# Physics opportunities: the battle for naturalness & the top-charm front

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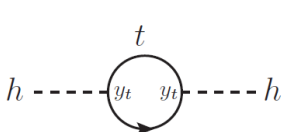
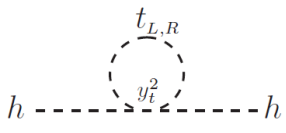
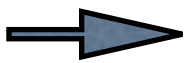
*CLIC Detector & Physics Collaboration Meeting Oct/13*

# Top partners & Searches

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

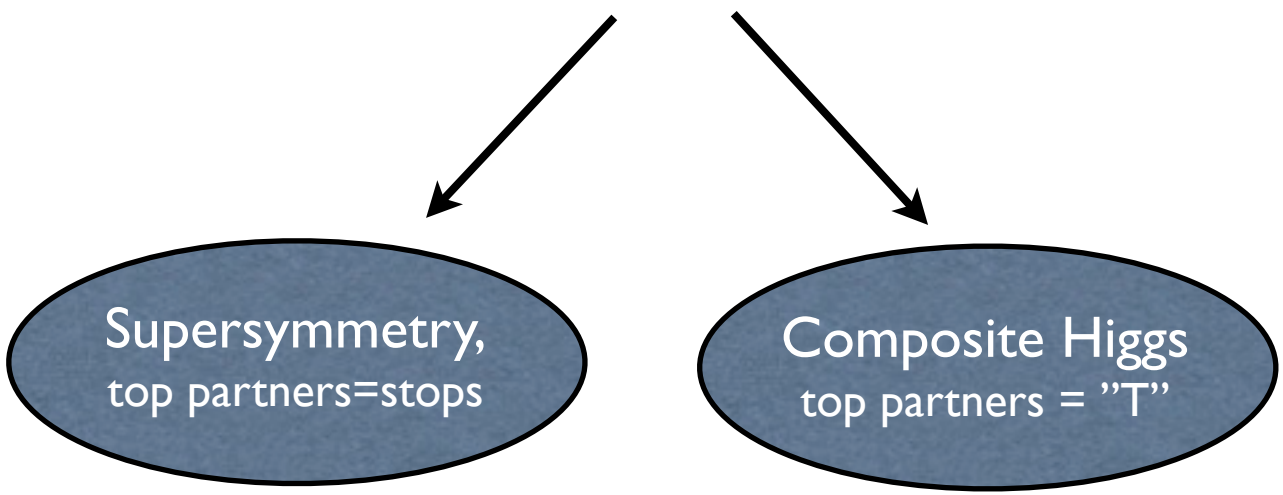


$$\frac{\delta m_h^2}{m_h^2} \sim \left(\frac{\tilde{m}_t}{400\,\mathrm{GeV}}\right)^2$$

2 leading frameworks
of naturalness



# Top partners & LHC Searches

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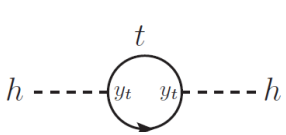


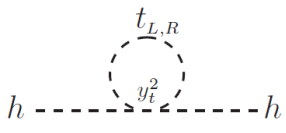


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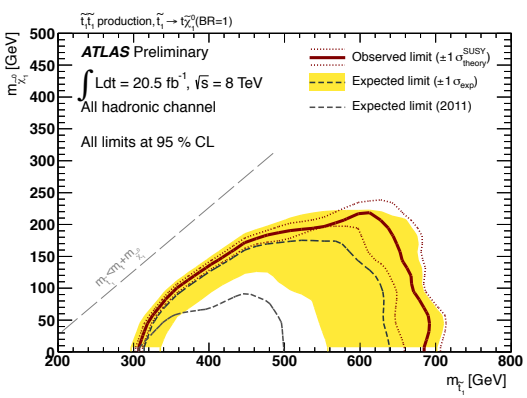
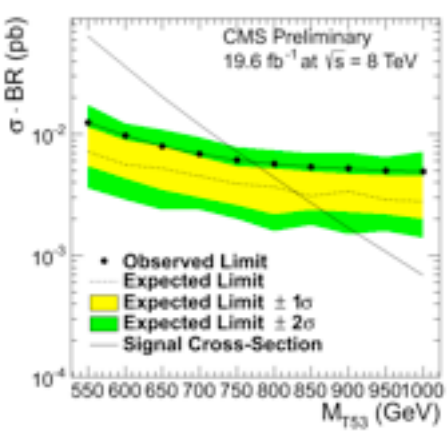
2 leading frameworks of naturalness

SUSY

composite Higgs

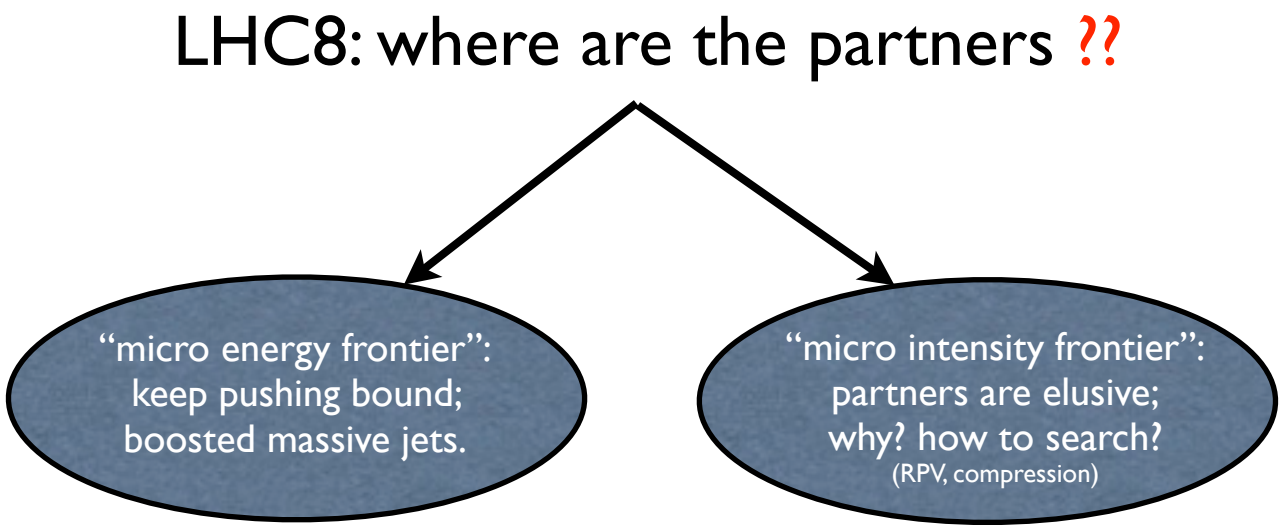



$m_{\mathrm{stop}} \gtrsim 700\,\mathrm{GeV}$



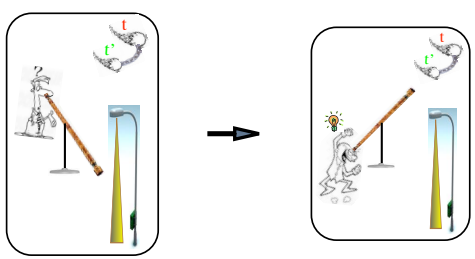

$m_{\mathrm{T}^{5/3}} \gtrsim 800\,\mathrm{GeV}$

# The Battle for Naturalness



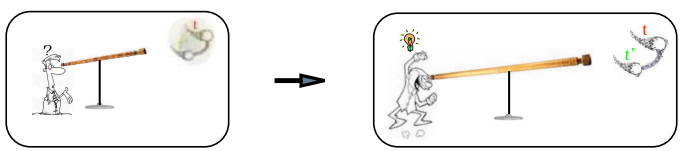
# 2 complementary routes for top partners discovery -

*(ii) Light partners:* region of flavourful naturalness.



flavourful naturalness.

*(i) Heavy partners:* region of boosted quasi-naturalness.



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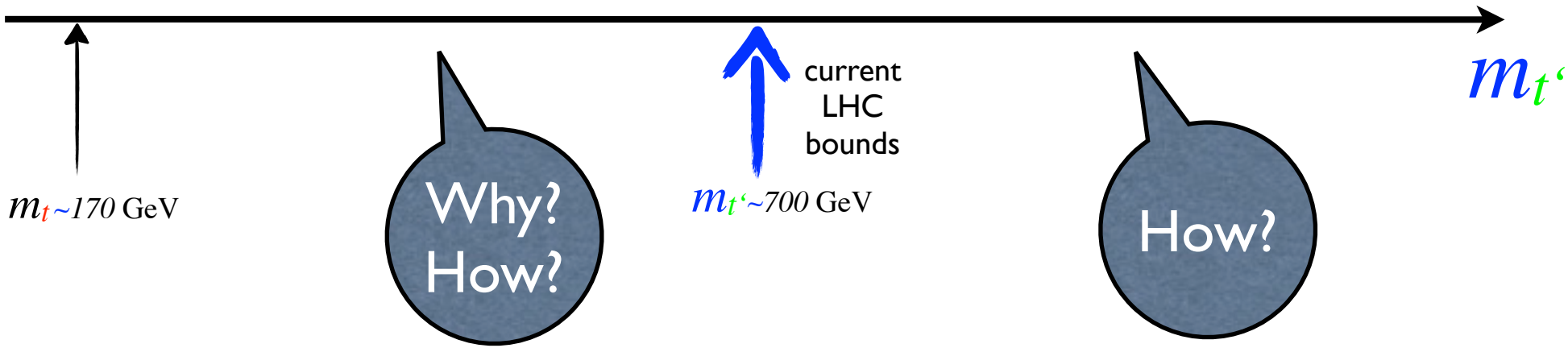


# Outline

- Flavorful naturalness & the charm front:

  *(i)* Light non-degenerate partners (squarks or c's) at the LHC;

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

  *(iii)* $H \to c\bar{c}$. (+ extra on CP violation & general lesson ...)

- Commenting on: quasi-natural, boosted tops.

- Summary.

# Flavorful Naturalness

(some implications of split first two generation squark spectrum)

# Flavourful naturalness

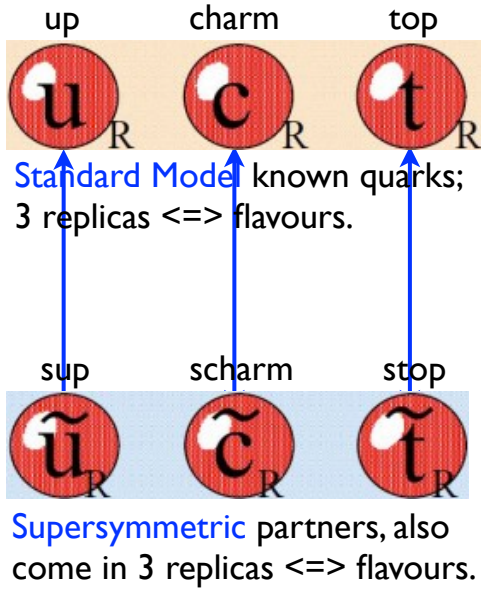
- Standard model: 3 copies (flavours) of quarks;

  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) > 1000 citations !



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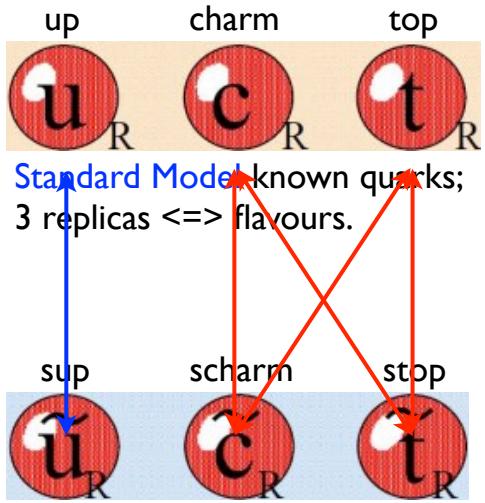
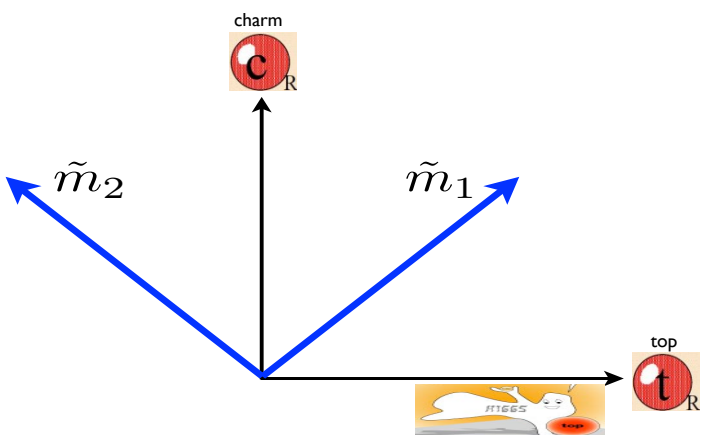



- This need not be the case, top-partner => "stop-scharm" admixture.



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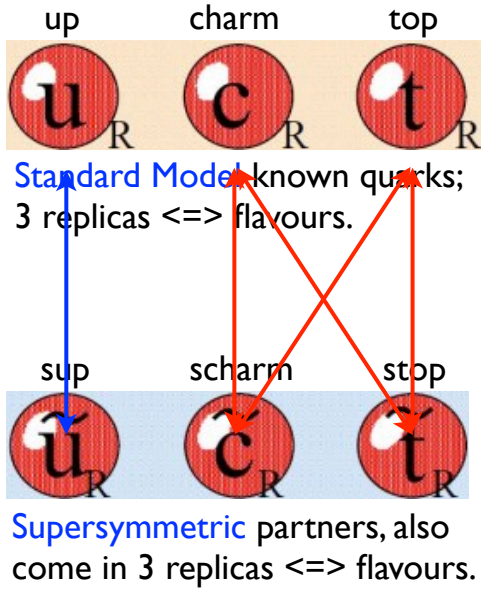


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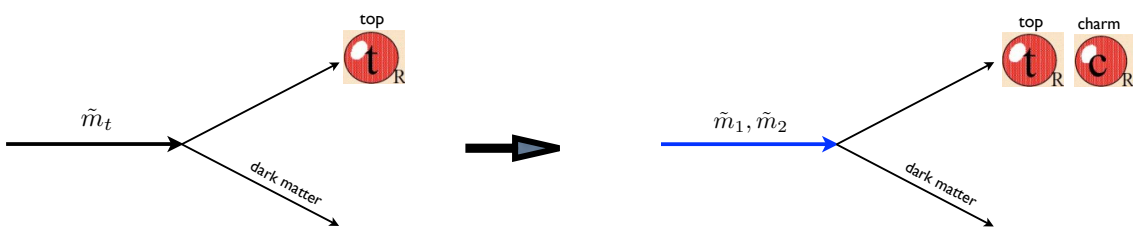


Signatures dramatically change, opening the charm front at high energy & in D-meson CP violation!

Grossman, Nir & Perez, PRL (09); Gedalia, Kamenik, Ligeti & Perez, PLB; Mahbubani, Papucci, Perez, Ruderman & Weiler, PRL (12);
Blanke, Giudice, Paradisi, Perez & Zupan JHEP (13).

# 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 ...

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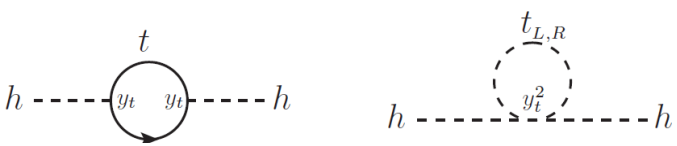

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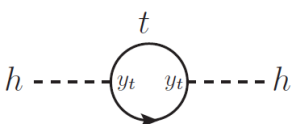
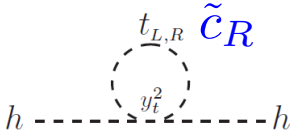
- Naively sounds crazy as worsening the fine tuning problem.



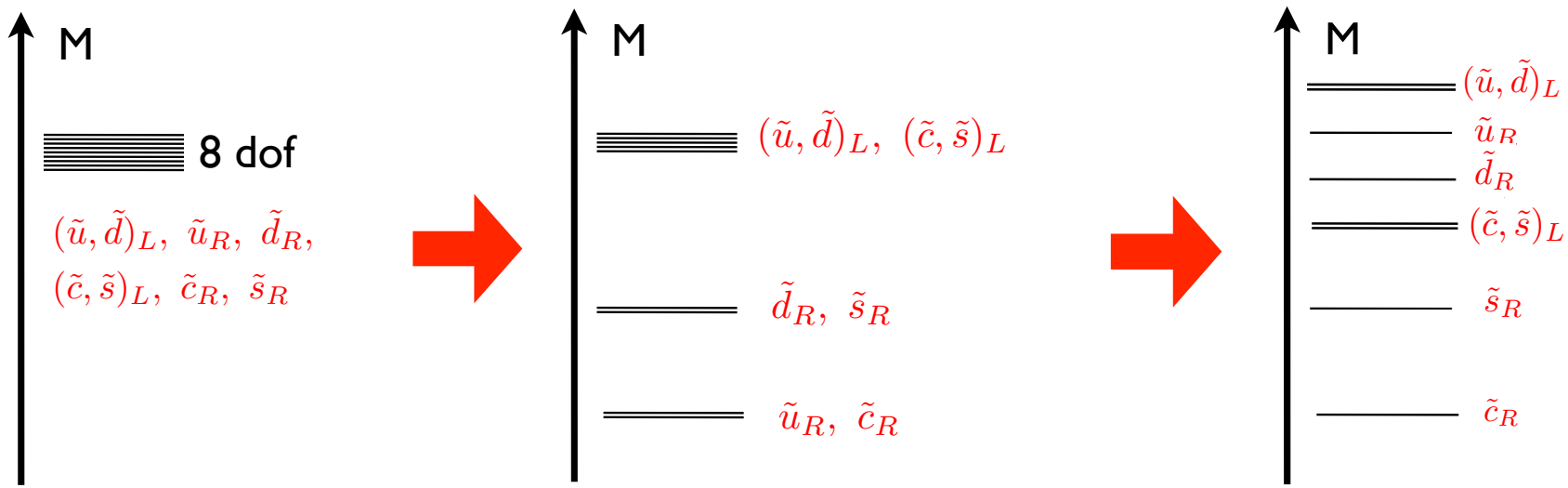

$$\delta m_{Hu}^2 = -\frac{3y_t^2}{8\pi^2}\left(m_{\tilde{t}_L}^2 + \cos^2\theta_{23}^{RR} m_1^2 + \sin^2\theta_{23}^{RR} m_2^2\right)$$

- 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 $\left(\cos\theta_{23}^R\right)^4$.

Potentially: new hole in searches, possibly improve naturalness

# What if first 2 generation squark not degenerate?

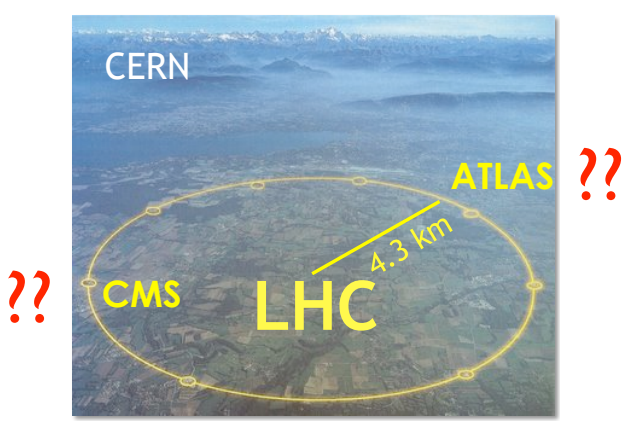
Mahbubani, Papucci, GP, Ruderman & Weiler (12).




Everything degenerate

Split, but MFV

Anarchy!



# 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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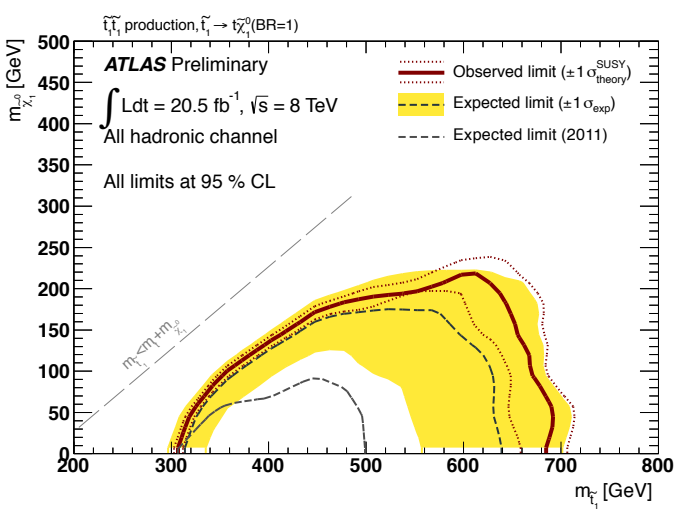


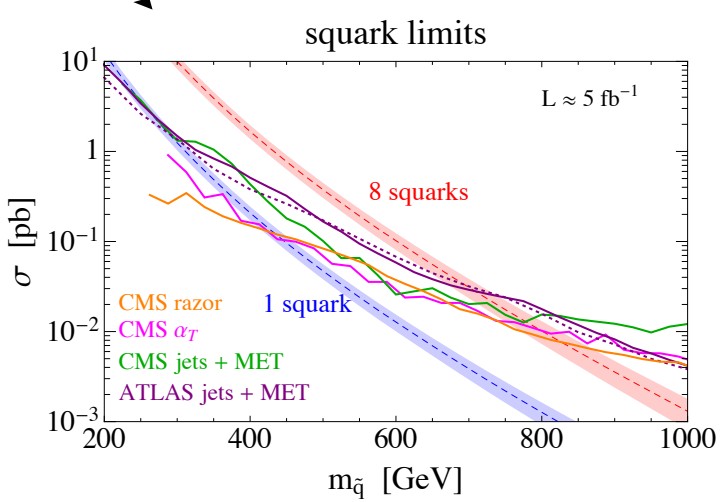


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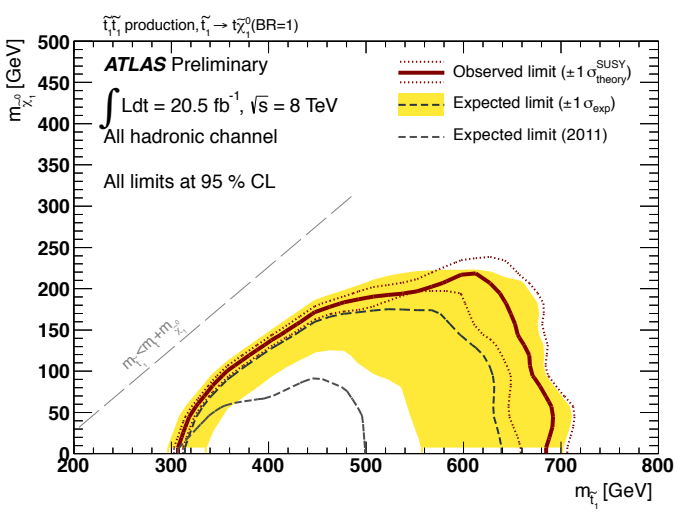


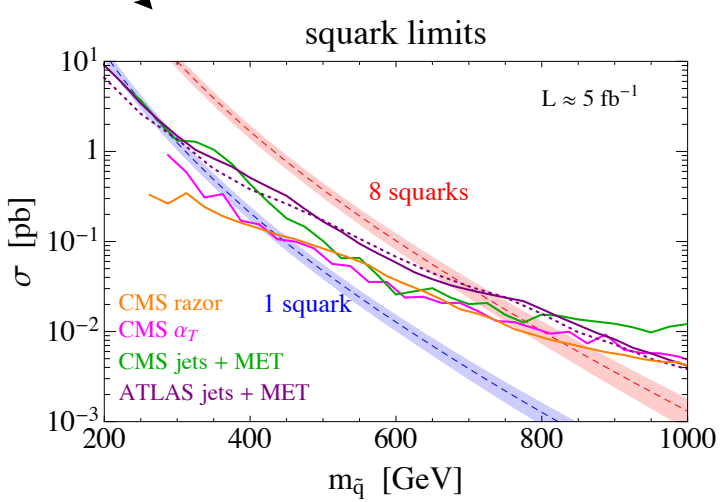


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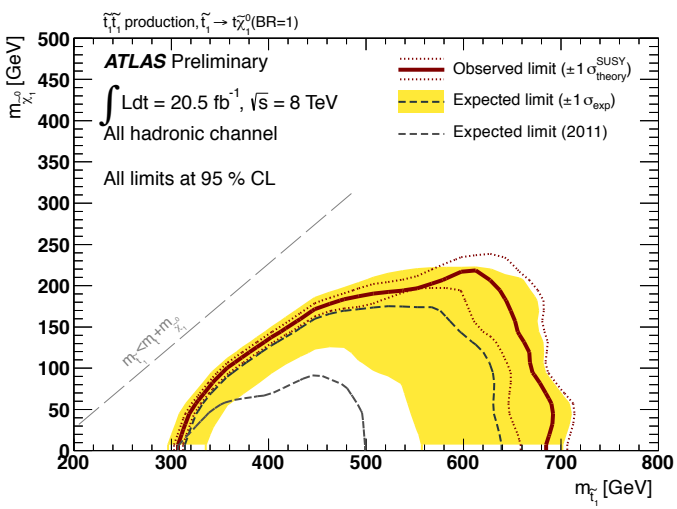
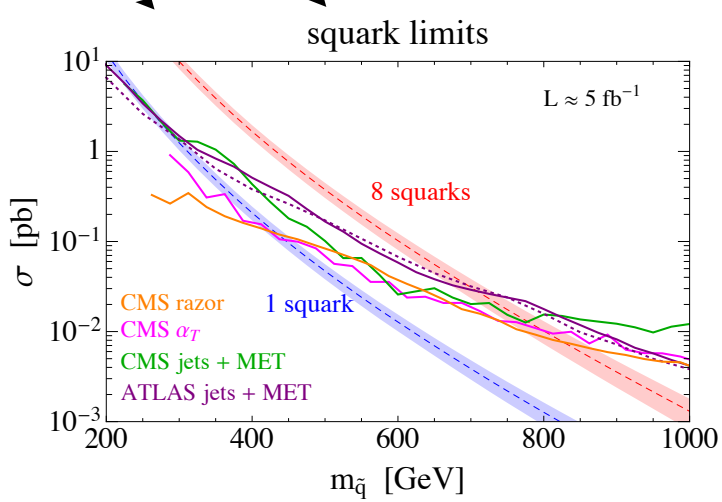
??

compromise




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

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

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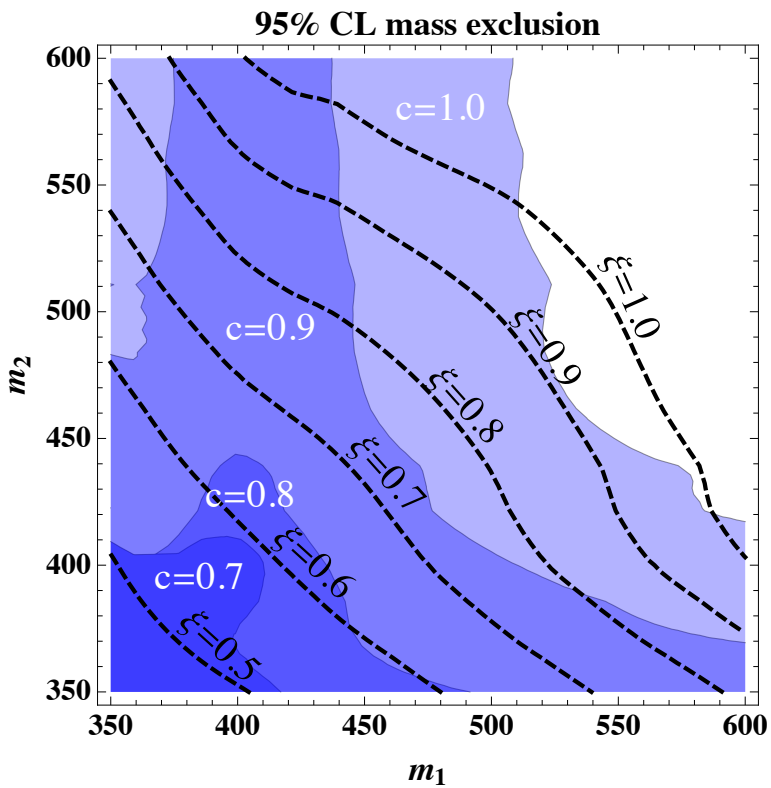
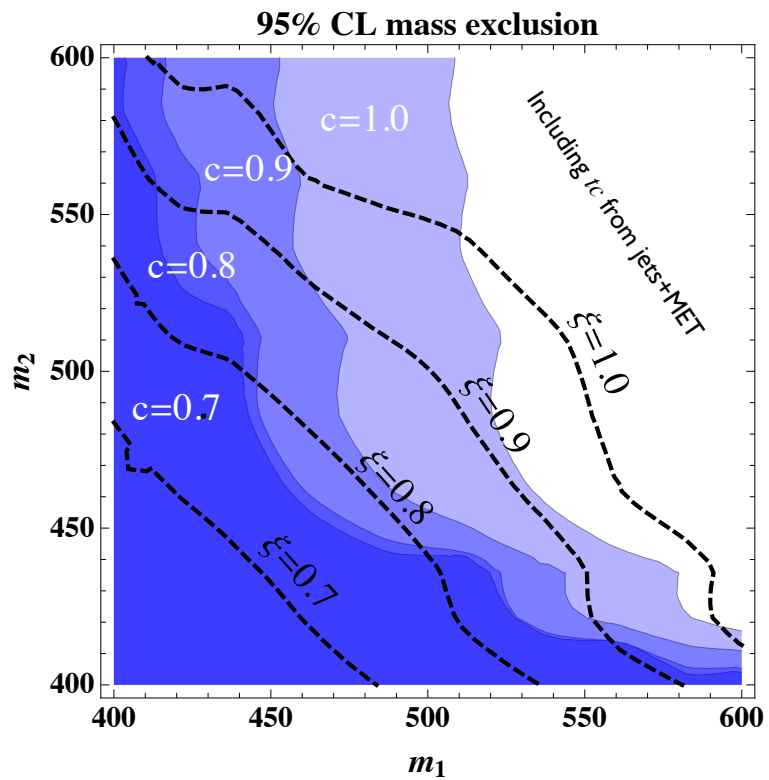


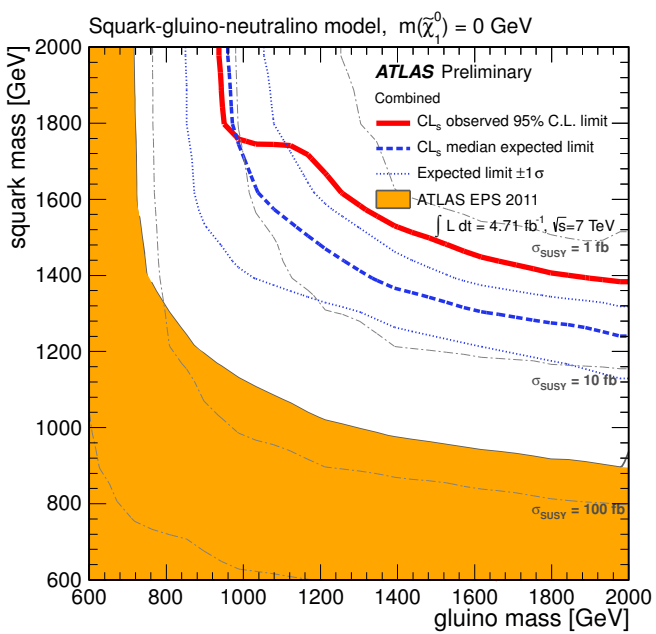




Can get $\xi \sim 0.5 - 0.8$ for $\theta_{23}^{RR} \sim 45^o$ !

# 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 drives the experimental limits?

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

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- Signal efficiencies;
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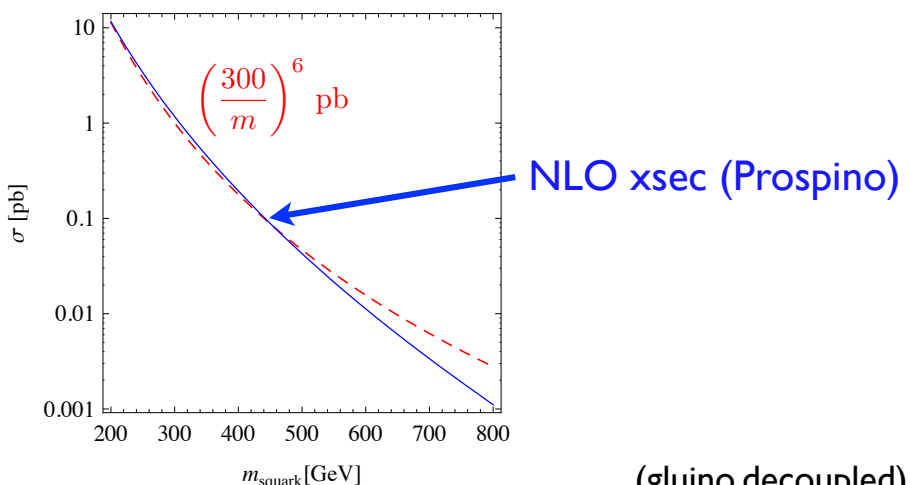
Multiplicity: how bound changes when one doublet is made lighter ?

## Cross-sections vs. mass

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




(gluino decoupled)

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

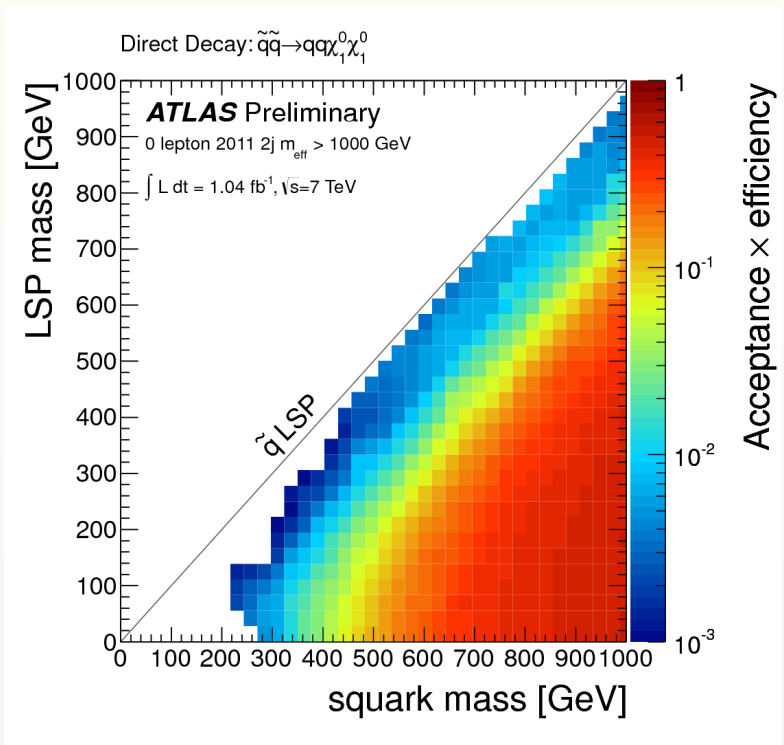
$$(m_L/m_H) = (1/4)^{1/6} \sim 0.8$$

gain is marginal

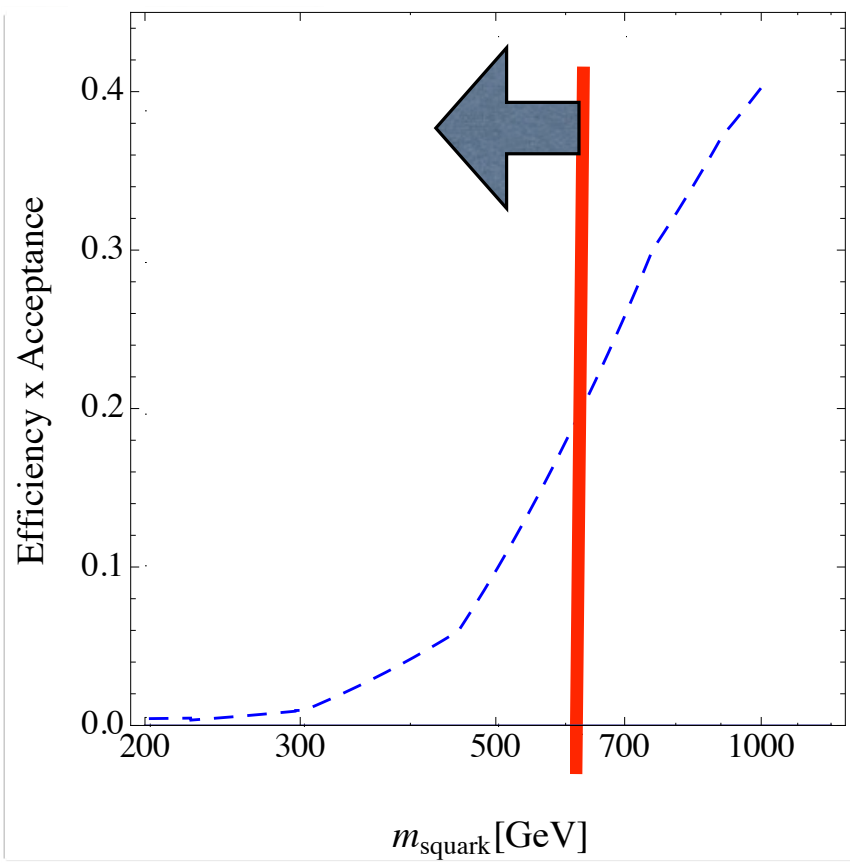
# Efficiencies, strong mass dependence!

Signal efficiency falls very rapidly with decreasing squark mass

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

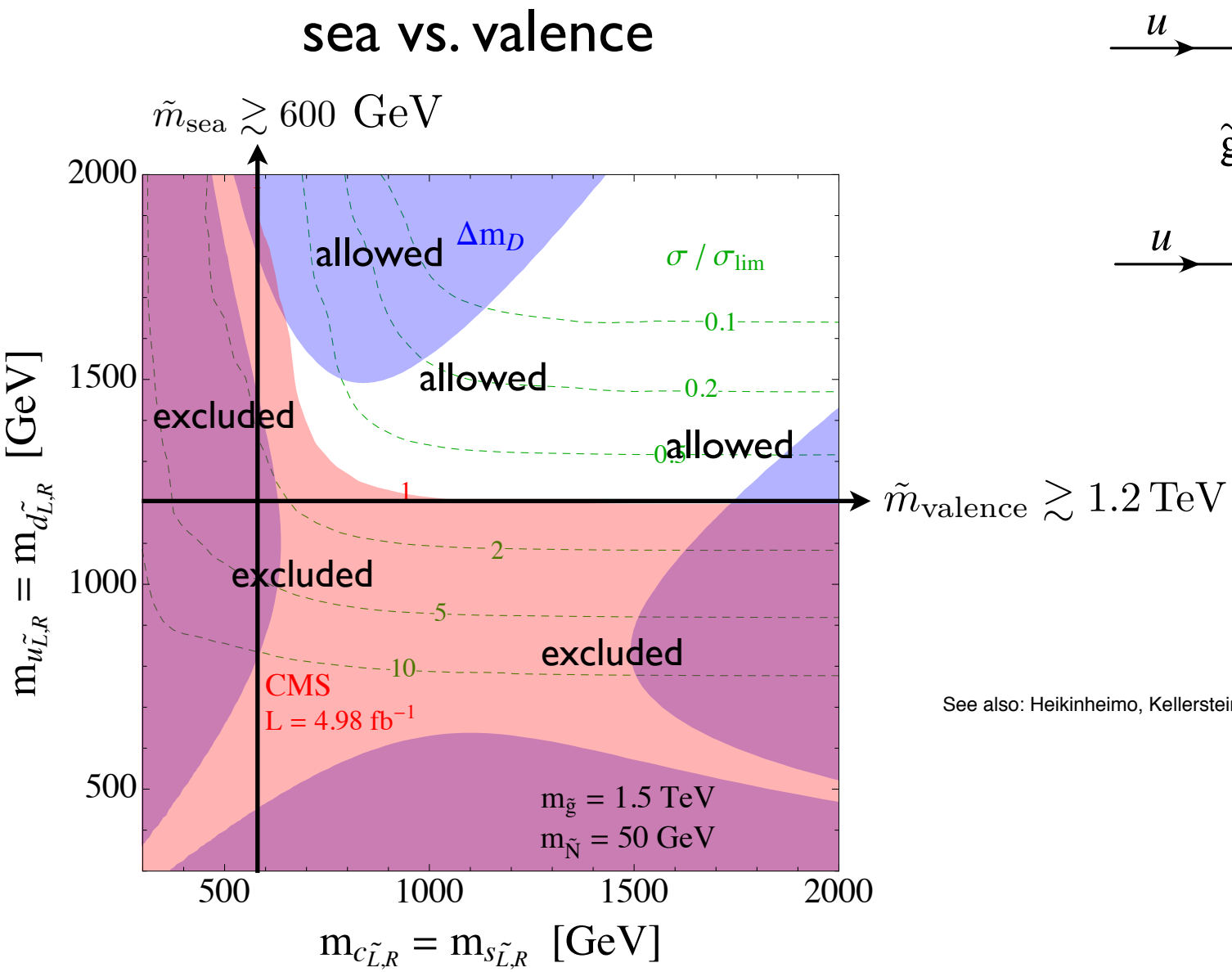


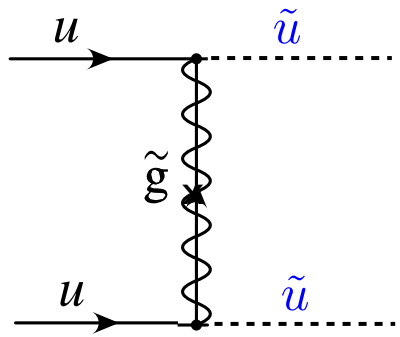

ATLAS 1/fb,
2jet $M_{eff}$>1TeV




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!

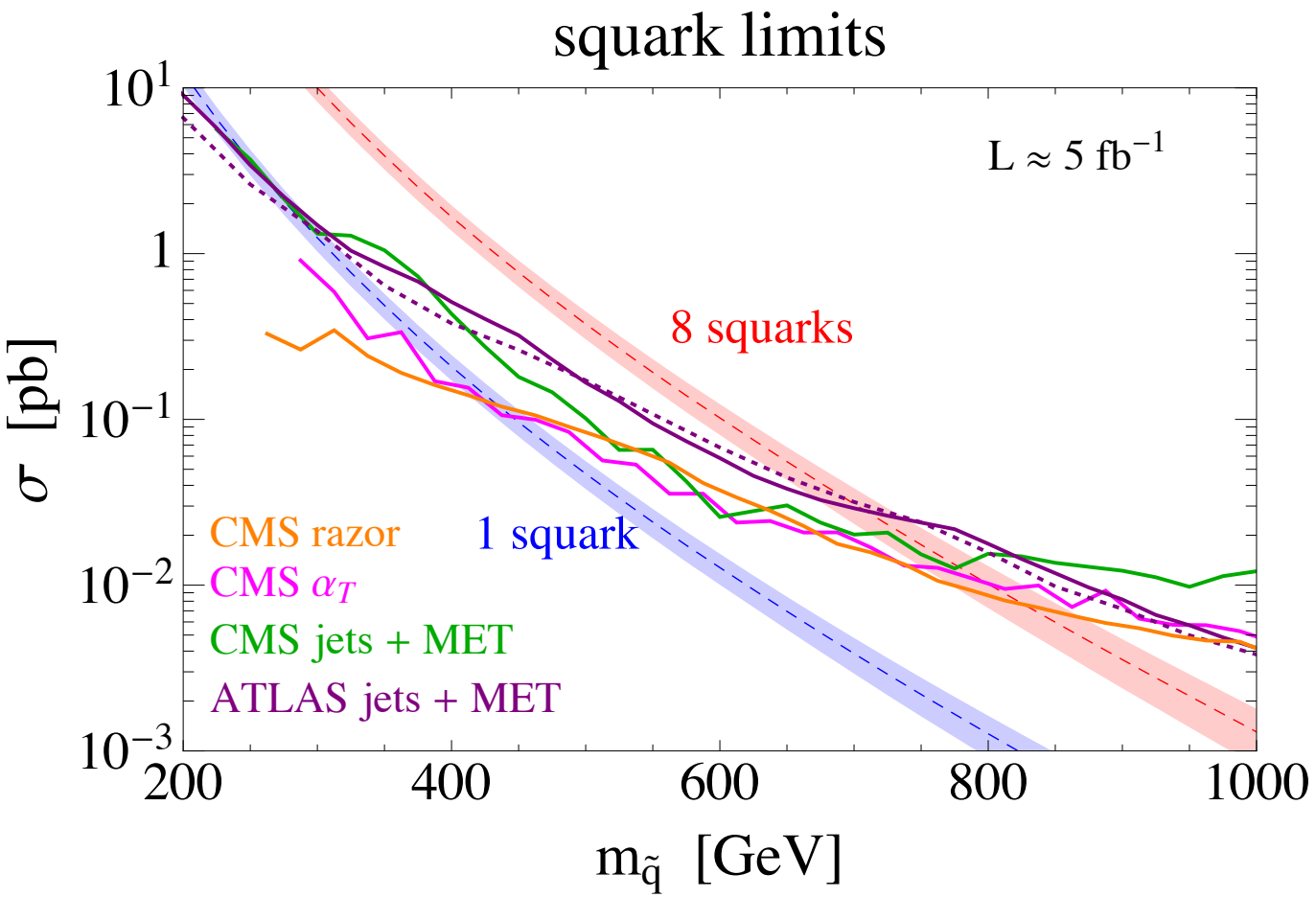



Mahbubani, Papucci, GP, Ruderman & Weiler (12).

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

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




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

# 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.*

# Open parenthesis (CLIC can do better ...)

## 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

# 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:

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

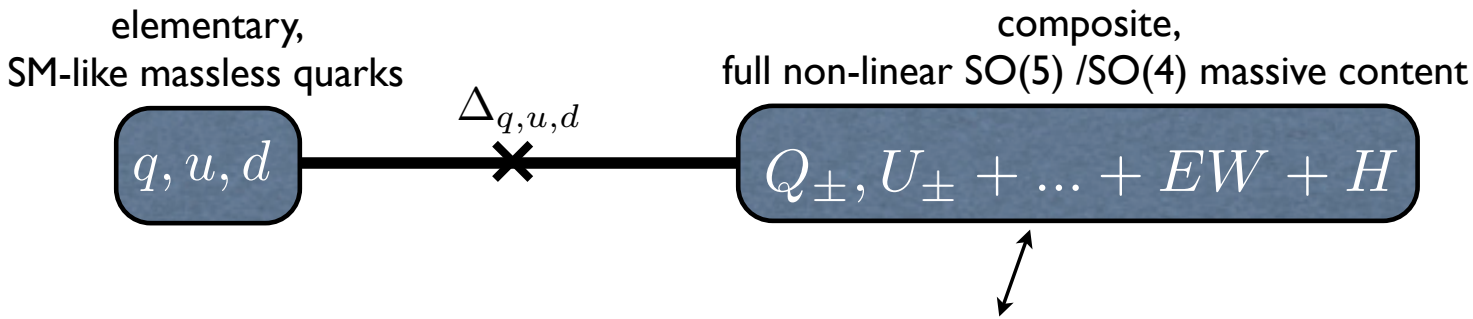
Delaunay, Fraille, Flacke, Lee, Panico & GP Perez in prep.

*(ii)* non-standard modification to Higgs decays.

Delaunay, Grojean & GP (13)

# pNGB Higgs & composite light RH quarks

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




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

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

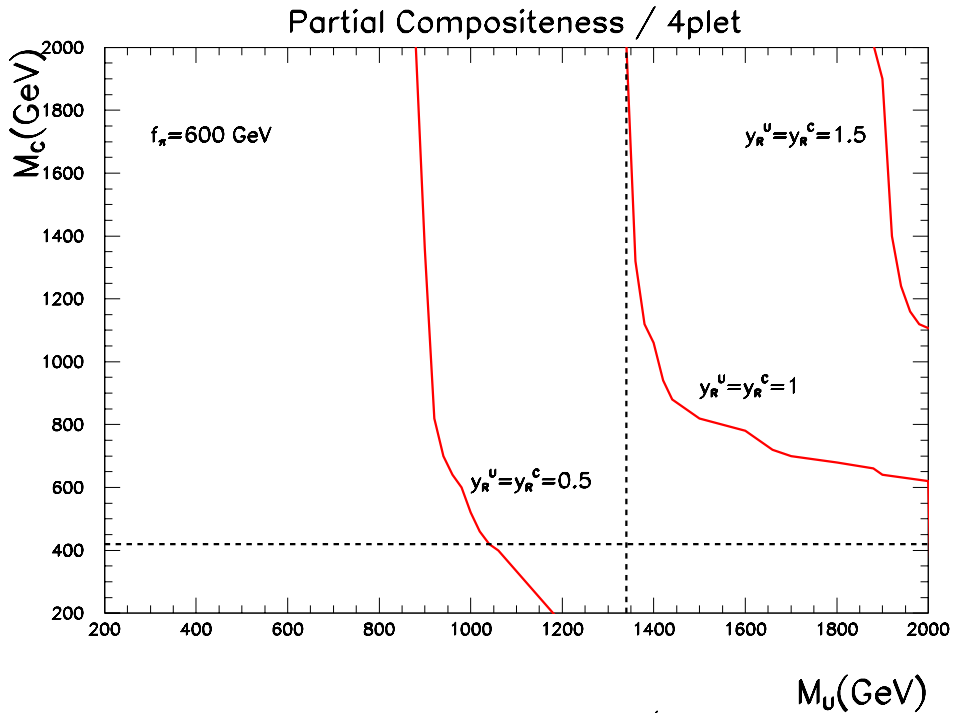
- What if the first two generations of RH quarks are composite but not at the same level, for instance:

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

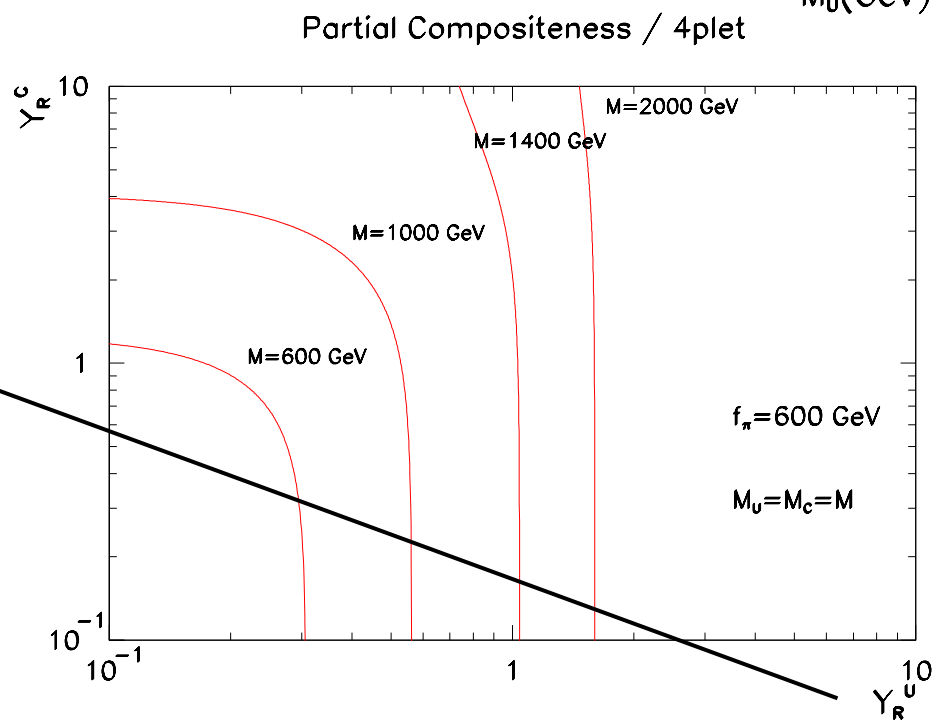
# Collider implications for split 2 gen' (similar to SUSY case)

Delaunay, Fraille, Flacke, Lee, Panico & GP Perez in prep.

$$M_c \ll M_U$$




$$y_c \gg y_u$$



$$H \rightarrow c\bar{c}$$

# $H \to c\bar{c}$

Delaunay, Golling, GP & Soreq, to appear.

- SM: charm Yukawa 1/5 of bottom one, Higgs charm BR~3%.
- However, moderate cancellation => enhance Yukawa coupling,

Effective Field Theory ex.: $\mathcal{L}_{\rm EFT} \supset \lambda^u_{ij} \bar{Q}_i \tilde{H} U_j + \frac{g^u_{ij}}{\Lambda^2} \bar{Q}_i \tilde{H} U_j \left(H^\dagger H\right)$

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

- Define: $\mathcal{L}_0 = \frac{h}{v} \left[ c_V \left( 2 m_W^2 W^+_\mu W^{\mu -} + m_Z^2 Z_\mu Z^\mu \right) - \sum_q c_q m_q \bar{q} q - \sum_\ell c_\ell m_\ell \bar{\ell} \ell \right],$
- Dramatic change to pheno’’’ $\mathrm{BR}_{h \to b\bar{b}} = \frac{\mathrm{BR}^{\rm SM}_{h \to b\bar{b}}}{1 + (|c_c|^2 - 1) \mathrm{BR}^{\rm SM}_{h \to c\bar{c}}}.$

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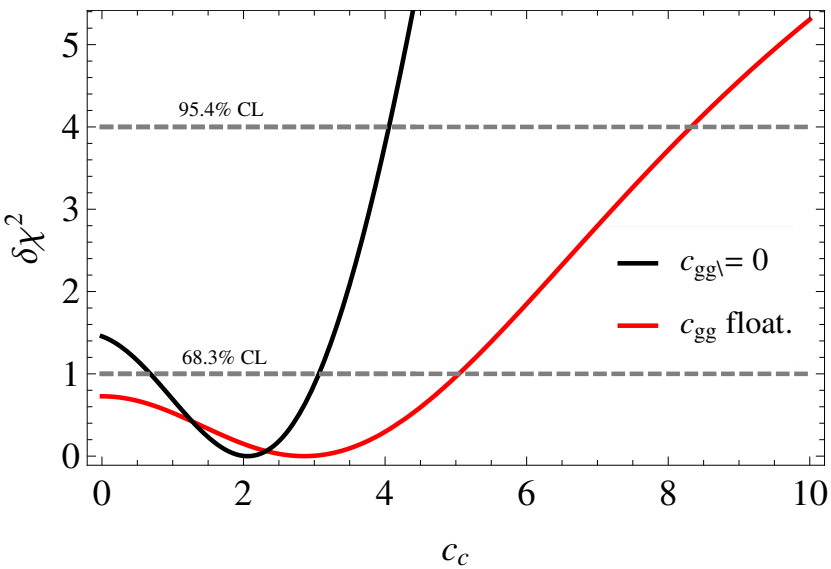
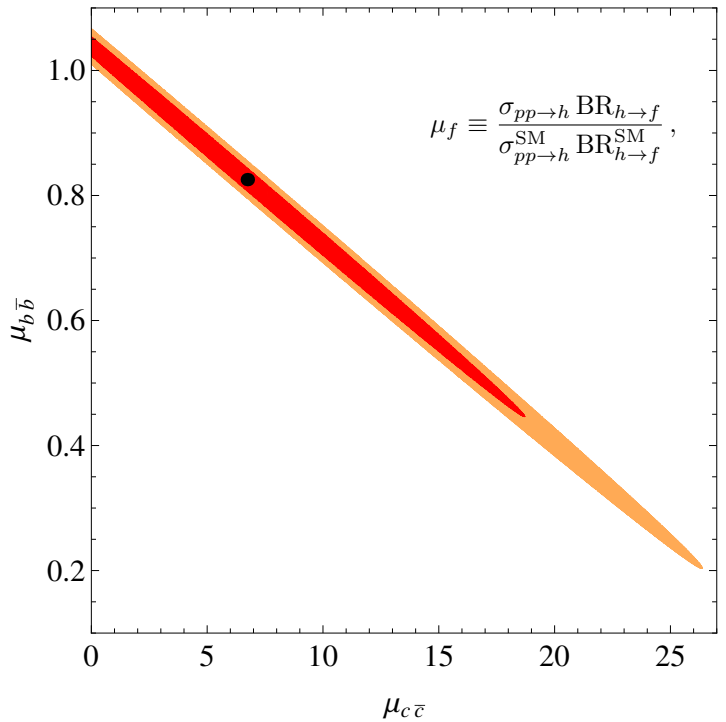


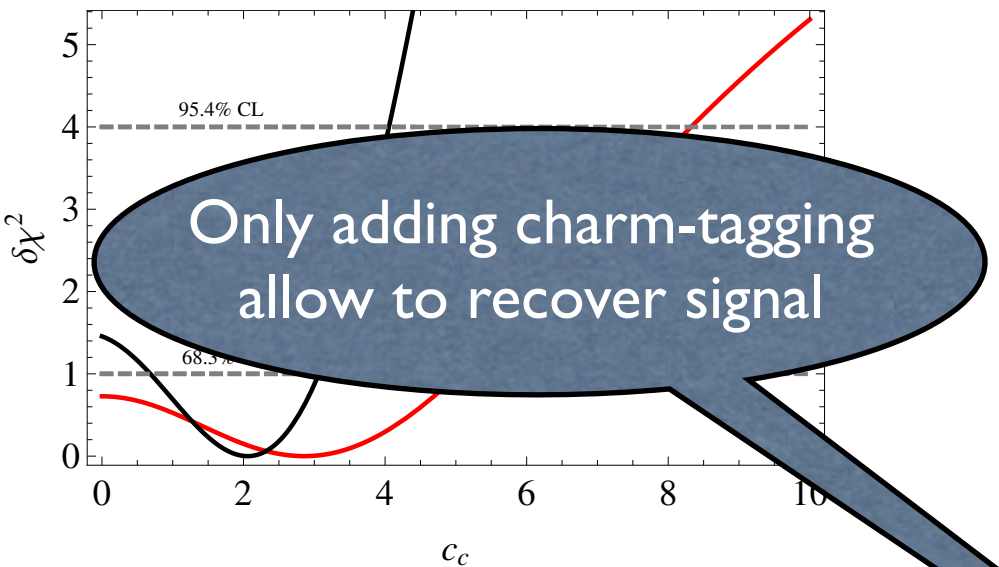

$\delta\chi^2 = \chi^2 - \chi^2_{\rm min}$ as a function of the charm Yukawa coupling $c_c$. The black and red curves correspond respectively to case a), where all Higgs coupling but the charm Yukawa are SM-like, case b), where only $c_c$ and $c_{gg}$ deviate from the SM and marginalizing over the latter. Horizontal dashed lines denotes the 68% and 95.4% CL ($\delta\chi^2 = 1$ and 4, respectively).



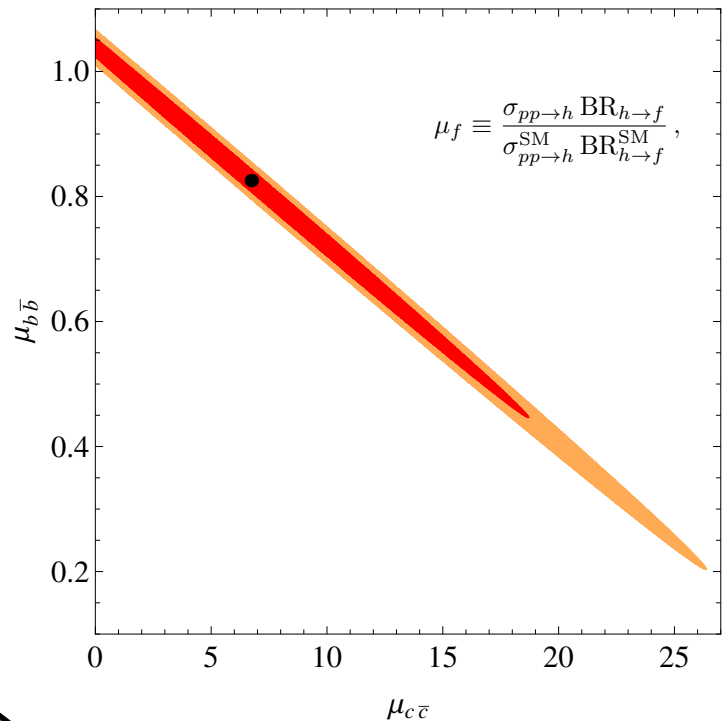

$\mu_{c\bar{c}}$ vs. $\mu_{b\bar{b}}$ for case b) where both $c_c$ and $c_{gg}$ are not SM-like. Efficiencies of the ATLAS analysis [10] are assumed for both signal strengths. The red (brown) region is consistent within 68.3% and 95.4% CL with Higgs data. The black dot represents the best fit point.

# $H \to c\bar{c}$

Delaunay, Golling, GP & Soreq, to appear.




Only adding charm-tagging allow to recover signal

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$$\mu_{b\bar{b}+c\bar{c}} \equiv \frac{\sigma_{pp\to h}\left(\epsilon_b^2 \mathrm{BR}_{h\to b\bar{b}} + \epsilon_c^2 \mathrm{BR}_{h\to c\bar{c}}\right)}{\sigma^{\mathrm{SM}}_{pp\to h}\left(\epsilon_b^2 \mathrm{BR}^{\mathrm{SM}}_{h\to b\bar{b}} + \epsilon_c^2 \mathrm{BR}^{\mathrm{SM}}_{h\to c\bar{c}}\right)}$$

where $r_{cb} \equiv \epsilon_c^2/\epsilon_b^2 \times (\mathrm{BR}^{\mathrm{SM}}_{h\to c\bar{c}}/\mathrm{BR}^{\mathrm{SM}}_{h\to b\bar{b}})$

$$R \equiv \frac{\mu_{b\bar{b}+c\bar{c}}}{\mu_{b\bar{b}}} = \frac{1+|c_c|^2\, r_{cb}}{1+r_{cb}}\,, \qquad R < 1.3(2.1)\,, \quad \text{at } 95.4\%\ \mathrm{CLs}\,,$$

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

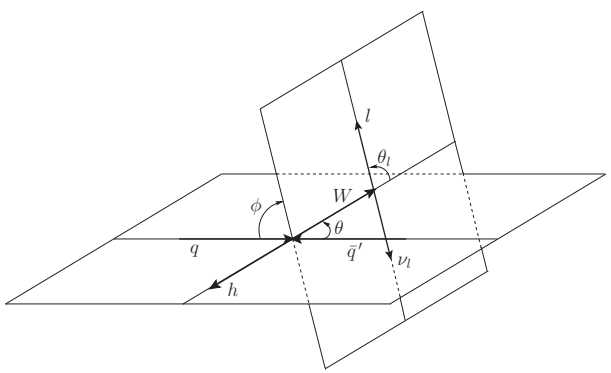
# Comment on CP violating Higgs phys. & diff' dist'

Delaunay, De Sanda, GP & Skiba; Isidori & Trott (13)

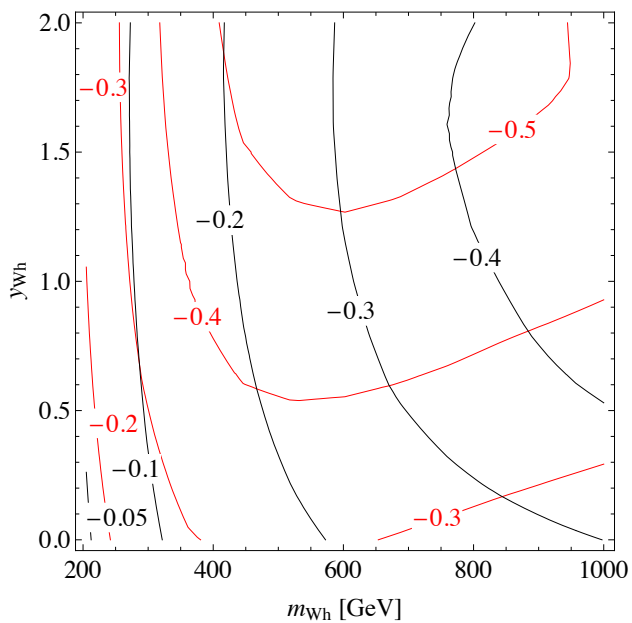
- In the presence of heavy CP violating physics: $\widetilde{\mathcal{O}}_{WW} = \frac{g^2}{2} H^\dagger H \, W^a_{\mu\nu} \widetilde{W}^{\mu\nu\, a}$ $\qquad \widetilde{V}_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta} V^{\alpha\beta}/2.$

- Define up-down HCP assymmetry:

$$A_{\rm CP}^{p\bar{p}} \simeq \frac{\int d\tau \, \mathcal{L}_{q\bar{q}'}(\tau) \left[\hat{\sigma}_{\phi>0}(\tau) - \hat{\sigma}_{\phi<0}(\tau)\right]}{\int d\tau \, \mathcal{L}_{q\bar{q}'}(\tau) \left[\hat{\sigma}_{\phi>0}(\tau) + \hat{\sigma}_{\phi<0}(\tau)\right]} .$$



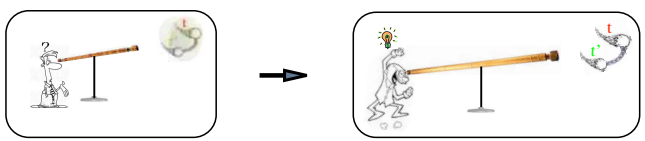

Definition of the production and decay angles. The $W$ and $h$ directions are drawn in the $q\bar{q}'$ center-of-mass frame, while the leptons are drawn in their parent $W$ rest frame. $\phi$ is the angle between the production plane and the $W$ decay plane.



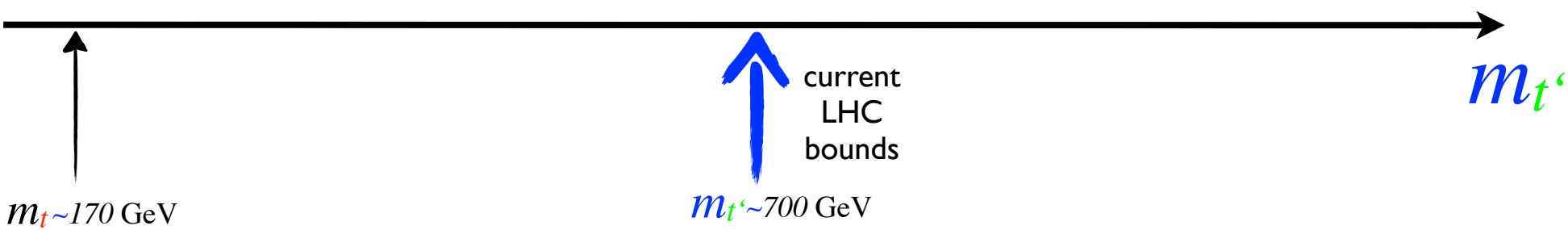

- Effect grows \w energy, focusing only on $q^2 = m_h^2$ <=> mistake !

# Comment: boosted quasi-naturalness, $m_{t'} \gg m_t$

*(i) Heavy partners:* region of boosted quasi-naturalness;



boosted quasi-naturalness.



# Boosted quasi-naturalness, $m_{t'} \gg m_t$

- The challenge of searching for heavy partners:

  a new phenomena => emergence of collimated top jets; linked to new subfield of jet substructure physics:

Agashe, Belyaev, Krupovnickas, Perez & Virzi (06); Lillie, Randall & Wang (07)

As $m_{t'} \gg m_t$ outgoing tops are ultra-relativistic, their products collimate

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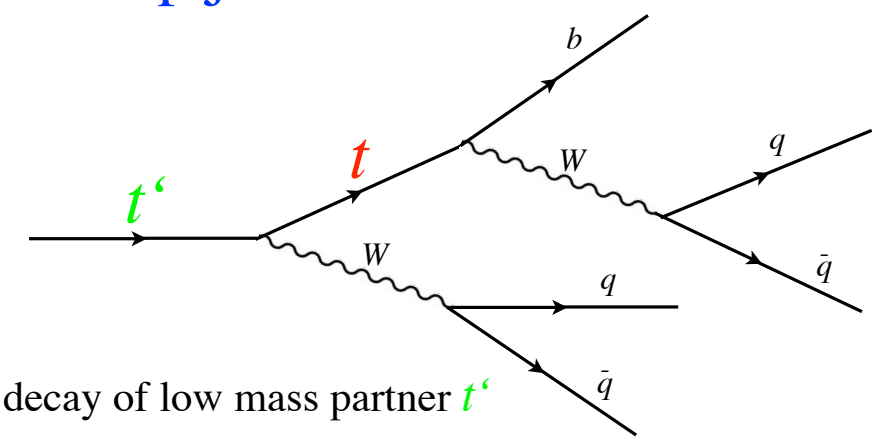


decay of low mass partner $t'$

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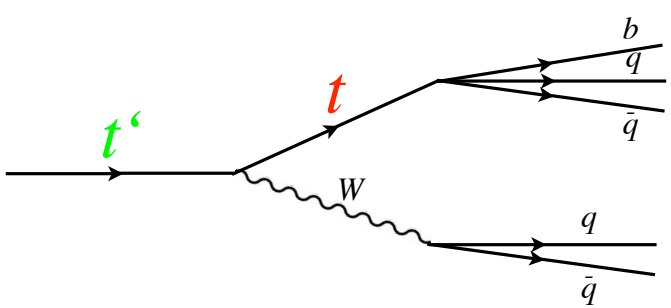
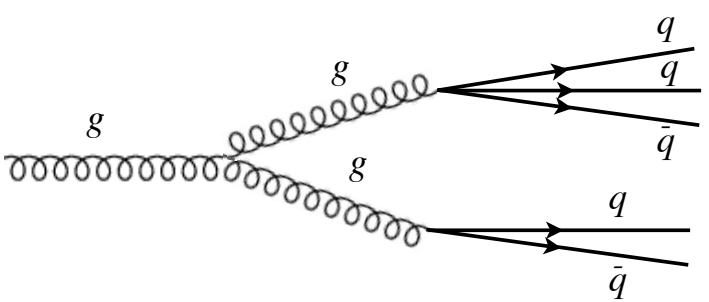



decay of heavy partner $t'$

Similar to ordinary 2-jet QCD process impossible to observe ??



# Overview

- Lot more to be done on top physics, a window to naturalness;

by the time of CLIC: 2 mini frontiers ("elusive" & "boosted").

- The charm frontier:

  stop-scharm mixing;

  light charm partners / scharms;

  $H \to c\bar{c}$;

  Interplay with D phys., mixing and CP violation.

- Lesson form Higgs phys.: advantage in looking at differential distributions.

# *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?

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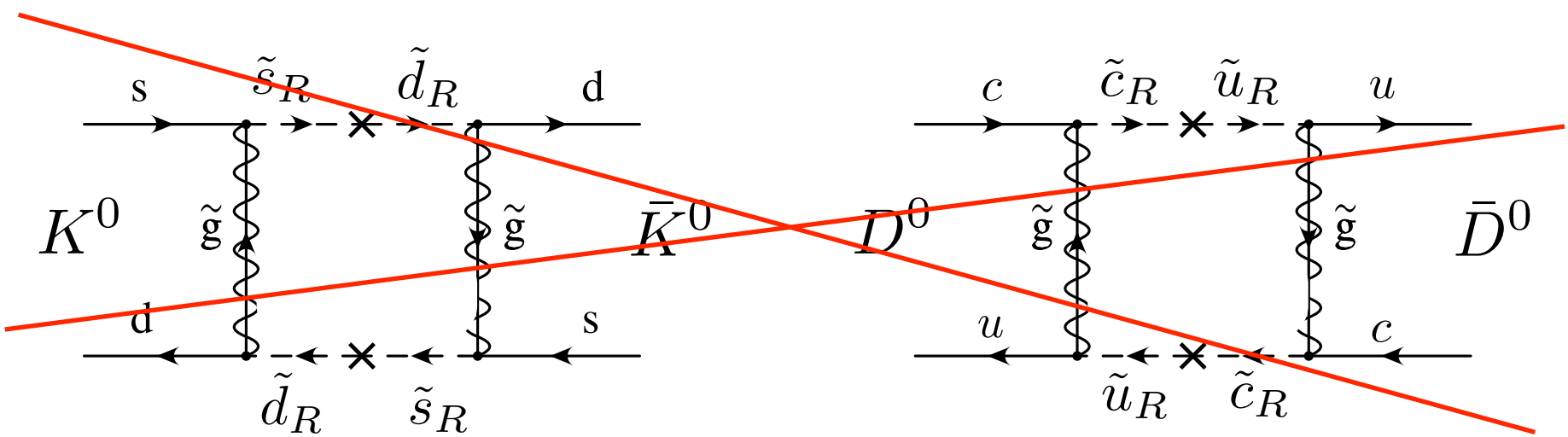


# The SUSY left handed flavor challange

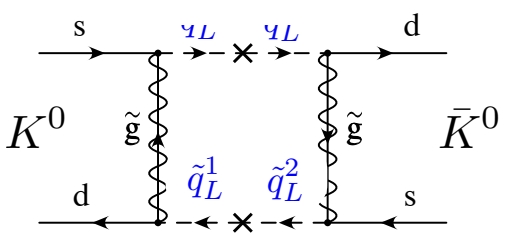
- SM LH sector consist of 2 flavor breaking sources: $Y_d Y_d^\dagger$ & $Y_u Y_u^\dagger$

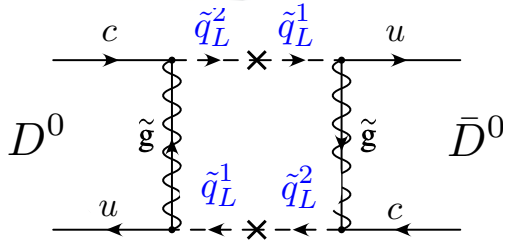
- SUSY: cannot align LH masses simultaneously with both sources! Dangerous direction wins to reduce bounds ...

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

$\Delta M_K, \epsilon_K$

$\Delta M_D, A_\Gamma^D$



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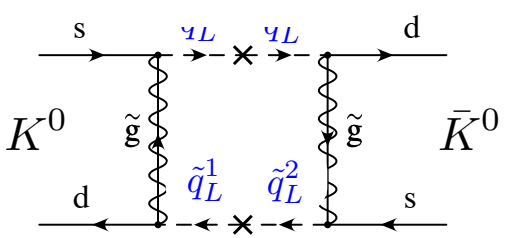


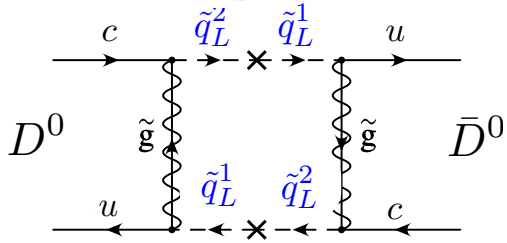

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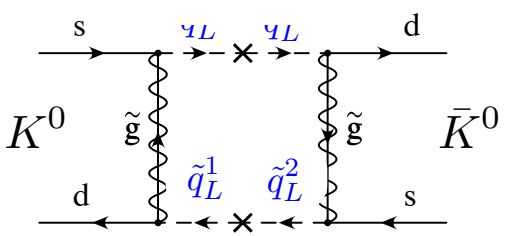


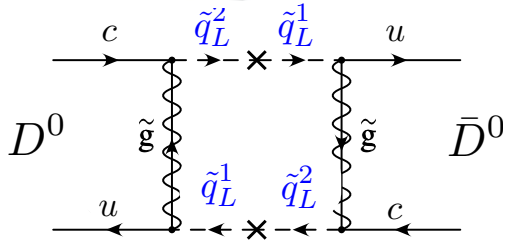

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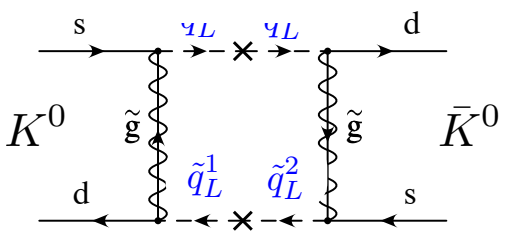


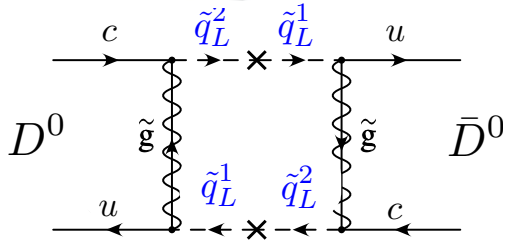

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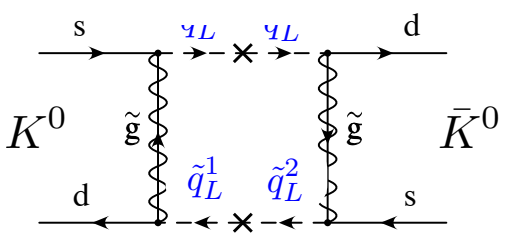


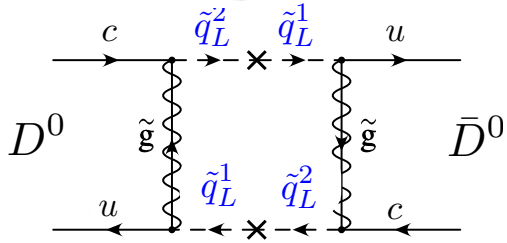

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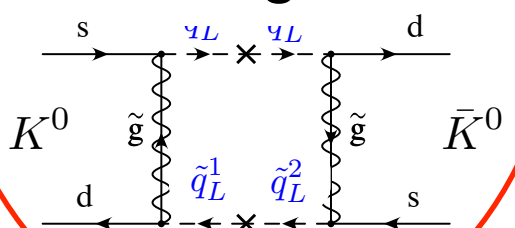
down alignment

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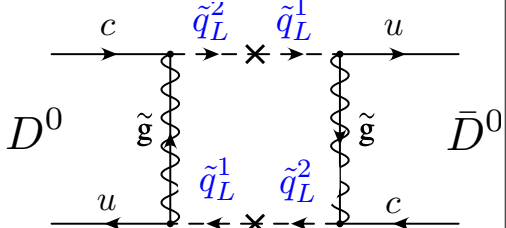
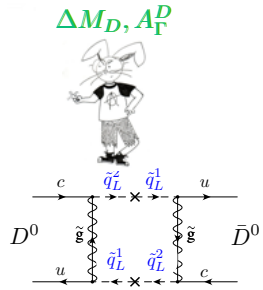



Nir & Seiberg (93)

# Last 4 yrs: dramatic progress in studying charm CPV




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

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

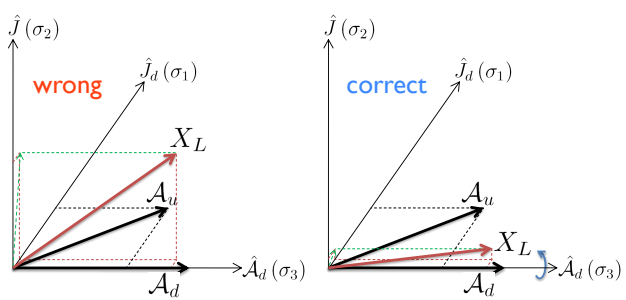
(squark doublets, gluino, 1TeV)

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 ...

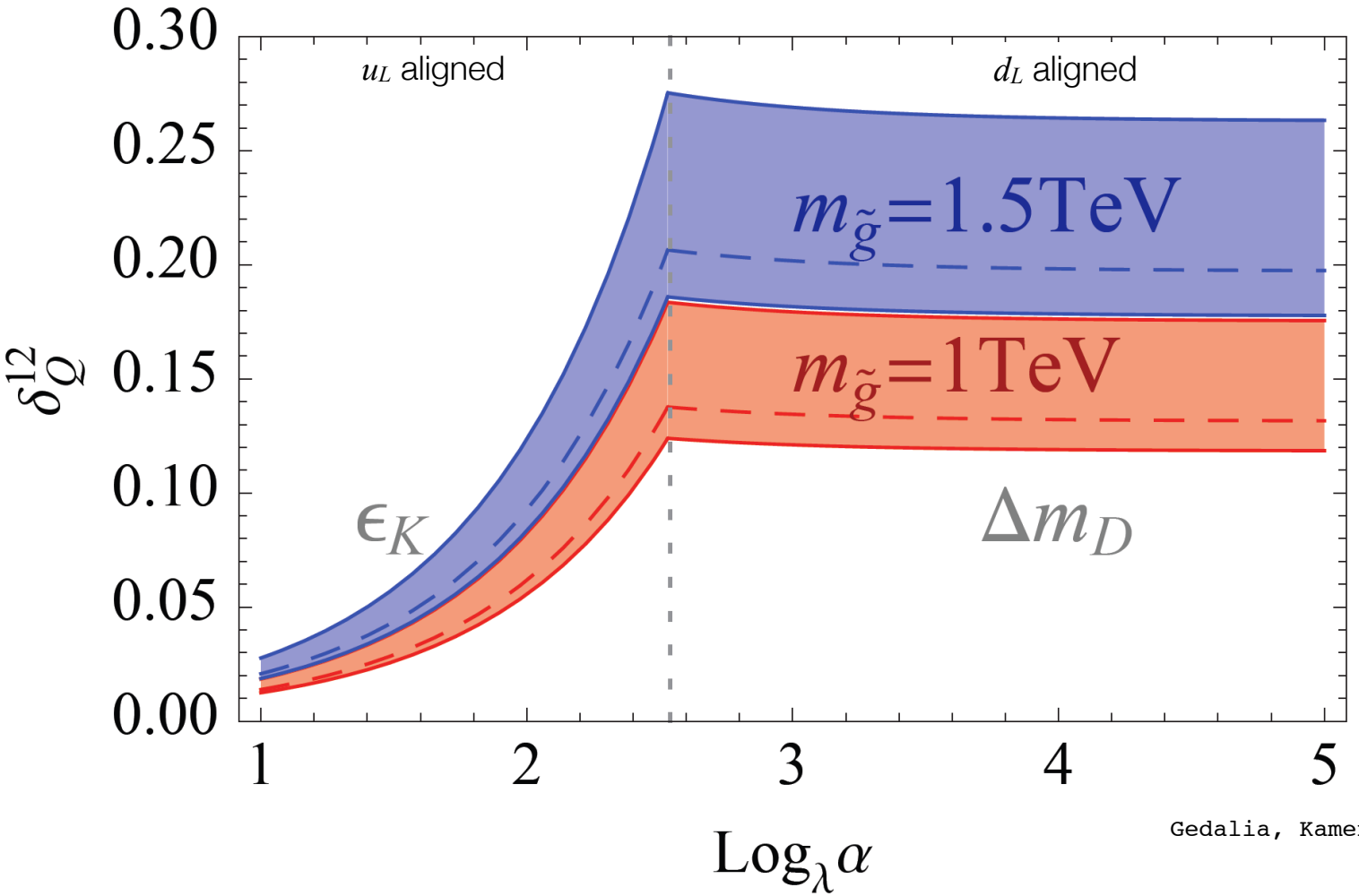
## Successful alignment models guarantee small physical CP phase!




Gedalia, Kamenik, Ligeti & GP (12);

Formalism: Gedalia, Mannelli & GP (10) x2

# Degeneracy of Squarks

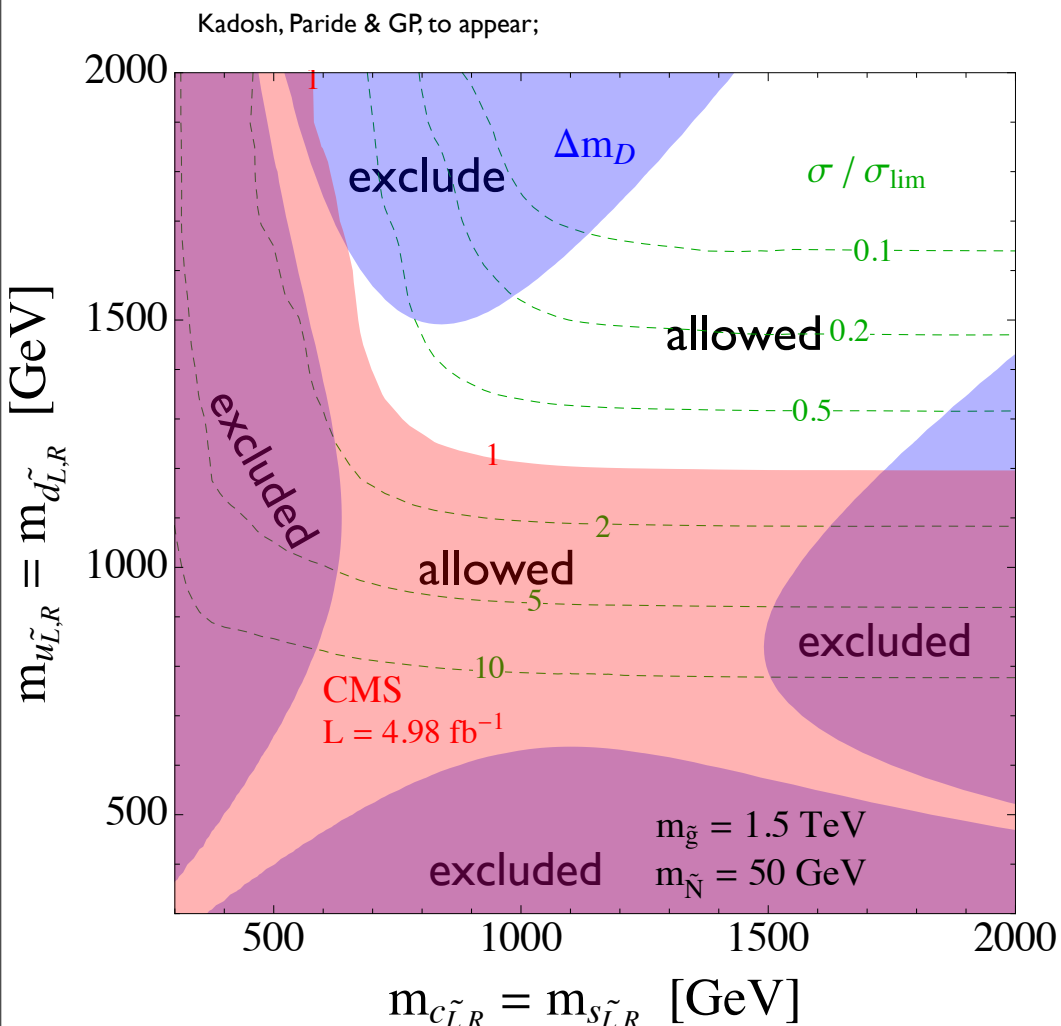



$$\delta_Q^{12} \equiv \frac{m_{\tilde{Q}_2} - m_{\tilde{Q}_1}}{m_{\tilde{Q}_2} + m_{\tilde{Q}_1}}$$

Gedalia, Kamenik, Ligeti & GP (12);

# Sea LH squarks vs. valence RH squarks

Adding flavor constraints ( $\Delta m_D$ ) for LH squarks:



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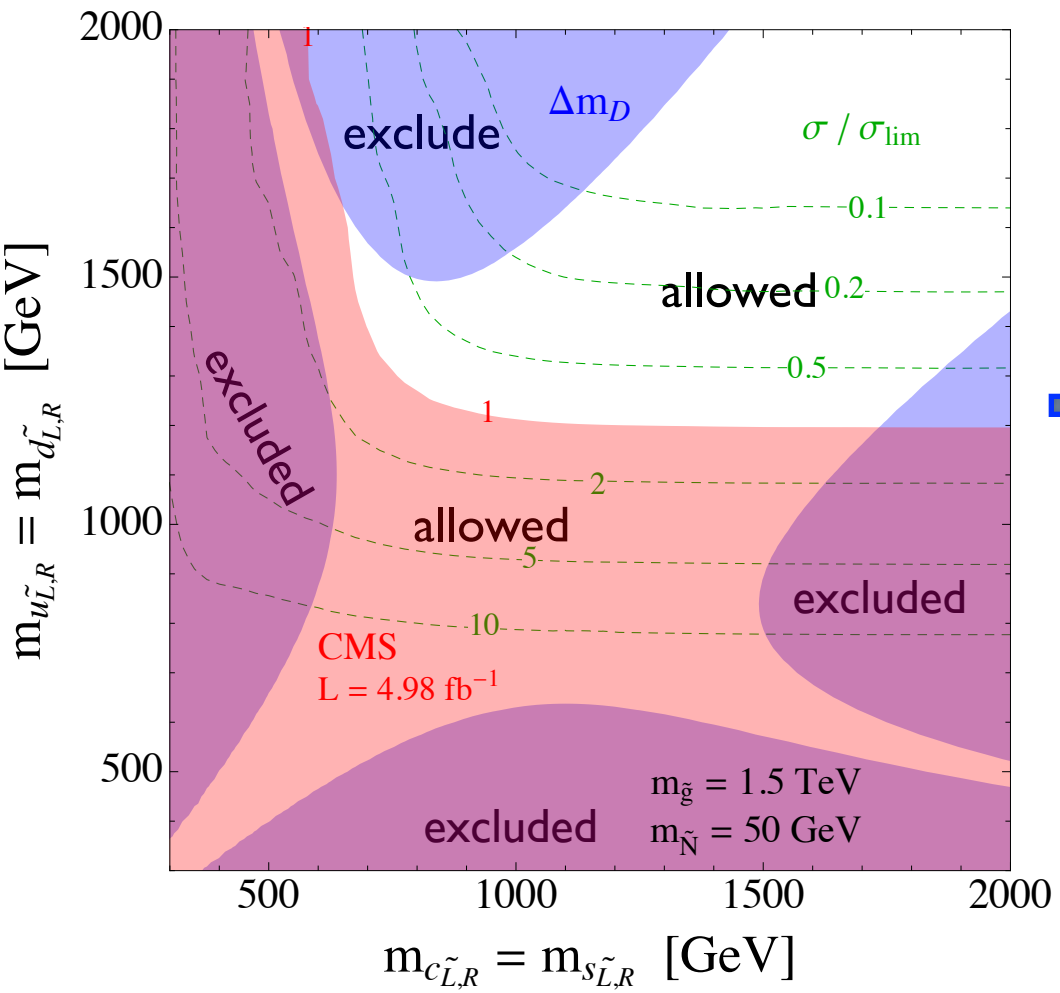
Kadosh, Paride & GP, to appear;




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

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

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

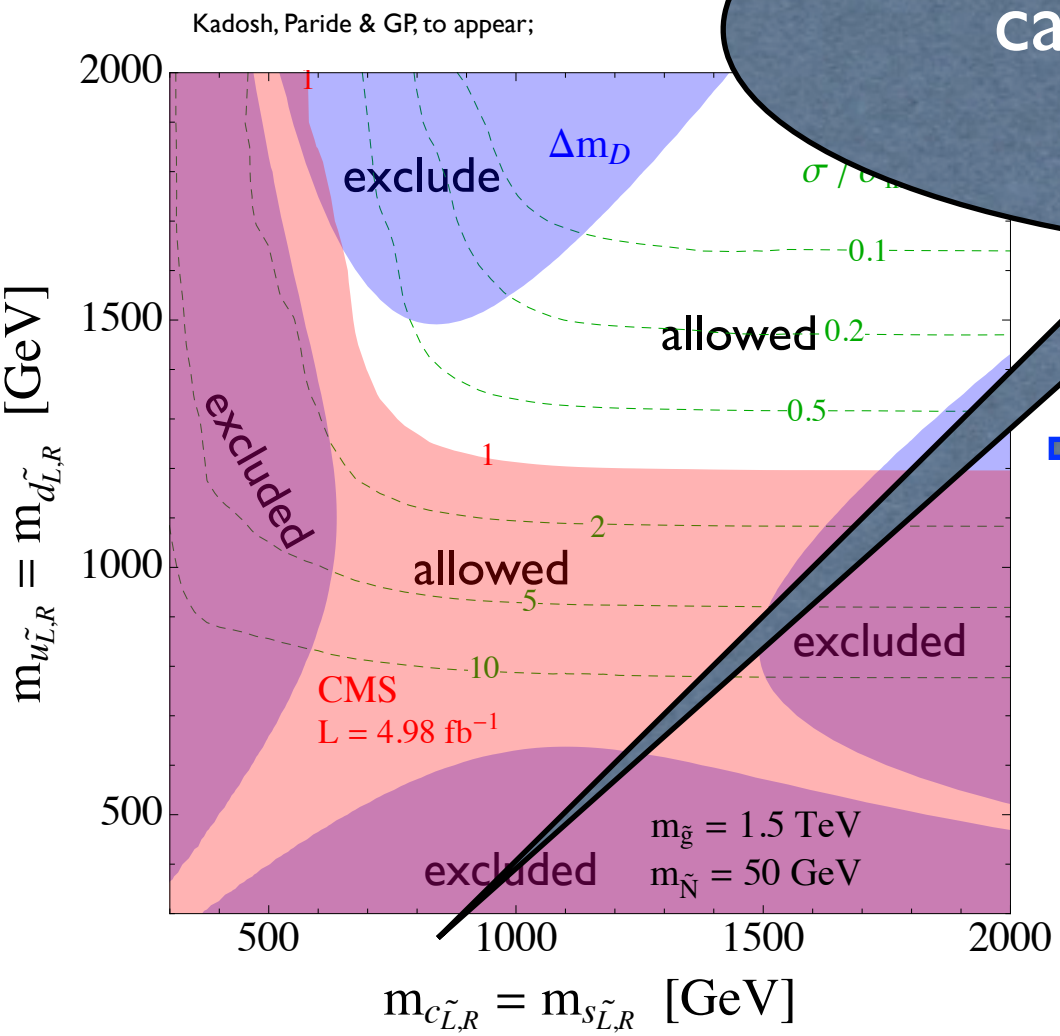
**LHCb soon start testing alignment paradigm!**

Kadosh, Paride & GP, to appear.

# Sea LH squarks vs. valence RH squarks

Adding flavor constraints (

ATLAS & CMS
can improve sensitivity
via charm tagging !

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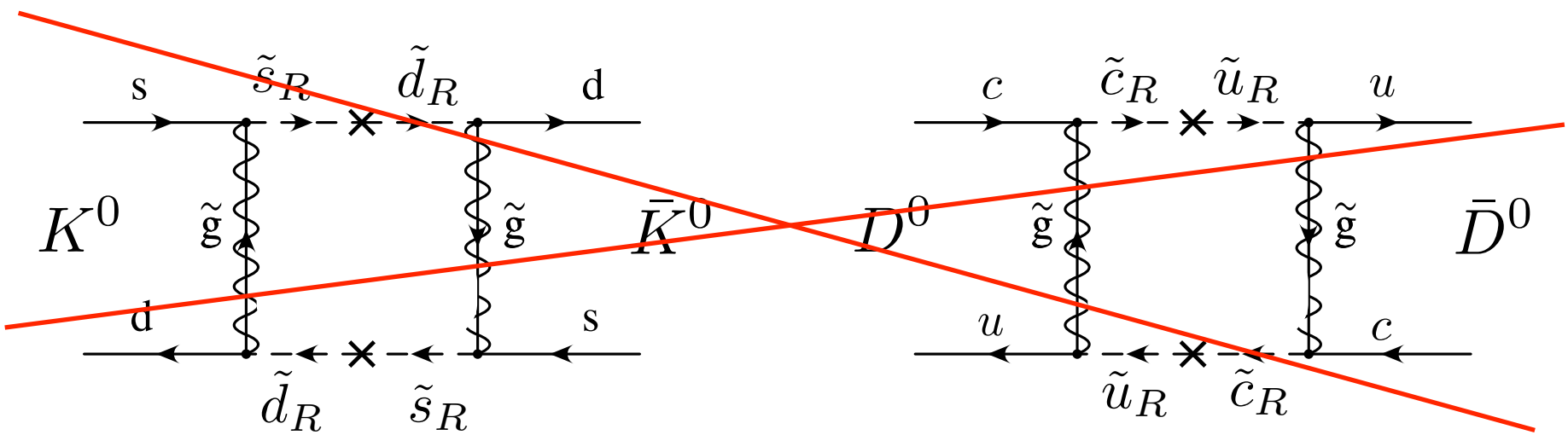

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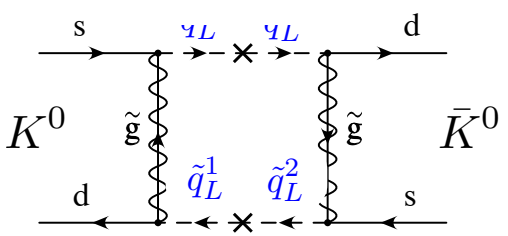


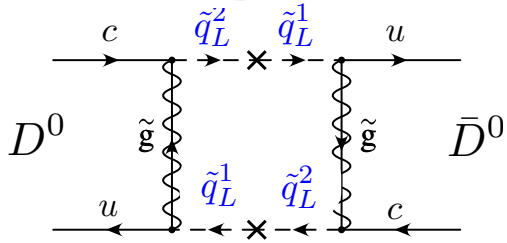

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- SM LH sector consist of 2 flavor breaking sources: $Y_d Y_d^\dagger$ & $Y_u Y_u^\dagger$

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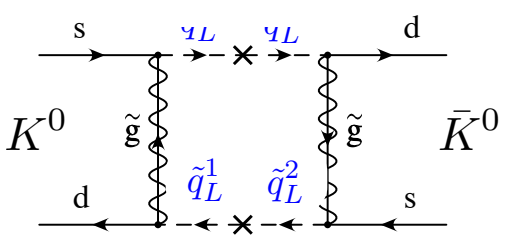


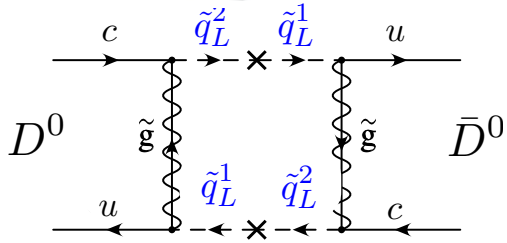

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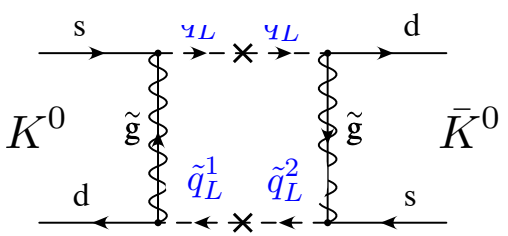


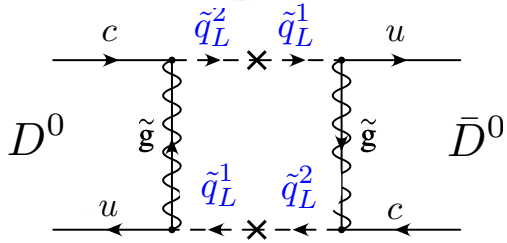

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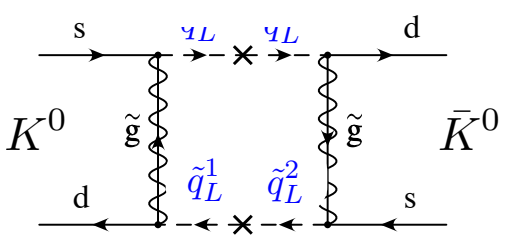


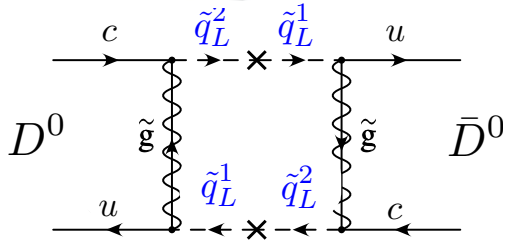

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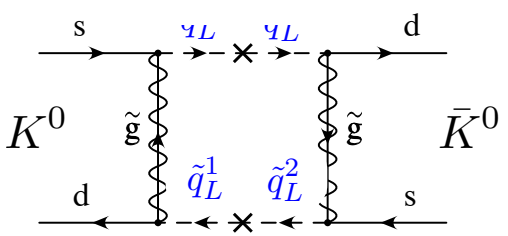


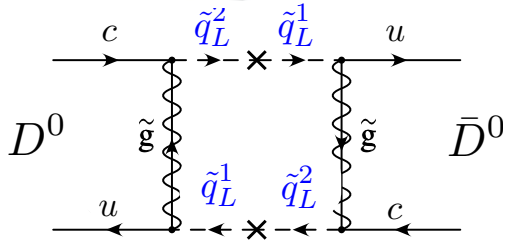

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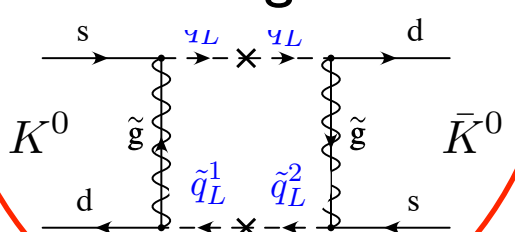
down alignment

Nir & Seiberg (93)

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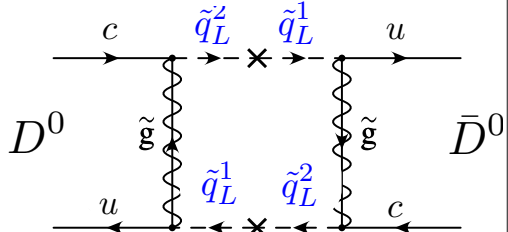
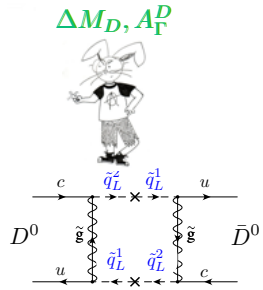


# Last 4 yrs: dramatic progress in studying charm CPV




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

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

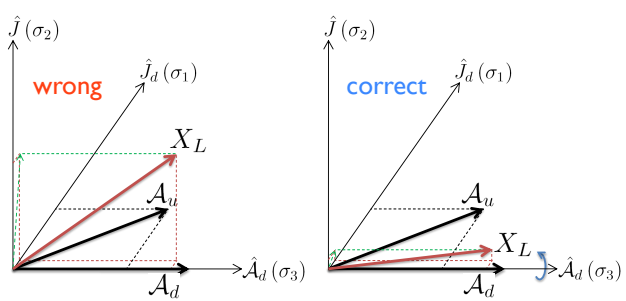
(squark doublets, gluino, 1TeV)

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 ...

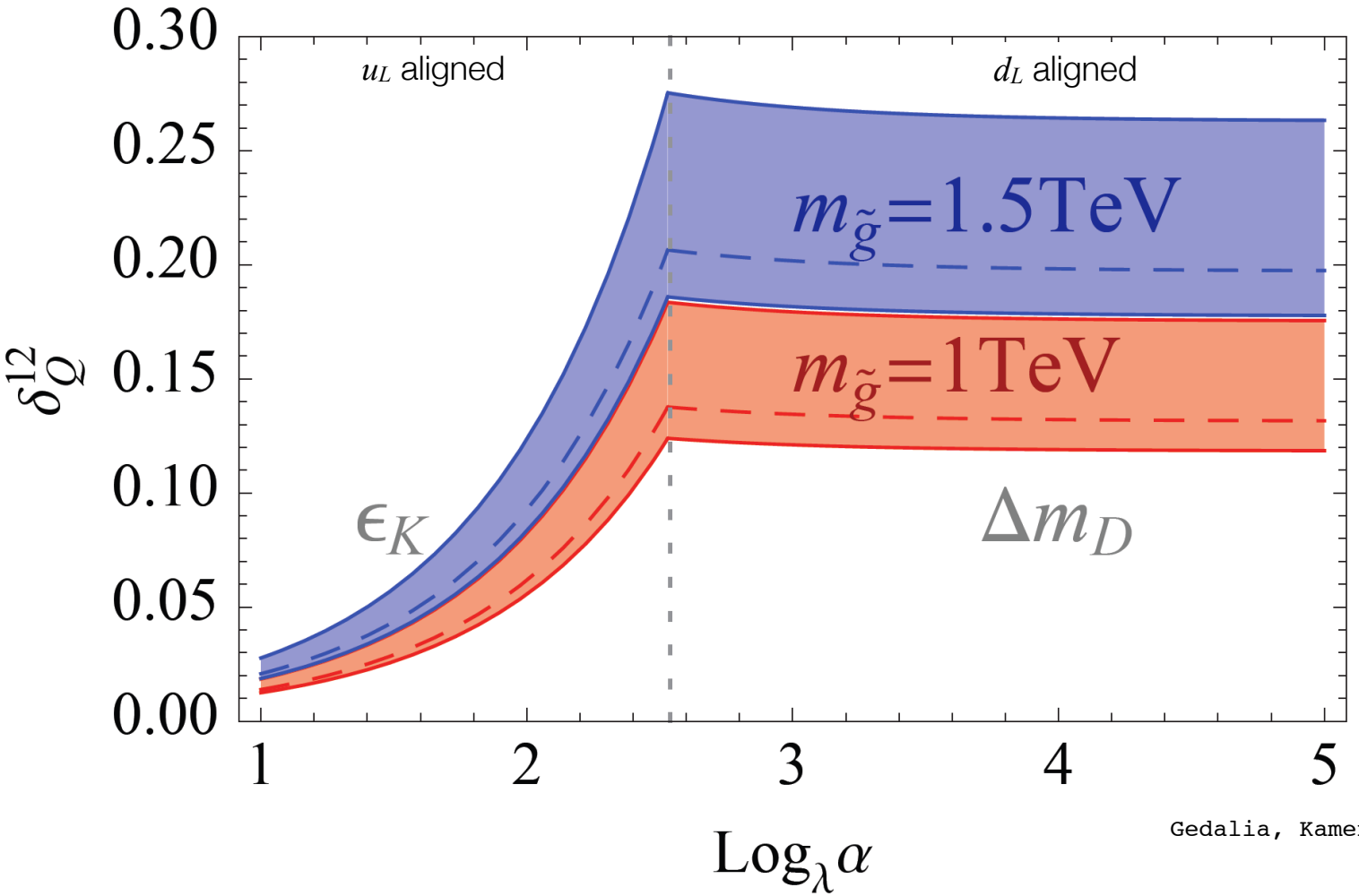
## Successful alignment models guarantee small physical CP phase!




Gedalia, Kamenik, Ligeti & GP (12);

Formalism: Gedalia, Mannelli & GP (10) x2

# Degeneracy of Squarks




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

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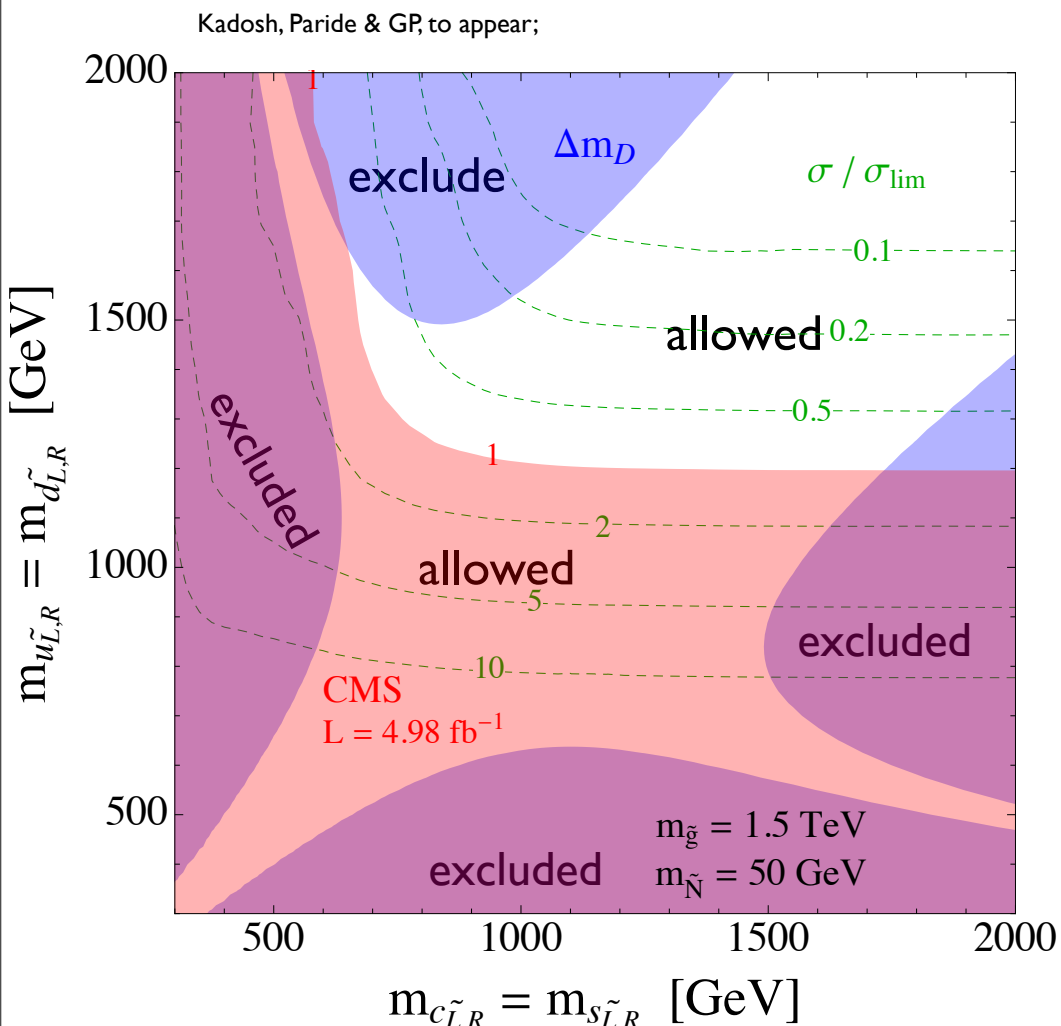
# Sea LH squarks vs. valence RH squarks

Adding flavor constraints ( $\Delta m_D$ ) for LH squarks:



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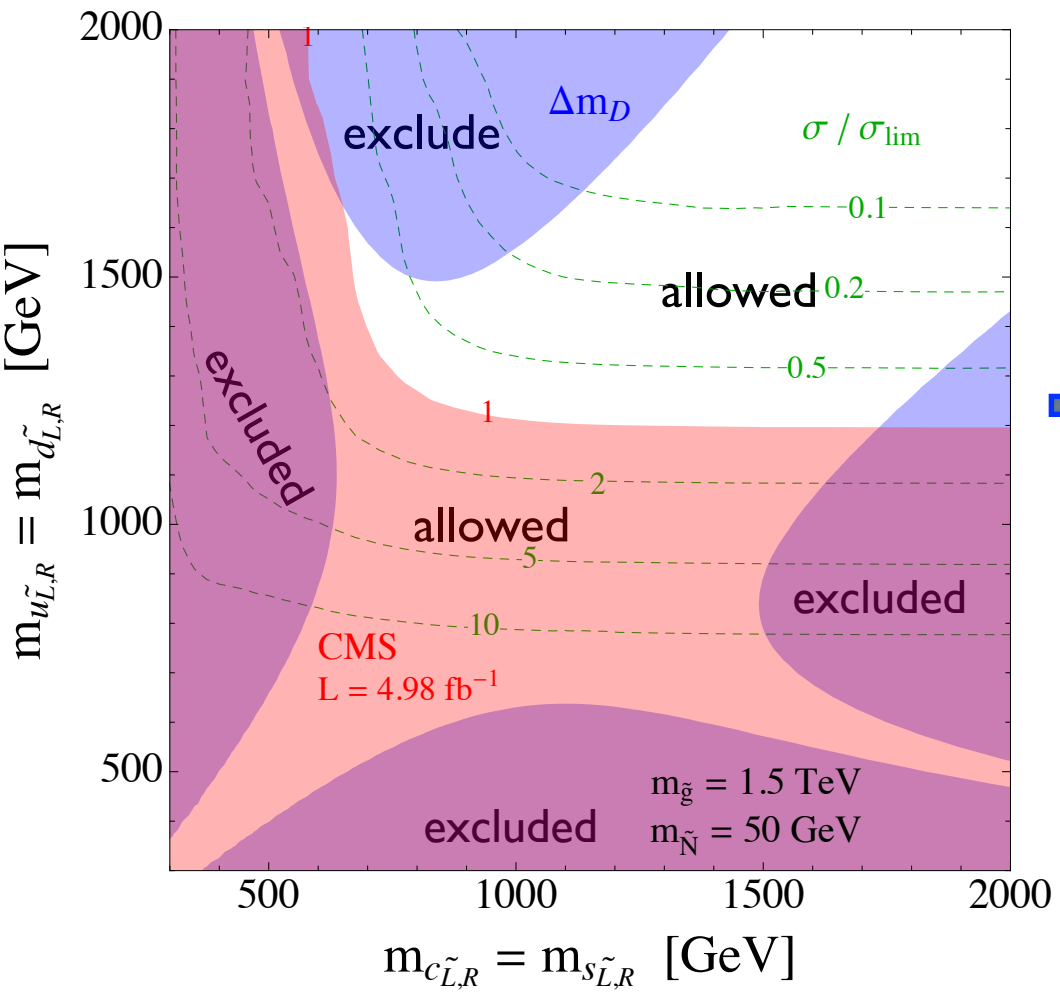



alignment: new upper bound on CP violation (CPV) in *D-phys.*:

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

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

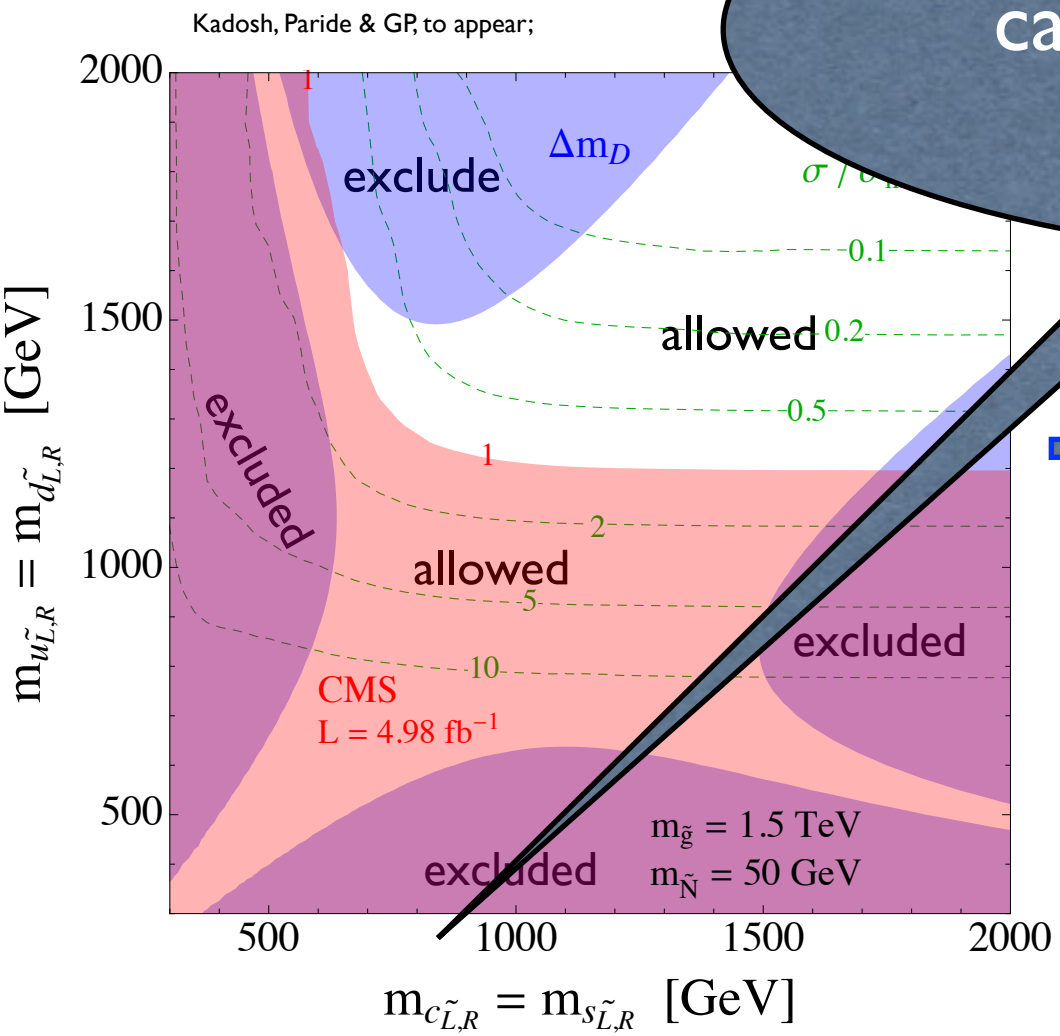
**LHCb soon start testing alignment paradigm!**

Kadosh, Paride & GP, to appear.

# Sea LH squarks vs. valence RH squarks

Adding flavor constraints (

ATLAS & CMS
can improve sensitivity
via charm tagging !

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