What are the key open questions for the current b $\rightarrow$s measurements?

Marie-Hélène Schune
IJCLab – CNRS Univ. Paris-Saclay

Apologies to my Belle-II colleagues for a talk strongly LHCb-biased

In general BR are $\mathcal{O}(10^{-7})$

→ LHC large production is clearly a plus

→ comes with the cost of a very challenging experimental environment

- b→s μμ channels :
  - clean experimental signature
  - precise experimental results on a large number of BR and angular observables
- b→s ee channels :
  - low p_T electrons in the harsh LHC context
  - limited number of results (few LFU ratios, one very specific angular analysis)

there is no free lunch

Branching Ratios

Angular observables

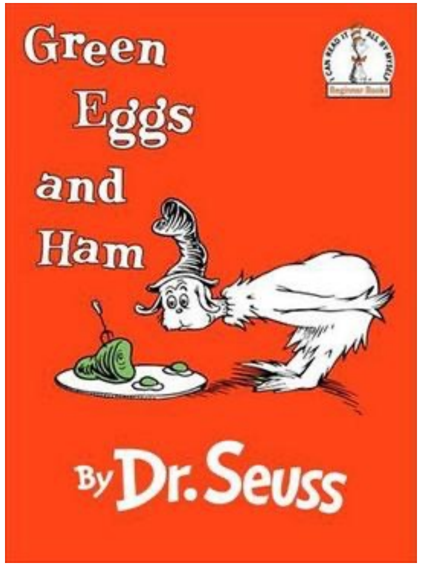
LFU observables :
R-ratios
angular observables ratios

theoretical cleanness

all LFV modes omitted even if they are very important to constraint NP models

Why does it take so long ?

Usage of Run1-Run2 data ?



and then ?

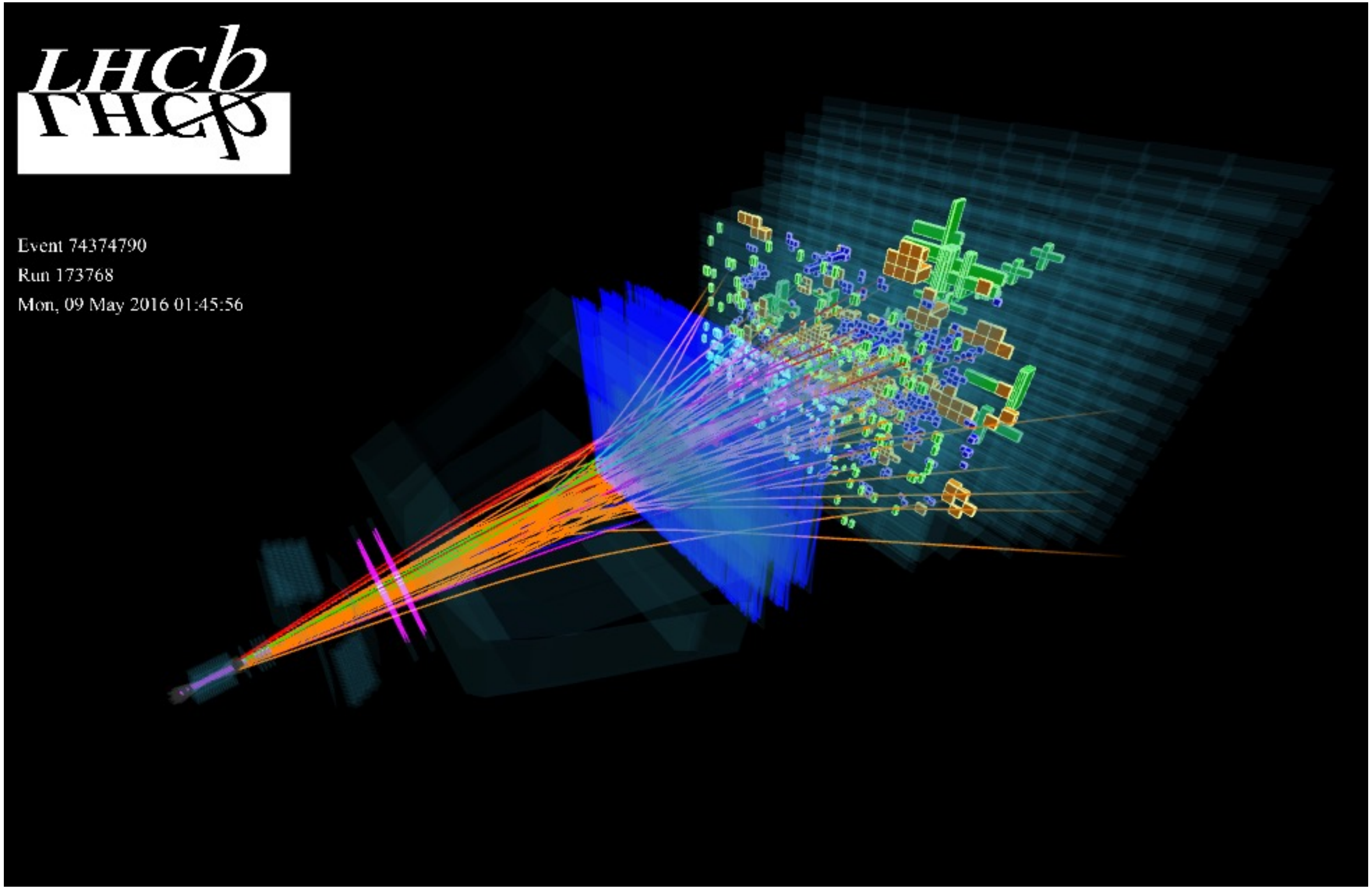
Many more details in the other talks at this workshop

Crédits : *Dr. Seuss / Editions du Nouvel Attila*

Why does it take so long ?

What are the experimental challenges ?

Taking $B \rightarrow K^{*} \ell\ell$ as a proxy for explanations



For each event in ~ 100 tracks:

- find a K^+ a π^- a pair of opposite charge leptons and compute $M(K^+ \pi^- \ell^+ \ell^-) + q^2$
  → crucial role of vertexing and tracking to reduce the number of tracks to be considered

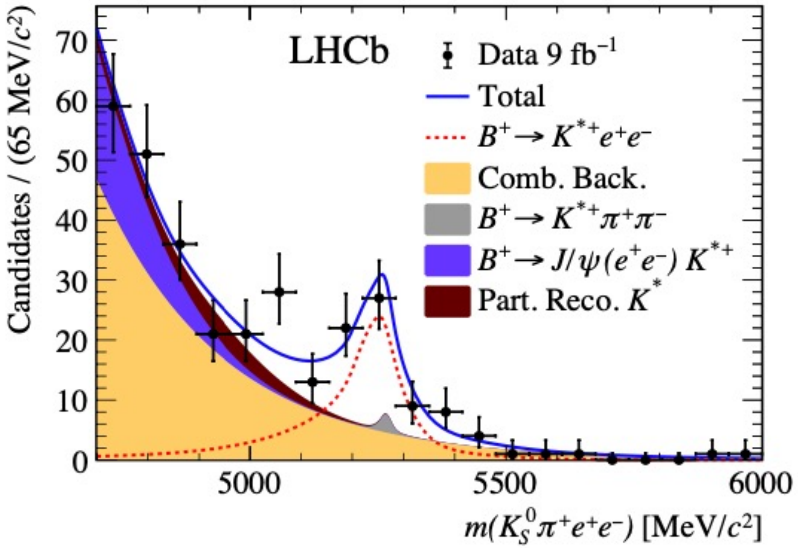
→ crucial role of

- hadron PID (RICH) otherwise you could mix B and $\bar{B}$ (K* is large)
- lepton PID do not want to confuse K* $\pi\pi$ with K* $\ell\ell$

Backgrounds :

- random combination of 4 tracks
- double semileptonic decays : $H_b \to H_c(\to K^* \ell^- \nu_\ell)\ \ell^+ \nu_\ell$
  - very large Branching Ratios
  - select mainly very-low momentum neutrinos (phase space corner)
- partially reconstructed backgrounds : $B \to K^* (n)\ \pi\ \ell^+ \ell^-$, $B \to K^* \gamma\ \ell^+ \ell^-$ ....
  - badly known
  - try to reject them, try to measure them

arXiv:2110.09501



Ideally a lot of other physics input needed :

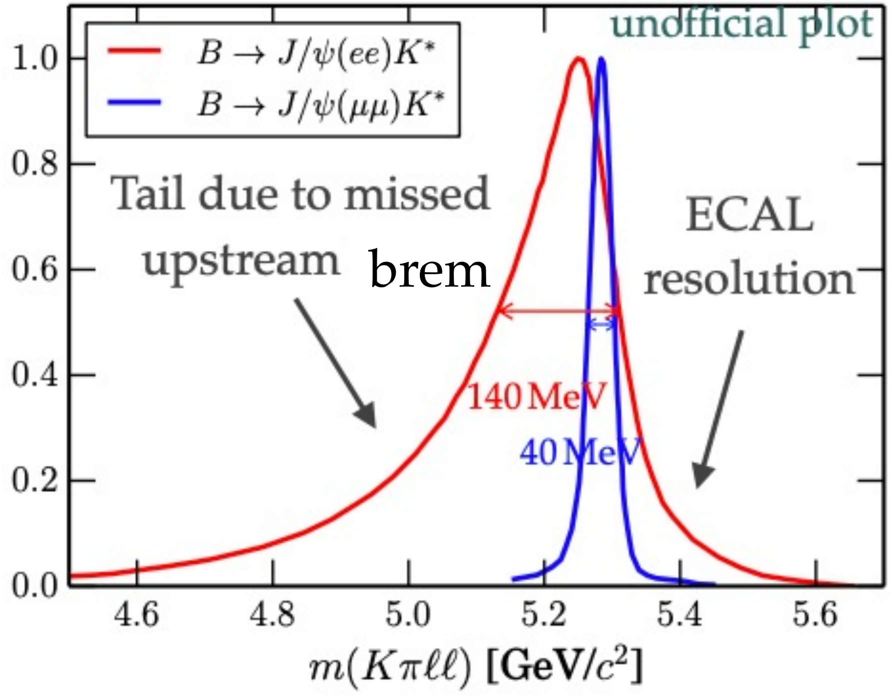
$B \to K\pi\ \pi\ \ell^+ \ell^-$

Dalitz distribution

$B \to K^*\ \pi\ \pi$

Dalitz distribution

… and the additional complication of electrons

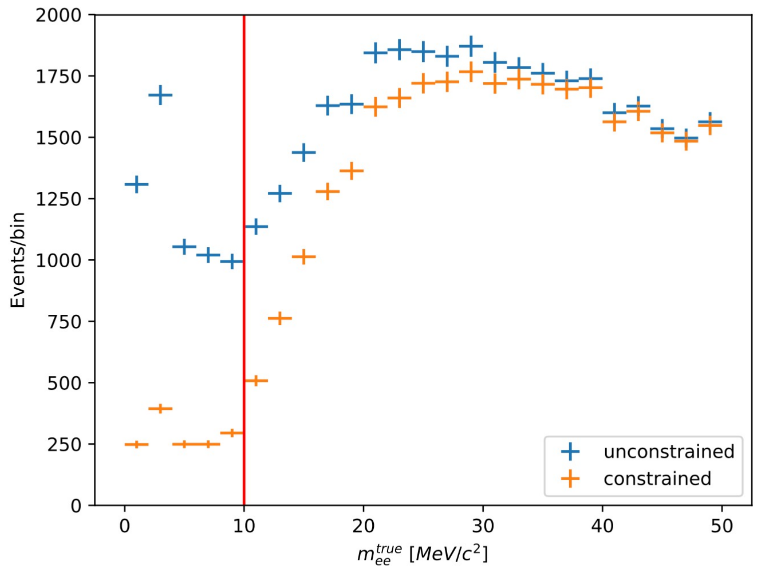


from Martino Borsato

widening of the mass ranges and thus of the level of backgrounds

→ Experimental 'tricks'

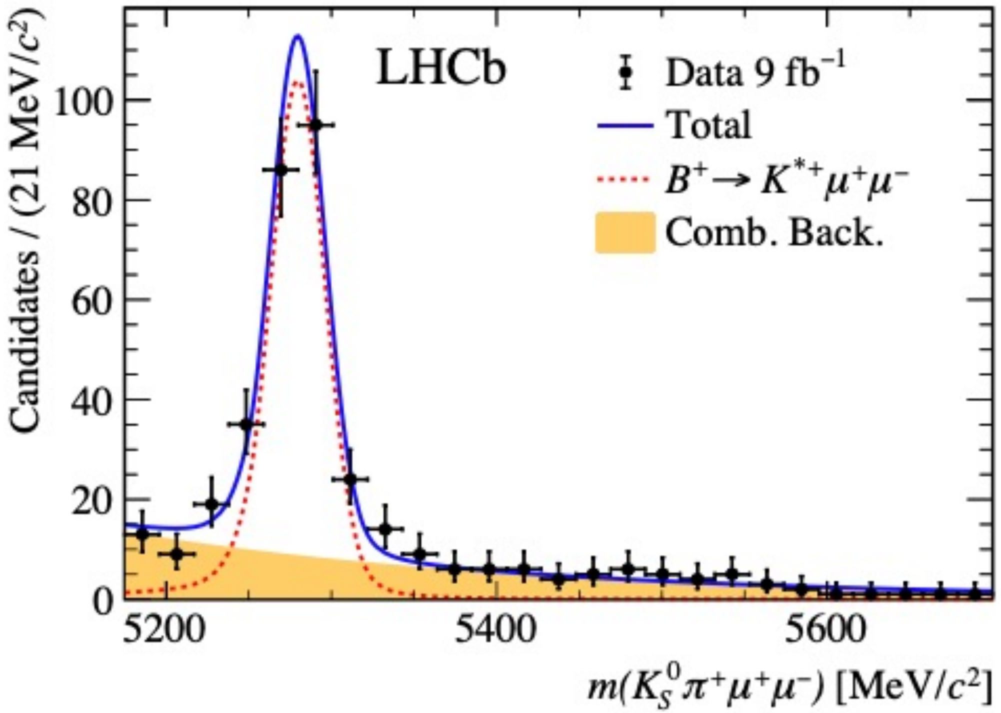
- compute q^2 using the B mass constraint

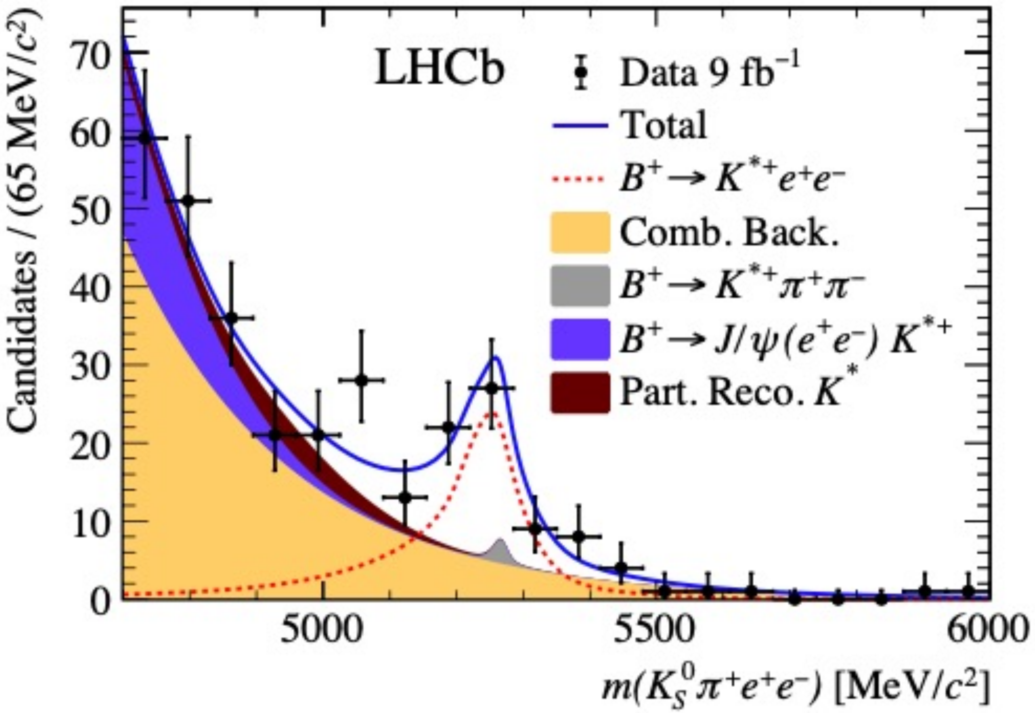


CERN-THESIS-2020-112

- different for the high-q^2 region

arXiv:2110.09501





Yet yields extraction is possible (!)

Go for the BR measurement

$$BR = \frac{N_{sig}}{\epsilon_{ff} \int \mathcal{L}\,dt \times \sigma_{b\bar{b}} \times f_d}$$

- At the LHC b bbar cross section and f_x not precisely known
- efficiency : MC cannot be fully trusted (worse at LHC than at B-Factories) :
  - MC is corrected using data control modes for trigger efficiencies, PID efficiencies …

- Measure it relative :

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2} = \frac{1}{q^2_{\mathrm{max}} - q^2_{\mathrm{min}}} \frac{N_{\mathrm{sig}}}{N_{K^{*0}J/\psi}} \frac{\varepsilon_{K^{*0}J/\psi}}{\varepsilon_{K^{*0}\mu^+\mu^-}} \times \mathcal{B}(B^0 \to K^{*0}J/\psi) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)$$

reduction of the systematic uncertainties (more than a factor few * 10 !)

angular analyses :

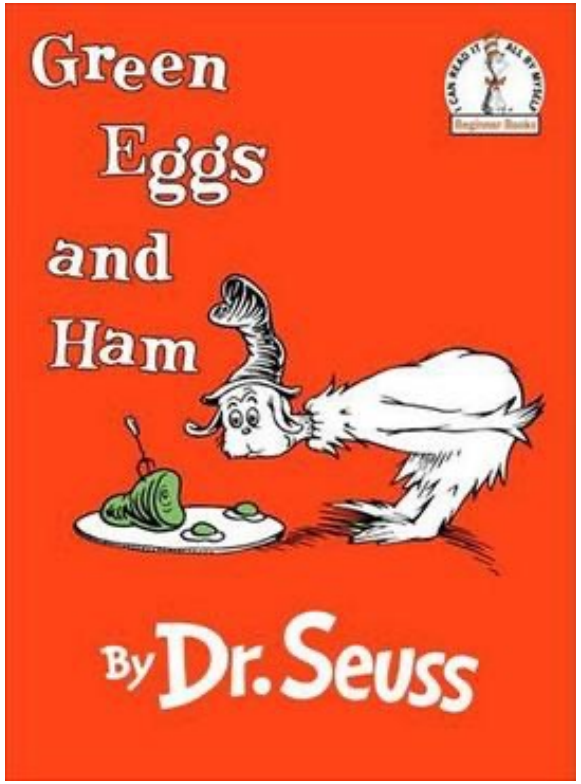
- **muon channel** : 'easy' modelling (or background substraction)

- **electron channel** :
  - Double semileptonic : use of $b \to s\, e\mu$ proxy
  - partially reconstructed backgrounds : $B \to K^* (n)\, \pi\, \ell^+ \ell^-$, $B \to K^* \gamma\, \ell^+ \ell^-$: guess and control !

More observables → more handles to check the modelling

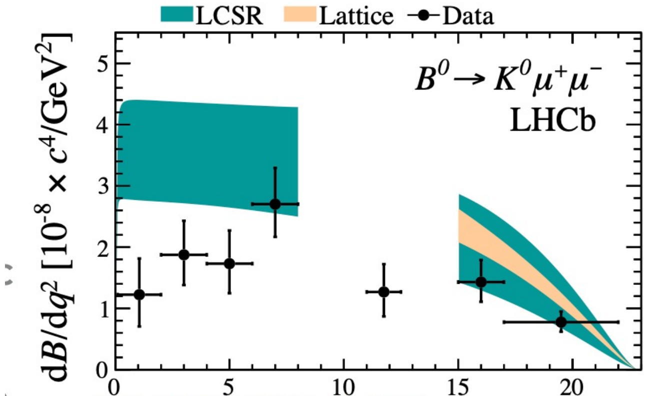
What are we doing with Run1+Run2 dataset ?

What will we do with Run1+Run2 dataset ?

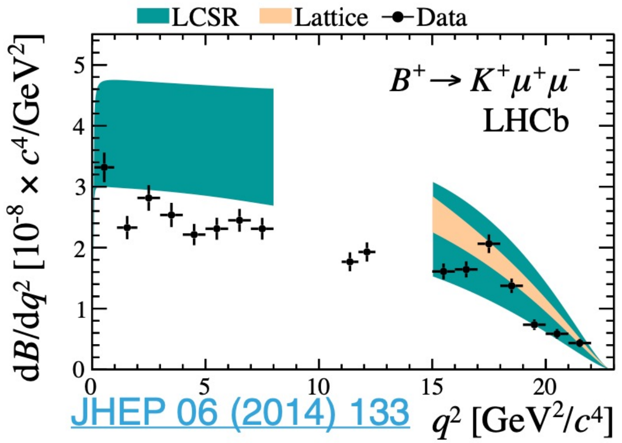


Where do we stand for b→s μμ channels and what could we do more ?

All BR(b → sμμ) have a tendency to be low wrt SM prediction (but predictions uncertainties correlated)

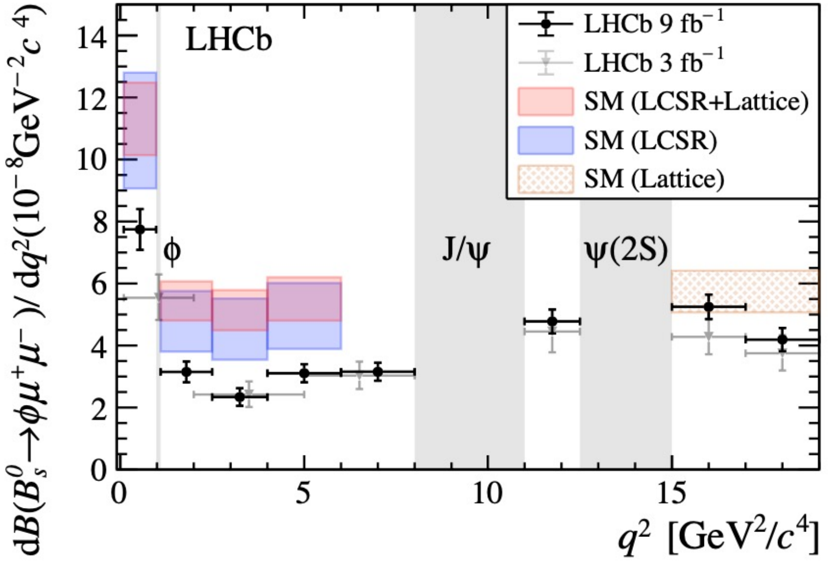


JHEP 06 (2014) 133



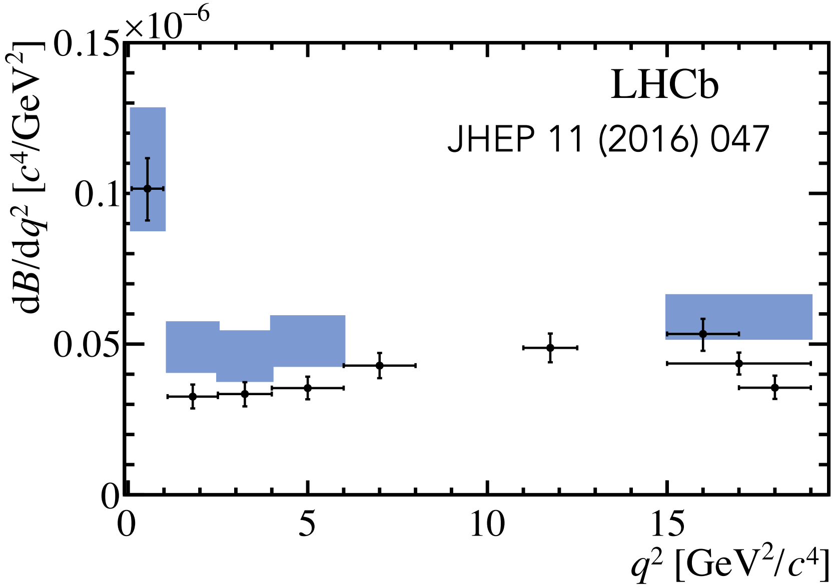
JHEP 06 (2014) 133

A recent example : BR ($B_s \to \phi\mu\mu$)



arXiv:2105.14007

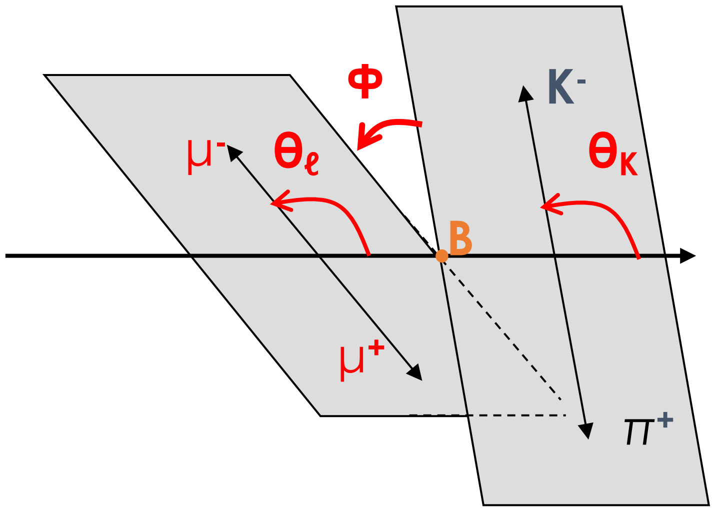
BR ($B_d \to K^{*0}\ \mu\mu$)

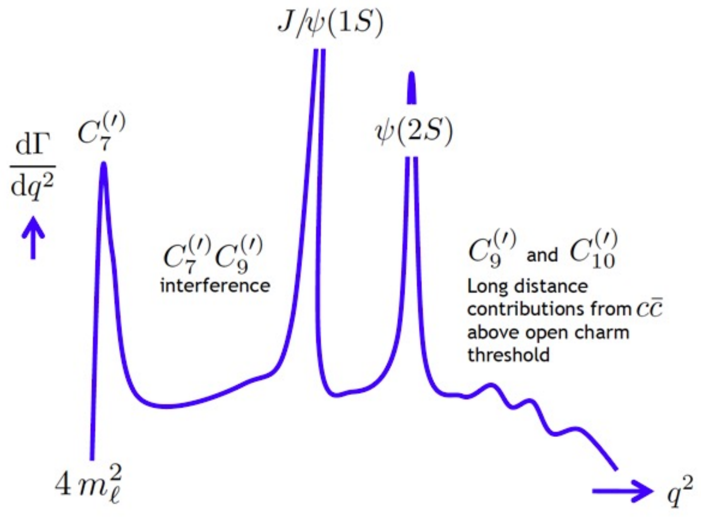


4 particles final state

System described by:

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





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

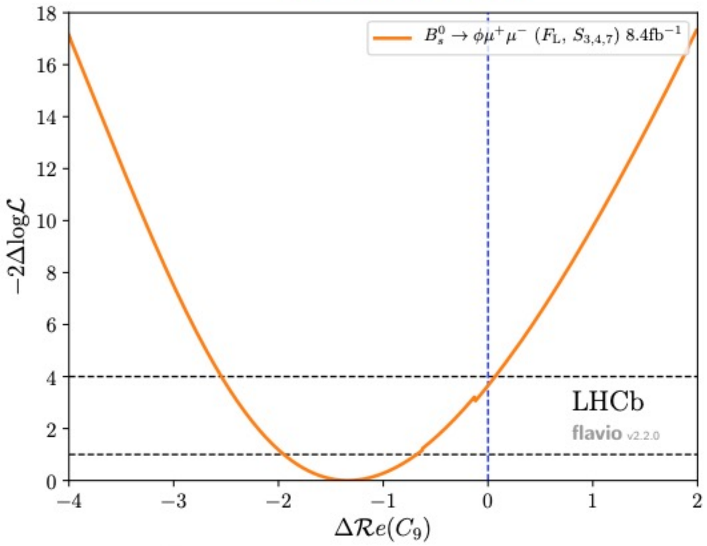
$$\frac{d^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega})$$

+ S-wave component

the three B→V μμ angular analyses consistently favour a negative shift in ΔRe(C₉)

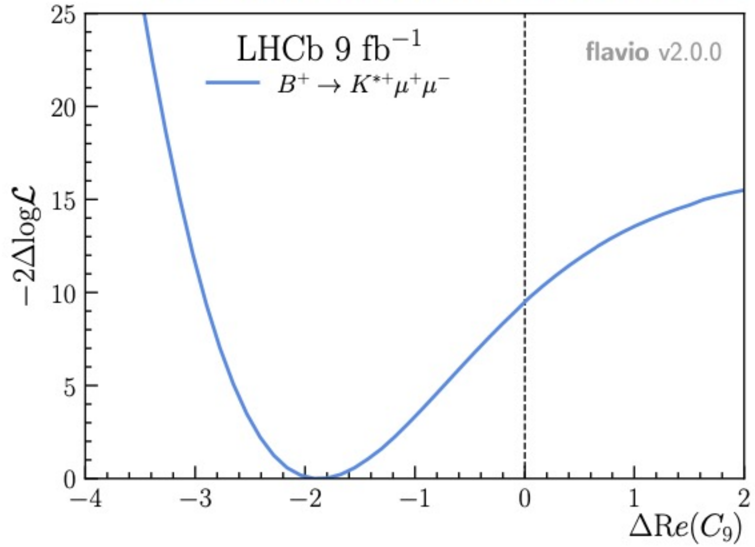
$B_s^0 \to \phi\mu^+\mu^-$

[PAPER-2021-014]



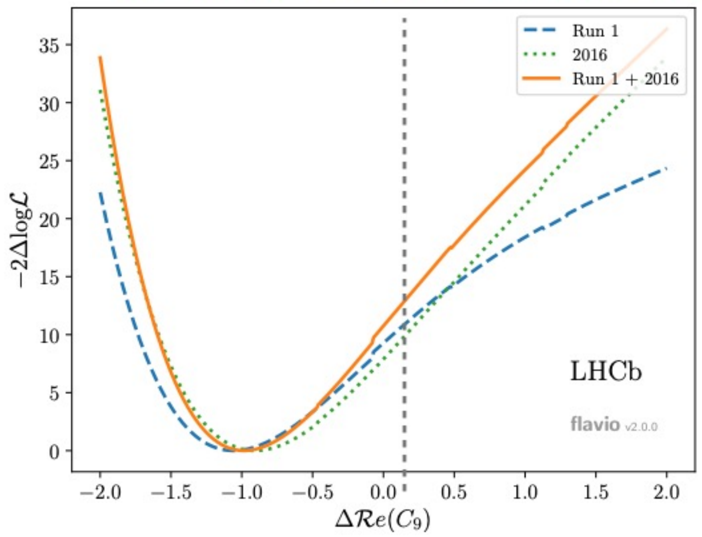
$B^+ \to K^{*+}\mu^+\mu^-$

[PAPER-2020-041] / PRL 126 (2021) 161802



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

[PAPER-2020-002] / PRL 125 (2020) 011802

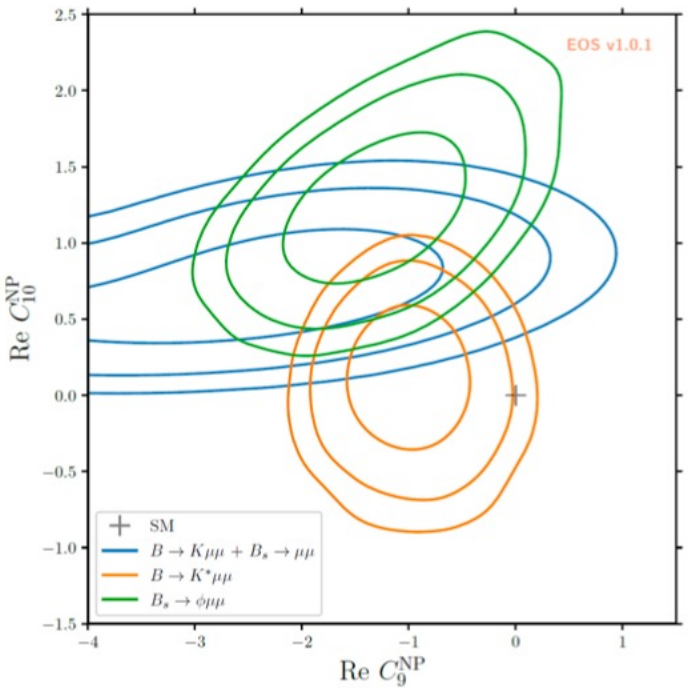


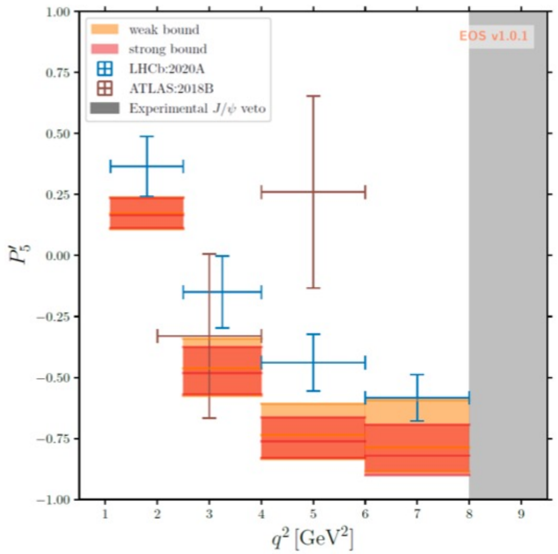
2017 – 2018 data to be added

Still a lot of theoretical work on-going to improve the precision of the predictions

See talks from Tuesday morning

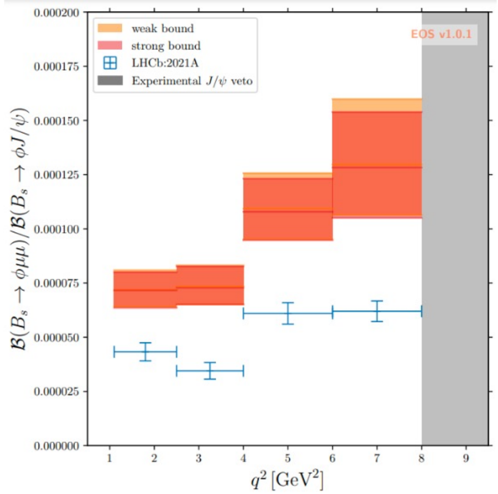
example : https://moriond.in2p3.fr/QCD/2022/TuesdayAfternoon/Gubernari.pdf

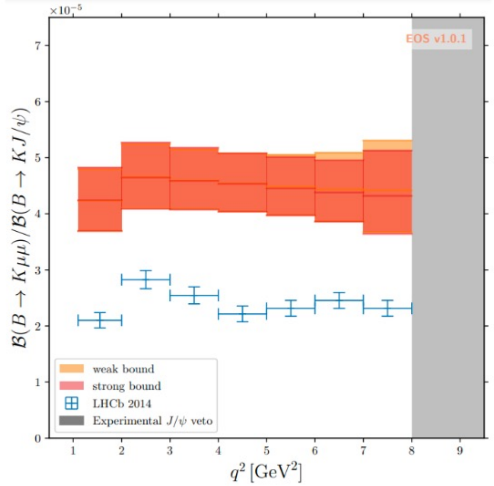




2017 – 2018 data to be added for $K^{*0}\ \mu\mu$

Branching ratios





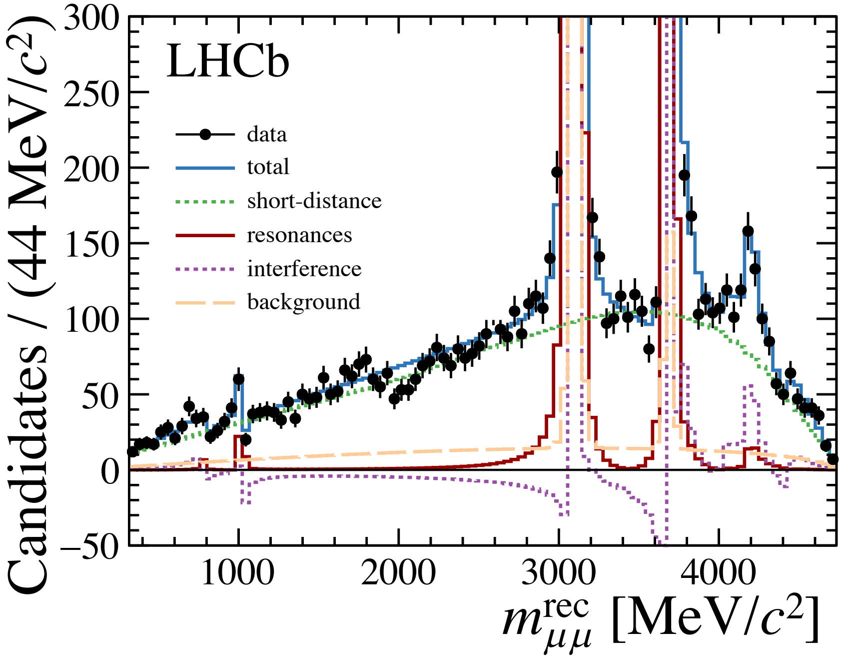
Is most of the tension coming from BR observables ?

What could we do more with the data we have at hand ?

See talk from Rafael & Tom

- Standard analyses :
  - more q^2 bins (coming with larger samples)
  - analyse the full Run1+Run2 datasets (not yet done for $K\mu\mu$, $K^{*0}\mu\mu$, $\Lambda\mu\mu$, …)
  - extract all accessible observables (CP)

- $K\mu\mu$: analyse the full q2 spectrum at once (https://arxiv.org/abs/1612.06764) to measure the phase difference between the short and long distance amplitudes



- and …
  - Full q^2 analysis also for $K^{*0}\mu\mu$ (but more challenging)

  - Unbinned angular fit over the full q^2 spectrum → distinguish between NP and cc loops.

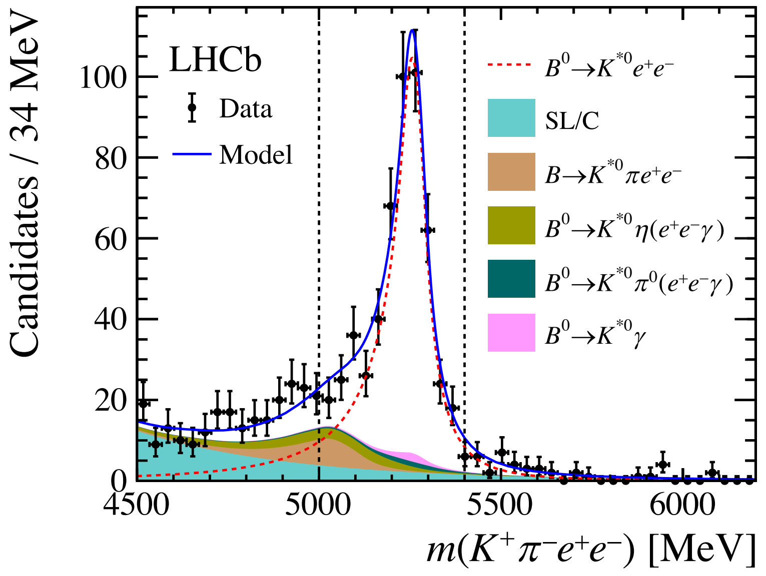
Where do we stand for b→s ee channels and what could we do more ?

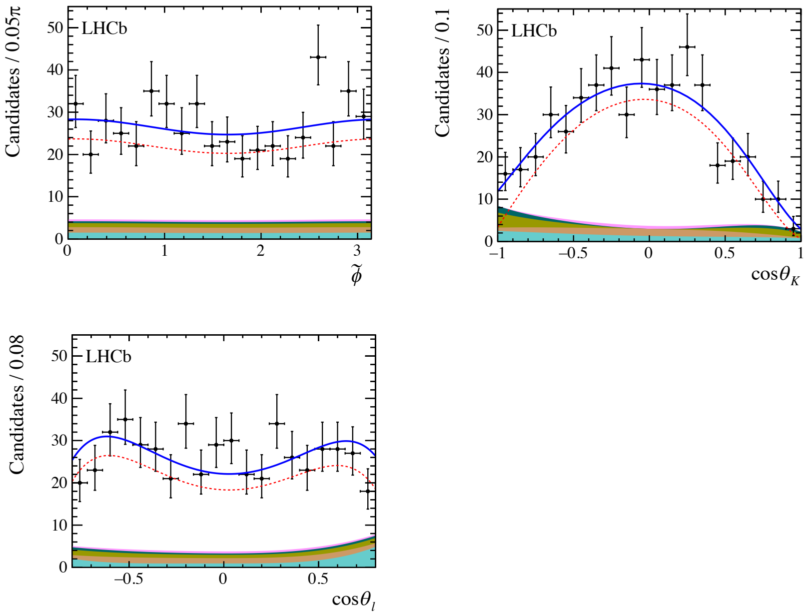
See talks from
Rafael & Tom
Yasmine & Gianluca

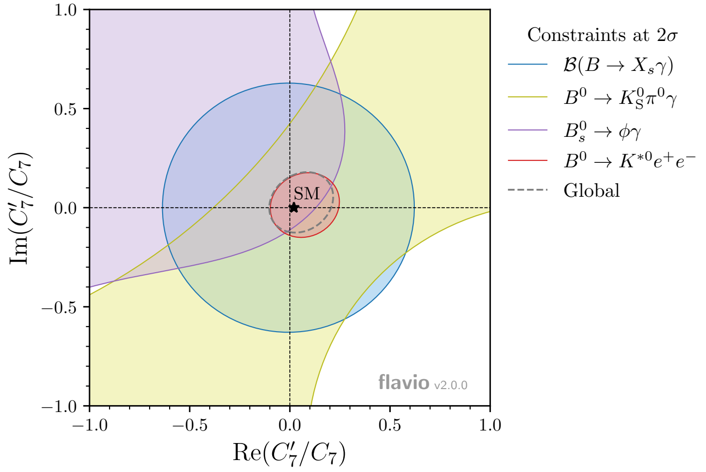
Not a lot (yet) of experimental information :

- R ratios only K, K^{*0}, pK, K^{*+}, Ks
    - statistically (very) limited, not full data sample analysed yet
    - hadronic resonances (Kππ, pK, …) still not studied

- one angular analysis (K*ee) at q^2 < .25 focussing on the photon pole.







Full data sample

Explore the high-q^2 region (which is exp. different from the other q^2 bins)

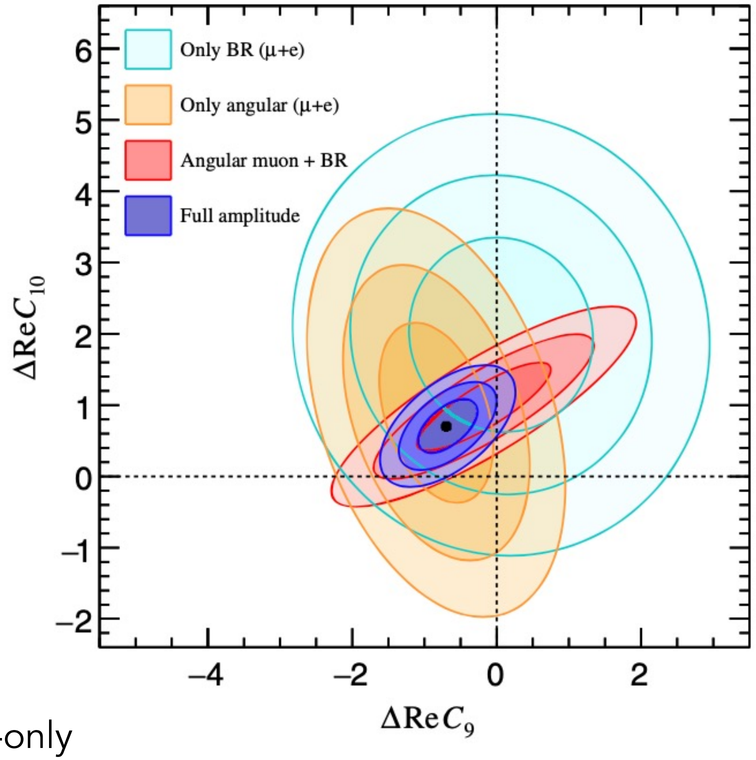
Angular analyses to be performed (eventually some constraints using the muon channels)

… → Combined amplitude fit

$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

Local form factors **Non local ($c\bar{c}$)**

A.Mauri et al Phys. Rev. D 99, 013007 (2019)



NP scenario : μ-only

Cross-checks which could/should be done:

- R measurement where we know the answer (validate the MC corrections and efficiencies computations) ($D_s \to \phi(\to \ell\ell)\,\pi$), but also $B \to D\ell\,\nu$, $\ell = e/\mu$) .

- Use the photon pole region (assumed to be SM-dominated)
  - $\left[\dfrac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}\gamma)}\right]$

  - Angular analyses (difference between B_s and B_d)

    different dependence on C'_7 and C_7 due to mixing

https://arxiv.org/abs/1502.05509

Electron channels

- BR : many analyses not (yet) performed (samples, q^2..)
- angular : analyses not (yet) performed (q^2..)
- statistics (still) scarce
- experimentally challenging, still learning !
- are we using in the best way the photon-pole region ?

Muon channels

- BR and angular : experimentally mature field
- switching to (very) complex analyses to better constraint theoretical nuisance parameters

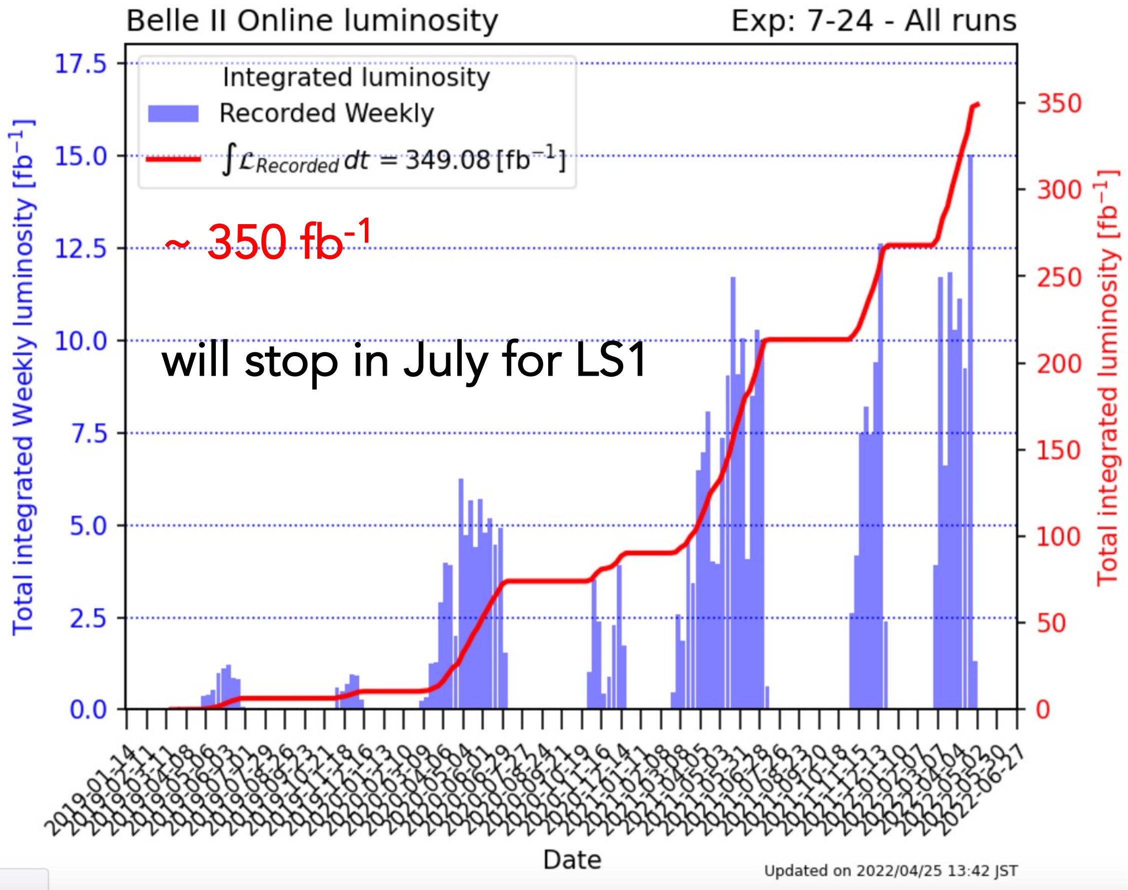
$\Rightarrow$

LFU

- Many R ratios not yet measured
- … and no angular analyses yet

and then ?

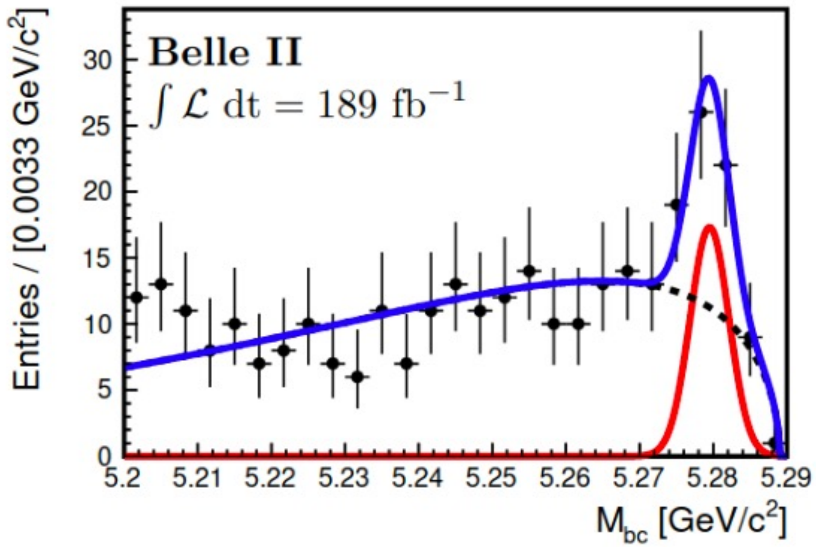
Belle-II starts to collect a significant amount of data



b→sℓℓ channels seen !

See talk from Yasmine & Gianluca

Maximilian Welsch @Moriond QCD2022



M(ee)>0.14 GeV

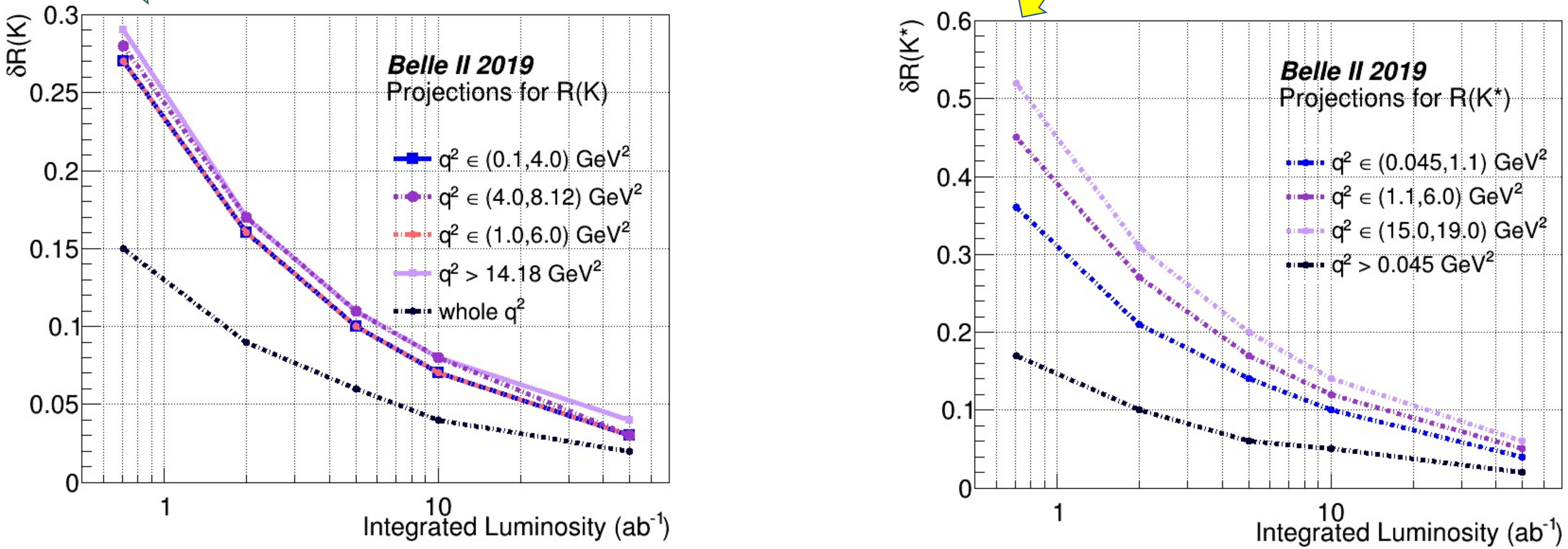
189 fb^{-1} : ~35 evts

J/Psi and Psi(2S) excluded

$\mathcal{B}(B \to K^* \mu^+ \mu^-) = (1.28 \pm 0.29^{+0.08}_{-0.07}) \times 10^{-6}$ (PDG: $(1.06 \pm 0.09) \times 10^{-6}$)

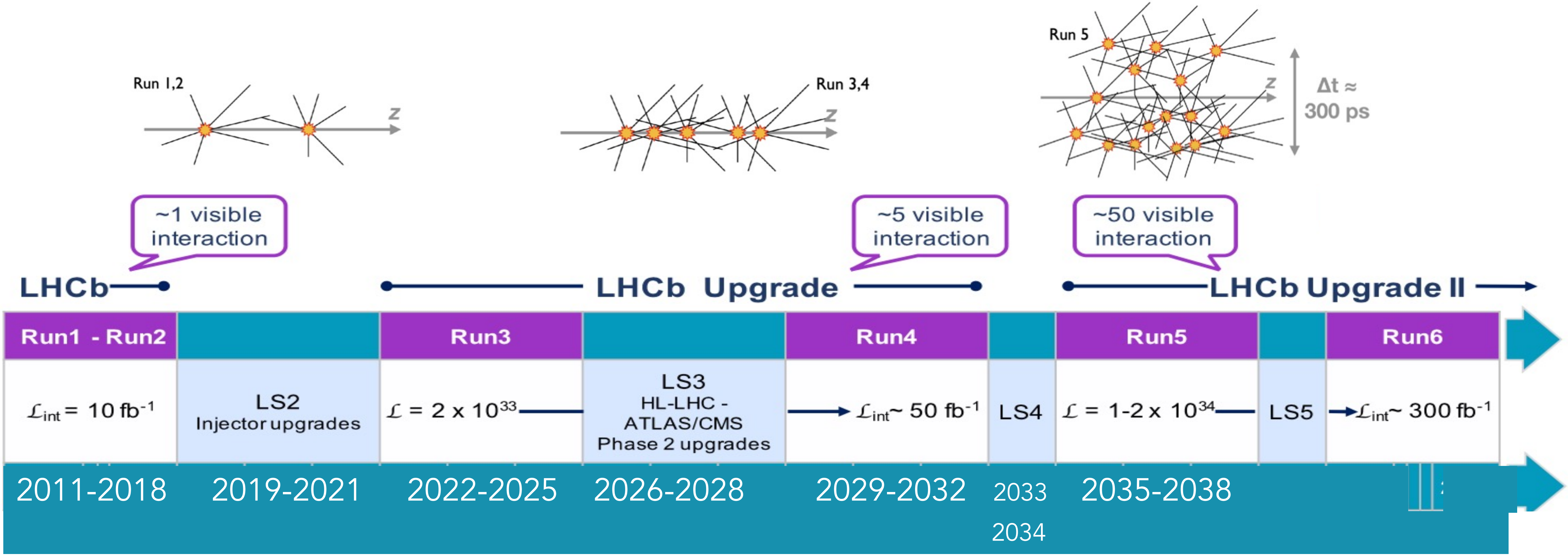
$\mathcal{B}(B \to K^* e^+ e^-) = (1.04 \pm 0.48^{+0.09}_{-0.09}) \times 10^{-6}$ (PDG: $(1.19 \pm 0.20) \times 10^{-6}$)

this summer (been optimistic) ?



→ interesting information in 2025 ?

LHC schedule

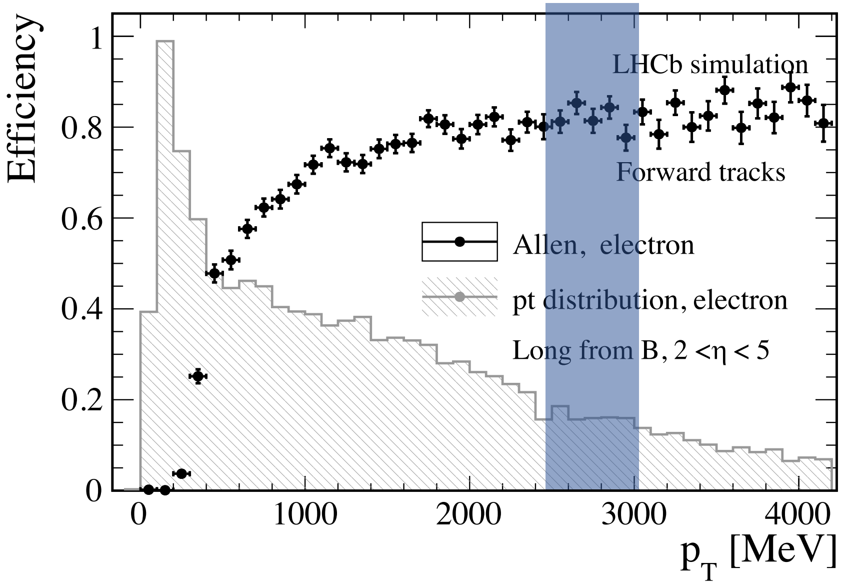


23 fb^{-1} 50 fb^{-1}

Run3 and Run4 :

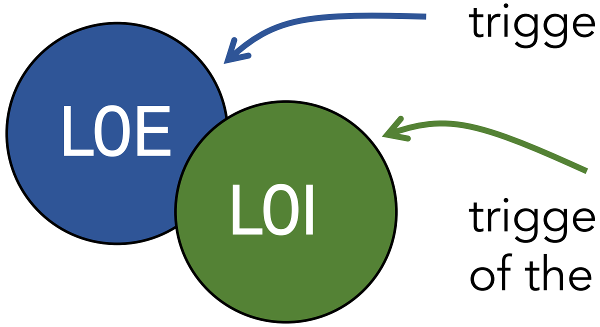
See talk from Paula

Run2 L0 Electron threshold



We will trigger much more directly on electrons

→ get rid of the Run1-Run2 'trick' :



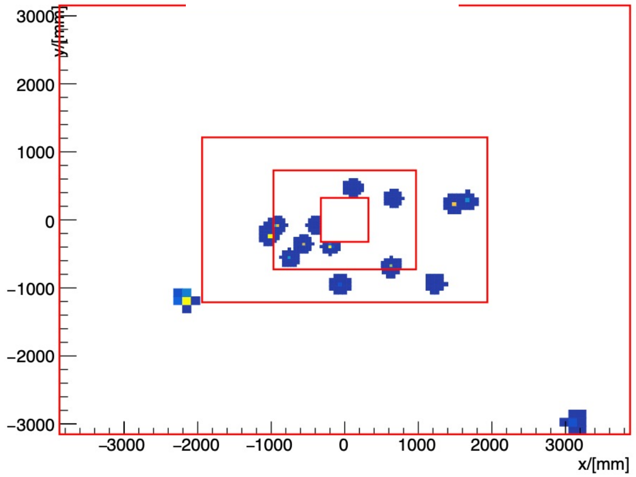
trigger on one of the electron

trigger on one mun/hadron/electron of the other b-hadron decay

NB : LHCb have conservatively assumed that the trigger efficiency will not change for $b \to s\ell\ell$

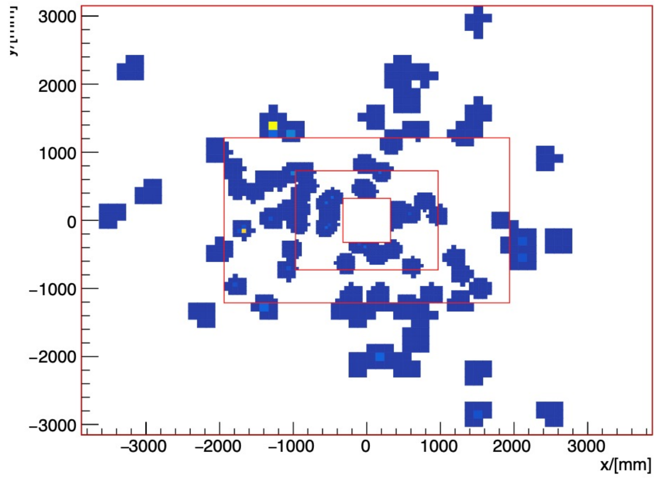
Life during Run3 and Run4 will probably be challenging …

MC 2 10^{32}



in fact 4 10^{32} during Run1 and Run2

MC 2 10^{33}



and a new detector for tracking !

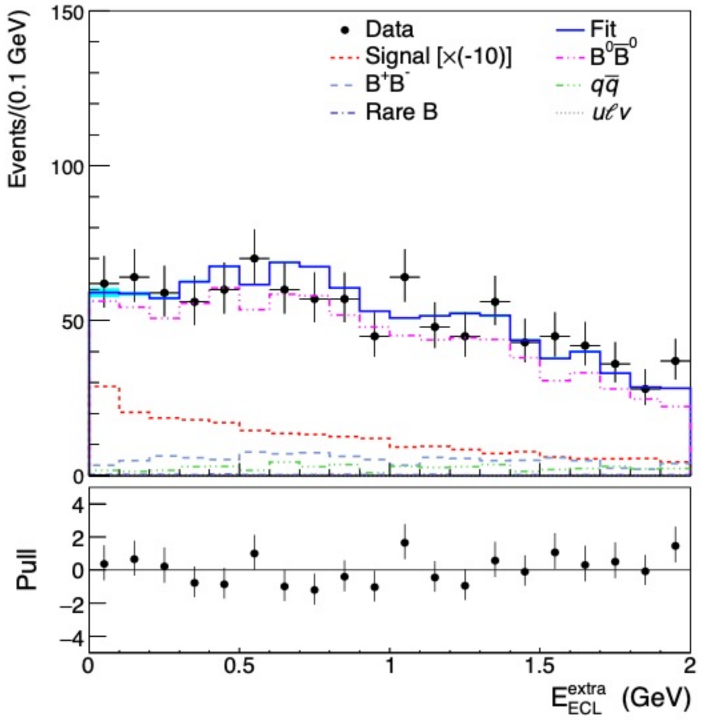
electrons : $\Rightarrow \cancel{\times \int \mathcal{L} dt}$?

……but we have learnt a lot with the data of Run1 and Run2 !

Additional modes : example #1 B → K* ττ

Belle data : 0.7 ab^{-1}

arXiv:2110.03871



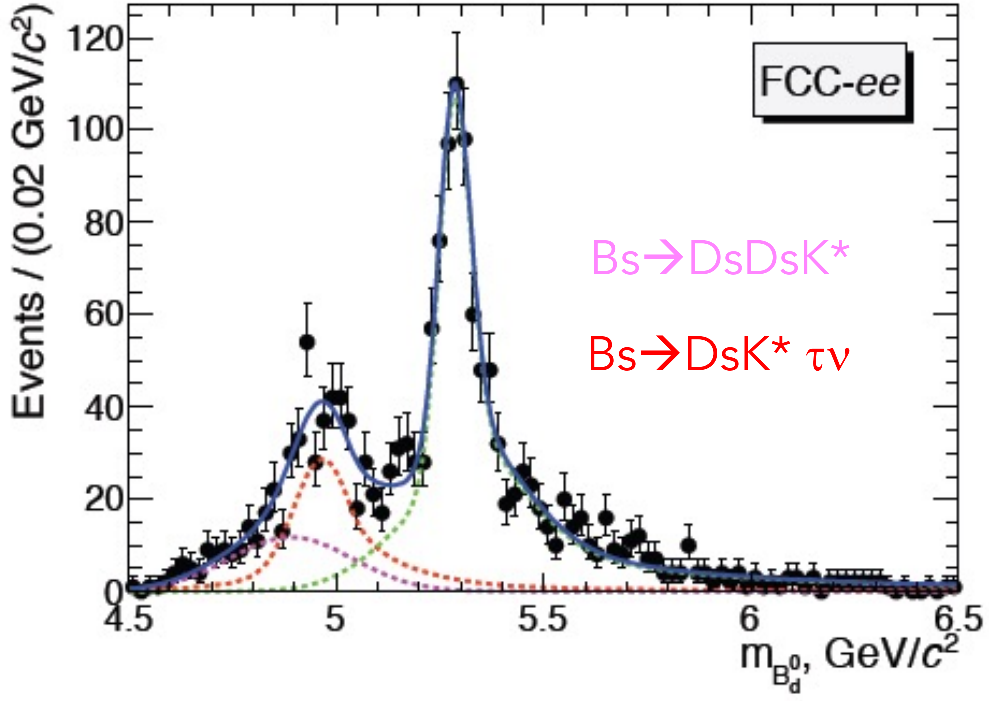
τ→ 1 prong (e, μ , π)

Efficiency ~ 1.2 10^{-5}

BR($B^0 \to K^{0*} \tau\tau$) < 2 10^{-3} @ 90%

FCCee for precise measurements

arXiv:1705.11106



10^{13} Z^0 and SM BR assumed

Improved analyses techniques

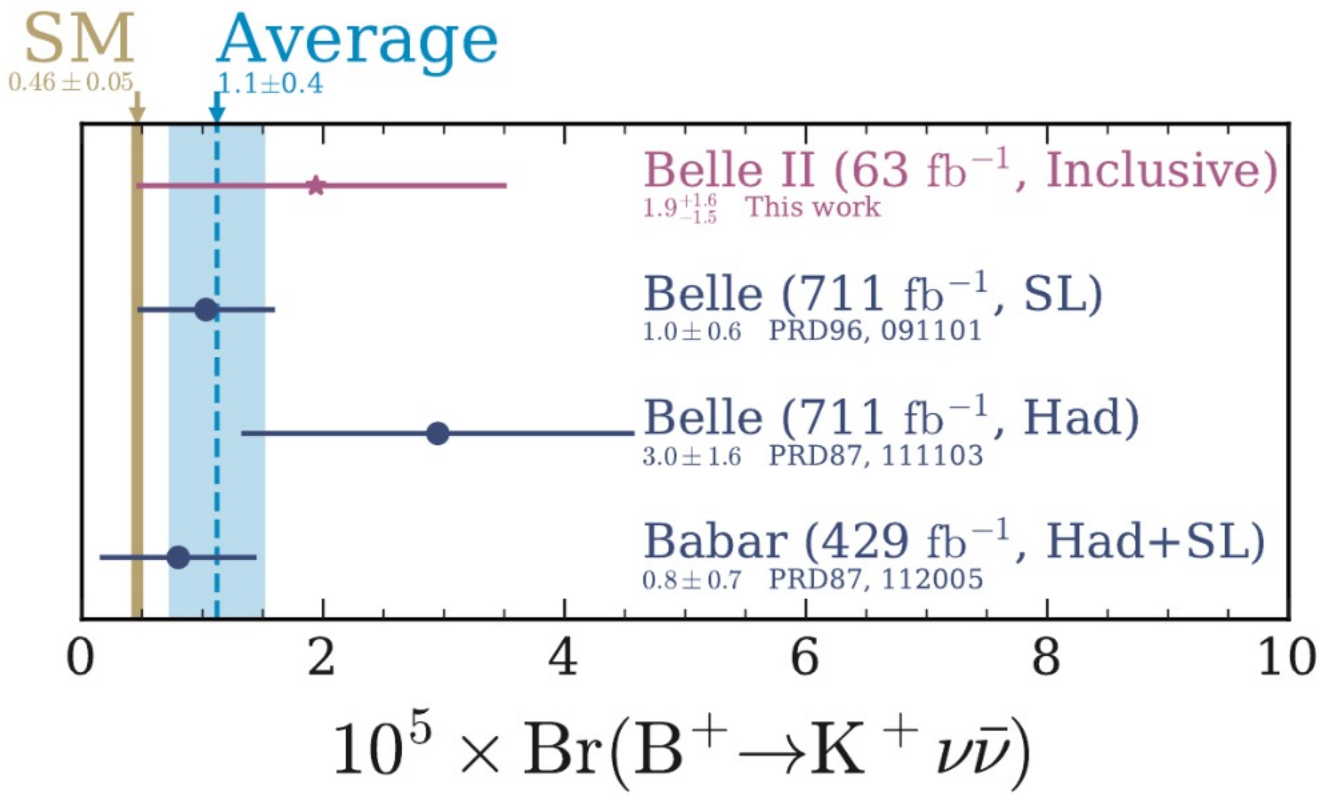
See talk from Lakshan & Hanae

and LHCb ?

Additional modes : example #2 $B \to K^{(*)} \nu\nu$

[PRL 127, 181802 (2021)]

More powerful analysis technique



Clean SM computation (no charm loop contributions)

Interesting to constraint NP (eg arXiv:2005.03734)

Compare $\dfrac{BR(B \to K^{(*)}\nu\nu)}{BR(B \to K^{(*)}\ell\ell)}$

Summary

- A lot of hard work and a lot of interesting & intriguing results
- More data and more challenging analyses to come

See talk from Wolfgang & Michael

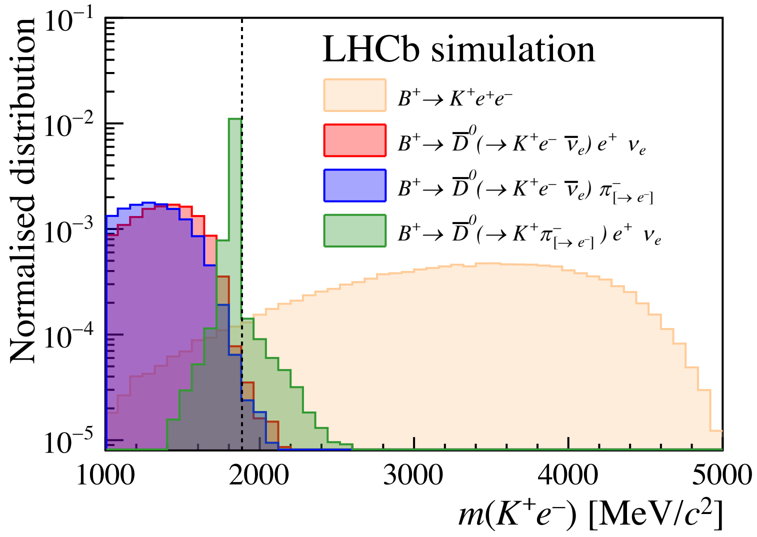
- During Run3 we will start playing (more seriously) with $b \to d\ell\ell$:
  - but more issues with loops (cc & uu)
  - would it be interesting to try to relate information from $\Lambda_b \to \Lambda(1520)\, \ell\ell$ and $\Lambda_b \to N^*(p\pi)\, \ell\ell$?
  - Let's be crazy : does it make any sense to use B_c decays ?
    - forgetting about statistical issues $B_c \to D^{*+} \ell\ell$ may be a very clean way to access $b \to d\ell\ell$ for the $PS \to V\ell\ell$ case.

back-up slides

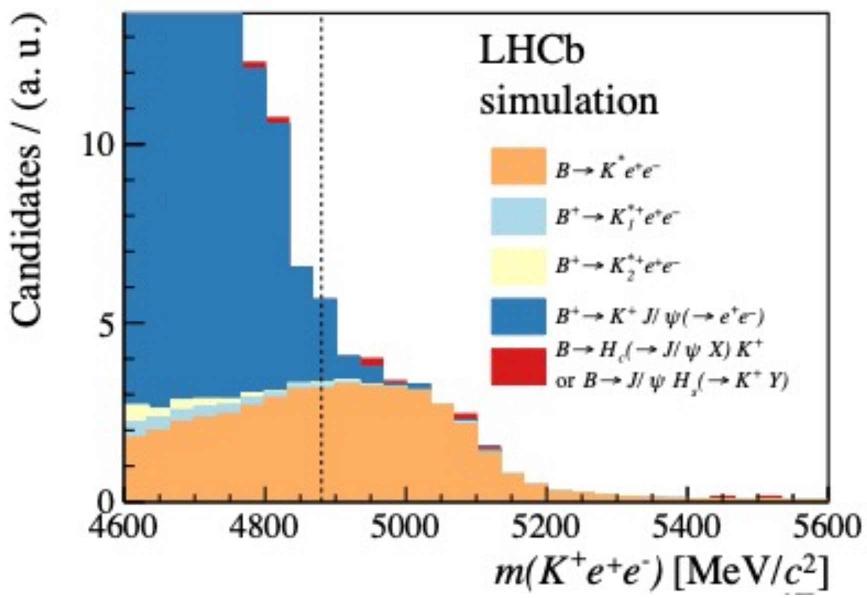
B → Kee case :

arXiv:2103.11769

semileptonic backgrounds veto:



backgrounds (simulation) :



from https://indico.cern.ch/event/1055780/