ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

XIII Rencontres du Vietnam, Flavour Physics Conference
13-19th Aug 2017, Quy Nhon, Vietnam

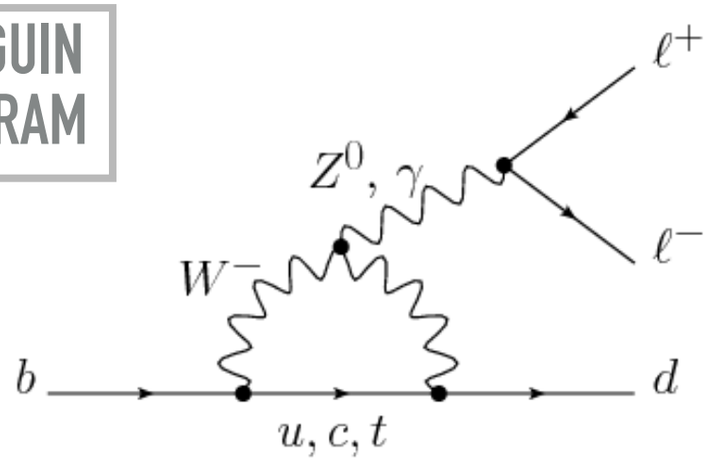
LUCA PESCATORE on behalf of the LHCb collaboration

NEW PHYSICS SEARCHES WITH RARE DECAYS AT THE LHCB EXPERIMENT

Rare decays at LHCb

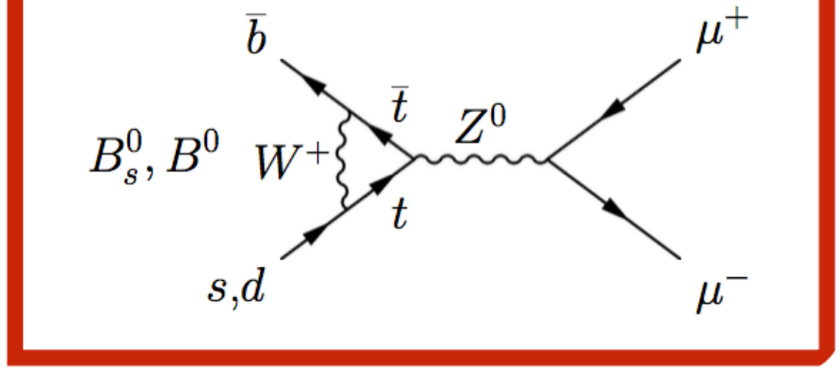
- **Rare decays:** processes suppressed in the SM that can happen only at loop level
  - Flavour Changing Neutral Currents
    → forbidden at tree level in the SM (e.g b→s or b→d transitions)
    → branching fractions typically ~10^{-6} or less

PENGUIN DIAGRAM

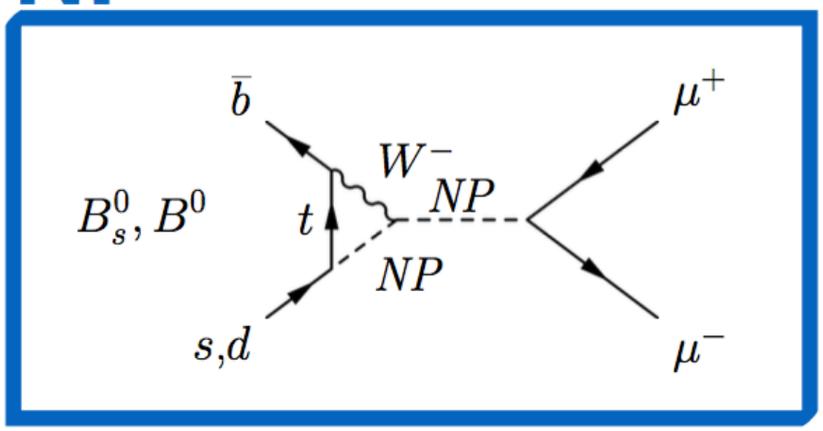


- **New Physics** can enter in the loops
  - Very sensitive to new physics effects
    → NP can enter at the same level as SM
  - No evidence in direct searches so far
    → loops can probe high energy scales

SM



NP



[Ann.Rev.Nucl.Part.Sci. 65 (2015) 113143]

Effective Hamiltonian

Effective Hamiltonian for b→d and b→s in terms of Operator Product Expansion.

With possible left-handed and right-handed components:

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{\alpha_e}{4\pi} \sum_{i=1}^{10} [C_i\mathcal{O}_i + C'_i\mathcal{O}'_i]$$

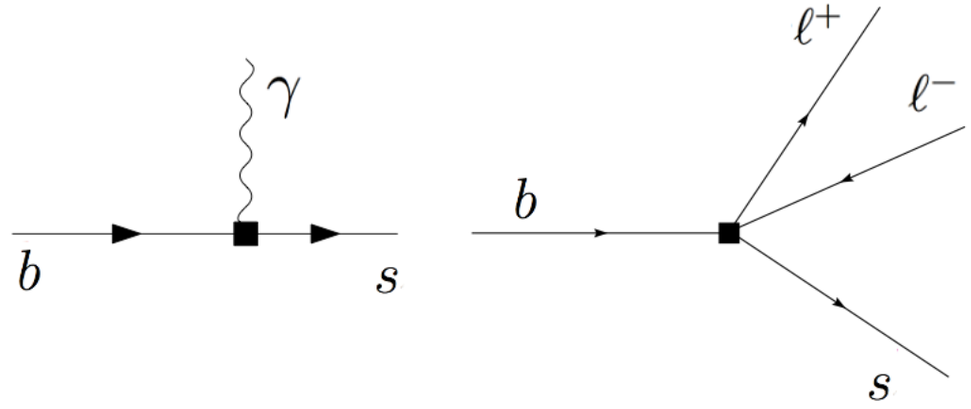
Suppressed
C' / C ~ m_s or m_d / m_b

[Ann.Rev.Nucl.Part.Sci. 65 (2015) 113143]

Relevant operators:

- ✓ $O_{S,P}$: purely leptonic decay
- ✓ O_7 : radiative penguin
- ✓ $O_{9,10}$: semileptonic decays

  (Z penguin and W-box)



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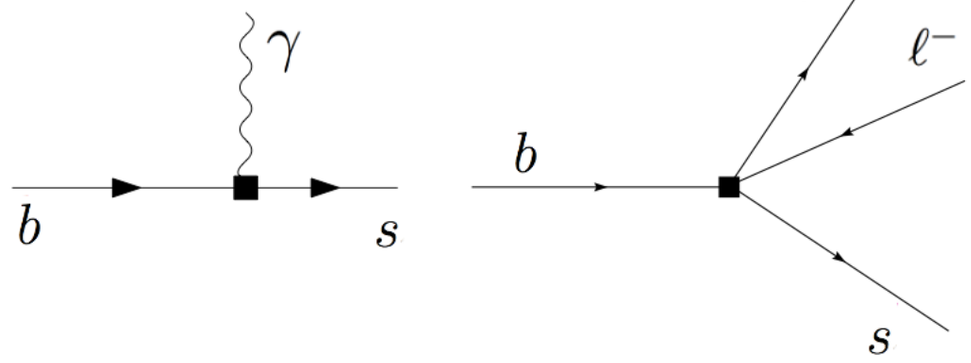
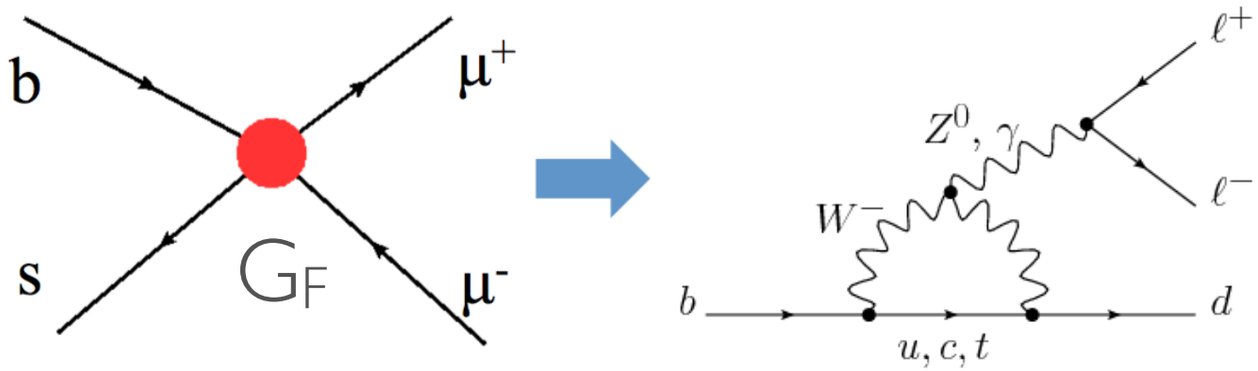


Nothing different than what was done for the Fermi theory of EW interactions.



Rare decays at LHCb

Very rich physics program!

Very rare

$B_s \to \mu\mu$

$B_s \to \tau\tau$

$B_s \to \mu\mu\mu\mu$

Electroweak penguin

$B^{0/+} \to K^{(*0)/+}\mu\mu$

$B^0_s \to \phi\mu\mu$

$\Lambda_b \to \Lambda/\Lambda^*\mu\mu$

$\Lambda_b \to (p\pi)/(pK)\mu\mu$

Radiative

$B \to K\gamma$

$B^0_s \to \phi\gamma$

$B \to K\pi\pi\gamma$

LFV

$D^0 \to e\mu$

$B \to e\mu$

$\tau \to \mu\mu\mu$

Covered by G. Onderwater.

LFU tests

R_K, R_{K^*} … R_ϕ, R_{pK}, R_Λ

Covered by J. G. Pardiñas

Rare charm

$D^0 \to \mu\mu$

$D \to hh\mu\mu$

$\Lambda_c \to p\mu\mu$

Rare strange

$K_s \to \mu\mu$

$\Sigma^+ \to p\mu\mu$

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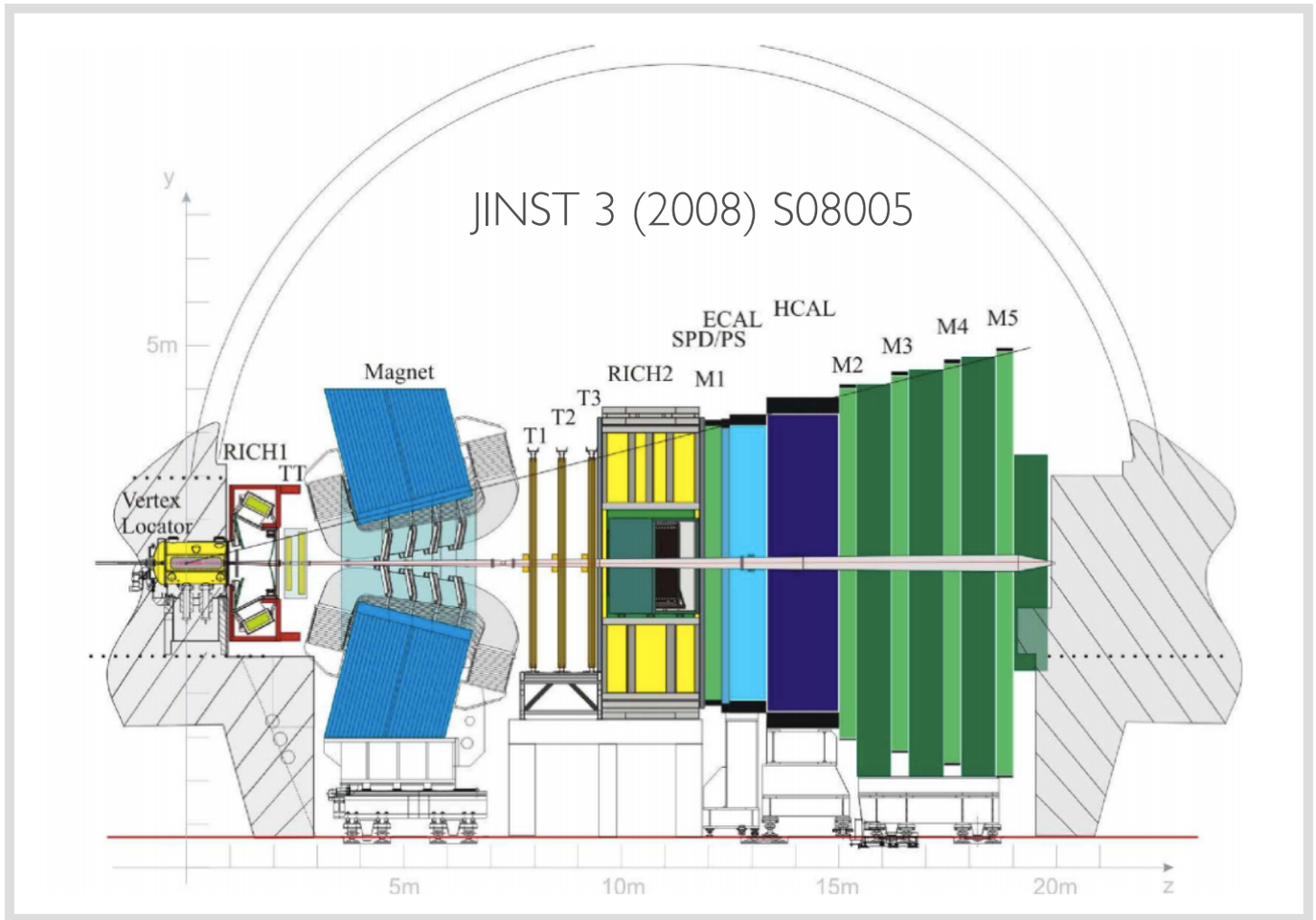
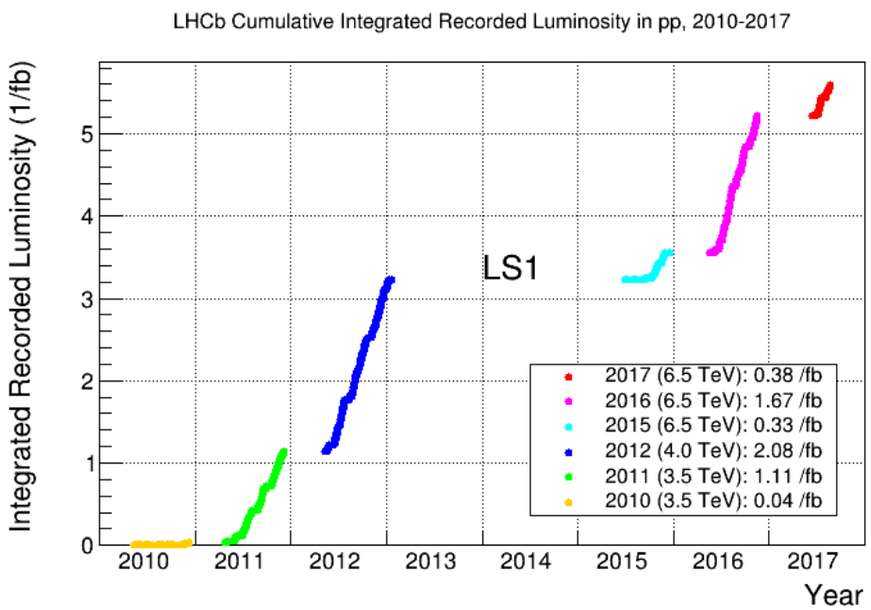
The LHCb detector

Forward geometry optimised for b and c decays

Fully instrumented in 2 < η < 5



Very good
secondary vertices detection
and particle identification
to cleanly reconstruct
specific final states.



Run I : 1fb^{-1} in 2011 and 2fb^{-1} in 2012.

Run II : 0.3 1fb^{-1} in 2015 and 1.6 1fb^{-1} in 2016

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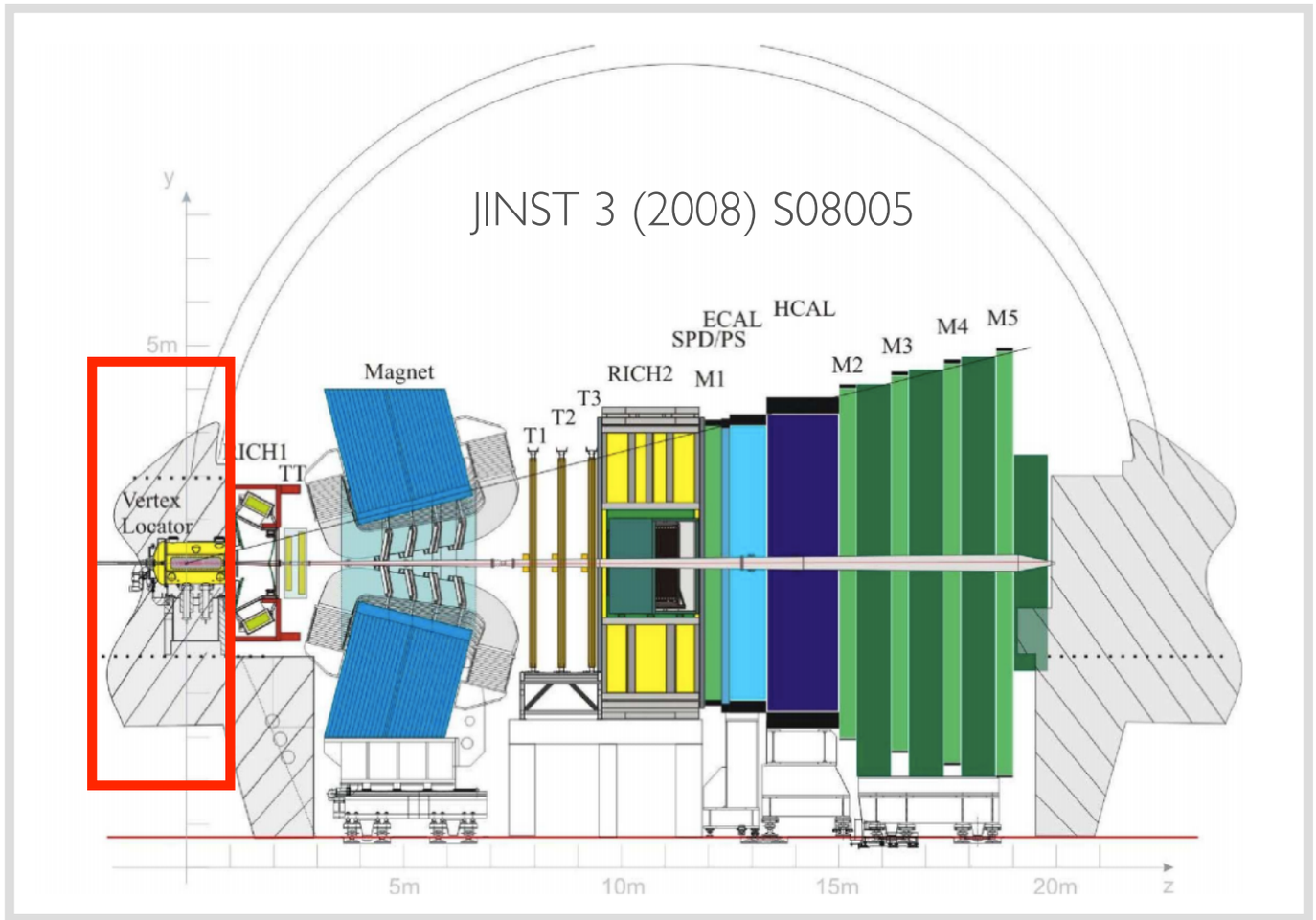

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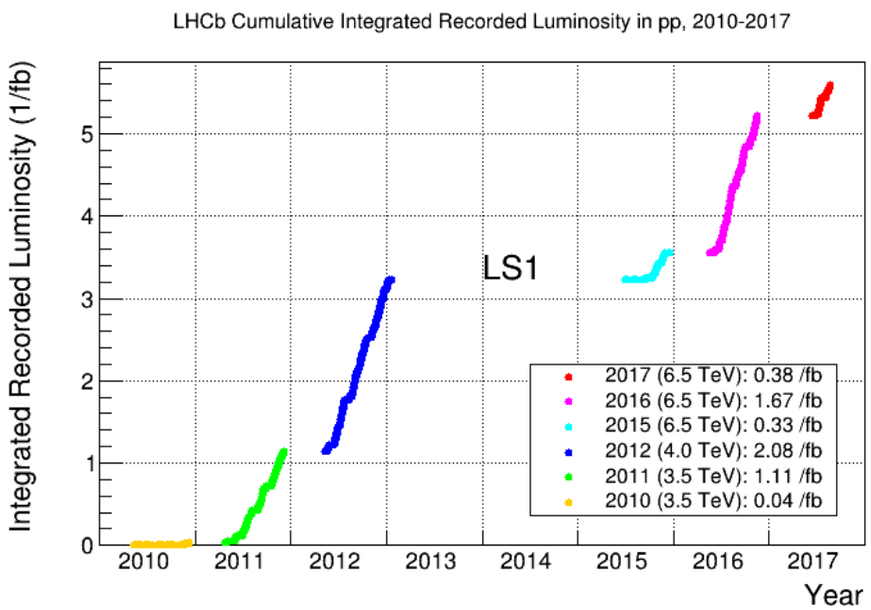

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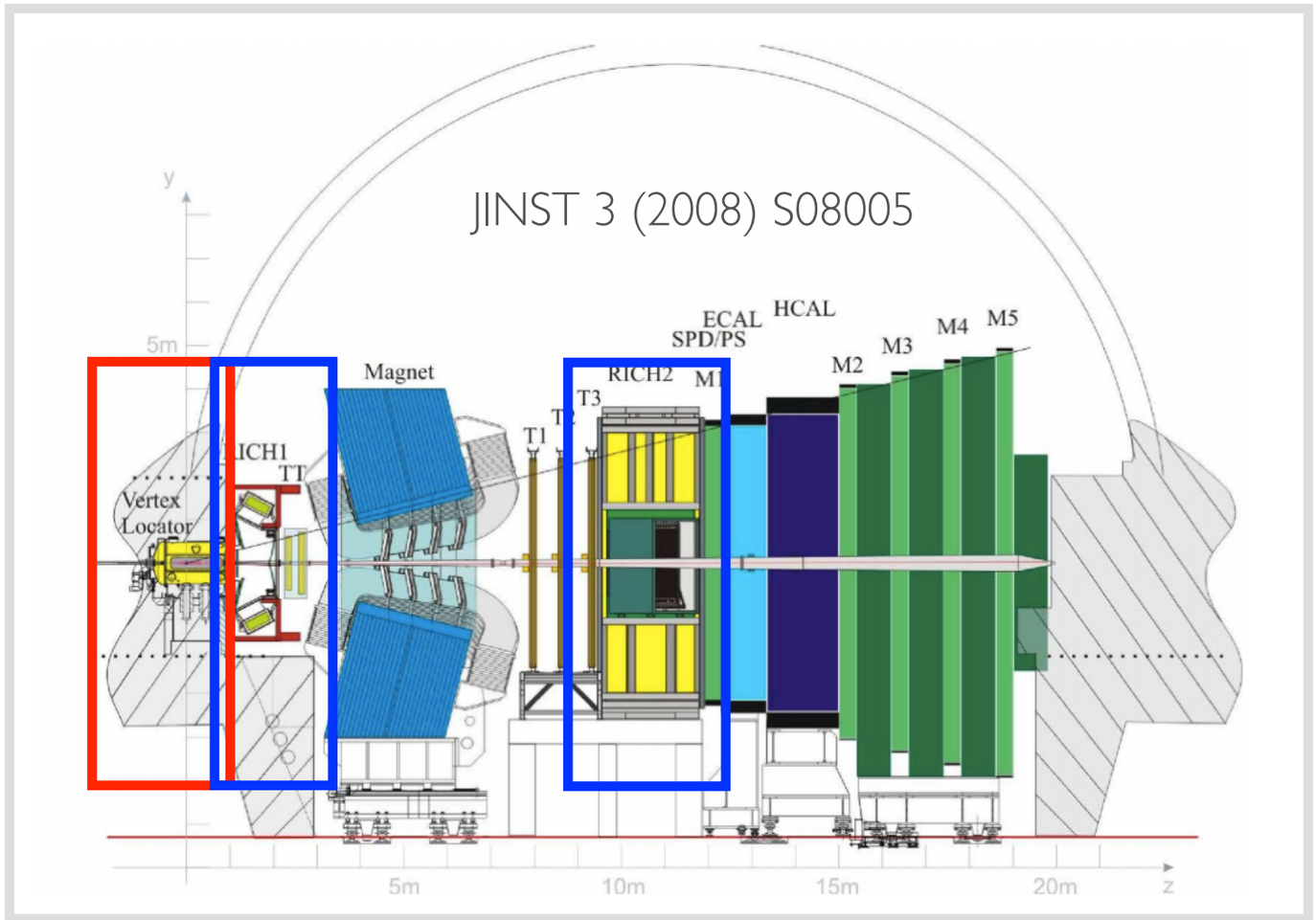

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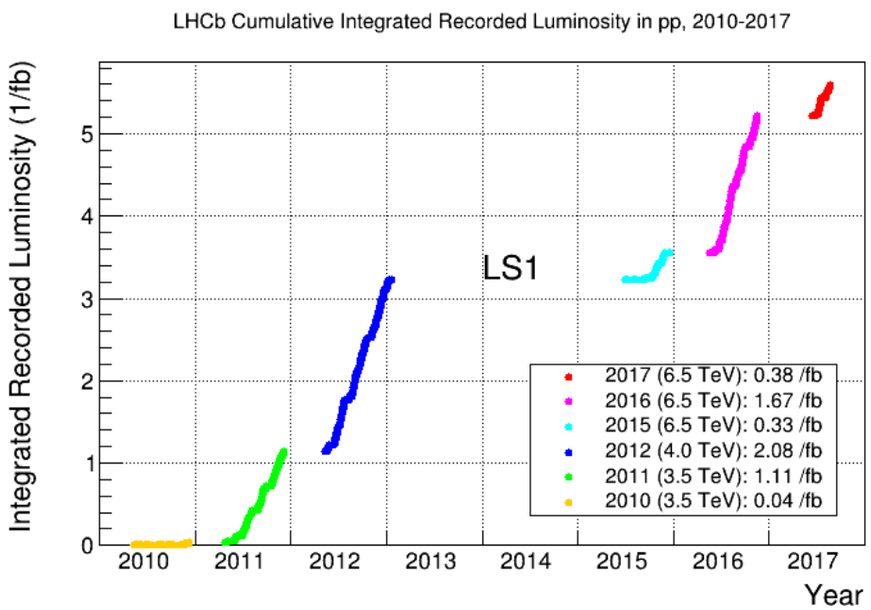

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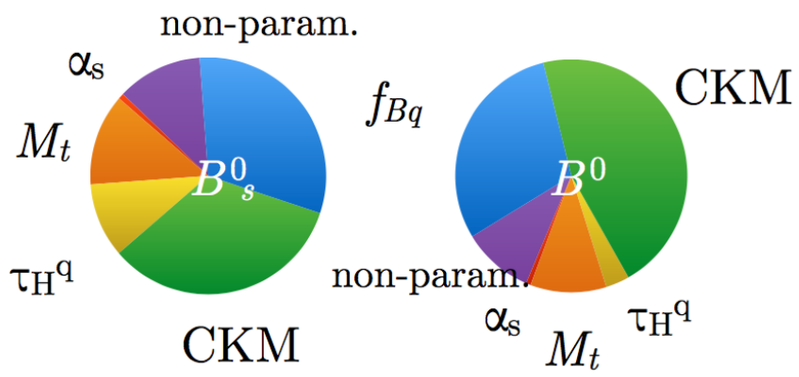
$B(B_{d/s} \to \mu^+\mu^-)$

- Highly suppressed in the SM FCNC + CKM + helicity
- Possible tree level BSM contributions → very sensitive
- Ratio between B_s and B^0 highly constrains MFV
- Leptonic decay (no hadronic uncertainties) → Very well predicted

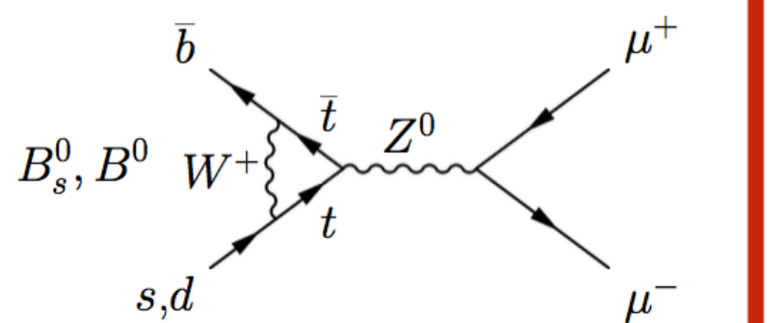
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

error budgets

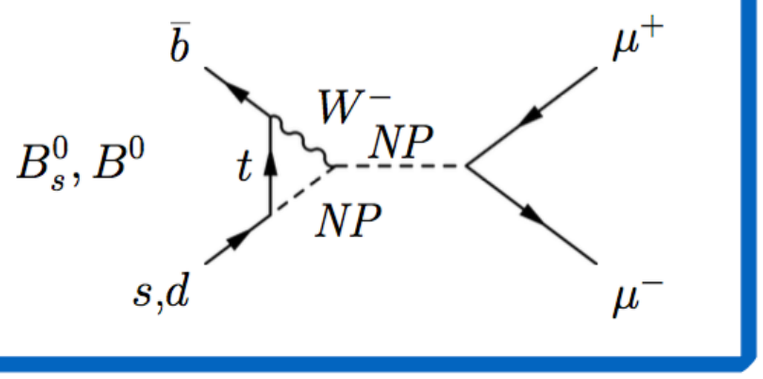


[PRL 112 (2014) 101801]

SM



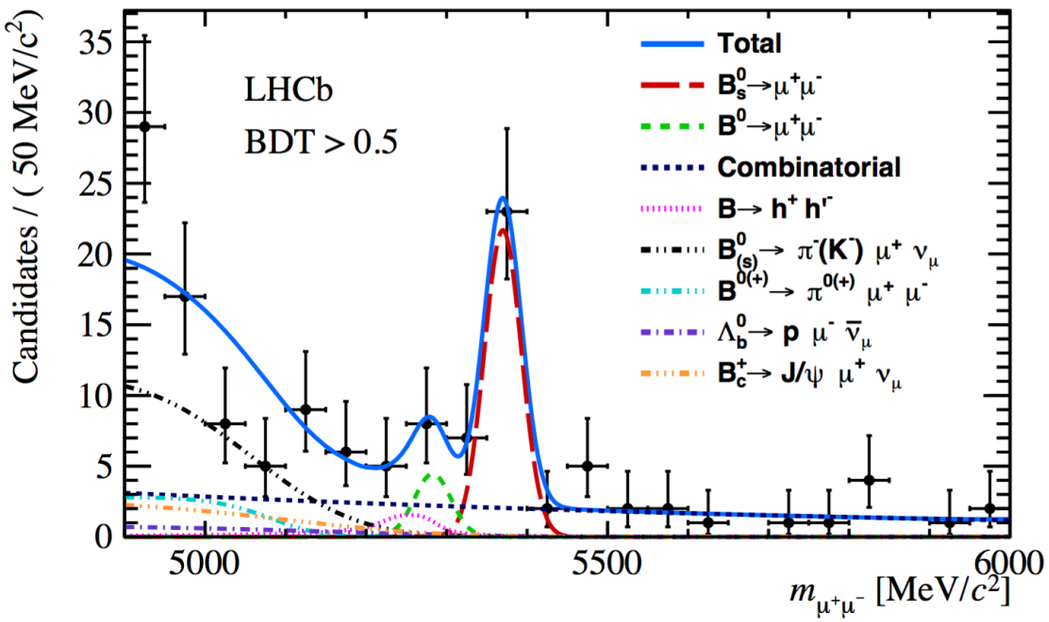
NP

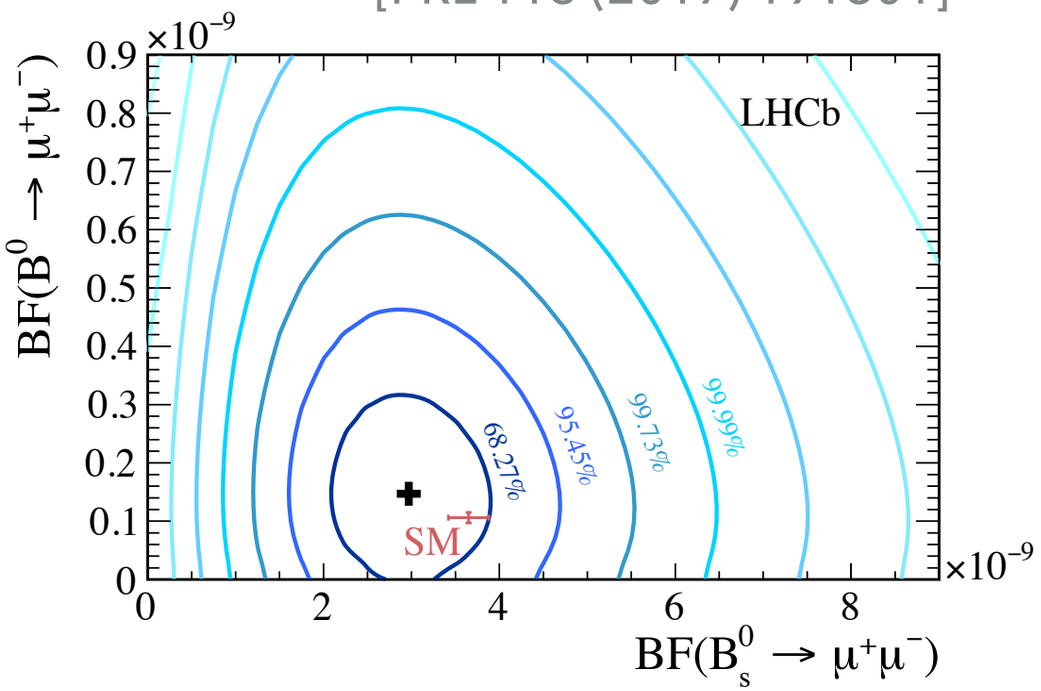


$B(B_{d/s} \to \mu^+\mu^-)$: the peak

- Adding Run II: 4.6 fb^{-1} of luminosity in total and a reoptimised analysis.
- Two normalisation channels $B^0 \to K\pi$ and $B^0 \to (J/\psi \to \mu^+\mu^-)K$
- Backgrounds: mis-ID and/or missing particles:
  - $B \to hh$, peaking under the signal, reduced by a factor of 2

[PRL 118 (2017) 191801]





$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$ **7.8σ** LHCb alone!

As no evidence for B^0 a limit is set : $\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \cdot 10^{-10}$ @ 95% CL

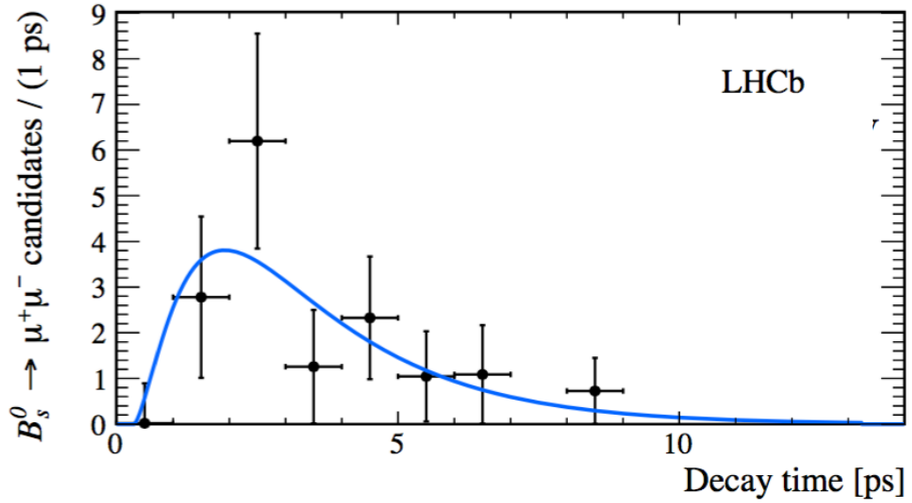
Effective lifetime

- B_s light and heavy eigenstates are characterised by a sizeable $\Delta\Gamma$
- In the Standard Model only the heavy state can decay into $\mu^+\mu^-$

$$A_{\Delta\Gamma}^{\ell^+\ell^-} = \frac{\Gamma_{B_{s,H}\to\ell^+\ell^-} - \Gamma_{B_{s,L}\to\ell^+\ell^-}}{\Gamma_{B_{s,H}\to\ell^+\ell^-} + \Gamma_{B_{s,L}\to\ell^+\ell^-}} \overset{SM}{=} 1$$

Can assume values in [-1,1] BSM!

- Effective lifetime to access $A_{\Delta\Gamma}$



$$\tau(B^0 \to \mu^+\mu^-) = 2.04 \pm 0.44_{(\text{stat})} \pm 0.05_{(\text{syst})}\ \text{ps}$$

PDG: 1.505 ± 0.005 ps

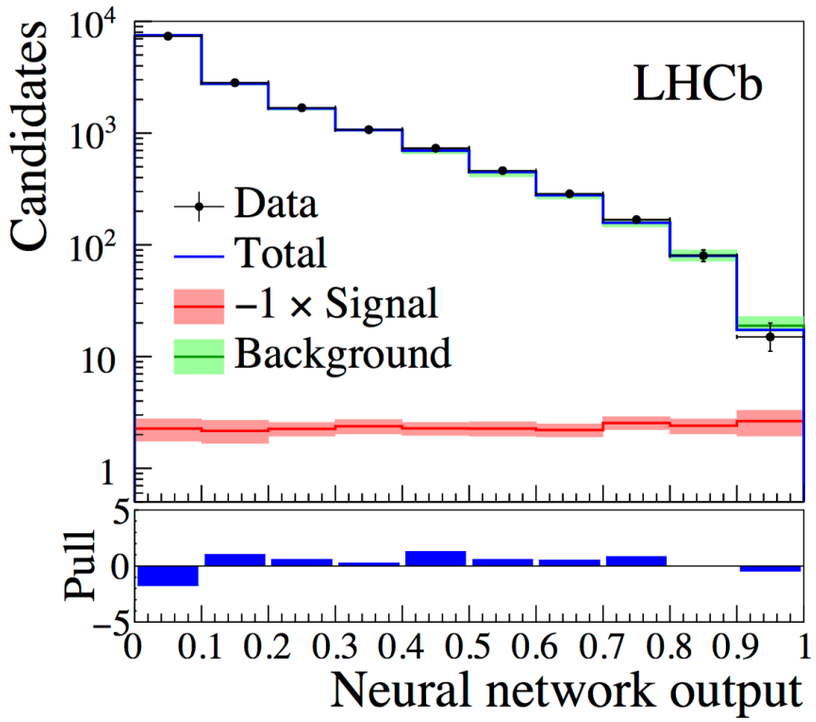
- Toys used to calculate compatibility with $A_{\Delta\Gamma}$ = 1/-1
- Compatible with 1 (-1) at 1σ (1.4σ) level.

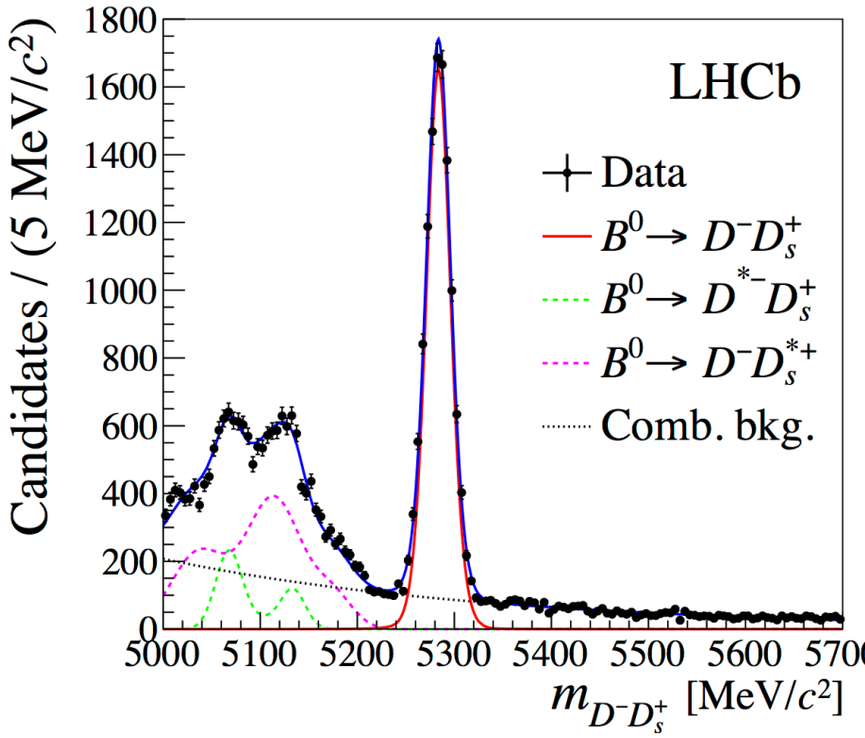
[PRL 118 (2017) 191801]

$B_s \to \tau^+\tau^-$

- Can be used to study LFU when combined with $B_s \to \mu\mu$
- Less helicity suppression → higher BR ~10^{-7} vs 10^{-9}
- Reconstructed using $\tau \to 3\pi\nu$. Challenging due to the neutrinos.
- Normalised with respect to $B^0 \to D^+(K^-\pi^+\pi^+)D^-(K^-K^+\pi^+)$
- As there is no peak the MVA output is fitted

[PRL 118 (2017) 251802]





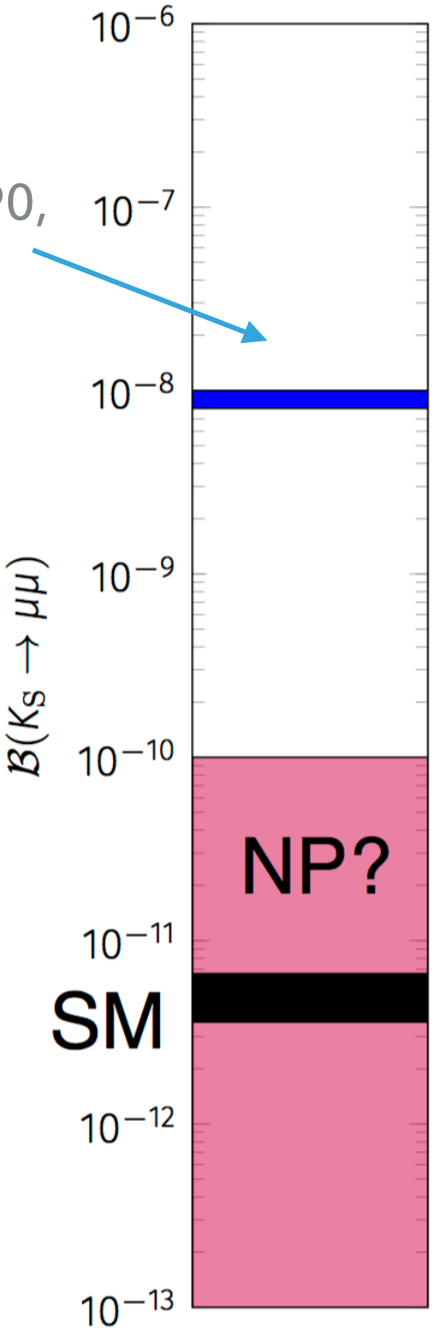
First measurement!

Assuming Bs dominates: $\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 5.2(6.8) \times 10^{-3}$ @ 90(95)% CL

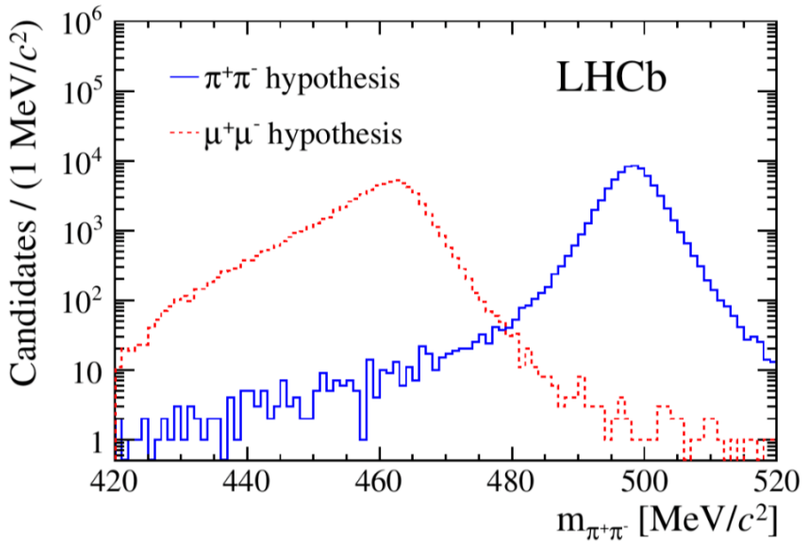
$K_s \to \mu^+\mu^-$

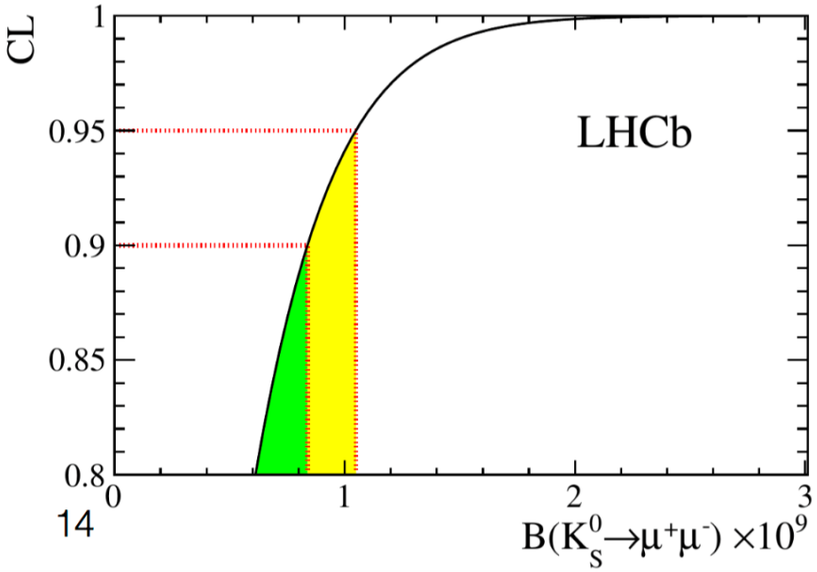
- SM prediction: BR = $(5.0 \pm 1.5) \times 10^{-12}$ JHEP 0401 (2004) 009
- Can be enhanced by up to factor 100
- LHCb analysis using 3 fb^{-1}, improved trigger efficiency
- $K_s \to \pi^+\pi^-$: normalisation channel and main background
- Two BDTs: for combinatorial and for $K_s \to \pi^+\pi^-$

Previous limit
JHEP 01 (2013) 090,



$$\mathcal{B}(K_s^0 \to \mu^+\mu^-) = 1.0 \times 10^{-9} \,@\, 95\%\,\mathrm{CL}$$





[arXiv:1706.00758]

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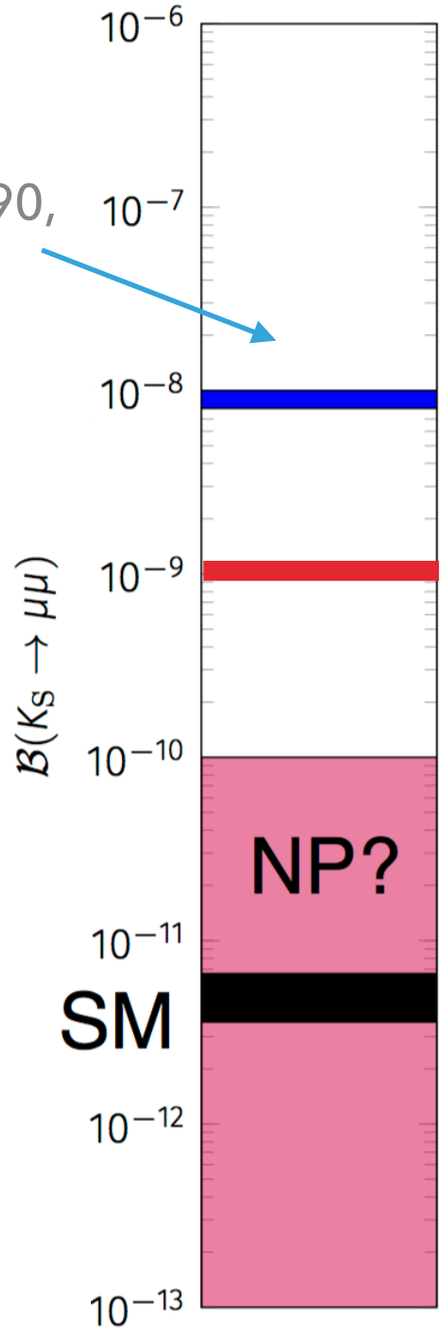

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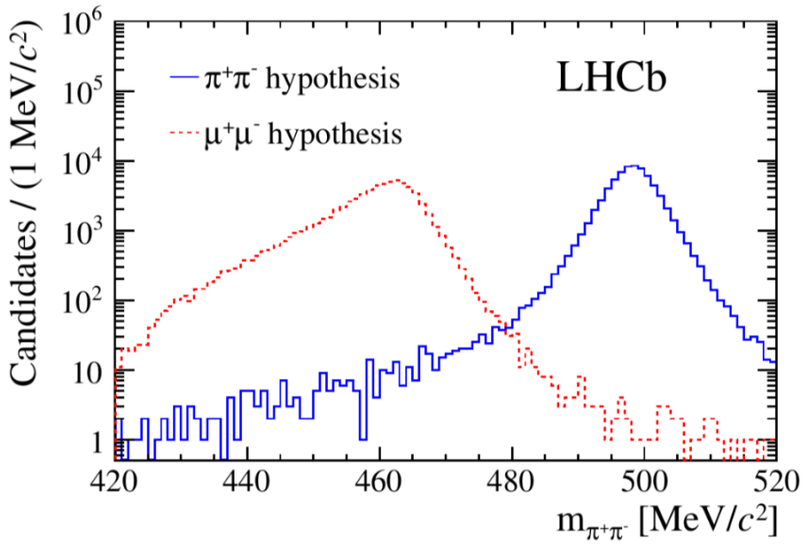
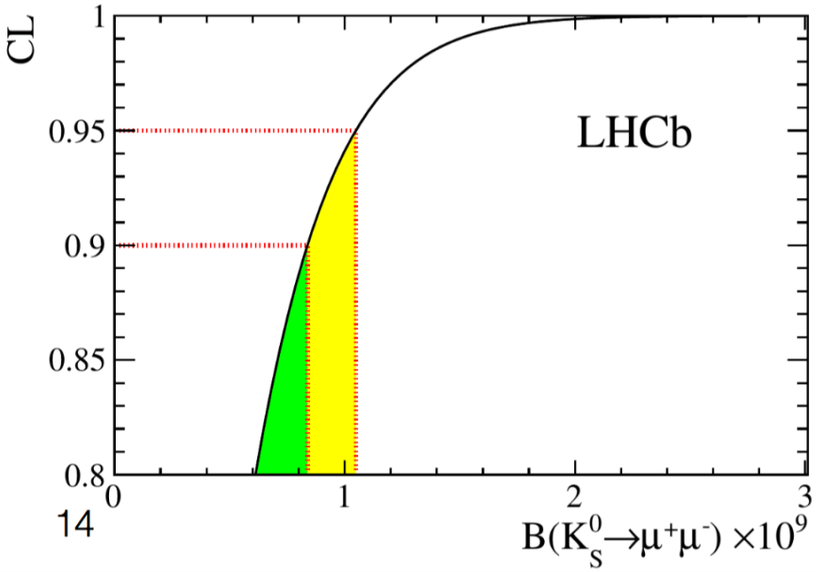
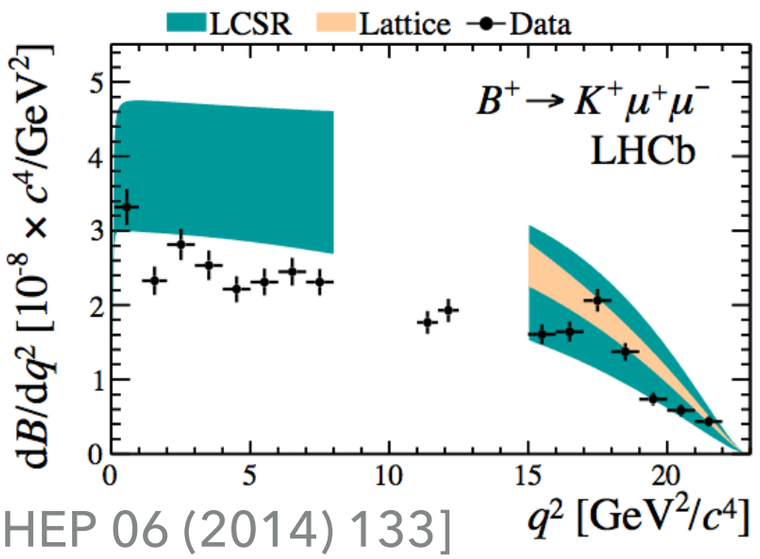


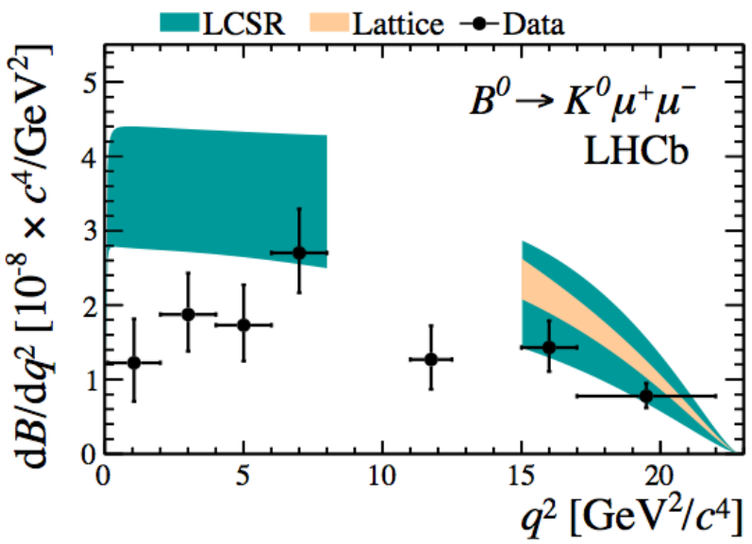


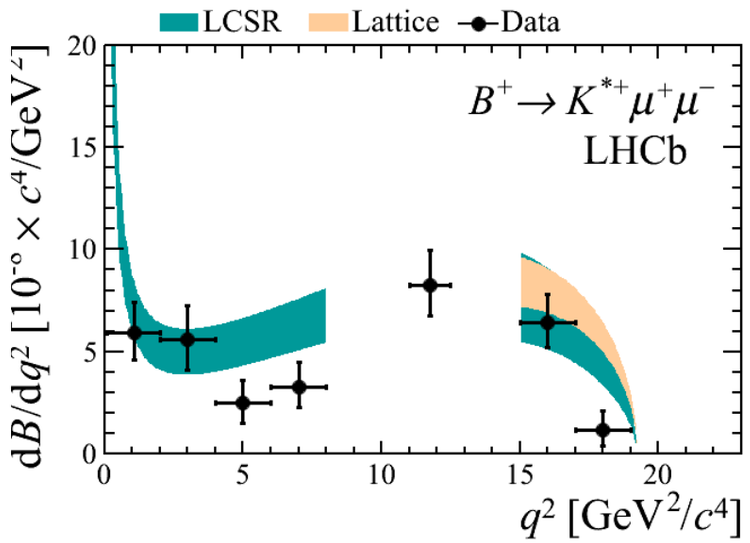
[arXiv:1706.00758]

Semileptonic decays

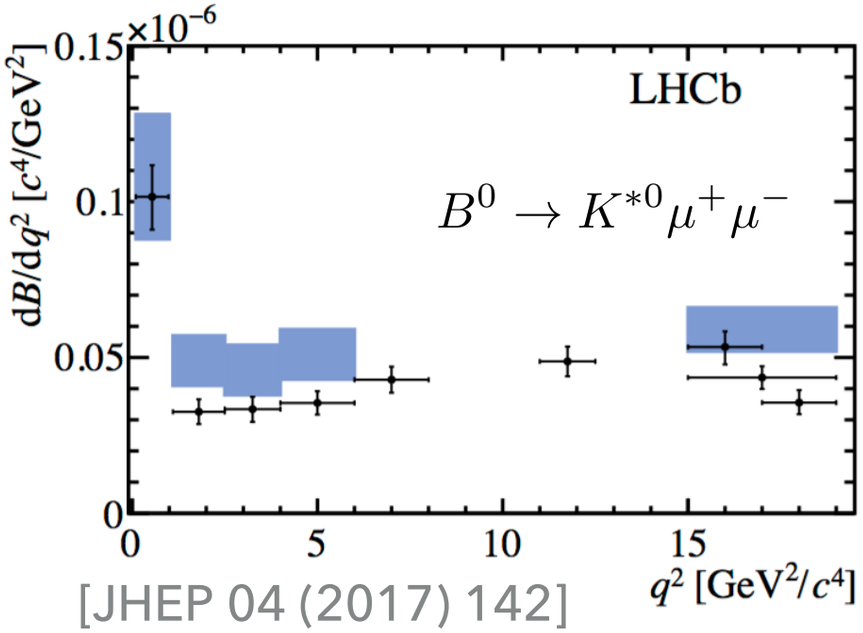
Various observables measured starting with branching ratios.



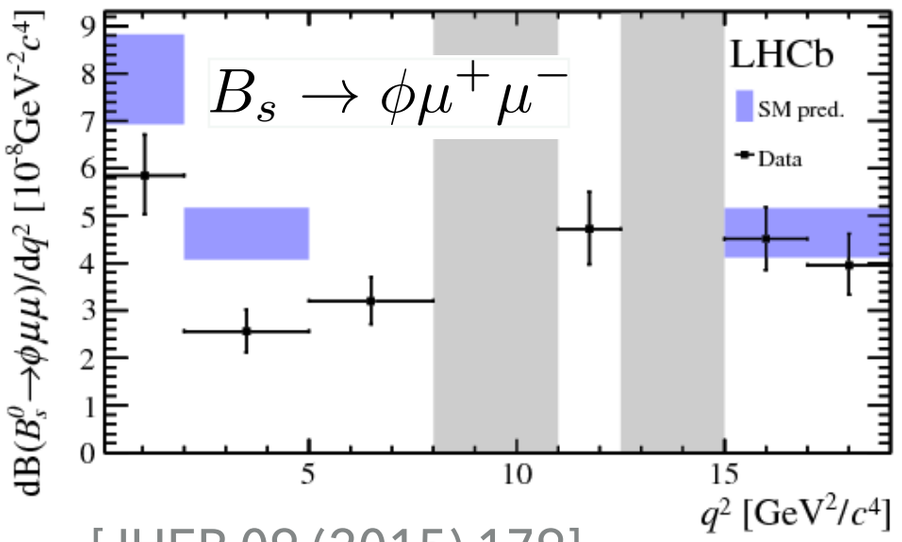




[JHEP 06 (2014) 133]



[JHEP 04 (2017) 142]

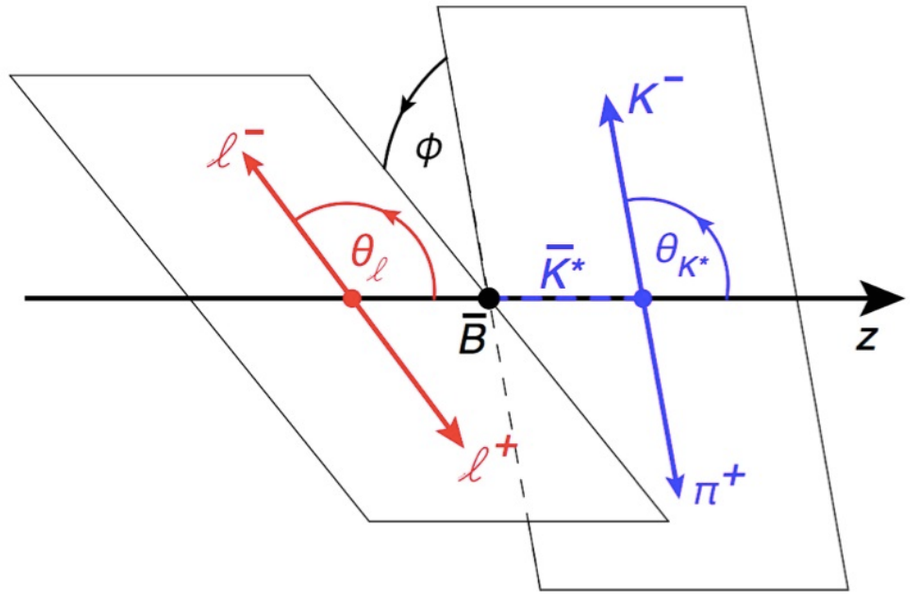


[JHEP 09 (2015) 179]

Measurements systematically lower than the SM.

$B^0 \to K^{*0}\mu\mu$ angular analysis

- Angular distributions described by 3 angles: θ_ℓ, θ_K, ϕ
- Distributions depend on:
  - ✓ Wilson coefficients: sensitive to NP :-)
  - ✓ and form factors :-(
- Measure variables with reduced form factor uncertainties (JHEP, 05, 2013, 137)



[JHEP 08 (2013) 131]
[PRL 111 (2013) 191801]

$$P'_{(4,5,6,8)} = \frac{S_{(4,5,7,8)}}{\sqrt{F_L(1-F_L)}}$$

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_l d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi}[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_l$$
$$-F_L\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi$$
$$+S_5\sin 2\theta_K\sin\theta_l\cos\phi + S_6\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi]$$

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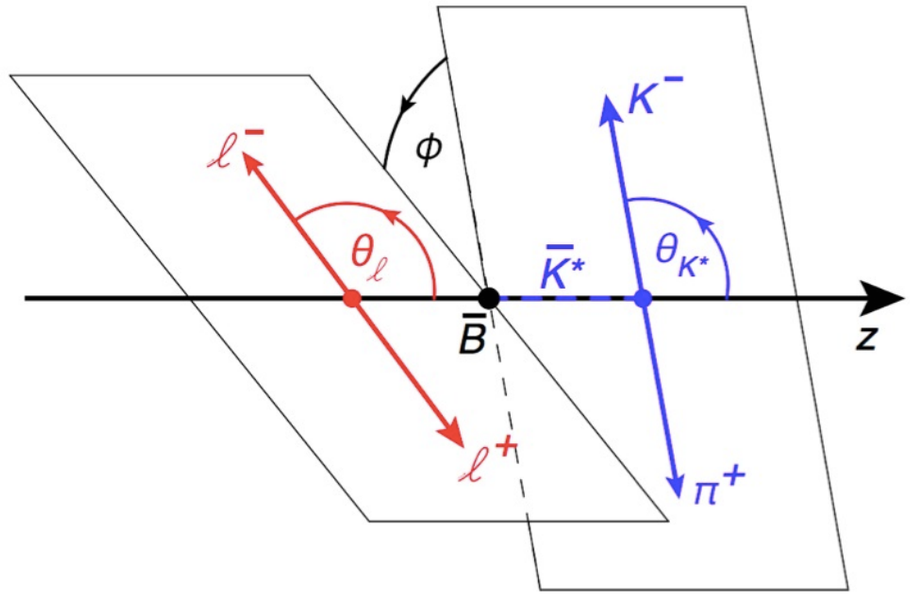
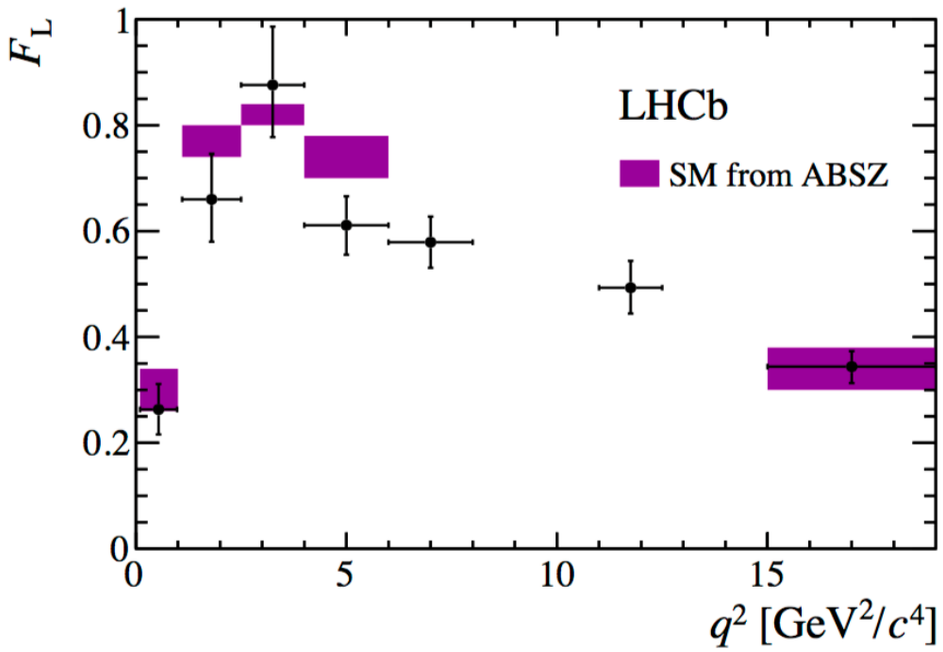


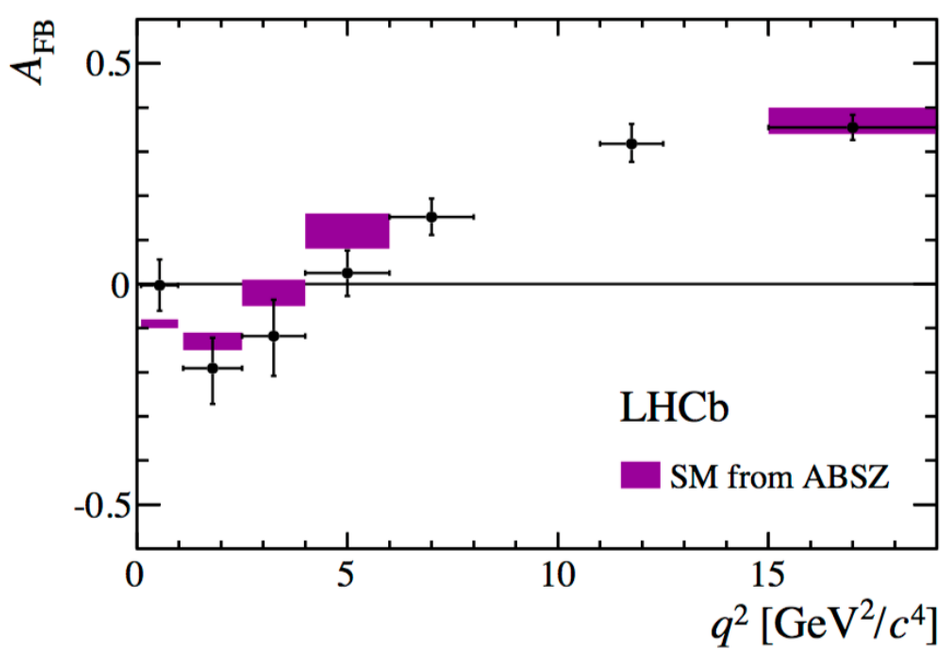
[JHEP 08 (2013) 131]
[PRL 111 (2013) 191801]

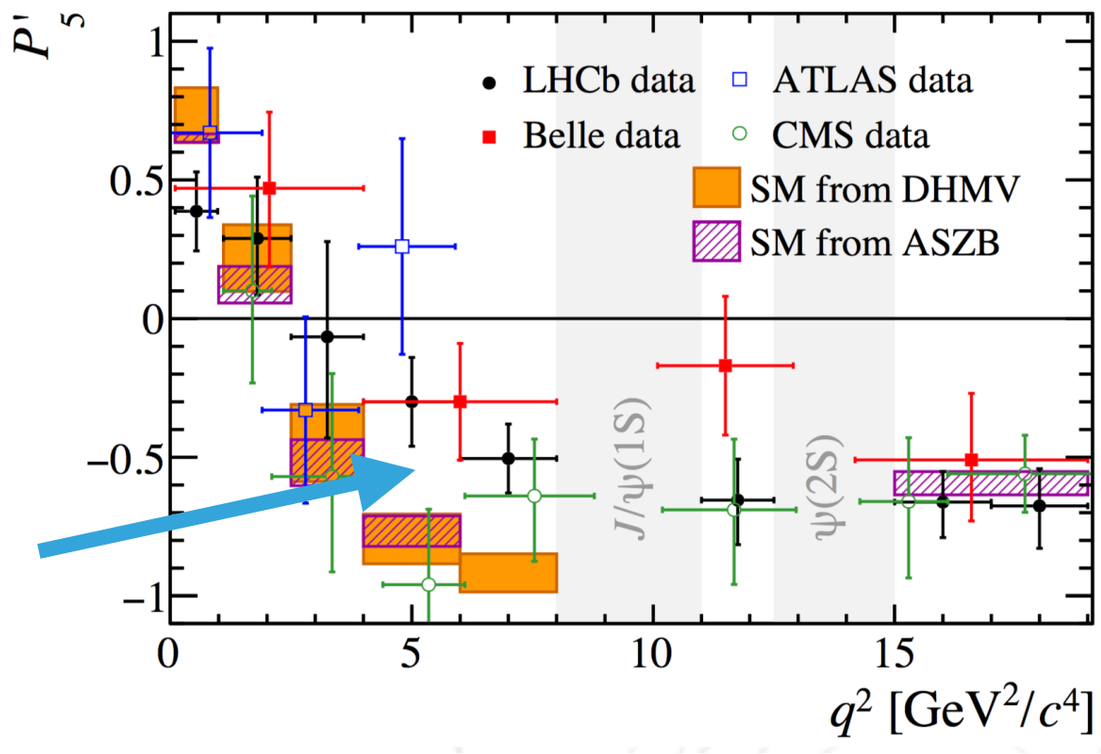
$$P'_{(4,5,6,8)} = \frac{S_{(4,5,7,8)}}{\sqrt{F_L(1-F_L)}}$$

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_l d\cos\theta_K d\phi dq^2} = \frac{9}{32\pi}[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_l$$
$$-F_L\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi$$
$$+S_5\sin 2\theta_K\sin\theta_l\cos\phi + S_6\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi]$$

$B^0 \to K^{*0}\mu\mu$ angular analysis







[JHEP 02 (2016) 104]

Many observables found to be in agreement with the SM predictions

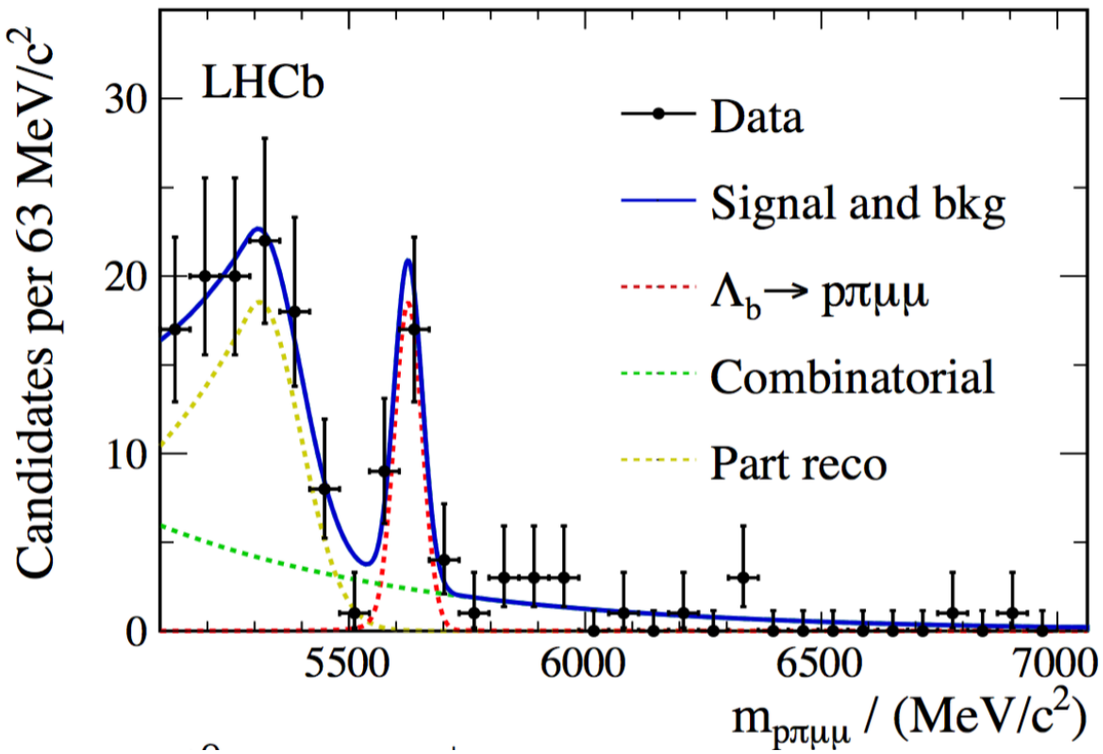
BUT

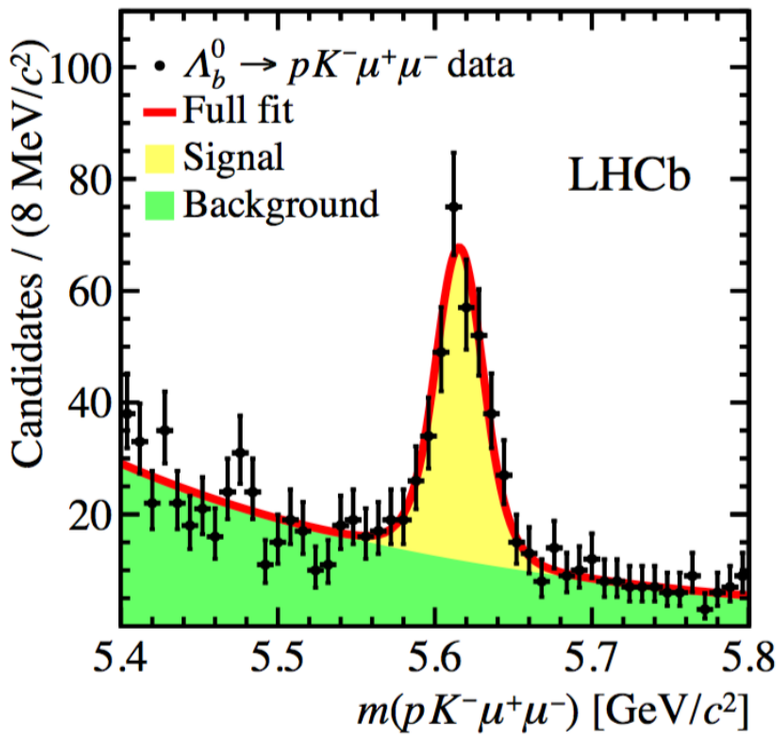
LHCB: LOCAL 3.7σ DEVIATION ON P'_5 FOUND ON 2011 DATA AND CONFIRMED ON 2012.

ATLAS-CONF-2017-023, CMS-PAS-BPH-15-008, PRL 118 (2017) 111801

Progress with Λ_b

- Two first observations: $\Lambda_b \to p\pi\mu\mu$ and $\Lambda_b \to pK\mu\mu$!



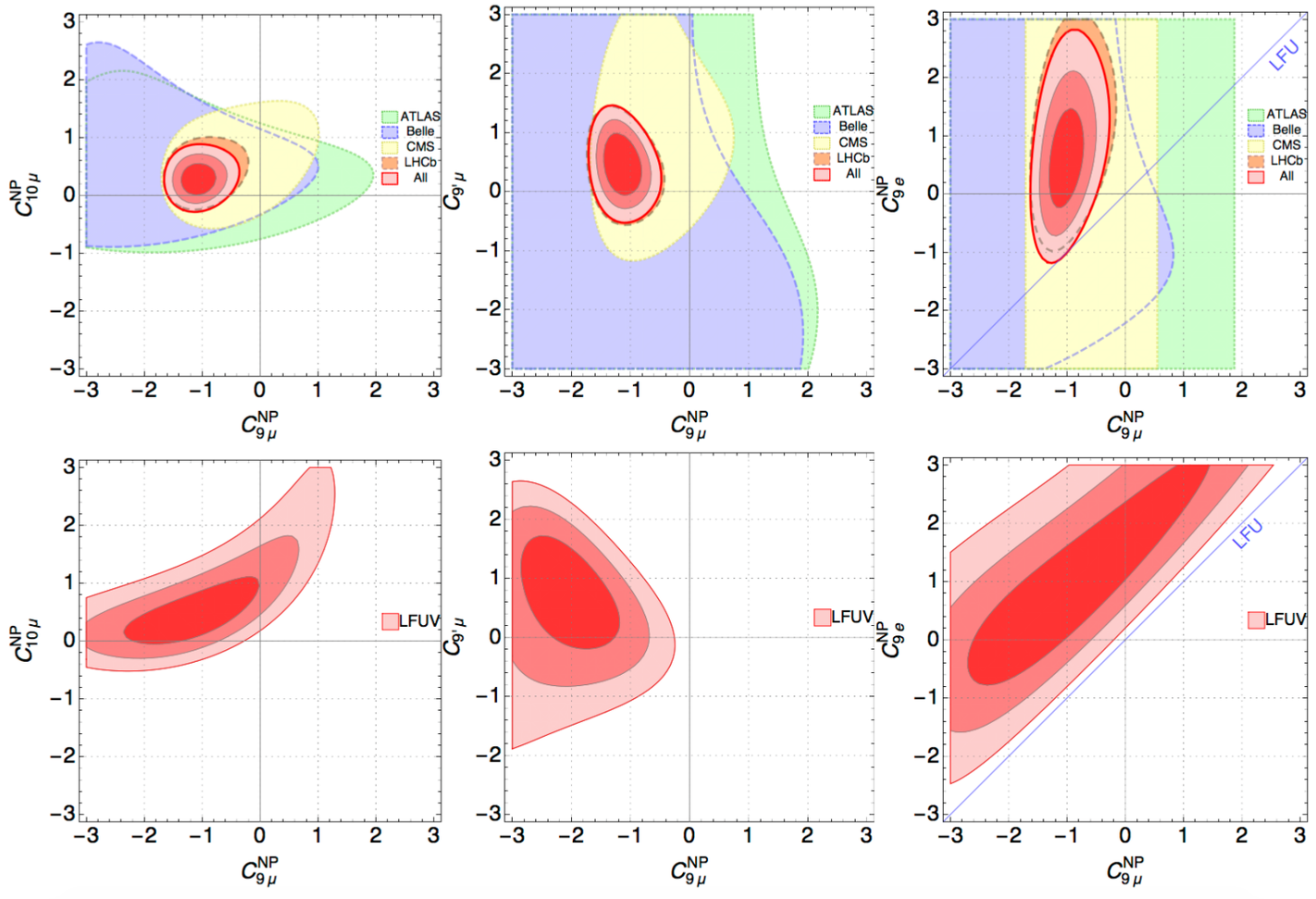


- Using Run I: 3fb^{-1}. Together can be used to measure $|V_{td}|/|V_{ts}|$
- Different form factors: independent measurements wrt mesons
- $\Lambda_b \to p\pi\mu\mu$: first observation of a $b \to d$ baryonic decay [JHEP 04 (2017) 029]
- CP violation measured in $\Lambda_b \to pK\mu\mu$, no evidence found [JHEP 06 (2017) 108]

Global fits

Model independent global fits performed using inputs from several decays

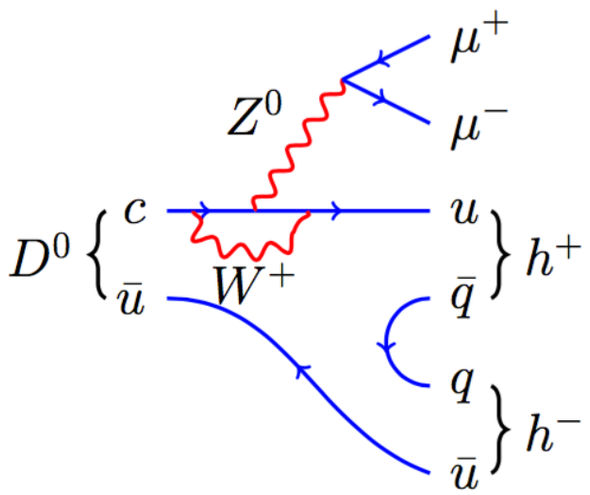
[arXiv 1704.05340]

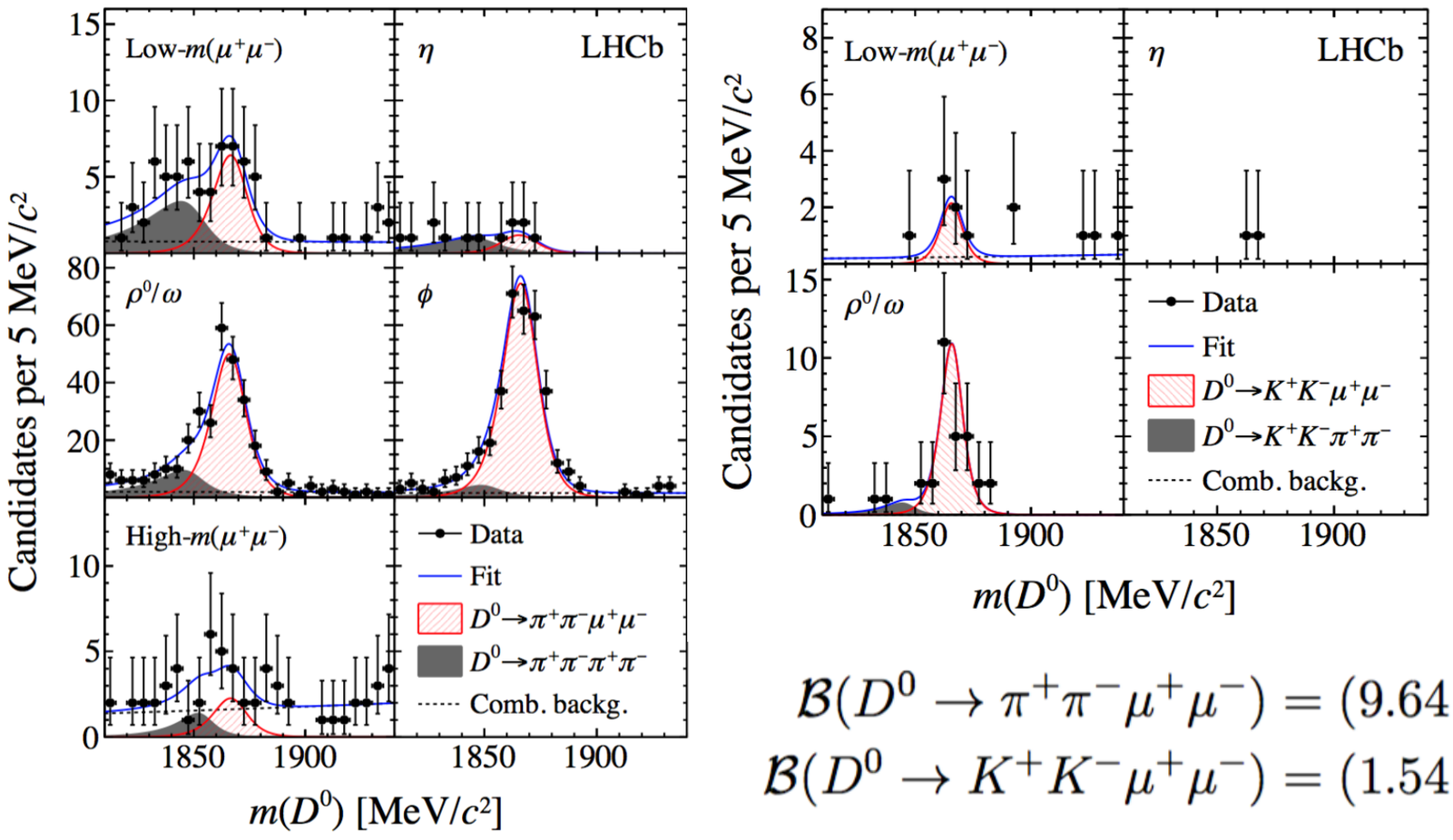


A scenario with a new physics contribution $C_9^{NP} = -1$ is favoured.
Other approaches from different groups yield the same conclusion.

Charming progress: $D^0 \to hh\mu\mu$

- Looking at c→u FCNC processes:
  - Benefits from high charm σ but GIM suppressed
- Difficult to separate resonances: ω,ρ
  - 4-body decays give access to angular observables





First observation of $D^0 \to \pi\pi\mu\mu$ and evidence for $D^0 \to KK\mu\mu$!

Compatible with SM

[arXiv:1707.08377]

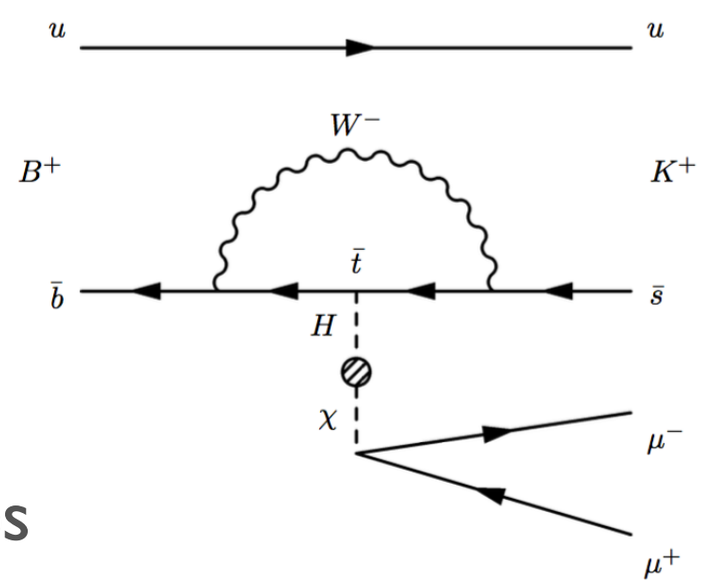
$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7},$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}.$$

Long lived particles

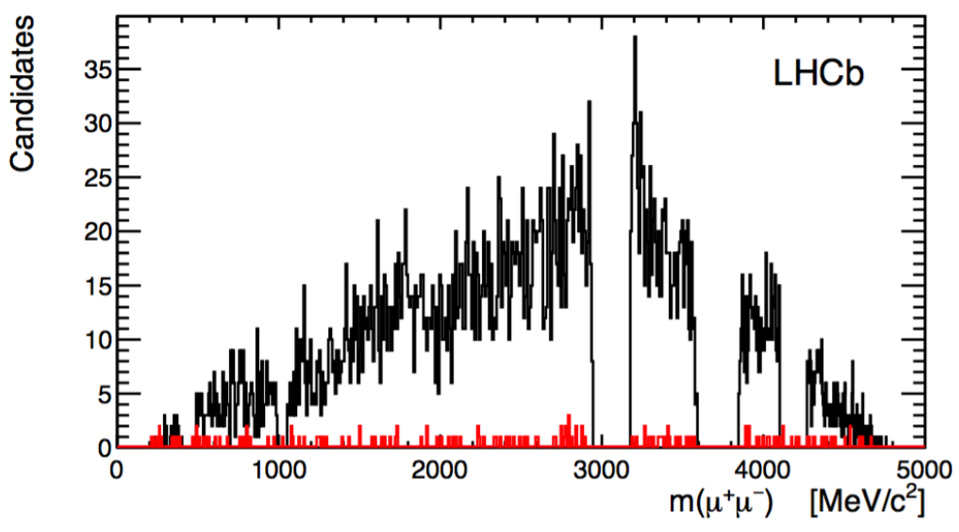
- No direct detection of dark matter

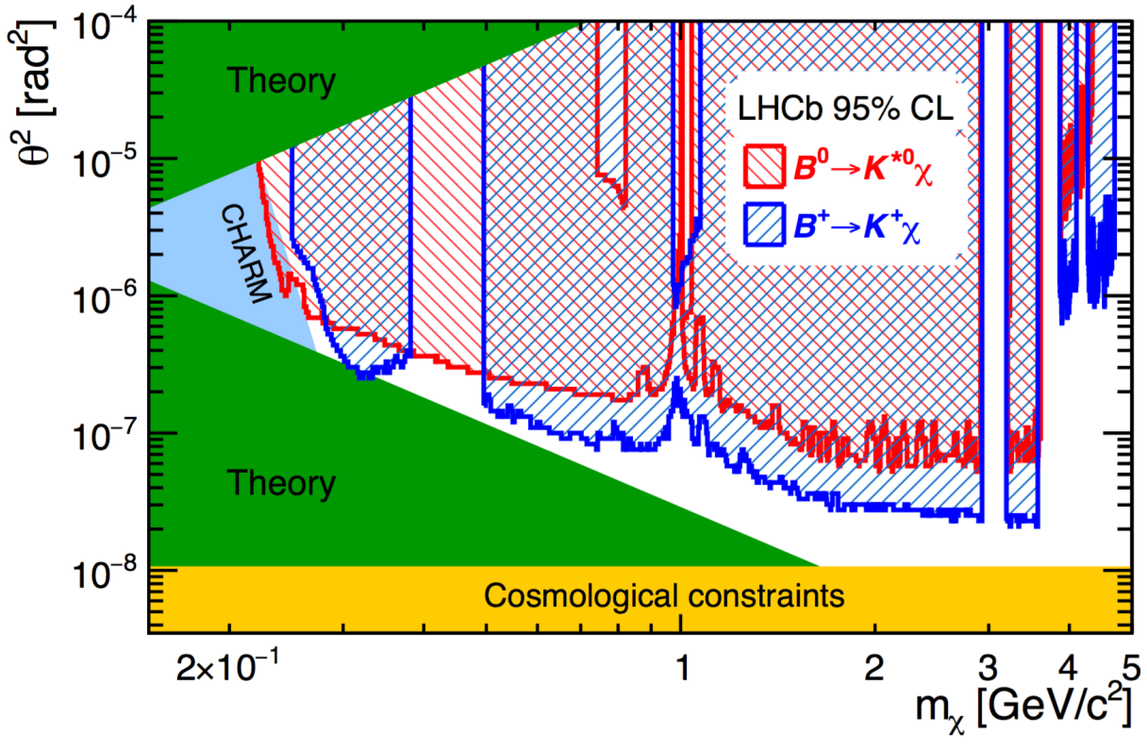
  ⇒ Search for $B^+/B^0 \to (X \to \mu\mu)K^+/K^{*0}$

  Vetoes for J/ψ, ψ, ϕ, K_S, Λ^0
- Normalising by $B^+/B^0 \to (J/\psi \to \mu\mu)K^+/K^{*0}$
- Three lifetime regions: [0,1] [1,10] and >10 ps
- No signal: limits with CLs



[PRD 95 071101 (2017)]





SUMMARY AND CONCLUSIONS

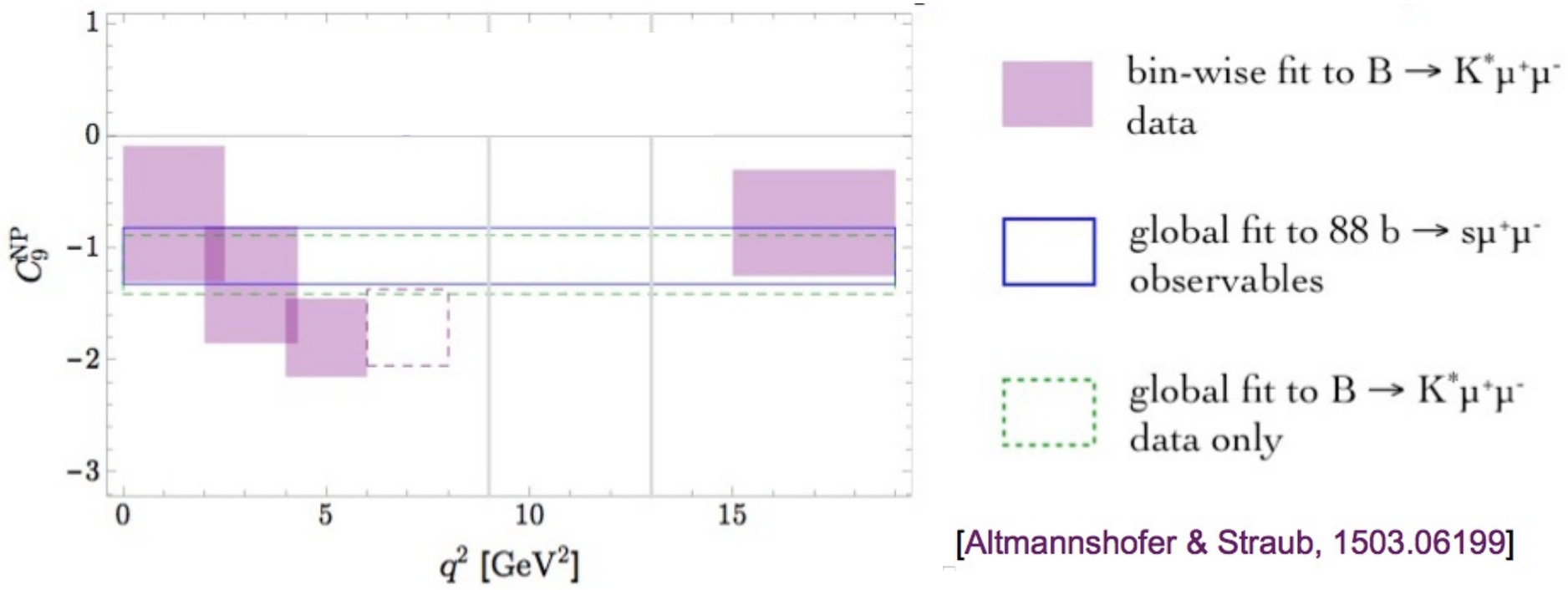
- Rare decays offer a rich environment to test the Standard Model and probe new physics models
  - ✓ The observation of a SM-like $B_s \to \mu^+\mu^-$ strongly constrains BSM
  - ✓ Hints of anomalies make very interesting to continue these studies.

- As we deal with rare decays most results are still statistically limited…
  - ✓ Many analyses are working to include Run II
  - ✓ New modes will be analysed: Λ_b and charm

… stay tuned!

BACKUP

Global fits: interpretation



[Altmannshofer & Straub, 1503.06199]

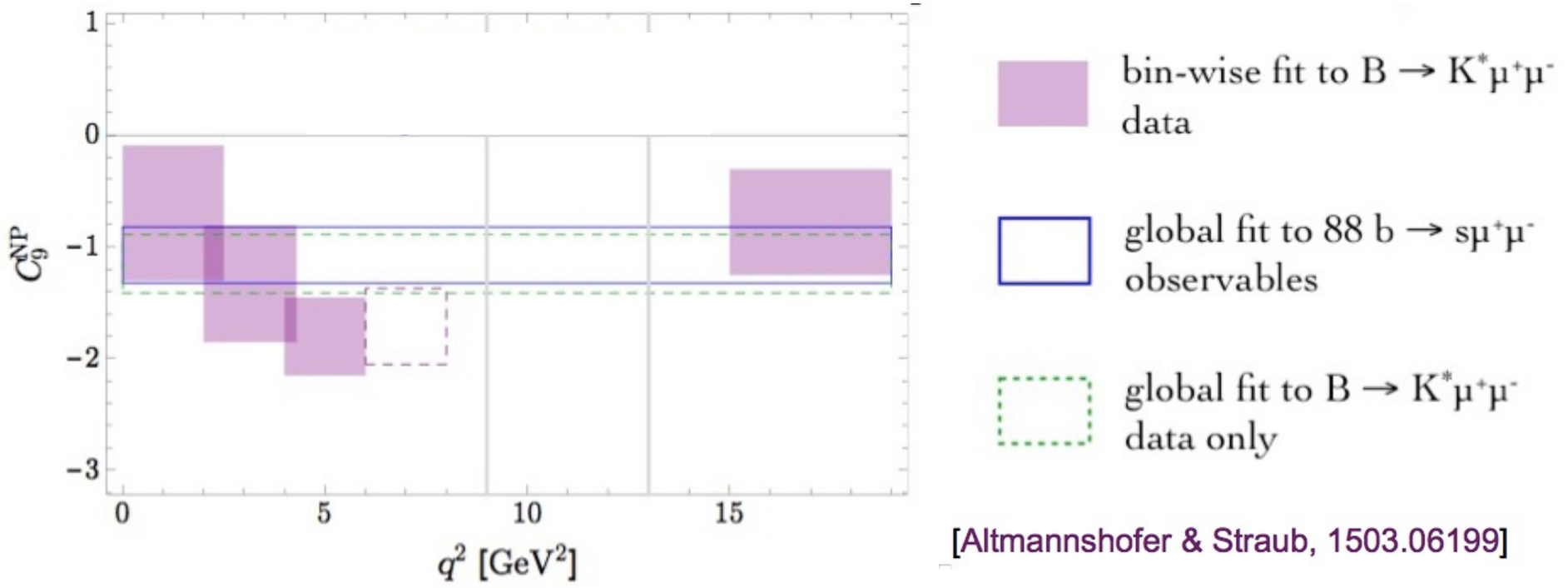
✓ A consistent picture can be built

✓ Possible explanation with Z' bosons.

✓ Or for pessimist theorists… charm loops

✓ If it is NP → it should be q^2 independent

Global fits: interpretation



[Altmannshofer & Straub, 1503.06199]

- ✓ A consistent picture can be built
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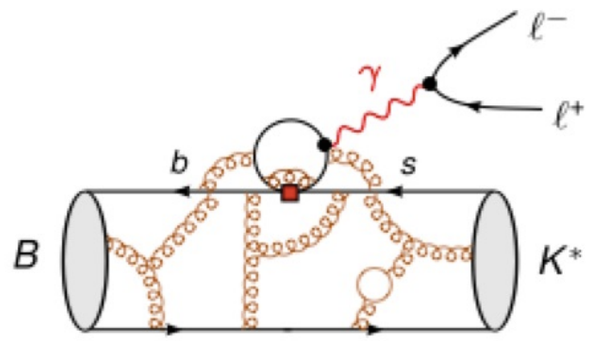
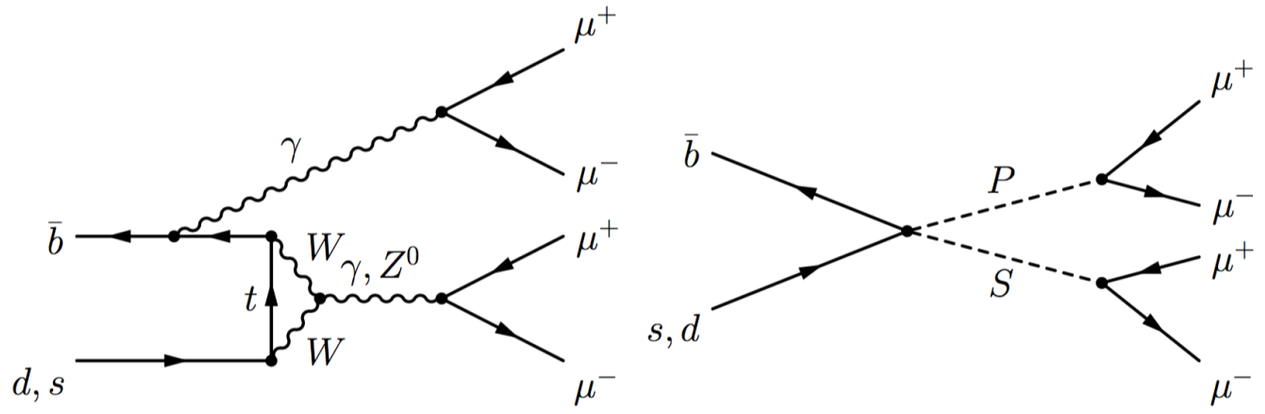
- ✓ If it is NP → it should be q^2 independent

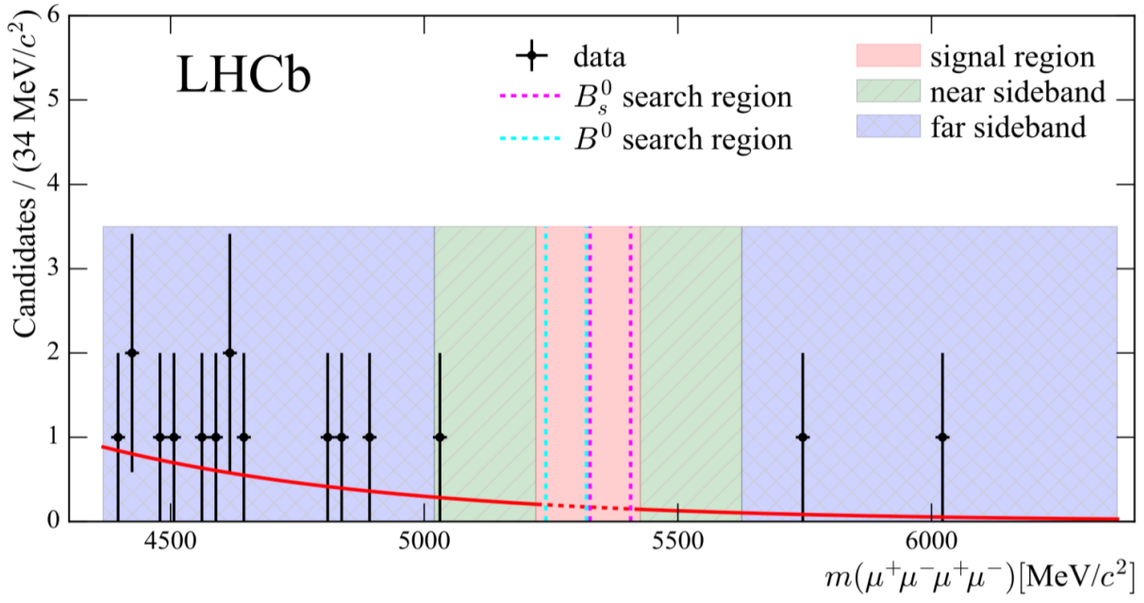


$B_{d/s} \rightarrow \mu^+\mu^-\mu^+\mu^-$

- Can proceed via scalar and pseudo scalar sgoldino decays.
- SUSY BR up to ~10^{-4}
- Related to the $\Sigma \rightarrow p\mu\mu$ excess observed by HyperCP

[PRL 94 (2005) 021801]





Using full Run I: $3fb^{-1}$.
Limits improved by a factor ~6 (10) for B_s (B^0) wrt previous LHCb results.

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\mu^+\mu^-) < 2.5 \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 6.9 \times 10^{-10},$$
$$\mathcal{B}(B_s^0 \to S(\to \mu^+\mu^-)P(\to \mu^+\mu^-)) < 2.2 \times 10^{-9},$$
$$\mathcal{B}(B^0 \to S(\to \mu^+\mu^-)P(\to \mu^+\mu^-)) < 6.0 \times 10^{-10}.$$

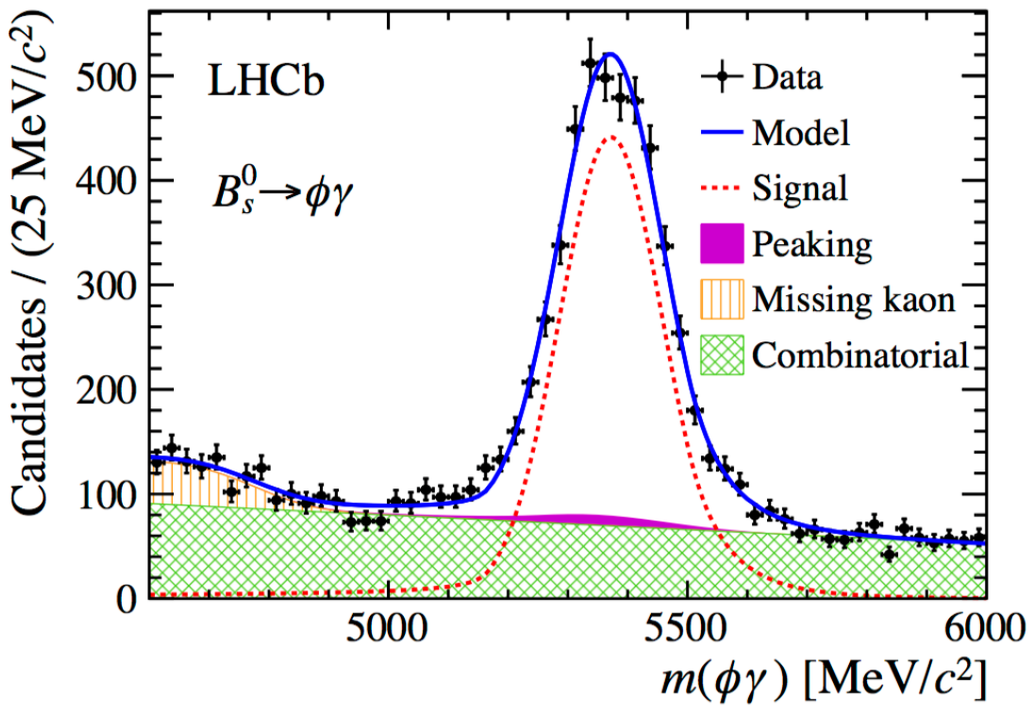
@ 95% CL

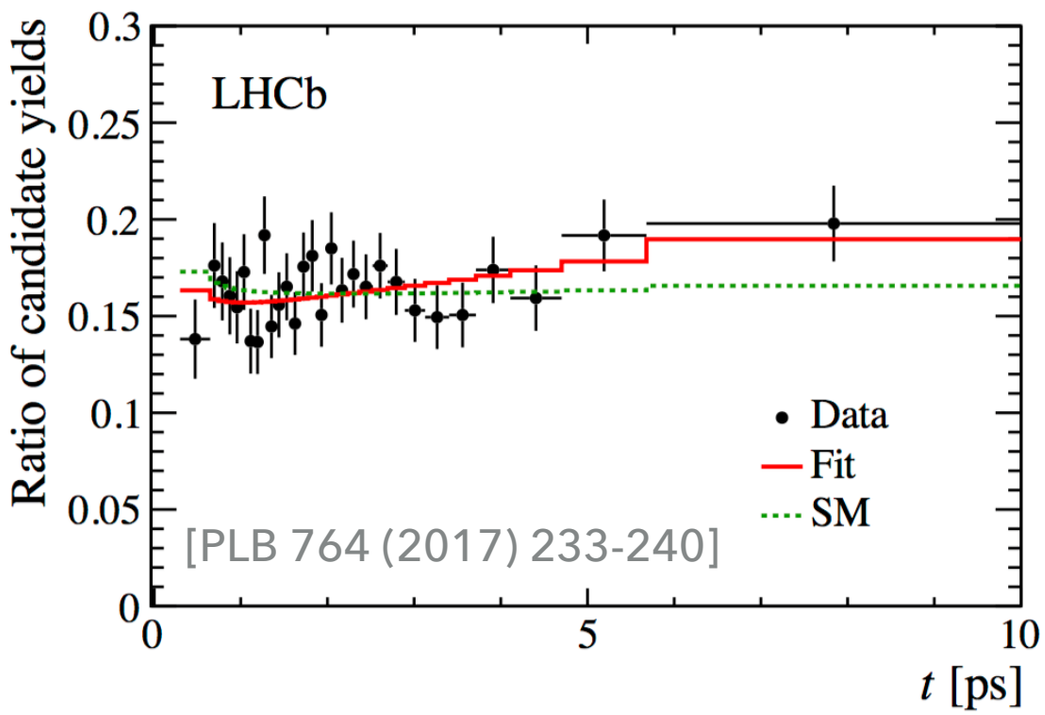
[JHEP 03 (2017) 001]

Polarisation of Bs mesons

- In SM photon is pre-dominantly left-handed
- Non-zero polarisation first observed in $B^+ \to K\pi\pi\gamma$ [PRL 112 (2014) 161801]
- Further studies of photon polarisation using $B_s \to \phi\gamma$
- Using $B^0 \to K^{*0}\gamma$ as normalisation

$$\mathcal{A}^{\Delta} = -0.98\,^{+0.46}_{-0.52}\,^{+0.23}_{-0.20} \qquad \mathcal{A}^{\Delta}_{\rm SM} = 0.047\,^{+0.029}_{-0.025}$$





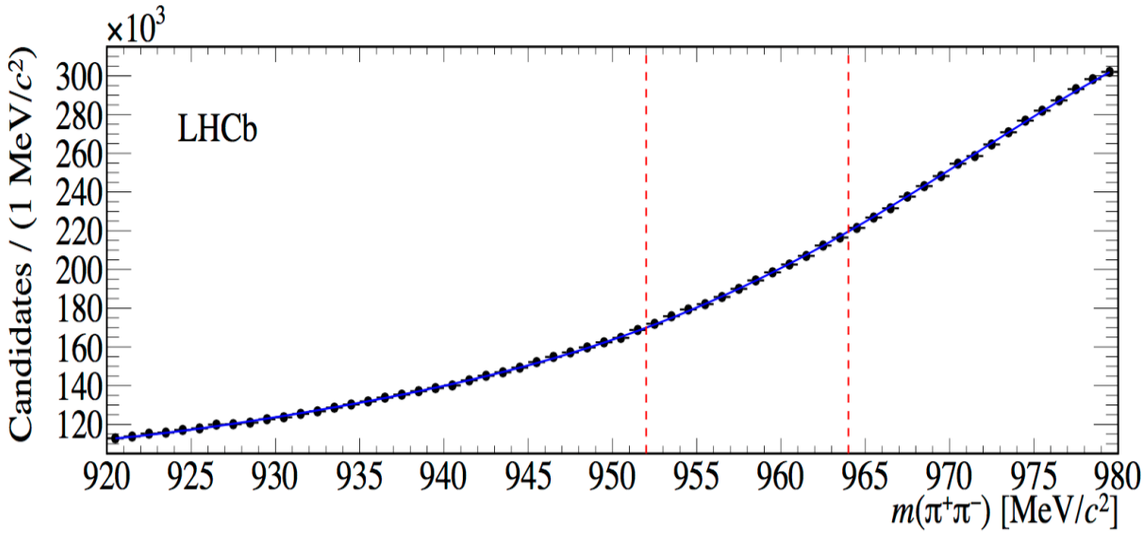
Rare decays vs the "strong CP problem"

- The QCD lagrangian can contain an extra term
- Experimental limits on the nEDM set $\theta<10^{-10}$
- Regarded as a fine-tuning problem [Phys.Atom.Nucl. 70 (2007) 349-357]

$$\mathcal{L} = \theta \frac{1}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu a}$$

The $\eta \to \pi\pi$ and $\eta'(958) \to \pi\pi$ would both violate CP symmetry

- Looking for these decays using high statistics $D_{(s)} \to \eta^{(')}\pi$ samples
- Several background vetoes including $\eta^{(')} \to \pi\pi\gamma$, $D \to K\pi\pi/3\pi\pi^0$



[PLB 764 (2017) 233-240]

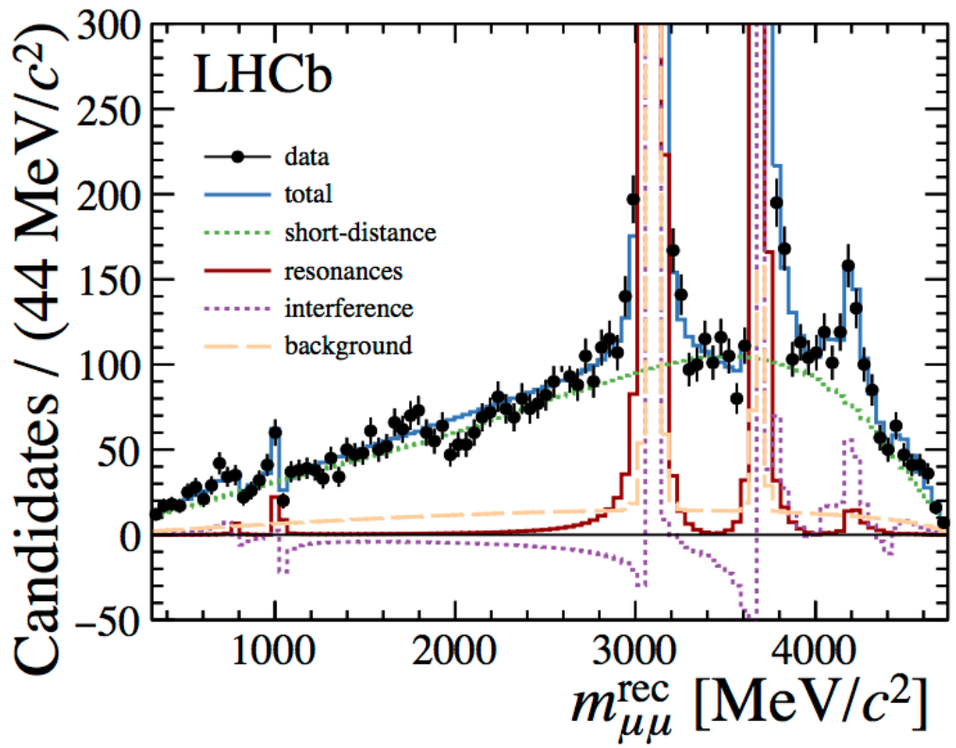
- No signal observed
- Limits set with CLs comparable to KLEO previous ones

$$\mathcal{B}\left(\eta \to \pi^+\pi^-\right) < 1.6 \times 10^{-5},$$
$$\mathcal{B}\left(\eta' \to \pi^+\pi^-\right) < 1.8 \times 10^{-5},$$

@95%CL

Phase difference

- Fit of to full dimuon mass distribution
- Relativistic Breit–Wigner amplitudes to describe resonances
- Short-distance contribution in terms of an effective field theory
- Relative parameters between resonances and the short-distance allowed to vary
- Model includes: ρ, ω, φ, J/ψ, ψ(2S) and boroad ψ resonances



[Eur. Phys. J. C (2017) 77 161]

$$\mathcal{B}(B^+ \to K^+\mu^+\mu^-) = (4.37 \pm 0.15 \pm 0.23) \times 10^{-7}$$

C9 = 0 excluded at > 5 σ. Compatible with other measurements.

Effective Hamiltonian

Effective Hamiltonian for b→d and b→s in terms of Operator Expansion.

With possible left-handed and right-handed components:

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{\alpha_e}{4\pi} \sum_{i=1}^{10} [C_i\mathcal{O}_i + C'_i\mathcal{O}'_i]$$

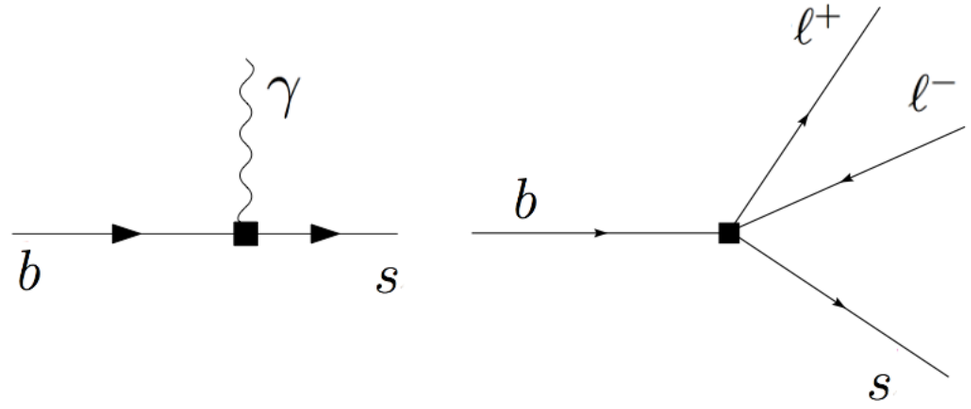
Suppressed
C' ~ m_s/m_b C

[arXiv:1501.03309]

Relevant operators:

- ✓ $O_{S,P}$: purely leptonic decay
- ✓ O_7 : radiative penguin
- ✓ $O_{9,10}$: semileptonic decays

  (Z penguin and W-box)



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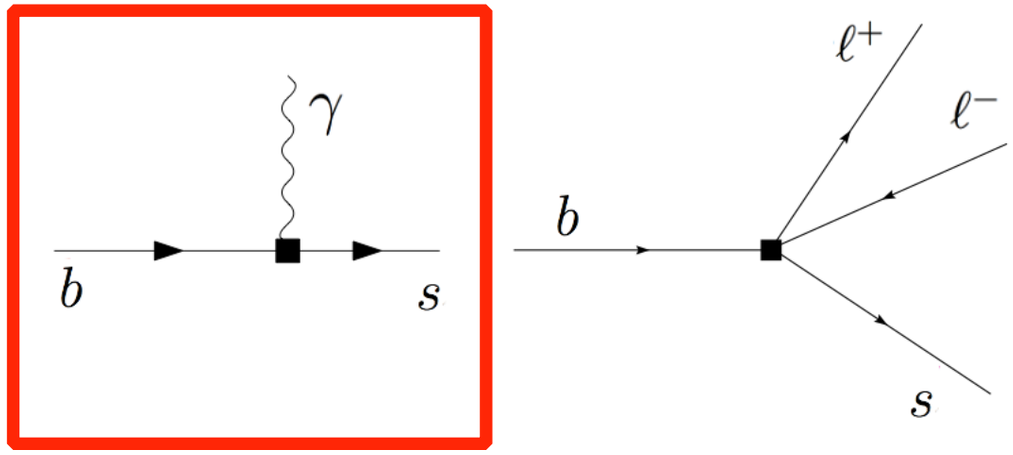

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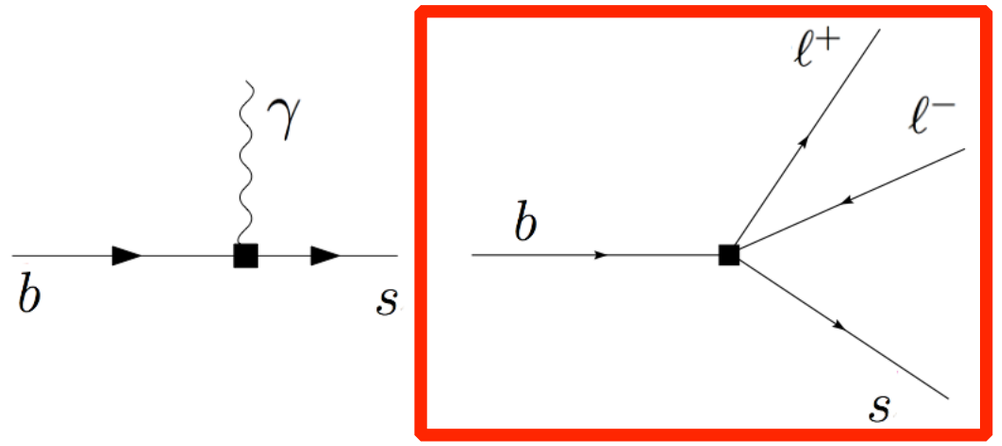

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- ✓ O_7 : radiative penguin
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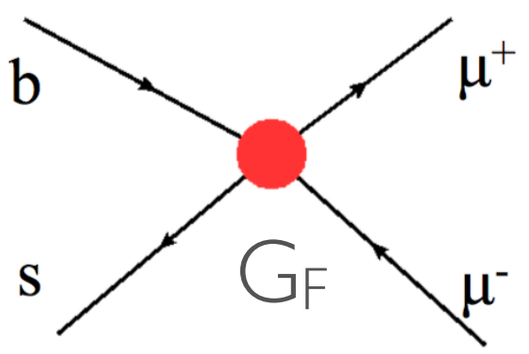
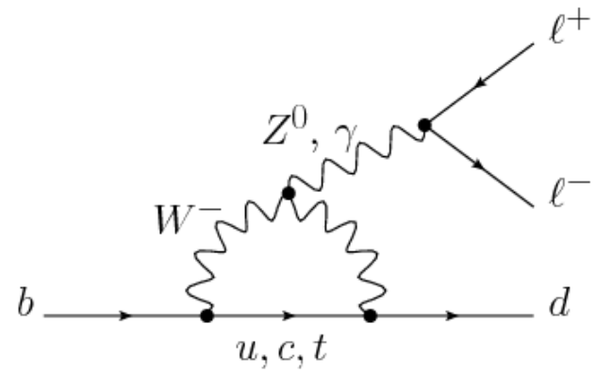
  (Z penguin and W-box)

Nothing different than what was done for the Fermi theory of EW interactions.





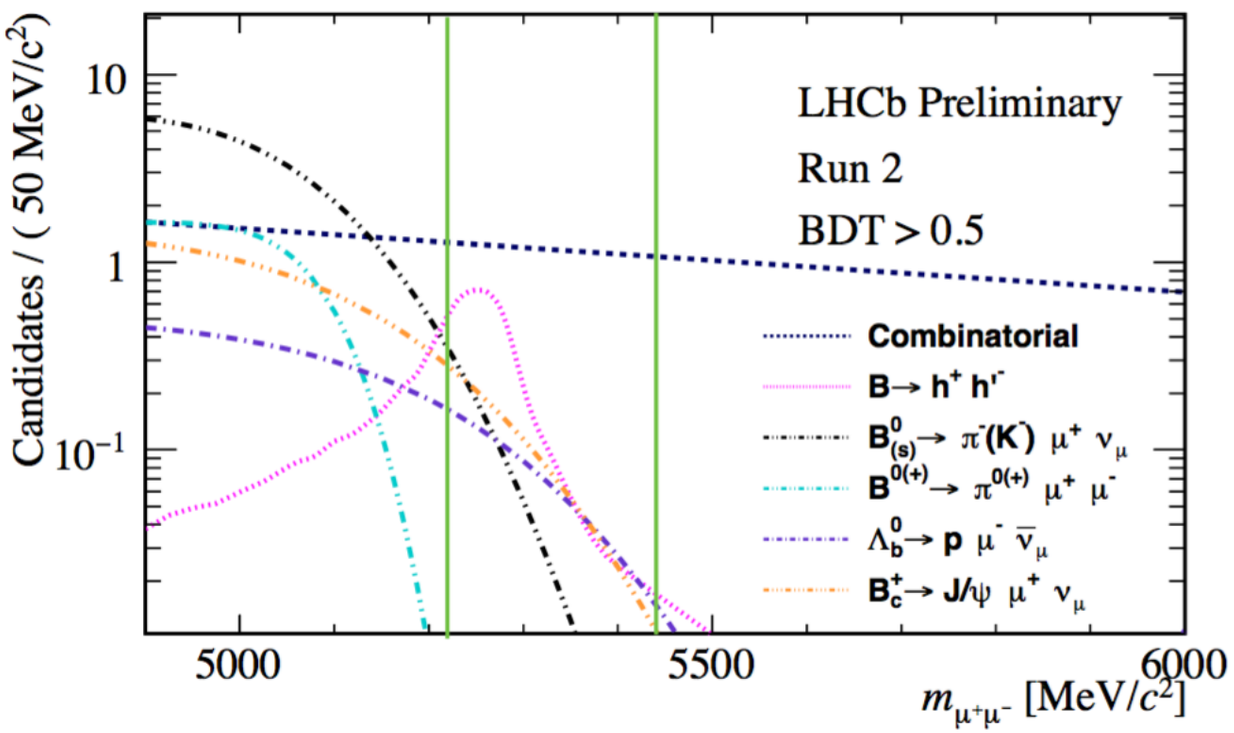
$B(B_{d/s} \to \mu^+\mu^-)$

- Two normalisation channels $B^0 \to K\pi$ and $B^0 \to (J/\psi \to \mu^+\mu^-)K$
- New isolation variables based on → MVAs help rejecting backgrounds
- Backgrounds: mis-ID and/or missing particles:

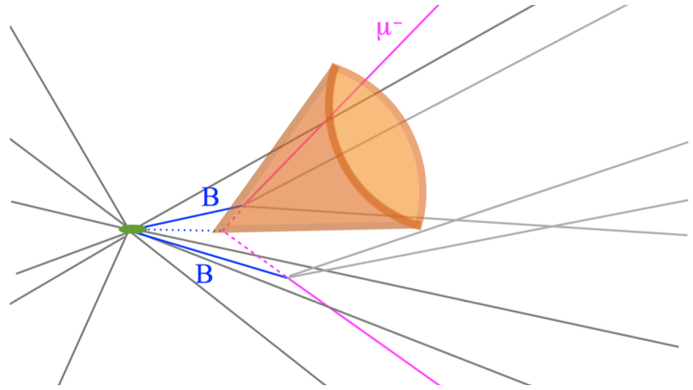
- $B \to h^+h'^-$
- $B^0 \to \pi^-\mu^+\nu_\mu$
- $B^0_s \to K^-\mu^+\nu_\mu$
- $\Lambda^0_b \to p\mu^-\overline{\nu}_\mu$
- $B_c^+ \to J/\psi(\to\mu^+\mu^-)\mu^+\nu_\mu$
- $B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$

- Less then 5 expected events in total, mostly at low masses
- $B \to hh$, peaking under the signal, reduced by a factor of 2 wrt previous analysis

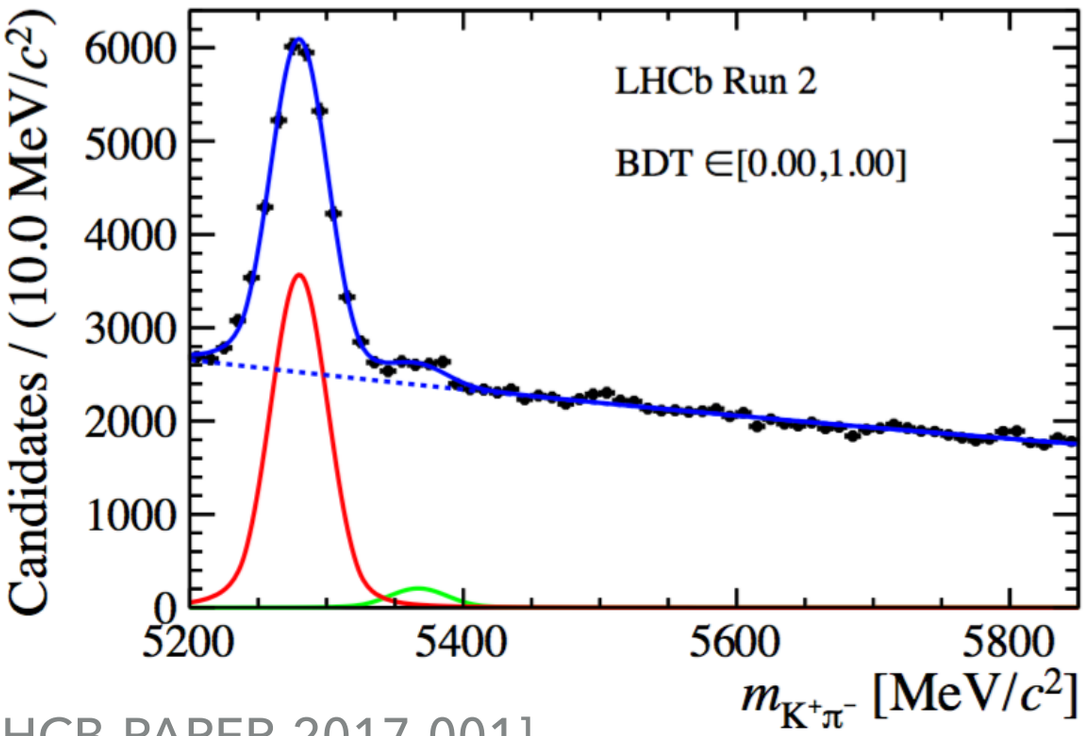
[LHCB-PAPER-2017-001]

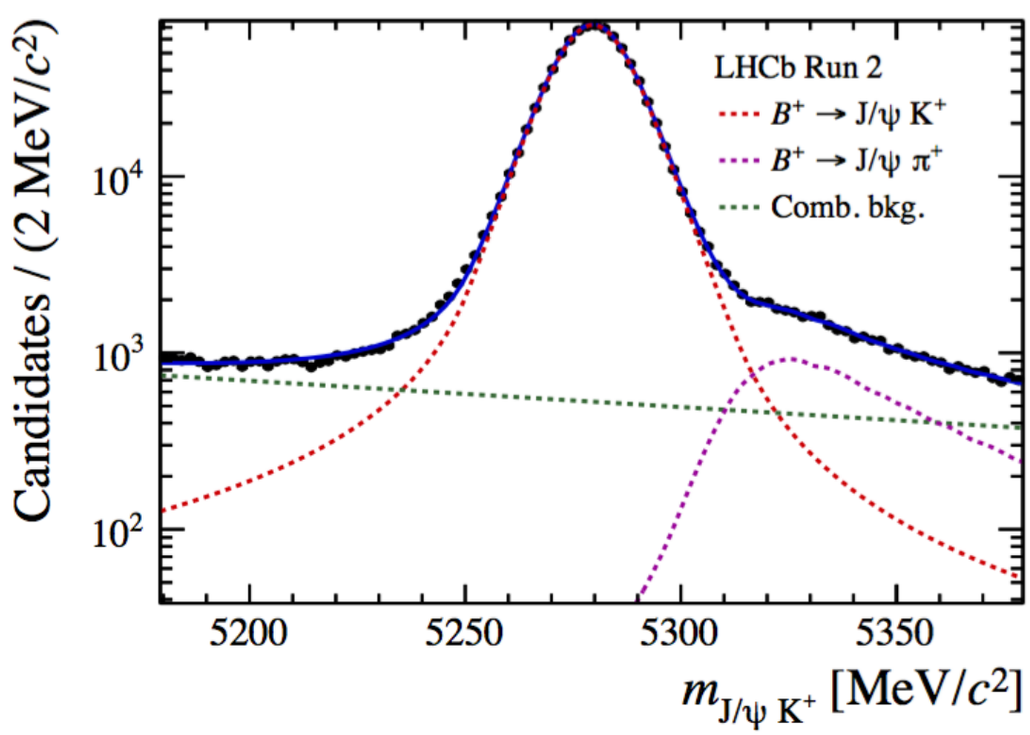


$B(B_{d/s} \to \mu^+\mu^-)$: adding Run II



- Includes the re-analysis of Run I data
- New improved isolation variables based on MVAs help rejecting backgrounds
- Two normalisation channels $B^0 \to K\pi$ and $B^0 \to (J/\psi \to \mu^+\mu^-)K$
  - Using $f_s/f_d = 0.259 \pm 0.015$ [LHCb-CONF-2013-011]
  - Scaled to 13 TeV using the ratio $B_s \to J/\psi\phi$ / $B^0 \to J/\psi K$

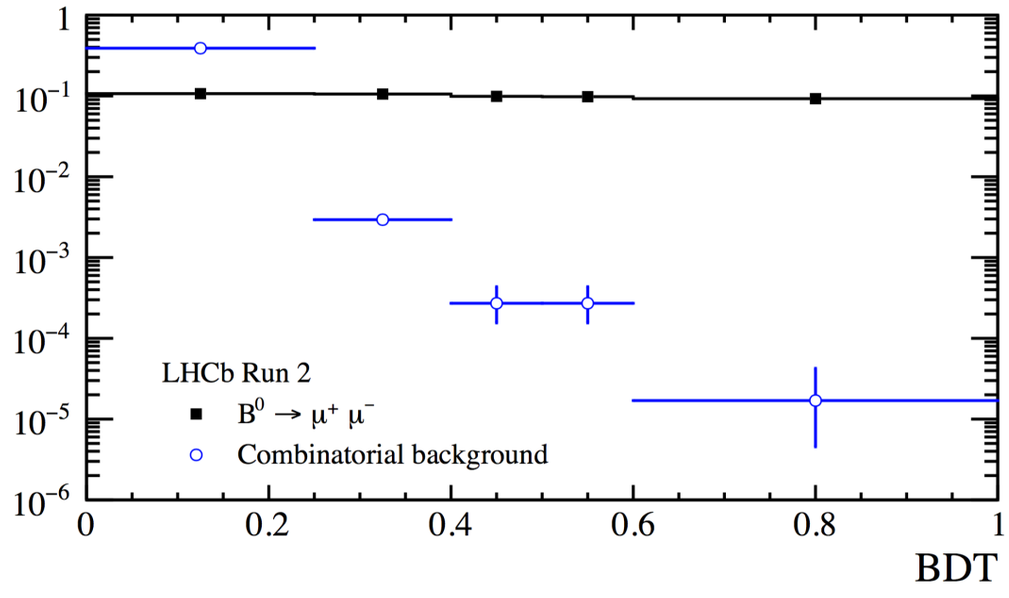


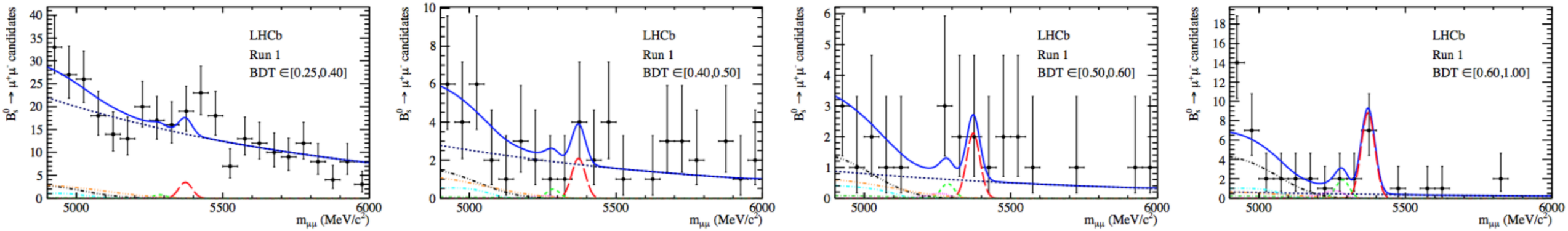


[LHCB-PAPER-2017-001]

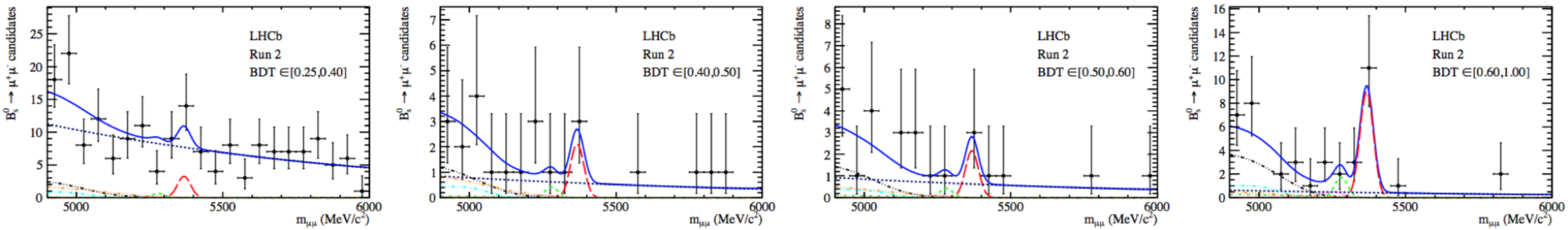
$B(B_{d/s} \to \mu^+\mu^-)$: mass fits

- BDT calibrated to have flat response on signal
  → Reduce uncertainty in efficiency estimation
- Simultaneous fit in 8 bins of BDT output.
- Systematics on nuisance parameters and background model





[LHCB-PAPER-2017-001]

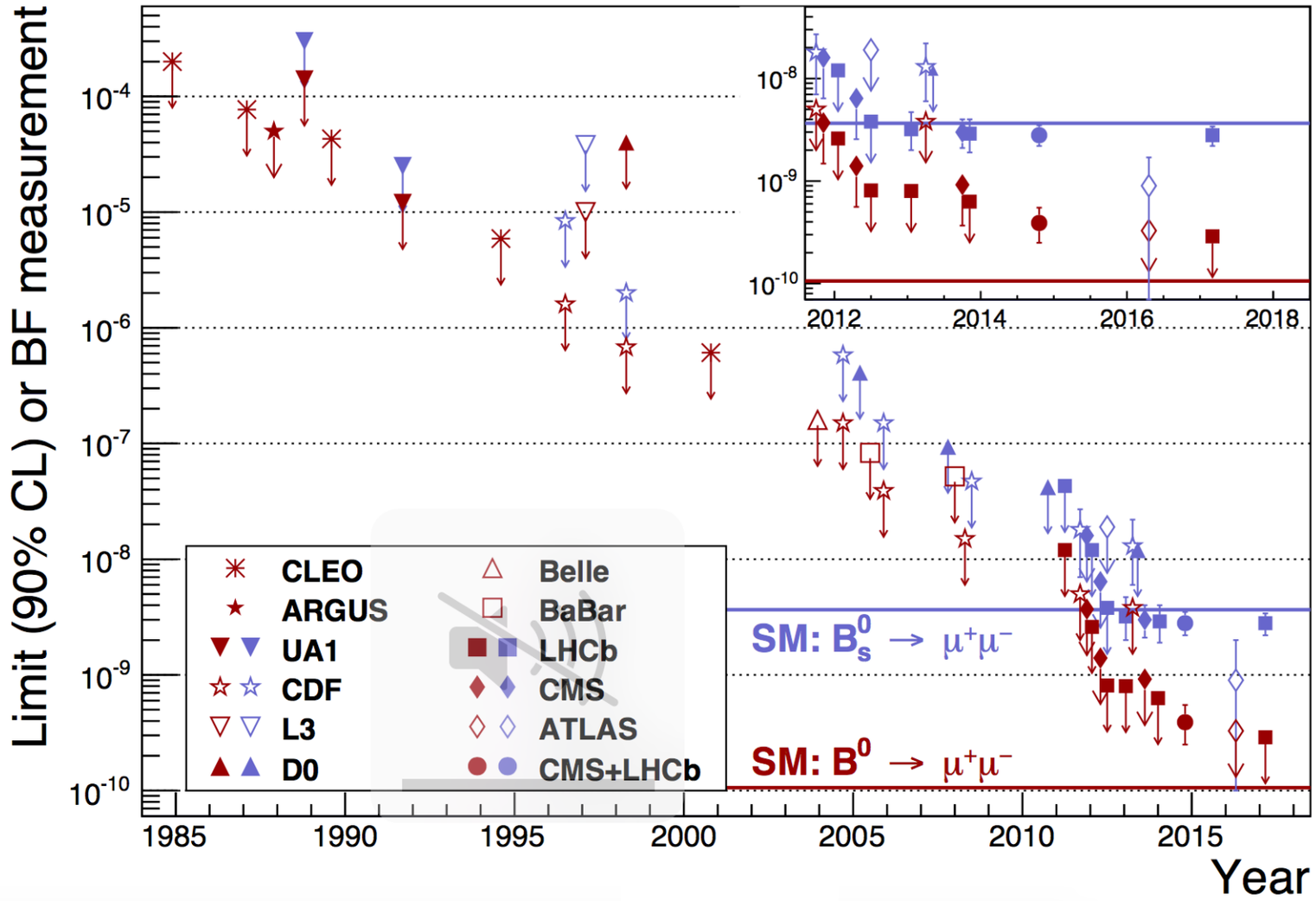


$B(B_{d/s} \rightarrow \mu^+\mu^-)$: a 30 years long story

- First limit set by CLEO in 1985.
- First observation by a single experiment in 2017 by LHCb
- Strongly constrains the phase-space for BSM. Particularly SUSY.

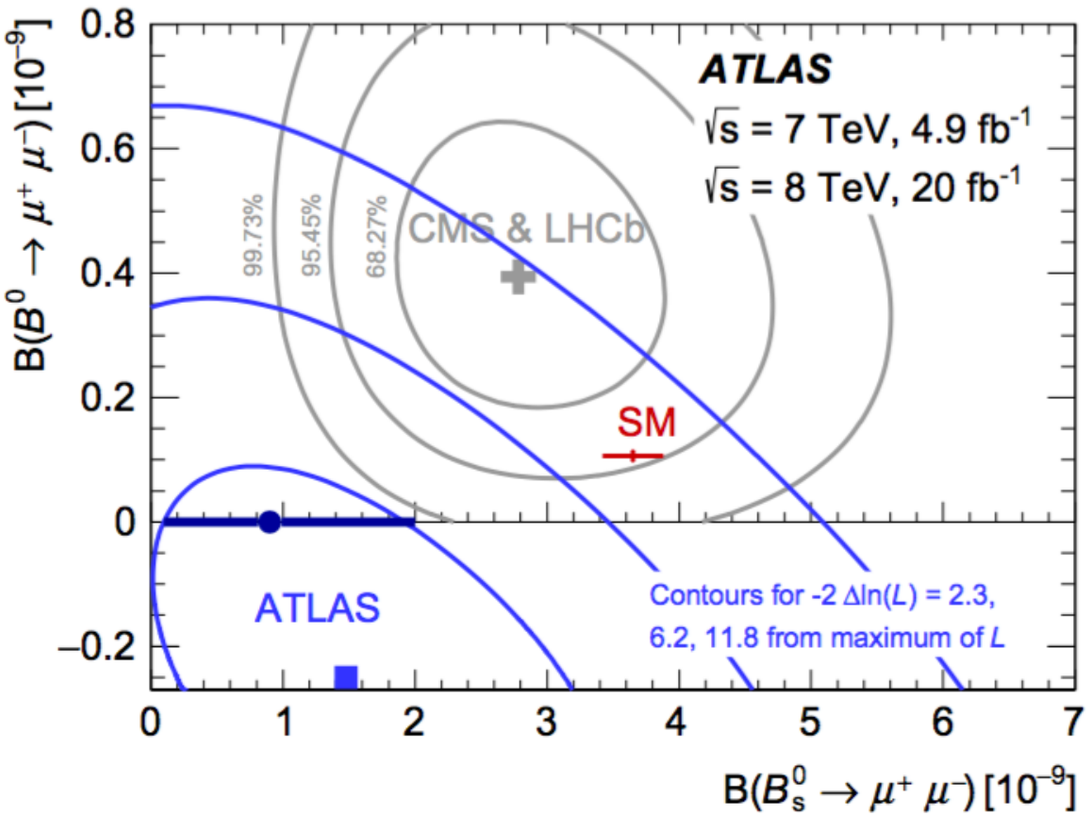
And the story goes on:

- Still important to observe B^0, as the ratio between B_s and B^0 highly constrains MFV models.
- Effective lifetime (see next slides)



$B(B_{d/s} \rightarrow \mu^+\mu^-)$ @ LHC

- Highly suppressed in the SM FCNC + CKM + helicity
- Possible tree level BSM contributions → very sensitive
- Ratio between B_s and B^0 highly constrains MFV
- Leptonic decay (no hadronic uncertainties) → Very well predicted



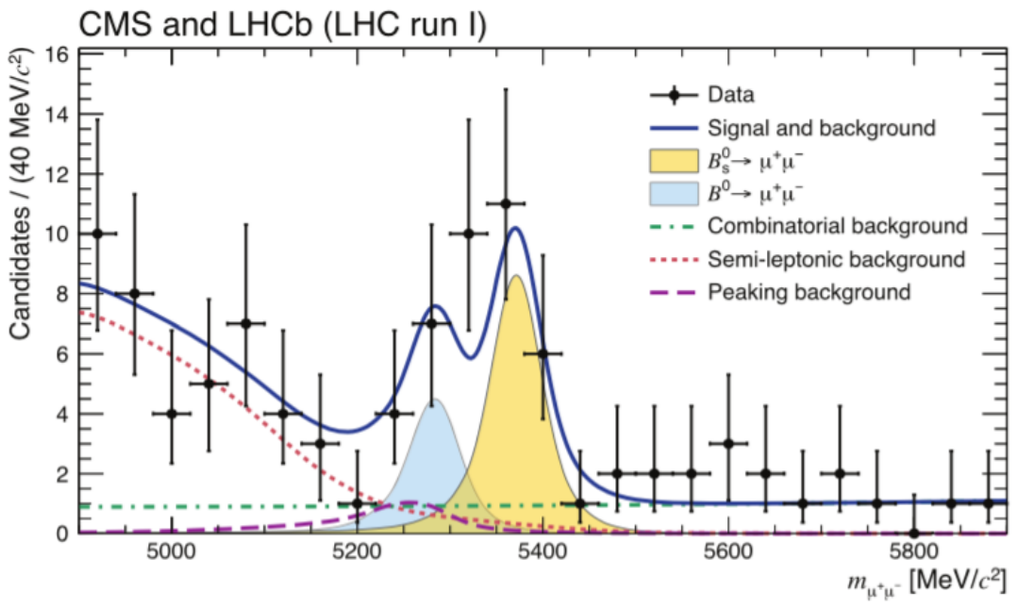
[Nature 522, 68-72]

[EPJ C76 (2016) 9, 513]

CMS + LHCb Run I combination:

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

6.2σ significance, compatible with SM



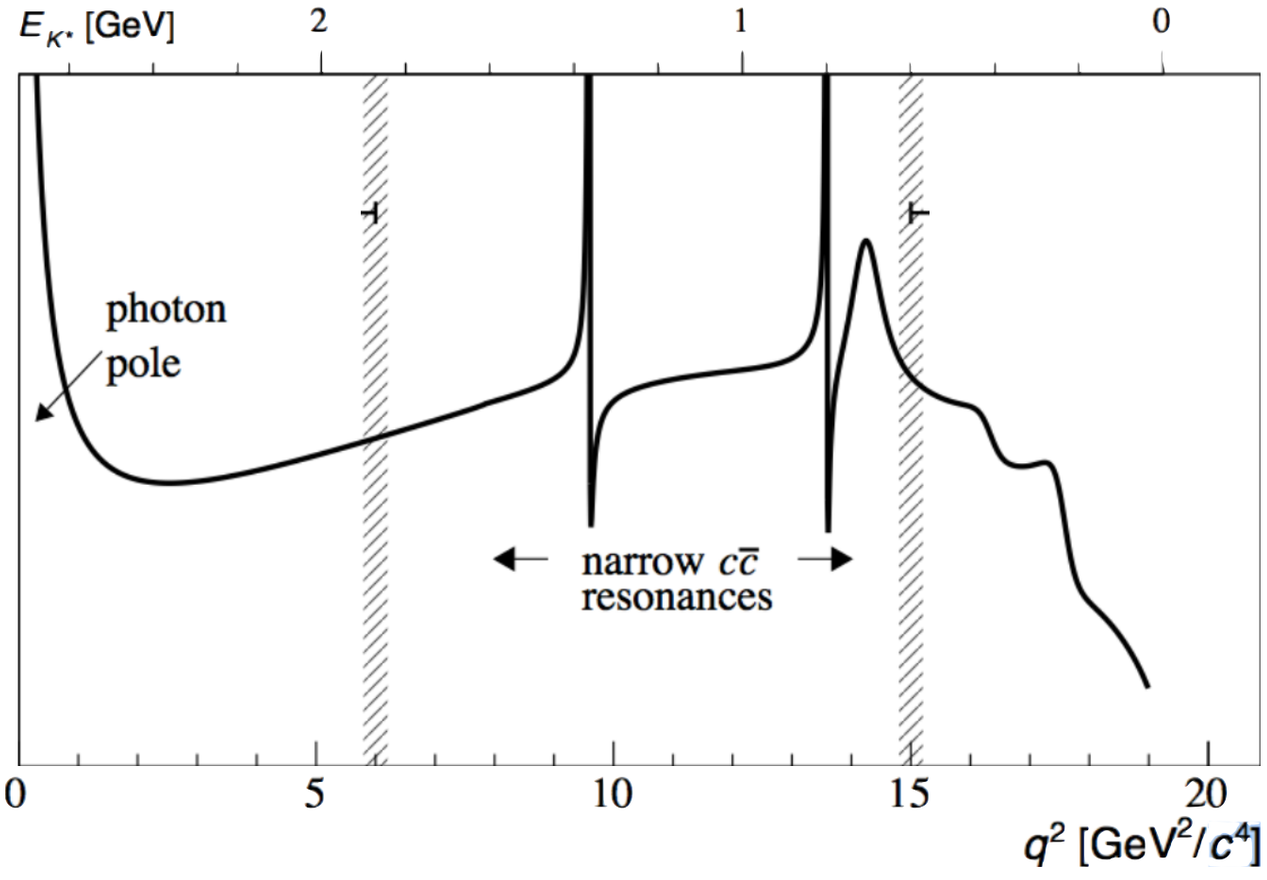
Analysis strategy

- Three q^2 regions considered:
  - Low-q^2: $0.0004 < q^2 < 1.1$ dominated by the photon pole
  - Central-q^2: $1.1 < q^2 < 6$ most interesting to observe new physics
  - High-q^2: $q^2 > 15 GeV^2/c^4$

- Normalisation channels
  - ✓ J/ψ→μμ/ee

- Control samples for ee channels:
  - ✓ B→K*(γ→ee)
  - ✓ B→K*(ψ(2S)→ee)

$$q^2 = m^2_{\ell\ell}$$



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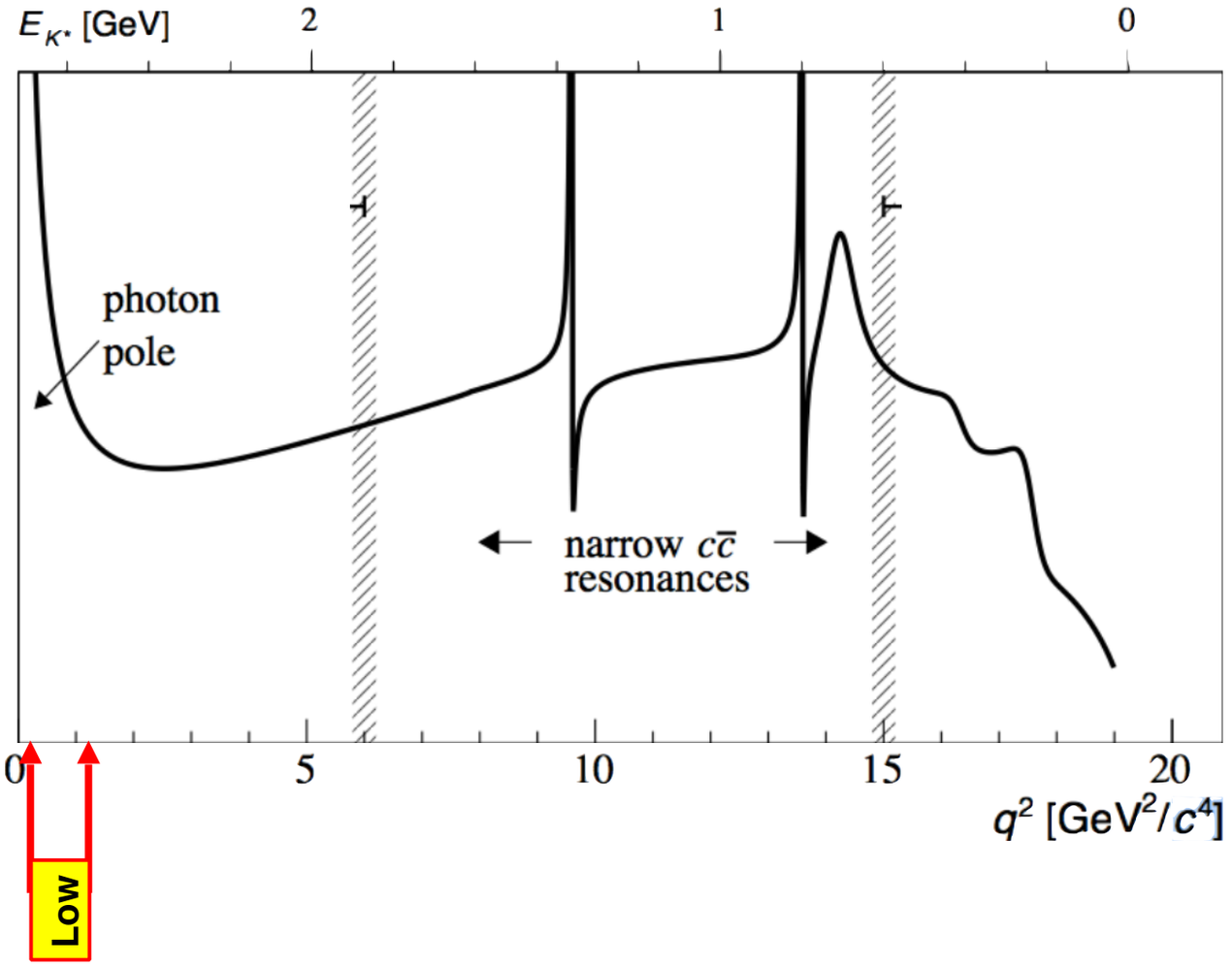

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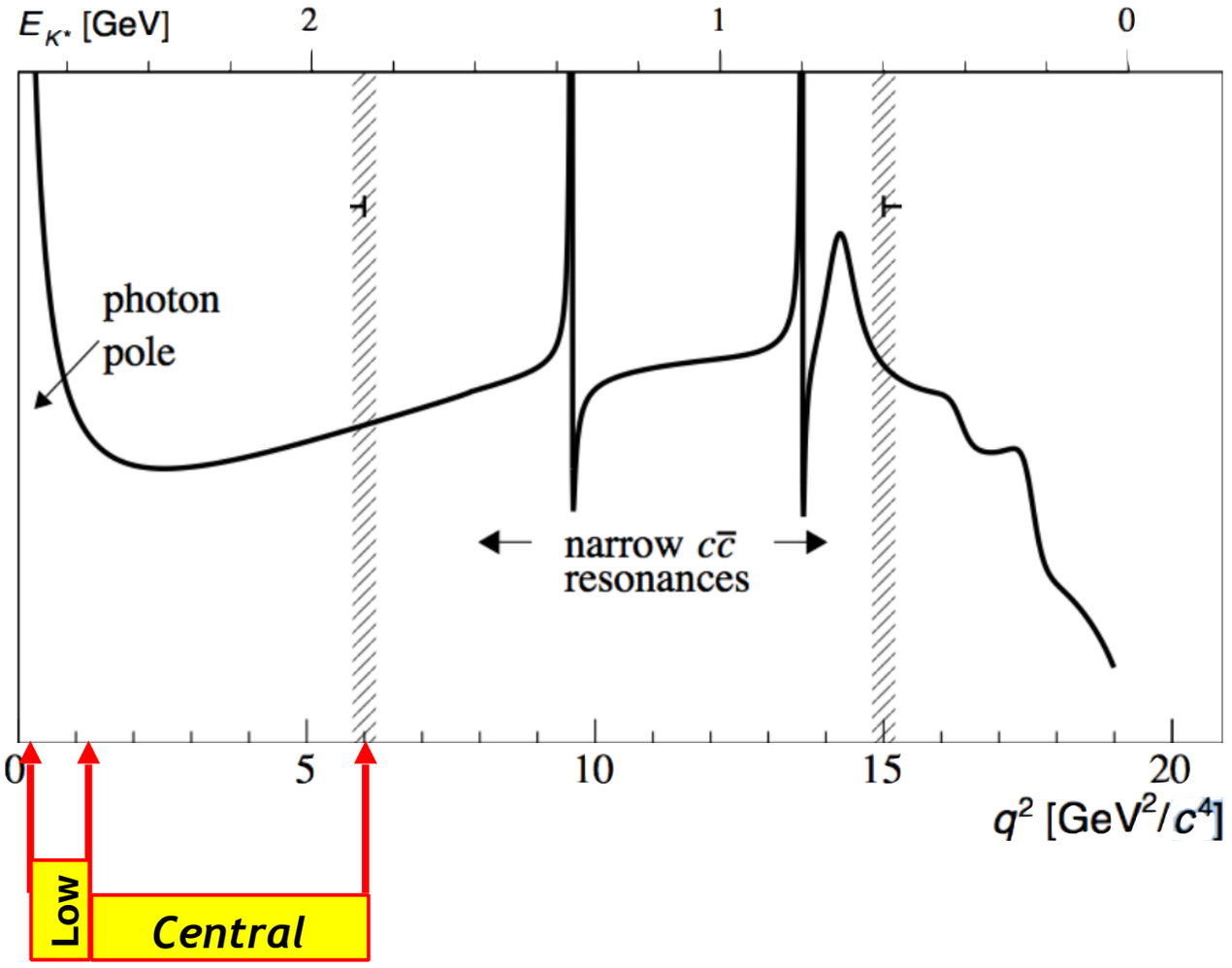

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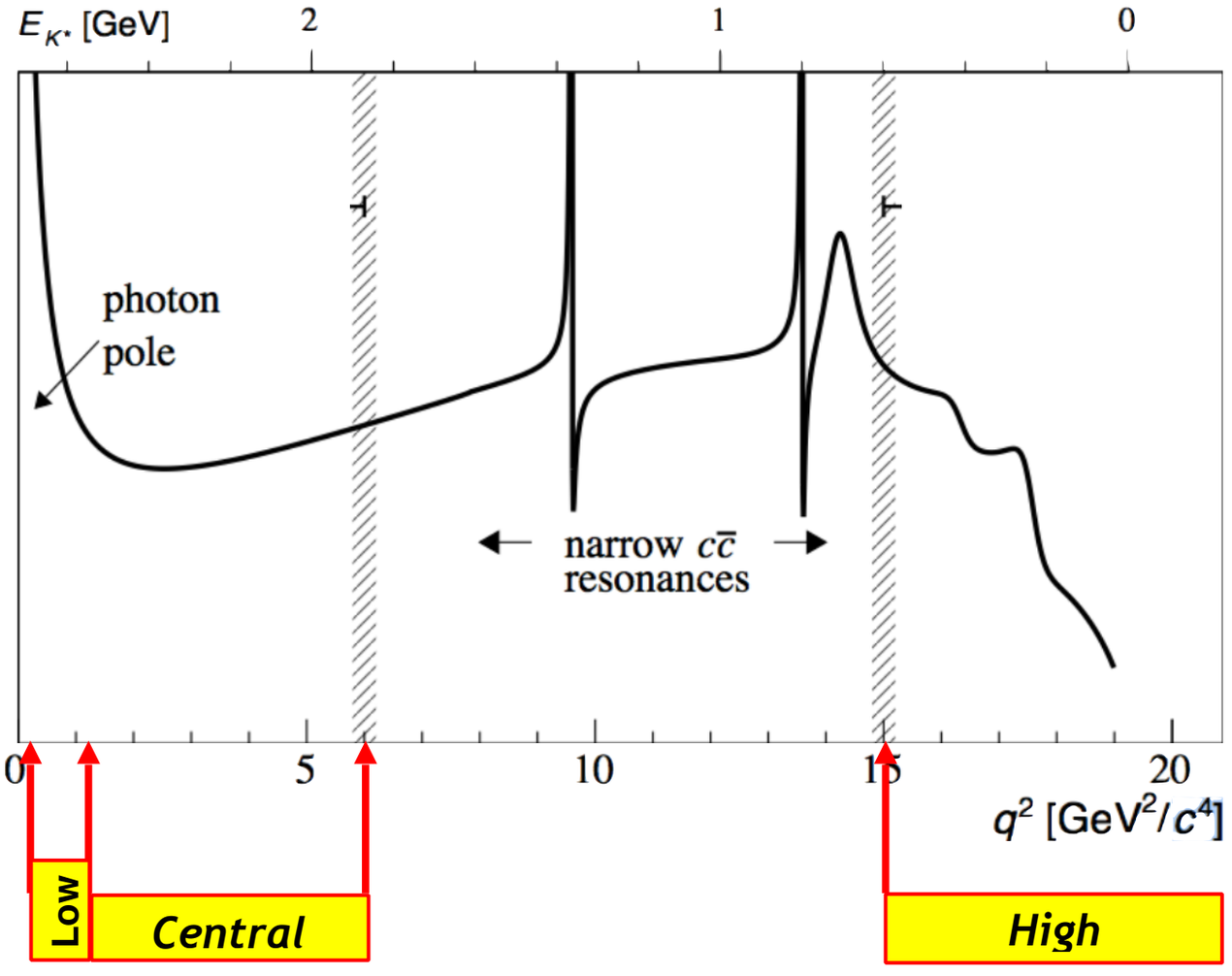

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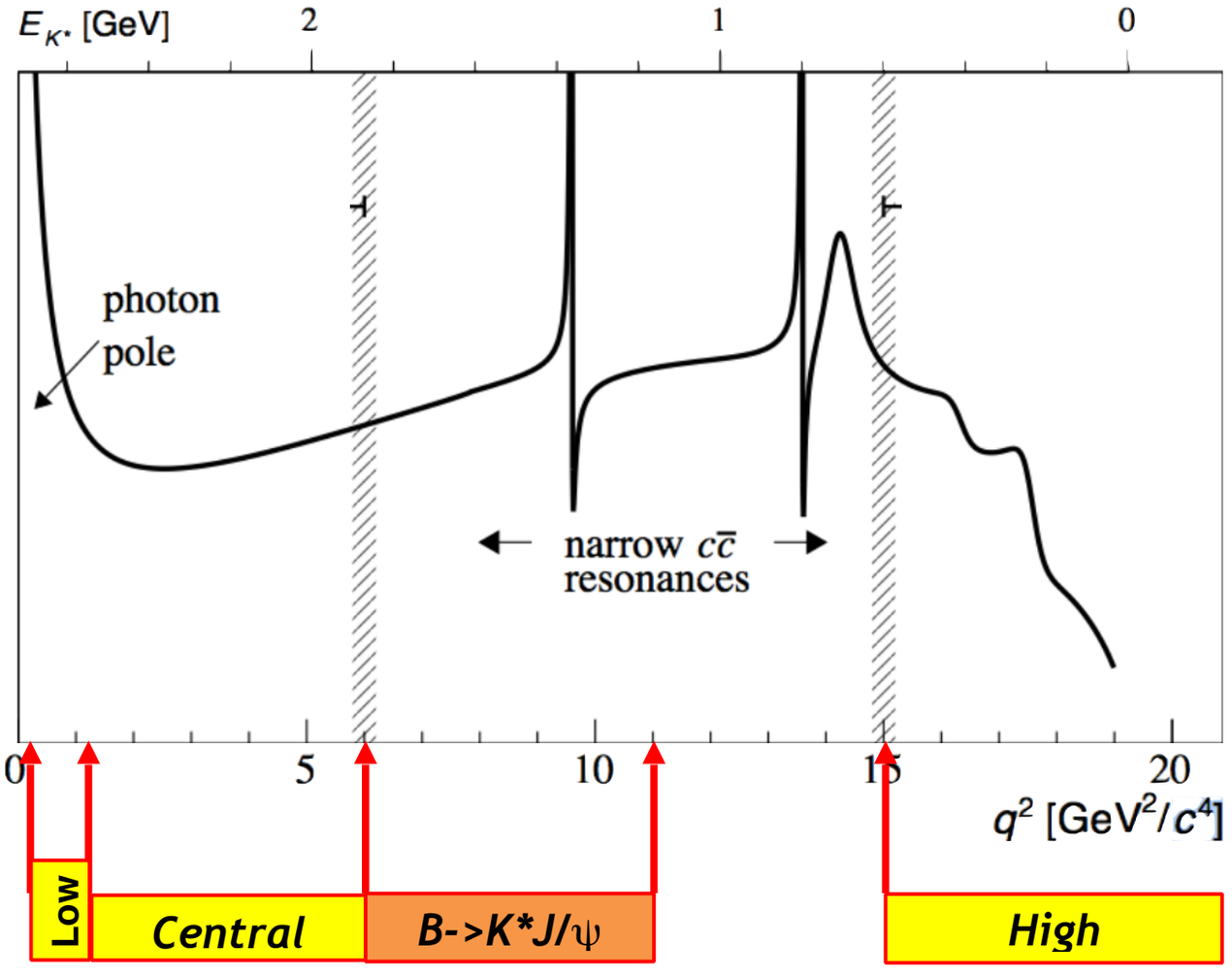

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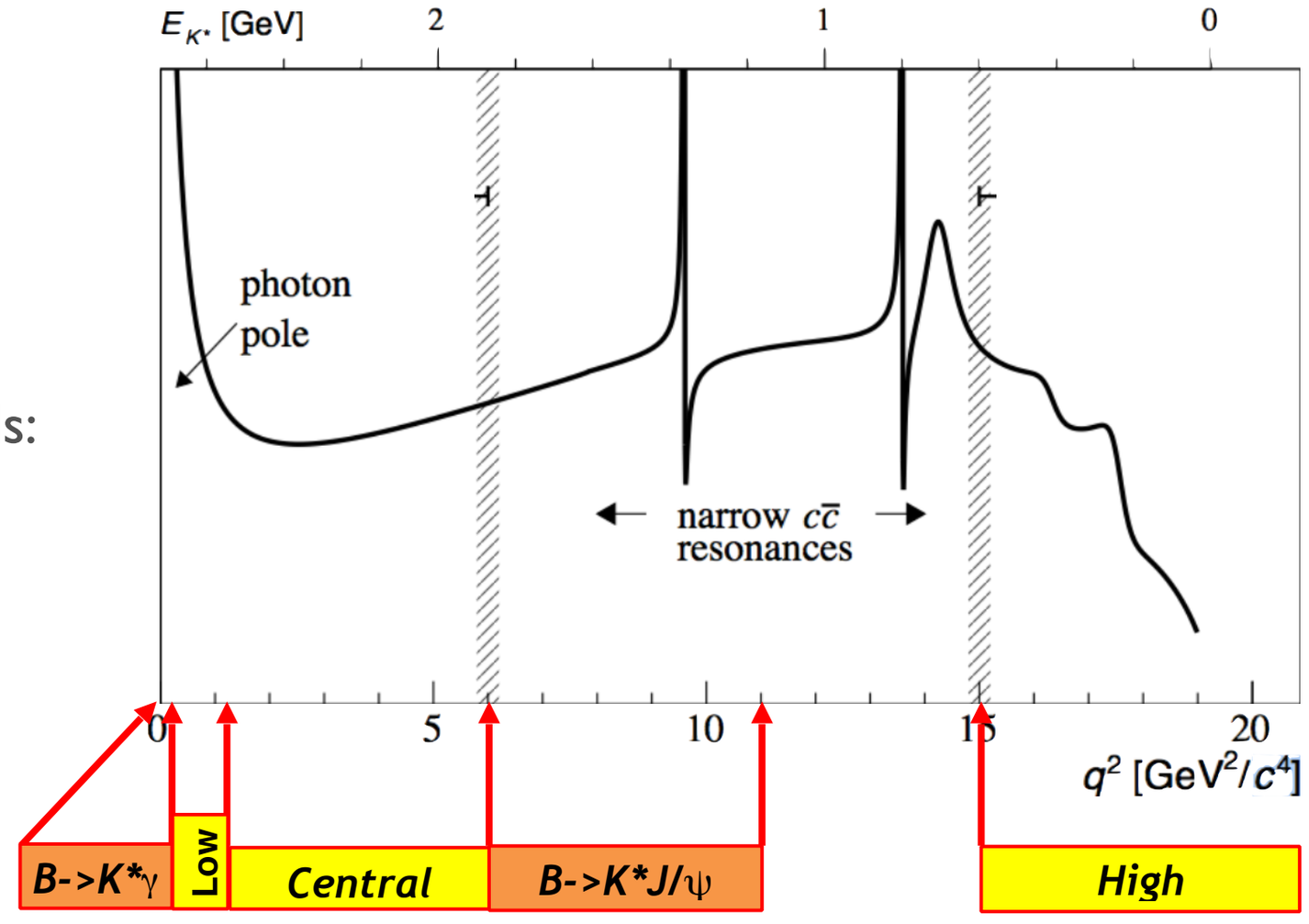

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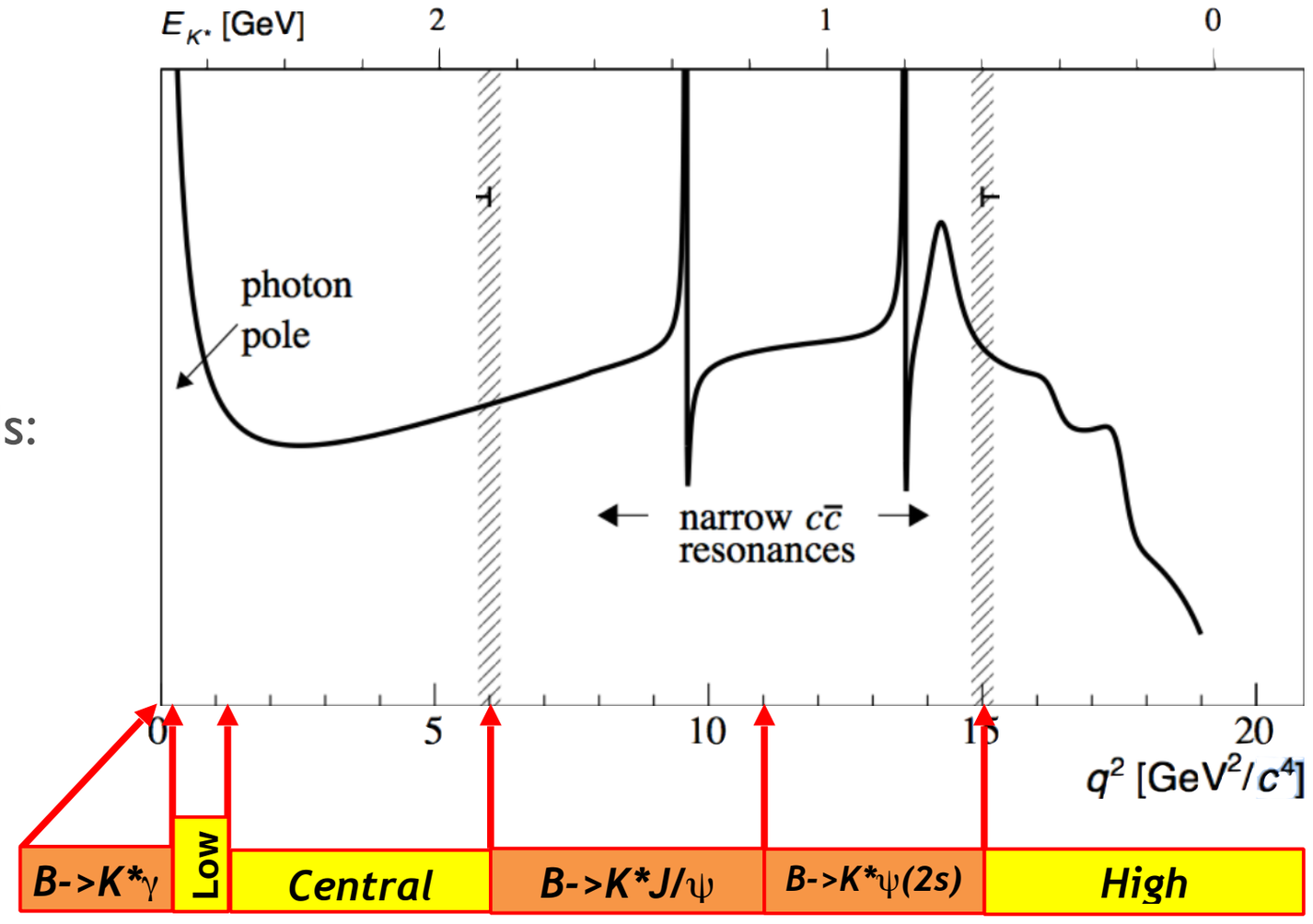

Theoretical framework: the effective Hamiltonian

Effective Hamiltonian for b→d and b→s transitions

$$\mathcal{H}_{eff} = \frac{-4G_F}{\sqrt{2}} \left[\lambda_q^t \sum C_i(\mu) \mathcal{O}_i(\mu) + \lambda_q^u \sum C_i(\mu) (\mathcal{O}_i(\mu) - \mathcal{O}_i^u(\mu)) \right]$$

Phys.Lett. B400 (1997) 206–219

Theoretical framework: the effective Hamiltonian

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physics encoded in

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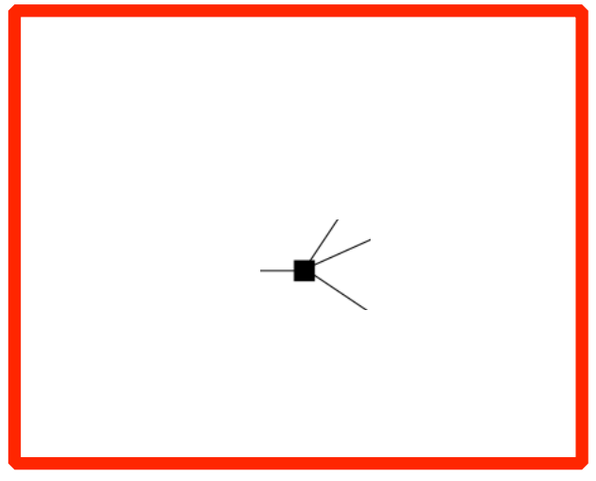

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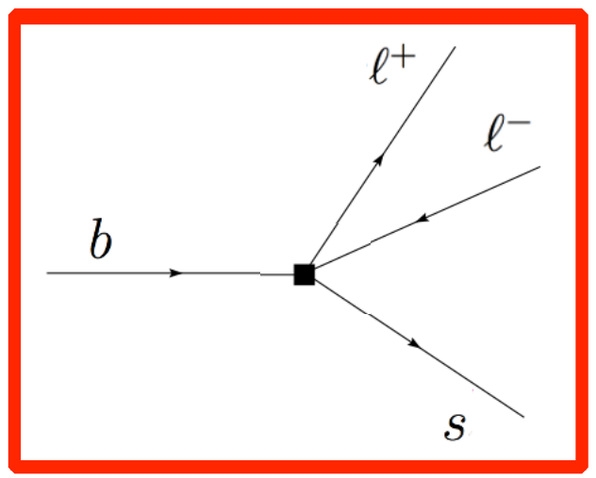

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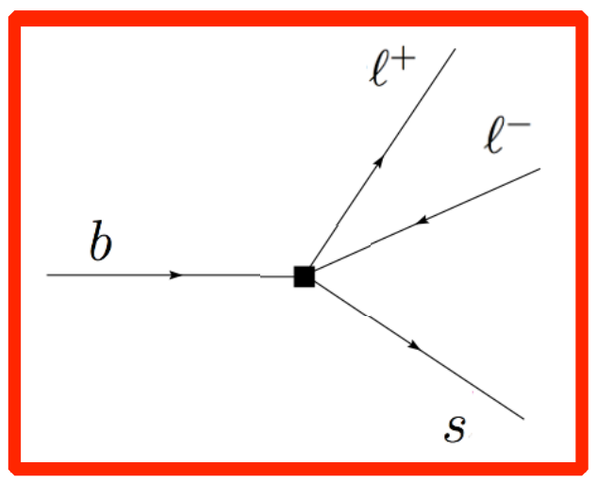
CKM factors: $\lambda_q^{q'} = V_{q'b} V_{q'q}^*$

For b→s transitions $V_{us} << V_{ts}$

⇒ the second term can be neglected



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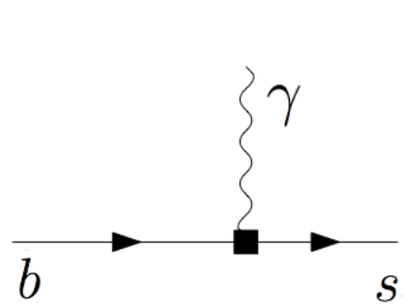
$$\mathcal{H}_{eff} = \frac{-4G_F}{\sqrt{2}} \left[\lambda_q^t \sum C_i(\mu) \mathcal{O}_i(\mu) \right]$$

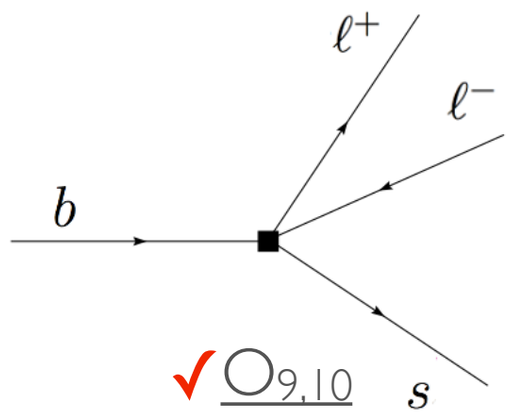
Contributions to b→s$\ell^+\ell^-$:

- ✓ O_7 : radiative penguin
- ✓ $O_{9,10}$: semileptonic decays

  (Z penguin and W-box)



✓ O_7



✓ $O_{9,10}$

Theoretical framework: the effective Hamiltonian

Effective Hamiltonian for b→d and b→s transitions

Short distance

physics encoded in

the Wilson Coefficients

Long-distance

described by a finite

set of operators

Left-handed and right-handed

$$\mathcal{H}_{eff} = \frac{-4G_F}{\sqrt{2}} \left[\lambda_q^t \sum C_i(\mu) \mathcal{O}_i(\mu) \right]$$

$$C_i \mathcal{O}_i + C'_i \mathcal{O}'_i$$

In the SM: C' ~ m_s/m_b C

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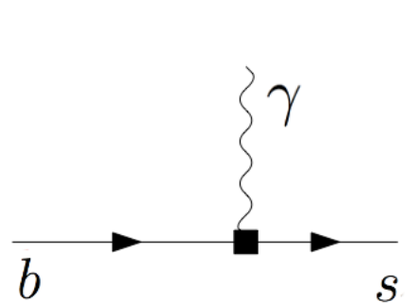

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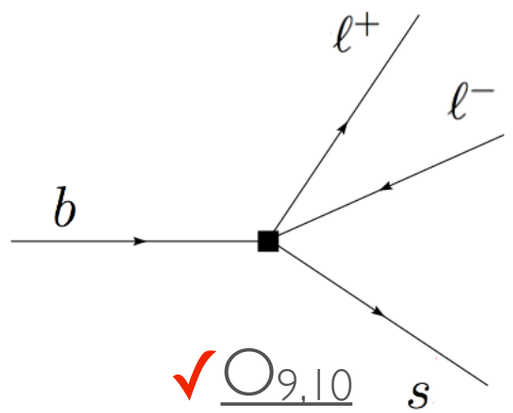


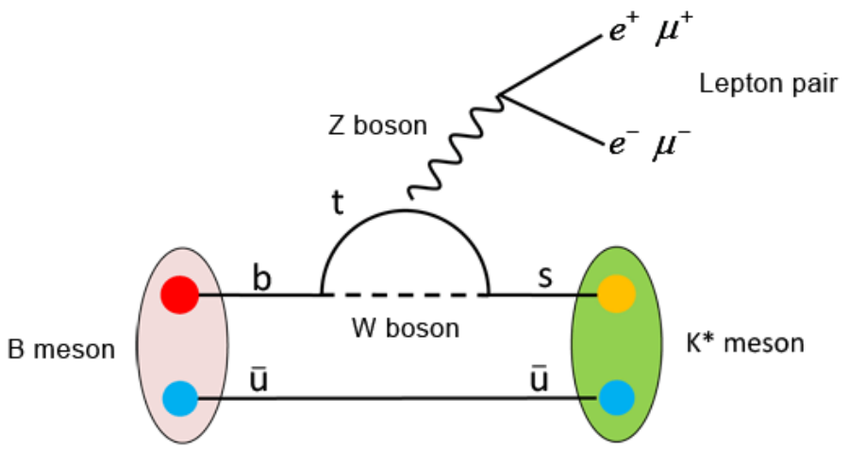
✓ $O_{9,10}$

Calculating exclusive decay amplitudes

The decay amplitude of an exclusive decay

→ expectation value of H_{eff} given the initial and final states

$$A(M \to F) = \langle M|\mathcal{H}_{eff}|F\rangle = \\ = \frac{G_F}{\sqrt{2}} \sum V^i_{CKM} C_i(\mu) \langle M|\mathcal{O}_i(\mu)|F\rangle$$



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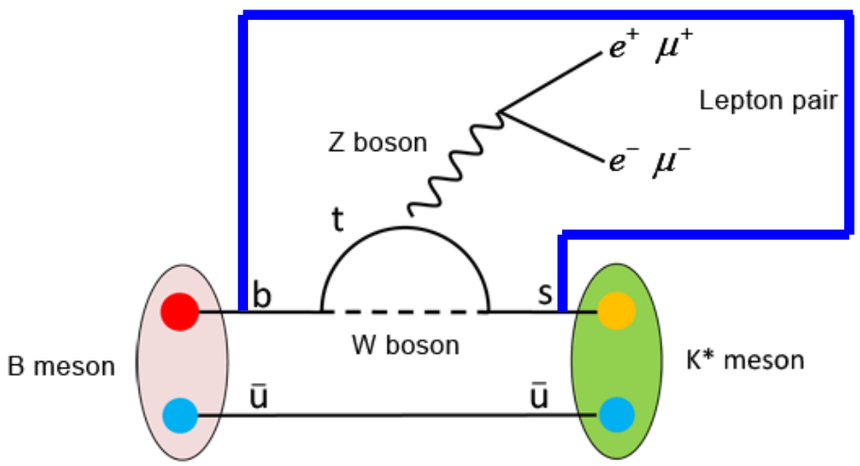
$$A(M \to F) = \langle M|\mathcal{H}_{eff}|F\rangle = \quad \text{Perturbative contribution}$$

$$= \frac{G_F}{\sqrt{2}} \sum V^i_{CKM} C_i(\mu) \langle M|\mathcal{O}_i(\mu)|F\rangle \quad \text{Wilson Coefficients}$$



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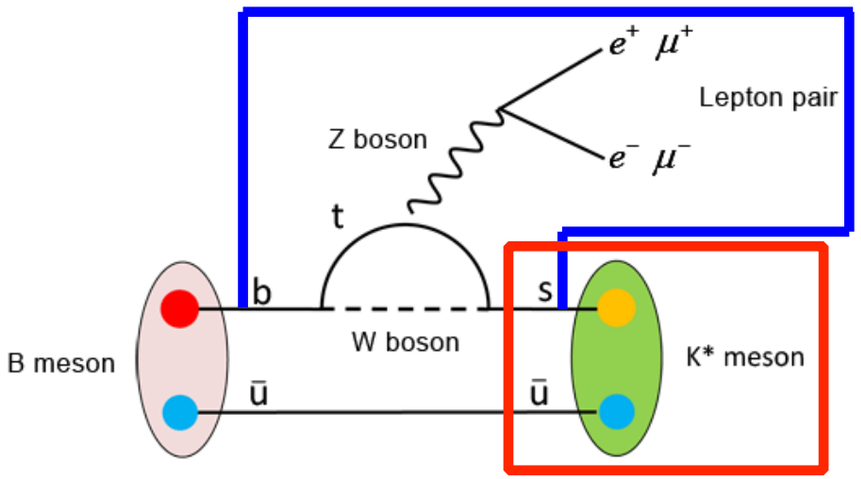
Perturbative contribution

Wilson Coefficients



Form factors: describing the hadronic physics.

Need to be obtained with non perturbative methods e.g. Lattice QCD

Form factors = <u>main source of uncertainty</u> in theory predictions

Isospin asymmetry in B → K(*)μμ

✓ Observables in semileptonic decays: asymmetries

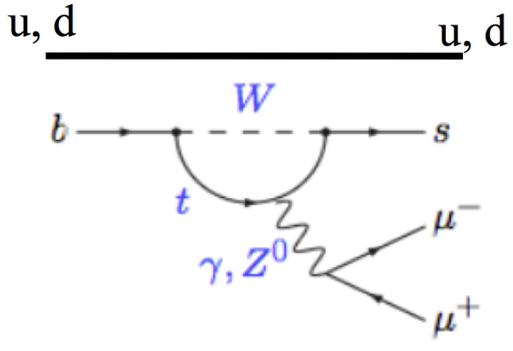
✓ **Isospin asymmetry**: same quark level transition but different spectator quark

$$A_I = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - (\tau_0/\tau_+)\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + (\tau_0/\tau_+)\mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}$$

Two ratios are measured for K and K*

B^0 over B^+ lifetimes ratio

~ O(1%) in SM



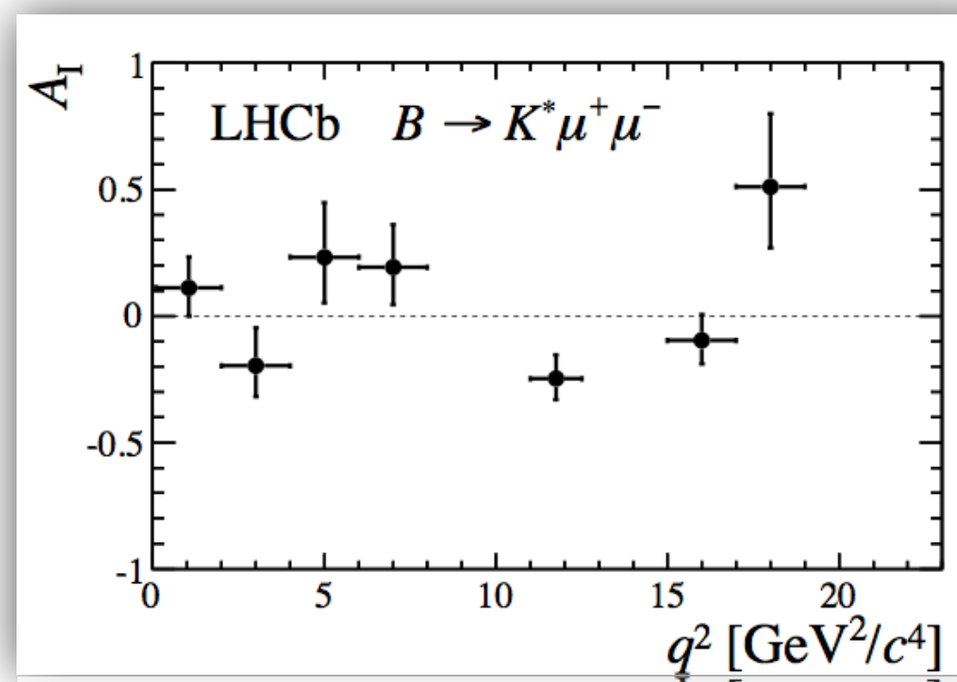
✓ **CP asymmetry:** tiny in the SM due to small CKM factors
BSM models can introduce new sources of CP violation

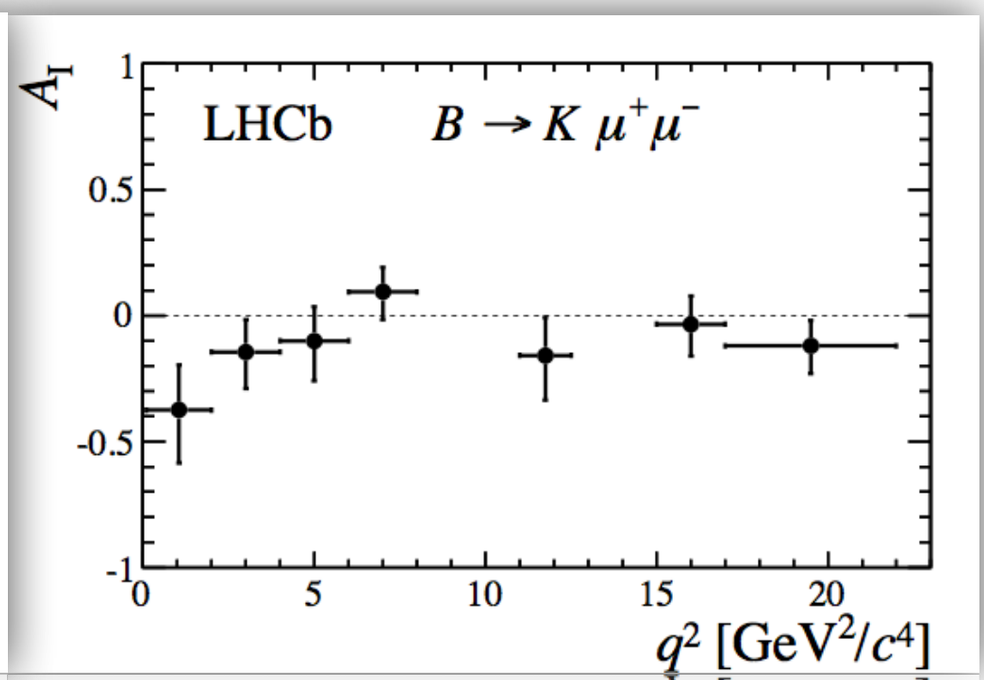
JHEP 06 (2014) 133,

Asymmetries measurements

✓ Isospin asymmetries:

JHEP 06 (2014) 133, [arXiv:1403.8044]



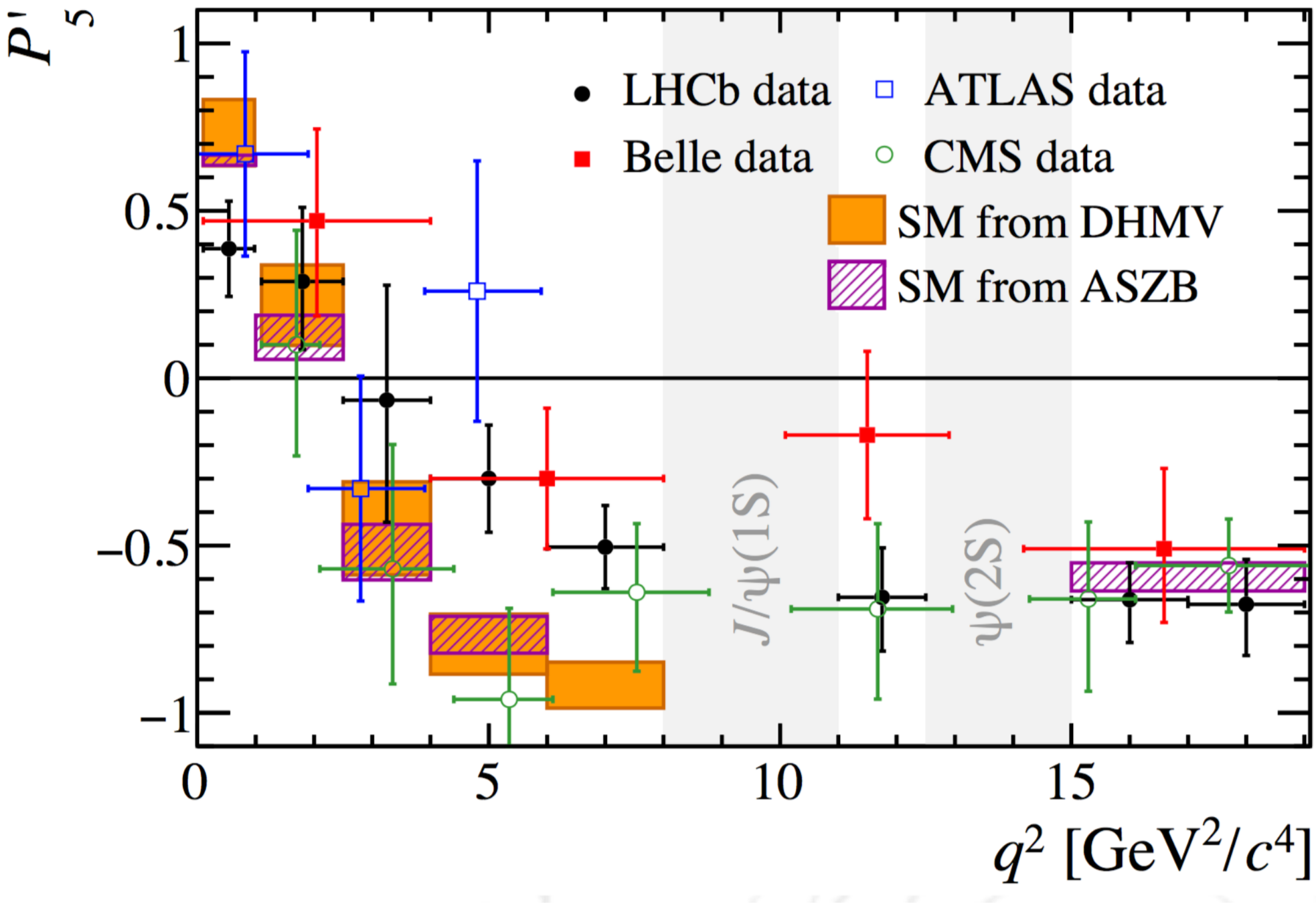


Both compatible with SM within 1-2σ

✓ CP asymmetries

	$B^0 \to K^+ \mu^+ \mu^-$		$B^0 \to K^{*0} \mu^+ \mu^-$	
	1.1–6 [GeV$^2/c^4$]	15.0–22.0 [GeV$^2/c^4$]	1.1–6 [GeV$^2/c^4$]	15.0–19.0 [GeV$^2/c^4$]
$\mathcal{A}_{CP}$	0.004 ± 0.028	-0.005 ± 0.030	0.094 ± 0.047	-0.074 ± 0.044
$\mathcal{A}_I$	$-0.10^{+0.08}_{-0.09} \pm 0.02$	$-0.09 \pm 0.08 \pm 0.02$	$0.00^{+0.12}_{-0.10} \pm 0.02$	$0.06^{+0.10}_{-0.09} \pm 0.02$

P'_5: ATLAS AND CMS JOIN THE CLUB



LFV at LHCb: $B^0_{(s)}/D^0 \to e\mu$

- $B^0 \to e\mu$ on $1fb^{-1}$: update to $3fb^{-1}$ coming soon! LHCb, PRL 108 (2012) 231801
- $B^0 \to Ke\mu$ coming soon as well.
- $D^0 \to e\mu$ analysed on full Run I: $3fb^{-1}$

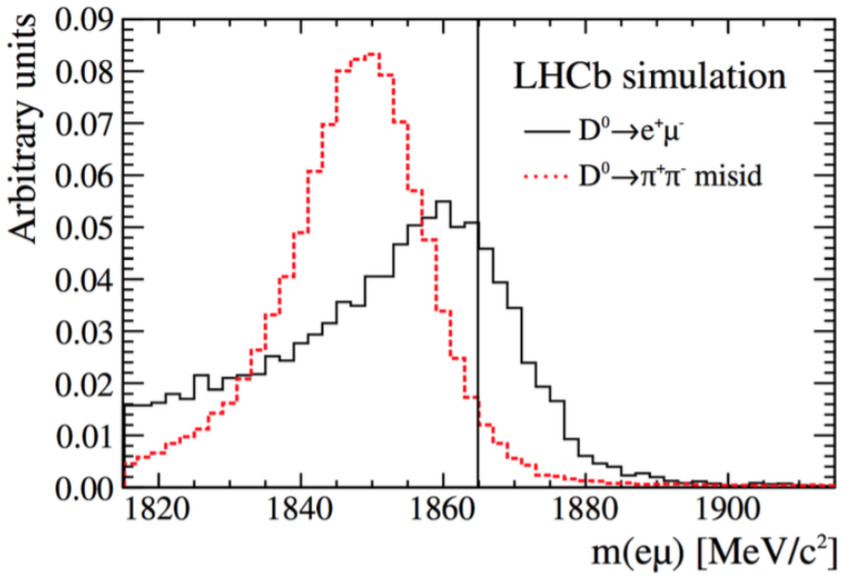
Using $D^{*+} \to D^0\pi^+$ to limit combinatorics

$D^0 \to \pi\pi$ main background (BR ~10^{-3})

✓Rejected by PID cuts

✓Fit in 2D m(eμ) vs $|m(D^0) - m(D^{*+})|$

LHCb, PLB 754 (2016) 167

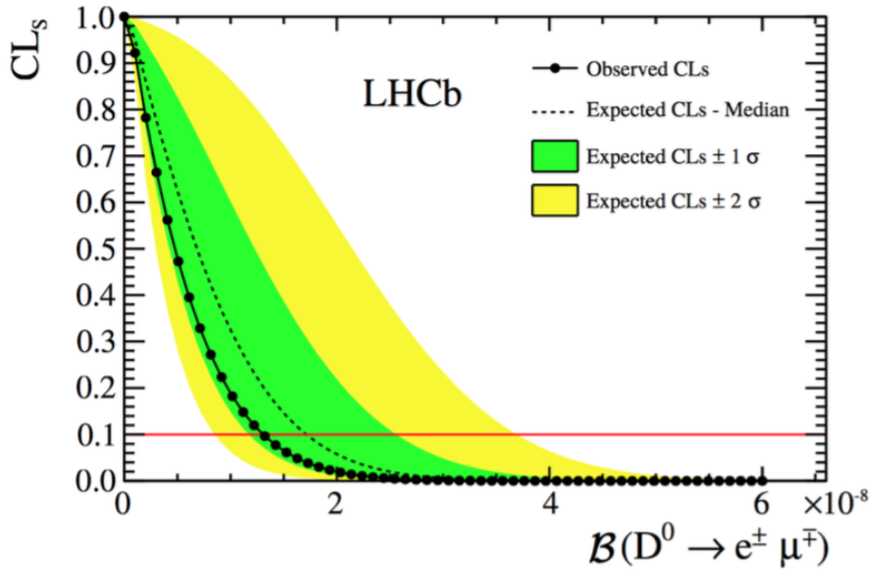


- No signal observed so limits are set.

$$\mathcal{B}(D^0 \to e\mu) < 1.3 \times 10^{-8} \text{ @ } 90\% \text{ CL}$$

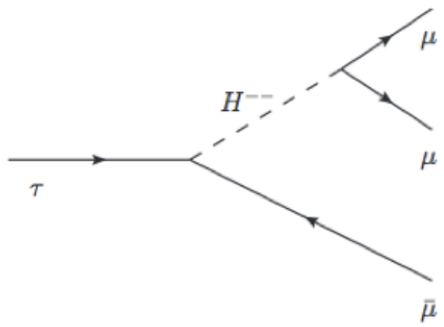
$$\mathcal{B}(B^0 \to e\mu) < 2.8 \times 10^{-9} \text{ @ } 90\% \text{ CL}$$

$$\mathcal{B}(B_s \to e\mu) < 1.1 \times 10^{-9} \text{ @ } 90\% \text{ CL}$$

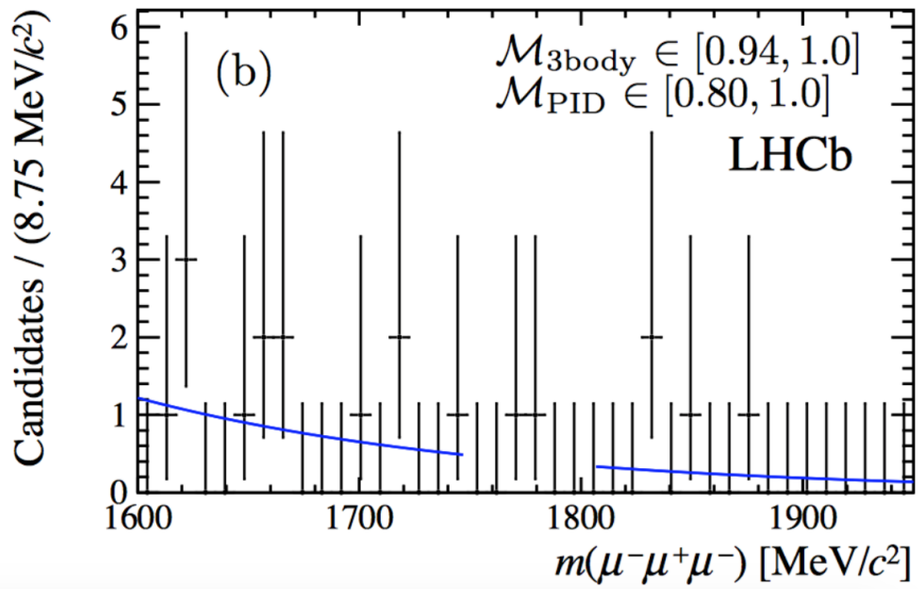


LFV at LHCb: $\tau \to \mu\mu\mu$

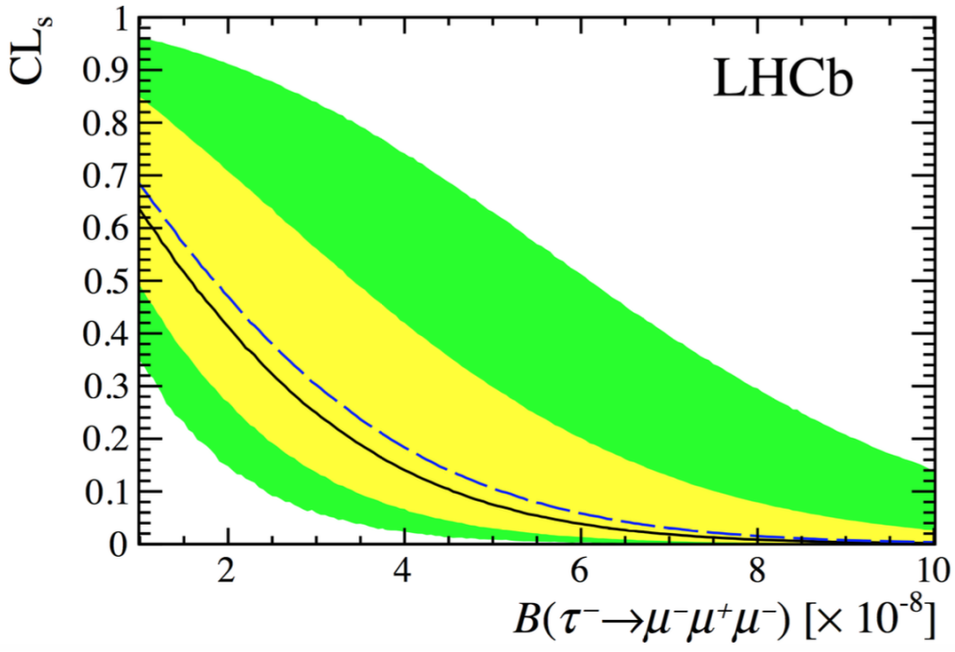
- Possible contribution from doubly charged Higgs
- Using full Run I ($3fb^{-1}$)



[JHEP 02 (2015) 121]



- Events studied in a 3D binned space:
  - Invariant mass of τ candidate
  - Output of a MVA based on topological information: vertex quality, displacement
  - Output of a MVA based on PID



$$\mathcal{B}(\tau \to \mu\mu\mu) < 4.6 \times 10^{-8} \text{ @ } 90\% \text{ CL}$$

Compatible with best limit from Belle.

LFU and LFV

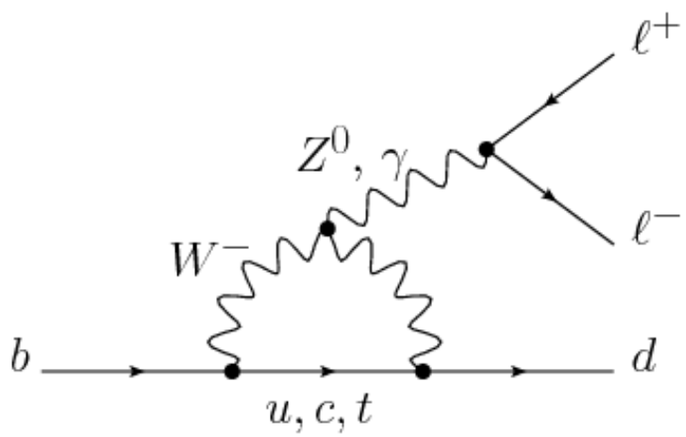
Lepton Flavour Universality (LFU): equality of lepton couplings in the SM

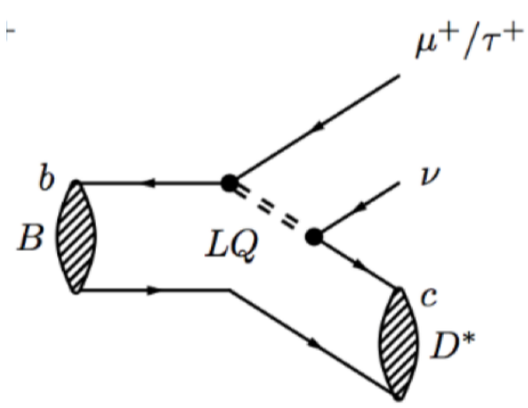
- Signature: comparisons between e/μ/τ channels
- Especially interesting for channels sensitive to NP: rare decays!
- Usually exploiting ratios as hadronic uncertainties cancel

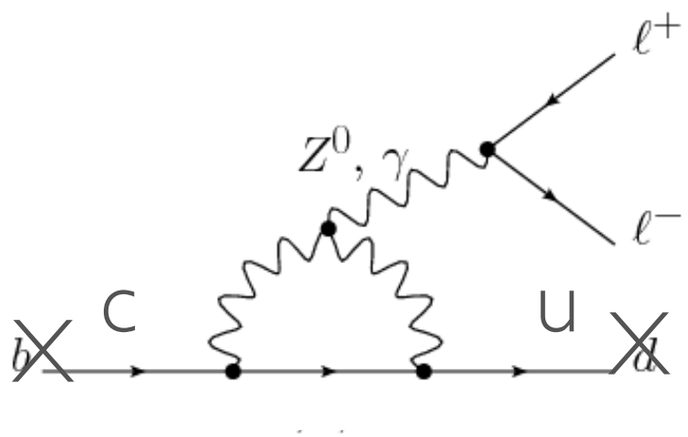
b PENGUINS (b→s FCNC): B→K/K*/ϕ ℓℓ, $\Lambda_b \to \Lambda/\Lambda^* \ell\ell$

TREE LEVEL LQ EMISSION: B→ D*ℓν

CHARM PENGUINS (c→u FCNC): D→hℓℓ, $\Lambda_c \to p\ell\ell$







LFU and LFV

Lepton Flavour Universality (LFU): equality of lepton couplings in the SM

- Signature: comparisons between e/μ/τ channels
- Especially interesting for channels sensitive to NP: rare decays!
- Usually exploiting ratios as hadronic uncertainties cancel

b PENGUINS (b→s FCNC): $B \to K/K^*/\phi\, \ell\ell$, $\Lambda_b \to \Lambda/\Lambda^* \ell\ell$

TREE LEVEL LQ EMISSION: $B \to D^* \ell \nu$

CHARM PENGUINS (c→u FCNC): $D \to h\ell\ell$, $\Lambda_c \to p\ell\ell$

Lepton Flavour Violation (LFV): non-conservation of lepton number

- Signature: searches for forbidden decays in the SM (eμ/μτ/eτ)
- Neutrino oscillations already allow these decays with very small BR

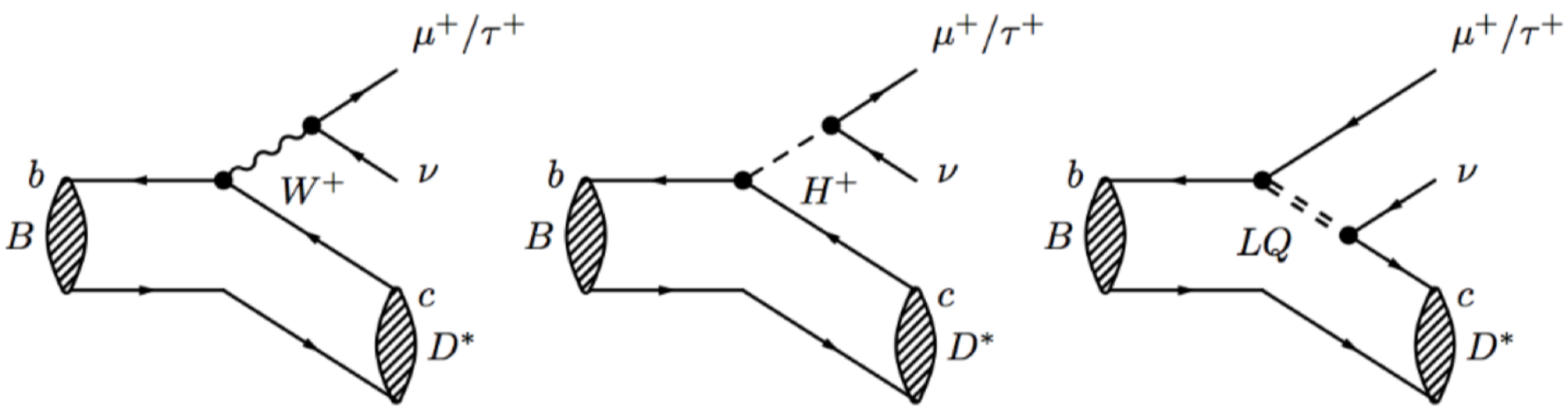
B DECAYS: $B \to e\mu$, $B \to Ke\mu$, $\Lambda_b \to \Lambda e\mu$

CHARM DECAYS: $D^0 \to e\mu$

τ DECAYS: $\tau \to \mu\mu\mu$

LFU in R(D*)

- Testing LFU in B→D*$\ell\nu$ decays: tree level lepto-quark exchange.



- Well predicted as hadronic uncertainties cancel
- Prediction is not unity in the SM uniquely due to the different lepton mass

$$R(D^*)^{SM} = \frac{BR(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{BR(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)} = 0.252 \pm 0.003$$

[PRD85 (2012) 094025]

- Reconstructed using $\tau\to\mu\nu\nu$: similar final state between the two channels
- Main backgrounds from part-reco B decays: B→D**μν, B→(D→Xμ)D*X

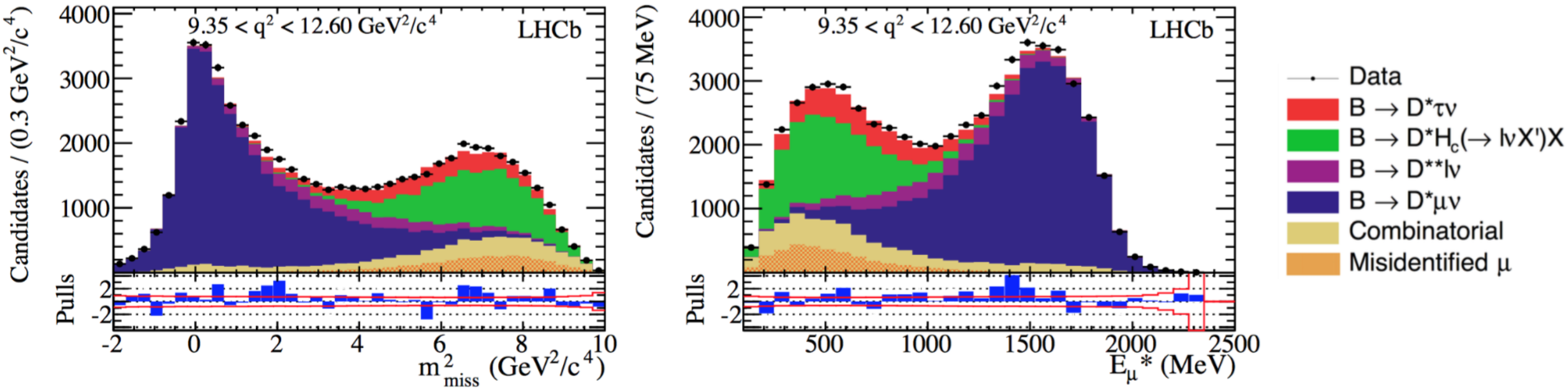
R(D*): fitting without a peak

- Missing neutrino → no narrow peak to fit
- Template fit in three variables: missing mass (m_{miss}), E_μ, q^2
  - ✓ Simulated samples for signal and physics background
  - ✓ Background from μ mis-ID and combinatorial from data

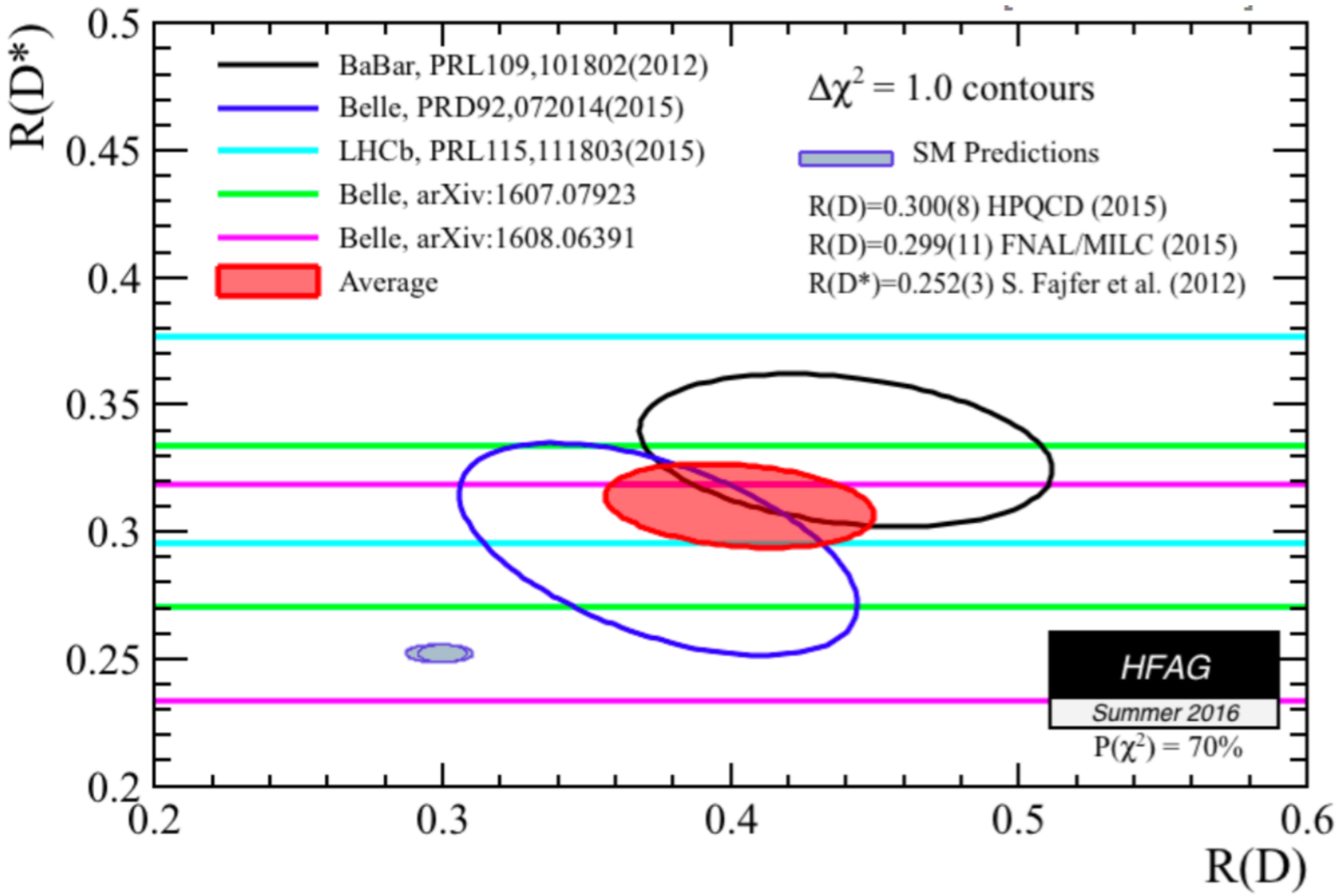
$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

Compatible with SM at 2.1σ level

[LHCb, PRL 115 (2015) 111803]



R(D*) combination



- Combination with other experiments yields 3.9σ from SM
- Independent measurement using $\tau \to 3\pi\nu$ coming soon from LHCb.

  ➡ Different trigger, topology, backgrounds, …

Testing LFU in loops

- LFU tested via rare decays sensitive to new particles in the loops

$$R_H = \frac{\int_{4m_\mu^2}^{m_b} \frac{d\mathcal{B}(B\to H\mu^+\mu^-)}{dq^2}}{\int_{4m_\mu^2}^{m_b} \frac{d\mathcal{B}(B\to He^+e^-)}{dq^2}} dq^2 \qquad H = K, K^{*0}, \phi, ...$$

- Universality: $R_H \sim 1$ with $O((m_\mu/m_b)^2)$ corrections
- Hadronic uncertainties cancel in the ratio

$$\begin{cases} \mathcal{R}_{X_s} = 0.987 \quad \pm 0.006\,, \\ R_K = 1.0000 \pm 0.0001\,, \\ R_{K^{*0}} = 0.991 \quad \pm 0.002\,, \end{cases}$$

- Different ratios are sensitive to different combinations of Wilson Coefficients

JHEP 1502 (2015) 055
[arXiv:1411.4773]

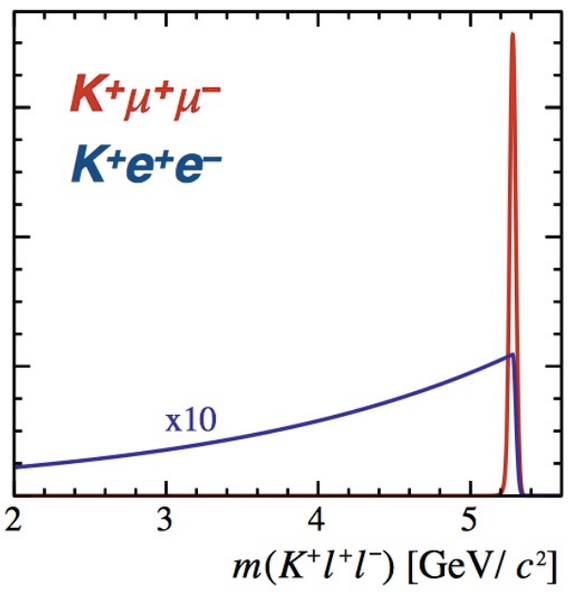
$$C + C' : \quad K, K_\perp^*, ...$$
$$C - C' : \quad K_0(1430), K_{0,\parallel}^*, ...$$

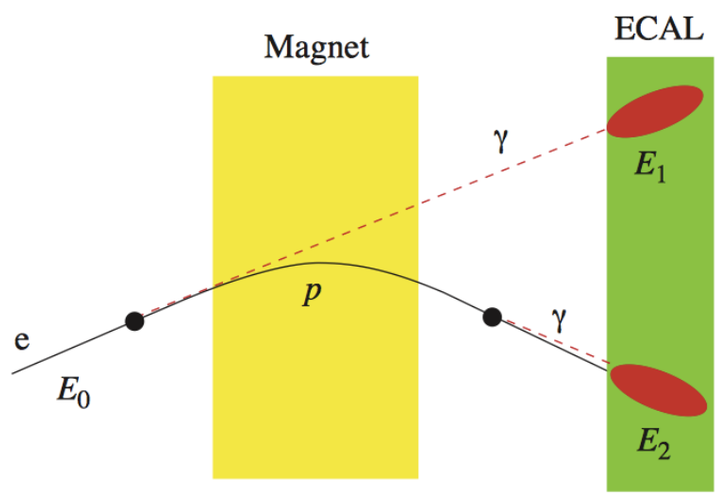
Dealing with electrons

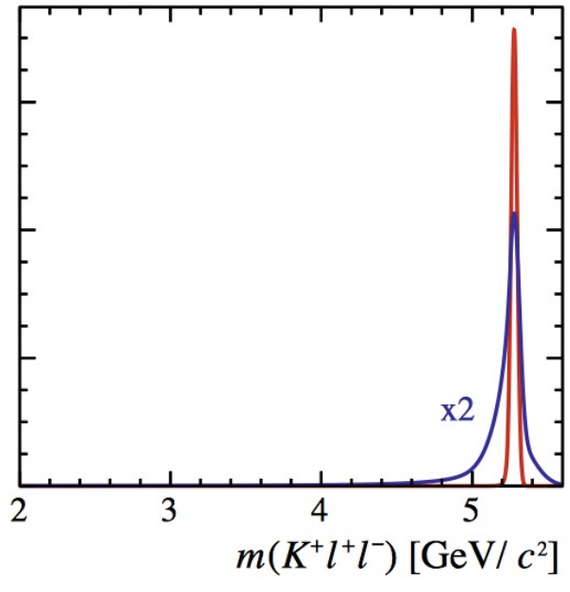
The ee channels are the challenge in this analysis:

- **Bremsstrahlung** affects the e momentum
  → energy recovered looking at calorimeter hits

[PRL 113.151601]
arXiv:1406.6482

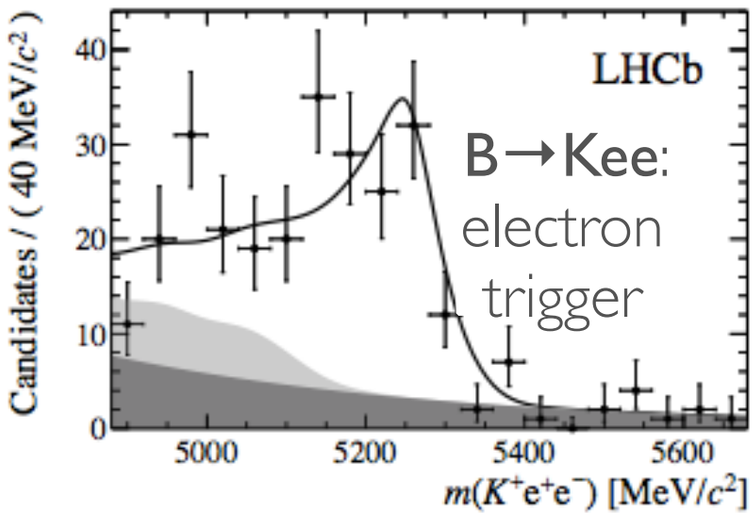


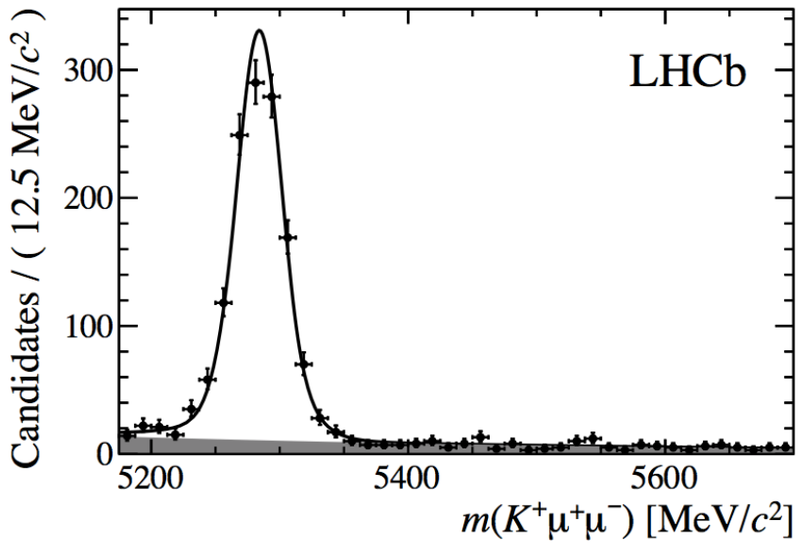




- **Low trigger efficiency**
  → Trigger by the **electron, hadron** and other particles in the event
  → Final result comes from likelihoods combination

The R_K measurement





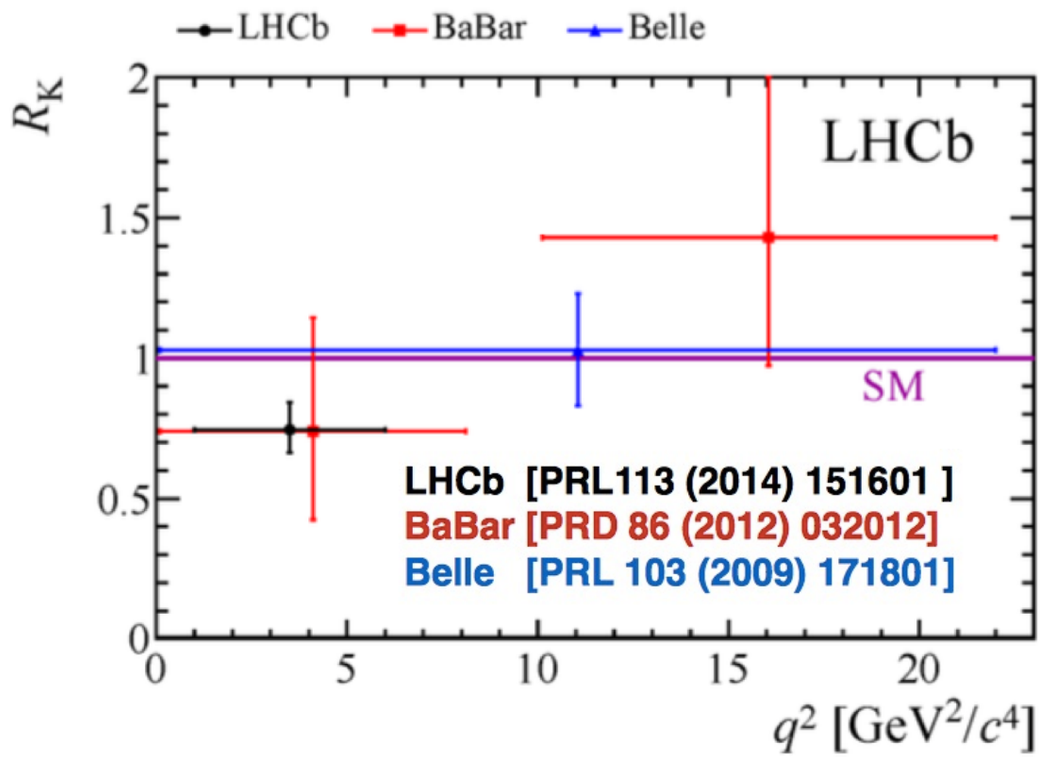
Challenging due to electrons: bremsstrahlung and low trigger efficiency.

Measured as a double ratio normalising by $B^0 \to (J/\psi \to \ell\ell)K$ to cancel systematics.

$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat})\,^{+0.036}_{-0.036}\,(\text{syst}),$$

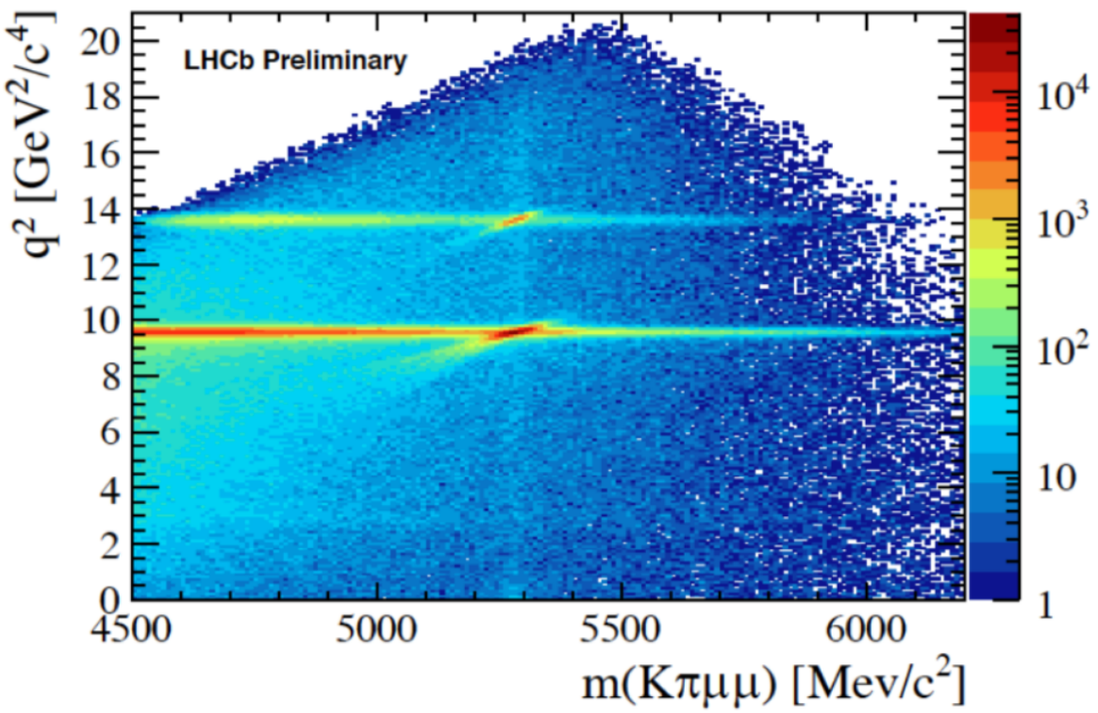
LHCB: 2.6σ FROM THE SM

No smoking gun but clear motivation to continue explore such ratios.
Given also other $b \to s\mu\mu$ anomalies.

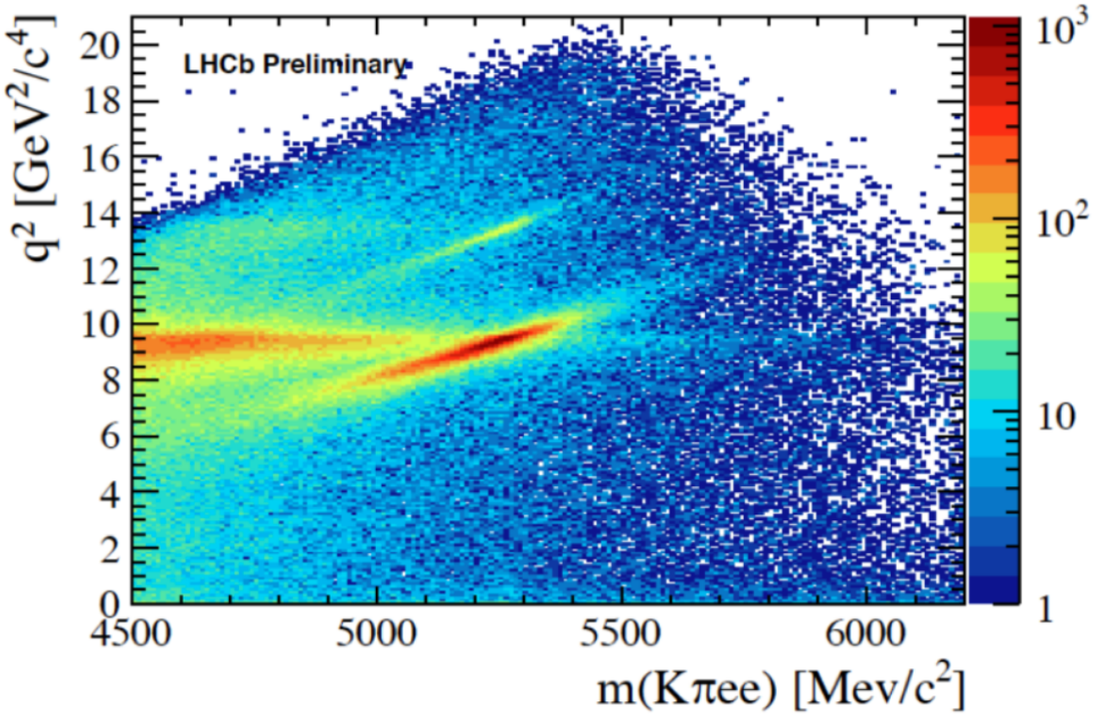


The R_{K^*} measurement

- R_{K^*}: long awaited; it should come in the next few weeks.



Muon channel



Electron channel

Prospects for more LFU @LHCb

- R_K and R_{K^*}: will be updated using Run II data.

- Λ_b decays :
  - Progress on the theory side (e.g. improved form factor calculation)
  - Different spin and hadronic physics allows independent verifications
  - Experimental precision start to be comparable to B decays.

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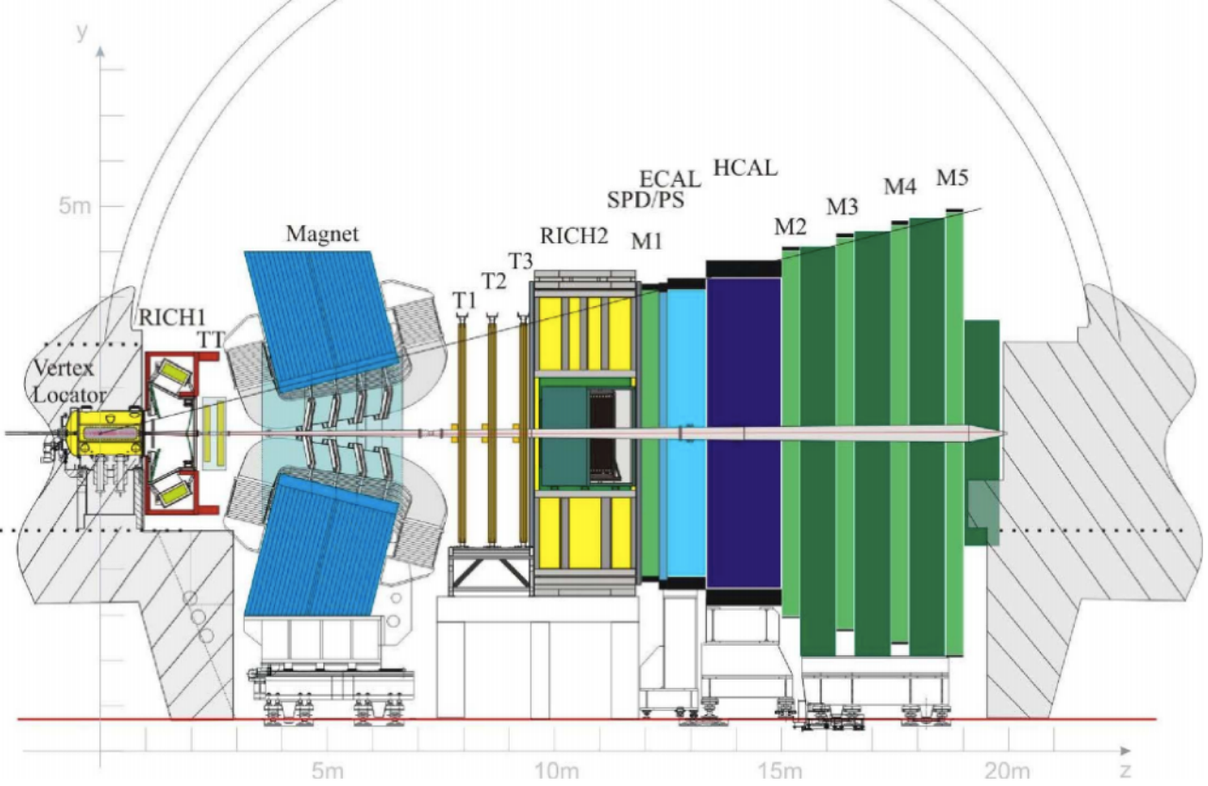
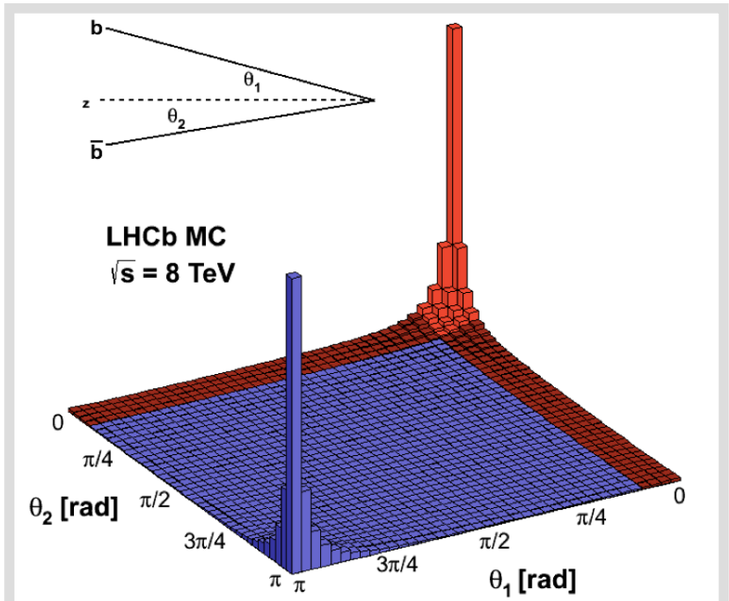
Links with LFV → Important to build a consistent picture [arXiv: 1609.08895v2]

$$\mathcal{B}(B \to K\mu^{\pm}e^{\mp}) \sim 3 \cdot 10^{-8} \left(\frac{1-R_K}{0.23}\right)^{\prime}, \; \mathcal{B}(B \to K(e^{\pm},\mu^{\pm})\tau^{\mp}) \sim 2 \cdot 10^{-8} \left(\frac{1-R_K}{0.23}\right)^{\prime}$$

$$\frac{\mathcal{B}(B_s \to \mu^+ e^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} \sim 0.01 \left(\frac{1-R_K}{0.23}\right)^2, \quad \frac{\mathcal{B}(B_s \to \tau^+(e^-,\mu^-))}{\mathcal{B}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} \sim 4 \left(\frac{1-R_K}{0.23}\right)^2 .$$

The LHCb detector





JINST 3 (2008) S08005

Forward geometry optimised for for b and c decays.

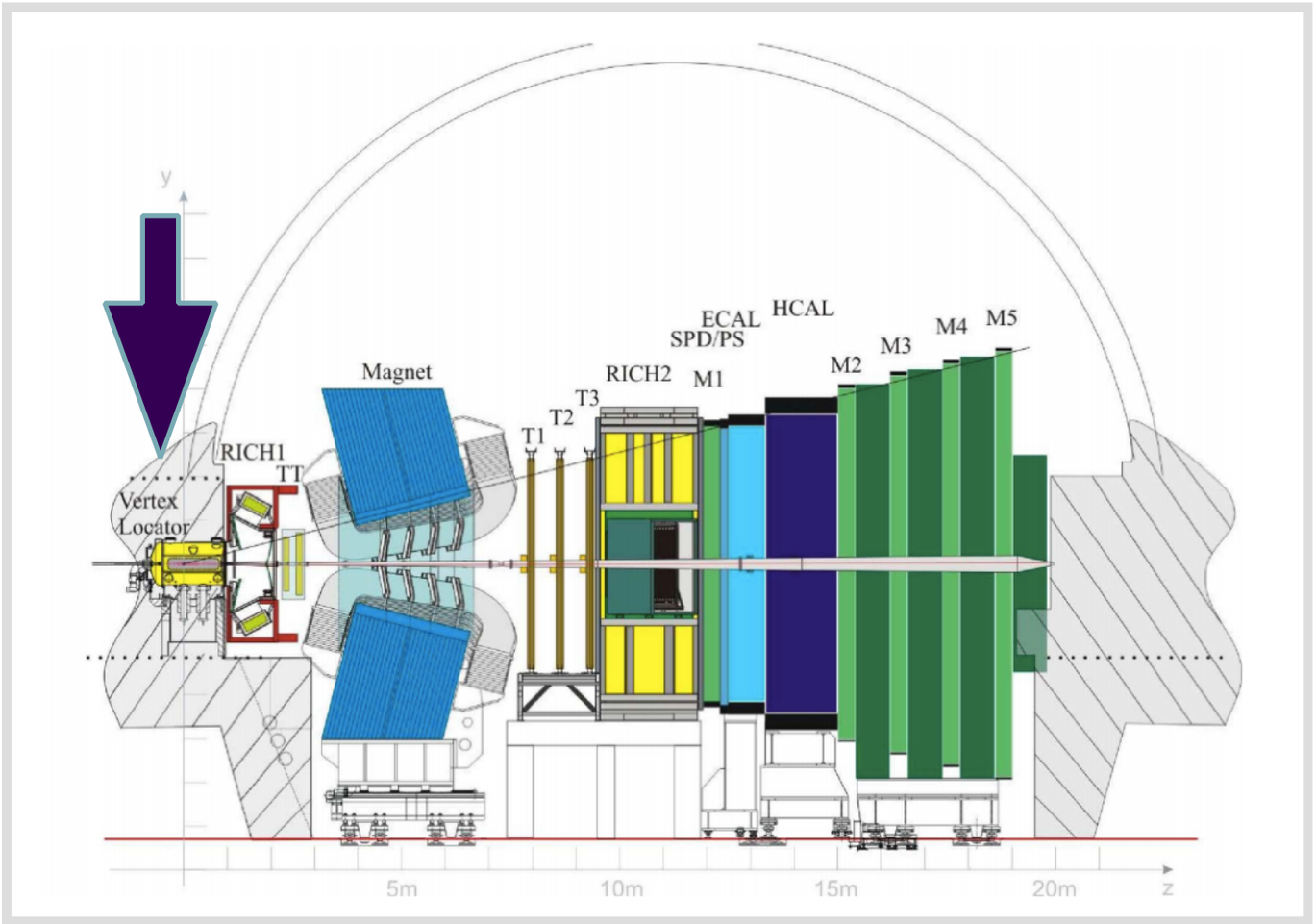
Fully instrumented in $2 < \eta < 5$

Cleanest LHC events: <Pile-Up> ~ 2 in Run I

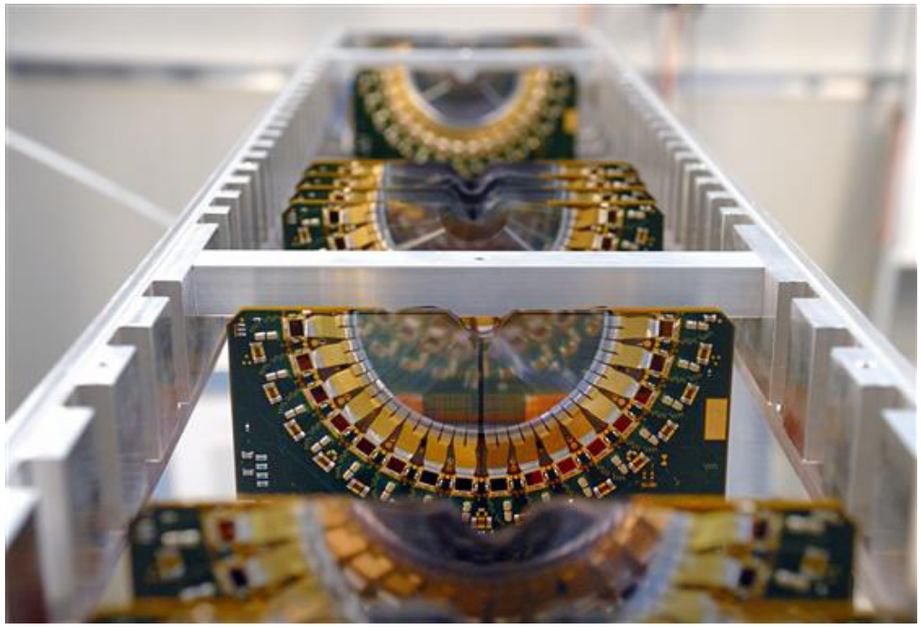
$3fb^{-1}$ collected: $1fb^{-1}$ in 2011 at TeV and $2fb^{-1}$ in 2012 at 8TeV

The LHCb detector

JINST 3 (2008) S08005

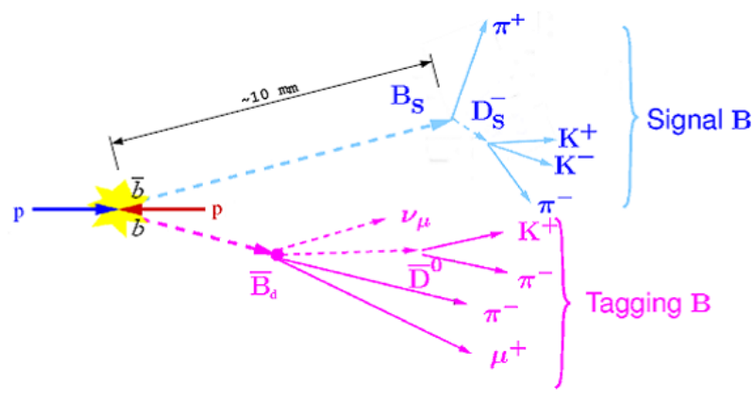


VeLo



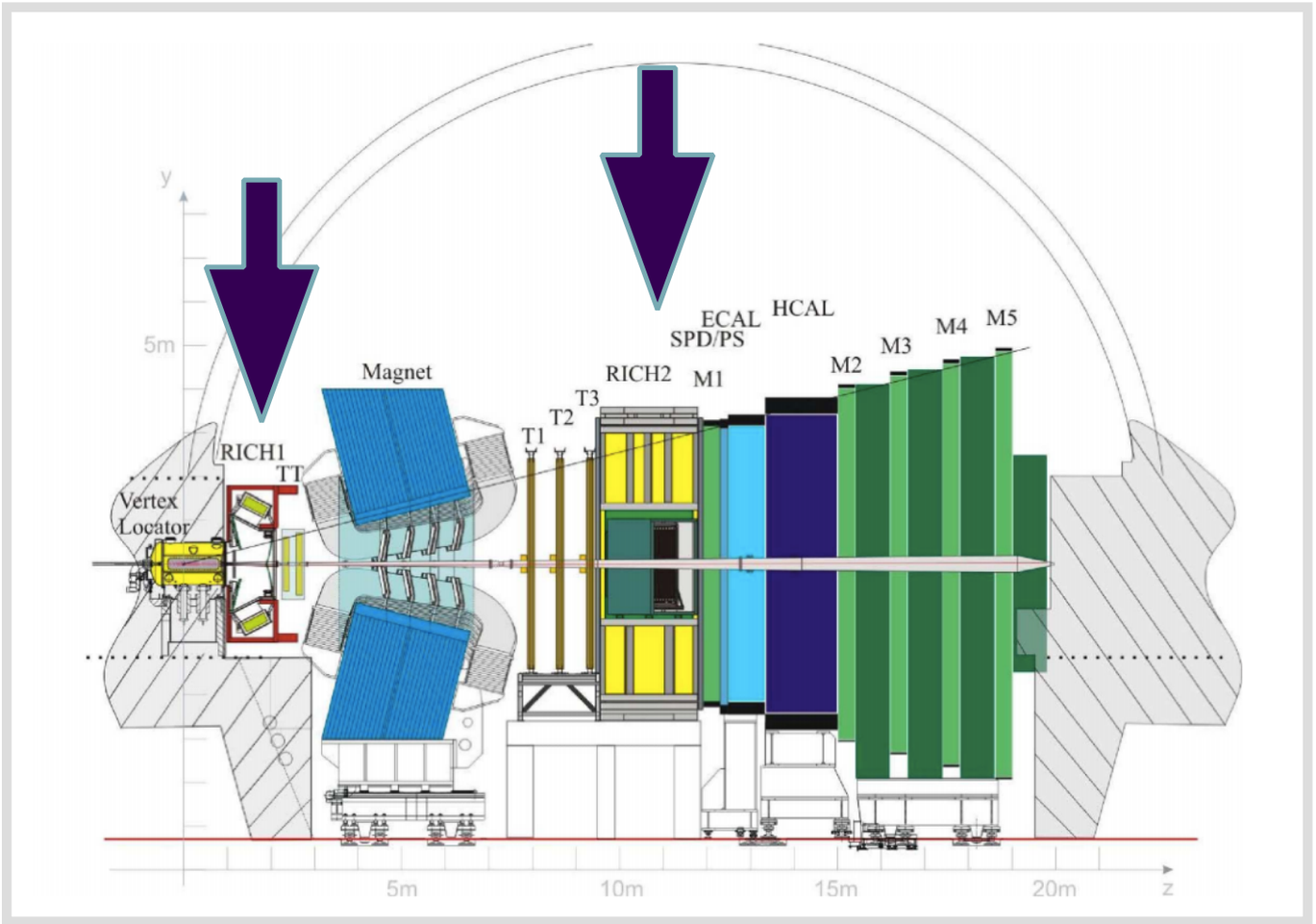
Silicon tracker → Needed for precise determination of secondary vertices

B mesons travel ~1cm into the detector.
VeLo is essential to reconstruct secondary vertices of B and D hadrons.



The LHCb detector

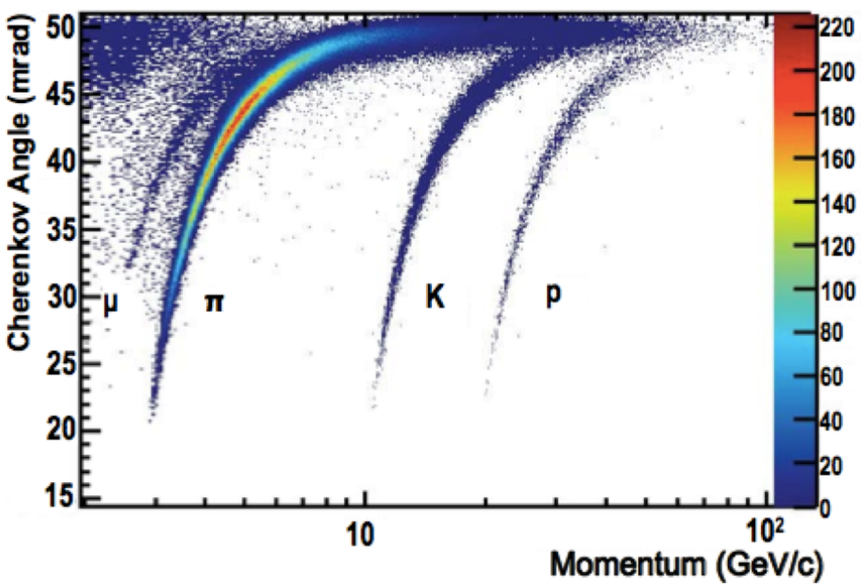
JINST 3 (2008) S08005

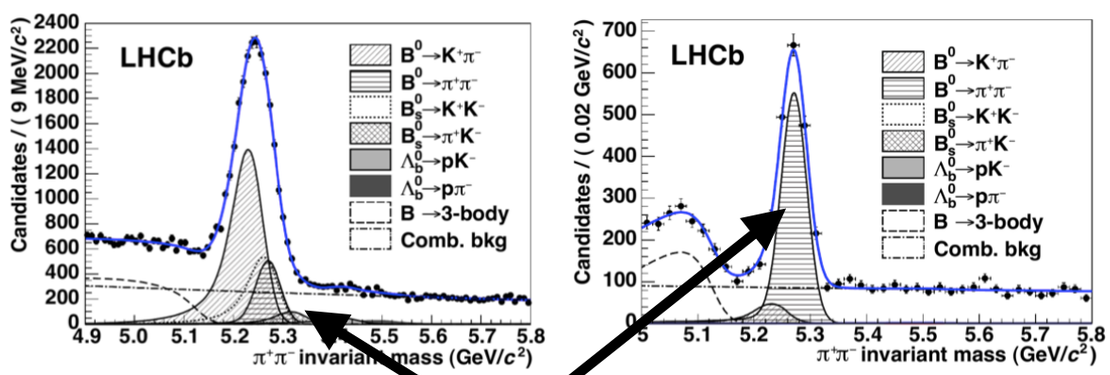


RICH

RICH 1: before magnet
for 1 < p < 70 GeV/c
RICH 11: before magnet
for 20 < p < 200 GeV/c

Provide particle ID





Essential to distinguish kinematically similar decays with different final states

The LHCb detector

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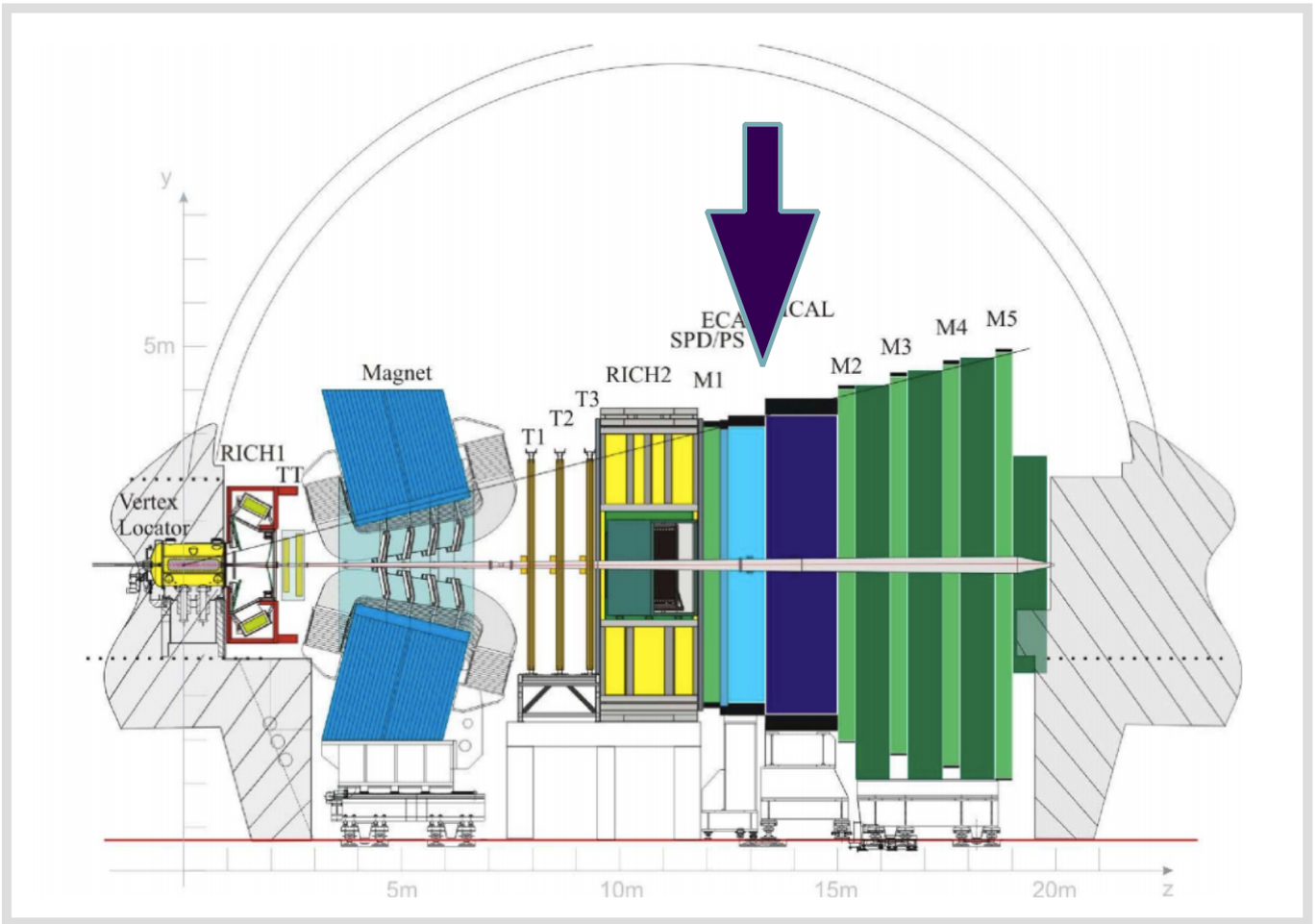
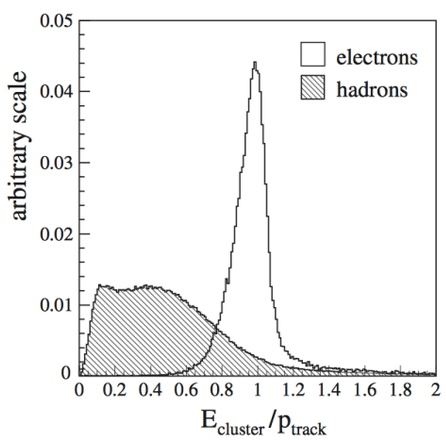
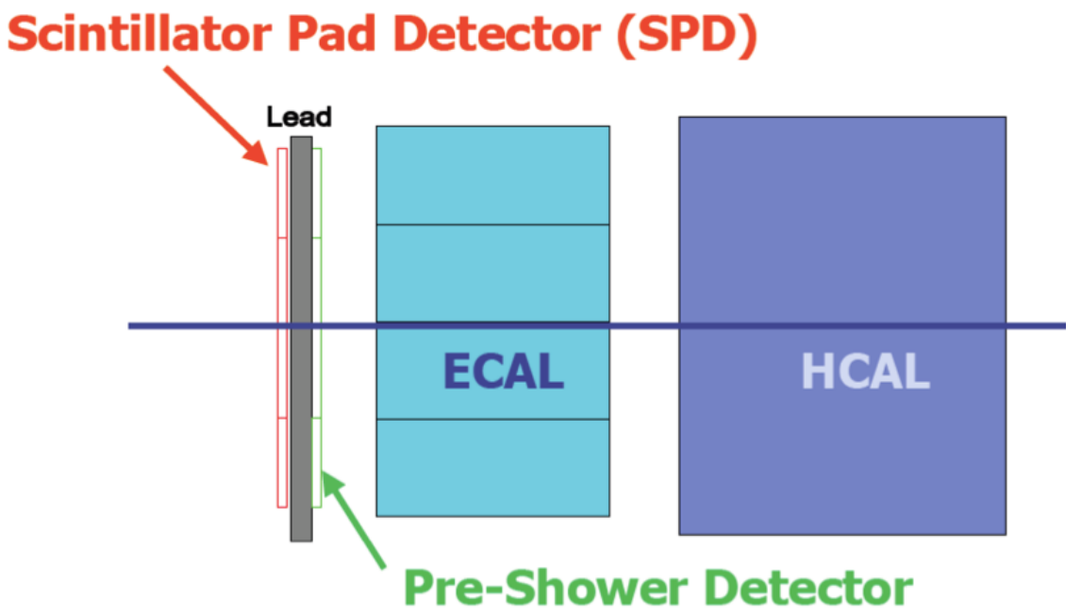


Calorimeters

PD for charged pions rejection
SPD for neutral pions rejection
ECAL fully contains electrons
HCAL for hadrons ID

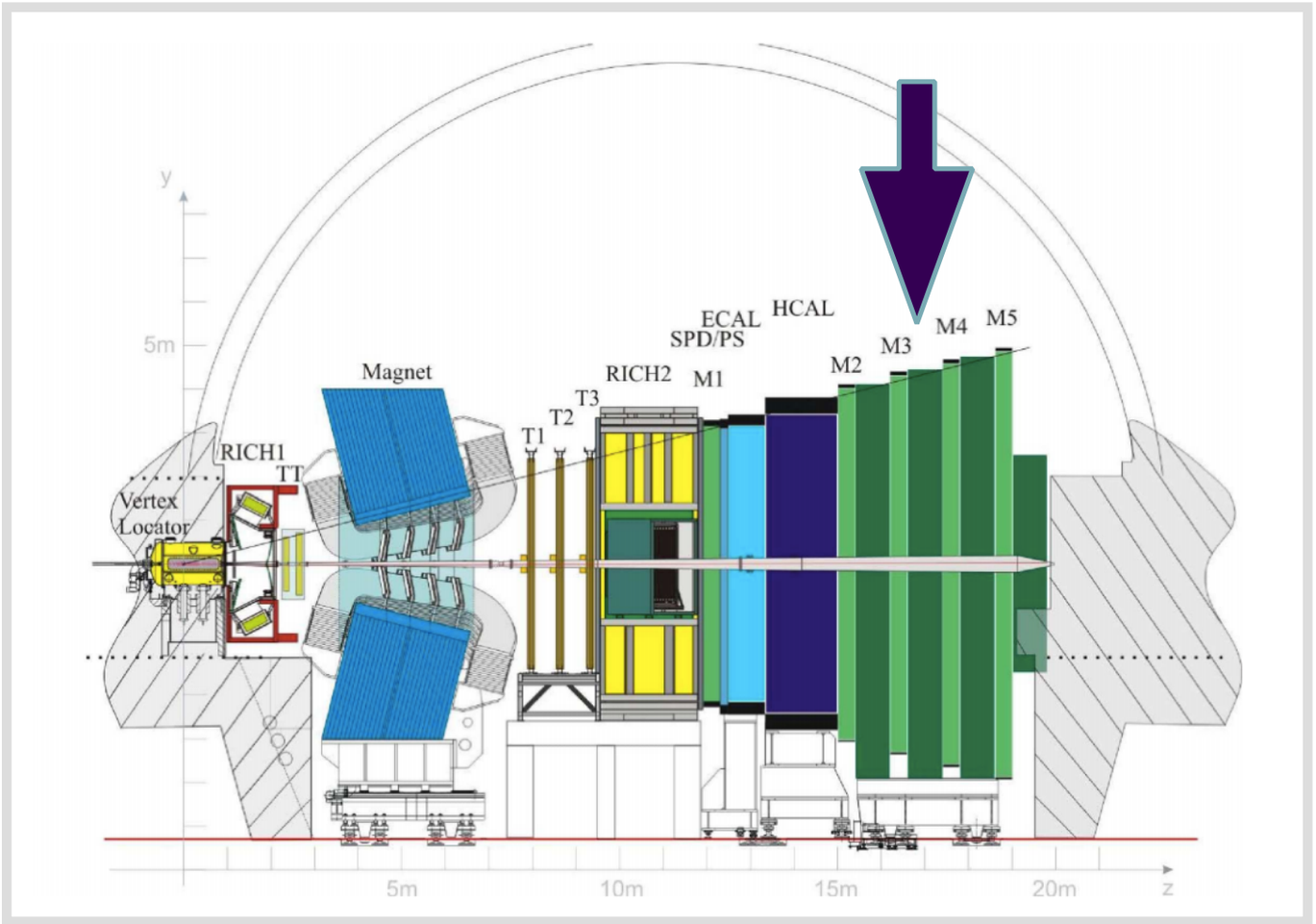
Example of e/h discrimination





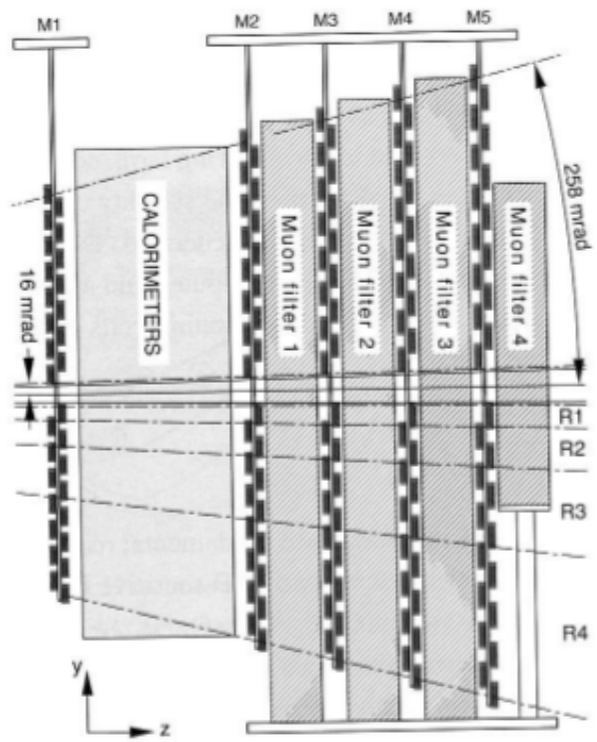
The LHCb detector

JINST 3 (2008) S08005



Muon detector

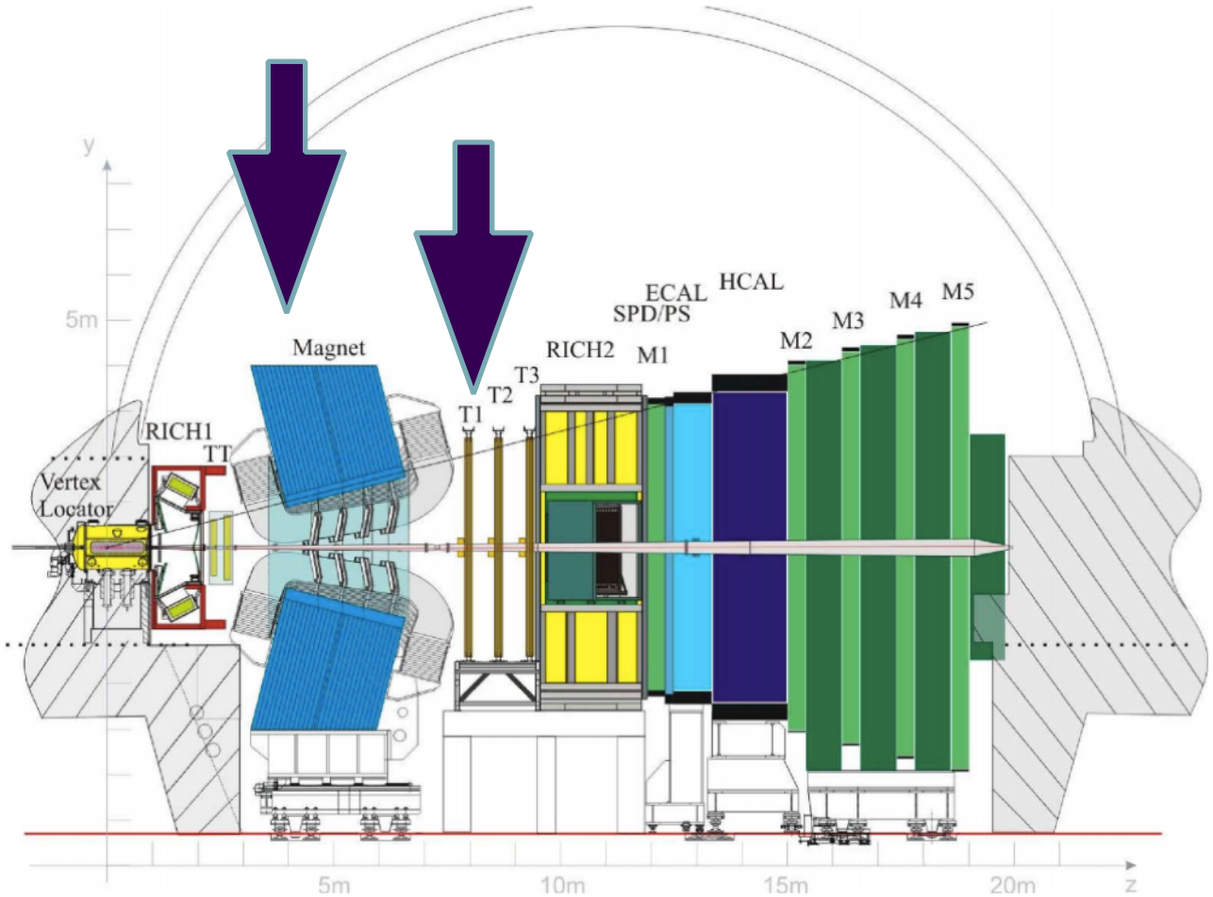
5 tracking station separated
by iron layers
Drift tubes in the outer region
GEM in the inner region
due to higher track density



Each station has 95% efficiency.
Provides good triggering.
Only 10 GeV/c muons pass through.

The LHCb detector

JINST 3 (2008) S08005

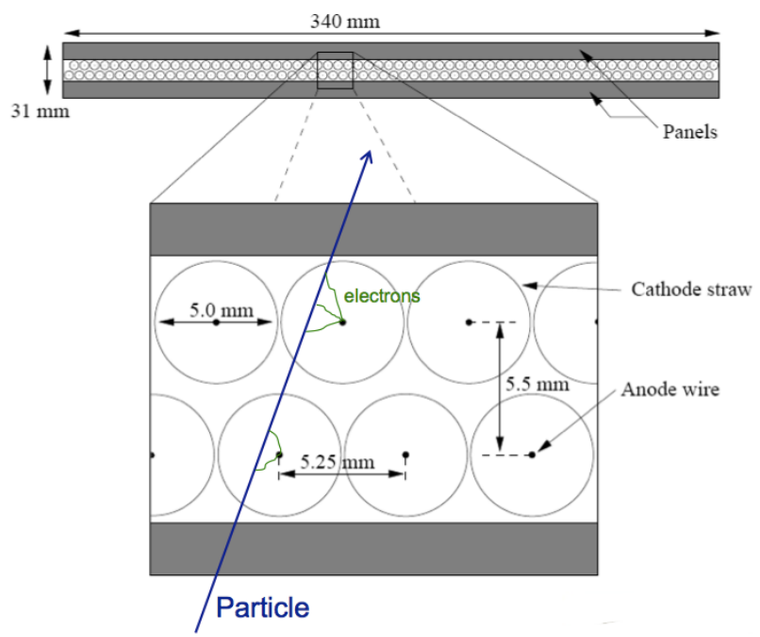


Magnet

Power: 4 Tm
Polarity periodically reversed
to reduce systematics

Tracking system

TT → before magnet
OT → after magnet

Precision:
0.4% at 5 GeV/c
1% at 200 GeV/c

Silicon strip and drift chambers