(buried) Non-degenerate squarks, from flavor precision to the LHC

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CERN & Weizmann

`Gedalia, Kamenik, Ligeti & GP, 1202.5038, to appear in PLB;`
`Mahbubani, Papucci, GP, Ruderman & Weiler, to appear.`

FLASY12 - Workshop on Flavor Symmetries

Outline

- Intro': why is the up quark sector interesting ?

- Where are we regarding flavor *d*-alignment models?

- Collider constraints on non-degenerate/"universal" squarks.

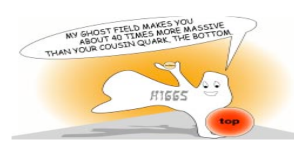
- Summary.

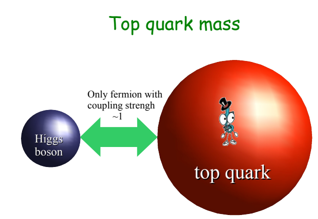
The importance of isospin up physics

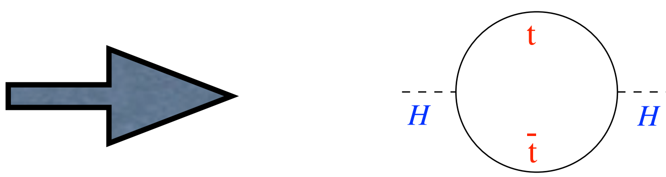
- The up sector $(u, c, t,\ \nu's)$ contains the top quark.

Uniqueness of the top quark (relevant to this talk):

i. Most massive point like particle known, induces the most severe hierarchy problem, our main LHC hopes are due to $\Lambda_t \lesssim 7\,\mathrm{TeV}$ for fine tuning $\lesssim 1:100.$







ii. Controls flavor violation within the SM (standard model) => expect up flavor violation.

iii. Makes the weak scale unstable => eventually tunnel into weakless universe.

The importance of isospin up physics

- The up sector $(u, c, t,\ \nu' s)$ contains the top quark.

  Uniqueness of the top quark (relevant to this talk):

  ii. Controls flavor violation within the SM (standard model) => expect up flavor violation.

- u-FCNC (flavor changing neutral currents), only way to constrain alignment models,

where we have up anarchy but down flavor physics is boring, SM like.

- We have fresh precision data, maybe hints towards up anarchy:

  neutrino flavor parameters, t-charge asymm', charm CPV ?

Some interesting up sector data

(i) Top charge asymmetries;

(ii) Charm CPV.

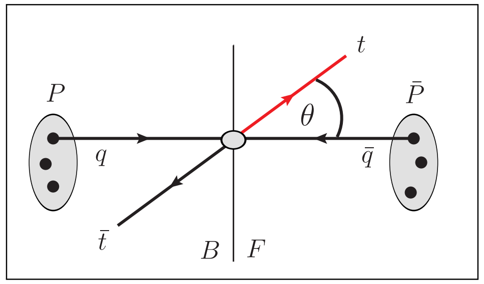
Look Down

Look Up

Tevatron's $t\bar{t}$ forward backward asymmetry.

Two kind of interesting asymmetries:

(i) Top charge asymmetry.



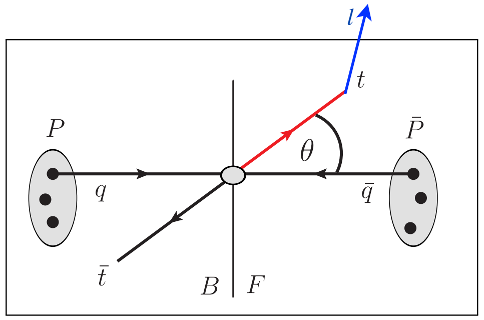
- Combined CDF+DO results: $A_{FB}^{\text{inclusive}} \approx (18\pm4)\%$ *in ttbar rest frame*

  post-Moriond 2012 $A_{FB}^{>450\text{GeV}} \approx (28\pm6)\%$

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

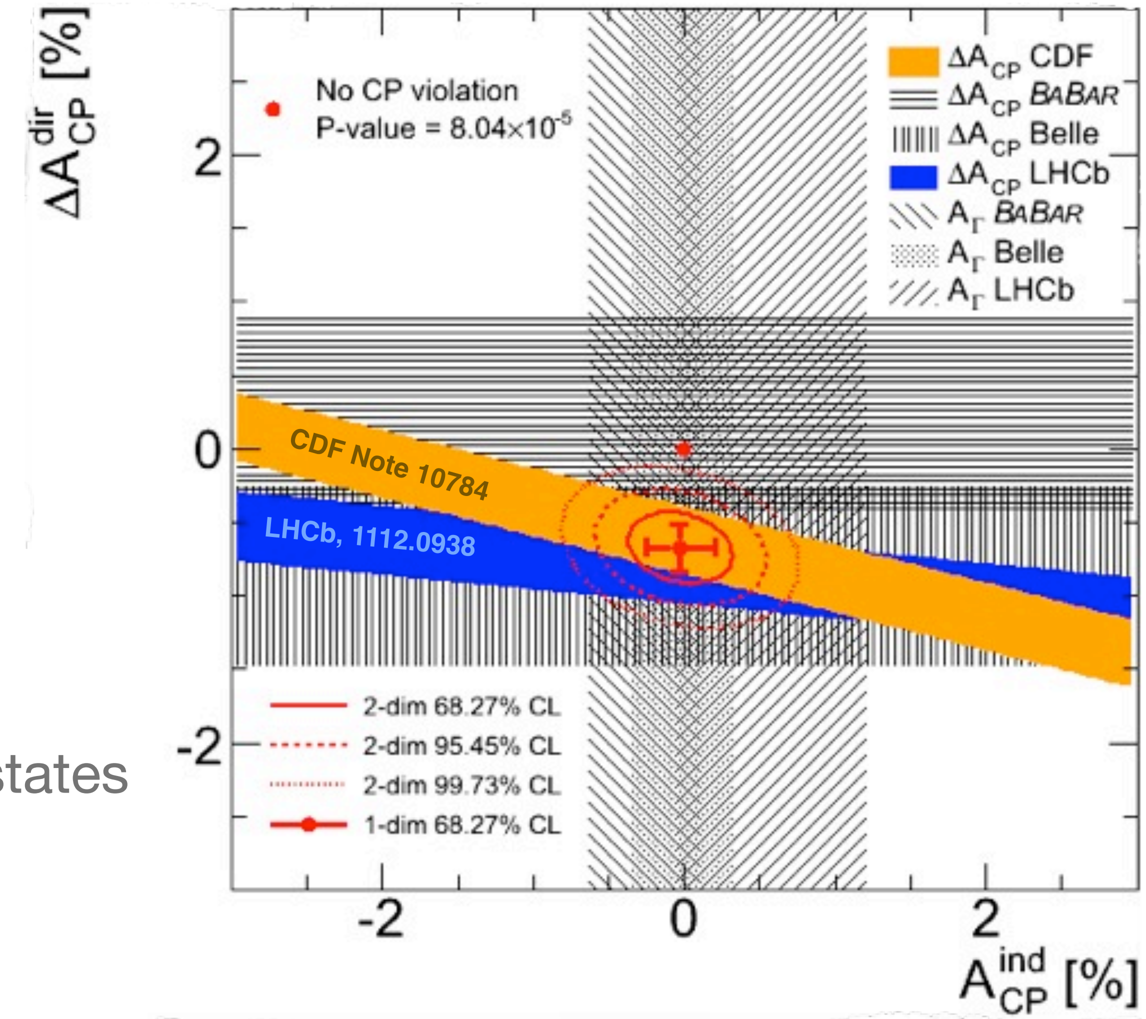
Delaunay, Top physics workshop, CERN 12.

(ii) Lepton asymmetry.



CDF with 8.7 fb^{-1}	**D0** with 5.4 fb^{-1}	**SM**
• $A_\ell = 6.6 \pm 2.5\%$ (folded!)	• $A_\ell = 15.2 \pm 4.0\%$	• $A_\ell = 2\%$

LHCb charm CPV



See: J. Kamenik, Planck 12.

- **CPV in decays (direct CPV)**
  - Time-integrated CPV decay asymmetries to CP eigenstates

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}\,.$$

  - Focus on K^+K^- and $\pi^+\pi^-$ final states: $\Delta a_{CP} \equiv a_{K^+K^-} - a_{\pi^+\pi^-}$

$$\boxed{\Delta a_{CP}^{\mathrm{World}} = -(0.67 \pm 0.16)\% \qquad (\sim 4\sigma \text{ from } 0)}$$

Some common feature of new physics (NP) interpretations*

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

  Large asymmetry (PDFs) => new dynamics couple to both $u\bar{u}$ & $t\bar{t}$
  but in a non-universal manner => direct test of up NP sector.
  (Furthermore the lepton asymmetry need not be related to top physics)

Falkowski, GP & Schmaltz (11).

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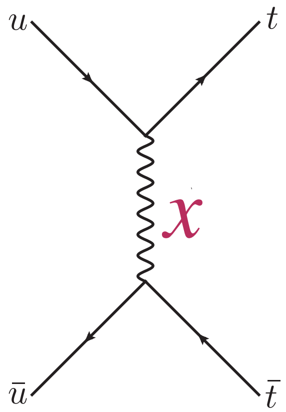
Before moving to charm CPV =>
let's see it explicitly
using geometrical picture of
flavor breaking.

Naively, the AFB has nothing to do with up flavor

All interpretation linked to up flavor physics:

Ex.: AFB from particle exchange (same holds for s-channel):



(i) Again dijet kills the universal case.

Grinstein, et al.; Ligeti, et al. (11)

(ii) By itself flavor diagonal: $g^x_{u\bar{t}} = g^x_{1\bar{1}} - g^x_{3\bar{3}}$

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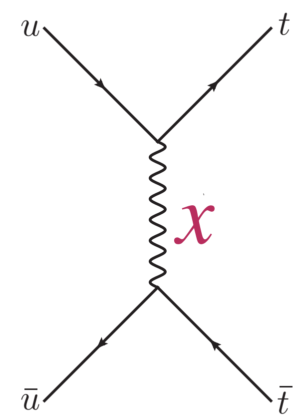

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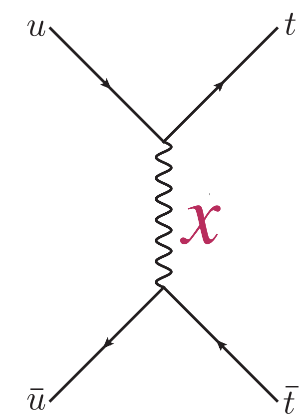

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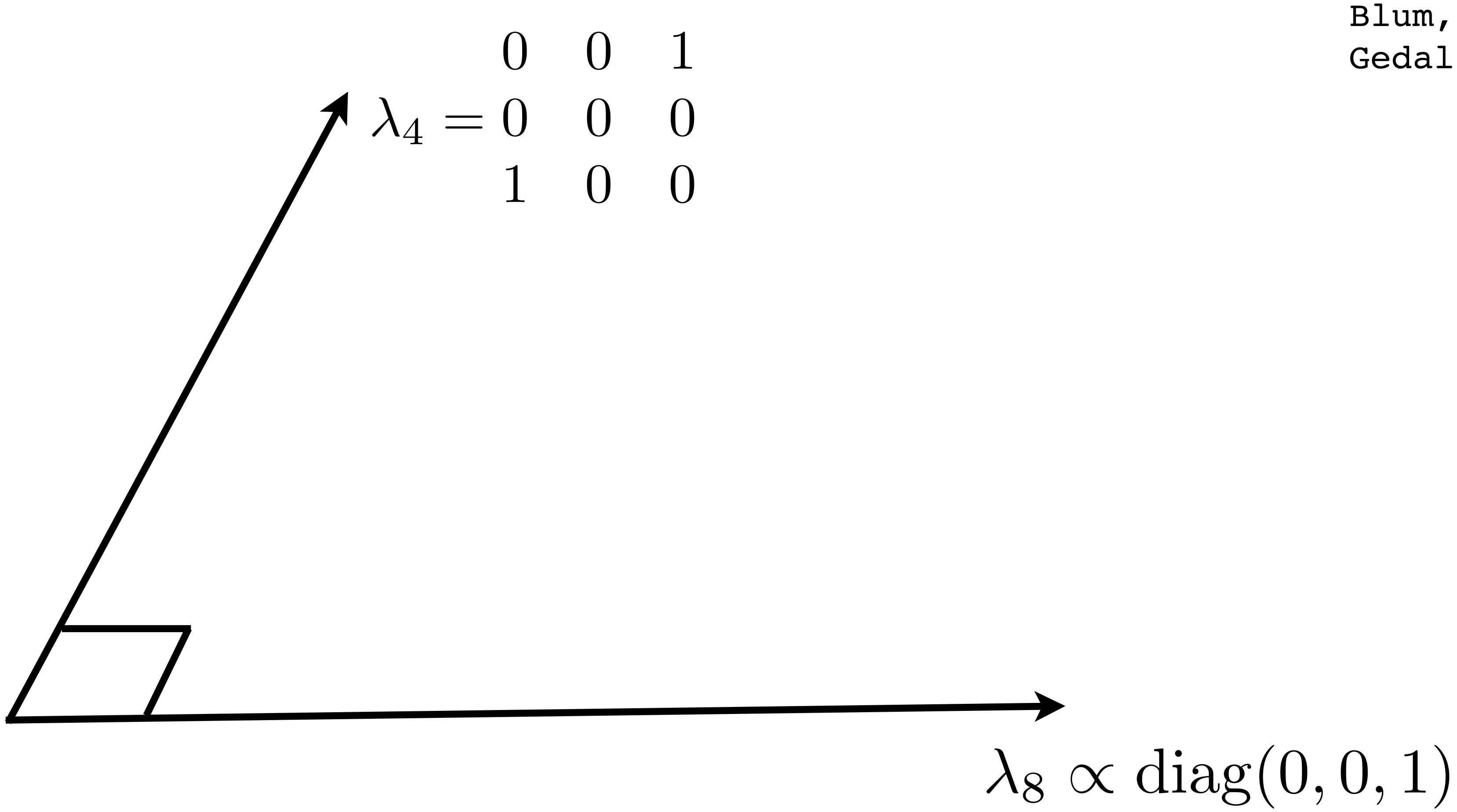

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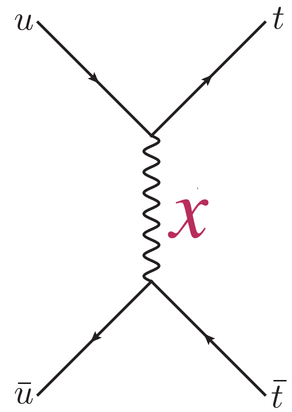

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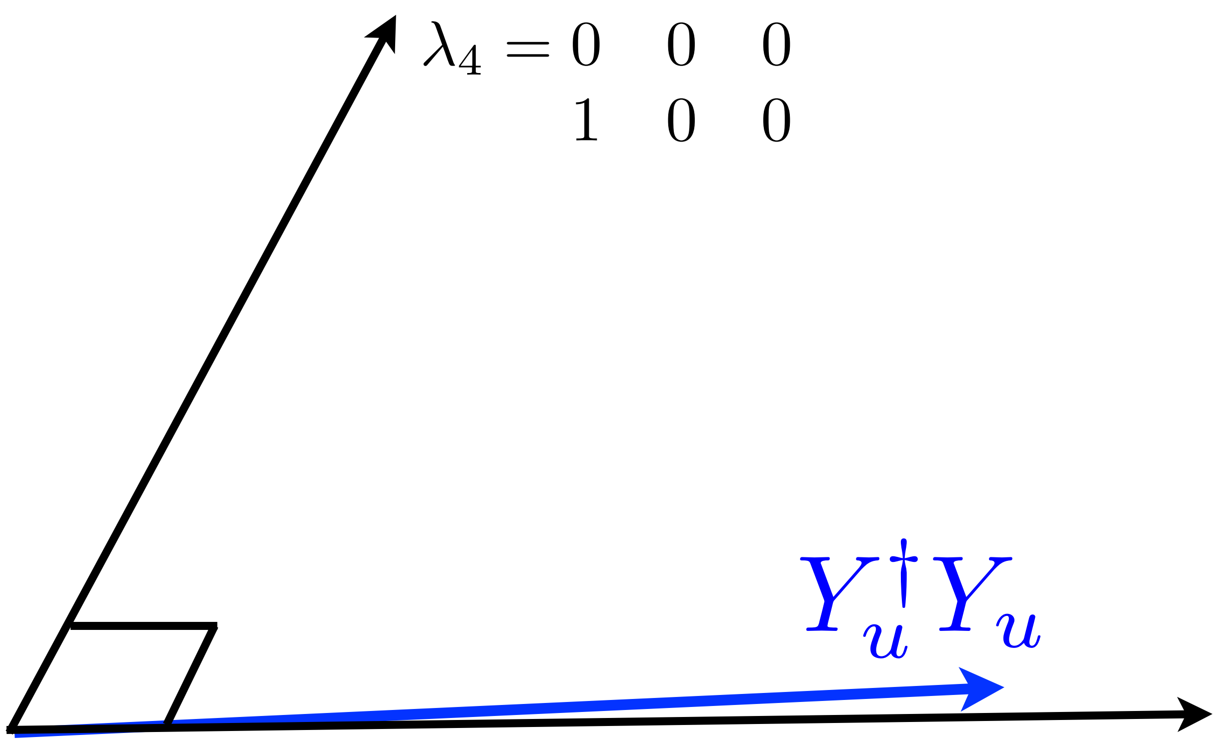
$$\lambda_4 = \begin{matrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{matrix}$$



$\lambda_8 \propto \mathrm{diag}(0,0,1)$

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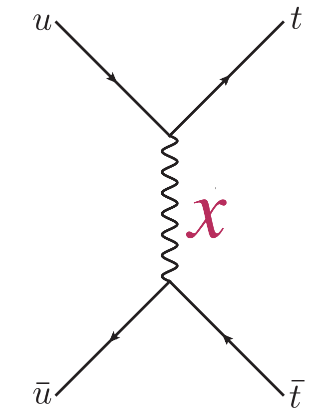

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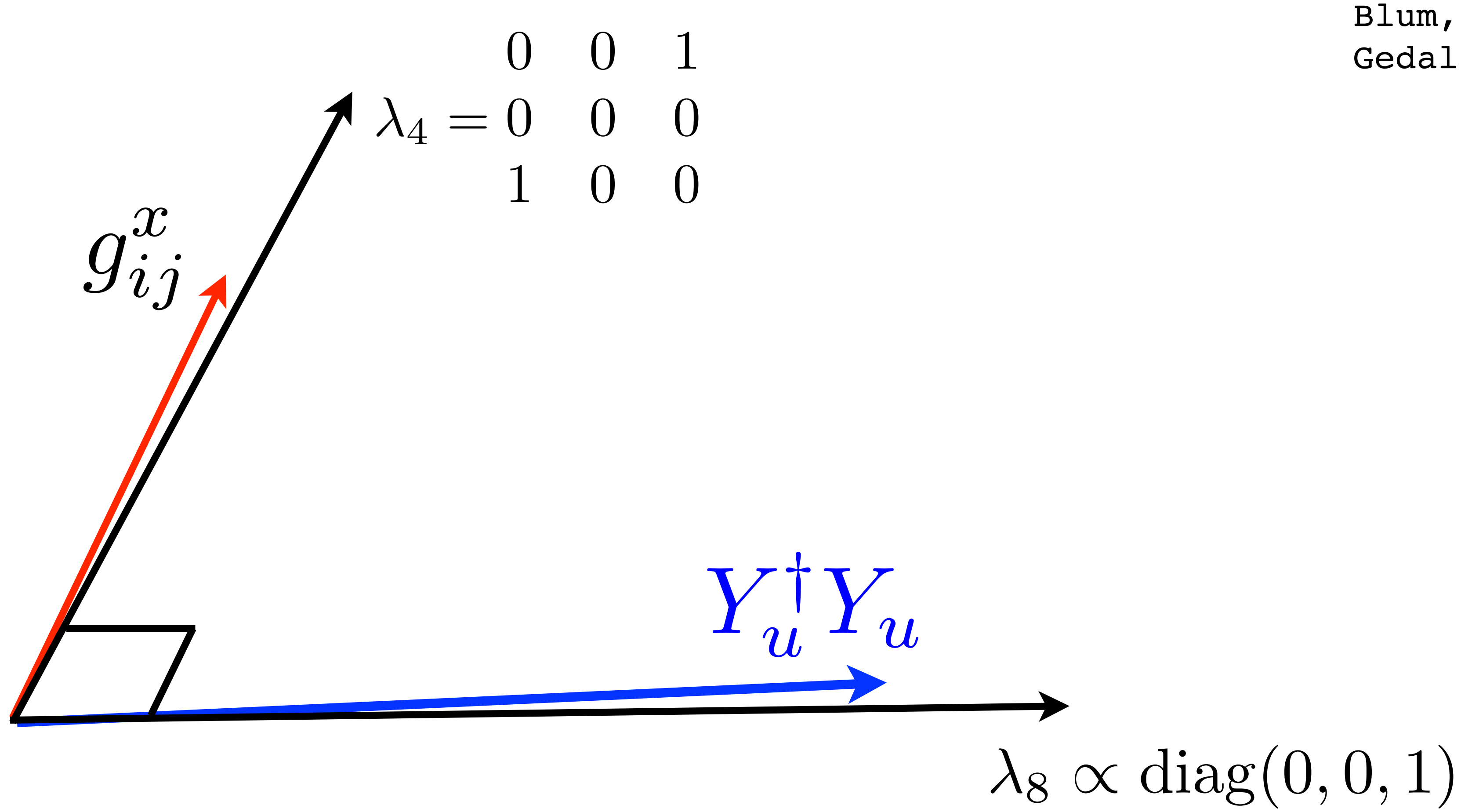

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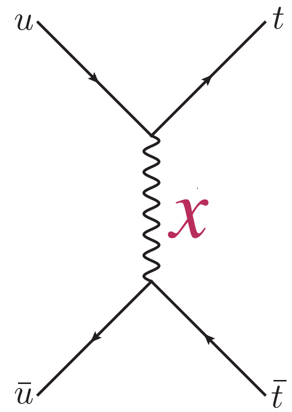

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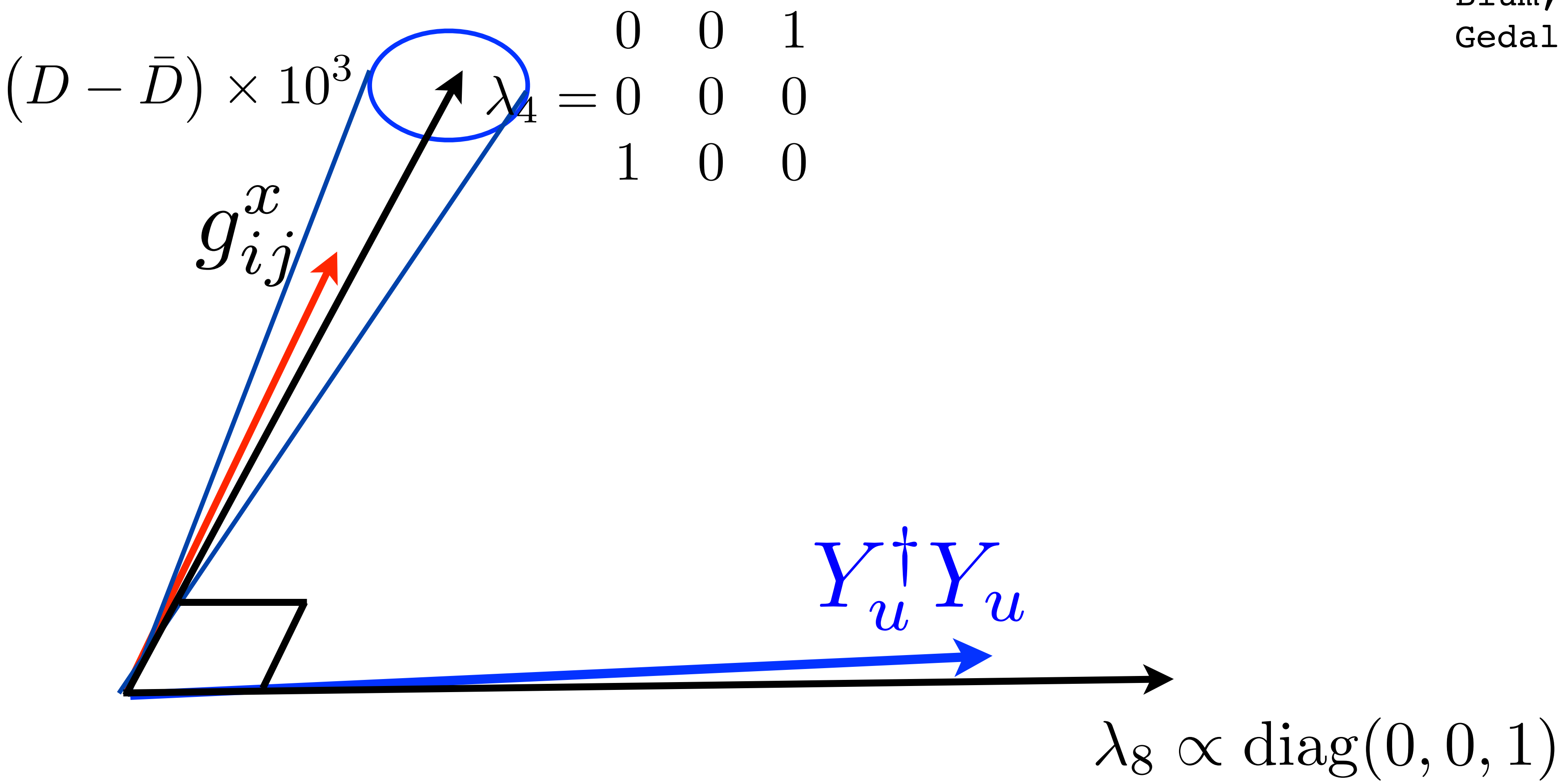

Some common feature of new physics (NP) interpretations*

- Top asymmetry is special, not only top sector is probed => uFCNC (& possibly dFCNC) needs to be considered.

- Charm "anomaly" requires large $\bar{c}uX$ couplings.

  Needless to say, such coupling can potentially lead to disastrous contributions to $D-\bar{D}$ mixing & ϵ'/ϵ_K . (C: J. Kamenik's talk)

  Isidori, Kamenik, Ligeti & GP (11).

Options: $X = G^{\mu\nu}$ Grossman, Nir & Kagan (07); Giudice, Isidori & Paradisi (12); Keren-Zur et al. (12); Delaunay, Kamenik, GP & Randall, today! (12).

$X = (s\bar{s})_{V+A}$ Da Rold, Delaunay, Grojean & GP, to appear.

* Not clear whether the charm CPV measurement requires NP.

Golden & Grinstein (89); Brod, Kagan & Zupan (11); Brod, Grossman, Kagan & Zupan; Feldmann, Nandi & Soni (12).

uFCNC data, a crucial test of alignment

♦ Down & lepton flavor violation => removed via alignment, where anarchic NP is diagonal in down/charged-lepton mass basis.

[Nir & Seiberg, PLB (93); Fitzpatrick, GP & Randall, PRL (08); Csaki, GP, Surujon, & Weiler, PRD (09)]

careful domino *alignment*

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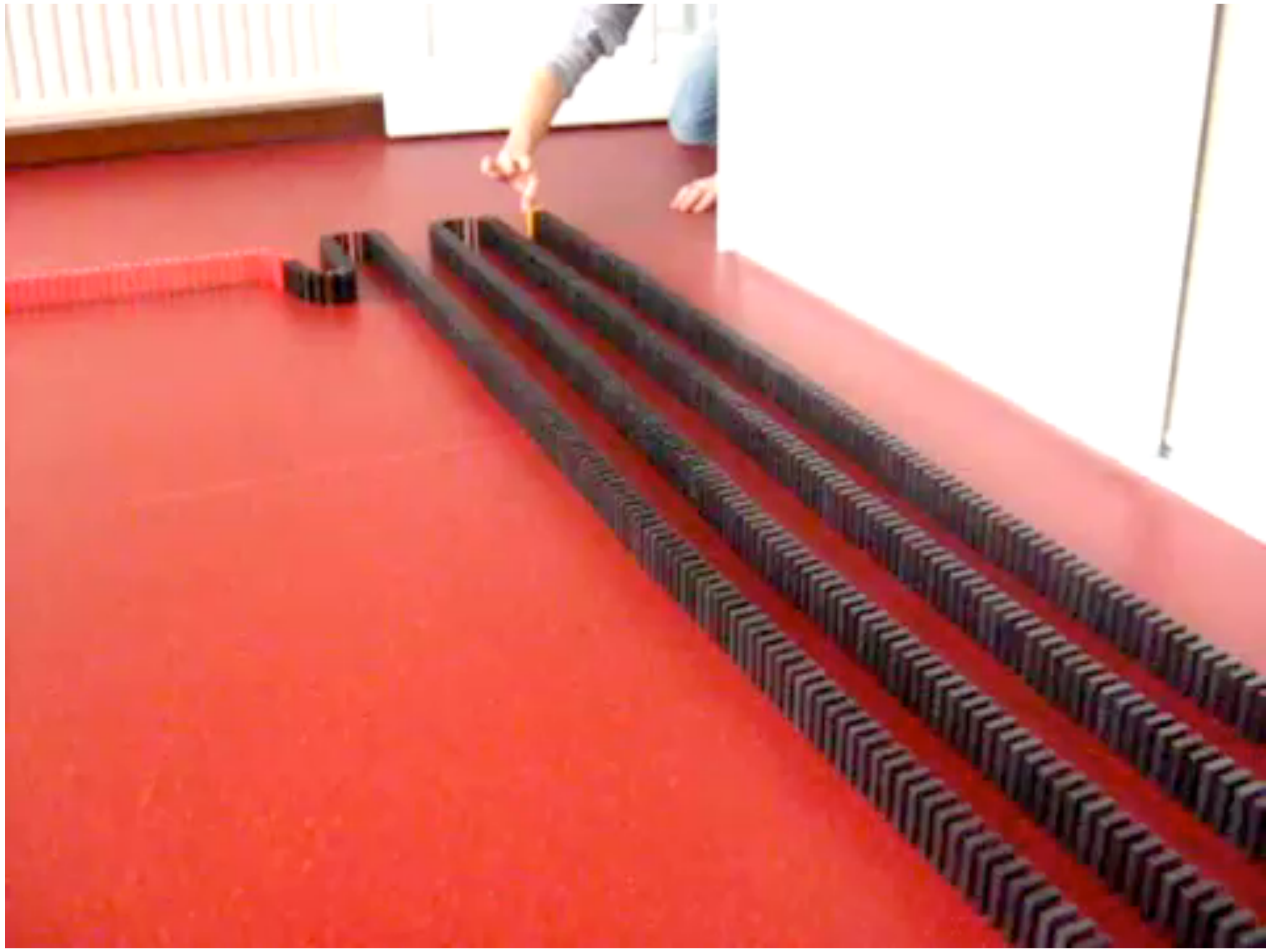

careful domino *alignment*

The importance of up-type FCNC

What if down/lepton alignment is at work ?

The importance of up-type FCNC

What if down/lepton alignment is at work ?

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	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		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}
$(\bar{t}_L\gamma^\mu u_L)^2$					same sign t's
$\bar{L}_i\sigma^{\mu\nu}e_{Rj}HF_{\mu\nu}$	1.7×10^4				$Br\,(\mu\to e\gamma)$
	3.3×10^2				$Br\,(\tau\to\mu\gamma)$
	2.6×10^2				$Br\,(\tau\to e\gamma)$
$(\bar{\mu}\gamma^\mu P_L e)\,(\bar{u}\gamma_\mu P_L u)$	1.9×10^2				$\frac{\sigma(\mu^- Ti\to e^- Ti)}{\sigma(\mu^- Ti\to capture)}$

The importance of up-type FCNC

What if down/lepton alignment is at work ?

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$\bar{L}_i\sigma^{\mu\nu} e_{Rj} H F_{\mu\nu}$	1.7×10^4				$Br\,(\mu\to e\gamma)$
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$(\bar c_R u_L)(\bar c_L u_R)$	[illegible]	[illegible]	[illegible]	[illegible]	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar b_L \gamma^\mu d_L)^2$	[illegible]	[illegible]	[illegible]	[illegible]	Δm_{B_d}; $S_{\psi K_S}$
$(\bar b_R d_L)(\bar b_L d_R)$	[illegible]	[illegible]	[illegible]	[illegible]	Δm_{B_d}; $S_{\psi K_S}$
$(\bar b_L \gamma^\mu s_L)^2$	[illegible]		[illegible]		Δm_{B_s}
$(\bar b_R s_L)(\bar b_L s_R)$	[illegible]		1.3×10^{-5}		Δm_{B_s}
$(\bar t_L \gamma^\mu u_L)^2$					same sign t's

uFCNC remove immunities

$\bar L_i \sigma^{\mu\nu} e_{Rj} H F_{\mu\nu}$	1.7×10^4 3.3×10^2 2.6×10^2			$Br(\mu \to e\gamma)$ $Br(\tau \to \mu\gamma)$ $Br(\tau \to e\gamma)$
$(\bar\mu \gamma^\mu P_L e)(\bar u \gamma_\mu P_L u)$	1.9×10^2			$\frac{\sigma(\mu^- Ti \to e^- Ti)}{\sigma(\mu^- Ti \to capture)}$

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

Two generation covariance description (crash course)

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

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

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

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

Space can be span via the SM Yukawas (useful for CPV, see later):

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

(RH up/down lavor violation can be removed via aligment with the signle up/down SM Yukawa)

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

Two generation covariance description (crash course)

Use EFT to describe flavor violation:

$$K-\bar{K} \text{ mixing: } \frac{1}{\Lambda_{NP}^2}\left(\bar{d}_L\gamma_\mu s_L\right)^2$$

$$D-\bar{D} \text{ mixing: } \frac{1}{\Lambda_{NP}^2}\left(\bar{u}_L\gamma_\mu c_L\right)^2$$

Assuming $SU(2)_L$:

$$\frac{1}{\Lambda_{\rm NP}^2}(\overline{Q_{Li}}(X_Q)_{ij}\gamma_\mu Q_{Lj})(\overline{Q_{Li}}(X_Q)_{ij}\gamma^\mu Q_{Lj}),$$

$$Q_{L_i}=(u_L,d_L)_i\,,\quad i,j\in 1,2\,.$$

Two generation covariance crash course, cont'

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

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

Two generation covariance crash course, cont'

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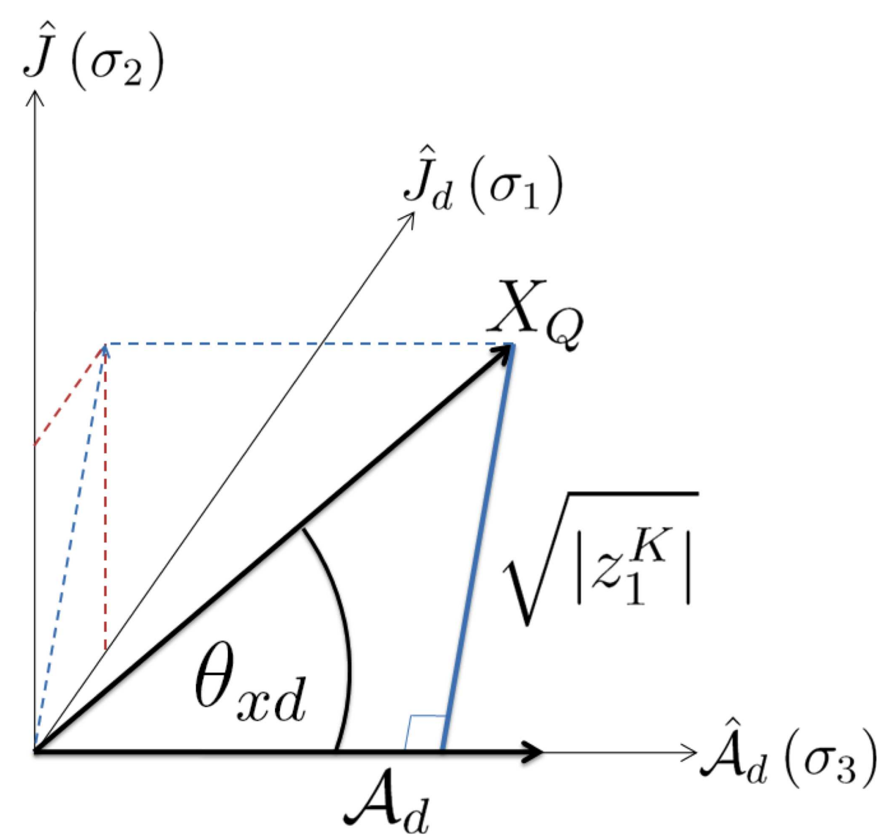
X_Q is a vector in this space:

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



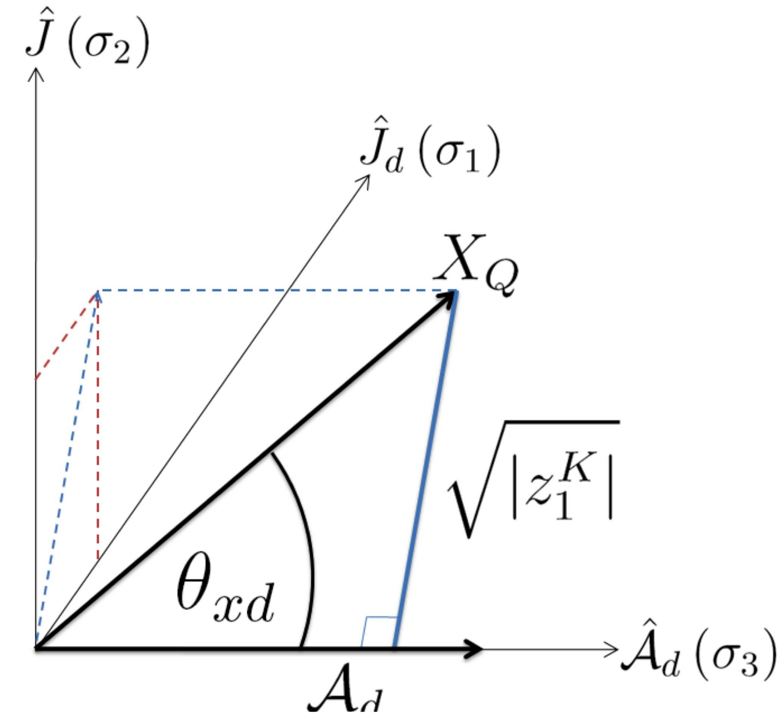
: The contribution of X_Q to $K^0 - \overline{K^0}$ mixing, Δm_K, given by the solid blue line. In the down mass basis, $\hat{\mathcal{A}}_d$ corresponds to σ_3, $\hat{J}$ is σ_2 and $\hat{J}_d$ is σ_1.

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: $J = \mathrm{Tr}\left\{X\left[Y_D Y_D^\dagger, Y_U Y_U^\dagger\right]\right\}$

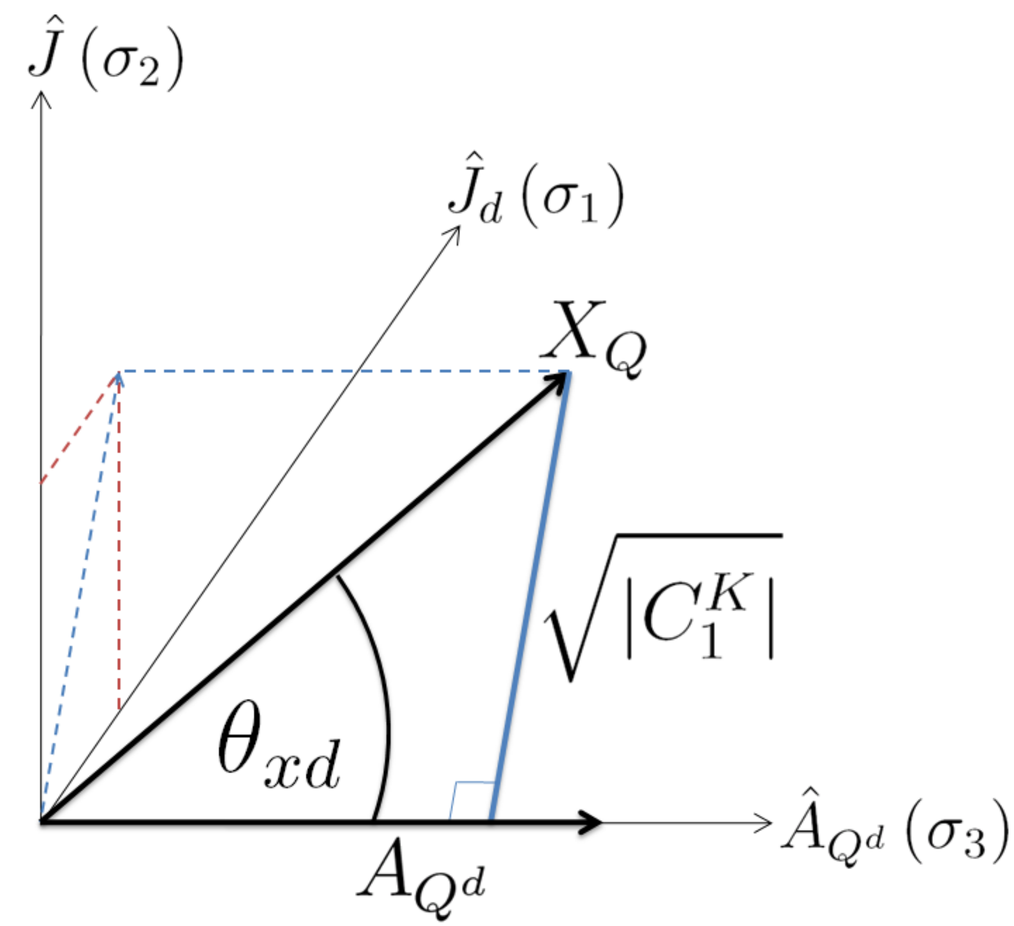
Projection of X_Q onto $\hat{J}$ is measuring the physical CPV phase.



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

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

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

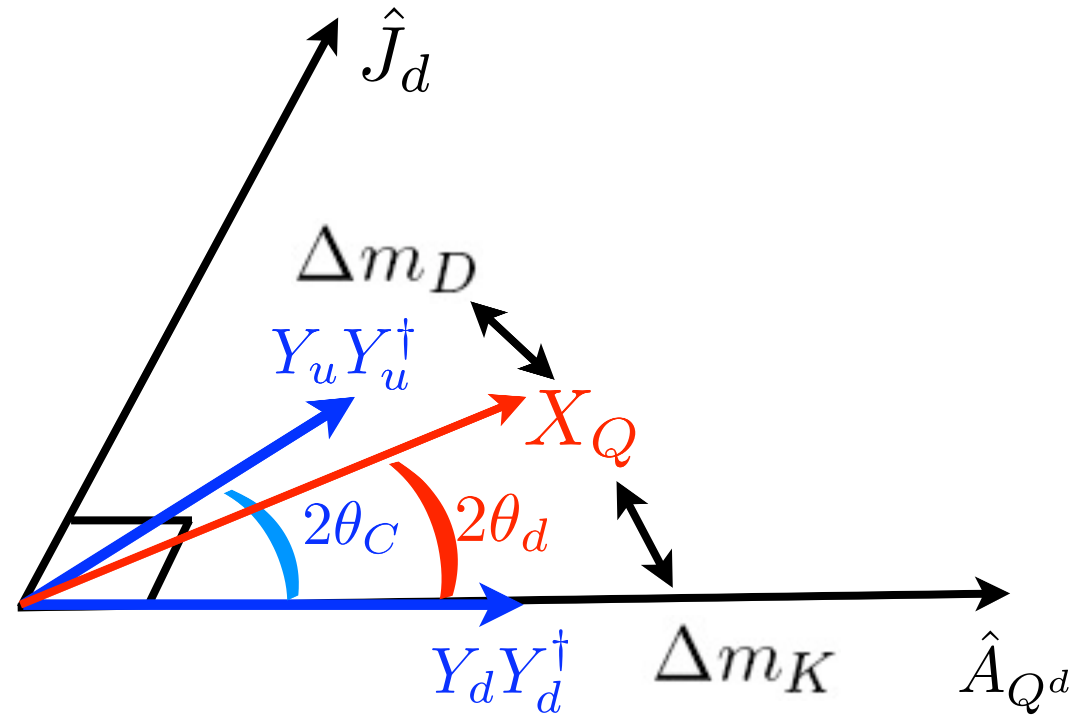


$$\mathrm{Im}\left(C_1^{K,D}\right) = 2\left(X_Q \cdot \hat{J}\right)\left(X_Q \cdot \hat{J}_{u,d}\right) \ .$$

Finding the weakest robust bound, no CPV

$$C_1^K = L^2\left[\left(X^J\right)^2 + \left(X^{J_d}\right)^2\right],$$

$$C_1^D = \frac{L^2}{2}\left[2\left(X^J\right)^2 + \left(X^d\right)^2 + \left(X^{J_d}\right)^2 + \left(\left(X^{J_d}\right)^2 - \left(X^d\right)^2\right)\cos(4\theta_\mathrm{C}) + 2X^d X^{J_d}\sin(4\theta_\mathrm{C})\right].$$



In order to minimize both contributions, we first need to set $X^J = 0$. Next we define

$$\tan\alpha \equiv \frac{X^{J_d}}{X^d}, \qquad r_{KD} \equiv \sqrt{\frac{\left(C_1^K\right)_\mathrm{exp}}{\left(C_1^D\right)_\mathrm{exp}}},$$

Finding the weakest robust bound, no CPV

Then the weakest bound is obtained for

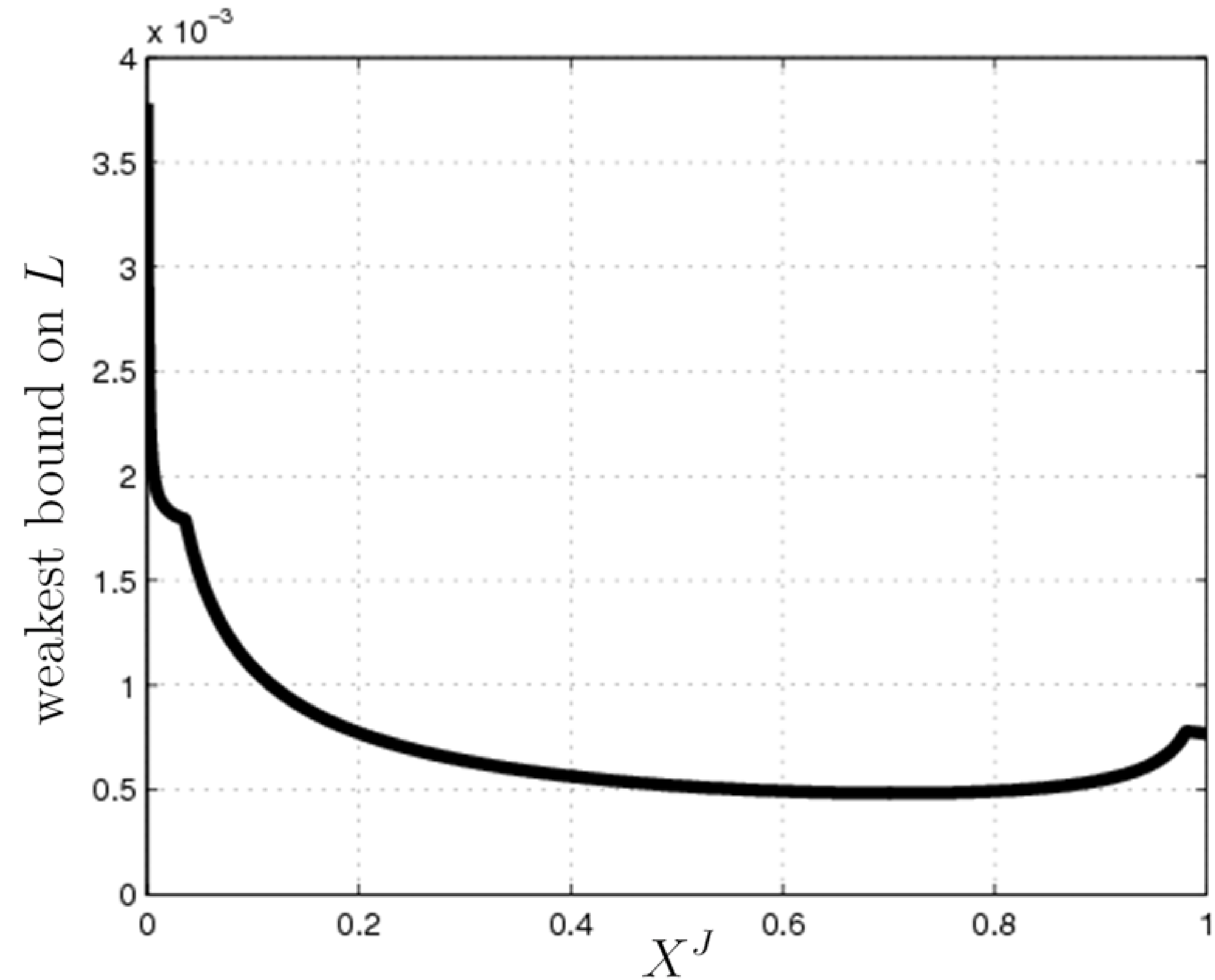
$$\tan\alpha = \frac{r_{KD}\sin(2\theta_{\rm C})}{1 + r_{KD}\cos(2\theta_{\rm C})}\,,$$

and is given by

$$L \le 3.8 \times 10^{-3}\left(\frac{\Lambda_{\rm NP}}{1\,{\rm TeV}}\right)\,.$$

Finding the weakest robust bound, with CPV

$$L \leq \frac{3.4 \times 10^{-4}}{\left[(X^J)^2 - (X^J)^4\right]^{1/4}} \left(\frac{\Lambda_{\rm NP}}{1\,{\rm TeV}}\right)$$



Blum, Grossman, Nir & GP (09)
Gedalia, Mannelli & GP (11)

The weakest upper bound on L coming from flavor and CPV in the K and D systems, as a function of the CP violating parameter X^J, assuming $\Lambda_{\rm NP} = 1$ TeV.

SUSY implications, naively looks like alignment is dead!!

What is X_Q in the SUSY case?

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

(squark doublets, 1TeV)

K. Blum, Y. Grossman, Y. Nir and G. Perez, PRL (2009)

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

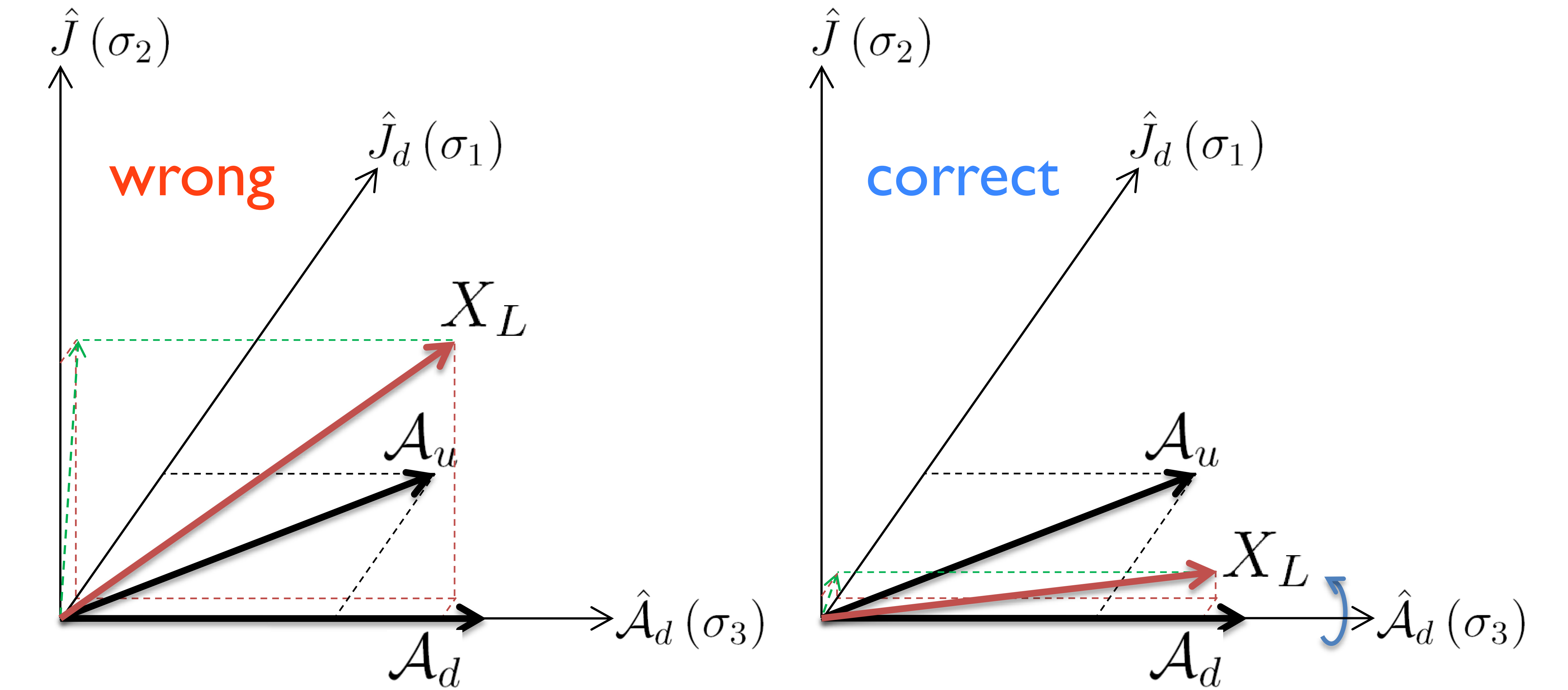
Looks like squark anarchy/alignment is dead!

However ...

How alignment models really work?

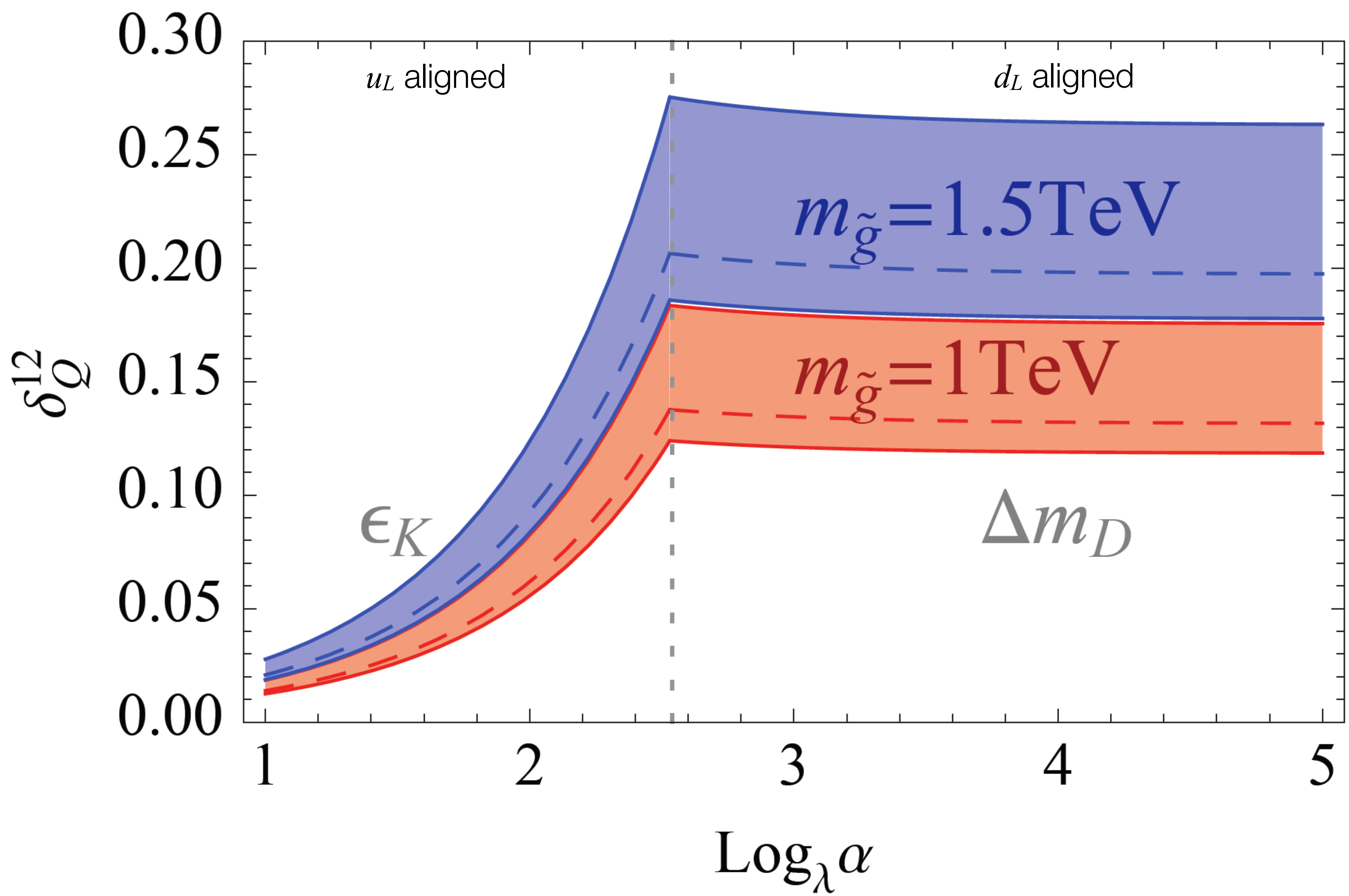
- Maximal phases => not correspond to an alignment model.
- Alignment makes both real and imaginary parts small.

$\hat{J}$ is universal (σ_2 is SO(2) invariant) $\Rightarrow$ small physical phase!



Degeneracy of Squarks

Gedalia, Kamenik, Ligeti & GP (12)



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

The bound on δ_Q^{12} as a function of the angle α (see text). The angle α is plotted on a log scale in the basis $\lambda_C = 0.23$, so that a value of 1 on the x axis corresponds to $\alpha = \lambda_C$ (large angle), while a value of 5 gives $\alpha = \lambda_C^5$ (small angle — down alignment). The vertical doted line shows the angle of optimal alignment (weakest bound). The red (blue) shaded region corresponds to a gluino mass $m_{\tilde{g}}$ of 1 (1.5) TeV, and inside each region the average squark mass $\bar{m}_{\tilde{Q}}$ is varied in the range $[0.8\, m_{\tilde{g}},\, 1.2\, m_{\tilde{g}}]$. The upper edge of each region (weakest bound) comes from the lowest $\bar{m}_{\tilde{Q}}$. The two dashed lines correspond to $\bar{m}_{\tilde{Q}} = m_{\tilde{g}}$.

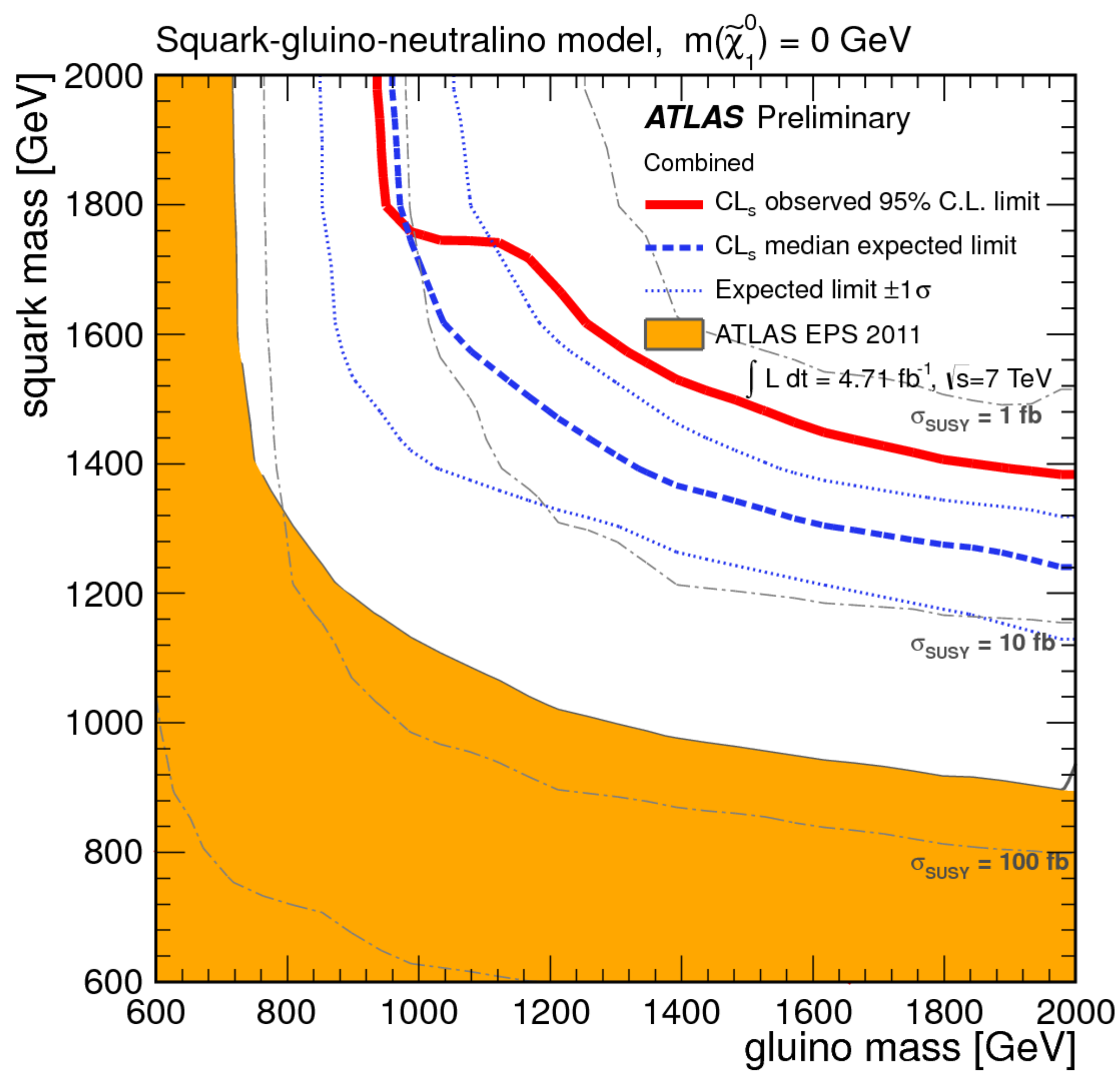
(non) Degeneracy of Squarks

- No strong degeneracy required!
- Ex.: $m_{\tilde{g}}$=1.3 TeV, $m_{\tilde{Q}_1}$=550 GeV, $m_{\tilde{Q}_2}$=950 GeV
- This can be generated by*: Dine, Kagan & Samuel (90); Nir & Raz (02).
  - Anarchy at the SUSY breaking mediation scale
  - SUSY renormalization group flow to the TeV scale
  - Can lead to modest level of degeneracy

However is this consistence with the LHC data??

Mahbubani, Papucci, GP, Ruderman & Weiler, to appear.

$$m_{\tilde{g}} = 1.3\,\mathrm{TeV},\, m_{\tilde{Q}_1} = 550\,\mathrm{GeV},\, m_{\tilde{Q}_2} = 950\,\mathrm{GeV}$$



How do limits change?

Estimate:

$$\boxed{\sigma \sim \frac{1}{m_{\tilde{q}}^5}}$$

Decouple 6 dof:

$$\Rightarrow \frac{\Delta m_{\max}}{m_{\max}} = 1 - 4^{-\frac{1}{5}} \sim 25\%$$

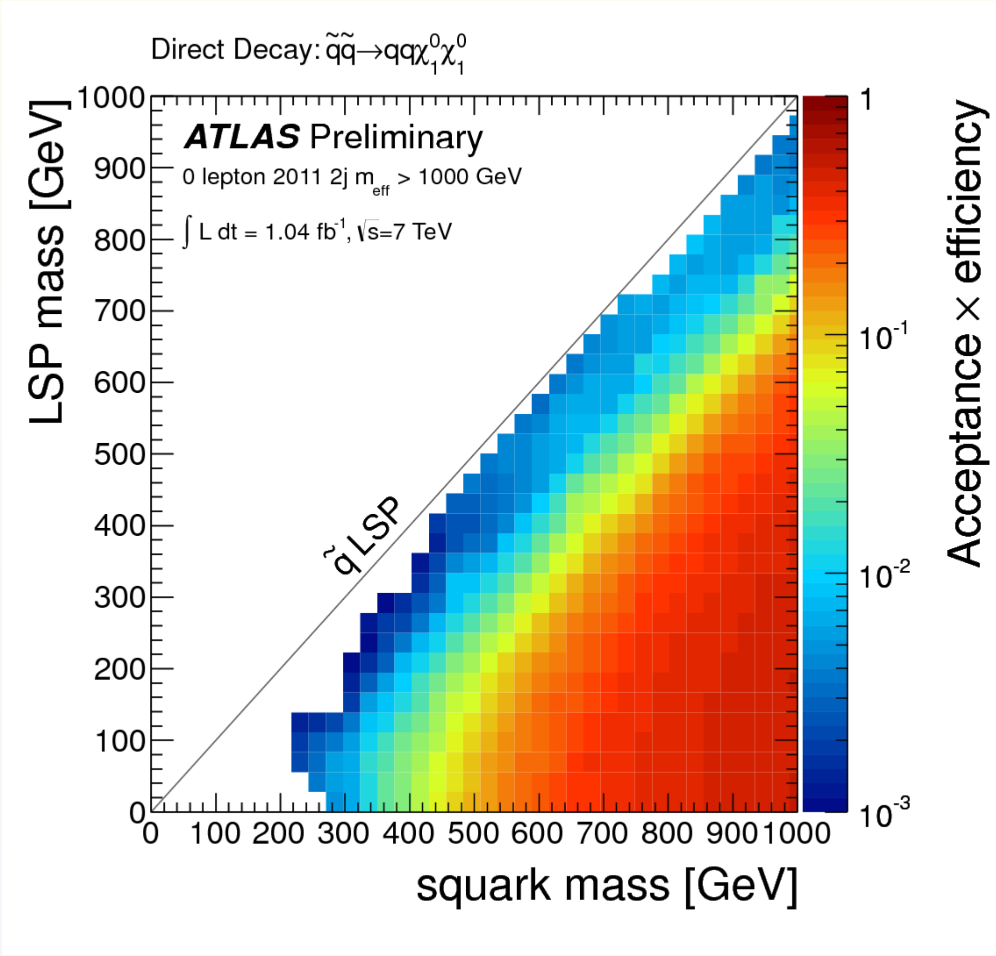
TOO NAIVE!

Limits affected by:

- squark multiplicity
- signal efficiencies
- PDFs

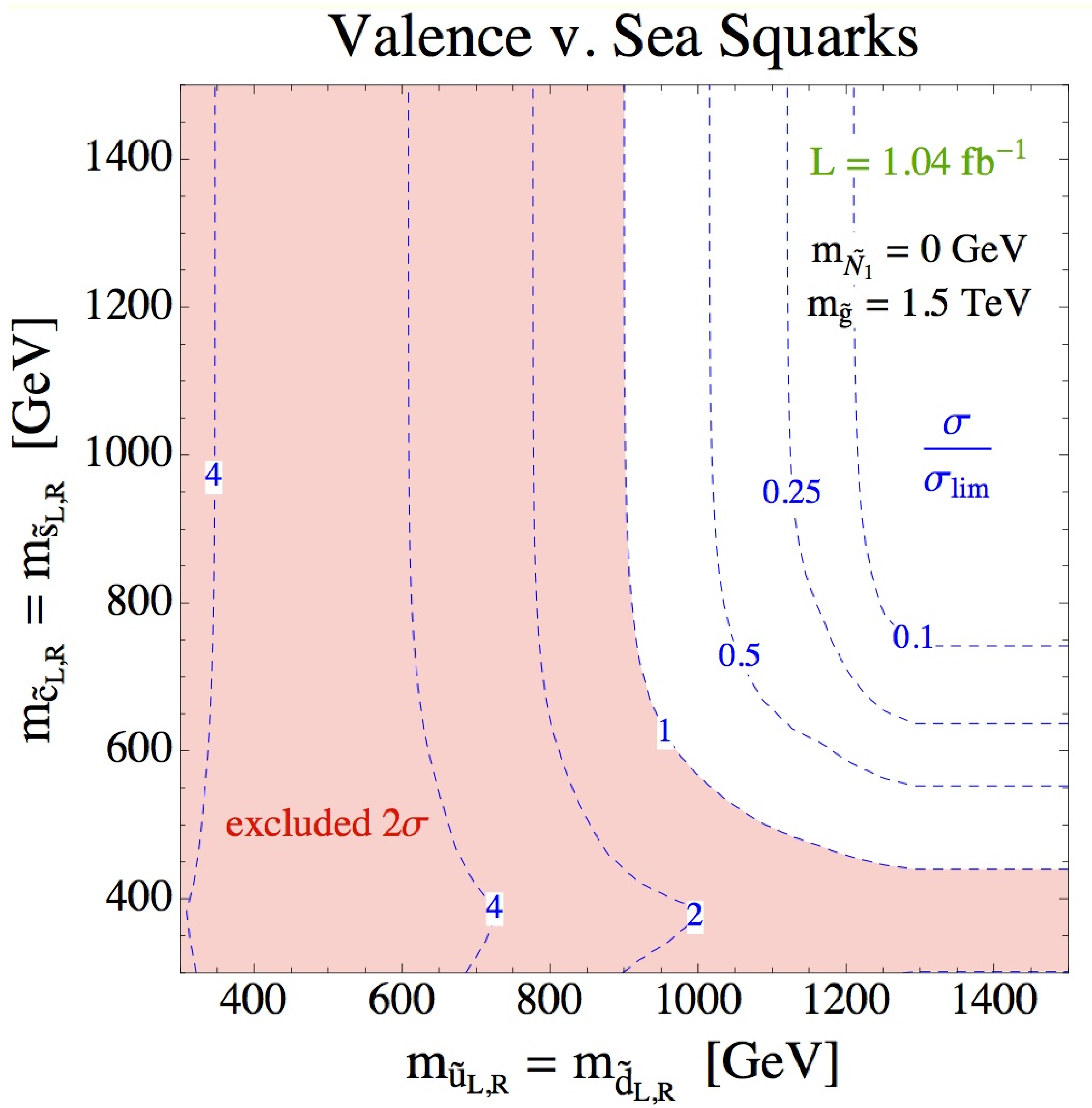
Efficiencies

Signal efficiency falls very rapidly with decreasing squark mass



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

In fact, all 4 flavor “sea” squarks can be light!



Mahbubani, Papucci, GP, Ruderman & Weiler, to appear.

Summary

- Probing up sector is invaluable => era of precision u-data.

- Down alignment (& up anarchy?) is consistent & simple possibility (simple SUSY breaking models?).

- Despite lore very light squarks are consistent data (regardless of alignment).

The U(2)/MFV limit