*Workshop on semileptonic decays. Frascati, 12-14/04*

# Exclusive semileptonic measurements and prospects at LHCb

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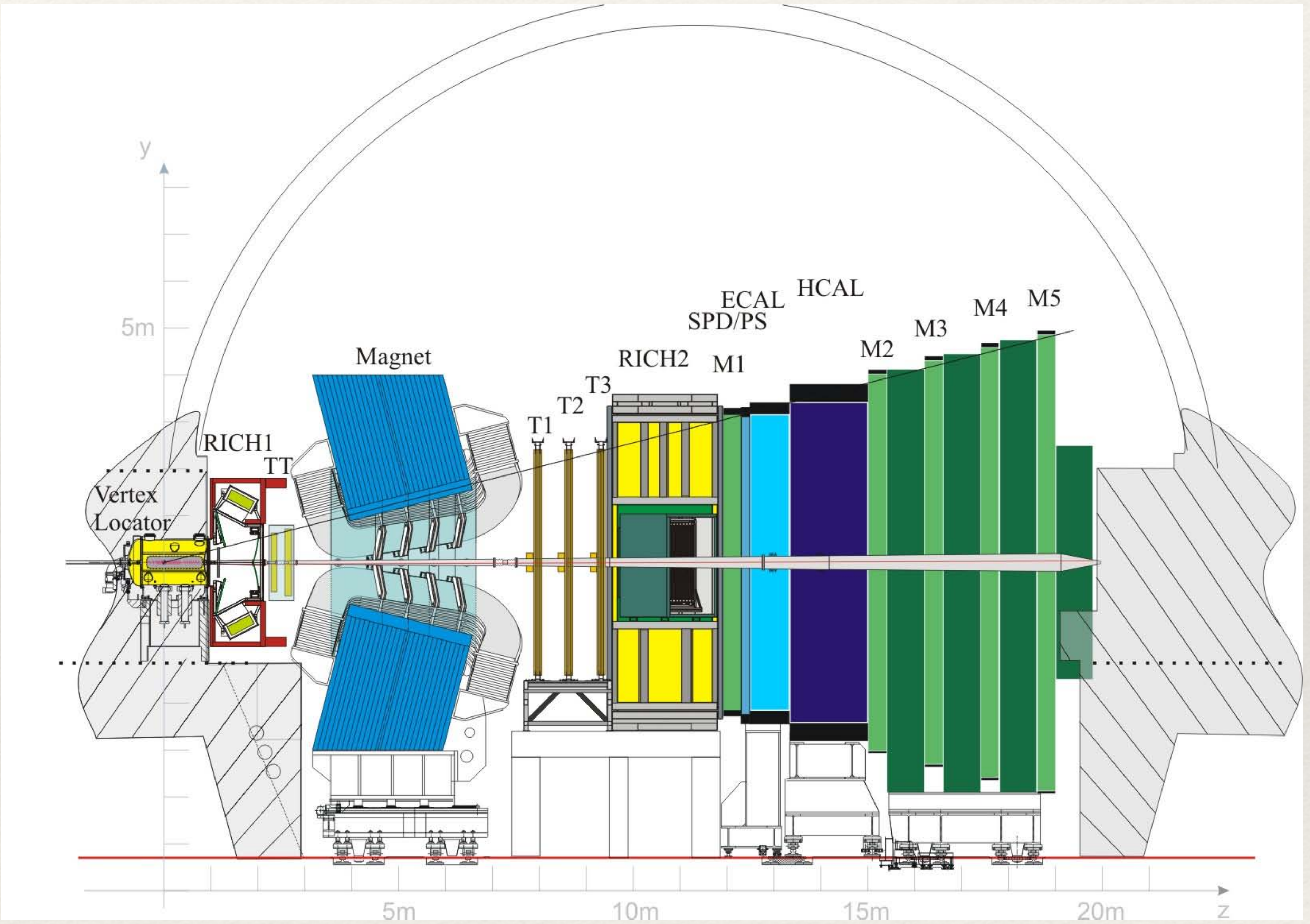
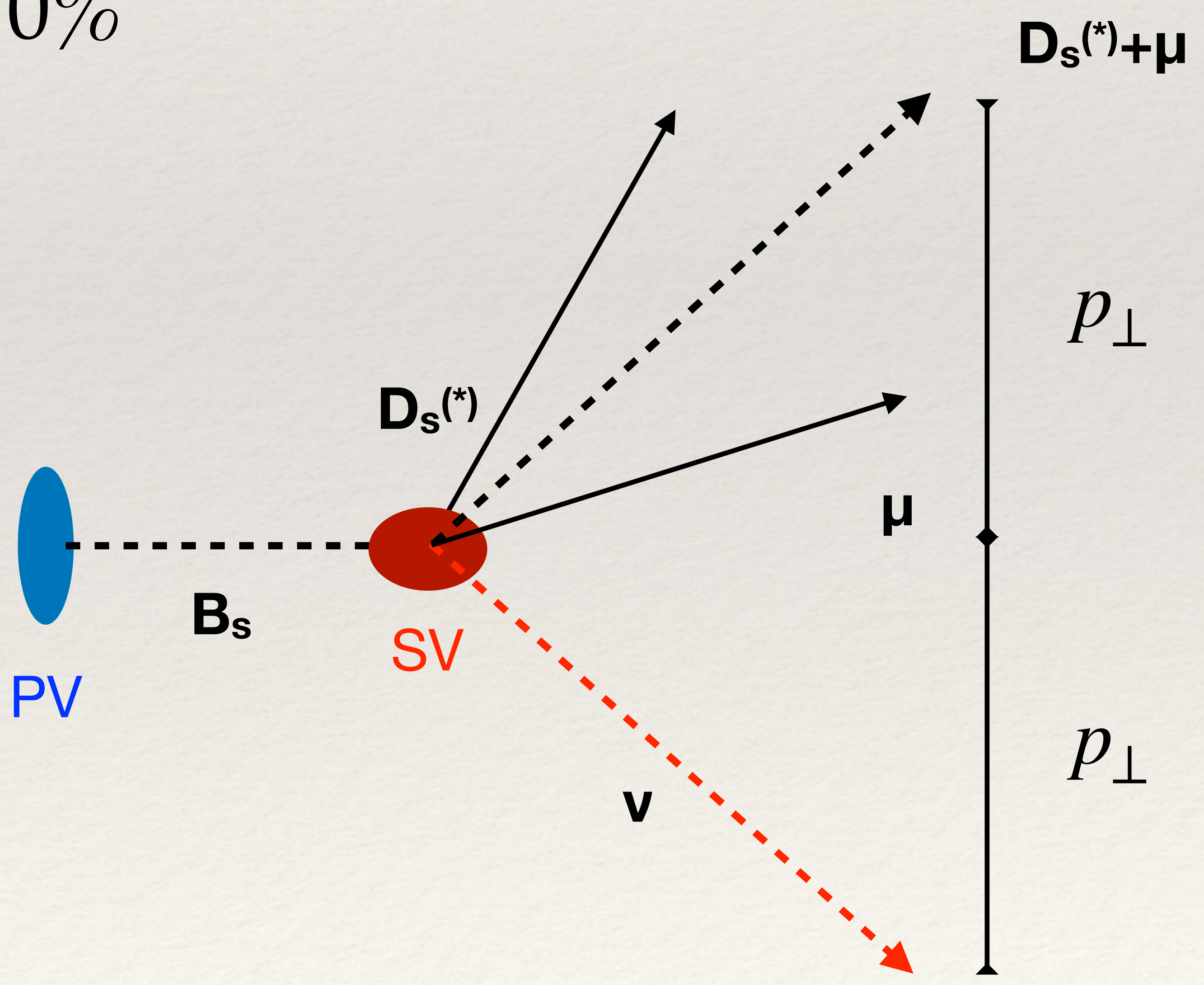
# LHCb detector

- Likely not the first place one can think to study semileptonic decays.
- Analyses take profit from:
  - Large production: $10^{10} - 10^{11}$ B-hadrons produced in the acceptance per $fb^{-1}$. [PRL 118 (2017) 052002, PRL 119 (2017) 169901].
  - Excellent vertex resolution (down to 15μm at high $p_T$).
  - Particle ID capabilities ($\varepsilon_{PID}(\mu)$>97% for $\varepsilon_{misID}$<5%)
  - Good momentum resolution $\delta p/p$ in [0.5-1]% for p in [5-200]GeV.
  - Flexible and efficient trigger.



# Reconstructing B kinematics

- Decays cannot be fully reconstructed. Difficult to get $q^2$.
- B-hadron flight direction is well-measured. Use B-hadron mass to constrain the decay and solve $q^2$ with a two-fold ambiguity.
- Improve on finding the correct solution by using an MVA based on the B-hadron flight direction [JHEP 02 (2017) 021]. Gives the correct solution in ~70% of the cases.
- Reconstruct the corrected mass ($m_{corr}$) using the imbalance of momentum transverse to B-hadron flight direction.
  - $m_{corr}$ peaks at the $B_{(s)}$ mass if only one neutrino is missing.
  - $m_{corr} = \sqrt{m_{vis}^2 + p_\perp^2} + p_\perp$

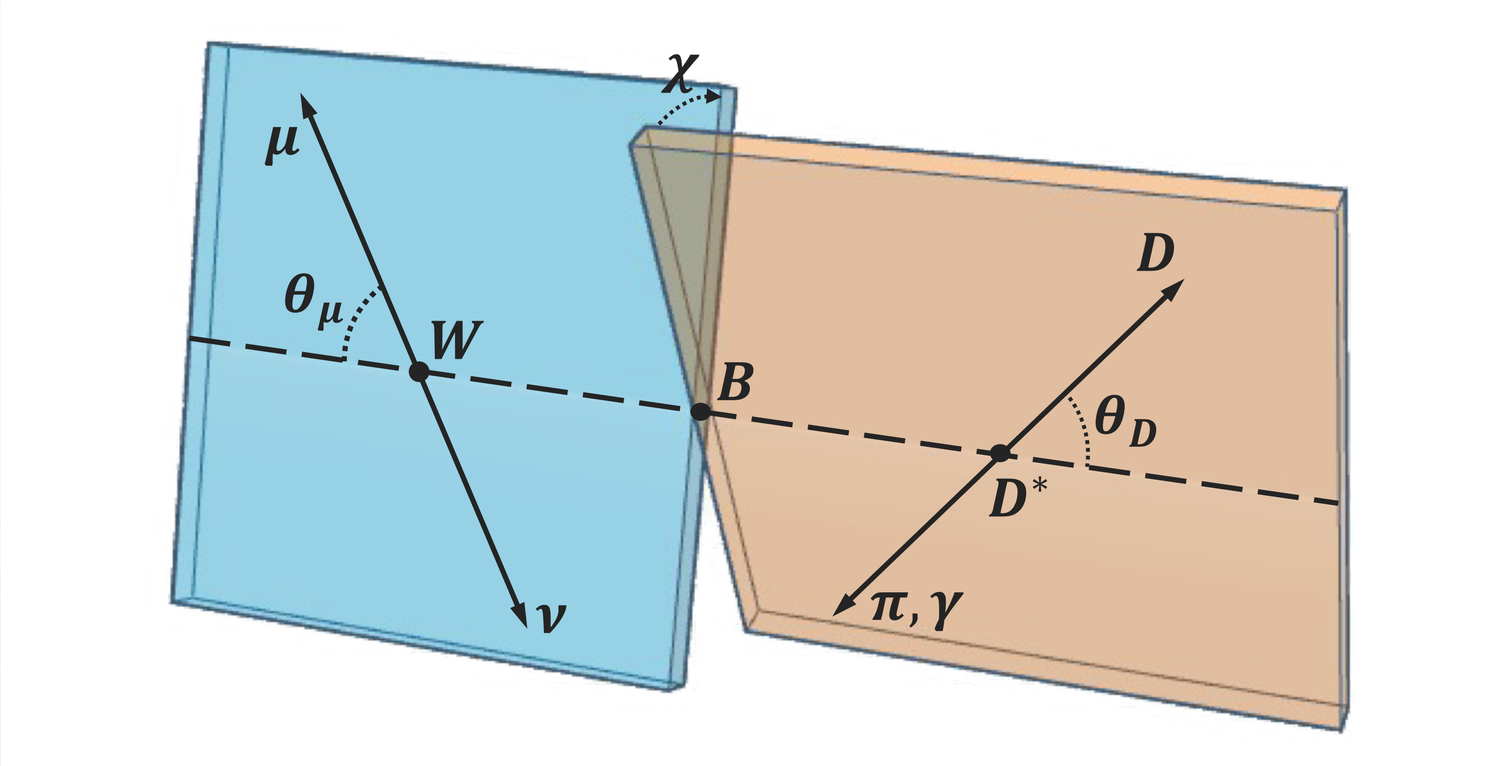


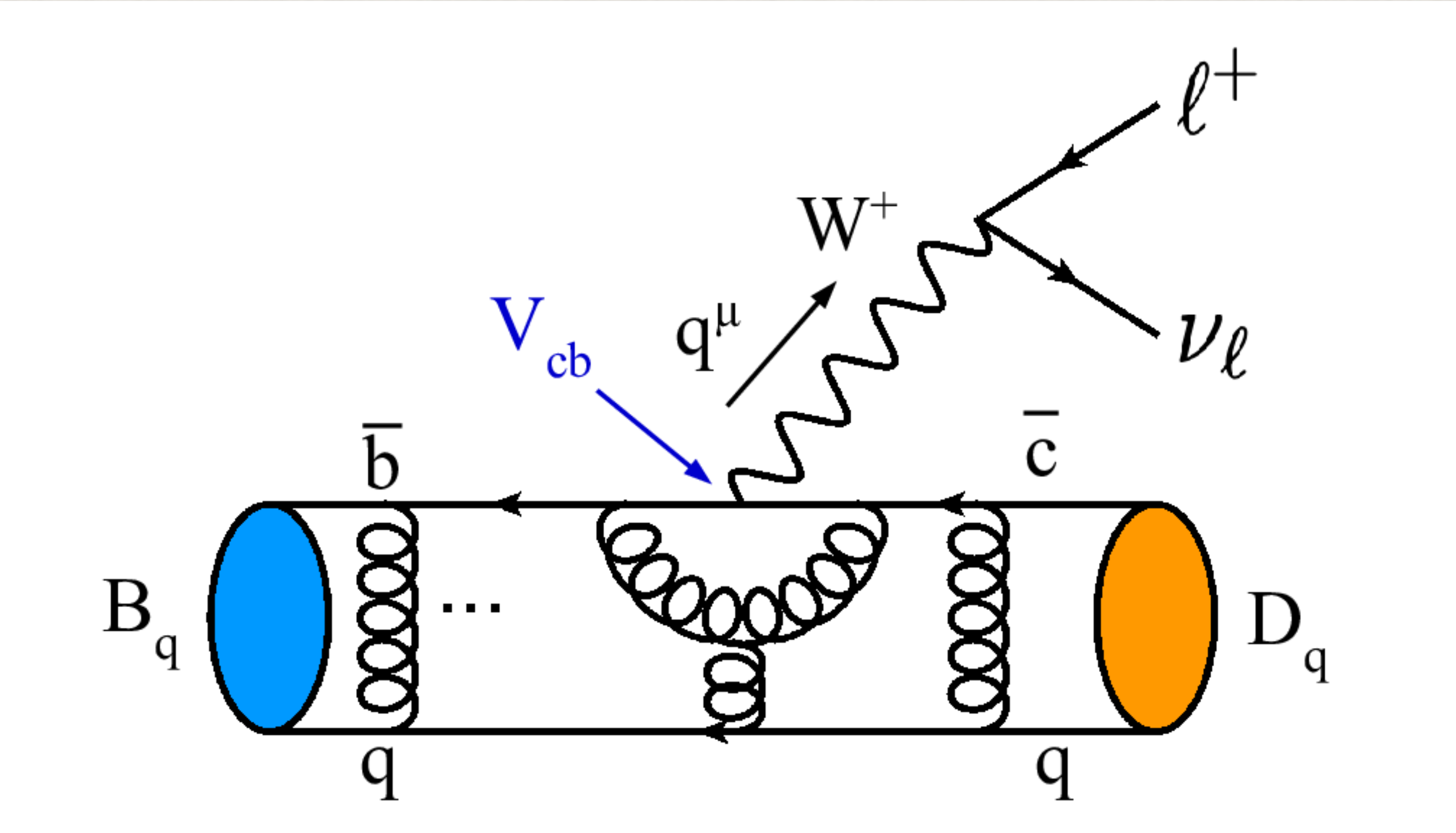
# Measuring CKM matrix elements

- Semileptonic B decays are used to extract the magnitude of $V_{ub}$ and $V_{cb}$.
  - Two approaches: inclusive vs exclusive
- Experimental and theoretical techniques are independent and complementary.
  - Inclusive: Sum of all possible final states. Uncertainty dominated by theory inputs.
  - Exclusive: Decays involve a specific meson. Uncertainty contributions from theory and experiment are comparable.
- Expect both approaches to be compatible but observed long lasting discrepancy.

# Exclusive measurements

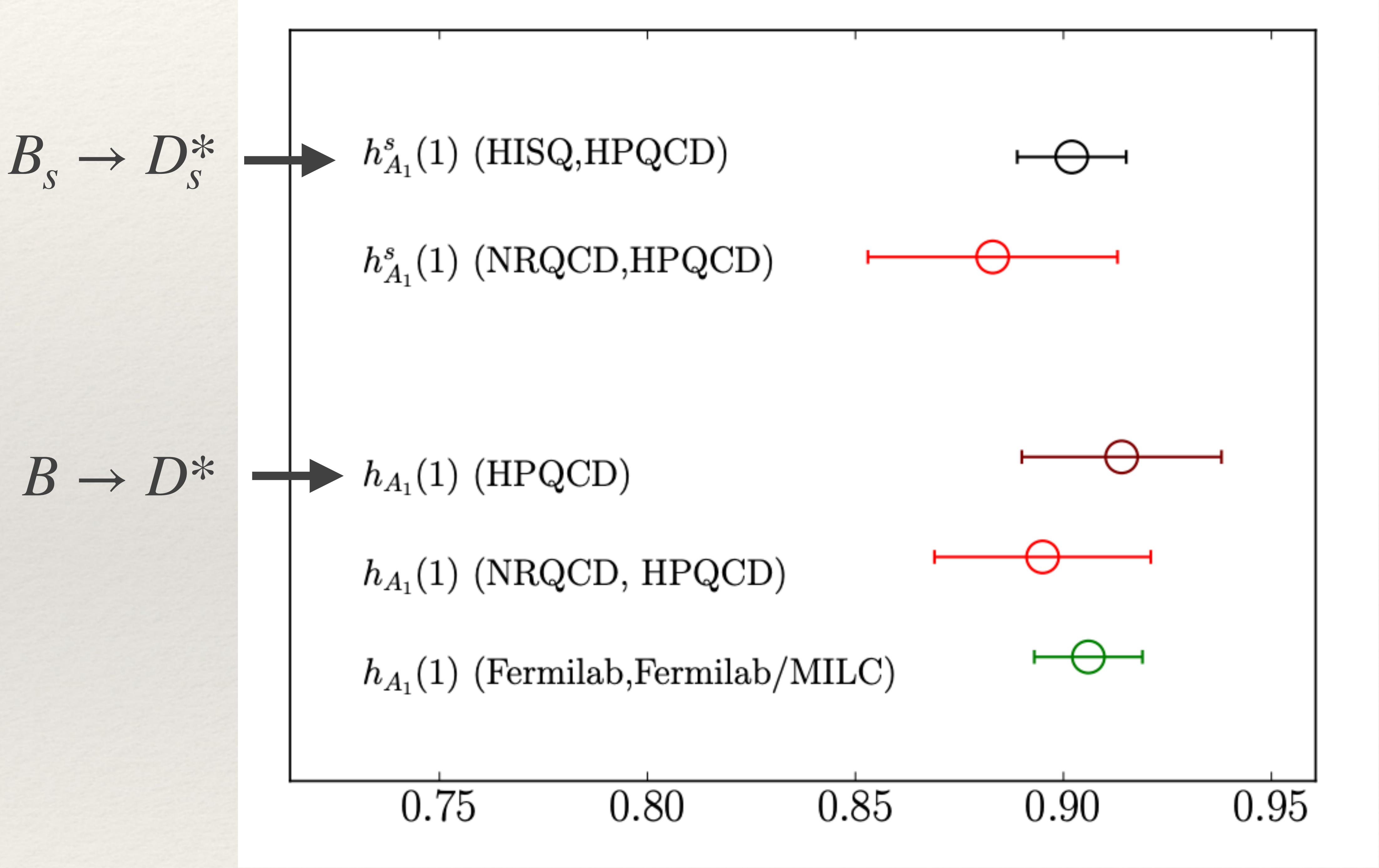
- Measure the differential decay rate of $B_{(s)} \rightarrow D^{(*)}_{(s)}\mu\nu$ decays as a function of the di-lepton momentum transfer squared ($q^2$).
- Factorise the EW and strong parts of the decay.
    - The strong part can be described in terms of scalar functions, **form factors**, as a function of $q^2$. FF cannot be computed in perturbation theory.
    - Experimental measurement is $V_{cb}$ x FF($q^2$). The determination of $V_{cb}$ requires a determination of the form factors (either from data or from lattice QCD).



# Beyond B$^0$ and B$^+$

- Measurements on $B_s$ and $\Lambda_b$ are complementary to those from B$^0$ and B$^+$.
- Lattice QCD calculations are easier due to the heavier spectator quark -> more precise predictions [PRD 99 (2019) 114512].
- In $B_s$ decays, Different background composition from excited $D_s$ mesons than in $B \to D^{(*)}$ decays.
    - Above certain mass of the $D_s^{**}$ mesons, the decay is through $D^{(*)}K$.



# The measurements

[PRD 96 (2017) 112005]

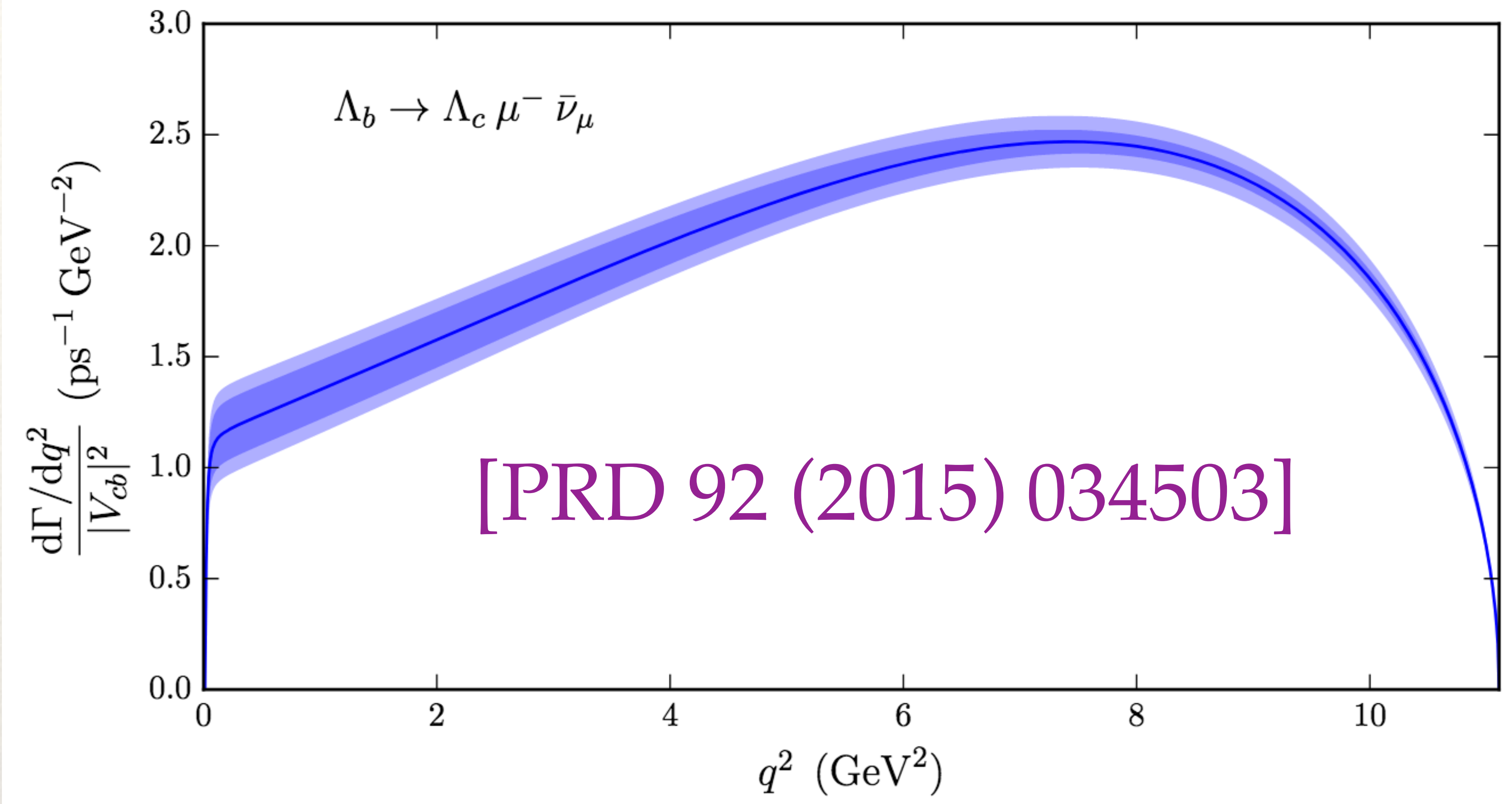
# $\Lambda_b \to \Lambda_c \mu\nu$ differential spectrum

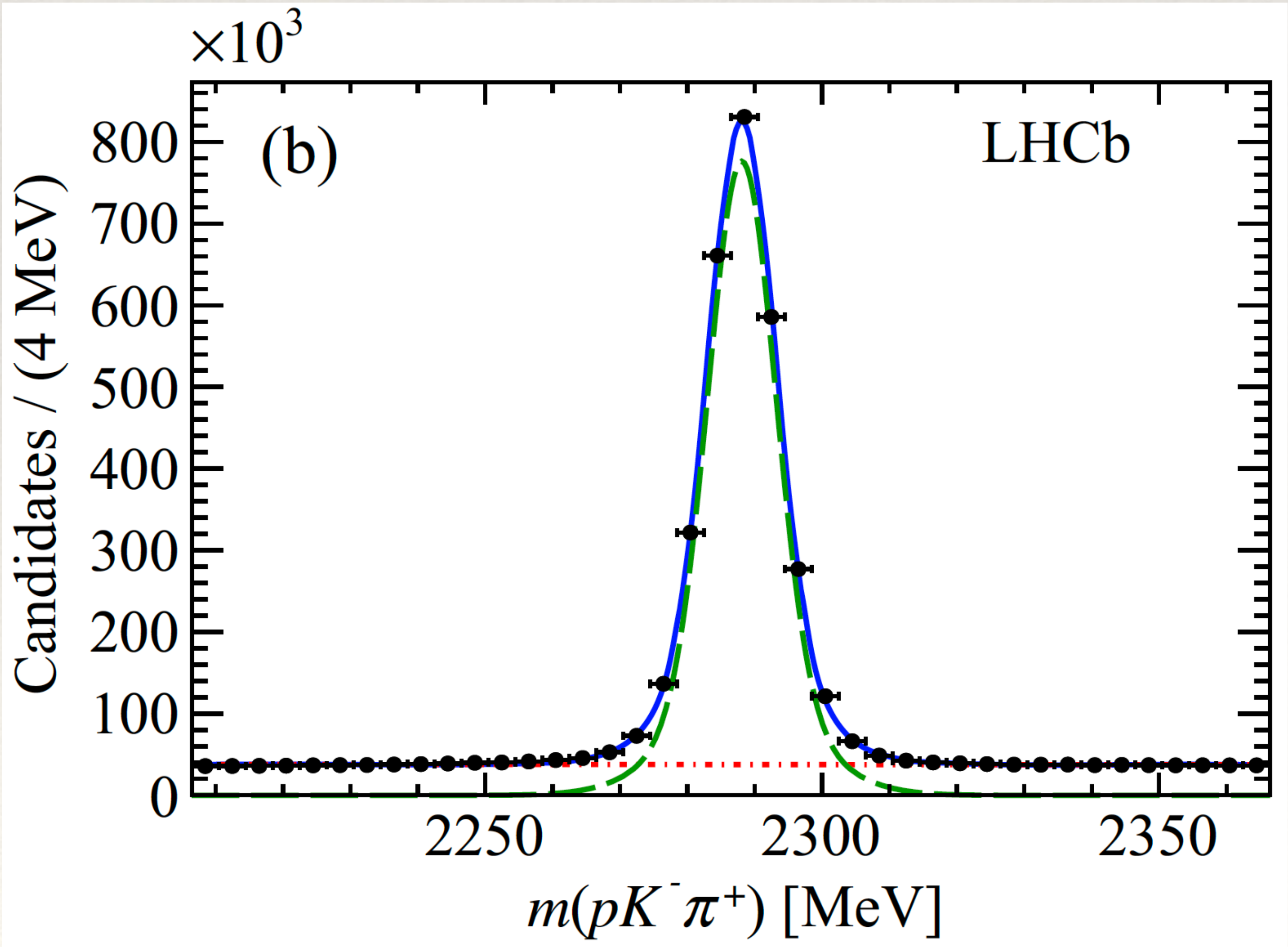
- $\Lambda_b$ (udb) has a different spin structure than $B^0/B^+$ and because the (ud) di-quark has j=0, HQET makes cleaner predictions.

- Measure the differential spectrum $\frac{d\Gamma}{dq^2} = GK(q^2)\xi_B^2(q^2)$.

  Extract the information on $\xi_B(q^2)$ assuming parametrisations based on phenomenological models or simple expansion around w=1.

- Large and clean sample of $\Lambda_b \to \Lambda_c \mu\nu X$, with main backgrounds from $\Lambda_b \to \Lambda_c^* \mu\nu$ and $\Lambda_b \to \Sigma_c^{++/0} \pi\mu\nu$

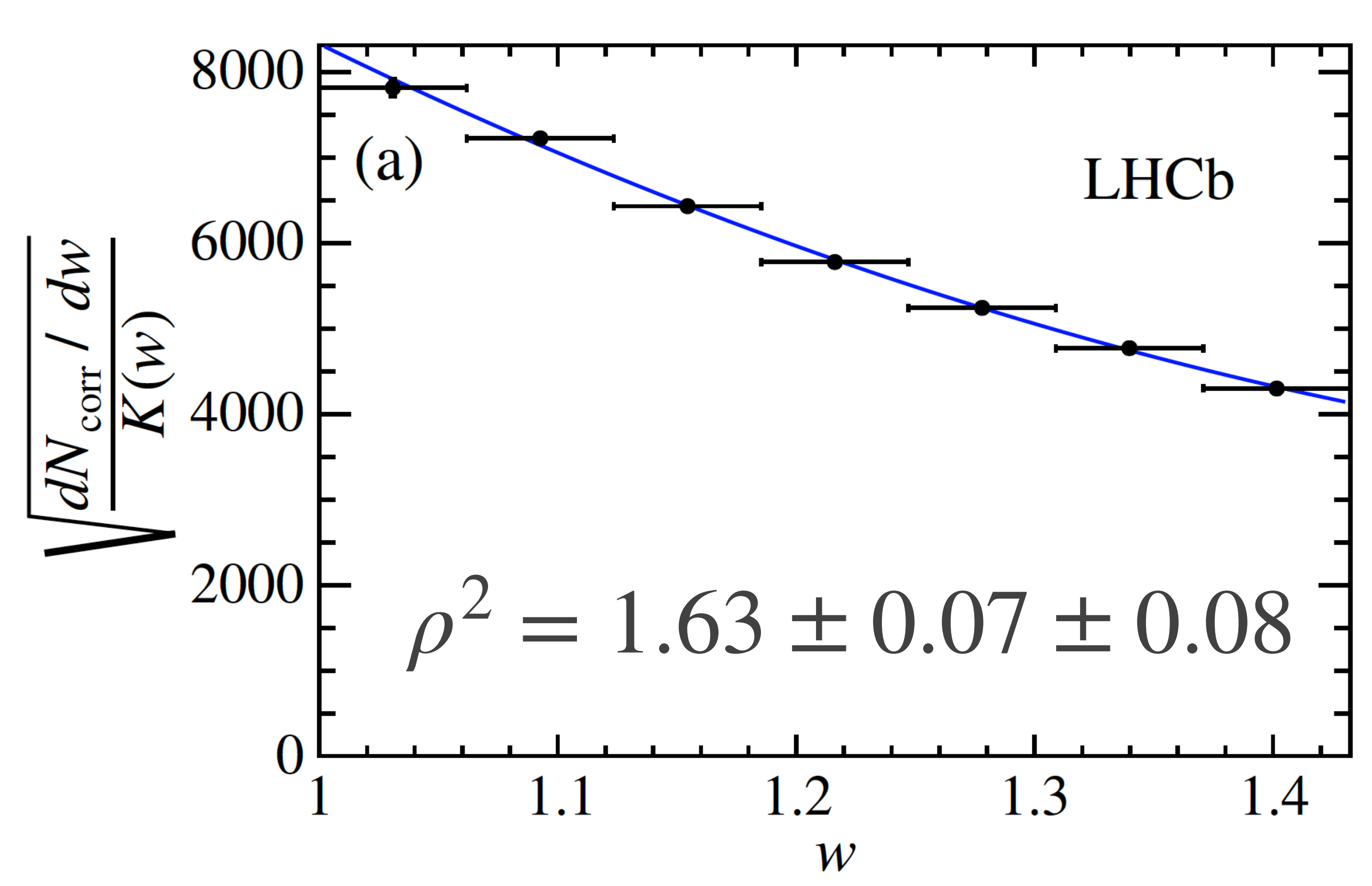


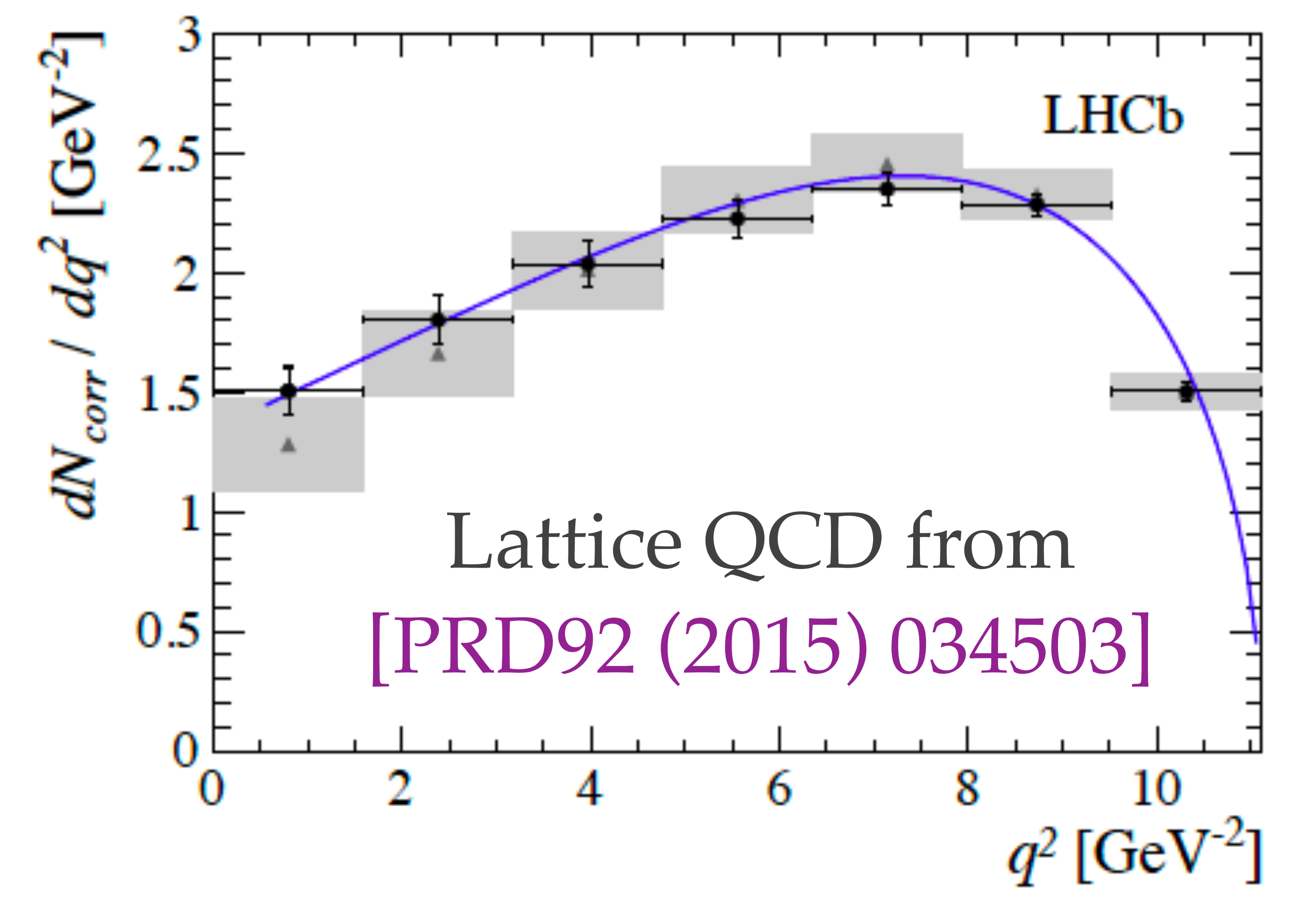



[PRD 96 (2017) 112005]

# $\Lambda_b \to \Lambda_c \mu \nu$ differential spectrum

- $\Lambda_b$ yield in bins of $q^2$. Correct for feed-down from background, efficiencies and unfold.
- Different parametrisations have good fit quality. Data/HQET predictions agree.
- Knowledge of $\Lambda_b \to \Lambda_c$ FF crucial for $R(\Lambda_c)$.
- Opened the route to measurements of FF in other B-hadrons.
- Significant yields of excited states O(10k). Good opportunity to study them.

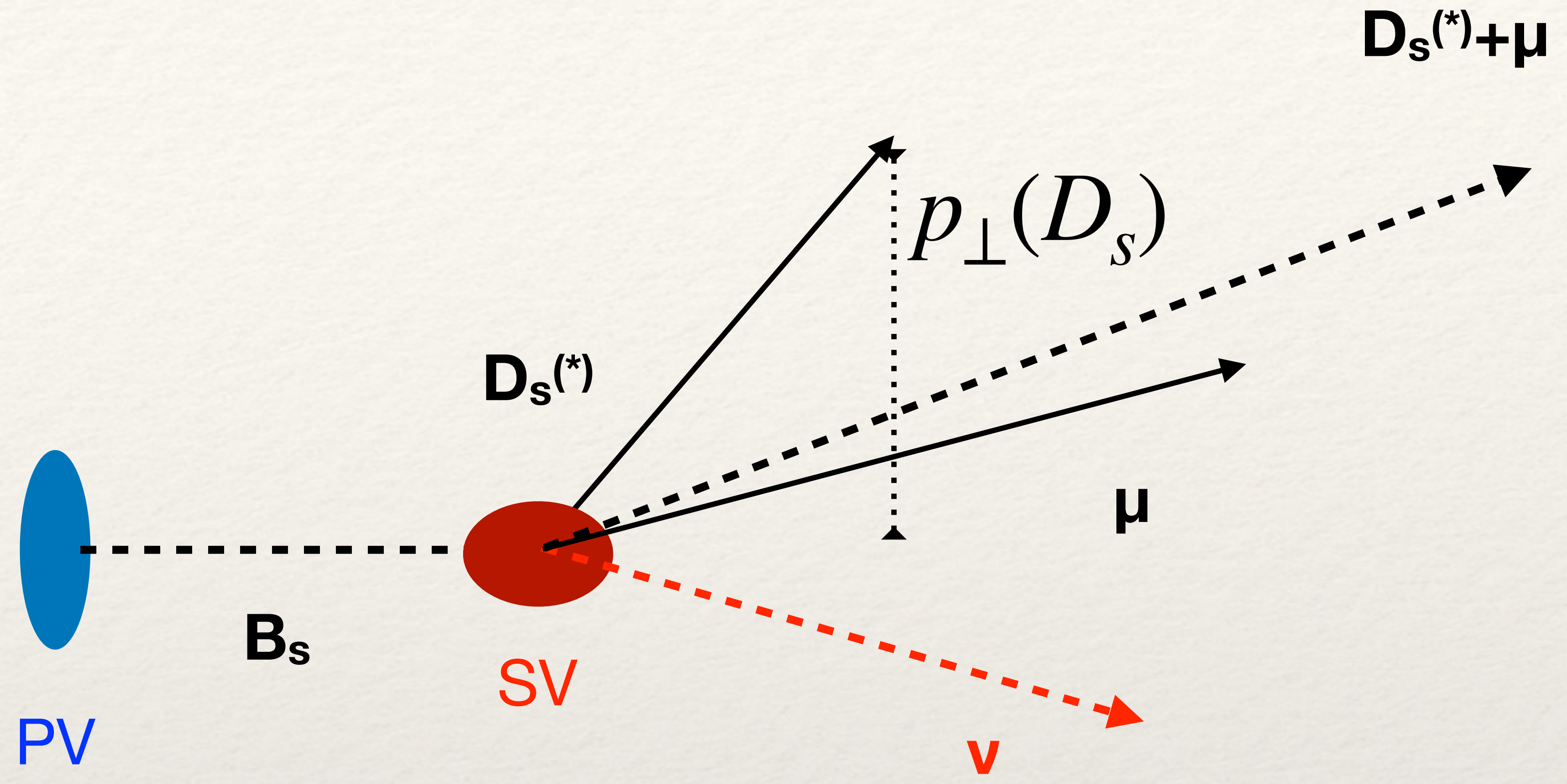


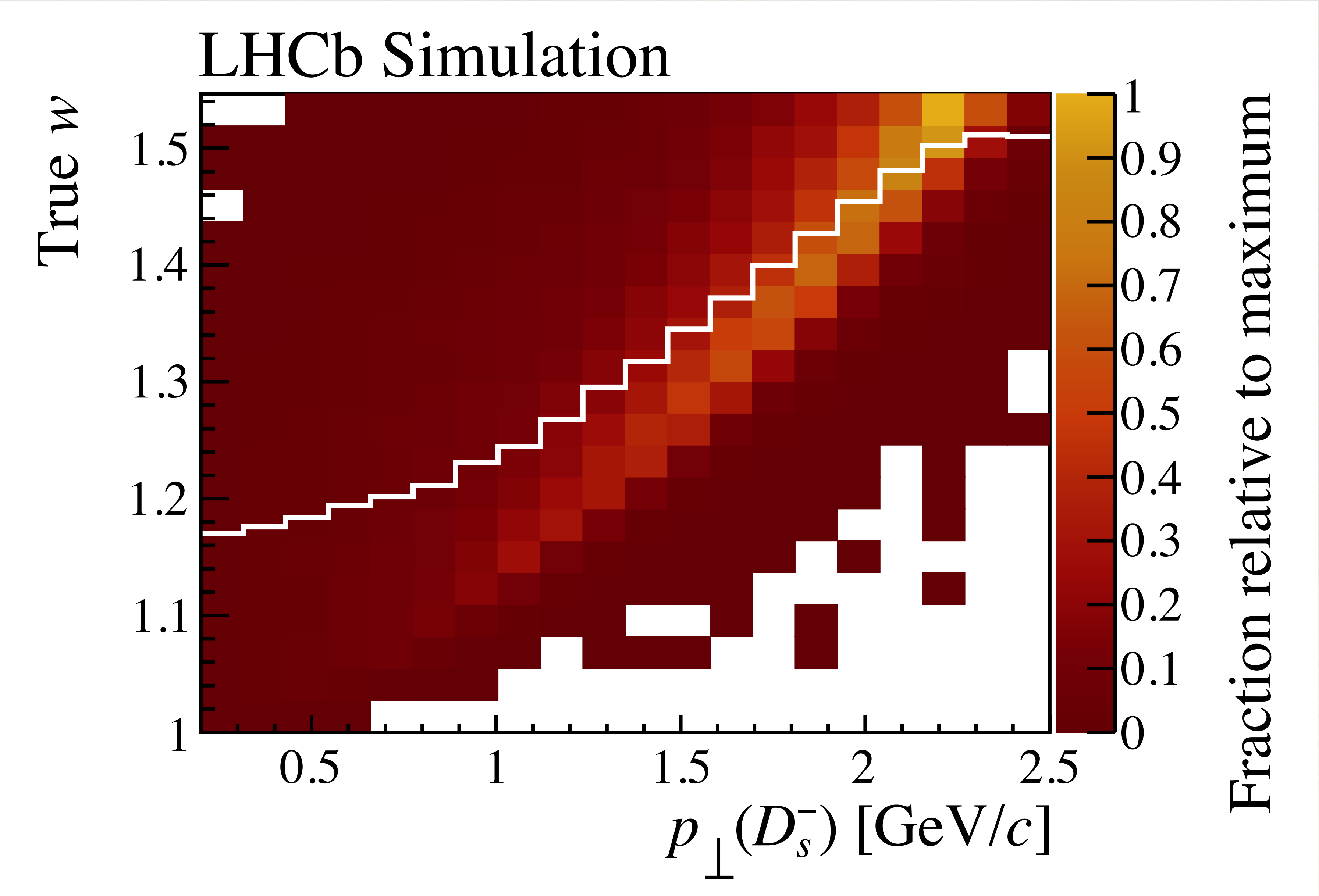



# $V_{cb}$ from $B_s$ decays

[PRD 101 (2020) 072004]

- Extract the value of $V_{cb}$ from $B_s \to D_s^- \mu^+ \nu$ and $B_s \to D_s^{*-} \mu^+ \nu$ decays reconstructing only the $D_s^-(\to K^- K^+ \pi^-)\mu^+$ final state.
  - Use $B^0 \to D^{-(*)}\mu^+\nu$ as normalisation. Ratio of yields is proportional to $V_{cb}$. $BR(B^0 \to D^{-(*)}\mu^+\nu)$ and $f_s/f_d$ are taken as external inputs. Kinematically identical decays -> reduce systematic uncertainties.
- Use $p_\perp(D_s)$ which is correlated with w. Avoid to use any approximation.



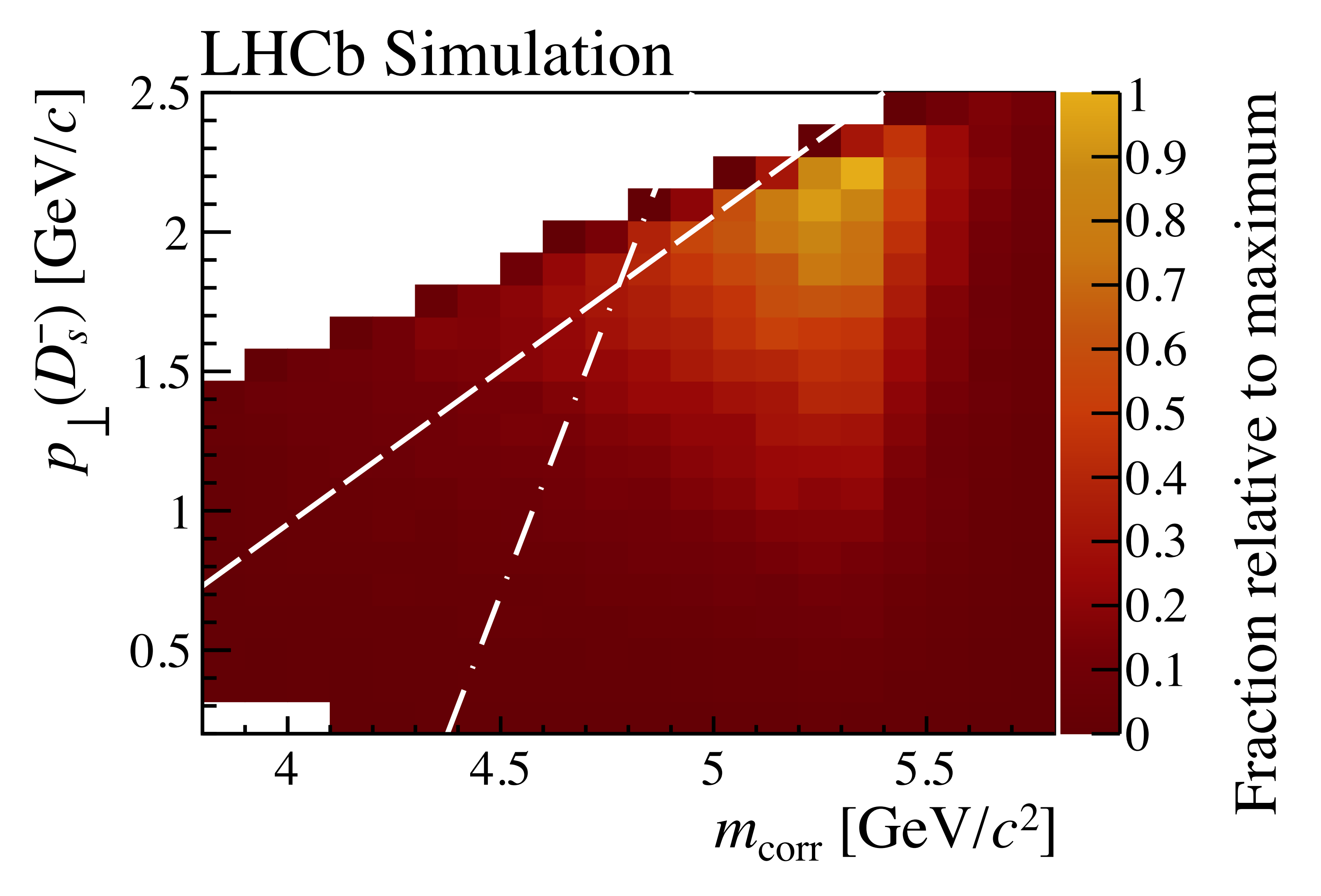



# Analysis strategy

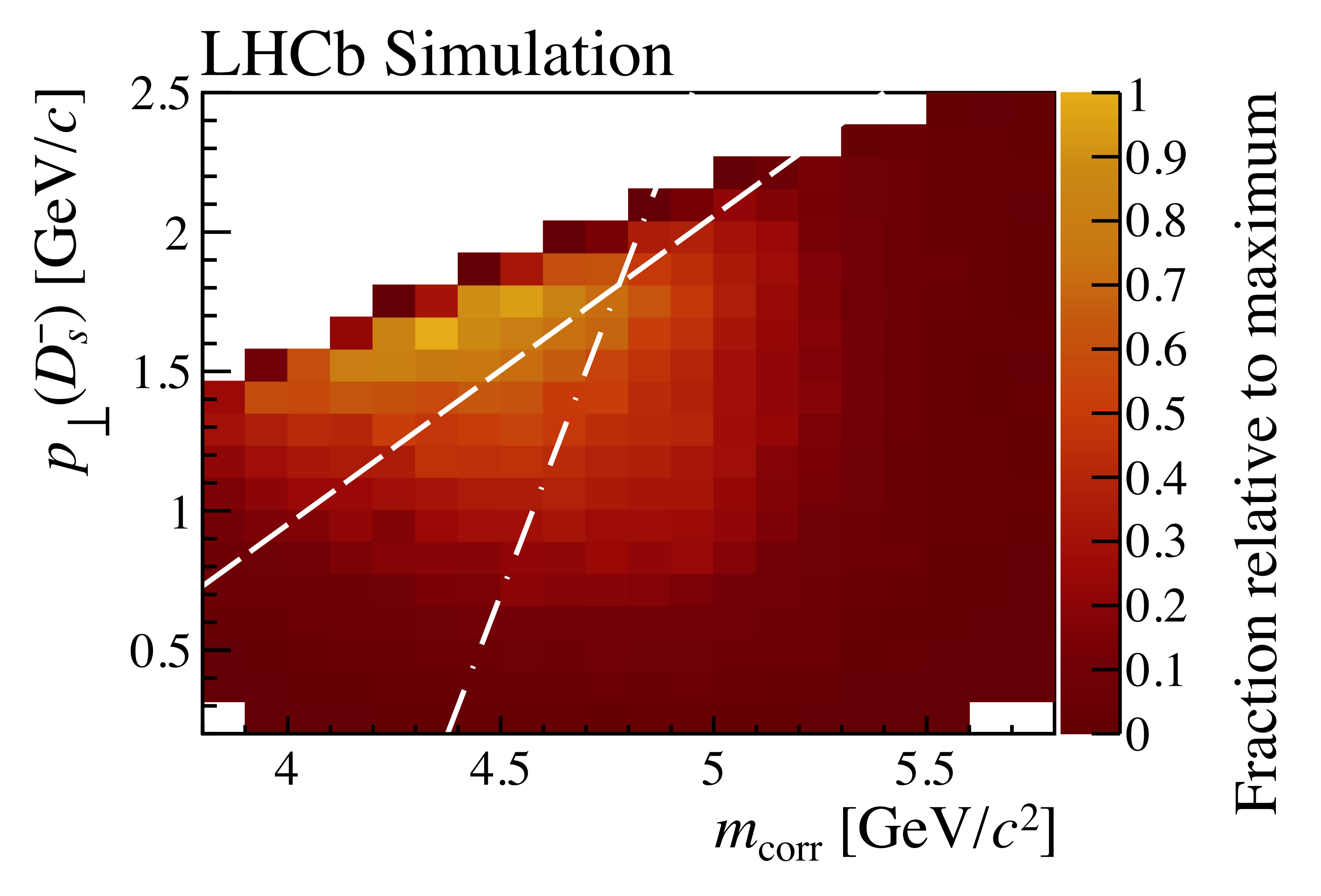
[PRD 101 (2020) 072004]

- Template fit to $m_{corr}$ and $p_{\perp}$ to identify the signal decays and to measure $V_{cb}$ and the form factors.
- Signal templates depend on form factors which are recalculated at each fit iteration. Use CLN and BGL parametrisations.
    - Fit is simultaneous to signal and normalisation mode. Also provide sensitivity to form factors.

$B_s \to D_s^{(*)} \mu \nu$




**Physics background**



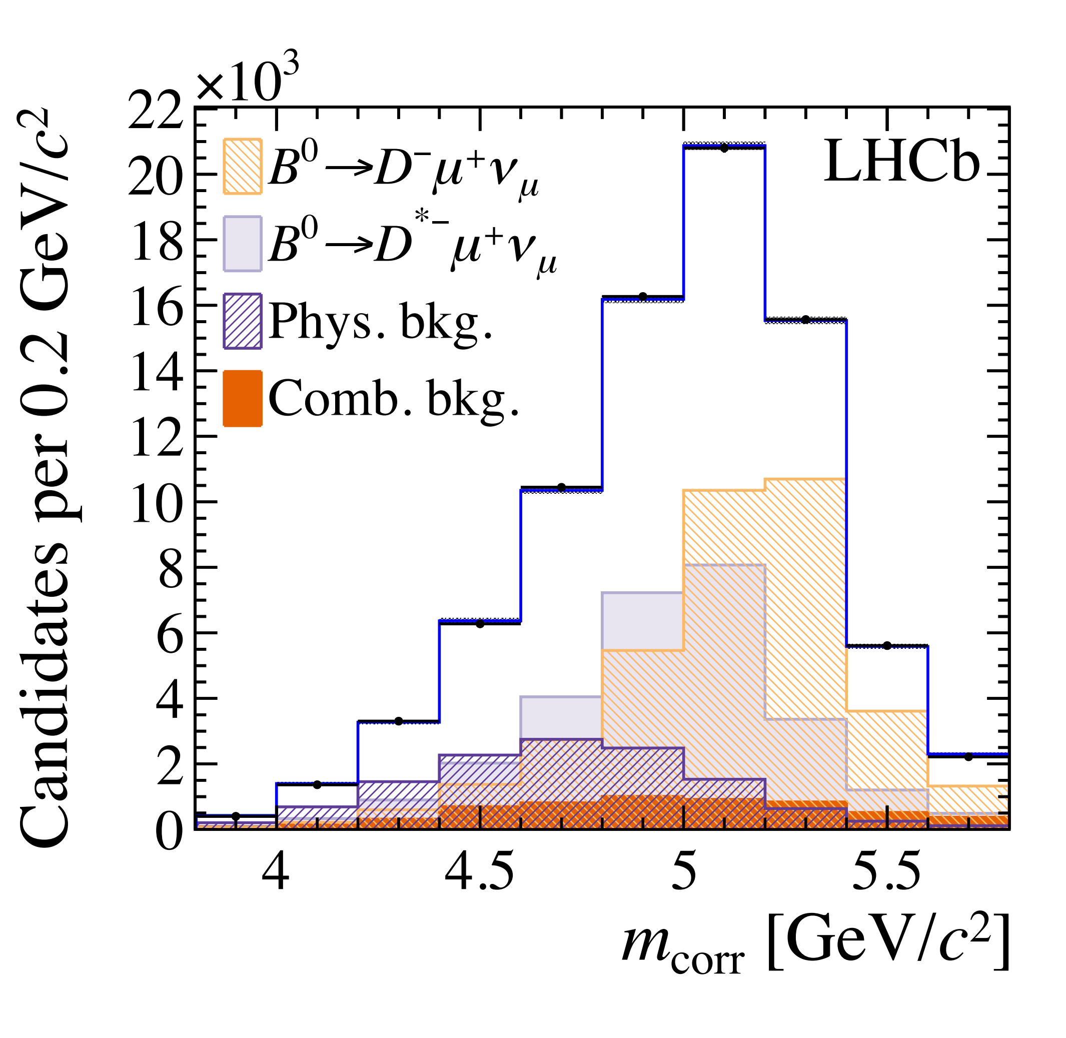
# Fit results

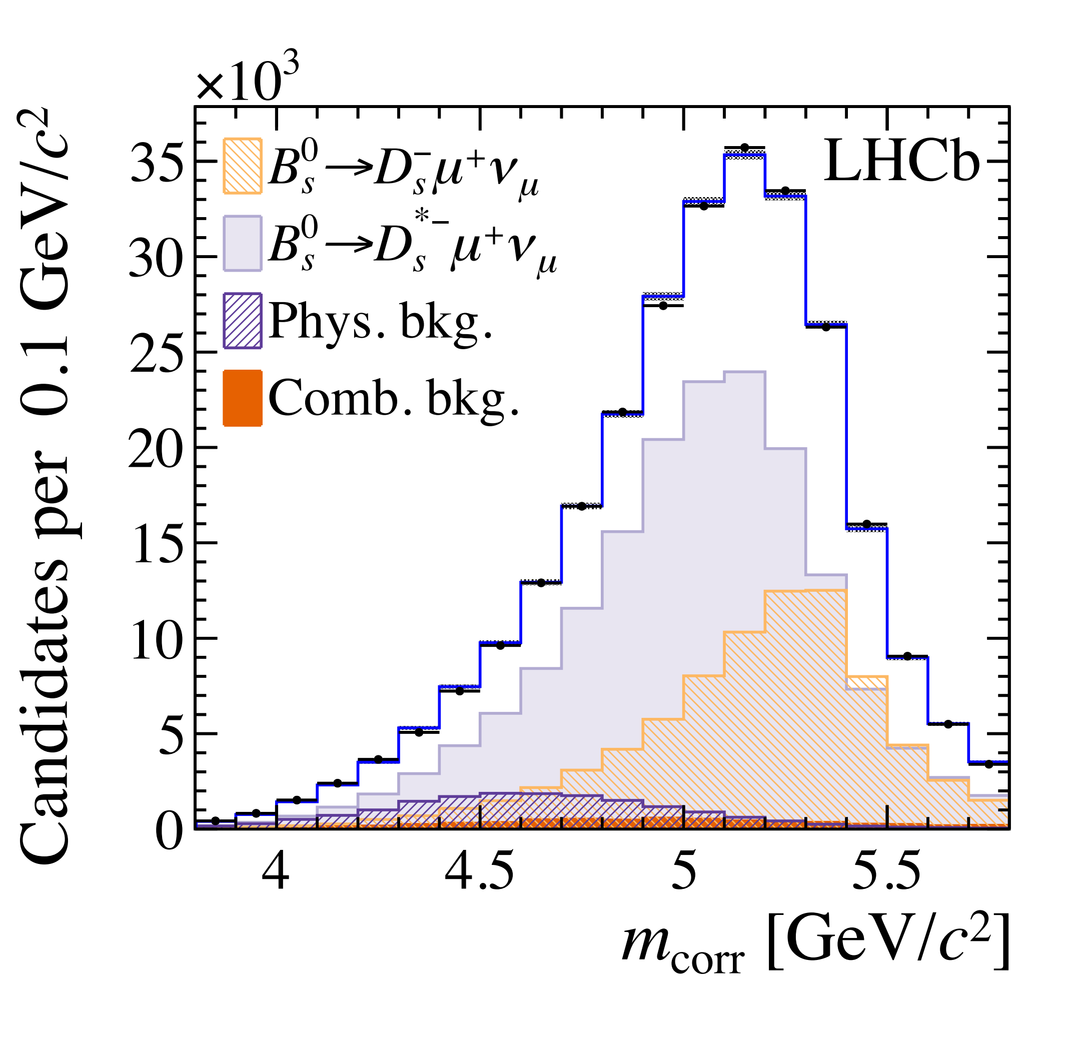
[PRD 101 (2020) 072004]

- Yields for signal, normalisation and form factors are free parameters.
  - Use only CLN for the normalisation as it contain less parameters.
  - FF in normalisation mode consistent with world averages.
- For the signal use CLN and BGL parametrisations. No significant differences found between both parametrisations.

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

- Parametrisation does not seem to be responsible for the exclusive vs inclusive disagreements.



# $B_s \to D_s^*$ FF measurement

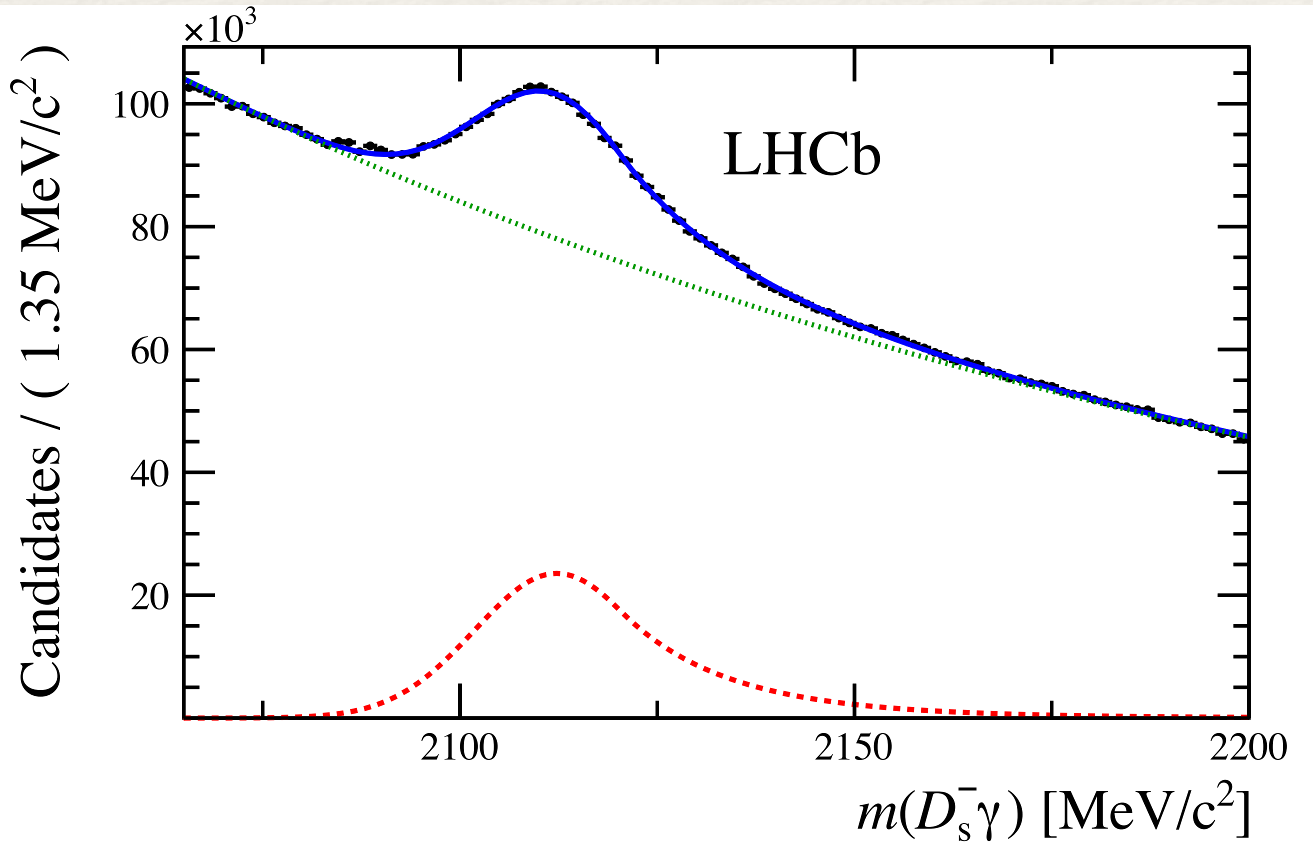
[JHEP 12 (2020) 144]

- Aim to measure more accurately the $B_s \to D_s^*$ FF.
- Extract the differential decay rate of $B_s \to D_s^{*-}\mu^+\nu$ decays as a function of w by fitting $m_{corr}$
  - Full reconstruction of $D_s^{*-} \to D_s^-\gamma$ decay.
- Correct the raw yields for detector resolution (unfolding) and selection and reconstruction efficiencies.
- Fit the unfolded and efficiency corrected spectrum with CLN (extract $\rho^2$) and BGL parametrisations (extract $a_1^f, a_2^f$).
  - Other parameters are taken from external sources.

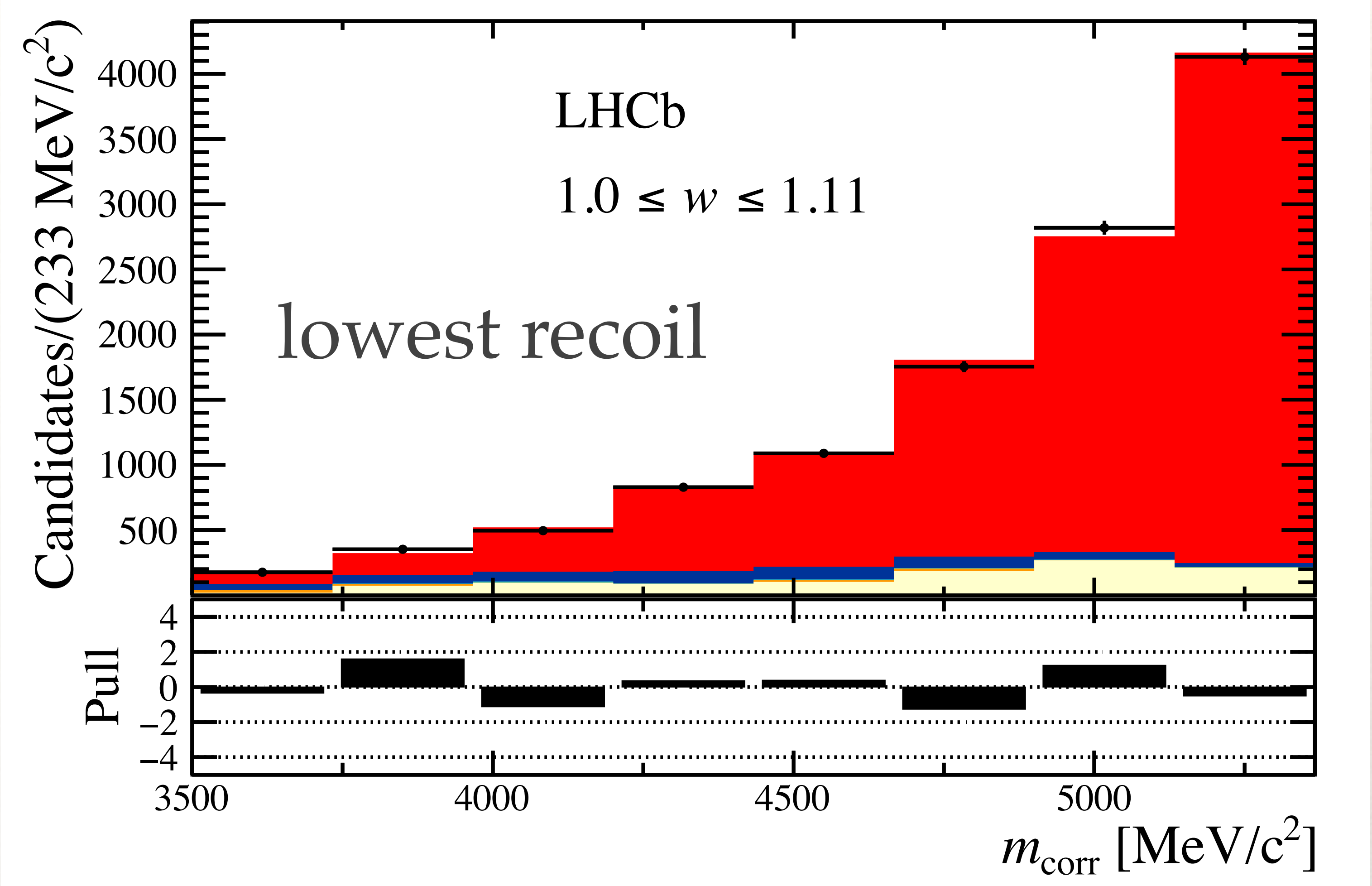
# Selection and signal yields

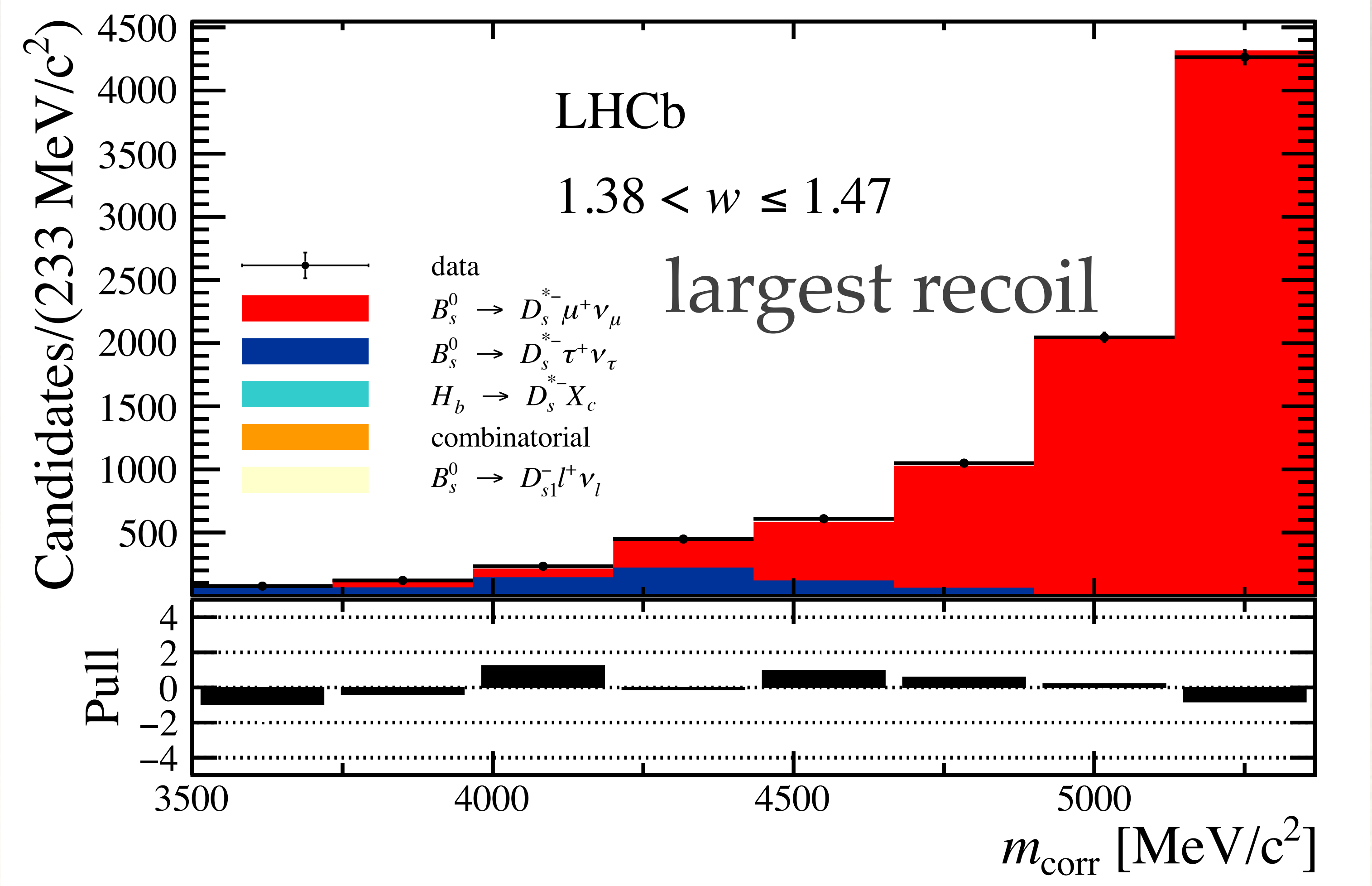
[JHEP 12 (2020) 144]

- Consider only photons close to the $D_s^-$ flight direction.
  - Use sPlot to subtract the combinatorial photon background.




- Efficiencies extracted from data calibration samples

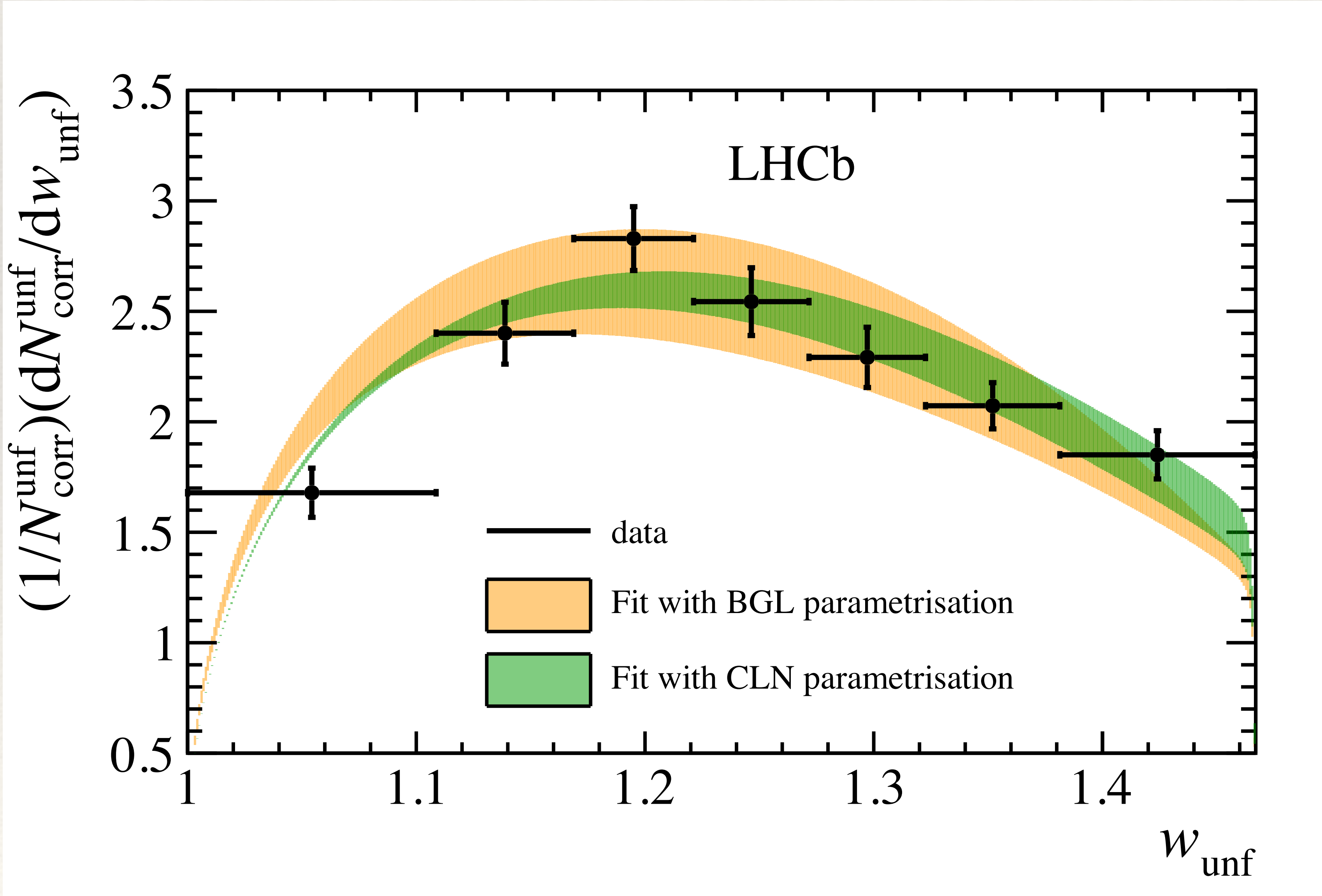


# FF results

[JHEP 12 (2020) 144]

- After unfolding and correcting the measured yield for the efficiencies, fit the differential decay rate with CLN and BGL parametrisations. No significant differences found between both.
- Provide unfolded spectrum for phenomenological analysis for the first time.




For CLN:

$$\rho^2 = 1.17 \pm 0.05 \pm 0.07$$

in agreement with those from $B^0 \to D^{*-}\mu^+\nu$

No flavour SU(3) breaking.

For BGL:

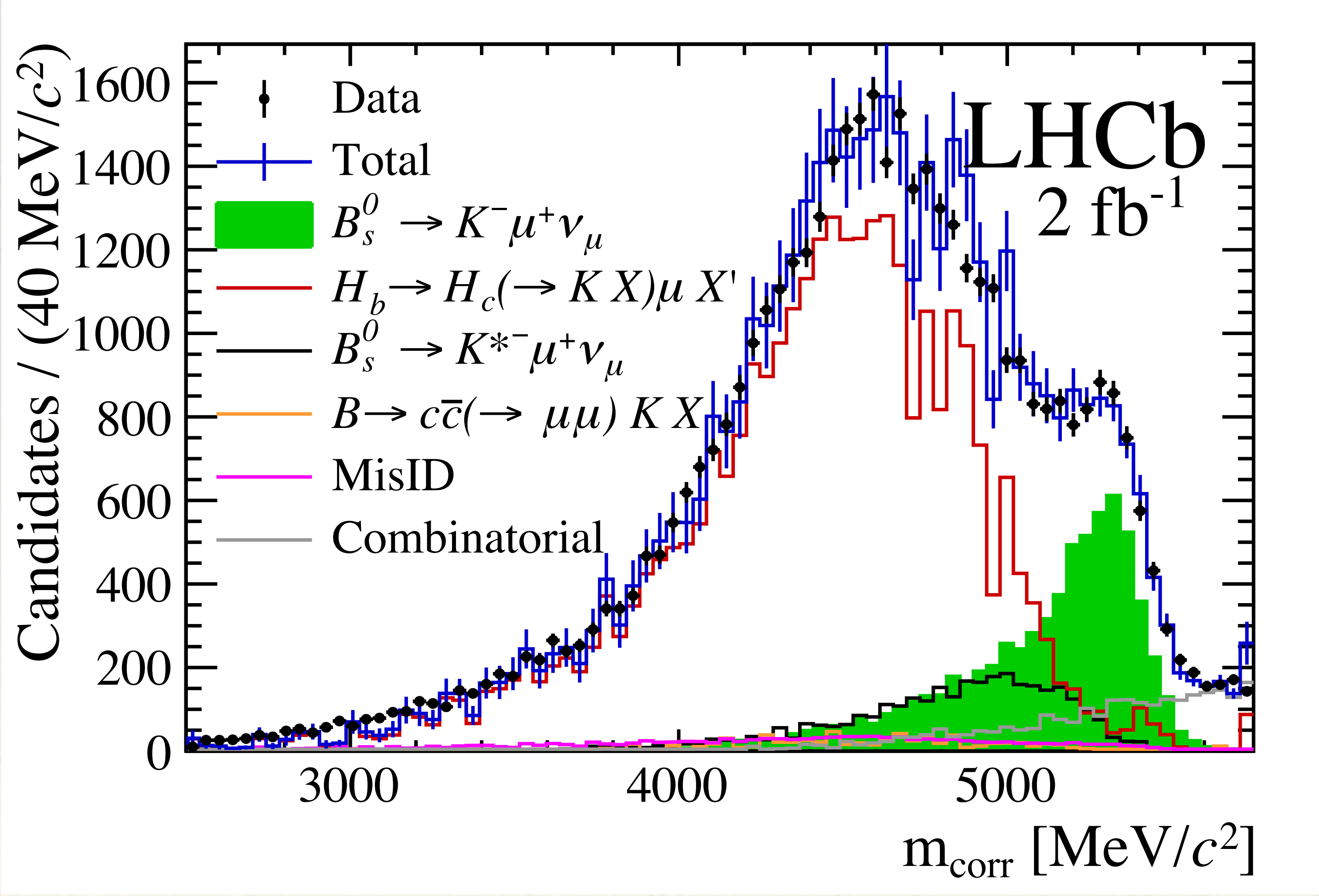
$$a_1^f = -0.002 \pm 0.034 \pm 0.046$$

$$a_2^f = 0.93^{+0.05+0.04}_{-0.20-0.38}$$

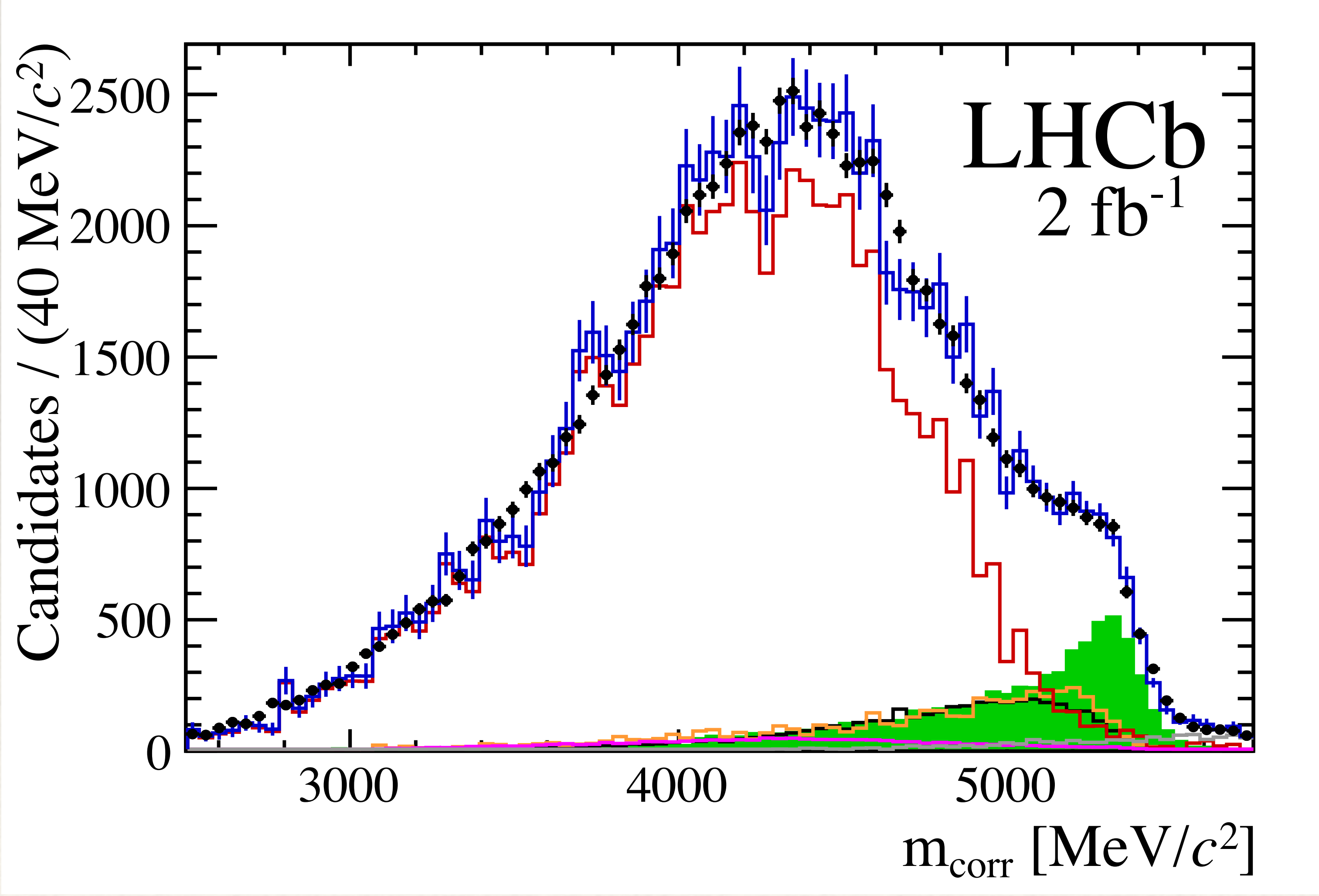
# $V_{ub}/V_{cb}$ from $B_s \to K^+\mu^-\nu$

[PRL 126 (2021) 081804]

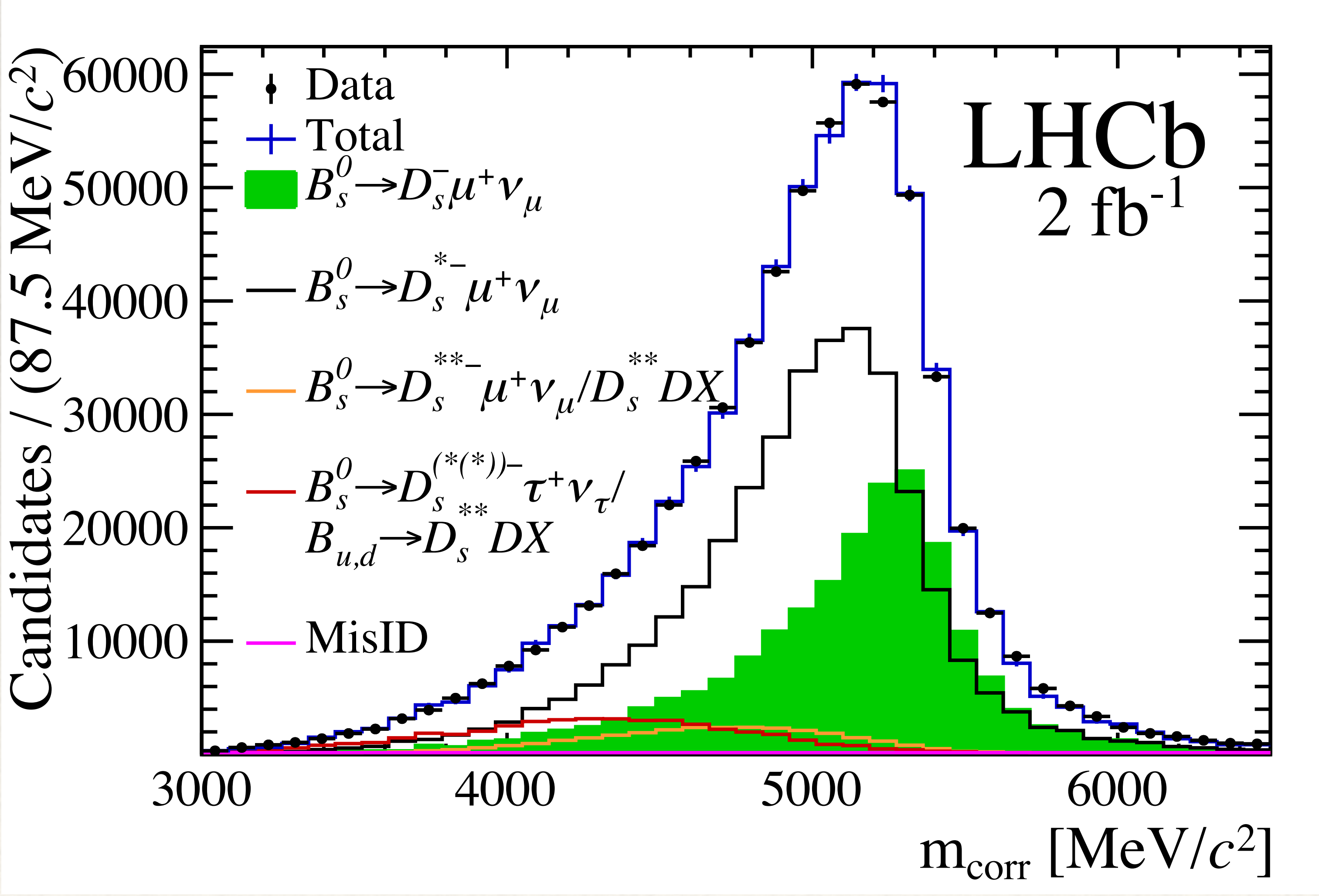
- Use $B_s \to K^-\mu^+\nu$ decays to measure $V_{ub}$. First observation of $B_s \to K^-\mu^+\nu$ decay.
    - Normalise with $B_s \to D_s^-\mu^+\nu$ so the measurement is $V_{ub}/V_{cb}$. Use $m_{corr}$ to discriminate signal and background.
- Divide signal in two bins of $q^2$ with equal number of signal events.




signal at $q^2 < 7\,\text{GeV}^2$




signal at $q^2 > 7\,\text{GeV}^2$

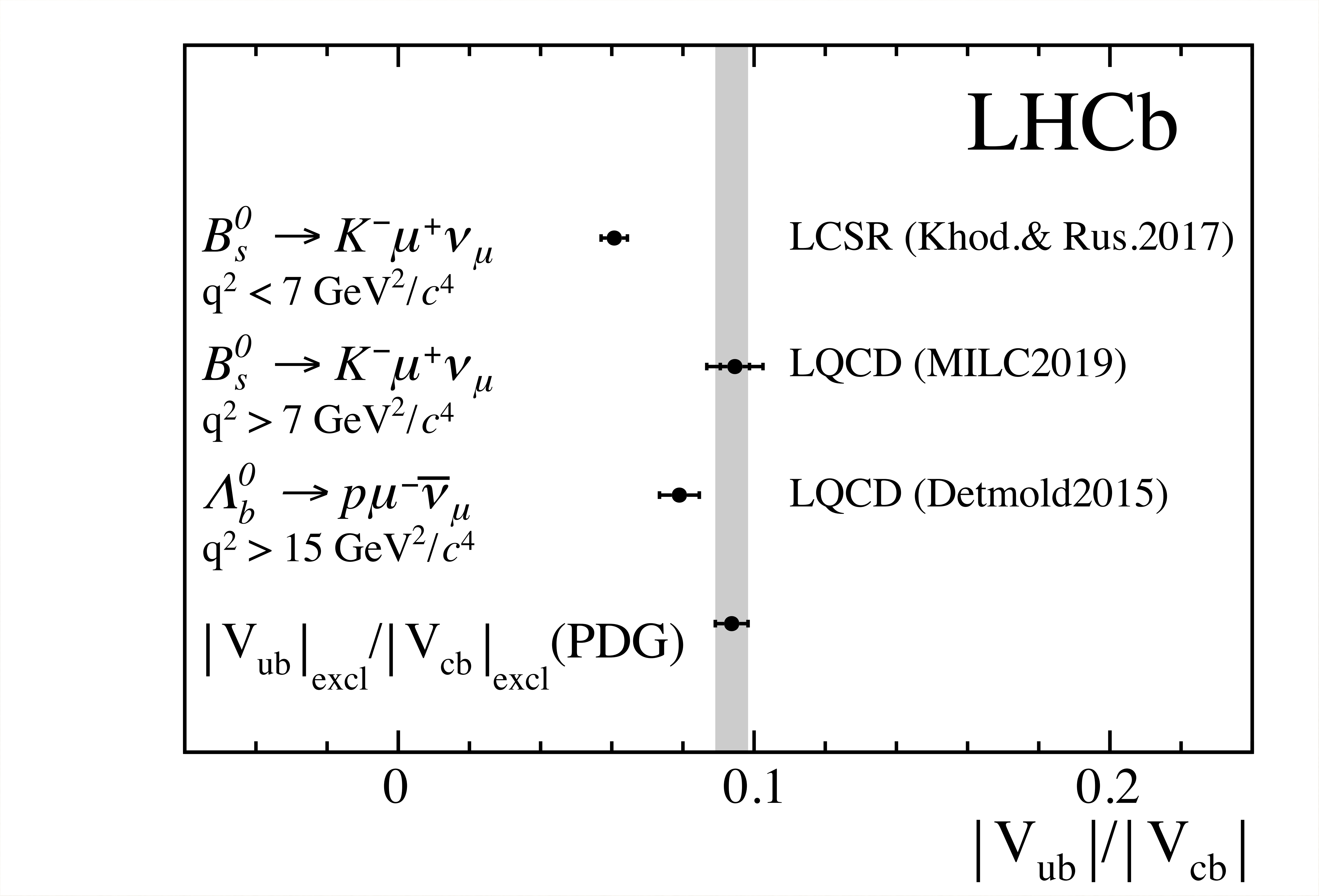



normalisation

# $V_{ub}/V_{cb}$ from $B_s \to K^+\mu^-\nu$

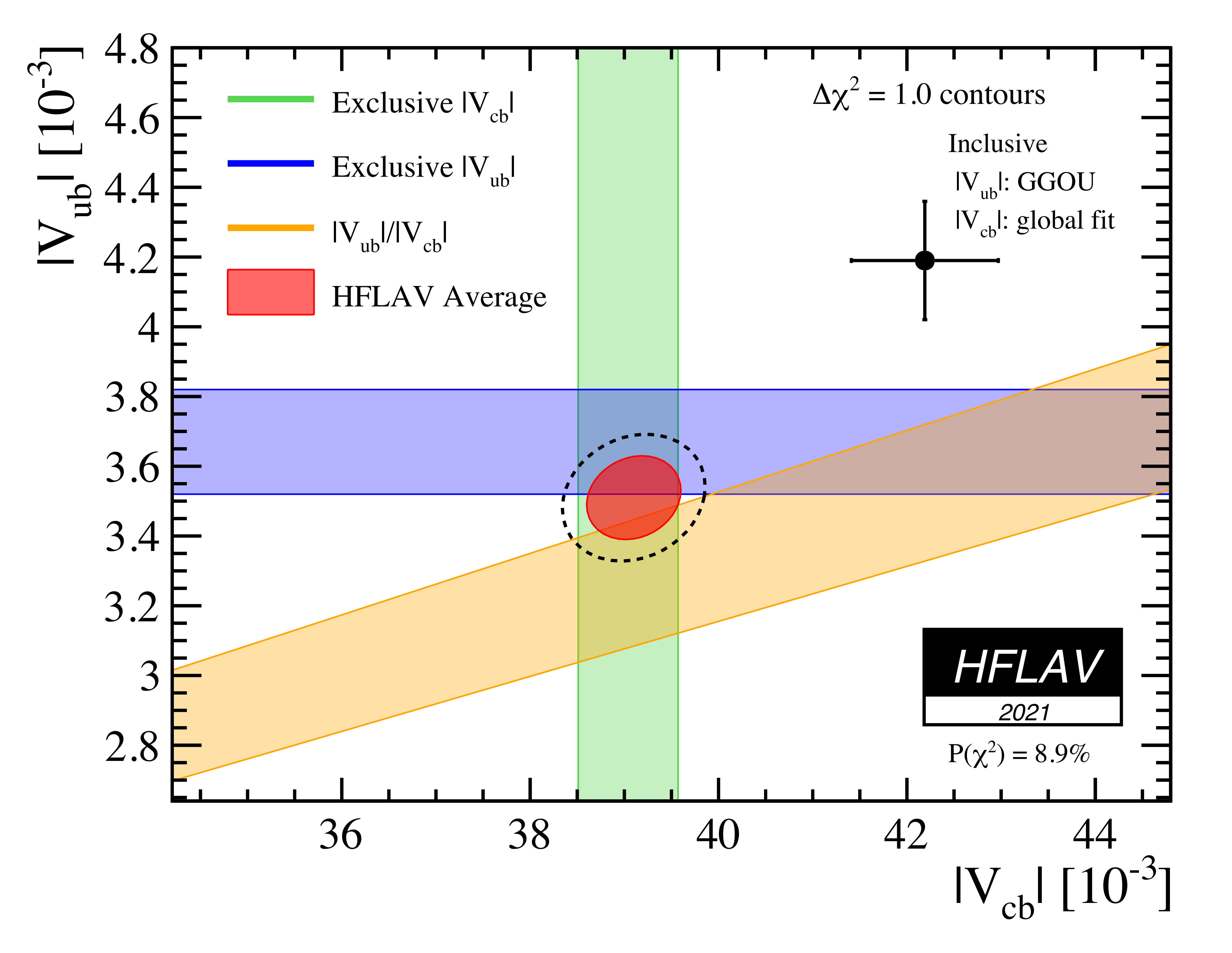
[PRL 126 (2021) 081804]

- Two different FF predictions for $B_s \to K^-\mu^+\nu$ used to extract $V_{ub}$.
  - Low $q^2$: LCSR based on [JHEP 08 (2017) 112].
  - High $q^2$: LQCD based on [PRD 100 (2019) 034501].
- Provide two values of $V_{ub}$.



# Exclusive $V_{ub}$ vs $V_{cb}$

- Averaging all the results shown and adding $V_{ub}$ from $\Lambda_b \to p\mu\nu$ normalised to $\Lambda_b \to \Lambda_c\mu\nu$ [Nature Phys. 11 (2015) 743].
    - Contains updates on normalisation $BR(\Lambda_c \to pK\pi)$, and LQCD for $q^2 > 7\,\mathrm{GeV}^2$
- Tension between exclusive and inclusive measurements still present.

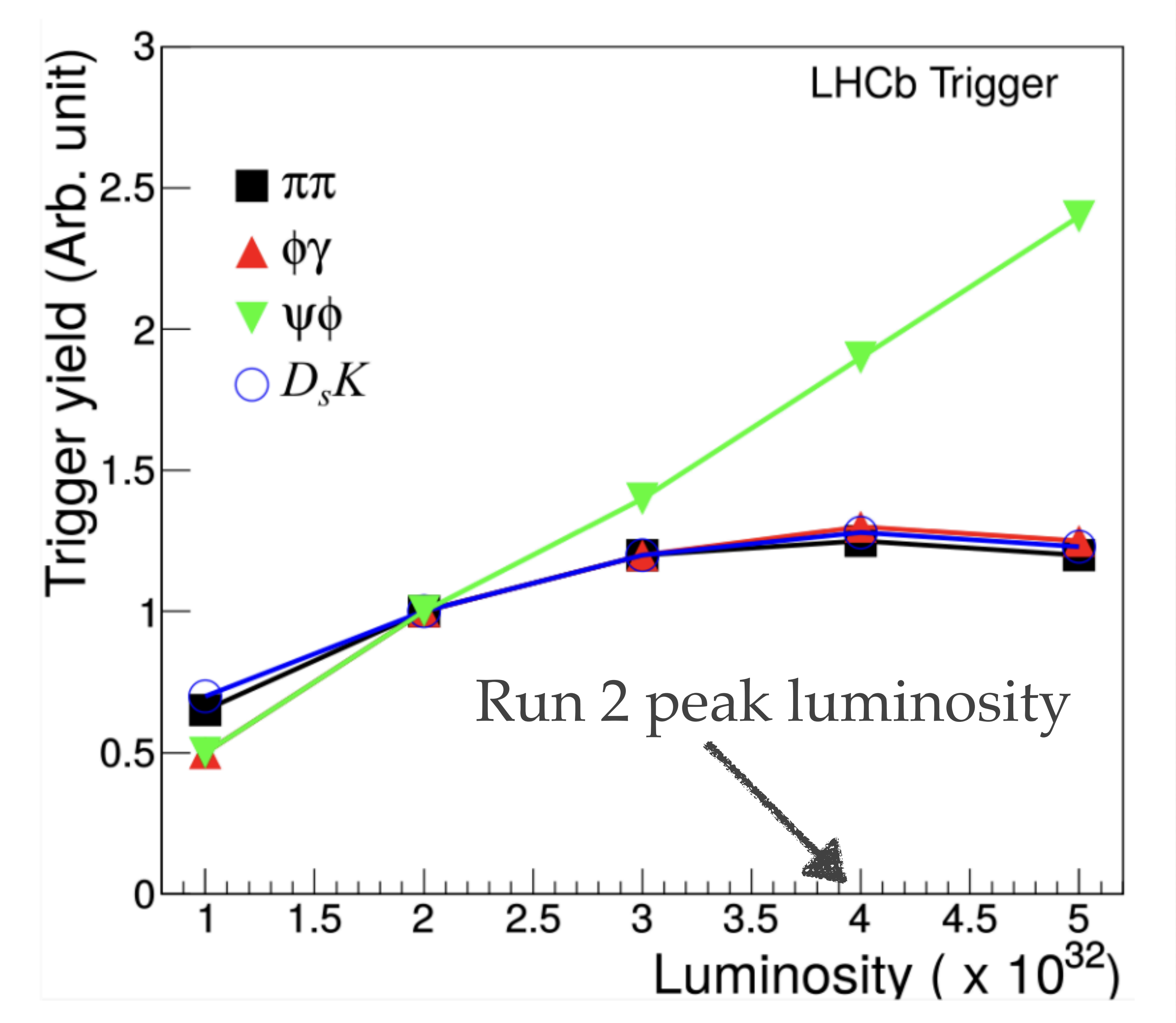


# The future

- $V_{cb}$ from $\Lambda_b \to \Lambda_c \mu \bar{\nu}_\mu$
  - Based on PRD 96 (2017) 112005 to measure $d\Gamma/dq^2$ by fitting the corrected mass in bins of $q^2$and compare with lattice predictions to obtain $V_{cb}$.
  - Additionally, will produce a precise measurement of $BF(\Lambda_b \to \Lambda_c \mu\nu)$ and get the fraction of inclusive rate going to $\Lambda_c^*$ $(N(\Lambda_c^* \mu\nu / \Lambda_c \mu\nu X))$.
- $V_{ub}/V_{cb}$ from $B_c \to D^{(*)0} \mu\nu$
  - Normalise to $B_c \to J/\psi \mu\nu$. Use LQCD and QCDSR to get the ratio of FF. [PRD 105, 014503; PRD 102, 094518; JHEP 02 (2020) 171 ]
  - Analysis strategy formulated to reduce the sensitivity to $q^2$. Single fit to $m_{corr}$

# The LHCb upgrade

- In Run3 LHCb has removed the hardware trigger, being able to reconstruct in software the 30MHz of visible collisions.
  - The removal of L0 is crucial for hadronic modes as their yield saturated with luminosity.
  - Effects on the majority of $b \to c l \nu_l$ decays as the hadrons are (partly) used to select the events.
  - When only muons were used to trigger, now hadrons can provide extra statistics.
- Hadronic triggers are mandatory to access low $p_T$ muons.



# Conclusions

- Properties of B-hadrons can be studied in LHCb with semileptonic decays with high precision.
- Several measurements of FF done, fundamental inputs for $R(X_c)$ measurements.
- CKM matrix elements $V_{ub}$, $V_{cb}$ measured exclusively with similar precision as the inclusive.
  - Long lasting ~$3\sigma$ tension between inclusive and exclusive measurements is still present.
- Crucial collaboration with the theory community.
- New measurements of CKM matrix elements ongoing with $\Lambda_b$ and $B_c^+$.
- Run 3 with the upgraded detector and fully software trigger will provide more data.

# Backup

# Form factors from $B_s \to D_s^* \mu\nu$ decays

- The decays $B_s \to D_s^* \mu\nu$ are described by four form factors.

EW + phase space contribution

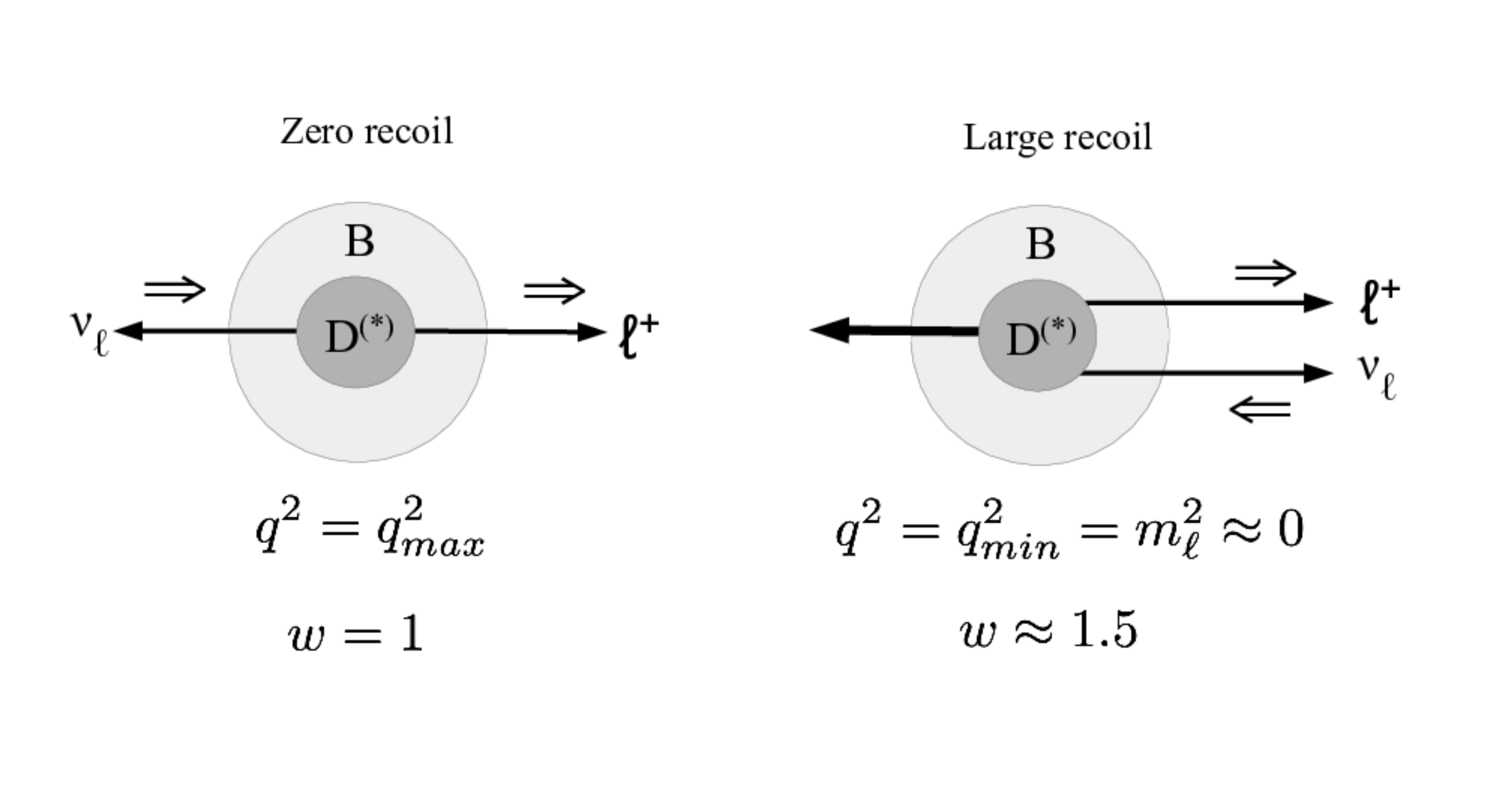
QCD contribution

$$\frac{d\Gamma(B_s^0 \to D_s^{*-}\mu^+\nu_\mu)}{dq^2} = \frac{G_F^2\,|V_{cb}|^2\,|\eta_{EW}|^2\,|\vec{p}|q^2}{96\,\pi^3\,m_{B_s^0}^2}\left(1-\frac{m_\mu^2}{q^2}\right)^2 \times \left[(|H_+|^2+|H_-|^2+|H_0|^2)\left(1+\frac{m_\mu^2}{2\,q^2}\right)+\frac{3}{2}\frac{m_\mu^2}{q^2}|H_t|^2\right]$$

- The helicity amplitudes ($H_{+,-,0,t}$) can be described in terms of the form factors.
- At the zero recoil point ($q^2_{max}$) the FF can be computed with precision in LQCD.
- Experimentally the zero recoil point is not accessible as the phase space vanishes.
  - Need an extrapolation of the measured distribution of the decay rate to $q^2_{max}$.
  - The extrapolation relies on the FF parametrisation: CLN [Nucl. Phys. B530 (1998) 153] vs BGL [PRL 74 (1995) 4603, PLB 353 (1995) 306].

# $q^2$ vs w

- The quantity $q^2$ represents the di-lepton momentum transfer squared. Commonly used by the experimentalists.
  - Easier to obtain experimentally after accessing the B momentum.
- The quantity w represents the hadron recoil (Lorentz boost of the D meson in the B rest frame). Commonly used by the theorists.
  - Dimensionless and better defined properties in the $m_{b,c} >> \Lambda_{QCD}$ limit (w=1).
- Related by $w = \dfrac{m_B^+ + m_D^2 - q^2}{2 m_B m_D}$. The *zero recoil point* means $q^2 = q^2_{max}$ or $w = 1$.



# FF results

[JHEP 12 (2020) 144]