An introduction to Quark Flavour Physics

Part 4

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Warwick Week 2019

An introduction to Flavour Physics

- What's covered in these lectures:

1. An introduction to flavour in the SM.
2. CP violation (part 1).
3. CP violation (part 2).
4. **Flavour changing neutral current processes.**
   - ➡ **Neutral meson mixing, rare decays, lepton flavour violation and constraints on new particles.**

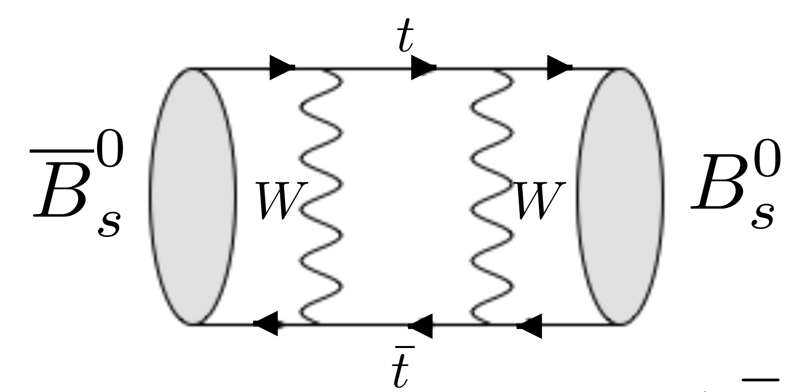
The “flavour problem”

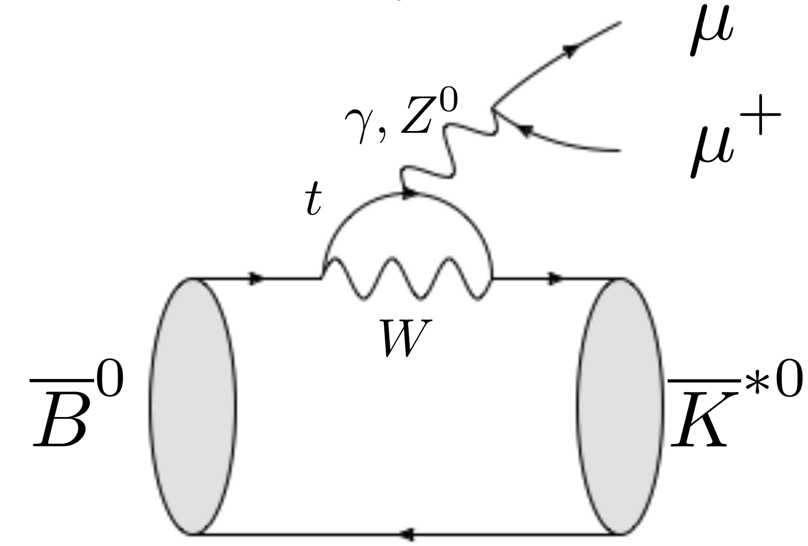
- Flavour changing neutral current processes can probe mass scales well beyond those accessible at LHC.
  - ➡ If there are new particles at the TeV-scale, why don’t they manifest themselves in FCNC processes?

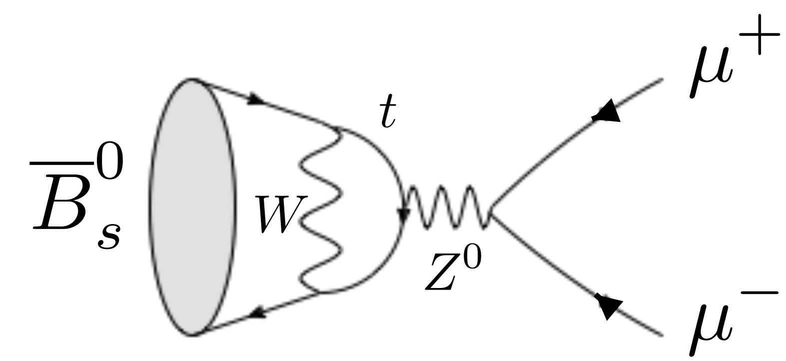
    This is often referred to as the **flavour problem**.

FCNC processes

- Two types of FCNC process:
  - ➡ ΔF = 2, meson anti-meson mixing.
  - ➡ ΔF = 1, *e.g.* $B_s \rightarrow \boldsymbol{\mu}^+ \boldsymbol{\mu}^-$.
    (commonly described as rare decays).
- In the SM these processes are suppressed:
  - ➡ Loop processes that are CKM suppressed and can (depending on the process) be highly GIM suppressed.







Effective theories

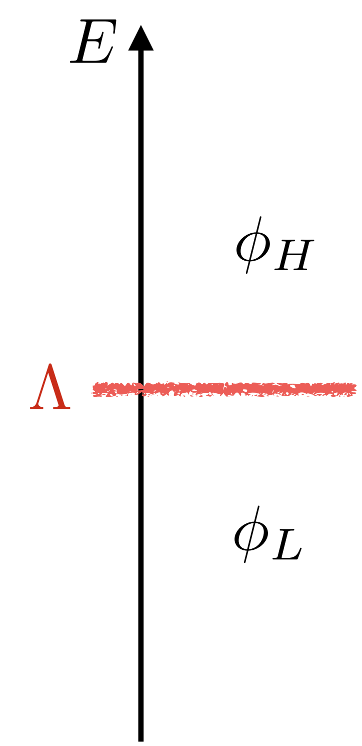
Probing scale of NP with FCNC processes

Effective theories

- In mesons/baryon decays there is a clear separation of scales:

$$m_W \gg m_b > \Lambda_{\rm QCD}$$

- We want to study the physics of the mixing/decay at or below a scale Λ, in a theory in which contributions from particles at a scale below and above Λ are present. Replace the full theory with an effective theory valid at Λ,

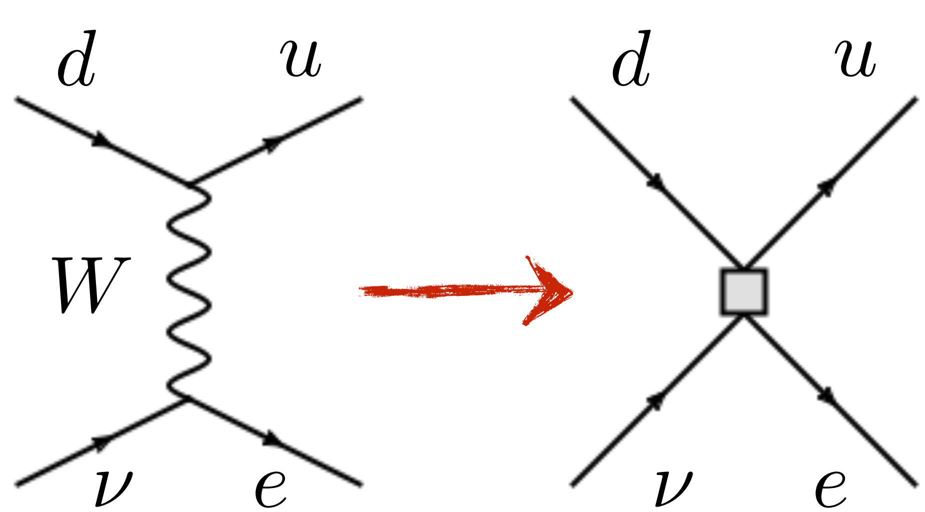


$$\mathcal{L}(\phi_{\rm L},\phi_{\rm H}) \to \mathcal{L}(\phi_{\rm L}) + \mathcal{L}_{\rm eff} = \mathcal{L}(\phi_{\rm L}) + \sum_i C_i \mathcal{O}_i(\phi_{\rm L})$$

operator product expansion

Fermi's theory

- In the Fermi model of the weak interaction, the full electroweak Lagrangian (which was unknown at the time) is replaced by the low-energy theory (QED) plus a single operator with an effective coupling constant.



At low energies:

$$\lim_{q^2 \to 0} \left(\frac{g^2}{m_W^2 - q^2} \right) = \frac{g^2}{m_W^2}$$

i.e. the full theory can be replaced by a 4-fermion operator and a coupling constant, G_F.

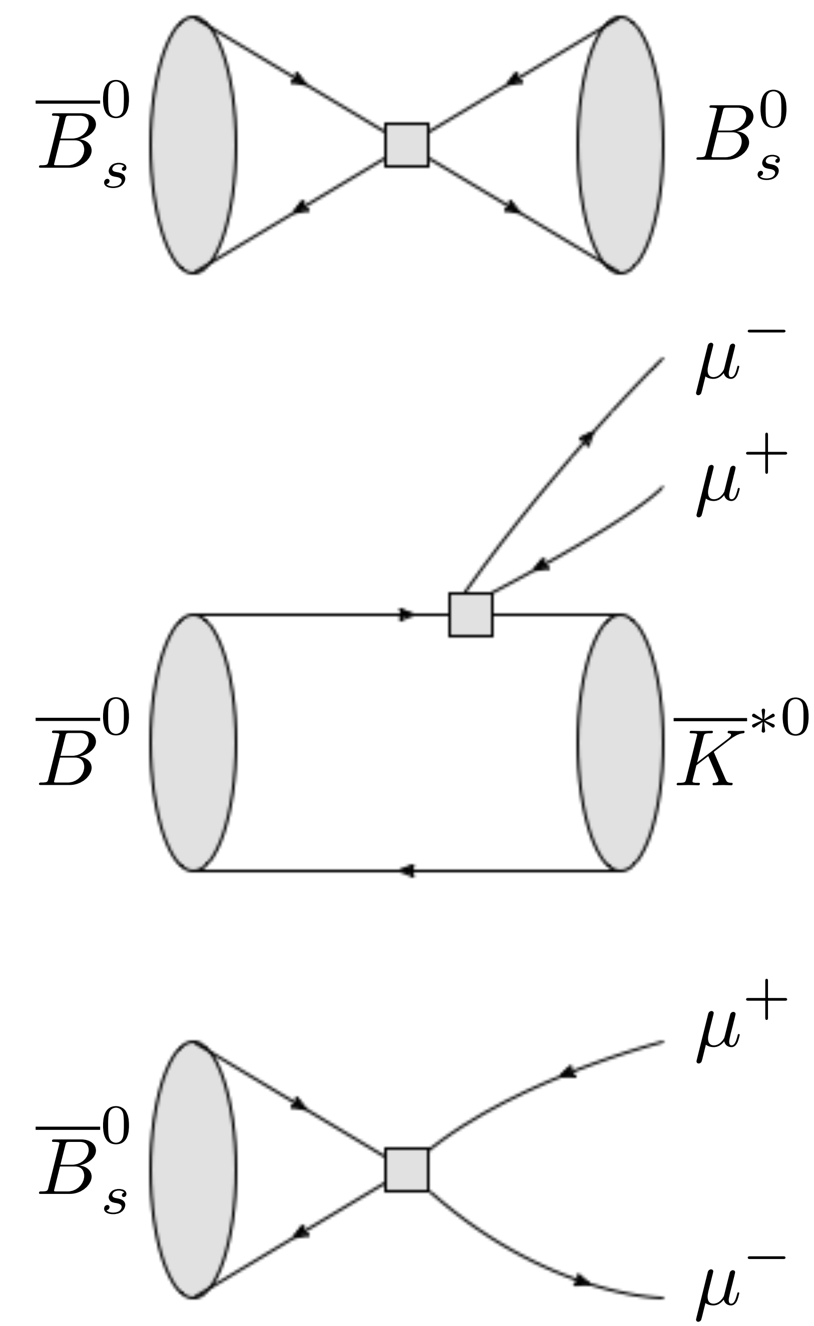
Simplifies Lagrangian

$$\mathcal{L}_{\mathrm{EW}} \to \mathcal{L}_{\mathrm{QED}} + \frac{G_{\mathrm{F}}}{\sqrt{2}} (\overline{u}d)(e\overline{\nu})$$

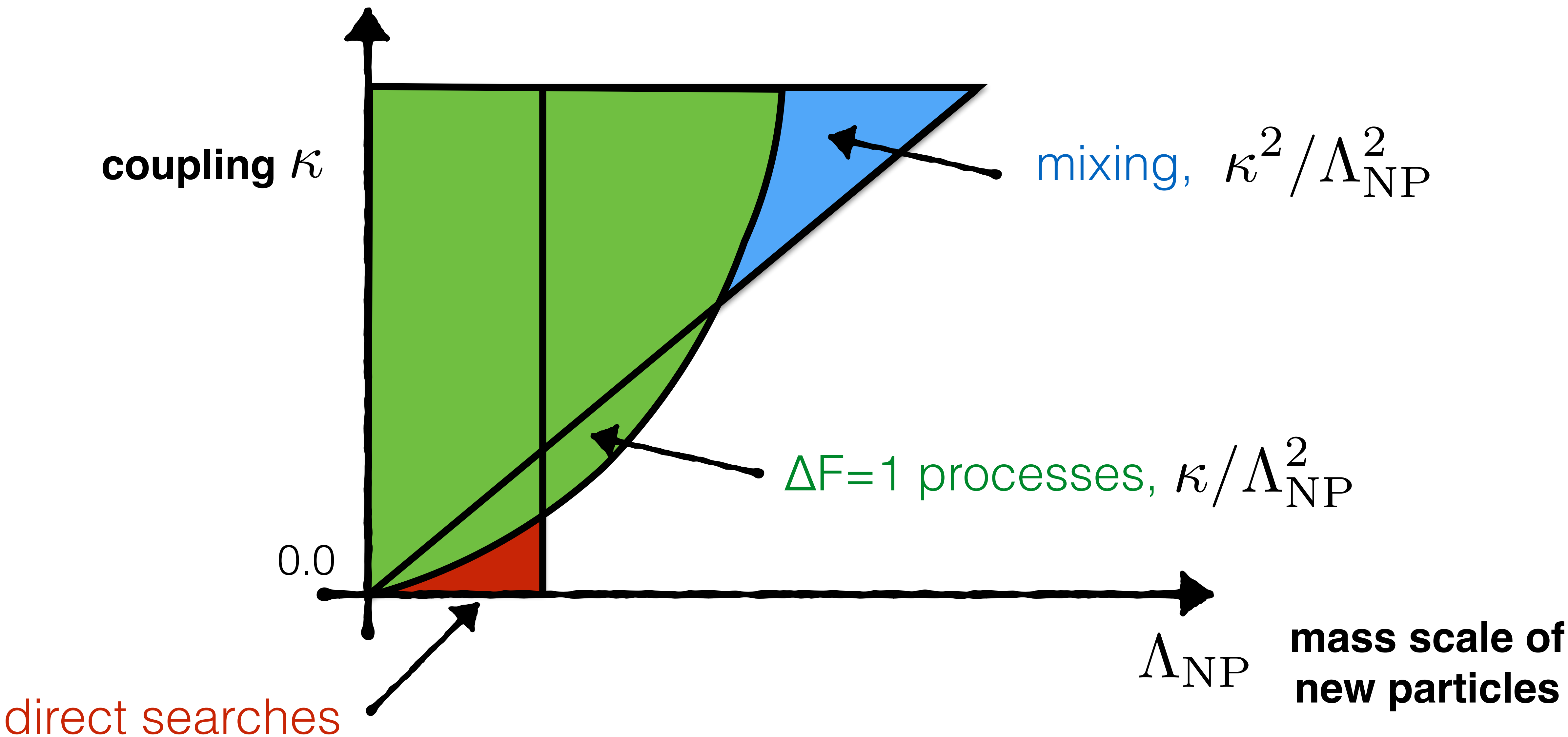
FCNC processes

- Two types of FCNC process:
  - ➡ $\Delta F = 2$, meson anti-meson mixing.
  - ➡ $\Delta F = 1$, e.g. $B_s \to \mu^+\mu^-$. Commonly described as rare decays.
- In the SM these processes are suppressed:
  - ➡ Loop processes which are CKM suppressed and can be highly GIM suppressed.

In an effective theory



FCNC constraints



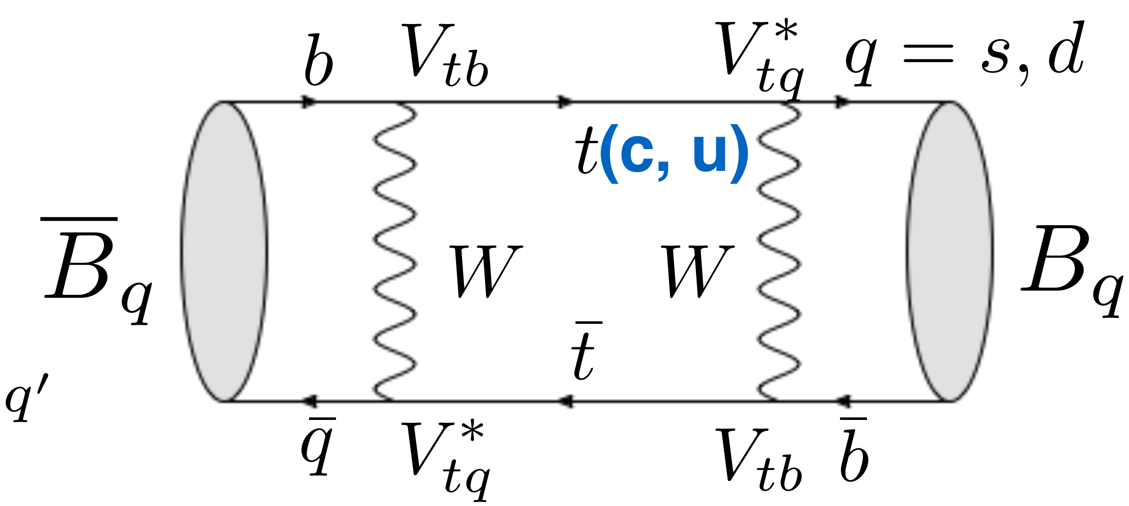
(in reality this won't be completely independent of κ, you need some coupling to SM particles to produce particles in *pp* collisions).

$\Delta F = 2$ proceses

NP in B mixing

GIM mechanism

- Take mixing diagram as an example, have an amplitude



$$\mathcal{A}(B^0 \to \overline{B}^0) = \sum_{q,q'} (V_{qb}^* V_{qd})(V_{q'b}^* V_{qd}) A_{qq'}$$

summing over the internal up-type quarks

Can then plug-in $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb} * V_{td} = 0$

$$\mathcal{A}(B^0 \to \overline{B}^0) = \sum_{q} (V_{qb}^* V_{qd})[V_{tb}^* V_{td}(A_{tq} - A_{uq}) + V_{cb}^* V_{cd}(A_{cq} - A_{uq})]$$

for the *B* system the top dominates $\propto m_q m_{q'} / m_W^2$

New physics in *B* mixing?

- Introducing new physics with at some higher energy scale $\Lambda_{\rm NP}$ with coupling $\kappa_{\rm NP}$

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{\kappa_{\rm NP}^2}{\Lambda_{\rm NP}^{d-4}} \mathcal{O}_i^{(d)}$$

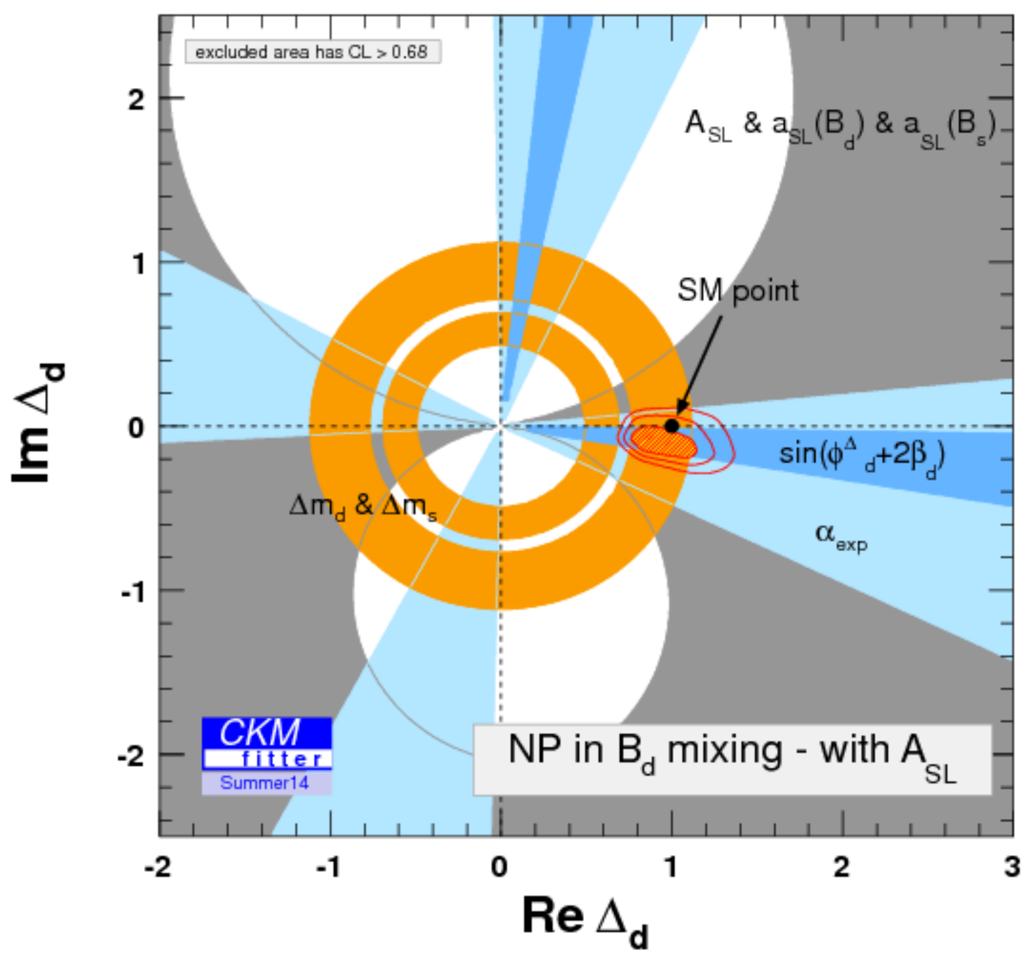
$$(V_{tb}^* V_{td})^2 \frac{g^4 m_t^2}{16\pi^2 m_W^4} \quad \text{c.f.} \quad \frac{\kappa_{\rm NP}^2}{\Lambda_{\rm NP}^2}$$

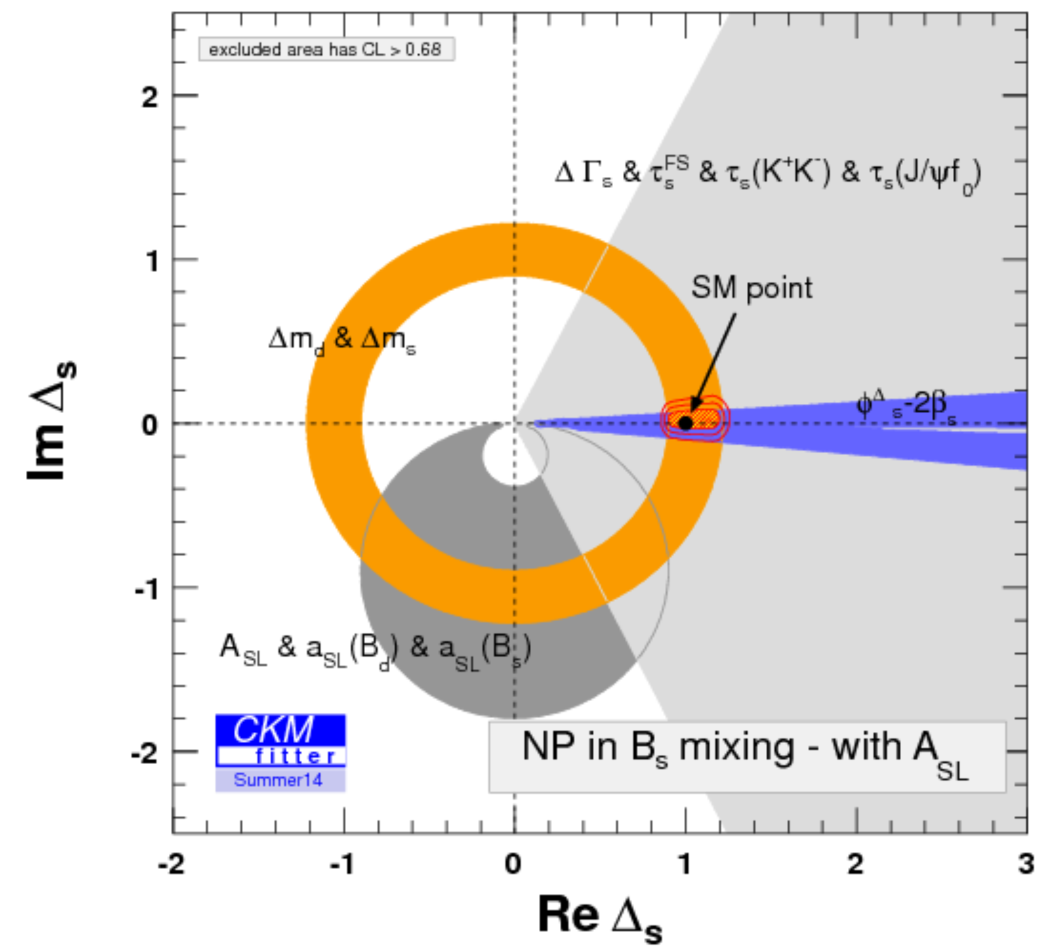
SM contribution
from box diagram

NP contribution
(at dimension 6)

New physics in B mixing?

- Introduce a multiplicative factor $M_{12} = M_{12,\mathrm{SM}} \cdot \Delta_{s,d}$





Result is consistent with SM, i.e. Re Δ =1, Im Δ = 0

Mixing constraints

- Everything is consistent with the SM, so instead can set constraints on NP scale from mixing.

Operator	$\mathrm{Re}(\Lambda)$	$\mathrm{Im}(\Lambda)$	$\mathrm{Re}(c)$	$\mathrm{Im}(c)$	Constraint
$(\bar{s}_L\gamma^\mu d_L)(\bar{s}_L\gamma_\mu d_L)$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K,\ \varepsilon_K$
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K,\ \varepsilon_K$
$(\bar{c}_L\gamma^\mu u_L)(\bar{c}_L\gamma_\mu u_L)$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D,\ \lvert q/p\rvert,\ \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D,\ \lvert q/p\rvert,\ \phi_D$
$(\bar{b}_L\gamma^\mu d_L)(\bar{b}_L\gamma_\mu d_L)$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_d,\ S_{J/\psi K^0_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_d,\ S_{J/\psi K^0_S}$
$(\bar{b}_L\gamma^\mu s_L)(\bar{b}_L\gamma_\mu s_L)$	1.1×10^2	1.3×10^2	7.6×10^{-6}	7.6×10^{-6}	Δm_s
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2	3.7×10^2	1.3×10^{-5}	1.3×10^{-5}	Δm_s

Λ_{NP} in TeV when coupling =1

coupling ($c = \kappa$) when Λ_{NP} = 1TeV

Small couplings?

- New flavour violating sources (if there are any) are highly tuned, i.e. must come with a small coupling constant or must have a very large mass. For O(1) effect:

generic tree-level

$$\kappa_{\rm NP} \sim 1 \longrightarrow \Lambda_{\rm NP} \gtrsim 2\times 10^4\,{\rm TeV}$$

generic loop-order

$$\sim \frac{1}{(4\pi)^2} \longrightarrow \Lambda_{\rm NP} \gtrsim 2\times 10^3\,{\rm TeV}$$

tree-level with “alignment”

$$\sim (y_t V_{ti}^* V_{tj})^2 \longrightarrow \Lambda_{\rm NP} \gtrsim 5\,{\rm TeV}$$

loop-order with “alignment”

$$\sim \frac{(y_t V_{ti}^* V_{tj}^*)^2}{(4\pi)^2} \longrightarrow \Lambda_{\rm NP} \gtrsim 0.5\,{\rm TeV}$$

Minimal Flavour Violation

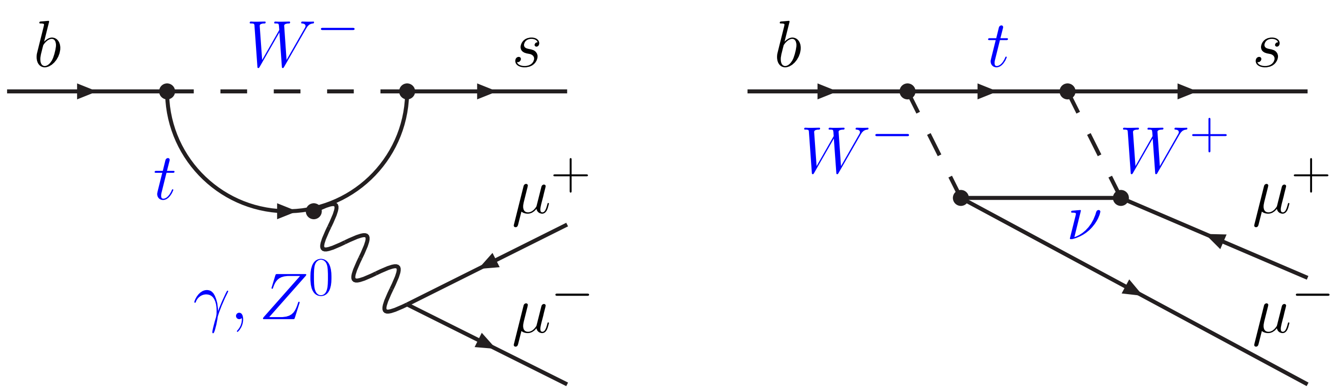
- One good way to achieve small couplings is to build models that have a flavour structure that is aligned to the CKM.
  - ➡ Require that the Yukawa couplings are also the unique source of flavour breaking beyond the SM.
- This is referred to as **minimal flavour violation**.
- The couplings to new particles are naturally suppressed by the Hierarchy of the CKM elements.

$\Delta F = 1$ proceses

Rare B hadron decays

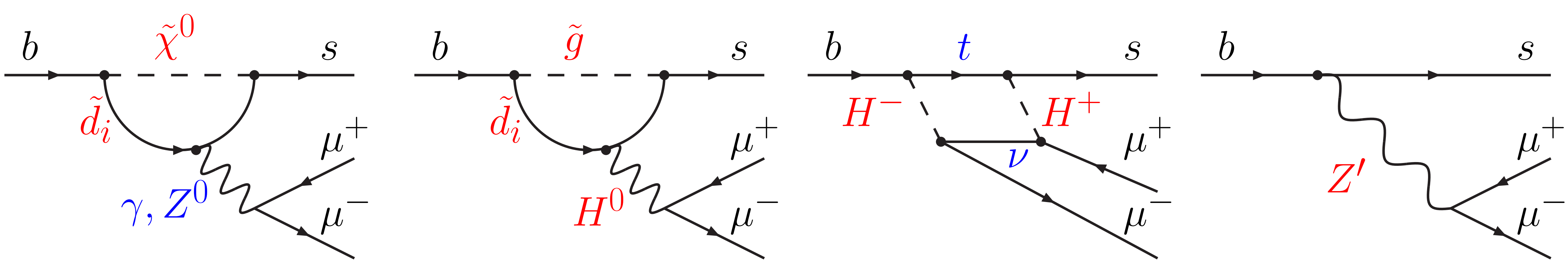
ΔF = 1 FCNC decays

- Flavour changing neutral current transitions only occur at loop order (and beyond) in the SM.



SM diagrams involve the charged current interaction.

- New particles can also contribute:

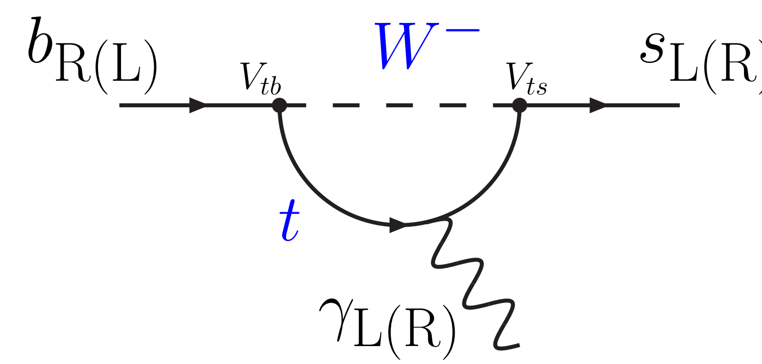


Enhancing/suppressing decay rates, introducing new sources of *CP* violation or modifying the angular distribution of the final-state particles.

Properties of ΔF = 1 processes

Large number of other observables that can be considered

- In the SM, photons from $b \to s\gamma$ decays are predominantly left-handed ($C_7/C'_7 \sim m_b/m_s$) due to the charged-current interaction.



- Flavour structure of SM implies that the rate of $b \to d$ processes is suppressed by $|V_{td}/V_{ts}|^2$ compared to $b \to s$ processes.
- In the SM, the rate $\Gamma[B \to M\mu^+\mu^-] \approx \Gamma[B \to Me^+e^-]$ due to the universal coupling of the gauge bosons (except the Higgs) to the different lepton flavours. Any differences in the rate are due to phase-space.
- Lepton flavour violation is unobservable in the SM at any conceivable experiment due to the small size of the neutrino mass.

Rare $b \to s$ decays

- Can write a Hamiltonian for the effective theory as

$$\mathcal{H}_{\text{eff}} = -\frac{4\boxed{G_F}}{\sqrt{2}}\boxed{V_{tb}V_{ts}^*}\frac{\alpha_e}{\boxed{4\pi}}\sum_i C_i(\mu)\mathcal{O}_i(\mu)\,,$$

Weak decay
$(1/m_W)^2$

CKM suppression

Loop suppression
$(1/4\pi)^2$

- Conventional to pull SM loop contributions out the front as constants.

Rare $b \to s$ decays

- Can write a Hamiltonian for the effective theory as

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \frac{\alpha_e}{4\pi} \sum_i C_i(\mu) \mathcal{O}_i(\mu)\,,$$

Wilson coefficient
(integrating out
scales above μ)

Local operator with
different Lorentz structure
(vector, axial vector current etc)

Beyond the SM

- In the same way can introduce new particles that give rise to corrections

$$\Delta\mathcal{H}_{\rm eff} = \frac{\kappa_{\rm NP}}{\underline{\Lambda^2_{\rm NP}}} \boxed{\mathcal{O}_{\rm NP}}$$

NP scale

local operator

- Once again, the constant, κ, can share some, all or none of the suppression of the SM process.

Operators

photon penguin

right handed currents
(suppressed in SM)

$$\boxed{\mathcal{O}_7} = \frac{m_b}{e}\bar{s}\sigma^{\mu\nu}P_R b F_{\mu\nu}\,, \qquad \mathcal{O}_7' = \frac{m_b}{e}\bar{s}\sigma^{\mu\nu}P_L b F_{\mu\nu}\,,$$

$$\mathcal{O}_8 = g_s\frac{m_b}{e^2}\bar{s}\sigma^{\mu\nu}P_R T^a b G^a_{\mu\nu}\,, \qquad \mathcal{O}_8' = g_s\frac{m_b}{e^2}\bar{s}\sigma^{\mu\nu}P_L T^a b G^a_{\mu\nu}\,,$$

vector
current

$$\boxed{\mathcal{O}_9} = \bar{s}\gamma_\mu P_L b\,\bar{\ell}\gamma^\mu\ell\,, \qquad \mathcal{O}_9' = \bar{s}\gamma_\mu P_R b\,\bar{\ell}\gamma^\mu\ell\,,$$

$$\boxed{\mathcal{O}_{10}} = \bar{s}\gamma_\mu P_L b\,\bar{\ell}\gamma^\mu\gamma_5\ell\,, \qquad \mathcal{O}_{10}' = \bar{s}\gamma_\mu P_R b\,\bar{\ell}\gamma^\mu\gamma_5\ell\,.$$

axialvector
current

Operators (beyond SM)

- Scalar and pseudo-scalar operators (e.g. from Higgs penguins)

$$\mathcal{O}_{\rm S} = \bar{s} P_R b\, \bar{\ell}\ell\,, \qquad \mathcal{O}'_{\rm S} = \bar{s} P_L b\, \bar{\ell}\ell\,,$$

$$\mathcal{O}_{\rm P} = \bar{s} P_R b\, \bar{\ell}\gamma_5\ell\,, \qquad \mathcal{O}'_{\rm P} = \bar{s} P_L b\, \bar{\ell}\gamma_5\ell$$

- Tensor operators

$$\mathcal{O}_{\rm T} = \bar{s}\sigma_{\mu\nu} b\, \bar{\ell}\sigma^{\mu\nu}\ell\,, \qquad \mathcal{O}_{\rm T5} = \bar{s}\sigma_{\mu\nu} b\, \bar{\ell}\sigma^{\mu\nu}\gamma_5\ell\,,$$

- All of these are vanishingly small in SM.
- In principle could also introduce LFV versions of every operator.

Generic ΔF = 1 process

- In the effective theory, we then have

$$\mathcal{A}(B \to f) = V_{tb}^* V_{tq} \sum_i C_i(M_W) U(\mu, M_W) \langle f | \mathcal{O}_i(\mu) | B \rangle$$

Hadronic matrix element

- For inclusive processes can relate sum over exclusive states to calculable quark level decays,

$$\mathcal{B}(B \to X_s \gamma) = \mathcal{B}(b \to s\gamma) + \mathcal{O}(\Lambda^2_{QCD}/m^2_B)$$

- For exclusive processes, need to compute form-factors / decay constants etc.

Theoretical Framework

- In leptonic decays the matrix element for the decay can be factorised into a leptonic current and *B* meson decay constant:

$$
\begin{aligned}
\langle \ell^+\ell^- | j_\ell \, j_q | B_q \rangle &= \langle \ell^+\ell^- | j_\ell | 0 \rangle \langle 0 | j_q | B_q \rangle \\
&\approx \langle \ell^+\ell^- | j_q | 0 \rangle \cdot f_{B_q}
\end{aligned}
$$

- In semileptonic decays, the matrix element can be factorised into a leptonic current times a form-factor:

$$
\begin{aligned}
\langle \ell^+\ell^- M | j_\ell \, j_q | B \rangle &= \langle \ell^+\ell^- | j_\ell | 0 \rangle \langle M | j_q | B_q \rangle \\
&\approx \langle \ell^+\ell^- | j_\ell | 0 \rangle \cdot F(q^2) + \mathcal{O}(\Lambda_{\mathrm{QCD}}/m_B)
\end{aligned}
$$

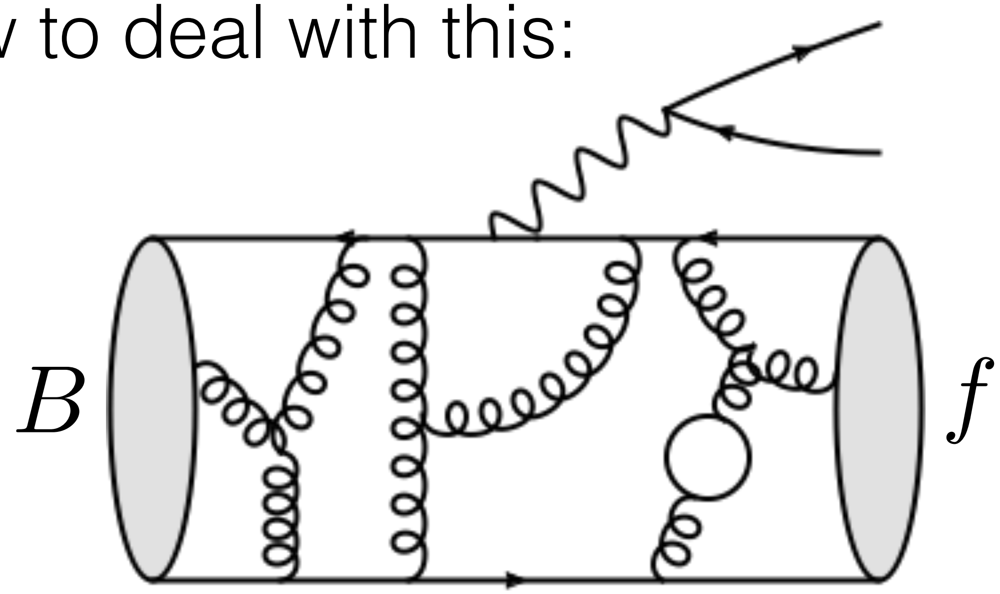
however this factorisation is not exact (due to hadronic contributions).

Form factors

- Unfortunately, we don't just have free quarks and we need to compute hadronic matrix elements (form-factors and decay constants).

  ➡ Non-perturbative regime of QCD, i.e. difficult to estimate.

e.g
how to deal with this:



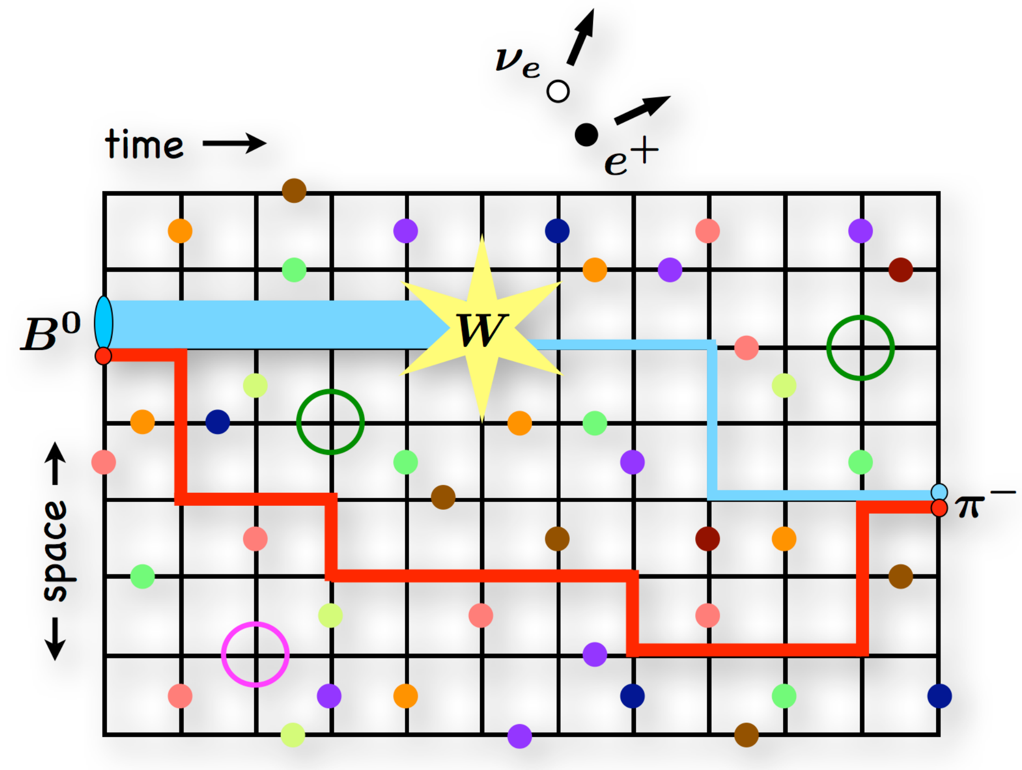
Fortunately we have tools to help us in different kinematic regimes.

Theoretical tools (crib sheet)

- Lattice QCD
  - ➡ Non-perturbative approach to QCD using discretised system of points in space and time. As the lattice becomes infinitely large and the points infinitely close together the continuum of QCD is reached.
- Light-Cone-Sum-Rules
  - ➡ Exploit parton-hadron duality to compute form-factors and decay constants.
- Operator product expansions.
  - ➡ Used to match physics to relevant scales.

Lattice QCD

- QCD lagrangian has massless gluon fields sand almost massless quarks.
- Strong coupling → non-perturbative.
- Lattice QCD is a numerical approach to non-perturbative calculations.
- Perform path integral in Euclidean space on the lattice (space-time grid) using MCMC.
- Correlation lengths → masses.
- Amplitudes → matrix elements.



Theoretical tools (crib sheet)

- Heavy quark expansion.
  - ➡ Exploit the heaviness of the b-quark, $m_b \gg \Lambda_{QCD}$
- QCD factorisation.
  - ➡ Light quark has large energy in the meson decay frame, e.g. quarks in π have large energy in $B \to \pi$ decays in the B rest frame.
- Soft Collinear Effective Theory.
  - ➡ Model system as highly energetic quarks interacting with soft and collinear gluons.
- Chiral perturbation theory.

Which processes?

- Will mainly focus on recent measurements of *B* decay processes, $b \to s$ transitions are some of the least well tested.
- You can also study FCNC decays of charm and strange mesons.
- The GIM mechanism is more effective in both charm and strange meson decays:
  - ➡ For charm mesons the masses and mass differences, e.g. (m_b - m_s), are small.
  - ➡ For strange mesons top contribution is suppressed relative to *B* meson decays because $V_{ts} \ll V_{tb}$.

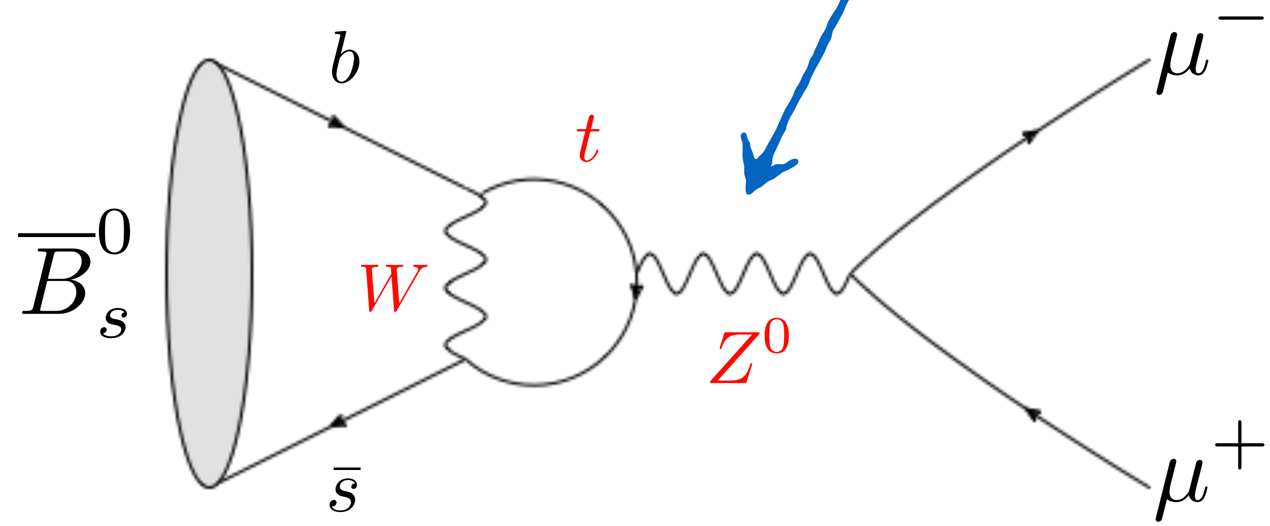
$\Delta F = 1$ proceses

Experimental results

$B_s \rightarrow \mu^+ \mu^-$

- Golden channel to study FCNC decays.
- Highly suppressed in SM.
    1. Loop suppressed.
    2. CKM suppressed
       (at least one off diagonal element)
    3. Helicity suppressed
       (pseudo-scalar B to
       two spin-½ muons)

neutral current
(axial-vector)



also receives contributions from W box diagrams

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

- Golden channel to study FCNC decays.
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  1. Loop suppressed.
  2. CKM suppressed
     (at least one off diagonal element)
  3. Helicity suppressed
     (pseudo-scalar B to
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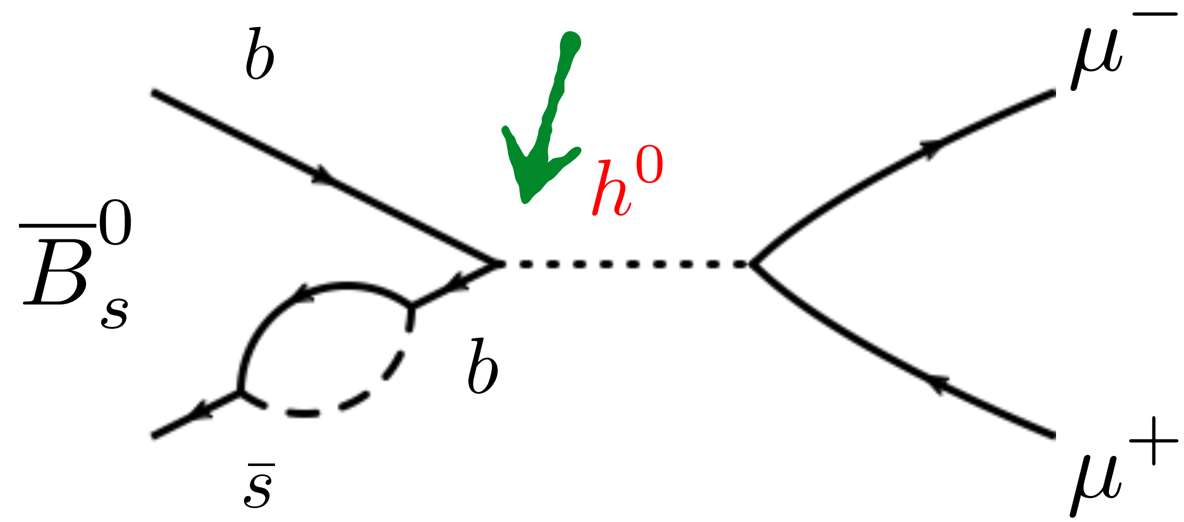
Interesting probe of models with new or enhanced scalar operators (no helicity suppression), e.g. SUSY at high tan β.



$B_s \to \mu^+\mu^-$ in the SM

- Only one operator contributes in SM:

$$\mathcal{O}_{10} = (\bar{s}_{\rm L}\gamma_\mu b_{\rm L})(\bar{\mu}\gamma^\mu\gamma_5\mu)$$

- Branching fraction in SM:

Single hadronic matrix element (decay constant)
$\langle 0|\bar{s}\gamma^\mu\gamma_5 b|B\rangle = i f_B p^\mu$

CKM factors

$$\overline{\mathcal{B}}(B^0_{d,s}\to\mu^+\mu^-) \approx \frac{\left|V^*_{tb}V_{tq}\right|^2 G_F^2\,\alpha_e^2\,M_B M_\mu^2 f_B^2}{16\pi^3\Gamma_{\rm H}}\sqrt{1-\frac{4M_\mu^2}{M_B^2}}\,|C_{10}(m_b)|^2$$

helicity suppression

$$\times\left(\frac{M_\mu^2}{M_B^2}\right)$$

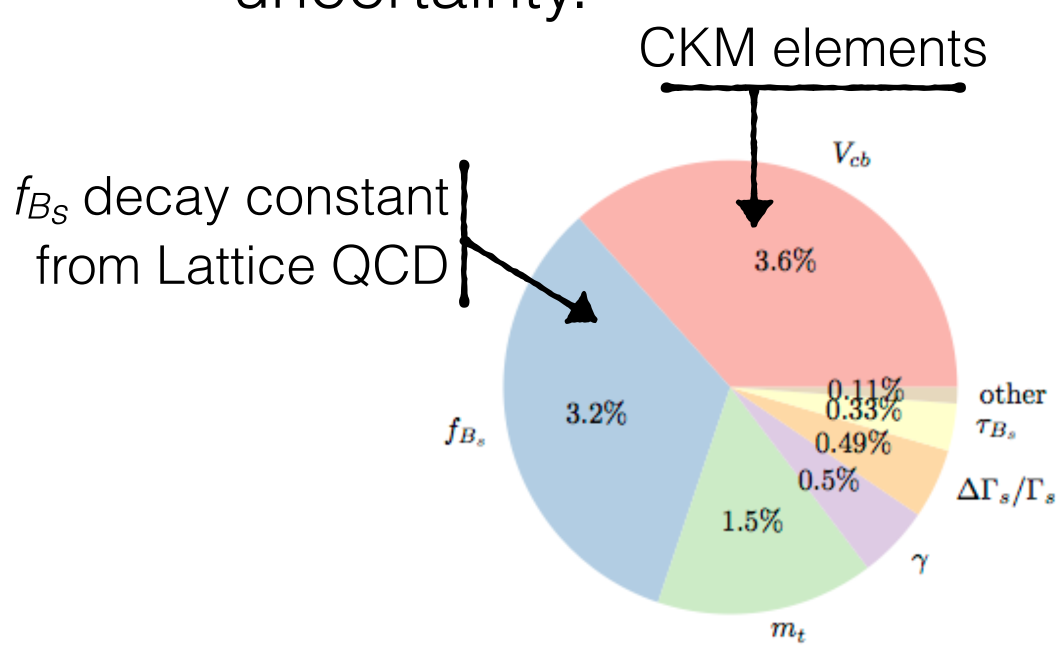
Rare leptonic decays

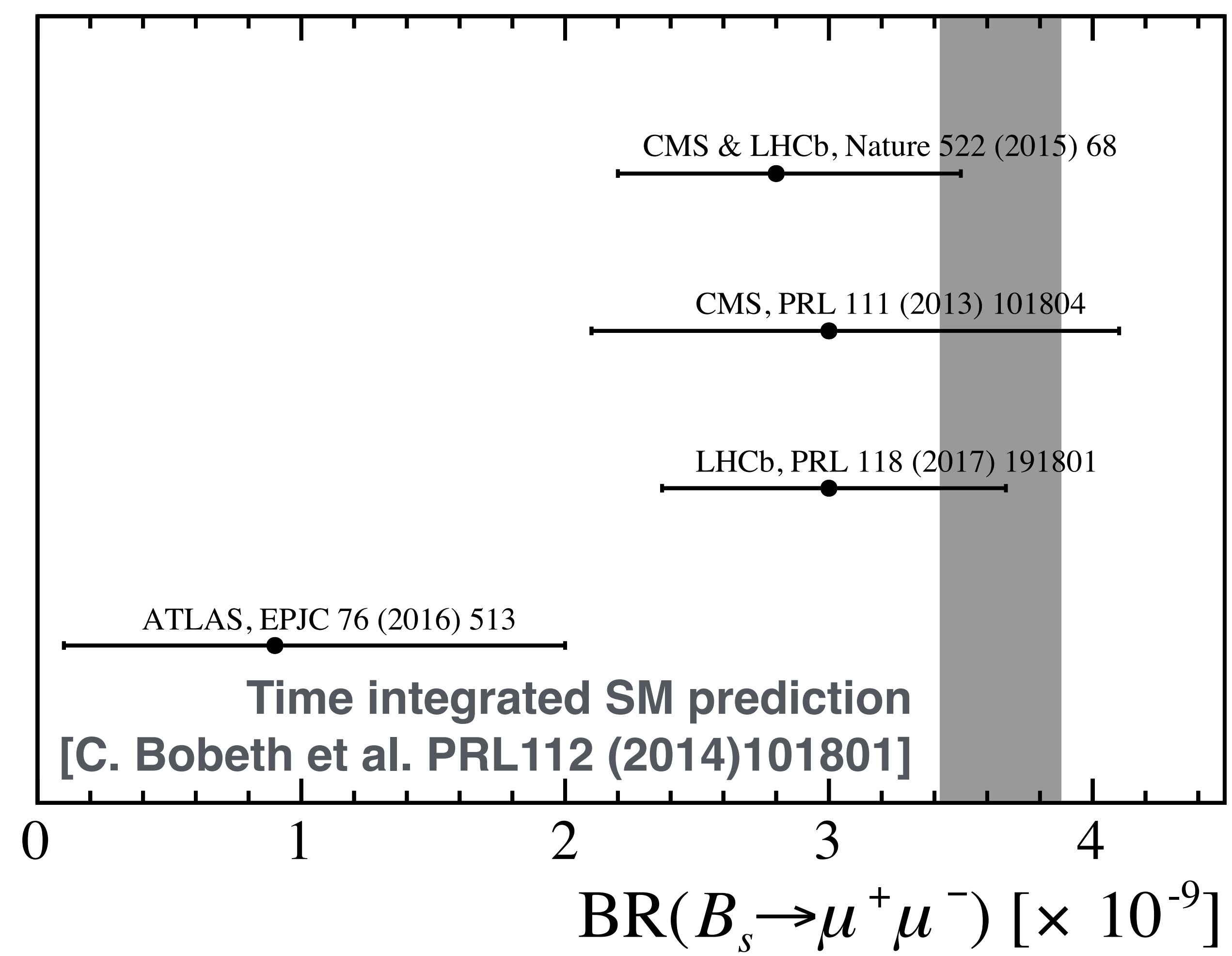
- Beyond the SM:

$$\frac{\mathcal{B}(B_q \to \ell^+\ell^-)_{\rm NP}}{\mathcal{B}(B_q \to \ell^+\ell^-)_{\rm SM}} = \frac{1}{|C_{10}^{\rm SM}|^2} \left\{ \left(1 - 4\frac{m_\ell^2}{m_{B_q}}\right) \left| \frac{m_{B_q}}{2m_\ell} (C_S - C_S') \right|^2 + \left| \frac{m_{B_q}}{2m_\ell} (C_P - C_P') + (C_{10} - C_{10}') \right|^2 \right\}$$

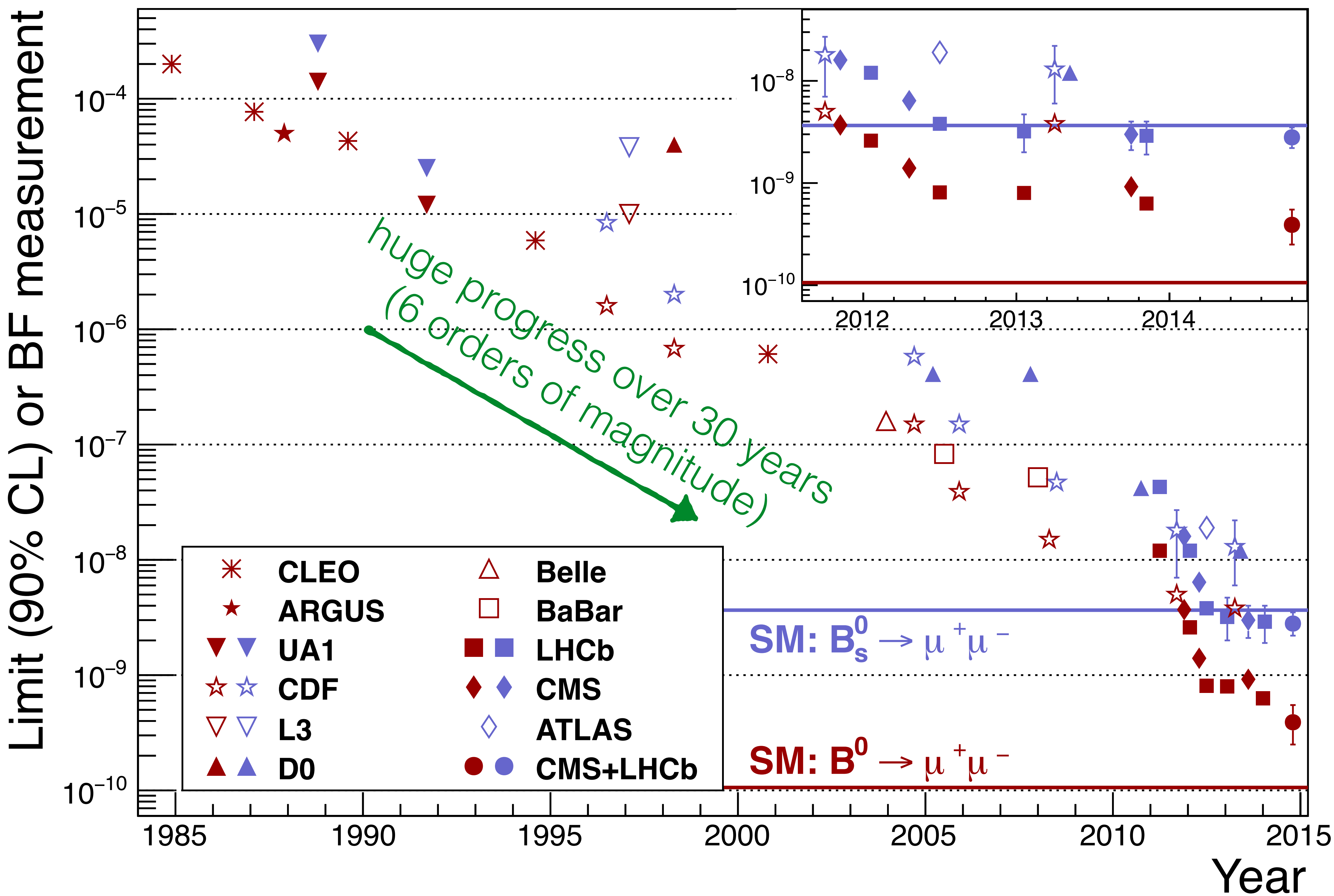
$B_s \to \mu^+\mu^-$

- Recent LHCb analysis using Run 1 and 2 data (3fb^{-1} +1.4fb^{-1}) provides the first single experiment observation of the $B_s \to \mu^+\mu^-$ decay at more than 7σ **[LHCb, PRL 118 (2017) 191801]**.
- Measurements are all consistent with the SM expectation.
  - ➡ Can exclude large scalar contributions.
- Branching fraction predicted precisely in the SM with a ~6% uncertainty.



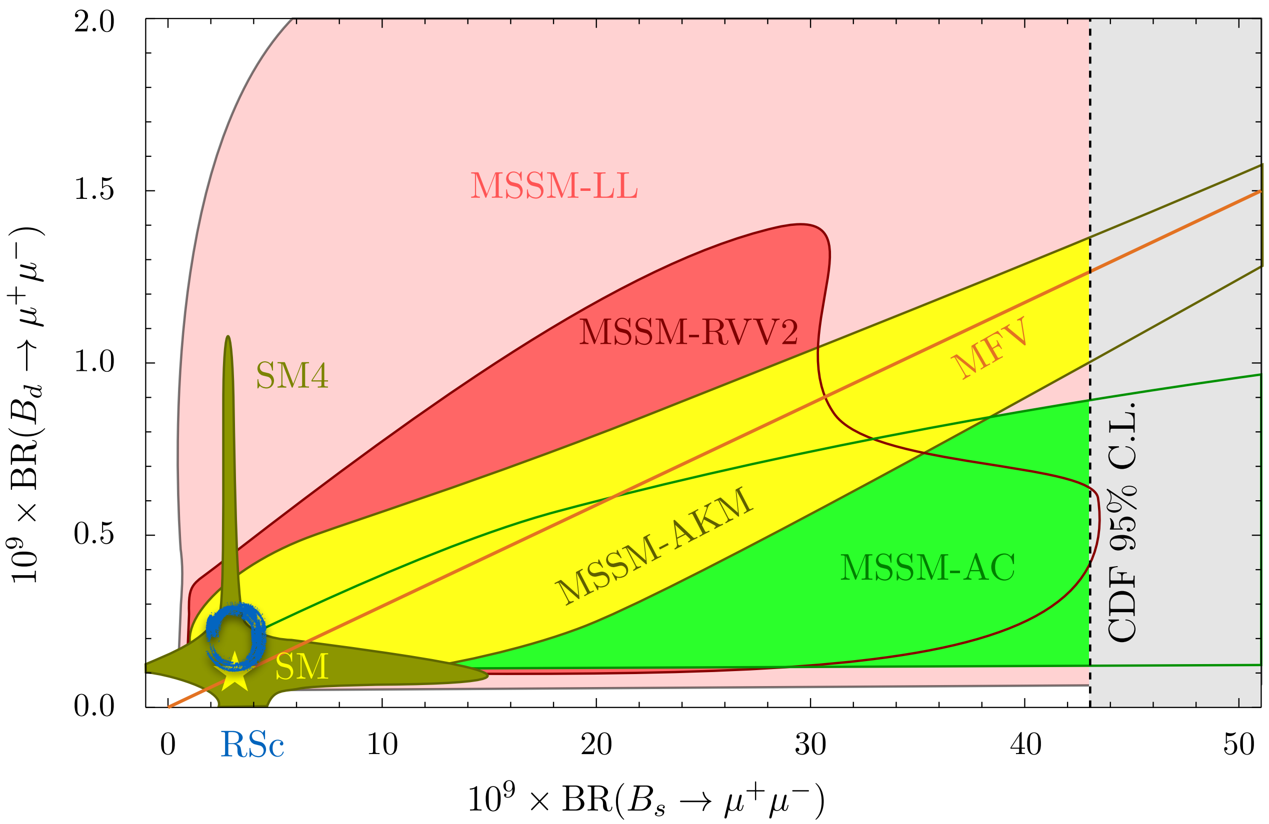


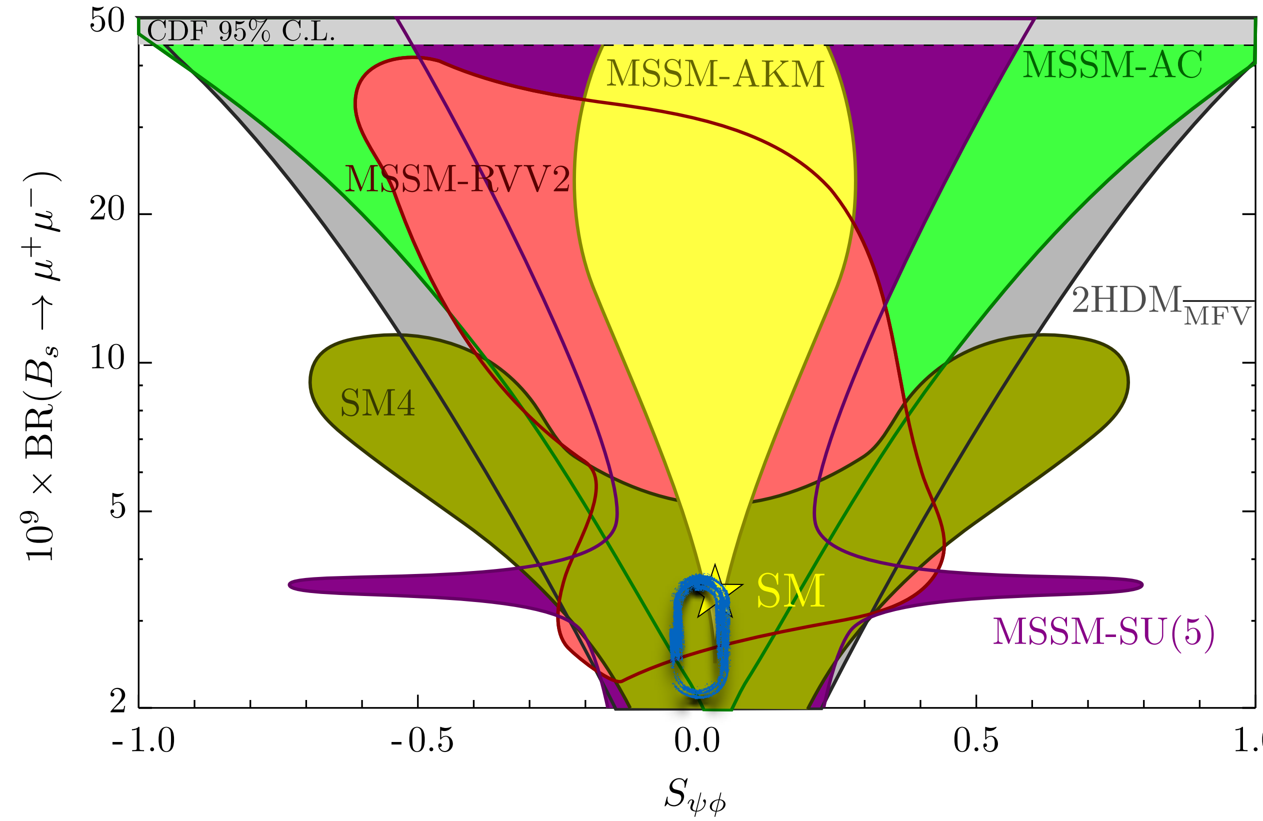
Observation is the end of a long road …



Flavour constraints

[Straub, arXiv:1107.0266]





constraints prior to LHC, constraints at the end of Run 1

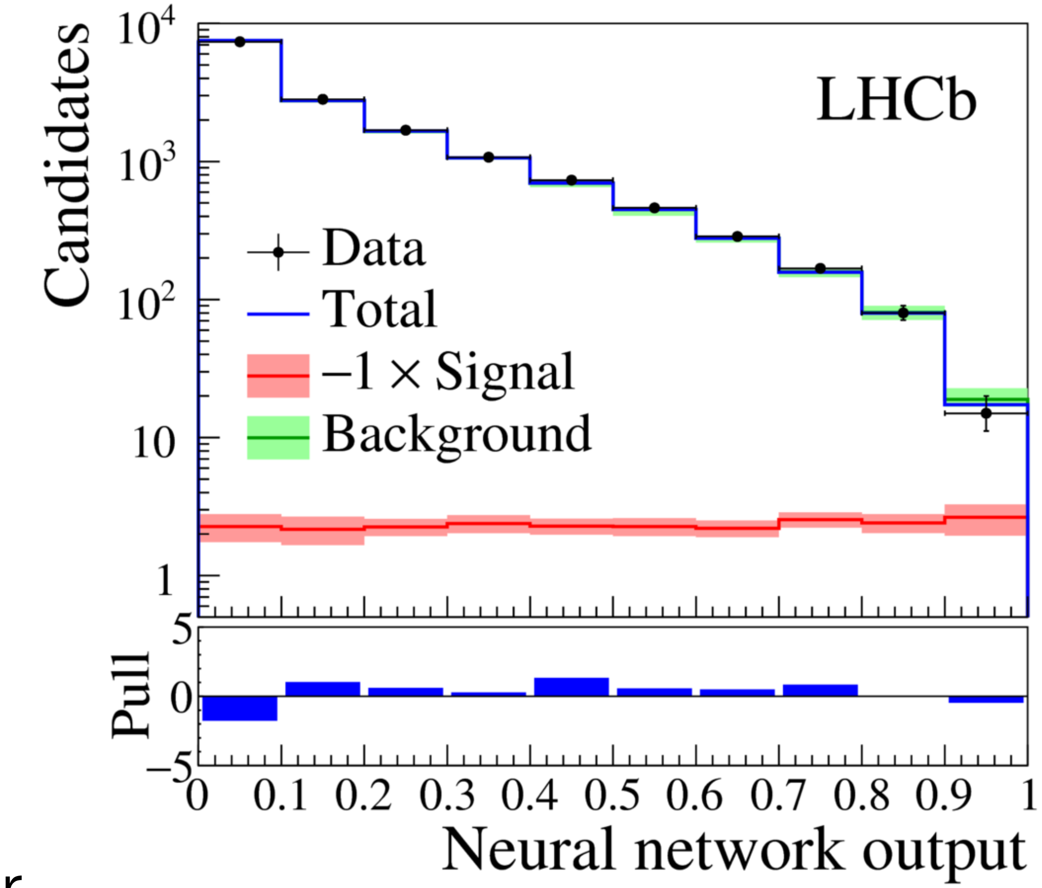
- FCNC processes can be highly sensitive to the presence of new TeV-scale particles.

  e.g. $B_s \to \mu^+\mu^-$ branching fraction or CP violation in Bs mixing.

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

- LHCb performs a search for $B_{(s,d)} \to \tau^+\tau^-$ decays using $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$.
  - ➡ Exploit the $\tau^- \to a_1(1260)^-\nu_\tau$ and $a_1(1260)^- \to \rho(770)^0\pi^-$ decays to select signal/control regions of dipion mass.
- Fit Neural network response to discriminate signal from background.
  - ➡ Ditau mass is not a good discriminator due to missing neutrino energy.
- LHCb sets limits on:

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3} \ (95\% \text{ CL})$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \ (95\% \text{ CL})$$



[LHCb, PRL 118 (2017) 251802]

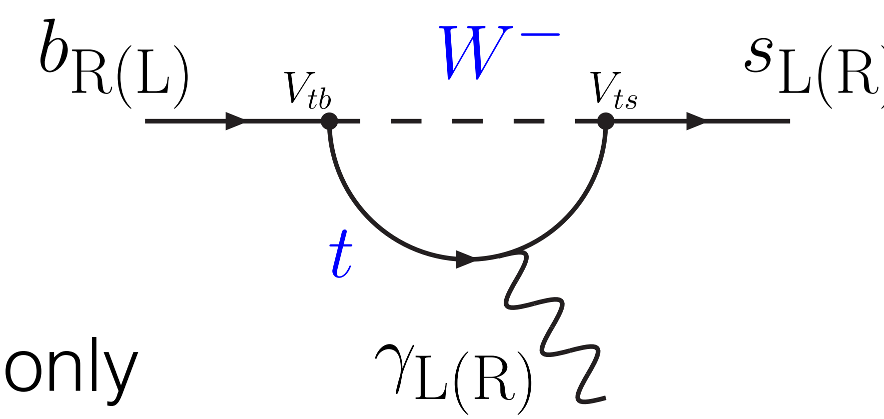
First limit on $B_s \to \tau^+\tau^-$ and best limit on $B^0 \to \tau^+\tau^-$

Photon polarisation

- In radiative B decays, angular momentum conservation allows

$$b_{\rm L} \to s_{\rm R}\gamma_{\rm R}$$

$$b_{\rm R} \to s_{\rm L}\gamma_{\rm L}$$



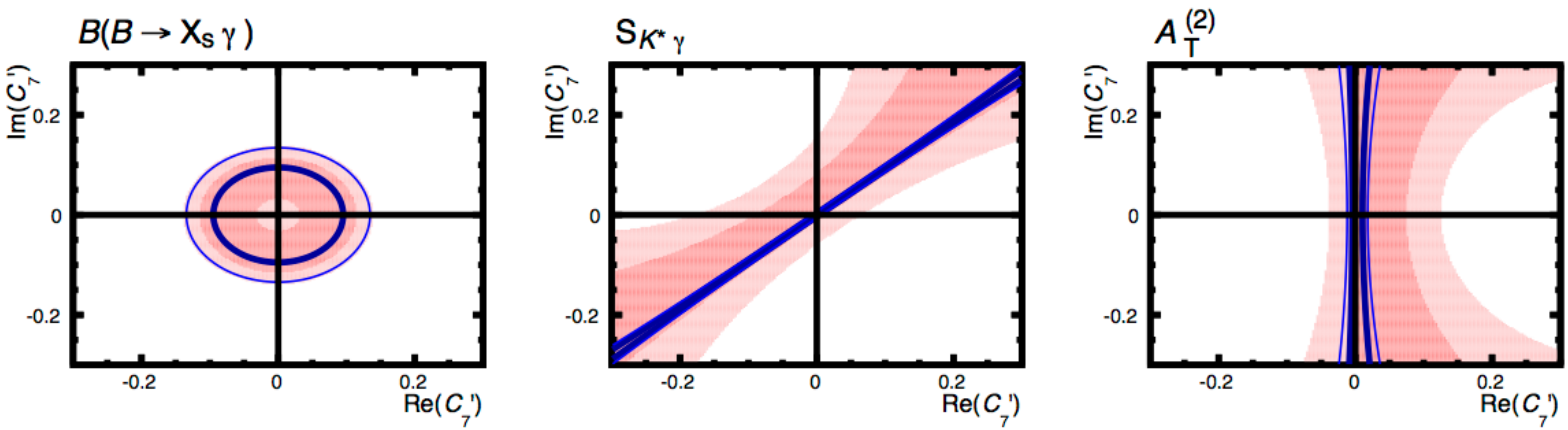
- However, the charged current interaction only couples to left handed quarks. Need to helicity flip the b- or s-quark.

- The right-handed contribution is therefore suppressed by

$$\frac{\mathcal{A}(b_{\rm L} \to s_{\rm R}\gamma_{\rm R})}{\mathcal{A}(b_{\rm R} \to s_{\rm L}\gamma_{\rm L})} \sim \frac{m_s}{m_b}$$

Radiative decays

- Constraints on right-handed currents in $b \to s\gamma$ decays:



inclusive branching fraction.

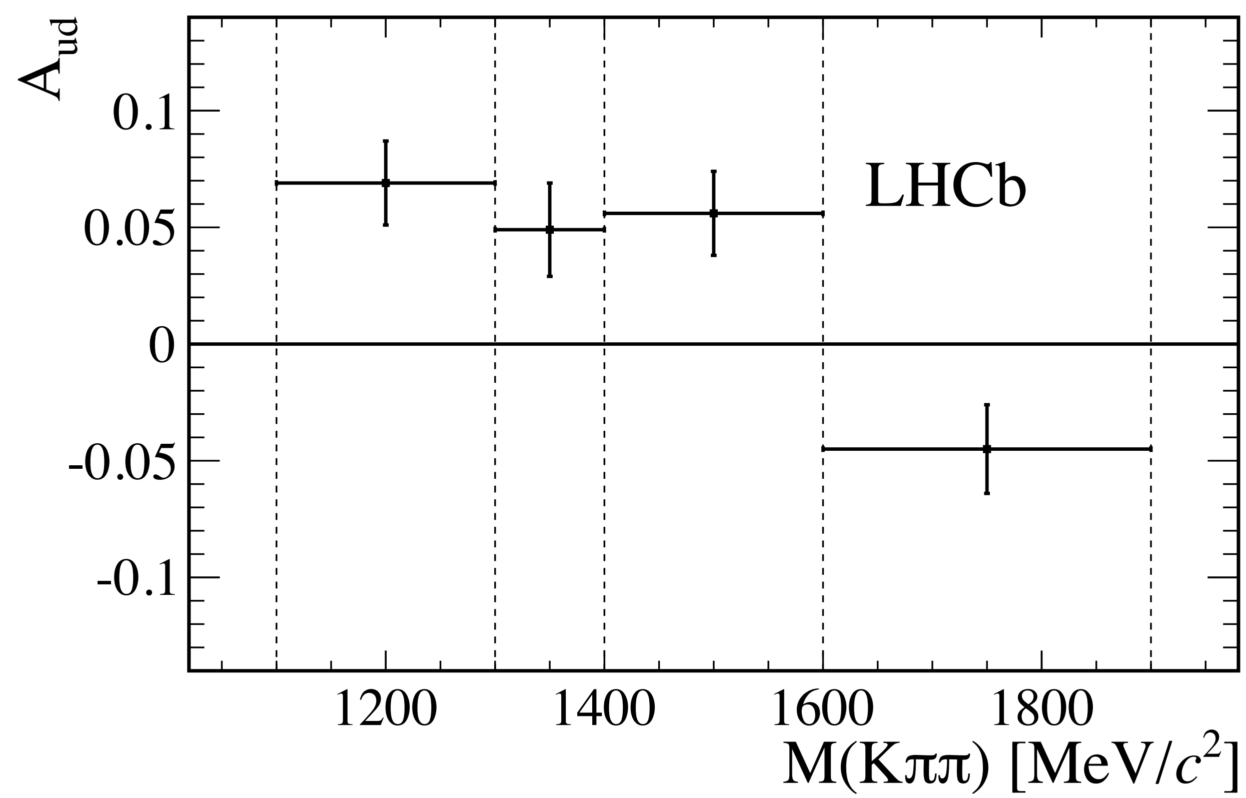
time dependent CP violation in $B \to [K^0_S \pi^0]\gamma$

angular distribution of $B \to K^* e^+ e^-$

Results are consistent with LH polarisation expected in SM

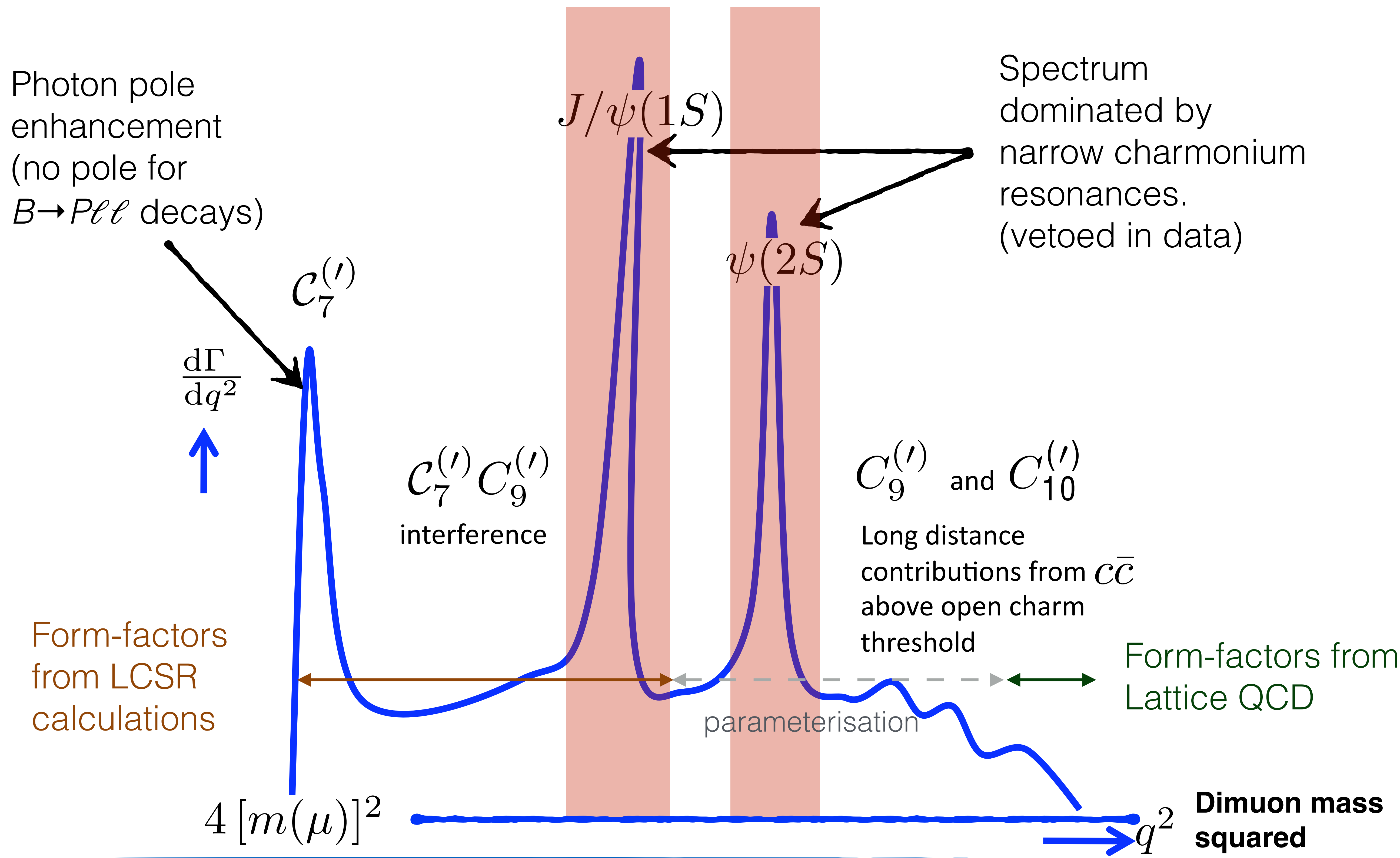
Is the photon polarised?

- Yes, in $B^+ \to K^+\pi^-\pi^+\gamma$ decays the photon has a preferred direction w.r.t. the $K^+\pi^-\pi^+$ decay plane. This can only happen is the photon is polarised.



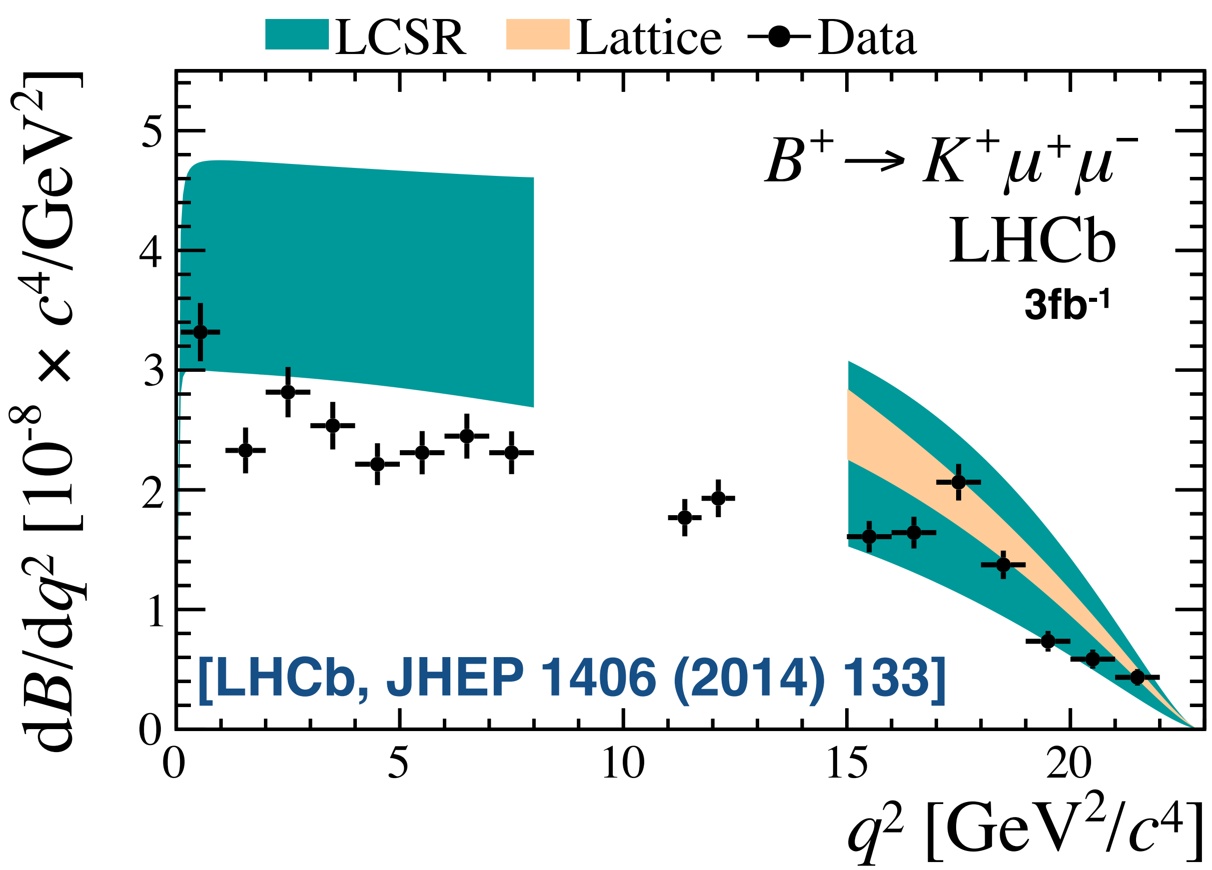
[LHCb, Phys. Rev. Lett. 112 (2014) 161801]

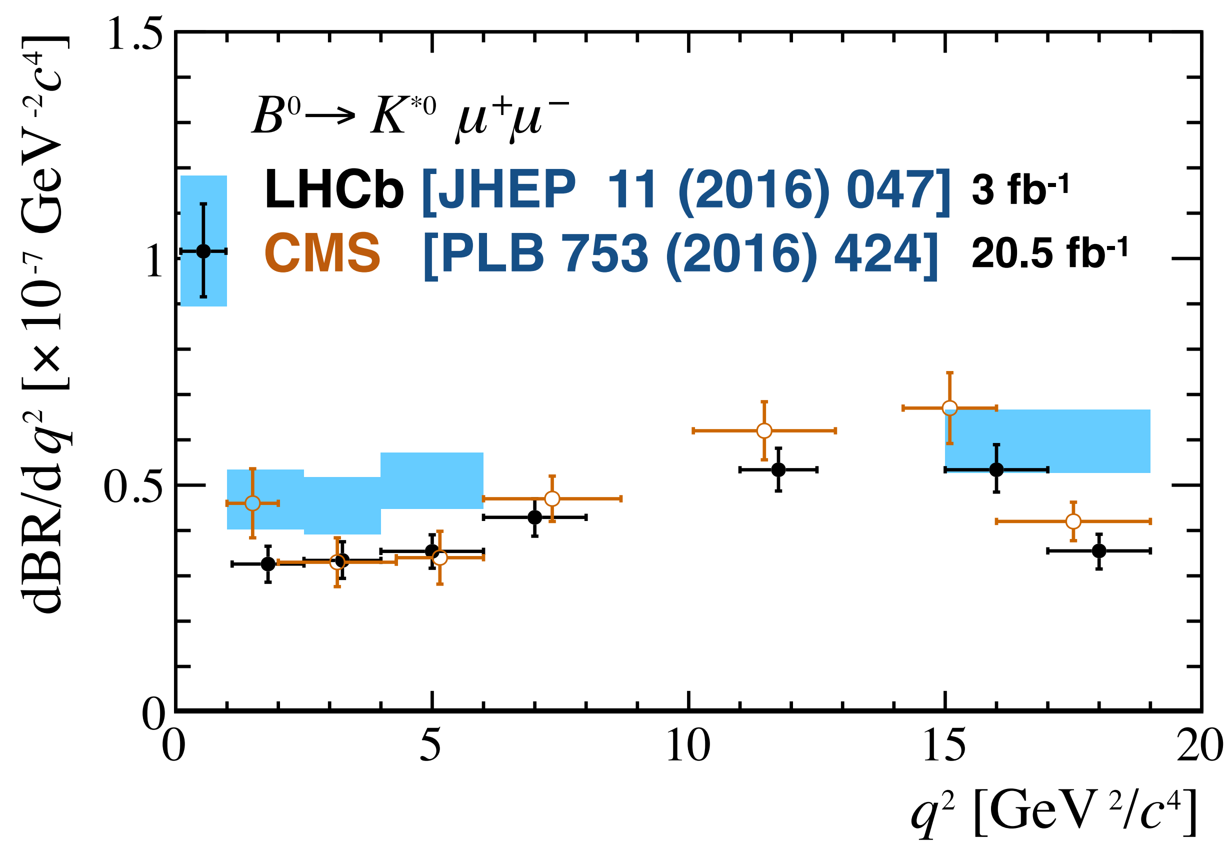
$b \to s\ell^+\ell^-$ decay spectrum



Branching fraction measurements

- We already have precise measurements of branching fractions in the run1 datasets with at least comparable precision to SM expectations:





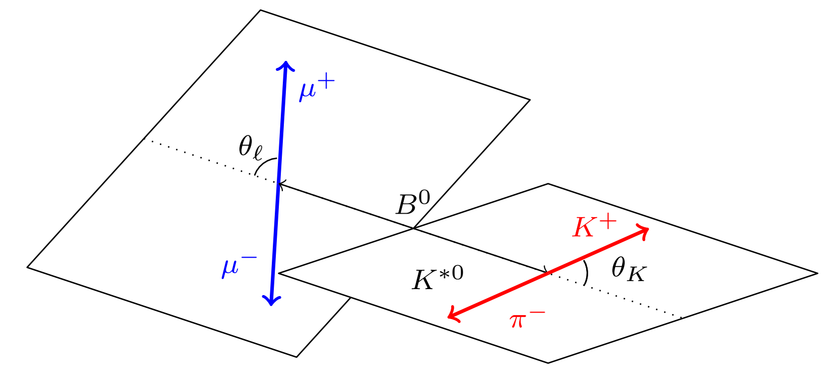
- SM predictions have large theoretical uncertainties from hadronic form factors (3 for $B\to K$ and 7 for $B\to K^*$ decays). For details see **[Bobeth et al JHEP 01 (2012) 107] [Bouchard et al. PRL111 (2013) 162002] [Altmannshofer & Straub, EPJC (2015) 75 382]**.

$B^0 \to K^{*0}\mu^+\mu^-$ angular basis

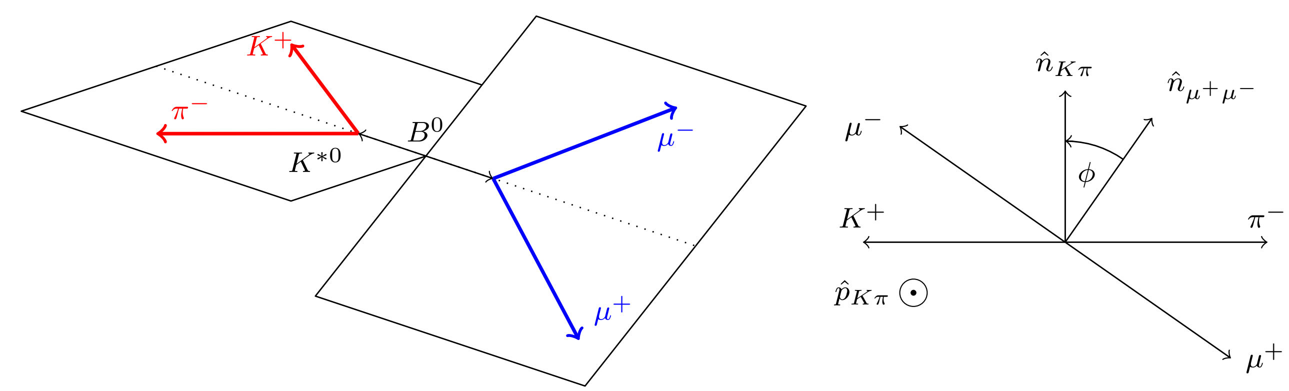
- Four-body final state.
  - ➡ Angular distribution provides many observables that are sensitive to NP.

  e.g. at low q^2 the angle between the decay planes, ϕ , is sensitive to the photon polarisation.

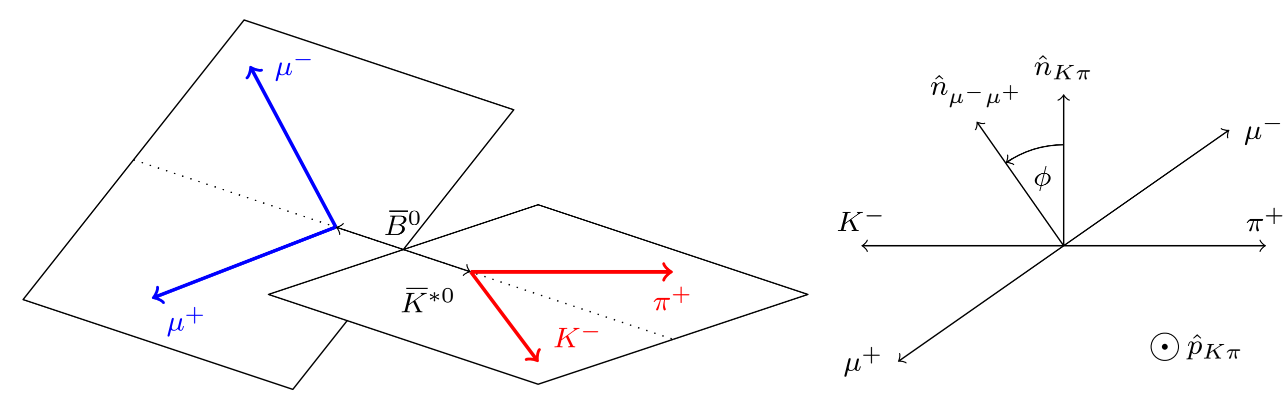
- System described by three angles and the dimuon invariant mass squared, q^2.
  - ➡ Use helicity basis for the angles.



(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay



(c) ϕ definition for the $\overline{B}^0$ decay

$B^0 \to K^{*0}\mu^+\mu^-$ angular distribution

- Complex angular distribution:

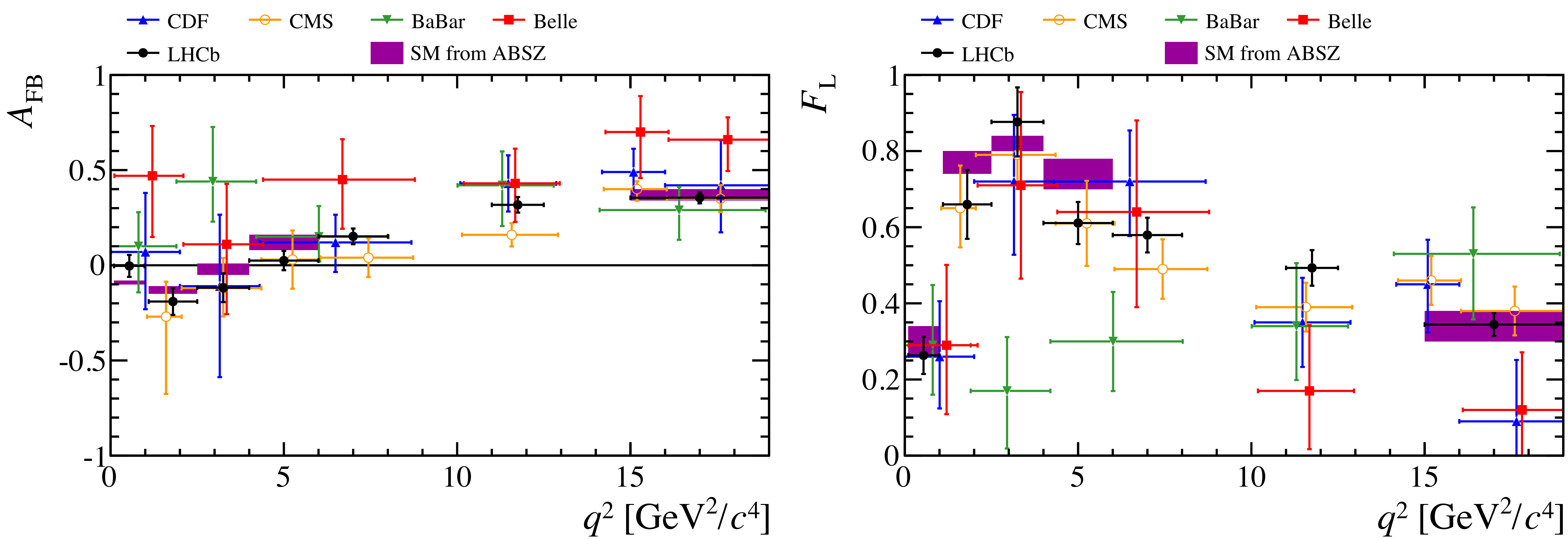
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\Bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K + \boxed{F_{\mathrm{L}}}\cos^2\theta_K + \\ +\tfrac{1}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K\cos 2\theta_l \\ -\boxed{F_{\mathrm{L}}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi \\ +S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + \boxed{S_5}\sin 2\theta_K\sin\theta_l\cos\phi \\ +\tfrac{4}{3}\boxed{A_{\mathrm{FB}}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi \\ +S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

fraction of longitudinal polarisation of the K*

forward-backward asymmetry of the dilepton system

The observables depend on form-factors for the $B \to K^*$ transition plus the underlying short distance physics (Wilson coefficients).

$B^0 \to K^{*0}\mu^+\mu^-$ angular observables

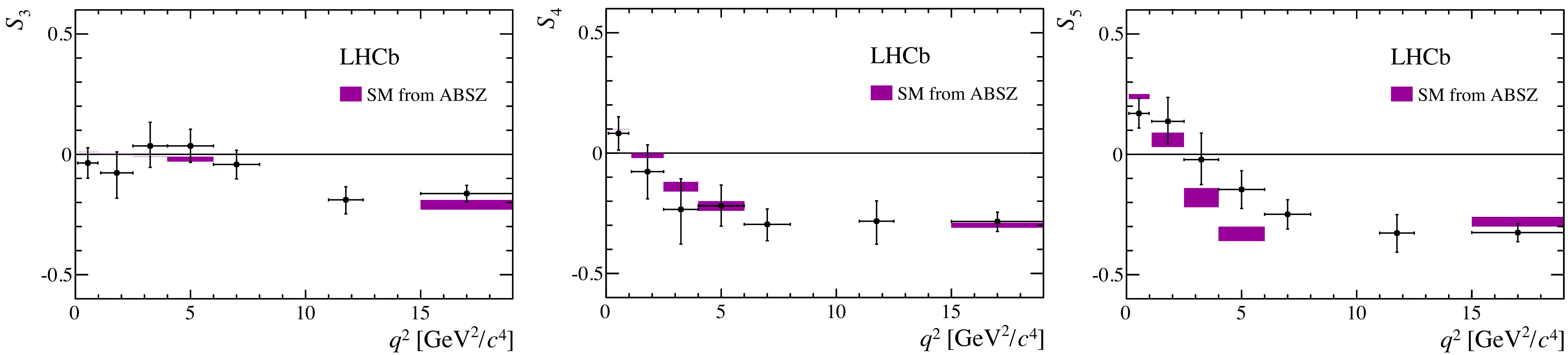


- New results for F_L and A_{FB} last year from LHCb **[JHEP 02 (2016) 104]** , CMS **[PLB 753 (2016) 424]** and BaBar **[arXiv:1508.07960]** + older measurements from CDF **[PRL 108 (2012) 081807]** and Belle **[PRL 103 (2009) 171801].**
- SM predictions based on
  [Altmannshofer & Straub, arXiv:1411.3161]
  [LCSR form-factors from Bharucha, Straub & Zwicky, arXiv:1503.05534]
  [Lattice form-factors from Horgan, Liu, Meinel & Wingate arXiv:1501.00367]

Results

- LHCb has performed the first full angular analysis of the decay:
  - ➡ Extract the full set of CP-averaged angular terms and their correlations.
  - ➡ Determine a full set of CP-asymmetries.

[LHCb, JHEP 02 (2016) 104]



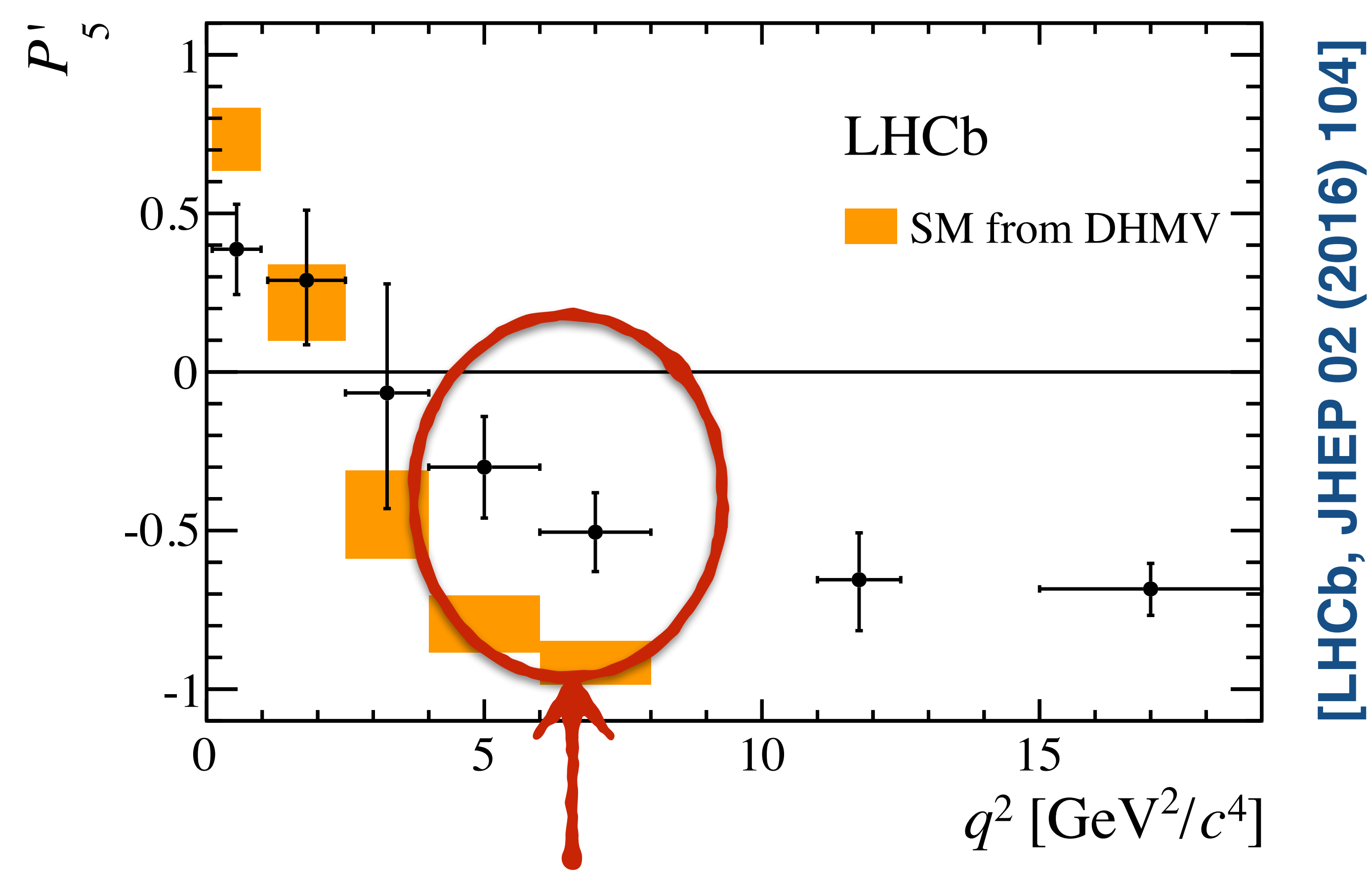
NB: These observables cancel when integrating over the ϕ-angle (e.g. in the CMS analysis).

Statistical coverage of the observables corrected using Feldman-Cousins (treating the nuisance parameters with the plug-in method).

Form-factor “free” observables

- In QCD factorisation/SCET there are only two form-factors
  - ➡ One is associated with A_0 and the other $A_{||}$ and $A_{\perp}$.
- Can then construct ratios of observables which are independent of form-factors at leading order, e.g.

$$P'_5 = S_5/\sqrt{F_{\mathrm{L}}(1 - F_{\mathrm{L}})}$$



local tension with SM predictions (2.8 and 3.0σ)

- P'_5 is one of a set of so-called form-factor free observables that can be measured **[S. Descotes-Genon et al. JHEP 1204 (2012) 104]**.

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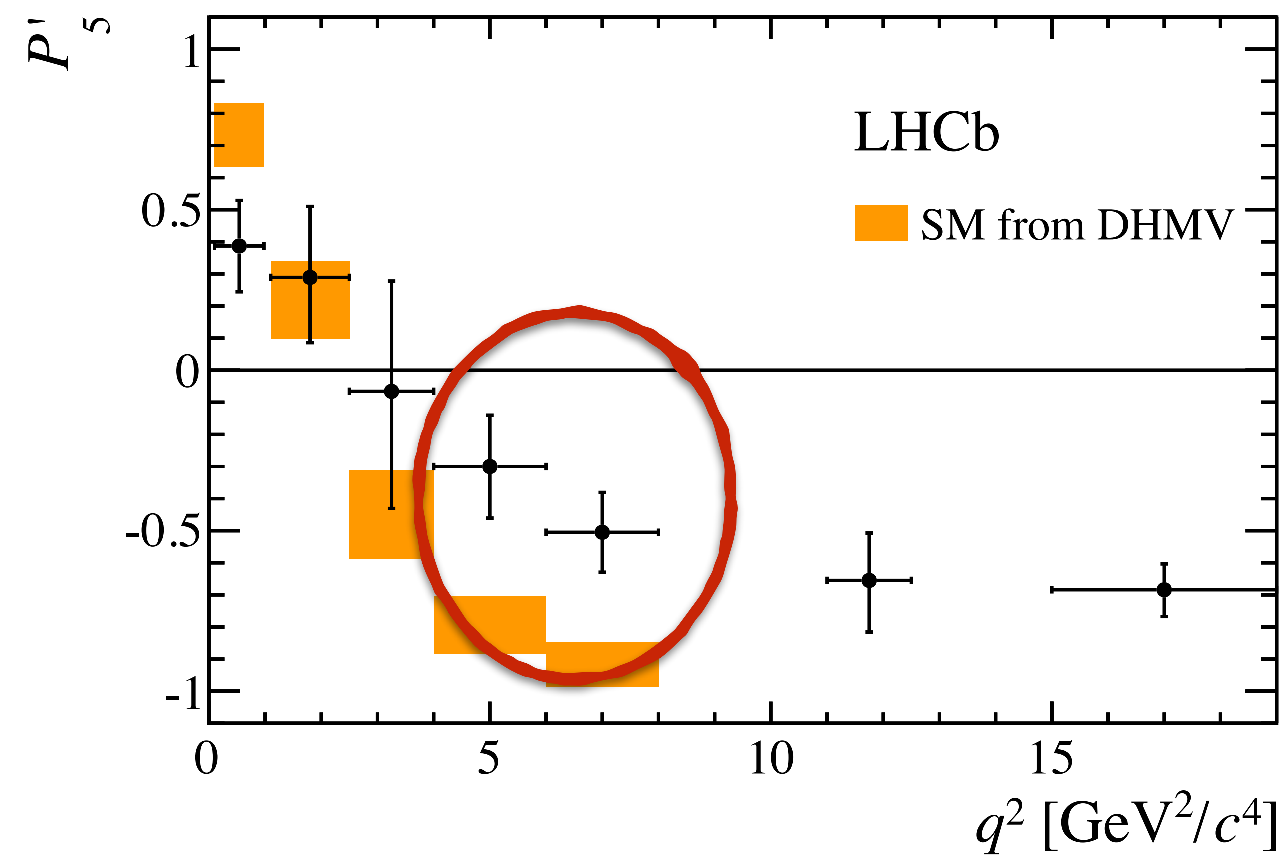

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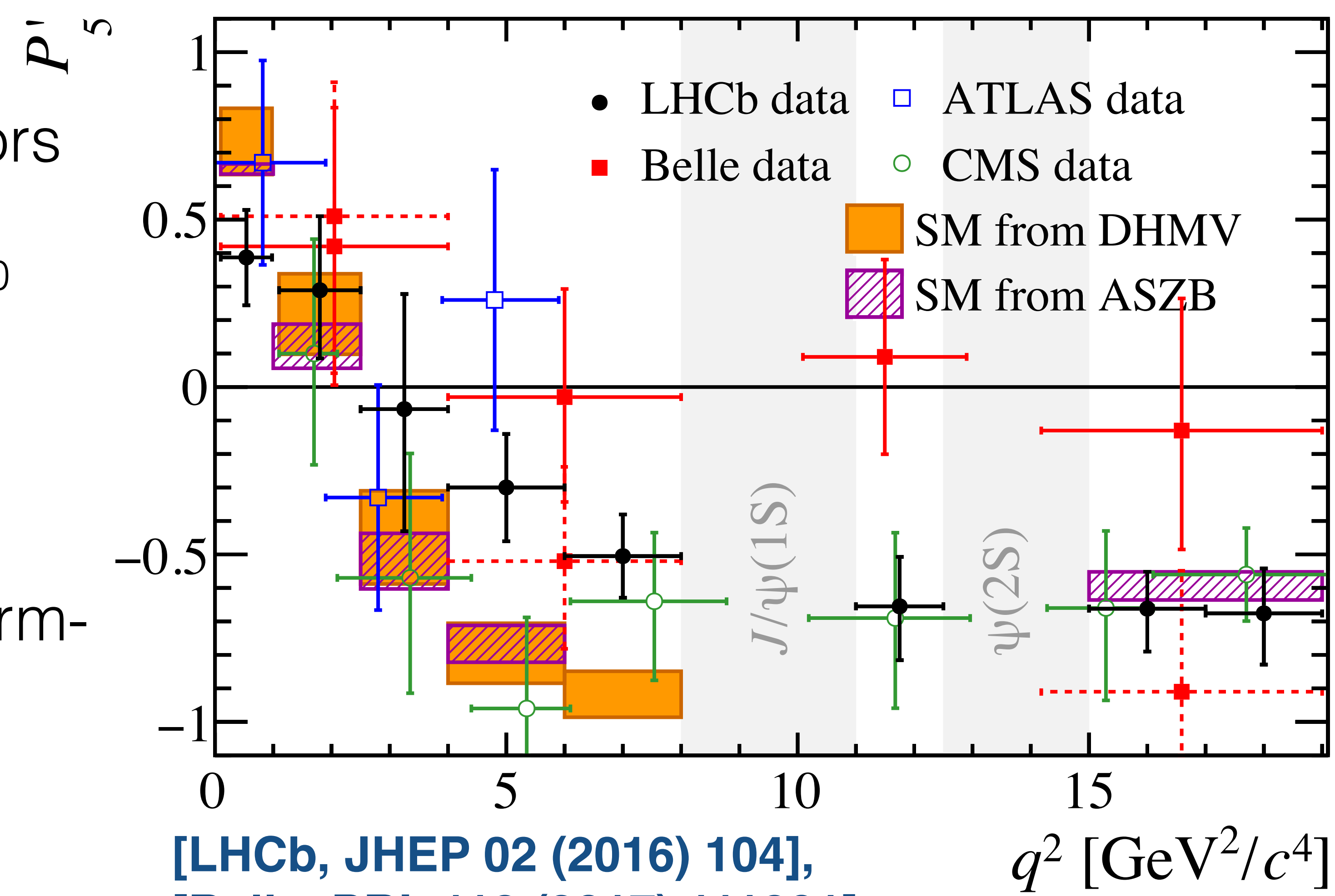

[LHCb, JHEP 02 (2016) 104], [Belle, PRL 118 (2017) 111801], [ATLAS-CONF-2017-023], [CMS-PAS-BPH-15-008]

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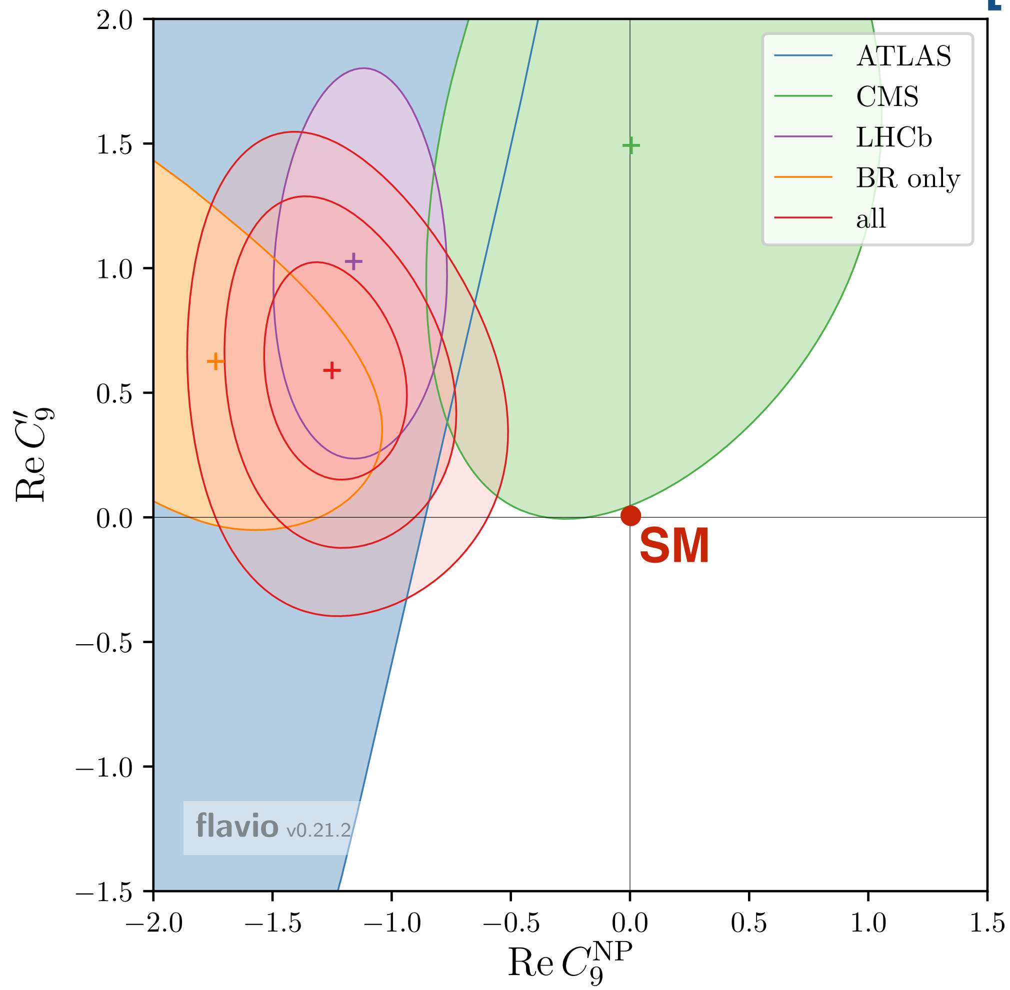
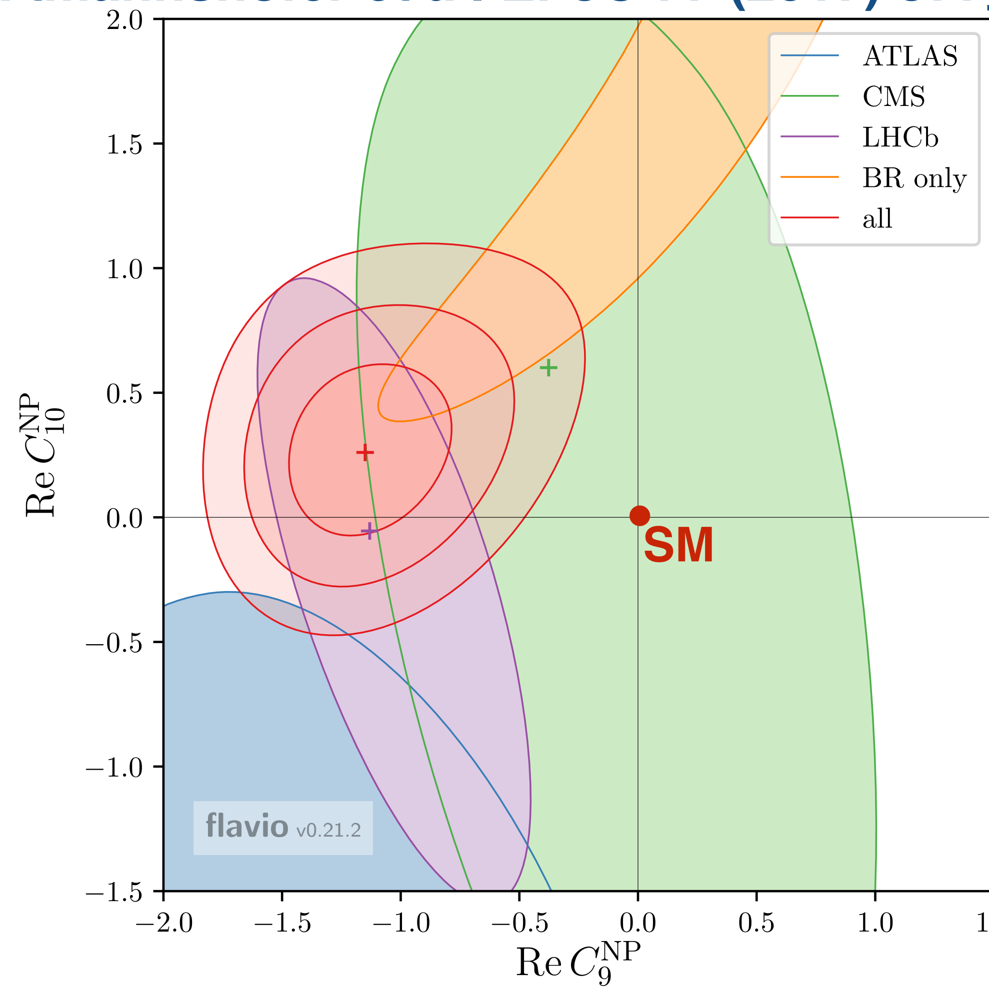
Global fits

- Several attempts to interpret our results through global fits to $b \to s$ data.

[W. Altmannshofer et al. EPJC 77 (2017) 377]

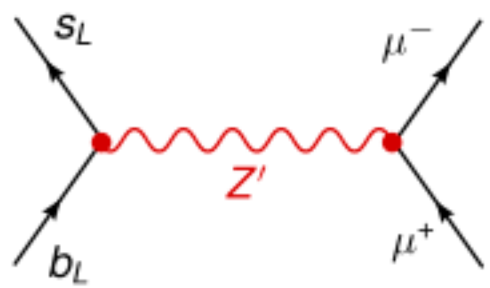




- General pattern of consistency between experiments/measurements. **Data favours a modified vector coupling ($C_9^{\mathrm{NP}} \neq 0$) at 4-5σ.**

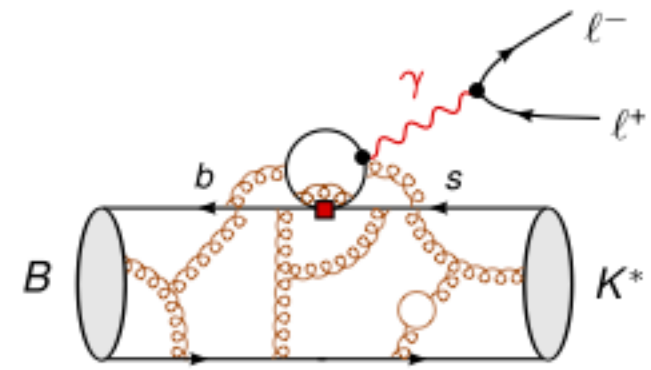
Interpretation of global fits

Optimist's view point



Vector-like contribution could come from new tree level contribution from a Z' with a mass of a few TeV (the Z' will also contribute to mixing, a challenge for model builders)

Pessimist's view point



Vector-like contribution could point to a problem with our understanding of QCD, e.g. are we correctly estimating the contribution for charm loops that produce dimuon pairs via a virtual photon.

More work needed from experiment/theory to disentangle the two

Lepton universality

- In the SM, ratios

$$R_{\mathrm{K}} = \frac{\int \mathrm{d}\Gamma[B^+ \to K^+\mu^+\mu^-]/\mathrm{d}q^2 \cdot \mathrm{d}q^2}{\int \mathrm{d}\Gamma[B^+ \to K^+e^+e^-]/\mathrm{d}q^2 \cdot \mathrm{d}q^2}$$

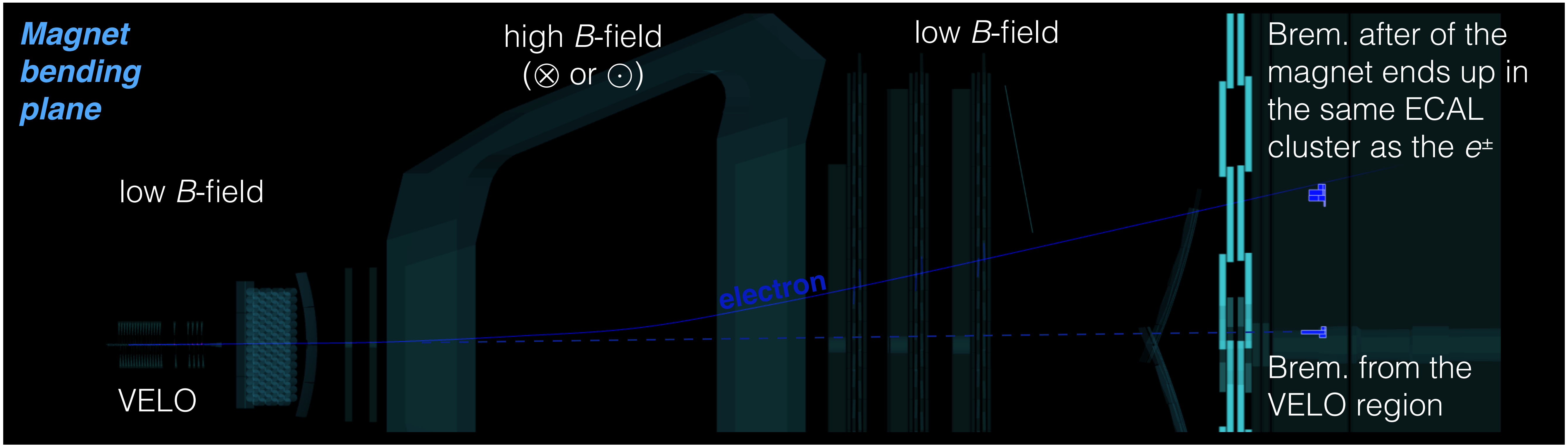
  only differ from unity by phase space.

- The dominant SM processes couple equally to the different lepton flavours (with the exception of the Higgs).

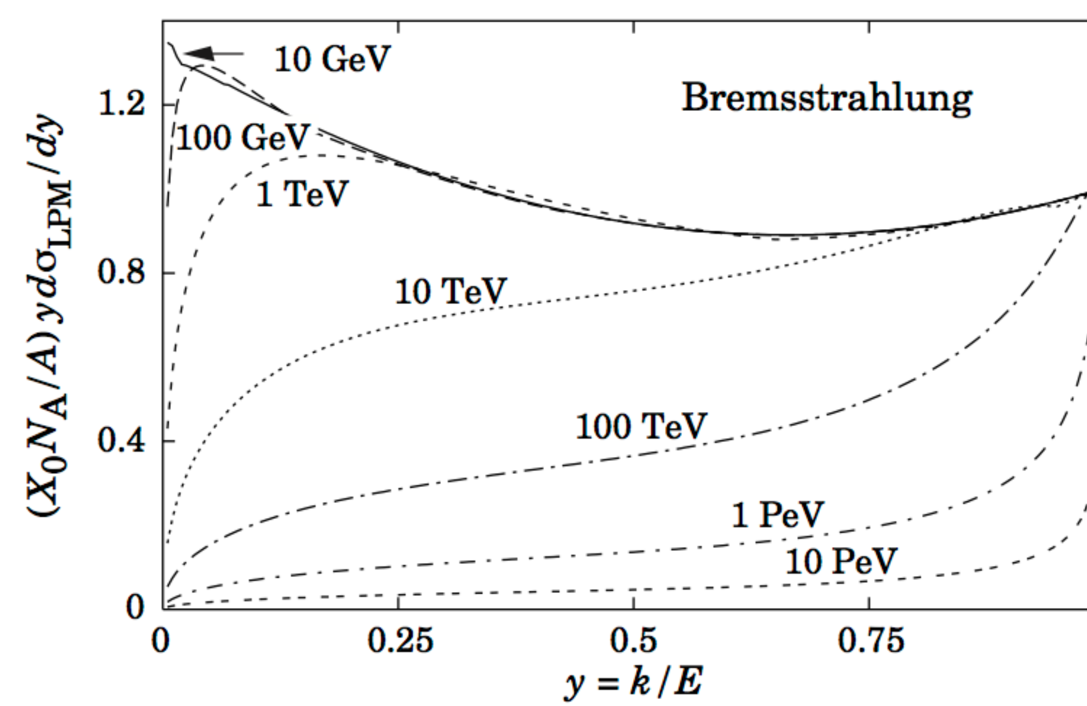
- Theoretically clean since hadronic uncertainties cancel in the ratio (same hadronic matrix element).

- Experimentally more challenging due to differences in muon/electron reconstruction (in particular Bremsstrahlung from the electrons).

Bremsstrahlung recovery



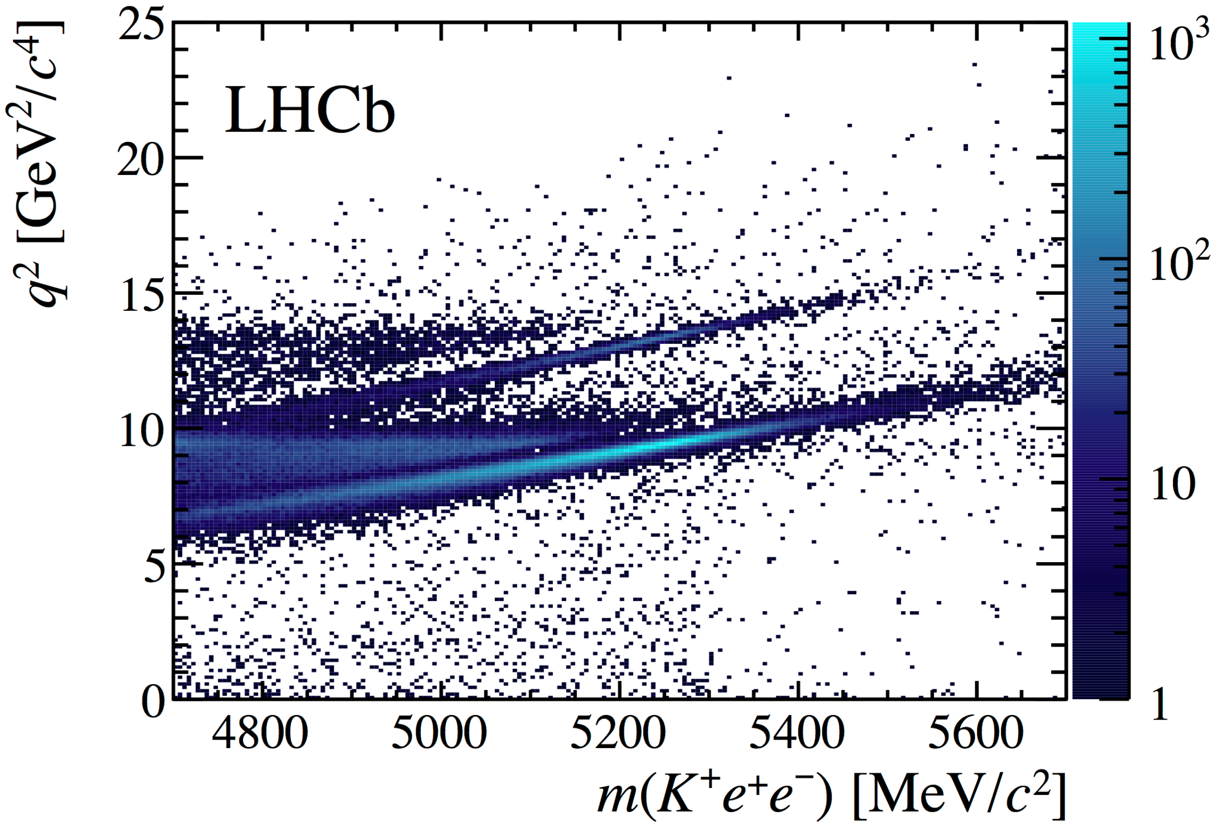
- Large energy loss through Bremsstrahlung in the detector (significant fraction of the $e^{\pm}$ energy).
- Recover clusters with $E_{\mathrm{T}} > 75\ \mathrm{MeV}/c^2$ to correct for Bremsstrahlung emission.



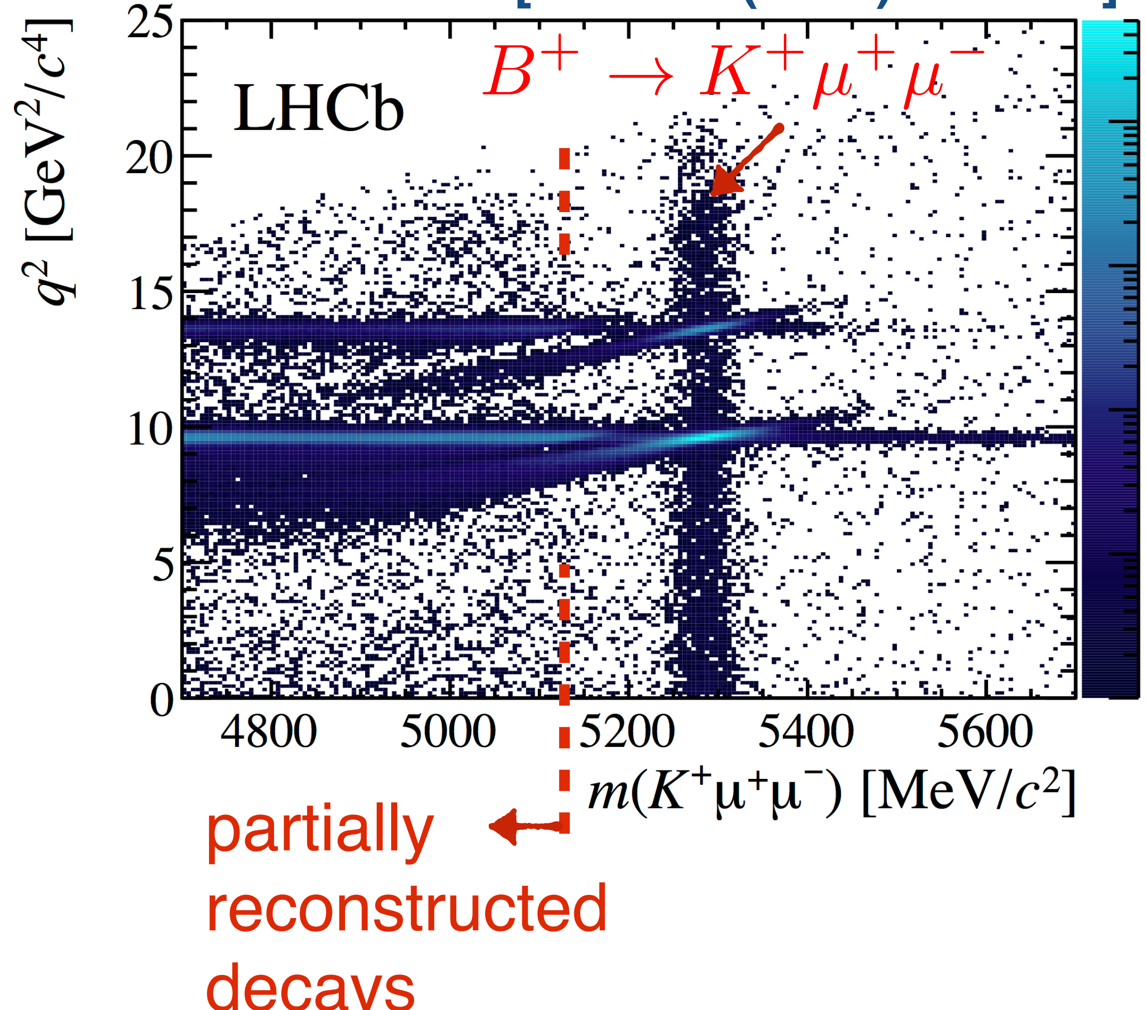
[http://pdg.lbl.gov/2017/reviews/rpp2016-rev-passage-particles-matter.pdf]

$B^+ \to K^+\ell^+\ell^-$ candidates

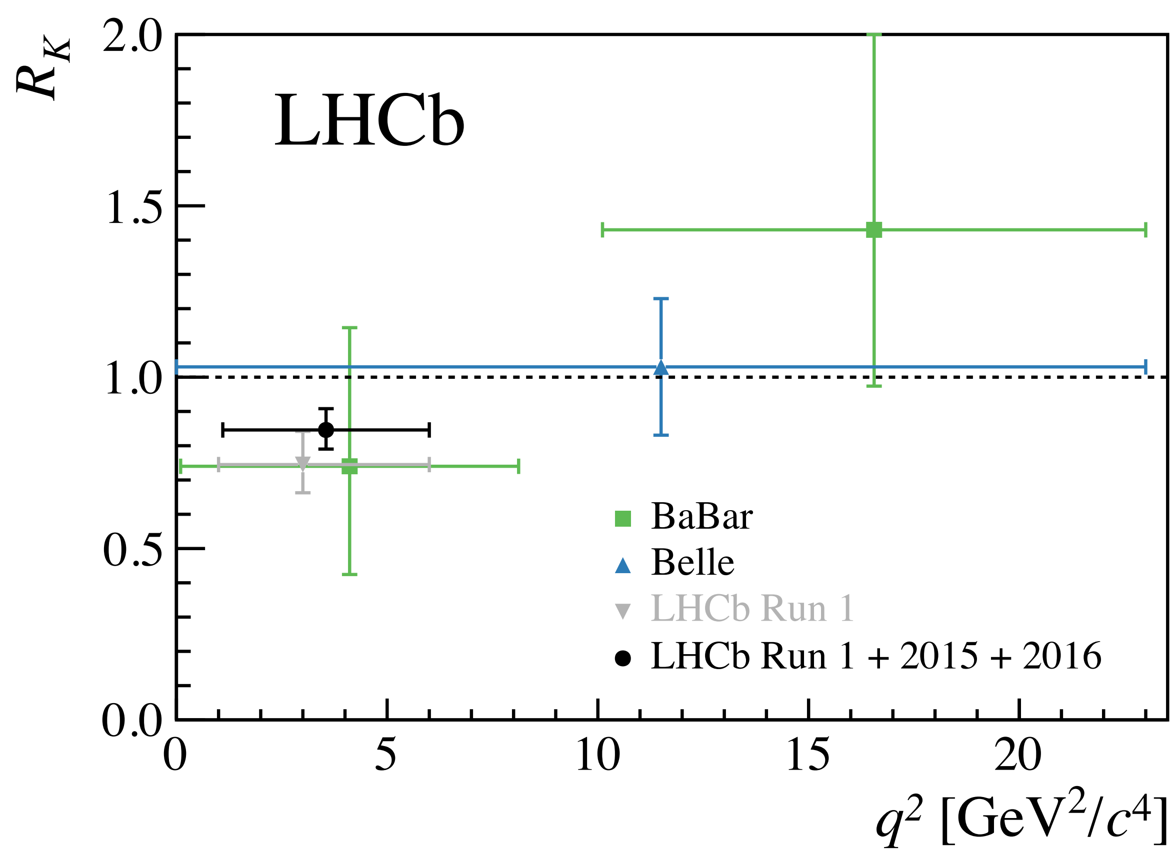
- Have to correct for energy loss due to Bremmstrahlung (look for photons in the detector).
- Even after Bremsstrahlung recovery there are significant differences between dielectron and dimuon final states:

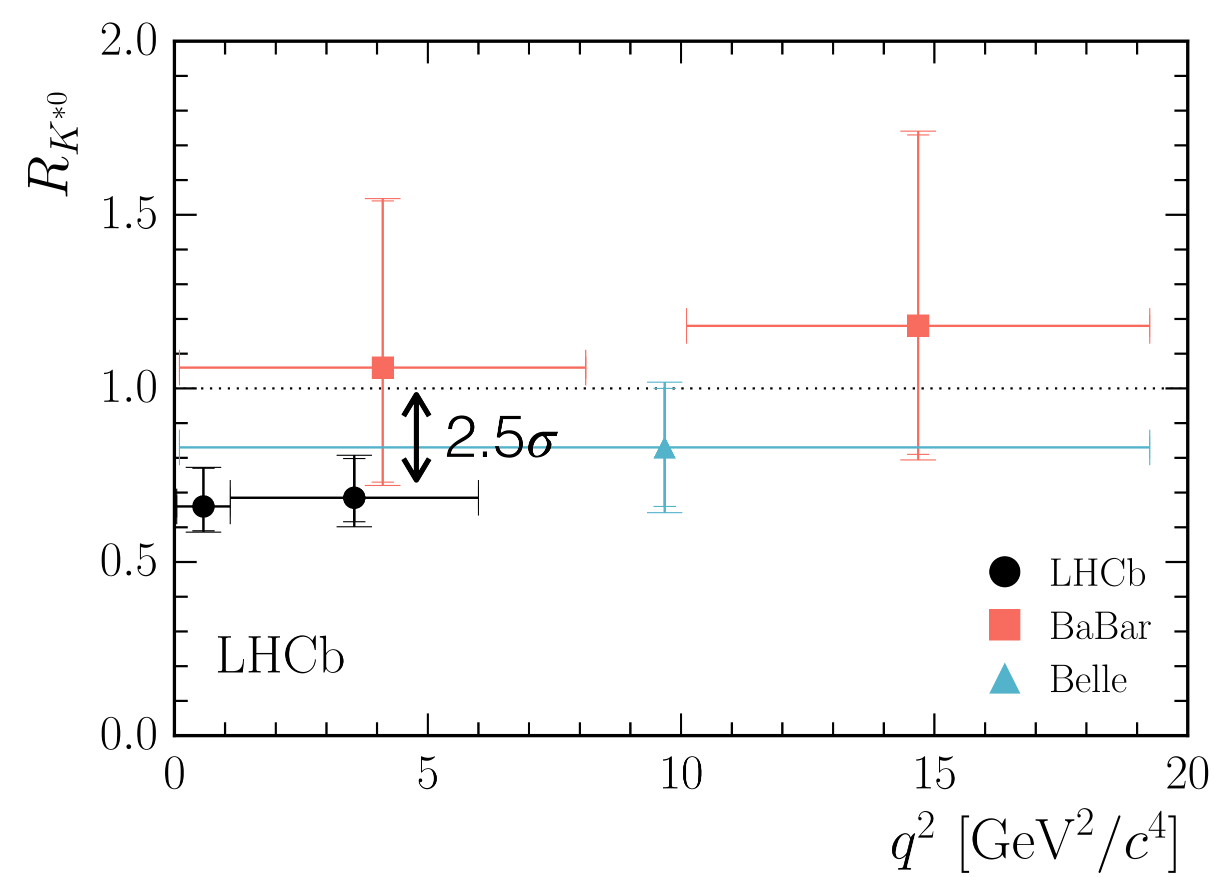


LHCb [PRL113 (2014) 151601]



Lepton universality tests



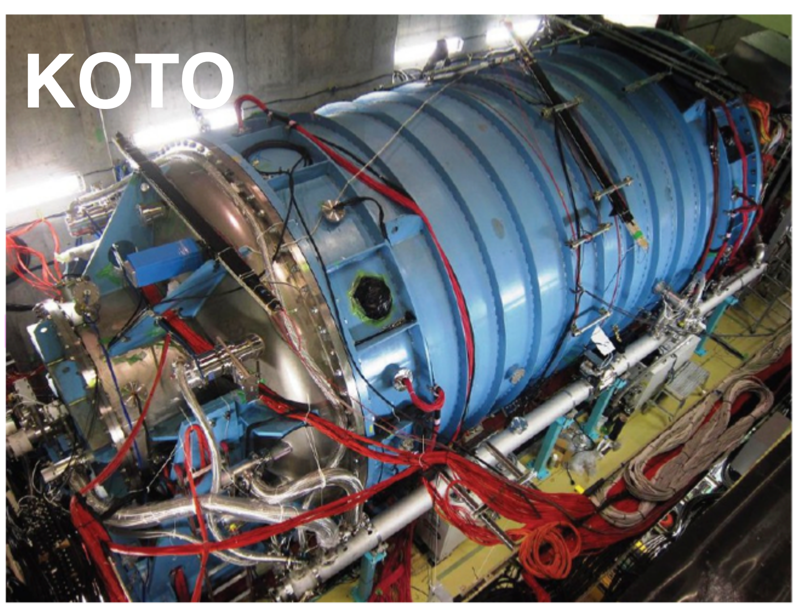


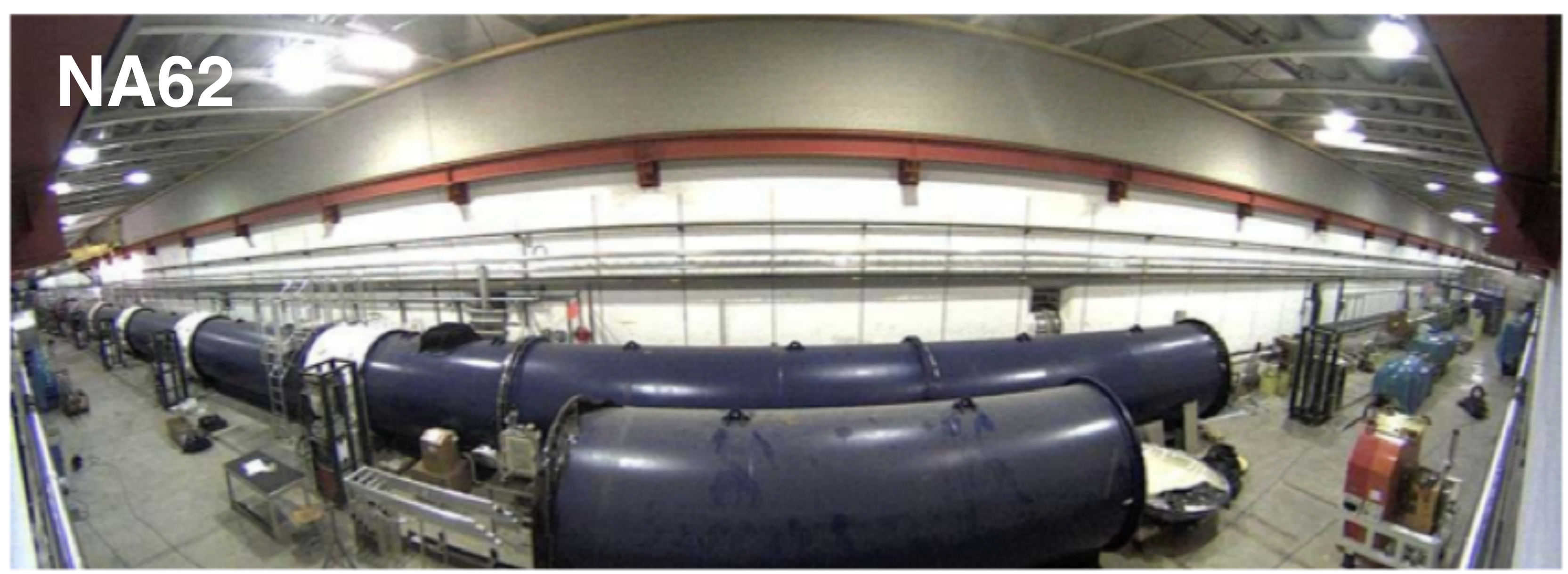
[LHCb , PRL113 (2014) 151601]
[LHCb, JHEP 08 (2017) 055]
[LHCb, arXiv:1903.09252]
[BaBar, PRD 86 (2012) 032012]
[Belle, PRL 103 (2009) 171801]

NB $R_K \simeq 0.8$ is a prediction of one class of model explaining the $B^0 \to K^{*0}\mu^+\mu^-$ angular observables, see L_μ - L_τ models
W. Altmannshofer et al. [PRD 89 (2014) 095033]

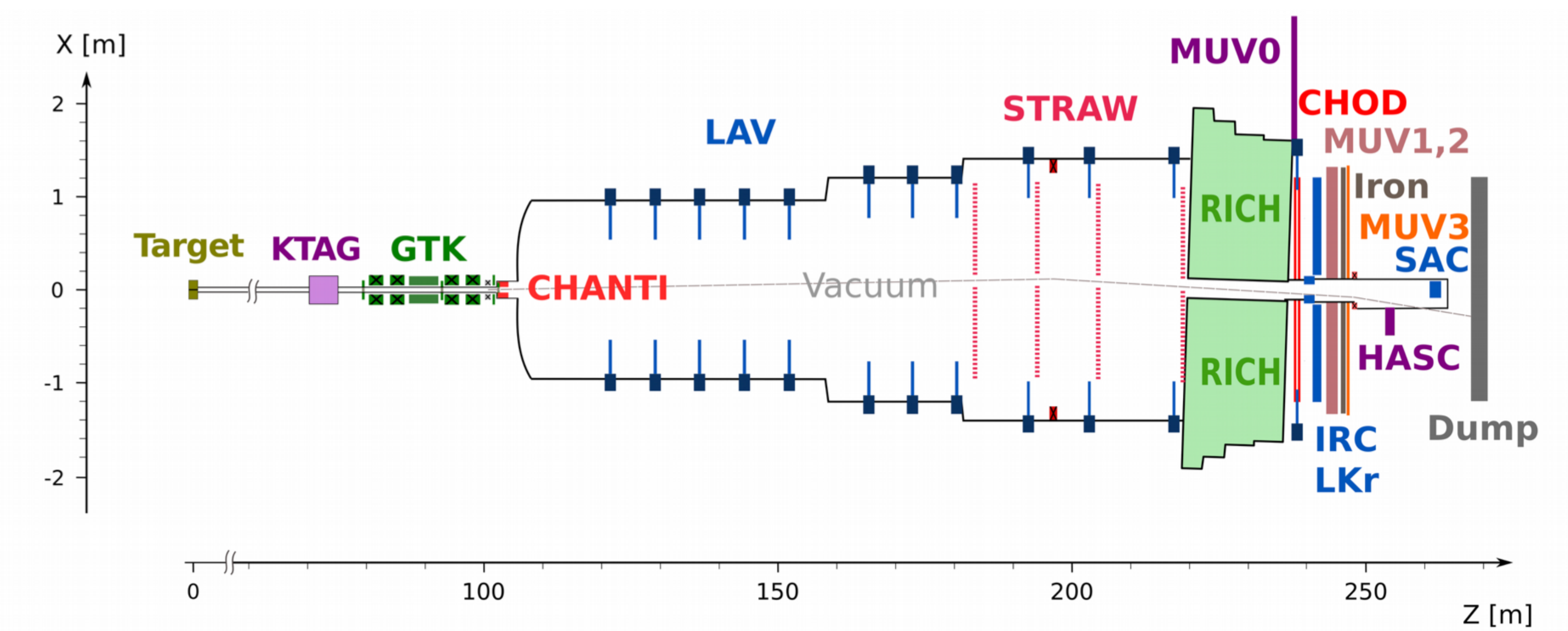
Rare kaon decays

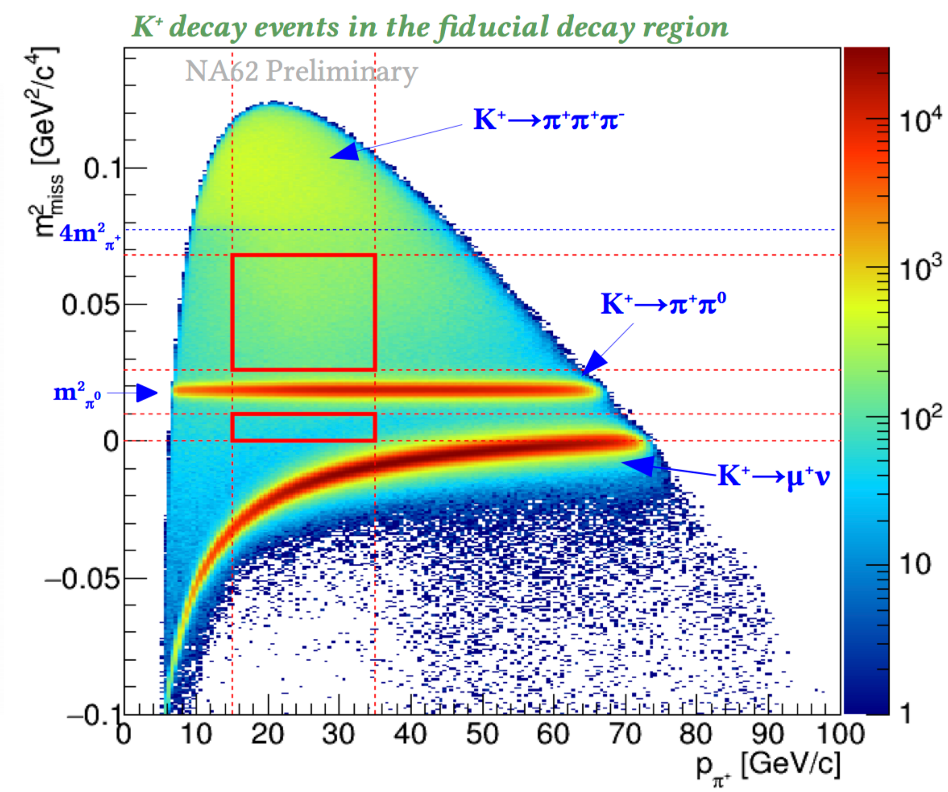
- Two new rare kaon decay experiments:
  - ➡ KOTO at J-PARC, searching for $K^0_{\rm L} \to \pi^0 \nu\bar{\nu}$
  - ➡ NA62 at CERN, searching for $K^+ \to \pi^+ \nu\bar{\nu}$
- The main advantage of final states with neutrinos is that there is no contribution from quark loops involving light quarks (which can annihilate to produce charged leptons).





NA62





- Aim to collect a dataset of ~100 $K^+ \to \pi^+ \nu\bar{\nu}$ decays.
- Current best measurement from BNL:

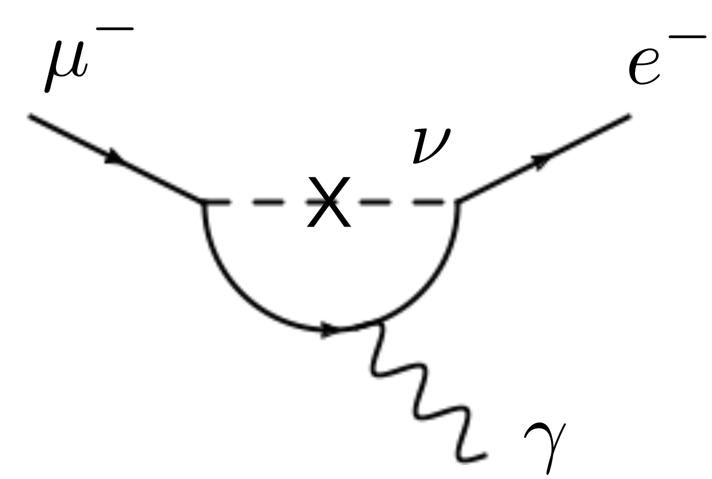
$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (17.3\,^{+11.5}_{-10.5}) \times 10^{-11}$$

Lepton Flavour Violation

LFV muon and tau decays

Lepton flavour violation

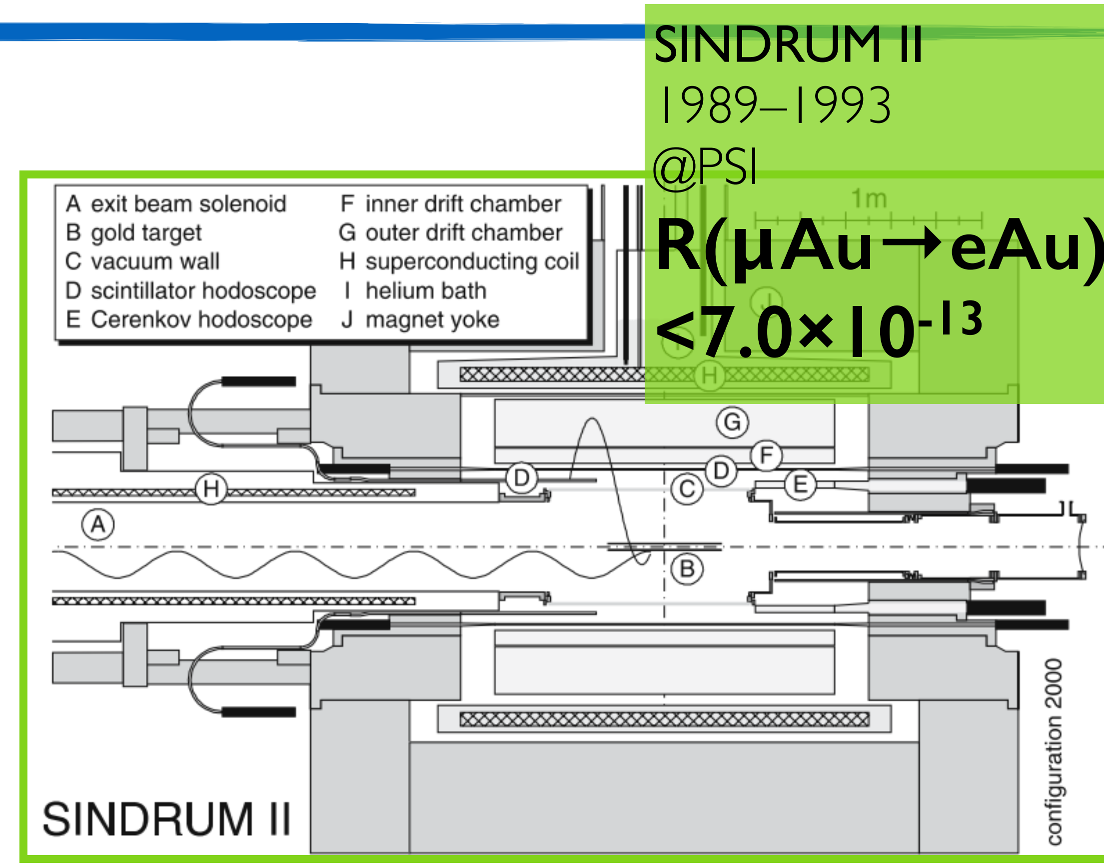
- Essentially forbidden in SM by smallness of the neutrino mass.
  - ➡ Powerful null test of the SM.
- Any visible signal would be an indication of BSM physics.

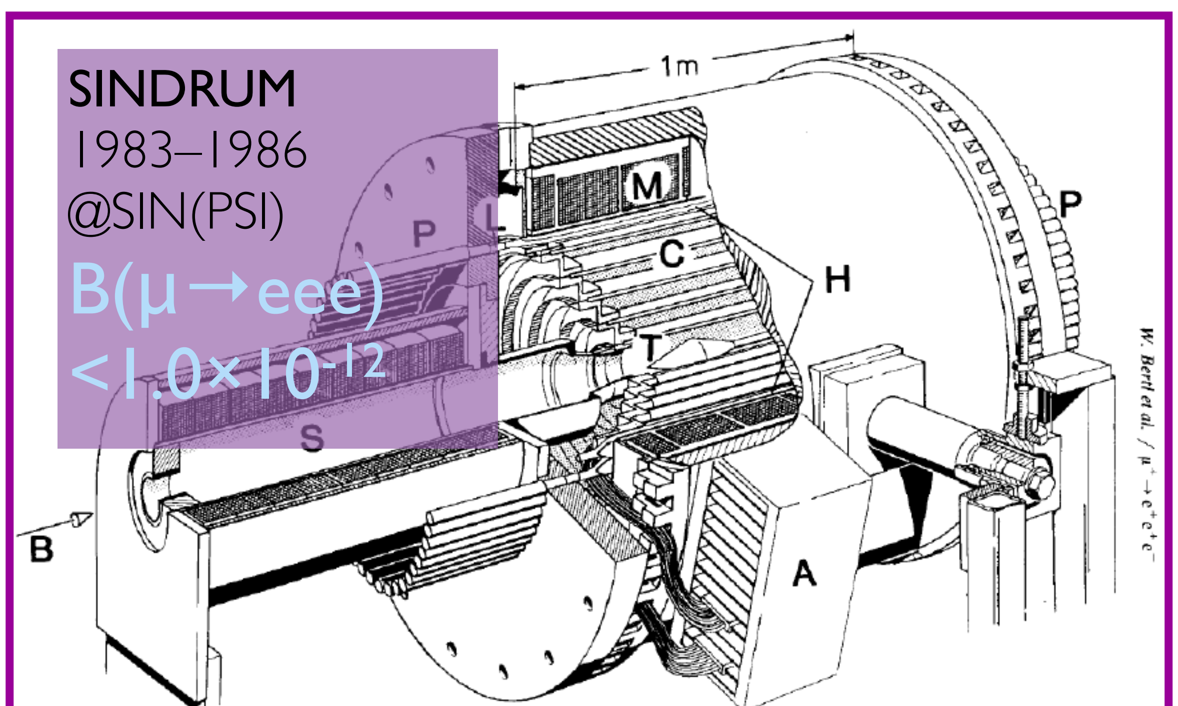


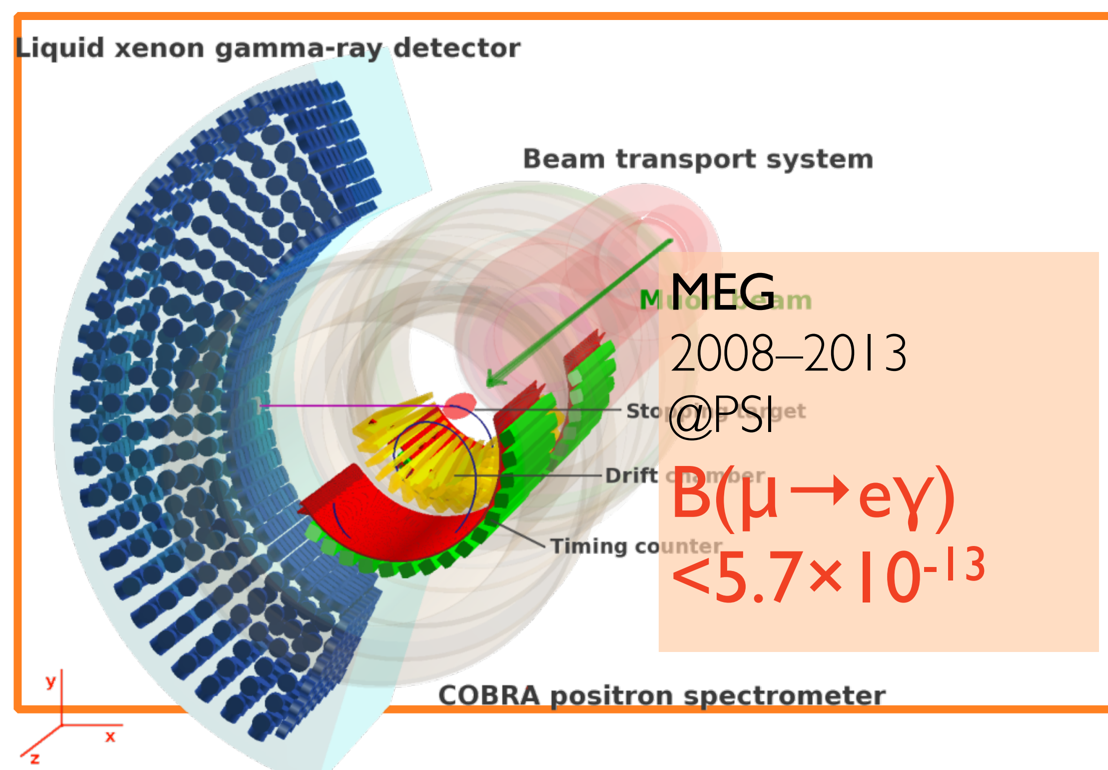
$$\mathcal{B}(\mu \to e\gamma) \propto \frac{m_\nu^4}{m_W^4}$$
$$\sim 10^{-54}$$

μ LFV

- Three different signatures
  1. $\mu \to e\gamma$ at rest (MEG at PSI).
  2. $\mu \to 3e$ (SINDRUM at PSI).
  3. μ conversion in field of nucleus.



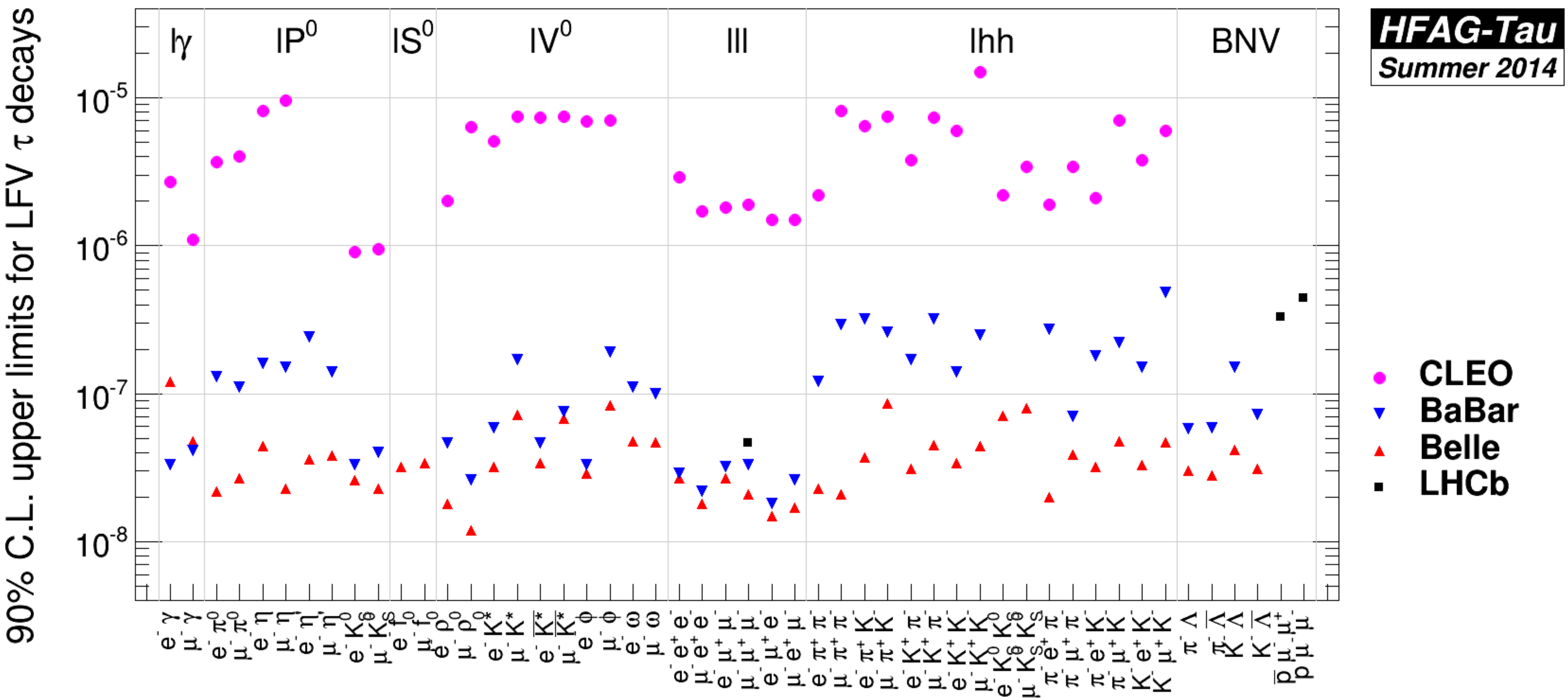




25 year's ago

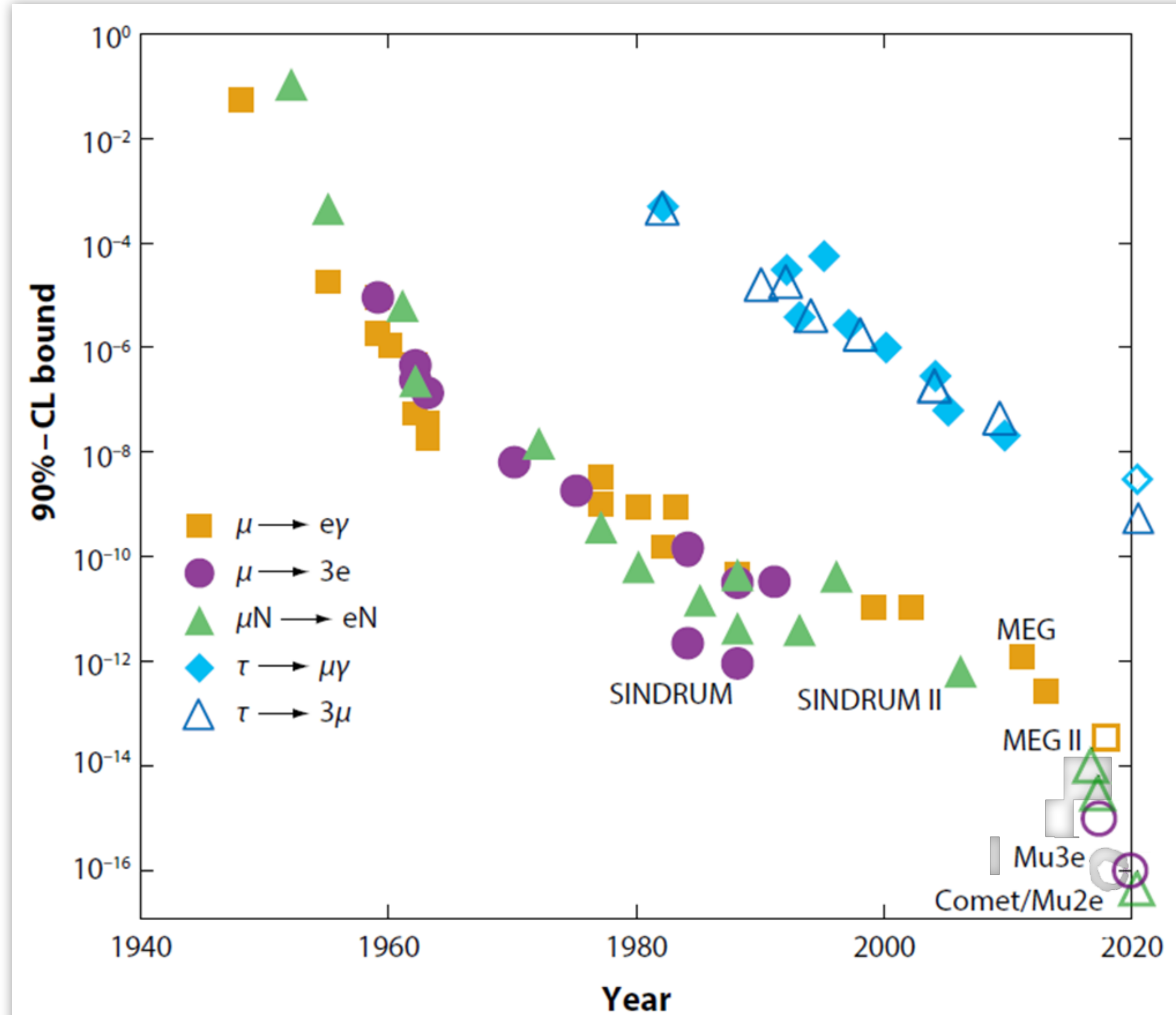
τ LFV

Large number of experimental signatures



Charged LFV

- Upgrade to MEG underway, aiming for O(10^{-14}). Expected to start data taking soon.
- New μ →3e experiment (Mu3e) at PSI.
- Two new conversion experiments, one at PSI (Mu2e) and one at J-PARC (COMET).
- Expect improvements for LFV τ decays from Belle 2.



Interesting challenges, e.g. very thin detectors for $\mu \rightarrow 3e$.

Flavour anomalies

Does the pattern make sense?

New Physics?

- As we saw in the last lecture, measurements of the CKM matrix and the properties (closure) of the Unitarity triangle are consistent with the Standard Model picture of flavour physics.
  - ➡ Nobel prize for Kobayahsi and Maskawa in 2008.
- However, there are some interesting "hints" of new physics:
  - ➡ Tension in V_{ub} (and V_{cb}).
  - ➡ Enhancement of $D^{(*)}\tau\nu$.
  - ➡ Anomalies in $B \to K^{*0} \mu^+\mu^-$.
  - ➡ Muon g-2.

all at ≥ 3σ

- We should be able to resolve all of these in the next 5 years.

Recap

- In today's lecture we discussed:
  - ➡ Flavour changing neutral current processes and constraints on new particles.
  - ➡ Minimal flavour violation.
  - ➡ Charged lepton flavour violation.
  - ➡ Future flavour experiments.

Further reading

- There are a number of good sets of lecture notes on flavour physics available on arXiv that give a more detailed overview of this field.
  - ➡ A. J. Buras, "Weak Hamiltonian, CP violation and rare decays," **[arXiv:hep-ph/9806471]**.
  - ➡ A. J. Buras, "Flavor physics and CP violation," **[arXiv:hep-ph/0505175].**
  - ➡ G. Isidori, "Flavor physics and CP violation," **[arXiv:1302.0661]**.
  - ➡ Y. Grossman, "Introduction to flavor physics," **[arXiv:1006.3534]**.
  - ➡ Y. Nir, "Flavour physics and CP violation," **[arXiv:1010.2666]**.
  - ➡ M. Neubert, "Effective field theory and heavy quark physics," **[arXiv:hep-ph/0512222]**.

Further reading

- Most introductory particle physics text books include a basic introduction to flavour physics.
- There are also more specialist books available, e.g.
  - ➡ I. I. Bigi and A. I. Sanda. “CP violation”
  - ➡ CP violation, G.C.Branco, L.Lavoura & J.P.Silva

Fin

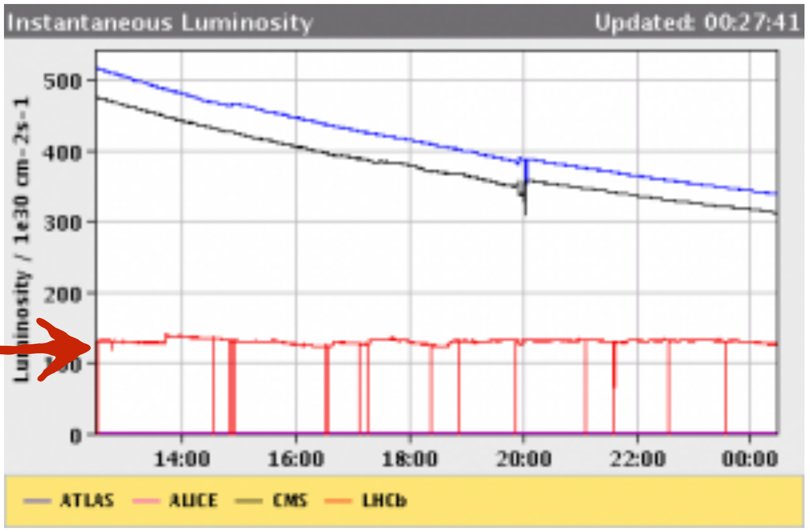
Future experiments

What next?

LHCb running conditions

- LHCb is currently running at a luminosity of $4 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.
- Displacing LHC beams to run at a lower luminosity that ATLAS and CMS.

running at a levelled luminosity



- How do we interpret this number?

$$\sigma(pp \to b\bar{b}) = (75.3 \pm 5.4 \pm 13.0)\mu\mathrm{b}$$ in LHCb acceptance

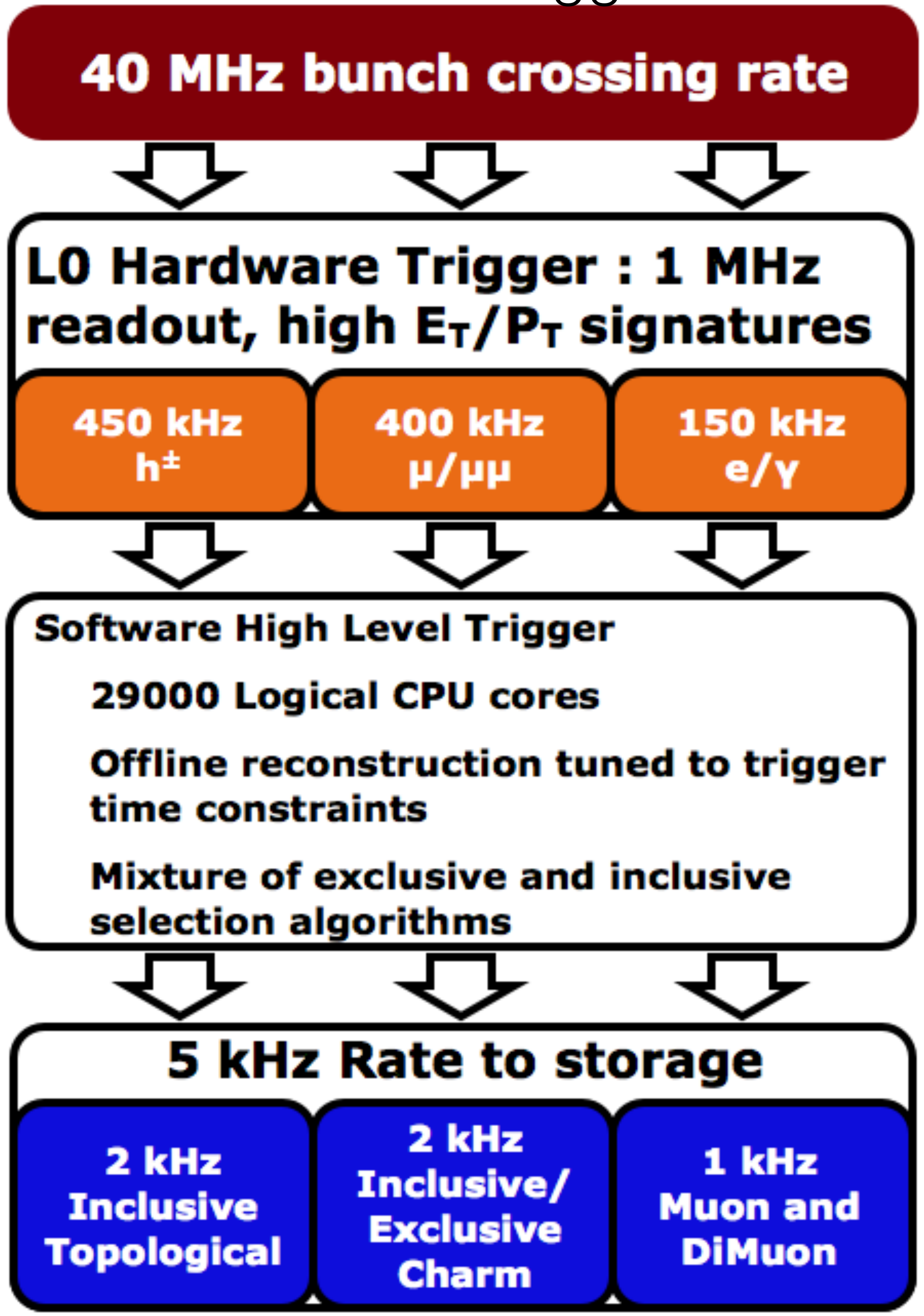
$$\longrightarrow \sim 30\,\mathrm{k}\ b\bar{b}\ \text{pairs per second}$$

- Higher luminosity means more B mesons produced per year and in turn better statistical precision.

LHCb upgrade

- Aim to run at 2×10^{33}.
- Main limitation with the current detector is the 1 MHz readout rate.
- Need to cut much harder maintain the 1MHz rate with higher luminosity (end up removing as much signal and background).
- Ambitious plan to read out the full detector at 40 MHz to a software farm.
- Also plans to replace vertex and tracking detectors to cope with higher luminosity.
- Upgrade planned for LS2 (2018).

current trigger scheme



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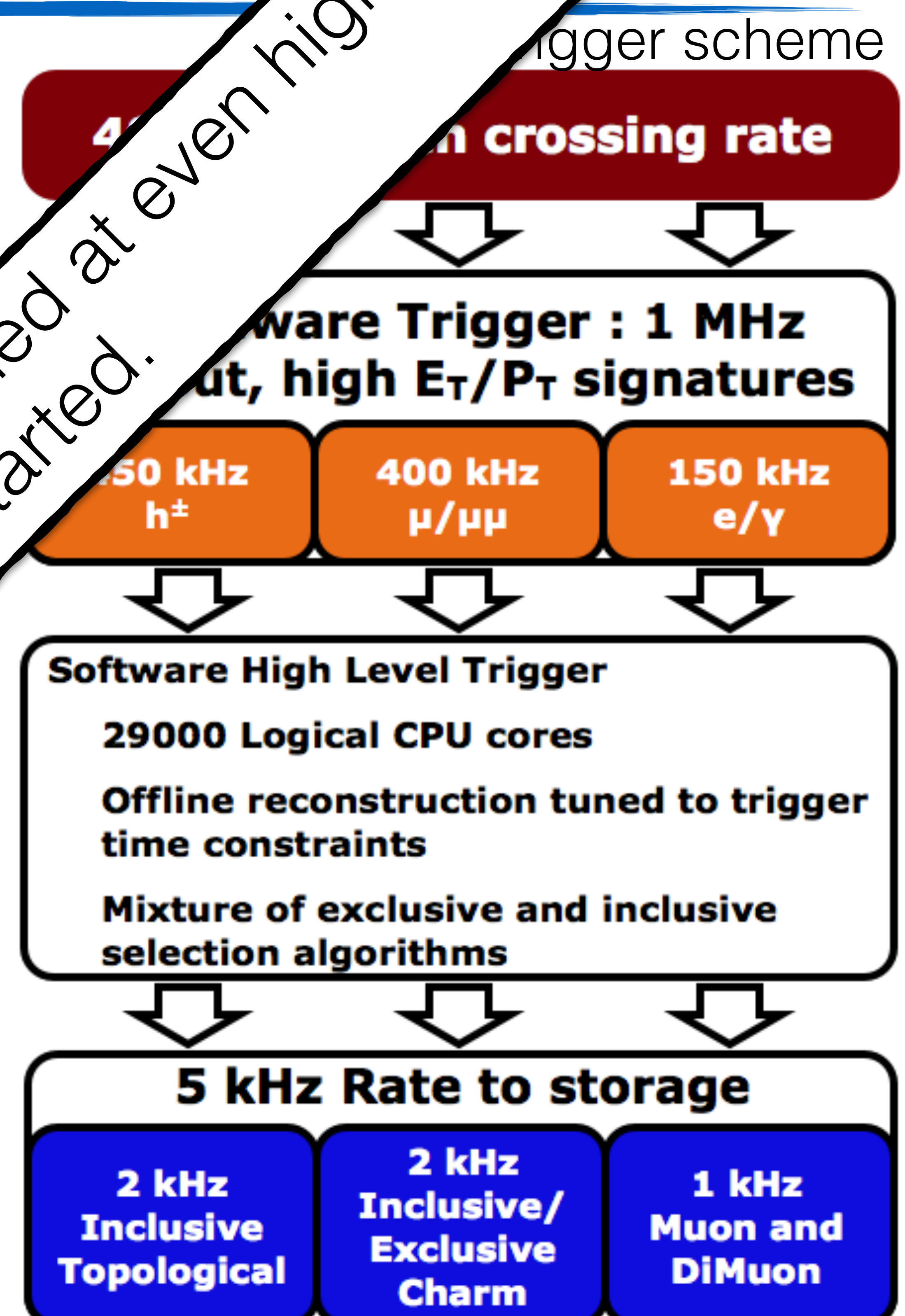
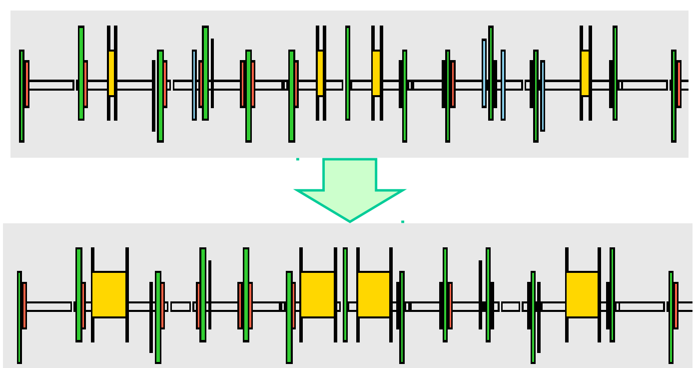
- Also plans t… …tex and tracking detectors … …higher luminosity.
- Upgra… …for LS2 (2018).



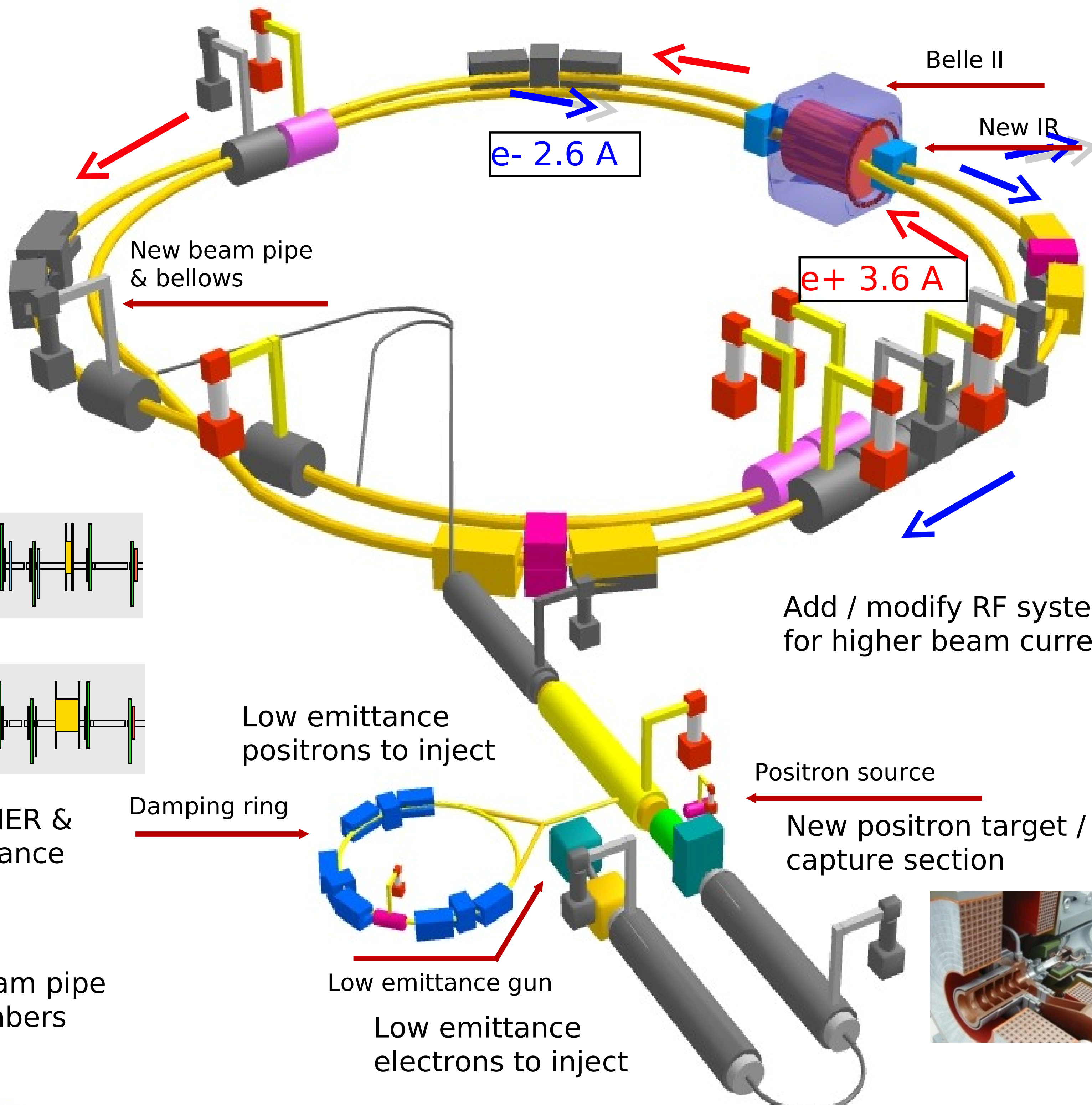
Discussion of a future upgrade aimed at even higher luminosities has started.

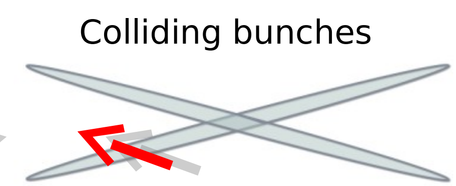
KEKB to SuperKEKB

Replace short dipoles with longer ones (LER)

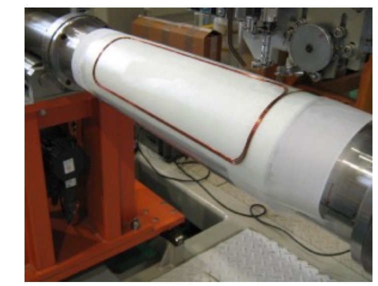


Redesign the lattices of HER & LER to squeeze the emittance





New superconducting /permanent final focusing quads near the IP



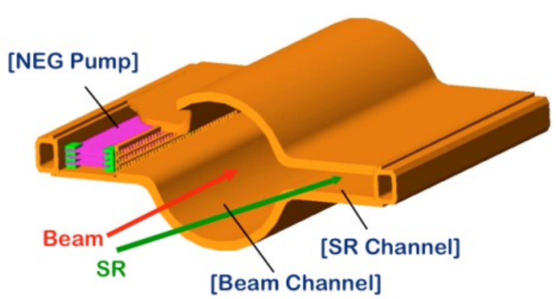
Add / modify RF systems for higher beam current

Low emittance positrons to inject

New positron target / capture section

Low emittance electrons to inject

TiN-coated beam pipe with antechambers



To obtain x40 higher luminosity

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

- The $A_{\Delta\Gamma}$ parameter modifies the effective lifetime of the decay:

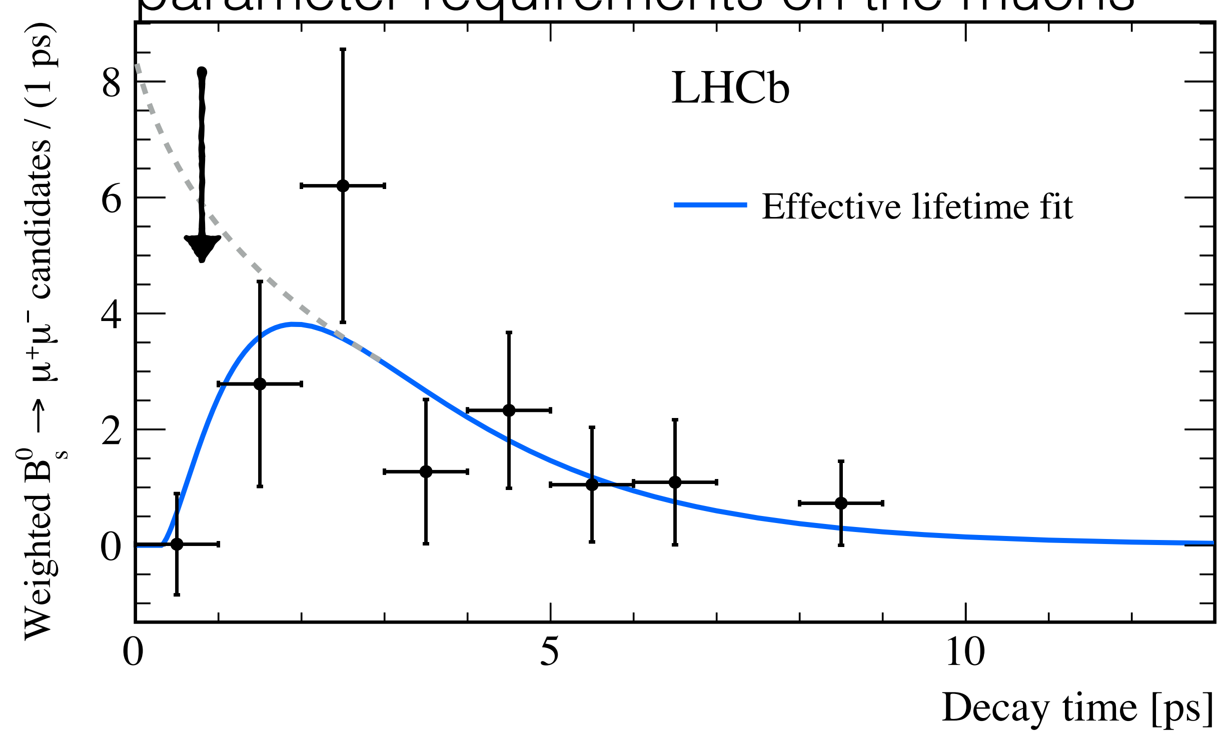
$$\tau_{\rm eff} = \frac{\tau_{B_s}}{1-y_s^2}\left(\frac{1+2A_{\Delta\Gamma}\,y_s+y_s^2}{1+A_{\Delta\Gamma}\,y_s}\right) \quad \text{where} \quad y_s = \tau_{B_s}\frac{\Delta\Gamma}{2}$$

- LHCb have performed a first measurement of $\tau_{\rm eff}$, giving

$$\tau[B_s^0\to\mu^+\mu^-] = 2.04 \pm 0.44 \pm 0.05\,{\rm ps}$$

NB Not yet sensitive to $A_{\Delta\Gamma}$ (the stat. uncertainty is larger than the change in the lifetime from $\Delta\Gamma_s$). This will become more interesting during Run 3 and 4.

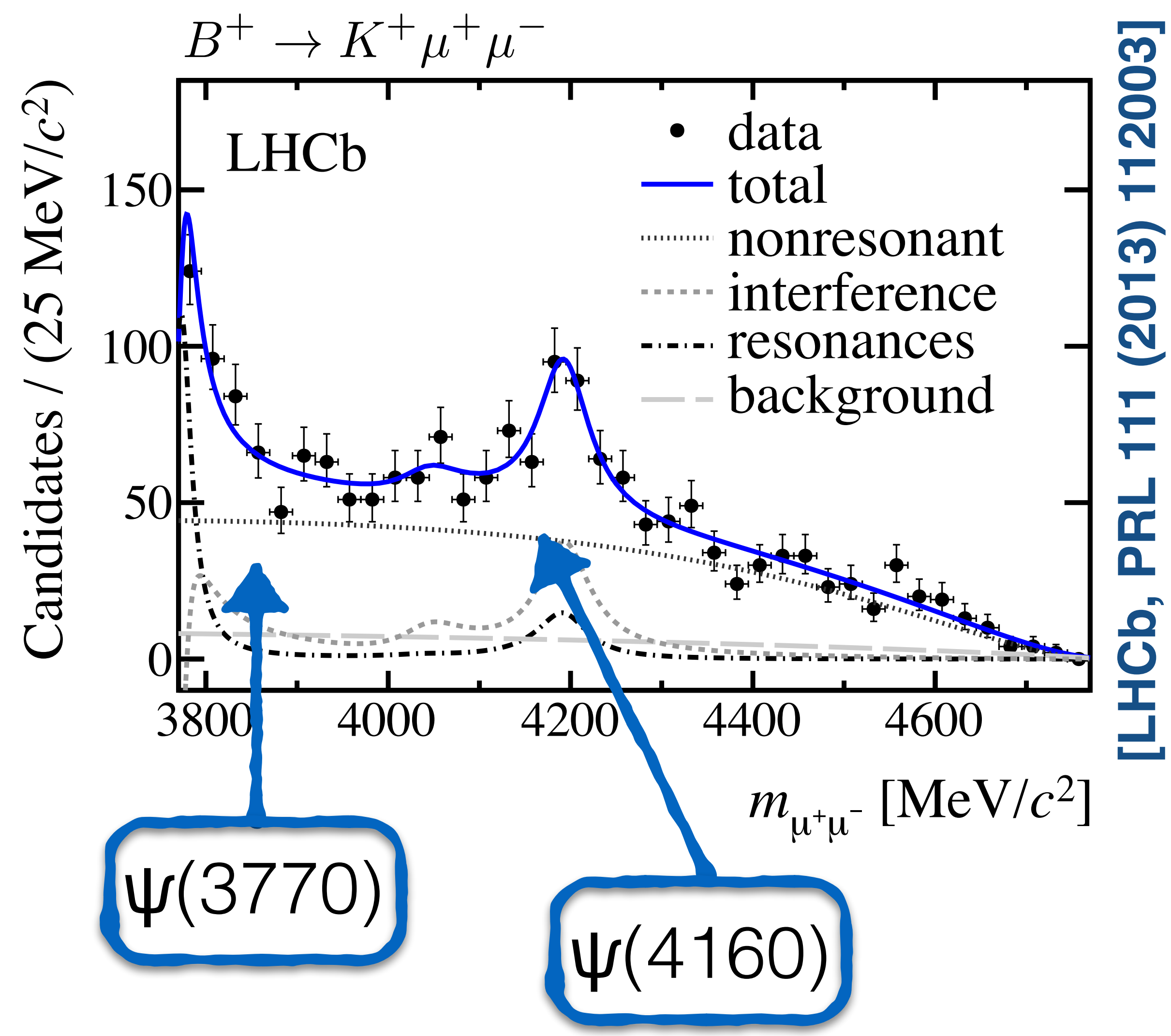
lifetime acceptance, due to impact parameter requirements on the muons



[LHCb, PRL 118 (2017) 191801]

Resonance structure

- See large resonant contributions from $c\bar{c}$ states at large dimuon masses.
- We can fit this with a Breit-Wigner ansatz (but only after assuming some q^2 parameterisation for the non-resonant part) to extract magnitudes and relative phases.



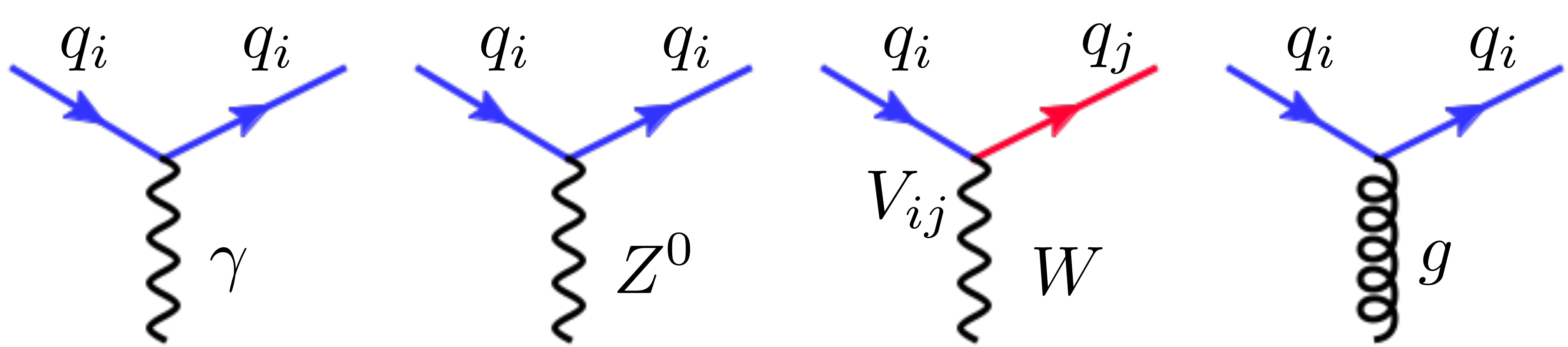
i.e. use a shape

$$\text{phsp} \times (|\mathcal{A}_{\rm V}(m_{\mu\mu}) + \sum_i e^{i\phi_i}\mathcal{A}_i(m_{\mu\mu}, \mu_i, \Gamma_i)|^2 + |\mathcal{A}_A|^2) f_+^2(m_{\mu\mu})$$

for narrow states this needs to be convoluted by our experimental resolution

No FCNC at tree level in SM

- Charged current interaction is the only flavour changing process in the SM.

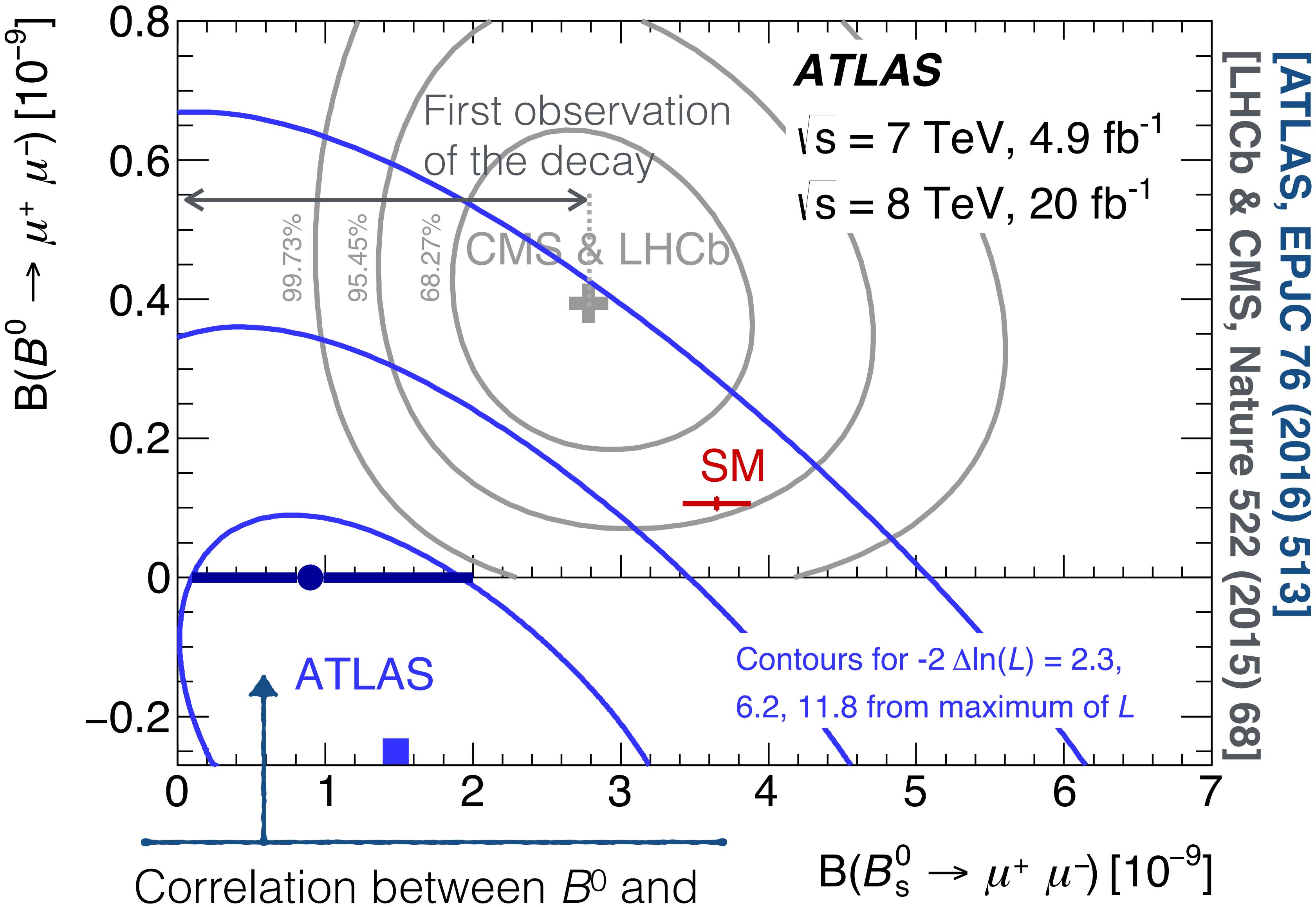


- Flavour changing neutral current processes are therefore forbidden at tree level (require a loop process involving a virtual W exchange).
- Consequence of the GIM mechanism.

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

- Experiments perform a simultaneous fits to determine the B^0 and B_s branching fractions.

- Signal normalised to $B^+ \to J/\psi K^+$ ($B^0 \to K^+\pi^-$ and $B_s \to J/\psi\phi$ in LHCb), with input on the b-meson production fractions.



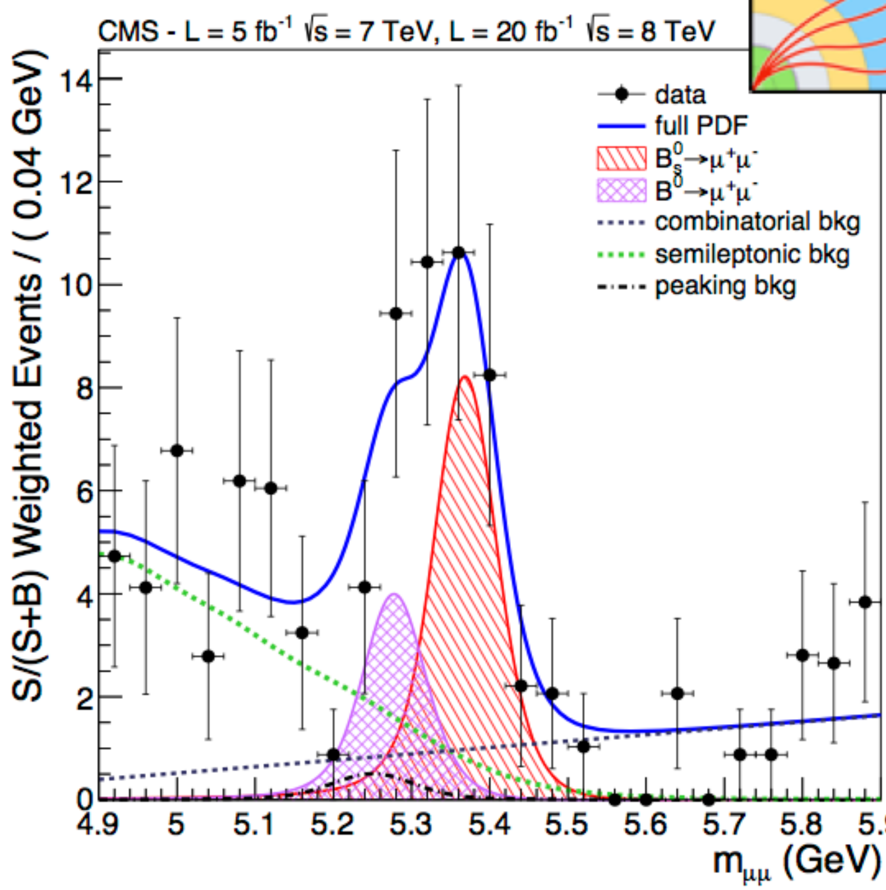
Correlation between B^0 and B_s due to mass resolution

$B_s \rightarrow \mu^+ \mu^-$

- Very rare decay with branching fraction of 10^{-9}:

25fb^{-1} and 3fb^{-1} respectively

[PRL 111 (2013) 101804]

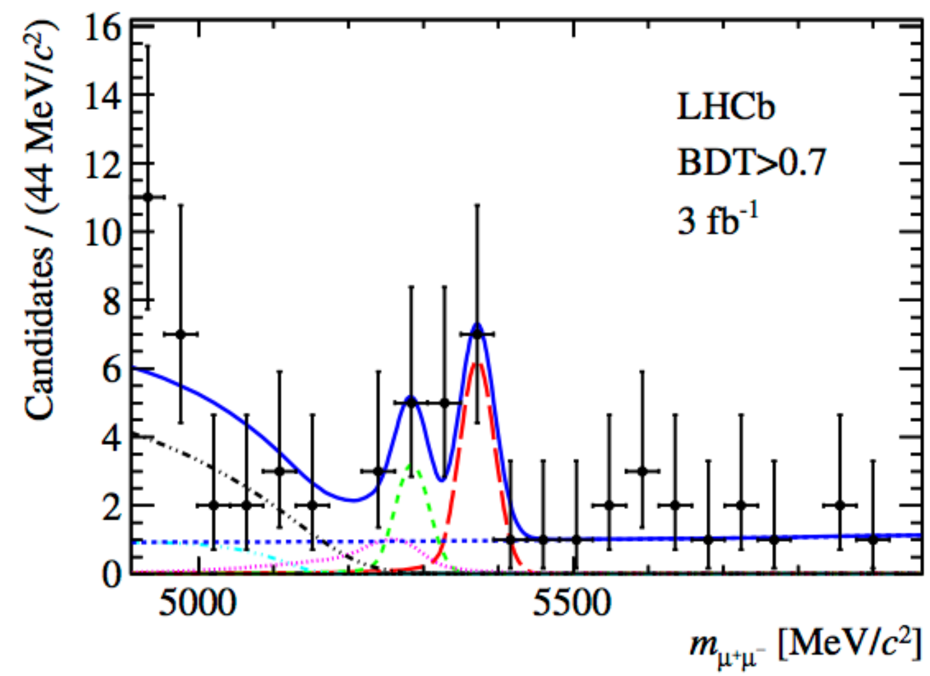


$$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = 3.0^{+1.0}_{-0.9} \times 10^{-9} \quad (4.3\sigma)$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = 3.5^{+2.1}_{-1.8} \times 10^{-10} \quad (2.0\sigma)$$

Nov. 2012: LHCb found the first evidence of the $\mathcal{B}(B^0{}_s \rightarrow \mu^+\mu^-)$ with 2.1fb^{-1}

[PRL 111 (2013) 101805]



$$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = 2.9^{+1.1}_{-1.0} \times 10^{-9} \quad (4.0\sigma)$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = 3.7^{+2.4}_{-2.1} \times 10^{-10} \quad (2.0\sigma)$$

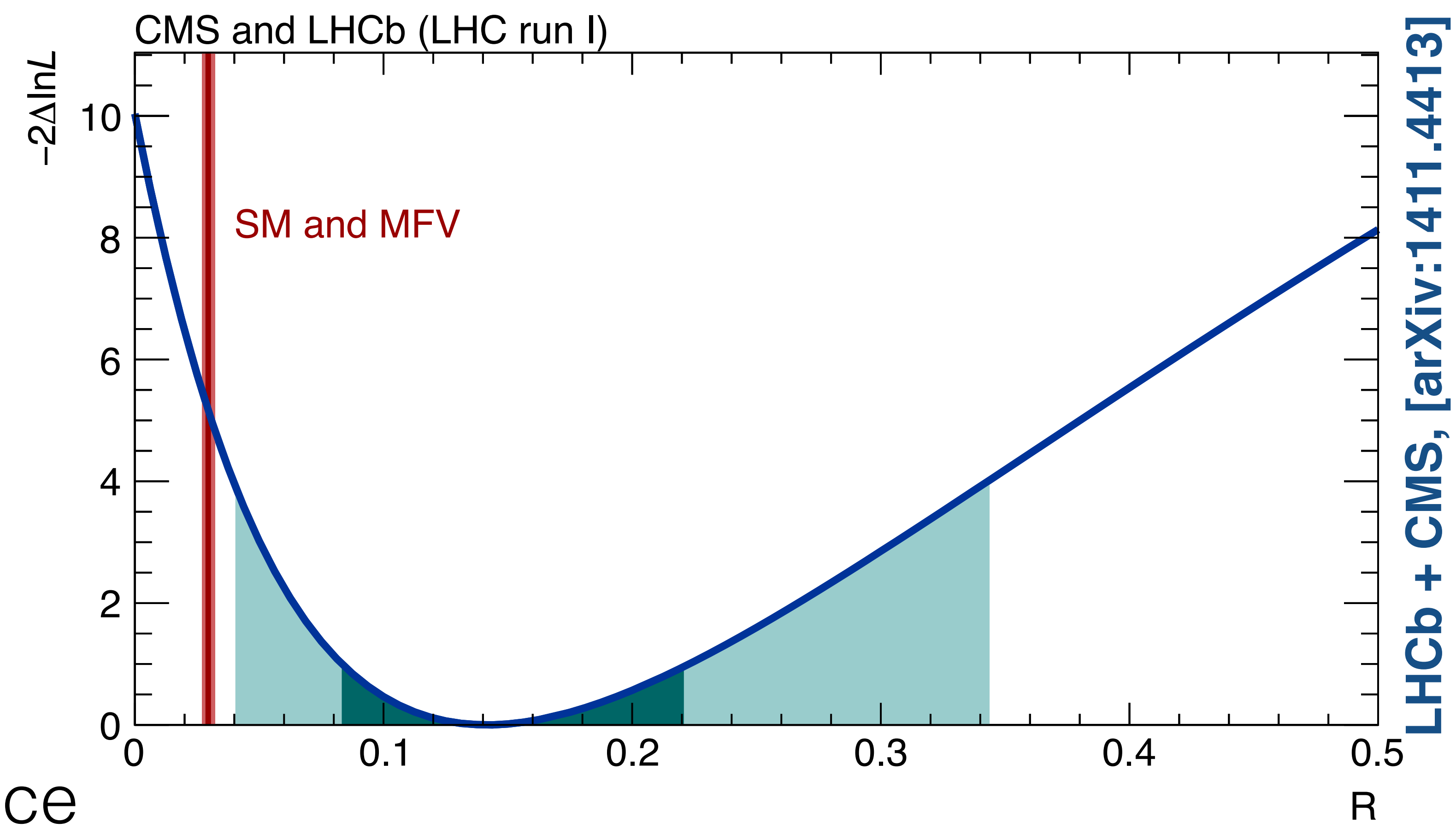
Testing MFV

- Ratio of the rates of the two decays is a test of MFV which predicts:

$$\mathcal{R}(B^0/B^0_s) \propto \frac{|V_{td}|^2}{|V_{ts}|^2}\frac{f^2_{B^0}}{f^2_{B^0_s}}$$

~1/25

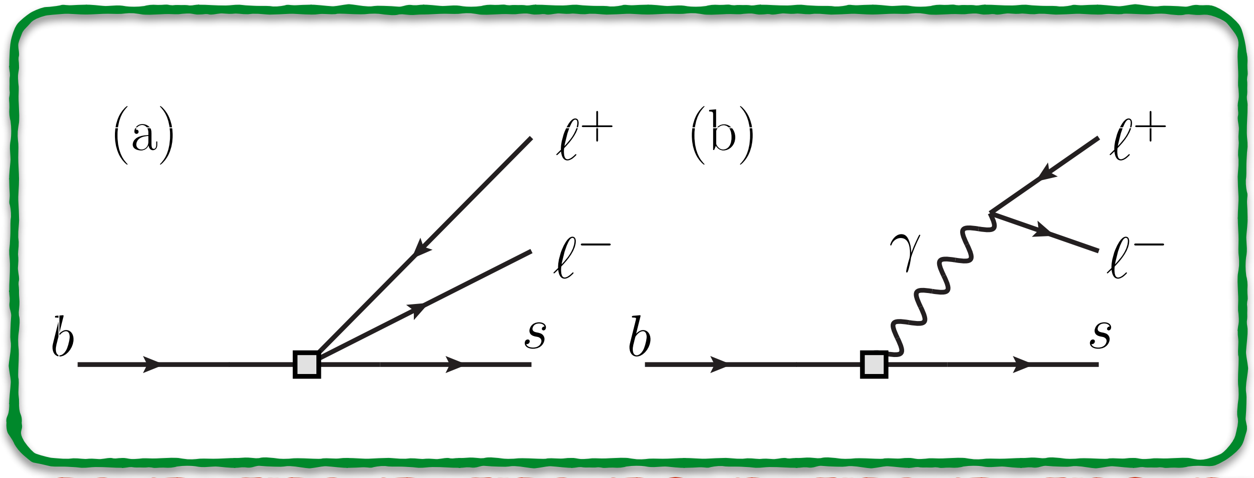
from Lattice



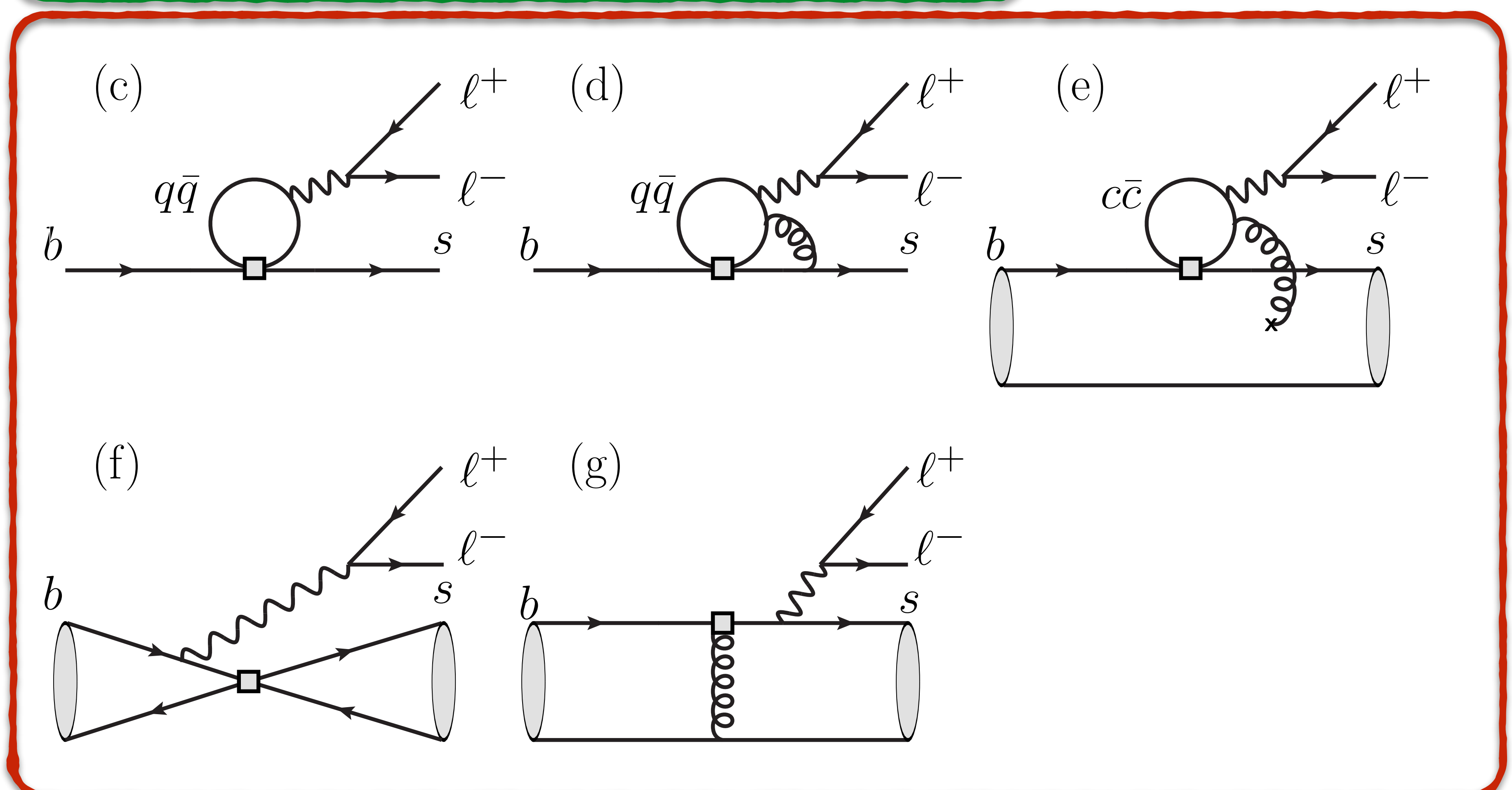
Data are consistent with SM/MFV

SM contributions

- Interested in new short distance contributions.
- We also get long-distance hadronic contributions.
- Need estimate of non-local hadronic matrix elements **[Khodjamirian et al. JHEP 09 (2010) 089]**



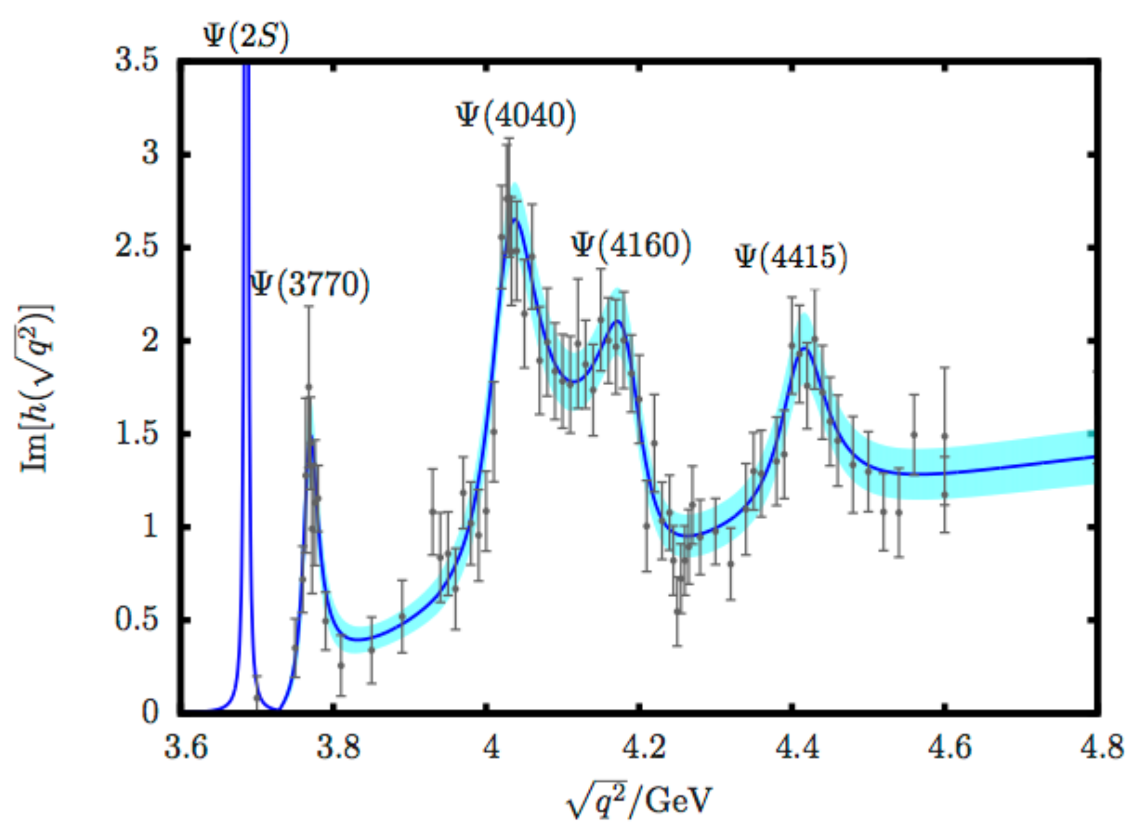
Short distance part integrates out (as a Wilson coefficient)

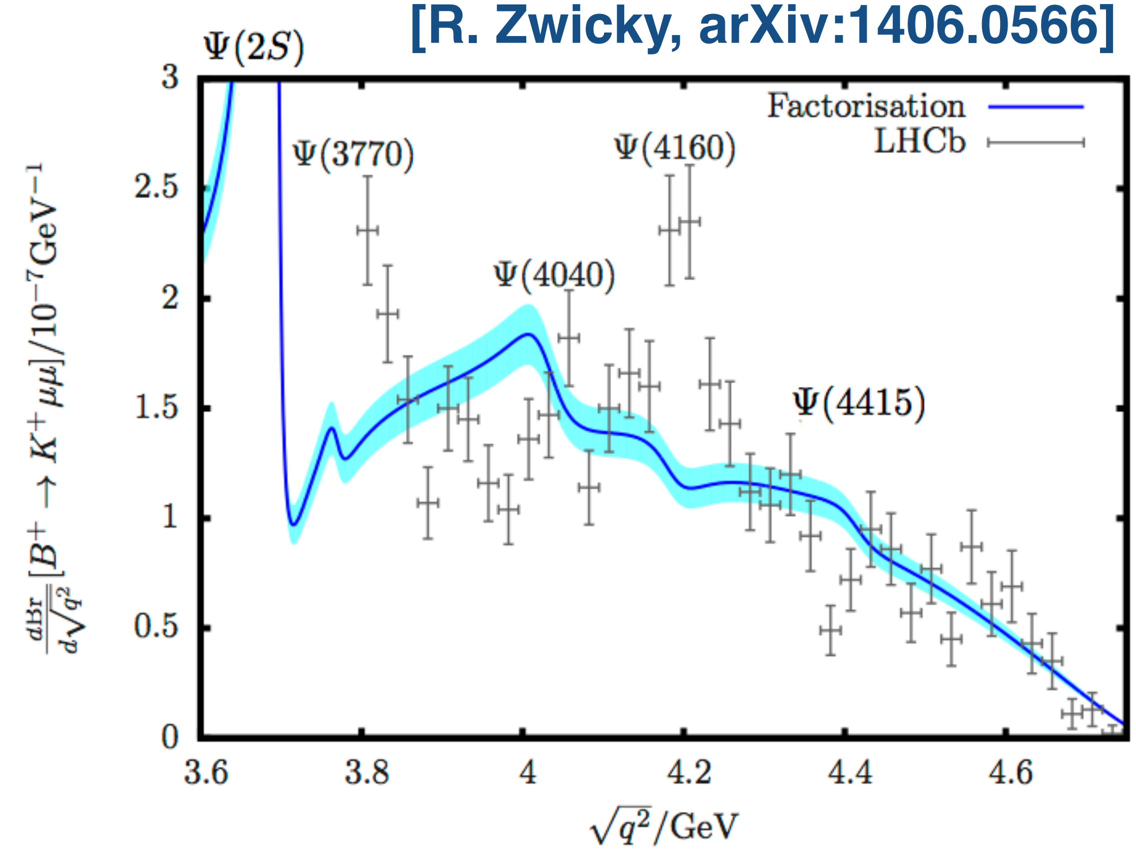


Resonance structure

- Can try determine the factorisable charm loop contribution from vacuum polarisation data , i.e. from $\sigma(e^+e^- \to \text{hadrons})$

[R. Zwicky, arXiv:1406.0566]

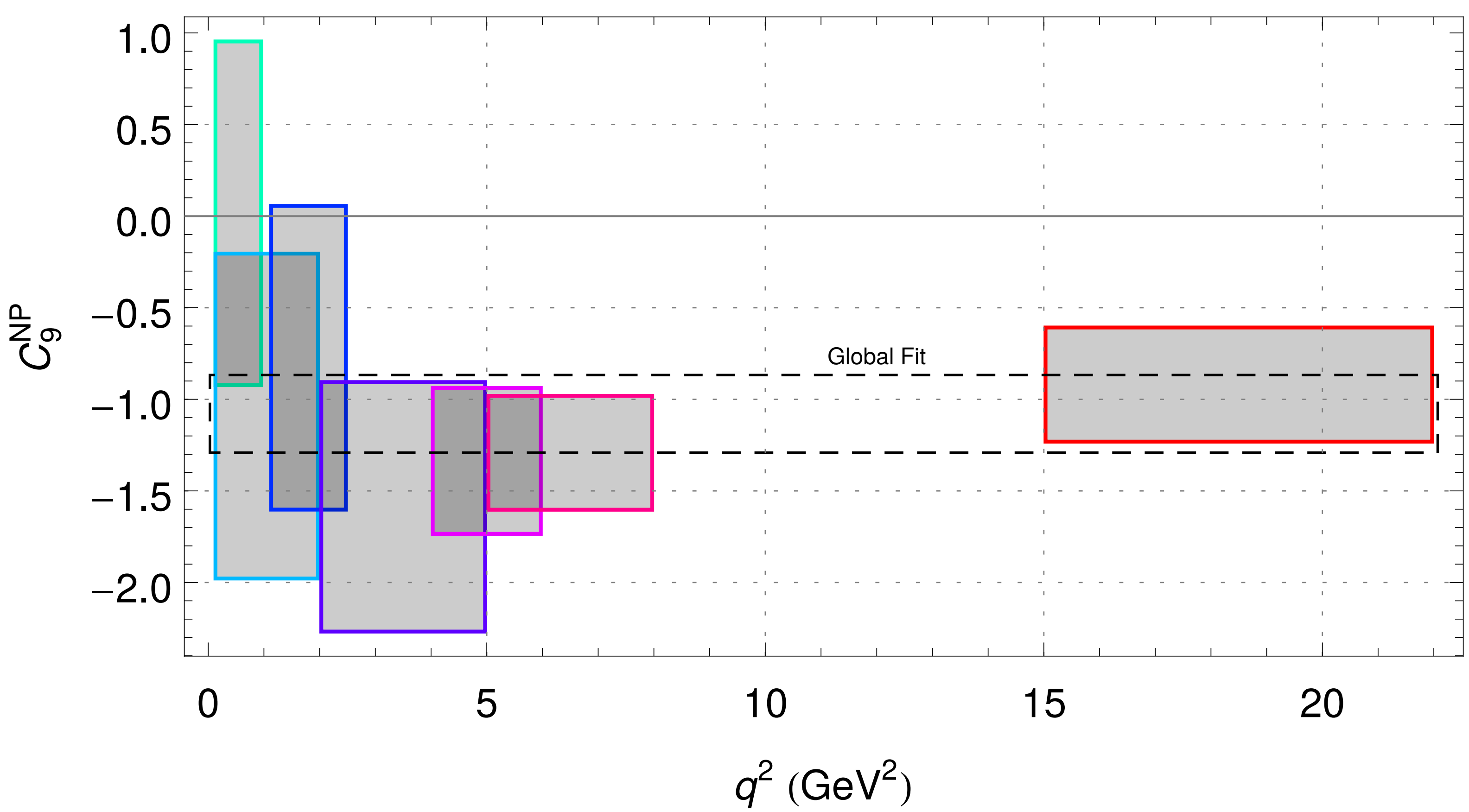




- Large difference between prediction and observed spectrum seems to imply that there are huge non-factorisable effects.

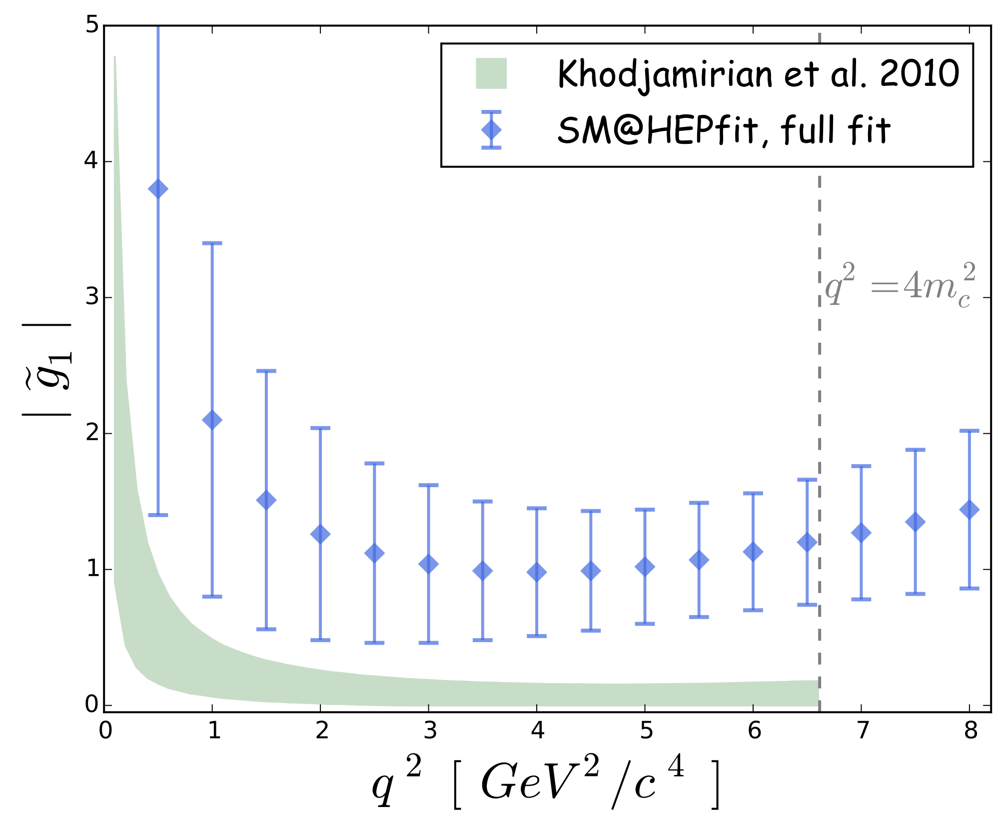
What can we learn from the data?

- If we are underestimating $c\bar{c}$ contributions then naively expect to see the shift in C_9 get larger closer to the narrow charmonium resonances.



[Decotes-Genon et al JHEP 06 (2016) 092]

Fitting separately for C_9 in different q^2 regions.



[M. Ciuchini et al, JHEP 06 (2016) 116]

Parameterised fit for charm contributions in $B^0 \to K^{*0}\mu^+\mu^-$ decays with $C_9 = C_9^{SM}$.

➡ **No clear evidence for a rise in the data (but more data is needed).**

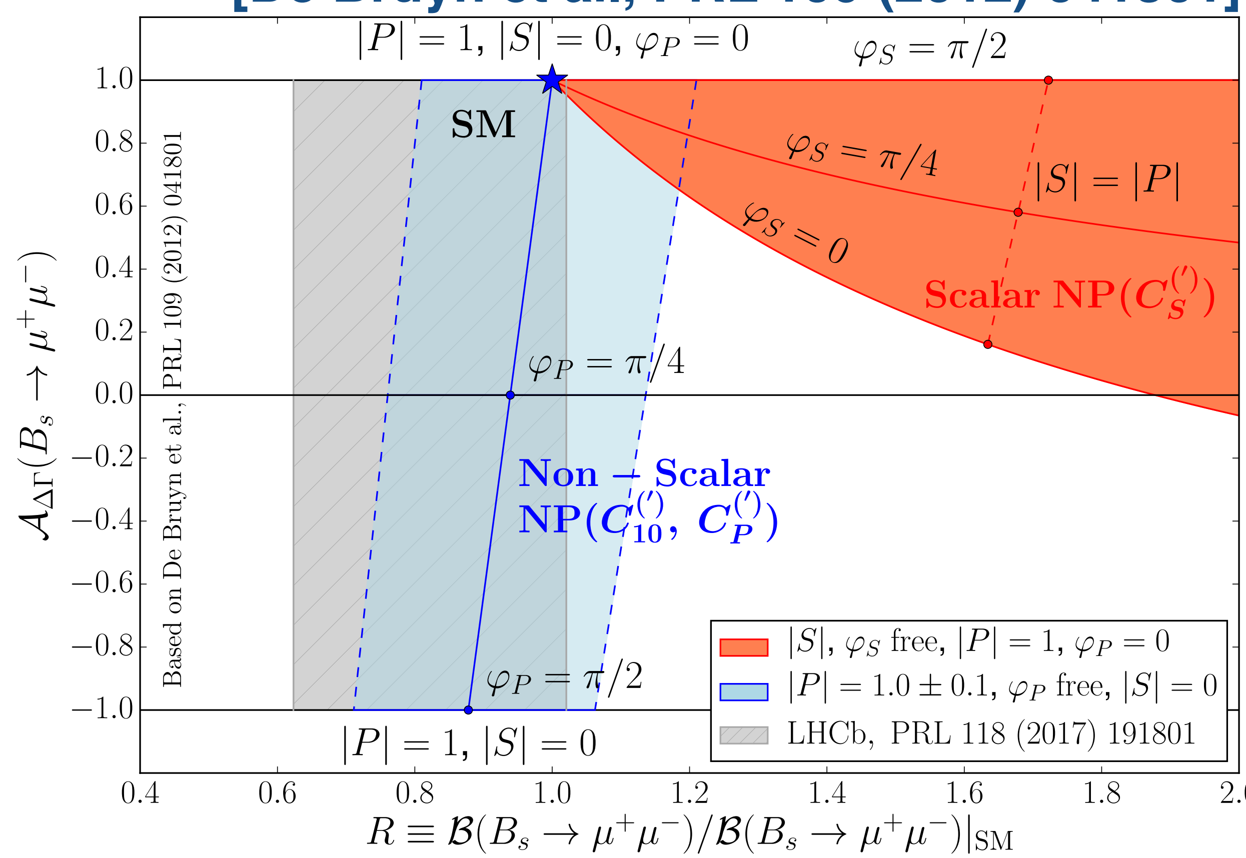
Effective lifetime

- The untagged time dependent decay rate is

$$\Gamma[B_s(t) \to \mu^+\mu^-] + \Gamma[\bar{B}_s(t) \to \mu^+\mu^-] \propto$$
$$e^{-t/\tau_{B_s}} \left\{ \cosh\left(\frac{\Delta\Gamma_s}{2} t\right) + A_{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_s}{2} t\right) \right\}$$

- $A_{\Delta\Gamma}$ provides additional separation between scalar and pesudoscalar contributions.
- In the SM $A_{\Delta\Gamma} = 1$ such that the system evolves with the lifetime of the heavy B_s mass eigenstate.

[De Bruyn et al., PRL 109 (2012) 041801]



ATLAS $B_{(s,d)} \to \mu^+\mu^-$ result

- A new result from ATLAS was presented at Moriond EW using their full Run 1 data sample

- Observed limit (95% CL): $\mathcal{B}(B^0_s \to \mu^+\mu^-) < 3.0 \times 10^{-9}$

- Expected limit (95% CL): $\mathcal{B}(B^0_s \to \mu^+\mu^-) < 1.8 \times 10^{-9}$

NB ATLAS sensitivity is approaching that of LHCb and CMS.

[From talk by S. Palestini at Moriond EW 2016]