An introduction to Flavour Physics

Part 4

Thomas Blake

Warwick Week 2015

An introduction to Flavour Physics

- What's covered in these lectures:

1. An introduction to flavour in the SM.
2. Neutral meson mixing and sources of CP violation.
3. CP violation in the SM.
4. **Flavour changing neutral current processes.**

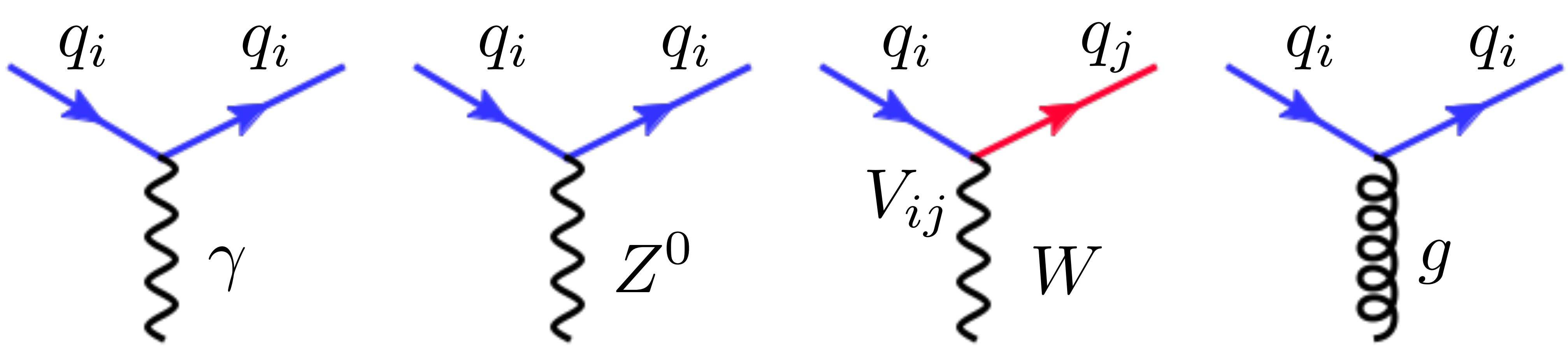
   ➡**Neutral meson mixing, rare decays, lepton flavour violation and constraints on new particles.**

The flavour problem

- If there is TeV-scale new physics (and we hope there is),

  why doesn't it manifest itself in flavour changing neutral currents (FCNCs)?

No FCNC at tree level in SM

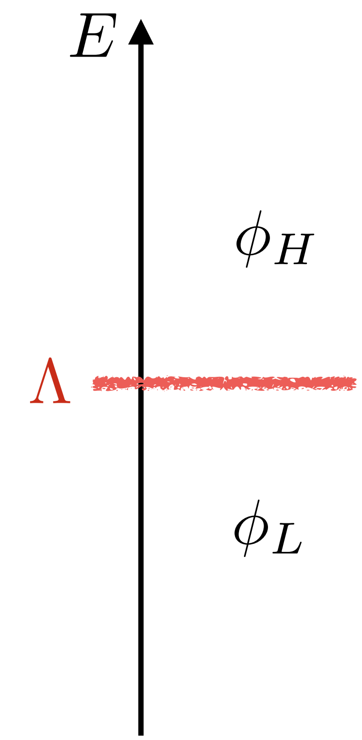


- Charged current interaction is the only flavour changing process in the SM.
- Flavour changing neutral current processes are therefore forbidden at tree level (require a loop process involving a virtual W exchange).

Effective theories

- In mesons/baryons there is a clear separation of scale.

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



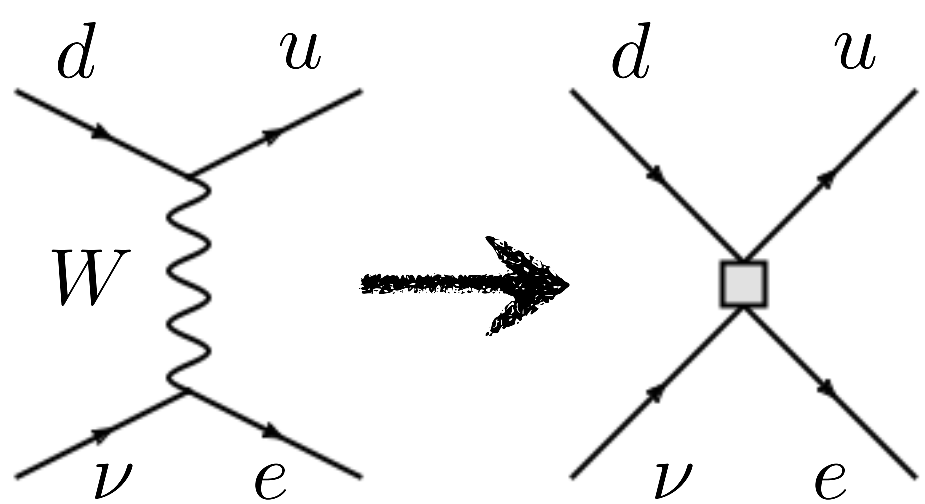
- We want to study the physics of the mixing/decay at or below a scale Λ, in a theory in which contributions from particles at a scale below and above Λ are present. Replace the full theory with an effective theory valid at Λ,

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

operator product expansion

Fermi's theory

- Example:
  - ➡ 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.

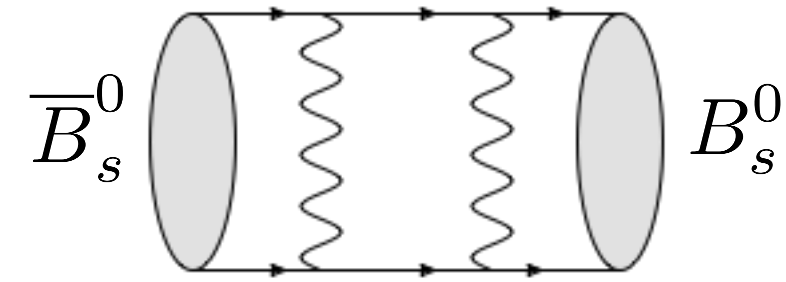


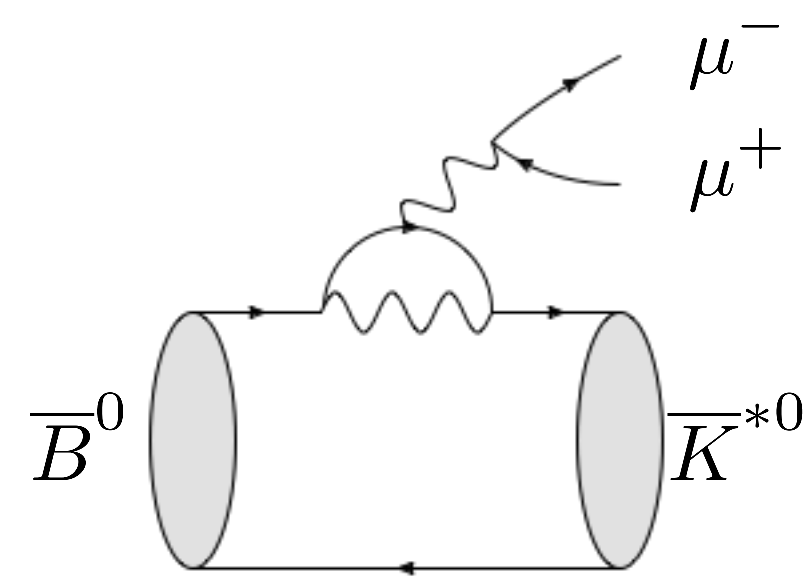
$$\mathcal{L}_{\mathrm{EW}} \to \mathcal{L}_{\mathrm{QED}} + \frac{G_{\mathrm{F}}}{\sqrt{2}}(\overline{u}d)(e\bar{\nu})$$

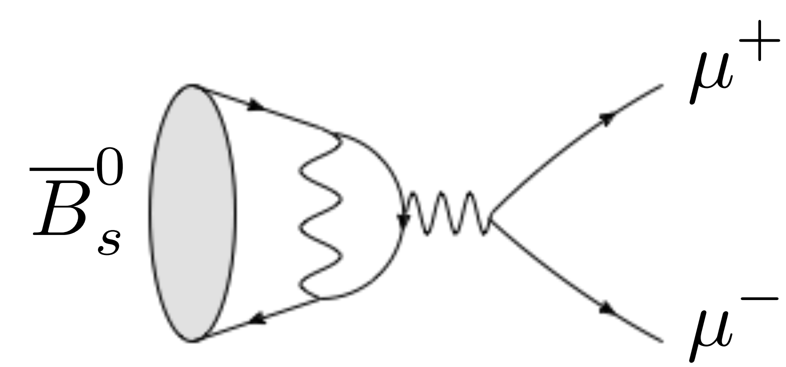
FCNC processes

- 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 which are CKM suppressed and can be highly GIM suppressed.







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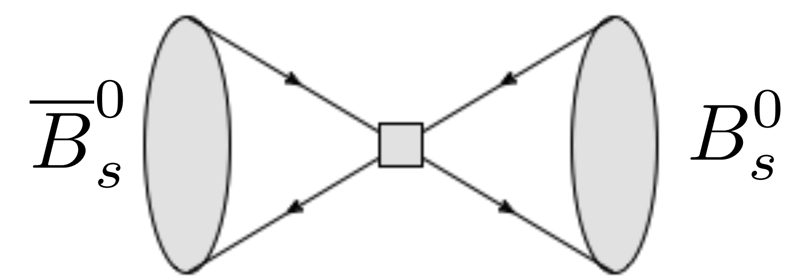

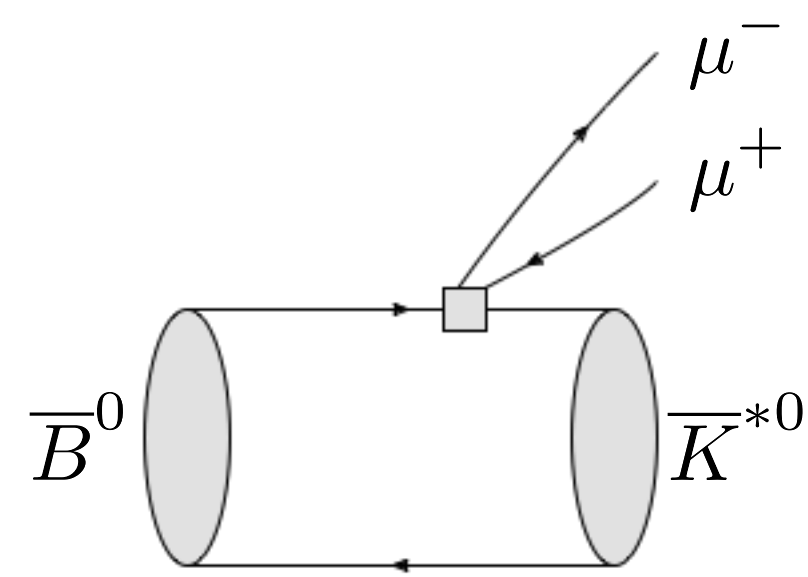

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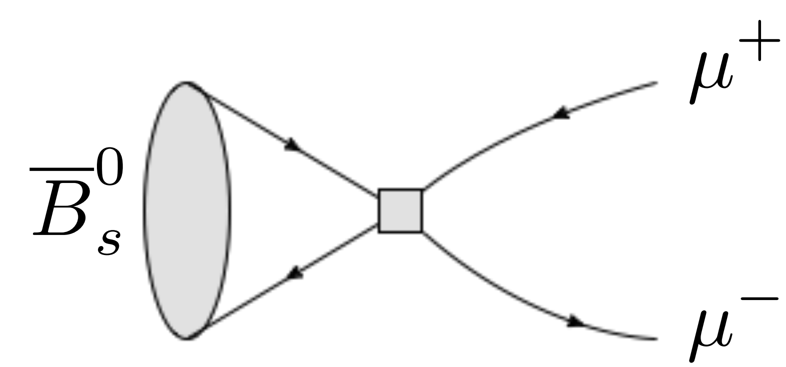
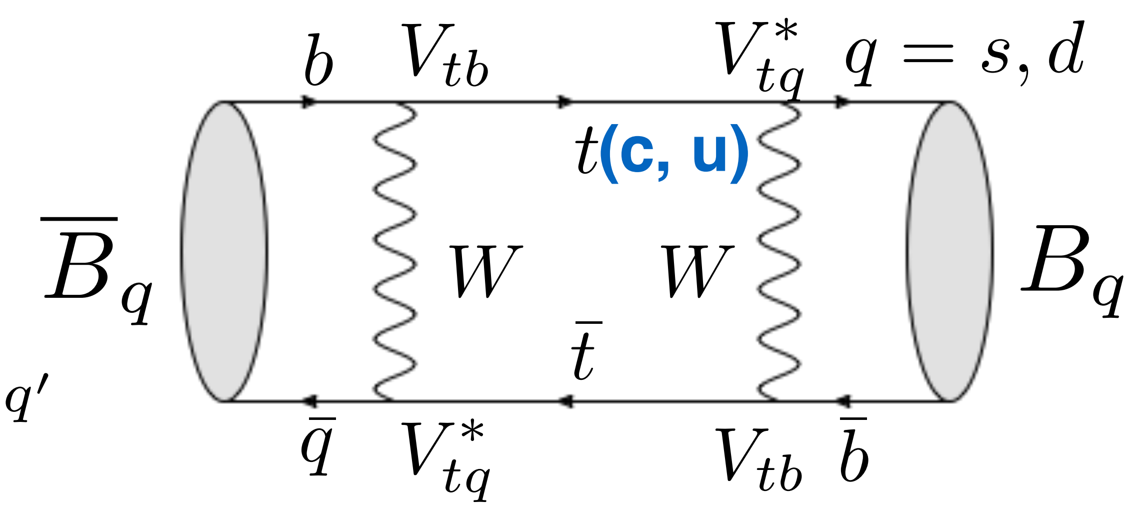


Mixing

Reminder: 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 $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb} * V_{td} = 0$

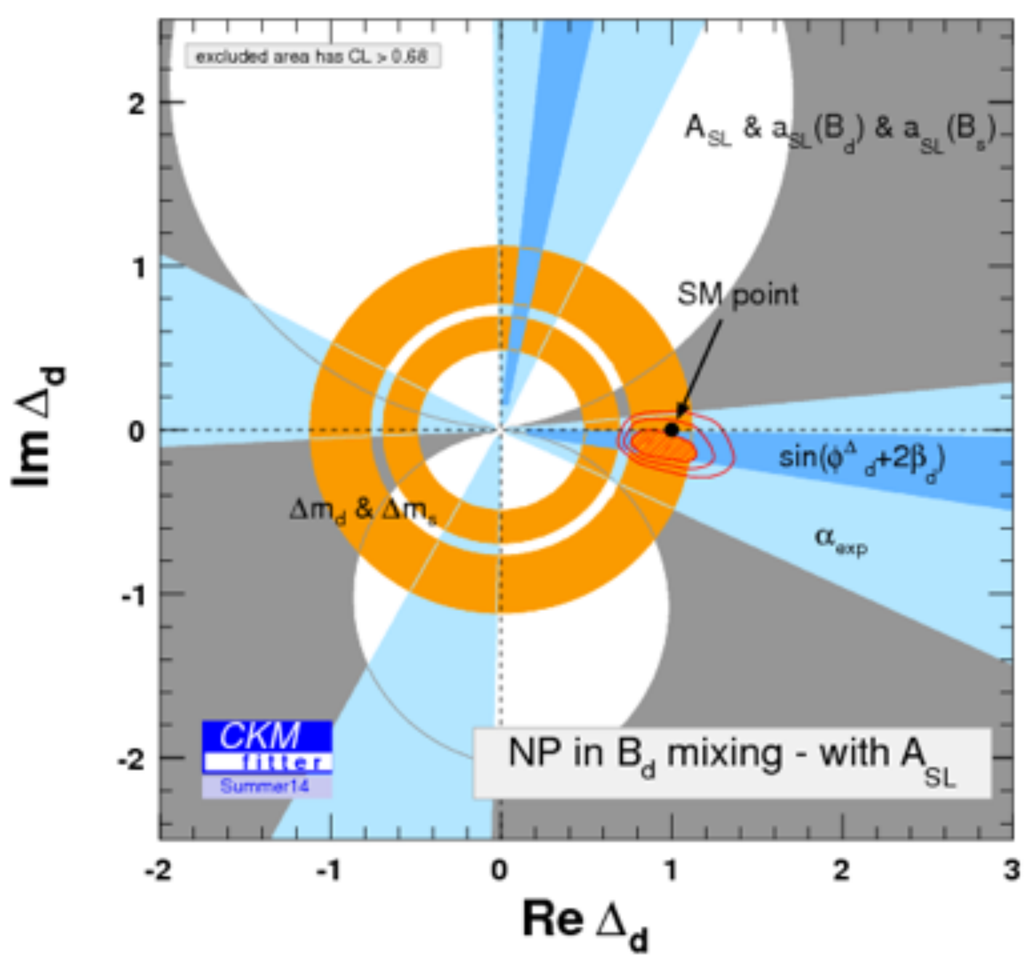
$$\mathcal{A}(B^0 \to \overline{B}^0) = \sum_{q} (V_{qb}^* V_{qd})[V_{tb}^* V_{td}(A_{tq} - A_{uq}) + V_{cb}^* V_{cd}(A_{cq} - A_{uq})]$$

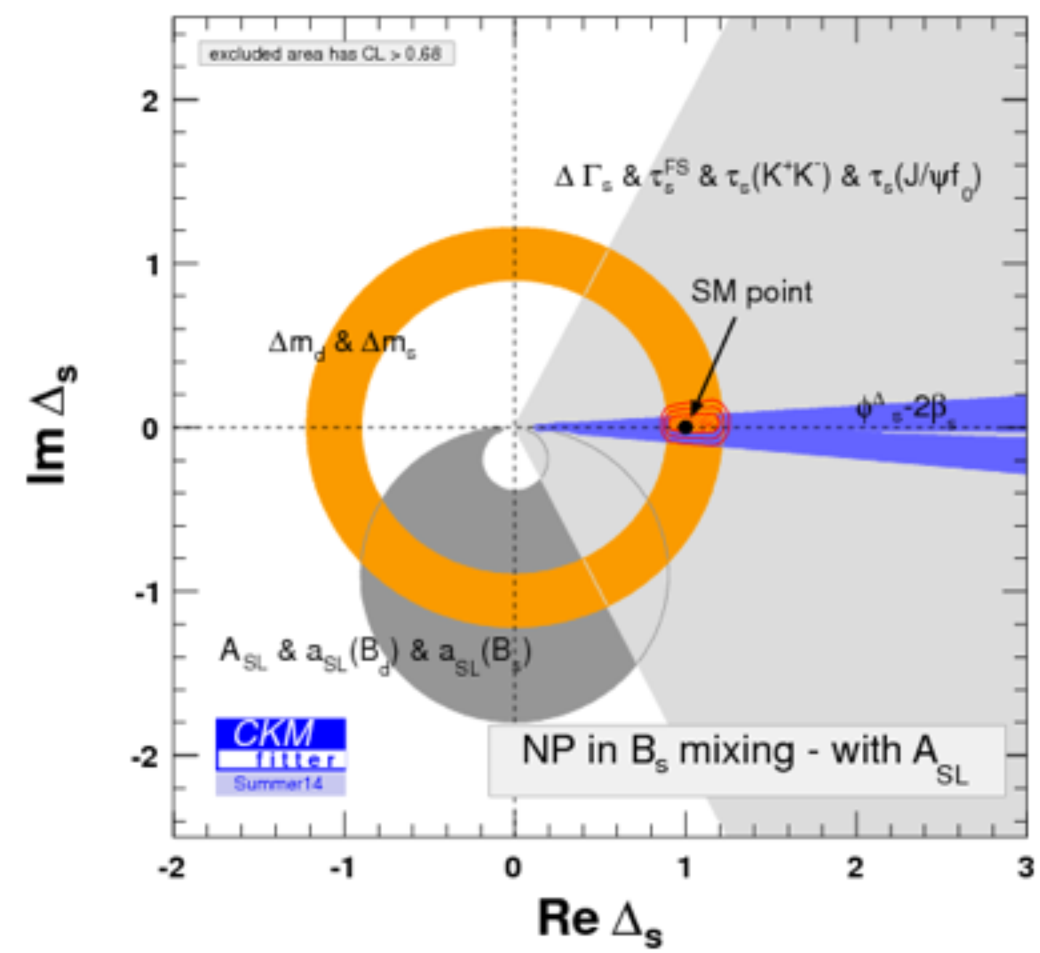
for the B system the top dominates

$\propto m_q m_{q'} / m_W^2$

New physics in B mixing?

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





consistent with SM (Re Δ =1, Im Δ = 0)

New physics in B mixing?

- Introducing new physics with at some higher energy scale Λ_{NP} with coupling κ_{NP}

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

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

SM contribution
from box diagram

NP contribution
(at dimension 6),
can include tree level FCNC

Mixing constraints

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

Operator	Re(Λ)	Im(Λ)	Re(c)	Im(c)	Constraint
$(\bar{s}_{\rm L}\gamma^{\mu}d_{\rm L})(\bar{s}_{\rm L}\gamma_{\mu}d_{\rm L})$	9.8×10^{2}	1.6×10^{4}	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K,\ \varepsilon_K$
$(\bar{s}_{\rm R}d_{\rm L})(\bar{s}_{\rm L}d_{\rm R})$	1.8×10^{4}	3.2×10^{5}	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K,\ \varepsilon_K$
$(\bar{c}_{\rm L}\gamma^{\mu}u_{\rm L})(\bar{c}_{\rm L}\gamma_{\mu}u_{\rm L})$	1.2×10^{3}	2.9×10^{3}	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D,\ \lvert q/p\rvert,\ \phi_D$
$(\bar{c}_{\rm R}u_{\rm L})(\bar{c}_{\rm L}u_{\rm R})$	6.2×10^{3}	1.5×10^{4}	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D,\ \lvert q/p\rvert,\ \phi_D$
$(\bar{b}_{\rm L}\gamma^{\mu}d_{\rm L})(\bar{b}_{\rm L}\gamma_{\mu}d_{\rm L})$	5.1×10^{2}	9.3×10^{2}	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_d,\ S_{J/\psi K^0_{\rm S}}$
$(\bar{b}_{\rm R}d_{\rm L})(\bar{b}_{\rm L}d_{\rm R})$	1.9×10^{3}	3.6×10^{3}	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_d,\ S_{J/\psi K^0_{\rm S}}$
$(\bar{b}_{\rm L}\gamma^{\mu}s_{\rm L})(\bar{b}_{\rm L}\gamma_{\mu}s_{\rm L})$	1.1×10^{2}	1.3×10^{2}	7.6×10^{-6}	7.6×10^{-6}	Δm_s
$(\bar{b}_{\rm R}s_{\rm L})(\bar{b}_{\rm L}s_{\rm R})$	3.7×10^{2}	3.7×10^{2}	1.3×10^{-5}	1.3×10^{-5}	Δm_s

$\Lambda_{\rm NP}$ in TeV when coupling =1

coupling (c = κ) when $\Lambda_{\rm NP}$ = 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.

$\boxed{\kappa_{\rm NP}}$

generic tree-level

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

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.

Rare decays

Rare b → s decays

- Can write a Hamiltonian for the effective theory as

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

Wilson coefficient
(integrating out
scales above μ)

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

Rare b → 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.

Beyond the SM

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

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

NP scale

local operator

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

Operators

right handed currents (suppressed in SM)

photon penguin

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

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

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

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

vector and axial-vector current

Operators (beyond SM)

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

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

- Tensor operators

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

- 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

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

Hadronic matrix element

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

$$\mathcal{B}(B \to X_s \gamma) = \mathcal{B}(b \to s\gamma) + \mathcal{O}(\Lambda_{QCD}^2 / m_B^2)$$

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

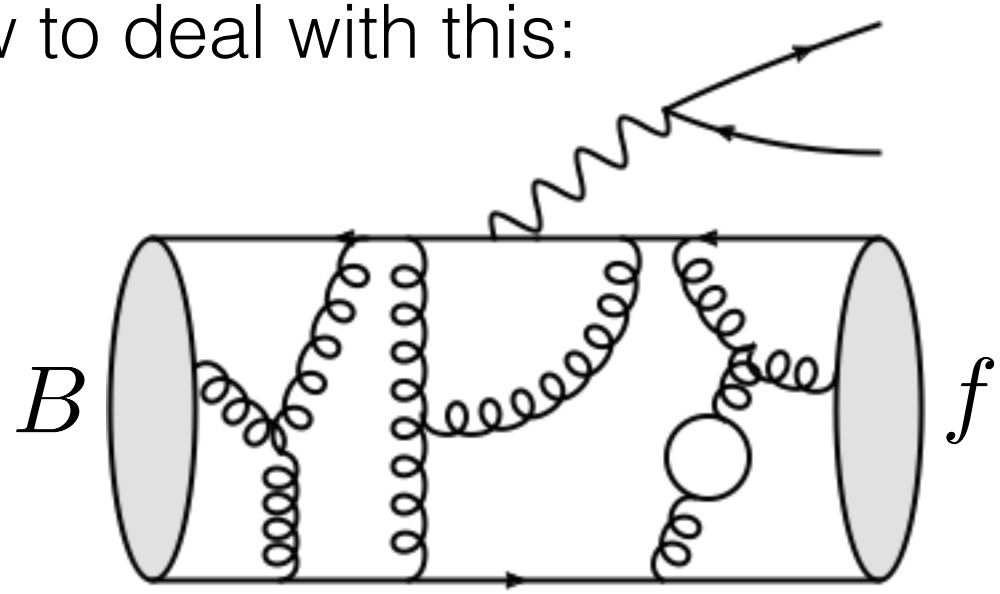
Generic $\Delta F = 1$ process

- Inclusive processes are theoretically clean, but experimentally challenging.
- Exclusive processes are theoretically challenging.
  - ➡ Involve non-perturbative quantities.
- Estimate form-factors using, light-cone-sum-rules and Lattice QCD.

Form factors

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

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 → π 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, $b \rightarrow s$ 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 $V_{ts} \ll V_{tb}$.

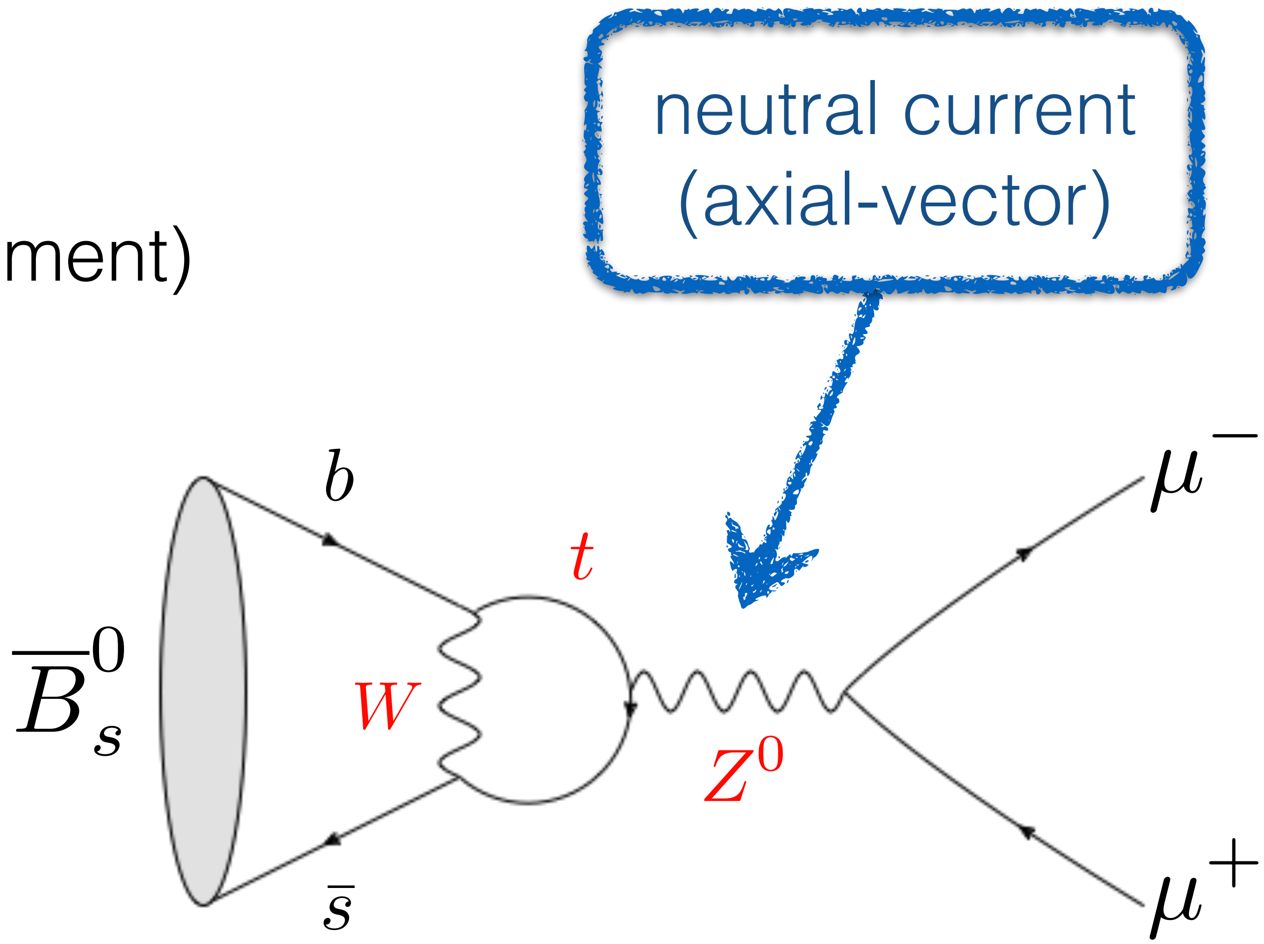
$B_s \rightarrow \mu^+ \mu^-$

- 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-1/2 muons)



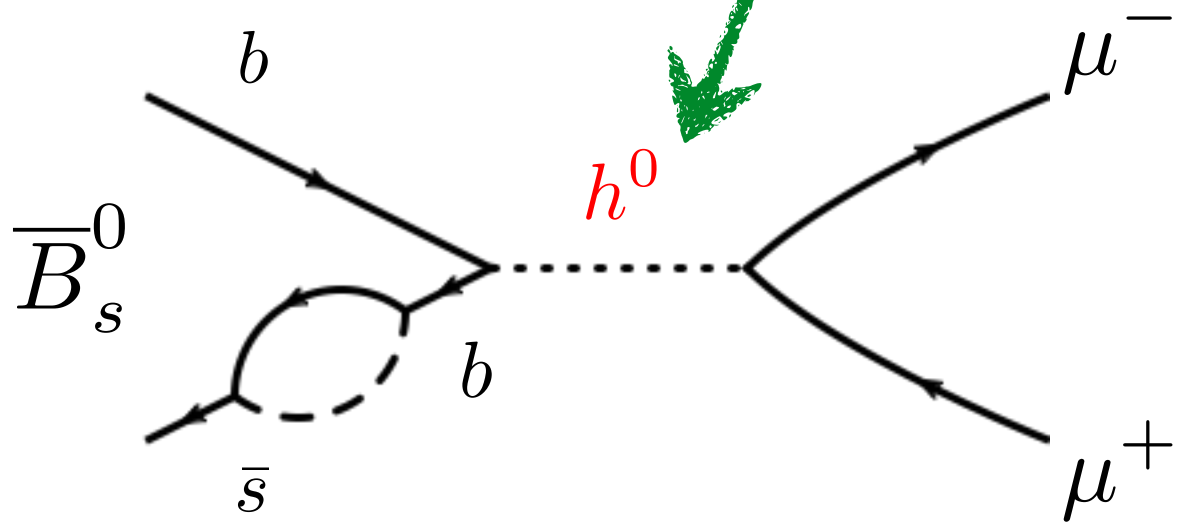
also receives contributions from W box diagrams

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

- 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)

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:

CKM factors

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

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

helicity suppression

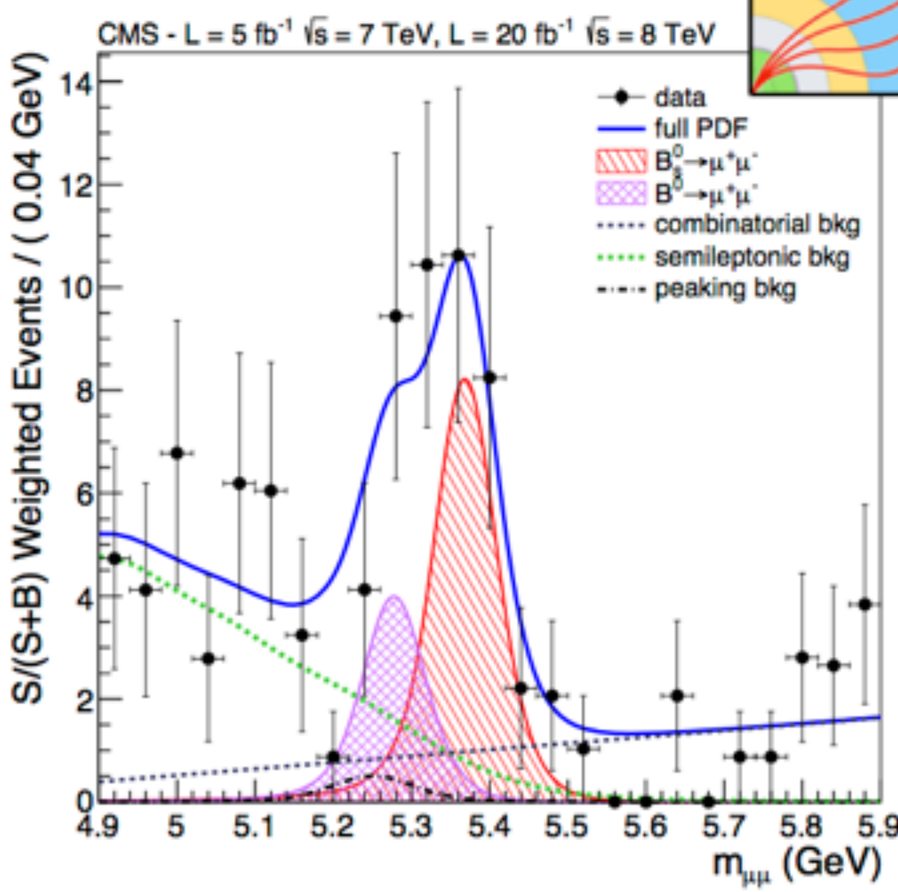
$$\times\left(\frac{M_\mu^2}{M_B^2}\right)$$

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

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

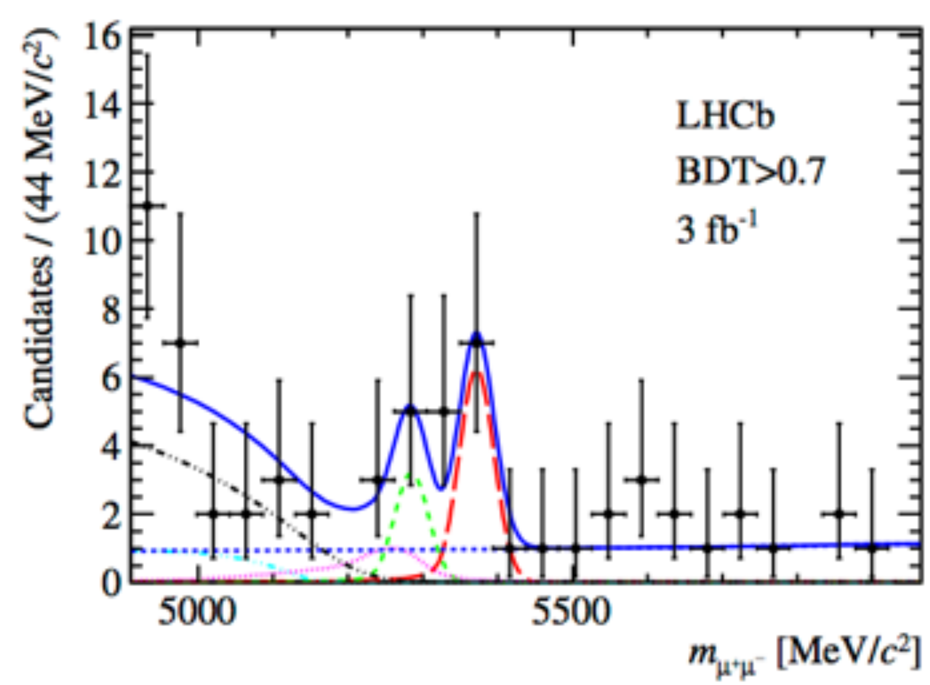
25fb^{-1} and 3fb^{-1} respectively

[PRL 111 (2013) 101804]



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]



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

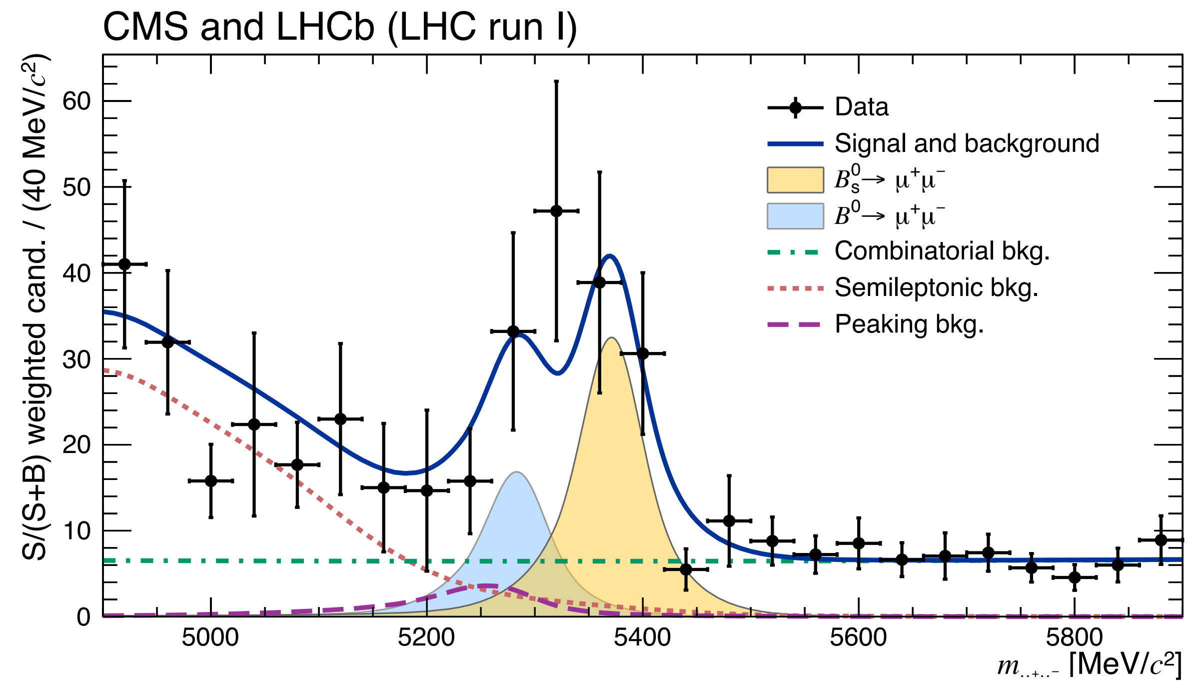
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = 3.5^{+2.1}_{-1.8} \times 10^{-10} \ \ (2.0\sigma)$$

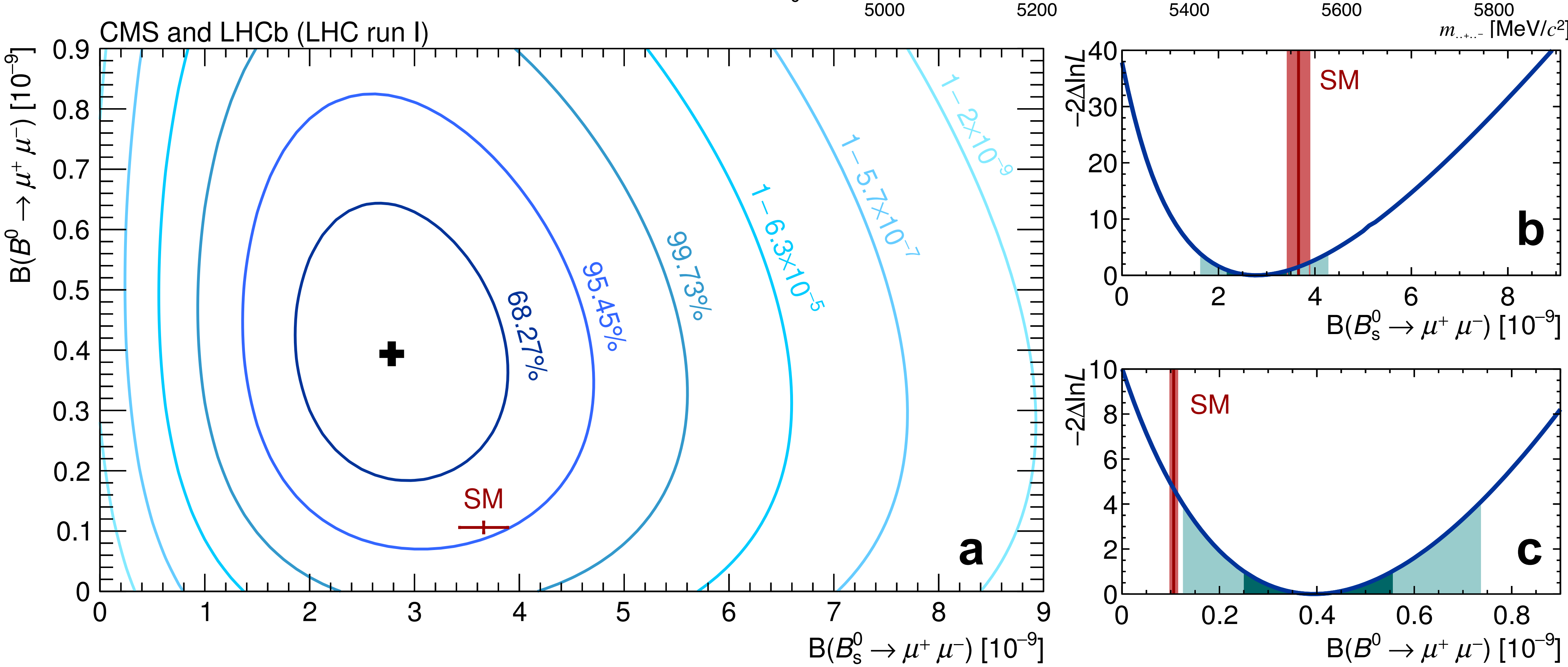
$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = 2.9^{+1.1}_{-1.0} \times 10^{-9} \ \ (4.0\sigma)$$

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

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

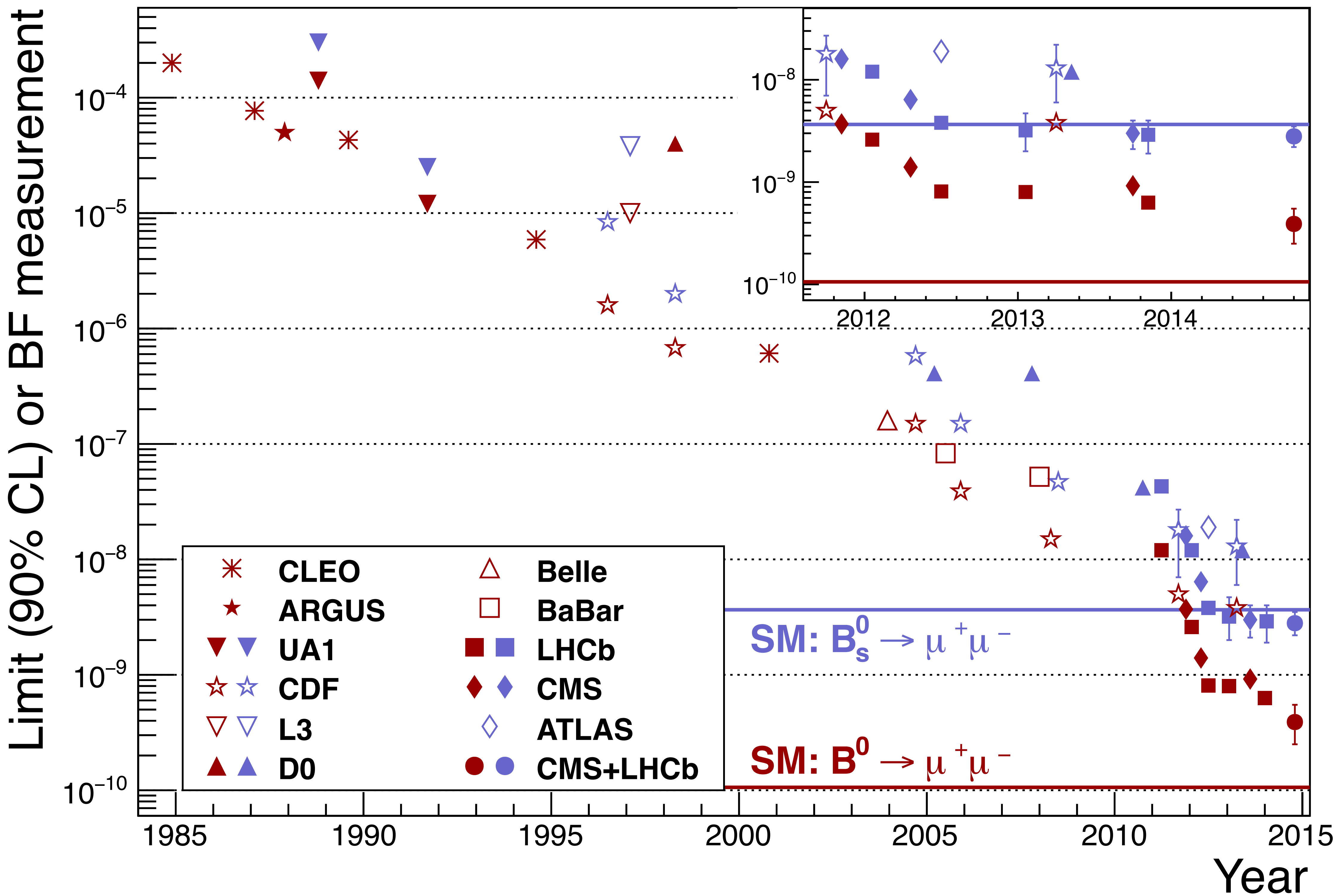
- Combining results from CMS and LHCb experiments from LHC run 1.
  - ➡ Observe B_s signal and evidence for B^0.





LHCb + CMS, [arXiv:1411.4413]

the end of a long road …



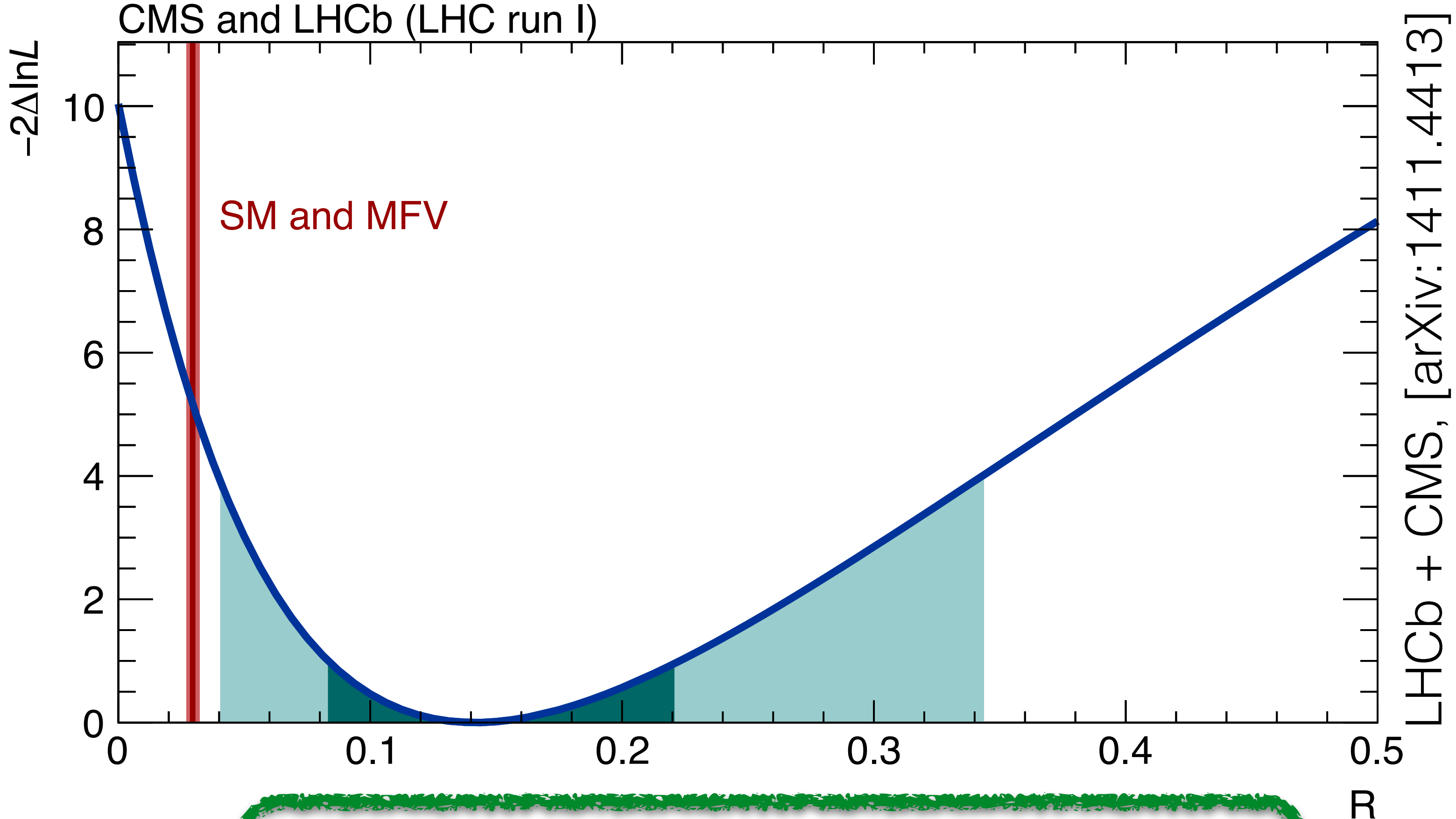
Testing MFV

- 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



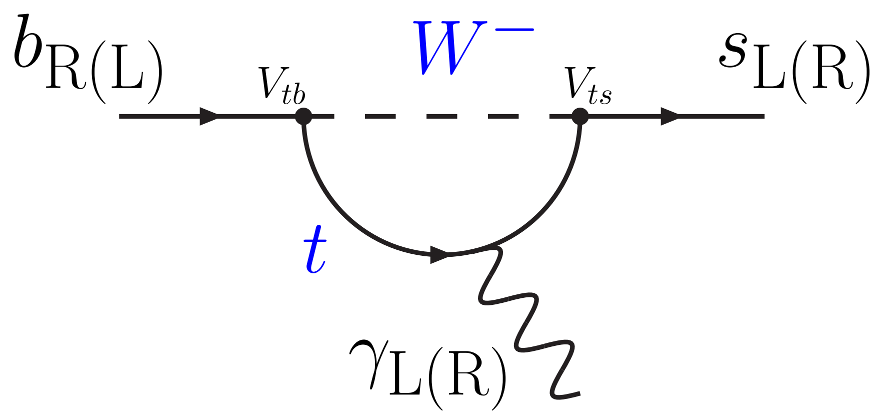
Data are consistent with SM/MFV

Photon polarisation

- In radiative B decays, angular momentum conservation allows

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

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



- 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

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

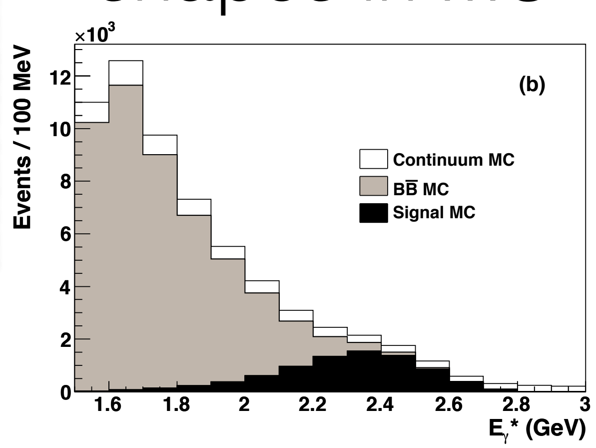
Inclusive b → s γ

- Can perform either a semi-inclusive measurement, summing a large number of X_s final states (e.g. K^+, K^*, …) or a fully inclusive measurement where X_s is not reconstructed.
  - ➡ Cuts on $M(X_s)$ or E_γ complicate theory calculations.

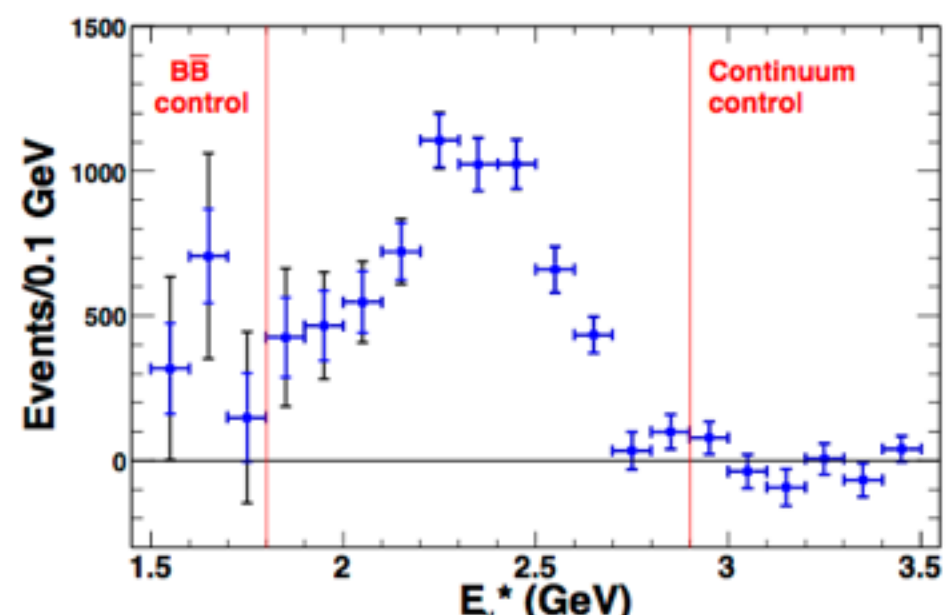
Result $\mathcal{B}(\overline{B} \to X_s\gamma)_{E_\gamma > 1.6\ \mathrm{GeV}} = (343 \pm 21 \pm 7) \times 10^{-6}$

BF consistent with SM expectation (impressive prediction of the SM)

shapes in MC



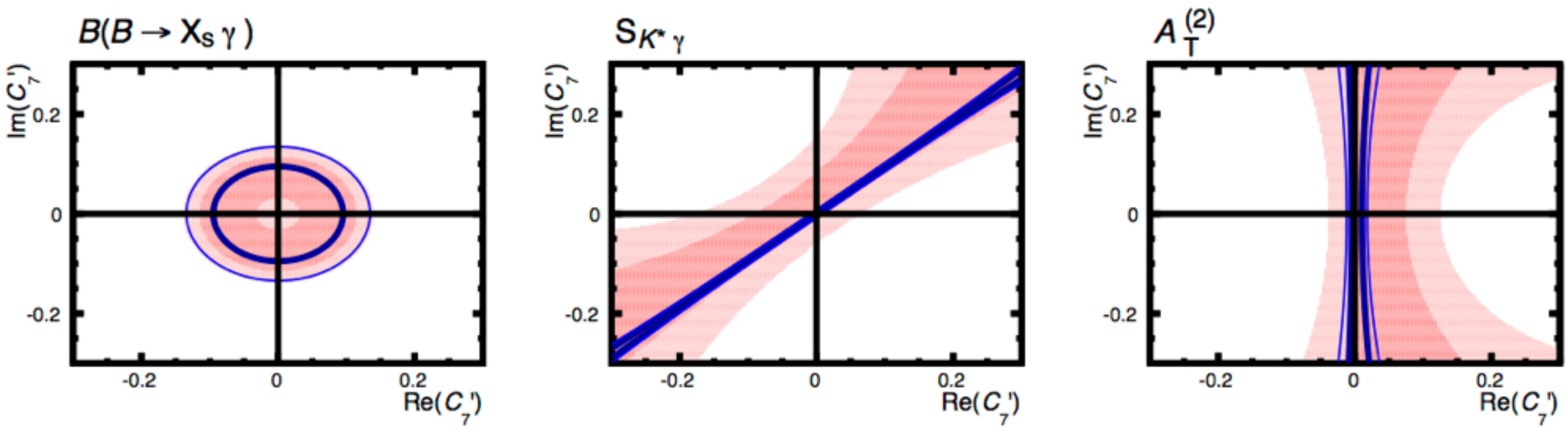
background subtracted data



BaBar, Phys. Rev. D. 86. 112008 (2012)

b → s γ constraints

- Constraints on right-handed currents in b → s γ decays:



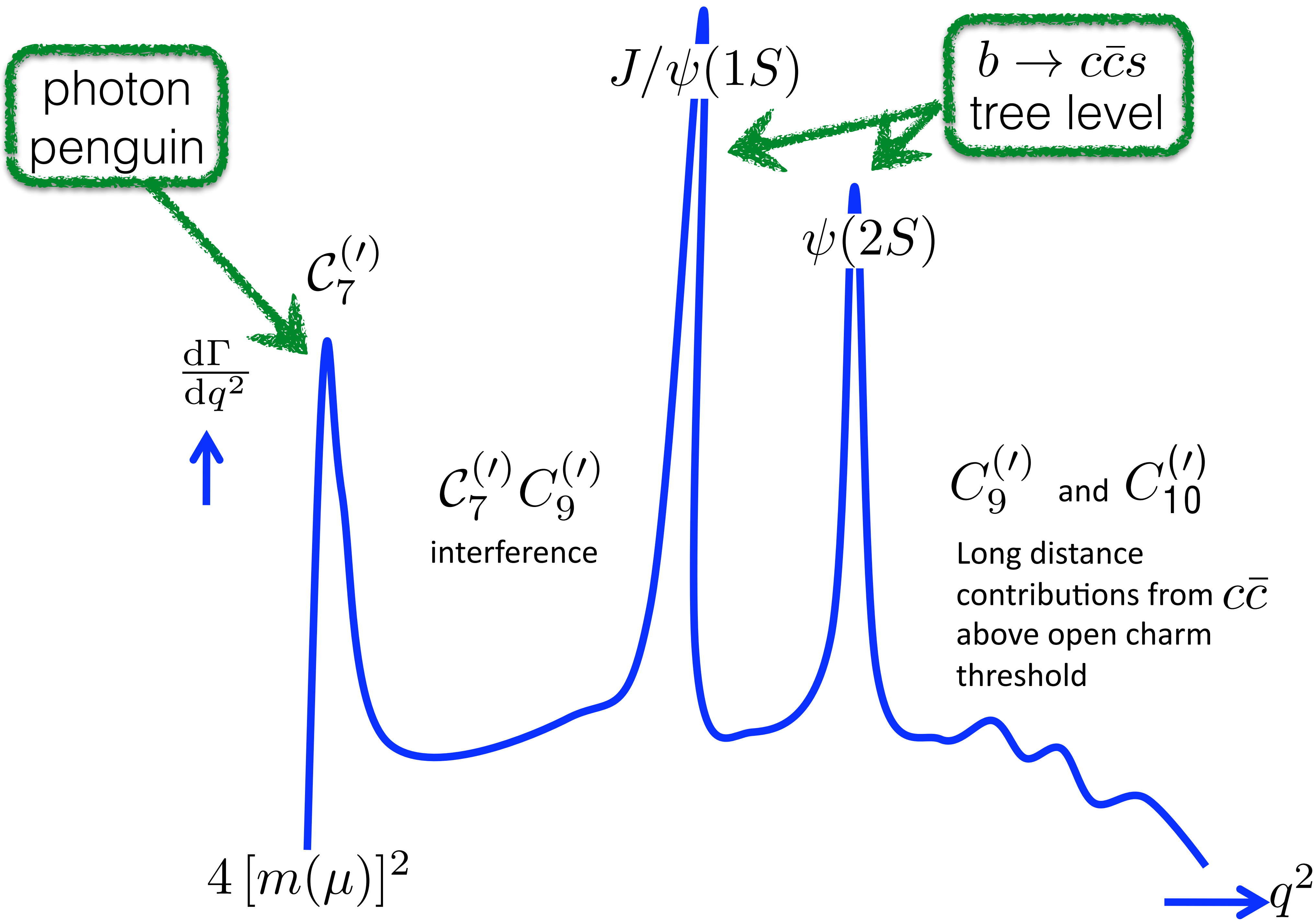
inclusive branching fraction.

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

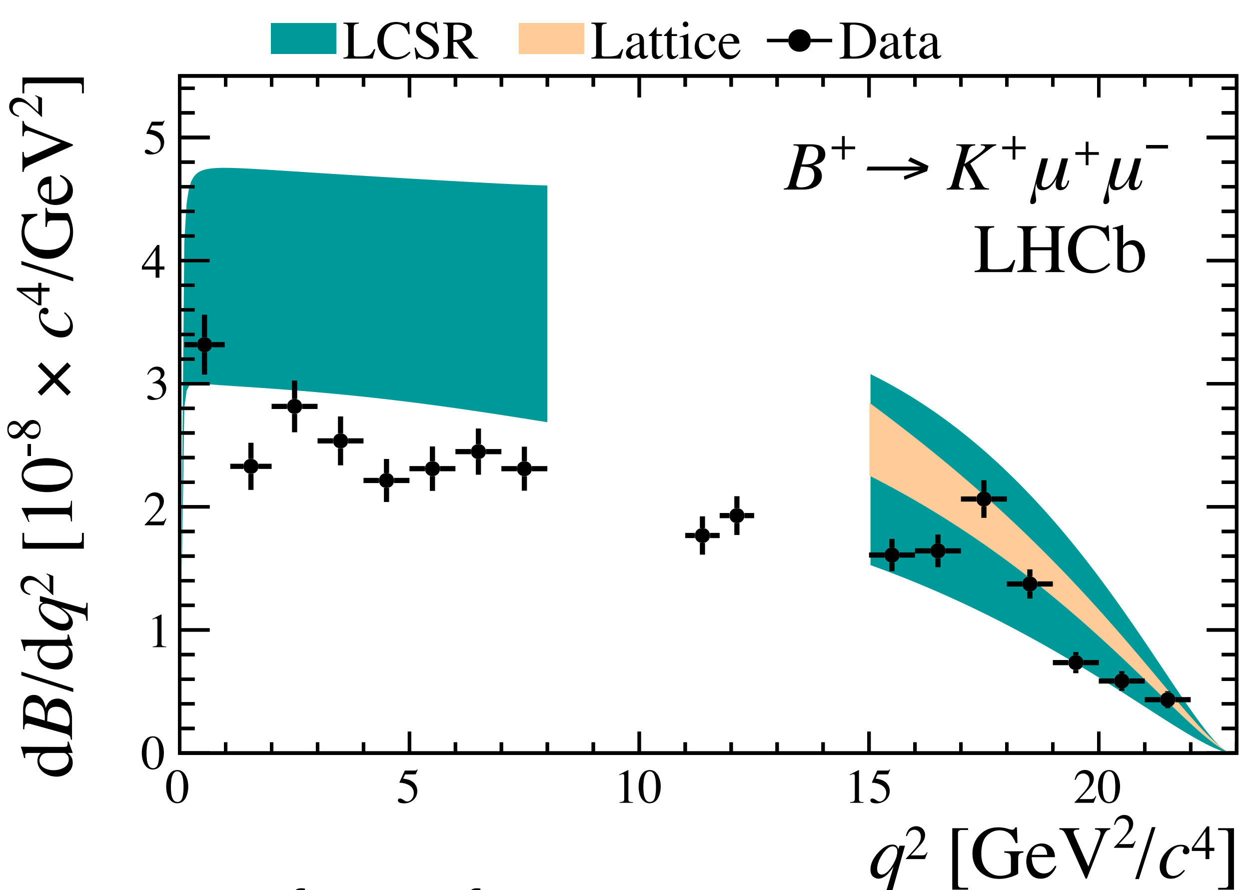
angular distribution of $B \to K^* e^+ e^-$

Results are consistent with LH polarisation expected in SM

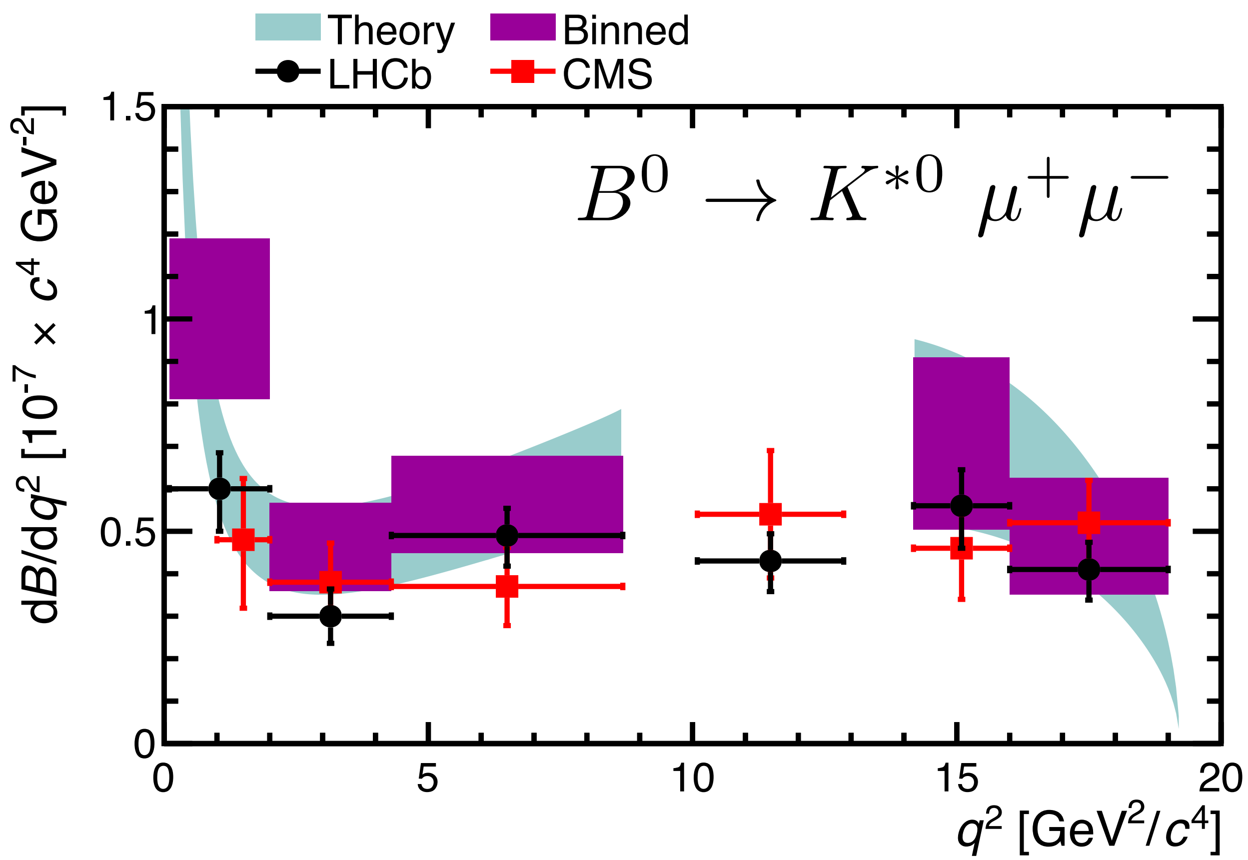
$b \to s\ell^+\ell^-$ decays



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



- 3 form-factors
- No enhancement at low q^2 from virtual photon (angular momentum conservation).



- 7 form-factors
- Enhancement at low q^2 from virtual photon

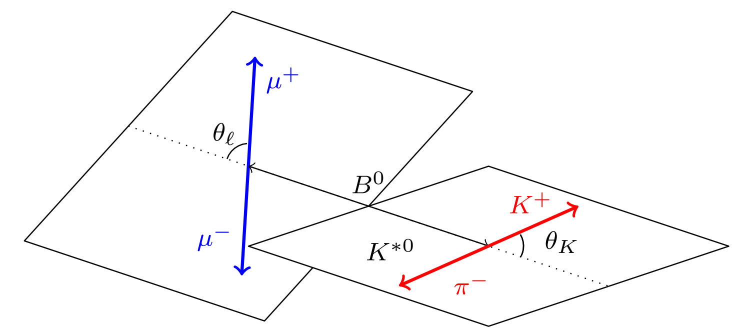
Large theory uncertainties (from QCD)

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

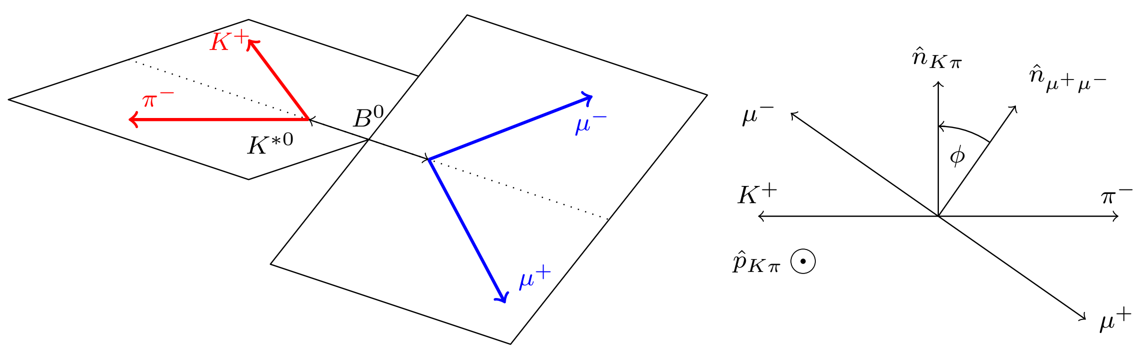
- Four-body final state.
  - ➡ Angular distribution provides many observables that are sensitive to NP.

  e.g. at low q² the angle between the decay planes is sensitive to the photon polarisation.

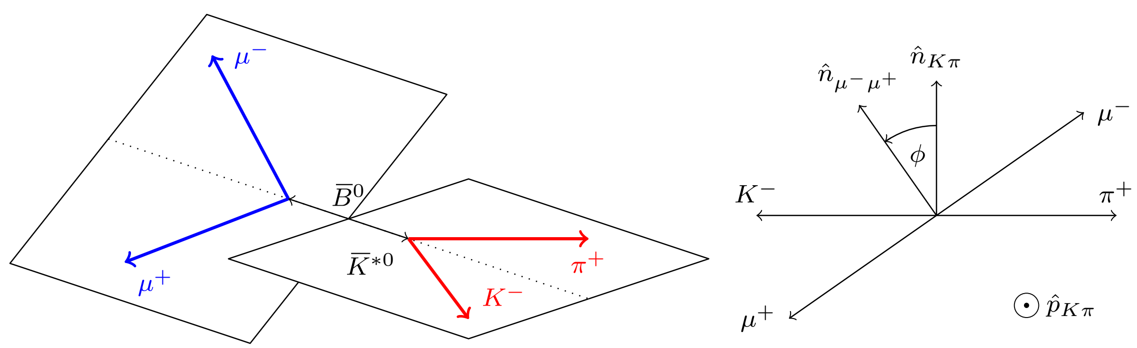
- System described by three angles and q².



(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

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

Angular distribution:

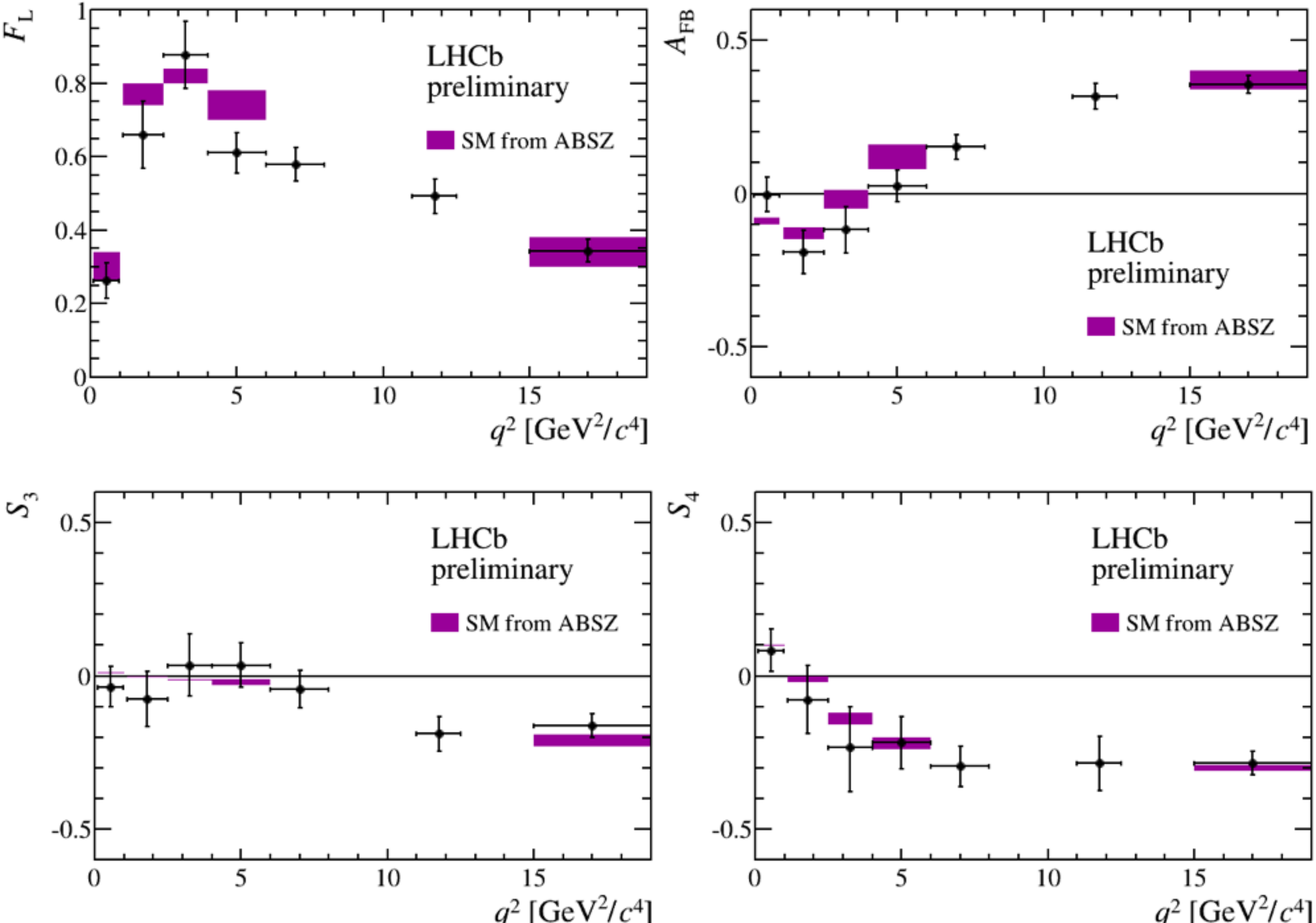
$$
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K + \boxed{F_{\mathrm{L}}}\cos^2\theta_K +
$$
$$
+\tfrac{1}{4}(1-\boxed{F_{\mathrm{L}}})\sin^2\theta_K\cos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

fraction of longitudinal polarisation of the K*

forward-backward asymmetry of the dilepton system

The observables depend on form-factors for the B → K* transition plus the Wilson coefficients.

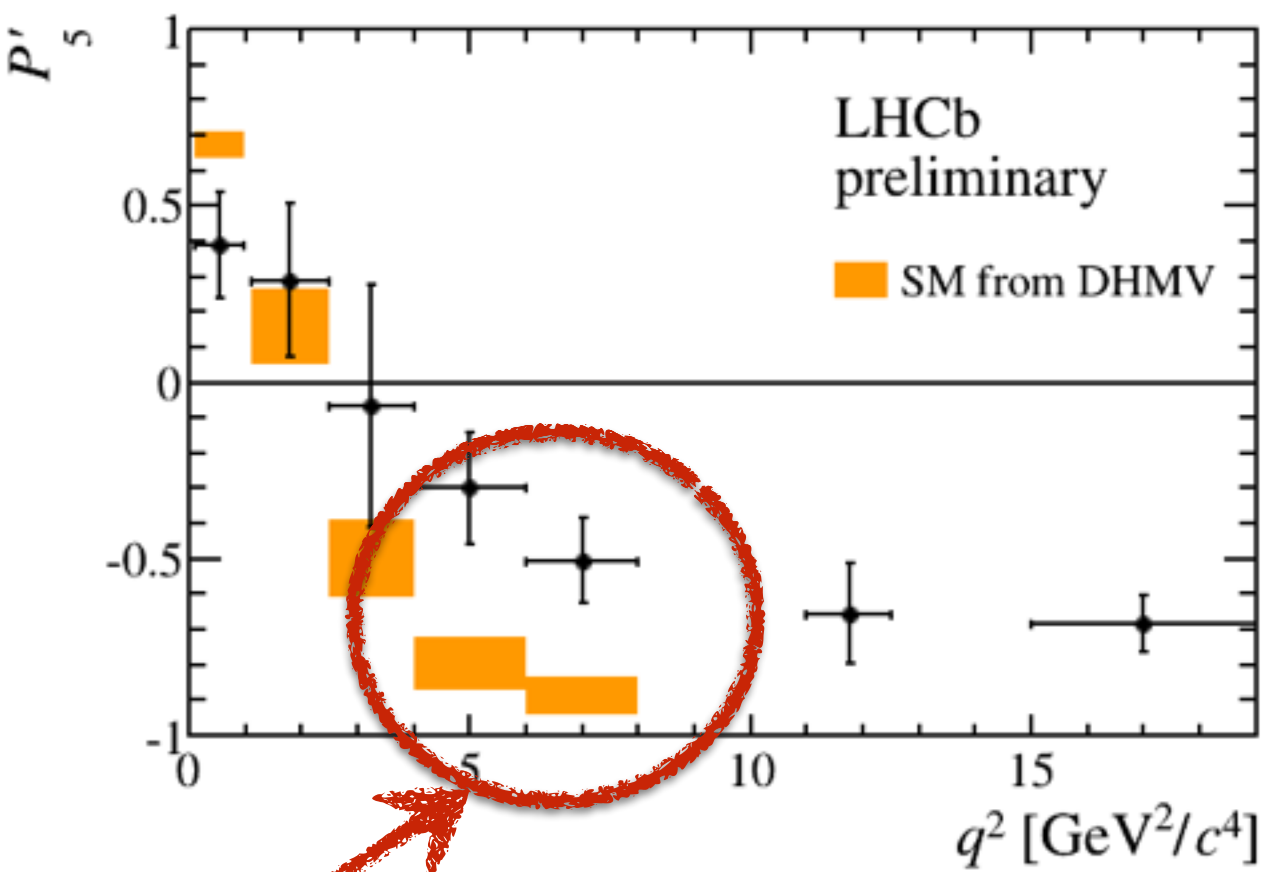
Latest LHCb result, shown at Moriond 2015, LHCb-CONF-2015-002



Form-factor “free” observables

- Can construct ratios of observables which in QCD factorisation/SCET are independent of form-factors.

$$P_5' = S_5/\sqrt{F_{\mathrm{L}}(1 - F_{\mathrm{L}})}$$

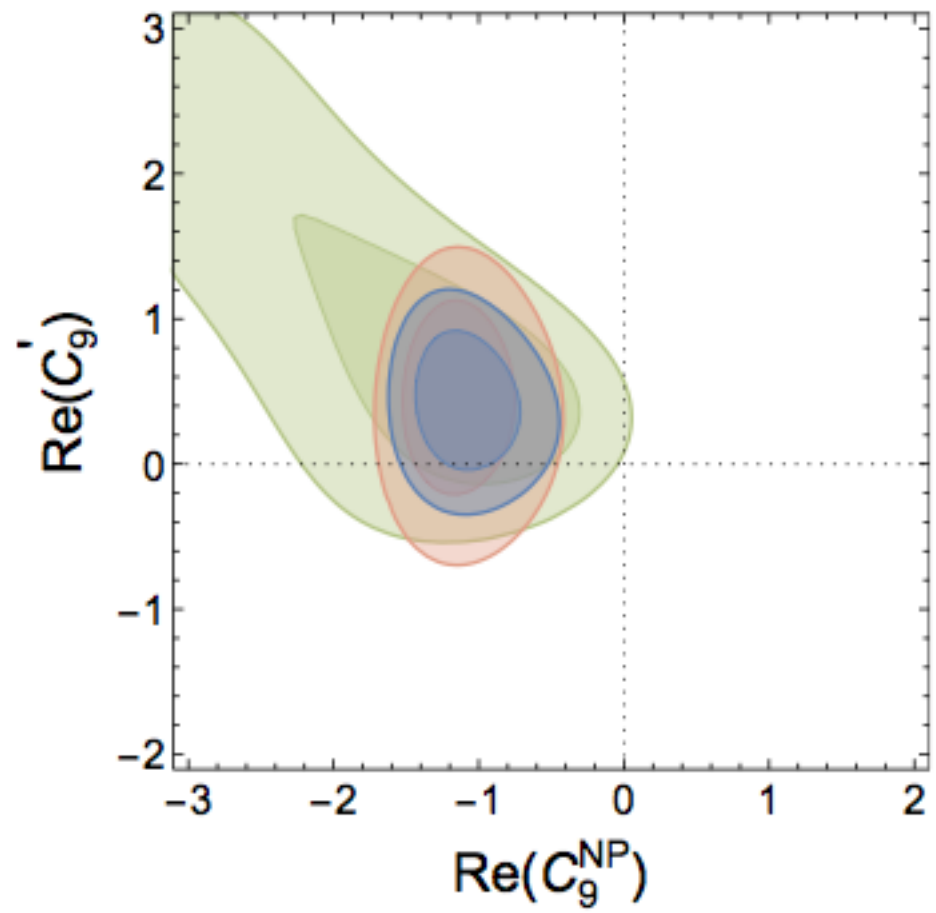


local tension with SM predictions (vector like NP contribution or unexpected large QCD effect?)

Latest LHCb result, shown at Moriond 2015, LHCb-CONF-2015-002

global fits to b → s data

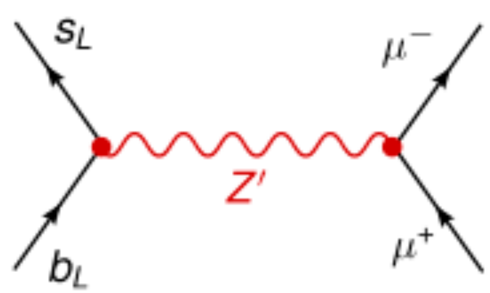
- Global fits to the b → s data favour a new vector like contribution.
  - ➡ Could be sign of new physics (heavier partner of the Z) or a sign that we don't understand something about QCD, $c\bar{c}$ loop contributions will also look vector-like.



branching fractions
angular observables
combination

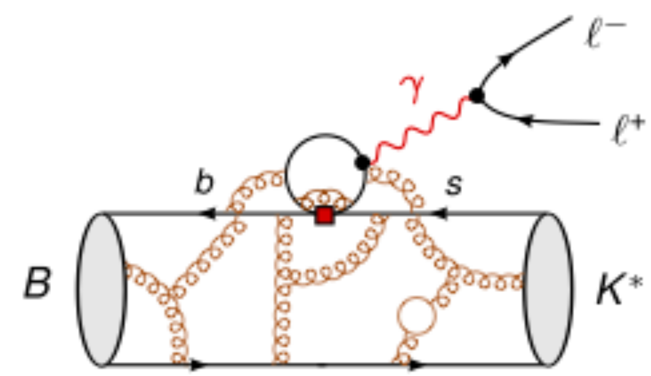
Interpretation of global fits

Optimist's view point



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

Pessimist's view point



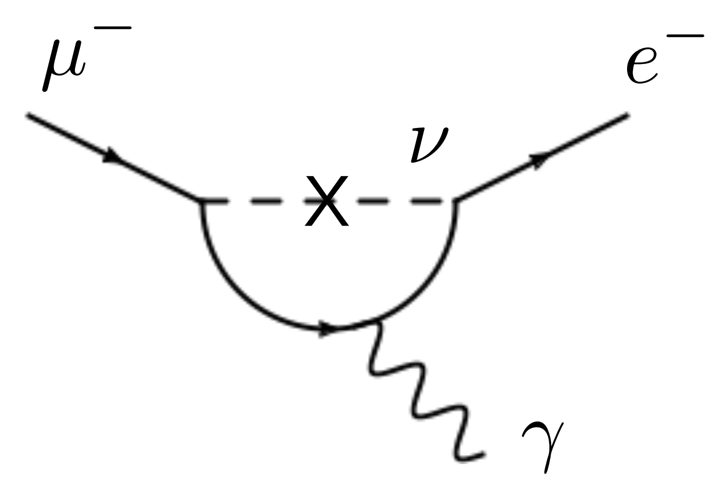
Vector-like contribution could point to a problem with our understanding of QCD, e.g. are we correctly estimating the contribution for charm loops that produce dimuon pairs via a virtual photon.

More work needed from experiment/theory to disentangle the two

(charged) lepton flavour violation

Charged LFV

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



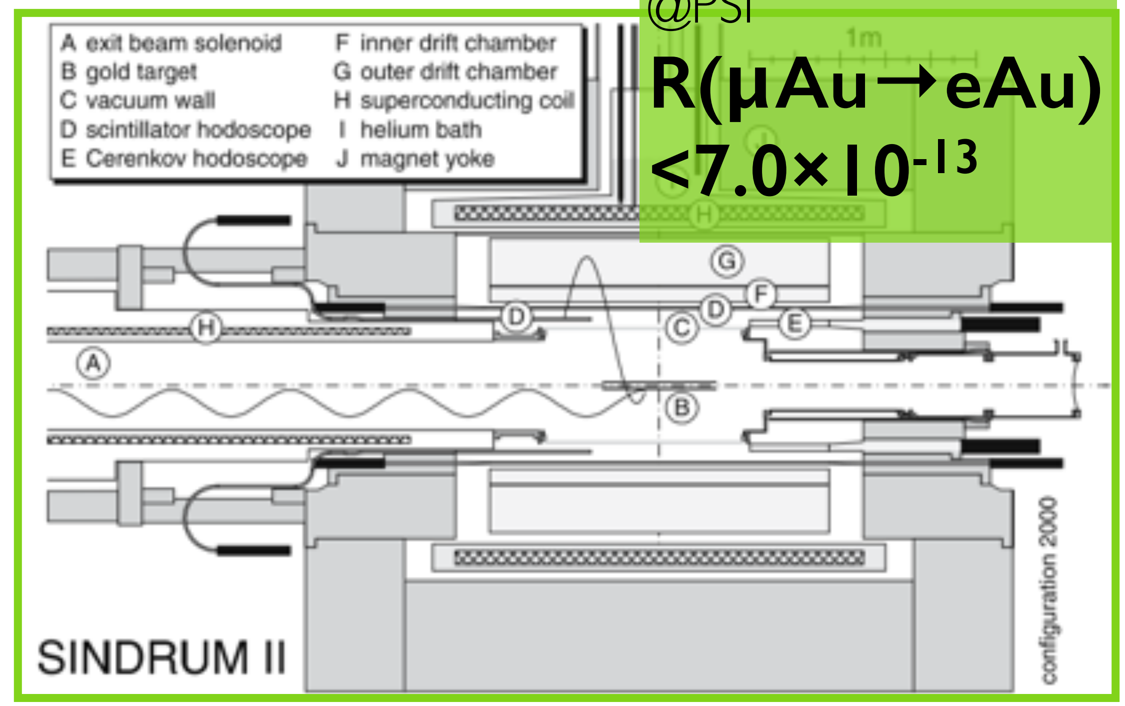
$$\mathcal{B}(\mu \to e\gamma) \propto \frac{m_\nu^4}{m_W^4}$$
$$\sim 10^{-54}$$

μ LFV

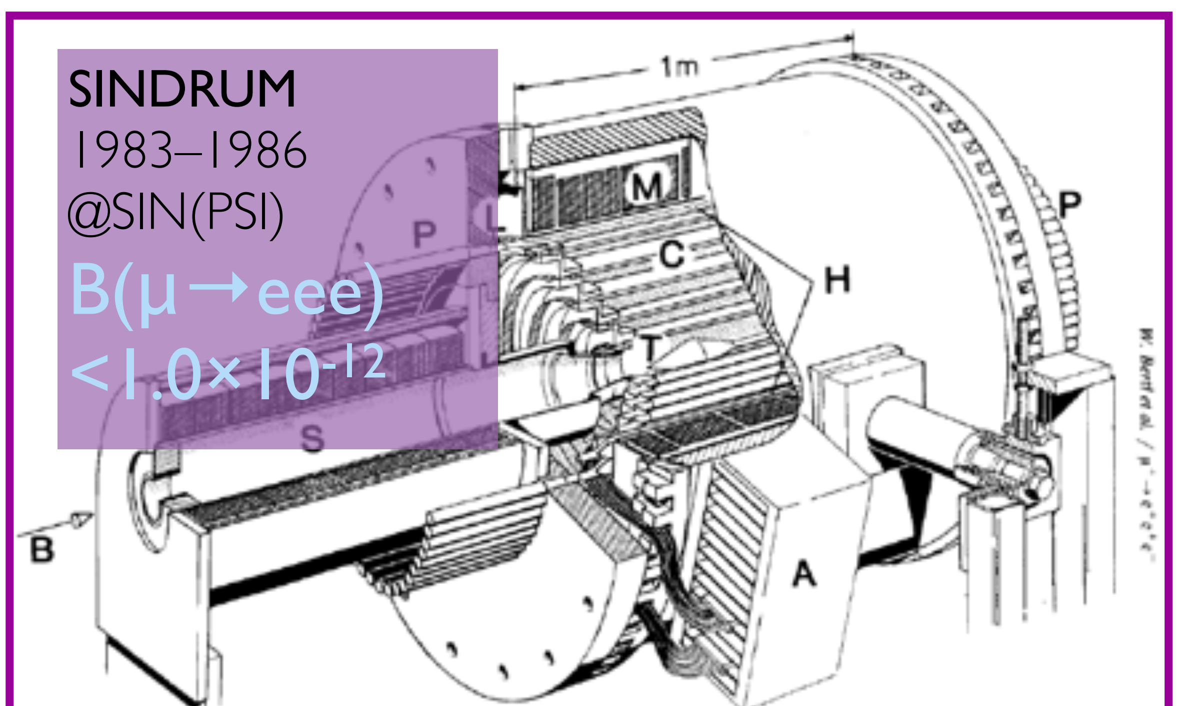
- Three different signatures

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

SINDRUM II
1989–1993
@PSI
$R(\mu Au \to eAu)$
$<7.0\times10^{-13}$

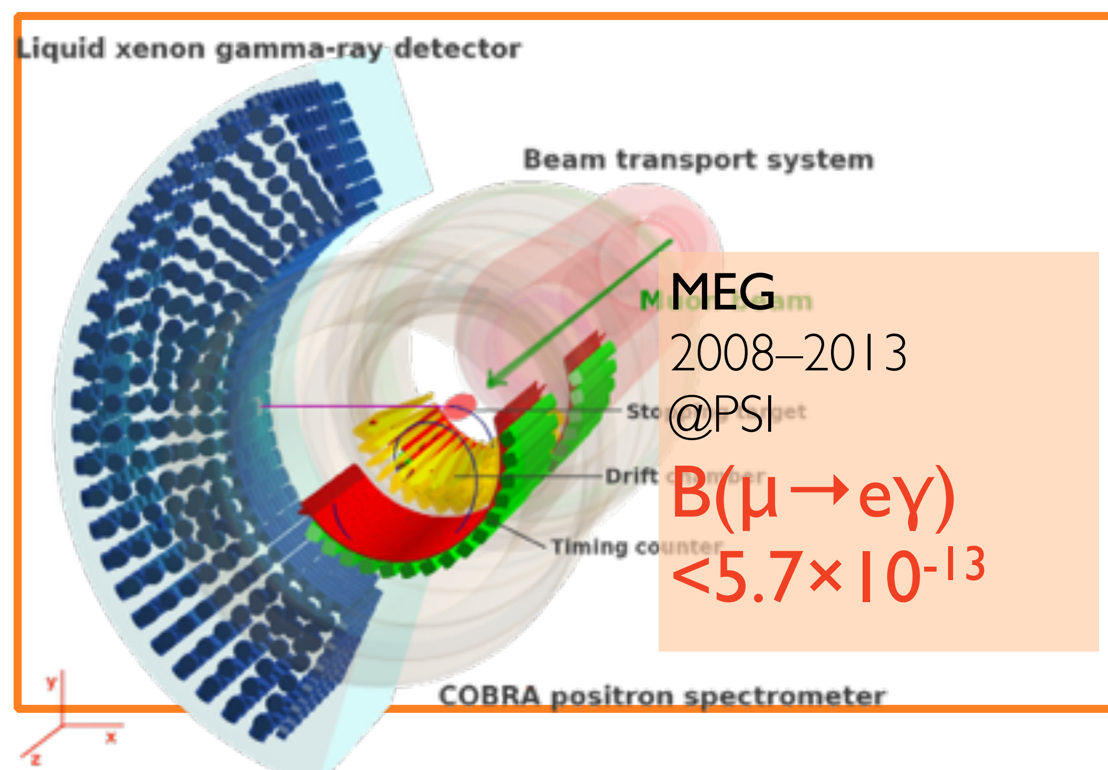


SINDRUM
1983–1986
@SIN(PSI)
$B(\mu \to eee)$
$<1.0\times10^{-12}$



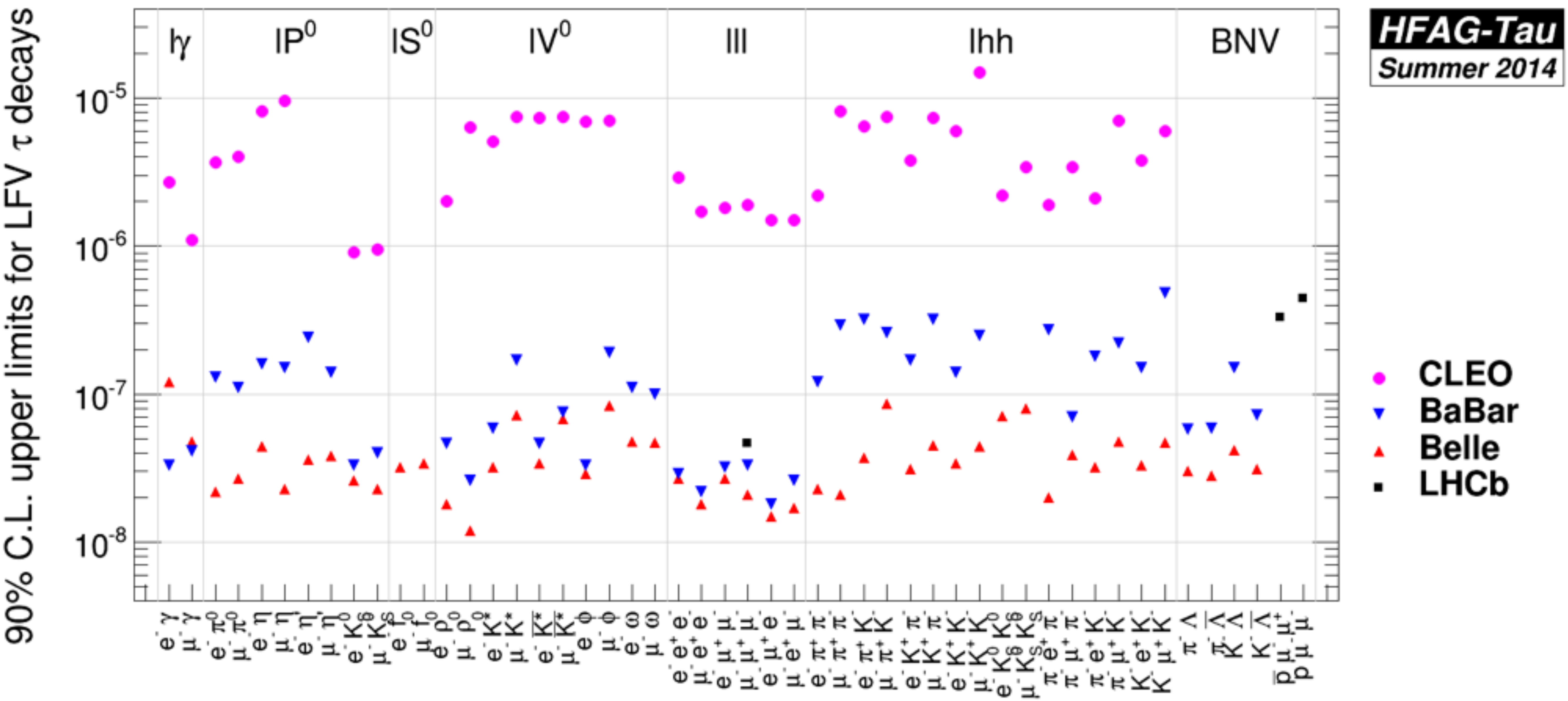
25 year's ago

MEG
2008–2013
@PSI
$B(\mu \to e\gamma)$
$<5.7\times10^{-13}$



τ LFV

large number of experimental signatures



- Expect improvement from Belle 2 and for $\tau \to 3\mu$ from LHCb.

A look into the future

New Physics?

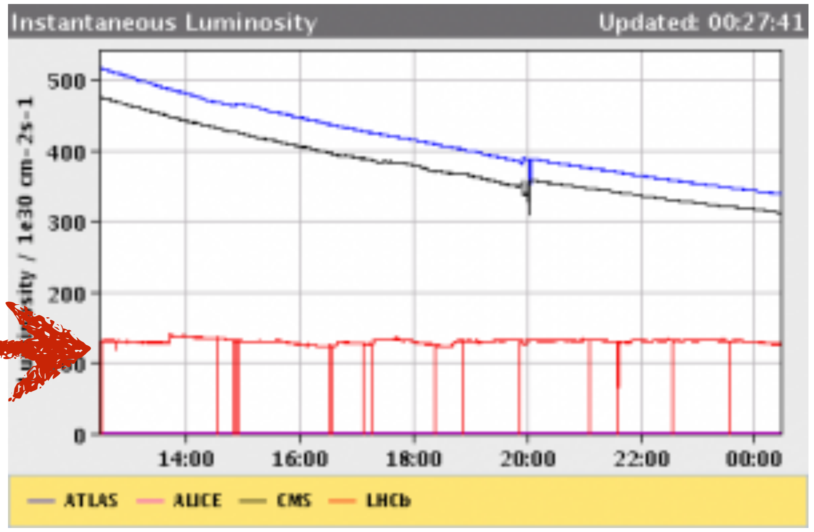
- As we saw in the last lecture, measurements of the CKM matrix and the properties (closure) of the Unitarity triangle are consistent with the Standard Model picture of flavour physics.
  - ➡ Nobel prize for Kobayahsi and Maskawa in 2008.
- However, there are some interesting "hints" of new physics:
  - ➡ Tension in V_{ub} (and V_{cb}).
  - ➡ Enhancement of $D^{(*)}\tau\nu$.
  - ➡ P5' anomaly in $B \to K^{*0} \mu^+\mu^-$.
  - ➡ Muon g-2.

all at $\sim 3\sigma$

- There's still plenty of room for discoveries …

LHCb running conditions

- LHCb is currently running at a luminosity of 4×10^{32} cm^{-2}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

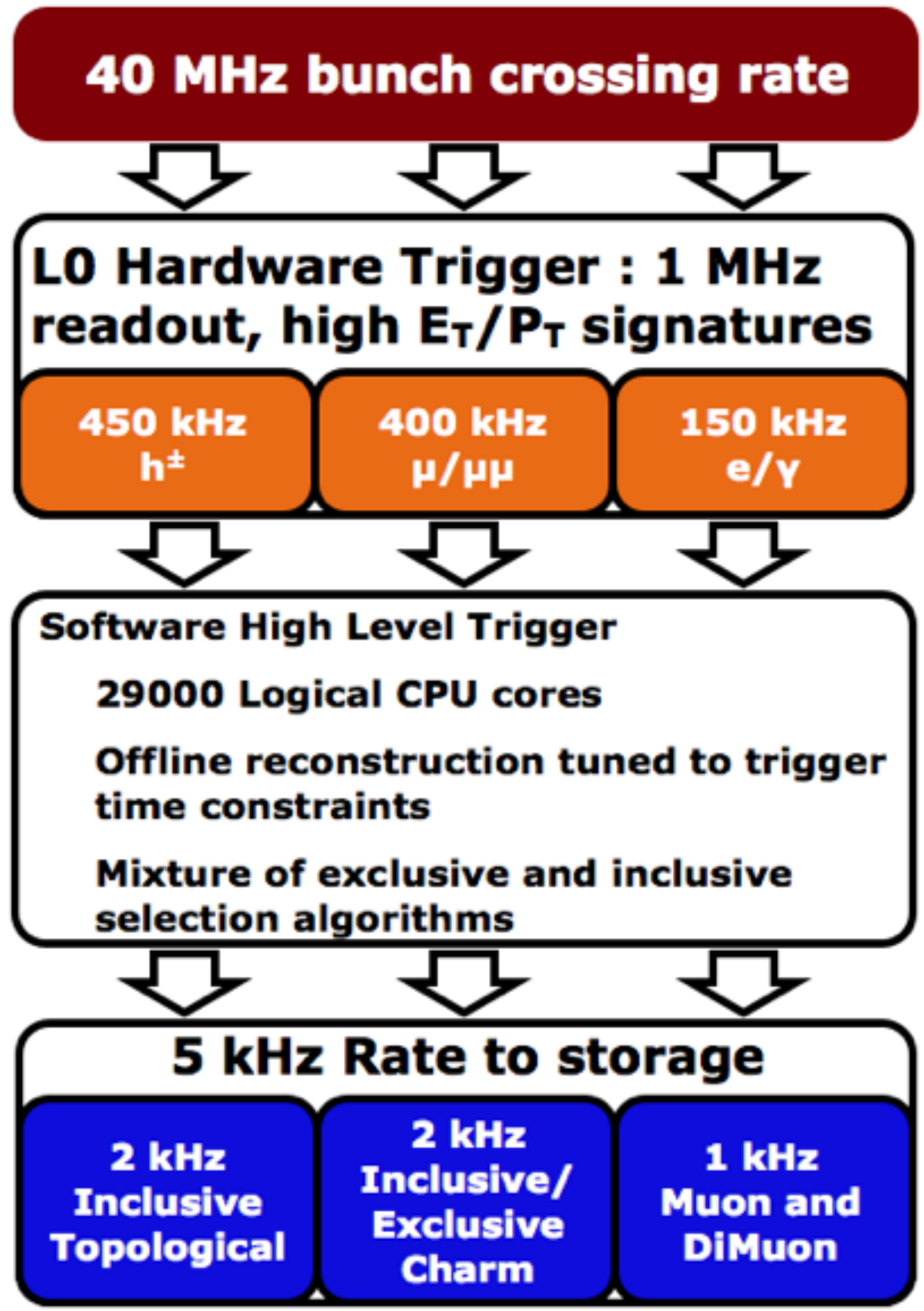
$$\longrightarrow \quad \sim 30\,\mathrm{k}\ b\bar{b}\ \text{pairs per second}$$

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

LHCb upgrade

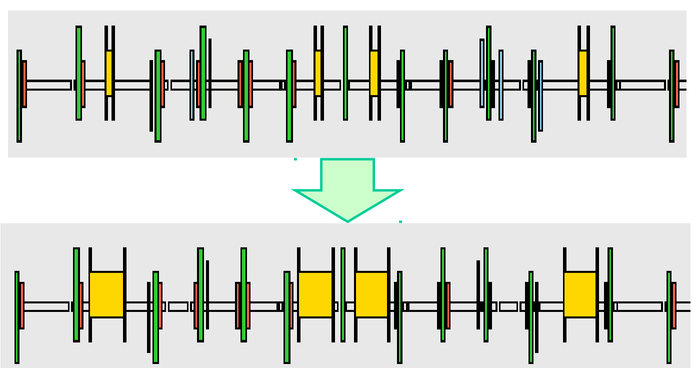
- Aim to run at 2×10^{33}.
- Main limitation with the current detector is the 1 MHz readout rate.
- Need to cut much harder maintain the 1MHz rate with higher luminosity (end up removing as much signal and background).
- Ambitious plan to read out the full detector at 40 MHz to a software farm.
- Also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

current trigger scheme

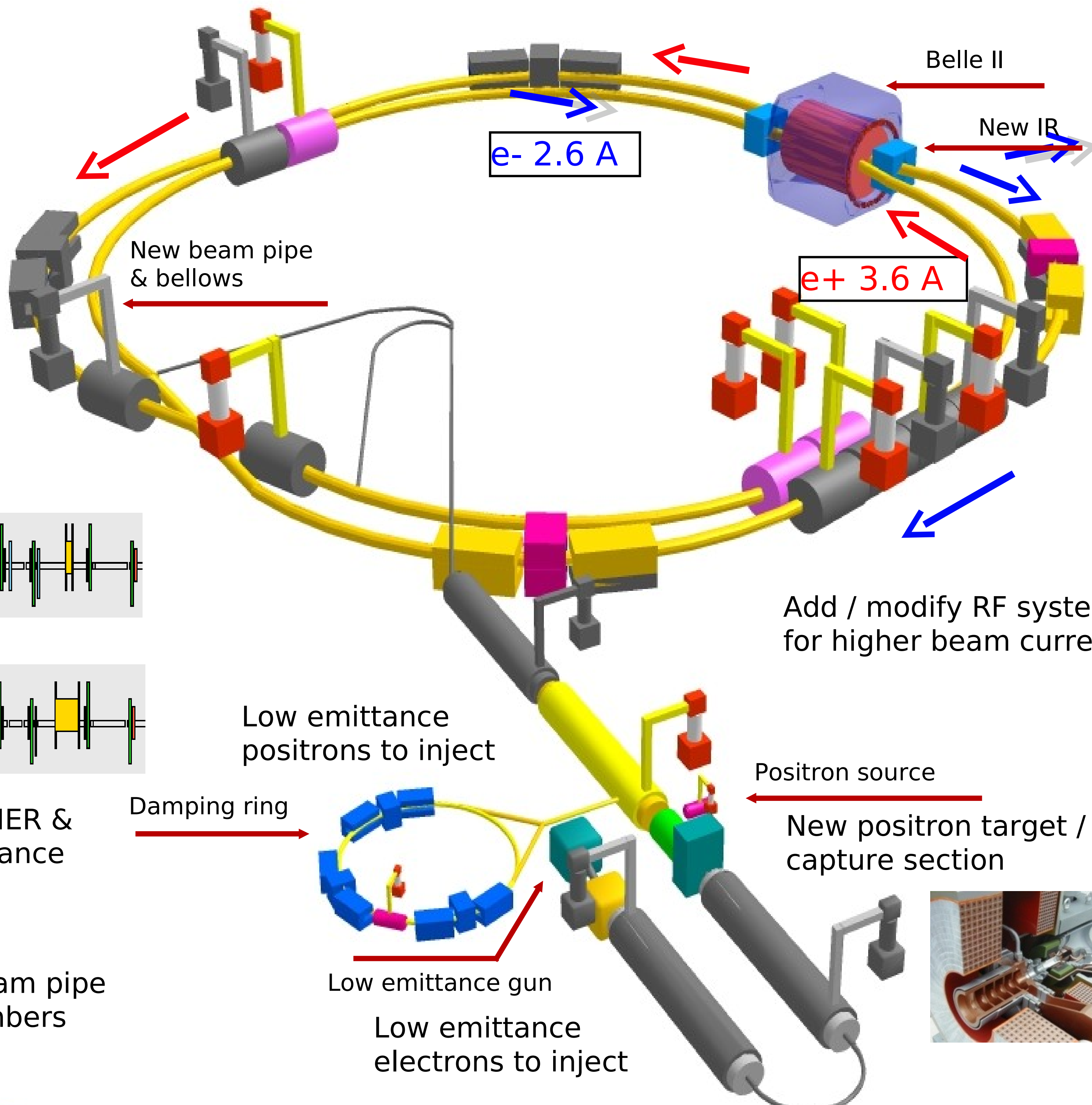


KEKB to SuperKEKB

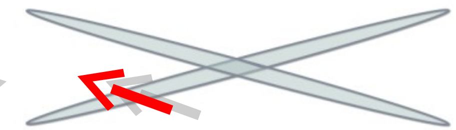
Replace short dipoles
with longer ones (LER)



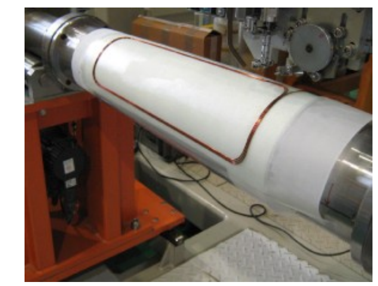
Redesign the lattices of HER &
LER to squeeze the emittance



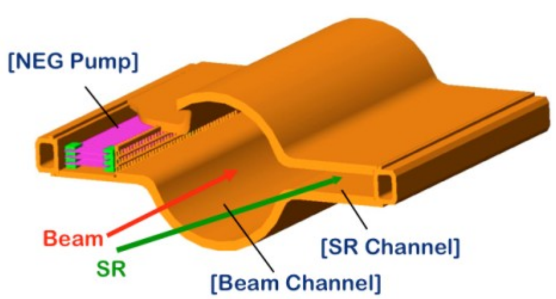
Colliding bunches



New superconducting
/permanent final focusing
quads near the IP



TiN-coated beam pipe
with antechambers



To obtain x40 higher luminosity

Rare kaon decays

also $C\!\!\!/P$

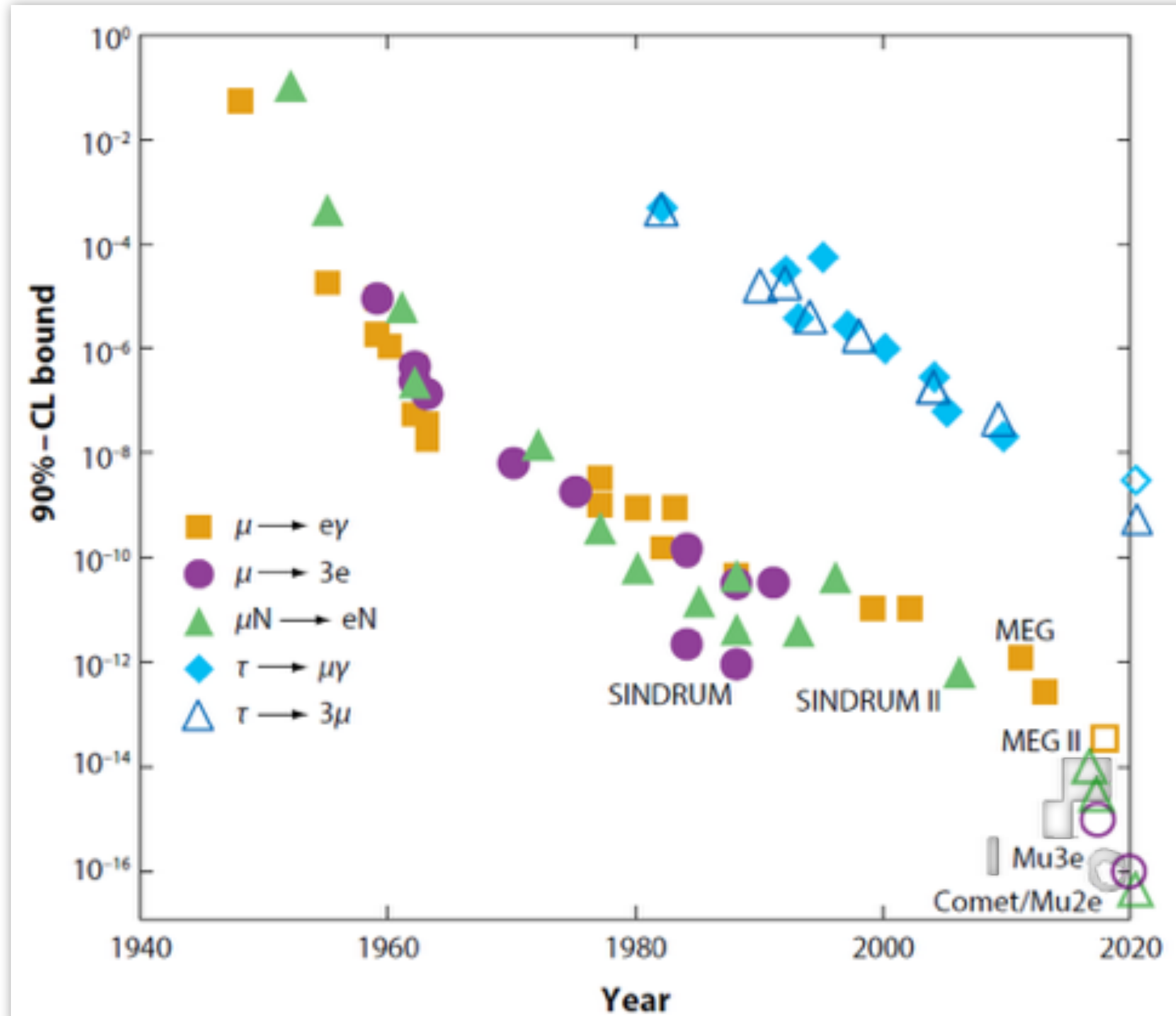
- Two rare kaon decay experiments are just starting:
  - ➡ KOTO at J-PARC, searching for $K^0_{\mathrm{L}} \to \pi^0 \nu \bar{\nu}$
  - ➡ NA62 at CERN, searching for $K^+ \to \pi^+ \nu \bar{\nu}$
- The main advantage of final states with neutrinos is that there is no contribution from quark loops involving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

KOTO

NA62

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 μ→3e.

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