PASCOS | 2012

Mérida, México June 3rd- 8th

18th International Symposium on Particles, Strings and Cosmology

www.fisica.unam.mx/pascos2012

PLENARY SPEAKERS INCLUDE

Nathan Berkovits, Alberto Casas, Daniel Chung, Laura Covi, Mirjam Cvetič, Abdelhak Djouadi, Jens Erler, Pavel Fileviez Pérez, Paul Frampton, Paolo Gondolo, André de Gouvêa, Steen Hannestad, Jonathan Heckman, Tobias Hurth, Jihn E. Kim, Manfred Lindner, Alessandro Melchiorri, Peter Mezsaros, Pran Nath, Stefano Profumo, Stuart Raby, Andreas Ringwald, Gary Shiu, Günther Sigl, Peter Tandy, José Valle, Dirk Zerwas.

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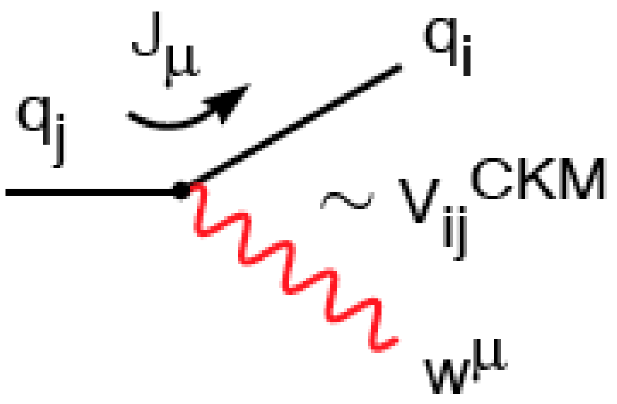
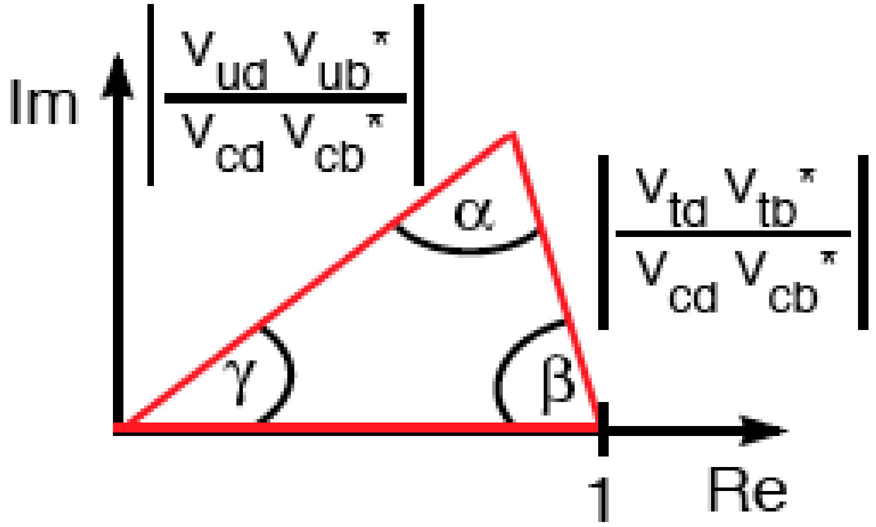
Flavour in the SM

CKM mechanism of flavour mixing and CP violation: $V_{\rm CKM}$, $J_{\rm CKM}$

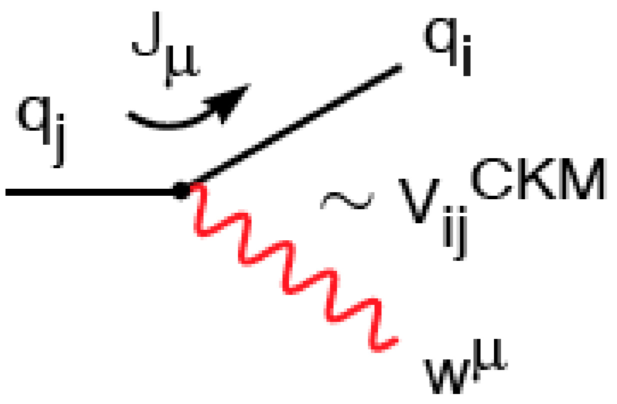


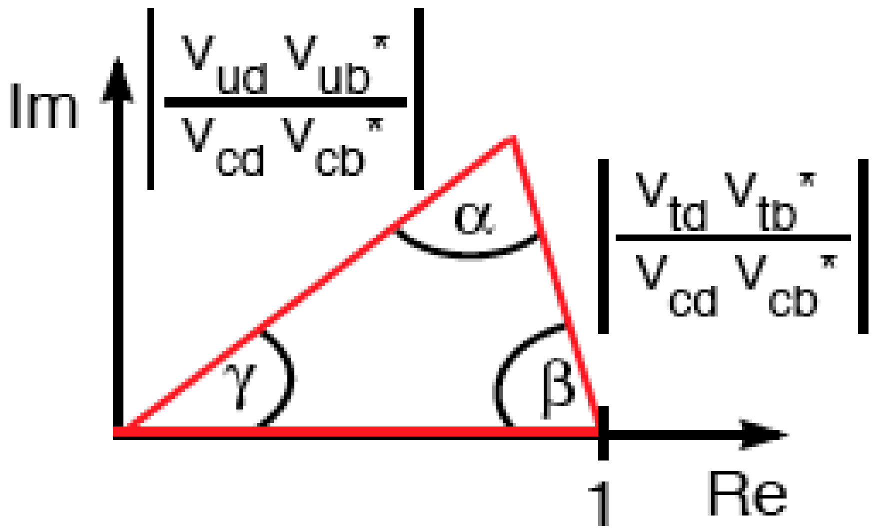


$$Im[V_{ij}\,V_{kl}\,V_{il}^*\,V_{kj}^*] = J_{\rm CKM}\sum_{m,n=1}^{3}\epsilon_{ikm}\,\epsilon_{jln}$$

$$J_{\rm CKM}\sim\mathcal{O}(10^{-5})$$

CKM mechanism of flavour mixing and CP violation: $V_{\rm CKM}$, $J_{\rm CKM}$





$$Im[V_{ij}\,V_{kl}\,V_{il}^*\,V_{kj}^*] = J_{\rm CKM}\sum_{m,n=1}^{3}\epsilon_{ikm}\,\epsilon_{jln} \qquad J_{\rm CKM} \sim \mathcal{O}(10^{-5})$$

Status of flavour physics in the pre-LHC(b) era:

All measurements (Babar, Belle, Cleo, CDF, DO, ...)

of rare decays ($\Delta F = 1$),

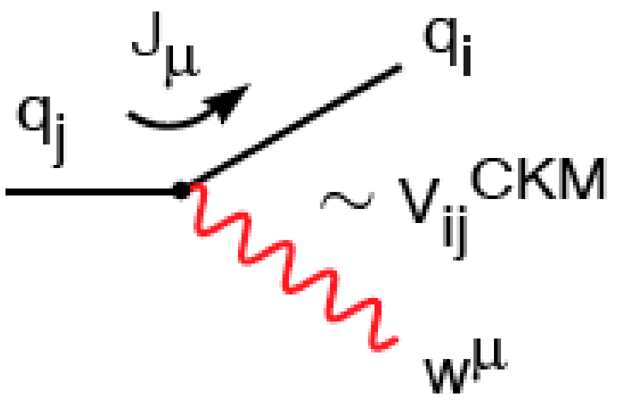
of mixing phenomena ($\Delta F = 2$) and

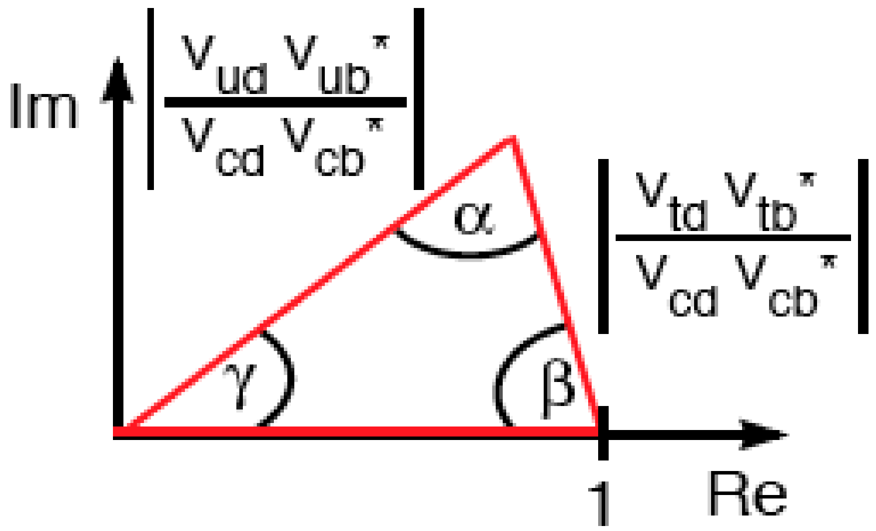
of all CP violating observables at tree and loop level

have been consistent with the CKM theory.

Impressing success of SM and CKM theory !!

CKM mechanism of flavour mixing and CP violation: $V_{\rm CKM}$, $J_{\rm CKM}$





$$Im[V_{ij}\, V_{kl}\, V_{il}^*\, V_{kj}^*] = J_{\rm CKM} \sum_{m,n=1}^{3} \epsilon_{ikm}\, \epsilon_{jln} \qquad J_{\rm CKM} \sim \mathcal{O}(10^{-5})$$

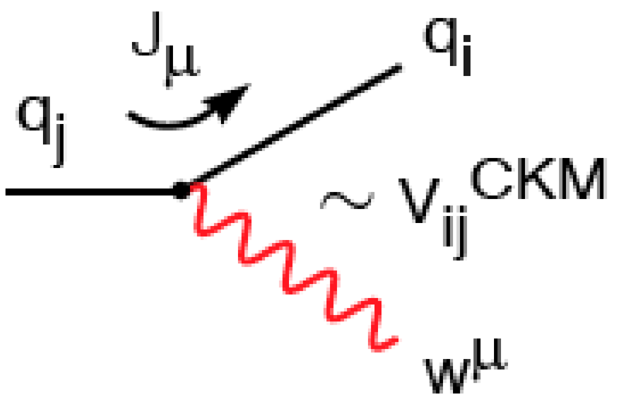
Status of flavour physics in the pre-LHC(b) era:

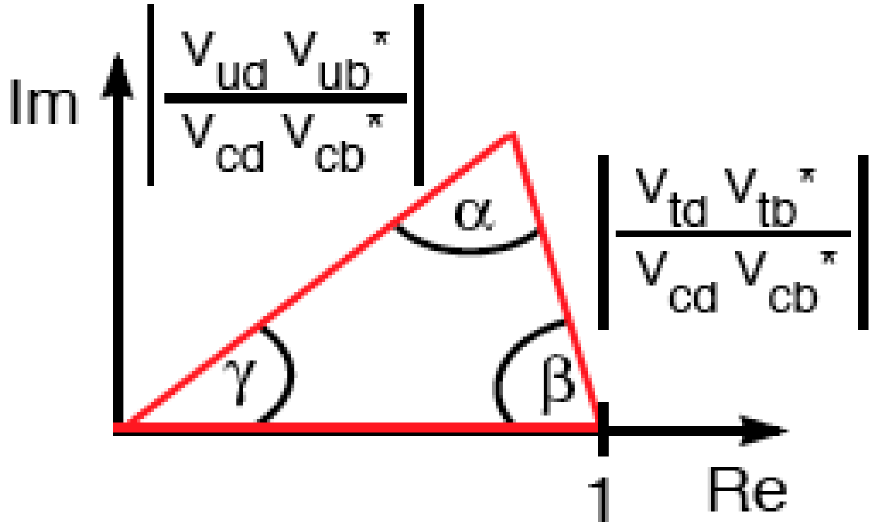
Of course there have been so-called puzzles, tensions, anomalies in the flavour data at the 1,2,or 3σ level.

For example: Tension between $\mathcal{B}(B \to \tau\nu)$ and $\sin\beta$.
Mixing phase in $B_s - \bar{B}_s$ mixing ....

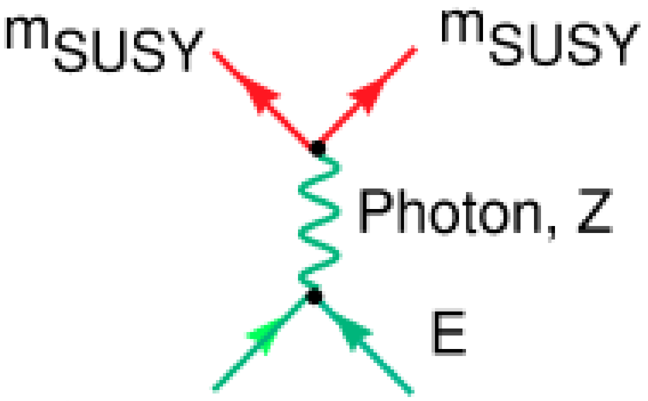
Impressing success of SM and CKM theory !!

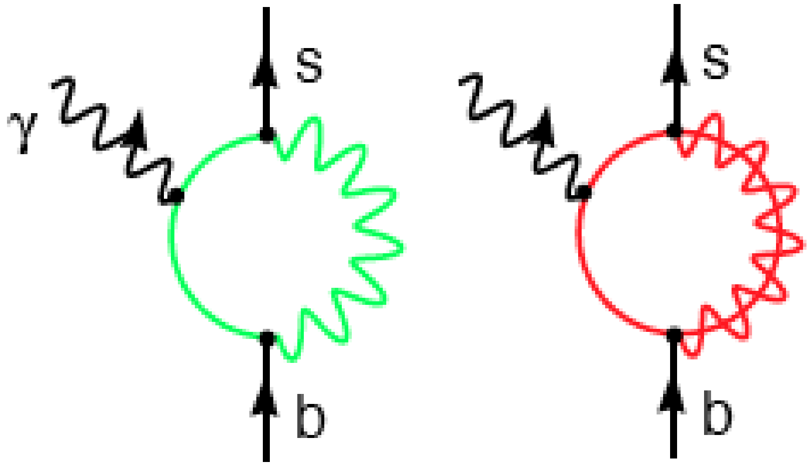
CKM mechanism of flavour mixing and CP violation: V_{CKM}, J_{CKM}





This success is somehow unexpected !!

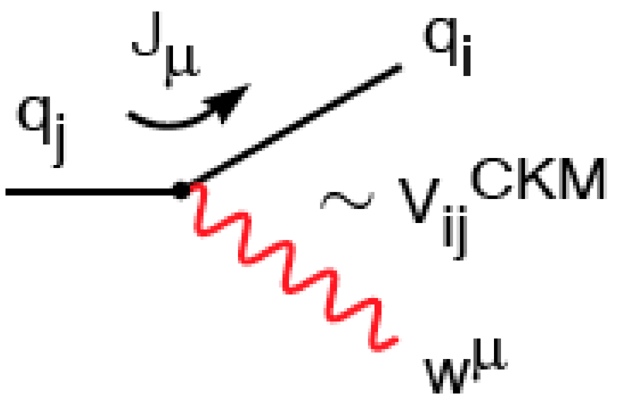


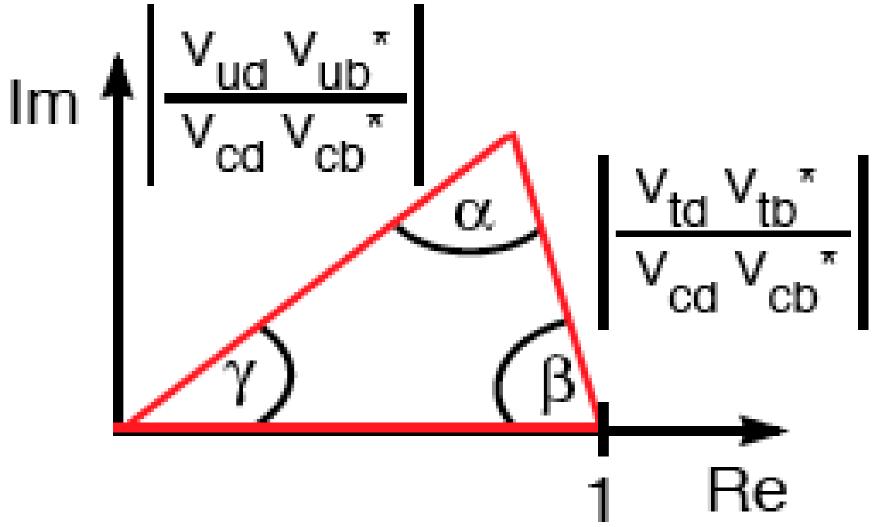


Flavour-changing-neutral-currents as loop-induced processes are highly-sensitive probes for possible new degrees of freedom

Impressing success of SM and CKM theory !!

CKM mechanism of flavour mixing and CP violation: $V_{\rm CKM}$, $J_{\rm CKM}$



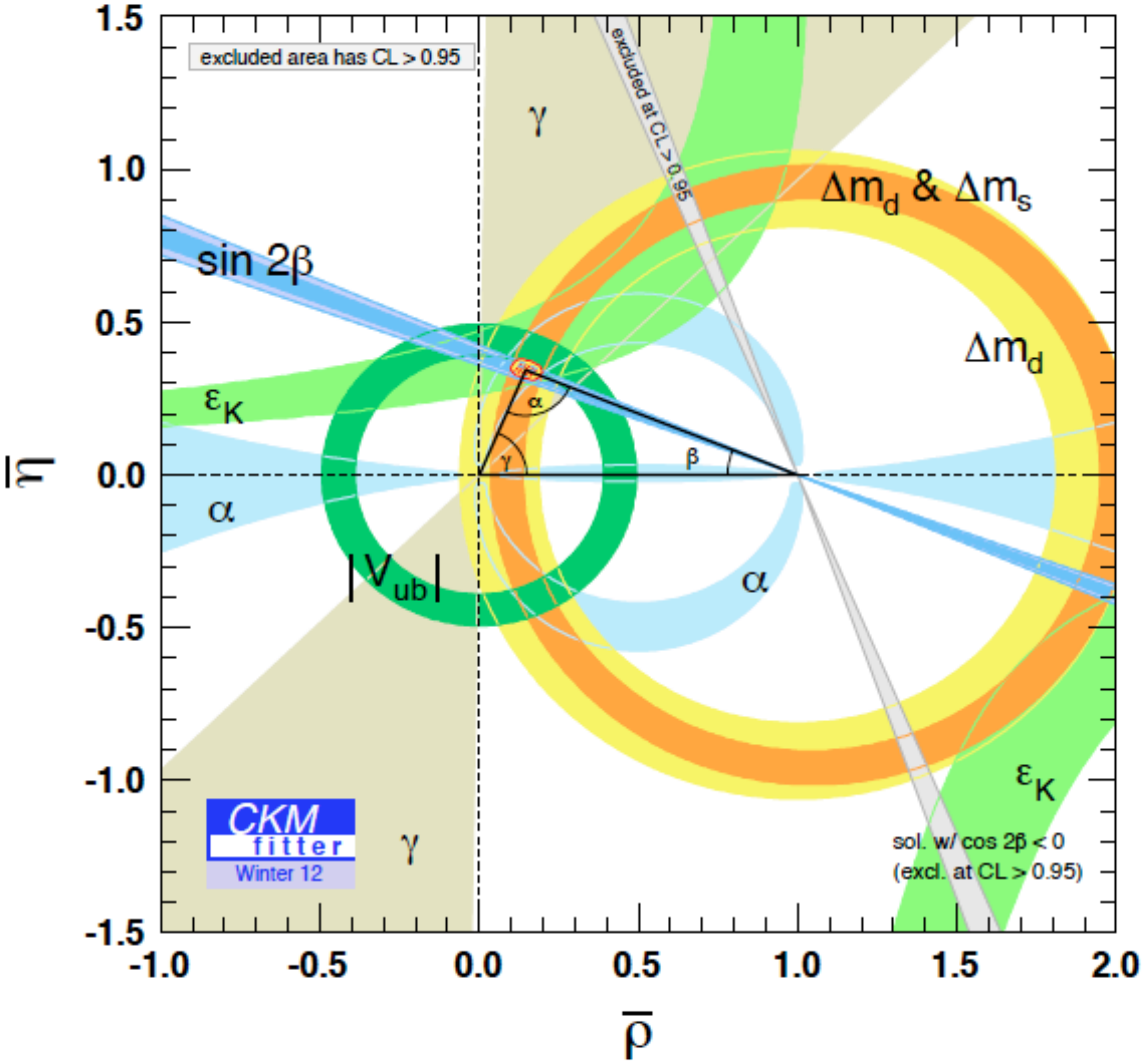


$$Im[V_{ij}\,V_{kl}\,V_{il}^*\,V_{kj}^*] = J_{\rm CKM} \sum_{m,n=1}^{3} \epsilon_{ikm}\,\epsilon_{jln} \qquad J_{\rm CKM} \sim \mathcal{O}(10^{-5})$$

LHC(b) has not changed this, in contrary !!

All measurements (Babar, Belle, Cleo, CDF, DO, **LHC(b),...)**
of rare decays ($\Delta F = 1$),
of mixing phenomena ($\Delta F = 2$) and
of all CP violating observables at tree and loop level
are consistent with the CKM theory.

Impressing success of SM and CKM theory !!



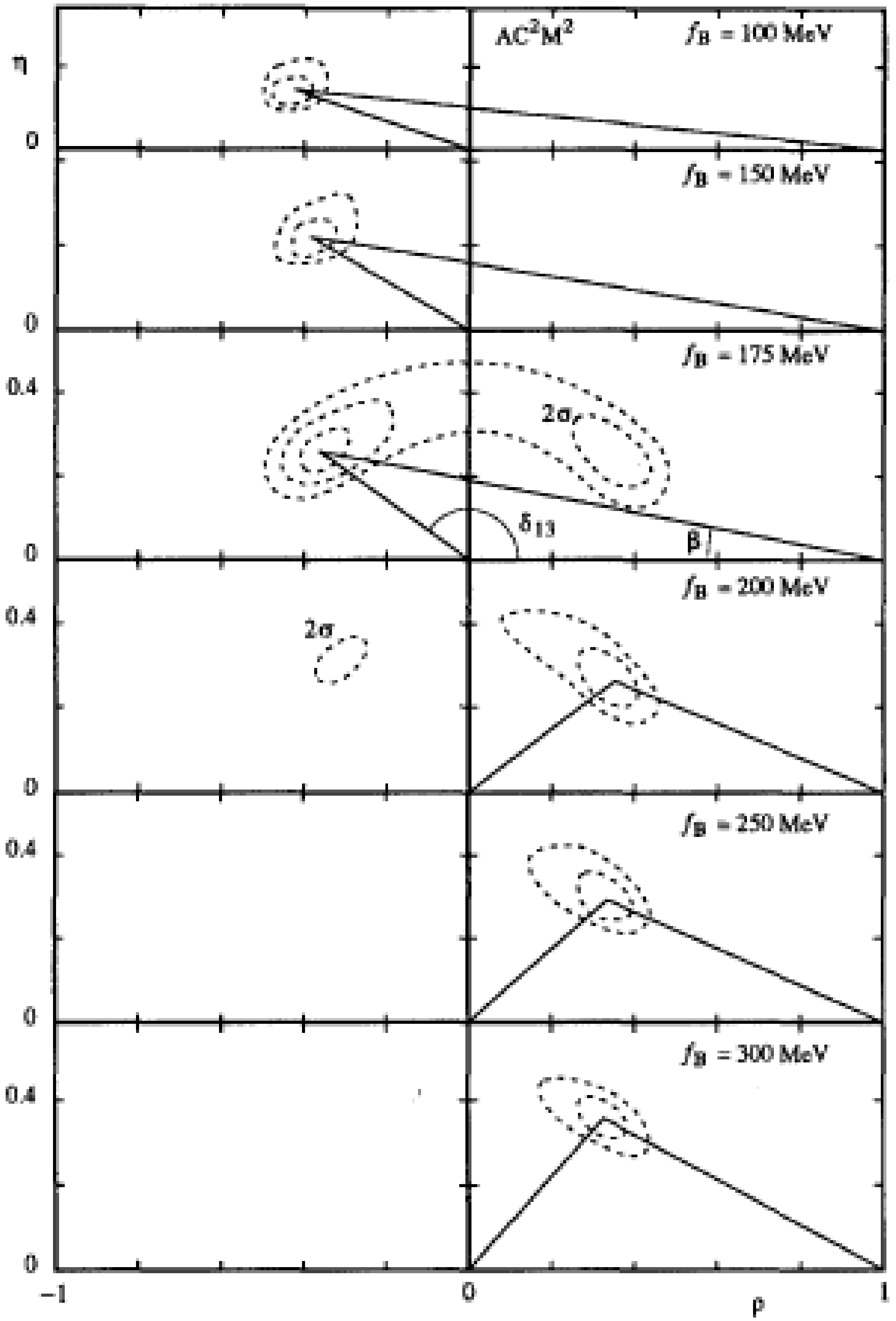
Global fit,

consistency check

of

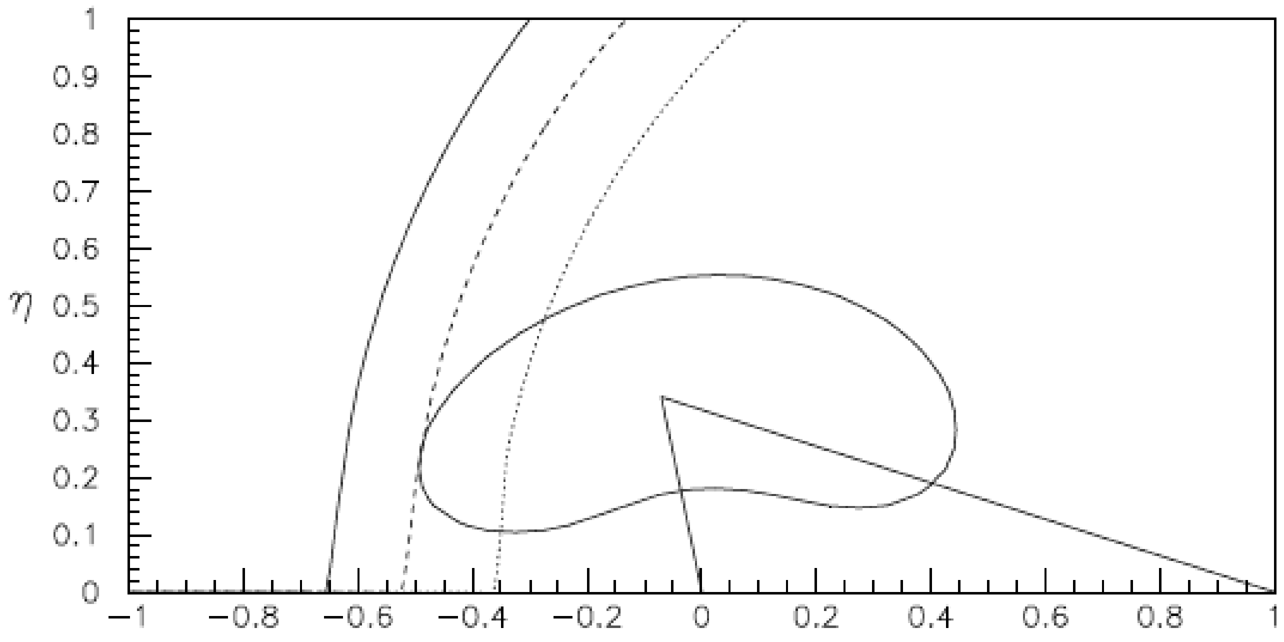
the CKM theory.

For comparison; some historical CKM fits

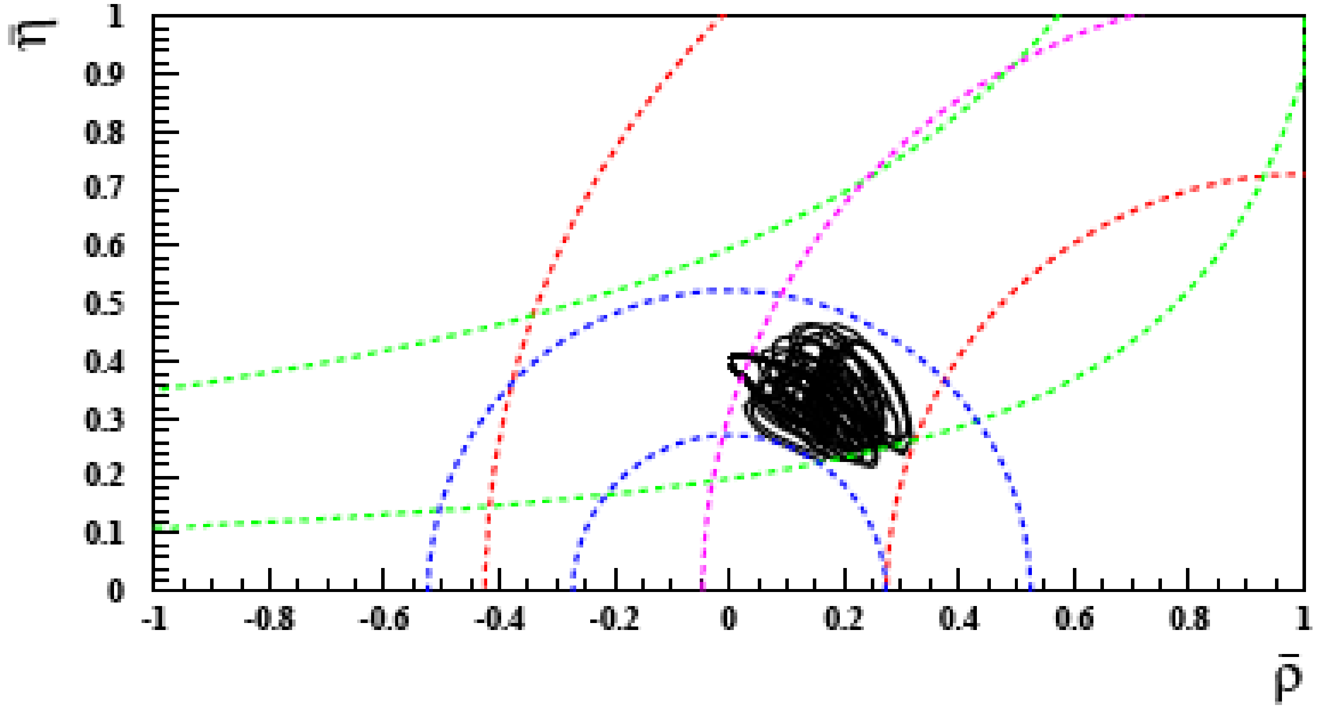


Schmidtler, Schubert 1992

$f_{B_d} = 180 \pm 50$ MeV , $B_{B_d} = 1.0 \pm 0.2$, $B_K = 0.8 \pm 0.2$

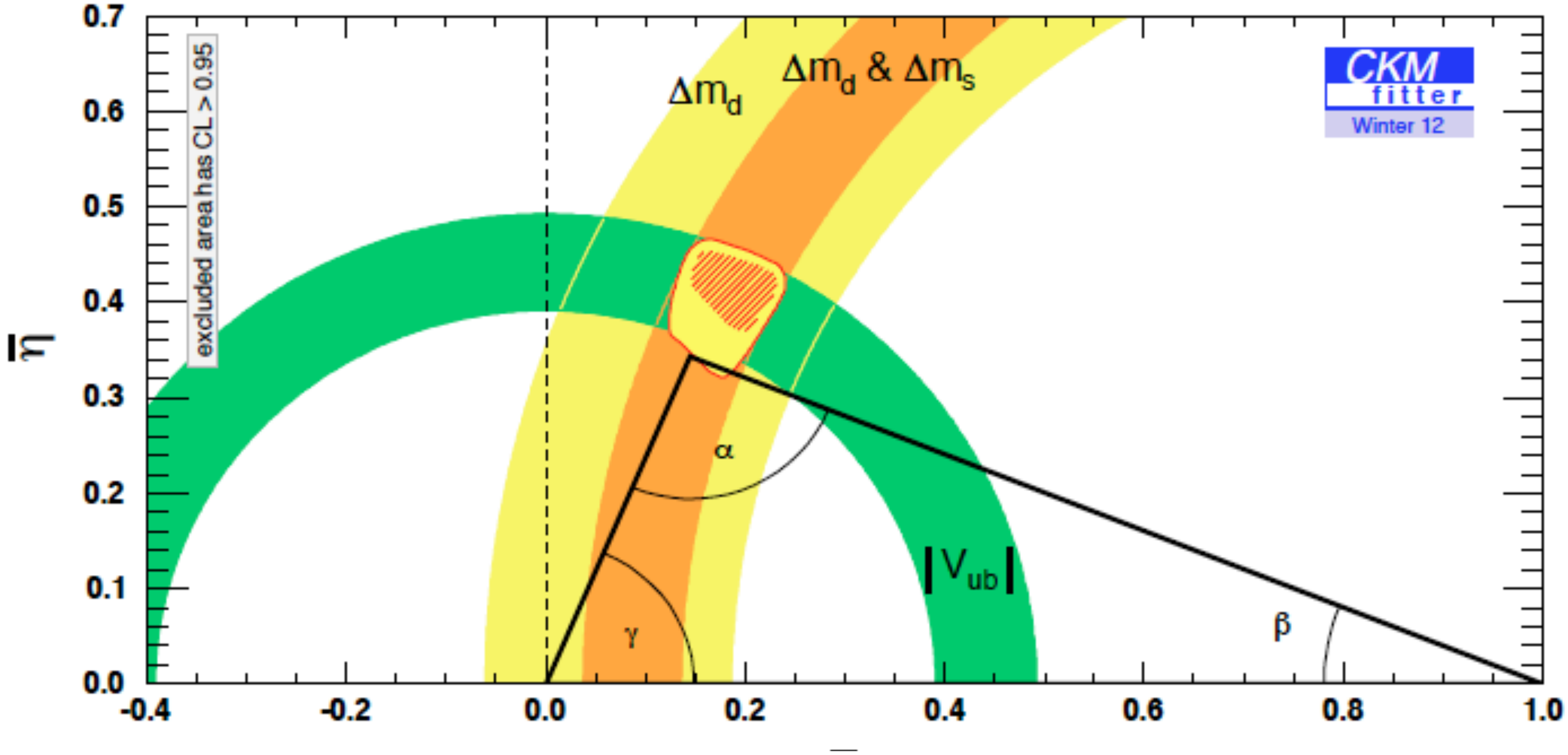


Ali, London 1995

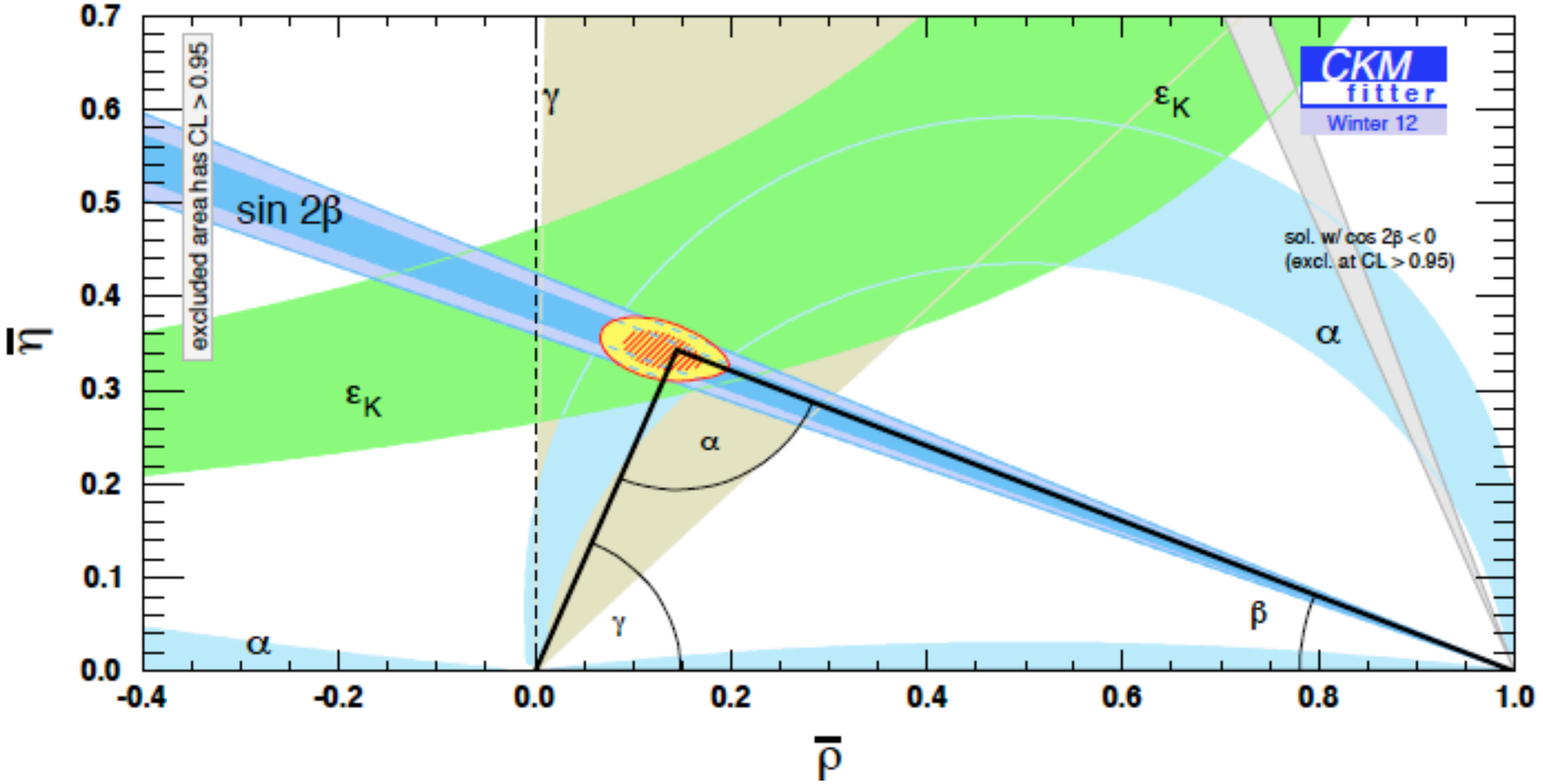


Plazczynski, Schune 1999

Closer Look:

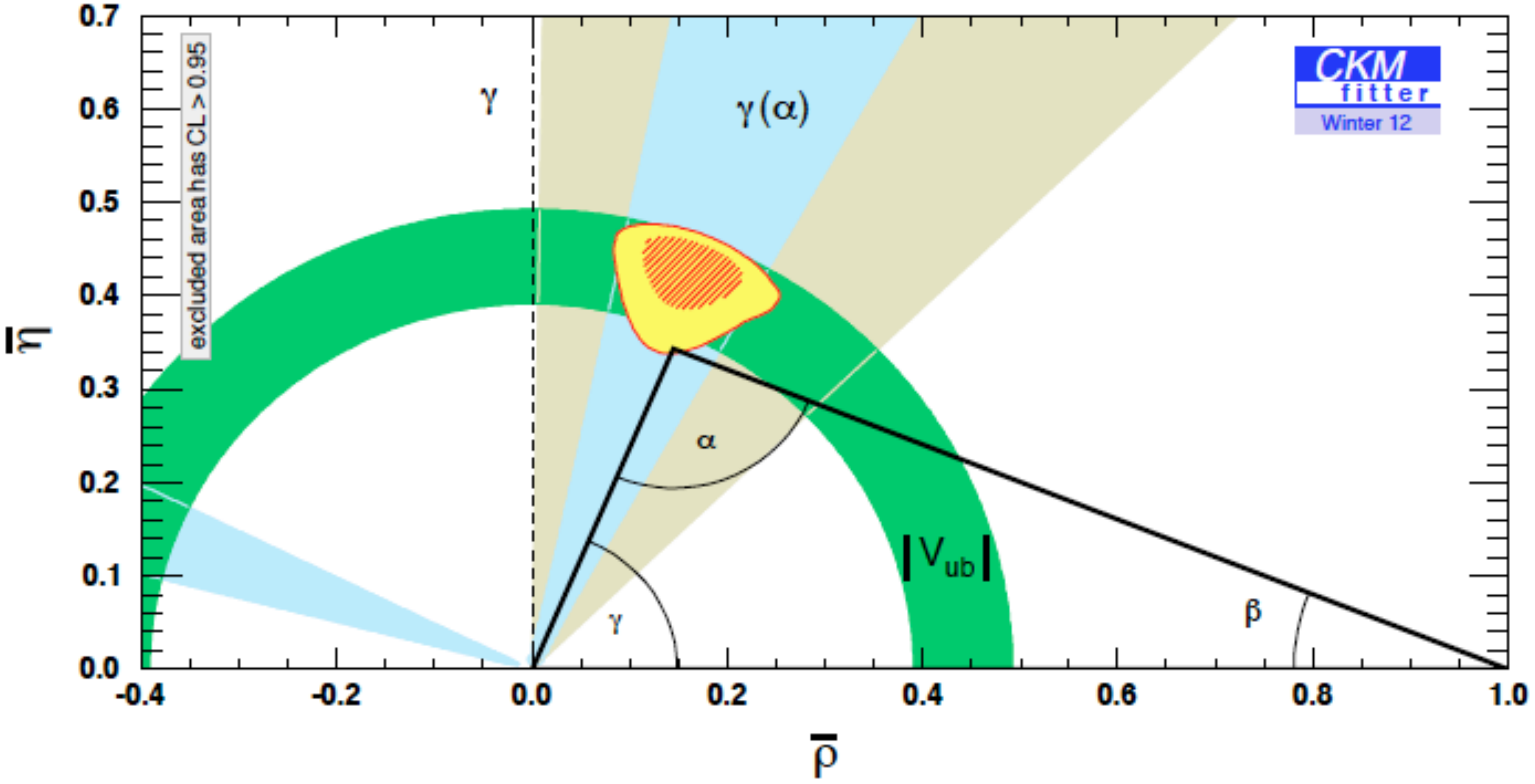


CP conserving

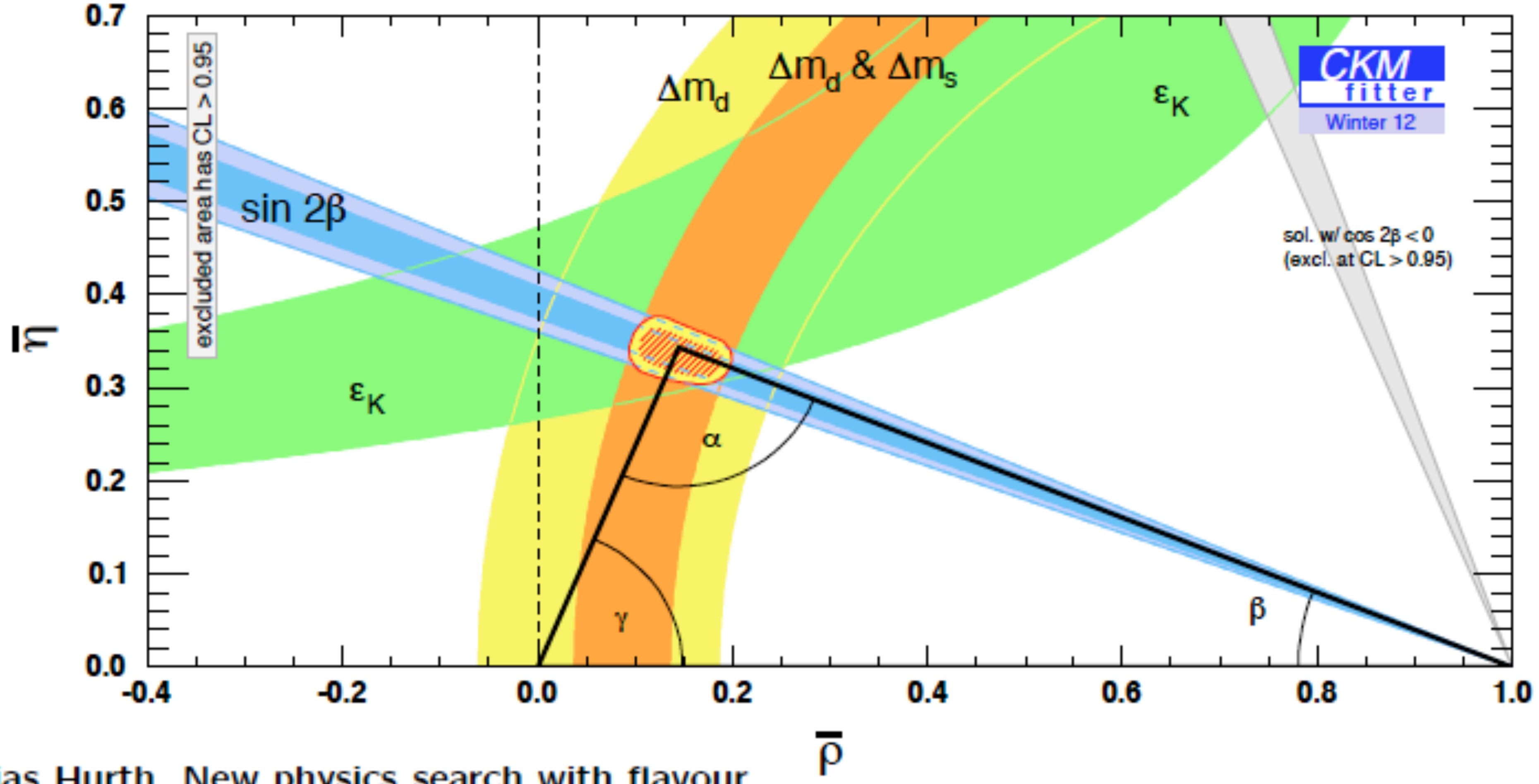


CP violating

observables

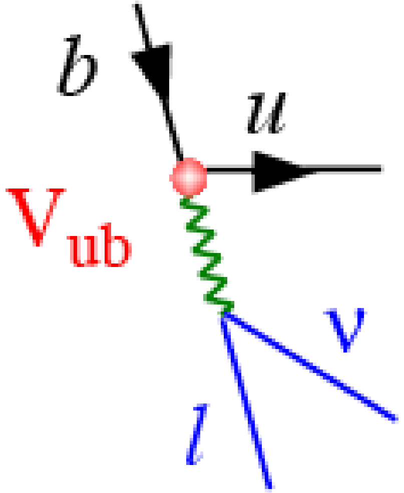


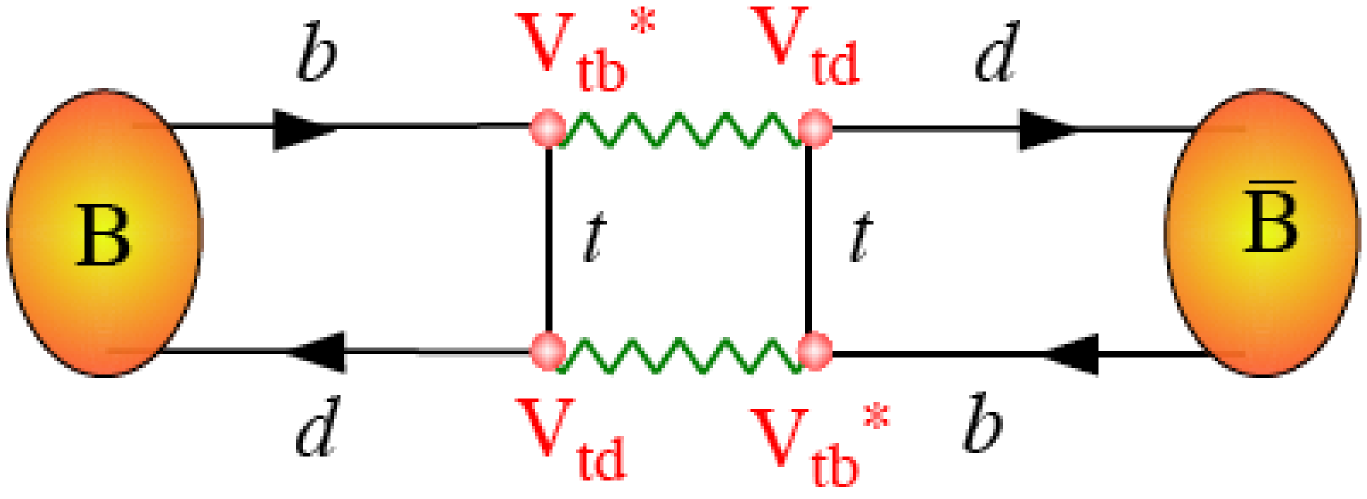
Tree processes



Loop processes

Most surprising is the consistency between the tree-level and loop-induced observables





Semileptonic tree-decays versus Neutral-meson mixing $\Delta F = 2$

SM-dominated

Potentially more sensitive to New Physics

There is much more data not shown in the unitarity fits which confirms the SM pedictions of flavour mixing like rare decays $(\Delta F = 1)$

Nobel Prize 2008

From left, Yoichiro Nambu, Makoto Kobayashi and Toshihide Masukawa, who shared the Nobel Prize in Physics on Tuesday

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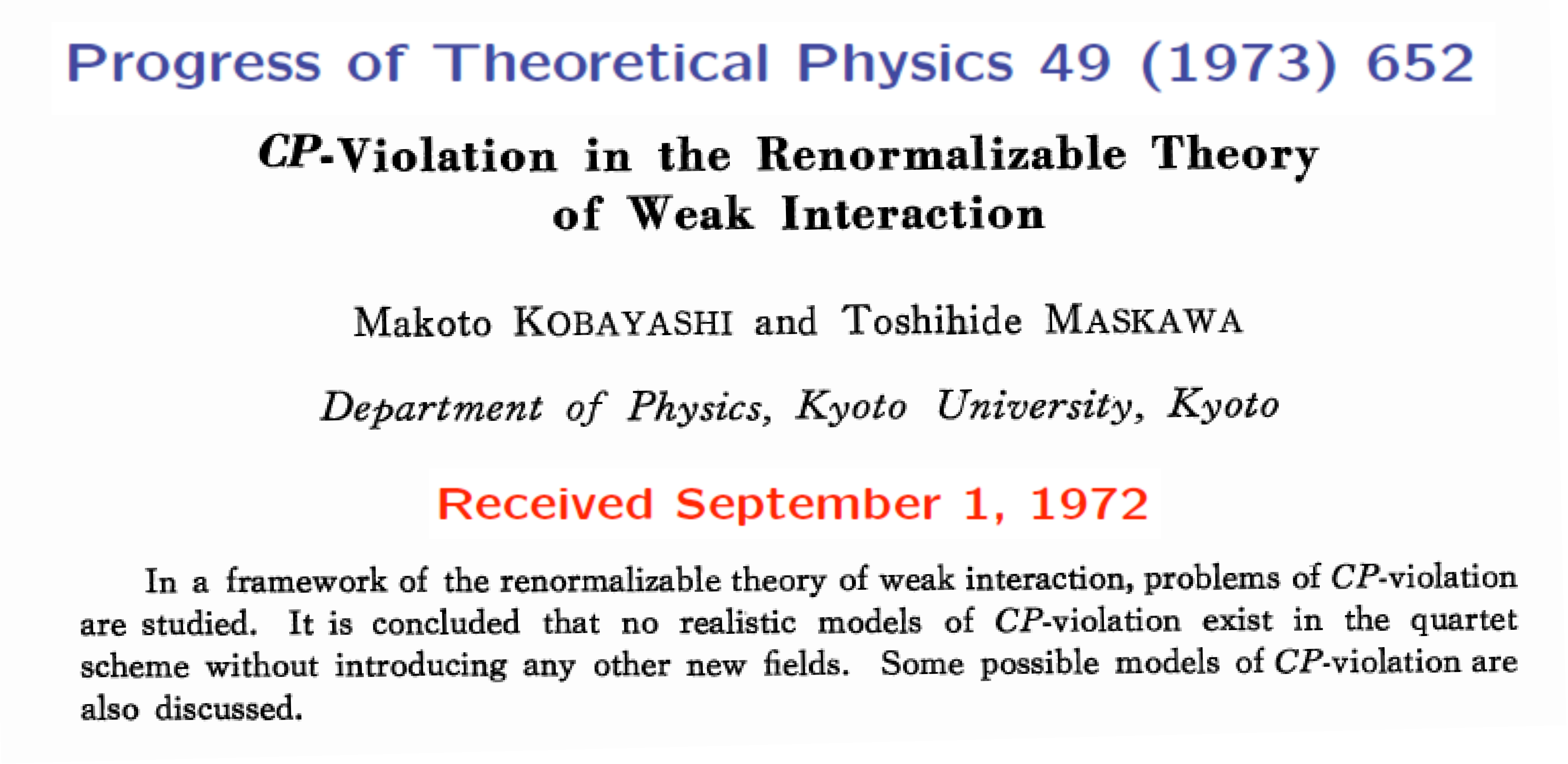

Progress of Theoretical Physics 49 (1973) 652

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

Received September 1, 1972

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

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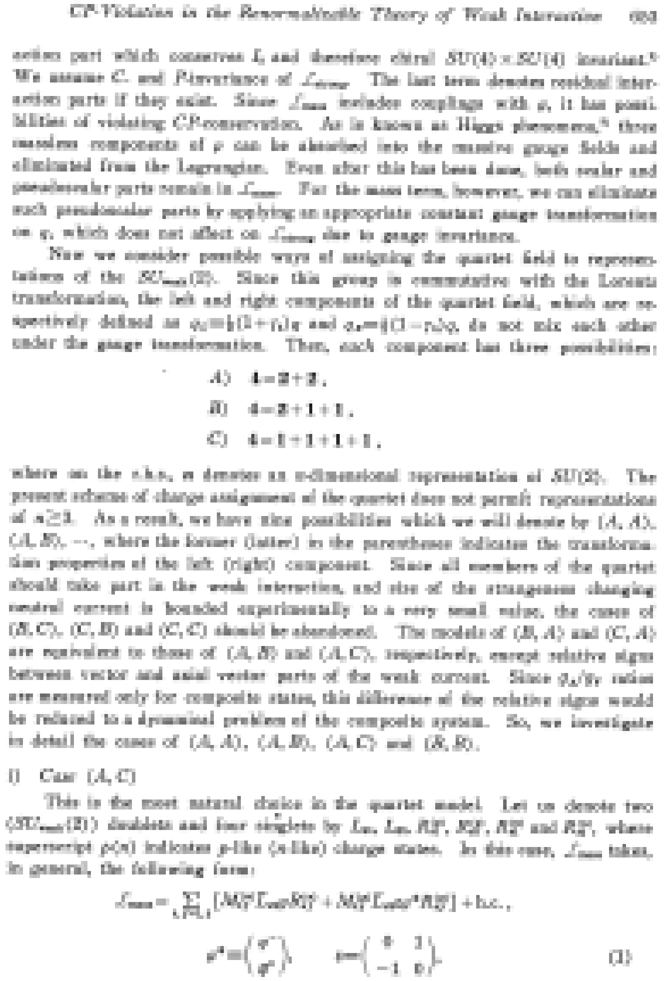
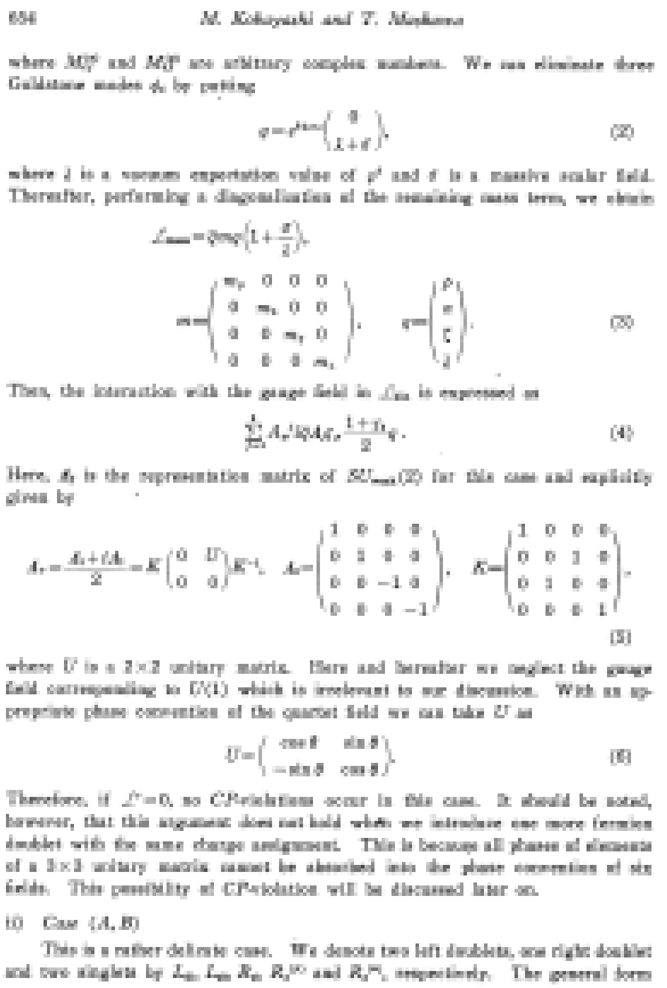
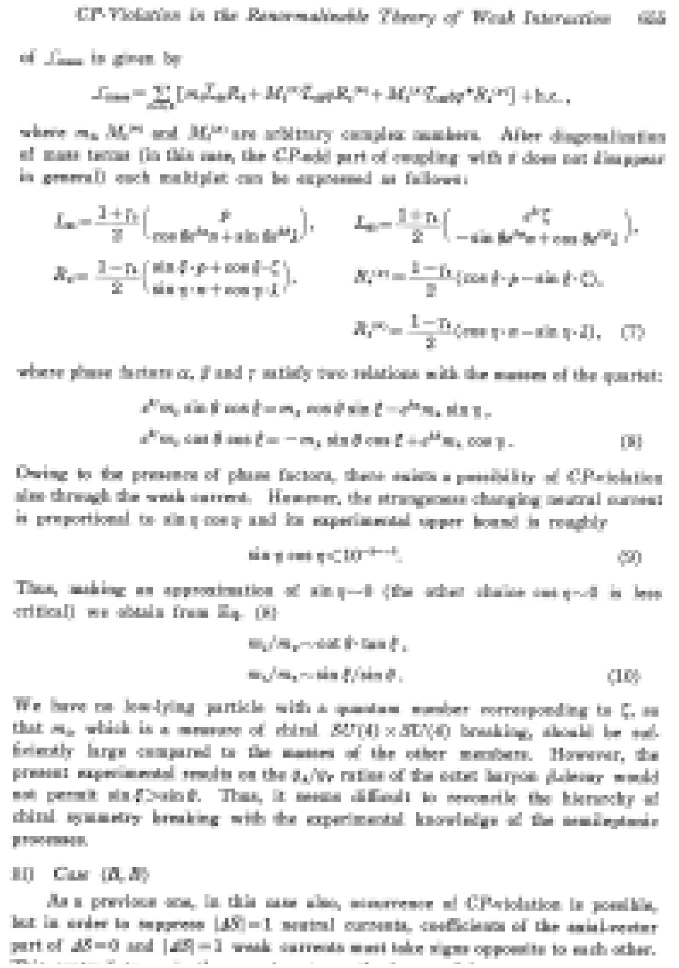
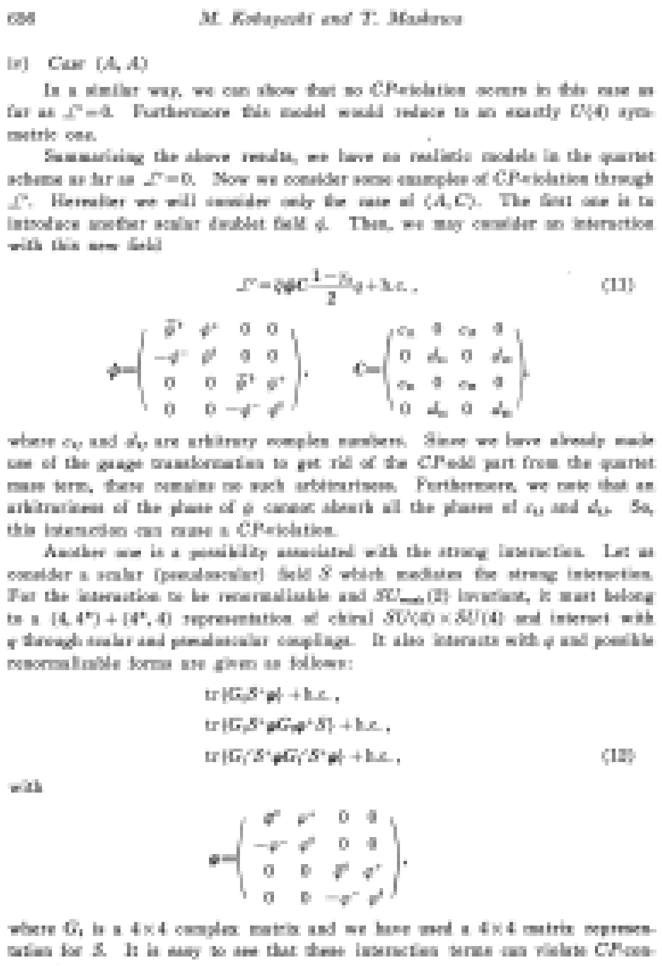
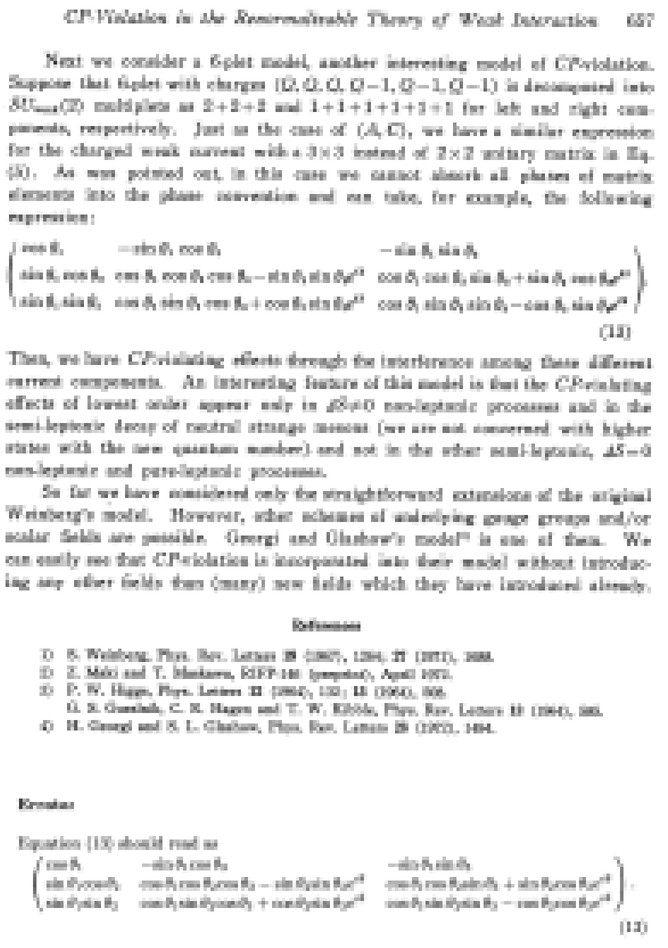
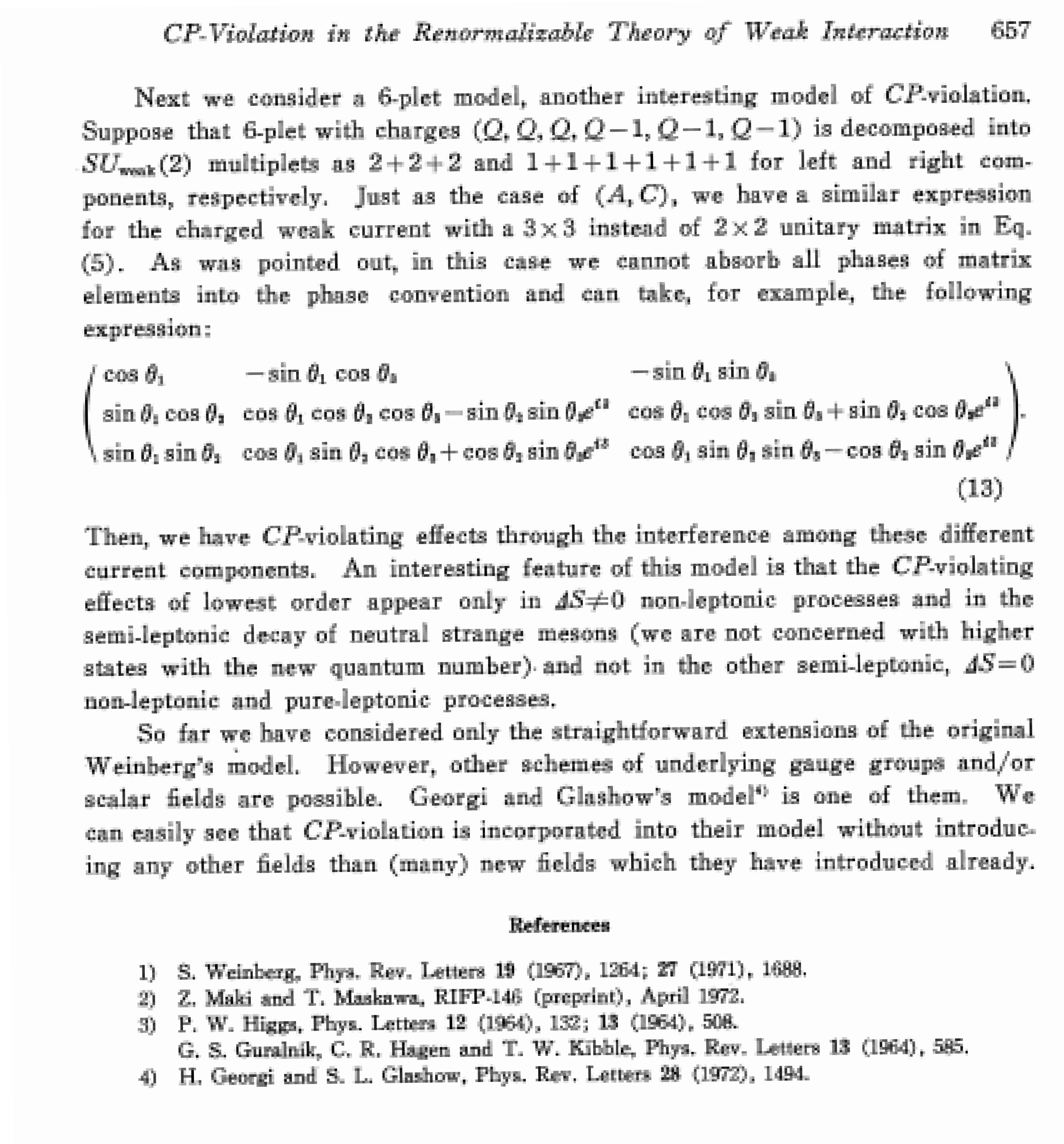












Next we consider a 6-plet model, another interesting model of CP-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{\text{weak}}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}. \tag{13}$$

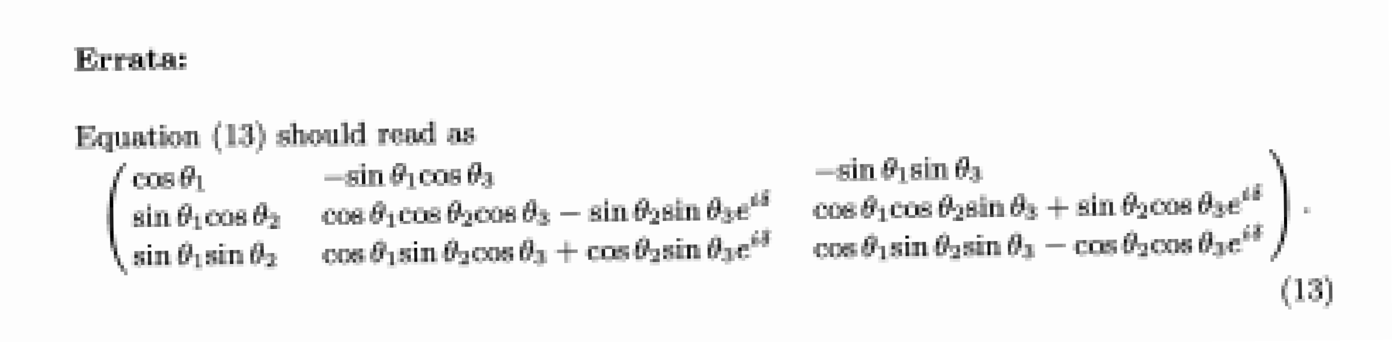
Then, we have CP-violating effects through the interference among these different current components. An interesting feature of this model is that the CP-violating effects of lowest order appear only in $\Delta S\neq0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

So far we have considered only the straightforward extensions of the original Weinberg's model. However, other schemes of underlying gauge groups and/or scalar fields are possible. Georgi and Glashow's model[4] is one of them. We can easily see that CP-violation is incorporated into their model without introducing any other fields than (many) new fields which they have introduced already.

References

1) S. Weinberg, Phys. Rev. Letters **19** (1967), 1264; **27** (1971), 1688.
2) Z. Maki and T. Maskawa, RIFP-146 (preprint), April 1972.
3) P. W. Higgs, Phys. Letters **12** (1964), 132; **13** (1964), 508.
G. S. Guralnik, C. R. Hagen and T. W. Kibble, Phys. Rev. Letters **13** (1964), 585.
4) H. Georgi and S. L. Glashow, Phys. Rev. Letters **28** (1972), 1494.

Erratum



Errata:

Equation (13) should read as

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3 - \sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3 + \sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3 + \cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3 - \cos\theta_2\cos\theta_3 e^{i\delta} \end{pmatrix}. \tag{13}$$

However,...

- CKM mechanism is the dominating effect for CP violation and flavour mixing in the quark sector;

  but there is still room for sizable new effects and new flavour structures (the flavour sector has only be tested at the 10% level in many cases).

- The SM does not describe the flavour phenomena in the lepton sector.

Flavour problem of SM

$$\mathcal{L}_{SM} = \mathcal{L}_{Gauge}(A_i, \psi_i) + \mathcal{L}_{Higgs}(\Phi, \psi_i, v)$$

- Gauge principle governs the gauge sector of the SM.

- No guiding principle in the flavour sector:

  CKM mechanism (3 Yukawa SM couplings) provides a phenomenological descripton of quark flavour processes, but leaves significant hierarchy of quark masses and mixing parameters unexplained.

  Compare for example:

  $|V_{us}| \approx 0.2, |V_{cb}| \approx 0.04, |V_{ub}| \approx 0.004$ versus $g_s \approx 1, g \approx 0.6, g' \approx 0.3$

Possible solutions to the SM flavour problem

- Approximate symmetries (Froggatt -Nielsen)
- Geometry in extra dimensions (Randall-Sundrum)

$$\Lambda_{\text{Flavour}} > \Lambda_{\text{NP}} \ ?$$

Many open fundamental questions of particle physics are related to flavour :

- How many families of fundamental fermions are there ?
- How are neutrino and quark masses and mixing angles are generated ?
- Do there exist new sources of flavour and CP violation ?
- Is there CP violation in the QCD gauge sector ?
- Relations between the flavour structure in the lepton and quark sector ?

Experimental evidence beyond SM:

- Dark matter (visible matter accounts for only 4% of the Universe)

- Neutrino masses (Dirac or Majorana masses ?)

- Baryon asymmetry of the Universe (new sources of CP violation needed)

Flavour problem of New Physics

How do FCNCs hide ?

Ambiguity of new physics scale from flavour data

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda_{\mathrm{NP}}} \mathcal{O}_i^{(5)} + \ldots$$

- SM as effective theory valid up to cut-off scale Λ_{NP}

Ambiguity of new physics scale from flavour data

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda_{\mathrm{NP}}} \mathcal{O}_i^{(5)} + \ldots$$

- SM as effective theory valid up to cut-off scale Λ_{NP}
- Typical example: $K^0 - \bar{K}^0$-mixing $\mathcal{O}^6 = (\bar{s}\, d)^2$:

$$c^{SM}/M_W^2 \times (\bar{s}\, d)^2 + c^{New}/\Lambda_{\mathrm{NP}}^2 \times (\bar{s}\, d)^2 \qquad \Rightarrow \quad \Lambda_{\mathrm{NP}} > 10^4\,\mathrm{TeV}$$

(tree-level, generic new physics)

Ambiguity of new physics scale from flavour data

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda_{\rm NP}} \mathcal{O}_i^{(5)} + \ldots$$

- SM as effective theory valid up to cut-off scale $\Lambda_{\rm NP}$

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(tree-level, generic new physics)

- Natural stabilisation of Higgs boson mass (hierarchy problem)

  (i.e. supersymmetry, little Higgs, extra dimensions) $\Rightarrow$ $\Lambda_{\rm NP} \leq 1\,{\rm TeV}$

- EW precision data $\leftrightarrow$ little hierarchy problem $\Rightarrow \Lambda_{\rm NP} \sim 3 - 10\,{\rm TeV}$

Ambiguity of new physics scale from flavour data

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda_{\mathsf{NP}}} \mathcal{O}_i^{(5)} + \ldots$$

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$$c^{SM}/M_W^2 \times (\bar{s}\,d)^2 + c^{New}/\Lambda_{\mathsf{NP}}^2 \times (\bar{s}\,d)^2 \qquad \Rightarrow \quad \Lambda_{\mathsf{NP}} > 10^4\,\mathsf{TeV}$$

(tree-level, generic new physics)

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(i.e. supersymmetry, little Higgs, extra dimensions) $\Rightarrow \quad \Lambda_{\mathsf{NP}} \leq 1\mathsf{TeV}$

- EW precision data ↔ little hierarchy problem $\Rightarrow \Lambda_{\mathsf{NP}} \sim 3 - 10\mathsf{TeV}$

Possible New Physics at the TeV scale has to have a very non-generic flavour structure

$$(\, C^i_{\mathsf{SM}}/M_W + C^i_{\mathsf{NP}}\,/\Lambda_{\mathsf{NP}}\ ) \times \mathcal{O}_i$$

Ambiguity of new physics scale from flavour data

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda_{\mathrm{NP}}} \mathcal{O}_i^{(5)} + \ldots$$

- SM as effective theory valid up to cut-off scale Λ_{NP}

- Typical example: $K^0 - \bar{K}^0$-mixing $\mathcal{O}^6 = (\bar{s}\, d)^2$:

$$c^{SM}/M_W^2 \times (\bar{s}\, d)^2 + c^{New}/\Lambda_{\mathrm{NP}}^2 \times (\bar{s}\, d)^2 \qquad \Rightarrow \quad \Lambda_{\mathrm{NP}} > 10^4\,\mathrm{TeV}$$

(tree-level, generic new physics)

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(i.e. supersymmetry, little Higgs, extra dimensions) $\Rightarrow$ $\Lambda_{\mathrm{NP}} \leq 1\mathrm{TeV}$

- EW precision data ↔ little hierarchy problem $\Rightarrow$ $\Lambda_{\mathrm{NP}} \sim 3 - 10\mathrm{TeV}$

The indirect information will be most valuable when the general nature of new physics will be identified in the direct search (LHC), especially when the mass scale of the new physics will be fixed.

$$(\, C^i_{\mathrm{SM}}/M_W + C^i_{\mathrm{NP}}\,/\Lambda_{\mathrm{NP}}\,) \times \mathcal{O}_i$$

Example: Supersymmetry

- In the general MSSM too many contributions to flavour violation
  - CKM-induced contributions from H^+, χ^+ exchanges (quark mixing)
  - flavour mixing in the sfermion mass matrix

- Possible solutions:
  - Decoupling: Sfermion mass scale high
    (i.e. split supersymmetry)
  - Super-GIM: Sfermion masses almost degenerate
    (i.e. gauge-mediated supersymmetry breaking)
  - Alignment: Sfermion mixing suppressed

- Dynamics of flavour ↔ mechanism of SUSY breaking
  ($BR(b \to s\gamma) = 0$ in exact supersymmetry)

Parameter bounds from flavour physics are model-dependent

Status of the inclusive mode $\bar{B} \to X_s\gamma$

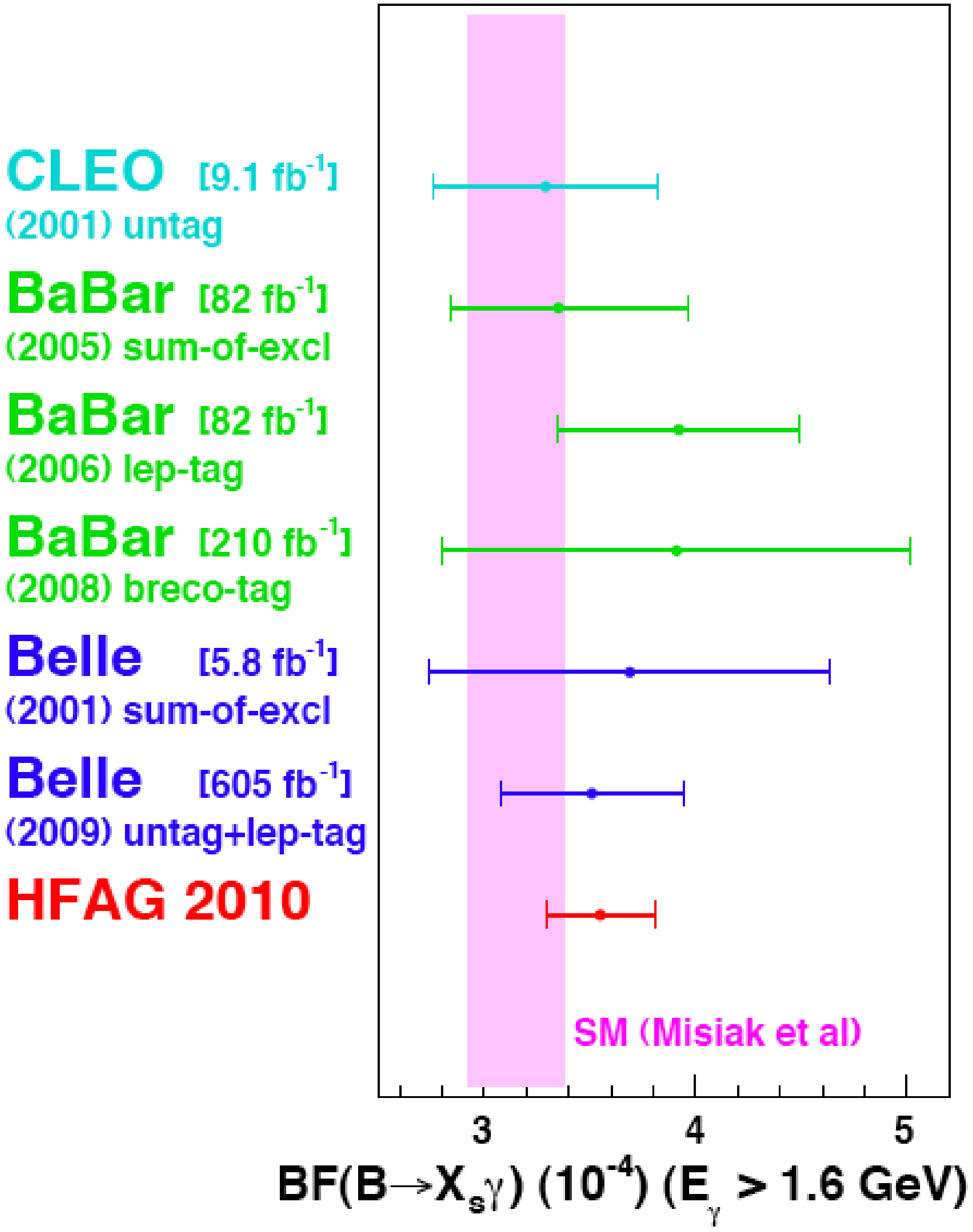
$$\text{HFAG: } \mathcal{B}(B \to X_s\gamma) = (3.55 \pm 0.24) \times 10^{-4} \text{ (for } E_\gamma > 1.6 \text{ GeV)}$$

VS

$$\text{SM: } \mathcal{B}(B \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4} \text{ (for } E_\gamma > 1.6 \text{ GeV)}$$

PRL98,022003(2007)

NNLL calculation by Misiak et al.
(collaboration of 17 theorists)



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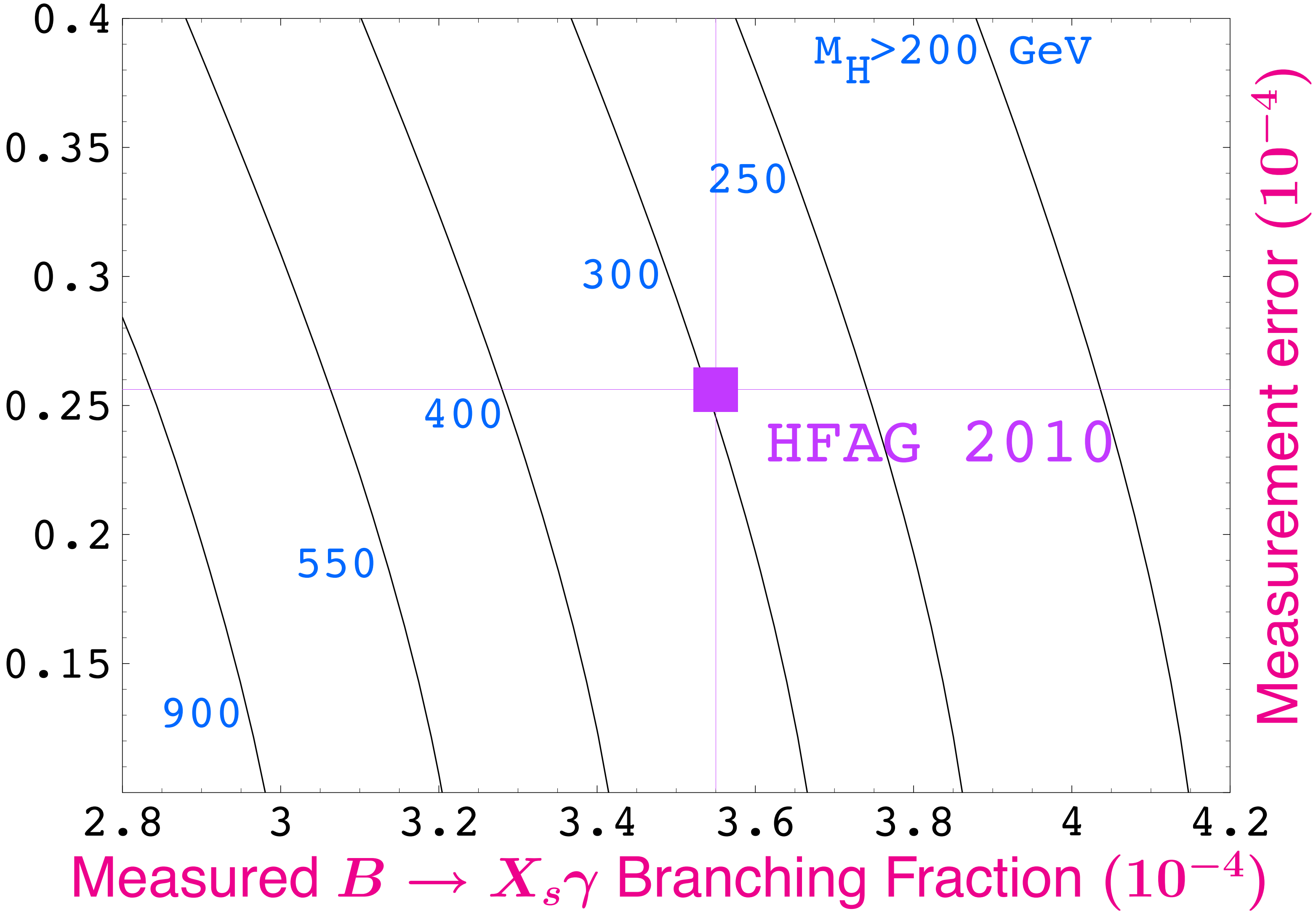
vs

SM: $\mathcal{B}(B \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ (for $E_\gamma > 1.6$ GeV) PRL98,022003(2007)

Bound on charged Higgs mass in Two-Higgs-Doublet model



$M_{H+} > 295$ GeV

at 95% CL

not

valid in MSSM

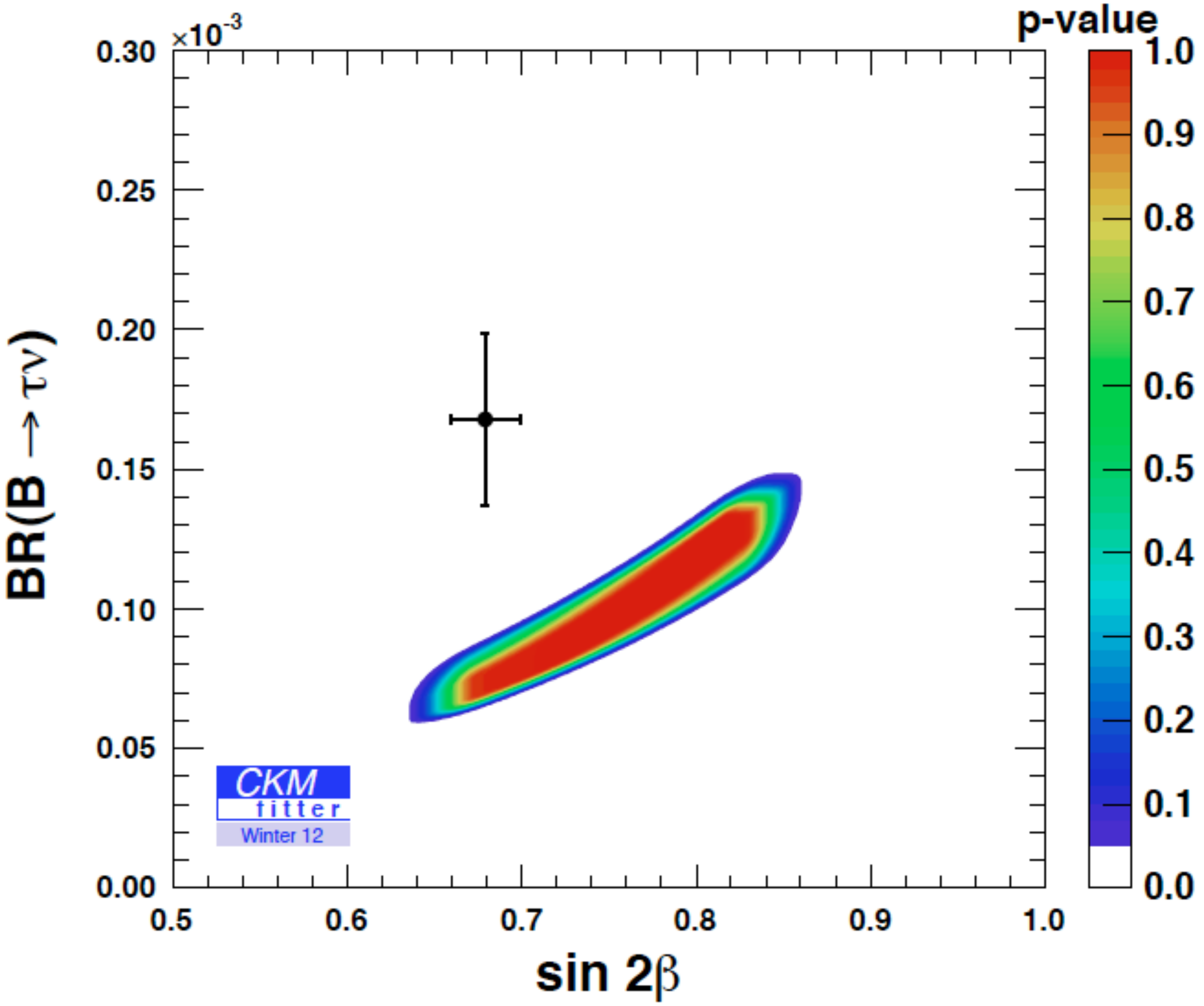
Courtesy of Mikihiko Nakao

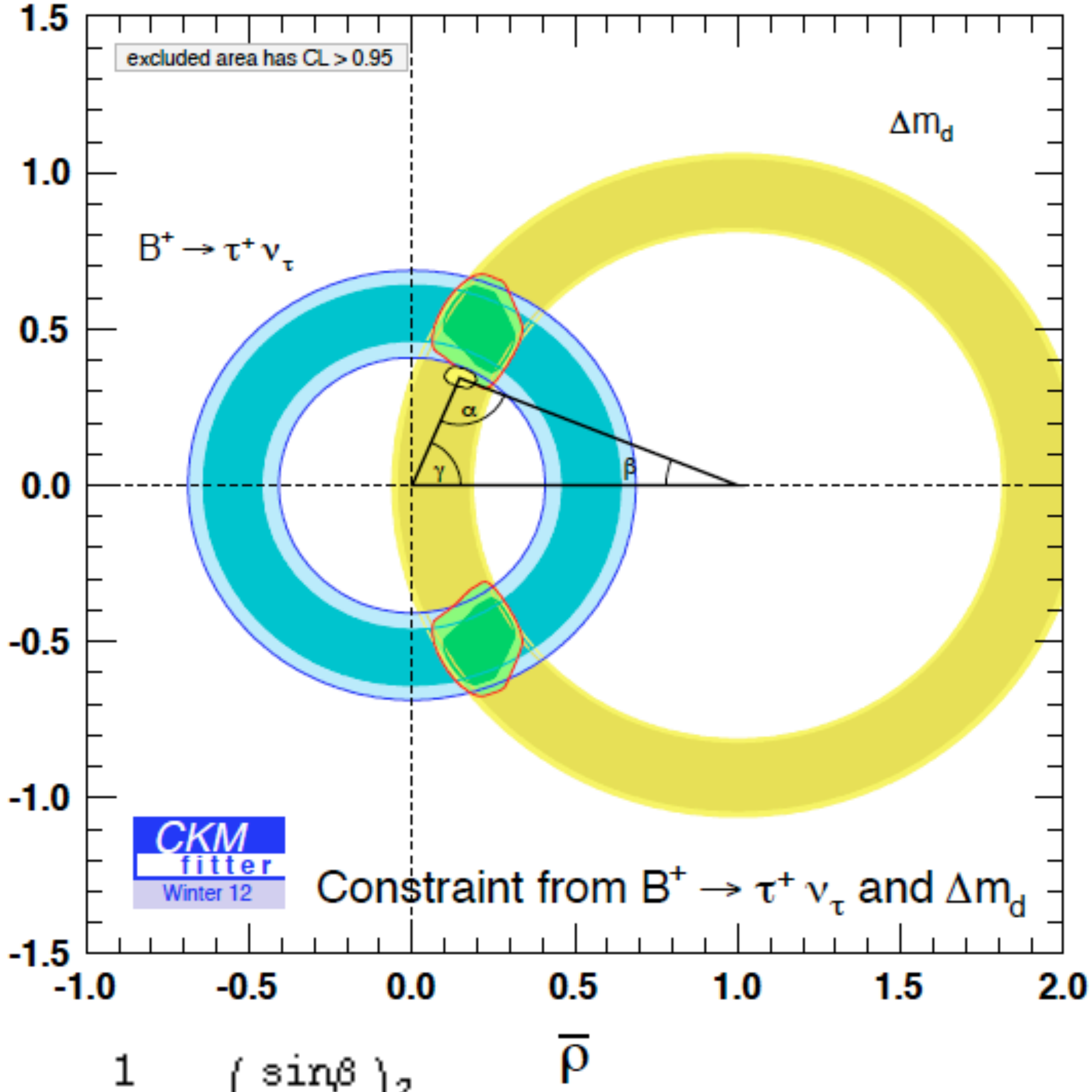
Status report in view of the latest LHCb data

$\mathcal{B}(B \to \tau\nu)$ versus $\sin\beta$ in the CKM-fit

Specific correlation between $\mathcal{B}(B \to \tau\nu)$ and $\sin\beta$

It is a bit at odds with the direct experimental determination: $\mathcal{B}(B \to \tau\nu)$ too high, $\sin\beta$ too low ! $(\approx 3\sigma)$



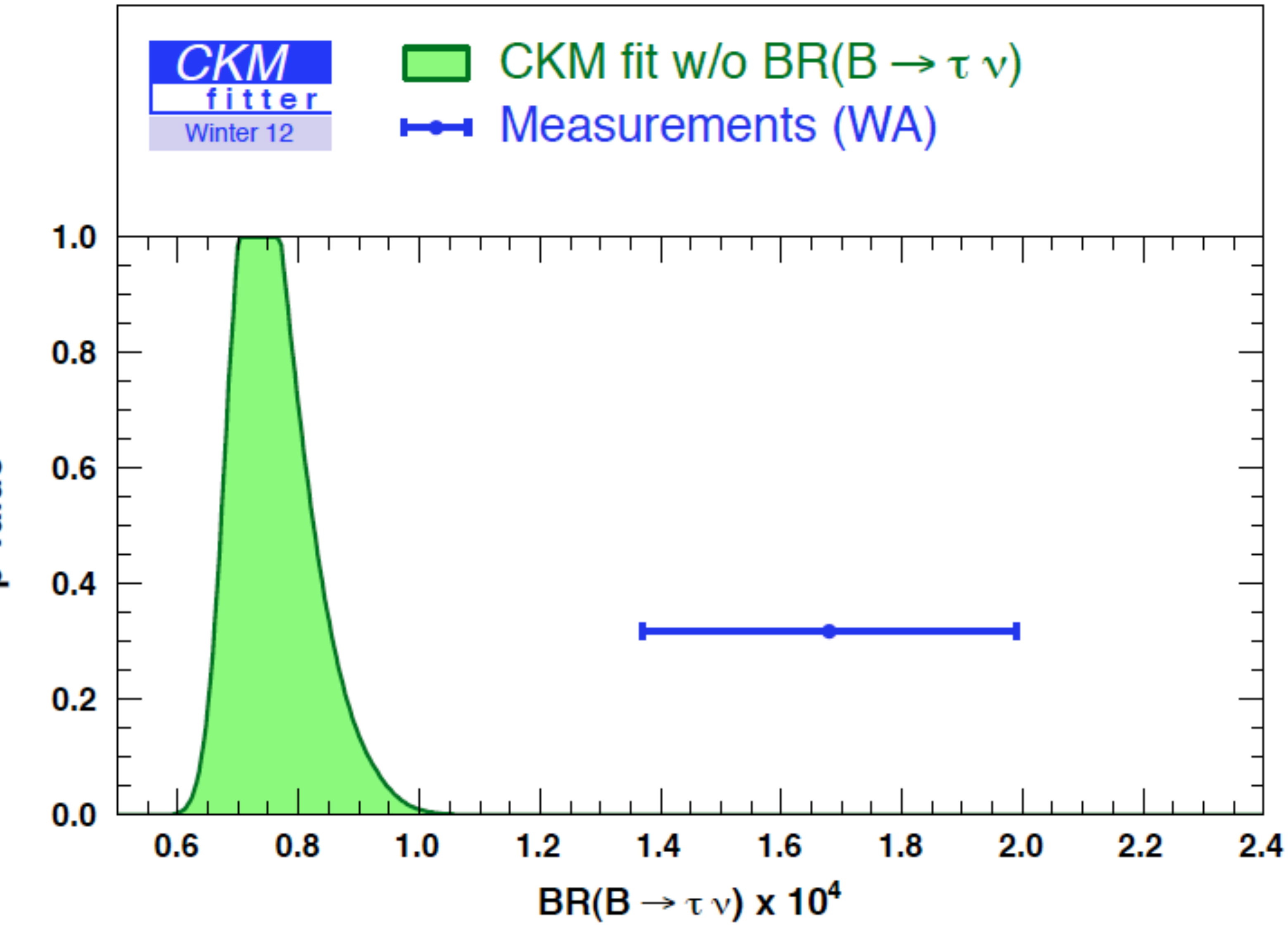


Constraint from $B^+ \to \tau^+ \nu_\tau$ and Δm_d

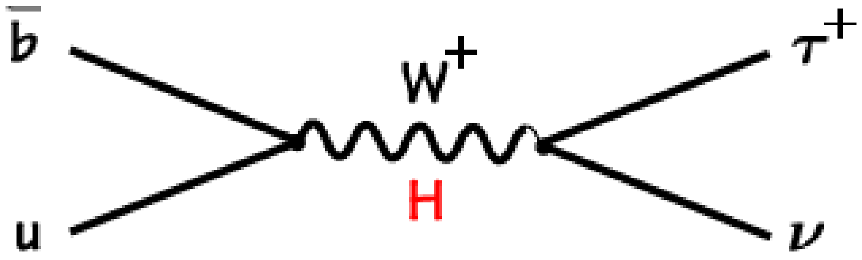
$$\frac{\mathrm{BR}\,(B \to \tau\,\nu)}{\Delta m_d} = \frac{3\,\pi}{4}\,\frac{m_\tau^2}{m_W^2\, S\,(x_t)}\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \tau_{B^+}\,\frac{1}{B_{Bd}}\,\frac{1}{|V_{ud}|^2}\left(\frac{\sin\beta}{\sin\gamma}\right)^2$$

May be solved by NP mixing phase $\Phi_d^\Delta < 0$

$\mathcal{B}(B \to \tau\nu)$: Tension between direct measurement and indirect fit



(2.8σ)

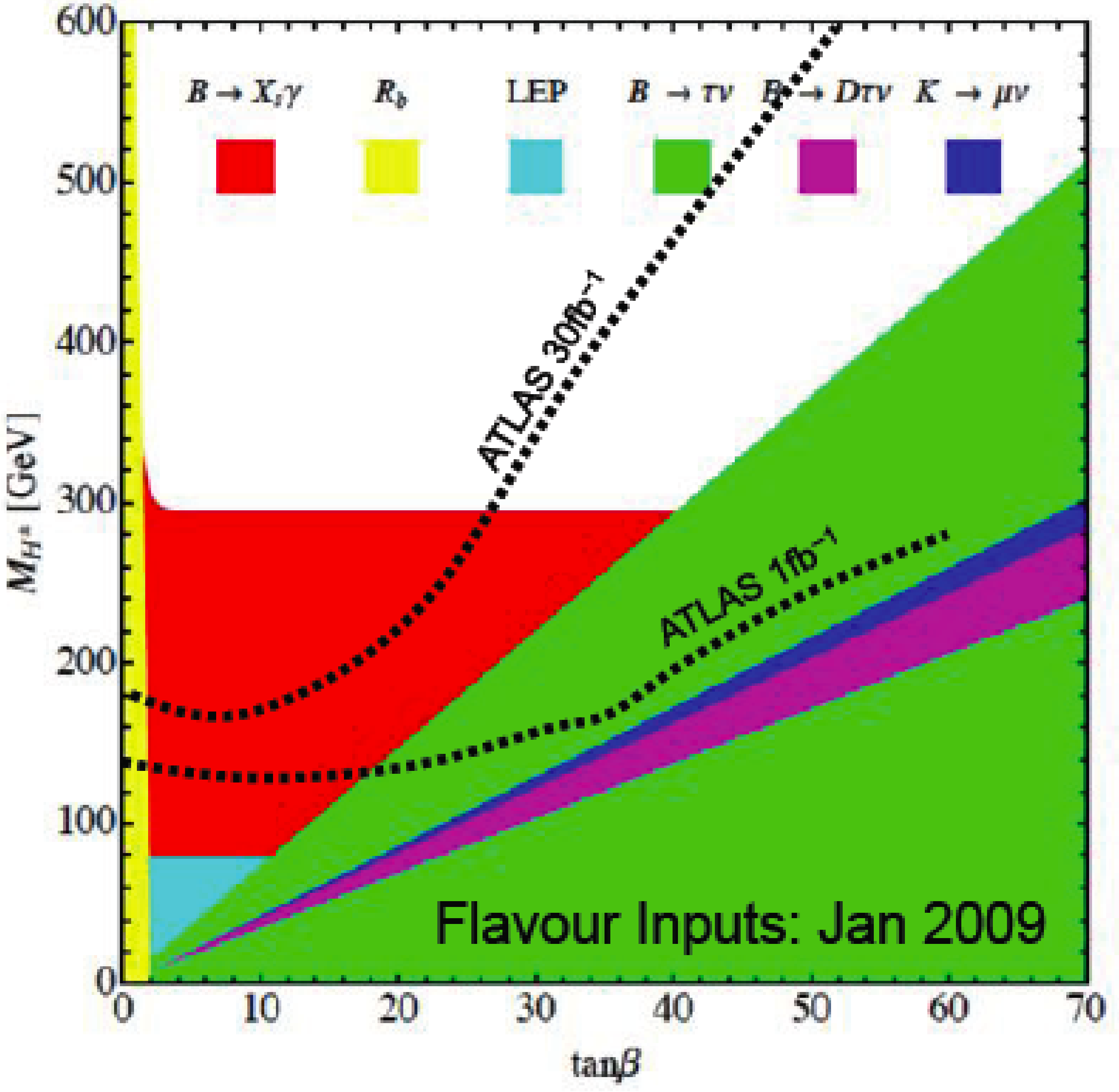


$$B_{SM}(B^+ \to \tau^+ \nu) = \frac{G_F^2 m_B m_\tau^2}{8\pi}(1 - \frac{m_\tau^2}{m_B^2}) f_B^2 |V_{ub}|^2 \tau_B$$

2HDM (type II): $B(B^+ \to \tau^+ \nu) = B_{SM} \times (1 - \frac{m_B^2}{m_{H^+}^2} \tan^2 \beta)^2$

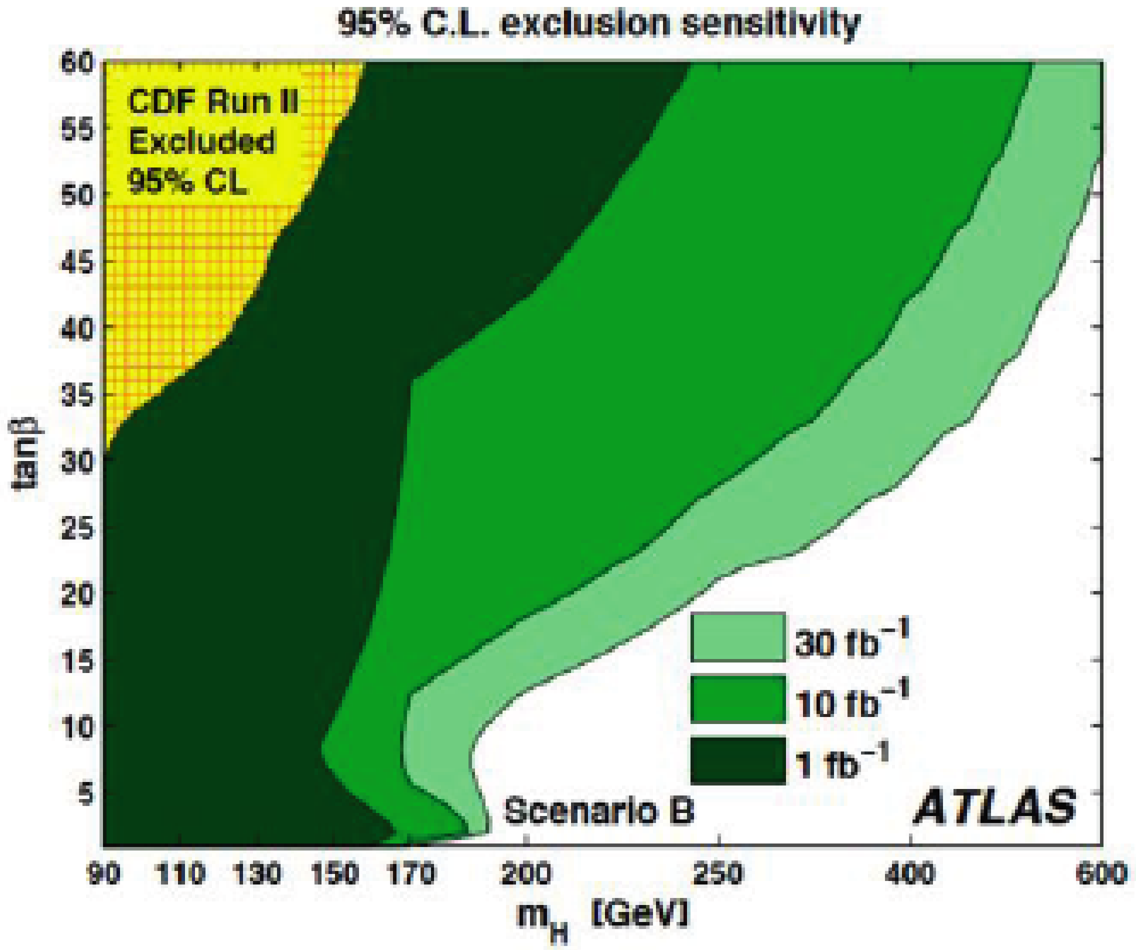
LHC versus Flavour constraints

Combined Higgs search constraint from ATLAS: arXiv:0901.1502



U. Haisch 0805.2141
2HDM

Converted constraints expected from ATLAS onto the plot by hand.



Courtesy of Adrian Bevan

LHC versus Flavour constraints

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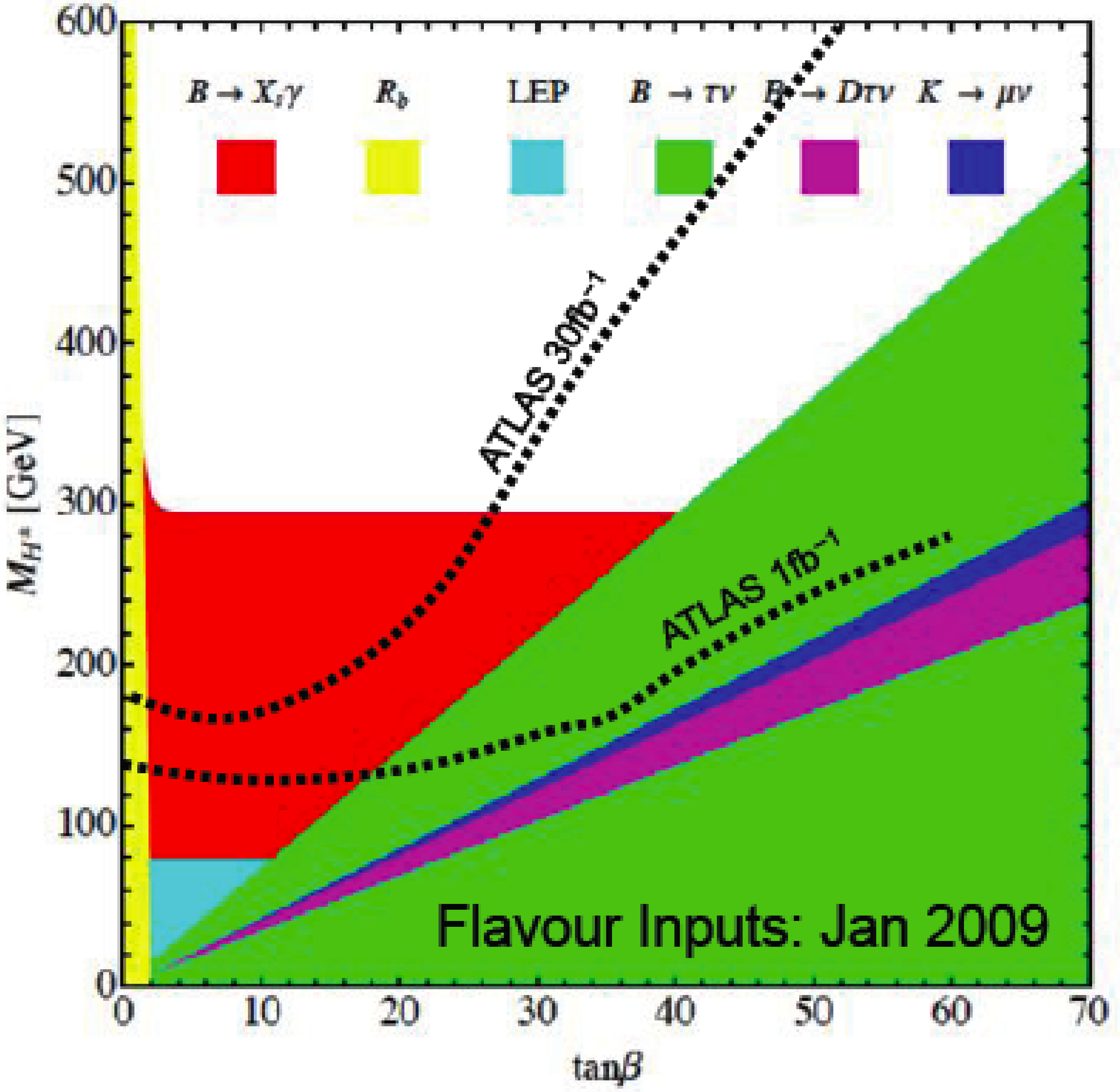
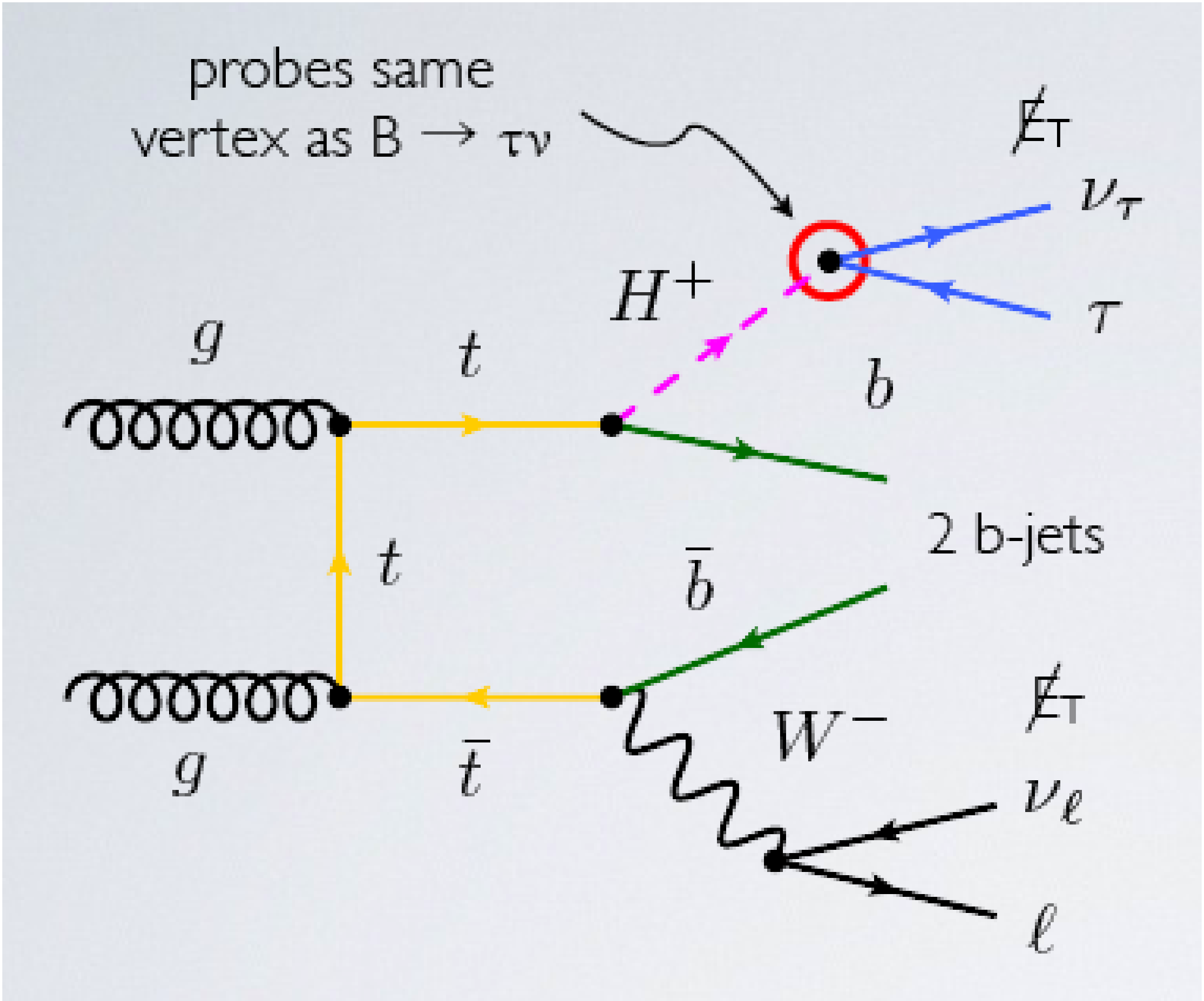


U. Haisch 0805.2141
2HDM



Courtesy of Uli Haisch

$B_q - \bar{B}_q$ mixing in the LHCb era

Is there new physics in the mixing phase ?

Some theory on B_q mixing

- $B_q - \bar{B}_q$ oscillations are governed by the Schrödinger equation

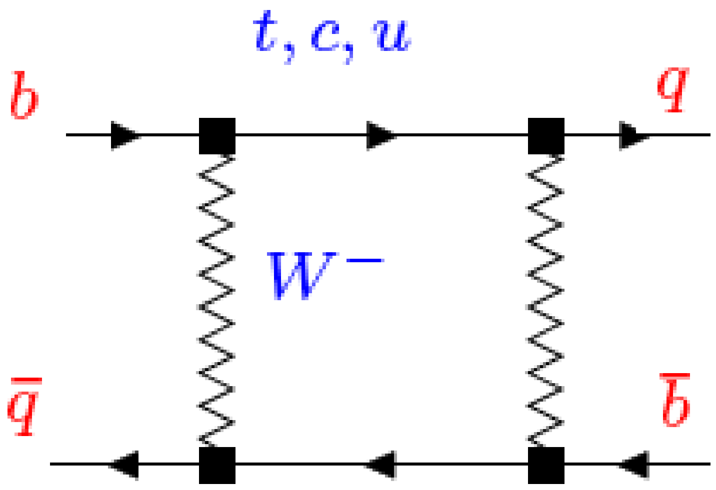
$$i\frac{d}{dt}\begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix} = \left(\hat{M} - \frac{i}{2}\hat{\Gamma}\right)\begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix}$$

- Off-diagonal elements M_{12} and Γ_{12} with $\phi^{\text{mix}} = arg(-M_{12}/\Gamma_{12})$

Mass difference of physical eigen states B_H and B_L

$$\Delta M := M_H - M_L = 2|M_{12}|$$

M_{12} dispersive part (sensitive to heavy particles)



Decay rate difference

$$\Delta\Gamma := \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos\phi$$

Γ_{12} absorptive part (light internal particles, not new physics)

- Large uncertainties: M_{12} (Bag parameter, f_B), Γ_{12} (OPE: $m_b \gg \Lambda_{QCD}$)

Γ_{12}/M_{12} best (improved by new operator basis)

Nierste,Lenz,hep-ph/0612167,0802.0977

Model-independent approach to $\Delta F = 2$ amplitudes

- $\prec B_q | \mathcal{H}_{\Delta F=2}^{SM+NP} | \bar{B}_q \succ \quad \equiv \quad \prec B_q | \mathcal{H}_{\Delta F=2}^{SM} | \bar{B}_q \succ \times \; \mathrm{Re}(\Delta_q) + i\mathrm{Im}(\Delta_q)$

  $2\theta_q \equiv arg(\Delta_q)$

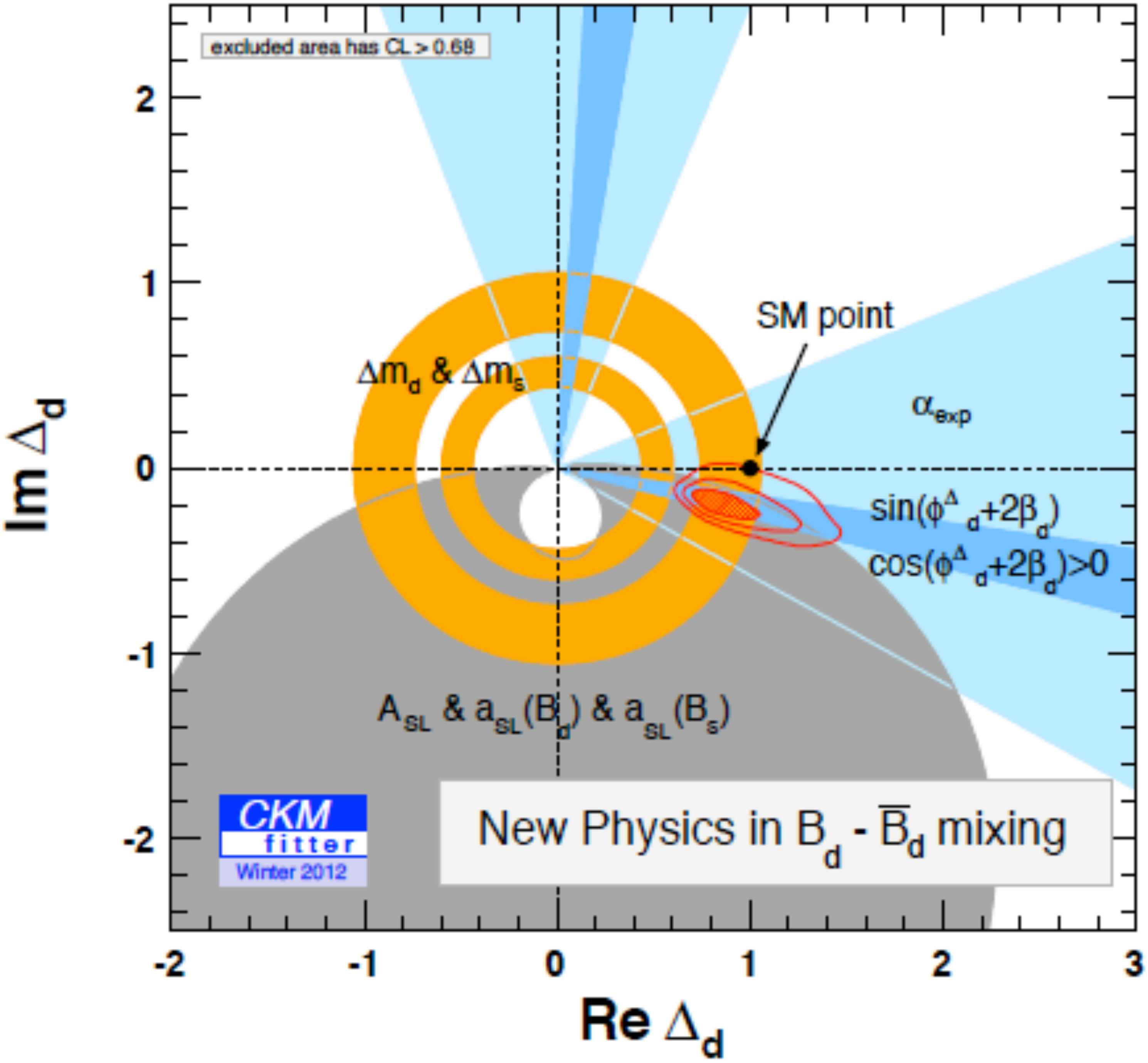
- If we assume $\Gamma_{12,q} = \Gamma_{12,q}^{\mathrm{SM}}$: $\quad M_{12,q} \equiv M_{12,q}^{\mathrm{SM}} \times \Delta_q$

- Some observables sensitive to $\Delta F = 2$ new physics:
  - $\Delta M_q = 2 |M_{12,q}^{\mathrm{SM}}| \times |\Delta_q|$
  - $\Delta |\Gamma_q| = 2 |\Gamma_{12,q}| \times \cos(\phi_q^{\mathrm{SM}} + 2\theta_q)$
  - $a_{\mathrm{sl}}^q = \mathrm{Im}(\Gamma_{12,q}/M_{12,q}) = (|\Gamma_{12,q}|/|M_{12,q}|) \times \sin(\phi_q^{\mathrm{SM}} + 2\theta_q)\,/\,|\Delta_q|$

  - $B_d \to J/\psi K : \; 2\beta_d^{SM} + 2\theta_d$
  - $B_s \to J/\psi \phi : \; 2\beta_s^{SM} - 2\theta_s$

New physics in $B_d - \bar{B}_d$ mixing ?

- $\prec B_q|\mathcal{H}^{SM+NP}_{\Delta F=2}|\bar{B}_q \succ \;\equiv\; \prec B_q|\mathcal{H}^{SM}_{\Delta F=2}|\bar{B}_q \succ \times\ \mathrm{Re}(\Delta_q) + i\mathrm{Im}(\Delta_q)$



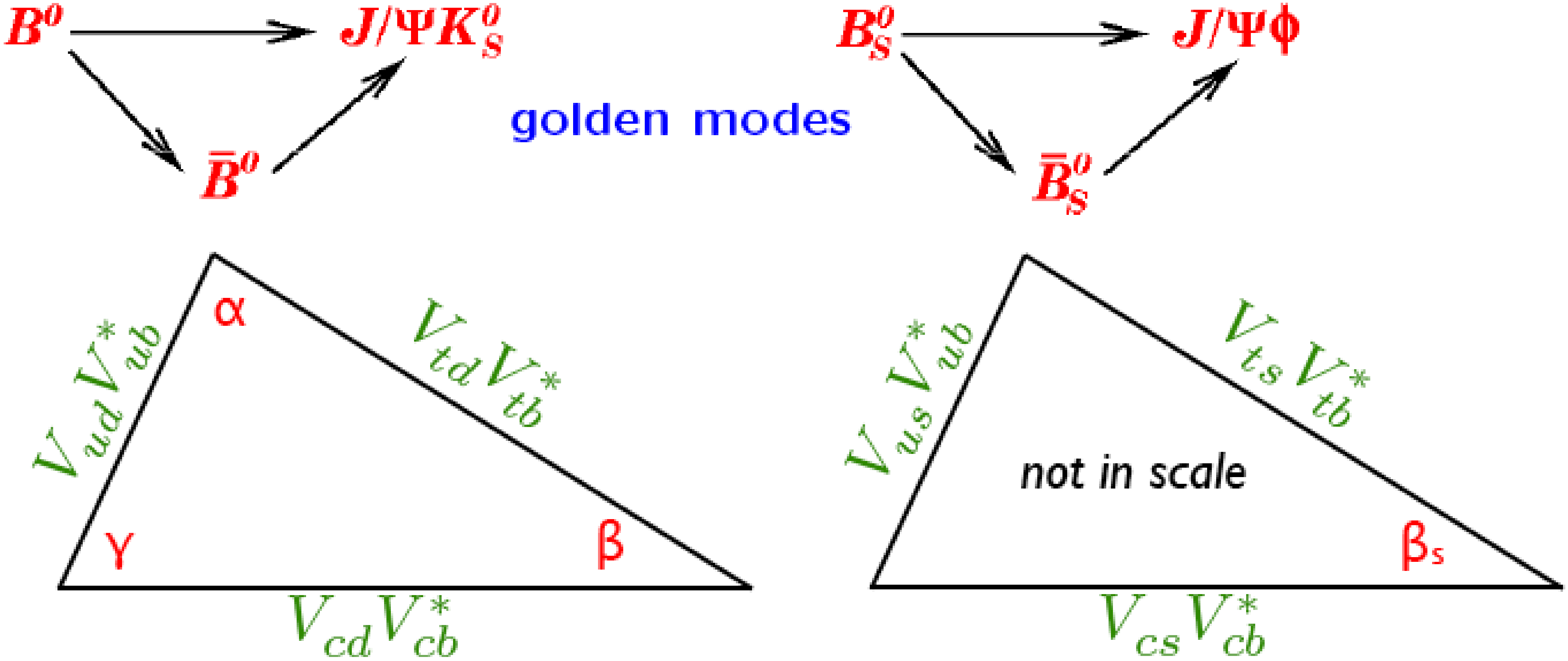
$arg(\Delta_q) = 2\theta_q = \Phi^\Delta_q,\ q = d$

- SM hypothesis $\Delta_d = 1$ (2D) disfavored by 3σ (2.7σ 2010)

- NP phase $\Phi^\Delta_d < 0$ would resolve $\mathcal{B}(B \to \tau\nu)$ - $\sin\beta$ tension

CP violation in $B_s \to J/\psi\Phi$ decays

- CP violation through interference of decay with and without mixing



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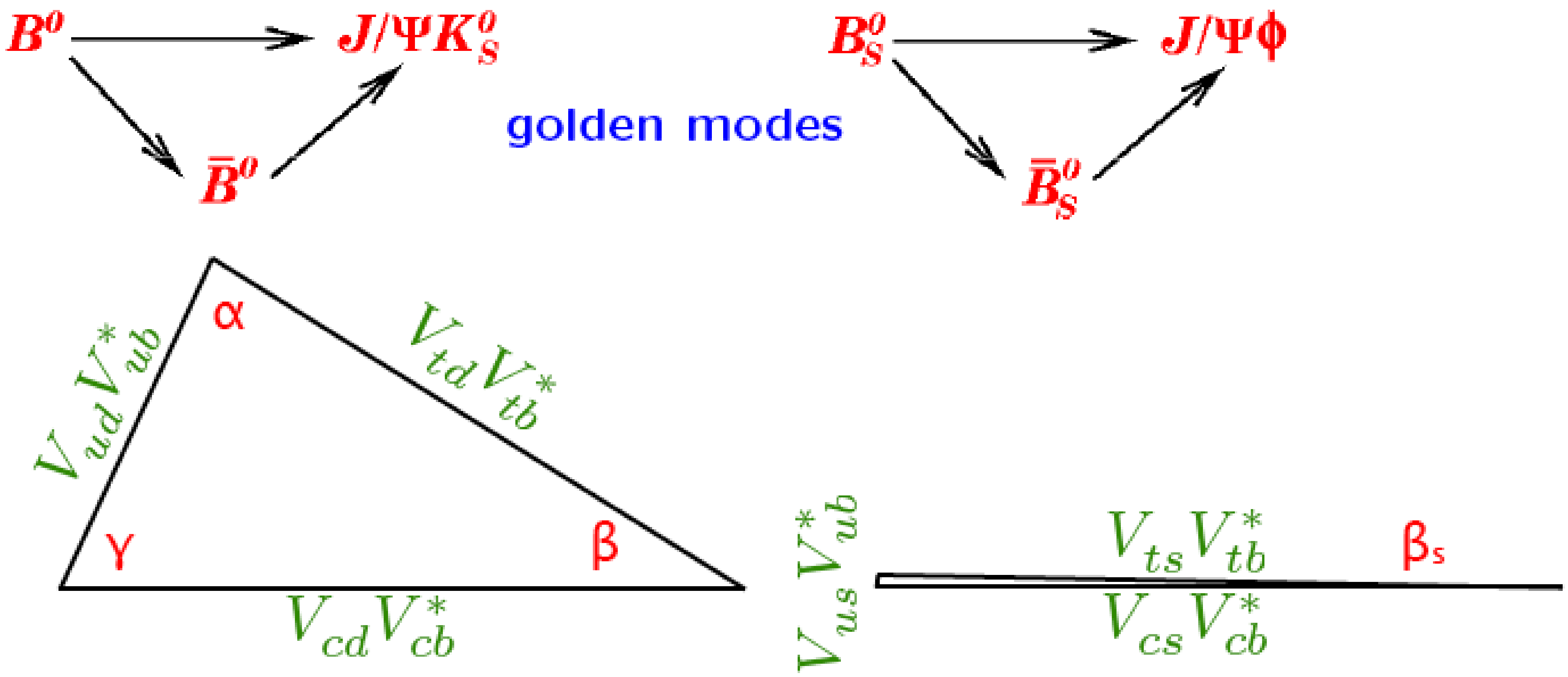


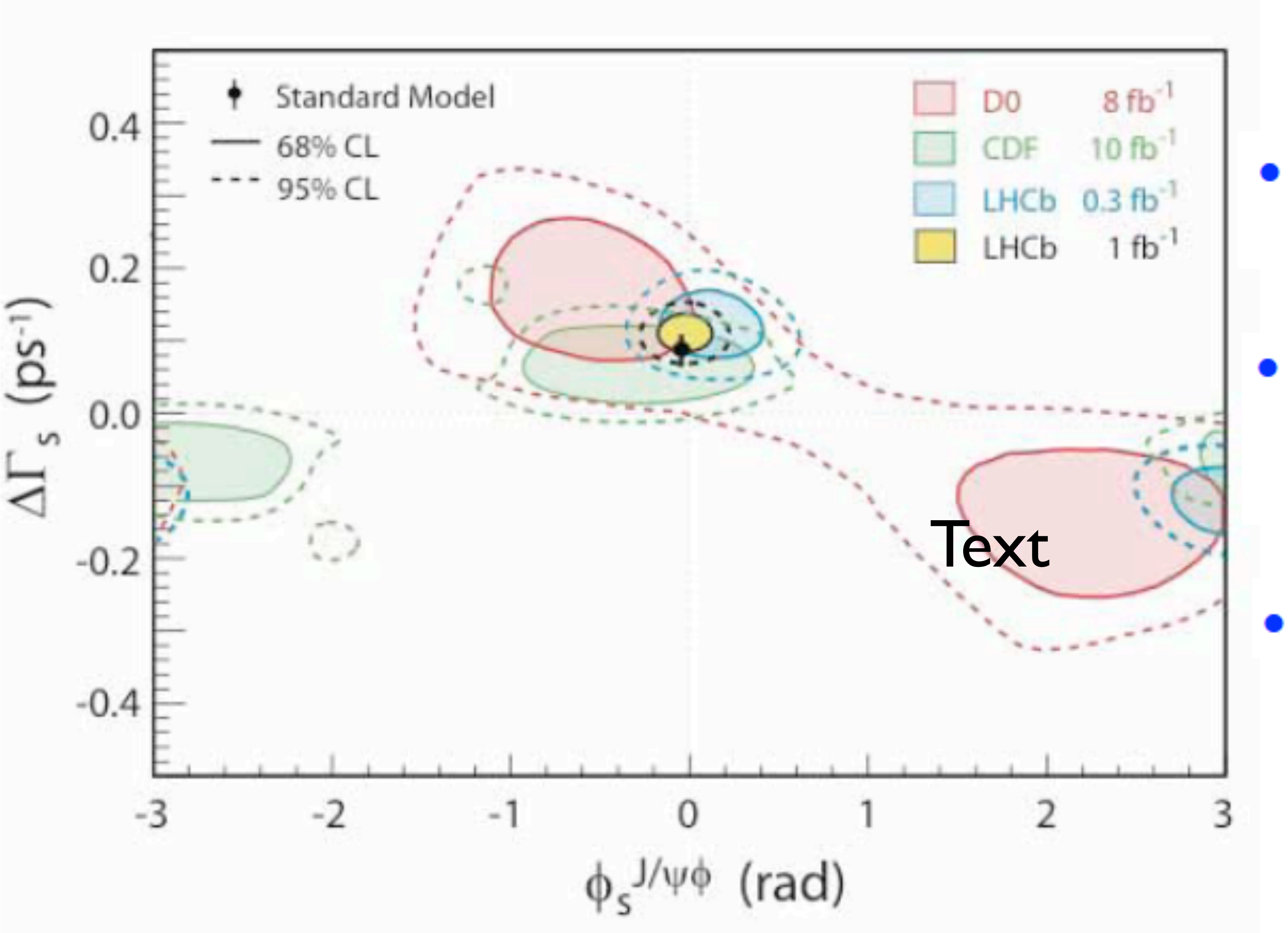
- Phase small: $2\beta_s^{\text{SM}} = -arg((V_{ts}V_{tb}^*)^2/(V_{cs}V_{cb}^*)^2) = (2.1 \pm 0.1)^o$

CKM-fitter, arXiv:1008.1593

- New physics affects the CP violation phase as: $2\beta_s^{\text{SM}} - 2\theta_s^{\text{NP}}$

New LHCb measurement ($1 fb^{-1}$)

LHCb-CONF-2012-002



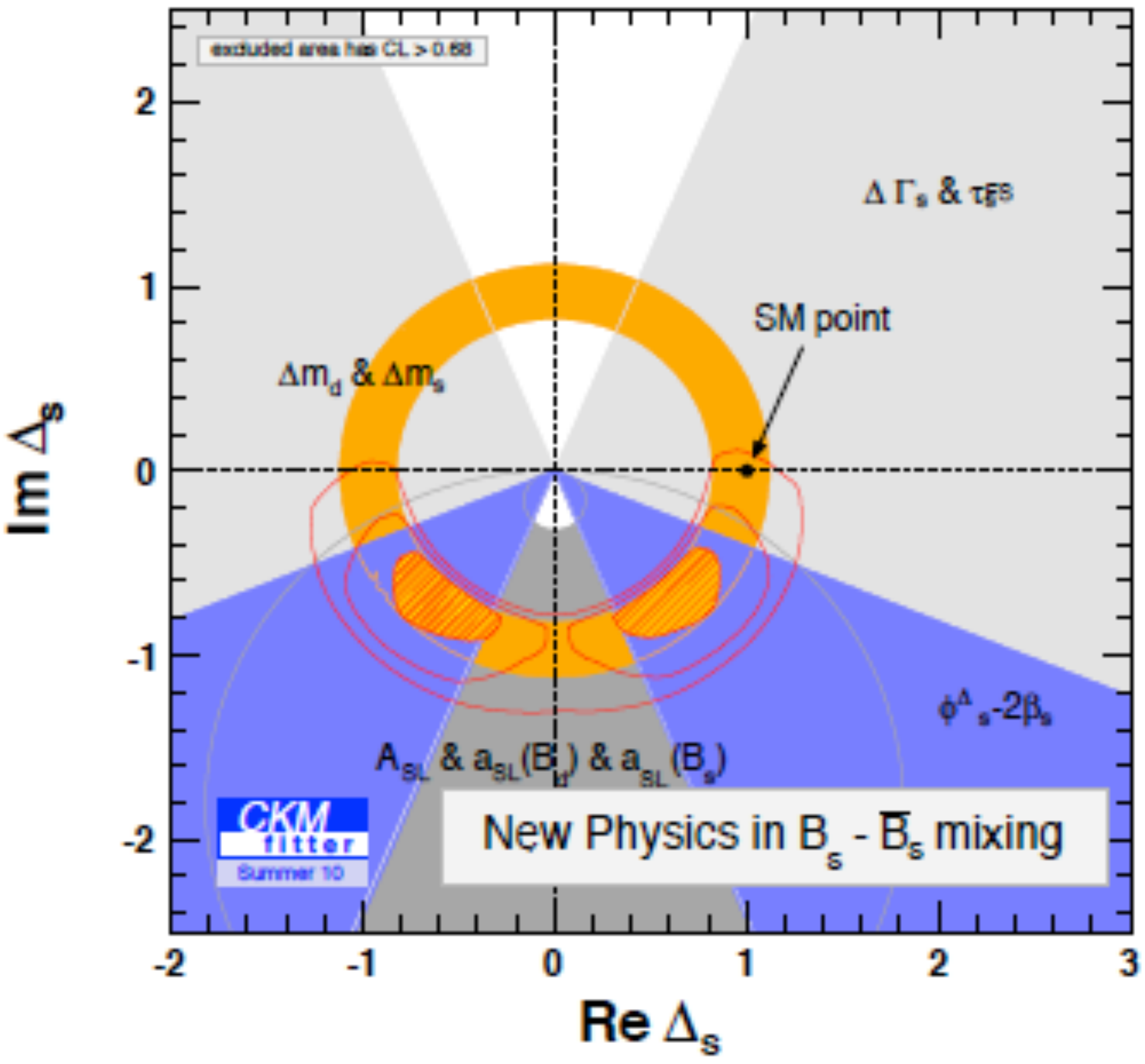
- Measurement right on the SM prediction!
- Fully consistent with previous CDF and D0 measurements of $B_s \to J/\psi\Phi$.
- Two-fold ambiguity resolved.

LHCb-PAPER-2012-28

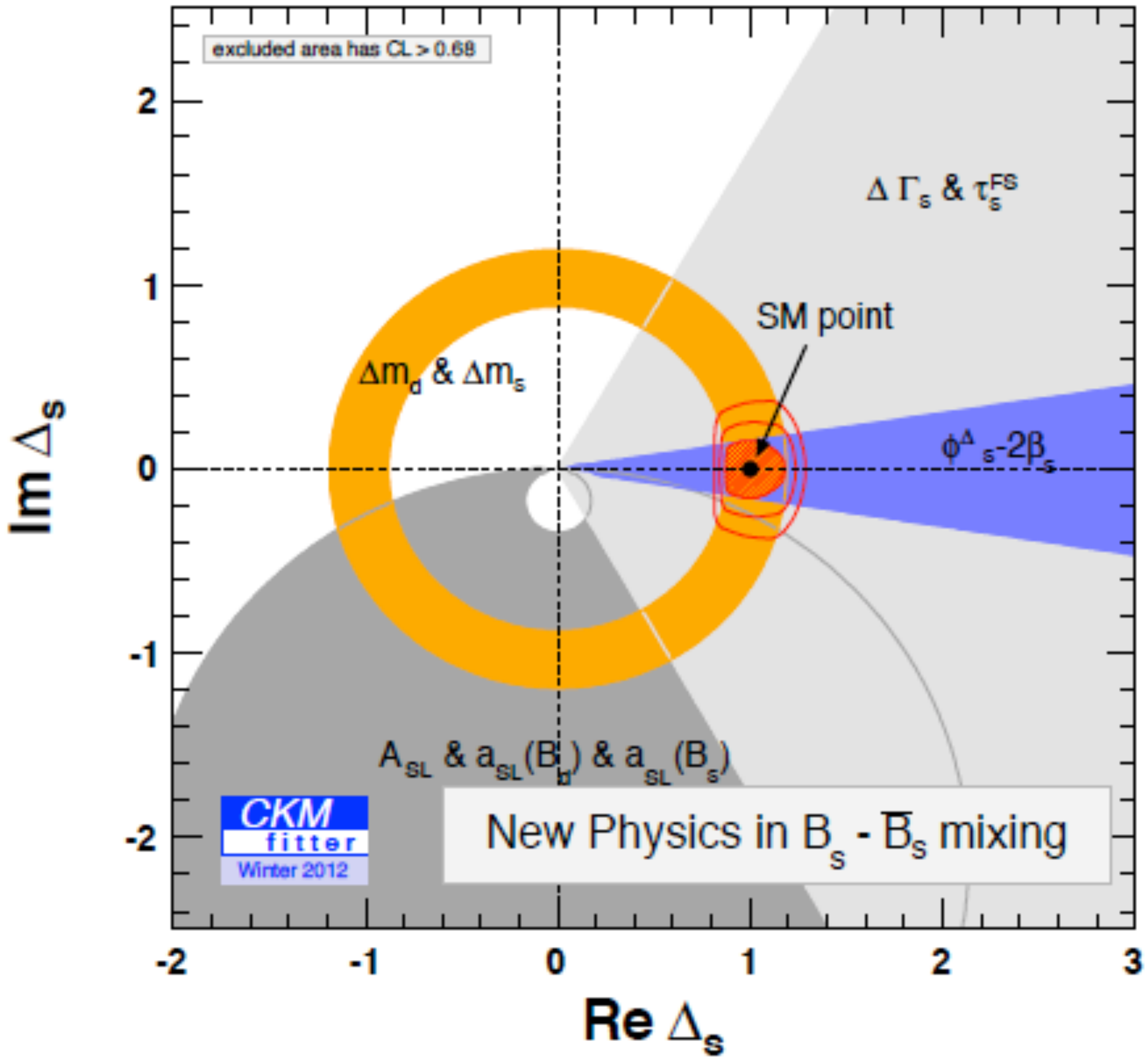
In $B_s \to J/\psi\Phi$ angular analysis for disentangling CP eigenstates necessary

Other decays like $B_s \to J/\psi f_0$ provide pure eigenstates, but lower BR

Pre-LHCb (2010)



LHCb (2012)



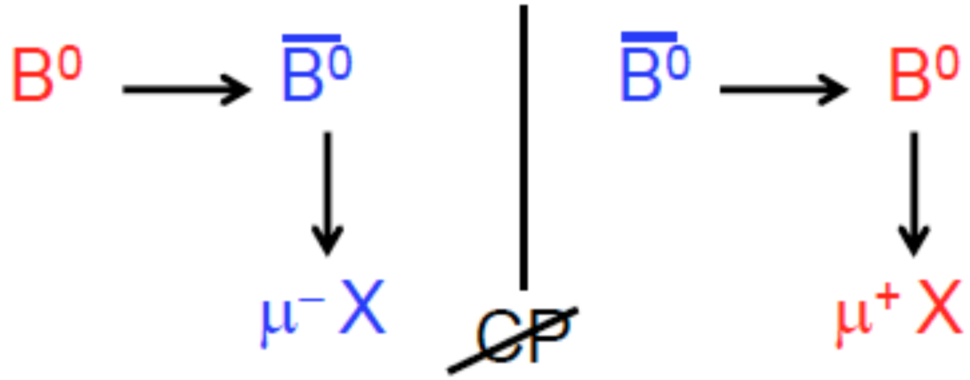
SM hypothesis of $\Delta = 1$ (2D) disfavored

by 0σ

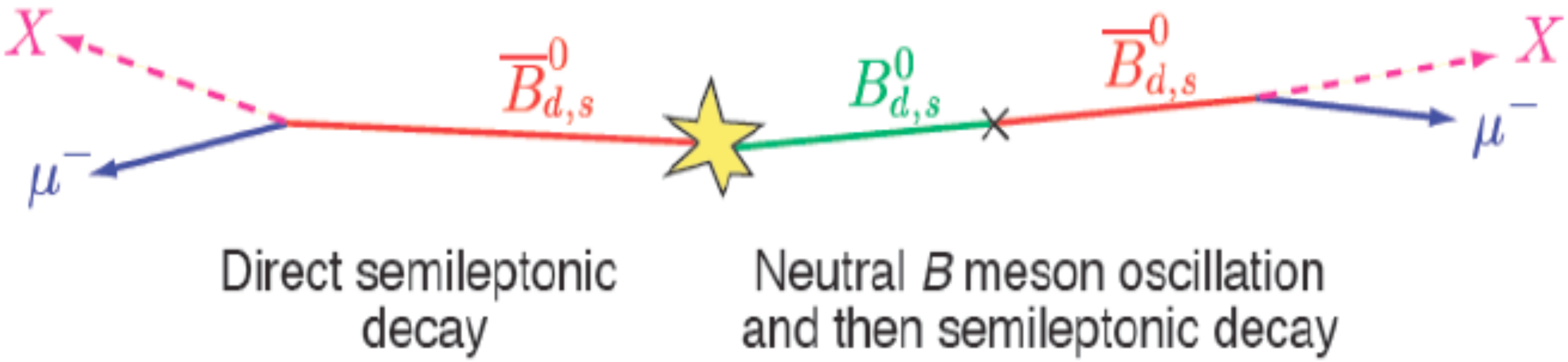
by 3σ

CKM-fitter, arXiv:1008.1593 1203.0238

However: Like-sign dimuon charge asymmetry



$$a_{Sl}^q \equiv \frac{\Gamma(\overline{B}_q^0 \rightarrow \mu^+ X) - \Gamma(B_q^0 \rightarrow \mu^- X)}{\Gamma(\overline{B}_q^0 \rightarrow \mu^+ X) + \Gamma(B_q^0 \rightarrow \mu^- X)}$$



$$A_{Sl}^b = \frac{N_{b\bar{b}}^{++} - N_{b\bar{b}}^{--}}{N_{b\bar{b}}^{++} + N_{b\bar{b}}^{--}}$$

$$= C_d a_{Sl}^d + C_s a_{Sl}^s$$

SM prediction

Lenz, Nierste arXiv:1102.4274 [hep-ph]

$$A_{Sl}^b(SM) = (-0.028^{+0.005}_{-0.006})\%$$

D0 measurement, update 2011

arXiv:1106.6308 [hep-ex]

$$A_{Sl}^b = (-0.787 \pm 0.172(stat) \pm 0.093(syst))\%$$

3.9σ from the SM value

LHCb versus D0

Possible solutions:

Neglected Penguins in $B_s \to J/\psi\Phi$?

$$S_{\psi\phi}^{\rm SM} = 0.0036 \pm 0.002 \to \sin\left(2\beta_s - \phi_s^{\Delta} - \delta_s^{\rm Peng,SM} - \delta_s^{\rm Peng,NP}\right) = 0.002 \pm 0.087$$

Lenz arXiv:1106.3200

Large new physics in Γ_{12}?

New operator $bs \to X$ with $M_x < M_B$ contributes not only to Γ_{12} but to many other observables

But $X = \tau\tau$ Bobeth,Haisch arXiv:1109.1826, Moriond talk 2012 by Haisch

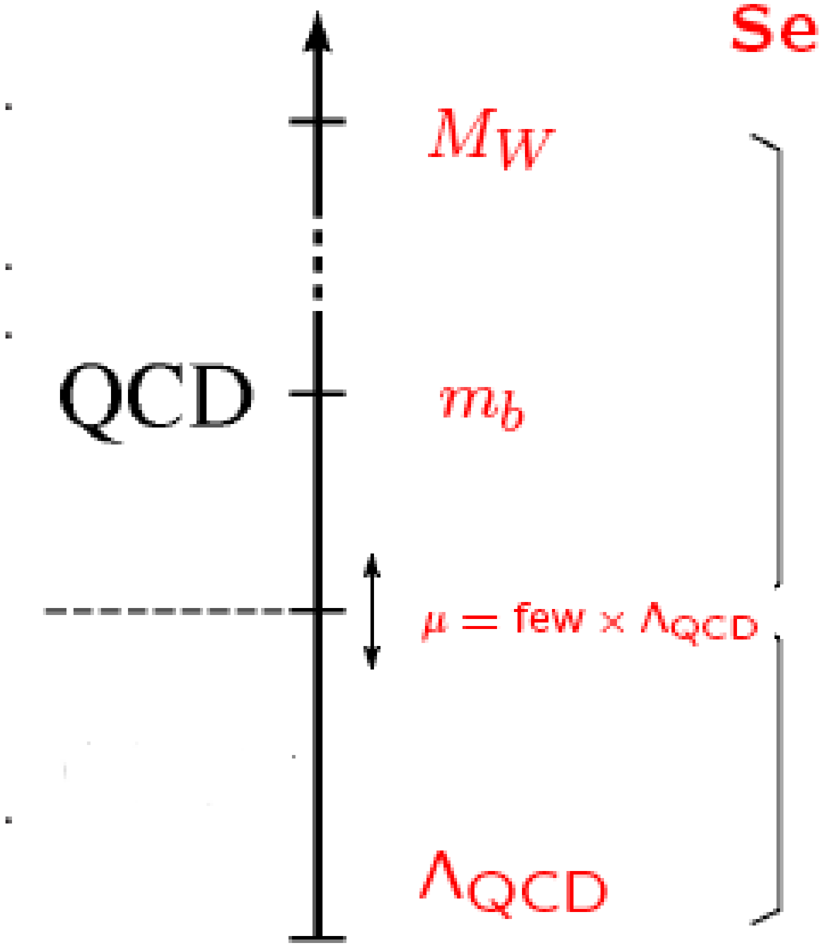
Obviously independent measurements of semileptonic asymmetries needed!

Radiative and semileptonic penguin decays

Separation of new physics and hadronic effects

Challenge for our understanding of QCD

Separation of new physics and hadronic effects



short-distance physics
perturbative

long-distance physics
nonperturbative

Factorization theorems: separating long- and short-distance physics

- Electroweak effective Hamiltonian: $H_{eff} = -\frac{4G_F}{\sqrt{2}} \sum C_i(\mu, M_{heavy})\ \mathcal{O}_i(\mu)$

- $\mu^2 \approx M_{New}^2 >> M_W^2$: 'new physics' effects: $C_i^{SM}(M_W) + C_i^{New}(M_W)$

How to compute the hadronic matrix elements $\mathcal{O}_i(\mu = m_b)$?

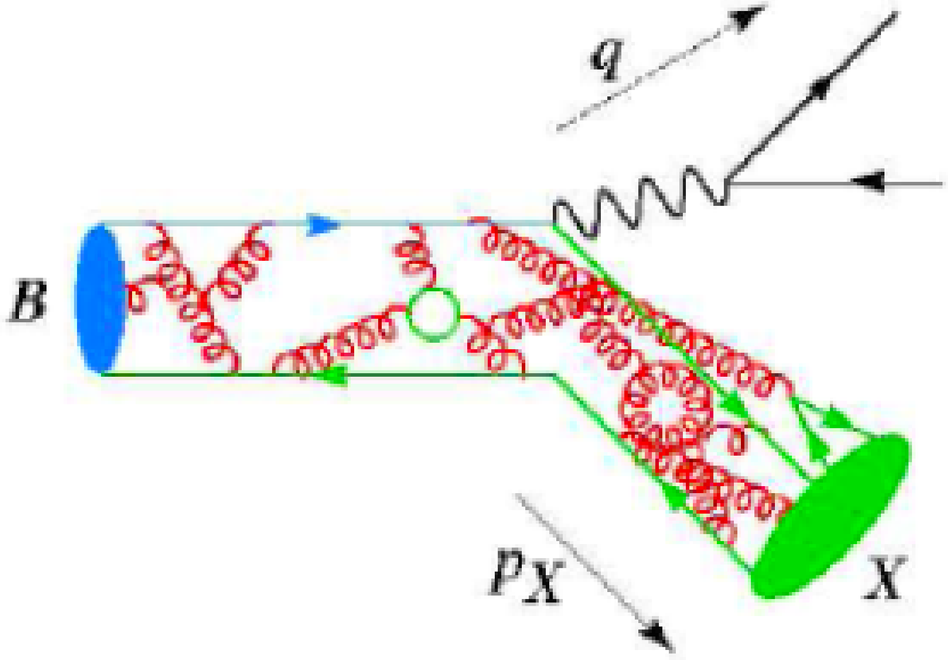
How to compute the hadronic matrix elements $\mathcal{O}_i(\mu = m_b)$?

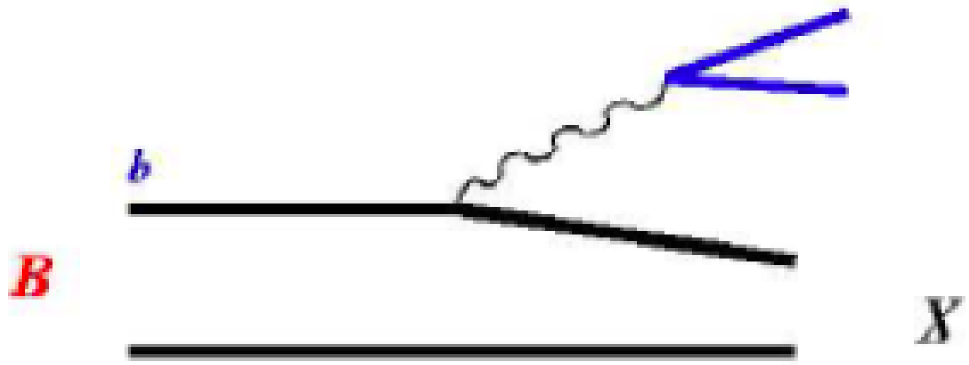
Inclusive modes $B \to X_s\gamma$ or $B \to X_s\ell^+\ell^-$

- Heavy mass expansion for inclusive modes:

$$\Gamma(\bar{B} \to X_s\gamma) \xrightarrow{m_b\to\infty} \Gamma(b \to X_s^{parton}\gamma)\,, \quad \Delta^{nonpert.} \sim \Lambda_{QCD}^2/m_b^2$$

No linear term Λ_{QCD}/m_b (perturbative contributions dominant)





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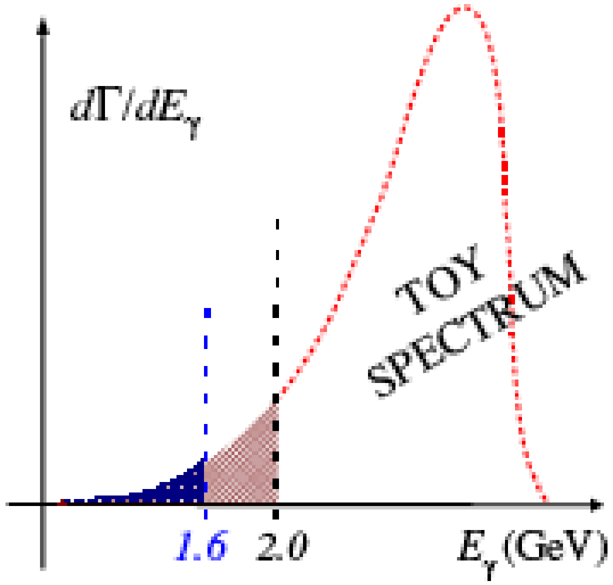
No linear term Λ_{QCD}/m_b (perturbative contributions dominant)

An old story:

- More sensitivities to nonperturbative physics due to kinematical cuts: shape functions; multiscale OPE (SCET) with $\Delta = m_b - 2E^0_\gamma$

Becher,Neubert,hep-ph/0610067



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No linear term Λ_{QCD}/m_b (perturbative contributions dominant)

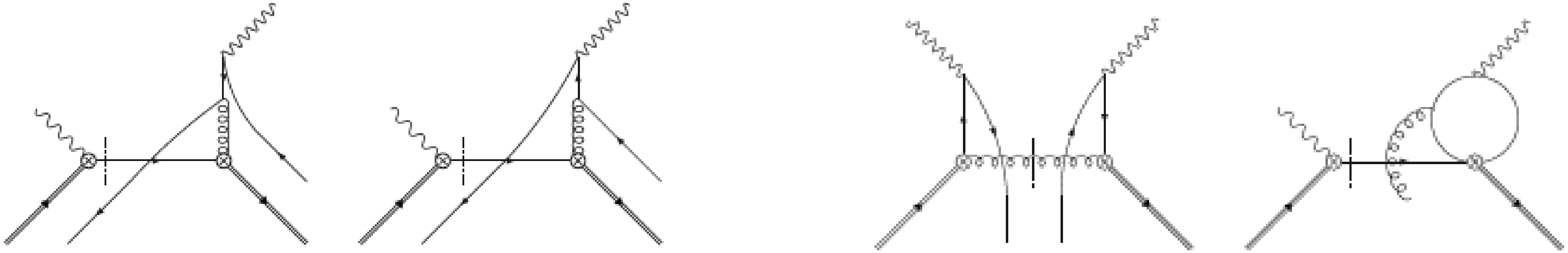
Another old story:

- If one goes beyond the leading operator ($\mathcal{O}_7$, $\mathcal{O}_9$):
  breakdown of local expansion

A new dedicated analysis:

naive estimate of non-local matrix elements leads to 5% uncertainty.

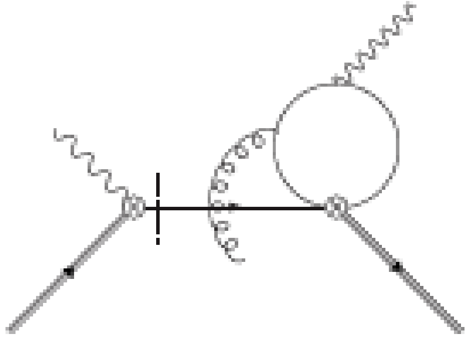
Benzke,Lee,Neubert,Paz,arXiv:1003.5012



Another consequence of this: a positive one $B \to X_d\gamma$

- In $B \to X_d\gamma$, there is no CKM suppression of the up-quark loop contributions like in $B \to X_s\gamma$

- General belief: There are large uncertainties due to the corresponding nonperturbative contributions



- However:
  It was shown that the dominating nonperturbative contribution due to the operator $\mathcal{O}_1^u$ (the $\mathcal{O}_1^u$-$\mathcal{O}_7$ interference term) vanishes in the CP-averaged rate at order Λ/m_b. Benzke,Lee,Neubert,Paz,arXiv:1003.5012

- The CP-averaged decay rate of $B \to X_d\gamma$ is theoretically as clean as the decay rate of $B \to X_s\gamma$

NLL prediction

Hurth,Lunghi,Porod, Nucl.Phys.B704(2004)56

$$\mathcal{B}(\bar{B} \to X_d \gamma) \times 10^5|_{E_\gamma > 1.6GeV} = (1.38 \; {}^{+0.14}_{-0.21}\Big|_{m_c/m_b} \pm 0.15_{\text{CKM}} \pm 0.09_{\text{param}} \pm 0.05_{\text{scale}})$$

NNLL update to be done

To be compared with NLL of $b \to s\gamma$, large CKM error due to V_{td}

$$\mathcal{B}(\bar{B} \to X_s \gamma) \times 10^4|_{E_\gamma > 1.6GeV} = (3.61 \; {}^{+0.24}_{-0.40}\Big|_{m_c/m_b} \pm 0.02_{\text{CKM}} \pm 0.25_{\text{param}} \pm 0.15_{\text{scale}})$$

Babar measurement 2010

$$\mathcal{B}(\bar{B} \to X_d \gamma) \times 10^5|_{E_\gamma > 1.6GeV} = (1.41 \pm 0.57)$$

But also a negative consequence: direct CP asymmetries in $b \to s/d\gamma$

$$A_{\rm CP}^{b \to q\gamma} \equiv \frac{\Gamma[\bar{B} \to X_q\gamma] - \Gamma[B \to X_{\bar{q}}\gamma]}{\Gamma[\bar{B} \to X_q\gamma] + \Gamma[B \to X_{\bar{q}}\gamma]}$$

- NLL prediction Hurth,Lunghi,Porod, hep-ph/0312260

$$A_{CP}(b \to s\gamma) = \left(0.44 \; {}^{+0.15}_{-0.10}\Big|_{m_c/m_b} \pm 0.03_{\rm CKM} \; {}^{+0.19}_{-0.09}\Big|_{\rm scale}\right) \times 10^{-2}$$

Smallness of $A_{CP}(b \to s\gamma)$ results from three factors:

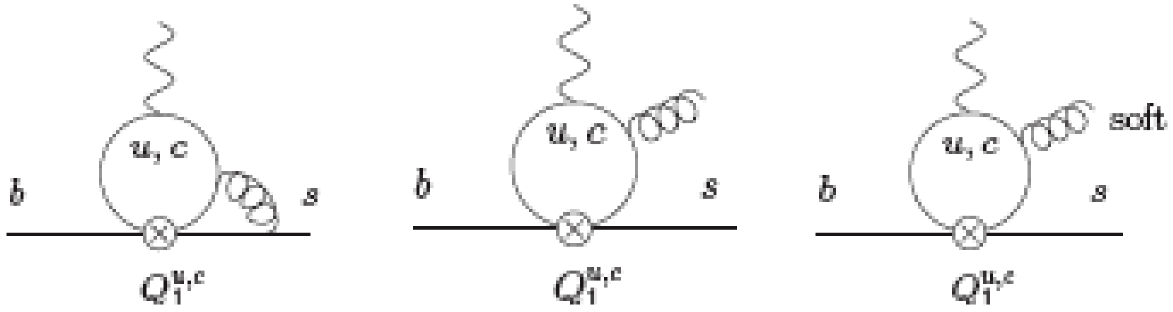
α_s (strong phase), λ^2 (CKM), m_c^2/m_b^2 (GIM)

- However: Long-distance dominance Benzke,Lee,Neubert,Paz arXiv:1012.31.67 [hep-ph]

$$-0.6 \times 10^{-2} < A_{CP}(b \to s\gamma) < +2.8 \times 10^{-2}$$

Resolved photon contribution:

no α_s-suppression



But untagged direct CP asymmetries in $b \to s/d$ transitions survives:

Resolved contributions cancel at order Λ/m_b

KM mechanism CKM unitarity + U spin symmetry of matrix elements $d \leftrightarrow s$:

$$|\Delta BR_{CP}(B \to X_s\gamma) + \Delta BR_{CP}(B \to X_d\gamma)| \sim 1 \cdot 10^{-9} \approx 0$$

Clean test, whether new CP phases are active or not

Hurth,Mannel,Phys.Lett.B511(2001)196; Hurth,Lunghi,Porod,Nucl.Phys.B704(2004)56

Three open issue in $\bar{B} \to X_s\gamma$

- The semileptonic phase factor:

$$\mathrm{BR}_\gamma(E_0) \equiv \mathrm{BR}[B \to X_s\gamma]_{E_\gamma > E_0} = \frac{\mathrm{BR}_{c\ell\nu}}{C} \left(\frac{\Gamma[B \to X_s\gamma]_{E_\gamma > E_0}}{|V_{cb}/V_{ub}|^2 \, \Gamma[B \to X_u e\bar{\nu}]} \right)$$

$$C = \left|\frac{V_{ub}}{V_{cb}}\right|^2 \frac{\Gamma[\bar{B}\to X_c e\bar{\nu}]}{\Gamma[\bar{B}\to X_u e\bar{\nu}]} = \begin{cases} 0.582 \pm 0.016, \\ 0.546^{+0.023}_{-0.033}, \end{cases}$$

1S scheme has to be updated!

Trott et al.,hep-ph/0408002

kinetic scheme

Gambino,Giordano,arXiv:0805.0271

Enhancement of BR_γ in kinematic scheme

+4.8%!? $\frac{\delta}{\delta m_c} Pert(E_0) \prec 0$, $\bar{m}_c(\bar{m}_c)_{1S} \prec \bar{m}_c(\bar{m}_c)_{kinetic}$

- Multiscale OPE: Becher,Neubert,hep-ph/0610067

Misiak et al.	BR_γ(1GeV)	BR_γ(1.6GeV)
hep-ph/0609232 'fixed order'	3.27 10^{-4}	$(3.15\pm0.23)\,10^{-4}$
hep-ph/0610067 multisc. OPE	3.27 10^{-4} (adapted from above)	$(2.98\pm0.26)\,10^{-4}$

without

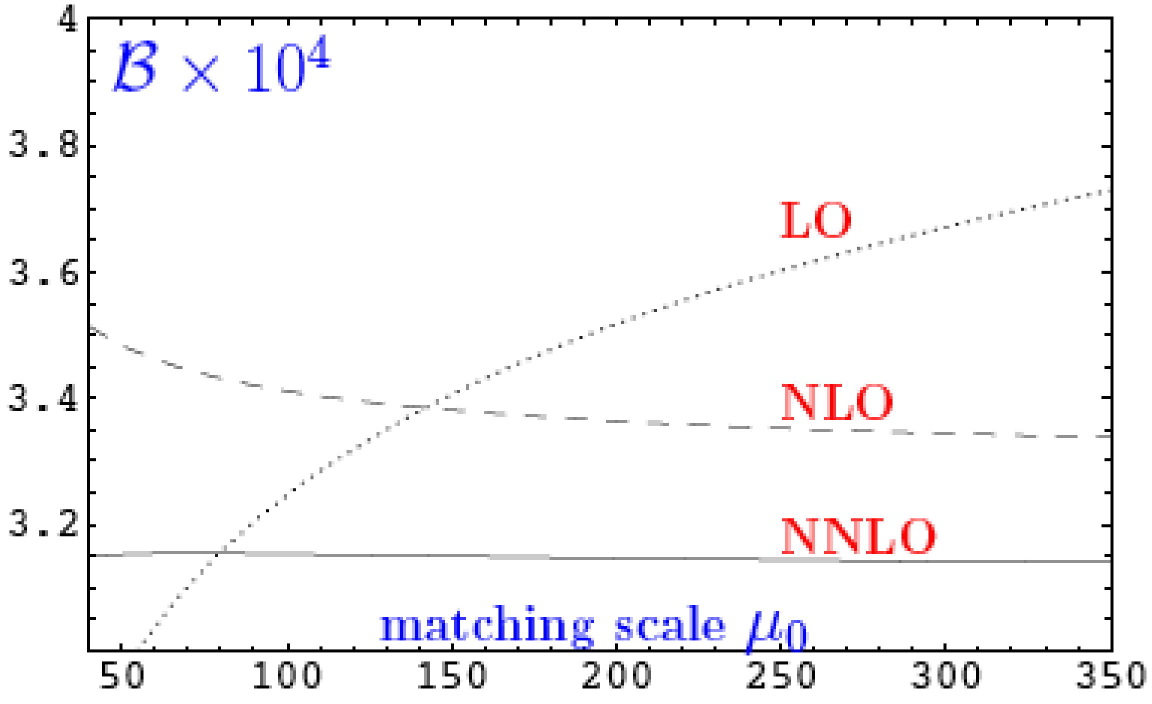
-1.5% of $\mathcal{O}(\alpha_s\Lambda/m_b)$

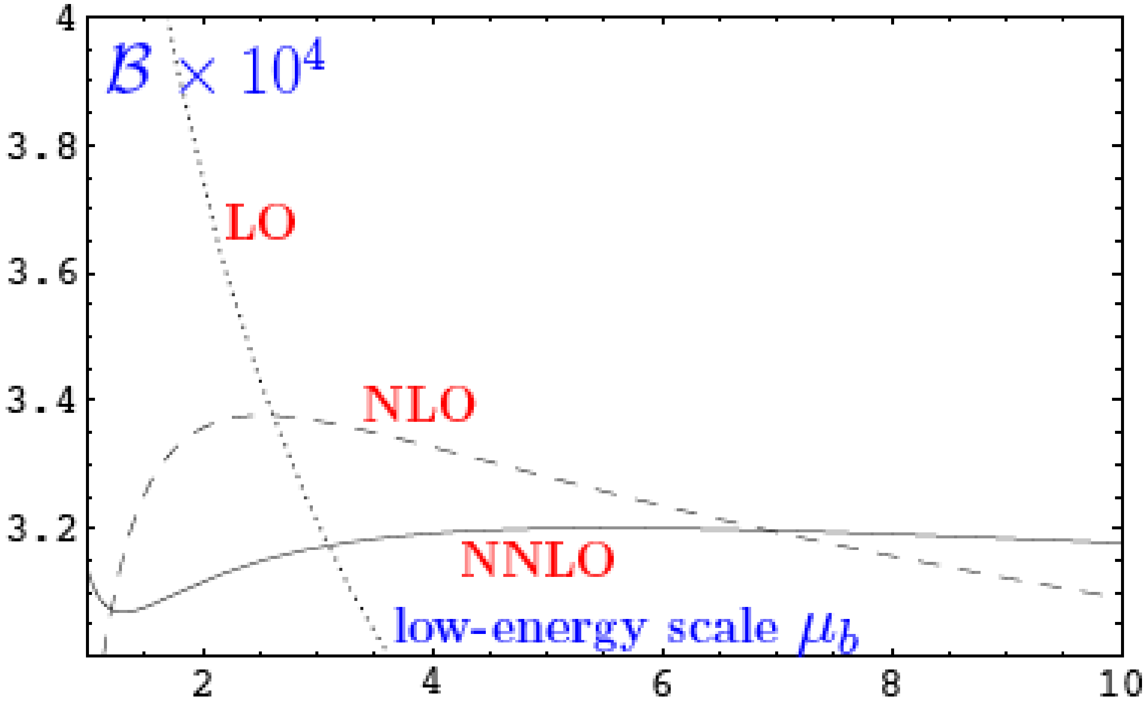
3.05 10^{-4}

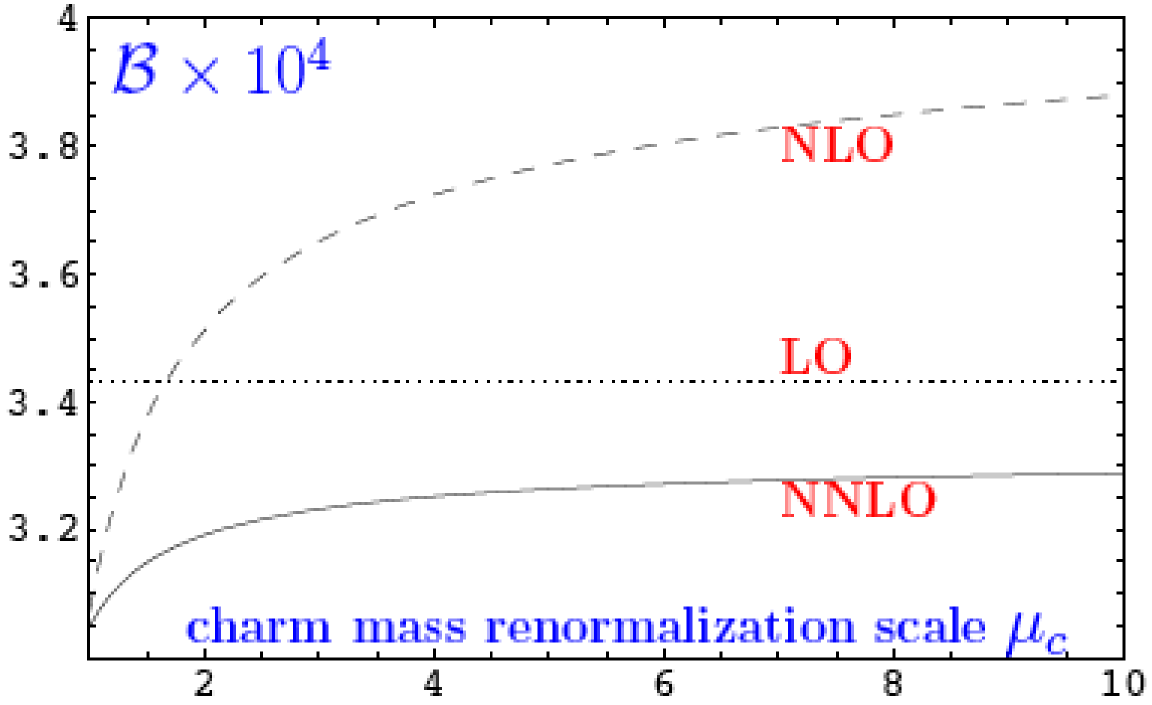
Applicability of M-OPE questioned by Misiak arXiv:0808.3134

- Perturbative calculation at NNLL:

NNLL calculation by Misiak et al.
PRL98,022003(2007)







“Central” values:

$\mu_0 = 160$ GeV

$\mu_b = 2.5$ GeV

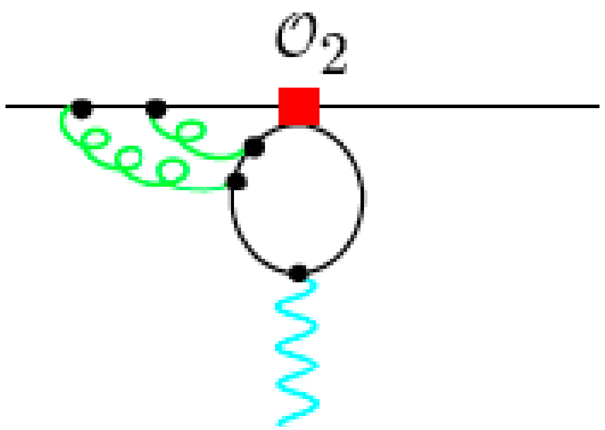
$\mu_c = 1.5$ GeV

Only the large charm mass renormalization scheme dependence made NNLO calculation really necessary.

- Perturbative calculation at NNLL:

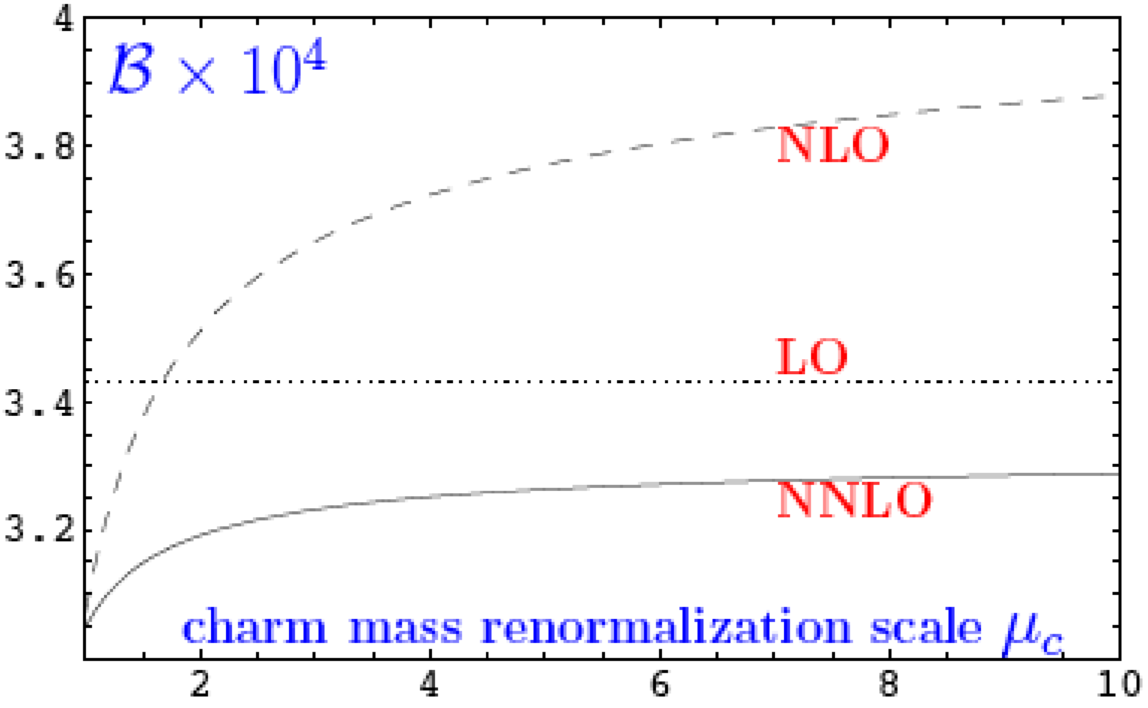
NNLL calculation by Misiak et al.
PRL98,022003(2007)

Matrix elements: $\prec O_2(\mu \simeq m_b) \succ$



Interpolation between the formal $m_c >> m_b/2$ limit and the $\alpha_s^2 n_f$ approximation, this part is the main origin of charm dependence ⇒ space for improvements

work in progress



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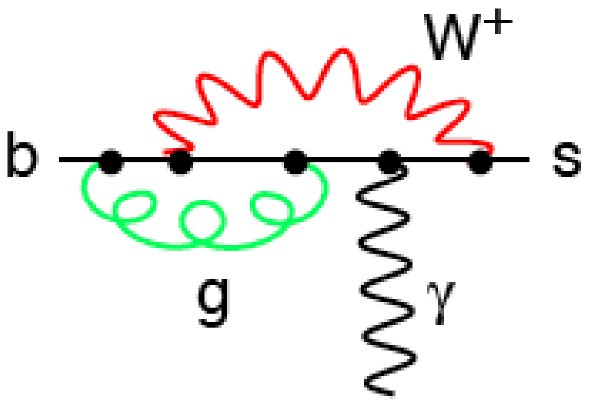
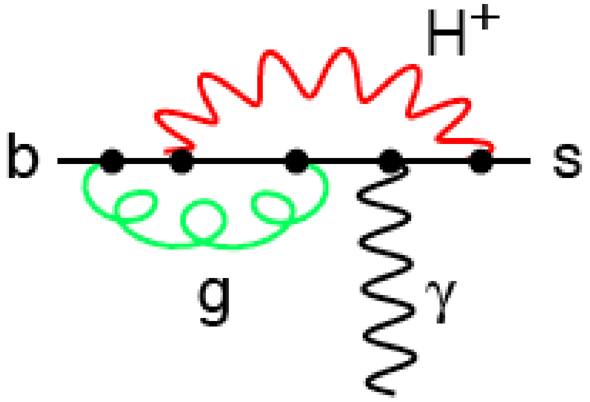
$$\mu_c = 1.5\ \mathbf{GeV}$$

Only the large charm mass renormalization scheme dependence made NNLO calculation really necessary.

$\bar{B} \to X_s\gamma$ in the MSSM



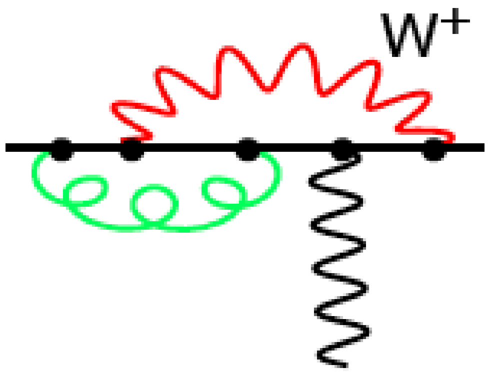


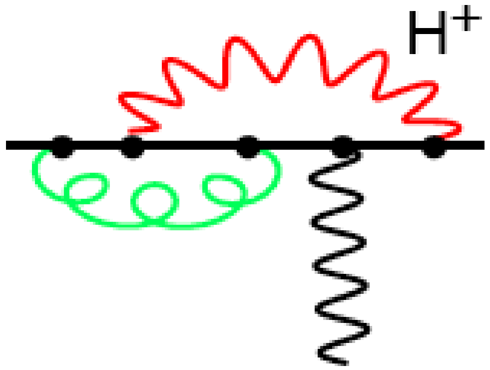
$M_{H+} > 295$ GeV

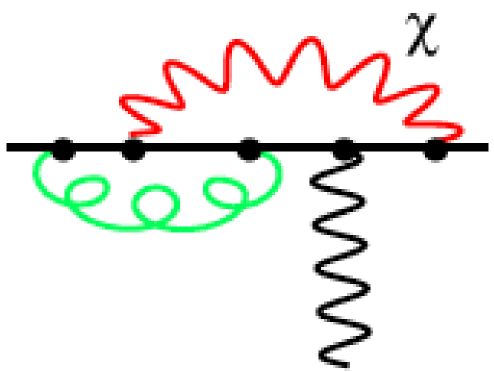
at 95% CL

$$C_{NLL}(M_W) = C_{NLL}{}^{SM}(M_W) + C_{NLL}{}^{NEW}(M_W)$$

Charged Higgs contribution always adds to SM one







$$C_{NLL}(M_W) = C_{NLL}{}^{SM}(M_W) + C_{NLL}{}^{H^+}(M_W) + C_{NLL}{}^{\chi}(M_W)$$

Within supersymmetry possible cancellation with chargino contribution

Existing NLL calculations in the MSSM:

NLL analysis in MFV-Supersymmetry Degrassi,Gambino,Slavich, hep-ph/0602198

NLL in general supersymmetry (uMSSM)

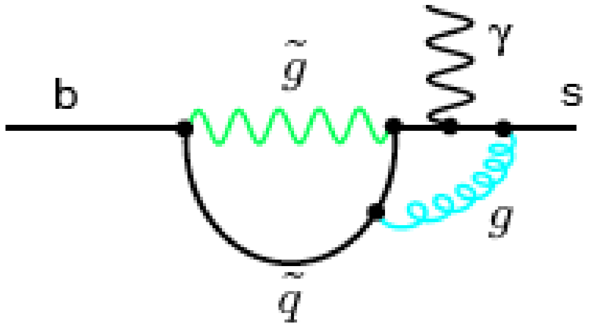
New sources of flavour violation via squark mixing

Complete NLL

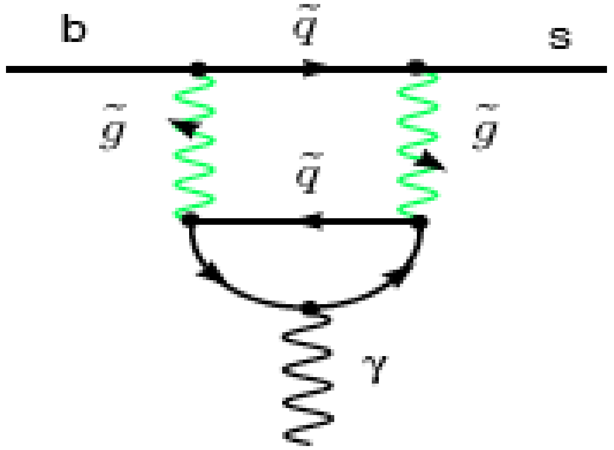
$W\,g$ $\quad H^+\,g$ $\quad \chi^+\,g$ $\quad \chi^0\,g$ $\quad \tilde{g}\,g$ Bobeth,Misiak,Urban hep-ph/9904413

$W\,\tilde{g}$ $\quad H^+\,\tilde{g}$ $\quad \chi^+\,\tilde{g}$ $\quad \chi^0\,\tilde{g}$ $\quad \tilde{g}\,\tilde{g}$

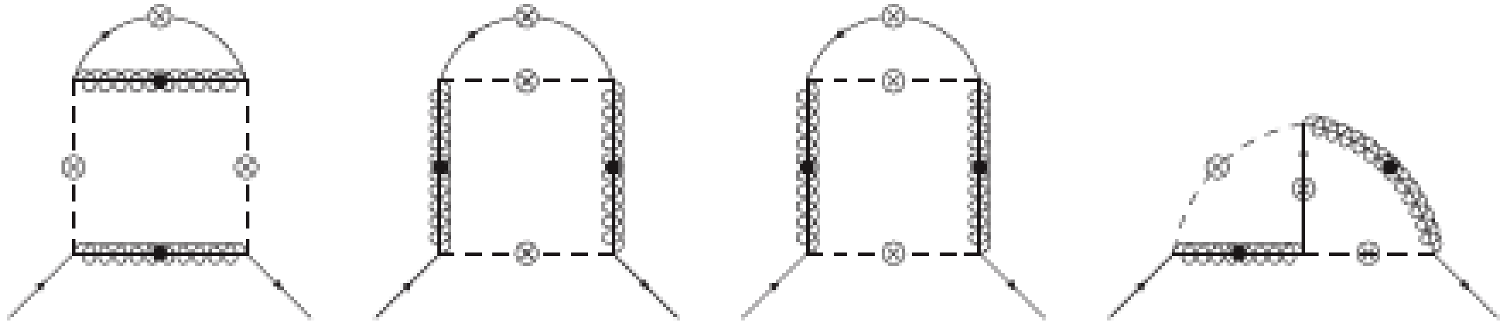
Gluonic Parts ($\tilde{g}\,g$)



Two-Gluino Parts ($\tilde{g}\,\tilde{g}$)



Greub,Hurth,Pilipp,Schupbach,Steinhauser arXiv:1105.1330 [hep-ph]



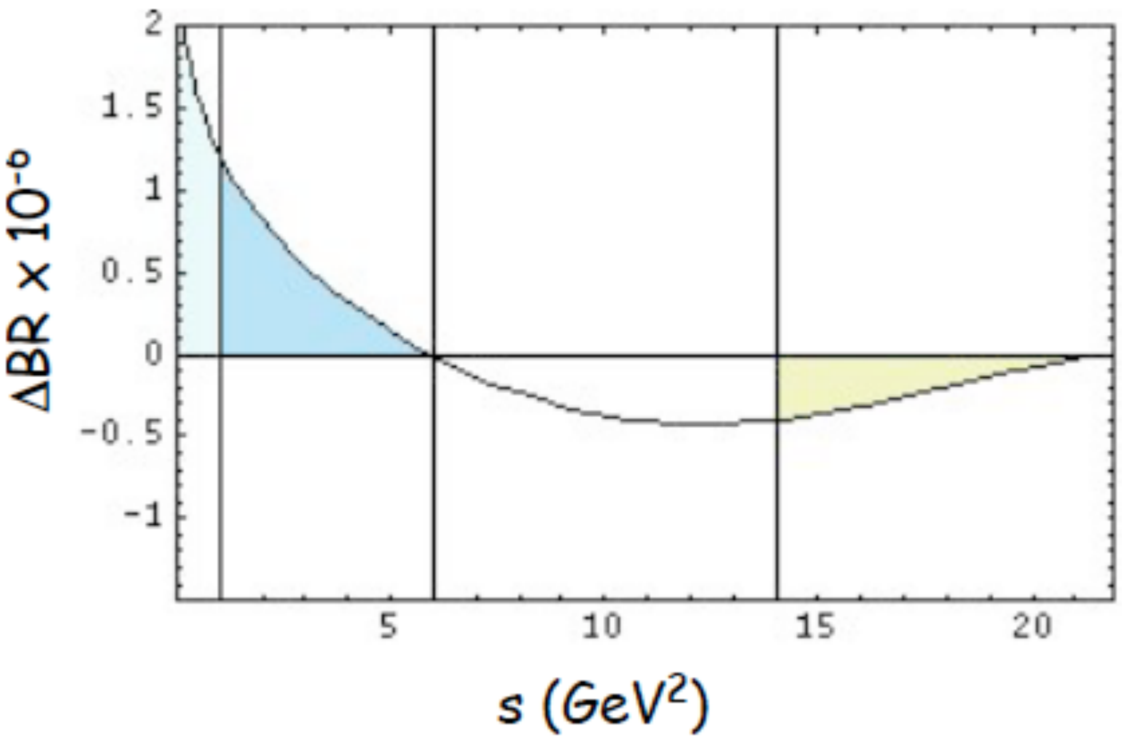
Gluino contribution dominant due to strong coupling

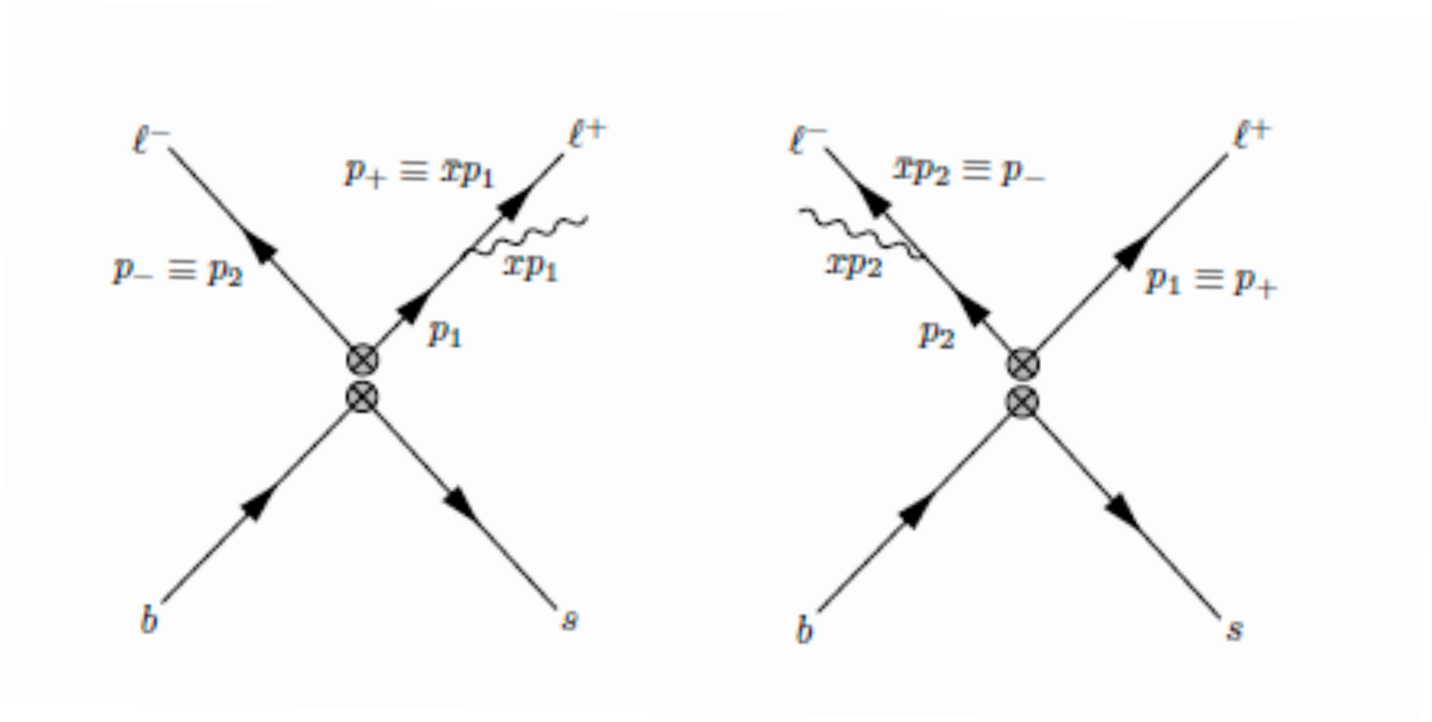
Latest improvements of inclusive $\bar{B} \to X_s \ell^+ \ell^-$

Beyond existing NNLL QCD precision electromagnetic corrections were calculated: Huber,Hurth,Lunghi,Nucl.Phys.B802(2008)40 and work in progress

Corrections to matrix elements lead to large collinear $Log(m_b/m_\ell)$

$$\delta\mathrm{BR}(B \to X_s \mu^+ \mu^-) = \begin{cases} (+2.0\%) & \text{low } q^2 \\ (-6.8\%) & \text{high } q^2 \end{cases} \quad \delta\mathrm{BR}(B \to X_s e^+ e^-) = \begin{cases} (+5.2\%) & \text{low } q^2 \\ (-17.6\%) & \text{high } q^2 \end{cases}$$



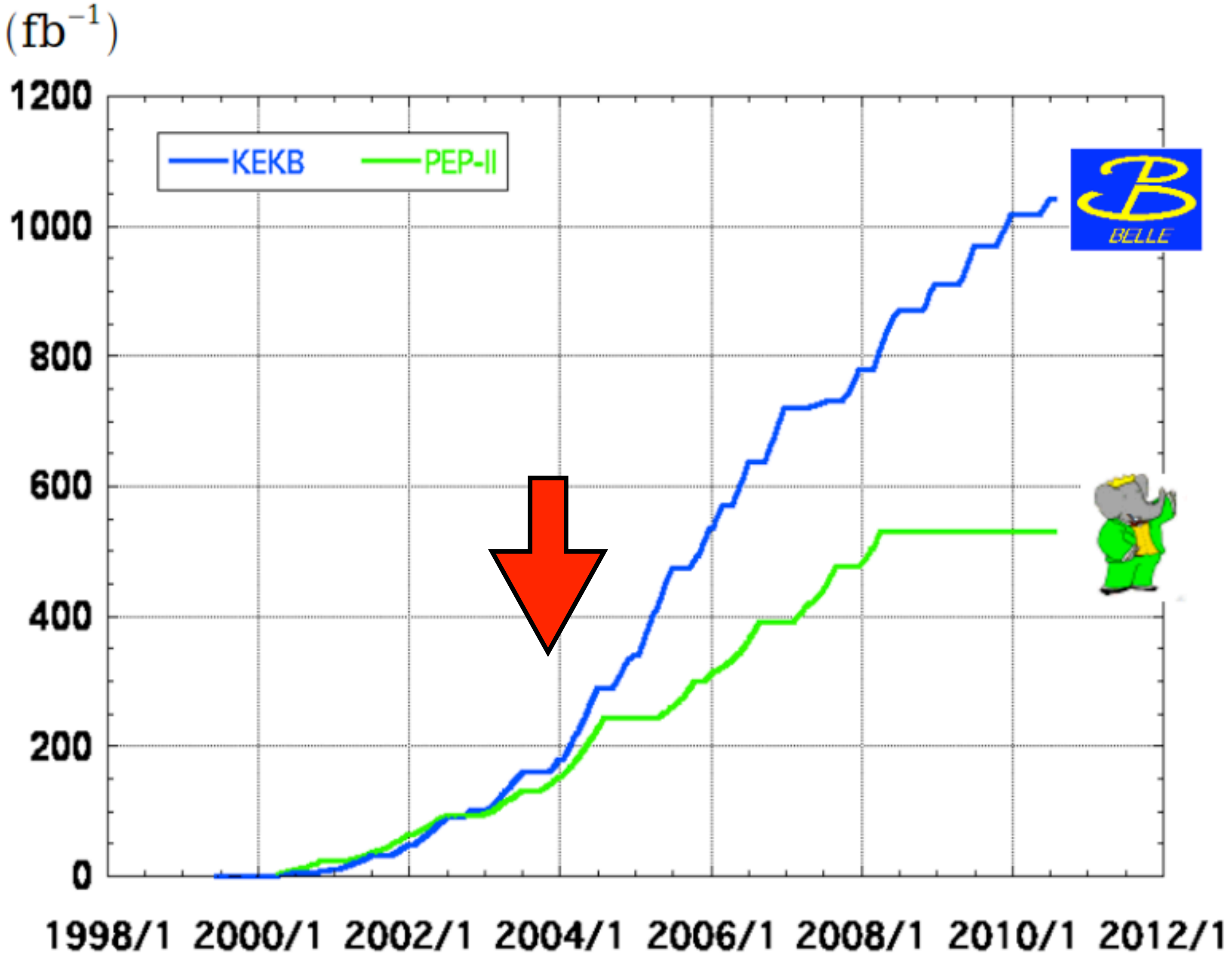


‘Latest‘ Babar and Belle measurements of inclusive $\mathcal{B}(b \to s\ell\ell)$

Belle hep-ex/0503044 (!!!) (based $152 \times 10^6 B\bar{B}$ events)

Babar hep-ex/0404006 (!!!) (based $89 \times 10^6 B\bar{B}$ events)

Integrated luminosity of B factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

Future measurements: Super-flavour factories in Italy and Japan

How to compute the hadronic matrix elements $\mathcal{O}(m_b)$?

Exclusive modes $B \to K^*\gamma$ or $B \to K^*\ell^+\ell^-$

Naive approach:

Parametrize the hadronic matrix elements in terms of form factors

Exclusive modes $B \to K^*\gamma$ or $B \to K^*\ell^+\ell^-$

QCD-improved factorization: BBNS 1999

$$\mathcal{T}_a^{(i)} = C_a^{(i)}\xi_a + \phi_B \otimes T_a^{(i)} \otimes \phi_{a,K^*} + O(\Lambda/m_b)$$

Existence of ‘non-factorizable’ strong interaction effects

which do *not* correspond to form factors

Exclusive modes $B \to K^*\gamma$ or $B \to K^*\ell^+\ell^-$

QCD-improved factorization: BBNS 1999

$$\mathcal{T}_a^{(i)} = C_a^{(i)}\xi_a + \phi_B \otimes T_a^{(i)} \otimes \phi_{a,K^*} + O(\Lambda/m_b)$$

– Separation of perturbative hard kernels from process-independent nonperturbative functions like form factors

– Relations between formfactors in large-energy limit

– Limitation: insufficient information on power-suppressed Λ/m_b terms (breakdown of factorization: 'endpoint divergences')

Phenomenologically highly relevant issue

general strategy of LHCb to look at ratios of exclusive modes

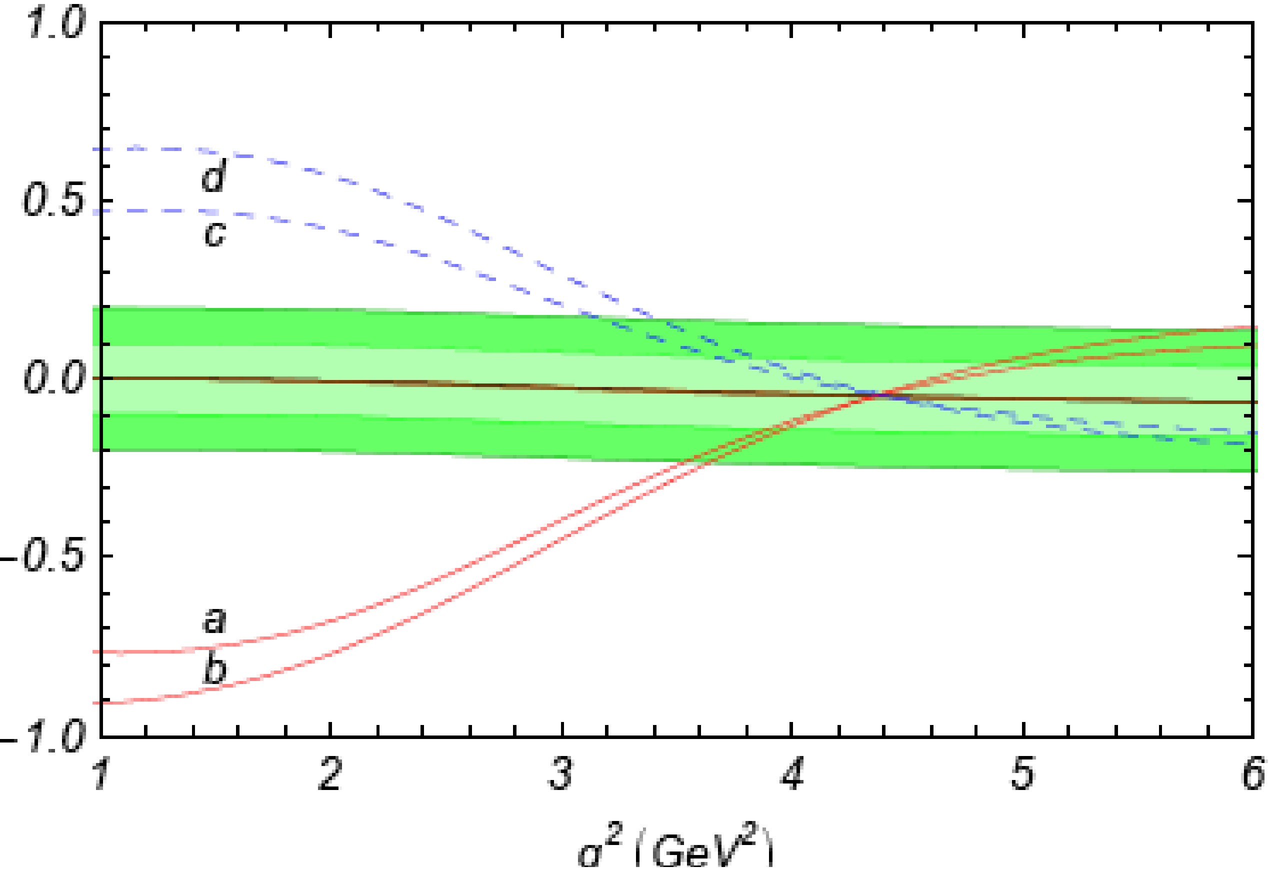
Egede,Hurth,Matias,Ramon,Reece,arXiv:0807.2589,arXiv:1005.0571

see also Altmannshofer et al.,arXiv:0811.1214; Bobeth et al.,arXiv:0805.2525

Careful design of theoretically clean angular observables in $B \to K^* \ell^+ \ell^-$

Egede,Hurth,Matias,Ramon,Reece,arXiv:0807.2589,arXiv:1005.0571

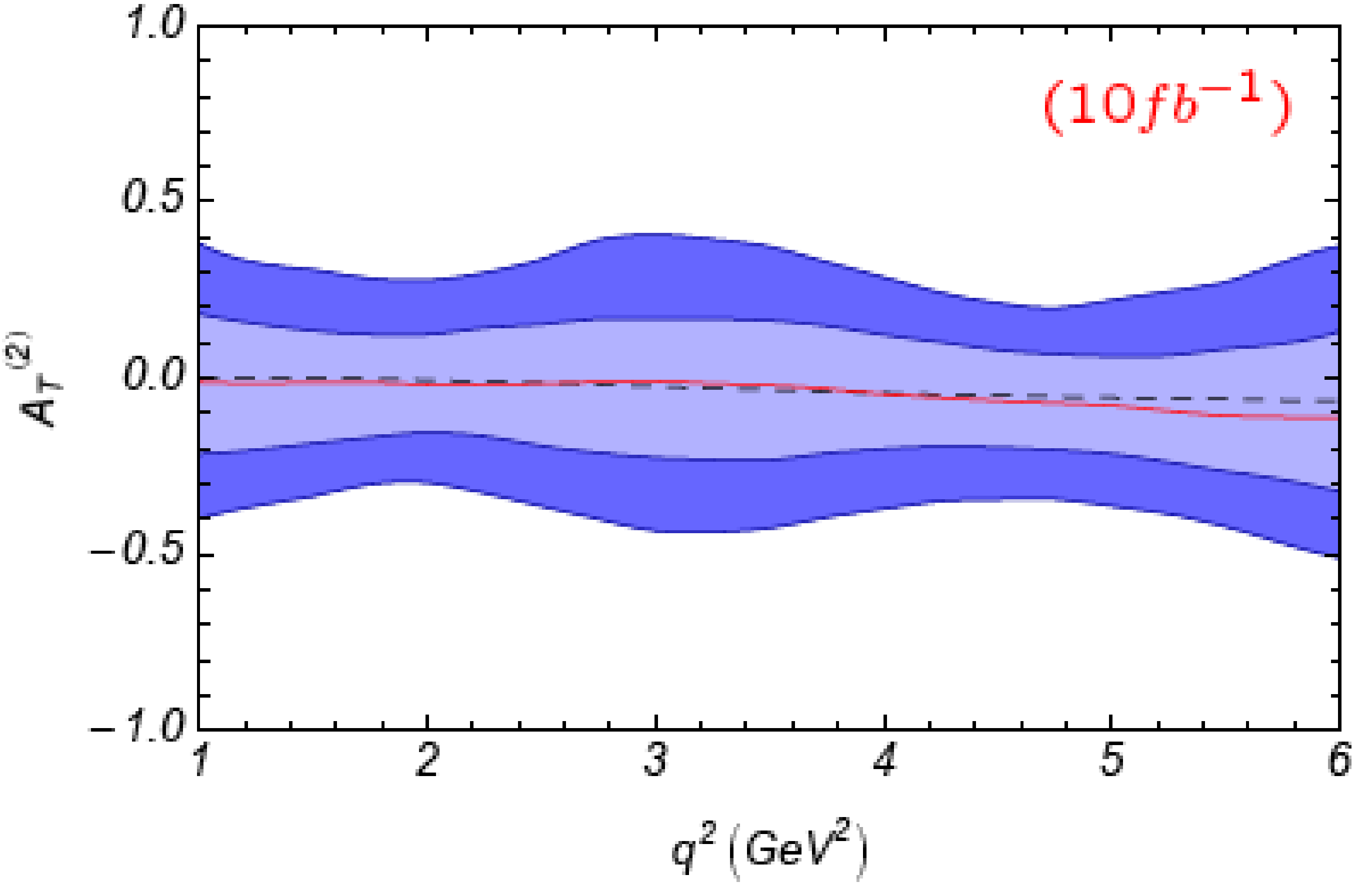
$$A_T^{(2)} = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}$$



Theoretical sensitivity

light green $\pm 5\% \Lambda/m_b$

dark green $\pm 10\% \Lambda/m_b$



Experimental sensitivity

light green 1 σ

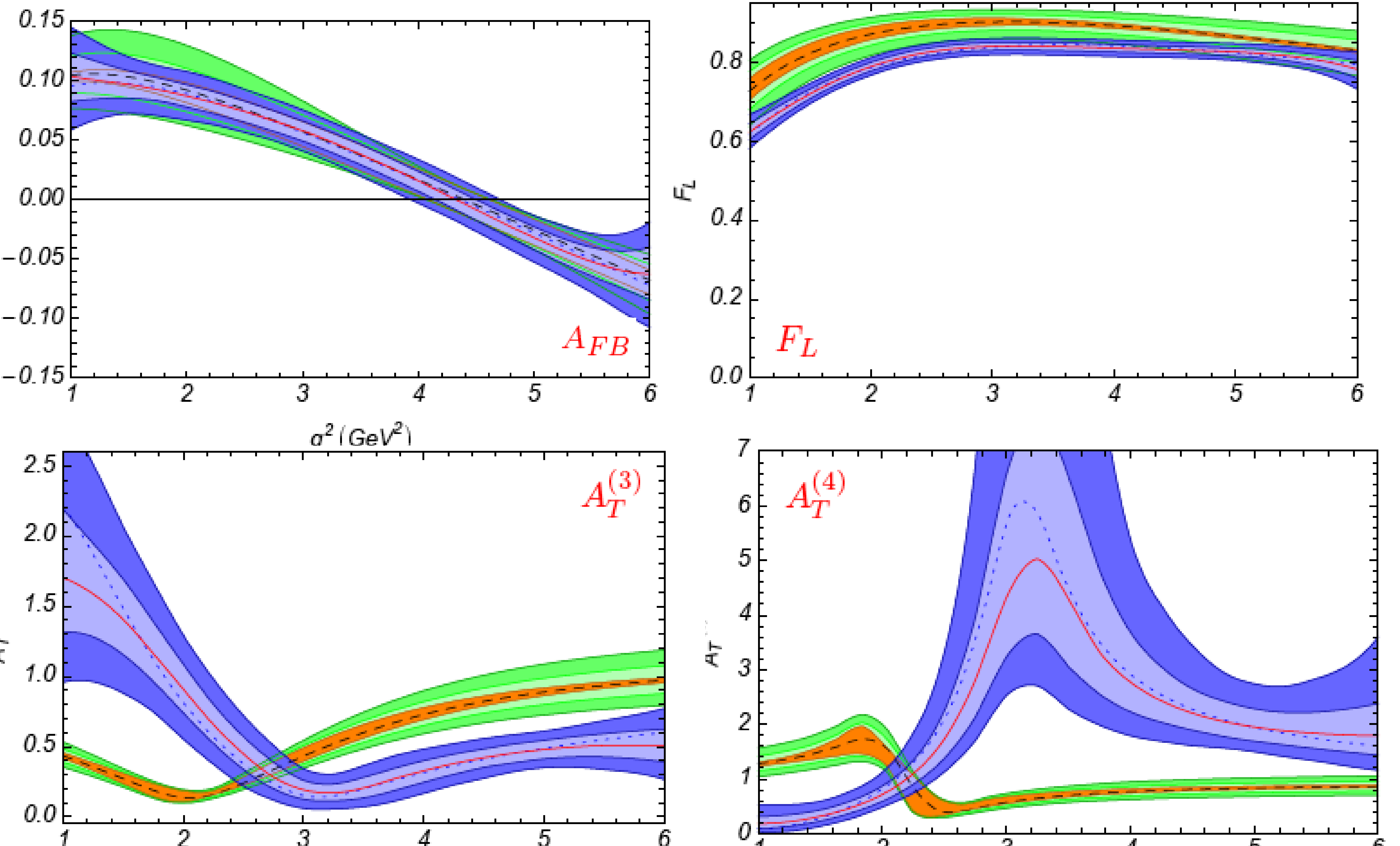
dark green 2 σ

SuperLHCB/SuperB can offer more precision

Crucial: theoretical status of Λ/m_b corrections has to be improved

Comparision of new physics reach of old and new observables

Egede,Hurth,Matias,Ramon,Reece,arXiv:0807.2589,arXiv:1005.0571



The experimental errors assuming SUSY scenario (b) with large-gluino mass and positive mass insertion, is compared to the theoretical errors assuming the SM.

New developments of angular $B \to K^* \ell^+ \ell^-$ observables defined in the high-q^2 region

Grinstein,Pirjol hep-ph/0404250, Beylich,Buchalla,Feldmann arXiv:1101.5118

Bobeth,Hiller,van Dyk arXiv:1006.5013,1105.0376

local operator product expansion is applicable ($q^2 \sim m_b^2$)

the leading power corrections are shown to be suppressed by $(\Lambda/m_b)^2$ or $\alpha_s \Lambda/m_b$

Magnitude of Λ/m_b can be estimated due to existence of an OPE/HQET

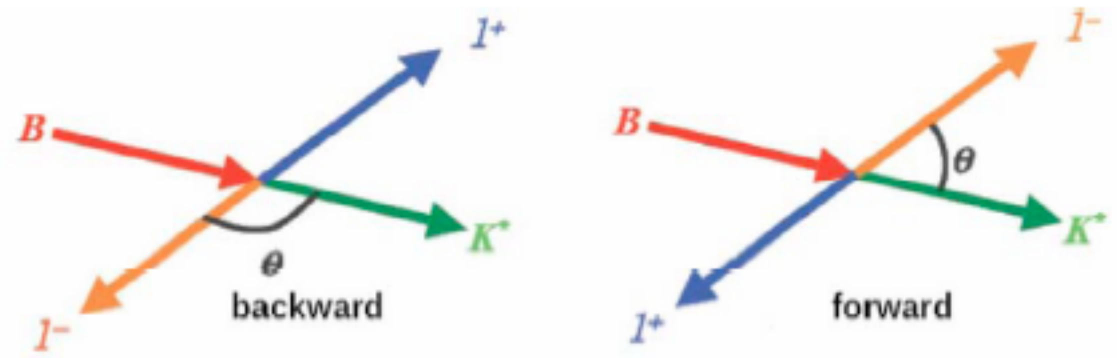
Formfactors at high-q^2: extrapolation, future unquenched lattice results

The theoretical treatment in the low- and high-q^2 based on different theoretical concepts.

$\Rightarrow$ the consistency of the consequences out of the two sets of measurements will allow for an important crosscheck.

Measurements of forward-backward asymmetry in $B \to K^* \mu^+ \mu^-$

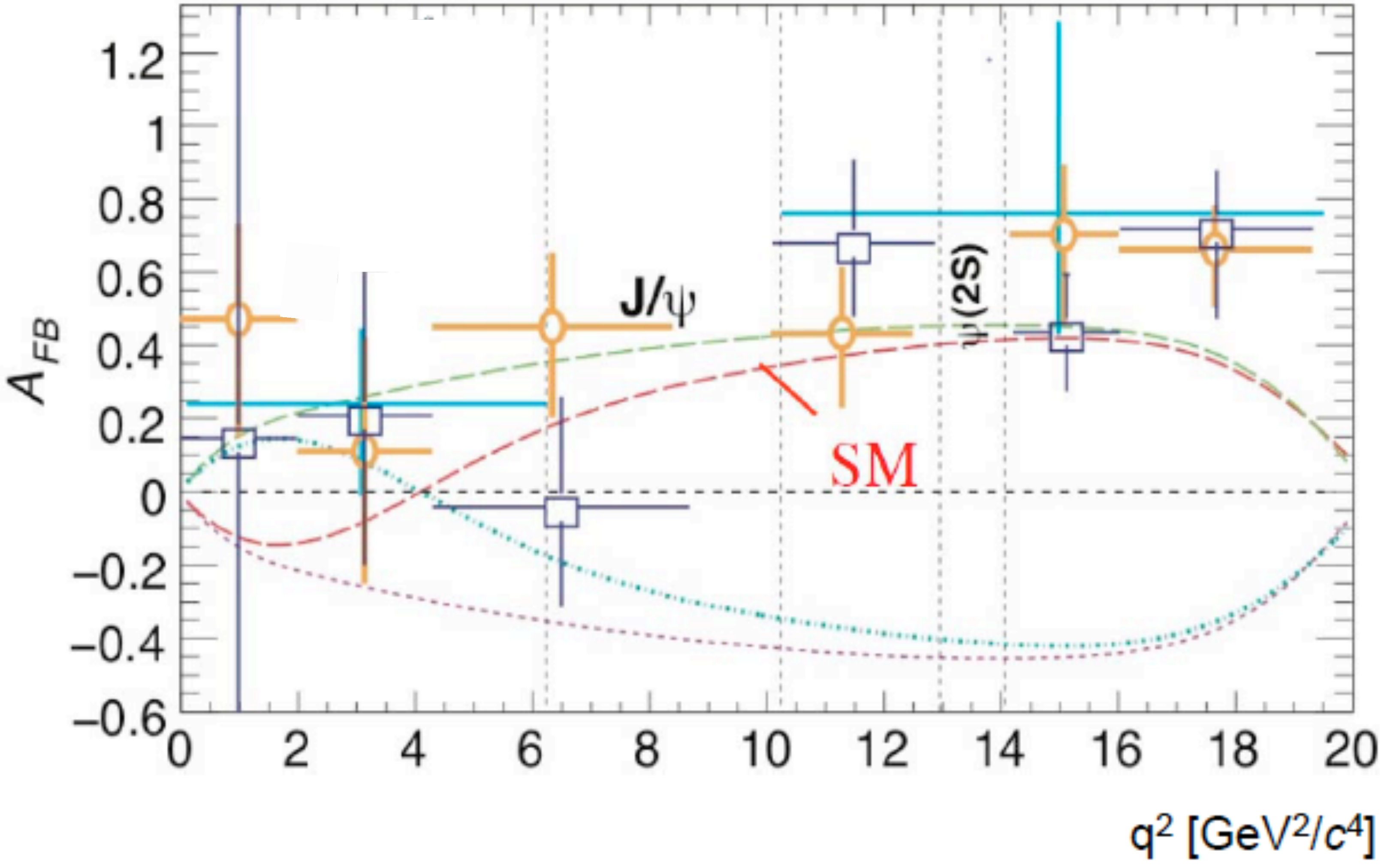
$$A_{FB}\left(s = m^2_{\mu^+\mu^-}\right) = \frac{N_F - N_B}{N_F + N_B}$$



250 $K^*l^+l^-$
80% of data

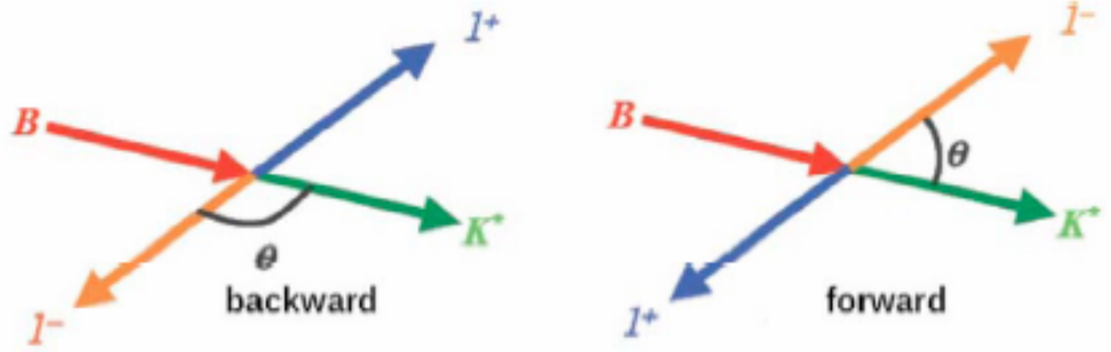
100 $K^*l^+l^-$
75% of data

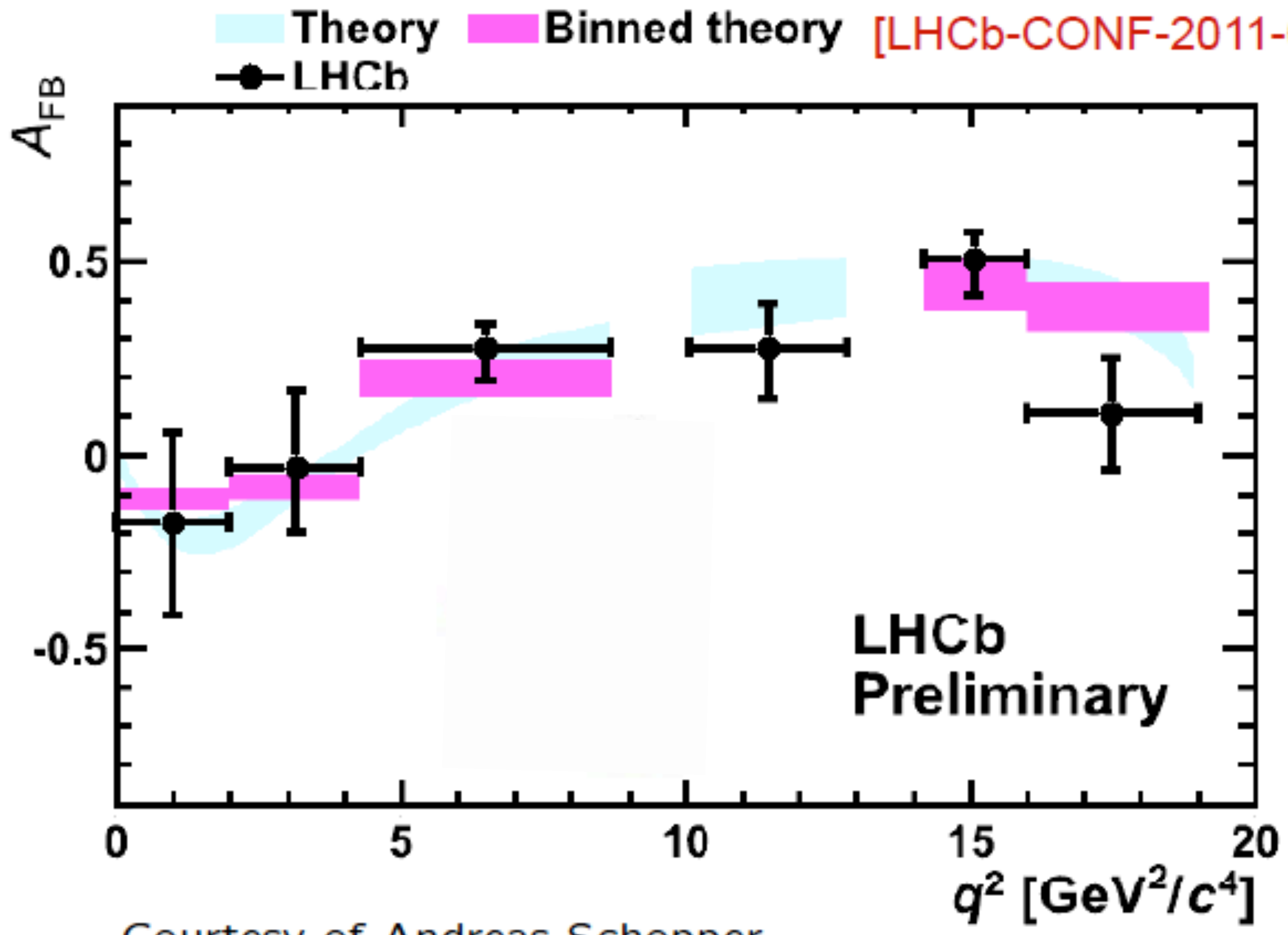
100 $K^*\mu^+\mu^-$
4.4 fb^{-1}



Measurements of forward-backward asymmetry in $B \to K^* \mu^+ \mu^-$

$$A_{FB}\left(s = m^2_{\mu^+\mu^-}\right) = \frac{N_F - N_B}{N_F + N_B}$$





[LHCb-CONF-2011-038]

Courtesy of Andreas Schopper

Excellent agreement with SM at current level of precision.

However:

Many more angular observables in $B \to K^* \mu\mu$ to be measured, more sensitive to NP than AFB. New flavour structures needed !

Minimal flavour violation hypothesis

Minimal flavour violation hypothesis

- SM gauge interactions are universal in quark flavour space: flavour symmetry $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$
- Symmetry is only broken by the Yukawa couplings Y_U and Y_D responsible for the quark masses
- Any new physics model in which all flavour- and CP-violating interactions can be linked to the known Yukawa couplings is MFV
- RG-invariant definition based on the flavour symmetry: Yukawa couplings are introduced as background values of fields (spurions) transforming under the flavour group

d'Ambrosio,Giudice,Isidori,Strumia,hep-ph/0207036

Chivukula,Georgi,Phys.Lett.B188(1987)99

Hall,Randall,Phys.Rev.Lett.65(1990)2939

MFV at work

- In MFV models with one Higgs doublet, all FCNC processes with external d-type quarks are governed by

$$(Y_U Y_U^{+})_{ij} \approx y_t^2 V_{3i}^* V_{3j} \qquad \text{CKM hierarchy}$$

- If additional Higgs-doublets are added, then another spurion combination is numerically important:

$$(Y_D Y_D^{+})_{ij} \approx 2 m_b^2 \tan^2\beta / v^2 \, \Delta_{ij}, \;\; \Delta = diag(0,0,1)$$

Thus, MFV allows for large-$\tan\beta$ effects in particular in helicity-suppressed observables $B \to \mu\mu$ and $B \to \tau\nu$.

$B \to \mu\mu$: $\quad A_{\text{SM}} \sim m_\mu / m_b \Leftrightarrow A_{H^0,A^0} \sim \tan^3\beta$

More details:

The flavour symmetry $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$

is broken by the Yukawa couplings only as in the SM $Y_D\ (3,1,\bar{3});\ Y_U\ (3,\bar{3},1)$

$$-\mathcal{L}^{\text{quarks}}_{\text{Yukawa}} = Y^d_{ij}\, \overline{Q^I_{Li}}\, \phi D^I_{Rj} + Y^u_{ij}\, \overline{Q^I_{Li}}\, \tilde{\phi} U^I_{Rj} + \text{h.c.}$$

$$\overline{Q_L}(\overline{3},1,1),\ D_R(1,1,3),\ U_R(1,3,1) \quad \Rightarrow \quad \mathcal{L}(1,1,1)$$

MFV: All effective field operators with higher dimension
also have to be invariant

Specific basis: $Y_D = diag(y_d, y_s, y_b),\ Y_U = V^{+}_{CKM} \times diag(y_u, y_c, y_t)$

Typical FCNC-operator with external d-type quarks $\overline{Q_L}^i_L\, (Y_U Y_U^{+})_{ij}\, Q^j_L \times L_L\, L_L$

$$\lambda_{FCij} = (Y_U Y_U^{+})_{ij} = (V^{+}_{CKM} \times diag(y_u^2, y_c^2, y_t^2) \times V_{CKM})_{ij} \approx$$

$$\approx (V^{+}_{CKM} \times diag(0,0,y_t^2) \times V_{CKM})_{ij} = y_t^2 \times V^*_{3,i} V_{3,j}$$

Coupling λ_{FC} is the effective coupling ruling all FCNCs with external d-type quarks.

- MFV predictions to be tested:
  - usual CKM relations between $[b \to s] \leftrightarrow [b \to d] \leftrightarrow [s \to d]$ transitions:
    -we need high-precision $b \to s$, but also $s \to d$ measurements
    -$\mathcal{B}(\bar{B} \to X_d\gamma) \leftrightarrow \mathcal{B}(\bar{B} \to X_s\gamma)$, $\mathcal{B}(\bar{B} \to X_s\nu\bar{\nu}) \leftrightarrow \mathcal{B}(K \to \pi^+\nu\bar{\nu})$
  - CKM phase only source of CP violation:
    -phase measurements in $B \to \phi K_s$ or $\Delta M_{B_{(s/d)}}$ are not sensitive to new physics

- The usefulness of MFV-bounds/relations is obvious; any measurement beyond those bounds indicate the existence of new flavour structures

$\Delta F = 2$ UTfit,arXiv:0707.0636 $\Delta F = 1$ H.,Isidori,Kamenik,Mescia,arXiv:0807.5039

Update CKM-fitter, arXiv: 1203.0238 H., Mahmoudi, work in progress

- The MFV hypothesis is far from being verified

New spurions allowed: Next-to-MFV

Minimal flavour violation: formal solution of NP flavour problem

$$M(B_d\text{-}\bar{B}_d) \sim \frac{(V_{tb}^{*}V_{td})^2}{16\,\pi^2 M_w^2} + c_{NP}\frac{1}{\Lambda^2}$$

contribution of the new heavy degrees of freedom

$$c_{NP} \rightarrow \sim 1 \xrightarrow{\text{tree/strong + generic flavour}} \Lambda \gtrsim 2\times 10^4 \text{ TeV [K]}$$

$$c_{NP} \rightarrow \sim 1/(16\,\pi^2) \xrightarrow{\text{loop + generic flavour}} \Lambda \gtrsim 2\times 10^3 \text{ TeV [K]}$$

$$c_{NP} \rightarrow \sim (V_{ti}^{*}V_{tj})^2 \xrightarrow{\text{tree/strong + MFV}} \Lambda \gtrsim 5 \text{ TeV } [\text{K} \,\&\, \text{B}_d]$$

$$c_{NP} \rightarrow \sim (V_{ti}^{*}V_{tj})^2/(16\,\pi^2) \xrightarrow{\text{loop + MFV}} \Lambda \gtrsim 0.5 \text{ TeV } [\text{K} \,\&\, \text{B}_d]$$

Courtesy of Gino Isidori

MFV is NOT a theory of flavour

We still have to find explicit dynamical structures to realise MFV:

- Gauge-mediated supersymmetry
- $SO(10)$ GUT model with family symmetries Dermisek,Raby,hep-ph/0507045
- Warped extra dimensions Weiler et al.,arXiv:0709.1714

CP-problem of NP (44 NP phases in MSSM)

- Add flavourblind phases in MFV → EDM constraints!

- CP violation in Susy with effective MFV

Barbieri et al. arXiv:1011.0730, 1102.0726

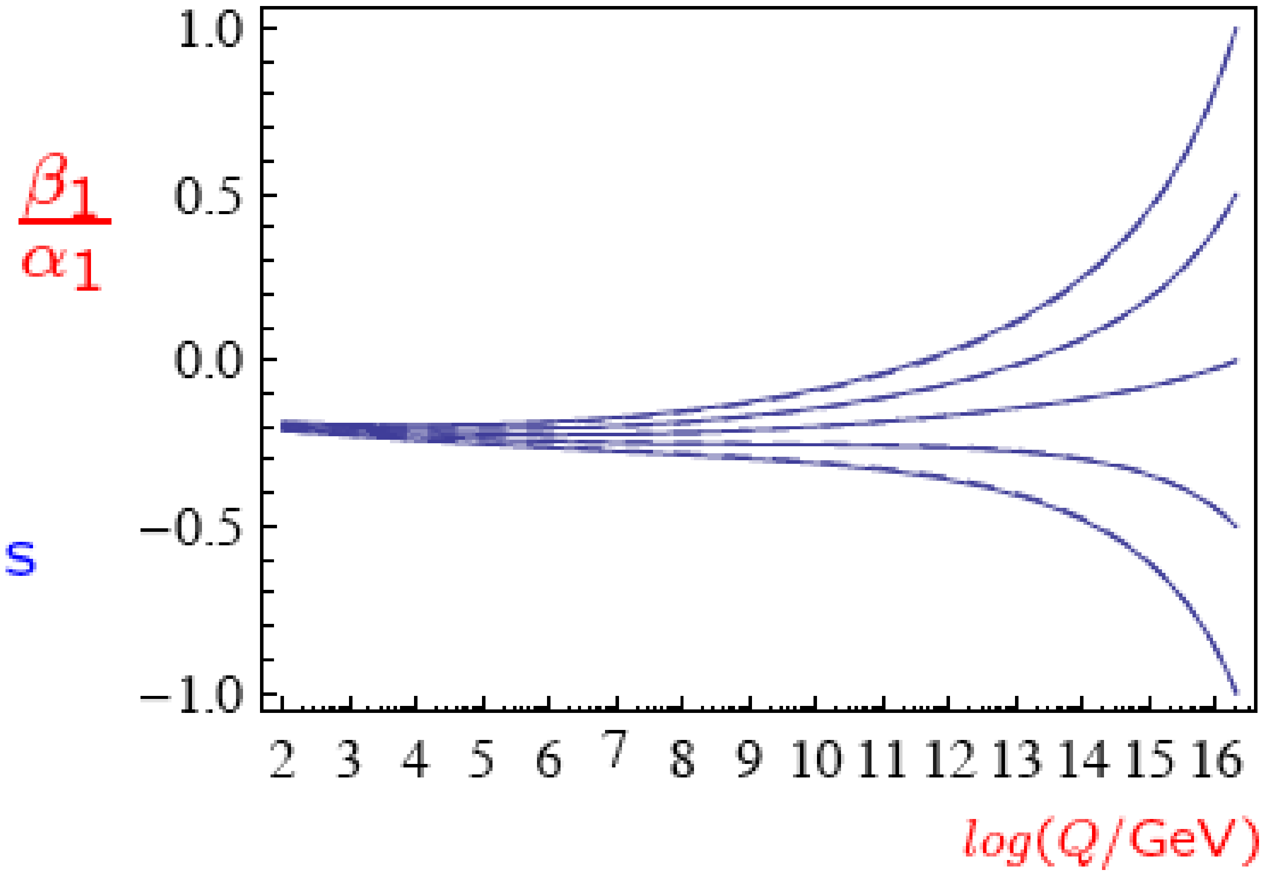
Running MFV in Supersymmetry

Paradisi,Ratz,Schieren,Simonetto,arXiv:0805.3989
Colangelo,Nikolidakis,Smith,arXiv:0807.0801

- MFV ansatz RG-invariant by construction

$$m_Q^2 = \alpha_1 \mathbb{1} + \beta_1 Y_u^\dagger Y_u + \beta_2 Y_d^\dagger Y_d + \beta_3 Y_d^\dagger Y_d Y_u^\dagger Y_u + \beta_3 Y_u^\dagger Y_u Y_d^\dagger Y_d \,,$$

$$\begin{aligned} m_u^2 &= \alpha_2 \mathbb{1} + \beta_5 Y_u Y_u^\dagger \,, \\ m_d^2 &= \alpha_3 \mathbb{1} + \beta_6 Y_d Y_d^\dagger \,, \\ A_u &= \alpha_4 Y_u + \beta_7 Y_u Y_d^\dagger Y_d \,, \\ A_d &= \alpha_5 Y_d + \beta_8 Y_d Y_u^\dagger Y_u \,, \\ A_e &= \alpha_e Y_e \,. \end{aligned}$$



'Spurion expansion' of soft terms

- MFV coefficients β_i at low energy insensitive to their GUT boundary conditions: (gluino contribution versus Yukawa effects)
- Result: MFV-compatible change of boundary conditions at the high scale has barely any influence on the low scale spectrum. 'fixed points'

MFV as a substitute for R-parity

Nikolidakis,Smith,arXiv:0710.3129

- Surprisingly, MFV sufficient to forbid a too fast proton decay
- MFV hypothesis applied to R-parity violating terms: spurion expansion lead to suppression by neutrino masses and light-fermion masses
- Proton decay could be very close to present bounds

See also:

MFV SUSY, a natural theory for R-parity violation

Csaki,Grossman,Heidenreich arXiv:1111.1239

MFV bounds

H., Mahmoudi, to appear

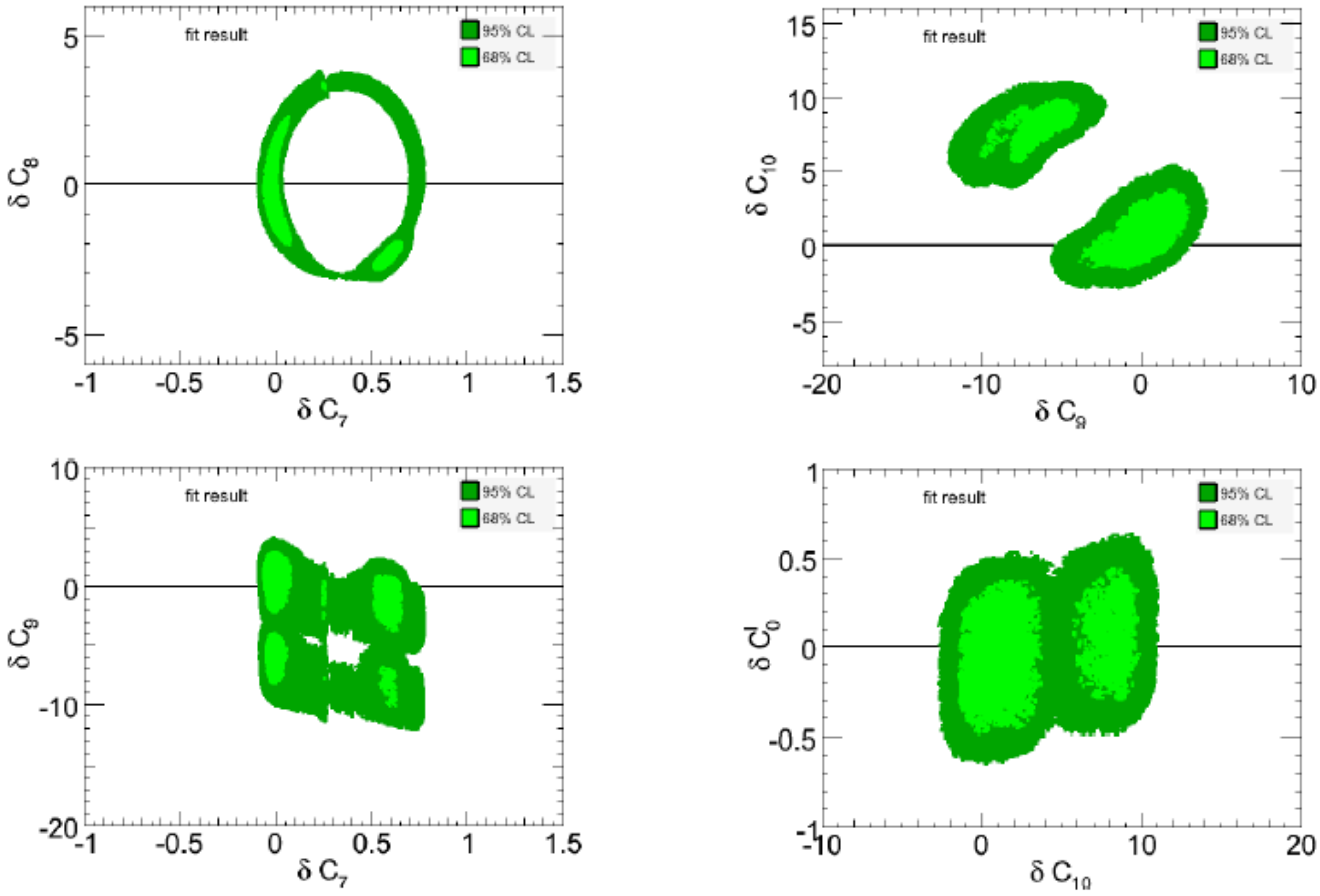
Relevent MFV Operators ($b \to s$): $\mathcal{O}_7, \mathcal{O}_8, \mathcal{O}_9, \mathcal{O}_{10}, \mathcal{O}_S = (\bar{s} P_R b)(\bar{\mu} P_L \mu)$

$$C_i(\mu) = C_i^{\mathrm{SM}}(\mu) + \delta C_i$$

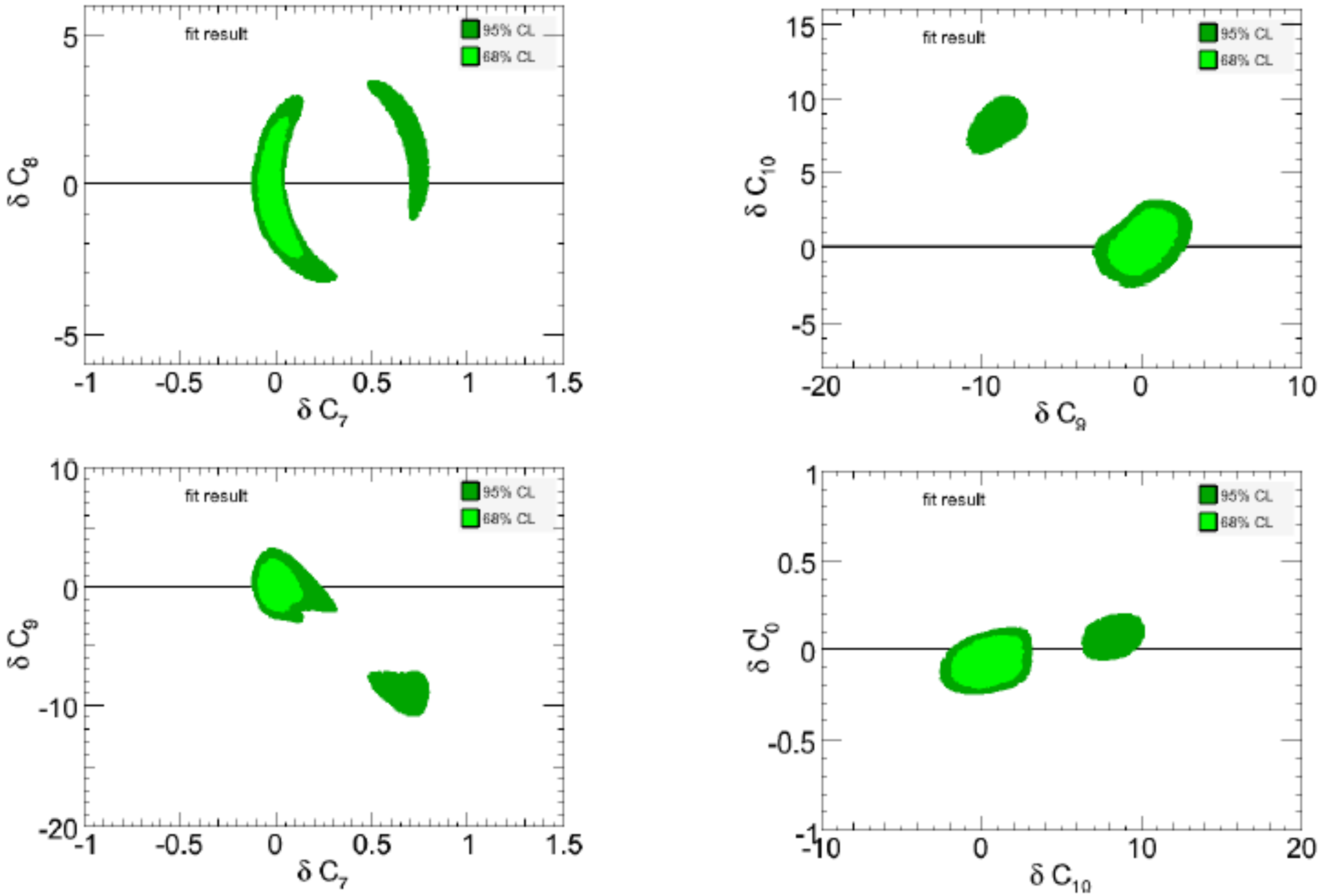
Observables

Observable	Experiment	SM prediction
$\mathrm{BR}(B \to X_s \gamma)$	$(3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$ [14]	$(3.08 \pm 0.24) \times 10^{-4}$
$\Delta_0(B \to X_s \gamma)$	$(5.2 \pm 2.6 \pm 0.09) \times 10^{-2}$ [14]	$(8.0 \pm 3.9) \times 10^{-2}$
$\mathrm{BR}(B \to X_d \gamma)$	$(1.41 \pm 0.57) \times 10^{-5}$ [15, 16]	$(1.49 \pm 0.30) \times 10^{-5}$
$\mathrm{BR}(B_s \to \mu^+ \mu^-)$	$< 4.5 \times 10^{-9}$ [17]	$(3.53 \pm 0.38) \times 10^{-9}$
$\langle dBR/dq^2(B \to K^* \mu^+ \mu^-)\rangle_{q^2 \in [1,6]\mathrm{GeV}^2}$	$(0.42 \pm 0.04 \pm 0.04) \times 10^{-7}$ [18]	$(0.47 \pm 0.27) \times 10^{-7}$
$\langle dBR/dq^2(B \to K^* \mu^+ \mu^-)\rangle_{q^2 \in [14.18,16]\mathrm{GeV}^2}$	$(0.59 \pm 0.07 \pm 0.04) \times 10^{-7}$ [18]	$(0.71 \pm 0.18) \times 10^{-7}$
$\langle A_{FB}(B \to K^* \mu^+ \mu^-)\rangle_{q^2 \in [1,6]\mathrm{GeV}^2}$	$-0.18 \pm 0.06 \pm 0.02$ [18]	-0.06 ± 0.05
$\langle A_{FB}(B \to K^* \mu^+ \mu^-)\rangle_{q^2 \in [14.18,16]\mathrm{GeV}^2}$	$0.49 \pm 0.06 \pm 0.05$ [18]	0.44 ± 0.10
$q_0^2(A_{FB}(B \to K^* \mu^+ \mu^-))$	$4.9^{+1.1}_{-1.3}$ GeV^2 [18]	4.26 ± 0.34 GeV^2
$\langle F_L(B \to K^* \mu^+ \mu^-)\rangle_{q^2 \in [1,6]\mathrm{GeV}^2}$	$0.66 \pm 0.06 \pm 0.04$ [18]	0.71 ± 0.13
$\mathrm{BR}(B \to X_s \mu^+ \mu^-)_{q^2 \in [1,6]\mathrm{GeV}^2}$	$(1.60 \pm 0.68) \times 10^{-6}$ [19, 20]	$(1.78 \pm 0.16) \times 10^{-6}$
$\mathrm{BR}(B \to X_s \mu^+ \mu^-)_{q^2 > 14.4\mathrm{GeV}^2}$	$(4.18 \pm 1.35) \times 10^{-7}$ [19, 20]	$(2.18 \pm 0.65) \times 10^{-7}$

Global MFV fit before LHCb



Global MFV with LHCb data



Test of MFV hypothesis:

Some positive and negative predictions

$\mathrm{BR}(B_d \to \mu^+\mu^-) < 0.32 \times 10^{-9}$

Current LHCb limit: $\mathrm{BR}(B_d \to \mu^+\mu^-) < 1.0 \times 10^{-9}$

$B \to K^*\mu^+\mu^-$ transverse asymmetries:

- $A_T^{(2)} \in [-0.068, -0.02]$
- $A_T^{(3)} \in [0.35, 1.00]$
- $A_T^{(4)} \in [0.18, 1.30]$
- $A_T^{(5)} \in [0.15, 0.49]$

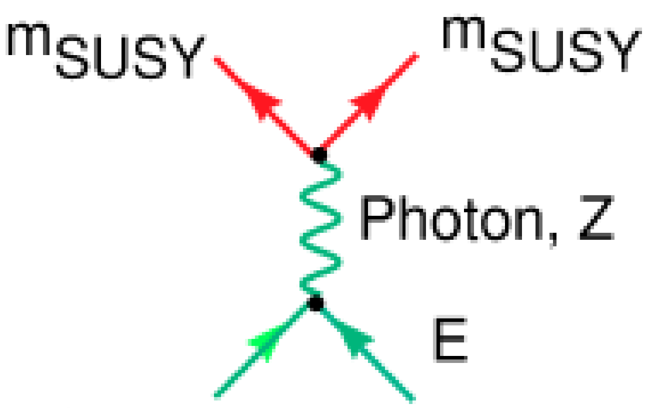
If there is MFV, LHCb will not measure any NP in A_i^T observables

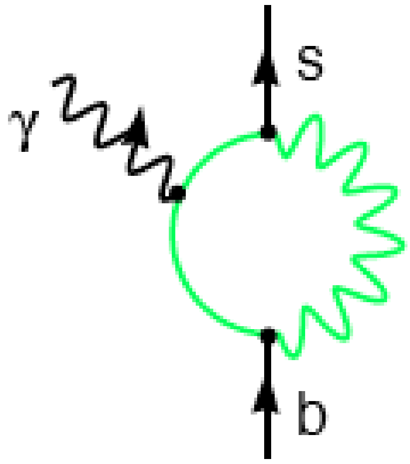
$B \to X_d\gamma$ measurement already within the MFV region

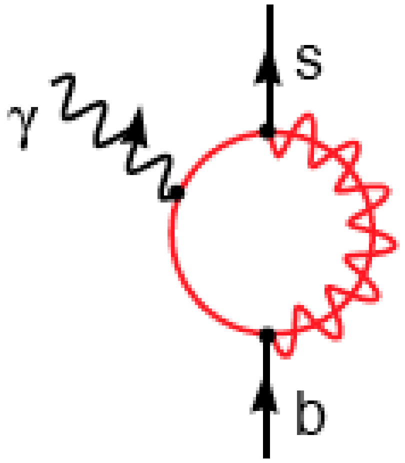
Another MFV correlation: $B \to X_s\nu\bar{\nu}$ versus $K \to \pi\nu\bar{\nu}$

Flavour@high-p_T interplay

Immense potential for synergy and complementarity between high-p_T and flavour physics within the search for new physics



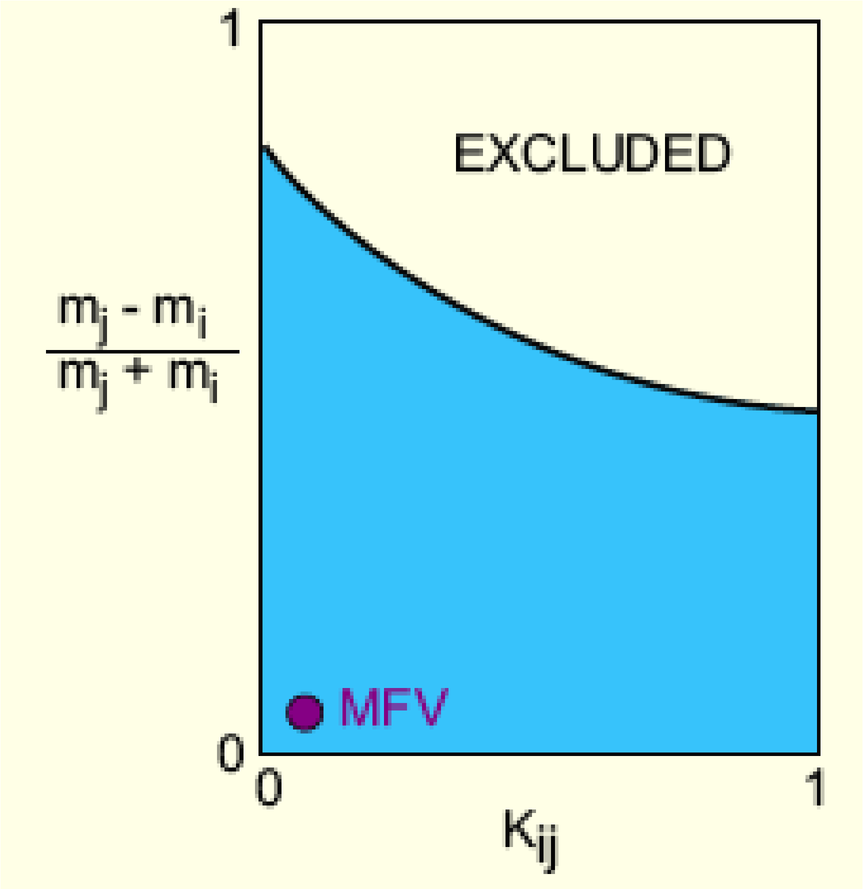


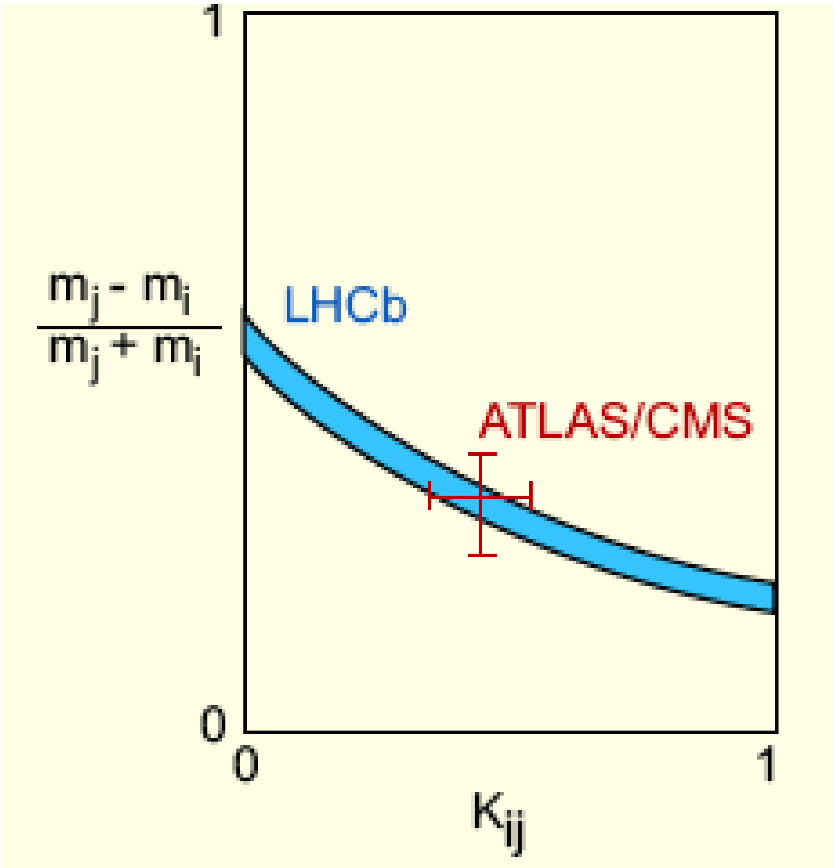


The indirect information will be most valuable when the general nature of new physics will be identified in the direct search, especially when the mass scale of the new physics will be fixed.

$$\left(C^i_{\text{SM}}/M_W + C^i_{\text{NP}}/\Lambda_{\text{NP}} \right) \times \mathcal{O}_i$$

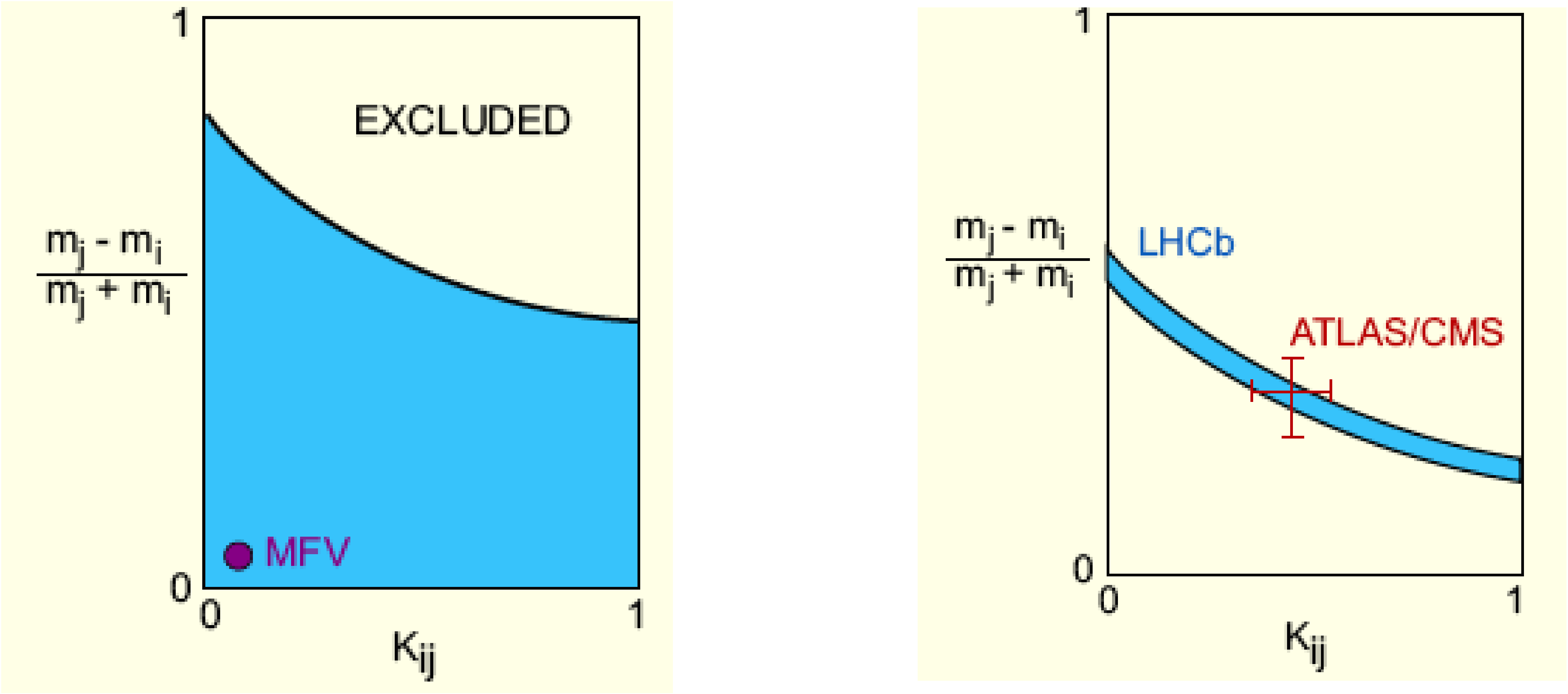
Immense potential for synergy and complementarity between high-p_T and flavour physics within the search for new physics





Courtesy of Yossi Nir

Immense potential for synergy and complementarity between high-p_T and flavour physics within the search for new physics



Courtesy of Yossi Nir

DNA-Flavour-test of NP models:

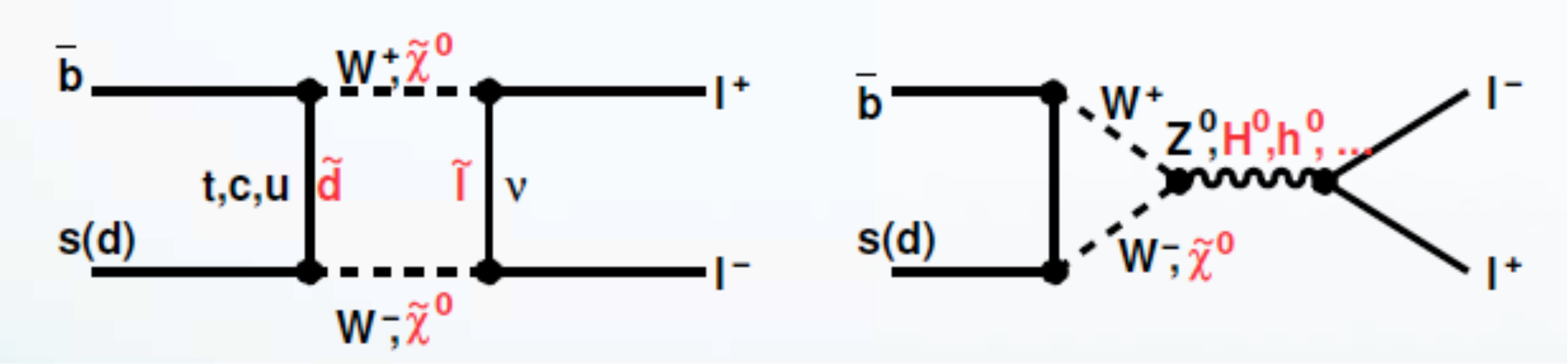
Correlations between flavour observables are significant pieces of information to identify a given extension of SM

Buras et al. arXiv:1012.1447,1204.5064

Implications of the latest LHCb measurement of $B_s \to \mu\mu$

Implications of the latest LHCb measurement of $B_s \to \mu\mu$

$$A_{\mathrm{SM}} \sim m_\mu/m_b \Leftrightarrow A_{H^0,A^0} \sim \tan^3\beta$$



ATLAS: Br($B_s \to \mu^+\mu^-$)<2.2 x 10^{-8} (2.4 fb^{-1})

CMS: Br($B_s \to \mu^+\mu^-$)<7.7 x 10^{-9} (4.9 fb^{-1})

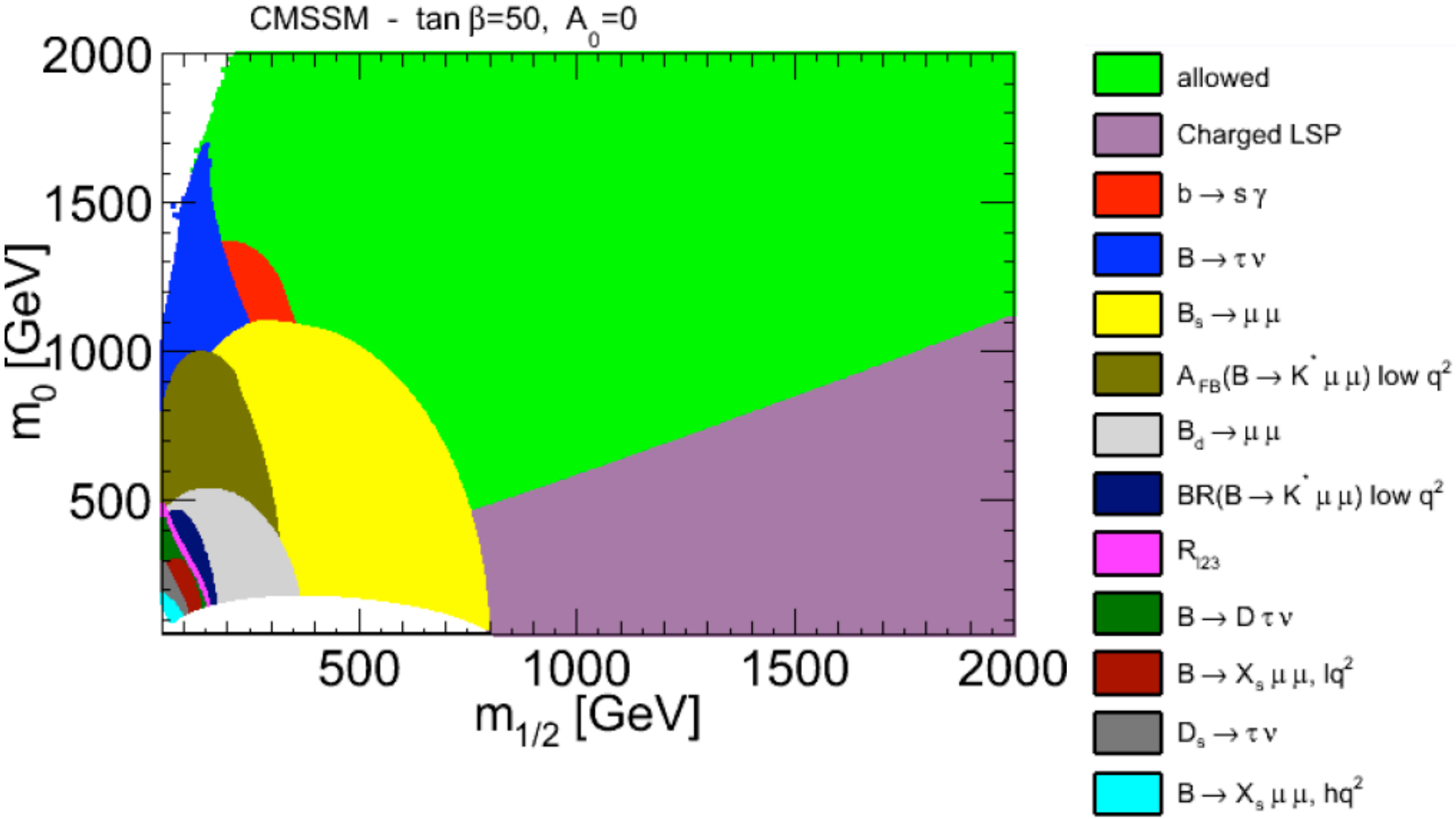
LHCb: Br($B_s \to \mu^+\mu^-$)<4.5 x 10^{-9} (1 fb^{-1})

Already very close to the SM prediction
Br$(B_s \to \mu\mu) = (3.53 \pm 0.38) \times 10^{-9}$!

CDF presented first double sided limit (9.6 fb^{-1})
$0.8 \times 10^{-9} <$ Br$(B_s \to \mu\mu) < 3.4 \times 10^{-8}$ at 95%$C.L.$

Constraints on CMMSM

Mahmoudi arXiv:1108.3018, 1205.3099



Constraints on CMMSM

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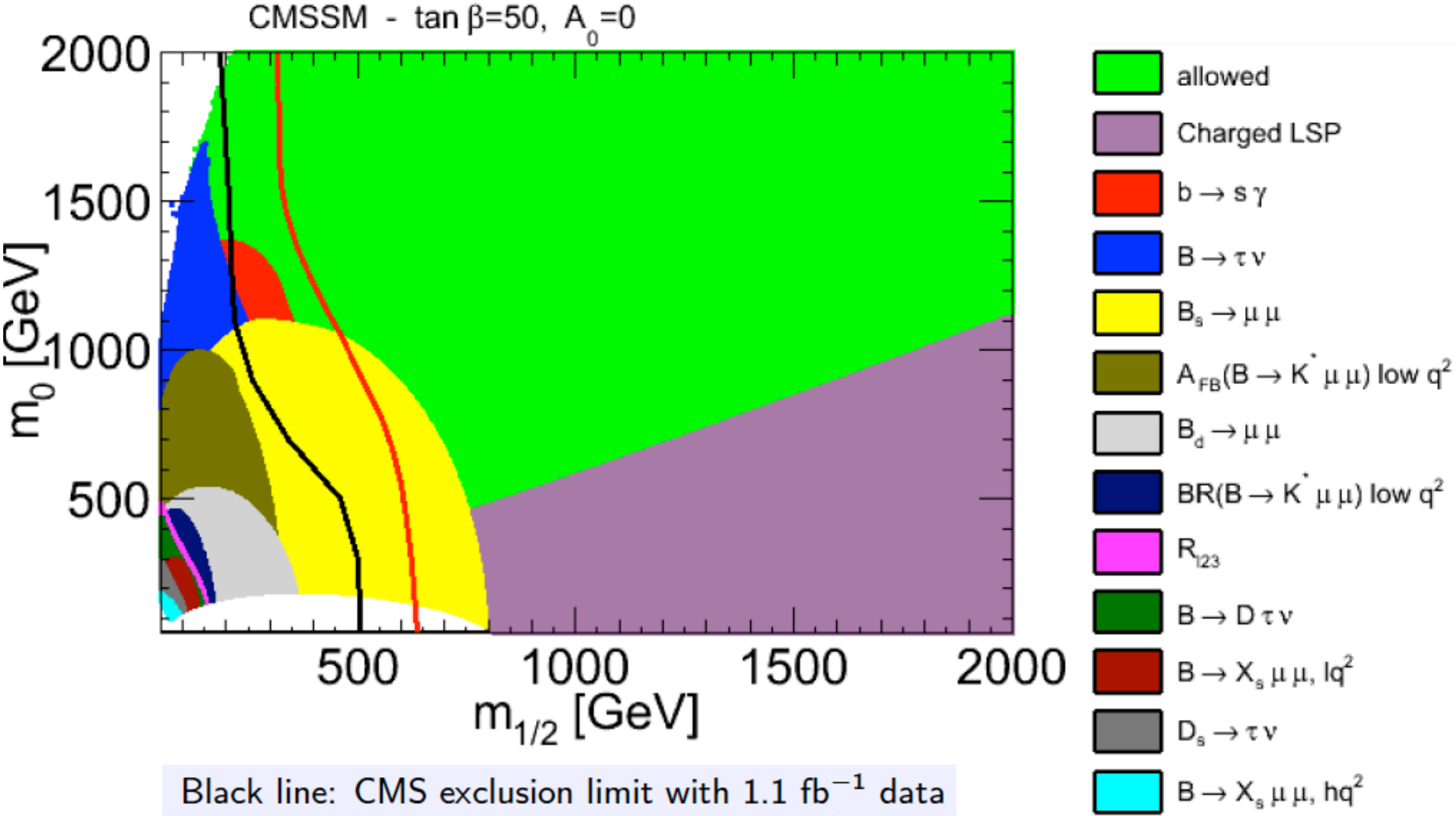

Black line: CMS exclusion limit with 1.1 fb^{-1} data
Red line: CMS exclusion limit with 4.4 fb^{-1} data

Constraints on CMMSM

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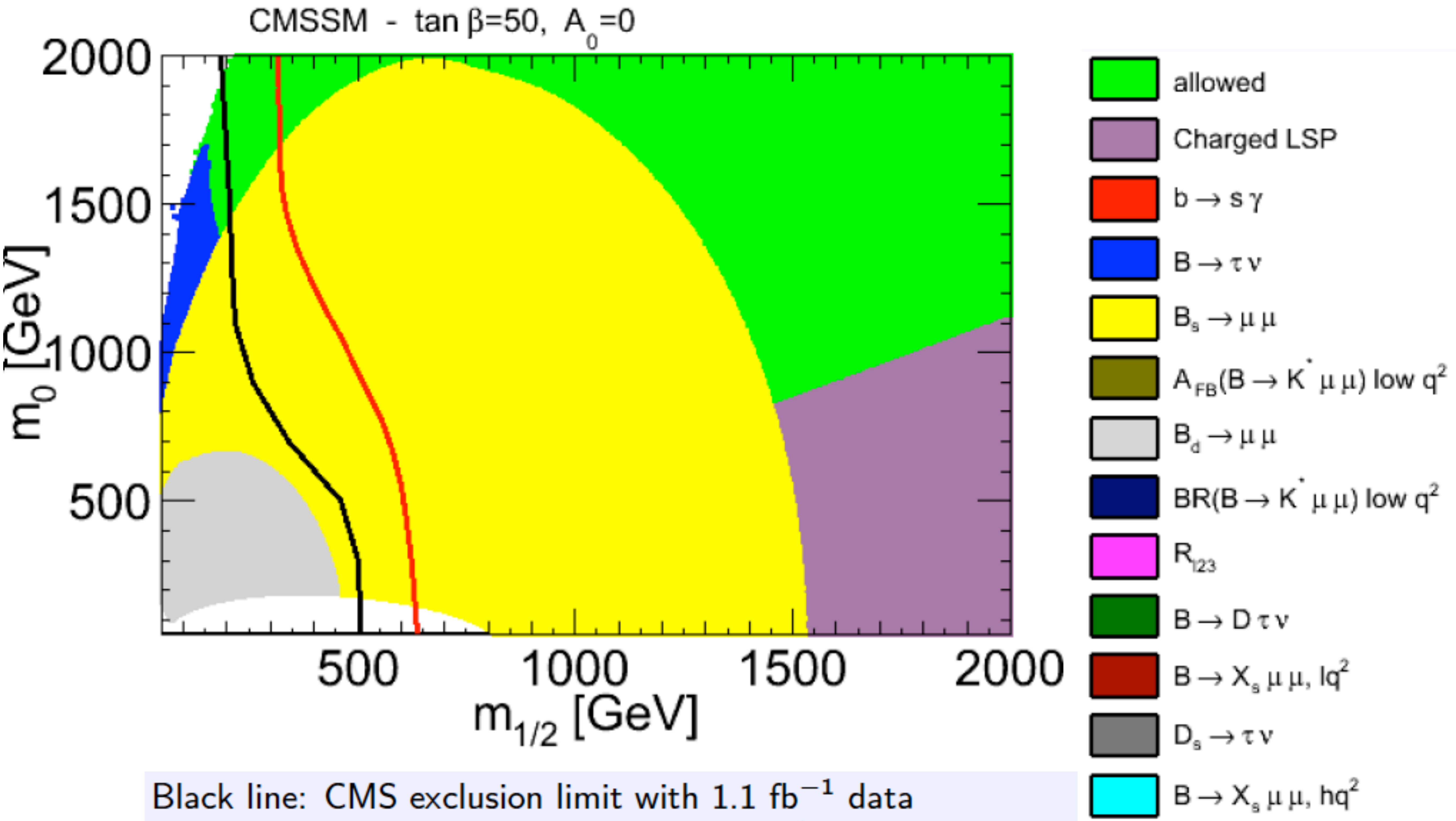

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New LHCb limits for BR($B_s \to \mu^+\mu^-$) and BR($B_d \to \mu^+\mu^-$)

Constraints on CMMSM

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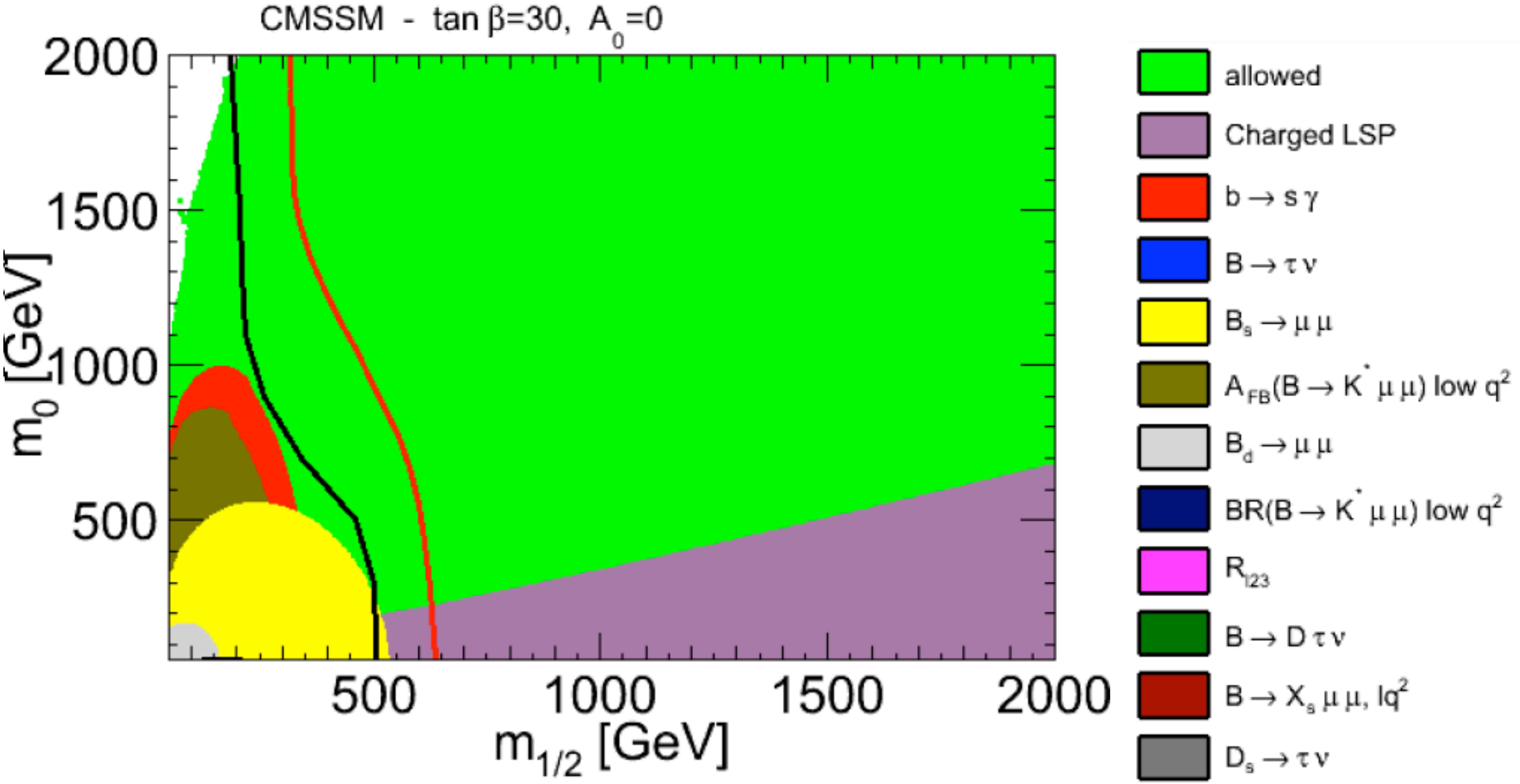

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New LHCb limits for $\text{BR}(B_s \to \mu^+\mu^-)$ and $\text{BR}(B_d \to \mu^+\mu^-)$

Future Opportunities

- **LHCb (5 years)** $5fb^{-1}$: allows for wide range of analyses,

  highlights: B_s mixing phase, angle γ, $B \to K^* \mu\mu$, $B_s \to \mu\mu$,$B_s \to \phi\phi$

  then possibility for **upgrade to** $50fb^{-1}$

- **Dedicated kaon experiments J-PARC E14 and CERN Na62:**

  rare kaon decays $K_L^0 \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$

- **Two partially-funded Super-B factories:**

  Belle II at KEK and SuperB in Frascati $(75ab^{-1})$

  Super-B is a Super Flavour factory: besides precise B measurements, CP violation in charm, lepton flavour violating modes $\tau \to \mu\gamma$,...

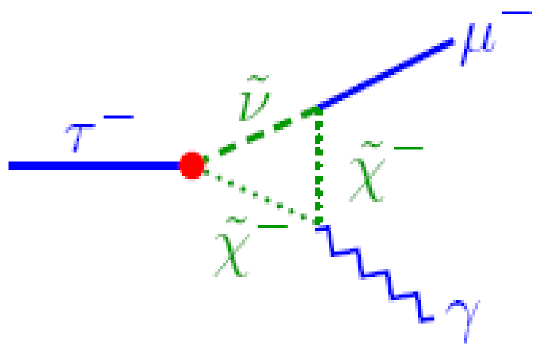
Opportunities at a Super Flavour Factory

see JHEP 0802 (2008) 110, arXiv:0710.3799

Measurement of lepton flavour violation

$\tau \to \mu\gamma$ and $\to 3\mu$

$$\text{BR}(l_j^- \to l_i^- \gamma)|_{\text{SM}_R} \approx (m_\nu/M_W)^2 \sim \mathcal{O}(10^{-54})$$



Process	Expected 90%CL upper limited	4σ Discovery Reach
$\mathcal{B}(\tau \to \mu\gamma)$	2×10^{-9}	5×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$	2×10^{-10}	8.8×10^{-10}

Use modes to distinguish SUSY vs LHT

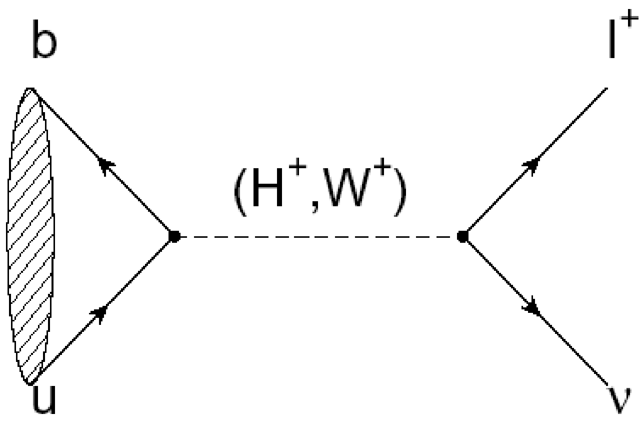
Blanke et al.

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{\mathcal{B}(\tau^- \to e^- e^+ e^-)}{\mathcal{B}(\tau \to e\gamma)}$	$0.4 \ldots 2.3$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{\mathcal{B}(\tau^- \to \mu^- \mu^+ \mu^-)}{\mathcal{B}(\tau \to \mu\gamma)}$	$0.4 \ldots 2.3$	$\sim 2 \cdot 10^{-3}$	$0.06 \ldots 0.1$
$\frac{\mathcal{B}(\tau^- \to e^- \mu^+ \mu^-)}{\mathcal{B}(\tau \to e\gamma)}$	$0.3 \ldots 1.6$	$\sim 2 \cdot 10^{-3}$	$0.02 \ldots 0.04$
$\frac{\mathcal{B}(\tau^- \to \mu^- e^+ e^-)}{\mathcal{B}(\tau \to \mu\gamma)}$	$0.3 \ldots 1.6$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{\mathcal{B}(\tau^- \to e^- e^+ e^-)}{\mathcal{B}(\tau^- \to e^- \mu^+ \mu^-)}$	$1.3 \ldots 1.7$	~ 5	$0.3 \ldots 0.5$
$\frac{\mathcal{B}(\tau^- \to \mu^- \mu^+ \mu^-)}{\mathcal{B}(\tau^- \to \mu^- e^+ e^-)}$	$1.2 \ldots 1.6$	~ 0.2	$5 \ldots 10$

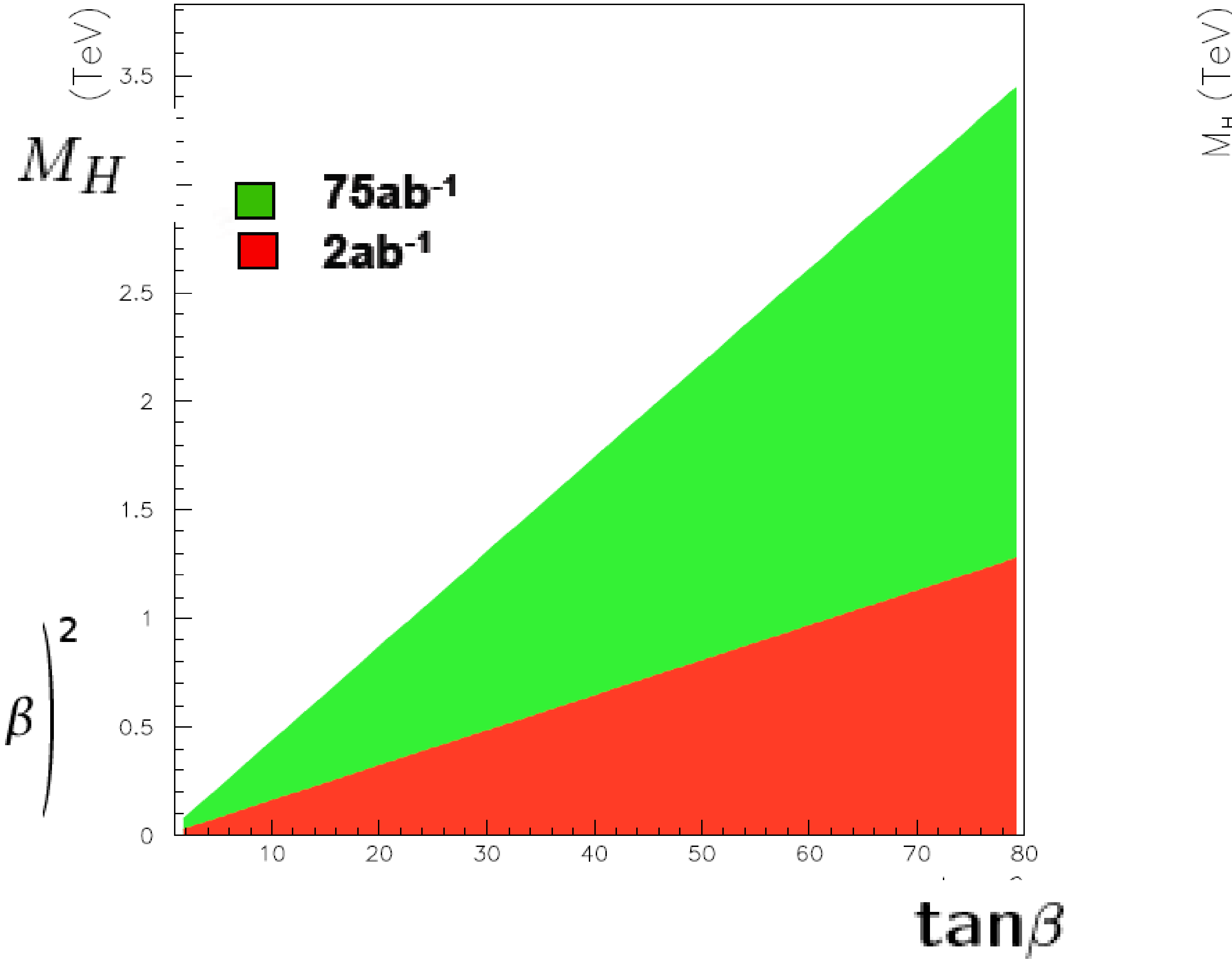
Superflavour factory: measurement of clean modes

$B \to \tau\nu$: **B factories 20%** **Super B factories 4%**

2HDM-II



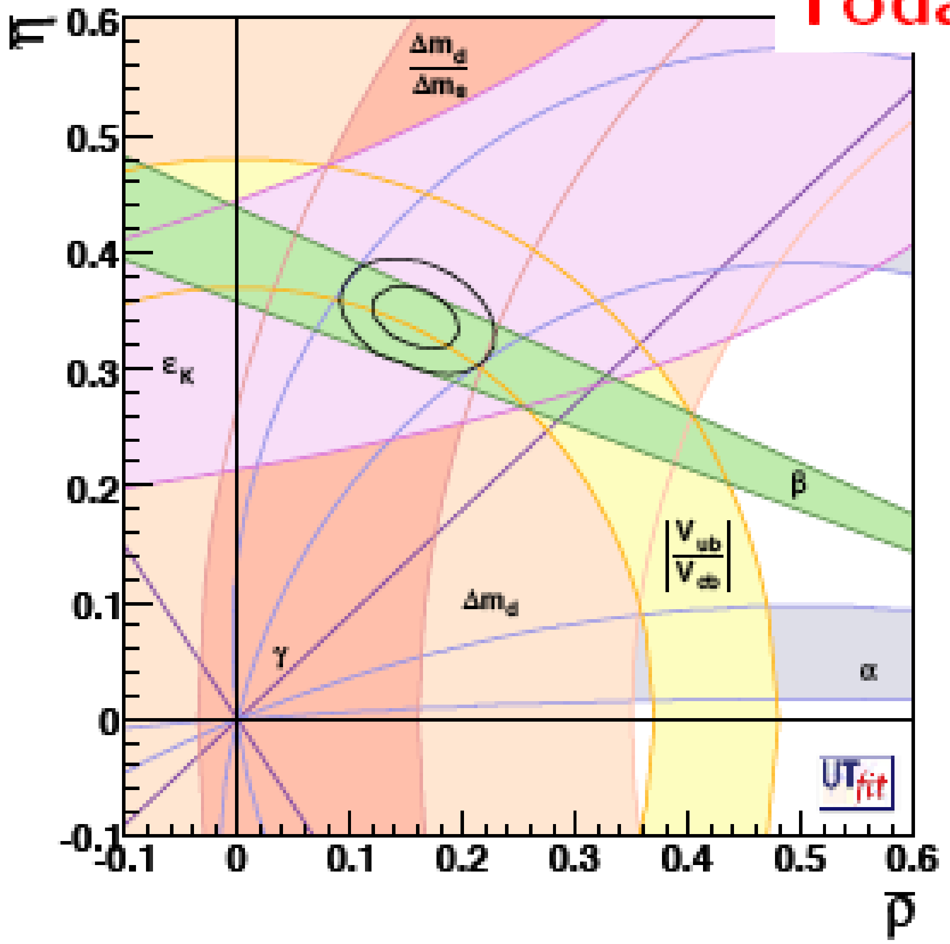
$$\mathrm{BR}(B\to\tau\,\nu)=\mathrm{BR}_{\mathrm{SM}}(B\to\tau\,\nu)\left(1-\frac{m_B^2}{M_H^2}\tan^2\beta\right)^2$$



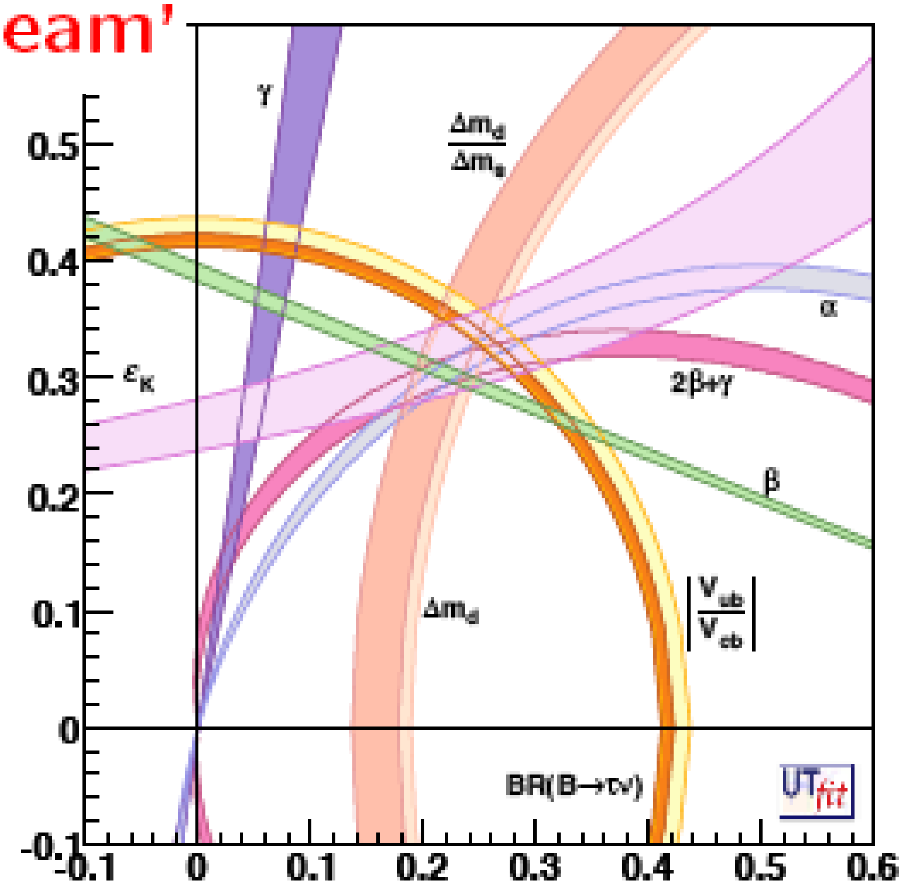
(Assuming SM branching fraction is measured)

Superflavour factory: CKM theory gets tested at 1%

Today



'the dream'



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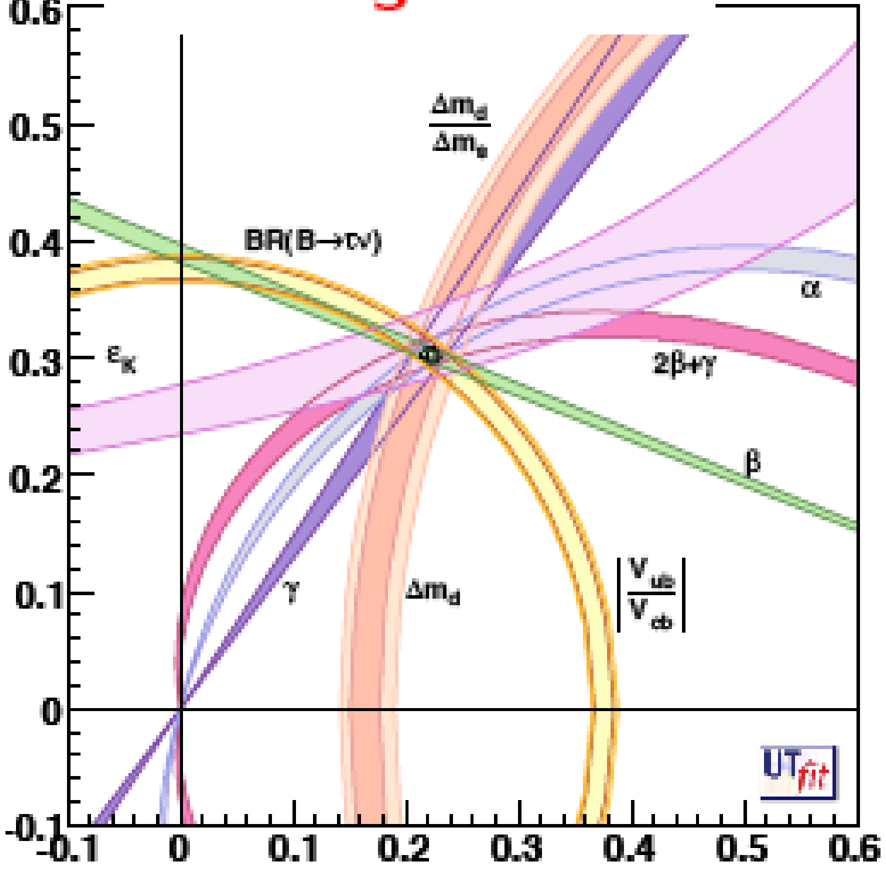


Epilogue

Possible future scenarios:
(see T. Nakada LHCb spokesperson at EuroFlavour06, Barcelona, 11/2006)

A couple of years after the start of the LHC, may be

1. many new degrees of freedom discovered at ATLAS and CMS, and new FCNCs at LHCb
2. many new particles discovered at ATLAS and CMS, but no new FCNCs at LHCb ⇒ important input to understand the New Physics
3. No new particles discovered at ATLAS and CMS (except one Higgs), but new FCNCs at LHCb ⇒ tells us something about the mass scale to aim at (modulo flavour problem)
4. ....
5. ....

LHC discovers ‘only‘ the Higgs,

then precision experiments like ILC and BelleII/SuperB/SuperLHCb

will show us the way to the NP energy scale

Charming surprises at LHCc

$\Delta A_{CP} = A^{dir}_{CP}(K^+K^-) - A^{dir}_{CP}(\pi^+\pi^-)$ = -$(0.82 \pm 0.21 \pm 0.11)$%

$\Rightarrow 3.5\sigma$ away from zero.. [LHCb Collaboration (2011)]

$\Delta A_{CP} = (-0.645 \pm 0.180)\%$ HFAG

Poorly known SM dynamics ?? BSM physics playing a role ??

Explanations of the LHCb result in SM, and in NP models:

Courtesy of Soumitra Nandi

- Isidori et.al. arxiv:1103.5785 ⇒ NP explanation in a model independent way
- Brod et.al. arxiv:1111.4987 ⇒ Large $1/m_c$ suppressed amplitude
- Rozanov et.al. arxiv:1111.5000 ⇒ Large penguin in sequential 4th generation model
- Pirtskhalava et.al. arxiv:1112.5451 ⇒ Badly broken $SU(3)_F$ symmetry
- Cheng et.al. arxiv:1201.0785 ⇒ Large weak penguin annihilation contribution
- Bhattacharya et.al. arxiv:1201.2351 ⇒ CP conserving NP in penguin
- Giudice et.al arxiv:1201.6204 ⇒ Left-right flavour mixing via chromomagnetic operator
- Altmannshofer et.al. arxiv:1202.2866 ⇒ Chirally enhanced chromomagnetic penguins
- Brod et.al. arxiv:1203.6659 ⇒ In SM via s- and d-quark penguin contraction

.........many more

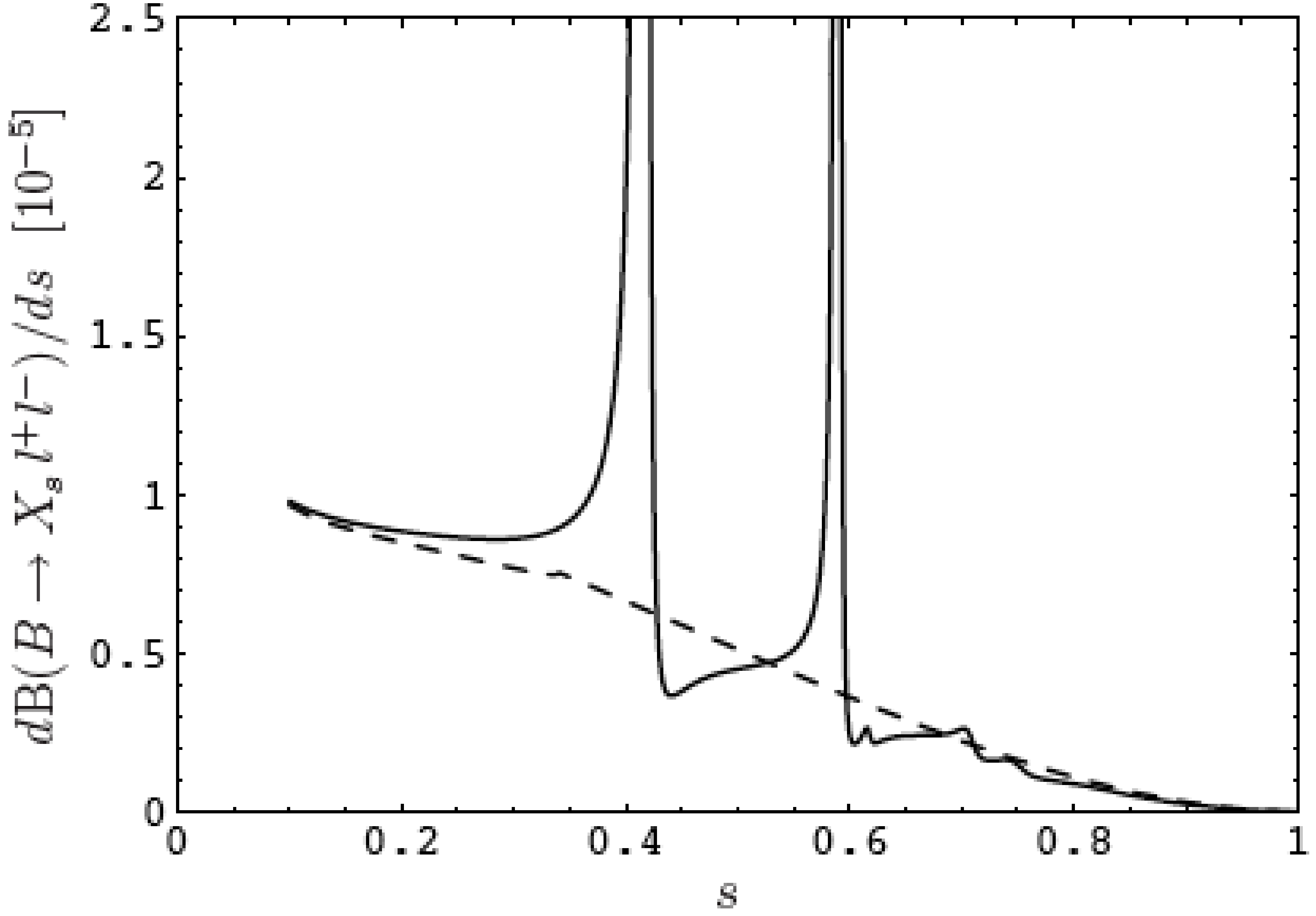
Read recommended SM papers first before move to NP explanations !

Extra

Quark-hadron duality violated in $\bar{B} \to X_s \ell^+ \ell^-$?

BBNS, arXiv:0902.4446

Within integrated branching ratio the resonances J/ψ and ψ' exceed the perturbative contributions by two orders of magnitude.



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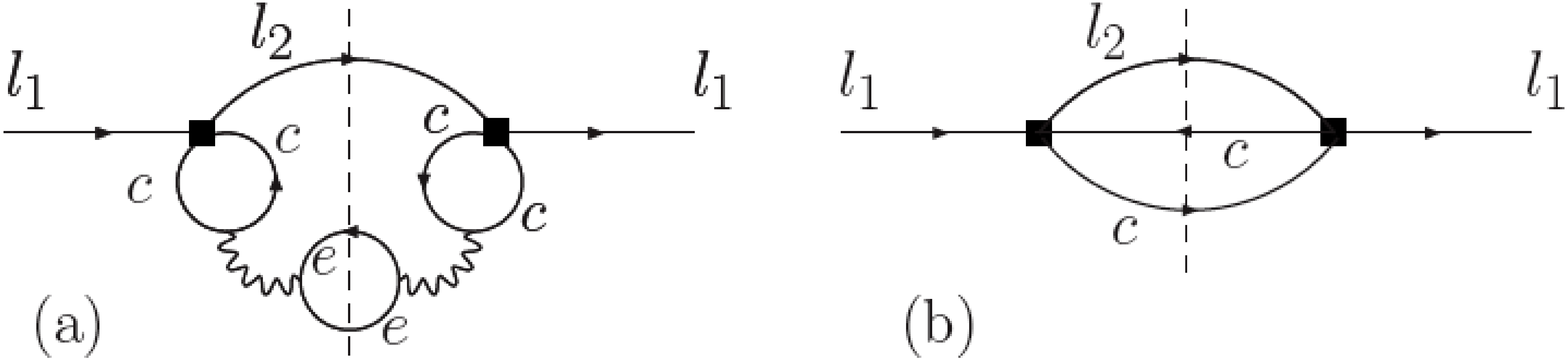
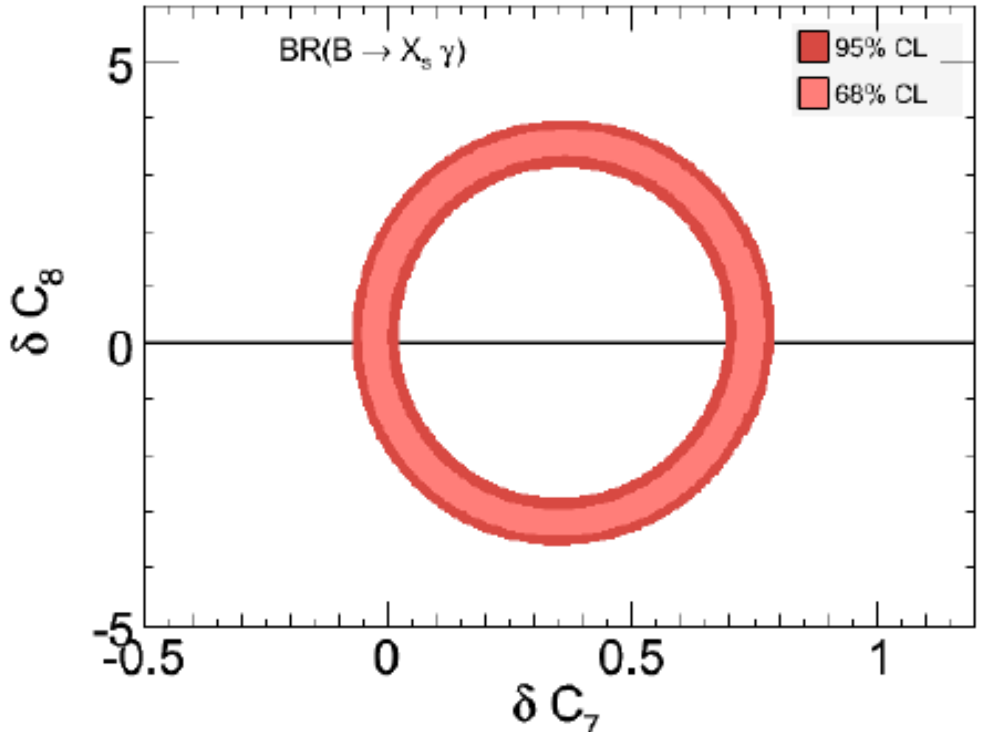


The rate $l_1 \to l_2 e^+ e^-$ (a) is connected to the integral over $|\Pi(q^2)|^2$ for which global duality is NOT expected to hold.

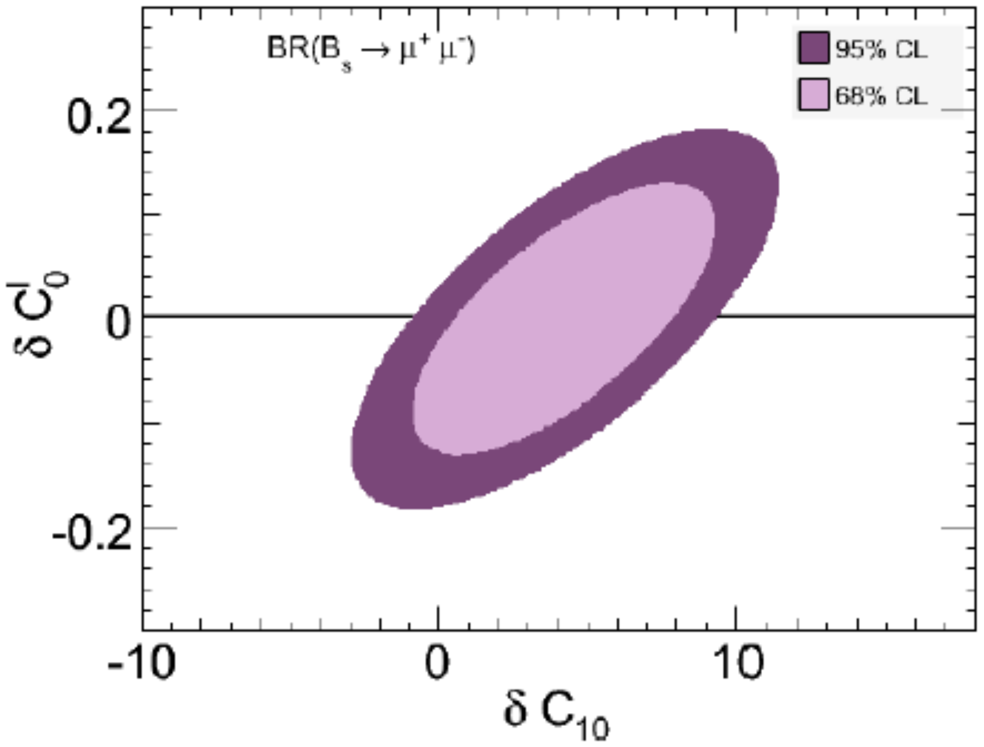
In contrast the inclusive hadronic rate $l_1 \to l_2 X$ (b) corresponds to the imaginary part of the correlator $\Pi(q^2)$.

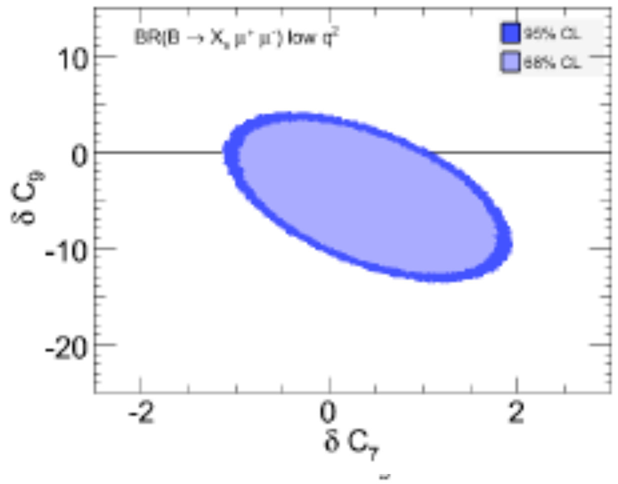
Main players

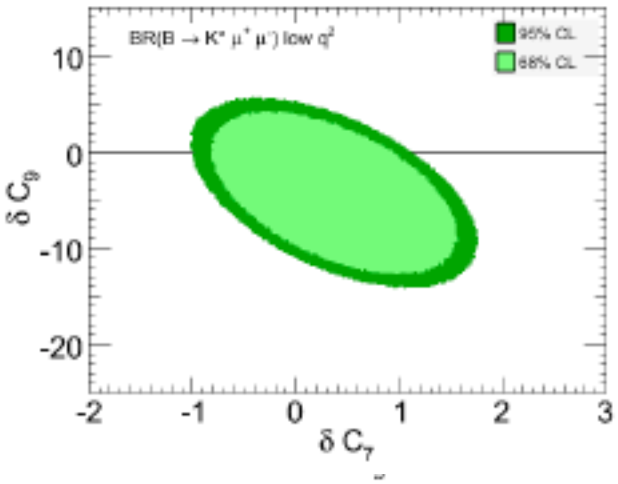
$B \to X_s \gamma$



$B_s \to \mu^+ \mu^-$







$B \to X_s \mu^+ \mu^-$ (left)

$B \to K^* \mu^+ \mu^-$ (right)