CKM metrology and B decays

adding a strange flavour to the $|V_{cb}|$ puzzle

Mirco Dorigo (INFN Trieste)
for the LHCb Collaboration

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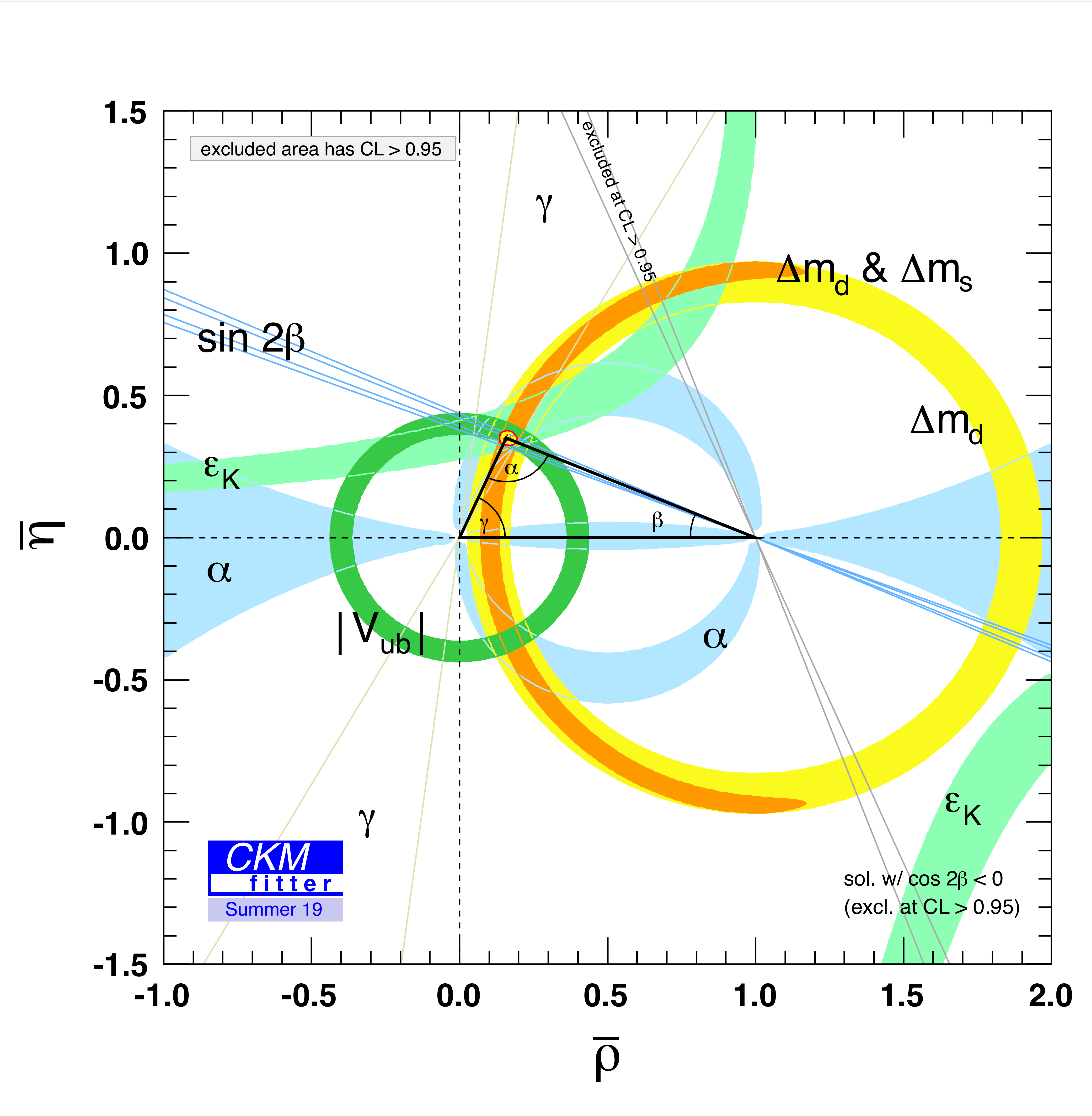
CKM metrology

Status

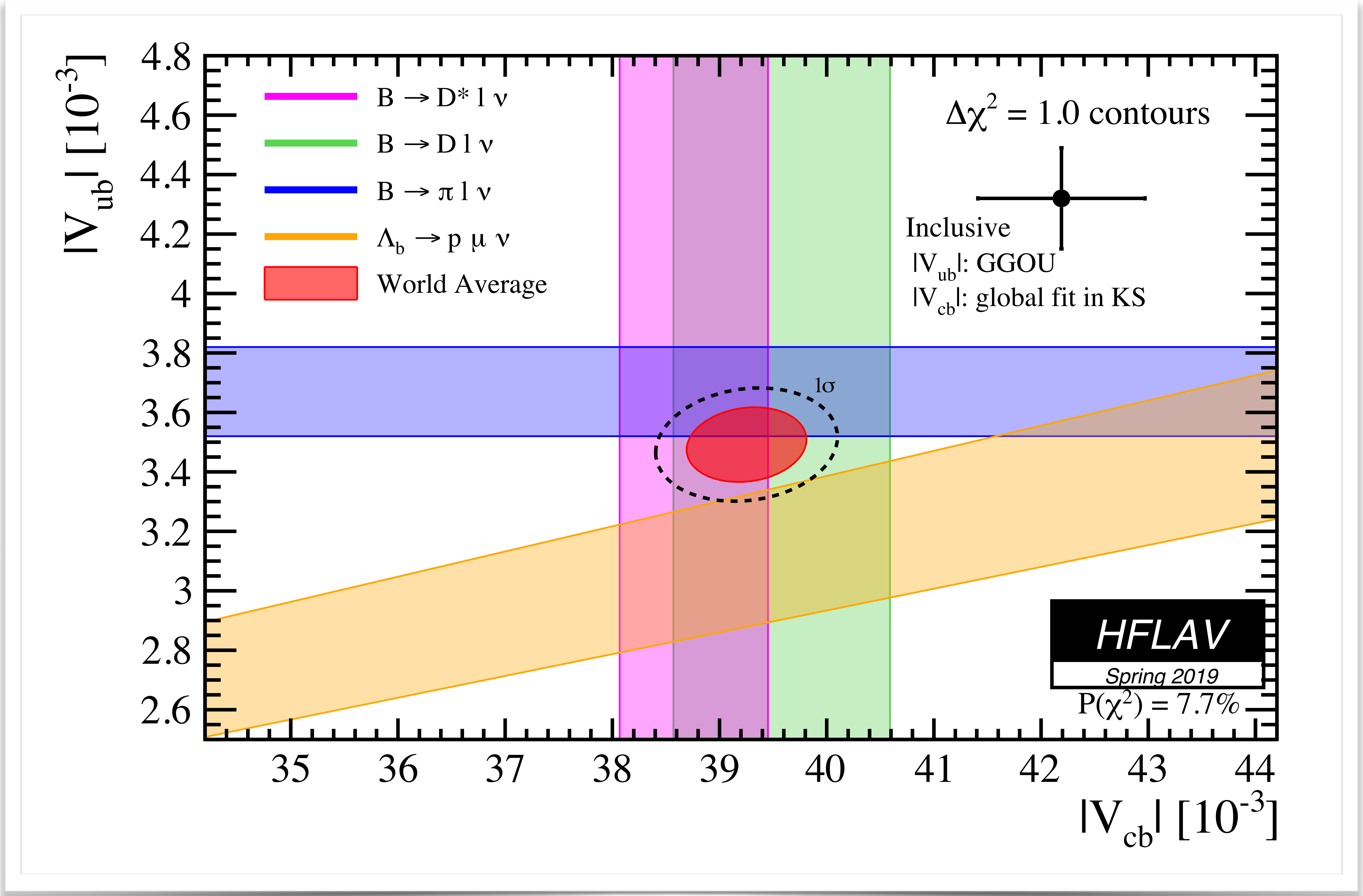
- Pletora of measurements confirm CKM paradigm at high precision.
- B decays
  - Angles from CPV measurements, getting more and more precise.
  - Oscillations constrain $|V_{td}|\&|V_{ts}|$. Limited by theory uncertainties.
  - $|V_{cb}|\&|V_{ub}|$ (mainly) from B-factories, long standing puzzle.



The puzzle

Inclusive vs Exclusive

- LHCb entered the game with measurement of $|V_{ub}|/|V_{cb}|$ [Nature Physics 11 (2015) 743].
- Λ_b decays, different source of systematics uncertainties. Bring independent information.
- B_s sector promising too, for both $|V_{ub}|$ ($B_s \to K^{(*)}\mu\nu$) and $|V_{cb}|$ ($B_s \to D_s^{(*)}\mu\nu$)



Adding strangeness

to the $|V_{cb}|$ puzzle

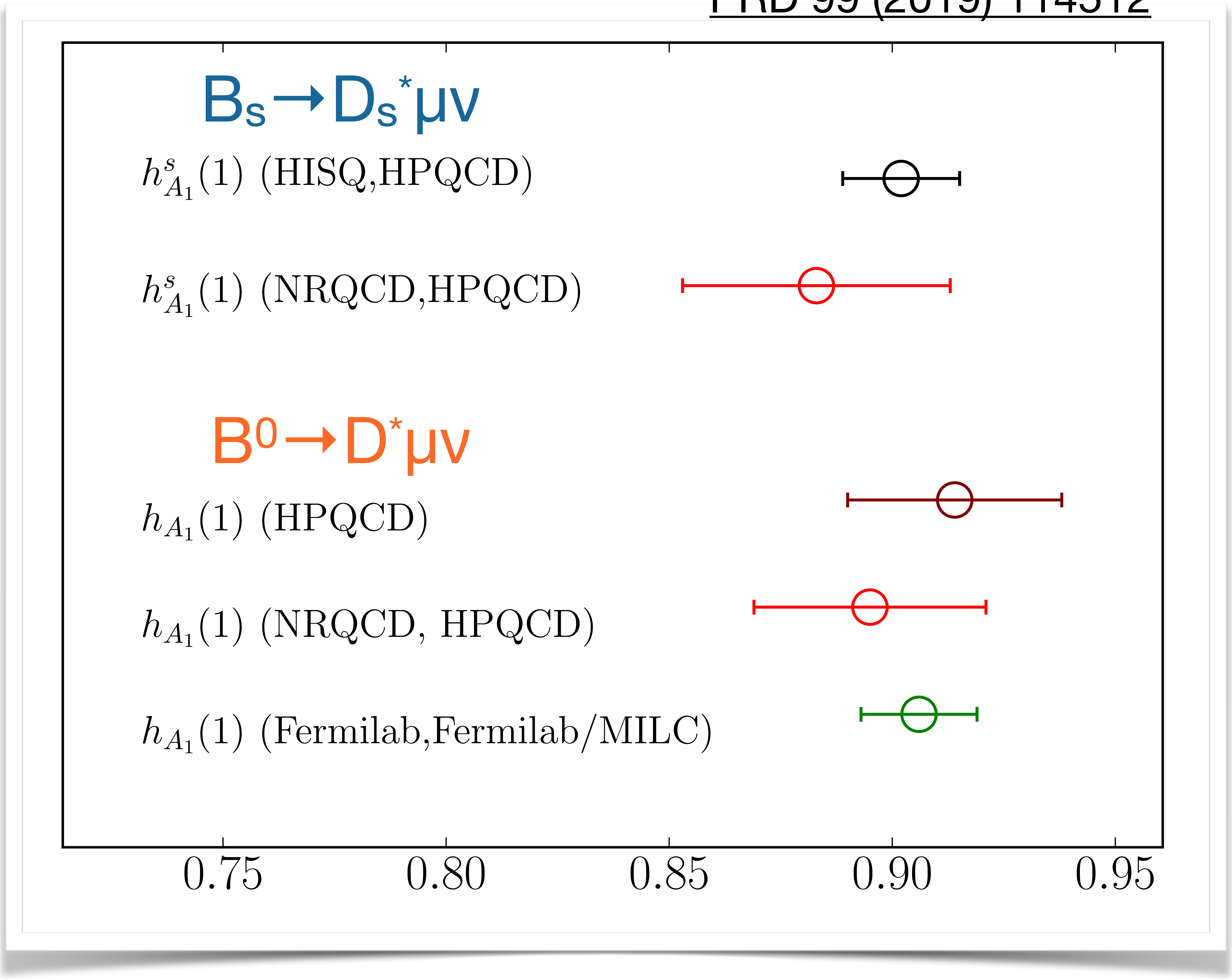
- LHCb potential triggered interesting theoretical work on B_s decays (eg. see talk by N. Gubernari)

- Promising lattice QCD calculations, expect very good precision for B_s form factors to extract $|V_{cb}|$

  - calculation on the full q^2 spectrum already available for $B_s \to D_s \mu\nu$ decays [PRD 101 (2020) 074513]

  - For $B_s \to D_s^{(*)} \mu\nu$ good precision at zero-recoil [PRD 99 (2019) 114512] Awaiting full spectrum calculation.

PRD 99 (2019) 114512



Bs@LHCb

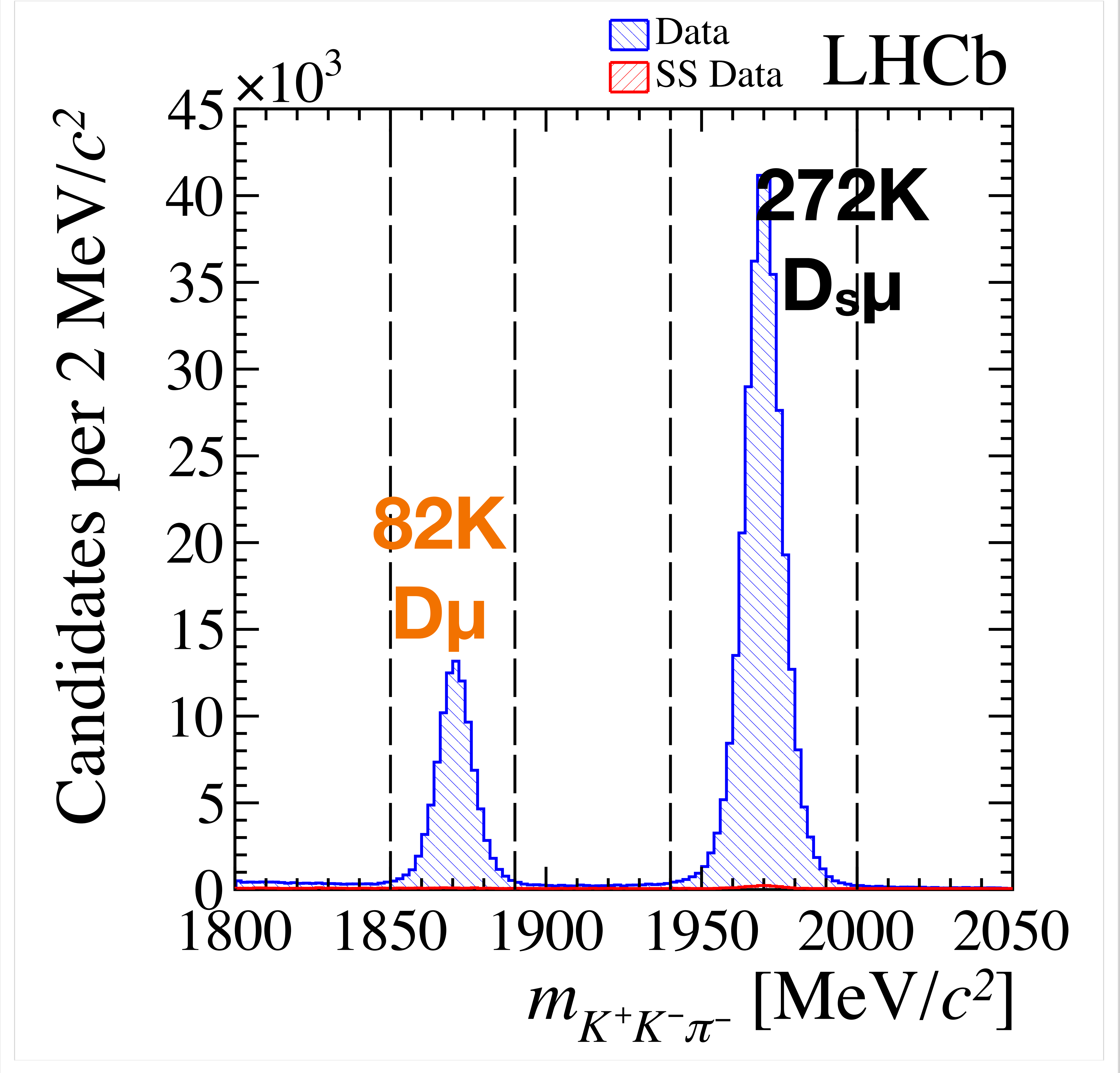
- 6 years of 7-8-13 TeV pp collisions at 40 MHz (9 fb^{-1}).
- About 10^{10} B_s/fb^{-1} produced @LHCb vs 10^5 B_s/fb^{-1} @Belle Y(5S).
- O(10^3/s) B_s reconstructible and interesting for physics.
- Store online 40-80% of them using muons, p_T and displacement.
- Talking about several hundred thousands of B_s decays on tape.
- **Large potential for a $|V_{cb}|$ measurement with $B_s \to D_s^{(*)} \mu \nu$ decays.**

Challenges

Know the number of B_s produced

- pp→bbX cross section known with O(10-15%) precision [PRL 118 (2017) 052002, PRL 119 (2017) 169901]. Limit possible precision on $|V_{cb}|$ to O(5-8%).
- Use instead a normalisation channel: $B^0 \to D^{(*)}\mu\nu$ reconstructed in the same dataset and final state [KKπ]μ.
- B_s-to-B^0 relative production (f_s/f_d) known at 5% [PRD 100 (2019) 031102]. Dominant uncertainty on $|V_{cb}|$ at 2.5%.

[PRD 101 (2020) 072004]

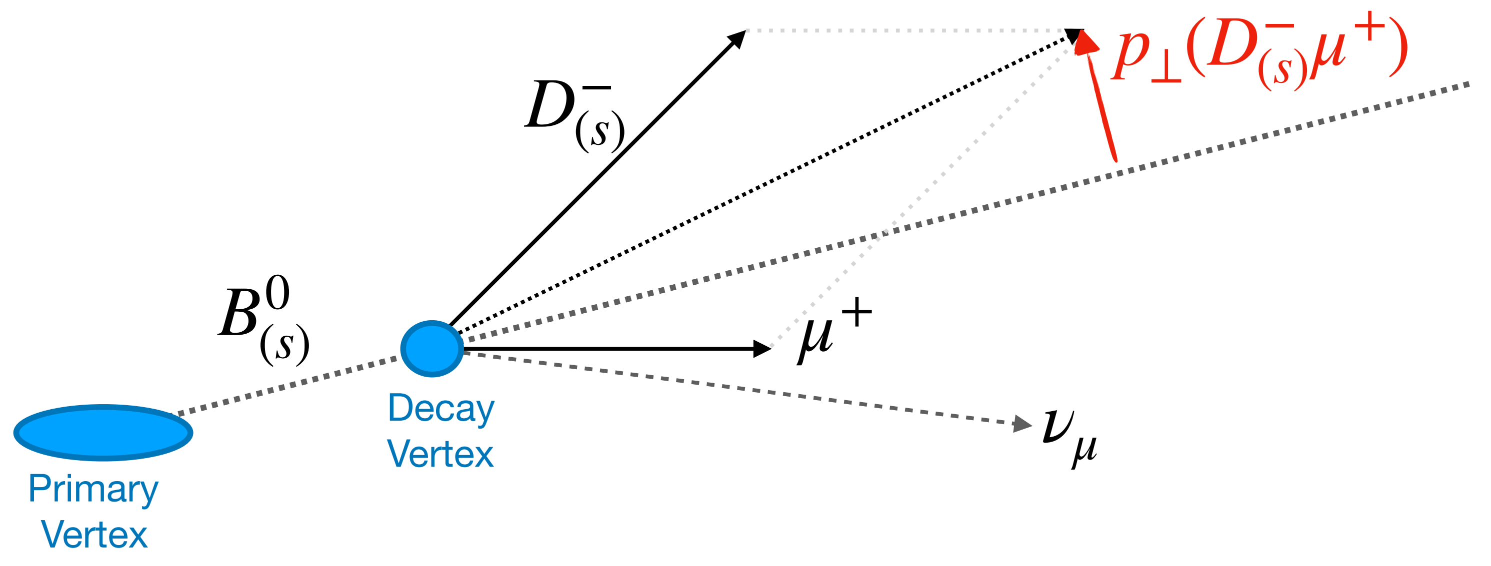


Inclusive sample of $D_s\mu$ and $D\mu$ candidates displaced from the primary vertex.

Challenges

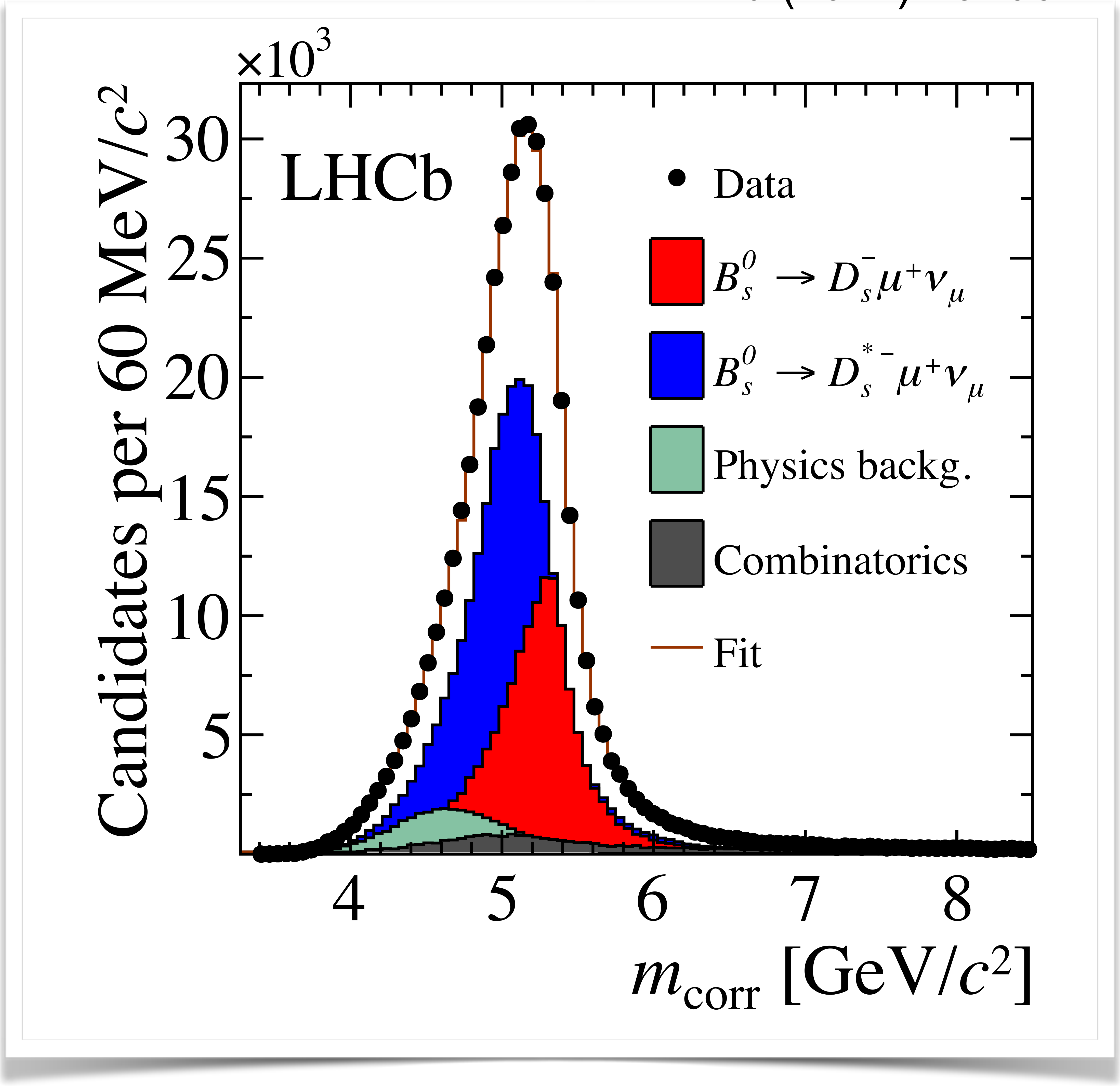
Discriminate signal and background

- Unreconstructed neutrino, cannot close the B_s kinematic *à la* B-factories.
  - No clean peaks to discriminate the signal decays and the background.
  - Recover part of the missing mass.



$$m_{corr} \equiv \sqrt{m^2(D_s^-\mu^+) + p_{\perp}^2(D_s^-\mu^+)} + p_{\perp}(D_s^-\mu^+)$$

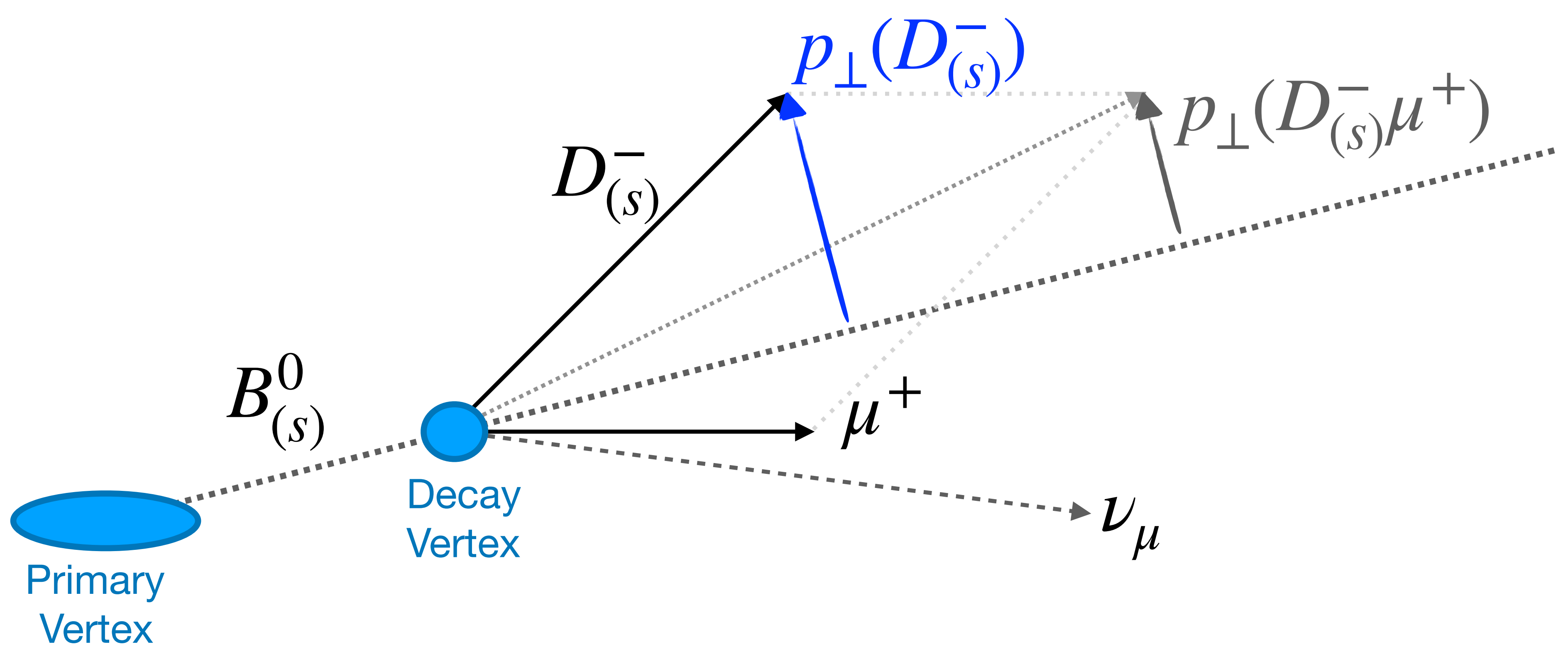
PRL 119 (2017) 101801



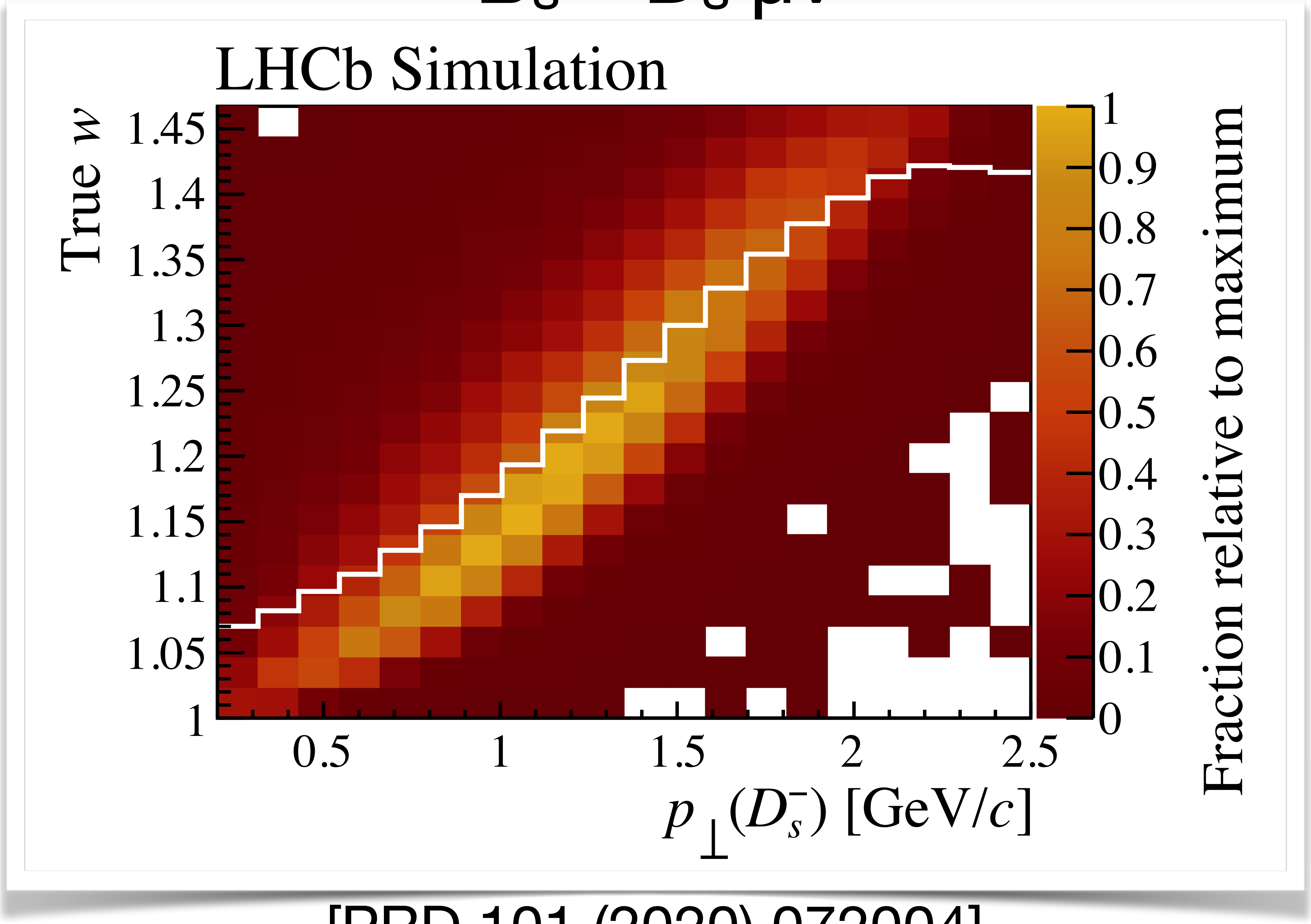
Challenges

B rest-frame kinematics

- $|V_{cb}|$ extracted from measurement of decay rate as a function of recoil w ($D_s^{(*)}$ energy in the B_s rest frame).
- Would need to approximate w because of the missing neutrino.
- New approach, use $p_\perp(D_s^-)$. Fully reconstructed and highly correlated with w.
- Very good sensitivity to the form factors, which are functions of w.



$B_s \rightarrow D_s^* \mu\nu$



[PRD 101 (2020) 072004]

Fitting the differential decay rate

for $|V_{cb}|$ and form factors

- Analyse inclusive sample of $D_s\mu$ final state (D_s^* partially reconstructed).
- Fit as a function of $m_{\rm corr}$ and $p_\perp$ to determine $|V_{cb}|$ and form factors.
  Use 2D templates to model data distribution including efficiency $\varepsilon(p_\perp, m_{\rm corr})$.

$$\frac{\mathrm{d}N_{\rm obs}}{\mathrm{d}p_\perp \mathrm{d}m_{\rm corr}} = \mathcal{N}\frac{\mathrm{d}\Gamma(|V_{cb}|, h_{A_1}, \ldots)}{\mathrm{d}p_\perp \mathrm{d}m_{\rm corr}}\varepsilon(p_\perp, m_{\rm corr})$$

- Constrain form factors from lattice QCD [PRD 101 (2020) 074513,PRD 99 (2019) 114512].
- Normalisation $\mathcal{N}$ contains measured B^0 reference yields, input branching fractions, B_s-to-B^0 production probabilities f_s/f_d, and B_s lifetime.

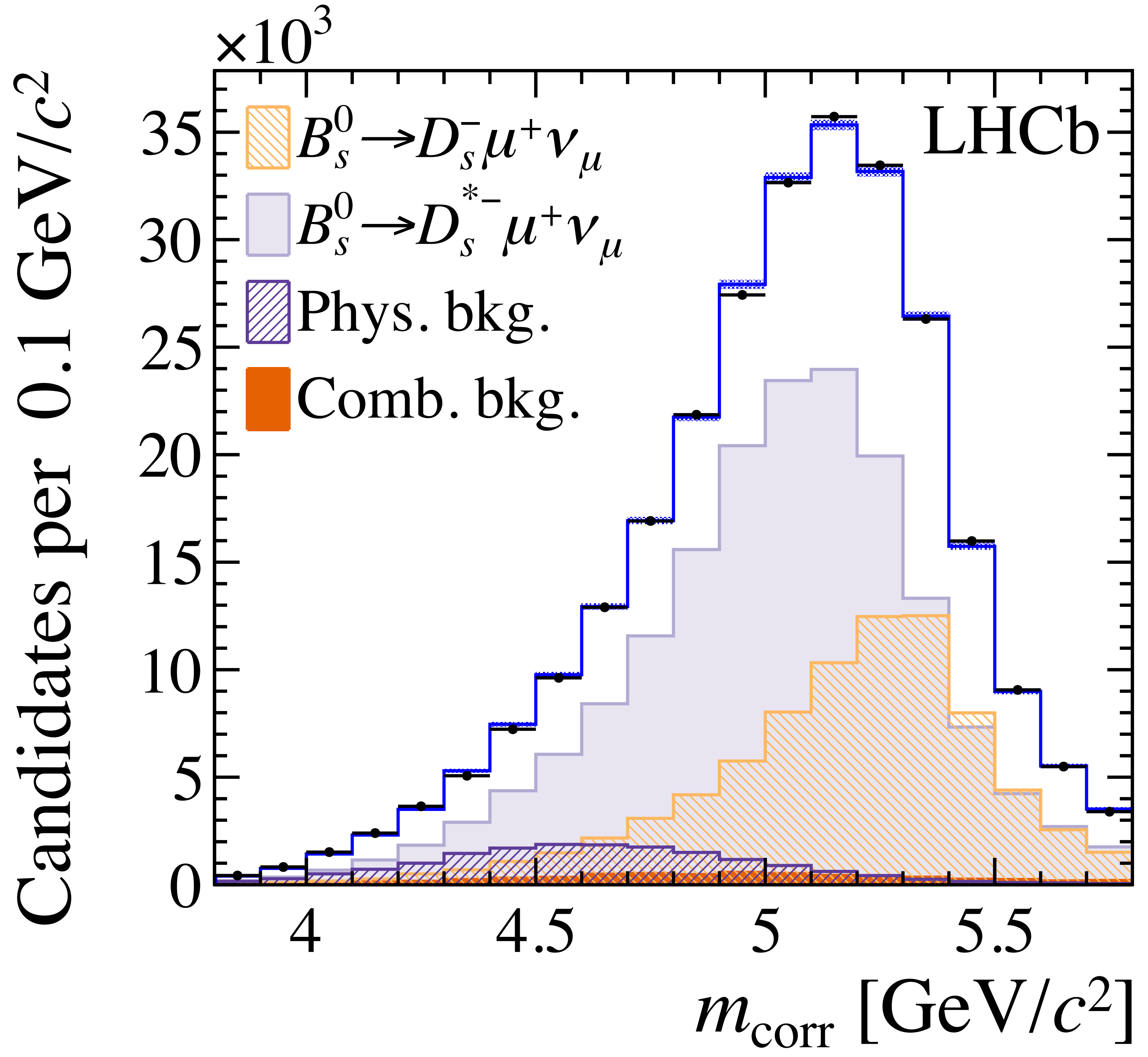
Results

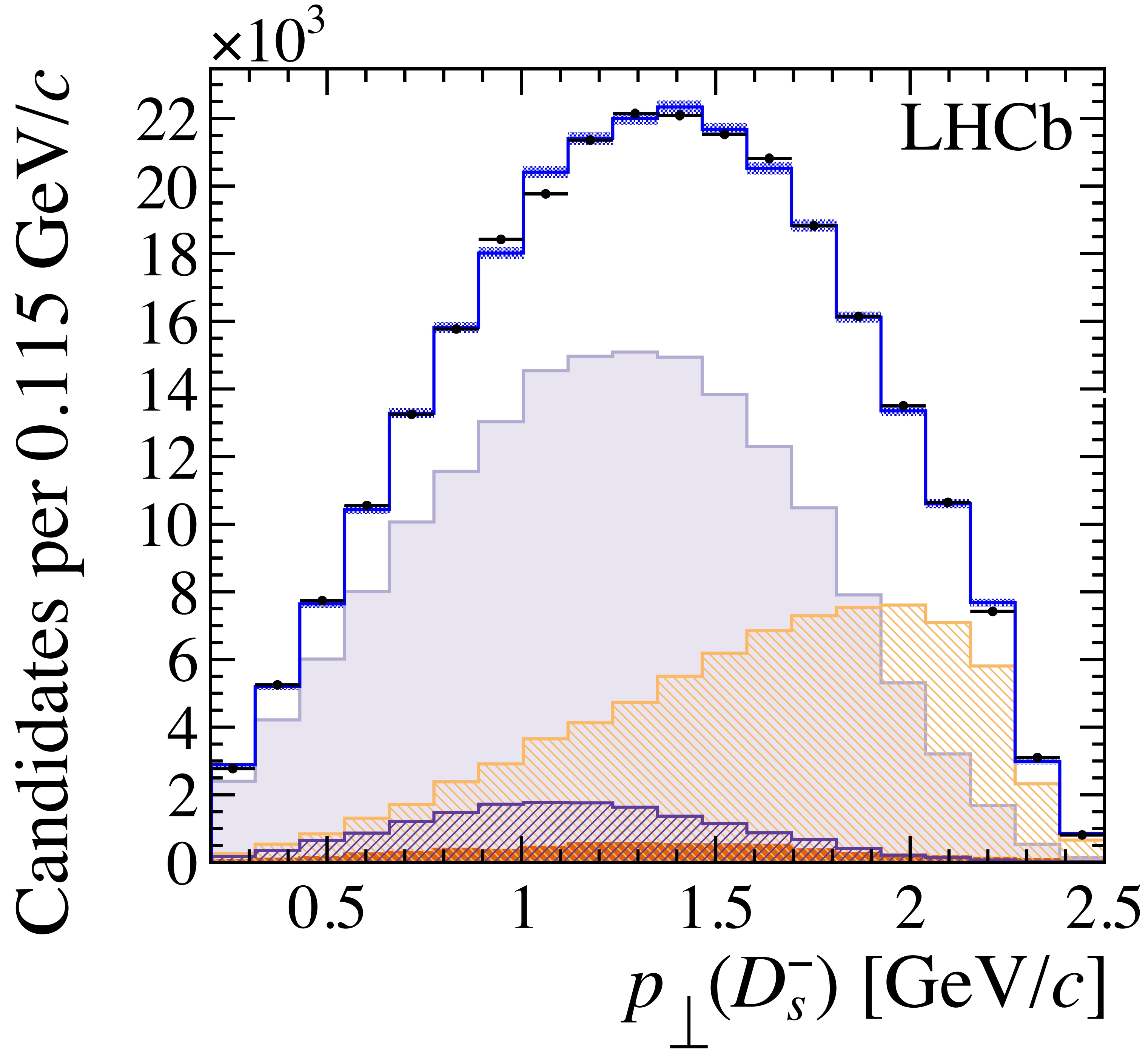
[PRD 101 (2020) 072004]

BGL form factors

Need form-factor parametrisation to determine $|V_{cb}|$. General model from Boyd, Grinstein and Lebed (BGL, PRL 74 (1995) 4603). Obtain

$$|V_{cb}| = (42.3 \pm 0.8(\text{stat}) \pm 0.9(\text{syst}) \pm 1.2(\text{ext})) \times 10^{-3}$$





χ^2/ndf=276/284
p-value of 63%

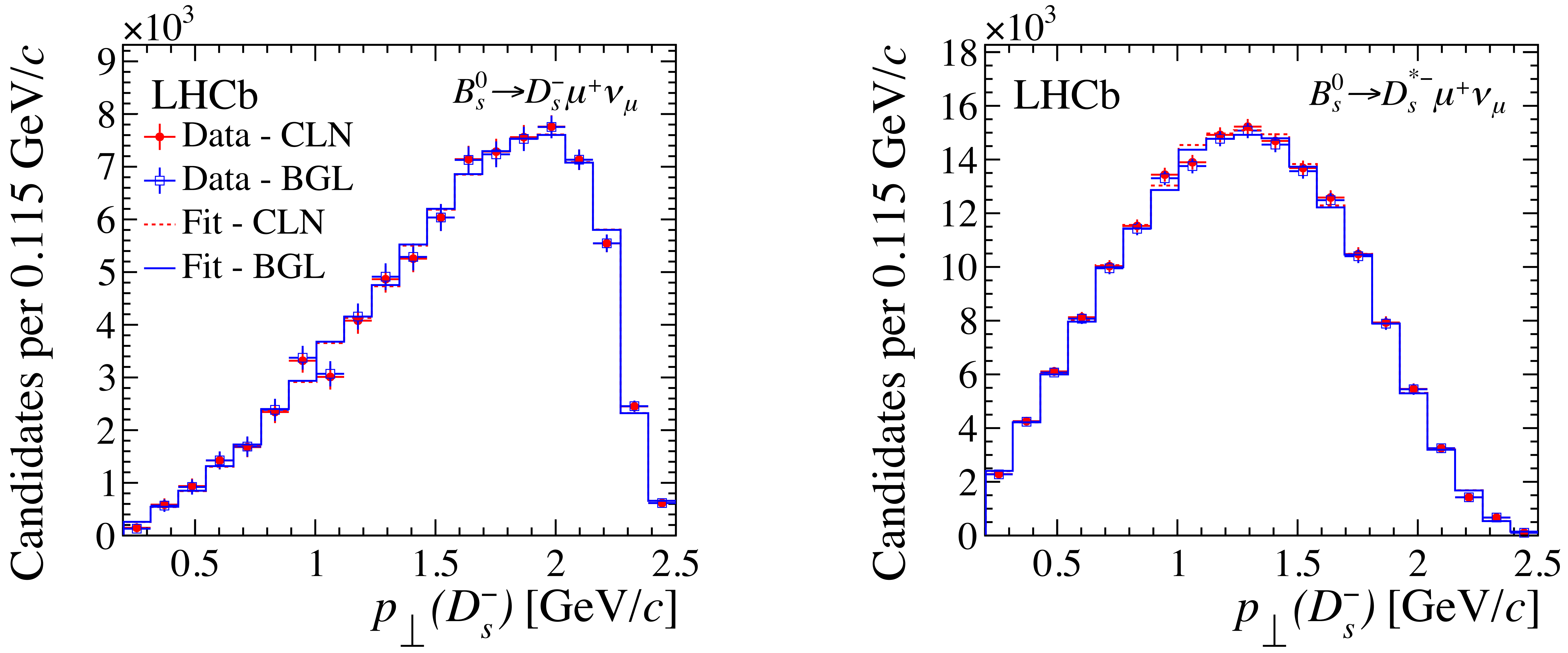
Results

[PRD 101 (2020) 072004]

CLN form factors

Test also with model from Caprini, Lellouch and Neubert (CLN, NPB 530 (1998) 153). No significant difference found. Obtain

$$|V_{cb}| = (41.4 \pm 0.6(\text{stat}) \pm 0.9(\text{syst}) \pm 1.2(\text{ext})) \times 10^{-3}$$



Systematic uncertainties & BR

- Dominant: external inputs, 3% relative on $|V_{cb}|$ (mostly from f_s/f_d).
- 2^{nd} largest: knowledge of $D_{(s)} \to KK\pi$ Dalitz structure, 2% relative on $|V_{cb}|$.
- 3^{rd} largest: knowledge of background contamination, 1% relative on $|V_{cb}|$.

By product of the analysis, first measurements of relative BR:

$$\frac{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^- \mu^+ \nu_\mu)} = 1.09 \pm 0.05\,(\mathrm{stat}) \pm 0.06\,(\mathrm{syst}) \pm 0.05\,(\mathrm{ext})$$

$$\frac{\mathcal{B}(B_s^0 \to D_s^{*-} \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \to D^{*-} \mu^+ \nu_\mu)} = 1.06 \pm 0.05\,(\mathrm{stat}) \pm 0.07\,(\mathrm{syst}) \pm 0.05\,(\mathrm{ext})$$

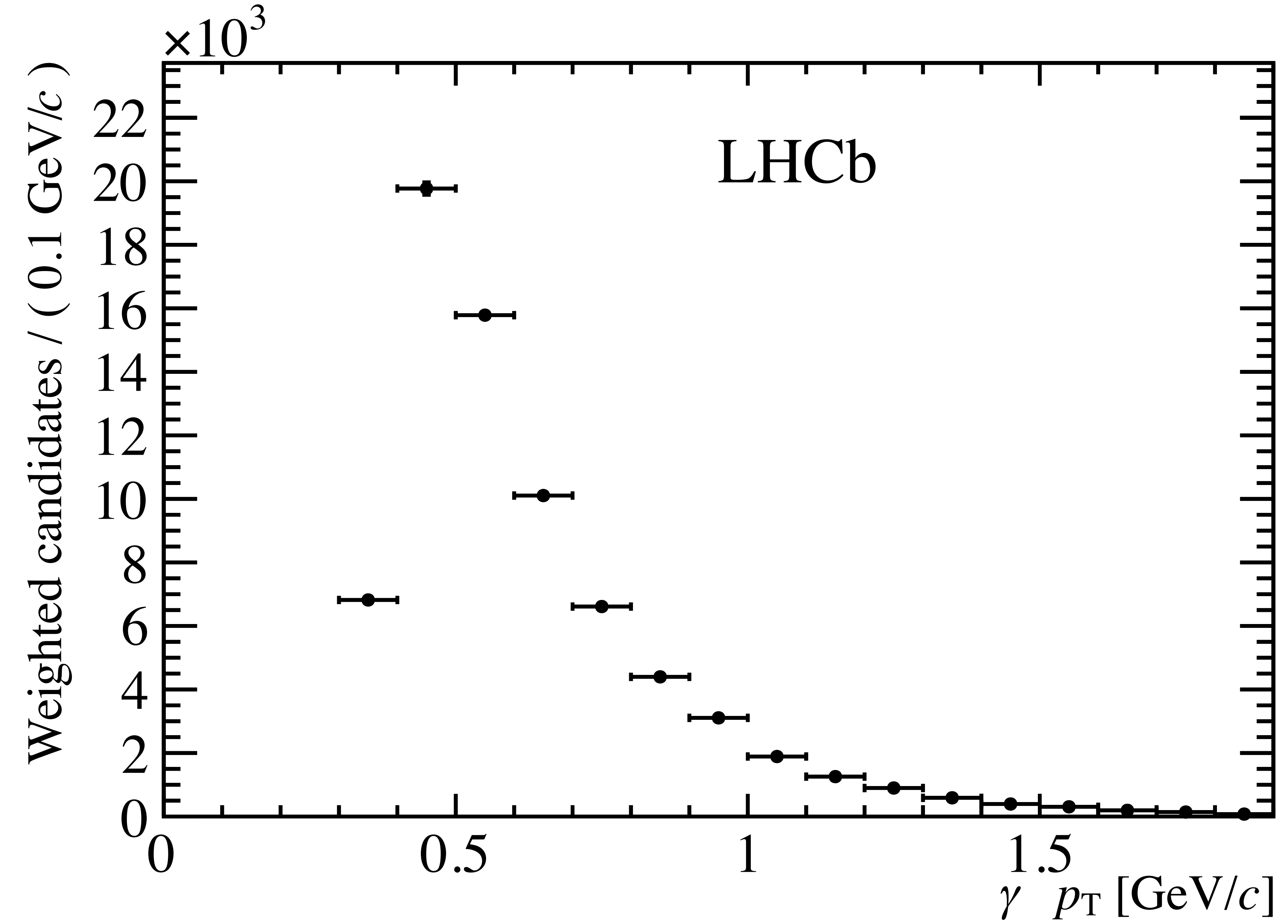
$$\frac{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^{*-} \mu^+ \nu_\mu)} = 0.464 \pm 0.013\,(\mathrm{stat}) \pm 0.043\,(\mathrm{syst})$$

[PRD 101 (2020) 072004]

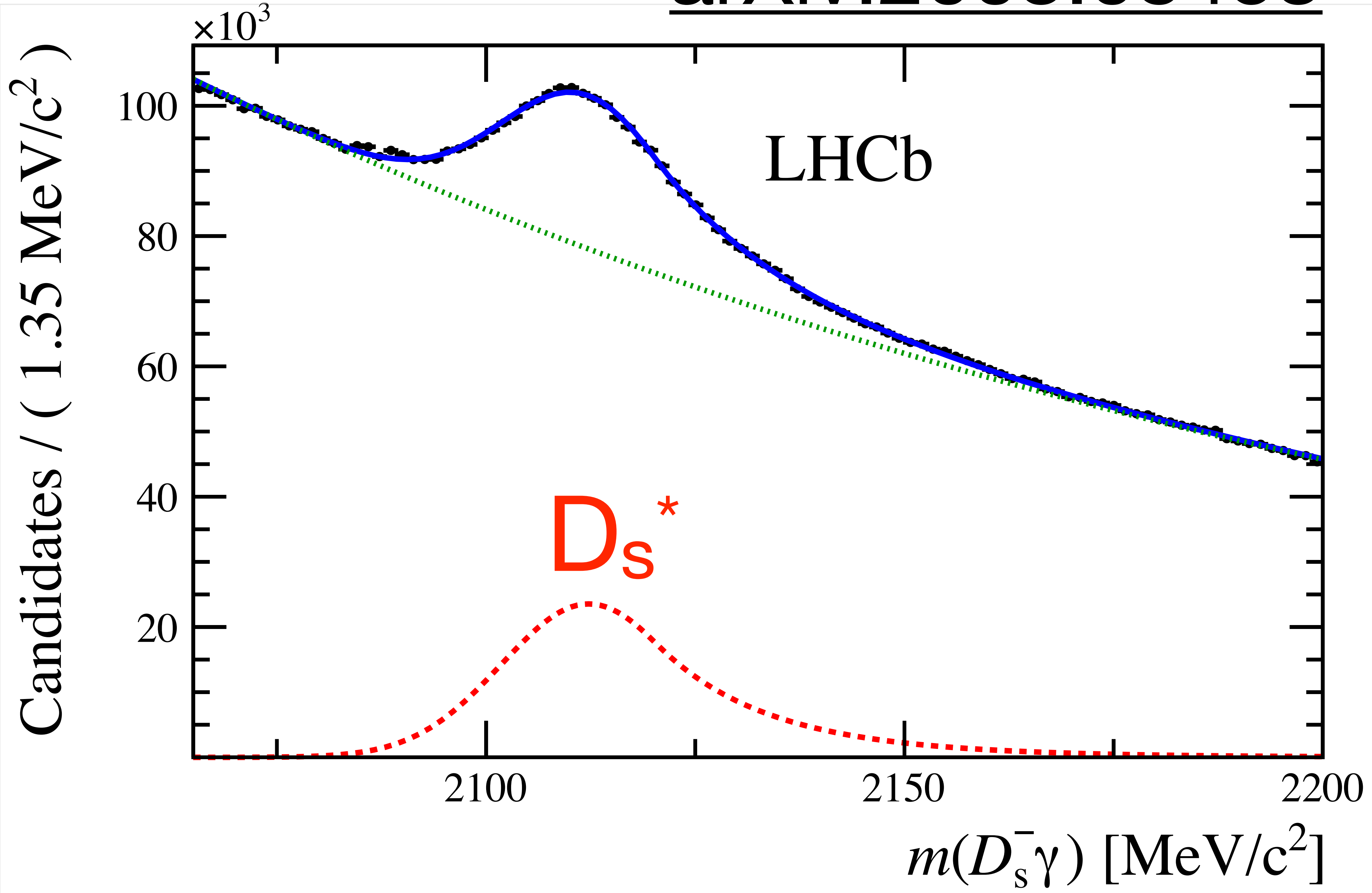
Supporting the form factors

Measurement of w distribution for $B_s \to D_s^* \mu \nu$ decays

- Independent data set. Fully reconstruct the $D_s^* \to D_s \gamma$ by selecting the soft photon in a cone around the D_s flight direction.



arXiv:2003.08453

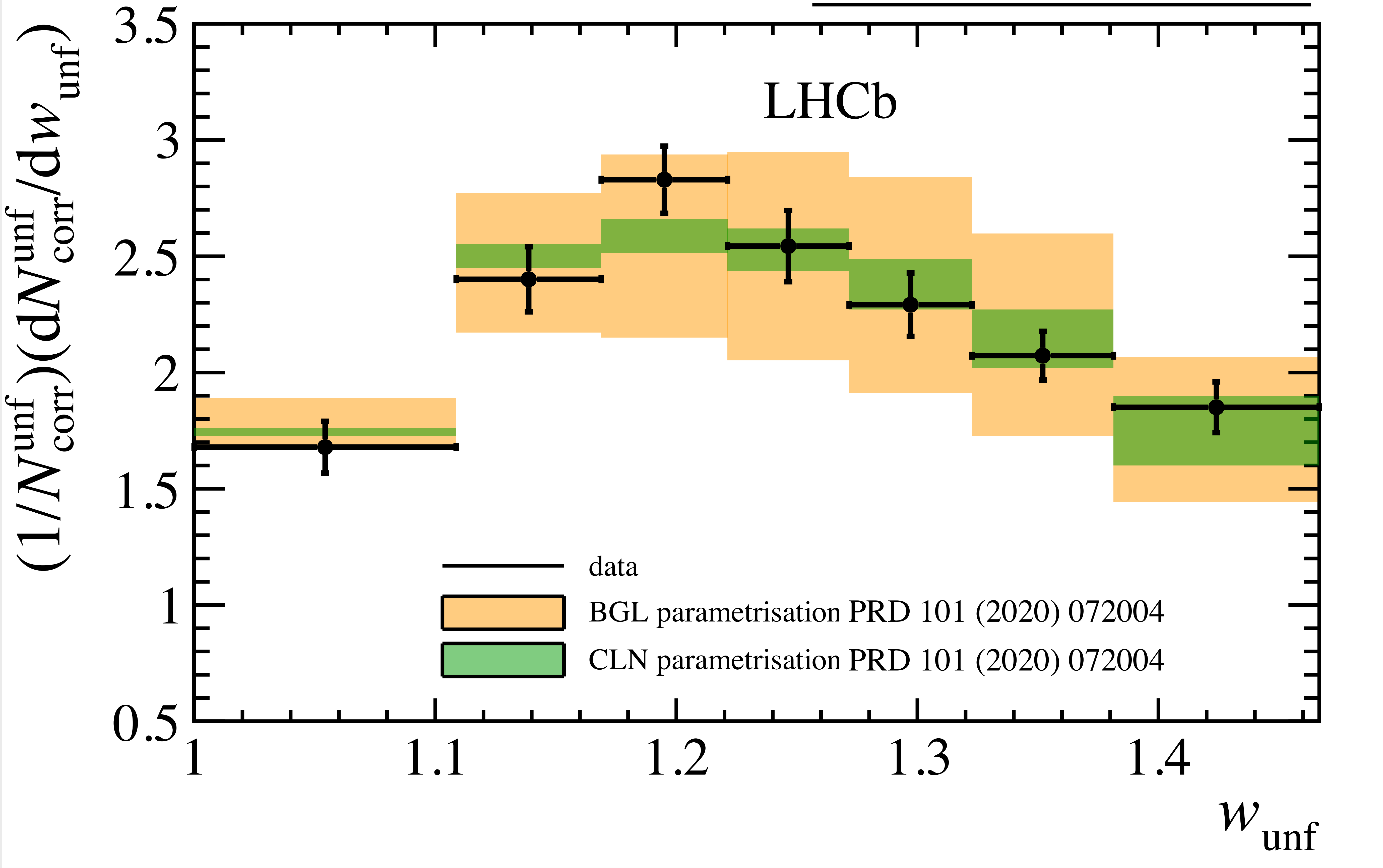


Supporting the form factors

Measurement of w distribution for $B_s \to D_s^* \mu \nu$ decays

- Use a MVA based algorithm to approximate w, the energy of the D_s^* in the B_s rest frame [JHEP 02 (2017) 021].
- Fit the corrected mass in bins of the approximate w.
- Unfold efficiency and resolution using MC.
- Good agreement of the measured distribution w.r.t. form factors measured in the $|V_{cb}|$ analysis

arXiv:2003.08453



Summary

- First measurement of the shape of the w distribution in $B_s \to D_s^* \mu\nu$ decays.
- First measurement of $|V_{cb}|$ at a hadron collider, using both $B_s \to D_s \mu\nu$ and $B_s \to D_s^* \mu\nu$ decays.

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

- In agreement with both exclusive and inclusive measurements.