LIO International Conference on Flavour, Composite Models
and Dark Matter (23-27 November 2015)

Status of Flavour Physics and Implications for New Physics

Semileptonic Penguin Decays

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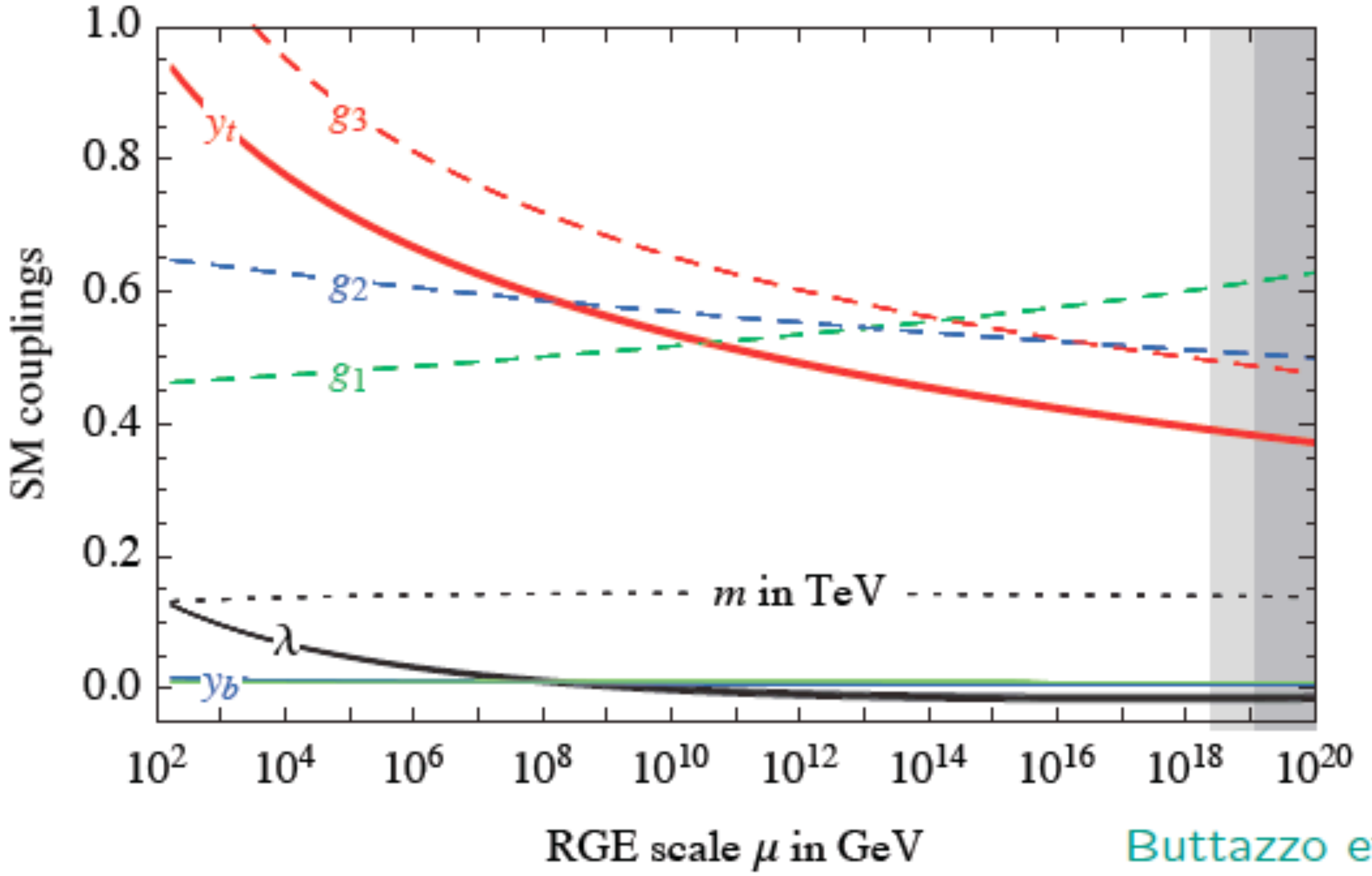
Prologue

Self-consistency of the SM

Do we need new physics beyond the SM ?

- It is possible to extend the validity of the SM up to the M_P as weakly coupled theory.



Buttazzo et al. arXiv:1307.3536

High-energy extrapolation shows that the Yukawa couplings, weak gauge couplings and the Higgs self coupling remain perturbative in the entire energy domain between the electroweak and Planck scale (no Landau poles !).

- Renormalizability implies no constraints on the free parameters of the SM Lagrangian.

Experimental evidence beyond SM

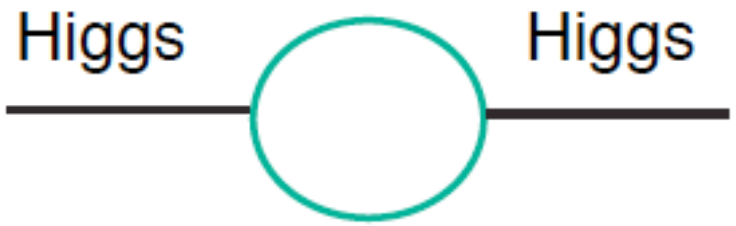
- Dark matter (visible matter accounts for only 4% of the Universe)
- Neutrino masses (Dirac or Majorana masses ?)
- Baryon asymmetry of the Universe (new sources of CP violation needed)

Caveat:

Answers perhaps wait at energy scales which we do not reach with present experiments.

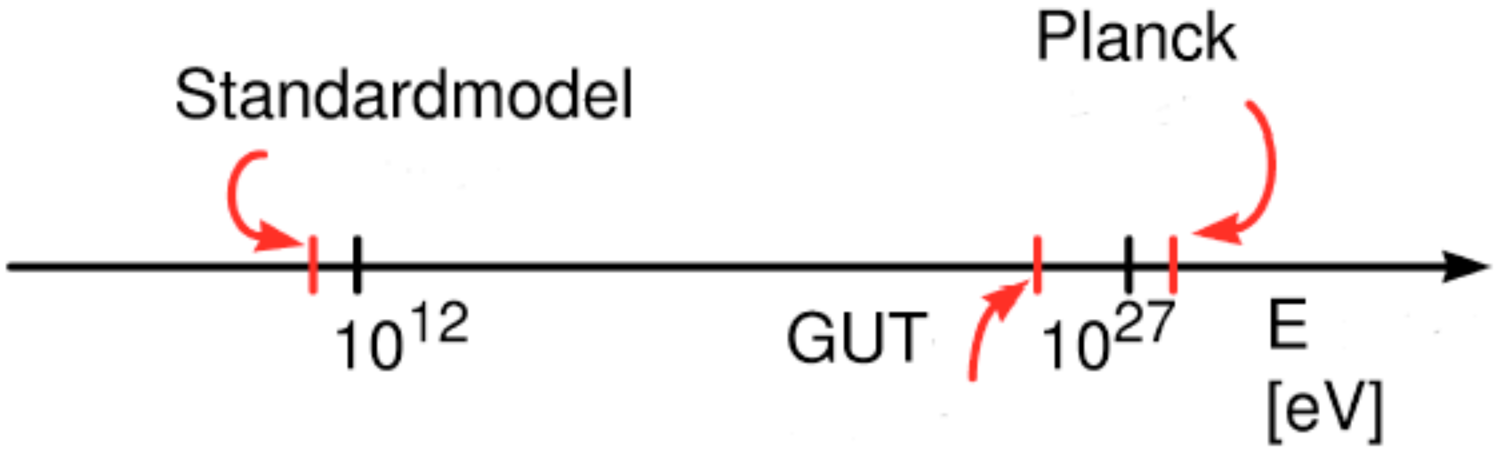
Hierarchy problem

Quantum corrections to Higgs boson mass:



$$m_{\mathrm{H}}^2 \approx (m_{\mathrm{H}}^2)_{\mathrm{tree}} + 1/(16\pi^2)\Lambda_{\mathrm{NP}}^2$$

$\Rightarrow$ Quadratic sensitivity to highest scale in the theory



After inclusion in larger theory: No stabilisation of the Higgs boson mass at the SM scale

Comparison:
Photon and quark masses protected by gauge symmetry and chiral symmetry, respectively

Many solutions to the hierarchy problem on the market:
Little Higgs Models, Extra Dimensions, Supersymmetry, ...

$$m_{\mathrm{H}}^2 \approx (m_{\mathrm{H}}^2)_{\mathrm{tree}} + 1/(16\pi^2)\Lambda_{\mathrm{NP}}^2 \Rightarrow \Lambda_{\mathrm{NP}} \leq 4\pi m_{\mathrm{W}} \approx 1\mathrm{TeV}$$

Summary of experimental searches for New Physics

by Günther Dissertori (CMS)

$$\infty \times 0 = ?$$

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$$\infty \quad \times \quad 0 \quad = \quad ?$$

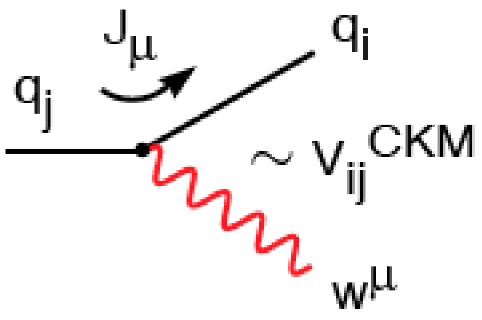
Infinite experimental measurements

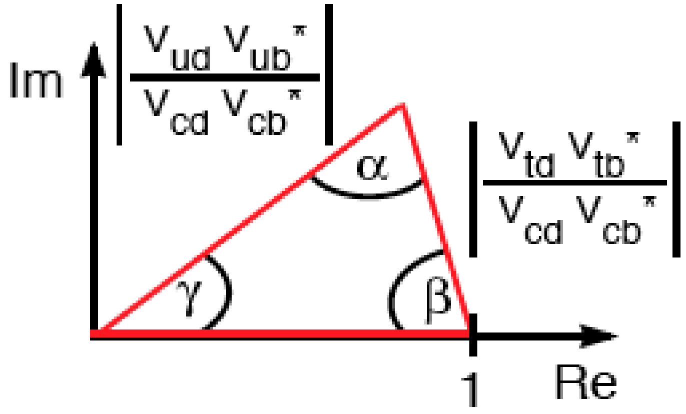
No deviation from SM

But still LHC Run-II, Belle-II, ... to come !

Flavour in the Standard Model

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





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

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

All previous and present measurements (BaBar, Belle, CLEO, CDF, D0, LHC, ...)
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.

Of course there have been and there are tensions in the flavour data at the 1,2,or 3σ level.

Impressing success of SM and CKM theory !!

Flavour in the Standard Model

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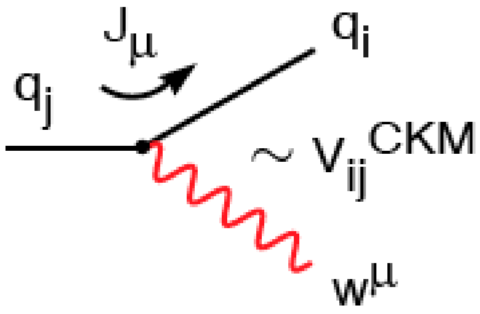

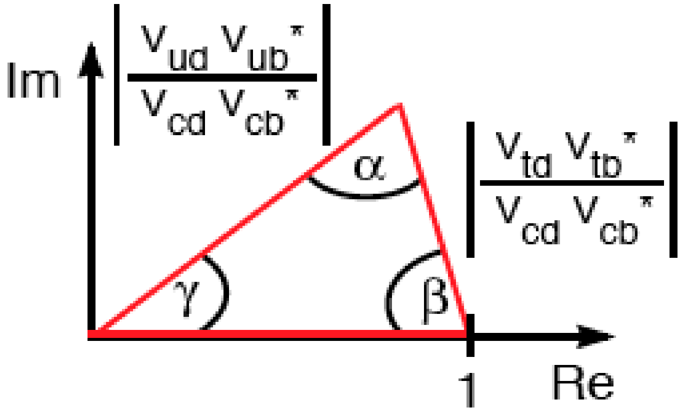

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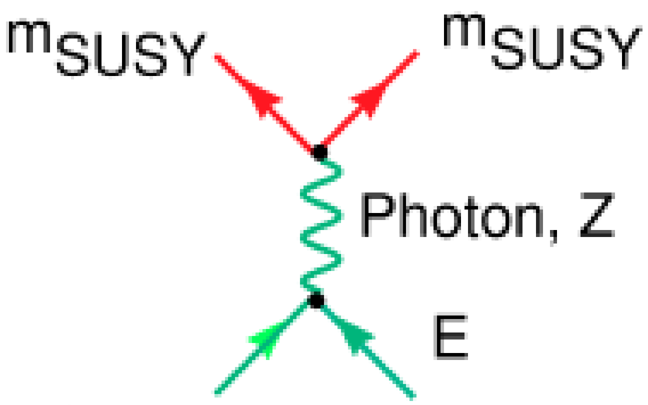
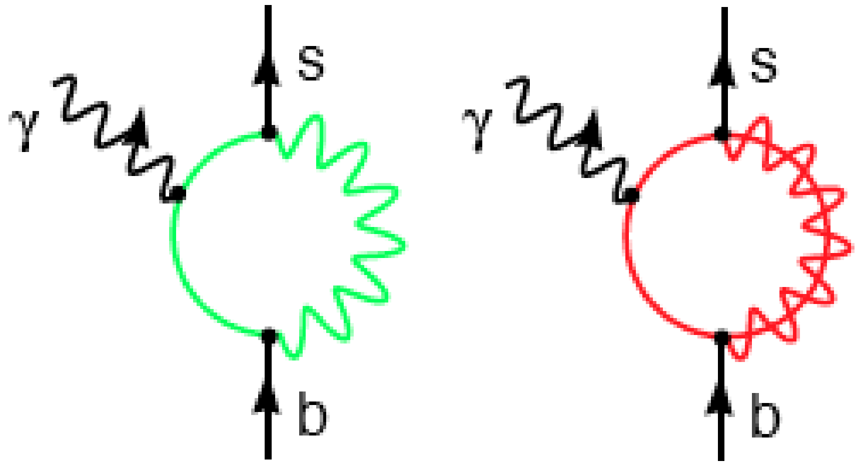
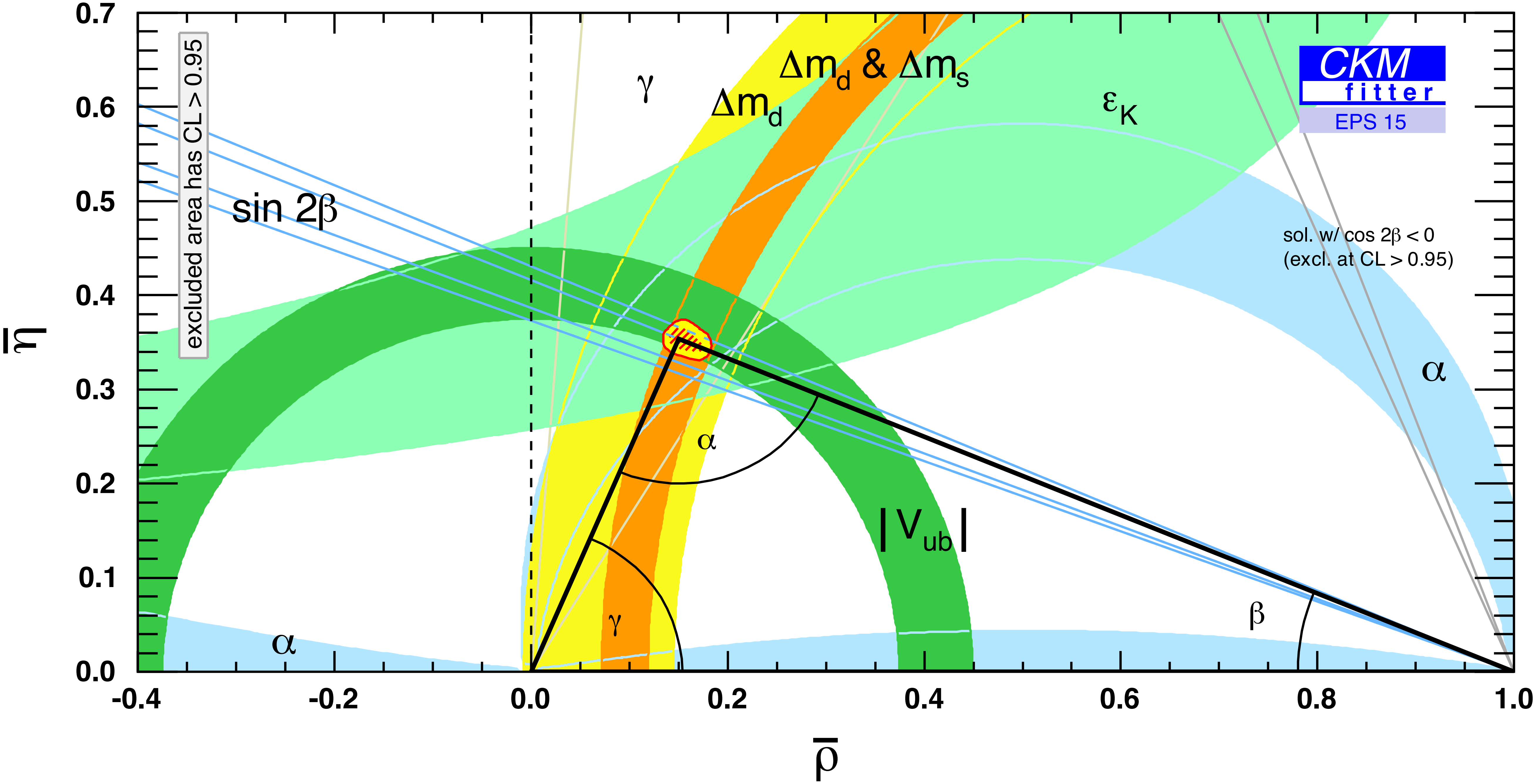




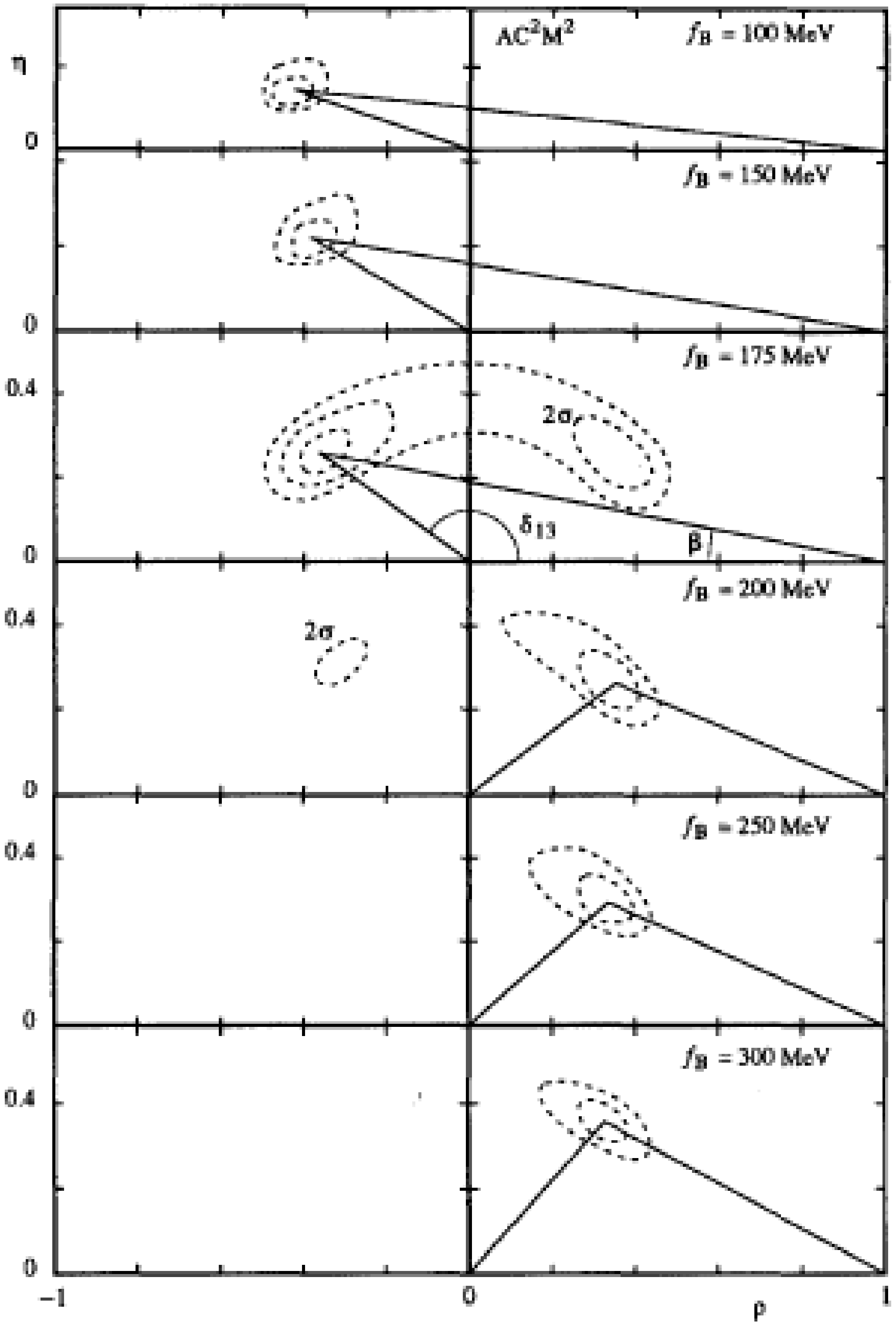
This success is somehow unexpected !!

Global fit, consistency check of the CKM theory



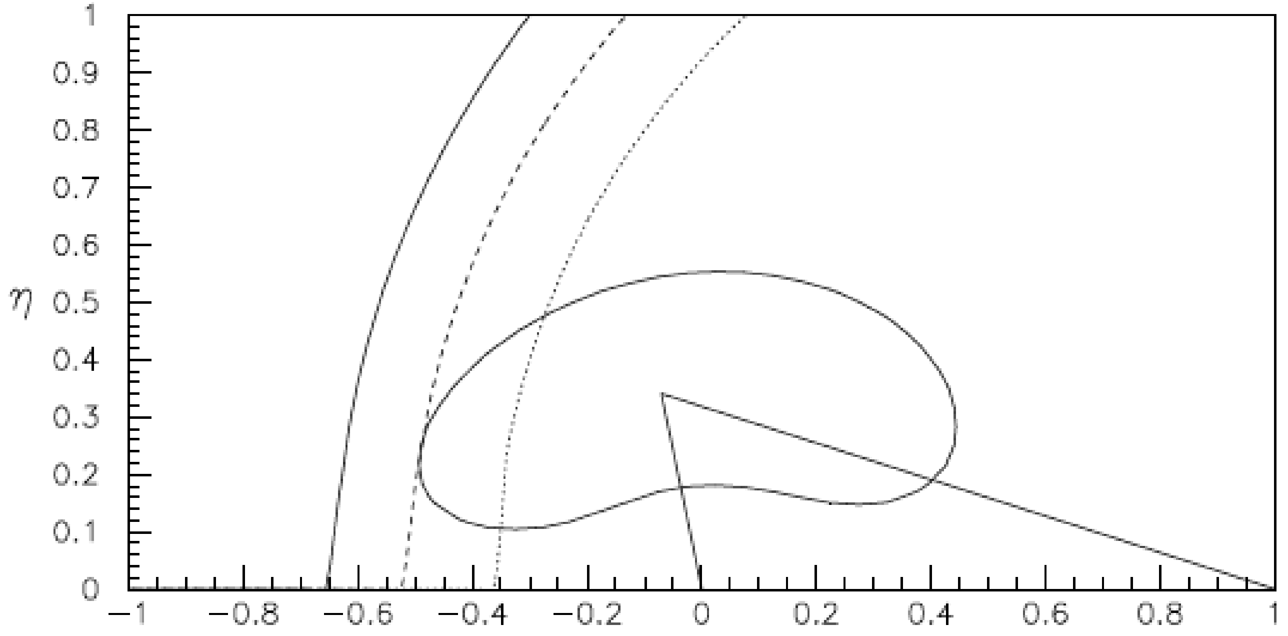
There is much more data not shown in the unitarity fits which confirm the SM predictions of flavour mixing like rare decays

For comparison: some historical CKM fits

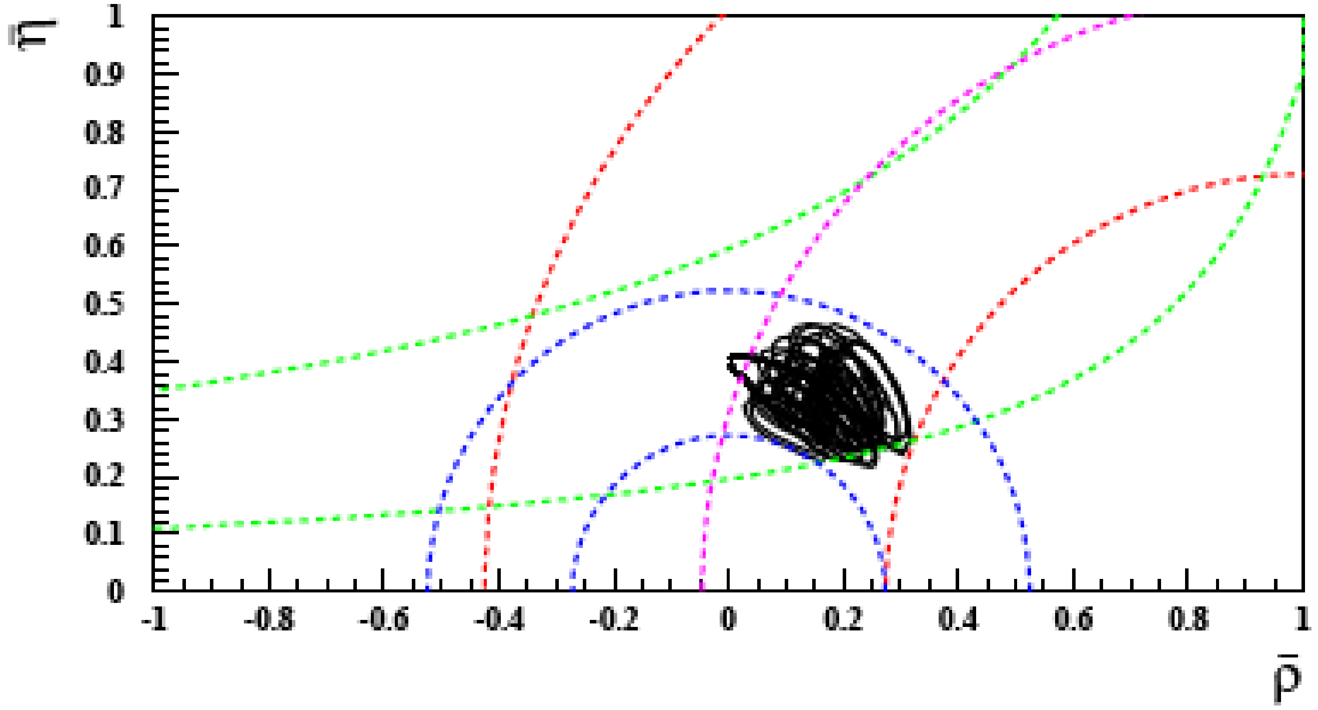


Schmidtler, Schubert 1992

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



Ali, London 1995



Plazczynski, Schune 1999

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.

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

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

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

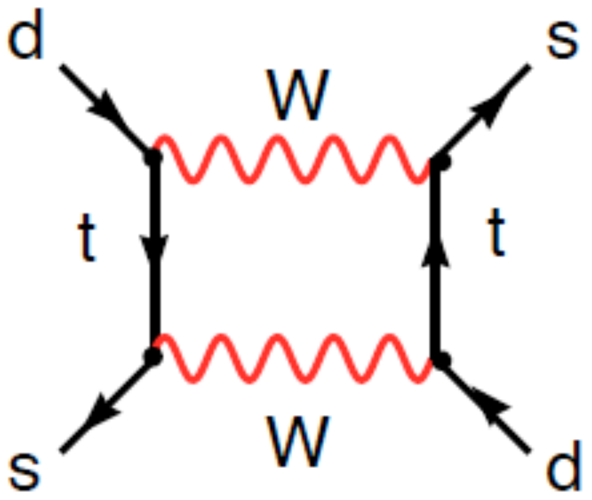
- How many families of fundamental fermions are there ?
- How are neutrino and quark masses and mixing angles are generated ?
- Do new sources of flavour and CP violation exist ?
- Is there CP violation in the QCD gauge sector ?
- Relations between the flavour structure in the lepton and quark sector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

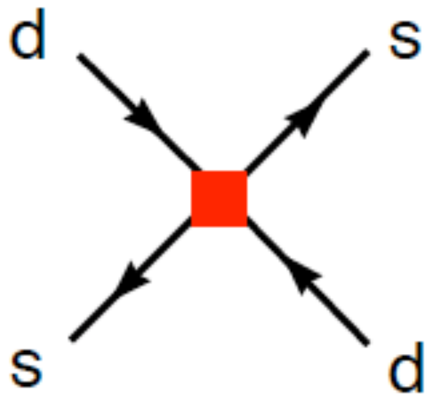
Flavour problem of New Physics or how FCNCs hide?

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

- SM as effective theory valid up to cut-off-scale Λ

- $K^0 - \bar{K}^0$-mixing $\mathcal{O}^6 = (\bar{s}\,d)^2$: $c^{SM}/M_W^2 \times (\bar{s}\,d)^2 + c^{New}/\Lambda^2 \quad \times (\bar{s}\,d)^2 \Rightarrow \quad \Lambda > 10^4$ TeV





- Natural stabilisation of Higgs boson mass (i.e. supersymmetry) $\Rightarrow \quad \Lambda \sim 1$TeV

Ambiguity of new physics scale from flavour data

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

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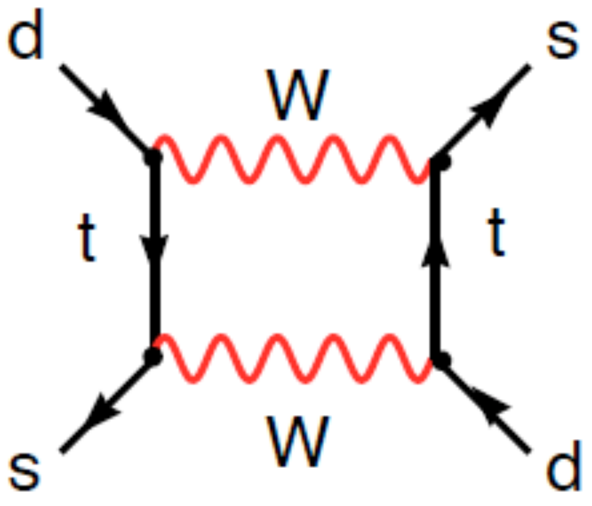

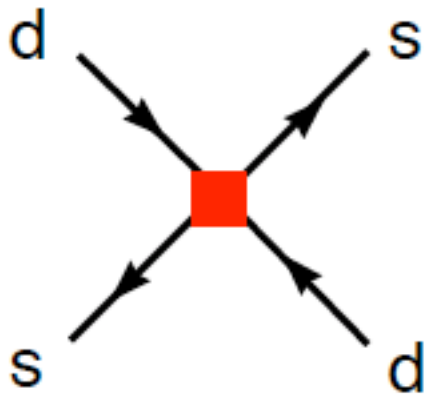

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Possible New Physics at the TeV scale has to have a very non-generic flavour structure

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

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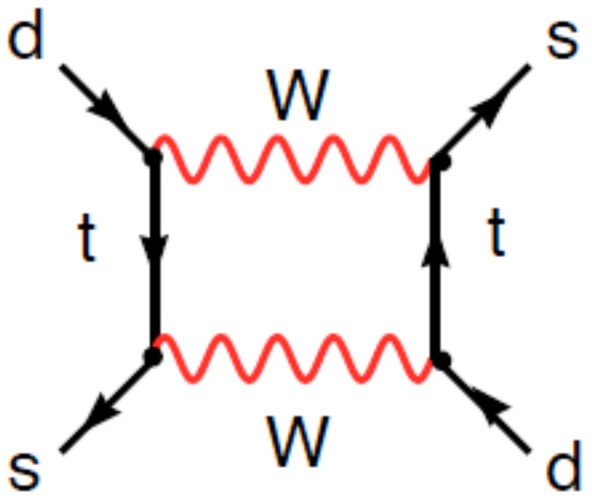
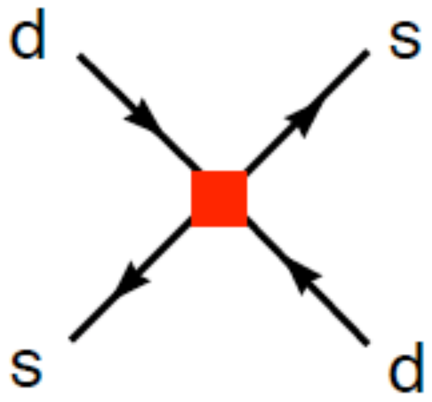




- Natural stabilisation of Higgs boson mass (i.e. supersymmetry) ⇒ $\Lambda \sim 1$TeV

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.

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

Minimal flavour violation as solution of NP flavour problem

$$M(\mathrm{B_d}\text{-}\overline{\mathrm{B}}_\mathrm{d}) \sim \frac{(V_{tb}{}^* V_{td})^2}{16\,\pi^2 M_\mathrm{w}{}^2} + \boxed{c_\mathrm{NP}\,\frac{1}{\Lambda^2}}$$

contribution of the new heavy degrees of freedom

c_NP

$$\sim 1 \xrightarrow{\text{tree/strong + generic flavour}} \Lambda \gtrsim 2\times10^4\ \mathrm{TeV}\ [\mathrm{K}]$$

$$\sim 1/(16\,\pi^2) \xrightarrow{\text{loop + generic flavour}} \Lambda \gtrsim 2\times10^3\ \mathrm{TeV}\ [\mathrm{K}]$$

$$\sim (V_{ti}{}^* V_{tj})^2 \xrightarrow{\text{tree/strong + MFV}} \Lambda \gtrsim 5\ \mathrm{TeV}\ [\mathrm{K}\ \&\ \mathrm{B_d}]$$

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

Courtesy of Gino Isidori

Minimal flavour violation hypoyhesis

- 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

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

- MFV implies model-independent relations between FCNC processes

  - 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

  Hurth,Isidori,Kamenik,Mescia,arXiv:0807.5039
  Hurth,Mahmoudi,arXiv1207.0688

MFV hypothesis is far from beeing verified

New Quarks ?

An additional chiral family of fermions (SM4)

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \begin{pmatrix} t' \\ b' \end{pmatrix} \qquad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \begin{pmatrix} \nu_4 \\ l_4^- \end{pmatrix}$$

Resurrection of the fourth family Kribs,Plehn,Spannowsky,Tait arXiv:0706.3718

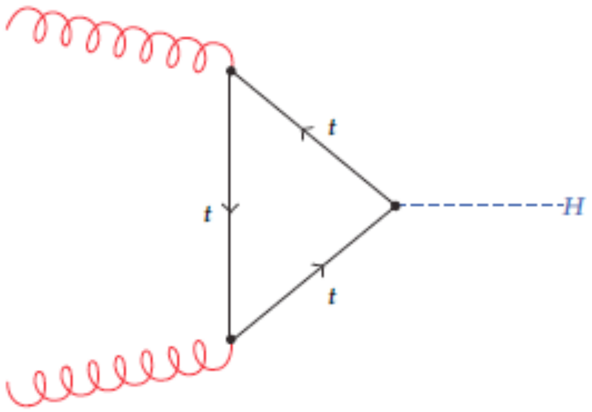
('Four statements about the fourth generations')
Holdom,Hou,Hurth,Mangano,Unel arXiv:0904.4698

- 3 CP-phases (enough for baryogenisis ?)
- not excluded by electroweak precision data (as often stated in the PDG)
- the mass of the fourth neutrino $m_\nu > M_Z/2$ (LEPI)
- large loop effects in flavour observables possible (weaker constraints on V_{ts}, V_{td})

- higgs production and decay are heavily affected by fourth generation via loops (enhancement of gluon fusion process by factor 9)

  → Data of the Higgs discovery rules out a perturbative fourth generation

Lenz et al. arXiv:1204.1252,1209.1101



loop hole: $m_\nu < M_H/2$ opens a new invisable decay channel, but $H \to \tau^+\tau^-$ data closes it .

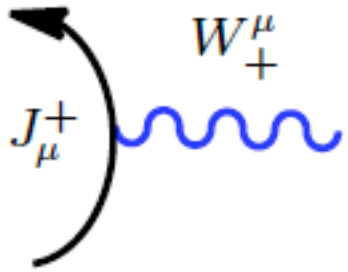
Vector-like quarks ?

- The left-handed and right-handed chiralities of a vector-like fermion transform in the same way under the SM gauge group $SU(3) \times SU(2)_L \times U(1)$.

  Example: weak charged current interactions

  SM chiral quarks (V-A) $J^\mu = \bar{\psi}\ \gamma^\mu(1 - \gamma_5)\ \psi' \quad = \bar{\psi}_L \gamma^\mu \psi'_L$

  Vector-like quarks (V) $J^\mu = \bar{\psi}\,\gamma^\mu\,\psi' \quad = \bar{\psi}_L \gamma^\mu \psi'_L + \bar{\psi}_R \gamma^\mu \psi'_R$



- Mass term of vector-like quarks $(m\bar{\psi}\psi)$ is $SU(3) \times SU(2) \times U(1)$ gauge-invariant (no need for Higgs mechanism!)

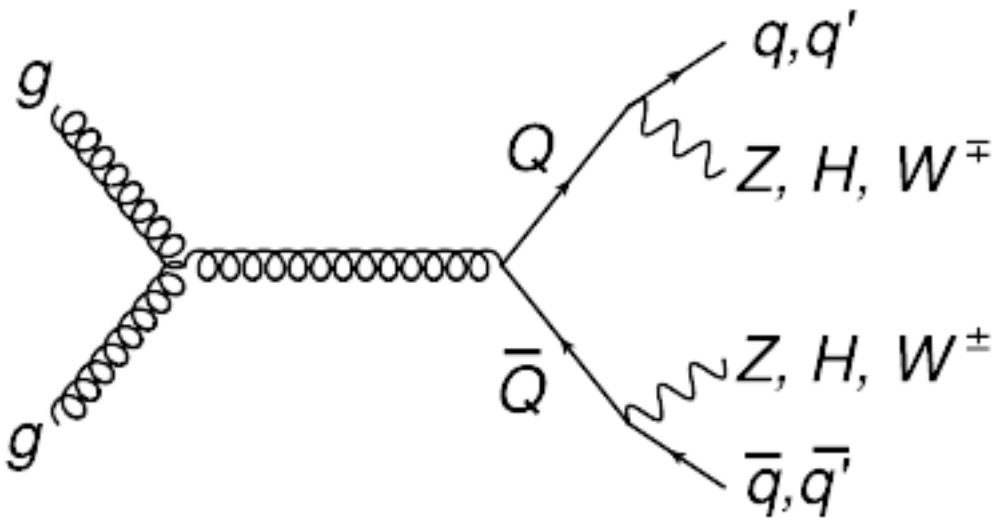
  → independent mass scale in the theory

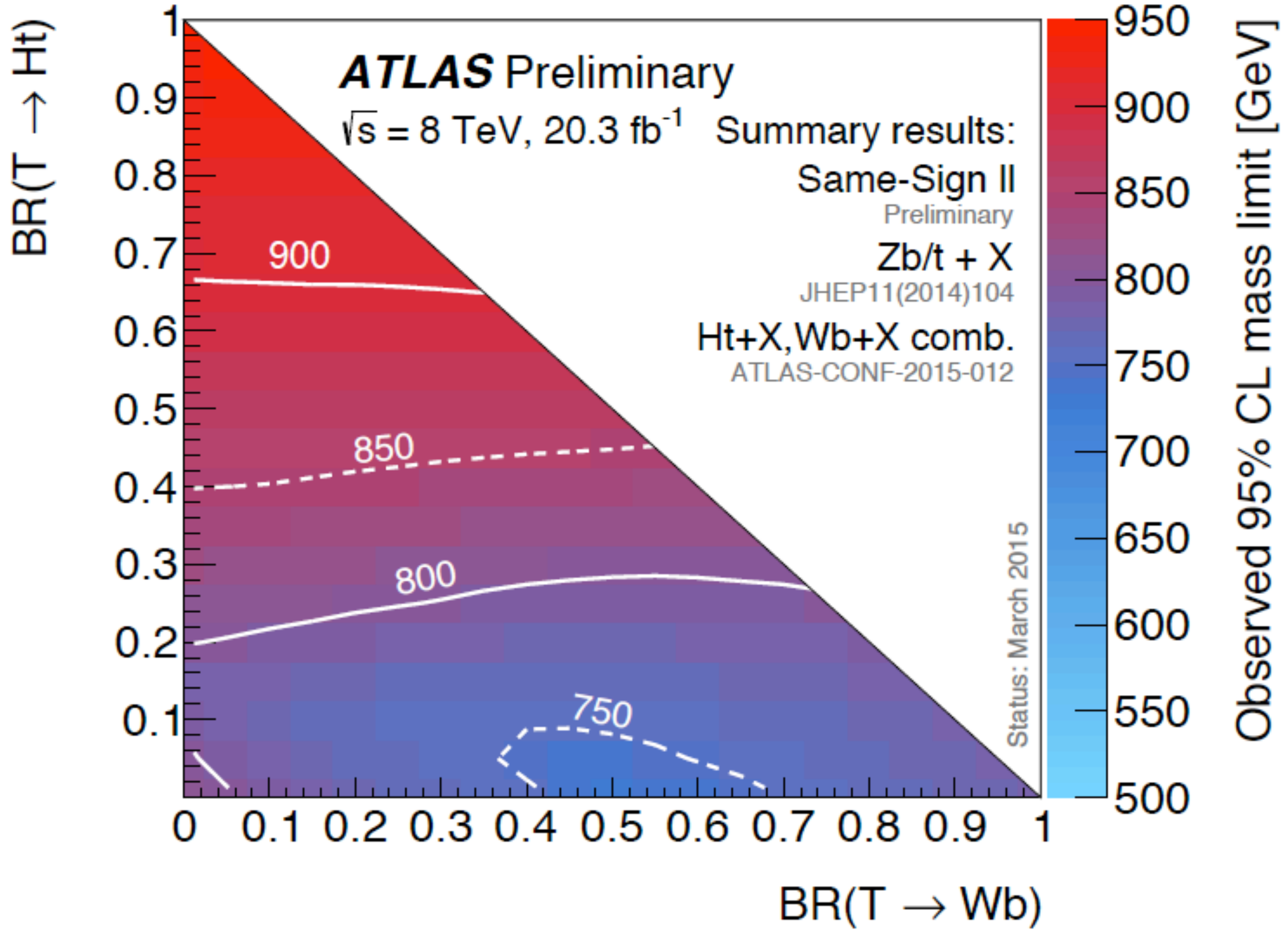
- Vector-like quarks are introduced in many new physics models:

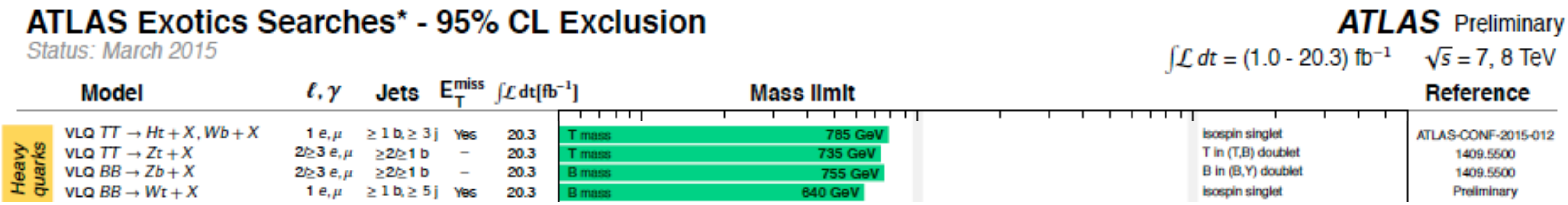
  Composite Higgs, Little Higgs, Warped and universal extra-dimensions, non-minimal Supersymmetry, E_6 grand unification,...

  Vector-like quarks can mix with SM quarks introducing large FCNC (even at tree level)

Search for vector-like quarks at LHC







ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2015

ATLAS Preliminary

$\int\mathcal{L}\,dt = (1.0 - 20.3)$ fb^{-1} $\sqrt{s} = 7, 8$ TeV

	Model	ℓ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[fb^{-1}]$	Mass limit		Reference
Heavy quarks	VLQ $TT \to Ht+X, Wb+X$	1 e,μ	≥ 1 b, ≥ 3 j	Yes	20.3	T mass 785 GeV	isospin singlet	ATLAS-CONF-2015-012
	VLQ $TT \to Zt+X$	2/$\geq$3 e,μ	$\geq$2/$\geq$1 b	–	20.3	T mass 735 GeV	T in (T,B) doublet	1409.5500
	VLQ $BB \to Zb+X$	2/$\geq$3 e,μ	$\geq$2/$\geq$1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $BB \to Wt+X$	1 e,μ	≥ 1 b, ≥ 5 j	Yes	20.3	B mass 640 GeV	isospin singlet	Preliminary

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

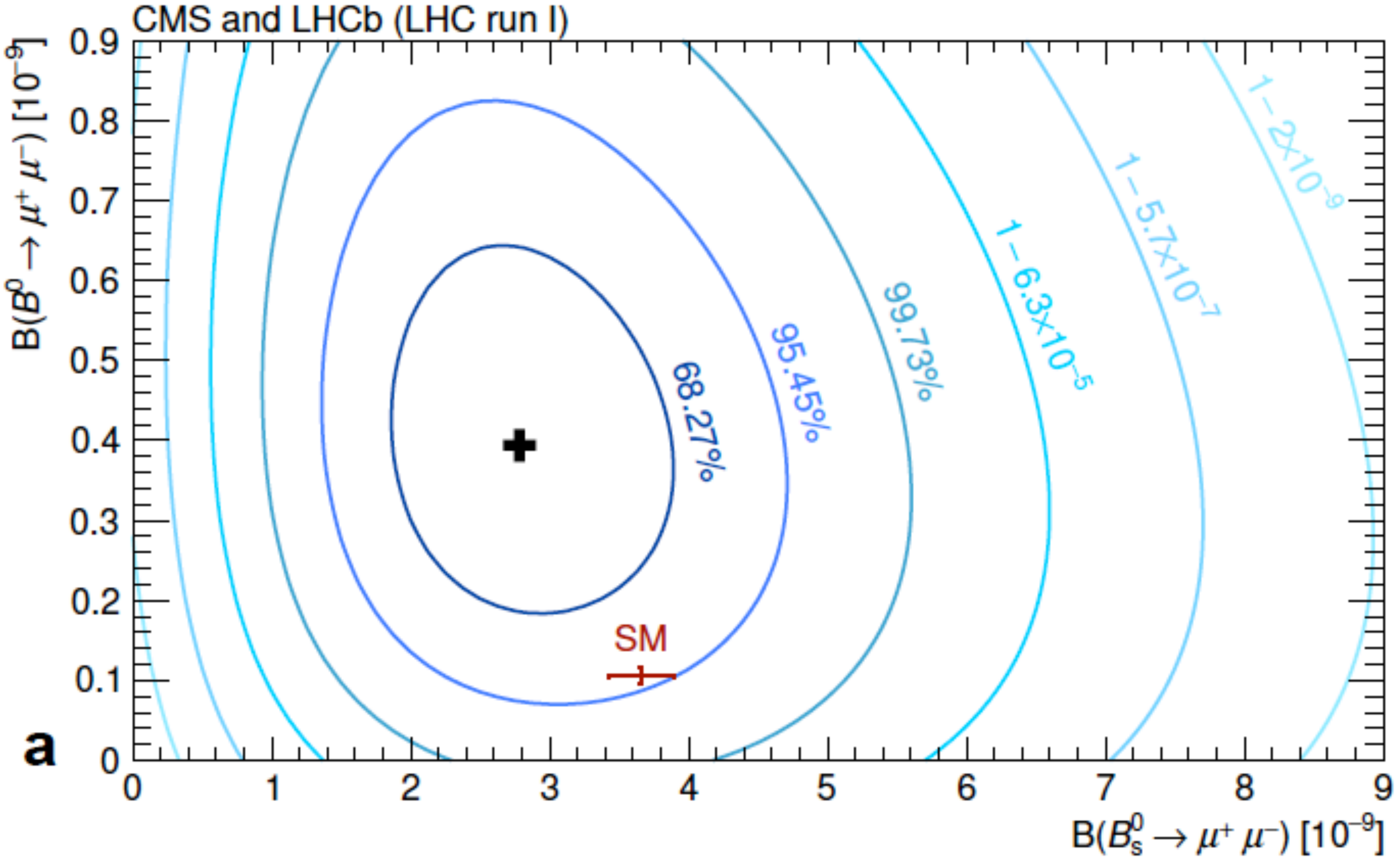
Recent theory effort to eliminate perturbative uncertainties of 7%

NLO QCD corrections Buchalla,Buras 1999, Misiak, Urban1999

→ NNLO QCD corrections Hermann,Misiak,Steinhauser arXiv:1311.1347

Leading-m_t NLO electroweak corrections Buchalla,Buras 1998

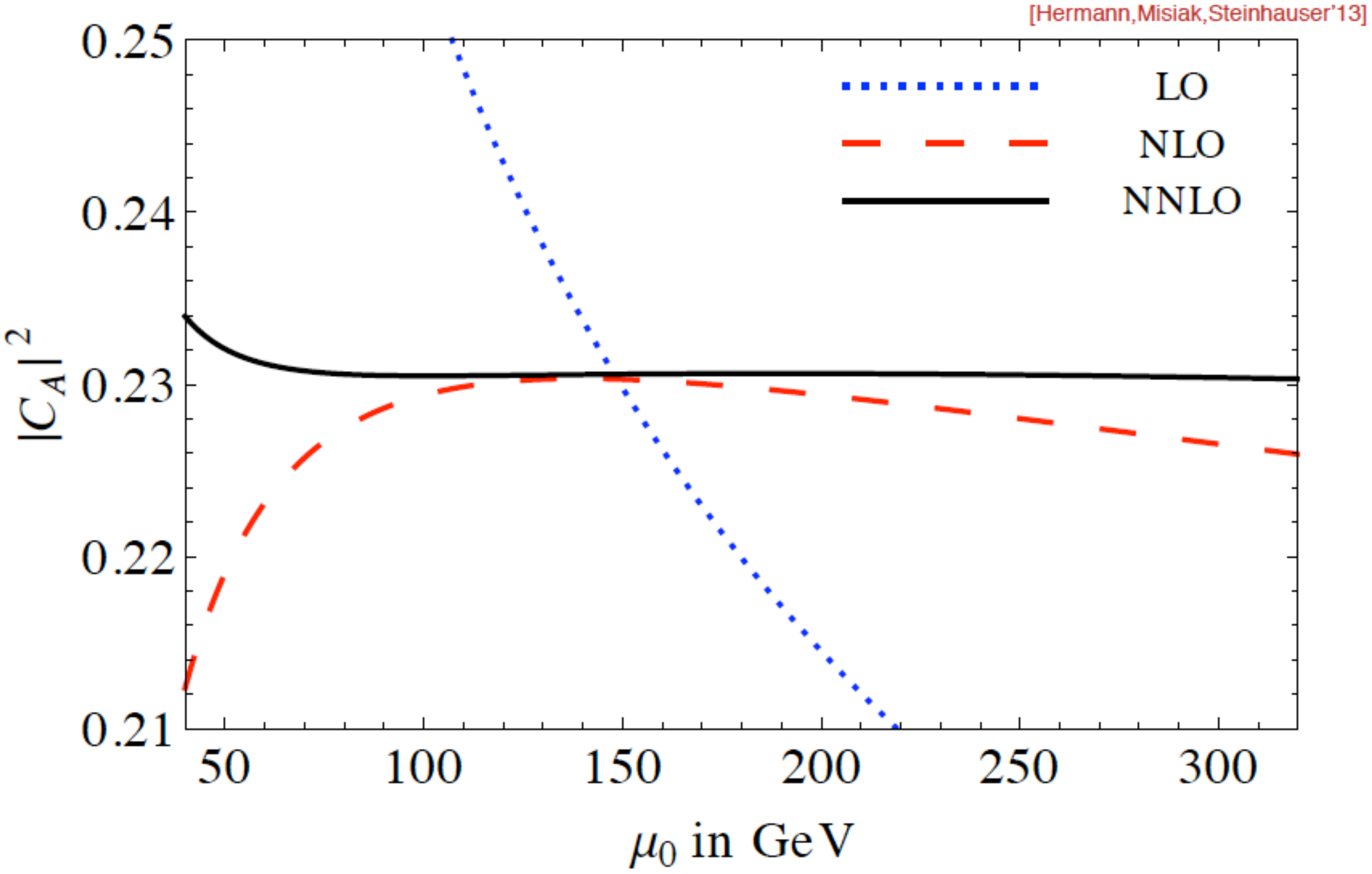
→ NLO electroweak corrections Bobeth,Gorbahn.Stamou arXiv:1311.1348



Error budget:

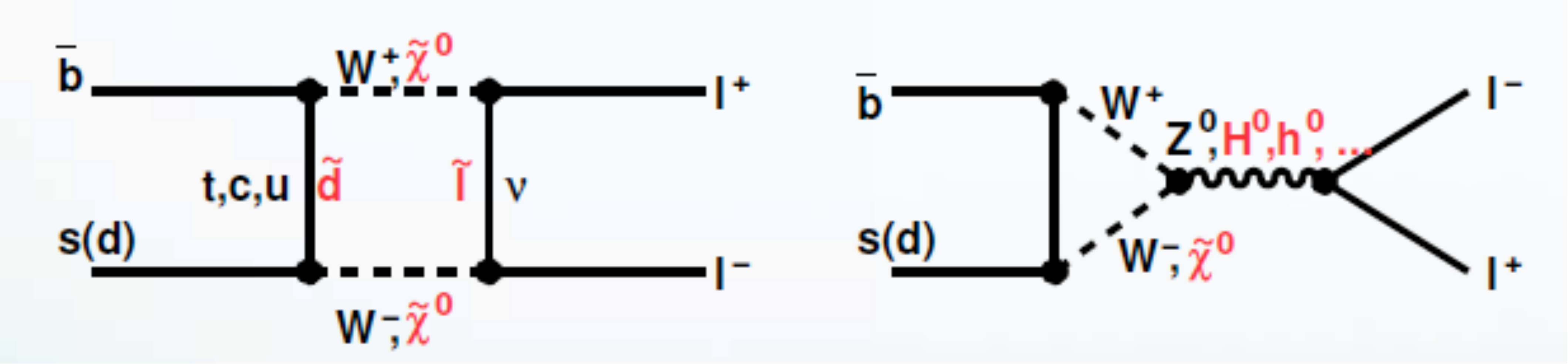
	f_{B_s}	CKM	τ_H^s	M_t	α_s	other param.	non-param.	$\sum$
$\overline{\mathcal{B}}_{s\ell}$	4.0%	4.3%	1.3%	1.6%	0.1%	$<0.1\%$	1.5%	6.4%

Scale dependence:



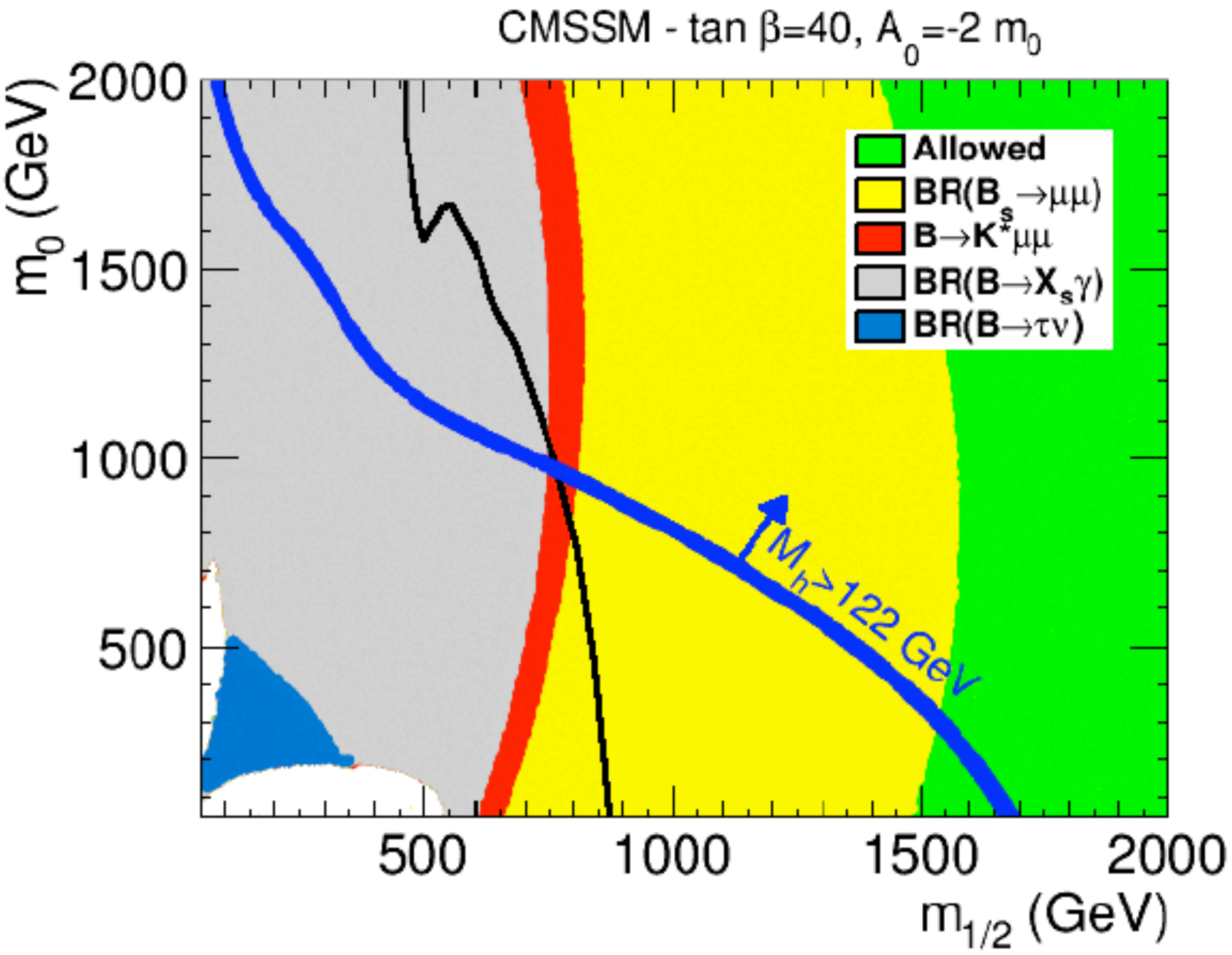
Implications of the latest measurements of $B_s \to \mu\mu$

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



Constraints on CMMSM

Mahmoudi,Neshatpour,Virto arXiv:1401.2145



Black line correponds to direct search: ATLAS with $20.3 fb^{-1}$

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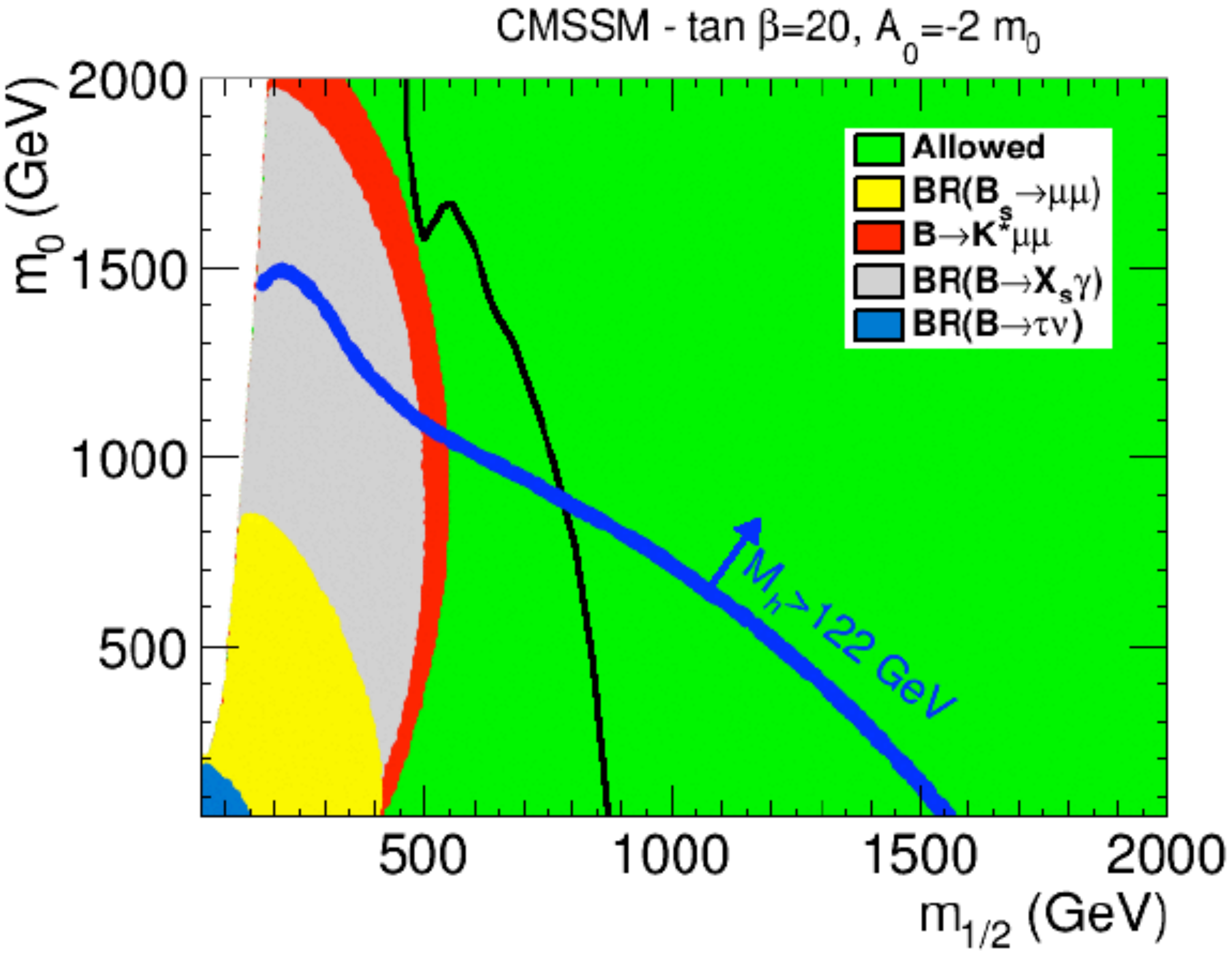


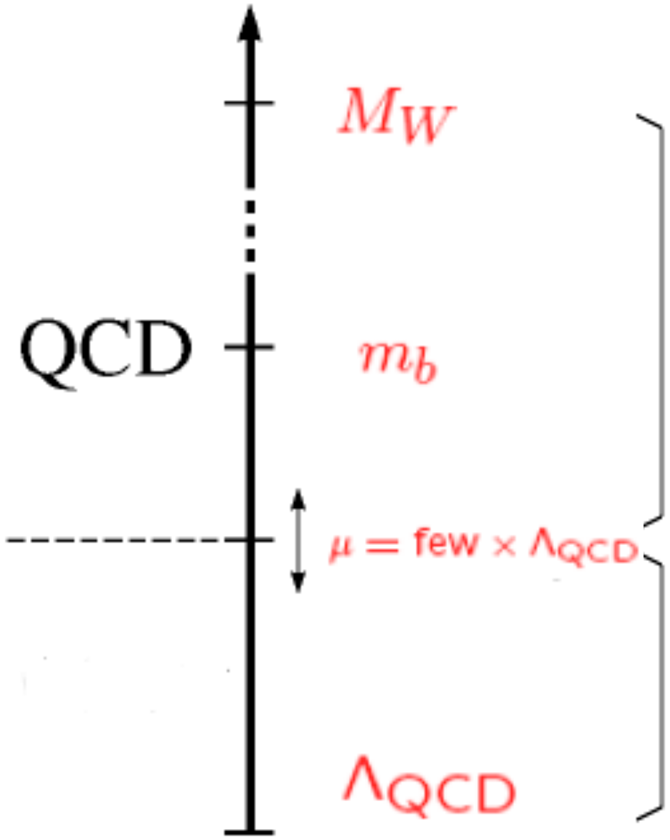
Black line correponds to direct search: ATLAS with $20.3 fb^{-1}$

Semileptonic penguin decays

Motivation

- Radiative and semileptonic rare B decayse are highly sensitive probes for new physics
- Exclusive modes are experimentally easier (LHCb), but have larger theoretical uncertainties (issue of unknown power corrections !)
- Inclusive modes require Belle-II for full exploitation (complete angular analysis) but are theoretically very clean
- Inclusive modes allow for crosschecks of recent LHCb anomalies

Theoretical tools for flavour precision observables



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 $\mathcal{O}_i(\mu = m_b)$?

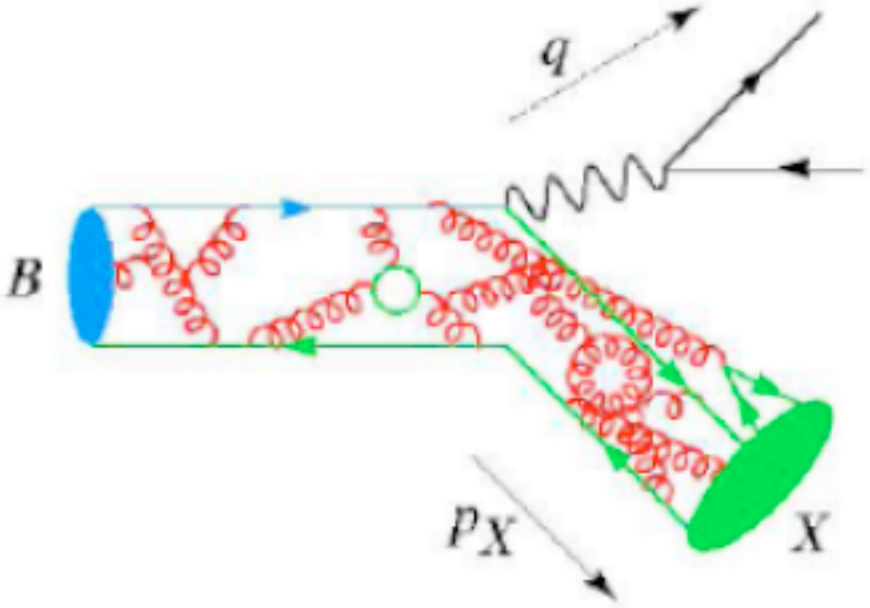
Inclusive modes $B \to X_s\gamma$ and $B \to X_s\ell^+\ell^-$

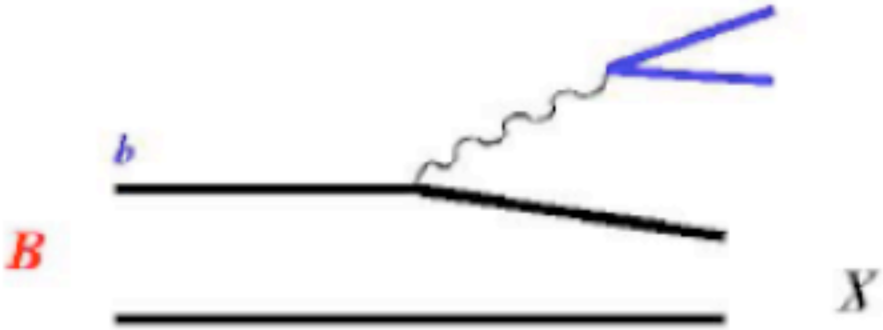
How to compute the hadronic matrix elements $\mathcal{O}_i(\mu = m_b)$?

- 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)





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

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

Heavy mass expansion for inclusive modes:

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

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

An 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

Analysis in $B \to X_s\ell\ell$ work in progress, Benzke,Fickinger,Hurth,Turczyk,..

Difference between exclusive and inclusive $b \to s\gamma, \ell\ell$ modes:

Inclusive

Λ^2/m_b^2 corrections can be calculated for the leading operators in the local OPE .

Λ/m_b corrections to the subleading operators correspond to nonlocal matrix elements and can be estimated !

Exclusive

No theory of Λ/mb corrections at all within QCD factorization formula (in the low-q^2 region); these corrections can only be "guesstimated" !

Perturbative calculations in $B \to X_s \gamma$

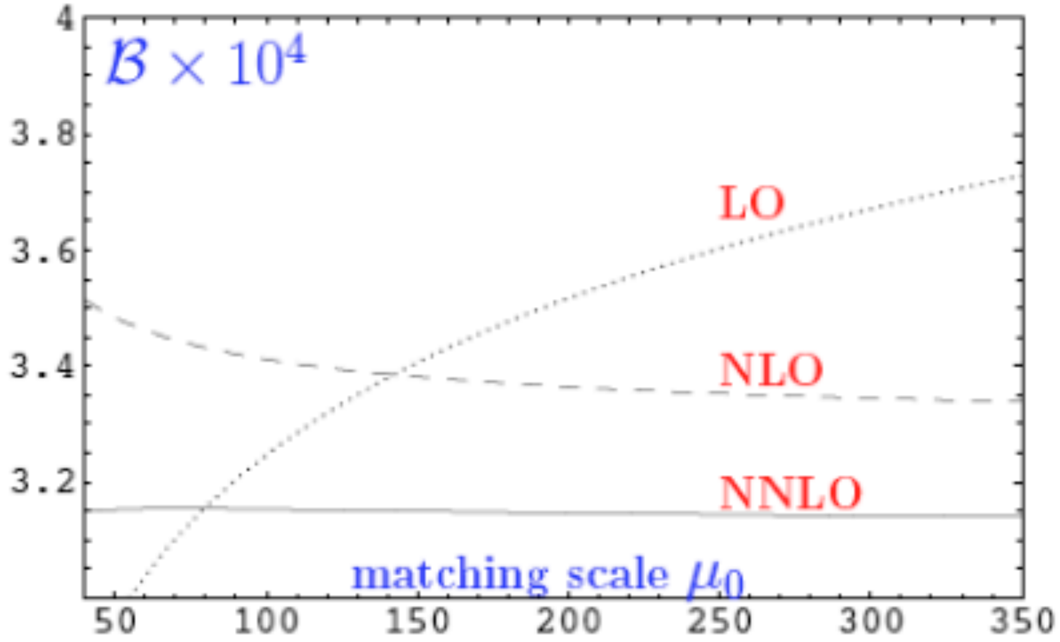
Perturbative QCD corrections double the rate and lead to large logarithms $\alpha_s(M_W) Log(m_b^2 / M_W^2) \to$ resummation of Logs necessary:

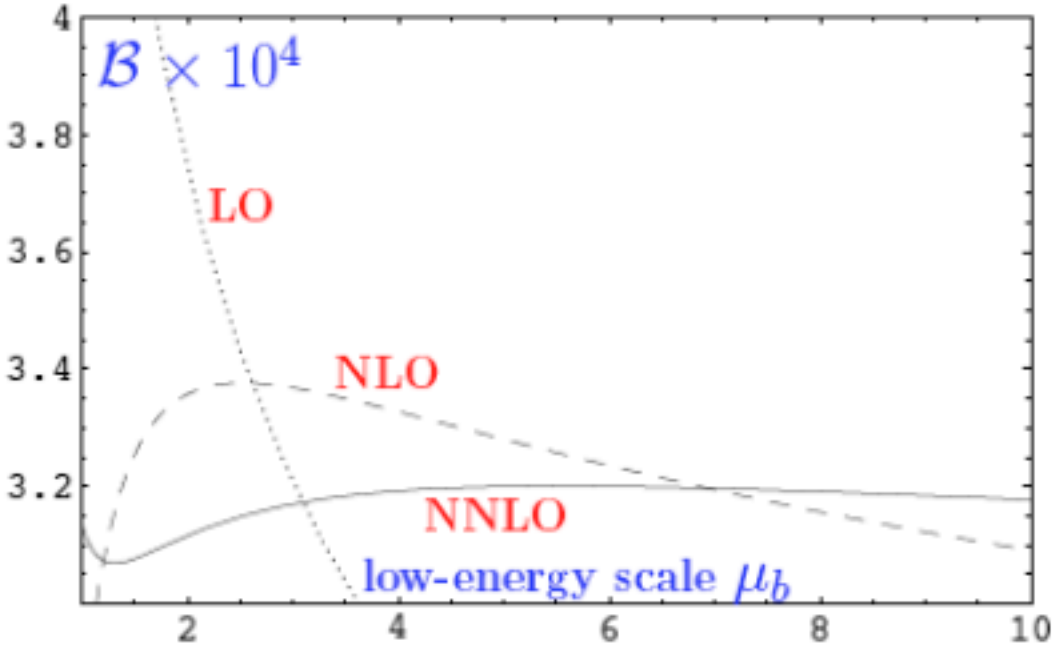
LL	Leading logs	$G_F\,(\alpha_s\,Log\,)^N$	$N = 0, 1, 2, ...$
NLL	Next-to-leading logs	$G_F\,\alpha_s\,(\alpha_s\,Log\,)^N$	
NNLL	Next-to-next-to-leading logs	$G_F\,\alpha_s^2\,(\alpha_s\,Log\,)^N$	

NLL 1996 Chertyrkin,Misiak,Münz; Greub,Hurth,Wyler; Adel Yao; 1996

NNLL 2006 Misiak et al.; collaboration of 17 scientists, arXiv: 0609232

Update of NNLL 2015 Misiak et al.; collaboration of 18 scientists, arXiv:1503.01789





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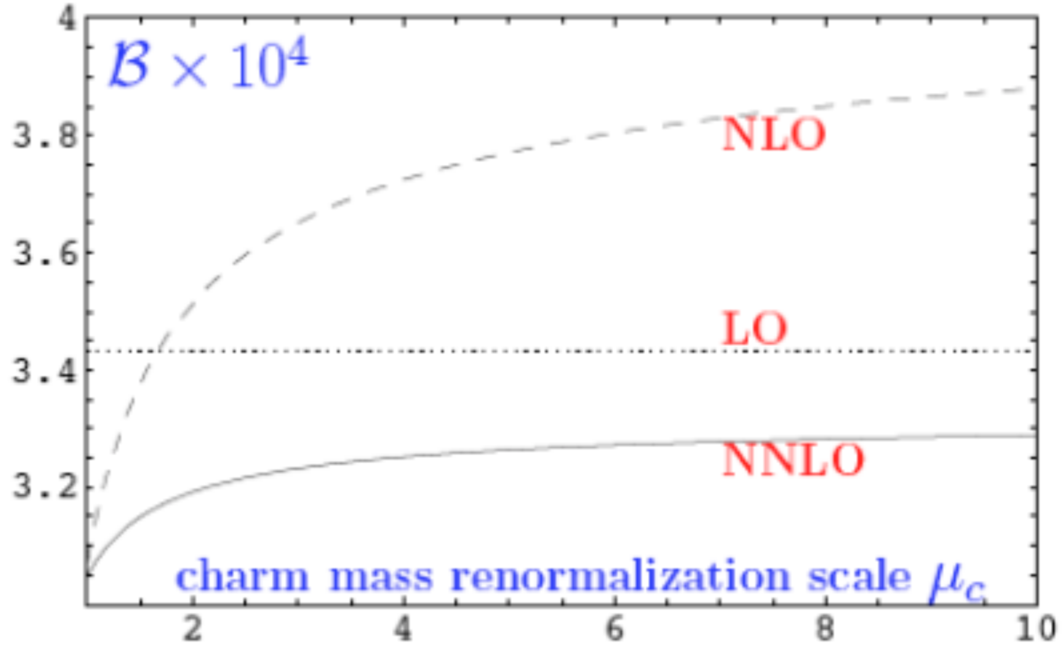

"Central" values:

$\mu_0 = 160$ **GeV**

$\mu_b = 2.5$ **GeV**

$\mu_c = 1.5$ **GeV**

Perturbative calculations in $B \to X_s\gamma$

Perturbative QCD corrections double the rate and lead to large logarithms $\alpha_s(M_W)Log(m_b^2\,/\,M_W^2) \to$ resummation of Logs necessary:

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Update of NNLL 2015 Misiak et al.; collaboration of 18 scientists, arXiv:1503.01789

Experiment:

$$\mathcal{B}_{s\gamma}^{\rm exp} = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$$

Theory:

$$\mathcal{B}_{s\gamma}^{\rm SM} \;=\; (3.36 \pm 0.23) \times 10^{-4}$$

The theoretical NNLL prediction of the SM branching ratio is consistent with the experimental data within 1σ.

Perturbative calculations in $B \to X_s\gamma$

Perturbative QCD corrections double the rate and lead to large logarithms $\alpha_s(M_W) Log(m_b^2 / M_W^2)$ → resummation of Logs necessary:

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Theory:

$$\mathcal{B}_{s\gamma}^{\text{SM}} \;=\; (3.36 \pm 0.23) \times 10^{-4}$$

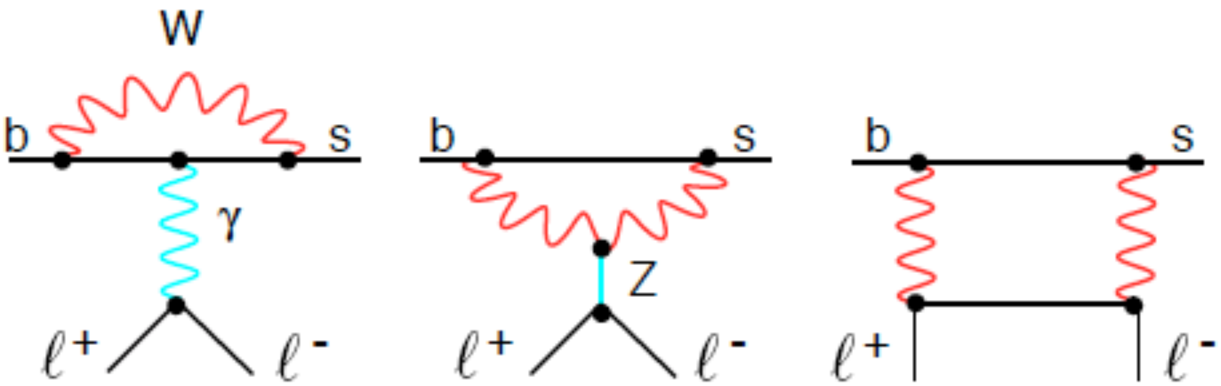
Bounds on NP parameters:

$$M_{H^\pm} > 480\,\text{GeV at } 95\%\text{C.L.}$$

$$M_{H^\pm} > 358\,\text{GeV at } 99\%\text{C.L.}$$

Complete angular analysis of inclusive $B \to X_s \ell\ell$

Huber,Hurth,Lunghi, arXiv:1503.04849



- Phenomenological analysis to NNLO QCD and NLO QED for all angular observables

- Electromagnetic effects due to energetic photons are large and calculated analytically and crosschecked against Monte Carlo generator events

  Size of logs depend on experimental set-up

  We assume no photons are included in the definition of q^2 (di-muon channel at Babar/Belle, di-electron at Belle)

  Babar's di-electron channel: Photons that are emitted in a cone of 35 mrad angular opening are included in q^2

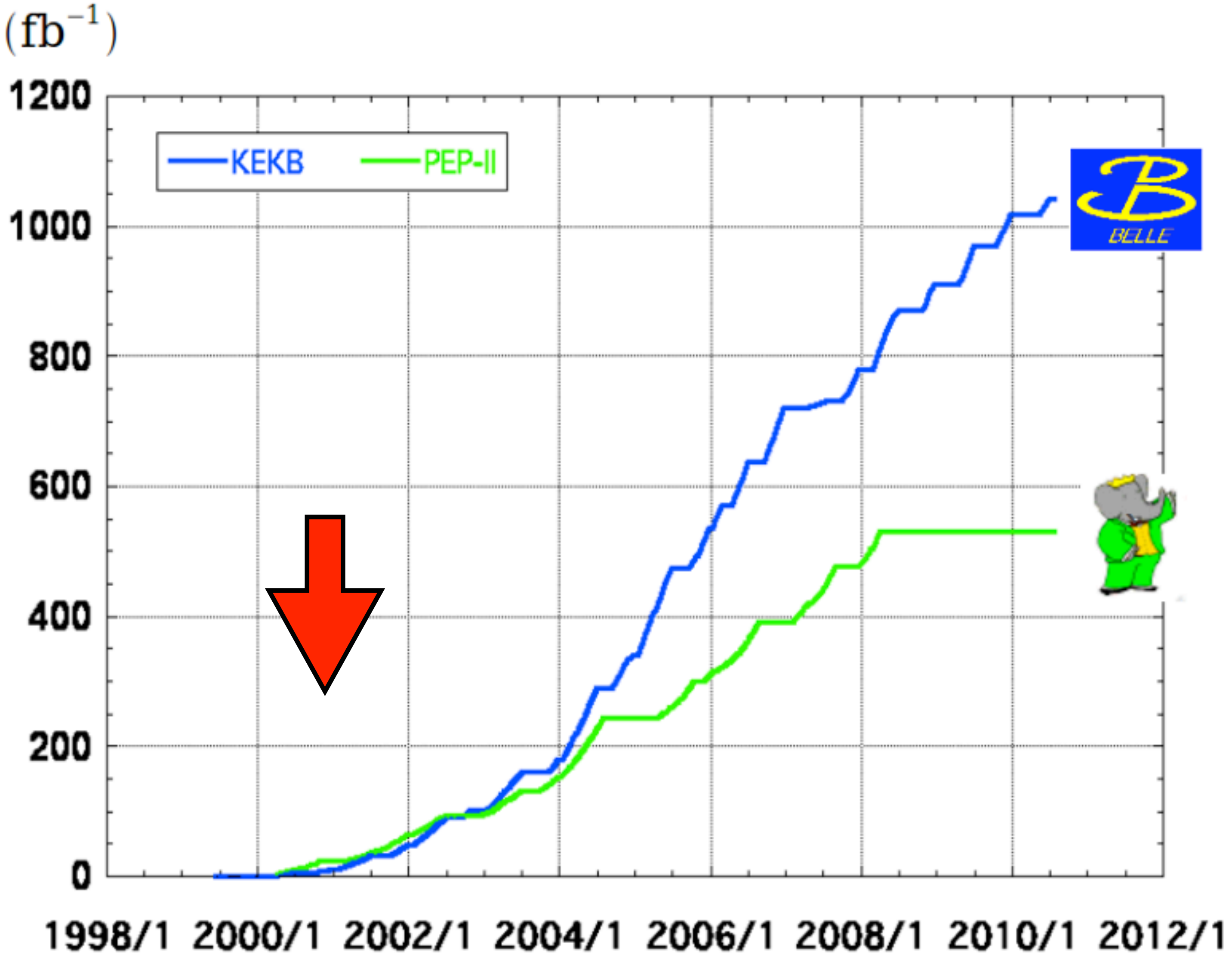
  Monte Carlo techniques needed to estimate this effect !

- "Latest" Belle measurement of branching ratio is based on less than 30% of the total luminosity

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}

Two new analyses from the B factories:

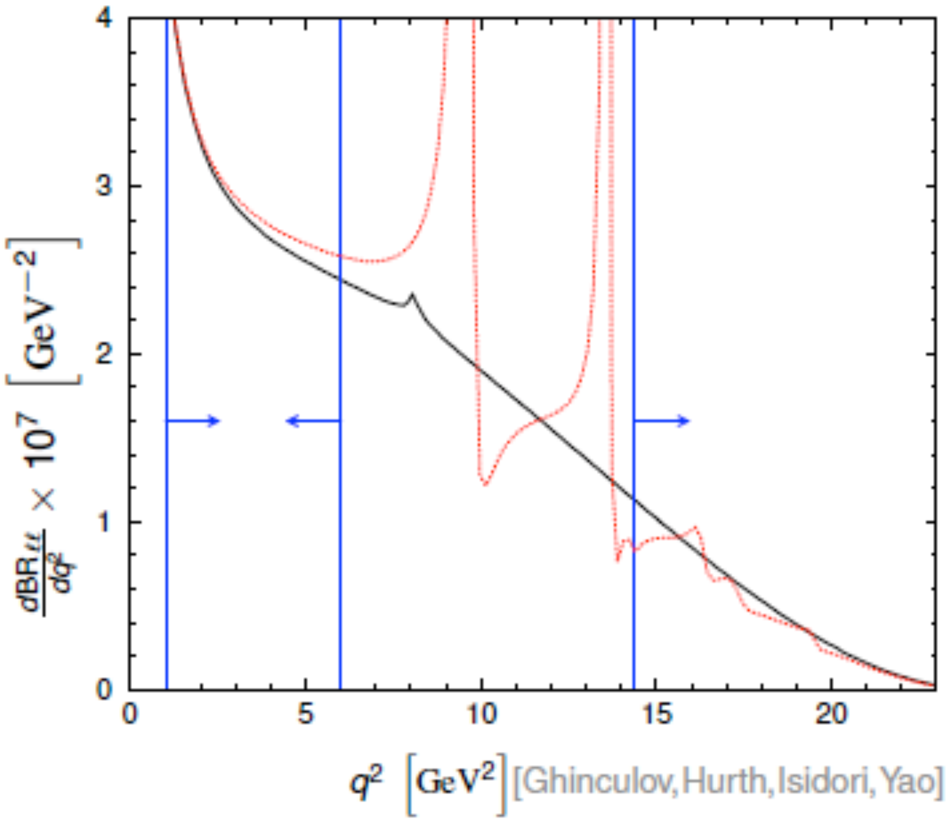
New Babar analysis on dilepton spectrum arXiv:1312.3664

New Belle analysis on AFB arXiv:1402.7134

- Observables

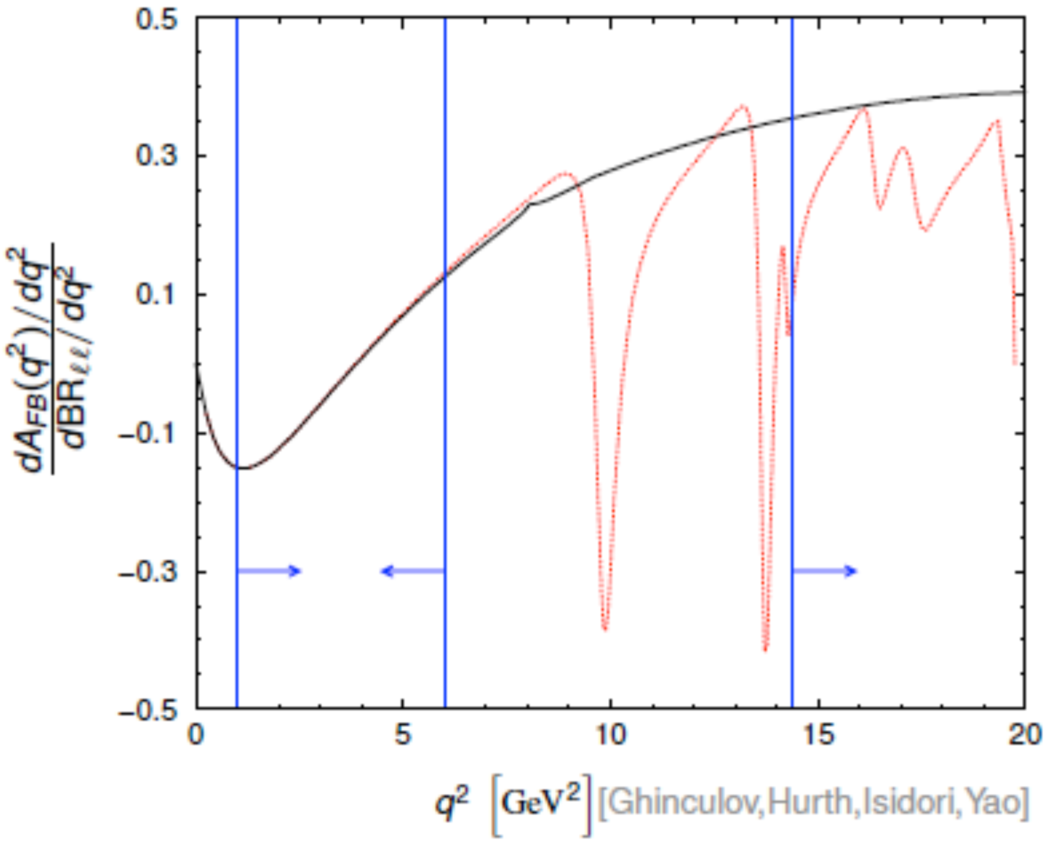
$$\frac{d^2\Gamma}{dq^2\,dz} = \frac{3}{8}\left[(1+z^2)\,H_T(q^2) + 2\,z\,H_A(q^2) + 2\,(1-z^2)\,H_L(q^2)\right] \qquad (z = \cos\theta_\ell)$$

$$\frac{d\Gamma}{dq^2} = H_T(q^2) + H_L(q^2)$$



[Ghinculov,Hurth,Isidori,Yao]

$$\frac{dA_{\mathrm{FB}}}{dq^2} = 3/4\,H_A(q^2)$$



[Ghinculov,Hurth,Isidori,Yao]

Low-q^2 region: $1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2$ High-q^2 region: $q^2 > 14.4\,\mathrm{GeV}^2$

Huber,Hurth,Lunghi

- Dependence on Wilson coefficients

$$H_T(q^2) \propto 2s(1-s)^2\left[\left|C_9 + \frac{2}{s}\,C_7\right|^2 + |C_{10}|^2\right]$$

$$H_A(q^2) \propto \,-4s(1-s)^2\ \mathrm{Re}\left[C_{10}\left(C_9 + \frac{2}{s}\,C_7\right)\right]$$

$$H_L(q^2) \propto (1-s)^2\left[\left|C_9 + 2\,C_7\right|^2 + |C_{10}|^2\right]$$

H_T suppressed in low-q^2 window

- Devide low-q^2 bin in two bins (zero of H_A in low-q^2)

Lee,Ligeti,Stewart, Tackmann hep-ph/0612156

- Most important input parameters

$$m_b^{1S} = (4.691 \pm 0.037)\mathrm{GeV}\,, \qquad \overline{m}_c(\overline{m}_c) = (1.275 \pm 0.025)\mathrm{GeV}$$

$$|V_{ts}^* V_{tb}/V_{cb}|^2 = 0.9621 \pm 0.0027\,, \qquad BR^{exp.}_{b\to c\,e\,\nu} = (10.51 \pm 0.13)\,\%$$

- Perturbative expansion (NNLO QCD + NLO QED) α_s $\kappa = \alpha_{\rm em}/\alpha_s$

$$\begin{aligned} A &= \kappa\left[A_{LO} + \alpha_s\,A_{NLO} + \alpha_s^2\,A_{NNLO} + \mathcal{O}(\alpha_s^3)\right] \\ &+ \kappa^2\left[A_{LO}^{em} + \alpha_s\,A_{NLO}^{em} + \alpha_s^2\,A_{NNLO}^{em} + \mathcal{O}(\alpha_s^3)\right] + \mathcal{O}(\kappa^3) \end{aligned}$$

LO = $\alpha_{\rm em}/\alpha_s$, NLO = $\alpha_{\rm em}$, NNLO = $\alpha_{\rm em}\,\alpha_s$

Huber,Hurth,Lunghi

- Normalization:

$$\frac{d\ BR(\bar{B} \to X_s ll)}{d\ \hat{s}} = BR^{exp.}_{b \to c\, e\, \nu} \left| \frac{V_{ub}}{V_{cb}} \right|^2 \frac{1}{C} \frac{d\Gamma(\bar{B} \to X_s\, ll)/d\hat{s}}{\Gamma(\bar{B} \to X_u e \bar{\nu})}$$

$$C = \left| \frac{V_{ub}}{V_{cb}} \right|^2 \frac{\Gamma(\bar{B} \to X_c e \bar{\nu})}{\Gamma(\bar{B} \to X_u e \bar{\nu})} = 0.574 \pm 0.019$$

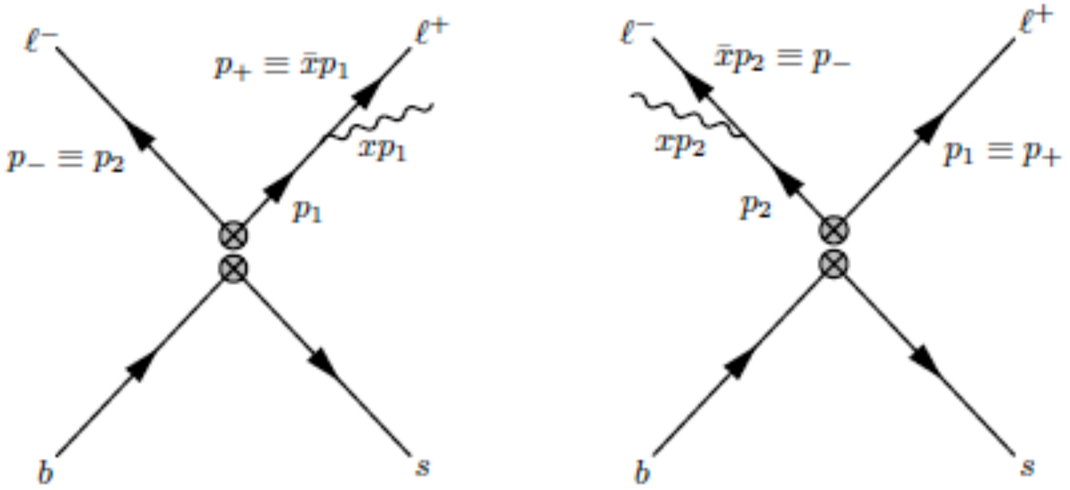
Gambino,Schwanda, arXiv:1307.4551

Huber,Hurth,Lunghi

- Collinear Photons give rise to log-enhanced QED corrections $\alpha_{\rm em} \log(m_b^2/m_\ell^2)$
- Higher powers of z in double differential decay width
  - Definition of H_i ? Sensitivity for QED observables ?

We use Legendre poynomials for H_T and H_L and $Sign(z)$ for H_A

We can construct QED sensitive observables (vanish in absence of QED) by Legendre projectors $P_3(z)$ or $P_4(z)$: 10^{-8}



Huber,Hurth,Lunghi

- Collinear Photons give rise to log-enhanced QED corrections $\alpha_{\rm em} \log(m_b^2/m_\ell^2)$
- Higher powers of z in double differential decay width
  - Definition of H_i ? Sensitivity for QED observables ?
- Size of logs depend on experimental set-up

$$q^2 = (p_{\ell^+} + p_{\ell^-})^2 \quad \text{vs.} \quad q^2 = (p_{\ell^+} + p_{\ell^-} + p_{\gamma,\rm coll})^2$$

  - We assume no photons are included in the definition of q^2 (di-muon channel at Babar/Belle, di-electron at Belle)
  - Babar's di-electron channel: Photons that are emitted in a cone of 35 mrad angular opening are included in q^2

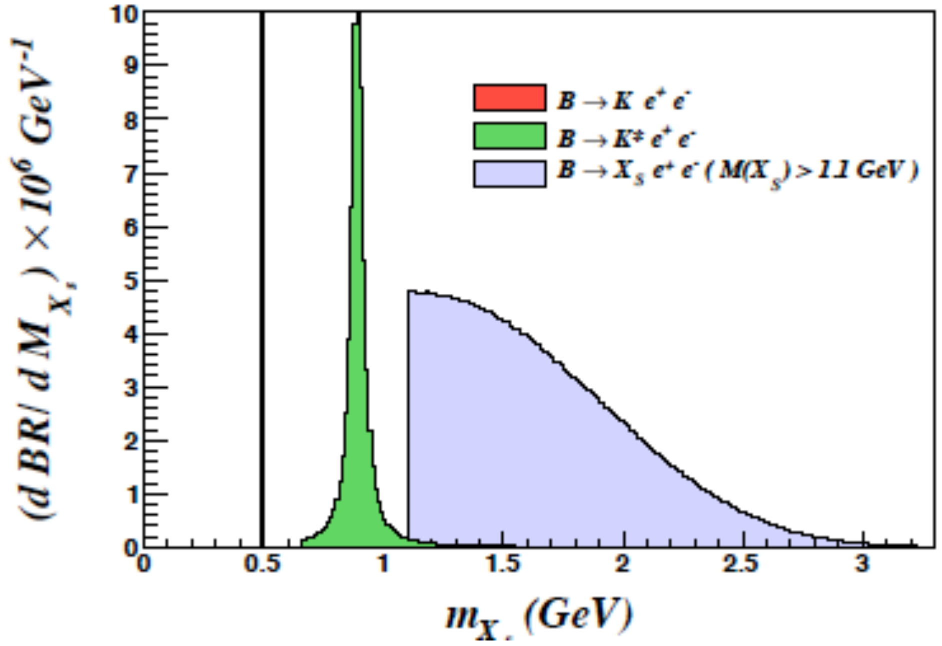
  Monte Carlo techniques needed to estimate this effect

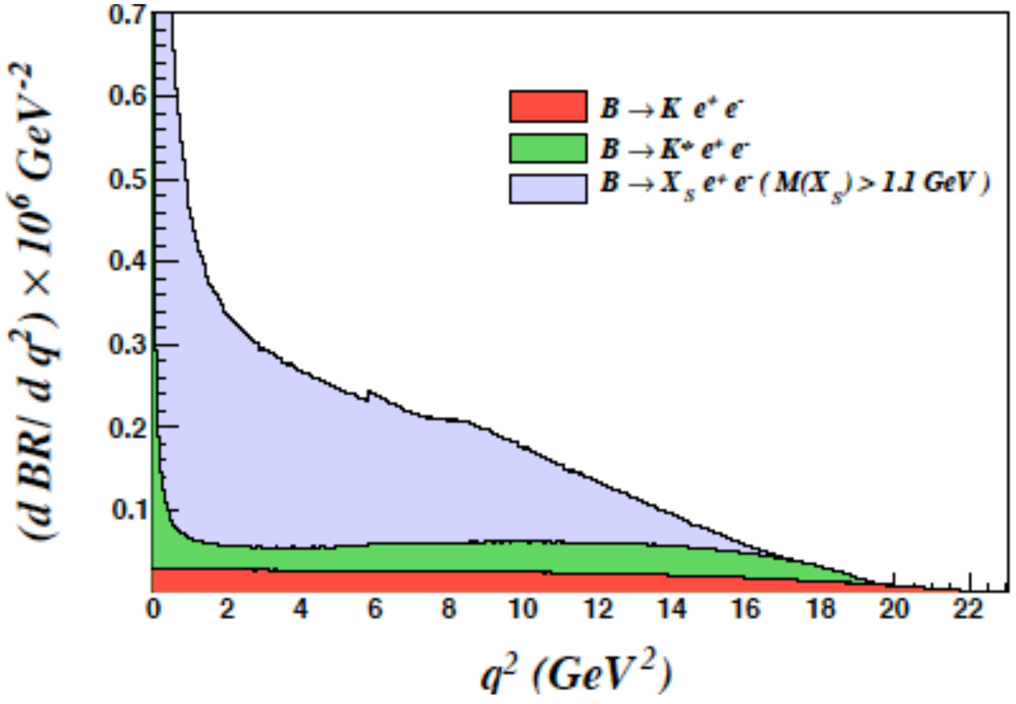
$$\frac{\left[\mathcal{B}_{ee}^{\rm low}\right]_{q=p_{e^+}+p_{e^-}+p_{\gamma_{\rm coll}}}}{\left[\mathcal{B}_{ee}^{\rm low}\right]_{q=p_{e^+}+p_{e^-}}} - 1 = 1.65\% \qquad \frac{\left[\mathcal{B}_{ee}^{\rm high}\right]_{q=p_{e^+}+p_{e^-}+p_{\gamma_{\rm coll}}}}{\left[\mathcal{B}_{ee}^{\rm high}\right]_{q=p_{e^+}+p_{e^-}}} - 1 = \quad 6.8\%$$

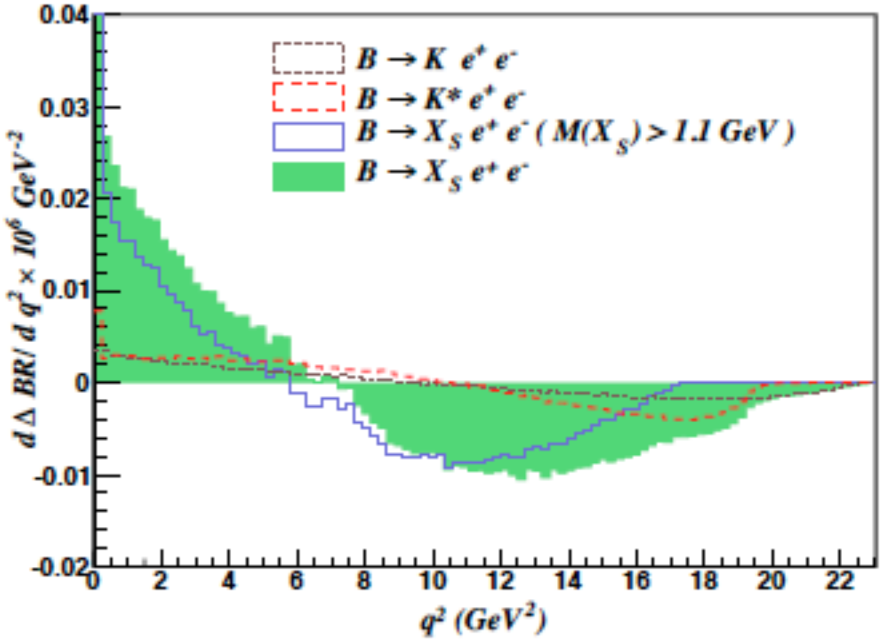
Monte Carlo analysis

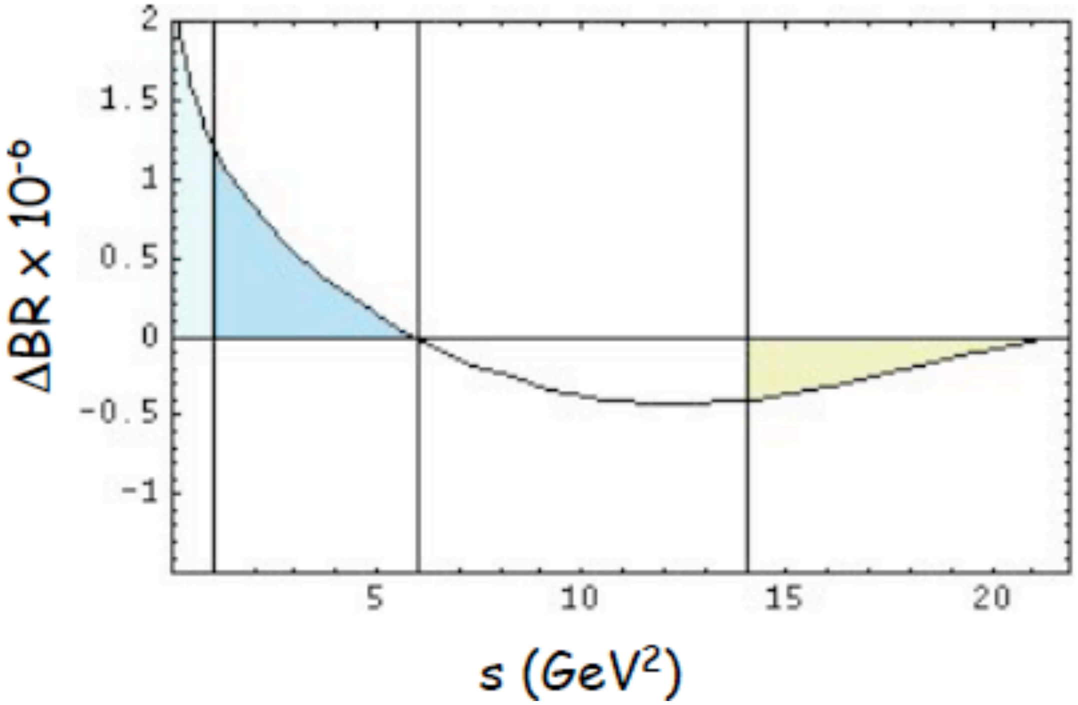
(event generator EVTGEN, hadronization JETSET, EM radiation PHOTOS)

$$\frac{\left[\mathcal{B}_{ee}^{\rm low}\right]_{q=p_{e^+}+p_{e^-}+p_{\gamma_{\rm coll}}}}{\left[\mathcal{B}_{ee}^{\rm low}\right]_{q=p_{e^+}+p_{e^-}}}-1=1.65\% \qquad \frac{\left[\mathcal{B}_{ee}^{\rm high}\right]_{q=p_{e^+}+p_{e^-}+p_{\gamma_{\rm coll}}}}{\left[\mathcal{B}_{ee}^{\rm high}\right]_{q=p_{e^+}+p_{e^-}}}-1=\ 6.8\%$$



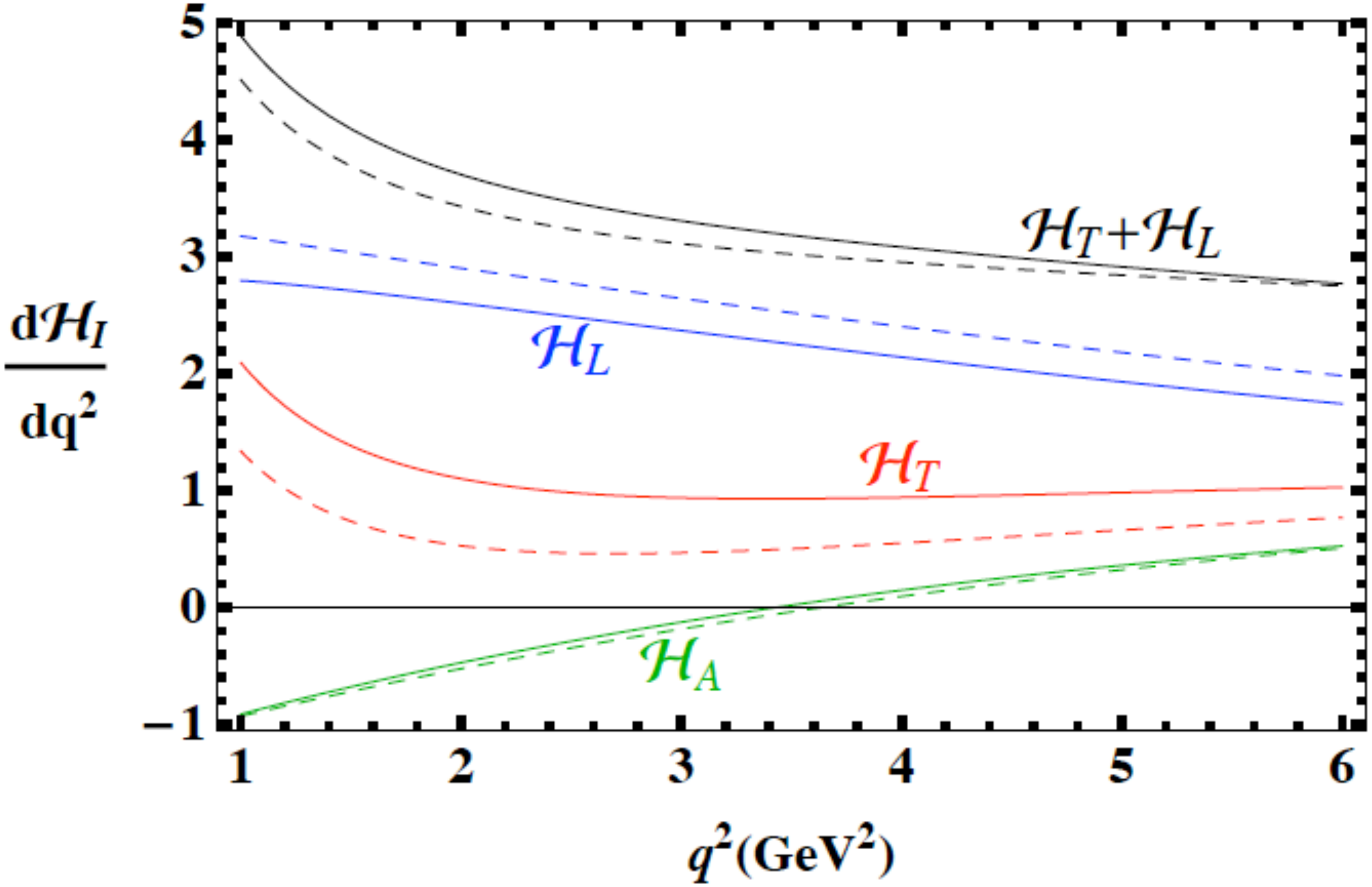






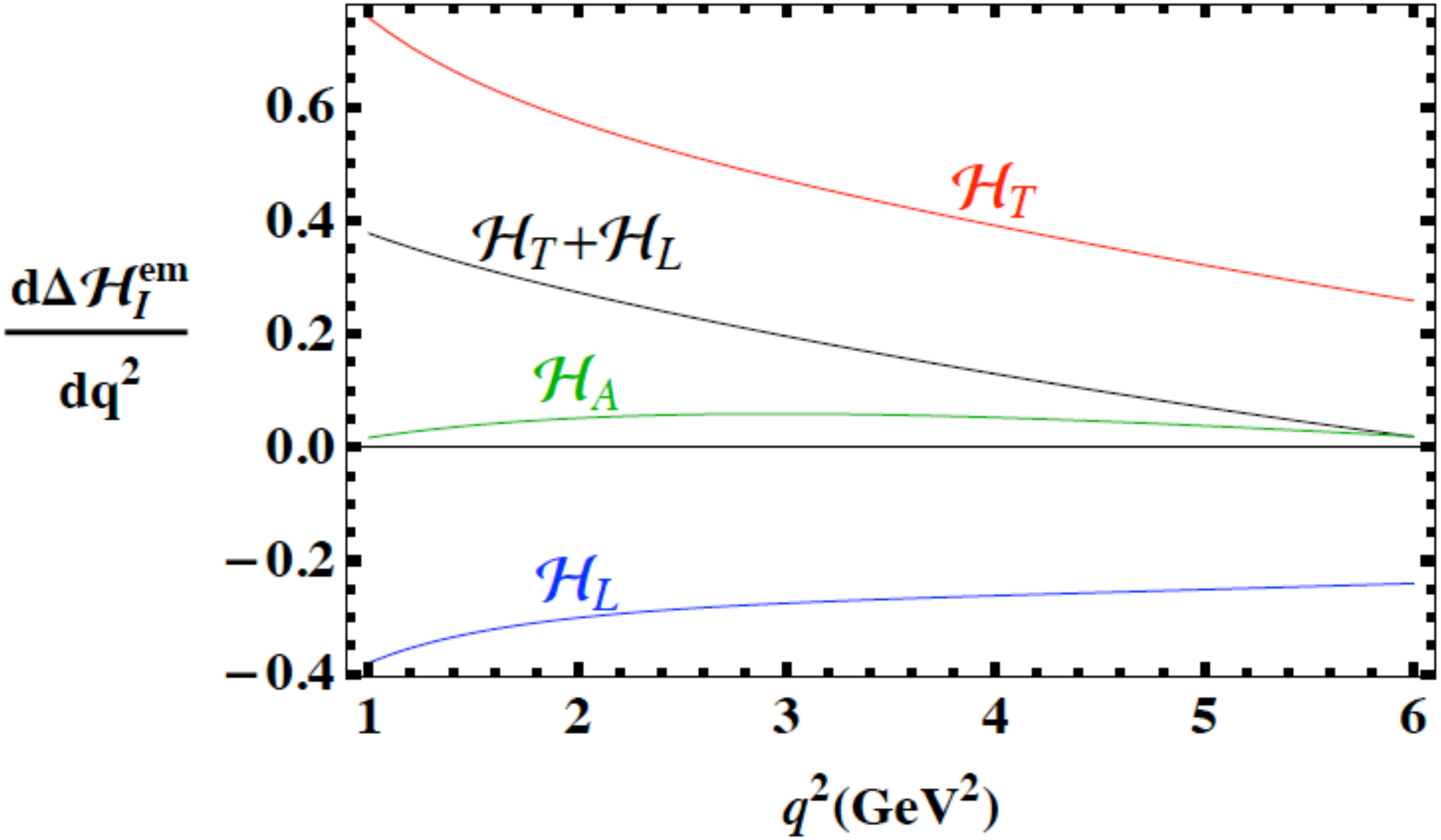
Results

Significant electromagnetic corrections:



Shift of H_T of 70% (no breakdown of perturbation theory)

Results Significant electromagnetic corrections:



Results

Low-q^2 $(1GeV^2 < q^2 < 6GeV^2)$

$$BR(B \to X_s ee) = (1.67 \pm 0.10)\, 10^{-6}$$

$$BR(B \to X_s \mu\mu) = (1.62 \pm 0.09)\, 10^{-6}$$

Babar:$BR(B \to X_s \ell\ell) =$

$$= (1.60\ (+0.41{-}0.39)_{stat}(+0.17{-}0.13)_{syst}(\pm 0.18)_{mod})\, 10^{-6}$$

good agreement with SM

Huber,Hurth,Lunghi

Results

High-q^2, Theory: $q^2 > 14.4 GeV^2$, Babar: $q^2 > 14.2 GeV^2$

$$BR(B \to X_s ee) = (0.220 \pm 0.070)\, 10^{-6}$$

$$BR(B \to X_s \mu\mu) = (0.253 \pm 0.070)\, 10^{-6}$$

Babar:$BR(B \to X_s \ell\ell) =$

$$(0.57\ (+0.16 - 0.15)_{stat}(+0.03 - 0.02)_{syst})\, 10^{-6}$$

2σ higher than SM

Significant higher values predicted in Greub et al. due to missing power and QED corrections and different cut Greub,Pilipp,Schupbach,arXiv:0810.4077

(but perfect agreement if we use their prescriptions)

Huber,Hurth,Lunghi

Further refinement

Normalization to semileptonic $B \to X_u \ell \nu$ decay rate with the same cut reduces the impact of $1/m_b$ corrections in the high-q^2 region significantly.

Ligeti,Tackmann arXiv:0707.1694

Theory prediction for ratio

$$R(s_0)_{ee} = (2.25 \pm 0.31)\, 10^{-3}$$

$$R(s_0)_{\mu\mu} = (2.62 \pm 0.30)\, 10^{-3}$$

Largest source of error are CKM elements (V_{ub})

Note: Additional O(5%) uncertainty due to nonlocal power corrections $O(\alpha_s \Lambda / m_b)$

Further results in units of 10^{-6}

$$H_L[1,3.5]_{ee} = 0.64 \pm 0.03 \qquad H_L[1,3.5]_{\mu\mu} = 0.68 \pm 0.04$$

$$H_L[3.5,6]_{ee} = 0.50 \pm 0.03 \qquad H_L[3.5,6]_{\mu\mu} = 0.53 \pm 0.03$$

$$H_L[1,6]_{ee} = 1.13 \pm 0.06 \qquad H_L[1,6]_{\mu\mu} = 1.21 \pm 0.07$$

$$H_T[1,3.5]_{ee} = 0.29 \pm 0.02 \qquad H_T[1,3.5]_{\mu\mu} = 0.21 \pm 0.01$$

$$H_T[3.5,6]_{ee} = 0.24 \pm 0.02 \qquad H_T[3.5,6]_{\mu\mu} = 0.19 \pm 0.02$$

$$H_T[1,6]_{ee} = 0.53 \pm 0.04 \qquad H_T[1,6]_{\mu\mu} = 0.40 \pm 0.03$$

$$H_A[1,3.5]_{ee} = -0.103 \pm 0.005 \qquad H_A[1,3.5]_{\mu\mu} = -0.110 \pm 0.005$$

$$H_A[3.5,6]_{ee} = +0.073 \pm 0.012 \qquad H_A[3.5,6]_{\mu\mu} = +0.067 \pm 0.012$$

$$H_A[1,6]_{ee} = -0.029 \pm 0.016 \qquad H_A[1,6]_{\mu\mu} = -0.042 \pm 0.016$$

Total error $\mathcal{O}(5-8\%)$. Still dominated by scale uncertainty.

Huber,Hurth,Lunghi

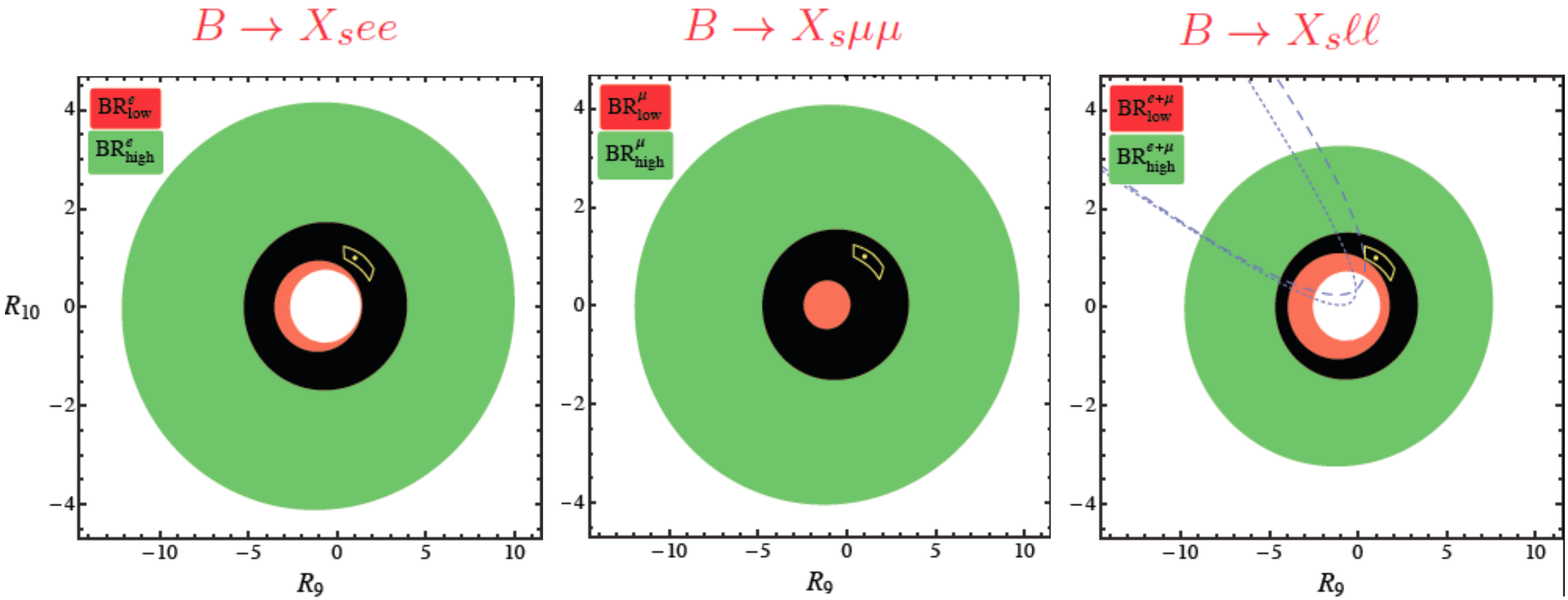
New physics sensitivity

Constraints on Wilson coefficients $C_9/C_9^{\rm SM}$ and $C_{10}/C_{10}^{\rm SM}$

$$R_i = \frac{C_i(\mu_0)}{C_i^{\rm SM}(\mu_0)}$$

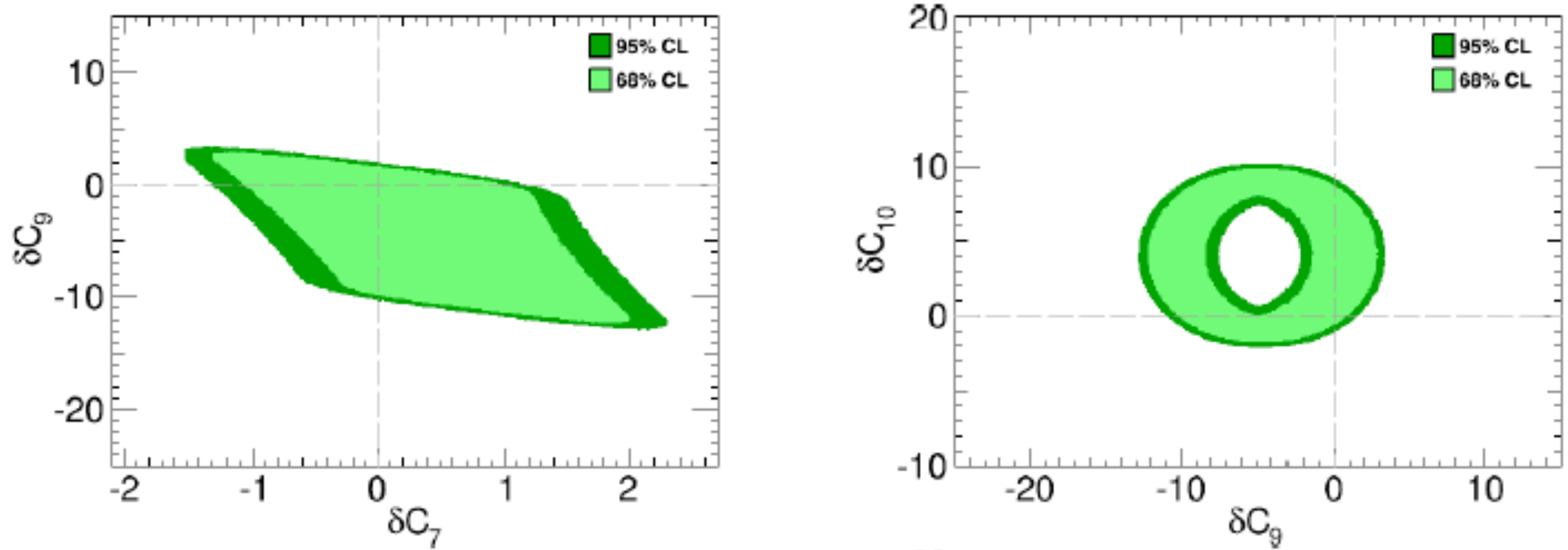
that we obtain at 95% C.L. from present experimental data
(red low q^2, green high q^2)

that we will obtain at 95% C.L. from $50ab^{-1}$ data at Belle-II
(yellow)



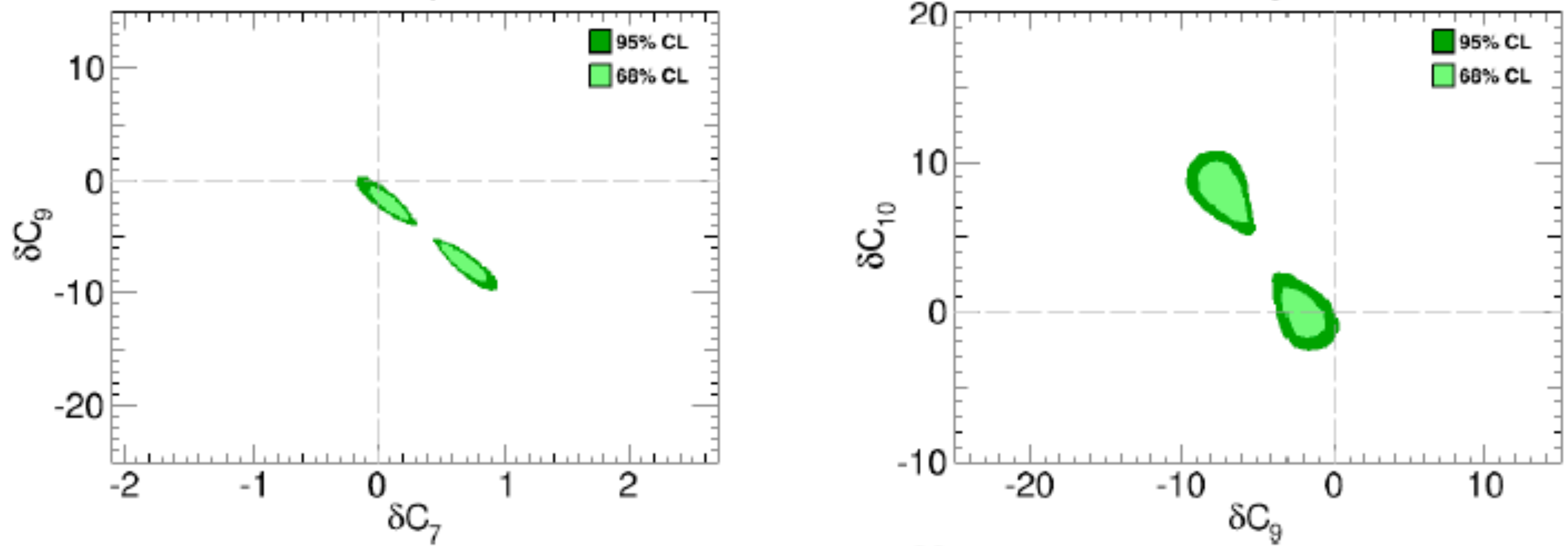
Constraining power of exclusive and inclusive modes

Hurth, Mahmoudi arXiv:1312.5276



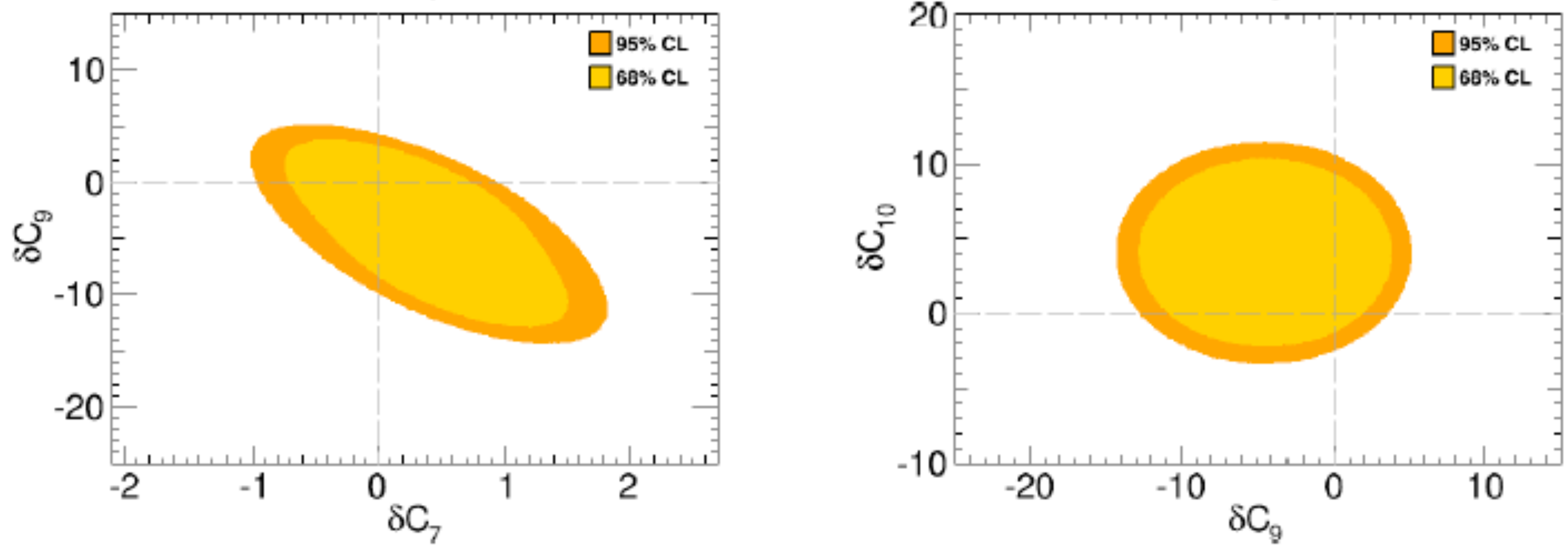
Exclusive observables

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



Exclusive observables

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



Inclusive observables

Exclusive modes $B \to K^{(*)}\ell\ell$

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')

Construction of optimised angular observables

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 ....

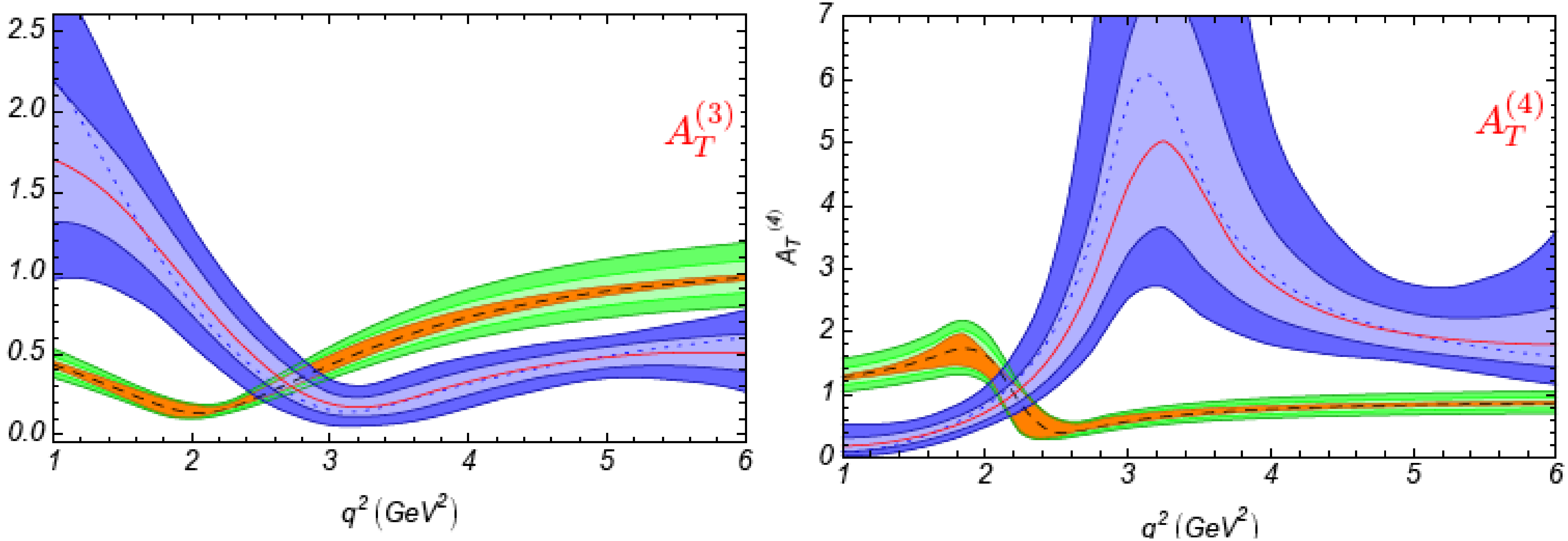
Careful design of theoretical clean angular observables

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

- Dependence of soft form factors, $\xi_\perp$ and $\xi_\parallel$, to be minimized !
  form factors should cancel out exactly at LO, best for all s
- unknown Λ/m_b power corrections

$A_{\perp,\parallel,0} = A^0_{\perp,\parallel,0}\left(1 + c_{\perp,\parallel,0}\right)$ vary c_i in a range of ±10% and also of ±5%

Guesstimate



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

Careful design of theoretical clean angular observables

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

- Dependence of soft form factors, $\xi_\perp$ and $\xi_\|$, to be minimized !
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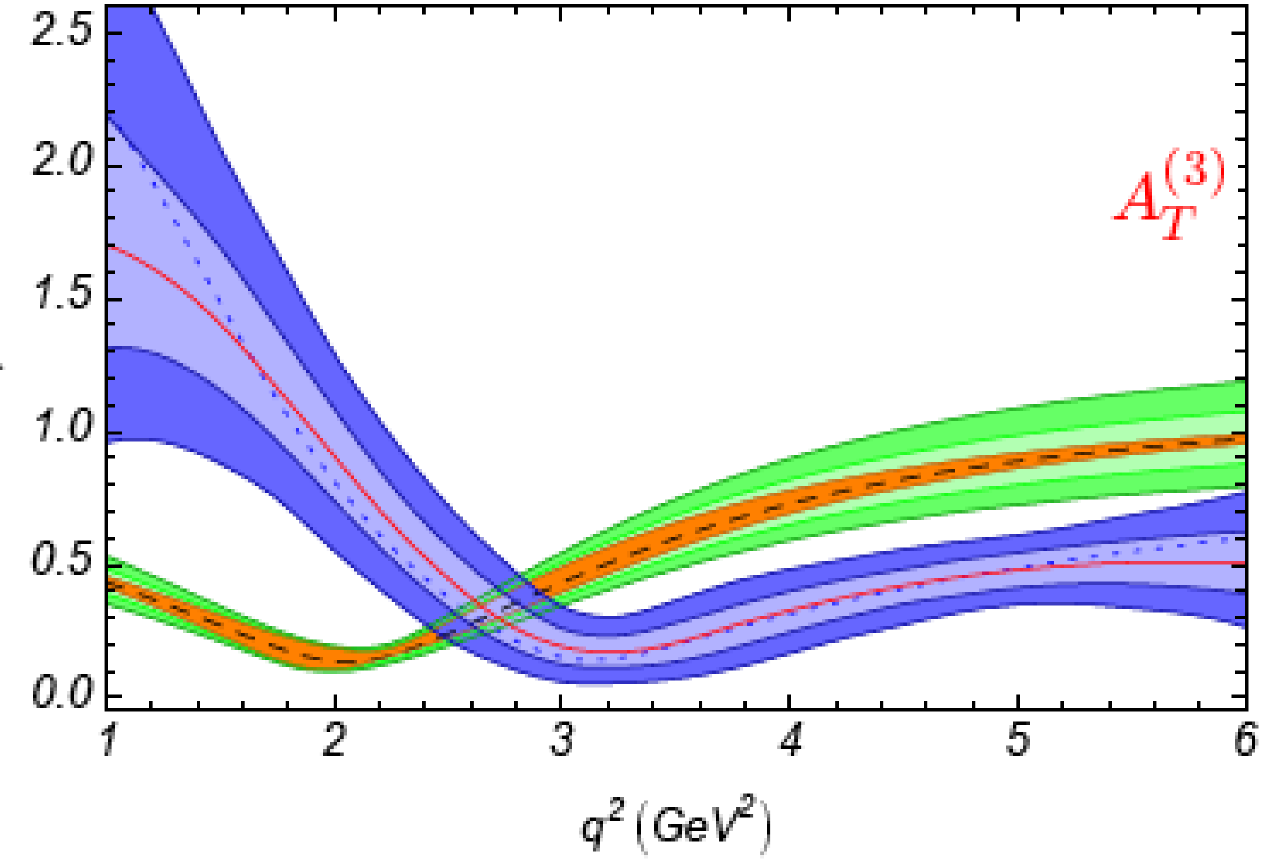
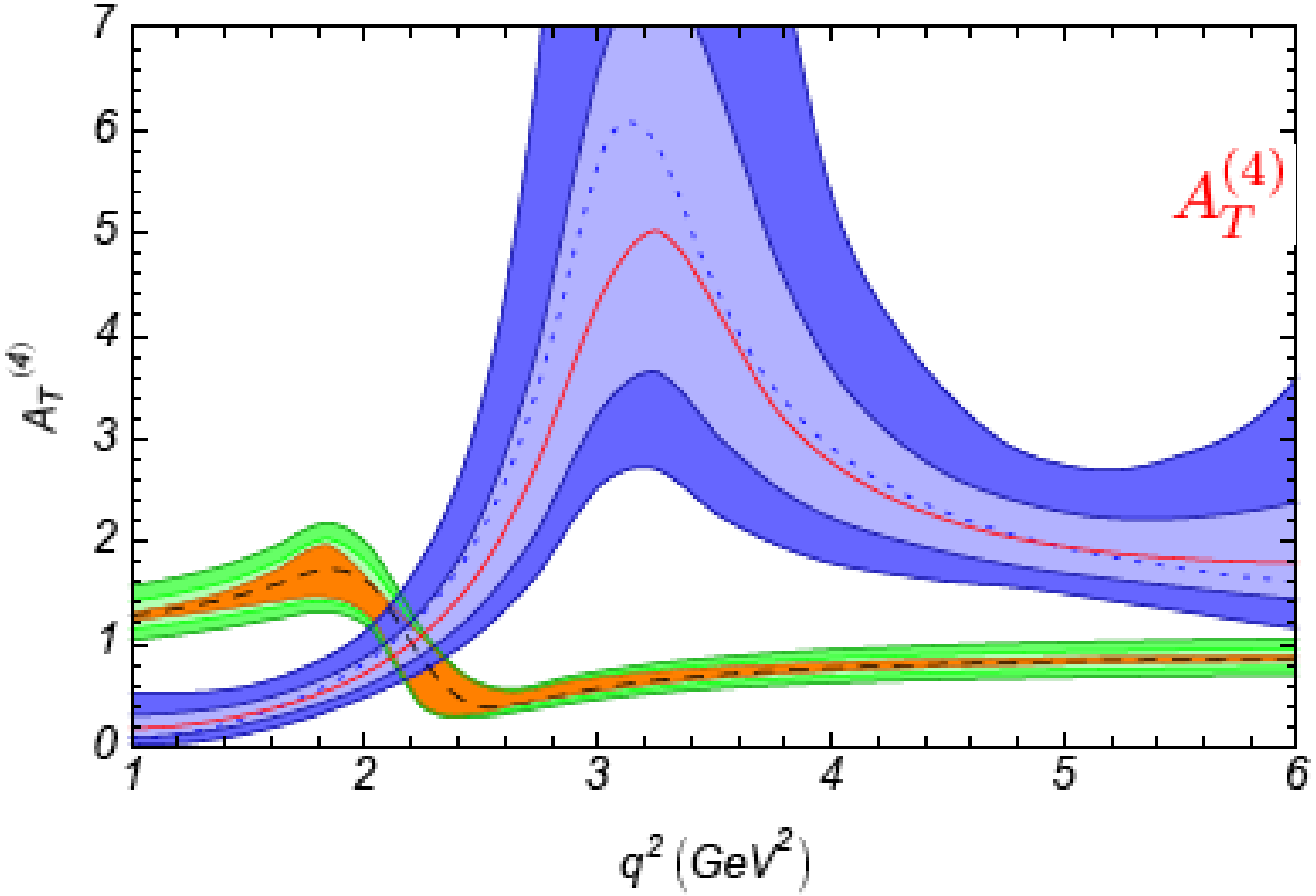


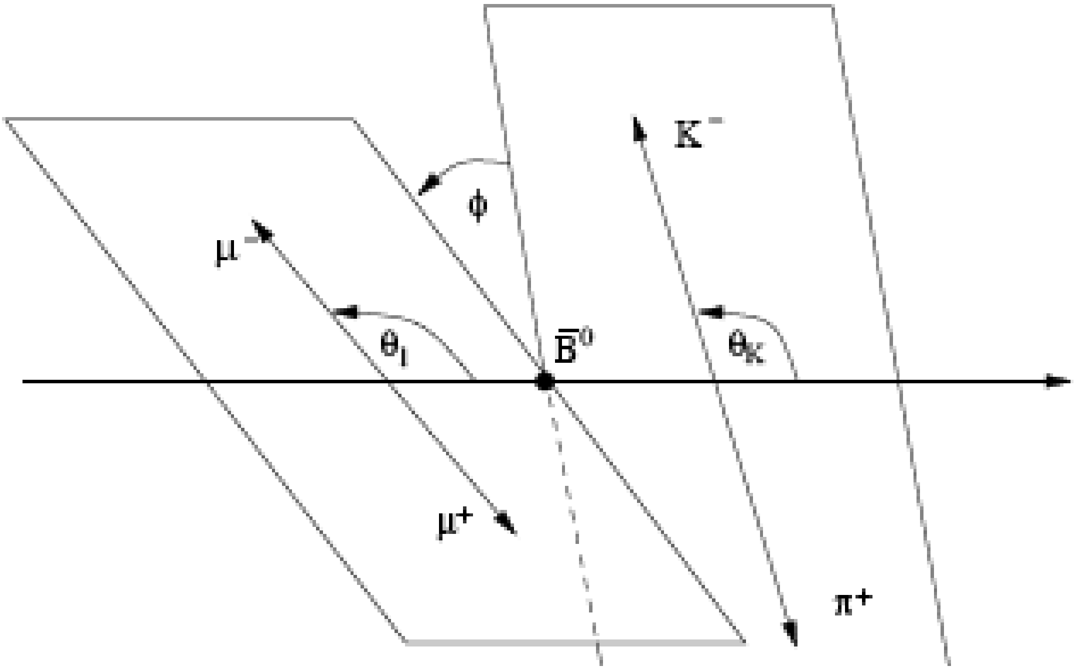
Guesstimate



This was the dream in 2008

Differential decay rate of $B \to K^*\ell\ell$

Assuming the $\bar{K}^*$ to be on the mass shell, the decay $\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+)\ell^+\ell^-$ described by the lepton-pair invariant mass, s, and the three angles θ_l, θ_{K^*}, ϕ.



$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_l, \theta_K, \phi)$$

$$J(q^2, \theta_l, \theta_K, \phi) =$$

$$= J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l + J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$

$$+ J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi + (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l$$

$$+ J_7\sin 2\theta_K\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi + J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi$$

Large number of independent angular obervables

Optimised basis of clean (formfactor-independent) observables: P_i

$$n_\| = \begin{pmatrix} A_\|^L \\ A_\|^{R*} \end{pmatrix} , \quad n_\perp = \begin{pmatrix} A_\perp^L \\ -A_\perp^{R*} \end{pmatrix} , \quad n_0 = \begin{pmatrix} A_0^L \\ A_0^{R*} \end{pmatrix}$$

$$P_1 = \frac{|n_\perp|^2 - |n_\||^2}{|n_\perp|^2 + |n_\||^2} = \frac{J_3}{2J_{2s}} ,$$

$$P_2 = \frac{\mathrm{Re}(n_\perp^\dagger n_\|)}{|n_\||^2 + |n_\perp|^2} = \beta_\ell \frac{J_{6s}}{8J_{2s}} ,$$

$$P_3 = \frac{\mathrm{Im}(n_\perp^\dagger n_\|)}{|n_\||^2 + |n_\perp|^2} = -\frac{J_9}{4J_{2s}} ,$$

$$P_4 = \frac{\mathrm{Re}(n_0^\dagger n_\|)}{\sqrt{|n_\||^2 |n_0|^2}} = \frac{\sqrt{2} J_4}{\sqrt{-J_{2c}(2J_{2s} - J_3)}} ,$$

$$P_5 = \frac{\mathrm{Re}(n_0^\dagger n_\perp)}{\sqrt{|n_\perp|^2 |n_0|^2}} = \frac{\beta_\ell J_5}{\sqrt{-2J_{2c}(2J_{2s} + J_3)}} ,$$

$$P_6 = \frac{\mathrm{Im}(n_0^\dagger n_\|)}{\sqrt{|n_\||^2 |n_0|^2}} = -\frac{\beta_\ell J_7}{\sqrt{-2J_{2c}(2J_{2s} - J_3)}} ,$$

Definition of P_5'

$$P_4' \equiv P_4 \sqrt{1 - P_1} = \frac{J_4}{\sqrt{-J_{2c} J_{2s}}}$$

$$P_5' \equiv P_5 \sqrt{1 + P_1} = \frac{J_5}{2\sqrt{-J_{2c} J_{2s}}}$$

$$P_6' \equiv P_6 \sqrt{1 - P_1} = -\frac{J_7}{2\sqrt{-J_{2c} J_{2s}}}$$

$B \to K^* \ell^+ \ell^-$ observables 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

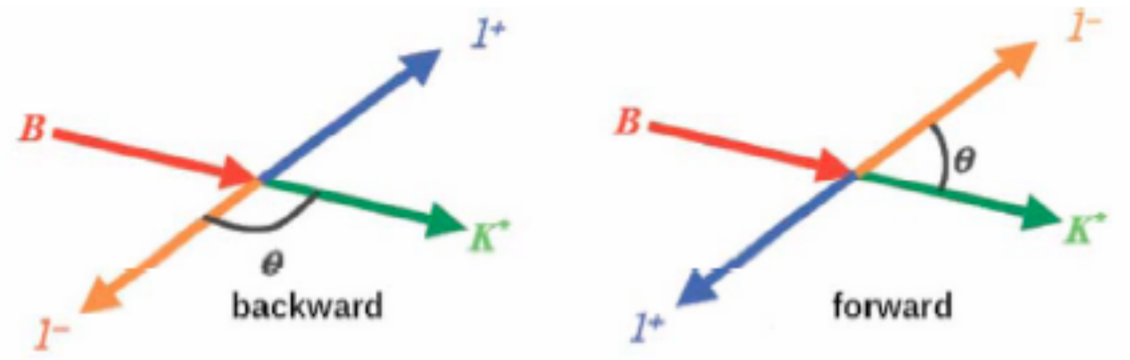
thus, small theoretical uncertainties,
but less sensitivity to short-distance
Wilson coefficients than in the low-q^2 region

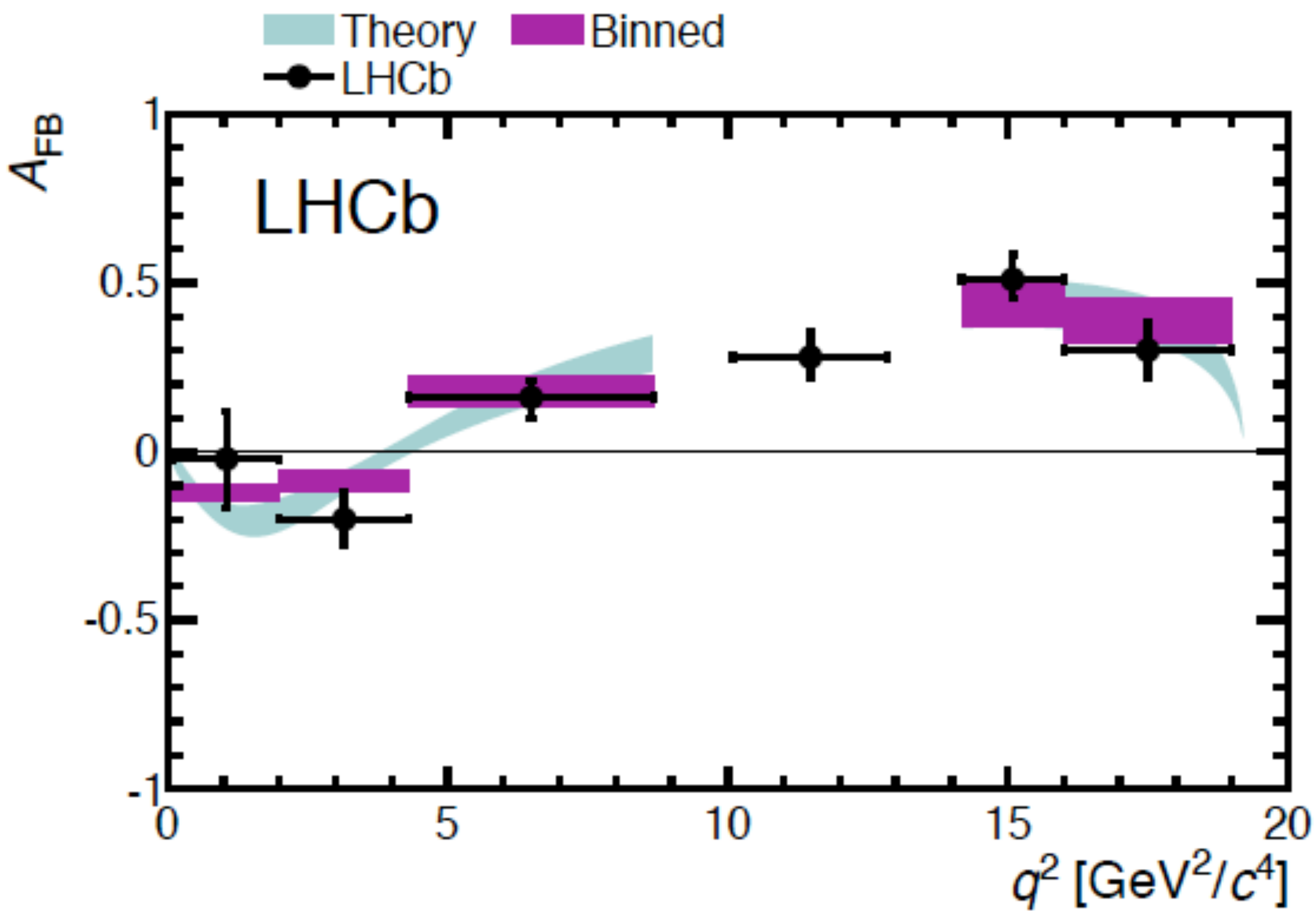
The theoretical treatment in the low- and high-q^2 based on different theoretical concepts.

⇒ the consistency of the consequences out of the two sets of measurements will allow for an important crosscheck.

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

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





Excellent agreement with SM at current level of precision.

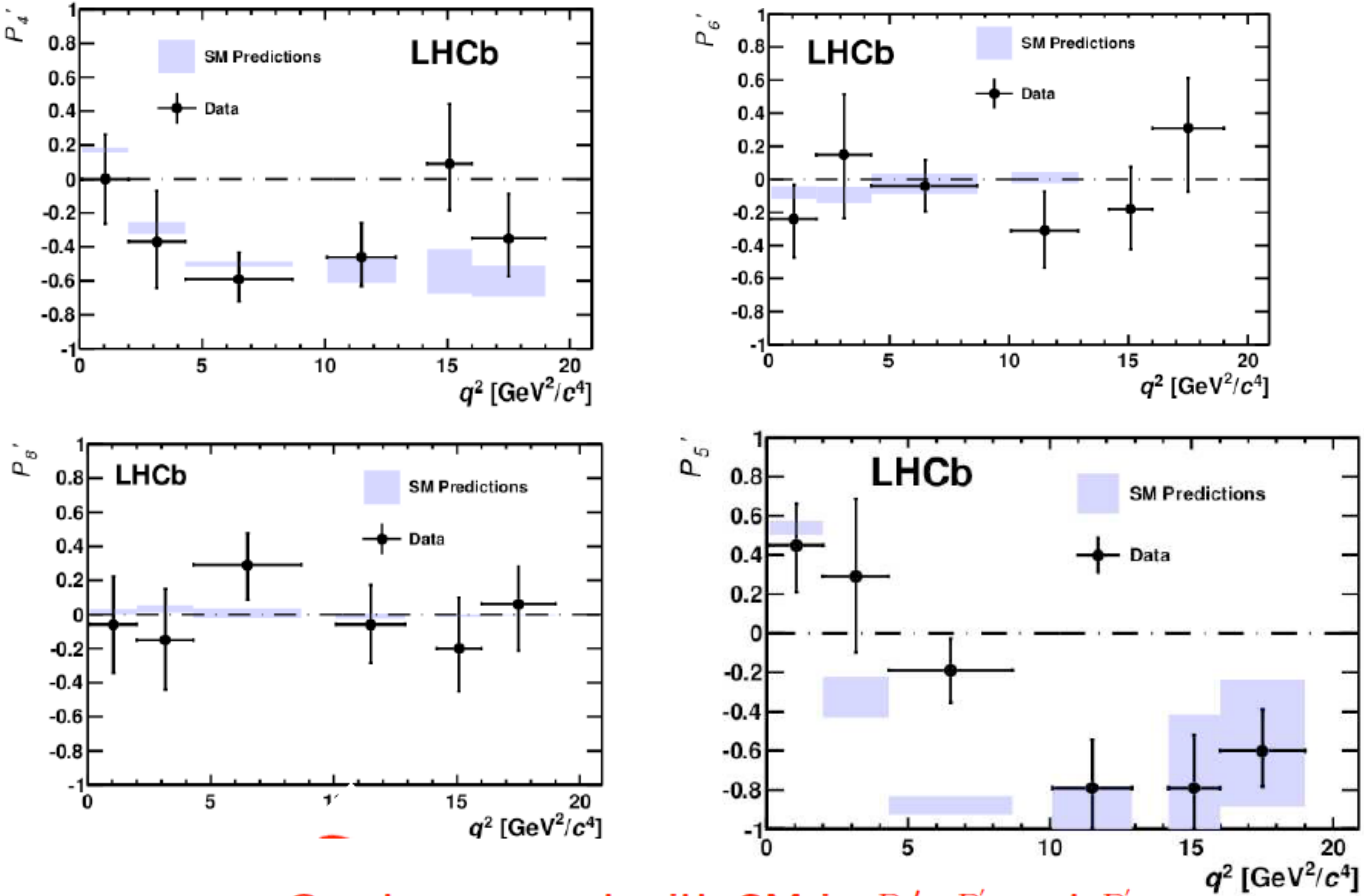
However:

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

LHCb arXiv:1304.6325

First measurements of new angular observables LHCb arXiv:1308.1707

SM predictions Descotes-Genon, Hurth, Matias, Virto arXiv:1303.5794

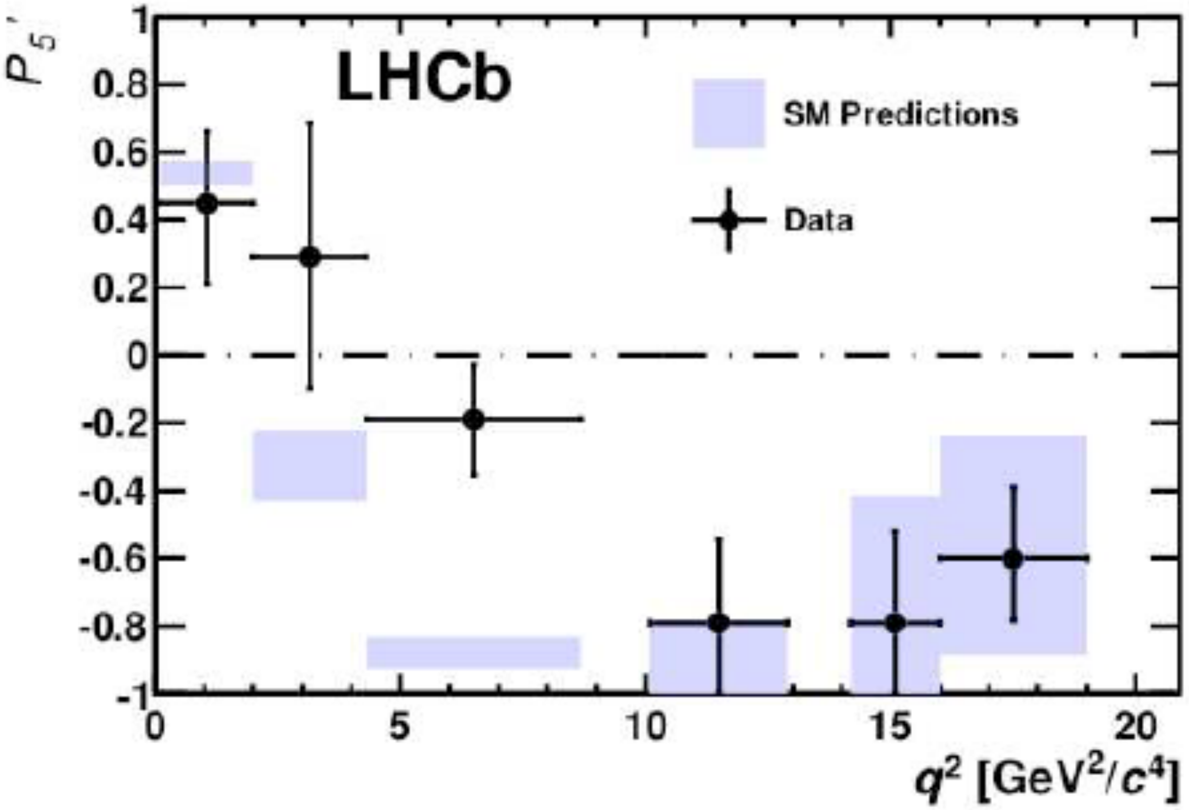


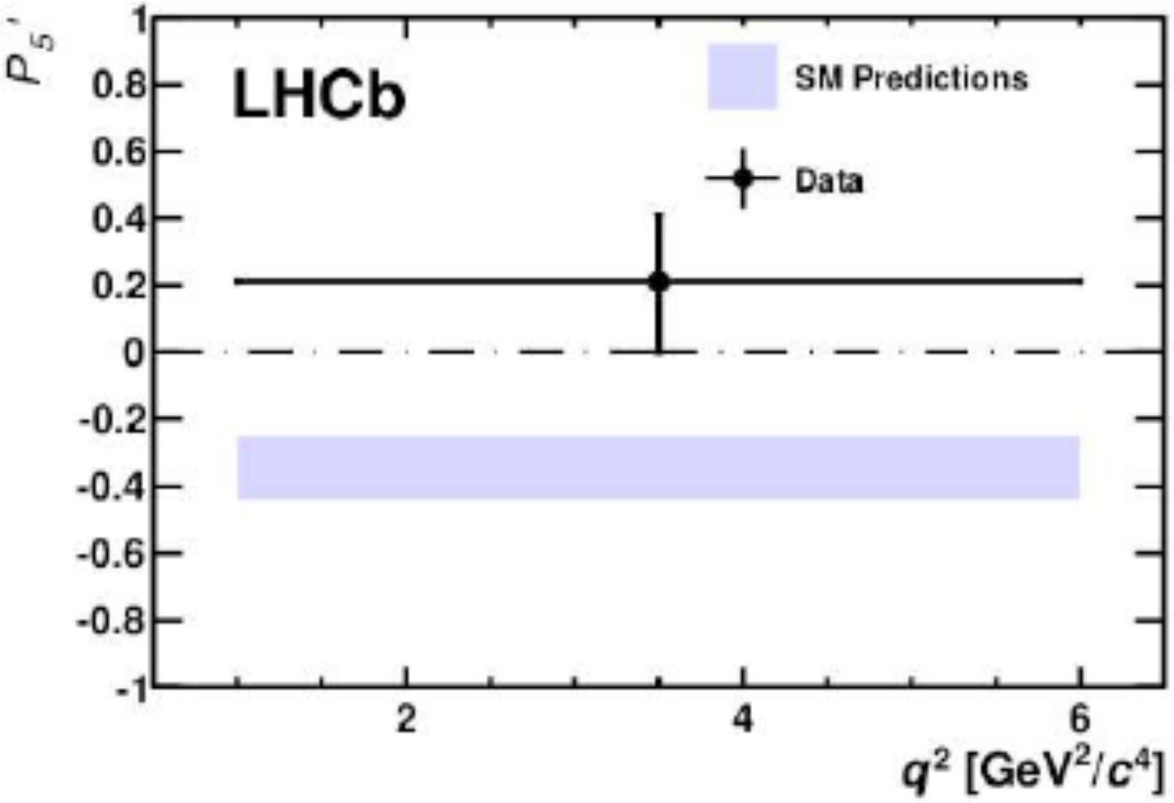
Good agreement with SM in P_4', P_6' and P_8',

but a 3.7σ deviation in the third bin in P_5'

First measurements of new angular observables LHCb arXiv:1308.1707

SM predictions Descotes-Genon, Hurth, Matias, Virto arXiv:1303.5794





LHCb Anomaly

a statistical fluctuation, an underestimation of Λ/m_b corrections or new physics in C_9 ?

$C_7 \quad (B \to X_s \gamma) \qquad C_{10} \quad (B \to \mu^+ \mu^-)$

LHCb Anomaly

Hurth, Mahmoudi arXiv:1312.5276,1411.2786

- **Power corrections:** No strict theory: $A_i' = A_i(1 + C_i)$, $|C_i|$ 10%

  3% on the observable level: 4.0σ

  More realistic: 10% on the observable level: 3.6σ

  Dimensional estimate, some soft arguments

  Assume 30% : 2.2σ

  Descotes,Matias,Virto arXiv:1307.5683

- **Validity of QCDf and of perturbative description of charm loops:** $[1GeV^2, 6GeV^2]$,
  but local bin is $q^2 \in [4.3, 8.63]GeV^2$

- **Issue of charm loops** Khodjamirian et al. arXiv:1006.4945

  Only soft gluon (but no spectator) contributions included yet

- **Analysis of factorizable power corrections**

Descotes,Hofer,Matias,Virto,arXiv:1407.8526

$$A_2(q^2) = \frac{m_B}{m_B - m_{K^*}} \left[\xi_\perp(q^2) - \xi_\|(q^2)\right] + \Delta A_2^{\alpha_s}(q^2) + \Delta A_2^{\Lambda}(q^2)\,,$$

$$A_0(q^2) = \frac{E}{m_{K^*}}\,\xi_\|(q^2) + \Delta A_0^{\alpha_s}(q^2) + \Delta A_0^{\Lambda}(q^2)\,, \qquad \xi_\|^{(2)}(q^2) \equiv \frac{m_{K^*}}{E} A_0(q^2)$$

Only central value of power corrections fixed
Guesstimate of factorizable power corrections: 10%
Nonfactorizable power corrections still open

- **Analysis of factorizable power corrections**

Descotes,Hofer,Matias,Virto,arXiv:1407.8526

$$A_2(q^2) = \frac{m_B}{m_B - m_{K^*}} \left[\xi_\perp(q^2) - \xi_\|(q^2)\right] + \Delta A_2^{\alpha_s}(q^2) + \Delta A_2^{\Lambda}(q^2)\,,$$

$$A_0(q^2) = \frac{E}{m_{K^*}}\,\xi_\|(q^2) + \Delta A_0^{\alpha_s}(q^2) + \Delta A_0^{\Lambda}(q^2)\,, \qquad \xi_\|^{(2)}(q^2) \equiv \frac{m_{K^*}}{E} A_0(q^2)$$

Only central value of power corrections fixed
Guesstimate of factorizable power corrections: 10%
Nonfactorizable power corrections still open

- **Suggestions beyond guessing numbers**

Direct calculation of QCD formfactors including correlations (problematic correlations used due to internal parameters of the QCD sum rule approach)

Altmannshofer et al.,arXiv:0811.1214 Zwicky et al., arXiv:1503.0553

Methods used in an analysis of $B \to K\ell\ell$

Kjodjamirian,Mannel,Wang,arXiv:1211.0234

Kjodjamirian et al.,arXiv:1006.4945

- **New physics explanations**
  - "The usual suspects, such as the MSSM, warped extra dimension scenarios, or models with partial compositeness, cannot accommodate the observed deviations ....."

    Gauld, Goertz, Haisch arXiv:1308.1959;1310.1082
    Altmannshofer, Straub arXiv:1308.1501

Coefficient	$1\,\sigma$	$2\,\sigma$	$3\,\sigma$
$\mathcal{C}_7^{\rm NP}$	$[-0.05,-0.01]$	$[-0.06,0.01]$	$[-0.08,0.03]$
$\mathcal{C}_9^{\rm NP}$	$[-1.6,-0.9]$	$[-1.8,-0.6]$	$[-2.1,-0.2]$
$\mathcal{C}_{10}^{\rm NP}$	$[-0.4,1.0]$	$[-1.2,2.0]$	$[-2.0,3.0]$
$\mathcal{C}_{7'}^{\rm NP}$	$[-0.04,0.02]$	$[-0.09,0.06]$	$[-0.14,0.10]$
$\mathcal{C}_{9'}^{\rm NP}$	$[-0.2,0.8]$	$[-0.8,1.4]$	$[-1.2,1.8]$
$\mathcal{C}_{10'}^{\rm NP}$	$[-0.4,0.4]$	$[-1.0,0.8]$	$[-1.4,1.2]$

Model-independent analysis Descotes,Matias,Virto arXiv:1307.5683

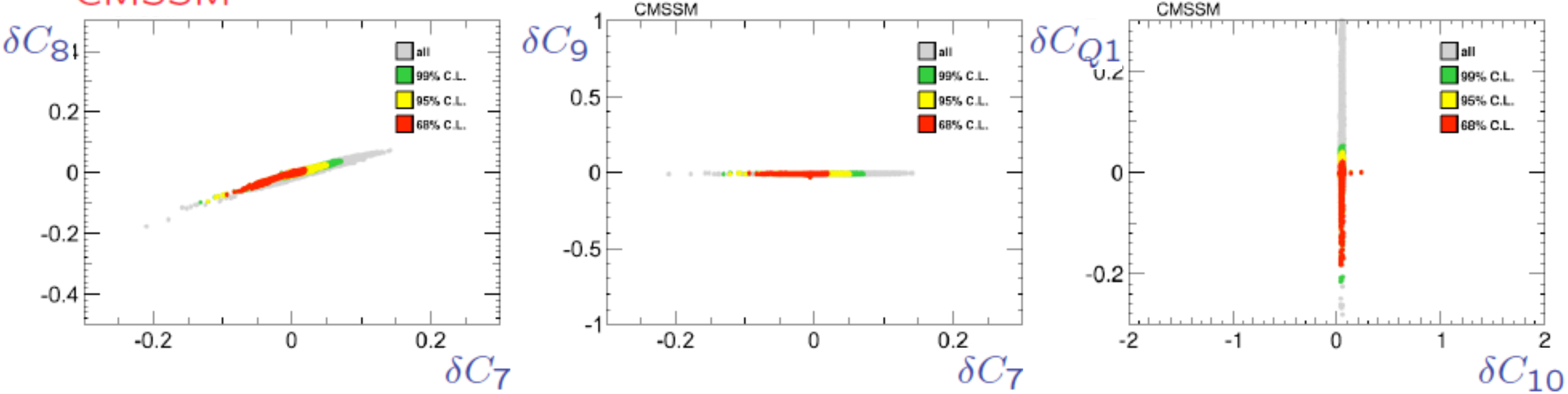
  - 1σ solutions: Z' -models (331-models....): only change C_9

    Descotes,Matias,Virto arXiv:1307.5683
    Altmannshofer, Straub arXiv:1308.1501
    Gauld, Goertz, Haisch arXiv:1308.1959;1310.1082
    Buras,De Fazio,Girrbach arXiv:1311.6729
    Altmannshofer,Gori,Pospelov,Yavin arXiv:1403.1269 ....

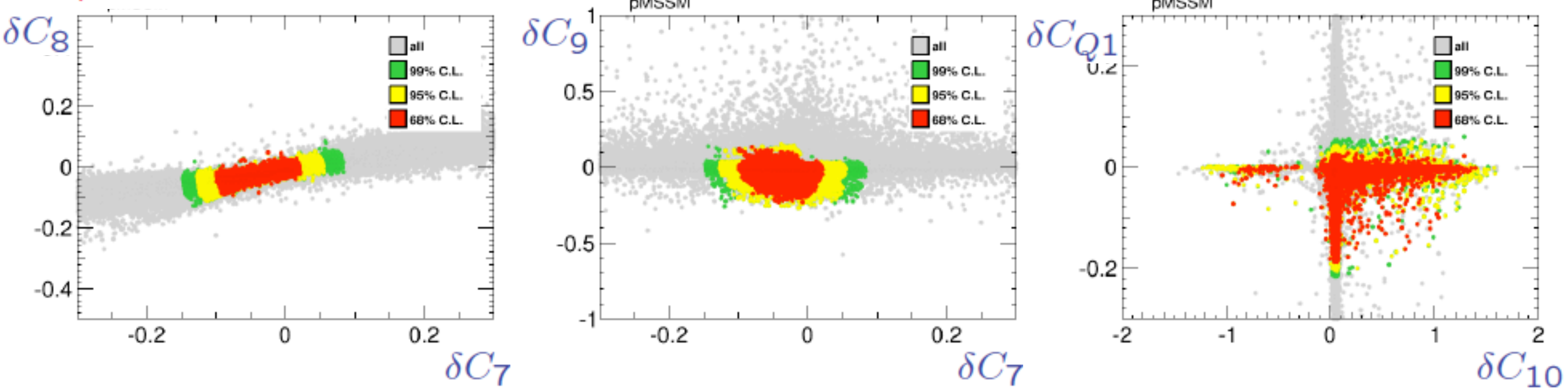
- SUSY are compatible with the anomaly at the 2σ level

Overall fit at the 1σ level Mahmoudi,Neshatpour,Virto arXiv:1401.2145

CMSSM

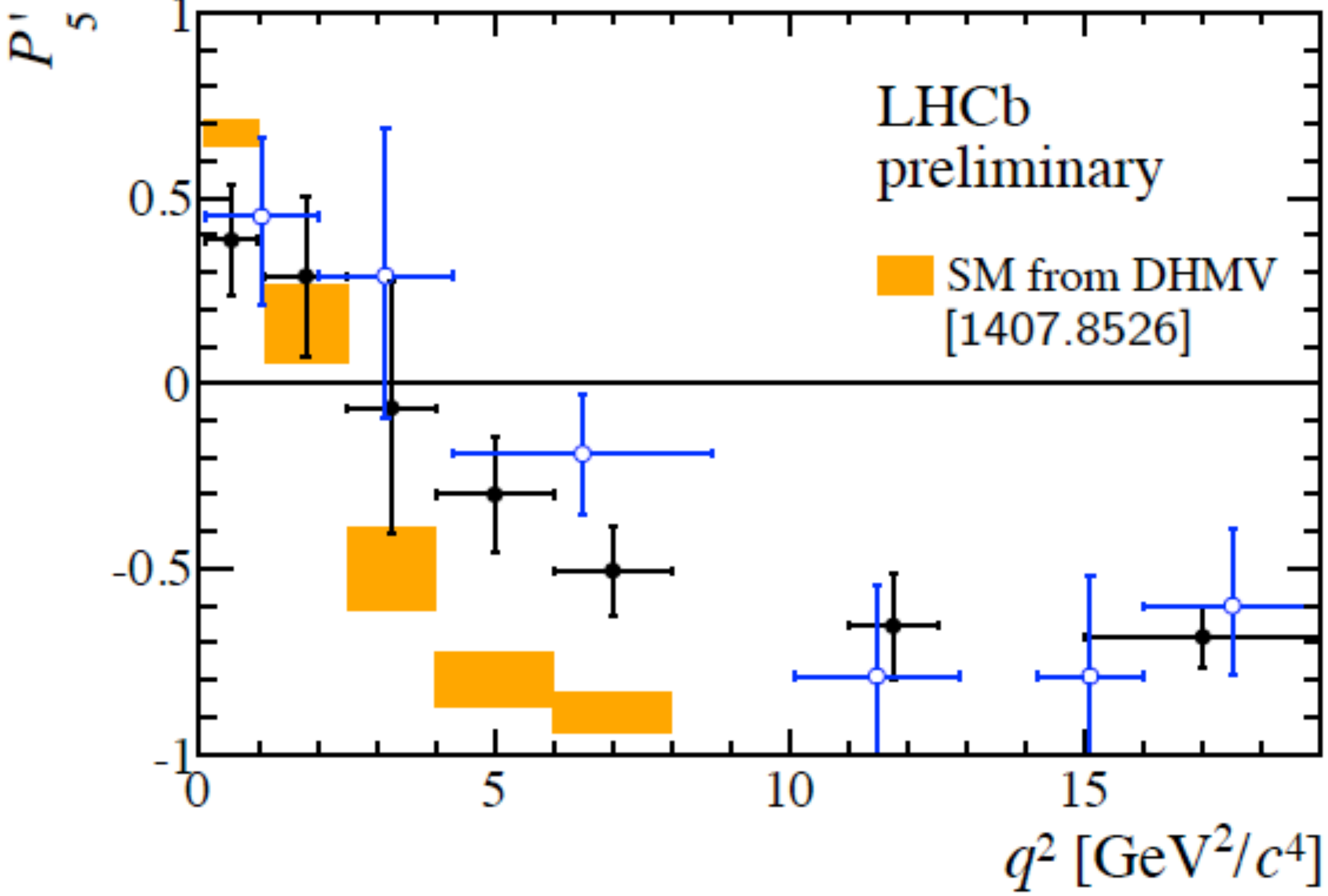


pMSSM



Update of LHCb at Moriond 2015

[LHCb-CONF-2015-002]



$3\,fb^{-1}$

- Tension seen in P'_5 in [PRL 111, 191801 (2013)] confirmed
- $[4.0, 6.0]$ and $[6.0, 8.0]\,\mathrm{GeV}^2/c^4$ show deviations of 2.9σ each
- Naive combination results in a significance of 3.7σ
- Compatible with $1\,fb^{-1}$ measurement

Signs for lepton non-universality ?

LHCb; arXiv:1406.6482

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074}\,(\mathrm{stat}) \pm 0.036\,(\mathrm{syst})$$

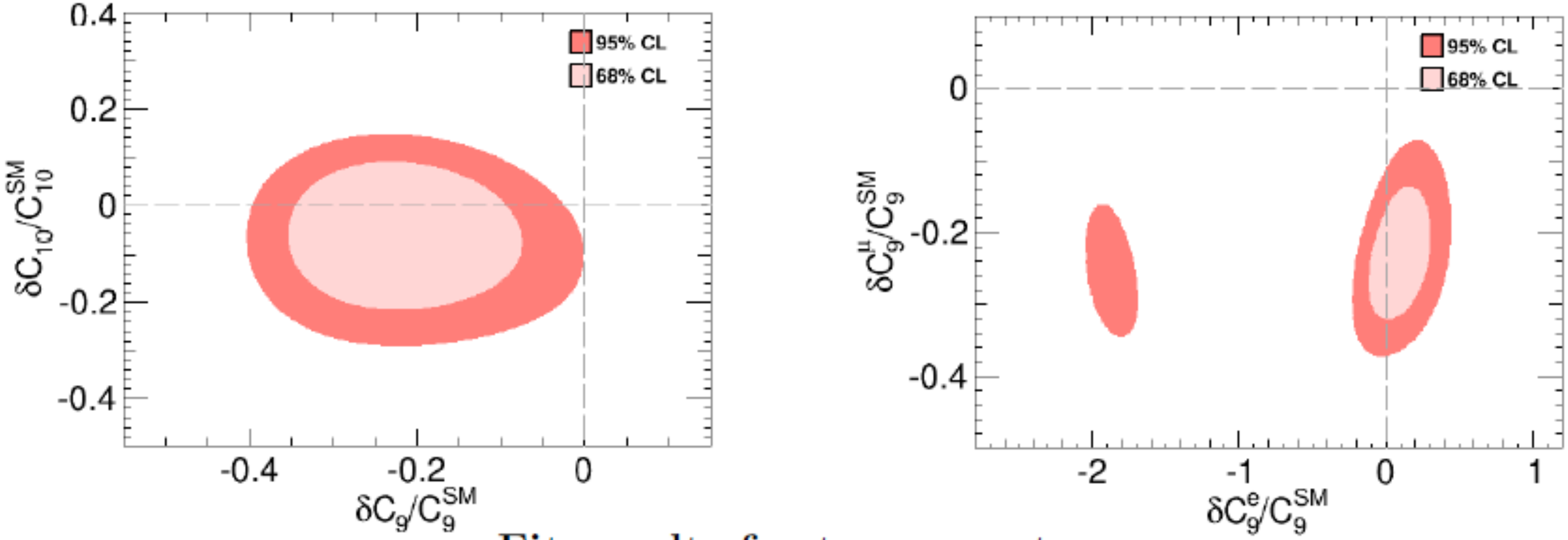
2.6σ deviation from SM

Theoretically rather clean

Hiller,Schmaltz; Ghosh et al.; Biswas et al.;
Straub et al.;Hurth et al.;Glashow et al. ....

Global fits to the $b \to s\ell\ell$ data

Hurth,Mahmoudi,Neshatpour,arXiv:1410.4545



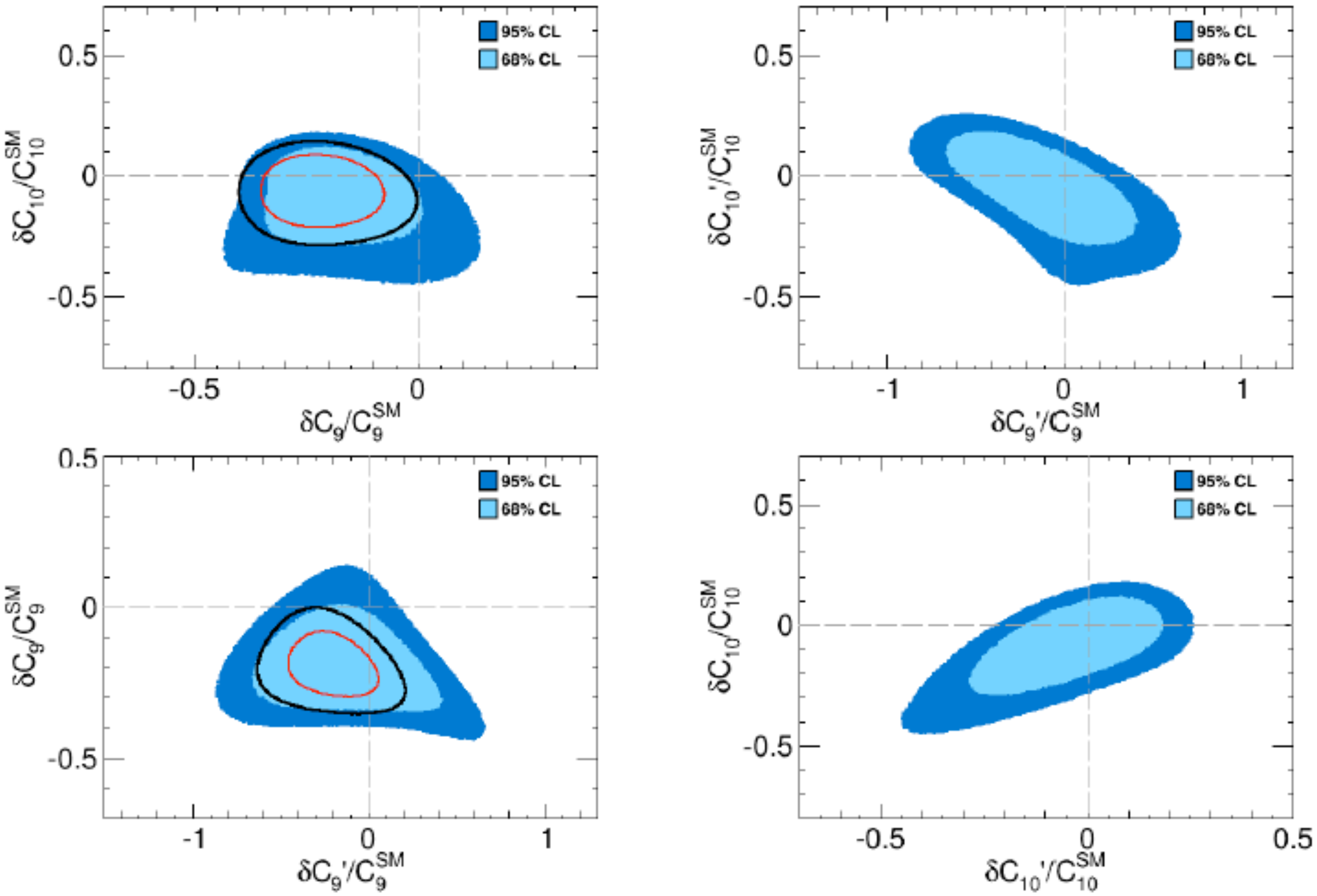
Fit results for two operators

Tensors, scalars difficult, sign for tension in C_9^{μ}

Electromagnetic corrections are taken into account !

Fit results for four operators $\{C_9, C_9', C_{10}, C_{10}'\}$

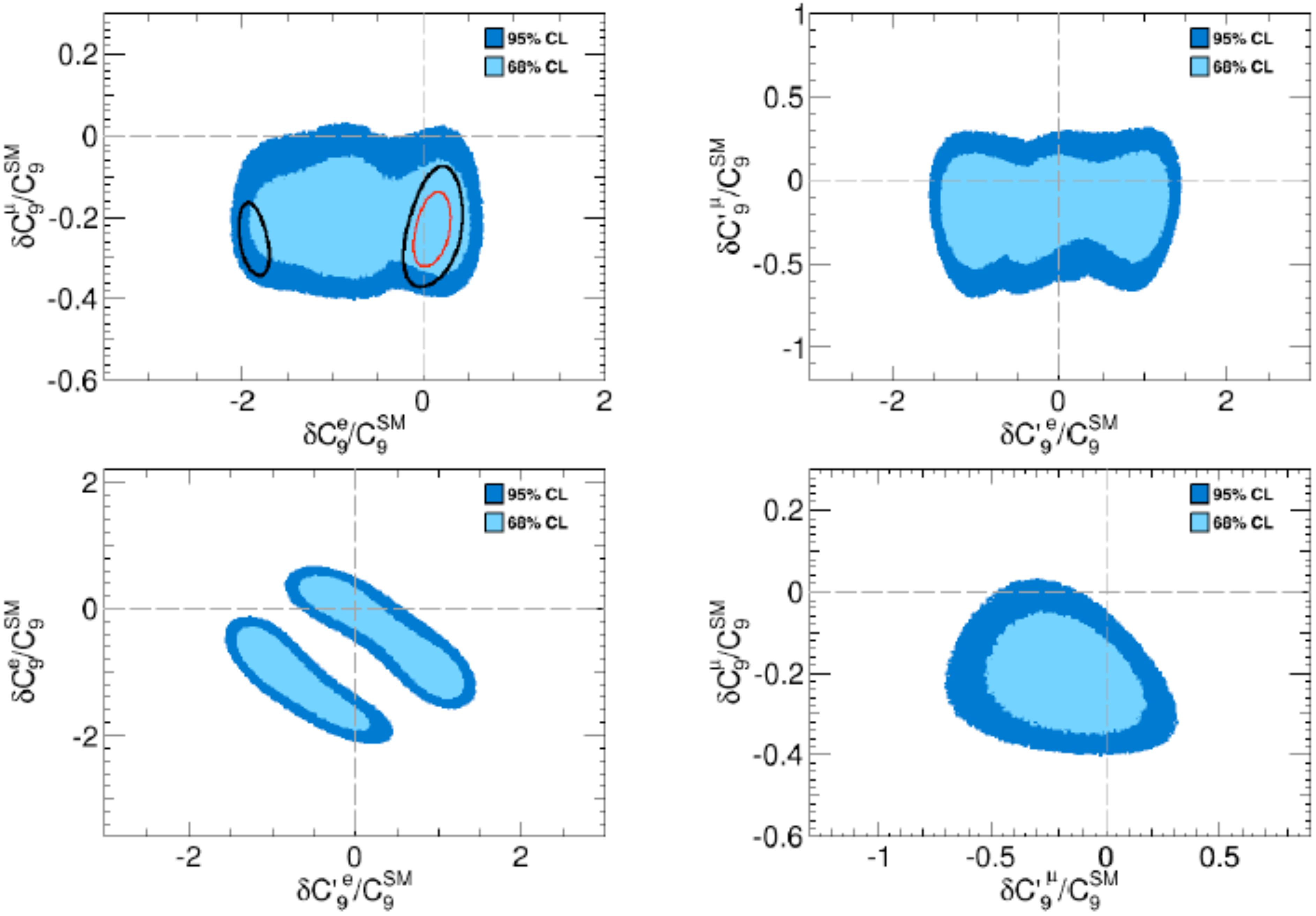
Larger new physics contributions are allowed within 1σ



	$\{C_9, C_9'\}$	$\{C_9, C_{10}\}$	$\{C_9, C_9', C_{10}, C_{10}'\}$
Best fit point: χ^2 :	52 (52)	52 (52)	51 (50)

Adding $C_{10}^{(\prime)}$ or primed operators does not improve the fit !

$\{C_9^\mu, C_9'^\mu, C_9^e, C_9'^e\}$

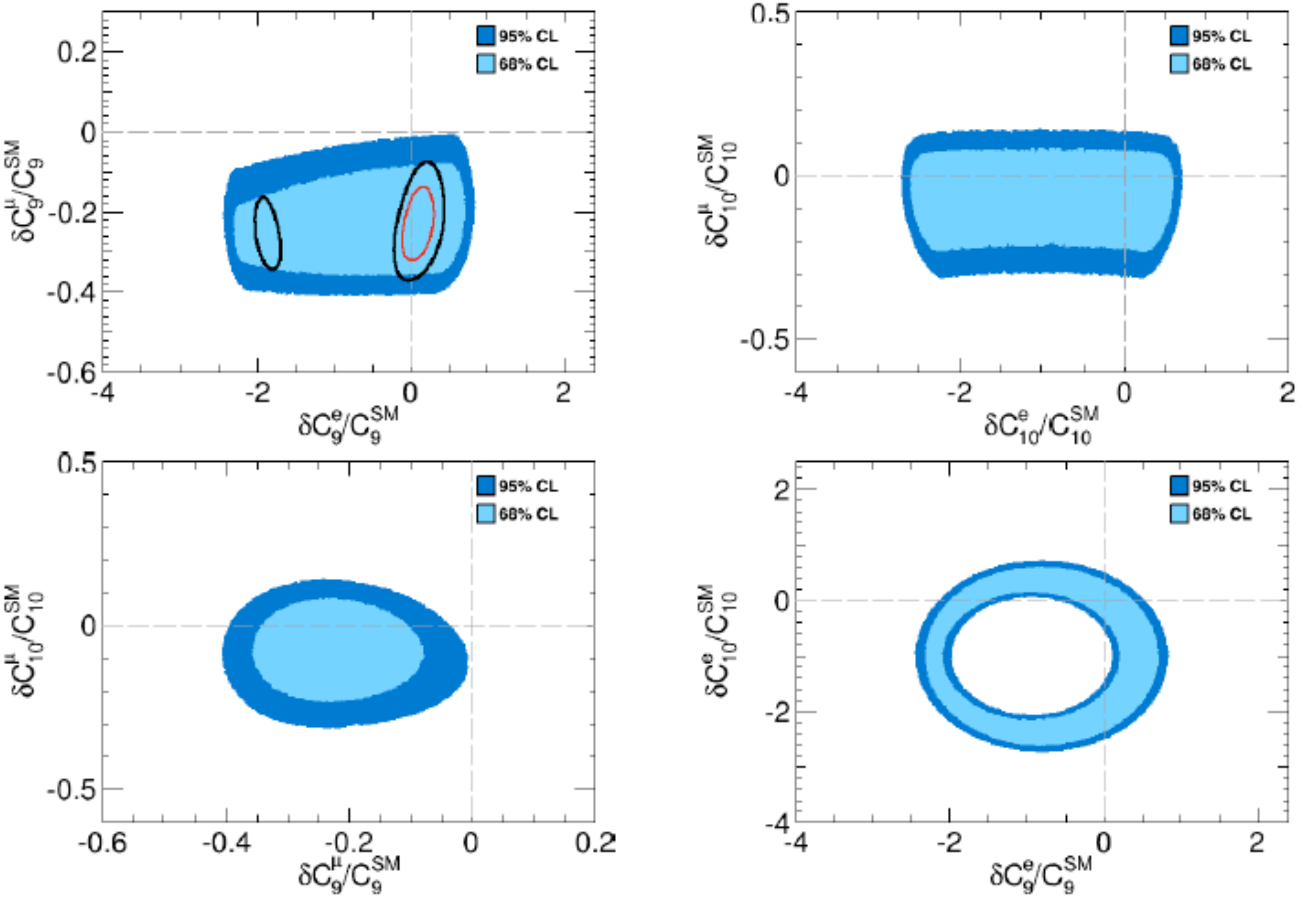


		$\{C_9, C_9'\}$	$\{C_9^\mu, C_9'^\mu, C_9^e, C_9'^e\}$
Best fit point:	$\chi^2:$	52 (52)	42 (50)

Fit improved by 2.6σ Assuming that this specific four-operator scenario is correct, the one with the two-operators is ruled out by 2.6σ

$\{C_9^\mu, C_9^e, C_{10}^\mu, C_{10}^e\}$

Larger new physics contributions are allowed within 1σ



	$\{C_9, C_{10}\}$	$\{C_9^\mu, C_9^e\}$.	$\{C_9^\mu, C_9^e, C_{10}^\mu, C_{10}^e\}$
χ^2 :	52 (52)	44 (52)	43 (50)

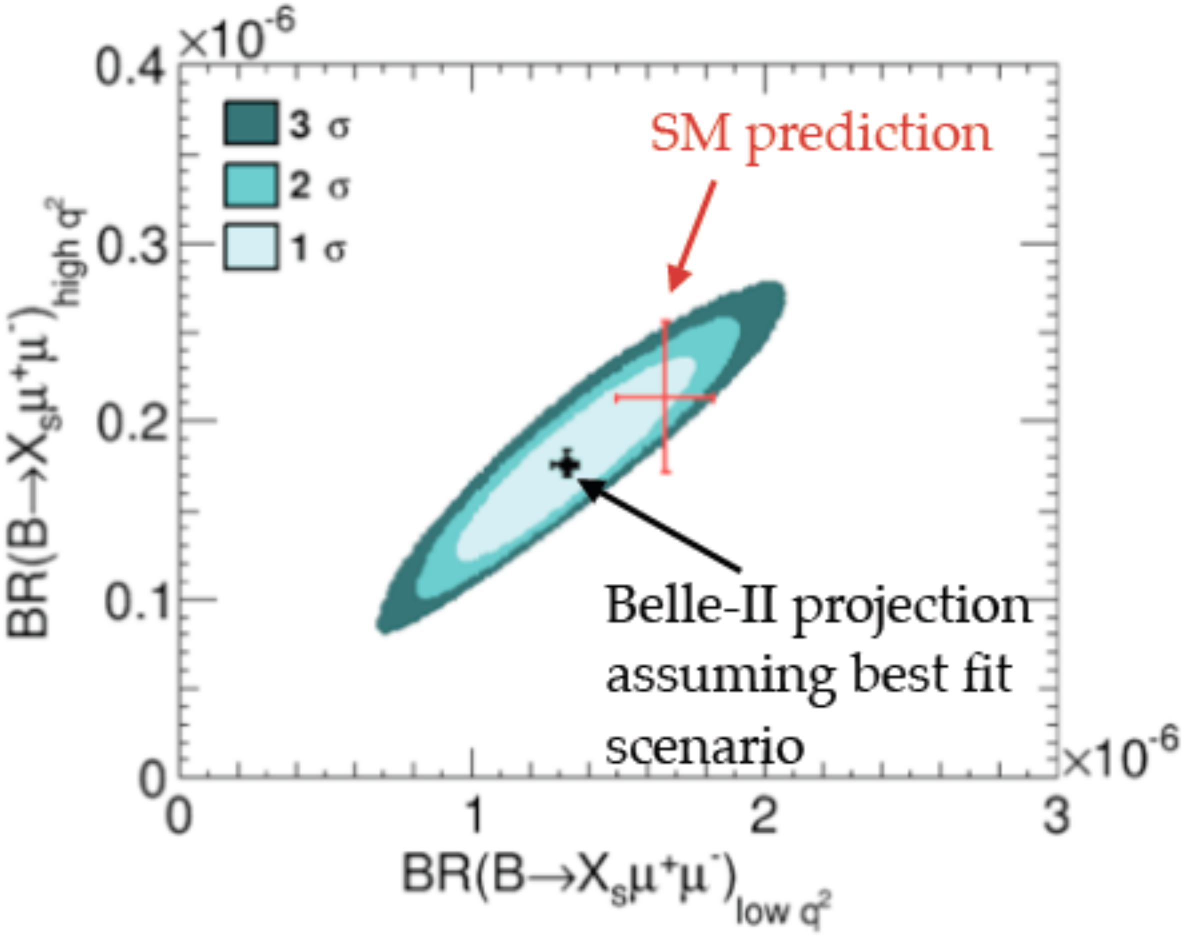
Again χ^2 favours the non-universal extension against the universal one

Many 1σ NP solutions on the market (even to resolve several anomalies R_K, $R_{D(*)}$, $g-2$)

Crosscheck of LHCb anomalies with inclusive modes

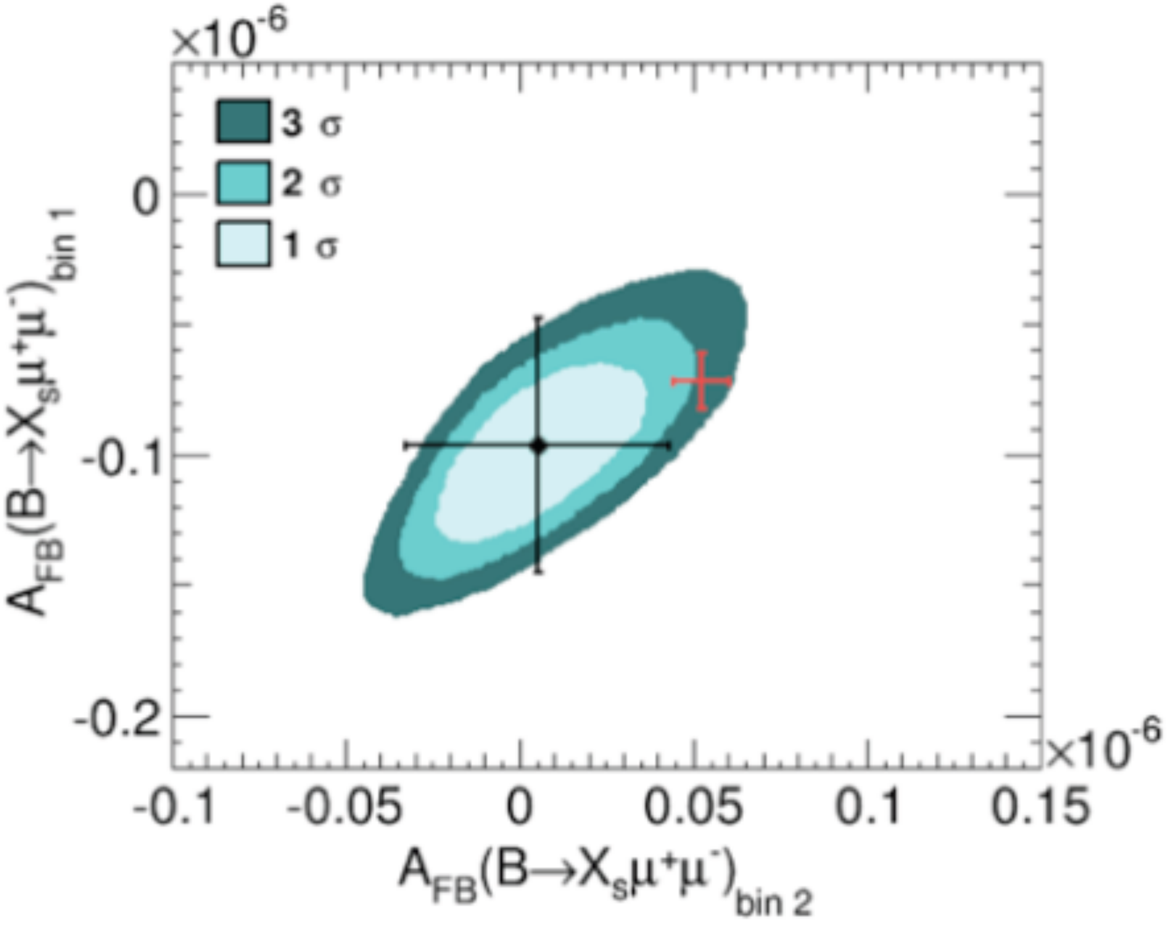
Hurth,Mahmoudi,Neshatpour,arXiv:1410.4545

if SM deviations in R_K and P_5' persist until Belle-II



SM prediction

Belle-II projection assuming best fit scenario



If NP then the effect of C_9 and C_9' are large enough to be checked at Belle-II with theoretically clean modes.

Future experimental opportunities

- LHCb $5fb^{-1}$, LHCb upgrade to $50fb^{-1}$
  allows for wide range of analyses, highlights:
  B_s mixing phase, angle γ, $B \to K^*\mu\mu$, $B_s \to \mu\mu$,$B_s \to \phi\phi$

- Dedicated kaon experiments J-PARC E14 and CERN P-326/NA62:
  rare kaon decays $K_L^0 \to \pi^0\nu\bar{\nu}$ and $K^+ \to \pi^+\nu\bar{\nu}$

- Super-B factory Belle-II at KEK ($50ab^{-1}$)
  Belle-II is a Super Flavour factory: besides precise B measurements,
  CP violation in charm, lepton flavour violating modes $\tau \to \mu\gamma$,...

Michelangelo Mangano (Aspen2014):

- The days of "guaranteed" discoveries or no-lose theorems in particle physics are over, at least for the time being .....
- but the big questions of our field remain open (hierarchy problem. flavour, neutrinos, dark matter, baryogenesis,...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias.

Mainz Institute for Theoretical Physics

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NA62 Kaon Physics Handbook

Augusto Ceccucci **CERN**, Giancarlo D'Ambrosio **INFN Naples**
Ulrich Haisch **Univ. Oxford**, Rainer Wanke **JGU**

January 11-22, 2016

Composite Dynamics: from Lattice to LHC Run II

Giacomo Cacciapaglia **IPN Lyon**
Francesco Sannino **CP^3 Origins**, Thomas Flacke **KAIST**

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Fabio Iocco **ICTP-SAIFR & IFT-UNESP, São Paulo**
Arianna Di Cintio **DARK, Univ. Copenhagen**
Miguel Pato **Univ. Stockholm**
Christoph Weniger **Univ. Amsterdam**

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Charles Horowitz **Indiana Univ.**
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Determination of the Fundamental Parameters in QCD

Irinel Caprini **IFIN-HH Bucharest**
Konstantyn Chetyrkin **INR Moskau**
Cesareo A. Dominguez **Univ. Cape Town**
Antonio Pich **Univ. Valencia**, Hubert Spiesberger **JGU**

March 7-12, 2016

Relativistic Hydrodynamics: Theory and Modern Applications

Francesco Becattini **Florence Univ.**
Dmitri Kharzeev **Stony Brook Univ. & BNL**
Dirk H. Rischke **Goethe Univ. Frankfurt**
Dam Thanh Son **Univ. Chicago**
Mikhail Stephanov **Univ. Illinois, Chicago**

October 10-14, 2016

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Call for proposals for activities in 2017

Dark Matter in the Milky Way
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Arianna Di C
Miguel Pato
Christoph W
May 2-13,

Deadline 31.1.2016

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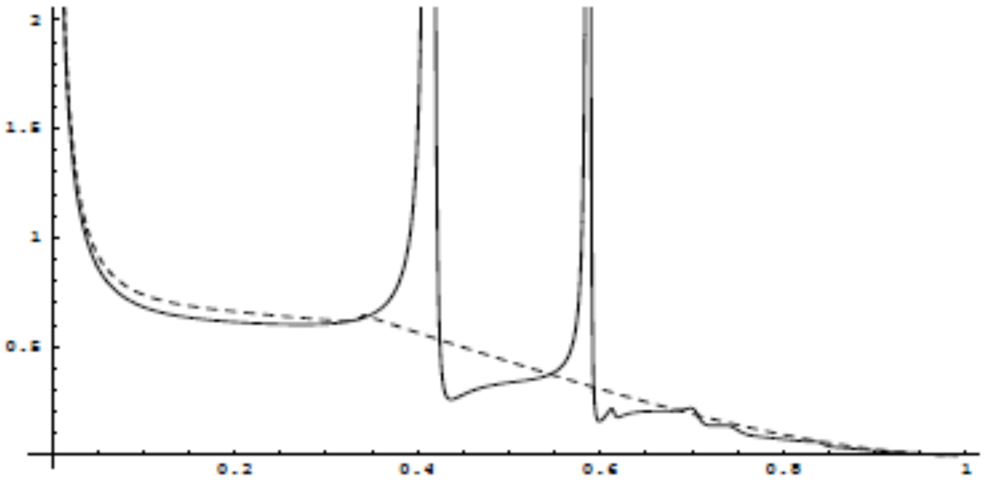
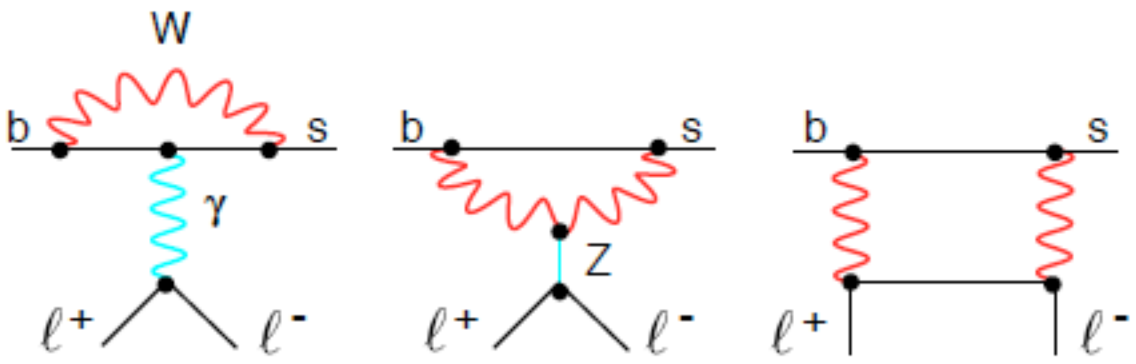
Extra

Review of previous calculations for $B \to X_s \ell\ell$

- On-shell-$c\bar{c}$-resonances $\Rightarrow$ cuts in dlepton mass spectrum necessary : $1\mathrm{GeV}^2 < q^2 < 6\mathrm{GeV}^2$ and $14.4\mathrm{GeV}^2 < q^2$ $\Rightarrow$ perturbative contributions dominant

$\frac{d}{d\hat{s}} BR(\bar{B} \to X_s l^+ l^-) \times 10^{-5}$





$\hat{s} = q^2/m_b^2$

- NNLL prediction of $\bar{B} \to X_s \ell^+\ell^-$: dilepton mass spectrum
  Asatryan, Asatrian, Greub, Walker, hep-ph/0204341;
  Ghinculov, Hurth, Isidori, Yao hep-ph/0312128:

$$BR(\bar{B} \to X_s \ell^+\ell^-)_{Cut:\ q^2 \in [1GeV^2, 6GeV^2]} = (1.63 \pm 0.20) \times 10^{-6}$$

$$BR(\bar{B} \to X_s l^+ l^-)_{Cut:\ q^2 > 14.4 GeV^2} = (4.04 \pm 0.78) \times 10^{-7}$$

NNLL QCD corrections $q^2 \in [1GeV^2, 6GeV^2]$

central value: -14%, perturbative error: $13\% \to 6.5\%$

- Further refinements:
  - Completing NNLL QCD corrections:
    Mixing into $\mathcal{O}_9$ (+1%), NNLL matrixelement of $\mathcal{O}_9$ (−4%)
  - NLL QED two-loop corrections to Wilson coefficients
    −1.5% shift for $\alpha_{em}(\mu = m_b)$, −8.5% for $\alpha_{em}(\mu = m_W)$
    Bobeth,Gambino,Gorbahn,Haisch, hep-ph/0312090
  - QED two-loop corrections to matrix elements
    Large collinear logarithm $Log(m_b/m_\ell)$ which survive intregration
    if a restricted part of the dilepton mass spectrum is considered
    +2% effect in the low-q^2 region for muons, for the electrons
    the effect depends on the experimental cut parameters
    Huber,Lunghi,Misiak,Wyler, hep-ph/0512066

- NNLL prediction of $\bar{B} \to X_s \ell^+ \ell^-$: forward-backward-asymmetry (FBA)
  Asatrian, Bieri, Greub, Hovhannisyan, hep-ph/0209006;
  Ghinculov,Hurth,Isidori,Yao, hep-ph/0208088, hep-ph/0312128:

$$A_{\text{FB}} \equiv \frac{1}{\Gamma_{semilep}} \left(\int_0^1 d(\cos\theta) \frac{d^2\Gamma}{dq^2 d\cos\theta} - \int_{-1}^0 d(\cos\theta) \frac{d^2\Gamma}{dq^2 d\cos\theta} \right)$$

(θ angle between ℓ^+ and B momenta in dilepton CMS)

$$A_{FB}(q_0^2) = 0 \quad \text{for} \quad q_0^2 \sim C_7/C_9 \quad q_0^2 = (3.90 \pm 0.25) GeV^2$$

- Again additional subtleties ⇒ additional uncertainties
  - Locally: breakdown of OPE in Λ_{QCD}/m_b in the high-s (q^2) endpoint
    Partonic contribution vanishes in the limit $s \to 1$, while the $1/m_b^2$ corrections in $R(s)$ tend towards a nonzero value.

    Theoretically: s-quark propagator in the correlator of OPE:

    $$S_s(k) = \frac{\not{k} + i \not{D}}{k^2 + 2ik \cdot D - \not{D}\not{D} + i\varepsilon} \; .$$

    Endpoint region of the q^2 spectrum in $\bar{B} \to X_s l^+ l^-$ different from endpoint region of the photon spectrum of $\bar{B} \to X_s \gamma$:
    $q^2 \approx m_b^2 \approx M_B^2 \;\Rightarrow\; k \sim \Lambda, \quad k^2 \sim \Lambda^2$ ⇒ complete breakdown of OPE
    no partial all-orders resummation possible, shape-function irrelevant
    Buchalla,Isidori

    Practically: for integrated high-s (q^2) spectrum one finds an effective expansion ($s_{\text{min}} \approx 0.6$): Ghinculov,Hurth,Isidori,Yao hep-ph/0312128

    $$\int_{s_{\text{min}}}^{1} ds \; R(s) = \left[1 - \frac{1.6\lambda_2}{m_b^2(1-\sqrt{s_{\text{min}}})^2} + \frac{1.8\rho_1 + 1.7 f_1}{m_b^3(1-\sqrt{s_{\text{min}}})^3}\right] \times \int_{s_{\text{min}}}^{1} ds \;\; R(s)|_{m_b \to \infty}$$

- Hadronic invariant-mass cut is imposed in order to eliminate the background like $b \to c\,(\to se^{+}\nu)e^{-}\bar{\nu} = b \to se^{+}e^{-}$ + missing energy
  - Babar,Belle: $m_X < 1.8$ or $2.0 GeV$
  - high-q^2 region not affected by this cut
  - kinematics: X_s is jetlike and $m_X^2 \leq m_b \Lambda_{QCD}$ ⇒ shape function region
  - SCET analysis: universality of jet and shape functions found:

    the 10-30% reduction of the dilepton mass spectrum can be accurately computed using the $\bar{B} \to X_s \gamma$ shape function

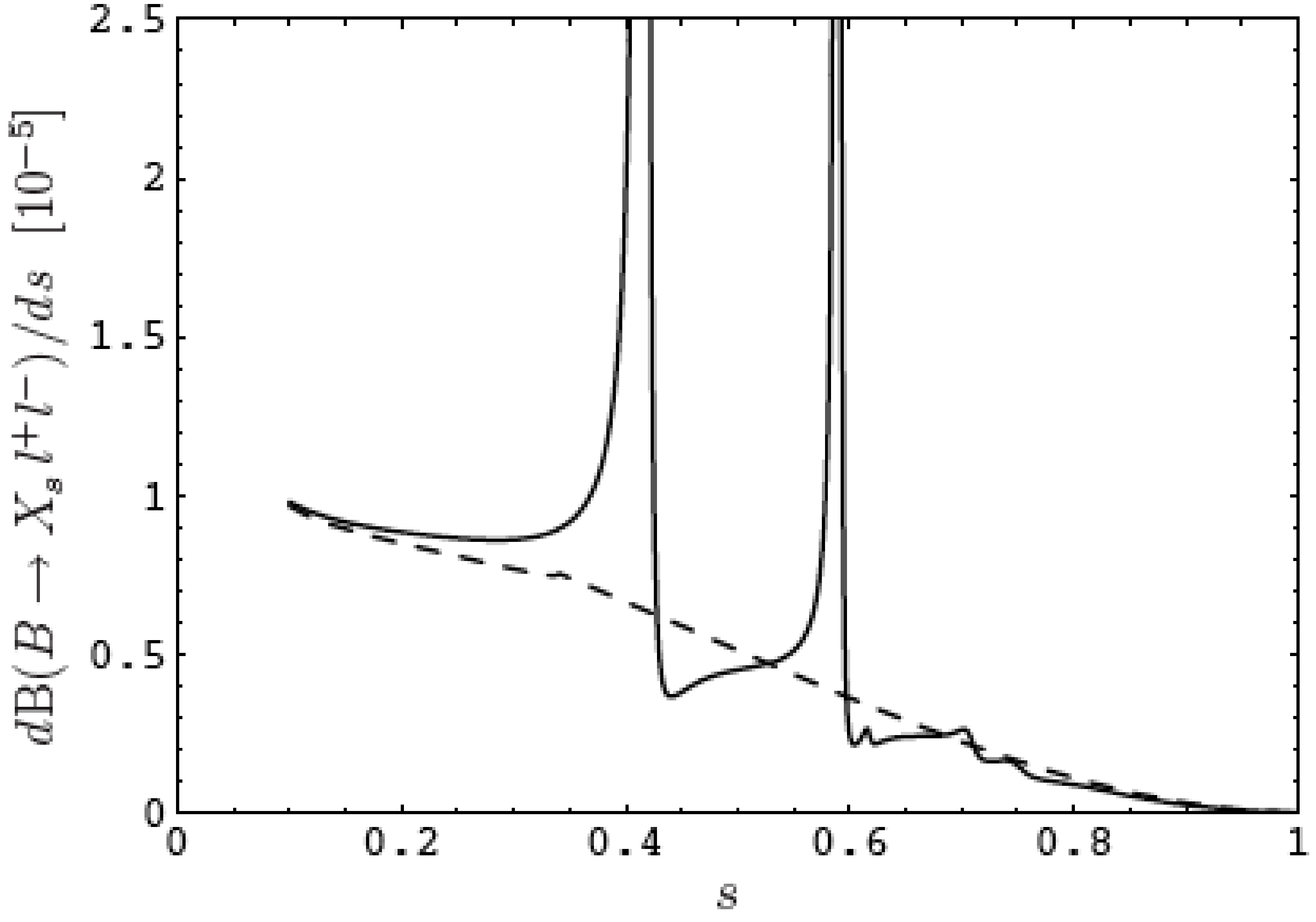
    5% additional uncertainty for $2.0 GeV$ cut due to subleading shape functions

    Lee,Stewart hep-ph/0511334
    Lee,Ligeti,Stewart,Tackmann hep-ph/0512191
    Lee,Tackmann arXiv:0812.0001 (effect of subleading shape functions)
    Bell,Beneke,Huber,Li arXiv:1007.3758 (NNLO matching QCD → SCET)

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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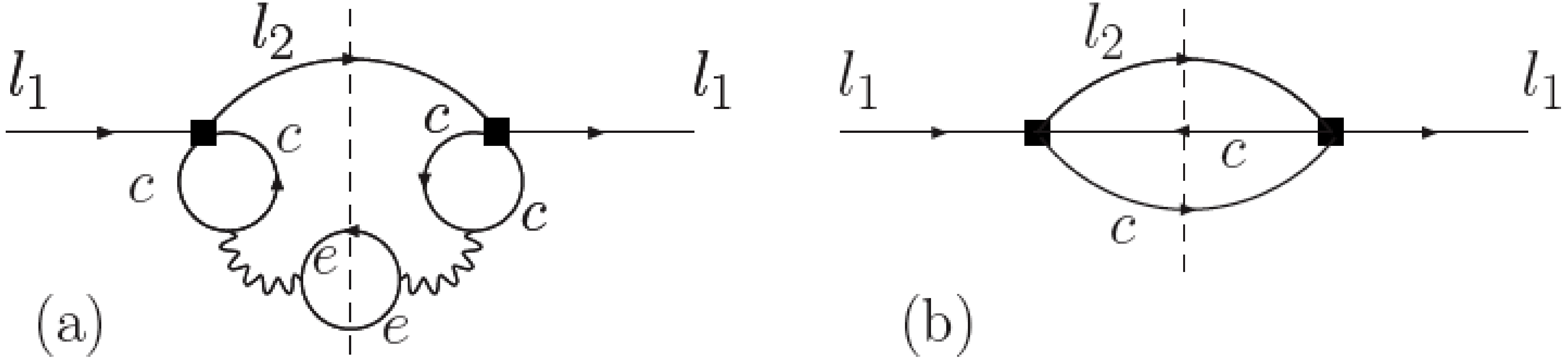

The rate $l_1 \to l_2 e^+ e^-$ (a) is connected to the integral over $|\Pi(q^2)|^2$ for which global duality is NOT expected to hold.

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