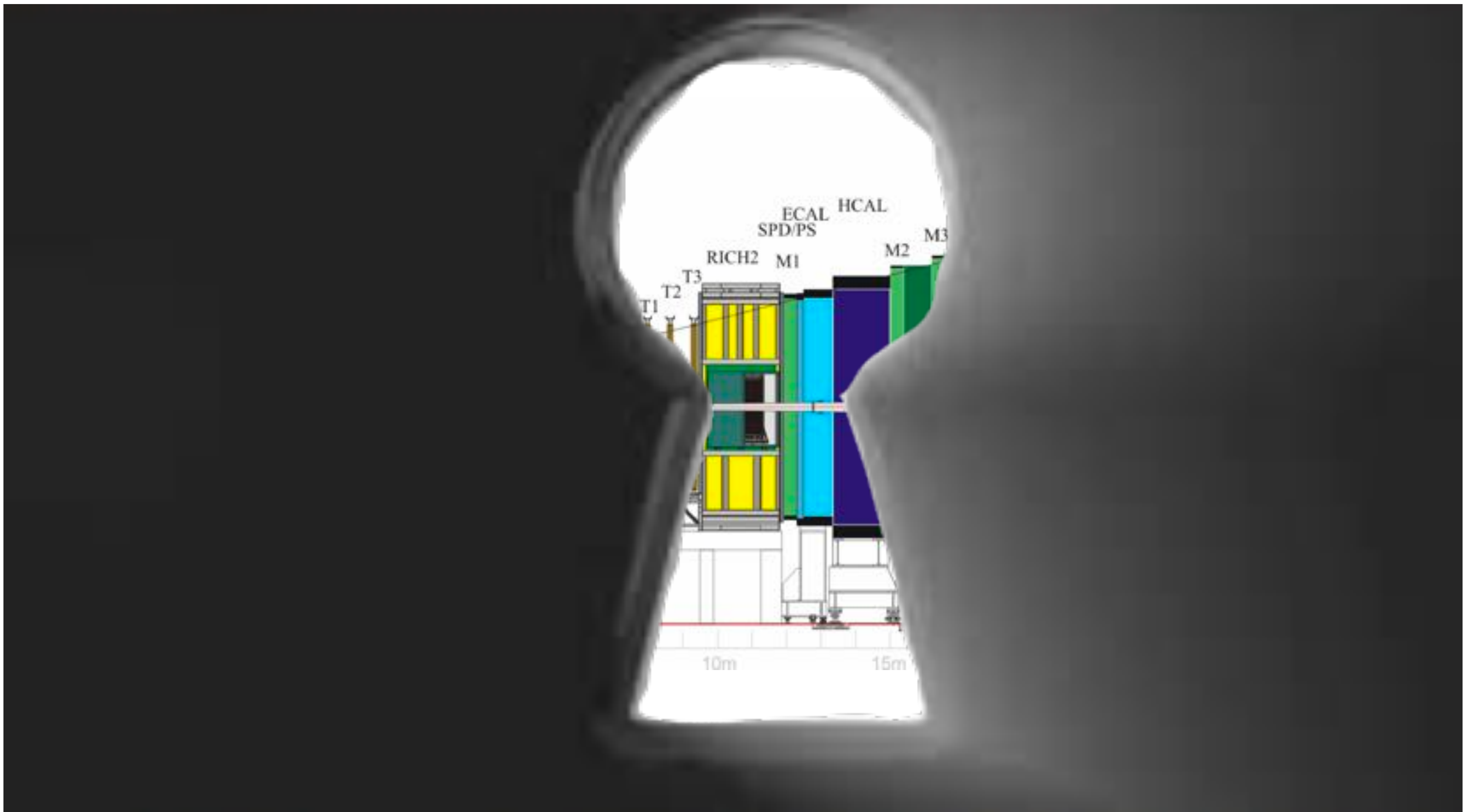
A view from the other side: Semileptonics at LHCb



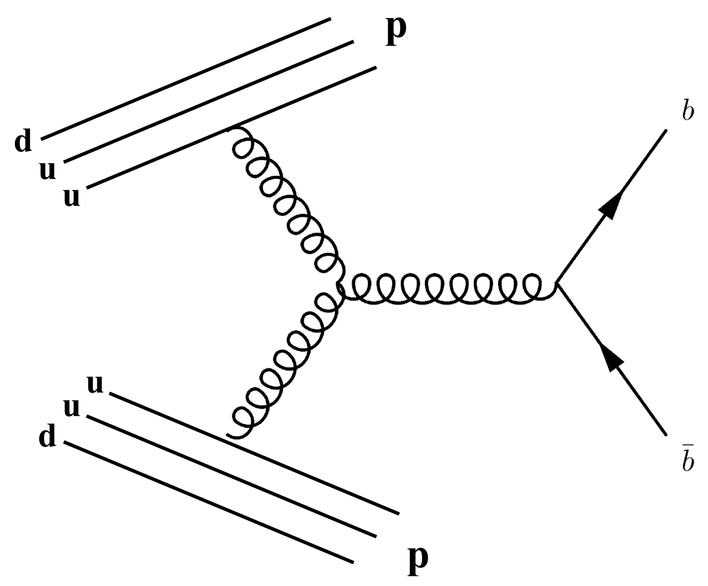
Patrick Owen Belle-II physics week 2/11/23

Aims

- Aims today:
  - Talk about main advantages/disadvantages of LHCb compared to Belle-II.
  - Discuss challenges that arise when doing semileptonics.
  - Introduce techniques that can address those challenges.
  - Discuss specifically how LHCb can contribute to the measurement of $|V_{cb}|$.

B-hadron production at a hadron collider

- b-hadrons also produced in pairs at the LHC, via gluon-gluon fusion.

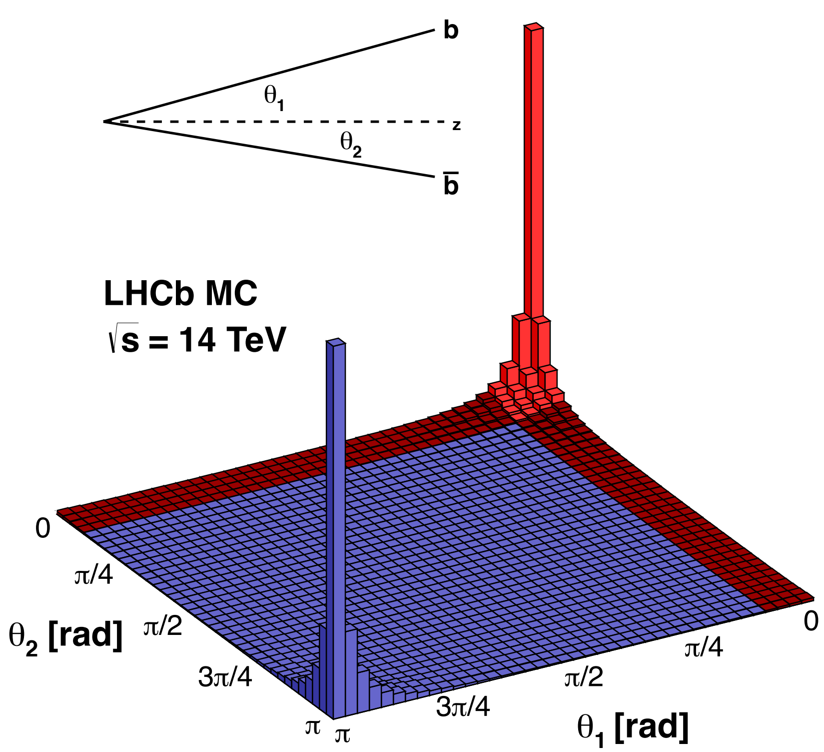


- The cross-section for this process at 13TeV is 500μb.

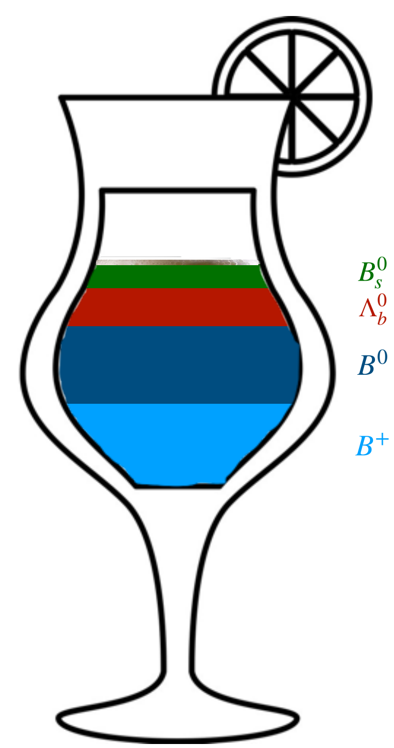
Peak luminosity at HL-LHC ~ 10^{35} cm^2s^{-1}.

N_{bb} = L x σ ~ 50M/s

- At the HL-LHC, 500M bb pairs produced every 10 seconds (!)

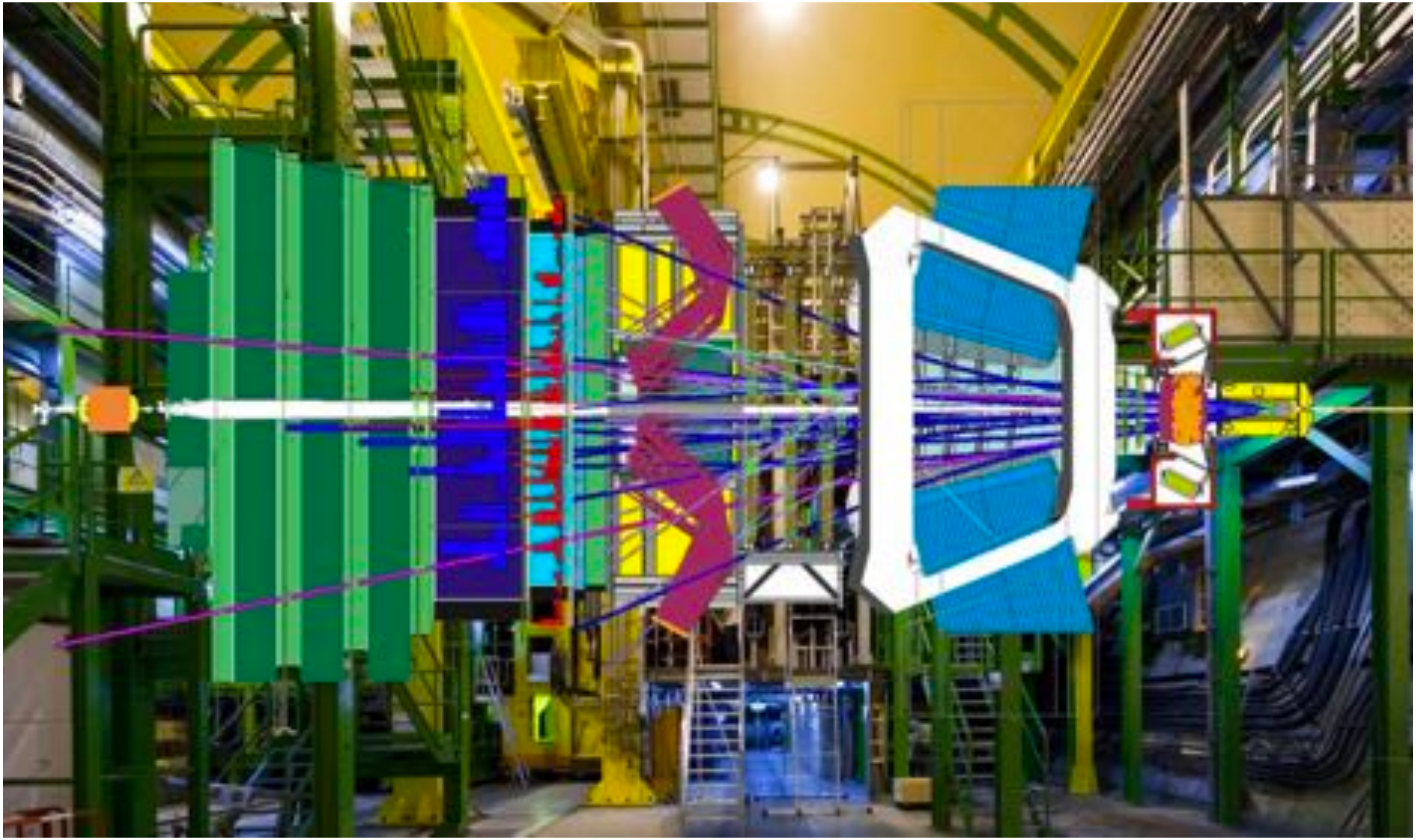


- b-hadron cocktail:



The LHCb experiment

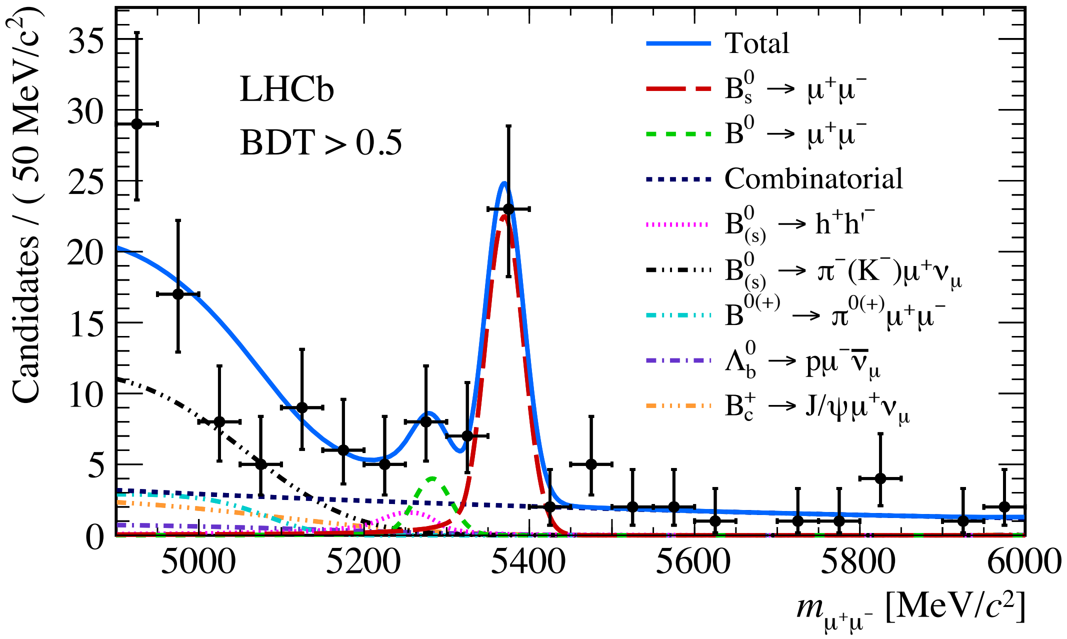
The LHCb experiment



- LHCb covers 5% of the solid angle but has acceptance for 20% of b-hadrons.

Performance numbers

- 20 MeV mass resolution

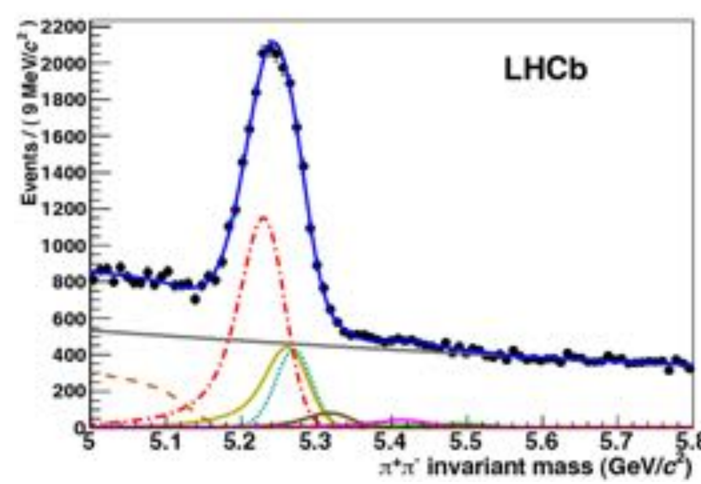


- Trigger efficiencies:

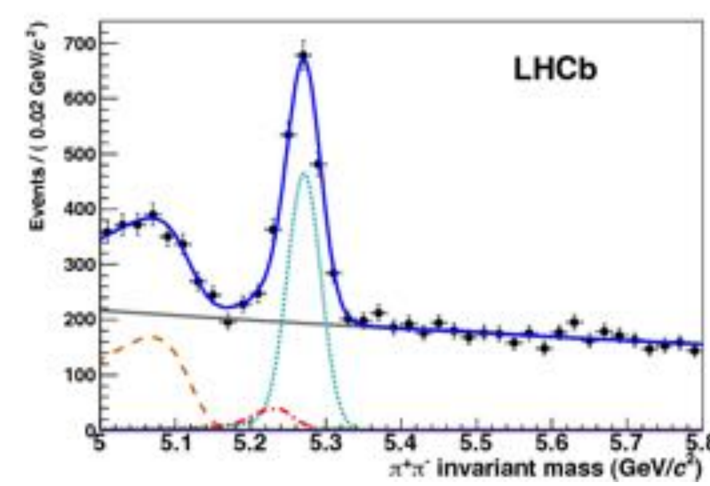
Mode	Trigger eff
Hadronic	30%
Electronic	40%
Muonic	60%
Dimuon	80%

- 5% K-pi misID for 95% efficiency.

Before PID

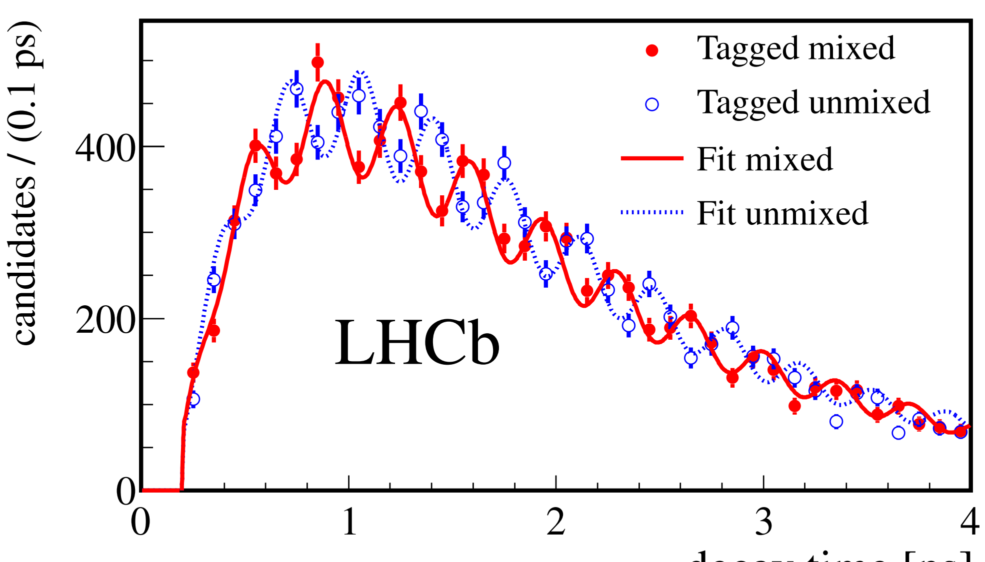


After PID



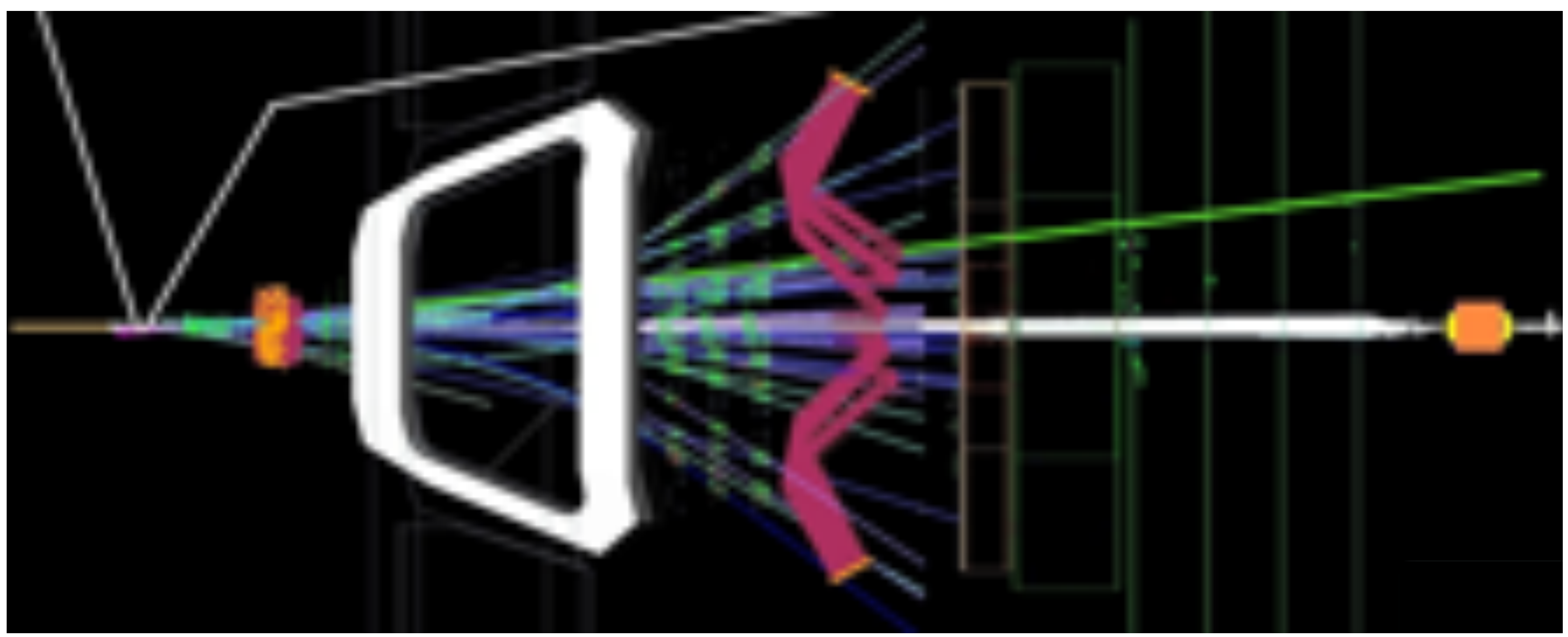
Eur. Phys. J. C 73 (2013) 2431

- 30-50fs timing

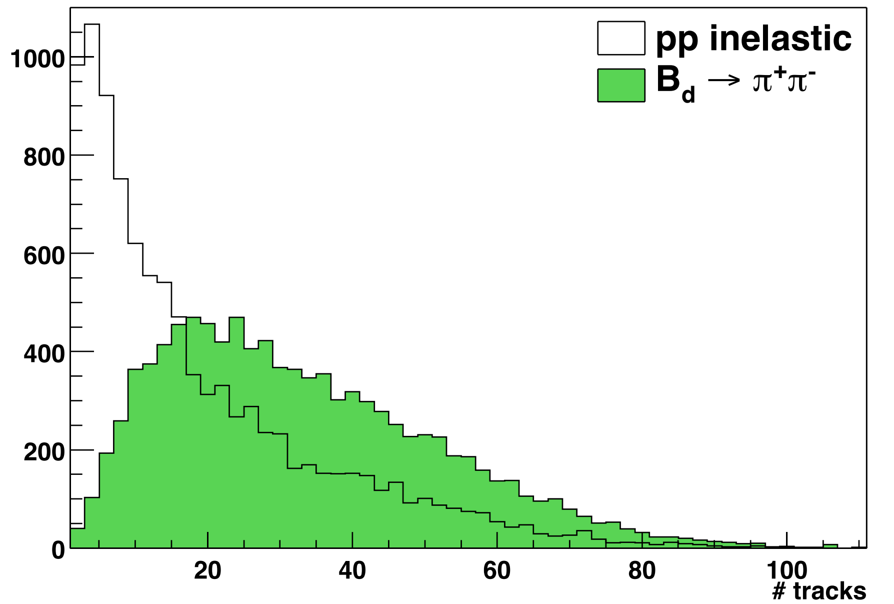


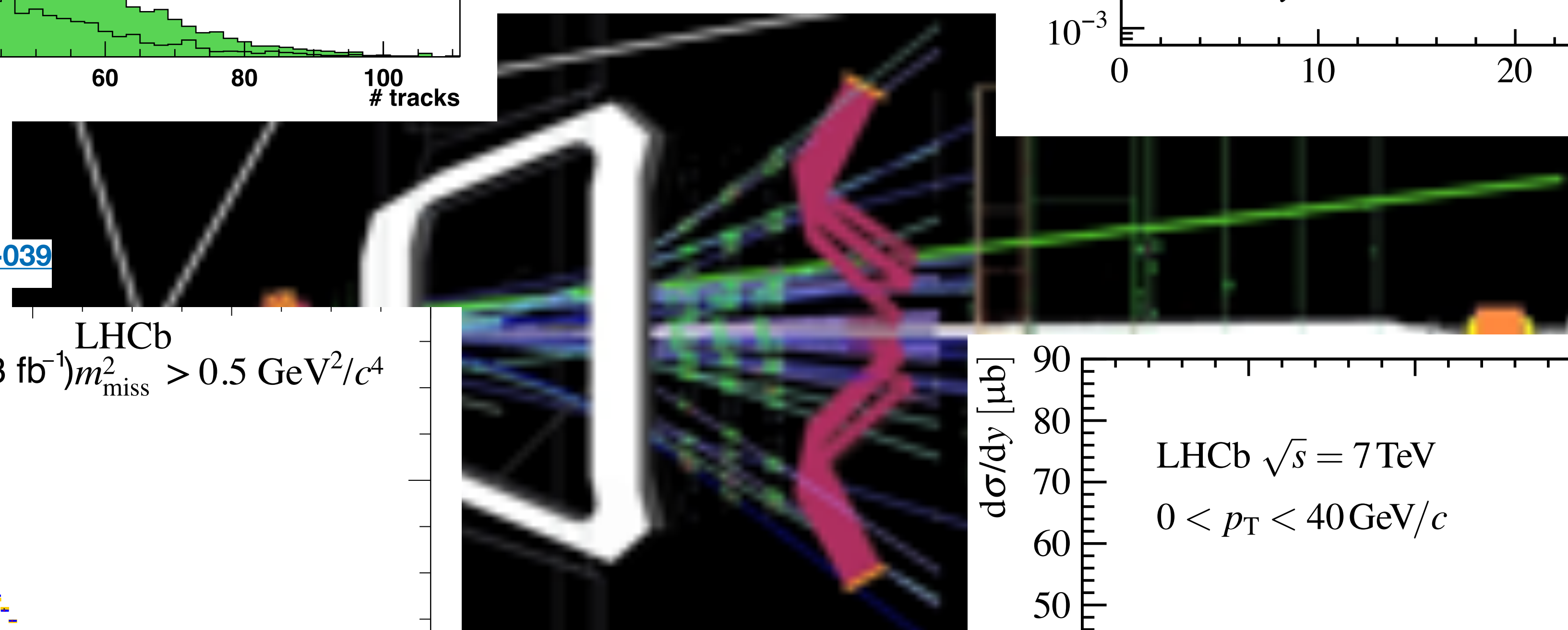
NEW J. PHYS. 15 (2013) 053021

A typical $b\bar{b}$ event

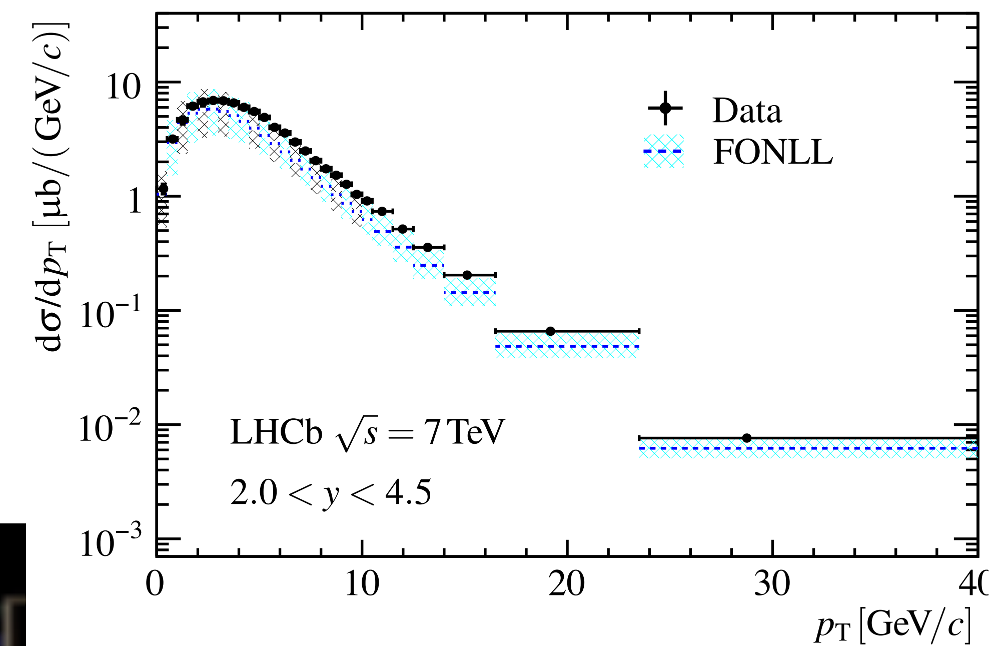


A typical $b\bar{b}$ event

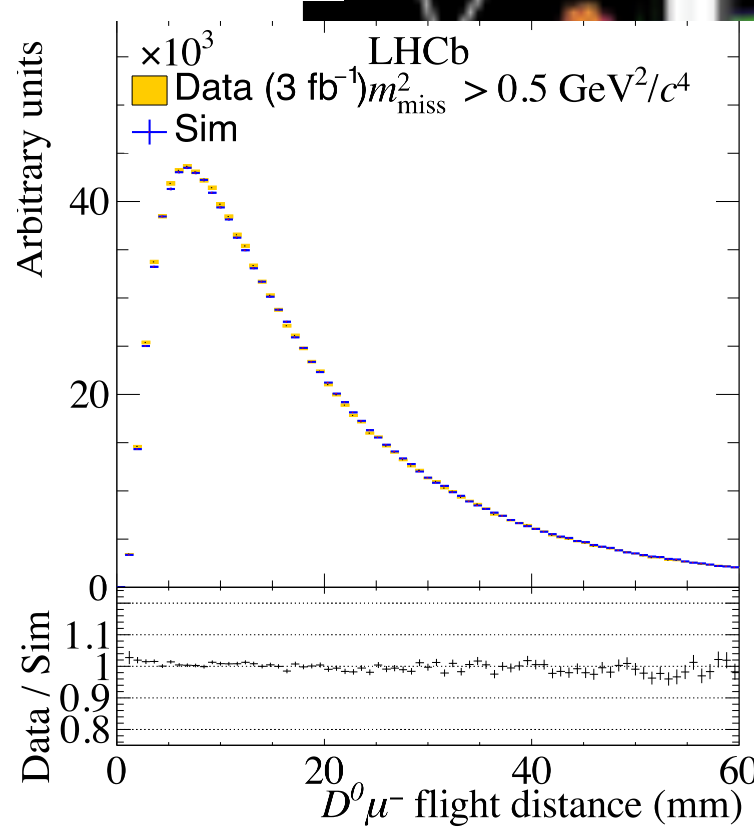


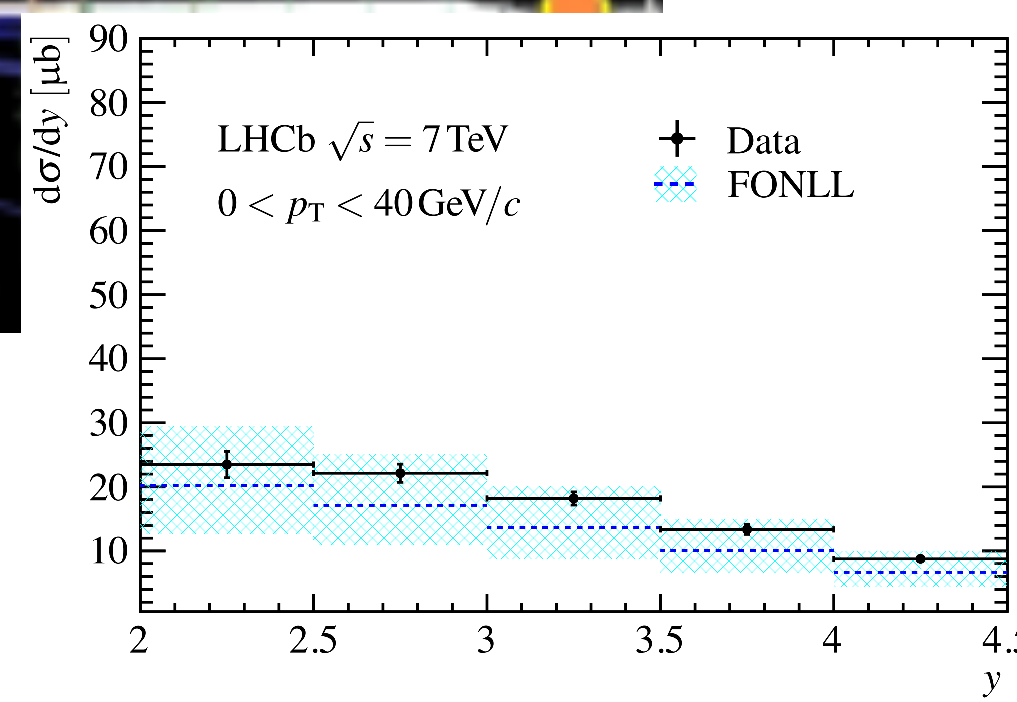


LHCB-PAPER-2017-037



LHCB-PAPER-2022-039



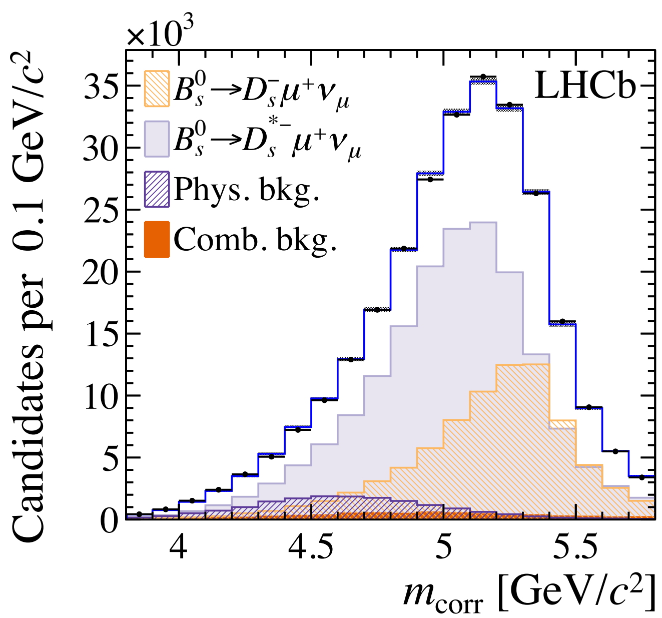


Semileptonic challenges

- Missing energy a complication for any experiment.
- Particularly challenging in a hadron collider because:
  - No beam energy constraint.
  - Busy events.
  - Large background for neutrals.
- Additional complication due to lack of precise absolute production knowledge.
  - Large branching fractions mandate precision (e.g. competitive $|V_{cb}|$ measurement needs 1% uncertainty).

statistical
"With great ^ power, comes great responsibility" - Uncle Ben

$|V_{cb}|$ from B_s, Phys. Rev. D101 (2020) 072004

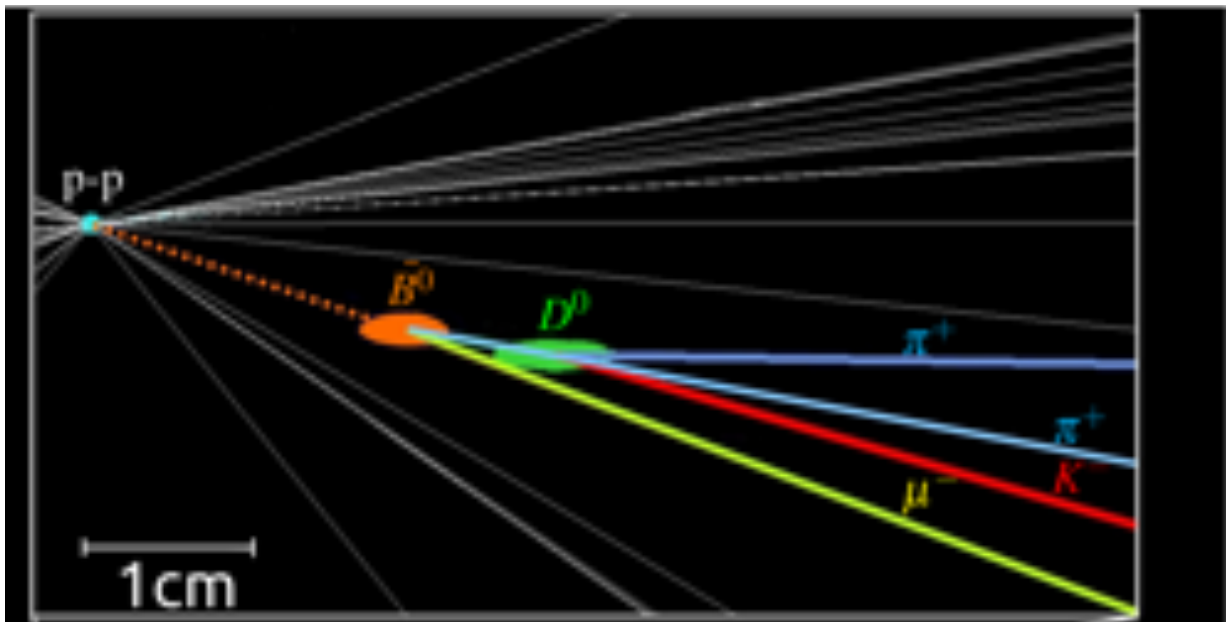


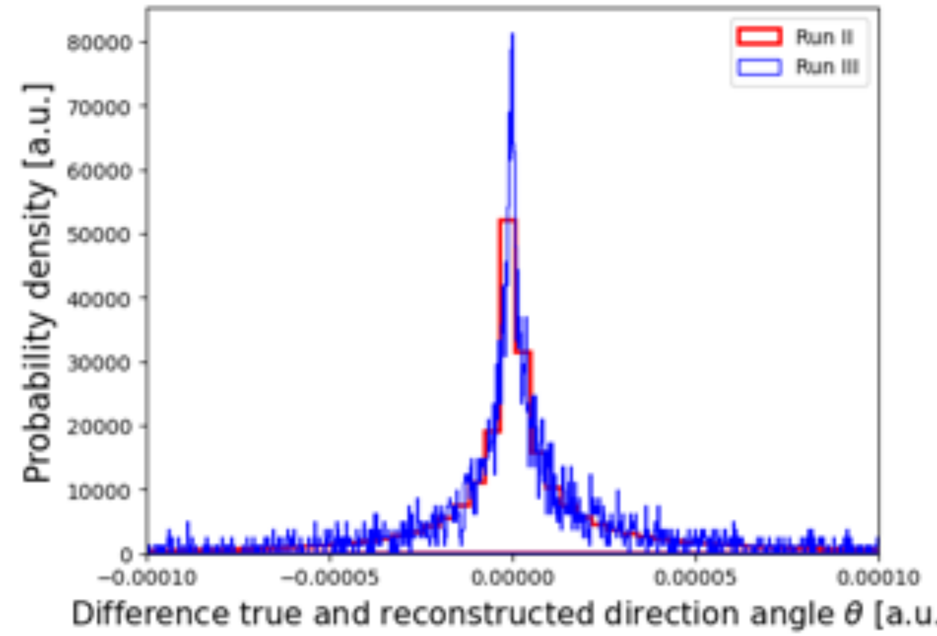
Techniques


Behold
The pointing
Data driven mis-ID
Corrected mass
Neutrino reco
Fast simulation
Isolation
My stuff

The pointing

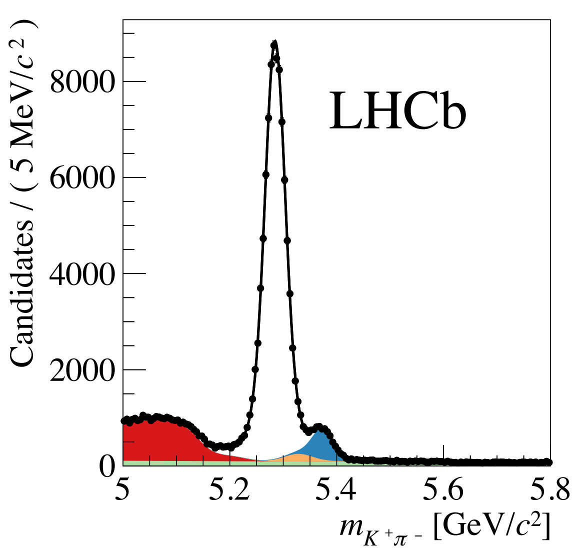
- Large boost coupled with vertex precision allows for excellent primary-secondary vertex direction.



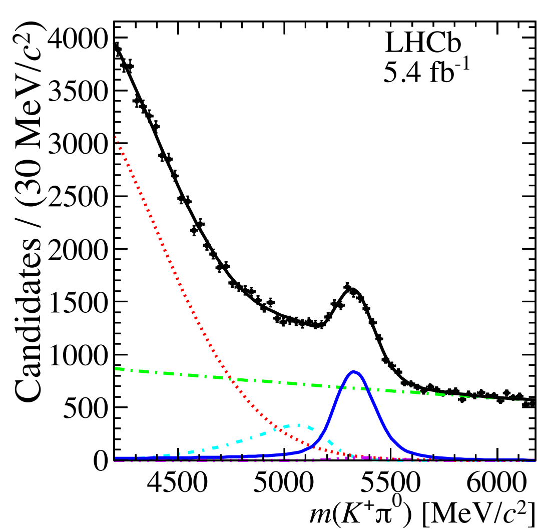


- For fully reconstructed decays pointing the THE variable to reduce background.

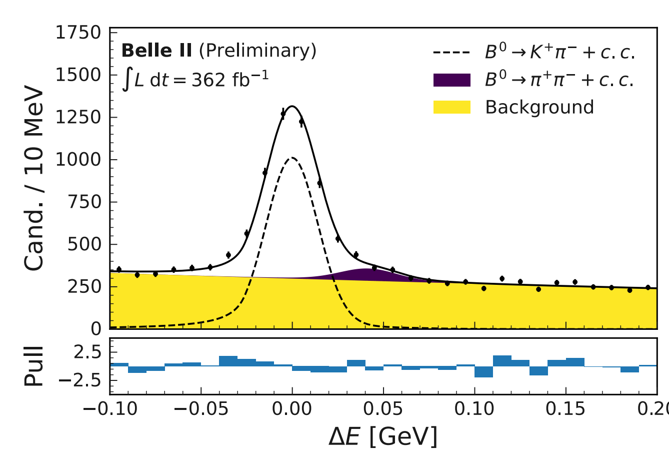
LHCB-PAPER-2018-006

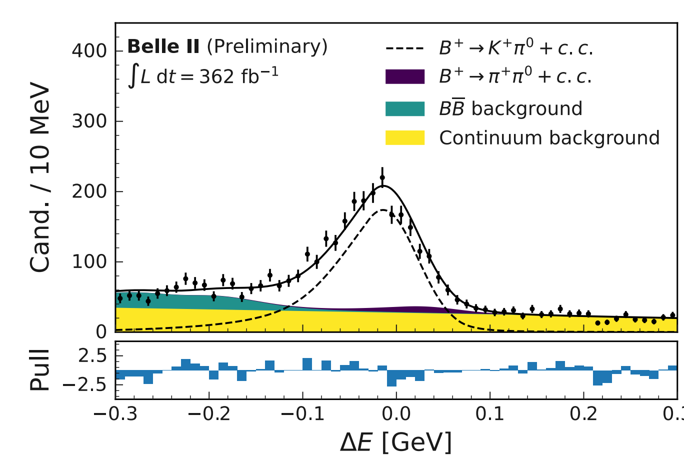


LHCB-PAPER-2020-040



arXiv:2310.06381

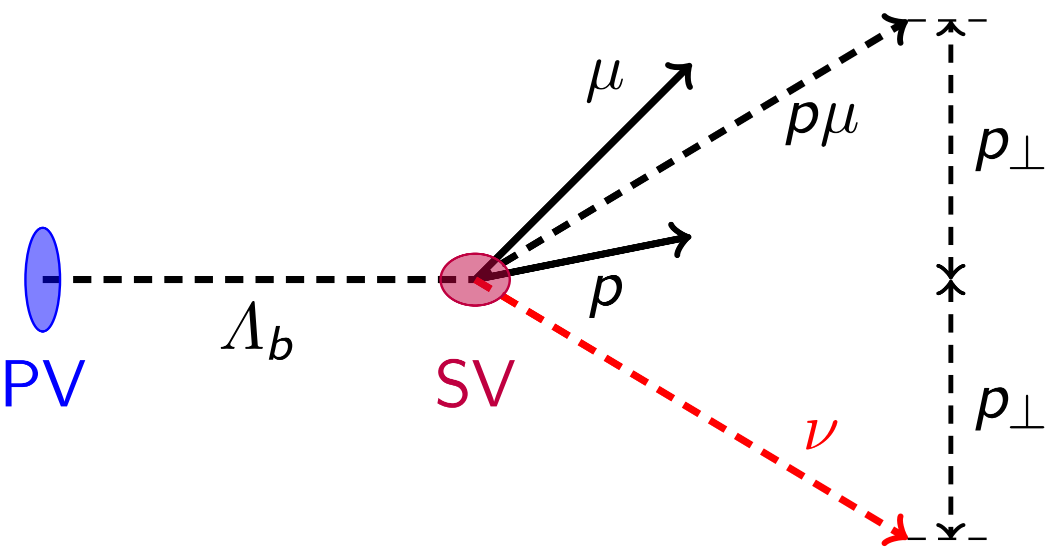




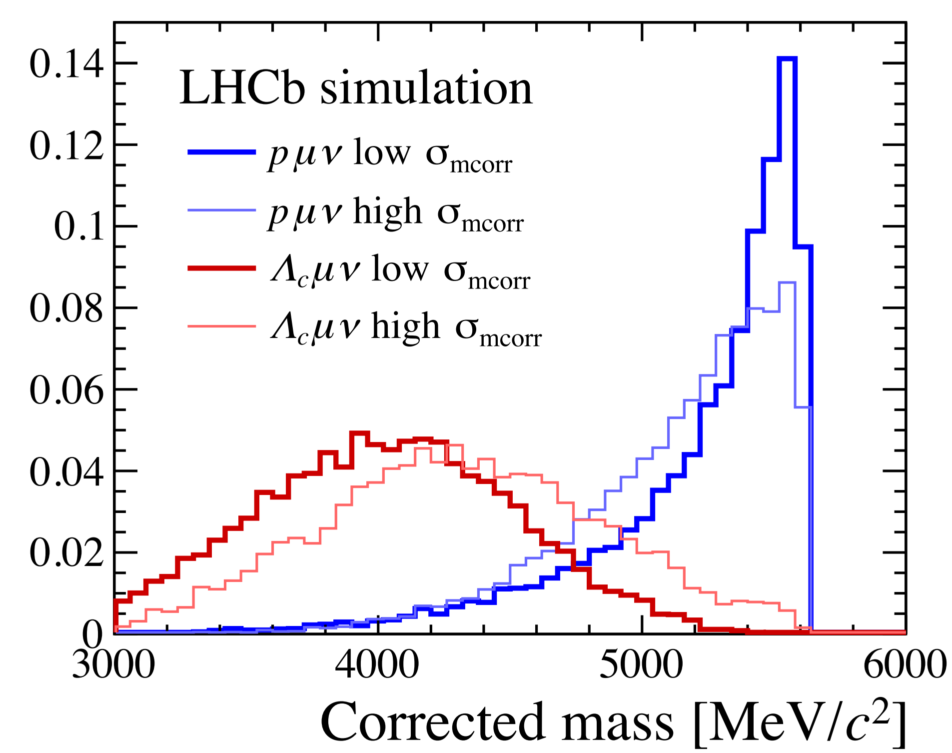
Corrected mass

- The corrected mass combines the visible mass with the component of momentum transverse to the B flight direction.

$$m_{\text{corr}} = \sqrt{p_\perp^2 + m_{\text{vis}}^2} + p_\perp$$



LHCB-PAPER-2015-013

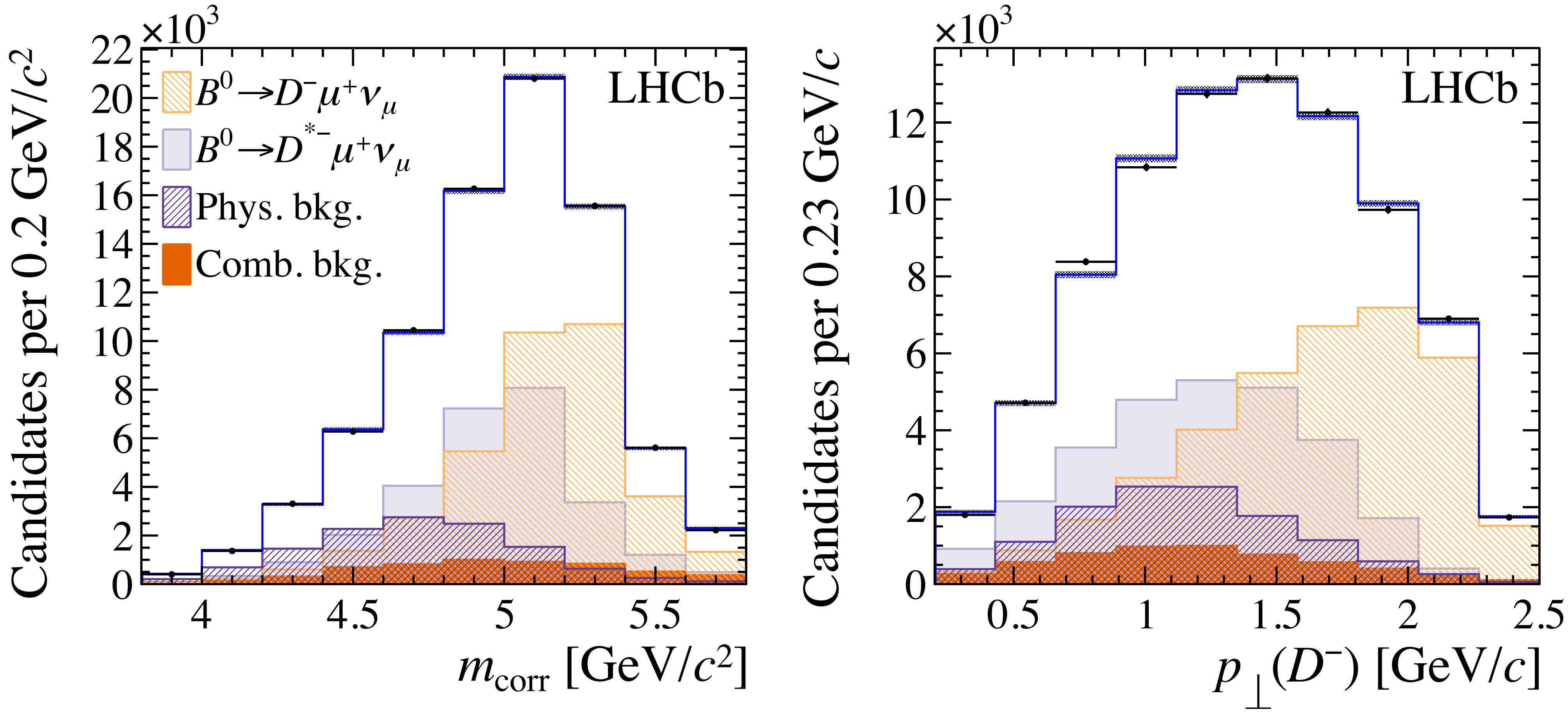


- For decays with a single missing neutrino, m_{corr} will peak at the true mass.

- Event-by-event vertex uncertainties allows to select candidates with good m_{corr} resolution.

Corrected mass fit

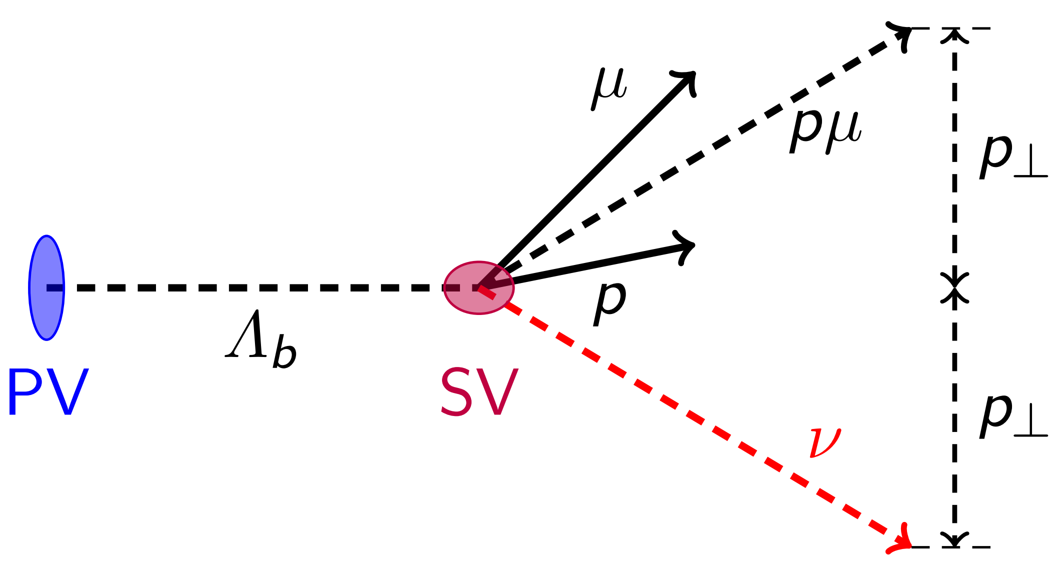
- Example from the |V$_{cb}$| measurement from $B_s^0 \to D_s^{(*)+}\mu^-\overline{\nu_\mu}$ decays

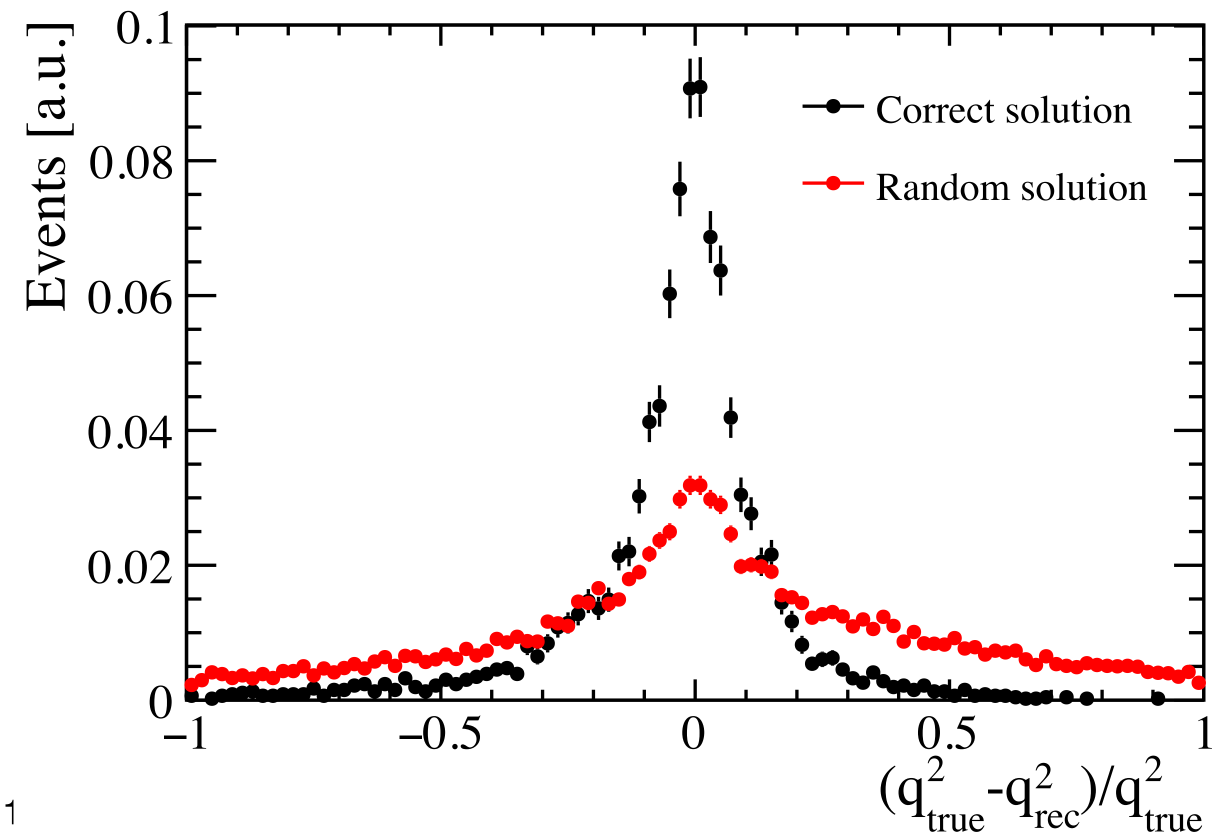


- In addition to m$_{corr,}$ fit for $p_\perp$ which can be interpreted once the resolution has been taken into account.
  - Alternative to neutrino reconstruction.

Neutrino reconstruction

- Three unknowns with a single missing neutrino.
- Pointing constraint gives us back two of them.
- Final unknown determined using the mass constraint of the b-hadron.
- Unfortunately left with ambiguity as mass constraint fixes $\sqrt{p^2}$ not p itself.
  - This ambiguity is the main source of resolution for q^2.

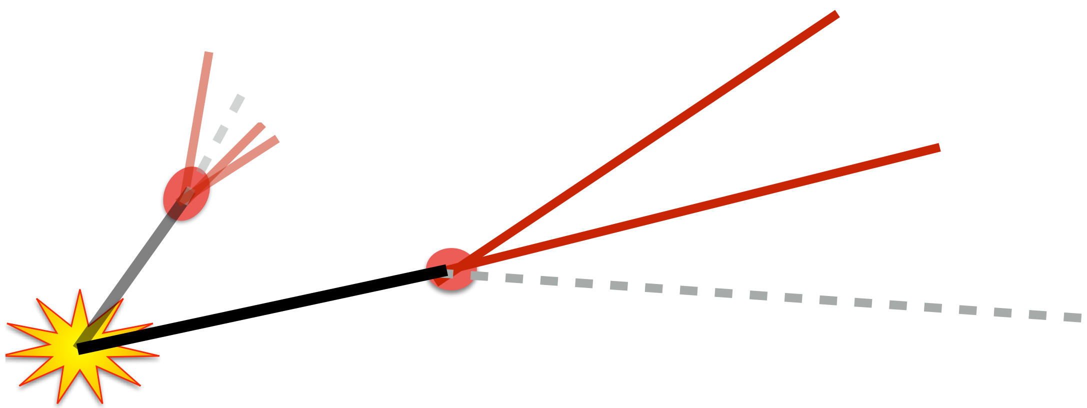


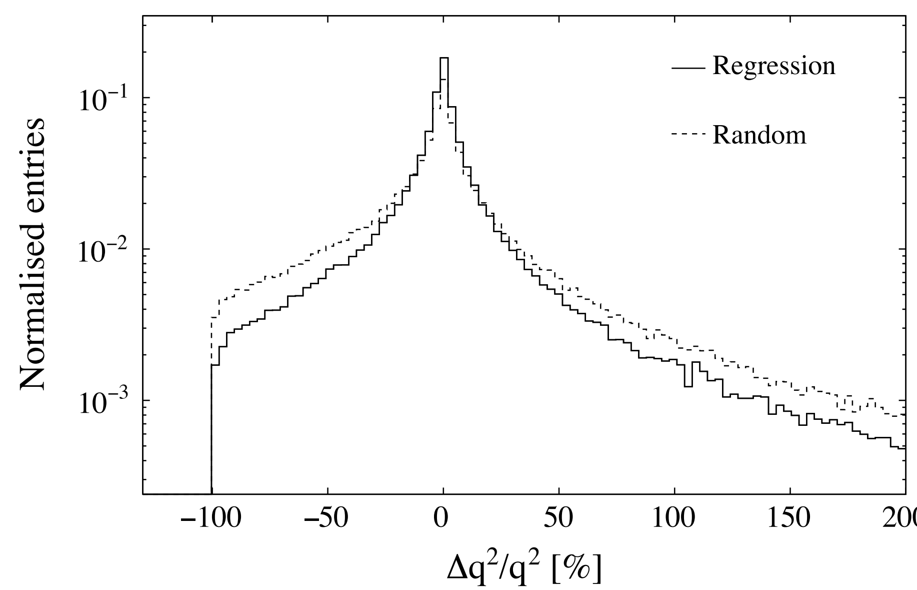


Choosing the neutrino solution

- Easiest choice is to randomly choose between the two solutions.
- Other methods involve comparing the solved b-hadron kinematics to what one expects on average.

arXiv:1611.08522

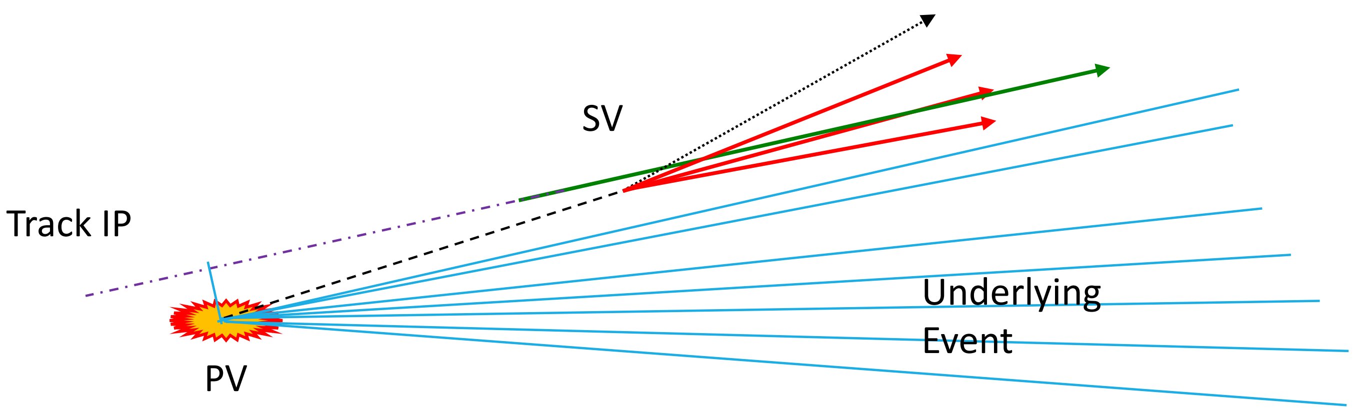


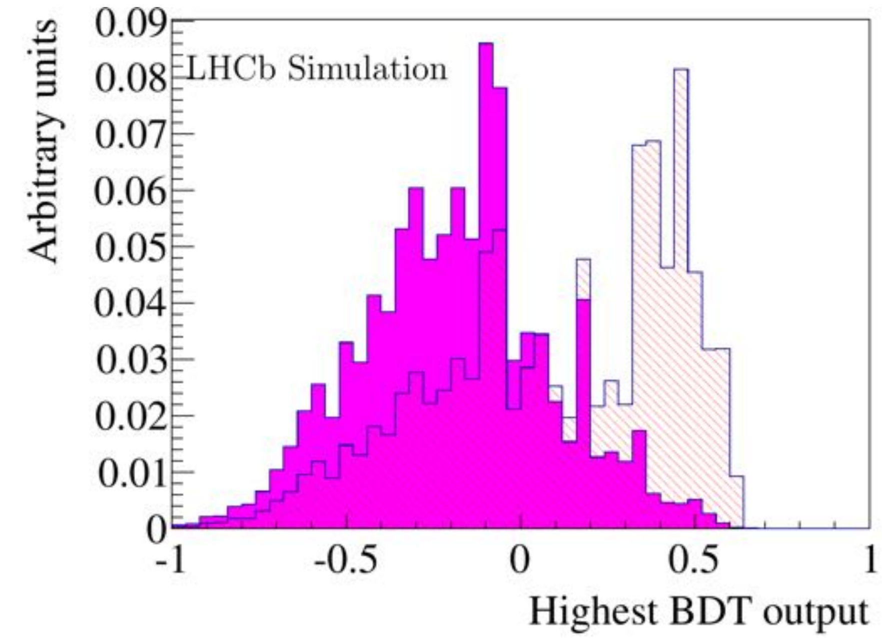


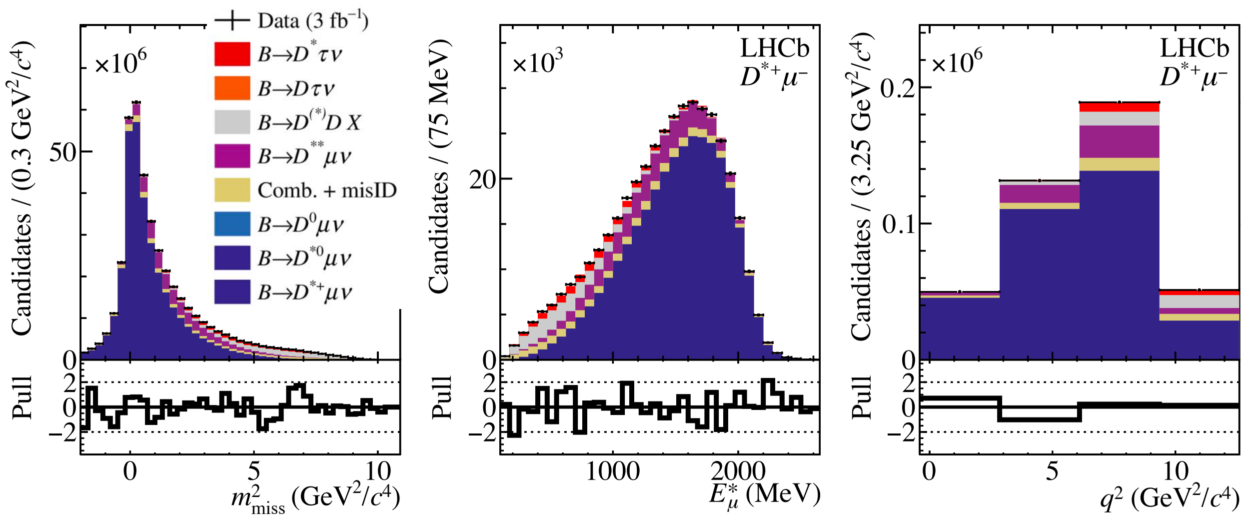
- Other ideas include using Gaussian processes.
- Interesting feature: For b—>c decays the solution that gives the smaller neutrino momentum is more often correct (60/40). Choosing randomly 50/50 less than ideal!

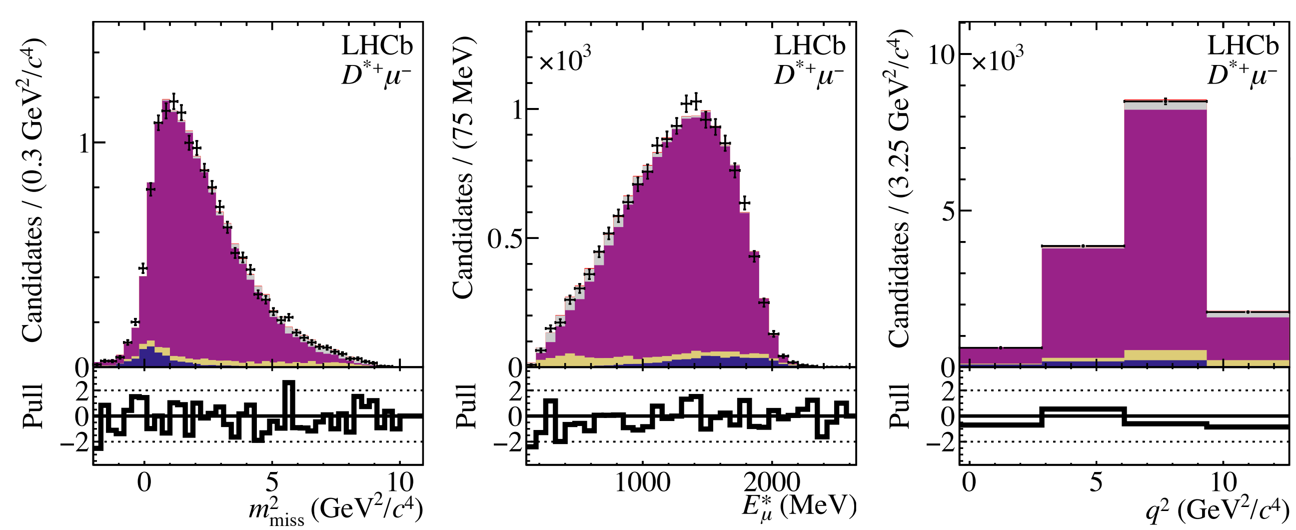
Isolation

- Many backgrounds from feed-down (e.g. D**), isolation can be used to reduce and then control these backgrounds.









- Particularly important for semitauonic decays and still useful for $b \to c\mu\nu$.

Isolation

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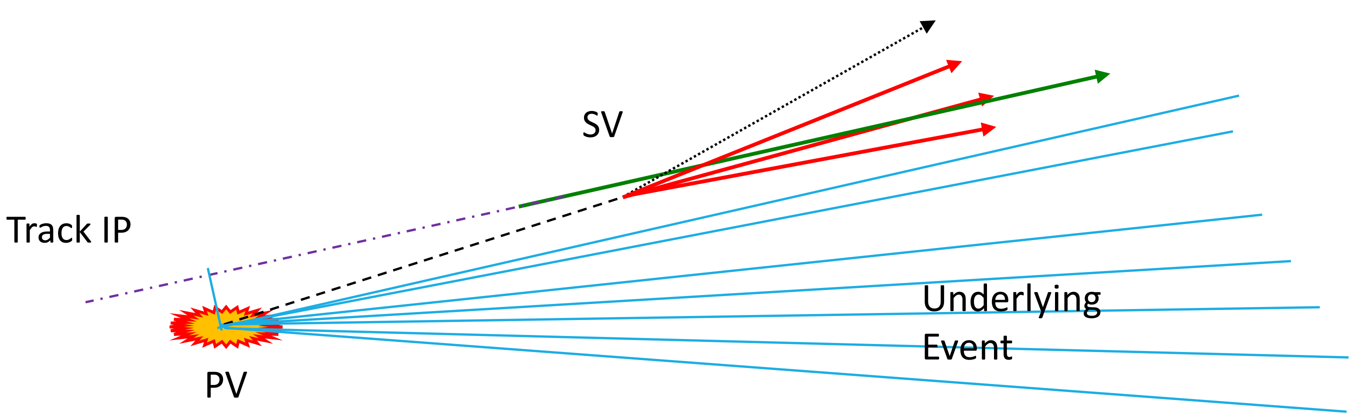
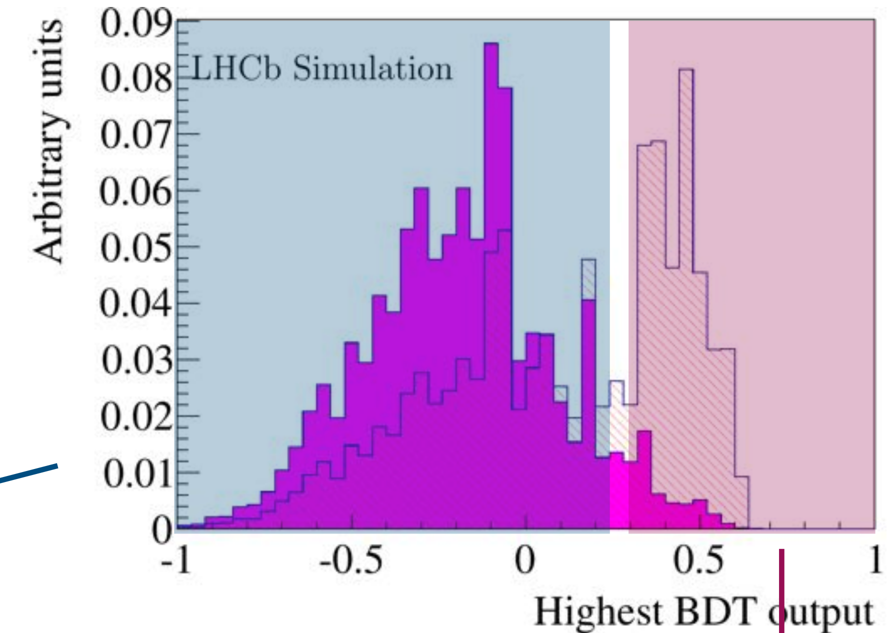
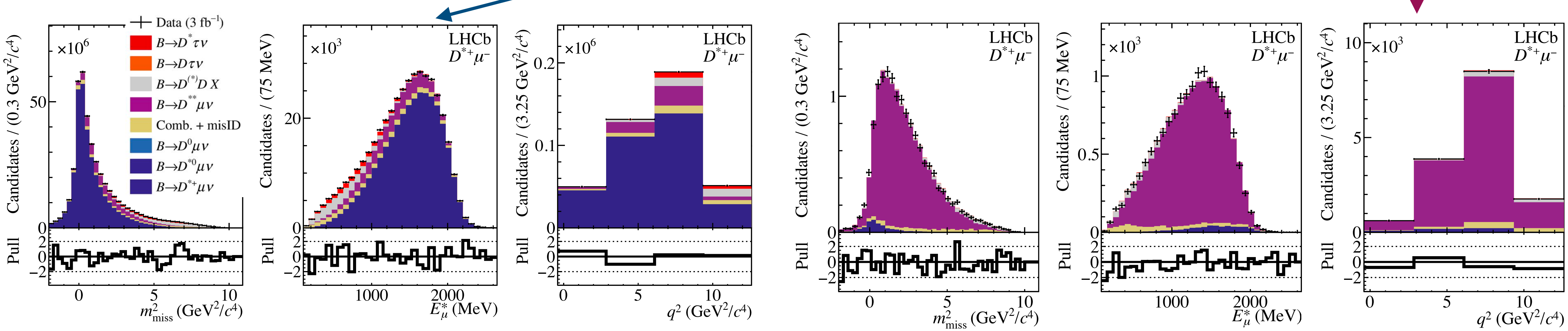




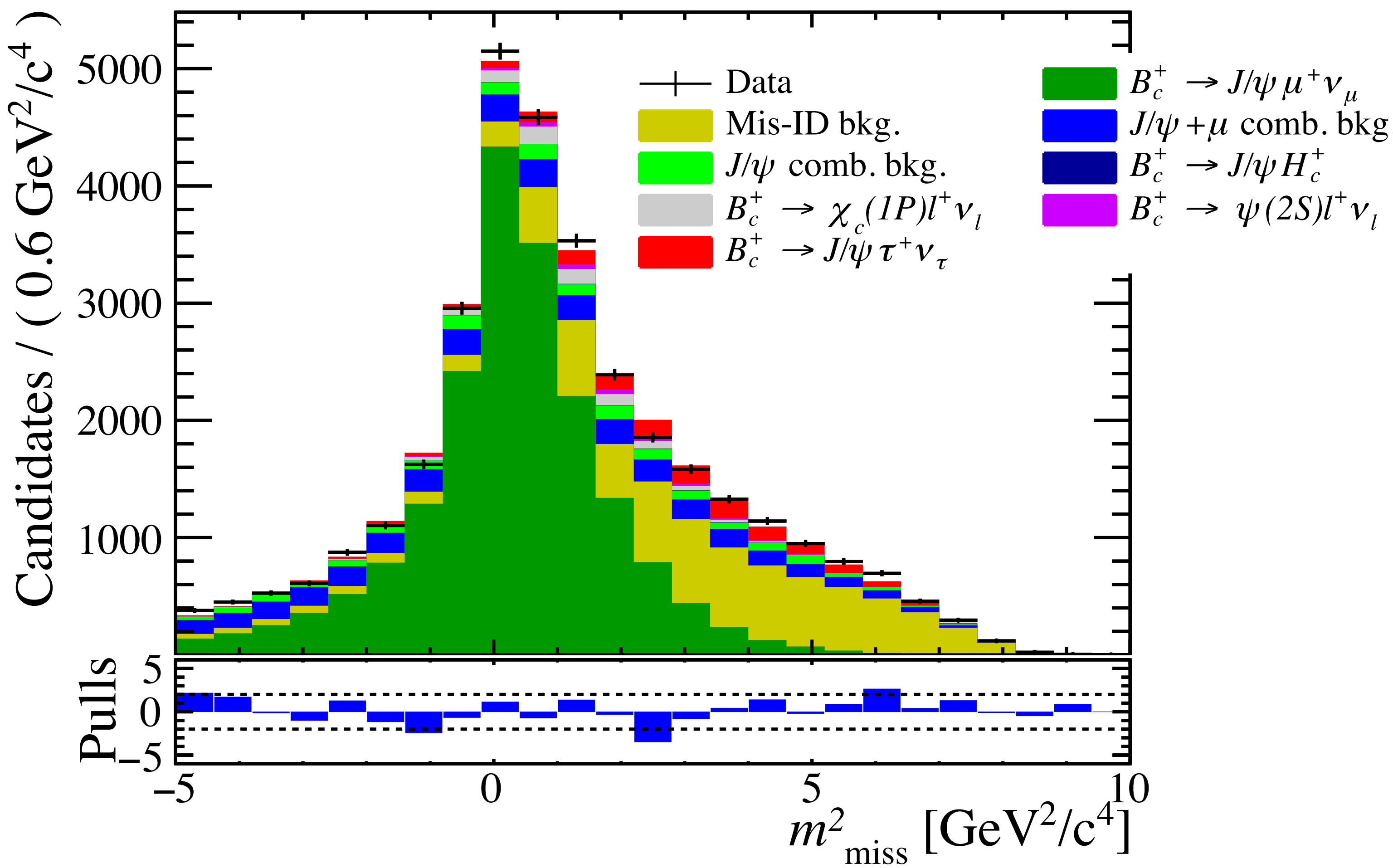


- Particularly important for semitauonic decays and still useful for $b \to c\mu\nu$.

Data driven mis-id background

- Particularly complicated background arises from $B \to X_c h X$ decays, followed by $h \to \mu$.

LHCB-PAPER-2017-035

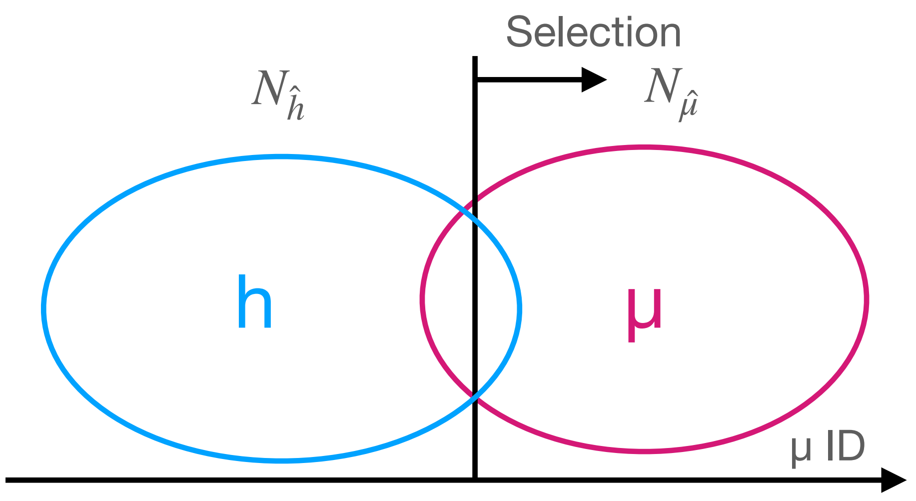


- The decay $B_c^+ \to J/\psi\tau^+\nu_\tau$ particularly sensitive as the signal is suppressed by ~200 compared to the mis-ID background.

- As it originates from a large cocktail of $B \to X_c h X$ decays, very difficult to model with simulation - derive it from data.

Data driven method

- Mis-ID data cleanly selected by reversing the lepton-ID.

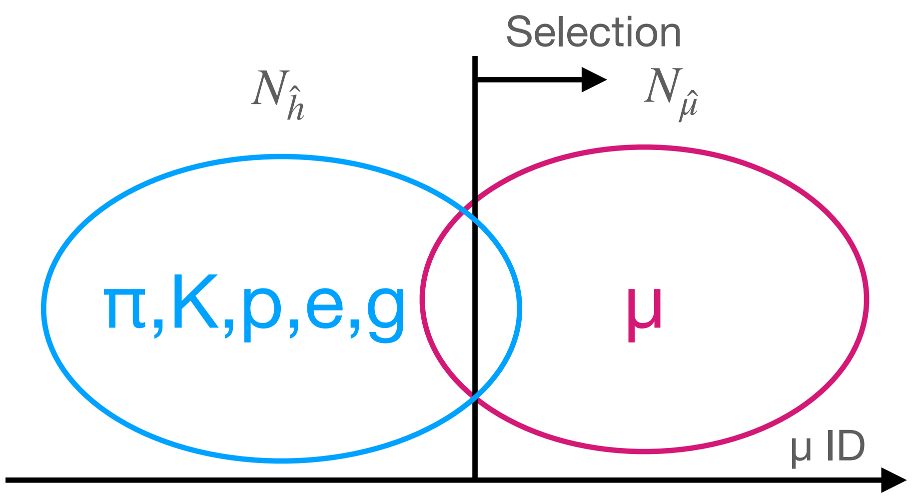


- Number mis-IDed, $N(h \to \mu)$ is then given by

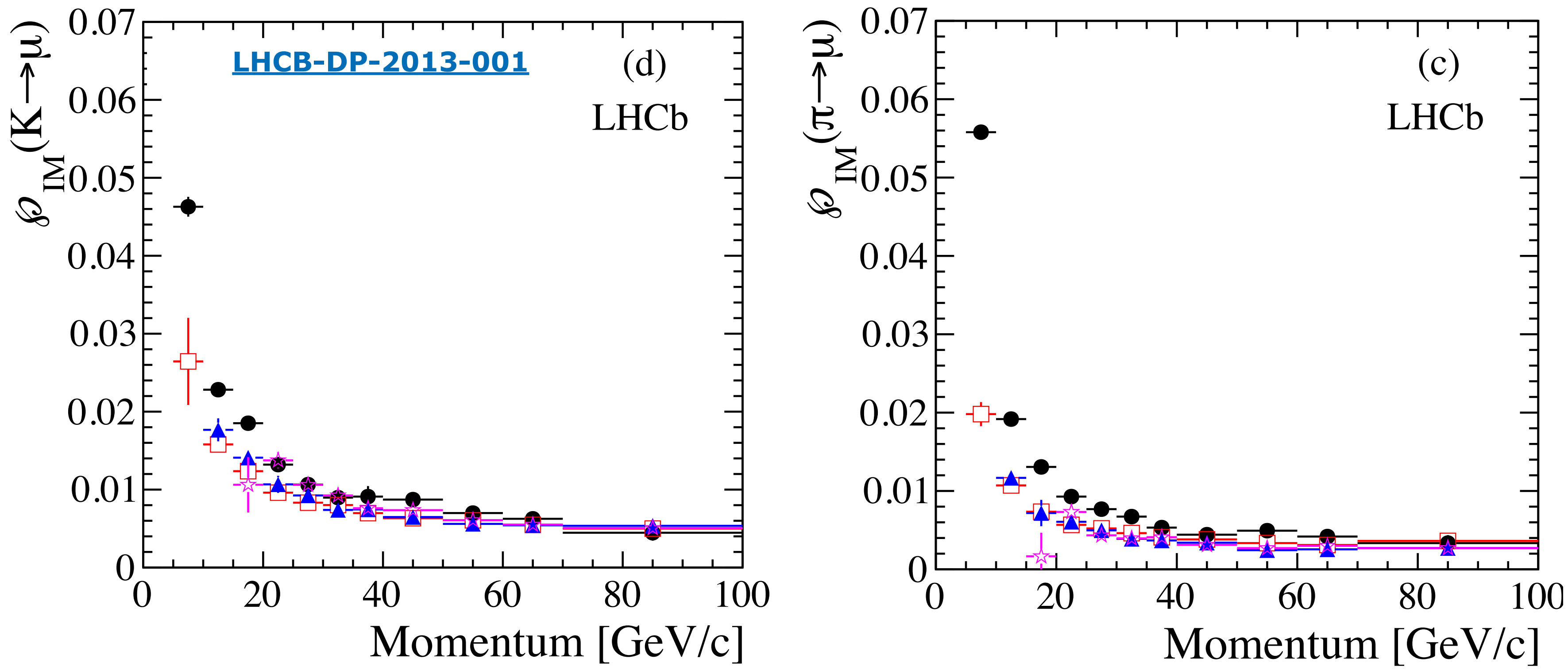
$$N(h \to \mu) \approx N_{\hat{h}} P(h \to \hat{\mu}) - N_{\hat{\mu}} P(\mu \to \hat{h})$$

The problem

- Mis-ID data cleanly selected by reversing the lepton-ID.



- Problem: mis-ID background consists of different hadron species which have different mis-ID probabilities.



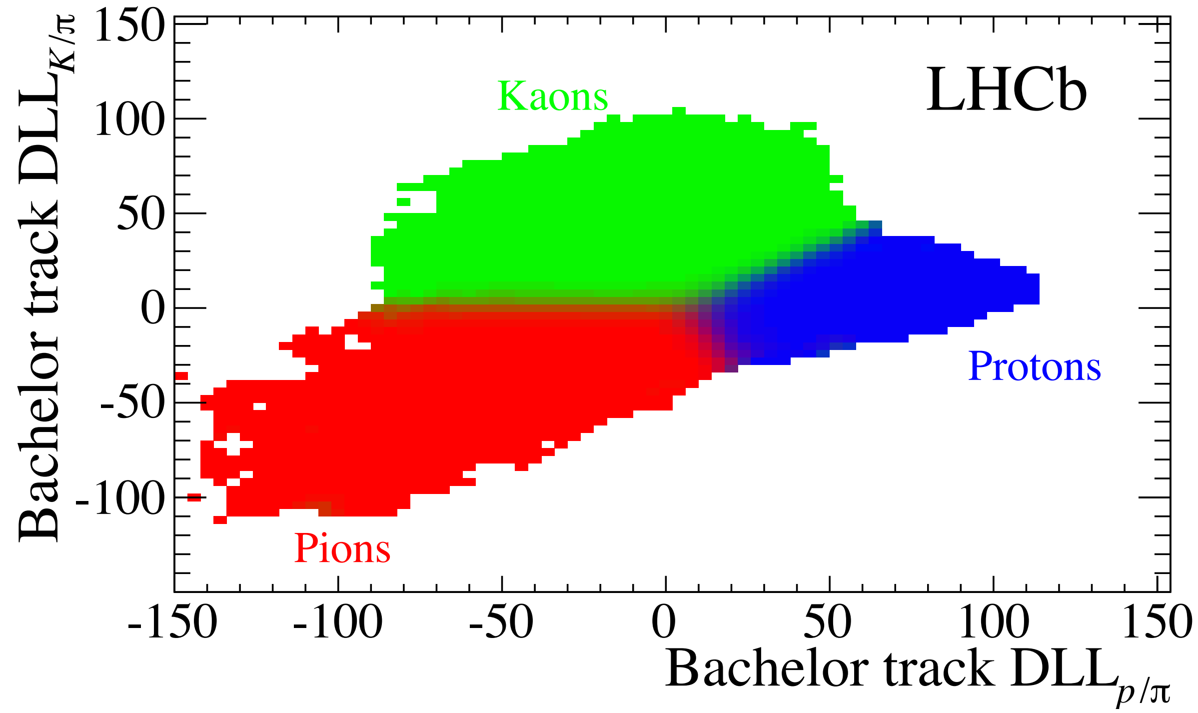
- Equation becomes more complicated:

$$N(h \to \mu) = N_\pi P(\pi \to \hat{\mu}) + N_K P(K \to \hat{\mu}) + N_p P(p \to \hat{\mu}) + N_e P(e \to \hat{\mu}) + N_g P(g \to \hat{\mu})$$

Solution

- Split the hadron sample into different regions depending on the PID response.

LHCb-PAPER-2013-063



- Cross feed turns the equation into a matrix equation

$$\begin{pmatrix} N_{\hat{\pi}} \\ N_{\hat{K}} \\ \vdots \end{pmatrix} = \begin{pmatrix} P(\pi \to \pi) & P(K \to \pi) & \cdots \\ P(\pi \to K) & P(K \to K) & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} N_{\pi} \\ N_{K} \\ \vdots \end{pmatrix}$$

- Can unfold using the usual approaches or fold in using a likelihood fit (preferred).

A word on simulation

- At the LHC, it takes 25ns to produce an event.
- It takes about a minute for fully simulate an event.
- Roughly 1 in 100 collisions has a bb pair.
- The branching fractions of the decays involved are O(%) level, multiplied by O(10%) for the D decay.
- That still leaves 4 orders of magnitude difference in the production rate between simulation and data.
- Producing enough simulation is difficult, and usually requires lots of tricks.

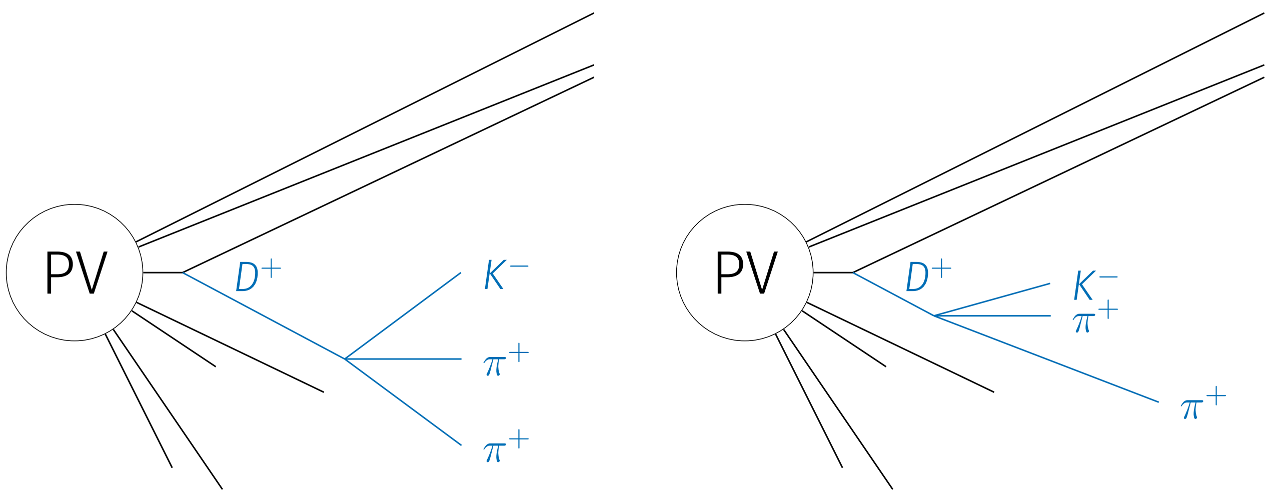
Patrick Owen

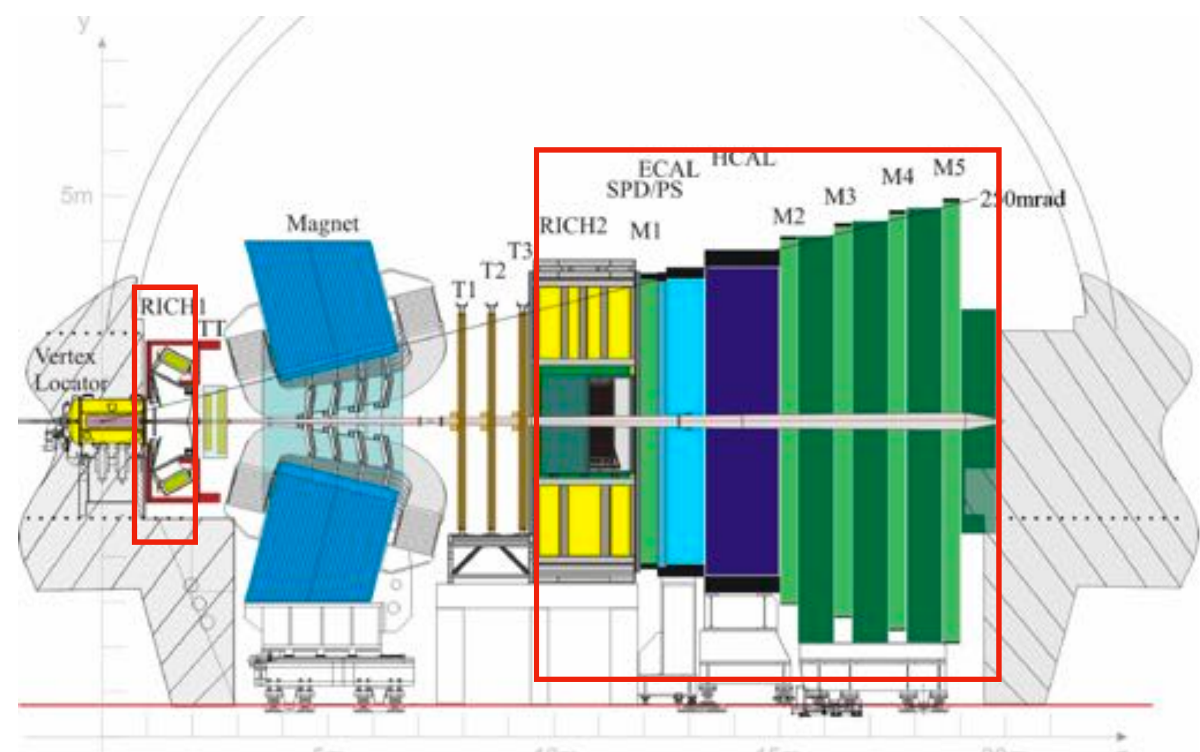
Fast simulation

Two main methods to make simulation faster, both used in semileptonic analyses

Redecay	Tracker only simulation
Reuse underlying event for different decays.	Turn off parts of the detector response (shower development, photon propagation in RICH).

arXiv:1810.10362





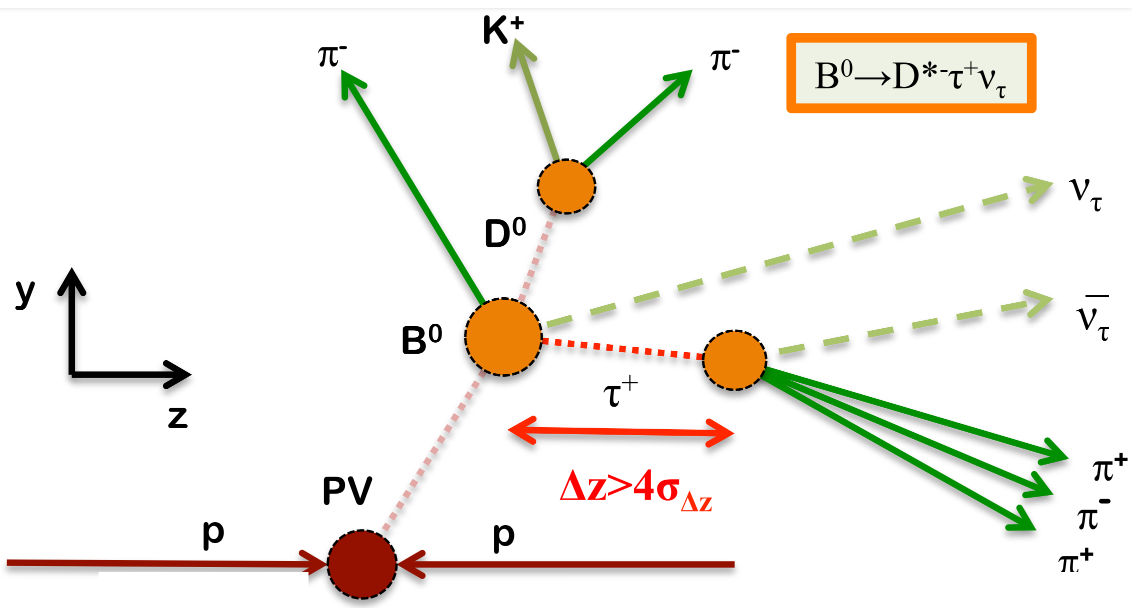
Speed up 10-100, same disk space.

Speed up by factor 8, disk space down by 40%

Flight distance

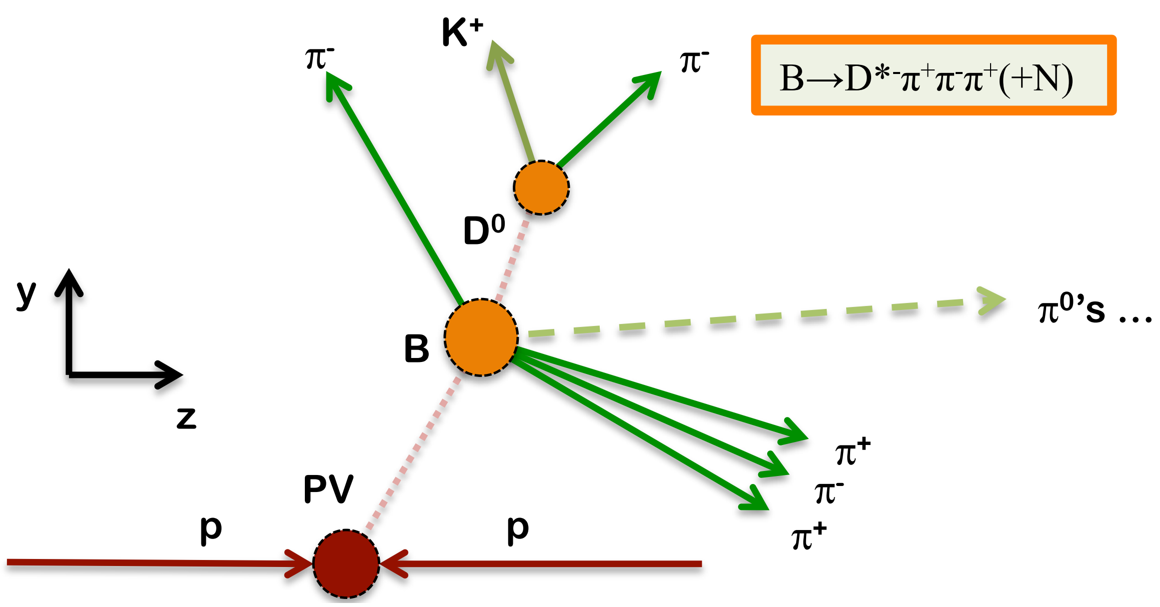
- One other useful aspect for $\tau \to 3\pi(\pi)\nu$ decays is to utilise the flight distance.

Signal



Phys. Rev. Lett. 120, 171802 (2018)

Background



- In principle could use it for $\tau \to \mu$ decays, but tends to increase combinatorial background.

How can LHCb contribute to $|V_{cb}|$?

$|V_{cb}|$ measurement from B_s decays

- Exploit diversity of b-hadrons to measure $|V_{cb}|$ with B_s decays.

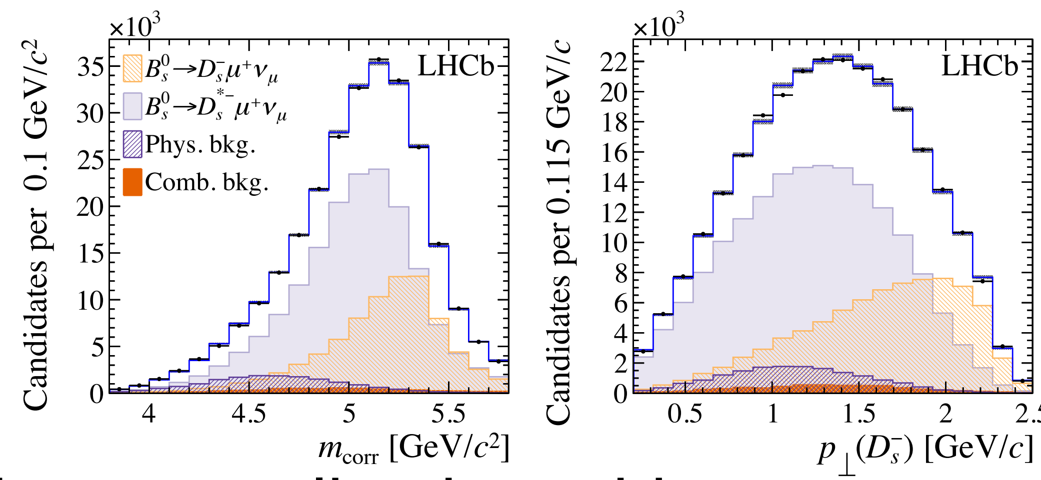
- Normalise B_s^0 signal to corresponding B^0 decays.

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

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

- Fit to determine form factors and signal yield.

LHCb, Phys. Rev. D101 (2020) 072004

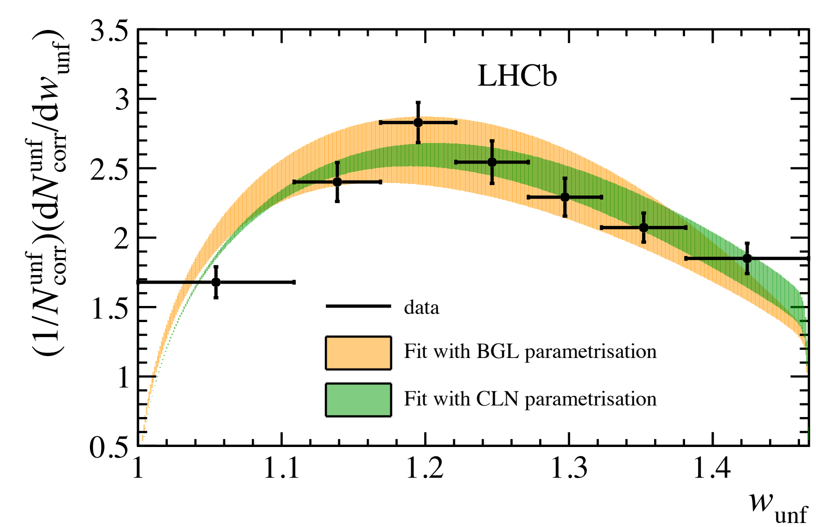


- Use $B^0 \to D^{(*)}\mu\nu$ branching fractions to determine normalisation with 4(3)% uncertainty from PDG.

- Measurement of f_s/f_d used for production fractions.

- Also limited by knowledge on $D_{(s)}$ branching fractions.

- Also measured $B_s \to D_s^{(*)}$ form factors: arXiv:2003.08453



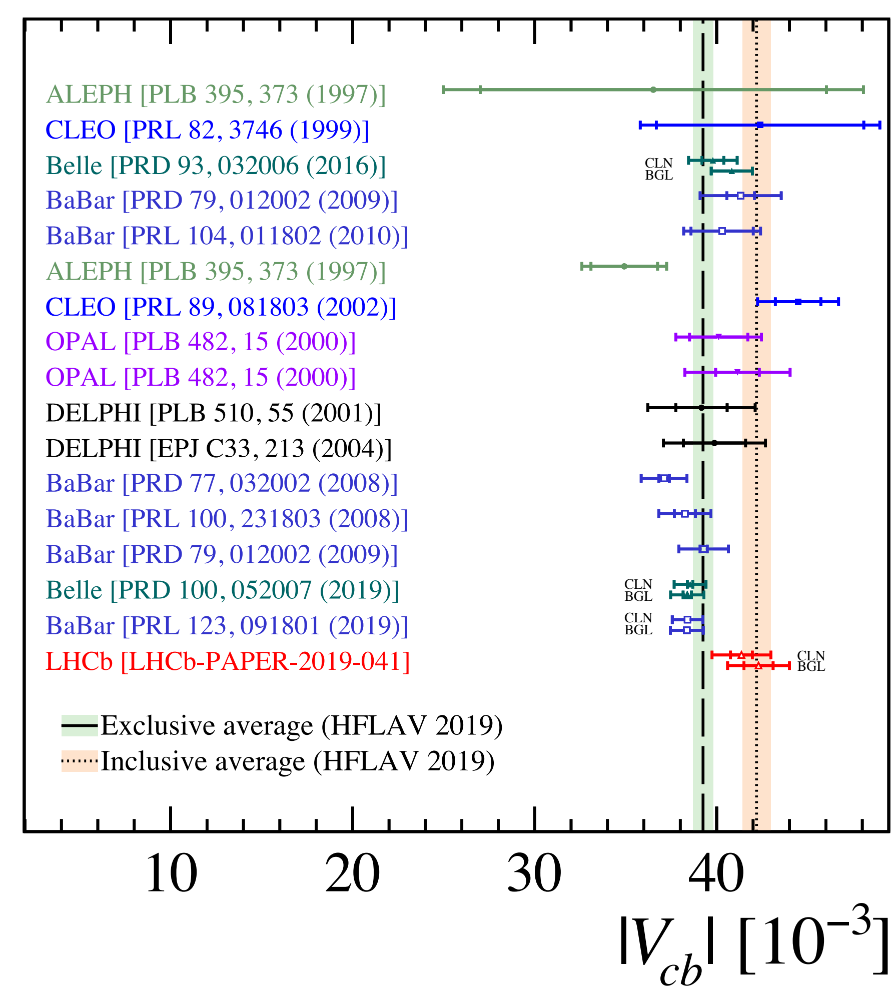
$|V_{cb}|$ results

- Performed analysis with CLN and BGL parameterisations.
  - Parameters have constraints from e.g. HPQCD [1].

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

- Both results compatible with each other and existing measurements.

LHCb, Phys. Rev. D101 (2020) 072004



Abstract

The shape of the $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential decay rate is obtained as a function of the hadron recoil parameter using proton-proton collision data at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 1.7 fb^{-1} collected by the LHCb detector. The $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ decay is reconstructed through the decays $D_s^{*-} \to D_s^-\gamma$ and $D_s^- \to K^-K^+\pi^-$. The differential decay rate is fitted with the CENSORED CENSORED Boyd-Grinstein-Lebed (BGL) parametrisation [redacted] of the form factors, and the relevant quantities [redacted] are extracted.

[1] McLean, Davies, Koponen, Lytle [HPQCD]: Phys. Rev. D 101, 074513 (2020), see also Judd, Davies https://arxiv.org/abs/2105.11433

Yes, it really is a $|V_{cb}|$ measurement

- If both numerator and denominator depend on $|V_{cb}|$, how can one be sensitive to $|V_{cb}|$?

- The point is that the denominator is measured, we do not use a prediction which depends on $|V_{cb}|$.

    - The $B^0 \rightarrow D^{(*)}$ branching fraction measurements could be correlated to the exclusive $|V_{cb}|$ B-factory measurements, but I understand this is a small effect(?).

Bigi, Mannel, Uraltsev, JHEP09(2011)012

- We do, however, rely on the equally of semileptonic widths.

    - We are heavily dependent on this in LHCb, so might be useful to provide precise validations in data. More lifetime measurements?

Planned measurements

- Plan to perform a similar measurement with Λ_b^0 decays.
  - Here the normalisation is a bit different, we instead normalise to inclusive Λ_b^0 semileptonic decays and employ equally of partial widths.

$$\Gamma(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu) = \frac{n_{\text{corr}}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)}{n_{\text{corr}}(\Lambda_b^0 \to X_c \mu^-) \times \Gamma(\Lambda_b^0 \to X_c \mu^- \overline{\nu}_\mu)}$$

- Plan is to use the differential measurement as a function of q^2 to control form factor uncertainties a la LHCb-PAPER-2017-016

- Also discussions on performing a measurement with $B^0 \to D^* \mu \nu$ decays using a similar method:

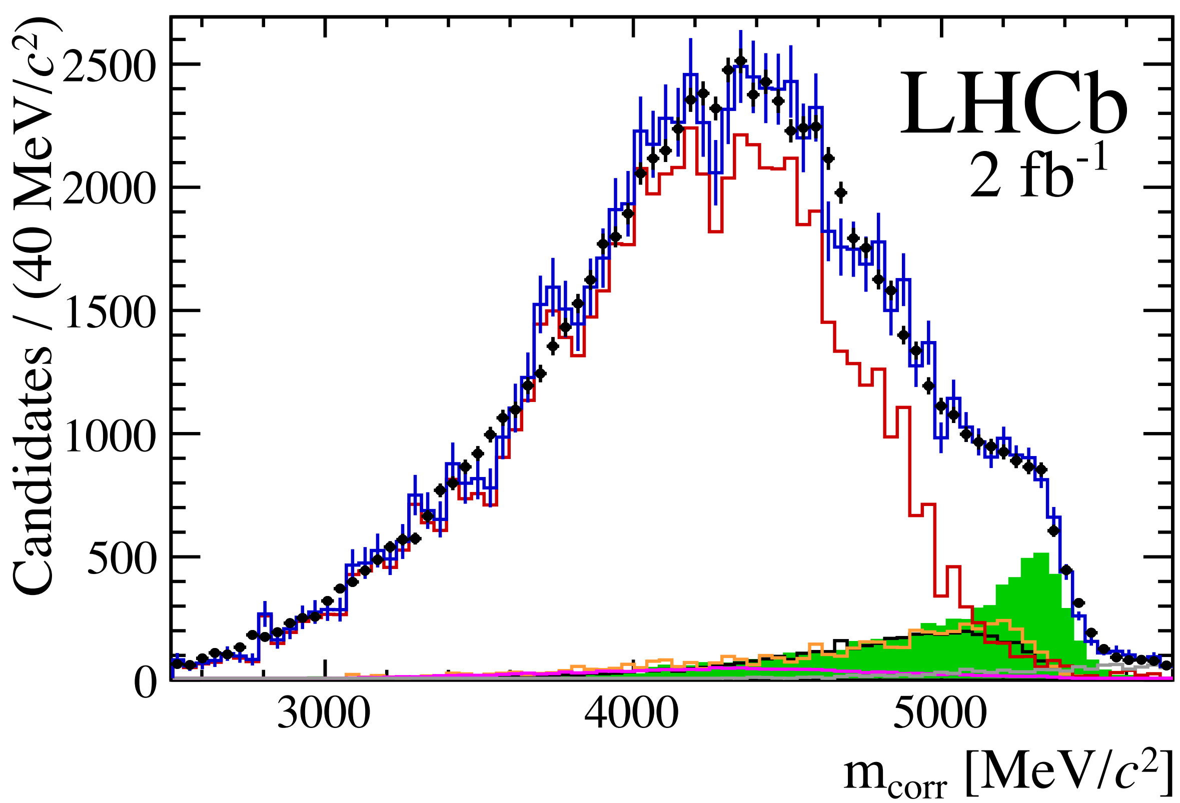
$$\frac{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}{\mathcal{B}(B \to \bar{X}_c \mu^+ \nu_\mu X)} = \frac{2 n_{corr}(B^0 \to D^{*-}\mu^+\nu_\mu)}{n_{corr}(\overline{D}^0 \mu^+ X) + n_{corr}(D^- \mu^+ X)}$$

- Finally, working on $B \to D^* \mu \nu$ angular analysis, which will help constrain form factors.

Summary

LHCb good at the y-axis, Belle (II) good at the x-axis.

LHCB-PAPER-2020-038



arXiv:2303.1730