How to measure semileptonic b-hadron decays at the LHC and beyond

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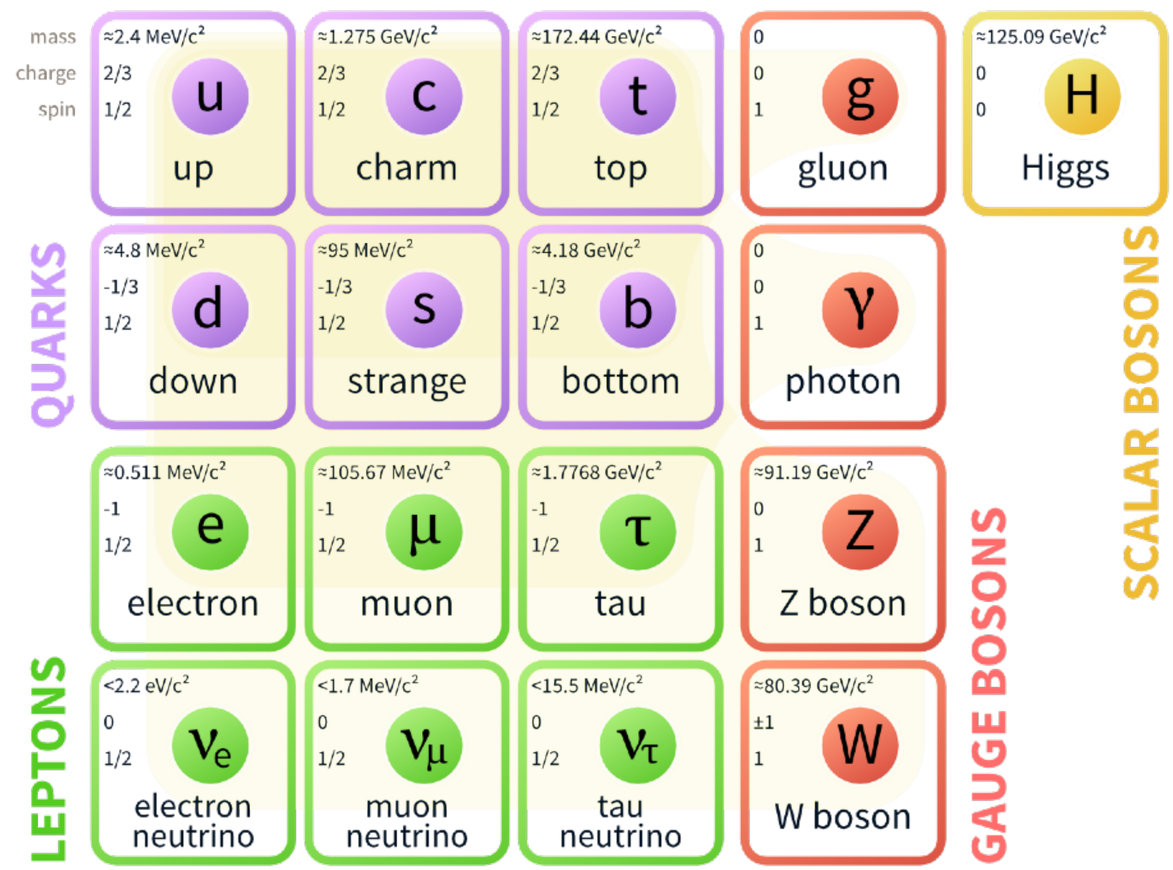
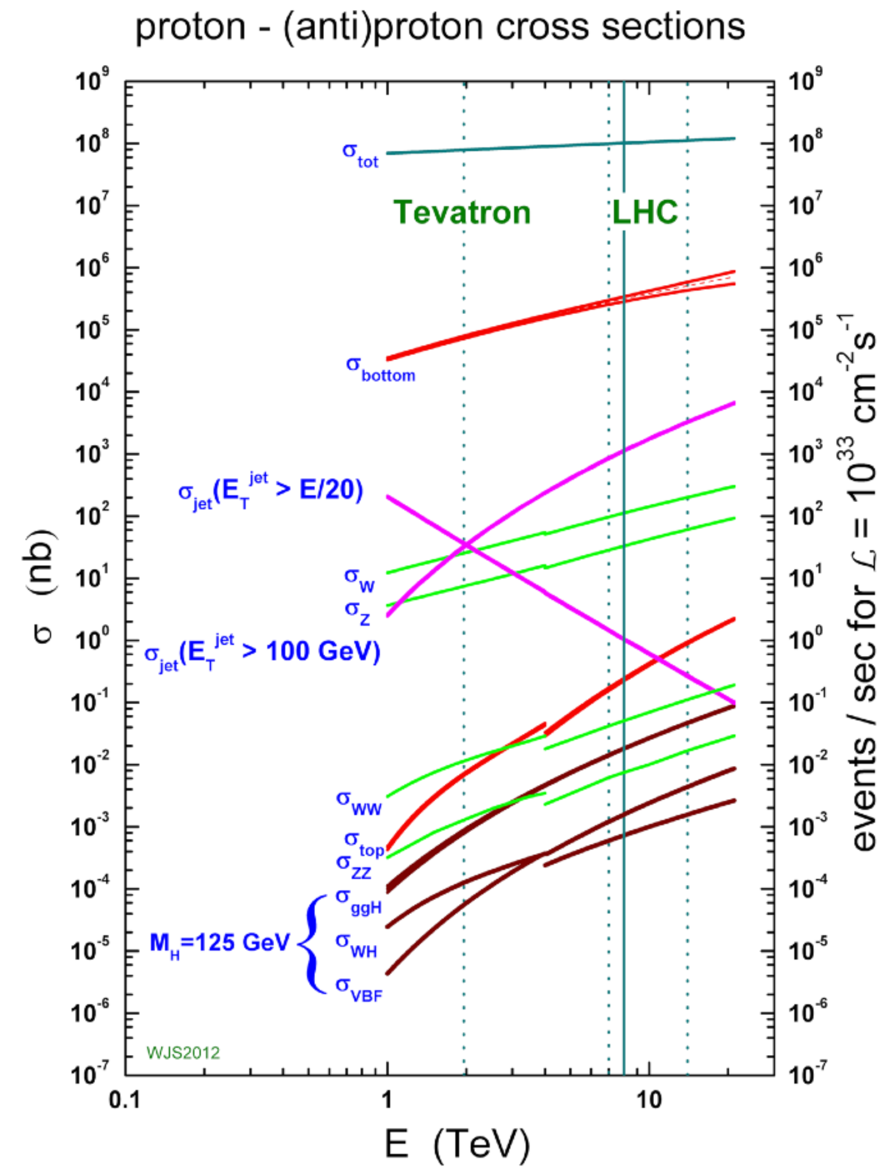
YETI '23

1-3 August 2023

B Physics



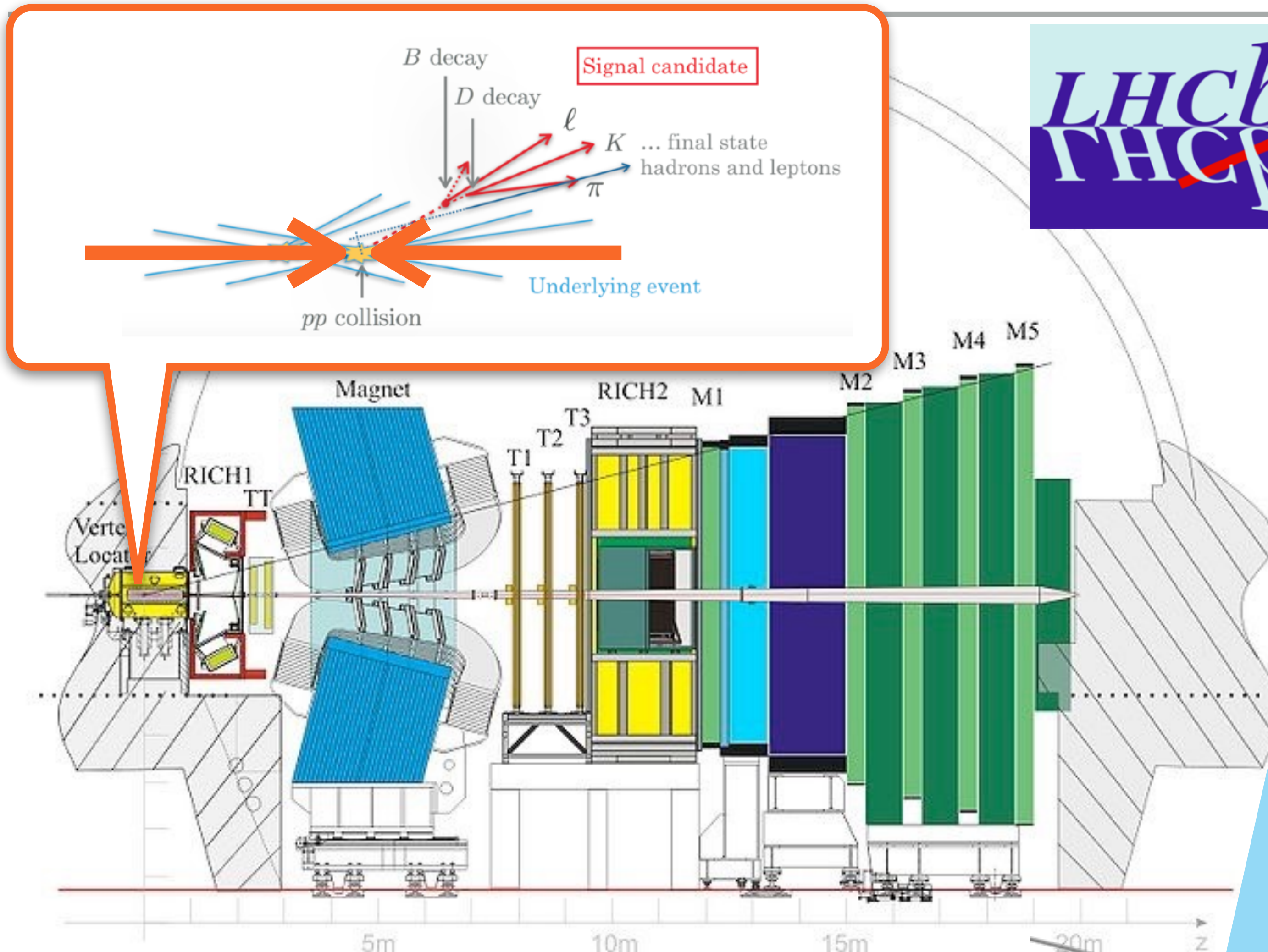


$$B^0 = |d\bar{b}\rangle;\ \ B^+ = |u\bar{b}\rangle;\ \ B_s^0 = |s\bar{b}\rangle$$

$$\Lambda_b^0 = |udb\rangle;\ \ B_c^+ = |c\bar{b}\rangle$$

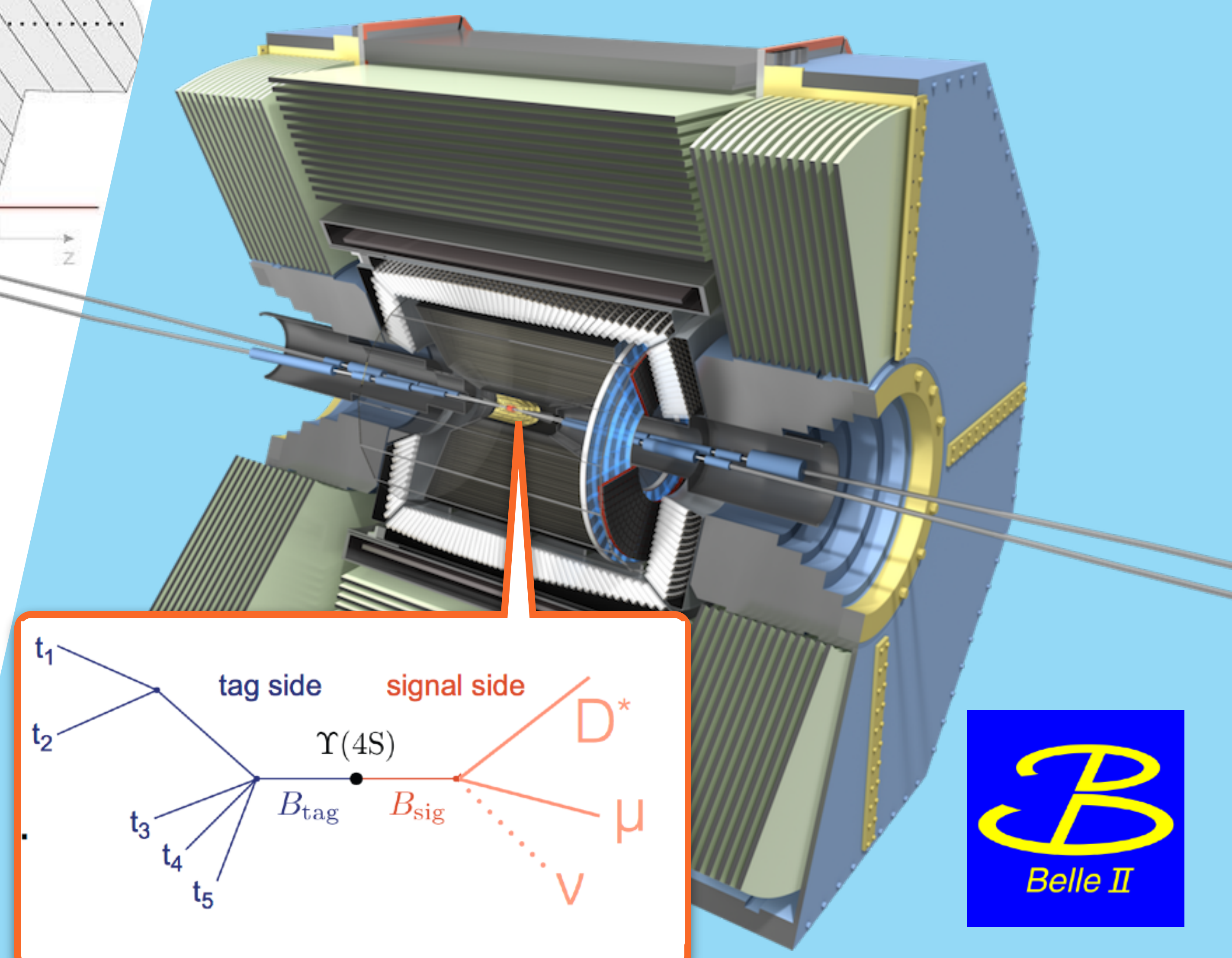
- B physics is the study of bound states containing one b quark and their decays/dynamics.
- b-hadrons decay in a multitude of final states, allowing the study of a wide range of physics.
- They are copiously produced at the LHC: $10^{11}\ b\bar{b}$ produced per fb^{-1}
- Non B physics is great too! But I had to somehow restrict the topic

Experiments (two out of many on the slides)



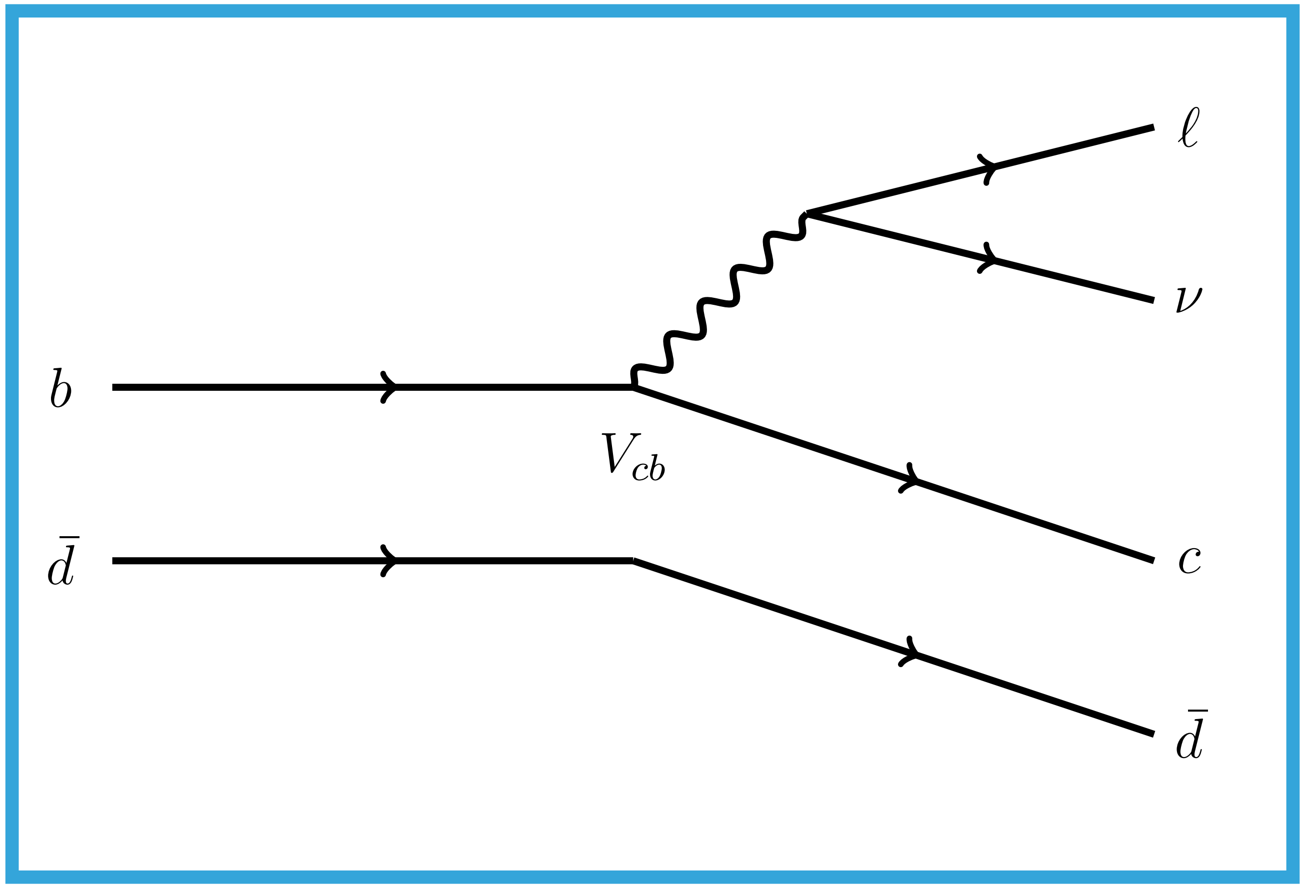
- @Hadron Colliders
  - Higher $b\bar{b}$ production cross-section
  - Many b-hadron species to study
  - Backgrounds: high particle density environment, b-hadron momentum determined from final state particles

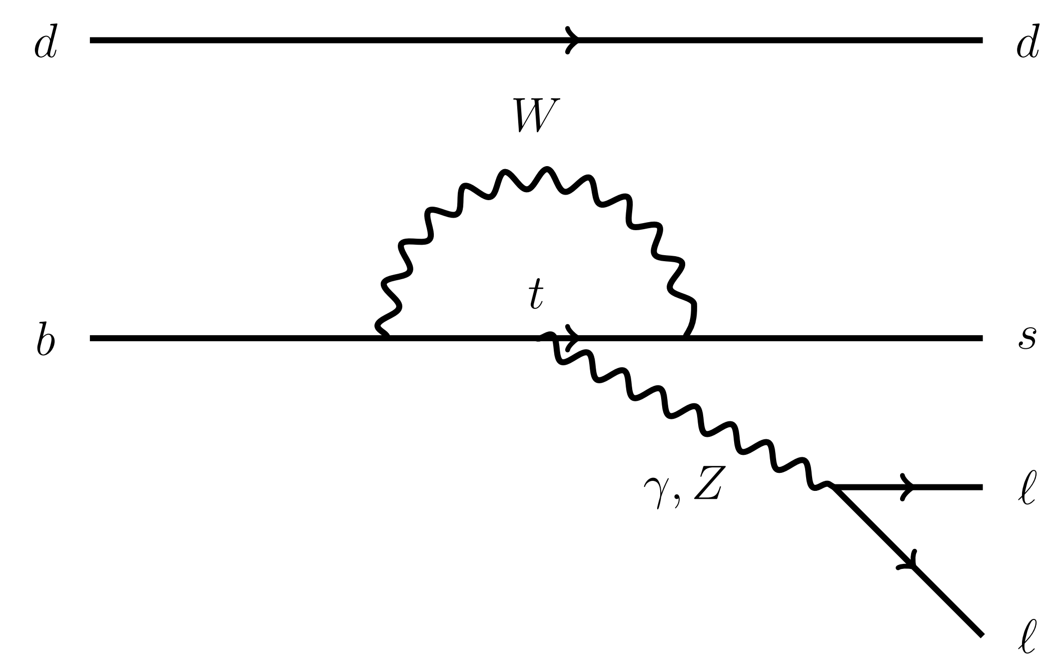
- @electron-positron collideres
  - Collisions @$\Upsilon(4S)$ (or $\Upsilon(5S)$) centre of mass energy
  - Constrained kinematics
  - Backgrounds: other physics processes, beam background



Linguistics

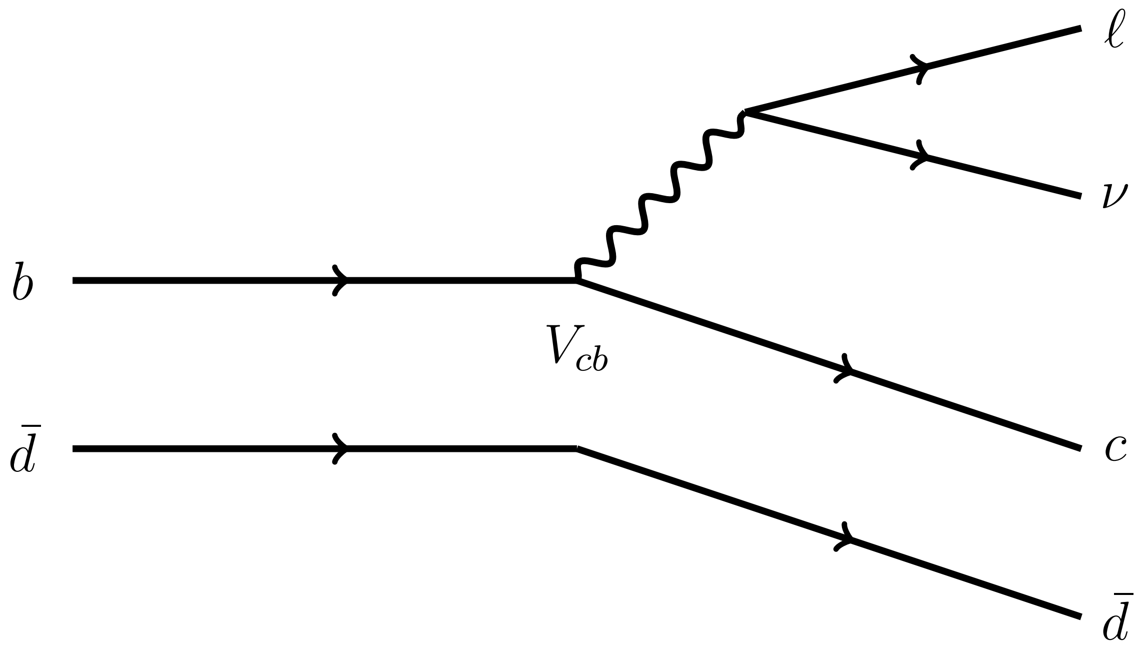
- Today's topic: Semileptonic b-hadron decays

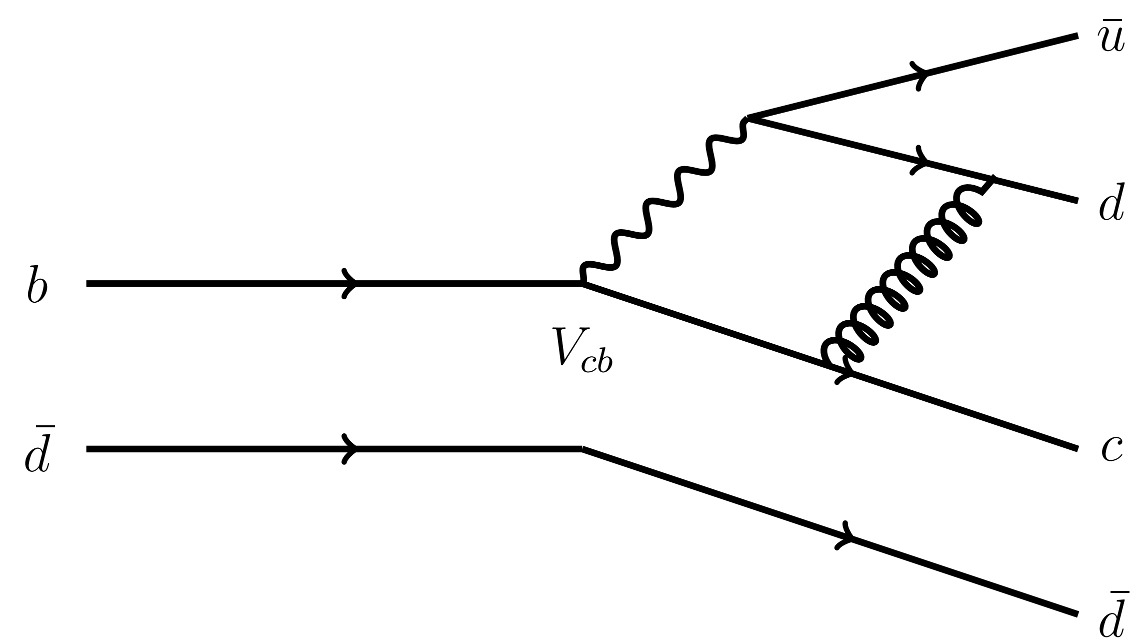




- "Semileptonic decay" refers to a final state with leptons and hadrons
- Except for LHCb people, where with "Semileptonic b-hadron decay " refers to tree level $b \to c$ and $b \to u$ transitions , with charged and neutral leptons in the final state
- Today not much about $b \to s\ell^+\ell$ transitions, e.g. $B^0 \to K^{*0}\ell^+\ell^-$ (again, they are great too…)

Why tree-level semileptonic b-hadron decays?





- The fundamental (theoretical) advantage of semi-leptonic decays is the non-coupling of the leptonic system to the outgoing hadron.
- The fundamental (experimental) disadvantage of semi-leptonic decays is the non-reconstructible neutrino in the final state
- Experimental advantage: about 10% of all b-hadrons decays → very large samples allow for precision tests of the SM (evaluation of systematic uncertainties is crucial)
- Access to many interesting observables

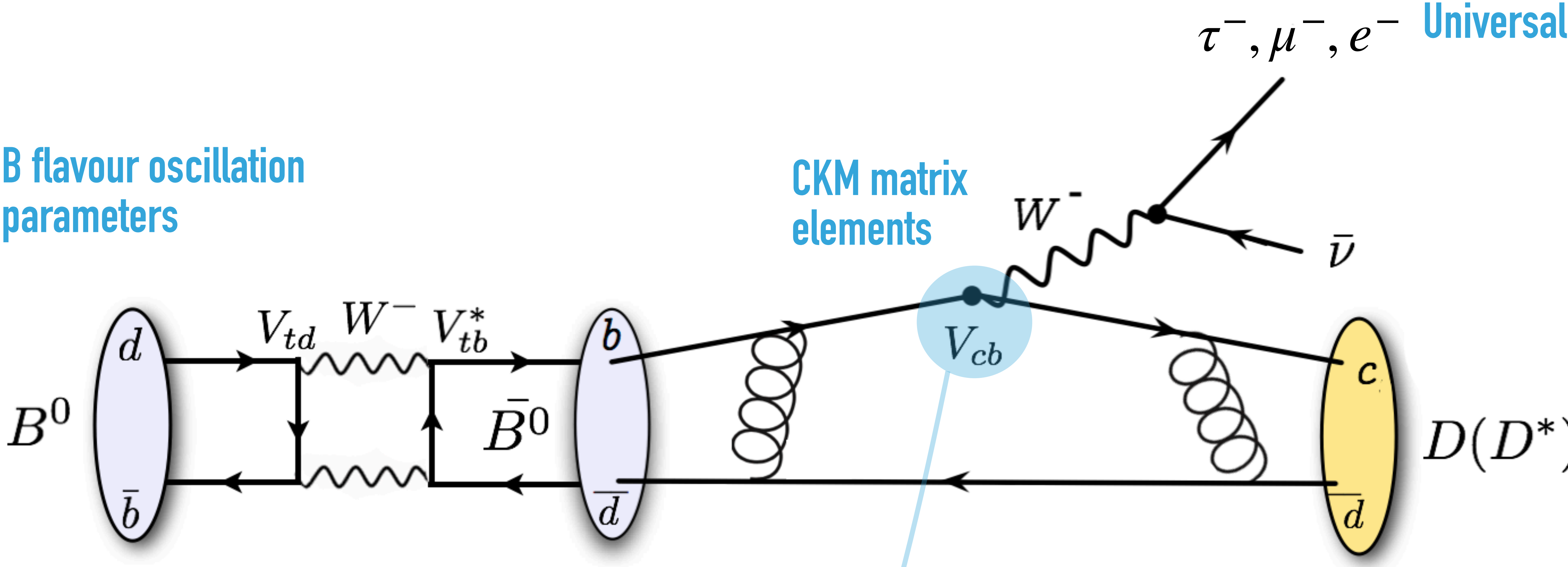
Why tree-level semileptonic b-hadron decays?

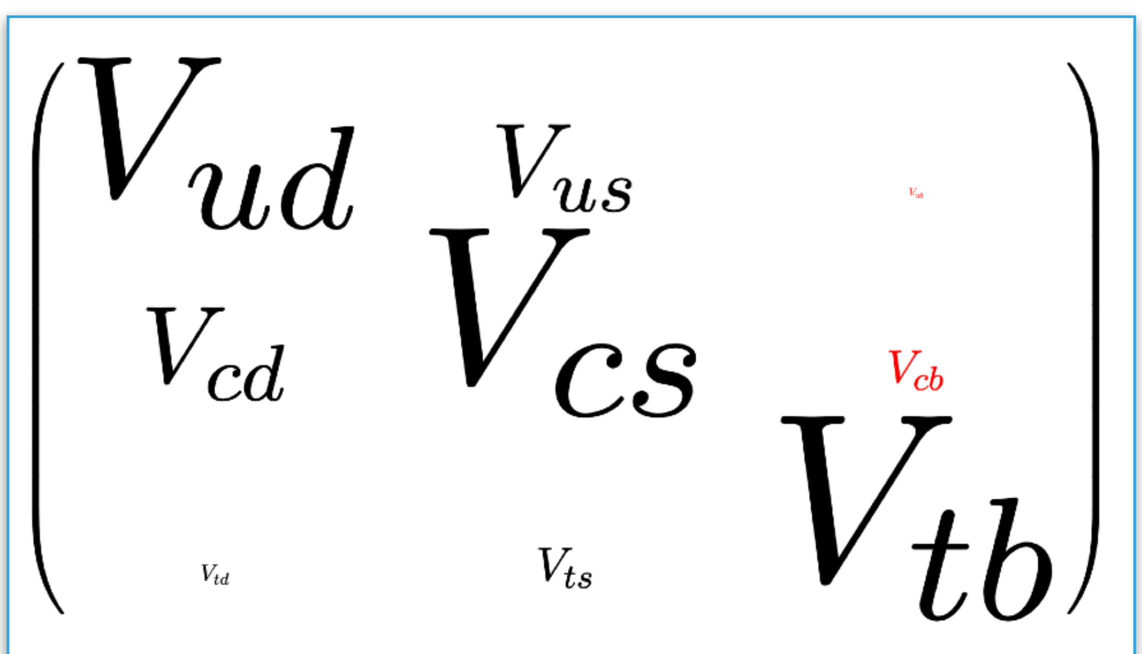
- Access to many interesting observables

Lepton Universality

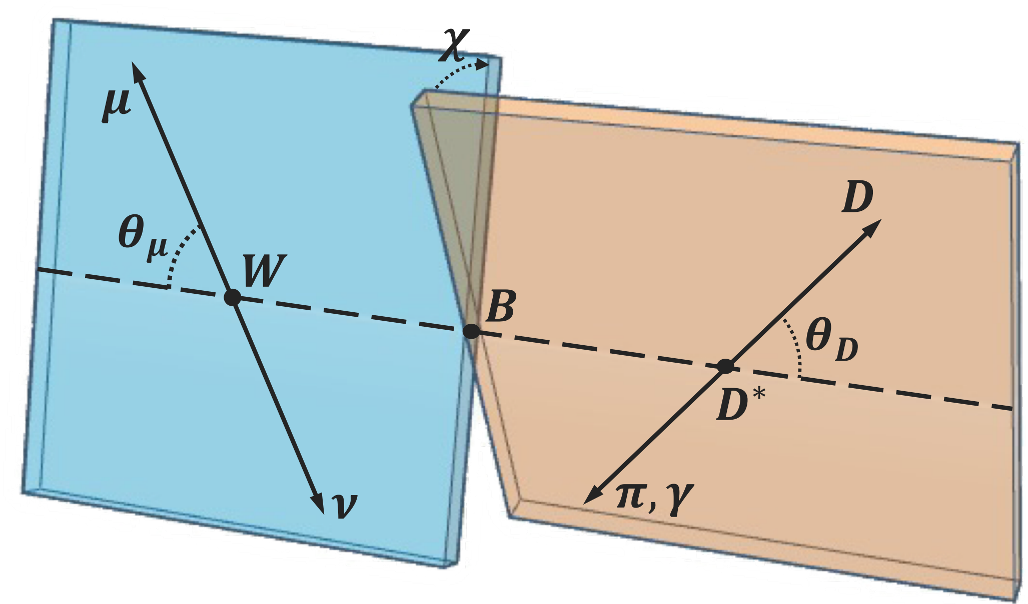
B flavour oscillation parameters

CKM matrix elements

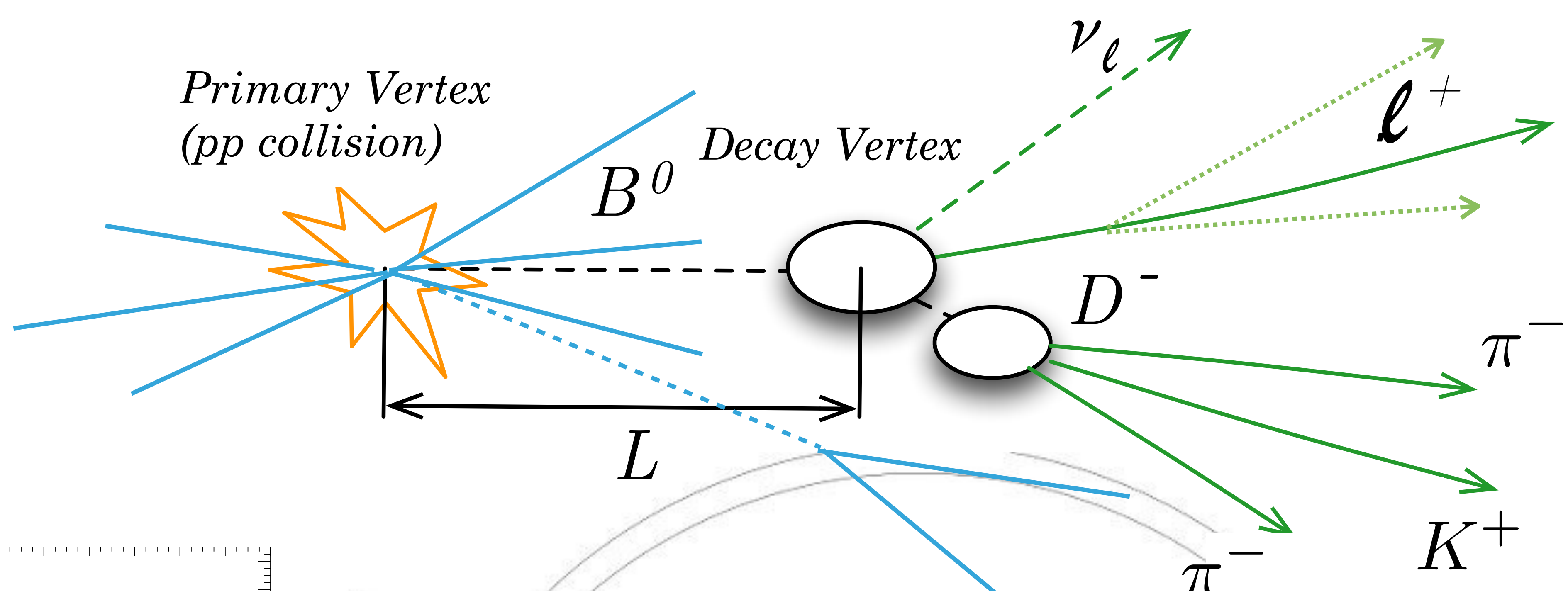


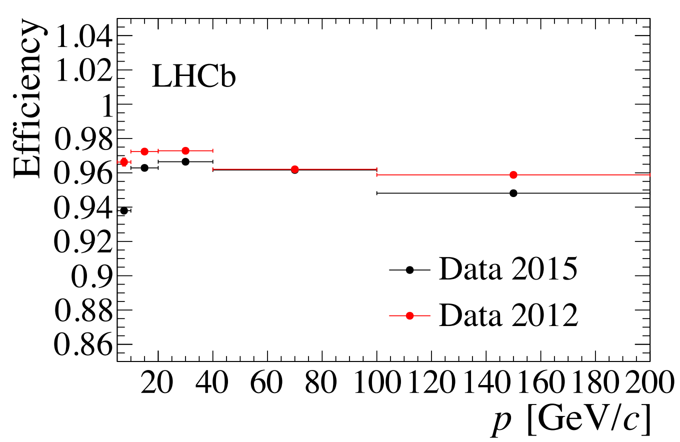


Hadronic interaction (Form Factors) and New Physics contributions



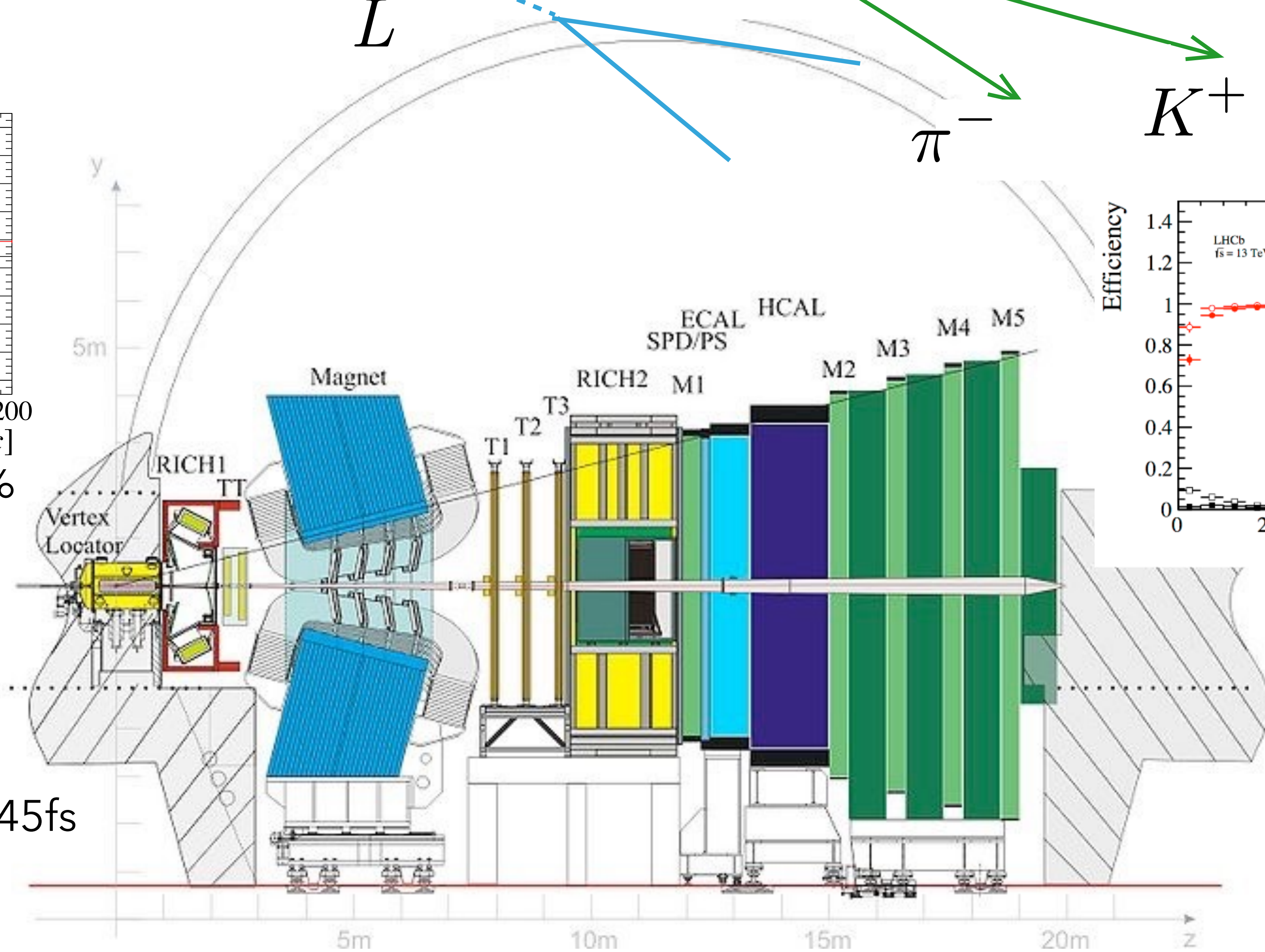
Semileptonic b-hadron decays @LHCb

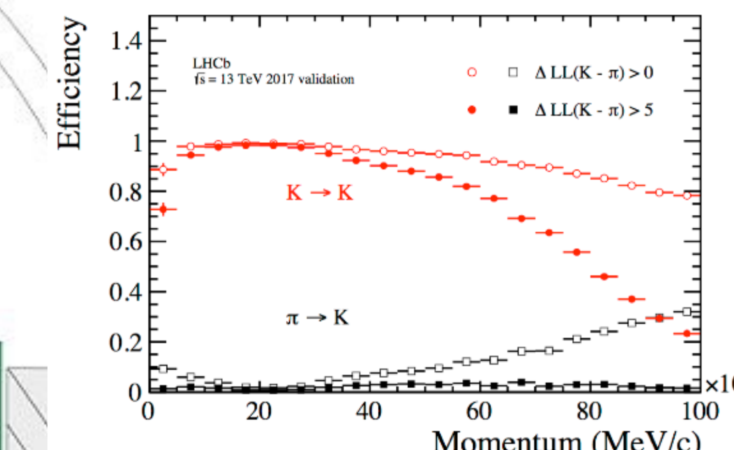




Tracking efficiency > 96%

σIPx~20μm





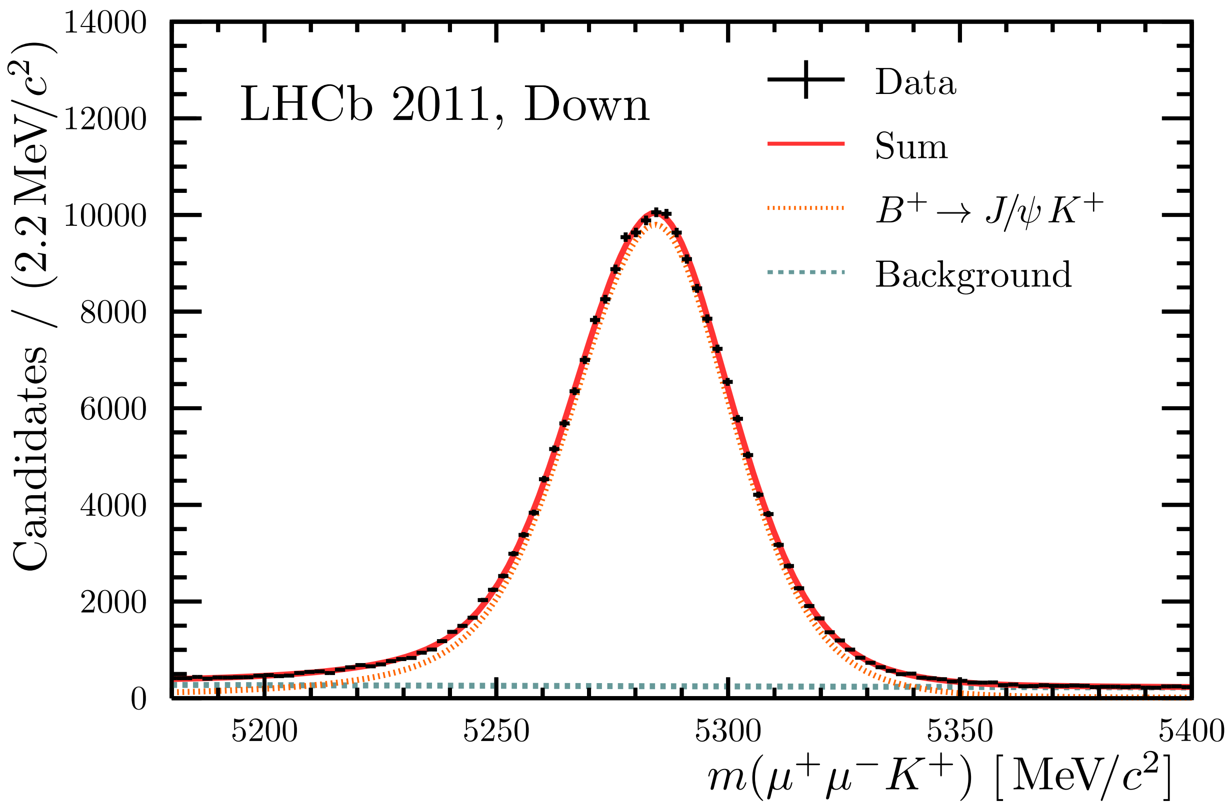
Δp/p = 0.5-1.0%

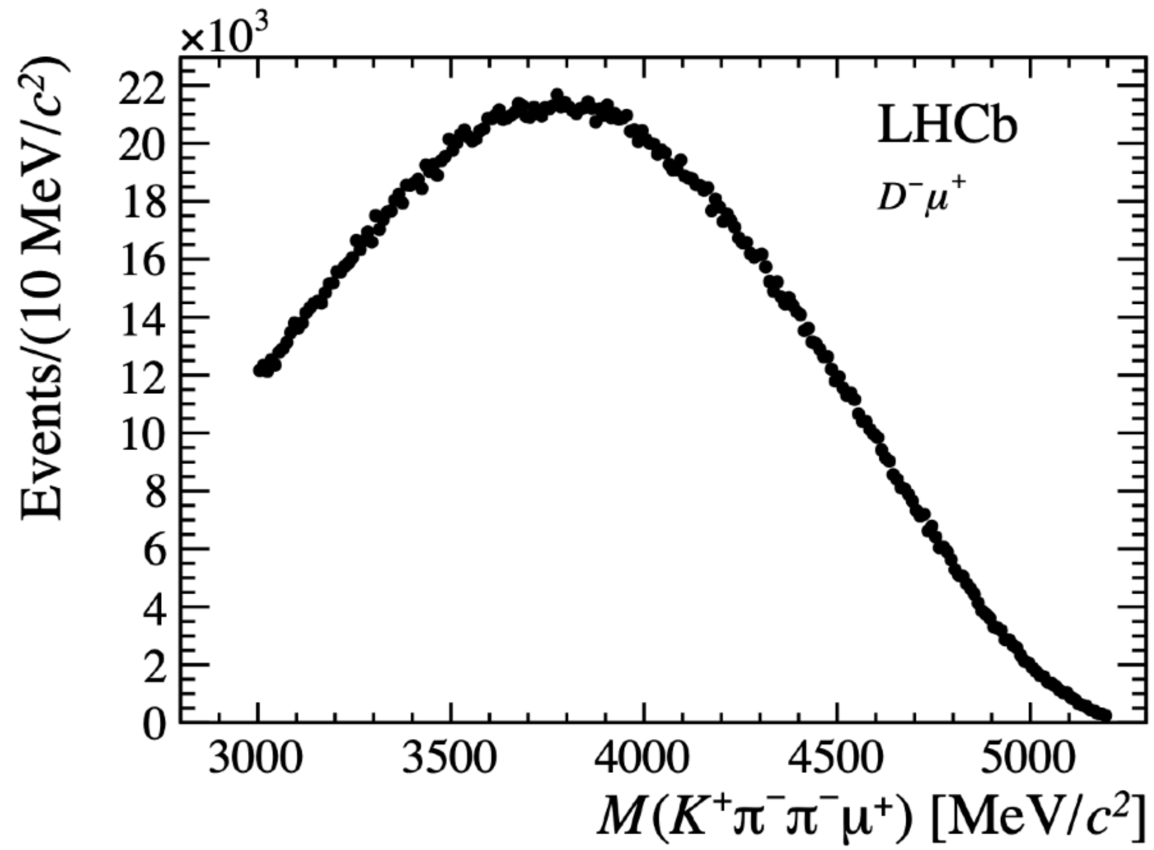
decay time resolution~45fs

JINST 14 (2019) P04013

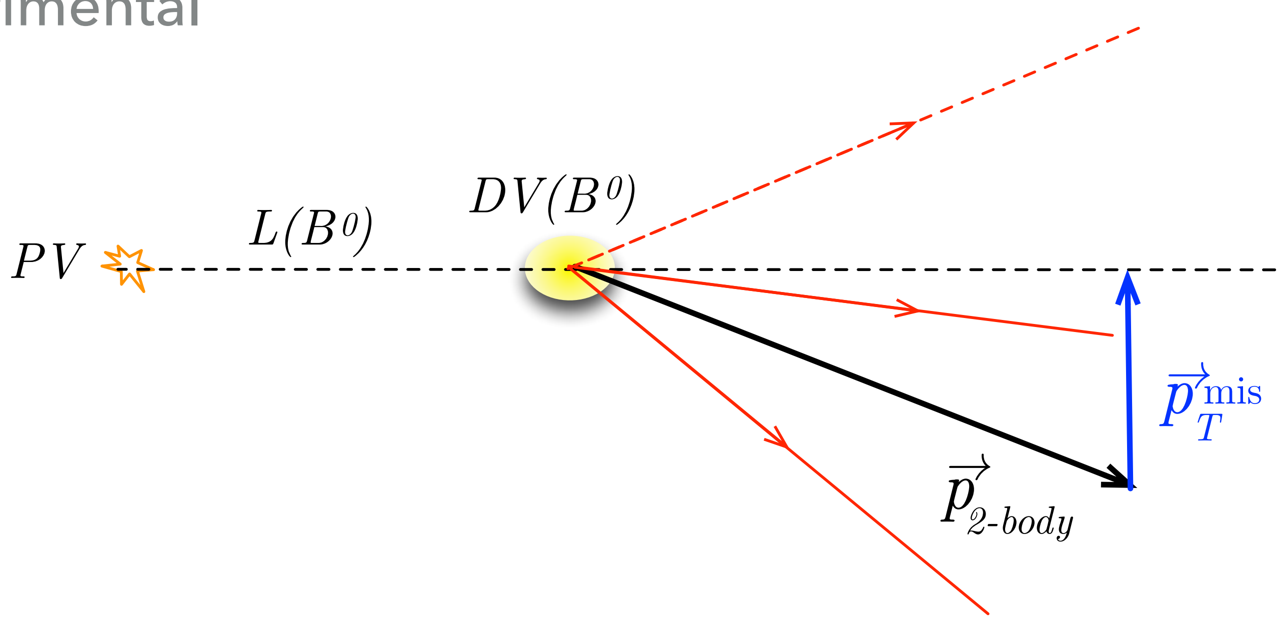
Techniques for semileptonic decays (@LHCb)

The fundamental problem: partial reconstruction

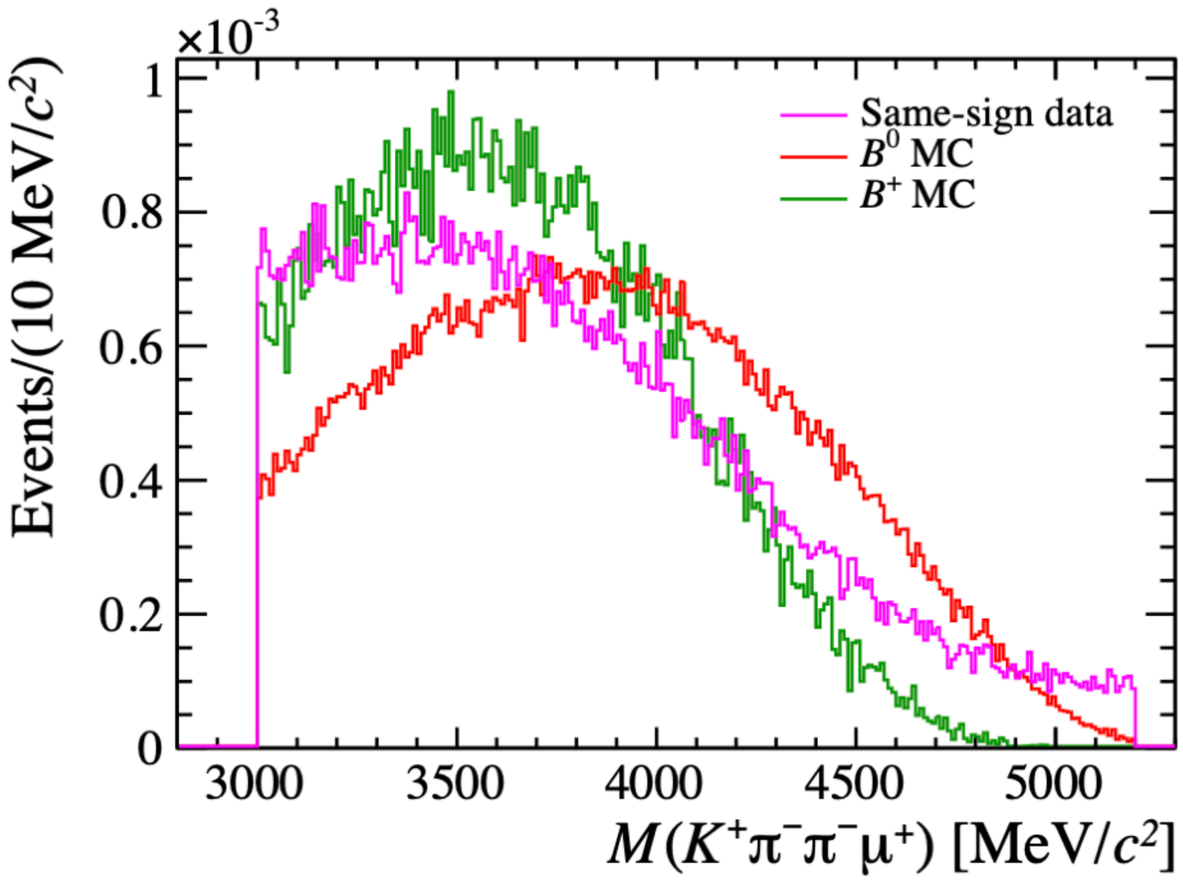


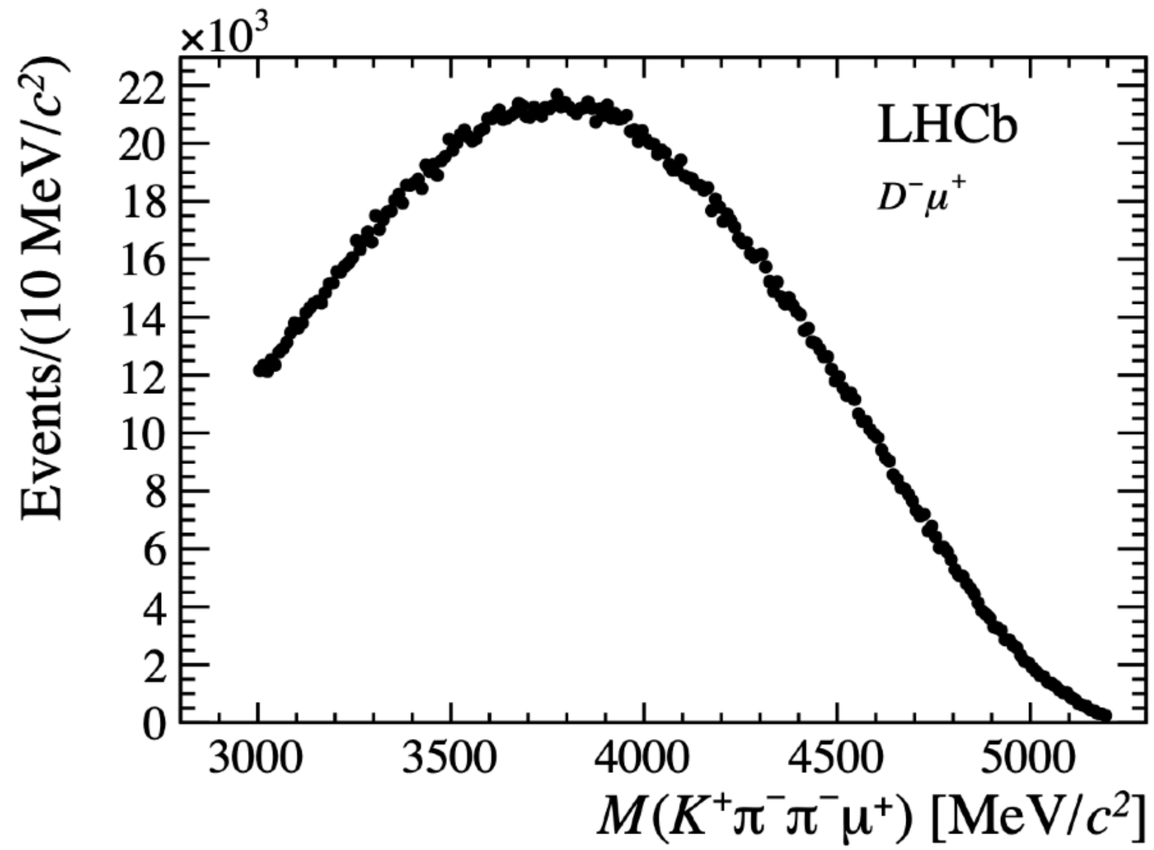


- The missing neutrino is the fundamental experimental problem with semileptonic decays (@LHCb)
- Cannot reconstruct the invariant mass of b-hadrons & the momentum of the b-hadron is underestimated

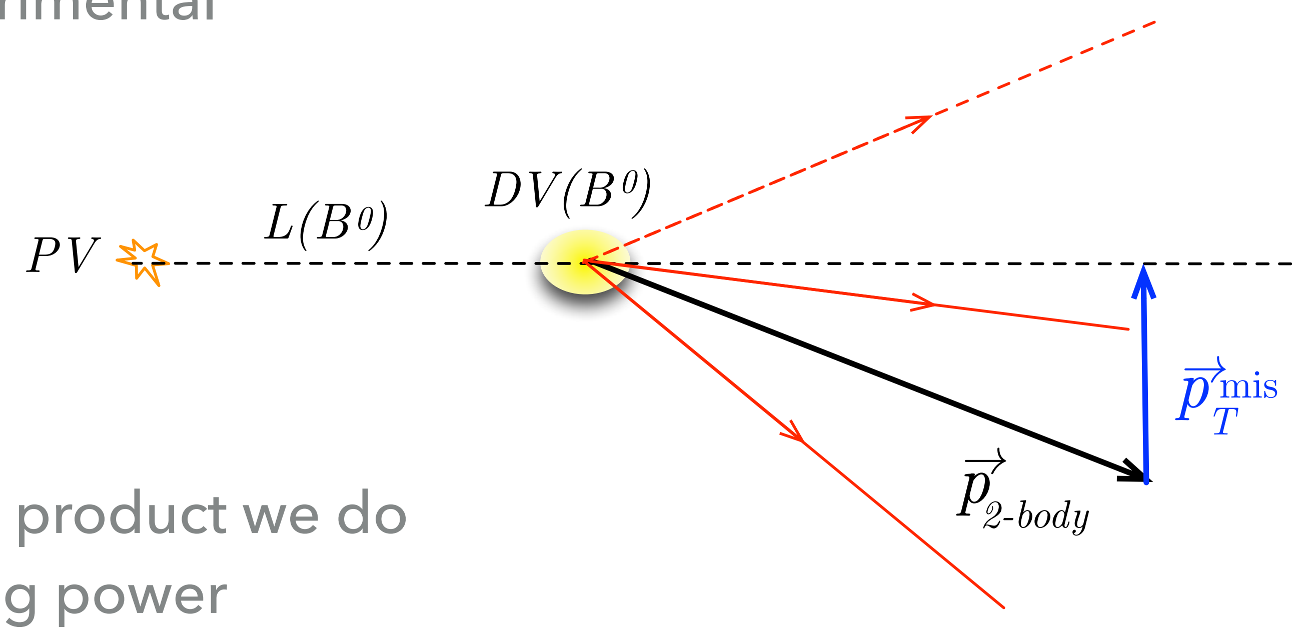


The fundamental problem: partial reconstruction





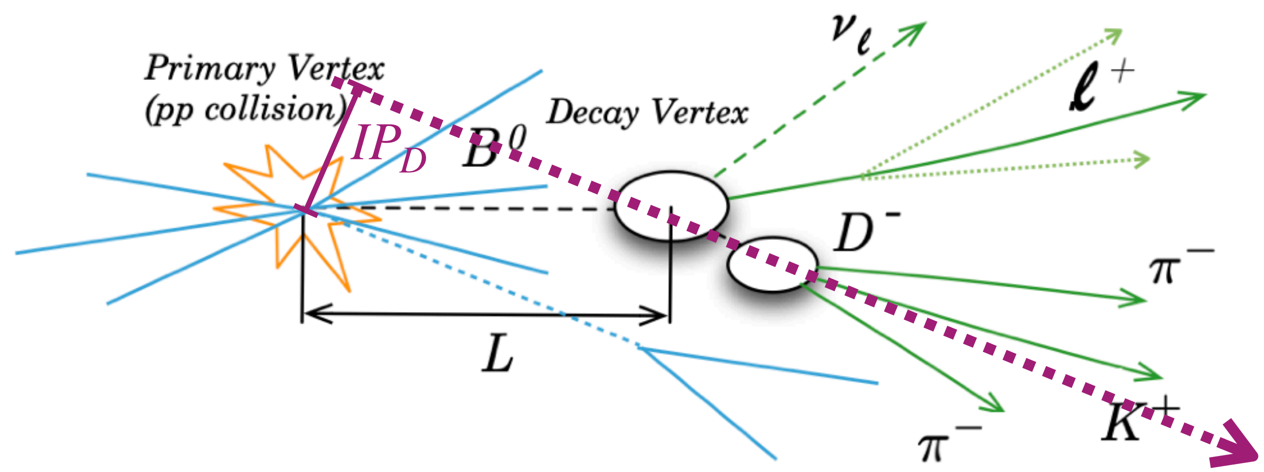
- The missing neutrino is the fundamental experimental problem with semileptonic decays (@LHCb)
- Cannot reconstruct the invariant mass of b-hadrons & the momentum of the b-hadron is underestimated
- The 'visible mass' (invariant mass of the decay product we do reconstruct) has poor signal/bkg discriminating power

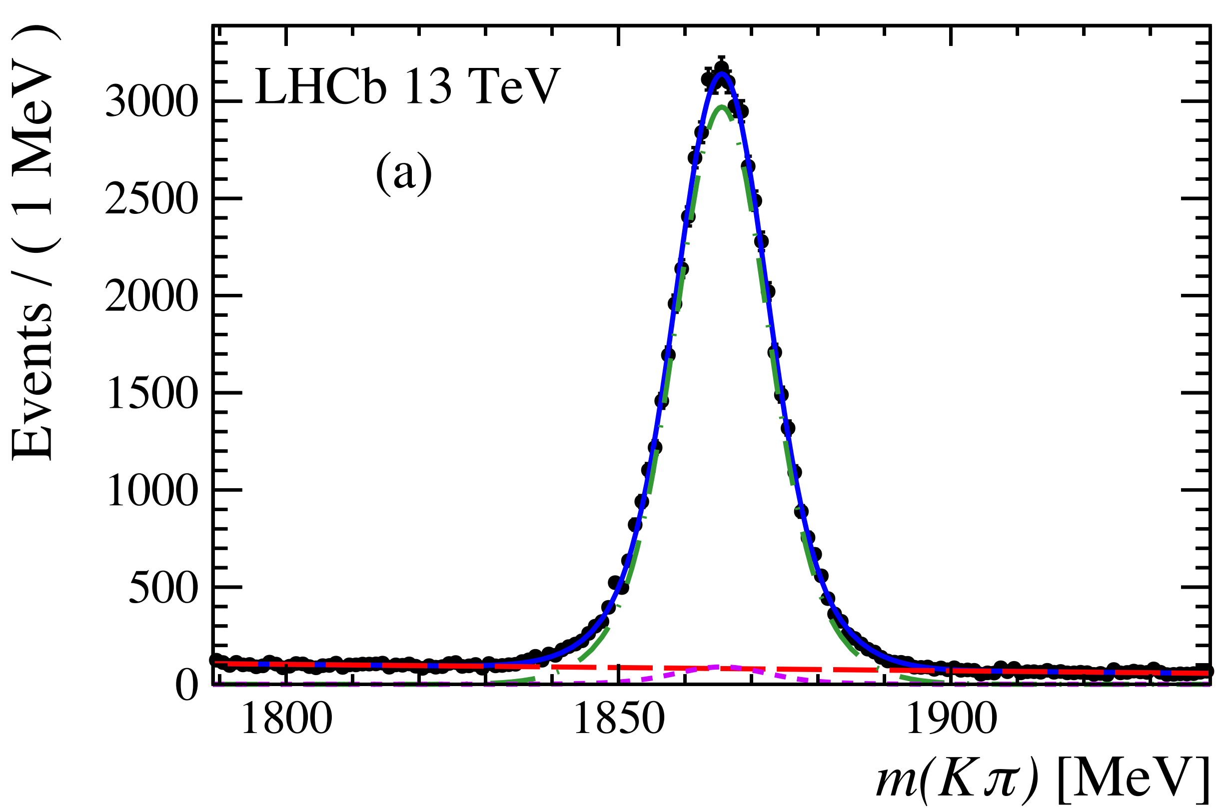


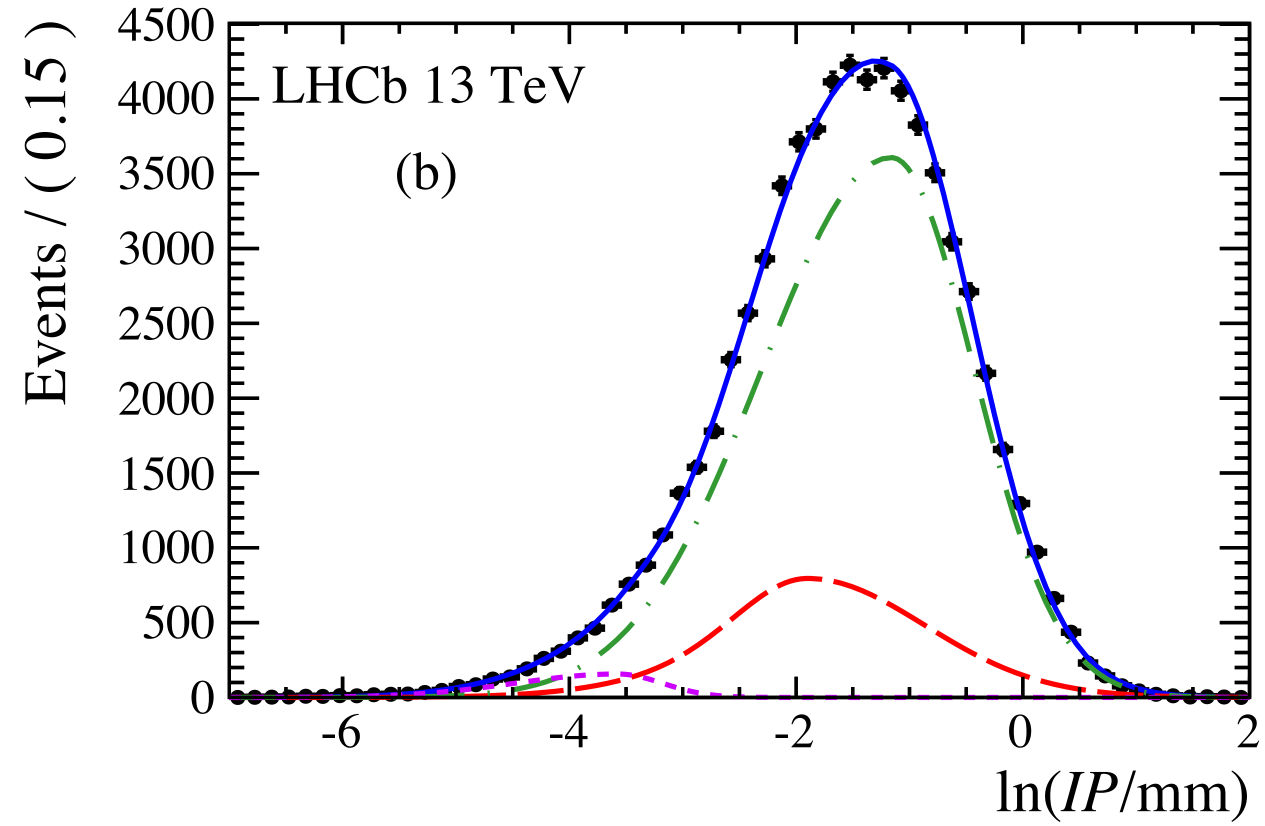
- Need approaches to (1) isolate the signal (2) get correct kinematics (within resolution)

Denial

- We may or may not need a B invariant mass like object, e.g. when studying $B \to D\mu\nu X$
  - Samples are signal dominated ($\mathscr{B}(B \to D\mu\nu X) \approx 10\,\%\,(|V_{cb}|)$)
  - Displaced muon
  - Clear D peak
- One can fit simultaneously $m(K^+\pi^-)$ and $log(IP_D)$ to separate the semileptonic decays from prompt charm

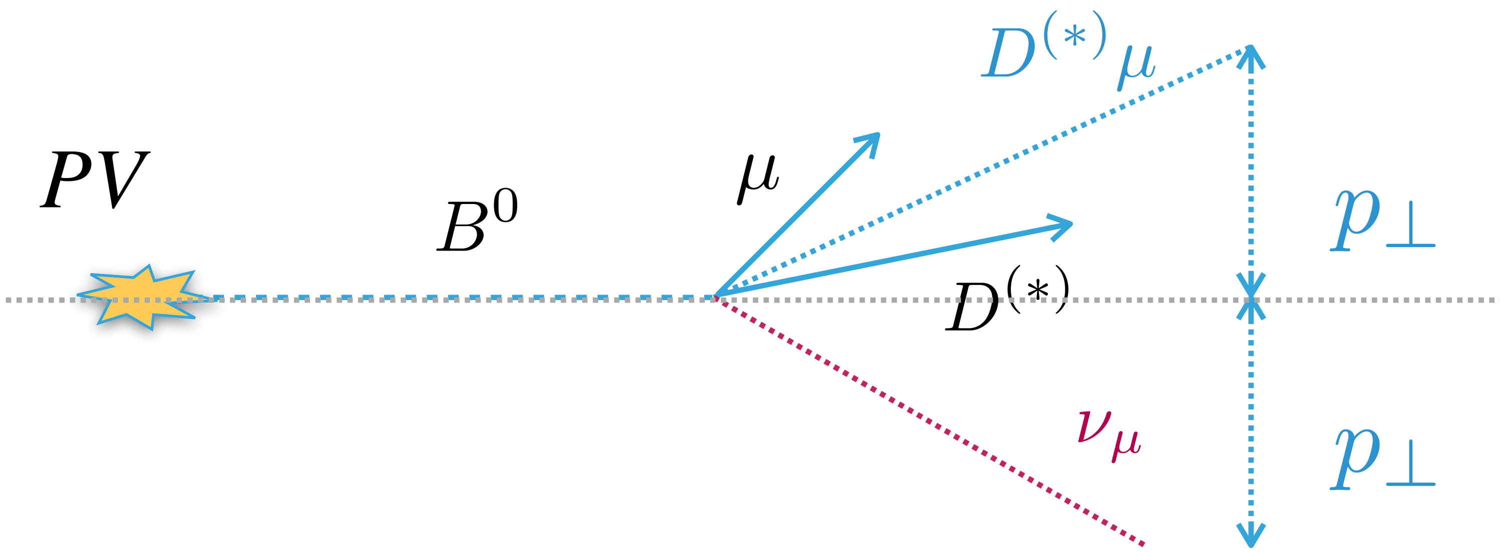






- Useful or not? - it depends on the analysis - no separation from other semileptonic b-hadron decays including $D\mu$ in the final state

Bargaining: use the (partial) information/make assumptions

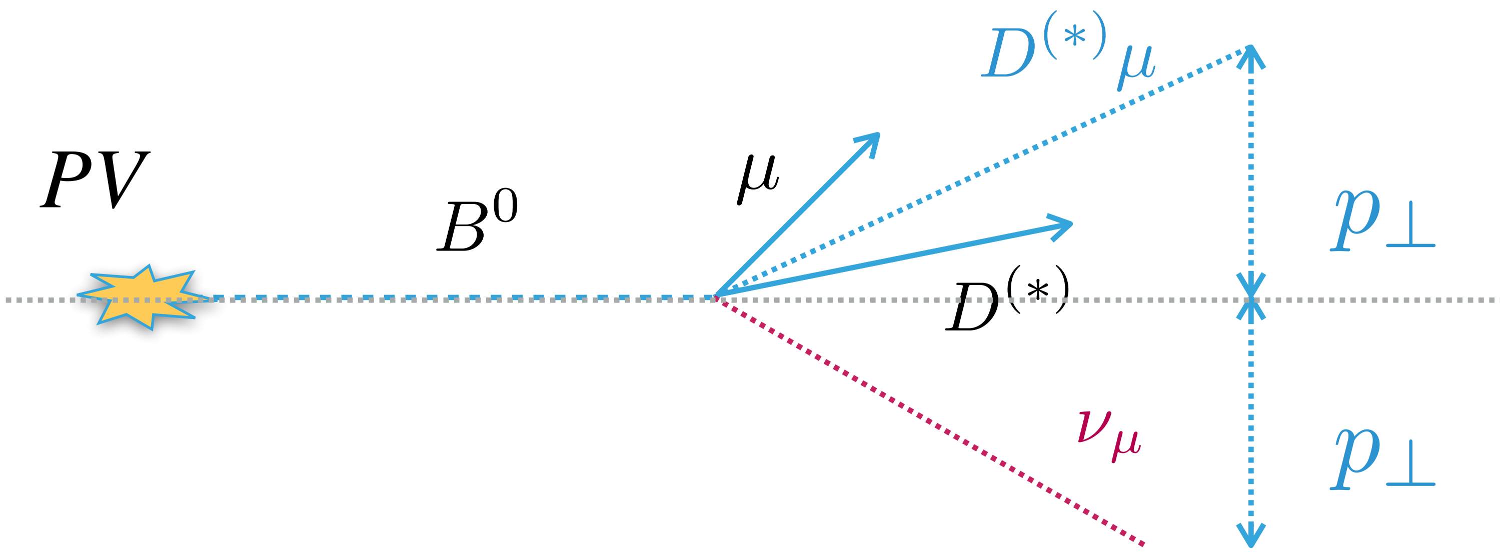


$$m_B^2 = (p_{vis} + p_\nu)^2$$
$$= m_{vis}^2 + m_\nu^2 + 2(p_{vis} \cdot p_\nu)$$
$$p_{vis} \cdot p_\nu = E_{vis}E_\nu - p_{\parallel vis}p_{\parallel \nu} - p_{\perp vis}p_{\perp \nu}$$
$$= E_{vis}E_\nu - p_{\parallel vis}p_{\parallel \nu} + p_\perp^2$$

$p_{\perp \nu} = -p_{\perp vis}$

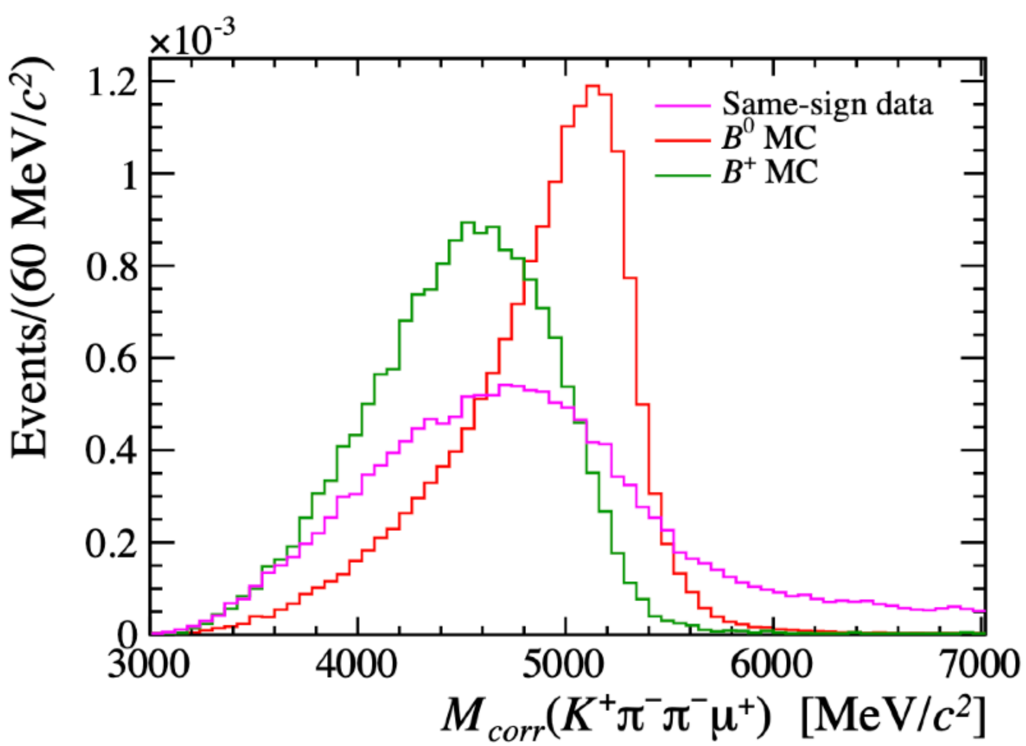
- We can make an assumption about the missing (parallel) component: $p_{\parallel \nu} = p_{\parallel vis}$
- $p_{vis} \cdot p_\nu$ s a Lorentz invariant: one can always boost along the flight direction, in a system where $p_{\parallel vis}$ vanishes
- $p_{vis} \cdot p_\nu = E_{vis} \cdot p_\perp + p_\perp^2 = \sqrt{m_{vis}^2 + p_\perp^2} \cdot p_\perp + p_\perp^2$

Bargaining: use the (partial) information/make assumptions



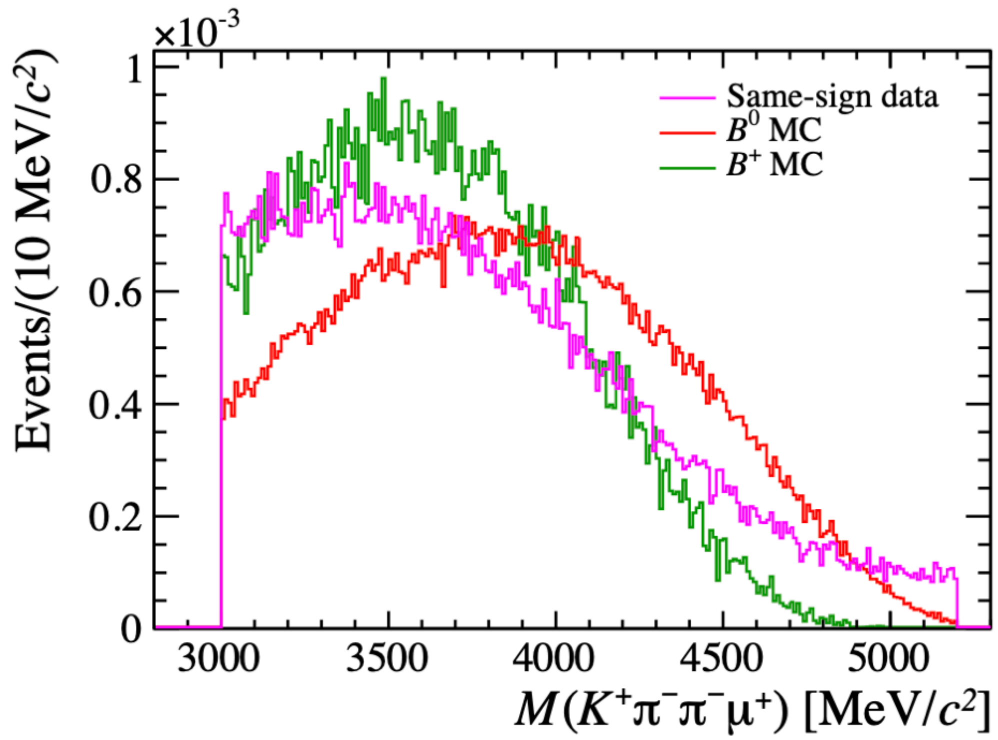
$$p_{vis} \cdot p_\nu = \sqrt{m_{vis}^2 + p_\perp^2} \cdot p_\perp + p_\perp^2$$

$$\begin{aligned} m_B^2 &= (p_{vis} + p_\nu)^2 \\ &= m_{vis}^2 + m_\nu^2 + 2(p_{vis} \cdot p_\nu) \\ &= m_{vis}^2 + 2\sqrt{m_{vis}^2 + p_\perp^2} \cdot p_\perp + 2p_\perp^2 \\ &= \left(\sqrt{m_{vis}^2 + p_\perp^2} + p_\perp\right)^2 \end{aligned}$$



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

Depression and acceptance



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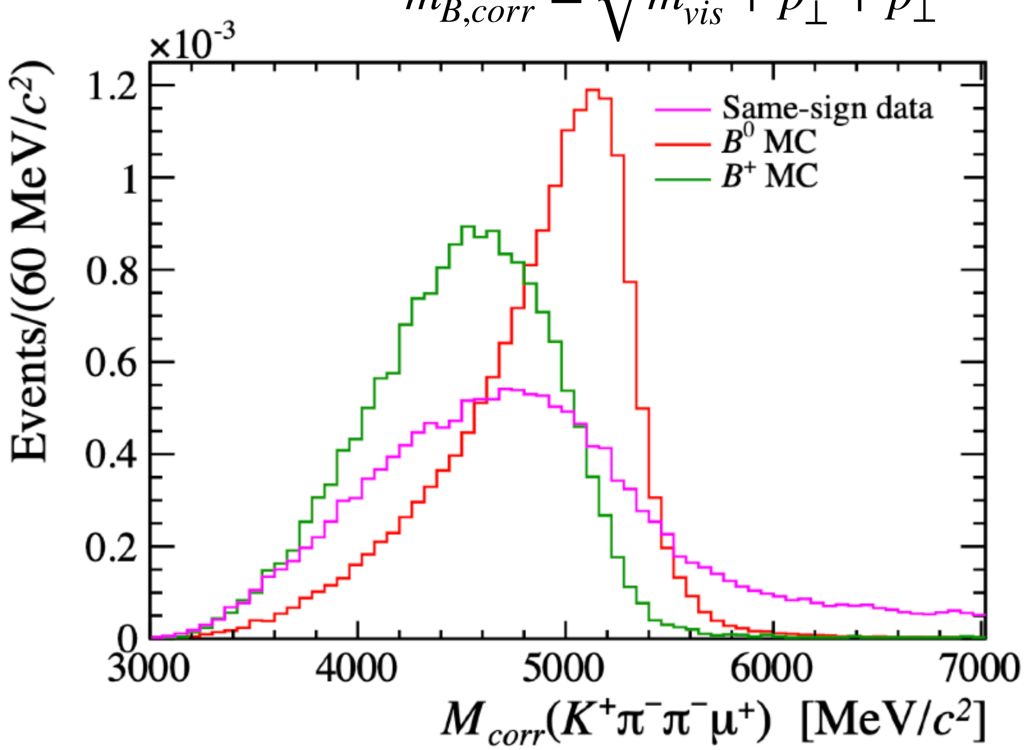
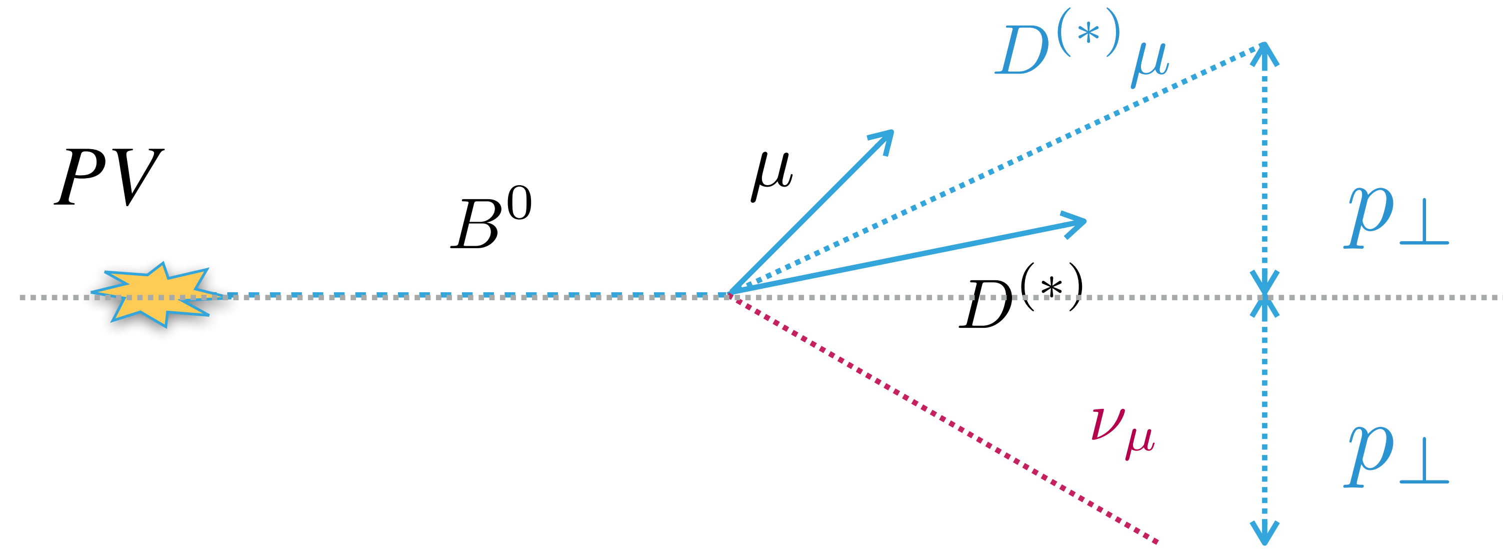
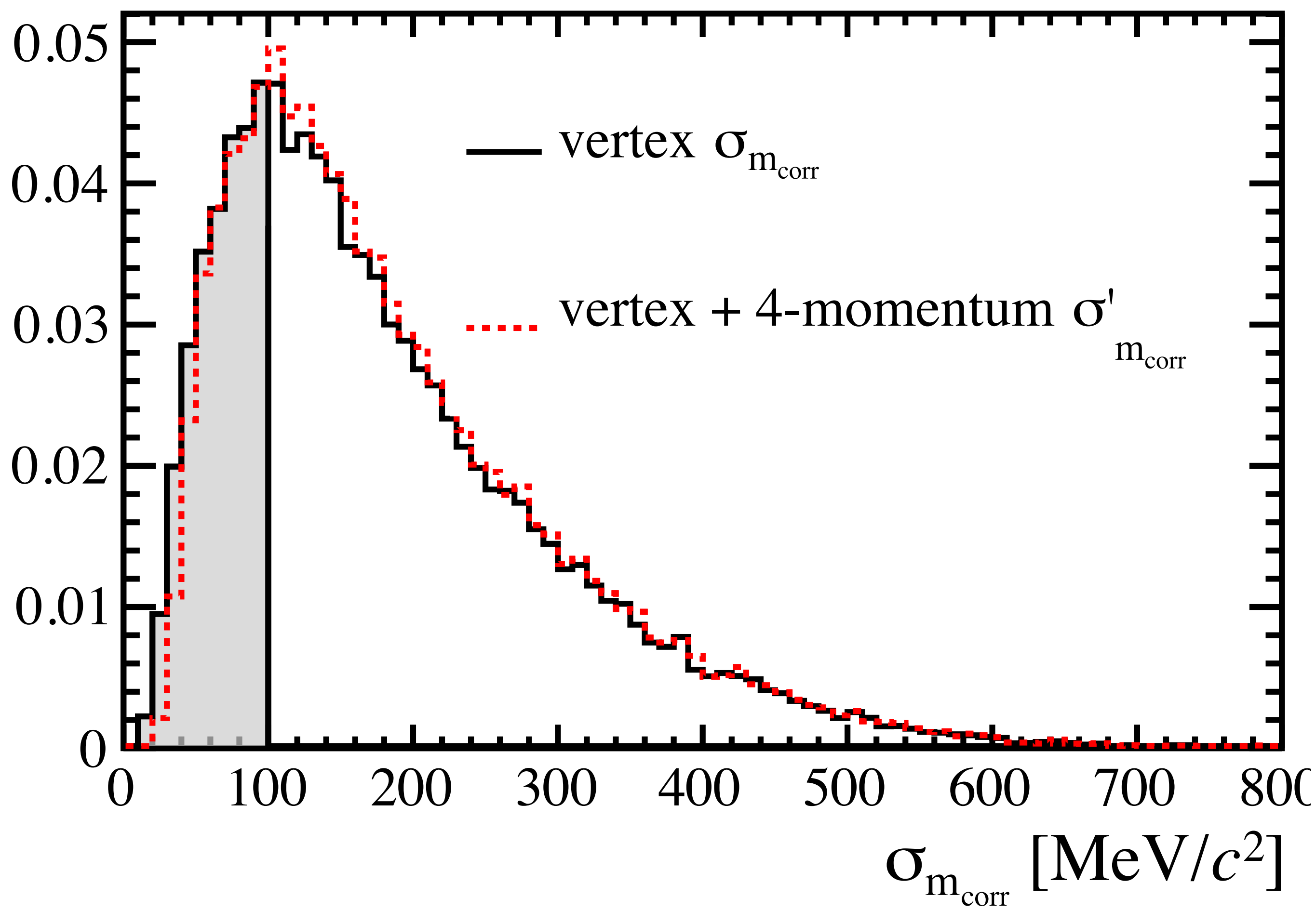
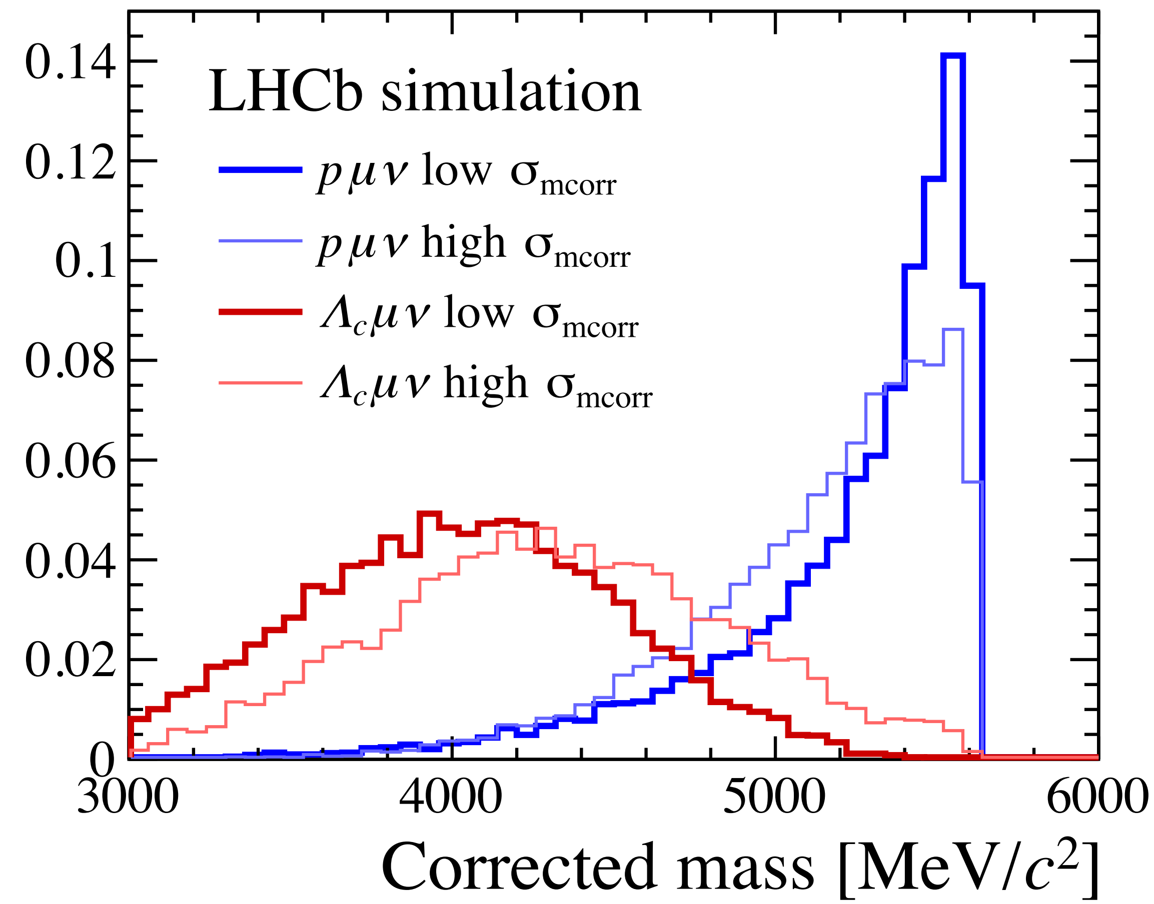




- The m_{corr} variables peaks at the nominal B mass (the case where, in the rest frame of the B, the visible system and the neutrino fly perpendicular to the flight direction).
- But it has a very long tail to lower masses
- This is a consequence of the assumption we made
- High-end of the spectrum: resolution effects
- One can define the corrected mass also for massive missing particles
- The width of the distribution depends on the available phase space

$\sigma(m_{corr})$





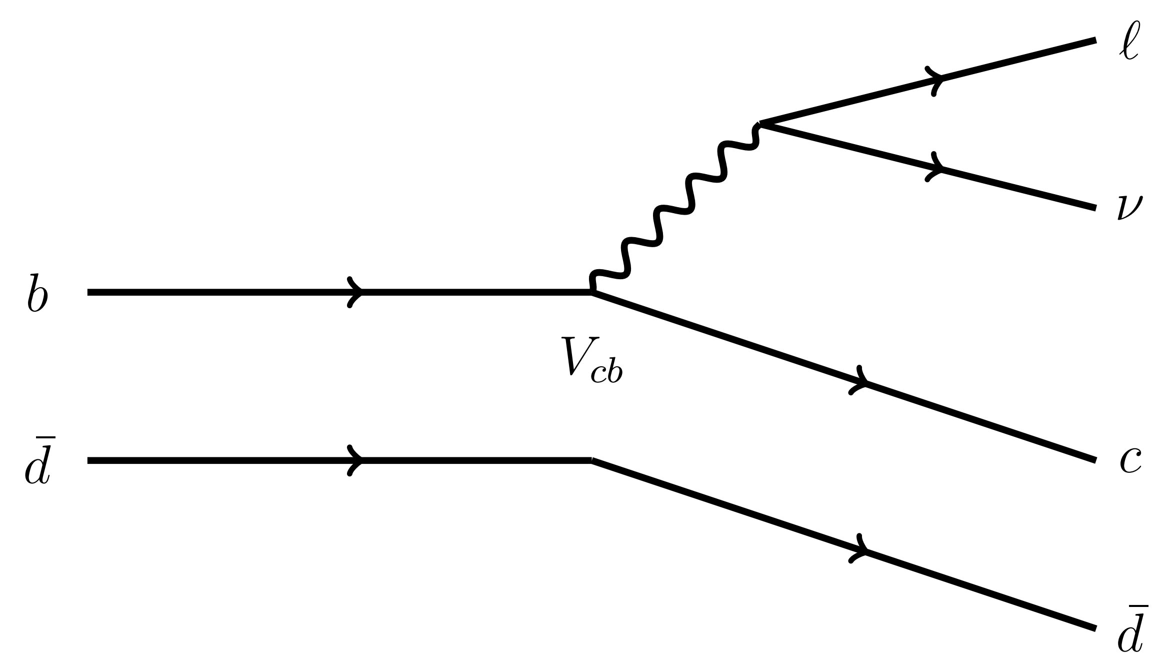
- One can calculate the expected error on m_{corr} (have fun with Jacobians)
  - As expected the error on secondary vertex dominates
- Select events with low $\sigma(m_{corr})$
  - Improves separation between signal and background, but greatly reduces event yield.

Getting the correct kinematics: q^2

- The corrected mass is constructed assuming $p_{\|\nu} = p_{\|vis}$ (only one quantity fixed)
- If we assume the nominal mass of the parent b-hadron, we can obtain $p_{\|\nu}$
- We can then calculate $q^2 =$ = squared invariant mass of the dilepton system = squared invariant mass of the virtual W
- The mass is a squared quantity (in energy-momentum conservation), one obtains two solutions (and only once is correct).

$$p_{\|} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a},$$

$$a = |2p_{\|,X_\mu} m_{X_\mu}|^2,$$
$$b = 4p_{\|,X_\mu}(2p_\perp p_{\|,,X_\mu} - m^2_{miss}),$$
$$c = 4p^2_\perp(p^2_{\|,X_\mu} + m^2_{\mathrm{B}^0_s}) - |m^2_{miss}|^2,$$
$$m^2_{miss} = m^2_{\mathrm{B}^0_s} - m^2_{X_\mu}.$$



q^2 : which solution to choose

- Randomly pick one?
- Or: experimentally one solution occurs more frequently than the other (due to the acceptance of the sub-detectors, selection criteria of the analysis…). One can choose this
- Or: Try to get an independent measure of the B momentum, and compare it with the two solutions. Pick the closest
- How to get an independent estimate: B momentum is correlated with flight length and angle wrt to beam axis → use a linear regression to predict B momentum

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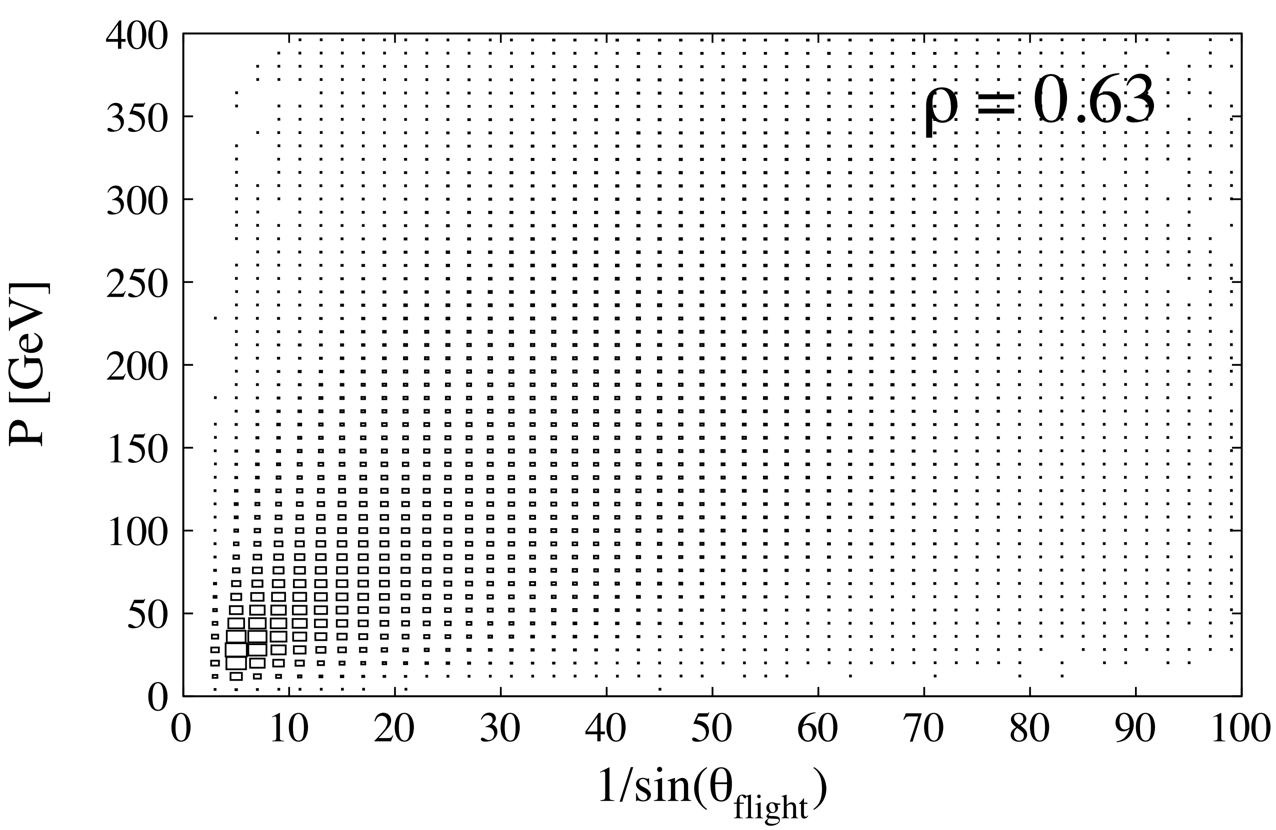

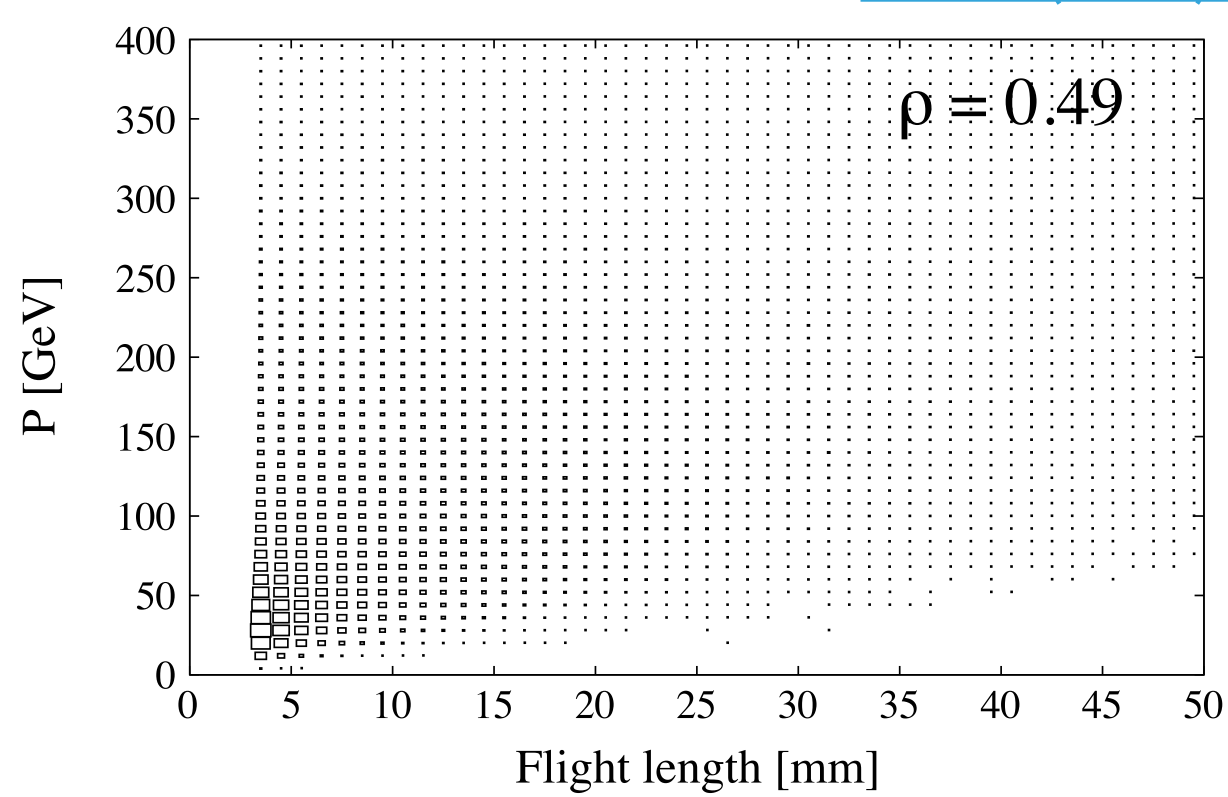

- Significantly better than random choice

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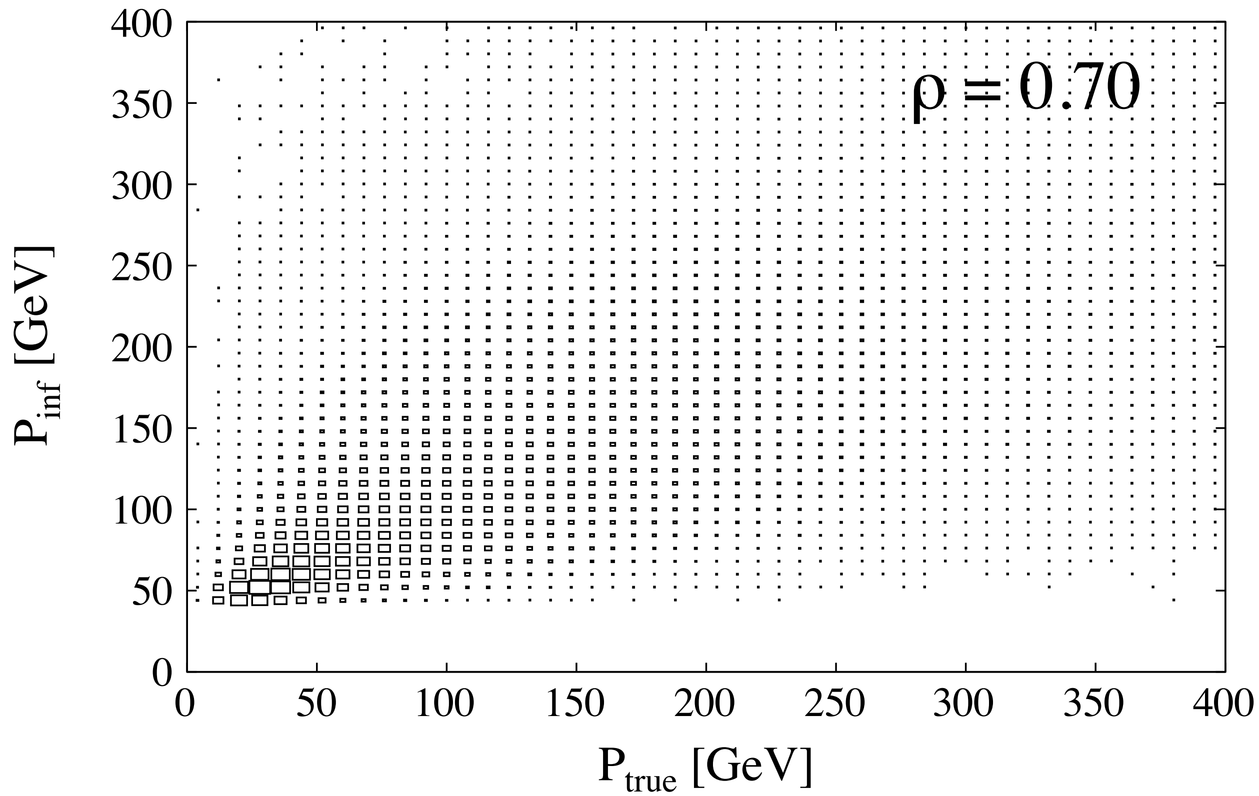

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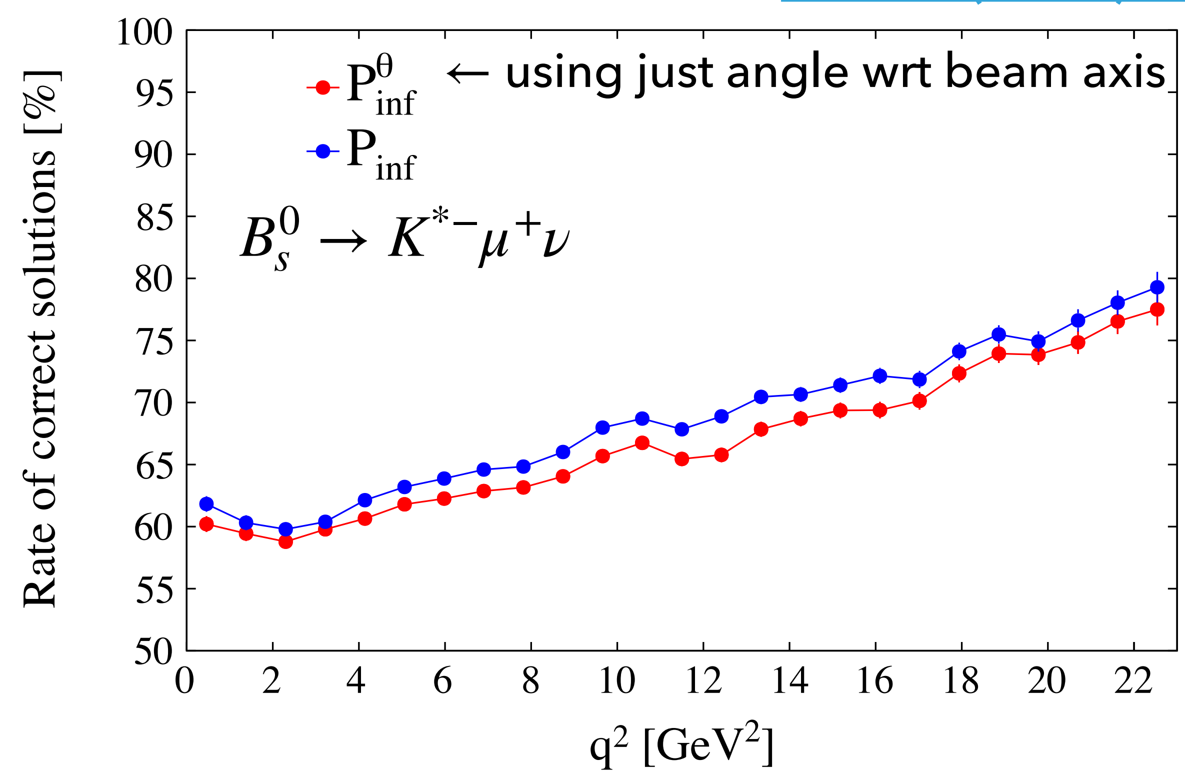

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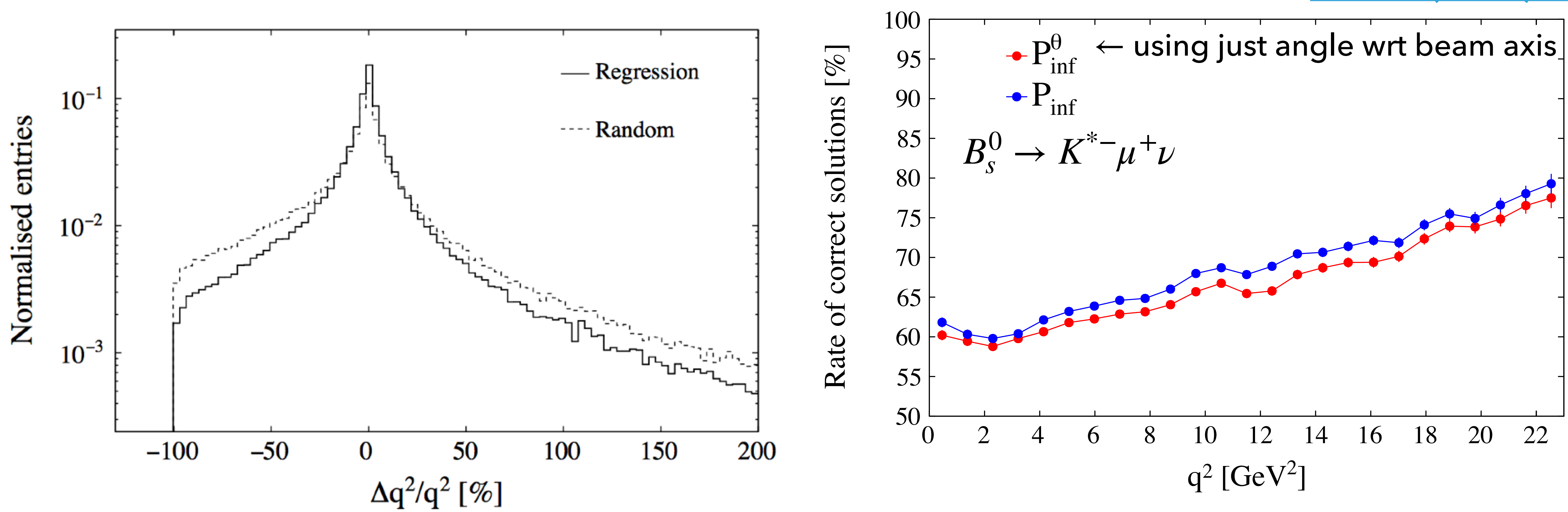

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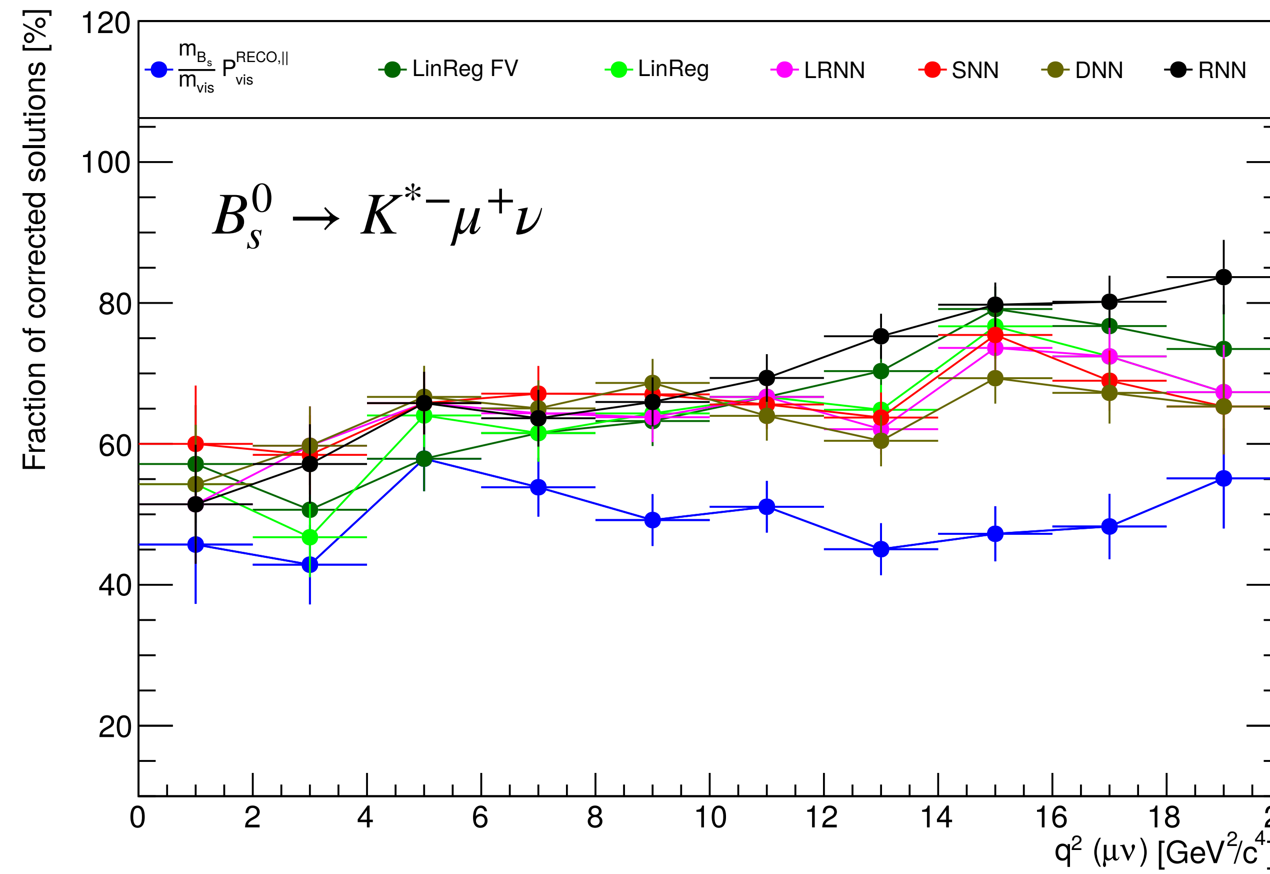
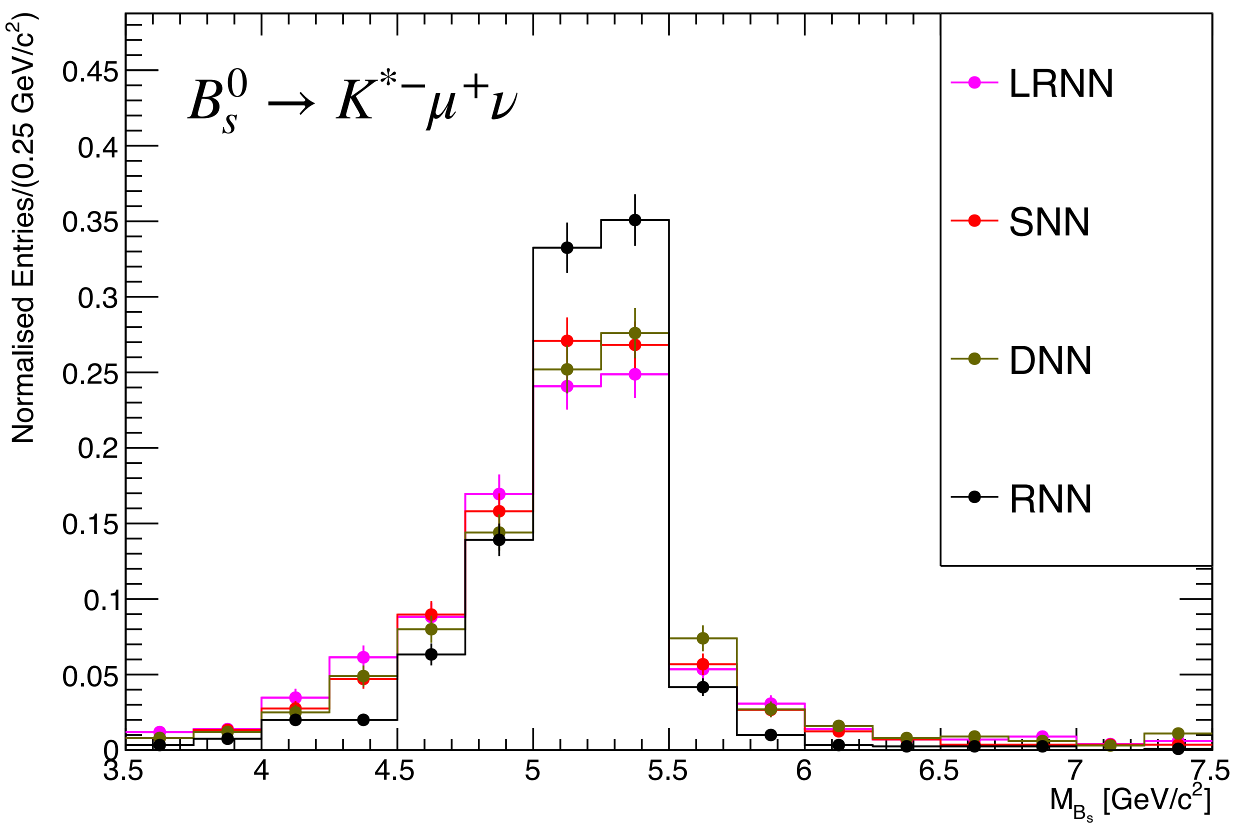
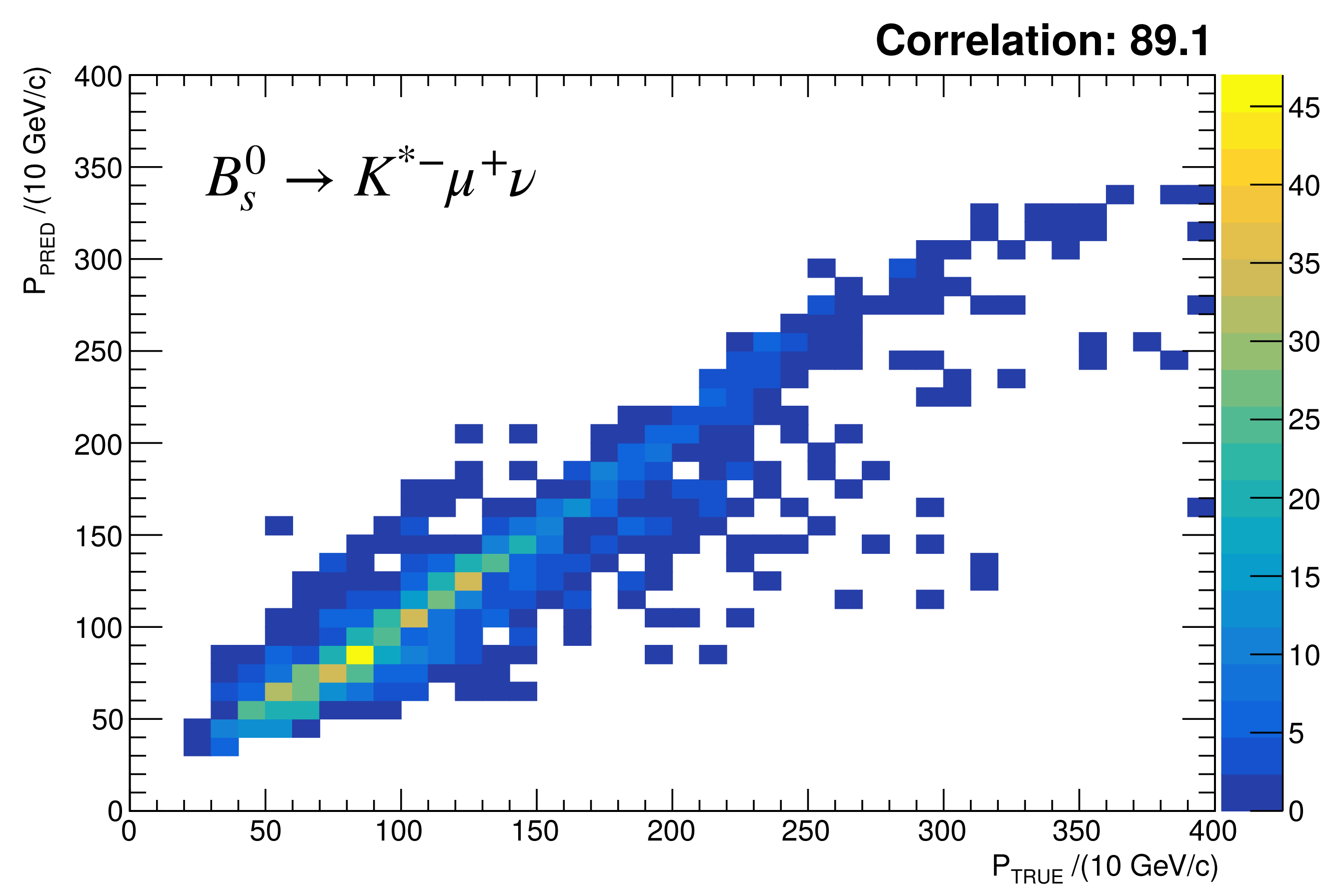
q^2 : DNNs?

- Using DNNs and training on specific decay mode works a bit better
- No silver bullet

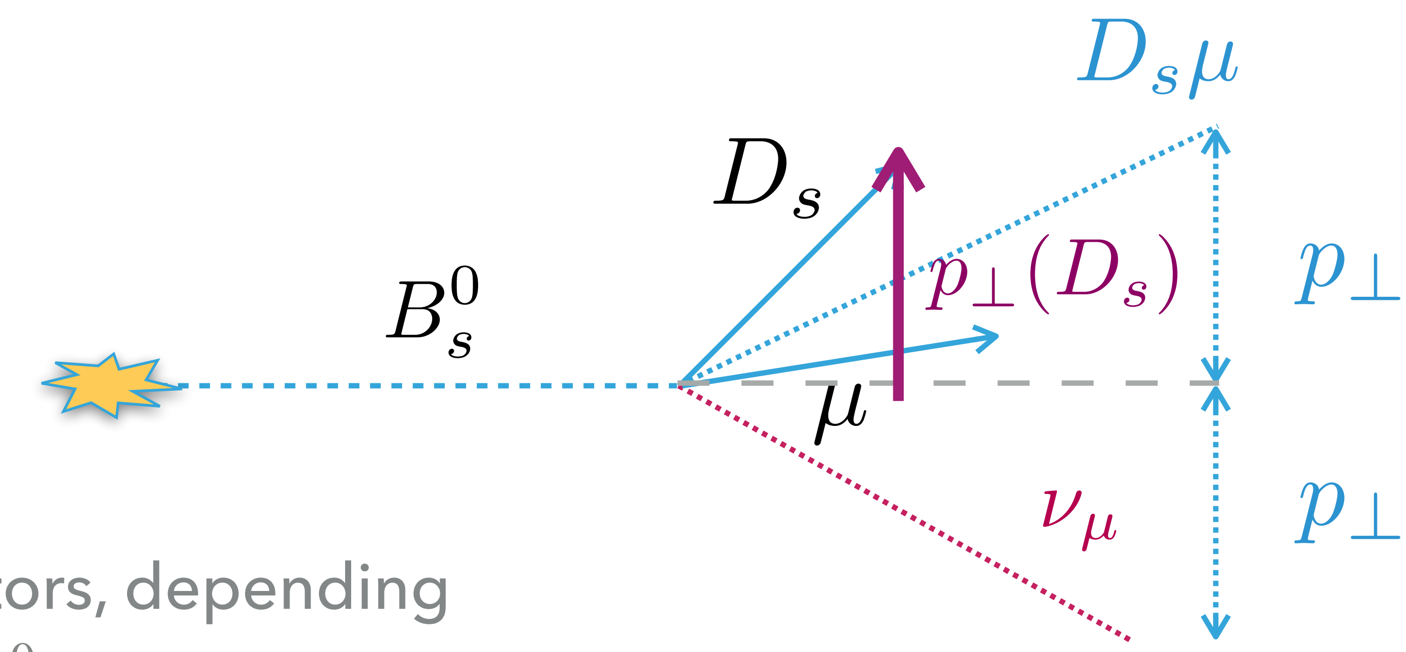


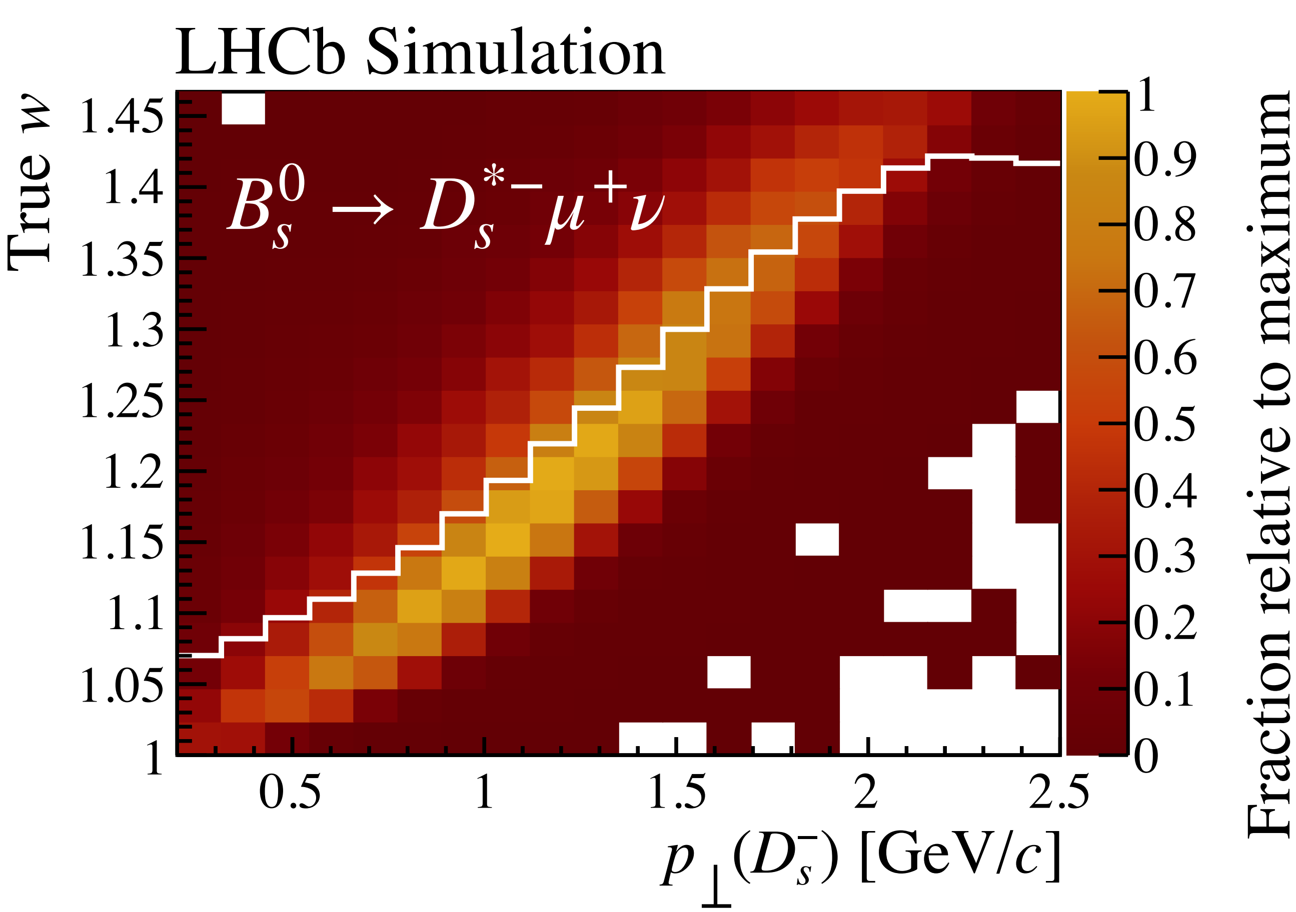


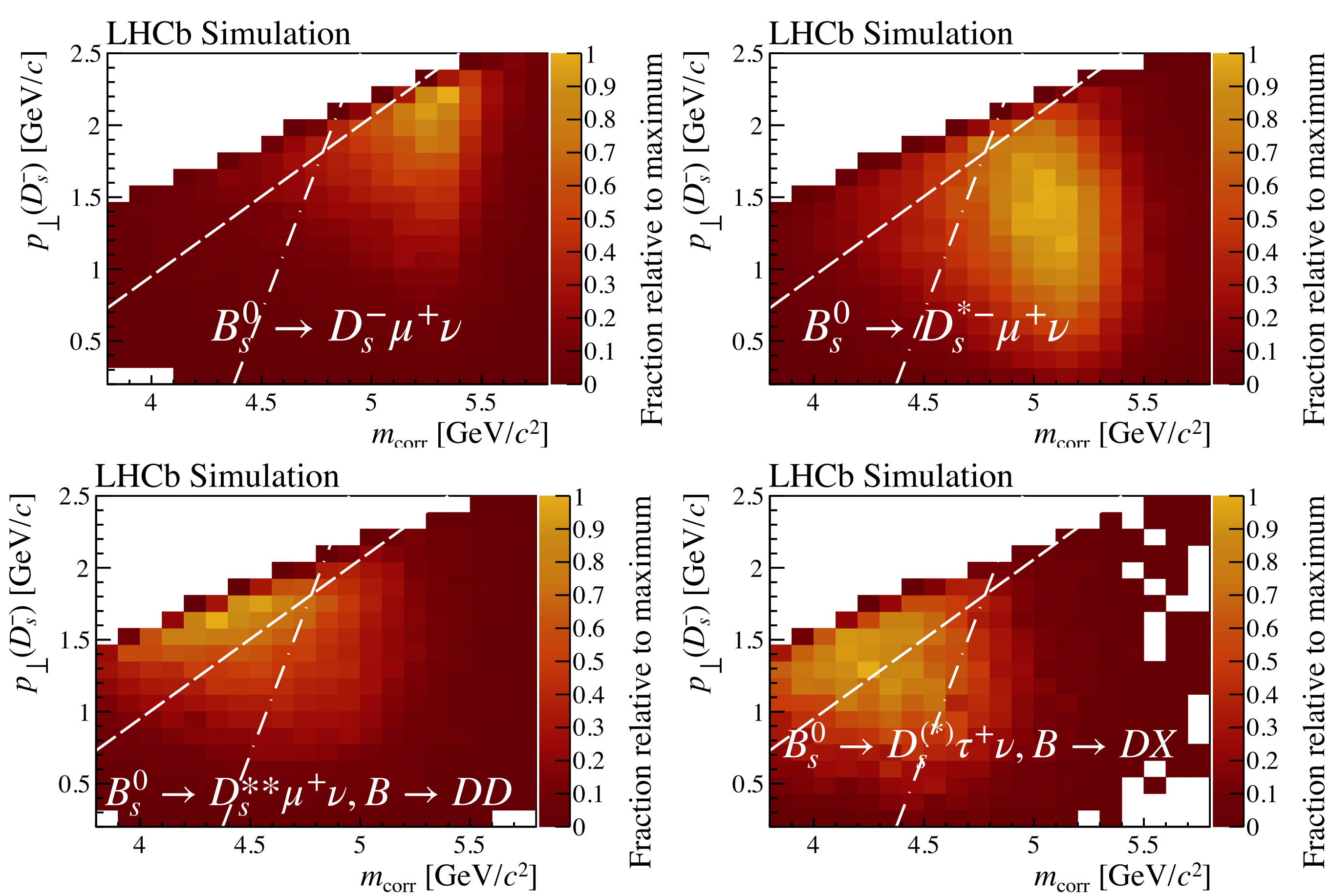


Other approaches: proxy variables

- $p_\perp(D_s)$: fully reconstructed and highly correlated with w (q^2)
- Useful, e.g. to extract $|V_{cb}|$ and hadronic form factors with B_s^0 decays
- Good sensitivity to the form factors, depending on w (energy of the $D_s^{(*)}$ in the B_s^0 rest frame)

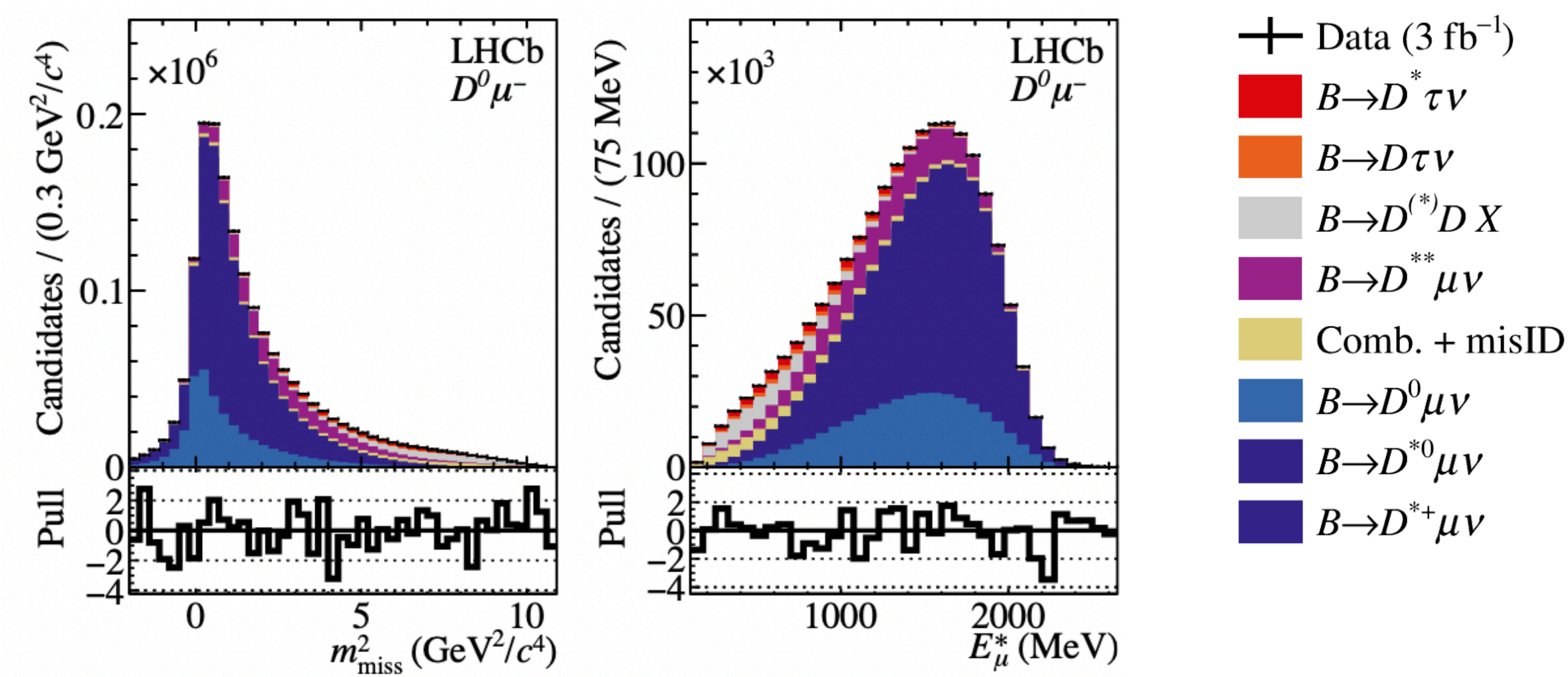






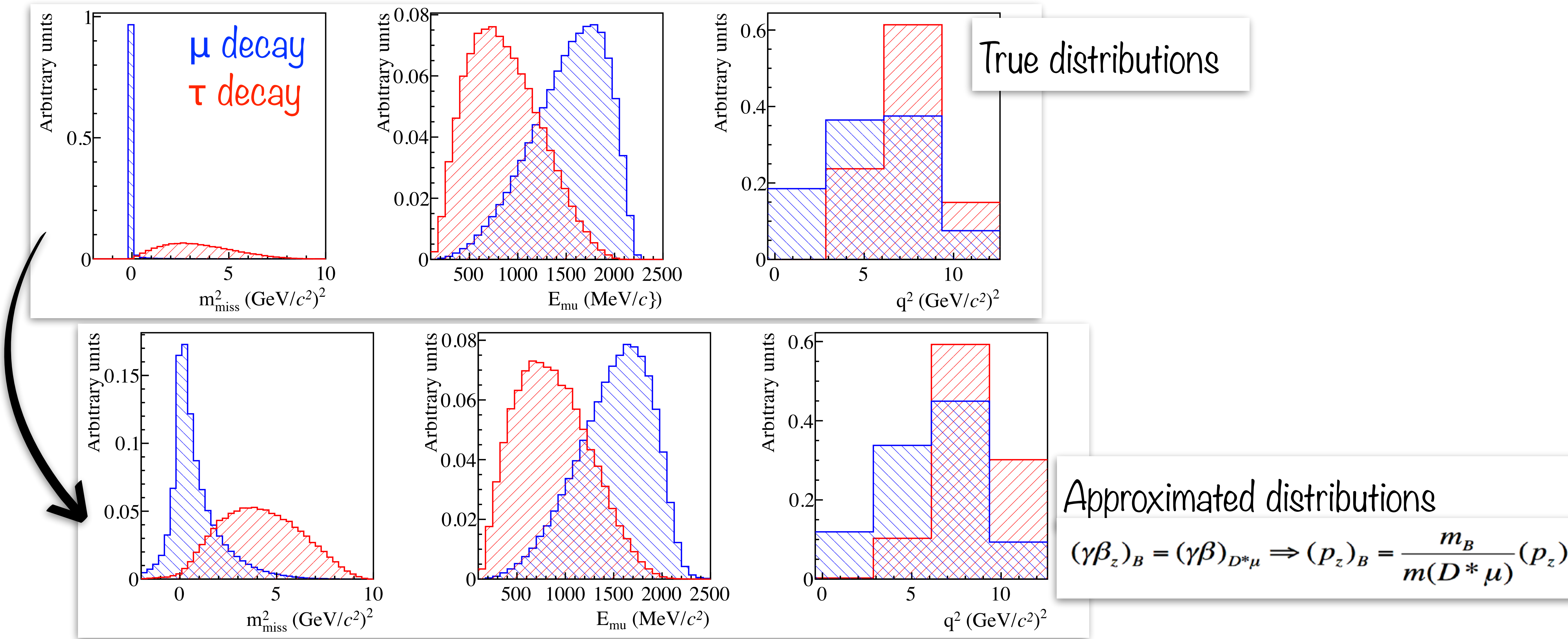
Other approaches: collinear approximation

- Other discriminating variables are often used: m^2_{miss}
- Approximate the B momentum with $p_{z,B} = \frac{m_B}{m_{vis}} \cdot p_{z,vis}$
- If only one neutrino missing, the distribution peaks at 0, otherwise higher values
- Also energy of the muon in the B rest frame is discriminating
- Note: m_{corr} and m^2_{miss} are highly correlated



Other approaches: collinear approximation

- Any approach you use to get the kinematics: you need to account for the resolutions, bin-to-bin migration (and their non-trivial dependences)
- Often used templated fits: let the MC tell you how your 'reconstructed' distribution is, given the physics model (using TRUE quantities) and the detector effects (which you measure and simulate)



- If you want to change physics model: need to re-weight in TRUE quantities…

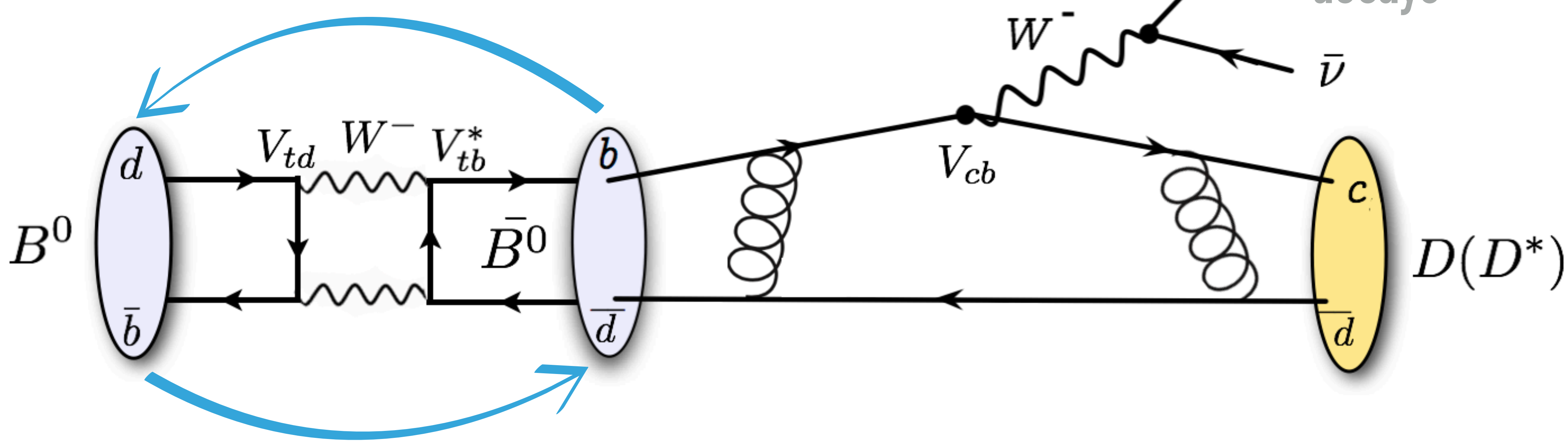
Other approaches: explicit case of modelling resolutions

Neutral mesons flavour oscillation parameters

$\mathcal{P}(\bar{B}\to B) \neq \mathcal{P}(B\to\bar{B})$

Flavour specific decays

Charge asymmetry



$$A_{\text{meas}}(t) = \frac{N(\mu^+,t) - N(\mu^-,t)}{N(\mu^+,t) + N(\mu^-,t)}$$

$$= \frac{a_{\text{sl}}^d}{2} - \left(A_P^d + \frac{a_{\text{sl}}^d}{2}\right)\frac{\cos(\Delta m_d t)}{\cosh(\Delta\Gamma_d t)} + A_D$$

CP-Violation

$$a_{\text{sl}} = a = 1 - \left|\frac{q}{p}\right|$$

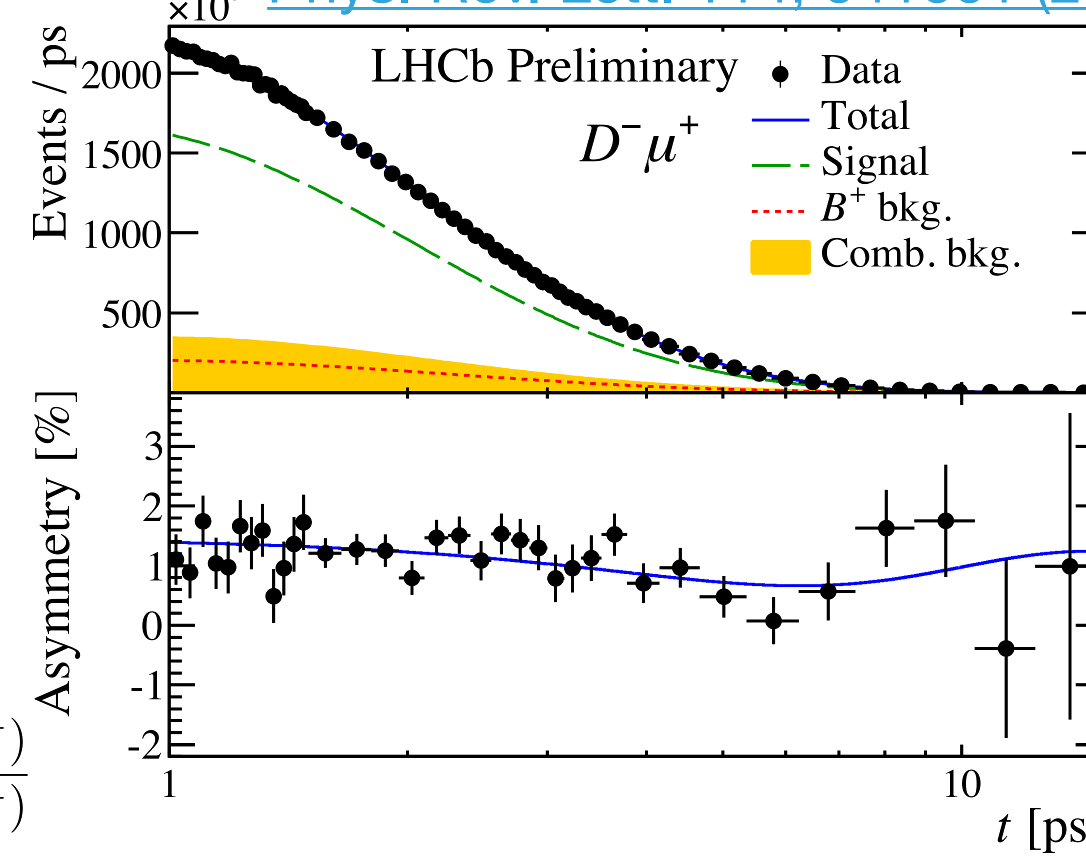
Production

$$A_P = \frac{\sigma(\bar{B}) - \sigma(B)}{\sigma(\bar{B}) + \sigma(B)}$$

Detection

$$A_D = \frac{\epsilon(\mu^+K^+\pi^-\pi^-) - \epsilon(\mu^-K^-\pi^+\pi^+)}{\epsilon(\mu^+K^+\pi^-\pi^-) + \epsilon(\mu^-K^-\pi^+\pi^+)}$$

[Phys. Rev. Lett. 114, 041601 (2015)]



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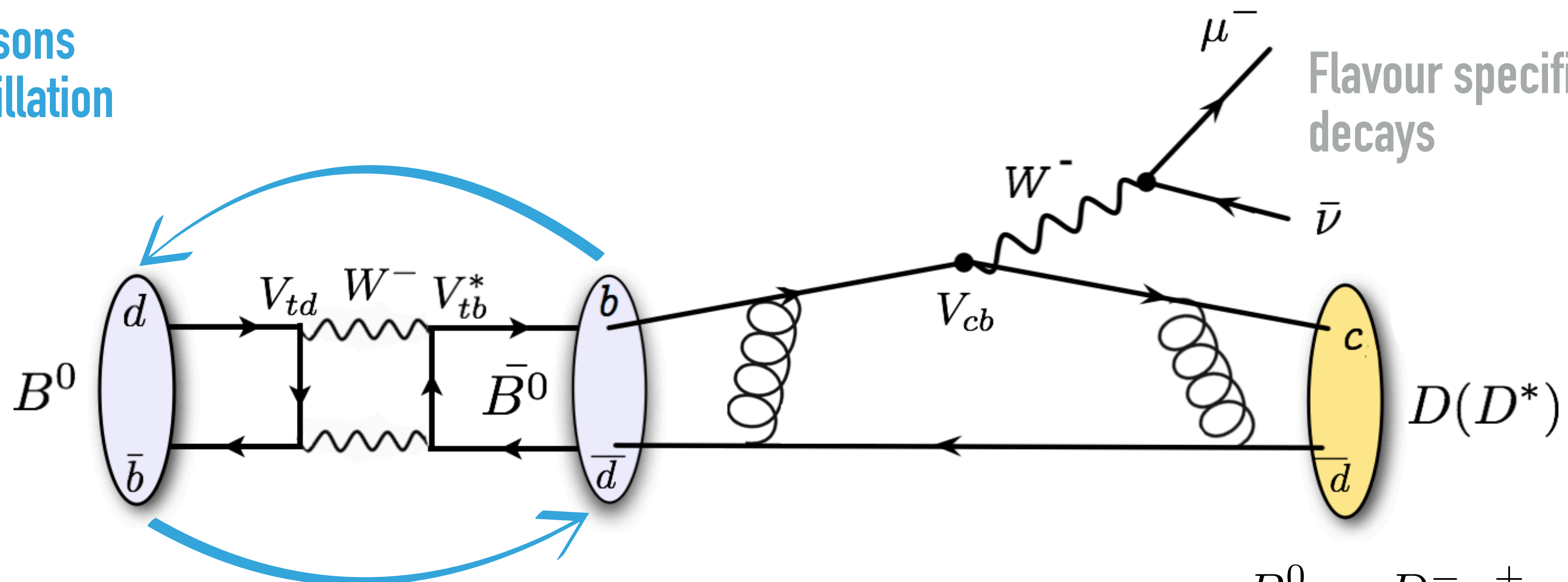
Charge asymmetry

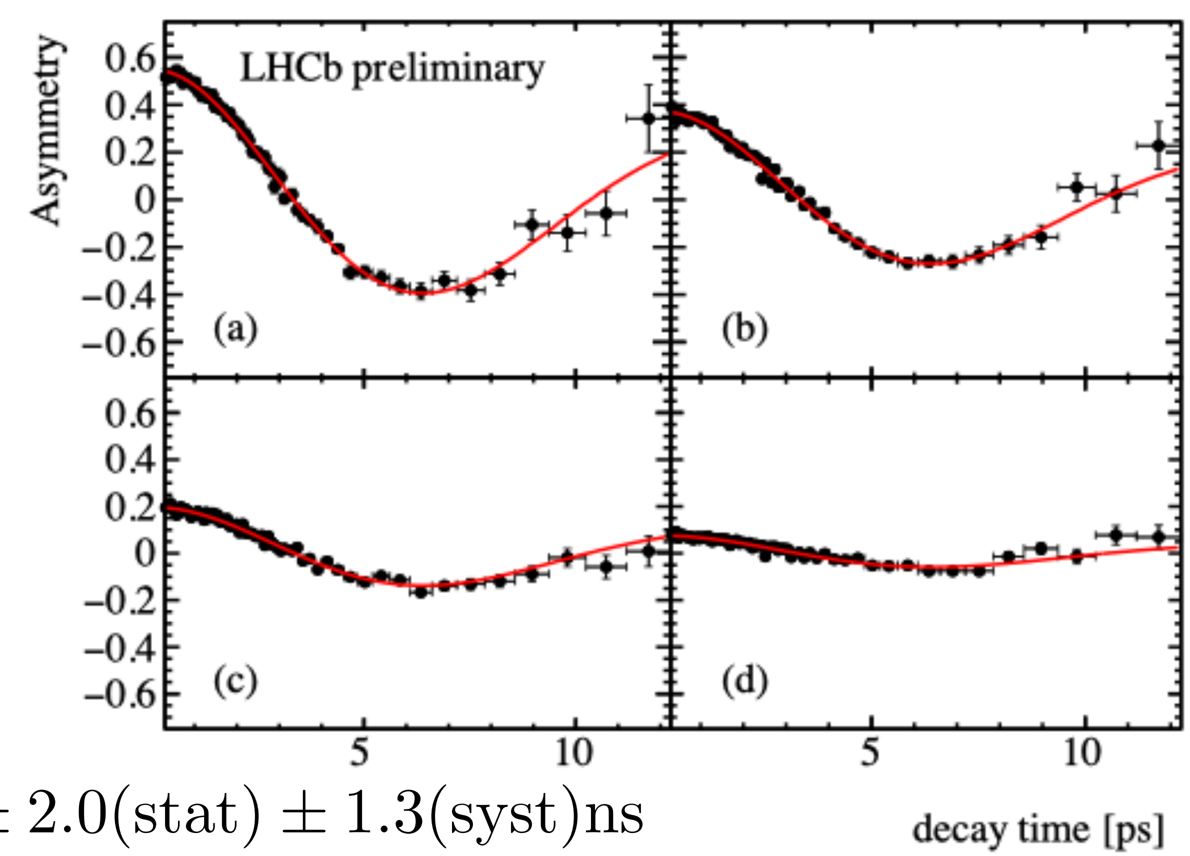
Flavour specific decays



$B^0 \to D^- \mu^+ \nu_\mu X$

$$A(t) = \frac{N^{not\ osc}(t) - N^{osc}(t)}{N^{not\ osc}(t) + N^{osc}(t)} = \cos(\Delta m_d t)$$

Oscillation frequency



$\Delta m_d = 503.6 \pm 2.0(\text{stat}) \pm 1.3(\text{syst})\text{ns}$

Other approaches: case of neutral meson mixing

- For decay-time dependent measurements

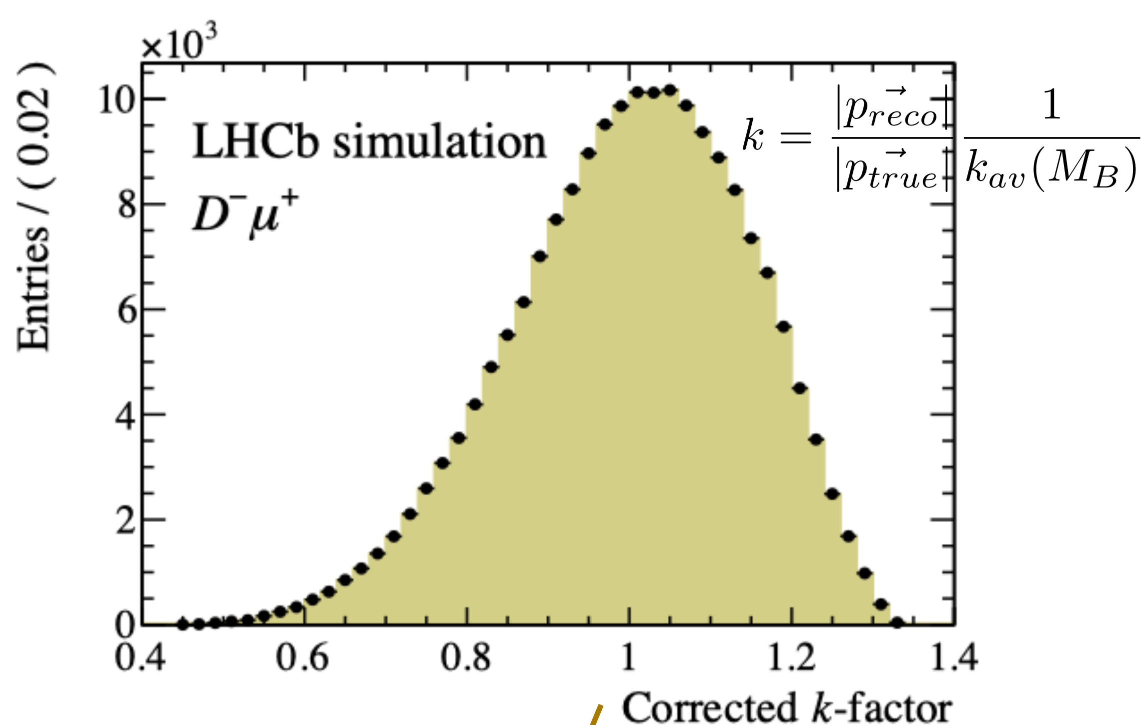
$$T(f, t_{true}) = N\mathrm{e}^{-\Gamma_d t_{true}} \left[1 + A_D + \frac{a_{\mathrm{sl}}^d}{2} - \left(A_P + \frac{a_{\mathrm{sl}}^d}{2}\right)\cos \Delta m t_{true}\right]$$

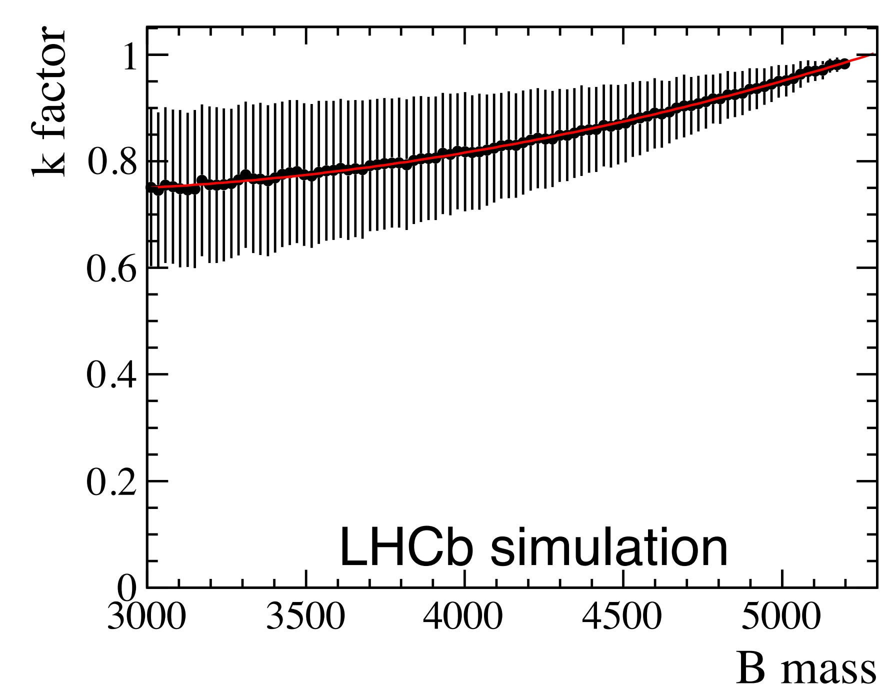
- The B decay time is corrected using the factor (from Monte Carlo):

$$k = p_{reco}/p_{true}$$

- The k-factors are also used to model the decay time resolution

$$t = \frac{L \cdot M_{PDG}}{|\vec{p}|} \cdot k_{av}(M)$$



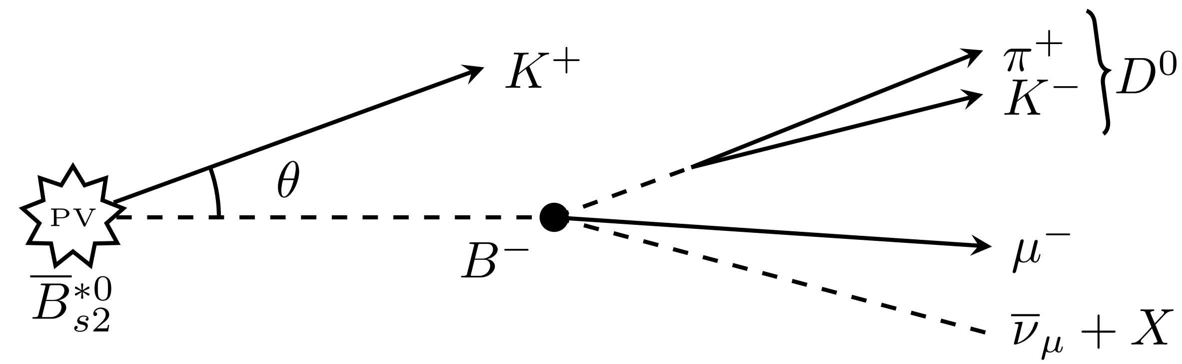


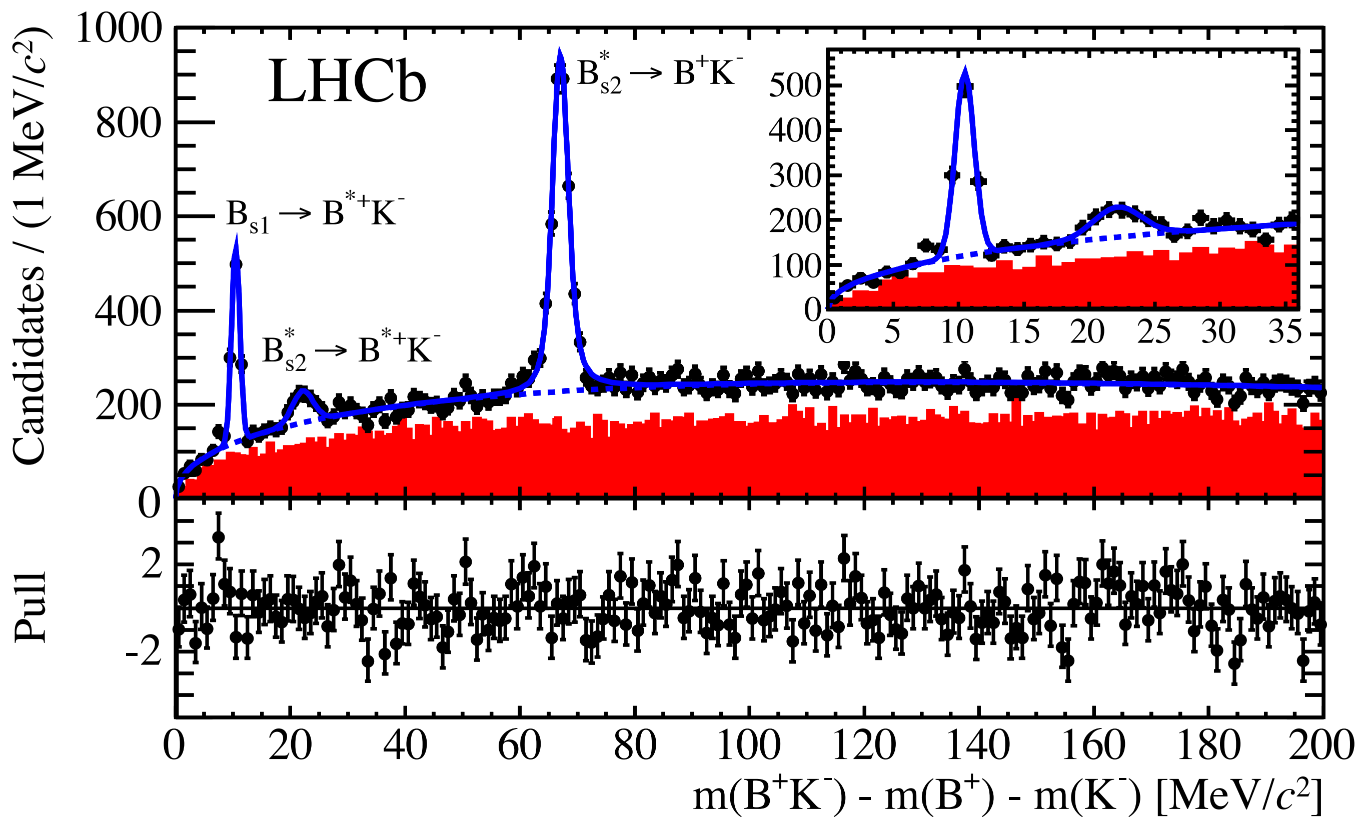
"L resolution"

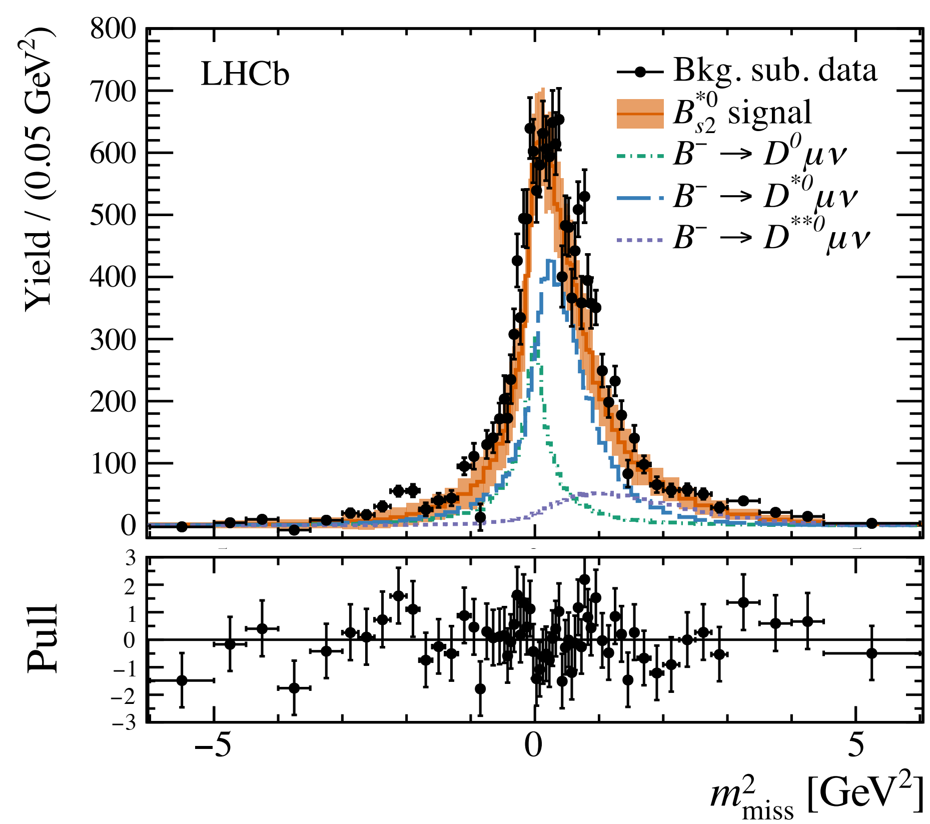
$$\mathcal{P}_{sig} = \boxed{(T(t) \otimes_t R(t) \otimes_k F(k))} \cdot A(t)$$

Other approaches: using $B^*_{s2} \to B^+K^-$ decays

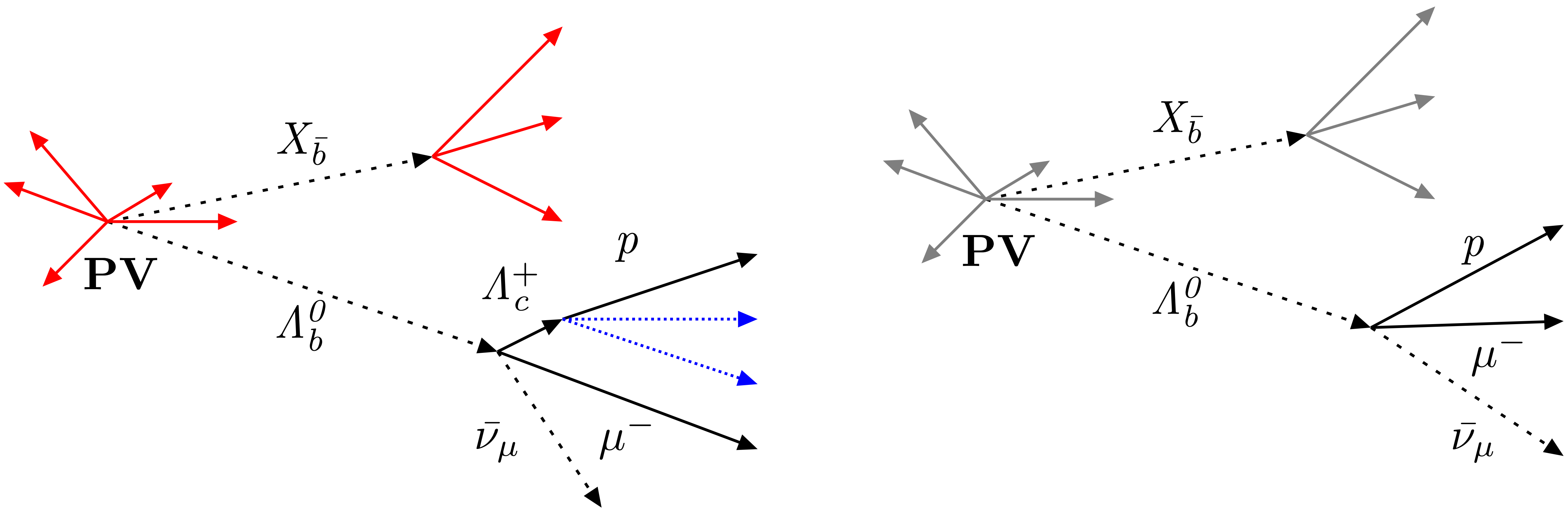
- Use $B^*_{s2} \to B^+K^-$ decays
- Add additional (narrow) resonance (kinematic constraint)to the decay chain
- Constrain B^+ mass, fit in B^*_{s2} mass (or constrain to B^*_{s2} mass), calculate m^2_{miss} (= m^2_ν)
- Useful to extract $B \to D, D^* D^{**} \mu\nu$ fractions
- Main issue: the number of B^+ gets reduced by a factor ~100 when requiring the B^*_{s2}







Vertex isolation: charged isolation

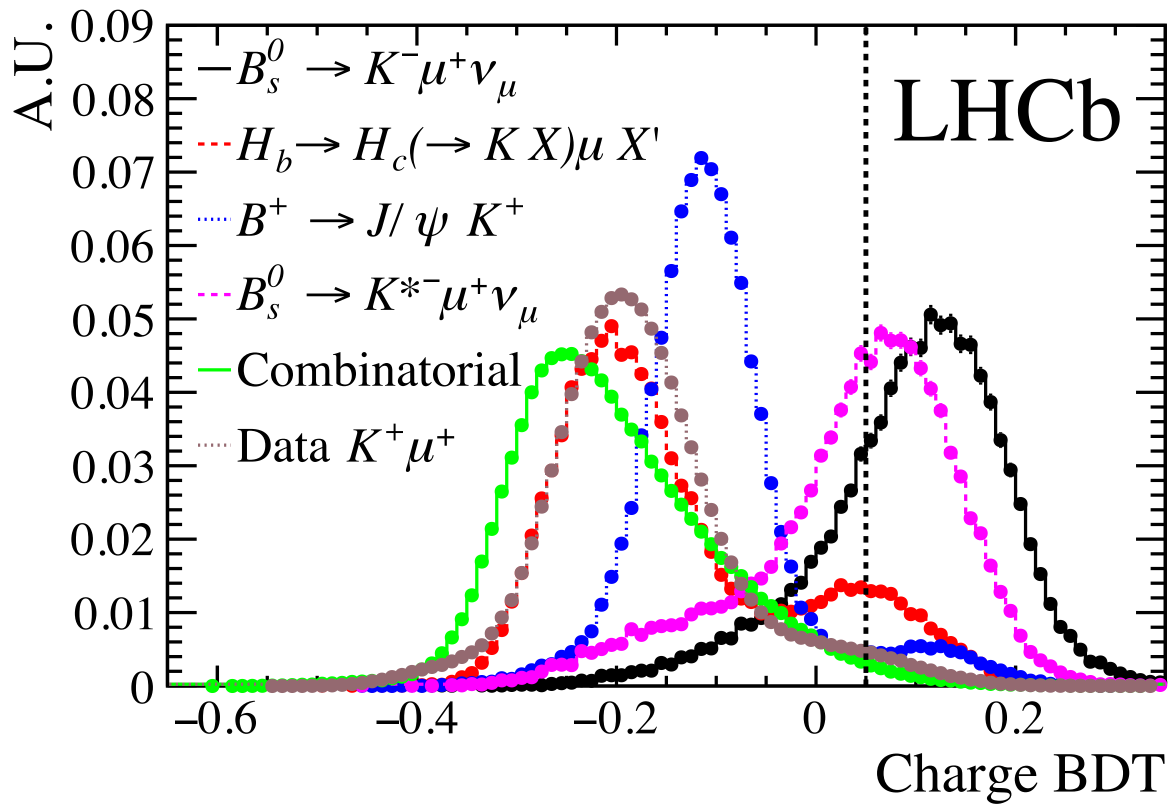


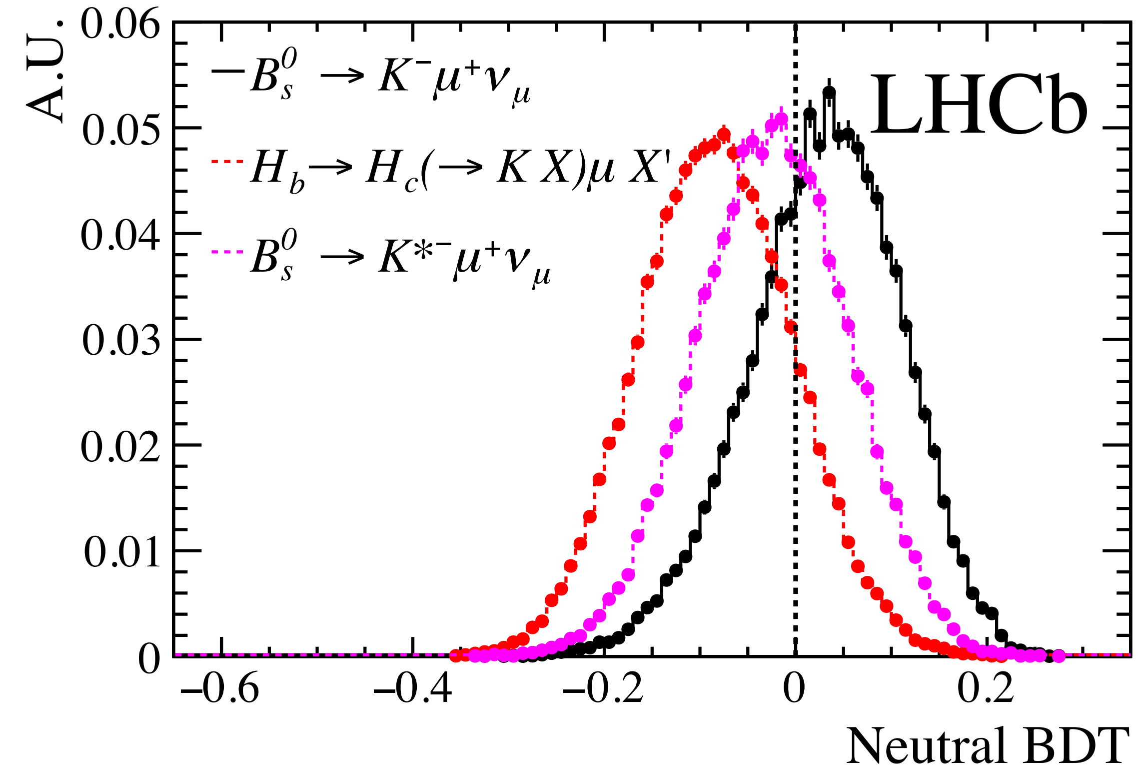
- When looking at Cabibbo-suppressed semileptonic decays ($|V_{ub}|$), need to fight $|V_{cb}|$ background.
- Two handles: c-hadron flies a few mm and decays (mostly) into few extra (displaced) tracks
  - Vertex χ^2 is poor for $|V_{cb}|$ background
  - Vertex χ^2 increases slowly when adding closest tracks
- In reality: construct a multivariate classifier to use as much as possible available information
- Run over all tracks in the event which are "close" to the $p\mu$ vertex, evaluate BDT for them

Vertex isolation: charged isolation

PAPER-2020-038, arXiv:2012.05143

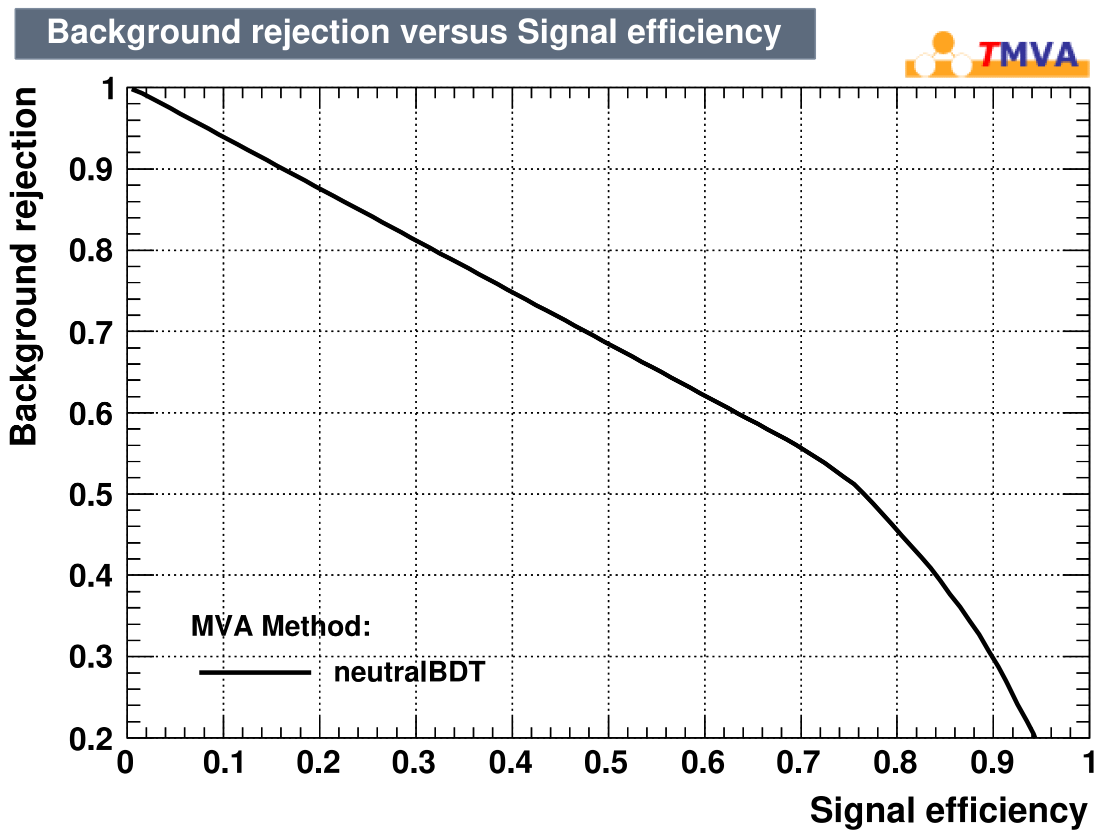
More difficult for neutral particles





- Run over all tracks in the event which are "close" to the $p\mu$ vertex, evaluate BDT for them
- As expected performs better for channels with at least one extra track than on channels with additional neutral particles
- Different analyses use different techniques, but the idea is the same
- Charged vertex isolation usually most powerful (high-level) variable to extract signal in semileptonic decays.
- Essential also to select regions enriched of specific physics backgrounds we want to model

Vertex isolation: neutral isolation

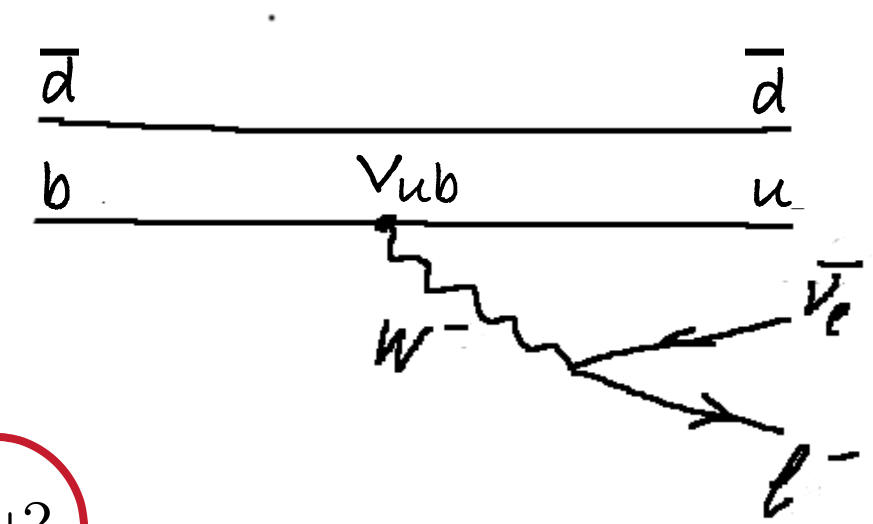


- Main issue with the neutral particles: one does not know their point of origin (e.g. PV or decay vertex)
- Neutral isolation mostly much less powerful than charged isolation
- Similar strategy: see if you find neutral objects in vicinity of signal decay

$|V_{ub}|$ and $|V_{cb}|$ and differential measurements

$|V_{ub}|$ and $|V_{cb}|$ measurement @LHCb

- How do you measure $|V_{ub}|$?
- $\mathscr{B}$ is proportional $|V_{ub}|^2 \rightarrow$ let's just count events!
- Or almost…



Electroweak + phase space

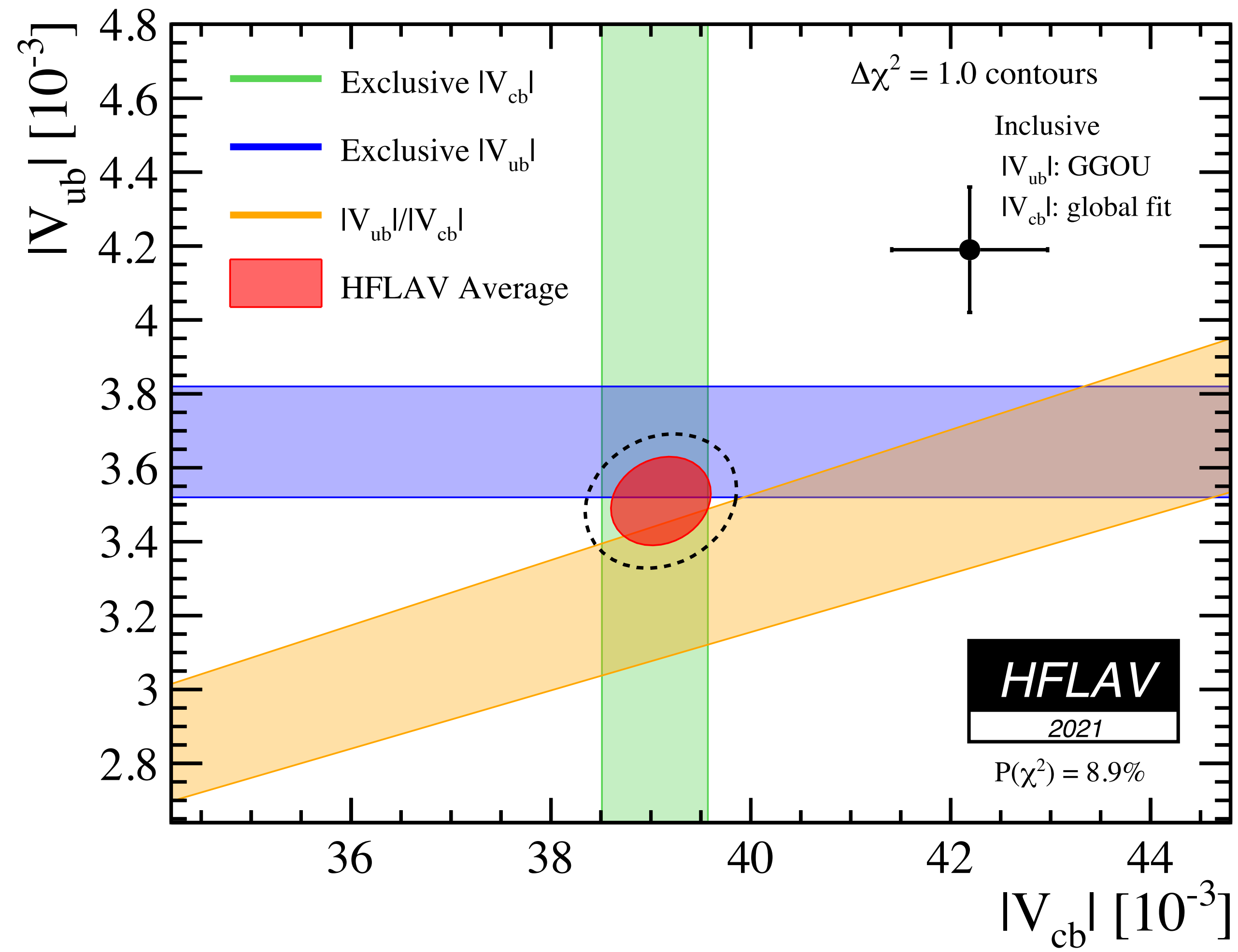
$$\frac{d\Gamma(\overline{B}^0 \rightarrow \pi^+\mu^-\nu_\mu)}{dq^2} = \frac{G_F^2|V_{ub}|^2|\vec{p_\pi}|^3}{24\pi^3}|f^+(q^2)|^2$$

QCD component encompassed by form factors

- Similar for $|V_{cb}|$ transitions, e.g. $B^0 \rightarrow D^-\mu^+\nu$
- Slightly more complicated with a vector meson in the final state, e.g. D^{*-} versus D^- (= more form factors)
- That means: to measure $|V_{ub}|$ (or $|V_{cb}|$) we need to know (or measure) the form factors
- Note: $|V_{ub}|$ (or $|V_{cb}|$) do not depend on the form factors, but the "QCD component" does
- Absolute branching fractions are hard to measure at LHCb: $\mathscr{L}$ luminosity, $b\bar{b}$ cross section, hadronisation fractions (e.g. f_s) not well known - $N_{B_s^0 \rightarrow K\mu\nu} = \mathscr{L} \cdot \sigma_{b\bar{b}} \cdot 2 \cdot f_s \cdot \mathscr{B}(B_s^0 \rightarrow K\mu\nu)$

Measuring $|V_{ub}|$ @LHCb

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



- $|V_{ub}|$ decays: much more background than $|V_{cb}|$ decays ($|V_{ub}| \ll |V_{cb}|$)
  - Use isolation techniques and multivariate classifiers
- Hadronic system has lower mass (e.g. K vs D_s) - coming usually with more background
- Samples are sizeably smaller → have not (yet) determined $|V_{ub}|$ and hadronic form factors at the same time (used theoretical predictions)

Measuring $|V_{ub}|$ using Λ_b^0 baryons

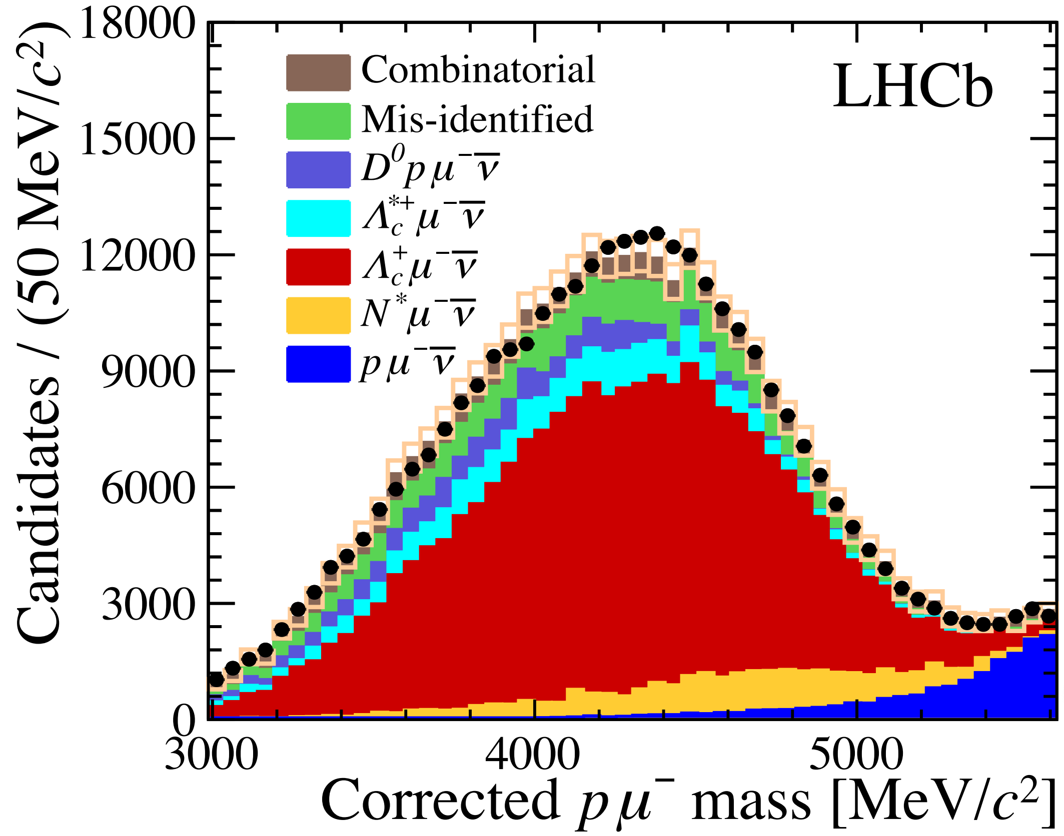
- Strategy: measure ratio of branching fractions of $\Lambda_b^0 \to p\mu^-\bar{\nu}$ and $\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}$

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu_\mu})} R_{FF}$$

$R_{FF} = 1.470 \pm 0.115(\text{stat}) \pm 0.104(\text{syst})$
W. Detmold, C. Lehner and S. Meinel
arXiv:1503.01421

Belle measurement arXiv:1312.7826

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu})_{q^2>15GeV^2/c^4}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu_\mu})_{q^2>7GeV^2/c^4}} = \frac{N(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu})}{N(\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\overline{\nu_\mu})} \times \frac{\epsilon(\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\overline{\nu_\mu})}{\epsilon(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu})} \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$$

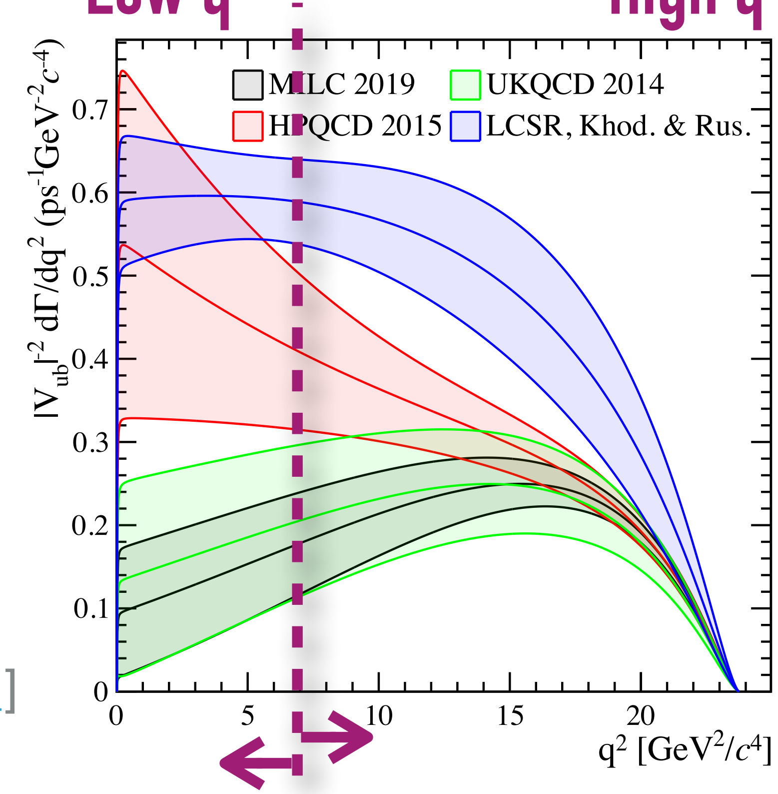


- Normalisation mode reduces systematic uncertainties and dependence on $f_{\Lambda_b^0}$
- Use the corrected mass variable - unfortunately not very clean - templated fit
- Histograms from MC that can be scaled up or down until the overall shape fits.

$\sim 15k$ $\Lambda_b^0 \to \Lambda_c^+\mu^-\nu$ decays

Measuring $|V_{ub}|$ using B_s^0 decays

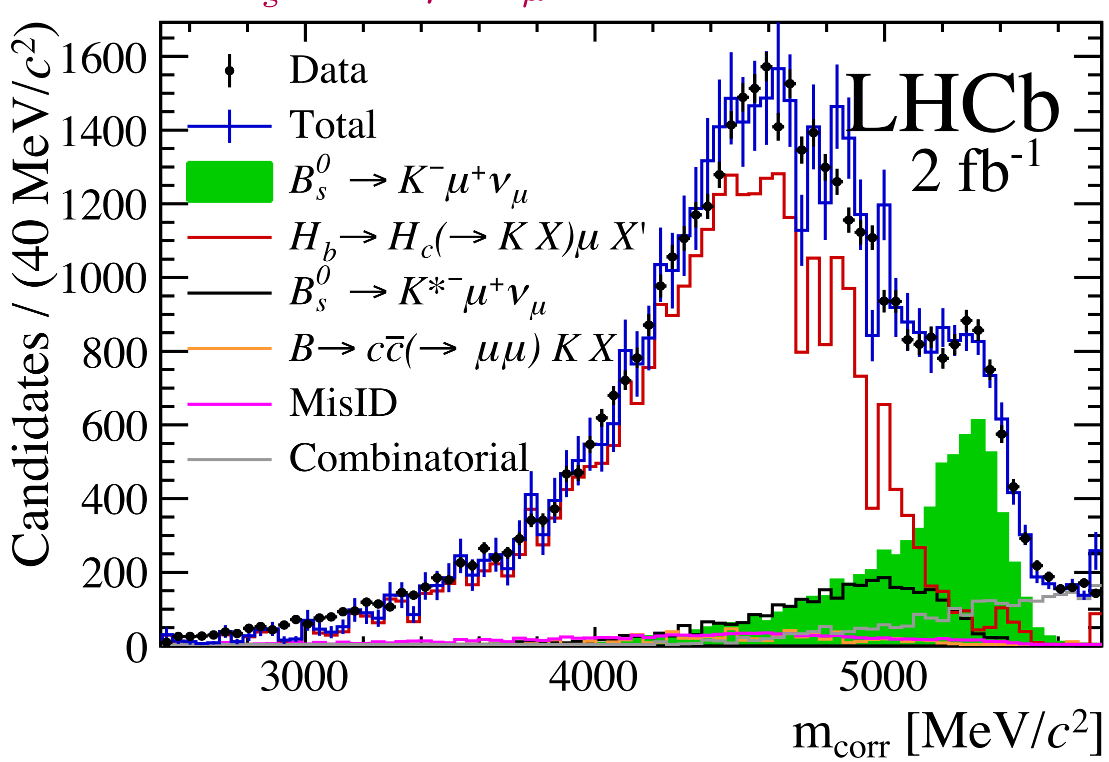
- Different spectator quark wrt $B^0 \to \pi\mu\nu$
- Measure $\frac{|V_{ub}|}{|V_{cb}|} = R_{FF}\frac{\mathcal{B}(B_s \to K\mu\nu)}{\mathcal{B}(B_s \to D_s\mu\nu)}$
- Use m_{corr} to identify signal and describe sample composition
- Different form factors predictions:
  - Low q^2: LCSR based on [JHEP08112]
  - High q^2: LQCD based on [Phys.Rev.D100,034501]



Fit templated from simulated samples corrected to describe the data

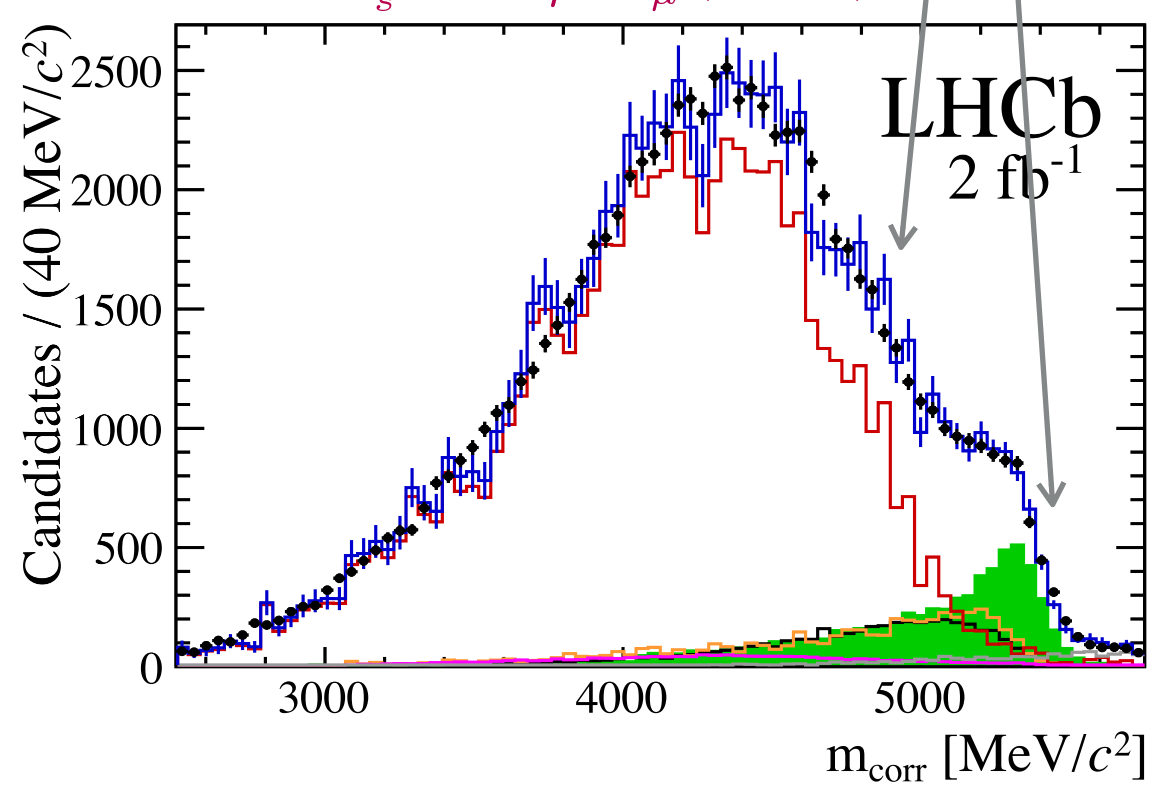
Low q²

$N_{B_s^0 \to K^-\mu^+\nu_\mu}(low) = 6922 \pm 285$



High q²

$N_{B_s^0 \to K^-\mu^+\nu_\mu}(high) = 6399 \pm 370$



Measuring $|V_{ub}|$ using B_s^0 decays

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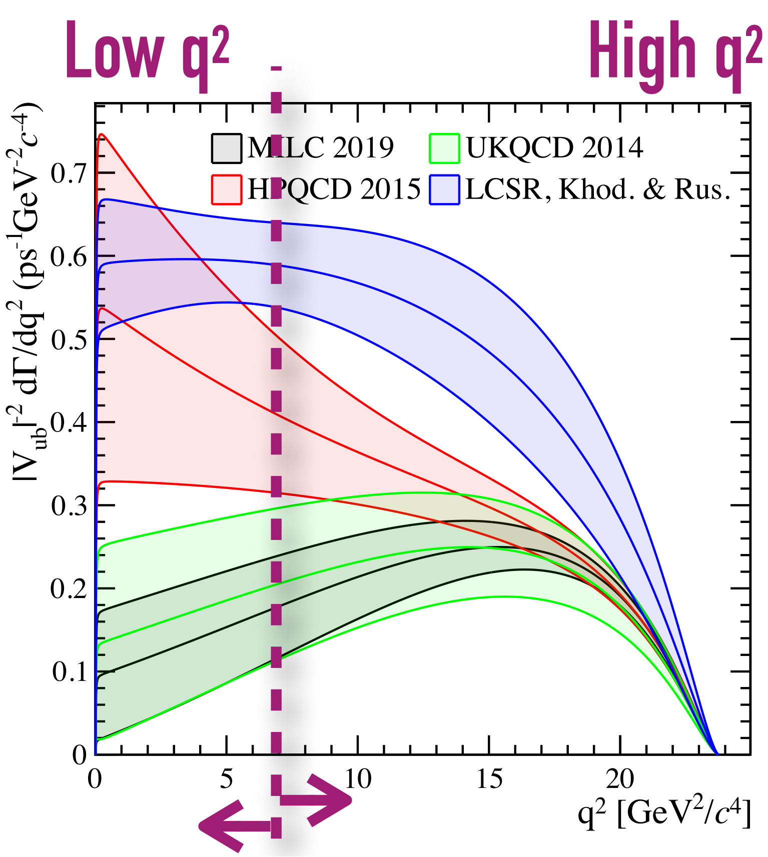
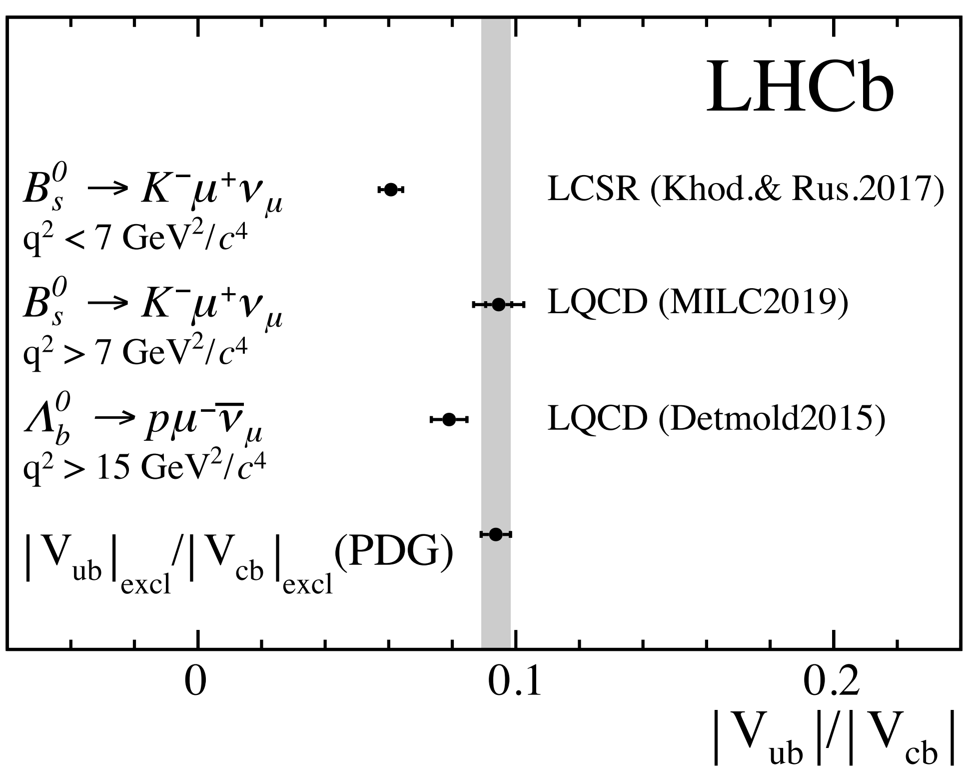
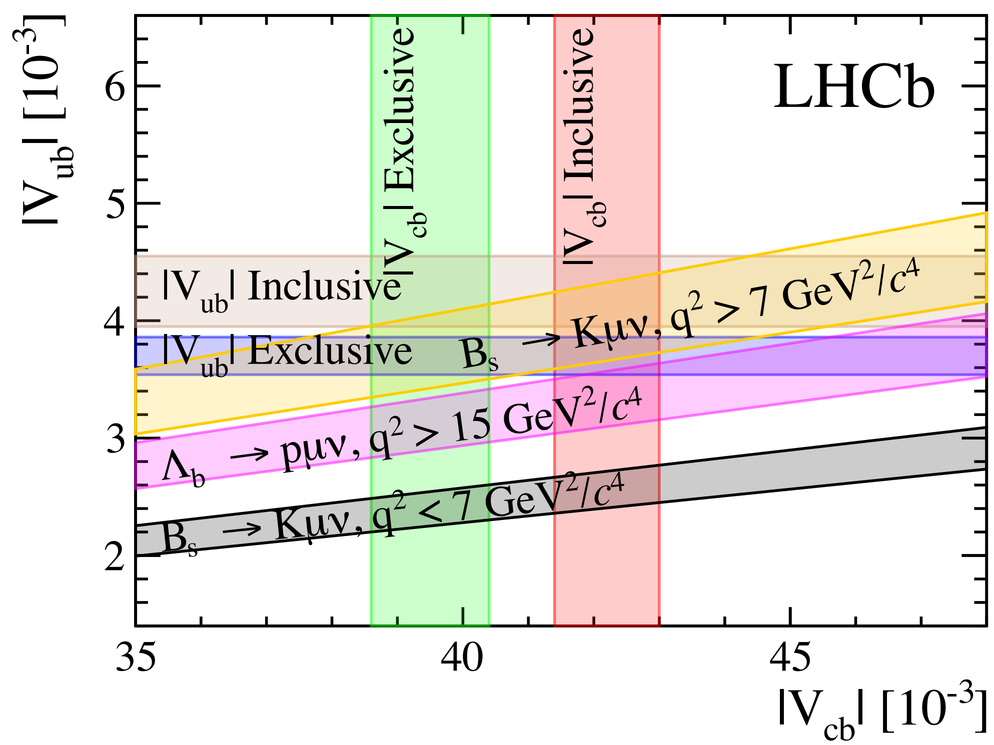




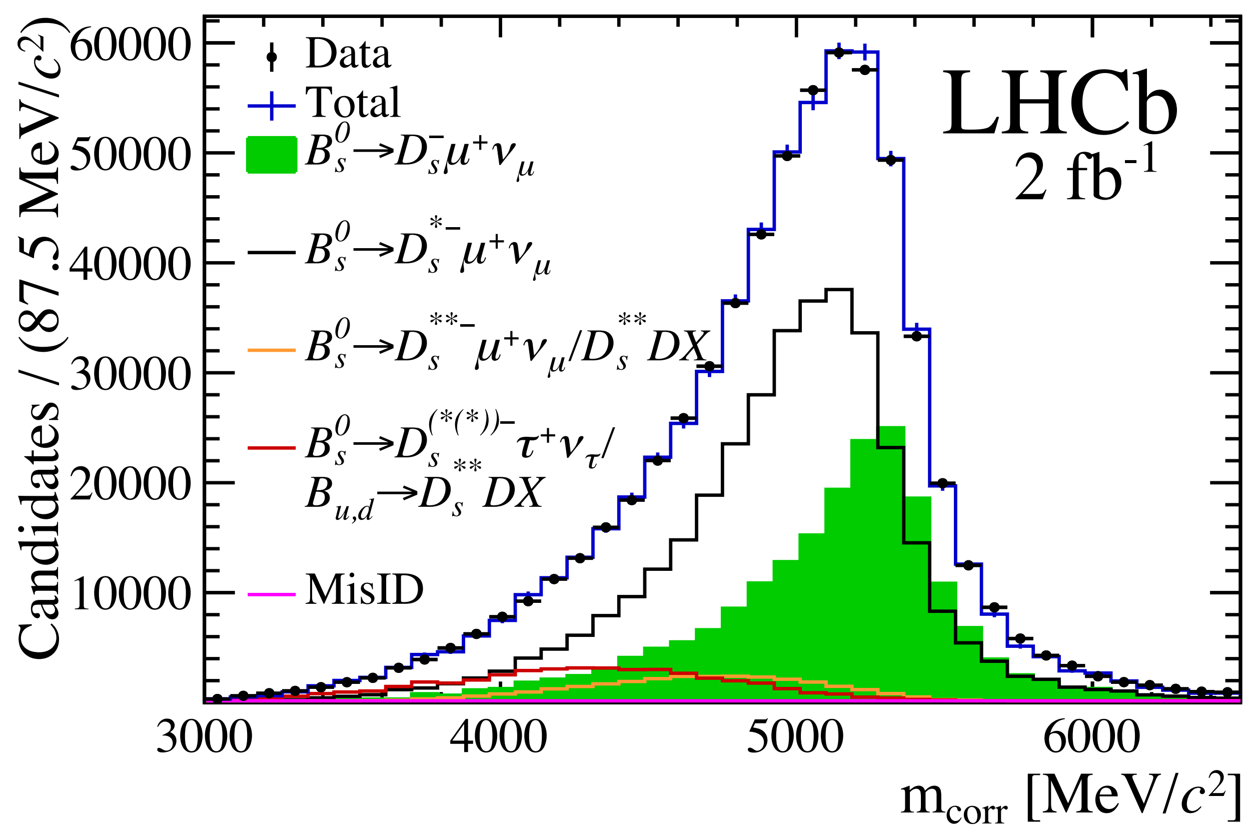


- Measuring differential decay rate will help understanding $B_s \to K\mu\nu$

Measuring $|V_{ub}|$ using B_s^0 decays

- Different spectator quark wrt $B^0 \to \pi\mu\nu$
- Measure $\frac{|V_{ub}|}{|V_{cb}|} = R_{FF}\frac{\mathcal{B}(B_s \to K\mu\nu)}{\mathcal{B}(B_s \to D_s\mu\nu)}$
- Use m_{corr} to identify signal and describe sample composition
- Different form factors predictions:
  - Low q^2: LCSR based on [JHEP08112]
  - High q^2: LQCD based on [Phys.Rev.D100,034501]
- Lots of interesting theoretical work on $B_s \to D_s^{(*)}\mu\nu$ (e.g. [PRD 99 (2019) 114512], [PRD 101 (2020) 074513])

$N_{B_s^0 \to D_s^- \mu^+ \nu_\mu} = 201450 \pm 5200$



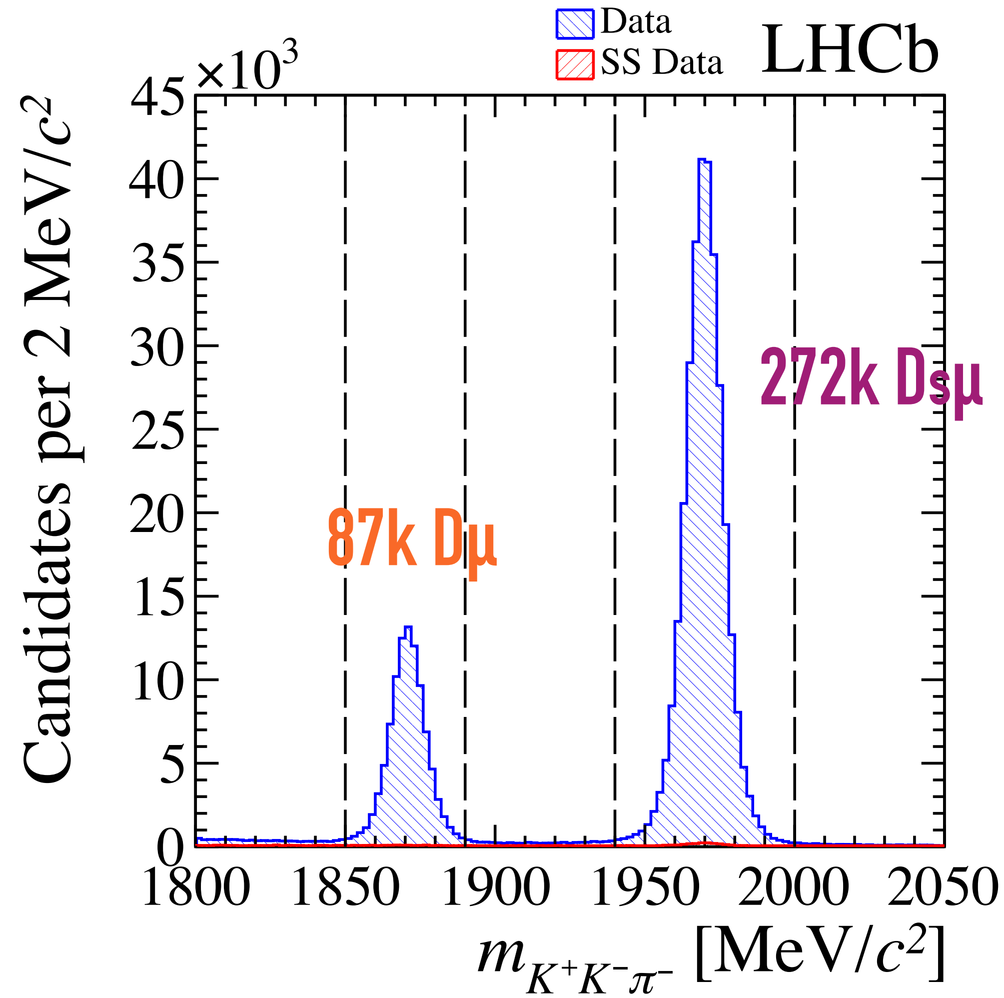
Measuring $|V_{cb}|$ using B_s^0 decays

- Perform relative measurement:
$$\frac{\mathcal{B}(B_s^0 \to D_s^{(*)-}\mu^+\nu)}{\mathcal{B}(B^0 \to D^{(*)-}\mu^+\nu)} = \frac{N_{B_s^0 \to D_s^{(*)-}\mu^+\nu}}{N_{B^0 \to D^{(*)-}\mu^+\nu}} \cdot R$$

- Fit to m_{corr} and $p_\perp(D)$ distributions to extract $|V_{cb}|$ and form factors. 2D template to model the data, including efficiency

$$\frac{dN_{\text{obs}}}{dp_\perp dM_{corr}} = \mathcal{N}\frac{d\Gamma(|V_{cb}|, h_{A_1}, \ldots)}{dp_\perp dM_{corr}} \times \epsilon(p_\perp, M_{corr})$$

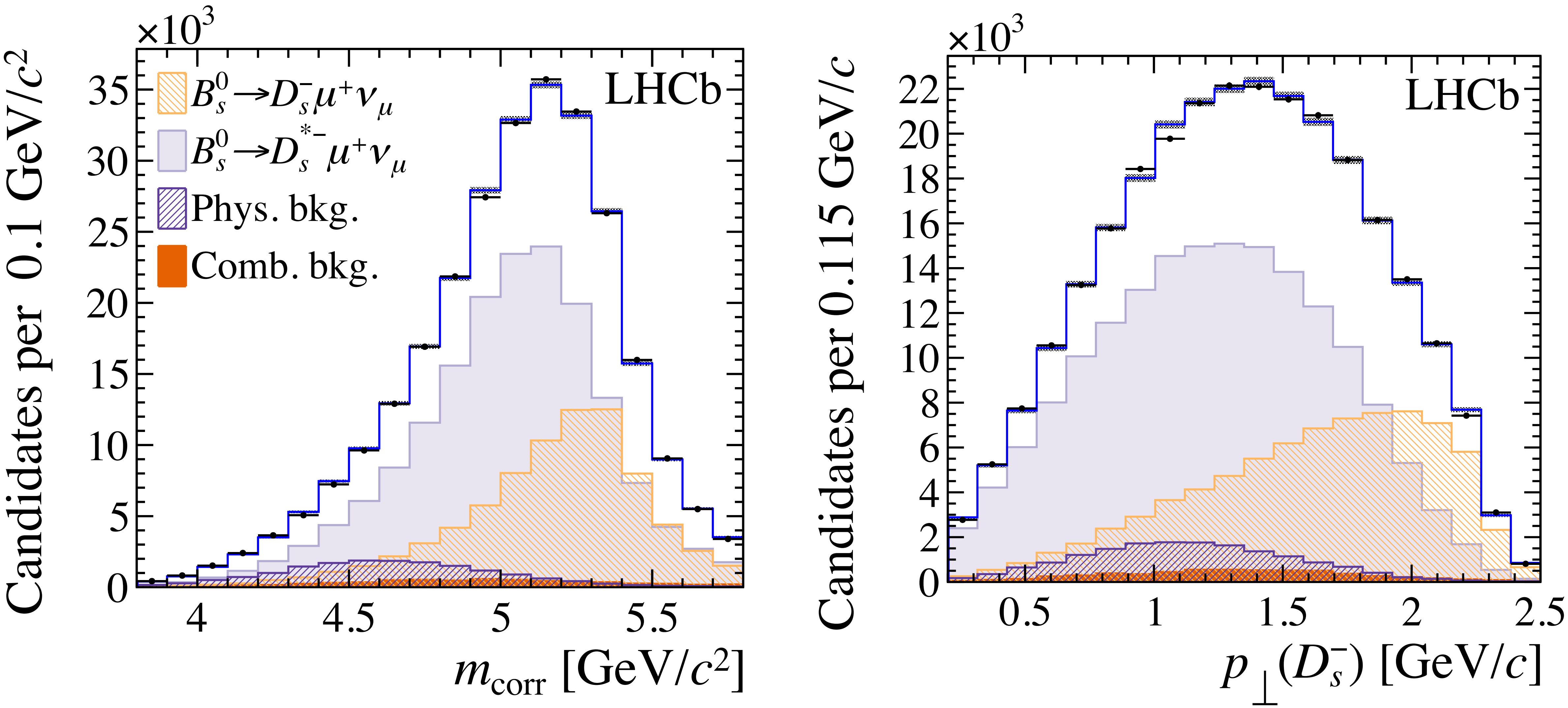
- Constrain form factors from lattice QCD [PRD 101 (2020) 074513, PRD 99 (2019) 114512].



- Normalisation $\mathcal{N}$ contains measured B^0 reference yields, input branching fractions, relative b-hadron production probabilities f_s/f_d and B_s^0 lifetime

Measuring $|V_{cb}|$ using B_s^0 decays

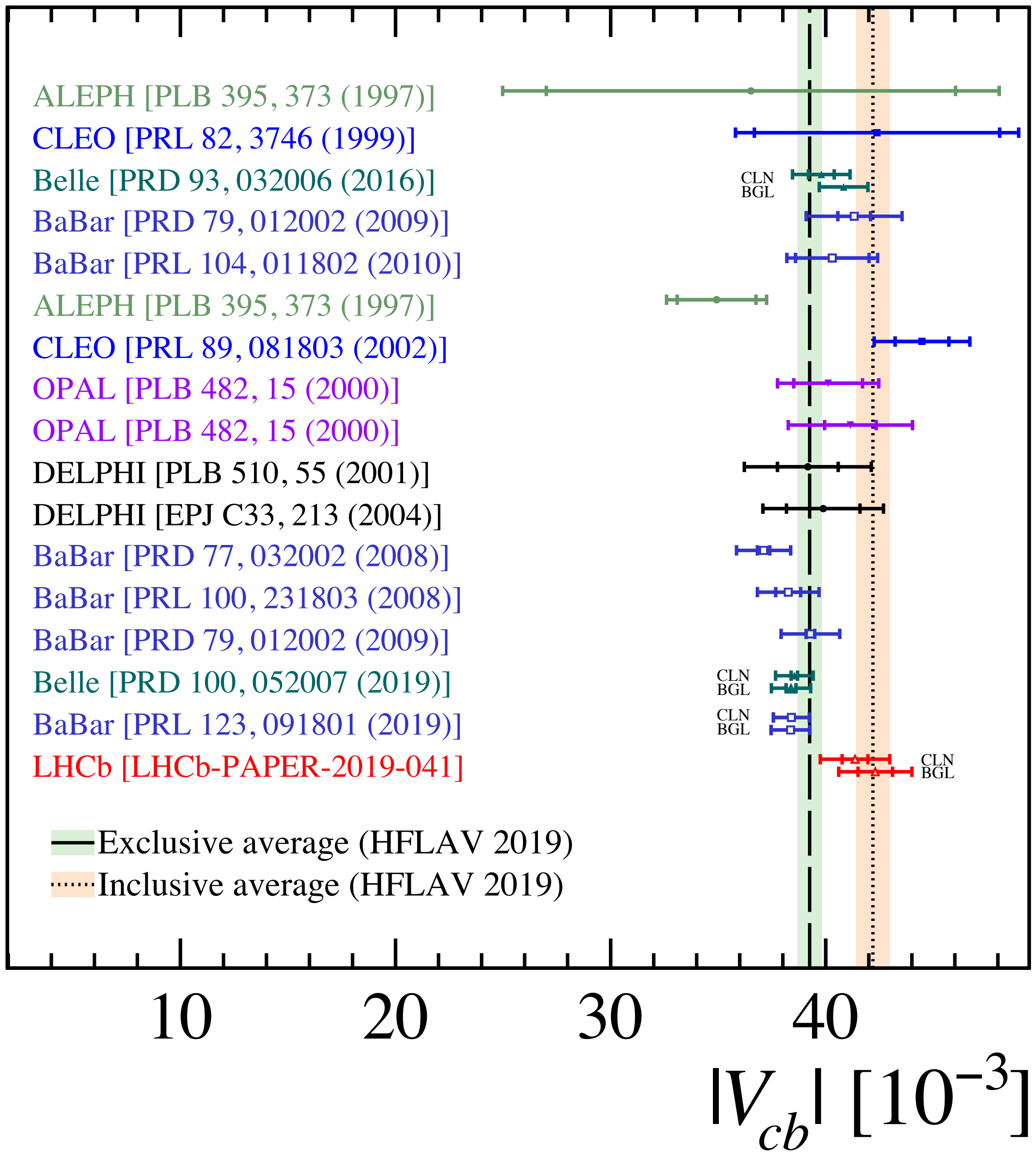
- Fit to m_{corr} and $p_\perp(D)$ distributions to extract $|V_{cb}|$ and form factors



- The sample is signal dominated
- m_{corr} allows to separate between D_s and D_s^*
- 2-Dimensional templated fit: Histograms from MC that can be scaled up or down until the overall shape fits.
- Take limited number of simulated events into account by allowing for fluctuations in each bin.

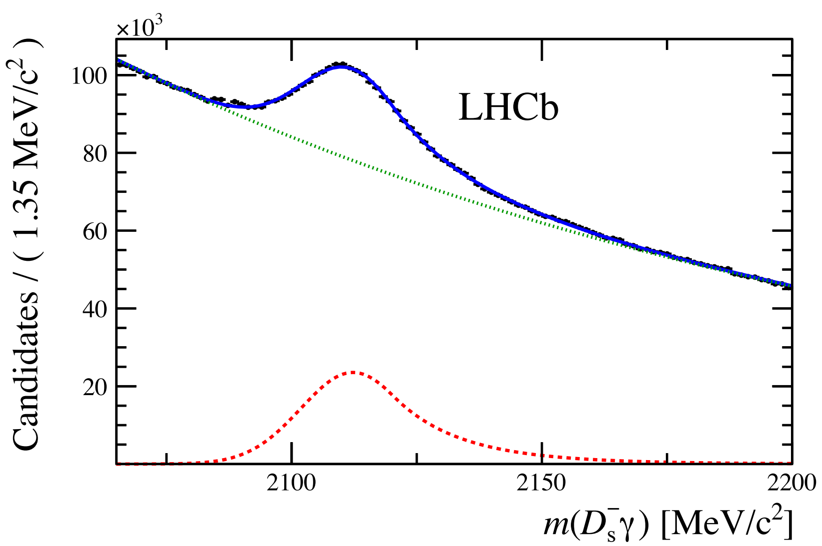
Measuring $|V_{cb}|$ using B_s^0 decays

- LHCb was not built to measure $|V_{cb}|$, but still achieves a good precision
- Always need to rely on precision of normalisation channel (i.e. an external measurement). For this measurement also rely on f_s/f_d
- No inclusive $|V_{cb}|$ measurement so far, investigating sun-of-exclusive approach
- Complementary measurement of $B_s^0 \to D_s^{(*)-}\mu^+\nu$ for factors

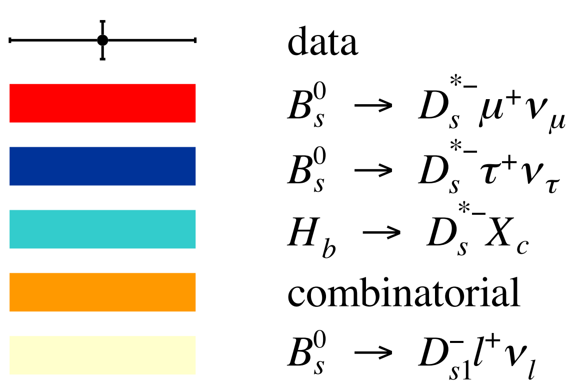


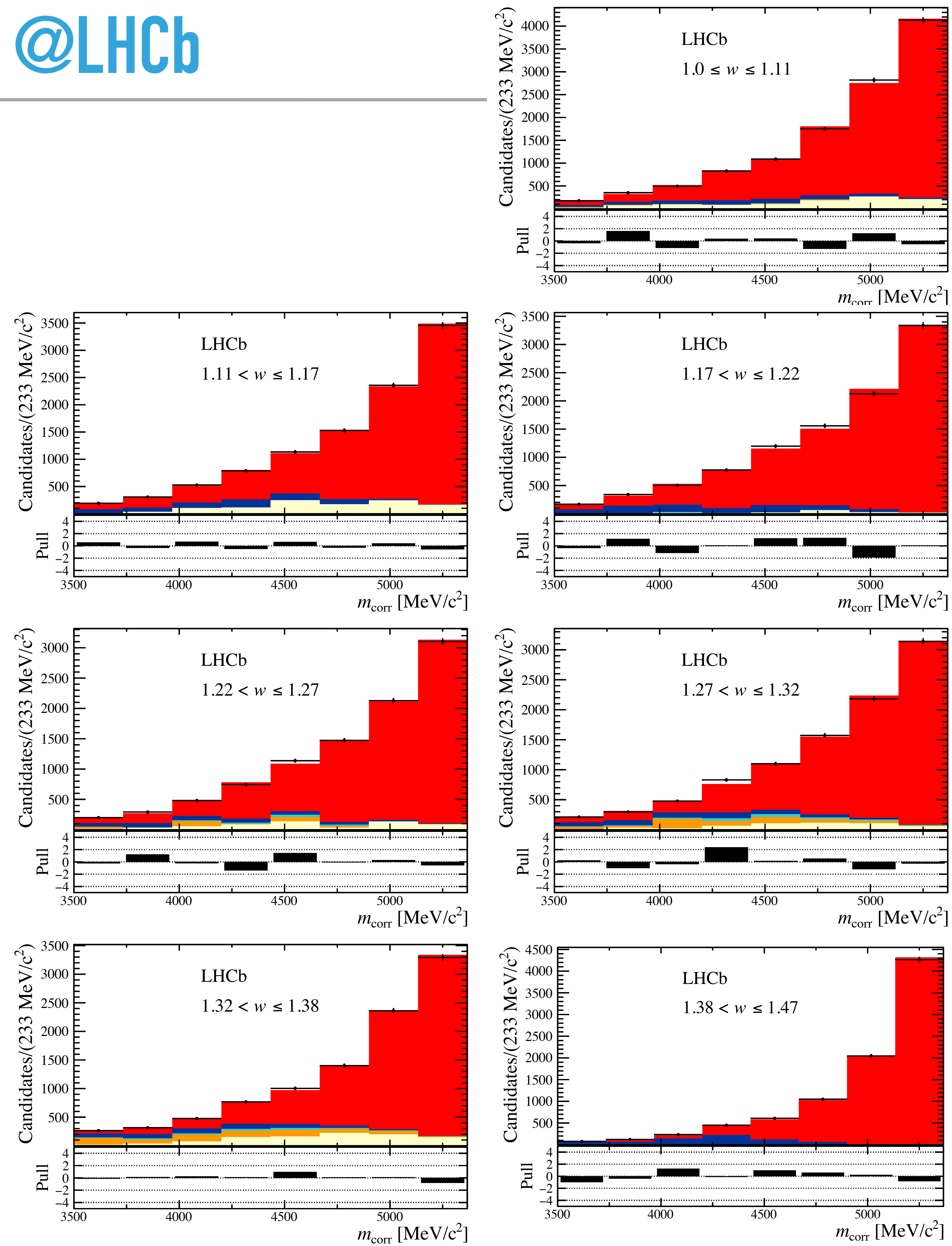
Differential measurements @LHCb

- First 1D-differential measurements
- Measurement of the shape of the $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ decay rate
- Fully reconstruct $D_s^{*-} \to D_s^- \gamma$



- Signal yield measured in bins of hadronic recoil parameter $w = v_{B_s^0} \cdot v_{D_s^{*-}}$





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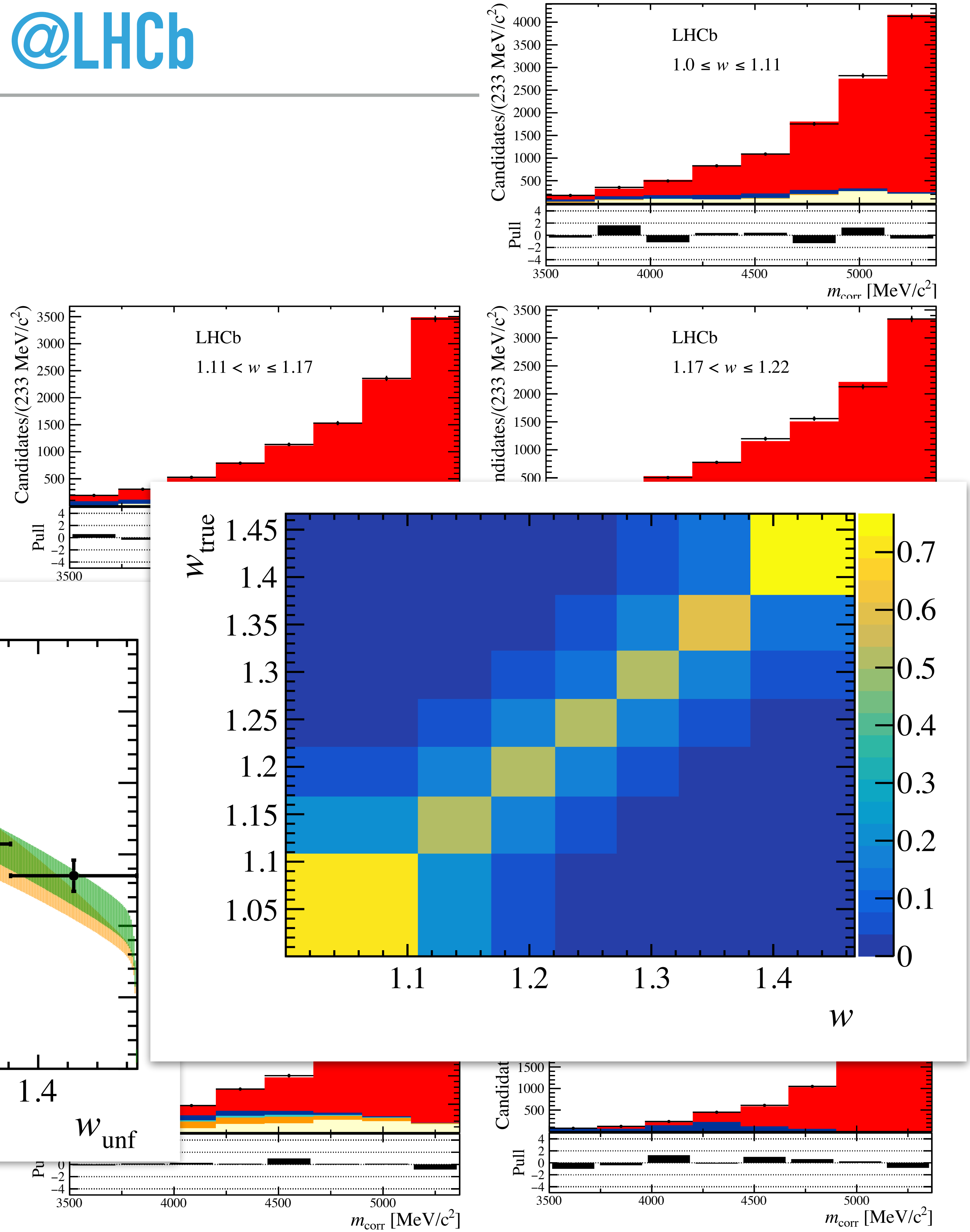

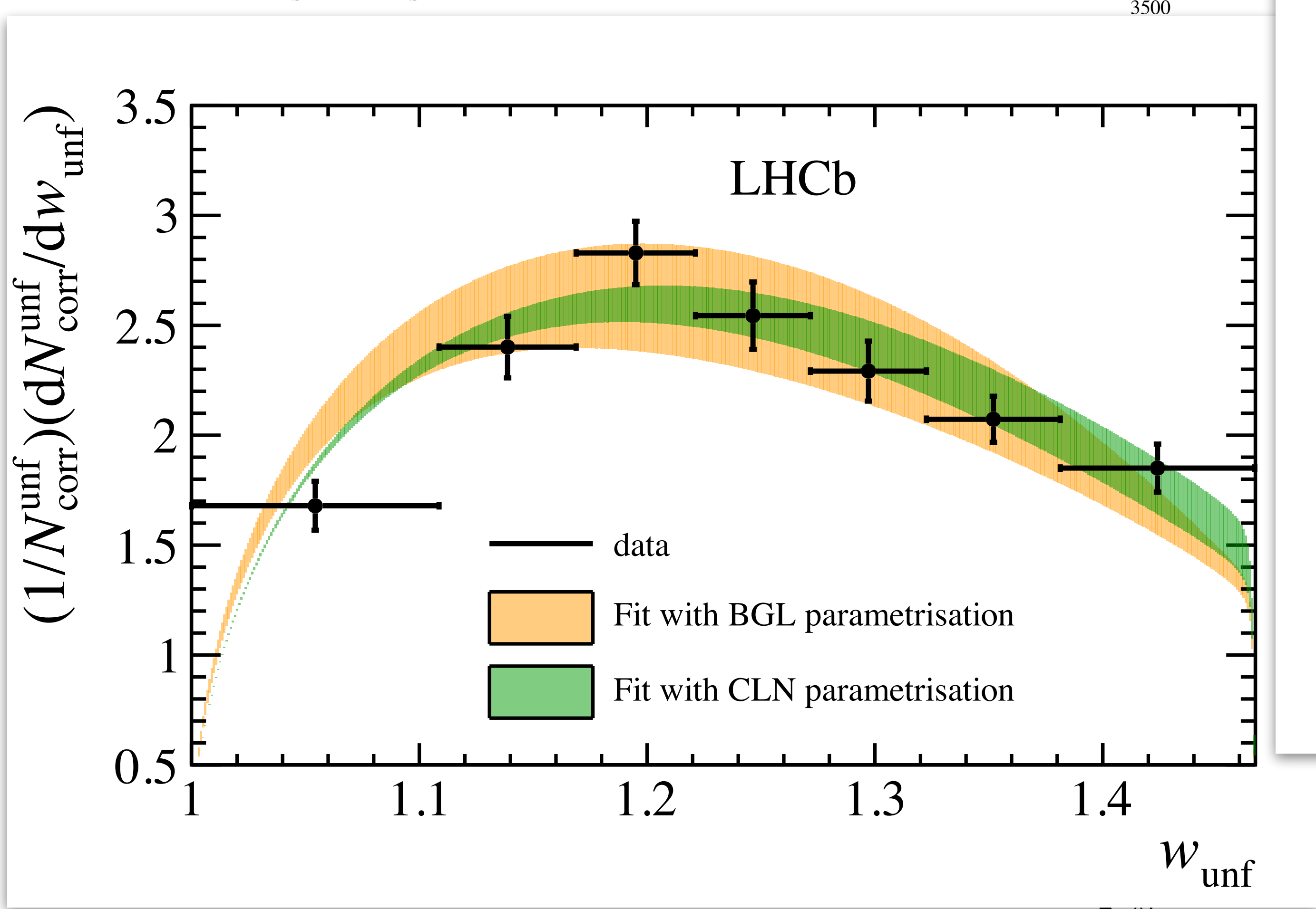

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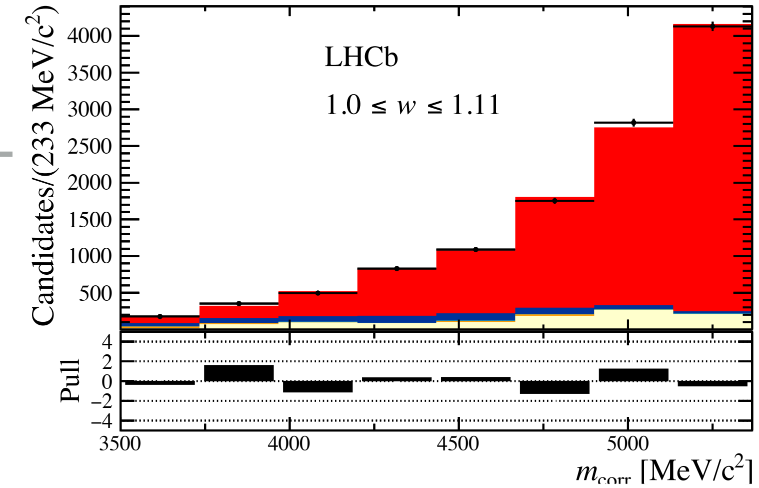
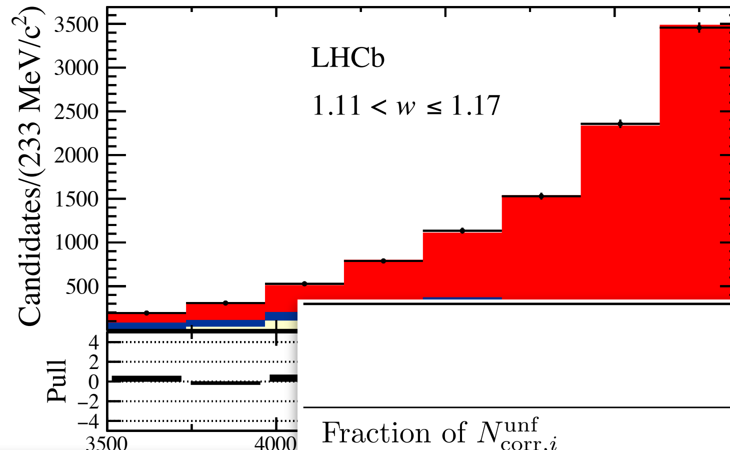
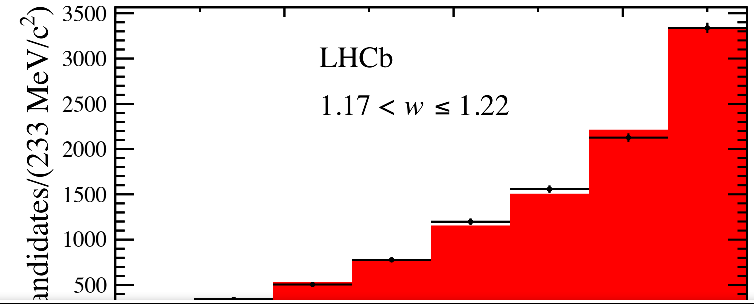
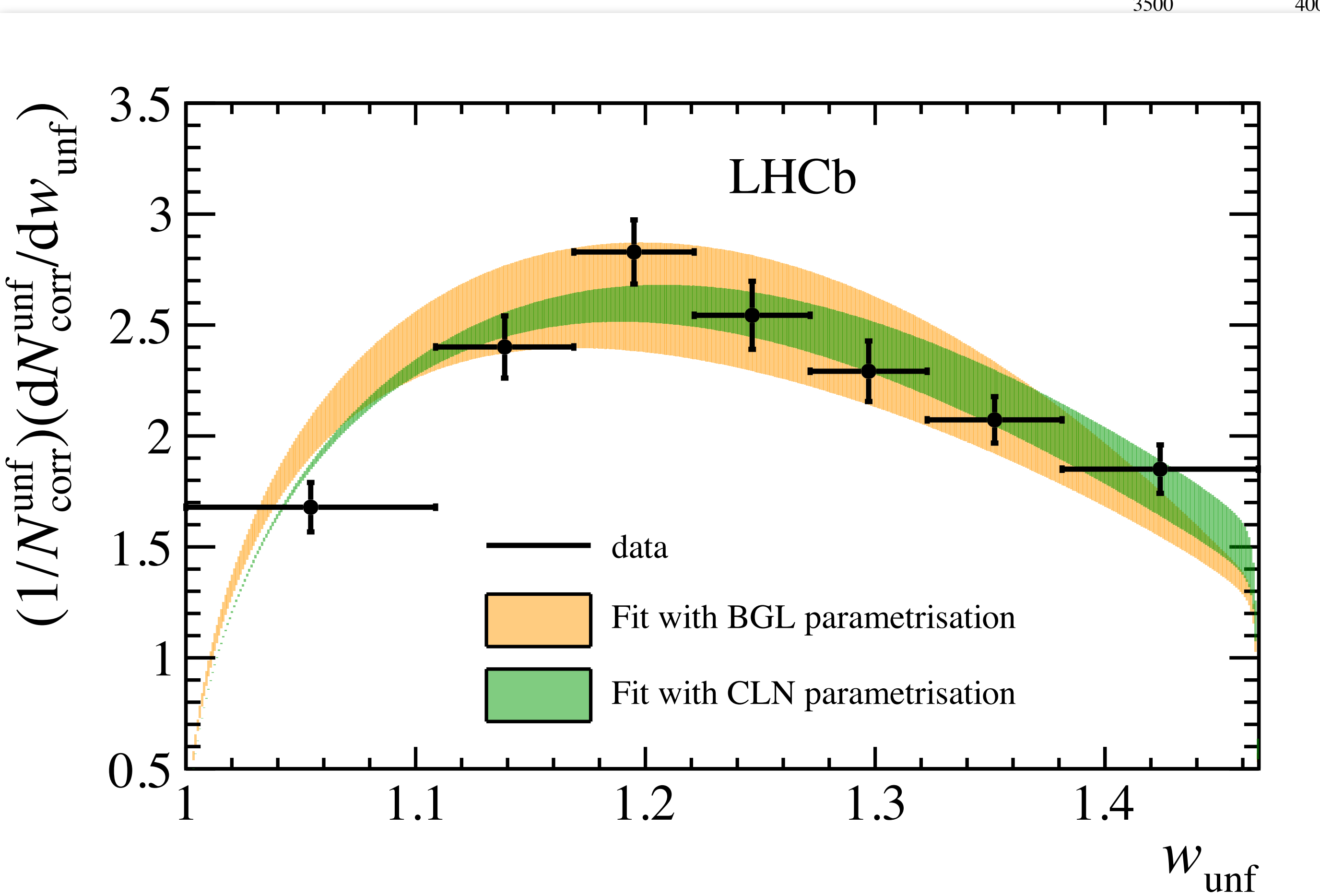


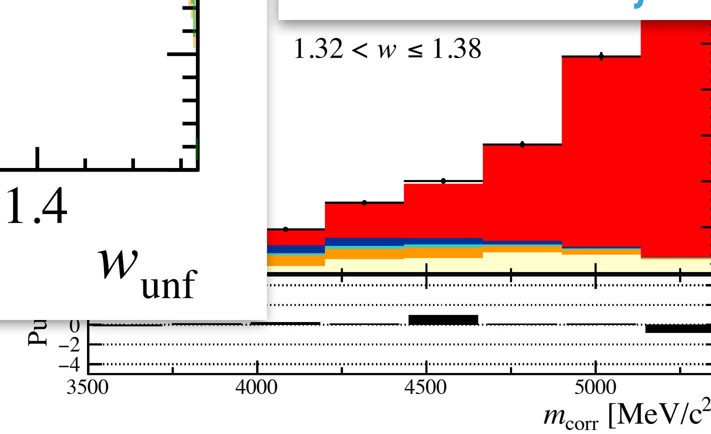


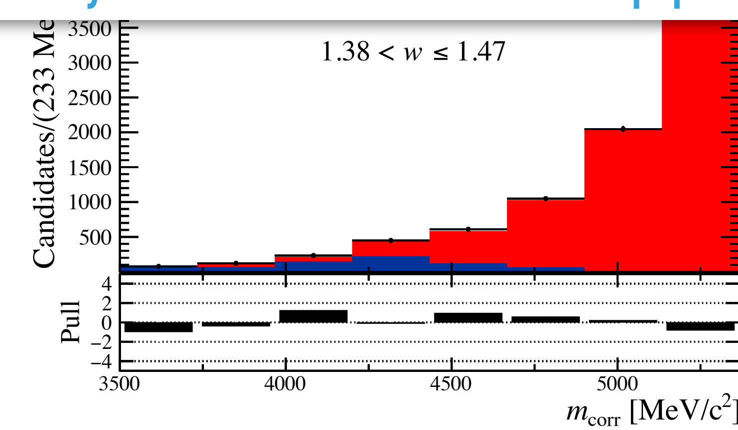




	w bin						
	1	2	3	4	5	6	7
Fraction of $N^{\rm unf}_{{\rm corr},i}$	0.183	0.144	0.148	0.128	0.117	0.122	0.158
Uncertainties (%)							
Simulation sample size	3.5	3.0	2.8	3.1	3.4	3.0	3.7
Sample sizes for effs and corrections	3.6	3.2	3.0	2.8	2.8	2.7	2.8
SVD unfolding regularisation	0.5	0.5	0.1	0.7	1.2	0.0	0.5
Radiative corrections	0.1	0.2	0.1	0.3	0.4	0.2	0.2
Simulation FF parametrisation	0.3	0.1	0.1	0.1	0.2	0.4	0.2
Kinematic corrections	2.4	1.0	1.1	0.1	0.2	0.1	0.9
Hardware-trigger efficiency	0.3	0.3	0.0	0.2	0.2	0.3	0.1
Software-trigger efficiency	0.0	0.1	0.0	0.0	0.1	0.0	0.0
D_s^- selection efficiency	0.5	0.2	0.3	0.3	0.2	0.1	0.3
Photon background subtraction	0.0	2.3	0.8	2.9	2.0	0.9	0.4
Total systematic uncertainty	5.6	5.1	4.4	5.2	5.0	4.2	4.8
Statistical uncertainty	3.4	2.9	2.7	3.1	3.2	2.9	3.4

Unfolded efficiency corrected yields+ correlation matrix in the paper





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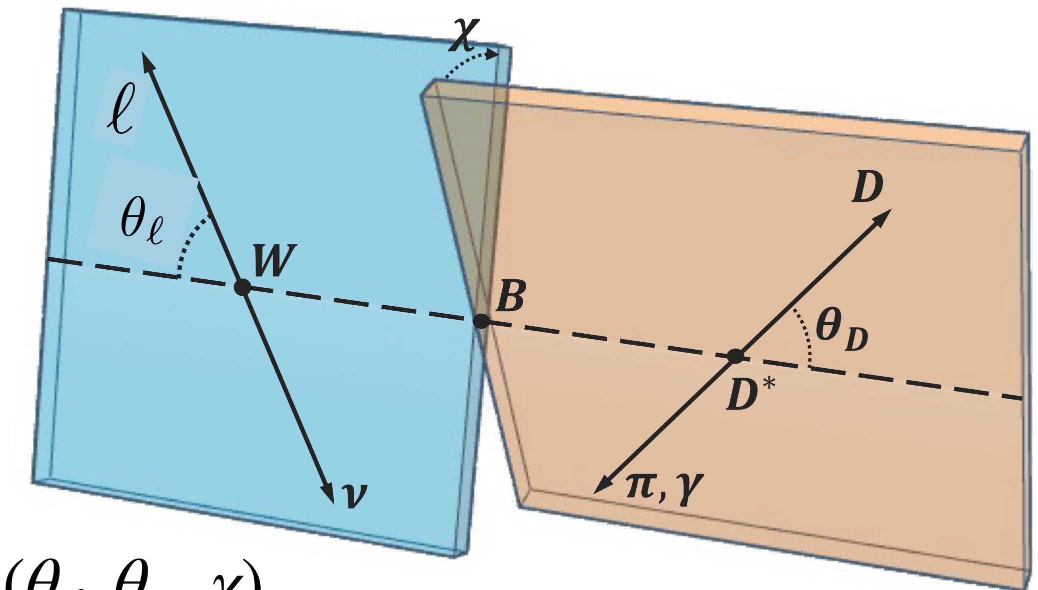
Expanding differential measurements

- Fully differential decay rate
- Helicity angles (and derived observables) are sensitive to New Physics contributions and hadronic interactions (Form Factors)



$$\frac{d\Gamma(B \to D^*\ell\nu)}{dw d\cos\theta_\ell d\cos\theta_d d\chi} = \frac{3m_B^3 m_{D^*}^2 G_F^2}{16(4\pi)^4}\eta_{EW}|V_{cb}|^2 \sum_i^6 \mathscr{H}_i(w) k_i(\theta_\ell, \theta_D, \chi)$$

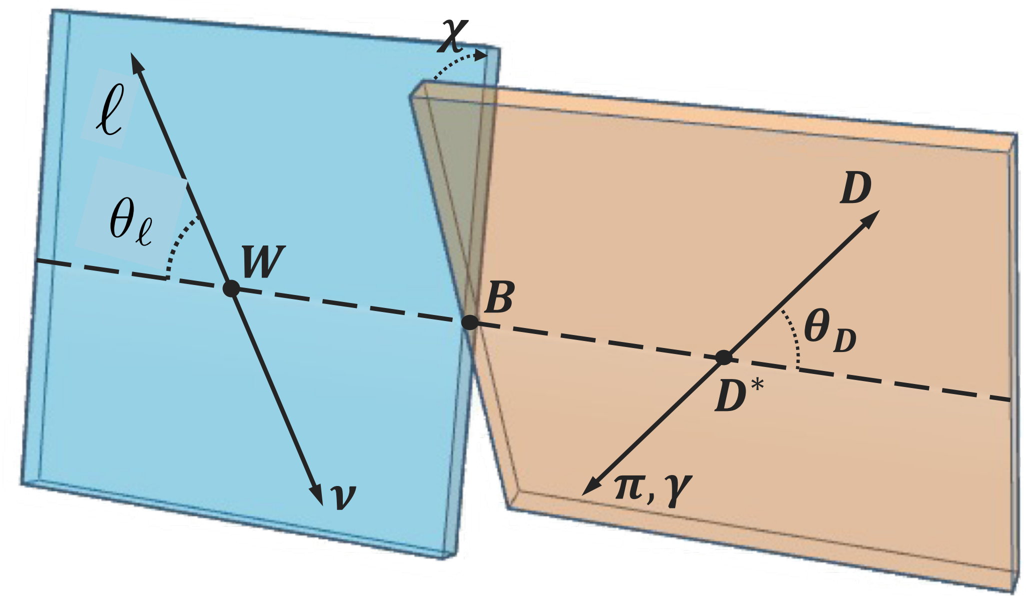
i	$\mathcal{H}_i(w)$	$k_i(\theta_\mu, \theta_D, \chi)$	
		$D^* \to D\gamma$	$D^* \to D\pi^0$
1	H_+^2	$\frac{1}{2}(1+\cos^2\theta_D)(1-\cos\theta_\mu)^2$	$\sin^2\theta_D(1-\cos\theta_\mu)^2$
2	H_-^2	$\frac{1}{2}(1+\cos^2\theta_D)(1+\cos\theta_\mu)^2$	$\sin^2\theta_D(1+\cos\theta_\mu)^2$
3	H_0^2	$2\sin^2\theta_D\sin^2\theta_\mu$	$4\cos^2\theta_D\sin^2\theta_\mu$
4	H_+H_-	$\sin^2\theta_D\sin^2\theta_\mu\cos 2\chi$	$-2\sin^2\theta_D\sin^2\theta_\mu\cos 2\chi$
5	H_+H_0	$\sin 2\theta_D\sin\theta_\mu(1-\cos\theta_\mu)\cos\chi$	$-2\sin 2\theta_D\sin\theta_\mu(1-\cos\theta_\mu)\cos\chi$
6	H_-H_0	$-\sin 2\theta_D\sin\theta_\mu(1+\cos\theta_\mu)\cos\chi$	$2\sin 2\theta_D\sin\theta_\mu(1+\cos\theta_\mu)\cos\chi$

Phys. Rev. D101 (2020) 072004

- Full description using the possible three helicity states of the D* - measuring the angular coefficients does not separate hadronic and NP effects, but also doesn't make assumptions
  - Measurement of Angular Asymmetries (Belle II)
  - Measurement of the 12 Angular Coefficients
  - Direct determination of New Physics Wilson Coefficients (and hadronic Form Factors)

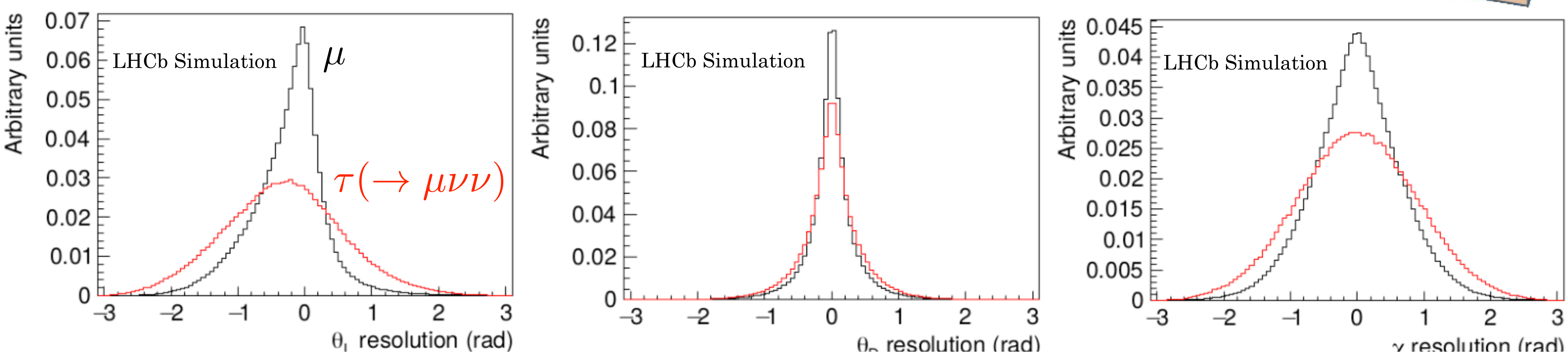
Towards full angular analyses @LHCb

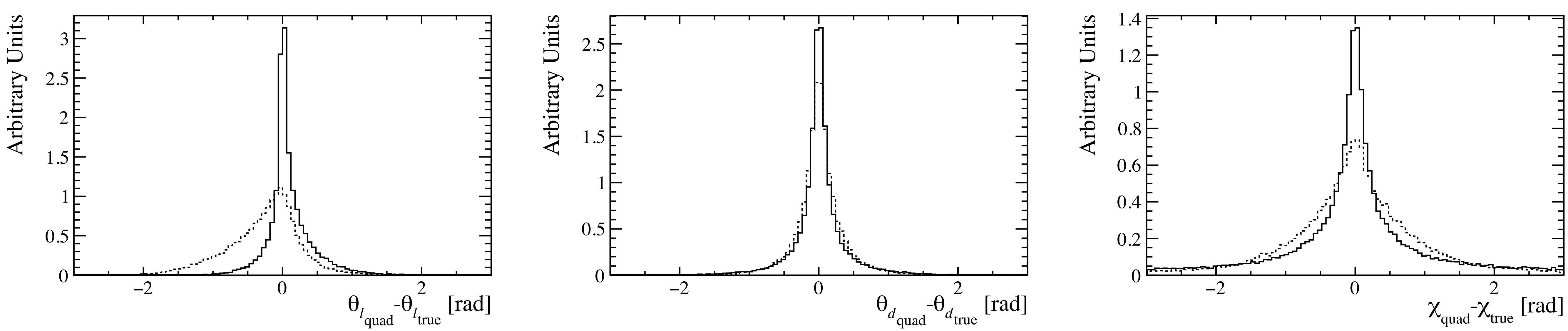
- Fully differential decay rate - in q^2 (or w) and helicity angles
- Resolutions (worst case: rest frame approximation)



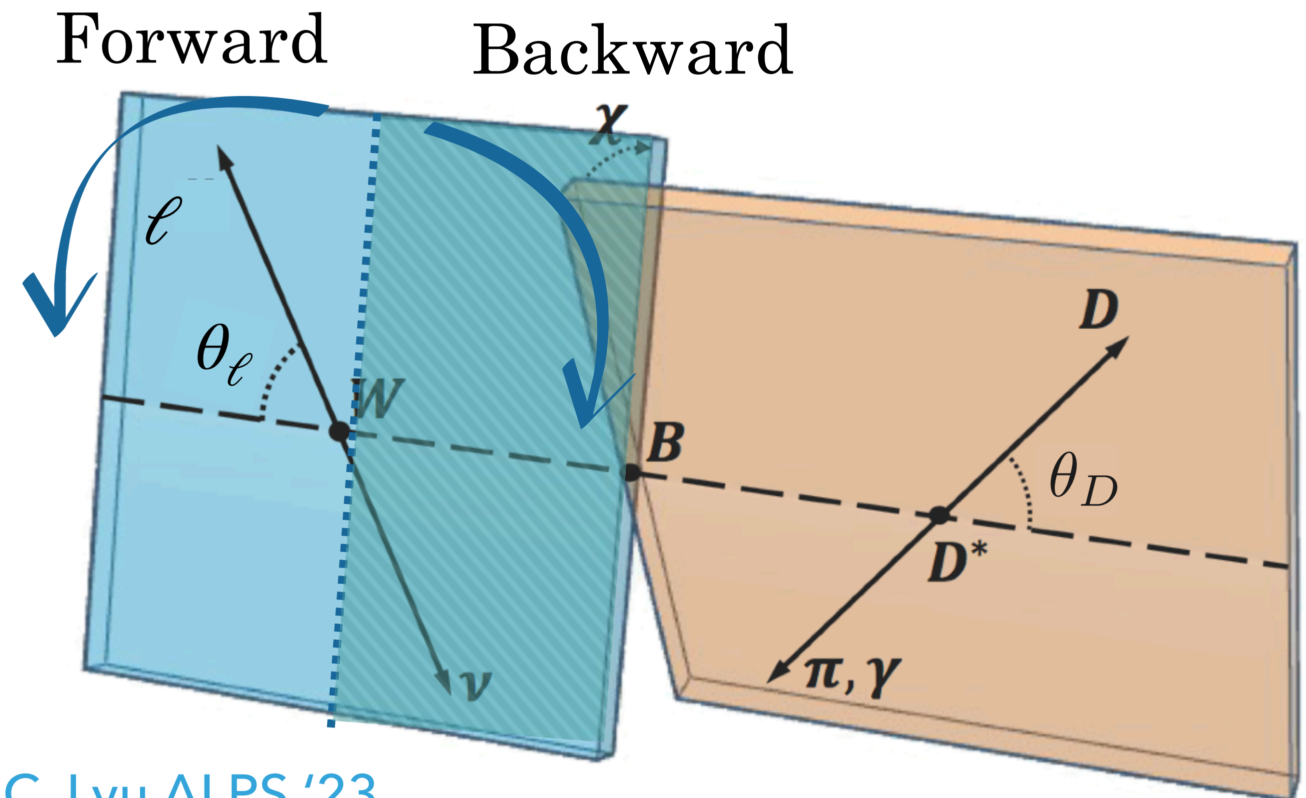
Resolutions to be modelled, but good sensitivity with large datasets!

LHCB-PUB-2018-009, arXiv:1808.08865

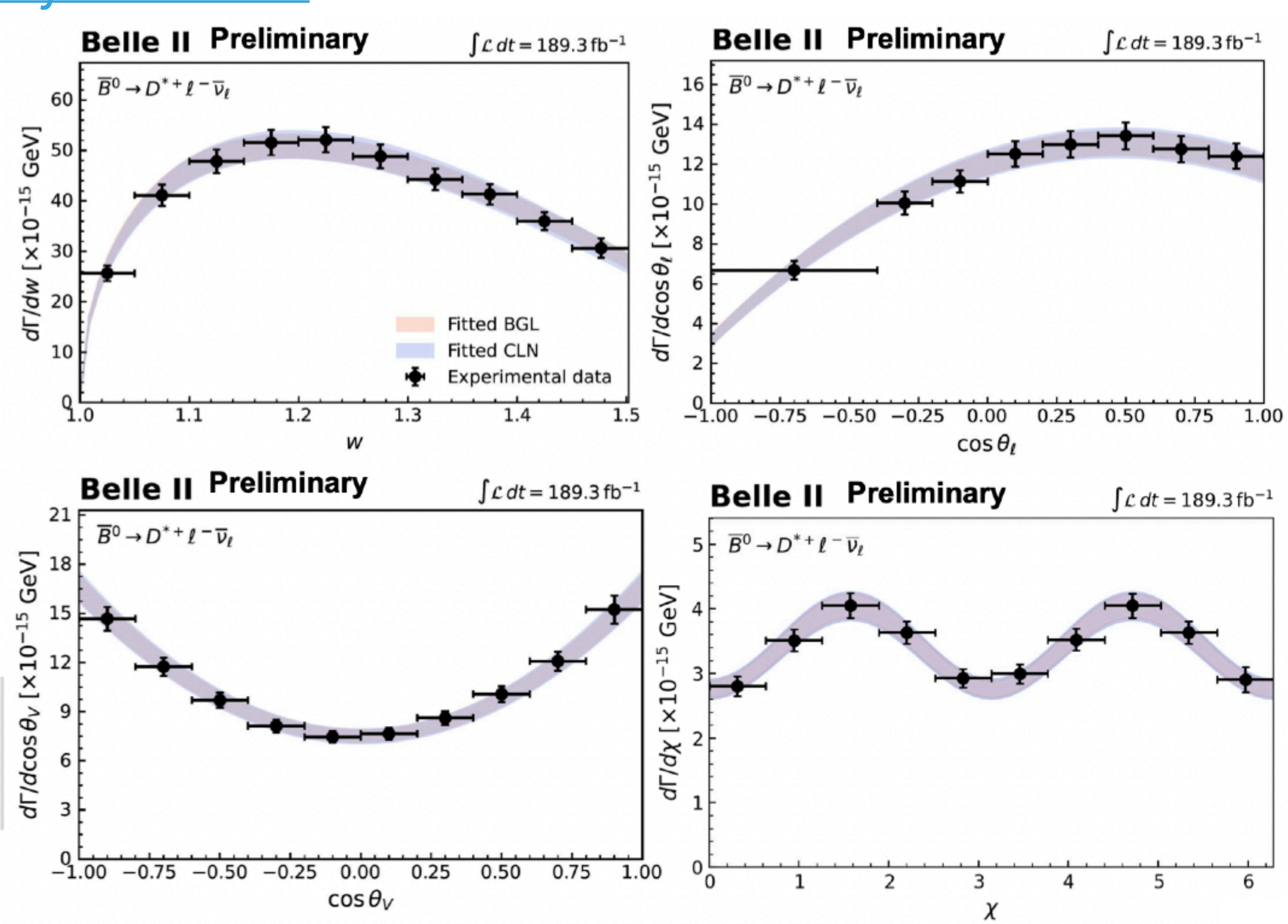




Wouldn't be nice to measure angular asymmetries?



C. Lyu ALPS '23



Untagged Belle II $\bar{B} \to D^{*+}\ell^-\bar{\nu}$

$$A_{\mathrm{FB}} = \frac{\int_0^1 \cos\theta_\ell \mathrm{d}\Gamma/\mathrm{d}\cos\theta_\ell - \int_{-1}^0 \cos\theta_\ell \mathrm{d}\Gamma/\mathrm{d}\cos\theta_\ell}{\int_0^1 \cos\theta_\ell \mathrm{d}\Gamma/\mathrm{d}\cos\theta_\ell + \int_{-1}^0 \cos\theta_\ell \mathrm{d}\Gamma/\mathrm{d}\cos\theta_\ell}$$

$$\Delta A_{\mathrm{FB}} = A^\mu_{\mathrm{FB}} - A^e_{\mathrm{FB}}$$
$$\Sigma A_{\mathrm{FB}} = A^\mu_{\mathrm{FB}} + A^e_{\mathrm{FB}}$$

$$R_{e/\mu} = 1.001 \pm 0.009(\mathrm{stat}) \pm 0.021(\mathrm{syst})$$

$$\mathcal{A}^e_{\mathrm{FB}} = 0.219 \pm 0.011 \pm 0.020\,,$$
$$\mathcal{A}^\mu_{\mathrm{FB}} = 0.215 \pm 0.011 \pm 0.022\,,$$
$$\Delta\mathcal{A}_{\mathrm{FB}} = (-4 \pm 16 \pm 18) \times 10^{-3}$$

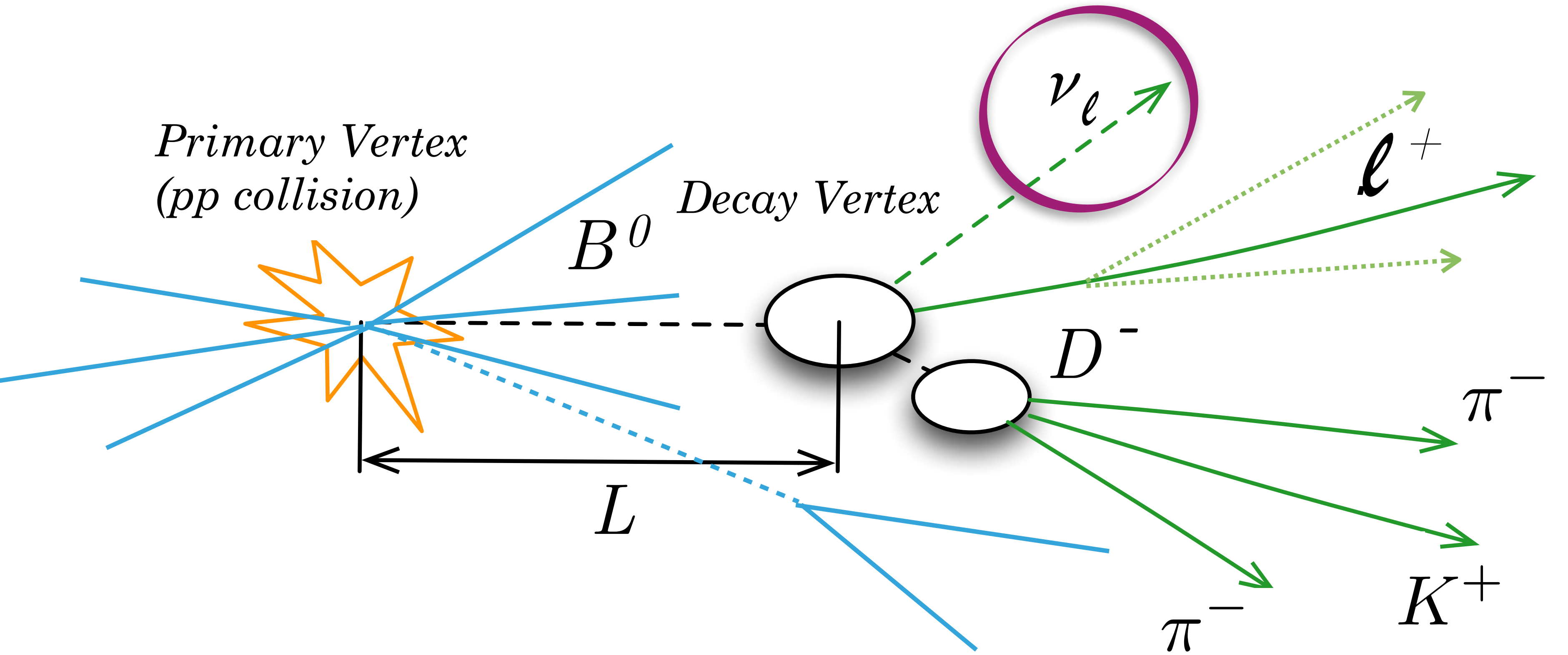
$$F^e_L = 0.521 \pm 0.005 \pm 0.007\,,$$
$$F^\mu_L = 0.534 \pm 0.005 \pm 0.006\,,$$
$$\Delta F_L = 0.013 \pm 0.007 \pm 0.007\,,$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{\mathrm{d}\cos\theta_V} = \frac{3}{2}\left(F_L\cos^2\theta_V + \frac{1-F_L}{2}\sin^2\theta_V\right)$$

Lepton flavour universality

More charged leptons ?

Non-reconstructable neutrino(s)

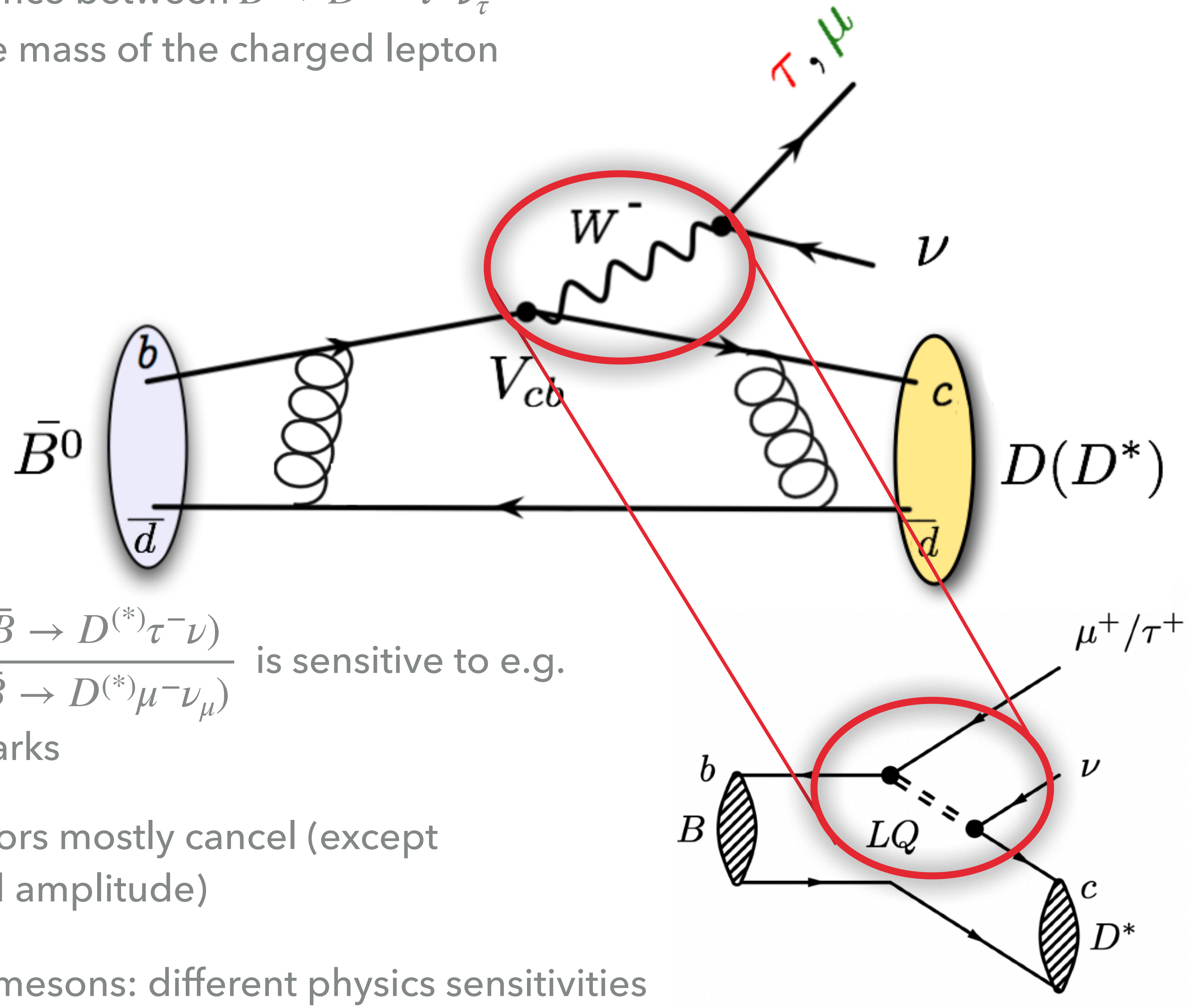


τ decay mode	BR[%]
$\tau \to \mu\bar{\nu}\nu$	17.39±0.04
$\tau \to e\bar{\nu}\nu$	17.82±0.04
$\tau \to 3\pi\nu$	9.31±0.05
$\tau \to 3\pi\pi^0\nu$	4.62±0.05
$\tau \to \pi\nu$	18.82±0.05
$\tau \to \rho\nu$	25.49±0.99

- Partial reconstruction → unconstrained kinematics
- Partial reconstruction → large backgrounds when missing more than one neutrino: need to fully exploit vertex topology information, track isolation, available kinematic information
- Taus @LHCb: muonic decay (direct comparison with Hb→Hcμν) or hadronic (3-prong) decay: better constrained kinematics using the tau decay vertex
- Electrons @LHCb: fewer electrons than muons (lower selection efficiency) and with worse resolution (Bremsstrahlung) - but less noticeable once you have already unconstrained kinematics

Lepton Universality

- In the SM the only difference between $\bar{B} \to D^{(*)+}\tau^-\bar{\nu}_\tau$ and $\bar{B} \to D^{(*)+}\mu^-\bar{\nu}_\mu$ is the mass of the charged lepton



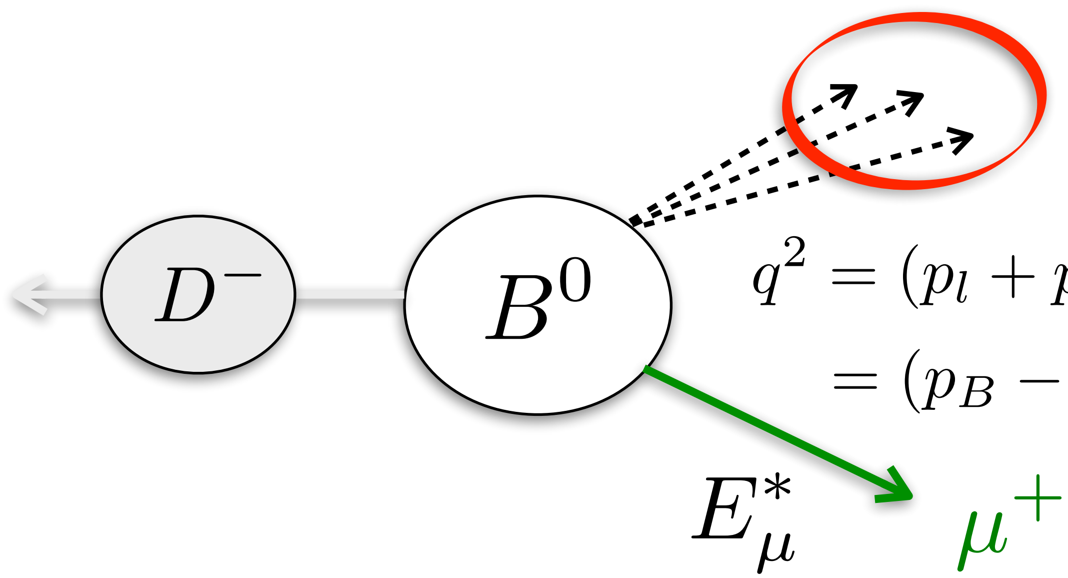
- The ratio $R(D^{(*)}) = \dfrac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\nu)}{\mathcal{B}(\bar{B} \to D^{(*)}\mu^-\nu_\mu)}$ is sensitive to e.g. charged Higgs, leptoquarks
    - Hadronic form factors mostly cancel (except helicity suppressed amplitude)
- D and D^* different spin mesons: different physics sensitivities
- Two recent LHCb results: $R(D^{(*)})$ with $\tau \to \mu\nu\nu$ and update of $R(D^*)$ with $\tau \to \pi\pi\pi\nu$

$R(D^{(*)})$ with $\tau \to \mu\nu\nu$ Measurement strategy

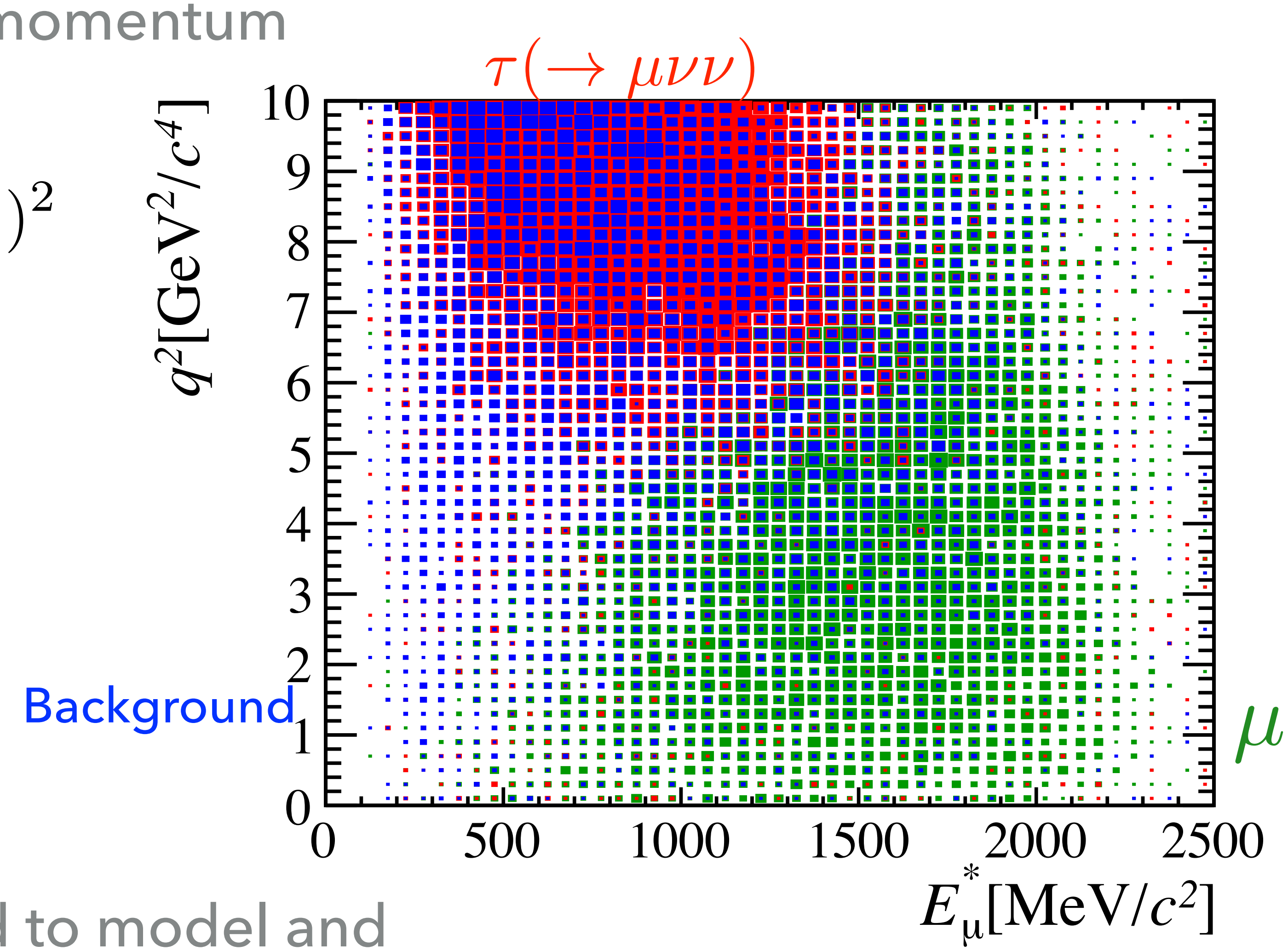
- Separate (partially reconstructed) signal, normalisation and background decays
- Can use B flight direction to measure transverse component of missing momentum (no way to measure longitudinal component)
- Use approximation to access rest frame kinematics
  - Collinear approximation $p_{z,B} = \frac{m_B}{m_{vis}} \cdot p_{z,vis}$
  - 20% (asymmetric) resolution on B momentum

$$R(D^{(*)}) = \frac{\mathcal{B}(B^0 \to D^{(*)}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)}l\nu)}$$

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



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

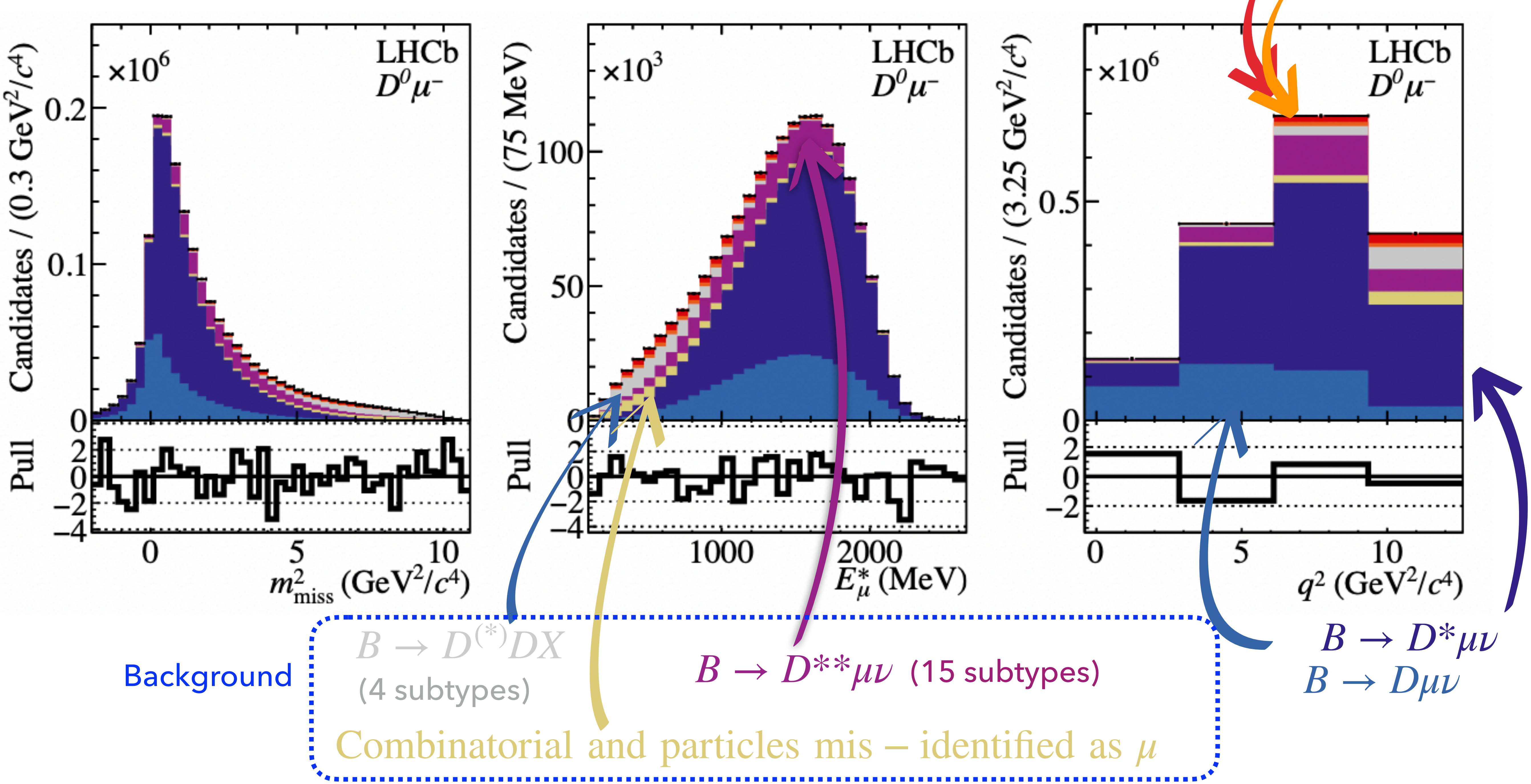


- Large MC (and data) samples needed to model and incorporate in the fit uncertainty on template shapes

$R(D^{(*)})$ with $\tau \to \mu\nu\nu$ Measurement strategy

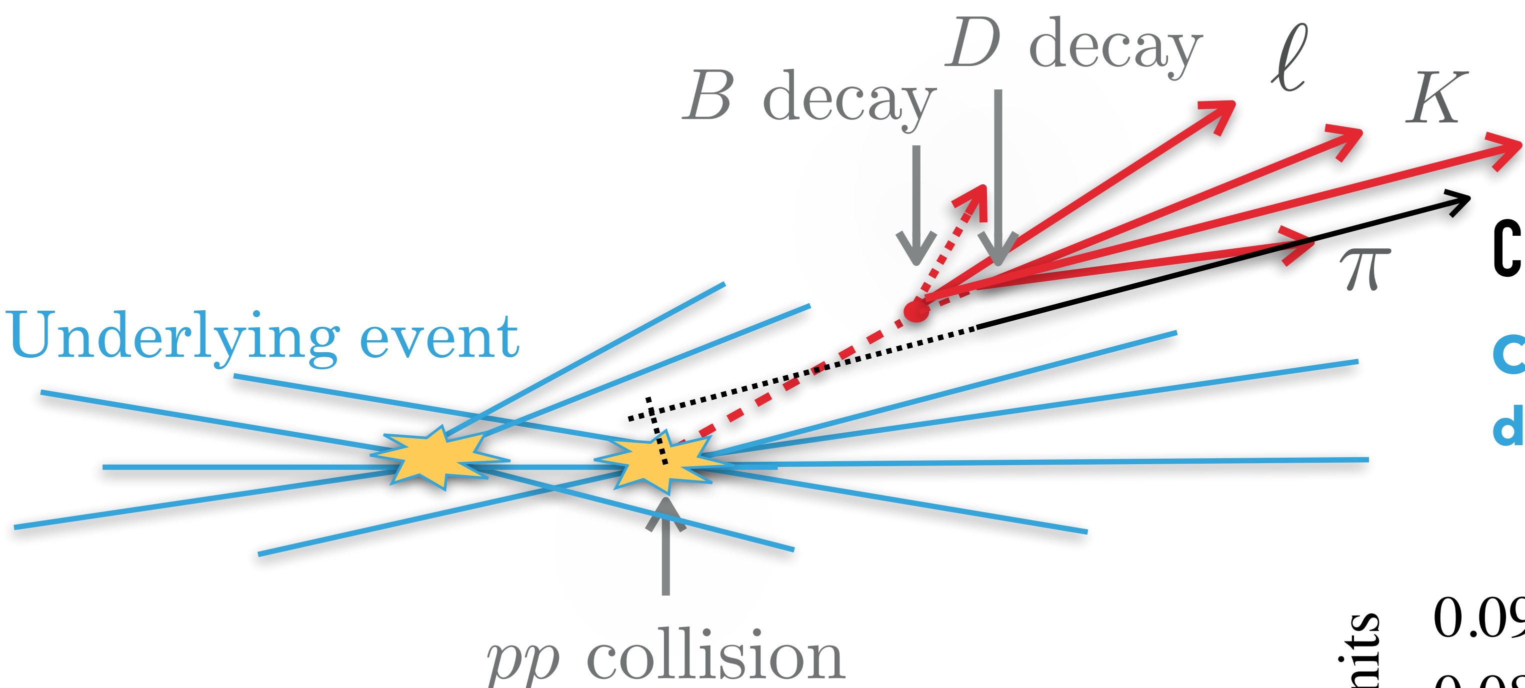
LHCb–PAPER–2022–039

- Three dimensional templated fit in $m^2_{\text{miss}}, E^*_\mu, q^2$
- Projections show signal enriched (isolated) region, Run 1 (2011-2012)



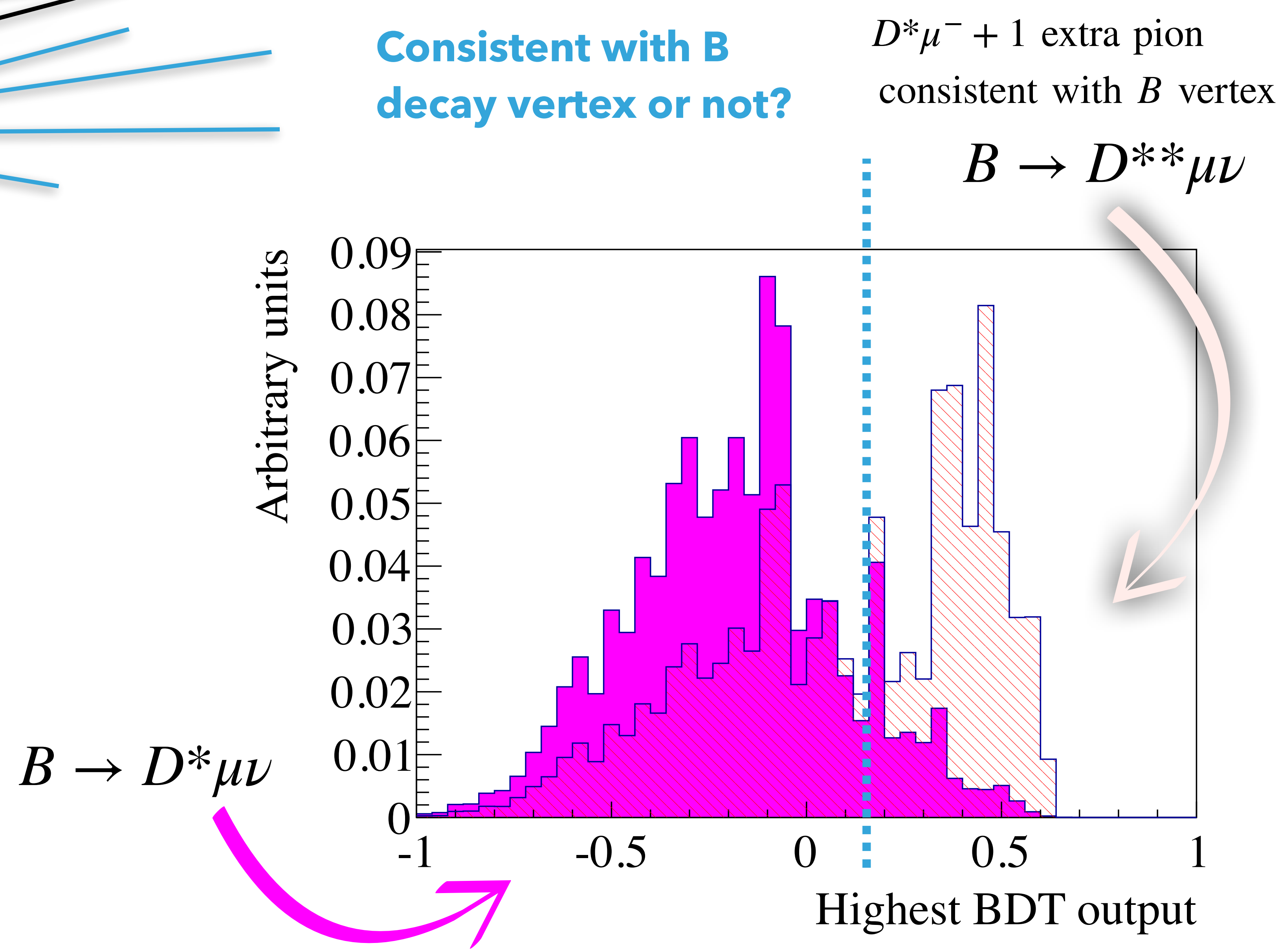
- Shape variations of all major backgrounds controlled using data samples

Track isolation and control regions

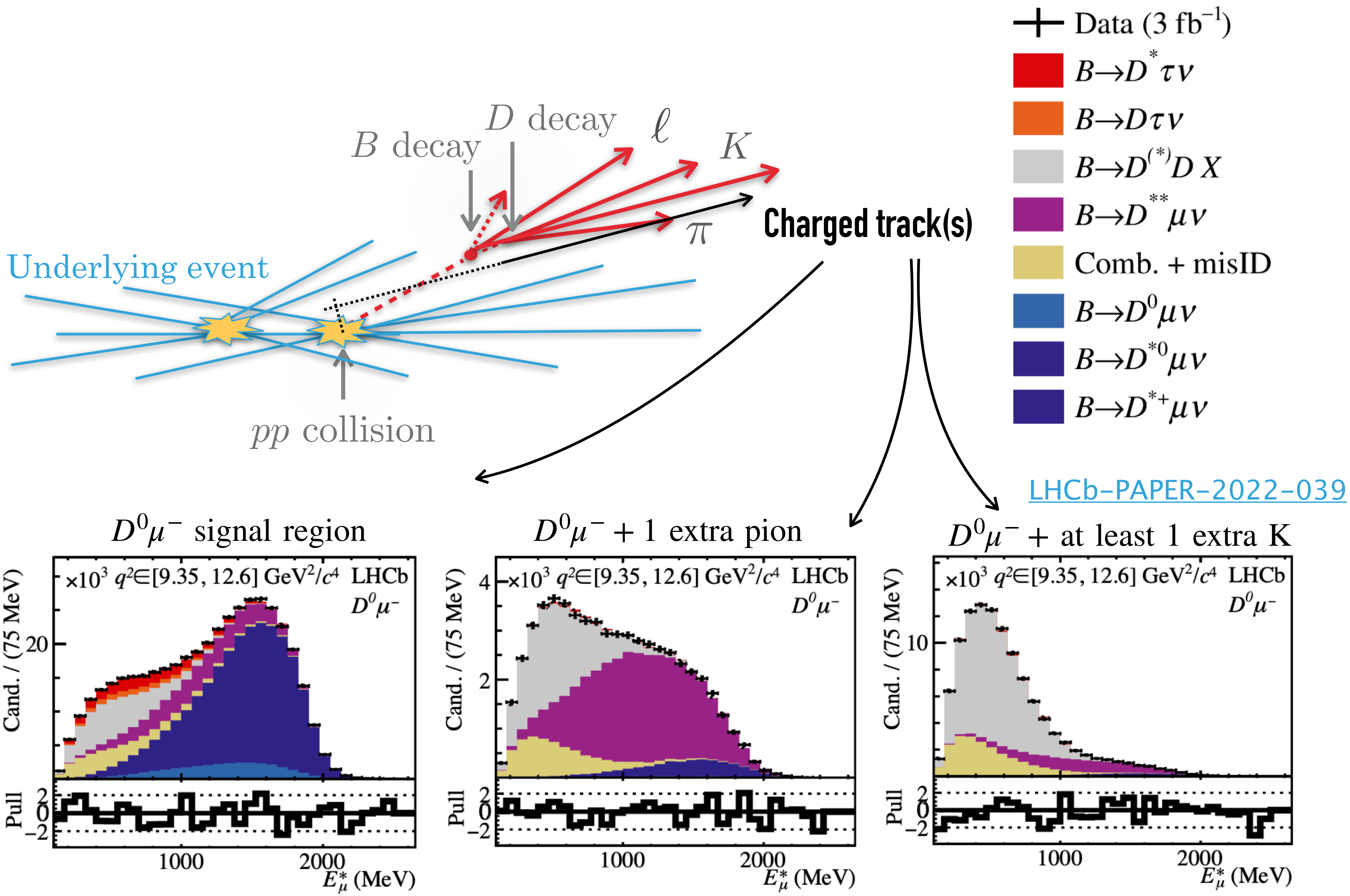


Charged track

Consistent with B decay vertex or not?



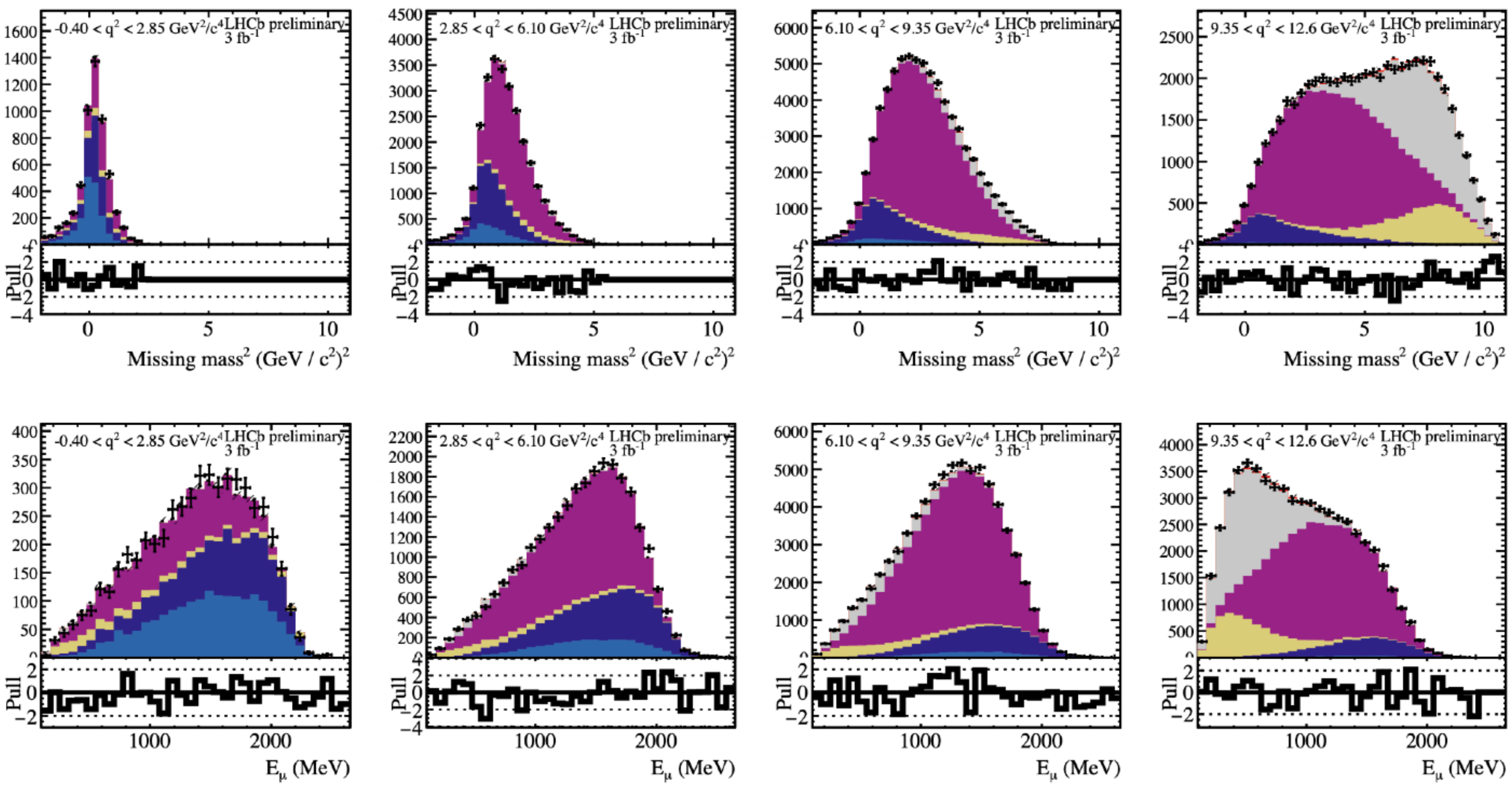
Track isolation and control regions

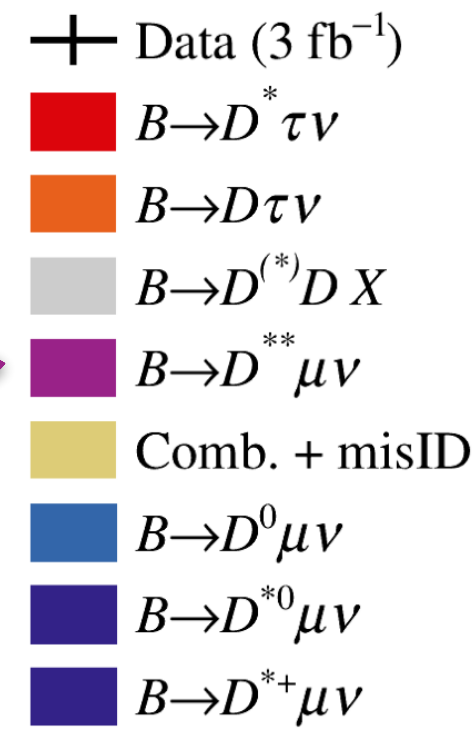


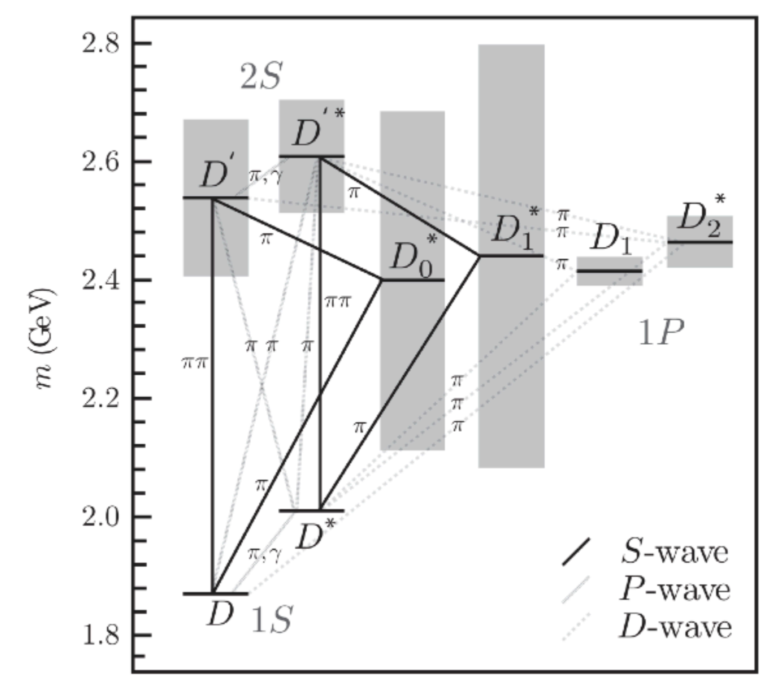
$B \to D^{**}$ backgrounds

- Signal region + 3 control region for D0 and D* - simultaneous fit in 8 regions

$D^0\mu^- + 1$ extra pion





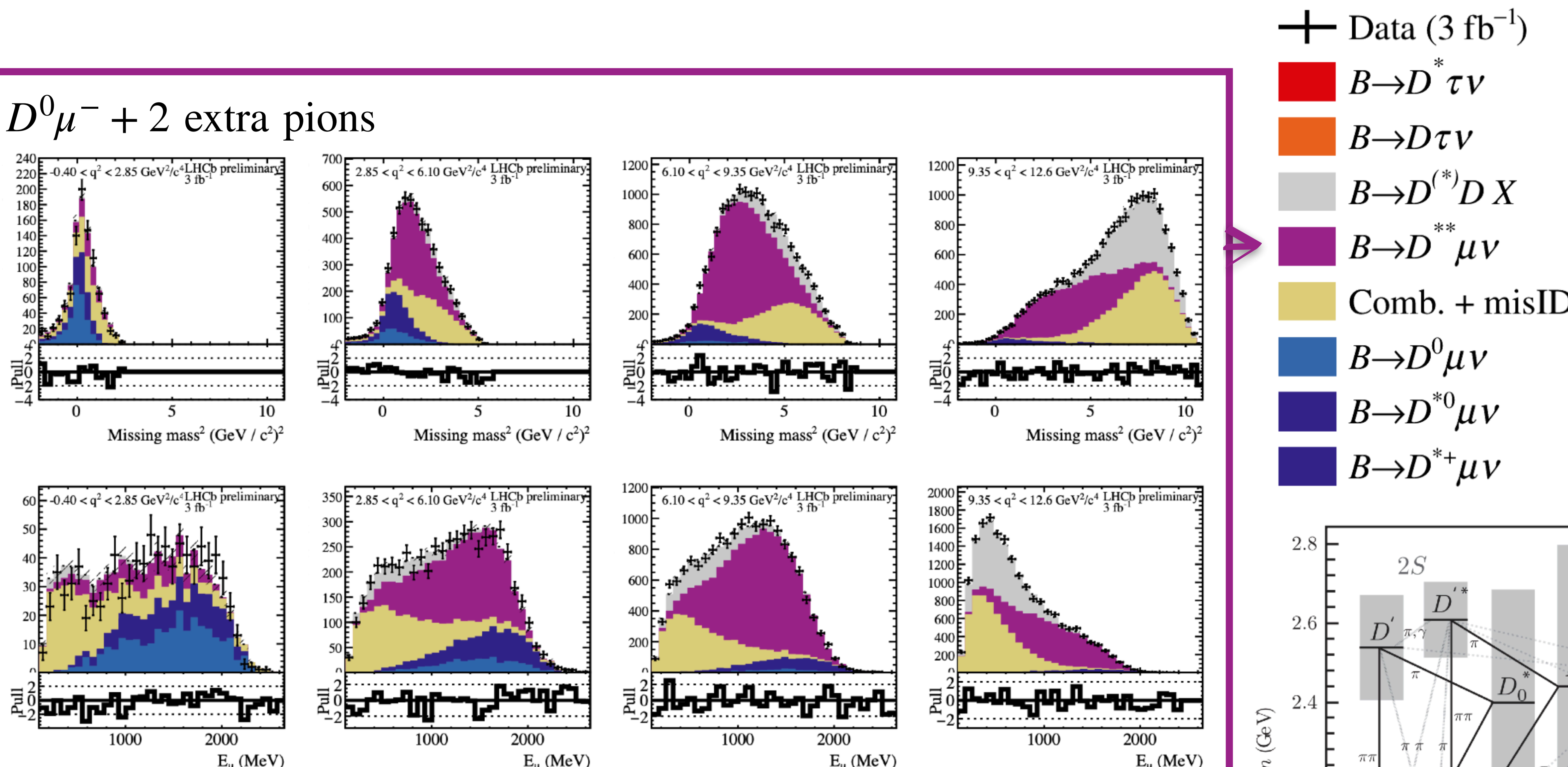


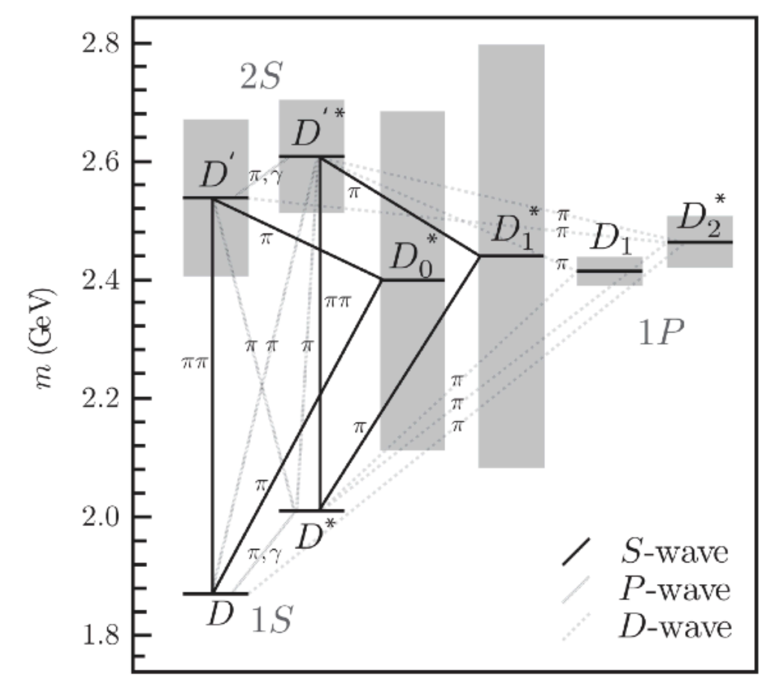
- D** backgrounds: include the four known resonances, individually floating yields
- Updated model from [Bernlochner and Ligeti] all parameters unconstrained

$B \to D^{**}$ backgrounds

- Signal region + 3 control region for D0 and D* - simultaneous fit in 8 regions

$D^0\mu^- + 2$ extra pions

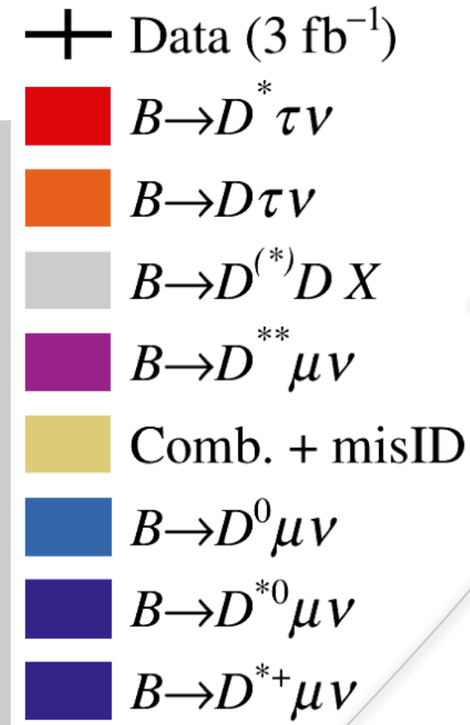




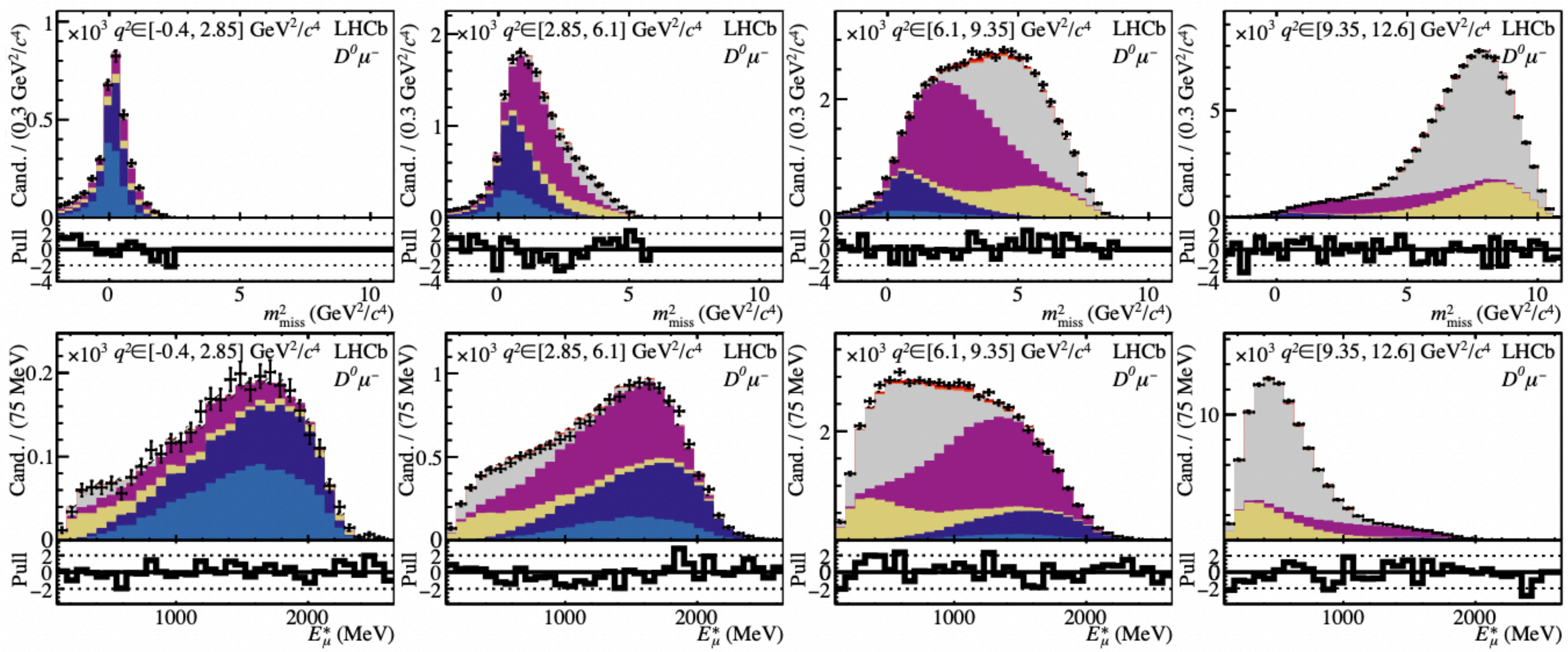
- Heavier D** backgrounds: (including non-resonant)
- No theory model: cocktail sample, variation in q^2 slope

$B \to DD$ backgrounds

- Signal region + 3 control region for D0 and D* - simultaneous fit in 8 regions



$D^0\mu^- +$ at least 1 extra K

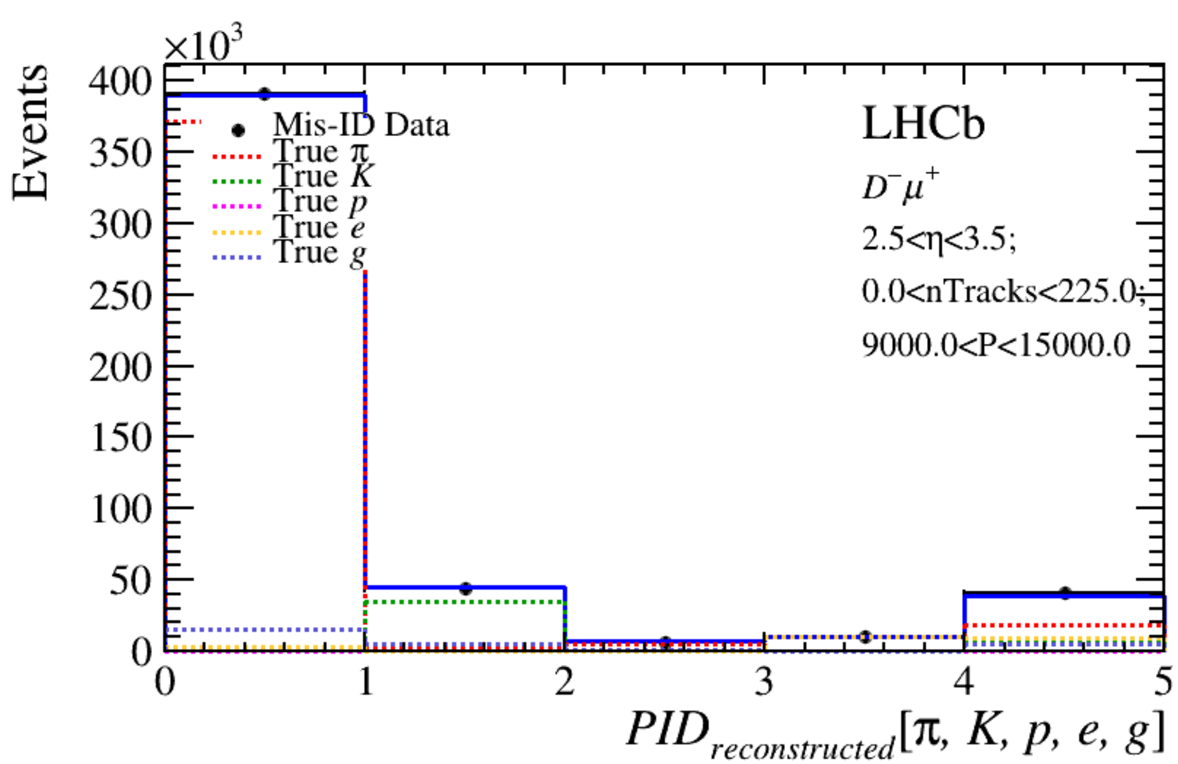


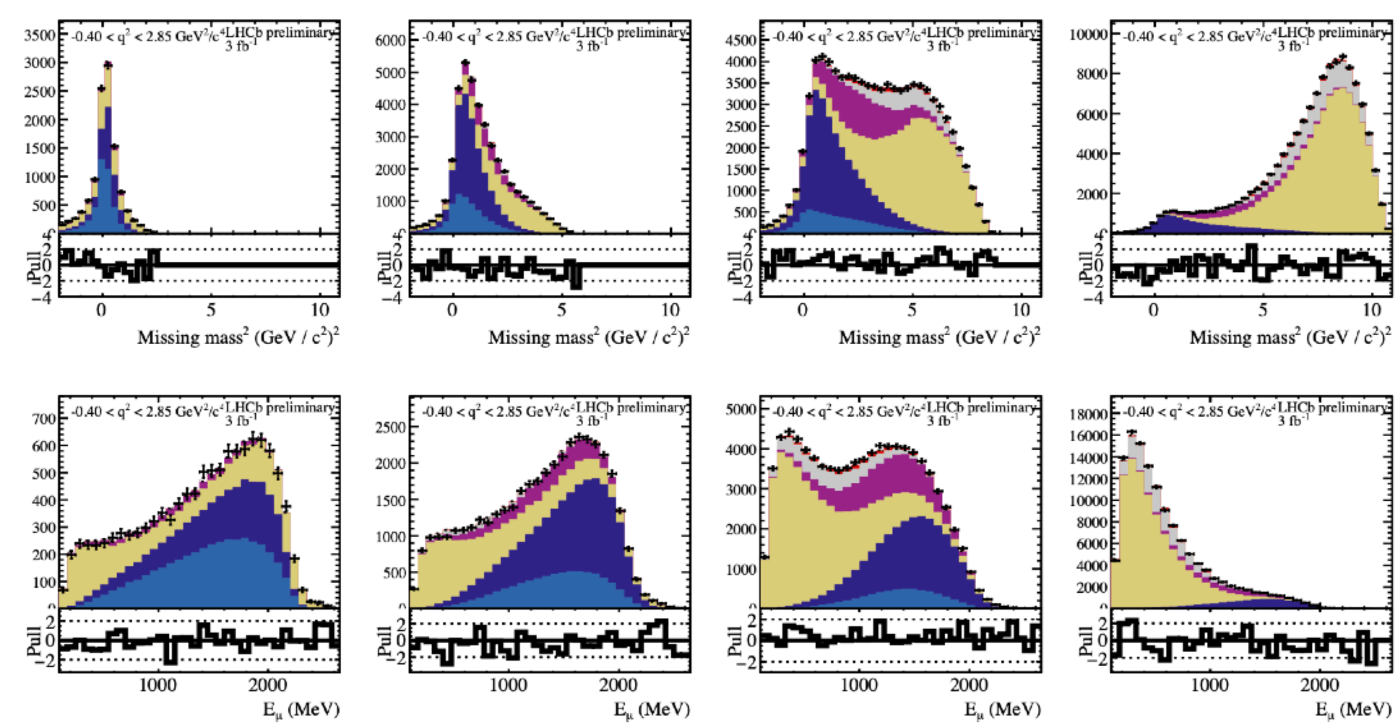
- $B \to D^0 DX$ backgrounds
- Spread from an ensemble of alternative models taken as systematic uncertainty

- Third largest uncertainty after statistical and systematic due to simulation statistics

Muon (mis)identification

- Background from particles mis-identified as muons
- Low momenta of muons from tau leptons: easy to mis-ID other particles as muon
- Data-driven methods needed to describe these backgrounds: reconstruct $B \to Dh$ decays (selection identical to the signal but the muon-ID), understand the composition of the $B \to Dh$ sample and estimate the background shape using PID efficiencies (from data too)
- Define a sample region to validate the model obtained
- Worry about details (e.g. how about $\pi \to \mu\nu$ decays?)



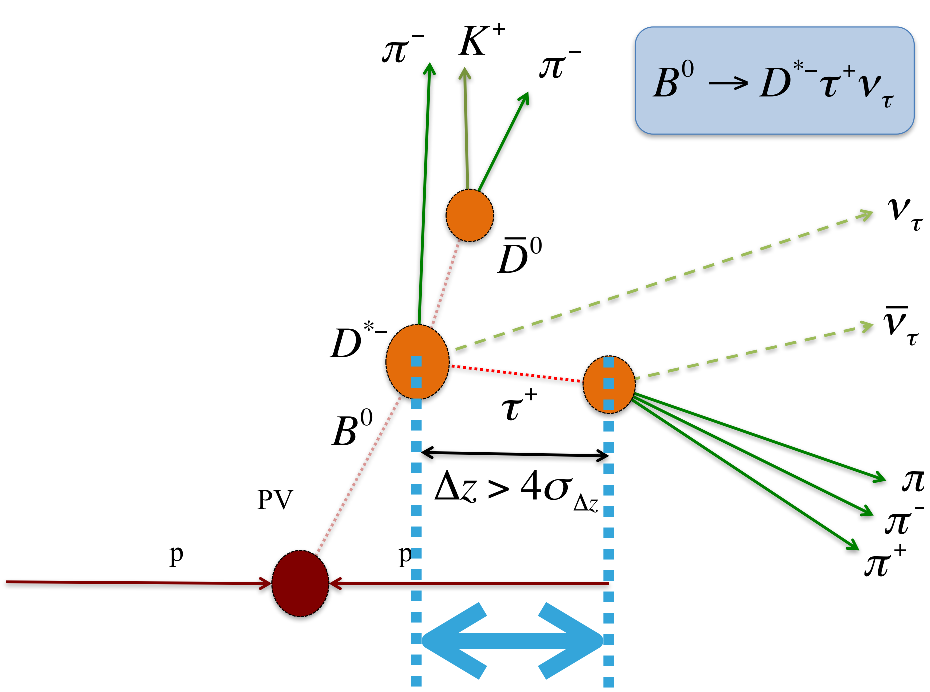


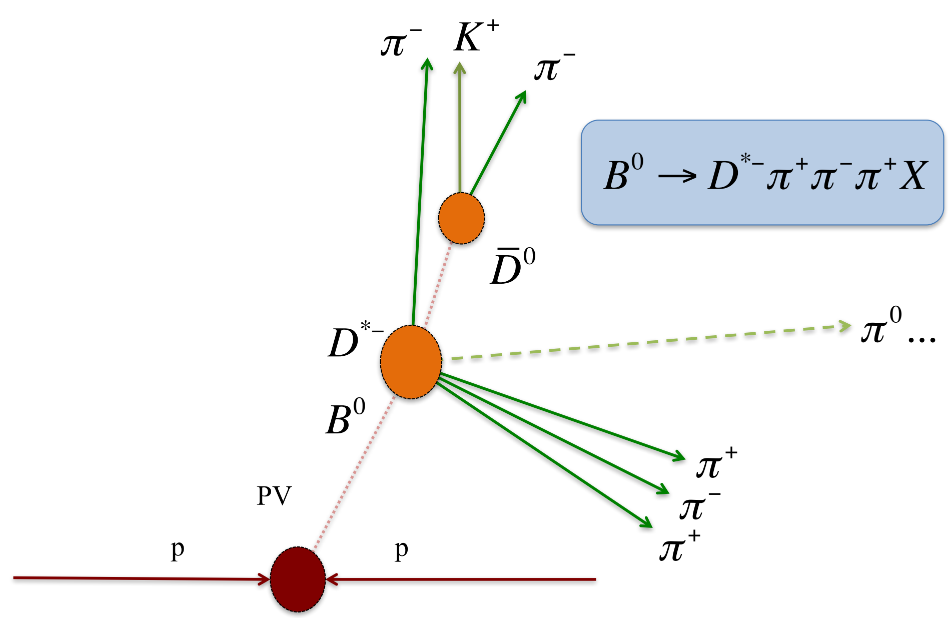
Systematics

Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	**Correlation**
Statistical uncertainty	1.8	6.0	−0.49
Simulated sample size	1.5	4.5	
$B \to D^{(*)}DX$ template shape	0.8	3.2	
$\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ form-factors	0.7	2.1	
$\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu$ form-factors	0.8	1.2	
$\mathcal{B}\ (\overline{B} \to D^* D_s^-(\to \tau^-\overline{\nu}_\tau)X\ )$	0.3	1.2	
MisID template	0.1	0.8	
$\mathcal{B}\ (\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau\ )$	0.5	0.5	
Combinatorial	< 0.1	0.1	
Resolution	< 0.1	0.1	
Additional model uncertainty	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
$B \to D^{(*)}DX$ model uncertainty	0.6	0.7	
$\overline{B}_s^0 \to D_s^{**}\mu^-\overline{\nu}_\mu$ model uncertainty	0.6	2.4	
Data/simulation corrections	0.4	0.8	
Coulomb correction to $\mathcal{R}(D^{*+})/\mathcal{R}(D^{*0})$	0.2	0.3	
MisID template unfolding	0.7	1.2	
Baryonic backgrounds	0.7	1.2	
Normalization uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
Data/simulation corrections	$0.4\times\mathcal{R}(D^*)$	$0.6\times\mathcal{R}(D^0)$	
$\tau^- \to \mu^-\nu\overline{\nu}$ branching fraction	$0.2\times\mathcal{R}(D^*)$	$0.2\times\mathcal{R}(D^0)$	
Total systematic uncertainty	2.4	6.6	−0.39
Total uncertainty	3.0	8.9	−0.43

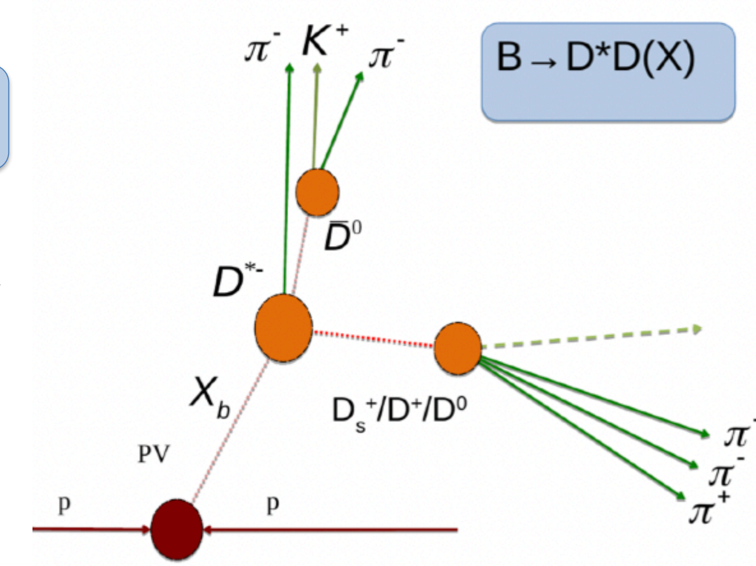
$R(D^*)$ with $\tau \to \pi\pi\pi\nu$ Measurement strategy

- Compared to measurements using $\tau \to \mu\nu\nu$
  - Different background composition:
    - No $B \to D^{*(*)}\mu\nu$ (large) components
    - Additional $B \to D^*\pi\pi\pi X$ backgrounds
    - $B \to D^*DX$ with $D^* \to \pi\pi\pi X$
  - Need external input: measure rate relative to $B \to D^*\pi\pi\pi$
- Update including LHCb 2015+2015 dataset
- Topology (e.g. flight distance of tau) suppresses "prompt" background



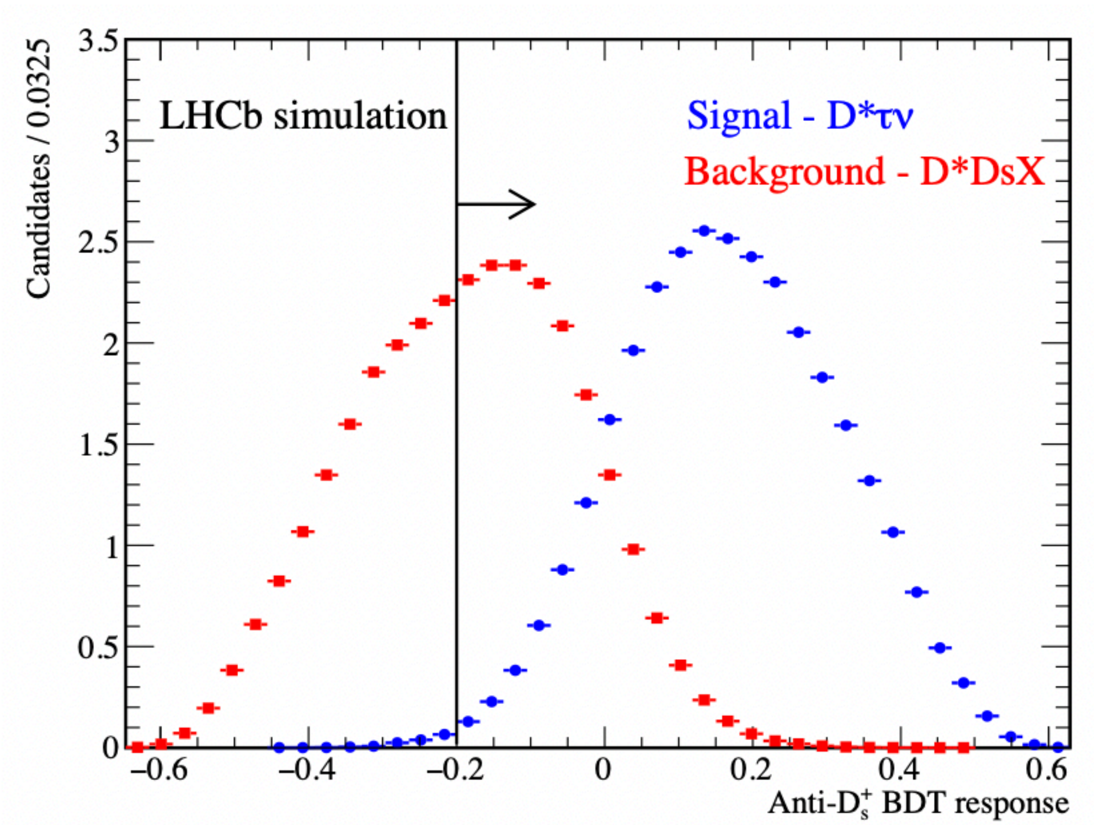


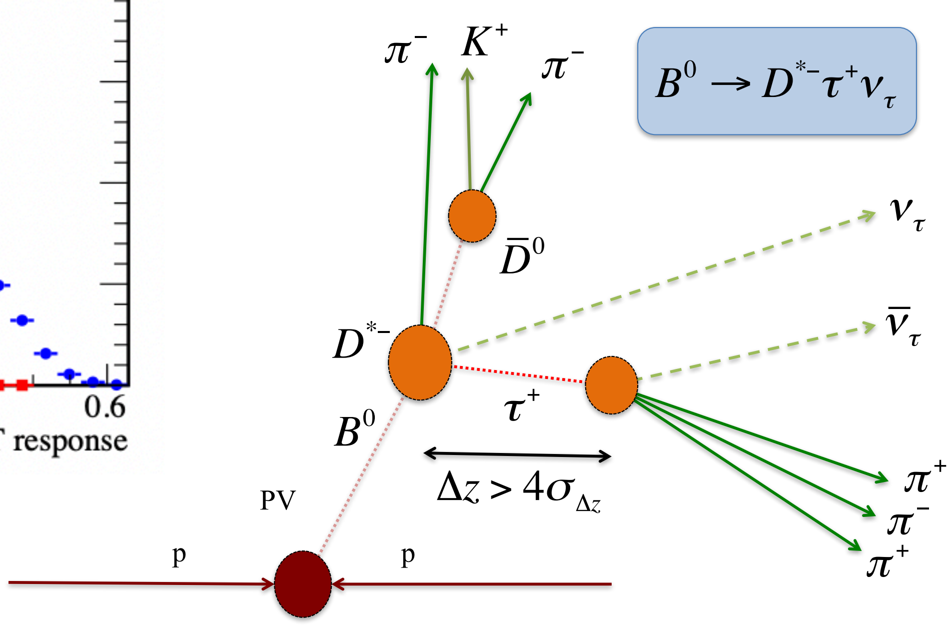
Suppress 99% of this bkg
(originally x100 the signal)

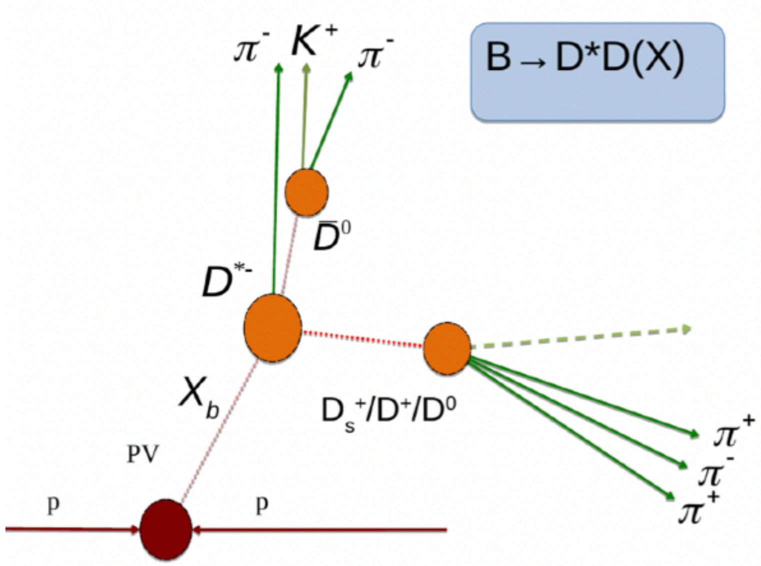


$R(D^*)$ with $\tau \to \pi\pi\pi\nu$ Background modelling

- $B \to D^{*-}(D^0, D^+, D_s^+)X$ backgrounds
- $B \to D^{*-}D_s^+X$ the largest contribution
- Use BDT classifier based on dynamics and the $\pi\pi\pi$ resonant (sub) structure to separate signal from $B \to D^{*-}D_s^+X$
- Use data control region to model backgrounds



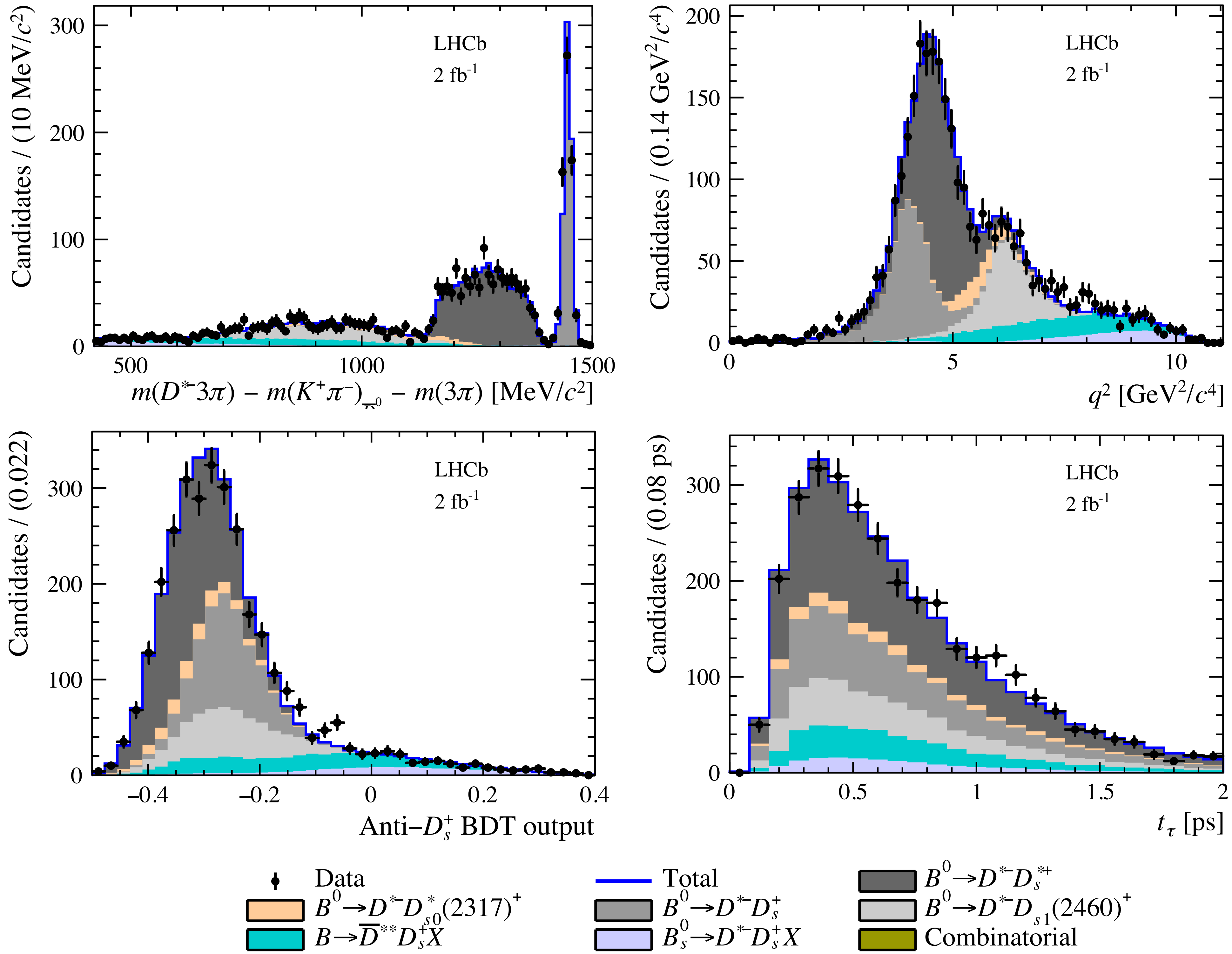


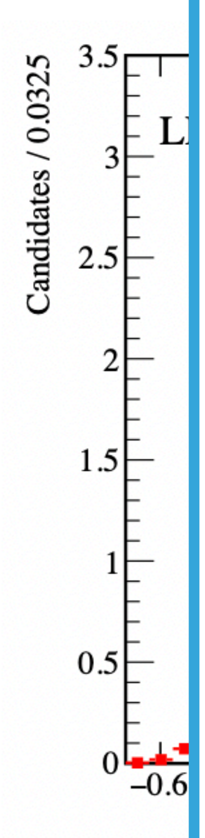


$R(D^*)$ with $\tau \to \pi\pi\pi\nu$ Background modelling

- $B \to D^{*-}(D^0, D^+, D_s^+)X$ backgrounds

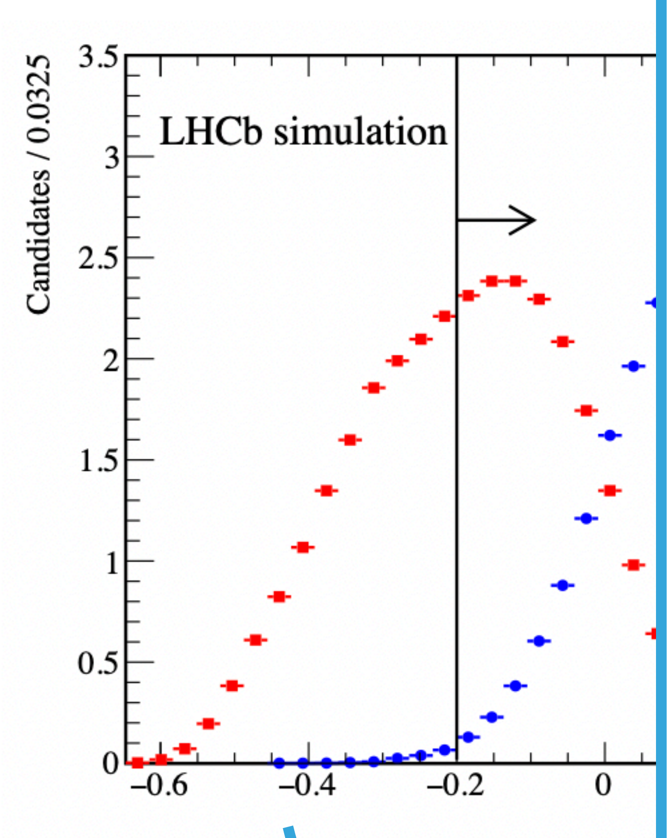
Can use $D_{(s)} \to \pi\pi\pi$ mass peak to select a pure $B \to D^*DX$ sample



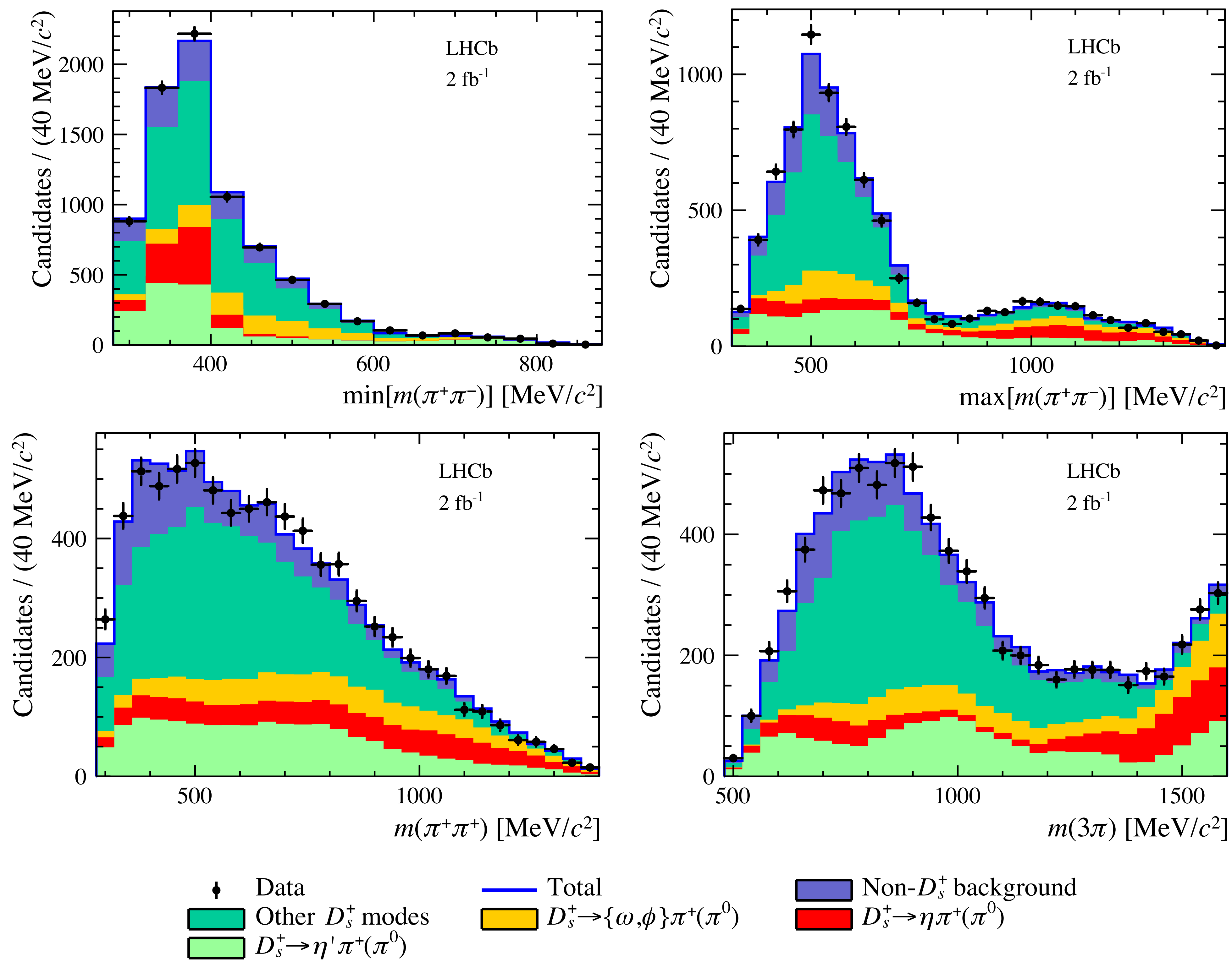


$R(D^*)$ with $\tau \to \pi\pi\pi\nu$ Background modelling

- $B \to D^{*-}(D^0, D^+, D_s^+)X$ backgrounds
- $B \to D^{*-}D_s^+X$ t
- Use BDT classifi
  to separate sign
- Use data contro



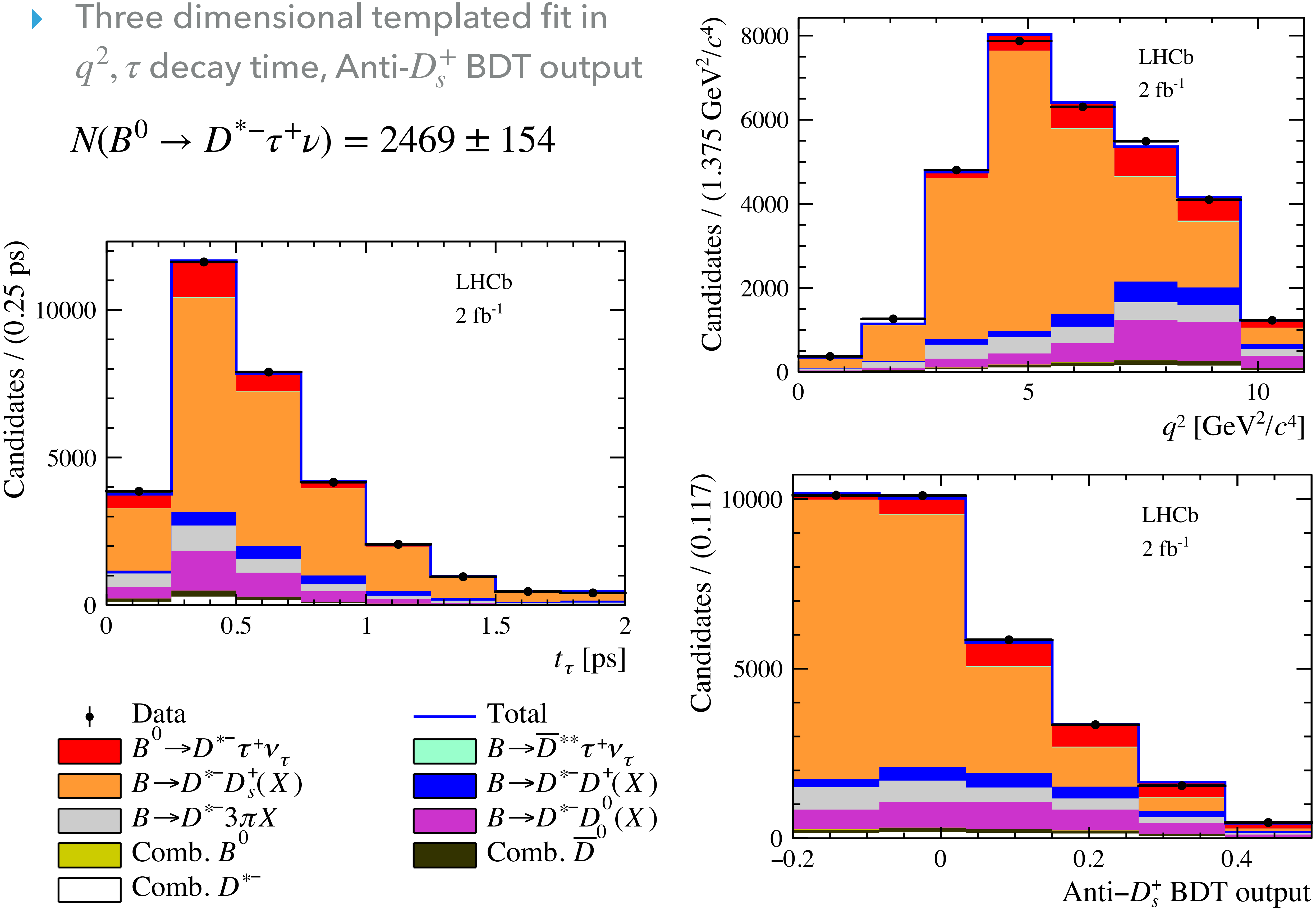
Use low anti-Ds BDT region to control $D_s \to \pi\pi\pi X$ structure



$R(D^*)$ with $\tau \to \pi\pi\pi\nu$ Fit

- Three dimensional templated fit in q^2, τ decay time, Anti-D_s^+ BDT output

$N(B^0 \to D^{*-}\tau^+\nu) = 2469 \pm 154$

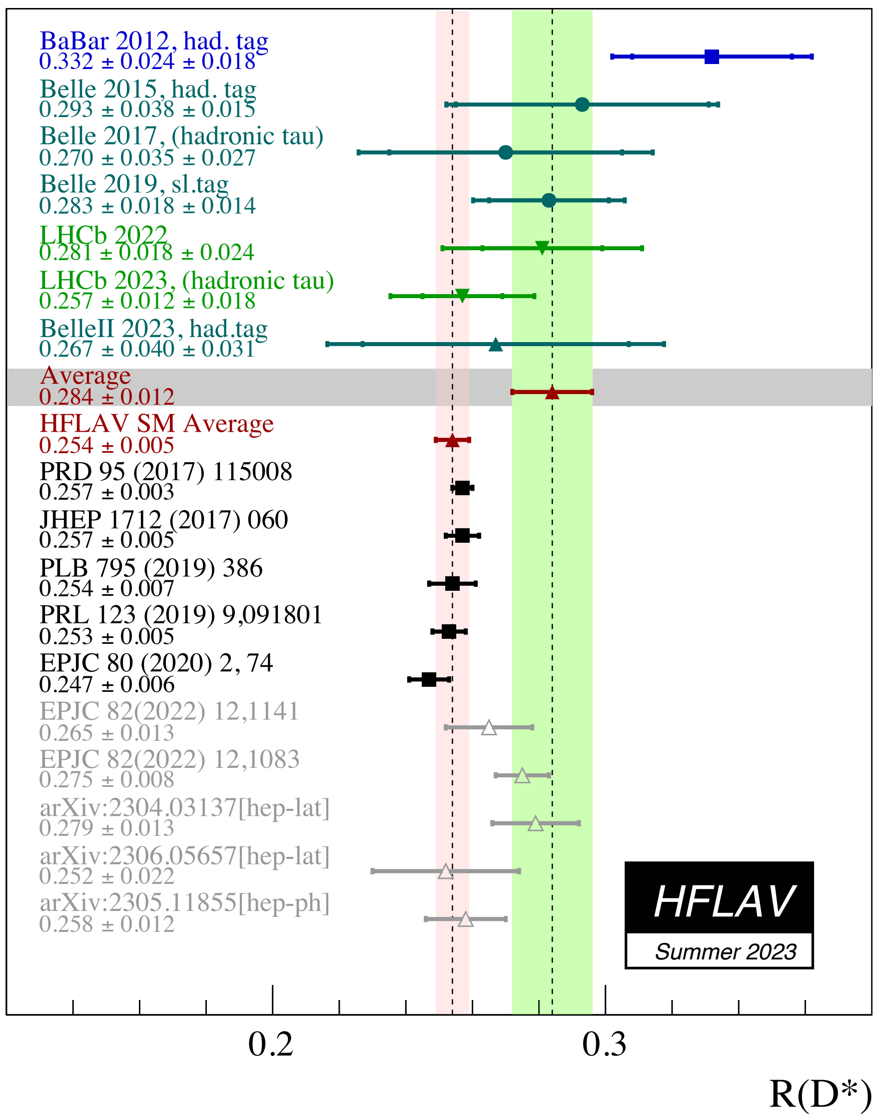


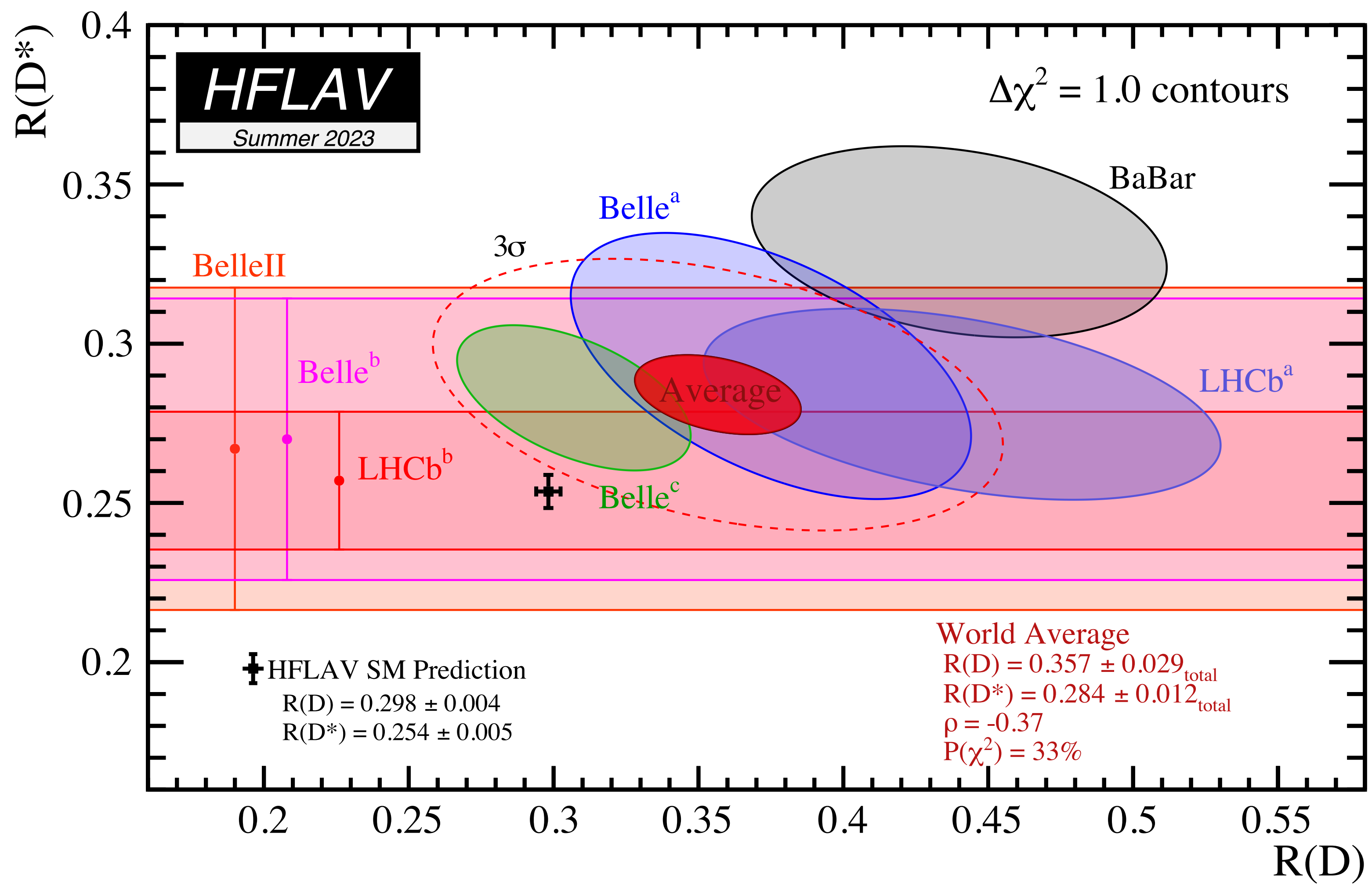
Latest LFU experimental results

$$R(D^{(*)}) = \frac{\mathcal{B}(B^0 \to D^{(*)}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)}l\nu)}$$

$$R(D^*) = 0.281 \pm 0.018 \pm 0.024 \quad \rho = -0.43$$
$$R(D) = 0.441 \pm 0.060 \pm 0.066$$

$$R(D^*) = 0.257 \pm 0.012(\text{stat}) \pm 0.014(\text{syst}) \pm 0.012(\text{ext}) \quad [\text{Run1} + 15 + 16]$$





$$R(D^*) = 0.267\ ^{+0.041}_{-0.039}(\text{stat.})\ ^{+0.028}_{-0.033}(\text{syst.})$$

New Belle II result at Lepton Photon

Conclusions

- Semileptonic decays are a great tool to probe the fundamental structure and parameters of the SM, with controlled theoretical uncertainties.
- Main experimental challenge with semileptonic decays (@LHCb) is the missing neutrino. Have developed ways to mitigate this in the last ~10 years.
- Many exciting results (and challenges) to come

Back-up

$R(D^*)$ with $\tau \to \pi\pi\pi\nu$ Systematics

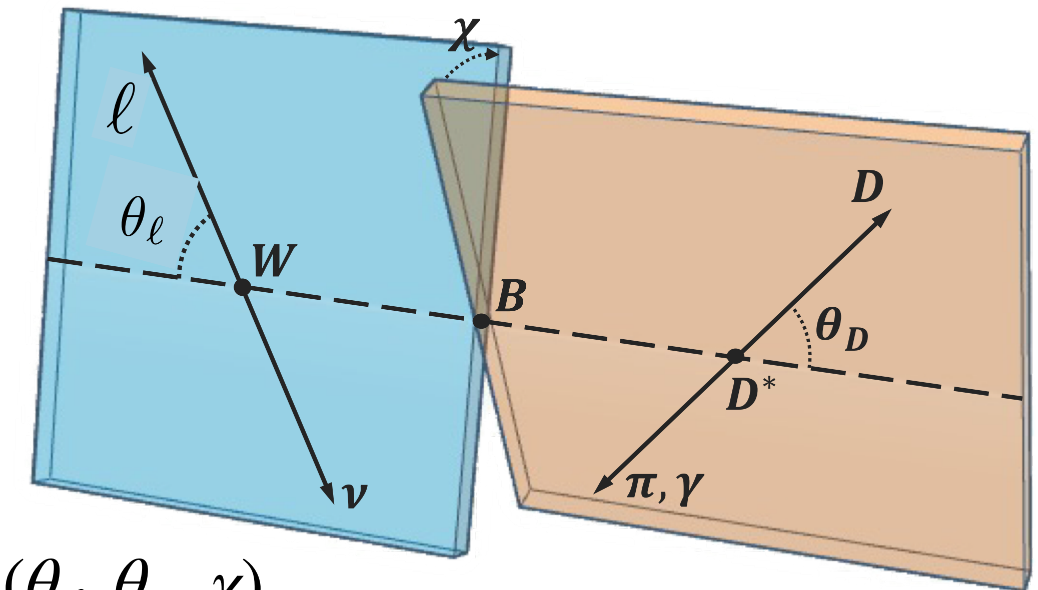
Source	systematic uncertainty (%)
PDF shapes uncertainty (size of simulation sample)	2.0
Fixing $B \to D^{*-} D_s^+(X)$ bkg model parameters	1.1
Fixing $B \to D^{*-} D^0(X)$ bkg model parameters	1.5
Fractions of signal τ^+ decays	0.3
Fixing the $\overline{D}^{**}\tau^+\nu_\tau$ and $D_s^{**+}\tau^+\nu_\tau$ fractions	$^{+1.8}_{-1.9}$
Knowledge of the $D_s^+ \to 3\pi X$ decay model	1.0
Specifically the $D_s^+ \to a_1 X$ fraction	1.5
Empty bins in templates	1.3
Signal decay template shape	1.8
Signal decay efficiency	0.9
Possible contributions from other τ^+ decays	1.0
$B \to D^{*-} D^+(X)$ template shapes	$^{+2.2}_{-0.8}$
$B \to D^{*-} D^0(X)$ template shapes	1.2
$B \to D^{*-} D_s^+(X)$ template shapes	0.3
$B \to D^{*-} 3\pi X$ template shapes	1.2
Combinatorial background normalisation	$^{+0.5}_{-0.6}$
Preselection efficiency	2.0
Kinematic reweighting	0.7
Vertex error correction	0.9
PID efficiency	0.5
Signal efficiency (size of simulation sample)	1.1
Normalisation mode efficiency (modelling of $m(3\pi)$)	1.0
Normalisation efficiency (size of simulation sample)	1.1
Normalisation mode PDF choice	1.0
Total systematic uncertainty	$^{+6.2}_{-5.9}$
Total statistical uncertainty	5.9

$$R(D^*) = \mathcal{K}(D^*) \left\{ \frac{\mathcal{B}(B^0 \to D^{*-} 3\pi^\pm)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)} \right\}$$

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-} 3\pi^\pm)} = \frac{N_{\rm sig}}{N_{\rm norm}} \frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}} \frac{1}{\mathcal{B}(\tau^+ \to 3\pi^\pm(\pi^0)\overline{\nu}_\tau)}$$

Expanding differential measurements

- Fully differential decay rate
- Helicity angles (and derived observables) are sensitive to New Physics contributions and hadronic interactions (Form Factors)



$$\frac{d\Gamma(B \to D^*\ell\nu)}{dw d\cos\theta_\ell d\cos\theta_d d\chi} = \frac{3m_B^3 m_{D^*}^2 G_F^2}{16(4\pi)^4}\eta_{EW}|V_{cb}|^2 \sum_i^6 \mathcal{H}_i(w) k_i(\theta_\ell, \theta_D, \chi)$$

- Hadronic Form Factor parametrisation
  - Boyd, Grinstein, Lebed (BGL) [Phys. Rev. D56, 6895 (1997)]:

$$g(z) = \frac{1}{P_g(z)\phi_g(z)} \sum_{n=0}^{n_a-1} a_n z^n,$$

$$f(z) = \frac{1}{P_f(z)\phi_f(z)} \sum_{n=0}^{n_b-1} b_n z^n, \qquad z = \frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}}$$

$$\mathcal{F}_1(z) = \frac{1}{P_{\mathcal{F}_1}(z)\phi_{\mathcal{F}_1}(z)} \sum_{n=0}^{n_c-1} c_n z^n,$$

  - Caprini, Lellouch, Neubert (CLN) [Nucl. Phys. B530, 153 (1998)]:

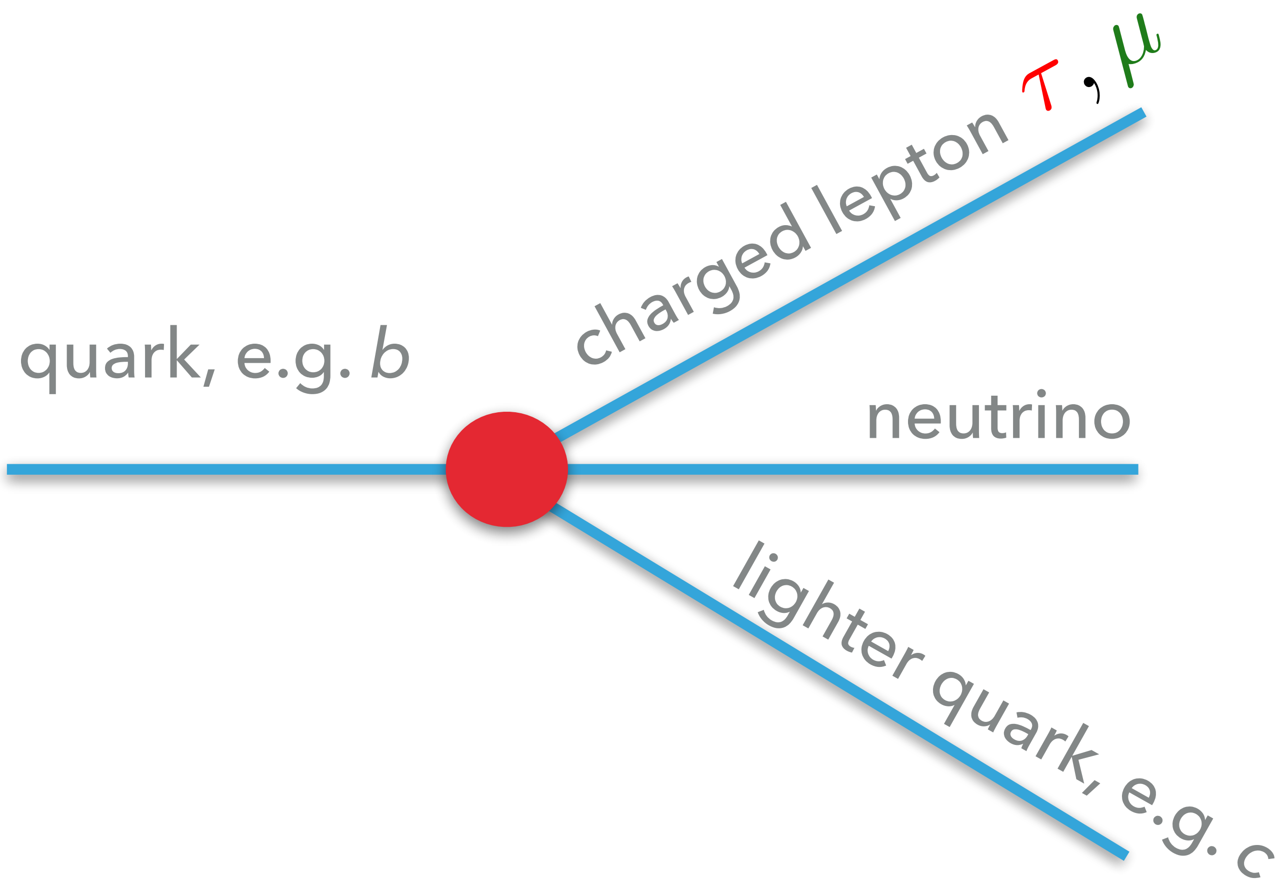
$$h_{A_1}(z) = h_{A_1}(w=1)\left(1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3\right)$$

$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$

$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2$$

EFT: modelling New Physics (and hadronic) effects

- What if we want to tell apart all possible NP contributions(s)



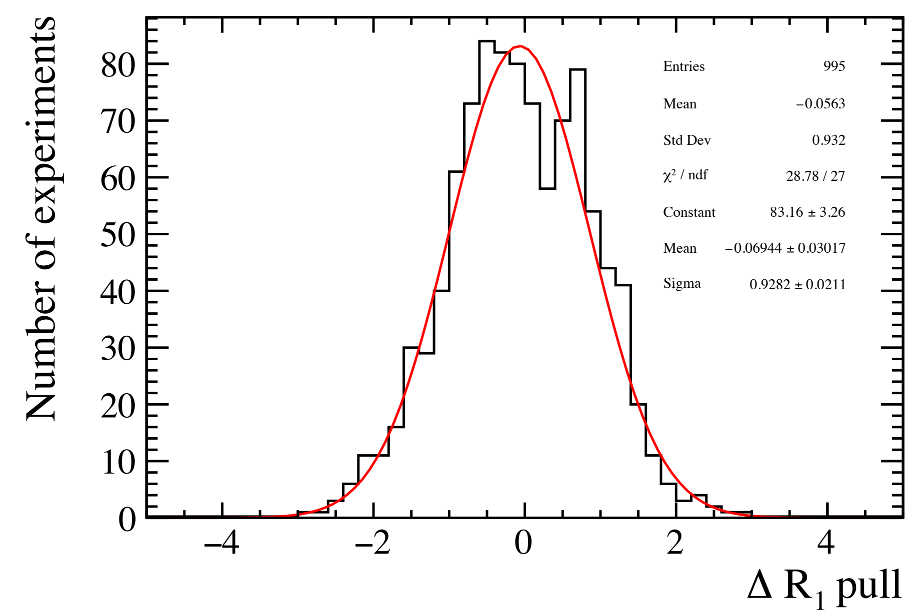
Wilson coefficients

$$\mathcal{C}_i = \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}$$

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{cb} \sum_i C_i \mathcal{O}_i$$

Effective operators

- HAMMER tool (F. Bernlochner, S. Duell, Z. Ligeti, M. Papucci, D. Robinson, Eur. Phys. J. C 80, 883 (2020)) to re-weight MC events and obtain "dynamic" templates, (for-)folding in the experimental resolution
- Extract Wilson Coefficients and hadronic Form Factor parameters from a fit to data (JINST 17 T04006)



EFT: modelling New Physics (and hadronic) effects

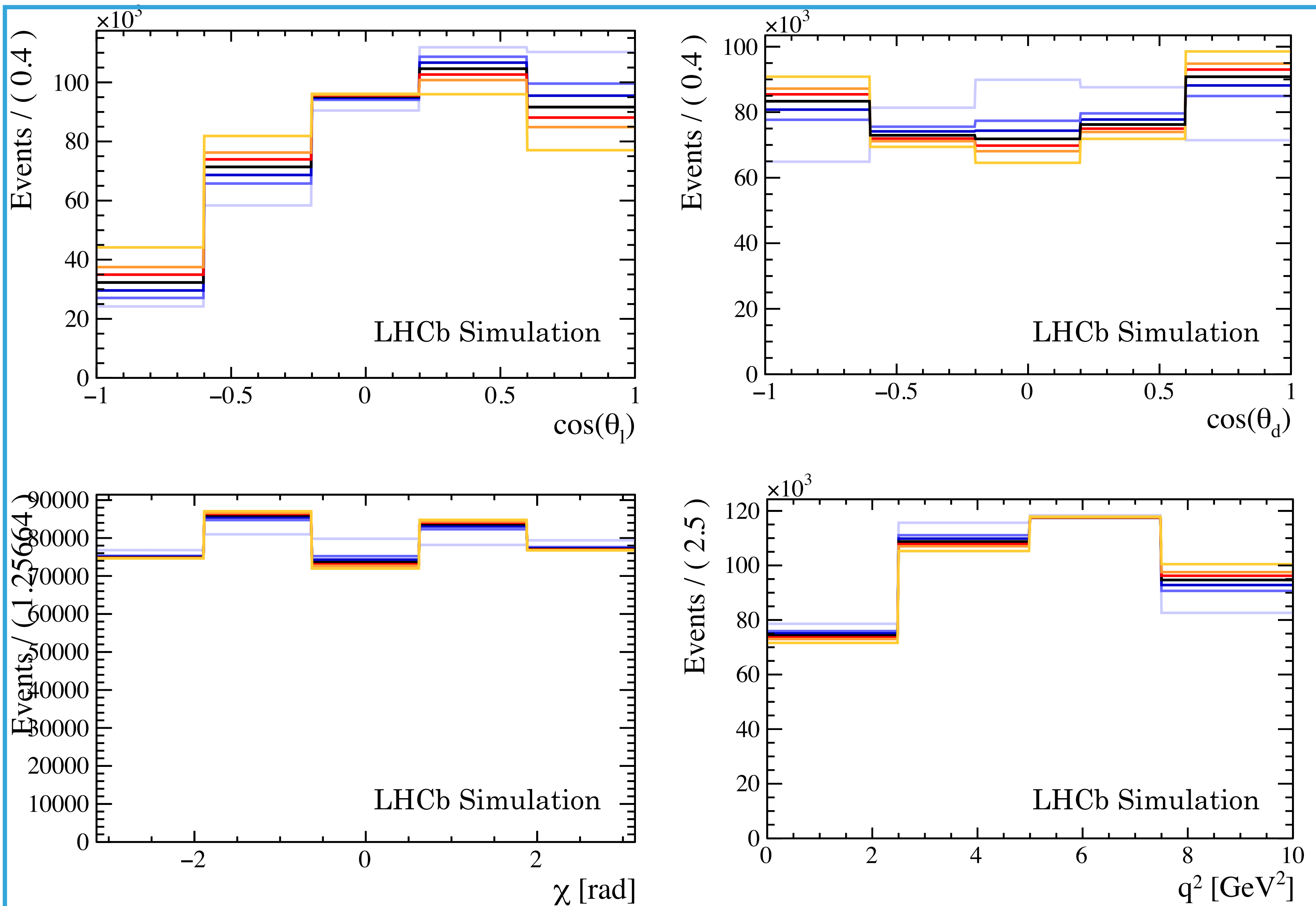
$B^0 \to D^{(*)}\mu\nu$

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{cb} \sum_i C_i \mathcal{O}_i$$

SM

$$= \frac{G_F}{\sqrt{2}} V_{cb} \Big[(1 + g_V)\bar{c}\gamma_\mu b + (-1 + g_A)\bar{c}\gamma_\mu\gamma_5 b + g_S i\partial_\mu(\bar{c}b) + g_P i\partial_\mu(\bar{c}\gamma_5 b) + g_T i\partial^\nu(\bar{c}i\sigma_{\mu\nu}b) + g_{T5} i\partial^\nu(\bar{c}i\sigma_{\mu\nu}\gamma_5 b) \Big] \bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell + h.c.$$

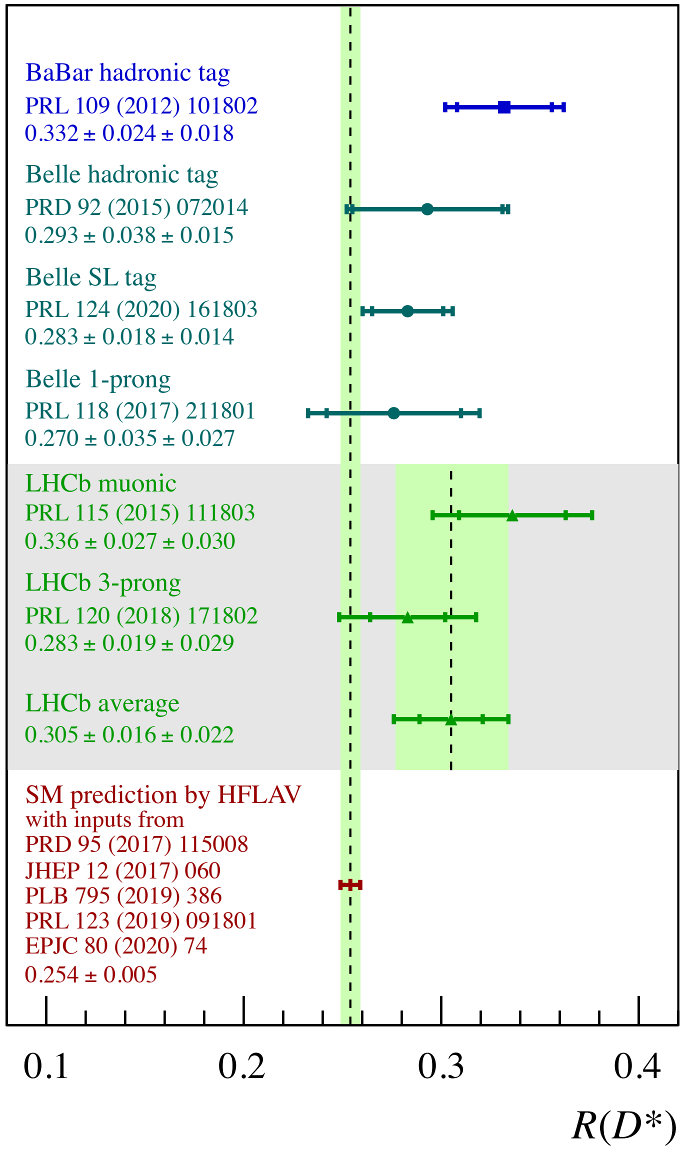
$$\mathcal{R}e(V_{qRlL}) = \{-0.5, -0.2, -0.1, 0.0, 0.1, 0.2, 0.5\}$$

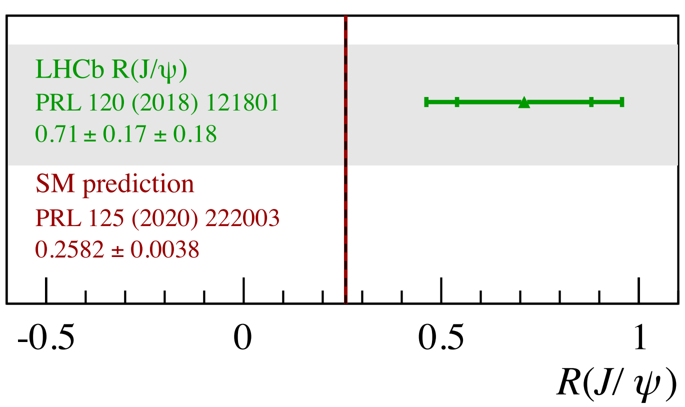


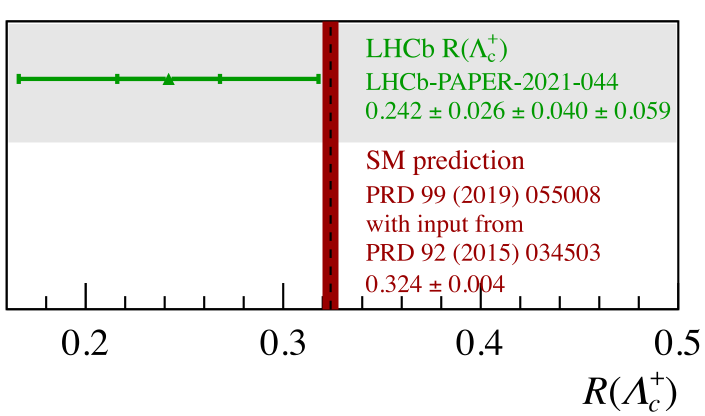
Current	WC Tag	WC	4-Fermi/$(i2\sqrt{2}V_{cb}G_F)$
SM	SM	1	$[\bar{c}\gamma^\mu P_L b][\bar{\ell}\gamma_\mu P_L\nu]$
Vector	V_qLlL	$\chi_L^V\lambda_L^V$	$[\bar{c}\chi_L^V\gamma^\mu P_L b][\bar{\ell}\lambda_L^V\gamma_\mu P_L\nu]$
	V_qRlL	$\chi_R^V\lambda_L^V$	$[\bar{c}\chi_R^V\gamma^\mu P_R b][\bar{\ell}\lambda_L^V\gamma_\mu P_L\nu]$
	V_qLlR	$\chi_L^V\lambda_R^V$	$[\bar{c}\chi_L^V\gamma^\mu P_L b][\bar{\ell}\lambda_R^V\gamma_\mu P_R\nu]$
	V_qRlR	$\chi_R^V\lambda_R^V$	$[\bar{c}\chi_R^V\gamma^\mu P_R b][\bar{\ell}\lambda_R^V\gamma_\mu P_R\nu]$
Scalar	S_qLlL	$\chi_L^S\lambda_L^S$	$[\bar{c}\chi_L^S P_L b][\bar{\ell}\lambda_L^S P_L\nu]$
	S_qRlL	$\chi_R^S\lambda_L^S$	$[\bar{c}\chi_R^S P_R b][\bar{\ell}\lambda_L^S P_L\nu]$
	S_qLlR	$\chi_L^S\lambda_R^S$	$[\bar{c}\chi_L^S P_L b][\bar{\ell}\lambda_R^S P_R\nu]$
	S_qRlR	$\chi_R^S\lambda_R^S$	$[\bar{c}\chi_R^S P_R b][\bar{\ell}\lambda_R^S P_R\nu]$
Tensor	T_qLlL	$\chi_L^T\lambda_L^T$	$[\bar{c}\chi_L^T\sigma^{\mu\nu}P_L b][\bar{\ell}\lambda_L^T\sigma_{\mu\nu}P_L\nu]$
	T_qRlR	$\chi_R^T\lambda_R^T$	$[\bar{c}\chi_R^T\sigma^{\mu\nu}P_R b][\bar{\ell}\lambda_R^T\sigma_{\mu\nu}P_R\nu]$

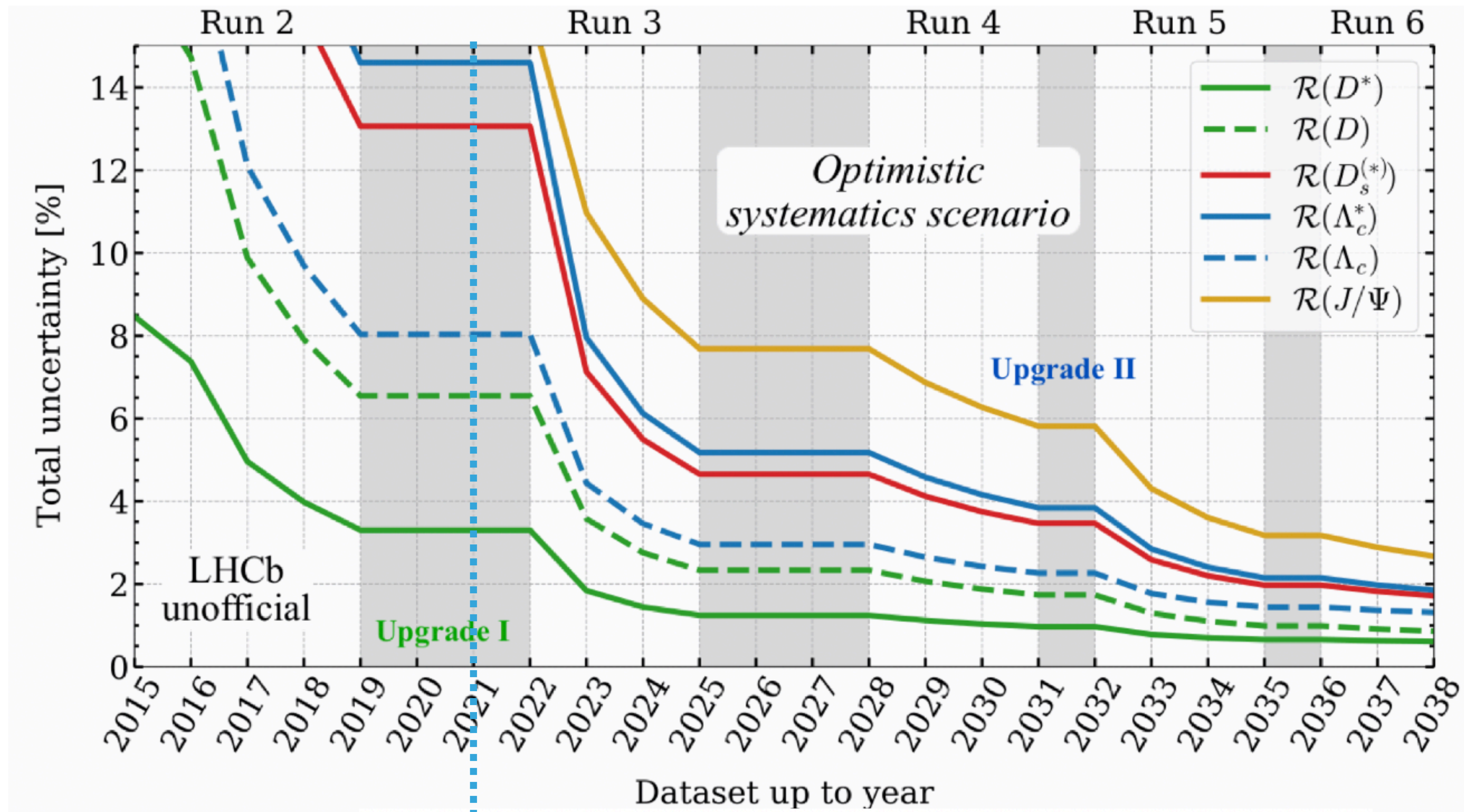
Hammer Manual

More semileptonic μ/τ LFU ratios





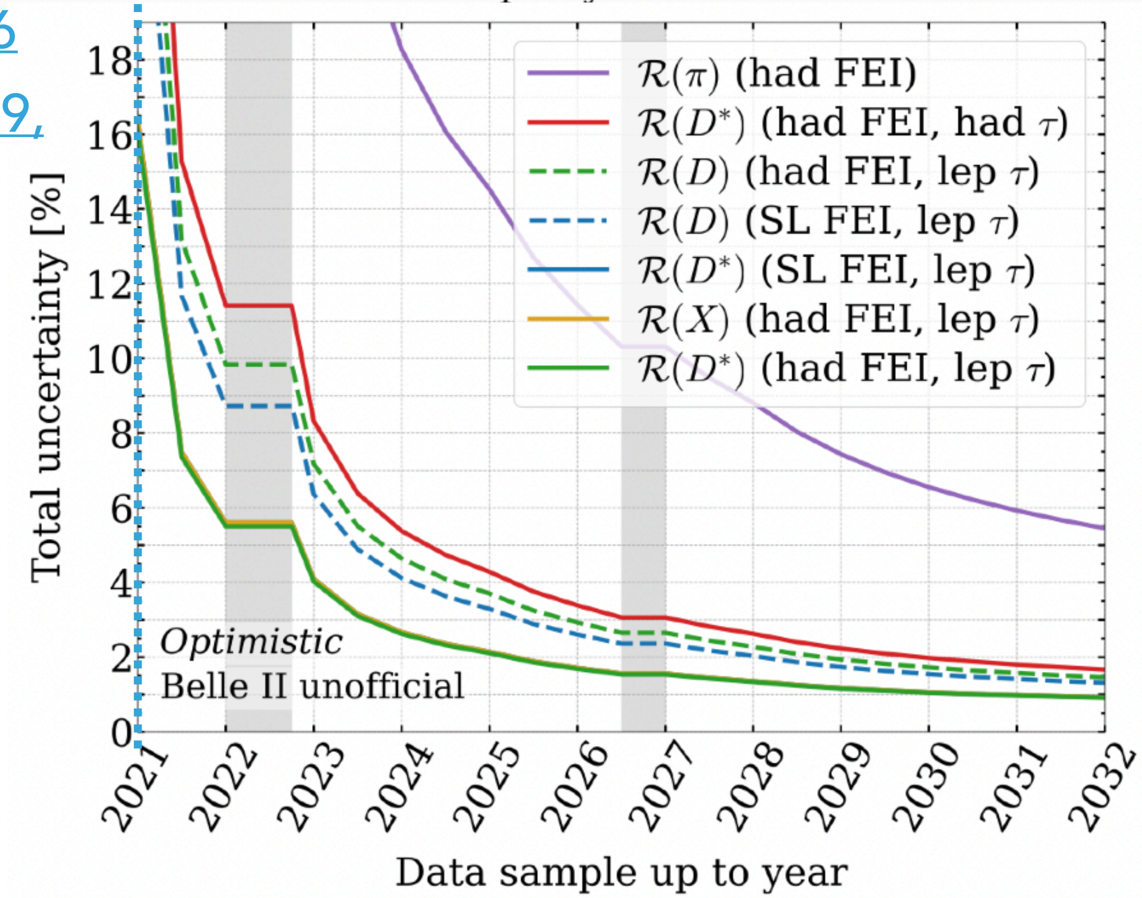




[arXiv:2101.08326](https://arxiv.org/abs/2101.08326)

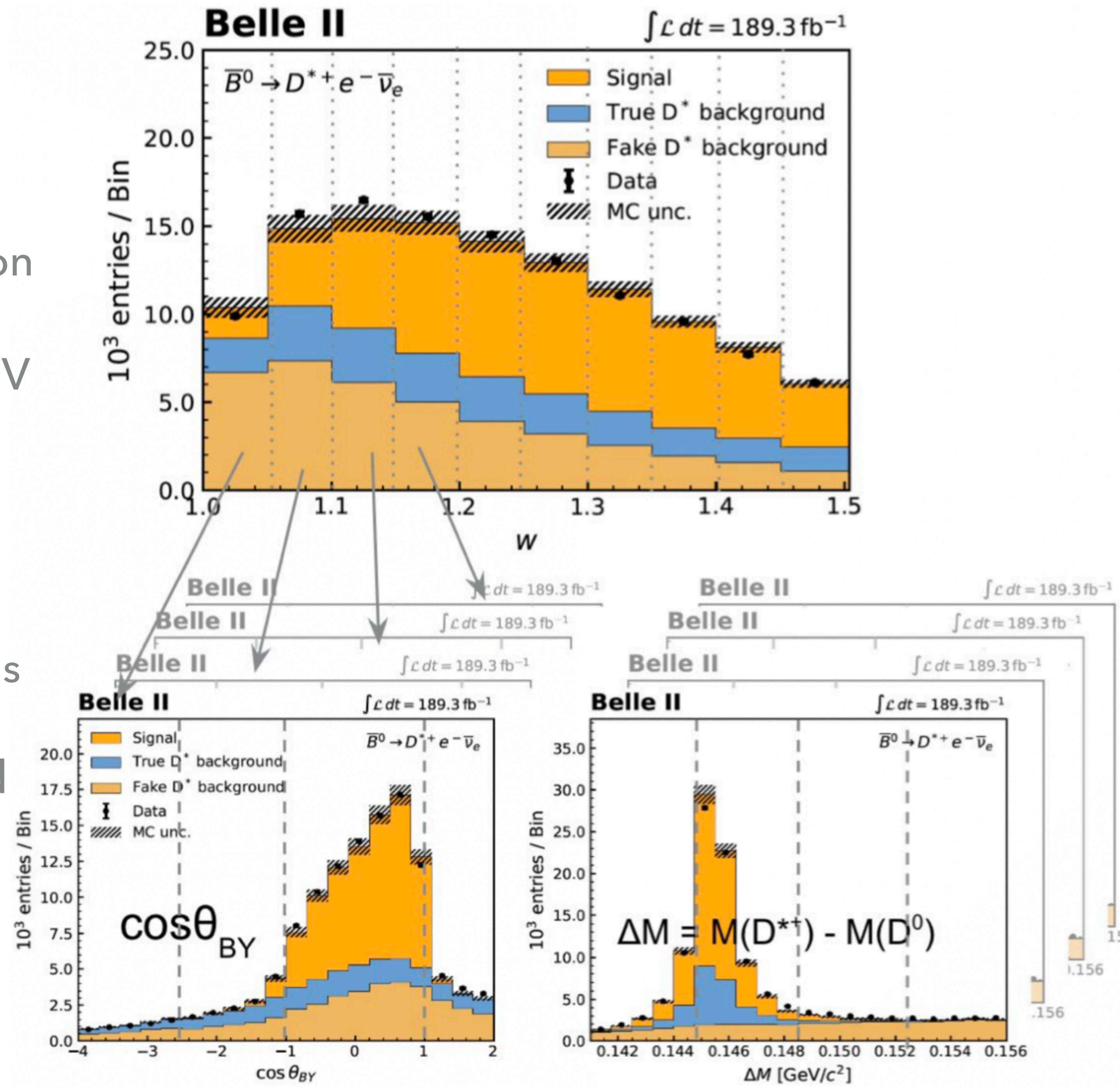
LHCB-PUB-2018-009,

arXiv:1808.08865



Untagged Belle II $\bar{B} \to D^{*+}\ell^-\bar{\nu}$

- $D^* \to D^0[\to K\pi]\pi$ + charged lepton
- The neutrino direction is reconstructed inclusively using the known angle $\cos\theta_{BY}$ between the B and the $Y = D^* + \ell$ direction
- The yield in 10 (8) bins of w, cos θl, cos θV and χ is extracted by fitting $\cos\theta_{BY}$ and ΔM = M(Kππ) – M(Kπ)
- Partial decay rates are determined from the unfolded (SVD arXiv:hep-ph/9509307) yields
- Main challenges: accurate background model, slow pion tracking and statistical correlations between bins



BGL truncation order determined by Nested Hypothesis Test [Phys. Rev. D100, 013005]

	Values	Correlations				χ^2/ndf
$\tilde{a}_0 \times 10^3$	0.89 ± 0.05	1.00	0.26	−0.27	0.07	40/31
$\tilde{b}_0 \times 10^3$	0.54 ± 0.01	0.26	1.00	−0.41	−0.46	
$\tilde{b}_1 \times 10^3$	-0.44 ± 0.34	−0.27	−0.41	1.00	0.56	
$\tilde{c}_1 \times 10^3$	-0.05 ± 0.03	0.07	−0.46	0.56	1.00	

Preliminary

LQCD used only for normalisation at zero recoil ($w = 1$)

Preliminary

$$|V_{cb}|\eta_{EW}\mathcal{F}(1) = \frac{1}{\sqrt{m_B m_{D^*}}}\left(\frac{|\tilde{b}_0|}{P_f(0)\phi_f(0)}\right)$$

$\mathcal{F}(1) = 0.906 \pm 0.013$

$$|V_{cb}|_{BGL} = (40.9 \pm 0.3(\text{stat}) \pm 1.0(\text{syst}) \pm 0.6(\text{theo})) \times 10^{-3}$$

C. Schwanda FFK'23

Untagged Belle II $\bar{B} \to D^{*+}\ell^-\bar{\nu}$

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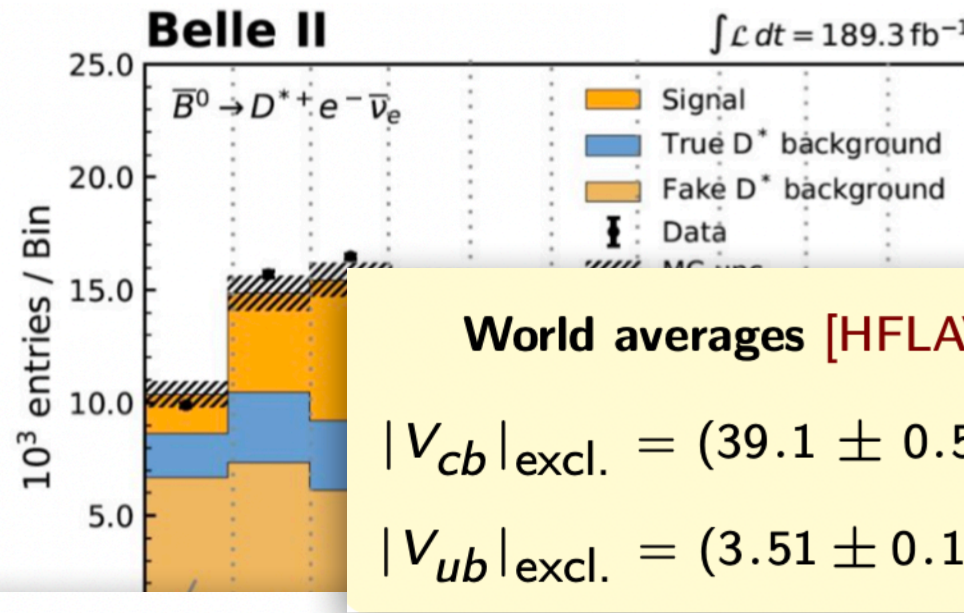
Δ



World averages [HFLAV 2021]

$|V_{cb}|_{\text{excl.}} = (39.1 \pm 0.5) \times 10^{-3}$

$|V_{ub}|_{\text{excl.}} = (3.51 \pm 0.12) \times 10^{-3}$

P. Horak FPCP'23

	$\lvert V_{cb}\rvert \times 10^3$	Reference
Untagged $B \to D^*\ell\nu$	40.9 ± 1.2 (BGL)	To be submitted to PRD
Untagged $B \to D\ell\nu$	38.3 ± 1.2 (BGL)	[arXiv:2210.13143]
Tagged $B \to D^*\ell\nu$	37.9 ± 2.7 (CLN)	[arXiv:2301.047169]

	$\lvert V_{ub}\rvert \times 10^3$	Reference
Untagged $B \to \pi\ell\nu$	3.55 ± 0.25	[arXiv:2210.04224]
Tagged $B \to \pi e\nu$	3.88 ± 0.45	[arXiv:2206.08102]

- P
u
- N
r
s

B
N

$\tilde{a}_0 \times 10^3$	0.89 ± 0.05	1.00	0.26	−0.27	0.07	40/31
$\tilde{b}_0 \times 10^3$	0.54 ± 0.01	0.26	1.00	−0.41	−0.46	
$\tilde{b}_1 \times 10^3$	-0.44 ± 0.34	−0.27	−0.41	1.00	0.56	
$\tilde{c}_1 \times 10^3$	-0.05 ± 0.03	0.07	−0.46	0.56	1.00	

Preliminary

C. Schwanda FFK'23

LQCD used only for normalisation at zero recoil ($w = 1$)

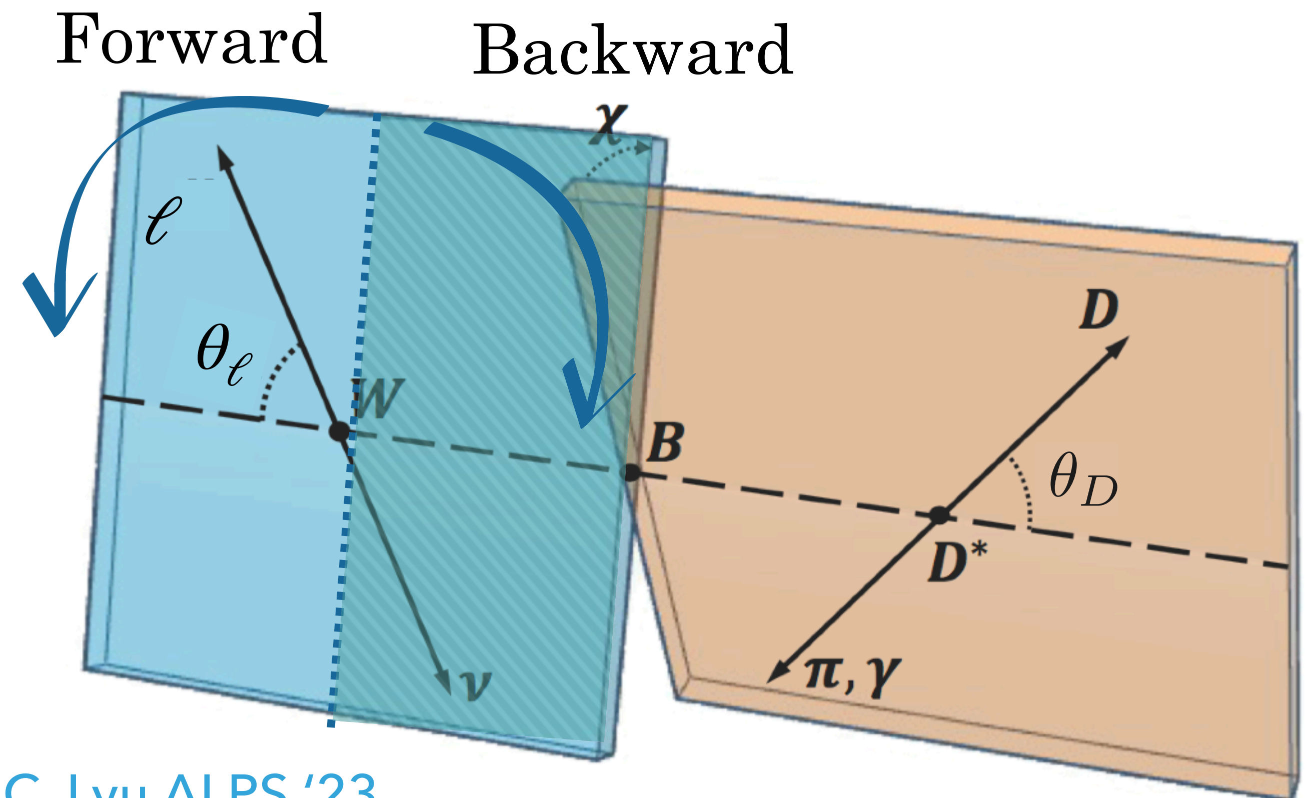
$$|V_{cb}|\eta_{\rm EW}\mathcal{F}(1) = \frac{1}{\sqrt{m_B m_{D^*}}}\left(\frac{|\tilde{b}_0|}{P_f(0)\phi_f(0)}\right)$$

$\mathcal{F}(1) = 0.906 \pm 0.013$

Preliminary

$$|V_{cb}|_{BGL} = (40.9 \pm 0.3(\text{stat}) \pm 1.0(\text{syst}) \pm 0.6(\text{theo})) \times 10^{-3}$$

Untagged Belle II $\bar{B} \to D^{*+}\ell^-\bar{\nu}$

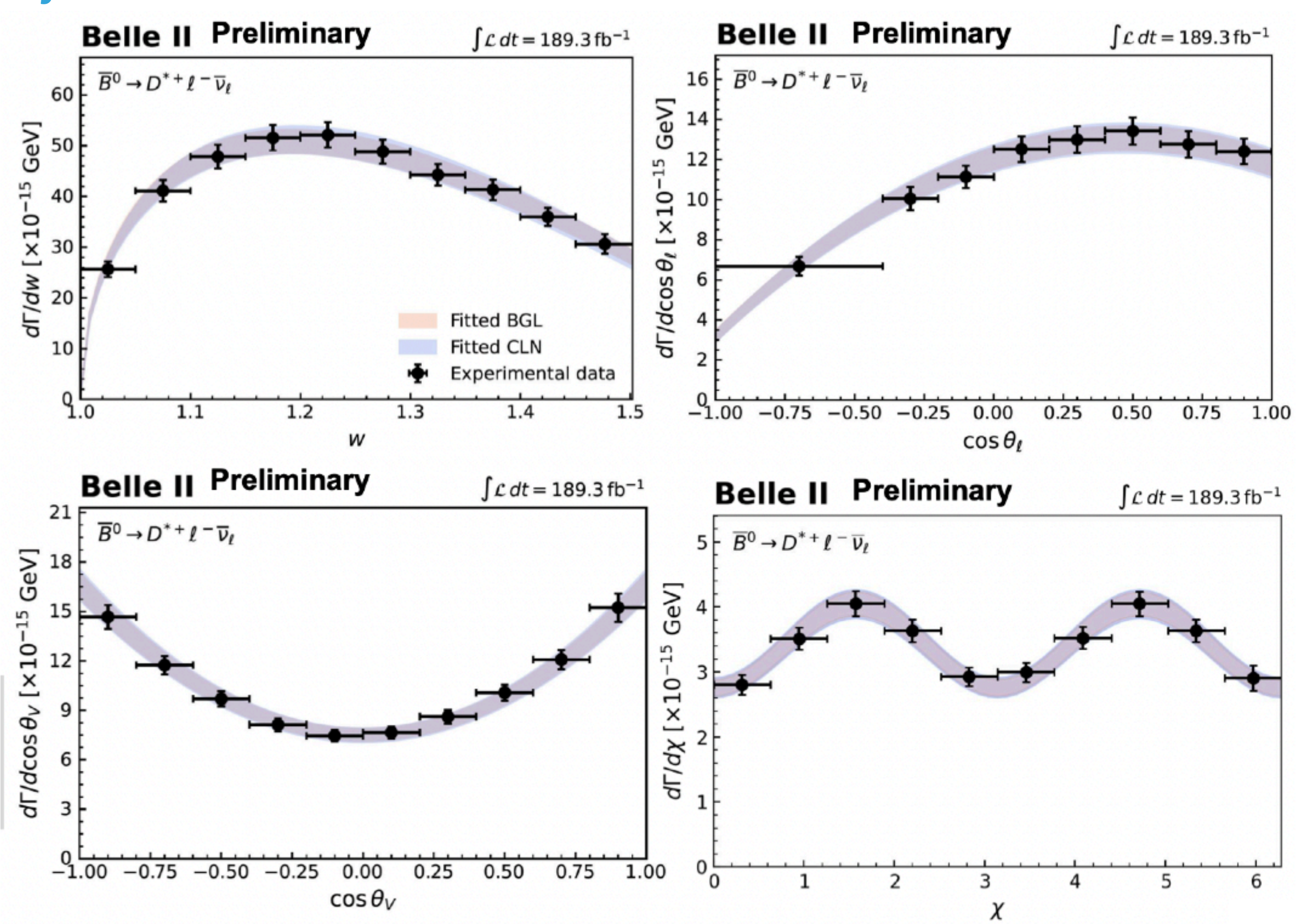


C. Lyu ALPS '23

$$A_{\rm FB} = \frac{\int_0^1 \cos\theta_\ell d\Gamma/d\cos\theta_\ell - \int_{-1}^0 \cos\theta_\ell d\Gamma/d\cos\theta_\ell}{\int_0^1 \cos\theta_\ell d\Gamma/d\cos\theta_\ell + \int_{-1}^0 \cos\theta_\ell d\Gamma/d\cos\theta_\ell}$$

$$\Delta A_{\rm FB} = A^\mu_{\rm FB} - A^e_{\rm FB}$$

$$\Sigma A_{\rm FB} = A^\mu_{\rm FB} + A^e_{\rm FB}$$



$$R_{e/\mu} = 1.001 \pm 0.009({\rm stat}) \pm 0.021({\rm syst})$$

$$\mathcal{A}^e_{\rm FB} = 0.219 \pm 0.011 \pm 0.020\,,$$
$$\mathcal{A}^\mu_{\rm FB} = 0.215 \pm 0.011 \pm 0.022\,,$$
$$\Delta\mathcal{A}_{\rm FB} = (-4 \pm 16 \pm 18) \times 10^{-3}$$

$$F^e_L = 0.521 \pm 0.005 \pm 0.007\,,$$
$$F^\mu_L = 0.534 \pm 0.005 \pm 0.006\,,$$
$$\Delta F_L = 0.013 \pm 0.007 \pm 0.007\,,$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_V} = \frac{3}{2}\left(F_L \cos^2\theta_V + \frac{1-F_L}{2}\sin^2\theta_V\right)$$

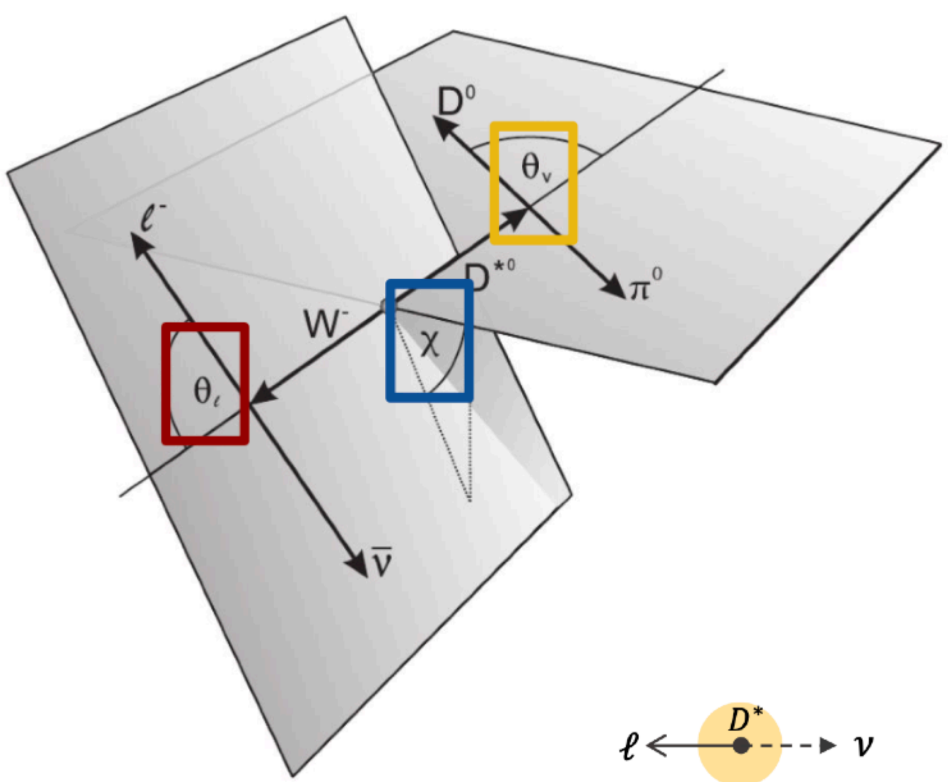
Angular asymmetries

- Aim: measure the full set of angular asymmetries as function of q^2 (or w)

$$A_{\mathrm{FB}} = \frac{\int_0^1 \cos\theta_\ell \mathrm{d}\Gamma/\mathrm{d}\cos\theta_\ell - \int_{-1}^0 \cos\theta_\ell \mathrm{d}\Gamma/\mathrm{d}\cos\theta_\ell}{\int_0^1 \cos\theta_\ell \mathrm{d}\Gamma/\mathrm{d}\cos\theta_\ell + \int_{-1}^0 \cos\theta_\ell \mathrm{d}\Gamma/\mathrm{d}\cos\theta_\ell}$$

$$\mathscr{A}_x(w) = \left(\frac{\mathrm{d}\Gamma}{dw}\right)^{-1}\left[\int_0^{+1} - \int_{-1}^{0}\right] dx \frac{\mathrm{d}^2\Gamma}{dwdx}$$

$$\begin{aligned} A_{\mathrm{FB}} &: \mathrm{d}X \to \mathrm{d}(\cos\theta_l) \\ S_3 &: \mathrm{d}X \to \mathrm{d}(\cos 2\chi) \\ S_5 &: \mathrm{d}X \to \mathrm{d}(\cos\chi\cos\theta_V) \\ S_7 &: \mathrm{d}X \to \mathrm{d}(\sin\chi\cos\theta_V) \\ S_9 &: \mathrm{d}X \to \mathrm{d}(\sin 2\chi) \end{aligned}$$

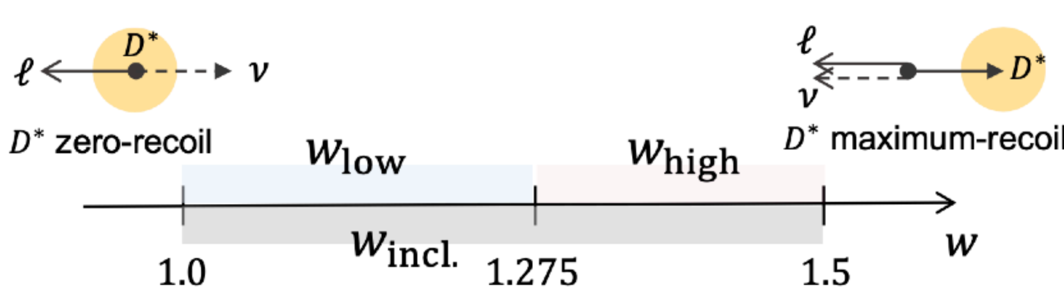


$$A_{FB}(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_\ell \frac{d^2\Gamma}{d\cos\theta_\ell dq^2},$$

$$S_3(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^{\pi/4} - \int_{\pi/4}^{\pi/2} - \int_{\pi/2}^{3\pi/4} + \int_{3\pi/4}^{\pi} + \int_{\pi}^{5\pi/4} - \int_{5\pi/4}^{3\pi/2} - \int_{3\pi/2}^{7\pi/4} + \int_{7\pi/4}^{2\pi}\right] d\chi \frac{d^2\Gamma}{dq^2 d\chi},$$

$$S_5(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^{\pi/2} - \int_{\pi/2}^{\pi} - \int_{\pi}^{3\pi/2} + \int_{3\pi/2}^{2\pi}\right] d\chi \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta^* \frac{d^3\Gamma}{dq^2 d\cos\theta^* d\chi},$$

$$S_7(q^2) = \left(\frac{d\Gamma}{dq^2}\right)^{-1}\left[\int_0^{\pi} - \int_{\pi}^{2\pi}\right] d\chi \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta^* \frac{d^3\Gamma}{dq^2 d\cos\theta^* d\chi}.$$

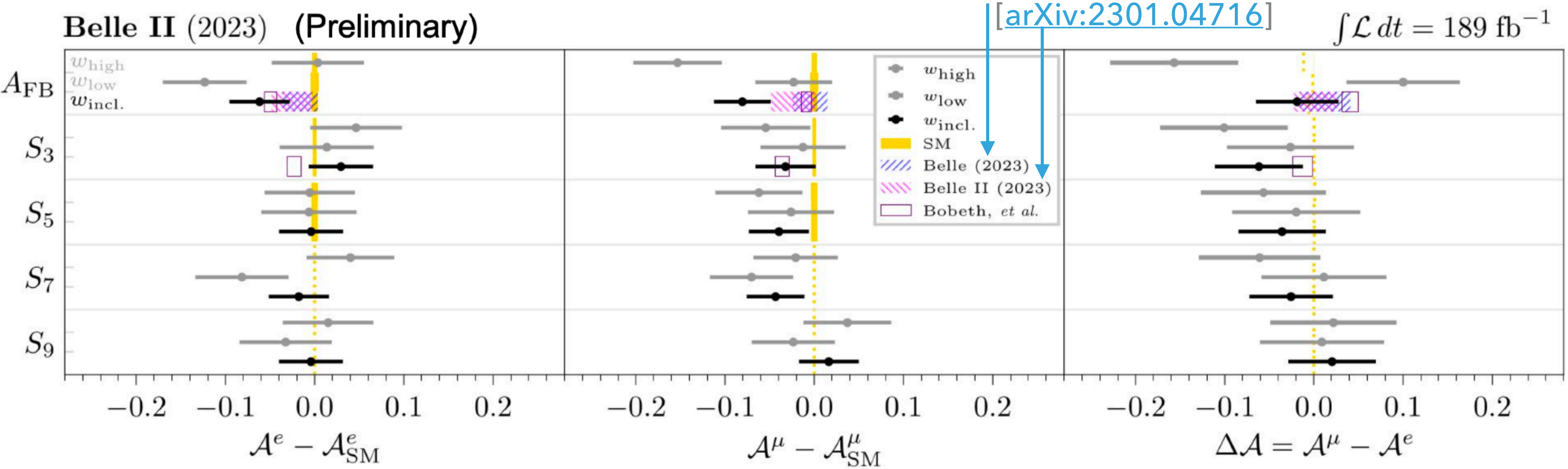


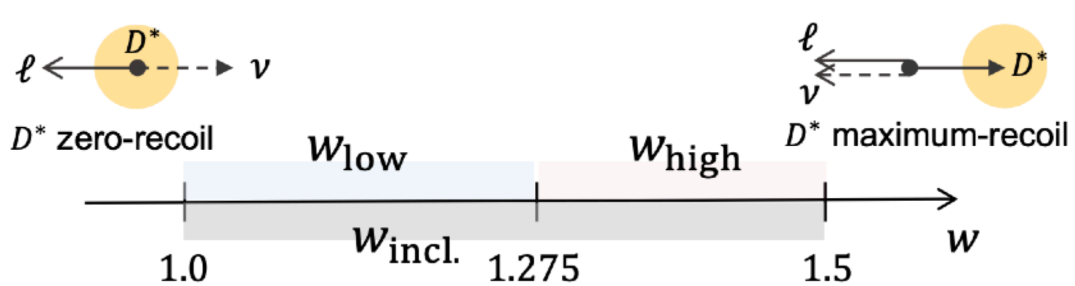
$$w = \frac{p_B \cdot p_{D^*}}{m_B m_{D^*}} = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$

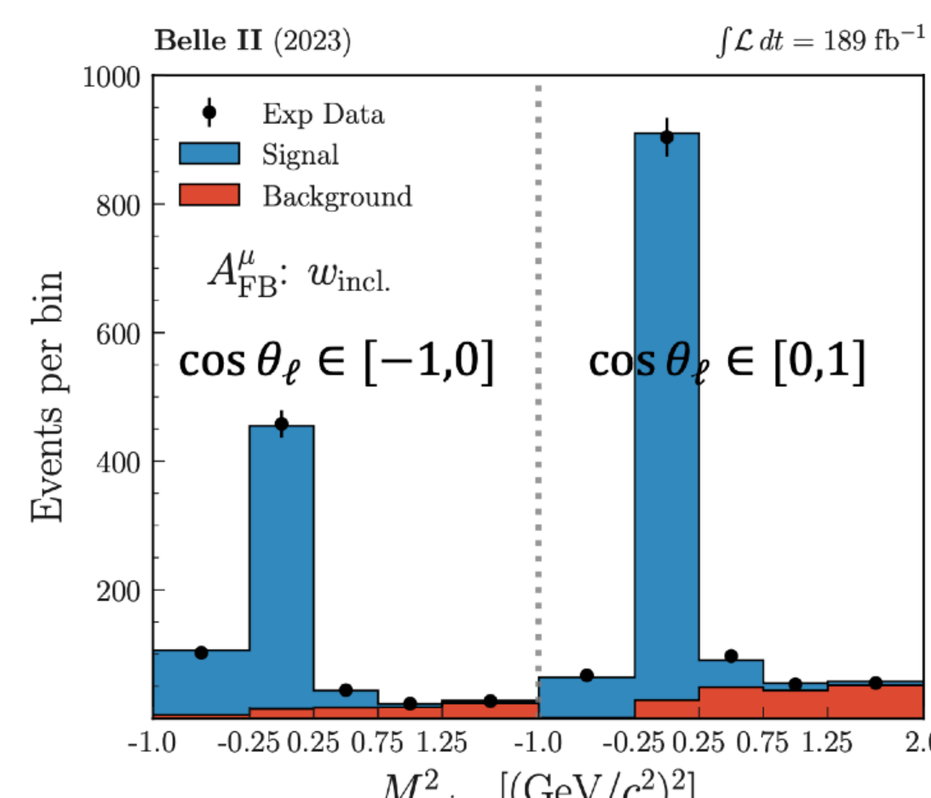
Angular asymmetries @ Belle II

[arXiv:2301.07529]

[arXiv:2301.04716]







$$M^2_{miss} \equiv \left(p_{e^+e^-} - p_{B_{tag}} - p_{D^*} - p_\ell\right)^2$$

- First experimental measurement of complete set of angular asymmetries
- Signal extraction in ν invariant mass-squared (M^2_{miss}) in two w-bins plus w-inclusive range
- No evidence of lepton universality violation with at least p-values of 0.12

M. Lewis FPCP '23

Systematics and Branching Fraction

$\frac{\mathcal{B}(B_s^0 \to K\mu\nu)}{\mathcal{B}(B_s^0 \to D_s\mu\nu)}$ [%]

Uncertainty	All q^2	low q^2	high q^2
Tracking	2.0	2.0	2.0
Trigger	1.4	1.2	1.6
Particle identification	1.0	1.0	1.0
$\sigma(m_{\mathrm{corr}})$	0.5	0.5	0.5
Isolation	0.2	0.2	0.2
Charged BDT	0.6	0.6	0.6
Neutral BDT	1.1	1.1	1.1
q^2 migration	–	2.0	2.0
Efficiency	1.2	1.6	1.6
Fit template	$^{+2.3}_{-2.9}$	$^{+1.8}_{-2.4}$	$^{+3.0}_{-3.4}$
Total	$^{+4.0}_{-4.3}$	$^{+4.3}_{-4.5}$	$^{+5.0}_{-5.3}$
$\mathcal{B}(D_s \to KK\pi)$	2.8	2.8	2.8

- Systematic can be reduced with larger data (and MC) samples

$$\mathcal{B}(B_s^0 \to K^-\mu^+\nu_\mu) = \tau_{B_s^0} \times |V_{cb}|^2 \times FF_{D_s} \times \frac{\mathcal{B}(B_s^0 \to K^-\mu^+\nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^-\mu^+\nu_\mu)}$$

External inputs: $\tau_{B_s^0} \times |V_{cb}|^2 \times FF_{D_s}$

Measured yields and efficiencies from simulation: $\frac{\mathcal{B}(B_s^0 \to K^-\mu^+\nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^-\mu^+\nu_\mu)}$

$$\mathcal{B}(B_s^0 \to K^-\mu^+\nu_\mu) = (1.06 \pm 0.05(\mathrm{stat}) \pm 0.04(\mathrm{syst}) \pm 0.06(\mathrm{ext}) \pm 0.04(\mathrm{FF})) \times 10^{-4}$$