FLAVOR PHYSICS: LECTURE 2

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REVIEW OF LECTURE 1

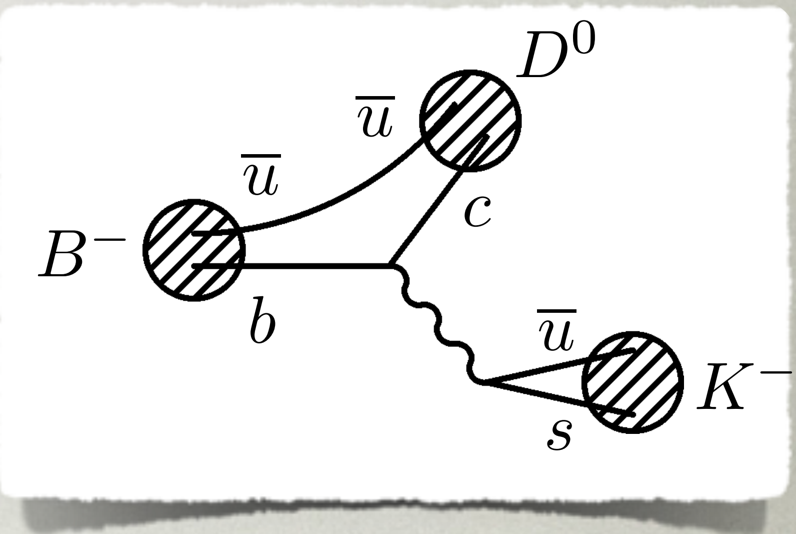
- have looked at the flavor structure in the SM
- experiments show it is predominantly due to Kobayashi-Maskawa mechnism

OUTLINE LECTURE 2

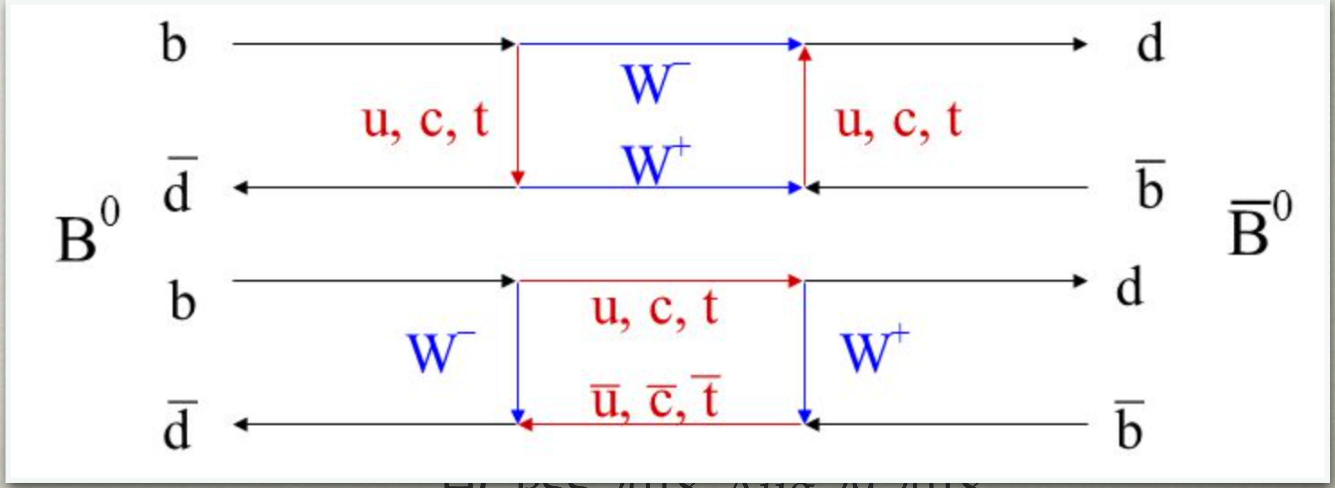
- meson mixing (left-over from lecture 1)
- searching for new physics
  - *B* physics anomalies
- Higgs and flavor

MEASUREMENTS

- two types of measurements shown in the CKM triangle plot
  - tree level transitions
    - less likely to be affected by new physics



  - loop level transitions
    - more likely to be affected by new physics



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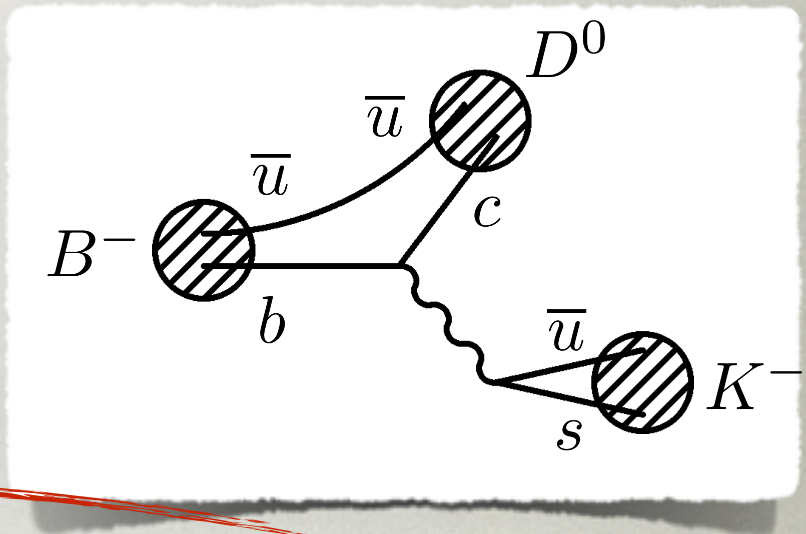

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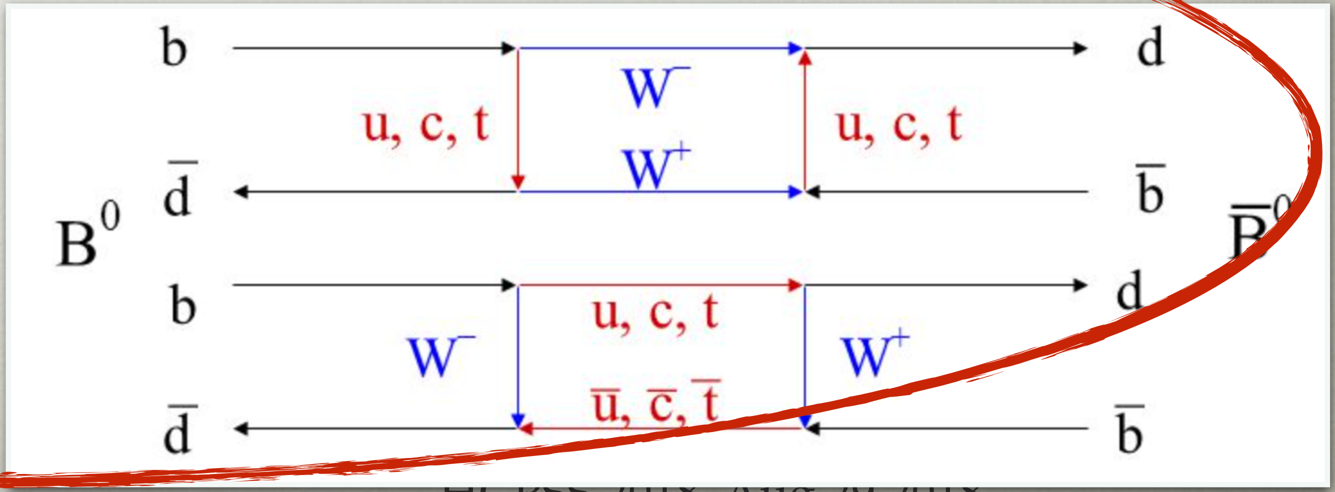
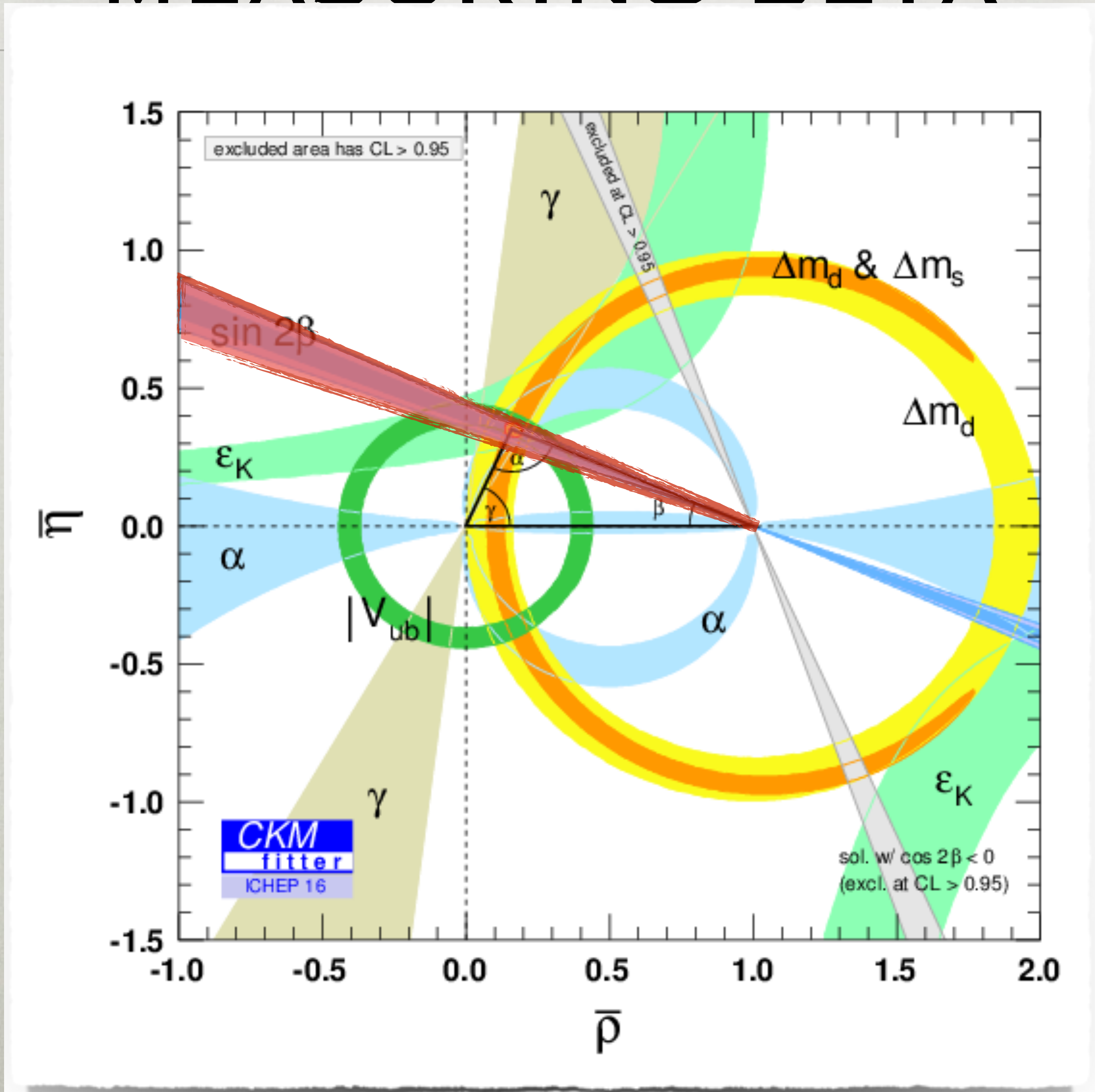
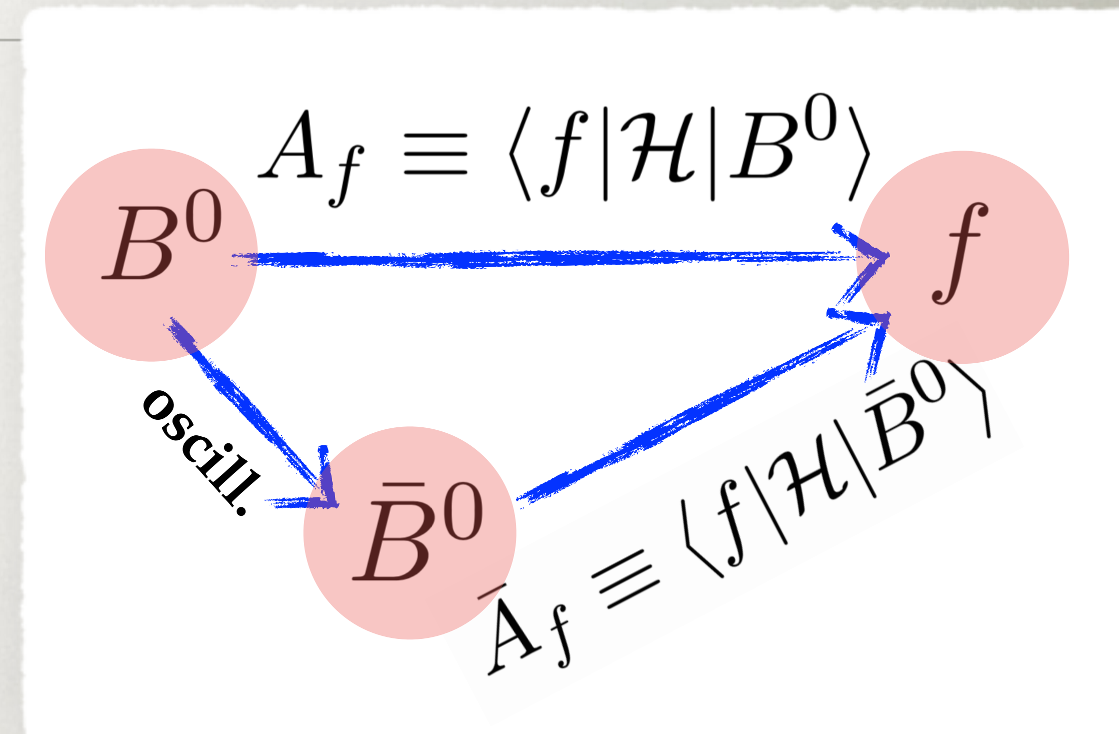


MEASURING BETA



CP violation



- 3 categories of CPV observables
  - *CPV in the decay*: interf. between decay amplitudes

$$|A_f| \neq |\bar{A}_f|$$

  - *CPV in mixing* : interf. between M_{12} and Γ_{12} (different ways to oscillate $B^0 \leftrightarrow \bar{B}^0$)

$$|q/p| \neq 1$$

$$|B_{L,H}\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle.$$

  - *CPV in interference between decays with and without mixing*

$$\mathrm{Im}\,\lambda_f \neq 0$$

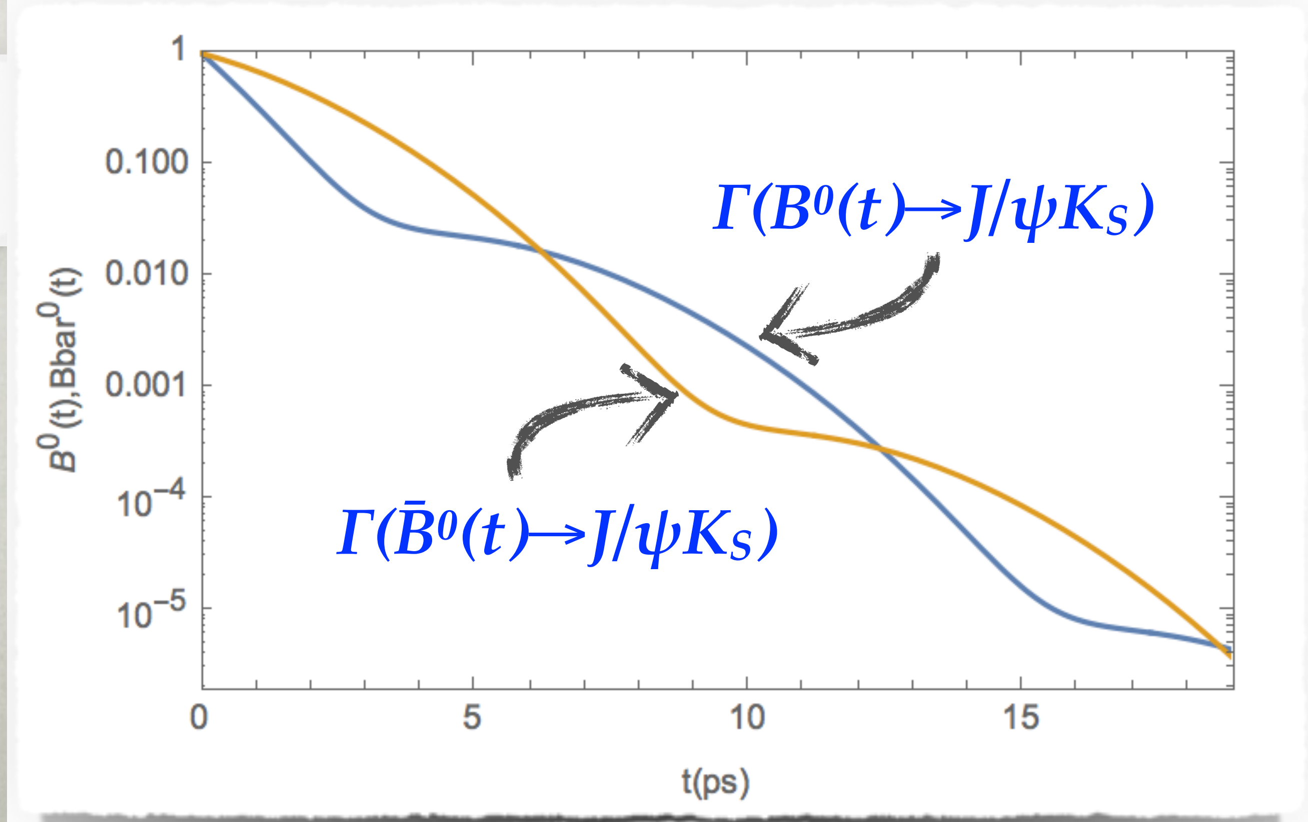
$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}.$$

B meson mixing

- for f that is a CP eigenstate, e.g., f=$J/\psi K_S$
  - time dependent CP asymmetry

$$\mathcal{A}_{f_{CP}}(t) \equiv \frac{\frac{d}{dt}\Gamma[\bar{B}^0(t) \to f_{\rm CP}] - \frac{d}{dt}\Gamma[B^0(t) \to f_{\rm CP}]}{\frac{d}{dt}\Gamma[\bar{B}^0(t) \to f_{\rm CP}] + \frac{d}{dt}\Gamma[B^0(t) \to f_{\rm CP}]},$$

$$\mathcal{A}_{f_{CP}}(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t).$$



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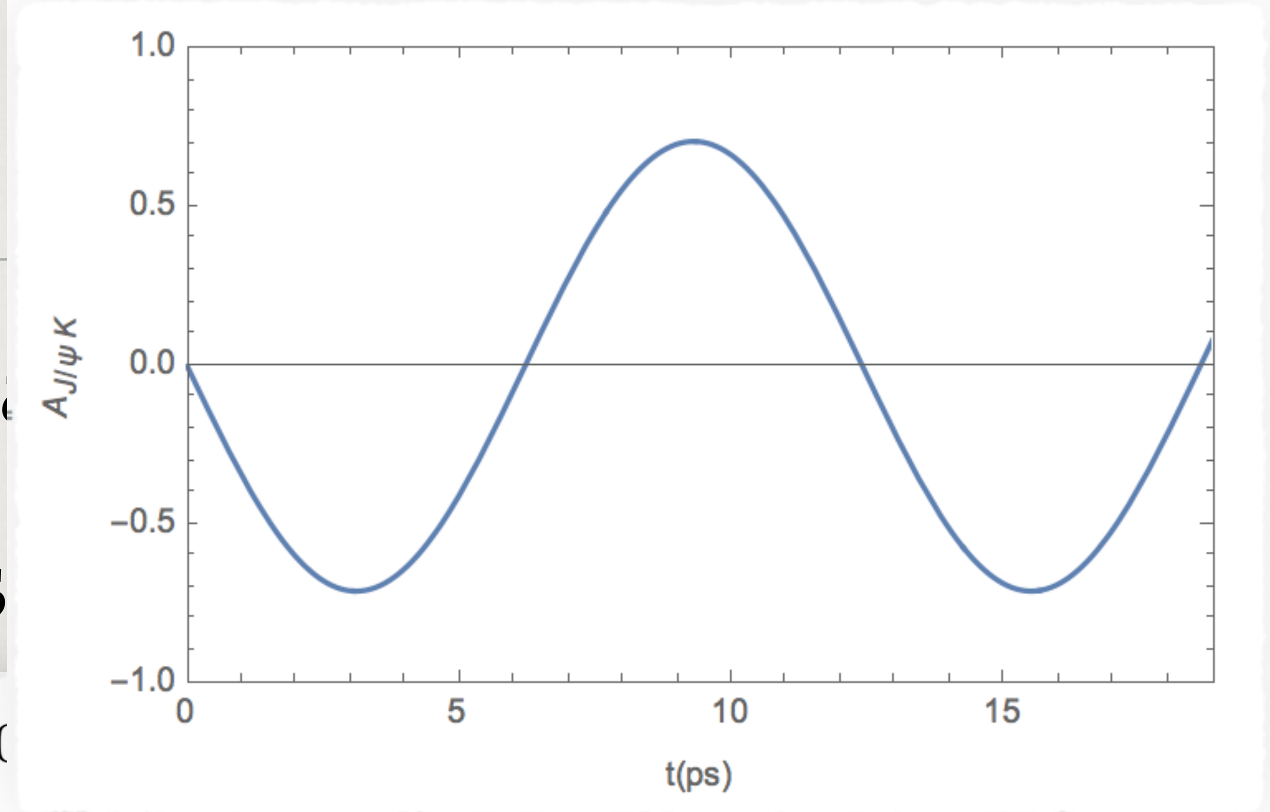

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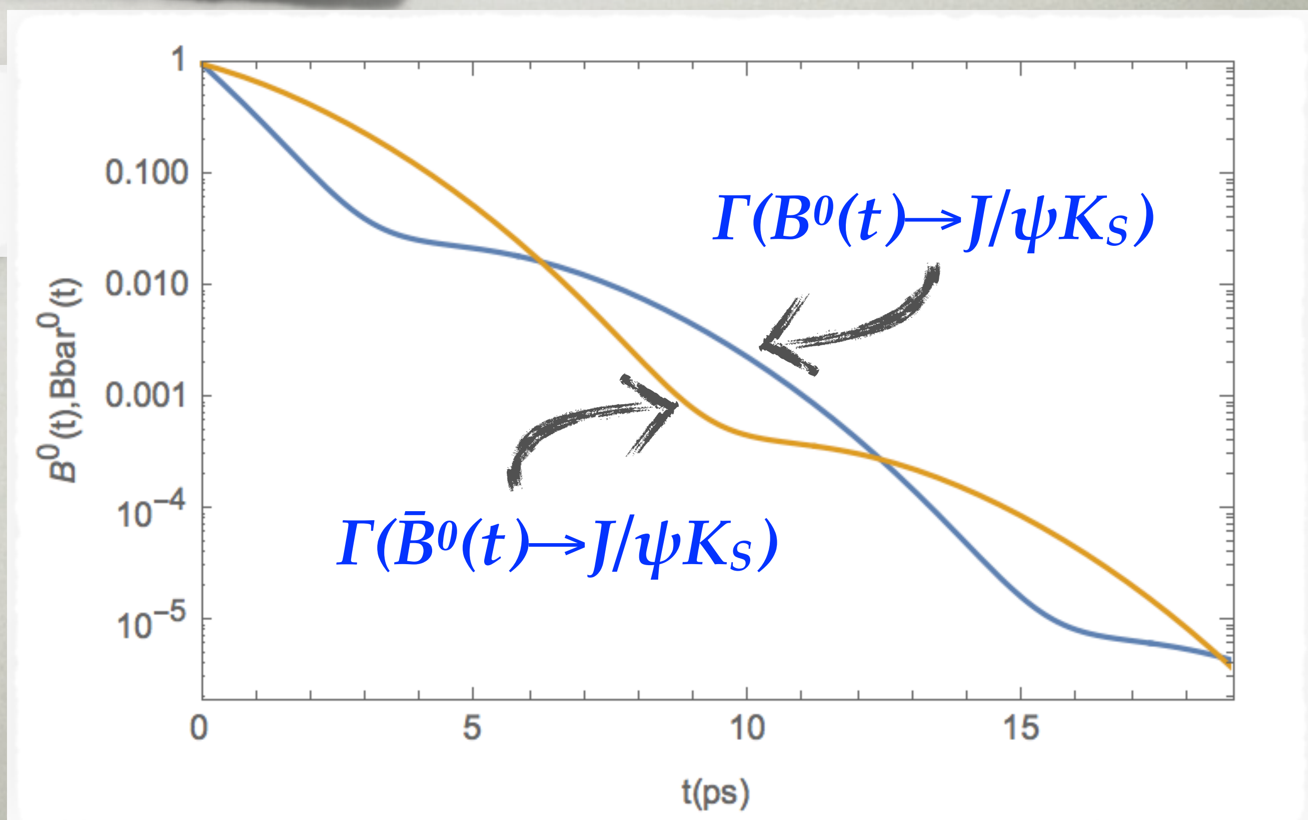
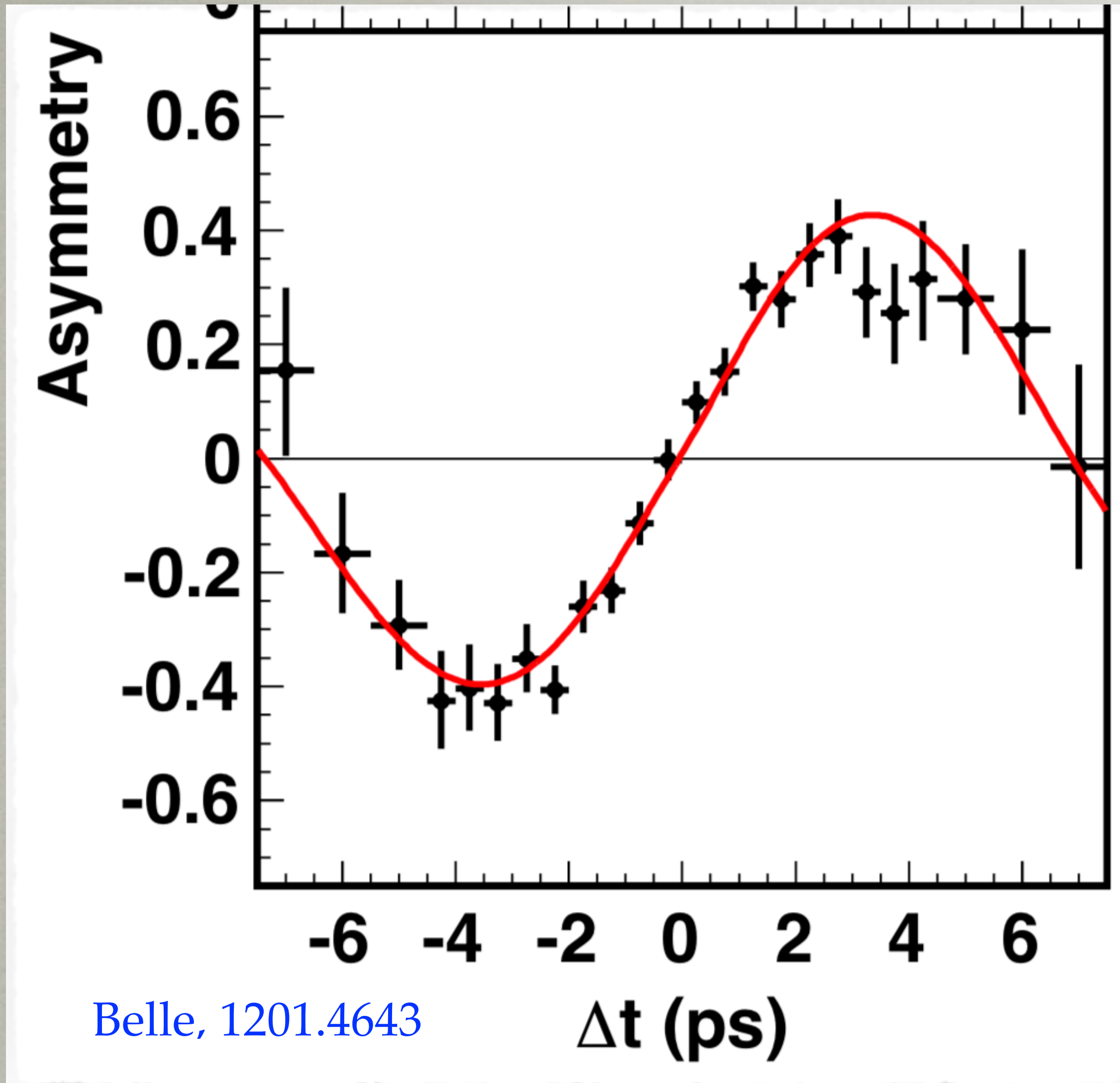


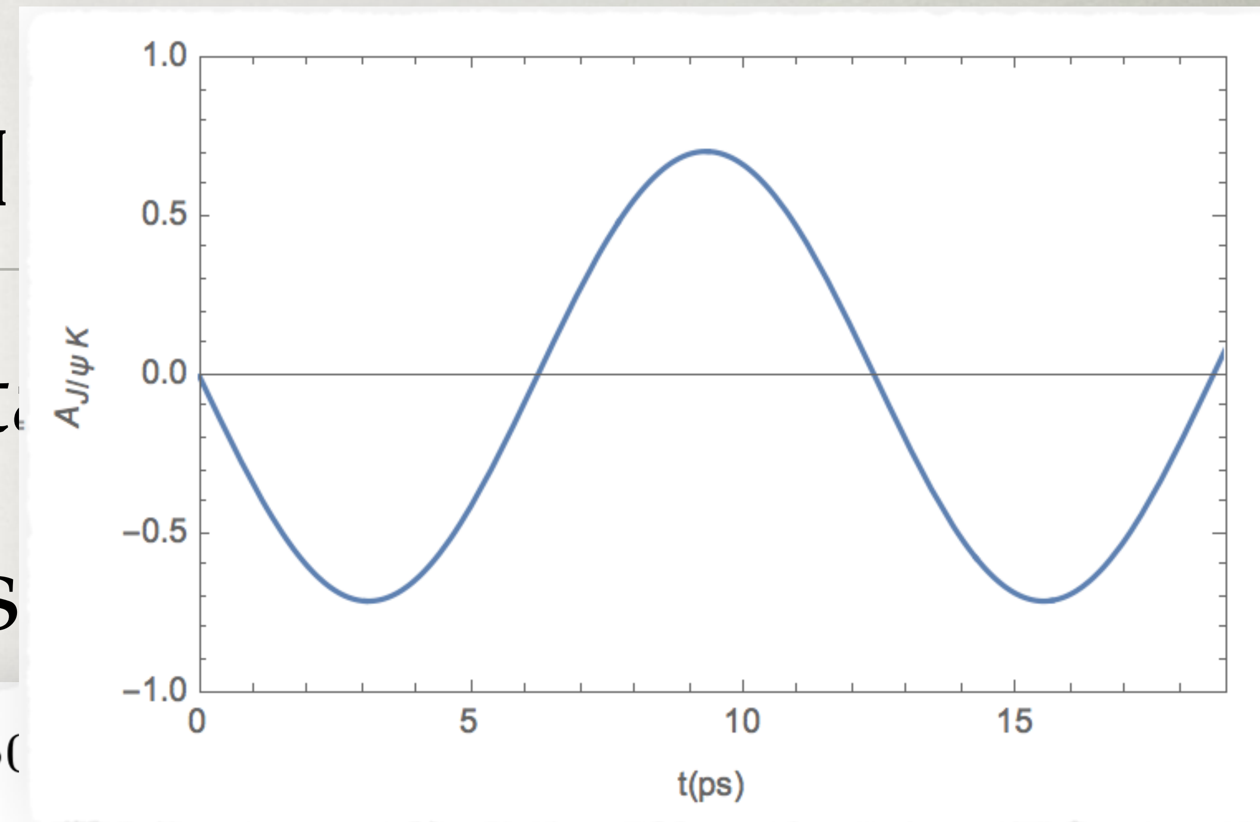


ON

...genst...

...CP as...

$$\frac{\frac{d}{dt}\Gamma[B^{...}}{\frac{d}{dt}\Gamma[B^0(t)\to f_{\rm CP}]},$$



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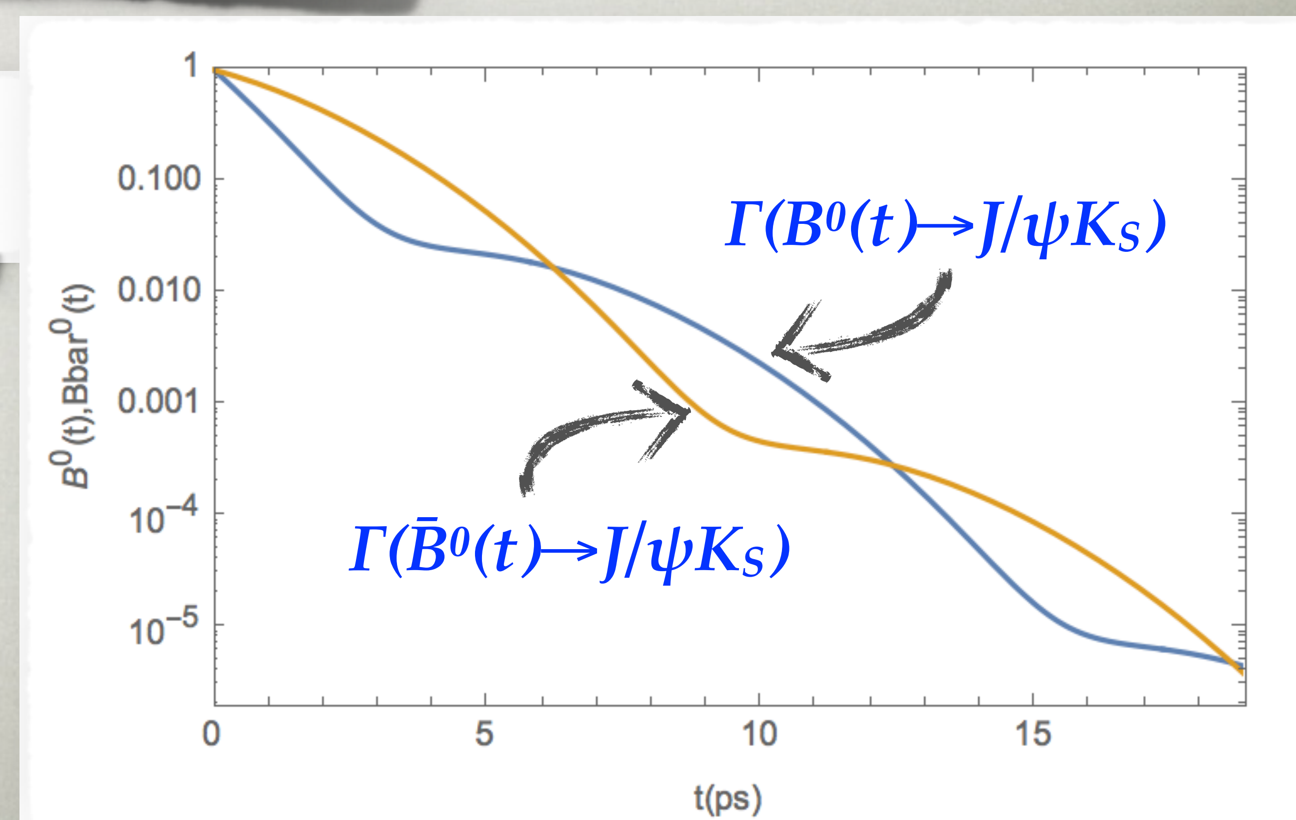


B meson mixing

$$\mathcal{A}_{f_{CP}}(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t).$$

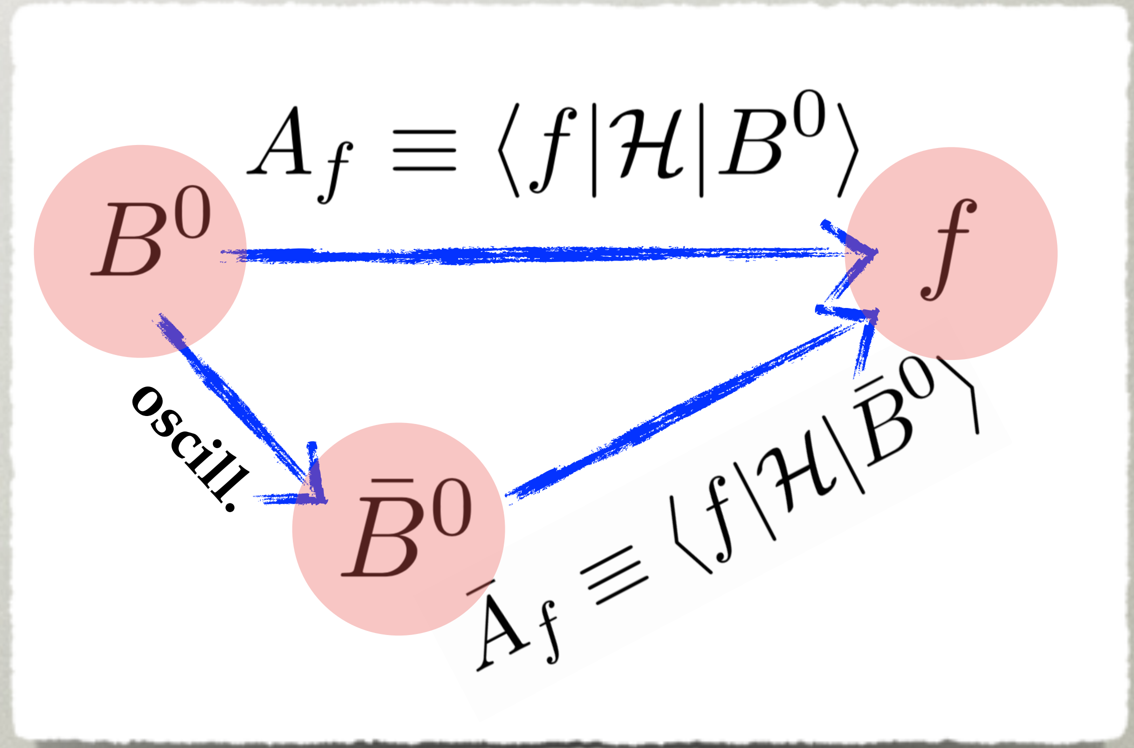
$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}.$$

- S_f measures CPV in interference between decays with and without mixing

$$S_f \equiv \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2},$$

- C_f is direct CPV asymmetry

$$C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$



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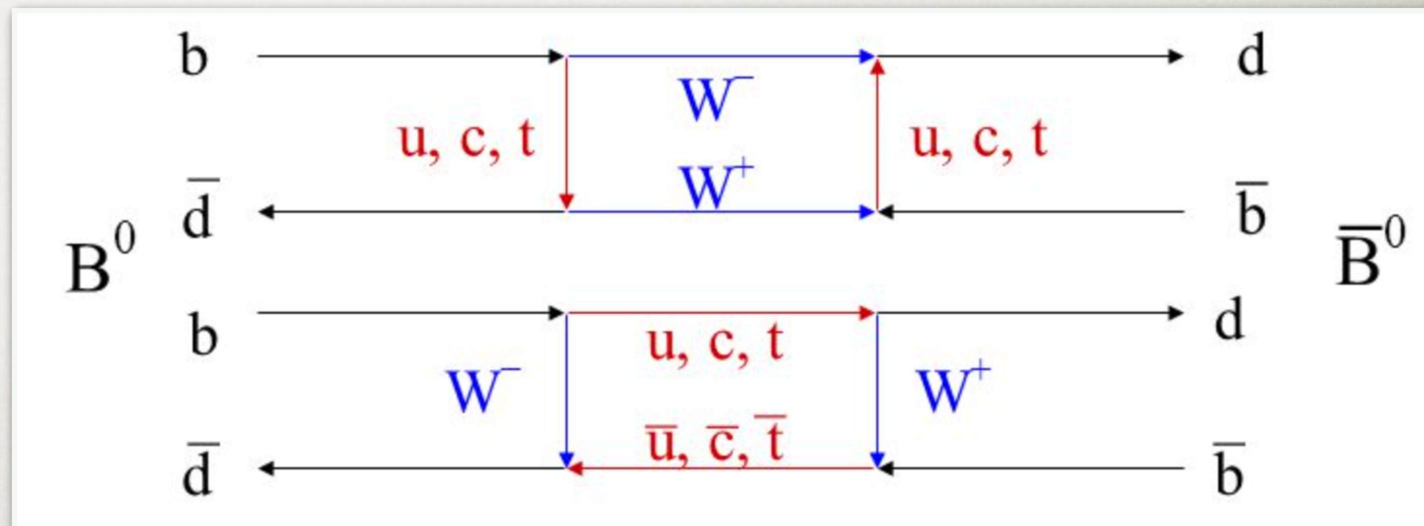
B meson mixing

$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}.$$

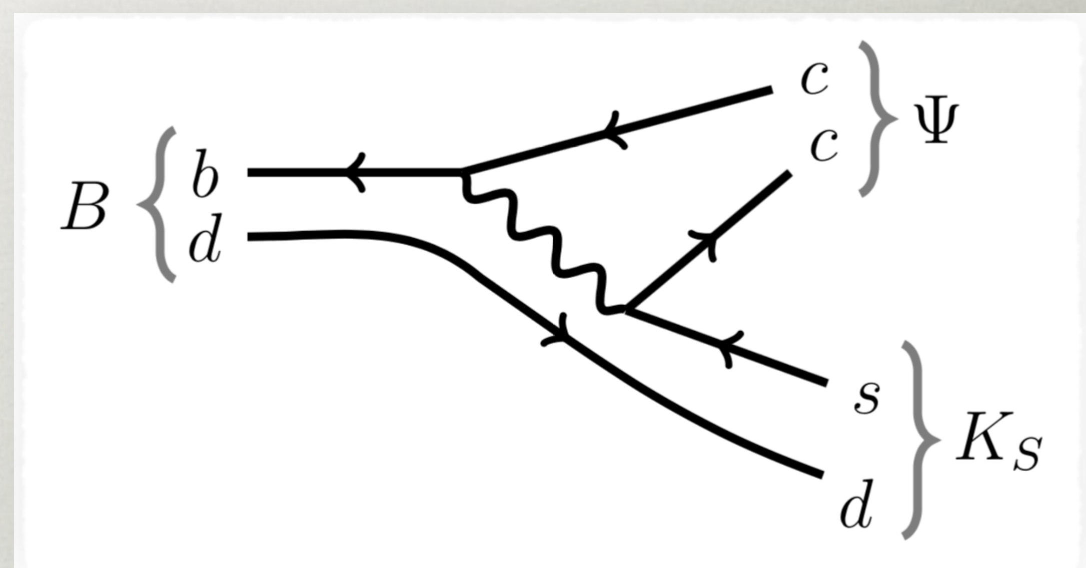
- q/p is universal for all final states f
  - in the SM

$$\frac{q}{p} = e^{-i\phi_B} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$$



- for $B \to J/\psi K_S$ in the SM

$$\frac{\bar{A}_{J/\psi K_S}}{A_{J/\psi K_S}} = \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} + \cdots$$



- so that the CPV parameter in the SM

$$\lambda_{J/\psi K_S} = \frac{V_{tb}^* V_{td} V_{cb} V_{cs}^*}{V_{tb} V_{td}^* V_{cb}^* V_{cs}} = e^{i2\beta}$$

$$\mathrm{Im}\,\lambda_{J/\psi K_S} = \sin 2\beta.$$

THE UPSHOT

- CPV an inherently quantum mechanical effect
  - governed by a phase in Lagrangian
- KM mechanism the dominant origin of CPV
  - measurements point to a consistent picture

$$A = 0.825(9), \qquad \lambda = 0.2251(3), \qquad \bar{\rho} = 0.160(7), \qquad \bar{\eta} = 0.350(6).$$

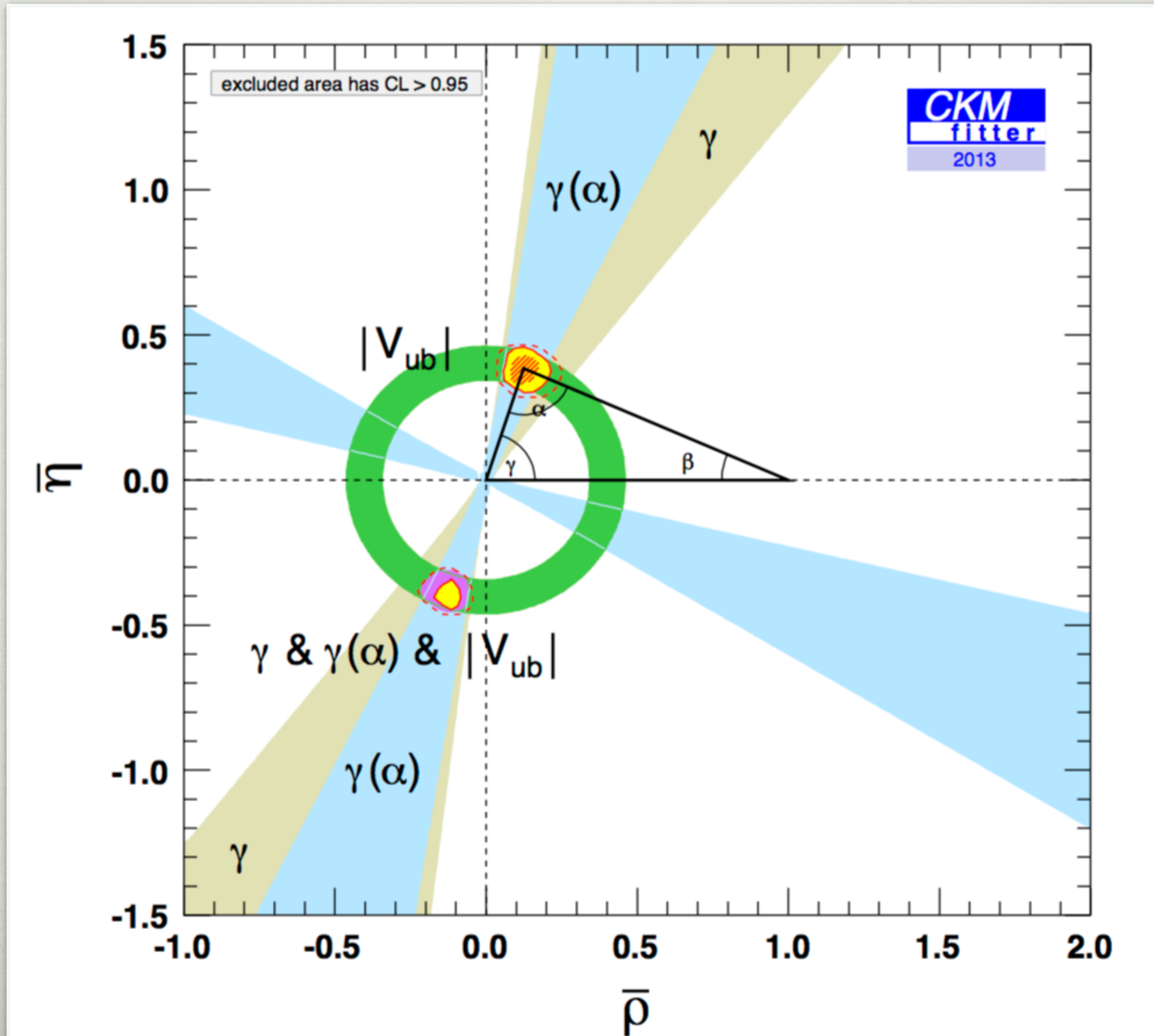
- since $\bar{\rho} \lesssim \bar{\eta}$ the CKM weak phase is large, O(1)

$$e^{i\gamma} = \frac{\bar{\rho} + i\bar{\eta}}{\bar{\rho}^2 + \bar{\eta}^2} = \arg(V_{ub}^*),$$

- tests will be significantly improved in the near future

THE FUTURE: TREE PROCESSES @ BELLE 2

Charles et al, 1309.2293



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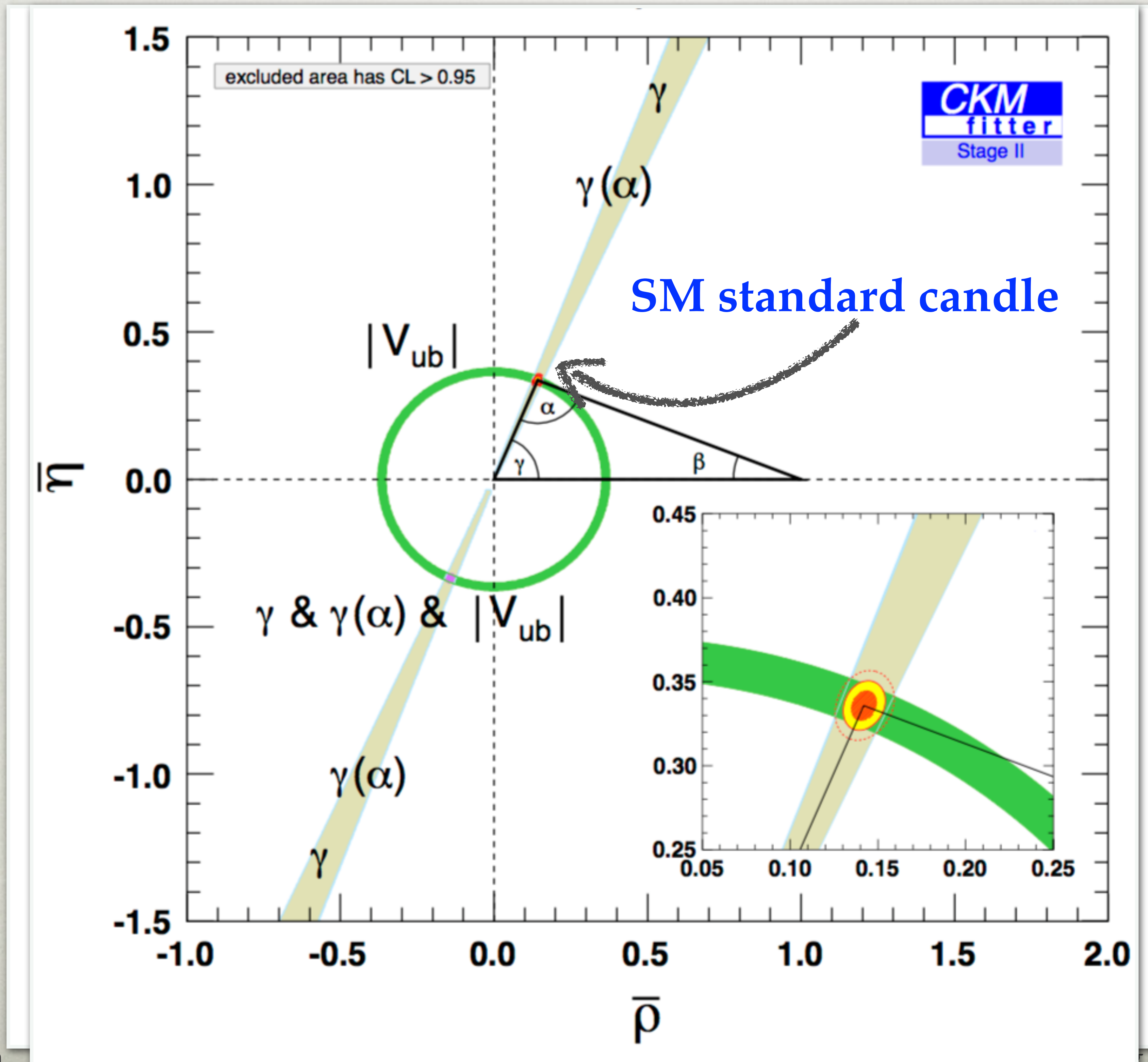
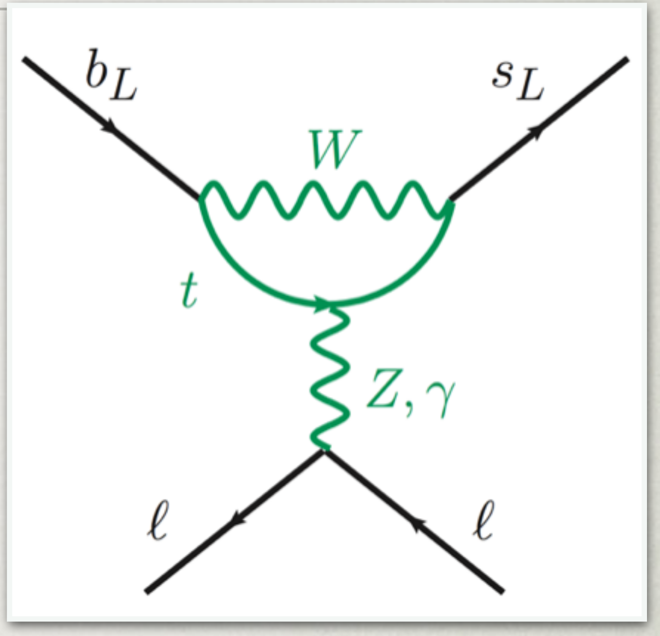
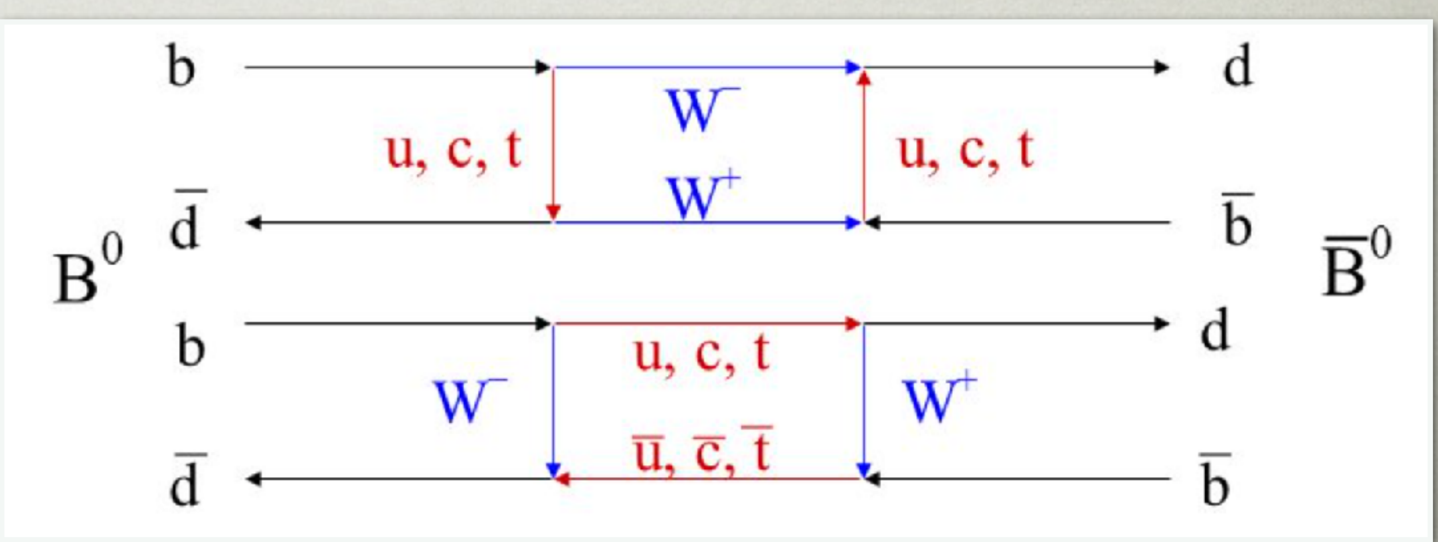


SEARCHING FOR NEW PHYSICS

TWO WAYS OF SEARCHING FOR BSM IN FLAVOR



- measuring rare decays
  - e.g., $b \to s l^+ l^-$
- measuring meson mixing amplitudes
  - e.g., B_d-$\bar{B}_d$ mixing



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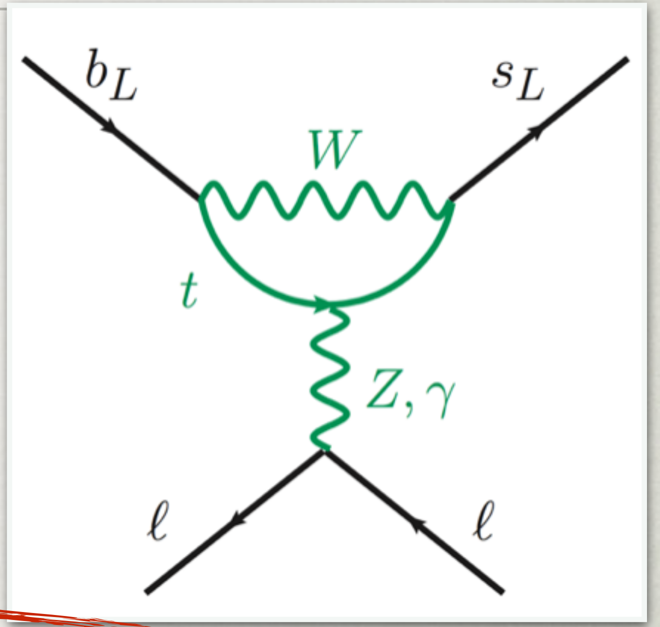

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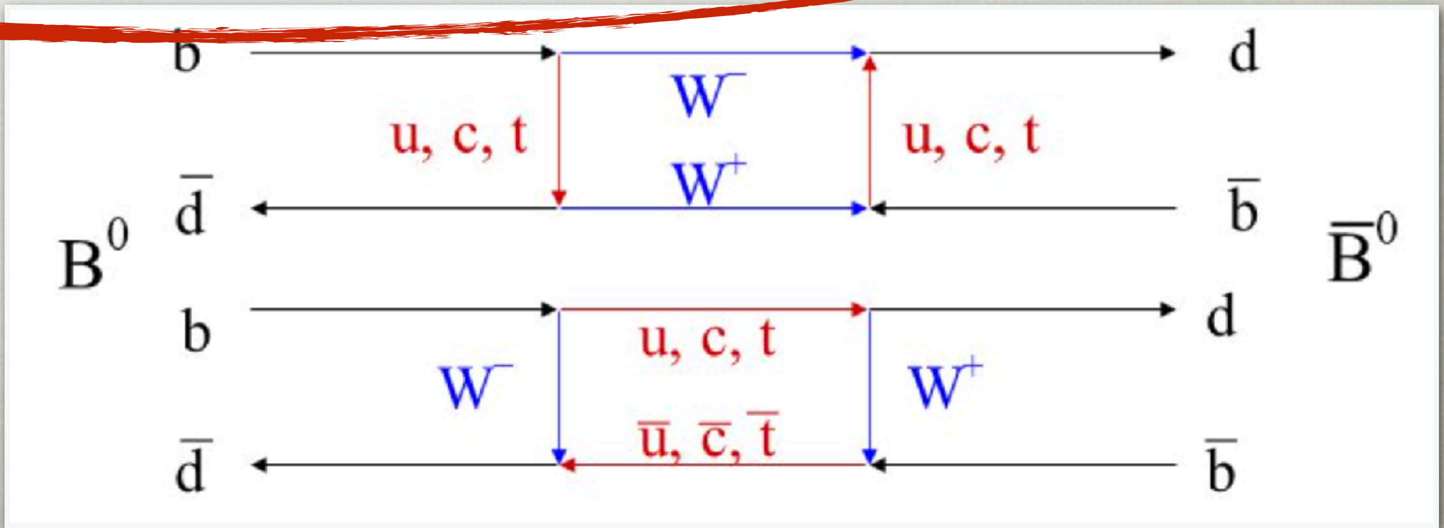
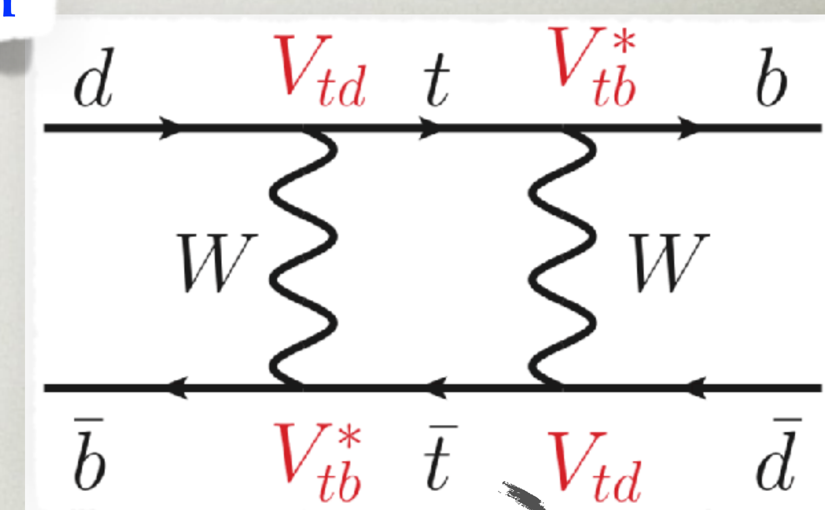


EFFECTIVE HAMILTONIAN

- effective hamiltonian for B mixing

$$\mathcal{H}_{\rm eff} = \frac{1}{8m_W^2}\frac{g^4}{16\pi^2}\underbrace{\eta_B S_0}_{1.26}\left(V_{tb}^* V_{td}\right)^2 \left(\bar{b}_L\gamma^\mu d_L\right)\left(\bar{b}_L\gamma_\mu d_L\right) + \text{h.c.}$$

1.26 ← QCD corrections + loop function



$$\mathcal{H}_{\rm eff} = \frac{1}{\Lambda_{\rm MFV}^2}\left(V_{tb}^* V_{td}\right)^2 \left(\bar{b}_L\gamma^\mu d_L\right)\left(\bar{b}_L\gamma_\mu d_L\right) + \text{h.c.}$$

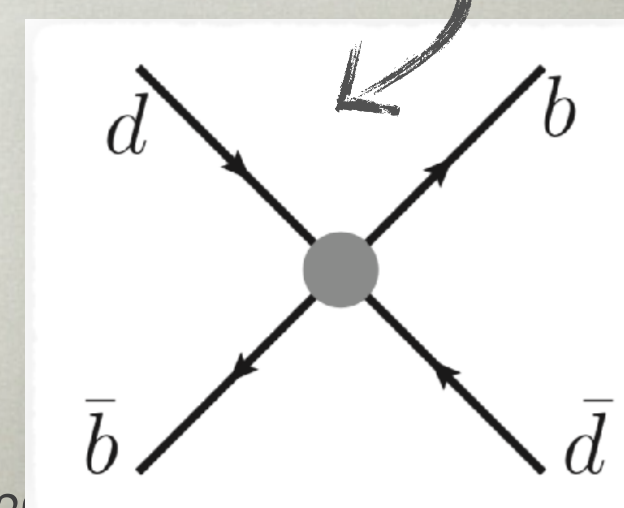
$\Lambda_{\rm MFV} \simeq 6.0\ \text{TeV}.$

$(\lambda^3)^2$

- for B_s mixing instead

$$\mathcal{H}_{\rm eff} = \frac{1}{\Lambda_{\rm MFV}^2}\left(V_{tb}^* V_{ts}\right)^2 \left(\bar{b}_L\gamma^\mu s_L\right)\left(\bar{b}_L\gamma_\mu s_L\right) + \text{h.c.}$$

$(\lambda^2)^2$



NEW PHYSICS IN MIXING

- measuring mixing amplitude precisely can probe for new physics
- can parametrize the new physics contributions as

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} + \mathcal{H}_{\rm eff}^{\rm NP}$$

$$M_{12} = M_{12}^{\rm SM} + M_{12}^{\rm NP} = M_{12}^{\rm SM}\left(1 + h_{d,s} e^{i\sigma_{d,s}}\right)$$

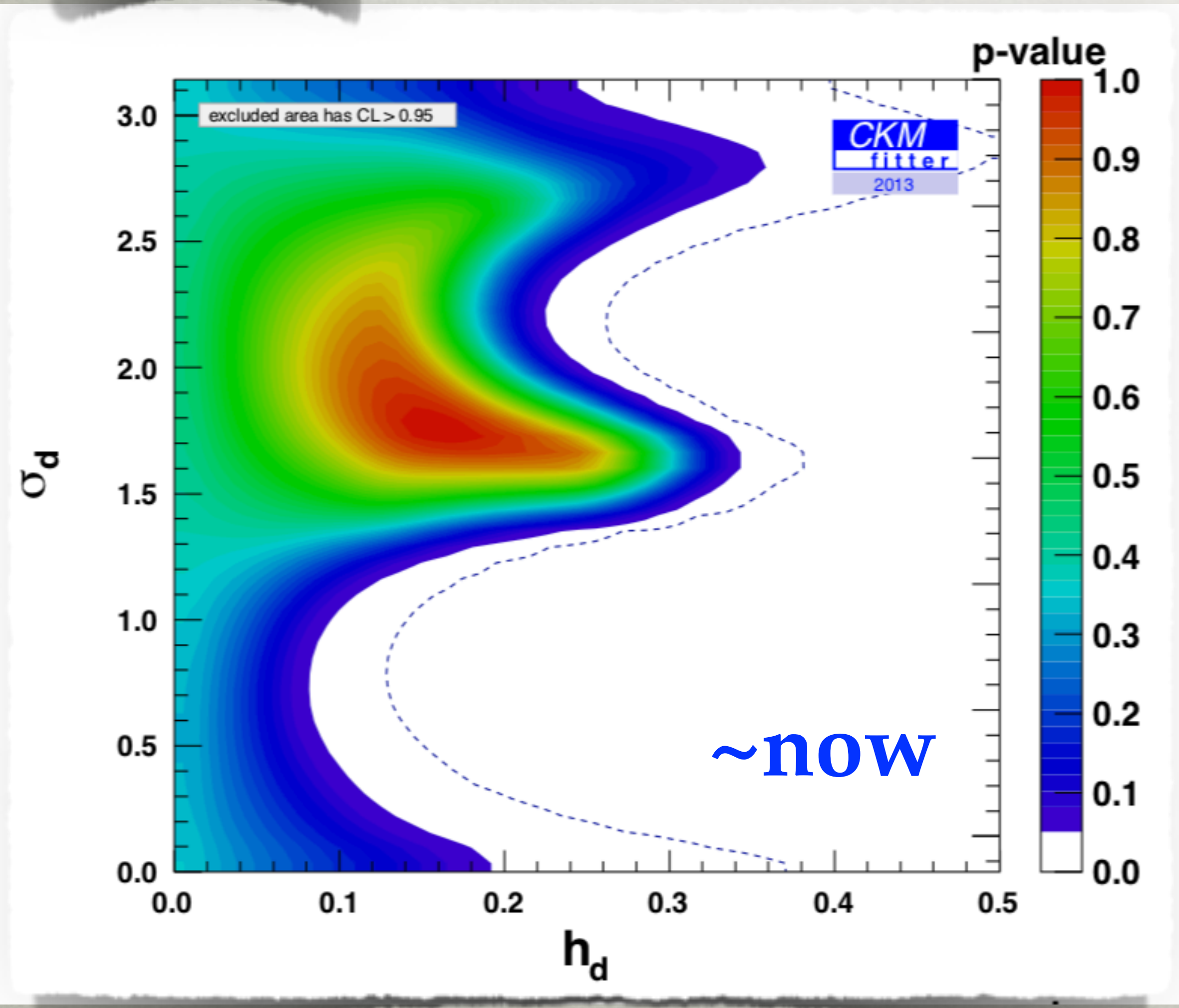
$$M_{12} = \frac{1}{2m_B}\langle \bar{B}_d^0|\mathcal{H}_{\rm eff}|B_d^0\rangle^*$$

$$\left(V_{tb}^* V_{td}\right)^2 \qquad \left(V_{tb}^* V_{ts}\right)^2$$

BOUNDS ON NEW PHYSICS IN MIXING

- ~20% corrections relative to the SM allowed at present
- to be reduced to ~5%

B^0-$\bar{B}^0$



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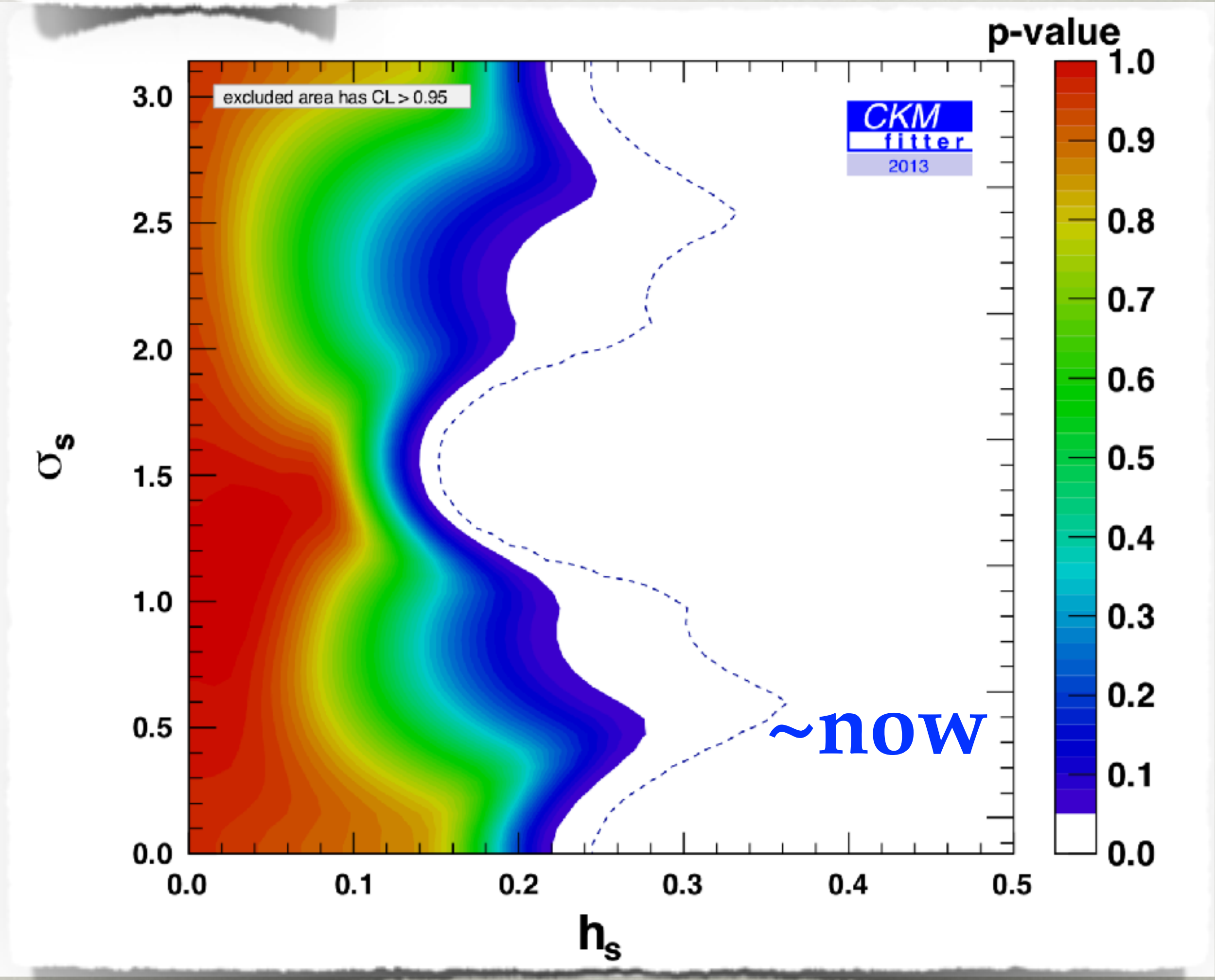

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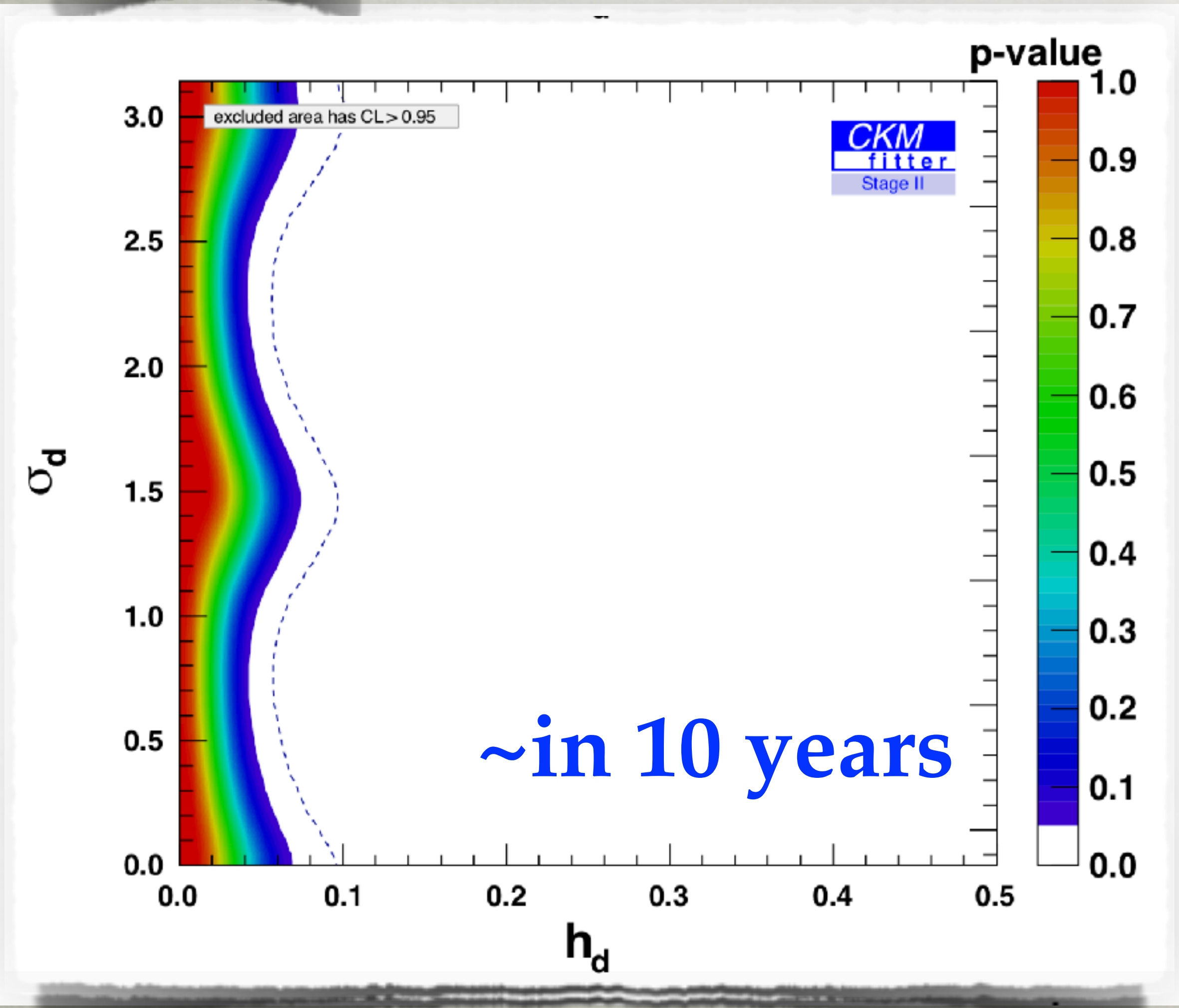

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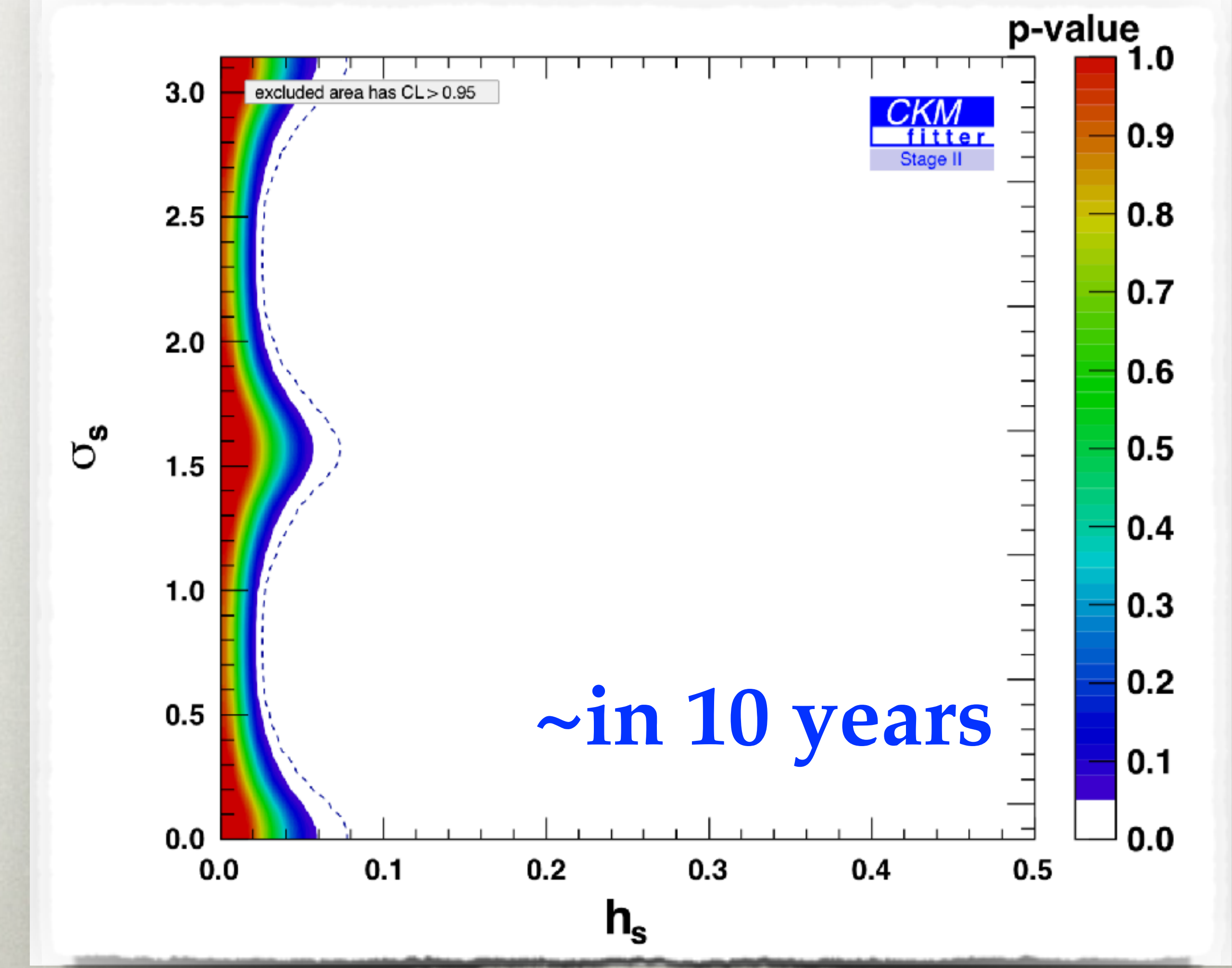
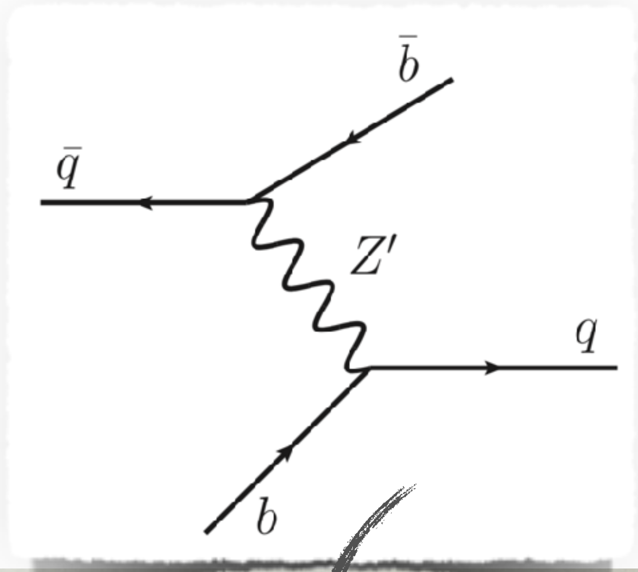


WHAT SCALE?

- what does this mean in terms of bounds on NP masses?
- assume for instance, that NP has the same *(V-A)x(V-A)* structure as the SM

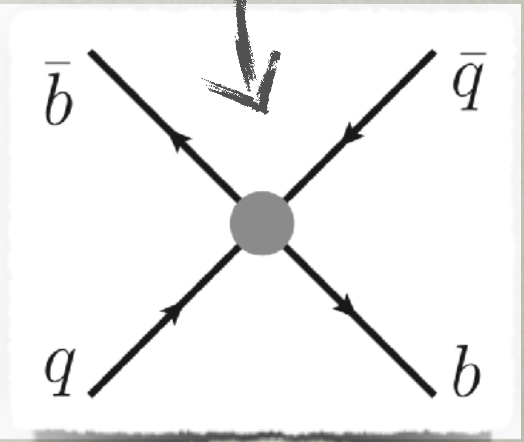
$$\mathcal{H}_{\rm eff} = \left(\frac{\left(V_{tb}^* V_{tq}\right)^2}{\Lambda_{\rm MFV}^2} + \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2} \right) \left(\bar b_L \gamma^\mu q_L\right)\left(\bar b_L \gamma_\mu q_L\right) + {\rm h.c.}$$



- e.g., could be due to Z' exchange

$$\mathcal{H}_{\rm eff} = i(ig_{Z'})^2 \left(\bar b_L \gamma_\mu q_L\right) \frac{-i g^{\mu\nu}}{q^2 - m_{Z'}^2} \left(\bar b_L \gamma_\nu q_L\right)$$

$$q^2 \ll m_{Z'}^2 . \quad \to \frac{g_{Z'}^2}{m_{Z'}^2} \left(\bar b_L \gamma^\mu q_L\right)\left(\bar b_L \gamma_\mu q_L\right) \qquad \frac{C_{\rm NP}}{\Lambda_{\rm NP}^2} = \frac{g_{Z'}^2}{m_{Z'}^2} .$$



- $h_d < 20\%$ correction to the SM gives, for $C_{NP} = 1$

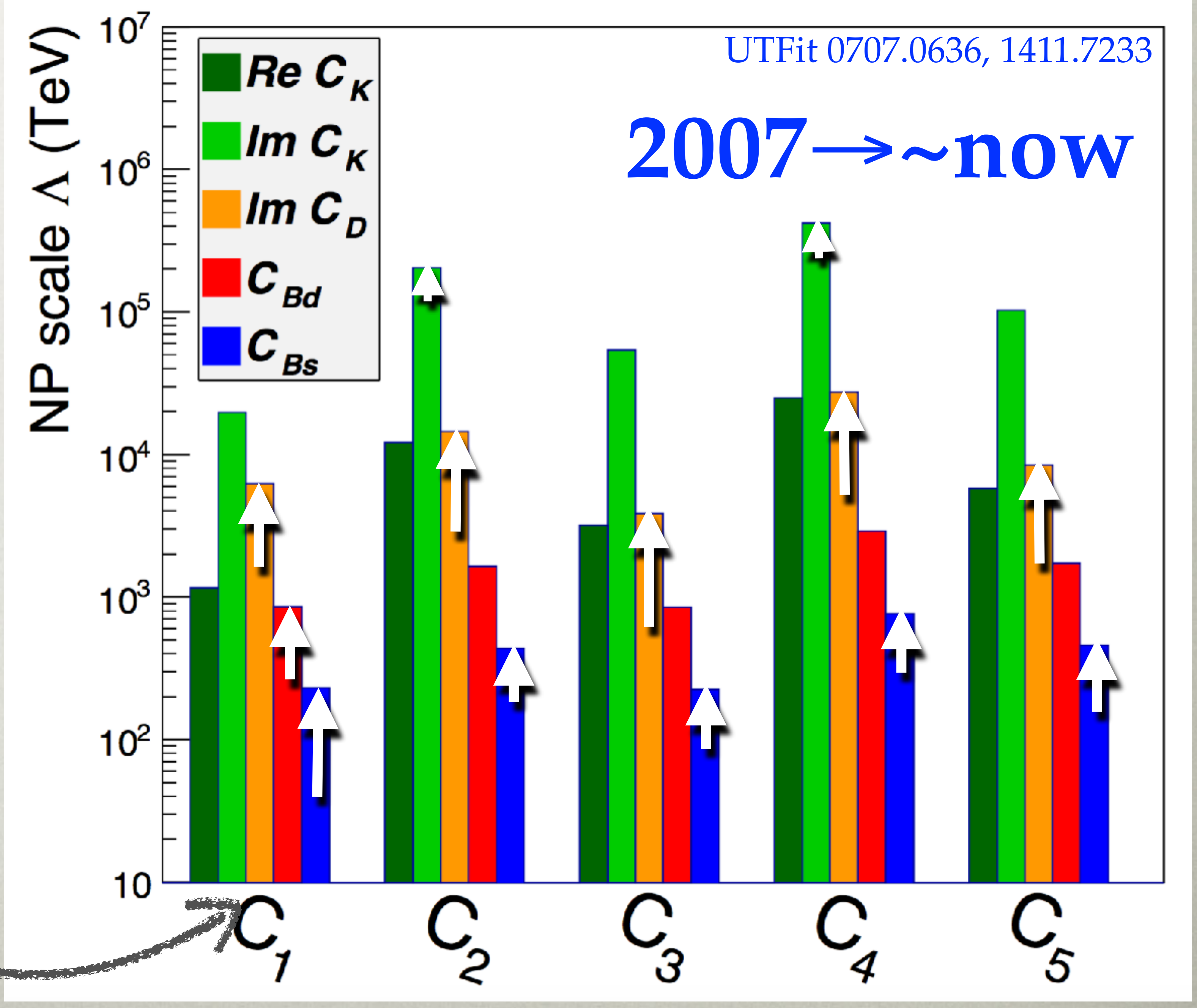
$$\Lambda_{{\rm NP},B_d} \gtrsim 1500 \text{ TeV}, \qquad \Lambda_{{\rm NP},B_s} \gtrsim 300 \text{ TeV},$$

  - the difference entirely due to $V_{ts} \simeq 5 V_{td}$

LOW ENERGY PRECISION BOUNDS

UTFit 0707.0636, 1411.7233
for latest charm see also Bazavov et al, 1706.04622

- an impressive progress on flavor bounds in last 10 years
- in D, B_s mixing ($c\bar{u}$, $\bar{b}s$)
- also from ε_K ($\bar{d}s$)



$$\frac{1}{\Lambda^2}(\bar{b}_L\gamma^\mu d_L)(\bar{b}_L\gamma_\mu d_L)$$

…ERGY PRECISION BOUNDS

$$Q_{1,q} = (\bar{b}_L \gamma^\mu q_L)(\bar{b}_L \gamma^\mu q_L),$$
$$Q_{2,q} = (\bar{b}_R q_L)(\bar{b}_R q_L),$$
$$Q_{3,q} = (\bar{b}_R^\alpha q_L^\beta)(\bar{b}_R^\beta q_L^\alpha)$$
$$Q_{4,q} = (\bar{b}_R q_L)(\bar{b}_L q_R),$$
$$Q_{5,q} = (\bar{b}_R^\alpha q_L^\beta)(\bar{b}_L^\beta q_R^\alpha),$$

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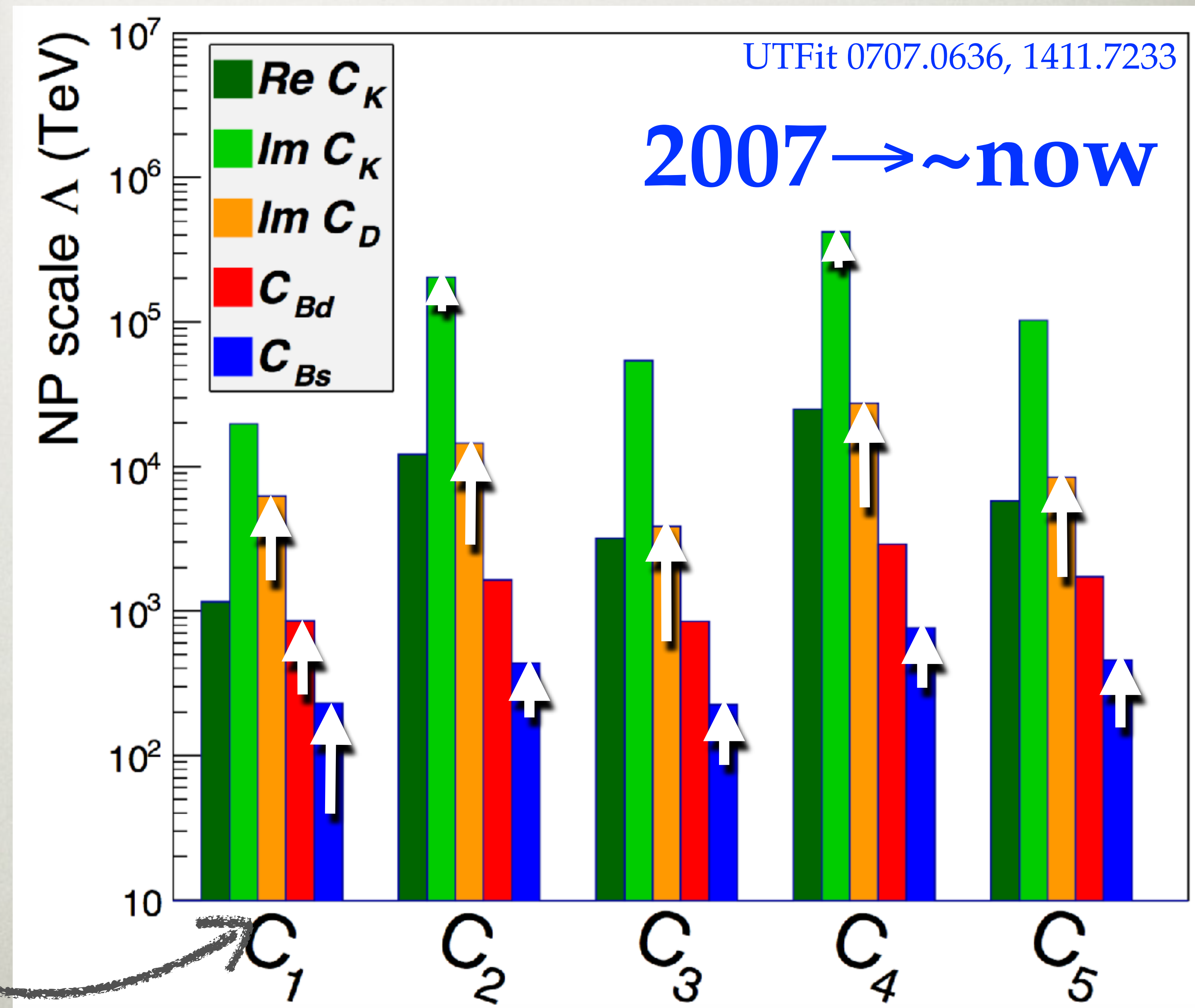

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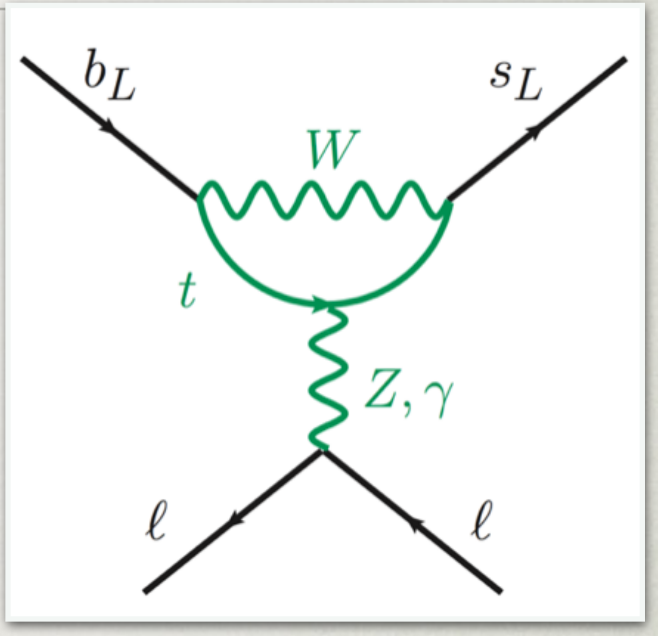

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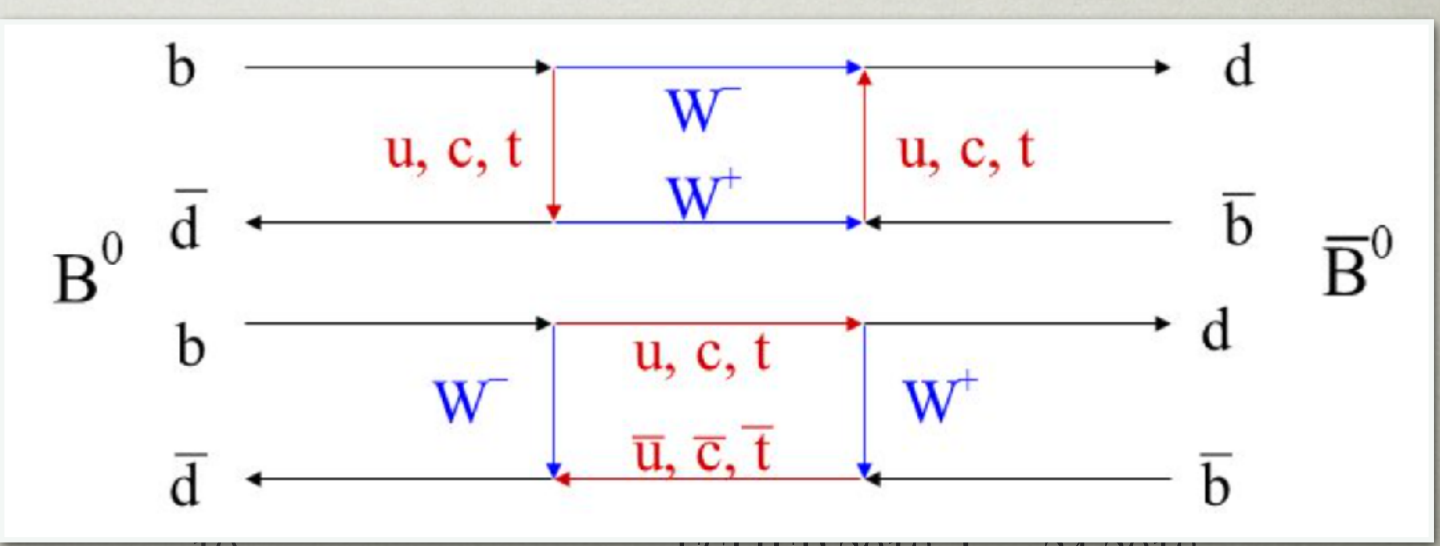


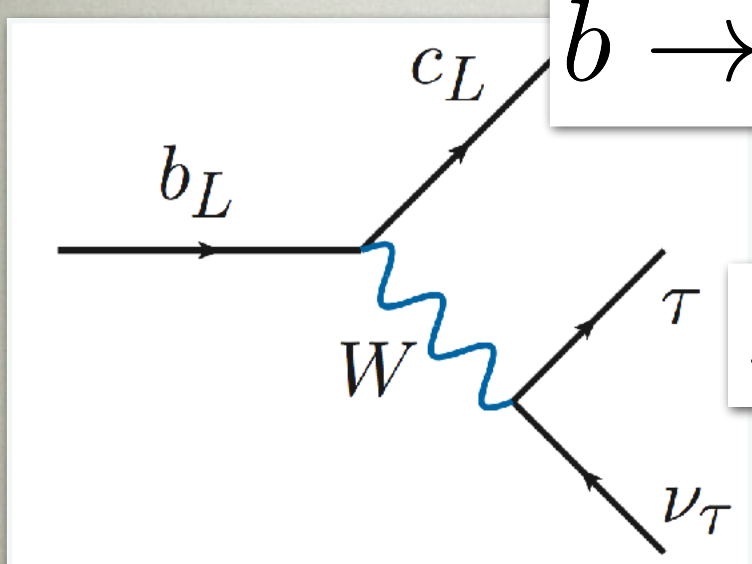
PRESENT EXPERIMENTAL SITUATION

- many different transitions measured
- two sets of quark level transitions show ~*4σ* deviations from the SM*

$$\mathcal{L}_{\rm SMEFT} \supset \frac{1}{\Lambda^2_{Q_{ij}L_{kl}}} \left(\overline{Q}_i \gamma^\mu \sigma^A Q_j\right) \left(\overline{L}_k \gamma_\mu \sigma^A L_l\right)$$

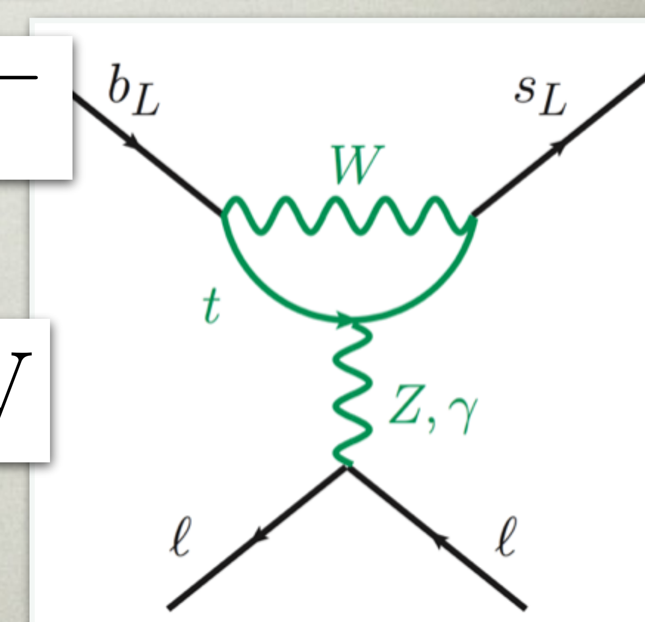
$b \to c\tau\nu$

$\Lambda_{\rm NP} \sim 3$ TeV



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

$\Lambda_{\rm NP} \sim 30$ TeV



* there are other interesting deviations, e.g., ~3σ deviation in ε'/ε, see, e.g., Buras et al, 1507.06345; RBC-UKQCD, 1502.00263

$b \longrightarrow s\mu\mu$

UPSHOT

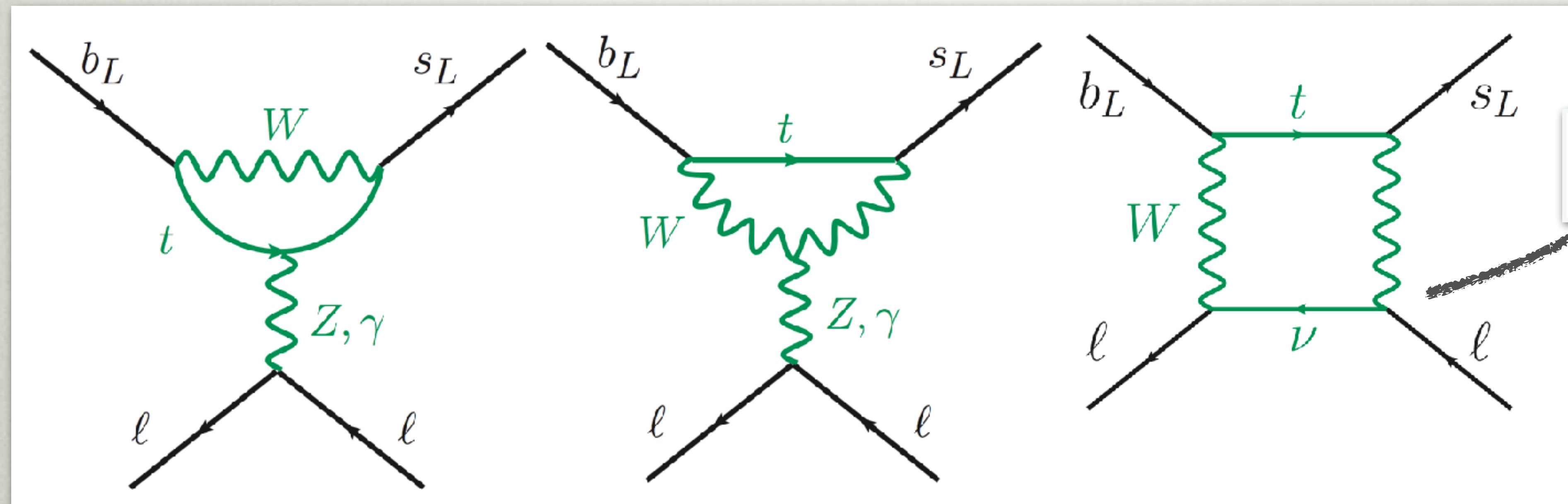
- $b \to sll$ flavor anomaly
  - theoretically clean, ~4σ excess
  - does it make sense from new physics perspective?
    - reasonable scale for NP models*

*mostly face the I. I. Rabi's muon question: "Who ordered that?"

EXPERIMENTAL SITUATION

- *b→sll* : generated at 1-loop in the SM

$$G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} C_{9(10)} \bar{s}_L \gamma^\mu b_L \; \bar{\ell}\gamma_\mu(\gamma_5)\ell$$



$$C_9^{\rm SM} \approx -C_{10}^{\rm SM}$$

- in the SM *b→see* the same as *b→sμμ*
  - Lepton Flavor Universality in the SM

$b \to sll$: EXPERIMENT

- three clean observables: R_K and R_{K^*}

two bins

$$R_K = \left. \frac{Br(B \to K\mu\mu)}{Br(B \to Kee)} \right|_{[1,6]\mathrm{GeV}^2}$$

$$R_{K^*} = \frac{\mathrm{BR}(B \to K^*\mu^+\mu^-)}{\mathrm{BR}(B \to K^*e^+e^-)}$$

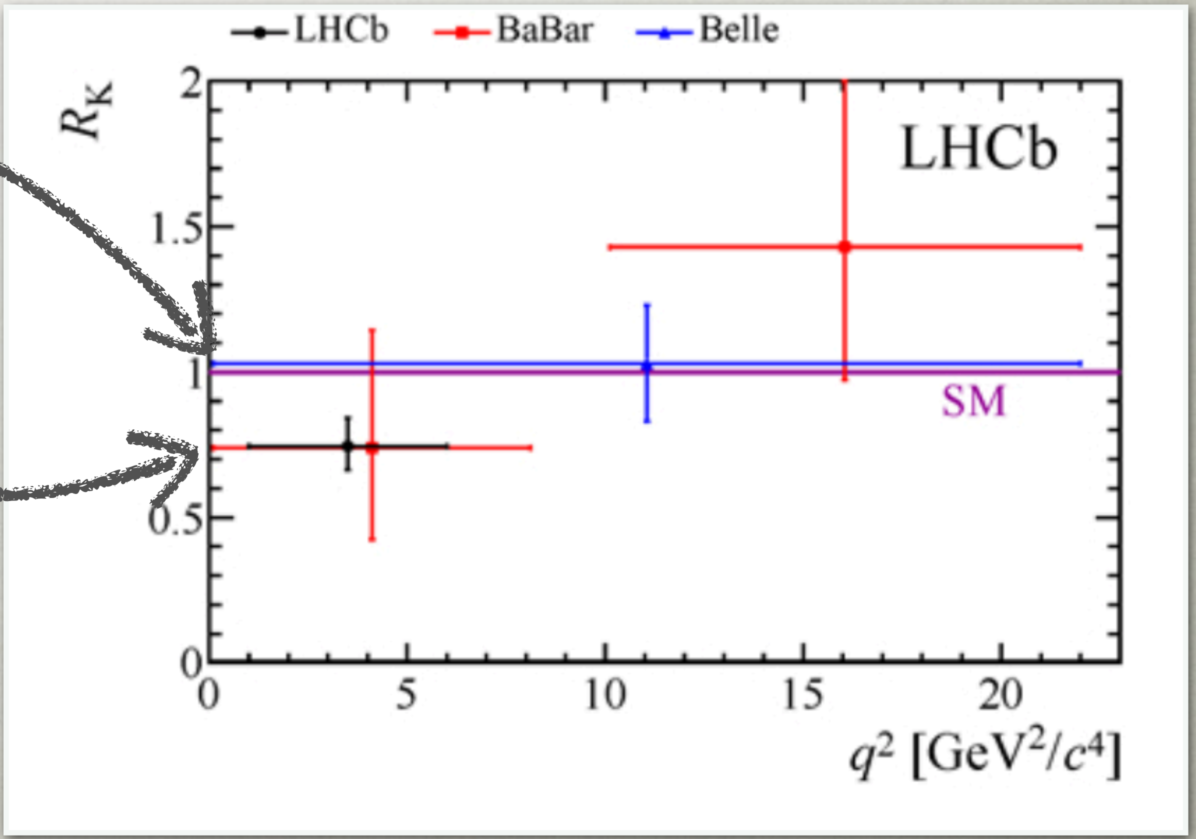
- 2.6σ anomaly in R_K

Bordone, Isidori, Pattori, 1605.07633

SM: $R_K = 1.00 \pm 0.01$

exp: $R_K = 0.745 \pm 0.082$

LHCb,1406.6482 (3.0 fb-1 @7+8TeV)

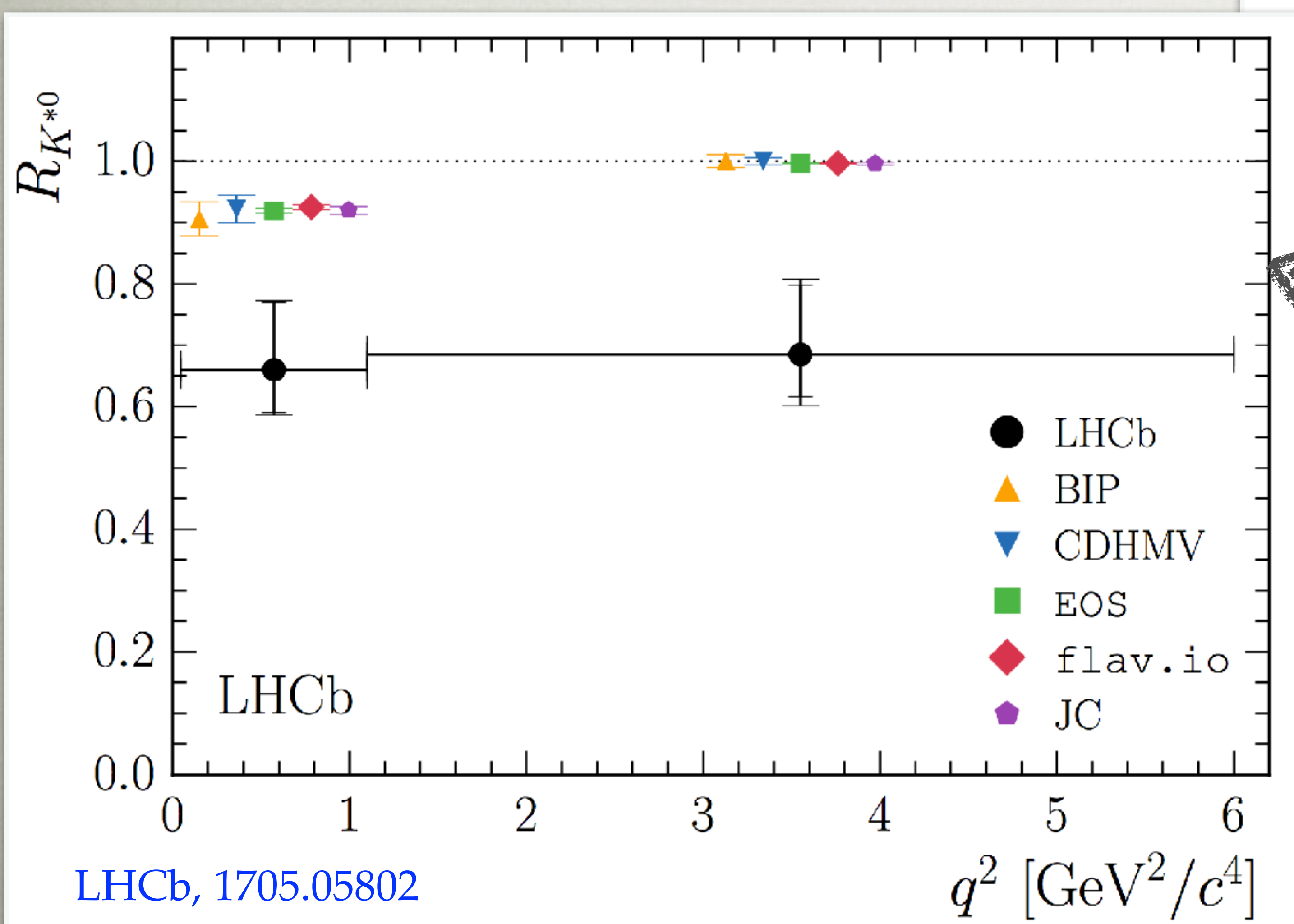


$b \to sll$: EXPERIMENT

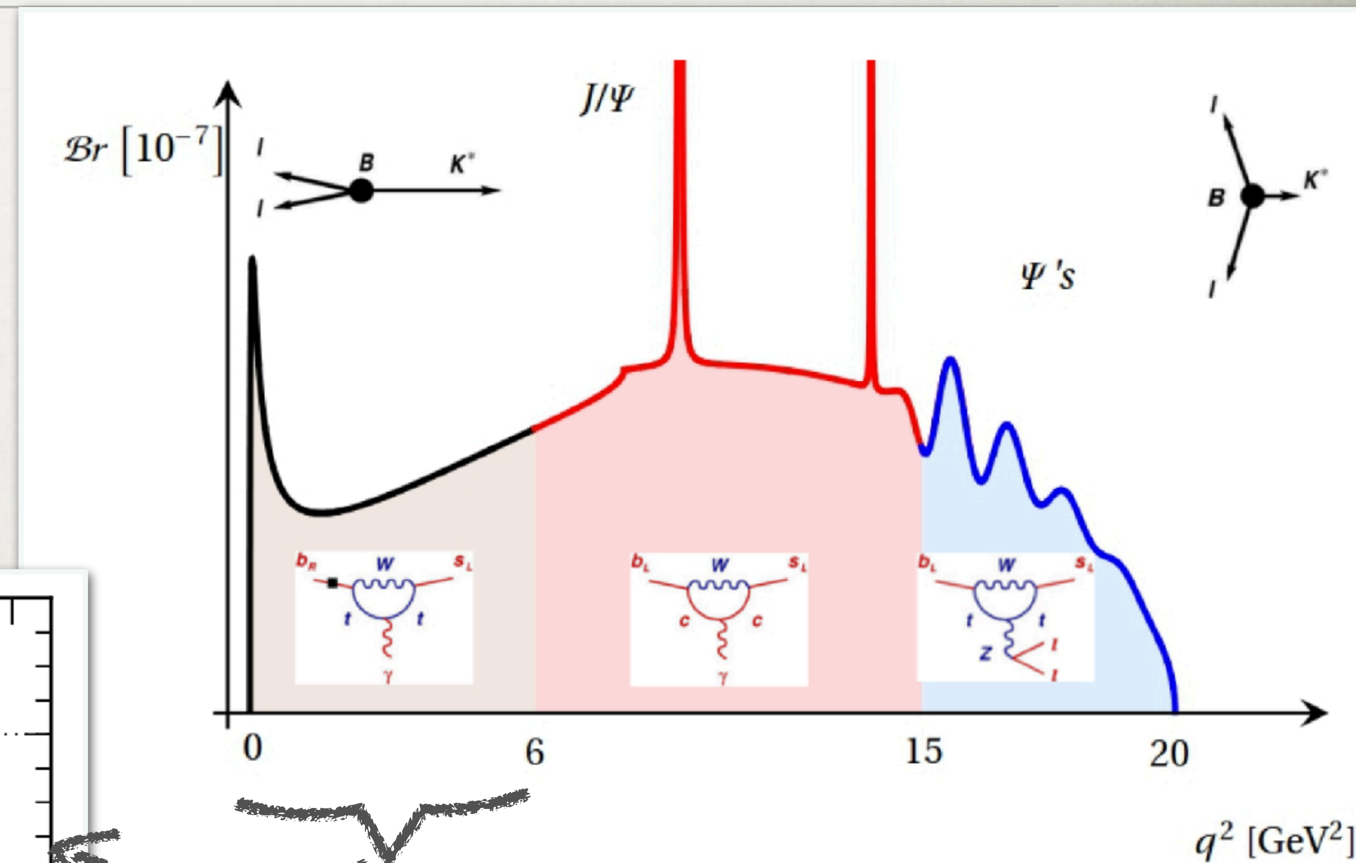
- 2 bins in R_{K^*}

$$R_{K^*} = \frac{\mathrm{BR}(B \to K^* \mu^+ \mu^-)}{\mathrm{BR}(B \to K^* e^+ e^-)}$$

- 2.2-2.5σ deviation in each



LHCb, 1705.05802



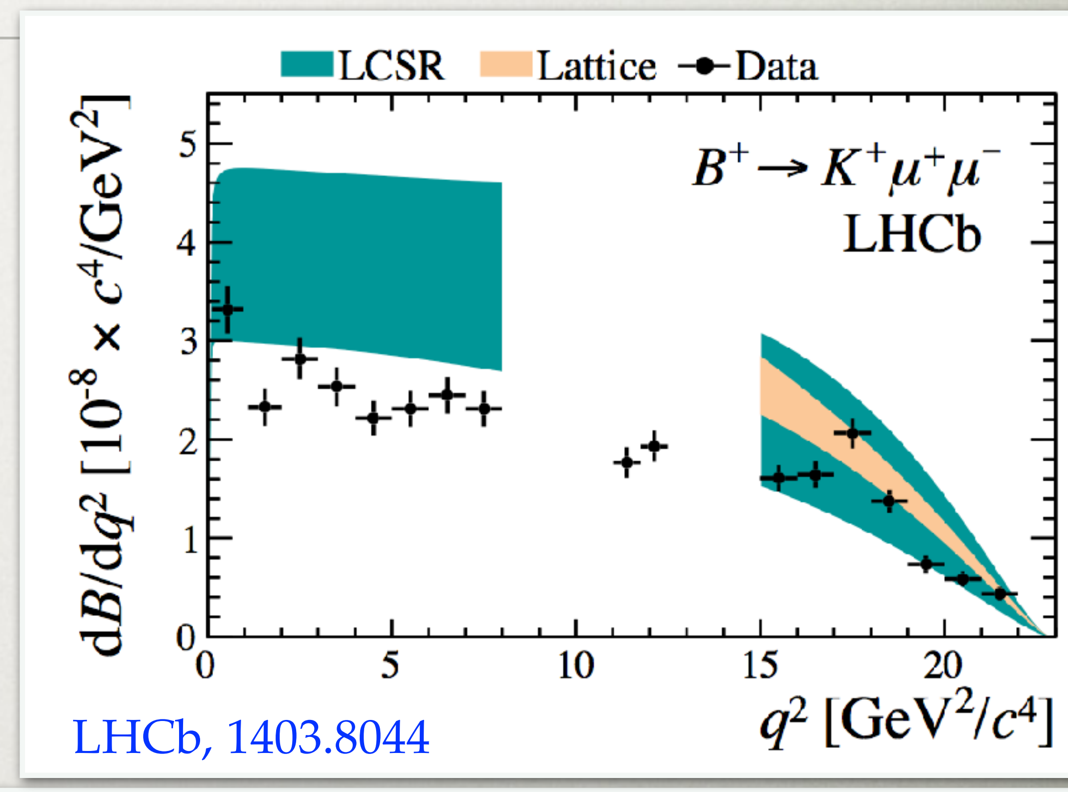
experiment: LHCb, 1705.05802 (3.0 fb-1 @7+8TeV)

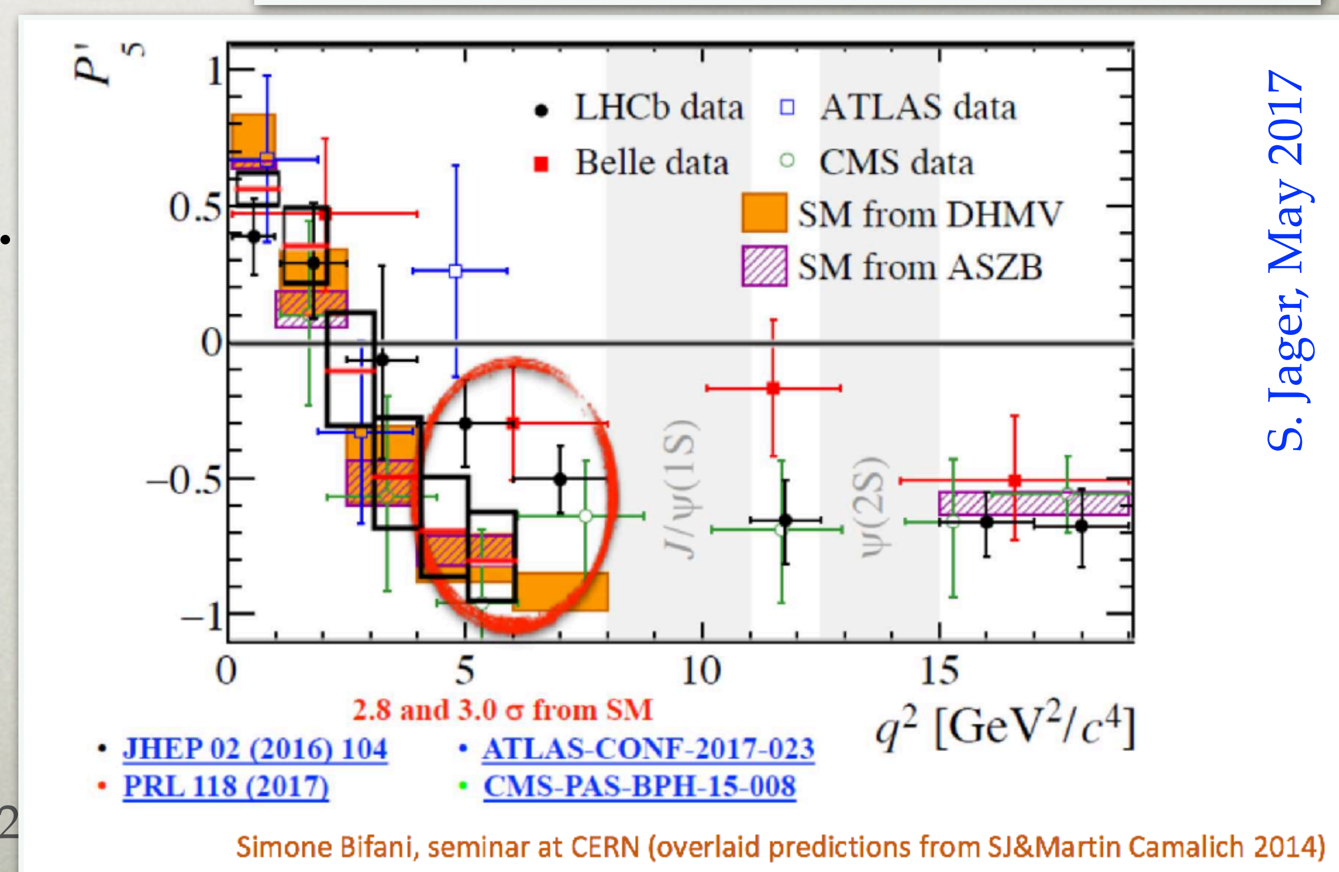
$$R_{K^*[0.045,\ 1.1]\ \mathrm{GeV}^2} = 0.660^{+0.110}_{-0.070} \pm 0.024,$$

$$R_{K^*[1.1,\ 6]\ \mathrm{GeV}^2} = 0.685^{+0.113}_{-0.069} \pm 0.047,$$

GLOBAL FITS

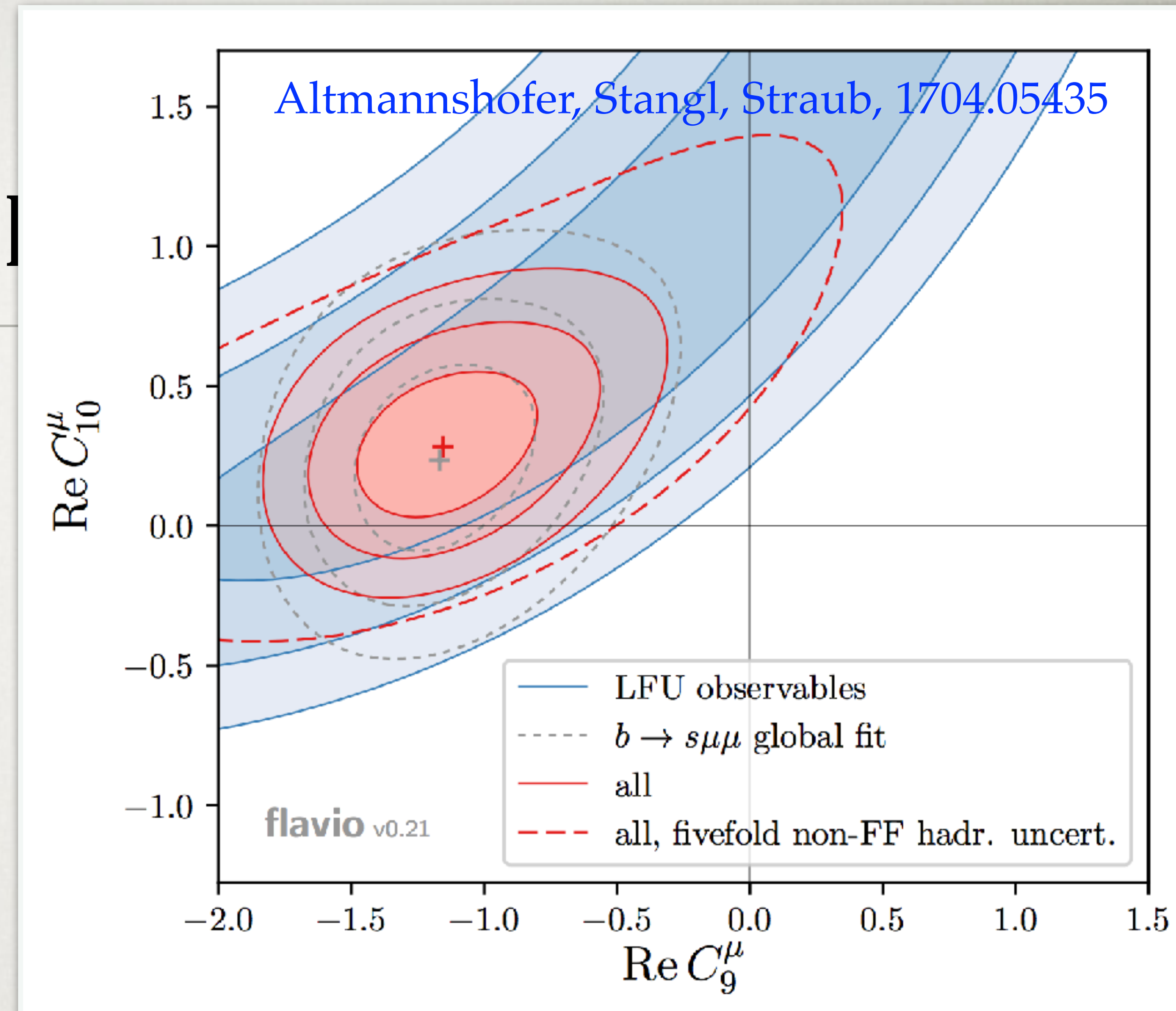
- in principle much more info
  - $Br(B \to K^{(*)}\mu\mu)$, $Br(B_s \to \phi\mu\mu)$, $Br(B \to X_s\mu\mu)$
  - angular obs. in $B^0 \to K^{*0}\mu\mu$, $B_s \to \phi\mu\mu$
- sensitive to hadronic inputs
  - require form factors predict. (QCD sum rules), charm loops, nonfactor. contribs.
- prefer NP in muons

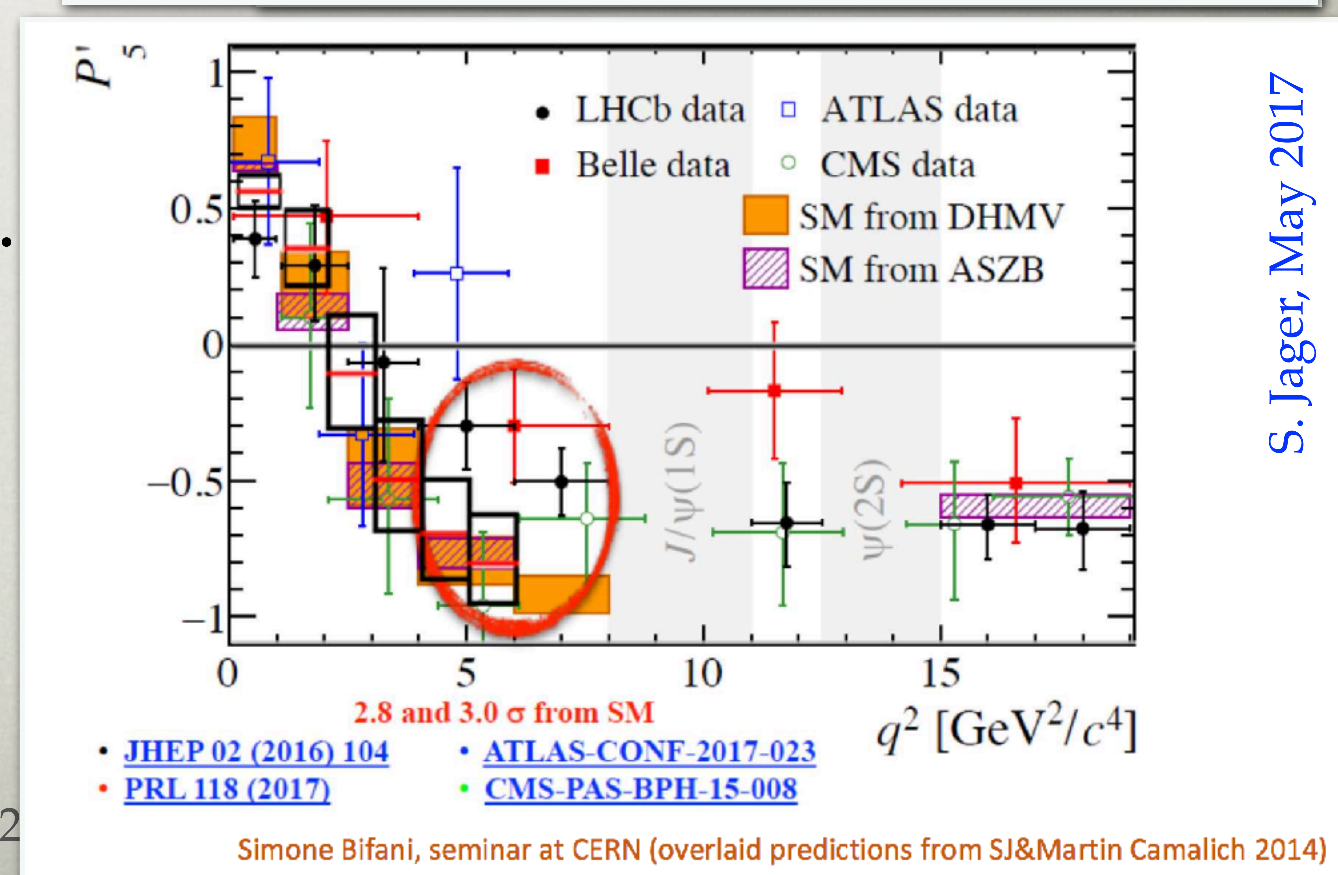




GLOBA

- in principle much more info
  - $Br(B \to K^{(*)}\mu\mu)$, $Br(B_s \to \phi\mu\mu)$, $Br(B \to X_s\mu\mu)$
  - angular obs. in $B^0 \to K^{*0}\mu\mu$, $B_s \to \phi\mu\mu$
- sensitive to hadronic inputs
  - require form factors predict. (QCD sum rules), charm loops, nonfactor. contribs.
- prefer NP in muons





WHAT KIND OF NP?

- from now on will assume that NP in $b \to s\mu\mu$
- what is the NP scale?
  - the Wilson coeffs. in previous slide

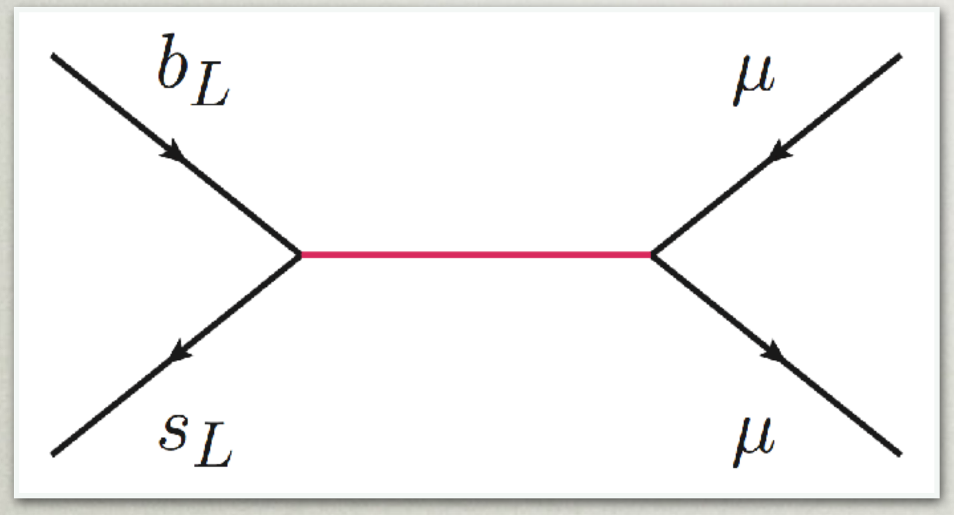
$$V_{tb}V_{ts}^* \frac{\alpha_{\rm em}}{4\pi v^2} C_I = \frac{C_I}{(36\,\mathrm{TeV})^2}$$

$C_I^{NP} \sim O(1)$

- types of NP
  - tree level (heavy or light)
  - loop level

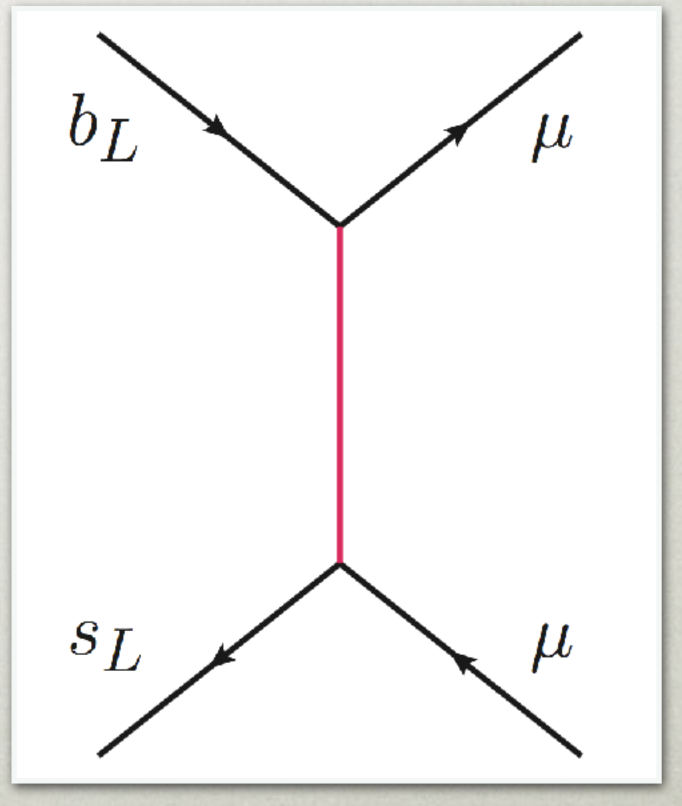
TREE LEVEL

- two distinct types:
- mediated by a Z'
  - $SU(2)_L$ singlet or triplet



Altmannshofer, Straub, 1308.1501;
Altmannshofer, Gori, Pospelov, Yavin, 1403.1269;
Greljo, Isidori, Marzocca, 1506.01705;
+many refs.

- leptoquark
  - spin 0 or 1

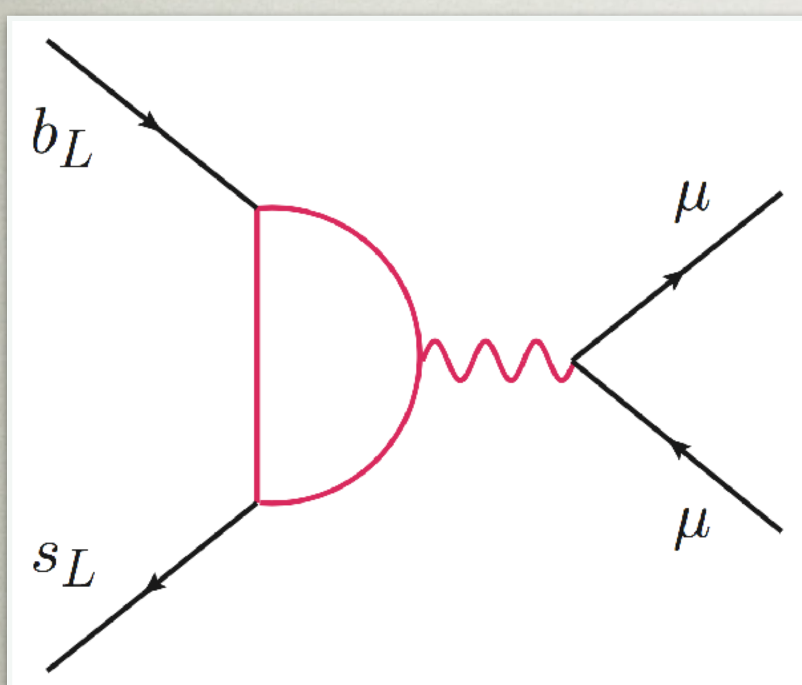


see, e.g., Hiller, Nisandzic, 1704.05444;
Hiller, Schmaltz, 1411.4773; +many refs

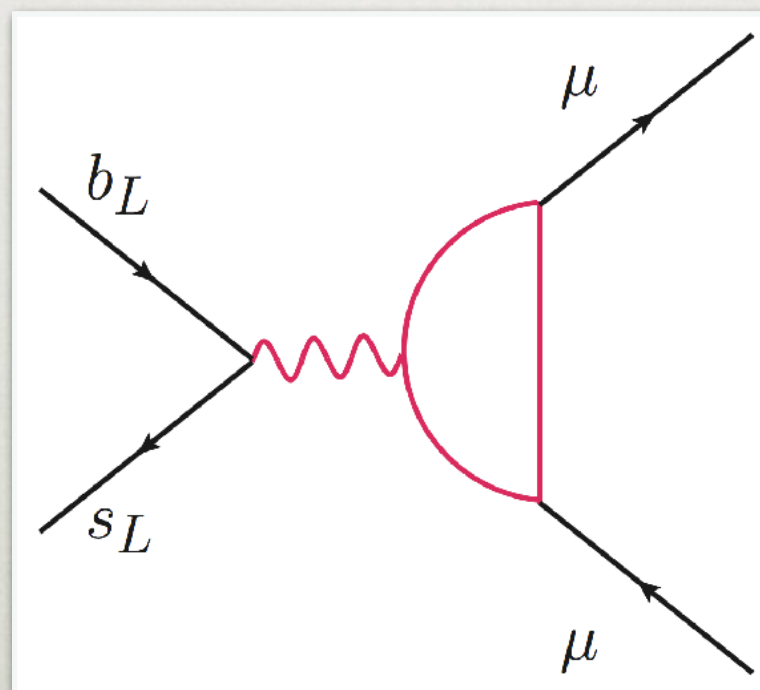
LOOP LEVEL

- three distinct options

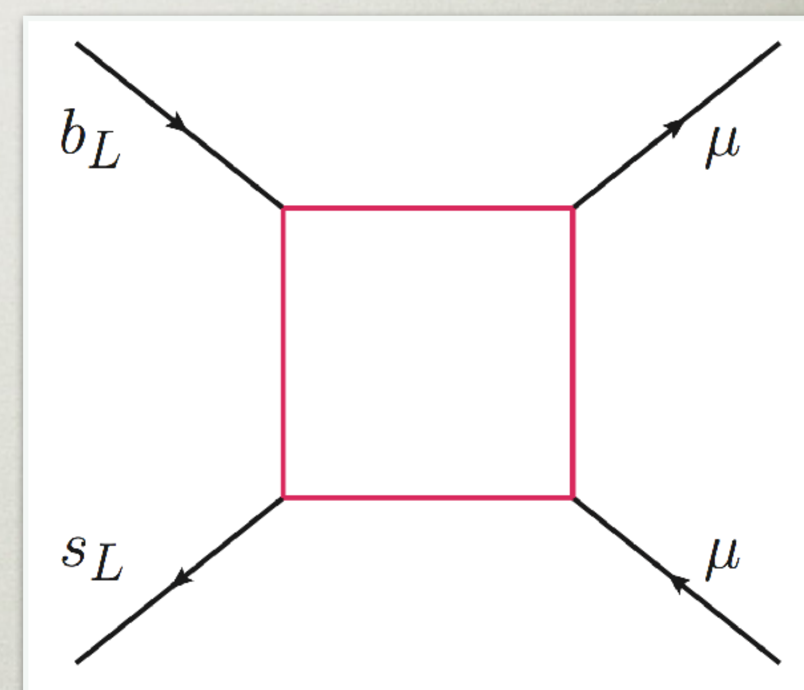
- Z′ w/ loop to *bs*
- Z′ w/ loop to $\mu\mu$
- box w/ NP fields



Kamenik, Soreq, JZ, 1704.06005



Bélanger, Delaunay, 1603.03333

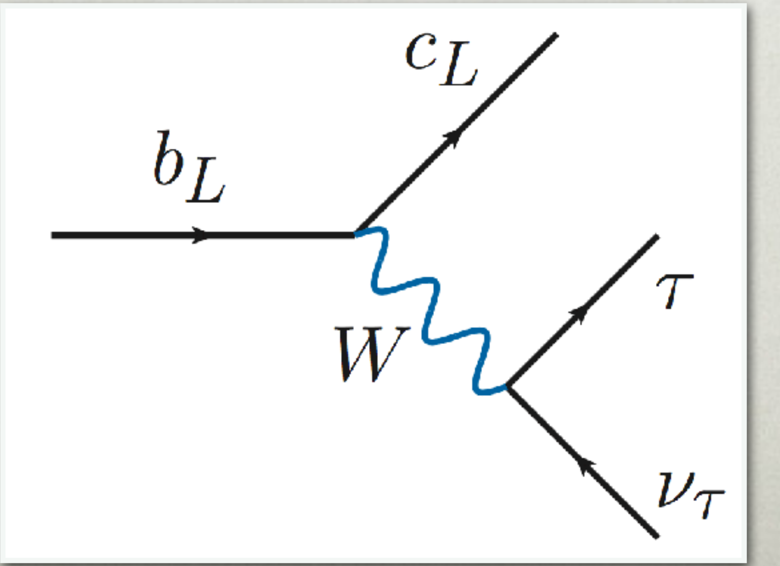


Gripaios, Nardecchia, Renner, 1509.05020;
Bauer, Neubert, 1511.01900;
Becirevic, Sumensari, 1704.05835

$b \to c \tau \nu$

UPSHOT

- $b \to c\tau\nu$ flavor anomaly
  - theoretically clean, ~4σ excess
  - NP effect large: *O(20%)* of SM tree level
    - NP interpr. often in conflict with other constraints



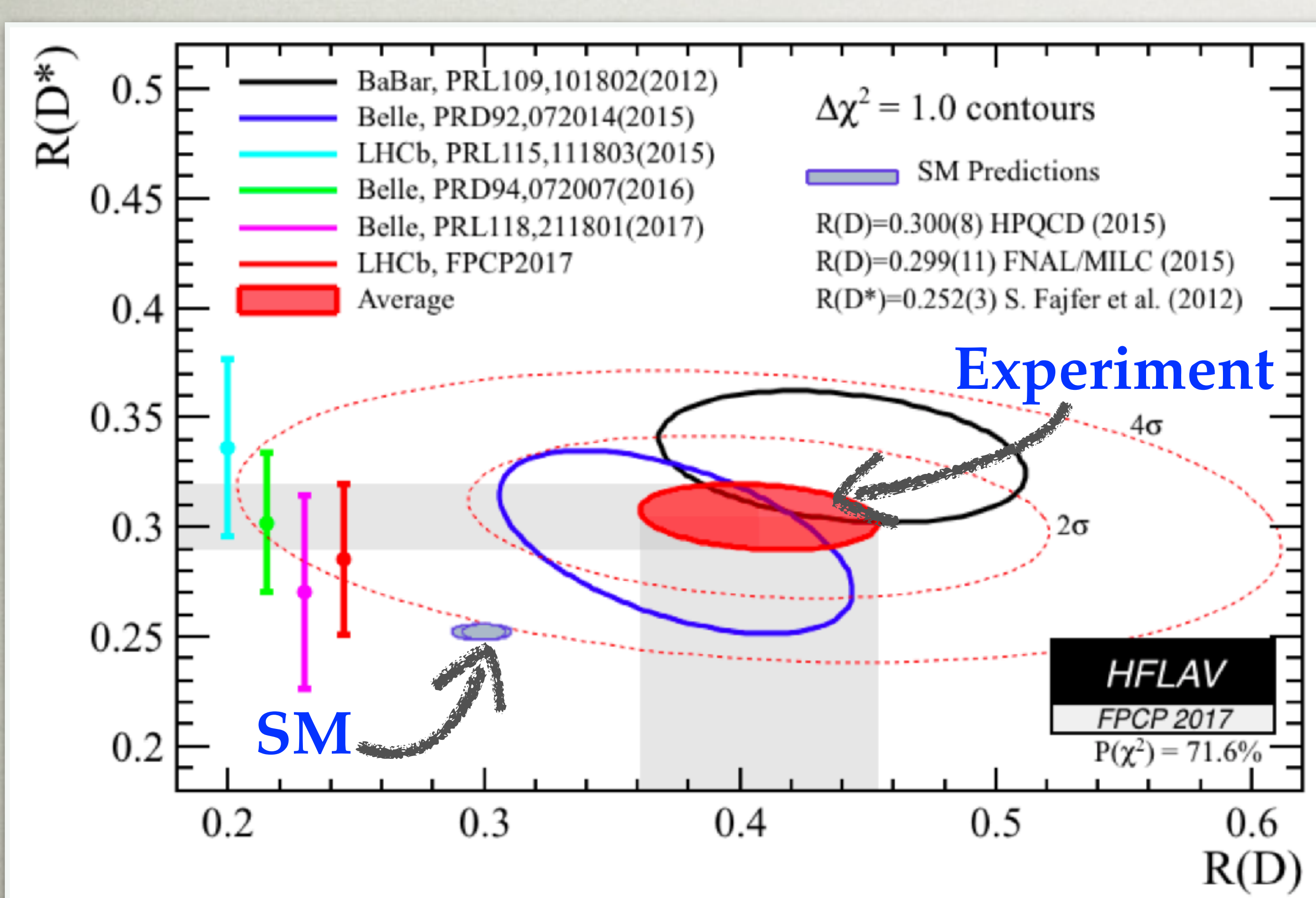
EXPERIMENTAL SITUATION

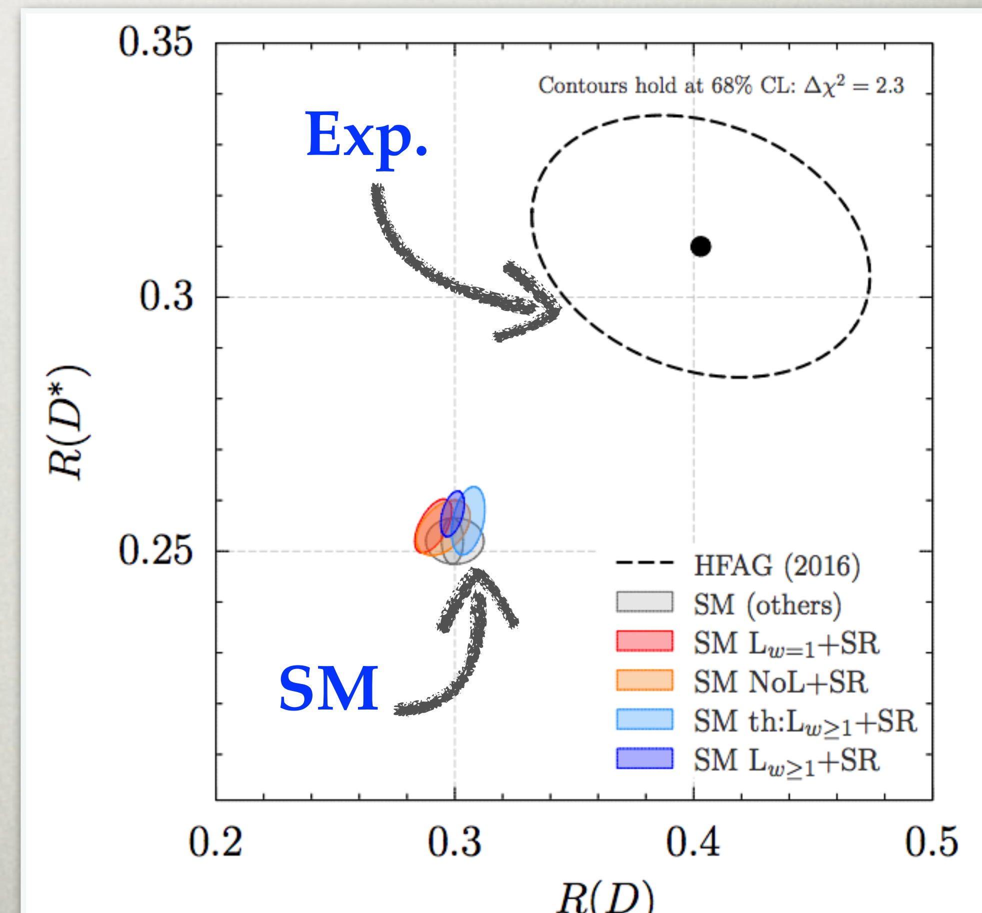
- seen in several experiments
- theory well under control

for theory predictions see, e.g.,
Fajfer, Kamenik, Nisandzic, 1203.2654
Bailey et al, 1206.4992
Becirevic, Kosnik, Tayduganov, 1206.4977
Bernlochner, Ligeti, Papucci, Robinson, 1703.05330
Bigi, Gambino, Schacht, 1707.09509

$$\frac{b\to c\tau\nu}{b\to cl\nu}$$

$$R(D^{(*)}) = \frac{\Gamma(\bar{B}\to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B}\to D^{(*)}l\bar{\nu})}\,, \qquad l=\mu,\, e$$



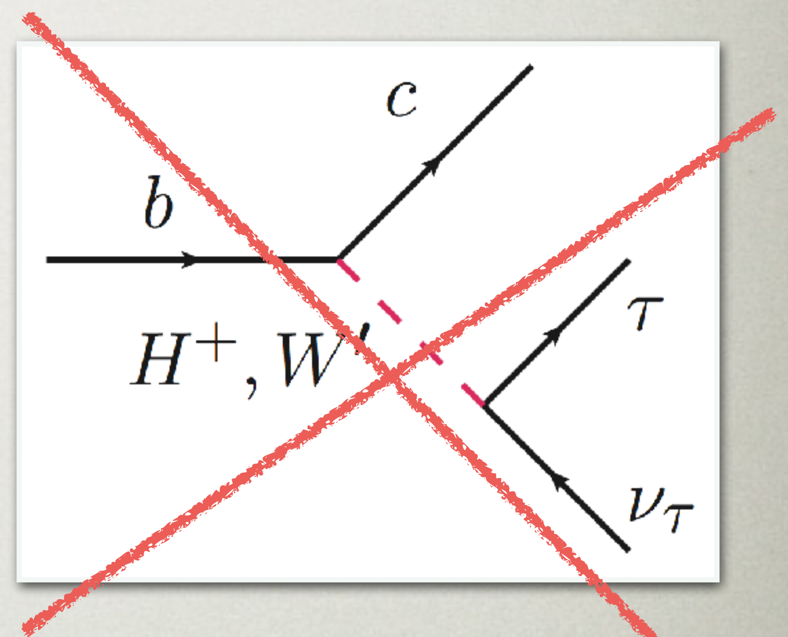


Bernlochner et al, 1703.05330

NEW PHYSICS INTERPRETATIONS

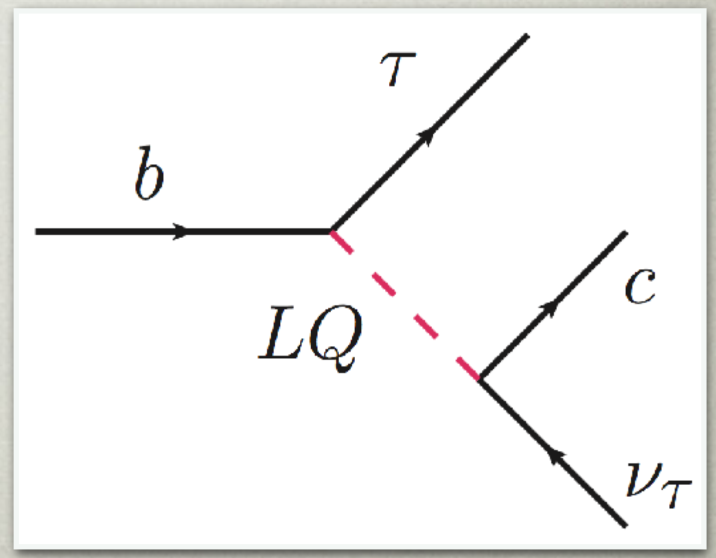
- the most obvious candidates ruled out
  - charged Higgs: total B_c lifetime, $b \to c\tau\upsilon$ q^2 distributions, searches in $pp \to \tau\tau$
  - W': related Z' ruled out from $pp \to \tau\tau$
    - viable, if RH neutrino $b \to c\tau N_R$

Greljo, Robinson, Shakya, JZ, 1804.04642



- several viable leptoquarks
  - vector leptoquark: explains $b \to c\tau\upsilon$ & $b \to s\mu\mu$
  - also possible if more than one scalar leptoquark

Crivellin, Muller, Ota, 1703.09226



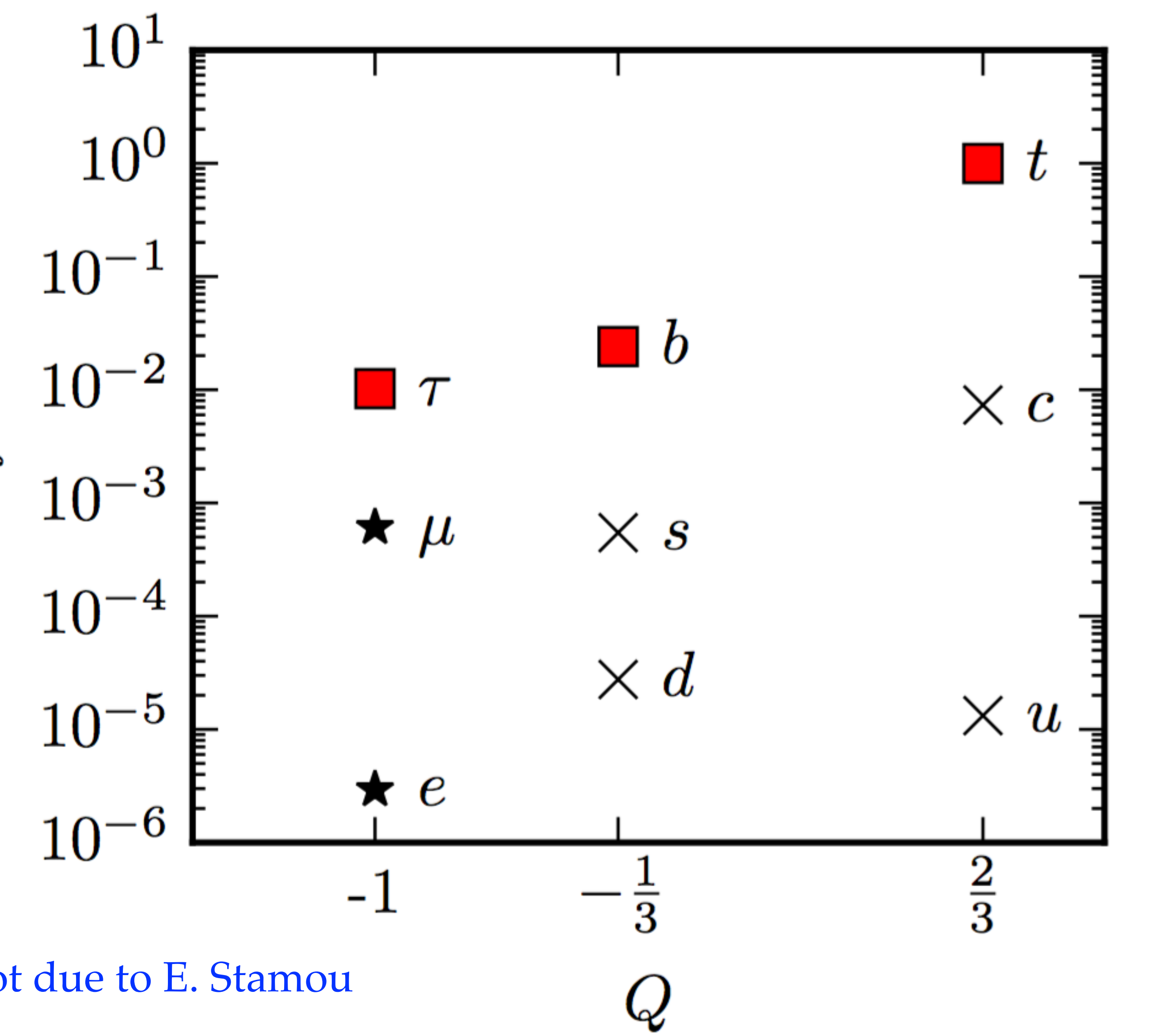
HIGGS AND FLAVOR

HIGGS - A NEW PROBE OF FLAVOR

- in the SM all flavor structure due to the Higgs Yukawa couplings

$$y_f = \sqrt{2} m_f / v$$

- implies Higgs has very hierarchical couplings to fermions
- how well have we tested this?



plot due to E. Stamou

TESTING THE FLAVOR OF THE HIGGS

Nir, 1605.00433

- several questions
  - proportionality

    $$y_{ii} \propto m_i$$

  - factor of proportionality

    $$y_{ii}/m_i = \sqrt{2}/v$$

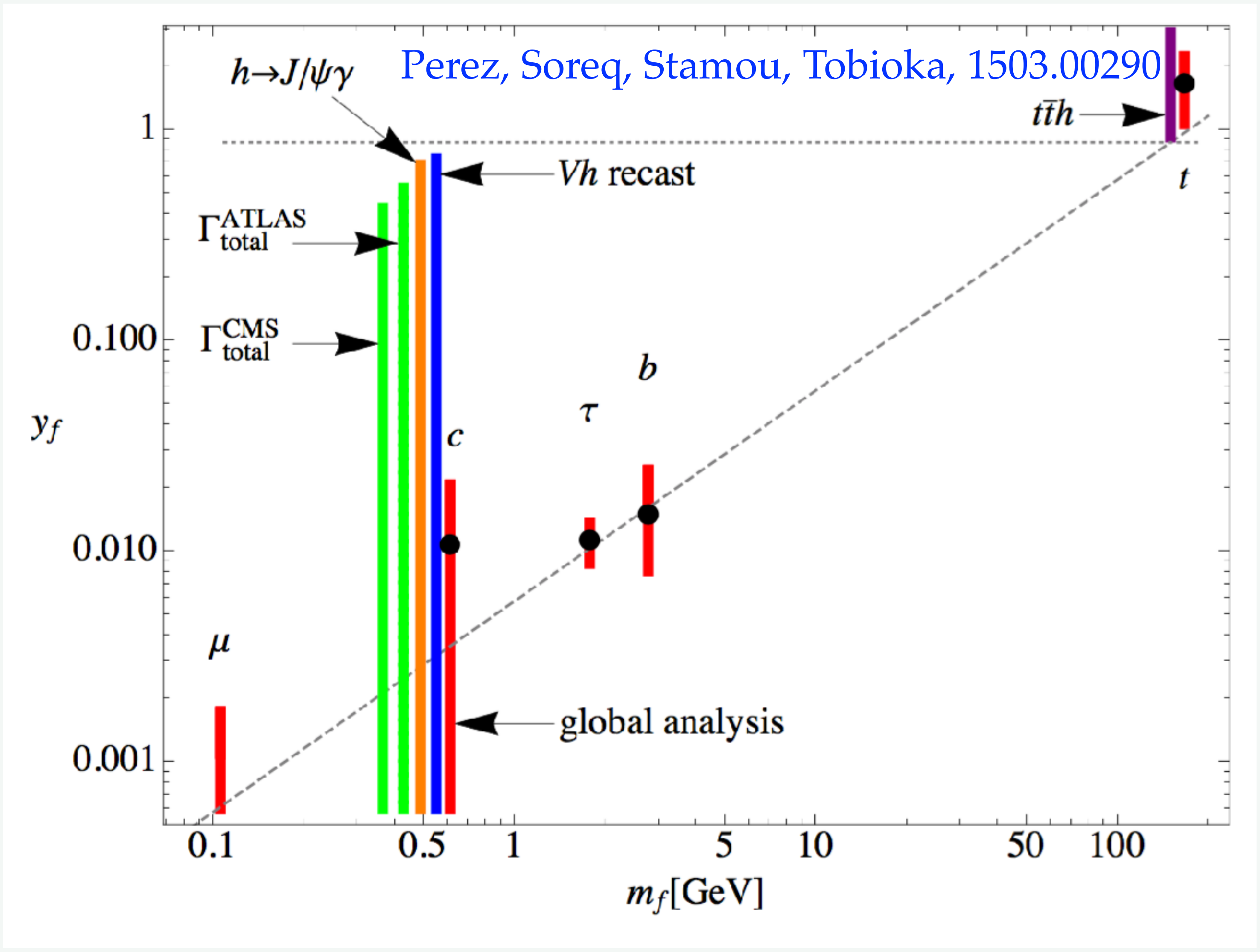
  - diagonality (flavor violation)

    $$y_{ij} = 0, \quad i \neq j$$

  - reality (CP violation)

    $$\mathrm{Im}(y_{ij}) = 0$$

$$y_f^{\mathrm{SM}} = \sqrt{2} m_f / v$$

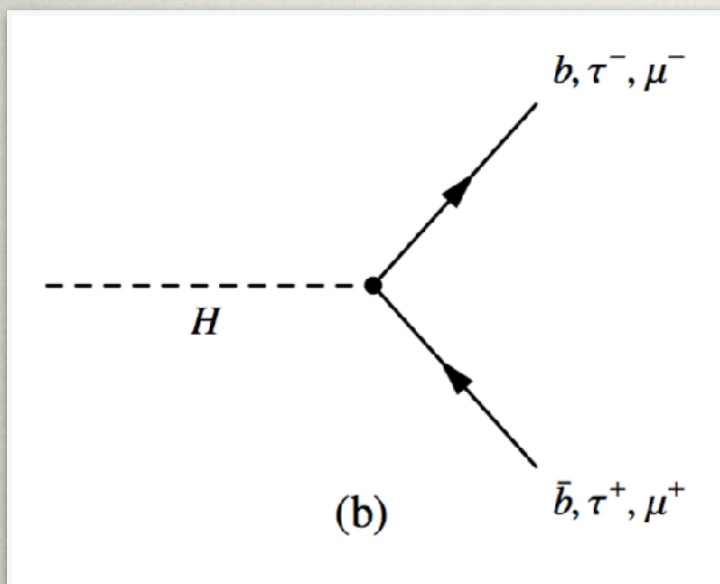


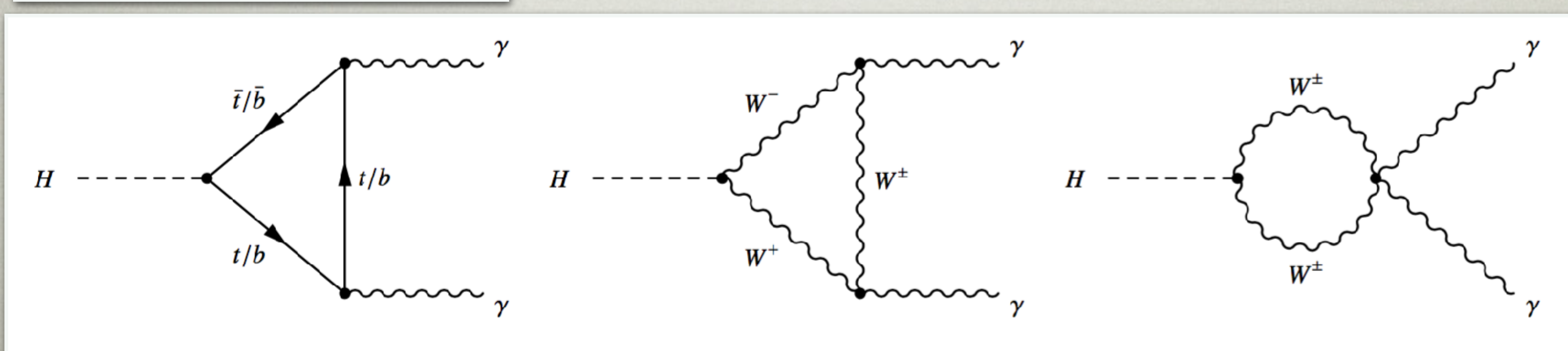
PROPORTIONALITY

- "proportionality" and "factor of proportionality"

$$y_{ii} \propto m_i \qquad\qquad y_{ii}/m_i = \sqrt{2}/v$$

- tested for 3rd generation fermions





PROPORTIONALITY

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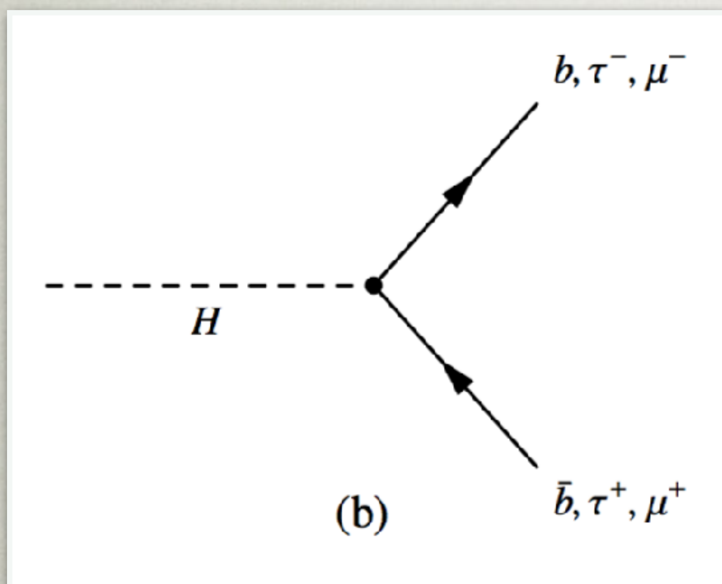
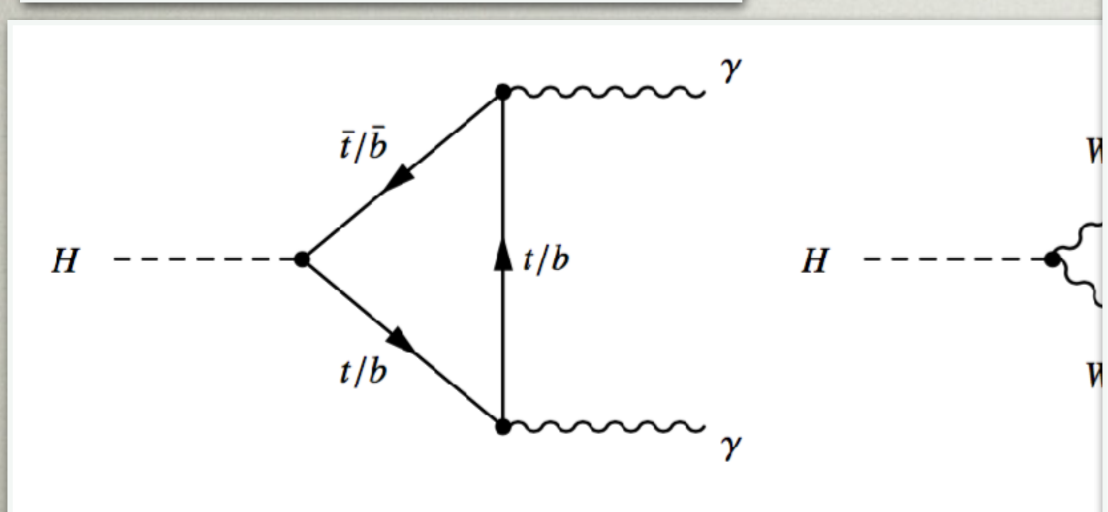
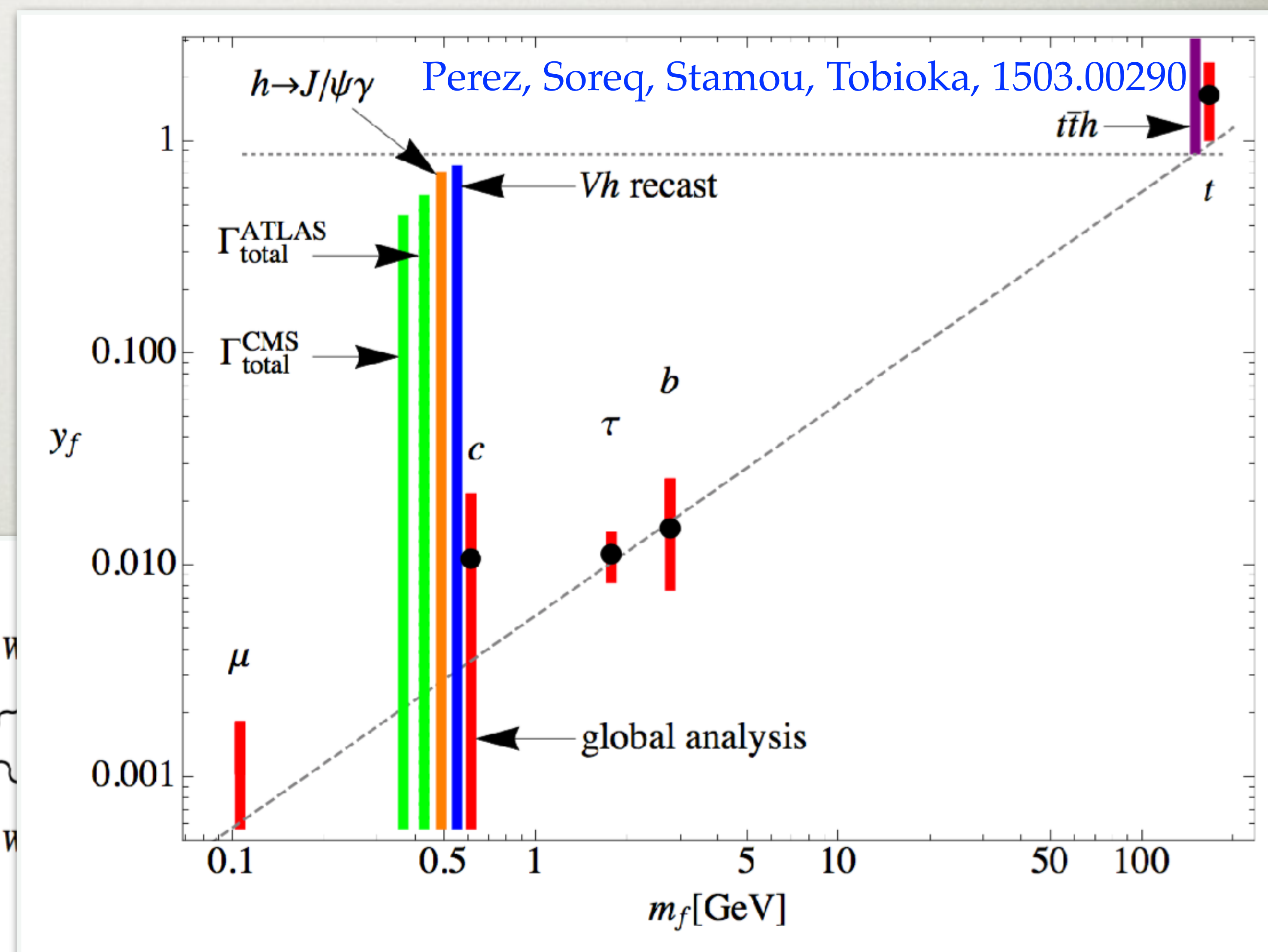






HIERARCHICAL COUPLINGS?

- does Higgs couple to the first two generations?
  - tough: couplings are small
- more modest question: can we show that the couplings are hierarchical?
  - yes, but for quarks with some assumptions

$$\frac{Y_{e(\mu)}^{\rm exp}}{Y_\tau^{\rm exp}} < 0.22(0.10), \qquad \frac{Y_{u(c)}^{\rm exp}}{Y_t^{\rm exp}} \lesssim 0.04, \qquad \frac{Y_{d(s)}^{\rm exp}}{Y_t^{\rm exp}} < 0.7(6)$$

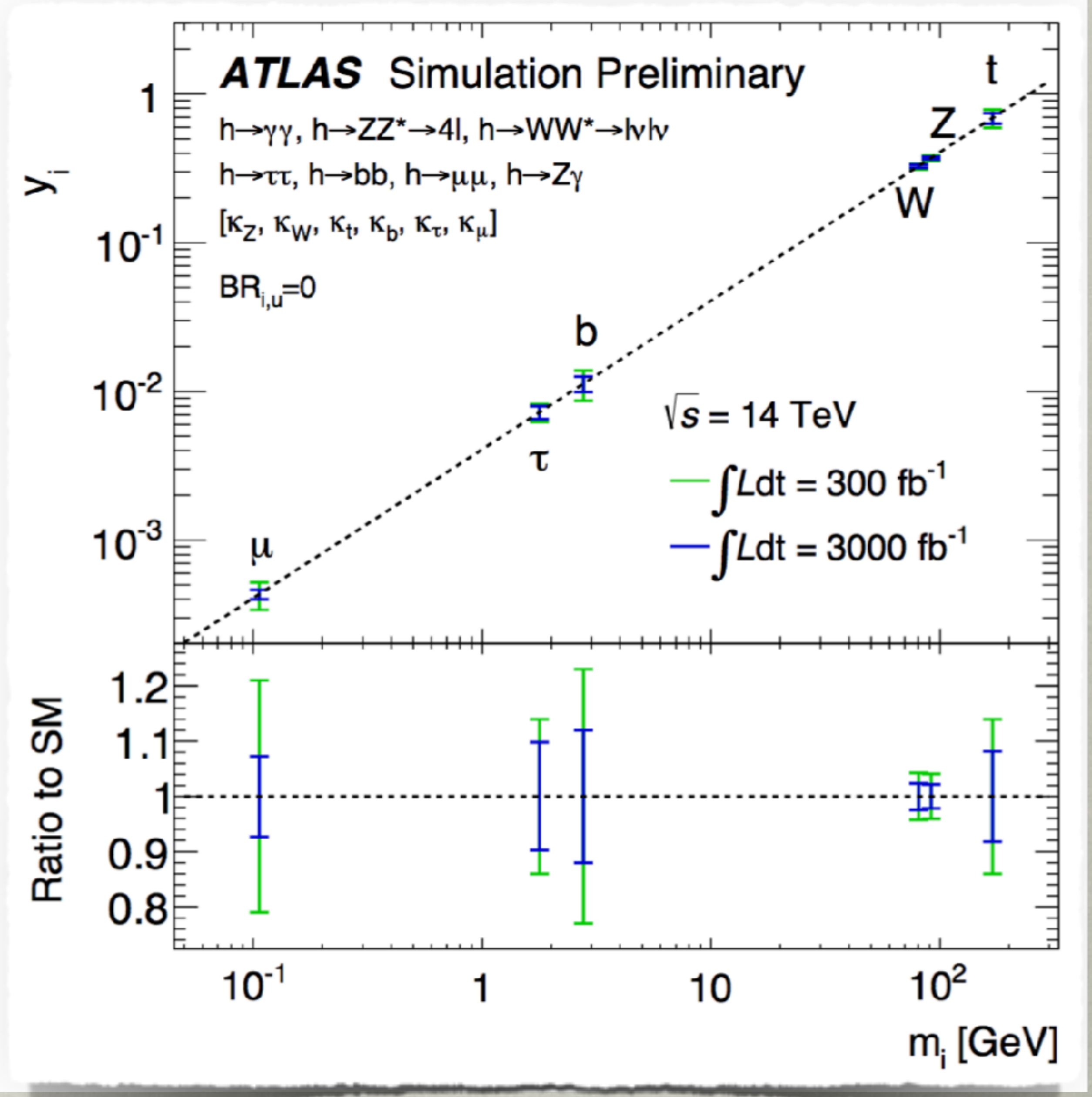
direct measurements

global fit

p_T distrib.

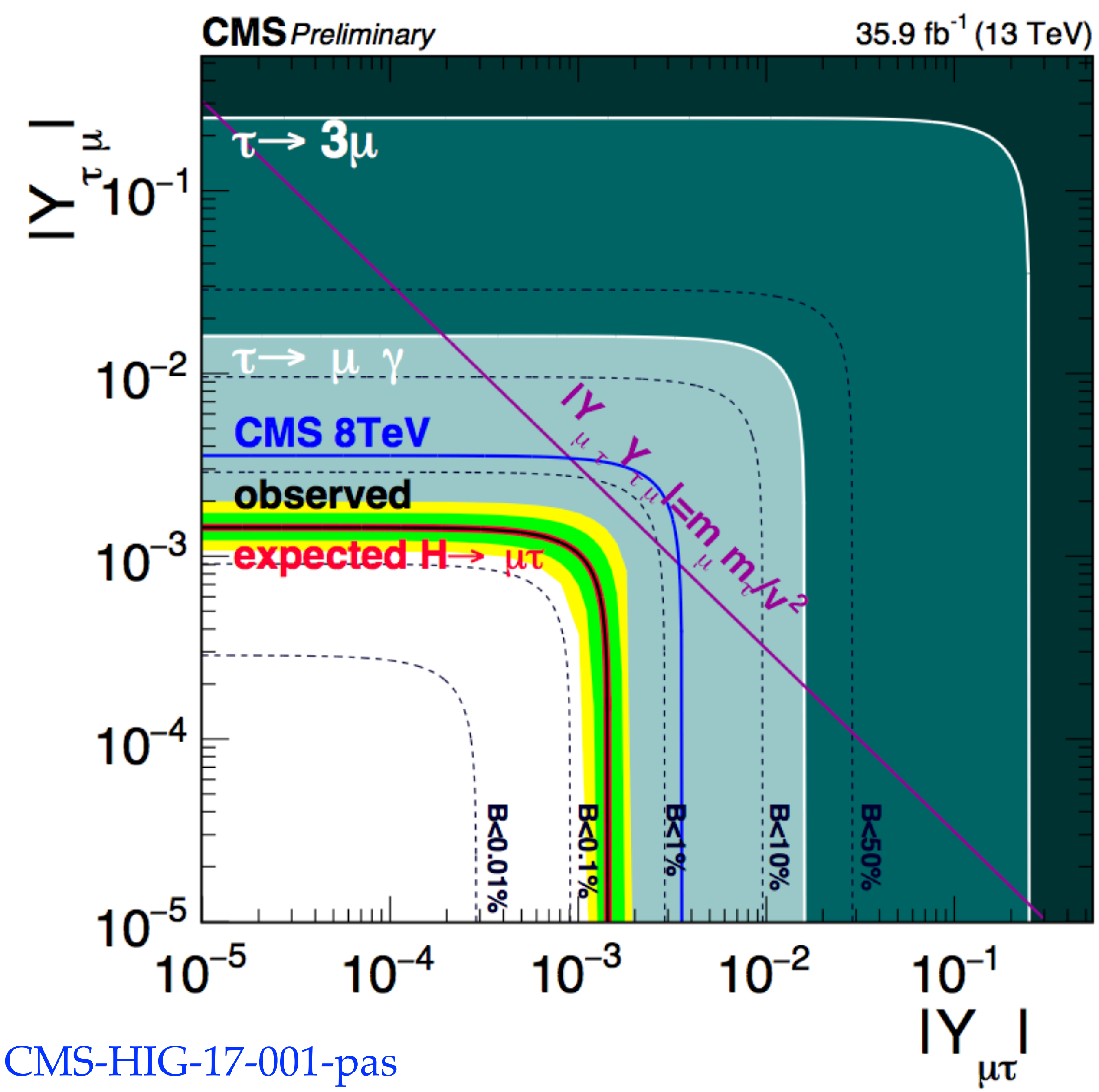
MUON YUKAWA

- the SM Higgs muon Yukawa accessible at high-luminosity LHC
- the only one among the first two generations of fermions
- could significantly deviate from the SM
  - could even be zero

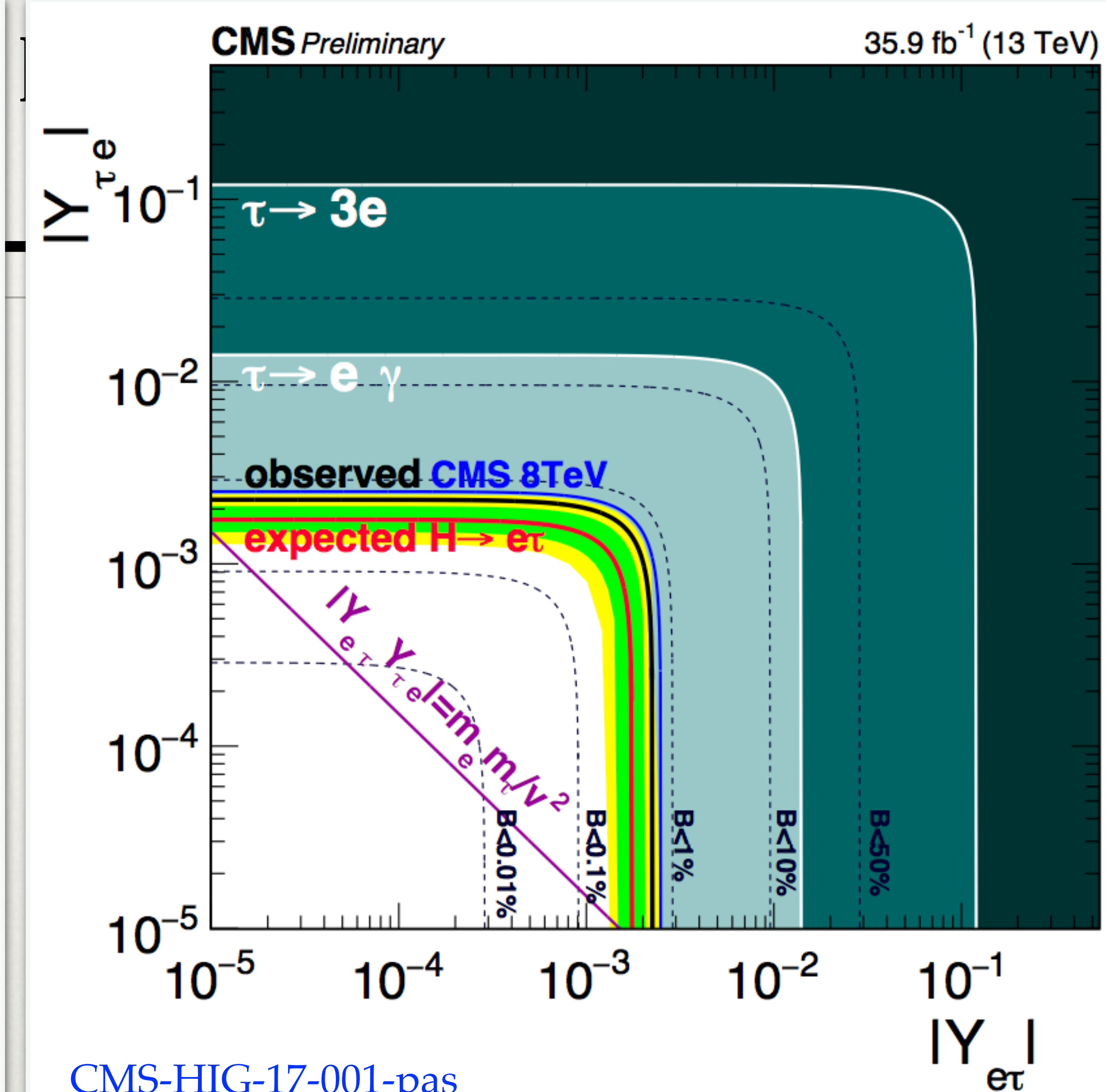


FLAVOR VIOLATING COUPLINGS

- in the SM Higgs couplings flavor diagonal
  - discovering flavor violating couplings means New Physics
- for charged lepton final states accessible directly
  - from $h \to \tau\mu$, $h \to \tau e$



CMS-HIG-17-001-pas



CMS-HIG-17-001-pas

$$\text{for } \hat{\lambda}_{ij} = 1$$

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

$$\Lambda_{\mu\tau} > 5.5 \text{ TeV}$$

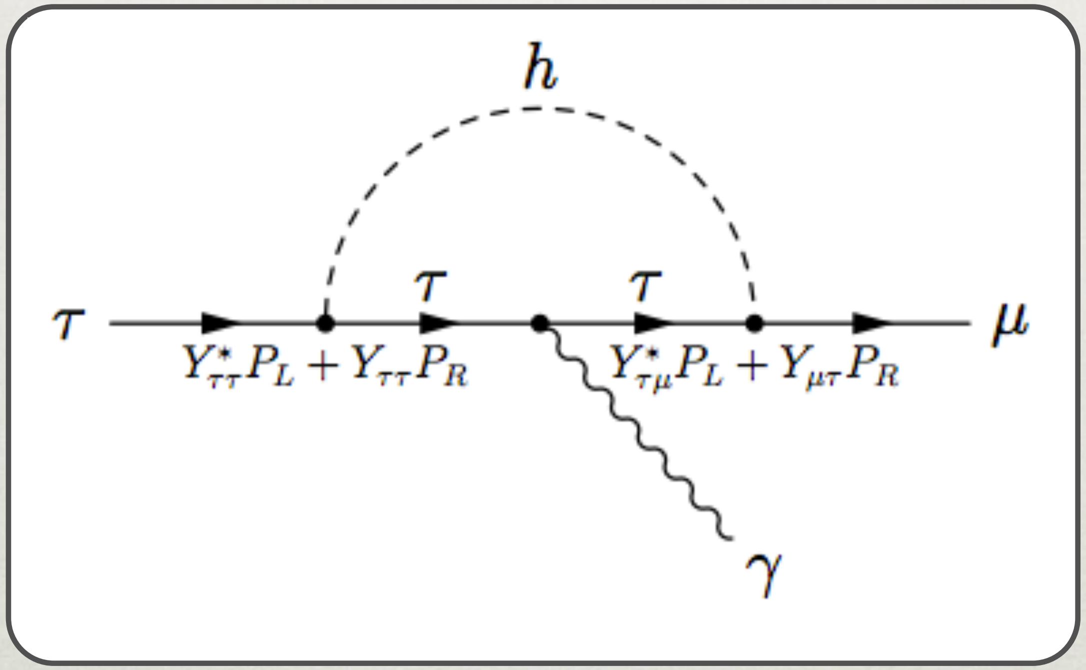
$$\Lambda_{e\tau} > 4.4 \text{ TeV}$$

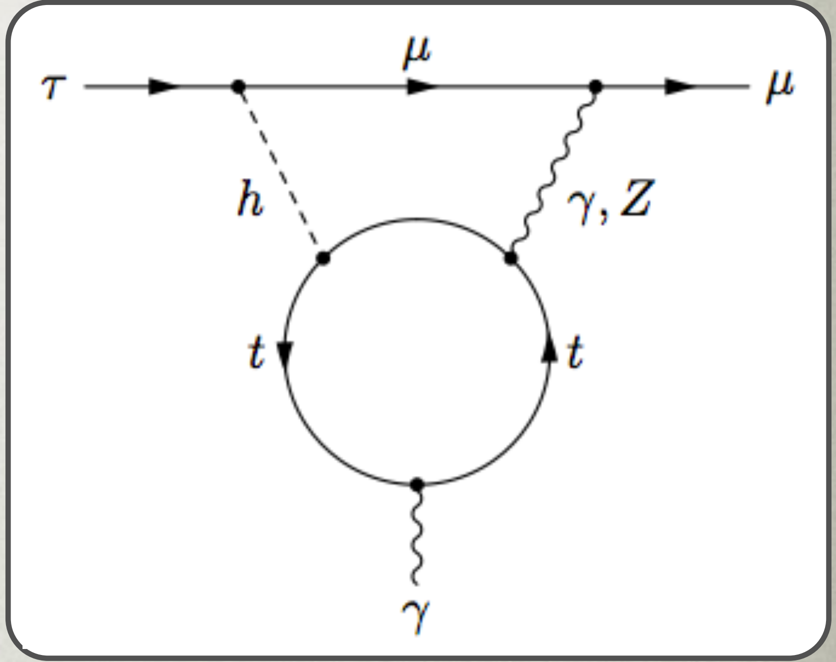
INDIRECT BOUNDS ON $h \to \tau\mu$

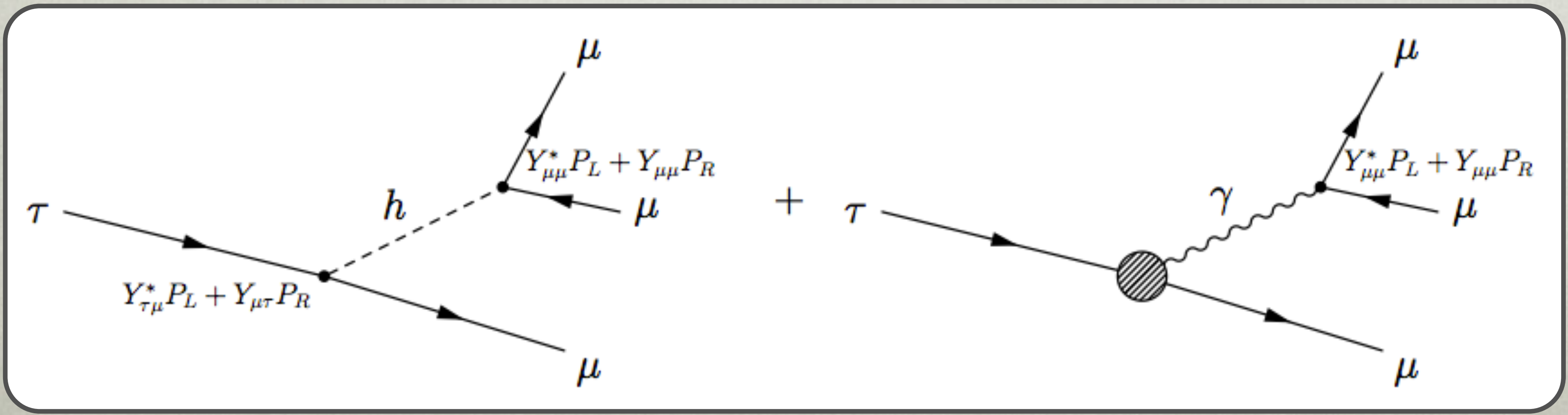
Harnik, Kopp, JZ, 1209.1397

see also Blankenburg, Ellis, Isidori, 1202.5704

- also indirect bounds from charged lepton FCNC transitions
  - $\tau \to \mu\gamma$
  - $\tau \to 3\mu$



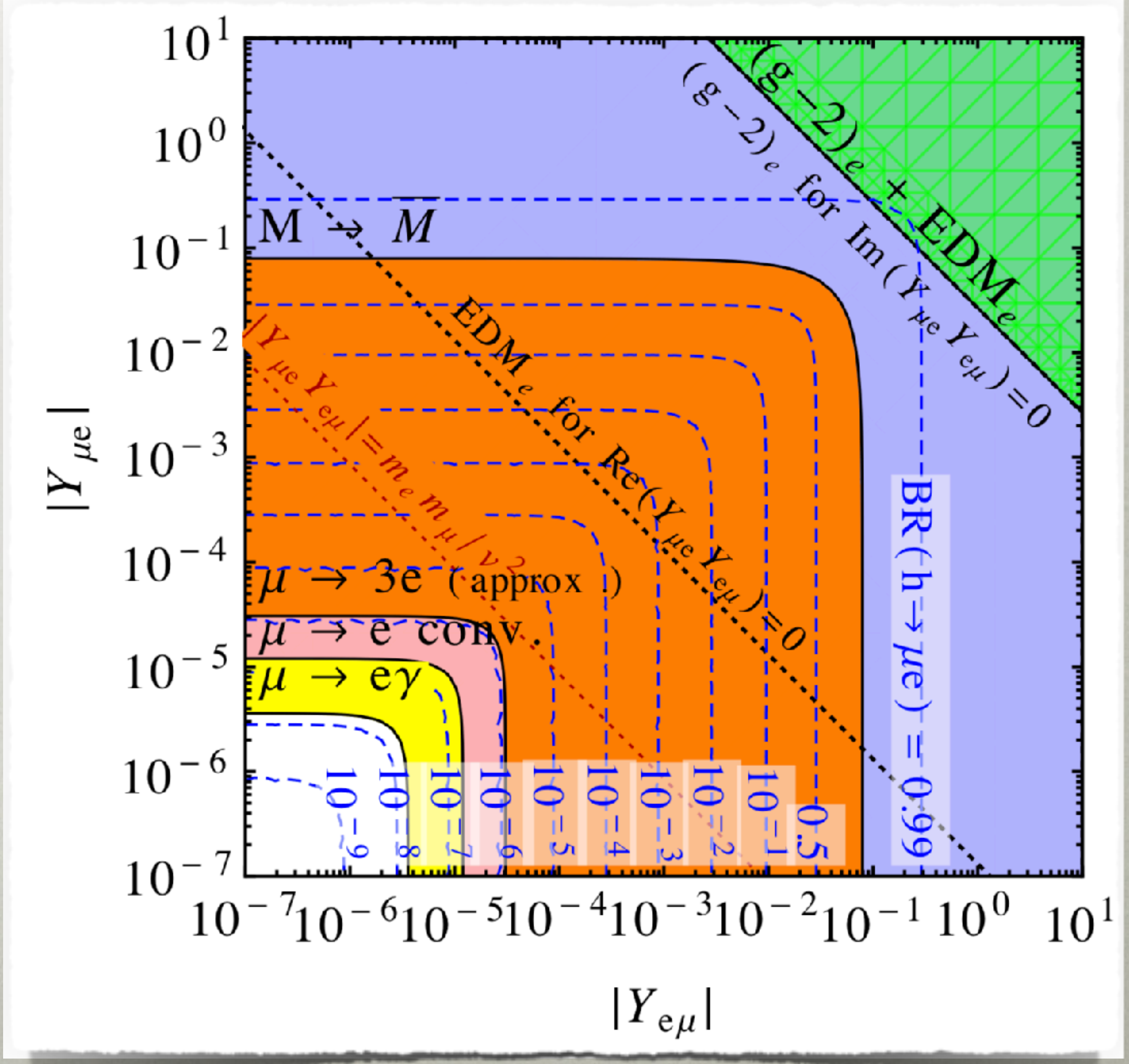




INDIRECT BOUNDS ON $h \to e\mu$

Harnik, Kopp, JZ, 1209.1397

- indirect bounds especially severe for $h \to e\mu$
- $Br(h \to e\mu) < 10^{-8}$ required to surpass the bound from $Br(\mu \to e\gamma)$
- caveat: could be cancellations in the loop



CONCLUSIONS

- CKM matrix the dominant source of flavor violation in nature
- hints of anomalies in $b \to c\tau\nu$ and $b \to s\mu\mu$ transitions
  - would imply many new signals at both high p_T (CMS, ATLAS) and in precision flavor (LHCb, Belle II, NA62, g-2,...)

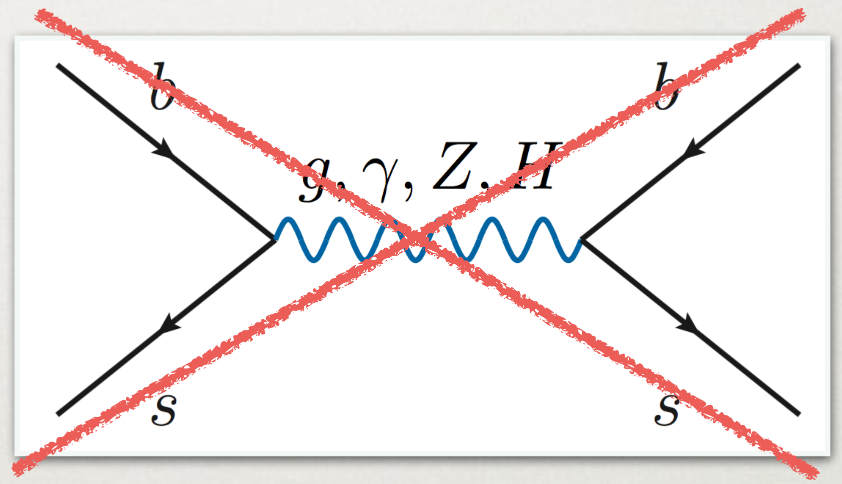
BACKUP SLIDES

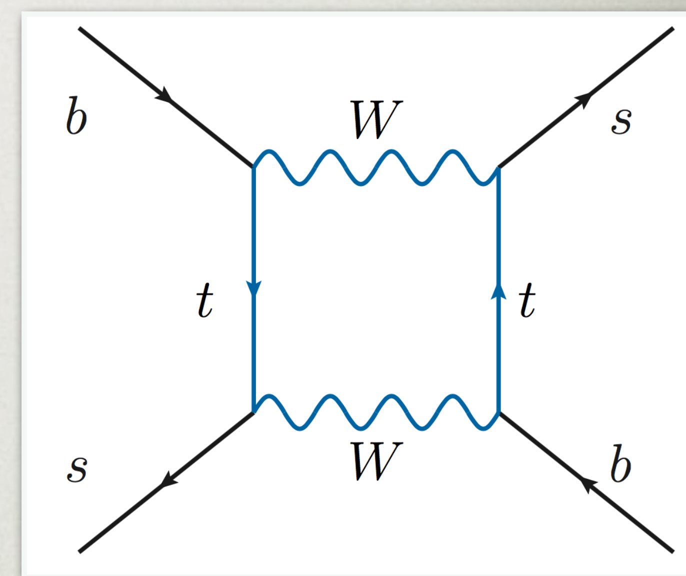
SENSITIVITY TO NEW PHYSICS

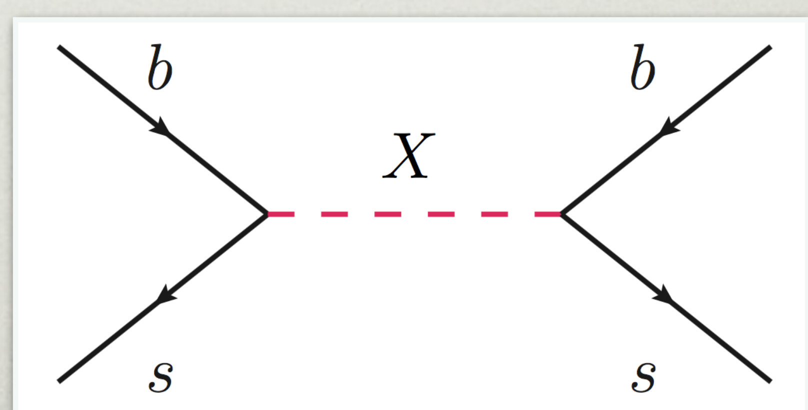
- SM@tree level: no Flavor Changing Neutral Currents
  - all FCNC processes loop suppressed
  - e.g., meson mixing
- can be modified by NP
- NP contribs. scale as

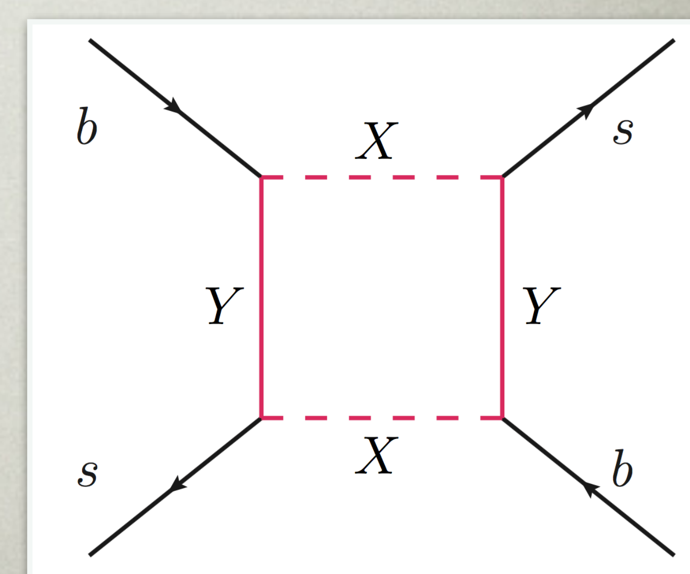
$$\delta C^{\mathrm{NP}} \propto \frac{g_{sb}^2}{M_{\mathrm{NP}}^2}$$

- depends on couplings and NP masses









USEFUL REFERENCES

- some excellent introductions to flavor physics
  - Kamenik, 1708.00771
  - Nir, 0708.1872, 1605.00433
  - Grossman, Tanedo, 1711.03624
  - Gedalia, Perez, 1005.3106
  - Blanke, 1704.03753
  - Ligeti, 1502.01372

FLAVOR STRUCTURE OF THE STANDARD MODEL

- in the SM flavor refers to the type/generation of fermion
- below electroweak scale the unbroken SM gauge group is $SU(3)_c \times U(1)_{em}$
  - three generations of fermions

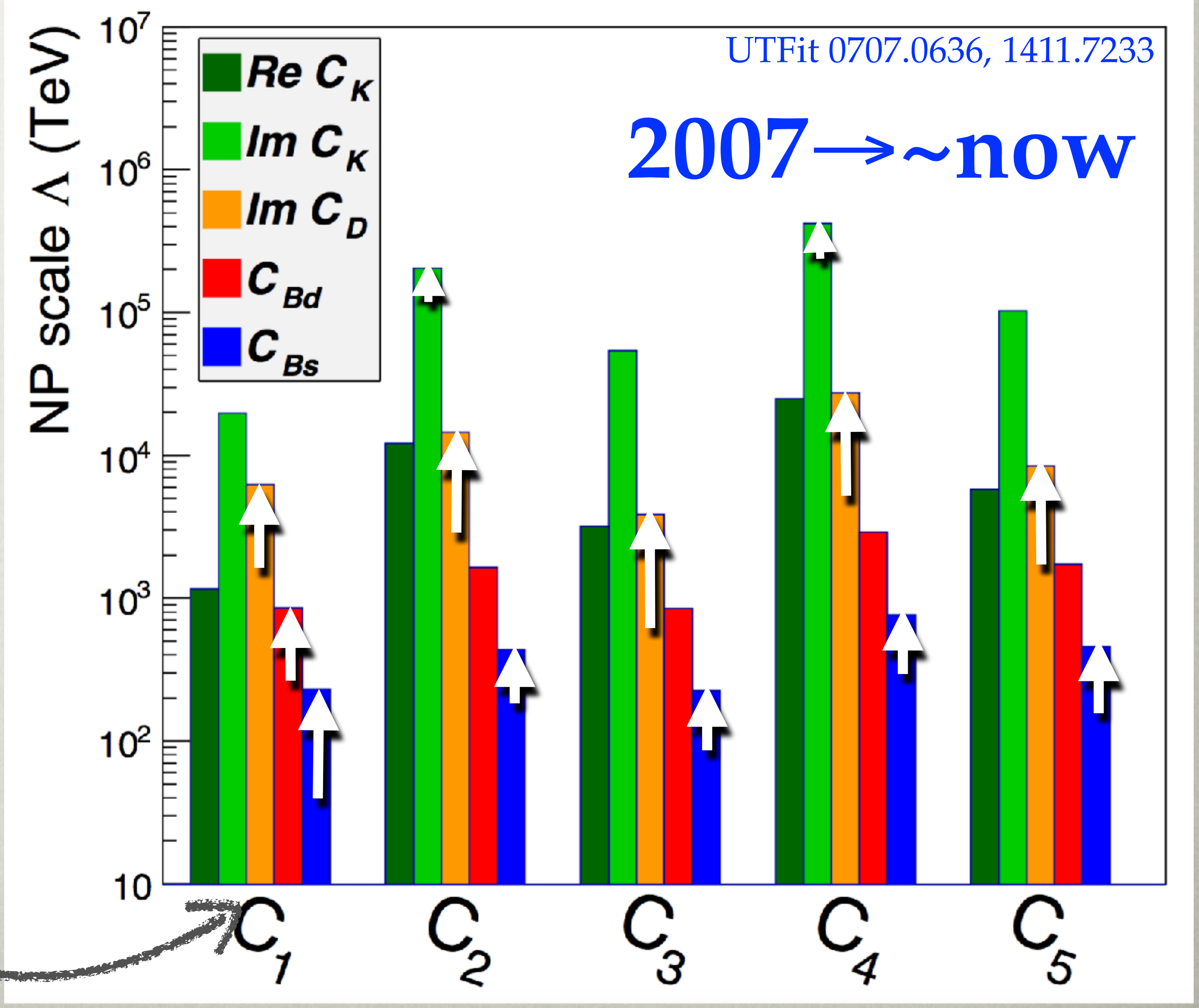
$3_{2/3}$:	up type quarks;	u, c, t
$3_{-1/3}$:	down type quarks;	d, s, b
1_{-1} :	charged leptons;	e, μ, τ
1_0 :	neutrinos;	ν_e, ν_μ, ν_τ

LOW ENERGY PRECISION BOUNDS

UTFit 0707.0636, 1411.7233
for latest charm see also Bazavov et al, 1706.04622

- an impressive progress on flavor bounds in last 10 years
- in D, B_s mixing ($c\bar{u}$, $\bar{b}s$)
- also from ε_K ($\bar{d}s$)

$$\frac{1}{\Lambda^2}(\bar{b}_L\gamma^\mu d_L)(\bar{b}_L\gamma_\mu d_L)$$

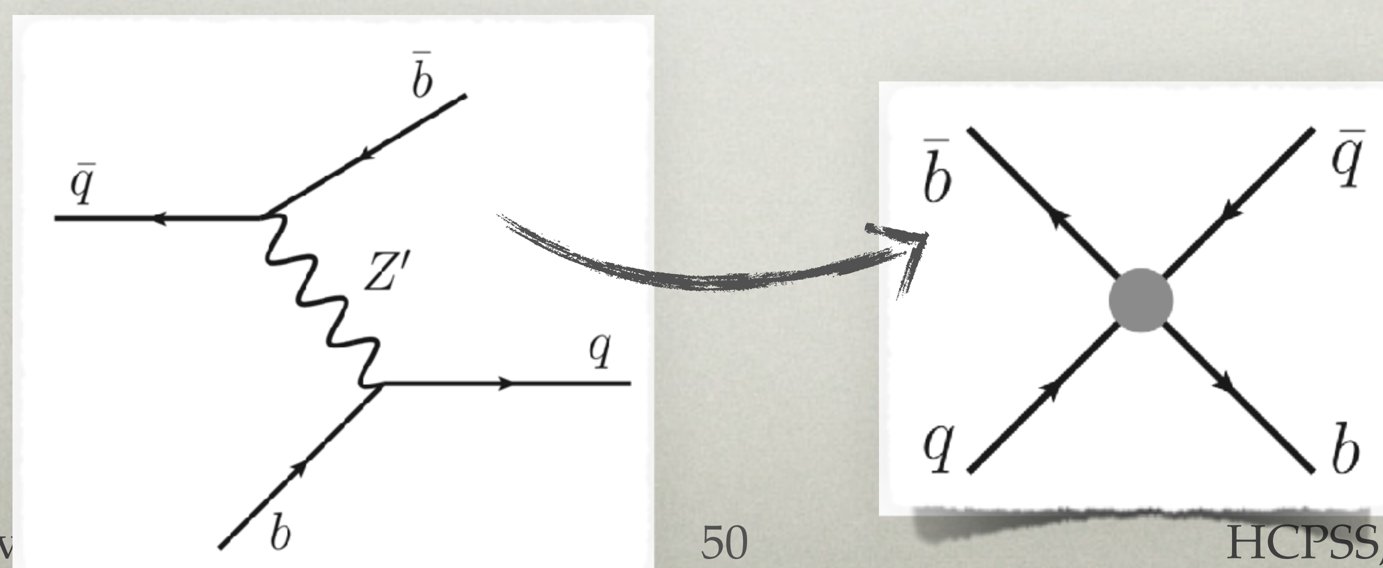


CORRECTION FROM NEW PHYSICS

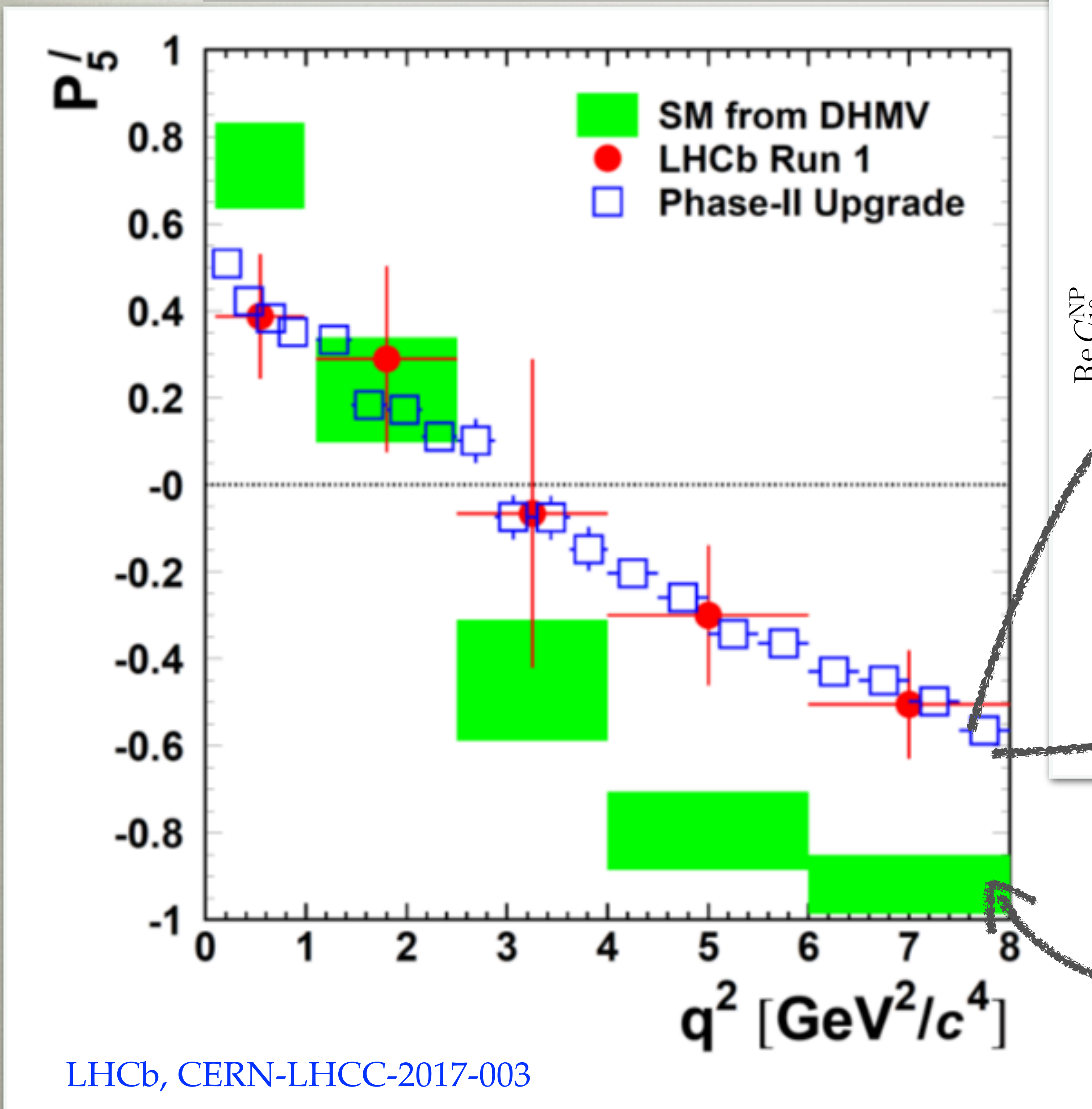
- heavy NP described by effective operator
- assume for instance, that NP has the same *(V-A)x(V-A)* structure as the SM

$$\mathcal{H}_{\rm eff} = \left(\frac{\left(V_{tb}^* V_{tq}\right)^2}{\Lambda^2_{\rm MFV}} + \frac{C_{\rm NP}}{\Lambda^2_{\rm NP}} \right) \left(\bar{b}_L \gamma^\mu q_L\right) \left(\bar{b}_L \gamma_\mu q_L\right) + \text{h.c.}$$

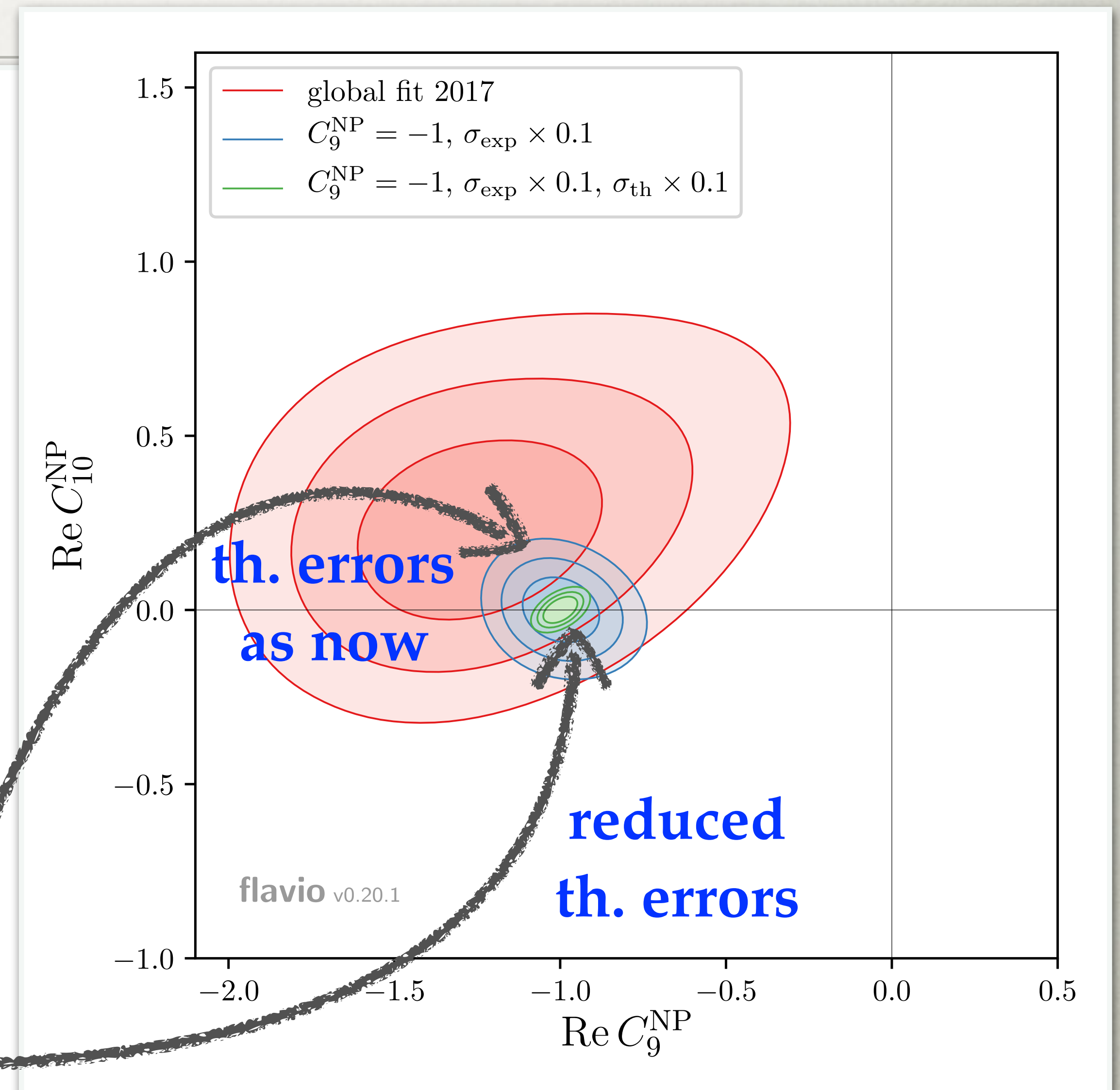
  - e.g., could be due to Z' exchange



P5' at LHCb



LHCb, CERN-LHCC-2017-003



many thanks to D. Straub for the plot

Descotes-Genon et al. 1407.8526

MESON MIXING BOUNDS

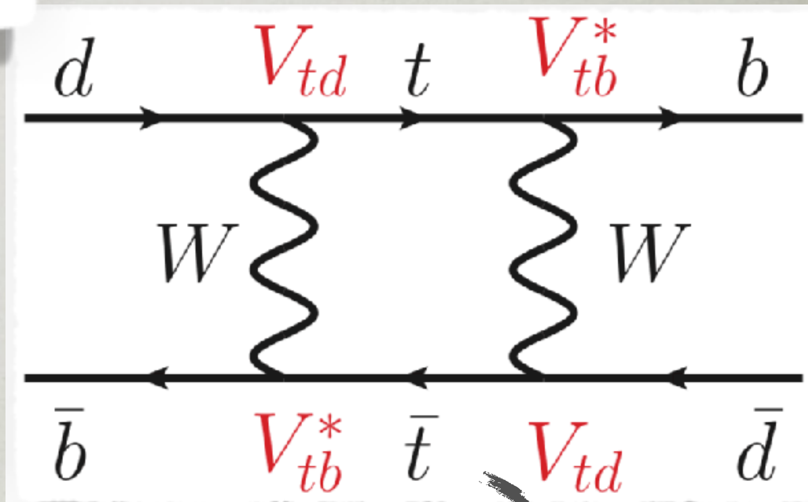
- new physics constraints from meson mixing
- several systems
  - K^0-$\bar{K}^0$ ($\bar{s}d \leftrightarrow s\bar{d}$)
  - D^0-$\bar{D}^0$ ($c\bar{u} \leftrightarrow \bar{c}u$)
  - B^0-$\bar{B}^0$ ($\bar{b}d \leftrightarrow \bar{d}b$)
  - B_s^0-$\bar{B}_s^0$ ($\bar{b}s \leftrightarrow \bar{s}b$)

EFFECTIVE HAMILTONIAN

- effective hamiltonian for B mixing

$$\mathcal{H}_{\rm eff} = \frac{1}{8m_W^2}\frac{g^4}{16\pi^2}\underbrace{\eta_B S_0}_{1.26}\left(V_{tb}^* V_{td}\right)^2 \left(\bar{b}_L\gamma^\mu d_L\right)\left(\bar{b}_L\gamma_\mu d_L\right) + \text{h.c.}$$

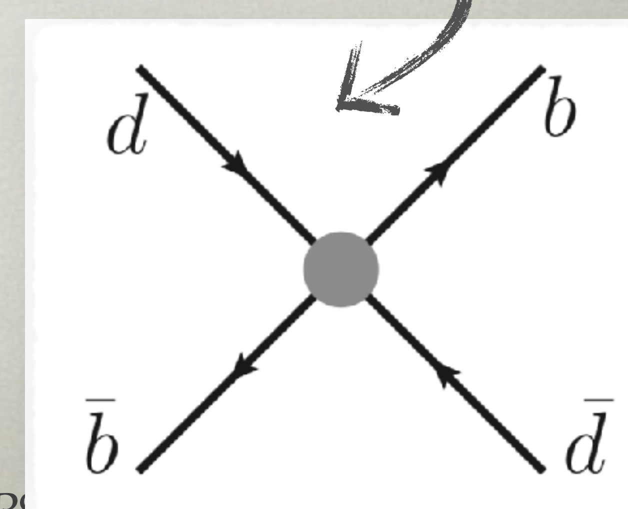
1.26 ← QCD corrections + loop function



$$\mathcal{H}_{\rm eff} = \frac{1}{\Lambda_{\rm MFV}^2}\left(V_{tb}^* V_{td}\right)^2 \left(\bar{b}_L\gamma^\mu d_L\right)\left(\bar{b}_L\gamma_\mu d_L\right) + \text{h.c.}$$

$\Lambda_{\rm MFV} \simeq 6.0$ TeV.

$(V_{tb}^* V_{td})^2$ ← $(\lambda^3)^2$



- for B_s mixing instead

$$\mathcal{H}_{\rm eff} = \frac{1}{\Lambda_{\rm MFV}^2}\left(V_{tb}^* V_{ts}\right)^2 \left(\bar{b}_L\gamma^\mu s_L\right)\left(\bar{b}_L\gamma_\mu s_L\right) + \text{h.c.}$$

$(V_{tb}^* V_{ts})^2$ ← $(\lambda^2)^2$

MORE GENERAL NP

- the general NP Effective Field Theory for mixing

$$\mathcal{H}_{\rm eff}^{\rm NP} = \sum_i \frac{C_i}{\Lambda^2_{{\rm NP},B_q}} Q_{i,q}$$

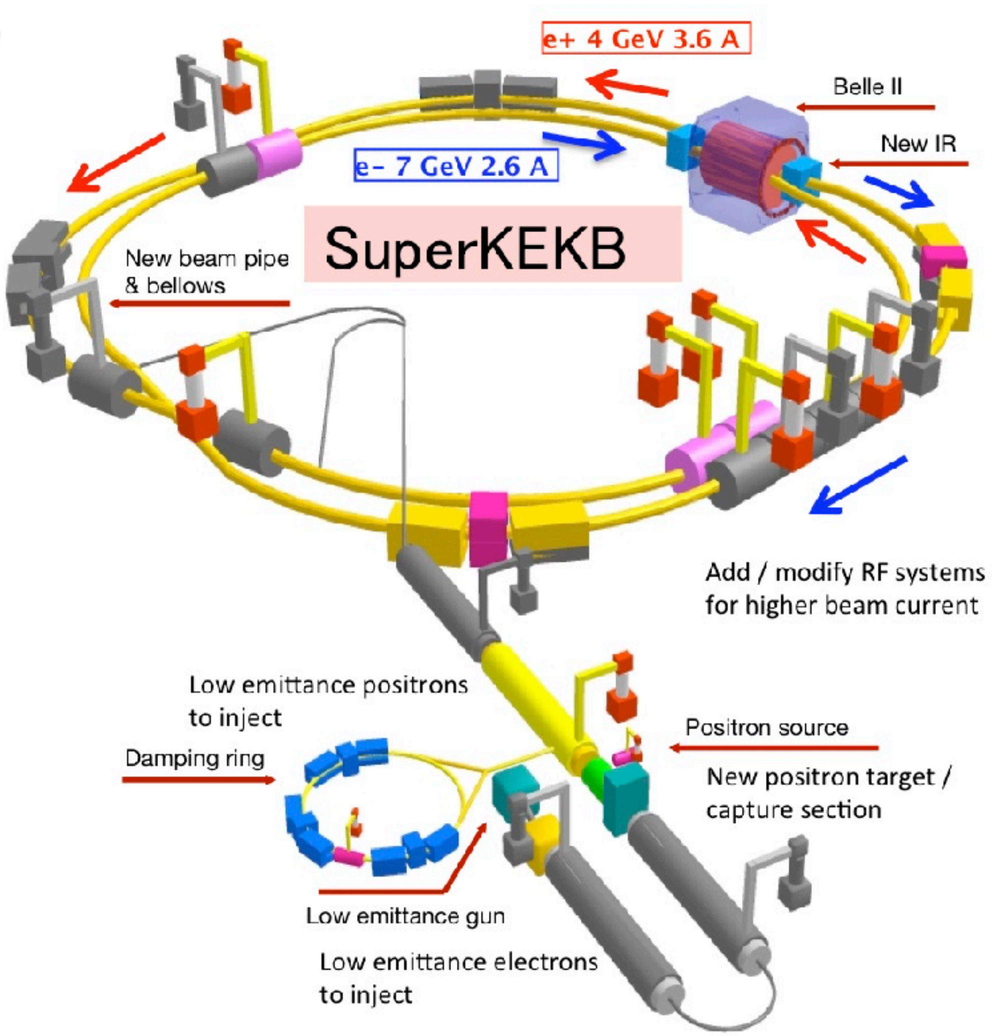
$$\begin{aligned}
Q_{1,q} &= (\bar b_L \gamma^\mu q_L)(\bar b_L \gamma^\mu q_L),\\
Q_{2,q} &= (\bar b_R q_L)(\bar b_R q_L),\\
Q_{3,q} &= (\bar b_R^\alpha q_L^\beta)(\bar b_R^\beta q_L^\alpha)\\
Q_{4,q} &= (\bar b_R q_L)(\bar b_L q_R),\\
Q_{5,q} &= (\bar b_R^\alpha q_L^\beta)(\bar b_L^\beta q_R^\alpha),
\end{aligned}$$

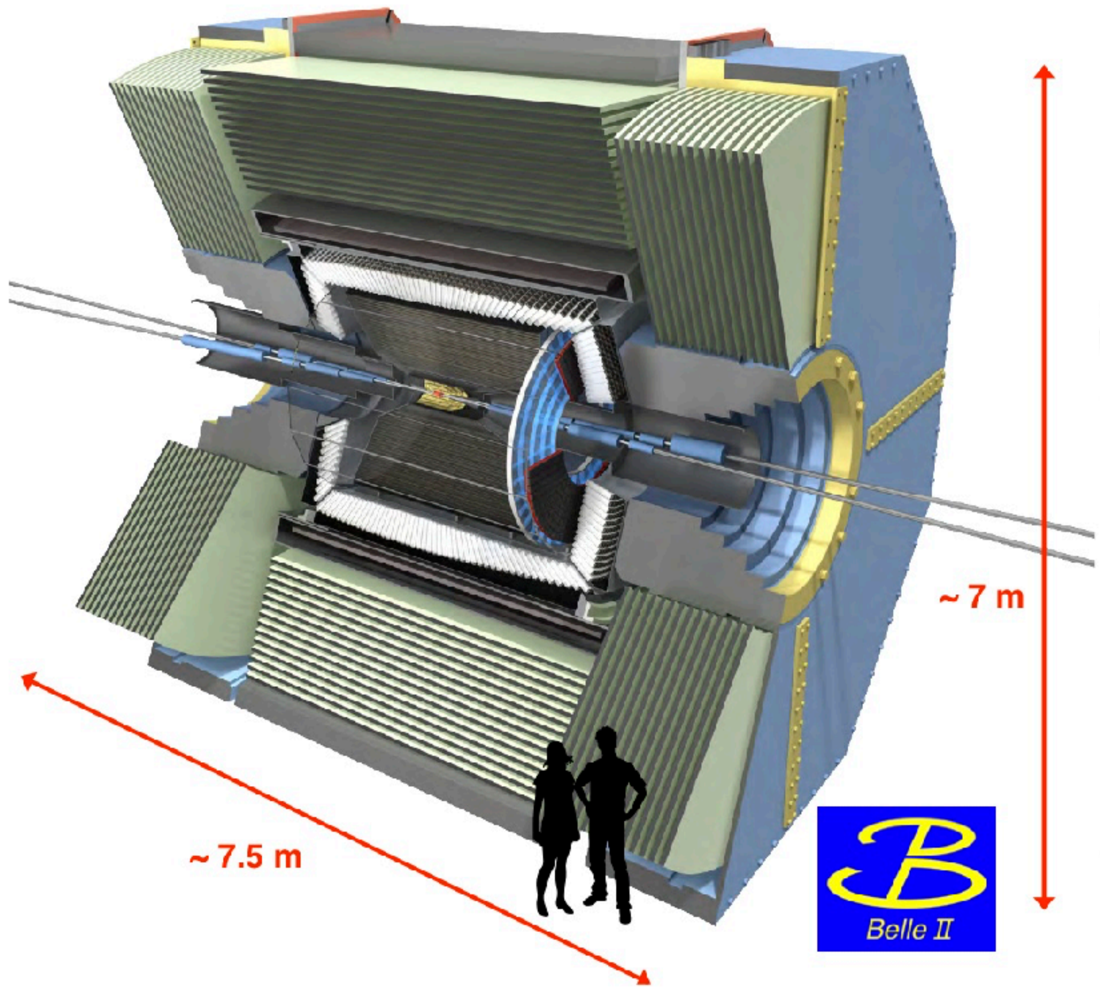
  - and in addition $\tilde{Q}_{1q}, \tilde{Q}_{2q}, \tilde{Q}_{3q}$ obtained from Q_{iq} through $L \leftrightarrow R$

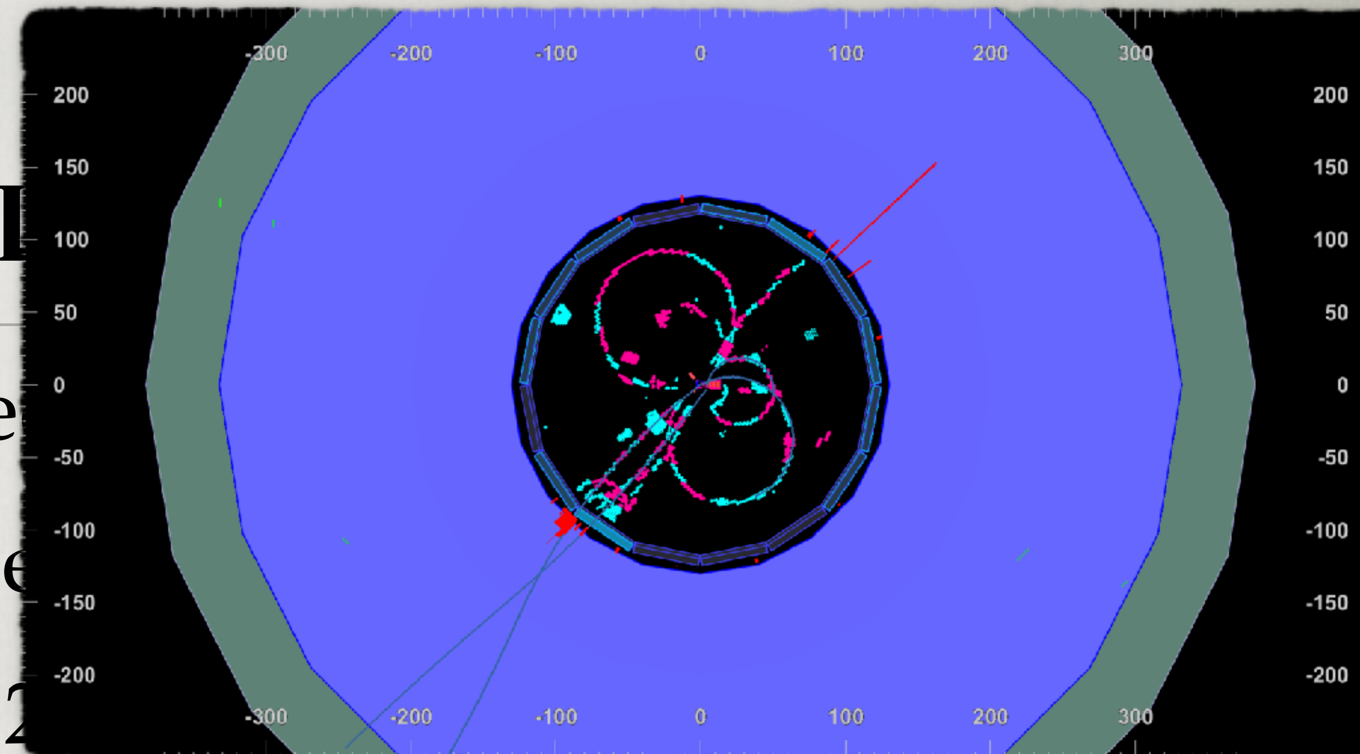
- heavy NP will match onto these local operators

BELLE 2

- upgrade of Belle, expected 50 x Belle dataset
  - first positron beam early April 2018
  - first collisions May 2018







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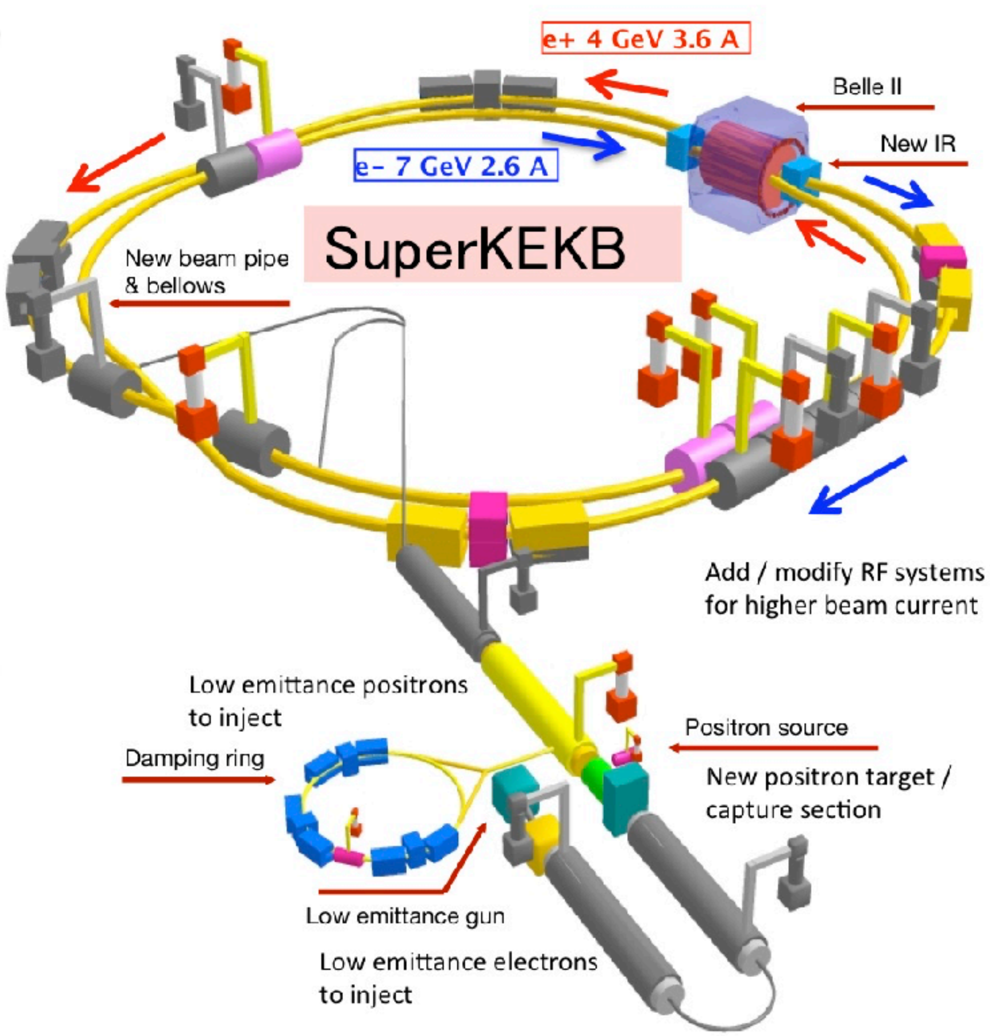
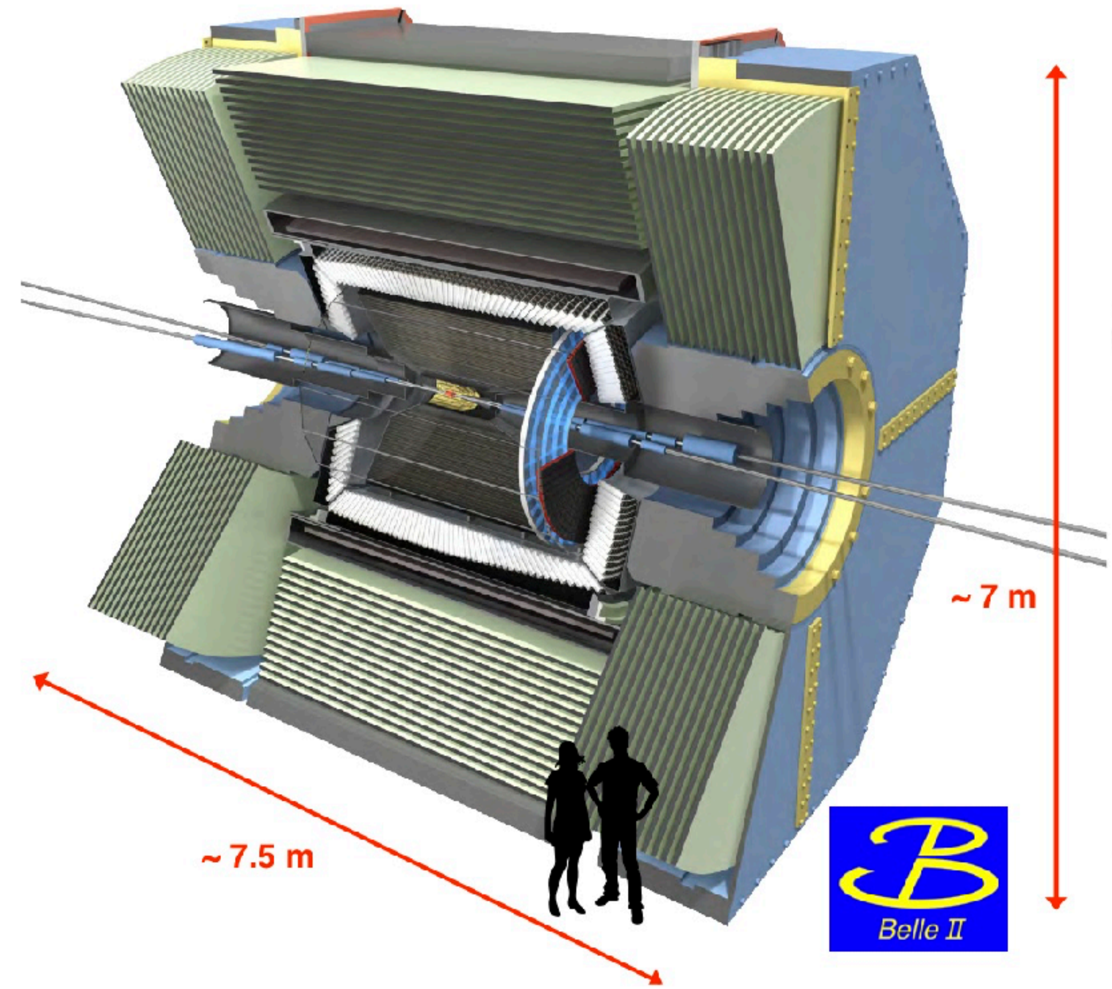


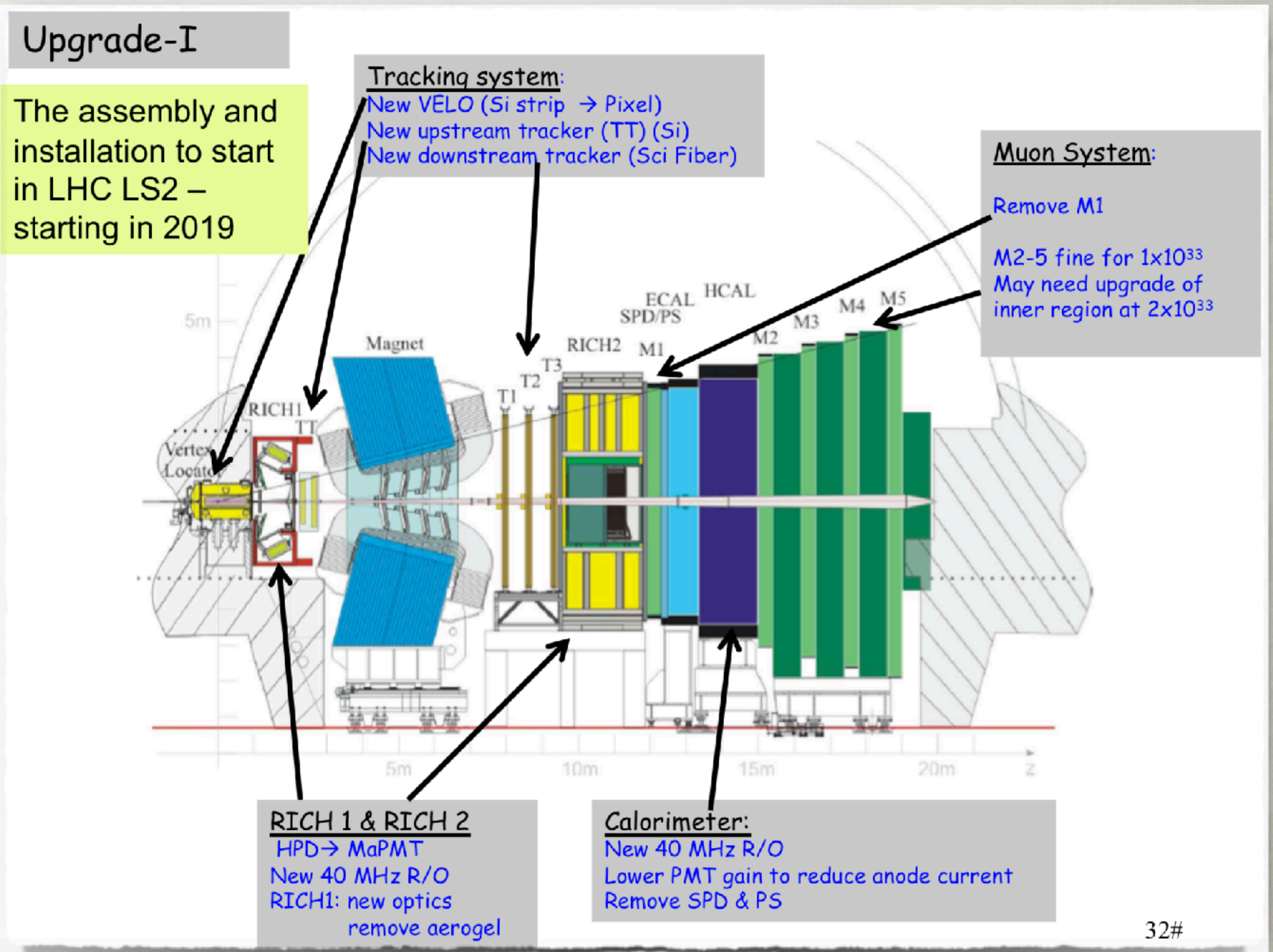
e+ 4 GeV 3.6 A
Belle II
New IR
e- 7 GeV 2.6 A
SuperKEKB
New beam pipe & bellows
Add / modify RF systems for higher beam current
Low emittance positrons to inject
Positron source
Damping ring
New positron target / capture section
Low emittance gun
Low emittance electrons to inject



~ 7 m
~ 7.5 m
Belle II

LHCB UPGRADE PLANS

- LHCb in the middle of upgrade plans
- after upgrade II
  - aim for 100x present data set
  - upgrading the detector



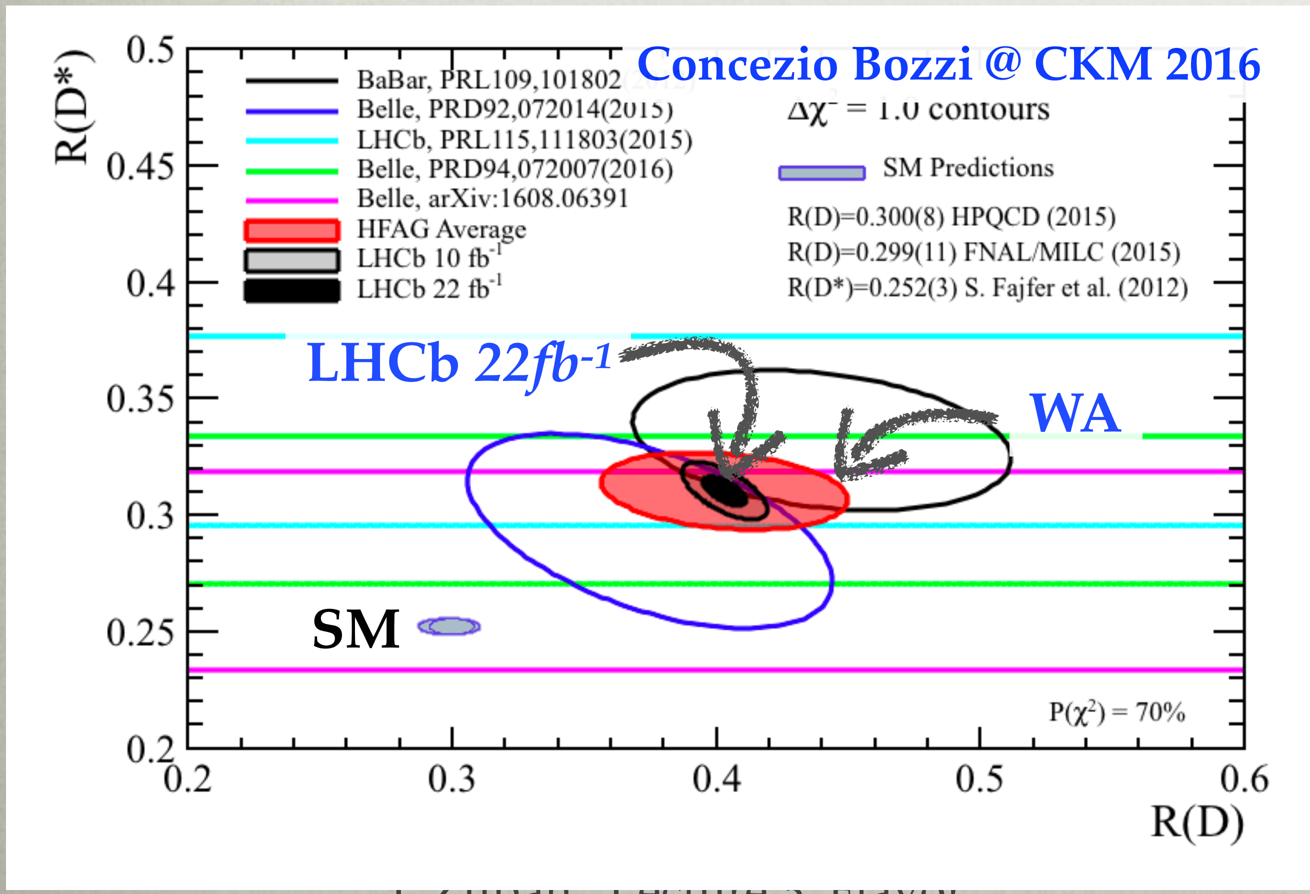
THE FUTURE

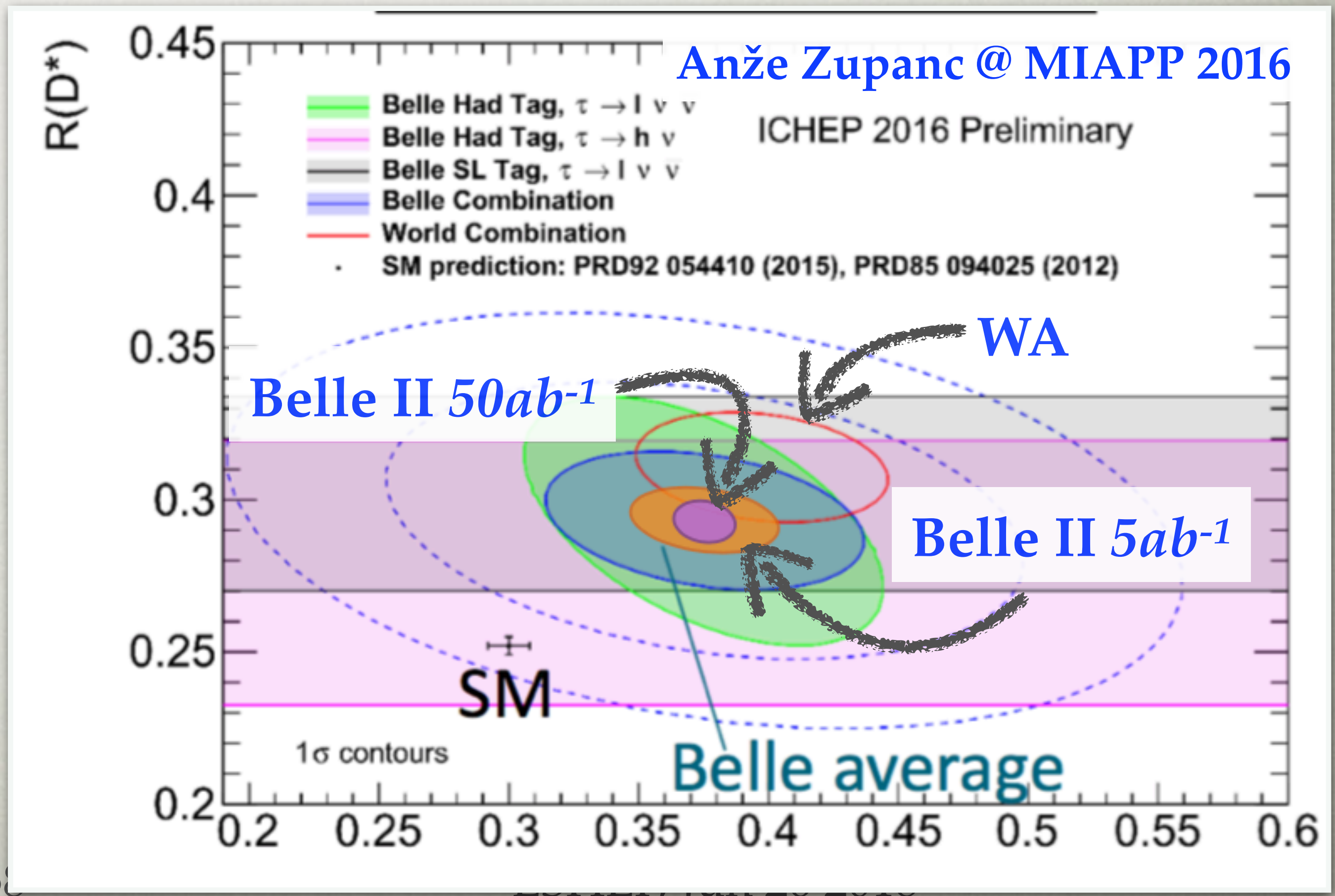
- a rule of thumb: Belle 2 50x statistics of Belle
  - corresponds to ~reach in Λ_{NP} of $\sqrt[4]{50}=2.7x$
  - like going from 13TeV LHC to 35TeV LHC
- similar for LHCb (Phase 2 Upgrade 100x stat.)

$B \to D^{(*)}\tau\upsilon$

- potential to confirm definitively $B \to D^{(*)}\tau\upsilon$ anomaly
  - significantly higher tagging eff. expected at Belle II
  - new observables for LHCb in $\Lambda_b \to \Lambda_c\tau\upsilon$, $B_C \to J/\psi\tau\upsilon$, $B_S \to D_s^{*}\tau\upsilon$
  - new discriminating power from angular distributions

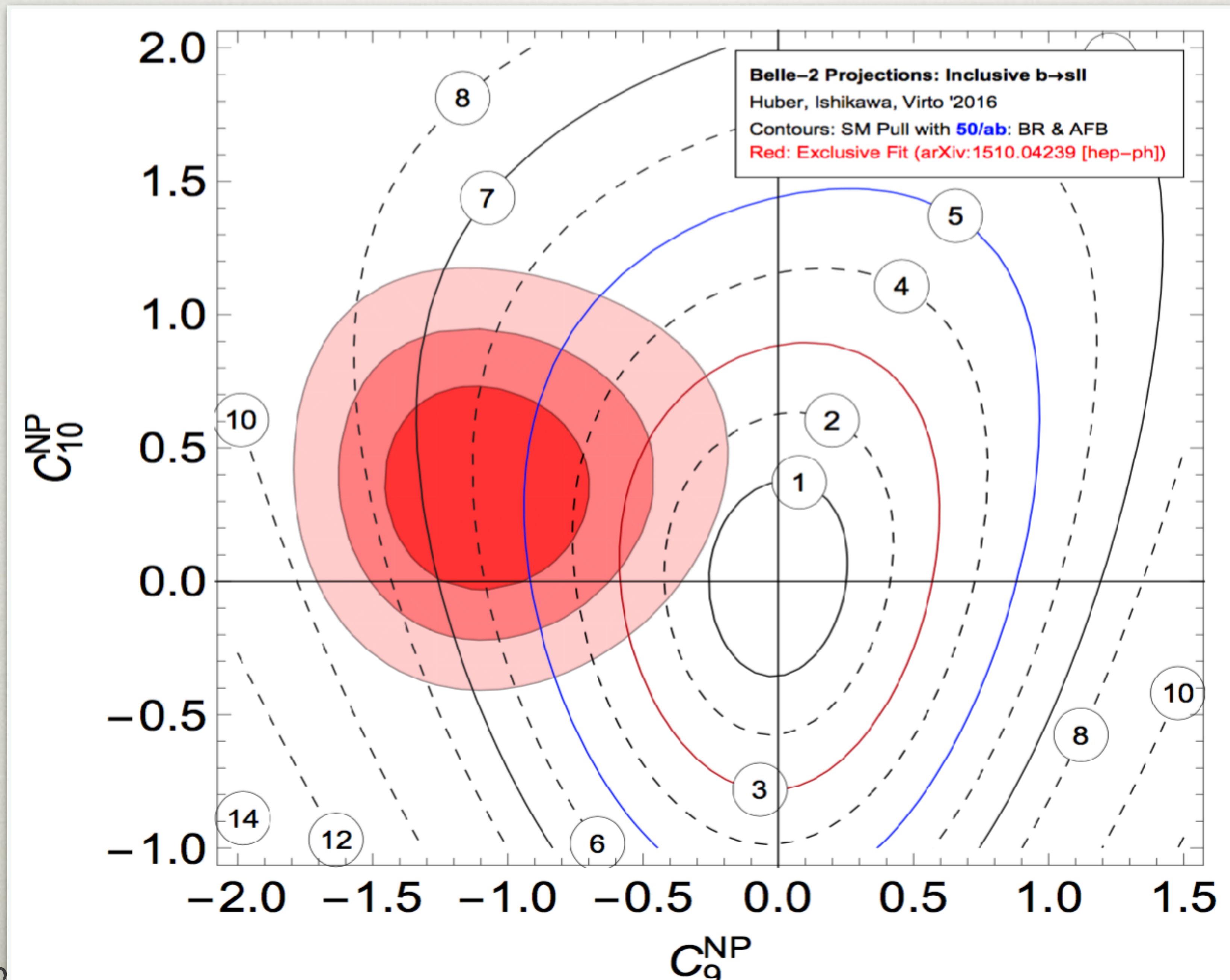
see, e.g., Bernlochner, Ligeti, Papucci, Robinson, 1703.05330





INCLUSIVE AT BELLE 2

- the $B \to K^* l^+ l^-$ anomaly can be confirmed even just from $b \to sll$ inclusive measurement alone at Belle 2



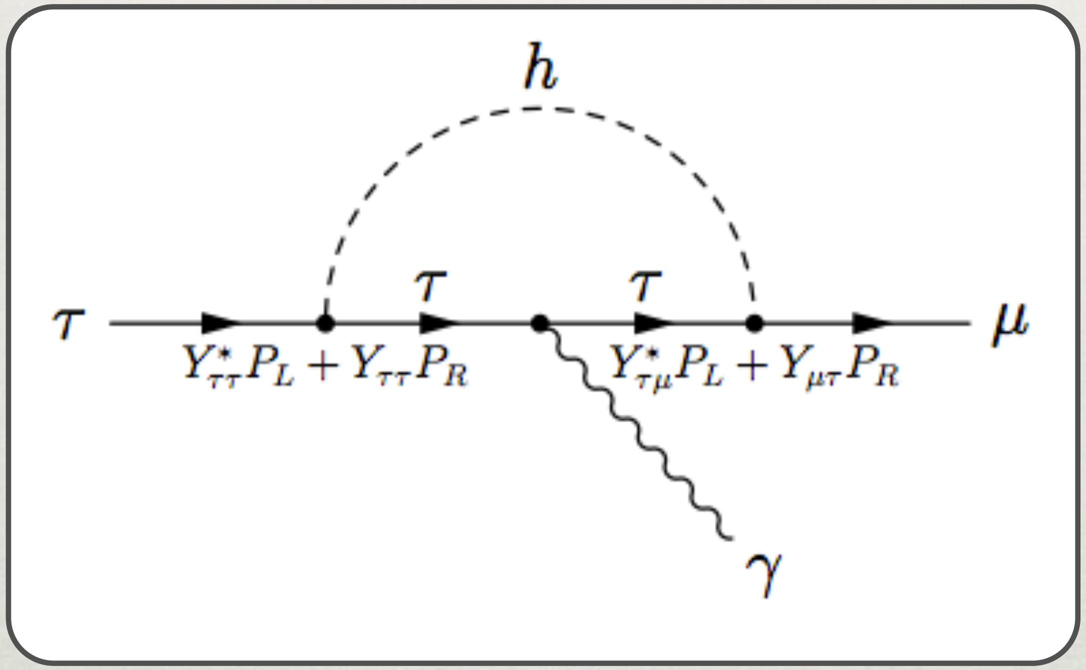
J. Virto @ CKM2016

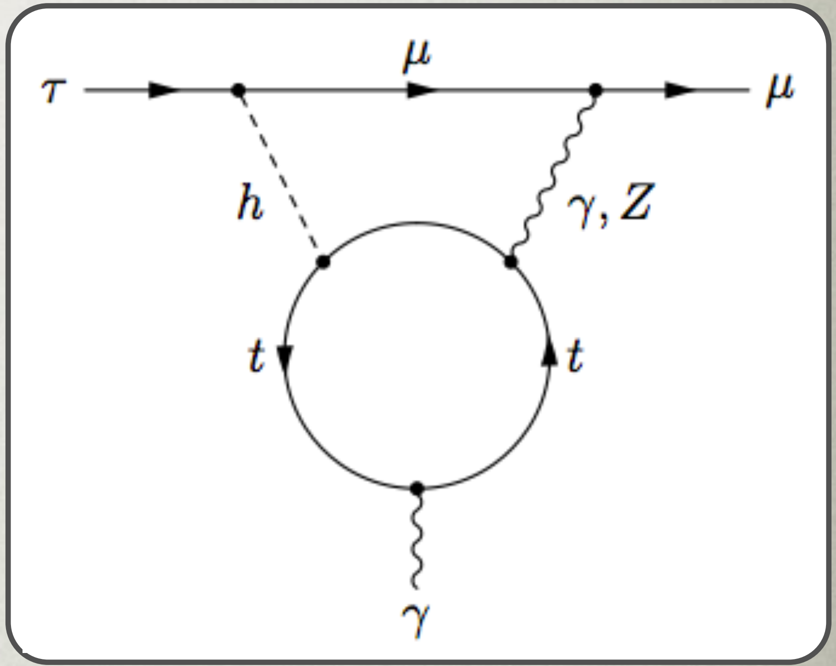
INDIRECT BOUNDS ON $h\to\tau\mu$

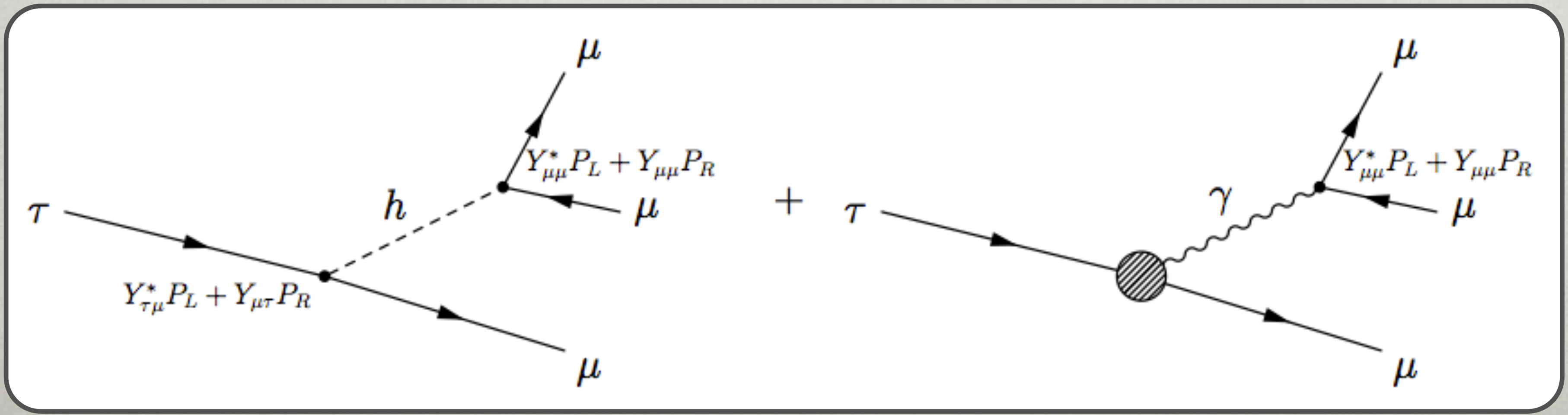
Harnik, Kopp, JZ, 1209.1397

see also Blankenburg, Ellis, Isidori, 1202.5704

- also indirect bounds from charged lepton FCNC transitions
  - $\tau\to\mu\gamma$
  - $\tau\to 3\mu$





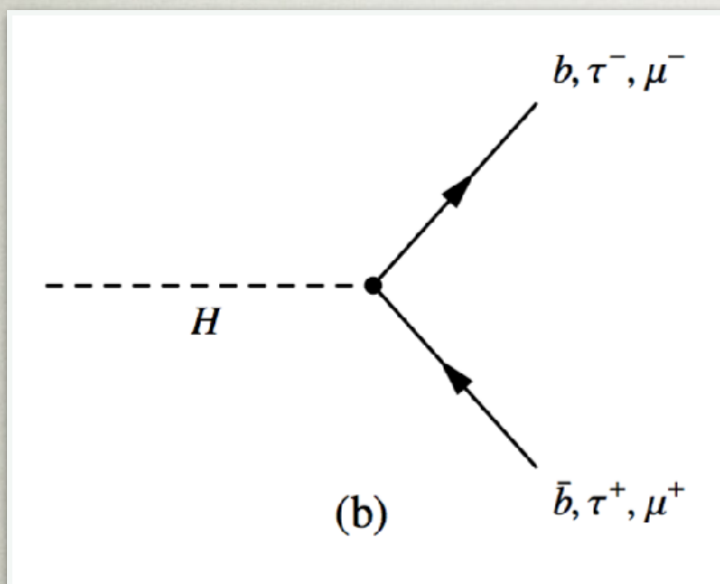


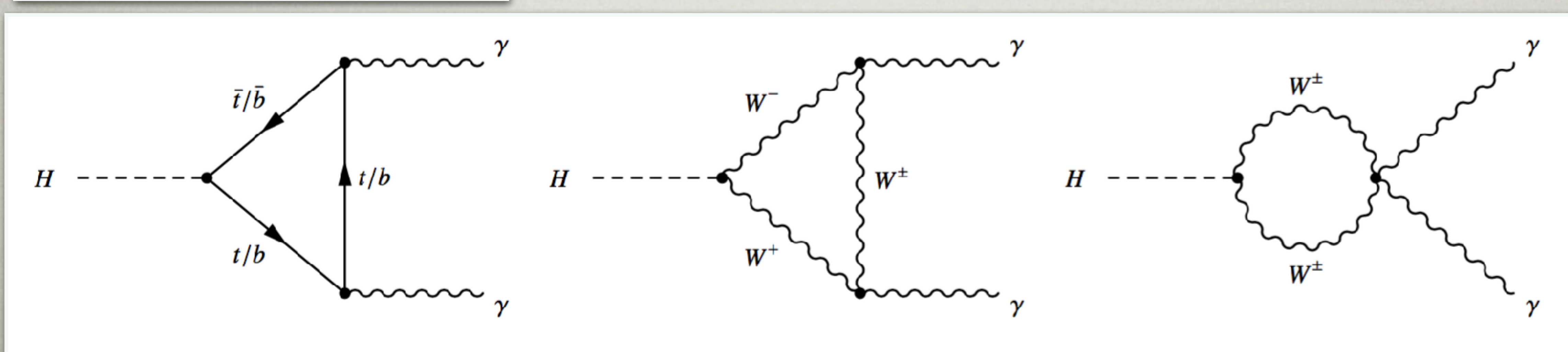
PROPORTIONALITY

- "proportionality" and "factor of proportionality"

$$y_{ii} \propto m_i \qquad\qquad y_{ii}/m_i = \sqrt{2}/v$$

- tested for 3rd generation fermions





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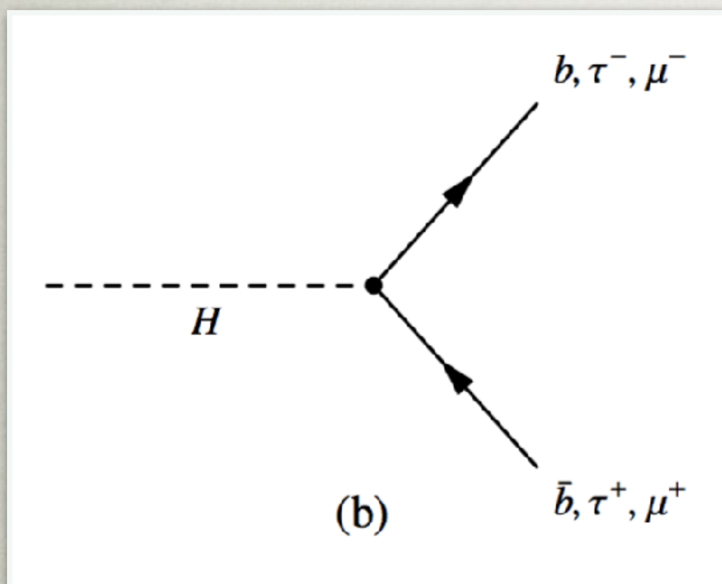
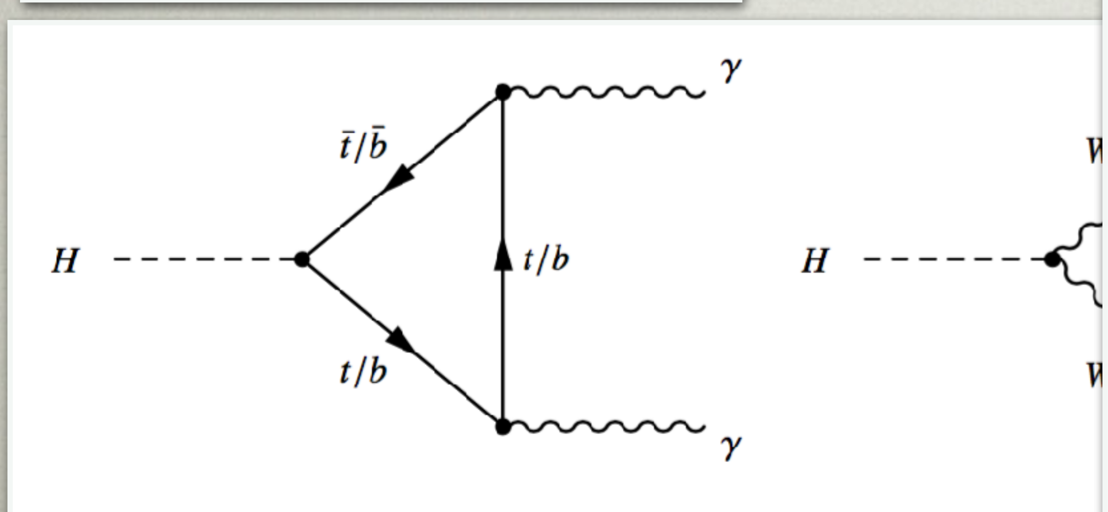
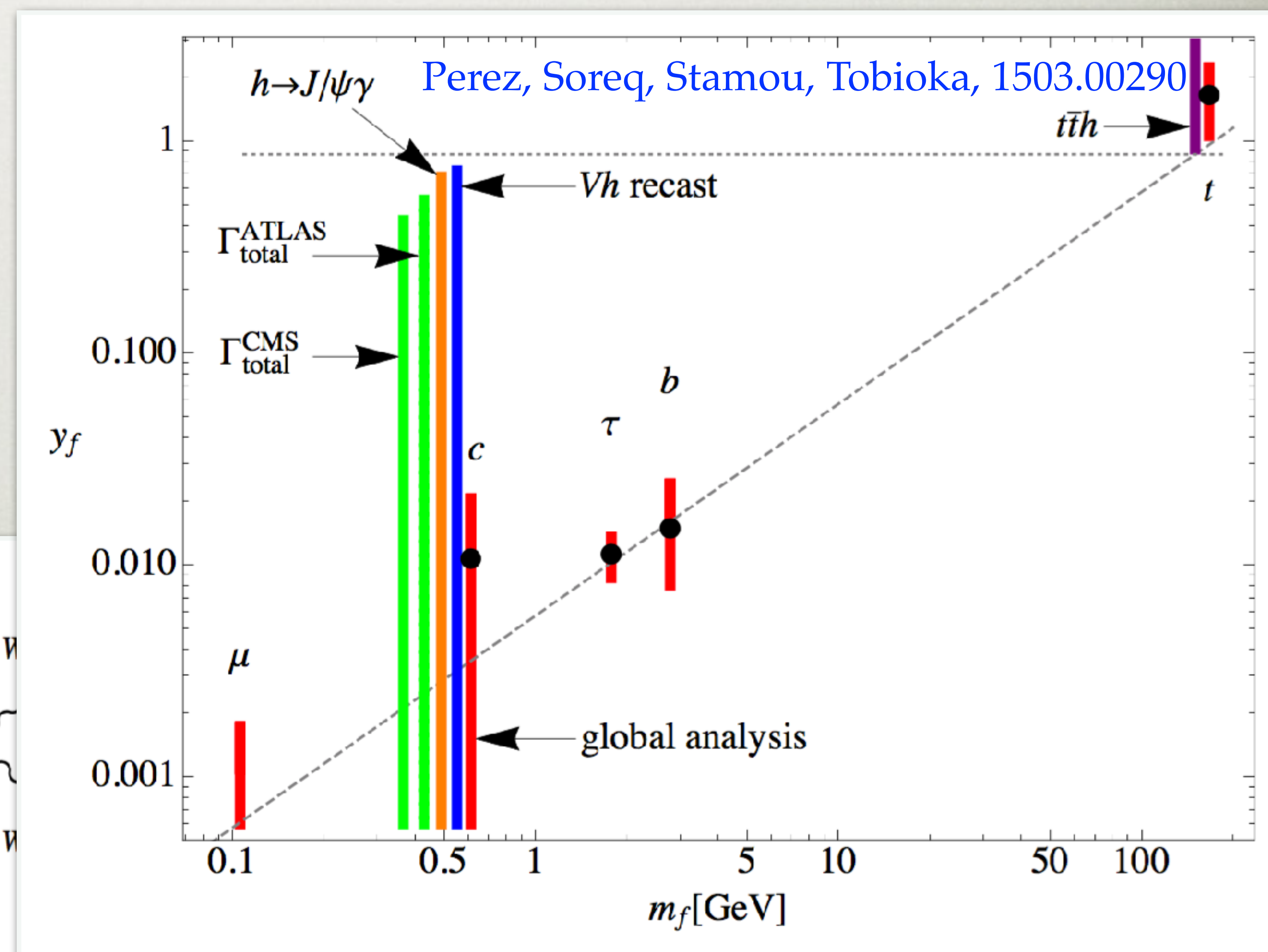


(b)





HIERARCHICAL COUPLINGS?

- does Higgs couple to the first two generations?
  - tough: couplings are small
- more modest question: can we show that the couplings are hierarchical?
  - yes, but for quarks with some assumptions

$$\frac{Y^{\text{exp}}_{e(\mu)}}{Y^{\text{exp}}_{\tau}} < 0.22(0.10), \qquad \frac{Y^{\text{exp}}_{u(c)}}{Y^{\text{exp}}_{t}} \lesssim 0.04, \qquad \frac{Y^{\text{exp}}_{d(s)}}{Y^{\text{exp}}_{t}} < 0.7(6)$$

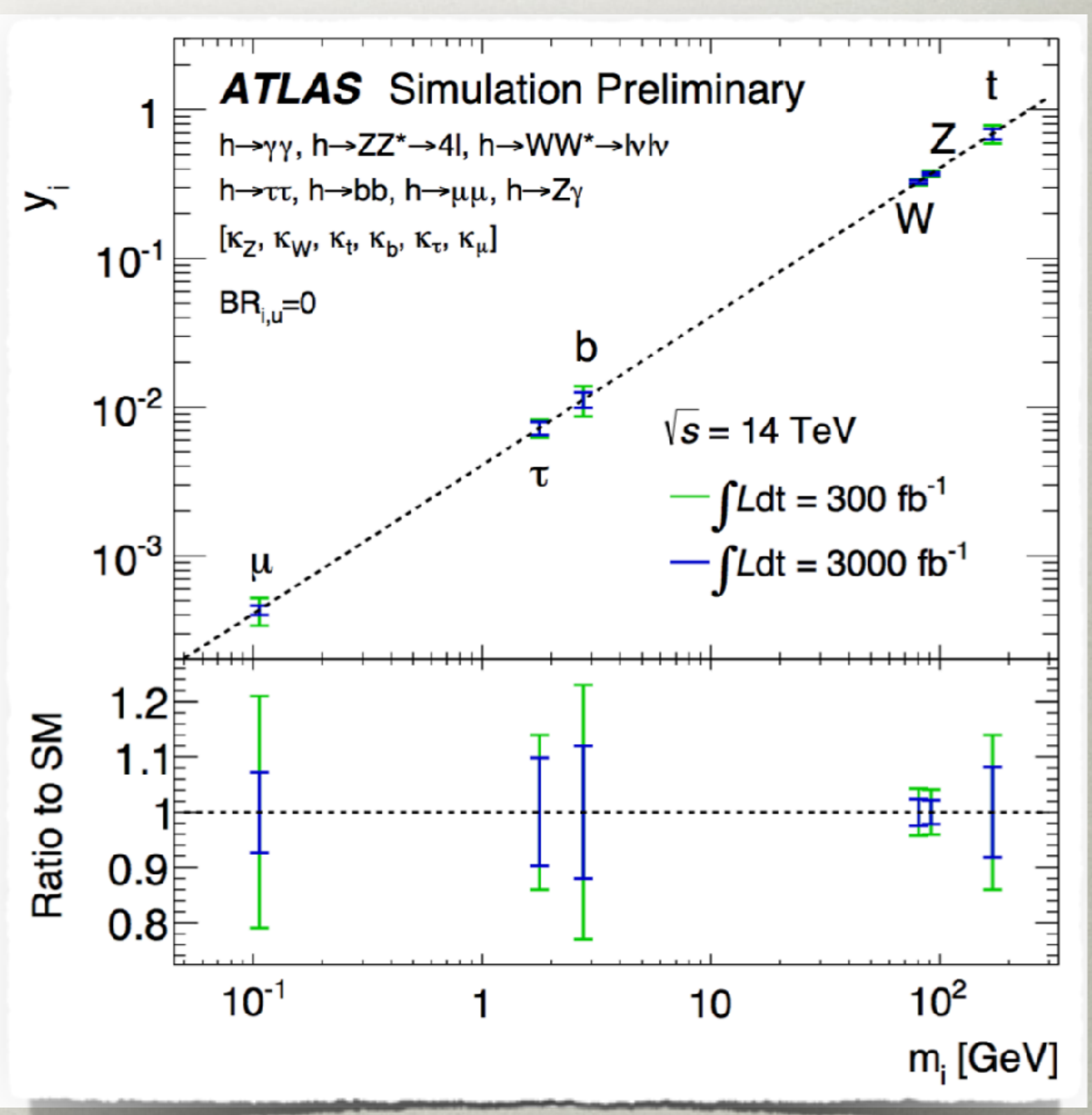
direct measurements

global fit

p_T distrib.

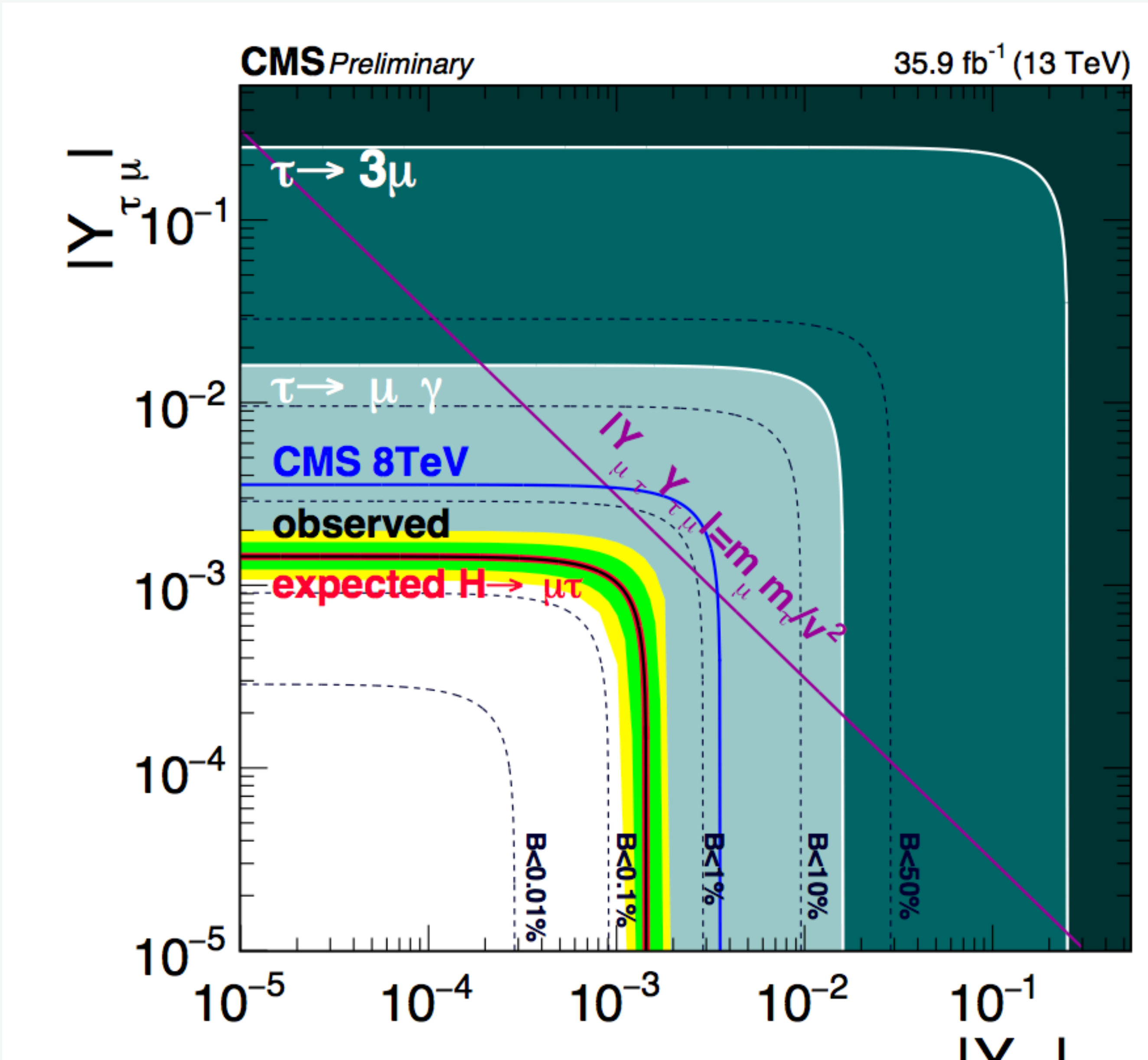
MUON YUKAWA

- the SM Higgs muon Yukawa accessible at high-luminosity LHC
- the only one among the first two generations of fermions
- could significantly deviate from the SM
    - could even be zero

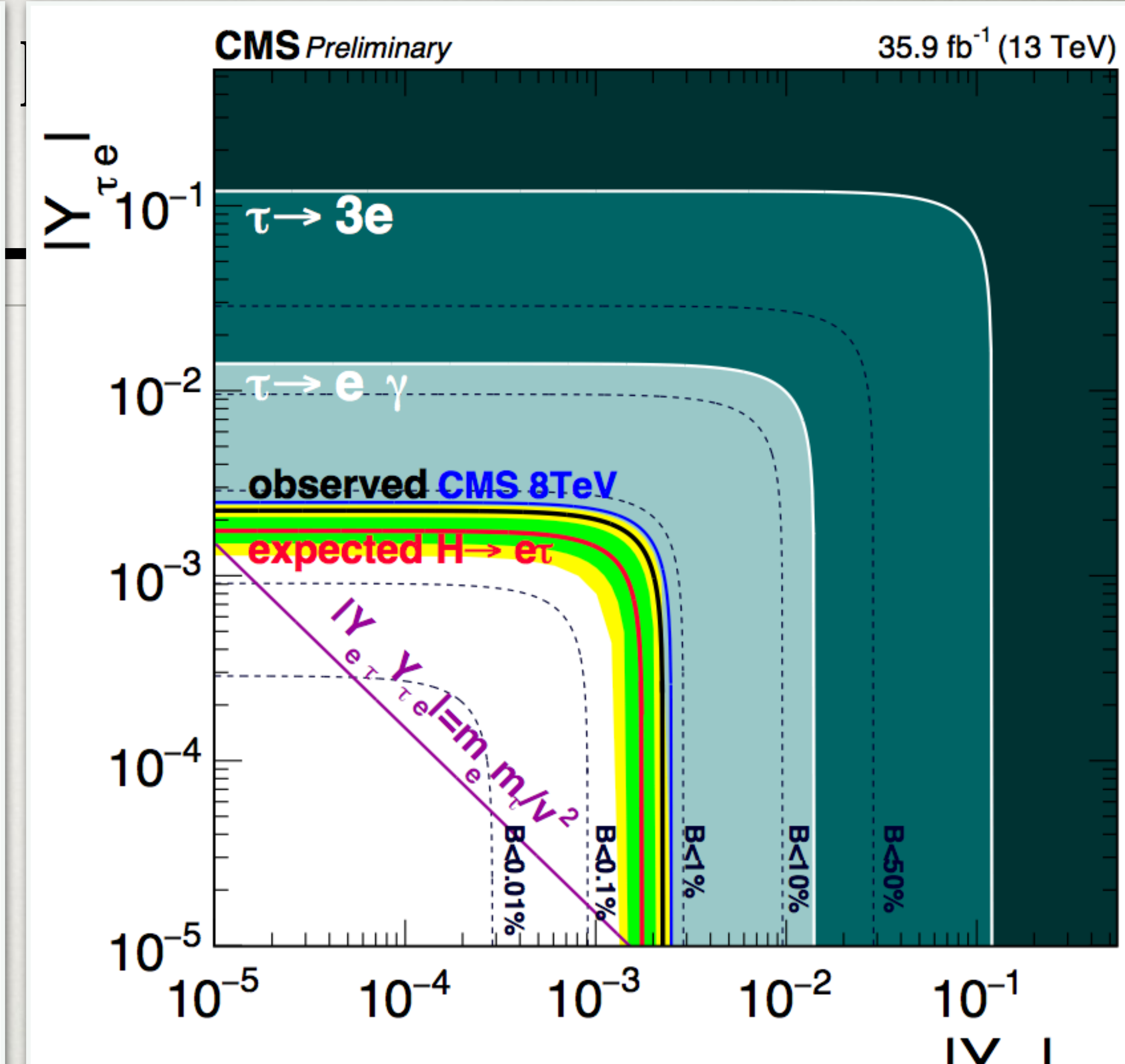


FLAVOR VIOLATING COUPLINGS

- in the SM Higgs couplings flavor diagonal
  - discovering flavor violating couplings mean New Physics
- for charged lepton final states accessible directly
  - from $h\to\tau\mu$, $h\to\tau e$



CMS-HIG-17-001-pas



CMS-HIG-17-001-pas

$$\text{for } \hat{\lambda}_{ij} = 1$$

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

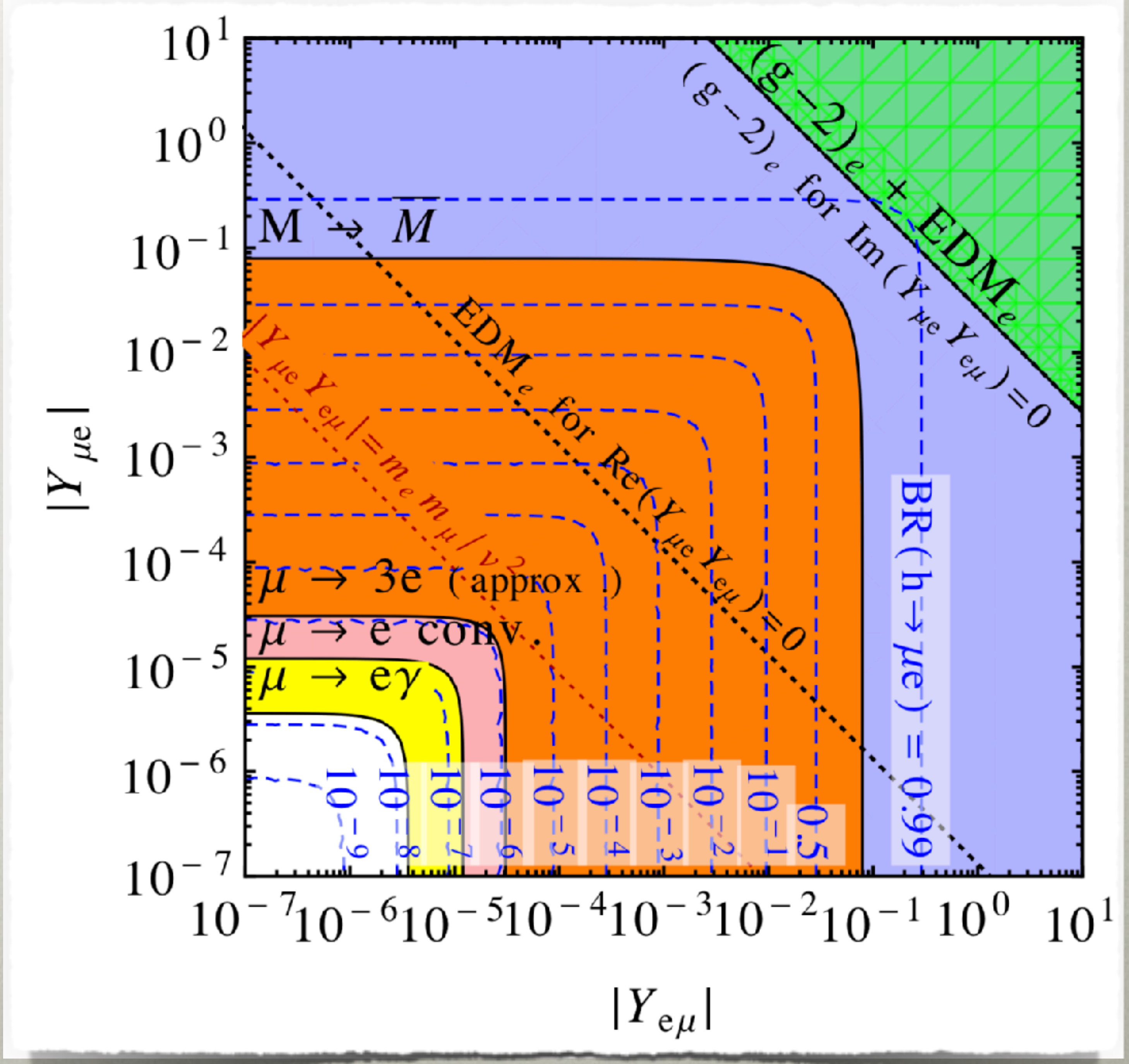
$$\Lambda_{\mu\tau} > 5.5 \text{ TeV}$$

$$\Lambda_{e\tau} > 4.4 \text{ TeV}$$

INDIRECT BOUNDS ON $h \to e\mu$

Harnik, Kopp, JZ, 1209.1397

- indirect bounds especially severe for $h \to e\mu$
- $Br(h \to e\mu) < 10^{-8}$ required to surpass the bound from $Br(\mu \to e\gamma)$
- caveat: could be cancellations in the loop

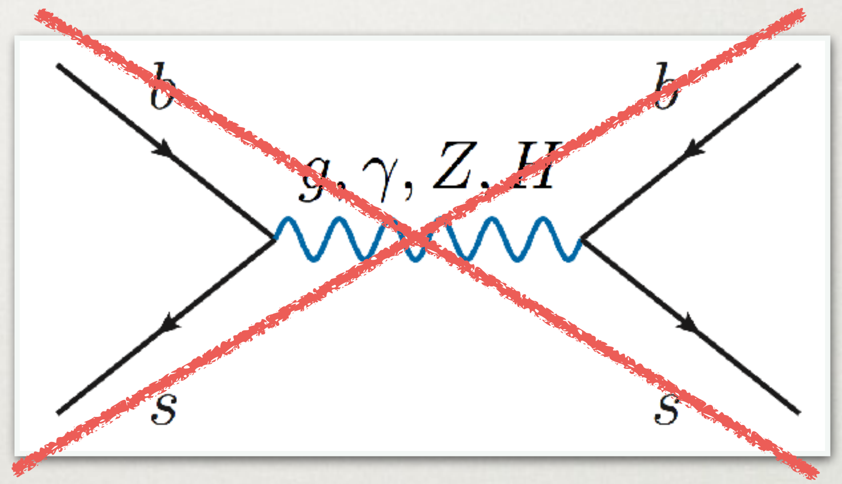


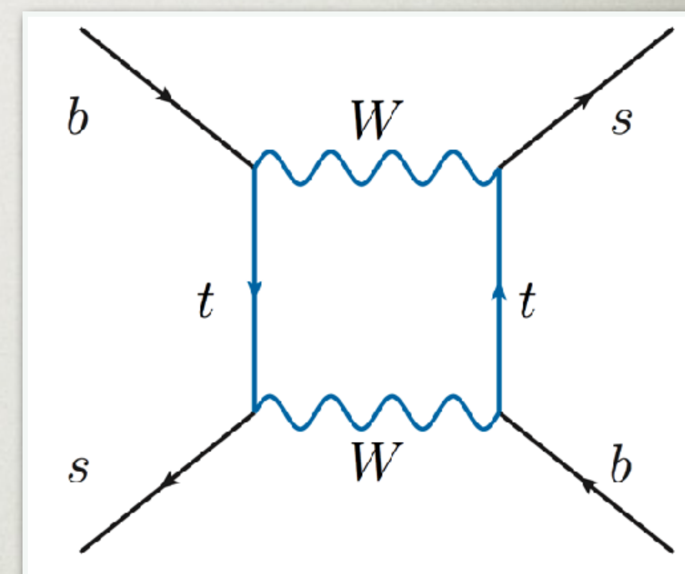
SENSITIVITY TO NEW PHYSICS

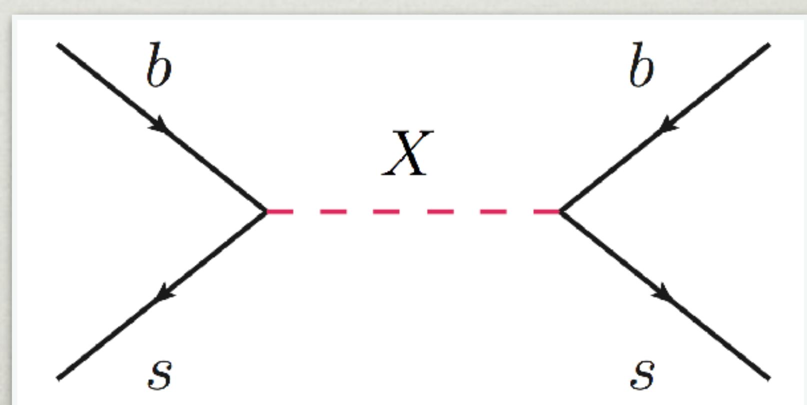
- SM@tree level: no Flavor Changing Neutral Currents
  - all FCNC processes loop suppressed
  - e.g., meson mixing
- can be modified by NP
- NP contribs. scale as

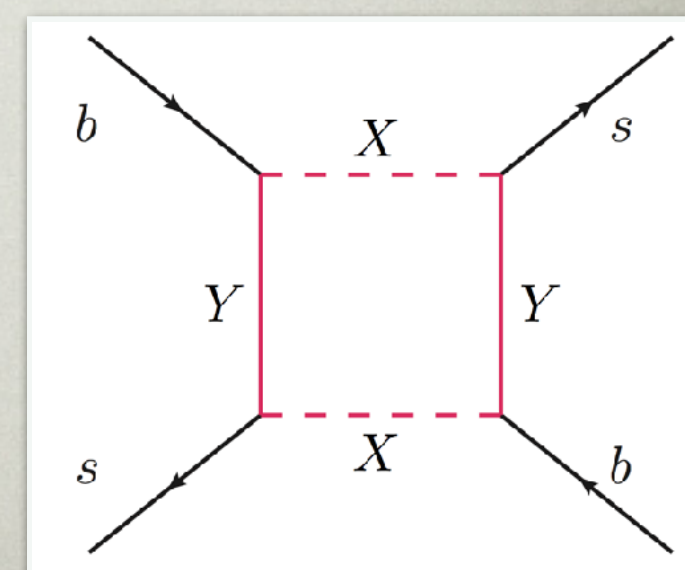
$$\delta C^{\rm NP} \propto \frac{g_{sb}^2}{M_{\rm NP}^2}$$

- depends on couplings and NP masses









CP VIOLATION IN THE STANDARD MODEL

- CP violation in the SM
  - all terms invariant apart from Yukawa terms

$$Y_{ij}\bar{\psi}^i_L H \psi^j_R + Y^*_{ij}\bar{\psi}^j_R H^\dagger \psi^i_L \xrightarrow{\text{CP}} Y_{ij}\bar{\psi}^j_R H^\dagger \psi^i_L + Y^*_{ij}\bar{\psi}^i_L H \psi^j_R$$

  - CP conserved if Yukawas real

$$Y^*_{ij} = Y_{ij}.$$

  - in the SM the CP violation controlled by one parameter: η, "the CKM phase"
- CPT conserved in Lorentz invariant QFTs
  - CP violation = T violation

SEARCHING FOR NEW PHYSICS

- so far: looked at the measurements of SM parameters
- how does one search for new physics?

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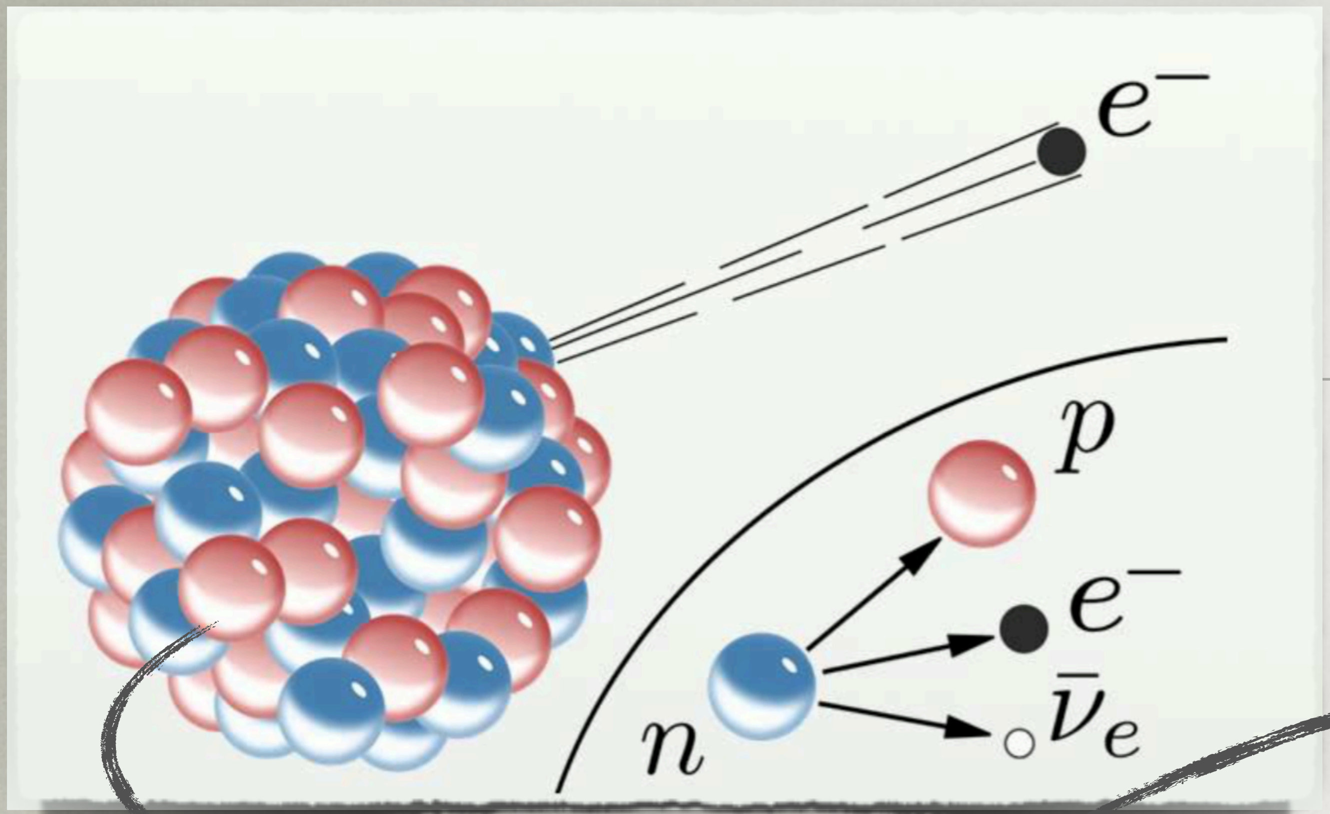
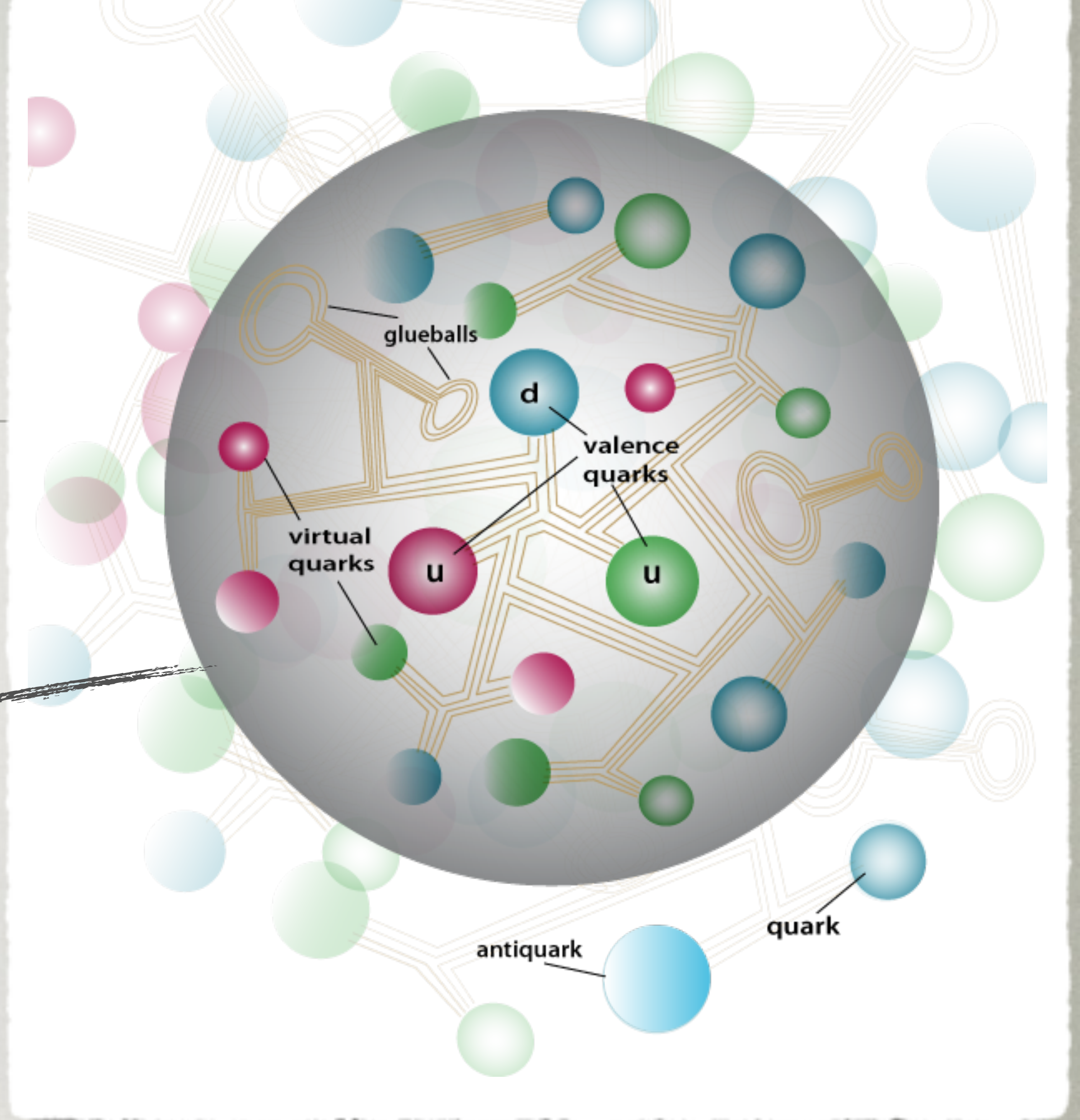
Why is weak force weak?



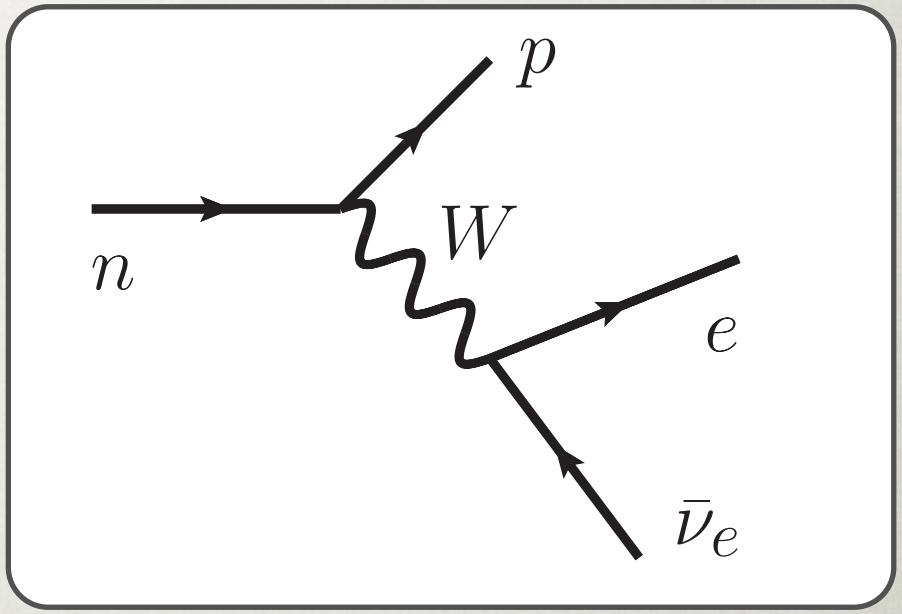


- *weak* and **strong** interactions similar in many respects
    - nonabelian gauge interactions
- so why is weak force so weak?
    - strength of interaction governed by couplings and masses of force carriers

BETA DECAY

- example of a weak transition: beta decay

$$n \to p^+ e^- \bar{\nu}_e$$



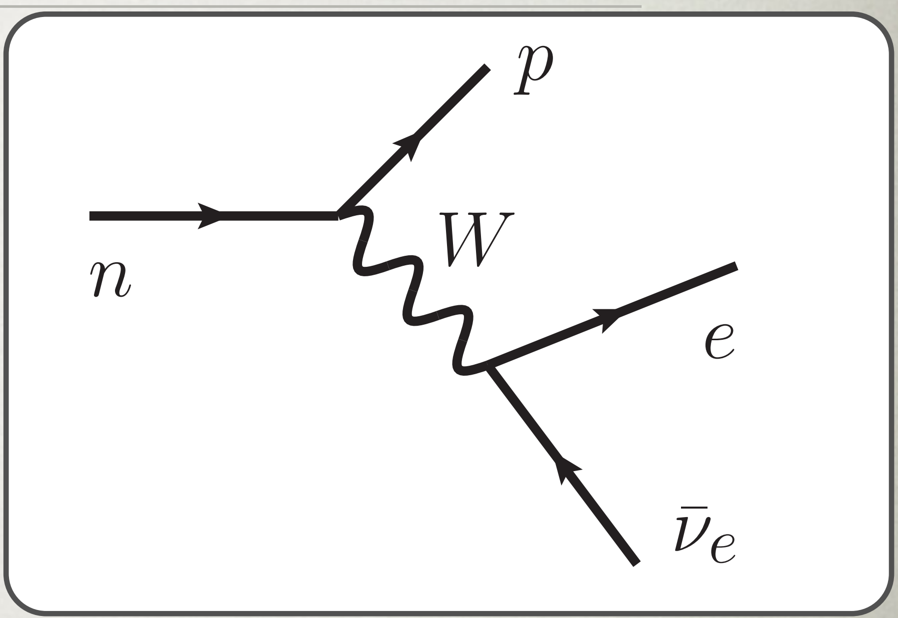
- weak force is weak because the carrier -*W* boson- is massive
  - it is not because couplings would be extremely small!
  - *W, Z* mass ~ 100 GeV~ 100 proton masses

$$\Gamma(n \to p e \bar{\nu}_e) \propto \frac{(m_p - m_n)^5}{m_W^4}$$

$$\sim 10^{-20}(m_p - m_n)$$

)

RECIPE FOR INDIRECT NEW PHYSICS SEARCHES



- rare processes can probe heavy mediators
- recipe for indirect new physics searches
  - identify processes that are rare in the Standard Model
  - search for deviations from predictions