注）引用している数値のreferenceが適当なので迷ったら2011-2012の国際会議のスライドを見てください。

Flavor and CP
(LHCとCosmology以外)

遠藤 基 (東京大学)

基研研究会 標準模型を超えた素粒子理論へ向けて
2012.3.20

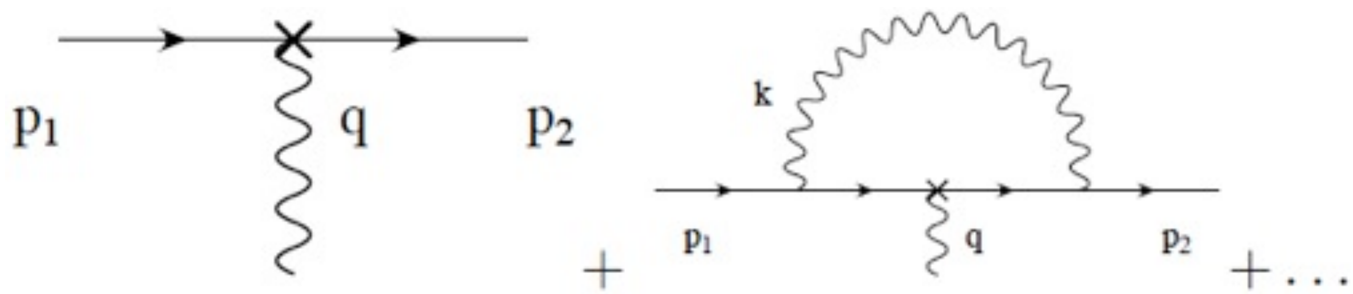
新しい物理のヒント

	SMからのずれ	NPのスケール
ニュートリノ振動	証拠	RH ν
初期宇宙	証拠	>TeV
暗黒物質	証拠	熱史次第
大統一理論	示唆	~10^{16}GeV
ヒエラルキー問題	示唆	TeV?
μ粒子異常磁気能率	示唆	TeV
フレーバー・CP	?	TeV
Top A_{FB}	?	TeV
EWP, ν ,...	?	?
宇宙線 (e^+,e^-)	?	TeV
DMの直接検出	?	~GeV

Muon g-2

Muon g-2

g-factor deviates from 2 due to radiative corrections



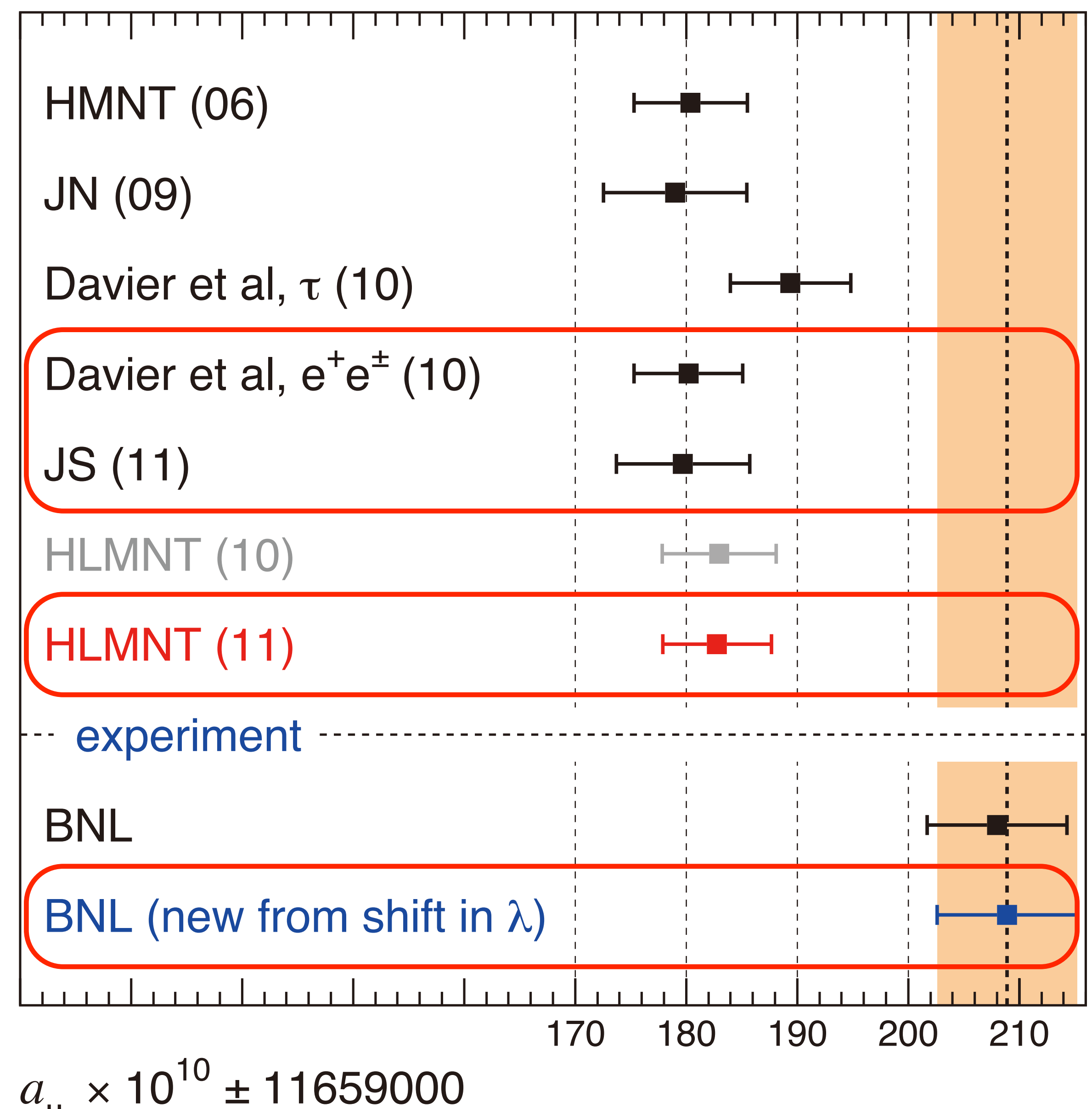
$$\gamma^\mu \rightarrow \Gamma^\mu(q) = \left(\gamma^\mu F_1(q^2) + \frac{i\,\sigma^{\mu\nu} q_\nu}{2m} F_2(q^2)\right)$$

$$F_2(0) = \frac{g-2}{2} \equiv a_\mu$$

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \cdot 10^{-10}$$

> 3σ deviation

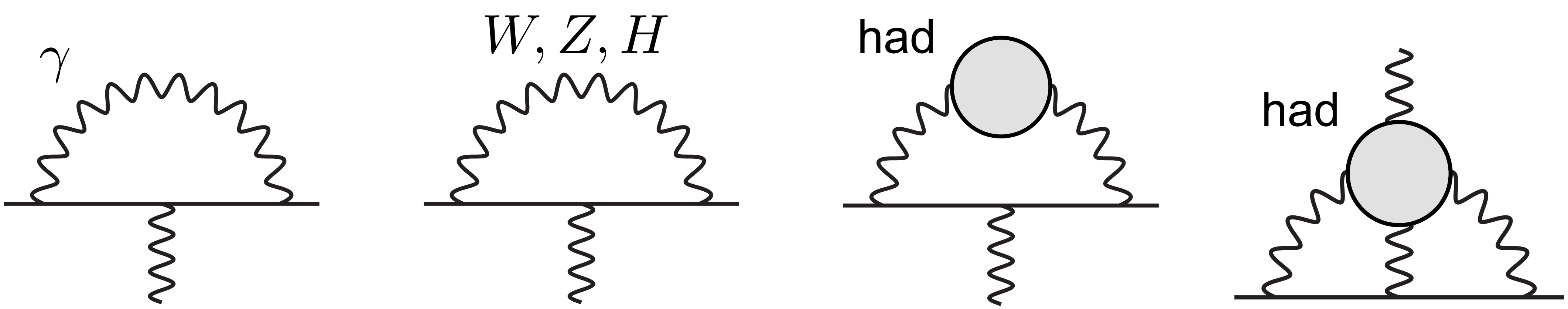
cf. $a_\mu(\mathrm{EW}) = 1.5 \times 10^{-9}$



SM Prediction

SM = QED + EW + Had (LO + HO + HLbL)

Exp: $116\,592\,089 \quad (63) \quad [\times 10^{-11}]$



QED EW Had(VP) Had(LbL)

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \cdot 10^{-10}$$

SM Prediction

SM = QED + EW + Had (LO + HO + HLbL)

Exp:	$116\,592\,089$	(63)	$[\times 10^{-11}]$
QED:	$116\,584\,718.952$	(0.08)	up to α^5
EW:	153.2	(1.8)	full two loop
Had(LO) [HLMNT]:	$6\,949.1$	$(43)^*$	e^+e^- data consistent with τ result
[DHMZ]:	$6\,923$	(42)	
Had(HO):	-98.4	(0.7)	
Had(LbL) [PdRV]:	105	$(26)^*$	model
[N,JN]:	116	(39)	

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (26.1 \pm 8.0) \cdot 10^{-10}$$

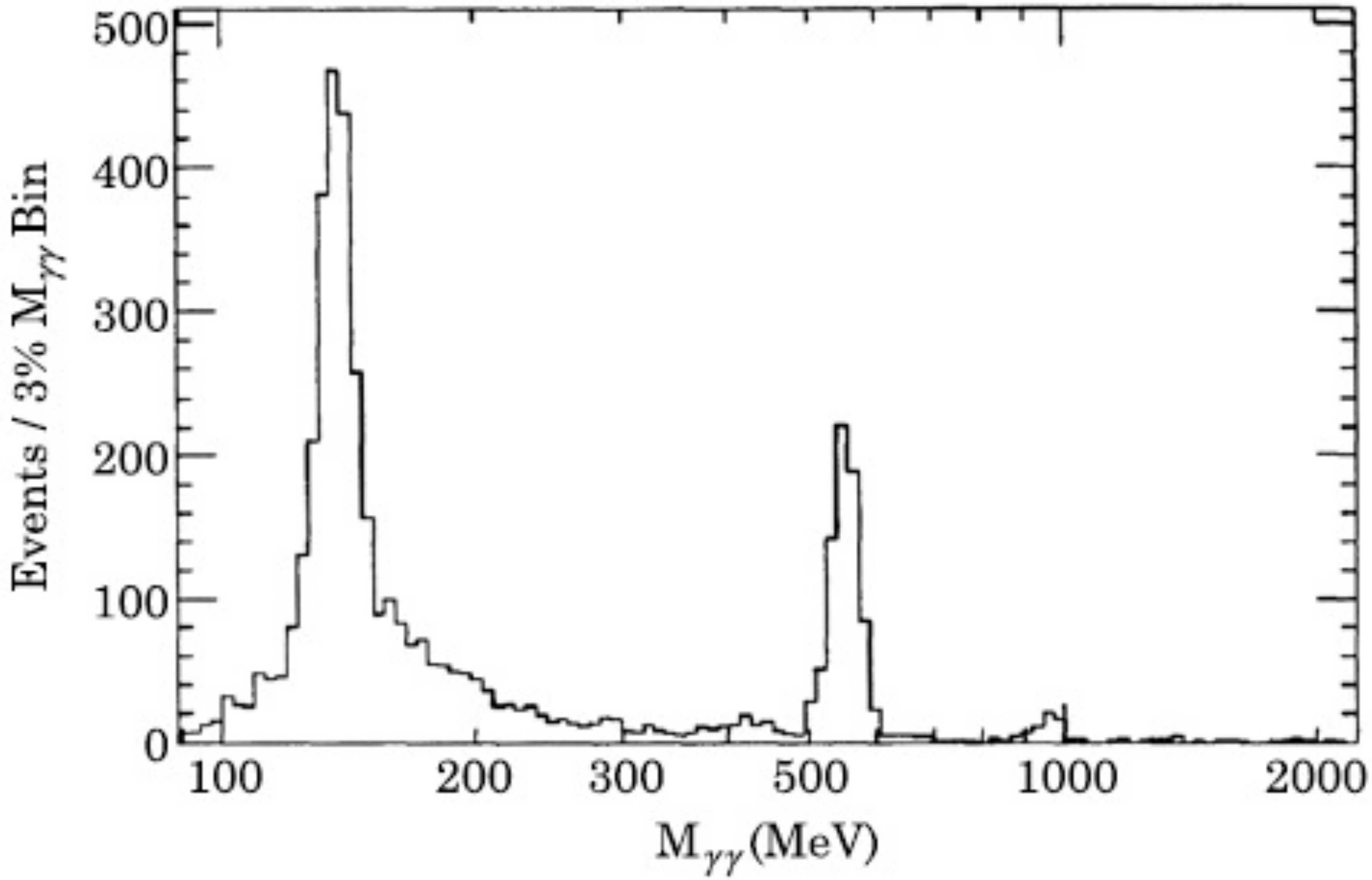
Hadronic light-by-light scattering in the muon $g-2$: Summary

Some results for the various contributions to $a_\mu^{\mathrm{LbyL;had}} \times 10^{11}$:

Contribution	BPP	HKS, HK	KN	MV	BP, MdRR	PdRV	N, JN	FGW
π^0, η, η'	85 ± 13	82.7 ± 6.4	83 ± 12	114 ± 10	–	114 ± 13	99 ± 16	84 ± 13
axial vectors	2.5 ± 1.0	1.7 ± 1.7	–	22 ± 5	–	15 ± 10	22 ± 5	–
scalars	-6.8 ± 2.0	–	–	–	–	-7 ± 7	-7 ± 2	–
π, K loops	-19 ± 13	-4.5 ± 8.1	–	–	–	-19 ± 19	-19 ± 13	–
π, K loops $+$subl. N_C	–	–	–	0 ± 10	–	–	–	–
other	–	–	–	–	–	–	–	0 ± 20
quark loops	21 ± 3	9.7 ± 11.1	–	–	–	2.3	21 ± 3	107 ± 48
Total	83 ± 32	89.6 ± 15.4	80 ± 40	136 ± 25	110 ± 40	105 ± 26	116 ± 39	191 ± 81

BPP = Bijnens, Pallante, Prades '95, '96, '02; HKS = Hayakawa, Kinoshita, Sanda '95, '96; HK = Hayakawa, Kinoshita '98, '02; KN = Knecht, Nyffeler '02; MV = Melnikov, Vainshtein '04; BP = Bijnens, Prades '07; MdRR = Miller, de Rafael, Roberts '07; PdRV = Prades, de Rafael, Vainshtein '09; N = Nyffeler '09, JN = Jegerlehner, Nyffeler '09; FGW = Fischer, Goecke, Williams '10, '11 (used values from arXiv:1009.5297v2 [hep-ph], 4 Feb 2011)

- Pseudoscalar-exchange contribution dominates numerically (except in FGW). But other contributions are not negligible. Note cancellation between π, K-loops and quark loops !
- PdRV: Do not consider dressed light quark loops as separate contribution ! Assume it is already taken into account by using short-distance constraint of MV '04 on pseudoscalar-pole contribution. Added all errors in quadrature ! Like HK(S). Too optimistic ?
- N, JN: New evaluation of pseudoscalars. Took over most values from BPP, except axial vectors from MV. Added all errors linearly. Like BPP, MV, BP, MdRR. Too pessimistic ?
- FGW: new approach with Dyson-Schwinger equations. Is there some double-counting ? Between their dressed quark loop (largely enhanced !) and the pseudoscalar exchanges.



$$\gamma\gamma \rightarrow \text{pseudoscalar}\,(\pi, \eta, \eta') \rightarrow \gamma\gamma$$

Crystal Ball detector (1988)

Future Prospects

$$\mathrm{E821}: 116\,592\,089(63)\times 10^{-11} \quad (0.54\mathrm{ppm})$$

$$\sigma_{\mathrm{stat}} = 0.46\mathrm{ppm} \qquad \sigma_{\mathrm{syst}} = 0.28\mathrm{ppm}$$

$$\left.\begin{array}{l}\text{Fermilab E989}: \quad \sigma = 0.14\mathrm{ppm} \\ \text{J-PARC}: \quad \sigma = 0.1\mathrm{ppm}\end{array}\right\}$$ Goal: 2015-2016

Hadronic VP: KLOE-2, VEPP-2000, Super-B factories

LbL: err reduced to 10% level in ~5years [INT workshop]

- E989 (3$\times$ smaller error) $\to\sim 5\sigma$
- E989+new HLBL theory $\to\sim 6\sigma$
- E989+new HLBL +new HVP (50% reduction) $\to\sim 8\sigma$

Blum, Fundamental Physics at the Intensity Frontier

New Physics

challenge to explain the deviation:

$$a_\mu(\mathrm{NP}) \sim \frac{\alpha_{\mathrm{NP}}}{4\pi}\frac{m_\mu^2}{m_{\mathrm{NP}}^2} \longleftrightarrow a_\mu(\mathrm{EW}) \sim \frac{\alpha_2}{4\pi}\frac{m_\mu^2}{m_W^2}$$

note: muon mass due to chirality flip

- current discrepancy is as large as a_μ(EW)
- light new particle or large coupling
- enhancement required for NP in TeV scale

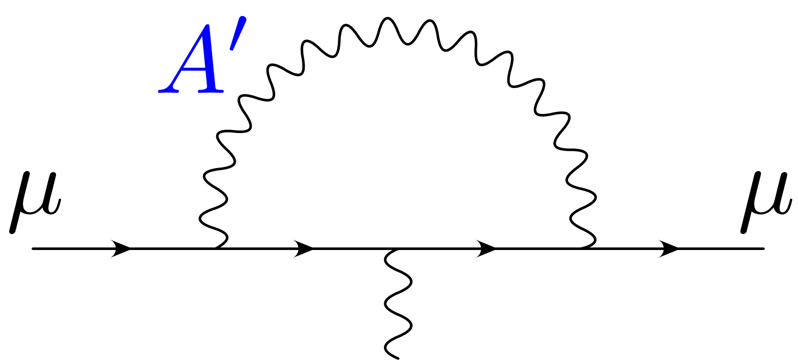
Heavy Photon

- kinetic mixing with $U(1)_Y$

$$\mathcal{L} = \frac{\epsilon}{2} F^Y F'$$

- behave as photon for a_μ

  [Pospelov]



- also light scalar, Z', ...

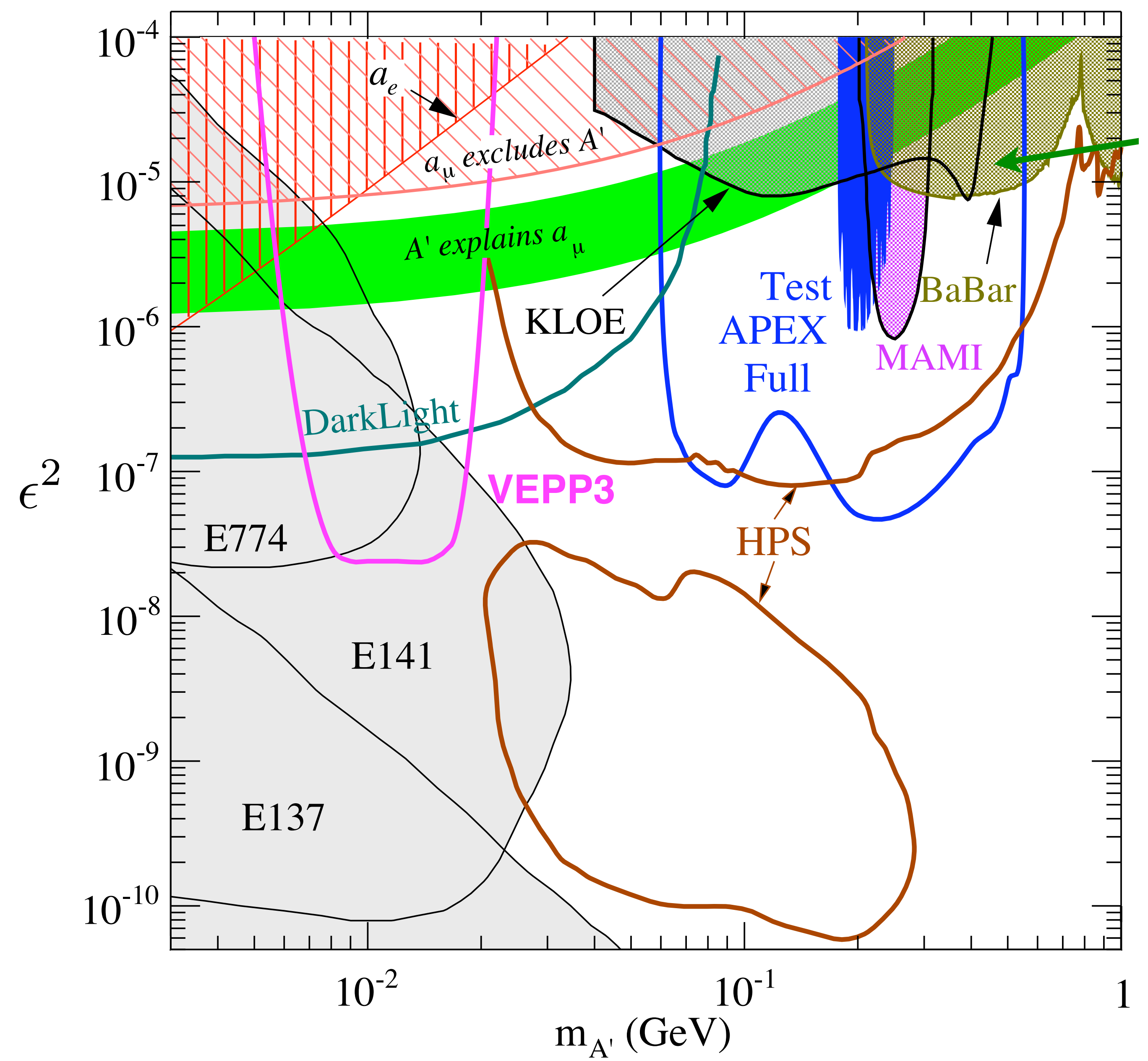


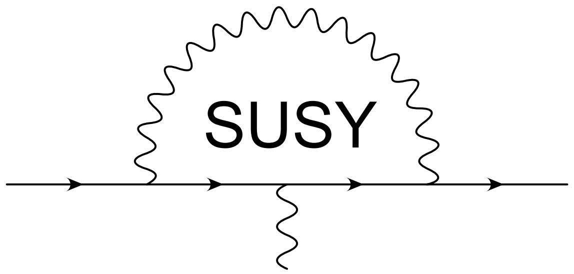
Figure from slide by Essig at "Fundamental Physics at the Intensity Frontier"

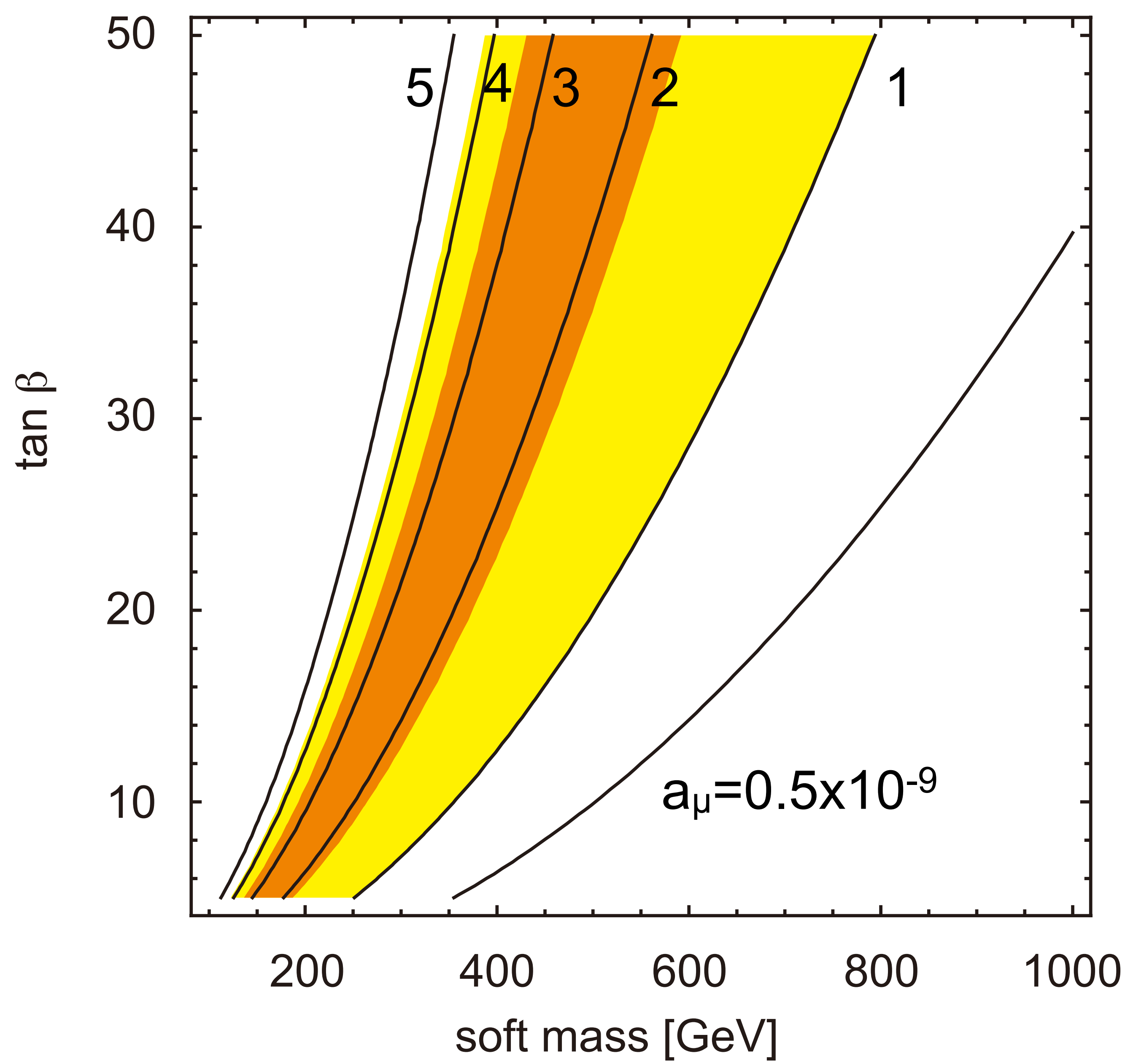
SUSY

- muon g-2 requires
  - small soft mass
  - large tanβ

$$\Delta a_\mu \sim \frac{\alpha_2}{4\pi} \frac{m_\mu^2}{m_{\rm soft}^2} \underline{\tan\beta}$$

- tension: Higgs mass of ~125GeV

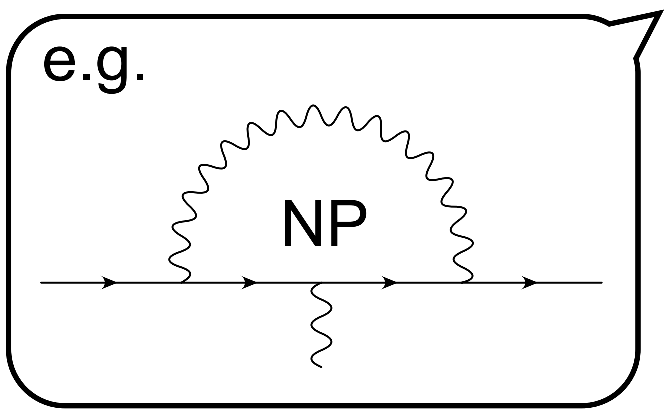


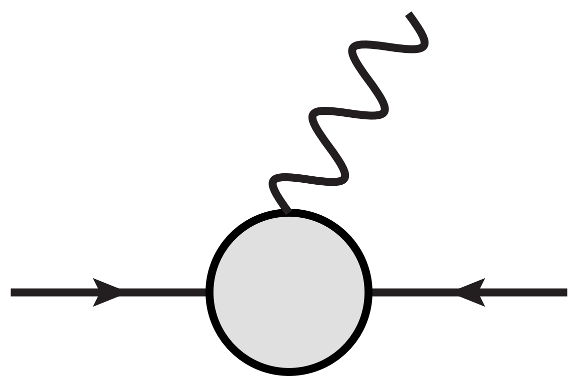


Leptonic flavor or CP violation

LFV and EDM

New Physics searches in rare (SM suppressed) processes

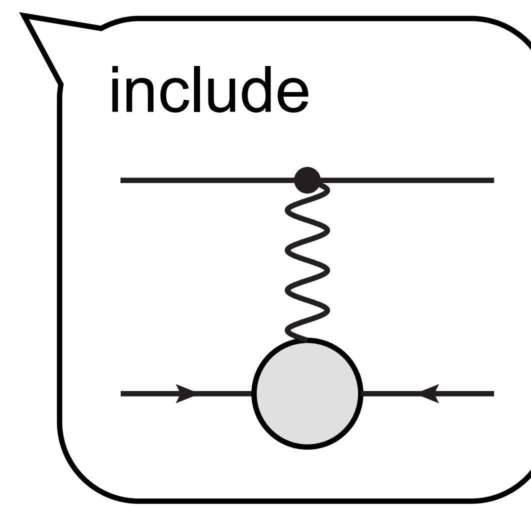




$$\bar{l}_j \sigma^{\mu\nu} l_i F_{\mu\nu}$$

$$(\bar{l}_j l_i)\underline{(\bar{f} f')}$$

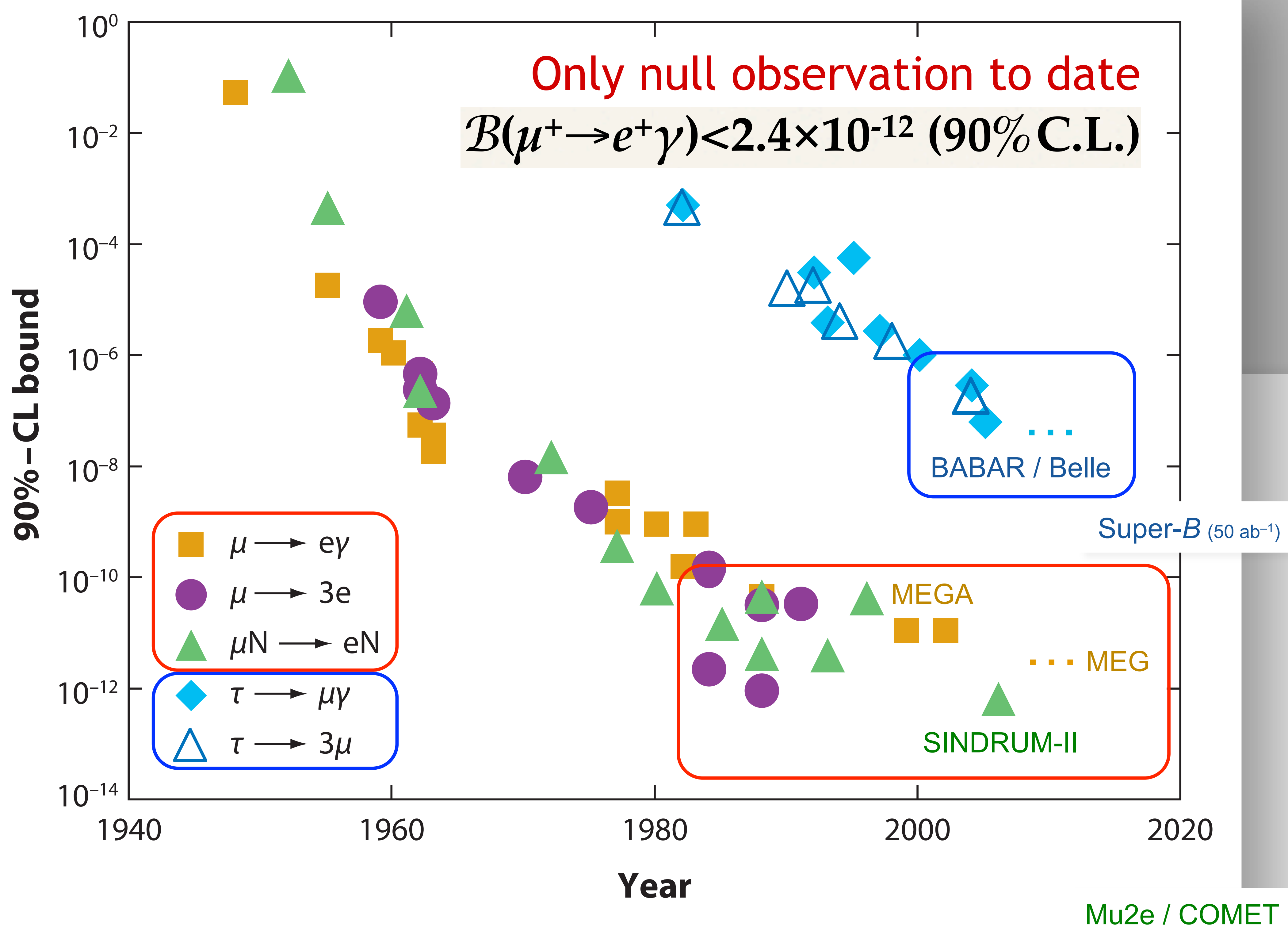
hadronize
if colored



... currently no excesses in measurements

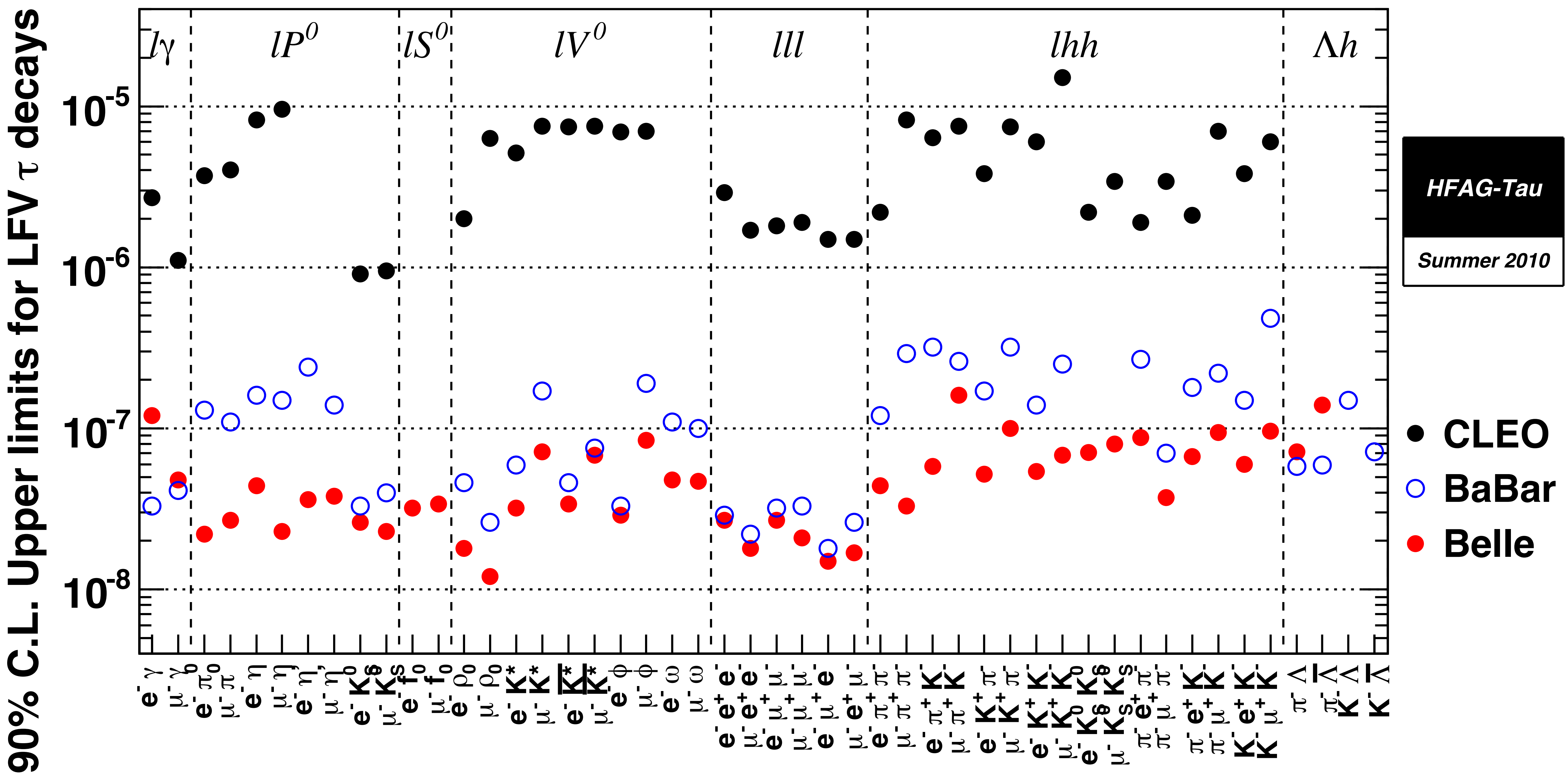
Charged-Lepton Flavour Violation

Marciano et al., Annu. Rev. Nucl. Part. Sci.58, 315 (2008)



Spectacular perspective !

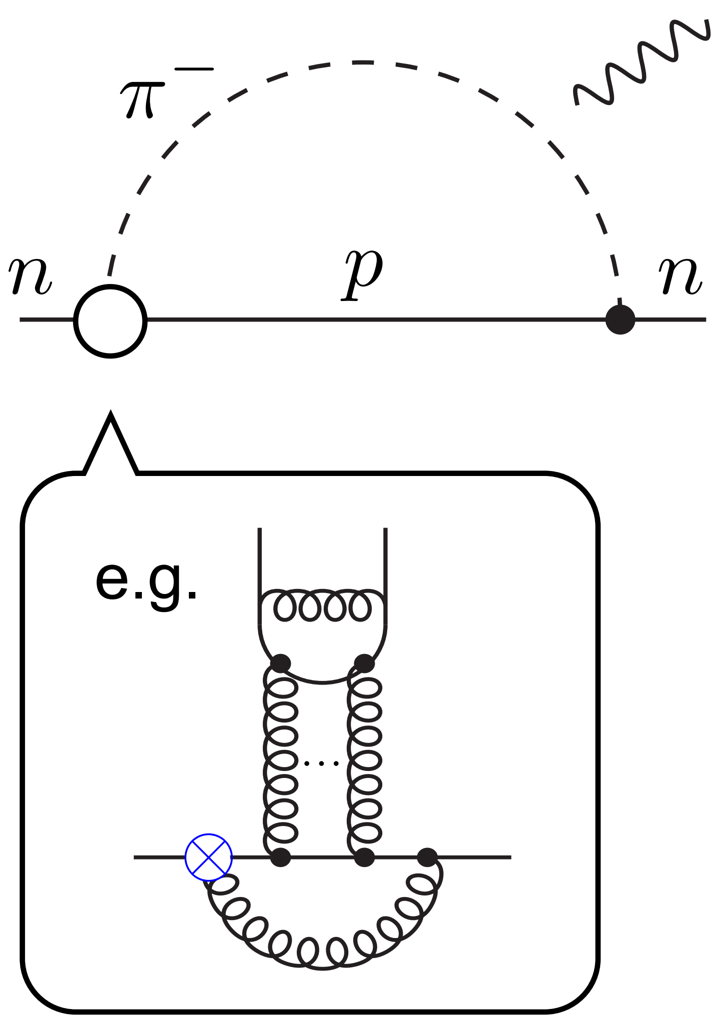
τ LFV



http://www.slac.stanford.edu/xorg/hfag/tau/HFAG-TAU-LFV.htm

CP violation: EDM

$$\mathcal{L}_{\rm eff} = \frac{g_s^2}{32\pi^2}\bar\theta\, G^a_{\mu\nu}\tilde G^{\mu\nu,a} - \sum_{i=u,d,s,e,\mu} i\frac{d_f}{2}\bar\psi_i(F\cdot\sigma)\gamma_5\psi_i - \sum_{i=u,d,s} i\frac{d_f^c}{2}g_s\bar\psi_i(G\cdot\sigma)\gamma_5\psi_i$$
$$+\frac{1}{3}w\, f^{abc}G^a_{\mu\nu}\tilde G^{\nu\rho,b}G^{\mu,c}_{\rho} + \sum_{i,j} C_{ij}\,(\bar\psi_i\psi_i)(\bar\psi_j i\gamma_5\psi_j) + \cdots\,,$$



particle	exp [e cm]
electron	1.6 x 10^{-27} (90%)
muon	1.9 x 10^{-19} (95%)
tau	4.6 x 10^{-17} (95%)
proton	0.54 x 10^{-23}
neutron	2.9 x 10^{-26} (90%)
mercury	3.1 x 10^{-29} (95%)
strong CP	$\bar\theta < 10^{-10}$

Neutrino

Status

- (total) mass ≲ O(0.1-1)eV
  [cf. cosmology, 0ν2β]
- Daya-Bay result on U_{e3}
  $\sin^2 2\theta_{13} = 0.092(0.016)(0.005)$
- future targets
  - CP violation
  - mass spectrum

parameter	best fit $\pm 1\sigma$
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	$7.59^{+0.20}_{-0.18}$
$\Delta m^2_{31}\ [10^{-3}\mathrm{eV}^2]$	$2.50^{+0.09}_{-0.16}$ $-(2.40^{+0.08}_{-0.09})$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$
$\sin^2\theta_{23}$	$0.52^{+0.06}_{-0.07}$ 0.52 ± 0.06
$\sin^2\theta_{13}$	$0.013^{+0.007}_{-0.005}$ $0.016^{+0.008}_{-0.006}$
δ	$\left(-0.61^{+0.75}_{-0.65}\right)\pi$ $\left(-0.41^{+0.65}_{-0.70}\right)\pi$

cf. MINOS anti-neutrino anomaly disappeared

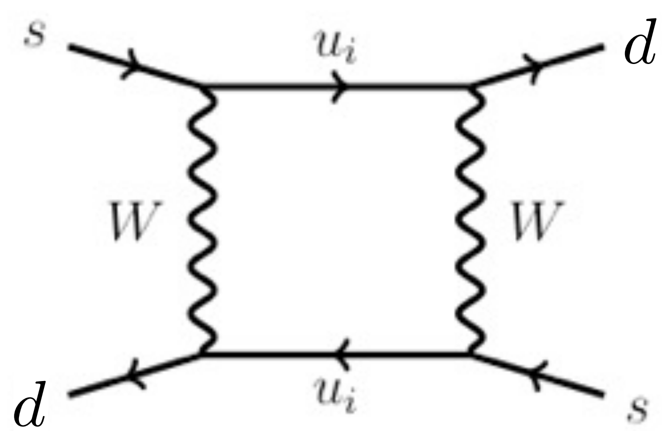
[Schwetz,Tortola,Valle,1108.1376]

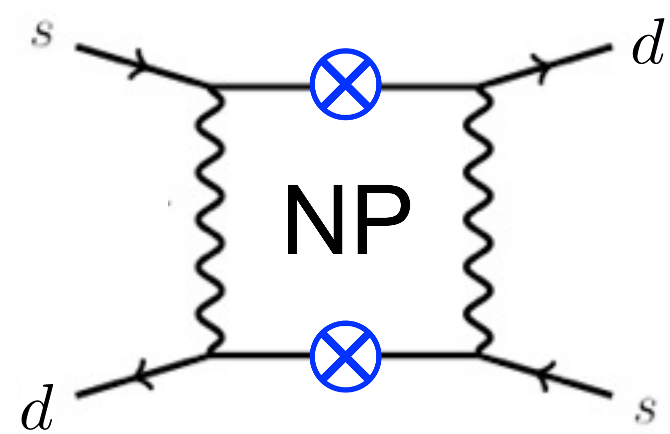
Hadron Physics

Status

- almost all results provide constraints
  - stringent bound from $K - \bar{K}$

SM





$\delta \ll 1$

- chirality flip is enhanced in a class of NP (SUSY)
  - caution: when you read literature, some of them discard this effect...

B Physics

Rare Decay

Rare decays (induced by CKM): $B_d \to X_s\ \gamma$, $B_{d,s} \to \mu\ \mu$

- $\mathrm{Br}(\bar{B} \to X_s \gamma) \quad [\bar{B} = \bar{B}^0 \text{ or } B^-]$

$$\begin{cases} \mathrm{Br}(\bar{B} \to X_s \gamma)^{\mathrm{exp}} = (3.55 \pm 0.24 \pm 0.09) \times 10^{-4} \\ \mathrm{Br}(\bar{B} \to X_s \gamma)^{\mathrm{SM}} = (3.15 \pm 0.23) \times 10^{-4} \end{cases}$$

$\longrightarrow \quad -0.29 \times 10^{-4} < \Delta \mathrm{Br}(\bar{B} \to X_s \gamma) < 1.09 \times 10^{-4}$ @2σ

$$\begin{aligned} |A(b \to s\gamma)|^2 &= |A^{\mathrm{SM}}(\mathrm{LO}) + A^{\mathrm{SM}}(\mathrm{HO}) + A^{\mathrm{NP}}(\mathrm{LO}) + A^{\mathrm{NP}}(\mathrm{HO})|^2 \\ &= |A^{\mathrm{SM}}(\mathrm{LO}) + A^{\mathrm{SM}}(\mathrm{HO})|^2 \\ &\quad + 2\mathrm{Re}[A^{\mathrm{SM}}(\mathrm{LO})^* A^{\mathrm{NP}}(\mathrm{LO})] \\ &\quad + 2\mathrm{Re}[A^{\mathrm{SM}}(\mathrm{NLO})^* A^{\mathrm{NP}}(\mathrm{LO})] \\ &\quad + 2\mathrm{Re}[A^{\mathrm{SM}}(\mathrm{LO})^* A^{\mathrm{NP}}(\mathrm{NLO})] + \ldots \end{aligned}$$

← estimated by models

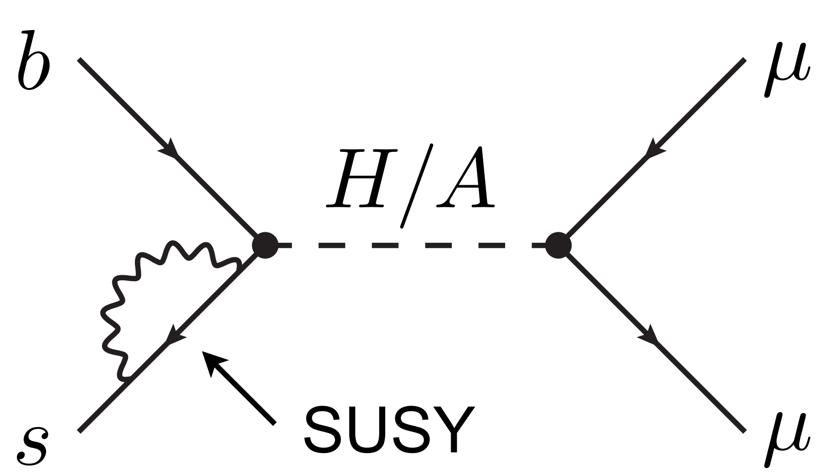
Rare Decay

Rare decays (induced by CKM): $B_d \to X_s\, \gamma$, $B_{d,s} \to \mu\, \mu$

- $\mathrm{Br}(\bar{B} \to X_s \gamma) \quad [\bar{B} = \bar{B}^0 \text{ or } B^-]$
- $\mathrm{Br}(B_q \to \mu\mu) \quad [q = d, s]$

LHCb@95%

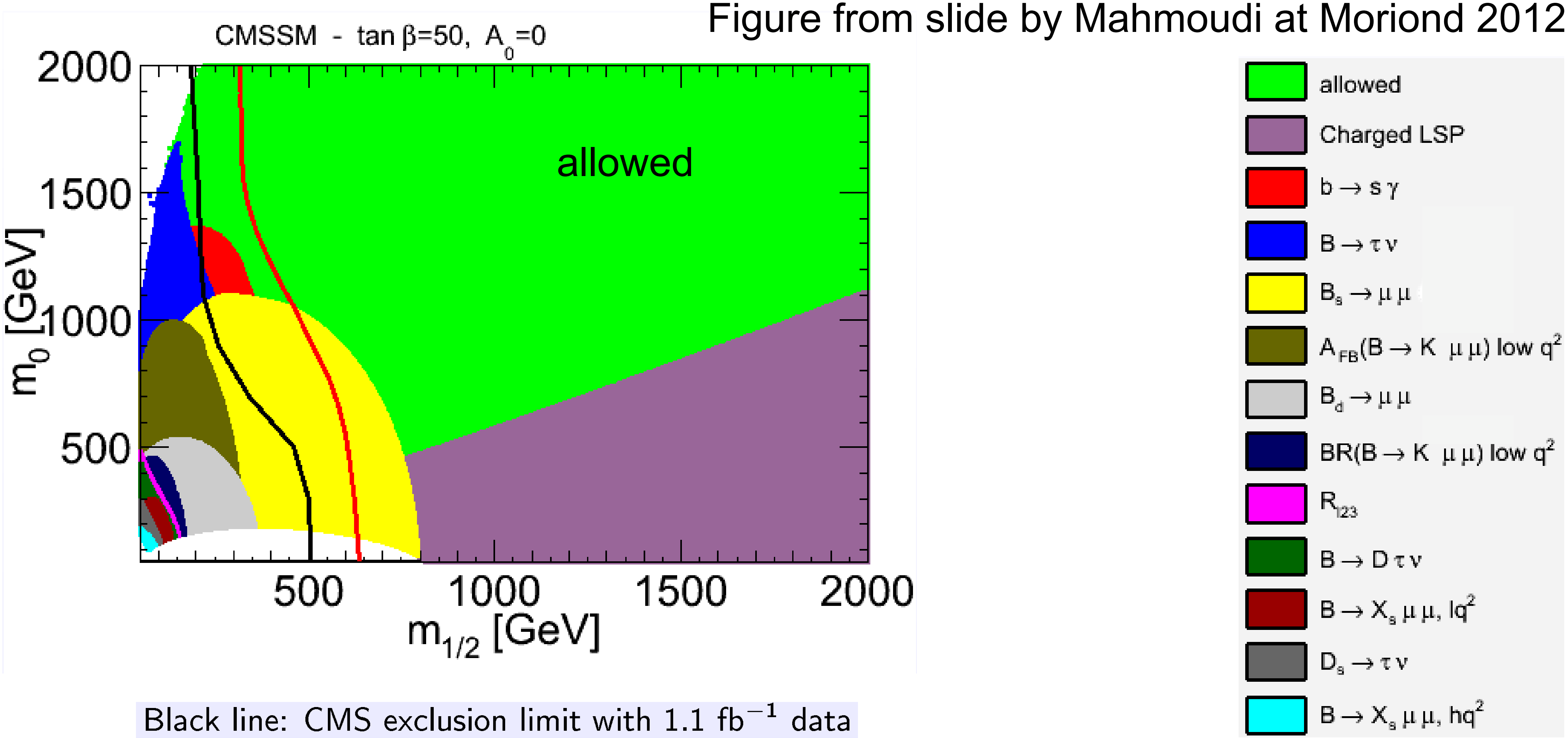
$$\begin{cases} \mathrm{Br}(B_d \to \mu\mu)^{\mathrm{exp}} < 1.03 \times 10^{-9} & [\mathrm{SM}: \ (0.1 \pm 0.01) \times 10^{-9}] \\ \mathrm{Br}(B_s \to \mu\mu)^{\mathrm{exp}} < 4.5 \times 10^{-9} & [\mathrm{SM}: \ (3.2 \pm 0.2) \times 10^{-9}] \end{cases}$$



sensitive to scalar exchange
e.g. large tanβ enhancement in SUSY

Rare Decay

Figure from slide by Mahmoudi at Moriond 2012

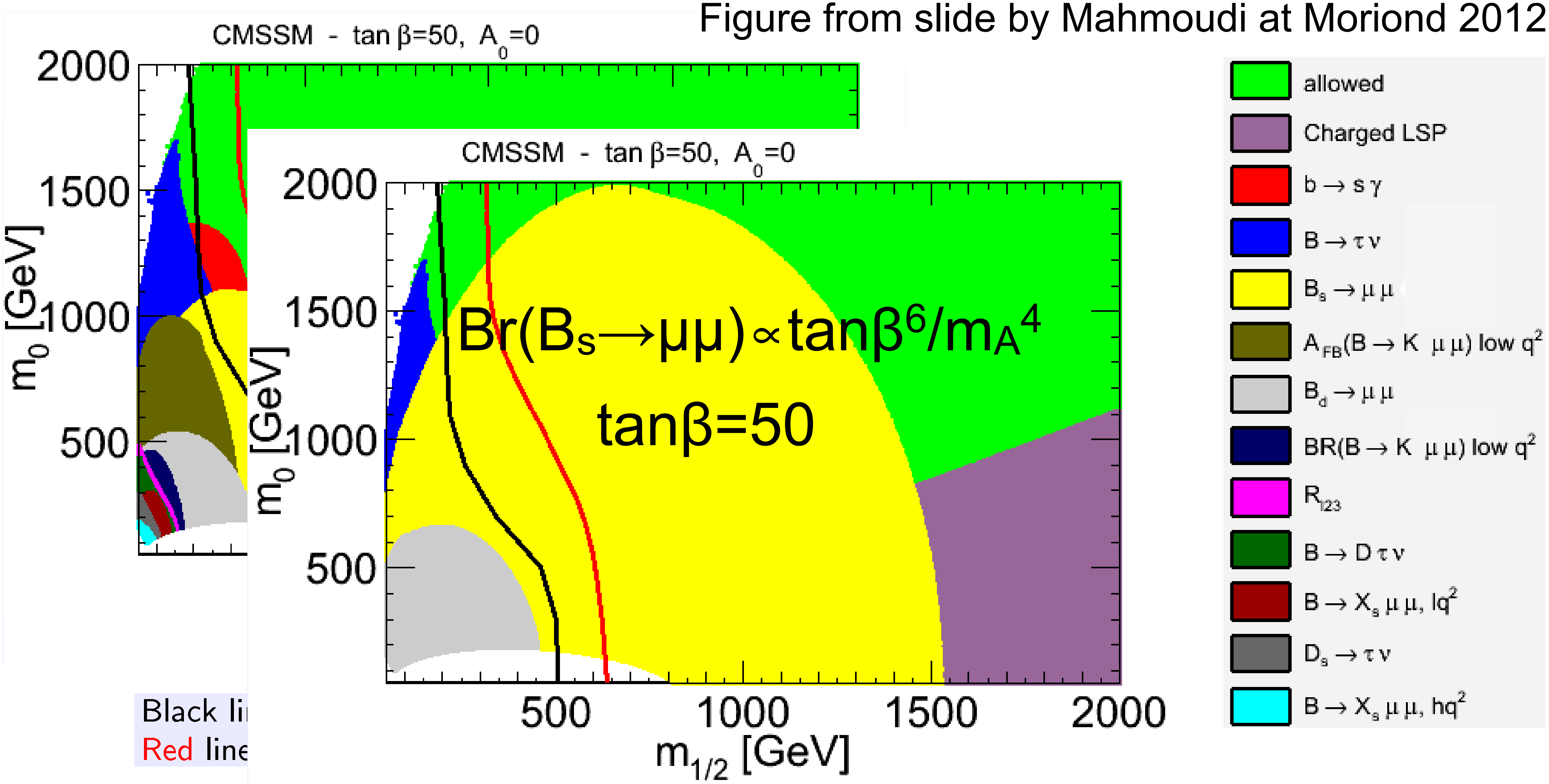


Black line: CMS exclusion limit with 1.1 fb^{-1} data
Red line: CMS exclusion limit with 4.4 fb^{-1} data

before LHCb 1fb^{-1}

Rare Decay

Figure from slide by Mahmoudi at Moriond 2012



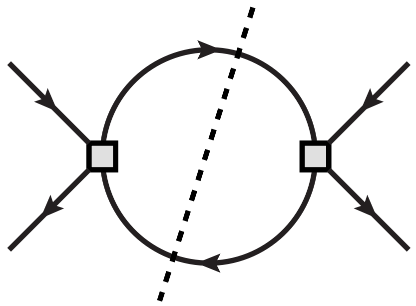
new LHCb result

B-B̄ Oscillation

Rare decays (induced by CKM): $B_d \to X_s\gamma$, $B_{d,s} \to \mu\mu$

- $\mathrm{Br}(\bar{B} \to X_s \gamma) \quad [\bar{B} = \bar{B}^0 \text{ or } B^-]$
- $\mathrm{Br}(B_q \to \mu\mu) \quad [q = d, s]$

B meson oscillation: $B_q^0 \leftrightarrow \bar{B}_q^o$



$$|\psi(t)\rangle = a(t)|B_0\rangle + b(t)|\bar{B}_0\rangle + \ldots$$

$$i\frac{\partial}{\partial t}\begin{bmatrix} a(t) \\ b(t) \end{bmatrix} = \begin{bmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{bmatrix} \begin{bmatrix} a(t) \\ b(t) \end{bmatrix}$$

M, Γ: Hermit
note: CPT

mass eigenstates: $|B_{H,L}\rangle = p|B_0\rangle \pm q|\bar{B}_0\rangle$

$$\Delta M \equiv M_H - M_L \sim 2|M_{12}| \qquad \Delta\Gamma \equiv |\Gamma_H - \Gamma_L| \sim 2|\Gamma_{12}|$$

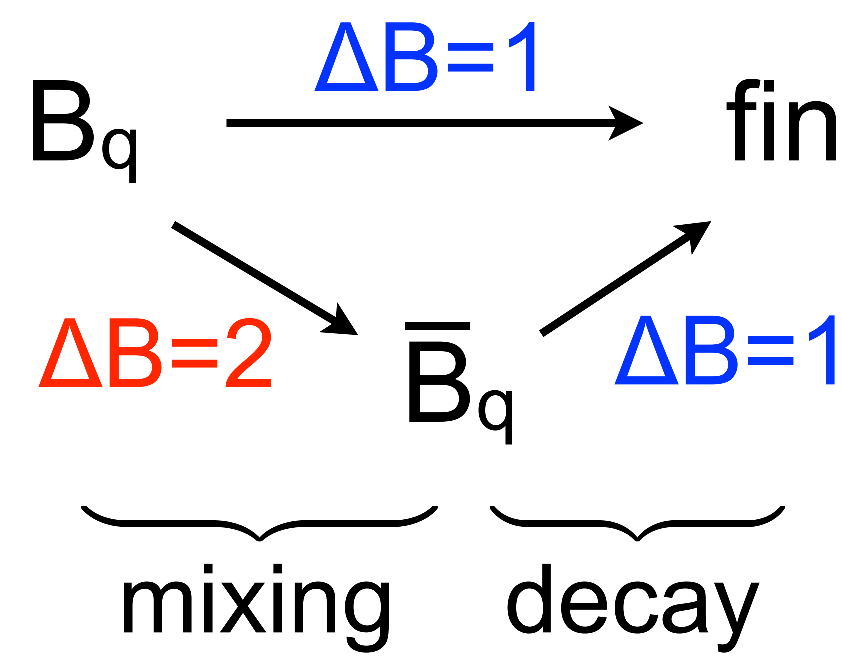
CP Violations

Rare decays (induced by CKM): $B_d \to X_s\gamma$, $B_{d,s} \to \mu\mu$

- $\mathrm{Br}(\bar{B} \to X_s\gamma) \quad [\bar{B} = \bar{B}^0 \text{ or } B^-]$
- $\mathrm{Br}(B_q \to \mu\mu) \quad [q = d, s]$

B meson oscillation: $B_q^0 \leftrightarrow \bar{B}_q^o$

- CP violations
  - direct CPV ($B \to K\pi$)
  - indirect CPV (semileptonic)
  - interference ($B \to J/\psi K$)



$$B^0 \to f \not\leftarrow \bar{B}^0$$
$$B^0 \not\to \bar{f} \leftarrow \bar{B}^0$$

$$B^0 \to f_{\mathrm{CP}} \leftarrow \bar{B}^0$$

Status

- mass difference

$$\Delta m_d(\mathrm{exp}) = 0.507 \pm 0.004\mathrm{ps}^{-1} \quad [\mathrm{SM}:\ 0.543 \pm 0.091\mathrm{ps}^{-1}]$$

$$\Delta m_s(\mathrm{exp}) = 17.63 \pm 0.11\mathrm{ps}^{-1} \quad [\mathrm{SM}:\ 17.30 \pm 2.6\mathrm{ps}^{-1}]$$

- width difference of B_s

$$\Delta\Gamma_s(\mathrm{exp}) = 0.116 \pm 0.019\mathrm{ps}^{-1} \quad [\mathrm{SM}:\ 0.087 \pm 0.021\mathrm{ps}^{-1}]$$

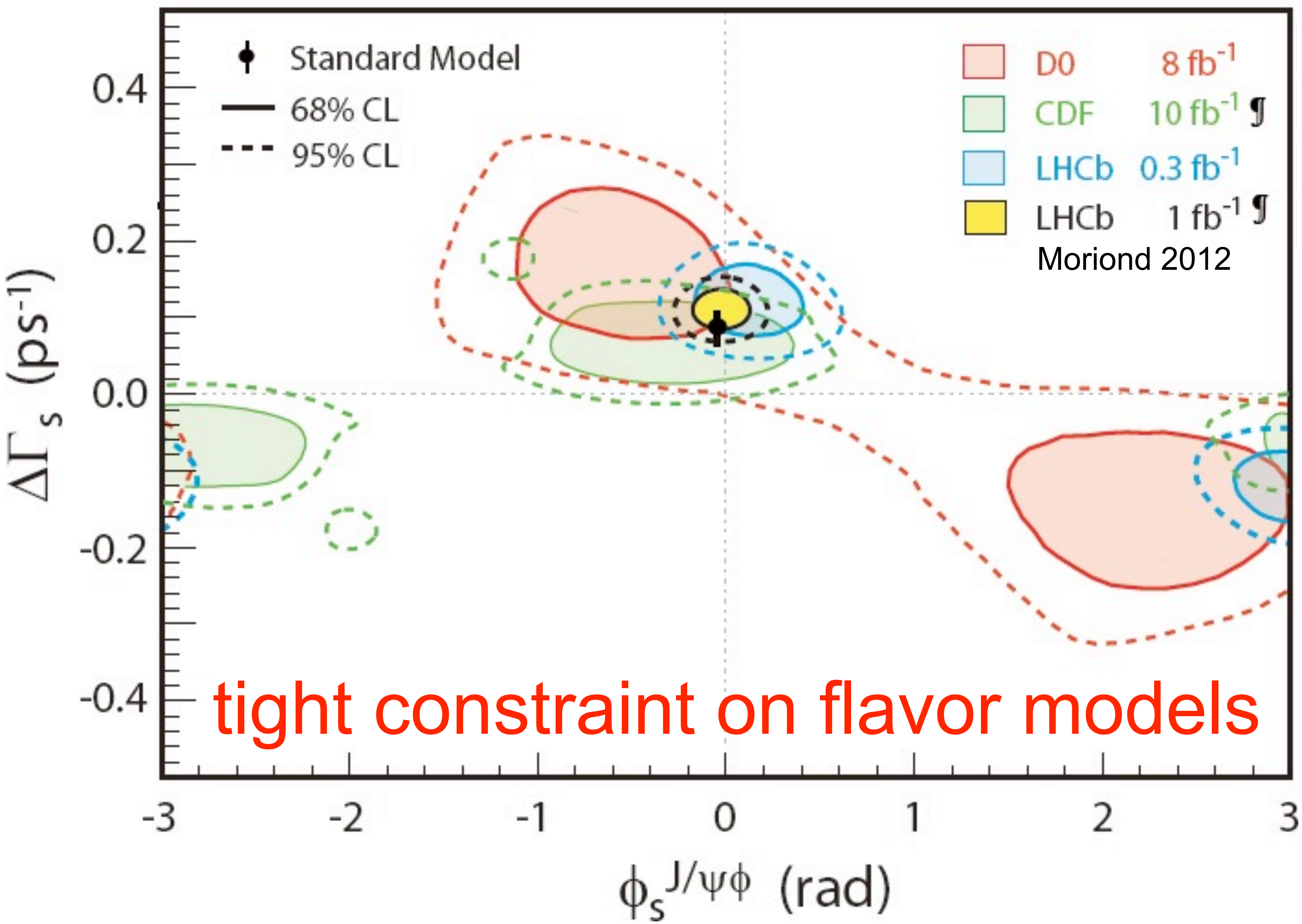
- CP violating phase of B_s $(\phi_s = -\arg M_{12}^s/\Gamma_{12}^s)$

$$\phi_s(\mathrm{exp}) = -0.001 \pm 0.105\mathrm{rad} \quad [\mathrm{SM}: -0.037 \pm 0.002\mathrm{rad}]$$

c.f. lifetime

$$\left.\frac{\tau_{B_s}}{\tau_{B_d}}\right|_{\mathrm{exp}} = 1.001 \pm 0.014 \quad [\mathrm{SM}:\ 0.996 - 1.000]$$

B_s Status



Standard Model
68% CL
95% CL
D0 8 fb-1
CDF 10 fb-1
LHCb 0.3 fb-1
LHCb 1 fb-1
Moriond 2012
0.4
0.2
0.0
-0.2
-0.4
ΔΓs (ps-1)
-3
-2
-1
0
1
2
3
φsJ/ψφ (rad)
tight constraint on flavor models

Anomalies in B physics

Belle, BaBarの結果（LHCｂとかも含む）

- CKM fit: Br($B_u \to \tau\nu$) or sin $2\phi_1$
- $B \to K\pi$のdirect CP violation

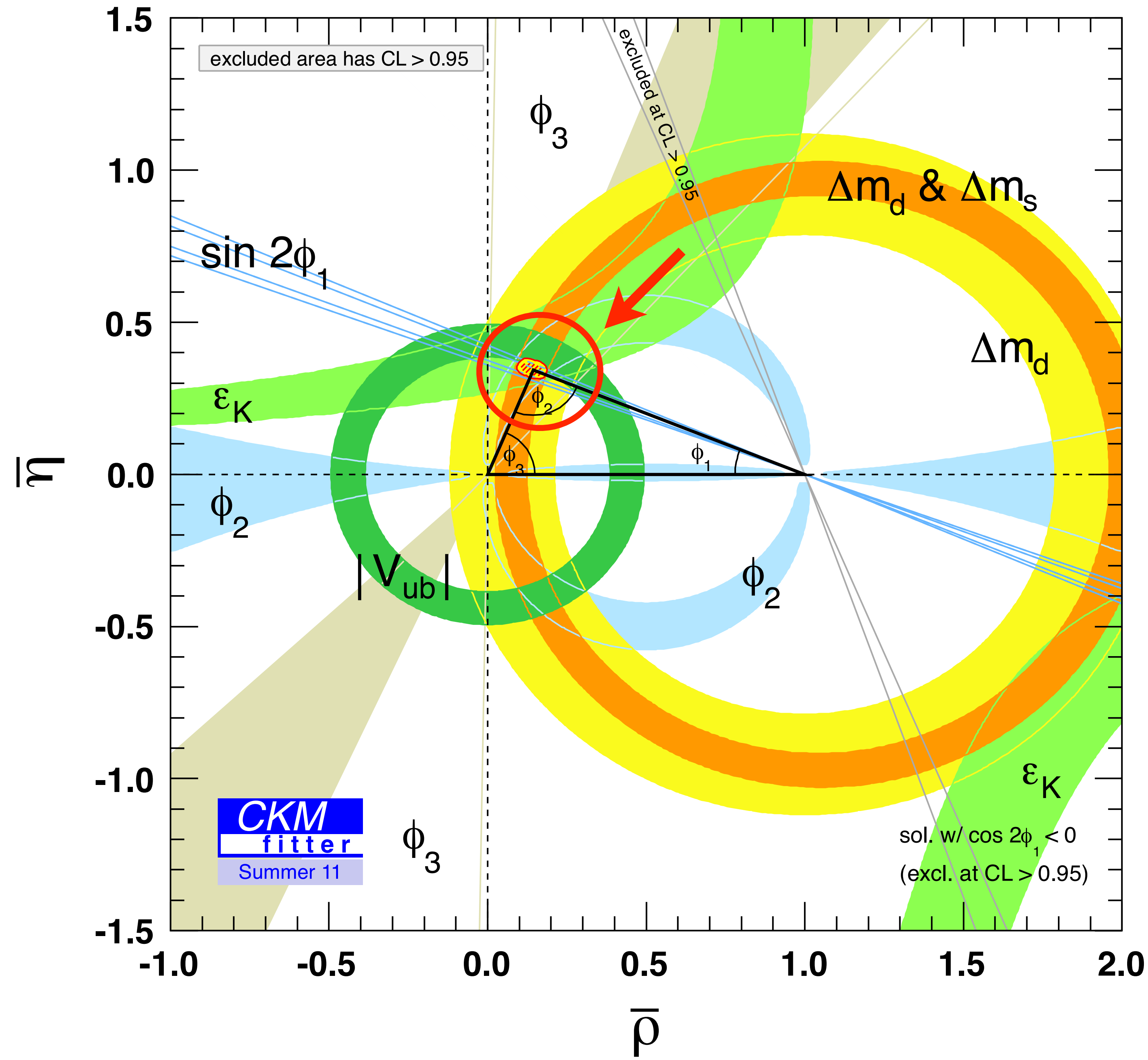
LHCbがSMを示唆 → 今回は話しません

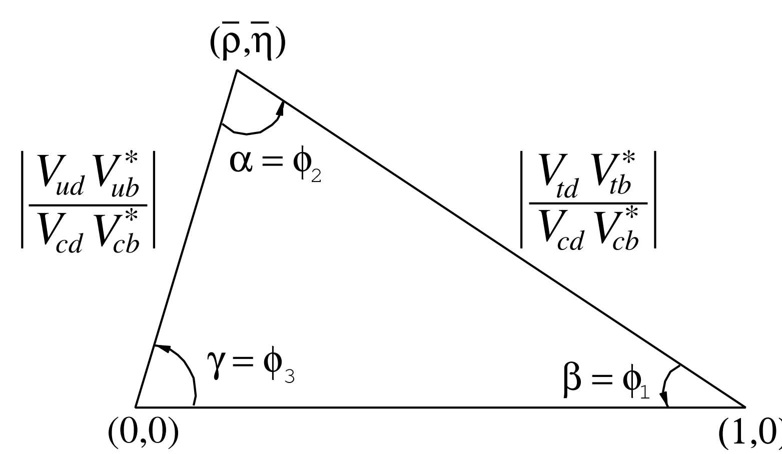
- $B \to K^*ll$のFB asymmetry

Tevatronの結果を間接的にLHCbが否定的

- like-sign dimuon charge asymmetry
  (for B_s-$\bar{B}_s$ oscillation)

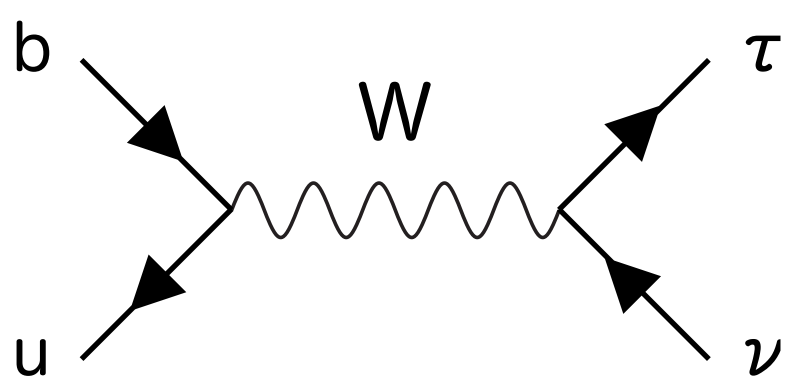
Tension in CKM fit



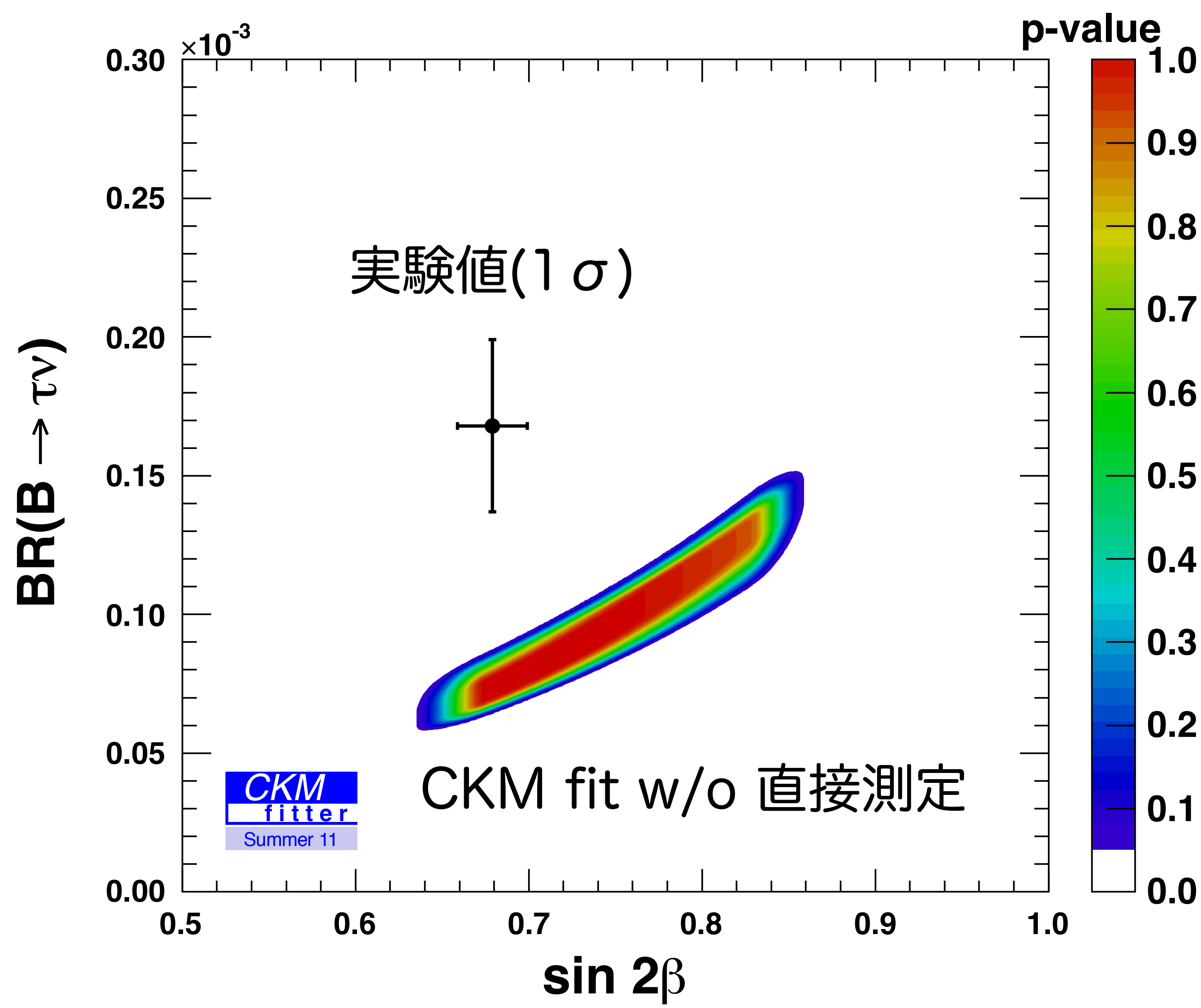


Br(B →τ ν)

・SMではtree levelの崩壊: 2σ以上のずれ (sin2φ₁を固定)



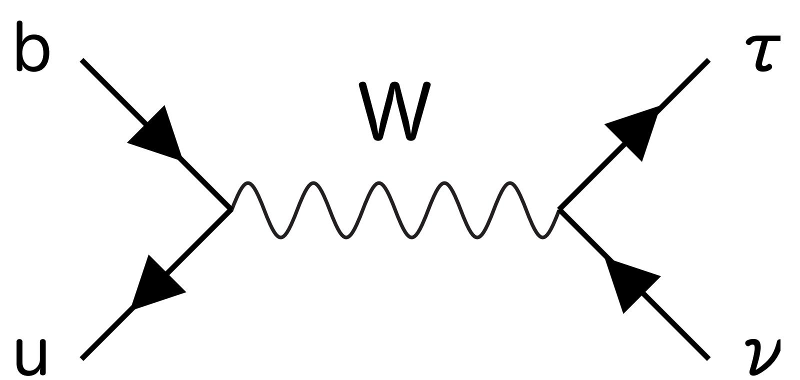
$$\mathcal{B}(B \to \tau\nu) = \frac{G_F^2 m_B \tau_B}{8\pi} m_\tau^2 \times \left[1 - \frac{m_\tau^2}{m_B^2}\right]^2 f_{B_d}^2 |V_{ub}|^2$$

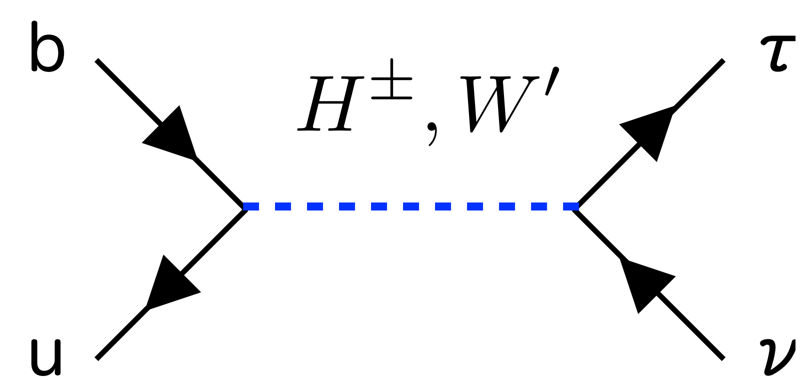


直接測定: B→τ ν , b→cc̄s

Br(B → τ ν)

・SMではtree levelの崩壊: 2σ以上のずれ (sin2ϕ_1を固定)





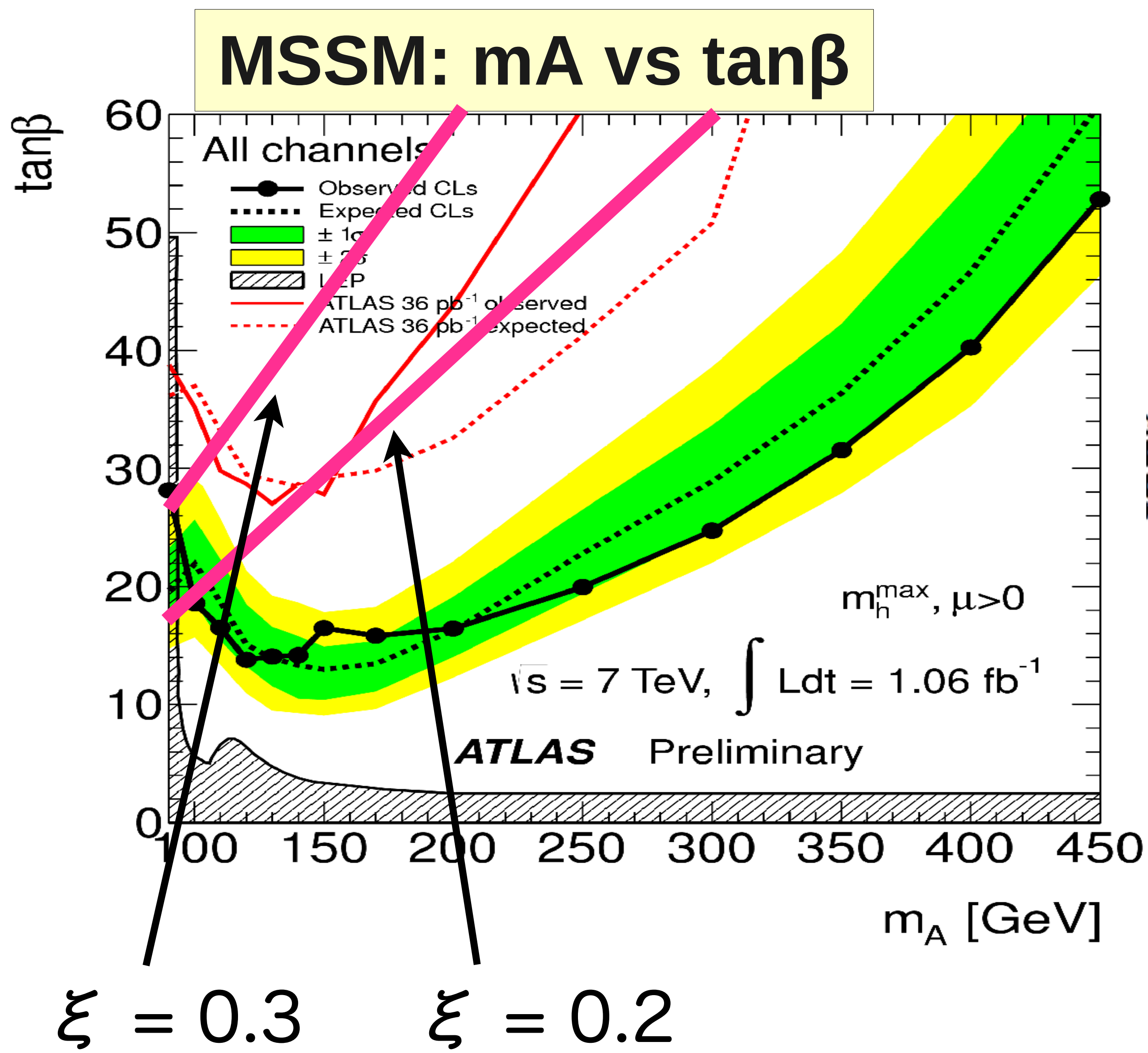
$$\mathcal{B}(B \to \tau\nu) = \frac{G_F^2 m_B \tau_B}{8\pi} m_\tau^2 \times \left[1 - \frac{m_\tau^2}{m_B^2}\right]^2 f_{B_d}^2 |V_{ub}|^2$$

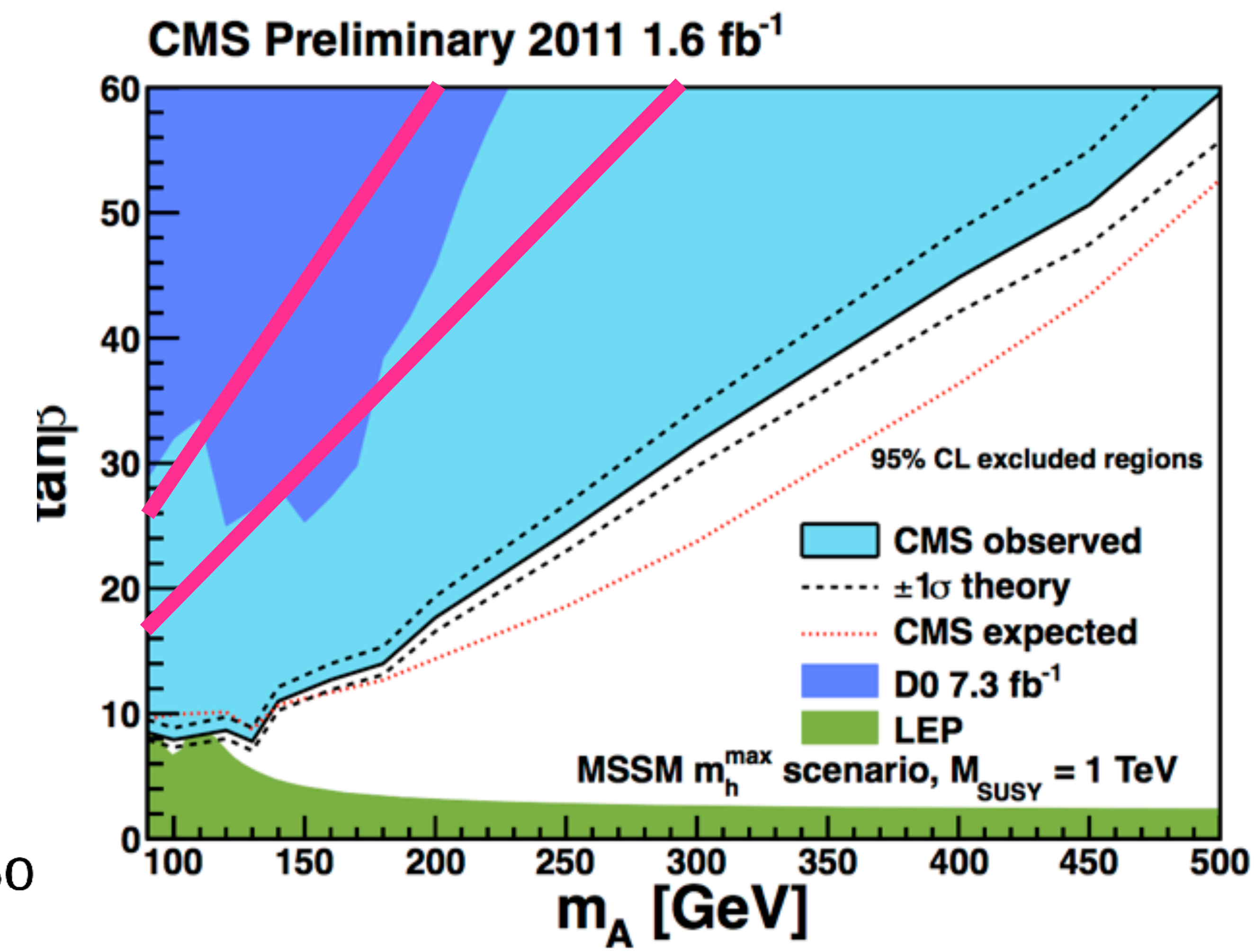
$$\frac{\mathcal{B}(B \to \tau\nu)}{\mathcal{B}(B \to \tau\nu)|_{\rm SM}} = \left[1 - \frac{m_B^2}{m_{H^\pm}^2} \tan^2\beta\right]^2$$

charged Higgsがある？

Heavy Higgs @ LHC

not include Moriond 2012

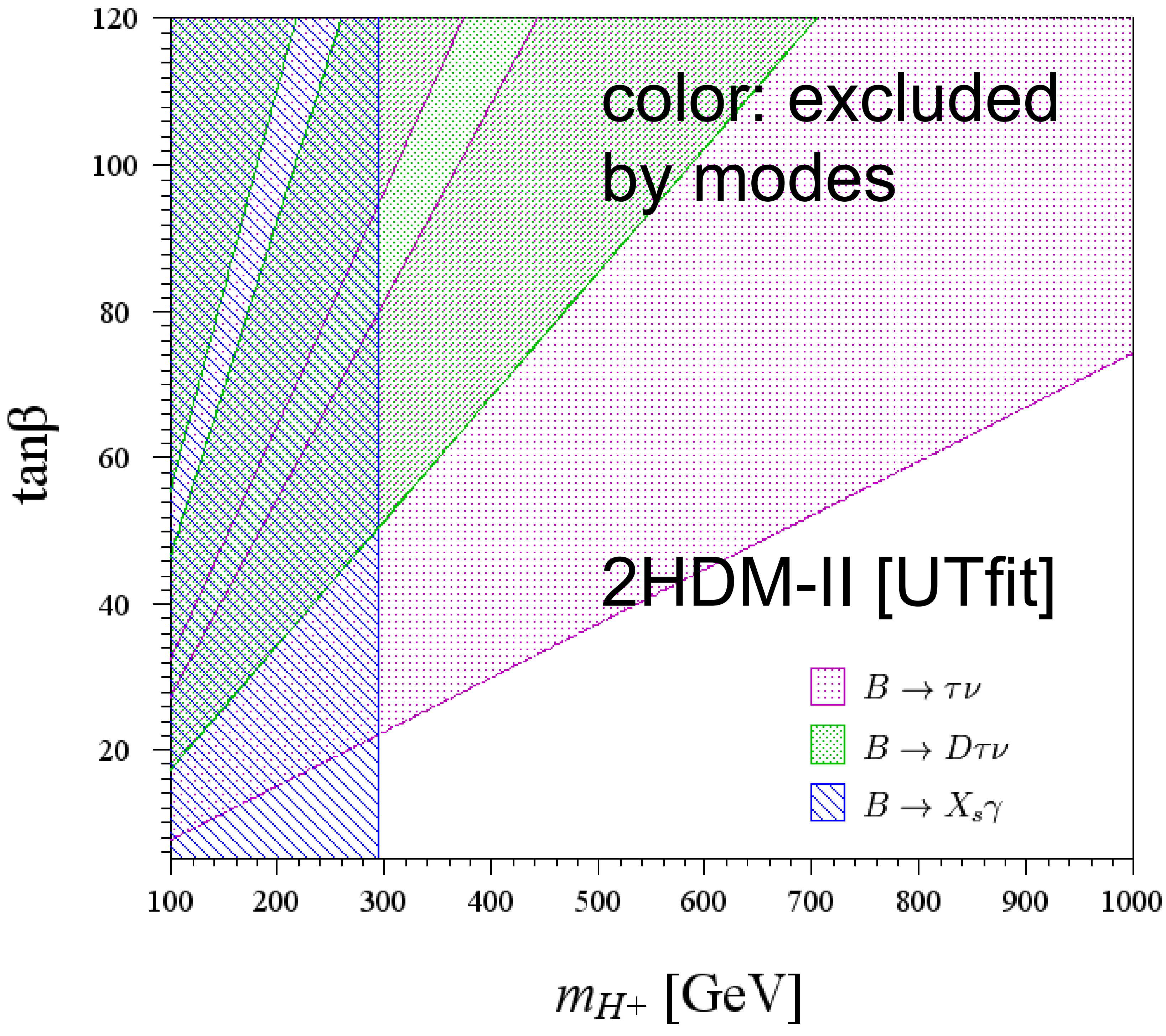




$m_A \simeq m_{H\pm}$

Br(B→$\tau\ \nu$): $\xi \equiv \dfrac{\tan\beta}{m_{H\pm}} \sim 0.3$

Contribution to B→D τ ν

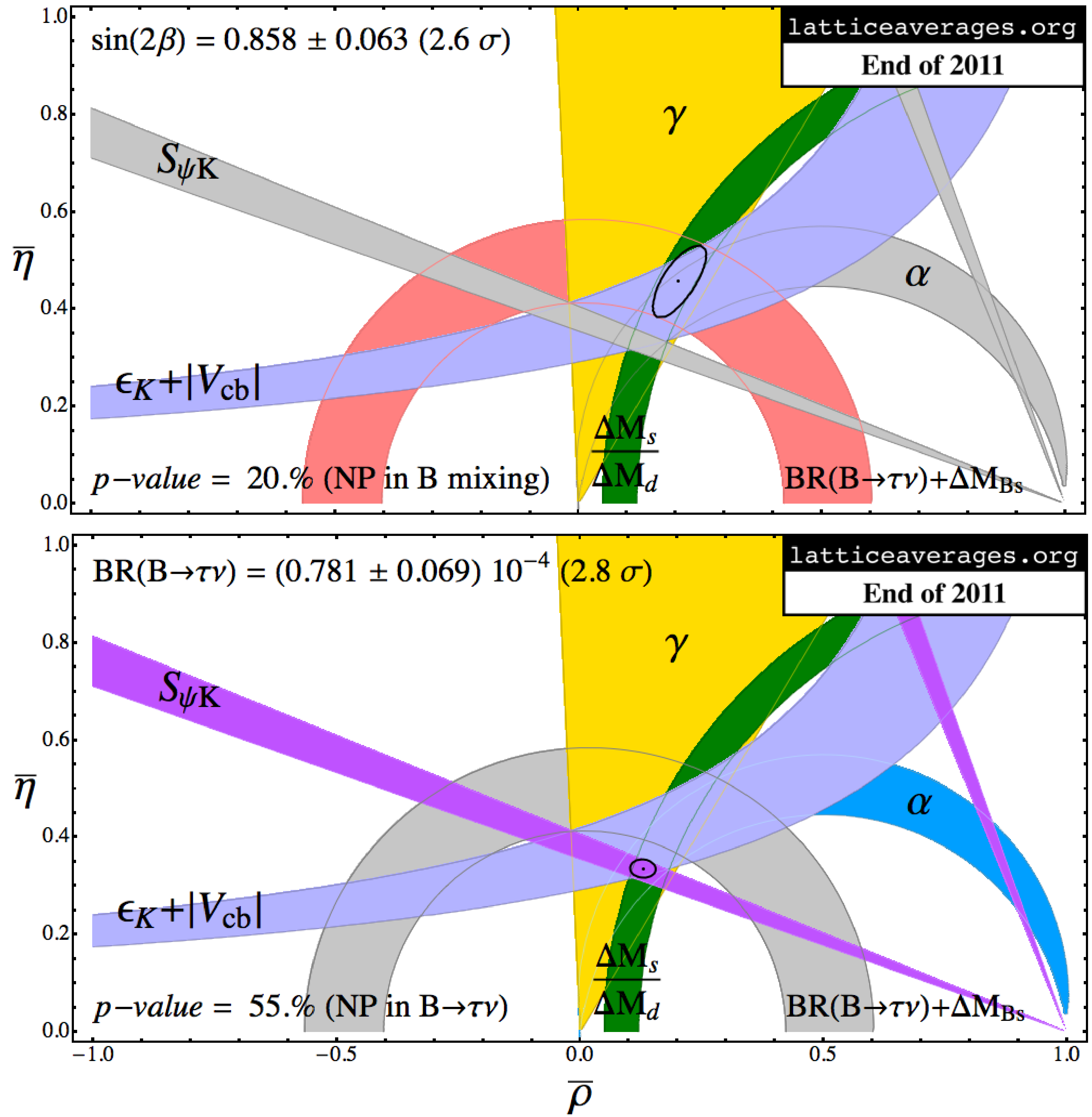


B $\rightarrow \tau \nu$ or sin2ϕ_1

Fit without $|V_{ub}|$ and grayed data
$\rightarrow$ next slide

NP in B_d mixing

NP in $B \rightarrow \tau\nu$



Tension in V_{ub}

- determination
  - inclusive: $B \to X_u \ell \nu$

$$|V_{ub}|_{\rm incl} = (4.27 \pm 0.38) \times 10^{-3}$$

  - exclusive: $B \to \pi \ell \nu$

$$|V_{ub}|_{\rm excl} = (3.12 \pm 0.26) \times 10^{-3}$$

⟶ 2-3σ tension

could be hint of NP in RH current

"Inclusive and exclusive V_{ub} are the most complicated calculations that enter the fits..."
Lunghi, KEK Flavor Factory WS

Table 1: $|V_{ub}|$ (in units of 10^{-5}) from inclusive $\overline{B} \to X_u \ell \overline{\nu}_\ell$ measurements. The first uncertainty on $|V_{ub}|$ is experimental, while the second includes both theoretical and HQE parameter uncertainties. The values are listed in order of increasing f_u (0.19 to 0.90).

Ref.	BLNP	GGOU	DGE
[108]	$383 \pm 45 \pm 33$	$368 \pm 43 \pm 32$	$358 \pm 42 \pm 27$
[111]	$428 \pm 29 \pm 37$	not avail.	$404 \pm 27 \pm 29$
[110]	$418 \pm 24 \pm 30$	$405 \pm 23 \pm 27$	$406 \pm 27 \pm 27$
[109]	$464 \pm 43 \pm 30$	$453 \pm 42 \pm 26$	$456 \pm 42 \pm 26$
[119]	$423 \pm 45 \pm 30$	$414 \pm 44 \pm 34$	$420 \pm 44 \pm 21$
[113]	$432 \pm 28 \pm 30$	$422 \pm 28 \pm 34$	$426 \pm 28 \pm 21$
[113]	$365 \pm 24 \pm 26$	$343 \pm 22 \pm 28$	$370 \pm 24 \pm 28$
[113]	$402 \pm 19 \pm 28$	$398 \pm 19 \pm 27$	$423 \pm 20 \pm 19$
[115]	$436 \pm 26 \pm 22$	$441 \pm 26 \pm 13$	$446 \pm 26 \pm 16$
	$420 \pm 16 \pm 23$	$427 \pm 16 \pm 18$	$433 \pm 15 \pm 17$

[PDG]

Tension in V_{ub}

- determination
  - inclusive: $B \to X_u \ell \nu$

$$|V_{ub}|_{\text{incl}} = (4.27 \pm 0.38) \times 10^{-3}$$

  - exclusive: $B \to \pi \ell$

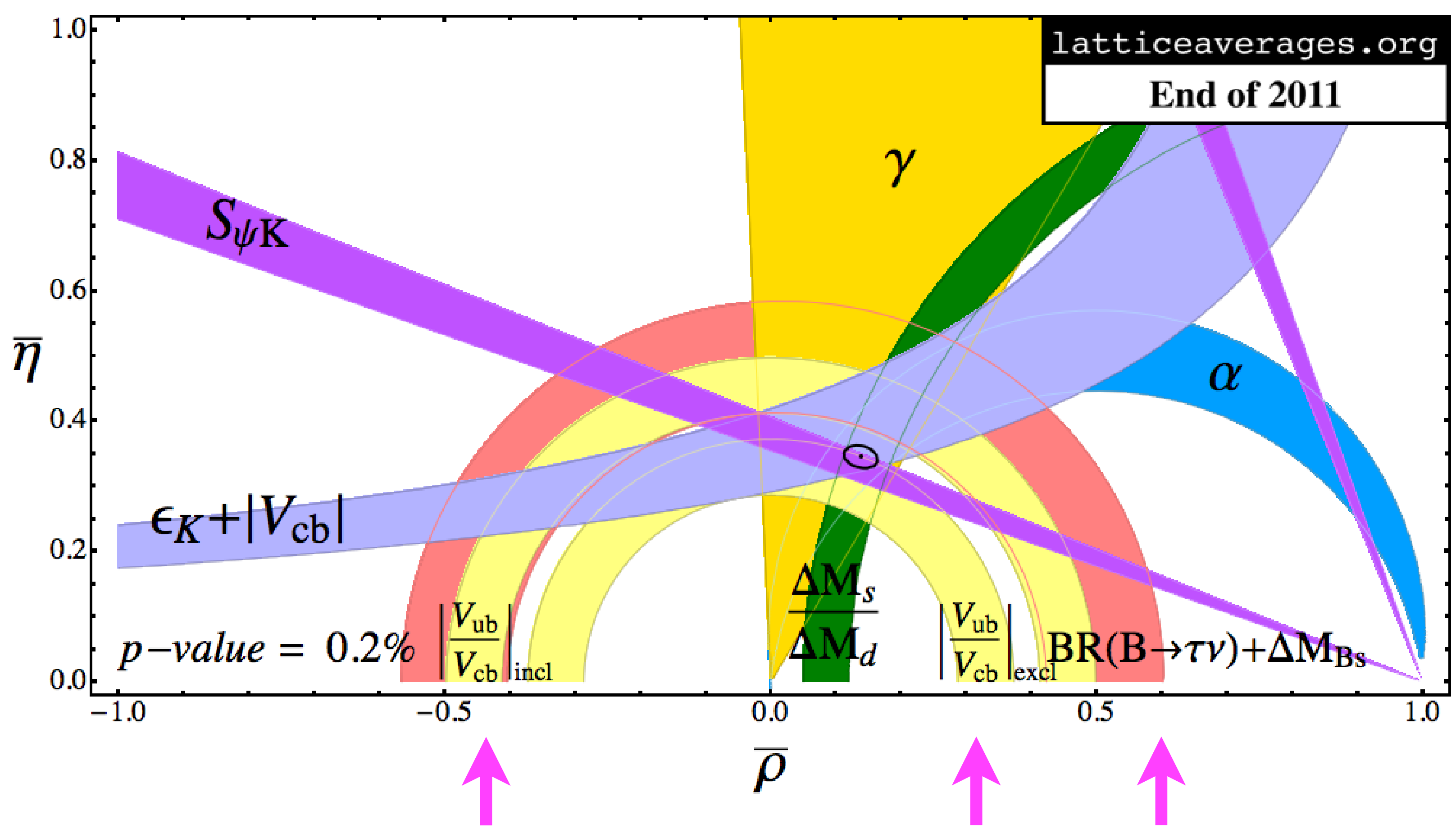
$$|V_{ub}|_{\text{excl}} = (3.12 \pm 0.26$$

⟶ 2-3σ tension

could be hint of NP in R

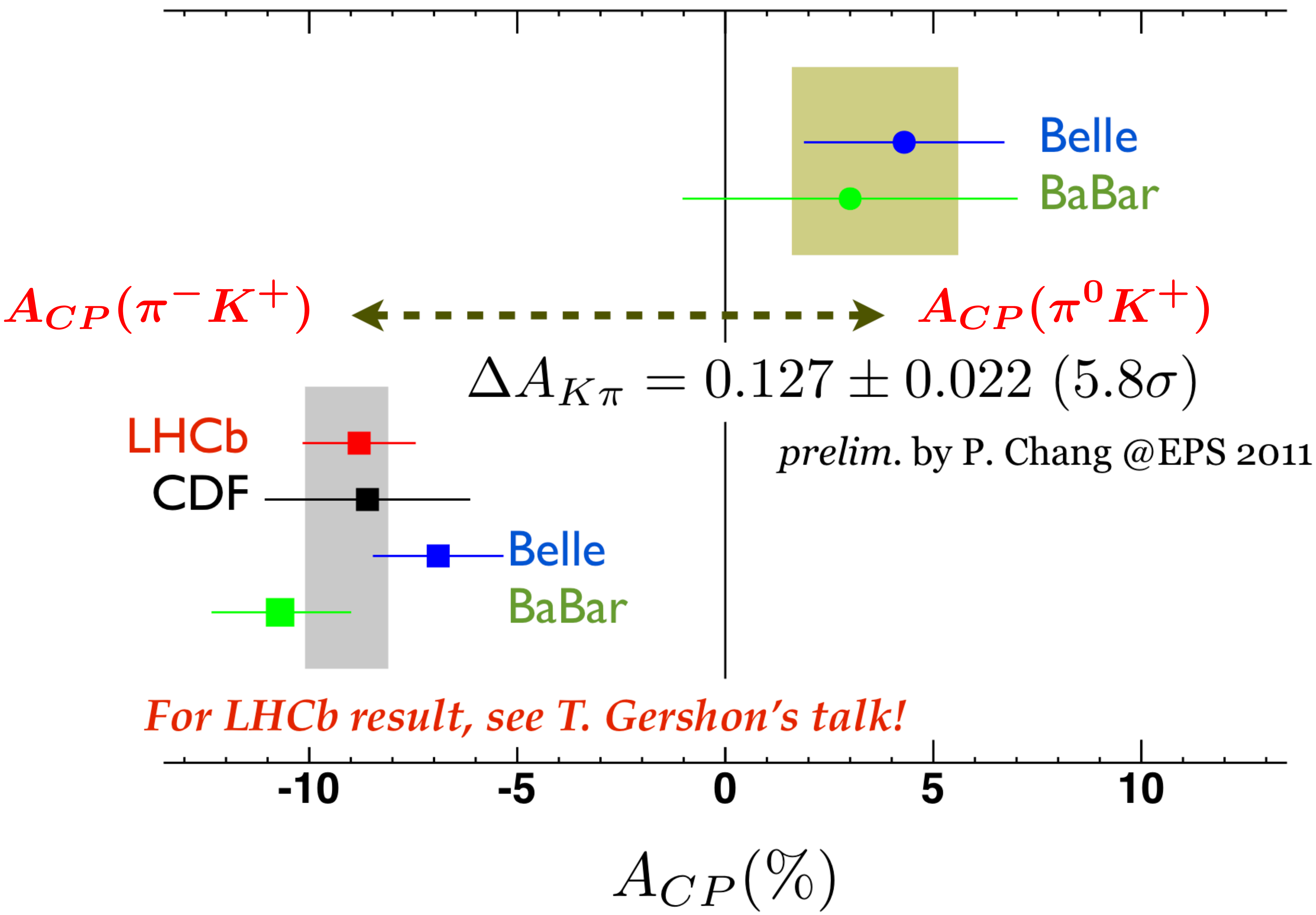
Table 1: $|V_{ub}|$ (in units of 10^{-5}) from inclusive $\overline{B} \to X_u \ell \overline{\nu}_\ell$ measurements. The first uncertainty on $|V_{ub}|$ is experimental, while the second includes both theoretical and HQE parameter uncertainties. The values are listed in order of increasing f_u (0.19 to 0.90).

Ref.	BLNP	GGOU	DGE



"Inclusive and exclusive V_{ub} are
complicated calculations that en
Lunghi, KEK Flavor

ACP of B → Kπ



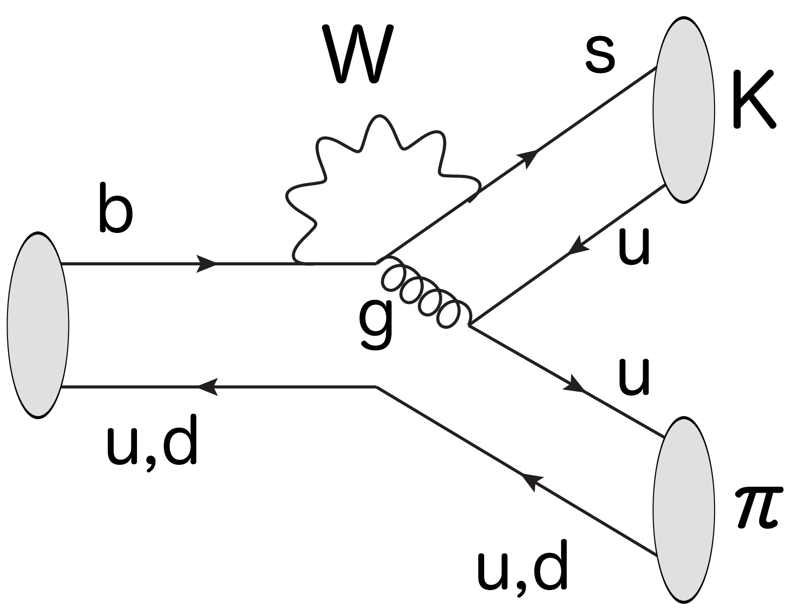
SM prediction ≃0
[≳ 2σ including hadronic err.]

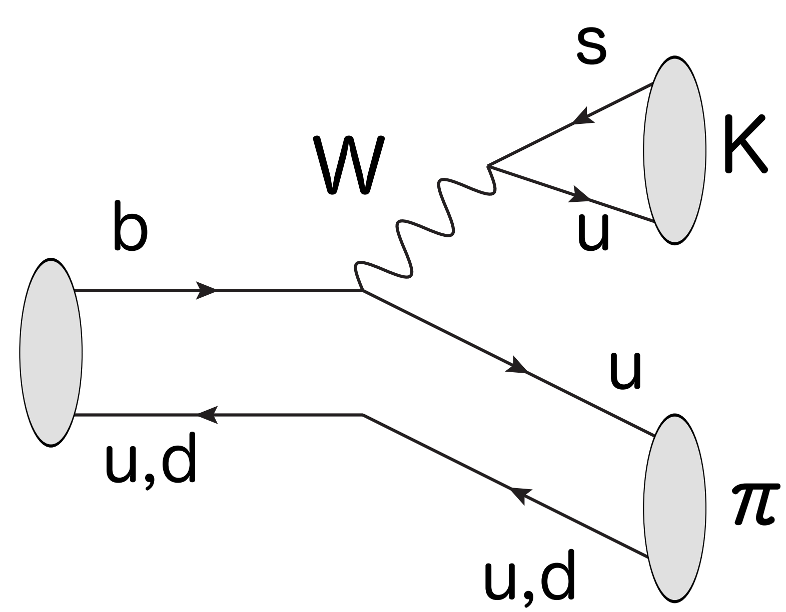
"Kπ puzzle"

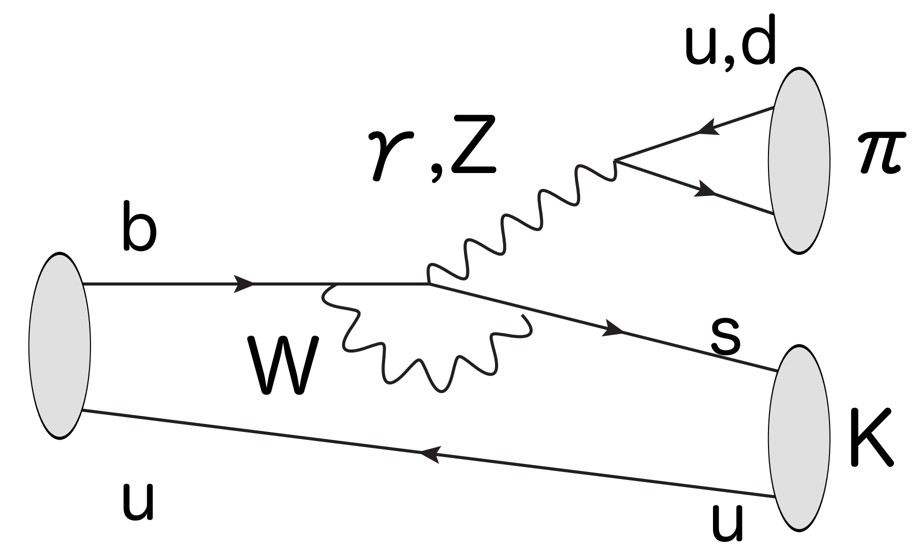
Figure from slide by Kwon at LP2011

A_{CP} of $B \to K\pi$

[Standard Model]



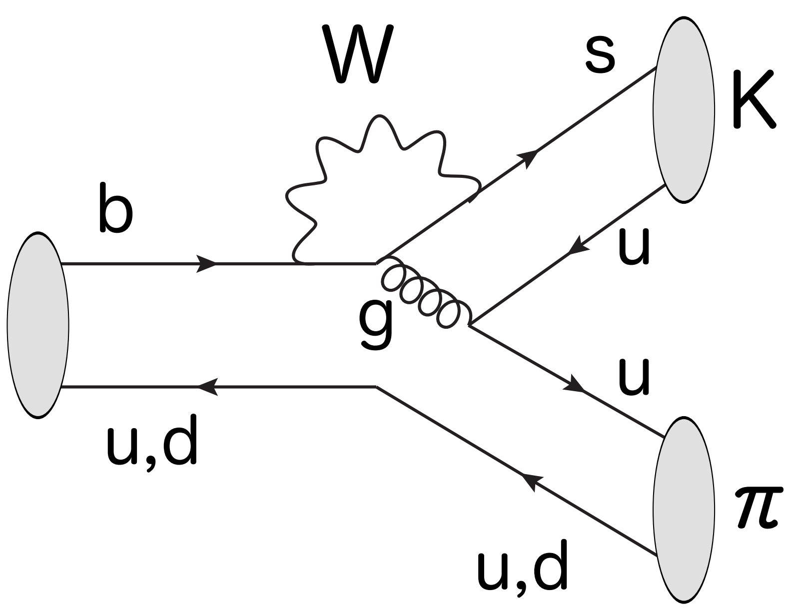


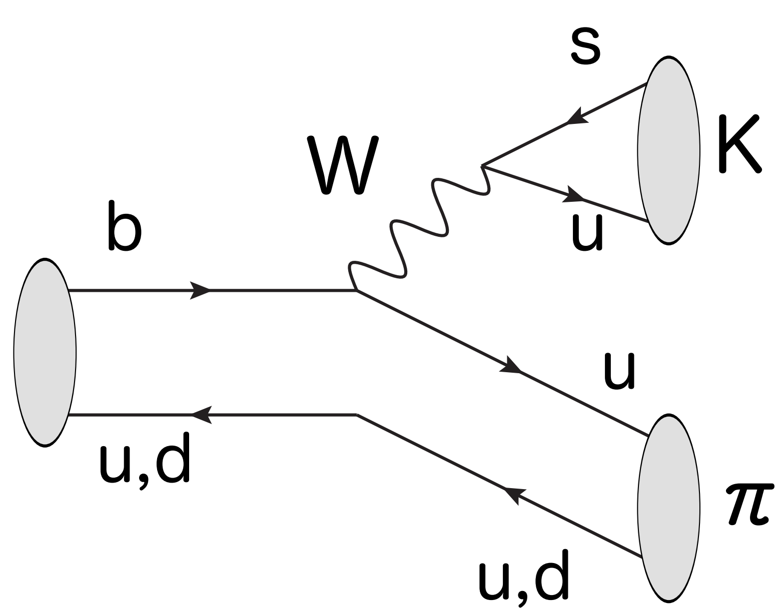


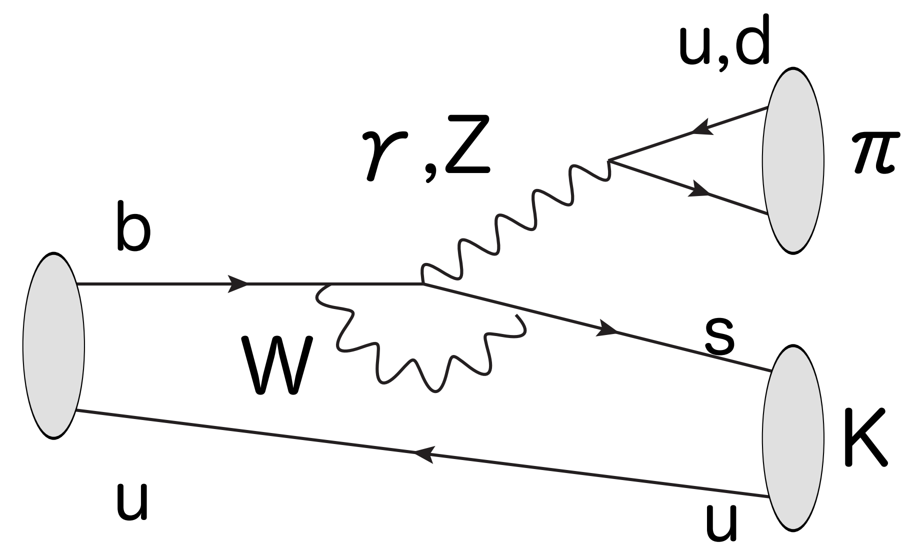
	Penguin(P)	Tree(T)	EW Penguin(P_{ew})
size	1	~0.1	~0.1
CP	-	$\exp(i\varphi_3)$	-
	main	← subdominant →	

A_{CP} of $B \to K\pi$

[Standard Model]





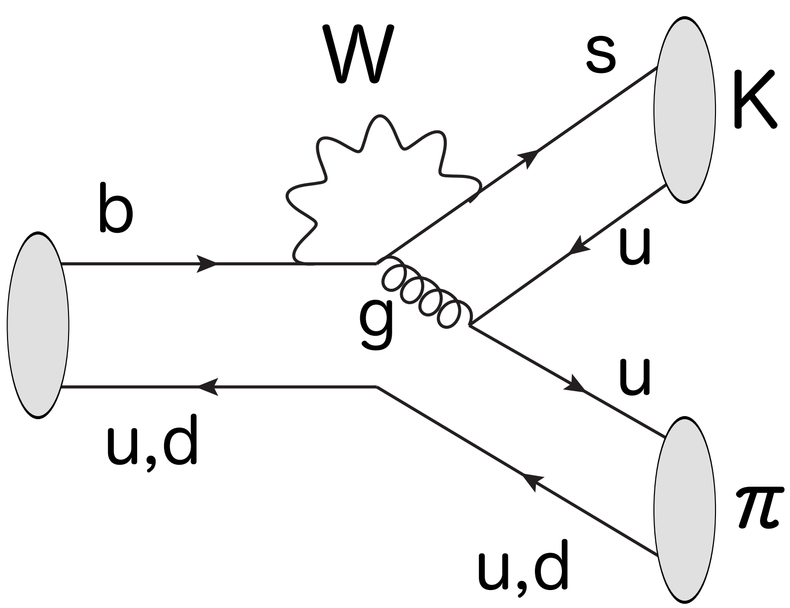


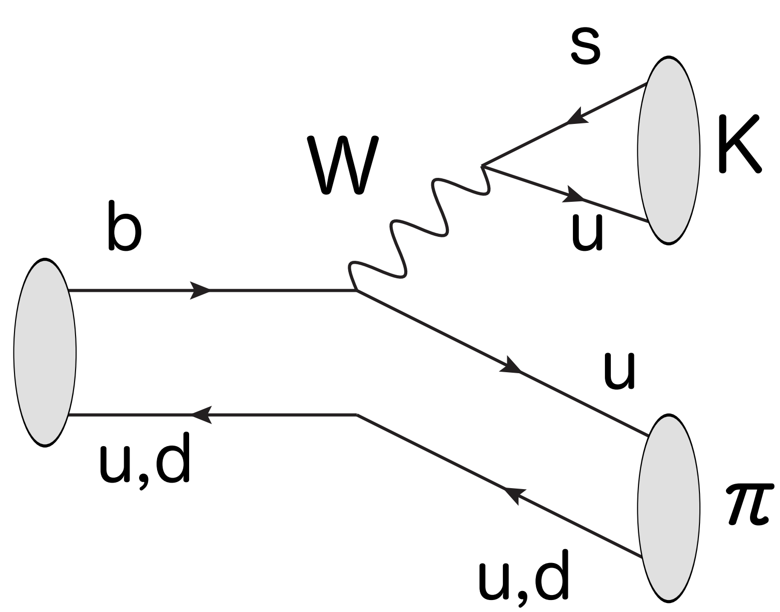
	Penguin(P)	Tree(T)	EW Penguin(P_{ew})
size	1	~0.1	~0.1
CP	-	$\exp(i\varphi_3)$	-

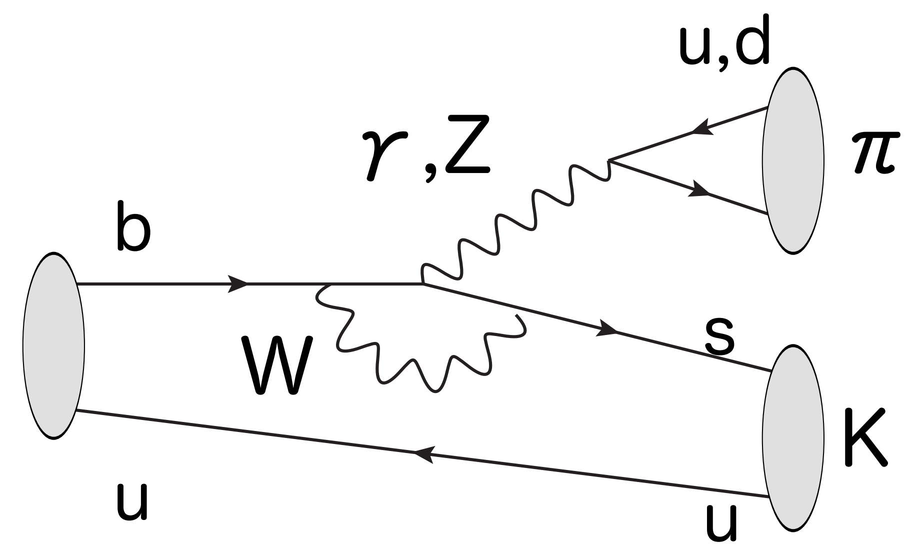
isospin breaking

A_{CP} of $B \rightarrow K\pi$

[Standard Model]





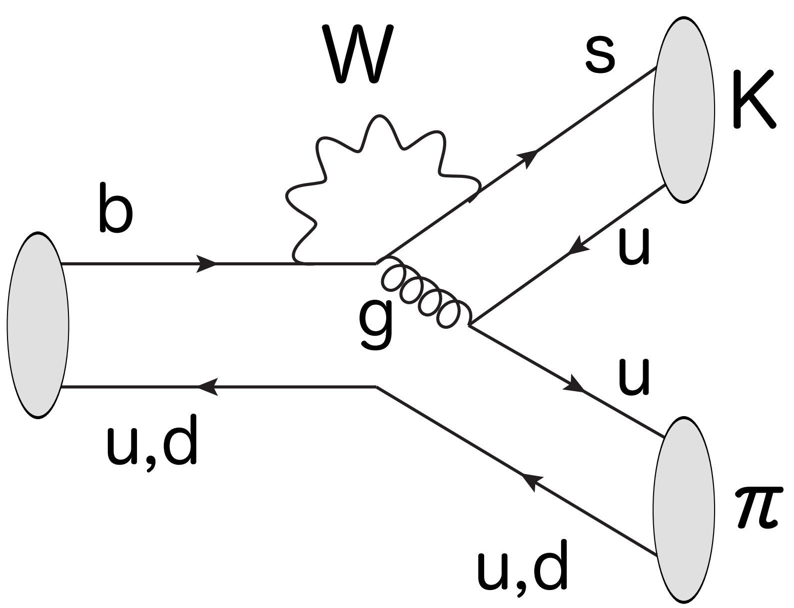


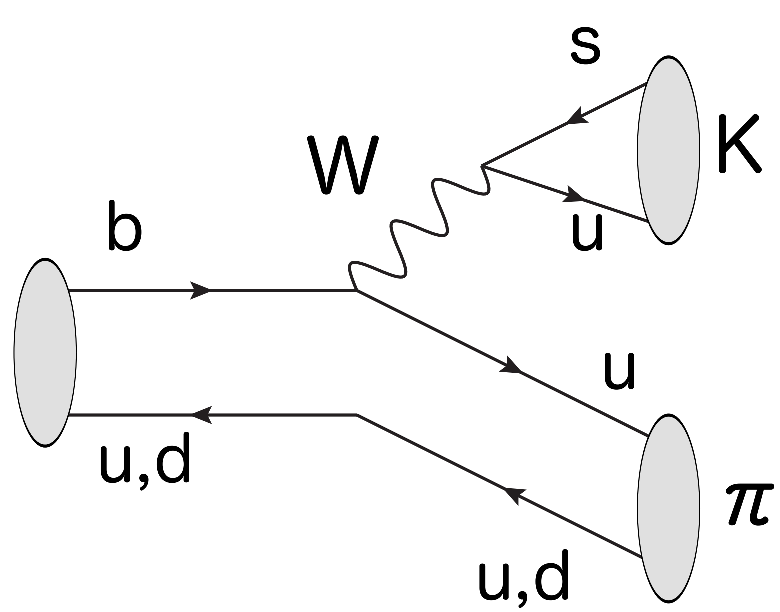
	Penguin(P)	Tree(T)	EW Penguin(P_{ew})
size	1	~0.1	~0.1
CP	-	exp($i\varphi_3$)	-

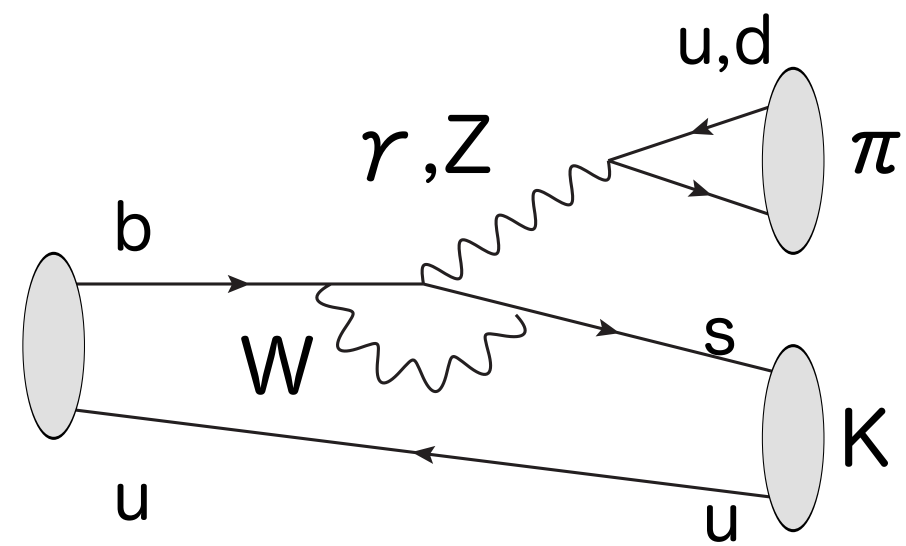
CP violation (common)

A_{CP} of $B \to K\pi$

[Standard Model]







	Penguin(P)	Tree(T)	EW Penguin(P_{ew})
size	1	~0.1	~0.1
CP	-	$\exp(i\varphi_3)$	-

small!!

difference of CP violation

A_{CP} of $B \to K\pi$

Topological decomposition

$$A(K^+\pi^-) = -P' - T' e^{i\phi_3}$$

$$\sqrt{2}\,A(K^+\pi^0) = -(P' + P'_{\rm ew}) - (T' + C')e^{i\phi_3}$$

Naive estimation

$$P' > T', P'_{\rm ew} > C' \quad [1 : O(10^{-1}) : O(10^{-2})]$$

$$\Delta A_{\rm CP} \simeq 2|P'_{\rm ew}/P'|\,|T'/P'|\sin(\delta_T + \delta_{\rm ew})\sin\phi_3 - 2|C'/P'|\sin\delta_C \sin\phi_3 \qquad (\ll 0.1)$$

Implications

larger C' with strong phase or larger P'_{ew} with large CP phase

A_{CP} of $B \to K\pi$

Color-suppressed Tree (C')

C' is sensitive to subleading corrections (c.f. pQCD)

$Br(B\to\pi^0\pi^0)$ imply larger C, though $Br(B\to\rho^0\rho^0)$ is consistent

Sum rule: RHS ≃ 0 cf. $A_{CP}^{+-} \equiv A_{CP}(B \to K^+\pi^-)$

$$-A_{\rm CP}^{0+} + \boxed{A_{\rm CP}^{00}} + \boxed{A_{\rm CP}^{+0} - A_{\rm CP}^{+-}} \simeq \underline{2|P'_{\rm ew}/P'|\,|T'/P'|\sin(\delta_T+\delta_{\rm ew})\sin\phi_3}$$

~0 C' C', P_{ew}' ~0.1 (exp) ~O(10^{-2}) [SM]

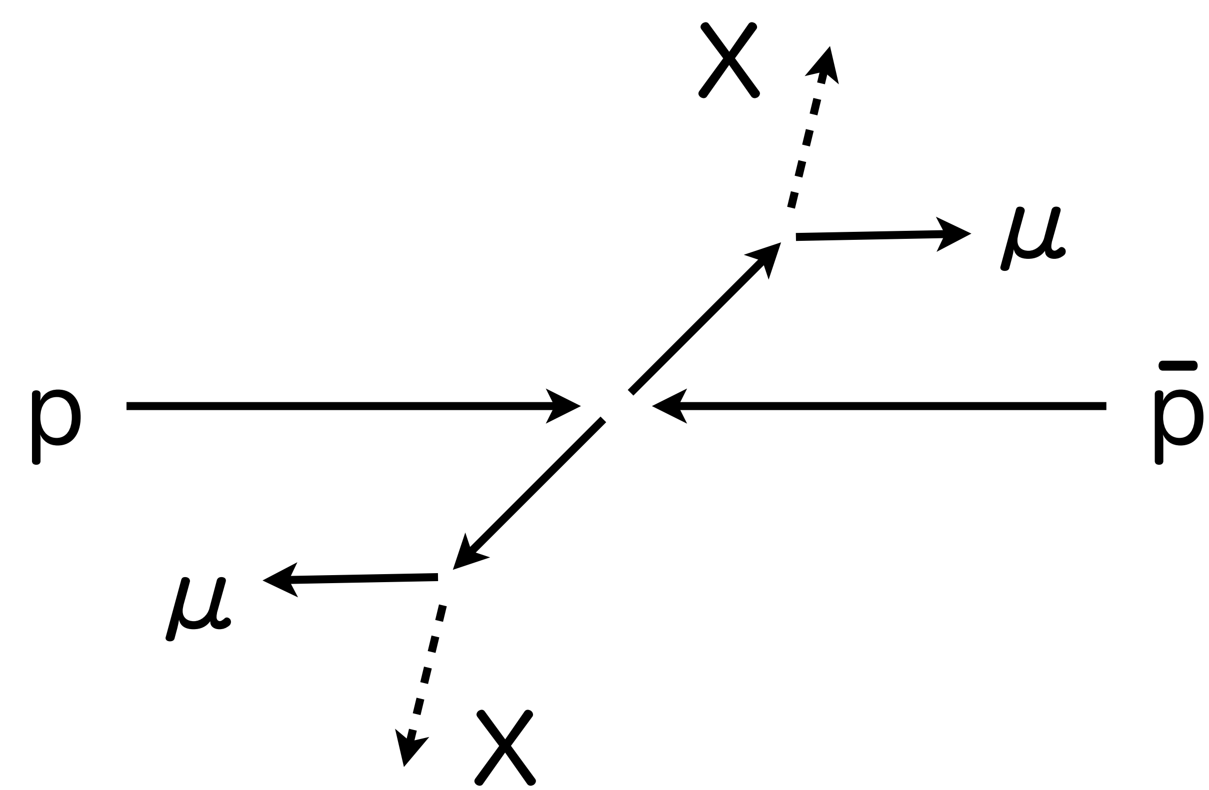
If C' (P_{ew}) is larger, sum rule is satisfied (violated)

$S_{CP}(B\to K^0\pi^0)$も面白い [see Fleischer,Jager,Pirjol,Zupan]

like-sign dimuon charge asymmetry

- $p\bar{p} \rightarrow \mu\mu XX$ event
- $\mu^+\mu^+$と$\mu^-\mu^-$の非対称性

$$A^b_{sl} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$



- SMではB_q-$\bar{B}_q$ mixingによりeventが生じる
- AsymmetryはCPの破れ

$B_q \rightarrow \mu^+ X$, $\bar{B}_q \rightarrow B_q \rightarrow \mu^+ X$

$$A^b_{sl} \simeq 0.5 a^d_{sl} + 0.5 a^s_{sl}$$

$$a^q_{sl} = \frac{\Gamma(\bar{B}^0_q(t) \rightarrow \mu^+ X) - \Gamma(\bar{B}^0_q(t) \rightarrow \mu^- X)}{\Gamma(\bar{B}^0_q(t) \rightarrow \mu^+ X) + \Gamma(\bar{B}^0_q(t) \rightarrow \mu^- X)}$$

like-sign dimuon charge asymmetry

- $p\bar{p} \rightarrow \mu\mu XX$ event
- $\mu^+\mu^+$と$\mu^-\mu^-$の非対称性

$$A^b_{sl} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

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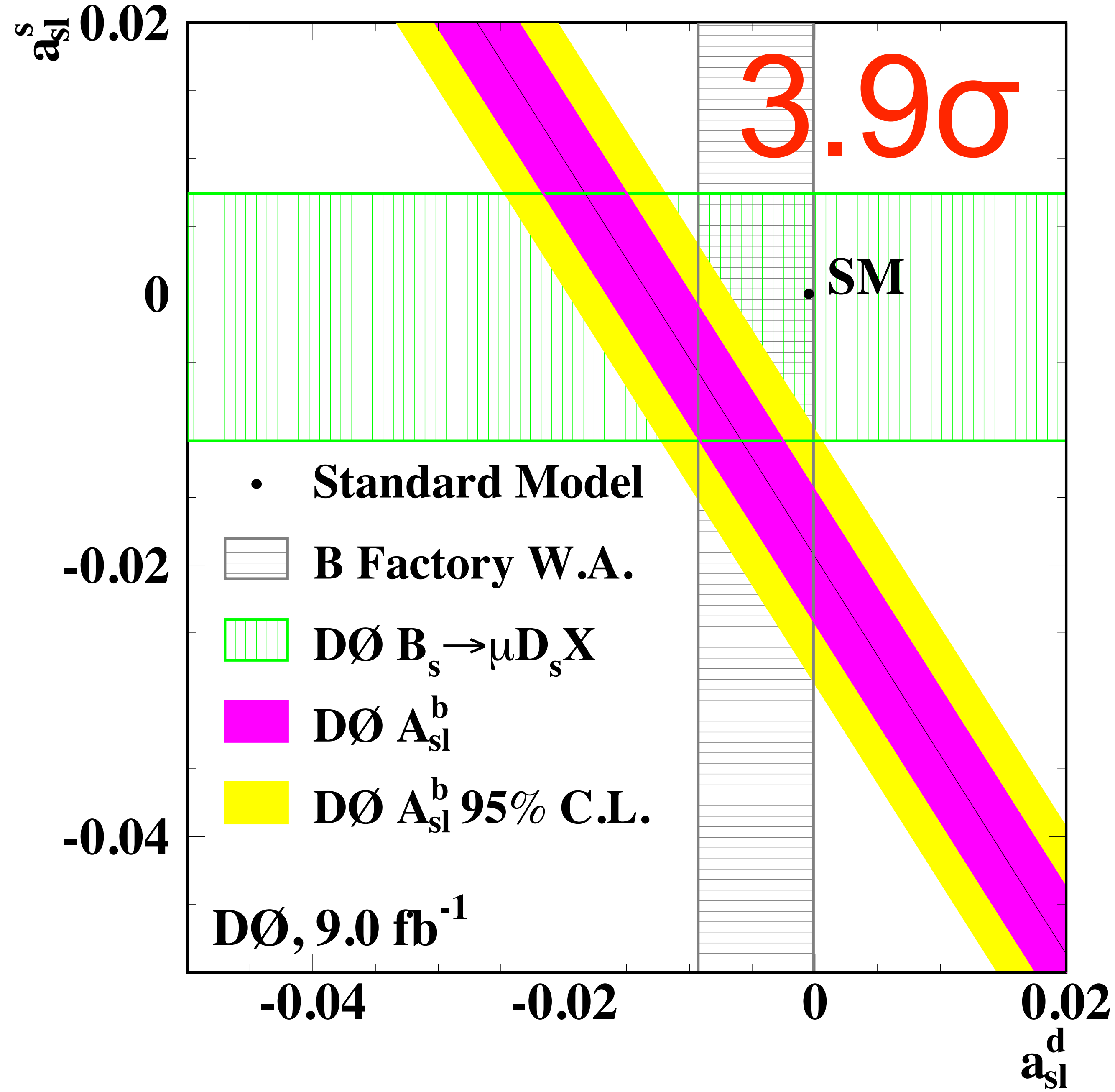
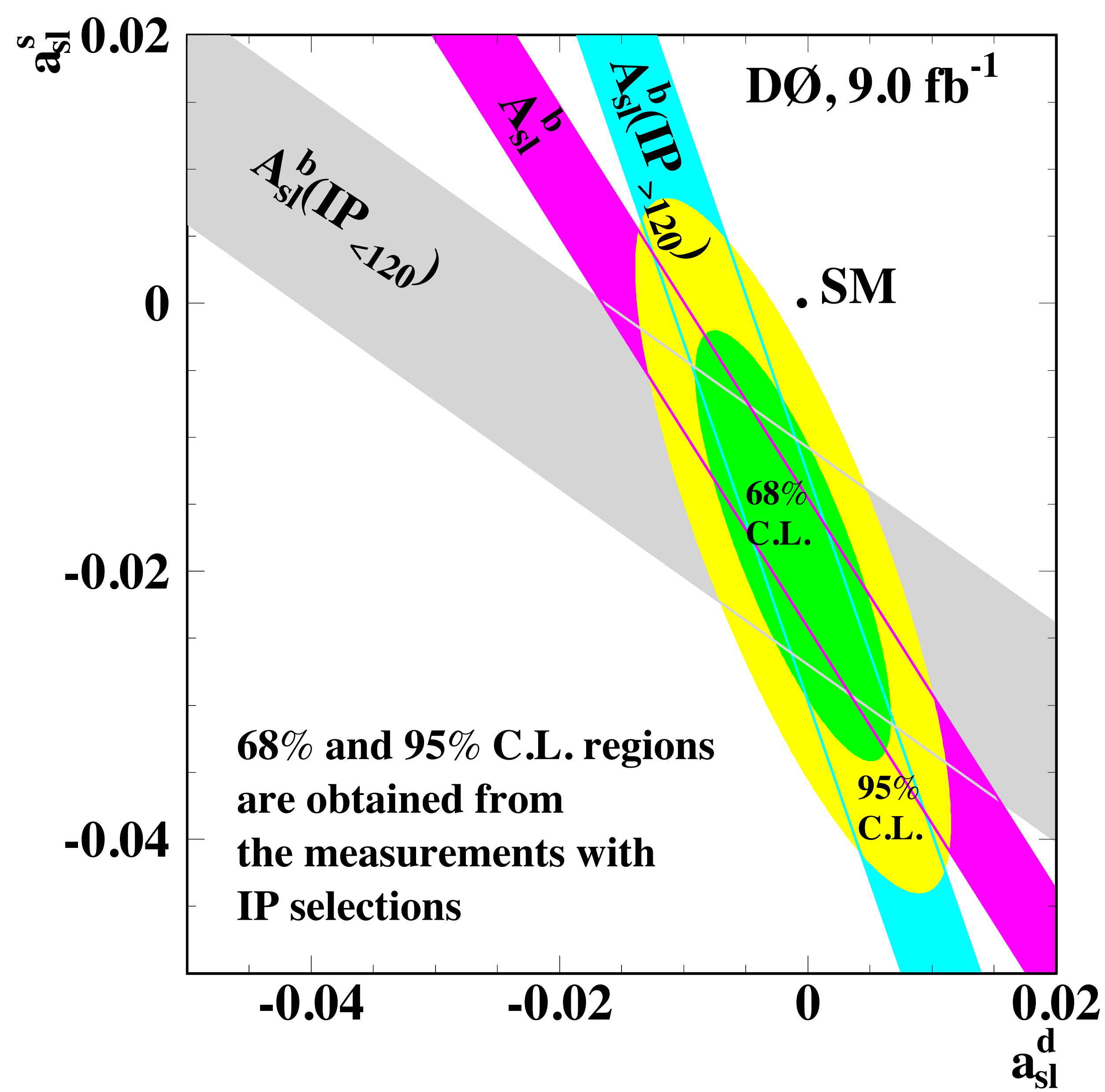


like-sign dimuon charge asymmetry

・B_dとB_sでmuonのimpact parameter分布が異なる
(振動周期の違いを利用)

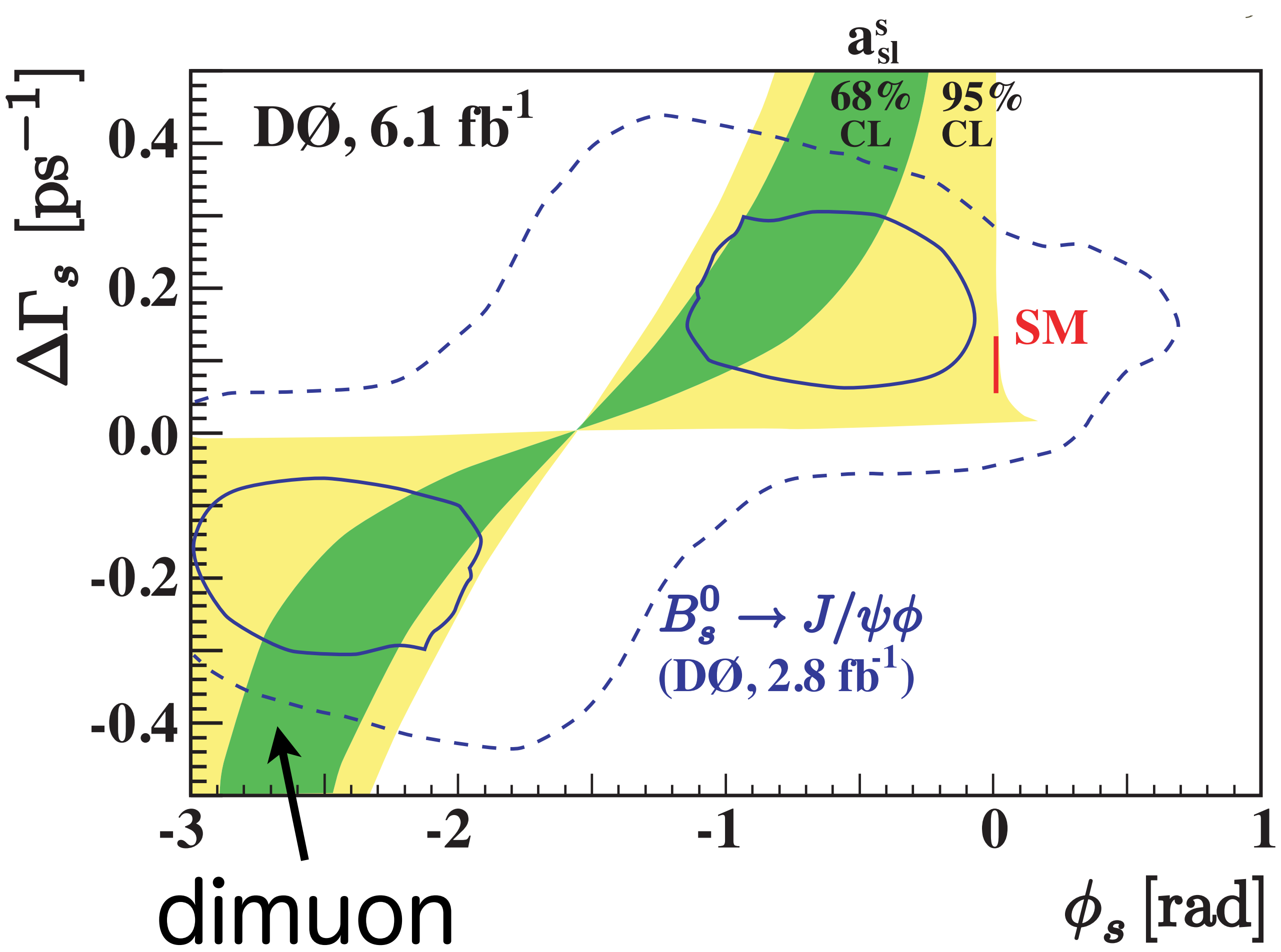
・impact parameter毎にdimuon eventをfit

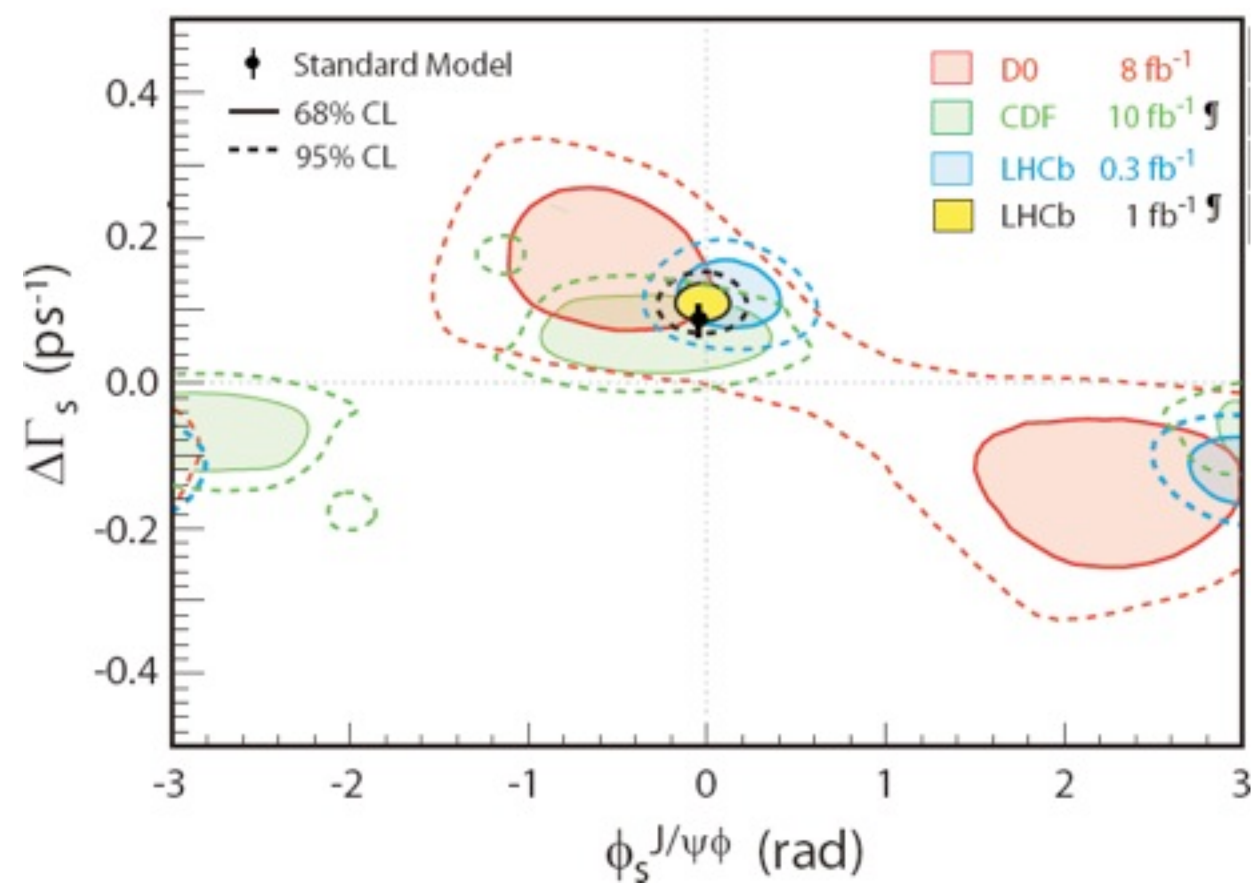
・B_sの方にSMからのずれの傾向がある



Status of B_s mixing

B_s mixingのCPの破れは$B_s \to J/\psi\,\phi$にも寄与する



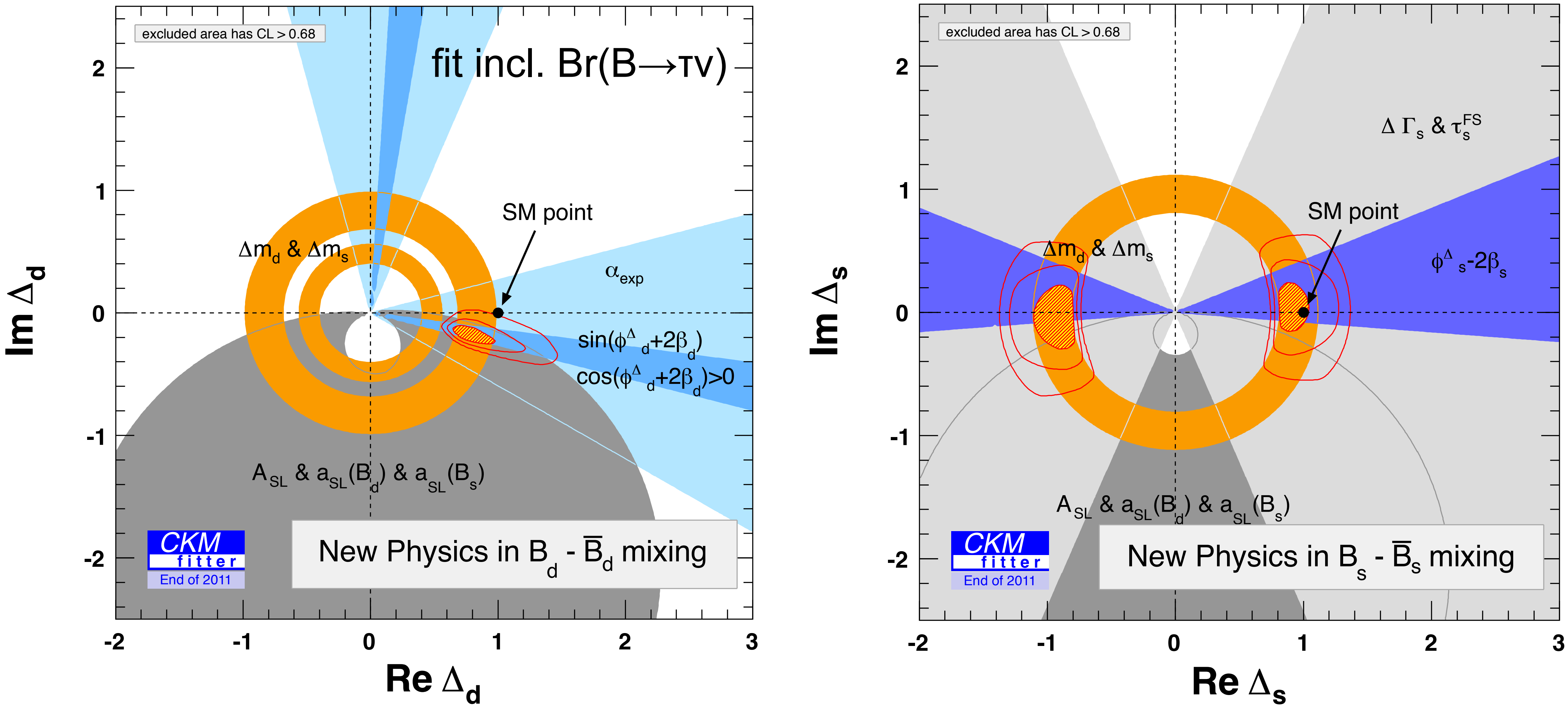


LHCb indicates SM --- tight bounds on mixing!

Global fit of B_d and B_s

Not include results of Moriond 2012

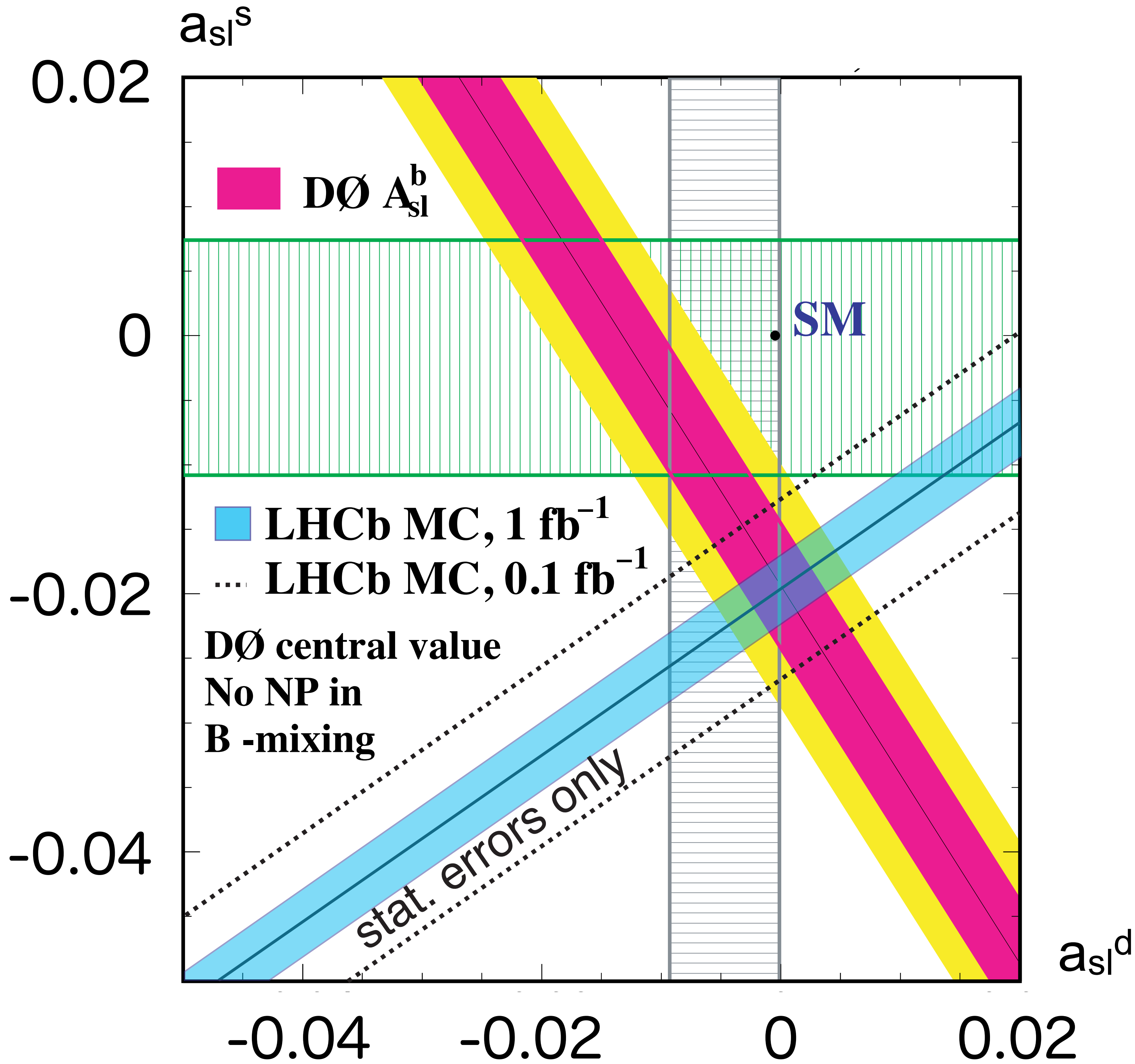
see 1008.1593 for details



$$\Delta_q \equiv \frac{M_{12}^q}{M_{12}^q(\mathrm{SM})}$$

color:1σ

LHCb

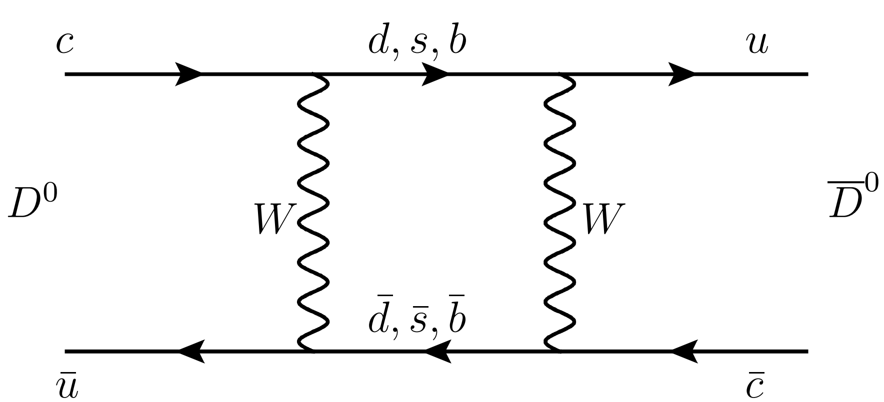


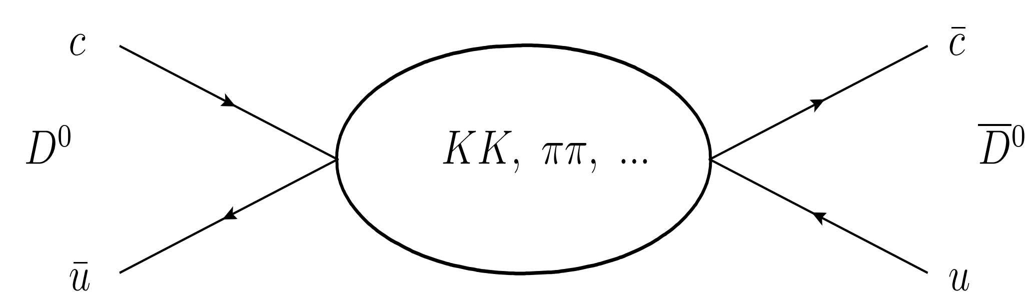
a_{sl}^s
0.02
0
-0.02
-0.04
DØ A_{sl}^b
SM
LHCb MC, 1 fb^{-1}
LHCb MC, 0.1 fb^{-1}
DØ central value
No NP in
B -mixing
stat. errors only
a_{sl}^d
-0.04
-0.02
0
0.02

Charm CP Violation

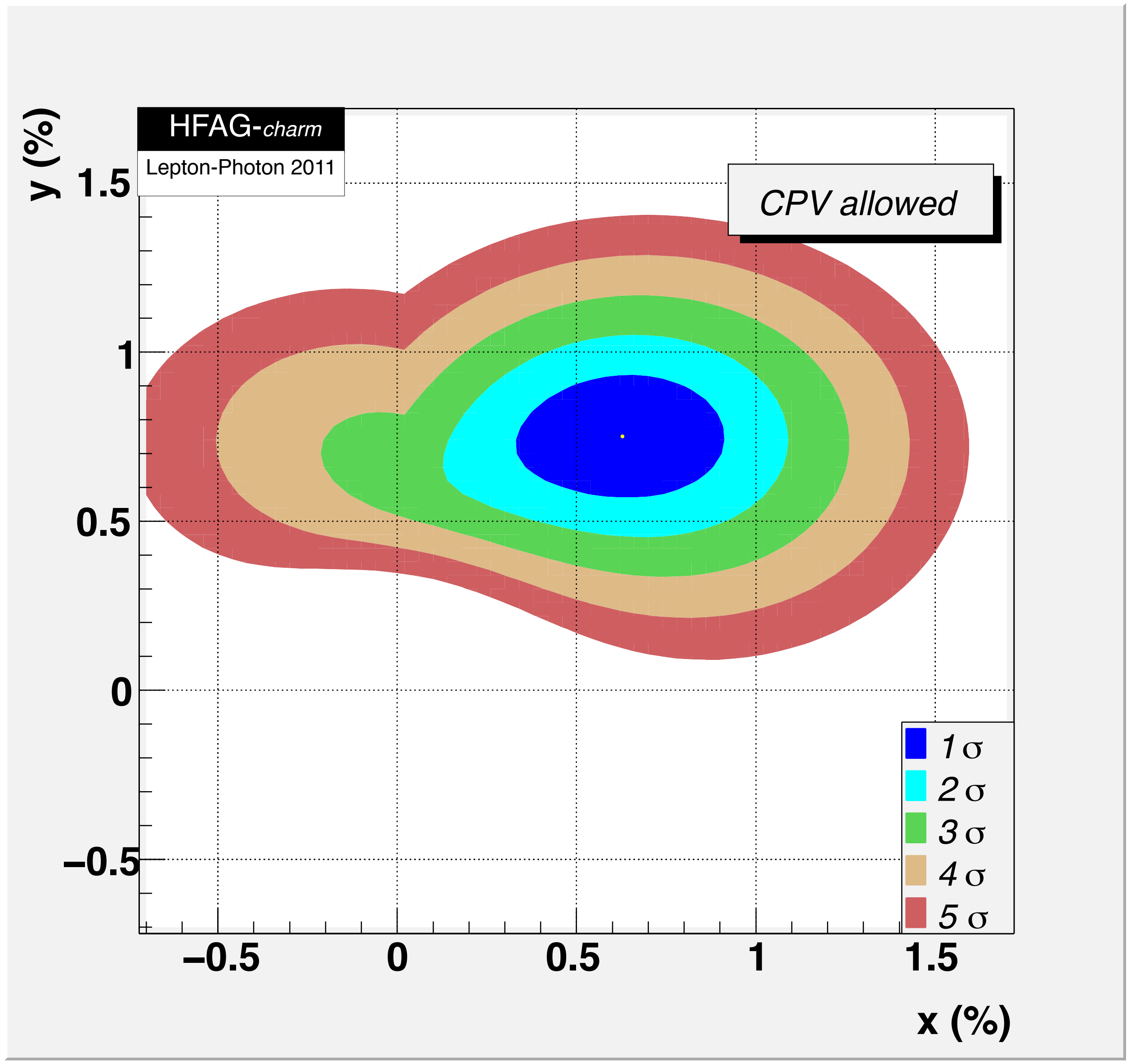
CP violation

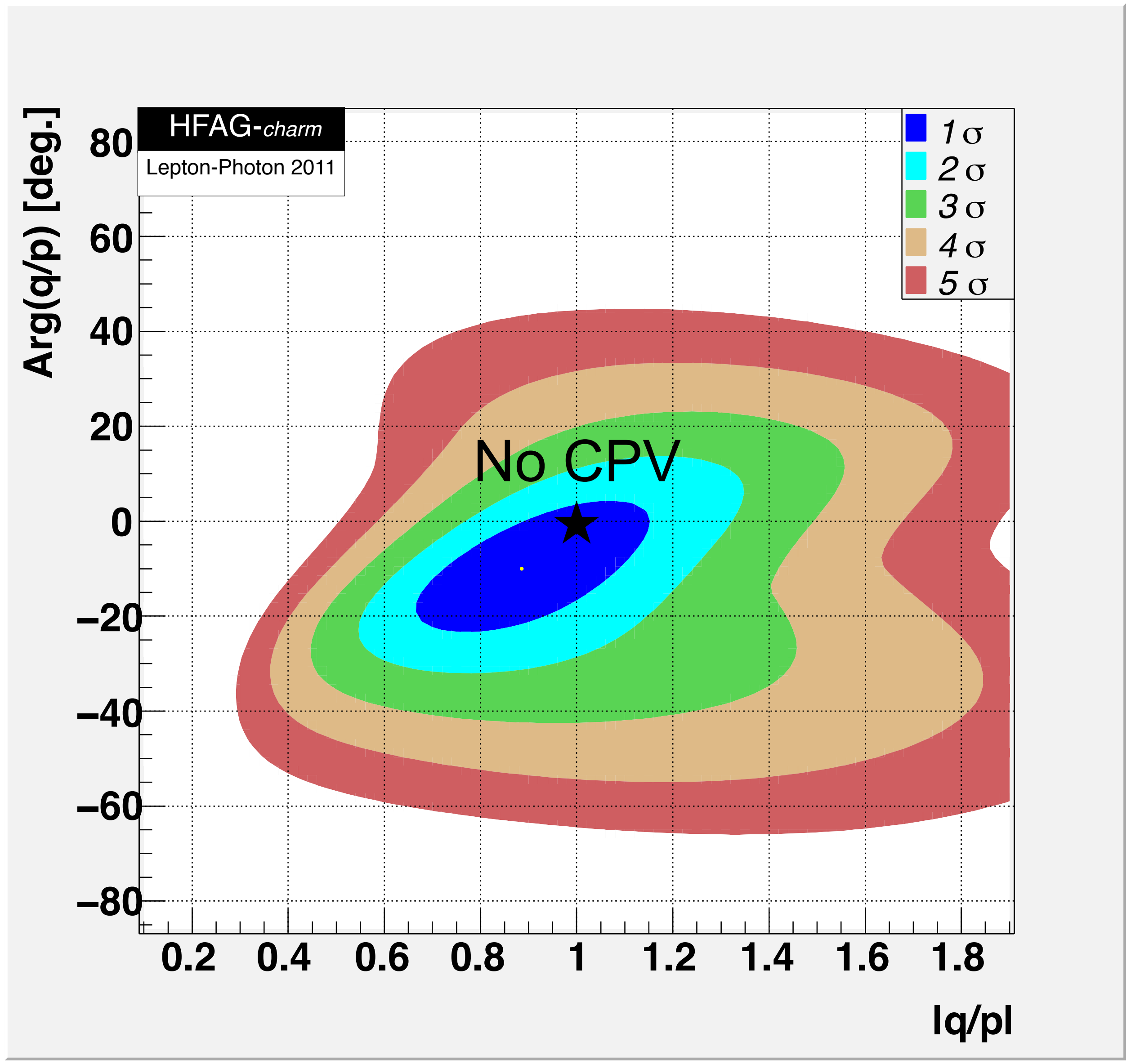
- charm CP is approximately conserved because of the dominance of the first two generations
  - direct and indirect CPV are expected to be tiny
  - large CP violation is a sign of new physics
- D meson mixing and indirect CP violation
  - oscillation is measured (10σ), but no CP violation
  - long-distance contributions dominate mixing





D meson Oscillation





$$x = \Delta m_D / \Gamma_D \quad y = \Delta\Gamma_D / 2\Gamma_D$$

Direct CP Violation

- time-integrated CP asymmetryの測定

  "A_{CP}" = (CPV in decay) + (CPV in mixing)

- mixingによるCPの破れの大きさが制限されている
- 大きなCPの破れはdirect CP violationのはず

$$\Delta A_{\mathrm{CP}} \equiv A_{\mathrm{CP}}(K^+K^-) - A_{\mathrm{CP}}(\pi^+\pi^-)$$
$$= (-0.67 \pm 0.16)\%$$

~4 σ from zero

LHCb, CDF

Direct CP Violation

- LHCb

$$\Delta A_{\mathrm{CP}} = (-0.82 \pm 0.21 \pm 0.11)\%$$

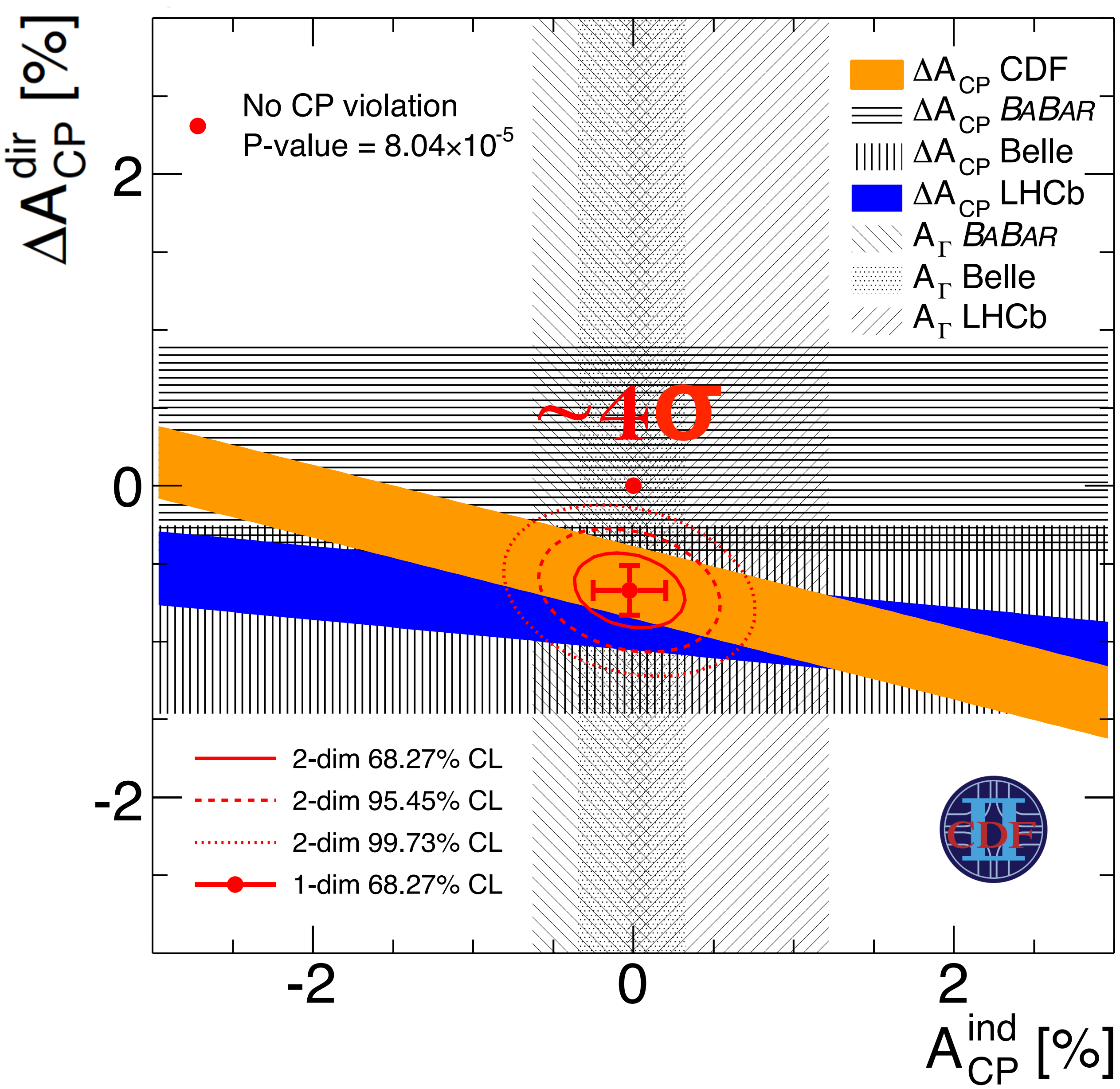
- CDF

$$\Delta A_{\mathrm{CP}} = (-0.62 \pm 0.21 \pm 0.10)\%$$

- world average

$$\Delta A_{\mathrm{CP}}^{\mathrm{dir}} = (-0.67 \pm 0.16)\%$$

~4σ from zero



SM Prediction

- CP violation in singly Cabibbo-suppressed decay is expected to be small

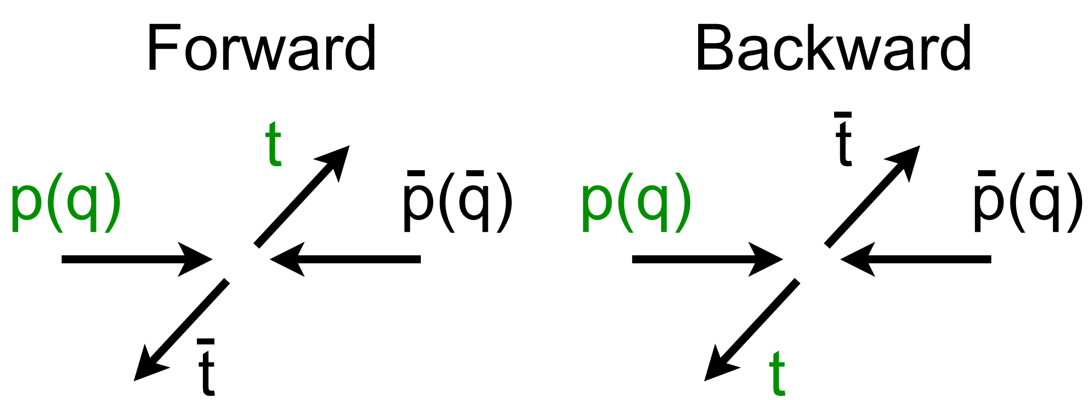
SCS CPV: $\mathcal{O}\left(\mathrm{Im}\left[\frac{V_{cb}^{*}V_{ub}}{V_{cd}^{*}V_{ud}}\right]\frac{\alpha_s}{\pi}\right) \sim 0.01\%$

- conventional method is not reliable
  - long-distance effects dominate in mixing
  - branching ratios are not explained by B method
  - $1/m_c$ expansion breaks down because $m_D \simeq \Lambda_{QCD}$
- approach
  - fit topological amplitudes based on $SU(3)_F$/isospin
  - large uncertainty in CPV (b-penguin) [O(0.1)%?]

Top FB Asymmetry
Top Charge Asymmetry

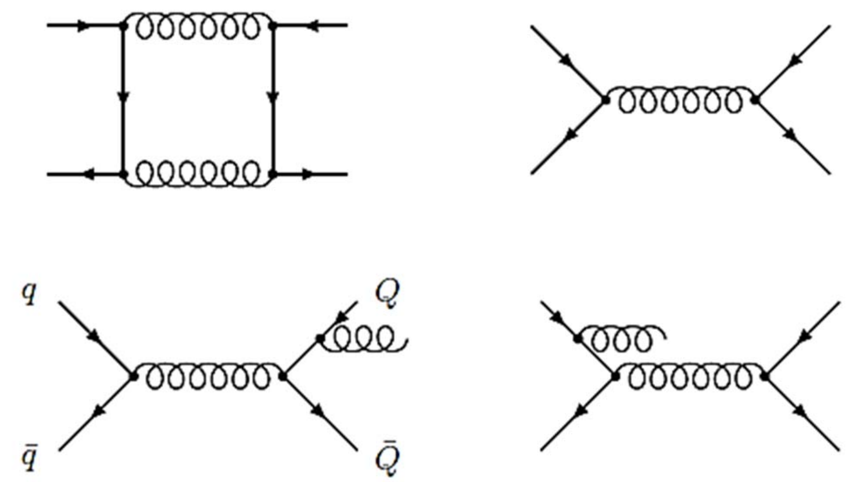
SM Prediction

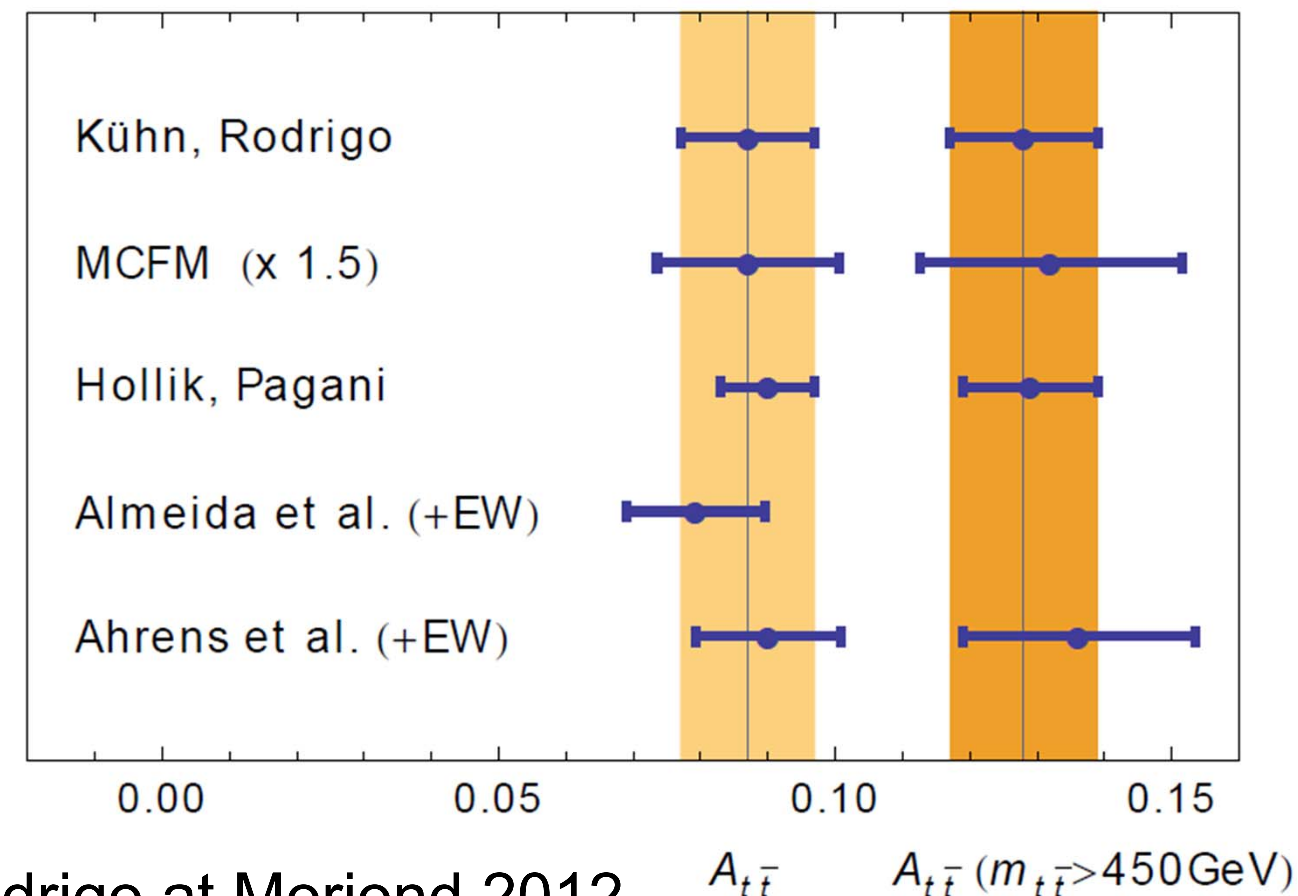
- No FB/charge asymmetry at leading order in QCD



$$A_{t\bar{t}} = \frac{N(y_t > y_{\bar{t}}) - N(y_t < y_{\bar{t}})}{N(y_t > y_{\bar{t}}) + N(y_t < y_{\bar{t}})}$$

- asymmetry arises at NLO
- top quarks are preferentially emitted “forward”





Figures from slide by Rodrigo at Moriond 2012

Tevatron Results

- lepton + jet mode of top-anti-top decay
- $\gtrsim 2\sigma$ excess for inclusive data
- excess tends to be enhanced in large M_{tt} and Δy

parton/production level asymmetry in % (except for green)

Preliminary

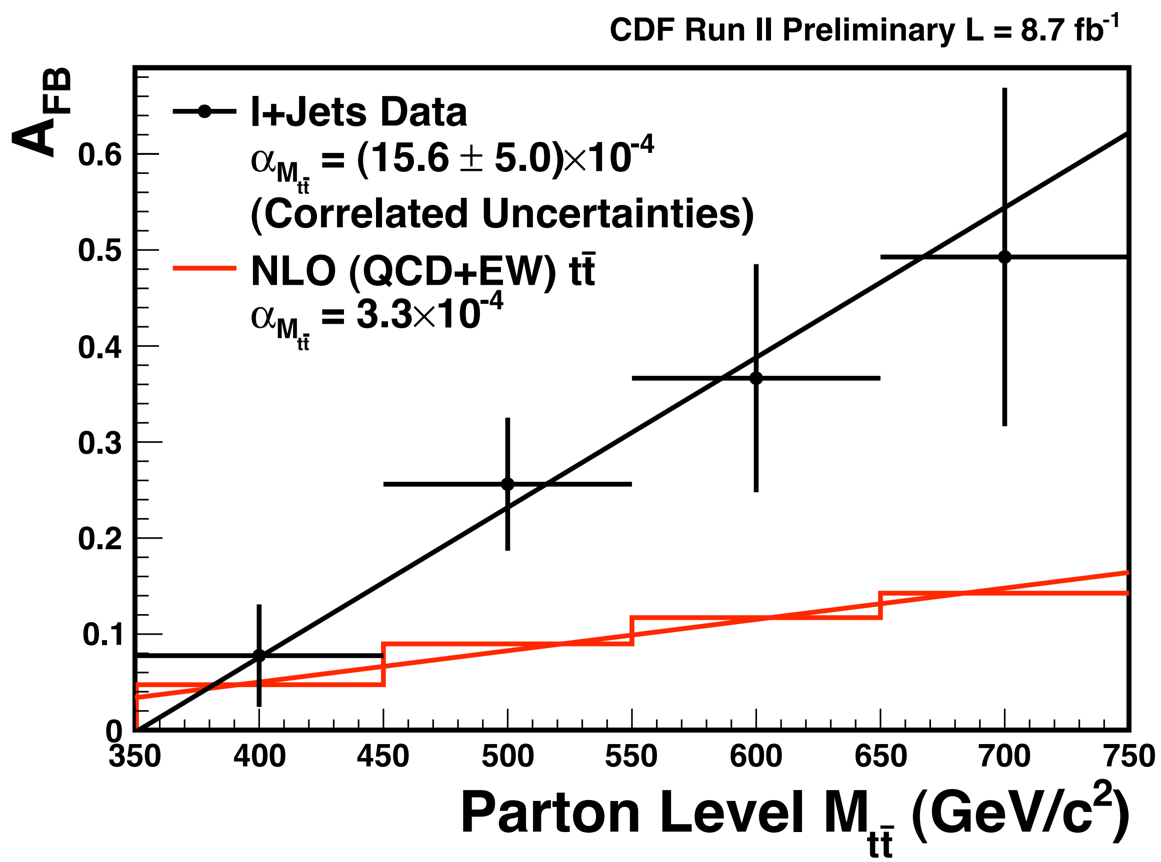
Selection	NLO (QCD+EW)	CDF, 5.3 fb^{-1}	D0, 5.4 fb^{-1}	CDF, 8.7 fb-1
Inclusive	6.6	15.8 ± 7.4	19.6 ± 6.5	16.2 ± 4.7
M_{tt} < 450 GeV/c^2	4.7	−11.6 ± 15.3	7.8 ± 4.8 (Bkg. Subtracted)	7.8 ± 5.4
M_{tt} ≥ 450 GeV/c^2	10.0	47.5 ± 11.2	11.5 ± 6.0 (Bkg. Subtracted)	29.6 ± 6.7
$\|\Delta y\|$ < 1.0	4.3	2.6 ± 11.8	6.1 ± 4.1 (Bkg. Subtracted)	8.8 ± 4.7
$\|\Delta y\|$ ≥ 1.0	13.9	61.1 ± 25.6	21.3 ± 9.7 (Bkg. Subtracted)	43.3 ± 10.9

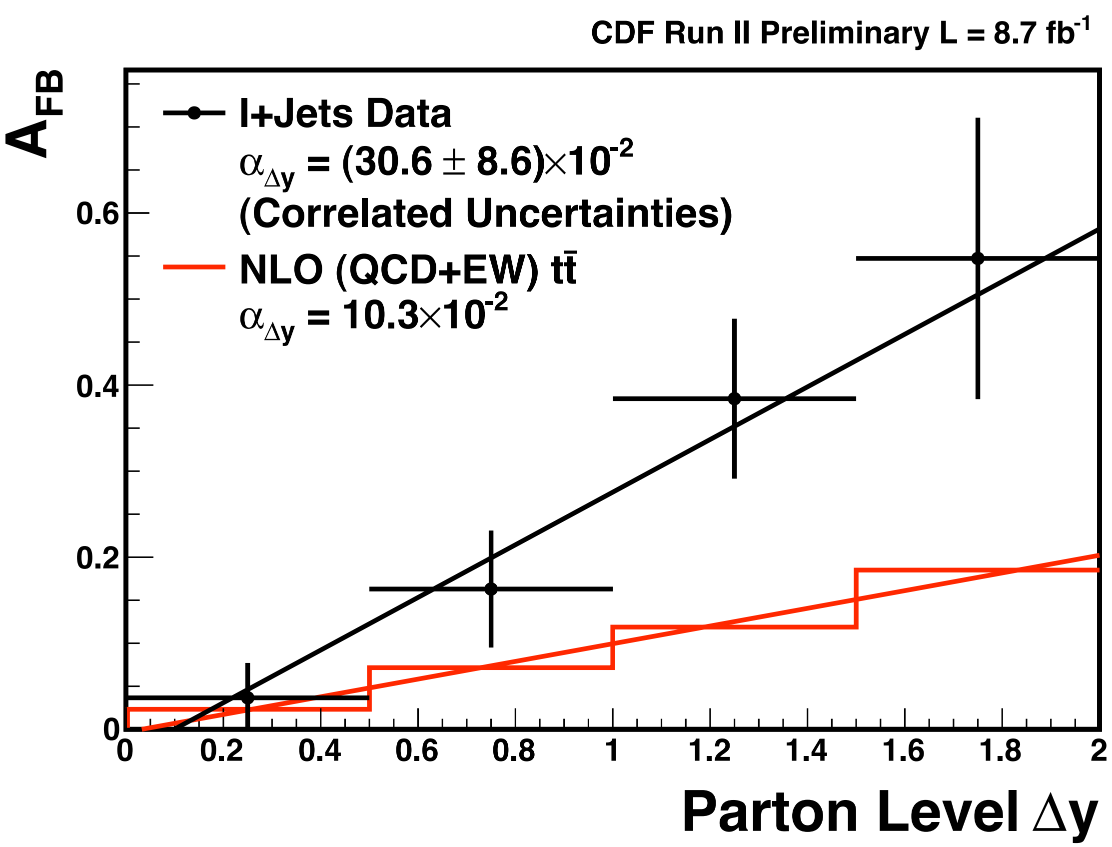
$\Delta y = y_t - y_{\bar{t}}$

From slide by Mietlicki, Moriond 2012

Tevatron Results

- lepton + jet mode of top-anti-top decay
- $\gtrsim 2\sigma$ excess for inclusive data
- excess tends to be enhanced in large M_{tt} and Δy





$\Delta y = y_t - y_{\bar{t}}$

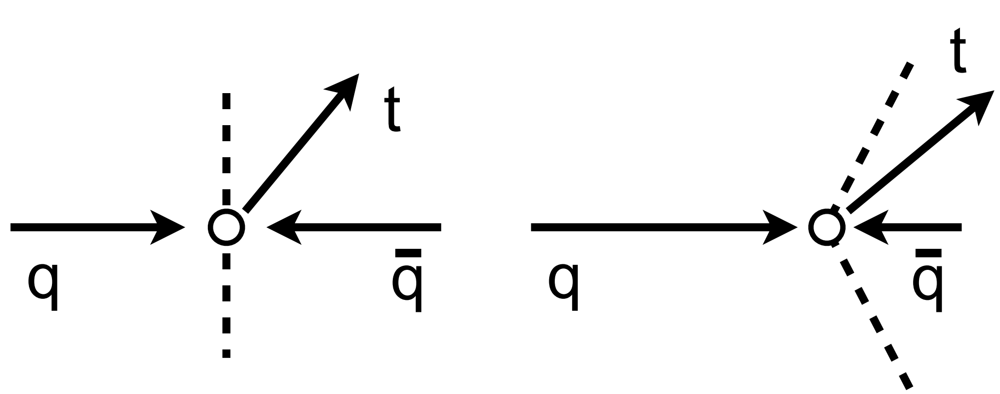
From slide by Mietlicki, Moriond 2012

LHC

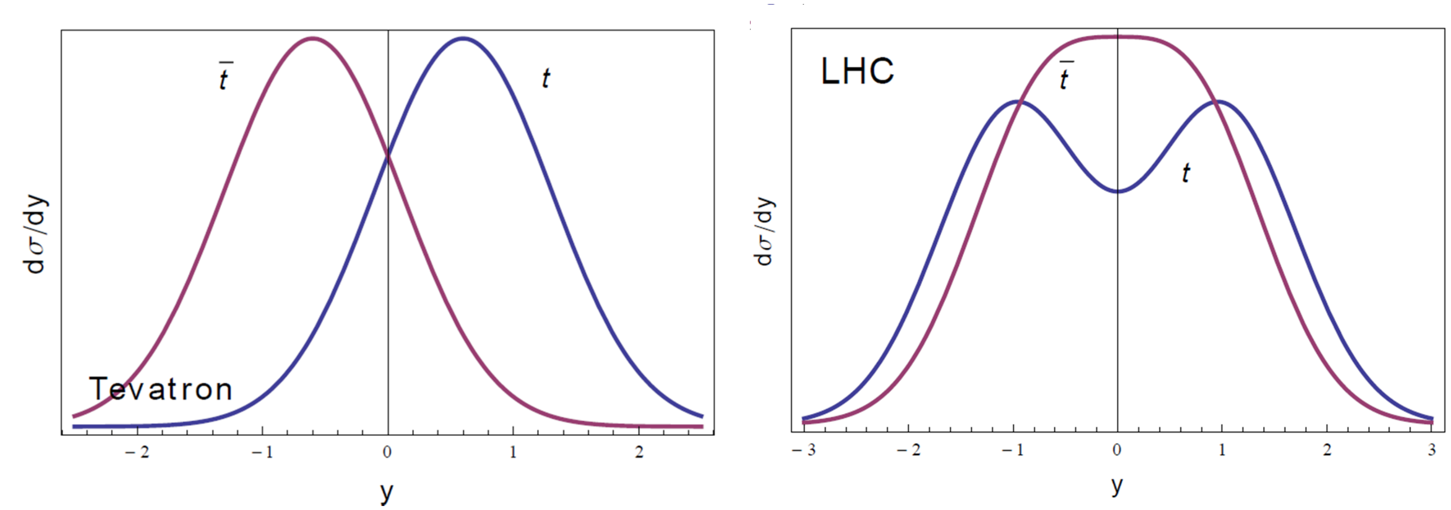
- No FB asymmetry in symmetric collider
- charge asymmetry: rapidity difference bet. t and $\bar{t}$
- cut to enhance $q\bar{q}$ production
  - invariant mass of t and $\bar{t}$
  - large rapidity region (gg is more central)

$$A_C^{\Delta} = \frac{N(\Delta>0)-N(\Delta<0)}{N(\Delta>0)+N(\Delta<0)}$$

$\Delta = |\eta_t| - |\eta_{\bar{t}}|, |y_t| - |y_{\bar{t}}|$ or ${y_t}^2 - {y_{\bar{t}}}^2$



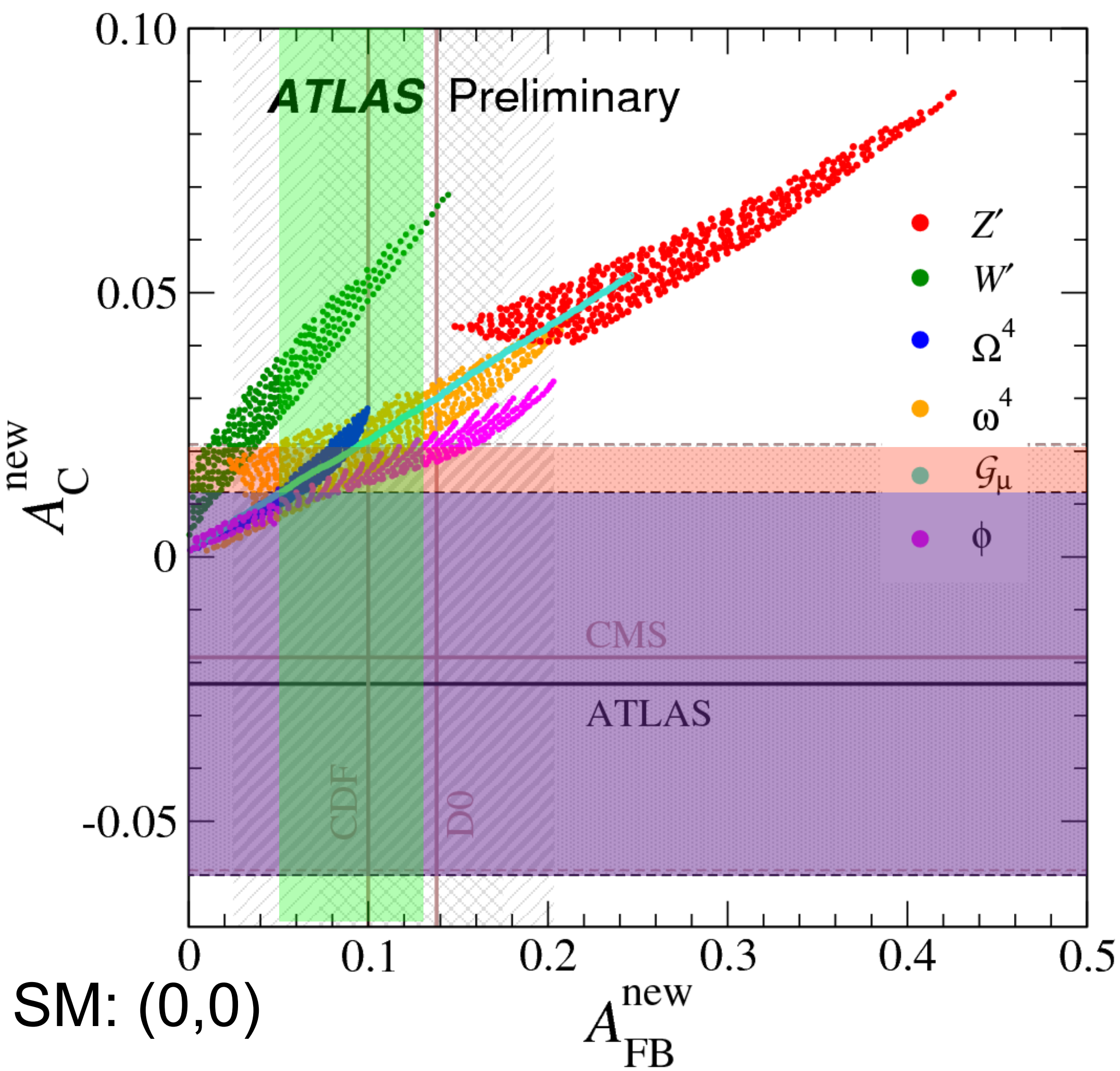
cms rest frame   lab frame



From slide by Rodrigo, Moriond 2012

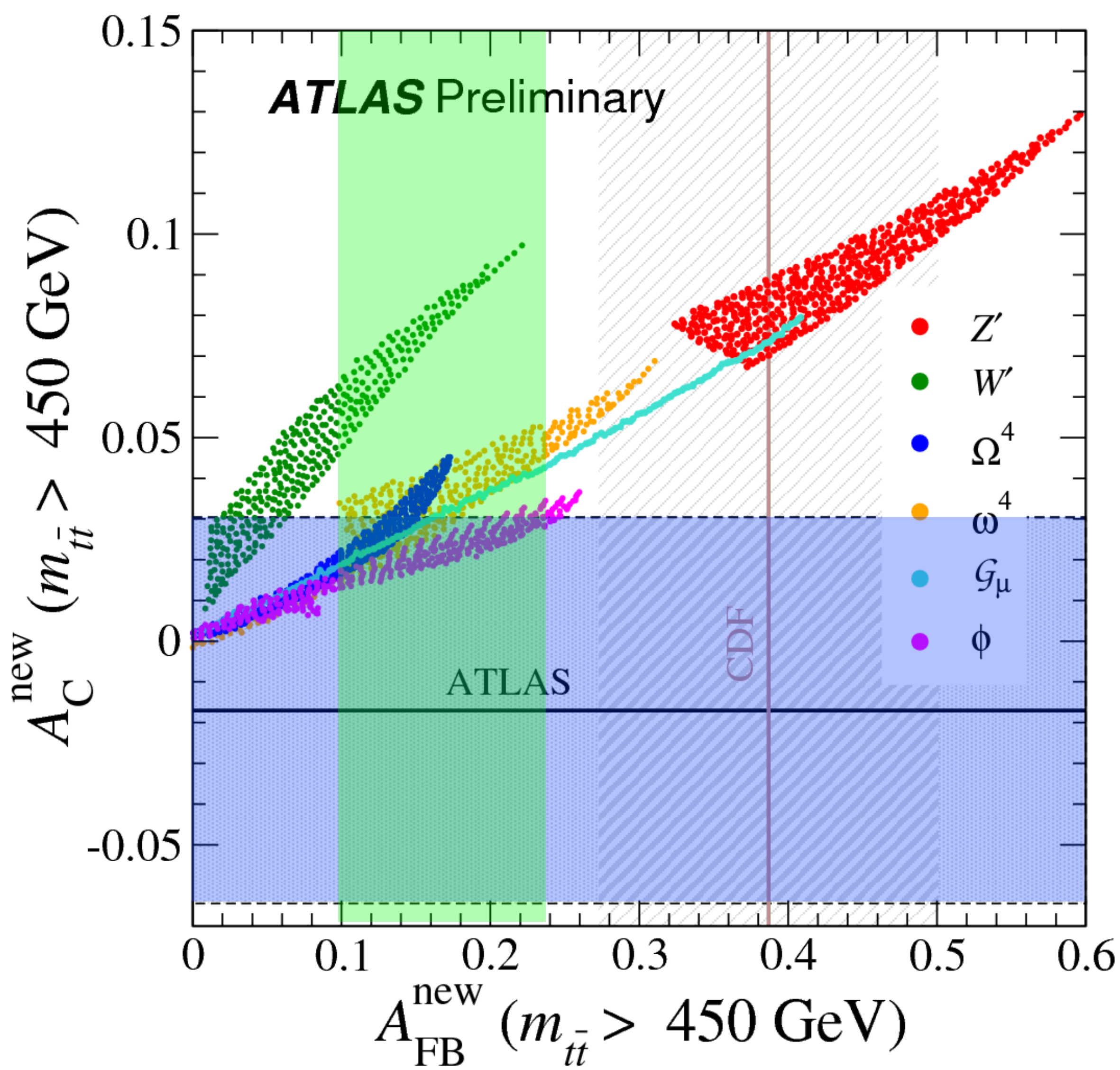
Correlation

- strong correlation between A_{FB}[TVT] and A_C[LHC]
- other constraints not considered in figures
  - $d\sigma/dM_{tt}$, same-sign top, dijet, ...



SM: (0,0)

see model details in 1105.4606



Original figure from slide by Lister, Moriond 2012

今回話してないもの

- EW precision関連
  - recent update: TevatronでW mass
  - jet asymmetry dataとlepton asymmetry dataのそれぞれでfitすると互いに~3σのずれ
    - 実験そのものやQCD correctionの寄与は？
  - など詳しくはPDGのreviewを見てください
- Lepton universality
  - LEPのW→lν（via $e^+e^-\to W^+W^-$）のcouplingの大きさがτに関してだけ2.8σずれてる
  - しかし他の測定はSM consistent

今回話してないもの

- LSND/MB (+reactor, Gallium) anomaly
  - excess of anti-ν_e → $\Delta m^2 \sim 1\text{eV}^2$
  - MB weakly supports LSND for anti-ν_e, but excludes for ν_e
    - (also excess of E < 475MeV in MB)
  - less ν_e flux in reactor and GALLEX, SAGE
  - may imply sterile neutrino(s) [3+2,CPV?]
    - severe constraints from disappearance data and cosmology
    - cannot explain MB, E < 475MeV

どれが“正しい”ヒントか？

	SMからのずれ	NPのスケール
ニュートリノ振動	証拠	RH ν
初期宇宙	証拠	>TeV
暗黒物質	証拠	熱史次第
大統一理論	示唆	~10^{16}GeV
ヒエラルキー問題	示唆	TeV?
μ粒子異常磁気能率	示唆	TeV
フレーバー・CP	?	TeV
Top A_{FB}	?	TeV
EWP, ν ,...	?	?
宇宙線 (e^+,e^-)	?	TeV
DMの直接検出	?	~GeV

Message

- いろいろなモードでSMからのずれらしきものが見つかっている
- 信じられるかどうかにはSMの理解が重要
- New Physicsだとすれば、LHC、cosmologyや他の実験でどのように見えるか

Backup

Electroweak Precision

Fit Result Updated

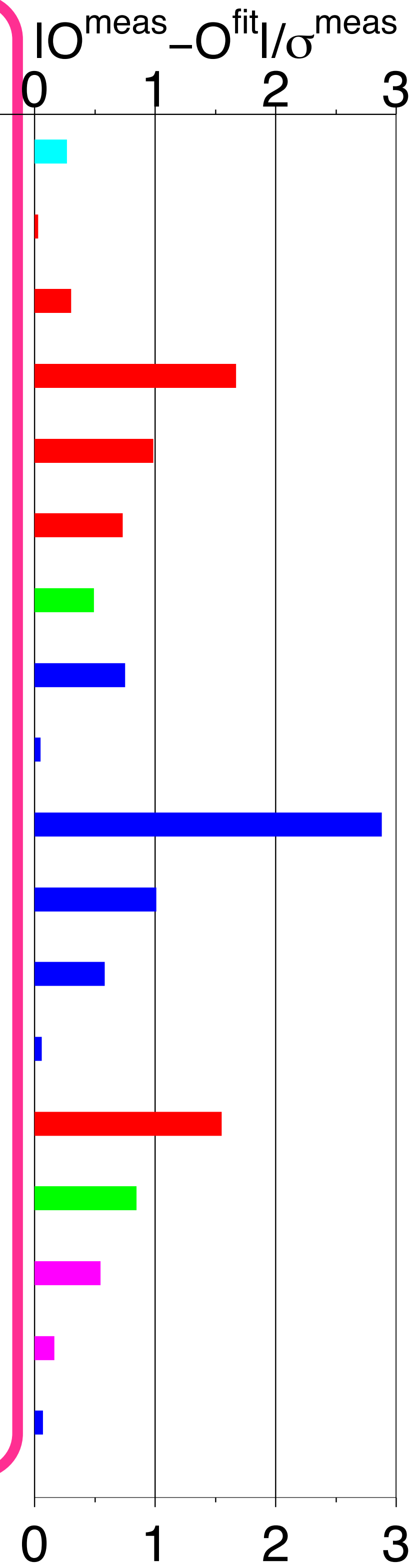
- SM predictions are compared with data
  - radiative correction

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

top, Higgs

- W mass updated by Tevatrons
- SM works very well
  - NP is constrained

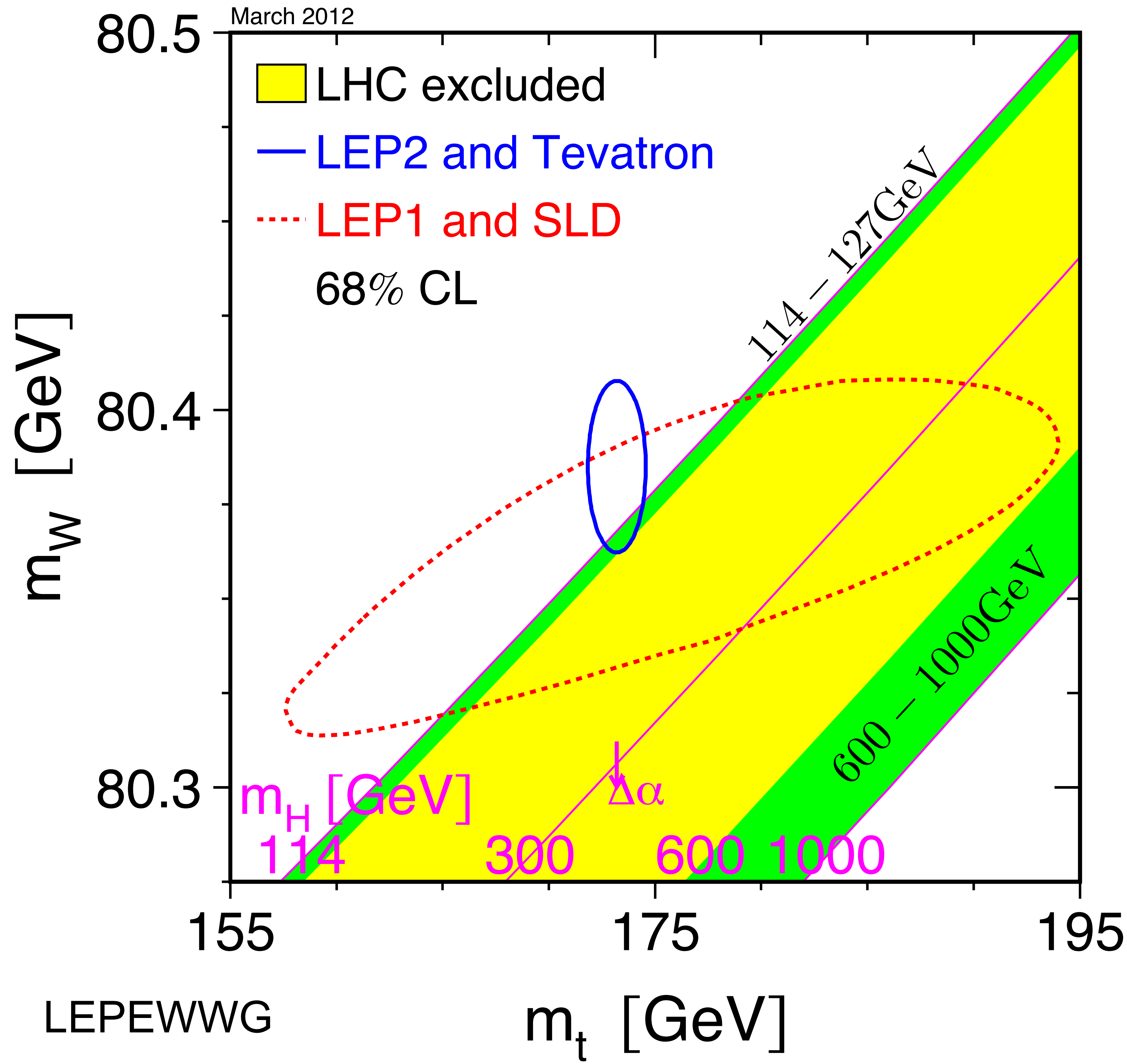
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



March 2012

LEPEWWG

Current Result



latest Higgs results

ATLAS

$117.5 - 118.5\mathrm{GeV}$

$122.5 - 129\mathrm{GeV}$

CMS

$114.5 - 127.5\mathrm{GeV}$

@95%

Lepton or Hadron

- worse fit in jet data
- fits are good with
  - only lepton asym.
  - only jet asym.
    - differ by ~3σ
- analysis of jet angular distribution may need revision [Hagiwara,Kirilin]

  (or experimental?)

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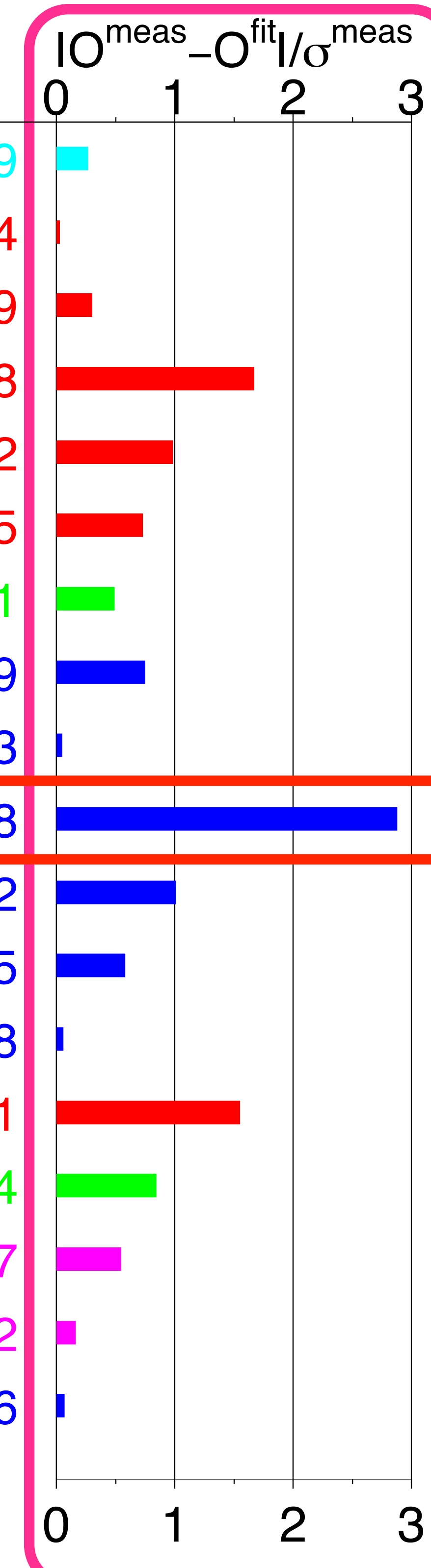

March 2012 LEPEWWG

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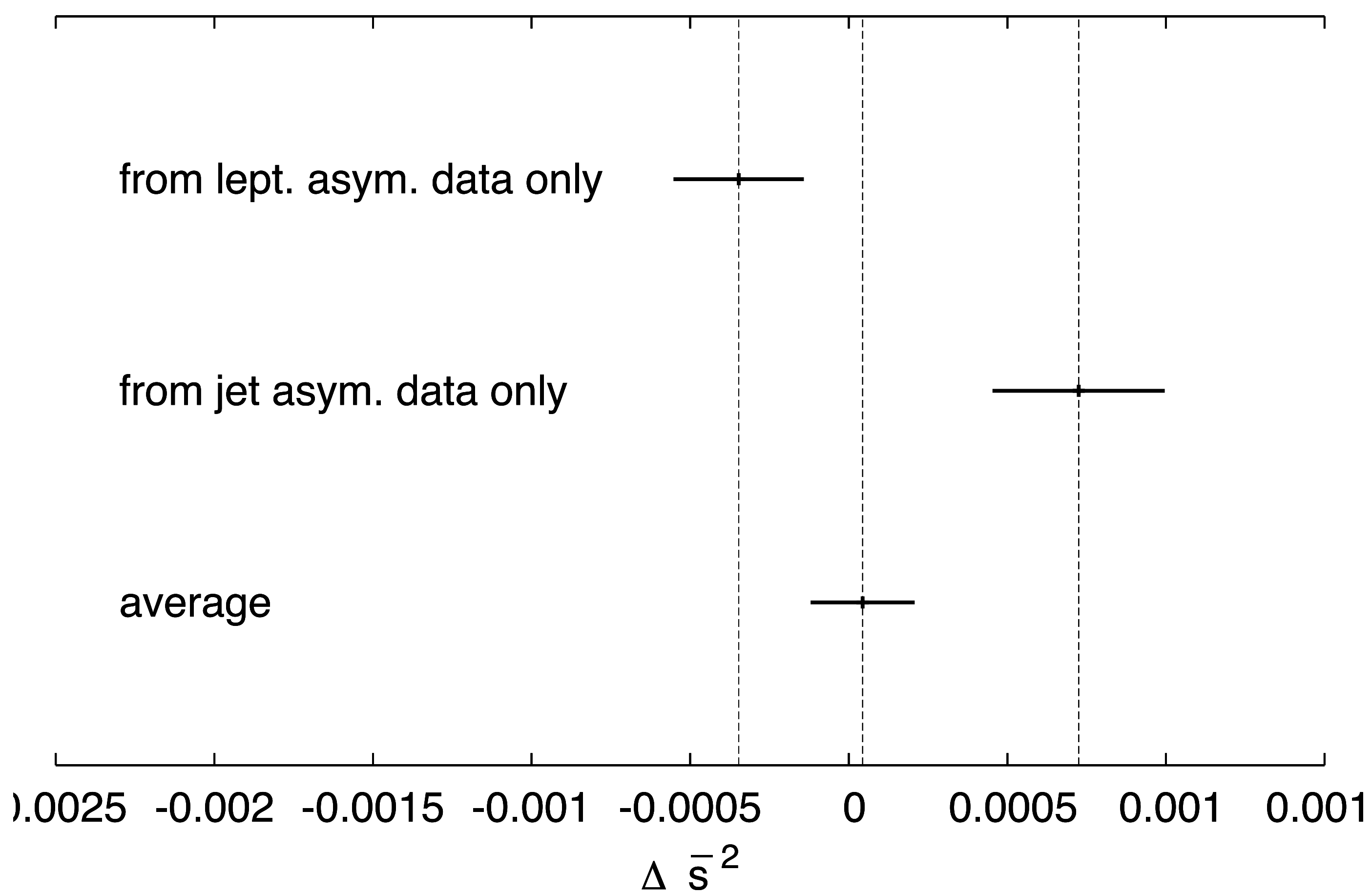
  (or experimental?)

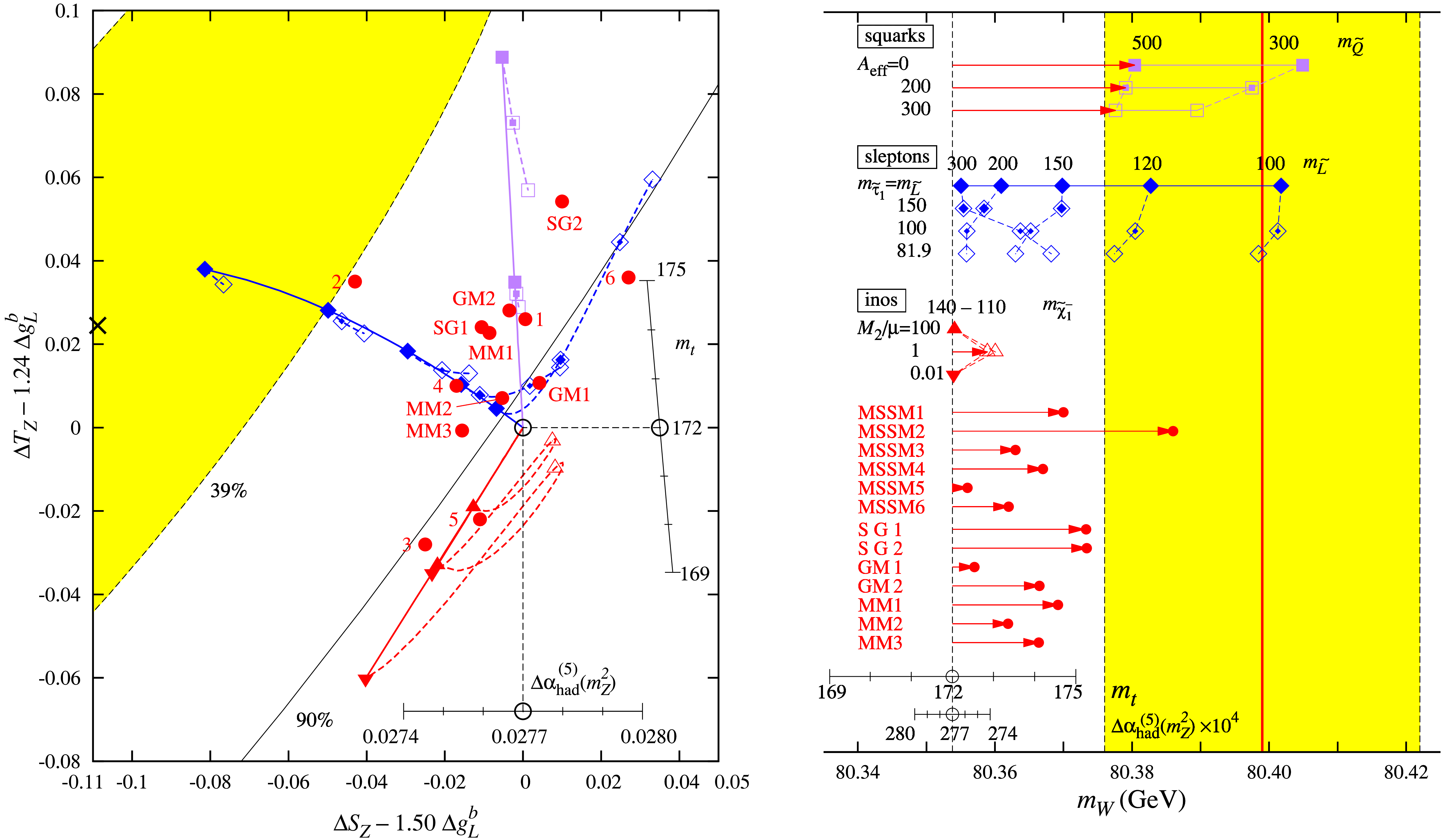
[Cho,Hagiwara,Matsumoto,Nomura]



Leptonic Asym Fit

Not include Tevatron update (2012) on M_W

[Cho,Hagiwara,Matsumoto,Nomura]



Leptonic non-universality

Status

- test of $W\ell\nu$ coupling for $\ell = e, \mu, \tau$ [SM: universal]
- consistent with universality perfectly in:

$$[\mu \to e\nu\nu, \tau \to e\nu\nu, \tau \to \mu\nu\nu], [\pi \to e\nu, \pi \to \mu\nu, \tau \to \pi\nu], \ldots$$

- LEP measurements of $e^+e^- \to W^+W^-$

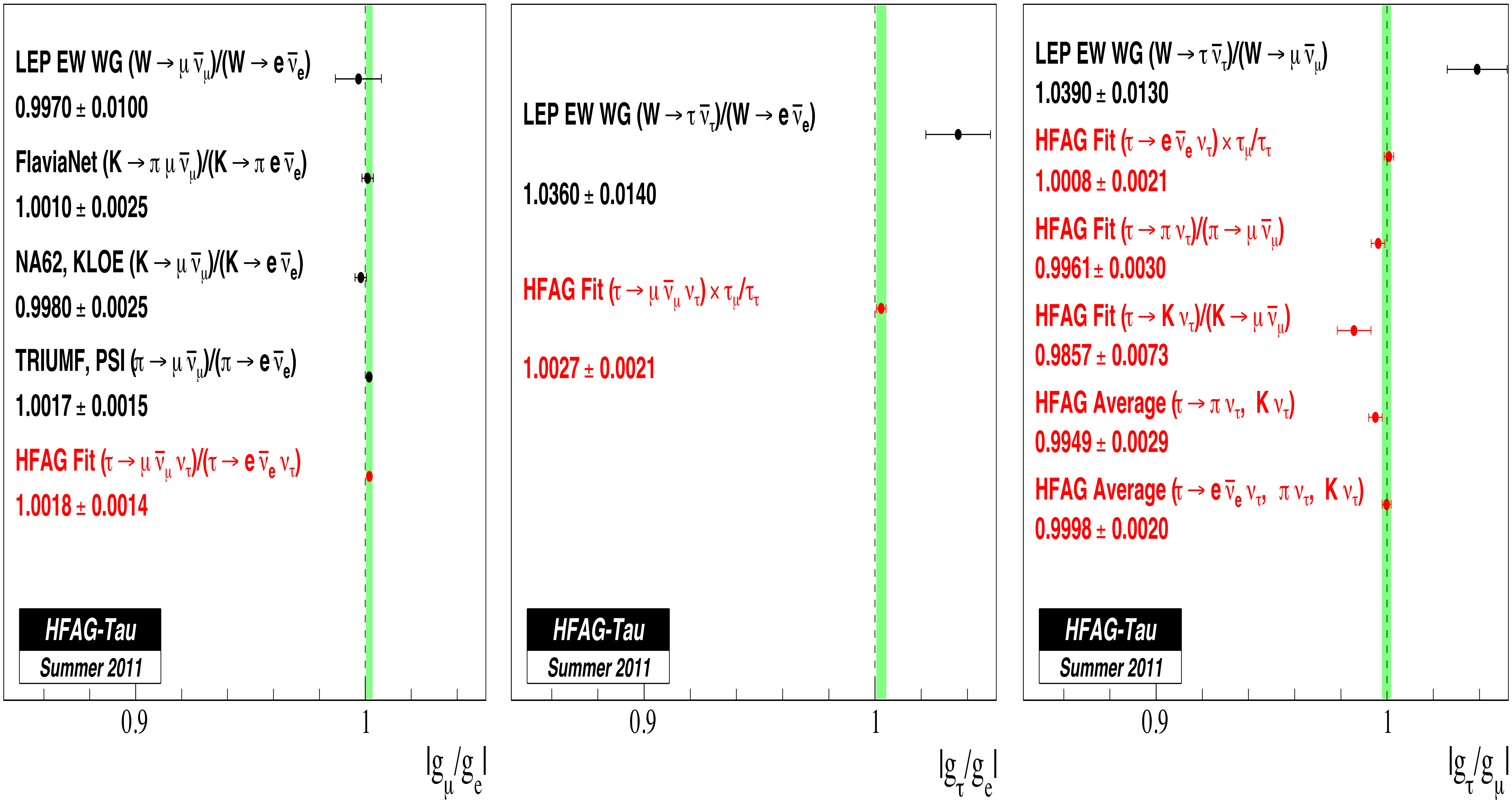
$$B(W \to e\nu_e), B(W \to \mu\nu_\mu), B(W \to \tau\nu_\tau)$$

Experiment	$B(W \to e\nu_e)$ [%]	$B(W \to \mu\nu_\mu)$ [%]	$B(W \to \tau\nu_\tau)$ [%]
ALEPH	$10.78 \pm 0.29^*$	$10.87 \pm 0.26^*$	$11.25 \pm 0.38^*$
DELPHI	$10.55 \pm 0.34^*$	$10.65 \pm 0.27^*$	$11.46 \pm 0.43^*$
L3	$10.78 \pm 0.32^*$	$10.03 \pm 0.31^*$	$11.89 \pm 0.45^*$
OPAL	10.40 ± 0.35	10.61 ± 0.35	11.18 ± 0.48
LEP	10.65 ± 0.17	10.59 ± 0.15	11.44 ± 0.22

$$\left.\frac{B(W \to \tau\nu_\tau)}{[B(W \to e\nu_e) + B(W \to \mu\nu_\mu)]/2}\right|_{\mathrm{LEP}} = 1.077 \pm 0.026$$

... 2.8σ!?

Status



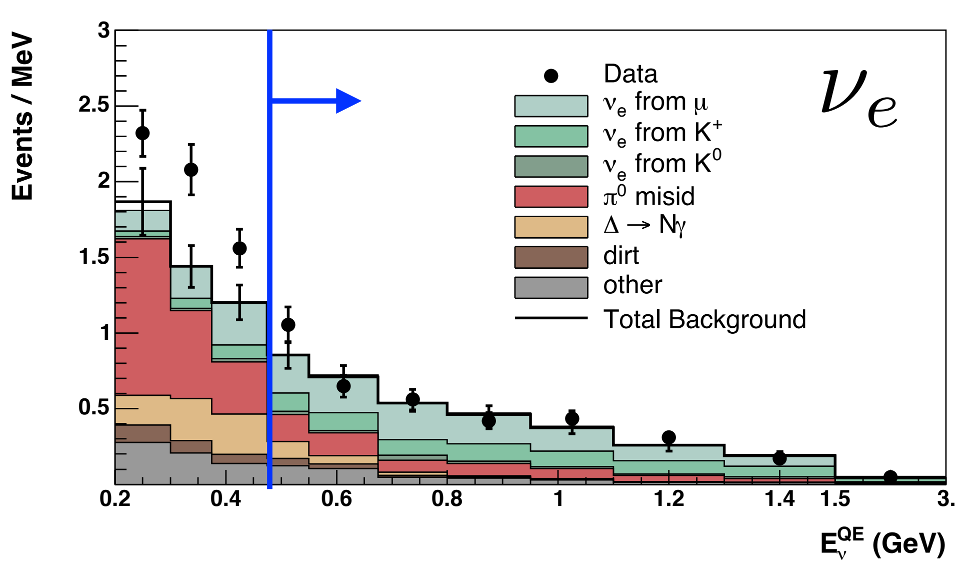
LEP EW WG $(W \to \mu \bar{\nu}_\mu)/(W \to e \bar{\nu}_e)$
0.9970 ± 0.0100
FlaviaNet $(K \to \pi \mu \bar{\nu}_\mu)/(K \to \pi e \bar{\nu}_e)$
1.0010 ± 0.0025
NA62, KLOE $(K \to \mu \bar{\nu}_\mu)/(K \to e \bar{\nu}_e)$
0.9980 ± 0.0025
TRIUMF, PSI $(\pi \to \mu \bar{\nu}_\mu)/(\pi \to e \bar{\nu}_e)$
1.0017 ± 0.0015
HFAG Fit $(\tau \to \mu \bar{\nu}_\mu \nu_\tau)/(\tau \to e \bar{\nu}_e \nu_\tau)$
1.0018 ± 0.0014
HFAG-Tau
Summer 2011
0.9
1
$|g_\mu/g_e|$
LEP EW WG $(W \to \tau \bar{\nu}_\tau)/(W \to e \bar{\nu}_e)$
1.0360 ± 0.0140
HFAG Fit $(\tau \to \mu \bar{\nu}_\mu \nu_\tau) \times \tau_\mu/\tau_\tau$
1.0027 ± 0.0021
HFAG-Tau
Summer 2011
0.9
1
$|g_\tau/g_e|$
LEP EW WG $(W \to \tau \bar{\nu}_\tau)/(W \to \mu \bar{\nu}_\mu)$
1.0390 ± 0.0130
HFAG Fit $(\tau \to e \bar{\nu}_e \nu_\tau) \times \tau_\mu/\tau_\tau$
1.0008 ± 0.0021
HFAG Fit $(\tau \to \pi \nu_\tau)/(\pi \to \mu \bar{\nu}_\mu)$
0.9961 ± 0.0030
HFAG Fit $(\tau \to K \nu_\tau)/(K \to \mu \bar{\nu}_\mu)$
0.9857 ± 0.0073
HFAG Average $(\tau \to \pi \nu_\tau, K \nu_\tau)$
0.9949 ± 0.0029
HFAG Average $(\tau \to e \bar{\nu}_e \nu_\tau, \pi \nu_\tau, K \nu_\tau)$
0.9998 ± 0.0020
HFAG-Tau
Summer 2011
0.9
1
$|g_\tau/g_\mu|$

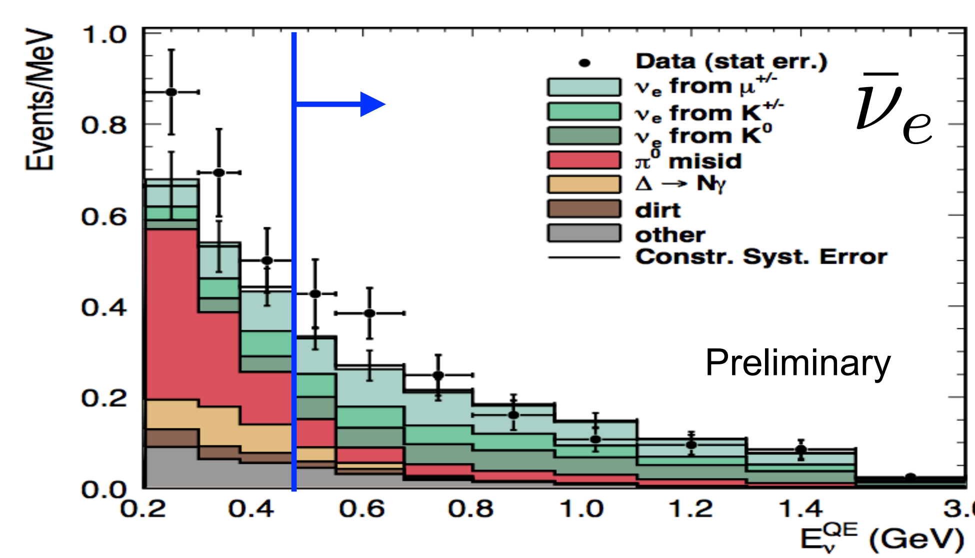
LSND/MiniBoone Anomaly (Reactor&Gallium)

Neutrino Anomalies

- LSND [LANL]: excess of anti-ν_e (anti-$\nu_\mu \rightarrow$ anti-ν_e)
  - $\Delta m^2 \sim 1\text{eV}^2$: inconsistent with sol. and atm.
- MiniBoone [FNAL]: appearance of ν_e and anti-ν_e
  - small excess in anti-ν_e for E > 475MeV
  - no excess in ν_e for E > 475MeV
  - (small) excess in (anti-) ν_e for E < 475MeV (inconsistent with LSND oscillation)

MiniBoone





Neutrino Anomalies

- Reactor anomaly
  - anti-ν_e flux is less than expectation (2.5σ)
  - distance to reactor: 10-100m
- Gallium anomaly [GALLEX, SAGE]
  - detect neutrino via $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$ from radioactive sources
  - ν_e flux is less than expectation (R=0.86±0.06)
- All these anomalies may imply sterile neutrino(s)
  - 3+2: CP violation can solve ν-anti-ν tension
  - constraints from disappearance and cosmology
  - MiniBoone low-energy excess is not explained