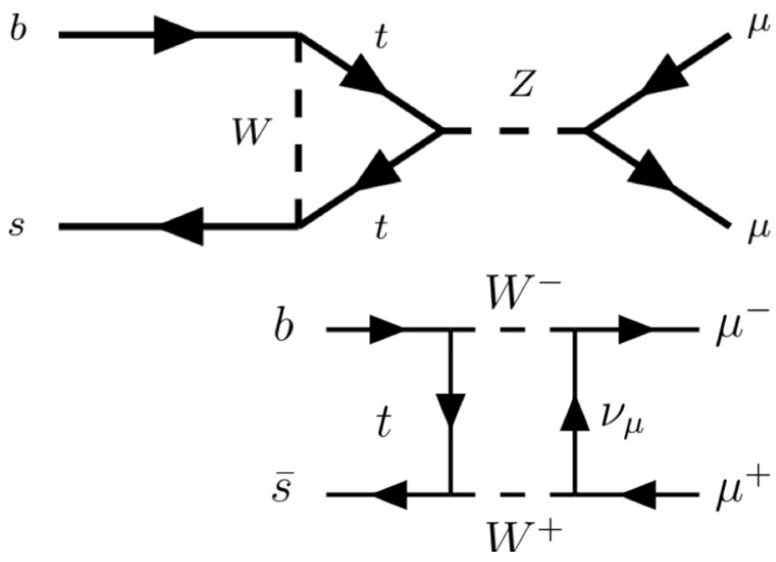
Rare decays

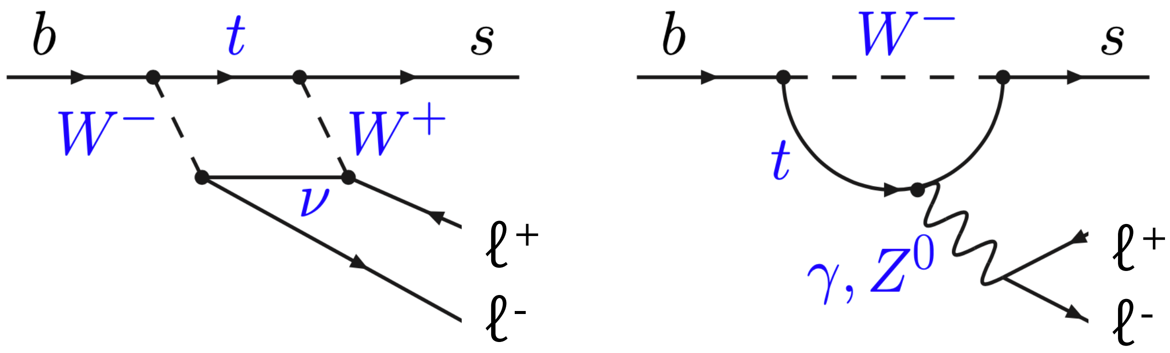

Les devises Shadok
EN ESSAYANT CONTINUELLEMENT
ON FINIT PAR RÉUSSIR. DONC:
PLUS ÇA RATE, PLUS ON A
DE CHANCES QUE ÇA MARCHE.

(very) rare decays: $b \rightarrow s\ \ell^+\ell^-$ transitions

$B_s \rightarrow \ell^+\ell^-$

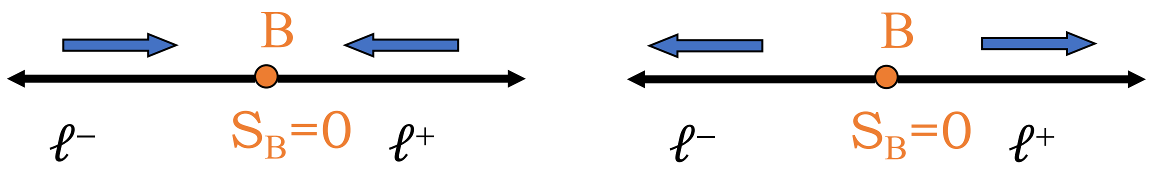


$H_b \rightarrow H_s\ \ell^+\ell^-$



$B_{s/d} \to \ell^+\ell^-$

ℓ = e or μ



left-handed particle
left-handed anti-particle

right-handed particle
right-handed anti-particle

SM : very rare (V_{tq}, helicity suppression)

In the SM, in the massless limit: left-handed anti-particle &right-handed particle are forbidden

$$\mathcal{B}(B_s^0 \to e^+e^-) = (8.60 \pm 0.36) \times 10^{-14}$$

$$\mathcal{B}(B^0 \to e^+e^-) = (2.41 \pm 0.13) \times 10^{-15}$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

JHEP10 (2019) 232

SM

Due to CKM, the B_d modes are further suppressed by a factor 1/30

Sensitive to the scalar sector

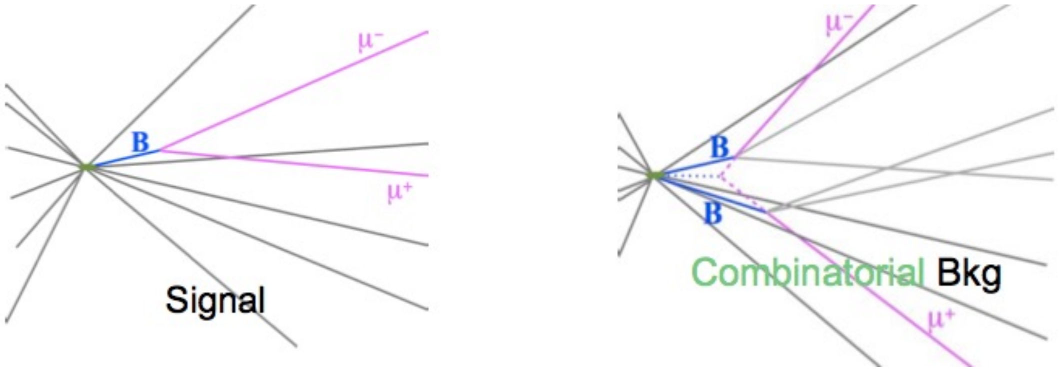
New Physics models with an extended Higgs sector $BR^{MSSM} \propto \tan^6\beta / M_A^4$

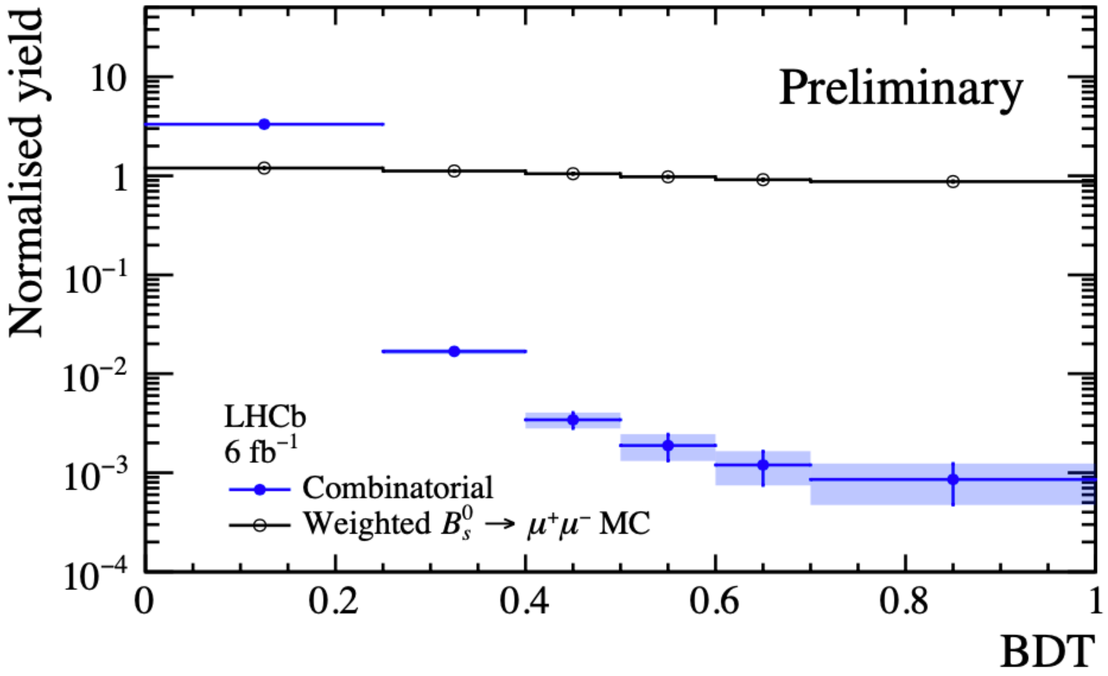
ratio of the vevs of the two Higgs doublets

First searches in 1985 (!) : CLEO BR < 10^{-4} @ 90% CL

Analysis in a nutshell

- Huge sample of B mesons
- Efficient trigger
- Powerful selection
  - Vertex resolution
  - Mass resolution
  - Muon ID
- BDT algorithm





Expectations (from SM)

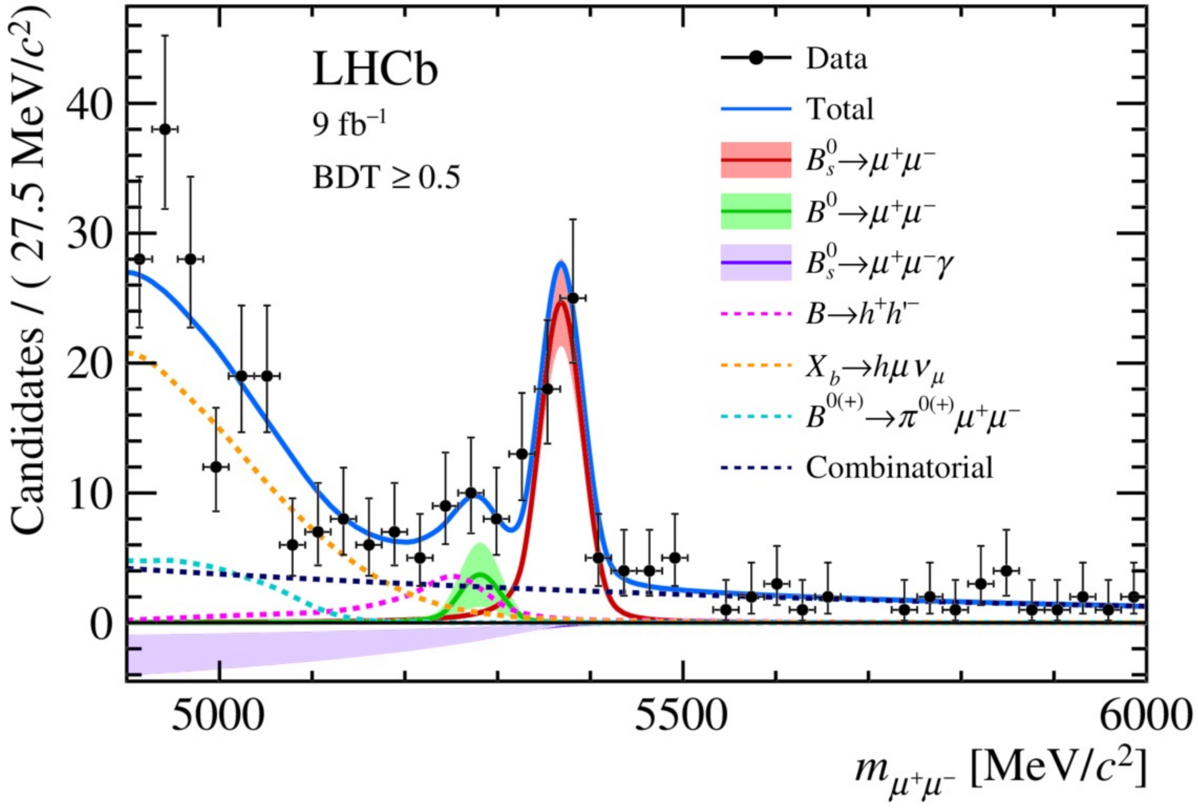
$$N(B_s^0 \to \mu^+\mu^-)_{SM} = 147 \pm 8$$

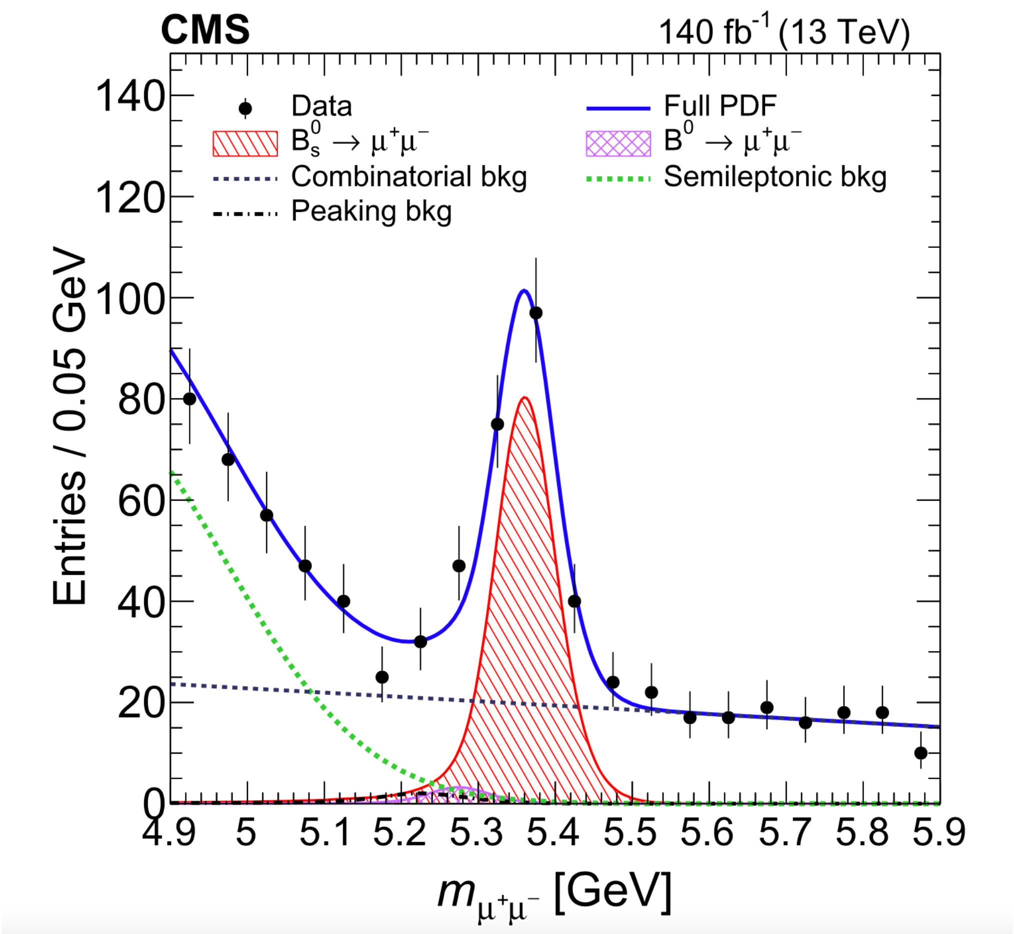
$$N(B^0 \to \mu^+\mu^-)_{SM} = 16 \pm 1$$

- Branching fraction estimated from a fit in 5 BDT bins (first one excluded since it's background dominated) and two run periods (Run1 & Run2)

Two most precise measurements: CMS & LHCb

https://doi.org/10.1016/j.physletb.2023.137955





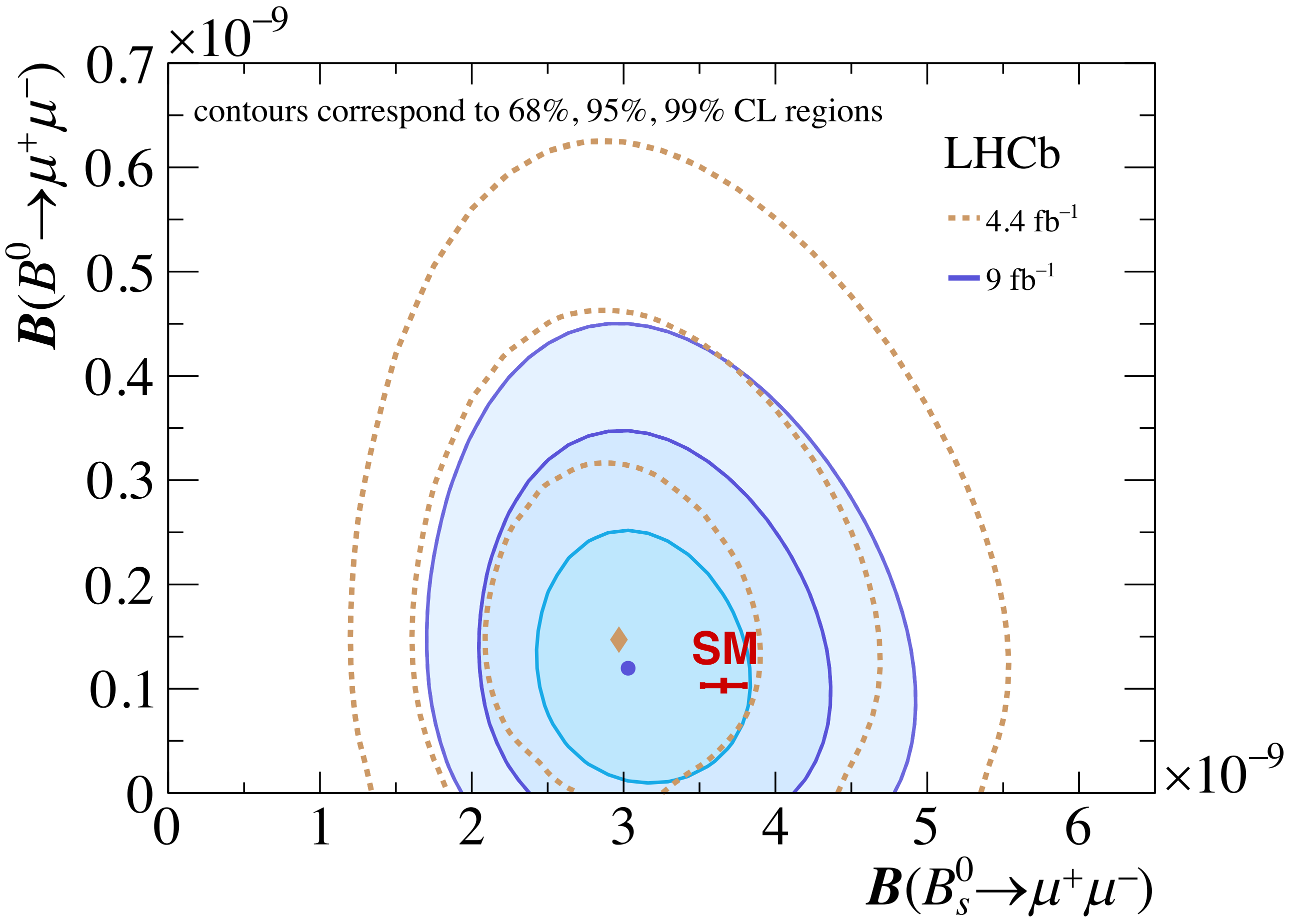
LHCb-PAPER-2021-007

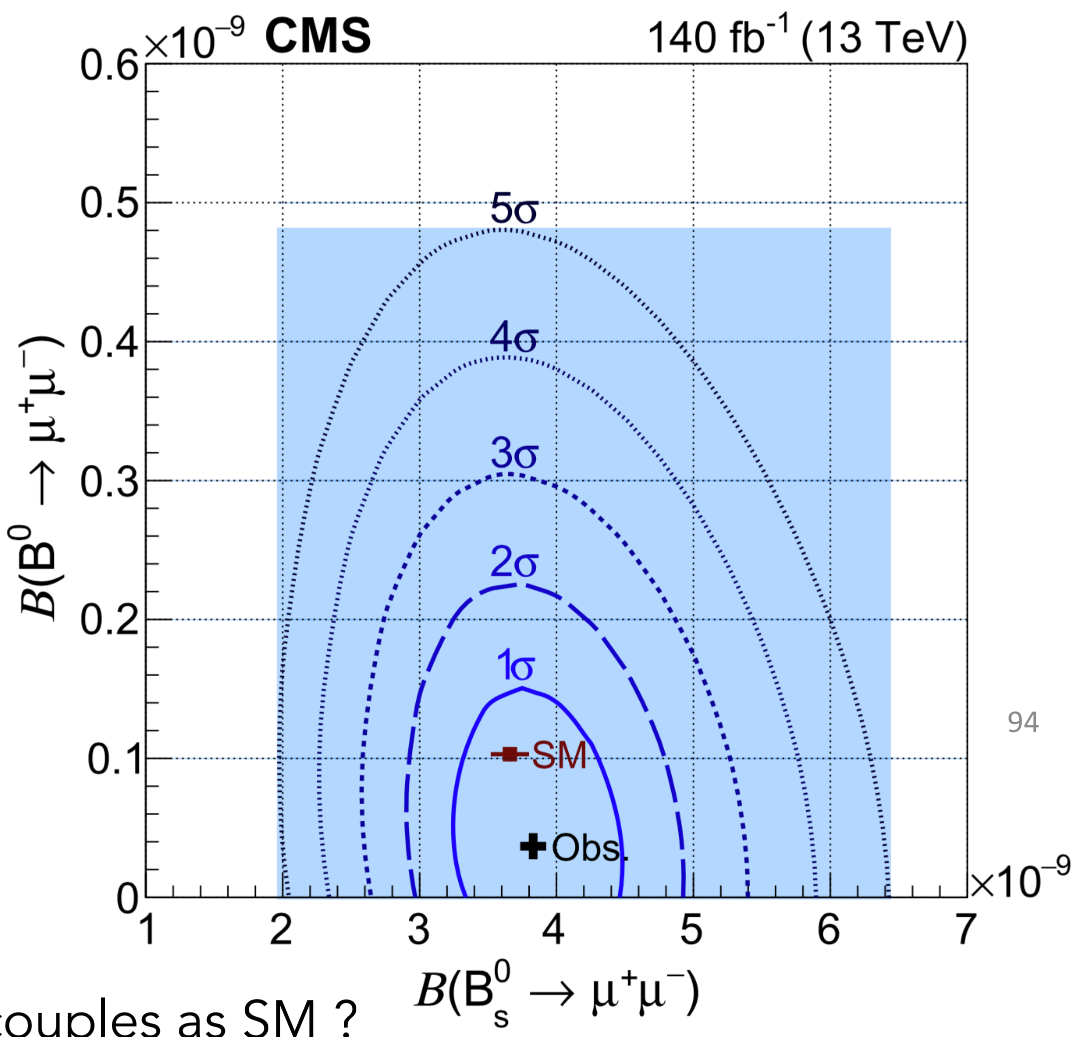
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$$ @ 95 % CL

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\,(\text{stat})\,^{+0.19}_{-0.16}\,(\text{syst})\,^{+0.14}_{-0.13}\,(f_s/f_u)\right] \times 10^{-9},$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ at 95\% CL.}$$





Important to check B_d vs B_s : if there is New Physics does it couples as SM ?

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = 3.52^{+0.32}_{-0.30} \times 10^{-9}$$

Combination from arXiv:2210.07221

SM-like given the current precision

$H_b \to H_s\, \ell^+\ell^-$: what do we measure ?

Branching Fractions

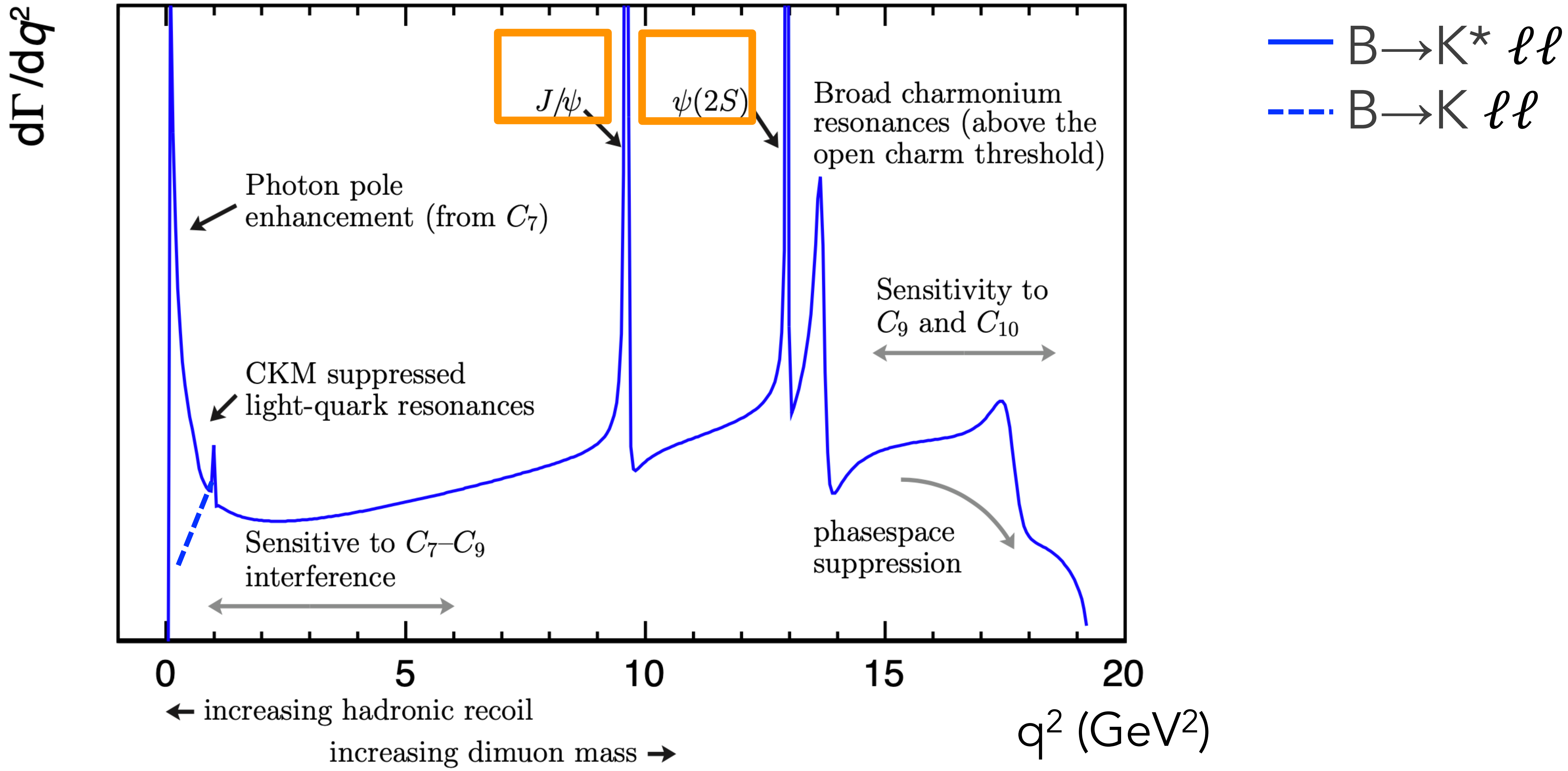
Angular observables

Lepton Flavour Universality observables:
Branching Fractions ratios
angular observables ratios

theoretical cleanness

there is no free lunch

resonant (control) modes



PRL 127 (2021) 151801

One example of a BF measurement: $B_s \to \phi\, \mu\, \mu$

$q^2 = M^2(\mu\mu)$

Experimentally 'easy' for LHCb

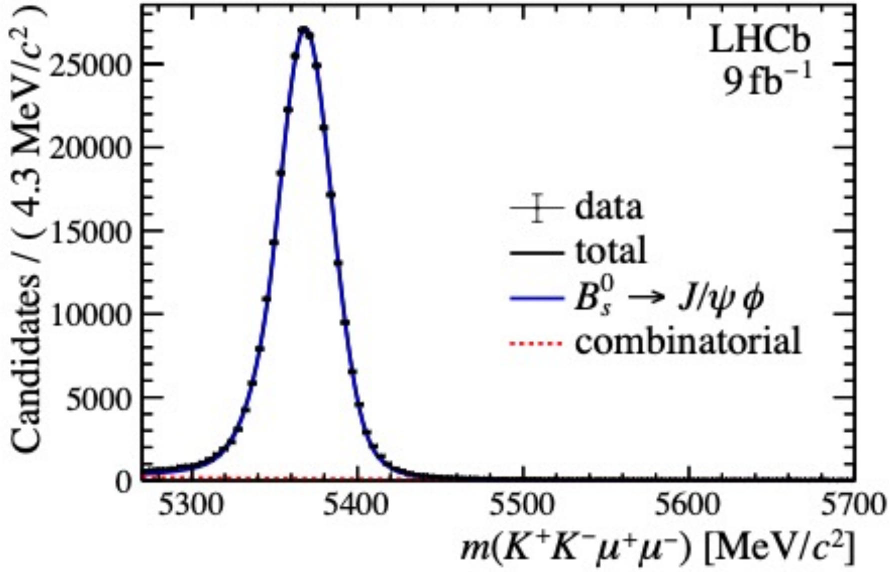
- two muons
- $\phi \to KK$ and is a narrow resonance

Use of $B_s \to J/\psi\ (\to \mu\, \mu)\ \phi$ as a normalisation mode

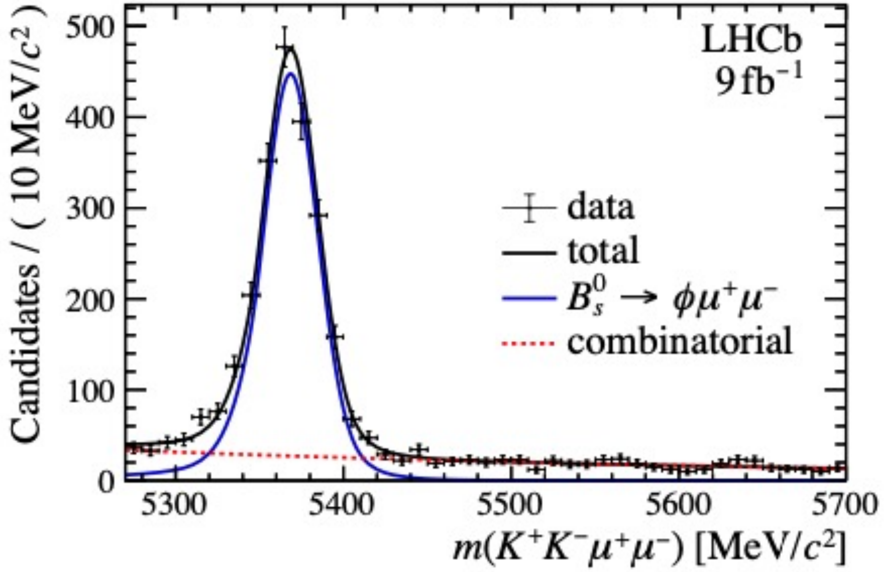
$$\mathcal{B}(B^0_s \to J/\psi\phi) = (1.018 \pm 0.032 \pm 0.037) \times 10^{-3}$$

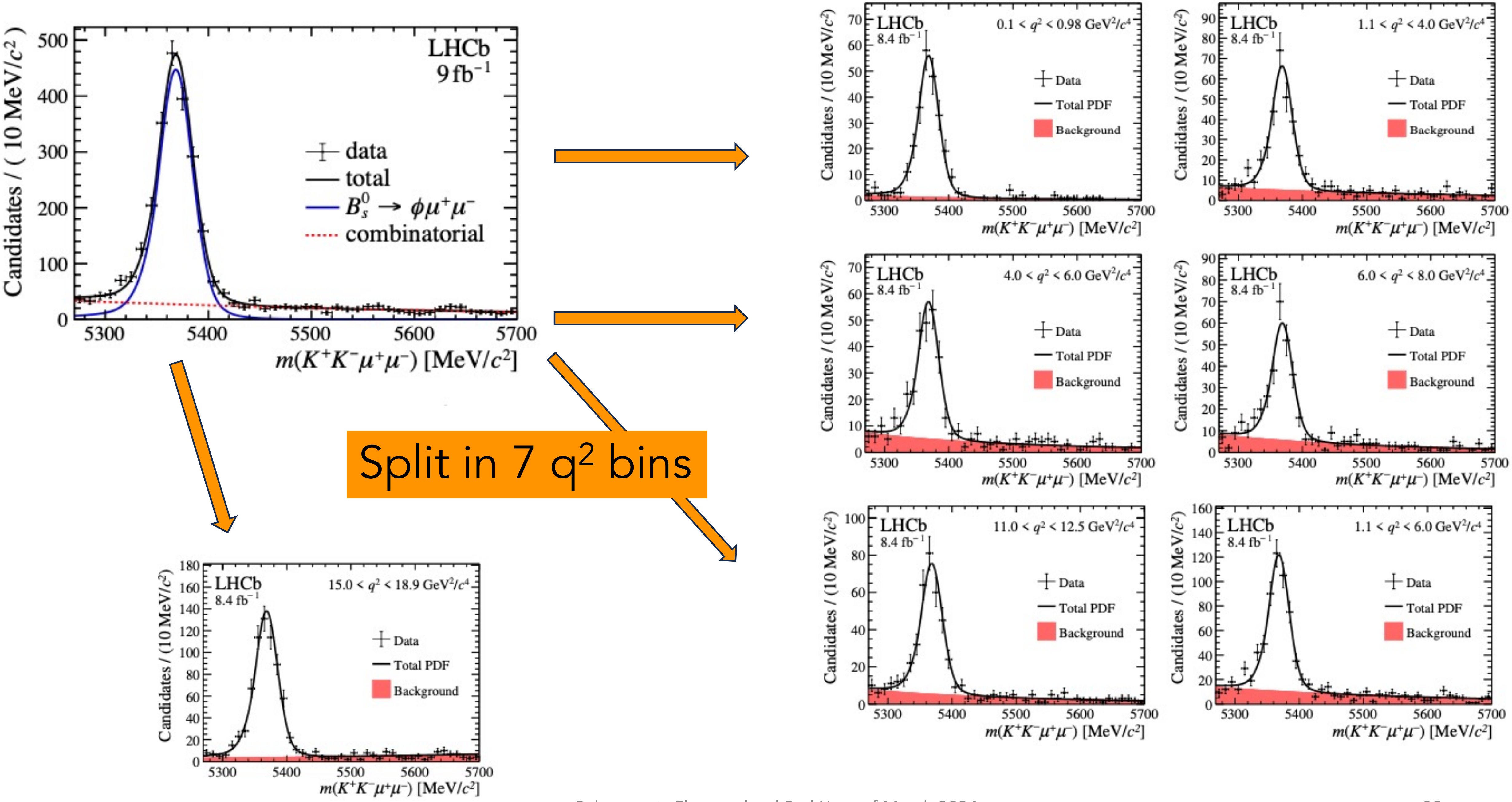
$$\frac{\mathrm{d}\mathcal{B}(B^0_s \to \phi\mu^+\mu^-)}{\mathrm{d}q^2} = \frac{\mathcal{B}(B^0_s \to J/\psi\phi) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)}{q^2_{\max} - q^2_{\min}} \times \frac{N_{\phi\mu^+\mu^-}}{N_{J/\psi\phi}} \times \frac{\epsilon_{J/\psi\phi}}{\epsilon_{\phi\mu^+\mu^-}}$$

$B_s \to J/\psi\ (\to \mu\, \mu)\ \phi$

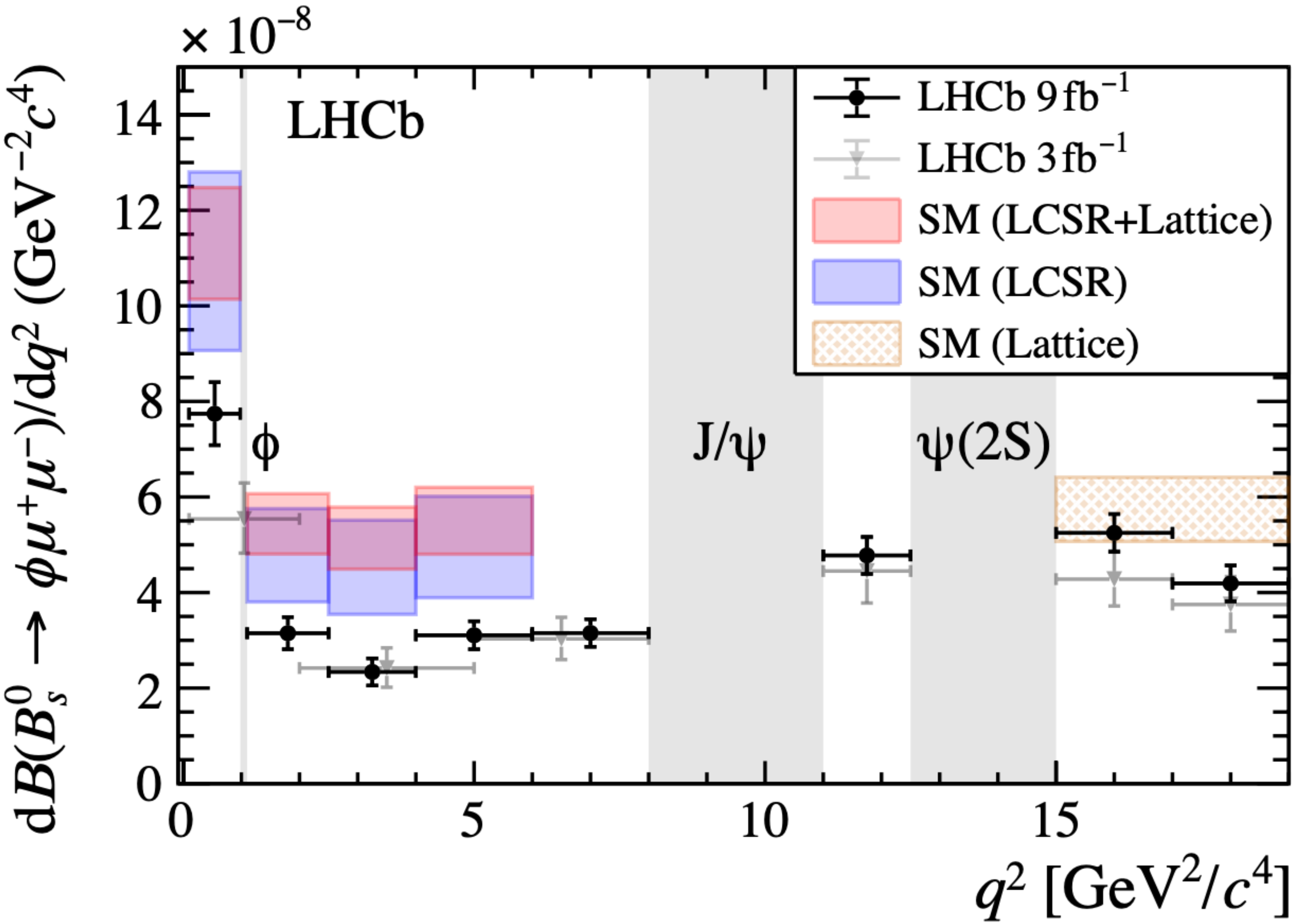


$B_s \to \phi\, \mu\, \mu$





LHCb
9 fb^{-1}
data
total
$B_s^0 \to \phi\mu^+\mu^-$
combinatorial
Candidates / (10 MeV/c^2)
$m(K^+K^-\mu^+\mu^-)$ [MeV/c^2]
Split in 7 q² bins
LHCb 8.4 fb^{-1}
$0.1 < q^2 < 0.98$ GeV^2/c^4
$1.1 < q^2 < 4.0$ GeV^2/c^4
$4.0 < q^2 < 6.0$ GeV^2/c^4
$6.0 < q^2 < 8.0$ GeV^2/c^4
$11.0 < q^2 < 12.5$ GeV^2/c^4
$1.1 < q^2 < 6.0$ GeV^2/c^4
$15.0 < q^2 < 18.9$ GeV^2/c^4
Data
Total PDF
Background
Candidates / (10 MeV/c^2)
$m(K^+K^-\mu^+\mu^-)$ [MeV/c^2]



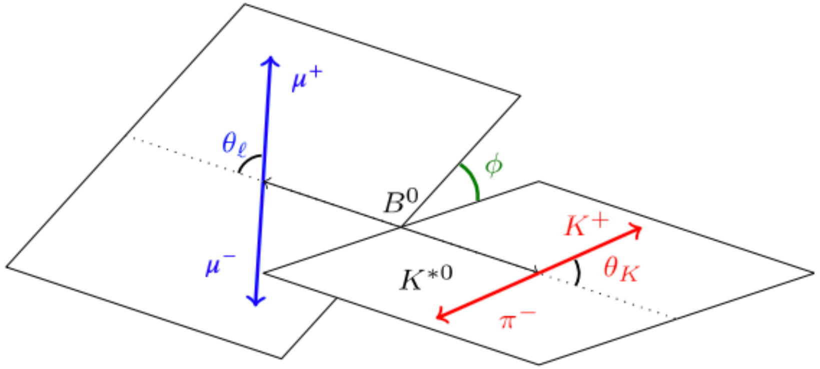
Measurements below predictions
Predictions correlated from a bin to another
Better agreement at higher-q^2 (LQCD)

Similar patterns for other decay modes

To have more information: angular analyses

3 angles and $q^2 = M^2(\ell\ell)$

$B \to V \ell\ell$



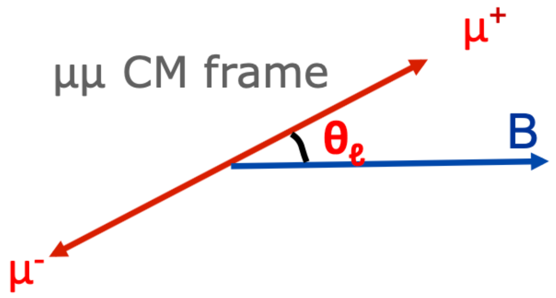
$\Lambda_b \to \Lambda^* \ell\ell$

$\Lambda_b \to \Lambda \ell\ell$

Assuming that the Λ_b is produced unpolarized at LHC

one angle and q^2

$B \to PS \ell\ell$



A set of anomalies in b→s μμ transitions

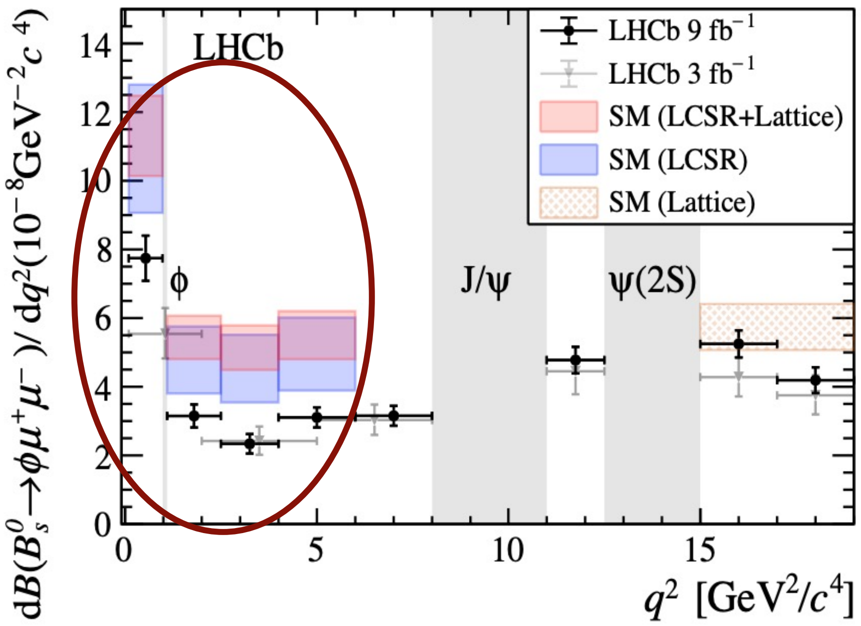
$B^0 \to K^{*0}\mu^+\mu^-$ with 6 fb^{-1} (~ 4600 evts .)

$B^+ \to K^{*+}\mu^+\mu^-$ with 9 fb^{-1} (~ 700 evts .)

$B_s \to \phi\mu^+\mu^-$ with 9 fb^{-1}(~ 1900 evts .)

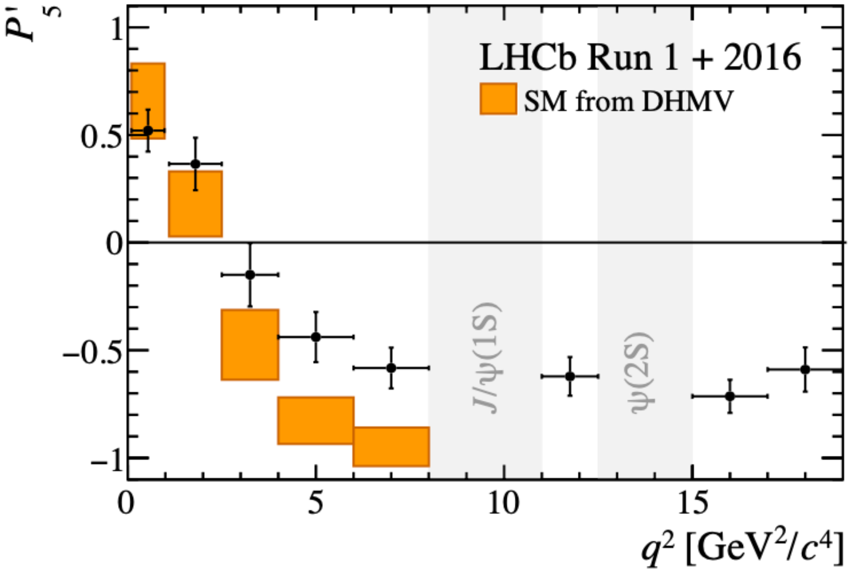
$B_s \to \phi\ \mu\ \mu$ dBR/dq^2

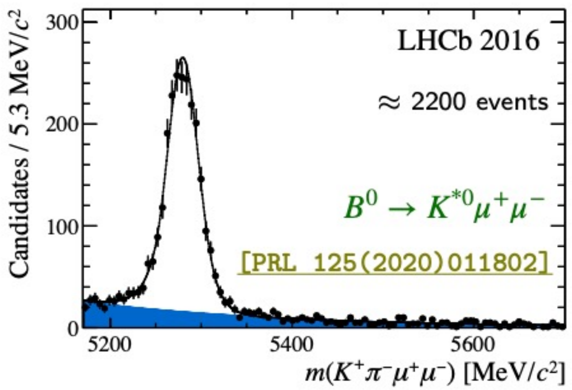
PRL 127 (2021) 151801

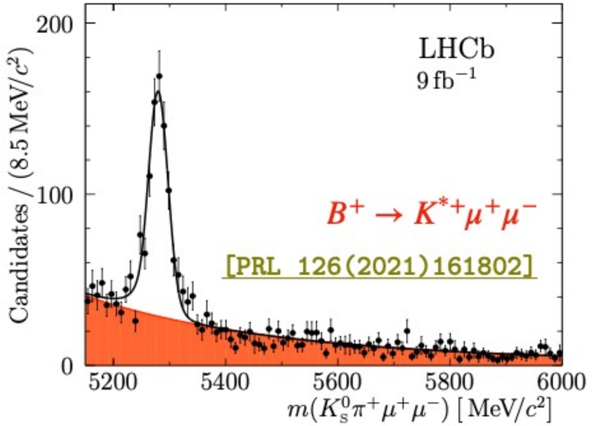


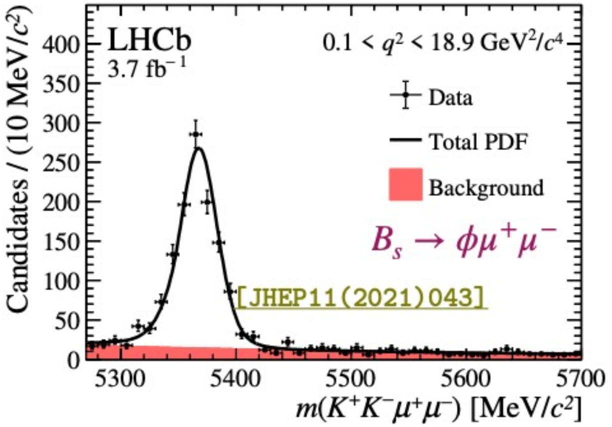
$B_d \to K^*\ \mu\ \mu$ angular fits

Phys. Rev. Lett. 125 (2020) 011802





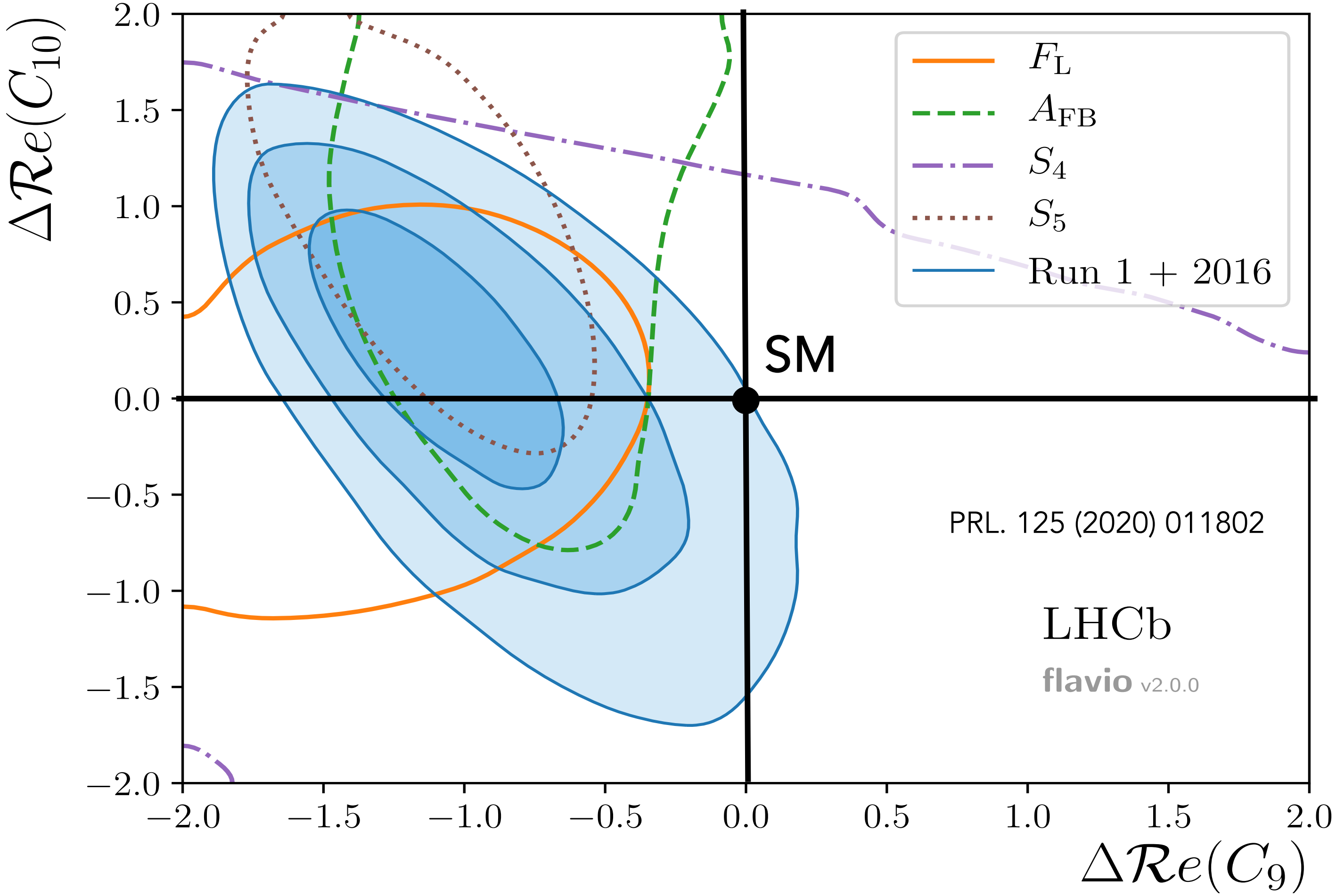


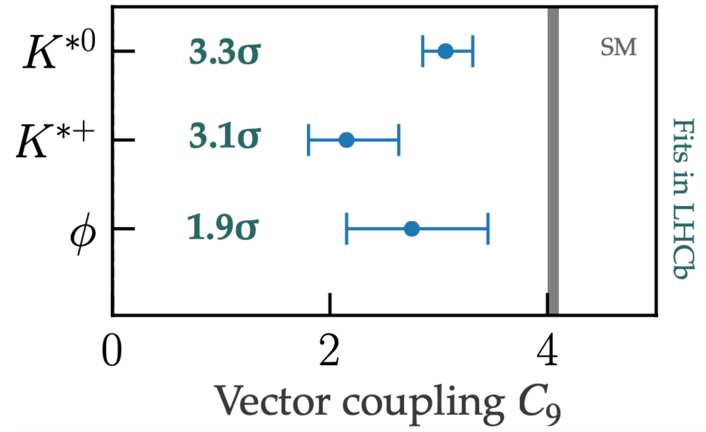


$$C_i = C_i^{SM} + C_i^{NP}$$

- In the SM Wilson coefficients are real, no necessarily the case for New Physics
- Many parameters fit… reduced configurations

B→ K*μμ alone

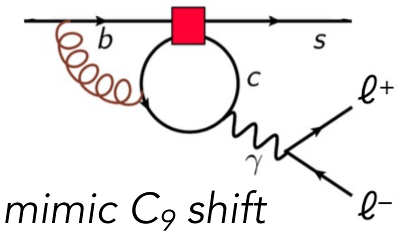




Global Wilson coefficients fit seems to indicate a pattern: different observables give a coherent picture

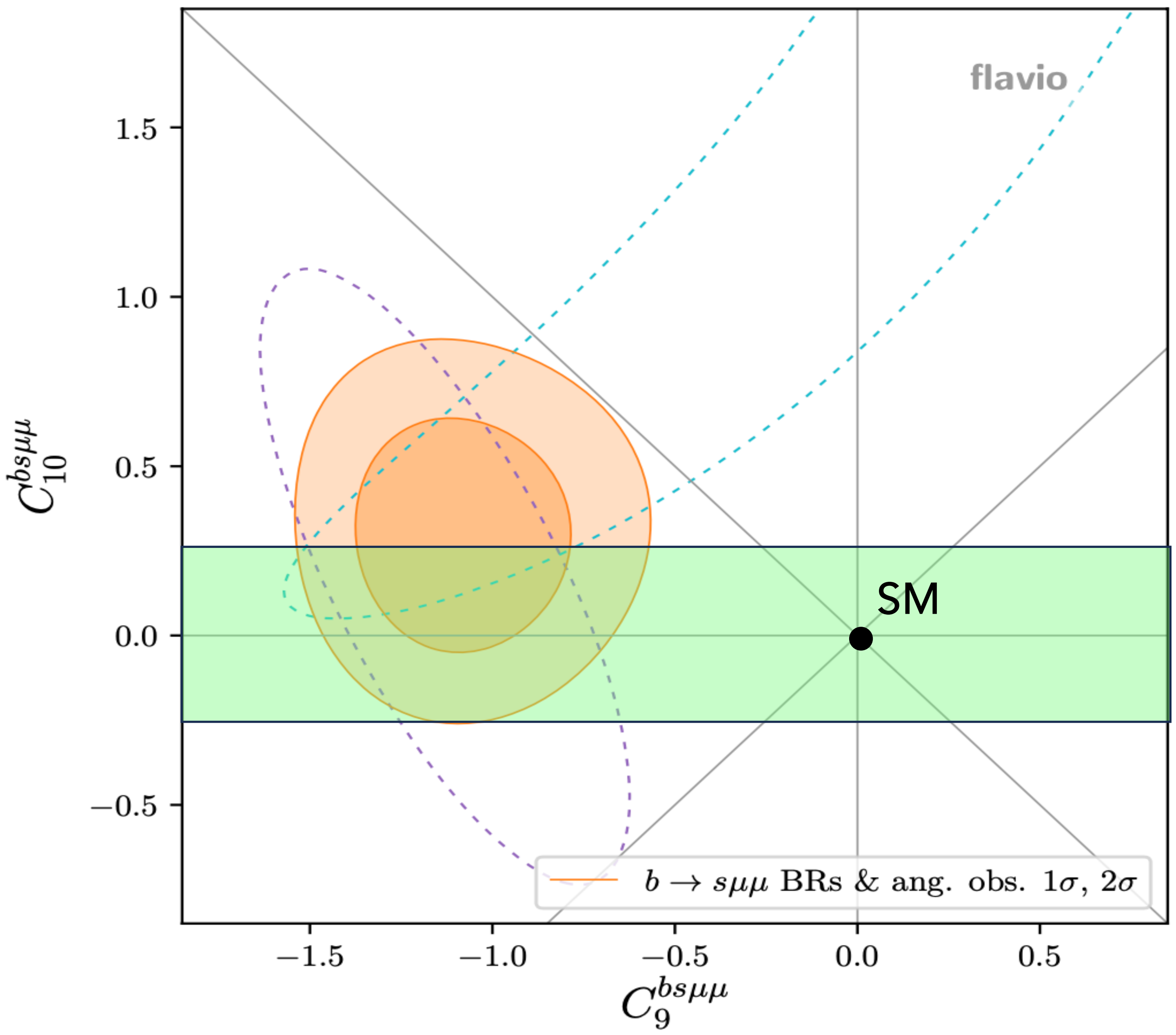
but

theoretical debate about $c\bar{c}$ loop impact



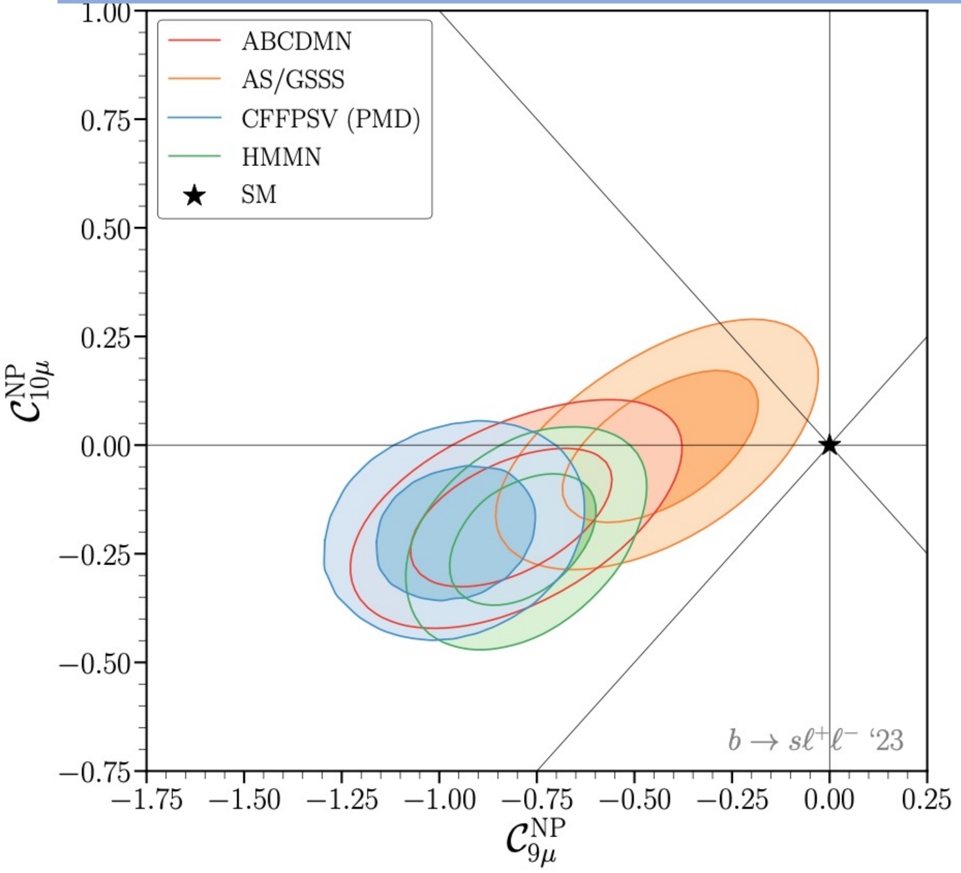
They can mimic C_9 shift

from plots from Peter Stangl La Thuile 2021

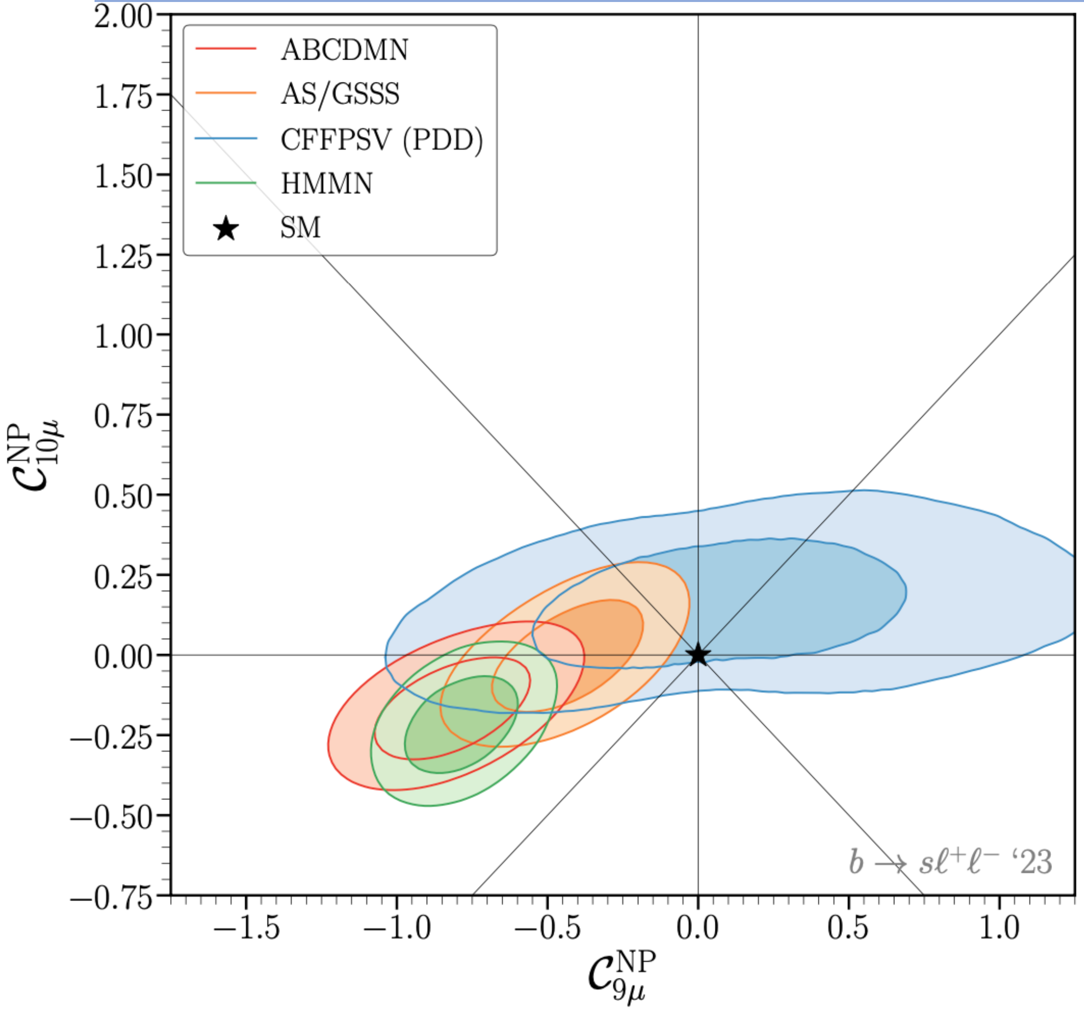


$B_s \to \mu\,\mu$

with TH input for the non-local contributions



No TH input for the non-local contributions



- ABCDMN (M. Algueró, A. Biswas, B. Capdevila, S. Descotes-Genon, J. Matias, M. Novoa-Brunet)
  Statistical framework: χ^2-fit, based on private code arXiv:2304.07330
- AS / GSSS (W. Altmannshofer, P. Stangl / A. Greljo, J. Salko, A. Smolkovic, P. Stangl)
  Statistical framework: χ^2-fit, based on public code **flavio** arXiv:2212.10497.
- CFFPSV (M. Ciuchini, M. Fedele, E. Franco, A. Paul, L. Silvestrini, M. Valli)
  Statistical framework: Bayesian MCMC fit, based on public code **HEPfit** arXiv:2212.10516
- HMMN (T. Hurth, F. Mahmoudi, D. Martínez-Santos, S. Neshatpour)
  Statistical framework: χ^2-fit, based on public code **SuperIso** arXiv:23xx.xxxxx

From B. Capdevila
FPCP 2023

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

- clean prediction (relative precision ~ 4 – 5 %)
- clean measurement for B_s (~ 10%) ; B_d not yet measured.

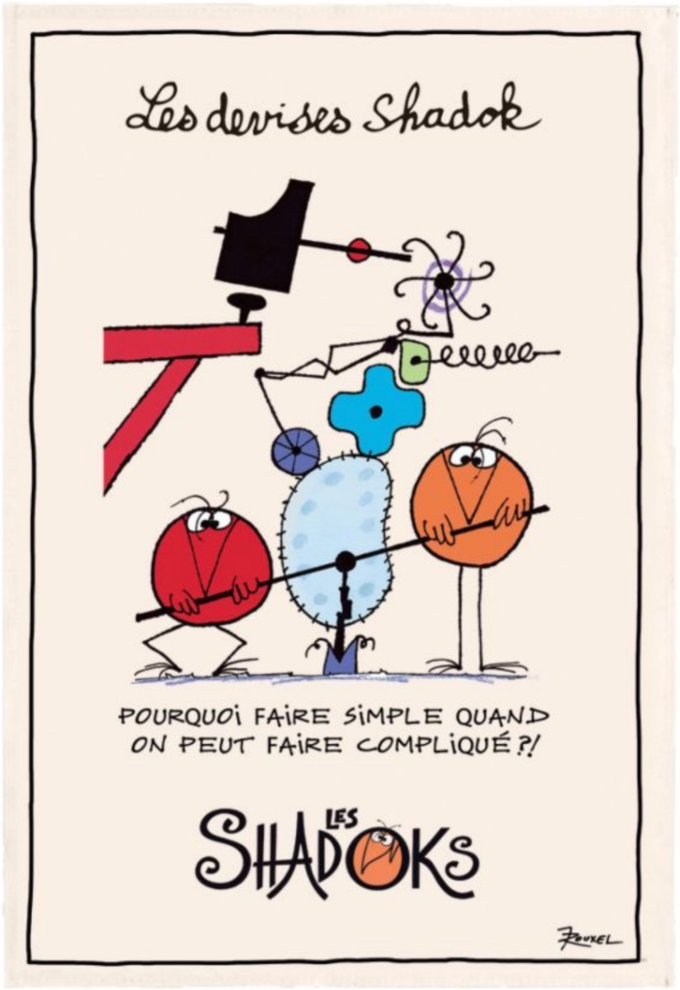
☺ clear road
C_{10} constraint

$H_b \rightarrow H_s\, \mu^+\mu^-$:

- clean measurements (~ 10% on BR in various q^2 bins)
- TH predictions not very precise for the BR. Better for angular observables.
- How to mitigate/constraint the impact of non-local contributions ?

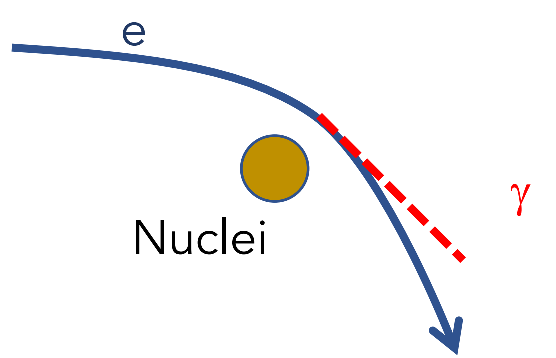
?????

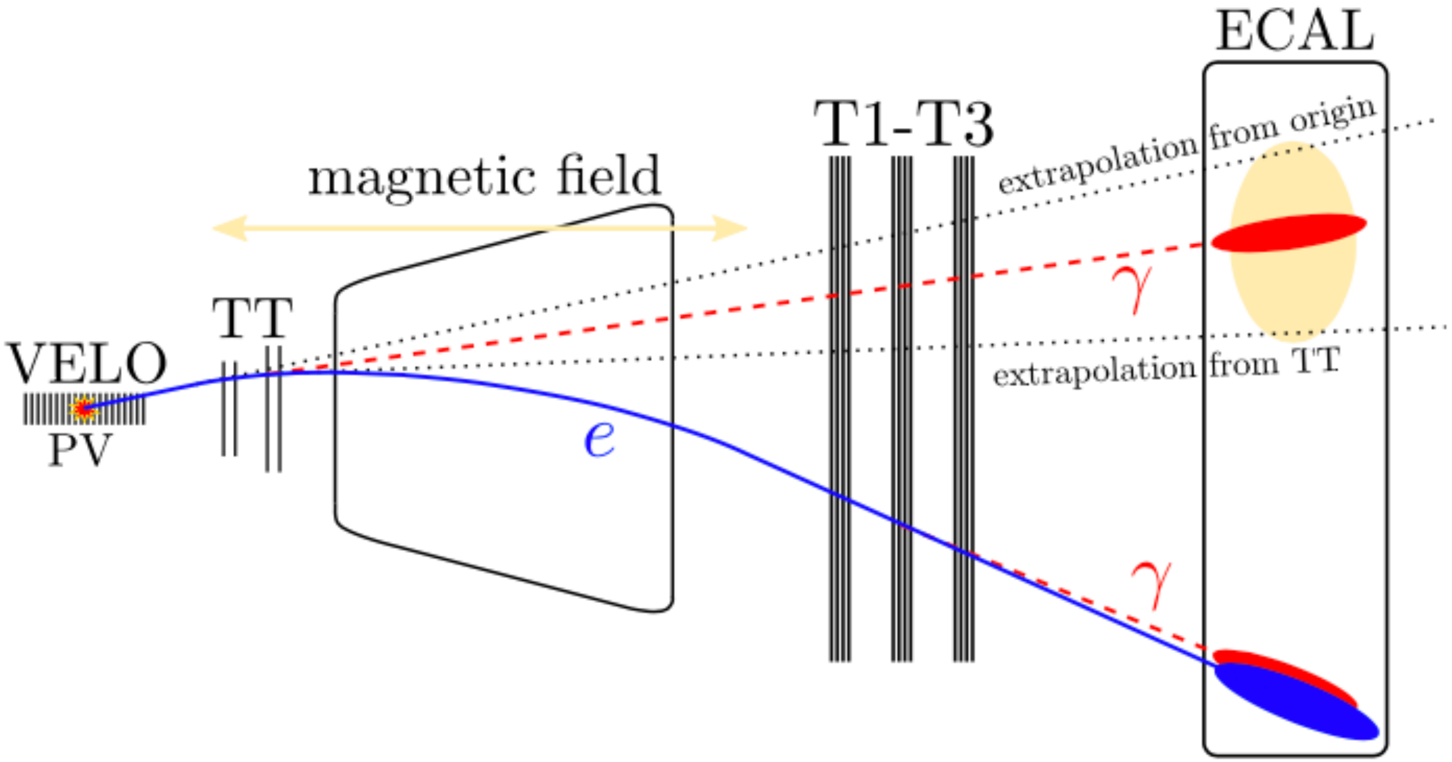
Why not electrons ?



Let's use the electrons and double our statistics !

Electrons emit Bremsstrahlung





Before the magnet

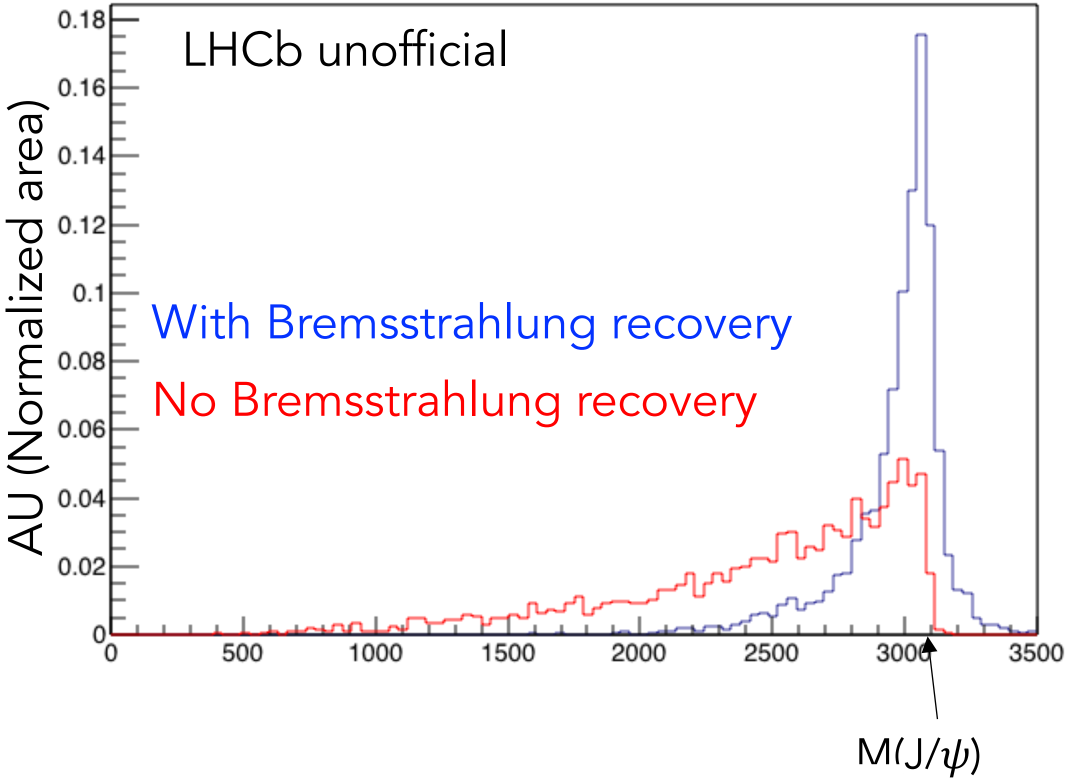
- electron can be swept out (=lost !)
- kinematics are "wrong"

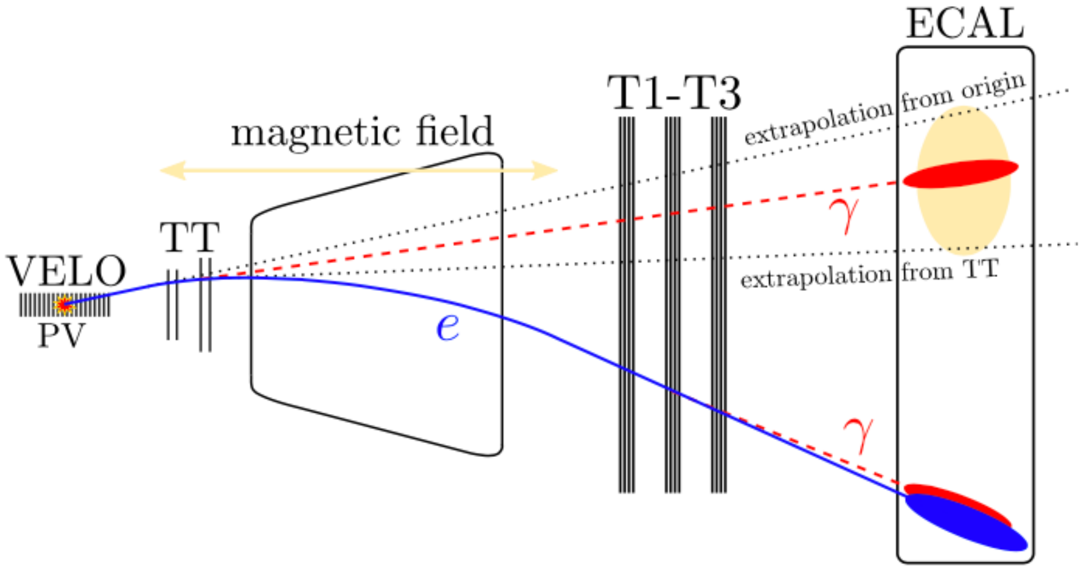
After the magnet

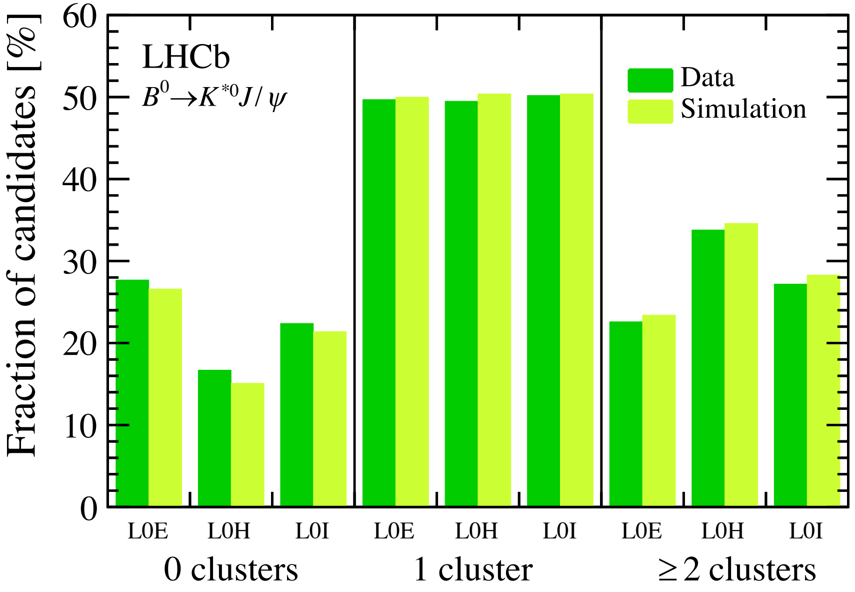
- not an issue

Energy loss ∝ E_e
Energy loss ∝ material

In both cases E/p is correct



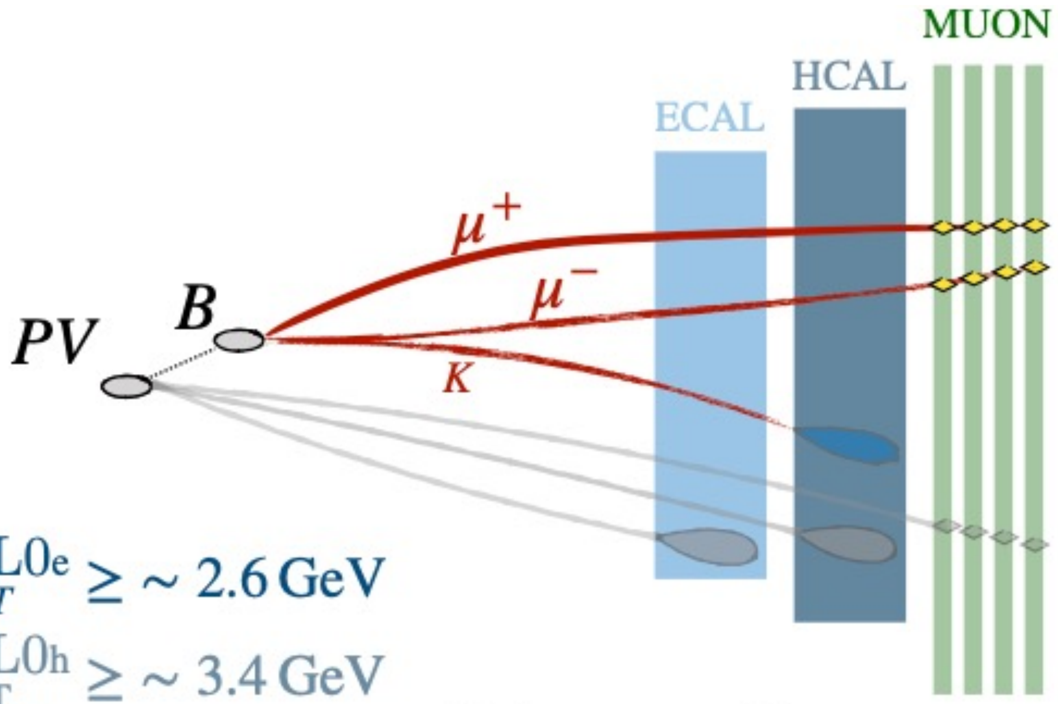




Bremsstrahlung recovery algorithm is ~ 50% efficient

Well described in simulation

Hardware trigger is very different for electrons and muons



$E_T^{L0e} \geq \sim 2.6\,\mathrm{GeV}$

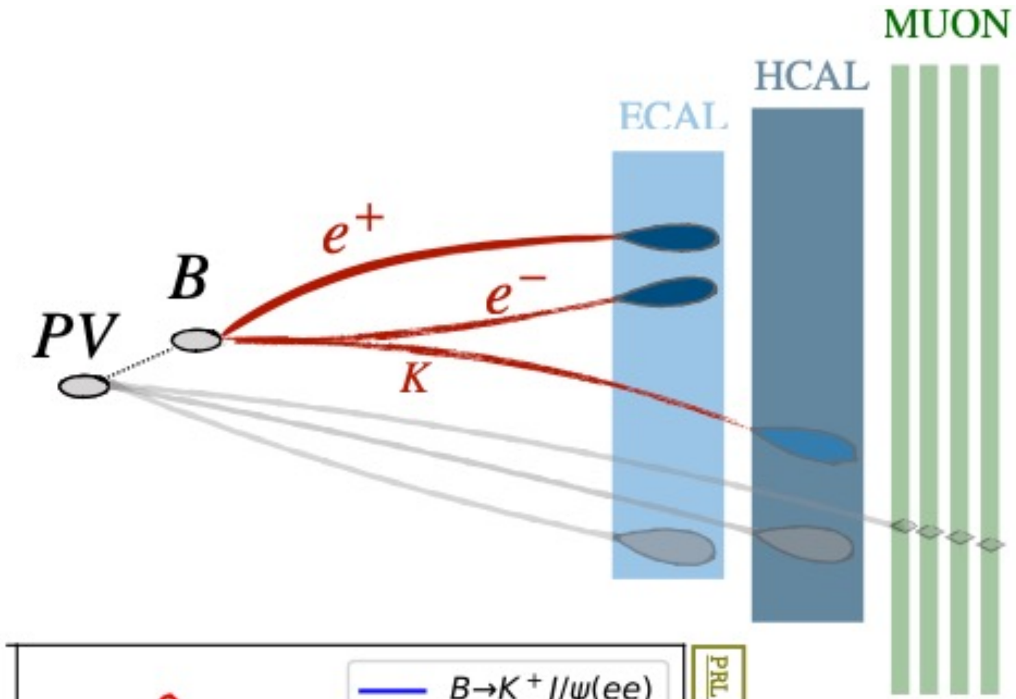
$E_T^{L0h} \geq \sim 3.4\,\mathrm{GeV}$

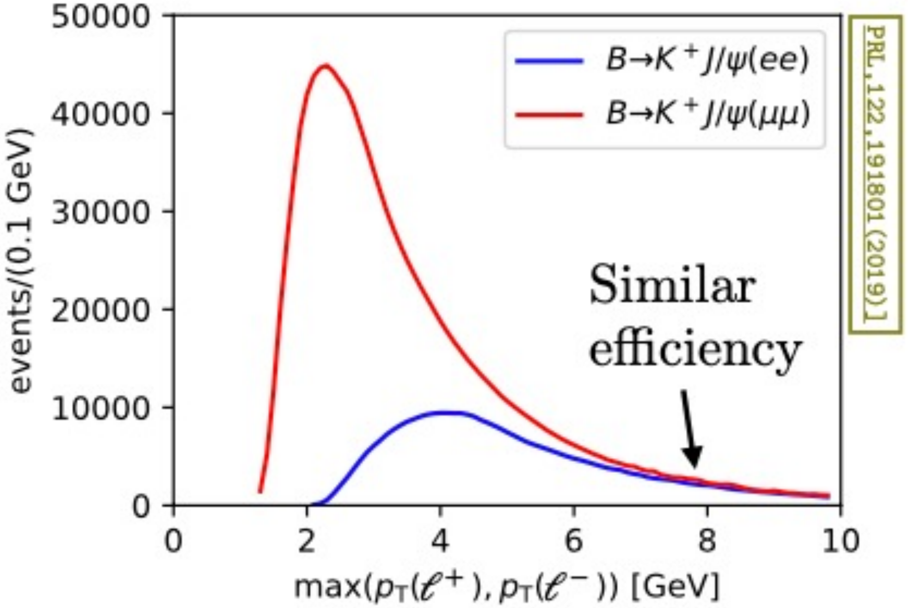
$p_T^{L0\mu} \geq \sim 1.4\,\mathrm{GeV}$

Selection effect

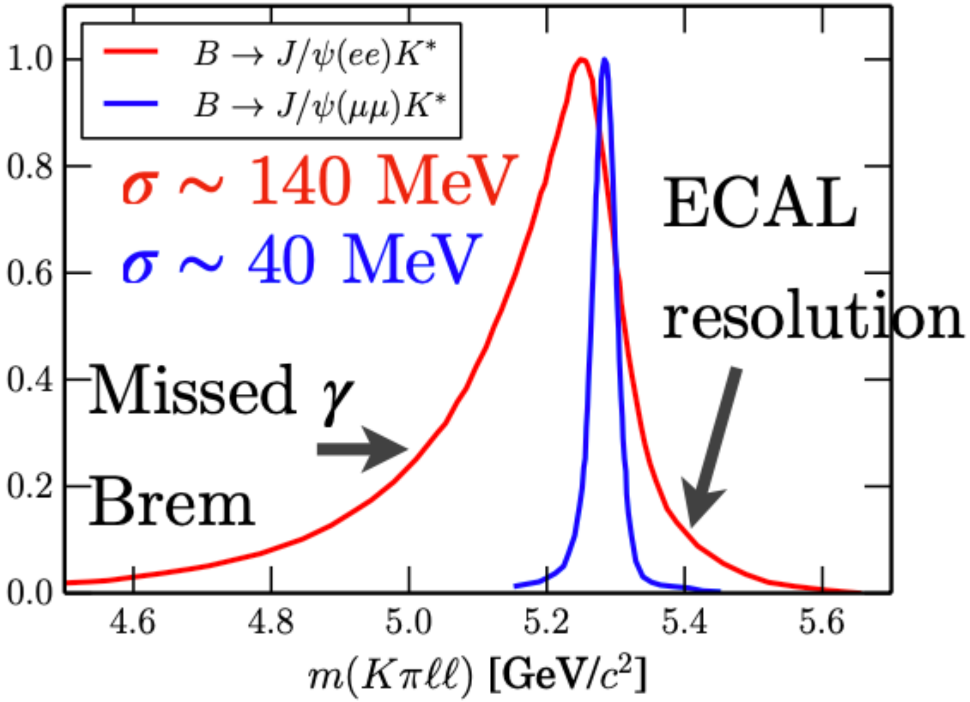
from L0e vs L0μ

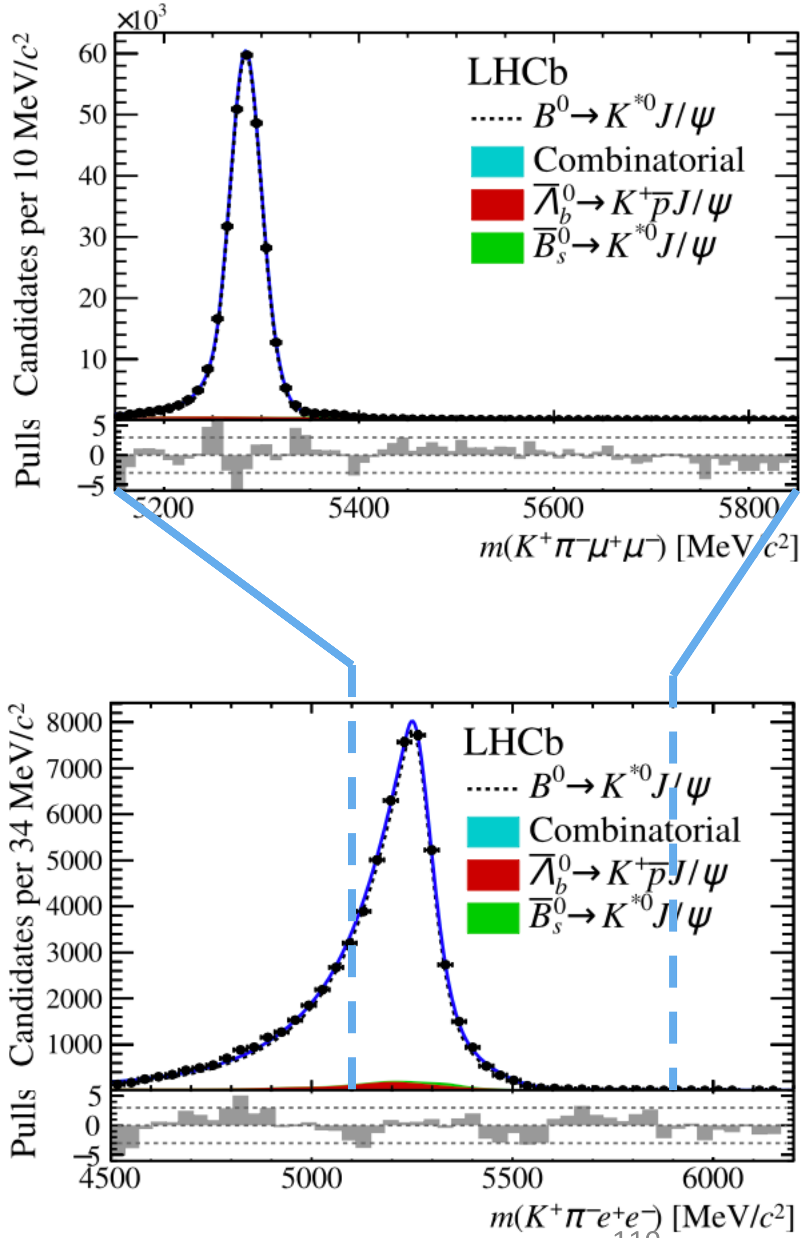
$\sim \frac{1}{3}$





Slide borrowed from Renato Quagliani


$B \to J/\psi(ee)K^*$
$B \to J/\psi(\mu\mu)K^*$
σ ~ 140 MeV
σ ~ 40 MeV
ECAL
resolution
Missed γ
Brem
1.0
0.8
0.6
0.4
0.2
0.0
4.6
4.8
5.0
5.2
5.4
5.6
$m(K\pi\ell\ell)$ [GeV/c^2]

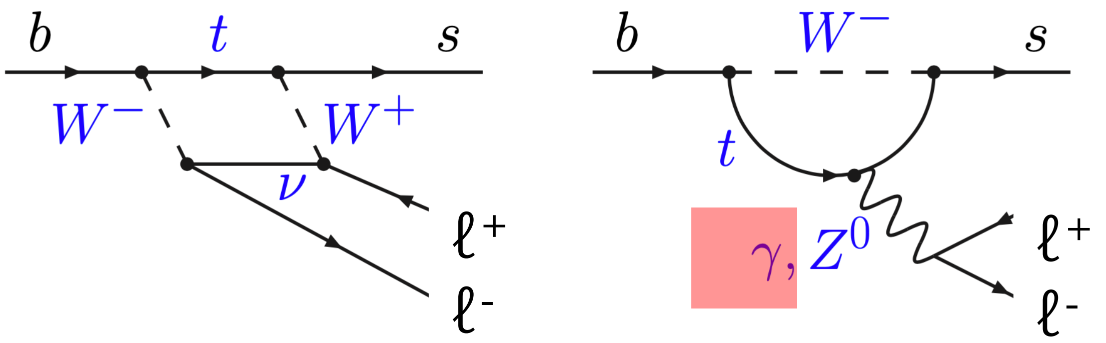

$\times 10^3$
LHCb
$B^0 \to K^{*0} J/\psi$
Combinatorial
$\overline{\Lambda}_b^0 \to K^+ \overline{p} J/\psi$
$\overline{B}_s^0 \to K^{*0} J/\psi$
Candidates per 10 MeV/c^2
Pulls
$m(K^+\pi^-\mu^+\mu^-)$ [MeV/c^2]
LHCb
$B^0 \to K^{*0} J/\psi$
Combinatorial
$\overline{\Lambda}_b^0 \to K^+ \overline{p} J/\psi$
$\overline{B}_s^0 \to K^{*0} J/\psi$
Candidates per 34 MeV/c^2
Pulls
$m(K^+\pi^-e^+e^-)$ [MeV/c^2]

Using modes with electrons to increase the statistics is not the best idea

Use electrons for:

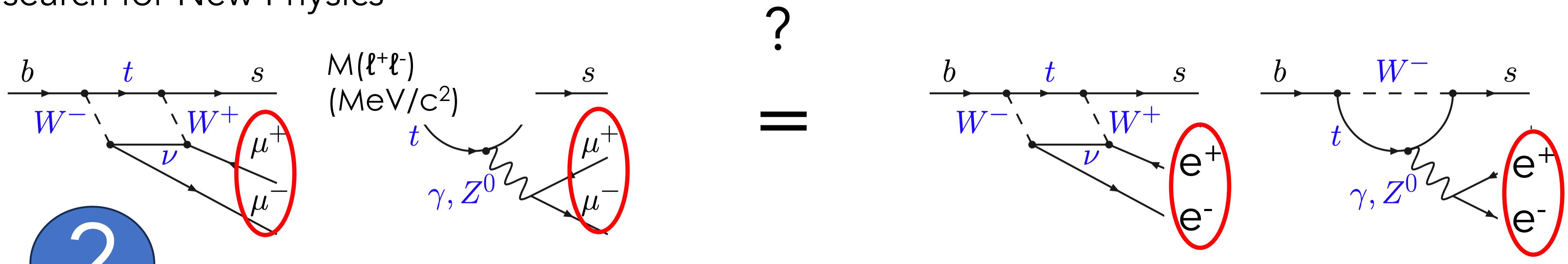
- measurements which **cannot** be done with muons or where the SM contribution is so tiny that any sign of a channel is NP

1



- search for New Physics

2



Why don't you look at $B_s \to ee$?

SM prediction

more helicity suppression !

$$\mathcal{B}(B^0_s \to e^+e^-) = (8.60 \pm 0.36) \times 10^{-14}$$

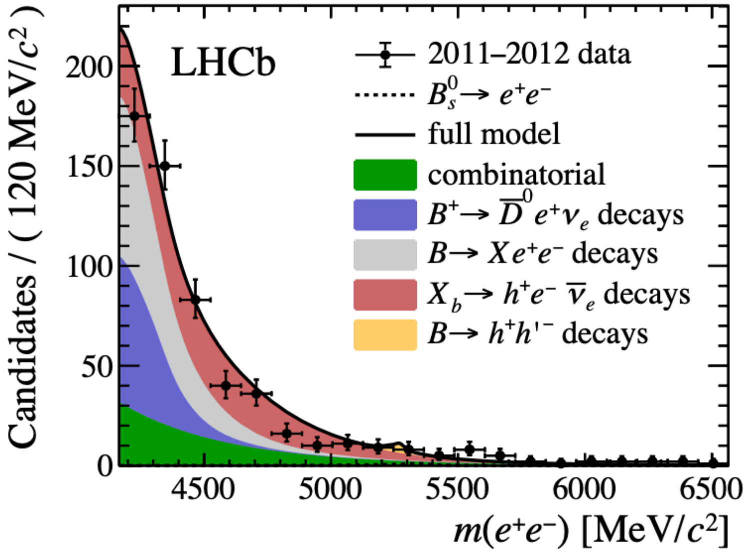
$$\mathcal{B}(B^0 \to e^+e^-) = (2.41 \pm 0.13) \times 10^{-15}$$

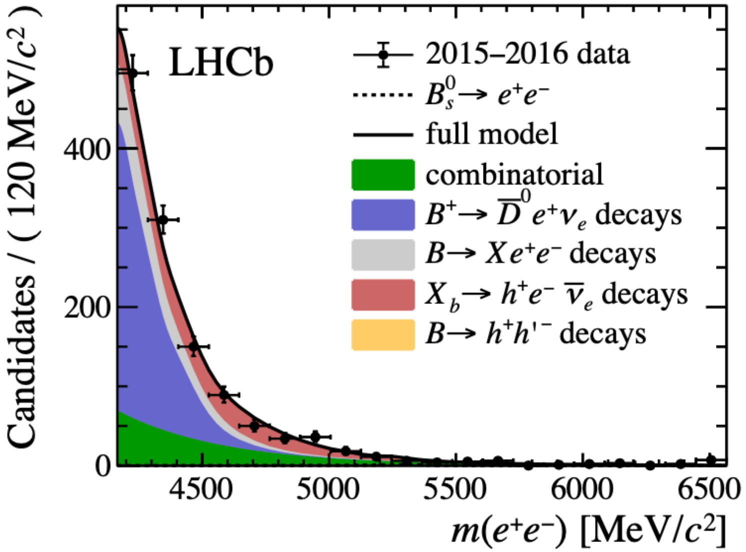
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

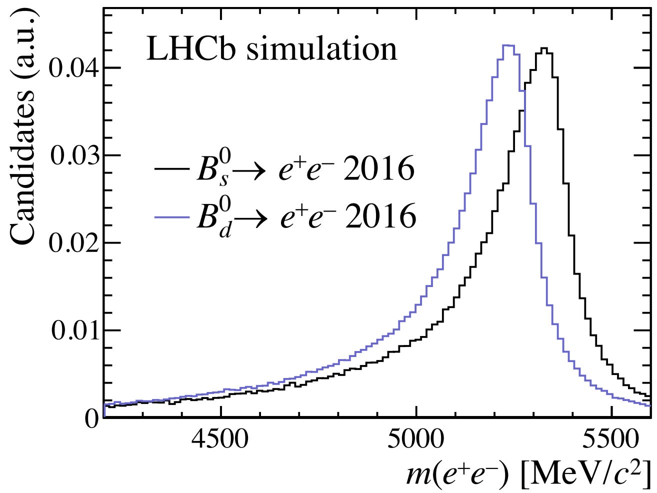
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

(5 fb^{-1}) LHCb-PAPER-2020-001

Not enough mass resolution to separate B_d from B_s



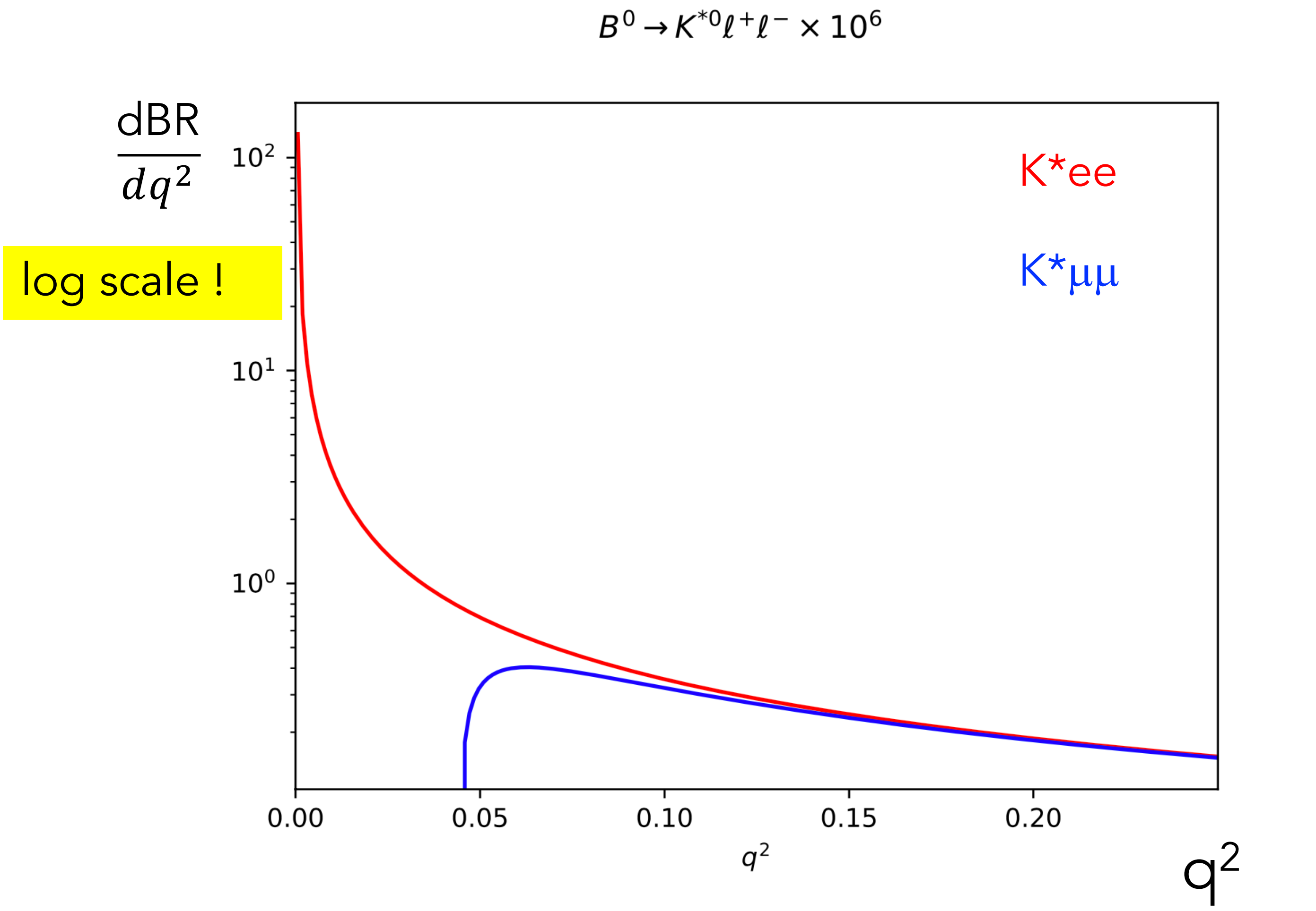


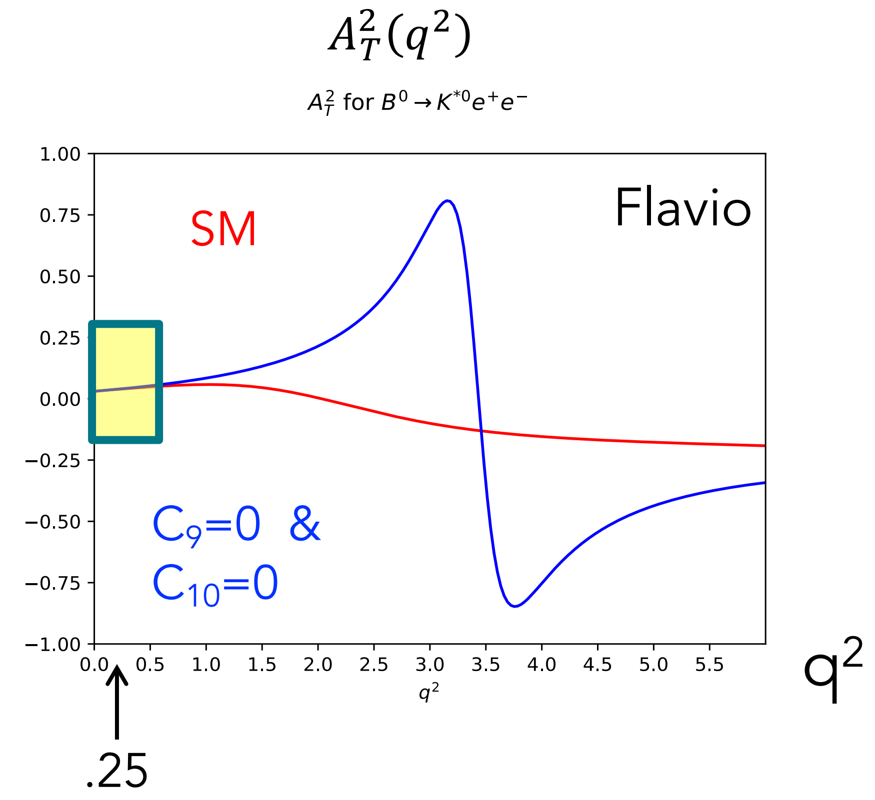


$$\mathcal{B}(B^0_s \to e^+e^-) < 9.4\,(11.2) \times 10^{-9} \text{ at } 90\,(95)\,\% \text{ confidence level}$$

no results from ATLAS or CMS

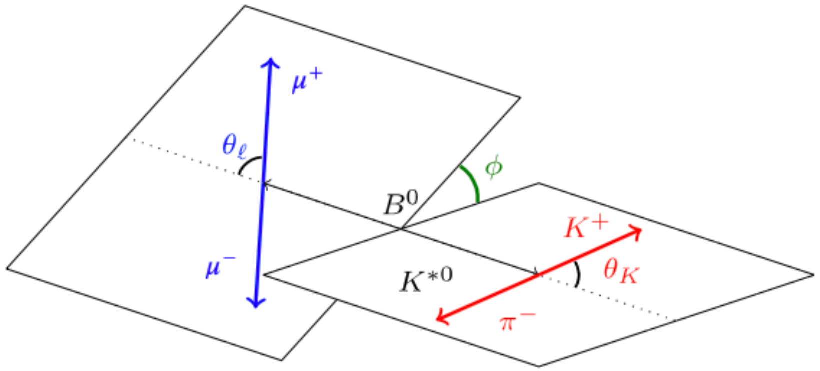
Want to know about the photon polarization in $b \to s\gamma$?





Electrons should give us access to C_7 and C'_7 Wilson coefficients

B→V $\ell\ell$



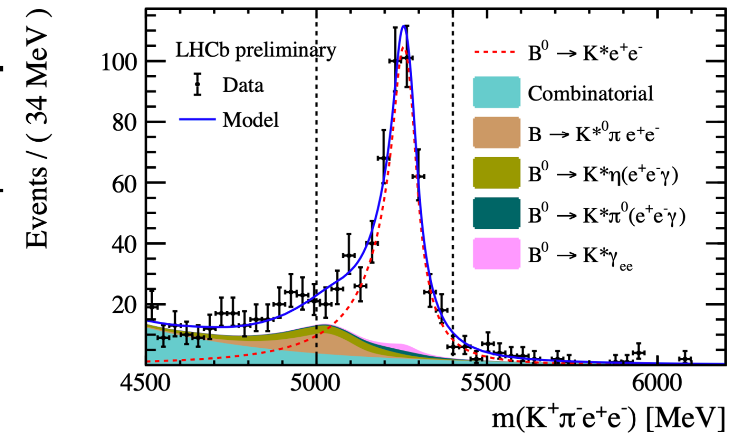
Complicated full B→K*$\mu\mu$ angular fit (8 parameters) can be reduced to the variables of interest to probe the photon pole (4 parameters)

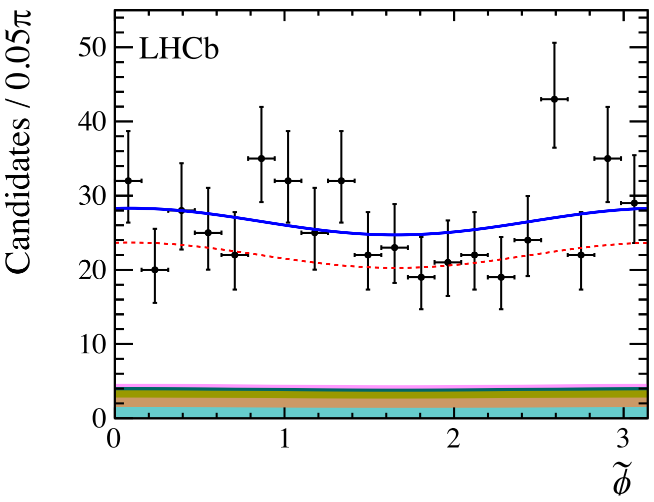
$$
\begin{aligned}
= \frac{9}{16\pi}\Big[&\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K \\
&+\tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell \\
&+(1-F_L)A_T^{Re}\sin^2\theta_K\cos\theta_\ell \\
&+\tfrac{1}{2}(1-F_L)A_T^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\tilde{\phi} \\
&+\tfrac{1}{2}(1-F_L)A_T^{Im}\sin^2\theta_K\sin^2\theta_\ell\sin 2\tilde{\phi}\Big].
\end{aligned}
$$

$$A_T^{(2)}(q^2\to 0) = \frac{2\mathcal{R}e\left(\mathcal{C}_7\mathcal{C}_7'^*\right)}{|\mathcal{C}_7|^2+|\mathcal{C}_7'|^2}$$

$$A_T^{Im}(q^2\to 0) = \frac{2\mathcal{I}m\left(\mathcal{C}_7\mathcal{C}_7'^*\right)}{|\mathcal{C}_7|^2+|\mathcal{C}_7'|^2}$$

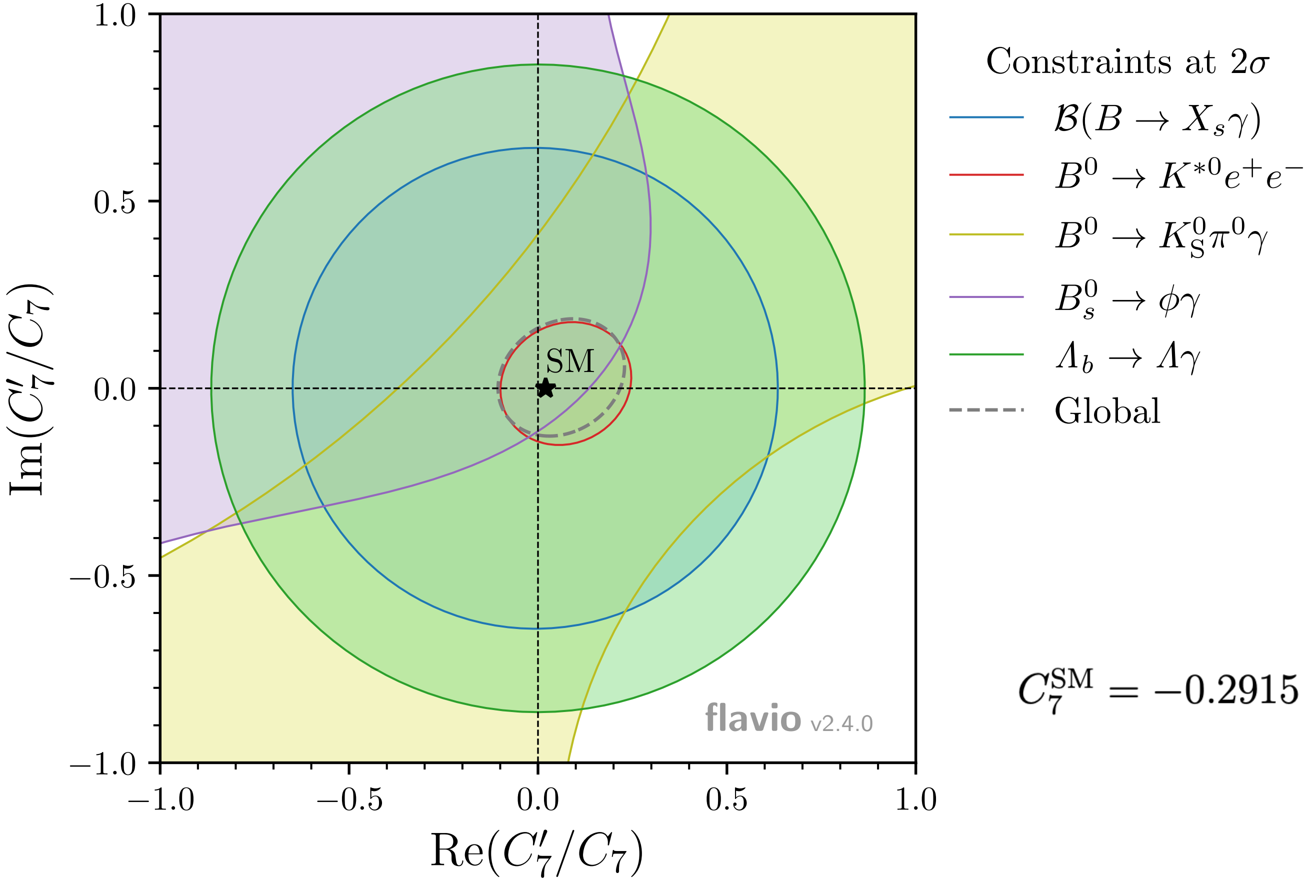
→0 for purely left-handed photon





$$F_L = 0.044 \pm 0.026 \pm 0.014,$$
$$A_T^{Re} = -0.06 \pm 0.08 \pm 0.02,$$
$$A_T^{(2)} = +0.11 \pm 0.10 \pm 0.02,$$
$$A_T^{Im} = +0.02 \pm 0.10 \pm 0.01,$$

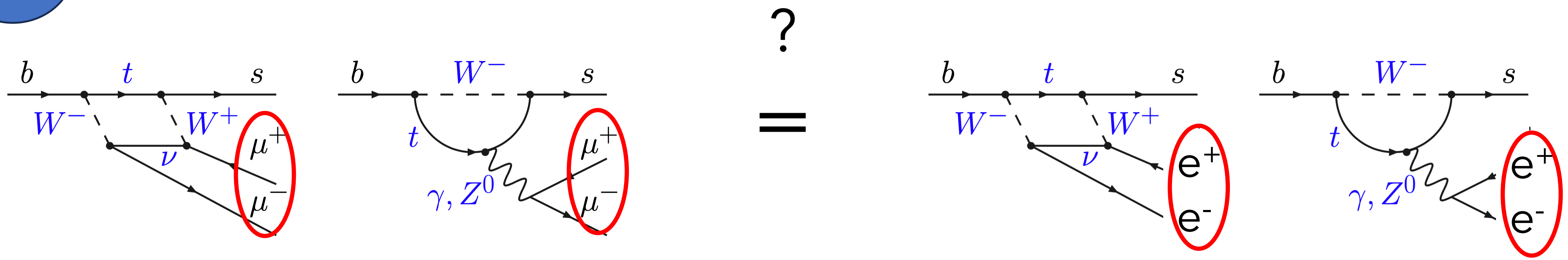
$$A_T^{(2)}(SM) = 0.033 \pm 0.020,$$
$$A_T^{Im}(SM) = -0.00012 \pm 0.00034.$$



5% precision on the photon polarization in b→sγ transitions

Lepton Flavour Universality tests in b→sℓℓ transitions

ℓ=e, μ



In the SM only difference : kinematics (lepton masses)

Any ratio of observables in principle

Start with the simplest (?) one: ratio of branching fractions

$B^{+,0}$, B_S, Λ_b → K, K^*, ϕ, pK …

$$R_{H_s} = \frac{\int \frac{d\Gamma(B \to H_s \mu^+ \mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B \to H_s e^+ e^-)}{dq^2} dq^2} \overset{SM}{\cong} 1$$

Practically at LHCb:

$$R_H = \frac{N(B \to H\mu^+\mu^-)}{N(B \to He^+e^-)} \times \frac{\epsilon(B \to He^+e^-)}{\epsilon(B \to H\mu^+\mu^-)}$$

+

$$r_{J/\psi} = \frac{BR(B \to HJ/\psi(\mu^+\mu^-))}{BR(B \to HJ/\psi(e^+e^-))} = 1$$

Yields from mass fits

Efficiencies from MC & data calibration samples

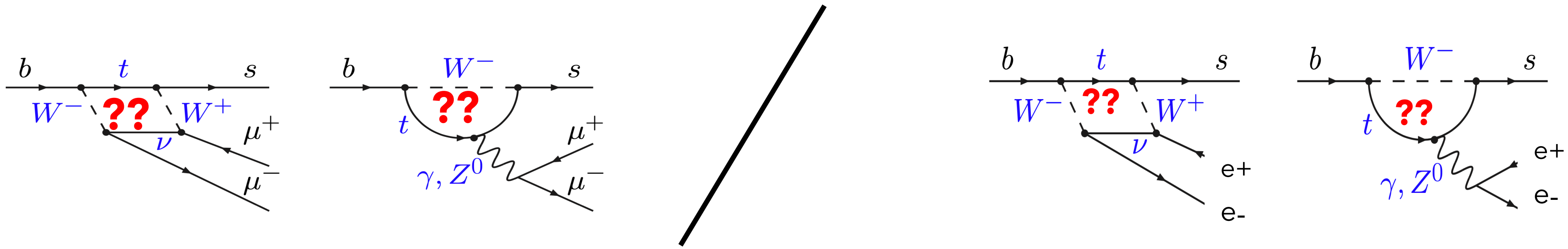
well tested LFU in J/ψ modes

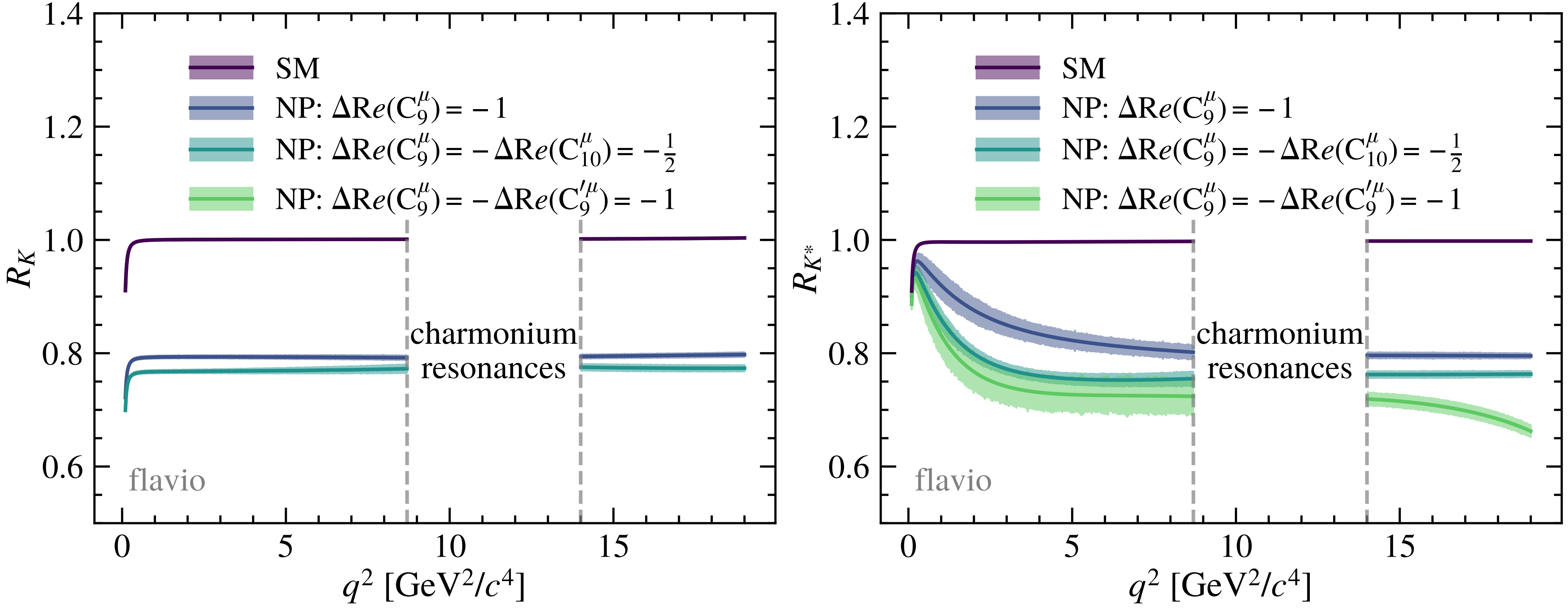
H = K, K*, pK …

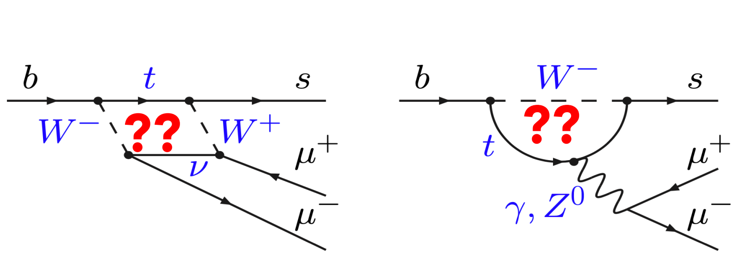
⇒ Use of the double ratio using the resonant channels

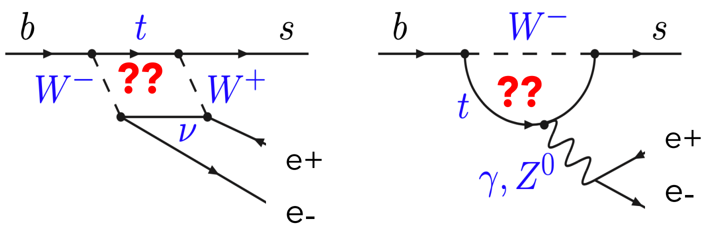
$$R_H = \frac{\dfrac{N(B \to H\mu^+\mu^-)}{N(B \to HJ/\psi(\mu^+\mu^-))}}{\dfrac{N(B \to He^+e^-)}{N(B \to HJ/\psi(e^+e^-))}} \times \frac{\dfrac{\epsilon(B \to He^+e^-)}{\epsilon(B \to HJ/\psi(e^+e^-))}}{\dfrac{\epsilon(B \to H\mu^+\mu^-)}{\epsilon(B \to HJ/\psi(\mu^+\mu^-))}}$$

⇒ cancels out most of the systematics due to e/μ differences


b
t
s
W−
W+
??
ν
μ+
μ−
b
W−
s
t
??
γ, Z0
μ+
μ−
b
t
s
W−
W+
??
ν
e+
e-
b
W−
s
t
??
γ, Z0
e+
e-

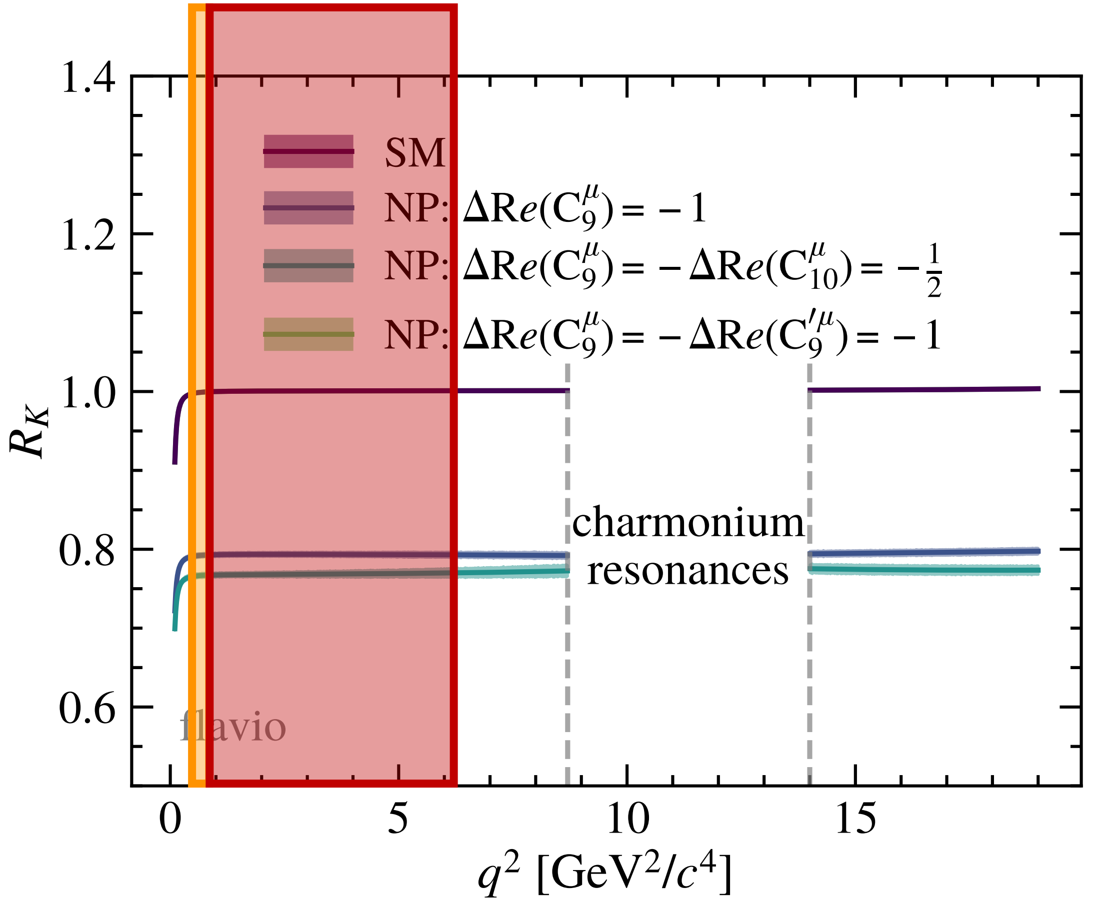

SM
NP: ΔRe(C9μ) = −1
NP: ΔRe(C9μ) = −ΔRe(C10μ) = −1/2
NP: ΔRe(C9μ) = −ΔRe(C′9μ) = −1
R_K
R_K*
charmonium resonances
flavio
q² [GeV²/c⁴]
0
5
10
15
0.6
0.8
1.0
1.2
1.4

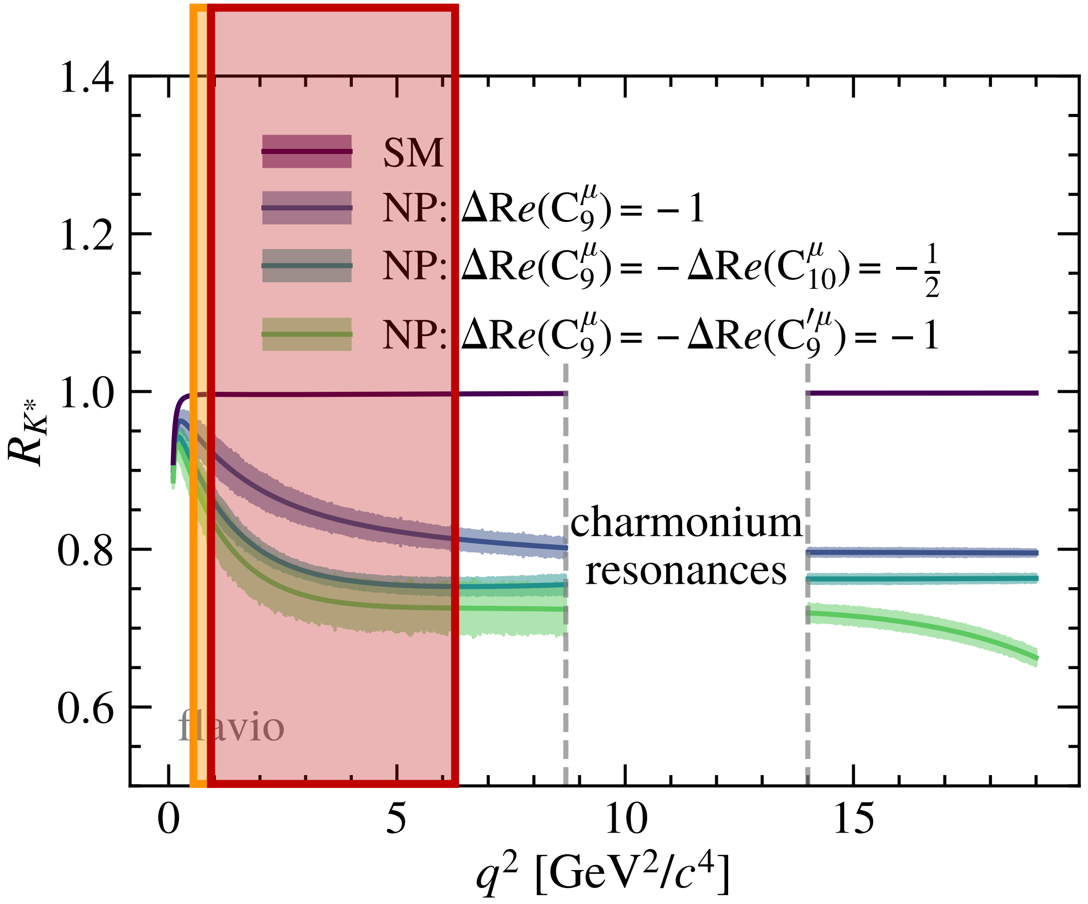




low-q^2

central-q^2





⇒ the LHCb R_X analysis

Simultaneous fit of

- $B \to K \ell\ell$ and $B \to K^* \ell\ell$
- in 2 kinematical regions (low and central-q^2)

Full correction of the MC samples using data control samples

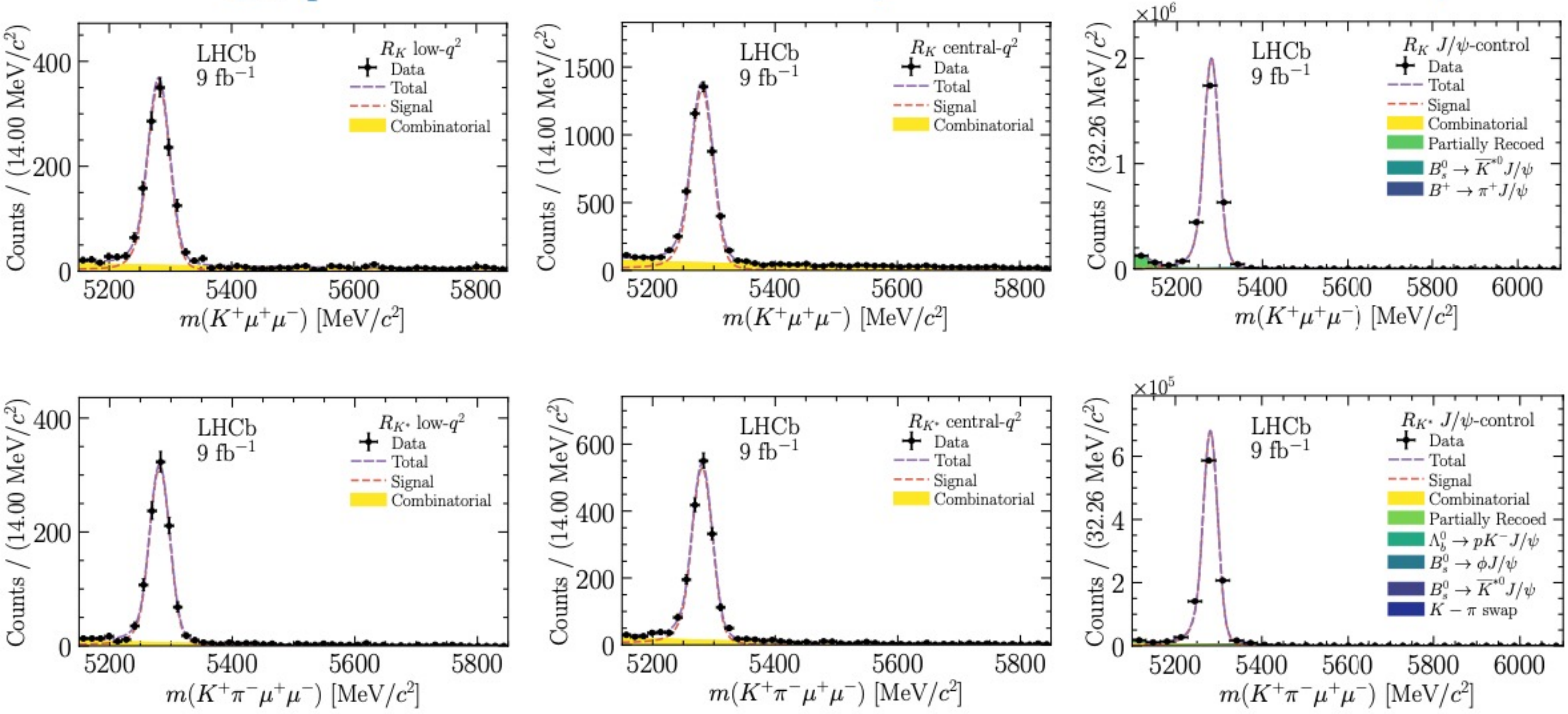
Extraction of the misId background in the ee- samples from the same data

Simultaneous fit for R_X extraction: muon modes

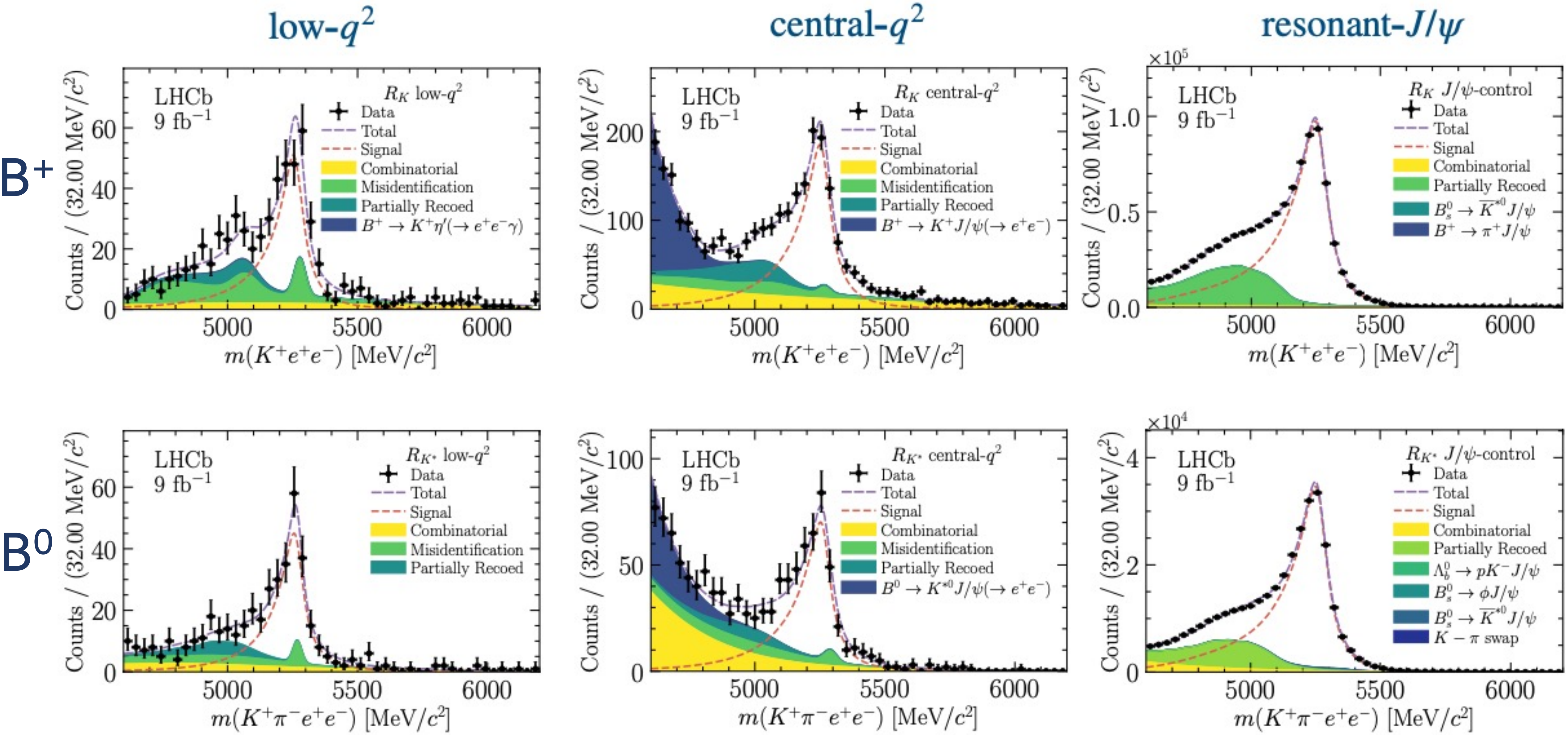
low-q^2 | central-q^2 | resonant-J/ψ

B⁺

B⁰



Simultaneous fit for R_X extraction: electron modes



A factor ~ 4 in yields between electron and muon modes

Measured yields from simultaneous fit to R_X

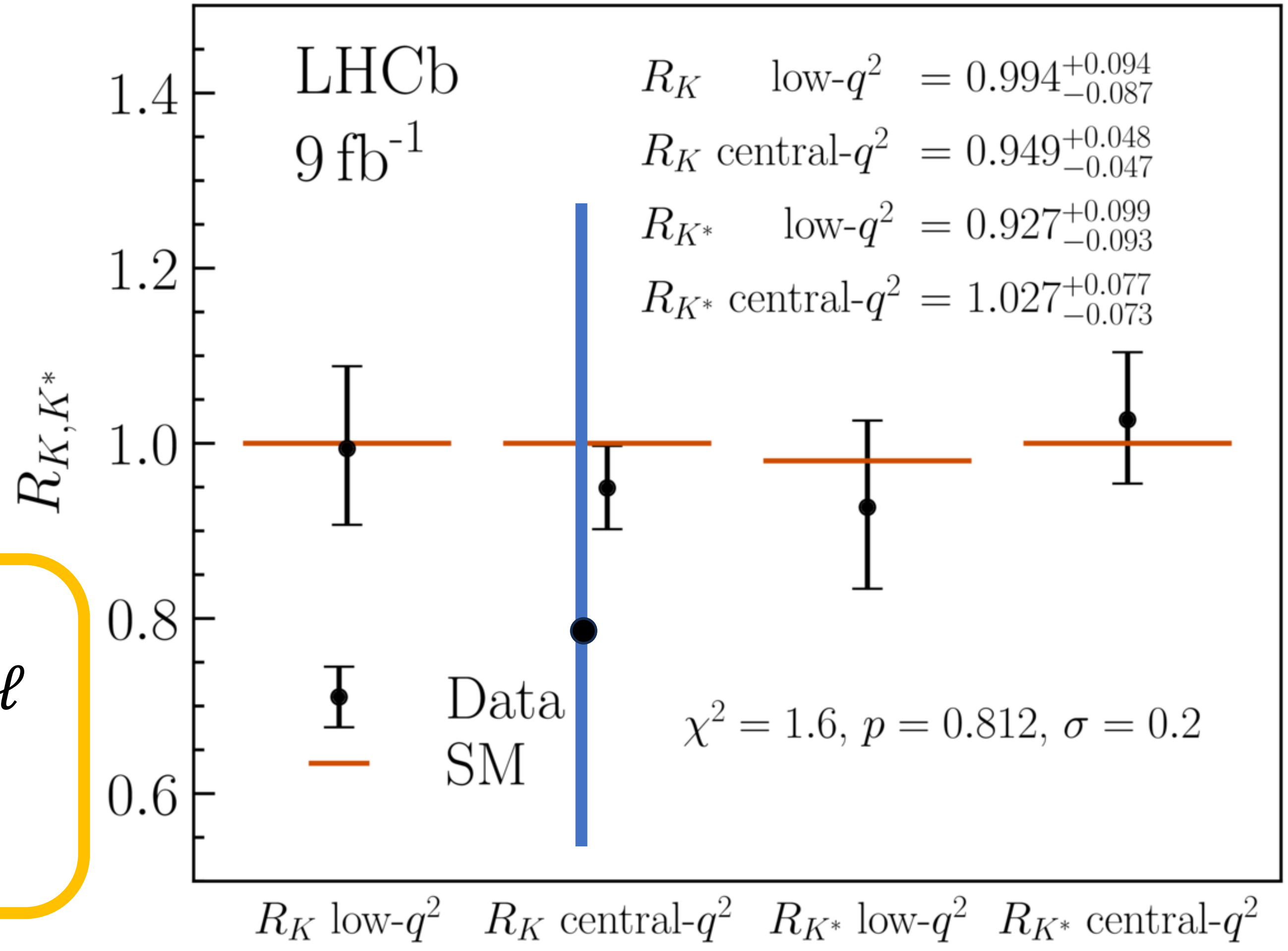
LU observable	Muon ($\times 10^3$)	Electron ($\times 10^3$)
low-q^2 R_K	1.25 ± 0.04	0.305 ± 0.024
low-q^2 R_{K^*}	1.001 ± 0.034	0.247 ± 0.022
central-q^2 R_K	4.69 ± 0.08	1.19 ± 0.05
central-q^2 R_{K^*}	1.74 ± 0.05	0.443 ± 0.028
J/ψ R_K	$(2.964 \pm 0.002) \times 10^3$	$(7.189 \pm 0.015) \times 10^2$
J/ψ R_{K^*}	$(9.733 \pm 0.010) \times 10^2$	$(2.517 \pm 0.009) \times 10^2$

Results

$$\text{low-}q^2 \begin{cases} R_K = 0.994\ ^{+0.090}_{-0.082}\,(\text{stat})\ ^{+0.029}_{-0.027}\,(\text{syst}), \\ R_{K^*} = 0.927\ ^{+0.093}_{-0.087}\,(\text{stat})\ ^{+0.036}_{-0.035}\,(\text{syst}), \end{cases}$$

$$\text{central-}q^2 \begin{cases} R_K = 0.949\ ^{+0.042}_{-0.041}\,(\text{stat})\ ^{+0.022}_{-0.022}\,(\text{syst}), \\ R_{K^*} = 1.027\ ^{+0.072}_{-0.068}\,(\text{stat})\ ^{+0.027}_{-0.026}\,(\text{syst}), \end{cases}$$

CMS
arXiv:2401.07090



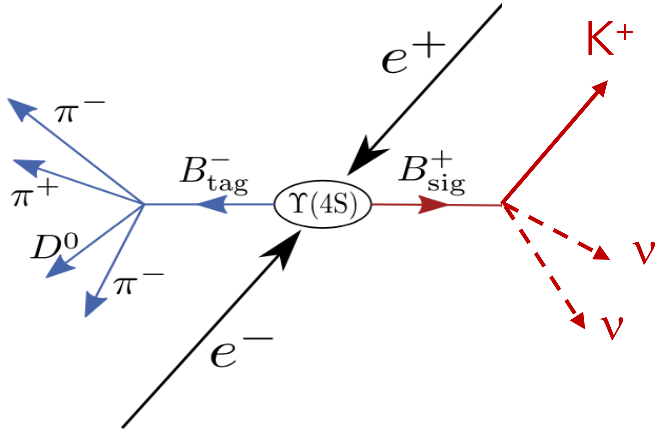
First or most precise test of LFU in $b \to s\ell\ell$

Compatible with the SM at 0.2 σ

$B \to K\nu\bar{\nu}$

B-Factories

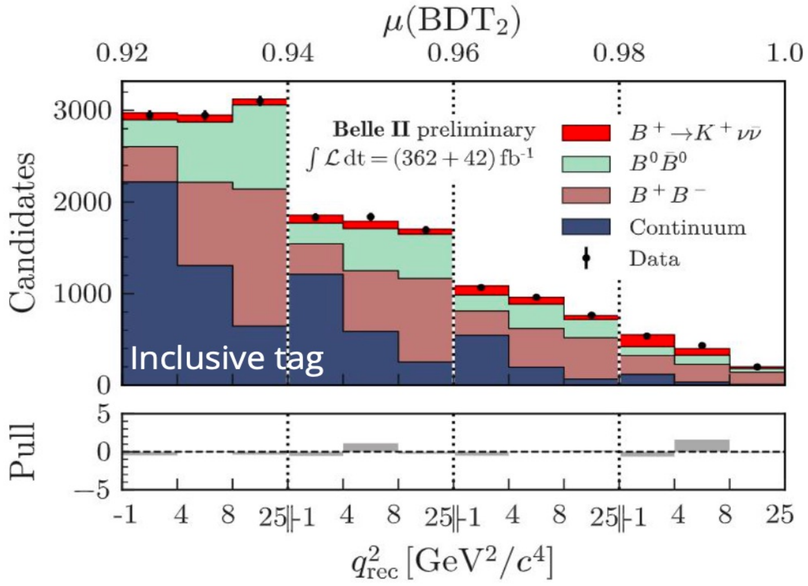
Experimentally very challenging
- Low branching fraction with large backgrounds (eg K+$K_L K_L$)
- No peak



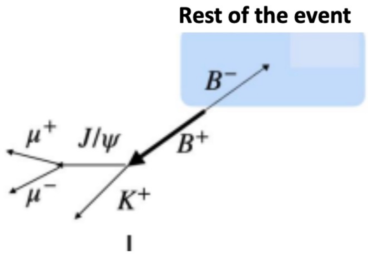
Theoretically cleaner ⇒ precise SM prediction:

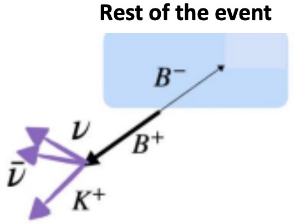
$$B(B \to K\nu\bar{\nu}) = (5.6 \pm 0.4)\ 10^{-6}$$

PRD 107, 119903 (2023)



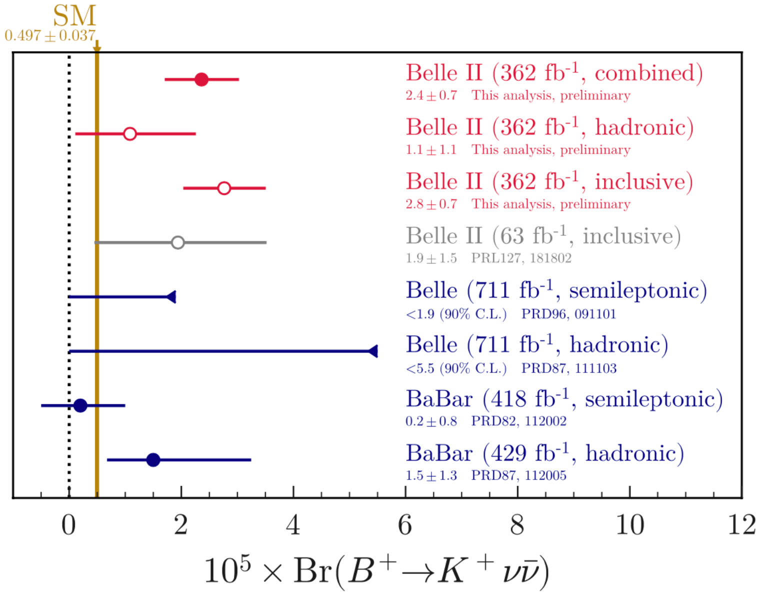
Check of the efficiency





$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = [2.4 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})] \times 10^{-5}$$

arXiv:2311.14647



Conclusion

- Mostly launched by B-factories (BaBar & Belle) even if started before (ARGUS, CLEO, LEP)
- Nowadays mostly LHCb and Belle-II : complementarity
- At the electroweak scale, the CKM mechanism dominates CP violation
- Still room for physics beyond SM at ~ 20% in FCNC
- In 1964 the discovery of the small amount of CP violation came as a surprise
- A bunch of tensions in FCNC $b \to s\ell\ell$ transitions, more data is needed to pin-point the origin.
- Heavy Flavour physics is much more that what I had time to touch upon

Precision !

new detectors / new data / more sophisticated analyses

⇒ exciting times ahead !

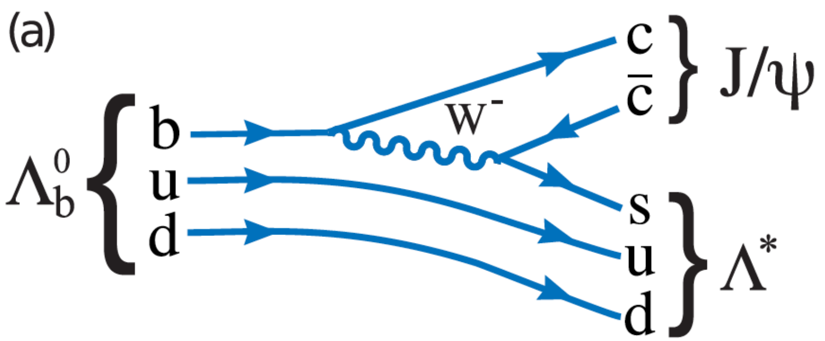
*Many thanks to J. Rouxel &
JP Couturier for the Shadoks*

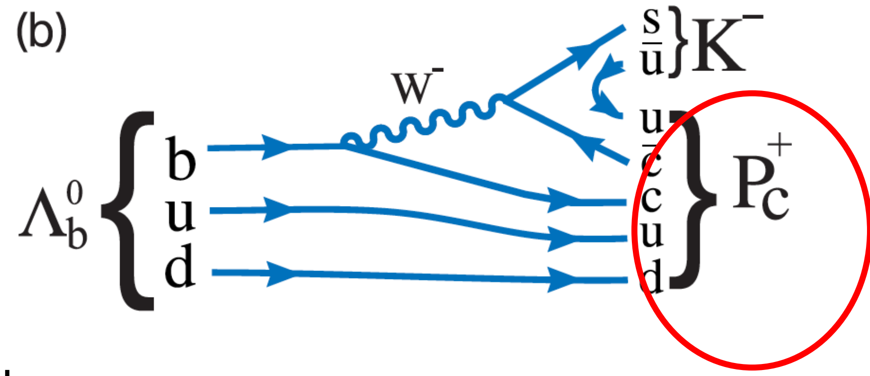
Back-up slides

Observed for the first time 4 years ago by LHCb

Pentaquark signals

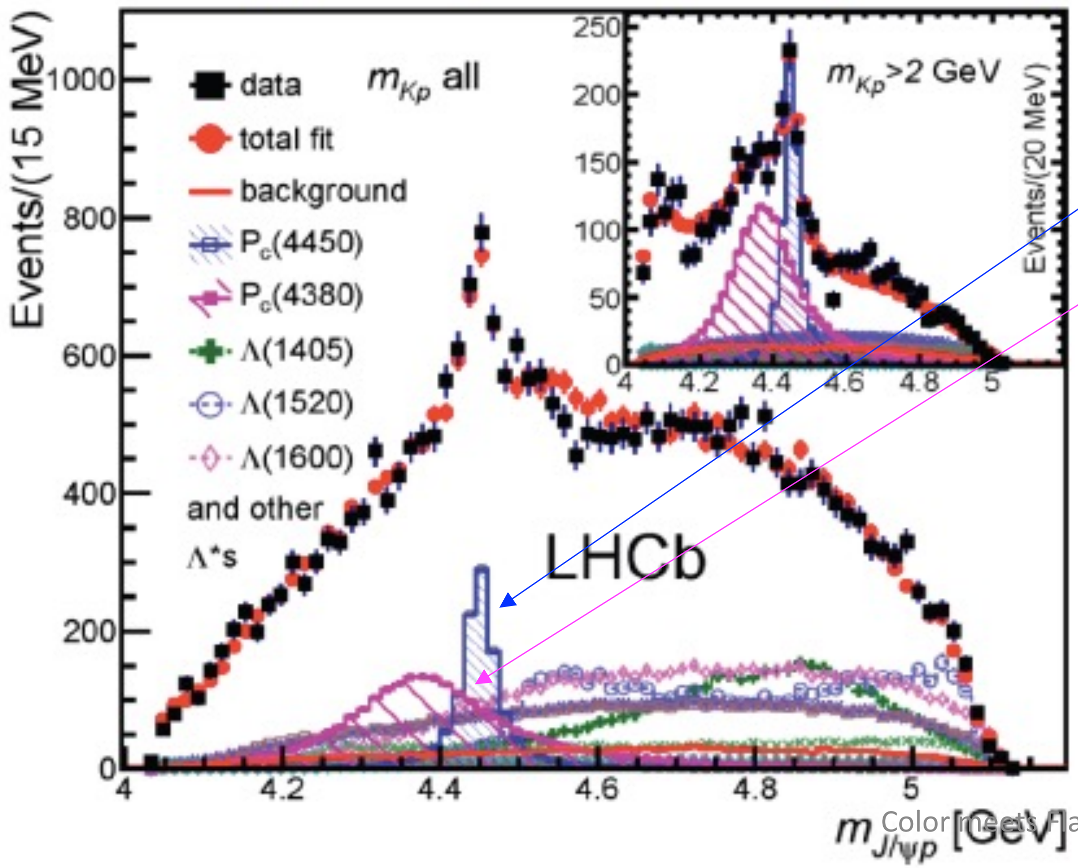
$\Lambda_b \rightarrow J/\psi pK$ decays





A pentaquark

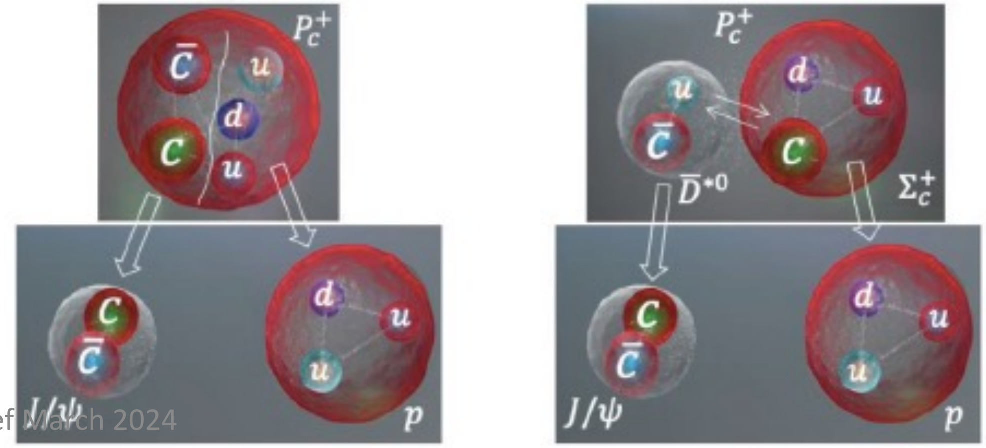
PRL 115 (2015) 072001



Two charged states:

- $P_c(4450)$ narrow
- $P_c(44380)$ broad

tightly bound or molecular ?



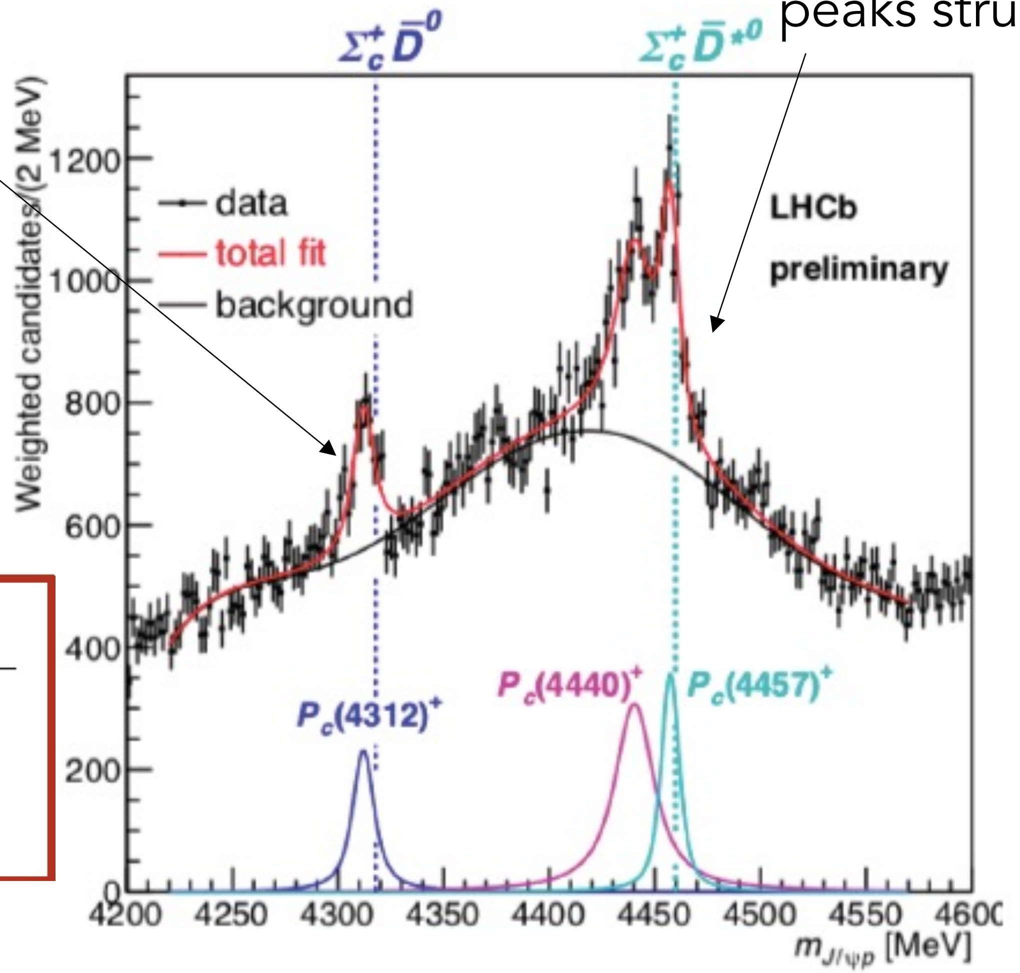
Update using Run2 full statistics ⇒x 9 statistics of the published result !
(x2 selection , x3 integrated luminosity, x cross section changes with energy)

Narrow bump hunting analysis with empirical background shape

"New" peak at 4312 MeV

$P_c(4450)$: a two peaks structure !

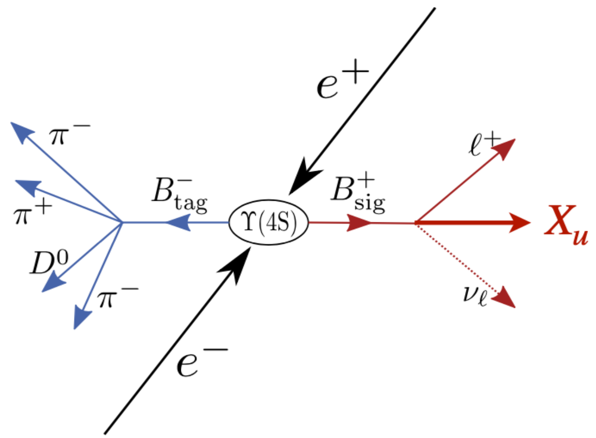
Full amplitude analysis ongoing especially needed to confirm the broad $P_c(4380)$



State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p)}{\mathcal{B}(\Lambda_b \to J/\psi p K^-)}$$

BFactories (Belle-II)



Beam energy const. + tag-side
→ kinematical constraints

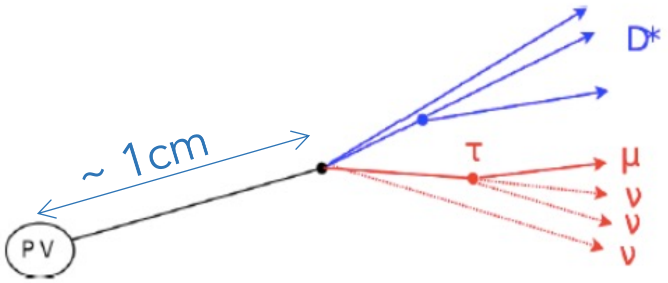
Inclusive decays

Access to absolute BR

BaBar & Belle ~ 1.1 ab^{-1}

Belle-II (ICHEP2020 schedule) :
10 ab^{-1} in 2025, 50 ab^{-1} in 2031

LHCb



Very large boost→ flight distance reconstruction
→ kinematical constraints

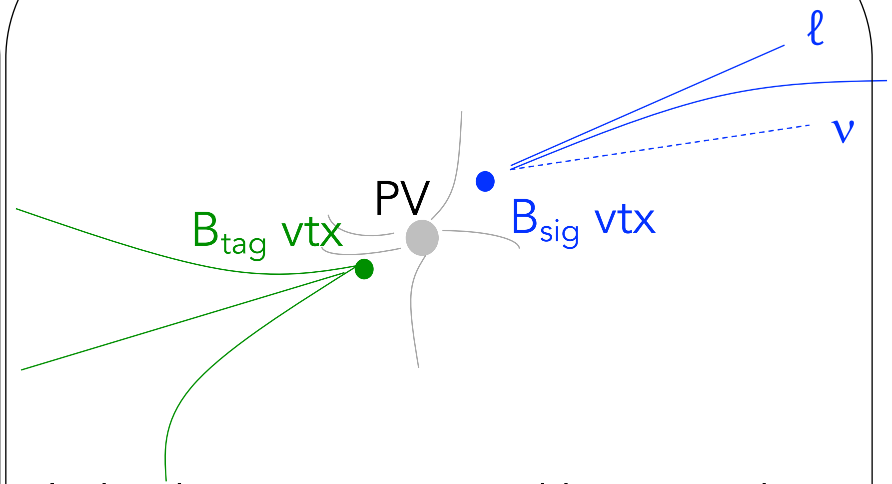
All b-hadrons species

No access to absolute BR

LHCb: $9fb^{-1}$ at hand

LHCb-Upgrade 1 (soft. trigger) :
at the end of Run3 (2024) : 23 fb^{-1}
at the end of 2020s : 50 fb^{-1}
LHCb-Upgrade 2 : 300 fb^{-1}

FCCee



Flight distance reco. and beam+other hemisphere
→ kinematical constraints

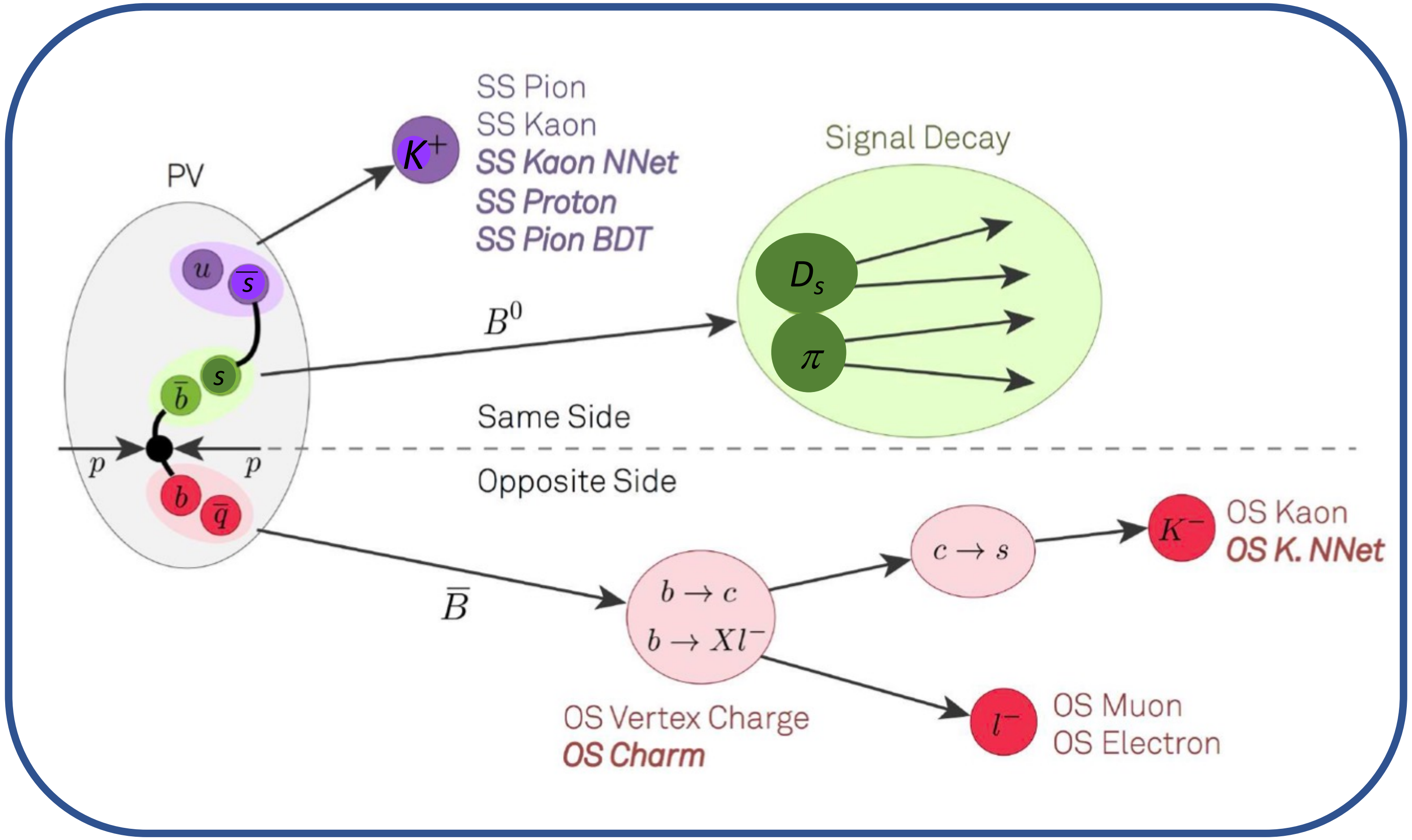
All b-hadrons species

Access to absolute BR

FCCee (from late 2030)

5 10^{12} Z^0

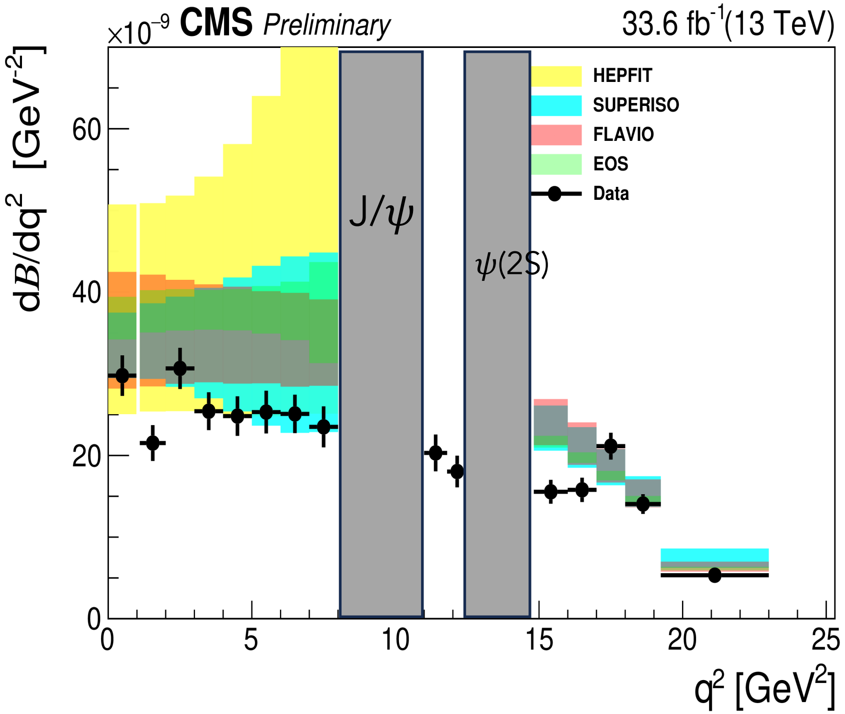
1.5 10^8 WW


SS Pion
SS Kaon
SS Kaon NNet
SS Proton
SS Pion BDT
K+
PV
u
s̄
s
b̄
Signal Decay
Ds
π
B0
Same Side
Opposite Side
p
p
b
q̄
B̄
b → c
b → Xl−
c → s
K−
OS Kaon
OS K. NNet
l−
OS Muon
OS Electron
OS Vertex Charge
OS Charm

Branching fractions for $b \to s\,\mu\mu$ transitions

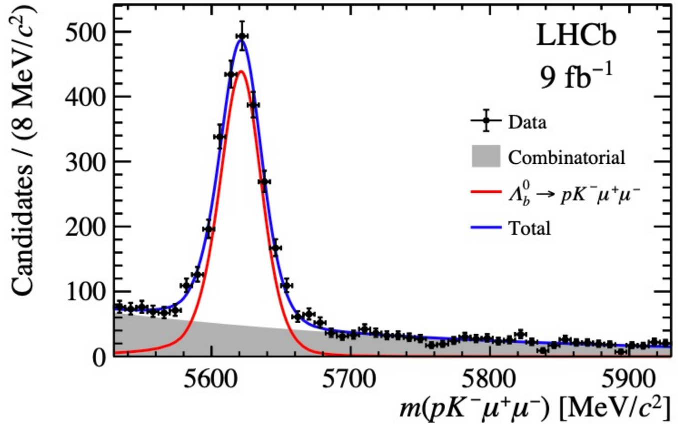
$B_d \to K^{*0}\,\mu\,\mu$

CMS-PAS-BPH-22-005

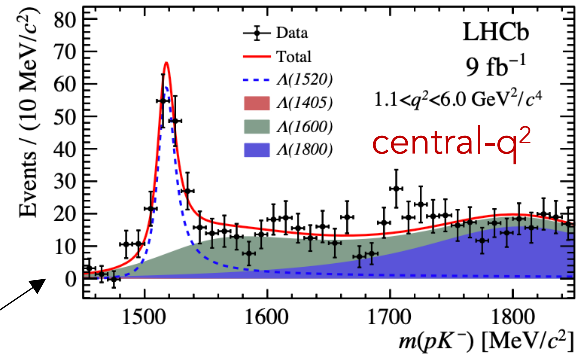


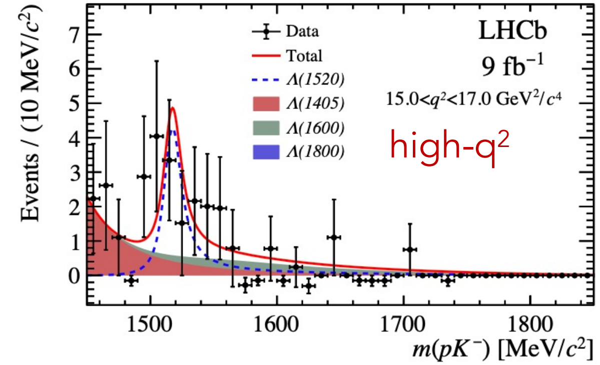
$\Lambda_b \to \Lambda(1520)\,\mu\mu$

arXiv:2302.08262

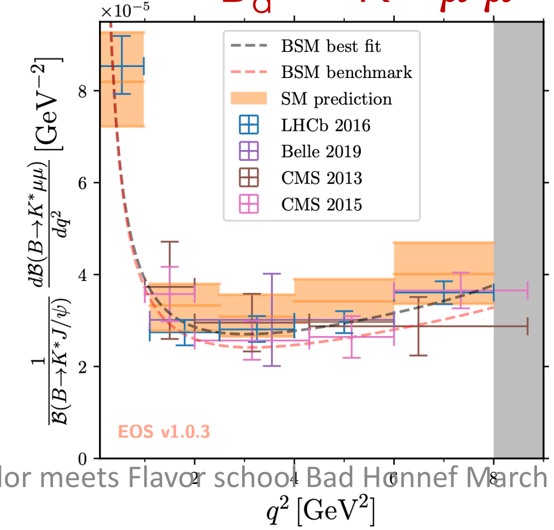


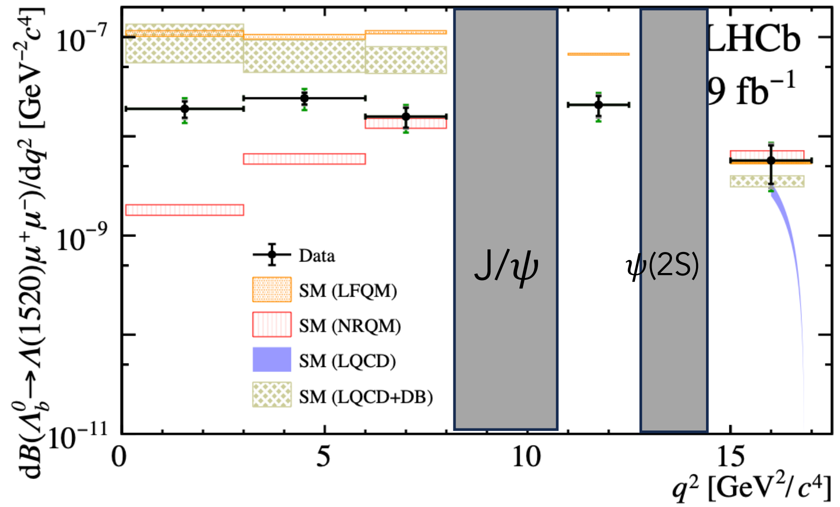
$N(\Lambda_b \to pK^-\mu^+\mu^-) = 2250 \pm 57 (stat)$





$B_d \to K^{*0}\,\mu\,\mu$



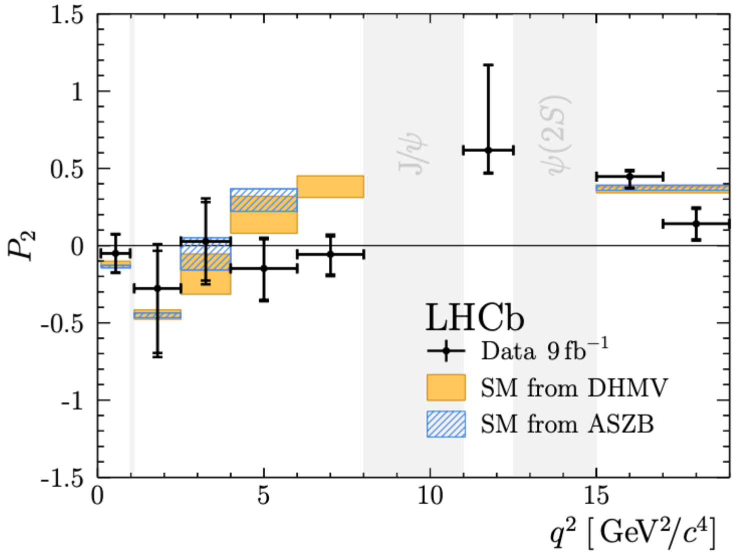


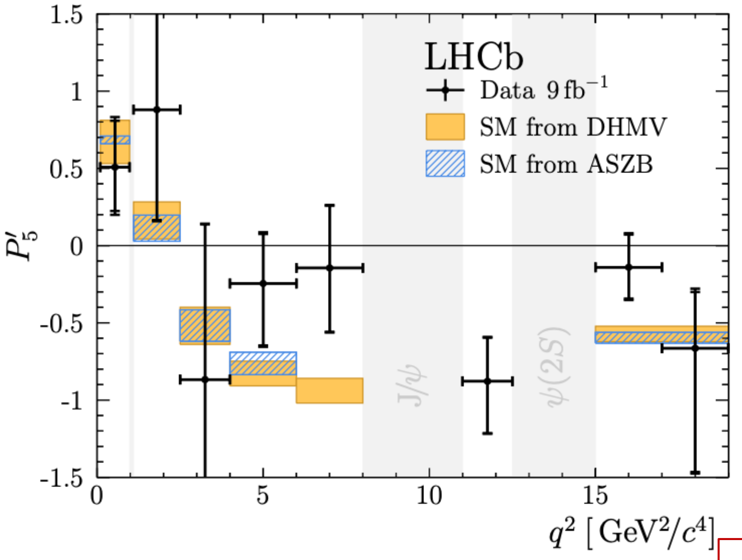
- Very clean signal peaks
- Measurements below predictions
- Predictions correlated from a bin to another
- Better agreement at higher-q^2 (LQCD)

Many parameters extracted in a large number of bins

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

[Phys. Rev. Lett.126 (2021) 161802]





Optimized variables
(less FF dependent)

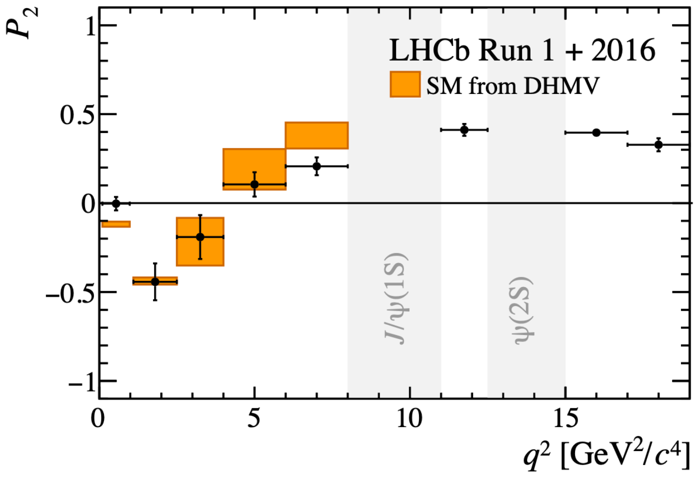
$$P_2 = \frac{2}{3} A_{\rm FB}/(1 - F_{\rm L})$$

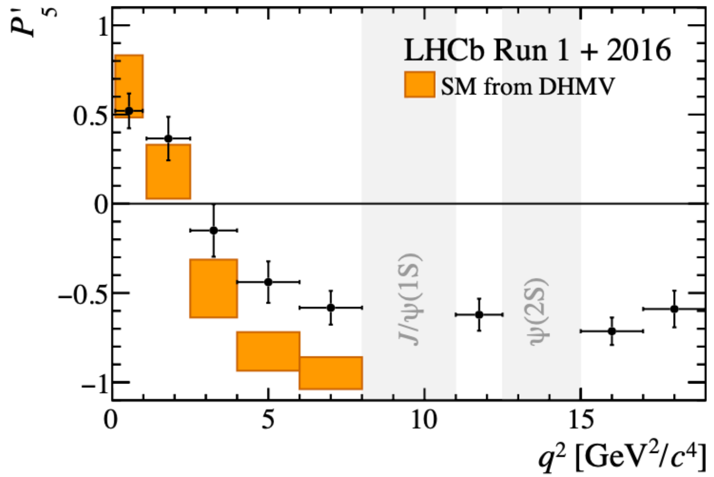
$$P_5' = S_5/\sqrt{F_{\rm L}(1 - F_{\rm L})}$$

$$P_5' = \sqrt{2}\frac{\mathrm{Re}\left(A_0^{\rm L}A_\perp^{\rm L*} - A_0^{\rm R}A_\perp^{\rm R*}\right)}{\sqrt{\left(|A_0^{\rm L}|^2 + |A_0^{\rm R}|^2\right)\left(|A_\parallel^{\rm L}|^2 + |A_\parallel^{\rm R}|^2 + |A_\perp^{\rm L}|^2 + |A_\perp^{\rm R}|^2\right)}}$$

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

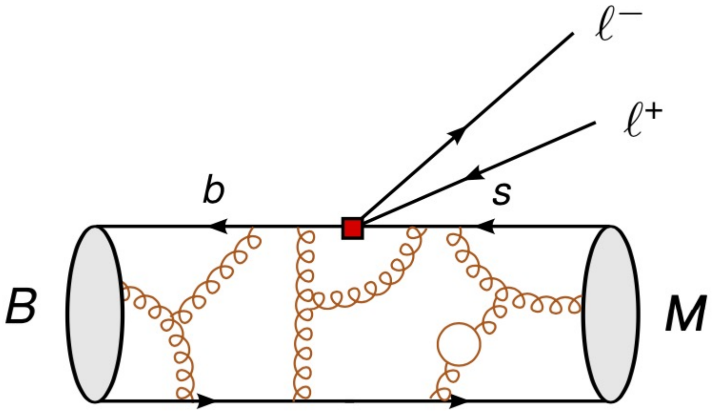
[Phys. Rev. Lett. 125 (2020) 011802]

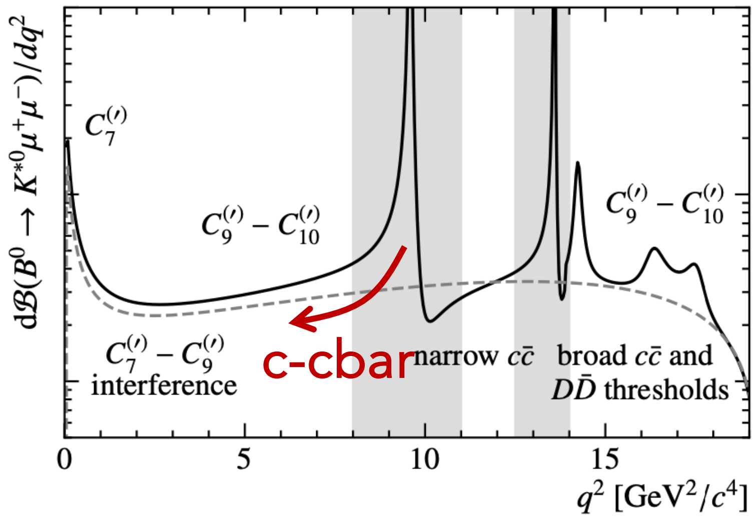




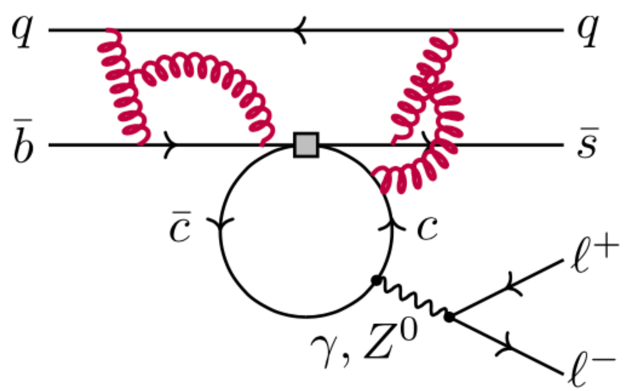
Life is not that simple …

$$\mathcal{L}_{\text{eff}} \propto G_F V_{tb} V_{ts}^* \sum_{i=7,9,10} (C_i \mathcal{O}_i + C_i' \mathcal{O}_i')$$



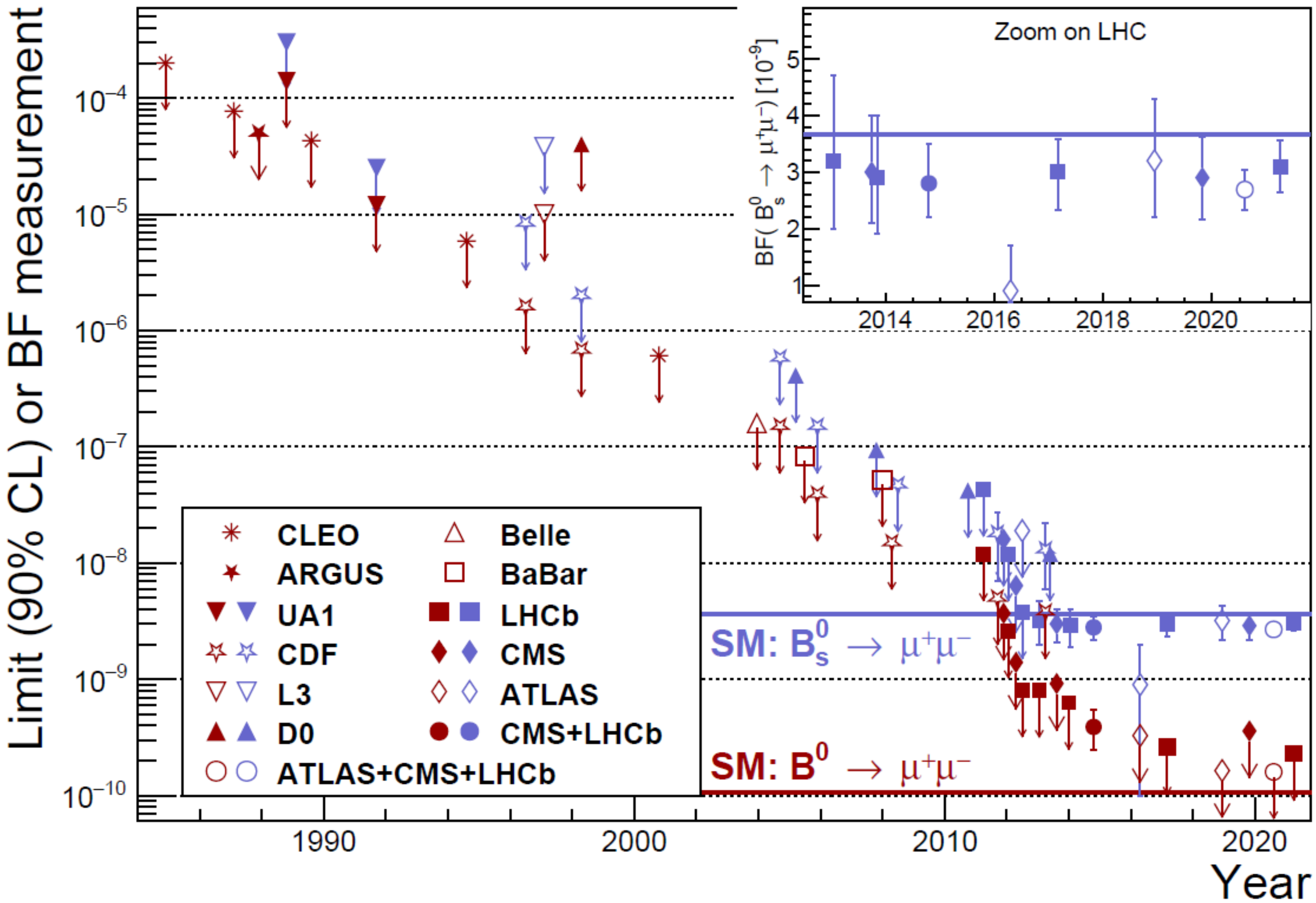


non-local contributions



Would appear as a shift in C_9
Varying as function of q^2 (not the case for NP)

Searched for during ~ 30 years. First evidence in Nov 2012 (LHCb)



From a yield to a BR

Number of observed decay

Efficiency

$$BR(B_s \to \mu\mu) = \frac{N(B_s \to \mu\mu)_{real}}{N(B_s)_{produced}} = \frac{N(B_s \to \mu\mu)_{obs} / \varepsilon}{L_{\text{int}} \times \sigma_{bb} \times f_s}$$

Integrated luminosity

bb cross section

Fraction of b quarks that hadronize into a B_s

$L_{\text{int}}, \sigma_{bb}, \varepsilon$ have large systematic errors

Normalize with respect to another decay with a very well known BR (BFactories crucial inputs) :

$B^+ \to J/\psi K^+$ or $B^0 \to K^+\pi^-$

$$\frac{BR(B_s \to \mu\mu)}{BR(B^+ \to J\Psi K^+)} = \frac{N(B_s \to \mu\mu)_{obs}}{N(B \to J\Psi K)_{obs}} \times \frac{\varepsilon_{B\to J\Psi K}}{\varepsilon_{B_s \to \mu\mu}} \times \frac{f_u}{f_s}$$

Most of systematic uncertainties cancel in the ratio of efficiency

This cancellation is very efficient if you have a normalization channel similar to your signal and selected in the same way!

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

$$\frac{d^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega})$$

$$\frac{d^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega})$$

$$\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$$

I_i (i=1,9) are encoding the matrix elements of the decay

$$\begin{aligned}\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[& I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K \\ & + I_2^s \sin^2\theta_K \cos 2\theta_\ell + I_2^c \cos^2\theta_K \cos 2\theta_\ell \\ & + I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi \\ & + I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + I_6 \sin^2\theta_K \cos\theta_\ell \\ & + I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi \\ & + I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big],\end{aligned}$$

The I_i depend on the amplitudes

CP violation in the mixing

Mass eigenstates Flavour eigenstates

$$|M_L\rangle = p|M\rangle + q|\bar{M}\rangle$$

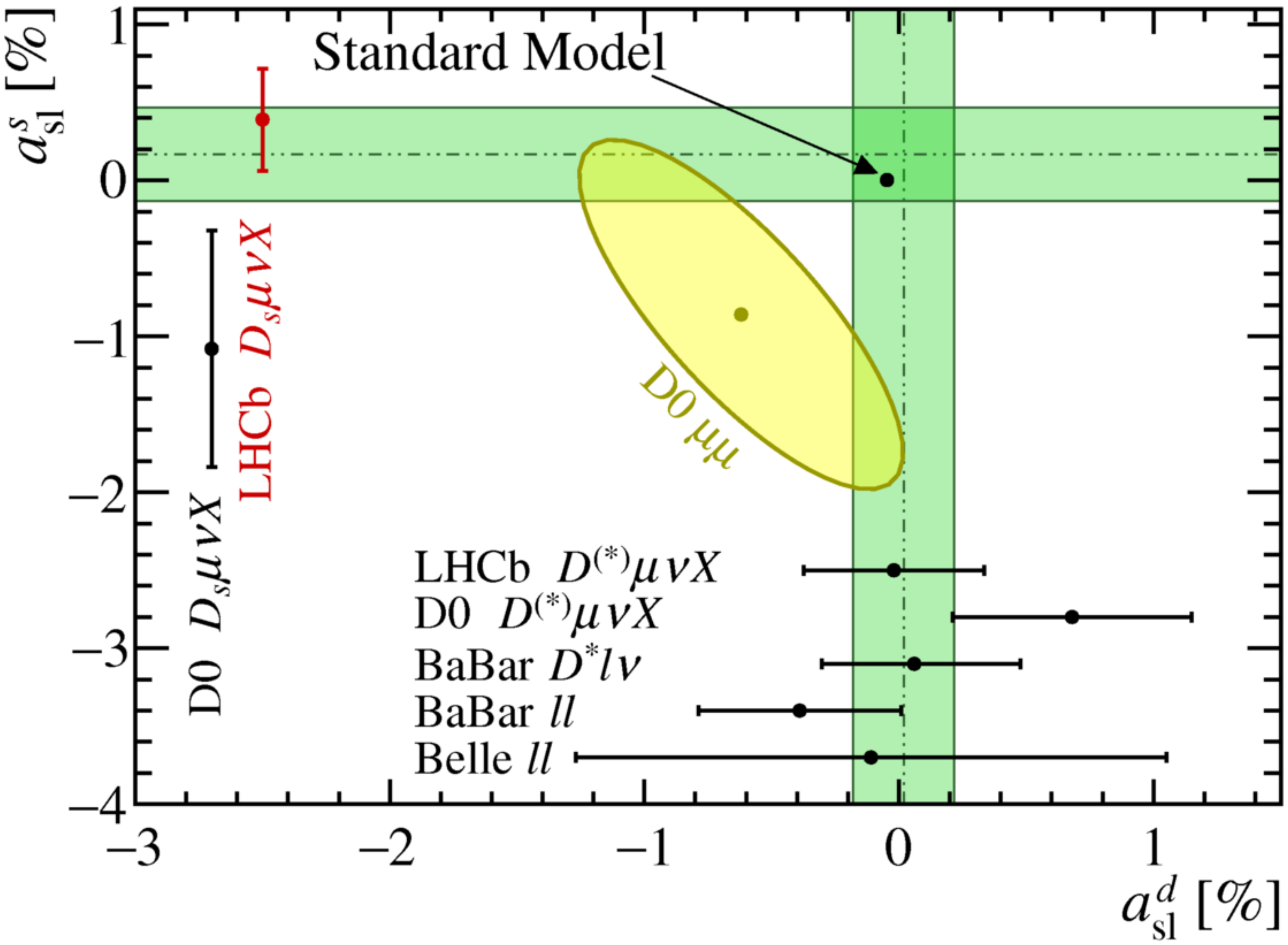
$$|M_H\rangle = p|M\rangle - q|\bar{M}\rangle$$

$$\left|\frac{q}{p}\right| \neq 1 \qquad P(B \to \bar{B}) \neq P(\bar{B} \to B)$$

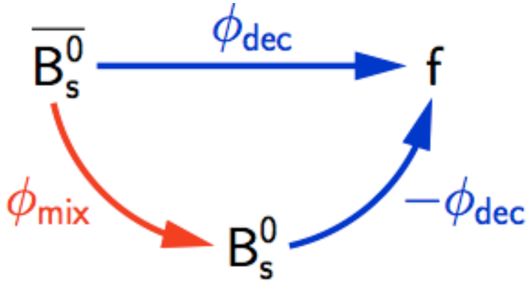
$$a_{sl}^q = \frac{P(\overline{B_q} \to B_q) - P(B_q \to \overline{B_q})}{P(\overline{B_q} \to B_q) + P(B_q \to \overline{B_q})} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \approx \frac{\Delta\Gamma_q}{\Delta m_q} \tan\phi_q^{12}$$

So far only observed in the K system
Expected to be small in the SM ; ~ -5 10^{-4} (B_d) and 2 10^{-5} (B_s)

[Phys. Rev. Lett. 117, 061803 (2016)](https://doi.org/10.1103/PhysRevLett.117.061803)



$B_s \to J/\Psi\ \phi$ analog of the previous case ($B_d \to J/\Psi\ K_s$)

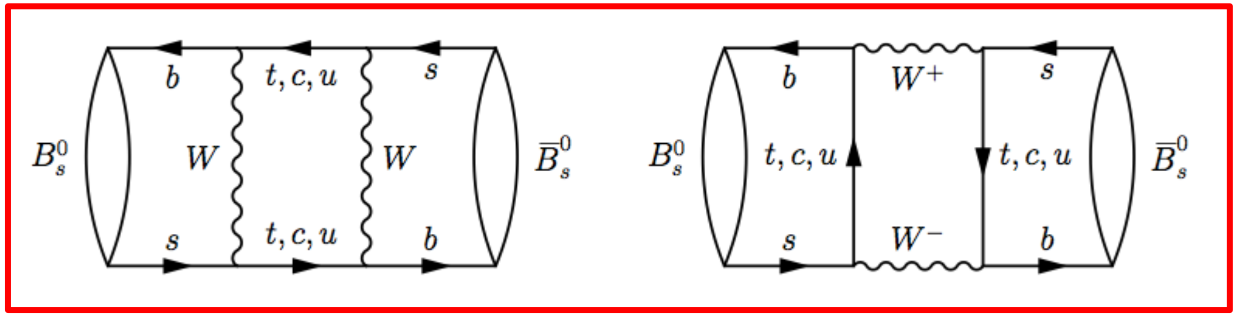


$$\phi_s = \phi_{mix} - 2\,\phi_{dec}$$

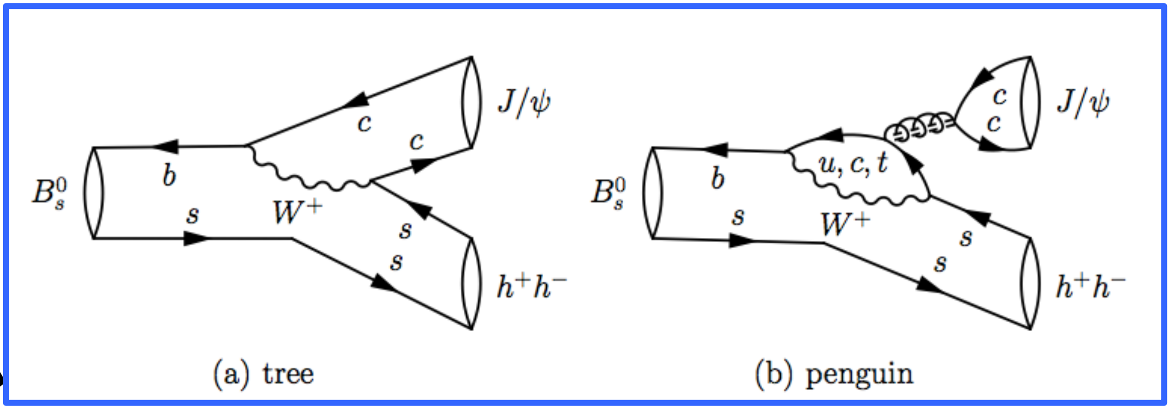
PS → VV, admixture of CP-odd and CP-even states, measure also $\Delta\Gamma_s$.

⇒ 3 "P-wave" amplitudes of KK system

- 1 "S-wave" amplitude (A_S)
- 10 terms with all the interferences
- φ_s , $\Delta\Gamma_s$, Γ_s



Mixing



Decay

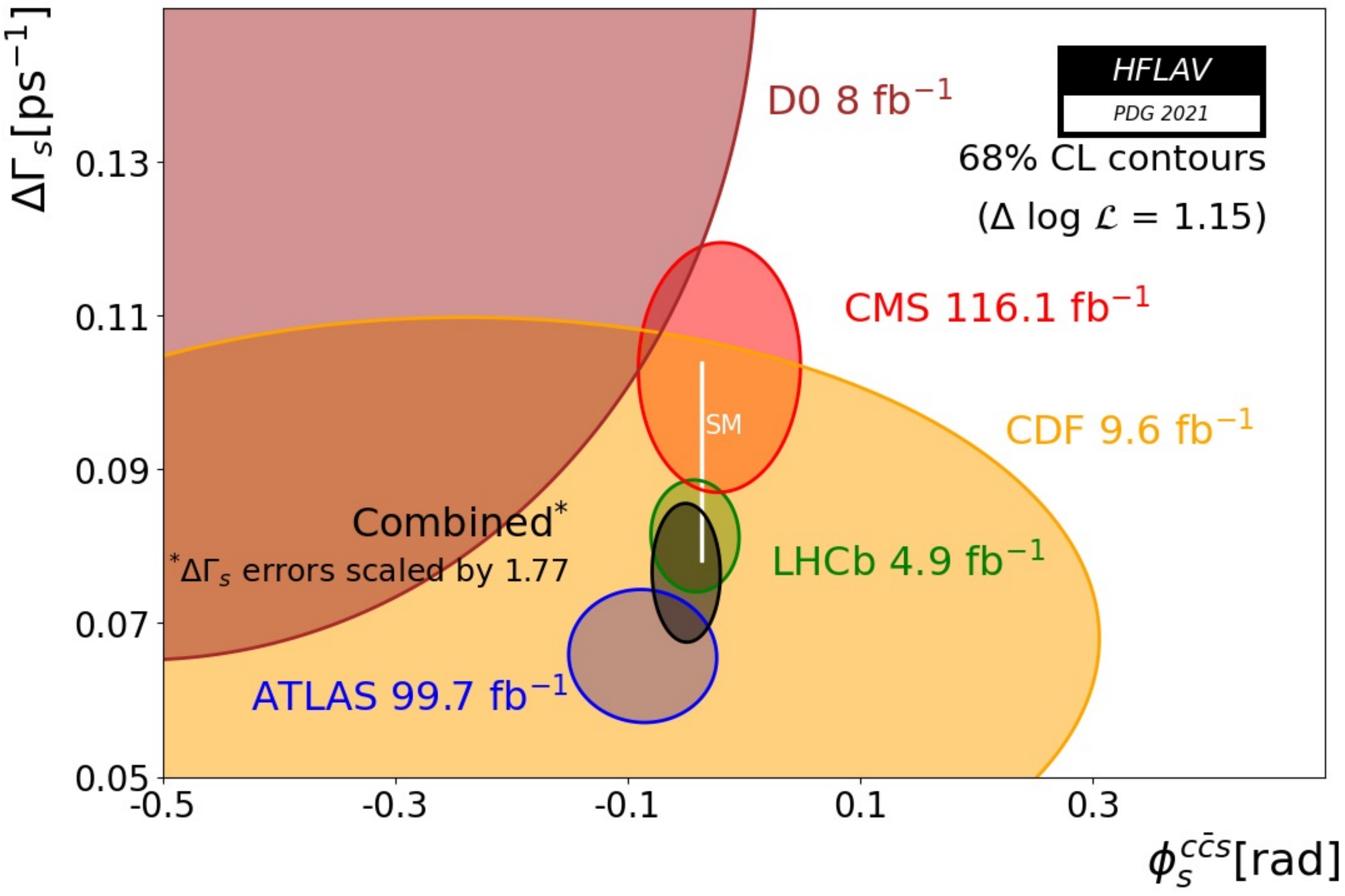
Probing CKM matrix elements complex at higher order

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\Rightarrow \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{A^2\lambda^5}{2}(1-2\rho)-i\,A^2\lambda^5\eta & 1-\lambda^2/2-\lambda^4(\frac{1}{8}+\frac{A^2}{2}) & A\lambda^2 \\ A\lambda^3(1-(1-\lambda^2/2)(\rho+i\eta)) & -A\lambda^2(1-\lambda^2/2)(1+\lambda^2(\rho+i\eta)) & 1-\frac{A^2\lambda^4}{2} \end{pmatrix} + \mathcal{O}(\lambda^6)$$

[HFLAV](#)

SM : Φ_s=-0.0370 ±0.0008 rad (prediction from a fit using other measurements)



Discovery of CP violation in charm decays

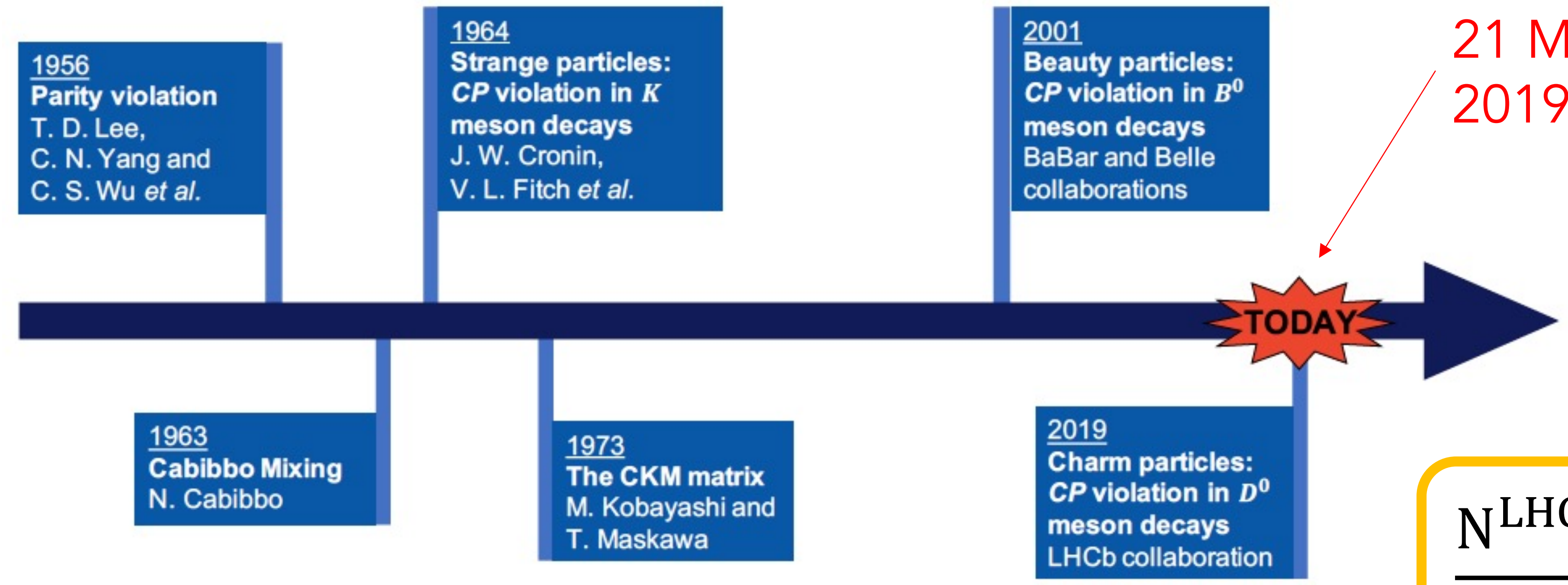
CP violation in up-type sector. SM expectations : 10^{-3} - 10^{-4}.

$\sigma_{cc} \simeq 20\sigma_{bb}$ at LHCb

Extremely large samples needed !

~ 80 10^{6} signal events

21 March 2019



$$\frac{N^{\text{LHCb-Upgrade II}}}{N^{\text{Belle II}}} \sim 100$$

in key-channels

Experimentally:

$$A_{raw} = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)} = A_{CP} + A_D(\pi_s^+/\mu) + A_P(D^{*+}/D^0_{\text{from } B})$$

$D^0 \to KK$ or $\pi\pi$

charge symmetric

$$\Delta A_{CP} = A_{raw}(KK) - A_{raw}(\pi\pi) \cong A_{CP}(KK) - A_{CP}(\pi\pi)$$

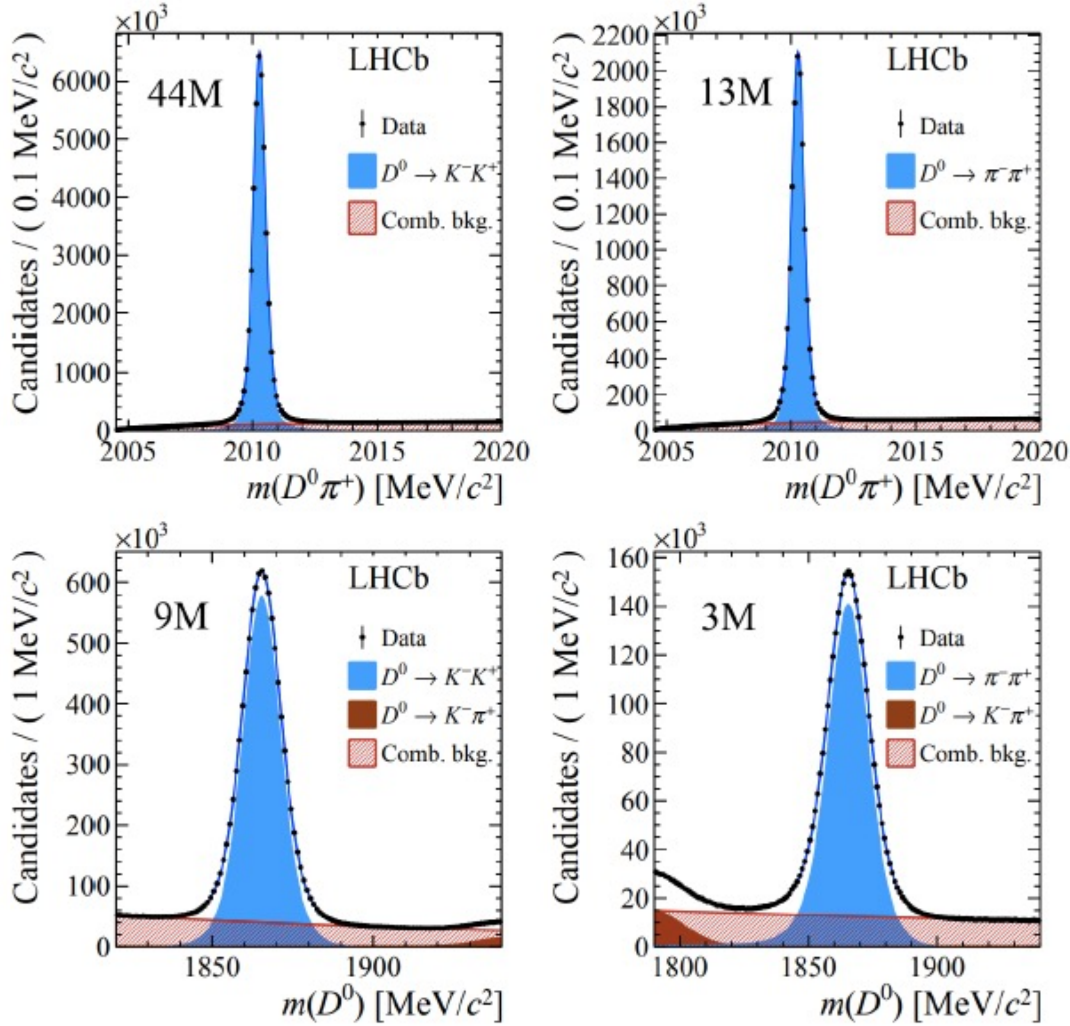
Kinematical reweighting ⇒ production and detection asymmetries cancel

ΔA_{CP}=(-0.154±0.029)%

Observation of CP violation at 5.3 σ

π tag

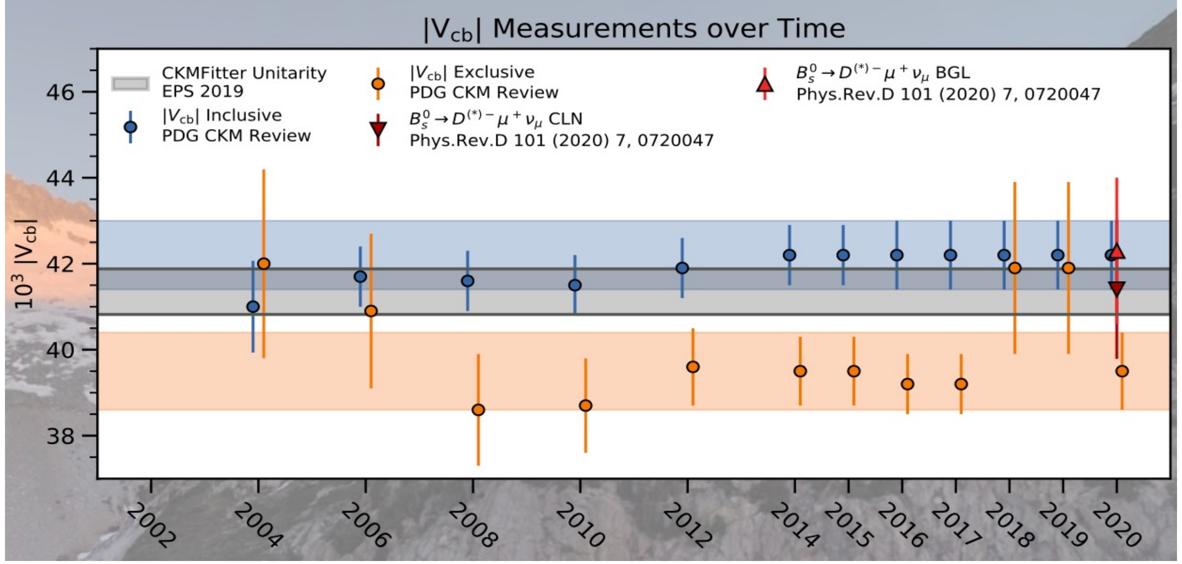
μ tag

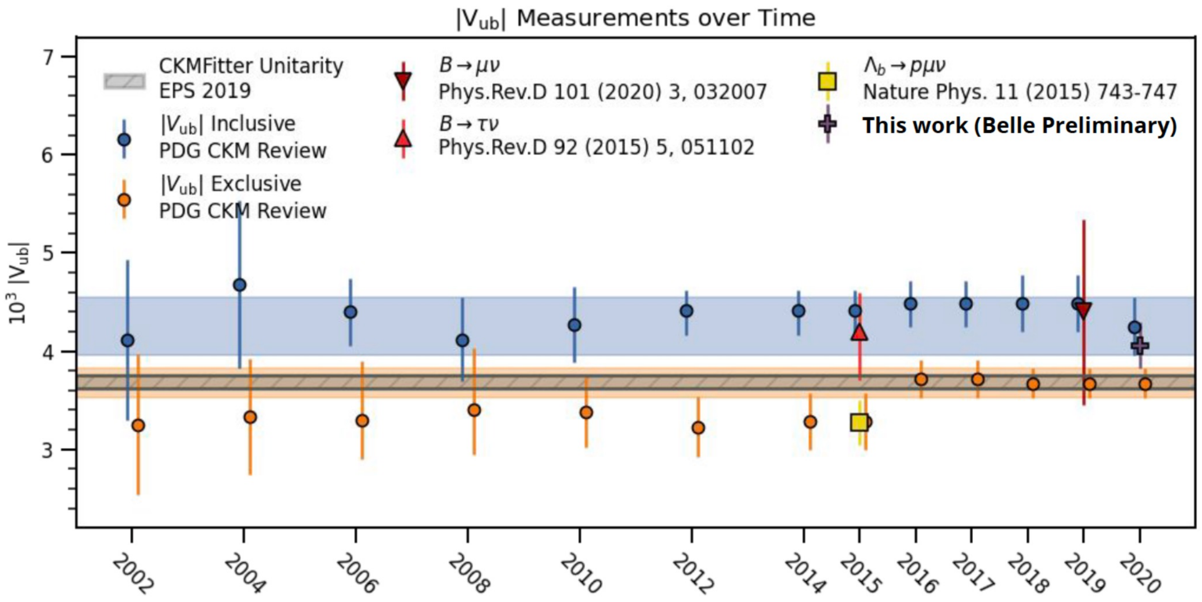


Run2 dataset (6 fb^{-1})

Phys. Rev. Lett. 122 (2019) 211803

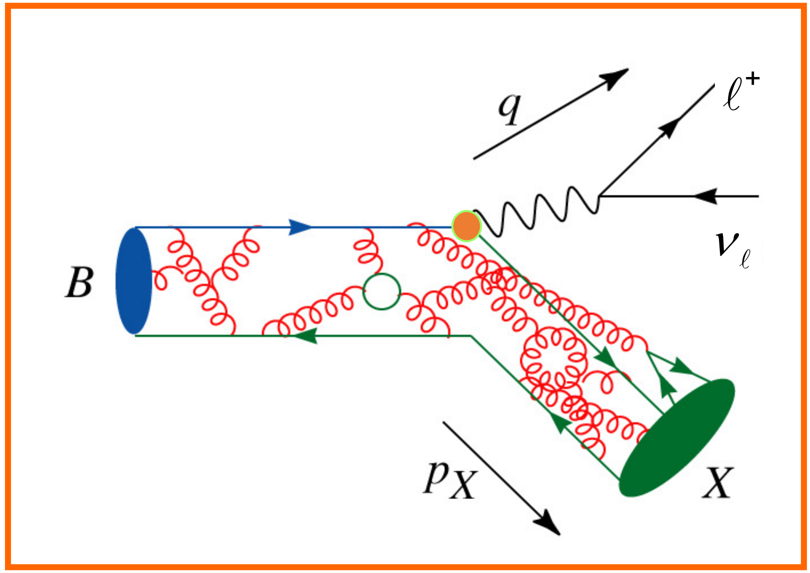
Snowmass 2021





Long standing discrepancies … (not due to statistics)

$|V_{cb}|$: inclusive determinations



Not a statistical issue

Kinematical constraints from other B reconstruction

$$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3}$$ PDG

Using q^2 moments and Belle + Belle-II data

$$|V_{cb}| = (41.69 \pm 0.59|_{\text{fit}} \pm 0.23|_{\text{h.o.}}) \cdot 10^{-3} = (41.69 \pm 0.63) \cdot 10^{-3}$$

arXiv:2205.10274

$|V_{cb}|$: exclusive determinations ($B \to D^{(*)} l\nu$)

$B \to D^* l\nu$ extremely clean samples, $B \to D l\nu$ less clean (D^* feed-down)
FF parametrization
Measurement of the differential rates

$$|V_{cb}| = (39.4 \pm 0.8) \times 10^{-3}$$

PRD 108, 092013 (2023)

$$|V_{cb}|_{\text{BGL}} = (40.57 \pm 0.31 \pm 0.95 \pm 0.58) \times 10^{-3},$$

$|V_{ub}|/|V_{cb}|$ by LHCb

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}}$$

$$\frac{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{K^-}\mu^+\nu_\mu)_{q^2<7}}{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{D_s^-}\mu^+\nu_\mu)_{\mathrm{Full}\ q^2}} \qquad \frac{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{K^-}\mu^+\nu_\mu)_{q^2>7}}{\mathcal{B}(\mathrm{B_s^0} \to \mathrm{D_s^-}\mu^+\nu_\mu)_{\mathrm{Full}\ q^2}}$$

$B_s^0 \to K^+\mu^-\nu$ vs $\Lambda_b^0 \to p\mu\nu$

Decay	Λ_b^0	B_s^0
theory error	5%	$\sim 5\%$
prod frac	20%	10%
BF	4×10^{-4}	1×10^{-4}
$\mathcal{B}(X_c)$ error	$\pm 5\%$	$\pm 2.8\%$
background	Λ_c^+	$\Lambda_c^+, D_s, D^+, D^0$

Importance of X_c BF measurements

Importance of FF knowledge for the backgrounds

2012 data !

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004$$

$$|V_{ub}|/|V_{cb}|(\mathrm{high}) = 0.0946 \pm 0.0030\,(\mathrm{stat})^{+\,0.0024}_{-\,0.0025}\,(\mathrm{syst}) \pm 0.0013\ (D_s) \pm 0.0068\ (\mathrm{FF})$$