Flavorful Naturalness, the Top Charm Frontier

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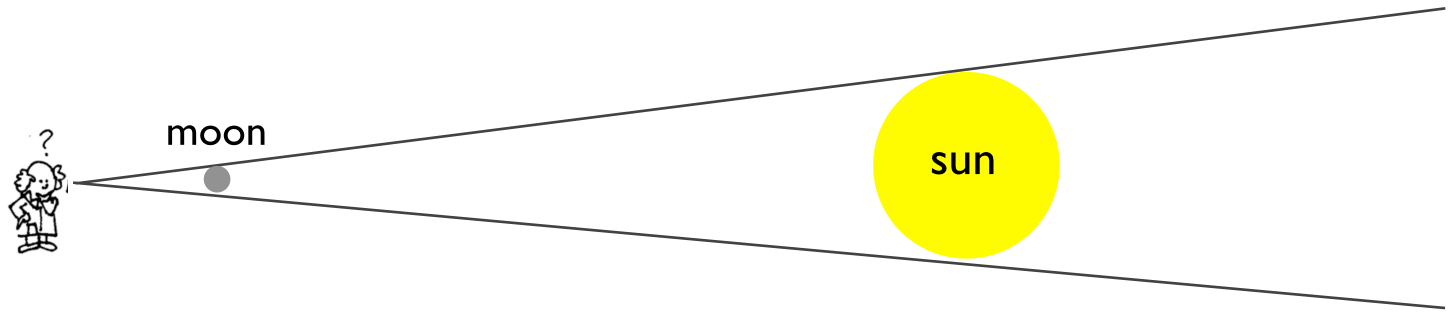
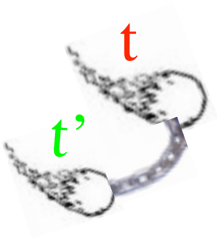
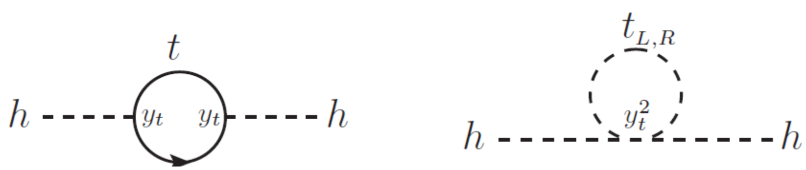
Rational

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







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

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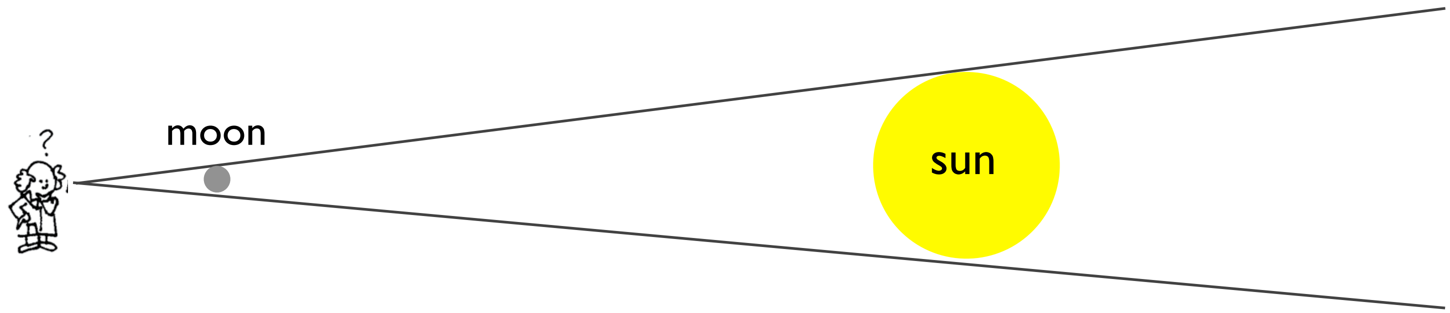

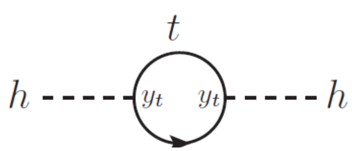

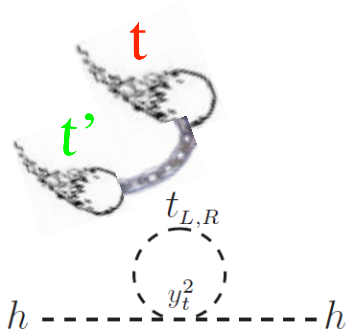

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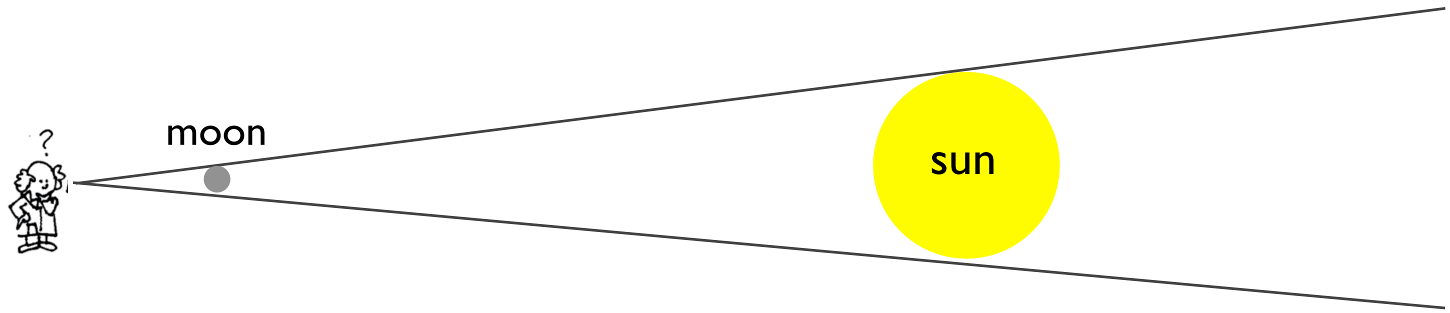

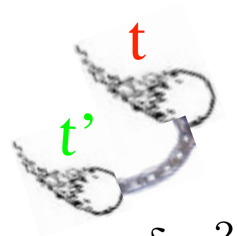

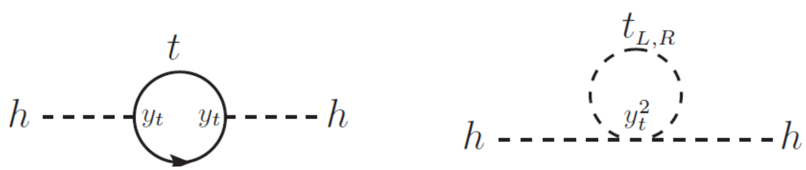

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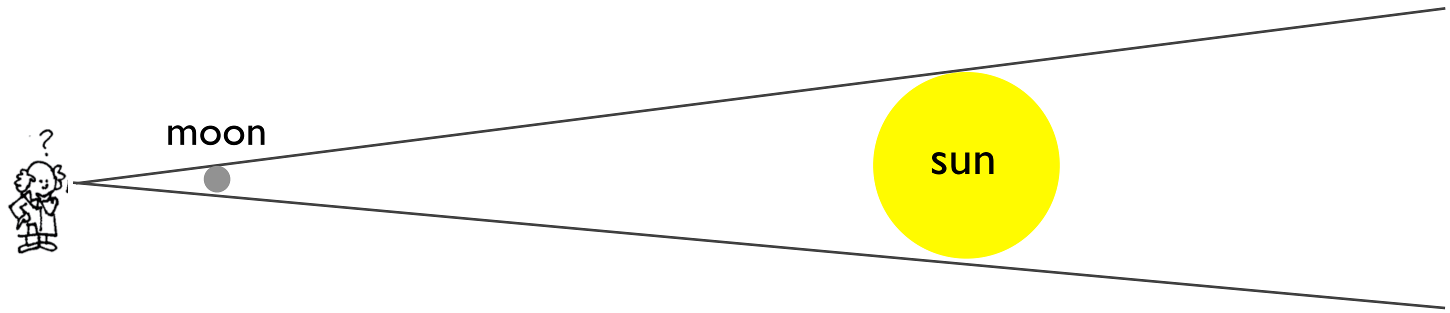

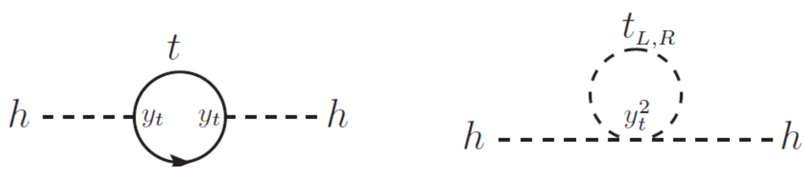

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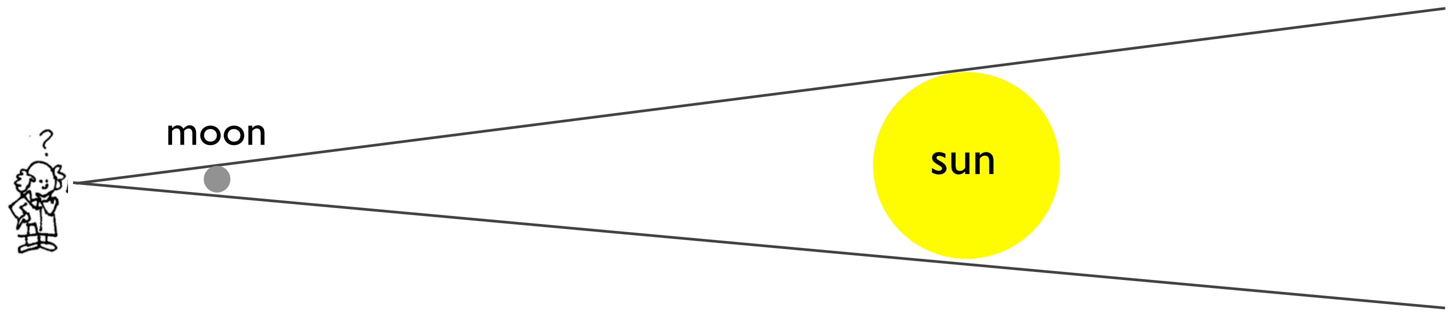

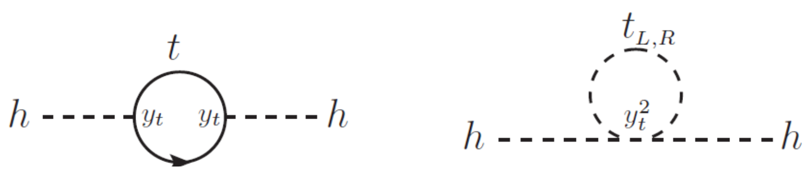

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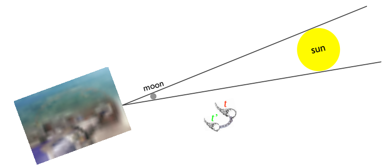
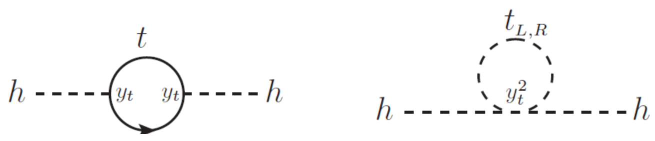
Top partners & LHC Searches

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

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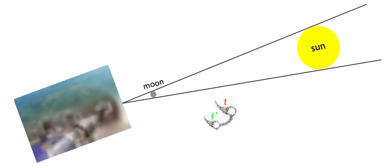

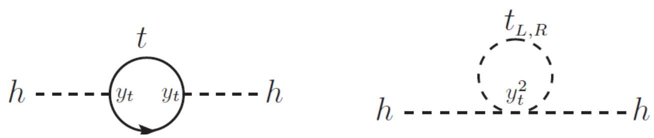

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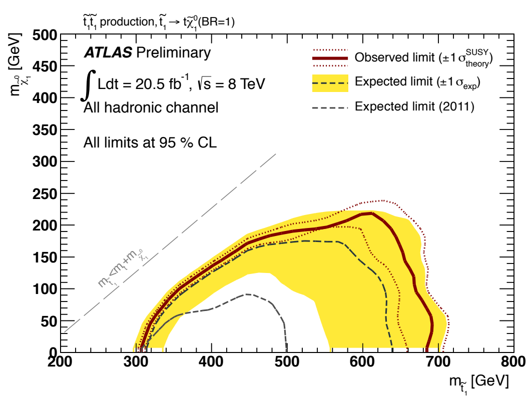
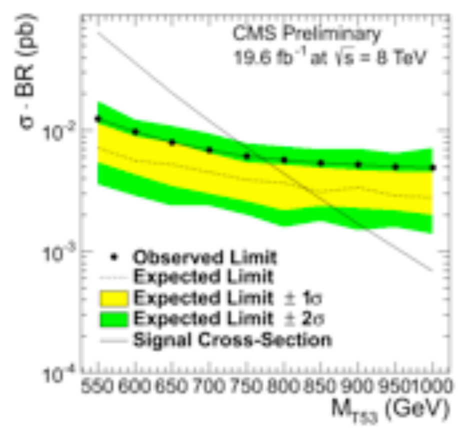
2 leading frameworks of naturalness

SUSY

composite Higgs



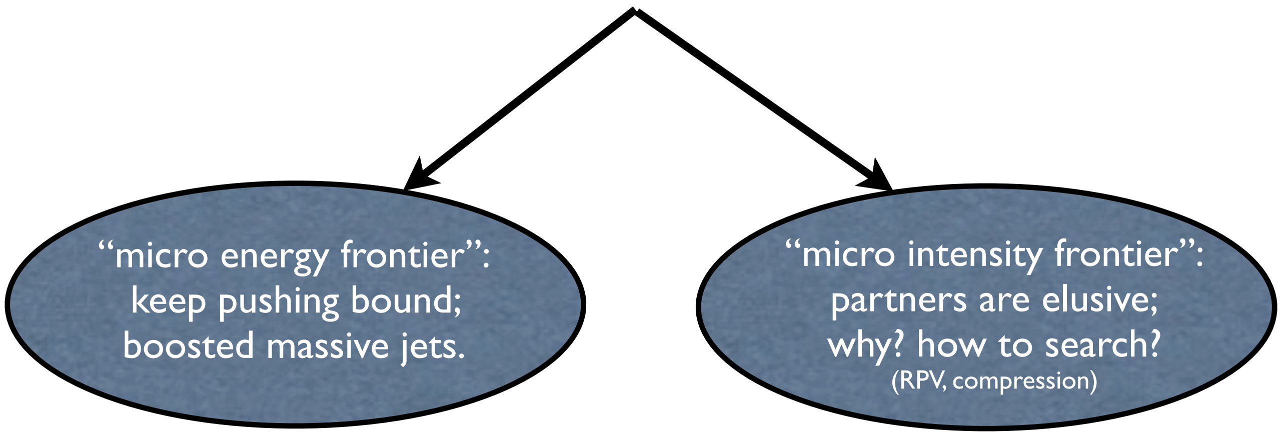
$m_{\text{stop}} \gtrsim 700\,\text{GeV}$



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

The LHC Battle for Naturalness

LHC8: where are the partners ??



Today's talk:

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

Partner are elusive because of non-trivial flavor physics effects that were conveniently ignored!

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

Outline (2 "flavorful" roads towards naturalness)

- Supersymmetric "flavorful naturalness":

  (i) Light non-degenerate squarks at the LHC (& LHCb);

  (ii) Impact of stop-scharm mixing on effective/visible fine tuning.

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

  (i) Models \w composite right handed quarks are viable;

  (ii) Higgs couplings: *t*-partner cancellation effects (& non-linearities);

  modified LHC Higgs Physics from composite light flavors.

- Summary.

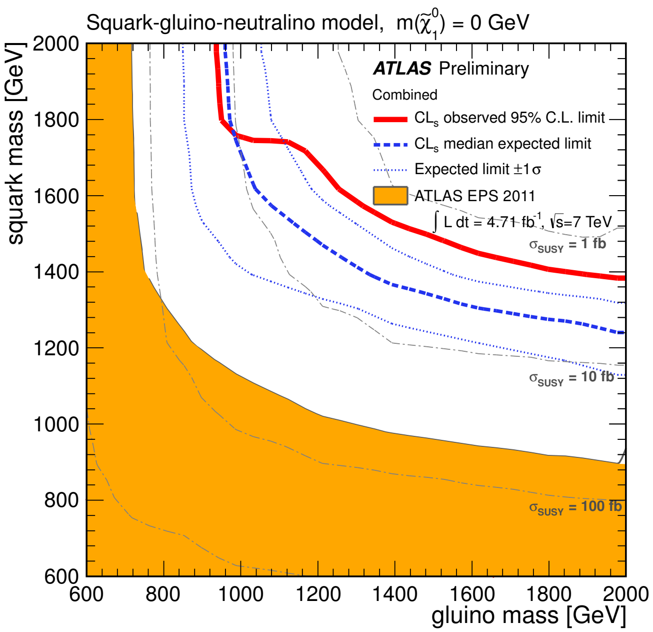
Supersymmetric Flavorful Naturalness

(some implications of split first two generation squark spectrum)

Current status of Supersymmetry

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

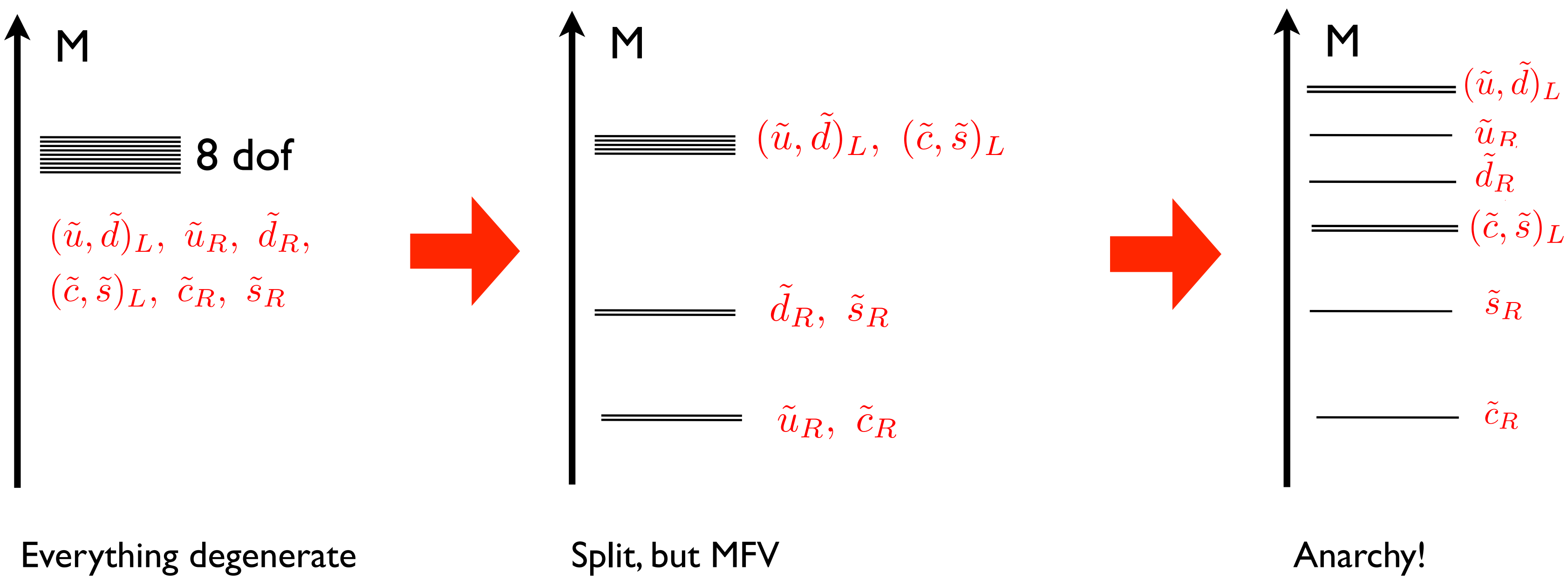
Summer bounds from ATLAS & CMS (*Etzion , Moortgat;* recent data shown yesterday):

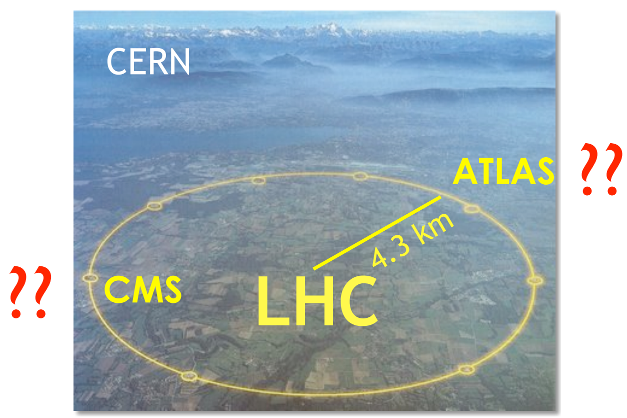


Light squarks > 1.4 TeV?

What if first 2 generation squark not degenerate?

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





What drives the experimental limits?

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

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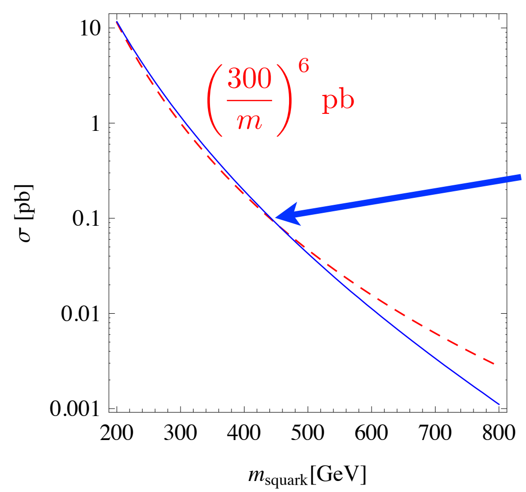
Multiplicity: how bound changes when one doublet is made lighter ?

Cross-sections vs. mass

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



(gluino decoupled)

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

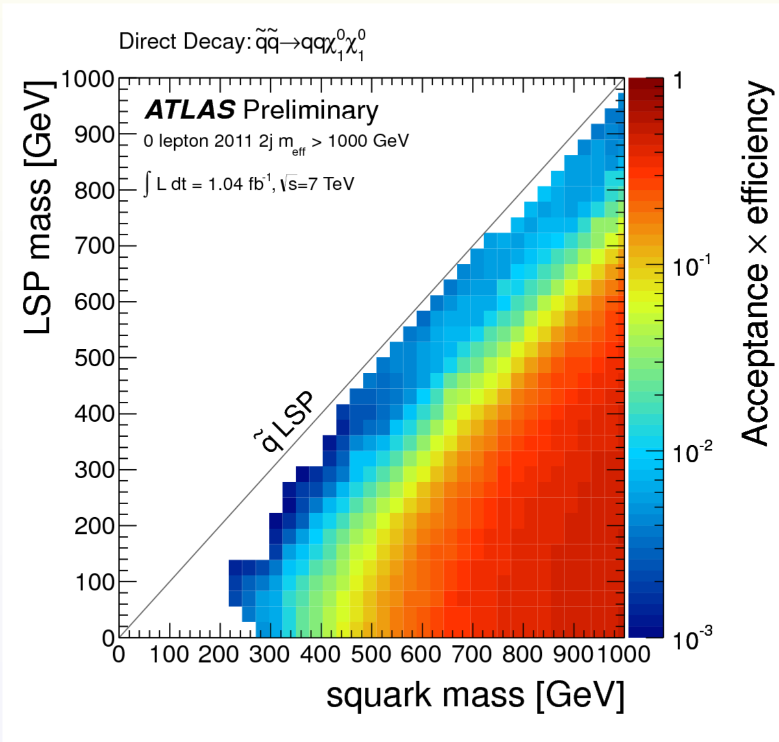
$$(m_L/m_H) = (1/4)^{1/6} \sim 0.8$$

gain is marginal

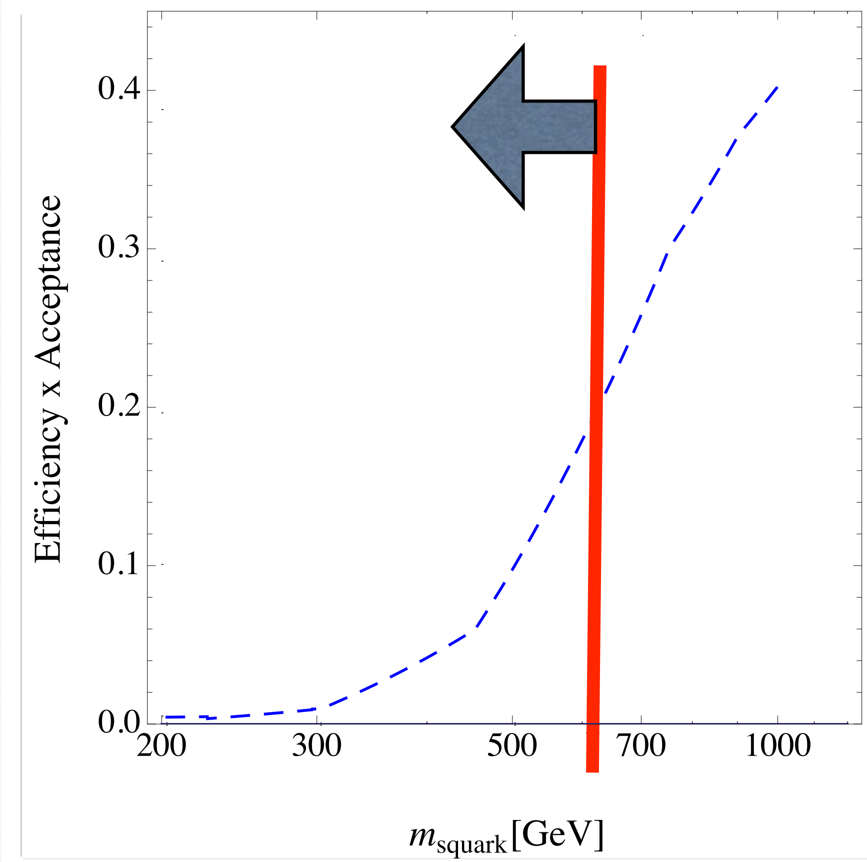
Efficiencies, strong mass dependence!

Signal efficiency falls very rapidly with decreasing squark mass

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



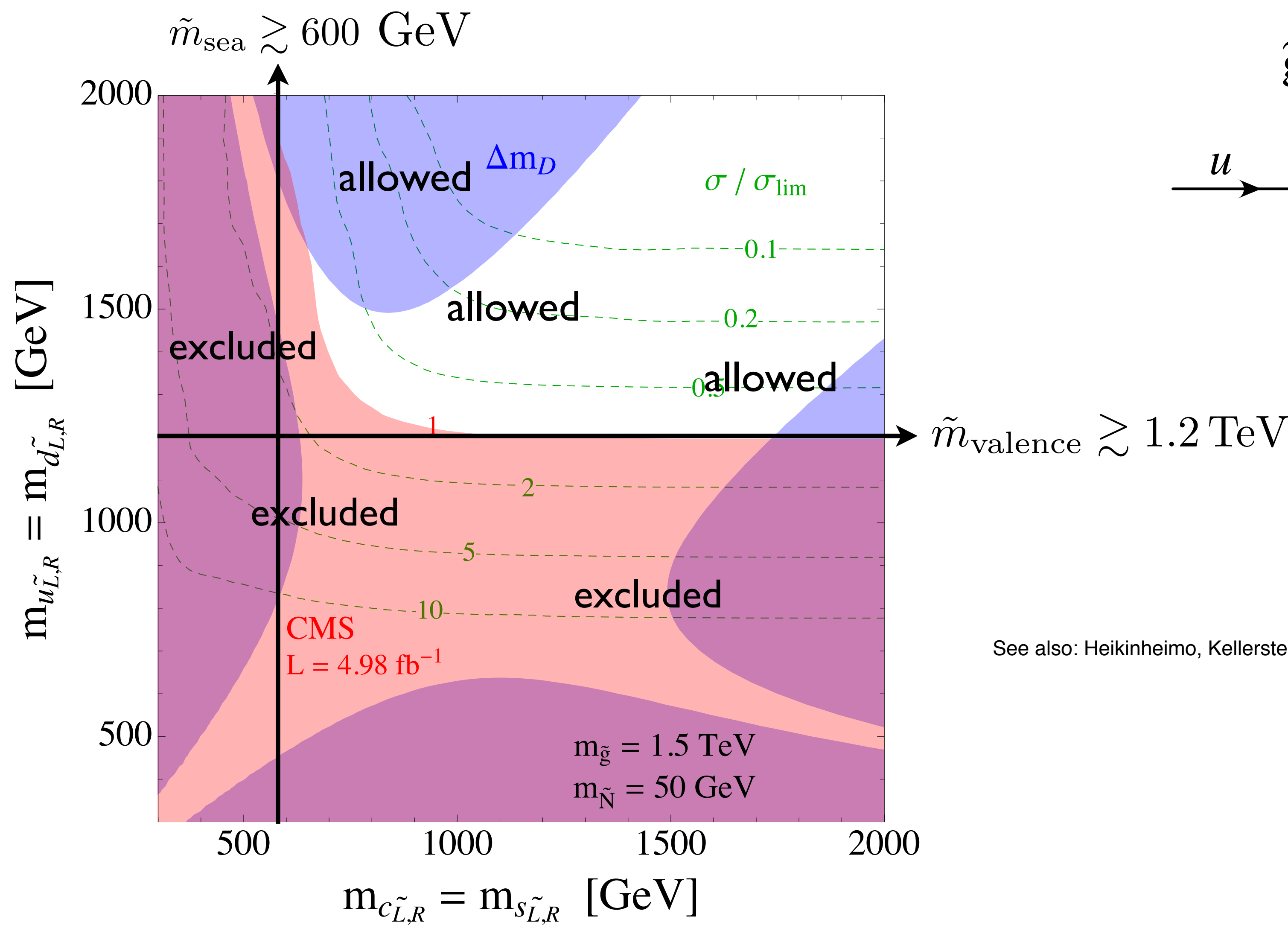
ATLAS 1/fb,
2jet M_{eff}>1TeV



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!

sea vs. valence



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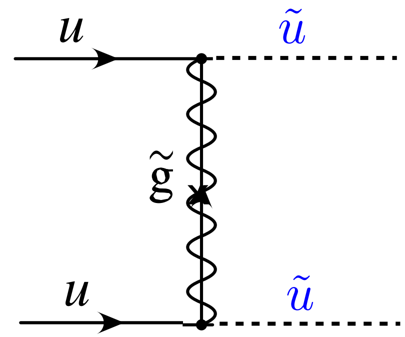
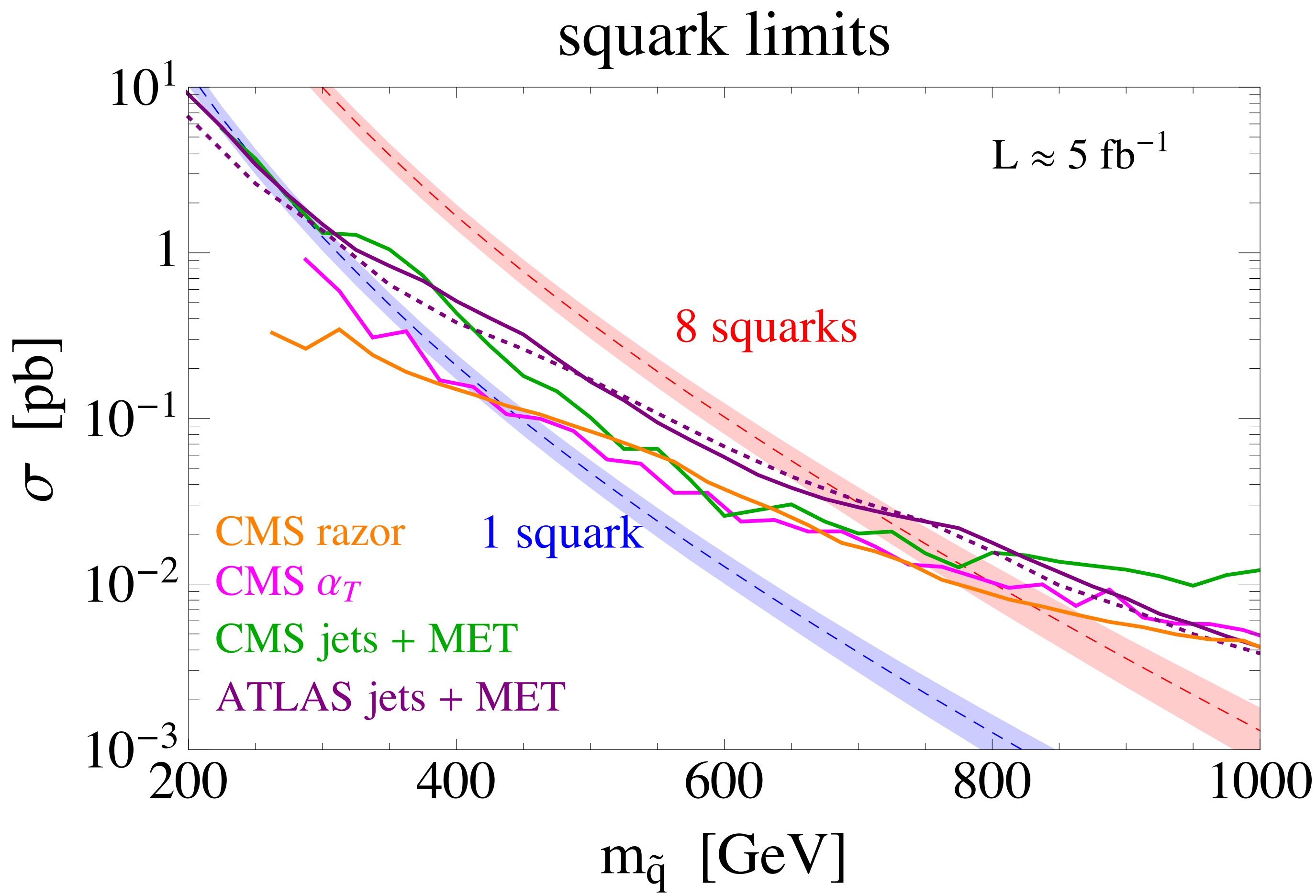


See also: Heikinheimo, Kellerstein & Sanz (11); Kribs & Martin (12),

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



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

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

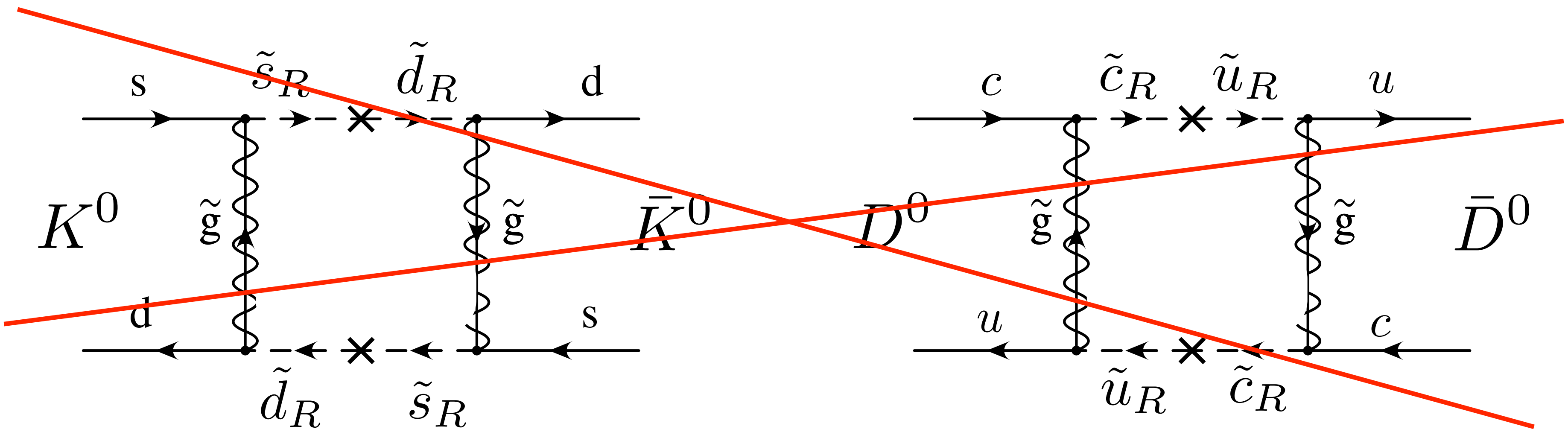
Let us focus on the low energy, model indep', effective story.

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

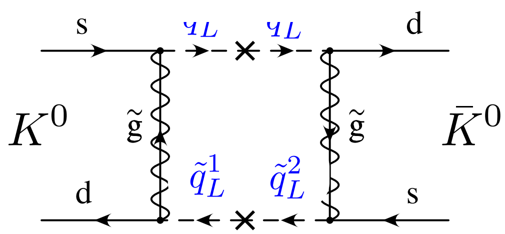
- SM LH sector consist of 2 flavor breaking sources: $Y_d Y_d^\dagger \ \& \ Y_u Y_u^\dagger$

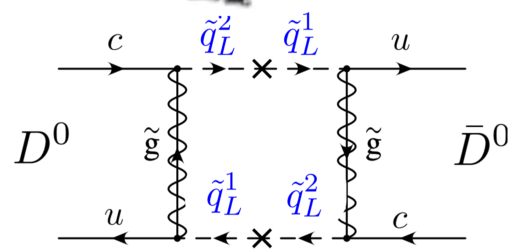
- SUSY: cannot align LH masses simultaneously with both sources! Dangerous direction wins to reduce bounds ...

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

$\Delta M_K, \epsilon_K$

$\Delta M_D, A_\Gamma^D$





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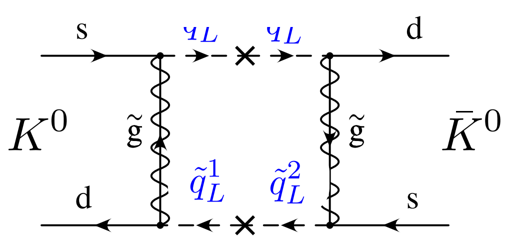

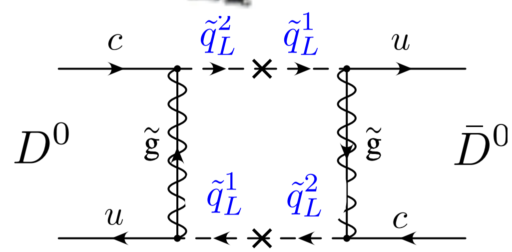

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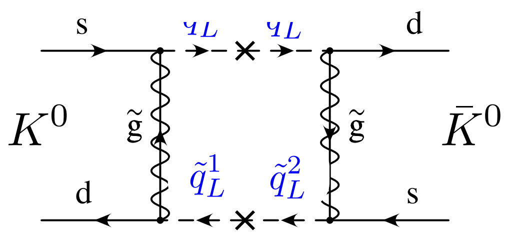

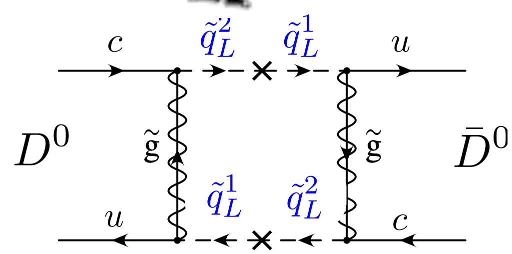

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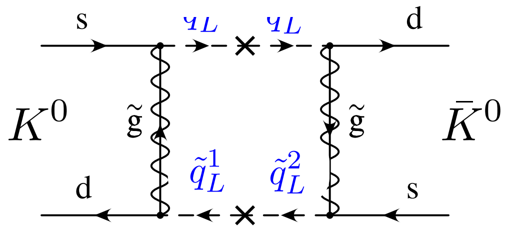

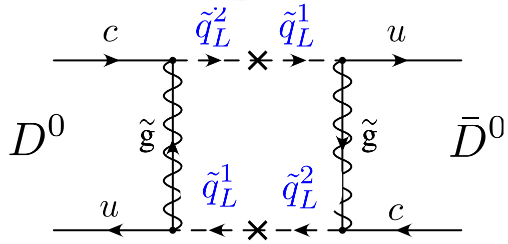

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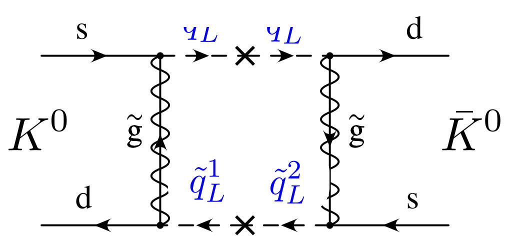

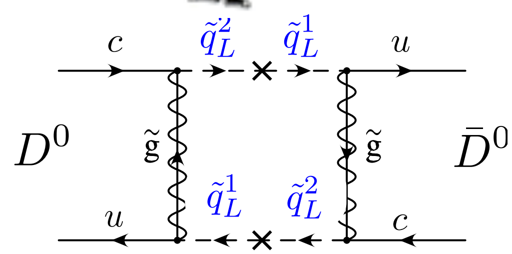

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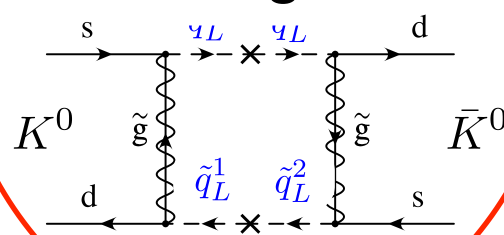
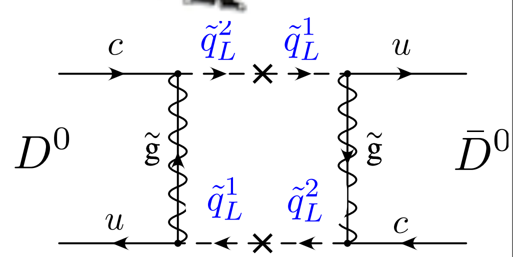
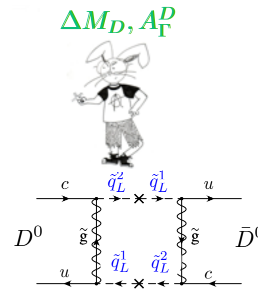
Nir & Seiberg (93)

down alignment





Last 4 yrs: dramatic progress in studying charm CPV



SUSY implications: no hope for non-degeneracy ...

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

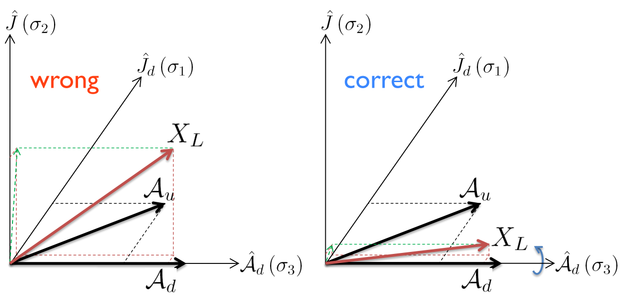
(squark doublets, gluino, 1TeV)

Blum, Grossman, Nir & GP (09)

With phases, first 2 gen' squark need to have almost equal masses.
Looks like squark anarchy/alignment is dead!

However ...

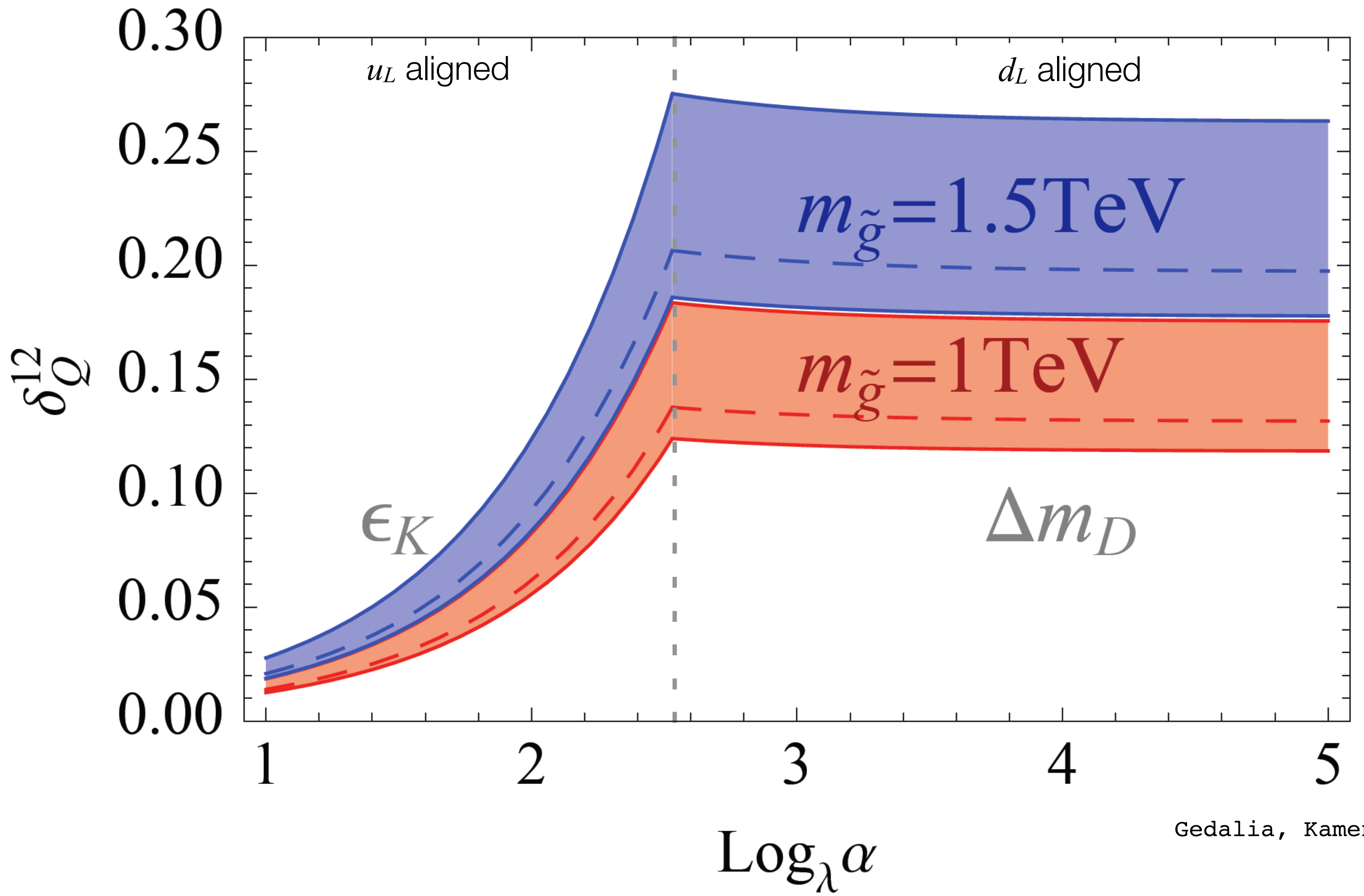
Successful alignment models guarantee small physical CP phase!



Gedalia, Kamenik, Ligeti & GP (12);

Formalism: Gedalia, Mannelli & GP (10) x2

Degeneracy of Squarks



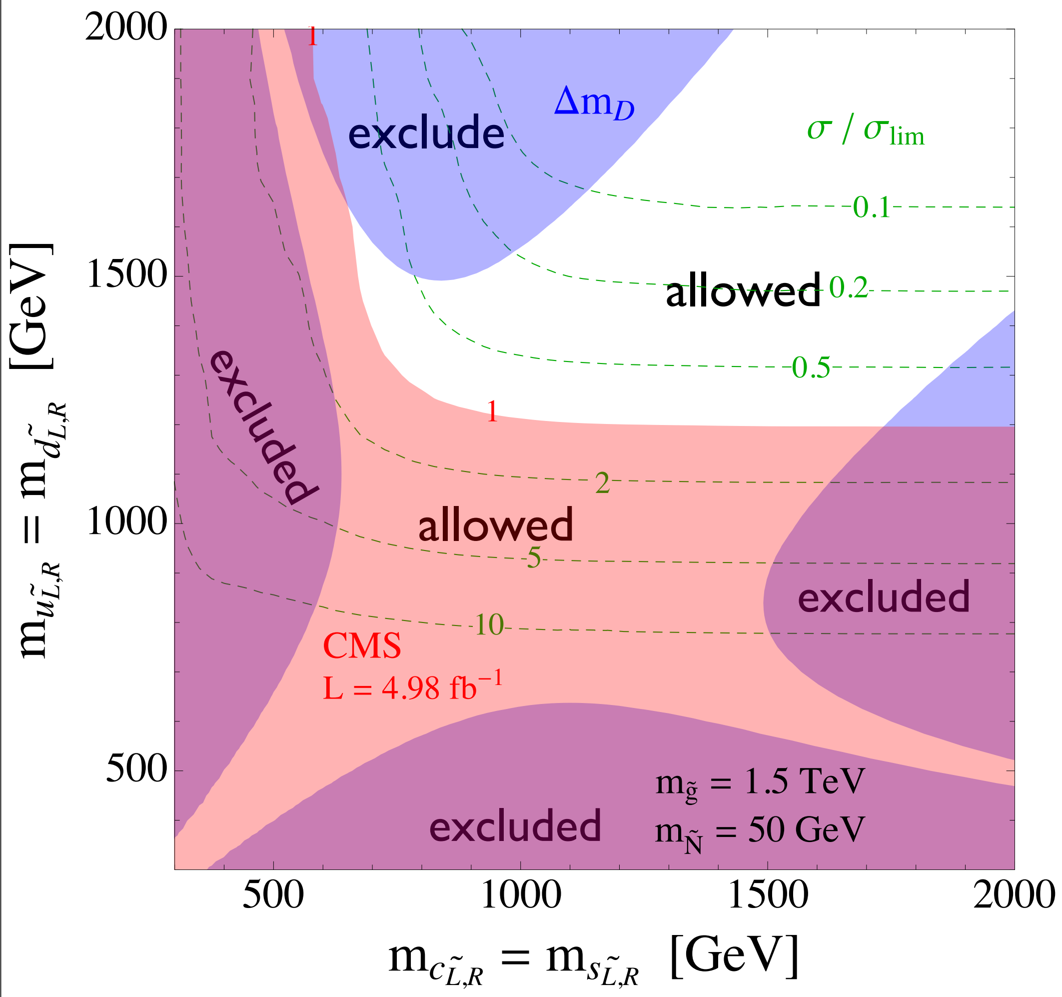
$$\delta_Q^{12} \equiv \frac{m_{\tilde{Q}_2} - m_{\tilde{Q}_1}}{m_{\tilde{Q}_2} + m_{\tilde{Q}_1}}$$

Gedalia, Kamenik, Ligeti & GP (12);

Sea LH squarks vs. valence RH squarks

Adding flavor constraints (Δm_D) for LH squarks:

Kadosh, Paride & GP, to appear;



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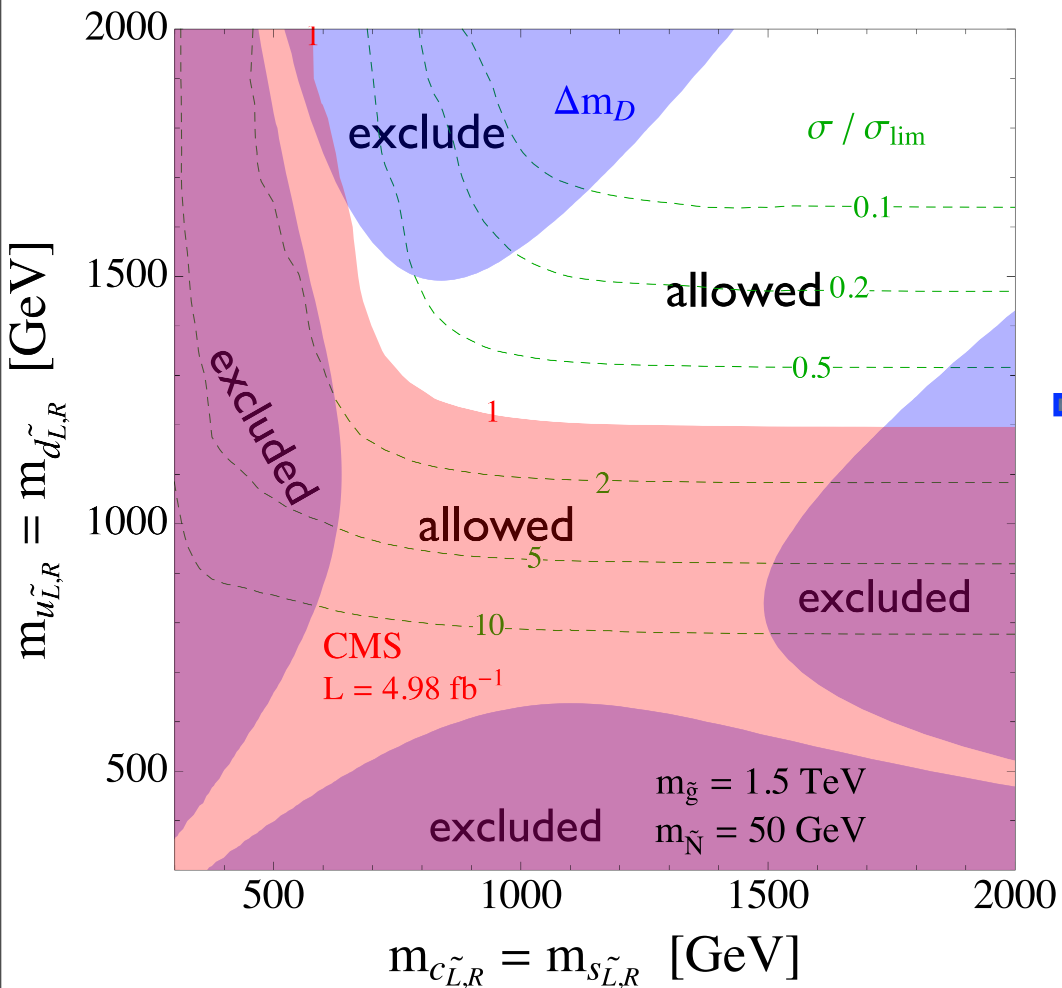

alignment: new upper bound on CP violation (CPV) in *D-phys.*:

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

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

LHCb soon start testing alignment paradigm!

Kadosh, Paride & GP, to appear.

Sea LH squarks vs. valence RH squarks

Adding flavor constraints (

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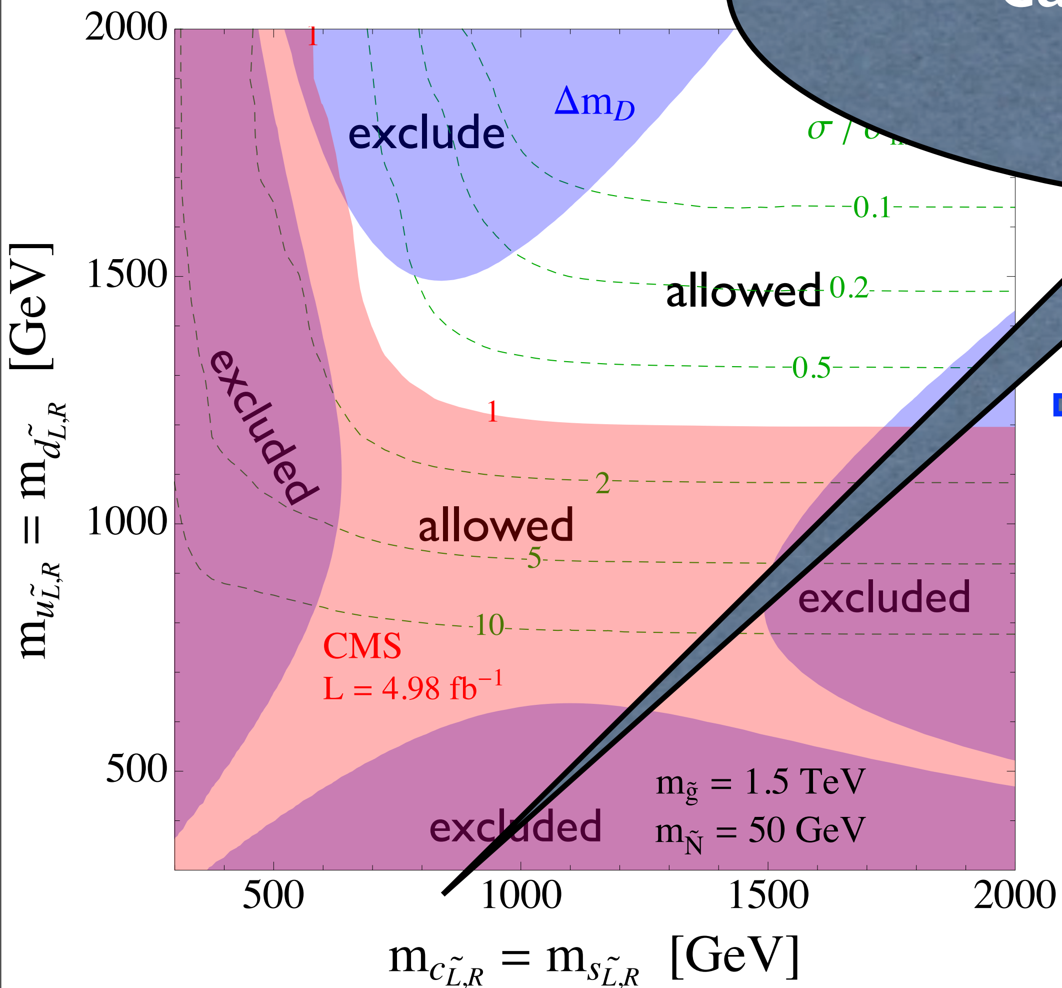

ATLAS & CMS can improve sensitivity via charm tagging !

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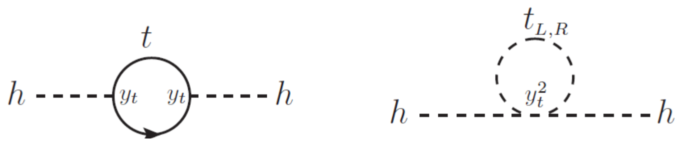
What is the impact of adding flavor violation on stop searches ? (flavored naturalness)

- 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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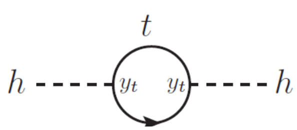
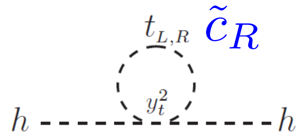
- Naively sounds crazy as worsening the fine tuning problem.





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

- However, just established the scharm can be light.

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

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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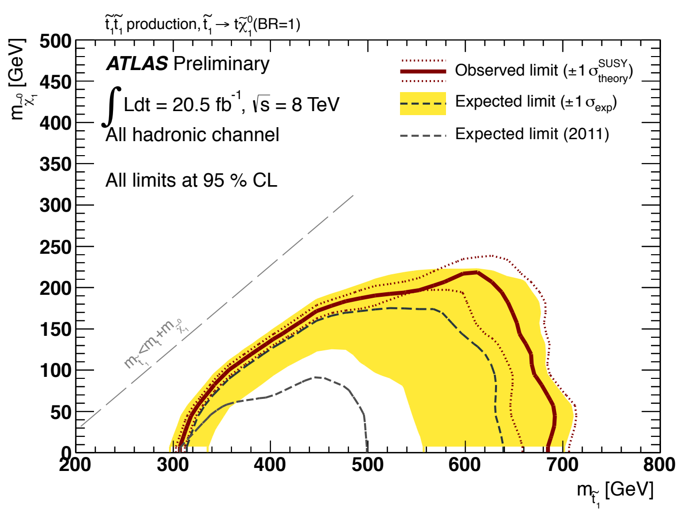

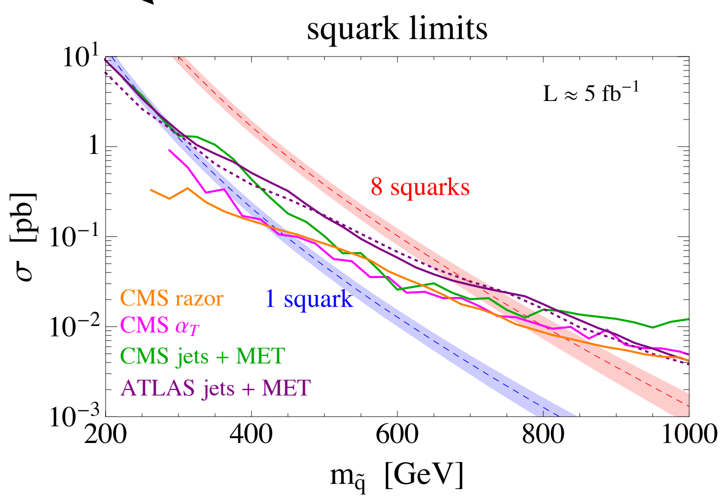

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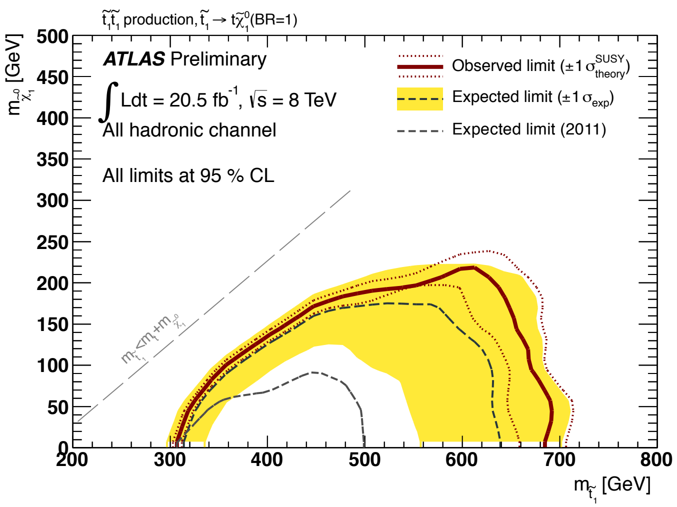

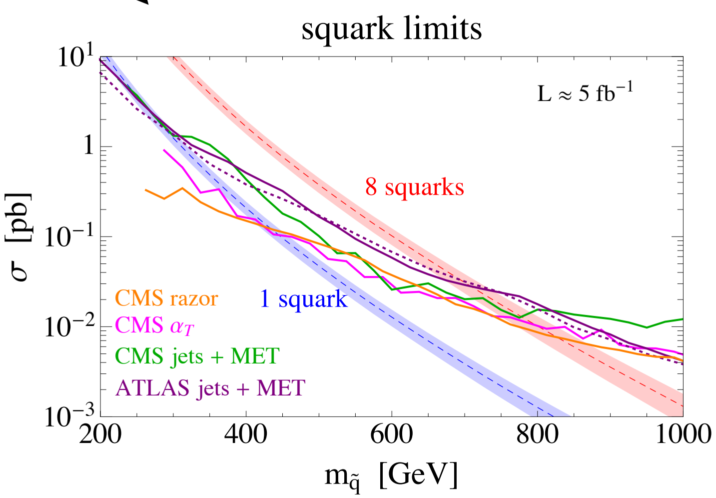

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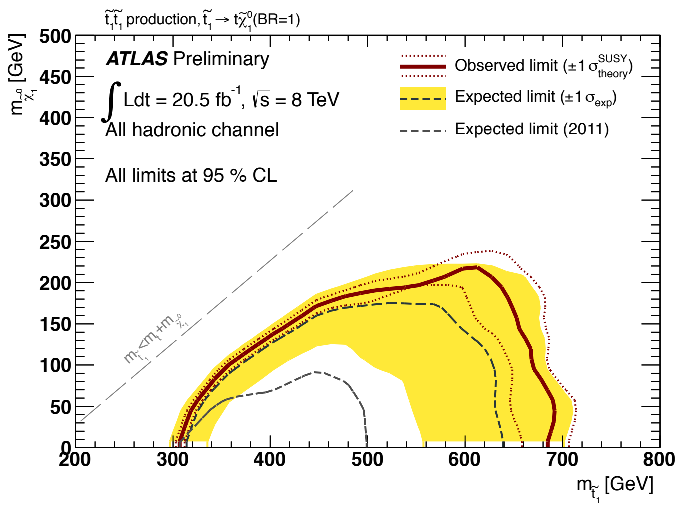
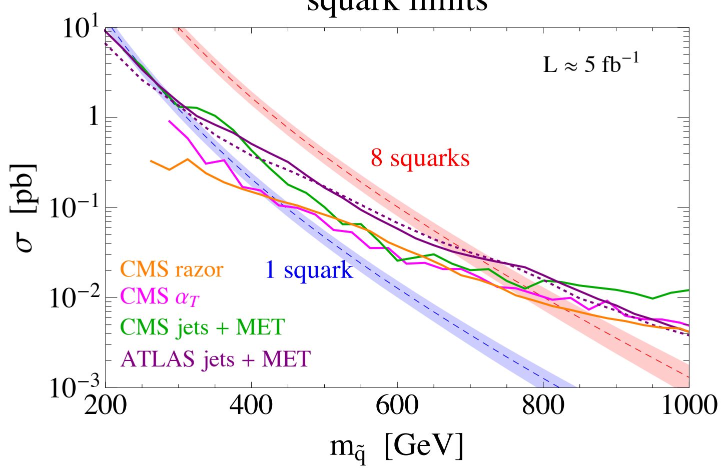
compromise



squark limits



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

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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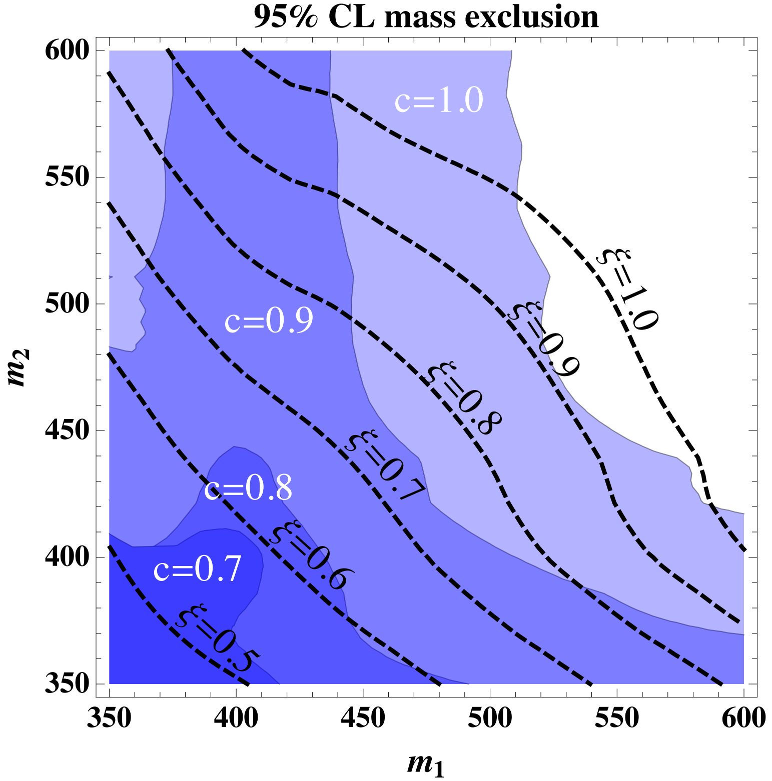

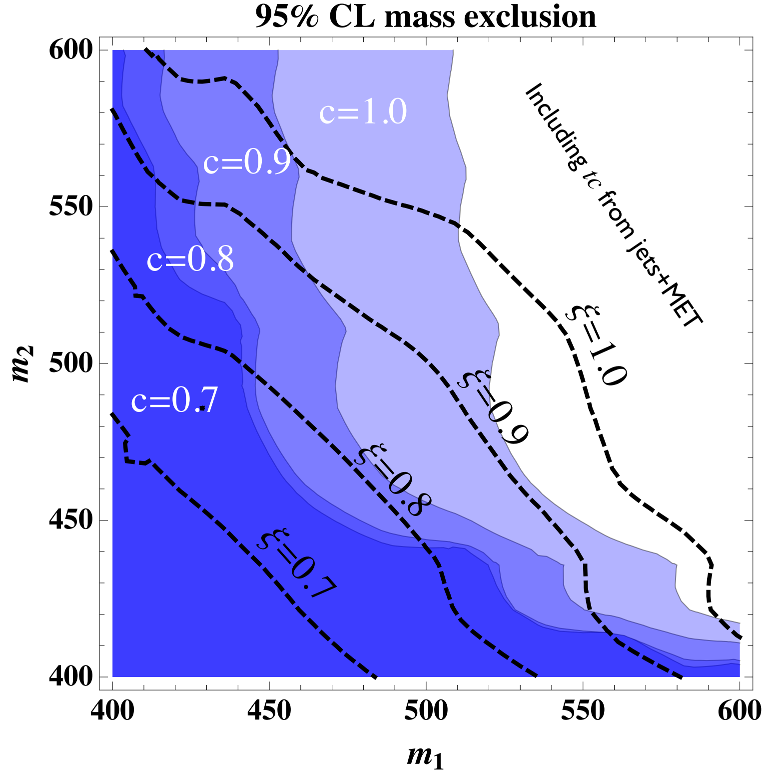

Can get $\xi \sim 0.5 - 0.8$ for $\theta_{23}^{RR} \sim 45^o$!

Summary, so far: supersymmetric flavorful naturalness

(some implications of split first two generation squark spectrum)

Can 2nd gen' squarks can be light?

Is it consistent with direct searches?

Is it consistent with indirect searches?

Can this be realized microscopically?

Can this be related to partner searches?

Is this scenario been looked for at the LHC?

Summary, so far: supersymmetric flavorful naturalness

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Can 2nd gen' squarks can be light?	Yes
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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).

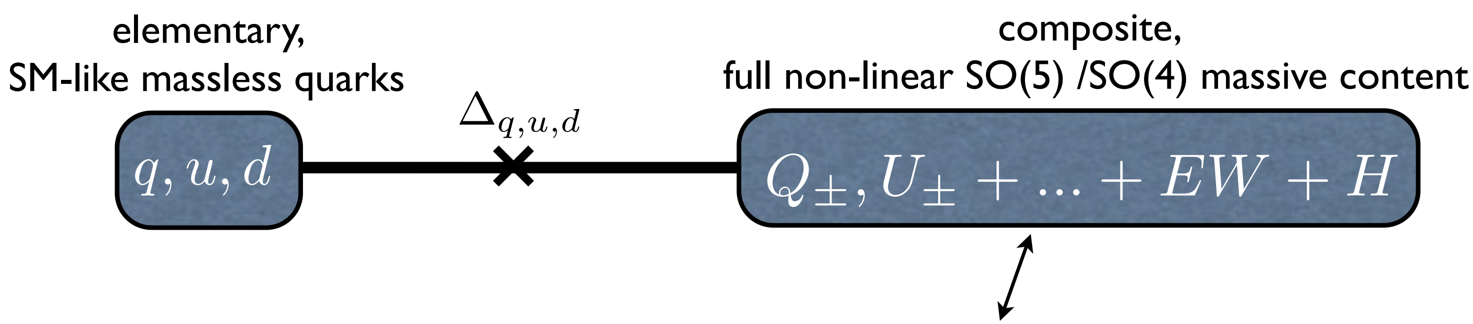
(ii) Repeat ex. using effective field theory (EFT).

(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 $\det \mathcal{M} = F(v/f) \times P(Y, M, f)$ $\Longrightarrow$ $\sigma_{gg\to h} = \sigma^{\rm SM}_{gg\to h}$

$F(0) = 0,$

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 ...

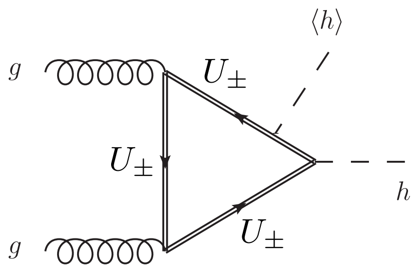
$$M_u = \begin{pmatrix} y_u^{00} v & 0 & y_u^{01} v \\ y_u^{10} v & m & y_u^{11} v \\ 0 & y_u^- v & m \end{pmatrix}$$

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

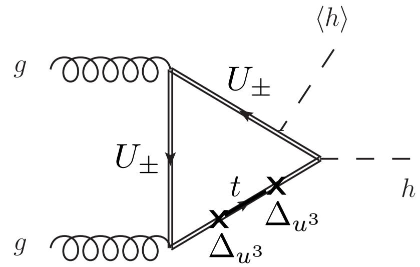
Cancellation of t-partners modification of Higgs rates, EFT:

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

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



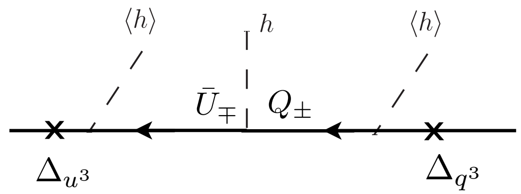
$\propto -vY^2/M^2$ **+**



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

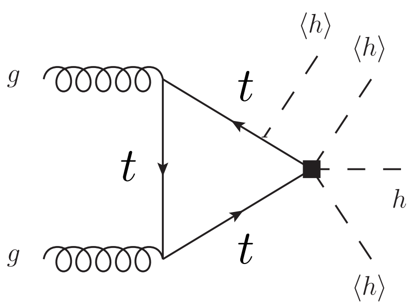
(ii) t-partner mix with the top-like SM fields, modifying their Yukawa:

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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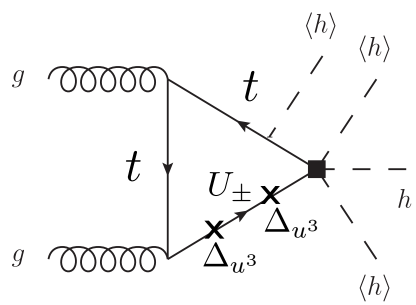

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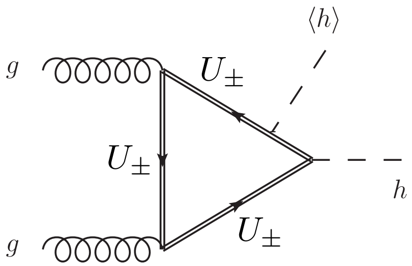
The cancellation of t-partners effects, adding all together



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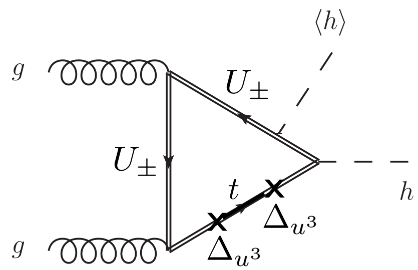

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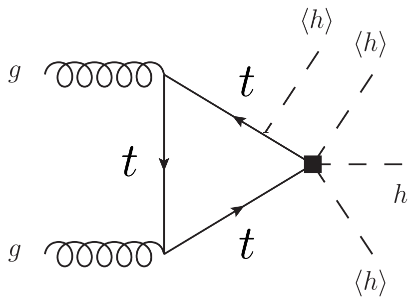

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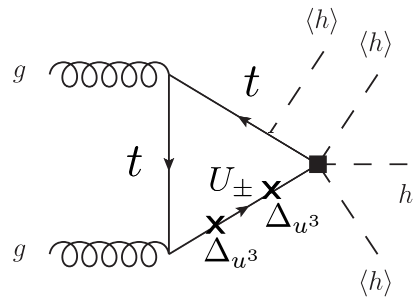

$\propto -vY^2/M^2 \times \Delta_{u^3}^2/M^2$

=

0

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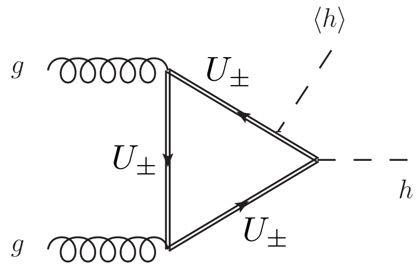

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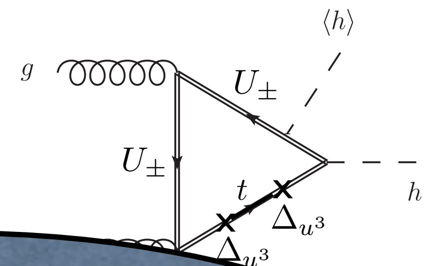

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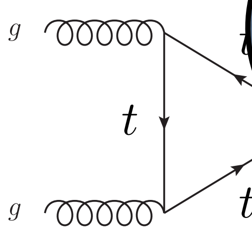

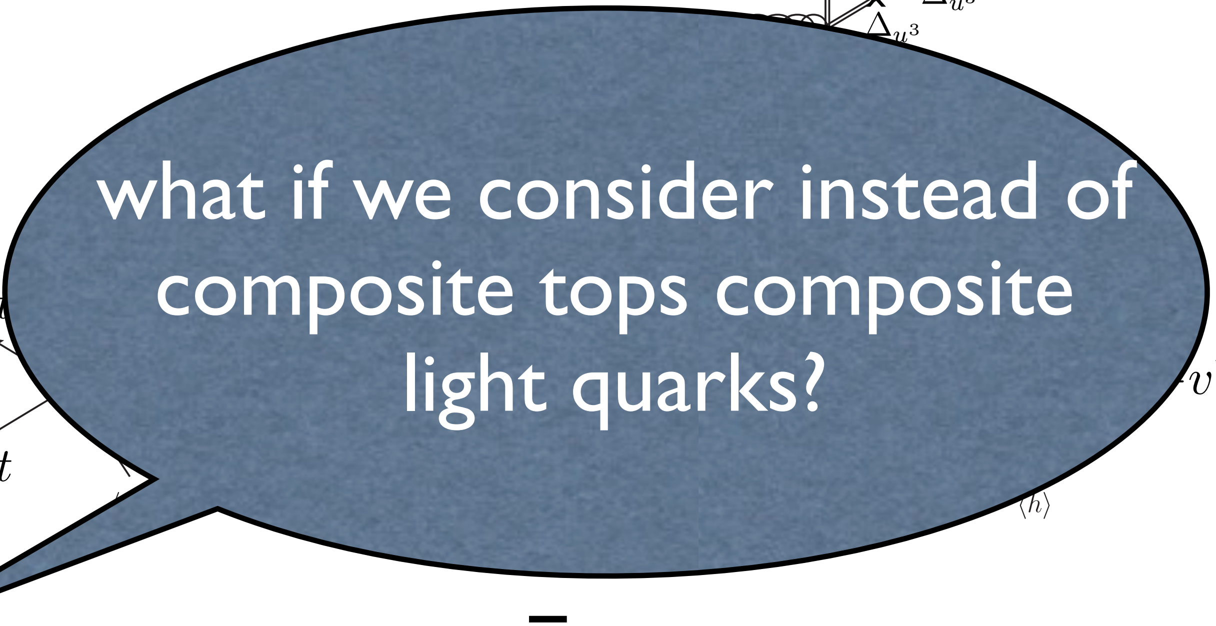

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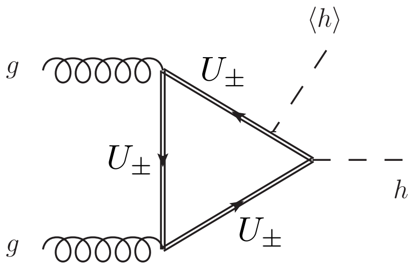
Cancellation for light composite quarks is ineffective!

Delaunay, Grojean & GP (13).



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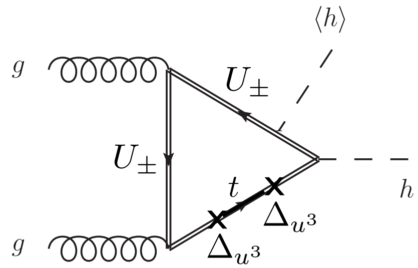

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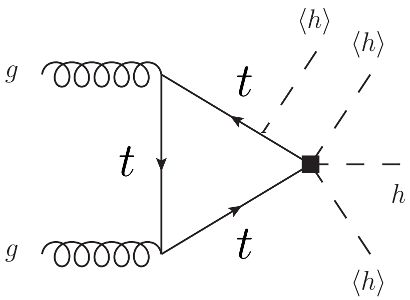

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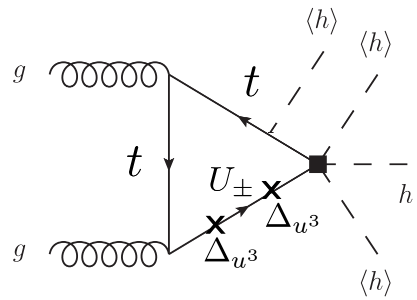

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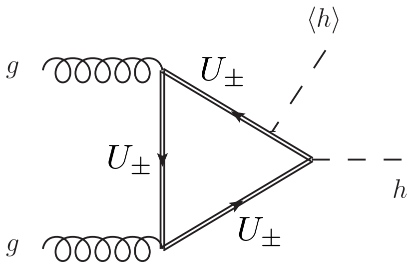

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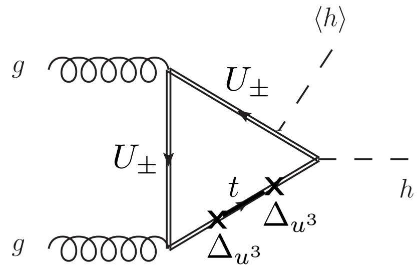

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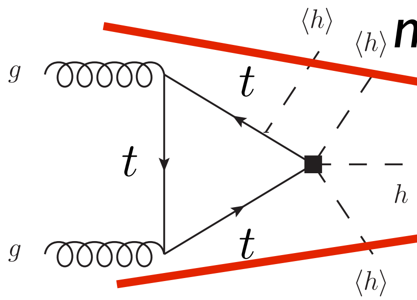
negligible when light quark runs in the loop



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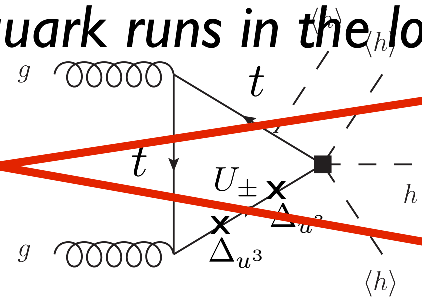

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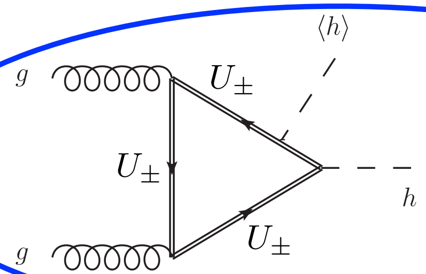
huge contribution, generic vector like theory Goertz, Haisch & Neubert; Carena, et al. (12)



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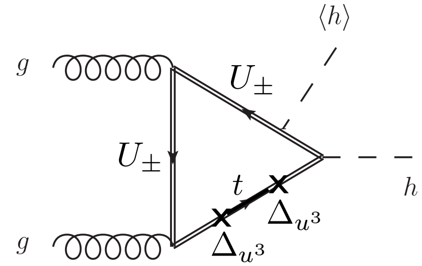

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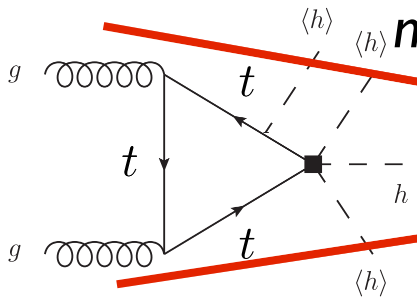

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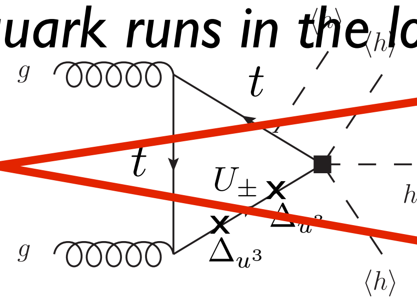

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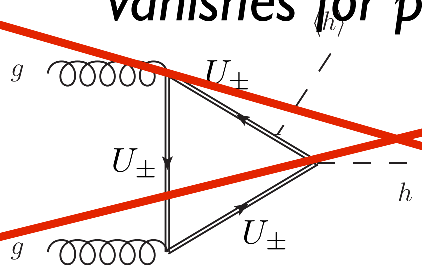
Delaunay, Grojean & GP.

vanishes for pNGB Higgs



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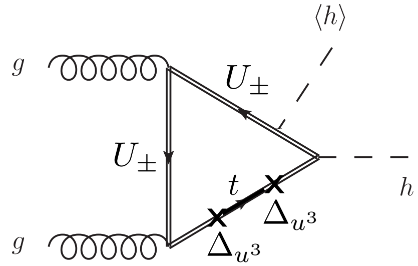

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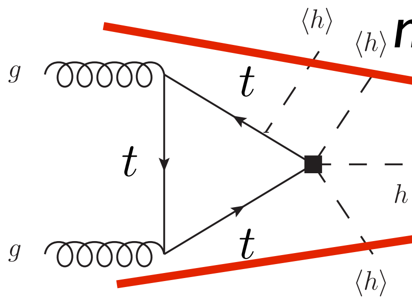

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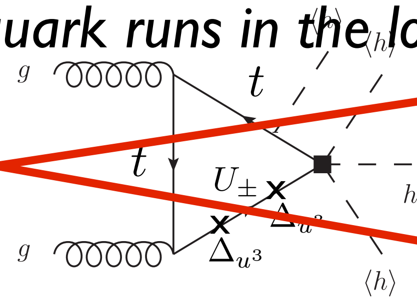

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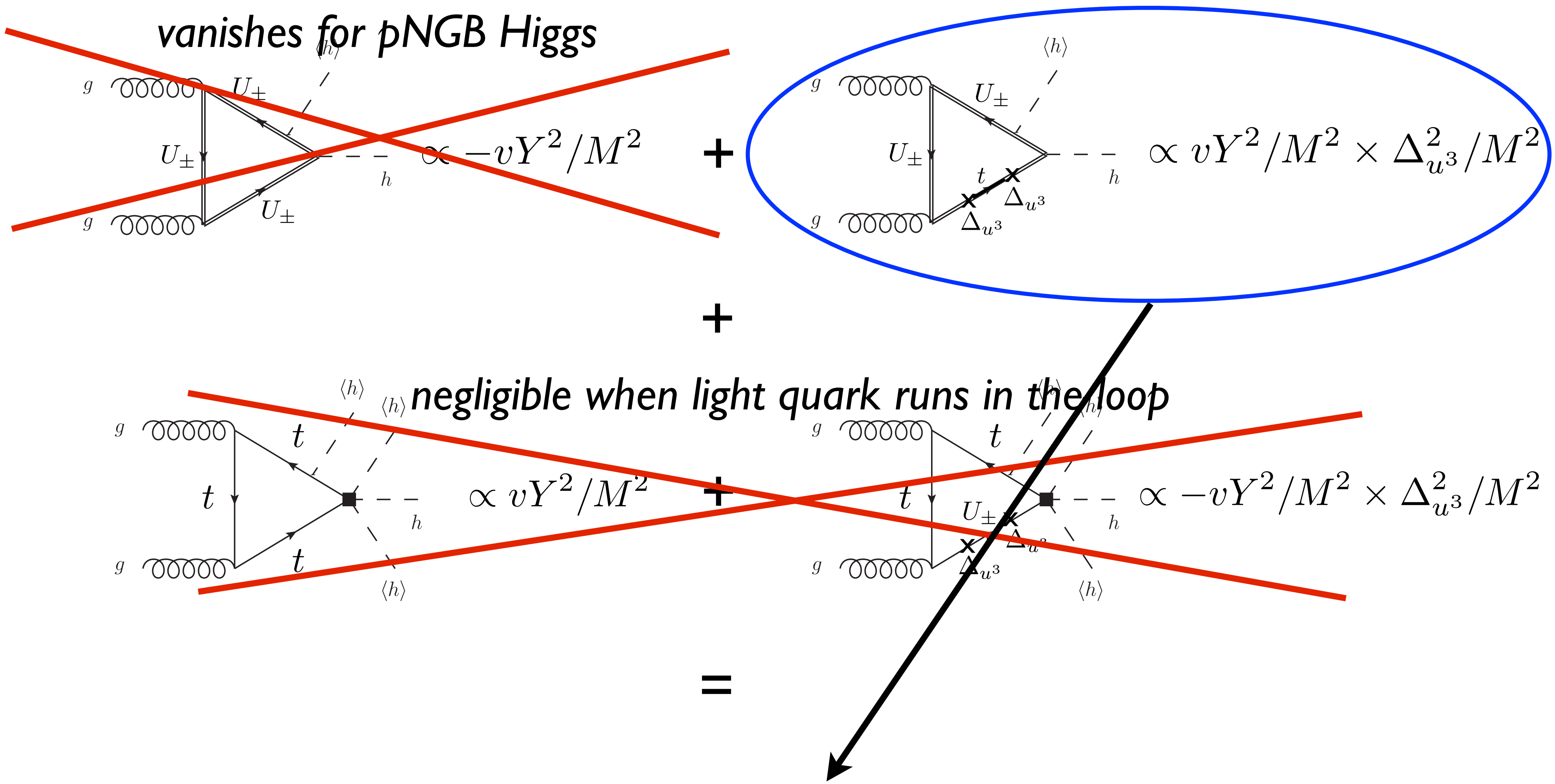
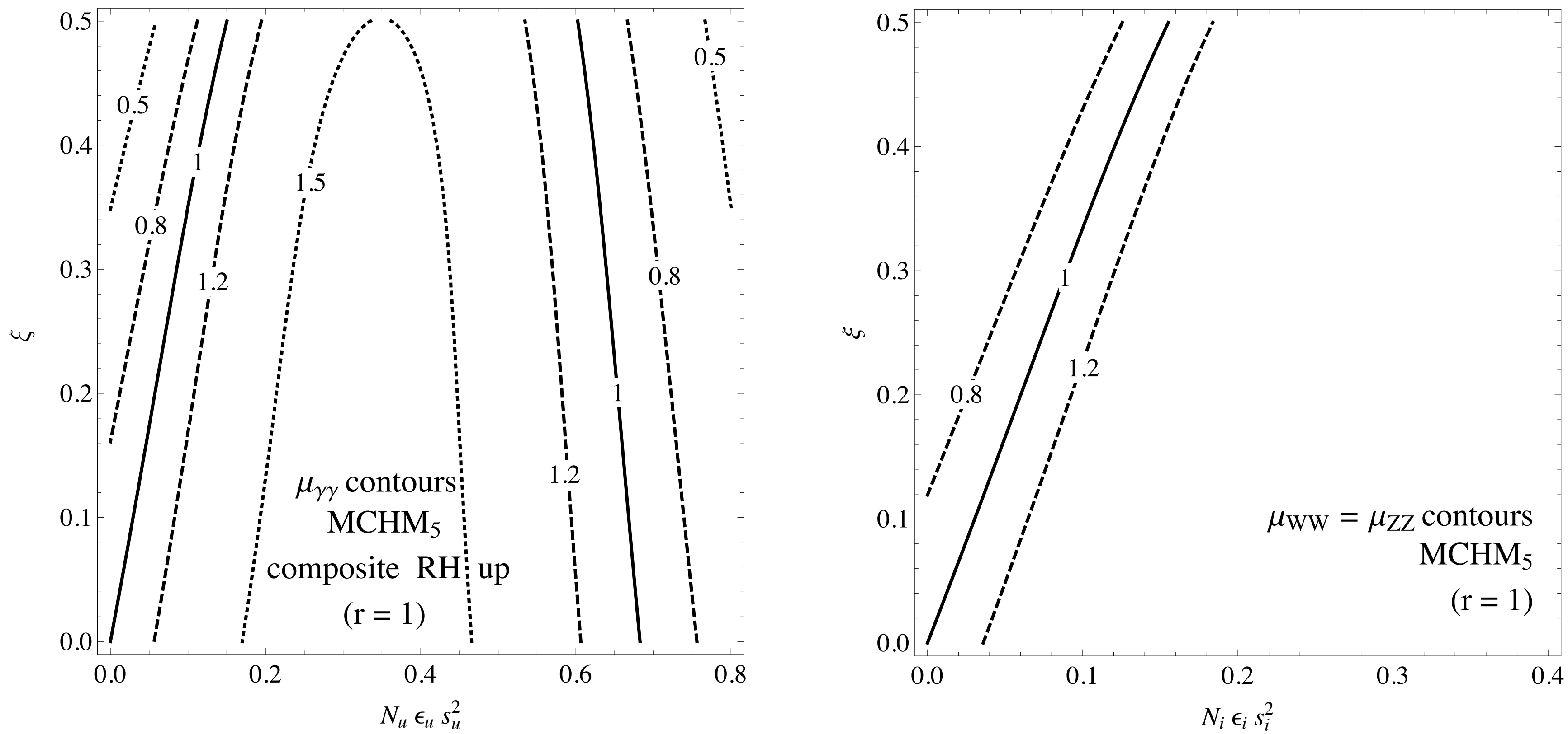


Sizable corrections for composite light quarks!

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

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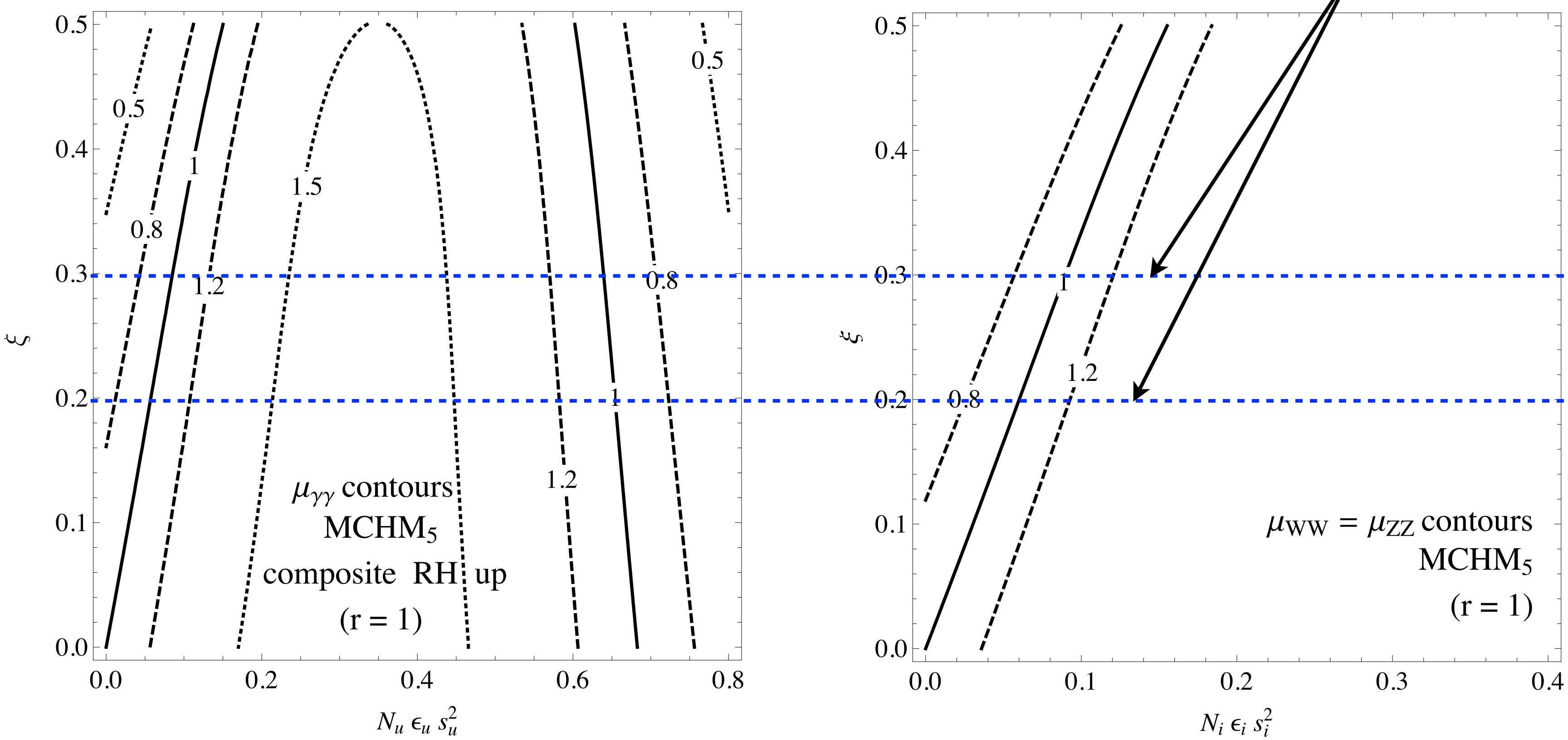
Interesting theoretically



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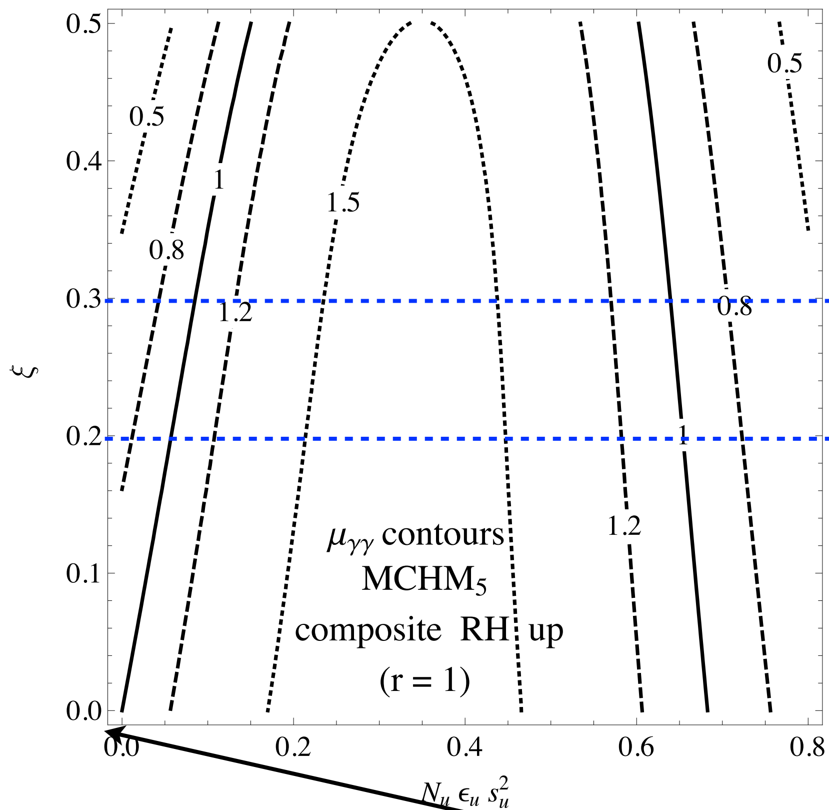

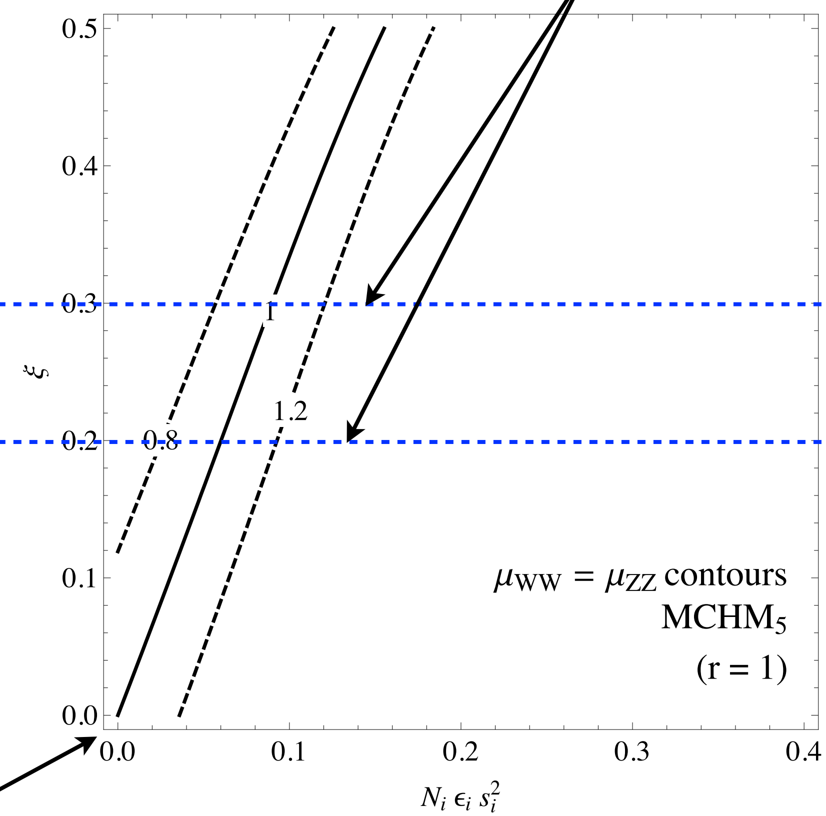

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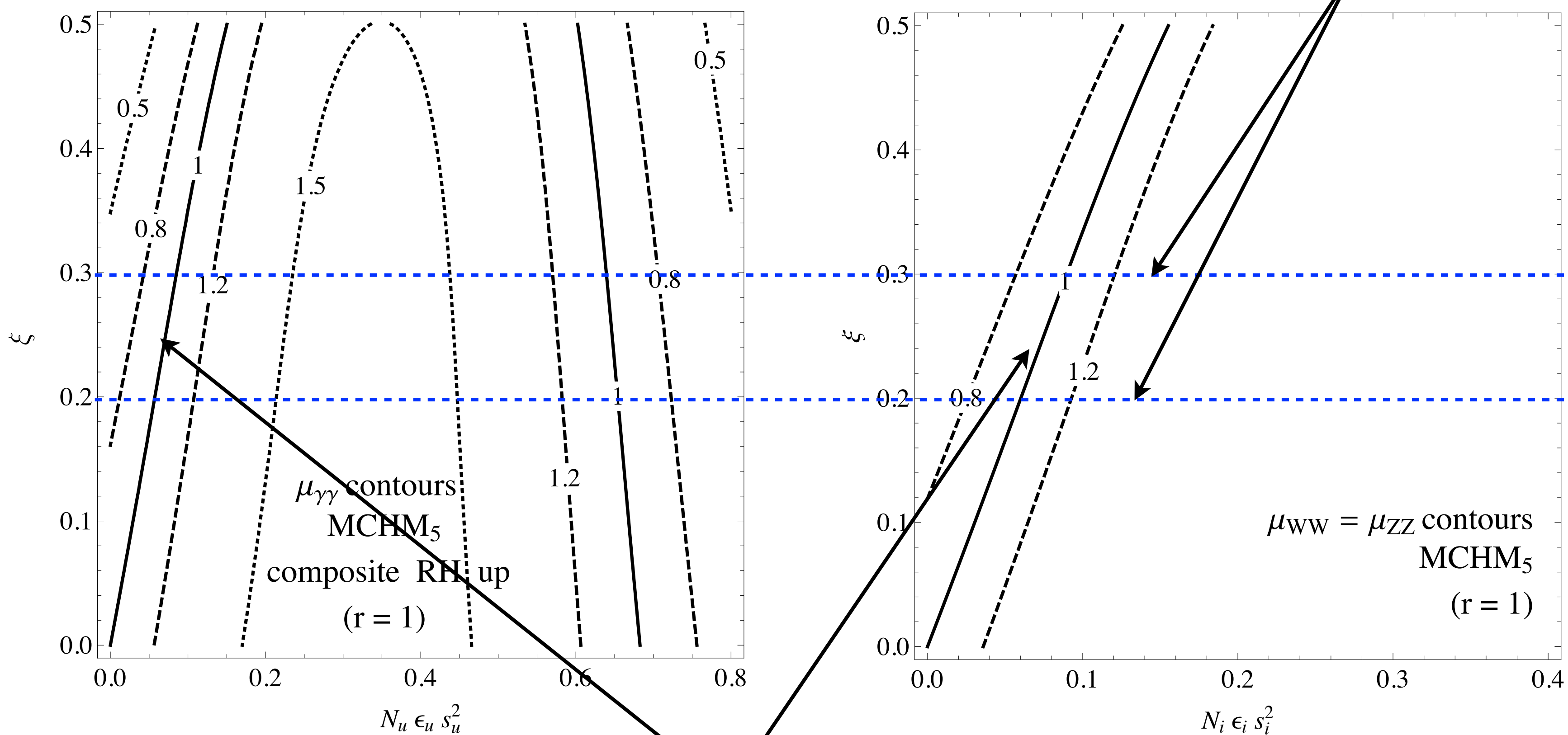
\wo mixing favorable region
of Higgs "non-linearity" excluded.

Composite light quarks & pseudo Goldstone boson Higgs

...ean & GP, to appear.

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

Interesting theoretically



s_R: level of compositeness ... 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

(top-charming) Conclusions

- Light (non-"sups") squarks maybe buried (regardless of flavor mechanism).

- Stop-scharm mixing might lead to improved naturalness.

- Interplay between composite Higgs physics & presence of light composite quarks.

- Ask for new type of searches, charm tagging important, linked to CPV in D mixing, soon to be tested at LHCb.

Backups

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

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

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

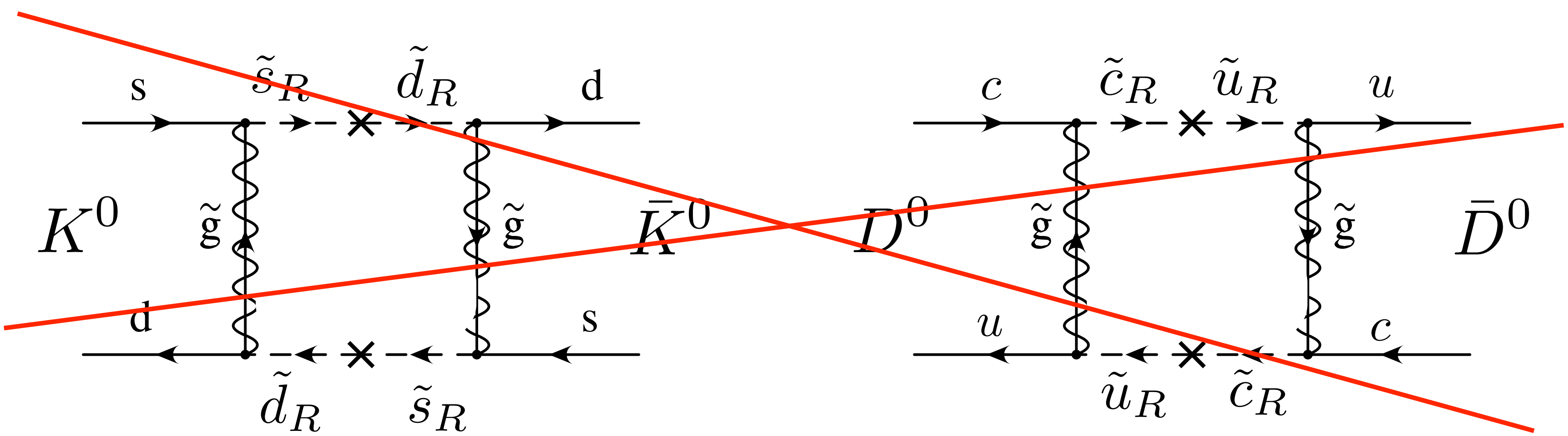
(ask if you want to hear the recents on UV story)

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

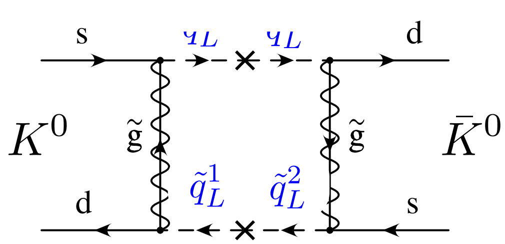
- SM LH sector consist of 2 flavor breaking sources: $Y_d Y_d^\dagger$ & $Y_u Y_u^\dagger$

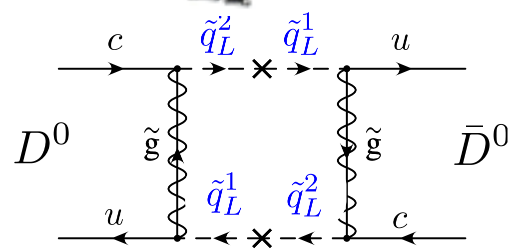
- SUSY: cannot align LH masses simultaneously with both sources! Dangerous direction wins to reduce bounds ...

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

$\Delta M_K, \epsilon_K$

$\Delta M_D, A_\Gamma^D$





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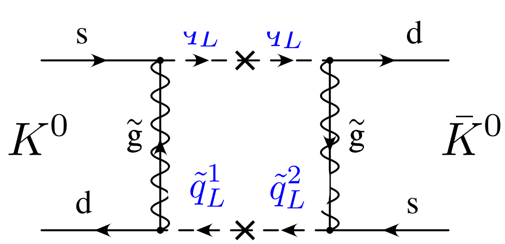

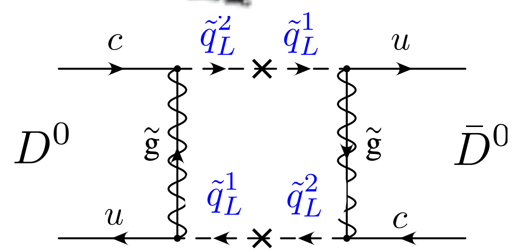

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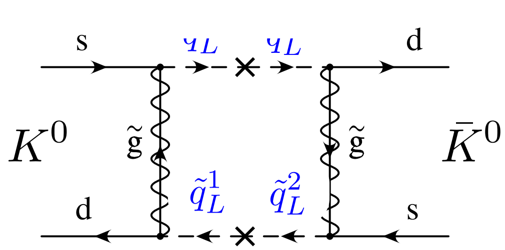

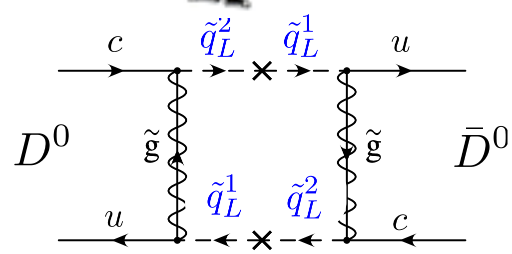

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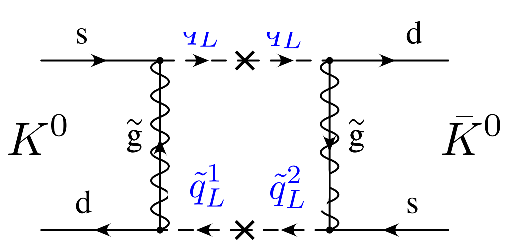

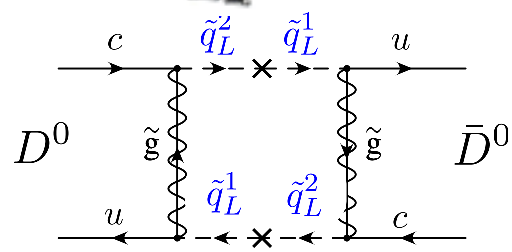

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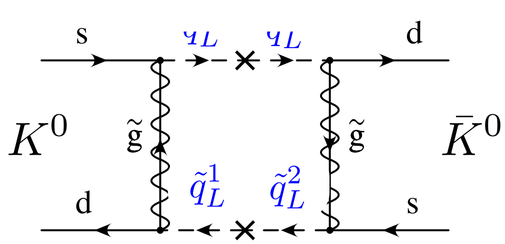

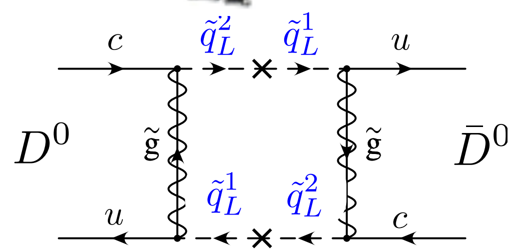

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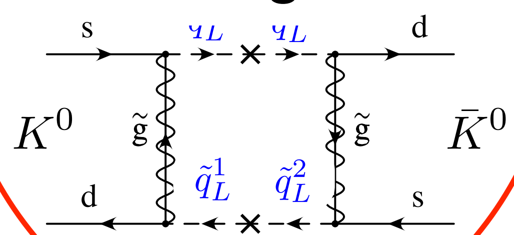
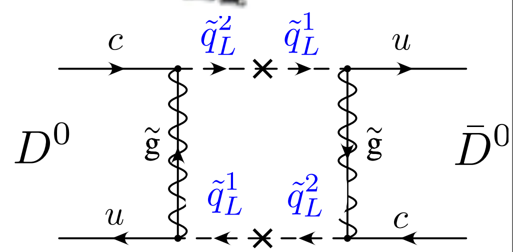
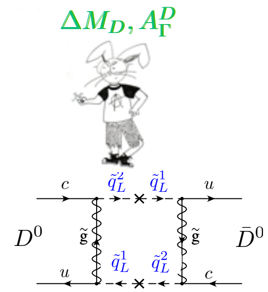
Nir & Seiberg (93)

down alignment





Last 4 yrs: dramatic progress in studying charm CPV



SUSY implications: no hope for non-degeneracy ...

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

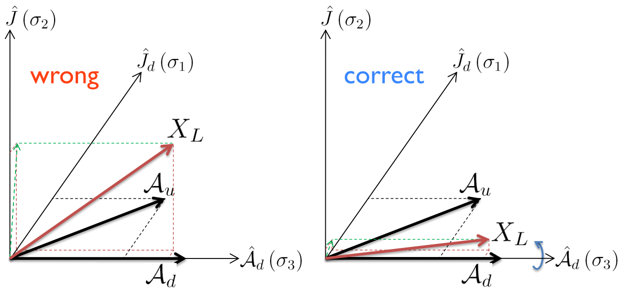
(squark doublets, gluino, 1TeV)

Blum, Grossman, Nir & GP (09)

With phases, first 2 gen' squark need to have almost equal masses.
Looks like squark anarchy/alignment is dead!

However ...

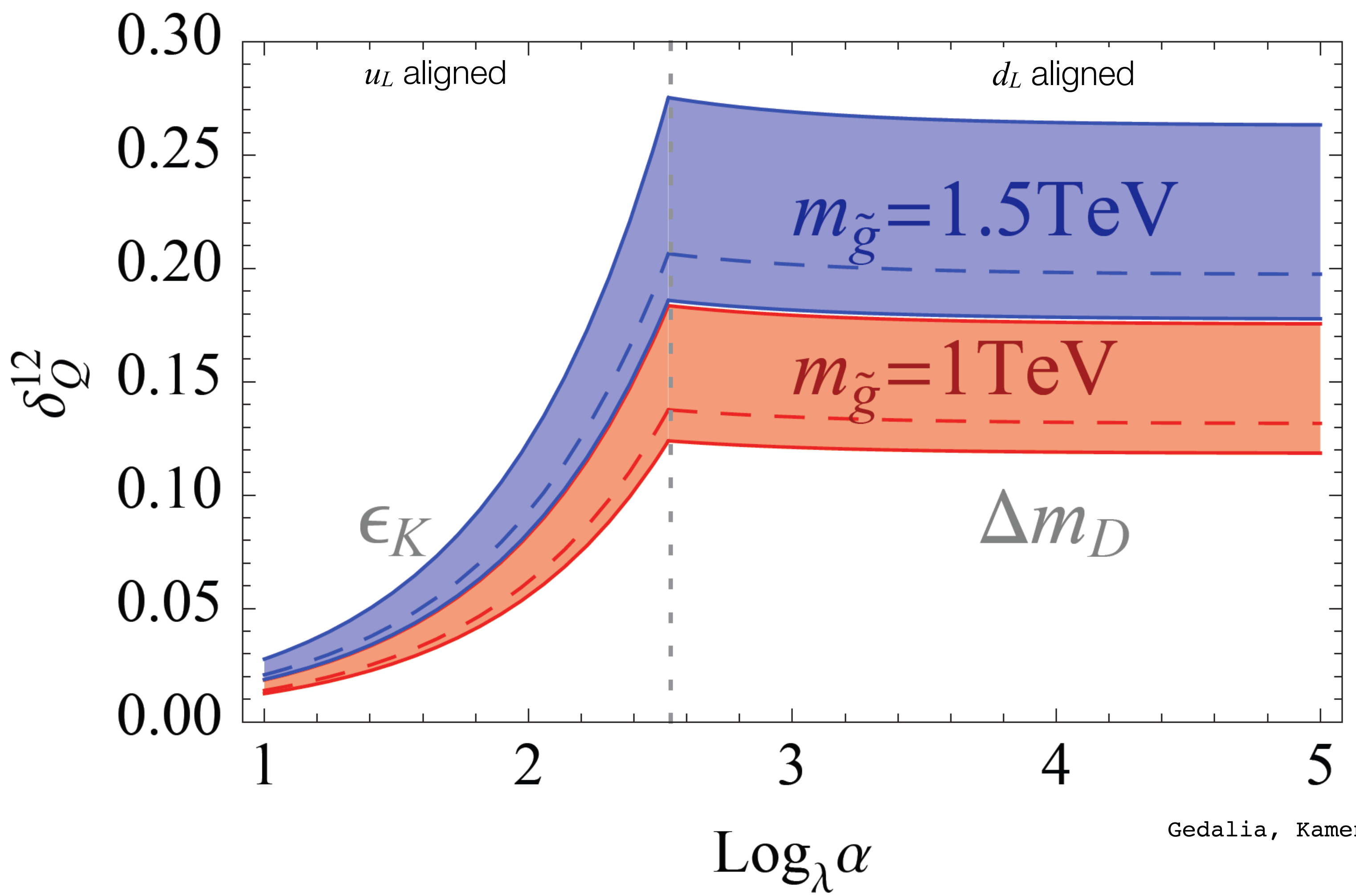
Successful alignment models guarantee small physical CP phase!



Gedalia, Kamenik, Ligeti & GP (12);

Formalism: Gedalia, Mannelli & GP (10) x2

Degeneracy of Squarks



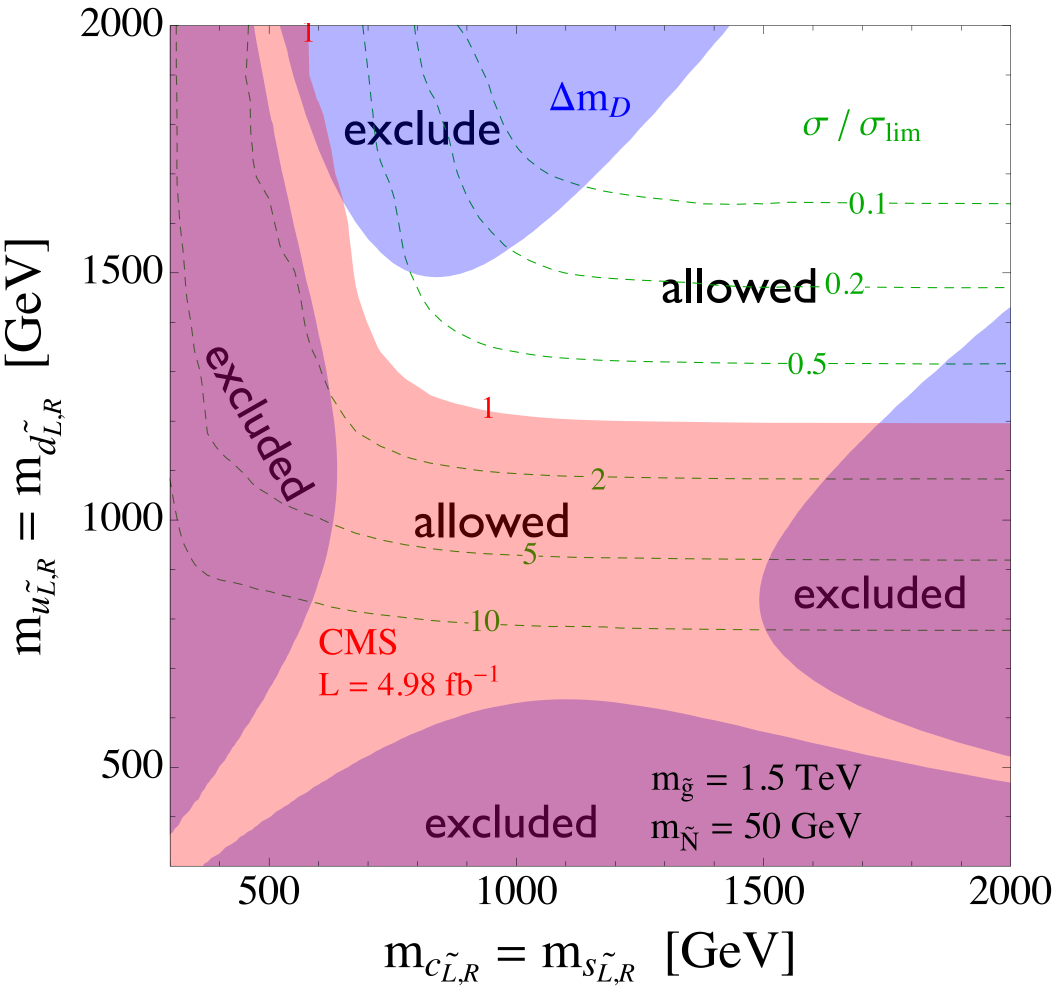
$$\delta_Q^{12} \equiv \frac{m_{\tilde{Q}_2} - m_{\tilde{Q}_1}}{m_{\tilde{Q}_2} + m_{\tilde{Q}_1}}$$

Gedalia, Kamenik, Ligeti & GP (12);

Sea LH squarks vs. valence RH squarks

Adding flavor constraints (Δm_D) for LH squarks:

Kadosh, Paride & GP, to appear;



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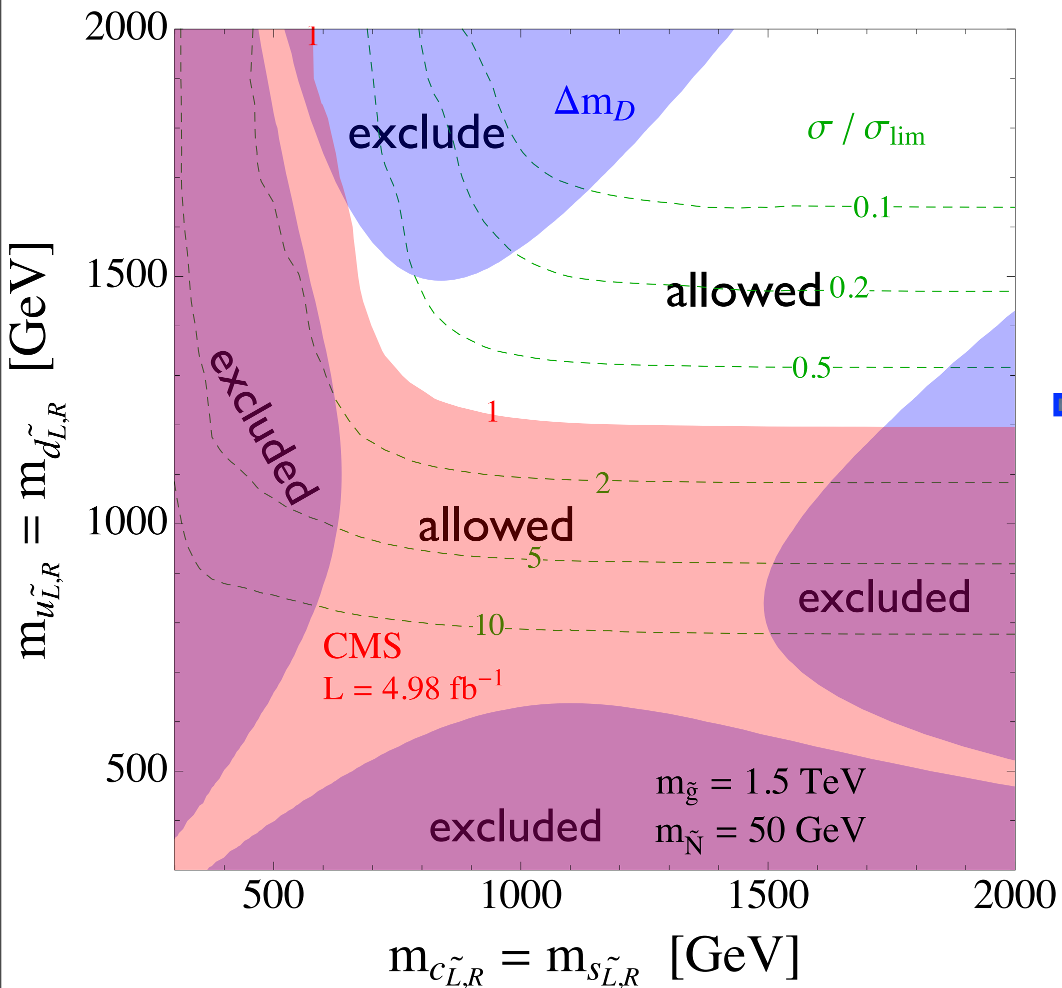

alignment: new upper bound on CP violation (CPV) in *D-phys.*:

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

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

LHCb soon start testing alignment paradigm!

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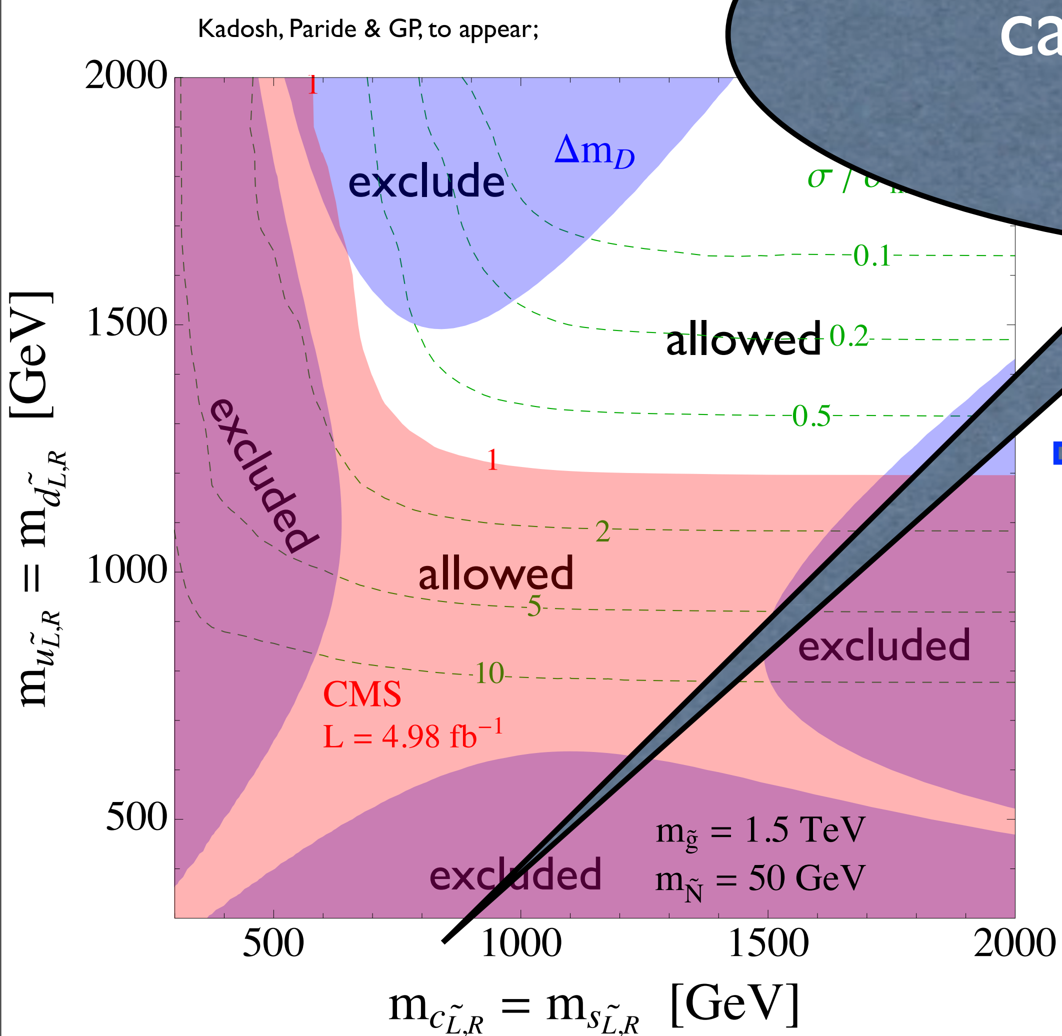

ATLAS & CMS
can improve sensitivity
via charm tagging !

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