New Physics Models
or
On the Rare Occasions When Naturalness Meets Flavor

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Flavorful Ways to New Physics

KHYS Young Scientists Workshop KIT

The Standard Model (SM) & Flavor Phys.

- *B*-factories+LHC have an experimental (exp') support that the CKM picture described nature (up to possibly small corrections):

Talk by: Krizan

- Based on several exp' observation (started in 64 many came in the last 10 years or so).

- CP violation (CPV) in the Kaon and *B* system => within the SM correlated => consistent with SM.

Talk by: Buras

- Flavor conversion => precision data confirmed the SM.

- New bounds on CPV in the *D* mixing also confirms SM picture.

Talk by: Gersabeck

This implies: severe bounds on non-SM phys. / does it exist?

Is this the end of the story?

Baryogenesis => SM cannot be the only source of CPV.

(otherwise, rapid proton-antip-protons annihilation of yield baryon asym' of < 10^{-18})

Almost any SM extension give new sources of flavor & CPV.

Integrating out new physics (NP) => di. 6 Ops.: $(\bar{d}_i d_j)^2/\Lambda_{NP}^2$

Precision measurements => $\Lambda_{NP} \gtrsim 10^4\text{TeV} \gg M_W$

⇓

Flavor NP hierarchy "problem" (puzzle not a problem, see later)

What are the problems of the Standard Model* (SM), before & during the LHC era?

WW/unitarity, masses	fine tuning, naturalness	neutrino masses	flavor puzzle
		dark matter	(strong CP)
		baryogenesis	unification, charge quantisation

* Let's set quantum gravity aside for simplicity …

What are the problems of the Standard Model* (SM), before & during the LHC era?

data driven, clear scale	conceptual vague scale	data driven, no clear reachable scale	conceptual
WW/unitarity, masses	fine tuning, naturalness	neutrino masses	flavor puzzle
		dark matter	(strong CP)
		baryogenesis	unification, charge quantisation

What kind of new phys. might be motivated during the LHC era?

data driven, clear scale	conceptual vague scale	data driven, no clear reachable scale	conceptual
WW/unitarity, masses	fine tuning, naturalness	neutrino masses	flavor puzzle
		dark matter	(strong CP)
		baryogenesis	unification, charge quantisation


Reminder: sym' structure of SM quark flavor sector

Talk by: Buras

Int' basis, the gauge part is trivial:

$$\bar{q}^I_i \not{D} q^I_j \delta^{ij}, \quad q \in Q, U, D \quad \rightarrow \quad q_i \to U^{(3\times 3)}_{ij} q_j$$

global sym': $U(3)_Q \times U(3)_U \times U(3)_D$

Yukawa sector is interesting:

The quark Yukawa interactions are given by

$$-\mathcal{L}^{\text{quarks}}_{\text{Yukawa}} = Y^d_{ij} \overline{Q^I_{Li}} \phi D^I_{Rj} + Y^u_{ij} \overline{Q^I_{Li}} \tilde{\phi} U^I_{Rj} + \text{h.c.}.$$

global sym': $U(1)^3_D \times U(1)^3_U \to U(1)_B$

Flavor puzzle vs. problem, tuning vs fine tuning

Flavor puzzle: parameters are small and hierarchical.

Is the flavor sector finely tuned? (quantum unstable?)

’t Hooft’s-technical-naturalness: a parameter is natural if when it’s vanishing a new non-anomalous sym’ is obtained.

Light masses are protected by residual $U(2)_D \times U(2)_U$ sym’.

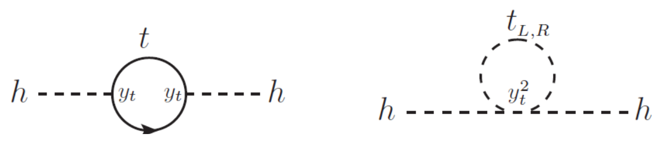
Mixing angles are protected by $U(1)_Q^3$ sym’.

Flavor puzzles => matter of tuning (nothing unnatural)

Higgs mass => fine tuning (unnatural)!

Conventional naturalness => vague scale => LHC perspective

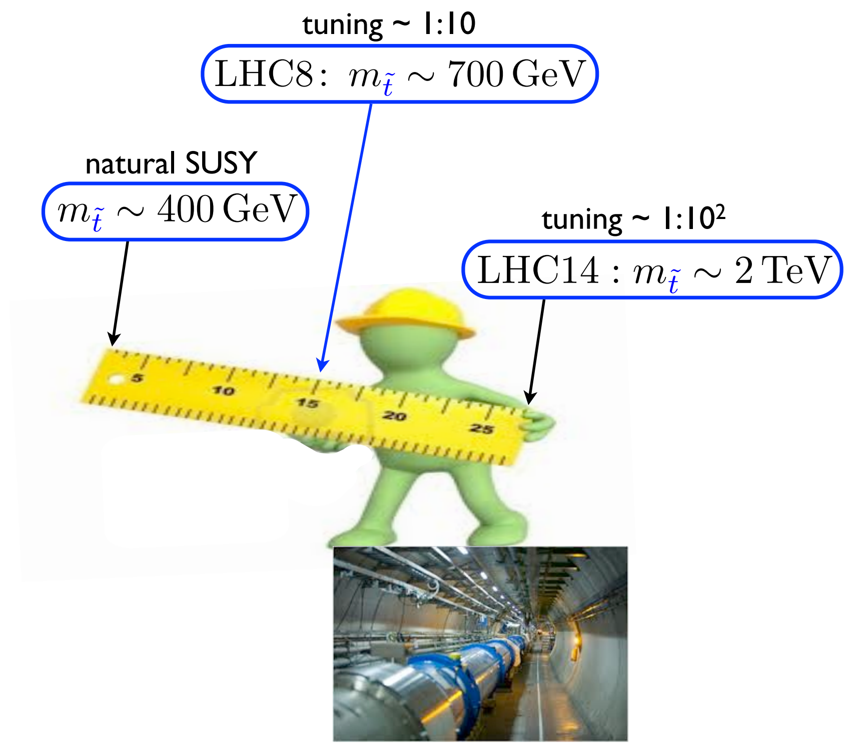
Screening away UV sensitivity => new partners, potentially within the LHC reach.



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

The LHC naturalness ruler:

(~ half way through)

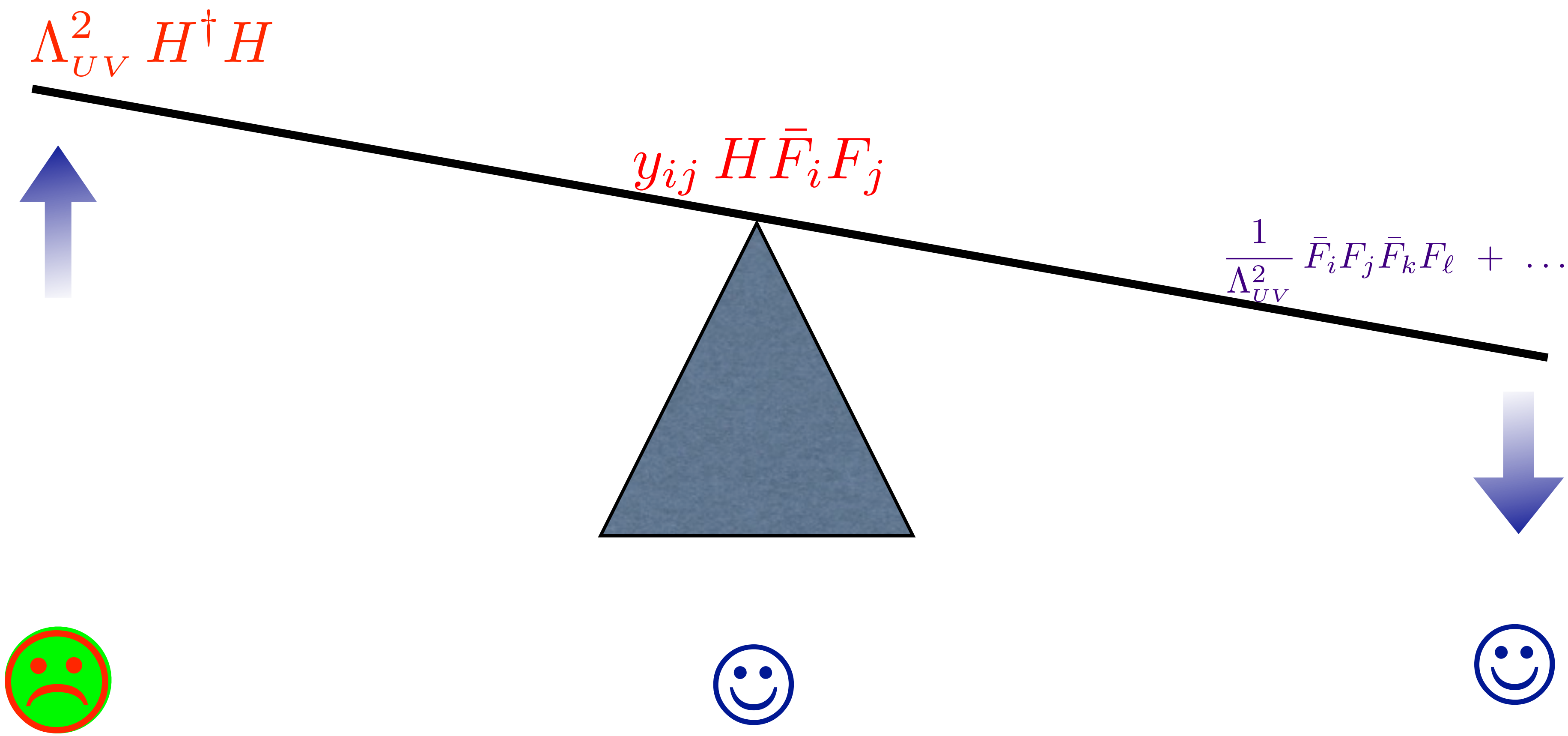


The LHC is a very limited telescope
but this is the best we have …

With NP new flavor problem might arise

Hierarchy see-saw

Standard Model up to some $\Lambda^2_{UV} \gg 1\,\mathrm{TeV}$



Rattazzi (12)

NP, model indep': $\Delta F = 2$ status

Isidori, Nir & GP, Ann. Rev. Nucl. Part. Sci. (10)

Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2	3×10^2	7.6×10^{-5}	2.5×10^{-5}	Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2	1.1×10^3	1.3×10^{-5}	4×10^{-6}	Δm_{B_s}
$(\bar{t}_L\gamma^\mu u_L)^2$					same sign t's

However little is known on tFCNC

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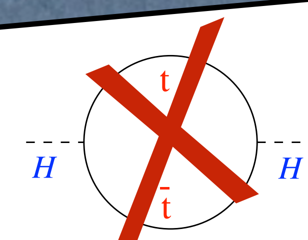
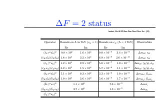
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	[illegible] $\times 10^{-7}$	1.7×10^{-7}	[illegible] K_S
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		[illegible]		[illegible]
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		[illegible]		[illegible]
$(\bar{t}_L \gamma^\mu u_L)^2$			[illegible]		[illegible]

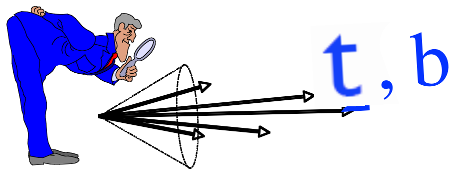
Do not directly couple to 3rd generation!

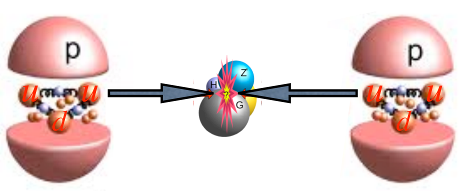




An experimental natural irony …

Our most precise probes are made of light quarks;
our initial states are made of light quarks and gluons.
However, natural phys. is about Higgs, top & massive gauge fields.





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$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		[illegible]	[illegible]	[illegible]
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$(\bar{t}_L\gamma^\mu u_L)^2$			[illegible]	[illegible]	…s

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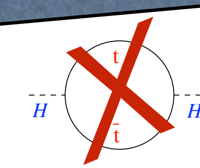
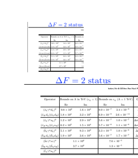


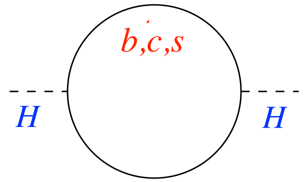


12

Reverse the logic with light flavors

D. Grossman, Hochberg, GP & Soreq, private com.; see also: Barbieri et al. JHEP (10).

- How large of non-univ. cutoff to sustain < $1{:}100$ fine tuning?



$$s: \quad \Rightarrow \Lambda_s \lesssim 2 \times 10^4 \,\mathrm{TeV}$$

$$c: \quad \Rightarrow \Lambda_c \lesssim 2 \times 10^3 \,\mathrm{TeV}$$

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$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2
[illegible]	[illegible] $\times 10^3$	3.6×10^3
[illegible]	1.1×10^2	
[illegible]	3.7×10^2	

Tension with LLRR
CP violation (CPV)!

Reverse the logic with light flavors

- How large of cutoff to sustain fine tuning of less than $1{:}100$?

$$s: \;\Rightarrow \Lambda_s \lesssim 2\times 10^4\,\text{TeV}$$

$$c: \;\Rightarrow \Lambda_c \lesssim 2\times 10^3\,\text{TeV}$$

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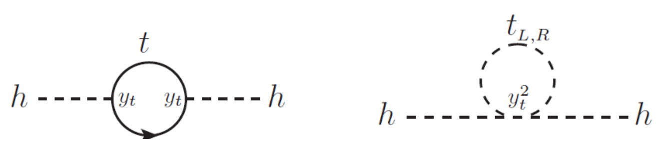
$(\bar c_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3
$(\bar c_R u_L)(\bar c_L u_R)$	6.2×10^3	1.5×10^4
$(\bar b_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2
$(\bar b_R d_L)(\bar b_L d_R)$	1.9×10^3	3.6×10^3
…$_L\gamma^\mu s_L)^2$	1.1×10^2	
…$)(\bar b_L s_R)$	3.7×10^2	

B system: only case with
tension with LLLL operators;
Improvement in Bs will
get us there as well.

Top partners & LHC Searches

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

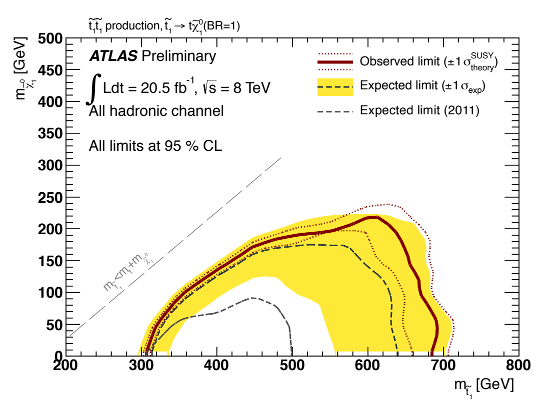


$$\frac{\delta m_h^2}{m_h^2} \sim \left(\frac{\tilde{m}_t}{400\,\mathrm{GeV}}\right)^2$$

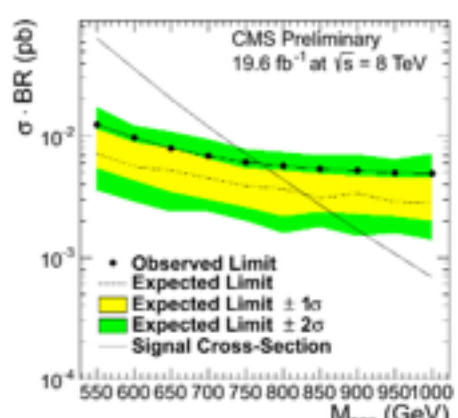
2 leading frameworks
of naturalness => top reach final state

SUSY

composite Higgs



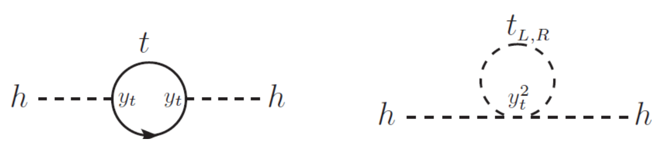
$m_{\mathrm{stop}} \gtrsim 700\,\mathrm{GeV}$



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

Top partners & naturalness

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



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

2 leading frameworks
of naturalness

Supersymmetry
top partners=stops

Composite Higgs
top partners = "T"

Before discussing flavor violation, crucial info in flavor diag' NP sector

Basic question regarding NP: what structure is realised in nature ??

spectrum or coupling →

U(3)

1		
	1	
		1

U(2)

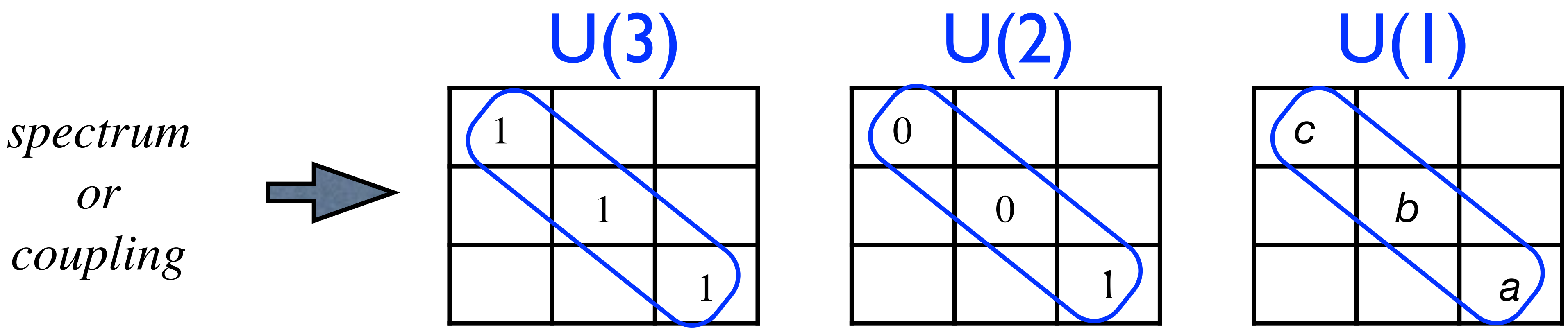
0		
	0	
		1

U(1)

c		
	b	
		a

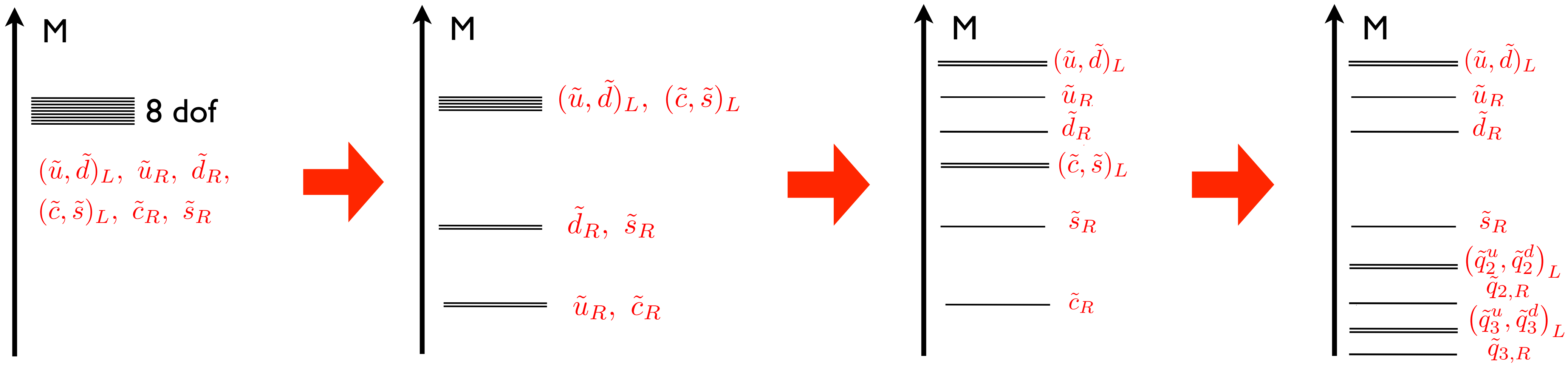
Before discussing flavor violation, crucial info in flavor diag' NP sector

Basic question regarding NP: what structure is realised in nature ??

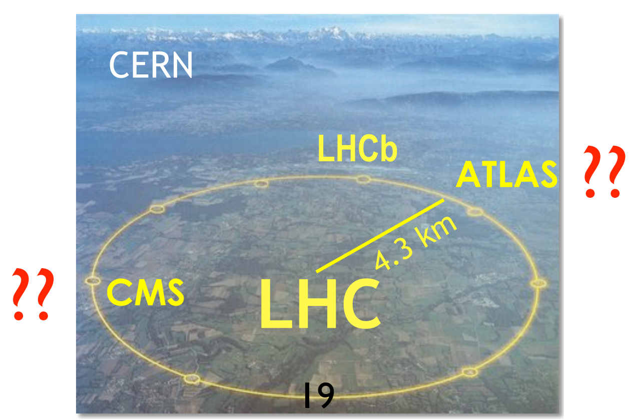


Info' not related to flavor conversion or CP violation, thus accessible at high energy measurements!

SUSY ex.: new physics spectrum, open question



Everything degenerate | Split, but MFV | Anarchy | Flavorful Naturalness



Naturalness & the two top frontiers

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]

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

Naturalness & the two top frontiers

tuning ~ 1:10

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

Elusive regime

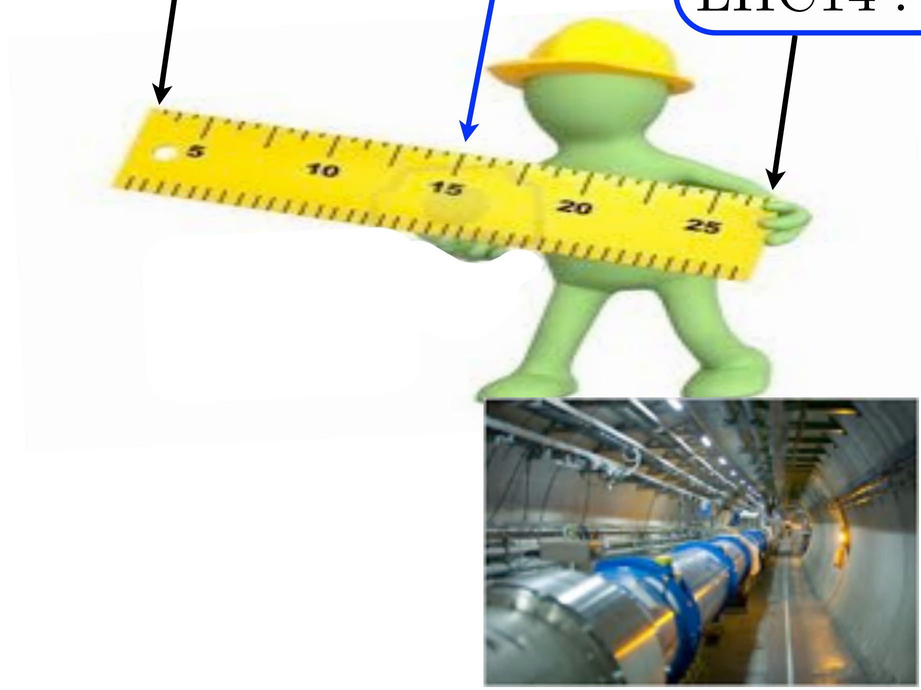
Boosted regime

natural SUSY

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

tuning ~ 1:10^2

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



Outline

- ♦ Supersymmetry & flavorful naturalness.

- ♦ Composite pseudo Nambu-Goldstone boson (pNGB) Higgs:

  i. Alignment: non-degenerate composite first two generation;

  ii. Anarchy: importance of top flavor violation & naturalness.

(♦ See appendix for recent development on Higgs-quarks phys.)

- ♦ Conclusions.

Supersymmetric Flavorful Naturalness

&

implications of split first two generation squark spectrum

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

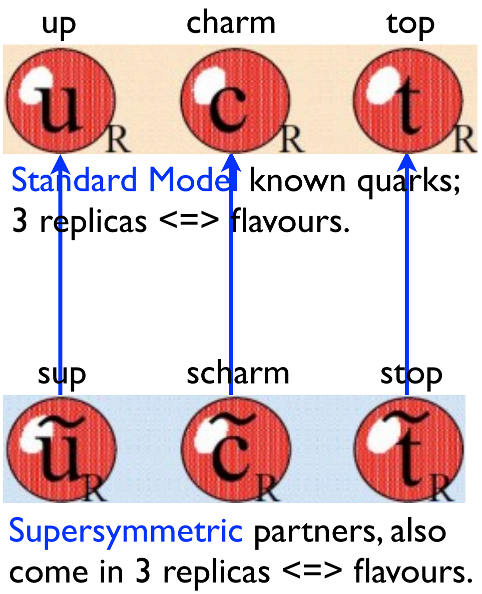
Partner are elusive because of non-trivial flavor physics effects

Supersymmetric (SUSY) Flavourful naturalness

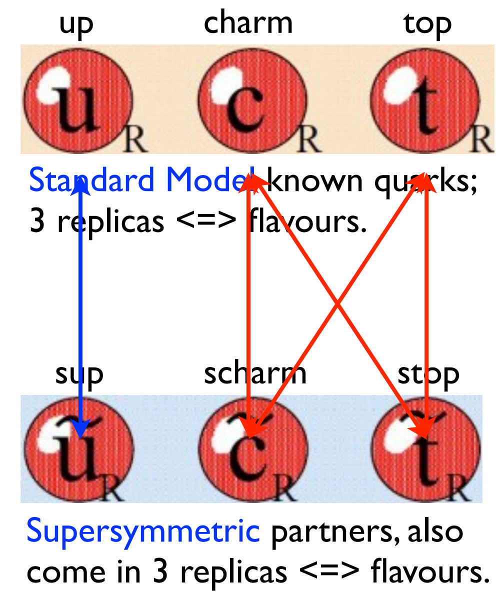
- Standard model: 3 copies (flavours) of quarks;
  same holds for new physics. (say supersymmetry)

- “Hardwired” assumption:
  top partner (stop) is mass eigenstate.

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



Flavourful naturalness



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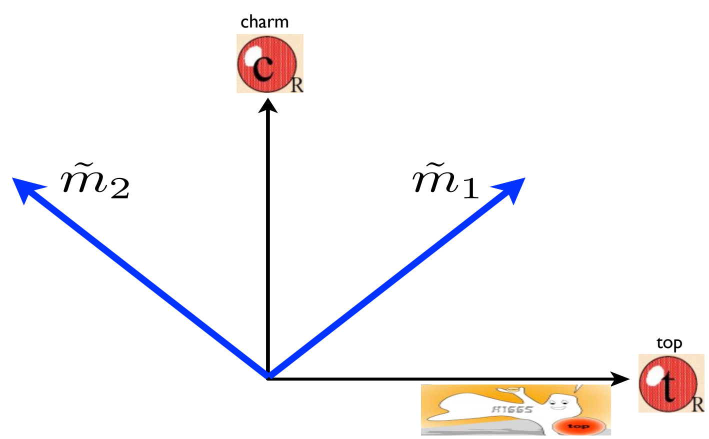
- This need not be the case, top-partner => "stop-scharm" admixture.



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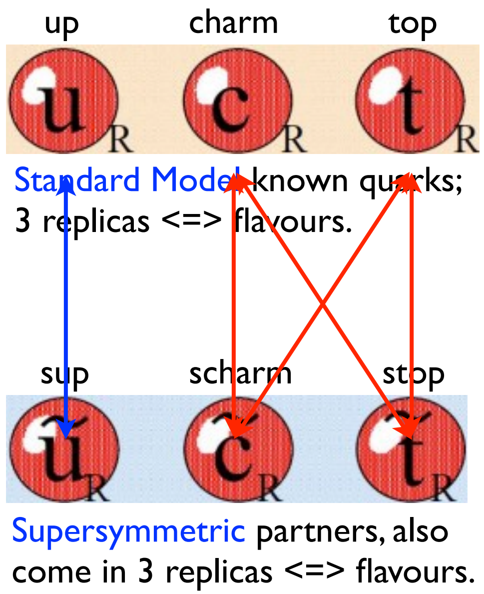

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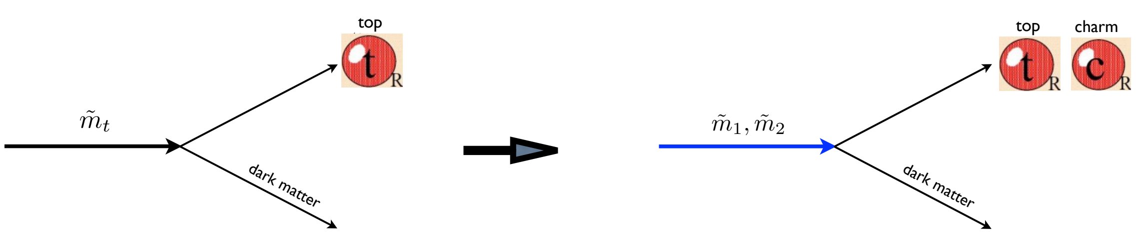


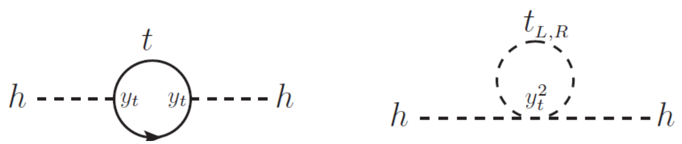
Signatures change, opening the charm front at high energy & in D-meson CP violation.

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 ...

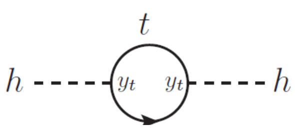
Dine, Leigh & Kagan (93); Dimopoulos & Giudice (95).

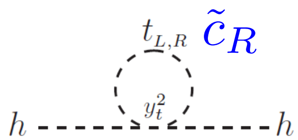


What is the impact of adding flavor violation on stop searches ? (flavorful naturalness)

- 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...

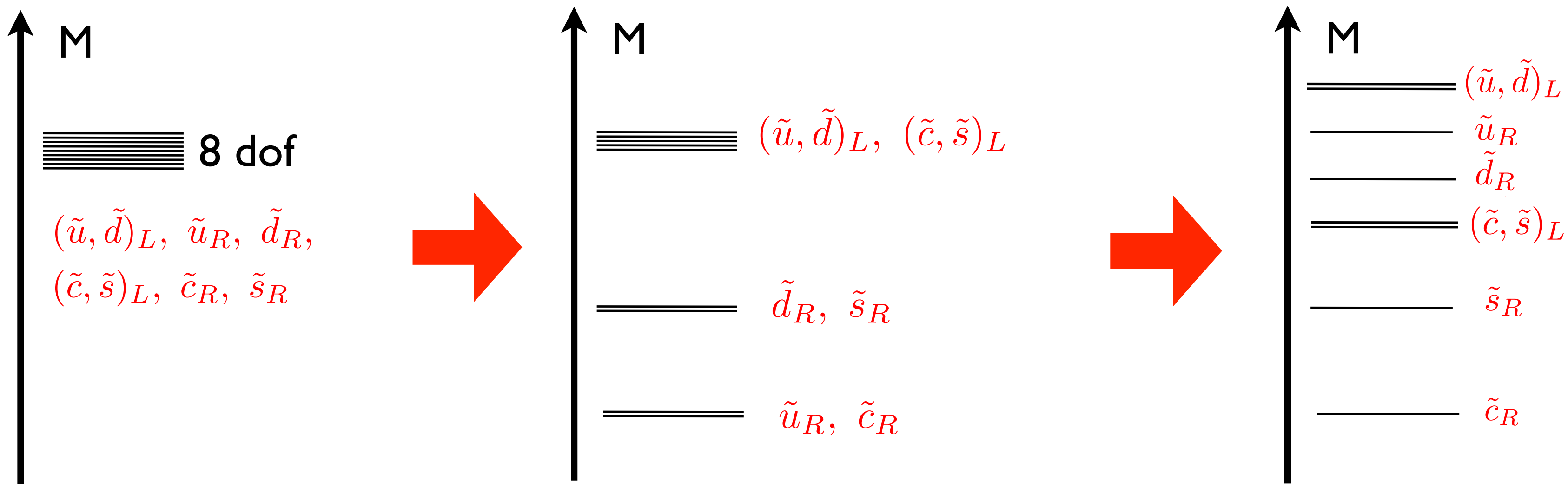
- The "$\tilde{t}_R\,\tilde{t}^*_R$" $\rightarrow t_R\, t^*_R$ production is suppressed by $\left(\cos\theta^R_{23}\right)^4$.

⬇

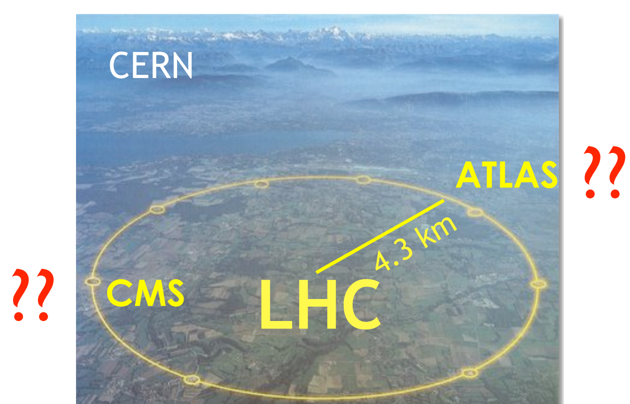
Potentially: new hole in searches, possibly improve naturalness

Light scrams at the LHC

What if first 2 generation squark not degenerate?

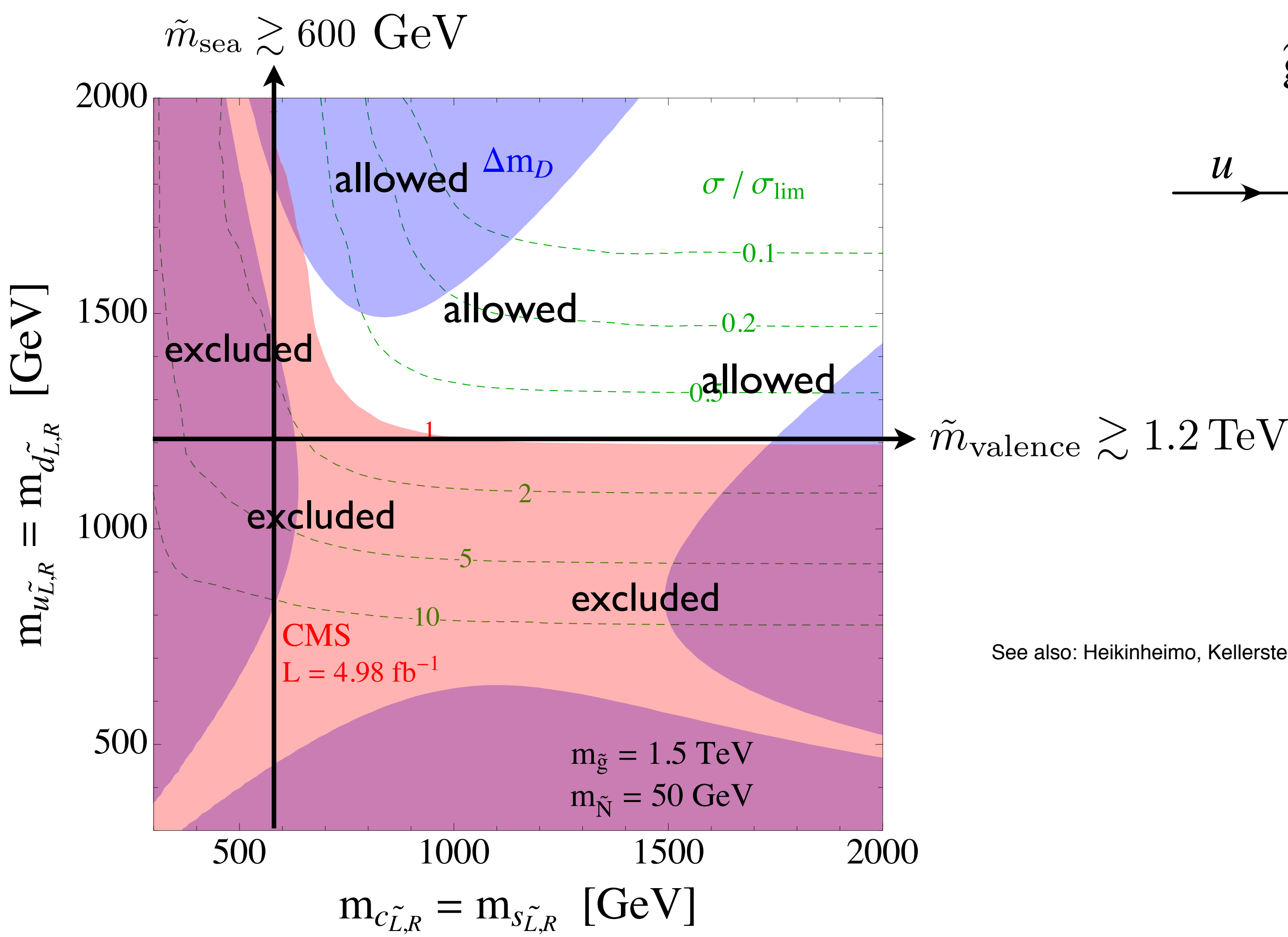


Everything degenerate | Split, but MFV | Anarchy! | Nir & Seiberg (92).

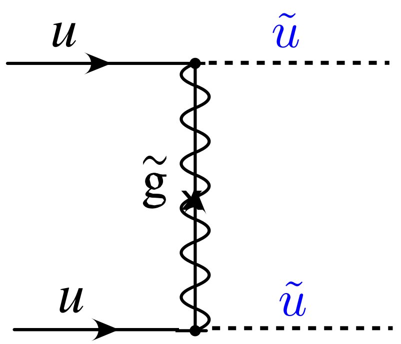


PDFs: all 4 flavor "sea" squarks can be rather light

sea vs. valence

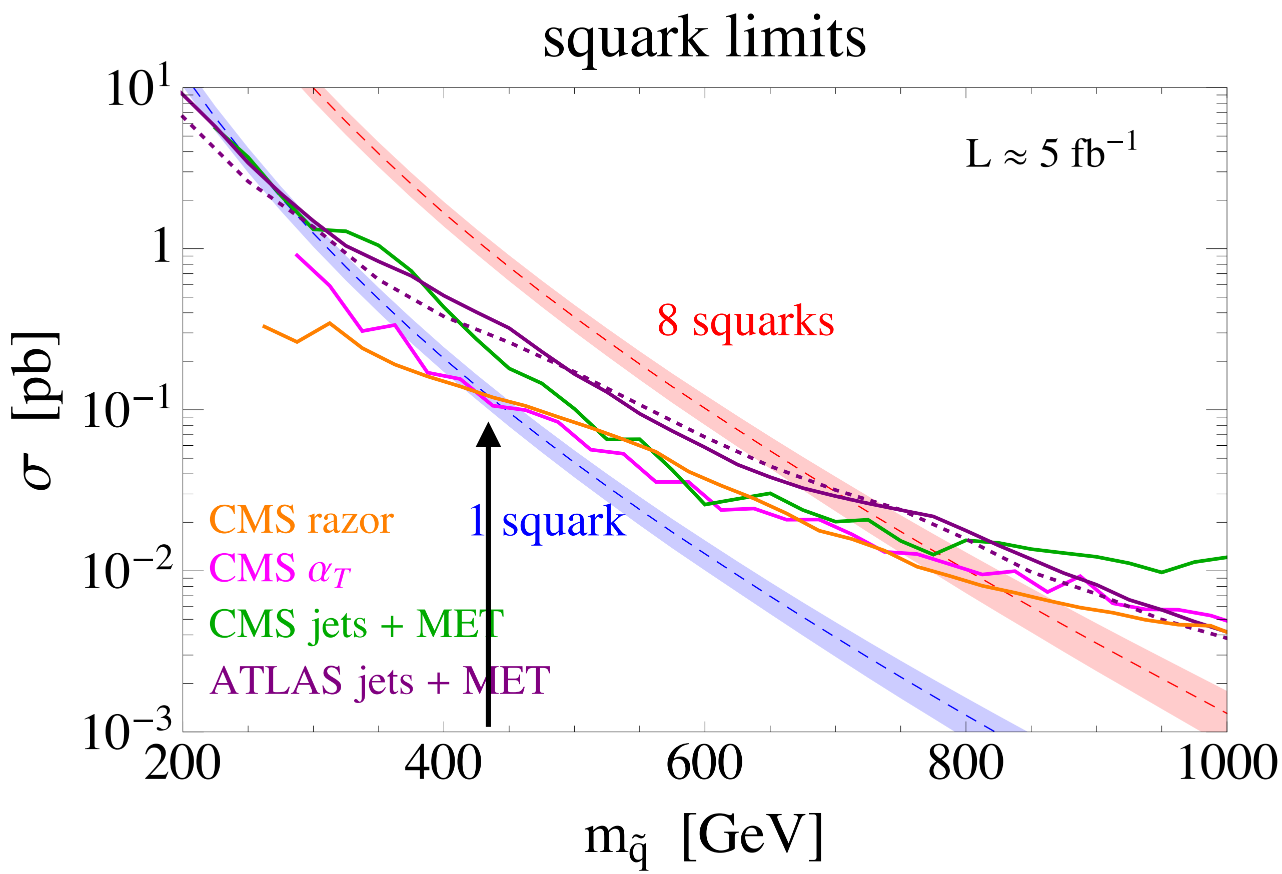


Mahbubani, Papucci, GP, Ruderman & Weiler (12).



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

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



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

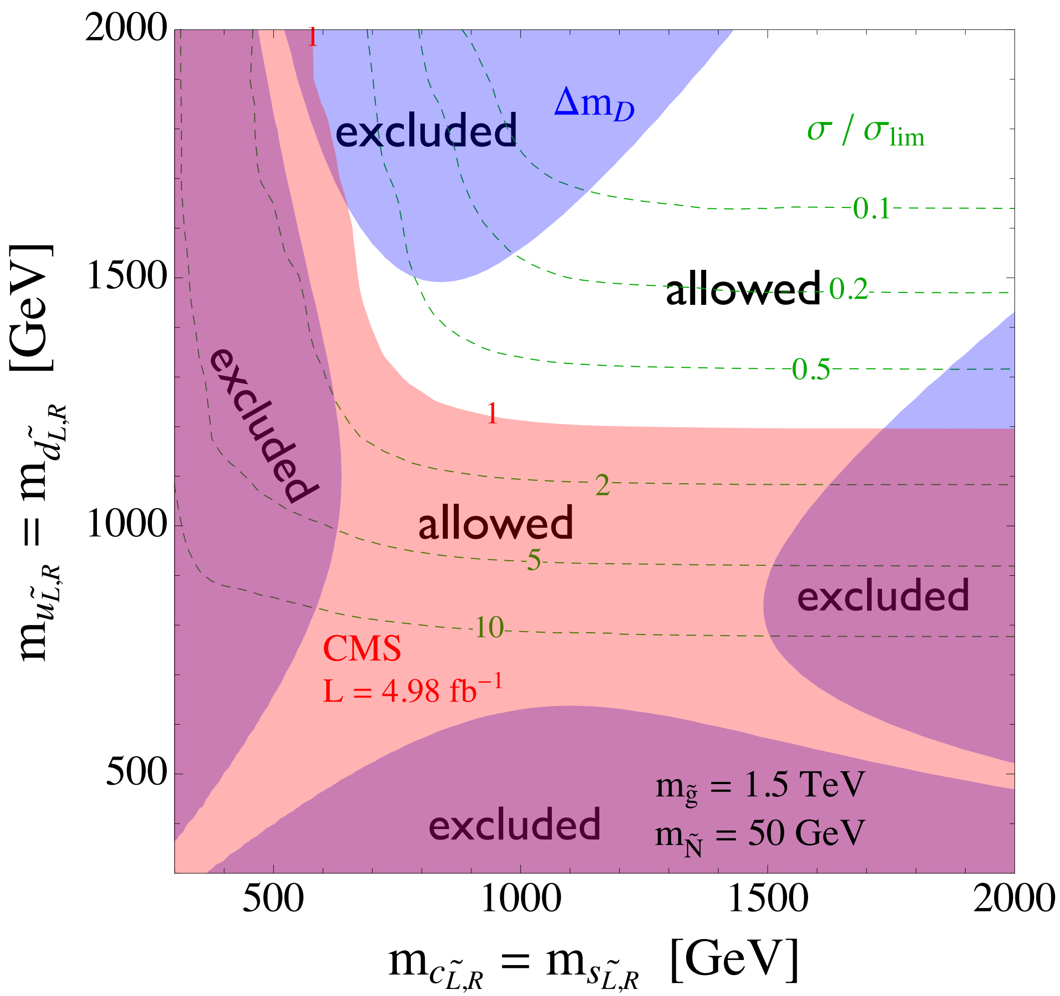
Are non-degenerate first 2-generation squarks consistent with flavor bounds?

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.

Sea LH squarks vs. valence LH squarks

Adding flavor constraints (Δm_D) for LH squarks:



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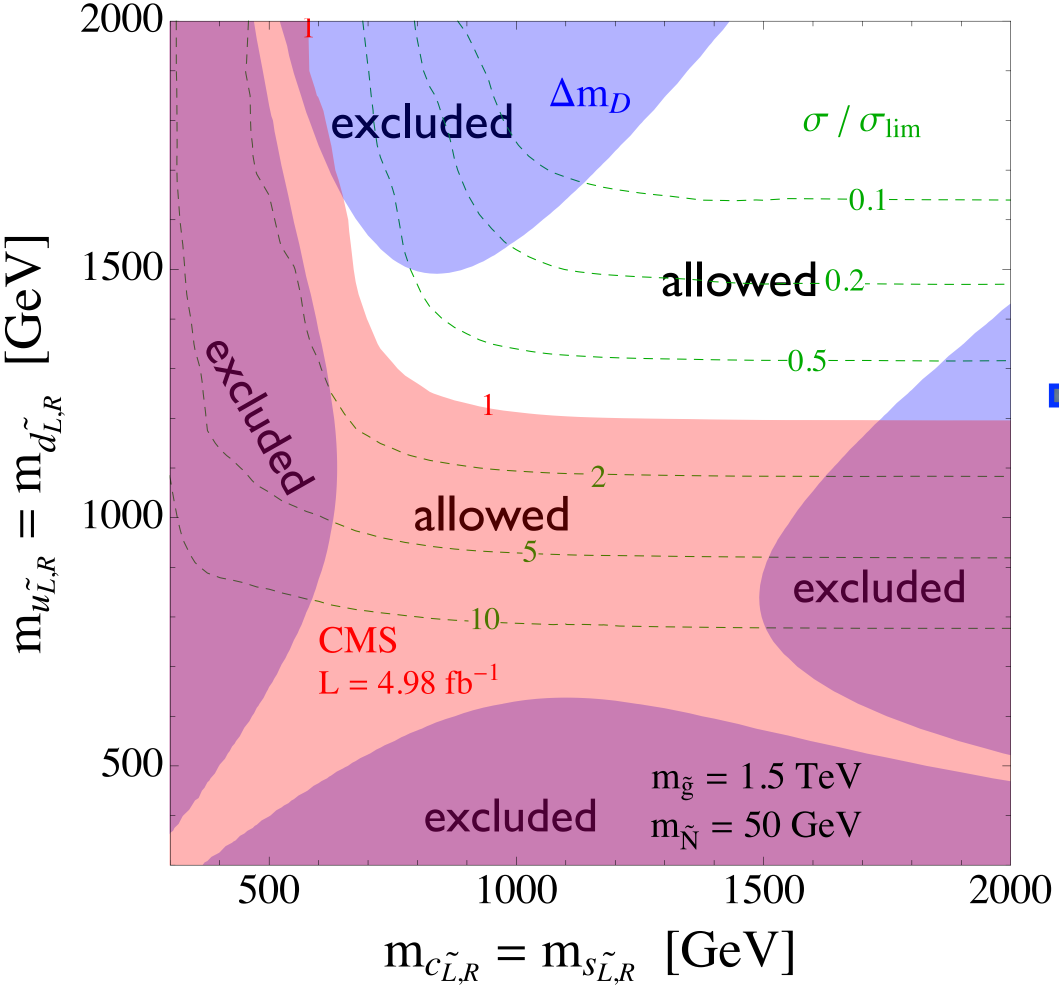


alignment: new upper bound on CP violation (CPV) in *D-phys.*:

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

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

LHCb started testing alignment paradigm.

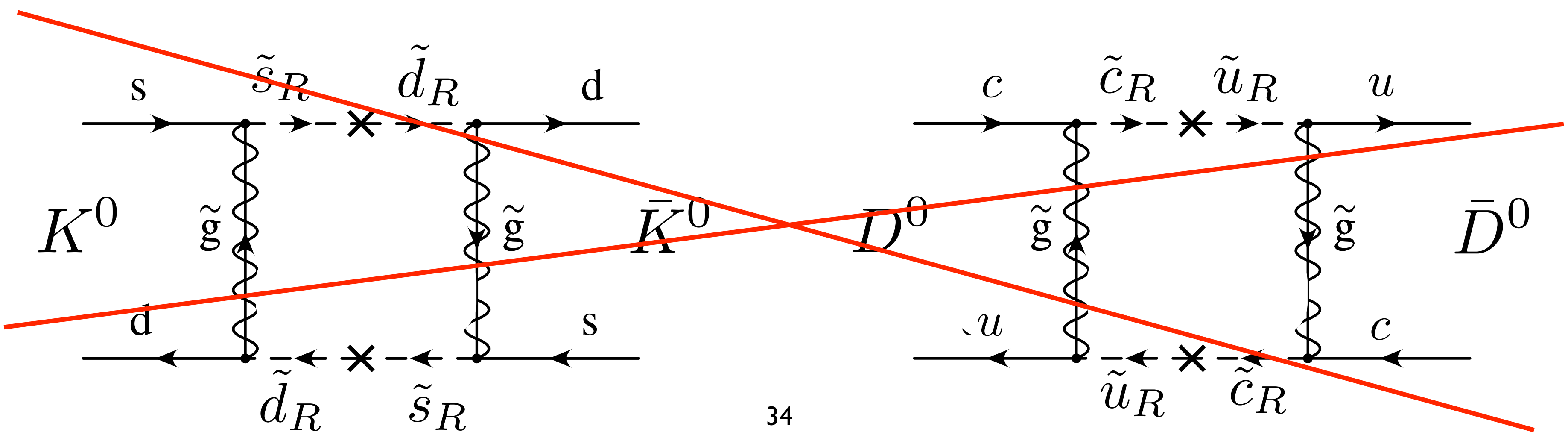
Kadosh, Paride, GP & Soreq to appear.

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

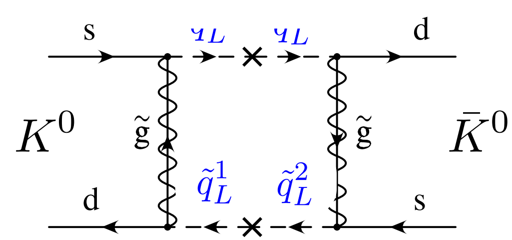
- SM LH sector consist of 2 flavor breaking sources: $Y_d Y_d^\dagger$ & $Y_u Y_u^\dagger$

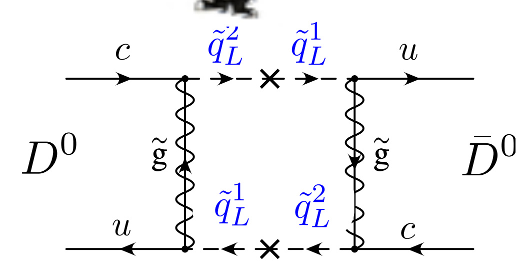
- SUSY: cannot align LH masses simultaneously with both sources!
  Dangerous direction wins to reduce bounds ...

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

$\Delta M_K, \epsilon_K$

$\Delta M_D, A_\Gamma^D$





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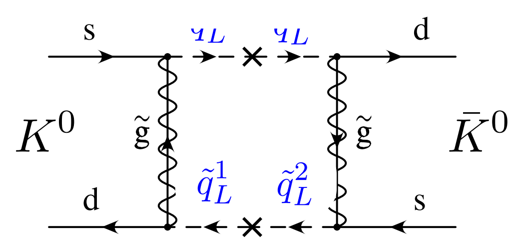

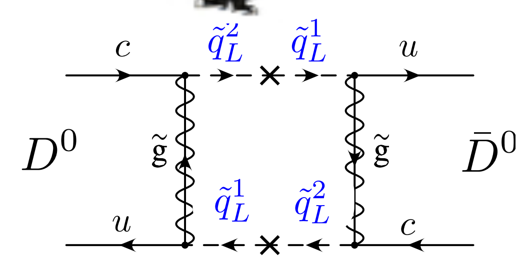

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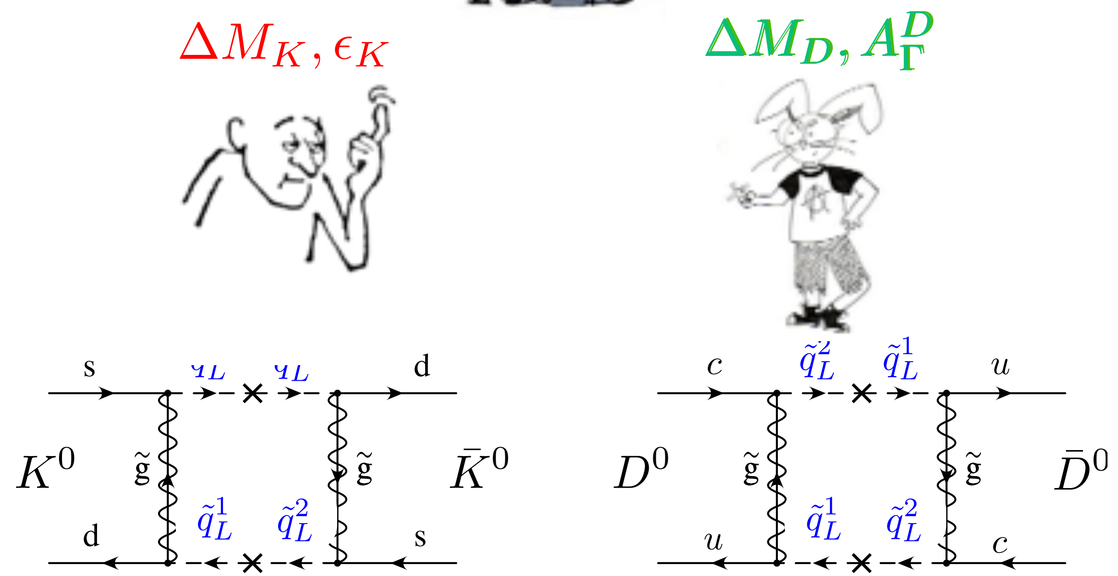

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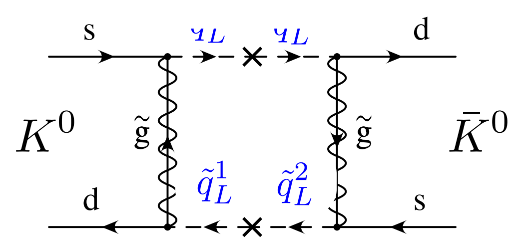

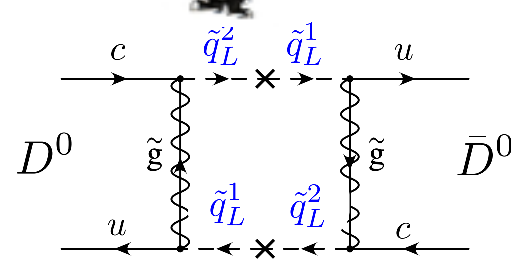

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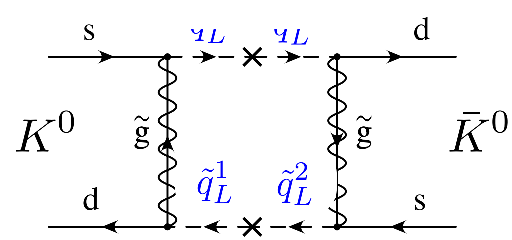

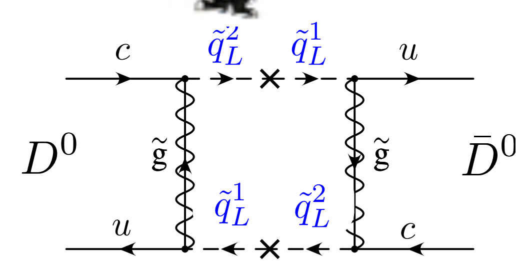

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$\Delta M_K, \epsilon_K$

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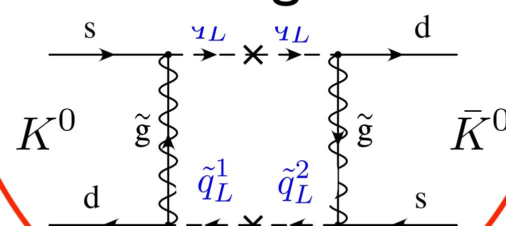
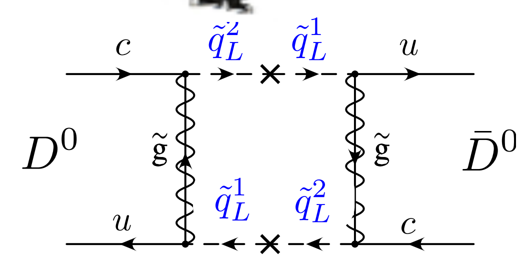
Nir & Seiberg (93)

down alignment





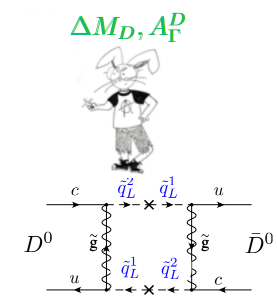
The charm frontier: recntly LHCb made impressive progress in CPV in mixing

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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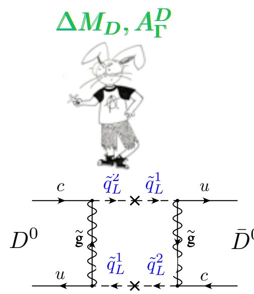

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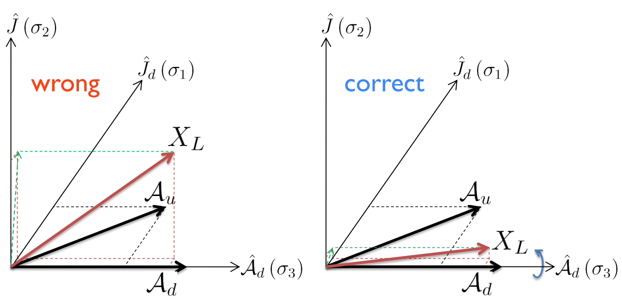
However ...

Successful alignment models guarantee small physical CP phase!



Gedalia, Kamenik, Ligeti & GP (12);

Formalism: Gedalia, Mannelli & GP (10) x2

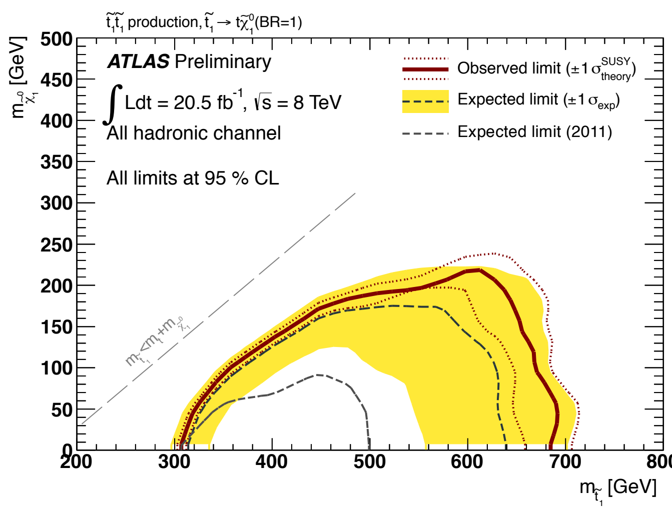
Constraining (RH) flavorful naturalness

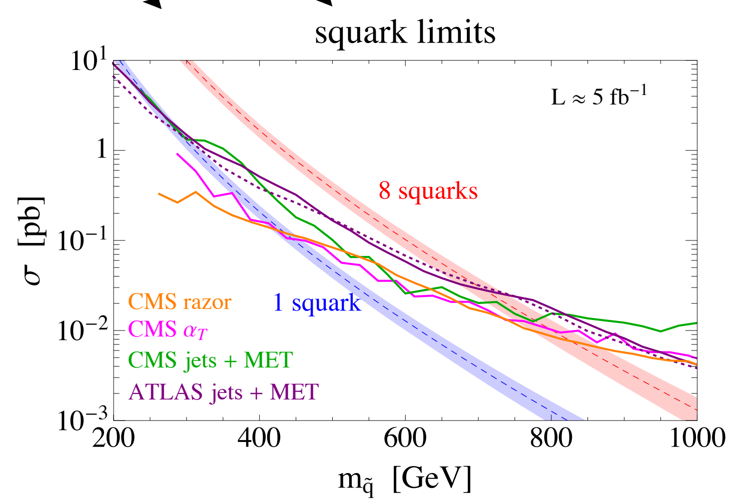
- RH stops & naturalness, $m_{\tilde{t}_R} \gtrsim m_0 = 570\,\mathrm{GeV}$

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).

compromise





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

Flavored naturalness LHC searches

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

- The relevant parameters to constrain are:

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

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

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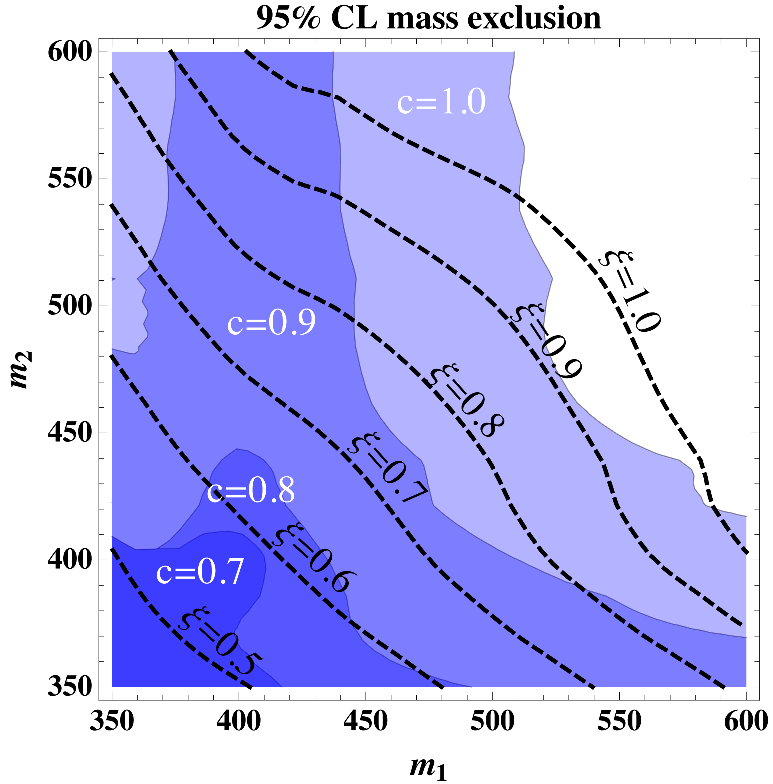
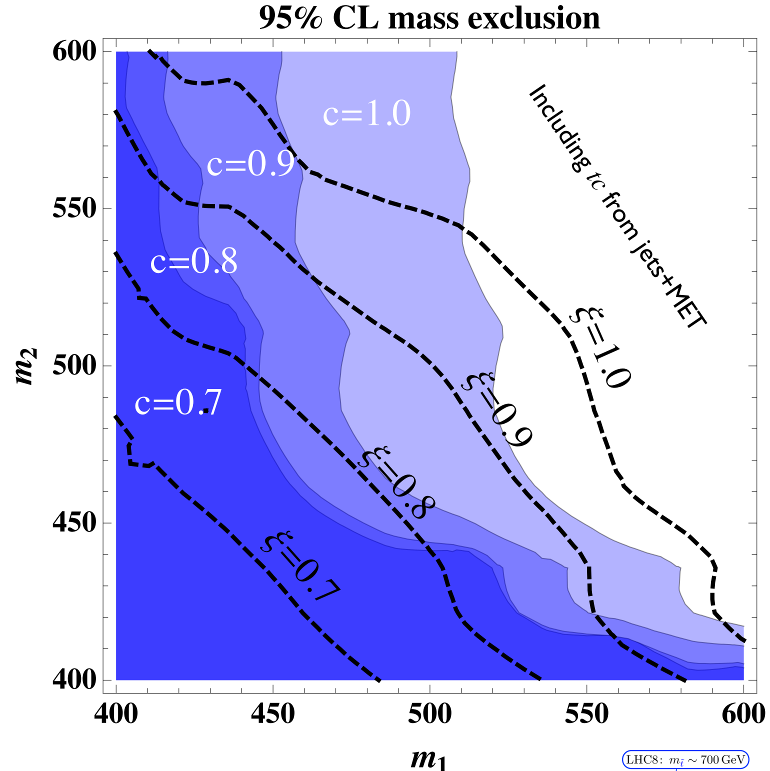
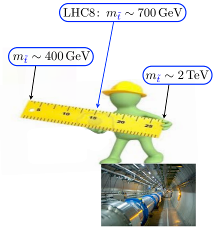




Can get $\xi \sim 0.5 - 0.8$ for $\theta_{23}^{RR} \sim 45^o$



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

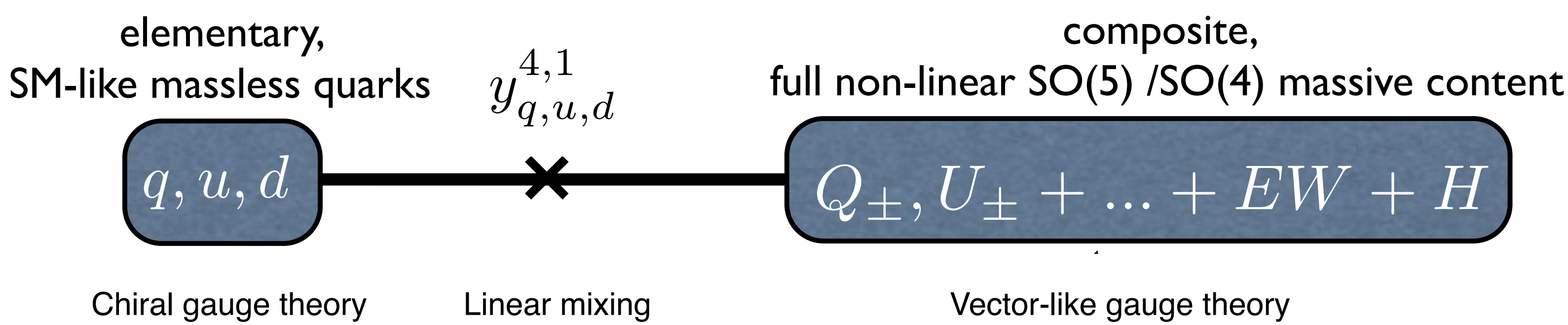
Composite light quarks & pseudo-NGB (pNGB) Higgs: Flavor & Naturalness

Delaunay, Grojean & GP (13);
Delaunay, Fraille, Flacke, Lee, Panico & GP (13);
Azatov, Panico, GP & Soreq (14);
Blanke, Delaunay, Martin & GP, in preparation.

Two slides on pNGB Composite H Models

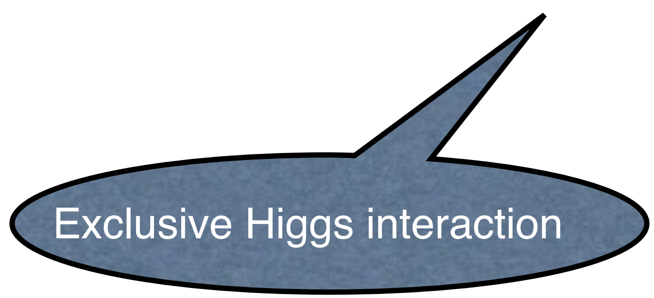
- ♦ Structure of minimal composite Higgs model SO(5)/SO(4):

Agashe, Contino & Pomarol (05)



PNGB H, SO(5) special basis: $y^{4,1}_{q,u,d} \Rightarrow y^{4,1}_{q,u,d} \times U_{\rm Gs}(H)$

See e.g.: Matsedonskyi, Panico & Wulzer;
Azatov & Galloway (12)



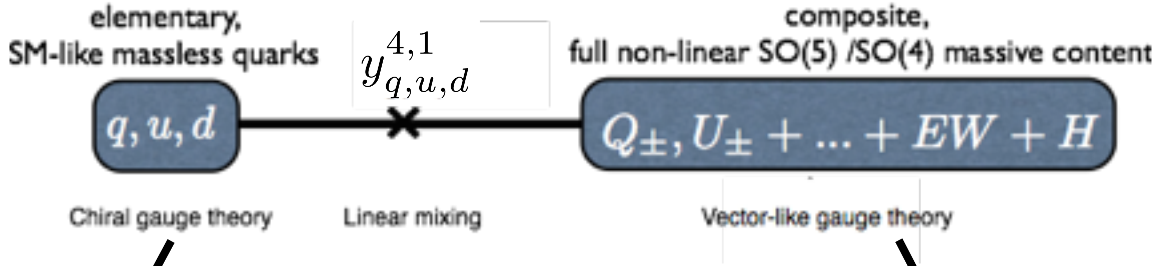
See also yesterday's talks by:
Archer, Konig, Matsedonski and Setzer.
RS: Today's talk by Neubert.

$$U_{gs} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \cos\bar{h}/f & \sin\bar{h}/f \\ 0 & 0 & 0 & -\sin\bar{h}/f & \cos\bar{h}/f \end{pmatrix}$$

$\bar{h} \equiv v + h$

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

2nd slide on pNGB Composite H Models & (up) flavor



Agashe, Perez & Soni (04);
Azatov, Panico, Perez & Soreq (14).

$SU(3)_q \times SU(3)_u \times SU(3)_d$

$SU(3)_{Q/4} \times SU(3)_{U/1} \times SU(3)_{D/1}$

$y^{4,1}_{q,u,d}$

$M_{Q/4,U/1,D/1}$

Finite Higgs potential extra constraint: $m_h^2 \propto \left[\mathrm{tr}\left(y^{4\dagger}_{q,u} y^4_{q,u}\right) - \mathrm{tr}\left(y^{1\dagger}_{q,u} y^1_{q,u}\right)\right] \Lambda^2$

⇓

Breaks spurion structure: $y_{L,R} \equiv y^4_{q,u} = y^1_{q,u}$

Composite flavor sector: $SU(3)_{\mathrm{Diag}}$

Anarchy vs. Hierarchy, LHC & Naturalness implications

- UV anarchy => low E hierarchy: $$y_R^u \ll y_R^c \ll y_R^t \,.$$

2 gen approx' symmetric

$$\lambda_L^3 : \lambda_L^2 : \lambda_L^1 \sim 1 : V_{cb} : V_{ub} \sim 1 : 4 \times 10^{-2} : 4 \times 10^{-3}\,,$$
$$\lambda_{R,u}^3 : \lambda_{R,u}^2 : \lambda_{R,u}^1 \sim 1 : \frac{m_c}{m_t V_{cb}} : \frac{m_u}{m_t V_{ub}} \sim 1 : 9 \times 10^{-2} : 2 \times 10^{-3}\,,$$

- Toward "composite flavourful naturalness" from RH anarchy low E, (allowed by EW precision tests):

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

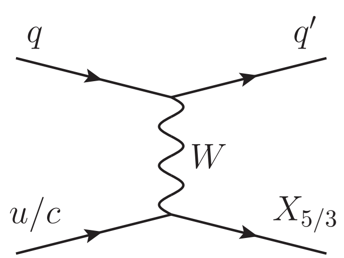
$$y_R^u \lesssim y_R^c \sim y_R^t \sim 1$$

split 2 gen'

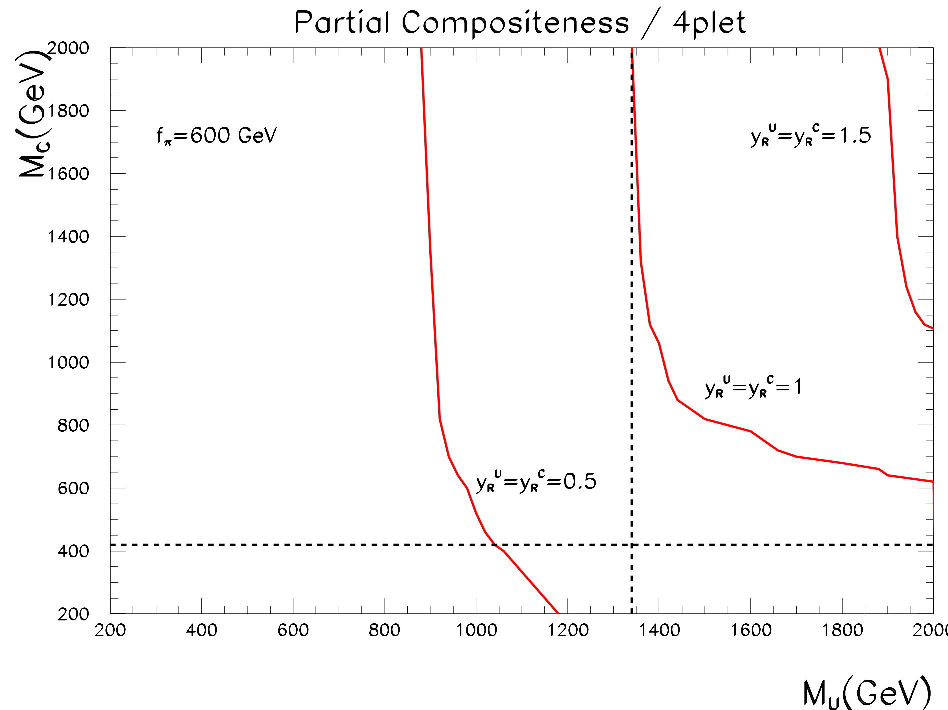
Delaunay, Fraille, Flacke, Lee, Panico & GP (13);
Blanke, Delaunay, Martin & GP, in preparation.

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

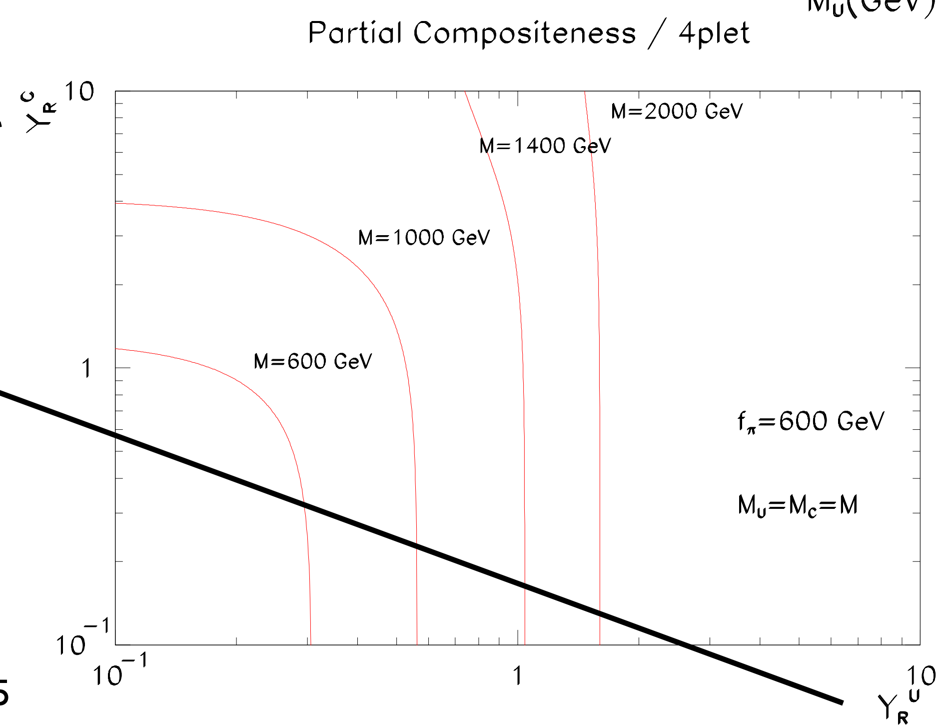
Delaunay, Fraile, Flacke, Lee, Panico & GP (13).



$$M_c \ll M_U$$

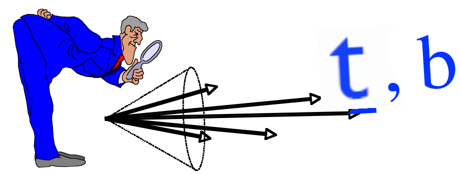


$$y_c \gg y_u$$

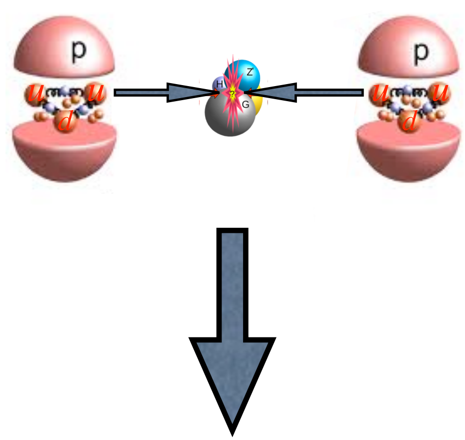


High p_T Quark Flavor Phys. at the LHC

- 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.

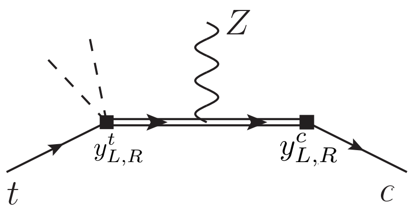


Second gen' physics is currently in a blind spot of the LHC;

Need to push boundaries to eliminate it.

Composite $t \to cZ$

- $t \to cZ$ null test of the SM.



- $t \to cZ$ in composite models could be large.

Agashe GP & Soni (06)

$$\mathrm{BR}(t \to cZ) \simeq 3.5 \times (g^2_{tc,R}\,,\, g^2_{tc,L}) \approx \left(\frac{g}{2c_W}\right)^2 \left(\left(\frac{m_c}{m_t V_{cb}}\right)^2 ,\, V^2_{cb}\right) \frac{v^4}{M^4_*} \times \left(\frac{y_{L,R}}{M_*}\right)^4$$

$$\sim (8.5\,,\, 1.8) \times 10^{-6} \left(\frac{500\,\mathrm{GeV}}{M_*}\right)^4 \times \left(\frac{y_{L,R}}{M_*}\right)^4$$

- Lesson (i) flavor anarchy: LH coupling is suppressed.

- Lesson (ii) strong dependence on level of top compositeness.

Composite natural $t \to cZ$

- $t \to cZ$ null test of the SM.
- $t \to cZ$ in composite models could be large.

Agashe GP & Soni (06)

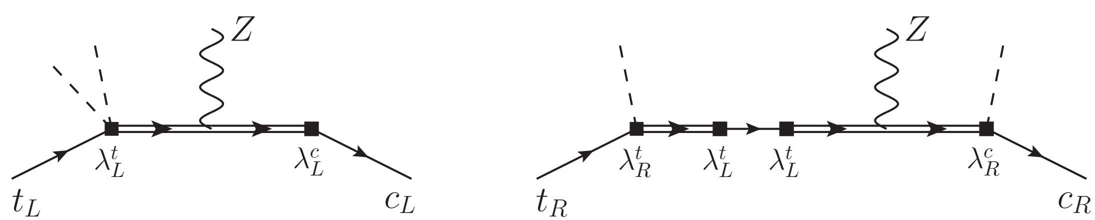
- $t \to cZ$ in custodial composite models could be small.

Agashe, Contino, Da Rold & Pomarol (06)

- $t \to cZ$ in natural custodial composite models should be large.

As both LH & RH tops needs to be composite, Azatov, Panico GP & Soreq (14)

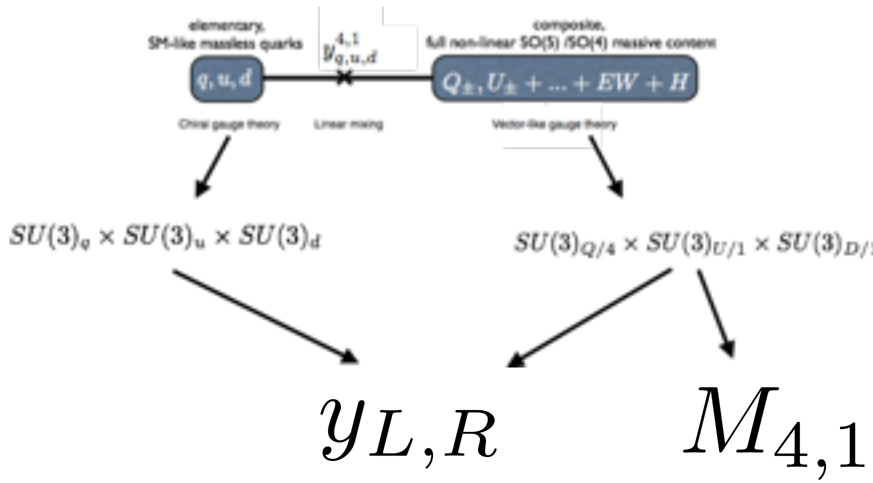
$$\mathrm{BR}(t \to cZ) \sim 10^{-5} \left(\frac{700}{M_*}\right)^4 .$$



- One extra prediction tops should be RH polarized.

Azatov, Panico, GP & Soreq (14)

Lessons from $t\to cZ$, anarchy in relation with naturalness



Azatov, Panico GP & Soreq (14)

♦ Anarchy <=> generic misalignment between $y's$ & $M's$.

$$\alpha^t_{L,R} \sim \frac{N_c}{16\pi^2} (y^t_{L,R})^\dagger M_* M_*^\dagger y^t_{L,R} \qquad \text{fine tuning} \propto \alpha^{-1}$$

See also yesterday's talks by: Archer, Azatov & Matsedonski.

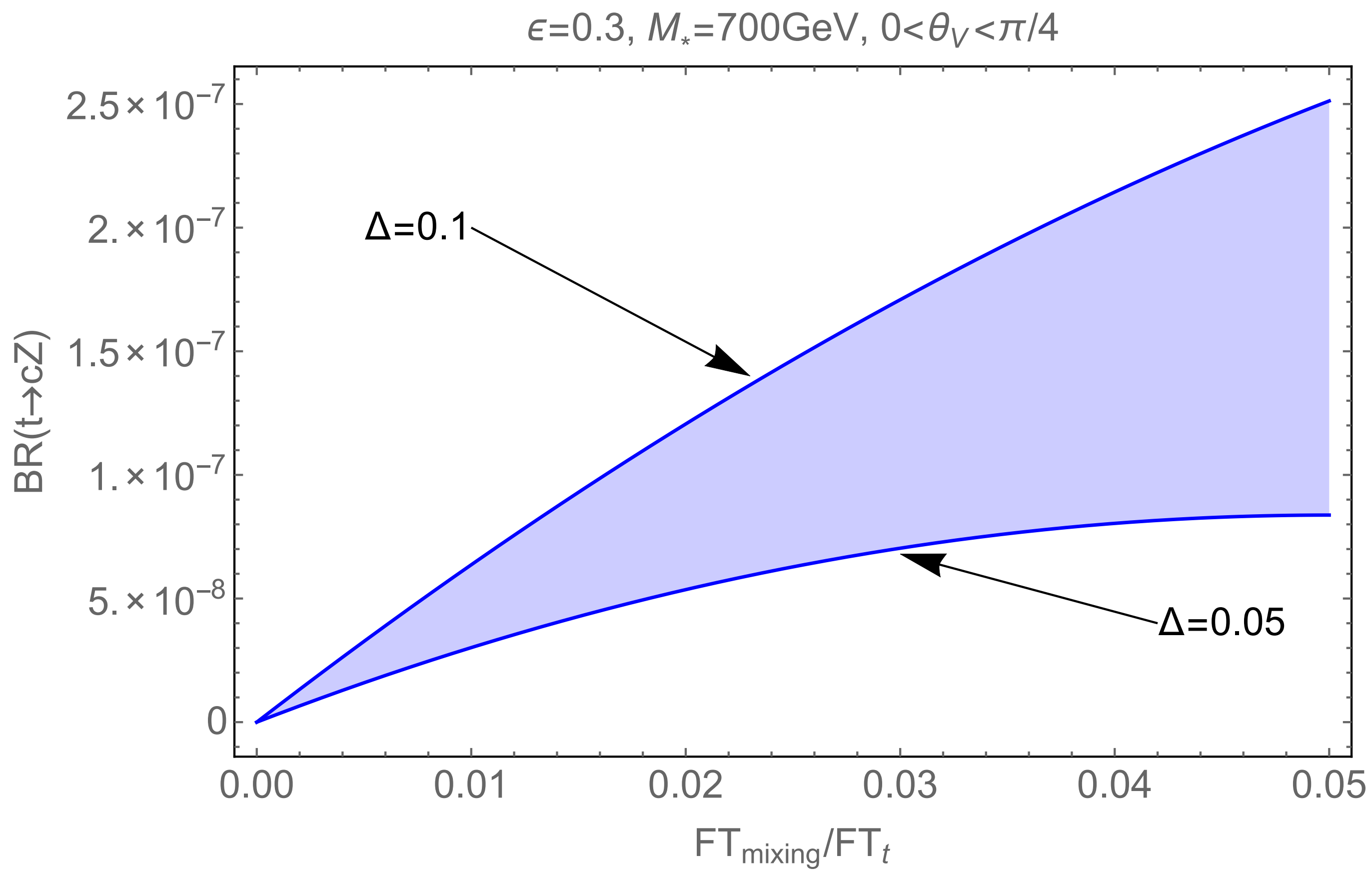
$$\approx \frac{N_c}{16\pi^2} \left[(y^t_L)^2 - 2(y^t_R)^2\right] \left(M^2_{1_1} + \Delta M^2_1\, s^2_{1L} - M^2_{4_1} - \Delta M^2_4\, s^2_{4L}\right) \qquad \Delta M^2_1 \equiv M^2_{1_2} - M^2_{1_1}$$

♦ Fine tuning & $t \to cZ$ within pNGB depends on misalignment between flavor breaking sources (& level of charm compositeness).

Blanke, Delaunay, Martin & GP, in preparation.

BR($t \to cZ$) vs. tuning

Azatov, Panico, GP & Soreq (14)



The correlation between BR($t \to cZ$) and the additional fine-tuning of the model FT_{mixing}/FT_t.

Conclusions

- Accommodating flavor violation => modifications of the usual estimation of fine tuning as well as phenomenology.
- SUSY: (i) scharms can be light & buried in LHC data;
  (ii) stop-scharm mixing might lead to improved naturalness.
- Composite pNGB-H:
  (i) charm-partners can be light & buried in LHC data;
  (ii) top-charm partner mixing might lead to improved naturalness;
  (iii) new anarchic contributions to sizeable $t \to cZ$ & fine tuning.
- Interplay \w CPV in D mixing & b-s transition, tested at LHCb.

Backups

Two generation covariance description

X_Q is 2x2 Hermitian matrix, can be described as a vector in SU(2) 3D flavor space.

$$|\vec{A}| \equiv \sqrt{\frac{1}{2}\mathrm{tr}(A^2)}\,, \quad \vec{A}\cdot\vec{B} \equiv \frac{1}{2}\mathrm{tr}(A\,B)\,, \quad \vec{A}\times\vec{B} \equiv -\frac{i}{2}\,[A,B]\;,$$

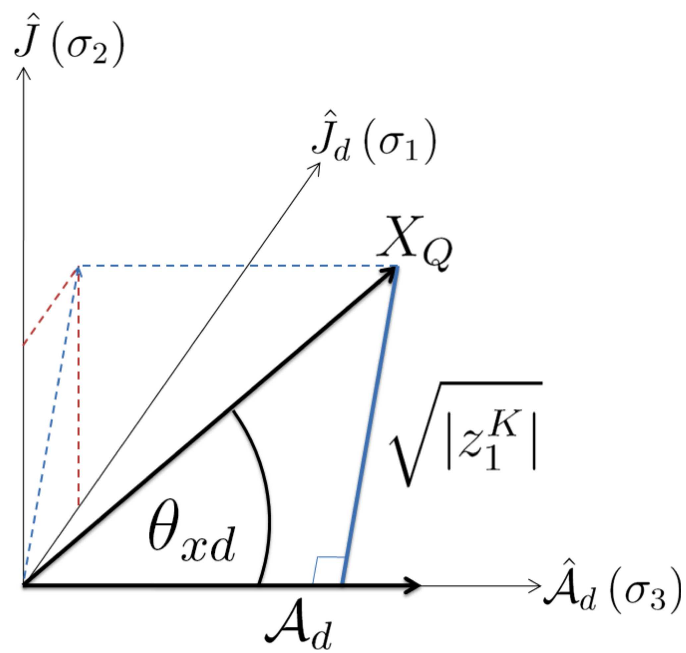
$$\cos(\theta_{AB}) \equiv \frac{\vec{A}\cdot\vec{B}}{|\vec{A}||\vec{B}|} = \frac{\mathrm{tr}(A\,B)}{\sqrt{\mathrm{tr}(A^2)\mathrm{tr}(B^2)}}\,.$$

The space can be span by using the SM Yukawas (very useful for CPV, see later):

$$\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{\not{\mathrm{tr}}} \quad \mathcal{A}_d \equiv (Y_d Y_d^\dagger)_{\not{\mathrm{tr}}}$$

Two generation covariance description, cont'

$$\hat{\mathcal{A}}_{u,d} \equiv \frac{\mathcal{A}_{u,d}}{|\mathcal{A}_{u,d}|}\,, \quad \hat{J} \equiv \frac{\mathcal{A}_d \times \mathcal{A}_u}{|\mathcal{A}_d \times \mathcal{A}_u|}\,, \quad \hat{J}_{u,d} \equiv \hat{\mathcal{A}}_{u,d} \times \hat{J}\,.$$



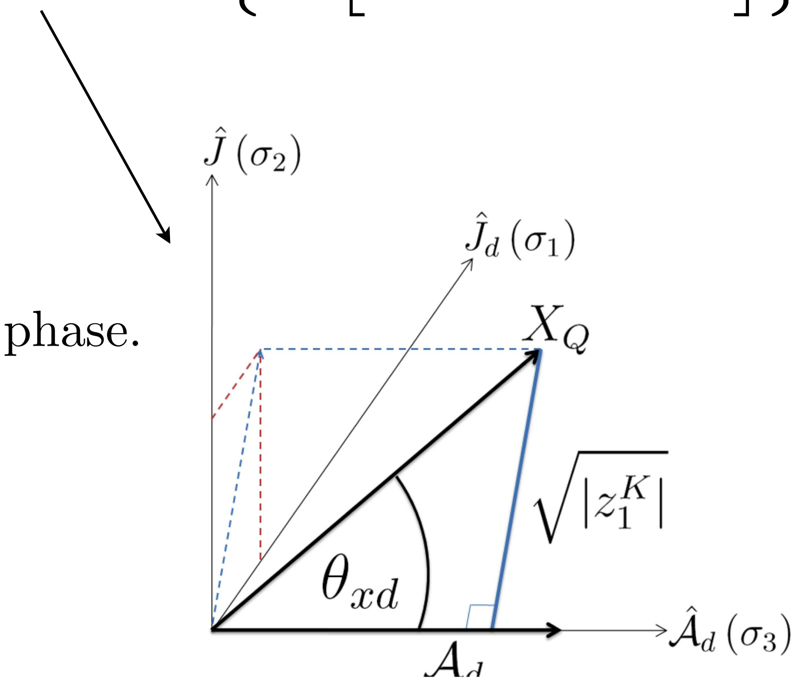
: The contribution of X_Q to $K^0 - \overline{K^0}$ mixing, Δm_K, given by the solid blue line. In the down mass basis, $\hat{\mathcal{A}}_d$ corresponds to σ_3, $\hat{J}$ is σ_2 and $\hat{J}_d$ is σ_1.

Combining $K^0 - \overline{K^0}$ mixing and $D^0 - \overline{D^0}$ mixing to constrain the flavor structure of new physics

Notice that:

A 2-gen' case, 3 adjoints yield CPV: $J = \mathrm{Tr}\left\{X\left[Y_D Y_D^\dagger, Y_U Y_U^\dagger\right]\right\}$

Projection of X_Q onto $\hat{J}$ is measuring the physical CPV phase.

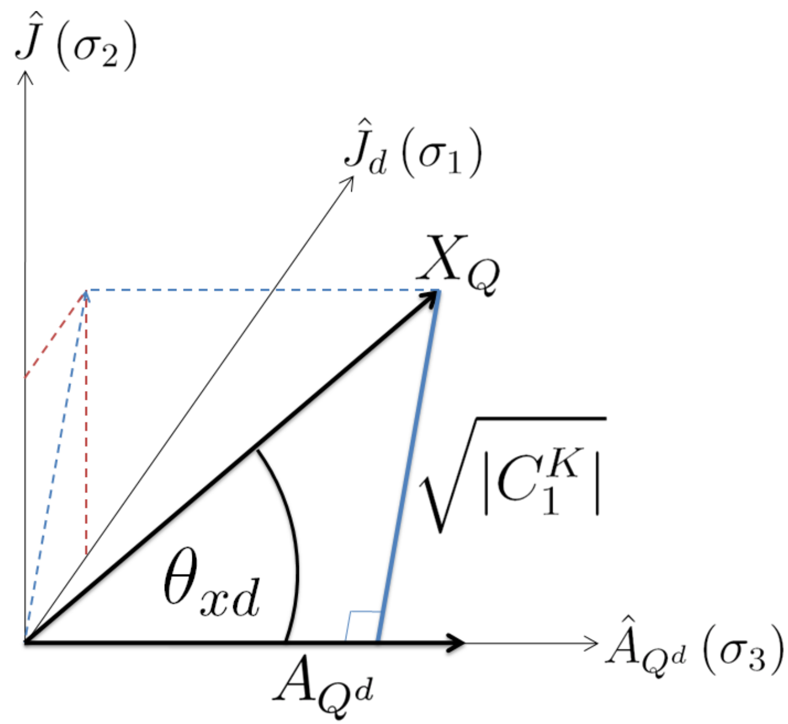


Assuming $SU(2)_L$: $\frac{1}{\Lambda_{\mathrm{NP}}^2}(\overline{Q_{Li}}(X_Q)_{ij}\gamma_\mu Q_{Lj})(\overline{Q_{Li}}(X_Q)_{ij}\gamma^\mu Q_{Lj}),$

Combining $K^0 - \overline{K^0}$ mixing and $D^0 - \overline{D^0}$ mixing to constrain the flavor structure of new physics

$$\frac{C_1}{\Lambda_{\rm NP}^2} O_1 = \frac{1}{\Lambda_{\rm NP}^2} \left[\overline{Q}_i (X_Q)_{ij} \gamma_\mu Q_j\right] \left[\overline{Q}_i (X_Q)_{ij} \gamma^\mu Q_j\right] \, ,$$

$$\left| C_1^{D,K} \right| = \left| X_Q \times \hat{A}_{Q^u,Q^d} \right|^2 \qquad \text{(Sorry } \mathcal{A}_{u,d} \equiv A_{Q^u,Q^d}\text{)}$$



$$\mathrm{Im}\left(C_1^{K,D}\right) = 2\left(X_Q \cdot \hat{J}\right)\left(X_Q \cdot \hat{J}_{u,d}\right) \, .$$

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.

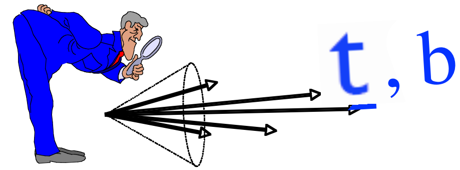
Delaunay, Fraille, Flacke, Lee, Panico & GP (13)

(ii) non-standard modification to Higgs decays.

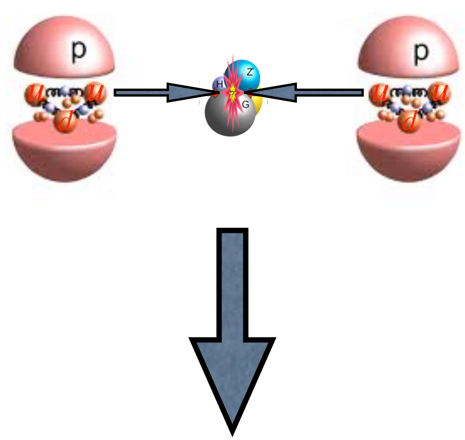
Delaunay, Grojean & GP (13); Delaunay, Golling, GP & Soreq (13).

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.

The model & relevant coupligs

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

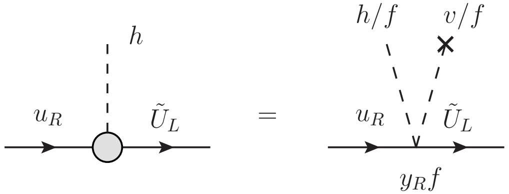
$$\mathcal{L}_{\rm comp} = i\,\bar{Q}(D_\mu + ie_\mu)\gamma^\mu Q + i\bar{\tilde{U}}\not{D}\tilde{U} - M_4\bar{Q}Q - M_1\bar{\tilde{U}}\tilde{U} + \left(ic\,\bar{Q}^i\gamma^\mu d^i_\mu \tilde{U} + \text{h.c.}\right),$$

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

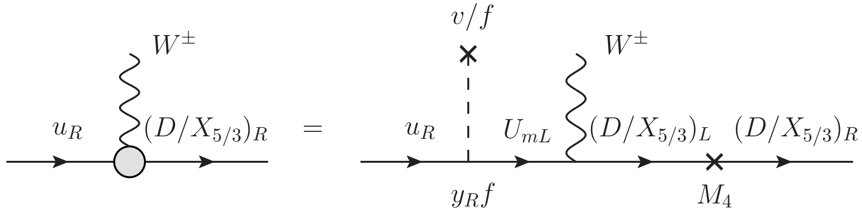
$$\psi = \begin{pmatrix} Q \\ \tilde{U} \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} iD - iX_{5/3} \\ D + X_{5/3} \\ iU + iX_{2/3} \\ -U + X_{2/3} \\ \sqrt{2}\tilde{U} \end{pmatrix}.$$

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

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



(a)



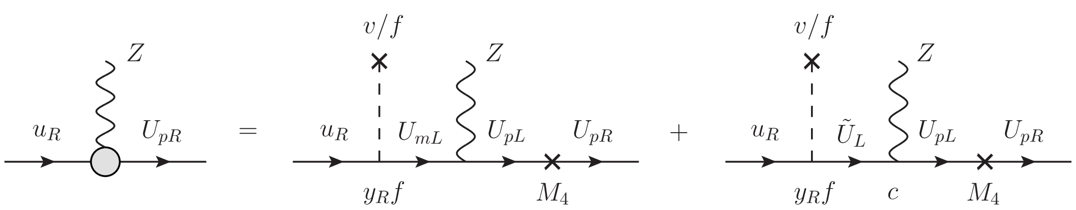
(b)

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

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

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).

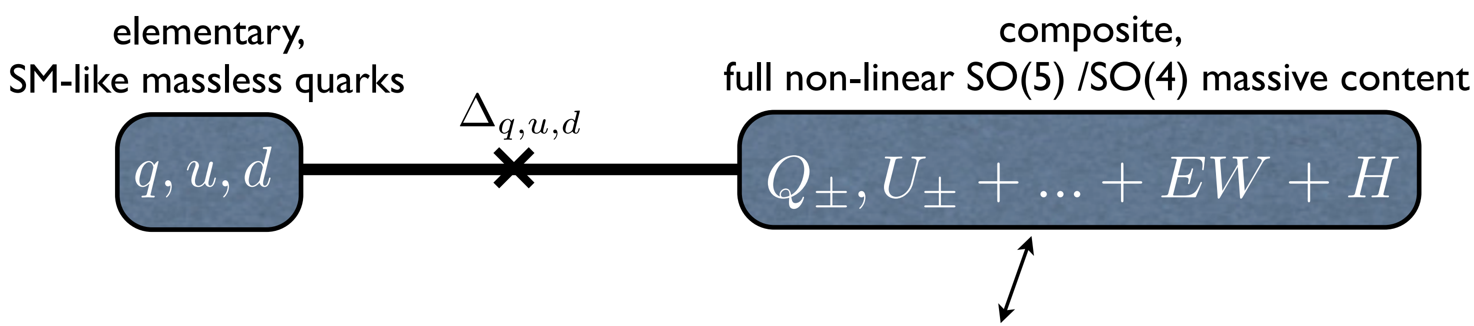
Shifman, Vainshtein, Voloshin & Zakharov (79); Kniehl & Spira (95).

(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, $m_f \gg m_h/2$.

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

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

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 ...

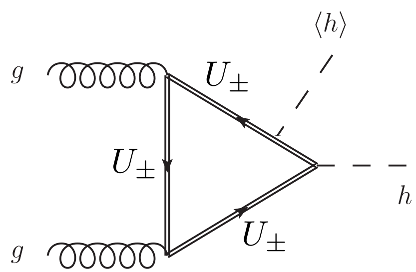
$$M_u = \begin{pmatrix} y_u^{00} v & 0 & y_u^{01} v \\ y_u^{10} v & m & y_u^{11} v \\ 0 & y_u^{-} v & m \end{pmatrix}$$

Perelestein, talk at ASPEN winter workshop (13).

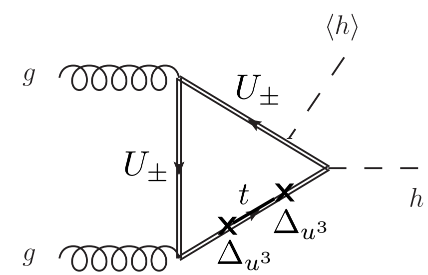
Cancellation of *t*-partners modification of Higgs rates, EFT:

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

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



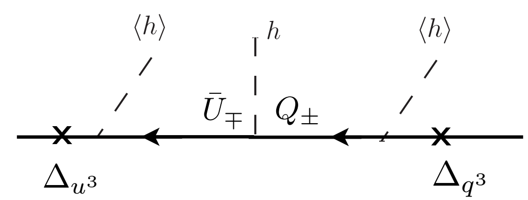
$\propto -vY^2/M^2$ **+**



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

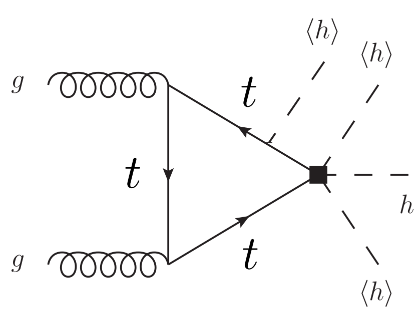
  (ii) *t*-partner mix with the top-like SM fields, modifying their Yukawa:

  1. integrating out heavy partners:

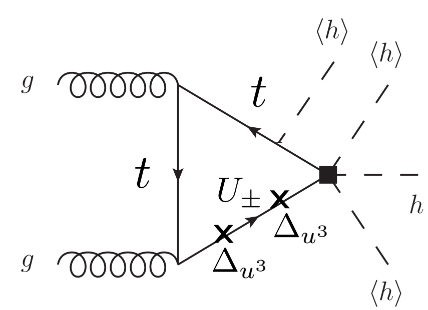


$\propto m_t \times v\,Y^2/M^2$

  2. substituting into the loop to obtain the amplitude:

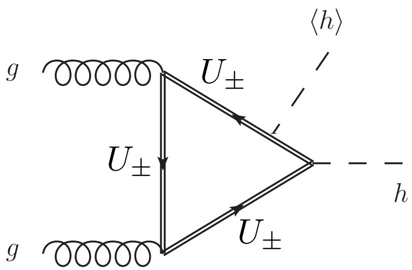


$\propto vY^2/M^2$ **+**



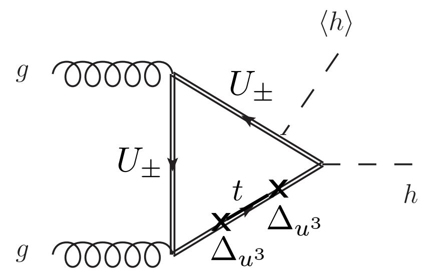
$\propto -vY^2/M^2 \times \Delta_{u^3}^2/M^2$

The cancellation of t-partners effects, adding all together



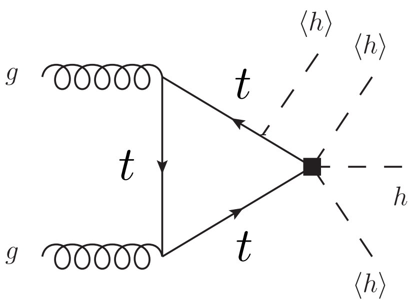
$\propto -vY^2/M^2$

+



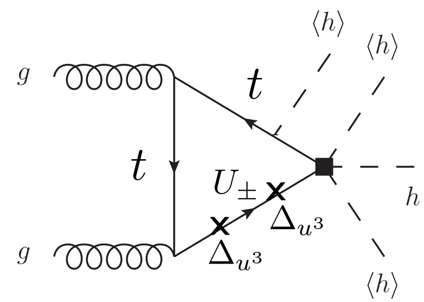
$\propto vY^2/M^2 \times \Delta_{u^3}^2/M^2$

+



$\propto vY^2/M^2$

+

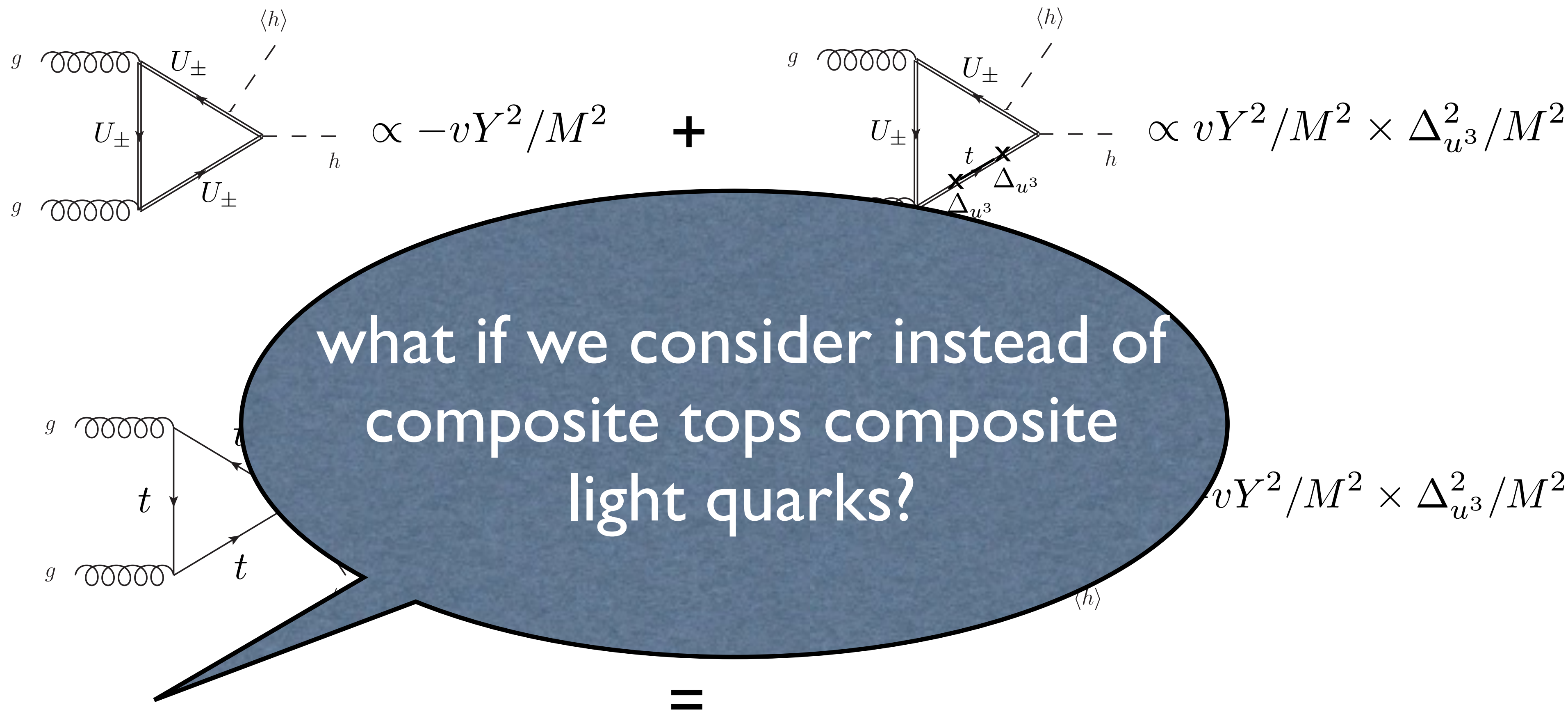


$\propto -vY^2/M^2 \times \Delta_{u^3}^2/M^2$

=

0

The cancellation of t-partners effects, adding all together



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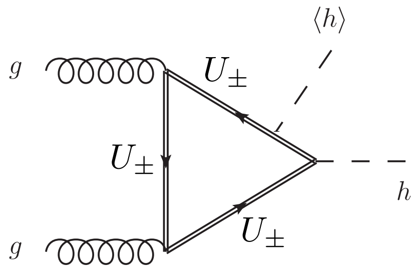
Cancellation for light composite quarks is ineffective!

Delaunay, Grojean & GP (13).



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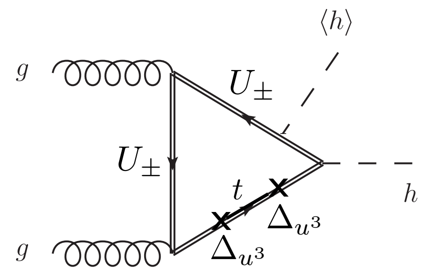

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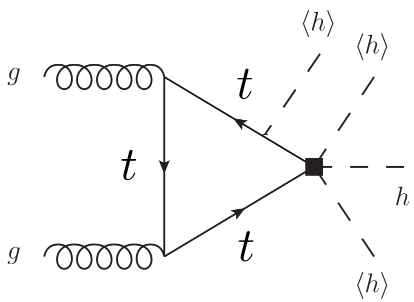
+



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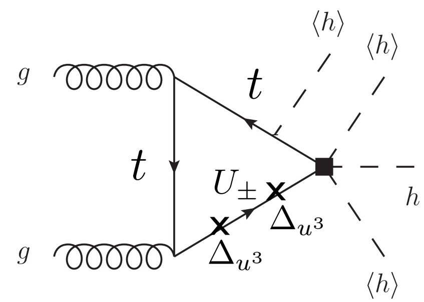

$\propto -vY^2/M^2 \times \Delta_{u^3}^2/M^2$

=

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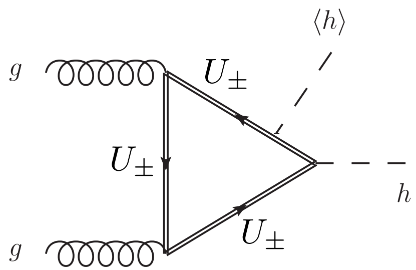

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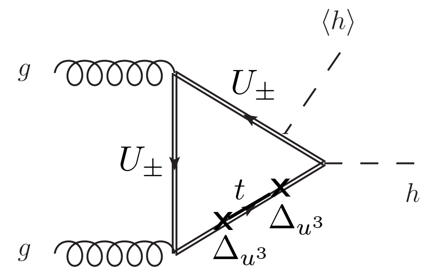
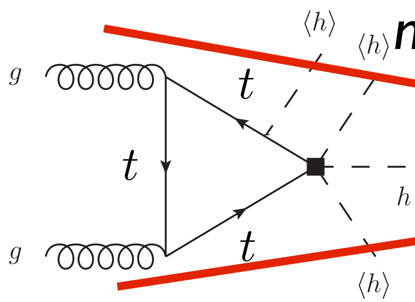


$\propto vY^2/M^2 \times \Delta_{u^3}^2/M^2$

+

negligible when light quark runs in the loop



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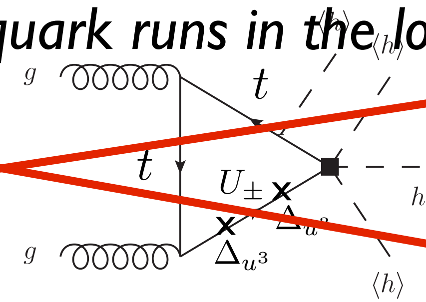


$\propto -vY^2/M^2 \times \Delta_{u^3}^2/M^2$

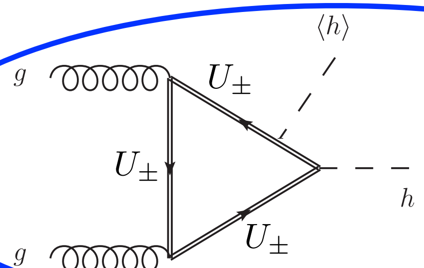
=

??

Cancellation for light composite quarks is ineffective!

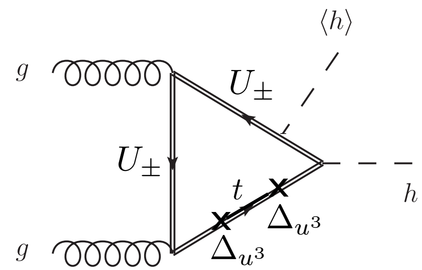
huge contribution, generic vector like theory Goertz, Haisch & Neubert; Carena, et al. (12)

Delaunay, Grojean & GP (13).



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

+



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

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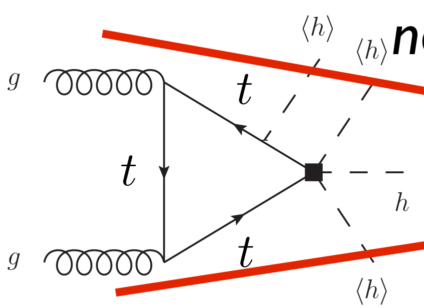

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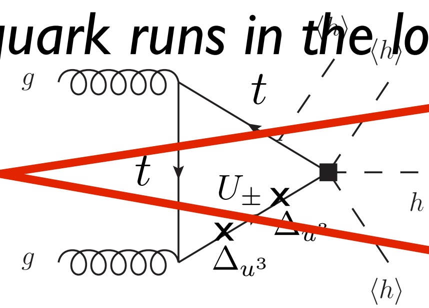

$\propto -vY^2/M^2 \times \Delta_{u^3}^2/M^2$

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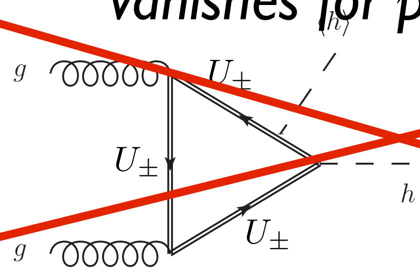
??

Cancellation for light composite quarks is ineffective!

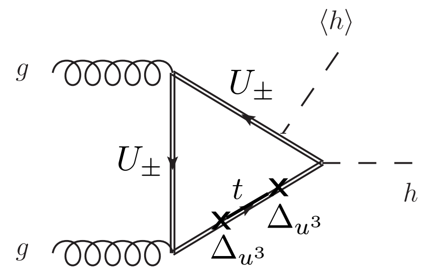
Delaunay, Grojean & GP.

vanishes for pNGB Higgs



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

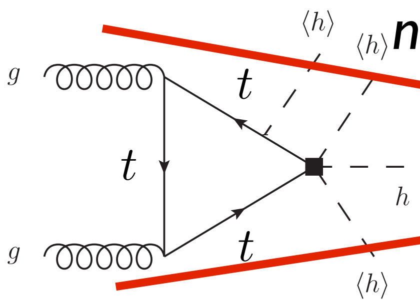
+



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

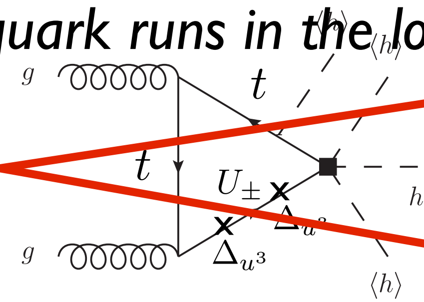
+

negligible when light quark runs in the loop



$\propto vY^2/M^2$

+

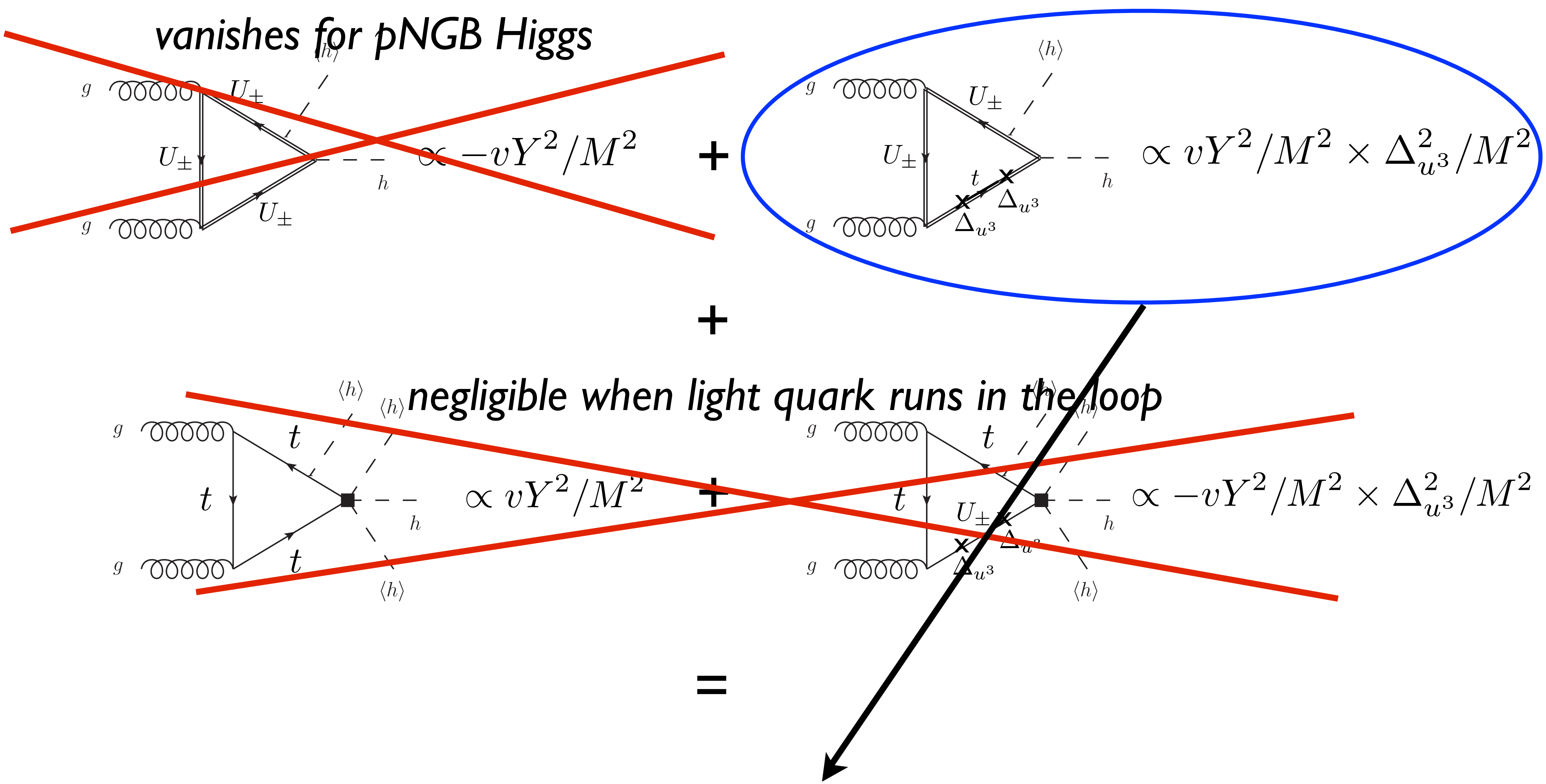


$\propto -vY^2/M^2 \times \Delta_{u^3}^2/M^2$

=

Cancellation for light composite quarks is ineffective!

Delaunay, Grojean & GP.

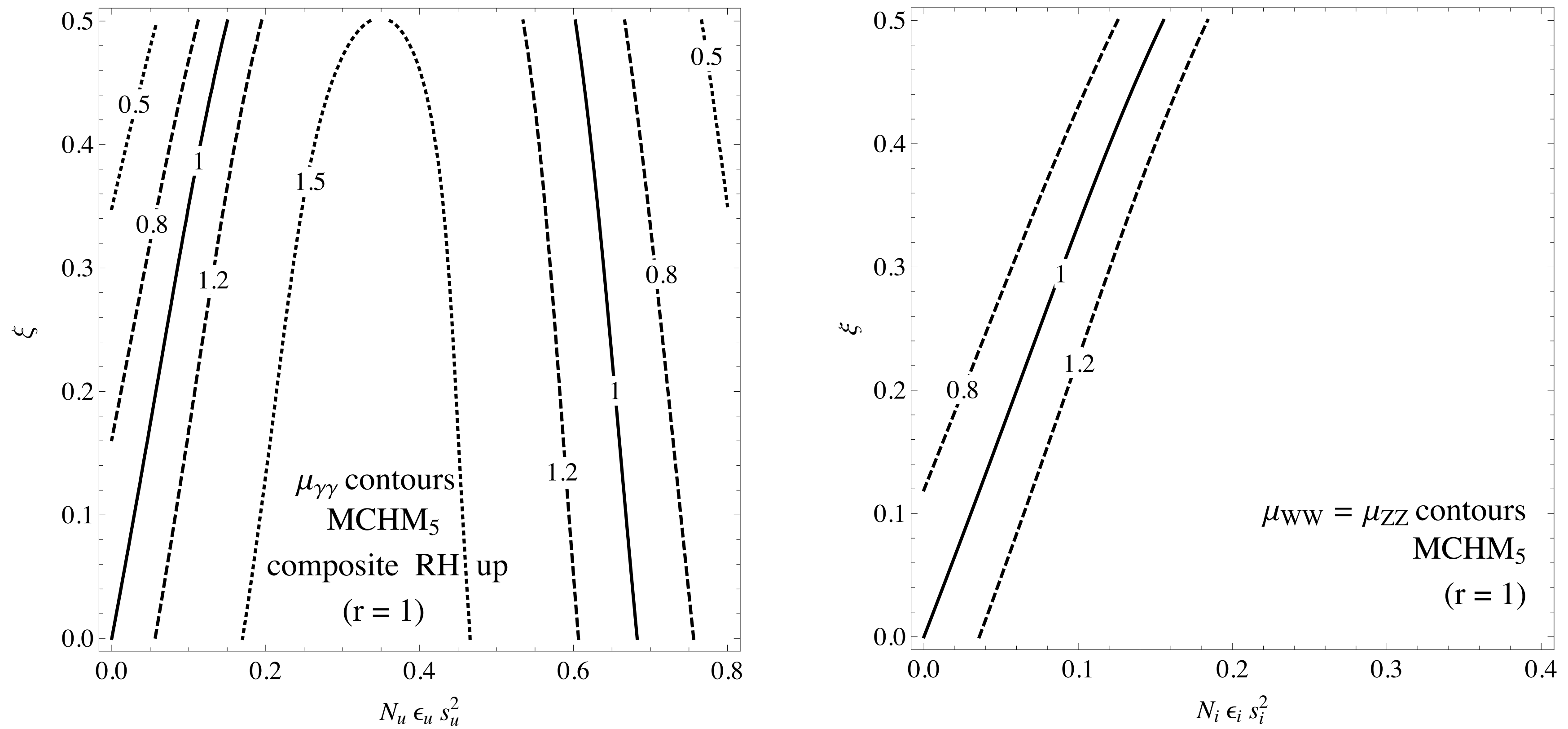


Sizable corrections for composite light quarks!

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 $\xi = v^2/f^2$, $\epsilon_i \equiv (Y_i v/M_i)^2$ $r = g_\Psi/Y$ $g_\Psi \equiv M/f$

Composite light quarks & pseudo Goldstone boson Higgs

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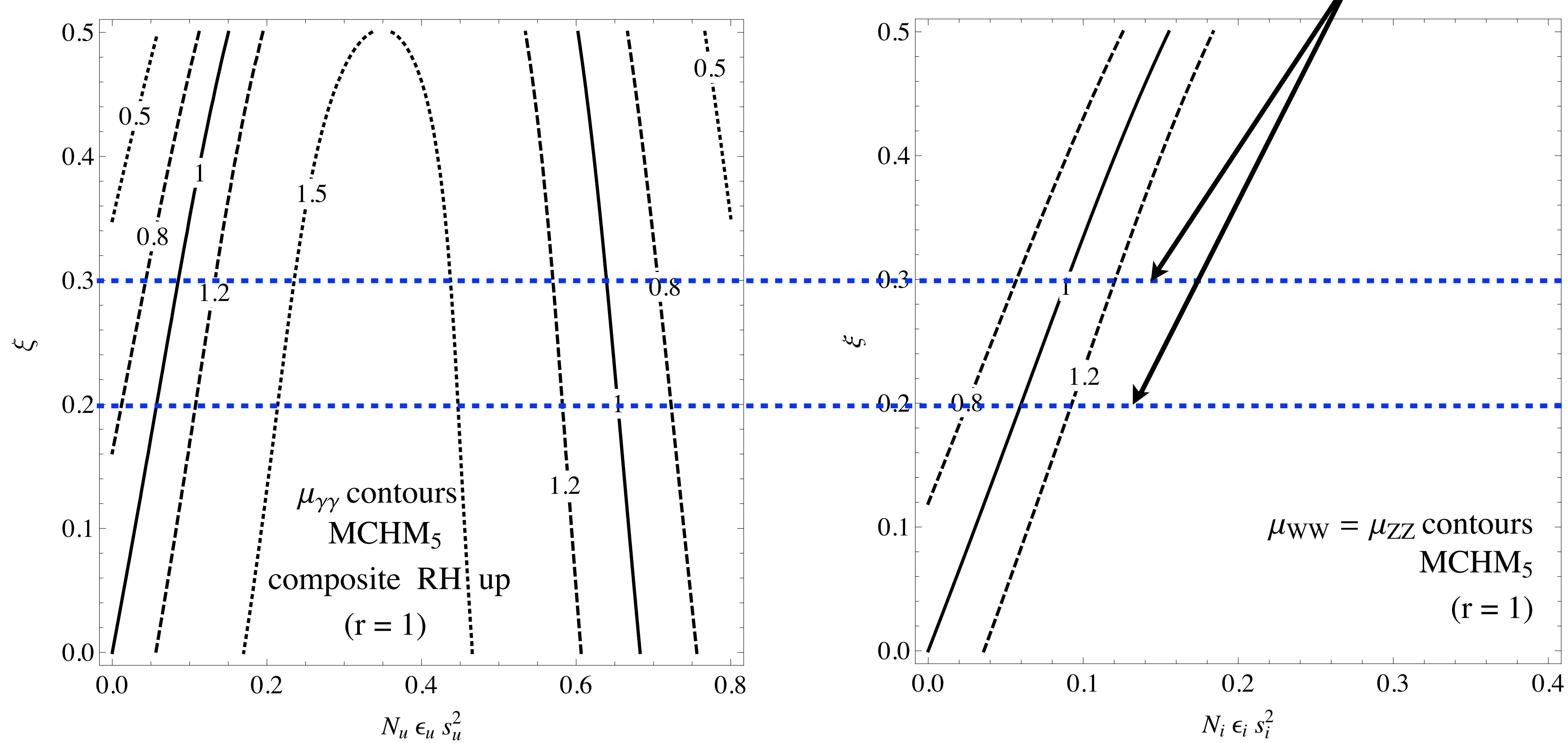
Interesting theoretically



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Composite light quarks & pseudo Goldstone boson Higgs

ean & GP (13)

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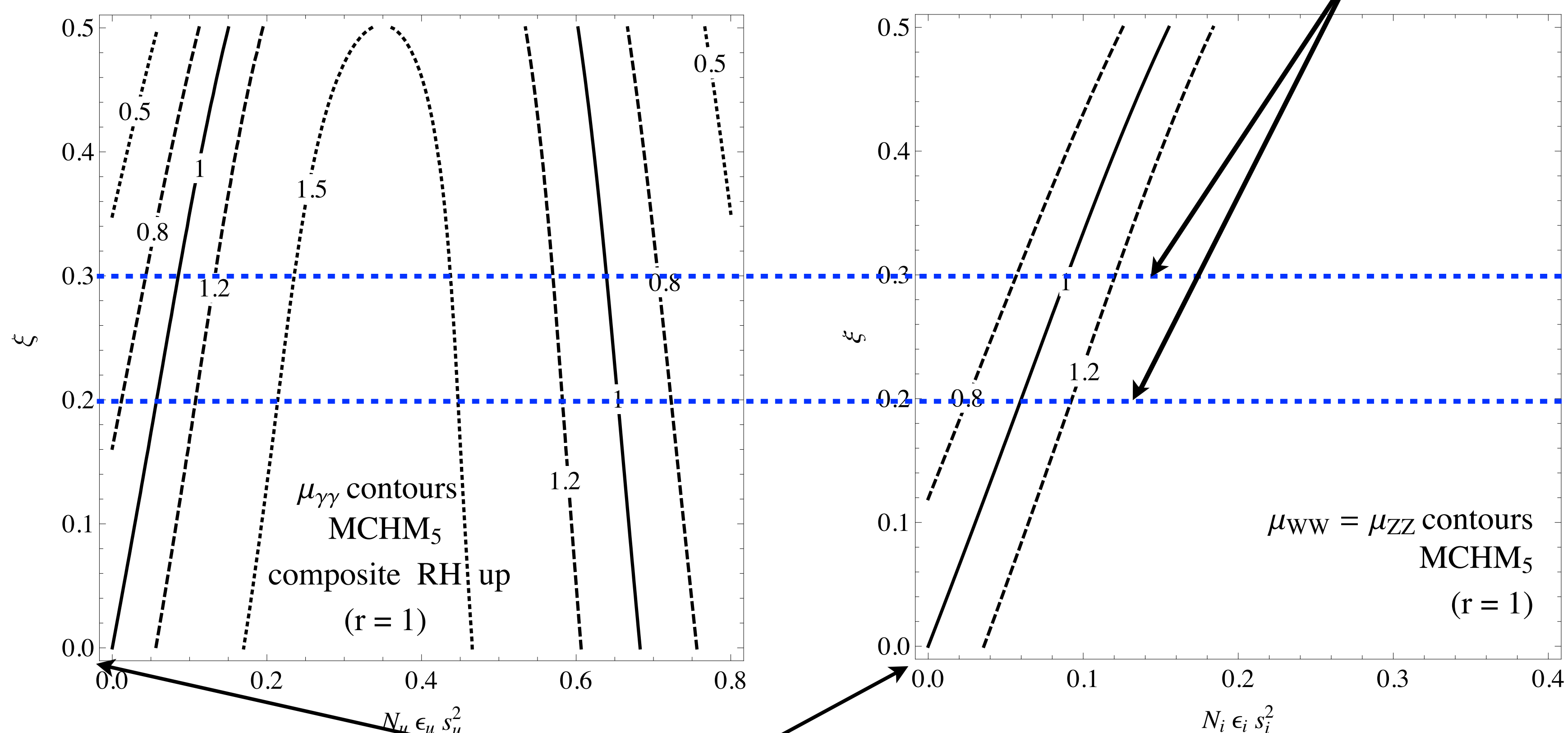
Interesting theoretically



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

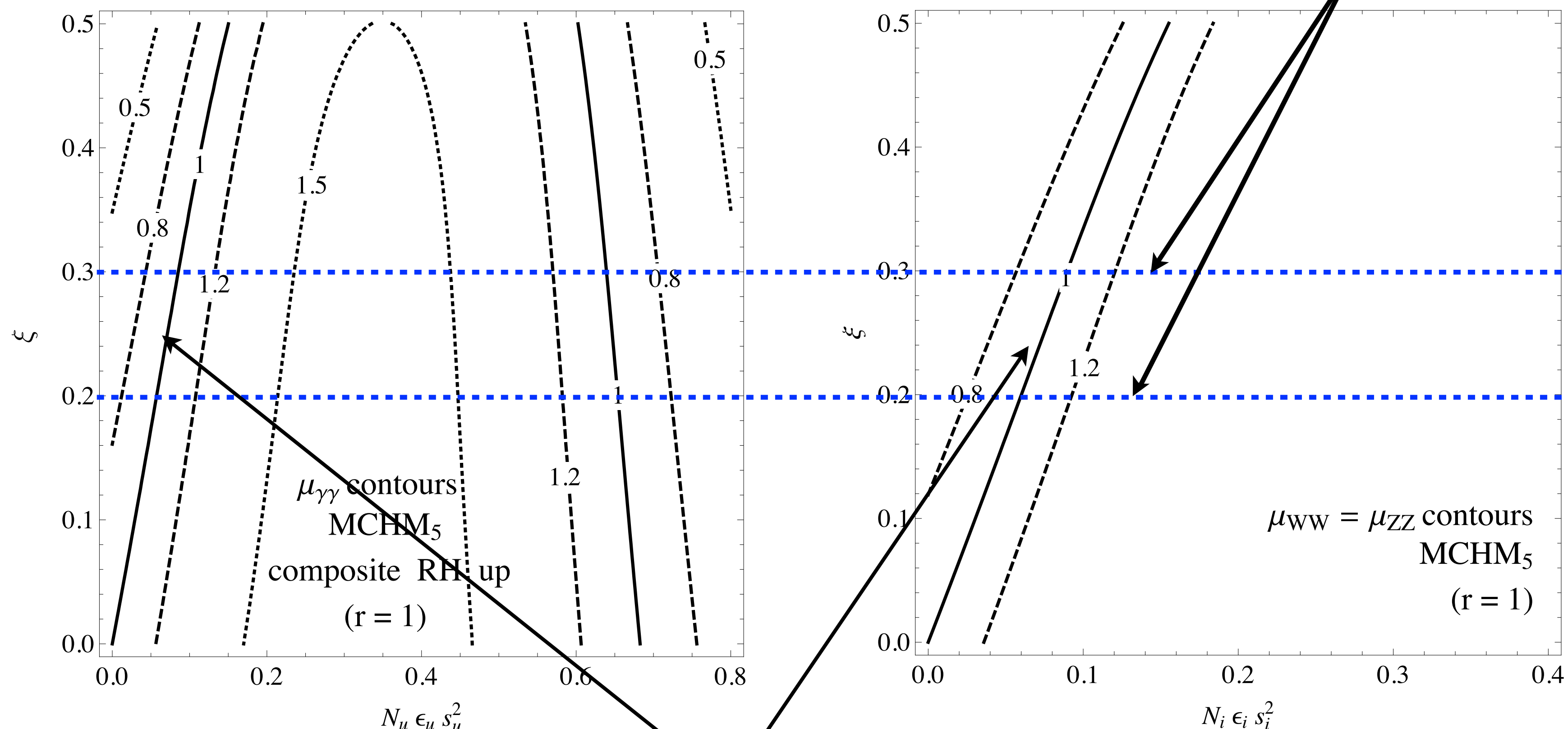
\wo mixing favorable region
of Higgs "non-linearity" excluded.

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

Composite light quarks & pseudo Goldstone boson Higgs

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

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

Delaunay, Grojean & GP, (13).

Left handed (LH) SUSY flavorful naturalness

Kats, GP, Stamou, Stolarski & Weiler, in progress.

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

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

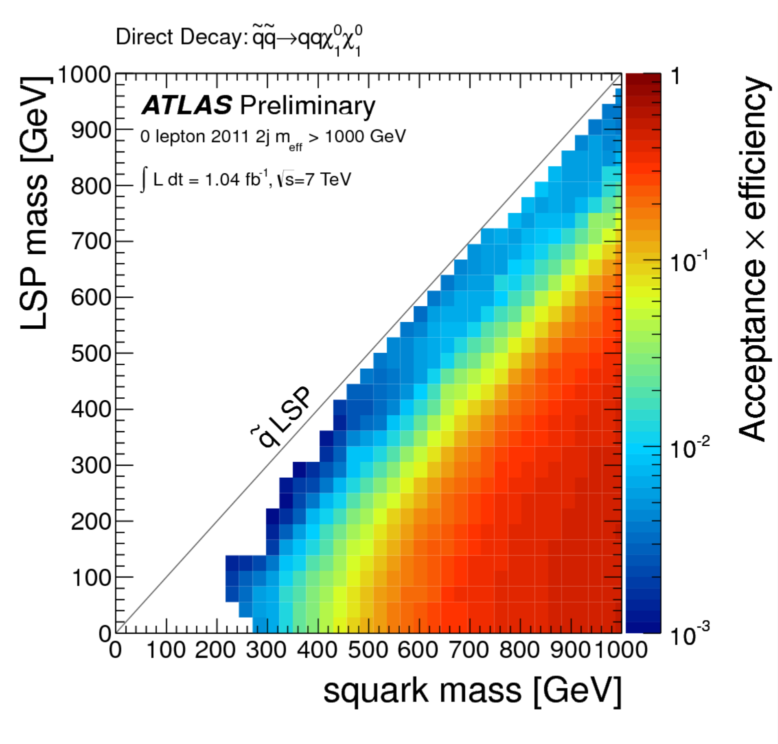
$$\left(b \to s\gamma \text{ weaker for} \tan\beta \sim \text{few} \;\&\; \tilde{b}_R \sim 3\,\text{TeV}\right)$$

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

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

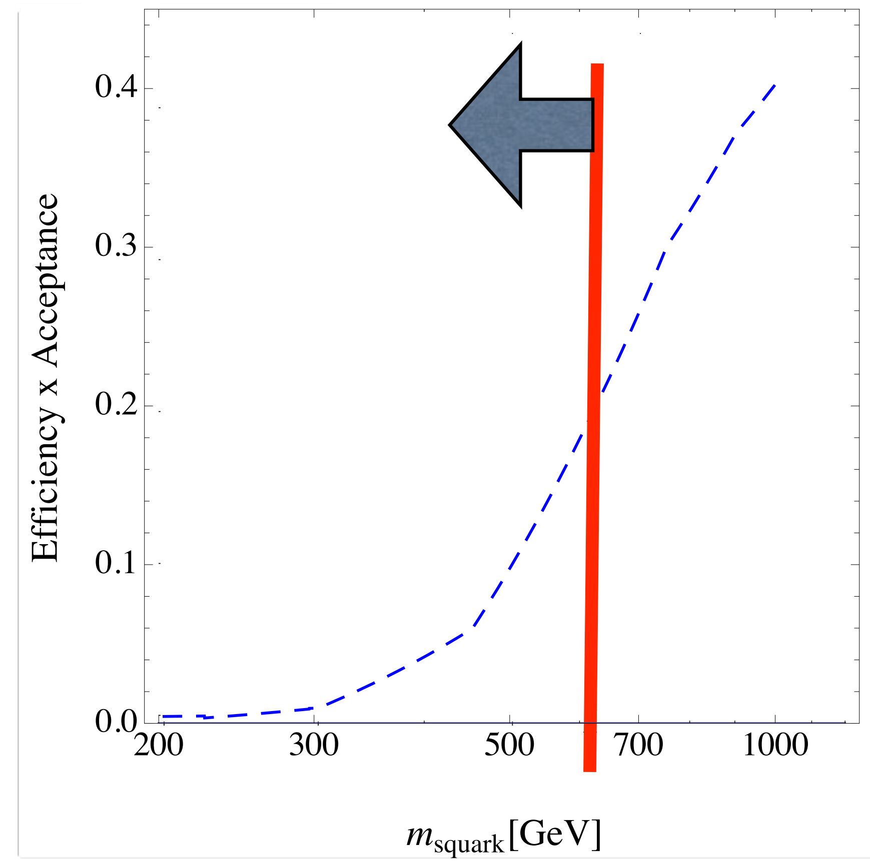
Efficiencies, strong mass dependence!

Signal efficiency falls very rapidly with decreasing squark mass



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

ATLAS 1/fb,
2jet Meff>1TeV

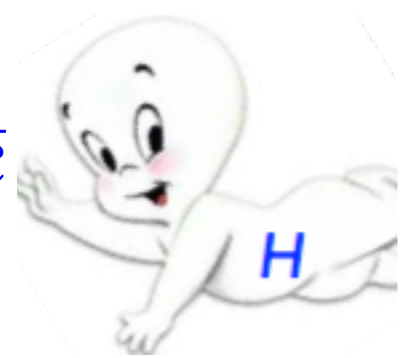


meff is the scalar sum of transverse momenta of the leading N jets with E^{miss}.

Charming the Higgs

Delaunay, Golling, GP & Soreq (13)

$c\bar{c}$



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...

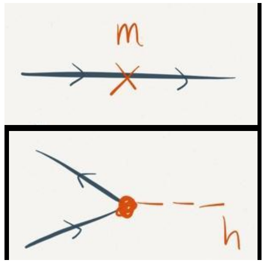
  See also: Bodwin, Petriello, Stoynev & Velasco (13), for charmonia production.

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

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

Delaunay, Golling, GP & Soreq (13)

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



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

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

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

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

Charming the Higgs, current status & projections

Delaunay, Golling, GP & Soreq (13)

- Ball park 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

BR(H→bb) is significantly suppressed:

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

≈ 40% (20%)

↑ with c_{gg}>0

$$\hat c_{gg} = c_{gg} + \Big[1.3\times 10^{-2} c_t - (4.0-4.3i)\times 10^{-4} c_b - (4.4-3.0i)\times 10^{-5} c_c\Big]\,,$$

$$\sigma_{c\bar c\to h} \simeq 3.0\times 10^{-3}\,|c_c|^2\,\sigma^{\mathrm{SM}}_{gg\to h}\,,$$

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

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

Open parenthesis

Charm tagging at the LHC

- 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

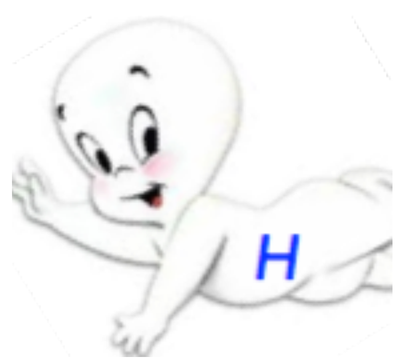
- charm jets identified by combining "information from the impact parameters of displaced tracks and topological properties of secondary and tertiary decay vertices" using multivariate techniques

  - '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

An Exclusive Window onto Higgs Yukawa Couplings to light quarks

Bodwin, Petriello, Stoynev & Velasco (13)
Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

$s\bar{b}$ $s\bar{s}$
$d\bar{b}$ $d\bar{d}$
$d\bar{s}$ $u\bar{u}$



Exclusive path towards Higgs-light quark couplings

- Use the eff. Lagrangian:

$$\mathcal{L}_{\rm eff} = -\sum_{q=u,d,s} \bar{\kappa}_q \frac{m_b}{v} h \bar{q}_L q_R - \sum_{q\neq q'} \bar{\kappa}_{qq'} \frac{m_b}{v} h \bar{q}_L q'_R + h.c.$$
$$+ \kappa_Z m_Z^2 \frac{h}{v} Z_\mu Z^\mu + 2\kappa_W m_W^2 \frac{h}{v} W_\mu W^\mu + \kappa_\gamma A_\gamma \frac{\alpha}{\pi} \frac{h}{v} F^{\mu\nu} F_{\mu\nu} \,,$$

Notice that: $\bar{\kappa}_q = y_q / y_b^{\rm SM}$,

where in the SM:

$\bar{\kappa}_s = m_s/m_b \simeq 0.020$

$\bar{\kappa}_d = m_d/m_b \simeq 1.0 \cdot 10^{-3}$

$\bar{\kappa}_u = m_u/m_b \simeq 4.7 \cdot 10^{-4}$

$\kappa_\gamma = \kappa_V = 1$

Exclusive path towards Higgs-light quark couplings

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

- Use the eff. Lagrangian: $$\mathcal{L}_{\rm eff} = -\sum_{q=u,d,s} \bar\kappa_q \frac{m_b}{v} h \bar q_L q_R - \sum_{q\neq q'} \bar\kappa_{qq'} \frac{m_b}{v} h \bar q_L q'_R + h.c. + \kappa_Z m_Z^2 \frac{h}{v} Z_\mu Z^\mu + 2\kappa_W m_W^2 \frac{h}{v} W_\mu W^\mu + \kappa_\gamma A_\gamma \frac{\alpha}{\pi}\frac{h}{v} F^{\mu\nu}F_{\mu\nu}\,,$$

Notice that: $$\bar\kappa_q = y_q / y_b^{\rm SM}\,,$$

where generically: $$|\bar\kappa_u| < 0.98\,, \quad |\bar\kappa_d| < 0.93\,, \quad |\bar\kappa_s| < 0.70$$

varying only one at the time (95%CL)

$$|\bar\kappa_u| < 1.3\,, \quad |\bar\kappa_d| < 1.4\,, \quad |\bar\kappa_s| < 1.4$$

varying all couplings (95%CL)

$|\bar\kappa_{qq'}| < 0.6\,(1)$ for $q, q' \in u, d, s, c, b$ and $q \neq q'$

same for the flavor violating case

(FCNC non-robust bound: $|\bar\kappa_{bs}| < 8\cdot 10^{-2}$ Harnik, Kopp & Zupan; Blankenburg, Ellis, Isidori, (12))

Exclusive path towards Higgs-light quark couplings

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

- Use the

Currently little is known directly on Higgs couplings to light quarks. They might be huge or zero; same holds for flavor violating couplings.

$$\sum \bar{\kappa}_q \frac{m_b}{v} h \bar{q}_L q_R - \sum_{q \neq q'} \bar{\kappa}_{qq'} \frac{m_b}{v} h \bar{q}_L q'_R + h.c.$$

$$Z^\mu + 2\kappa_W m_W^2 \frac{h}{v} W_\mu W^\mu + \kappa_\gamma A_\gamma \frac{\alpha}{\pi} \frac{h}{v} F^{\mu\nu} F_{\mu\nu} \,,$$

$$\text{SM}_b \,,$$

where generically:

$|\bar{\kappa}_u|$ $0.98 \,, \quad |\bar{\kappa}_d| < 0.93 \,, \quad |\bar{\kappa}_s| < 0.70$

varying only one at the time (95%CL)

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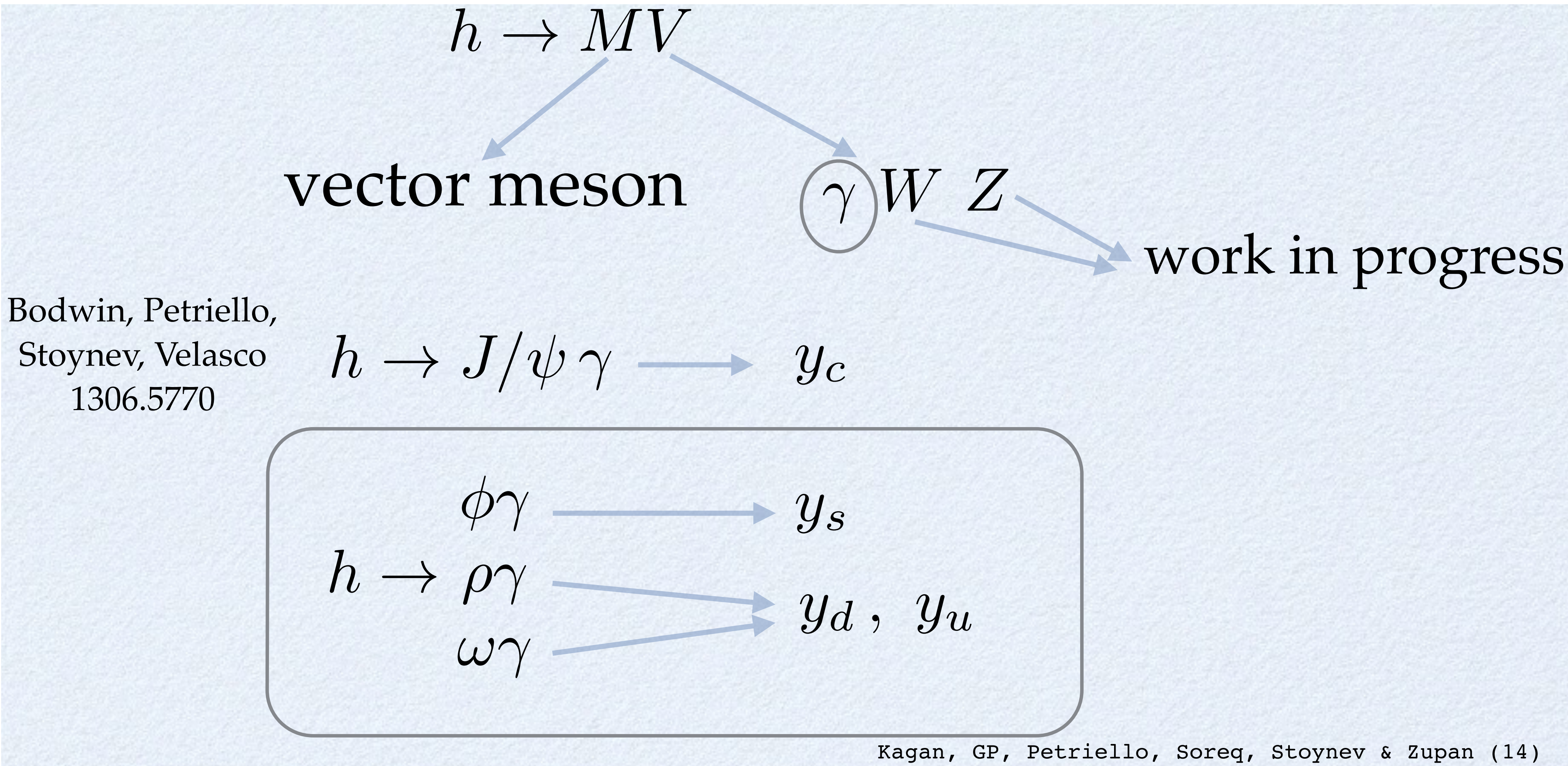
The main idea



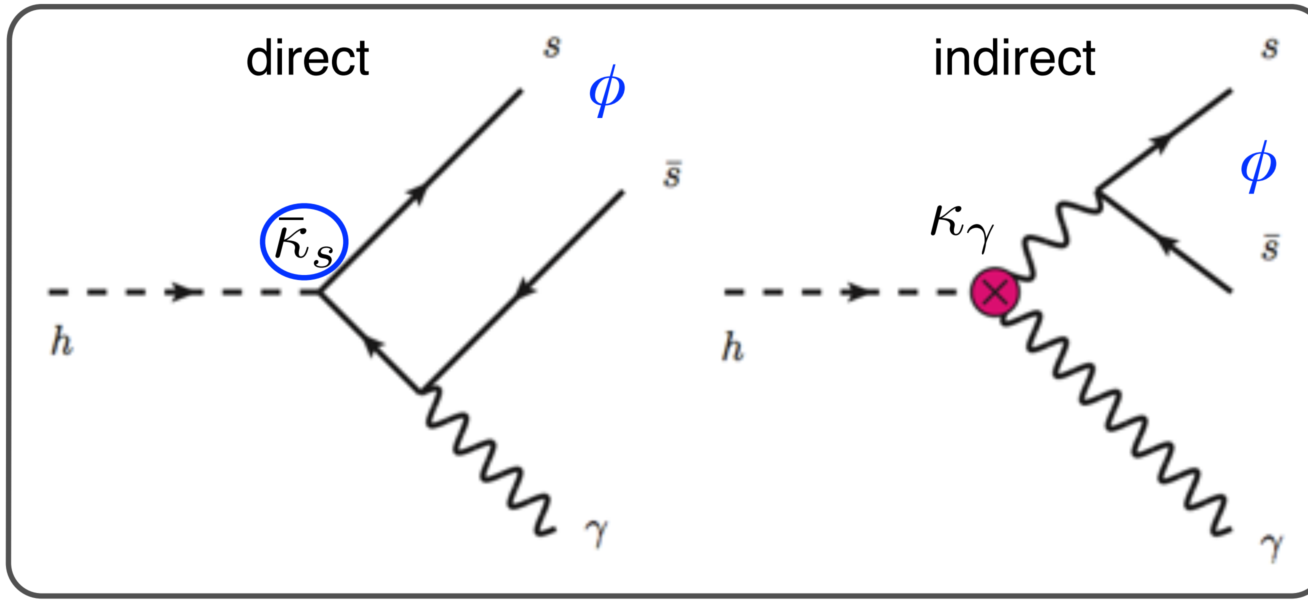
Adding off-diagonal: $h \to \bar{B}^{0*}\gamma$, $h \to \bar{B}^{0*}\gamma$, $h \to K^{0*}\gamma$, $h \to D^{0*}\gamma$

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

Ex.: $h \to \phi\gamma$

$$\Gamma_{h\to\phi\gamma} = \frac{1}{8\pi}\frac{1}{m_h}|M^{\phi}_{ss}|^2,$$

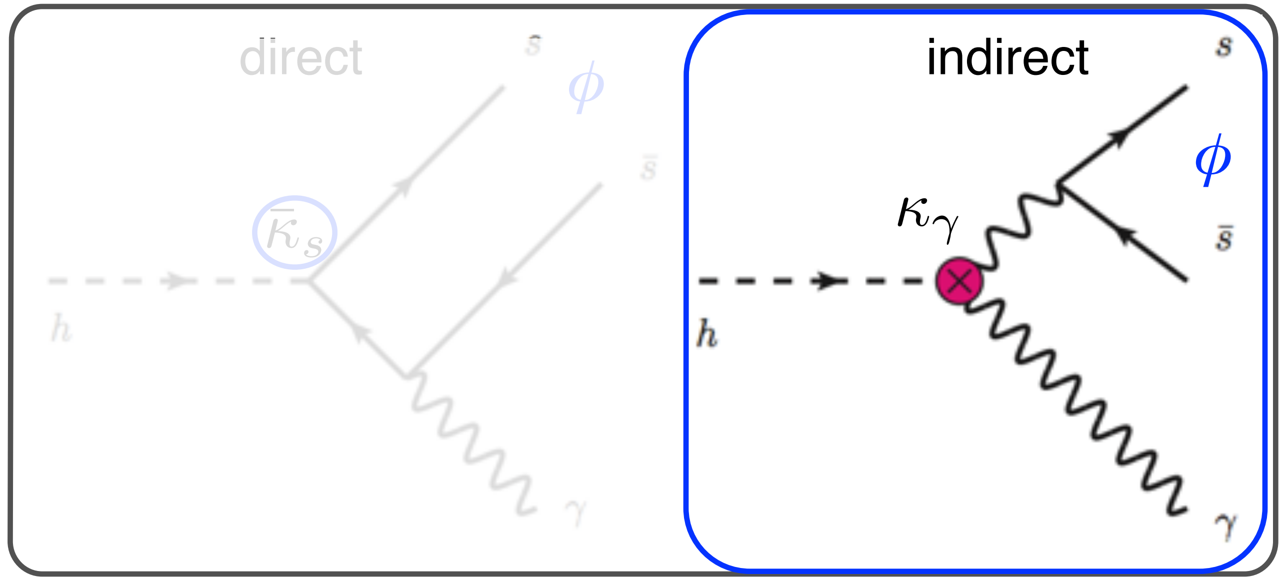
- Two paths to get $h \to \phi\gamma$:

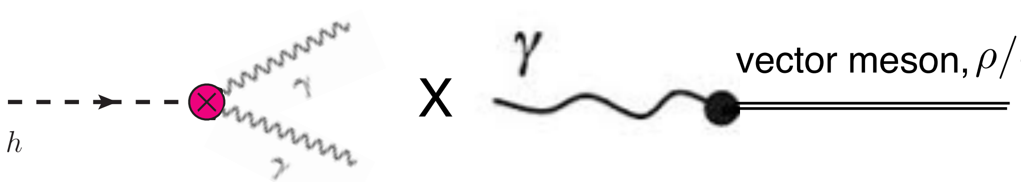


- Let us understand them one by one.

Ex.: $h \to \phi\gamma$, indirect contribution

- Two paths to get $h \to \phi\gamma$:





$\propto \dfrac{f_{\rho,\phi}}{m_{\rho,\phi}}$

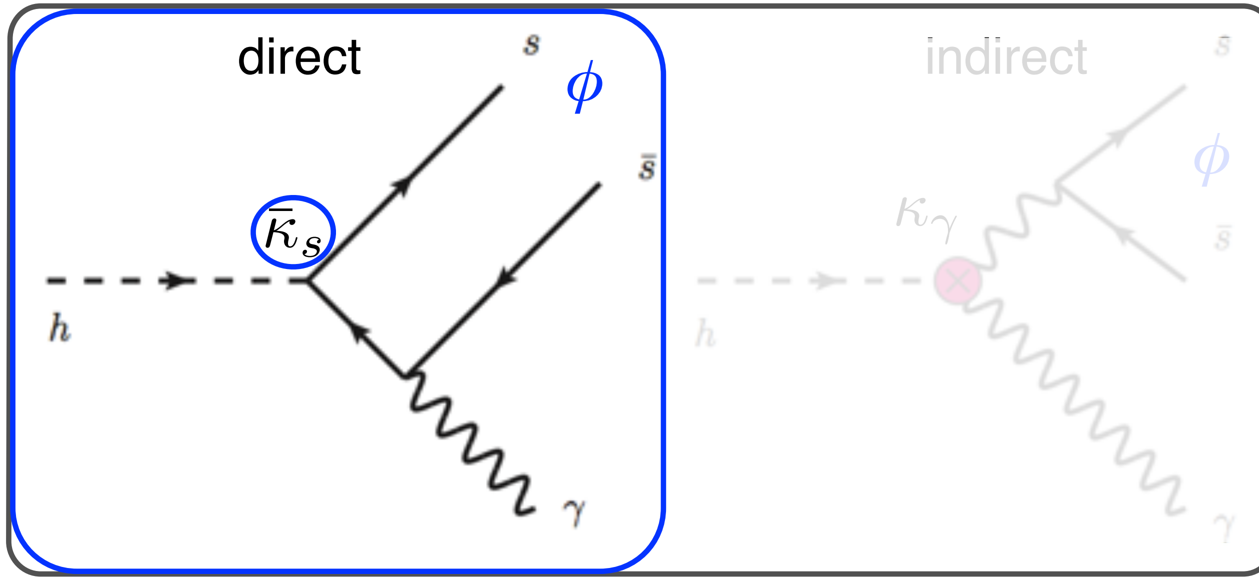
from experiment, $\phi \to e^+e^-$

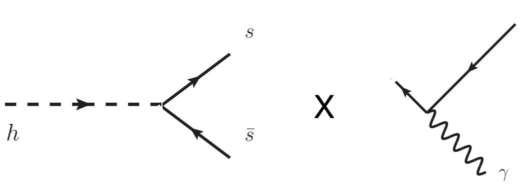
($f_\phi = 0.235(5)\,\mathrm{GeV}$)

$$\left(M^{\phi}_{ss}\right)_{\mathrm{indir}} \approx \frac{f_{\rho,\phi}}{m_{\rho,\phi}}\,\kappa_\gamma A_\gamma \frac{4\alpha m_h^2}{\pi v}$$

Ex.: $h \to \phi\gamma$, direct contribution

- Two paths to get $h \to \phi\gamma$:





$$\propto \frac{\bar{\kappa}_s m_b}{v} \frac{f_{\rho,\phi}^{\perp}}{m_h}$$

$(\text{"local" structure} : \bar{s}\sigma_{\mu\nu}s \times F^{\mu\nu})$

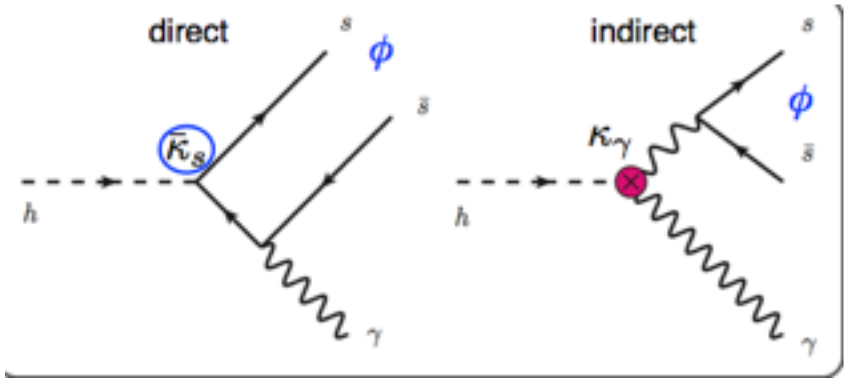
from experiment, $\phi \to e^+e^-$

$(f_{\perp}^{\phi} = 0.191(28))$

$$\left(M_{ss}^{\phi}\right)_{\text{dir}} \approx \frac{\bar{\kappa}_s m_b}{v} f_{\phi}^{\perp}$$

Final result for the BR$(h \to \phi\gamma)$

$$\Gamma_{h\to\phi\gamma} = \frac{1}{8\pi}\frac{1}{m_h}|M_{ss}^{\phi}|^2,$$



- The resulting sensitivity:

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\big[(3.0\pm 0.13)\kappa_\gamma - 0.78\bar{\kappa}_s\big]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2},$$

Similar holds
for 1st generation:

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\big[(1.9\pm 0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\big]\cdot 10^{-5}}{0.57\bar{\kappa}_b^2},$$

$$\frac{\mathrm{BR}_{h\to\omega\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\big[(1.6\pm 0.17)\kappa_\gamma - 0.59\bar{\kappa}_u - 0.29\bar{\kappa}_d\big]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2},$$

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

Experimental sensitivity

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)

- focus on $h \to \phi\gamma$, use **`Pythia 8.1`**
  - main decay modes: $\phi \to K^+K^-$ (49%), $K_L K_S$ (34%), $\pi^+\pi^-\pi^0$(15%)
  - for $pp \to h \to \phi\gamma$ at 14TeV LHC in 70 to 75% cases the kaons/pions and the prompt photon have $|\eta| < 2.4$
    - within the minimal fiducial volume of the ATLAS and CMS experiments
  - adopt the geometrical acceptance factor $Ag = 0.75$
    - do not include other efficiency or trigger factors
- assume $\kappa_\gamma = 1$, negligible background, 3σ reach

no theory error

$\sqrt{s}$ [TeV]	$\int \mathcal{L}\, dt$ [fb^{-1}]	# of events (SM)	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\text{stat.}} > (<)$
14	3000	770	0.39 (−0.97)	0.27 (−0.81)
33	3000	1380	0.36 (−0.94)	0.22 (−0.75)
100	3000	5920	0.34 (−0.90)	0.13 (−0.63)

two detectors

one detector

5x SM strange Yukawa

Future experiments

- only a few events expected at e^+e^- colliders
  - ILC, ILC with luminosity upgrade, CLIC
  - probably too small for observation of $h \to \phi\gamma$
- $\approx$ 30 events expected at FCC-ee (TLEP)
  - too small to probe a deviation from the SM prediction
- $h \to \phi\gamma$ measurements unique to future hadron machines

Thoughts about experimental strategy

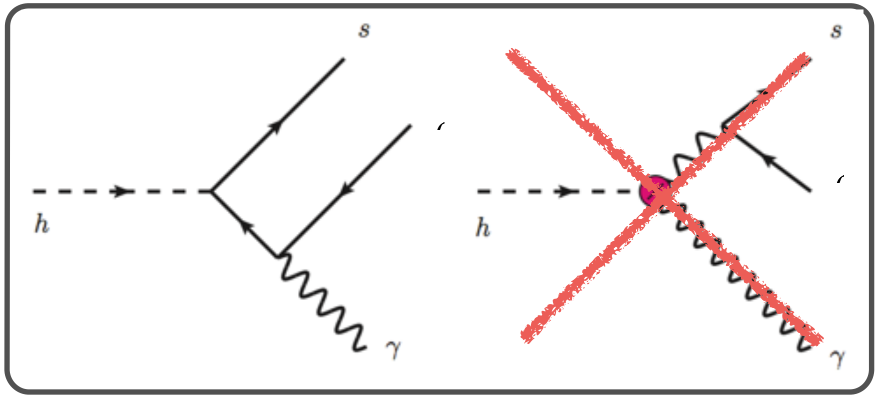
- for $h \to \phi\gamma$ decay most promising $\phi \to K^+K^-$
  - near collinearity of the photon and the ϕ-jet in the transverse plane
  - jet sub-structure information
    - two close high-p_T tracks in a narrow cone
  - di-track invariant mass distribution assuming kaons
    - 1.5% (better than 15 MeV) resolution (CMS)
- can probably be used to significantly cut on the background
  - on jet+γ QCD backgrounds
  - on $h \to \phi\gamma + n\pi^\circ,\ \eta^{(\prime)}(\to neutr.)\,\gamma$
- dedicated trigger probably required to enhance the reach

Thoughts about experimental strategy

- $h \to \rho^\circ \gamma$ mode
  - $Br(\rho^\circ \to \pi^+\pi^-) \sim 100\%$
  - relatively clean mode, similar to $\phi \to K^+K^-$ decay
- $h \to \omega\gamma$ mode
  - $Br(\omega \to \pi^+\pi^-\pi^\circ) \sim 89\%$
  - harder to trigger on
  - hard-to-identify π° smears the observable quantities
  - a detailed experimental study required

Flavor violating couplings

Kagan, GP, Petriello, Soreq, Stoynev & Zupan (14)



- FV modes $h \to \bar{B}_s^{0*}\gamma$, $h \to \bar{B}^{0*}\gamma$, $h \to \bar{K}^{0*}\gamma$, $h \to D^{0*}\gamma$
    - can probe $\bar{\varkappa}_{bs,sb}$, $\bar{\varkappa}_{bd,db}$, $\bar{\varkappa}_{sd,ds}$ and $\bar{\varkappa}_{cu,uc}$
- $h \to \bar{K}^{0*}\gamma$ similar expr. as $h \to \phi\gamma$
    - but only direct amplitude
- for $\bar{\varkappa}_{ds} \sim O(1) \Rightarrow Br(h \to \bar{K}^{0*}\gamma) \sim O(10^{-8})$
    - not observable at planned future colliders

$$\frac{BR_{h\to \bar{B}_s^{*0}\gamma}}{BR_{h\to b\bar{b}}} = \frac{(2.1 \pm 1.0)\cdot 10^{-7}}{0.57\bar{\kappa}_b^2}\frac{|\bar{\kappa}_{bs}|^2 + |\bar{\kappa}_{sb}|^2}{2},$$