Beauty 2014
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14th - 18th July 2014

Beyond the Standard Model

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Univerza *v Ljubljani*

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18/07/2014, Edinburgh

Introduction

SM phenomenologically very successful

Most likely just effective theory

Unification of interactions

$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{gauge}}(A_a, \psi_i) + D_\mu \phi^\dagger D^\mu \phi - V_{\mathrm{eff}}(\phi, A_a, \psi_i)$$

$$V_{\mathrm{eff}} = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 + Y^{ij} \psi_L^i \psi_R^j \phi + \frac{y^{ij}}{\Lambda} \psi_L^{iT} \psi_L^j \phi^T \phi + \ldots$$

EW scale stabilization

Origin of flavor

Introduction

SM phenomenologically very successful

Most likely just (experimentally accessible) effective theory

Baryogenesis

Unification of interactions

Dark matter?

$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{gauge}}(A_a, \psi_i) + D_\mu \phi^\dagger D^\mu \phi - V_{\mathrm{eff}}(\phi, A_a, \psi_i)$$

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EW scale stabilization

Origin of flavor

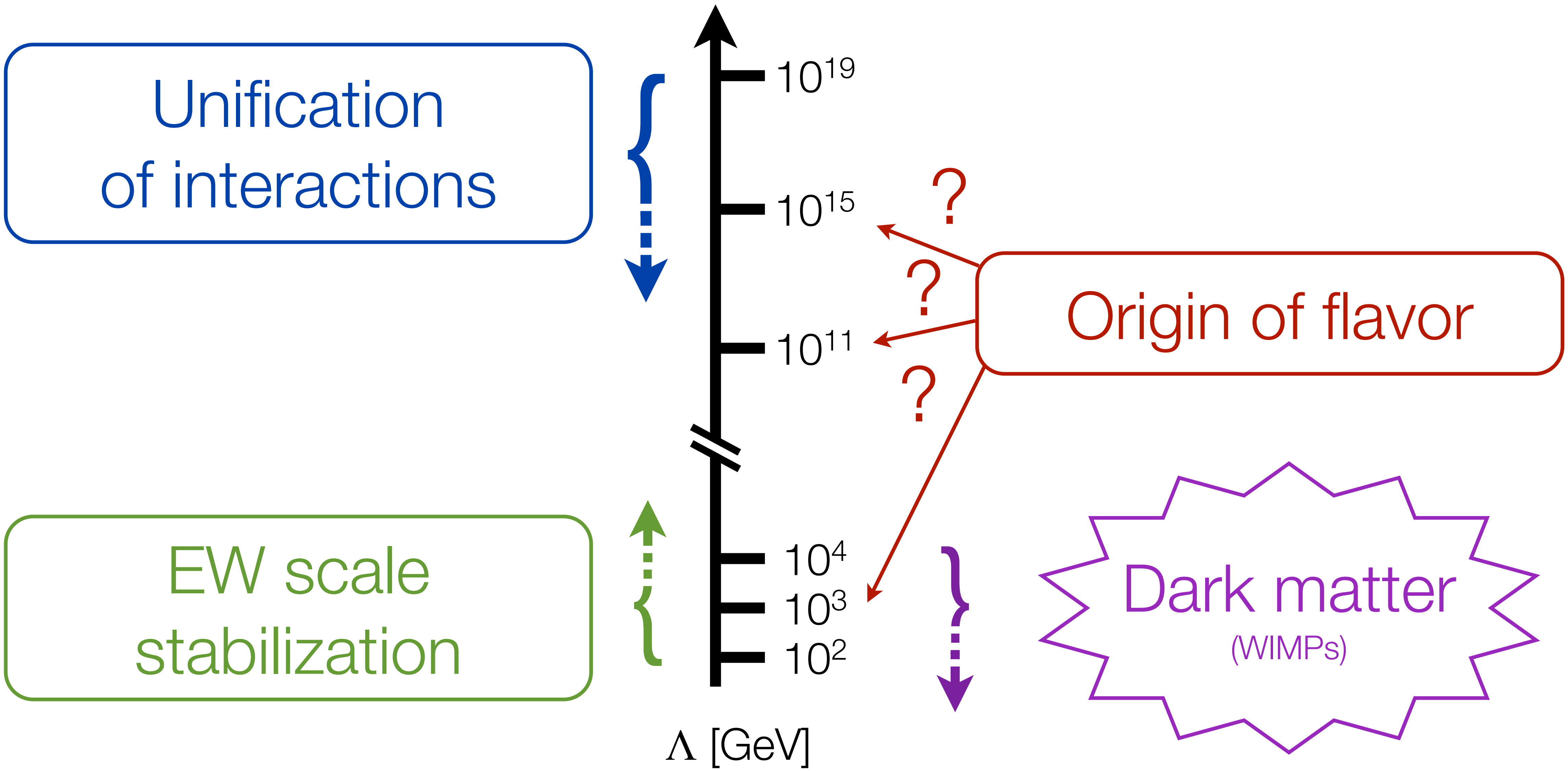
m_ν

Need to understand/constrain size of <u>additional terms in series</u>

Introduction

SM phenomenologically very successful

Most likely just (experimentally accessible) effective theory

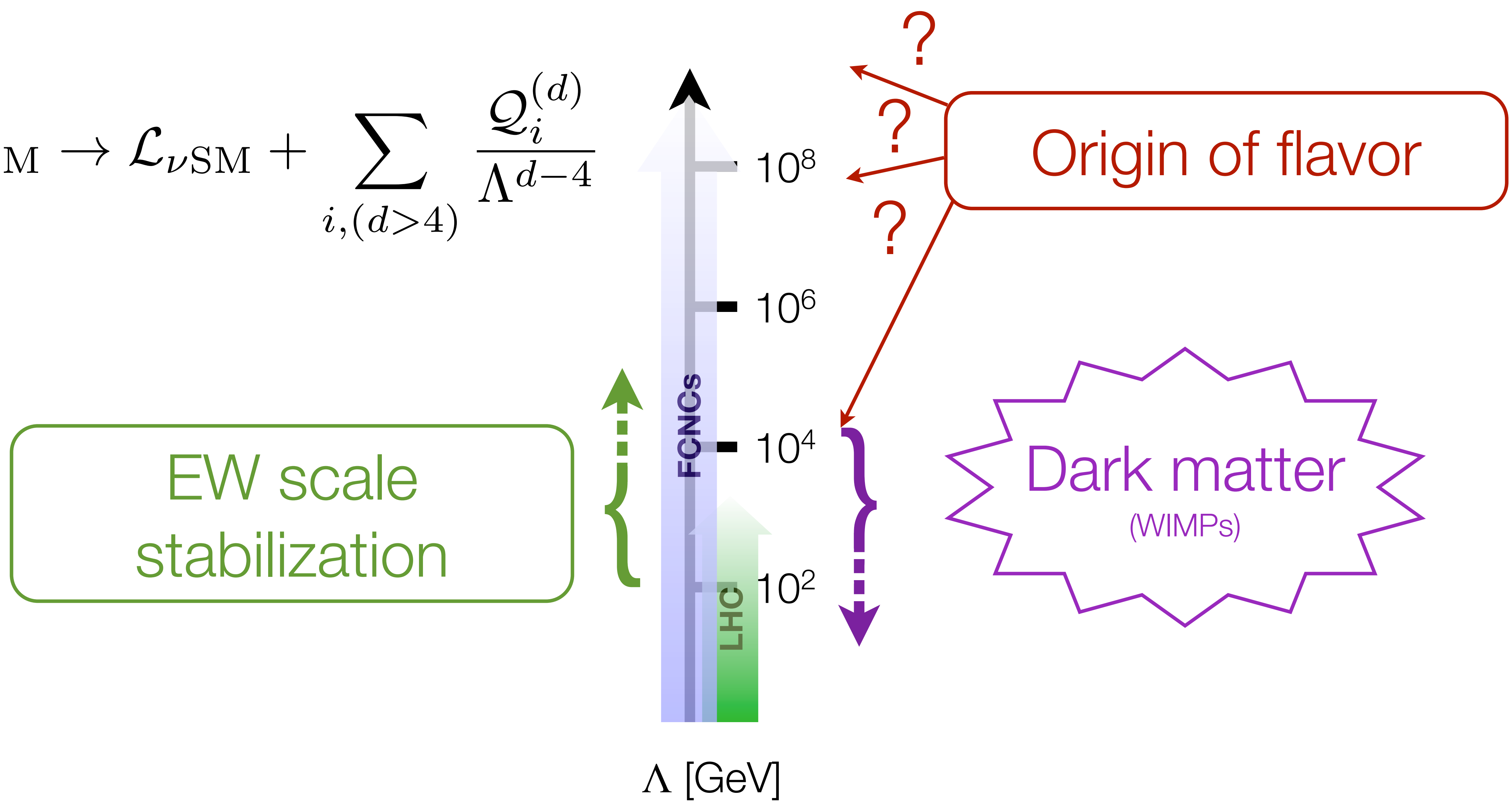


Introduction

Twofold role of flavor (B) physics

(1) Indirect probe of BSM physics beyond direct reach

$$\mathcal{L}_{\mathrm{BSM}} \to \mathcal{L}_{\nu\mathrm{SM}} + \sum_{i,(d>4)} \frac{\mathcal{Q}_i^{(d)}}{\Lambda^{d-4}}$$



Introduction

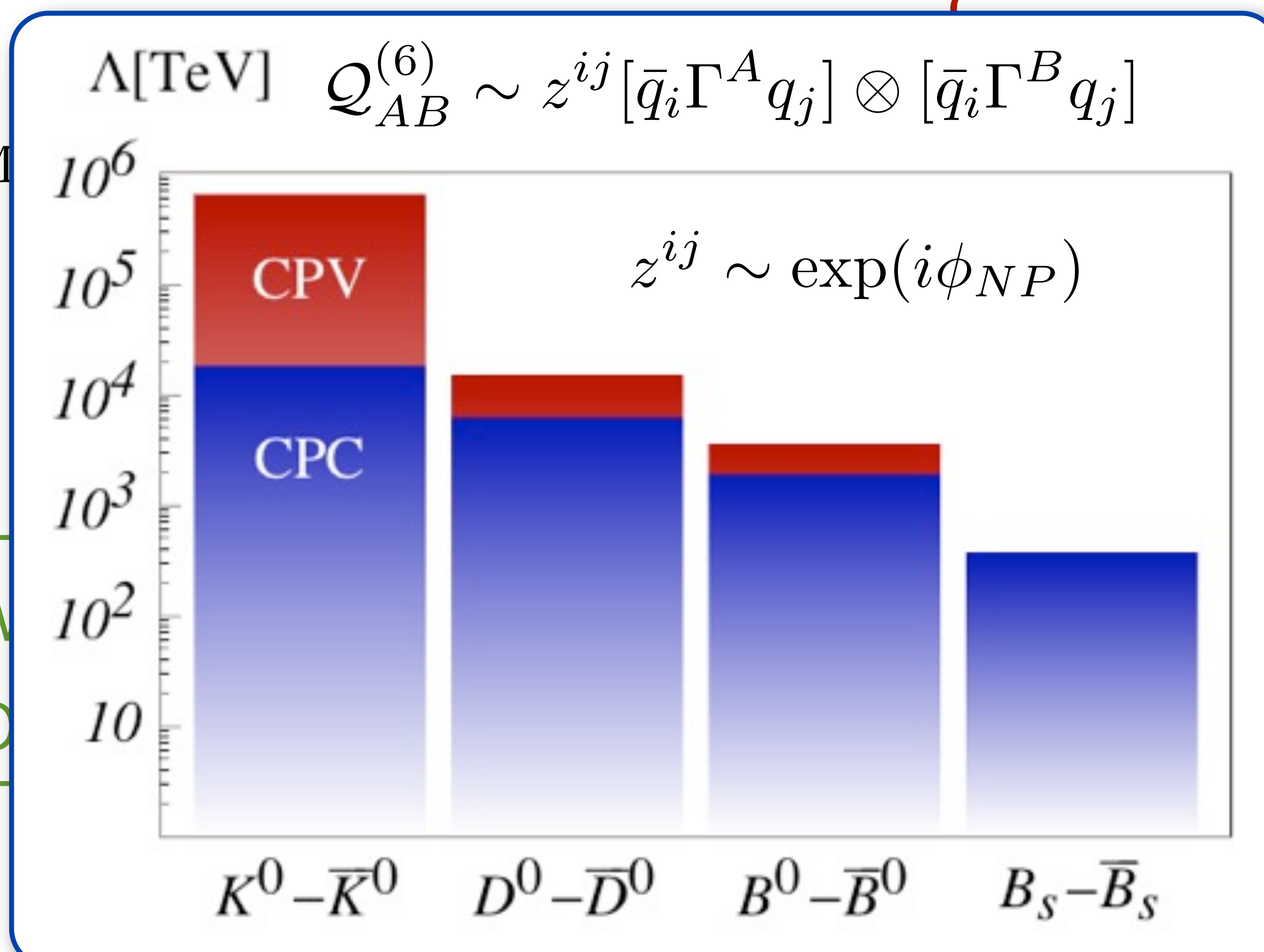
Twofold role of flavor (B) physics

(1) Indirect probe of BSM physics beyond direct reach

?

$\mathcal{L}_{\mathrm{BSM}} \to \mathcal{L}_{\nu\mathrm{SM}}$

n of flavor



EW
stab

matter
VIMPs)

Λ [GeV]

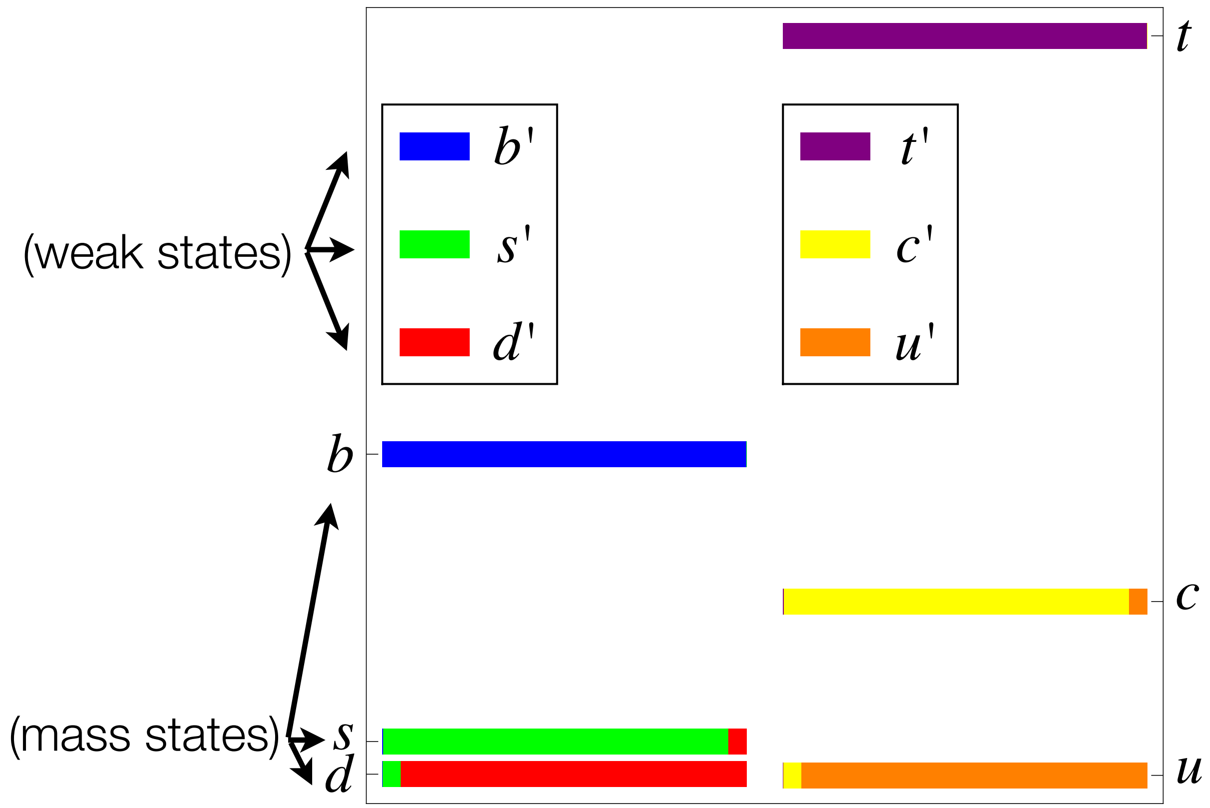
UTFit, 0707.0636
Isidori, Nir & Perez, 1002.0900
Lenz et al., 1203.0238
ETMC, 1207.1287

Introduction

Twofold role of flavor (B) physics

(2) Test sources of flavor symmetries & their violation

Suggestive pattern of masses and mixings



Accidental?

Dynamics?

Symmetries?

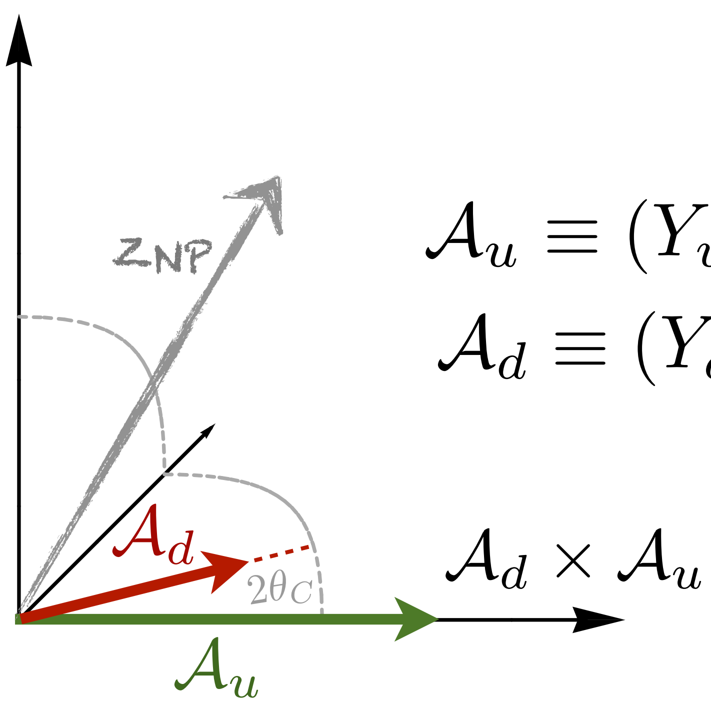
Introduction

Twofold role of flavor (B) physics

(2) Test sources of flavor symmetries & their violation

Global flavor symmetry of SM broken by Yukawas:

$$G_F = \boxed{SU(3)_Q} \times SU(3)_U \times SU(3)_D$$



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

SM contributions highly hierarchical & aligned

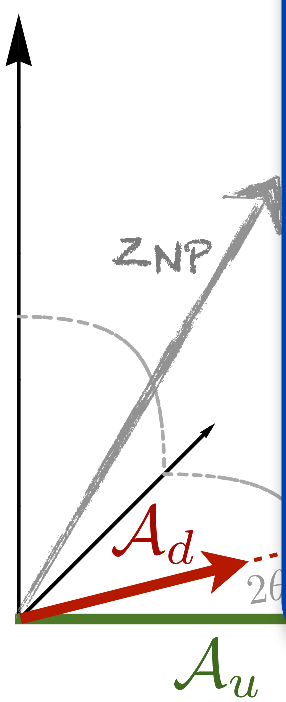
Severe constraints on generic BSM sources

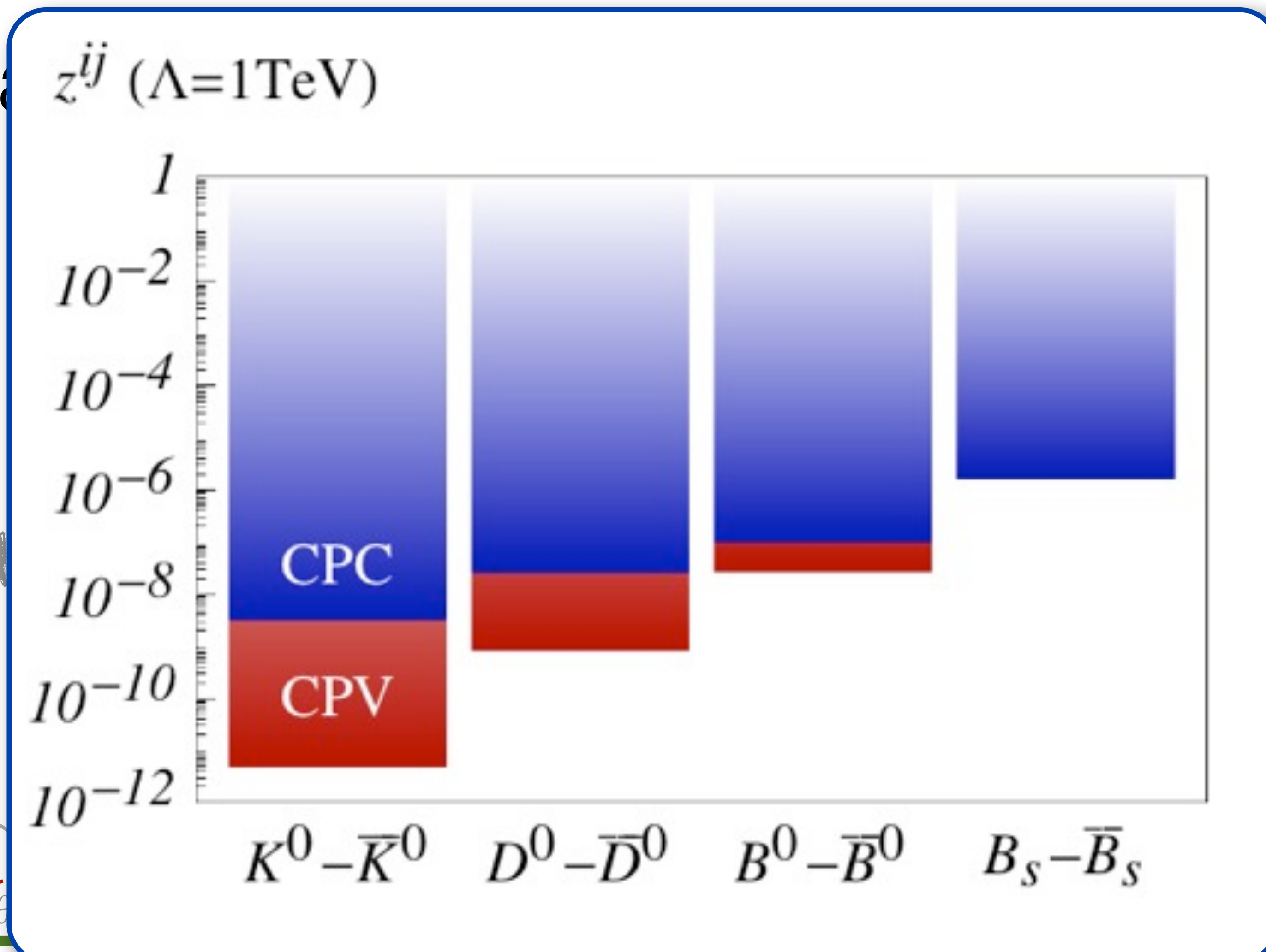
Introduction

Twofold role of flavor (B) physics

(2) Test sources of flavor symmetries & their violation

Global fl… …Yukawas:





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Reclaiming flavorful NP at EW scale

Reclaiming flavorful NP at EW scale

Global flavor symmetry of SM broken by Yukawas:

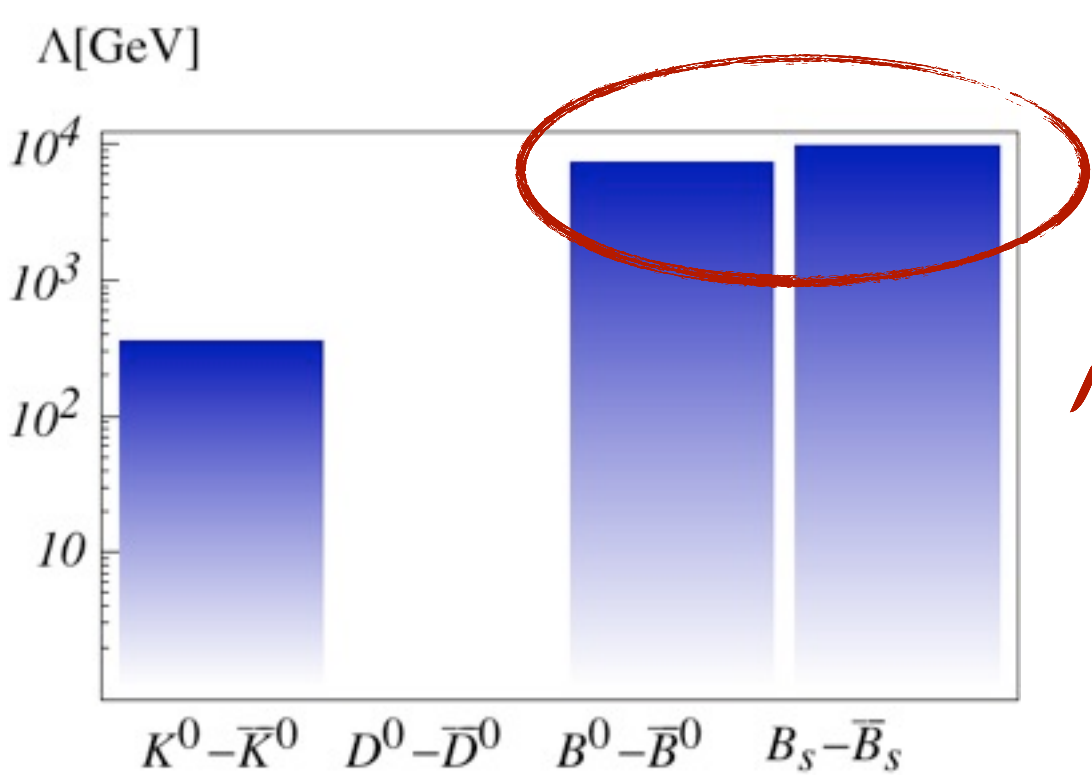
$$G_F = \boxed{SU(3)_Q} \times SU(3)_U \times SU(3)_D$$

Formally, <u>NP flavor cannot be completely trivial</u> $\int d^4x\, T\{\mathcal{Q}_{\rm NP}\, \mathcal{H}_{\rm SM}\}$

$$\mathbf{z} = \mathbf{1} + a_1 \mathcal{A}_u + a_2 \mathcal{A}_d + \ldots$$

$a_{i>2} \lesssim a_{1,2}$ “Minimal Flavor Violation”

d’Ambrosio et al., hep-ph/0207036
Colangelo et al., 0807.0801
...



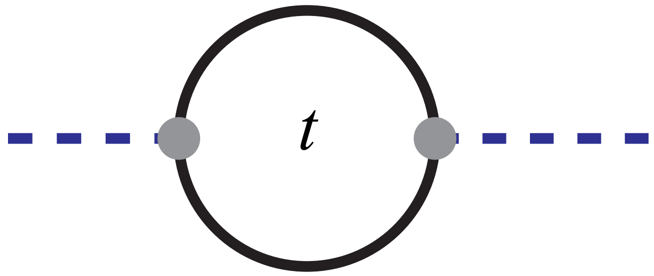
$$\mathcal{Q}^{(6)} \sim [\mathcal{A}_u^{ij} (\bar{Q}_i \gamma_\mu Q_j)]^2$$

Most stringent bounds from B sector

Reclaiming flavorful NP at EW scale

Flavor triviality imposes degeneracy in NP spectra - problematic for naturalness@LHC

In SM, top Yukawa imposes largest fine-tuning in Higgs potential ⇒



$$\delta m_h^2 \sim \frac{m_t^2}{v^2}\Lambda^2$$

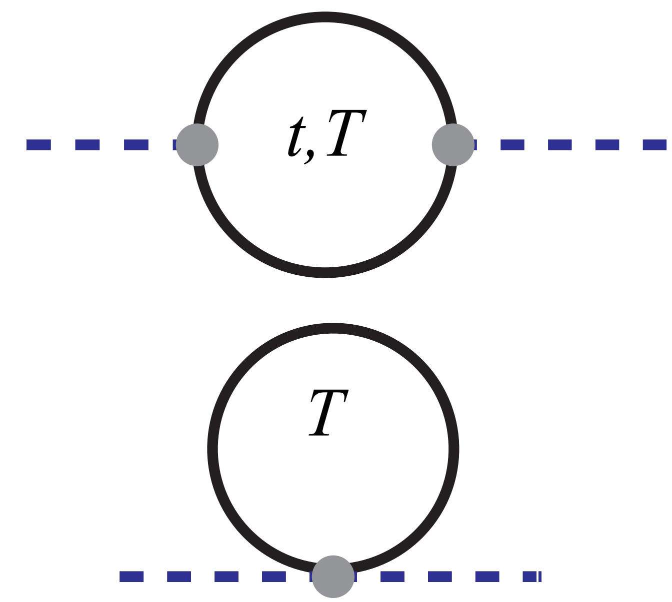
Reclaiming flavorful NP at EW scale

Flavor triviality imposes degeneracy in NP spectra - problematic for naturalness@LHC

In SM, top Yukawa imposes largest fine-tuning in Higgs potential ⇒

$$\delta m_h^2 \sim \cancel{\frac{m_t^2}{v^2}\Lambda^2} + \frac{m_t^2}{v^2} m_T^2 \log\frac{\Lambda^2}{m_T^2} + \dots$$

prefer light top partners ($m_T < 1\,\mathrm{TeV}$)



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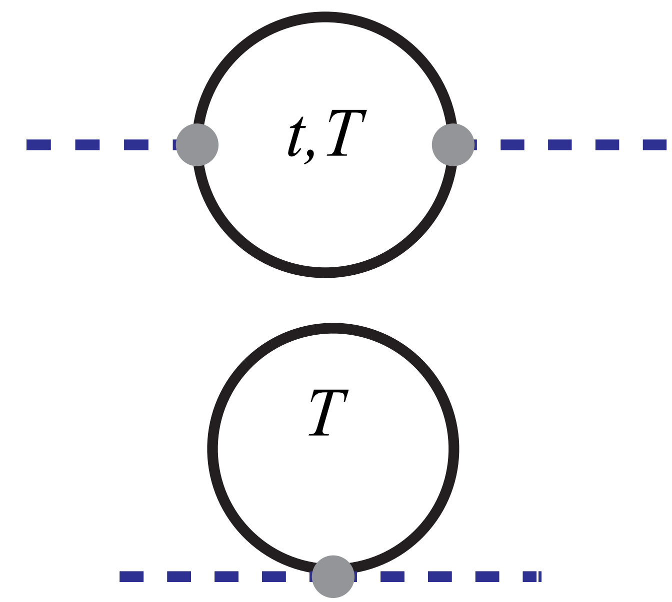
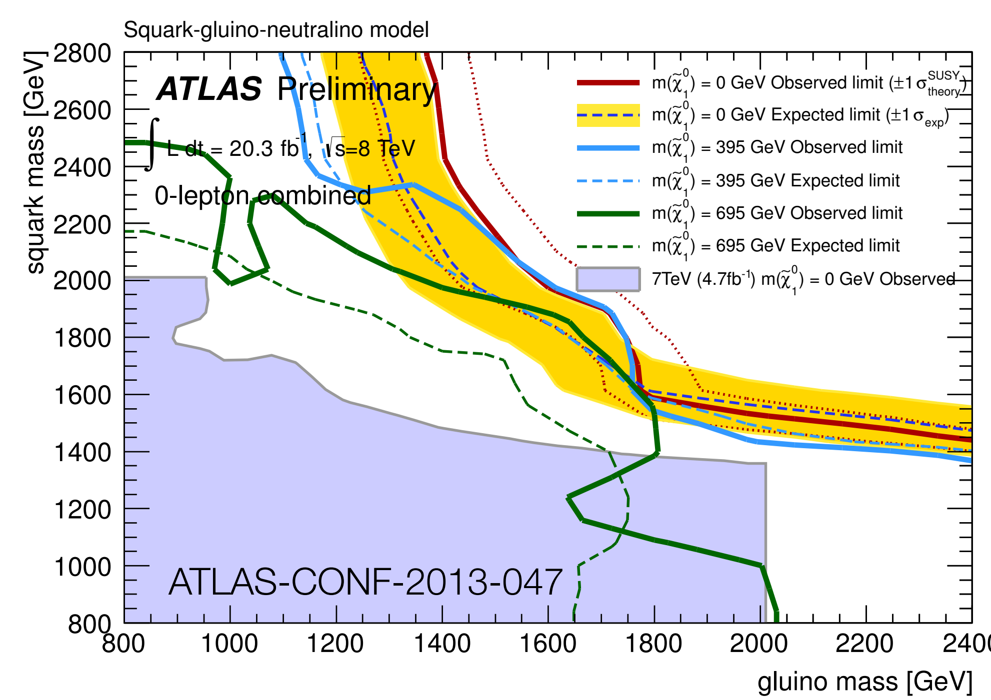


prefer light top partners ($m_T < 1\,\mathrm{TeV}$)

avoiding flavor bounds though triviality ⇒ presence of u,d,... partners ($m_U \sim m_T$)



Strong LHC direct search constraints
(MSSM example)

Reclaiming flavorful NP at EW scale

EW hierarchy stabilization only requires light 3rd generation partners ⇒ LHC bounds then imply flavor nontrivial spectra

Possible in flavor models mimicking the SM SU(3)/SU(2) flavor breaking pattern (i.e. $U(2)^3$)

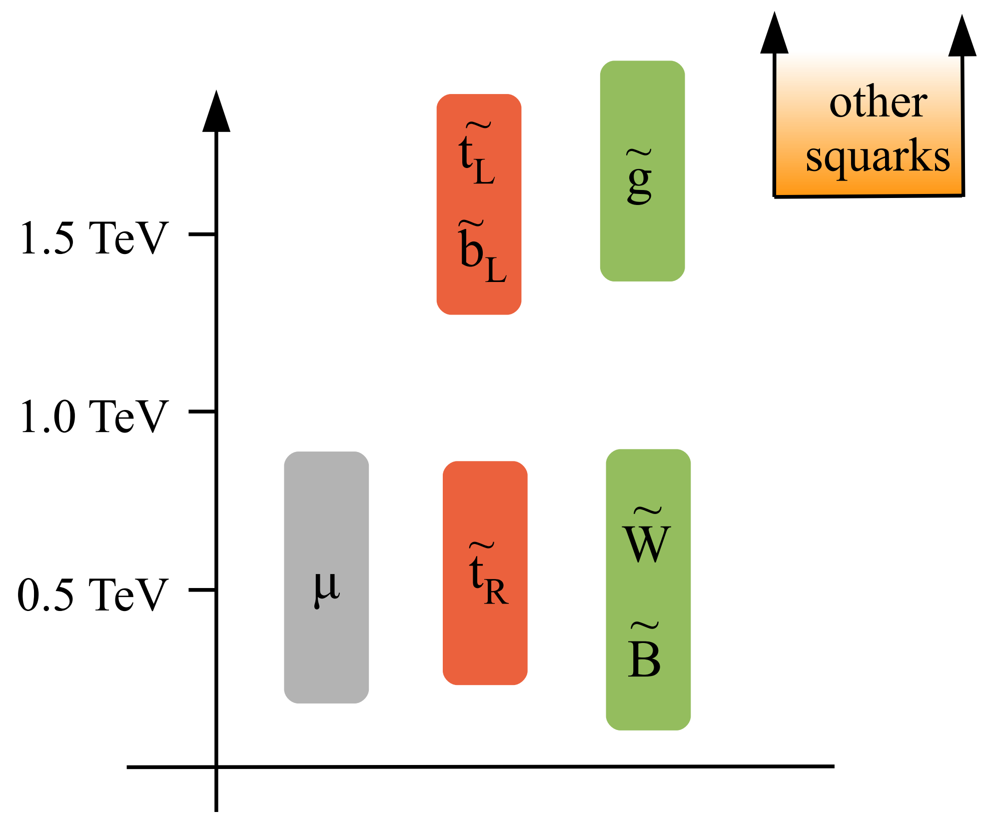
Kagan et al., 0903.1794
Buras & Girrbach, 1206.3878
Barbieri et al., 1105.2296
1108.5125
1203.4218
1206.1327
1211.5085

Example: natural SUSY

BSM flavor effects mediated by 3rd generation squarks (& sleptons)

Key observables:

- (CPV) in K(ε_K), B mixing (Δm_q, ϕ_q)
- Rare B decays ($B \to (X) l^+ l^-, \nu\nu$)
- LFV & EDMs



Isidory @ ICHEP'14

Reclaiming flavorful NP at EW scale

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Possible in flavor models mimicking the SM SU(3)/SU(2) flavor brea

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BSM gene

Key

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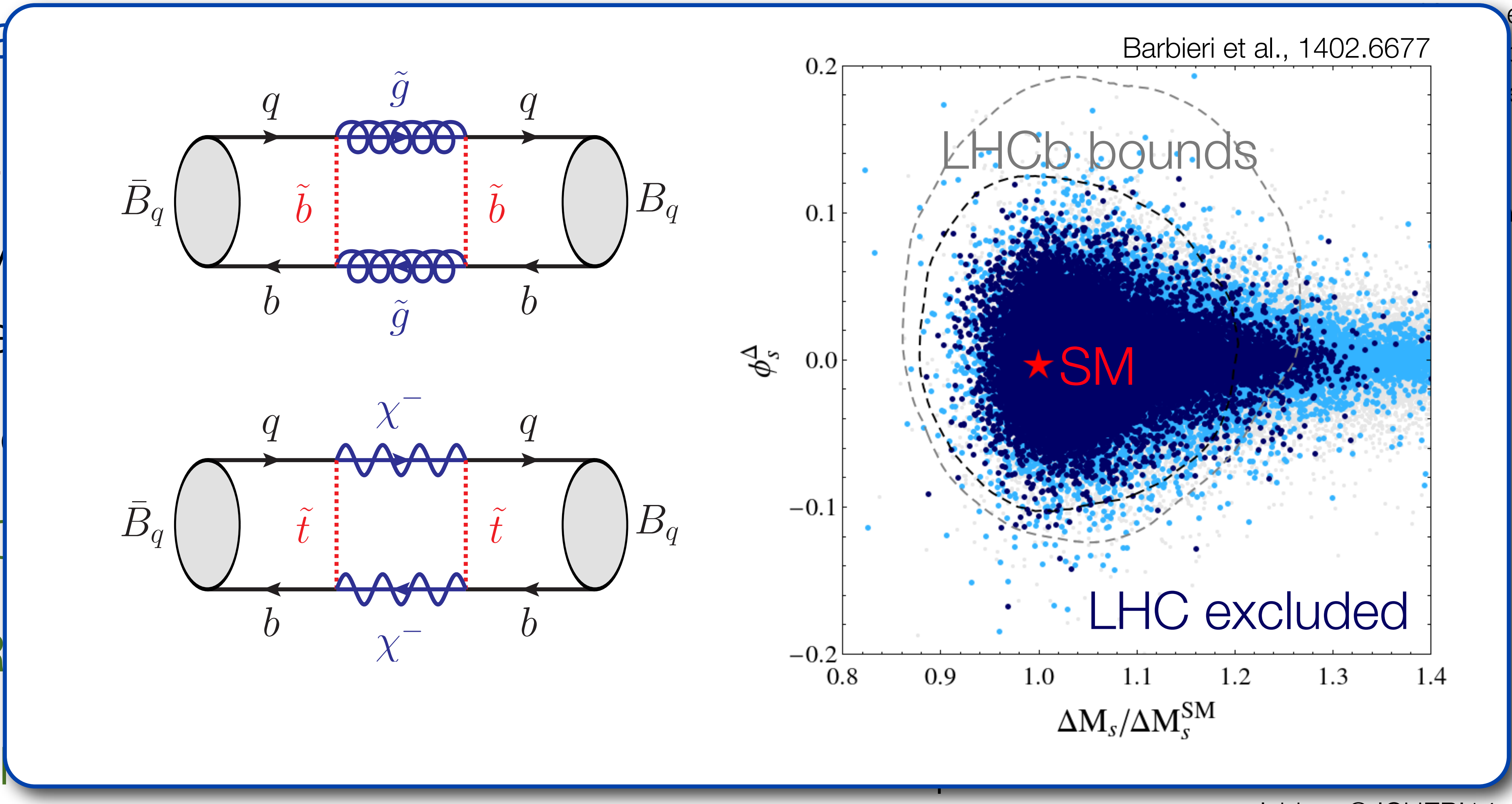

et al., 0903.1794
bach, 1206.3878
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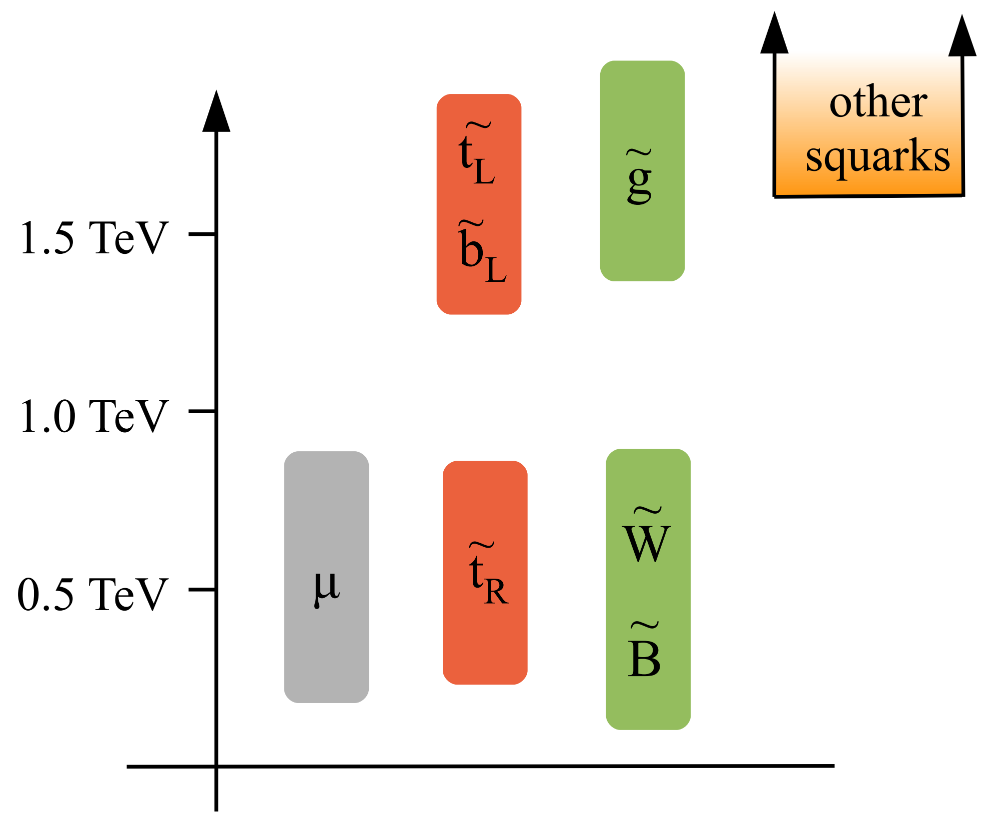


Isidory @ ICHEP'14

$B_{s,d} \to \mu^+\mu^-$

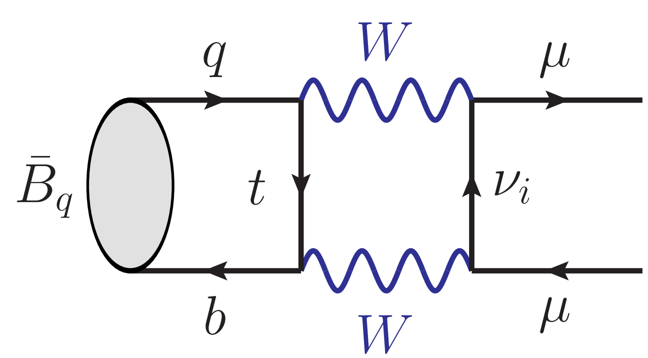
see talk by Misiak

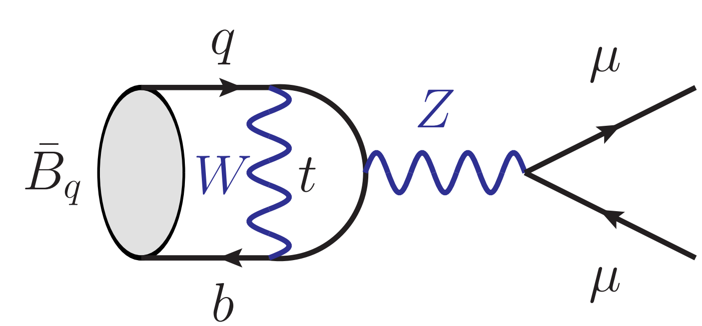
Particularly sensitive to FCNC scalar currents and FCNC Z penguins

Clean probe of the Yukawa interaction (⇒ Higgs sector)

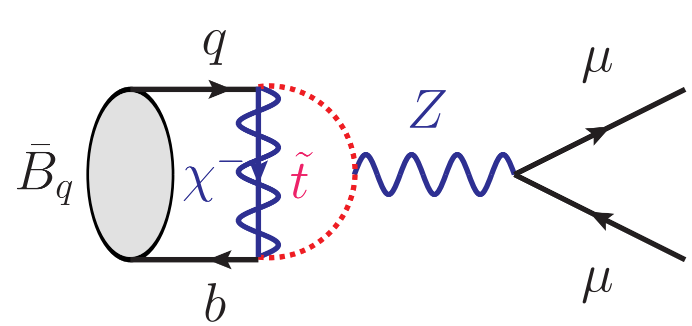
beyond tree level (virtually no long-distance contributions)

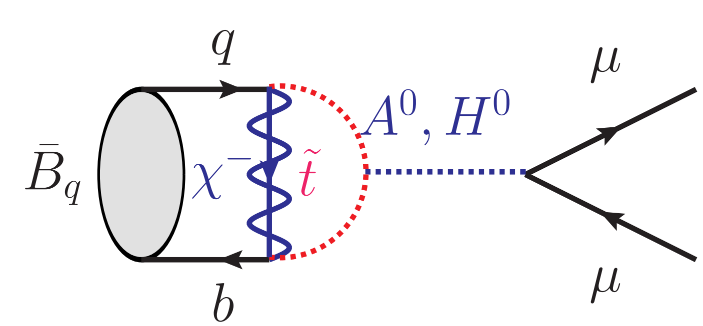
Leading SM contributions:





Examples in natural SUSY:





(large $\tan\beta$ solutions excluded)

$B_{s,d} \to \mu^+\mu^-$

Particularly sensitive to FCNC scalar currents and FCNC Z penguins

Clean probe of the Yukawa interaction (⇒ Higgs sector)

beyond tree level (virtually no long-distance contributions)

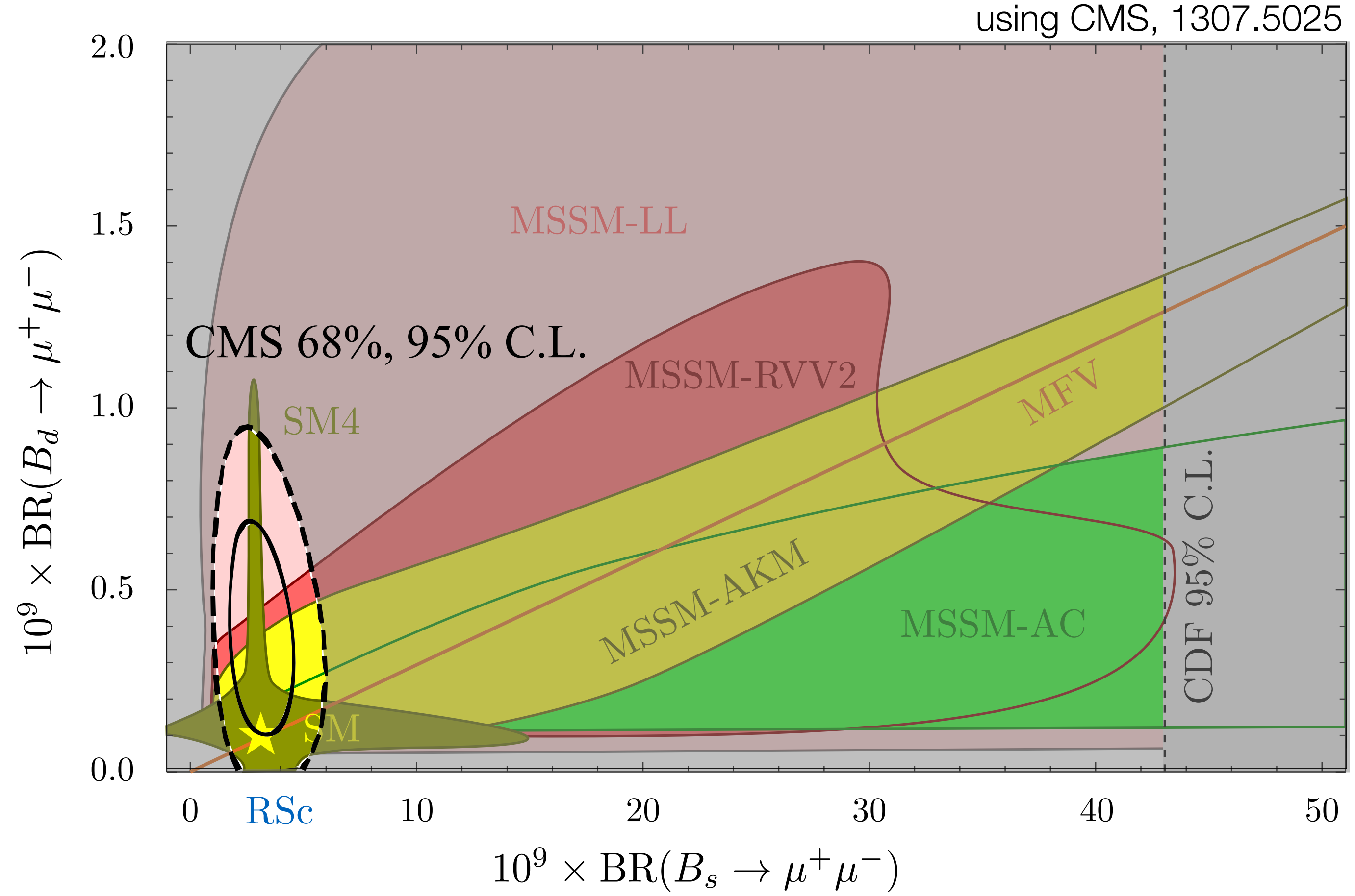
Latest results beginning to test possible $\mathcal{B}_d/\overline{\mathcal{B}}_s$ enhancement

Nontrivial test of MFV.
Hurth et al., 0807.5039

Example:

SUSY flavor models

update of Straub, 1012.3893
using CMS, 1307.5025



$b \to s\, \mu^+\mu^-$

Similar to $B_s \to \mu^+\mu^-$ in probing semileptonic $b \to s$ FCNCs and Z-penguins

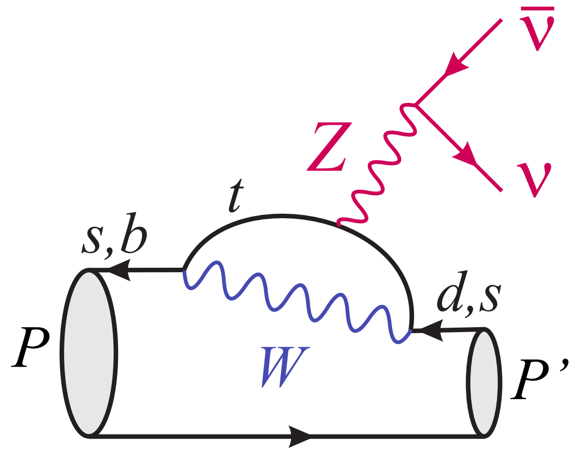
Caveat: LD (charming penguin) contributions need to be controlled!

see talk by Bobeth

Complementary observables: $b \to s\ \nu\nu$

No non-local QCD contributions (but need precise form factor estimates)

c.f. Altmannshofer et al., 0902.0160



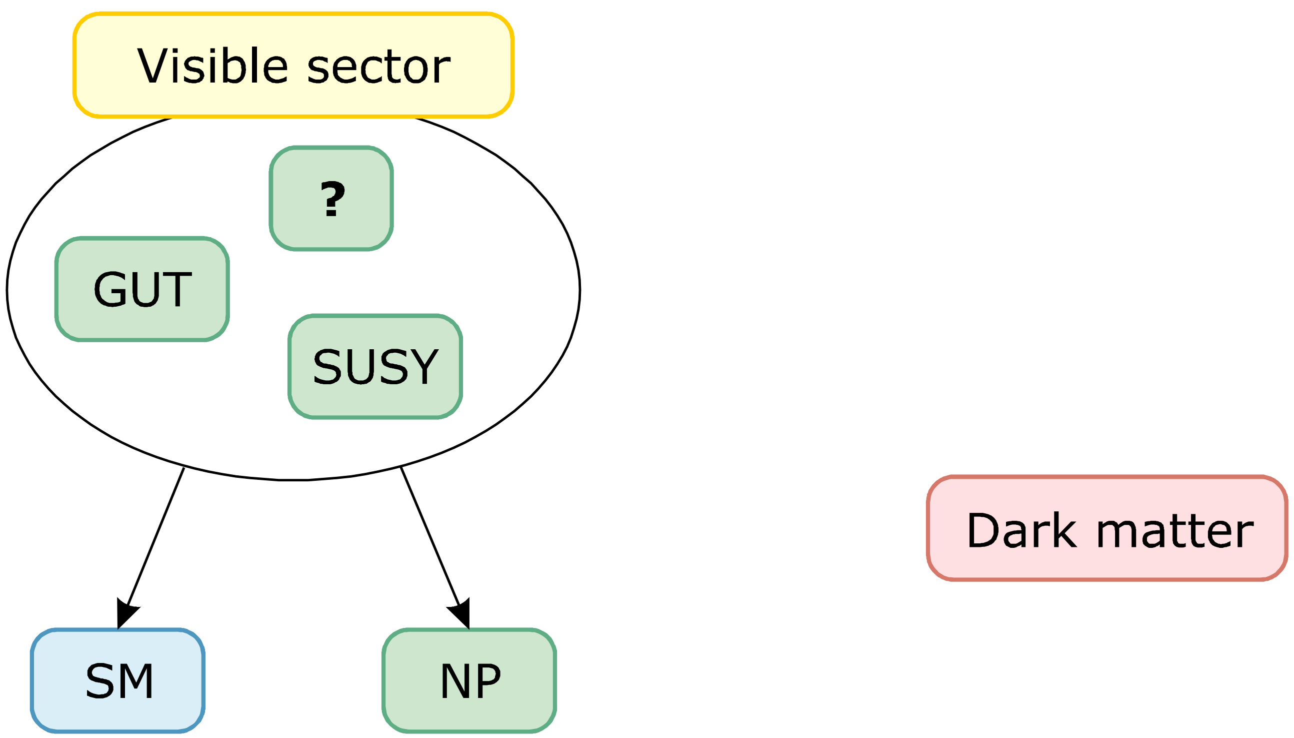
Key measurements for BelleII

Flavor portals to dark sector

Are there only SM particles at low-energy?

- **Experimentally:**
  - Even very light states could be missed if very weakly interacting,
  - There is dark matter in the Universe; it could be relatively light.
- **Theoretically:** Plenty of models predict new light particles
  - Pseudo-Goldstone scalars (axion, familon,...),
  - U(1) vectors (string, ED,...),
  - Hidden sectors & messengers (SUSY, mirror worlds,...)
  - Many others: millicharged fermions, dilaton, majoron, neutralino, sterile neutrino, gravitino,...

How to probe low-energy particle content?



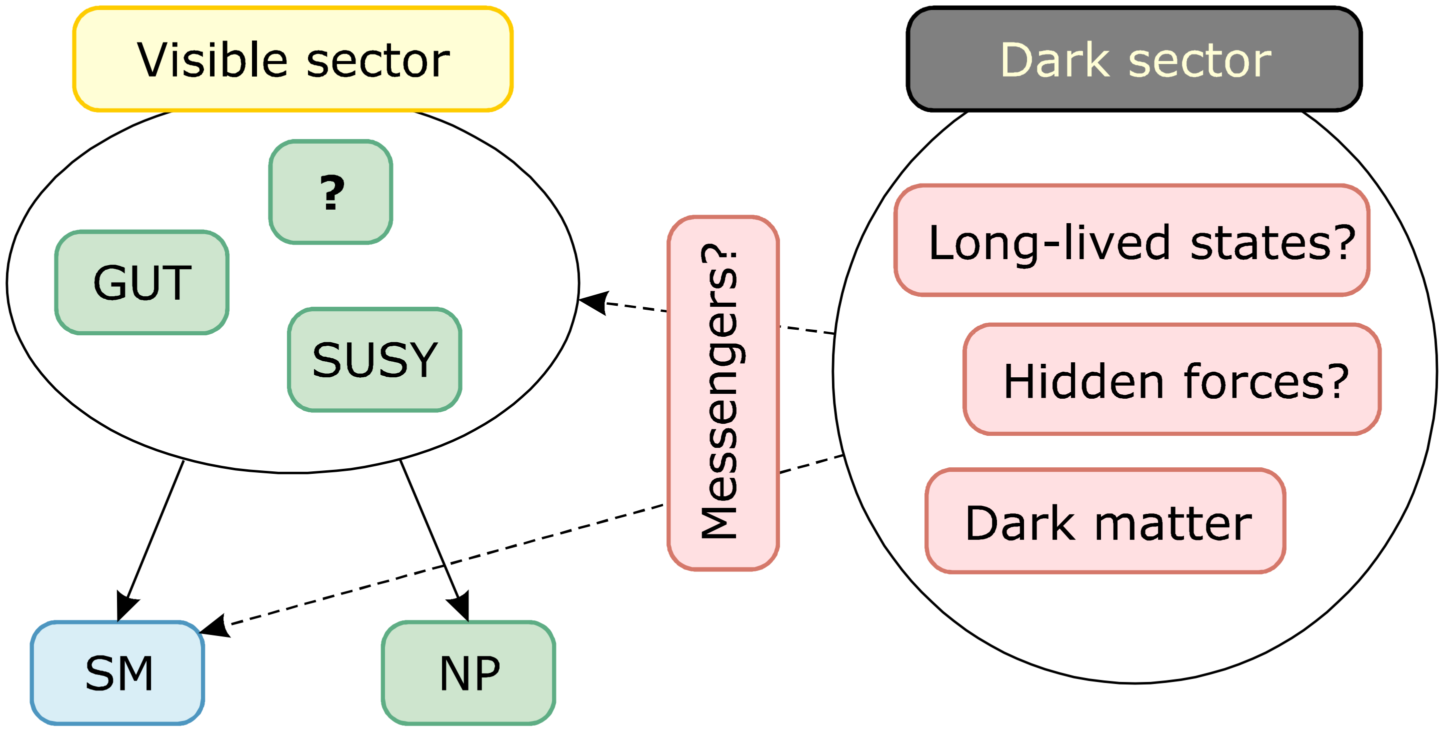
taken from C. Smith @ LPC - Clermont-Ferrand, 4/2012

- Heavy NP can be projected onto effective gauge-invariant operators built in terms of SM fields.

Buchmuller & Wyler, Nucl.Phys. B268 (1986) 621
Grzadkowski et al., arXiv:1008.4884

$$\mathcal{L}_{SM} + \frac{c_\nu}{\Lambda}(HL)^2 + \frac{c_i}{\Lambda^2} Q_i + \ldots$$

How to probe low-energy particle content?



X = dark sector state connected to the SM, or a light messenger.

taken from C. Smith @ LPC - Clermont-Ferrand, 4/2012

- Take X as neutral, but include all possible interactions as SM gauge-invariant effective operators.

J. F. K. & C. Smith, 1111.6402

$$\mathcal{L}_{SM} + \frac{c_\nu}{\Lambda}(HL)^2 + \frac{c_i}{\Lambda^2}Q_i + \ldots \qquad + \sum_{d\geq 3} \frac{c_i}{\tilde{\Lambda}^{d-4}} Q_i' + \ldots$$

How to probe low-energy particle content?

- Assumptions about the dark state X :
  - Not stable ⇒ No DM constraints!
  - Long-lived ⇒ Escapes as missing energy.
  - Weakly coupled ⇒ Does not affect SM processes.
- ⇒ Main impact is then to open new decay and production channels.

How to probe low-energy particle content?

- Assumptions about the dark state X :
  - Not
  - Lor
  - We
- ⇒ Ma

chann

m_X[GeV]	(decay probes)	(SM width suppression)
100	Higgs boson	loop, helicity, phase-space
10	Quarkonium	Zweig rule
	K & B FCNCs	loop, CKM
1	LFV	neutrino mass
0.1	Light mesons	loop, helicity
0.001	Orthopositronium	phase-space

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chann

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1		
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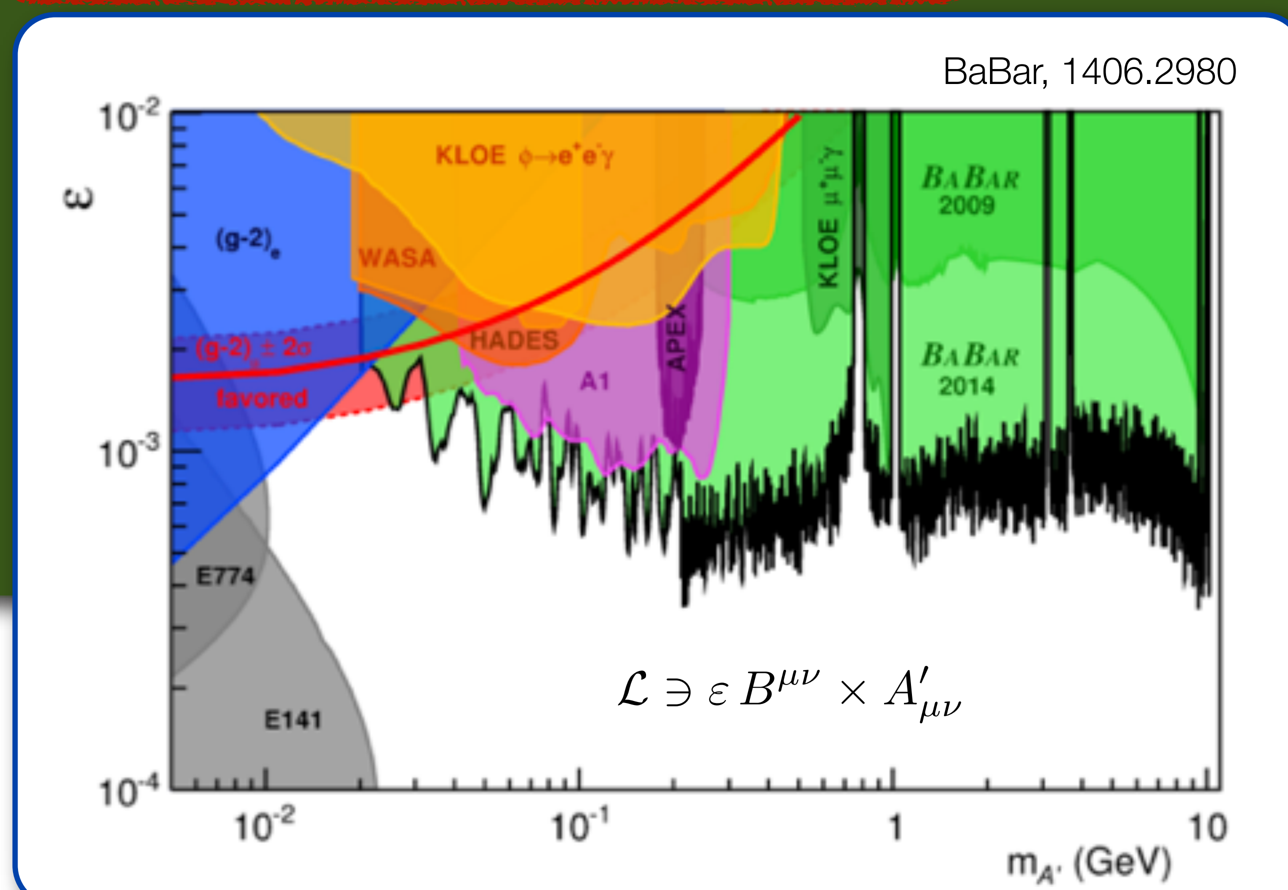

Recent example:
hidden photons

How to probe low-energy particle content?

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chann

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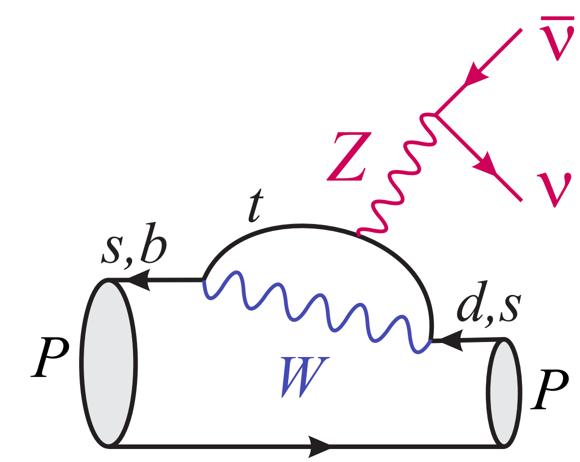
Flavor probes of the invisible

- FCNC meson decays with E_{miss} CKM suppressed in SM

$$d^I \to d^J X \; : \qquad \frac{g^2}{M_W^2}\frac{g^2}{16\pi^2}|V_{tI}^* V_{tJ}| \; ,$$

$$\mathcal{B}(K \to \pi E_{miss}) \sim 10^{-11}$$

$$\mathcal{B}(B \to K^{(*)} E_{miss}) \sim 10^{-6}$$

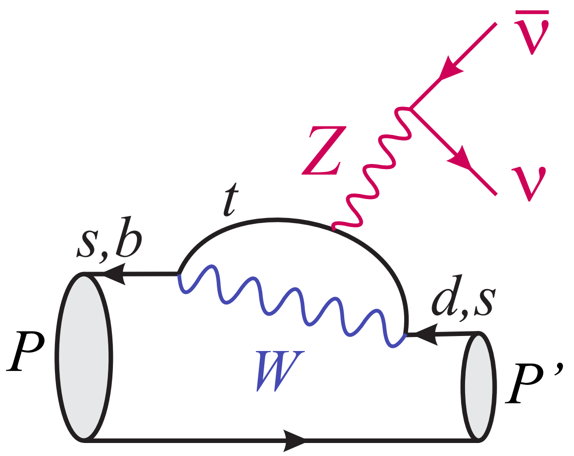


Flavor probes of the invisible

- FCNC meson decays with E_{miss} CKM suppressed in SM

$$d^I \to d^J X \,:\, c^{IJ}\frac{m_I^{n-6}}{\Lambda^{n-4}} \approx \frac{g^2}{M_W^2}\frac{g^2}{16\pi^2}|V_{tI}^* V_{tJ}| \,,$$

(n-dim X-NP ≈ SM)



- Potentially very high X-operator scales probed:

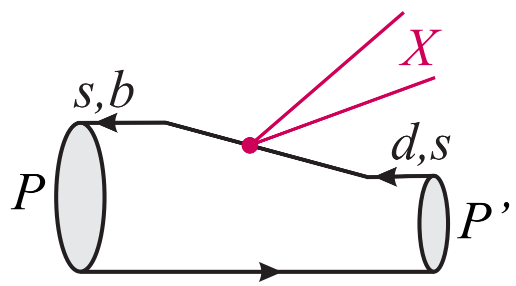
$c^{I\neq J} \sim \mathcal{O}(1)$

	$n=5$	$n=6$	$n=7$
$s \to d$	$3.3 \cdot 10^7$ TeV	130 TeV	2.0 TeV
$b \to d$	$1.3 \cdot 10^5$ TeV	26 TeV	1.5 TeV
$b \to s$	$2.7 \cdot 10^4$ TeV	12 TeV	0.9 TeV

$$\mathcal{H}_{eff}(q^I \to q^J X) = \frac{c^{IJ}}{\Lambda^n}\bar{q}^I q^J \times X$$

Flavor - based classification of dark operators

Flavor-violating ($c^{I \neq J} \neq 0$)



- Bounds directly derived from $d_I \to d_J X$ processes.

- When MFV holds, $c^{I\,J} \sim \lambda^{IJ}$ times appropriate chirality flip factors $(m_{I,J}/v)$.

$$\lambda^{IJ} = \mathbf{Y}_u^\dagger \mathbf{Y}_u \approx V_{tI}^* V_{tJ} \to \begin{cases} \lambda^{sd} \approx (-3.1 + i1.3) \times 10^{-4} \,, \\ \lambda^{bd} \approx (7.8 - i3.1) \times 10^{-3} \,, \\ \lambda^{bs} \approx (-4.0 - i0.07) \times 10^{-2} \,. \end{cases}$$

Flavor - based classification of dark operators

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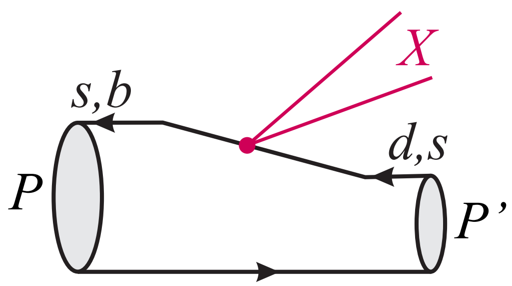
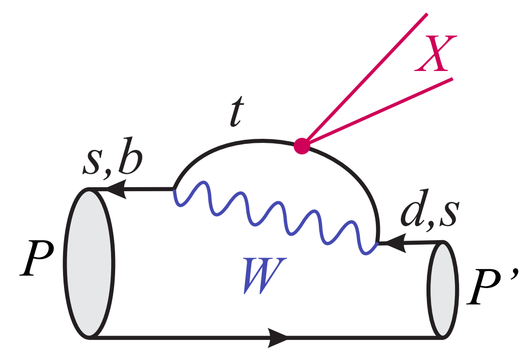


Flavor-conserving ($c^{I\neq J} = 0$)

Heavy quark: $q = (c), t$



- Same local operator basis, but with the coefficients rescaled as $c^{I\,J} \sim c^{tt}\, k^{IJ}$ times appropriate chirality flip factors $(m_{I,J}/v)$.

$$k^{IJ} = \frac{g^2}{16\pi^2}\lambda^{IJ} \to \begin{cases} k^{sd} \approx (-0.8 + i0.4) \times 10^{-6} \,, \\ k^{bd} \approx (2.1 - i0.8) \times 10^{-5} \,, \\ k^{bs} \approx (-1.1 - i0.02) \times 10^{-4} \,. \end{cases}$$

Flavor - based classification of dark operators

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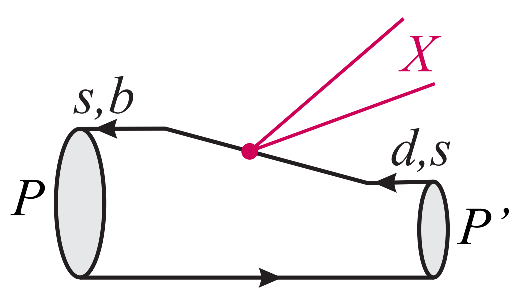

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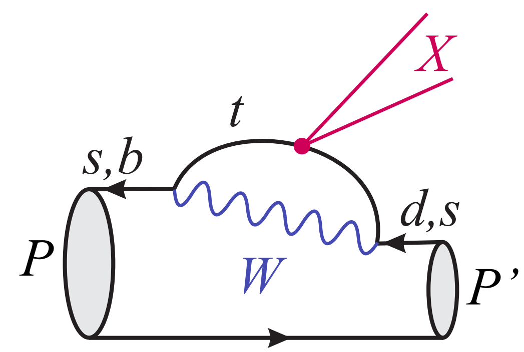
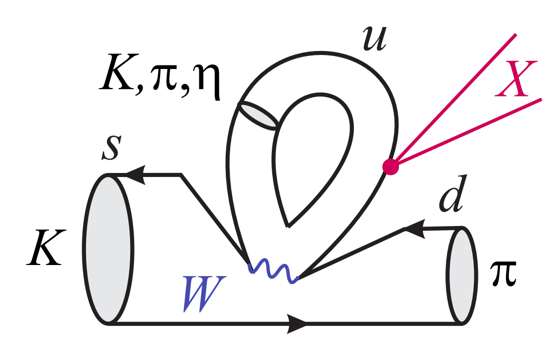
Heavy quark: $q = (c), t$



Light quarks: $q = u, d, s, (c)$

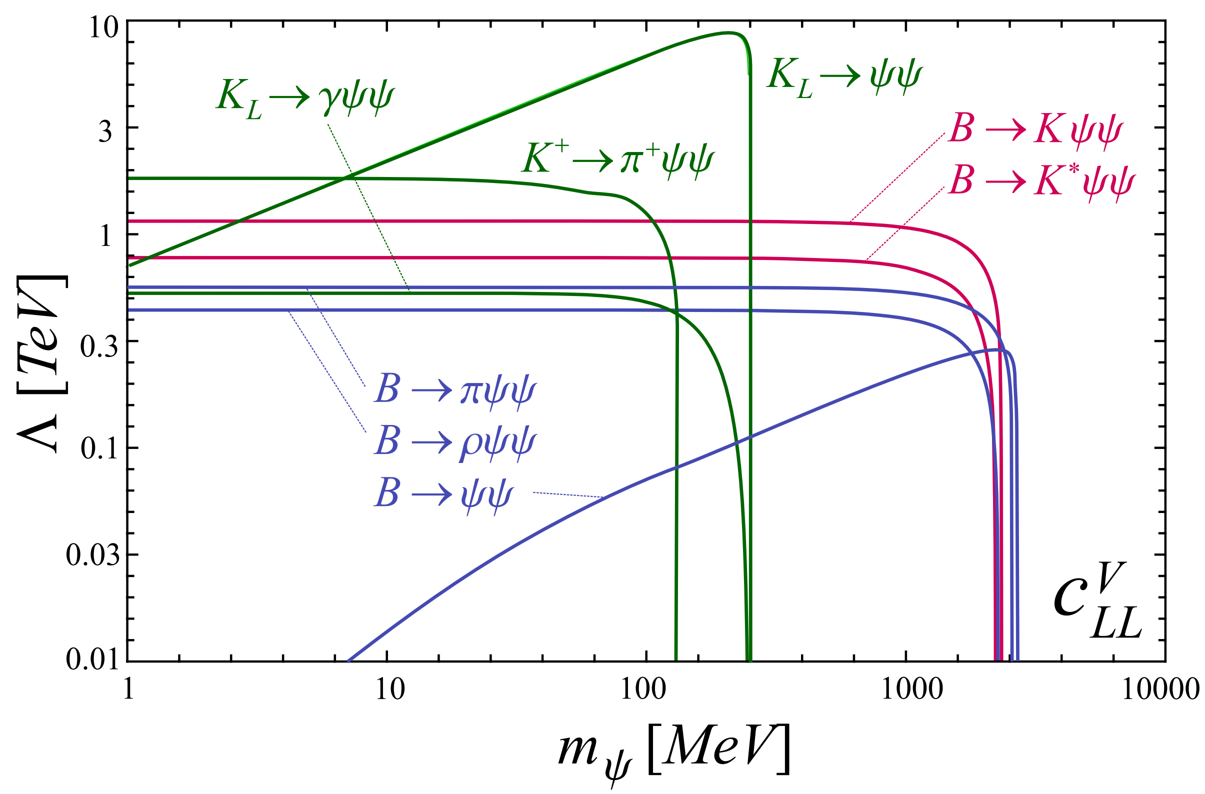


- Due to small V_{ub}, B decays not competitive.
- For K decays, $q = u$ contributions are dominant but non local, and require controlling long-distance hadronic effects.

Beyond the scaling argument: Kinematics

Importance of combining several available modes

MFV example: $$\frac{V_{ti}^* V_{tj}}{\Lambda^2} \bar{Q}^i \gamma_\mu Q^j \times \bar{\psi}_L \gamma^\mu \psi_L$$



Current bounds assuming flat exp. acceptances

Observational hints

Several recent intriguing flavor anomalies

ΔA_{CP}

A_{sl}^b

P_5'

$R_{\tau/\ell}^{(*)}$

R_K

Several recent intriguing flavor anomalies

ΔA_{CP}

A^b_{sl}

P'_5

$R^{(*)}_{\tau/\ell}$

R_K

Theorists often taken by surprise

⇒ Don’t listen to us too much

Several recent intriguing flavor anomalies

ΔA_{CP} A^b_{sl} P'_5 $R^{(*)}_{\tau/\ell}$ R_K ?

Theorists often taken by surprise

Proposed BSM explanations not always very elegant

Several recent intriguing flavor anomalies

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Prompt reevaluation of possible SM effects

Several recent intriguing flavor anomalies

ΔA_{CP}

A^b_{sl}

P_5'

$R^{(*)}_{\tau/\ell}$

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Proposed BSM explanations not always very elegant

Prompt reevaluation of possible SM effects

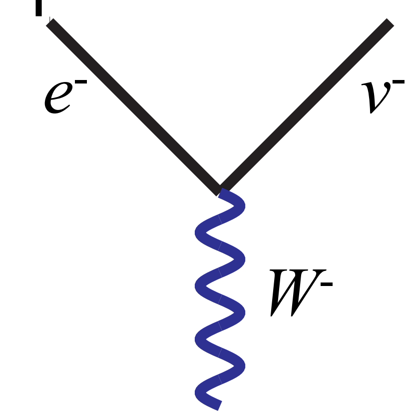
Unfortunately, some deviations of limited duration

If any such hint would be confirmed, tremendous implications for high p_T searches

Flavor as guide to high p_T

LFU in (semi)leptonic B decays

In SM weak charged current interactions are lepton flavor universal



- Tested directly at colliders via *W* decays ~1%

Additional charged (scalar) interactions could induce LFU violation in processes at low energies

Can be predicted accurately even in hadronic processes, since most QCD uncertainties cancel in ratios

- Pion, kaon, *D* processes well consistent with LFU expectations ~(0.1-1)%

c.f. HFAG, 1010.1589

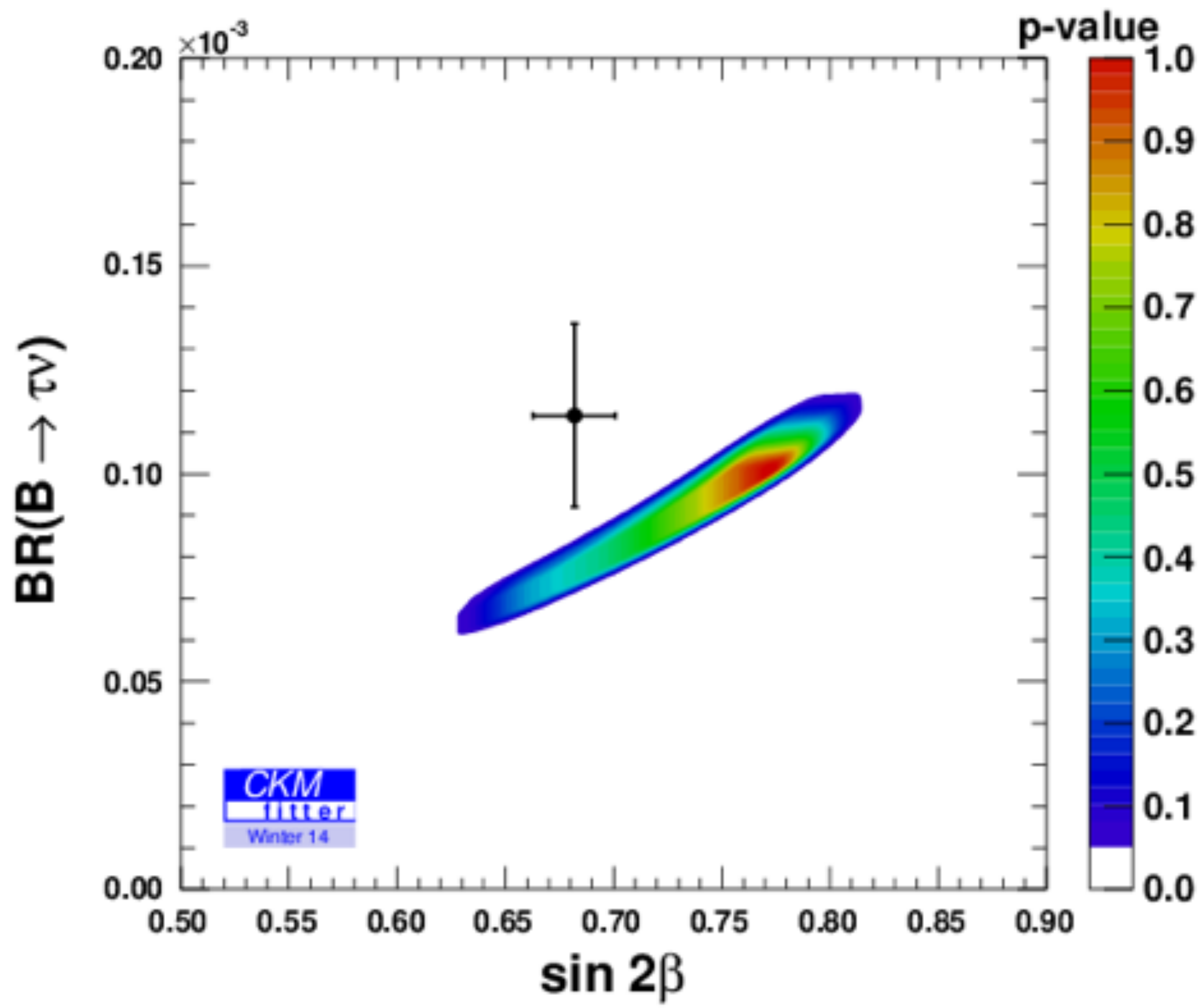
LFU in (semi)leptonic B decays

Apparent tension in global CKM unitarity fits

Discrepancy between $|V_{ub}|$ determinations see talks by Kwon, Bharucha

Most pronounced for taunic *B* decay

Somewhat reduced with updated Belle result Belle, 1208.4678



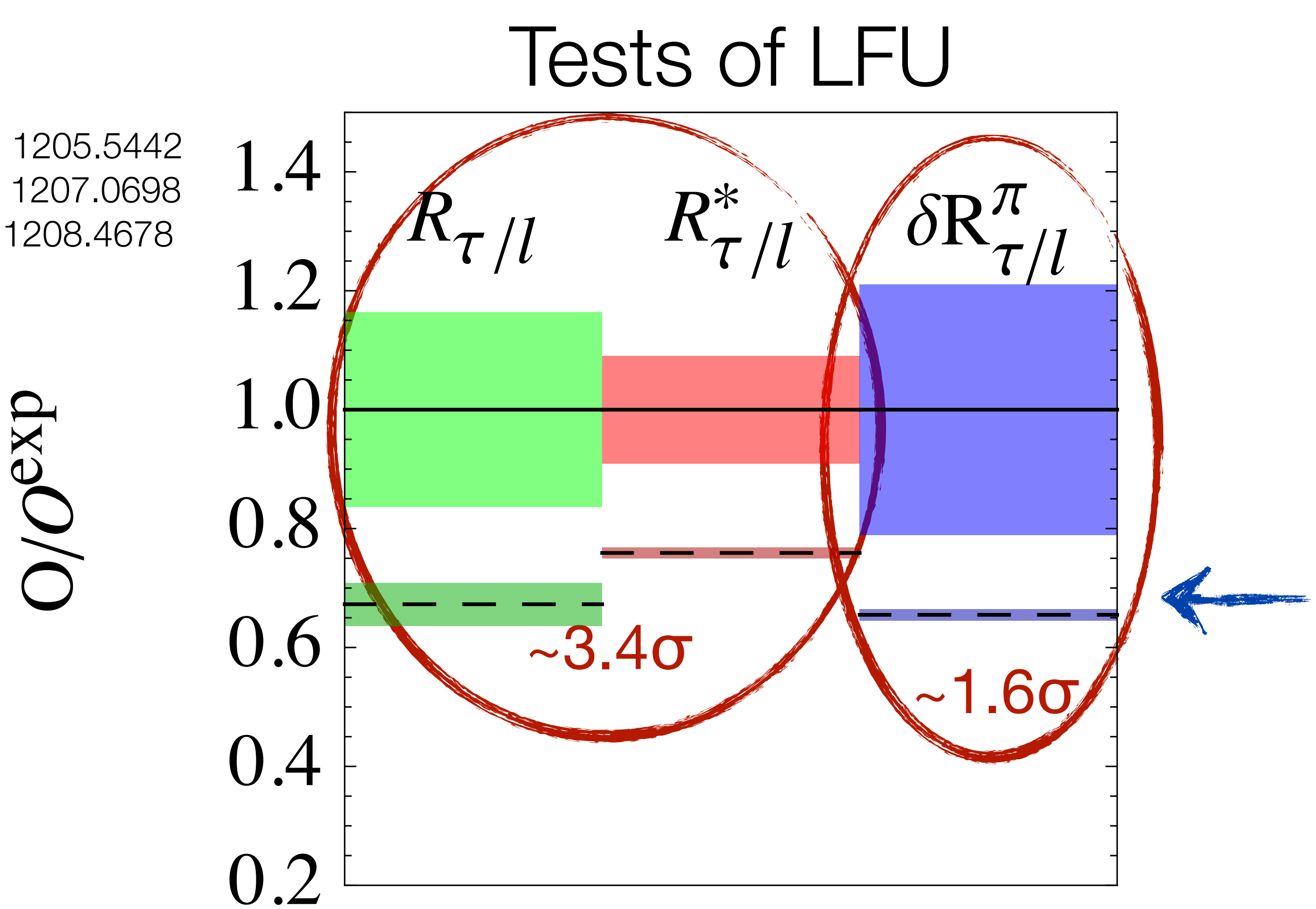
LFU in (semi)leptonic B decays

However, maybe not CKM issue at all

Can eliminate $|V_{ub}|$ in ratio $\Delta\mathcal{R}^{\pi}_{\tau/\ell} \equiv \frac{\tau(B^0)}{\tau(B^-)} \frac{\mathcal{B}(B^- \to \tau^-\bar{\nu})}{\Delta\mathcal{B}(\bar{B}^0 \to \pi^+\ell^-\bar{\nu})}$

Similarly in semitauonic decays $\mathcal{R}_{\tau/\ell} \equiv \frac{\mathcal{B}(B\to D\tau\nu)}{\mathcal{B}(B\to D\ell\nu)}$ $\mathcal{R}^*_{\tau/\ell} \equiv \frac{\mathcal{B}(B\to D^*\tau\nu)}{\mathcal{B}(B\to D^*\ell\nu)}$

BaBar, 1205.5442
Babar, 1207.0698
Belle, 1208.4678



SM predictions very robust

Fajfer, J.F.K., Nisandzic,1203.2654
J.F.K. & Mescia, 0802.3790
Nierste, Trine & Westhoff, 0801.4938
Tanaka & Watanabe, 1005.4306
Becirevic, Kosnik, Tayduganov, 1206.4977
Bailey et al., 1206.4992
Khodjamirian et al., 1103.2655
Fajfer, J.F.K., Nisandzic & Zupan, 1206.1872

LFU in (semi)leptonic B decays

Can it be NP? Need to satisfy severe constraints:

- no tree-level down quark / charged lepton FCNCs
- no LFU violations in pion, kaon sectors

} require flavor alignment

Points towards low NP scale: $\Lambda \lesssim 100\,\text{GeV}$ for $\mathcal{Q}_{AB}^{(6)} \sim V_{qb}[\bar{b}\,\Gamma_A q] \otimes [\bar{\nu}\,\Gamma_B \tau]$

Fajfer, J.F.K., Nisandzic & Zupan, 1206.1872

$$\mathcal{Q}_L = (\bar{q}_3 \gamma_\mu \tau^a q_3) \mathcal{J}^\mu_{3,a}\,, \qquad \mathcal{Q}_{LR} = i\partial_\mu(\bar{q}_3 \tau^a H b_R) \textstyle\sum_j \mathcal{J}^\mu_{j,a}\,,$$

$$\mathcal{Q}^i_R = (\bar{u}_{R,i} \gamma_\mu b_R)(H^\dagger \tau^a \tilde{H}) \mathcal{J}^\mu_{3,a} \qquad \mathcal{Q}^i_{RL} = i\partial_\mu(\bar{u}_{R,i} \tilde{H}^\dagger \tau^a q_3) \textstyle\sum_j \mathcal{J}^\mu_{j,a}\,,$$

Predict effects in top physics

$$pp \to t E_T^{\text{miss}}$$

Andrea, Fuks & Maltoni, 1106.6199
J.F.K. & Zupan, 1107.0623
CDF, 1202.5653
Ezequiel et al., 1310.7600
Agram et al., 1311.6478
CMS-PAS-B2G-12-022

Predict effects in Higgs physics

$$pp \to h \tau E_T^{\text{miss}}$$

Some of these implications remain largely unexplored
Interesting future research directions

Conclusions

Success of SM in describing flavor-changing processes implies that large new sources of flavor symmetry breaking at TeV scale are mostly excluded.

However, NP at TeV scale need not be flavor trivial!

If (properly aligned) new sources of flavor breaking present

- Precision B observables may hide NP signals @10% level in well motivated NP models (natural SUSY)
- can significantly affect & guide NP searches high p_T
- have implications for EW fine-tuning

Conclusions

Success of SM in describing flavor-changing processes implies that large new sources of flavor symmetry breaking at TeV scale are mostly excluded.

However, NP at TeV scale need not be flavor trivial!

There are sectors of the theory that are just starting to be tested

- Measurements of $B_{s,d} \to \mu^+\mu^-$ probe the Higgs Yukawa sector at loop level
- Several recent anomalies in rare B decays need to be clarified.

Worth to improve searches of exotic flavor-violating effects!

- Example: $b \to s\ E_{miss}$ modes as portals to dark BSM sectors

Thank you!