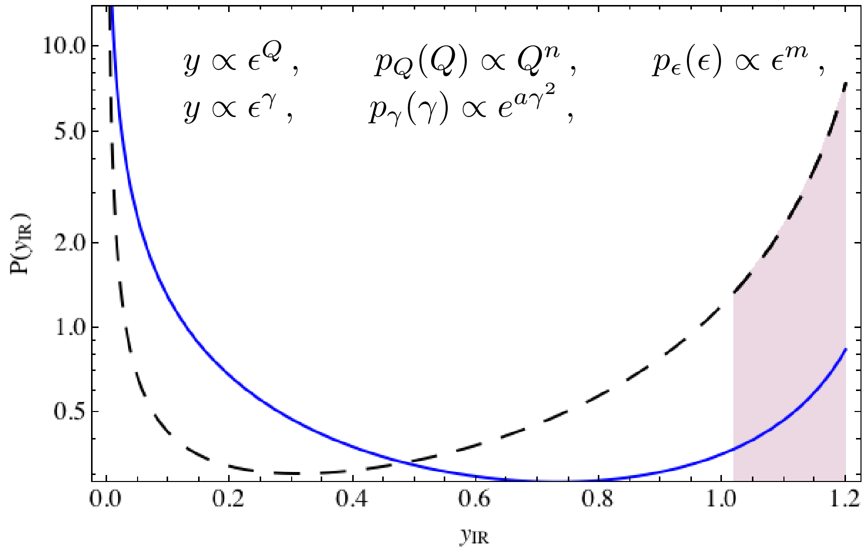
Getting a two-peaks distributions, ultra speculative solution to flavor puzzle (question more important than answer ...)

Giudice, GP & Soreq (12).

- Interpretation for quark spectrum, in view of new Higgs mass:



- RGE + “strong dynamics” inspired models can generate binary dist’.



Top Questions

♦ What is the origin of the various top-related asymmetries at the Tevatron? What can be further done (Tevatron/LHC/theory)?

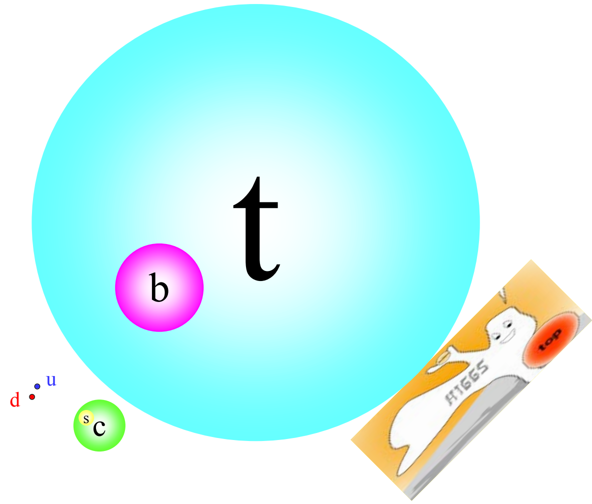
♦ Assuming naturalness: why haven't we found the top partners? Are they lightish/elusive? (what makes them elusive, sym'? flavor? more?) Heavyish? (how to improve bounds?)

♦ Is criticality of top Yukawa-Higgs mass coincidence?

Is the electroweak symmetry breaking scale finely tuned?

Top Quark Theory

The New Physics Searches Frontier



Thank you

Gilad Perez

CERN & Weizmann Inst.

Backups

Composite light quarks & pseudo-NGB (pNGB) Higgs

Composite light quarks

♦ Custodial sym' for *Z->bb* => allow for composite light

Agashe, Contino, Da Rold & Pomarol (06)

quarks \wo tension with precision tests.

Delaunay, Gedalia, Lee, GP & Ponton x 2 (10) Redi & Weiler (11)

♦ Drastic change to pheno': large production rates, top forward-backward asymmetry, non-standard flavor signals ...

Delaunay, Gedalia, Lee, GP & Ponton x 2 (10) Redi & Weiler (11); Da Rold, Delaunay, Grojean & GP; Weiler CKM12 talk (12); Atre, Chala & Santiago (13).

And, non-standard modification to Higgs decays as followed.

The argument: why composite light flavors lead to significant modifications of pNGB Higgs rates, unlike composite tops

Falkowski (07); Low & Vichi (10); Azatov & Galloway (11)

(i) t-partner contributions cancel due to "Nelson-Barr" structure of mass matrix => easy to see using low energy Higgs theorems (LEHTs).

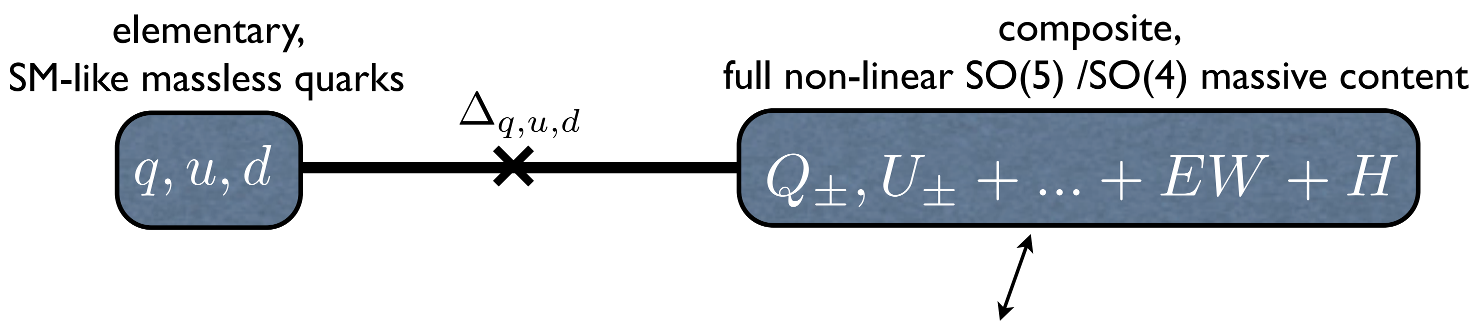
Shifman, Vainshtein, Voloshin & Zakharov (79); Kniehl & Spira (95).

(ii) Repeat ex. using effective field theory (EFT).

(iii) Modified LHC Higgs Physics from composite light quarks.

pNGB Higgs couplings: t-partner cancellation effects (LEHTs)

- Structure of minimal composite Higgs model SO(5)/SO(4): Agashe, Contino & Pomarol (05).



$$\text{Typically (anarchy): } \Delta_i \ll \Delta_{q^3,u^3} \sim M\,, \quad i = 1,2\,.$$

- t-partner cancellation via the LEHTs: Falkowski (07); Low & Vichi (10); Azatov & Galloway (11); Gillioz et al. (12).

(i) Consider a mass matrix of n heavy fermion states, $m_f \gg m_h/2$.

$$\sigma_{gg\to h} = \sigma^{\rm SM}_{gg\to h} \left| \sum_i \frac{Y_{ii} v}{M_i} \right|^2 ; \qquad \sum_i \frac{Y_{ii}}{M_i} = \frac{\partial \log(\det M)}{\partial v}$$

(ii) "Corollary": a mass matrix for which $\det \mathcal{M} = F(v/f) \times P(Y, M, f)$ $F(0) = 0,$ $\Longrightarrow$ $\boxed{\sigma_{gg\to h} = \sigma^{\rm SM}_{gg\to h}}$

where $F(0) = 0$, f is the Higgs decay constant of pNGB models, and Y and M stand for the heavy fermion Yukawa couplings and masses respectively, Gillioz et al. (12).

Holds for broad class of models, 2-site, composite Higgs ...

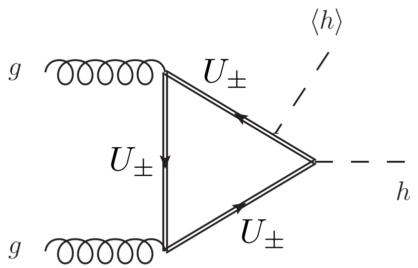
$$M_u = \begin{pmatrix} y_u^{00} v & 0 & y_u^{01} v \\ y_u^{10} v & m & y_u^{11} v \\ 0 & y_u^- v & m \end{pmatrix}$$

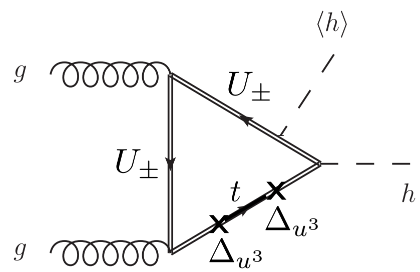
Delaunay, Kamenik, GP & Randall (12); Perelestein, talk at ASPEN winter workshop (13).

Cancellation of t-partners modification of Higgs rates, EFT:

- t-partners effect Higgs rates in 2 ways in the EFT:

(i) heavy vector-like t-partners run in the loop generating $H^\dagger H G^{\mu\nu} G_{\mu\nu}$:

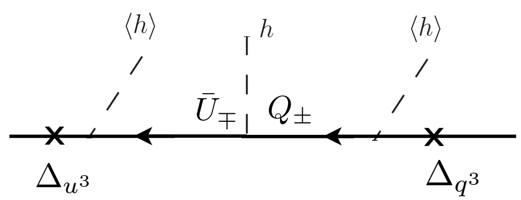


$\propto -vY^2/M^2$ **+**


$\propto vY^2/M^2 \times \Delta_{u^3}^2/M^2$

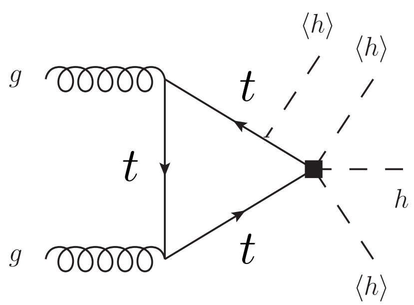
(ii) t-partner mix with the top-like SM fields, modifying their Yukawa:

1. integrating out heavy partners:



$\propto m_t \times v\, Y^2/M^2$

2. substituting into the loop to obtain the amplitude:



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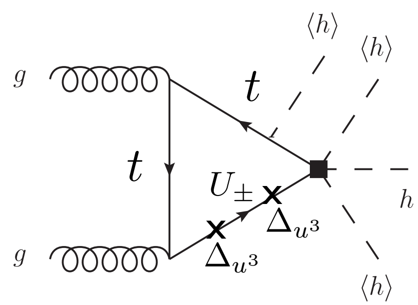
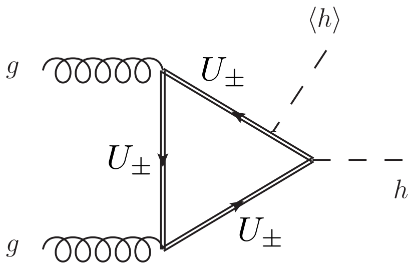


$\propto -vY^2/M^2 \times \Delta_{u^3}^2/M^2$

The cancellation of t-partners effects, adding all together



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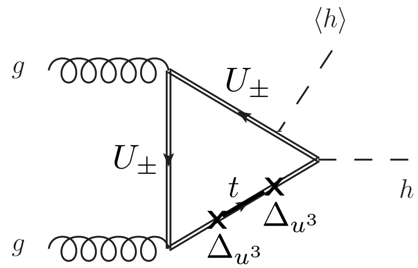

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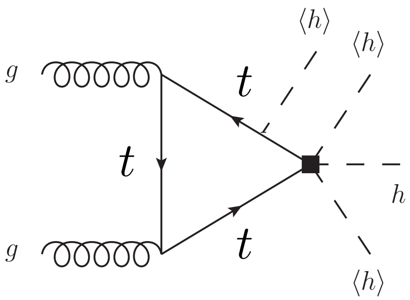

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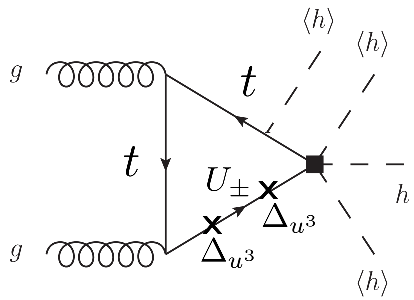
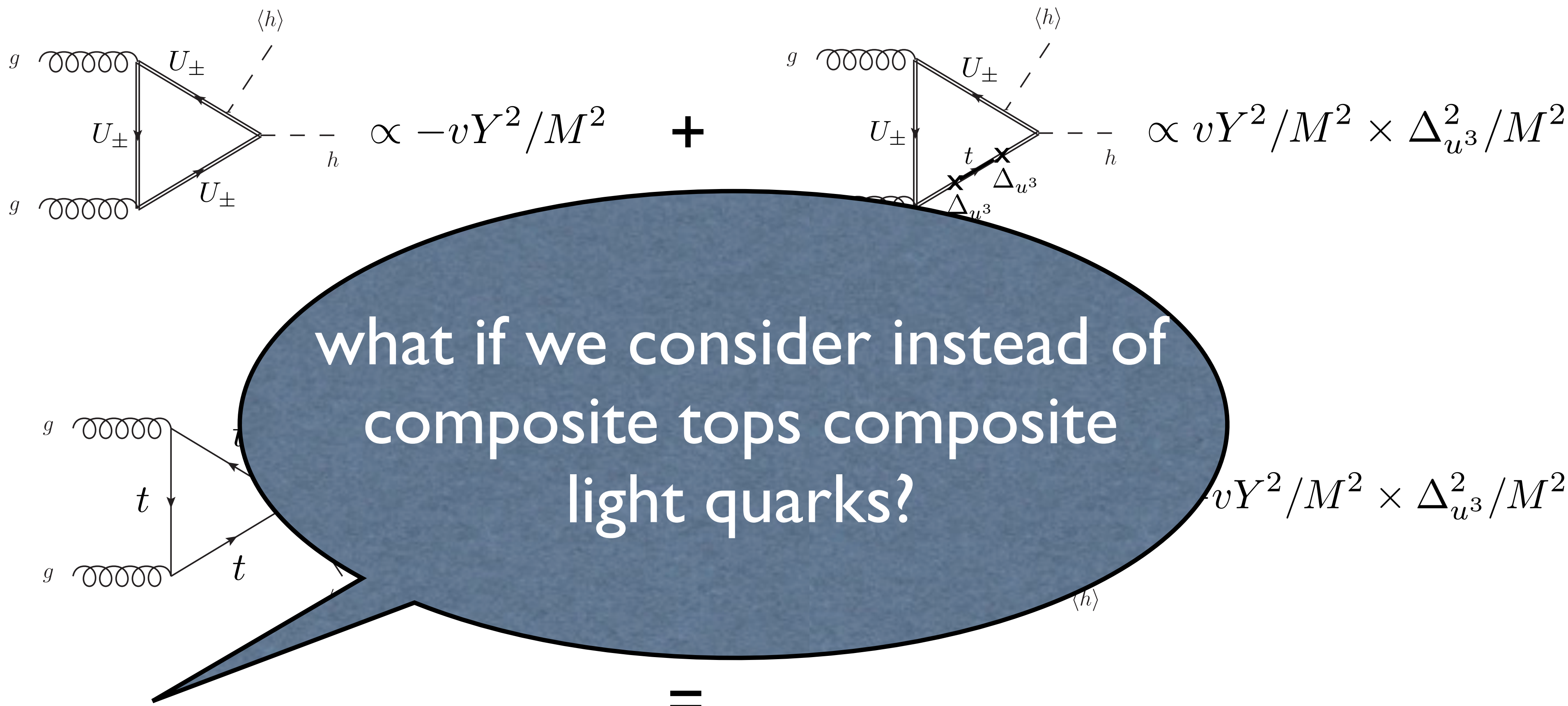


$\propto -vY^2/M^2 \times \Delta_{u^3}^2/M^2$

=

0

The cancellation of t-partners effects, adding all together



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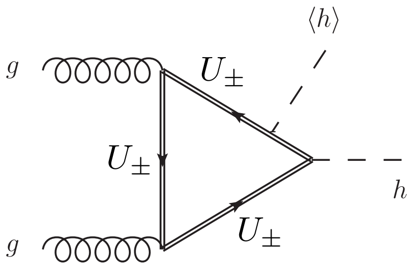
Cancellation for light composite quarks is ineffective!

Delaunay, Grojean & GP (13).



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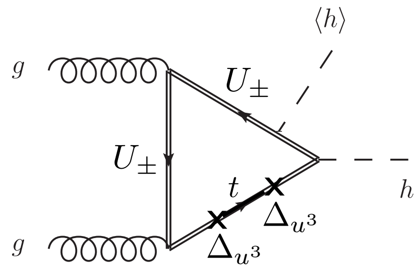

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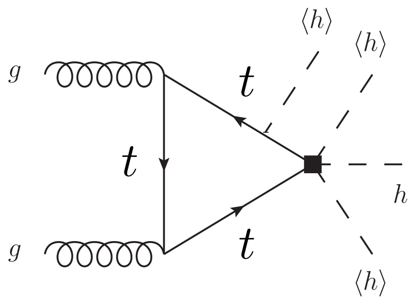

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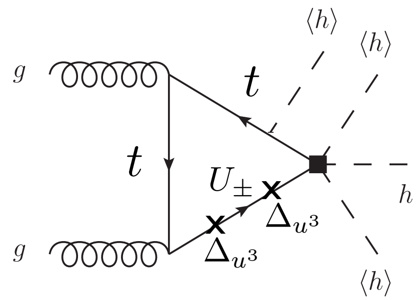

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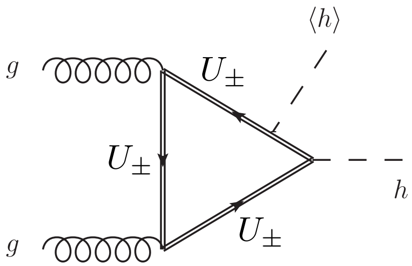

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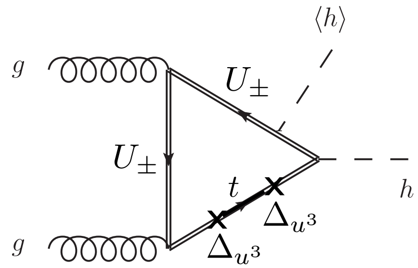

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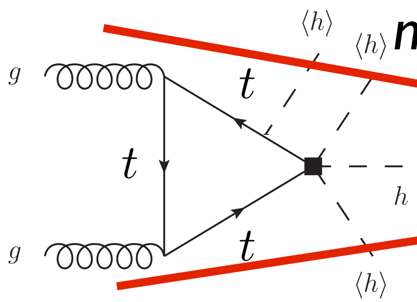
+

negligible when light quark runs in the loop



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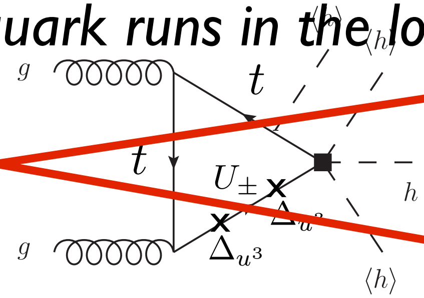

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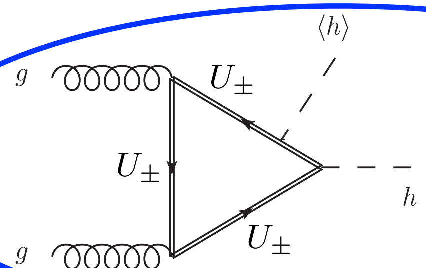
Delaunay, Grojean & GP (13).

huge contribution, generic vector like theory Goertz, Haisch & Neubert; Carena, et al. (12)



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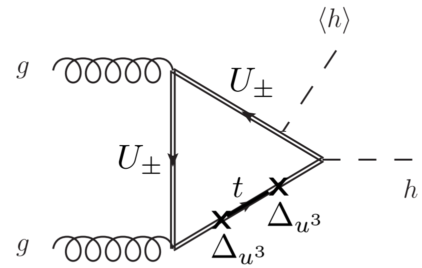

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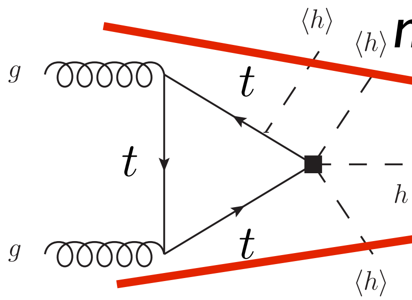

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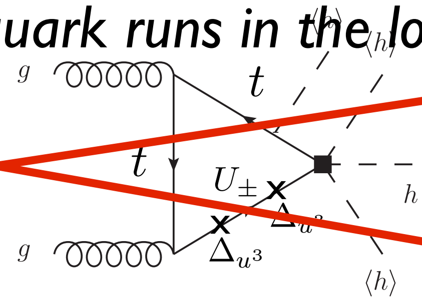

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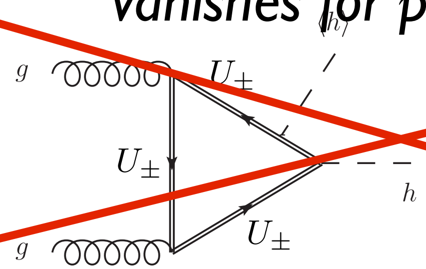
=

??

Cancellation for light composite quarks is ineffective!

Delaunay, Grojean & GP.

vanishes for pNGB Higgs



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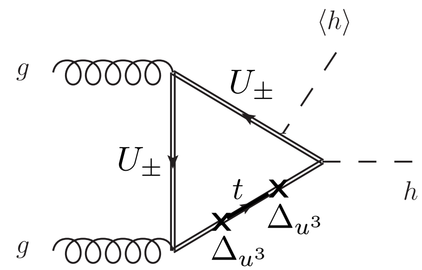

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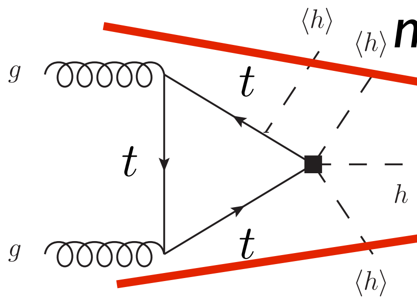

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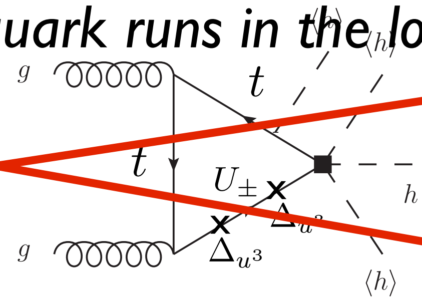

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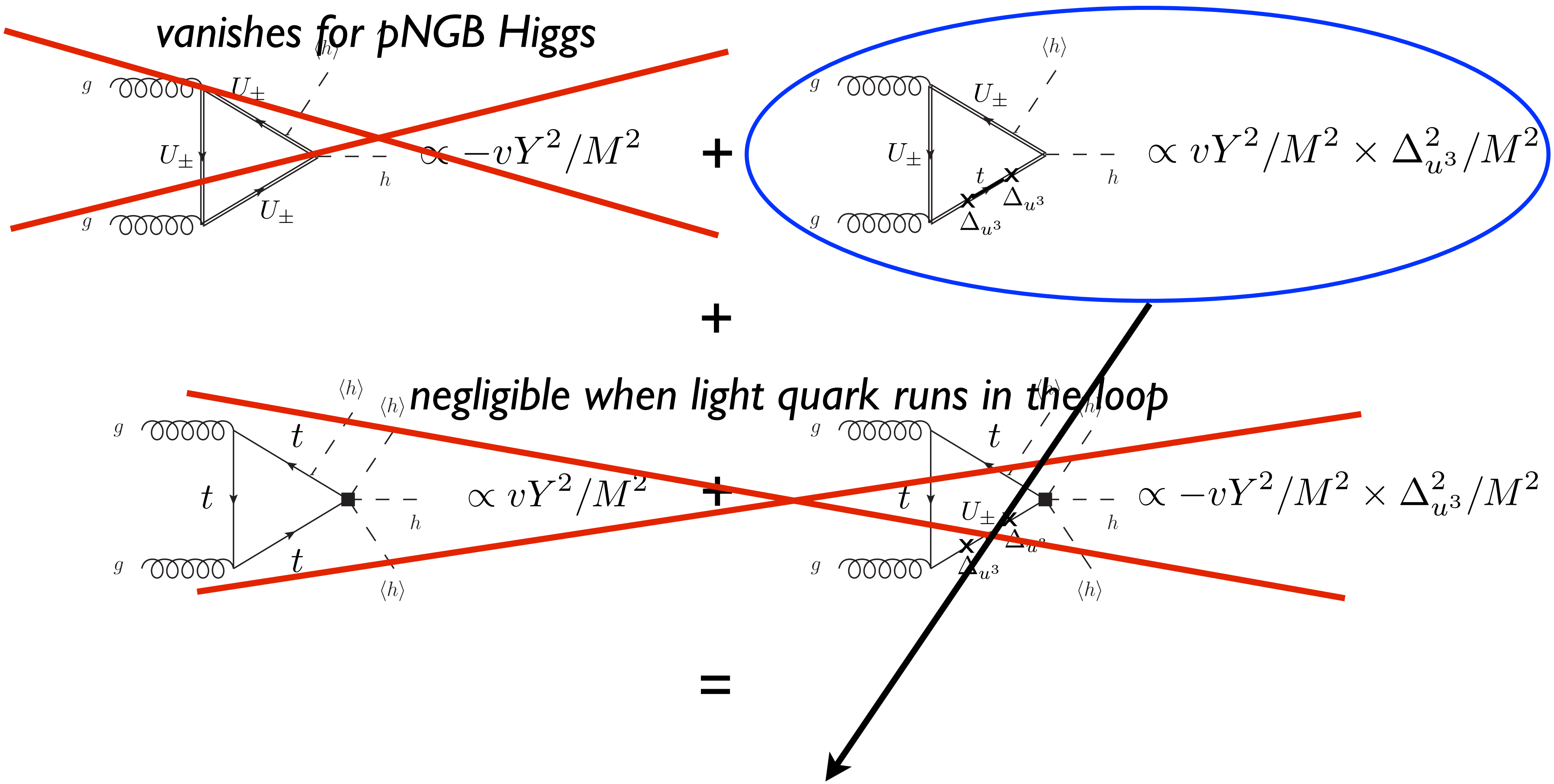
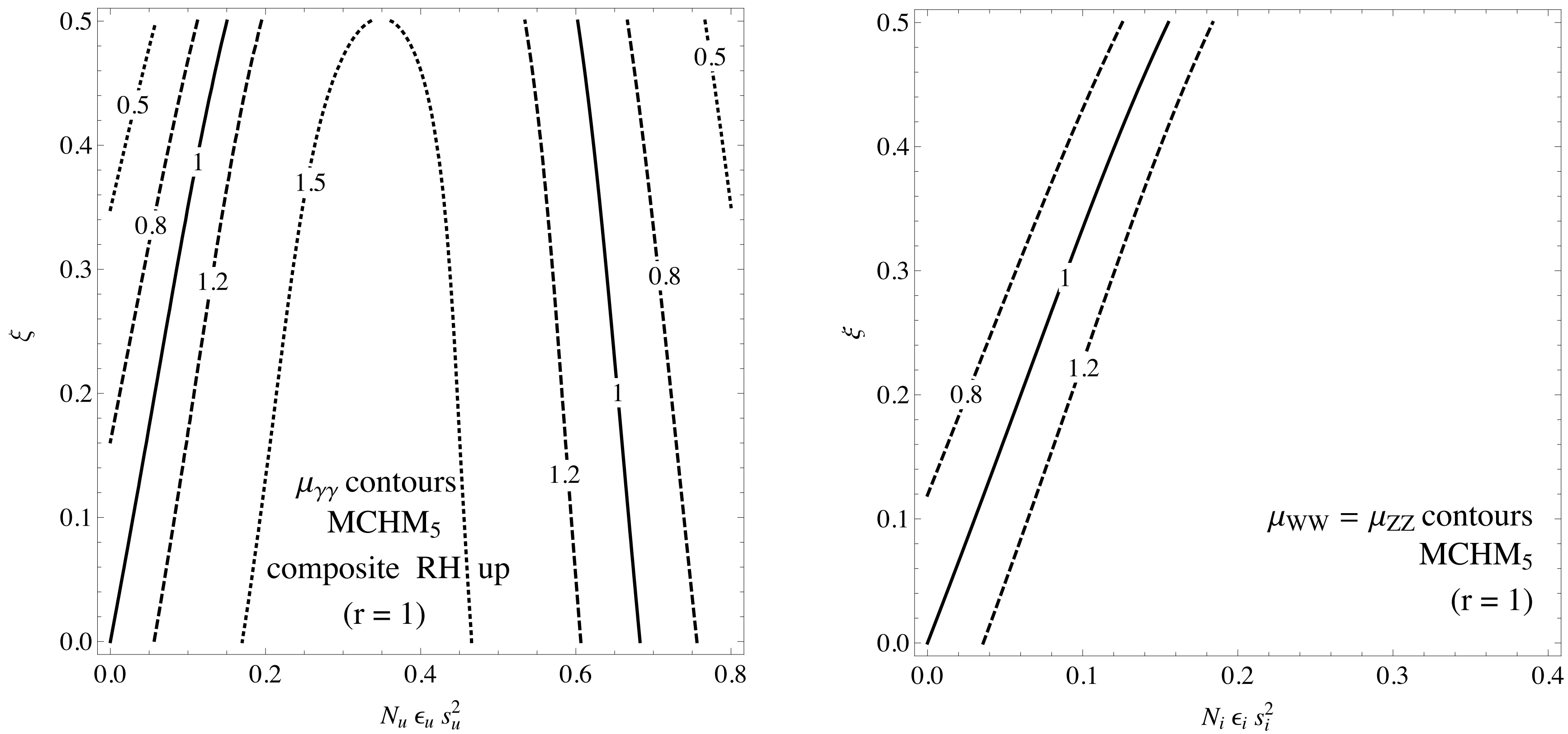


Sizable corrections for composite light quarks!

Composite light quarks & pseudo Goldstone boson Higgs

Delaunay, Grojean & GP,.

$$\mu_i = \frac{\sum_j \sigma_{j\to h} \times \mathrm{Br}_{h\to i}}{\sum_j \sigma^{\rm SM}_{j\to h} \times \mathrm{Br}^{\rm SM}_{h\to i}}\,, \qquad R_{gg} \equiv \sigma_{gg\to h}/\sigma^{\rm SM}_{gg\to h}$$



s_R: level of compositeness $\quad \xi = v^2/f^2, \quad \epsilon_i \equiv (Y_i v/M_i)^2 \quad r = g_\Psi/Y \quad g_\Psi \equiv M/f$

Composite light quarks & pseudo Goldstone boson Higgs

...ian & GP.

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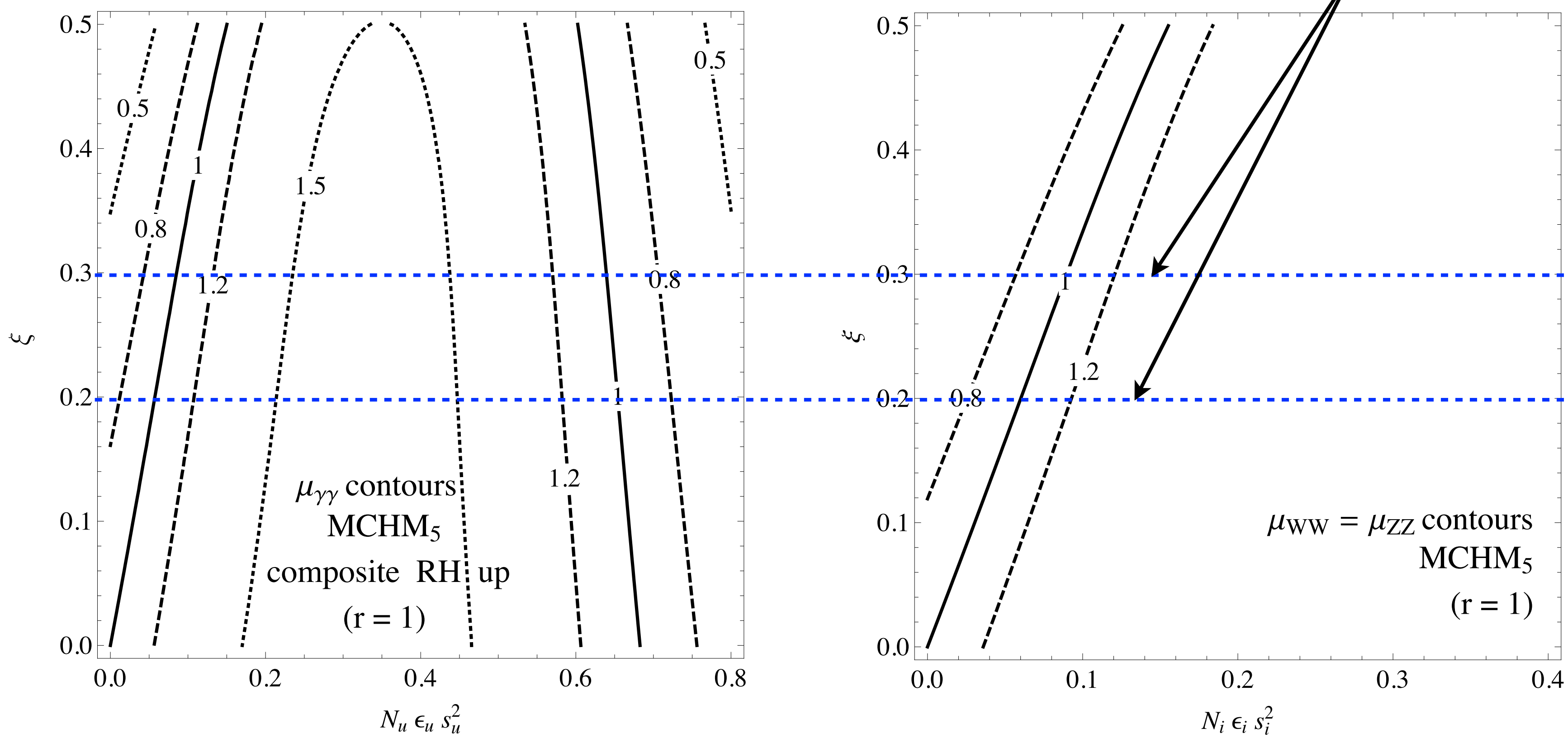
Interesting theoretically



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Composite light quarks & pseudo Goldstone boson Higgs

...an & GP (13)

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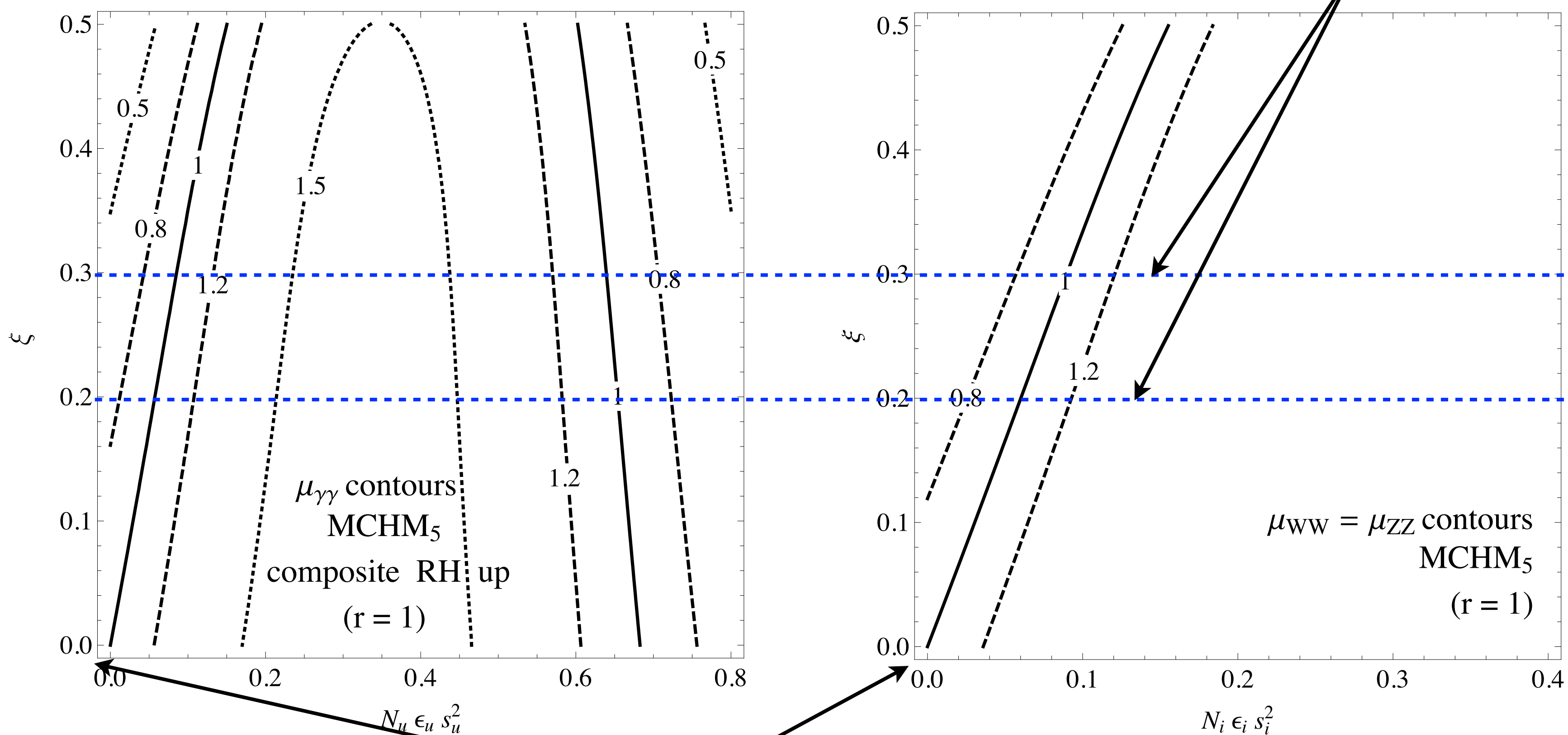
Interesting theoretically



s_R: level of compositeness $\xi = v^2/f^2$ $\quad \epsilon_i = (Y_i v/M_i)^2$ $\quad r = g_\Psi/Y$ $\quad g_\Psi \equiv M/f$

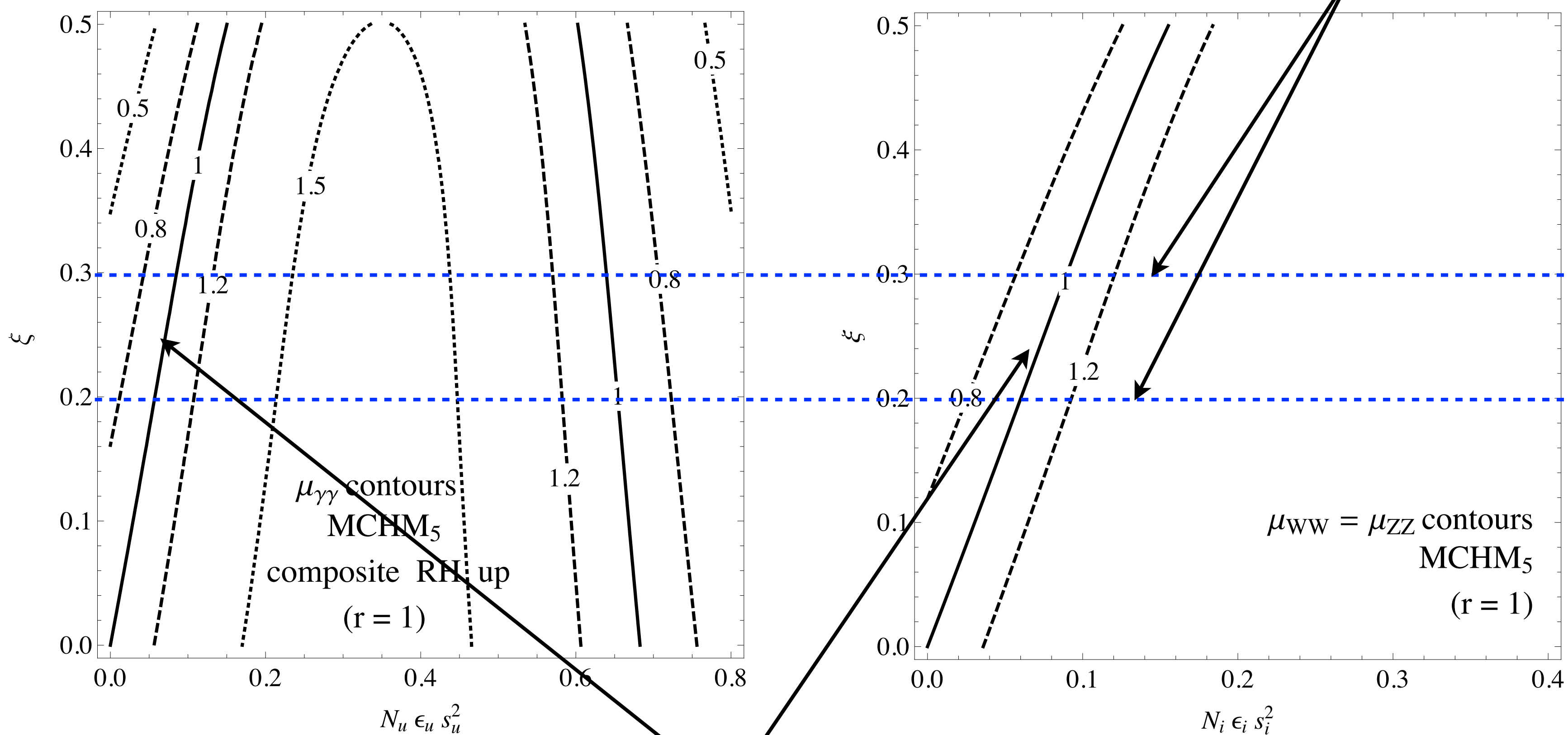
\wo mixing favorable region
of Higgs "non-linearity" excluded.

Composite light quarks & pseudo Goldstone boson Higgs

...ian & GP, to appear.

$$\mu_i = \frac{\sum_j \sigma_{j\to h} \times \mathrm{Br}_{h\to i}}{\sum_j \sigma_{j\to h}^{\mathrm{SM}} \times \mathrm{Br}_{h\to i}^{\mathrm{SM}}}, \qquad R_{gg} \equiv \sigma_{gg\to h}/\sigma_{g...}^{\mathrm{SM}}$$

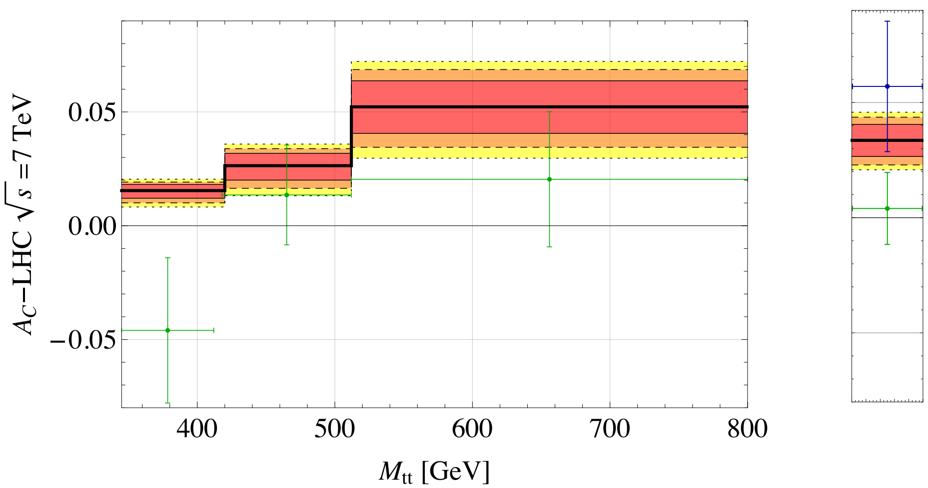
Interesting theoretically

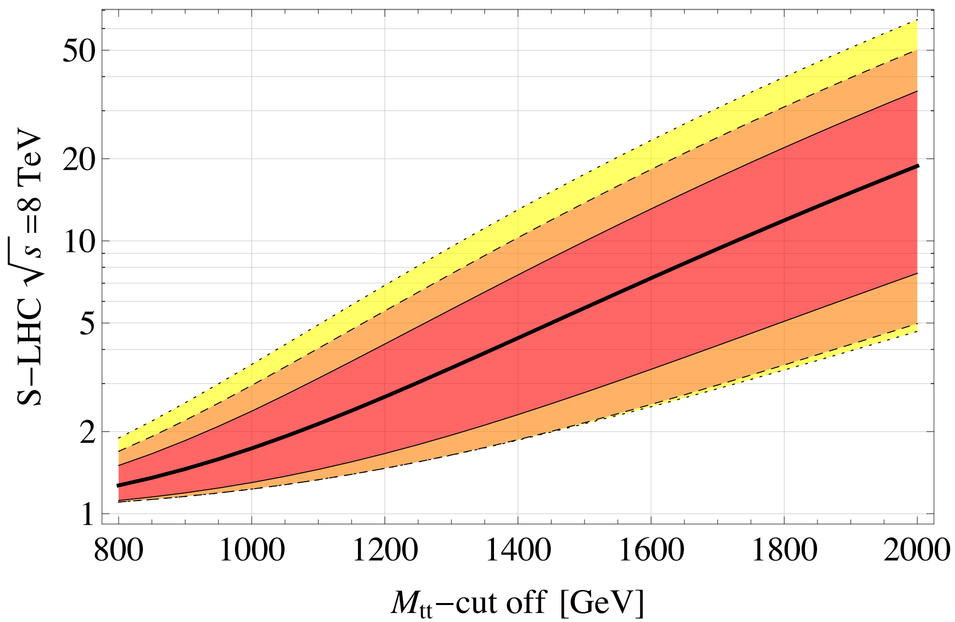


s_R: level of compositeness ... v^2/f^2 $\epsilon_i \equiv (Y_i v/M_i)^2$ $r = g_\Psi/Y$ $g_\Psi \equiv M/f$

with composite light quarks a reasonable allowed region

EFT constraints from charge asym' & enhancement of differential mass distribution





Delaunay, Gedalia, Hochberg & Soreq (12).

What is the fine tuning problem (personal view)?

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Coincidence of 1:10^2 - moon subtends an angle of ~ **0.52°** while sun of ~ **0.53°**.

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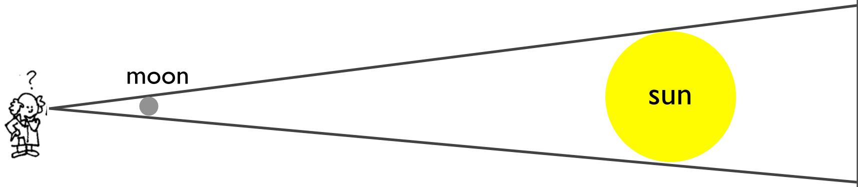
Coincidence of $1:10^2$ - moon subtends an angle of ~ **0.52°** while sun of ~ **0.53°**.

Imagine that they were equal to $1:10^{32}$!



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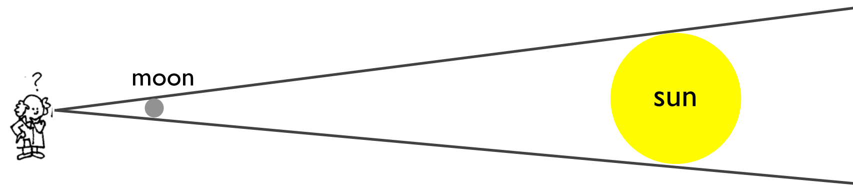
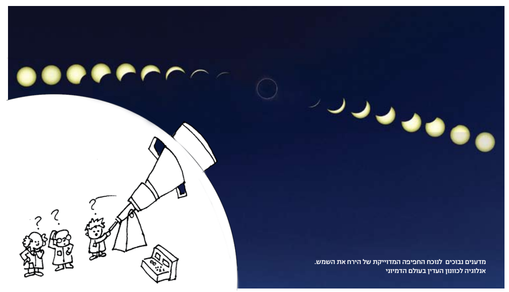


It would raise two questions:



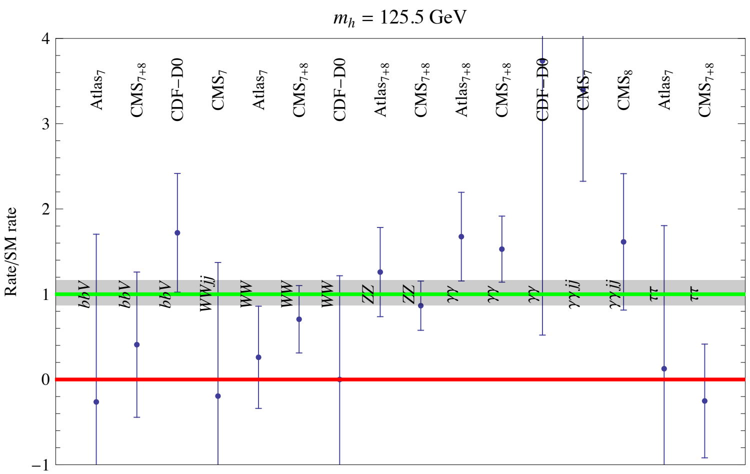
(i) What set their precise distance? <=> Tuning problem.

why is $\delta\theta/\theta_{\rm max} \sim 10^{-32} \ll 1\,?$ ⟷ why is $\left(m^2_{H,W}/m^2_{\rm Pl}\right)_{\rm obs} \sim 10^{-32} \ll 1\,?$

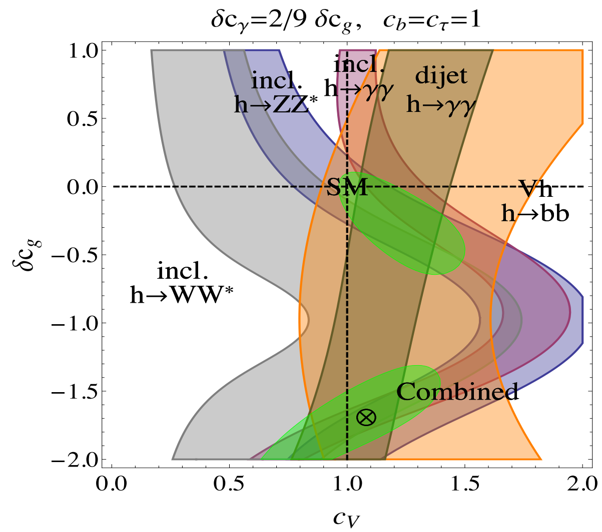
Indirect searches via Higgs precision tests (HPTs)

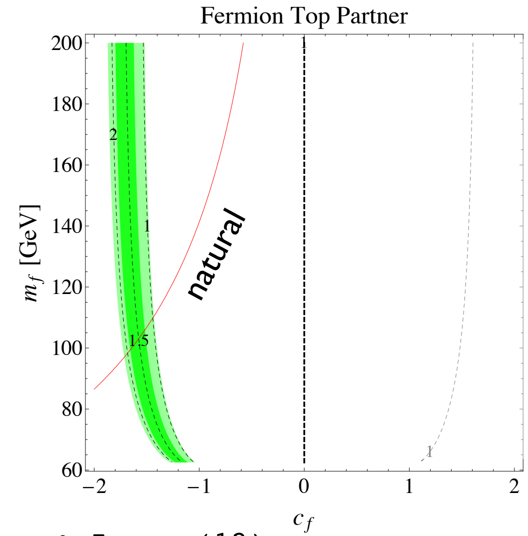
Beginning of HPTs era, sensitive to partners mass & couplings:

$$\frac{\text{Measured Higgs rate}}{\text{SM prediction}} = 1.02 \pm 0.15$$ Giardino, et al. (5/7)



Giardino, Kannike, Raidal & Strumia (12)





Carmi, Falkowski, Kuflik, Volansky & Zupan (12).

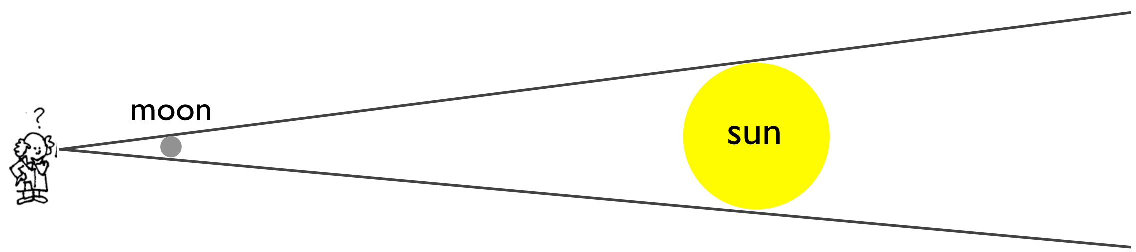
However, it's pretty hard to raise di-photon rate via t-partners in "real" natural theories ...

Falkowski (07); Low & Vichi (10); Azatov & Galloway (11); Gillioz, et al.; Blum, et al.; Carena, et al.; Corbett, et al.; Benbrik, et al.; Arbey, et al. (12);

The fine tuning problem

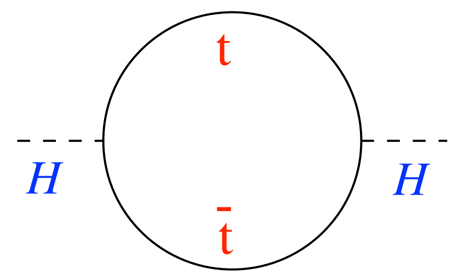
(ii) Why perturbations not destabilize system? <=> Fine tuning issue.

(displacing the sun by $\sim 10^{-19}\,\mathrm{m} \;\Rightarrow\; \delta\theta \sim 10^{-32}$)



“Additive” sensitivity / fine tuning due to top-Higgs coupling:

$$\left(m_W^2/m_{\mathrm{Pl}}^2\right)_{\mathrm{obs}} \sim \left(m_H^2 + \delta m_H^2\right)/m_{\mathrm{Pl}}^2 \sim \; m_H^2 +$$

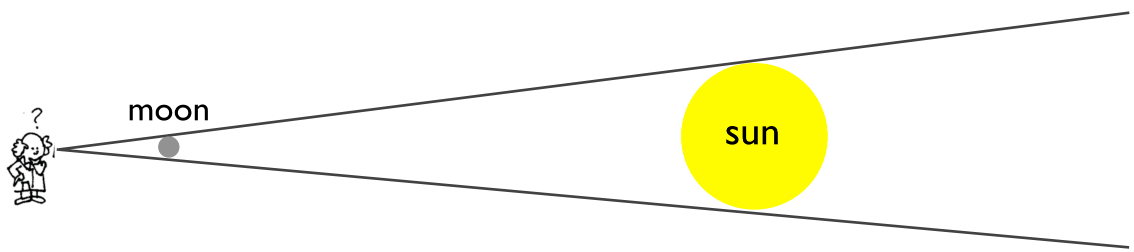


$$\sim 0.0100000000000000000000000000000001 - 0.01 \sim 10^{-32}$$

The fine tuning problem

(ii) Why perturbations not destabilize system? <=> Fine tuning issue.

$$\left(\text{displacing the sun by} \sim 10^{-19}\,\text{m} \;\Rightarrow\; \delta\theta \sim 10^{-32}\right)$$



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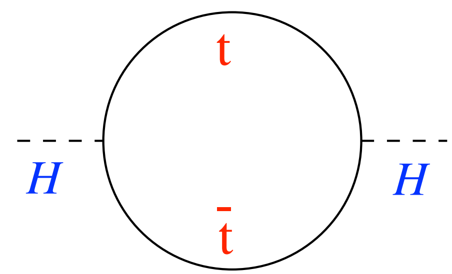

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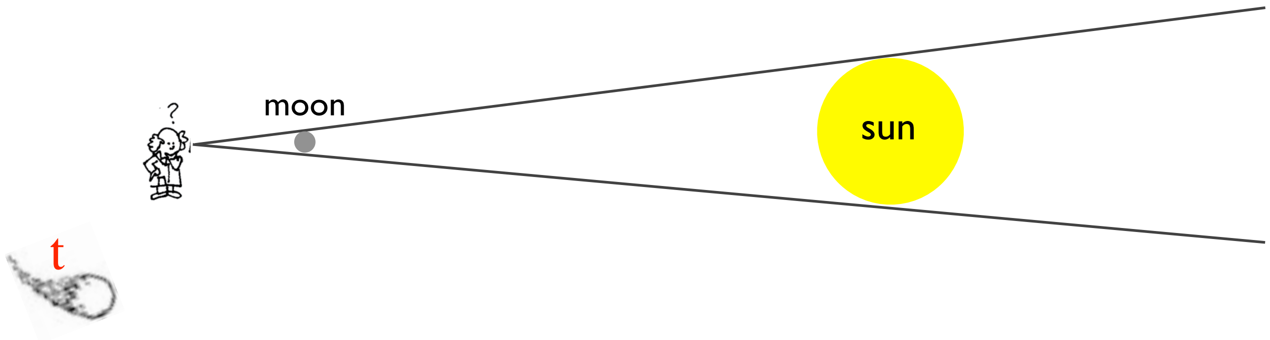

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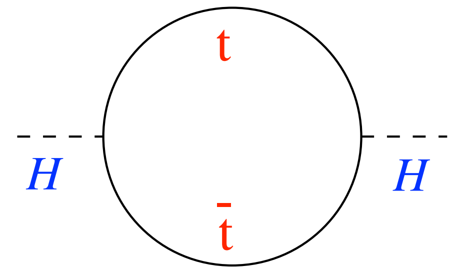

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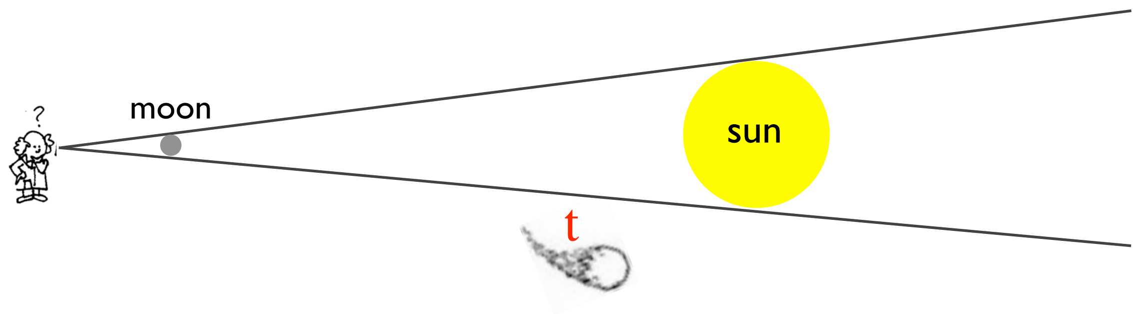

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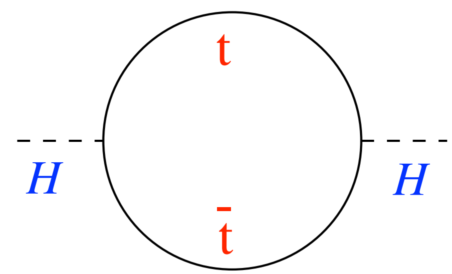

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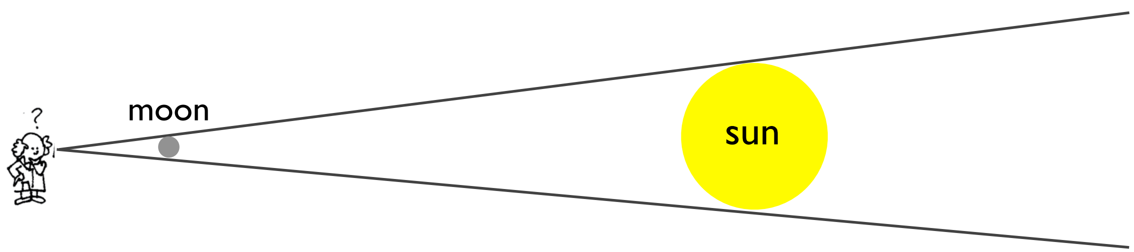

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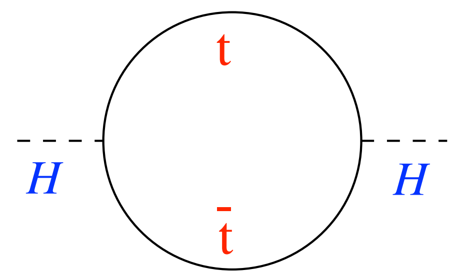

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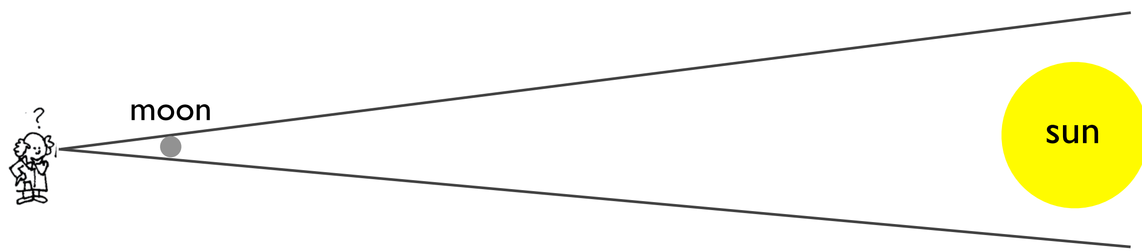

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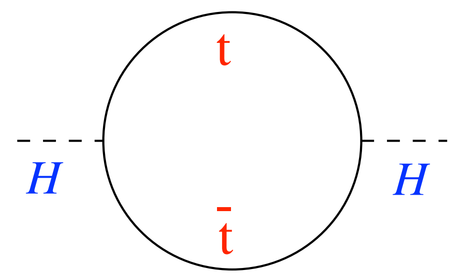

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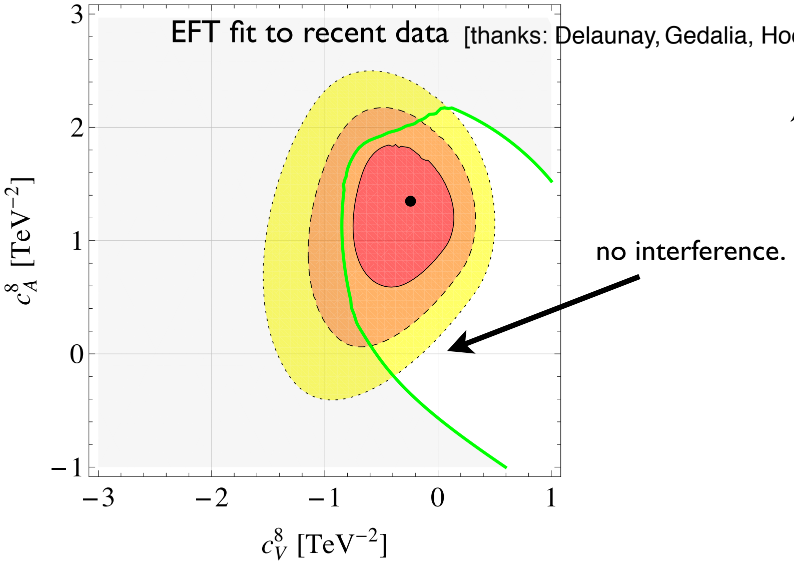
Hard physics explanation (*e.g.*: heavy axigluon-KKgluon variety)

- A rough idea is obtained from effective field theory (EFT) analysis:



[thanks: Delaunay, Gedalia, Hochberg & Soreq (just appear)]

Chivukula, et al.; Degrande, et al.; Cao, et al. (10); Delaunay, et al.; Aguilar-Saavedra, et al.; Westhoff (11).

$$\mathcal{L}_{\rm eff} = \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i \equiv \sum_i c_i \mathcal{O}_i\,, \quad \mathcal{O}_A^8 = (\bar{u}\gamma_\mu\gamma^5 T^a u)(\bar{t}\gamma^\mu\gamma^5 T^a t)\,, \quad \mathcal{O}_V^8 = (\bar{u}\gamma_\mu T^a u)(\bar{t}\gamma^\mu T^a t)\,.$$

Issues: spectrum; dijet; flavor $g_{u\bar{u}} = -g_{t\bar{t}}$.

Westhoff, et al.; Bai, et al.; Delaunay, et al. (11)

shaded area left of green curve excluded by CMS cumulative bound for $M_{t\bar{t}}$ > 1 TeV.

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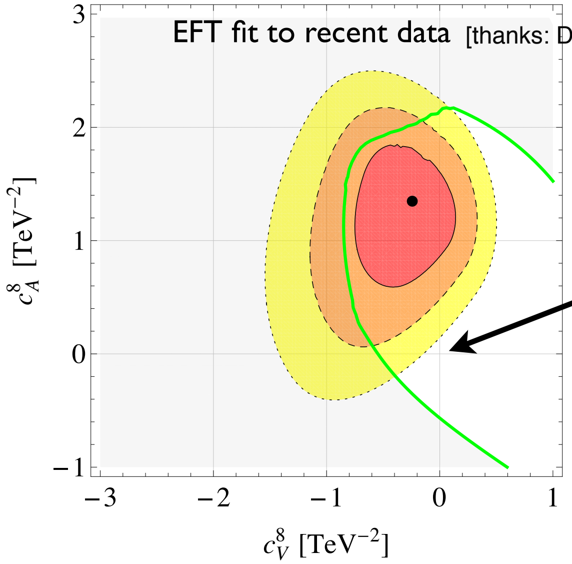

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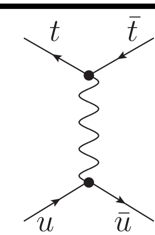
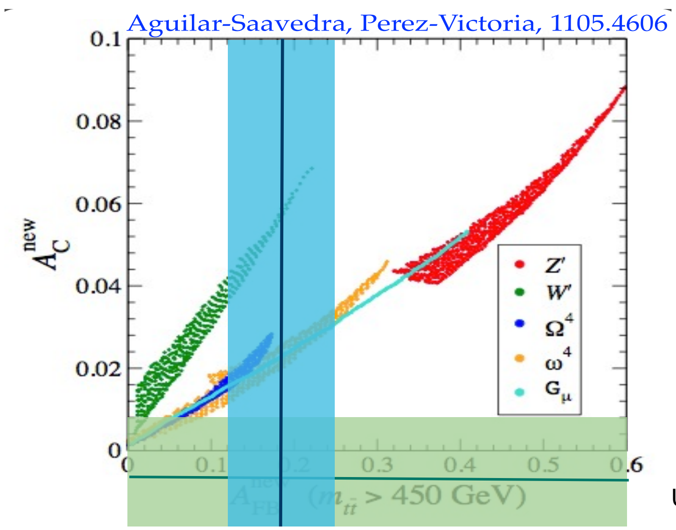
On shell (*e.g.*: "s-channel", "t-channel" models)

Impossible to cover all models, common exchange light particles.





Issues: spectrum; dijet; flavor; A_c; $t\bar{t} + j$;
& APV (atomic parity violation).

Isidori-Kamenik; Grinstein, et al.; Ligeti, et al.;
Gresham, et al. x 3; Blum, et al. x 2; Tavares-Schmaltz (11)

Update by J. Zupan, CERN, Th. colloquium, 6/12.