Flavorful Naturalness
&
The Top-Charm Frontier

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TH Theoretical Seminar & The top-charm frontier at the LHC Workshop

3-slides on naturalness & why the battle for naturalness should be continued

- With a light Higgs the Standard Model (SM), is compete, with no definite new scales. (modulo gravity & the Landau pole of hypercharge & the universe decay lifetime)

- Naturalness might give a hint: Higgs mass is additive, sensitive to microscopic scales. Within the SM it translates to UV sensitivity: $\frac{d\,m_H^2}{d\,\ln\mu} = \frac{3m_H^2}{8\pi^2}\left(2\lambda + y_t^2 - \frac{3g_2^2}{4} - \frac{3g_1^2}{20}\right)$.

See: Giudice (13)

- Beyond the SM: any scale that couples to the Higgs (or even to tops, gauge ...) will induce a large shift to the Higgs mass, $\delta m_H^2 \approx \frac{\alpha}{4\pi} M^2$. Farina, Pappadopulo & Strumia (13)

- Thus, even if we are to ignore gravity (strong assumption!) we are led to a desert-like scenario (end of phys., somehow resembles 19th century arguments ...).

Dubovsky, Gorbenko & Mirbabayi (13)

The weakness of the anthropic argument for the weak scale

♦ The standard argument: increasing Higgs VEV => deuteron would not bind.

Agrawal, Barr, Donoghue & Seckel (98)

♦ However, increasing Higgs VEV + rescaling Yukawas & keeping mass of stable fermions light => livable universe <=> The Weakless Universe.

Harnik, Kribs & GP (06)

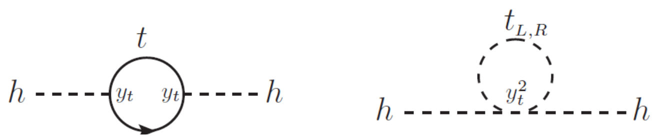
♦ Can easily be realized in a "Froggatt-Nielsen" multiverse (where Yukawa are dynamical), such a setup would favor the weakless universe.

Gedalia, Jenkins & GP (11)

♦ Essentially different from Weinberg's Cosmological Constant (CC) argument: (*i*) no natural solution to CC problem; (*ii*) the anthropic argument is robust.

Robustness test of naturalness & the LHC perspective

Conventional (IR) naturalness => new partners, potentially within the LHC reach.



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

tuning ~ 1:10

$\mathrm{LHC8:}\ m_{\tilde{t}} \sim 700\,\mathrm{GeV}$

natural SUSY

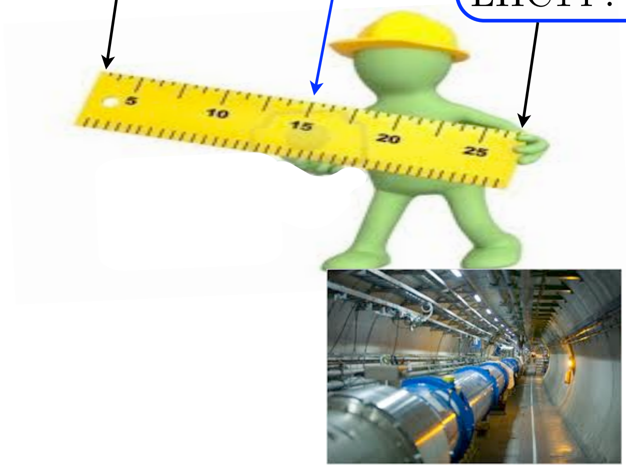
$m_{\tilde{t}} \sim 400\,\mathrm{GeV}$

tuning ~ 1:10²

$\mathrm{LHC14:}\ m_{\tilde{t}} \sim 2\,\mathrm{TeV}$

The LHC naturalness ruler:

(less than half way through)



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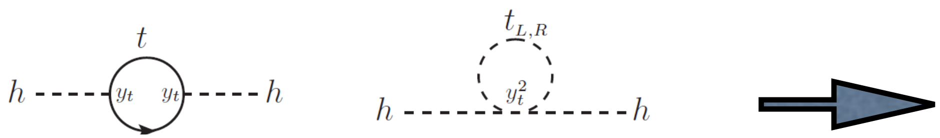
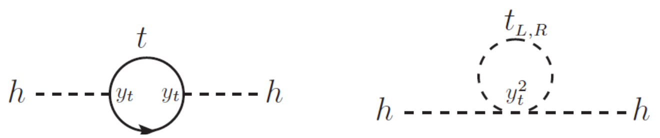


$$\frac{\delta m_h^2}{m_h^2} \sim \left(\frac{\tilde{m}_t}{400\,\mathrm{GeV}}\right)^2$$

♦ Despite the limitation, amidst the LHC era, stopping asking questions at this (early stage) might be a costly mistake.

Top partners & Naturalness

Robust test of naturalness => new colored partners, potentially within the LHC reach.



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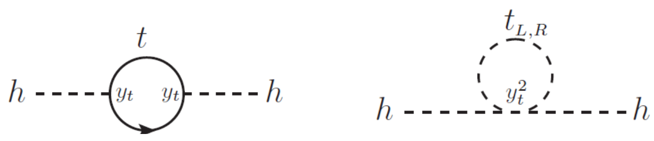
2 leading frameworks
of naturalness

Supersymmetry
top partners=stops

Composite Higgs
top partners = ”T”

Top partners & LHC Searches

Robust test of naturalness => new colored partners, potentially within the LHC reach.



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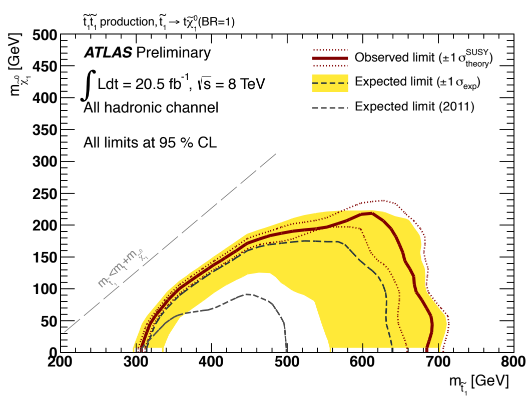
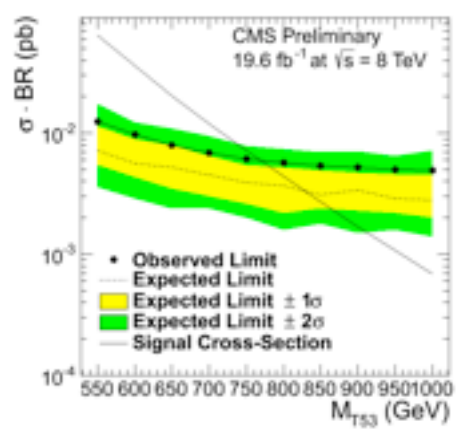


$m_{\mathrm{stop}} \gtrsim 700\,\mathrm{GeV}$



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

The Battle for Naturalness

LHC8: where are the partners ⁇

"micro energy frontier":
keep pushing bound;
boosted massive jets.

"micro intensity frontier":
partners are elusive;
why? how to search?
(RPV, compression)

Today's talk:

"micro intensity frontier":
partners are elusive;
why? how to search?

Partner are elusive because of non-trivial flavor physics effects

("first 2 gen' are completely irrelevant to naturalness & Higgs physics, LHC physics")

Outline (2 "flavorful" roads towards naturalness)

- ♦ Supersymmetric "flavorful naturalness":

  (i) Impact of stop-scharm mixing on effective/visible fine tuning;

  (ii) Light non-degenerate squarks at the LHC (& LHCb).

(see Ruderman's talk)

- ♦ Flavorful composite Nambu-Goldstone boson (NGB) Higgs:

  Models \w composite quark singlet are viable => interesting collider implications.

(see Fraile & Redi's talk)

- ♦ Conclusions.

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- Conclusions.

Supersymmetric Flavorful Naturalness

&

implications of split first two generation squark spectrum

Supersymmetric (SUSY) Flavourful naturalness

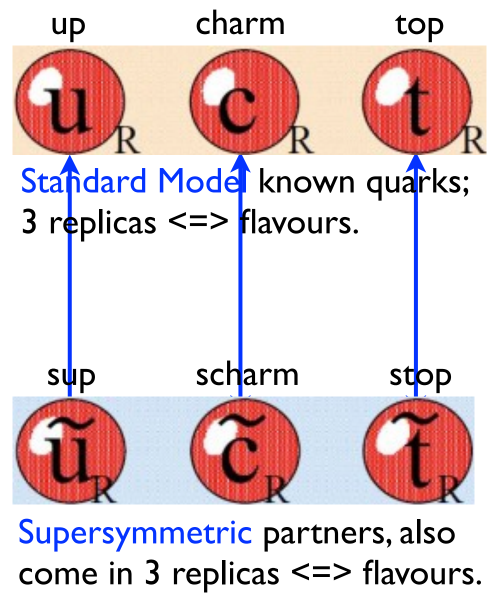
- Standard model: 3 copies (flavours) of quarks;

  same holds for new physics. (say supersymmetry)

- “Hardwired” assumption:

  top partner (stop) is mass eigenstate.

`Dine, Leigh & Kagan, Phys.Rev. D48 (93); Dimopoulos & Giudice (95);`
`Cohen, Kaplan & Nelson (96)`



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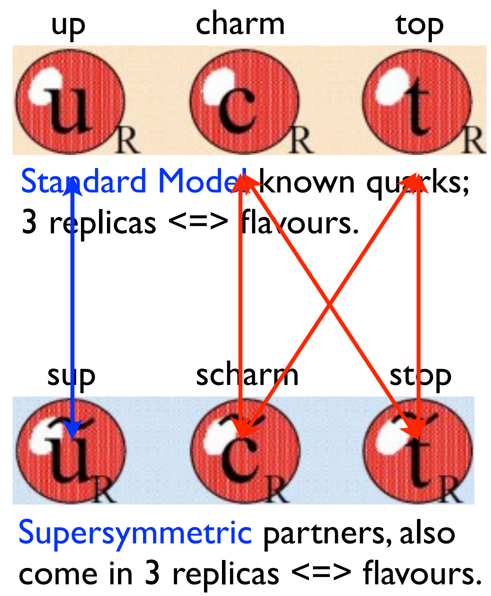
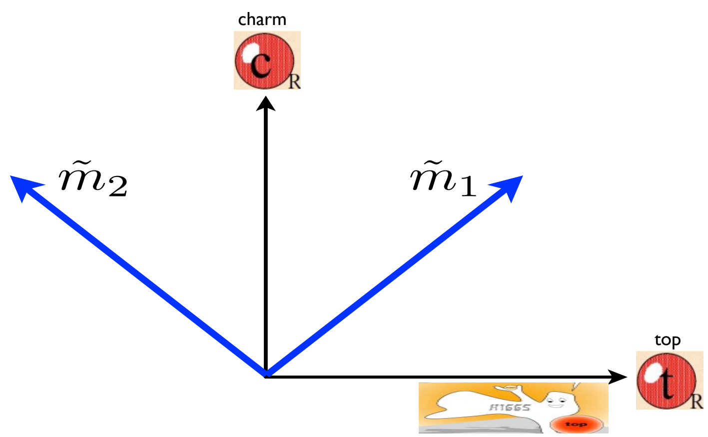


- This need not be the case, top-partner => "stop-scharm" admixture.



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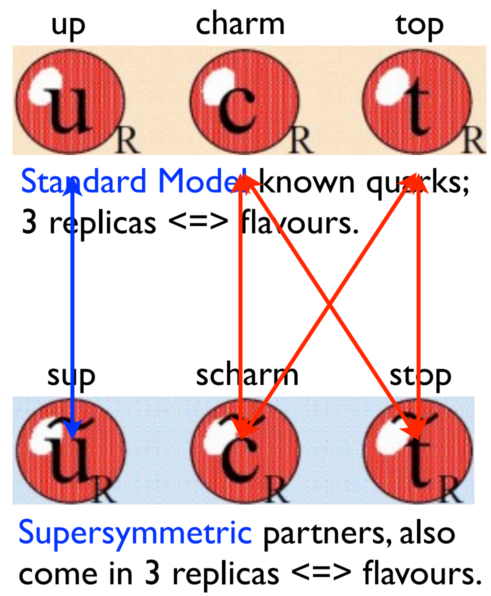

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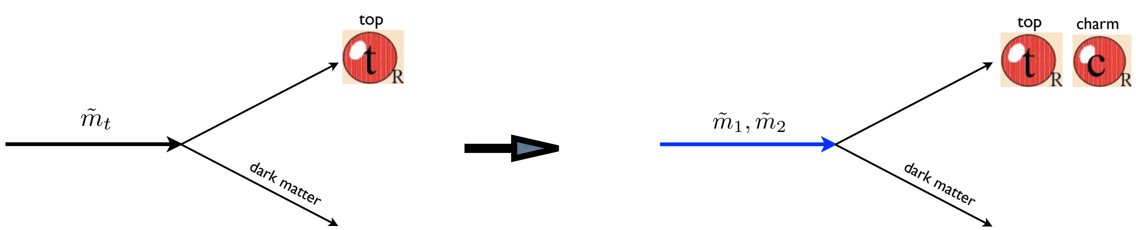

Signatures change, opening the charm front at high energy & in D-meson CP violation.

Blum, Grossman, Nir & GP (09); Gedalia, Kamenik, Ligeti & GP; Mahbubani, Papucci, GP, Ruderman & Weiler (12); Blanke, Giudice, Paradisi, GP & Zupan (13).

What is the impact of stop-flavor-violation on tuning ? (flavored naturalness)

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

- Naively sounds crazy ...

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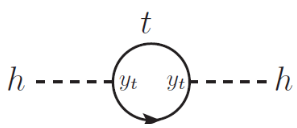
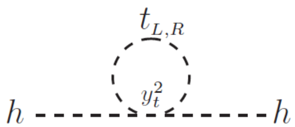
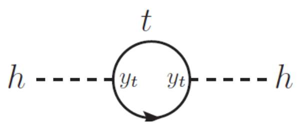


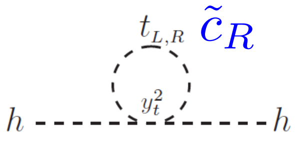


What is the impact of adding flavor violation on stop searches ? (flavorful naturalness)

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

- Naively sounds crazy as worsening the fine tuning problem.





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

- However, as you'll see soon the scharm can be light...

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

↓

Potentially: new hole in searches, possibly improve naturalness

Constraining (RH) flavorful naturalness

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

Analysis applies for ATLAS (12); now new bounds from ATLAS and CMS around 670 GeV.

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

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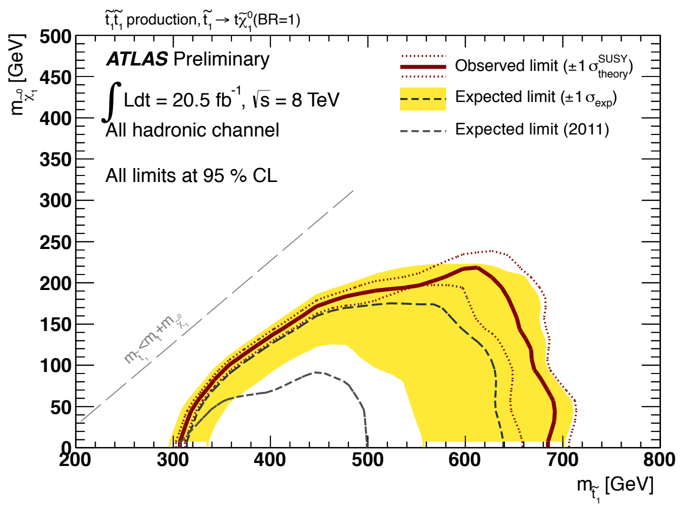

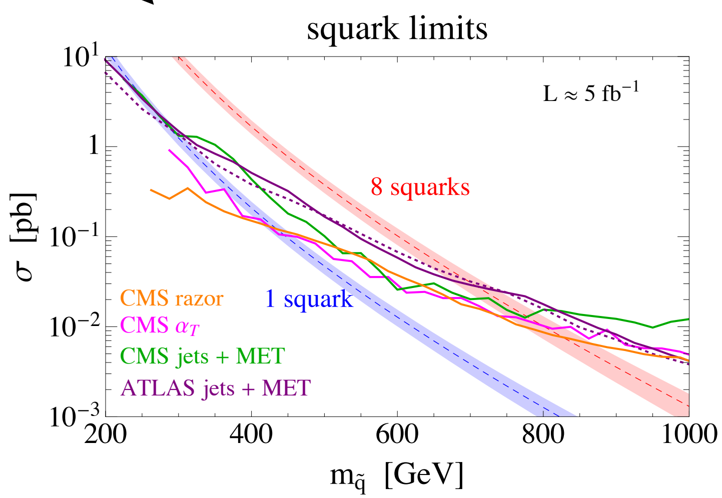

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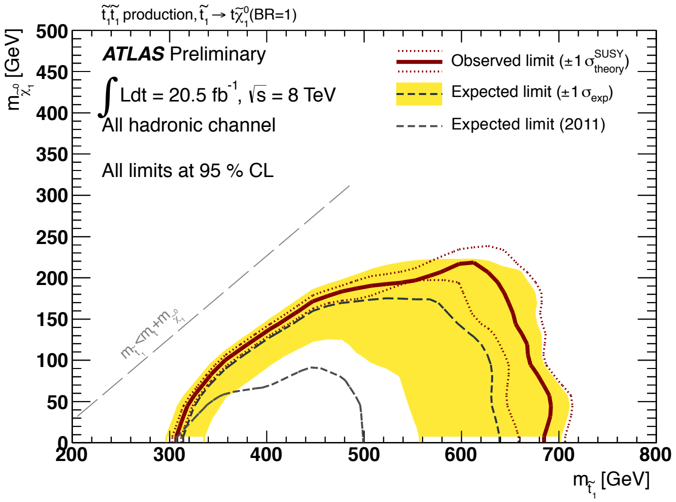

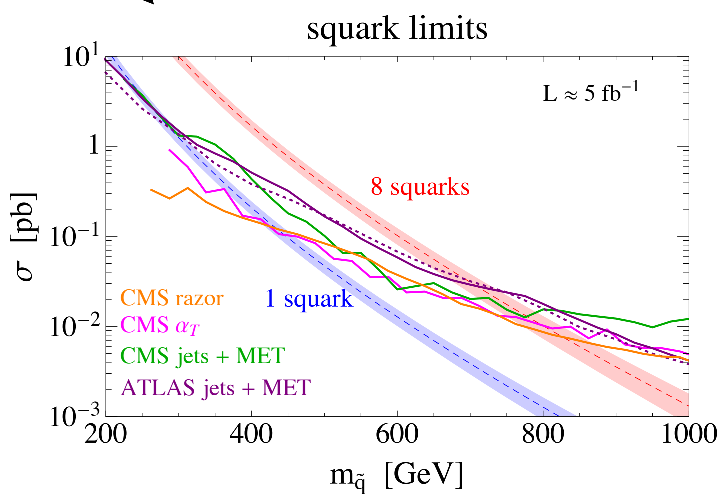

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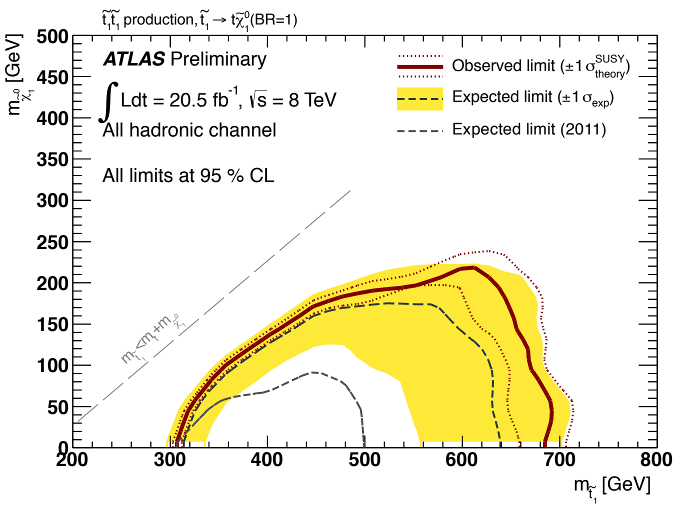
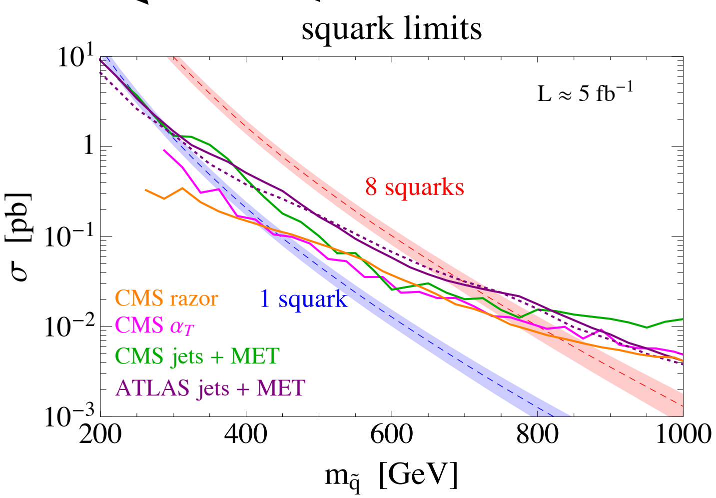
compromise





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Flavored naturalness LHC searches

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

- The relevant parameters to constrain are:

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

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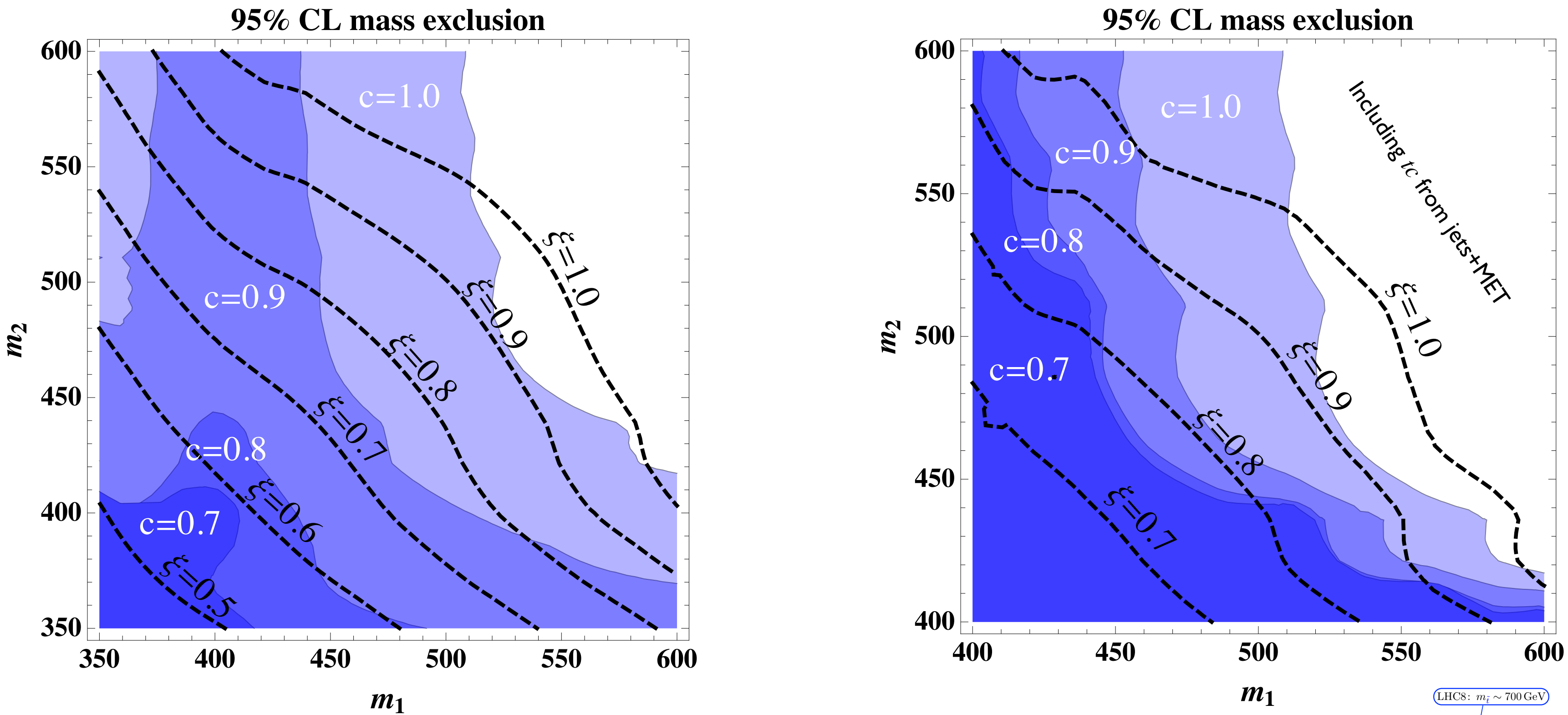
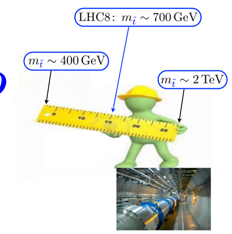


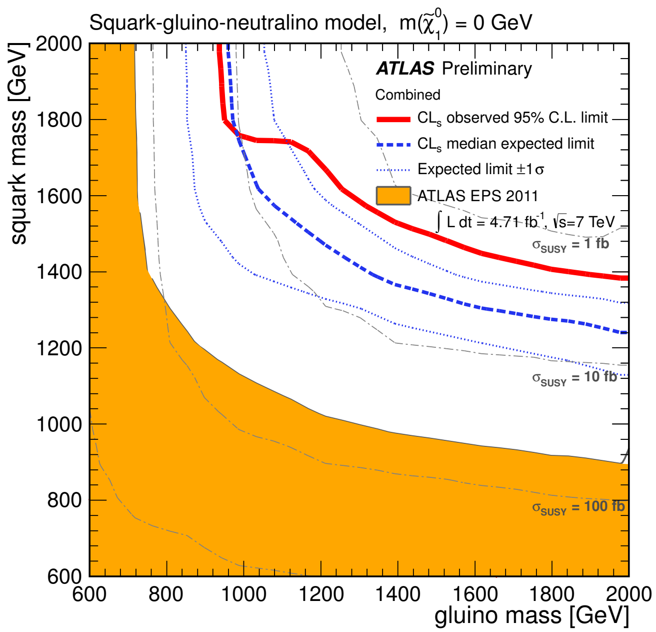
Can get $\xi \sim 0.5 - 0.8$ for $\theta_{23}^{RR} \sim 45^o$



Light scharms at the LHC

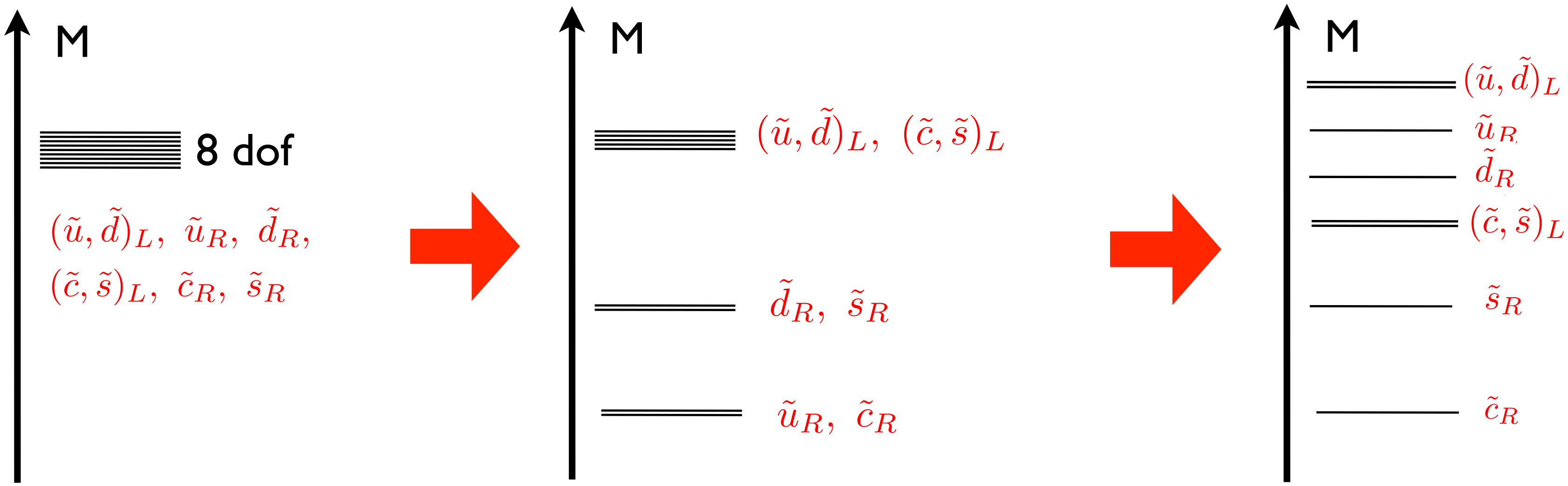
Putting stops aside, what are the bounds on first 2-generation "light" squarks?

Summer bounds from ATLAS & CMS :



Light squarks > 1.4 TeV?

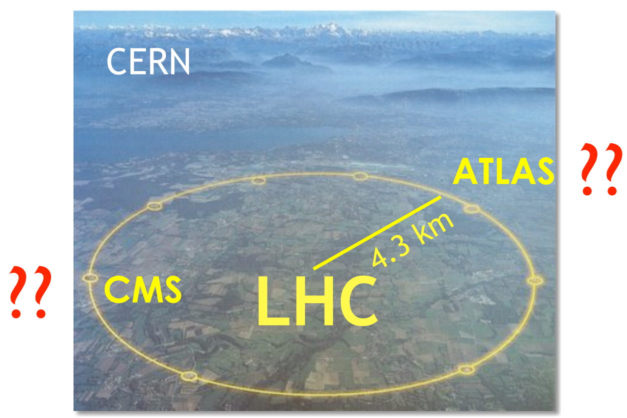
What if first 2 generation squark not degenerate?



Everything degenerate

Split, but MFV

Anarchy!



What drives the experimental limits?

Ruderman's talk.

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

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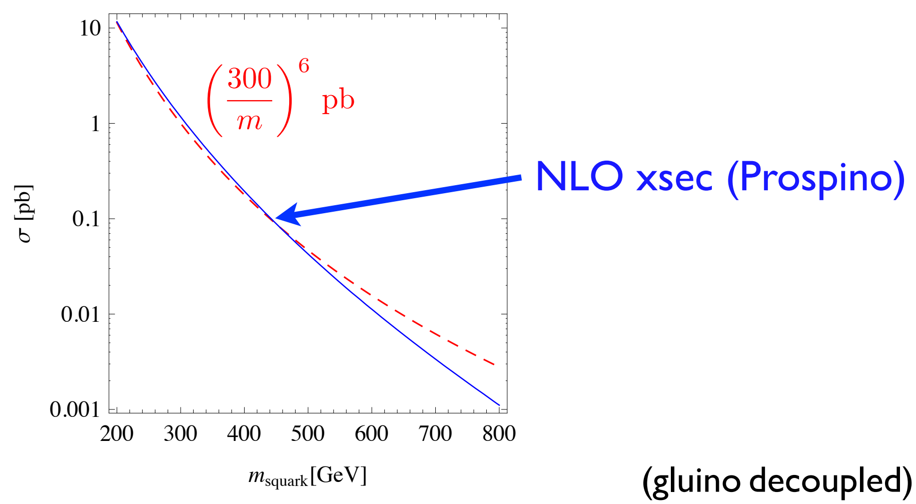
Multiplicity: how bound changes when one doublet is made lighter ?

Cross-sections vs. mass

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



(gluino decoupled)

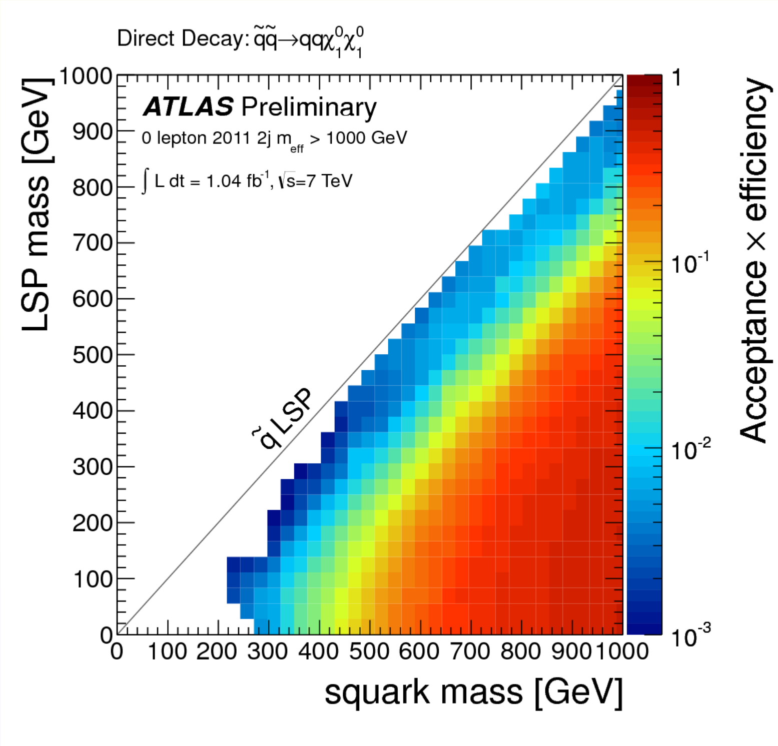
$$8/m^6 = 6/m_H^6 + 2/m_L^6$$

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

gain is marginal

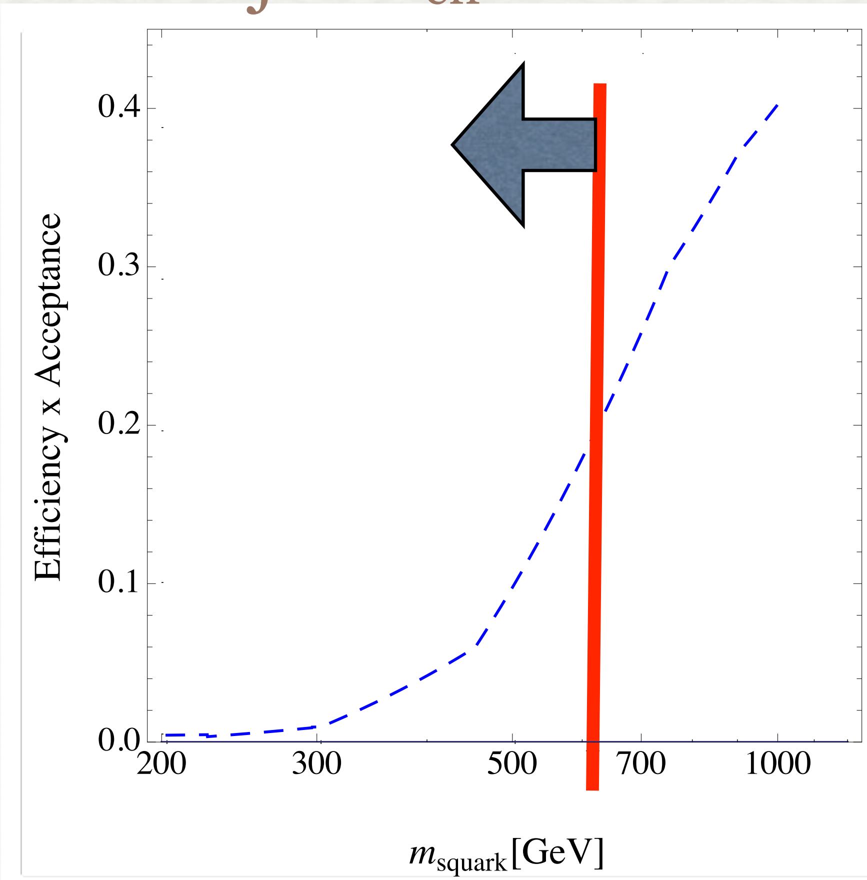
Efficiencies, strong mass dependence!

Signal efficiency falls very rapidly with decreasing squark mass



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

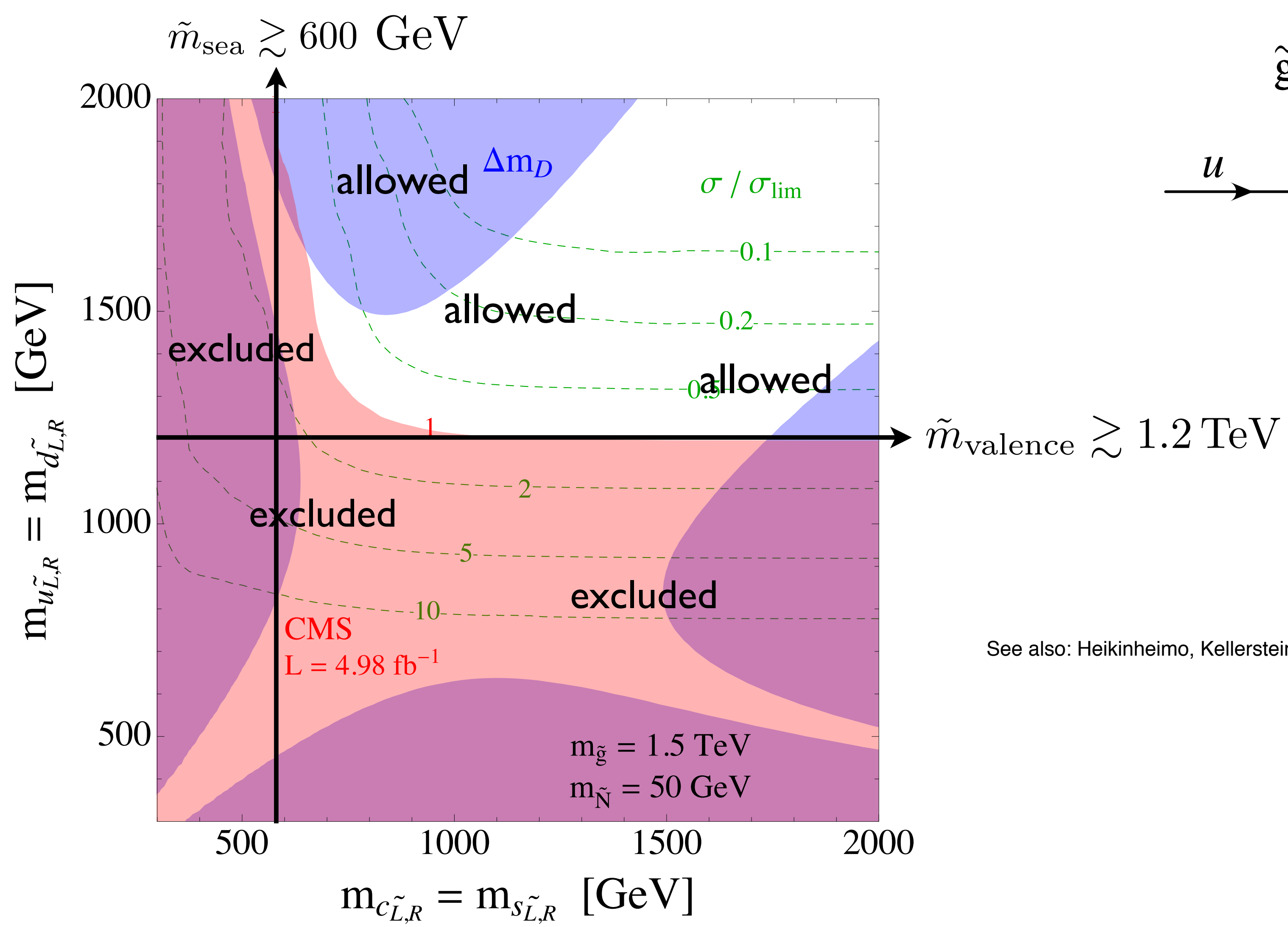
ATLAS 1/fb, 2jet M_{eff}>1TeV

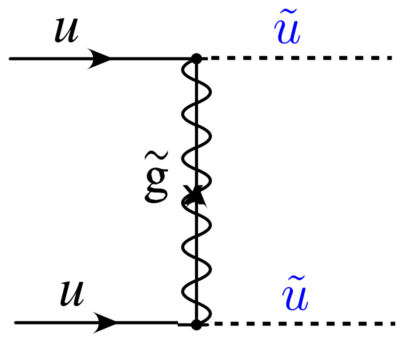


meff is the scalar sum of transverse momenta of the leading N jets with E^{miss}.

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

sea vs. valence



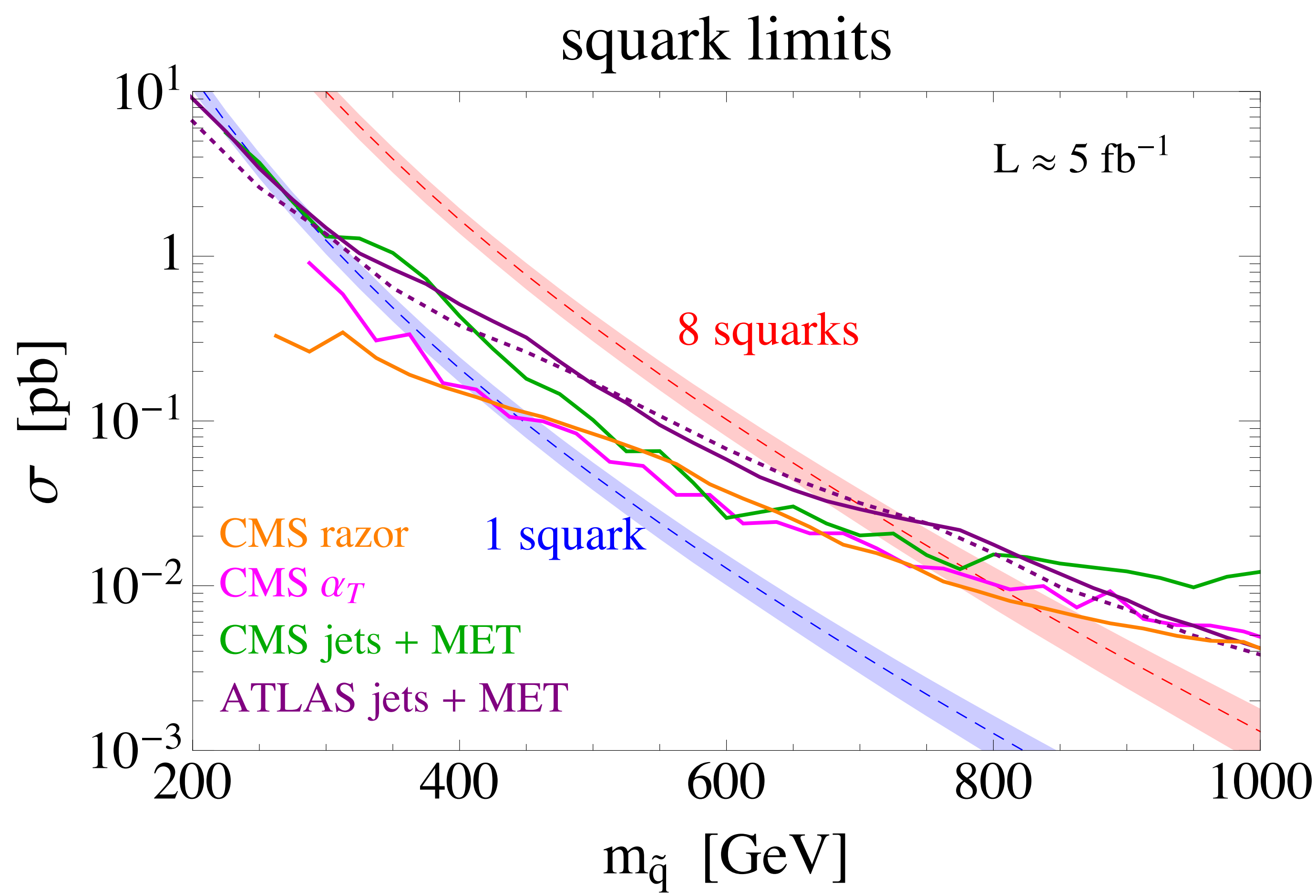


Mahbubani, Papucci, GP, Ruderman & Weiler (12).

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

Single squark can be as light as 400-500GeV!

Talk by Makovec.



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Are non-degenerate first 2-generation squarks consistent with flavor bounds?

Surprisingly: answer is probably yes both from low energy & UV perspectives.

See Galon, GP & Shadmi (13) for microscopic realization, aligned SUSY breaking flavored gauge mediation models.

See: Ziegler's talk for details

Let us focus on the low energy, model indep', effective story.

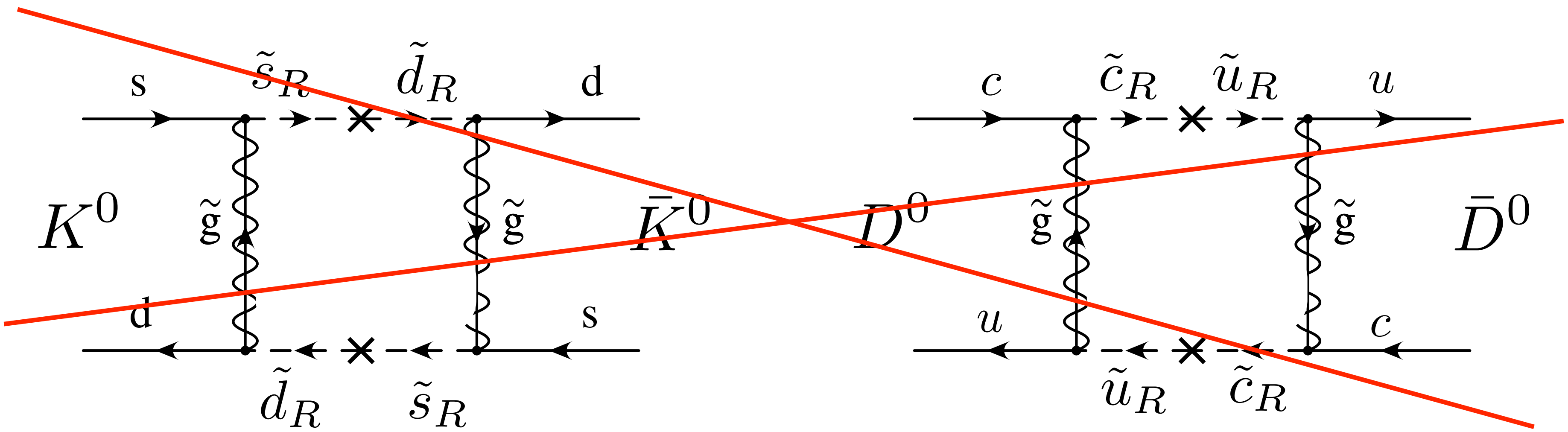
More in Kamenik's talk

Are non-degenerate first 2-generation squarks consistent with flavor bounds?

◆SUSY flavor & CP violation => misalignment between squark soft masses & standard model (SM) Yukawa matrices.

◆SM: right handed (RH) flavor violated by single source, $Y_d^\dagger Y_d$ or $Y_u^\dagger Y_u$, => RH SUSY masses are alignable removing RH flavor & CP violation:

$$[\tilde{m}_d^2\,, Y_d^\dagger Y_d] = 0 \;\&\; [\tilde{m}_u^2\,, Y_u^\dagger Y_u] = 0$$



The SUSY left handed flavor challange

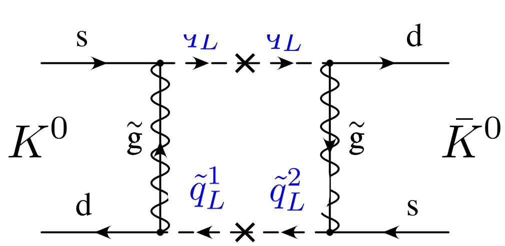
- SM LH sector consist of 2 flavor breaking sources: $Y_d Y_d^\dagger$ & $Y_u Y_u^\dagger$

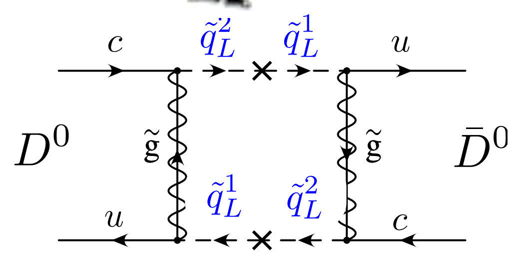
- SUSY: cannot align LH masses simultaneously with both sources! Dangerous direction wins to reduce bounds ...

$\mathrm{NP} = \tilde{m}_Q^2$

$\Delta M_K, \epsilon_K$

$\Delta M_D, A_\Gamma^D$





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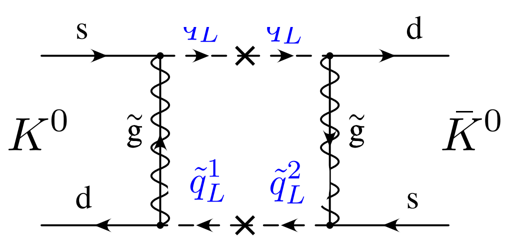

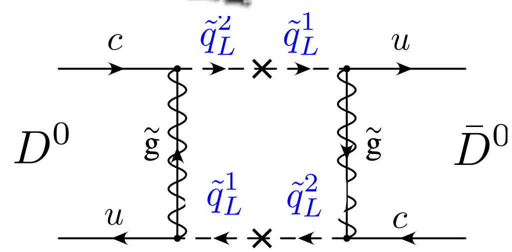

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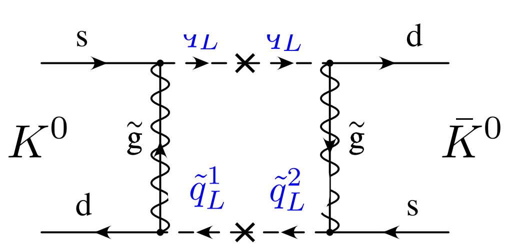

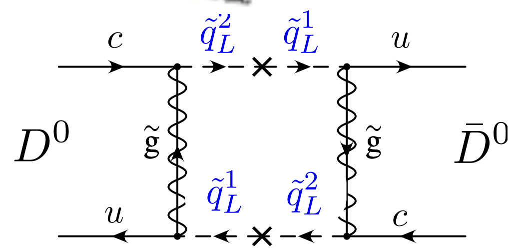

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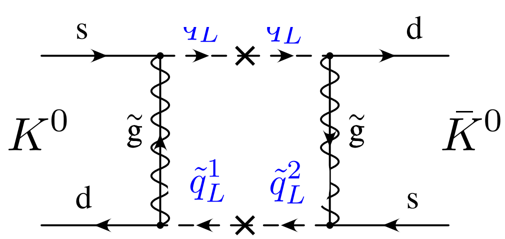
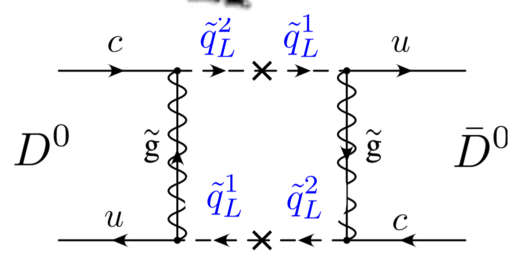
- SUSY: cannot align LH masses simultaneously with both sources! Dangerous direction wins to reduce bounds ...

$\mathrm{NP} = \tilde{m}_Q^2$

$\Delta M_K, \epsilon_K$

$\Delta M_D, A_\Gamma^D$





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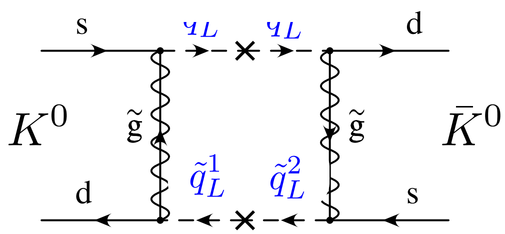

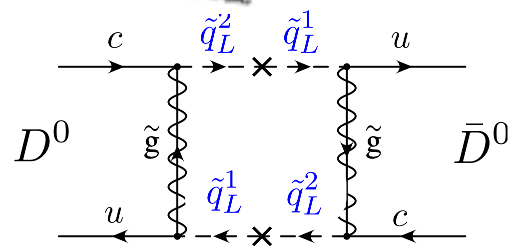

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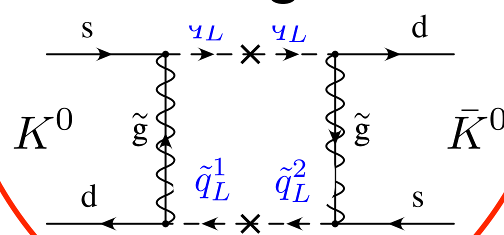
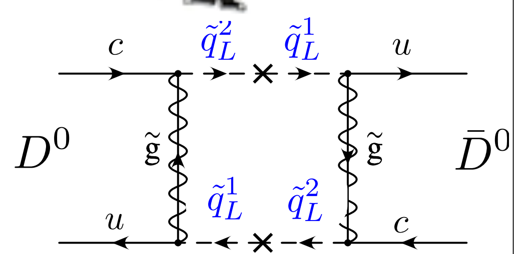
Nir & Seiberg (93)

down alignment





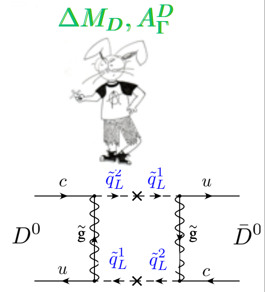
The charm frontier: this year LHCb made impressive progress in CPV in mixing

SUSY alignment implications: no hope for non-degeneracy?

$$\frac{m_{\tilde{Q}_2} - m_{\tilde{Q}_1}}{m_{\tilde{Q}_2} + m_{\tilde{Q}_1}} \leq \begin{cases} 0.034 & \text{maximal phases} \\ 0.27 & \text{vanishing phases} \end{cases}$$

(squark doublets, gluino, 1TeV)

Blum, Grossman, Nir & GP (09)



With phases, first 2 gen' squark need to have almost equal masses.

Looks like squark anarchy/alignment is dead!

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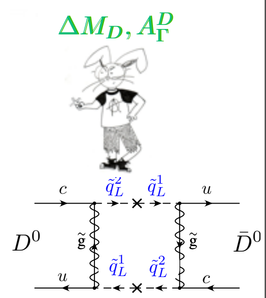

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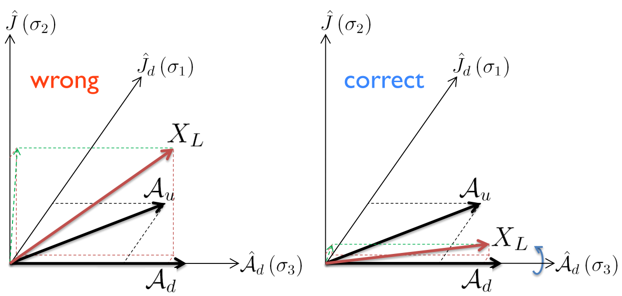
However ...

Successful alignment models guarantee small physical CP phase!



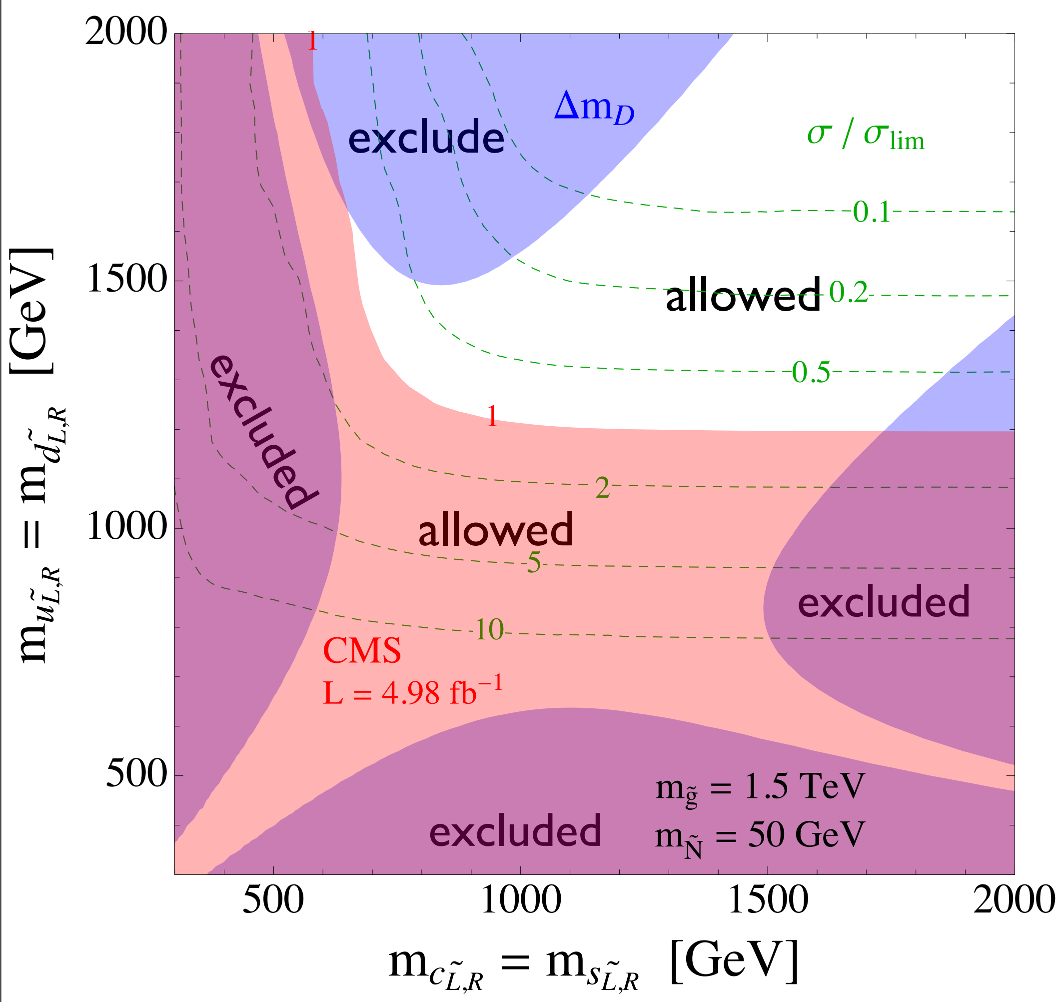
Gedalia, Kamenik, Ligeti & GP (12);

Formalism: Gedalia, Mannelli & GP (10) x2

Sea LH squarks vs. valence RH squarks

Adding flavor constraints (Δm_D) for LH squarks:

Kadosh, Paride & GP, to appear;



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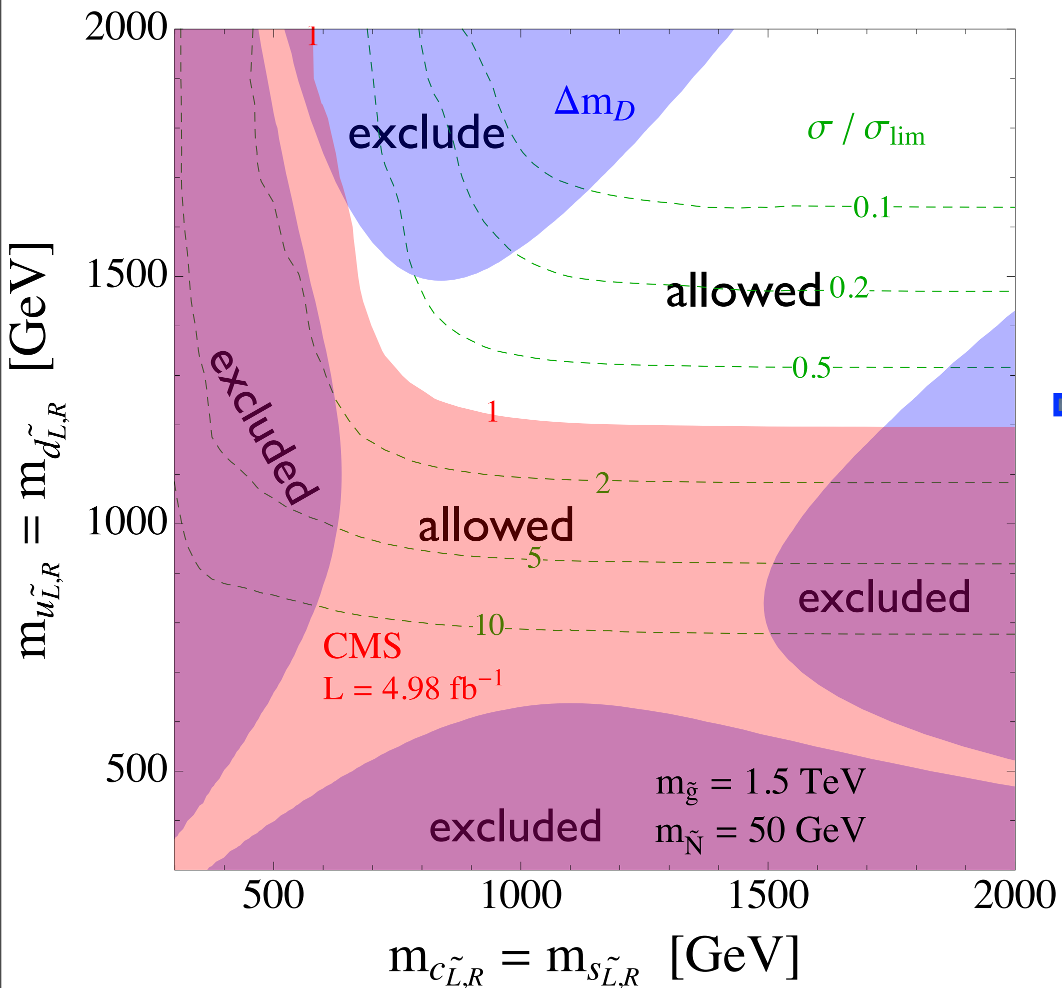


alignment: new upper bound on CP violation (CPV) in *D-phys.*:

$$\text{CPV in } D-\bar D:\ \delta_{\epsilon_K}/2\lambda_C\,\delta_Q^{12} \lesssim 10\% \times (0.3/\delta_Q^{12})$$

$$(\delta_{\epsilon_K} \sim 1\%)$$

LHCb started testing alignment paradigm.

Kadosh, Paride & GP, to appear.

Left handed (LH) SUSY flavorful naturalness

Kats, GP, Stamou & Stolarski, in progress.

- Is data on b-s transitions allows for large $\tilde{q}_3 - \tilde{q}_2$ mixing?

$$\text{LHCb}: S_{\psi\phi} \Rightarrow \sin 2\theta_{23}^{LL} \lesssim 0.9 \times \left(\frac{\delta\tilde{m}_{23}}{200\,\text{GeV}}\right) \times \left(\frac{1200\,\text{GeV}}{\tilde{m}_1 + \tilde{m}_2}\right) \times \left(\frac{1200\,\text{GeV}}{\tilde{m}_g}\right)$$

$$\left(b \to s\gamma \text{ weaker for } \tan\beta \sim \text{few } \& \ \tilde{b}_R \sim 3\,\text{TeV}\right)$$

⇓

$$\text{BR}\left(\tilde{b}_L\tilde{b}_L^*, \tilde{t}_L\tilde{t}_L^* \to b\bar{b}, t\bar{t}\right) = \cos^4\theta_{23}^{LL} \gtrsim 0.5$$

Seems to allow to apply the concept also on the LH sector!

Open parenthesis

Charm tagging at the LHC ATLAS EPS 2013

- In new ATLAS search for stop decay to charm + neutralino ($\tilde{t} \to c + \chi^0$) charm jet tagging has been employed for the first time at LHC

ATLAS-CONF-2013-068

- charm jets identified by combining "information from the impact parameters of displaced tracks and topological properties of secondary and tertiary decay vertices" using multivariate techniques

  - 'medium' operating point: c-tagging efficiency = 20%, rejection factor of 5 for b jets, 140 for light jets. #'s obtained for simulated $t\bar{t}$ events for jets with $30 < p_T < 200$, and calibrated with data

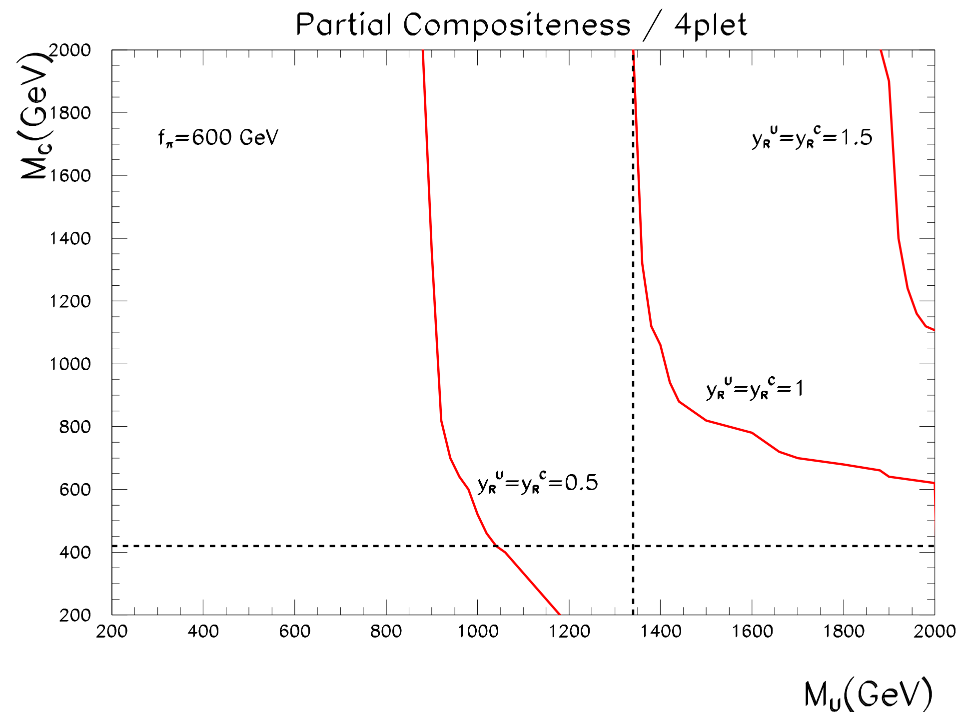
See talks by: Guest, Du Pree & Arnold.

Composite light quarks & pseudo-NGB (pNGB) Higgs

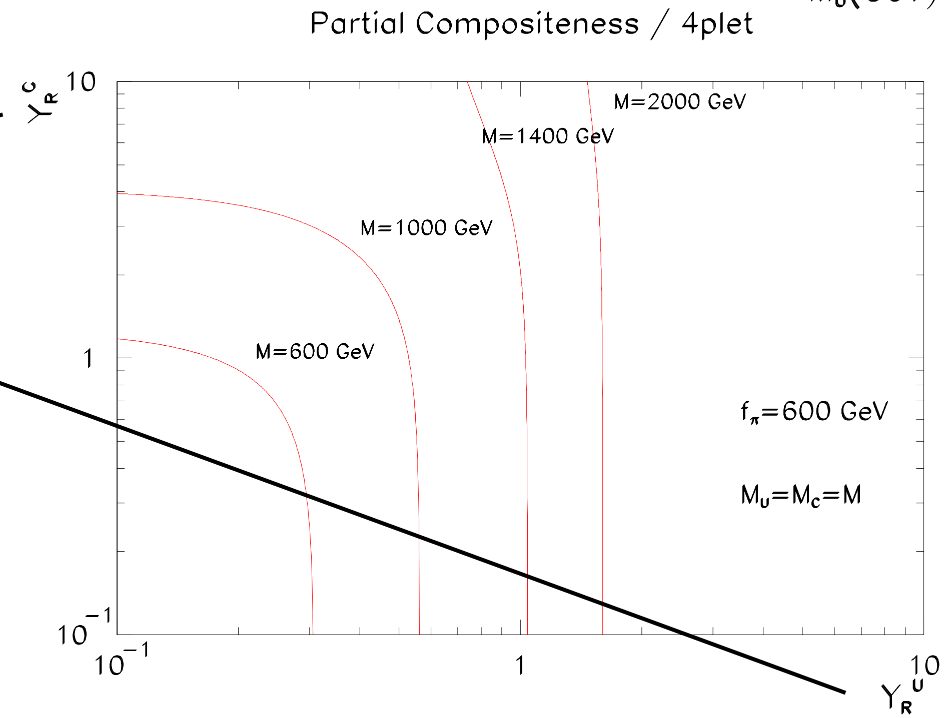
Collider implications for split 2 gen' (similar to SUSY case)

Delaunay, Fraile, Flacke, Lee, Panico & GP (13).

$$M_c \ll M_U$$



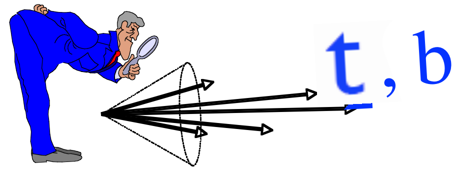
$$y_c \gg y_u$$



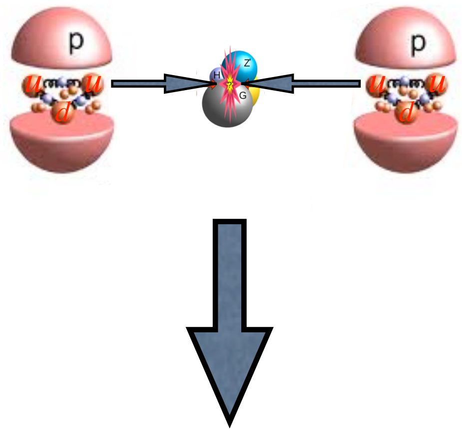
See talks by Fraile & Meehan.

Lesson (i): High p_T Quark Flavor Phys. at the LHC

- Tops & bottom are relatively easy to tag & measure precisely.

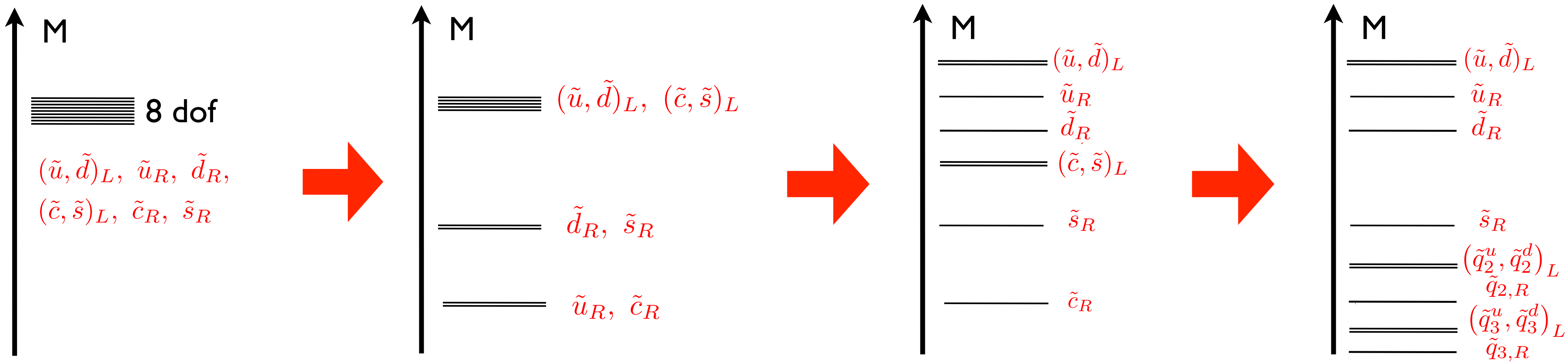


- As the protons are filled \w first gen' (valence) quarks their coupling to new physics are severely constrained.



Second gen' physics is currently in a blind spot of the LHC; push boundaries to eliminate it. (core of our workshop)

Lesson (ii): new physics spectrum, open question

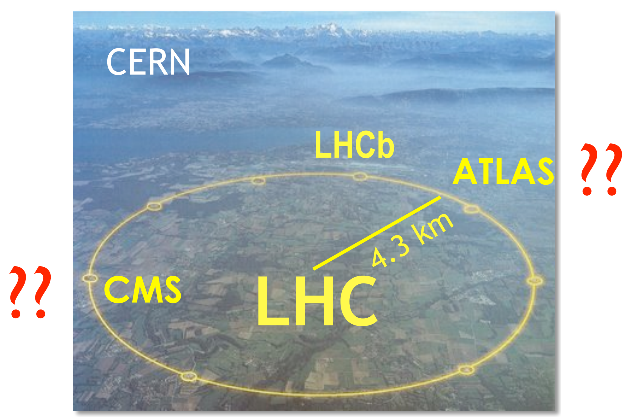


Everything degenerate

Split, but MFV

Anarchy

Flavorful Naturalness



Conclusions

♦ Light (non-"sups") squarks/partners maybe buried.

♦ Stop-scharm mixing might lead to improved naturalness.

♦ Ask for new type of searches, charm tagging important.

♦ Interplay \w CPV in D mixing & b-s transition, soon to be tested at LHCb.

Backups

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; Redi, Sanz, de Vries & Weiler (13); Atre, Chala & Santiago (13).

And:

(i) LHC implications for non-degenerate first 2-gen' partners.

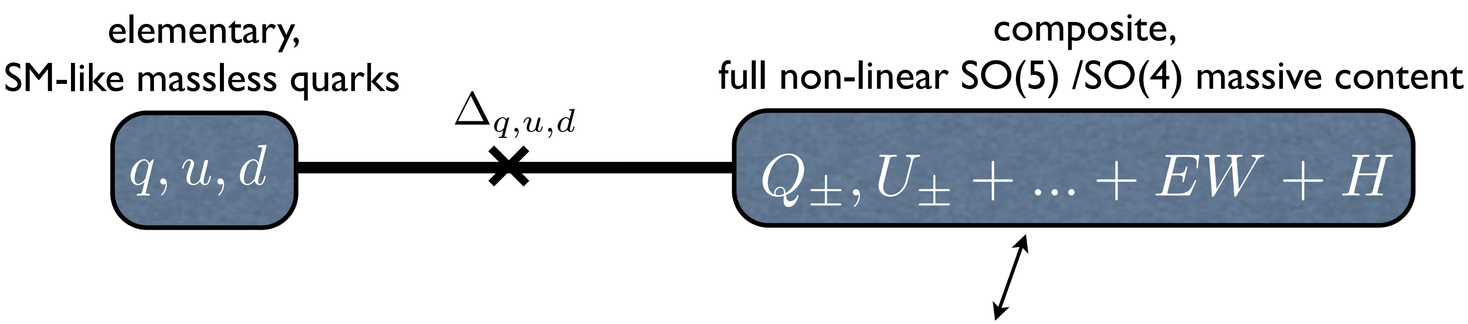
Delaunay, Fraille, Flacke, Lee, Panico & GP (13)

(ii) non-standard modification to Higgs decays.

Delaunay, Grojean & GP (13); Delaunay, Golling, GP & Soreq (13).

pNGB Higgs & composite light RH quarks

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



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

$$y_i f = \Delta_i \quad (f \Leftrightarrow \text{decay constant for the SO(5)/SO(4) breaking })$$

- What if the first two generations of RH quarks are composite but not at the same level, for instance:

$$y_u \lesssim y_c \sim y_t \sim 1$$

The model & relevant coupligs

Giudice, Grojean, Pomarol & Rattazz (07); De Simone, Matsedonskyi, Rattazzi & Wulzer (12); Delaunay, Fraille, Flacke, Lee, Panico & GP (13).

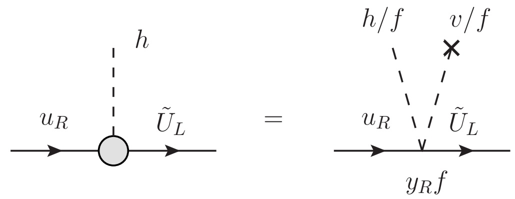
$$\mathcal{L}_{\rm comp} = i\,\bar{Q}(D_\mu + i e_\mu)\gamma^\mu Q + i\bar{\tilde{U}}\not{D}\tilde{U} - M_4\bar{Q}Q - M_1\bar{\tilde{U}}\tilde{U} + \left(ic\,\bar{Q}^i\gamma^\mu d^i_\mu\tilde{U} + \text{h.c.}\right),$$

$$\mathcal{L}_{\rm elem} = i\,\bar{q}_L\not{D}q_L + i\,\bar{u}_R\not{D}u_R - y_L f\bar{q}^5_L U_{gs}\psi_R - y_R f\bar{u}^5_R U_{gs}\psi_L + \text{h.c.},$$

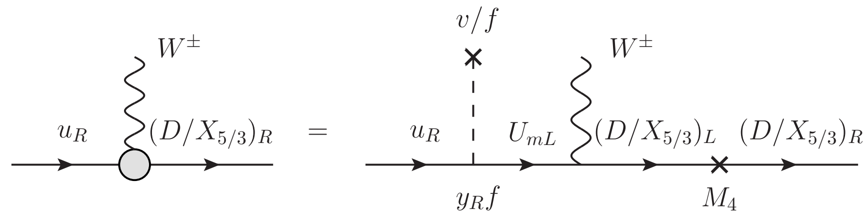
$$\psi = \begin{pmatrix} Q \\ \tilde{U} \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} iD - iX_{5/3} \\ D + X_{5/3} \\ iU + iX_{2/3} \\ -U + X_{2/3} \\ \sqrt{2}\tilde{U} \end{pmatrix}.$$

$$q^5_L \equiv \frac{1}{\sqrt{2}}(id_L\,, d_L\,, iu_L\,, -u_L\,, 0)^T\,.$$

$$u^5_R \equiv (0\,, 0\,, 0\,, 0\,, u_R)^T\,.$$



(a)



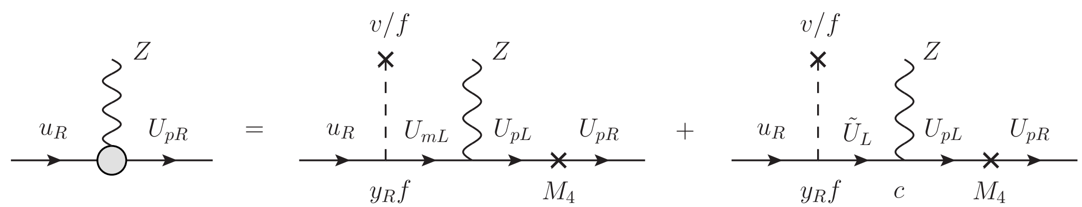
(b)

$$e^{1,2}_\mu = -\cos^2\left(\frac{\bar{h}}{2f}\right)gW^{1,2}_\mu\,,\quad e^3_\mu = -\cos^2\left(\frac{\bar{h}}{2f}\right)gW^3_\mu - \sin^2\left(\frac{\bar{h}}{2f}\right)g'B_\mu\,,$$

$$e^{4,5}_\mu = -\sin^2\left(\frac{\bar{h}}{2f}\right)gW^{1,2}_\mu\,,\quad e^6_\mu = -\cos^2\left(\frac{\bar{h}}{2f}\right)g'B_\mu - \sin^2\left(\frac{\bar{h}}{2f}\right)gW^3_\mu\,,$$

with $W^1_\mu = (W^+_\mu + W^-_\mu)/\sqrt{2}$, $W^2_\mu = i(W^+_\mu - W^-_\mu)/\sqrt{2}$, $W^3_\mu = c_w Z_\mu + s_w A_\mu$ and $B_\mu = c_w A_\mu - s_w Z_\mu$, while the d_μ components read

$$d^{1,2}_\mu = -\sin(\bar{h}/f)\frac{gW^{1,2}_\mu}{\sqrt{2}}\,,\quad d^3_\mu = \sin(\bar{h}/f)\frac{g'B_\mu - gW^3_\mu}{\sqrt{2}}\,,\quad d^4_\mu = \frac{\sqrt{2}}{f}\partial_\mu h\,.$$



(c)

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).

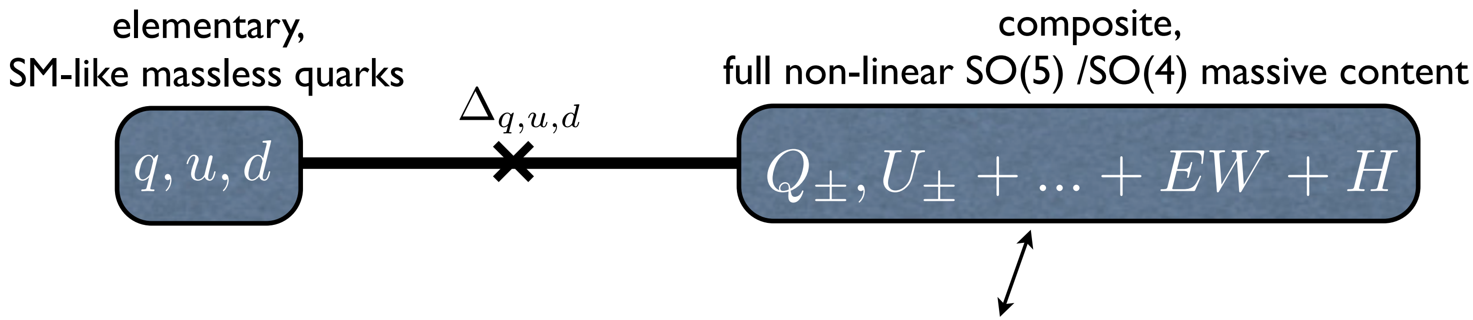
(ii) Repeat ex. using effective field theory (EFT).

(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 ...

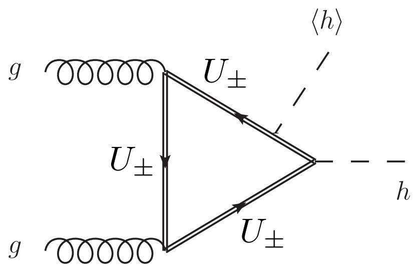
$$M_u = \begin{pmatrix} y_u^{00} v & 0 & y_u^{01} v \\ y_u^{10} v & m & y_u^{11} v \\ 0 & y_u^- v & m \end{pmatrix}$$

Perelestein, talk at ASPEN winter workshop (13).

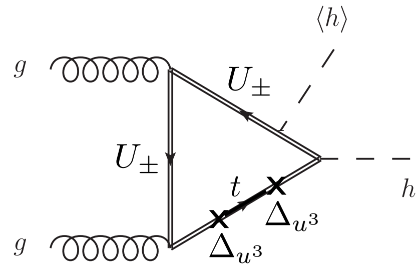
Cancellation of t-partners modification of Higgs rates, EFT:

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

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



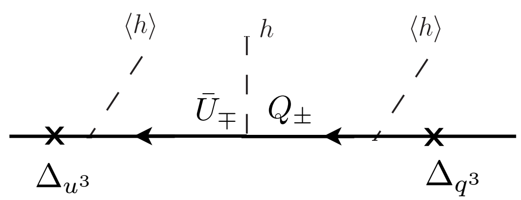
$\propto -vY^2/M^2$ **+**



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

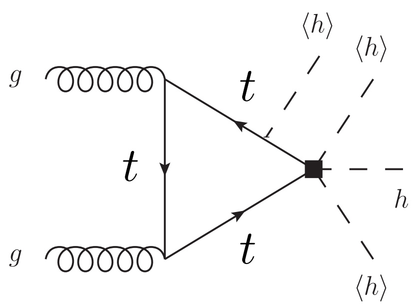
(ii) t-partner mix with the top-like SM fields, modifying their Yukawa:

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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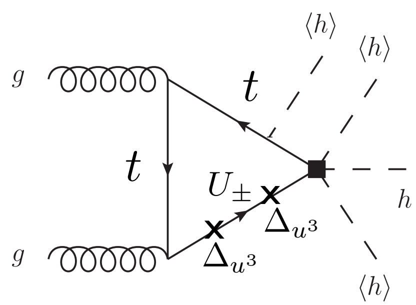
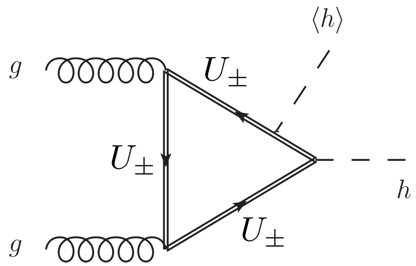


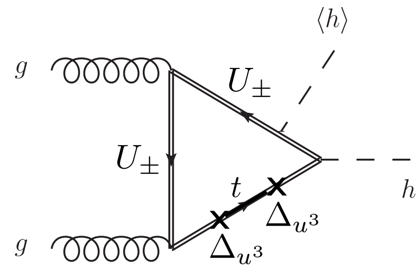
$\propto -vY^2/M^2 \times \Delta_{u^3}^2/M^2$

The cancellation of t-partners effects, adding all together



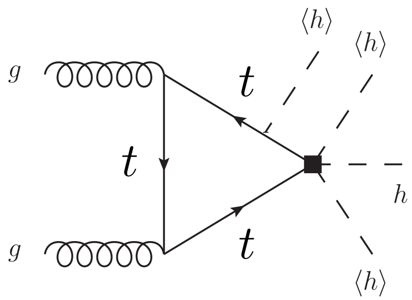
$\propto -vY^2/M^2$

+



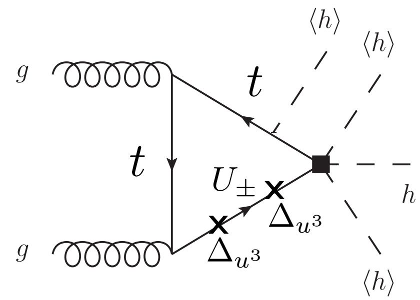
$\propto vY^2/M^2 \times \Delta_{u^3}^2/M^2$

+



$\propto vY^2/M^2$

+

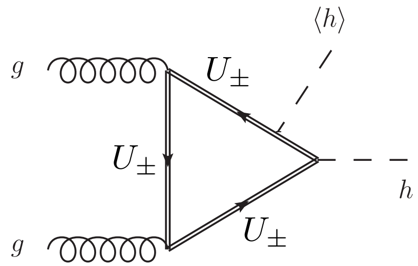


$\propto -vY^2/M^2 \times \Delta_{u^3}^2/M^2$

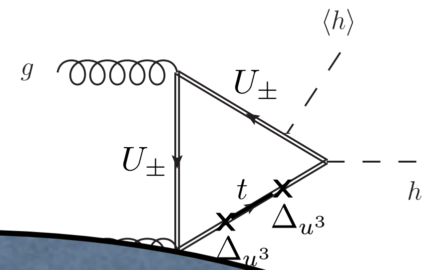
=

0

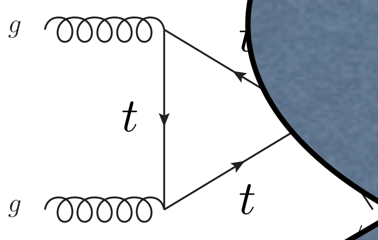
The cancellation of t-partners effects, adding all together



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



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



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

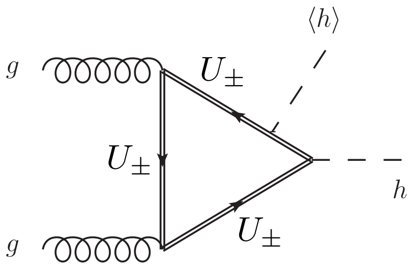
what if we consider instead of composite tops composite light quarks?

=

??

Cancellation for light composite quarks is ineffective!

Delaunay, Grojean & GP (13).



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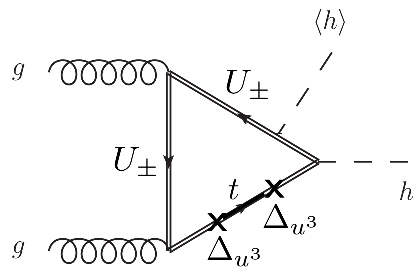
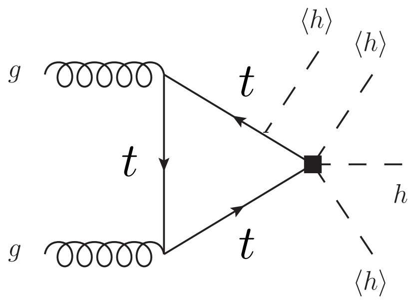


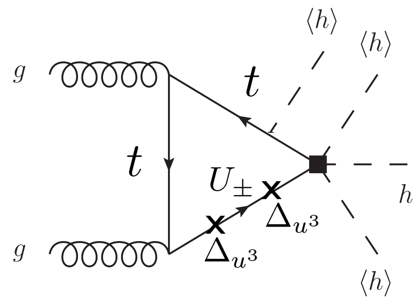
$\propto vY^2/M^2 \times \Delta_{u^3}^2/M^2$

+



$\propto vY^2/M^2$

+



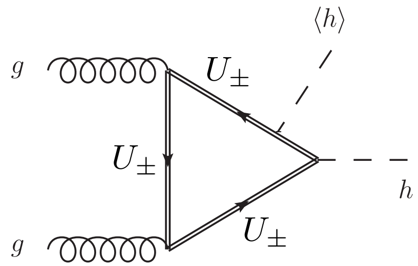
$\propto -vY^2/M^2 \times \Delta_{u^3}^2/M^2$

=

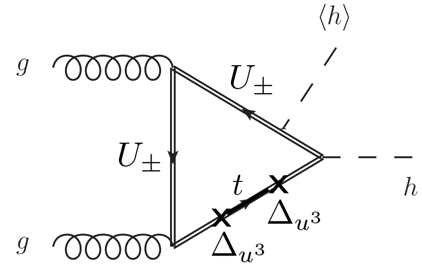
??

Cancellation for light composite quarks is ineffective!

Delaunay, Grojean & GP (13).



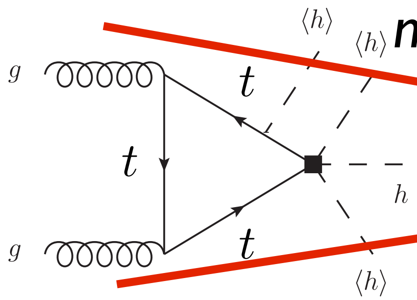
$\propto -vY^2/M^2$ **+**



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

+

negligible when light quark runs in the loop



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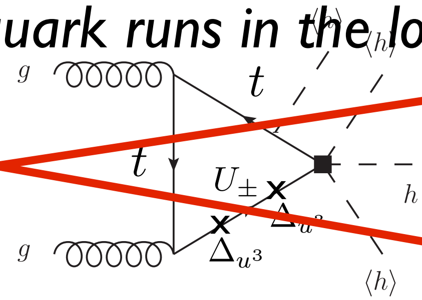


$\propto -vY^2/M^2 \times \Delta_{u^3}^2/M^2$

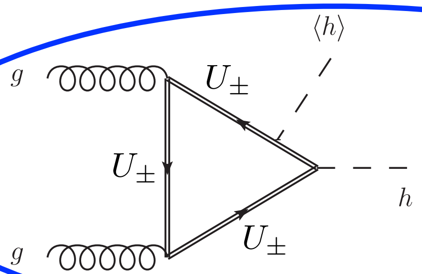
=

??

Cancellation for light composite quarks is ineffective!

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

Delaunay, Grojean & GP (13).



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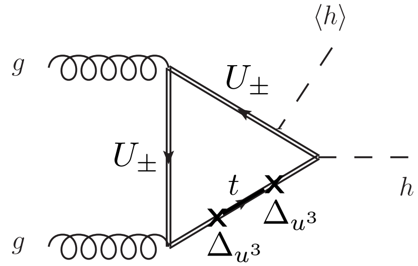

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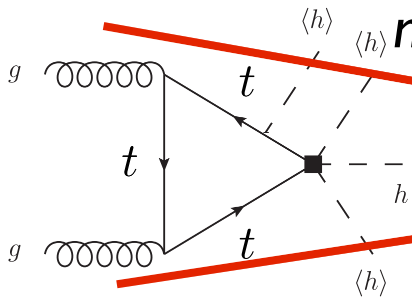

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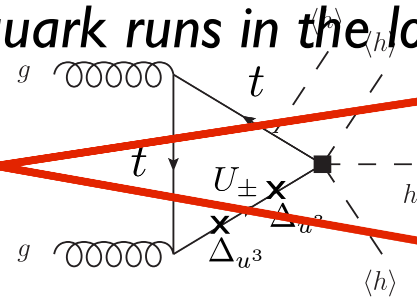

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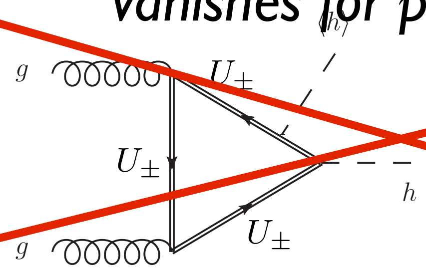
=

??

Cancellation for light composite quarks is ineffective!

Delaunay, Grojean & GP.

vanishes for pNGB Higgs



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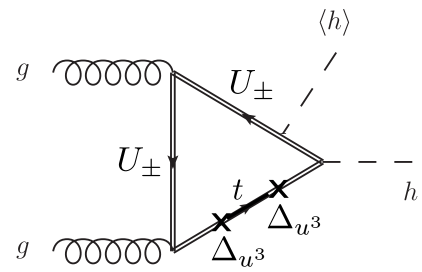

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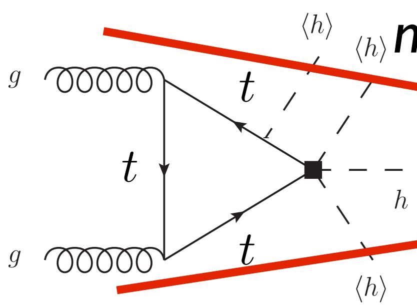

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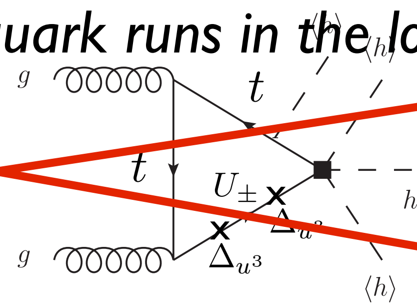

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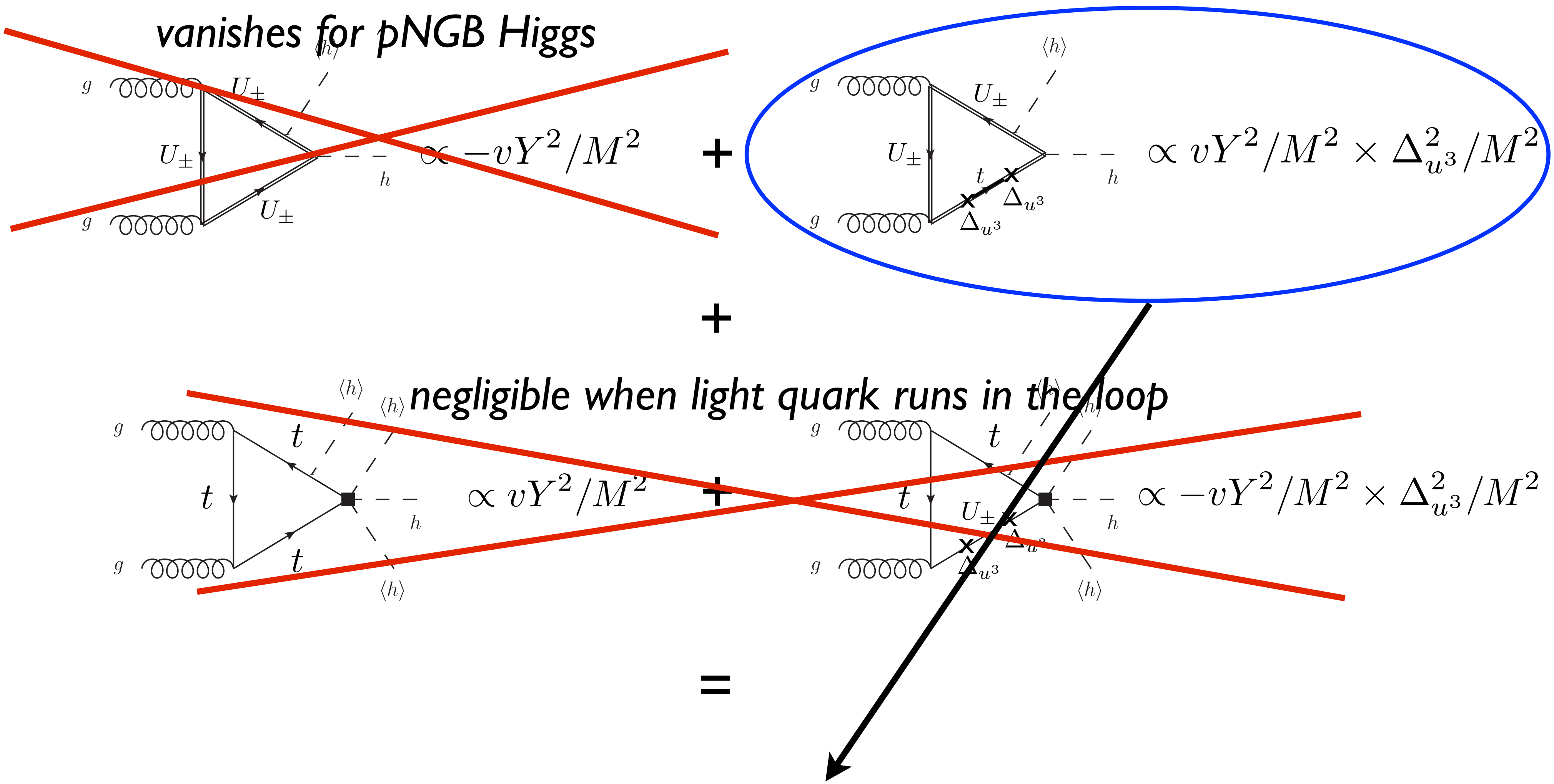
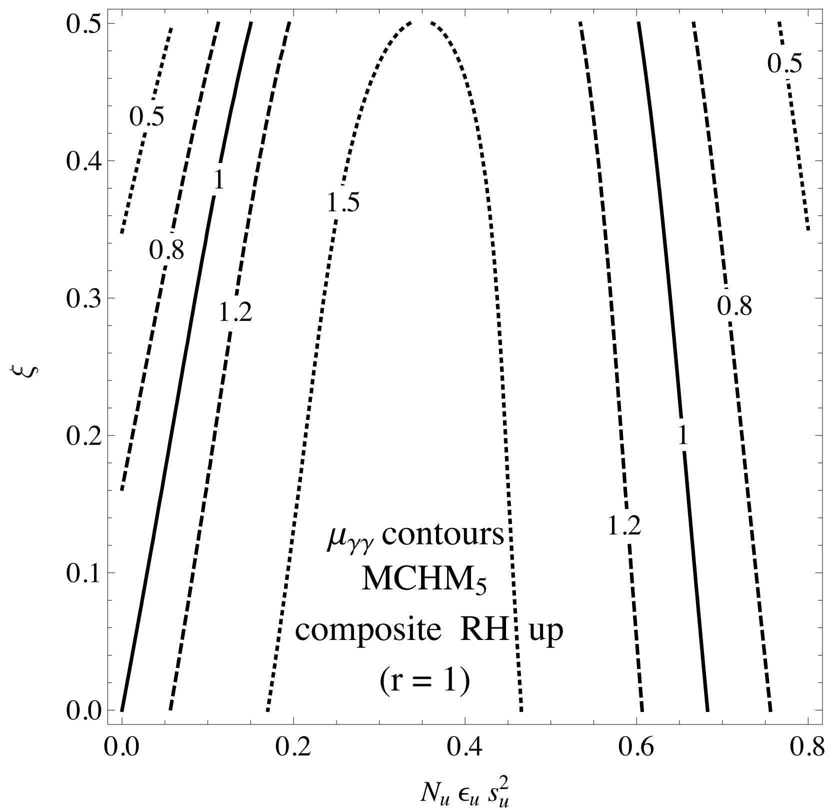


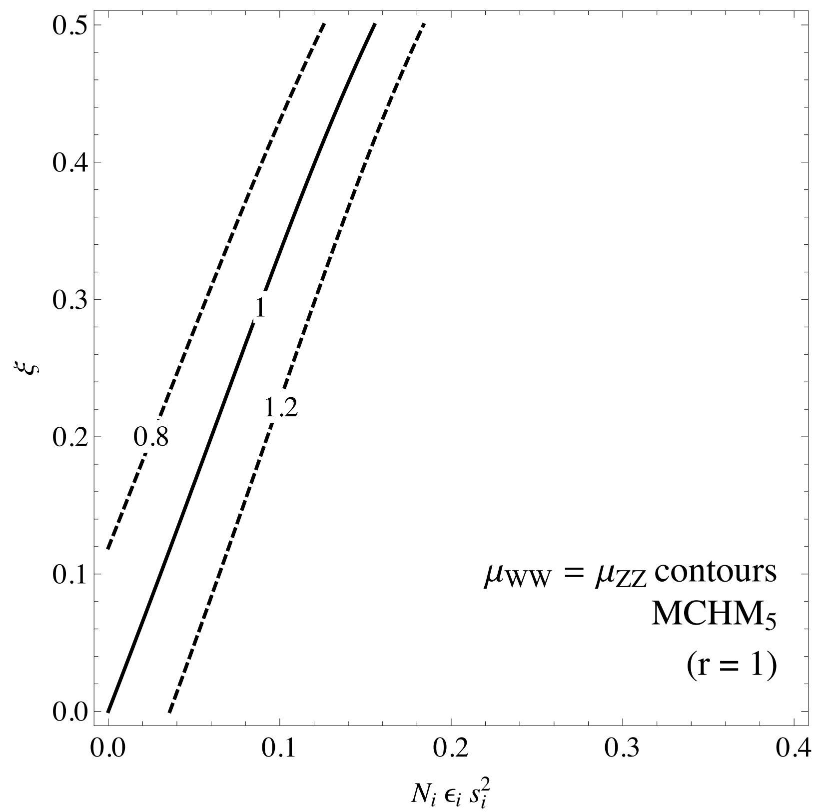
Sizable corrections for composite light quarks!

Composite light quarks & pseudo Goldstone boson Higgs

Delaunay, Grojean & GP,.

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





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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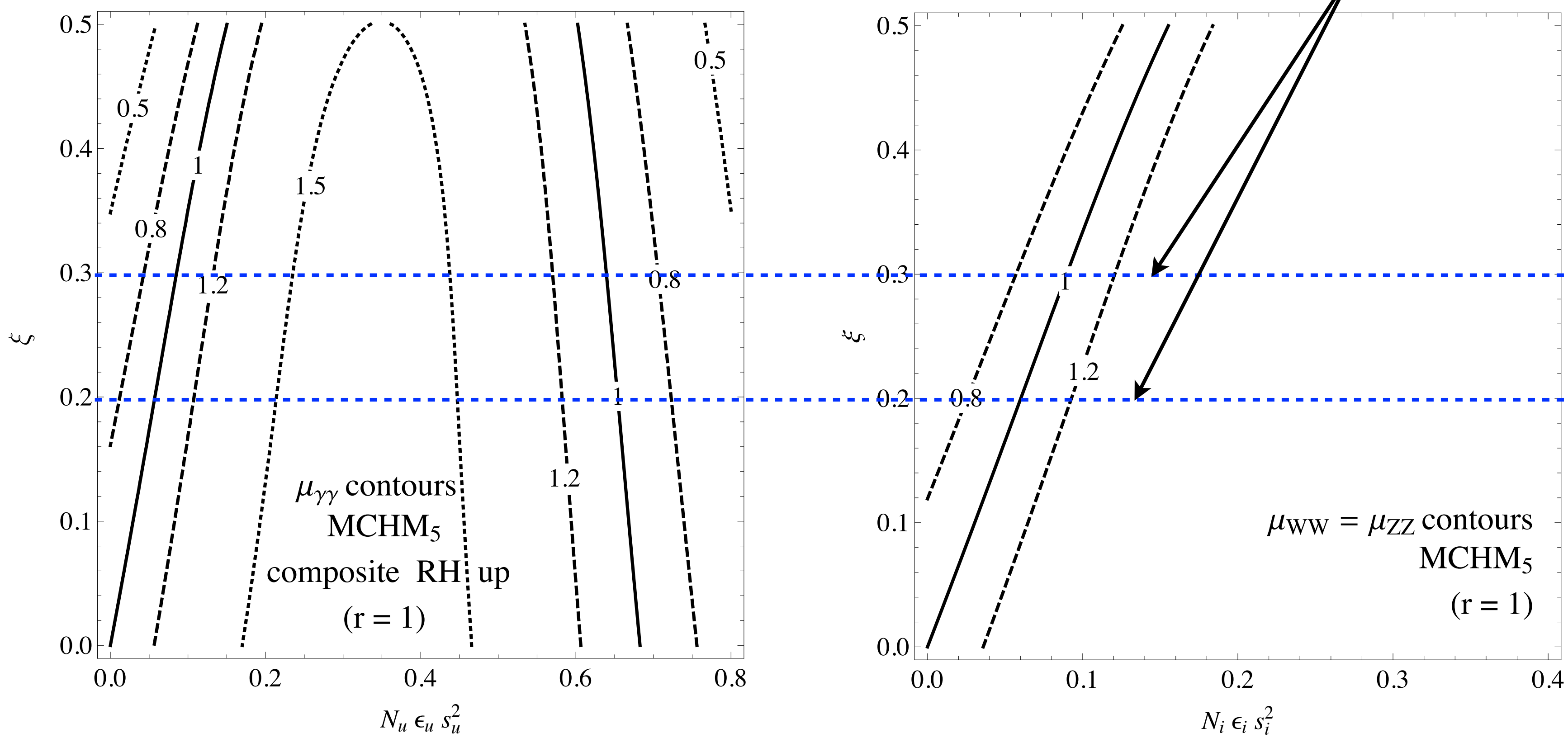
Interesting theoretically



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Composite light quarks & pseudo Goldstone boson Higgs

...jean & GP (13)

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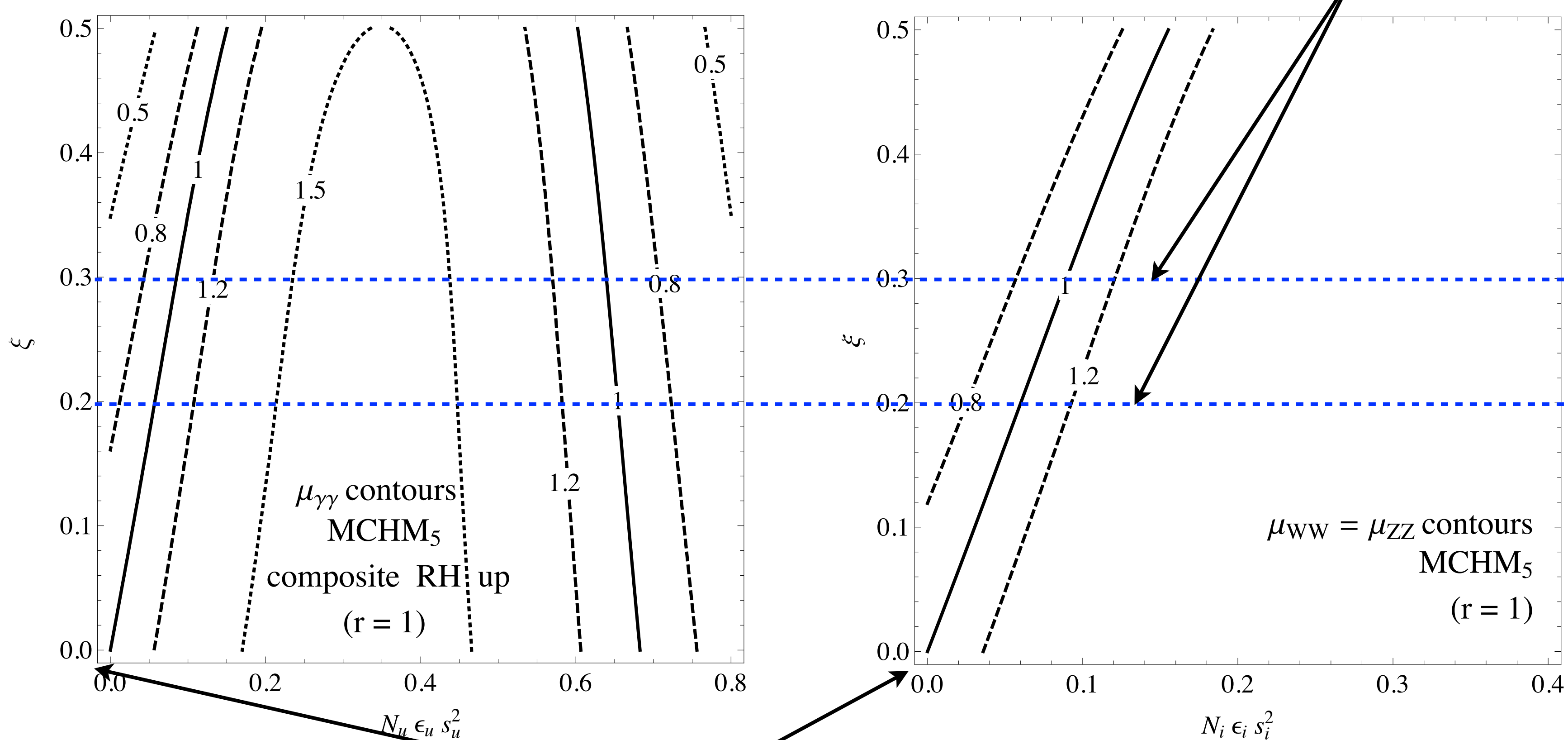
Interesting theoretically



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

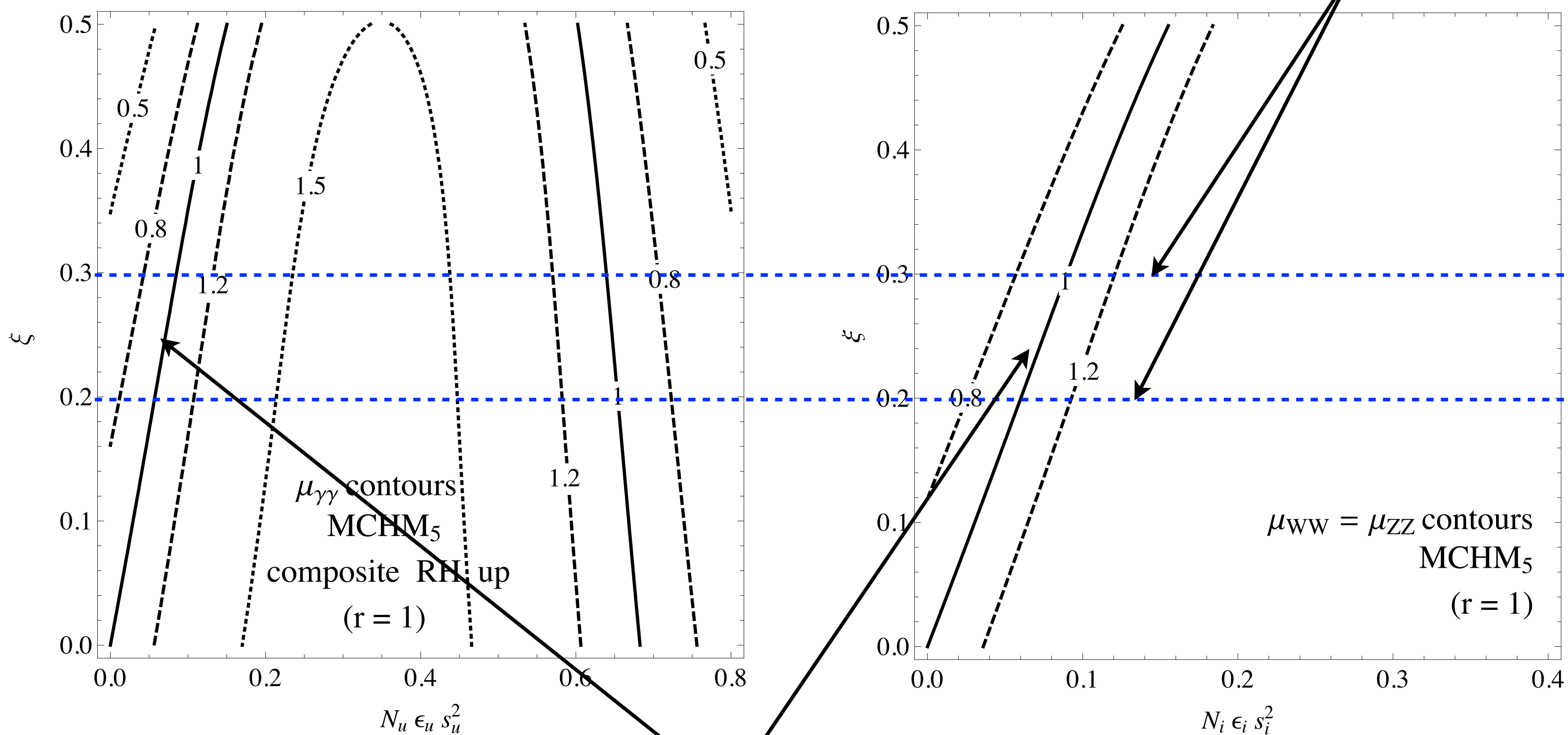
\wo mixing favorable region of Higgs "non-linearity" excluded.

Ciuchini, Franco, Mishima & Silvestrini; Grojean, Matsedonskyi & Panico (13)

Composite light quarks & pseudo Goldstone boson Higgs

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

Interesting theoretically



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

with composite light quarks a reasonable allowed region

Delaunay, Grojean & GP, (13).

Charming the Higgs

Delaunay, Golling, GP & Soreq, (13)

Charming the Higgs

- Currently not much known directly on the charm Yukawa:

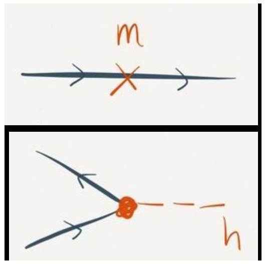
  (i) SM - $y_c = m_c/v \sim 0.4\ \%$ => $BR(H \to c\bar{c}) \sim 4\%$, very non-trivial to observe…

  See: Bodwin, Petriello, Stoynev & Velasco (13), for charmonia production.

- However, as $y_b \sim 2\ \%$ and $BR(H \to b\bar{b}) \sim 60\%$ Higgs collider pheno' is susceptible to small perturbation.

- Enlarging charm Yukawa by few leads to dramatic changes, for instance:

$$\mathcal{L}_{\rm EFT} \supset \lambda^u_{ij}\bar{Q}_i\tilde{H}U_j + \frac{g^u_{ij}}{\Lambda^2}\bar{Q}_i\tilde{H}U_j\left(H^\dagger H\right) + \text{h.c.}$$



$$= \frac{v}{\sqrt{2}}\left(\lambda^u_{ij} + g^u_{ij}\frac{v^2}{2\Lambda^2}\right),$$

$$= \frac{1}{\sqrt{2}}\left(\lambda^u_{ij} + 3g^u_{ij}\frac{v^2}{2\Lambda^2}\right).$$

$$\mathcal{L}_0 = \frac{h}{v}\Big[c_V\left(2m_W^2 W^+_\mu W^{\mu -} + m_Z^2 Z_\mu Z^\mu\right) - \sum_q c_q m_q \bar{q}q - \sum_\ell c_\ell m_\ell \bar{\ell}\ell\Big],$$

$$\Lambda \simeq \frac{44\ \text{TeV}}{\sqrt{c_c - 1}}$$

Charming the Higgs, current status & projections

- Current bounds are from Higgs "invisible" bound:

if all other "visible" couplings set to SM values:

Br_{inv} ~< 22% @95%CL

adding a new physics source of ggh: Br_{inv} ~< 50% @95%CL

Falkowski, Riva & Urbano (13)

BR($H \to bb$) is significantly suppressed:

$$\mathrm{BR}_{h\to b\bar{b}} = \frac{\mathrm{BR}^{\mathrm{SM}}_{h\to b\bar{b}}}{1+(|c_c|^2-1)\mathrm{BR}^{\mathrm{SM}}_{h\to c\bar{c}}}\,. \approx 40\%\ (20\%)$$

with c_{gg}>0

assume instead a speculative ε_c=40% c-tagging efficiency:

→ $\mu_{bb+cc} \approx 0.9\ (0.6)$ @8TeV

Perspective: The LHC (10yrs) naturalness ruler

tuning ~ 1:10

$\mathrm{LHC8}: \; m_{\tilde{t}} \sim 700\,\mathrm{GeV}$

natural SUSY

$m_{\tilde{t}} \sim 400\,\mathrm{GeV}$

tuning ~ 1:10^2

$\mathrm{LHC14}: \; m_{\tilde{t}} \sim 2\,\mathrm{TeV}$