FLAVOR PHYSICS BEYOND THE STANDARD MODEL

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STANDARD MODEL LAGRANGIAN

- Particle physics interactions are described with high accuracy by a simple & economic theory:

$$\mathcal{L}_{\mathrm{SM}} = \mathcal{L}_{\mathrm{gauge}}(A^a, \psi^i) + \mathcal{L}_{\mathrm{Higgs}}(\phi, A^a, \psi^i)$$

$\mathcal{L}_{\mathrm{gauge}}$:

- Natural
- Experimentally tested with great precision
- Stable with respect to quantum corrections
- Highly symmetric (gauge & flavor symmetries)

$\mathcal{L}_{\mathrm{Higgs}}$:

- Ad hoc
- Necessary to describe data (clear indication of broken symmetry) but poorly tested in its dynamical form
- Not stable under radiative corrections
- Determines the flavor structure of the Standard Model (SM)

BEYOND THE SM LAGRANGIAN

- Accumulating evidence, however suggests that SM is not a complete, but merely low-energy limit of a more fundamental theory:

$$\mathcal{L}_{\text{full}} = \mathcal{L}_{\text{gauge}}(A^a, \psi^i) + \mathcal{L}_{\text{Higgs}}(\phi, A^a, \psi^i) + \mathcal{L}_{\text{heavy}}$$

  - New heavy degrees of freedom (dofs) that stabilize the symmetry breaking sector & approximately respect SM symmetries

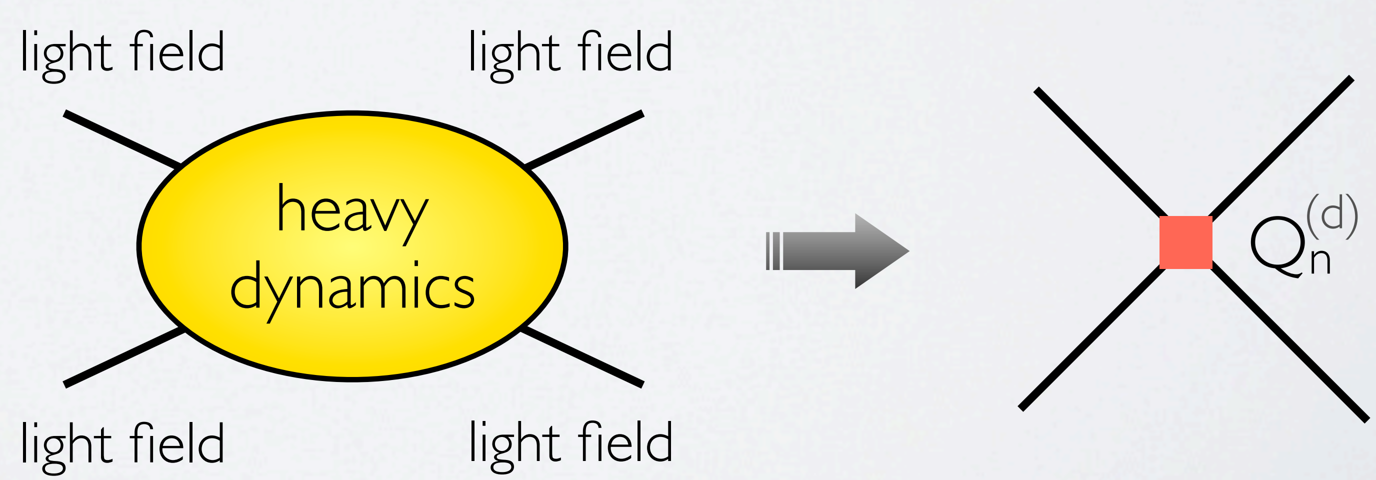
- A plethora of explicit models of beyond the SM (BSM) physics exists (supersymmetric models, scenarios with a new strongly interacting sector, ...). Yet, as long as we are not able to directly produce dofs, a useful general description is obtained by integrating them out

EFFECTIVE BSM DESCRIPTION

- As long as we do not have enough energy to directly produce new dofs, we can effectively describe their interactions by:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} Q_n^{(d)}(\phi, A^a, \psi^i)$$

  - Renormalizable part of effective Lagrangian = all operators with dimension $d \leq 4$ that transform trivial under SM gauge group
  - Operators $Q_n^{(d)}$ with $d \geq 5$ build out of SM fields, that respect SM gauge symmetry & are suppressed by heavy mass scale Λ



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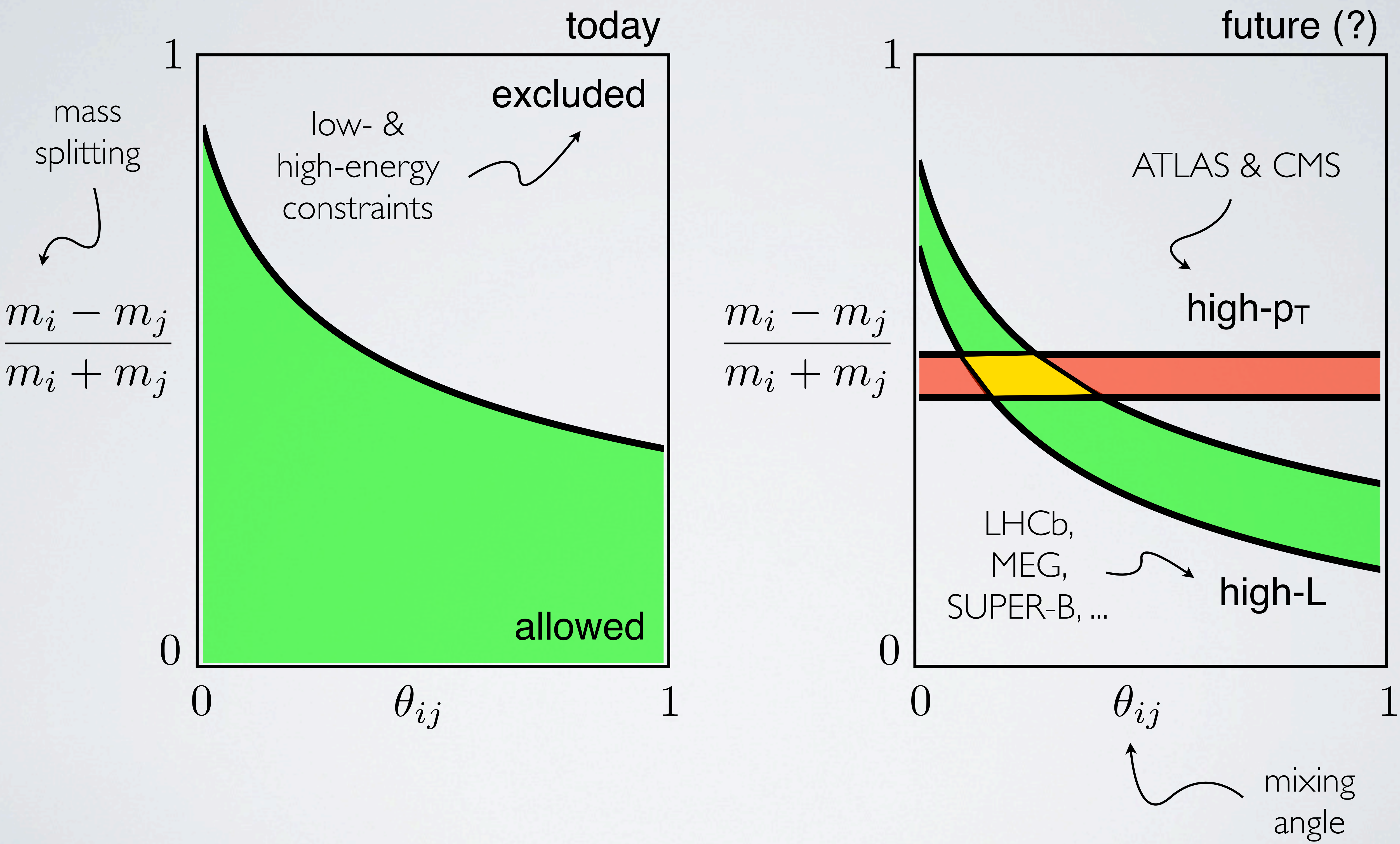
- New sources of flavor-symmetry breaking that we can only explore with low-energy experiments

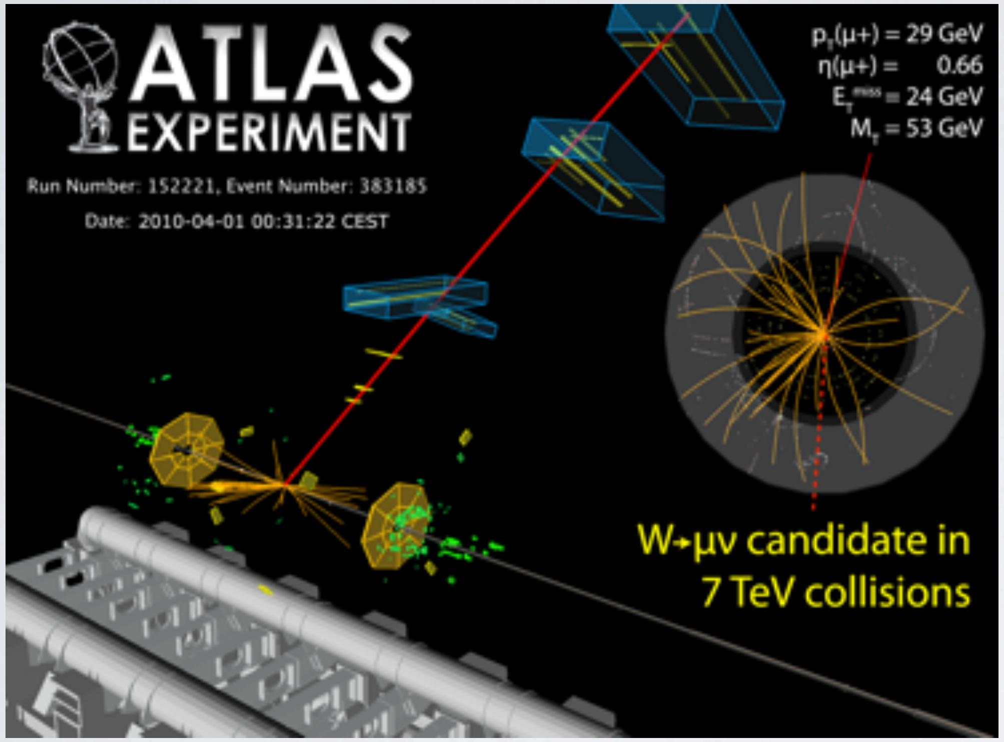
- Two key questions arise:
  - Which is the energy scale of new physics or how big is Λ? ➡ High-energy experiments [the high-energy frontier]
  - Which is the symmetry structure of new heavy dofs? ➡ Low-energy precision experiments [the high-intensity frontier]

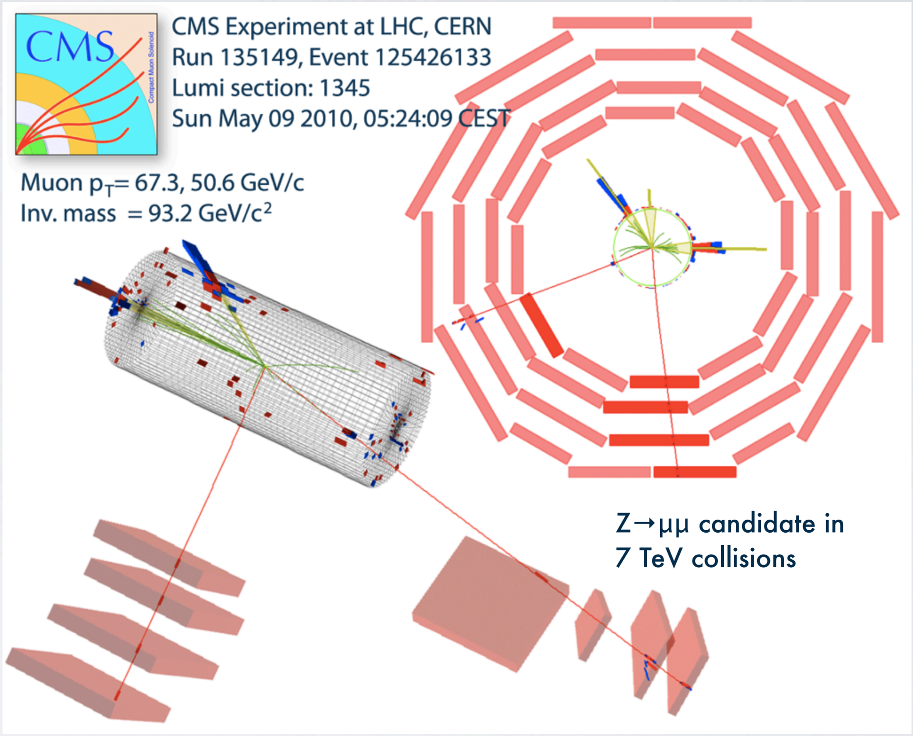
COMPLEMENTARITY & SYNERGY

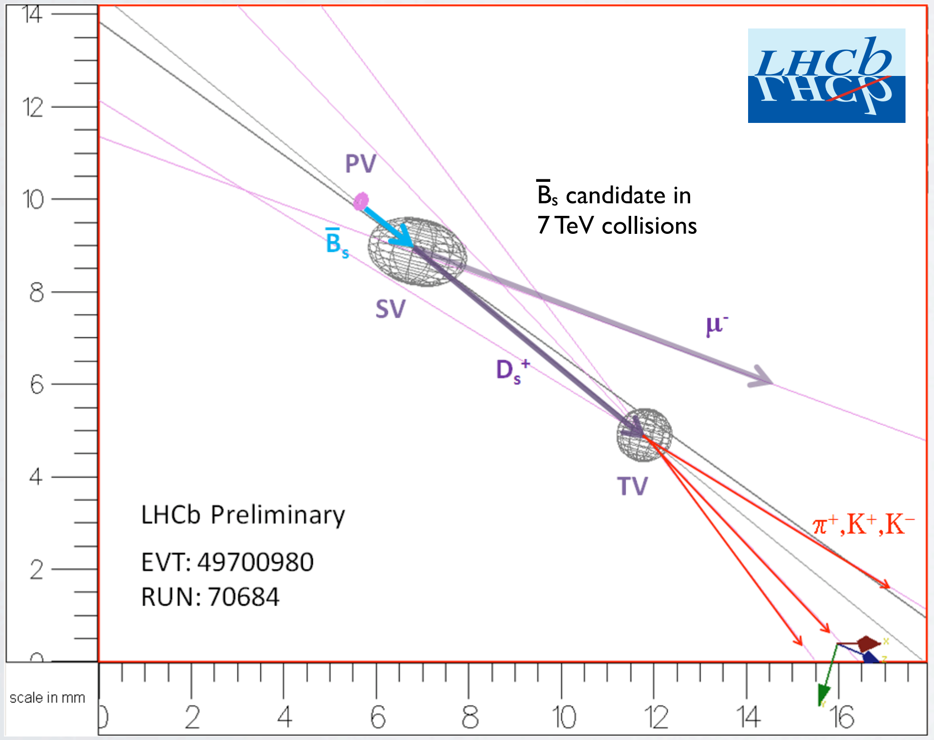


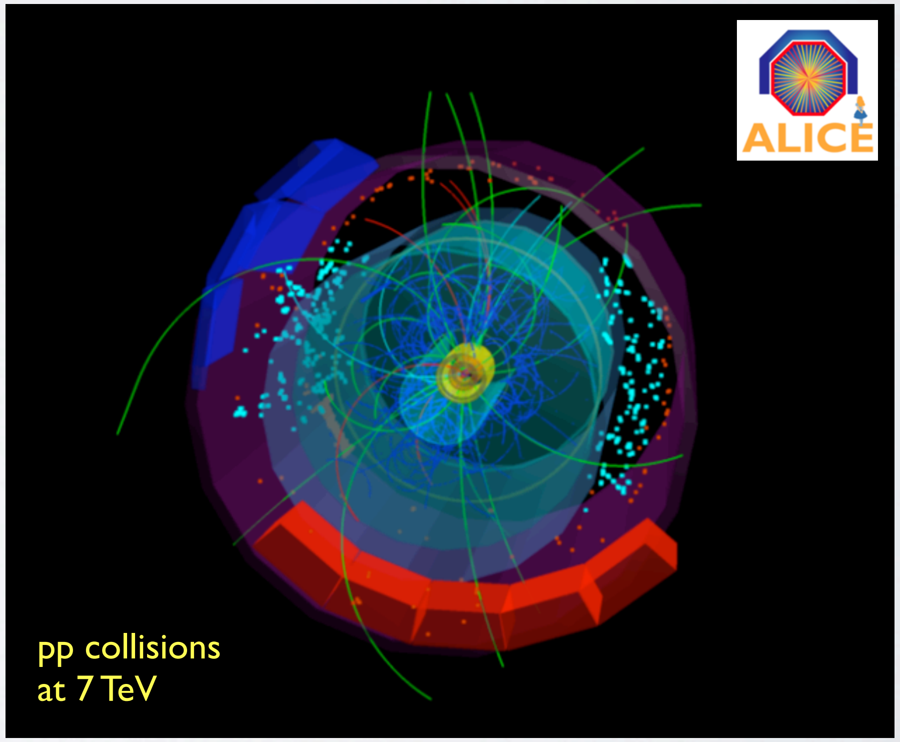
[plot inspired by Grossman, Ligeti & Nir, arXiv:0904.4262; Gedalia & Perez, arXiv:1005.3106]

LHC ALIVE

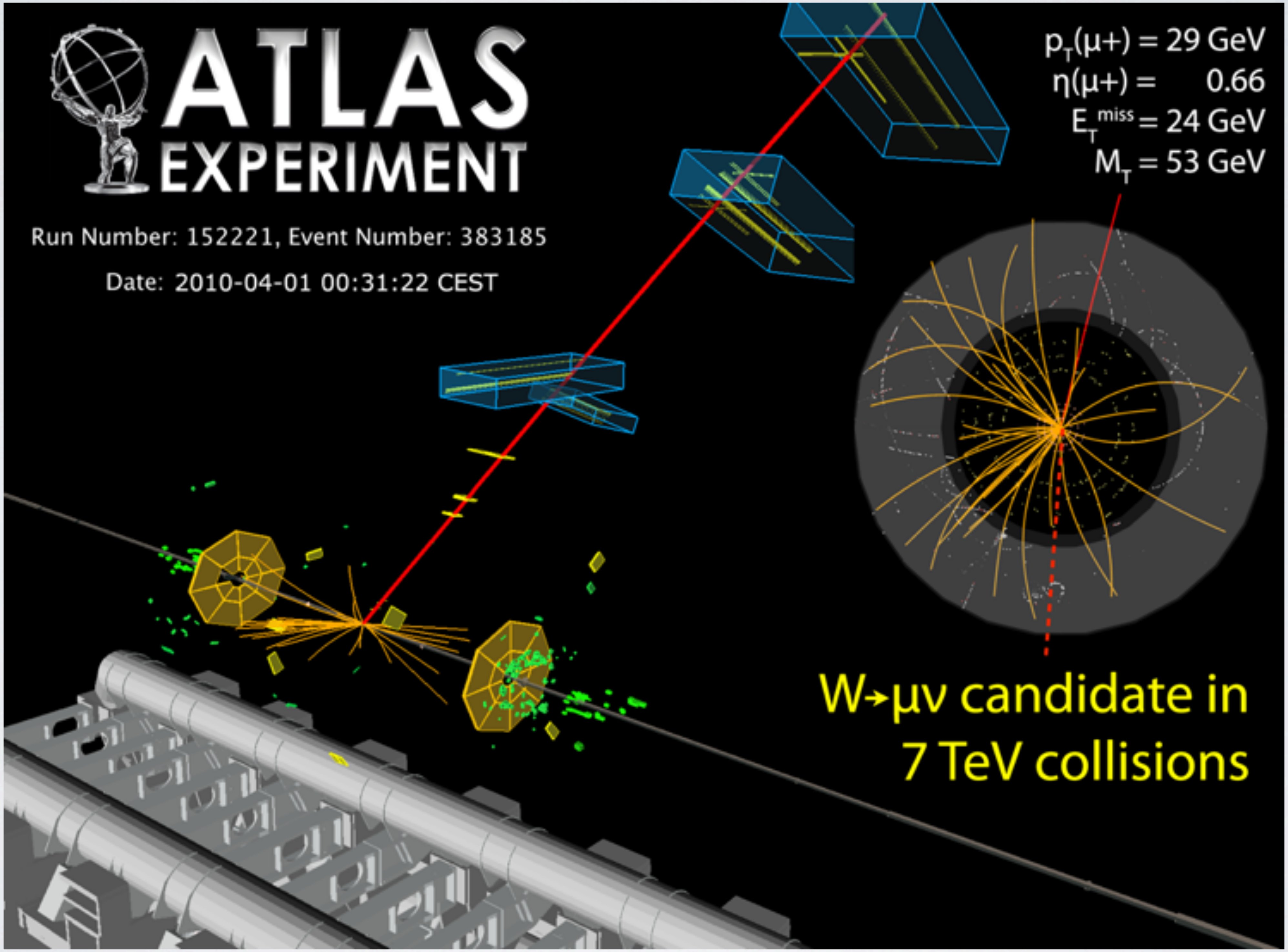

ATLAS EXPERIMENT
Run Number: 152221, Event Number: 383185
Date: 2010-04-01 00:31:22 CEST
$p_T(\mu+) = 29$ GeV
$\eta(\mu+) = 0.66$
$E_T^{miss} = 24$ GeV
$M_T = 53$ GeV
W→μν candidate in
7 TeV collisions


CMS
CMS Experiment at LHC, CERN
Run 135149, Event 125426133
Lumi section: 1345
Sun May 09 2010, 05:24:09 CEST
Muon p_T= 67.3, 50.6 GeV/c
Inv. mass = 93.2 GeV/c^2
Z→μμ candidate in
7 TeV collisions


LHCb
PV
$\overline{B}_s$
SV
D_s^+
μ^-
TV
π^+, K^+, K^-
$\overline{B}_s$ candidate in
7 TeV collisions
LHCb Preliminary
EVT: 49700980
RUN: 70684
scale in mm


ALICE
pp collisions
at 7 TeV

LHC ALIVE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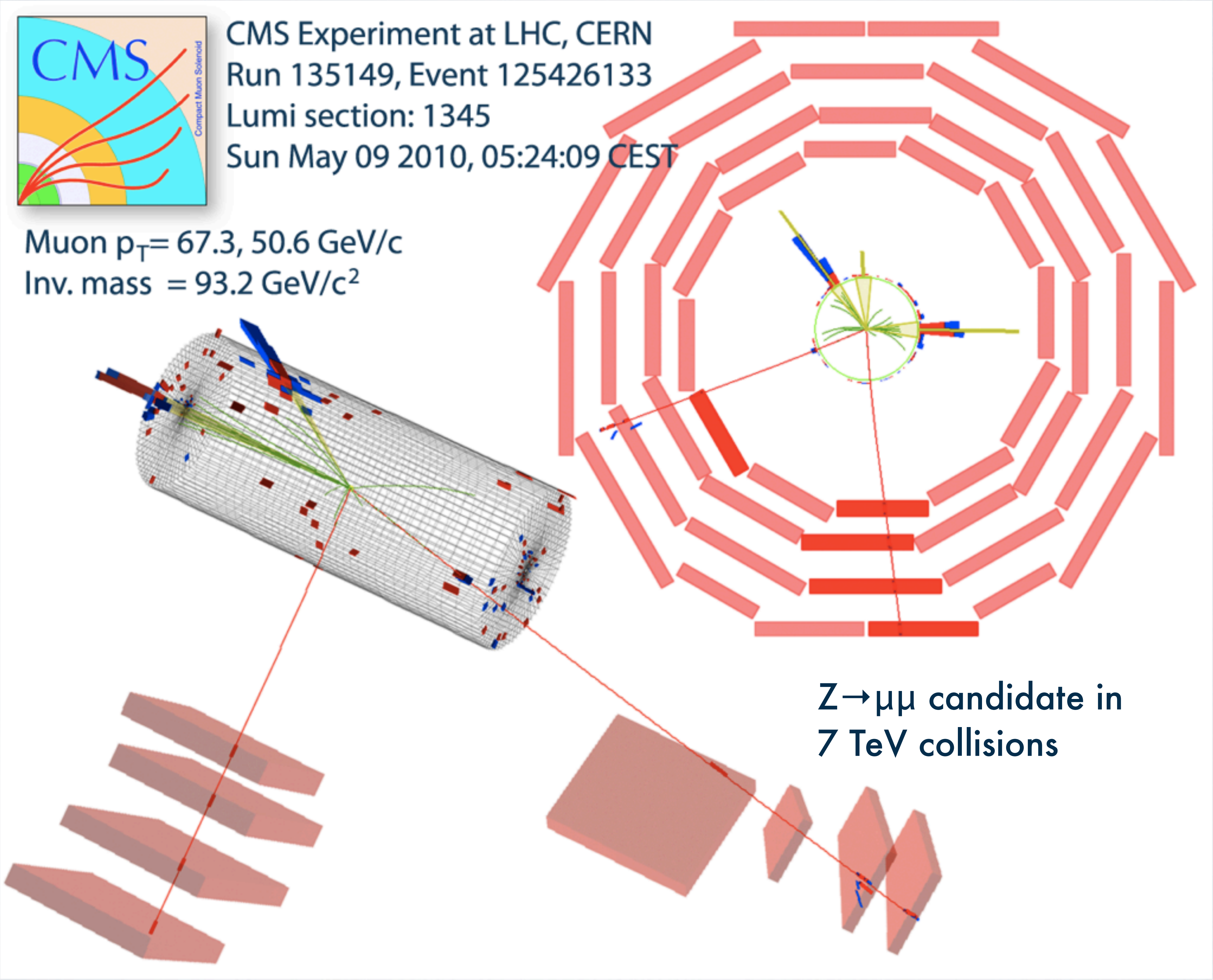

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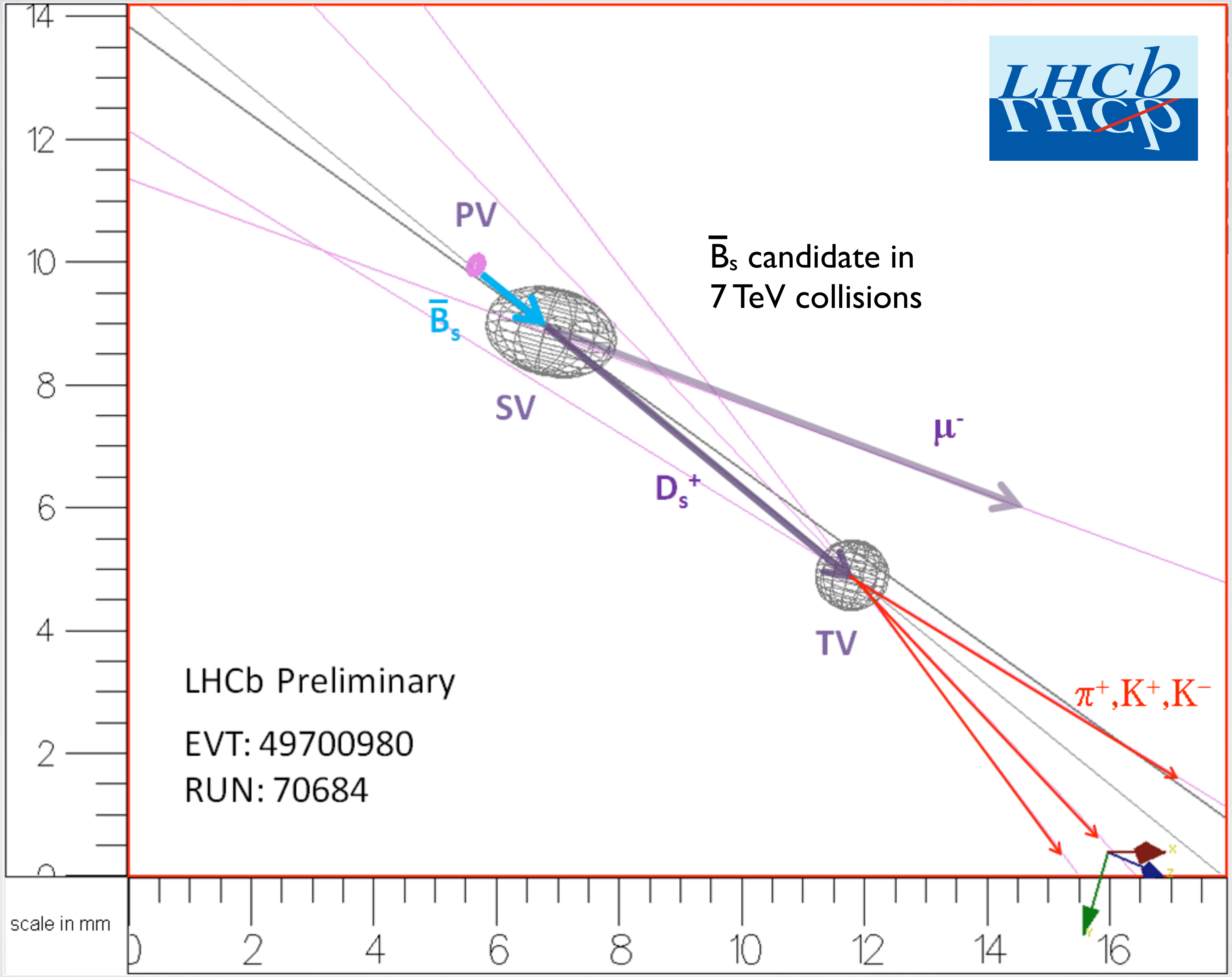

PV
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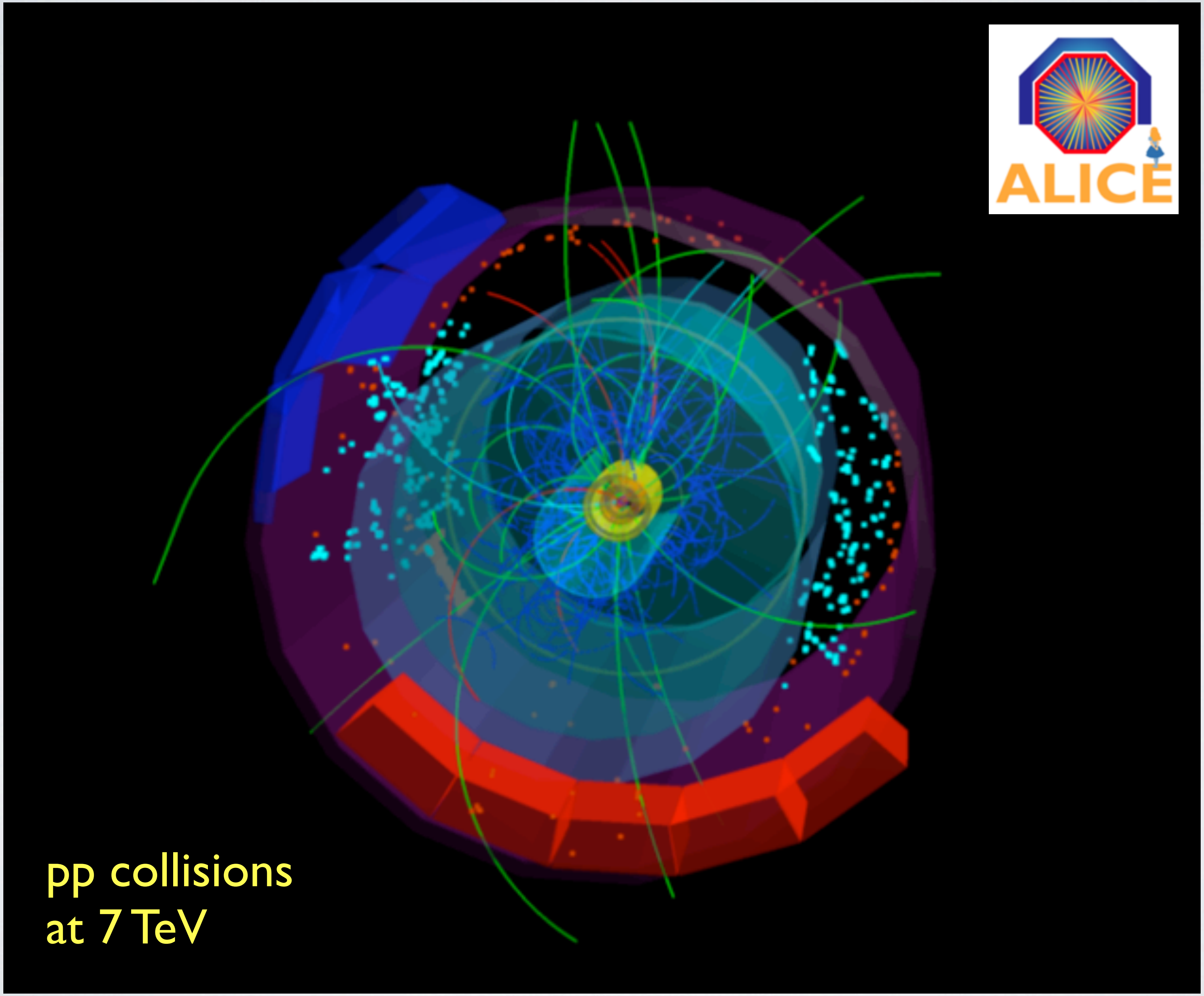
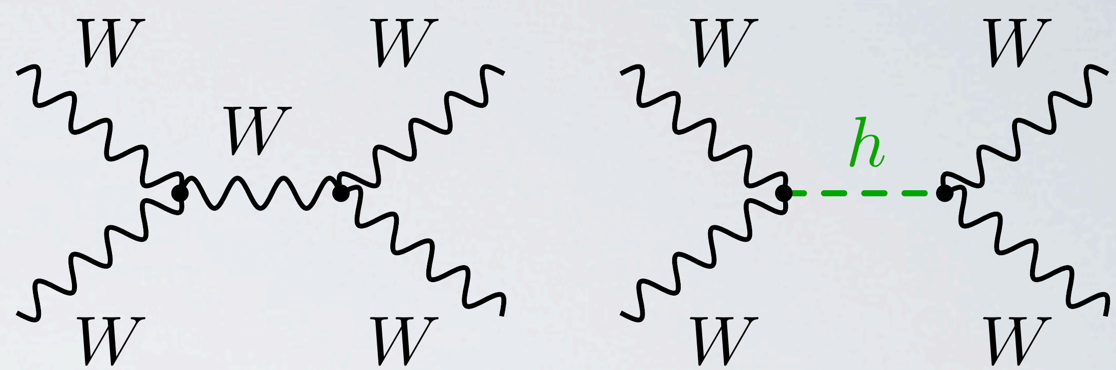


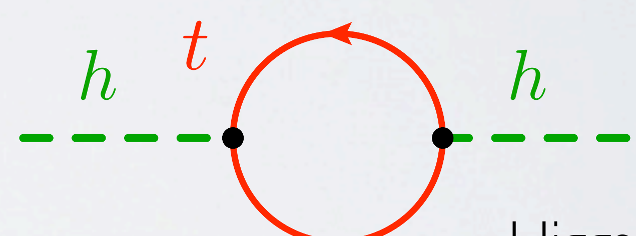
FLAVOR PHYSICS IN THE LHC ERA

- There are good reasons, based on the bad ultraviolet (UV) behavior of gauge-boson scattering amplitudes in combination with the UV sensitivity of the Higgs potential, to believe that new dofs appear below or around 1 TeV, the energy regime to be directly explored at the LHC

- Given the stringent constraints from low-energy experiments, can the mechanism that resolves this issues have a non-trivial flavor structure?



Higgs boson unitarizes WW scattering at high energies



Higgs-boson selfenergy

$$\delta M_h^2 = -\frac{4G_F}{\sqrt{2}}\, 12 m_t^2 \left(\frac{\Lambda}{4\pi}\right)^2$$

SM FLAVOR STRUCTURE

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm gauge}(A^a, \psi^i) + \mathcal{L}_{\rm Higgs}(\phi, A^a, \psi^i)$$

- 3 identical replica of the fermion multiplet ($\psi^i = Q_L, u_R, d_R, L_L, l_R$):

large global flavor symmetry

$$U(1)_B \times U(3)_Q \times U(3)_u \times U(3)_d \times \ldots$$

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- Flavor-degeneracy broken by the Yukawa interactions:

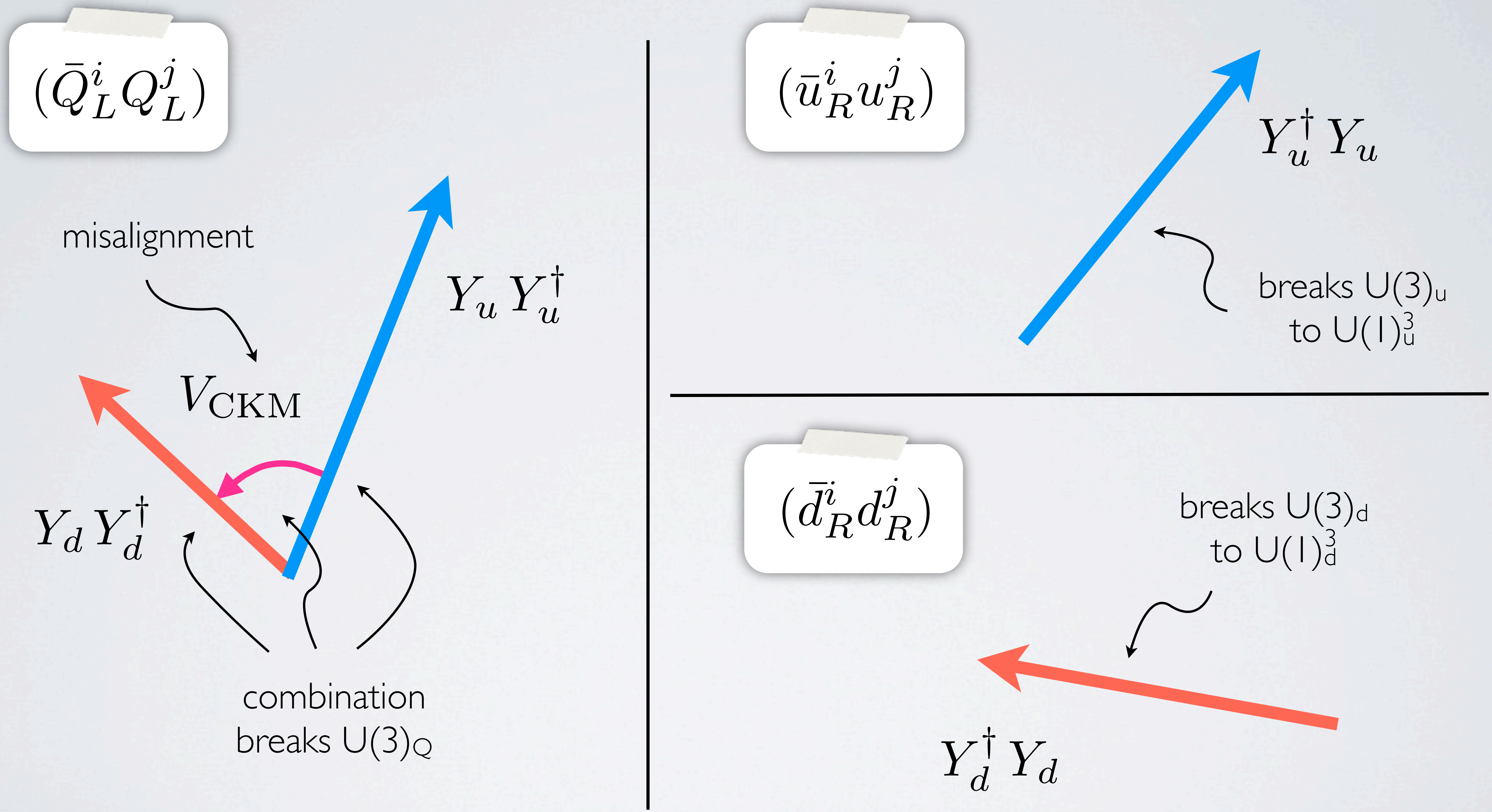
in the quark sector

$$\bar{Q}^i_L (Y_d)_{ij} d^j_R \phi \quad \rightarrow \quad \bar{Q}^i_L (M_d)_{ij} d^j_R$$

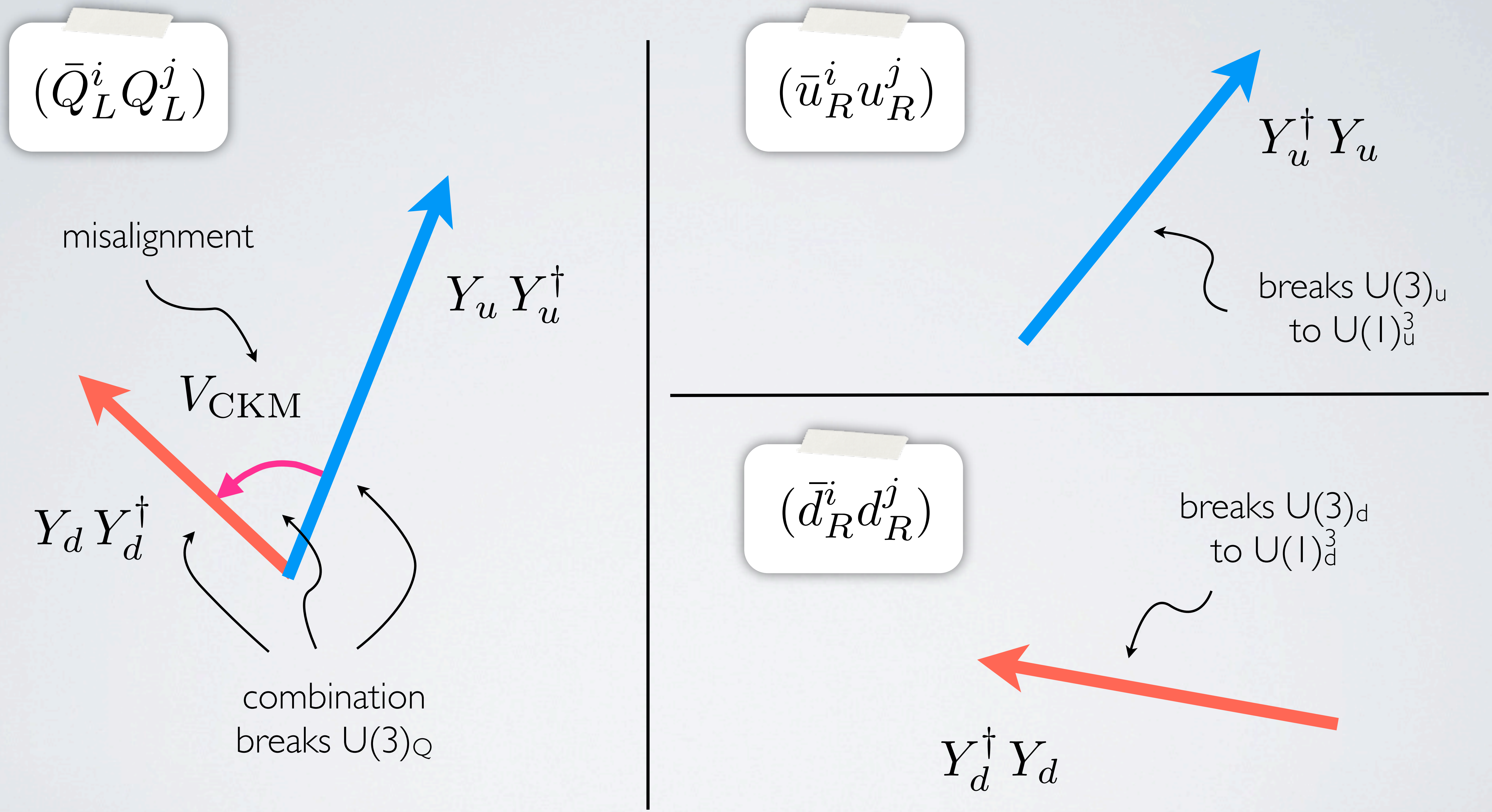
$$\bar{Q}^i_L (Y_u)_{ij} u^j_R \tilde{\phi} \quad \rightarrow \quad \bar{Q}^i_L (M_u)_{ij} u^j_R$$

$$M_d = \mathrm{diag}\,(m_d, m_s, m_b) \qquad M_u = V^\dagger_{\rm CKM}\, \mathrm{diag}\,(m_u, m_c, m_t)$$

U(3) FLAVOR PLANES



U(3) FLAVOR PLANES



Exercise 1: Derive the number of physical parameters in the quark sector of the SM using symmetry arguments

BSM FLAVOR STRUCTURE

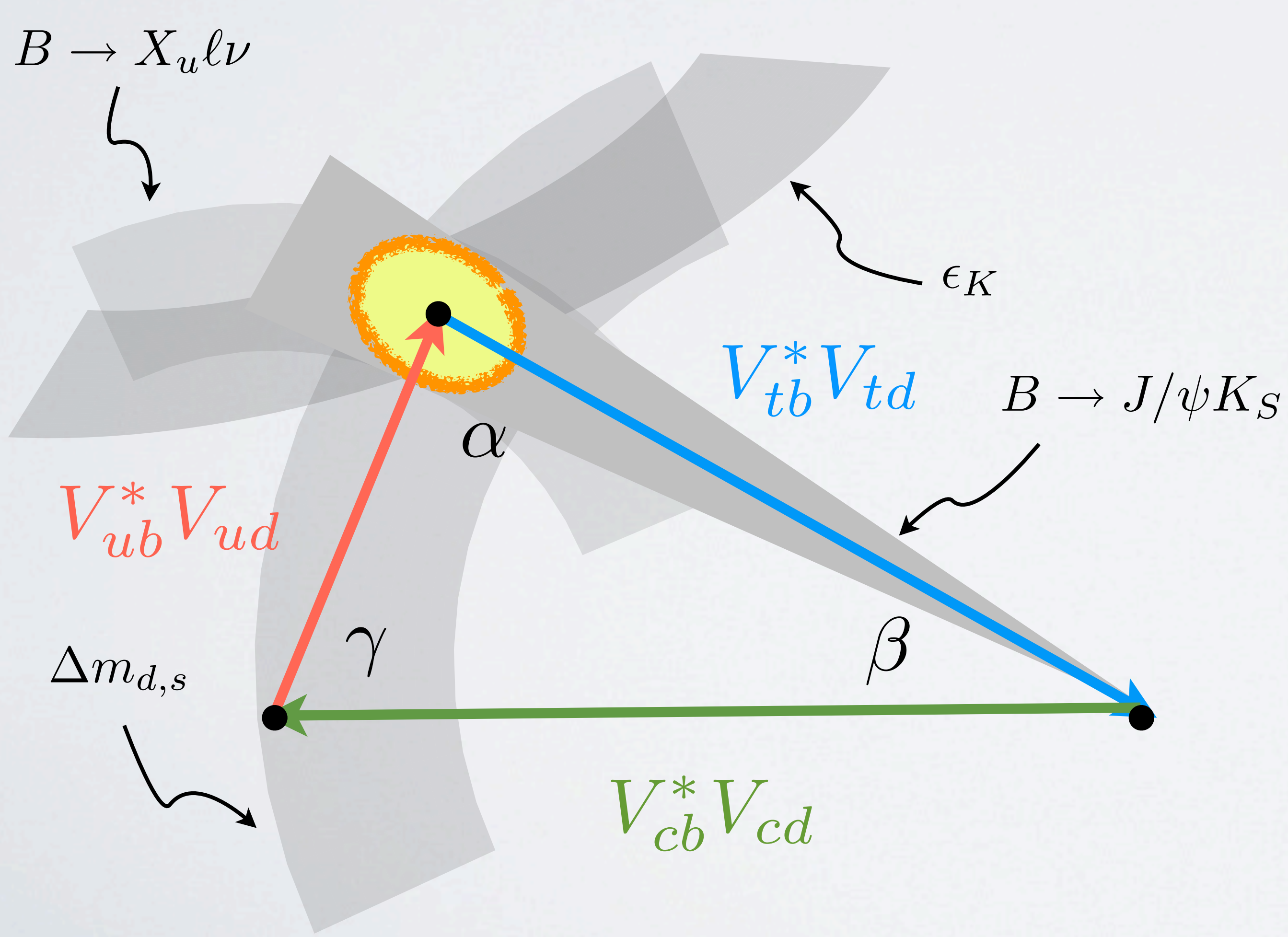
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm Higgs} + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} Q_n^{(d)}(\phi, A^a, \psi^i)$$

- As of today, we have not clearly identified the flavor structure of the new dofs (which we hope to discover at the LHC), but we know that additional sources of flavor breaking suppressed only by the TeV scale have to be non-generic, because ...

BSM FLAVOR STRUCTURE

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \sum_{d \geq 5} \frac{c_n}{\Lambda^{d-4}} Q_n^{(d)}(\phi, A^a, \psi^i)$$

i) Good overall consistency of the various experimental constraints appearing in the so-called unitarity triangle (UT) fits:



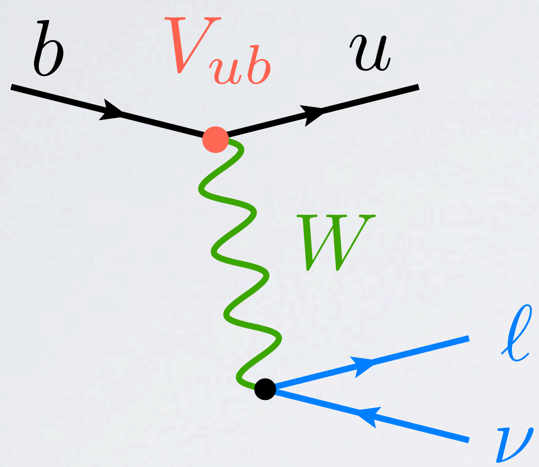
$$V_{\text{CKM}}^\dagger V_{\text{CKM}} = 1$$

⇓

$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

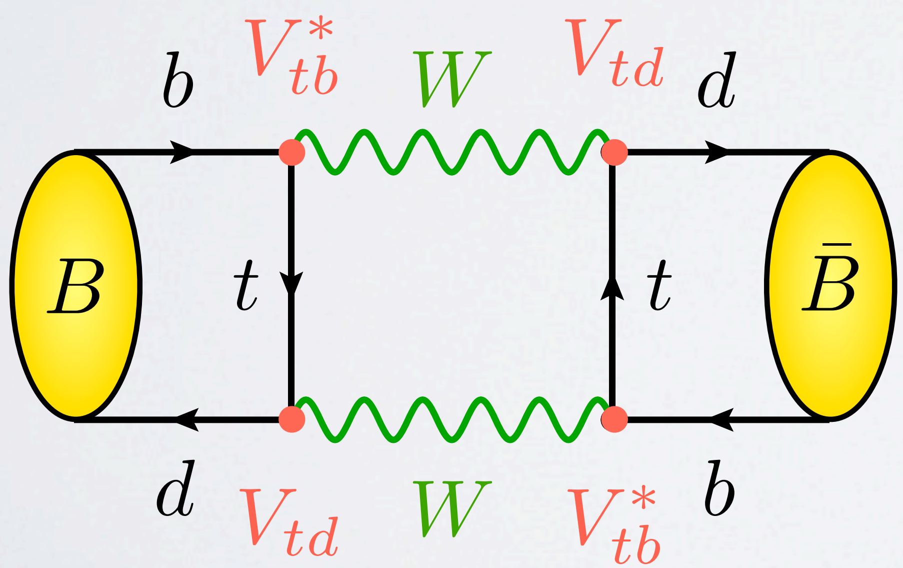
COMMENTS ON UT ANALYSES

- The most remarkable feature of the global CKM fits is the consistency between tree- ($\sin 2\beta, V_{xb}$) & loop-level ($\Delta m_{d,s}$, ε_K) constraints:



$$\frac{g^2}{M_W^2} V_{ub}$$

new physics has to be large to compete with SM

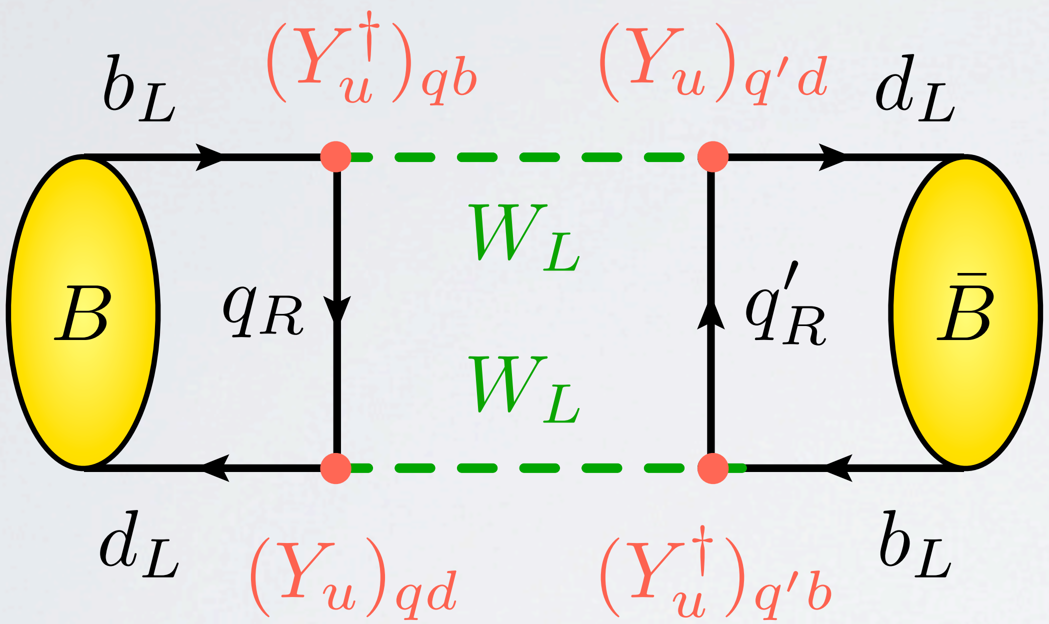


$$\frac{g^4 m_t^2}{16\pi^2 M_W^4} (V_{tb}^* V_{td})^2$$

loop- & CKM-suppressed & therefore potentially more sensitive to new physics

COMMENTS ON UT ANALYSES

- In fact, what we are testing in neutral meson-mixing amplitudes, as well as in other flavor-changing neutral currents (FCNCs), is the structure of the Yukawa interaction, beyond the tree level:



$$Y_u = V_{\rm CKM}^\dagger \, \mathrm{diag}\,(y_u, y_c, y_t)$$

$$\approx V_{\rm CKM}^\dagger \, \mathrm{diag}\,(0, 0, y_t)$$

$$\Rightarrow \quad \frac{y_t^4}{16\pi^2 m_t^2} \, (V_{tb}^* V_{td})^2 \propto \frac{g^4 m_t^2}{16\pi^2 M_W^4} \, (V_{tb}^* V_{td})^2$$

gaugeless limit reproduces leading term in heavy top-quark mass expansion of exact calculation

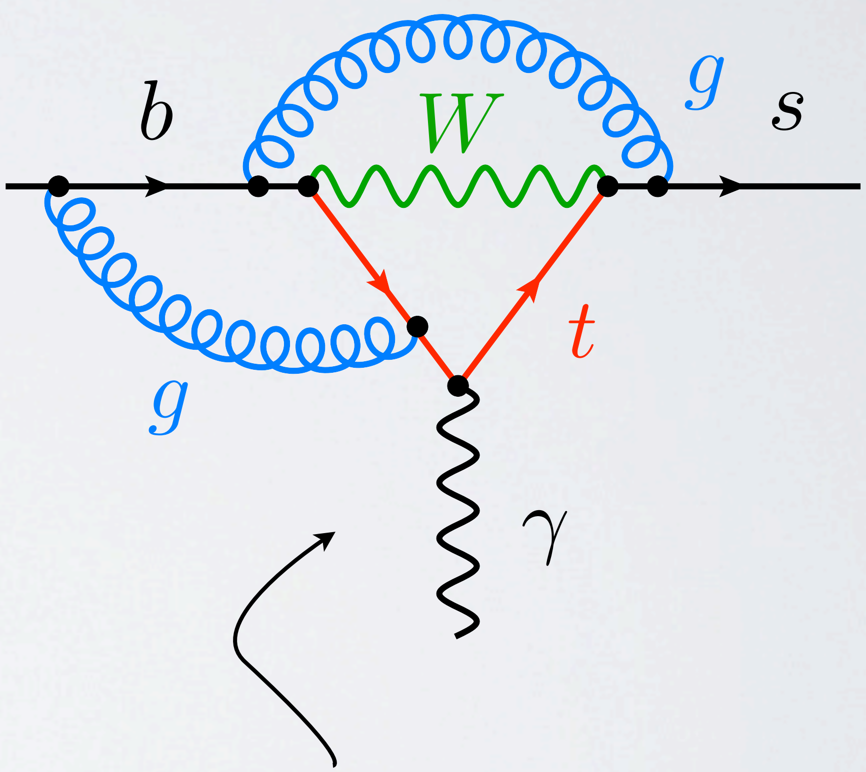
BSM FLAVOR STRUCTURE CONT'D

ii) Good agreement of rare and radiative FCNC decays with their SM expectations. Most remarkable example is inclusive B$\rightarrow X_s\gamma$ decay:

$$\mathcal{B}(B \to X_s\gamma)_{\rm SM}^{E_\gamma > 1.6\,{\rm GeV}} = (3.15 \pm 0.23) \cdot 10^{-4}$$

[Misiak *et al.*, hep-ph/0609232]

- Next-to-next-to-leading order (NNLO) calculation for the rate with cut on photon energy Eγ, including local and non-local power corrections, the later of which represent an irreducible (?) source of theory error at the level of 5%



one of the roughly 1000 3-loop diagrams needed to be computed to find O(α_s^2) matching condition for the electromagnetic dipole operator

BSM FLAVOR STRUCTURE CONT'D

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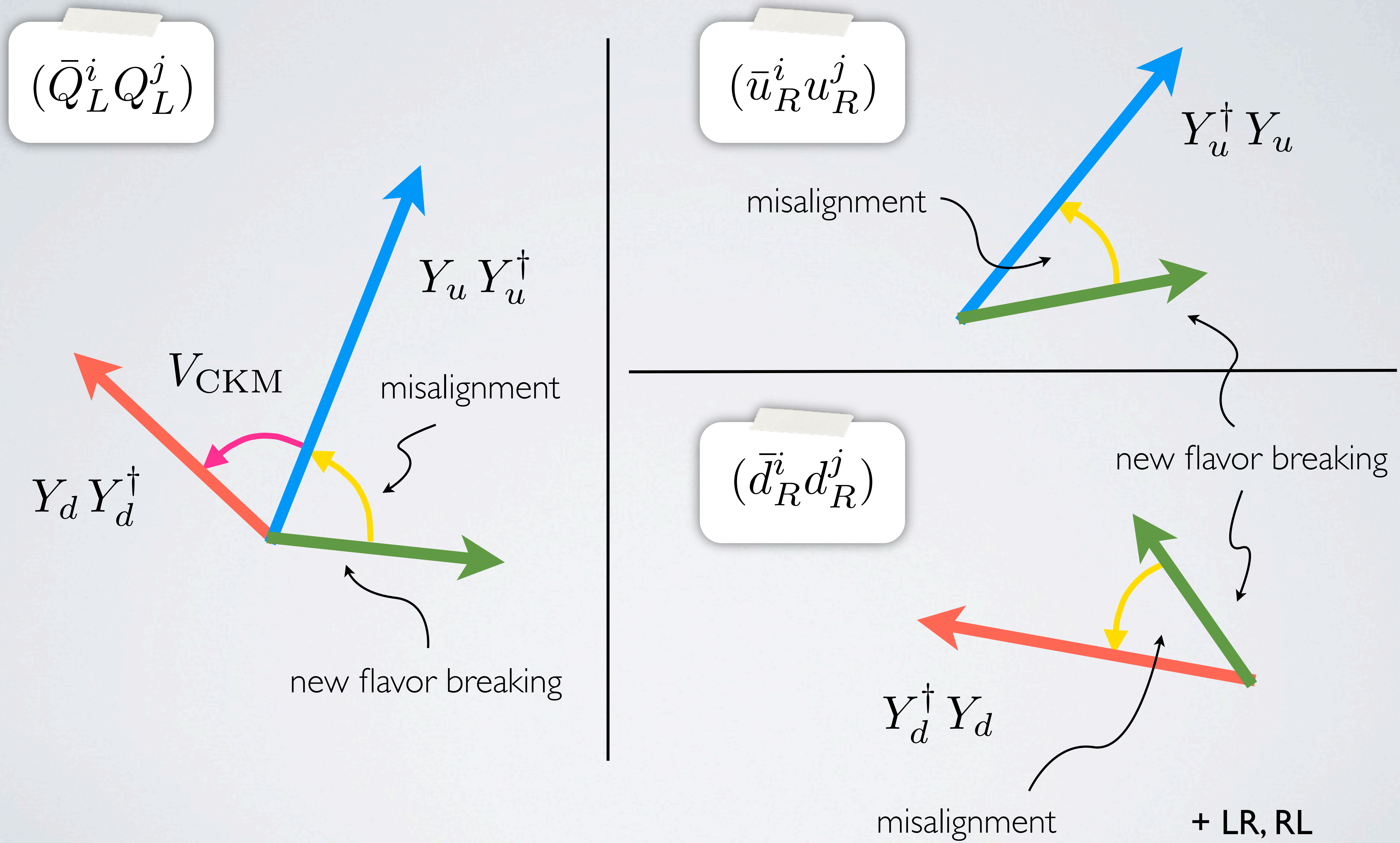
Mode	$\mathcal{B}$	$E_{\rm min}$	$\mathcal{B}(E_\gamma > E_{\rm min})$	$\mathcal{B}^{\rm cnv}(E_\gamma > 1.6)$
CLEO incl.	$321 \pm 43 \pm 27^{+18}_{-10}$	2.0	$306 \pm 41 \pm 26$	$327 \pm 44 \pm 28 \pm 6$
Belle semi.	$336 \pm 53 \pm 42^{+50}_{-54}$	2.24	–	$369 \pm 58 \pm 46^{+56}_{-60}$
BaBar semi.	$335 \pm 19^{+56+4}_{-41-9}$	1.9	$327 \pm 18^{+55+4}_{-40-9}$	$349 \pm 20^{+59+4}_{-46-3}$
BaBar incl.	–	1.9	$367 \pm 29 \pm 34 \pm 29$	$390 \pm 31 \pm 47 \pm 4$
BaBar full	$391 \pm 91 \pm 64$	1.9	$366 \pm 85 \pm 60$	$389 \pm 91 \pm 64 \pm 4$
Belle incl.	–	1.7	$345 \pm 15 \pm 40$	$347 \pm 15 \pm 40 \pm 1$
Average				$355 \pm 24 \pm 9$

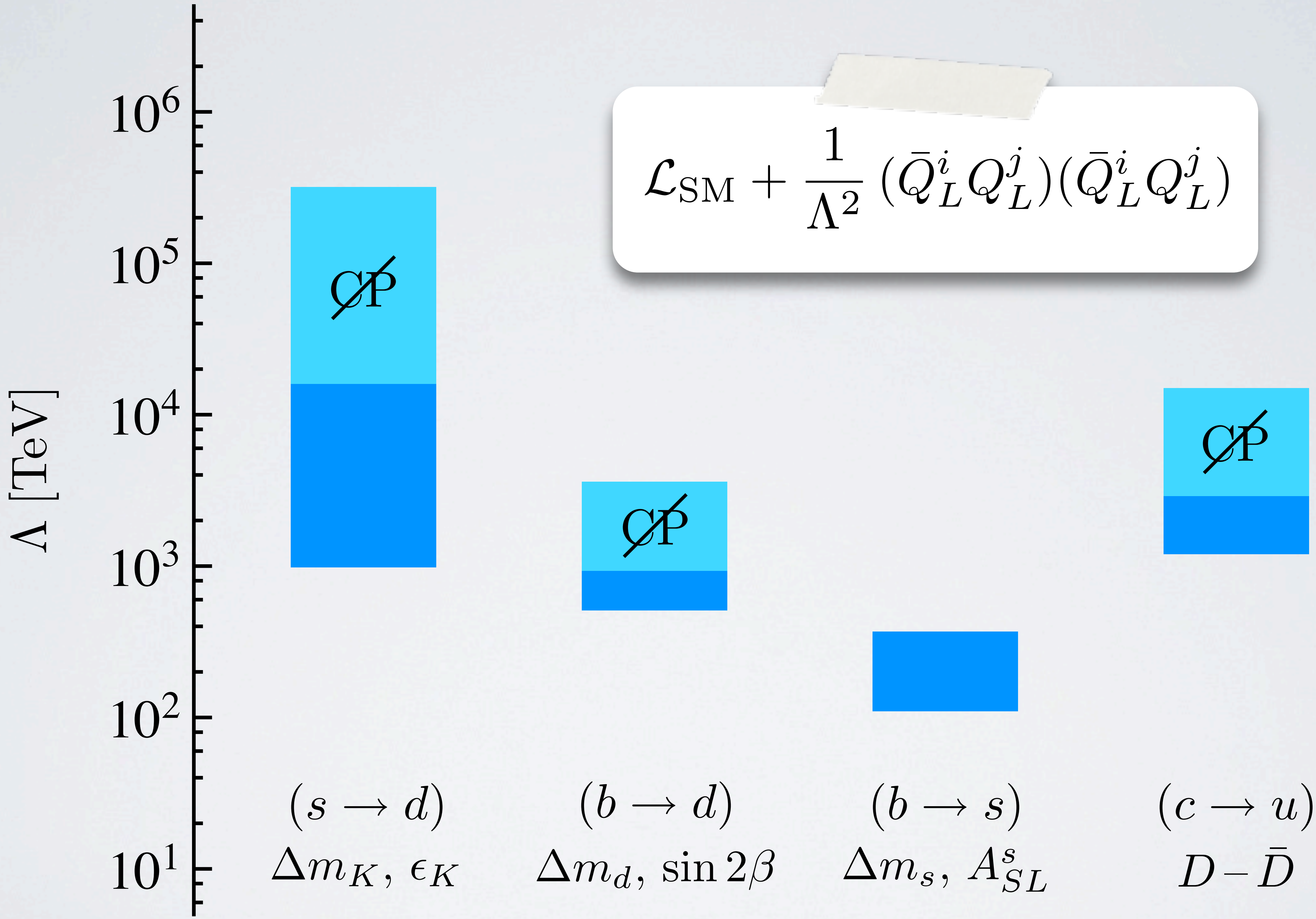
[http://www.slac.stanford.edu/xorg/hfag/rare/winter10/radll/btosg.pdf]

NEW PHYSICS IN U(3) FLAVOR PLANES



BOUNDS ON GENERIC FLAVOR VIOLATION

$$\mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2}\,(\bar{Q}^i_L Q^j_L)(\bar{Q}^i_L Q^j_L)$$



[numbers taken from UTfit Collaboration, arXiv:0707.0636; Gedalia *et al.*, arXiv:0906.1879]

BOUNDS ON GENERIC FLAVOR VIOLATION

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}	Δm_K; ϵ_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}	Δm_K; ϵ_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}	Δm_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}	Δm_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}	Δm_{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}	Δm_{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}
$(\bar{t}_L \gamma^\mu u_L)^2$	12		7.1×10^{-3}		$pp \to tt$

- Due to both chiral and renormalization group (RG) enhancement (factor 14 & 8), LR operators in neutral kaon system most strongly constrained. Assuming $SU(2)_L$ invariance, rare B-meson decays like $B \to X_s l^+ l^-$, also set bounds on operators with t_L. Operators leading to right-handed top-quark FCNCs essentially unbounded

[Fox *et al.*, arXiv:0704.1482; Gedalia & Perez, arXiv:1005.3106]

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Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Bounds on Λ in TeV ($c_{ij}=1$) Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Bounds on c_{ij} ($\Lambda = 1$ TeV) Im	Observables
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Exercise 2: Compute the bounds on Λ for the cases that the c_{ij}'s are of CKM type or arise from a strong loop

HOW TO EVADE THESES FCNC BOUNDS

$\Lambda >> 1$ TeV: Higgs-boson mass fined-tuned & new dofs too heavy to be produced at the LHC

$\Lambda \approx 1$ TeV: flavor mixing somehow protected & new dofs copiously produced at the LHC

Flavor structure of new dofs is a doppelgänger of the one present in the SM: Minimal flavor violation (MFV)

The mechanism that explains SM mass & mixing hierarchies also aligns new sources of flavor breaking

A PESSIMISTIC (RADICAL) CURE: MFV

- An interesting, though *ad hoc*, way to keep the amount of quark flavor & CP violation under control, is provided by the MFV hypothesis:

  "The down- & up-type quark Yukawa couplings Y_d & Y_u remain the only sources of flavor breaking even in physics beyond the SM"

[see for example Buras *et al.*, hep-ph/0007085; Chivukula & Georgi, Phys. Lett. B188, 99 (1987)]

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- Realize that, as of today, the assumption of MFV is still a theoretical speculation (mainly driven by the absence of new physics signals in neutral kaon & B_d-meson mixing) & far from being clearly established

- One main goal of flavor physics in the era of the LHC, will be to try to understand whether or not there are additional flavor-breaking terms besides the SM Yukawa couplings

MFV AS AN EFFECTIVE FIELD THEORY

- The popularity & power of the notion of MFV is mainly due to the fact that MFV can be formulated as an effective field theory (EFT)

- An EFT satisfies the MFV criterion, if all higher-dimensional operators constructed from the quark fields and Yukawas (acting as spurions)

$$Q_L \sim (3,1,1) \quad u_R \sim (1,3,1) \quad d_R \sim (1,1,3)$$

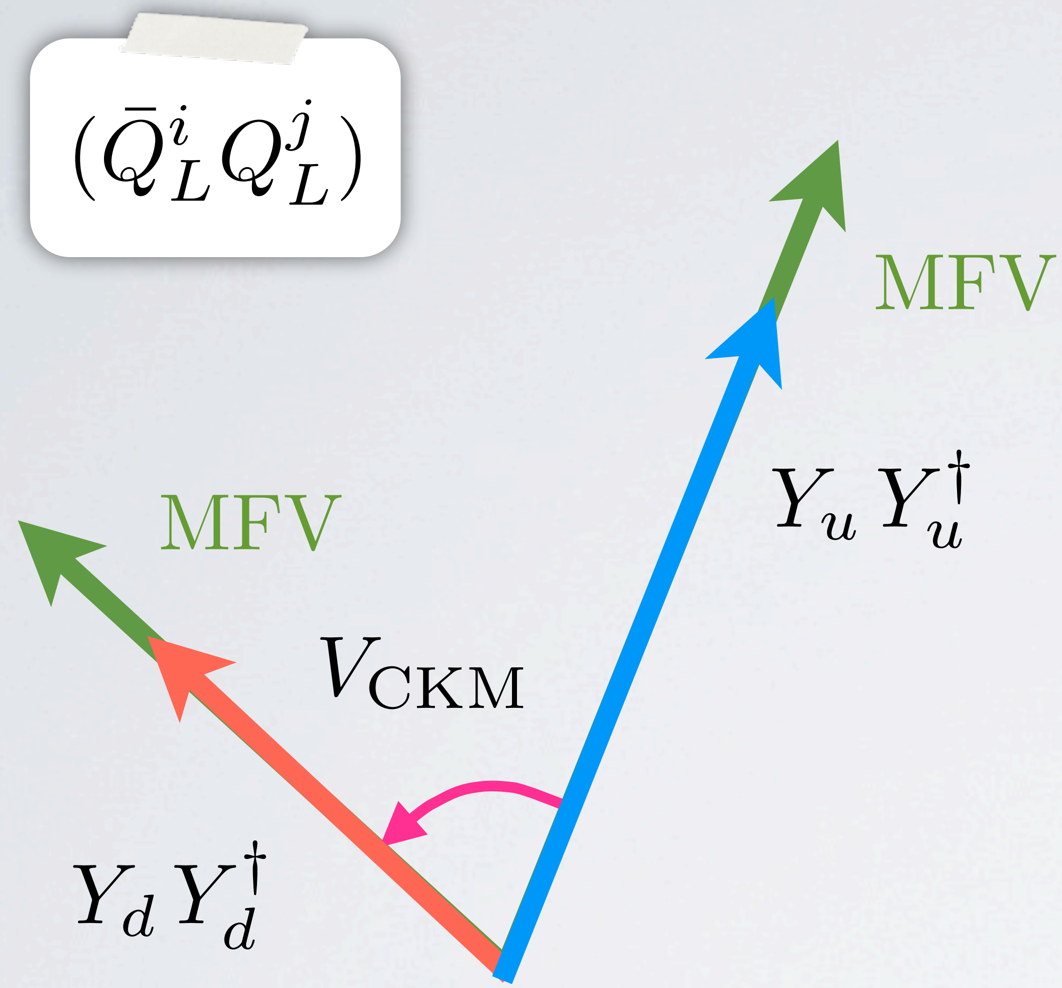
$$Y_d \sim (3,1,\bar{3}) \quad Y_u \sim (3,\bar{3},1)$$

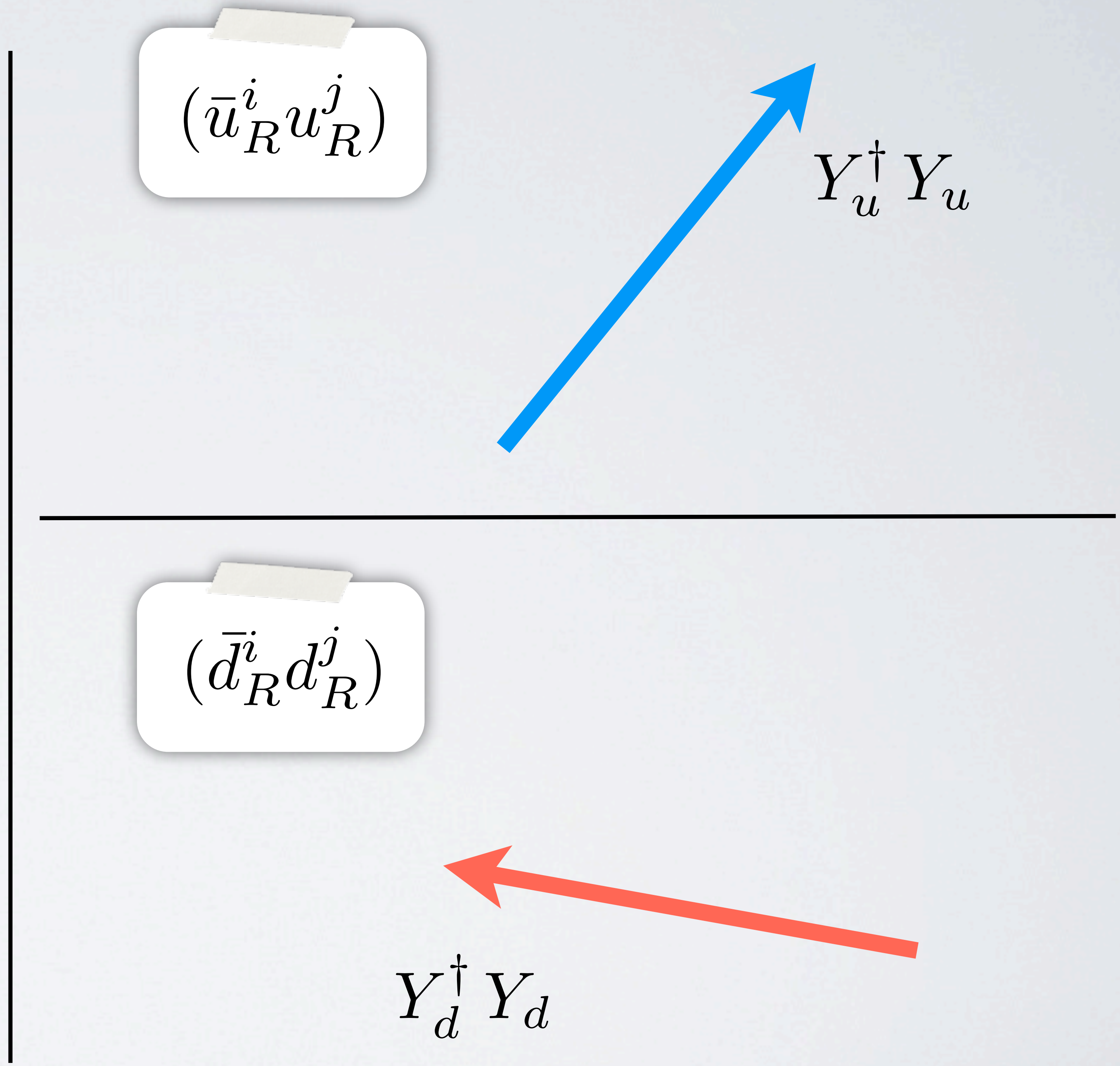
are formally invariant under the SM flavor group

$$U(3)^5 = U(3)_Q \times U(3)_u \times U(3)_d \times \ldots$$

[D'Ambrosio *et al.*, hep-ph/0207036]

MFV IN U(3) FLAVOR PLANES





$|{\rm MFV}| \approx |{\rm SM}|$

condition: moderate tanβ
or small U(1)$_{PQ}$ breaking

+ LR, RL

MFV DIMENSION-6 OPERATORS

- For processes with external down-type quarks three basic invariant bi-linear structures can be identified:

$$\bar{Q}_L Y_u Y_u^\dagger Q_L \approx \sum_{i,j=1}^{3} (V^*_{\rm CKM})_{ti} (V_{\rm CKM})_{tj}\, y_t^2\; \bar{d}_L^i d_L^j$$

$$\bar{d}_R Y_d^\dagger Y_u Y_u^\dagger Q_L \approx \sum_{j=1}^{3} (V^*_{\rm CKM})_{tb} (V_{\rm CKM})_{tj}\, y_b\, y_t^2\; \bar{b}_R d_L^j$$

$$\bar{d}_R Y_d^\dagger Y_u Y_u^\dagger Y_d d_R \approx |(V_{\rm CKM})_{tb}|^2\, y_b^2\, y_t^2\; \bar{b}_R b_R \approx 0$$

- Notice that 2nd & 3rd operator involving up-type quarks is negligible in MFV context due to smallness of down-type Yukawa couplings

[D'Ambrosio *et al.*, hep-ph/0207036]

MFV DIMENSION-6 OPERATORS

- From these bi-linears, we can construct complete set of operators:

$$Q_0 = \frac{1}{2}\left(\bar{Q}_L Y_u Y_u^\dagger \gamma^\mu Q_L\right)^2$$

$$Q_{\phi 1} = i\left(\bar{Q}_L Y_u Y_u^\dagger \gamma^\mu Q_L\right)\phi^\dagger D_\mu \phi \qquad Q_{\phi 2} = i\left(\bar{Q}_L Y_u Y_u^\dagger \tau^i \gamma^\mu Q_L\right)\phi^\dagger \tau^i D_\mu \phi$$

$$Q_{F1} = \phi^\dagger\left(\bar{d}_R \lambda_d Y_u Y_u^\dagger \sigma^{\mu\nu} Q_L\right)F_{\mu\nu} \qquad Q_{F2} = \left(\bar{Q}_L Y_u Y_u^\dagger \gamma^\mu Q_L\right)D^\nu F_{\mu\nu}$$

$$Q_{G1} = \phi^\dagger\left(\bar{d}_R \lambda_d Y_u Y_u^\dagger \sigma^{\mu\nu} T^a Q_L\right)G^a_{\mu\nu} \qquad Q_{G2} = \left(\bar{Q}_L Y_u Y_u^\dagger \gamma^\mu T^a Q_L\right)D^\nu G^a_{\mu\nu}$$

$$Q_{\ell 1} = \left(\bar{Q}_L Y_u Y_u^\dagger \gamma^\mu Q_L\right)\left(\bar{L}_L \gamma^\mu L_L\right) \qquad Q_{\ell 2} = \left(\bar{Q}_L Y_u Y_u^\dagger \gamma^\mu \tau^i Q_L\right)\left(\bar{L}_L \gamma_\mu \tau^i L_L\right)$$

$$Q_{\ell 3} = \left(\bar{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L\right)\left(\bar{\ell}_R \gamma_\mu \ell_R\right)$$

$$Q_{q1} = \left(\bar{Q}_L Y_u Y_u^\dagger \gamma^\mu Q_L\right)\left(\bar{Q}_L \gamma^\mu Q_L\right) \qquad Q_{q2} = \left(\bar{Q}_L Y_u Y_u^\dagger \gamma^\mu \tau^i Q_L\right)\left(\bar{Q}_L \gamma_\mu \tau^i Q_L\right)$$

$$Q_{q3} = \left(\bar{Q}_L Y_u Y_u^\dagger \gamma^\mu T^a Q_L\right)\left(\bar{Q}_L \gamma^\mu T^a Q_L\right) \qquad Q_{q4} = \left(\bar{Q}_L Y_u Y_u^\dagger \gamma^\mu T^a \tau^i Q_L\right)\left(\bar{Q}_L \gamma_\mu T^a \tau^i Q_L\right)$$

$$Q_{q5} = \left(\bar{Q}_L Y_u Y_u^\dagger \gamma^\mu Q_L\right)\left(\bar{d}_R \gamma^\mu d_R\right) \qquad Q_{q6} = \left(\bar{Q}_L Y_u Y_u^\dagger \gamma^\mu T^a Q_L\right)\left(\bar{d}_R \gamma_\mu T^a d_R\right)$$

$$Q_{q7} = \left(\bar{Q}_L Y_u Y_u^\dagger \gamma^\mu Q_L\right)\left(\bar{u}_R \gamma^\mu u_R\right) \qquad Q_{q8} = \left(\bar{Q}_L Y_u Y_u^\dagger \gamma^\mu T^a Q_L\right)\left(\bar{u}_R \gamma_\mu T^a u_R\right)$$

[D'Ambrosio *et al.*, hep-ph/0207036]

A CLOSER LOOK AT $Q_{\phi 1}$ & Q_{F1}

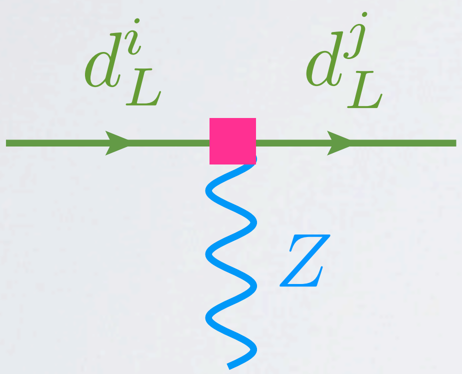
- After electroweak symmetry breaking (EWSB), the operators

$$Q_{\phi 1} = i \left(\bar{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L \right) \phi^\dagger D^\mu \phi$$

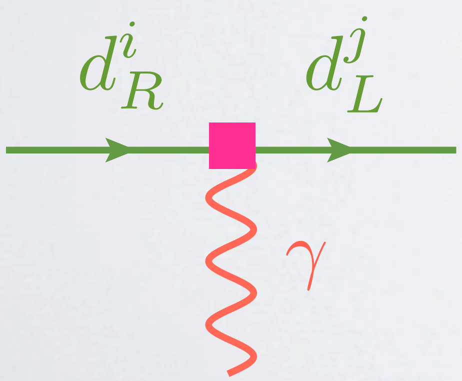
$$Q_{F1} = \phi^\dagger \left(\bar{d}_R \lambda_d Y_u Y_u^\dagger \sigma^{\mu\nu} Q_L \right) F_{\mu\nu}$$

induce the effective down-type quark vertices:

universal contribution to $B \to X_s l^+ l^-$, $K \to \pi \nu \bar{\nu}$, ...



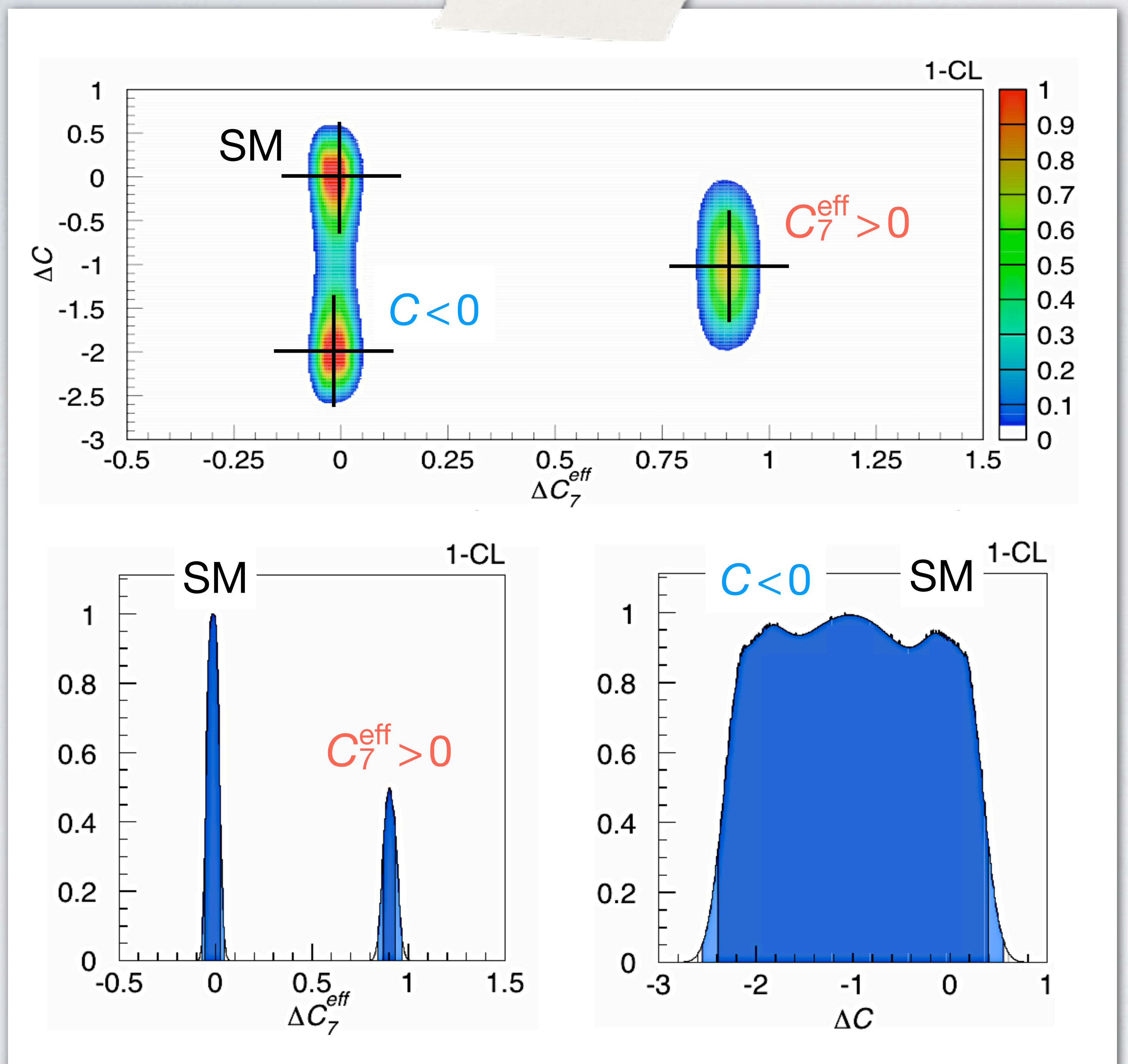
$$\propto \; (V^*_{\rm CKM})_{ti} \, (V_{\rm CKM})_{tj} \, \Delta C \, (\bar{d}_L^i \gamma^\mu d_L^j) Z_\mu$$

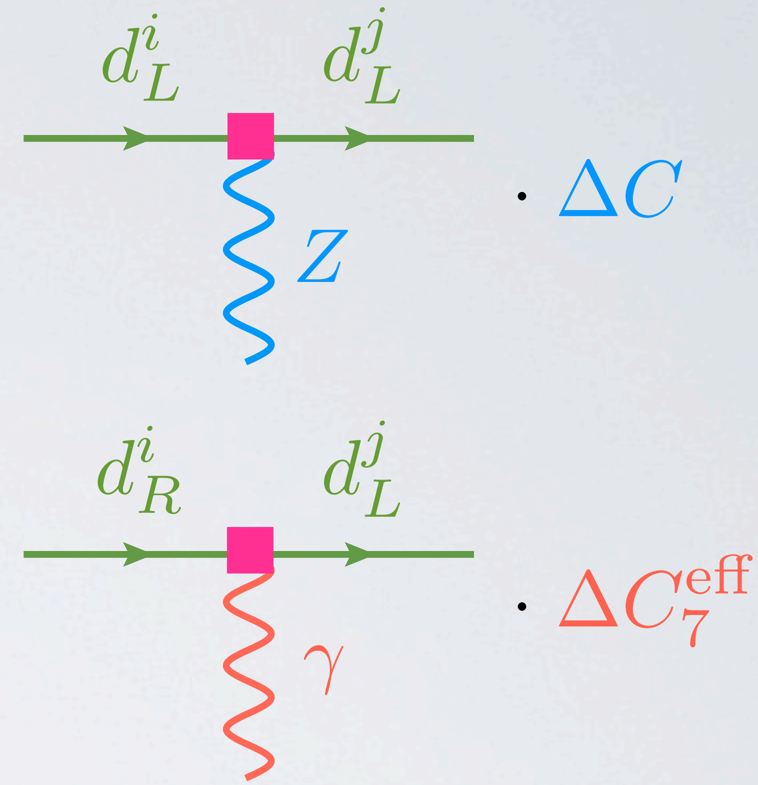


$$\propto \; (V^*_{\rm CKM})_{ti} \, (V_{\rm CKM})_{tj} \, \Delta C_7^{\rm eff} \, m_{d^i} \, (\bar{d}_R^i \sigma^{\mu\nu} d_L^j) F_{\mu\nu}$$

universal contribution to $B \to X_s \gamma$, $B \to X_s l^+ l^-$, ...

HUNTING & KILLING PENGUINS

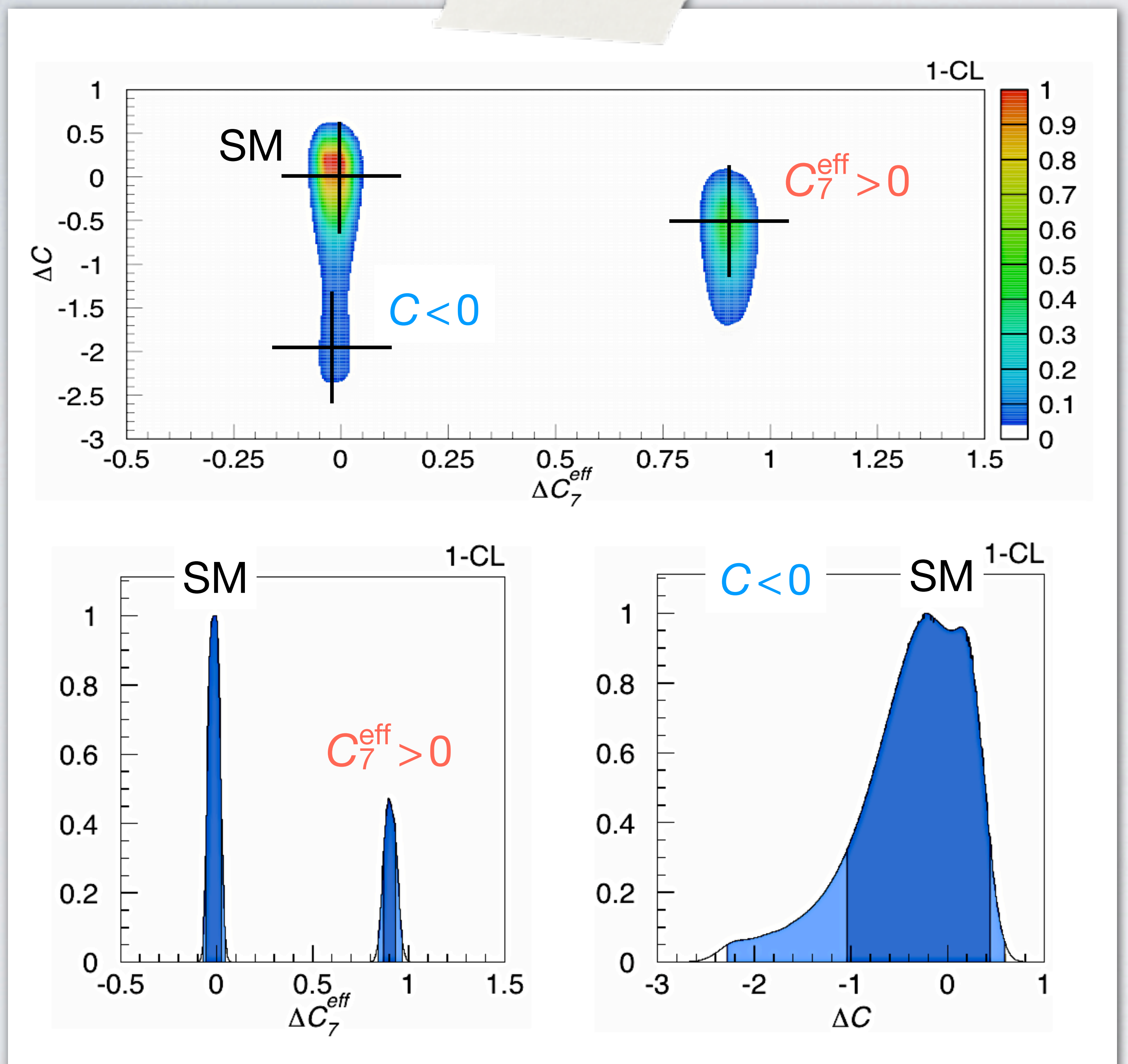


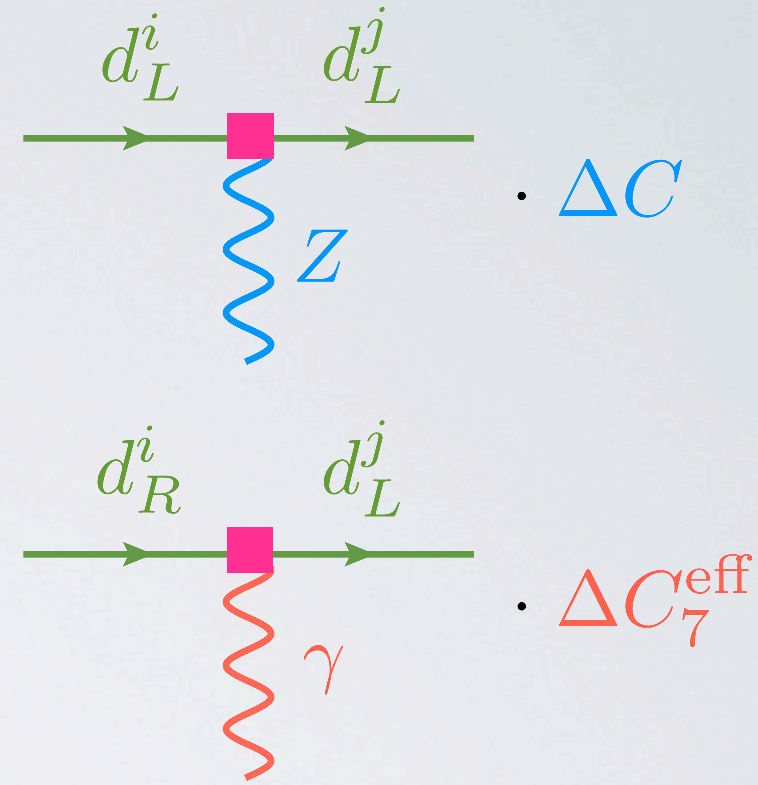


- The non-SM like sign solution of C_7^{eff} is disfavored by the measurement of the branching ratio of $B \to X_s l^+ l^-$

[Gambino, UH & Misiak, hep-ph/0410155]

HUNTING & KILLING PENGUINS

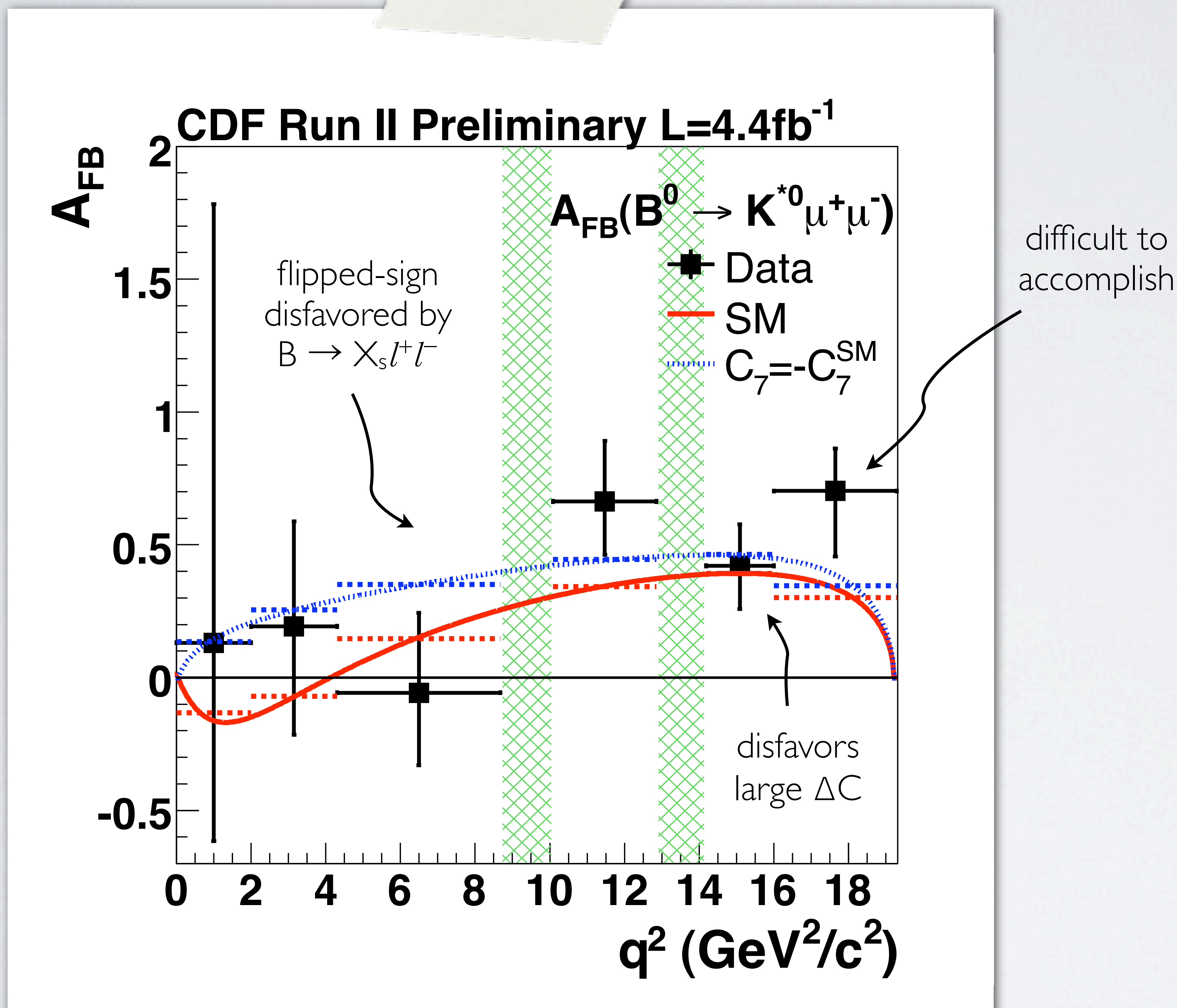


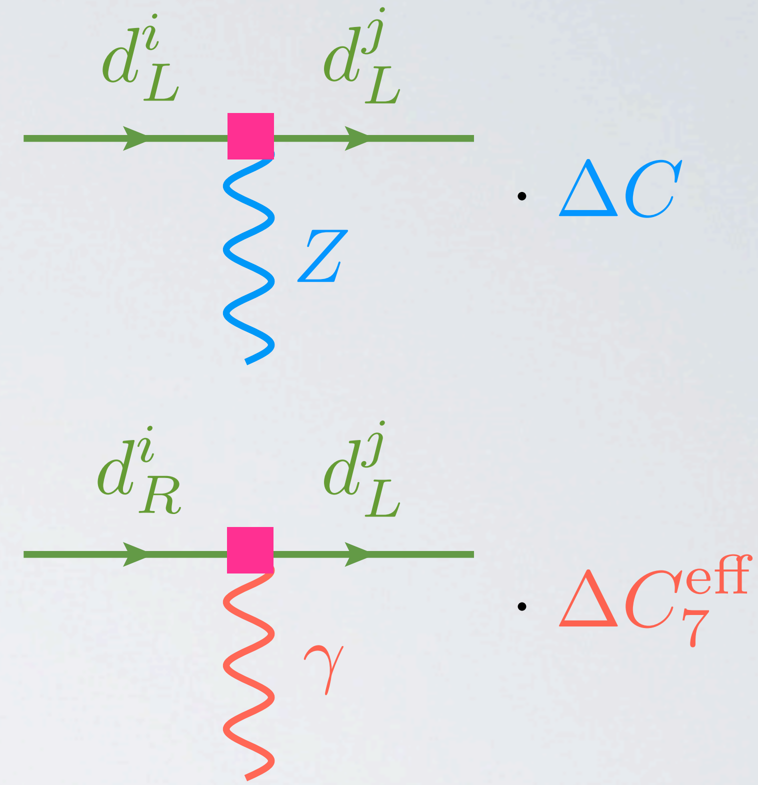


- 5 years ago, a large destructive universal left-handed Z-penguin was allowed by flavor data (b → s & s → d)

[Bobeth *et al.*, hep-ph/0505110]

HUNTING & KILLING PENGUINS

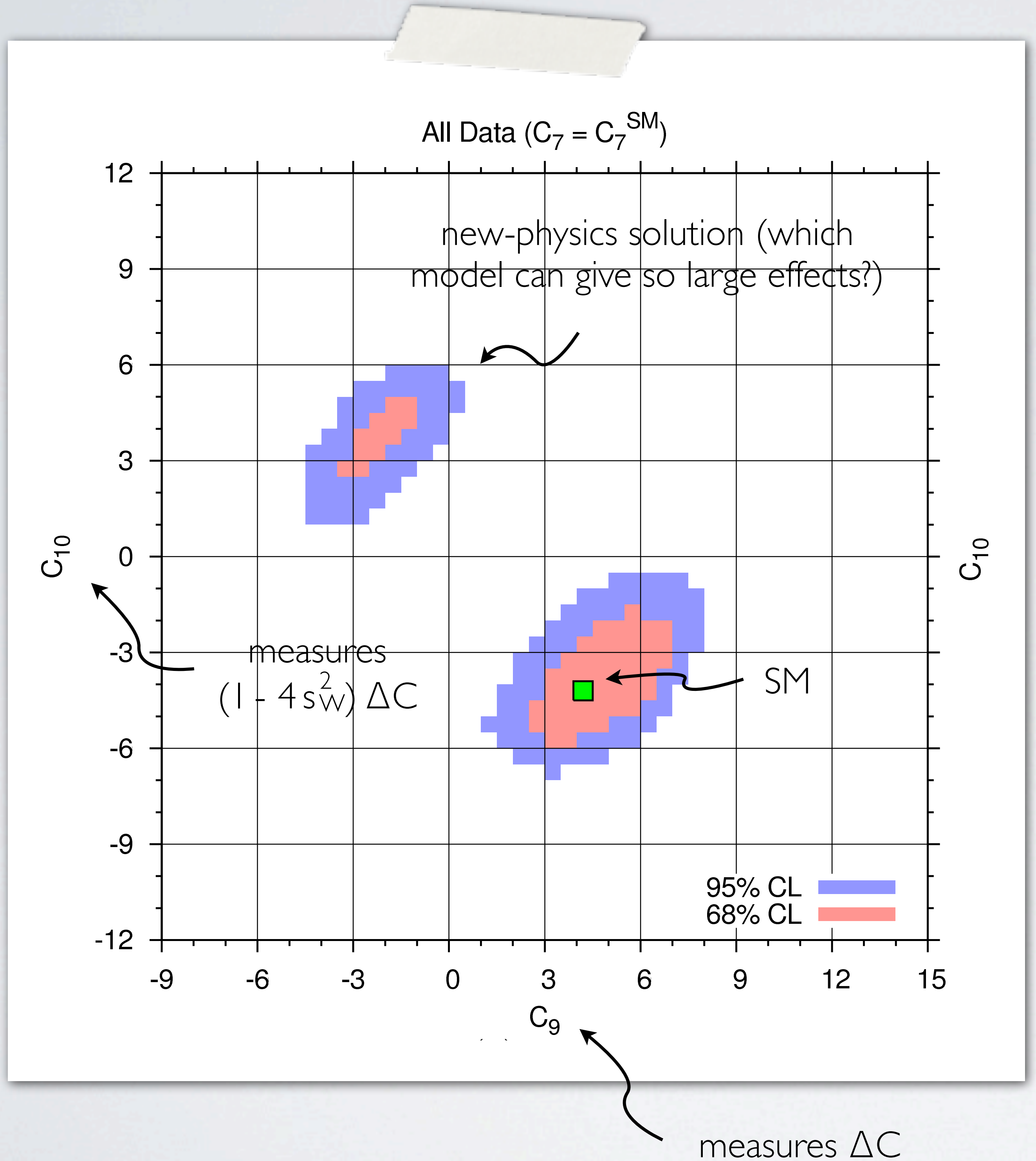


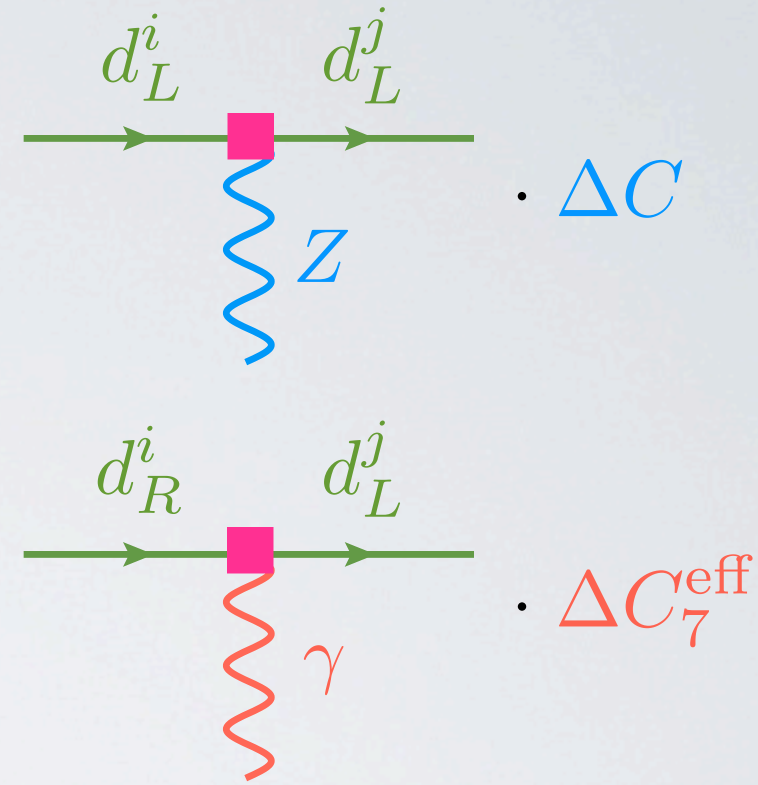


- Today this possibility is limited ($|\Delta C| \lesssim 1/2$) due to new data on exclusive $b \to s l^+ l^-$ (though quality of global fit is not good)

[CDF note 10047; BaBar Collaboration, arXiv:0804.4412; Belle Collaboration, arXiv:0904.0770]

HUNTING & KILLING PENGUINS





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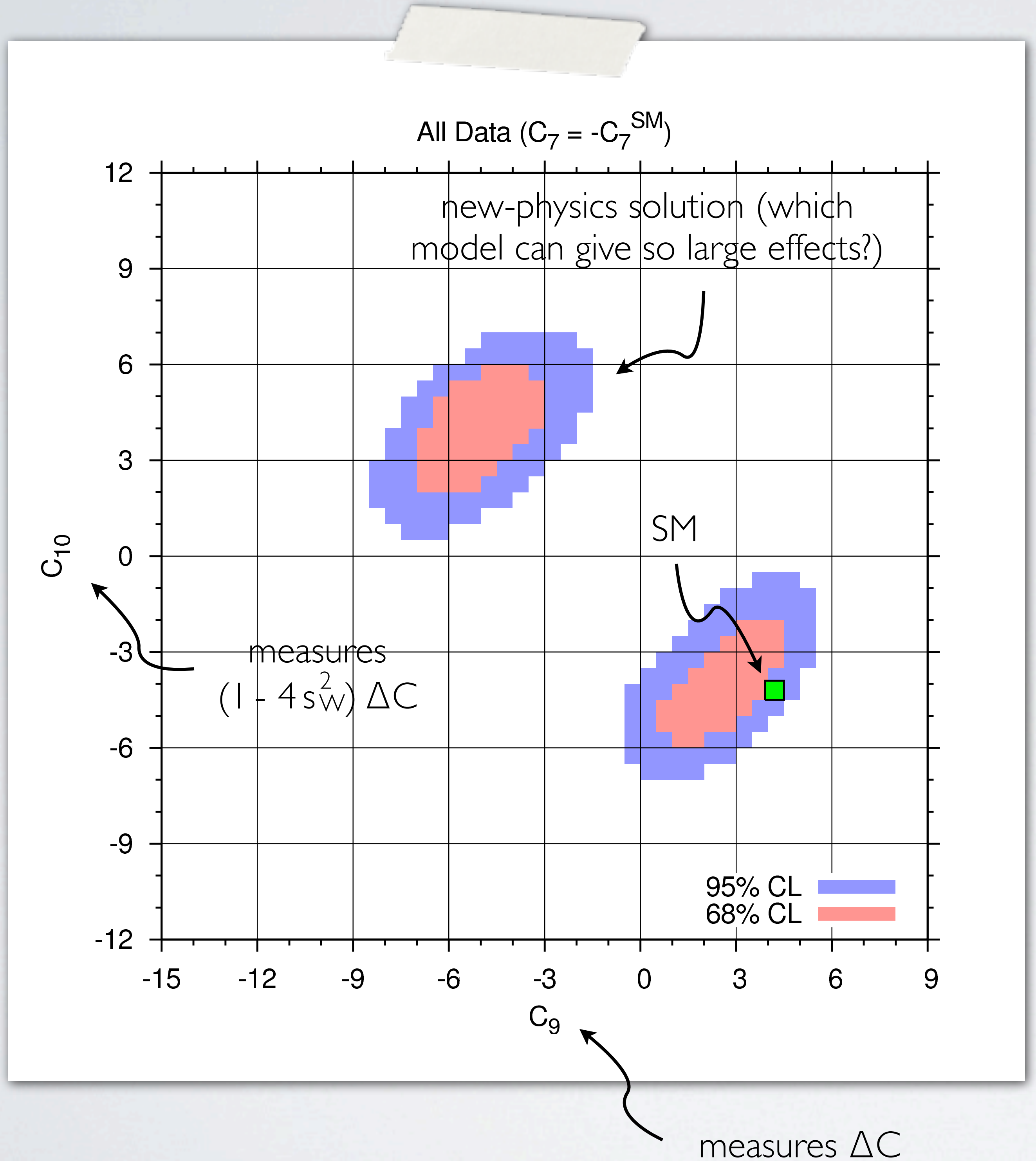
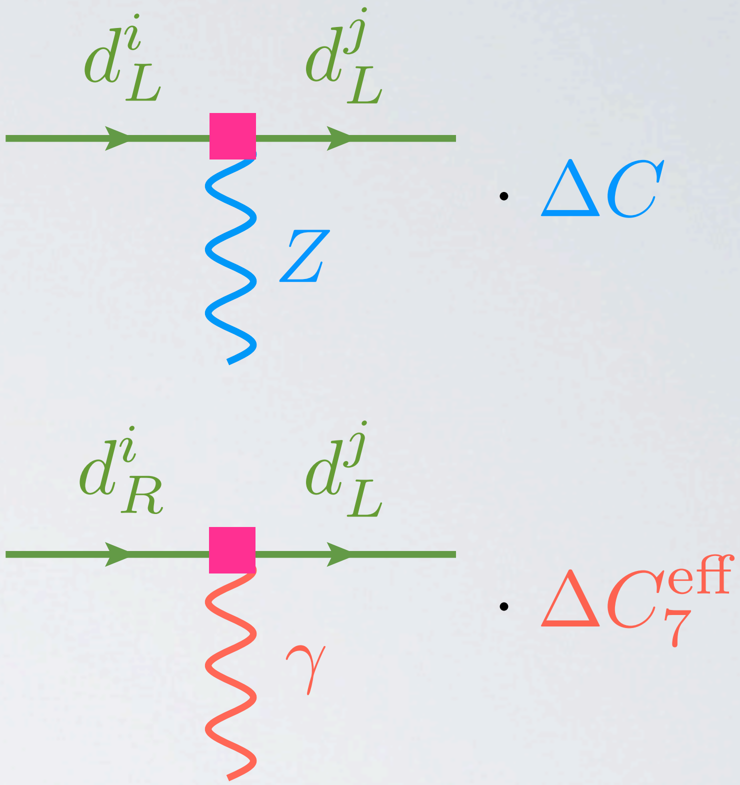
[Bobeth, Hiller & van Dyk, arXiv:1006.5013]

HUNTING & KILLING PENGUINS





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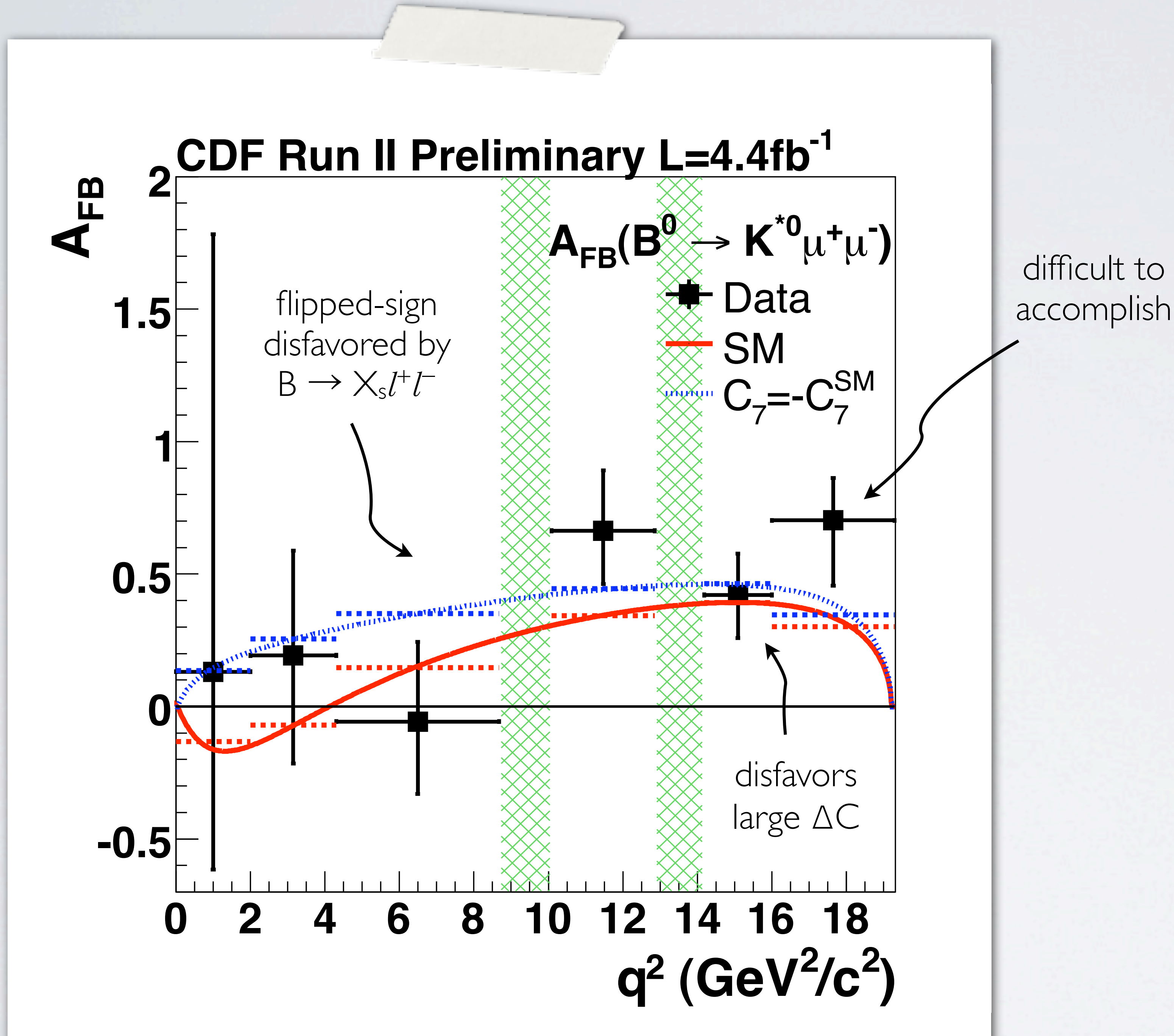

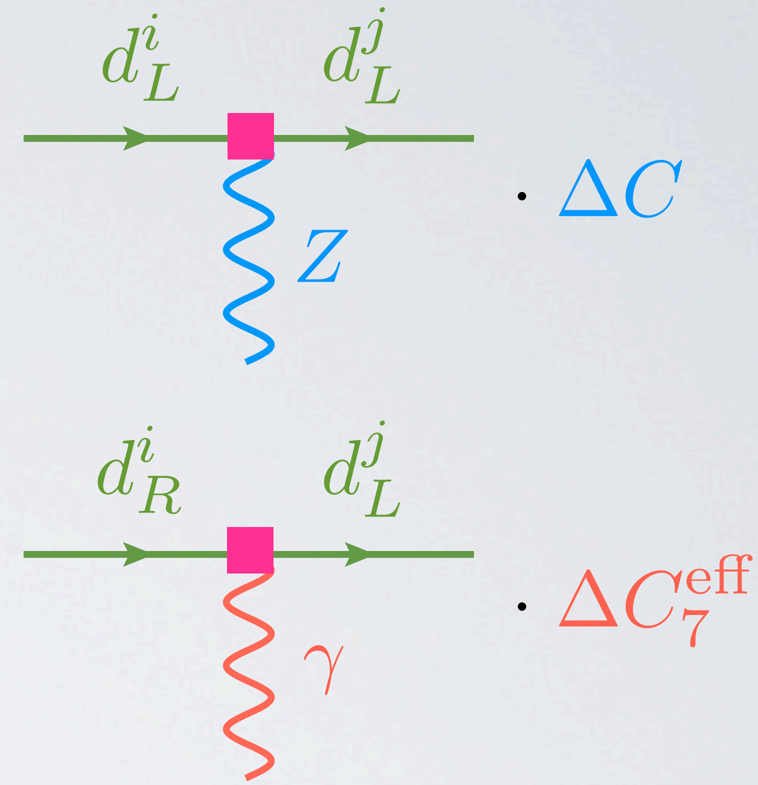

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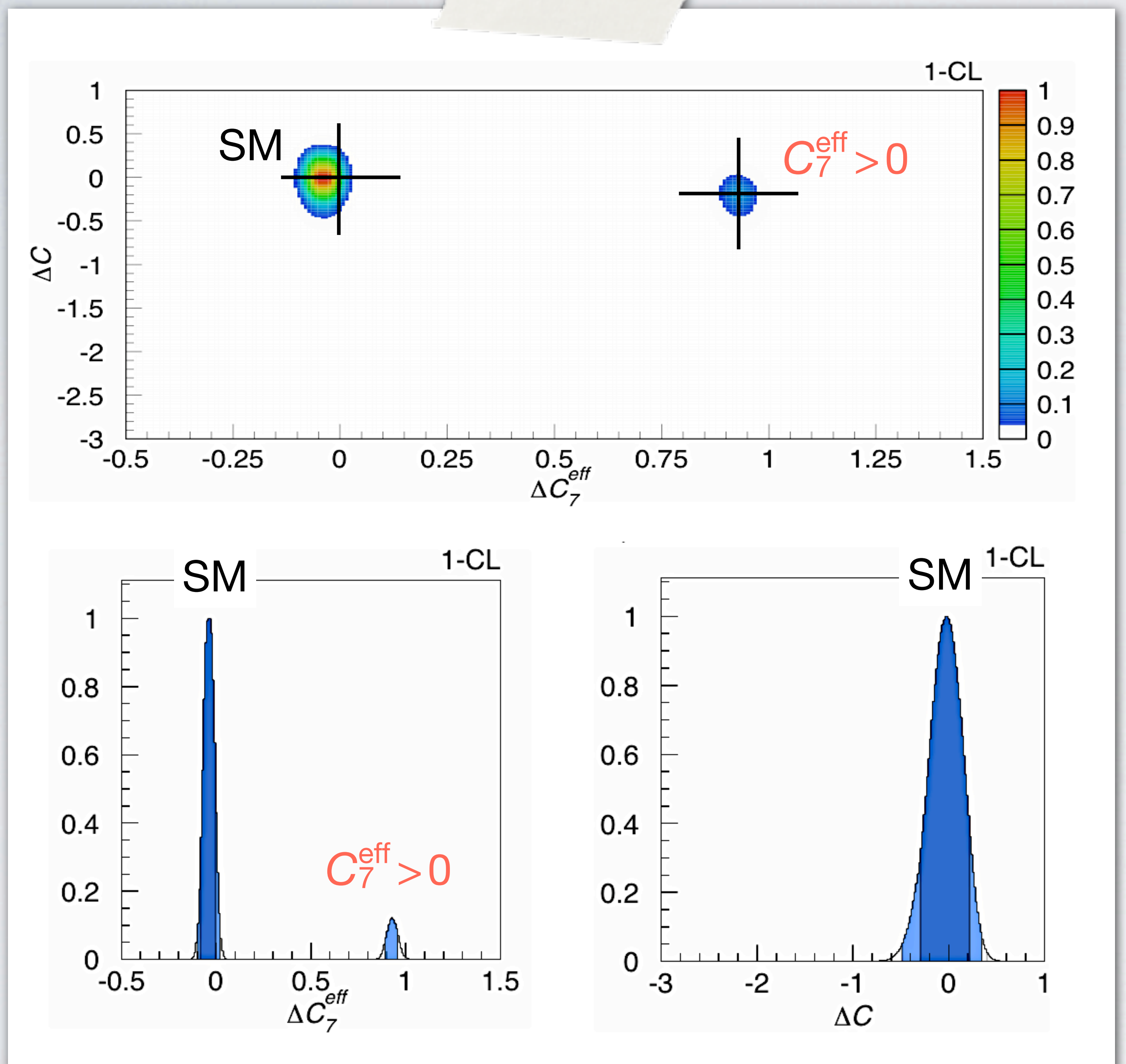
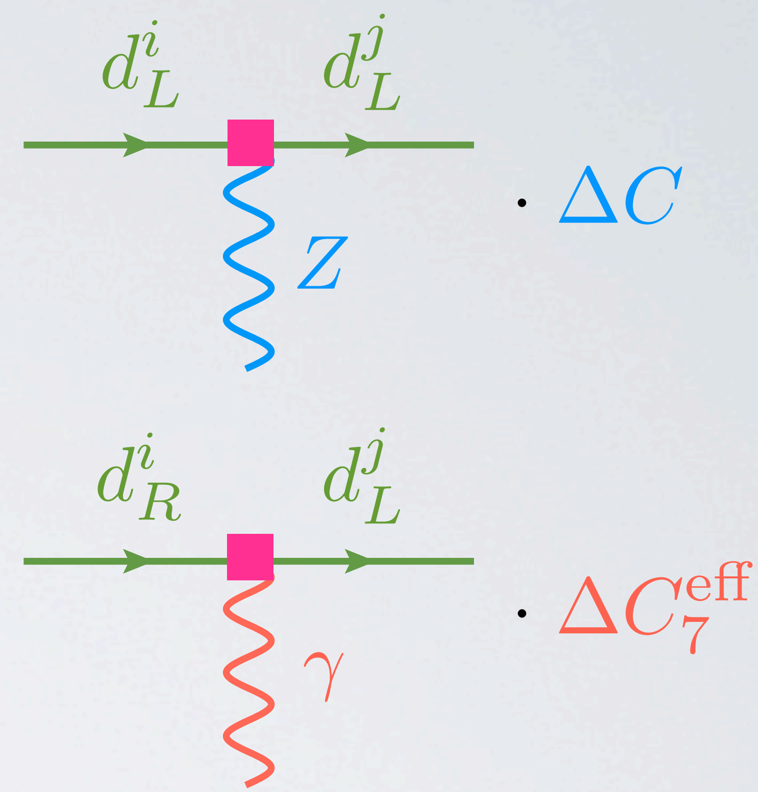
Exercise 3: To get more familiar with the basic ideas of model-independent analyses, go penguin hunting yourself

PRECISION OBSERVABLES & MFV INTERPLAY

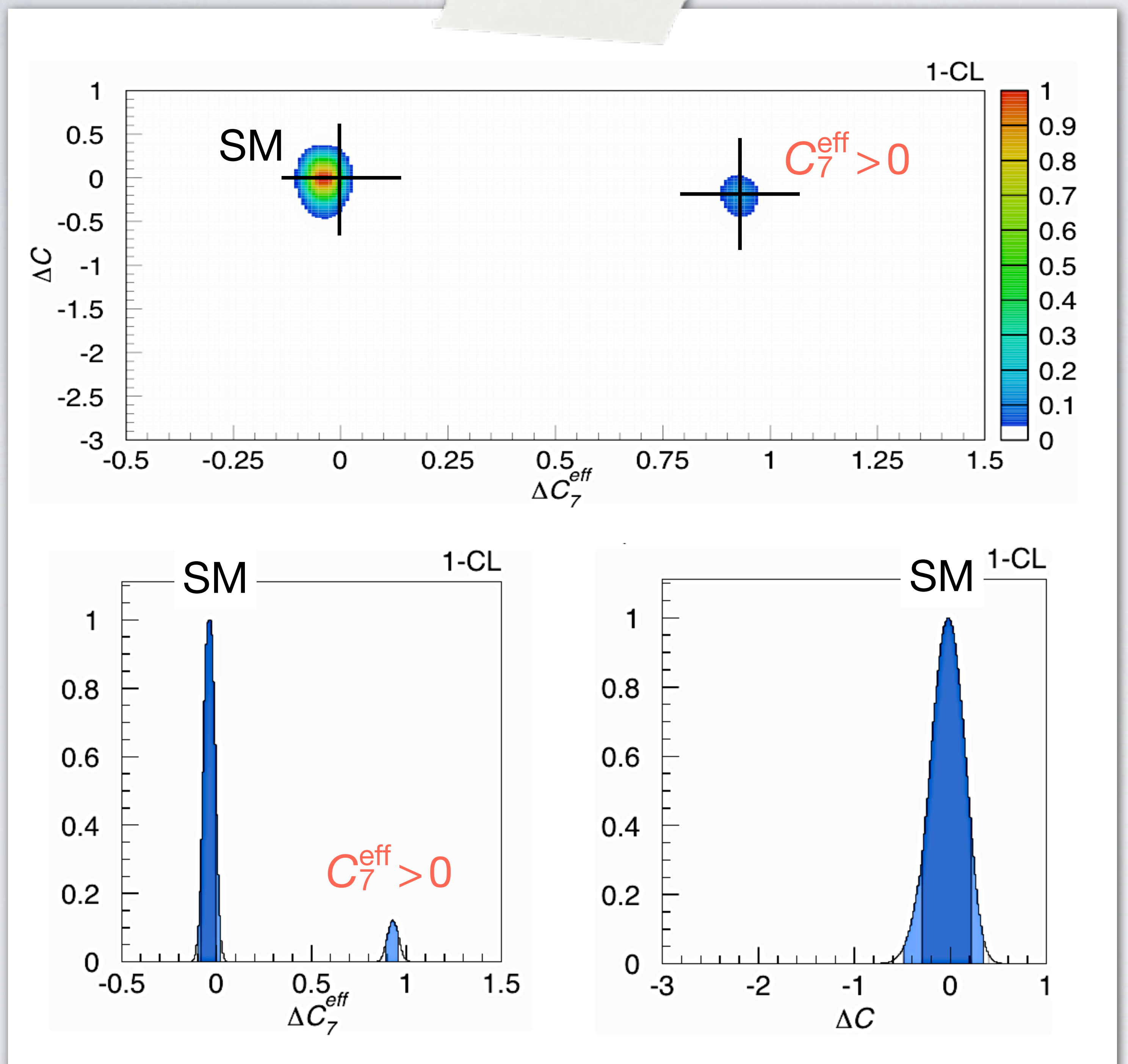


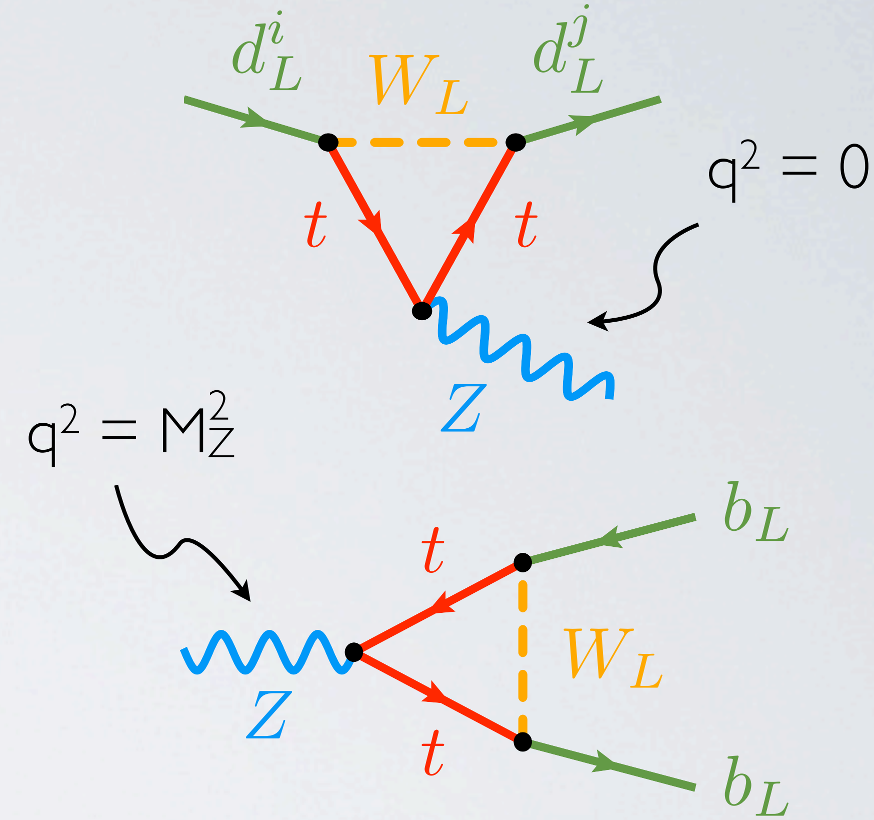


- In fact, FCNCs are compared to $Z \rightarrow b_L \bar{b}_L$ (as precisely measured at LEP & SLC) far less powerful in excluding sizable effects in ΔC

[UH & Weiler, arXiv:0706.2054]

PRECISION OBSERVABLES & MFV INTERPLAY





- This finding follows form the fact that in MFV, amplitudes for $d^i_L \to d^j_L Z$ & $Z \to b_L \bar{b}_L$ are related by a CKM factor (on-shell effects of Z boson are small)

[UH & Weiler, arXiv:0706.2054]

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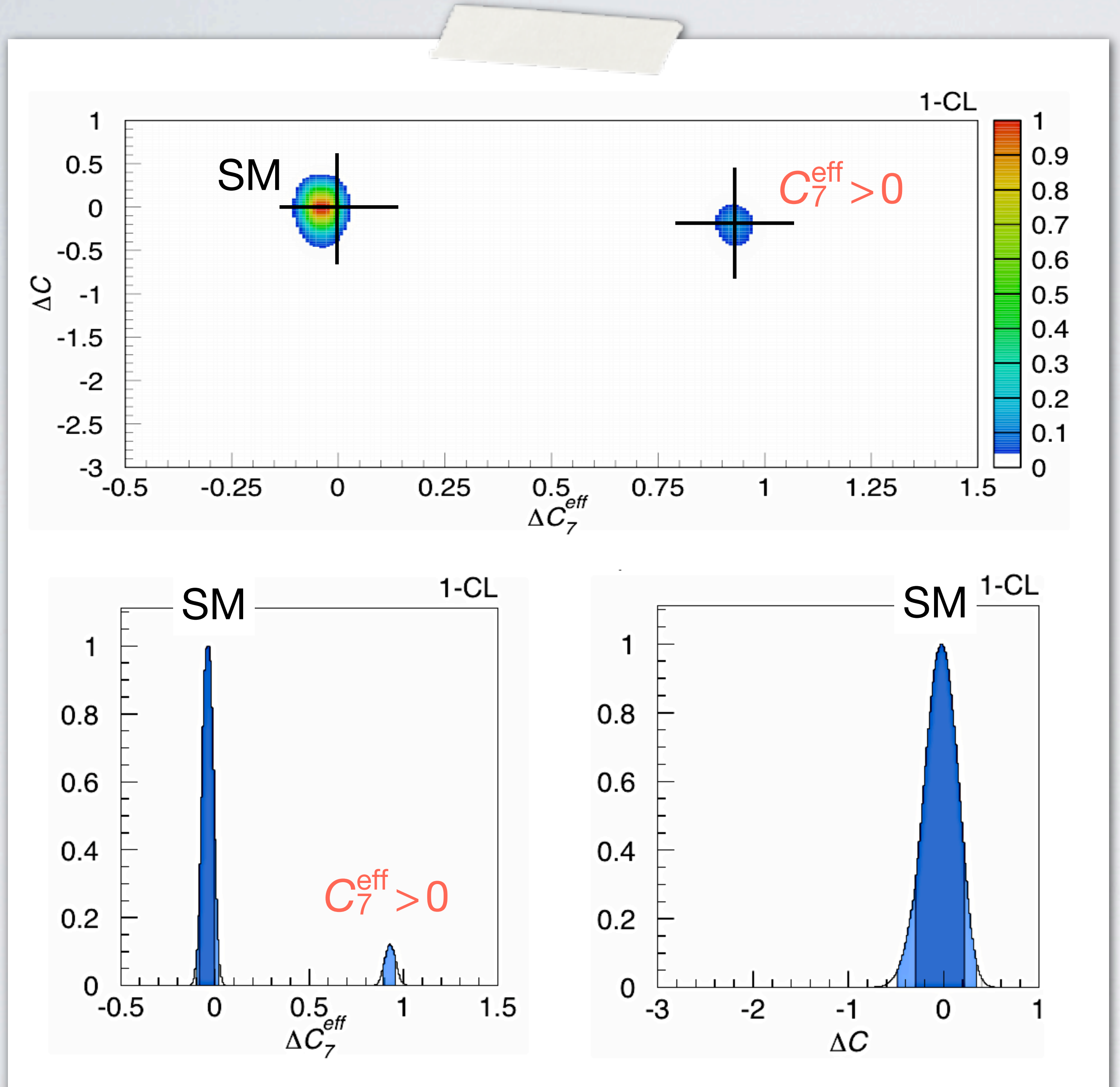

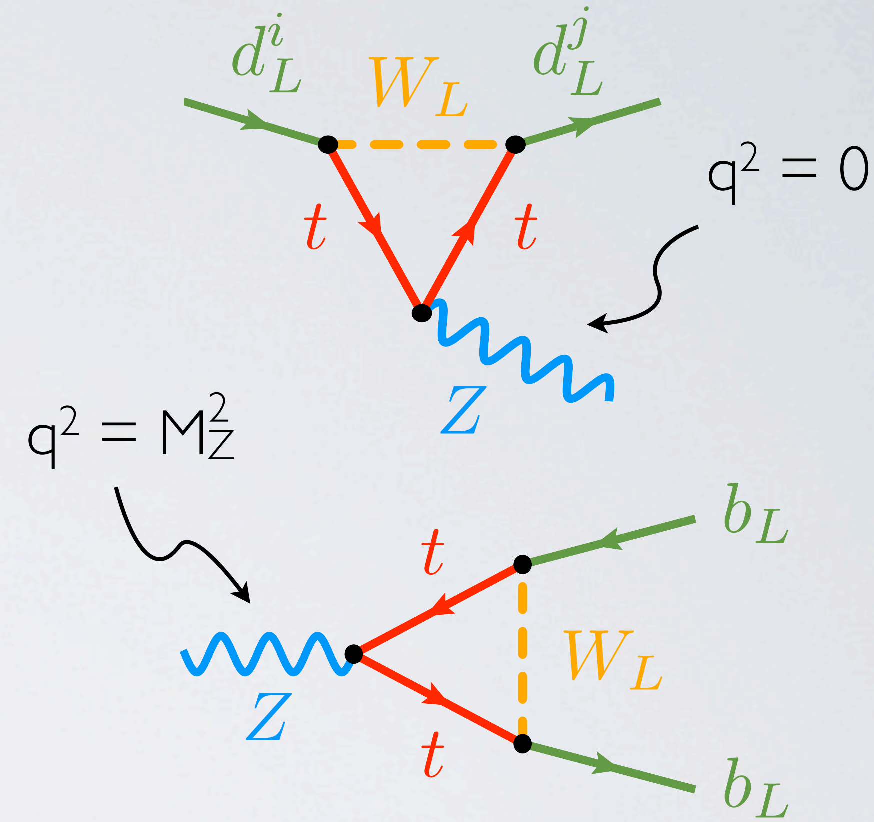

- This finding follows form the fact that in MFV, amplitudes for $d_L^i \to d_L^j Z$ & $Z \to b_L \bar{b}_L$ are related by a CKM factor (on-shell effects of Z boson are small)

Exercise 4: Can one do the same with $\mu \to e\gamma$ & $(g-2)_\mu$?

BOUNDS ON RARE DECAY

Observable	CMFV (95% CL)	SM (95% CL)	Experiment	Factor
$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) \times 10^{11}$	$[4.29, 10.72]$	$[5.40, 9.11]$	$(17.3^{+11.5}_{-10.5})$	–
$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \times 10^{11}$	$[1.55, 4.38]$	$[2.21, 3.45]$	$< 2.6 \cdot 10^3$ (90% CL)	920
$\mathcal{B}(K_L \to \mu^+\mu^-)_{\rm SD} \times 10^9$	$[0.30, 1.22]$	$[0.54, 0.88]$	–	–
$\mathcal{B}(B \to X_d \nu\bar{\nu}) \times 10^6$	$[0.77, 2.00]$	$[1.24, 1.45]$	–	–
$\mathcal{B}(B \to X_s \nu\bar{\nu}) \times 10^5$	$[1.88, 4.86]$	$[3.06, 3.48]$	< 64 (90% CL)	20
$\mathcal{B}(B_d \to \mu^+\mu^-) \times 10^{10}$	$[0.36, 2.03]$	$[0.87, 1.27]$	$< 7.6 \cdot 10^1$ (95% CL)	70
$\mathcal{B}(B_s \to \mu^+\mu^-) \times 10^9$	$[1.17, 6.67]$	$[2.92, 4.13]$	$< 4.3 \cdot 10^1$ (95% CL)	12

- In class of so-called constrained MFV (CMFV) models (MFV scenarios that involve no new operators beside those already present in the SM), stringent limit on ΔC translates into tight two-sided bounds for the branching ratios of all Z-penguin dominated flavor-changing kaon & B-meson decays

[UH & Weiler, arXiv:0706.2054; Blanke *et al.*, hep-ph/0604057]

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- In fact, the quoted bounds have be shown to hold in the two-Higgs-doublet model type I & II (2HDM-I & -II), the minimal-supersymmetric SM (MSSM) with MFV, all for small tanβ, minimal universal extra dimensions (mUED) & the littlest Higgs model with T-parity (LHT) & degenerate mirror quarks (to avoid new sources of flavor breaking)

[UH & Weiler, arXiv:0706.2054]

BOUNDS ON RARE DECAY

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- A strong violation of any of the found limits would signal presence of additional operators not present in SM and/or new sources of flavor breaking not encoded in the Yukawa couplings. Such an observation would exclude the whole class of CMFV scenarios

[UH & Weiler, arXiv:0706.2054]

BOUNDS ON MFV OPERATORS

Operator	Bound on Λ in TeV	Observables
Q_{F1}	6.1	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
Q_0	5.9	ϵ_K , Δm_d , Δm_s
Q_{G1}	3.4	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$Q_{\ell 3}$	2.7	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$Q_{\phi 1}$	2.3	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$Q_{\ell 1}$	1.7	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
Q_{F2}	1.5	$B \to X_s\ell^+\ell^-$

- Relative to the tree-level limits of $(10^3 - 10^5)$ TeV that apply in the case of general flavor violation, the MFV bounds are rather mild. The most severely constrained MFV operators are the electromagnetic dipole operator Q_{F1} & the left-handed $\Delta F = 2$ four-quark operator Q_0

[UTfit Collaboration, arXiv:0707.0636; Hurth *et al.*, arXiv:0807.5039]

BOUNDS ON MFV OPERATORS

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Q_0	5.9	ϵ_K , Δm_d , Δm_s
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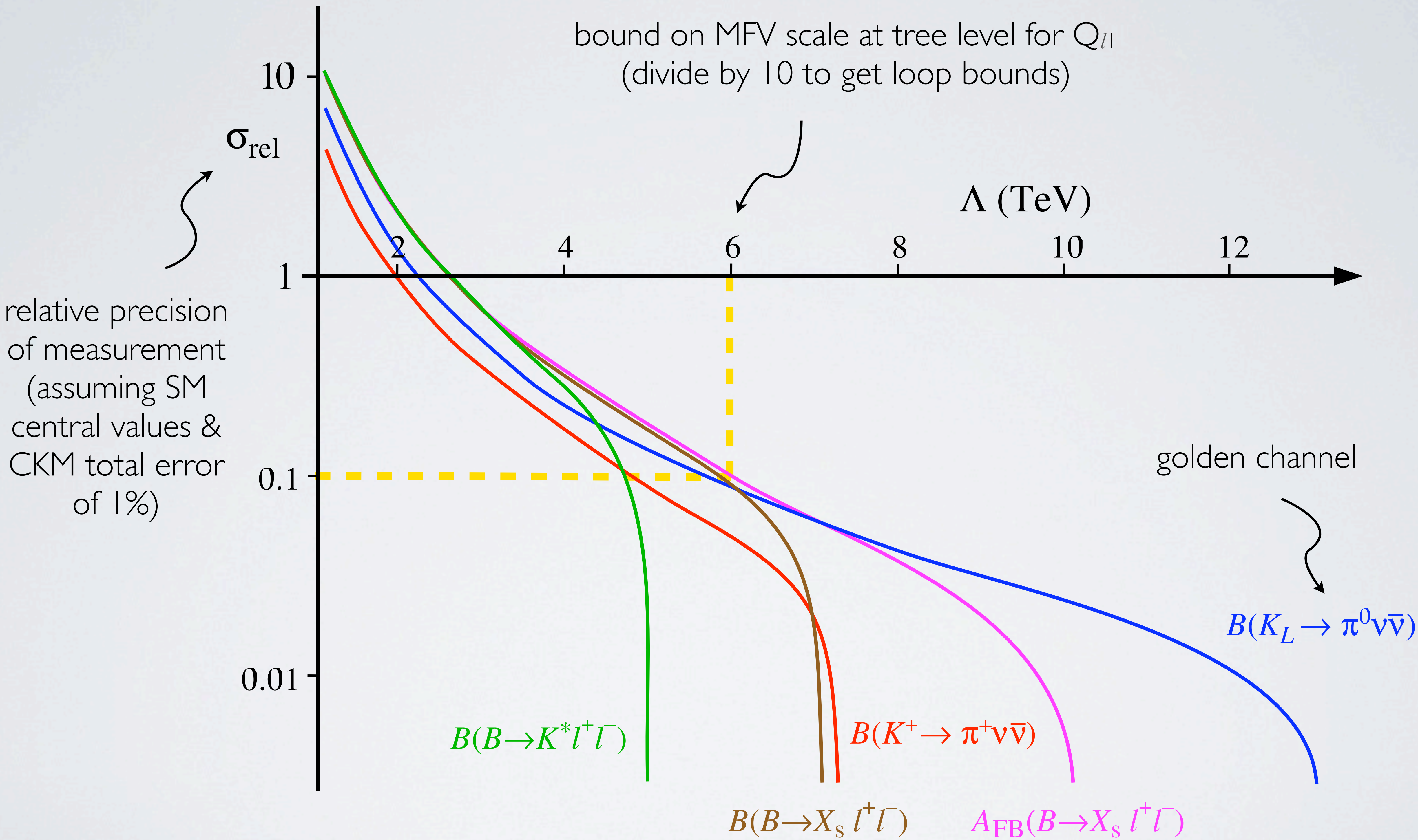
$Q_{\ell 3}$	2.7	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$Q_{\phi 1}$	2.3	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$Q_{\ell 1}$	1.7	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
Q_{F2}	1.5	$B \to X_s\ell^+\ell^-$

- Assuming a strong (weak) loop suppression the given lower limits for Q_{F1} & Q_0 translate into bounds of around 500 GeV (200 GeV). Even weaker limits apply in the case of the remaining operators

[UTfit Collaboration, arXiv:0707.0636; Hurth *et al.*, arXiv:0807.5039]

DISTINGUISHING MFV FROM SM IS HARD



[Bryman *et al.*,hep-ph/0505171; D'Ambrosio *et al.*,hep-ph/0207036]