# New measurements using semileptonic $B_s$ decays

## Or: what did Suzanne do in Frascati?

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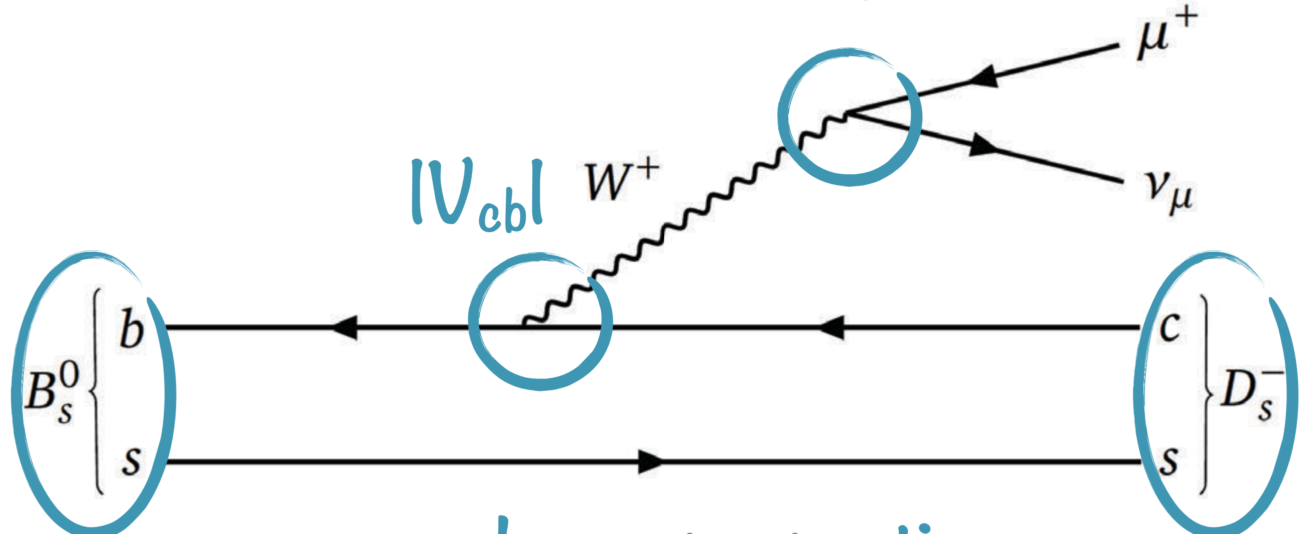
LNF Group 1 Seminar

Frascati, 13 December 2019

# Semileptonic decays

- Advantages:
  - large data samples
  - theoretically clean: only 1 hadronic current
  - trigger on muons
- Challenges:
  - neutrino: partially reconstructed decays
  - large amounts of backgrounds
  - huge simulation samples



# Overview

- Experiments:
  - B factories
  - LHCb
- LFU in $b \to c \ell \nu_\ell$ decays
  - current status
  - impact of radiative corrections
- Measurements with semileptonic $B_s$ decays
  - form factor measurements
  - $|V_{cb}|$
- Outlook and conclusion

**New results!**

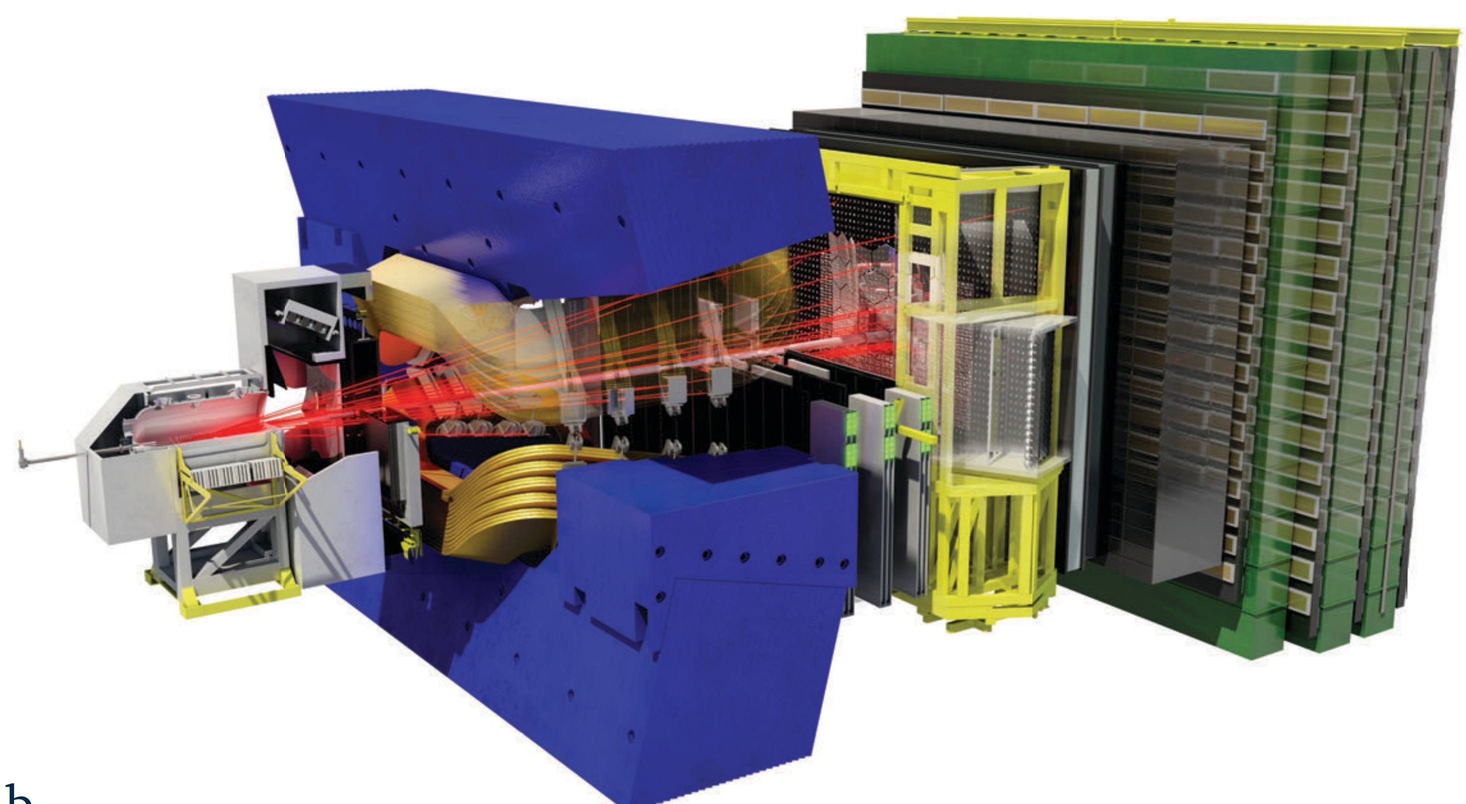
# Experiments: LHCb

JINST 3 (2008) S08005

- *pp* collisions @ LHC
- *b* quarks produced by gluon fusion → forward direction
- boosted CM energy helps to reconstruct vertices
- many more *b*'s, but a lot more background
- all *b*-hadron species are produced: $B^+$, $B^0$, $B_s$, $B_c$, $\Lambda_b$

Run 1: 2011–2012: 3 $fb^{-1}$ @ 7-8 TeV

Run 2: 2015–2018: 6 $fb^{-1}$ @ 13 TeV



# Is flavour universal?

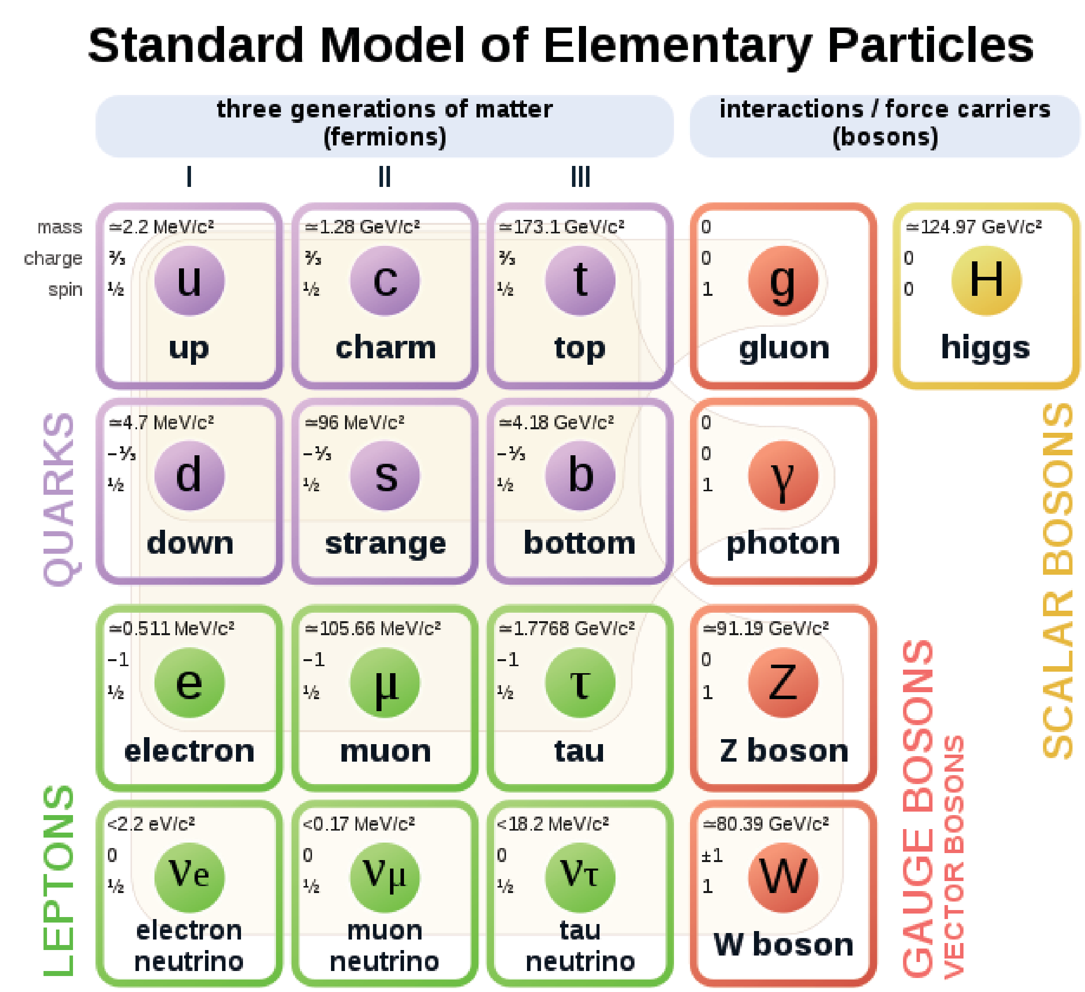
*UK* → *Roma*

→ *definitely not universal, always 'interesting'*

# Lepton flavour universality

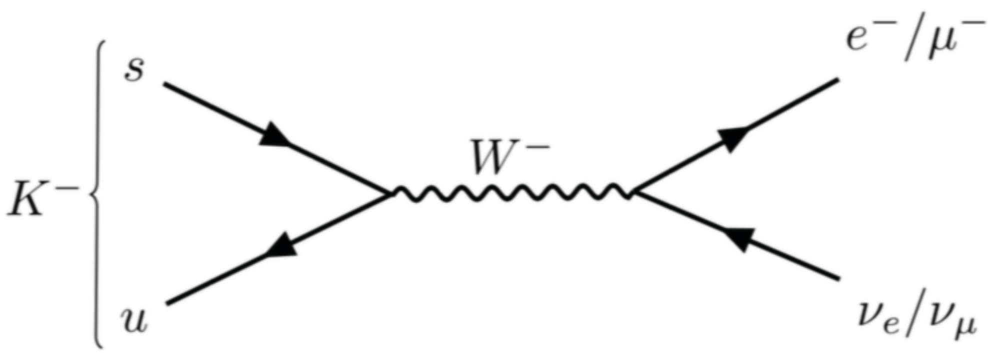
In the SM there are three families of fermions:

- they have same gauge charge assignments
  → same coupling (**universality**)
- only difference between the families comes from the Yukawa couplings with the Higgs field, resulting in **CKM** and **PMNS** matrices and **different masses**
- measure lepton universality in **ratios**: CKM elements cancel, and only difference is in **lepton mass**



# LFU in non b decays

- Most stringent results from kaon decays:




$$\frac{\Gamma_{K^-\to e^-\overline{\nu}_e}}{\Gamma_{K^-\to\mu^-\overline{\nu}_\mu}} = (2.488 \pm 0.009) \times 10^{-5}$$

Phys. Lett. B 719 326

- Prediction:

$$\left(\frac{\Gamma_{K^-\to e^-\overline{\nu}_e}}{\Gamma_{K^-\to\mu^-\overline{\nu}_\mu}}\right)^{\text{SM}} = \left(\frac{M_e}{M_\mu}\right)^2\left(\frac{M_K^2 - M_e^2}{M_K^2 - M_\mu^2}\right)(1 + \delta_{\text{QED}}) = (2.477 \pm 0.001) \times 10^{-5}$$

PRL 99 231801

- Also $Z\to\ell^-\ell^+$ in agreement with SM. Small deviation in $W\to\ell^-\nu_\ell$?
- Excellent agreement in charged-current coupling to leptons, *i.e.*

$$g_\mu/g_e = 1.0018 \pm 0.0014$$

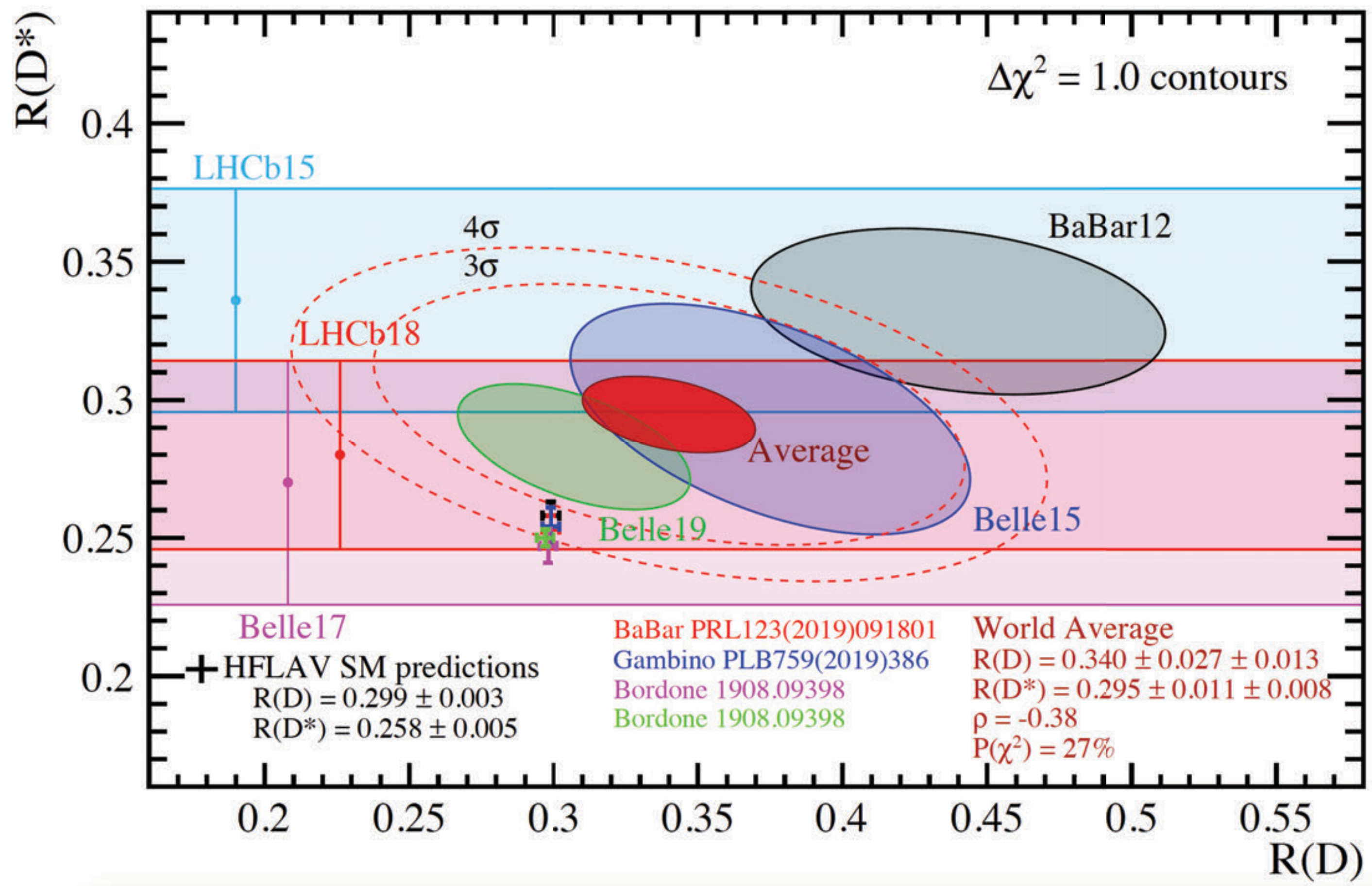
# Overview *R(D)* and friends

$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau \overline{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \ell' \overline{\nu}_{\ell'})}$$

ℓ' = μ (LHCb)

ℓ' = e/μ (B-factories)

- Tree-level processes are sensitive to new physics: charged Higgs, leptoquarks etc.
- Predictions are theoretically clean.
- 3-4σ tension with the SM for $R(D)$-$R(D^*)$.




https://hflav-eos.web.cern.ch/hflav-eos/semi/spring19/html/RDsDsstar/RDRDs.html

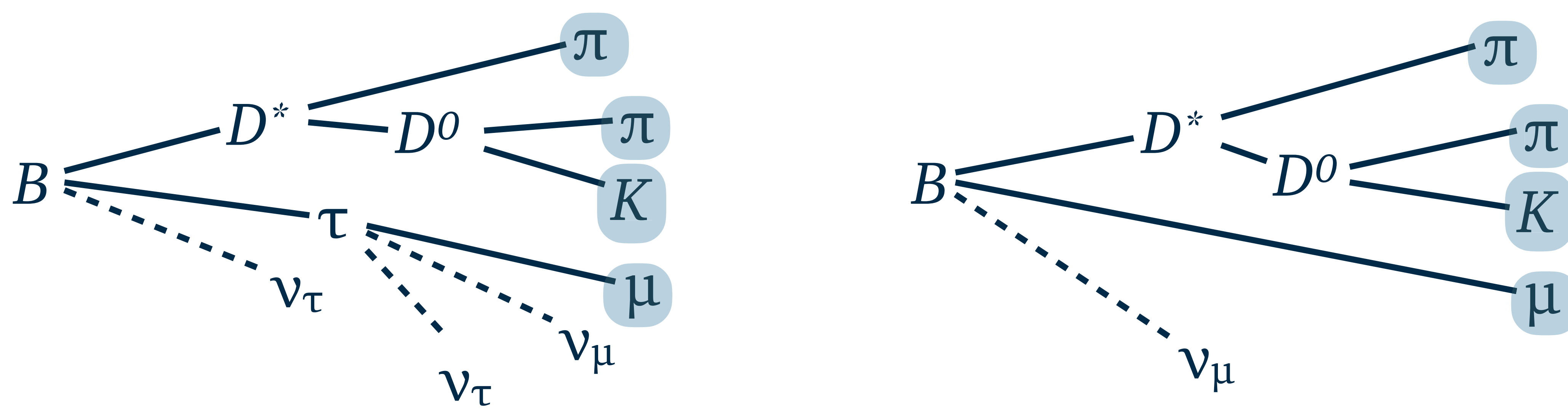
# Leptonic τ decays

## Reconstructing τ

- $\tau \to \mu\, \nu_\mu\, \nu_\tau$ $\mathscr{B}(\tau \to \mu\, \nu_\mu\, \nu_\tau) = 17.4\%$
- $\tau \to e\, \nu_e\, \nu_\tau$ $\mathscr{B}(\tau \to e\, \nu_e\, \nu_\tau) = 17.8\%$

## Strategy:

- Signal and normalisation channels have same visible final state




- Part of systematics cancels in the ratio.
- Backgrounds from inclusive semileptonic decays, with many unknowns (form factors, decay rates etc).

# Hadronic τ decays

## Reconstructing τ

- Hadronic decays:

| Decay | $\mathcal{B}$ (%) |
|---|---|
| $\tau^- \to \pi^-\pi^0 \nu_\tau$ | $25.49 \pm 0.09$ |
| $\tau^- \to \pi^- \nu_\tau$ | $10.82 \pm 0.05$ |
| $\tau^- \to \pi^-\pi^+\pi^- \nu_\tau$ | $9.02 \pm 0.05$ |
| $\tau^- \to \pi^-\pi^+\pi^-\pi^0 \nu_\tau$ | $4.49 \pm 0.05$ |

1-prong decays, only at *B* factories

3-prong decays, only at LHCb

## Strategy:

- Final states are not the same.
- Systematics (at LHCb) do not cancel in the ratio between signal and normalisation channel.
  → measure with respect to another decay with similar final state

# LHCb vs. *B*-factories

- LHCb:
  - use the *B* flight direction to measure transverse component of missing momentum
  - cannot measure longitudinal component, so use approximation to access rest frame kinematics:
    - $(\gamma\beta_z)_B = (\gamma\beta_z)_{D^*\mu}$
    - 18% resolution on *B* momentum
- *B* factories:
  - *B* momentum is known
  - tag algorithms use the other *B* in the event:
    - hadronic tag: 0.3% efficient, very pure: all backgrounds are fully reconstructed
    - SL tag: 1% efficient, less pure

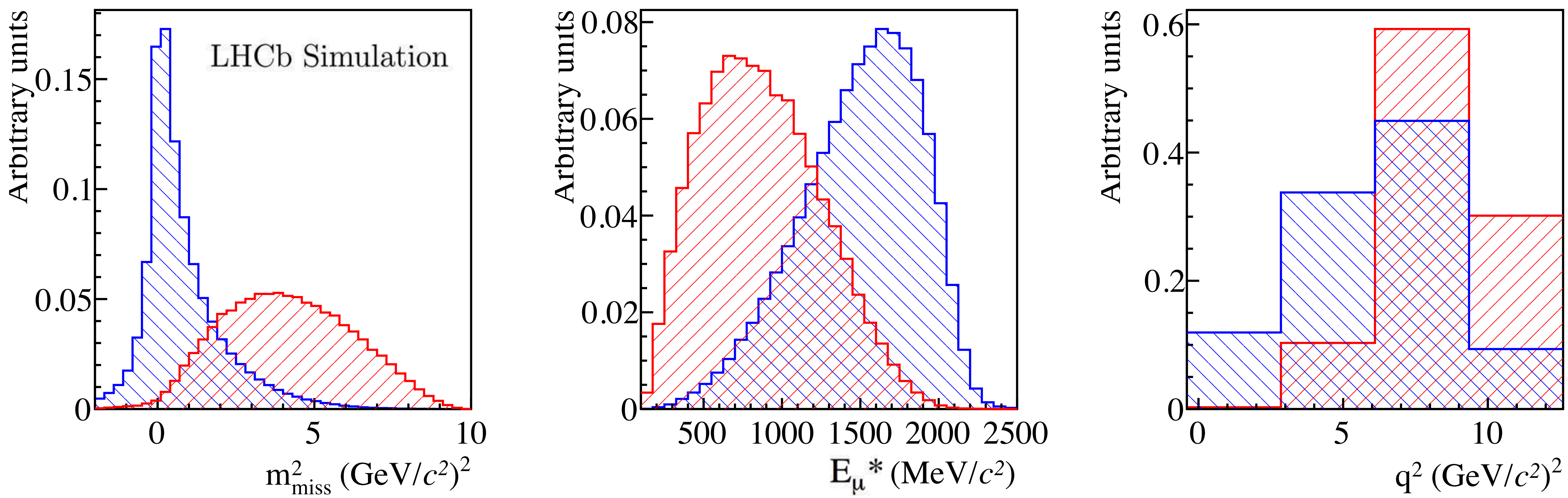
# Discriminating variables for *R(D)*

- Make the fit templates from most discriminating variables: kinematic
- As an *example**, the muonic *R(D*)* analysis from LHCb: **PRL 115 (2015) 111803**
  - signal channel: $\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$
  - normalisation channel: $\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$

* *Other analyses use different variables*

$m^2_{\text{miss}} = (p_B - p_{D^*} - p_\mu)^2$

$q^2 = (p_\ell + p_\nu)^2 = (p_B - p_{D^*})^2$



# Measurements of R(D*) in LHCb

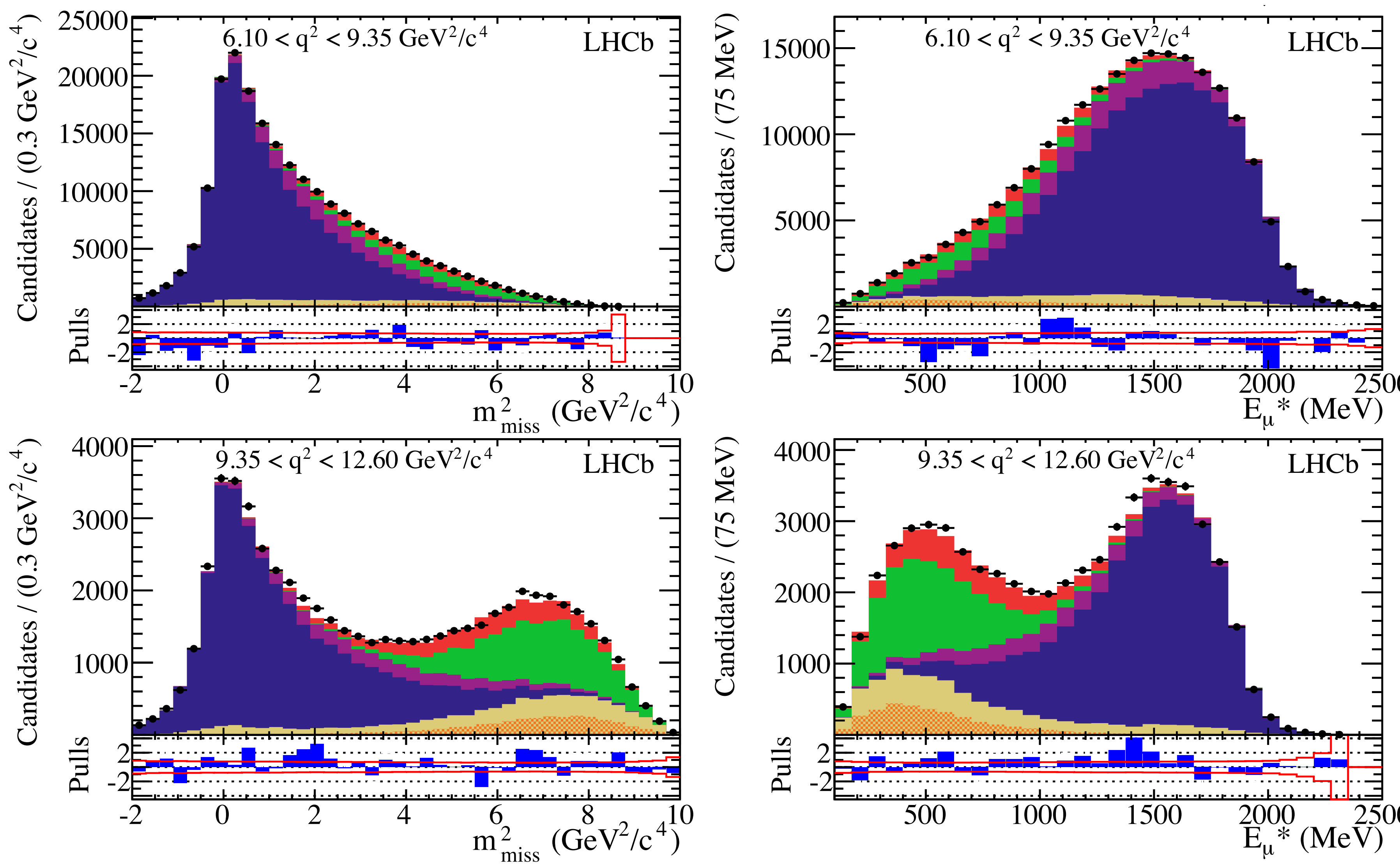
# *R(D*)* leptonic

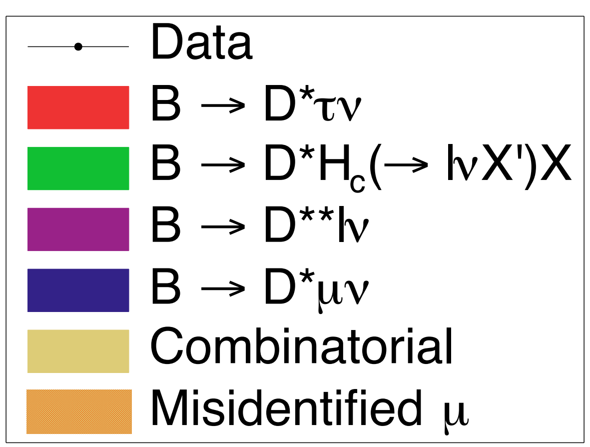
PRL 115 (2015) 111803

$$\mathcal{R}(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst}) \qquad \mathcal{R}(D^*) = \frac{\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau}{\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu}$$

- Compatible with SM within 2.1σ

Run 1



# $R(D^*)$ hadronic

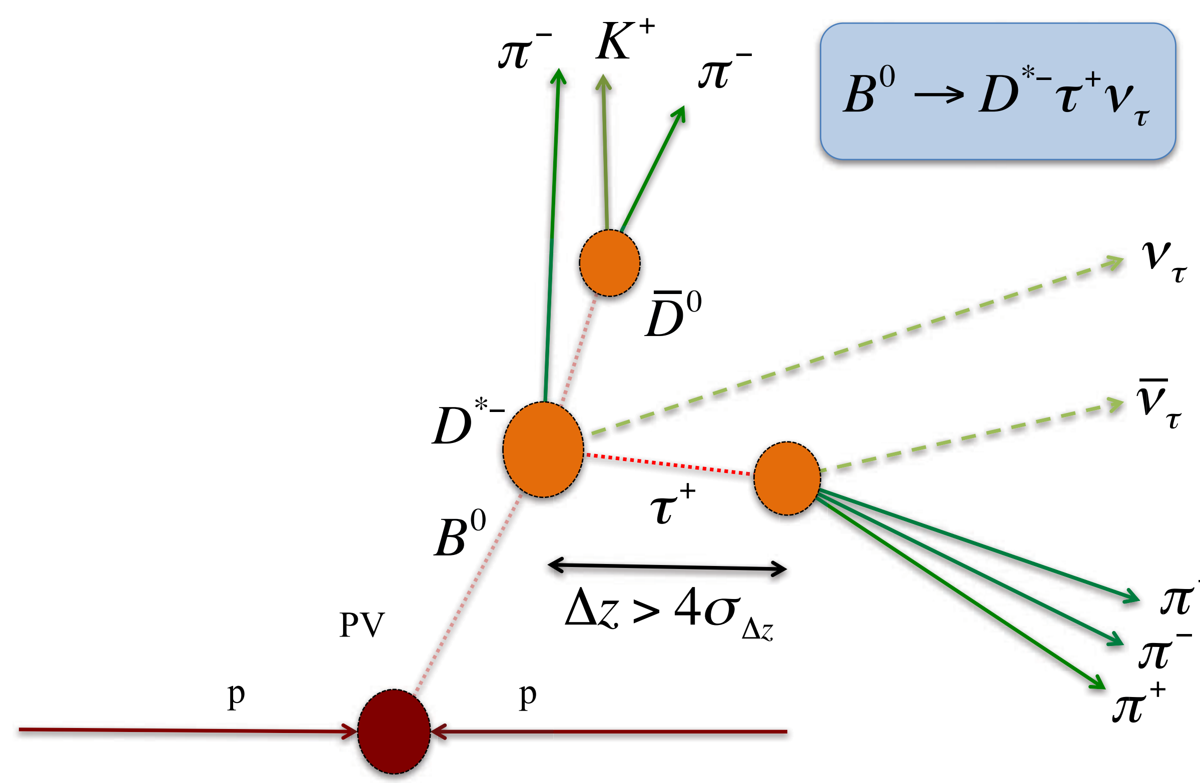
PRD 97, 072013 (2018)

PRL 120, 171802 (2018)

$$\mathcal{R}(D^*) = \underbrace{\left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}\right)_{\text{meas}}}_{\mathcal{K}(D^*)} \times \left(\frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}\right)_{\text{external}}$$

Run 1

- Signal and normalisation channels have the same final state, such that many systematics cancel in the ratio.
- Use topology of the decay to suppress backgrounds.



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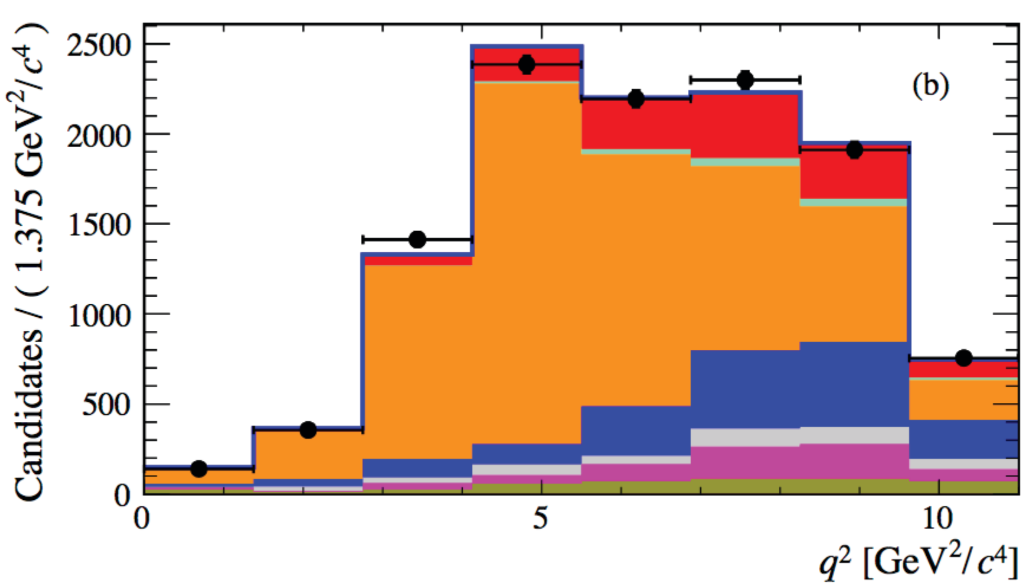
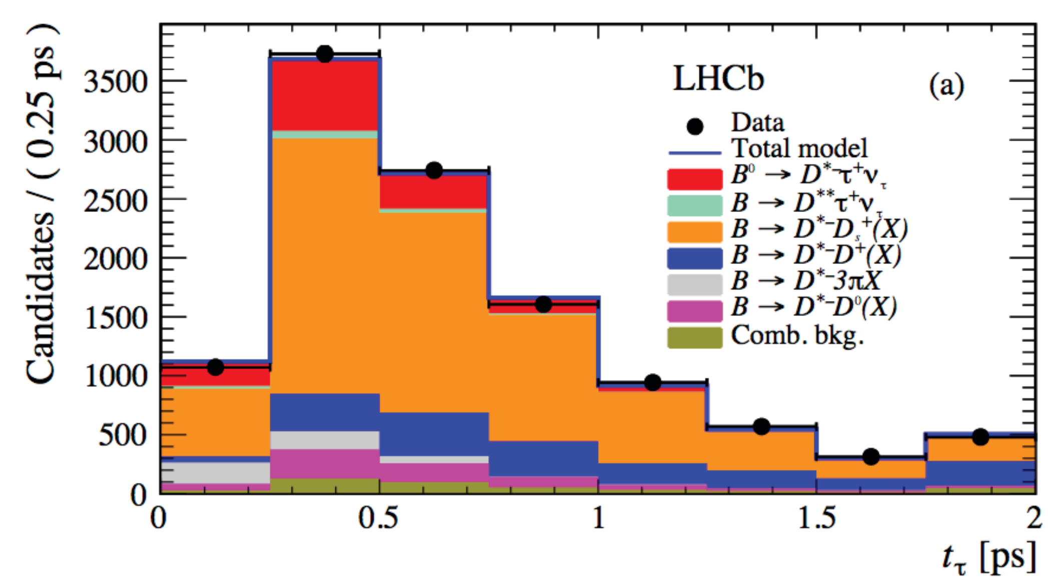
- $\mathcal{K}(D^*) = 1.93 \pm 0.12(\text{stat}) \pm 0.17(\text{syst})$
- $\mathcal{R}(D^*) = 0.280 \pm 0.018(\text{stat}) \pm 0.029(\text{syst})$
- Compatible with SM within 1σ



# Radiative corrections on *R*(*D*) measurements

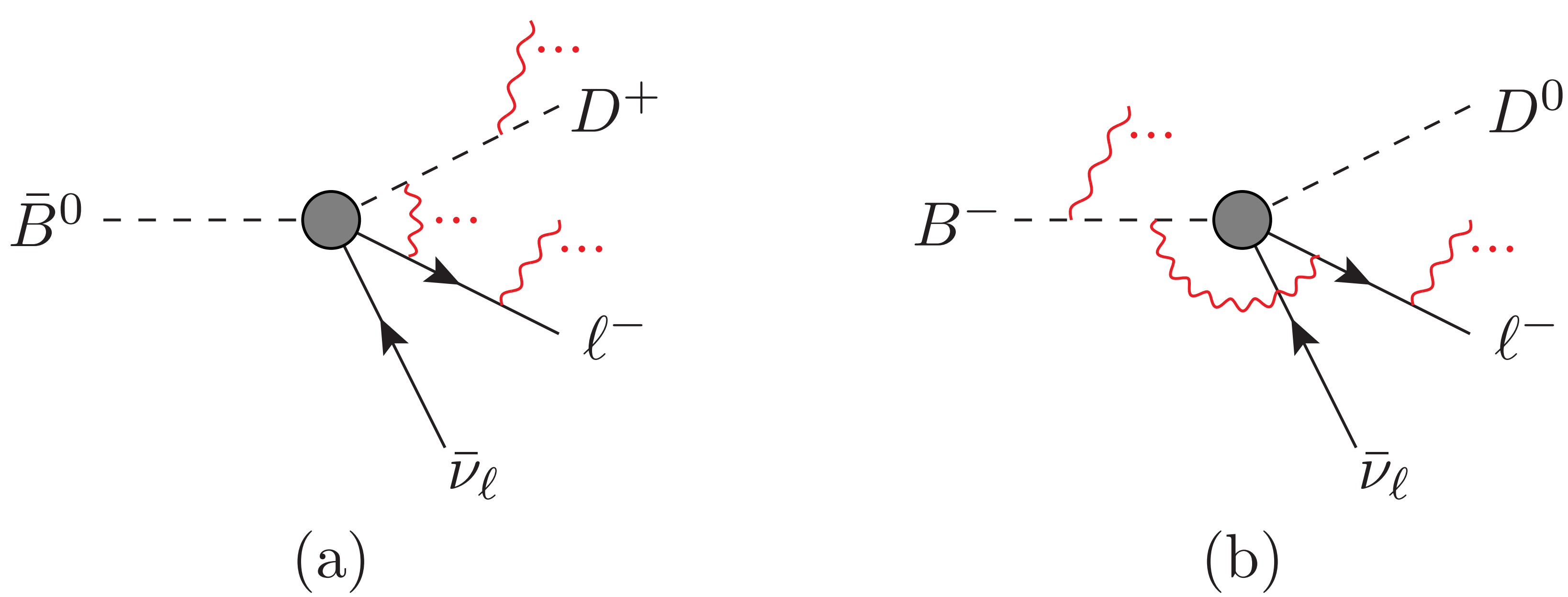
S.Calì, SK, M.Rotondo, B.Sciascia

# Radiative corrections

- Generally assumed to cancel in the ratio $R(H_c) = \dfrac{\mathcal{B}(H_b \to H_c \tau \overline{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \ell' \overline{\nu}_{\ell'})}$
- However, last year an article on soft-photon corrections claimed the following: PRL 120, 261804 (2018).
    - *Long-distance QED corrections on $R(D^+)$ and $R(D^0)$ are non-negligible and can amplify the theoretical predictions by respectively ∼5% and ∼3%. These corrections are not covered by PHOTOS. Since PHOTOS is used by LHCb, BaBar and Belle, all results could be influenced.*
- SM predictions could be amplified by 5.5% and 3.6%, which is larger than the uncertainties on the lattice predictions.
- How does this affect our measurements? (Caveat: it does <u>not</u> contain any corrections on published or ongoing LHCb analyses)
- Could this reduce the tension between experimental and theoretical values?

# Radiation in simulation: PHOTOS

- PHOTOS is a universal MC algorithm that simulates QED corrections.
- PHOTOS includes both soft and hard photon corrections. The latter are not included in the study in PRL 120, 261804 (2018), so we cannot compare this.
- Has successfully been tested for $W$, $Z$ and $B$ decays, should be tested for every type of measurements, especially when high precision is needed.
- It does not include Coulomb interactions, which PRL 120, 261804 (2018) does. These are relevant for the $D^+$ (and $D^{*+}$) mode, but not for the $D^0$ mode:



# Samples for studying radiative corrections

- Generated 3M events in 4 samples
  - $\overline{B}^0 \to D^+\ell^-\overline{\nu}_\ell$ and $B^- \to D^0\ell^-\overline{\nu}_\ell$ , with $\ell^- = \mu^-, \tau^-$
  - generator level only, no detector reconstruction
  - PHOTOS version 3.56, "Option with interference is active"
- Calculate the four-momentum carried away by the radiative photons as:

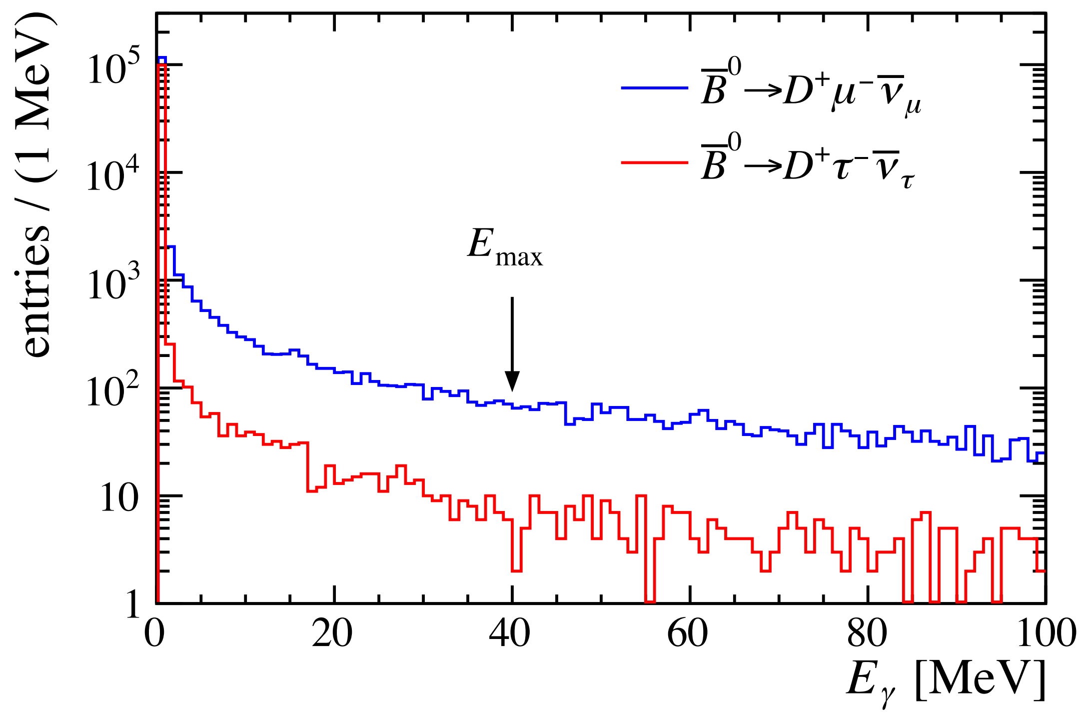
$$p_\gamma = p_B - (p_D + p_{\ell^-} + p_{\bar{\nu}_\ell})$$

  - Like in the paper, we only consider radiation from the *D* and not of its daughters.
- QED corrections are defined as relative variation of the branching ratio due to events lost because $E_\gamma > E_{max}$:

$$\delta_{\mathrm{QED}} = \frac{\int_0^{E_{\mathrm{max}}} N(E_\gamma)dE_\gamma}{\int_0^\infty N(E_\gamma)dE_\gamma} - 1$$

# The $E_{max}$ variable

EPJC 79 (2019) 744

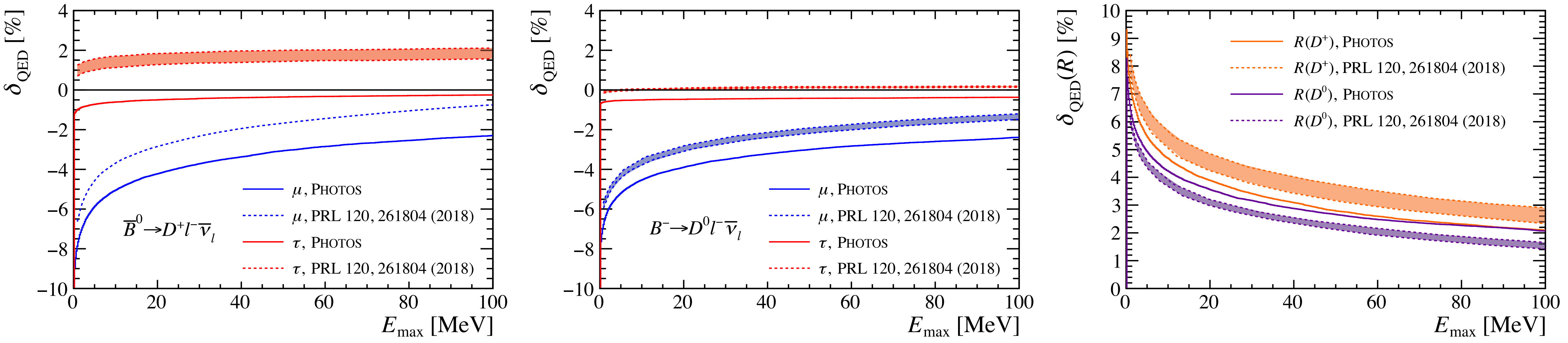



- Results are shown as a function of $E_{max}$: maximum energy that radiative photons in the event are allowed to have to be considered signal rather than background.
- Note, the effects of the QED corrections are global, so they are still there when not applying a cut on $E_{max}$.

# Comparing results

EPJC 79 (2019) 744

- Results are shown as a function of $E_{\text{max}}$, to be able to compare with the results from PRL 120, 261804 (2018):

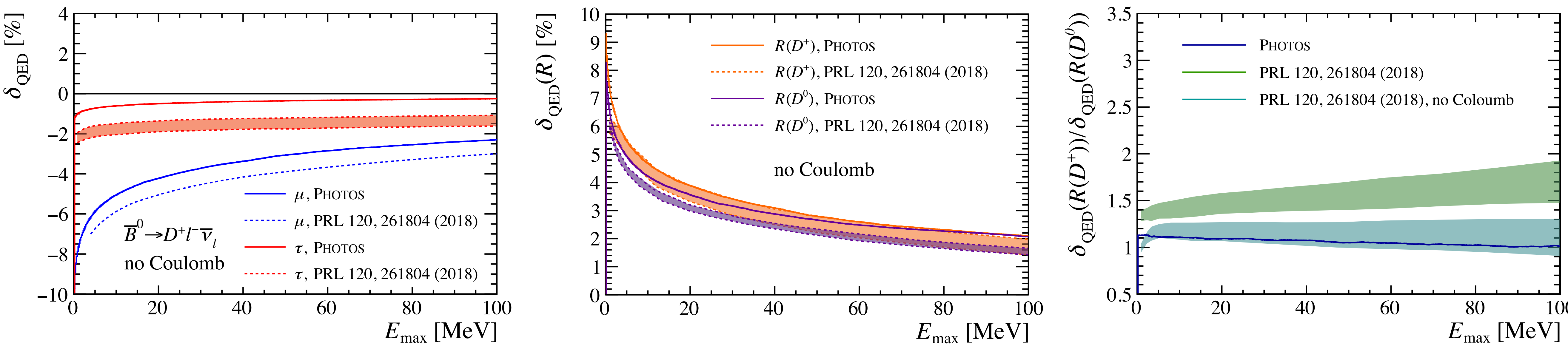



- Differences of 0.5-1% for $B^-$ decays, even up to 2% for $B^0$.
- Discrepancies cancel largely, but not completely in the ratios $R(D^0)$ and $R(D^+)$, discrepant by 0.5%.

# Comparing results II

EPJC 79 (2019) 744

- When discarding the Coulomb corrections from PRL 120, 261804 (2018), results for $B^0$ decay get in closer agreement and corrections on $R(D^+)$ are very consistent.




- PRL 120, 261804 (2018) gives different results for $R(D^0)$ and $R(D^+)$, breaking isospin symmetry, while those are not there in PHOTOS. This difference disappears when ignoring the Coulomb corrections that are used for $R(D^+)$.

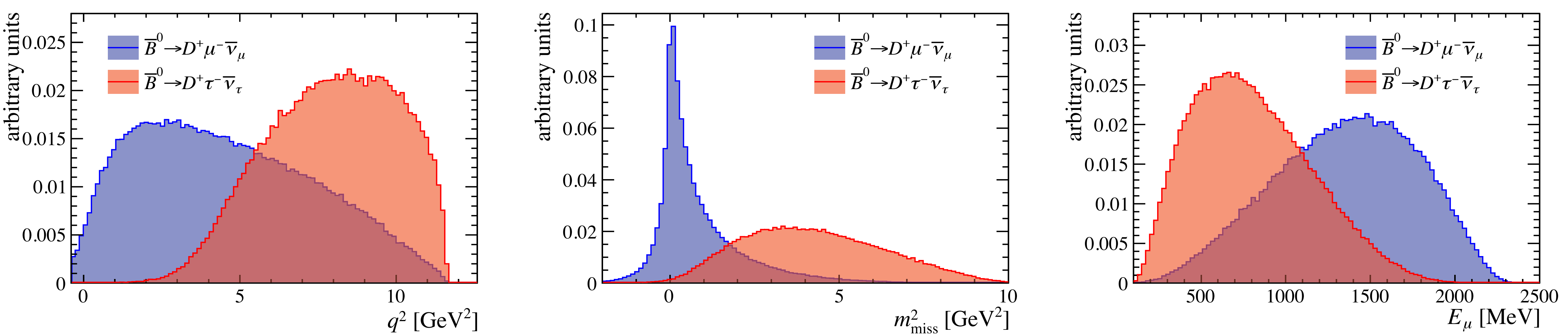
# Second part of our study

- What is the effect of mismodelling QED corrections in our MC on measurements of LHCb?
- Applied LHCb-like selection on generated samples (see next slide).
- Using this, we make a dummy analysis:
  - ➤ simplified: just signal and normalisation samples
  - ➤ generate 10.000 toy samples per decay mode with no cuts on $E_{\text{max}}$
  - ➤ generate templates with different cuts on $E_{\text{max}}$
  - ➤ fit for $R(D)$ using 3D templates ($q^2$, $m_{\text{miss}}$, $E_\ell$) (same as in muonic $R(D^*)$) and study the effect PRL 115 (2015) 111803
- This simulates worst-case scenario.
- Done to develop a method to determine the effect on measurements, does not give corrections to existing/future measurements.

# LHCb-like selection

EPJC 79 (2019) 744
based on JHEP 02 (2017) 021

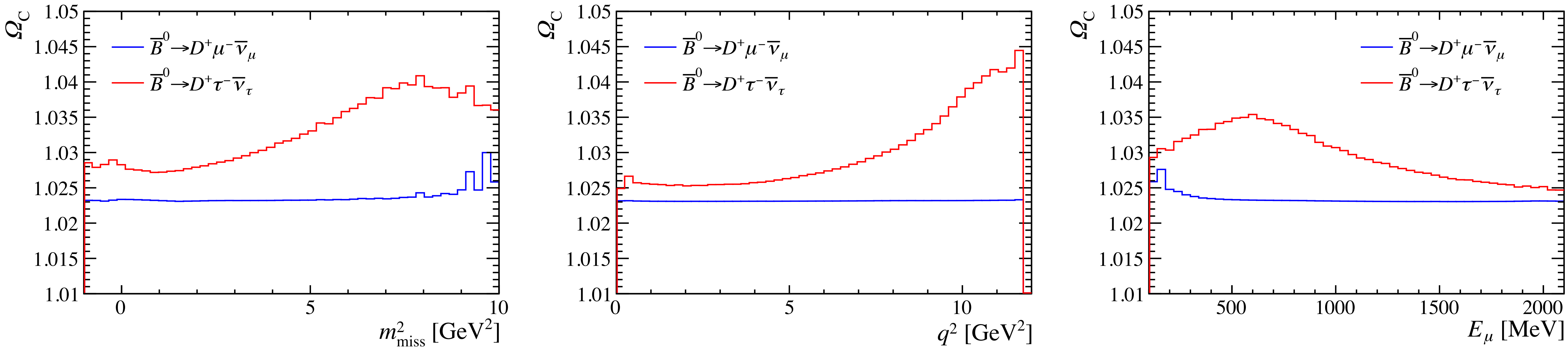
- Simulate vertex resolution by smearing the $pp$ vertex by (±13, ±13, ±70) μm and the $B$ decay vertex by (±20, ±20, ±200) μm
- Simulate LHCb acceptance using the cuts: $1.9 < \eta < 4.9$, $p > 5$ GeV, $p_T > 250$ MeV on kaons, pions and muons and a distance between $pp$ and $B$ vertex > 3 mm.
- Reconstruct $B$ meson momentum and related quantities using the LHCb rest frame approximation.




- Distributions look very similar to those from full detector simulation!

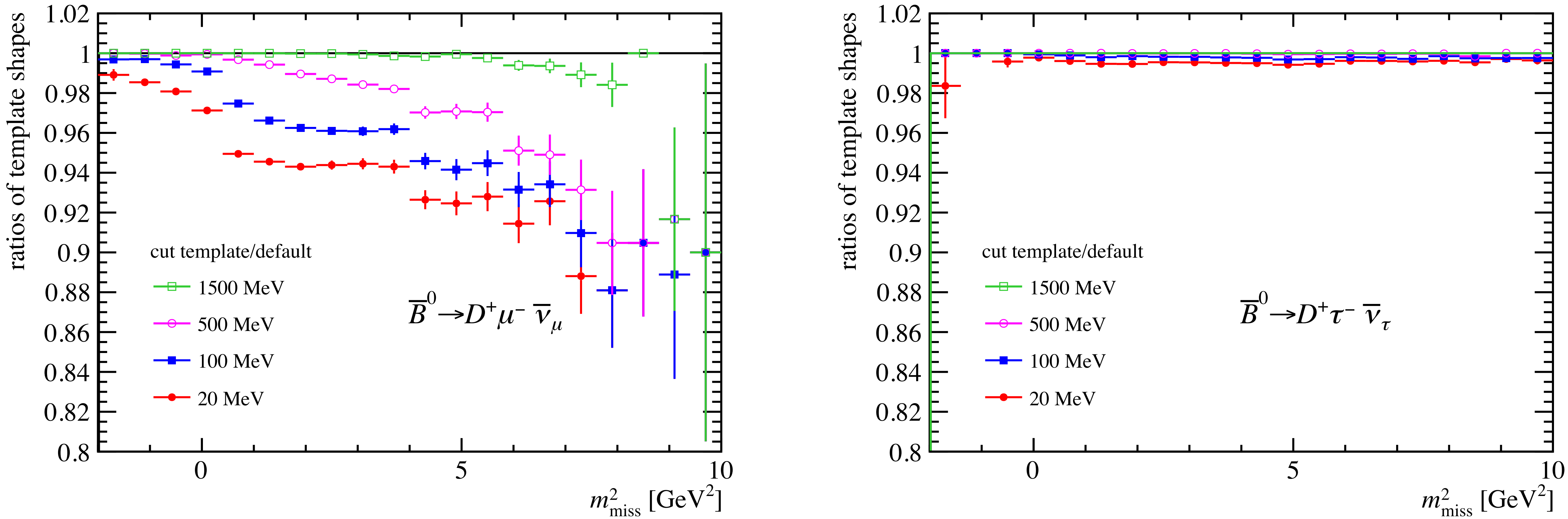
# Coulomb corrections in toys EPJC 79 (2019) 744

- Coulomb correction as a function of fit variables:



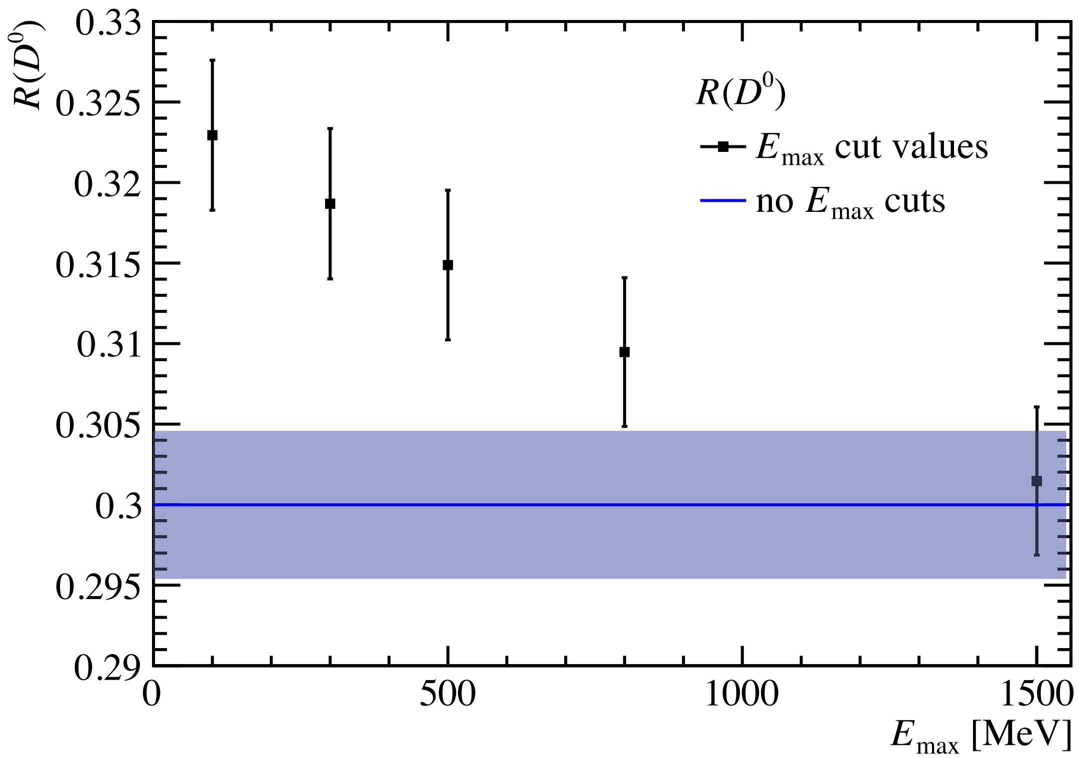

- This does not cancel in the ratios of $R(D)$.
- In our LHCb-like analysis, shift on $R(D^+)$ is -0.003 (-1%) when including Coulomb corrections on toys, but not templates.
- This can and should be studied for each analysis separately, because it depends on selection, reconstruction efficiency etc.

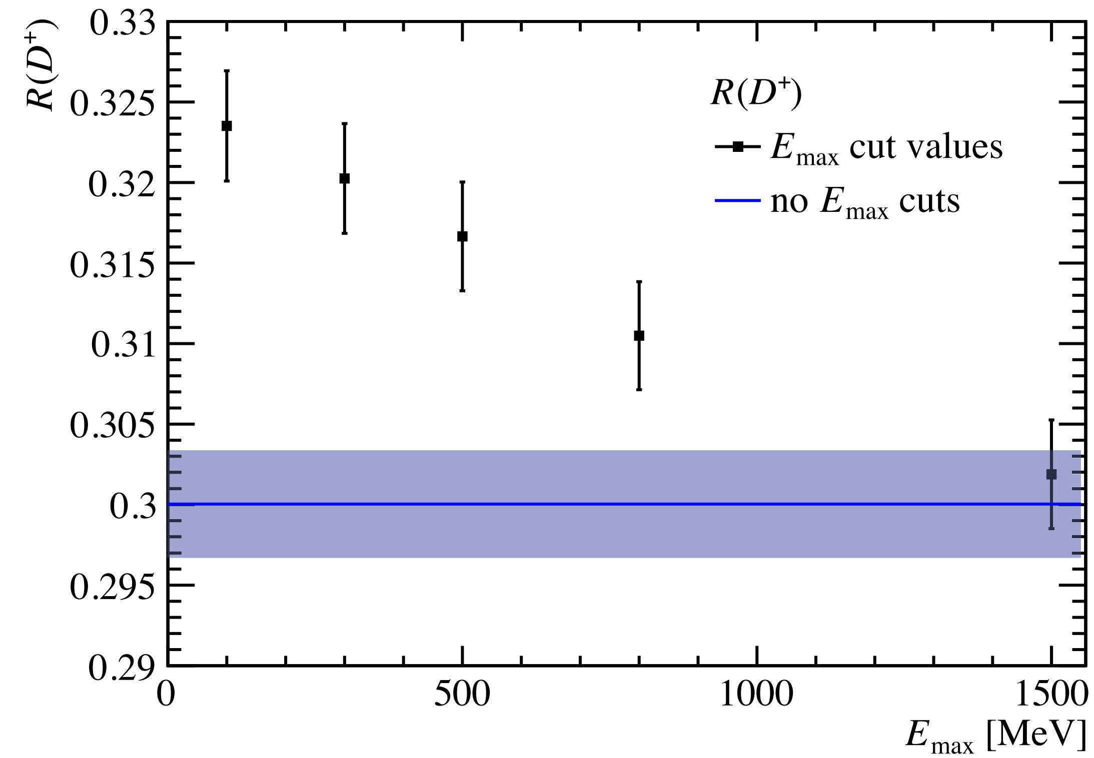
# Dummy analysis: effect on template




- Applying different cuts on $E_{max}$: at 20, 100, 500, and 1500 MeV changes shape of fit templates. Cutting on photon energy probes over- or underestimation of radiative corrections.
- Most clearly visible on missing mass variable, which is effected strongly in the μ decays, barely in the τ decay.

# Outcome dummy analysis




- By including cuts on $E_{max}$ in the templates, but not toys (or vice versa), study the effect of over- or underestimating radiative corrections in MC.
- Done for cuts on $E_{max}$, at 100, 300, 500, 800, and 1500 MeV.
- Change on $R(D)$ is very similar for $R(D^+)$ and $R(D^0)$
- Largest when applying a cut on $E_{max}$ around 100 MeV, shifting $R(D)$ by 0.02, or 7%.

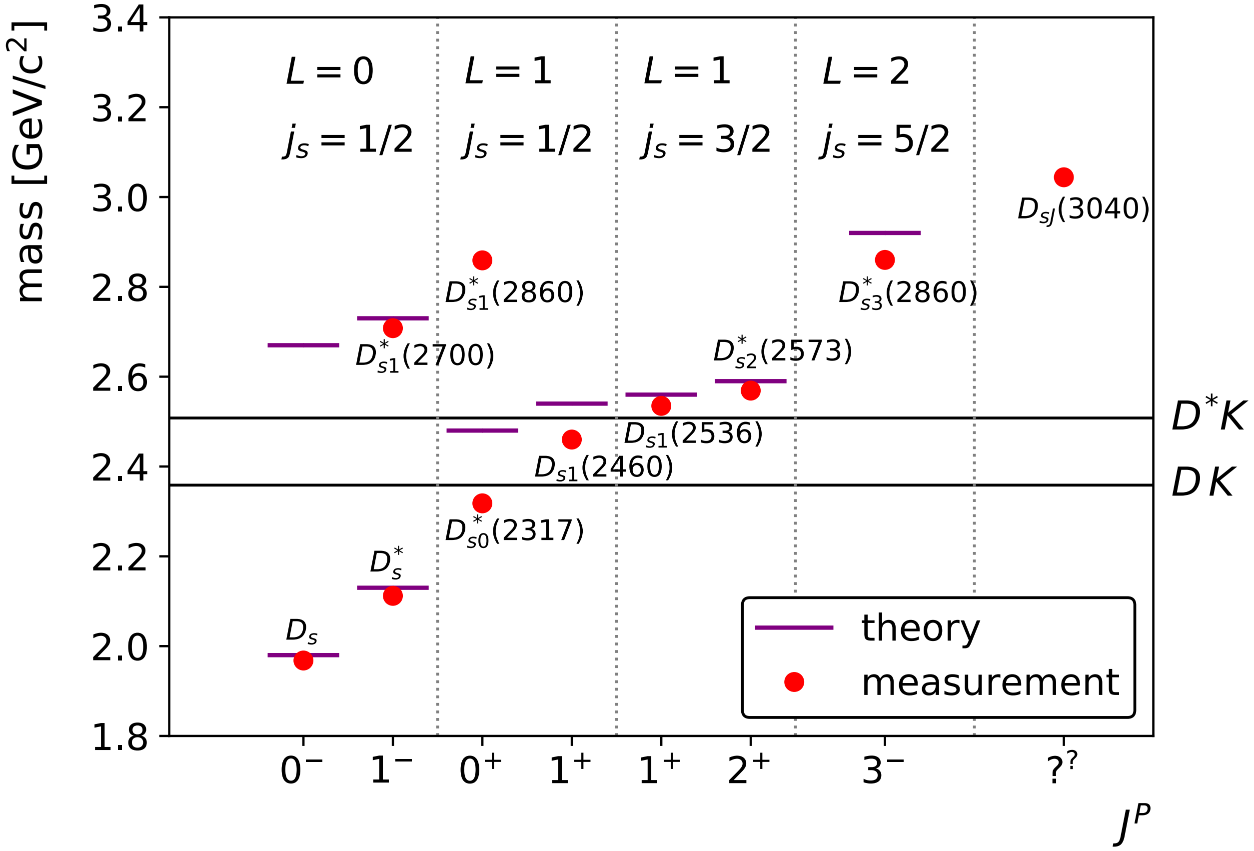
# Conclusions and recommendations

- Corrections described in PRL 120, 261804 (2018) are not fully included in PHOTOS.
- Small corrections largely cancel out in the ratio $R(D)$, but a 1% difference between $R(D^0)$ and $R(D^+)$ is due to Coulomb corrections.
- Coulomb corrections affect kinematics of $\tau$ decays, which impacts shapes templates, yielding corrections of 1% on LHCb-like analysis.
  - ➤ Can and should be determined for each analysis separately.
- Mis-modelling QED corrections in a **worst-case scenario** can lead to a bias of $\sim$7% in LHCb-like analysis.
  - ➤ Cuts on photon energy should be studied by analysts.
- Input is needed from the theory community to make accurate comparisons of radiative corrections, especially for future measurements with higher precision. Current studies stop at energies of 100 MeV, while we need also structure-dependent and high-energy photons.

# Semileptonic $B_s$ decays

# Motivation for $B_s$ decays

- Semiletponic $B_s$ decays offer a great environment to form factors, CKM matrix elements and LFU, complementary to $B^+/B^0$ decays, but have not been studied much yet
  - Lattice-QCD calculations are easier due to the heavier spectator quark → more precise predictions
  - Different backgrounds than in $B \to D^{(*)}$ decays, specifically from excited $D$ states:

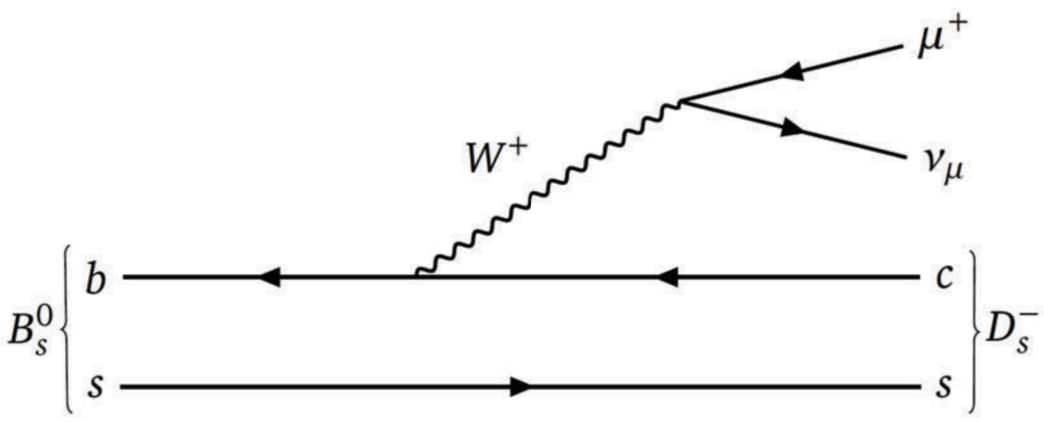


**NEW**

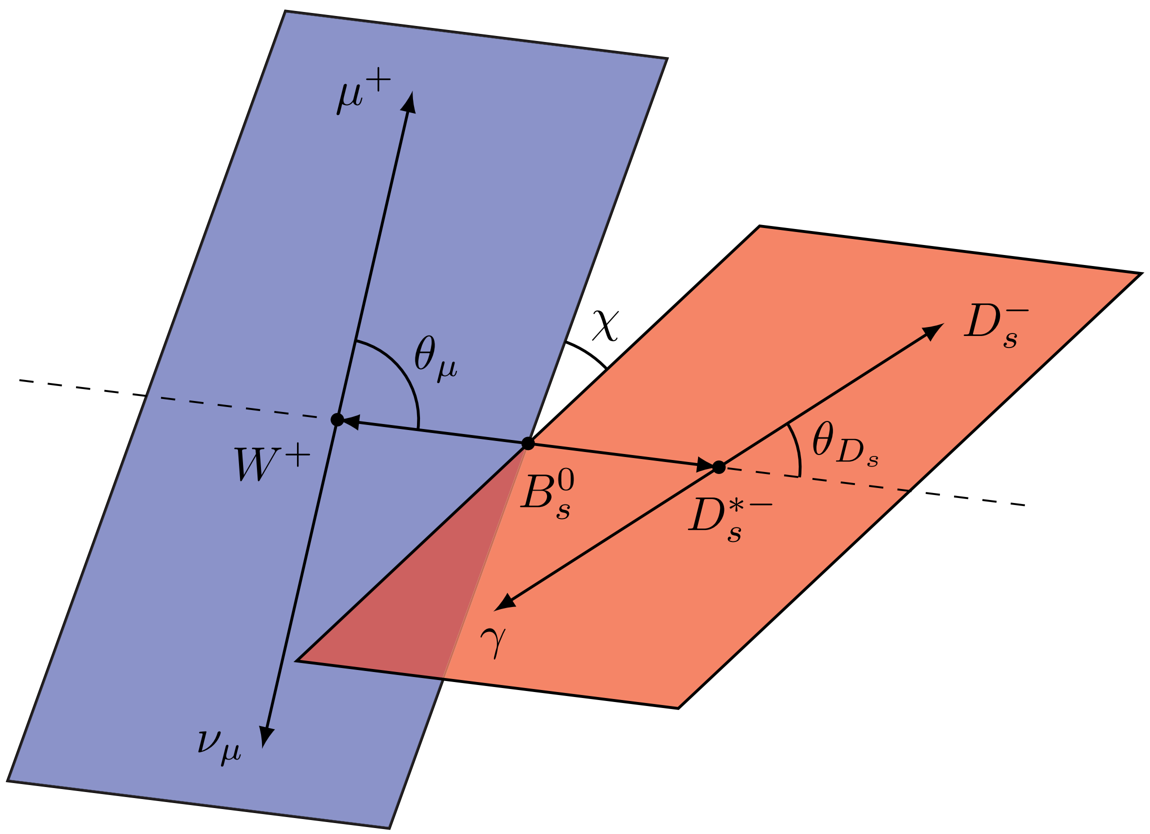
# Shape of the $B_s \to D_s^* \mu\nu$ decay distribution

# $B_s \to D_s^* \mu\nu$ decays

- Hadronic current in the decay can be described in terms of scalar functions, called *form factors*




- For this decay, there are four form factors, but this can be simplified to *one leading form factor,* which is the one that we fit




- Integrate over all angles of the decay
- Then measure the decay rate, as a function of lepton energy transfer ($q^2$), equivalent to hadron recoil ($w$)

$$w = \frac{p_{B_s^0} \cdot p_{D_s^{*-}}}{m_{B_s^0}\, m_{D_s^{*-}}} = \frac{m_{B_s^0}^2 + m_{D_s^{*-}}^2 - q^2}{2\, m_{B_s^0}\, m_{D_s^{*-}}}$$

- Decay rate is used to fit form factor, with two different parametrisations

# Form factor parametrisations

- Two commonly used parametrisations:
  - CLN (Caprini-Lellouch-Neubert):

$$h_{A_1}(w) = h_{A_1}(1)[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3]$$

    - $z = (\sqrt{w+1} - \sqrt{2})/(\sqrt{w+1} + \sqrt{2})$
    - fit for $\rho^2$, others FF parameters fixed to the world average from decays $B \to D^*$ and lattice-QCD
  - BGL (Boyd-Grinstein-Lebed):

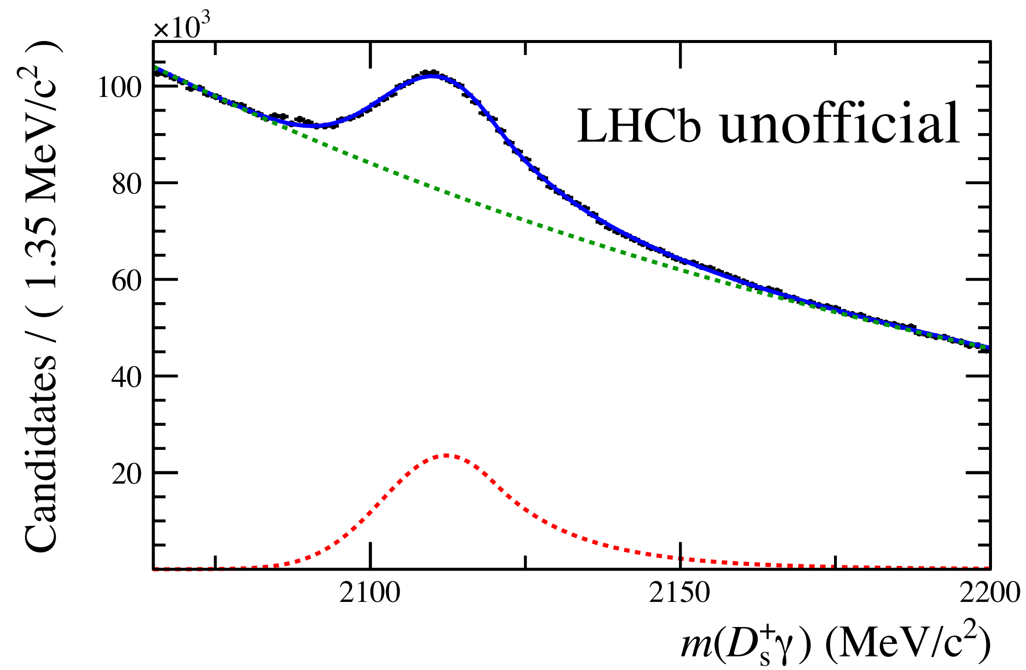
$$f(z) = \frac{1}{P_{1+}(z)\phi_f(z)} \sum_{n=0}^{\infty} a_n^f z^n$$

    - also fit only 1 form factor, constrain others from fits to $B \to D^*$ decays and lattice-QCD; fit parameters $a_1^f$ and $a_2^f$
    - BGL must be truncated at order $n$, here $n$=2

# Signal selection

- Measure the $B_s^0 \to D_s^{*+} \mu^- \nu_\mu$ decay, with $D_s^{*+} \to D_s^+ \gamma$
- Reconstruct the $D_s^+$ in $K^+ K^- \pi^+$ final state
  (specifically $\varphi\pi$ and $K^*K$ resonances to reduce backgrounds)
- Reconstruct soft photon, removing lots of background by fitting $D_s^*$ mass

Run 2

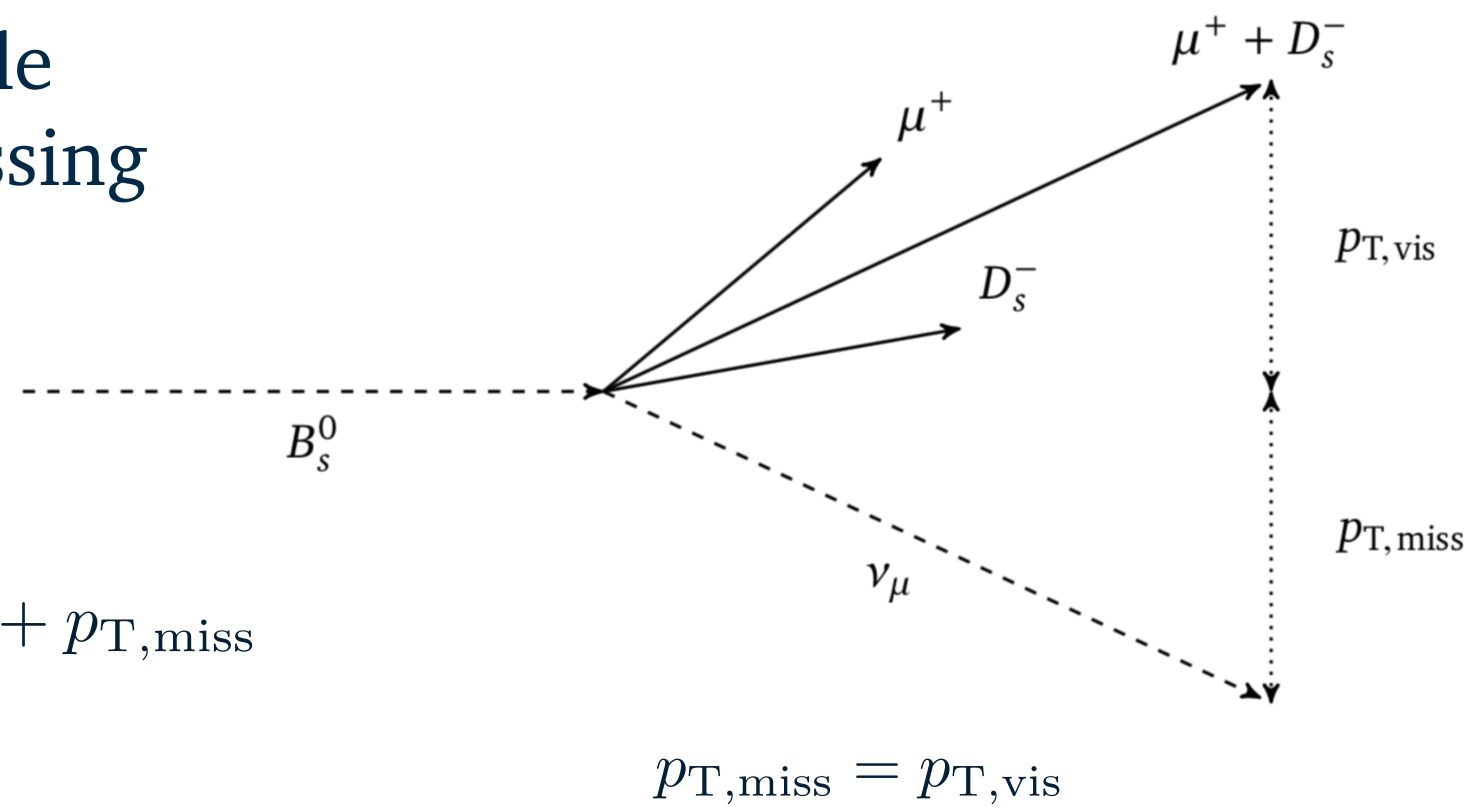



- Remove misID background by applying vetoes → very clean sample
- Apply $\mu$ $p_{\mathrm{T}}$ cut >1.2 GeV to remove backgrounds from $\tau$ decays

# Useful variables and tools

**Corrected mass:**

- use flight direction of visible particles to reconstruct missing mass

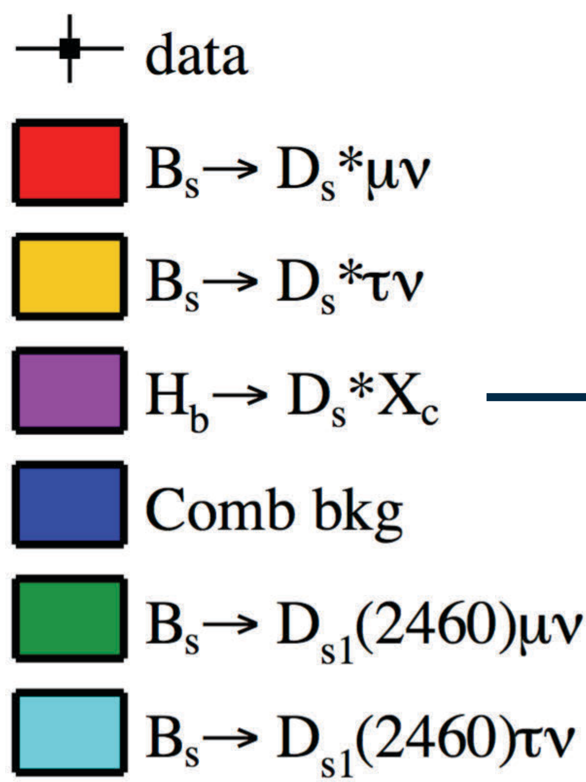



$$m_{\mathrm{corr}} = \sqrt{(m_{\mathrm{vis}})^2 + (p_{\mathrm{T,miss}})^2} + p_{\mathrm{T,miss}}$$

- quadratic ambiguity improved using MVA based on flight direction JHEP 02 (2017) 21

# Extracting signal yields

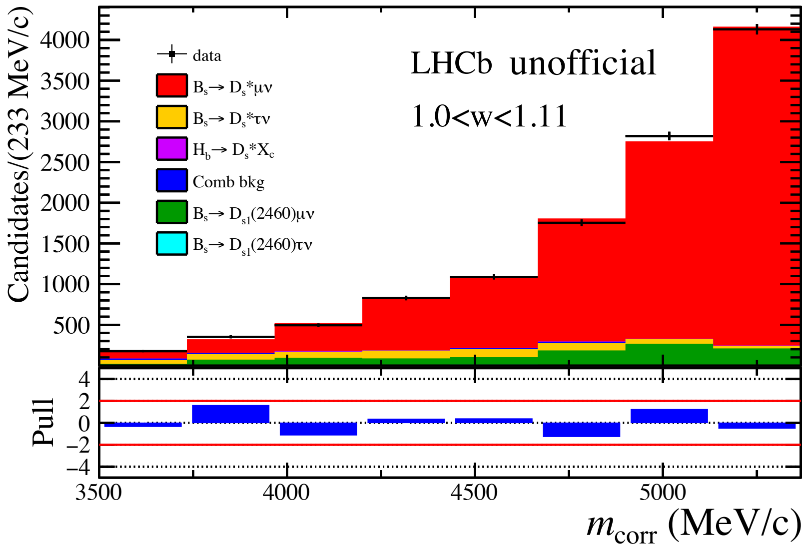
- Fitting the corrected mass using template fits in 7 bins of $w$, chosen such that each bin has same amount of (MC) signal.
- Templates are based on MC simulations, except for combinatorial background, which comes from $B_s^0 \to D_s^{*-}\mu^-\nu_\mu$ decays (same-sign)

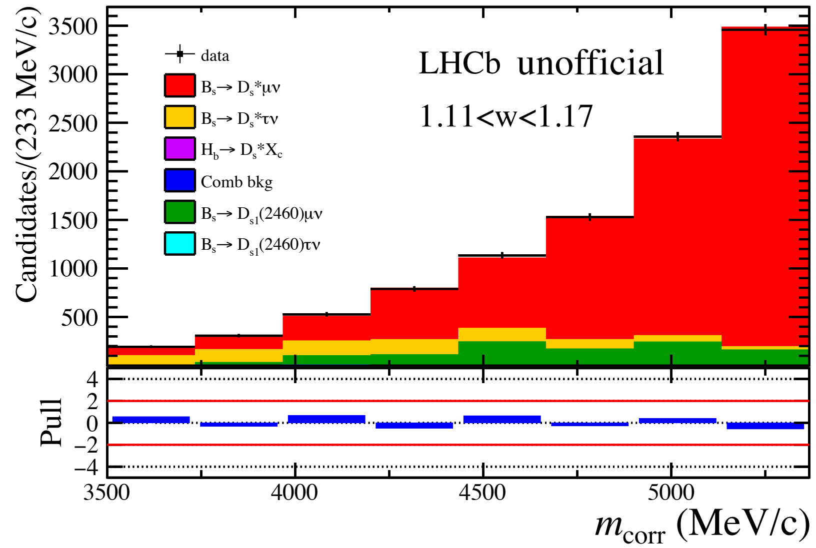


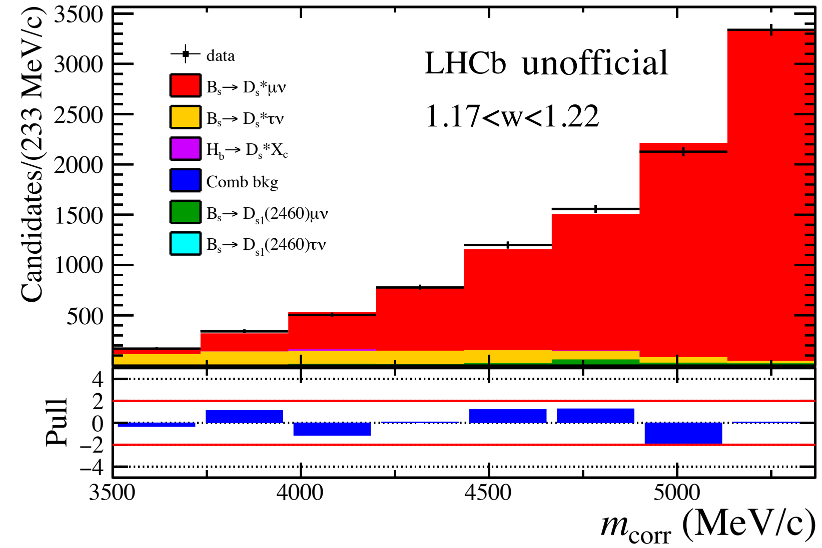

*fixed to expected values*

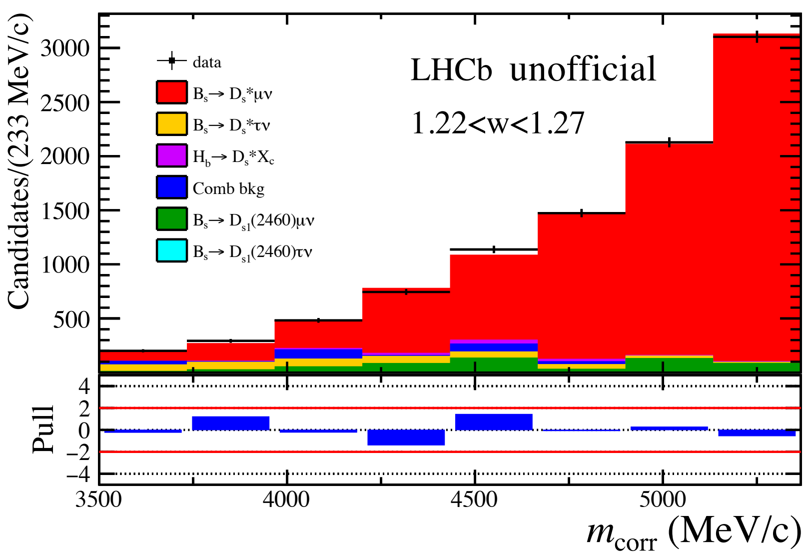
*fixed w.r.t. $D_{s1}\mu$ decays (negligible)*

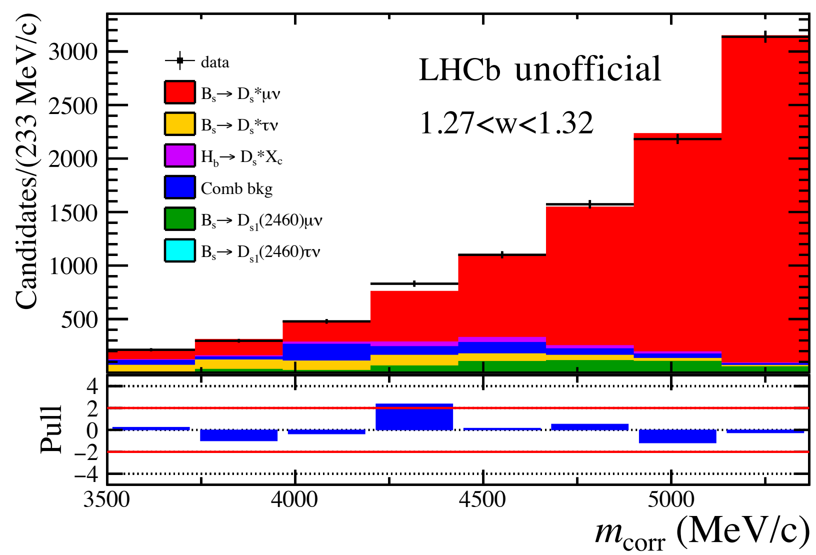
# Extracting signal yields II

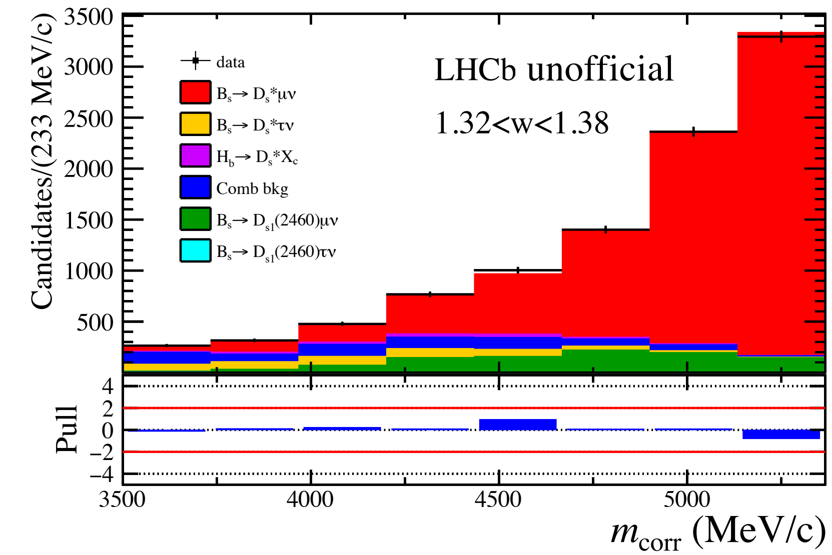


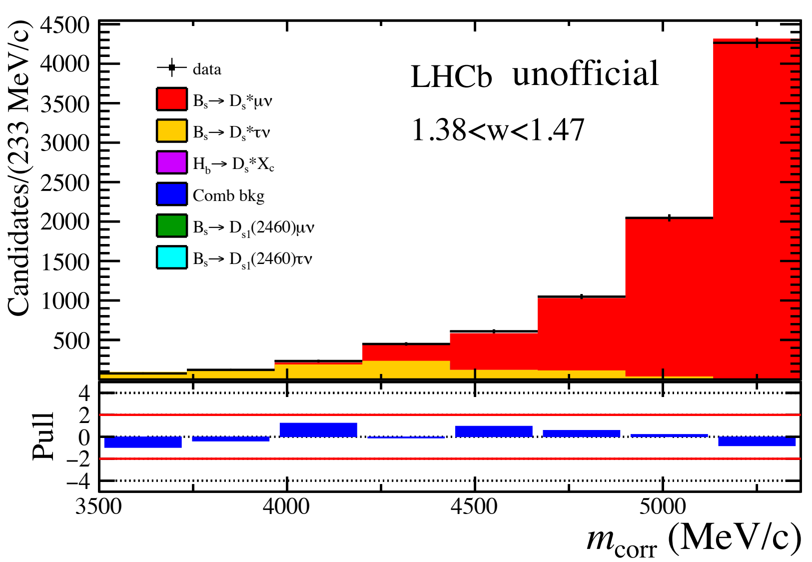



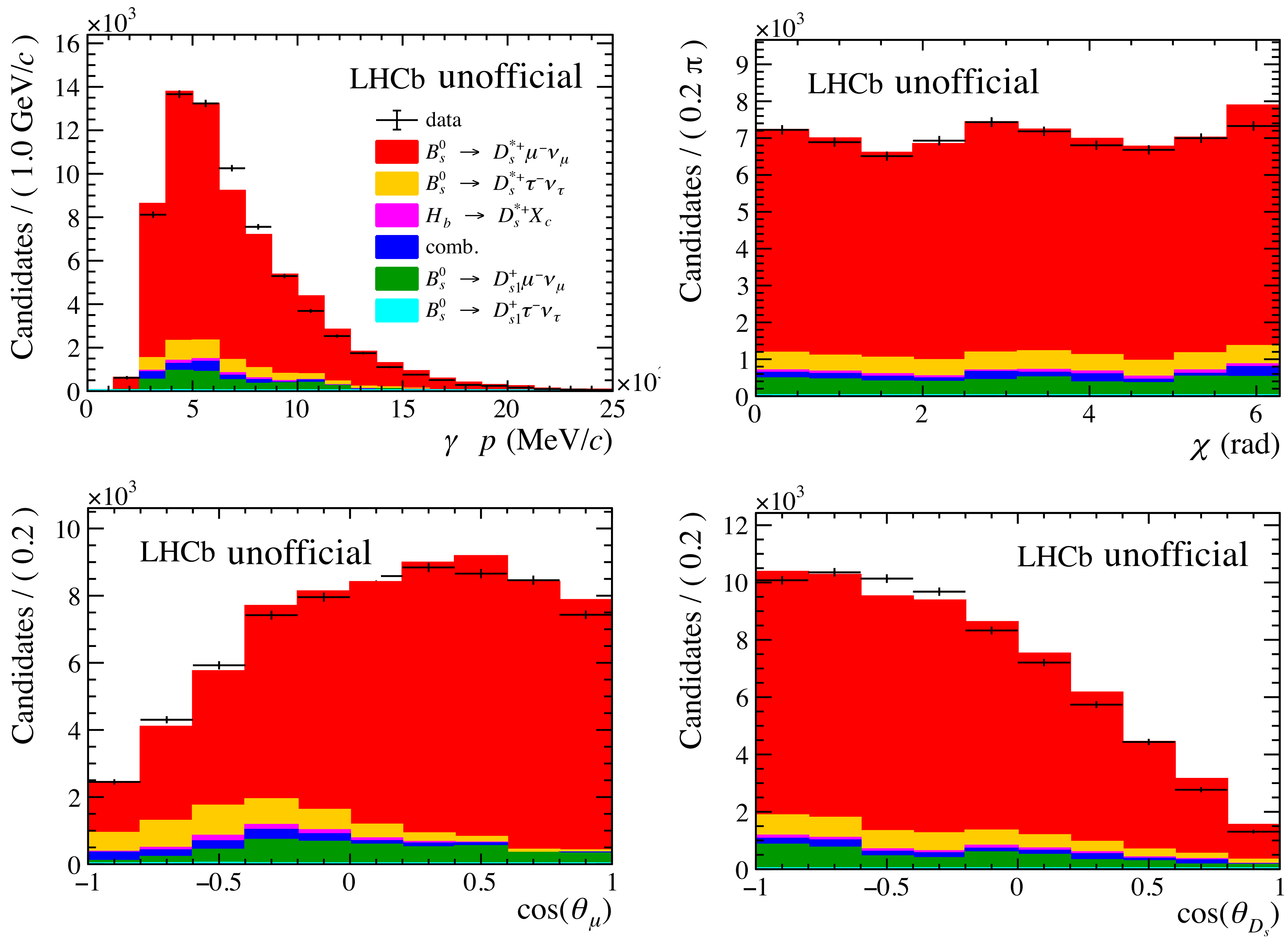




- Very little background!

# Data-MC comparison

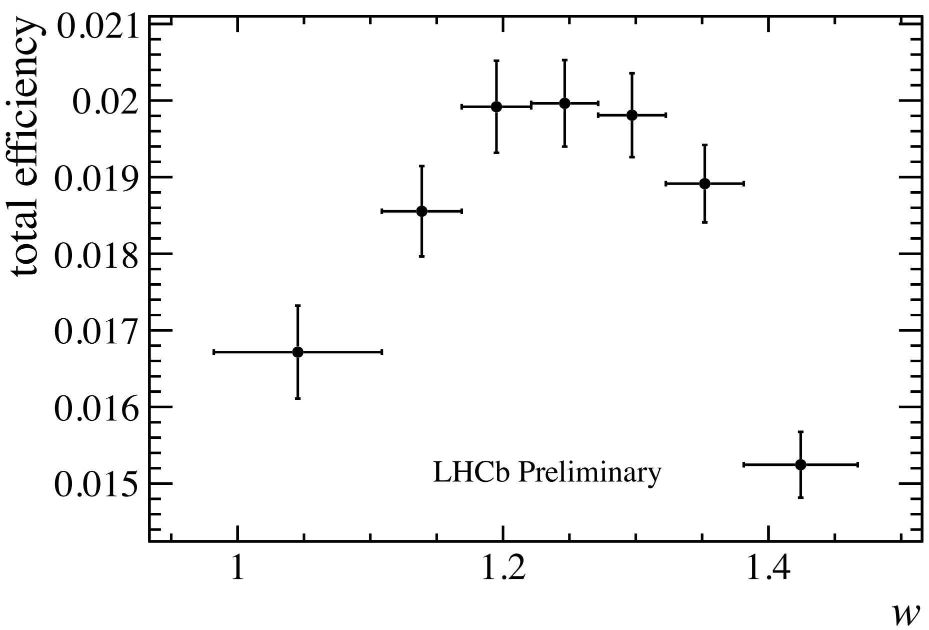
- After the fit, data-MC comparisons to check our understanding of MC in angular distributions, but also soft photon momentum

Good agreement!



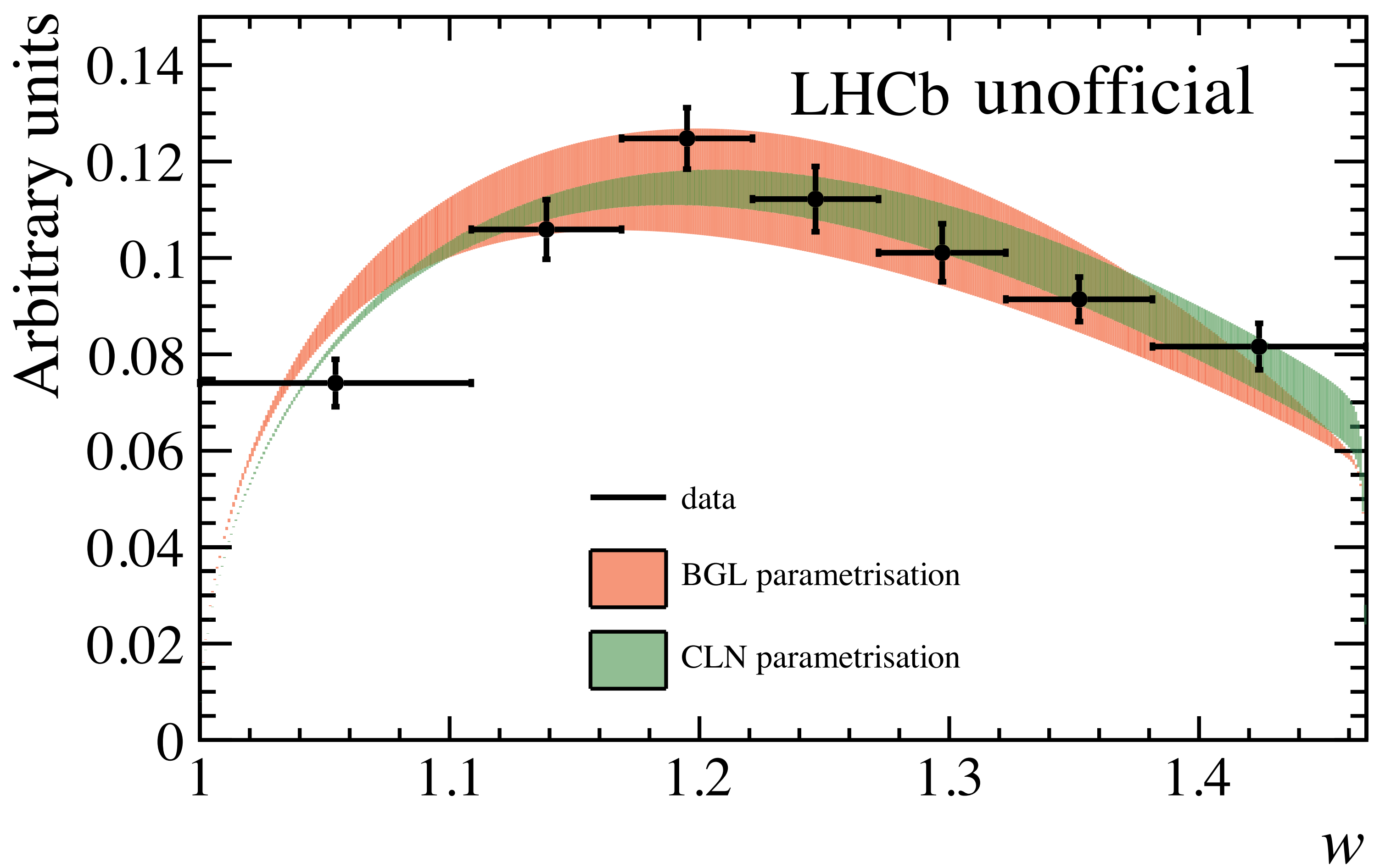
# Correct for efficiencies

- Most reconstruction efficiencies are determined from MC, comparing generator level with reconstructed MC
- MC is corrected for known inconsistencies:
  - trigger using $B^+ \to J/\psi K^+$ decays, tracking, photon and $B_s$ kinematics
- $D_s$ selection efficiency comes from fully reconstructed $B_s^0 \to D_s^{*+}\pi^-$ decays
- Muon PID is taken from $J/\psi \to \mu^+\mu^-$ decays
- Efficiencies are not absolute



# Fitting form factors

- After normalising, unfolding and correcting the measured yields, we can fit form factors:




- Only small differences between parametrisations, as expected.

# Systematic uncertainties

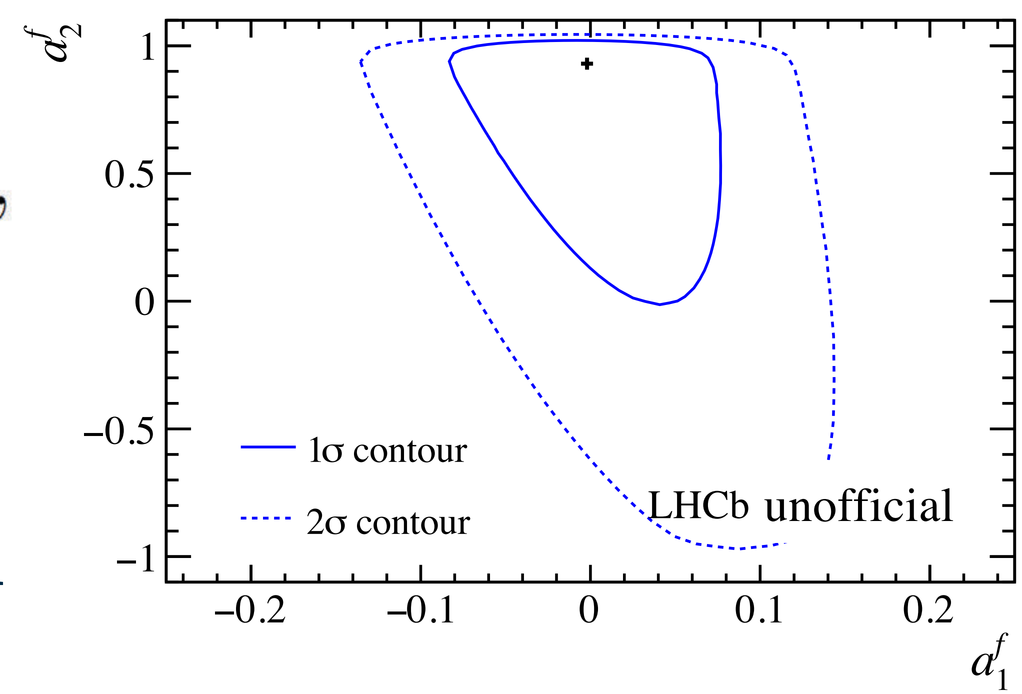
Study the effect on form factor parameters for:

| Source | $\sigma(\rho^2)$ | $\sigma(a_1^f)$ | $\sigma(a_2^f)$ |
|---|---|---|---|
| Simulation sample size | 0.053 | 0.036 | $^{+0.04}_{-0.35}$ |
| Control sample size | 0.020 | 0.016 | $^{+0.02}_{-0.16}$ |
| SVD unfolding regularisation | 0.008 | 0.004 | 0.00 |
| Radiative corrections | 0.004 | 0.000 | 0.00 |
| Simulation FF parametrisation | 0.007 | 0.005 | 0.00 |
| Kinematic weights | 0.024 | 0.013 | 0.00 |
| Hardware trigger efficiency | 0.001 | 0.008 | 0.00 |
| Software trigger efficiency | 0.004 | 0.002 | 0.00 |
| $D_s^-$ selection efficiency | 0.000 | 0.008 | 0.00 |
| $D_s^{*-}$ weights | 0.002 | 0.014 | 0.00 |
| External parameters in fit | 0.024 | 0.002 | 0.00 |
| Total systematic uncertainty | 0.068 | 0.046 | $^{+0.04}_{-0.38}$ |
| Statistical uncertainty | 0.052 | 0.034 | $^{+0.05}_{-0.20}$ |

# Results

- We find: $\rho^2 = 1.16 \pm 0.05\,(\text{stat}) \pm 0.07\,(\text{syst})$ (massive leptons)
- Or: $\rho^2 = 1.122 \pm 0.015\,(\text{stat}) \pm 0.019\,(\text{syst})$ (massless leptons)
- Results are in agreement with those from $B \to D^* \mu\nu_\mu$ decays ( $\rho^2 = 1.206$ ), as expected from SU(3) symmetry
- In BGL parametrisation: (results are highly correlated)

$$a_1^f = -0.002 \pm 0.034\,(\text{stat}) \pm 0.046\,(\text{syst}),$$
$$a_2^f = 0.93^{+0.05}_{-0.20}\,(\text{stat})^{+0.04}_{-0.38}\,(\text{syst}).$$



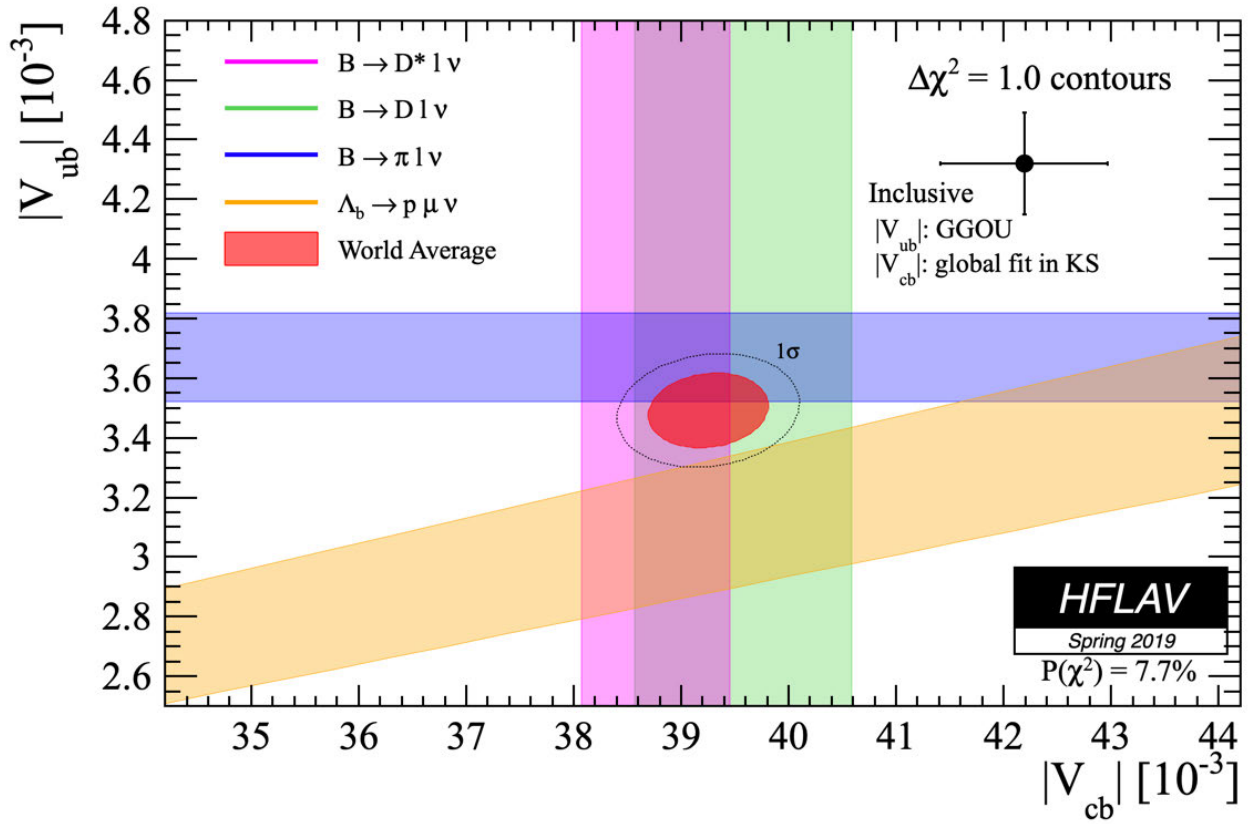

- Will publish also unfolded spectrum with covariance matrix so anyone can make their own fit

NEW

# Measurement of $|V_{cb}|$ using $B_s \to D_s^{(*)} \mu \nu$ decays

# $|V_{cb}|$

- Inclusive and exclusive measurements of $|V_{cb}|$ rely on different theoretical assumptions → complementary measurements
- For the past ~30 years, inclusive and exclusive showed disagreements
- Previously thought to be due to form factor parametrisation, but no longer true




- Since form factor parametrisations cannot explain the difference between inclusive and exclusive $|V_{cb}|$, could it be misunderstanding of backgrounds? We can test this with $B_s$ decays!

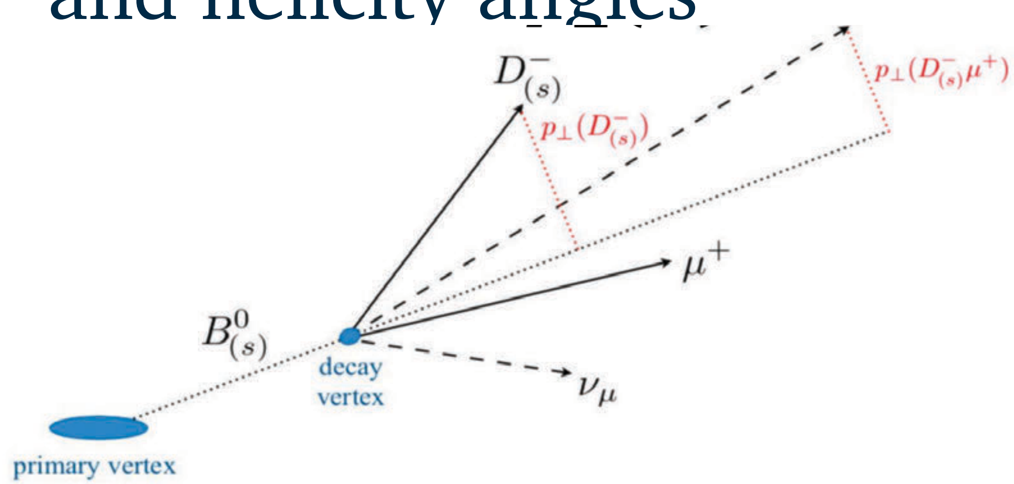
# Introduction

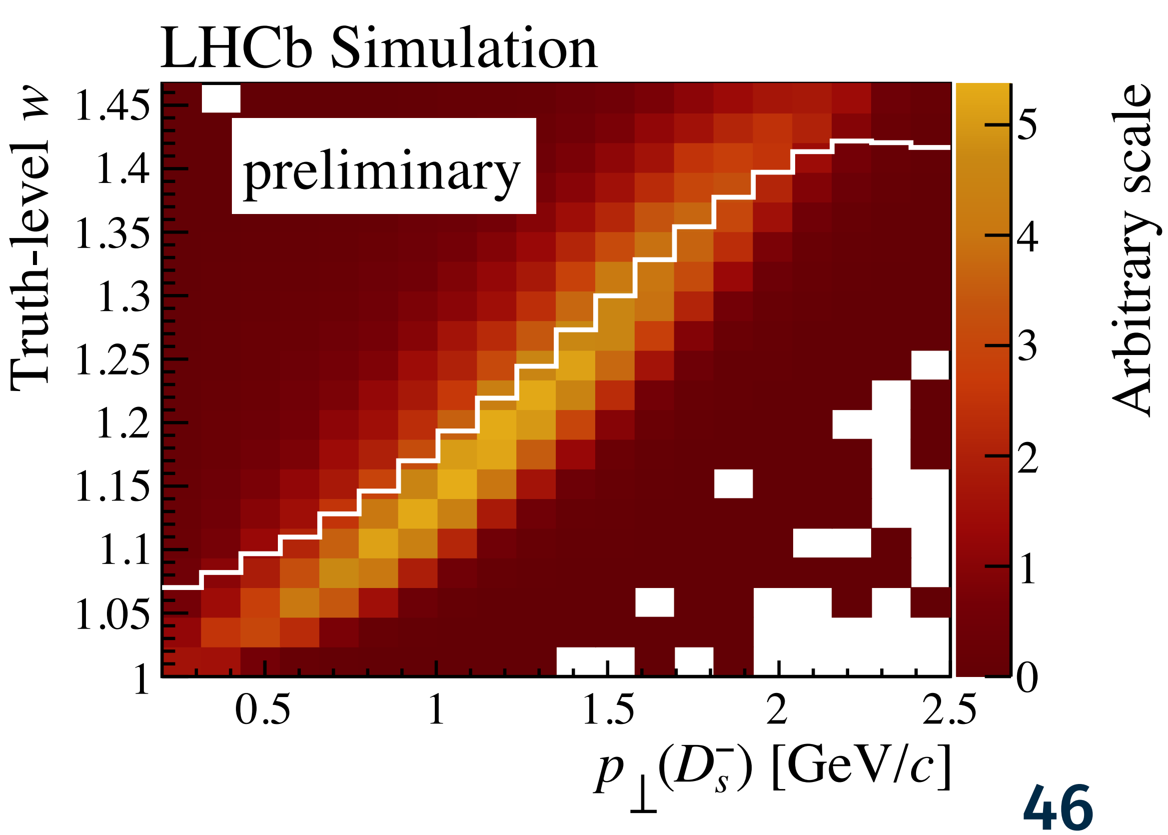
LHCb-PAPER-2019-041

- Extract $|V_{cb}|$ and branching fractions from ratios of decays:

$$\mathcal{R} \equiv \frac{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^- \mu^+ \nu_\mu)} \qquad \mathcal{R}^* \equiv \frac{\mathcal{B}(B_s^0 \to D_s^{*-} \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu_\mu)}$$

- Decay rate is proportional to $|V_{cb}|$
- Unlike previous analysis, this one does not reconstruct photon, and the different variable $p_\perp$:
    - the $D_s$ momentum in direction of $B_s$ flight, correlated with $w$ and helicity angles



# Analysis strategy

LHCb-PAPER-2019-041

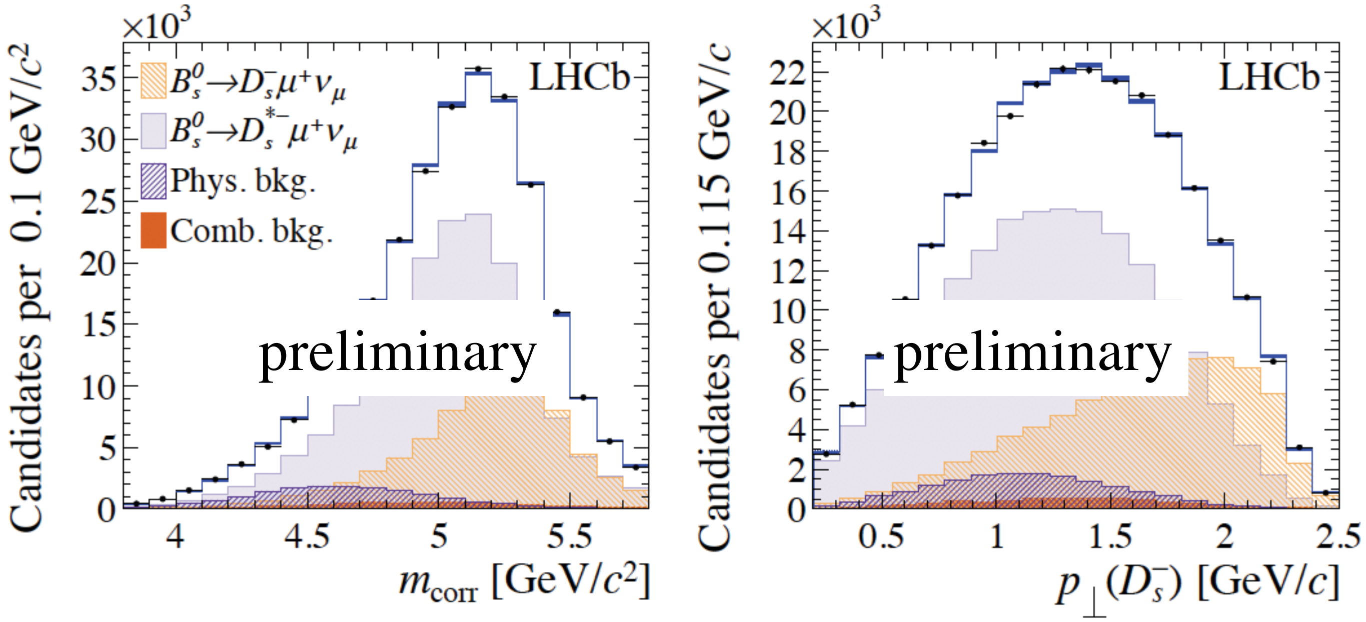
- Relies on template fit ($m_{\text{corr}}$ vs. $p_\perp$) with huge MC samples, except for combinatorial background, which comes from same-sign data
- Signal templates depend on form factors which are recalculated each iteration of the fit, so not only sensitive to the decay rates and $|V_{cb}|$, but also to form factor parameters
- Fit simultaneously the signal $D_s$ decays and the normalisation $D$ decays
- Fits performed with both BGL and CLN parametrisations

Run 1

# Signal fits

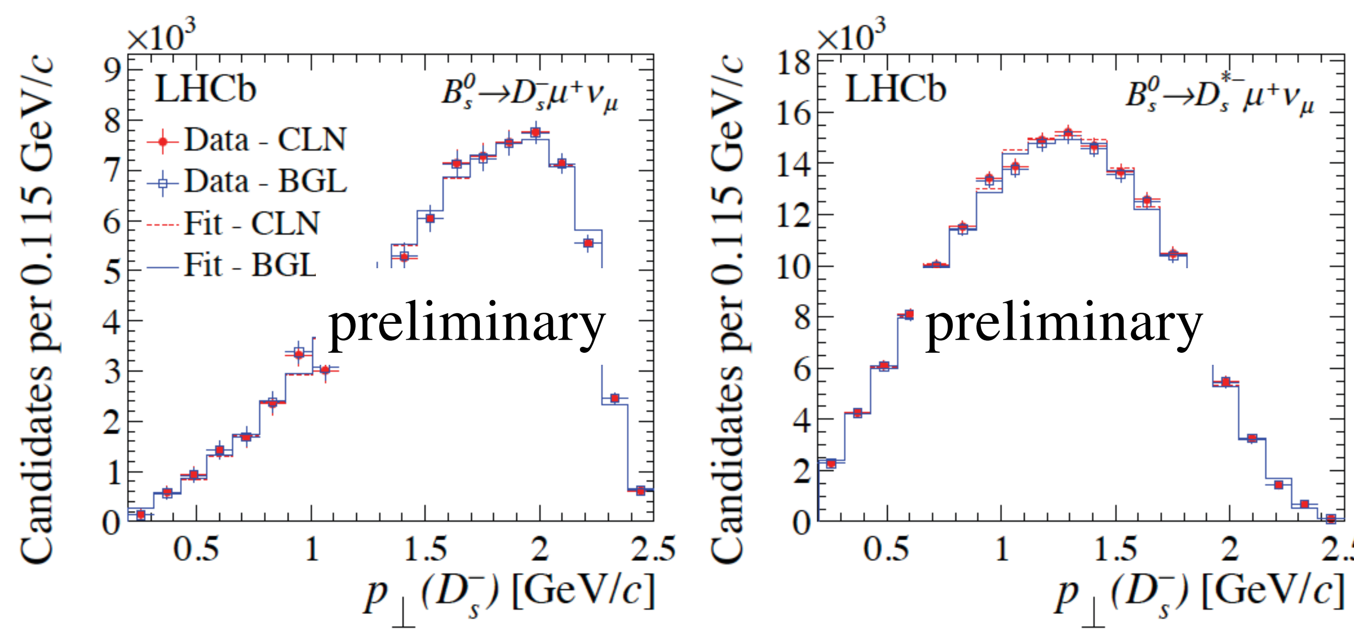
LHCb-PAPER-2019-041

- Signal fit using CLN parametrisation:




- Background-subtracted distributions of $D_s$ and $D_s^*$

**good agreement between CLN and BGL**



# Results branching fractions

LHCb-PAPER-2019-041

- Measured ratios are:

$$\frac{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^- \mu^+ \nu_\mu)} = 1.093 \pm 0.054\,(\text{stat}) \pm 0.060\,(\text{syst}) \pm 0.051\,(\text{ext})$$

$$\frac{\mathcal{B}(B_s^0 \to D_s^{*-} \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu_\mu)} = 1.059 \pm 0.047\,(\text{stat}) \pm 0.074\,(\text{syst}) \pm 0.053\,(\text{ext})$$

- Measured for the first time!

$$\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu) = (2.49 \pm 0.12\,(\text{stat}) \pm 0.14\,(\text{syst}) \pm 0.16\,(\text{ext})) \times 10^{-2}$$

$$\mathcal{B}(B_s^0 \to D_s^{*-} \mu^+ \nu_\mu) = (5.38 \pm 0.25\,(\text{stat}) \pm 0.46\,(\text{syst}) \pm 0.30\,(\text{ext})) \times 10^{-2}$$

- $D_s/D_s^*$ ratio:

$$\frac{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^{*-} \mu^+ \nu_\mu)} = 0.464 \pm 0.013\,(\text{stat}) \pm 0.043\,(\text{syst})$$

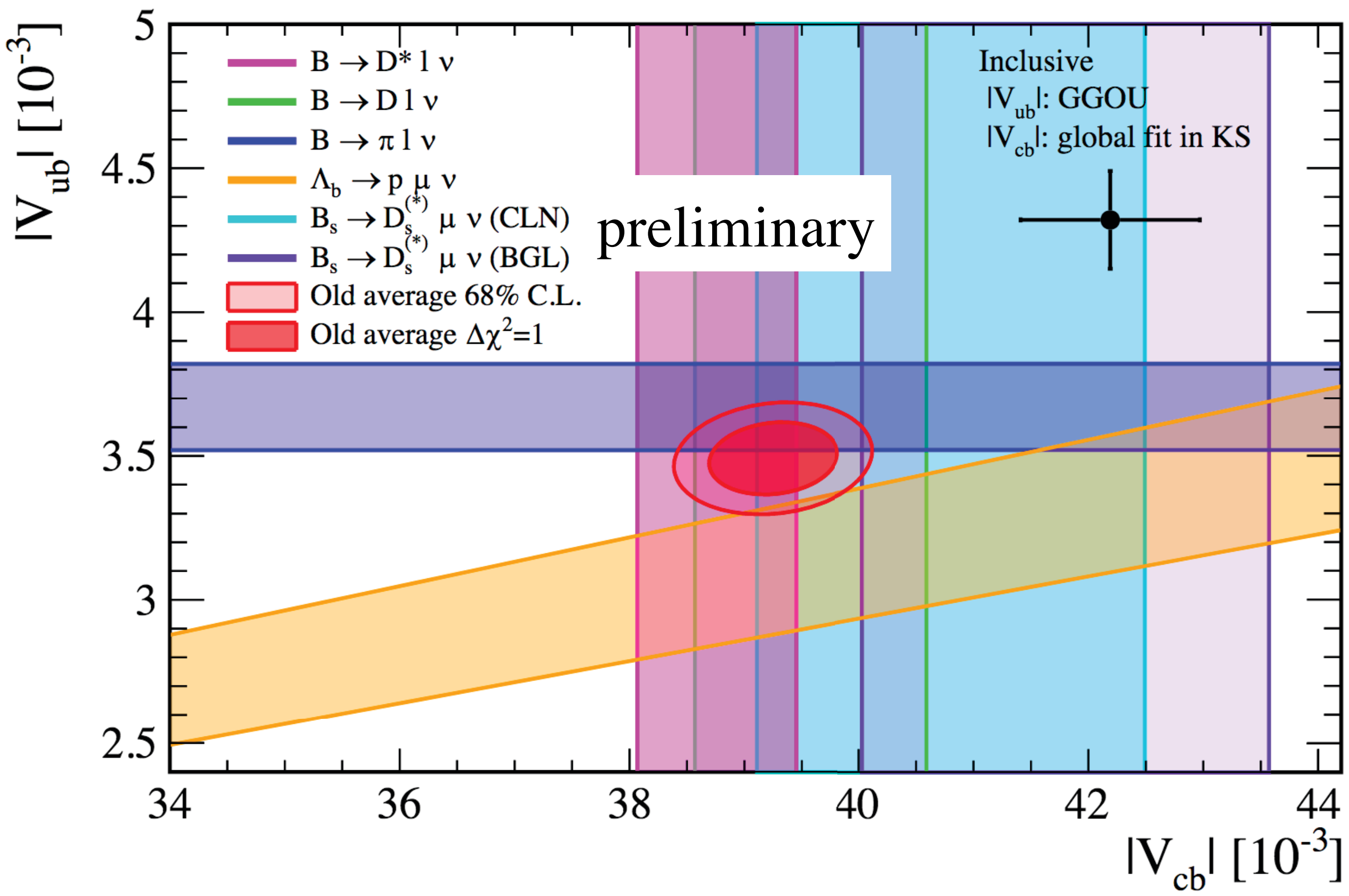
- Largest uncertainty comes from $f_s/f_d$

# Conclusion $|V_{cb}|$

LHCb-PAPER-2019-041

- These are the first exclusive $|V_{cb}|$ measurements from a hadron collider and the first using $B_s$ decays
- Consistent results with different form factor parametrisations:

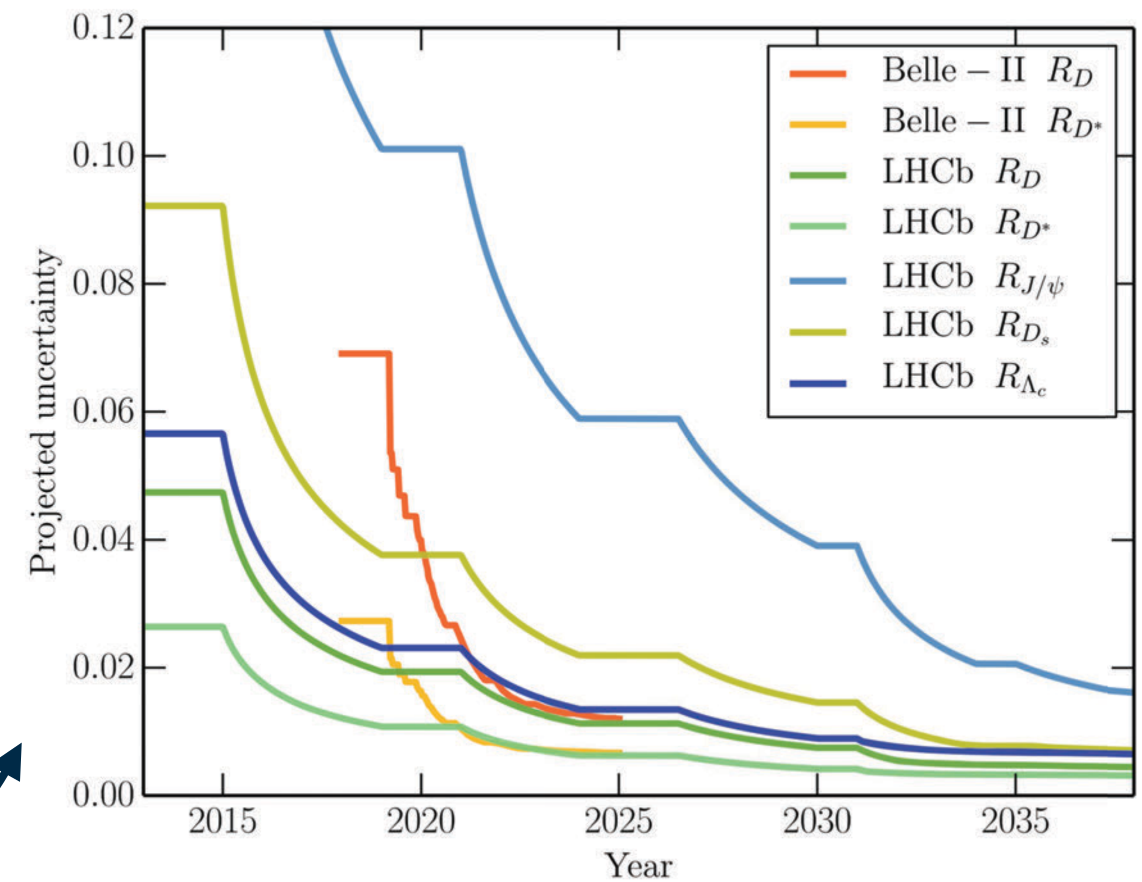
$$|V_{cb}|_{\mathrm{CLN}} = (41.4 \pm 0.6\,(\mathrm{stat}) \pm 0.9\,(\mathrm{syst}) \pm 1.2\,(\mathrm{ext})) \times 10^{-3}$$
$$|V_{cb}|_{\mathrm{BGL}} = (42.3 \pm 0.8\,(\mathrm{stat}) \pm 0.9\,(\mathrm{syst}) \pm 1.2\,(\mathrm{ext})) \times 10^{-3}$$



# Outlook and conclusions

# Prospects for LFU measurements

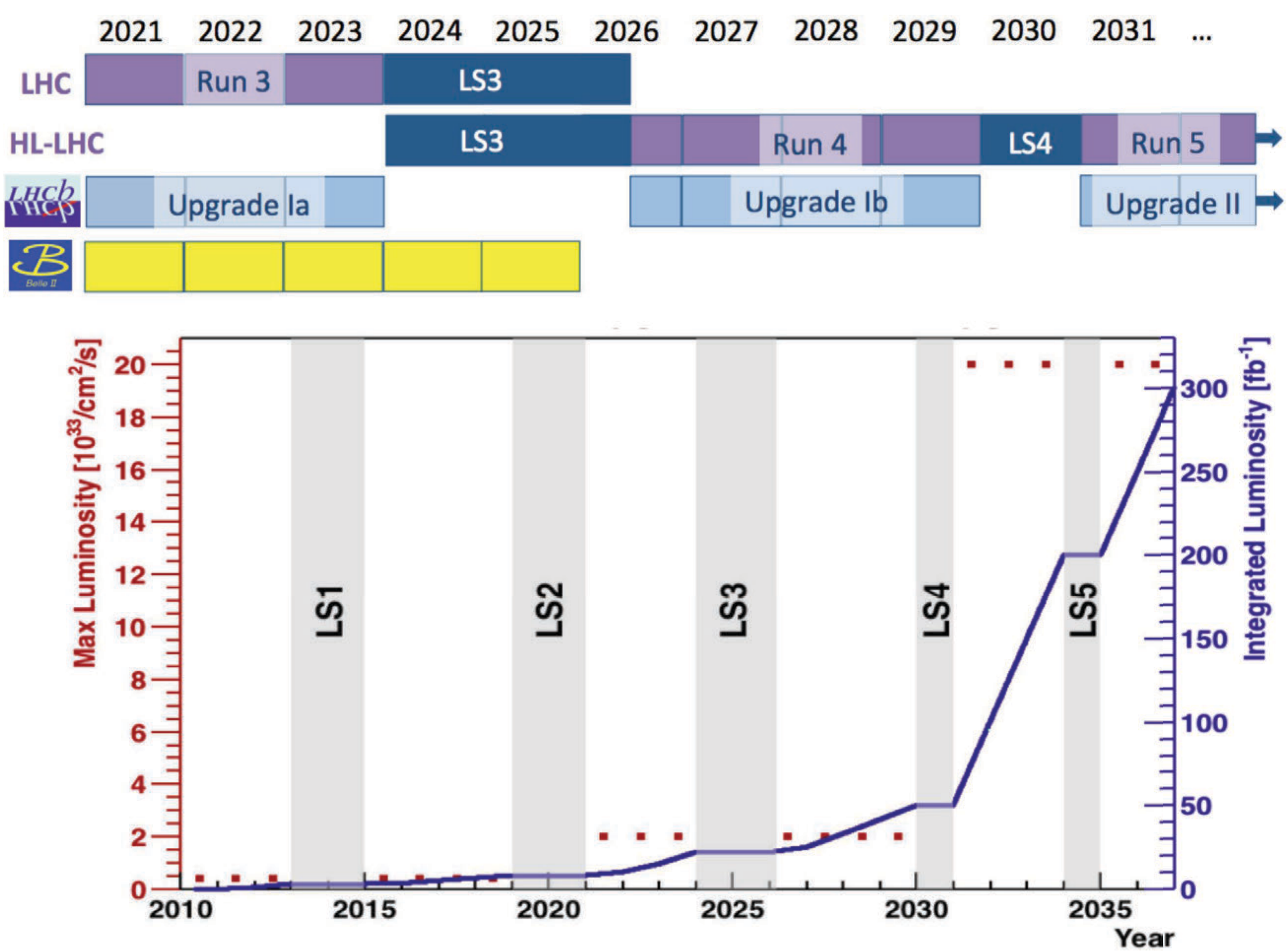
- So far, all LHCb's LFU measurements are only on Run 1 data. Run 2 is analysed as we speak and new results can be expected, including an extension of the muonic $R(D^*) \rightarrow R(D)$-$R(D^*)$.
- Other channels are also being studied: $R(D^+)$, $R(\Lambda_c)$, $R(D_s^{(*)})$, $R(pp)$, …
- Of course Belle II and LHCb upgrades are on their way
- Prospects of various decays modes in the coming years.




J. Phys. G: Nucl. Part. Phys. 46 (2019) 023001

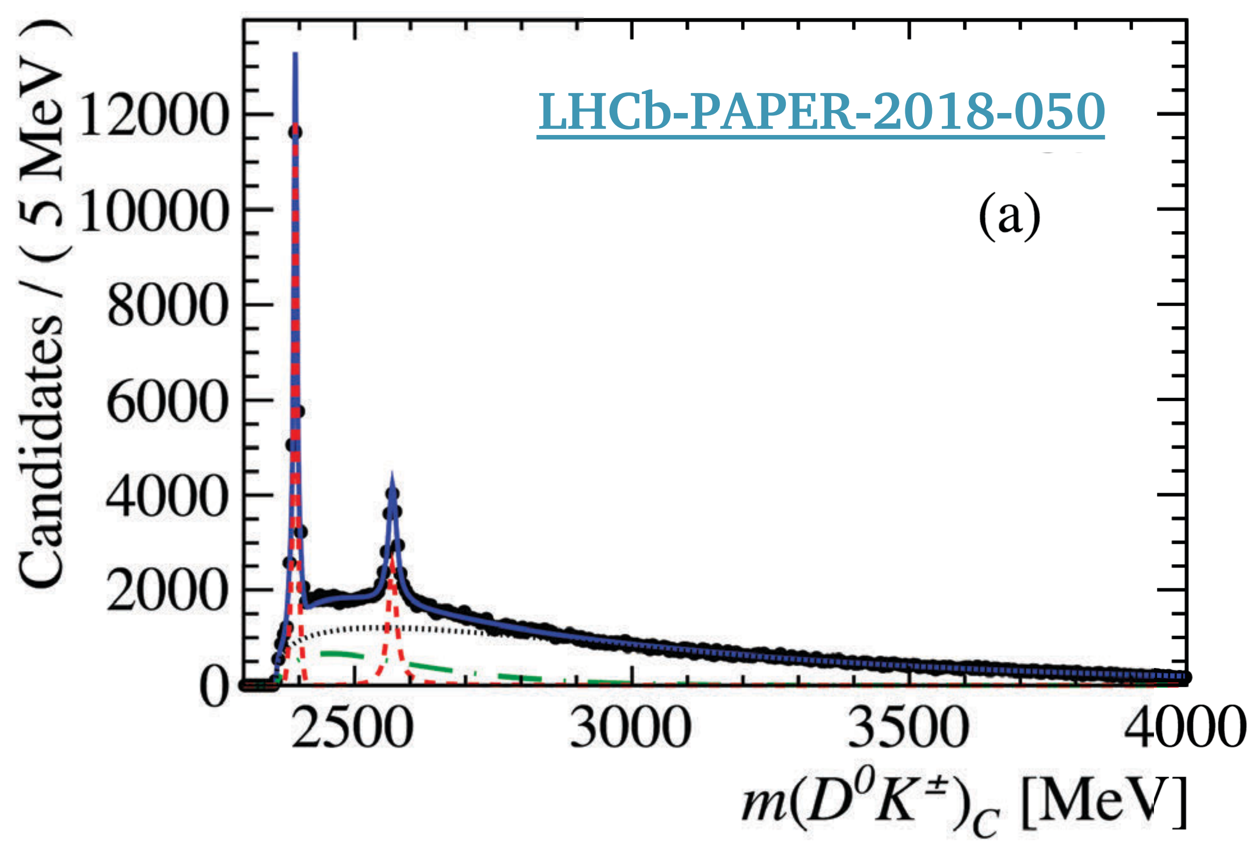
# LHCb upgrades

- LHCb upgrades are on their way, aiming for a dataset of 300 $fb^{-1}$



# Measurement of $R(D_s^{(*)})$

- Similar precision for Run II as current $\mathcal{R}(D^*)$
- Benefit of $\mathcal{R}(D_s^*)$ w.r.t. $\mathcal{R}(D^*)$
  - better understanding of bkg from excited states, which are also very narrow (easy to constrain) due to isospin violation.
  - looking forward to Stefano's thesis!
- In parellel: study $\mathcal{R}(D_s^{**})$ , to study different NP couplings, i.e. to tensors.



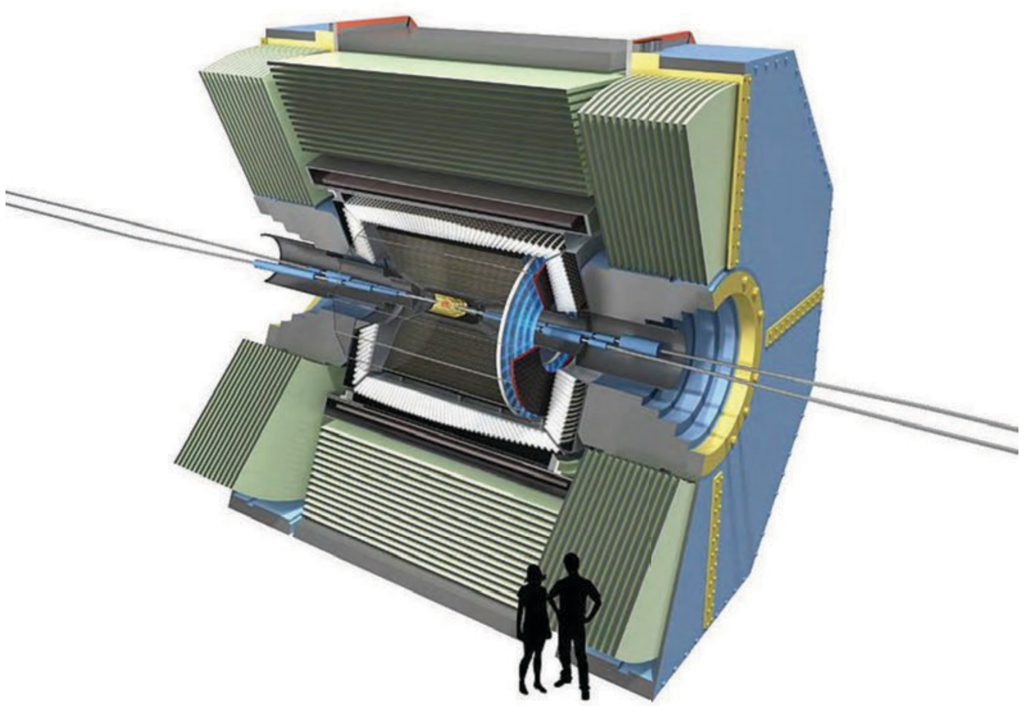
# Conclusions

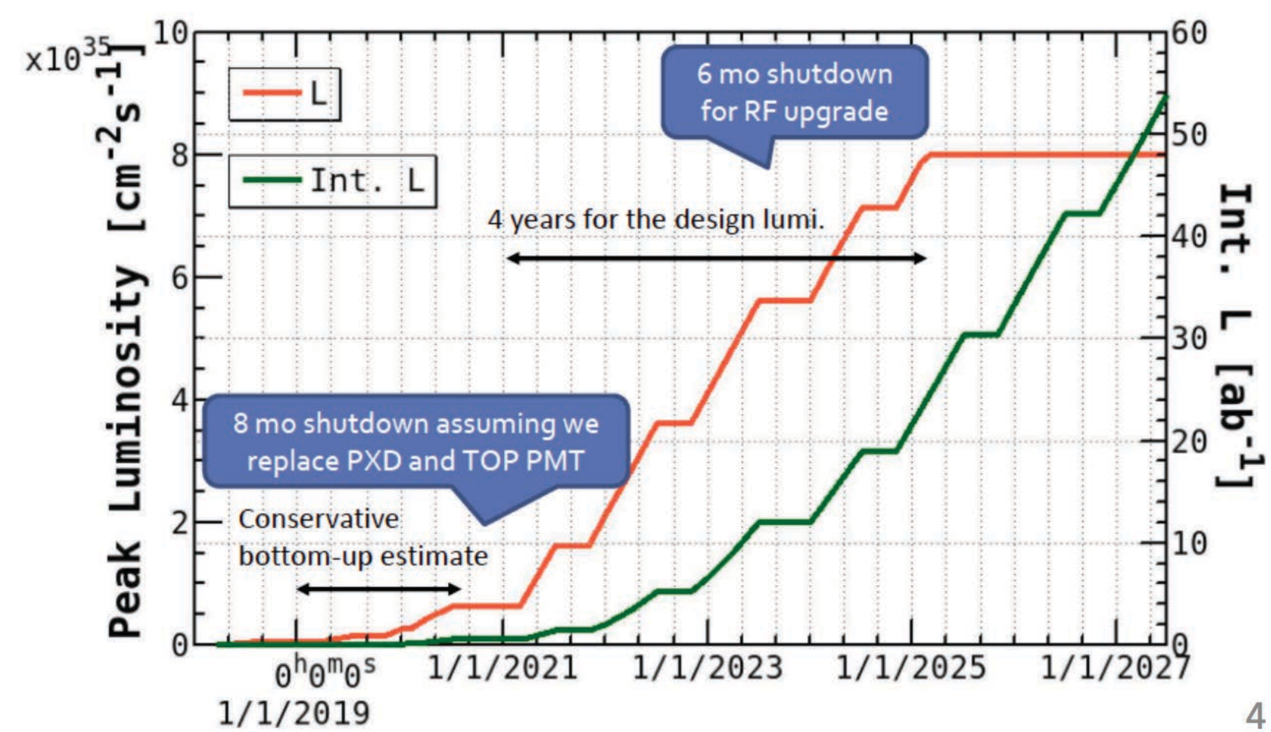
- We can measure form factors, $|V_{cb}|$ and LFU using semileptonic $B_s$ decays and the first of these measurements will be published soon!
- There's lots more data to be analysed, many different decay channels to study.
- Never forget to check the effect of radiative corrections!
  "*QED is the new QCD in terms of unaccounted for effects in so many areas.*"
- New experiments (LHCb upgrade and Belle II) will allow us to (hopefully) finally confirm or rule out LFU breaking.
- Rome is a lovely place to live, with much better flavour than other places I lived ;-)

# Backup

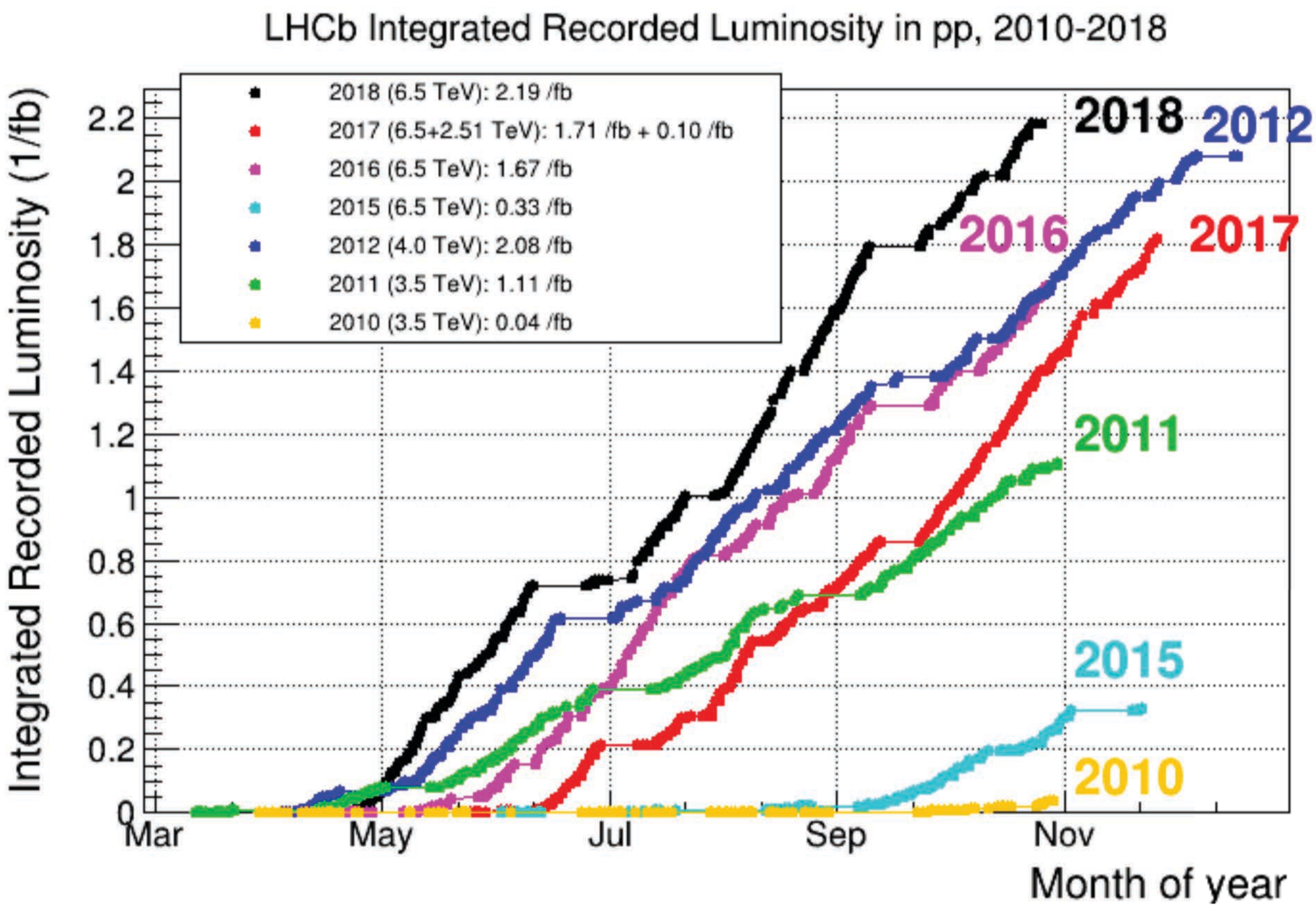
# Belle II

- Belle II has started taking physics data and will soon join us in these measurements!





# LHCb recorded luminosity



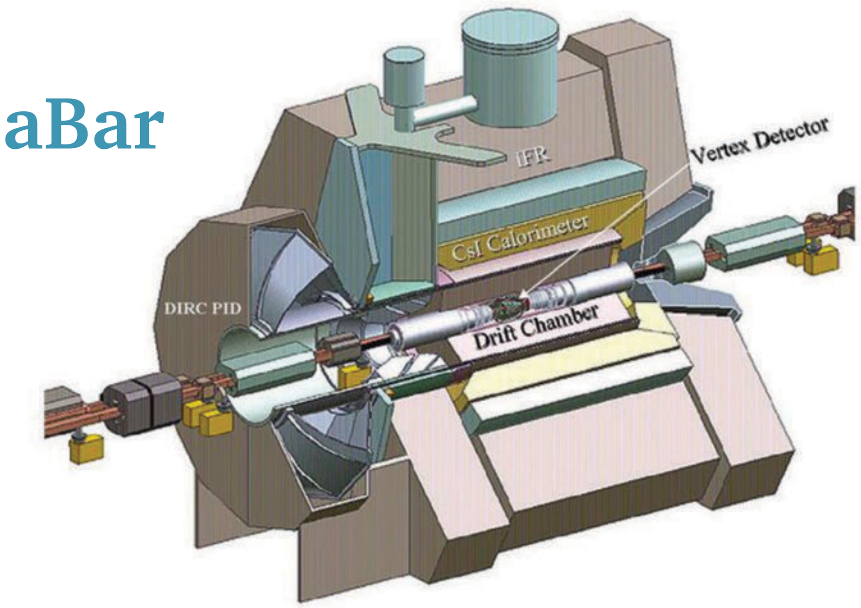
# Experiments: B-factories

- $e^+e^-$ colliders @ $\Upsilon(4S)$ resonance
- $b$ quarks produced from $\Upsilon(4S) \to B^+B^-$ or $B^0\bar{B}^0$, → $4\pi$ detectors (asymmetric, boost of $\Upsilon(4S)$ )
- very clean environment, little background
- well-constrained kinematics help reconstruct final states with neutrinos

BaBar: 1999–2008: 433 $fb^{-1}$ @ $\Upsilon(4S)$

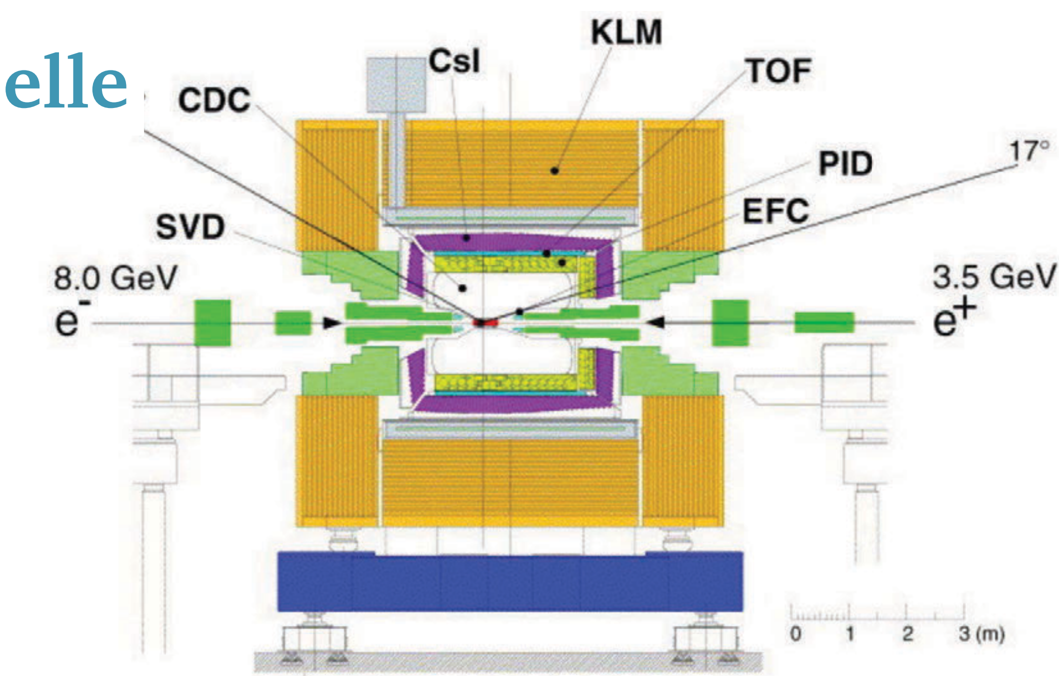
Belle: 1999–2010: 711 $fb^{-1}$ @ $\Upsilon(4S)$

BaBar




Nucl.Instrum.Meth.A479:1-116,2002

Belle



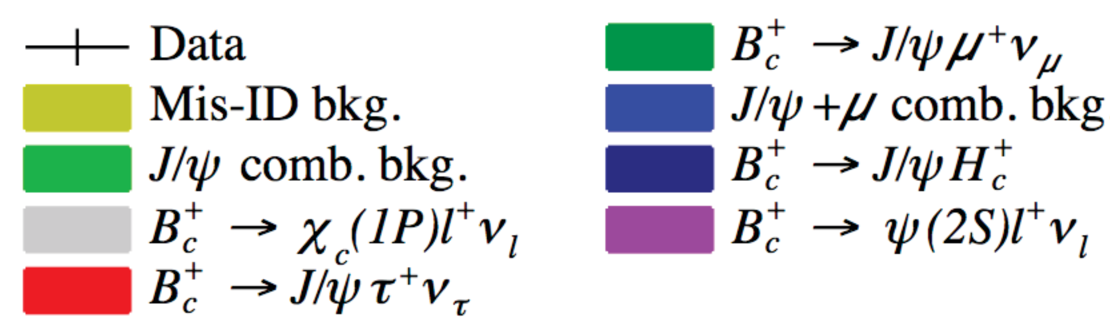

Nucl.Instrum.Meth. A479 (2002) 117-232

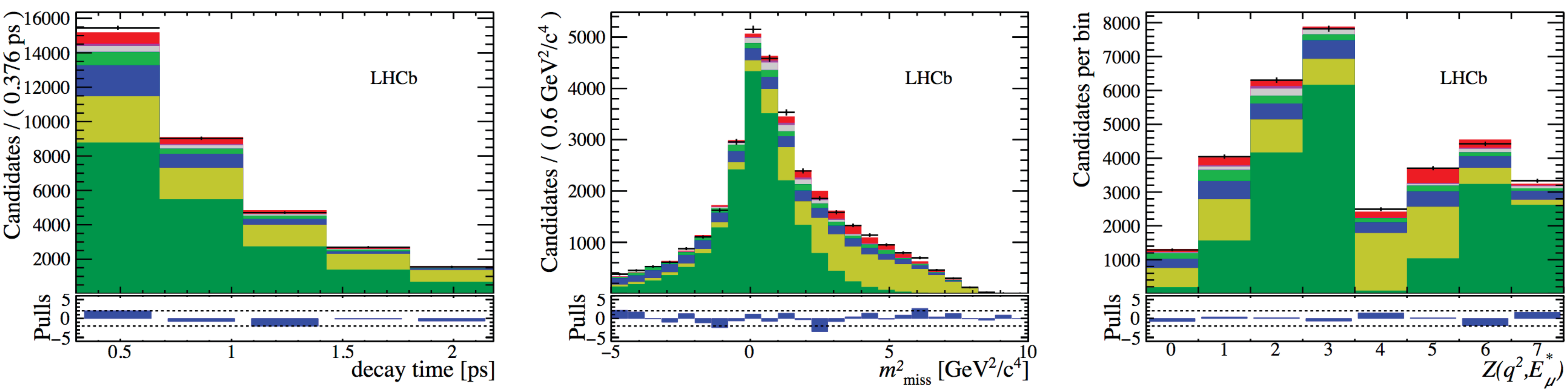
# $R(J/\Psi)$ muonic

PRL 120, 121801 (2018)

- $\mathcal{R}(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$ Run 1
- Compatible with SM within 2σ
- Systematics come from limited sample simulations, but largest from **uncertainty on form factors** (fit from data). Will improve with lattice calculations.

$$\mathcal{R}(J/\psi) = \frac{B_c^+ \to J/\psi \tau^+ \nu_\tau}{B_c^+ \to J/\psi \mu^+ \nu_\mu}$$



# Coulomb corrections

- The biggest discrepancy between our results and those in 1803.05881 seems to be that common from the Coulomb interactions, which is not implemented in PHOTOS.
- This correction term can be calculated for our generator level MC following the equations in the paper:

$$\Omega_C = -\frac{2\pi\alpha}{\beta_{D\ell}} \frac{1}{e^{-\frac{2\pi\alpha}{\beta_{D\ell}}} - 1}$$

$$\alpha = 1/137$$

$$\beta_{D\ell} = \left[1 - \frac{4m_D^2 m_\ell^2}{(s_{D\ell} - m_D^2 - m_\ell^2)^2}\right]^{1/2}$$

$$s_{D\ell} = (p_D + p_\ell)^2$$

- Using these expressions, we can see the effect of the Coulomb corrections as a function of our usual fit variables, *e.g.* $q^2$

# SL-tagged $R(D^{(*)})$ by Belle

- At Moriond EW, **new** results were presented by Belle, followed by a conference note: arXiv:1904.08794
- Update of the SL-tagged analysis: from measuring $R(D^*)$ to a simultaneous measurement of $R(D)$-$R(D^*)$.
- Using the full $\Upsilon(4S)$ data set with $772\times10^6$ $B\bar{B}$ events.
- First SL-tagged $R(D)$: $B_{\text{tag}}$ reconstructed using BDT and $B\to D^{(*)}\ell\nu$ decays, where $\ell = e, \mu$.
- On tag side: $\ell = \tau(\to\mu/e\ \nu\nu)$ vetoed by applying a cut on $\cos\theta_{B,D^{(*)}\ell}$: angle between $B$ and $D^{(*)}\ell$ in $\Upsilon(4S)$ rest frame.

$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E_{\text{beam}}E_{D^{(*)}\ell} - m_B^2 - m_{D^{(*)}\ell}^2}{2|p_B||p_{D^{(*)}\ell}|}$$

# Data samples and selection

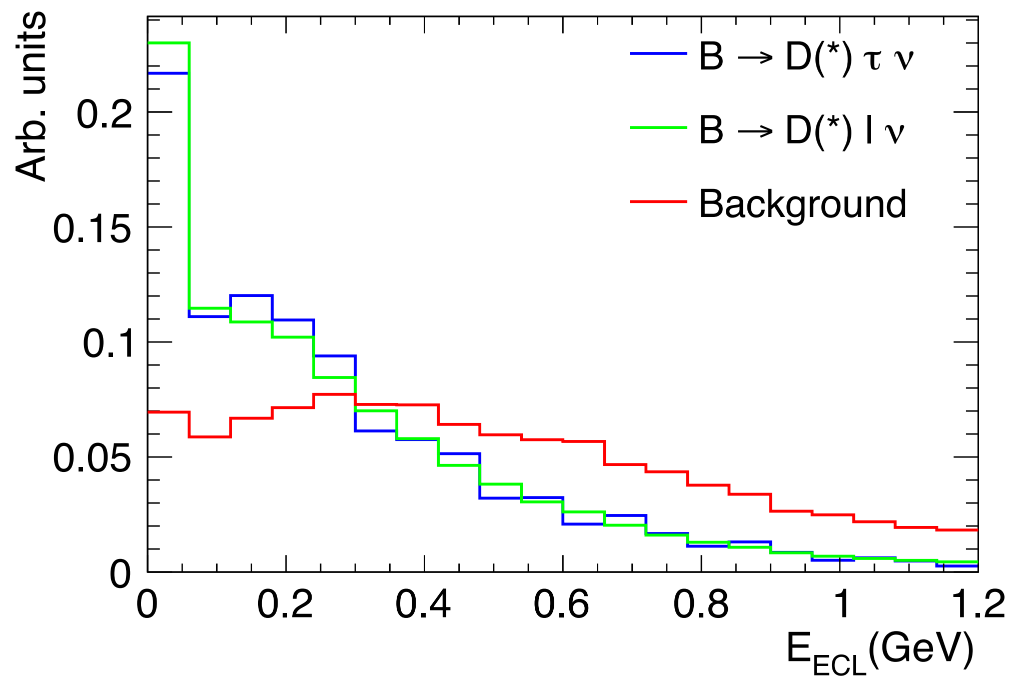
arXiv:1904.08794

- 4 data samples: $D^+\ell^-$, $D^0\ell^-$, $D^{*+}\ell^-$, $D^{*0}\ell^-$
  - $D^0$ reconstructed as $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K^-\pi^+$, $K^0_S\pi^+\pi^-$, $K^0_S\pi^0$, $K^0_S K^+K^-$, $K^+K^-$, $\pi^-\pi^+$ **30% of $D^0$ BRs**
  - $D^+$ reconstructed as $K^-\pi^+\pi^-$, $K^0_S\pi^+\pi^0$, $K^0_S\pi^+\pi^+\pi^-$, $K^0_S\pi^+$, $K^-K^+\pi^+$, $K^0_S K^+$ **22% of $D^+$ BRs**
  - $D^{*+}$ reconstructed as $D^0\pi^+$ or $D^+\pi^0$
  - $D^{*0}$ reconstructed as $D^0\pi^0$
- *D* candidates are required to be within a mass window around their nominal mass.
- *B* mesons are required to have opposite flavour to suppress combinatorial background.

# Fit parameters and components

- Use a 2D fit for these 4 samples
  - one parameter is $E_{\mathrm{ECL}}$: energy deposited in ECL not associated with reconstructed particles
  - other parameter is `class`: outcome of a BDT based on $E_{\mathrm{vis}}$, $m^2_{\mathrm{miss}}$, $\cos\theta_{B,D^{(*)}\ell}$

[arXiv:1904.08794]




- Fit is performed simultaneously on the 4 samples, components are:
  - $D^{(*)}\tau\nu$
  - $D^{(*)}\ell\nu$
  - $D^{**}\ell\nu$, where $D^{**} = D_1, D_2^*, D_1', D_0^*$
  - feed-down from $D^*\ell\nu$ to $D\ell\nu$ decays

*result from $D^*\ell$ ($D^*\tau$) samples is used to estimate contribution in $D\ell$ ($D\tau$)*

# Fit templates

arXiv:1904.08794

- Shapes of the templates are based on MC samples with a luminosity of 10× the total $B\bar{B}$ luminosity. For the $D^{**}$ backgrounds this was 5× the total luminosity.
- MC samples have corrections applied from measurements on control samples:
  - lepton identification: corrected separately for *e* and μ using $e^+e^- \to e^+e^-\ell^+\ell^-$ and $J/\psi \to \ell^+\ell^-$ decays.
- Backgrounds are fixed in fits, yields are based in $m_{D^*}$-$m_D$ sidebands for fake *D*'s, and others from MC.
- Yields of signal, normalisation, $D^{**}$ and feed-down are free in the fit.

$$\mathcal{R}(D^{(*)}) = \frac{1}{2\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)} \times \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \times \frac{N_{\text{sig}}}{N_{\text{norm}}}$$

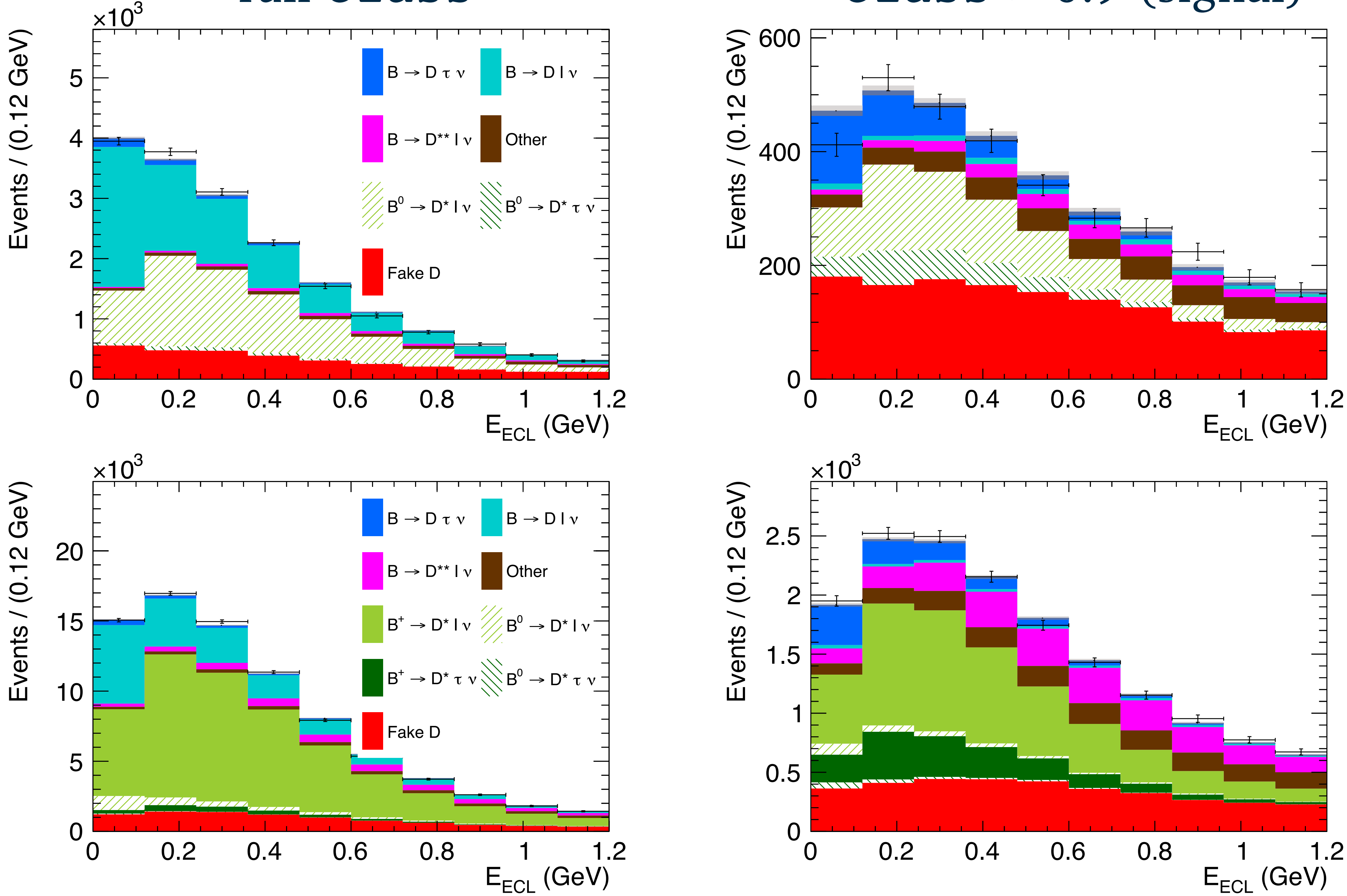
# Fit results $D^+$l and $D^0$l

arXiv:1904.08794

full class | class > 0.9 (signal)

$D^+\ell^-$

$D^0\ell^-$



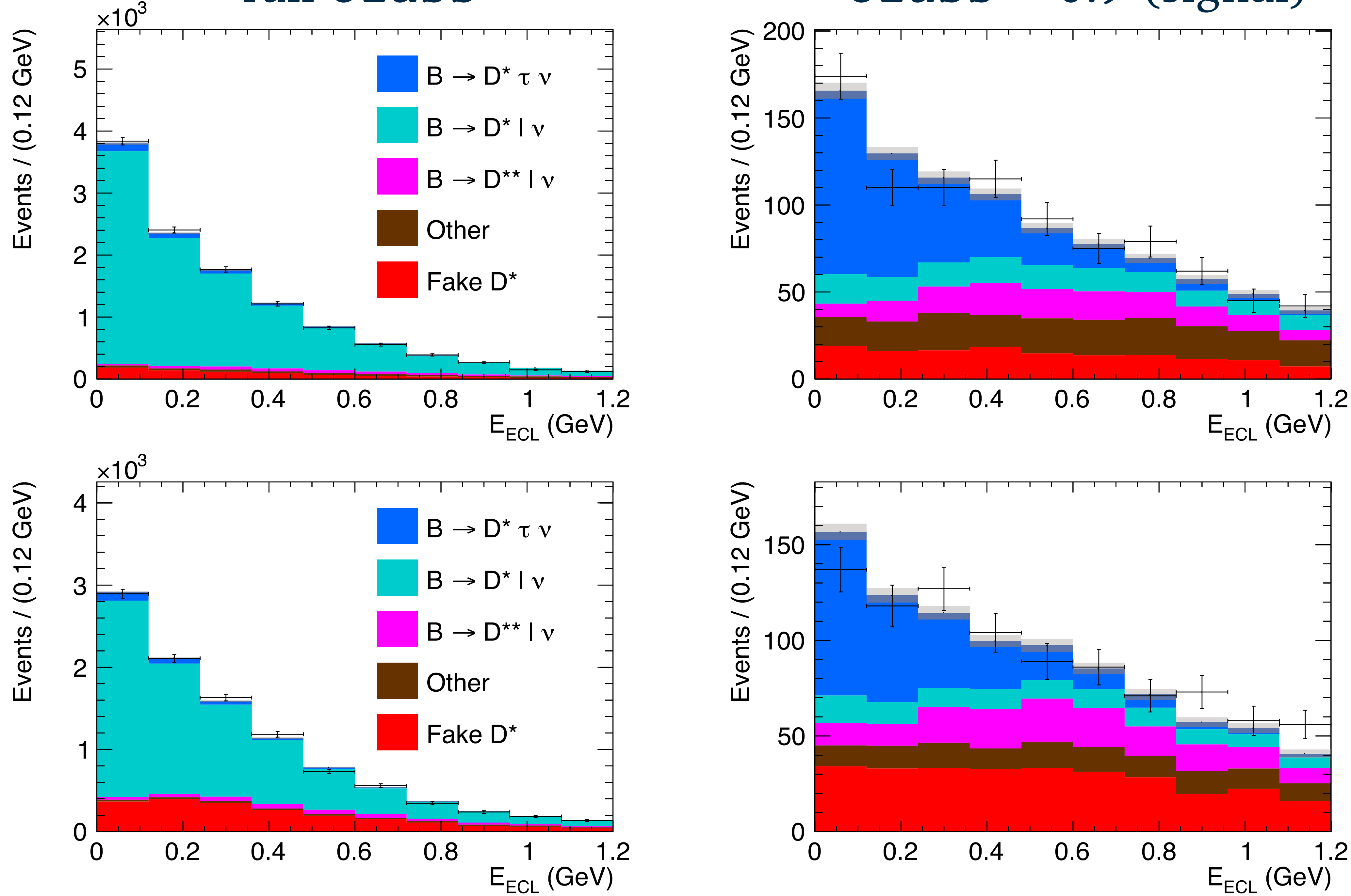
# Fit results $D^{*+}l$ and $D^{*0}l$

arXiv:1904.08794

full class | class > 0.9 (signal)

$D^{*+}\ell^-$

$D^{*0}\ell^-$



# Systematic uncertainties

arXiv:1904.08794

| Source | $\Delta R(D)$ (%) | $\Delta R(D^*)$ (%) |
|---|---|---|
| $D^{**}$ composition | 0.76 | 1.41 |
| Fake $D^{(*)}$ calibration | 0.19 | 0.11 |
| $B_{\text{tag}}$ calibration | 0.07 | 0.05 |
| Feed-down factors | 1.69 | 0.44 |
| Efficiency factors | 1.93 | 4.12 |
| Lepton efficiency and fake rate | 0.36 | 0.33 |
| Slow pion efficiency | 0.08 | 0.08 |
| MC statistics | 4.39 | 2.25 |
| $B$ decay form factors | 0.55 | 0.28 |
| Luminosity | 0.10 | 0.04 |
| $\mathcal{B}(B \to D^{(*)}\ell\nu)$ | 0.05 | 0.02 |
| $\mathcal{B}(D)$ | 0.35 | 0.13 |
| $\mathcal{B}(D^*)$ | 0.04 | 0.02 |
| $\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)$ | 0.15 | 0.14 |
| Total | 5.21 | 4.94 |

# Results SL-tagged $R(D^{(*)})$

- This analysis finds:

arXiv:1904.08794

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016 \qquad \rho = -0.53\,(\mathrm{stat})$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014 \qquad \rho = -0.52\,(\mathrm{syst})$$

- Most precise measurements of $R(D)$ and $R(D^*)$ to date!
- Breakdown between muon and electron modes:

electron:

$$\mathcal{R}(D) = 0.281 \pm 0.042 \pm 0.017$$
$$\mathcal{R}(D^*) = 0.304 \pm 0.022 \pm 0.016$$

muon:

$$\mathcal{R}(D) = 0.373 \pm 0.068 \pm 0.030$$
$$\mathcal{R}(D^*) = 0.245 \pm 0.035 \pm 0.020$$

- Different measurement from Belle shows LFU between $e$ and μ:

$$\frac{\mathcal{B}(B^0 \to D^{*-} e^+ \nu_e)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu_\mu)} = 1.01 \pm 0.01 \pm 0.03$$

→ see talk by Eiasha Waheed

arXiv: 1809.03290v3

# BGL parametrisation

- All form factors:

$$f(z) = \frac{1}{P_{1+}(z)\phi_f(z)} \sum_{n=0}^{\infty} a_n^f z^n \,, \qquad F_1(z) = \frac{1}{P_{1+}(z)\phi_{F_1}(z)} \sum_{n=0}^{\infty} a_n^{F_1} z^n \,,$$

$$g(z) = \frac{1}{P_{1-}(z)\phi_g(z)} \sum_{n=0}^{\infty} a_n^g z^n \,, \qquad F_2(z) = \frac{\sqrt{r}}{(1+r)P_{0-}(z)\phi_{F_2}(z)} \sum_{n=0}^{\infty} a_n^{F_2} z^n$$

- Unitarity constraints:

$$\sum_{n=0}^{N} (a_n^g)^2 < 1 \,, \qquad \sum_{n=0}^{N} (a_n^f)^2 + \sum_{n=0}^{N} (a_n^{F_1})^2 < 1 \,, \qquad \sum_{n=0}^{N} (a_n^{F_2})^2 < 1 \,.$$

# CLN parametrisation

- All form factors:

$$h_{A_1}(w) = h_{A_1}(1)[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3]$$
$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2\ ,$$
$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2\ ,$$
$$R_0(w) = R_0(1) - 0.11(w-1) + 0.01(w-1)^2\ ,$$

# 1D Toy fit

- Example of 1D toy fit.
- Fit separately on $q^2$, $m^2_{miss}$ and $E_l$.
- Same result on $f_\mu$ and $f_\tau$ of the 3D fit.