A guided tour on $b \to c \ell \bar{\nu}_\ell$ with $\ell = e, \mu \, \tau$

Marseille *Mini* Theory - Experiment Workshop on Semileptonic Decays

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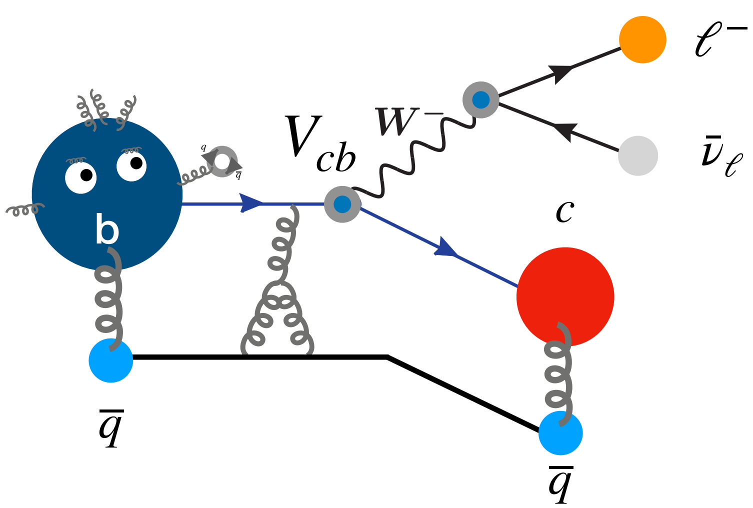
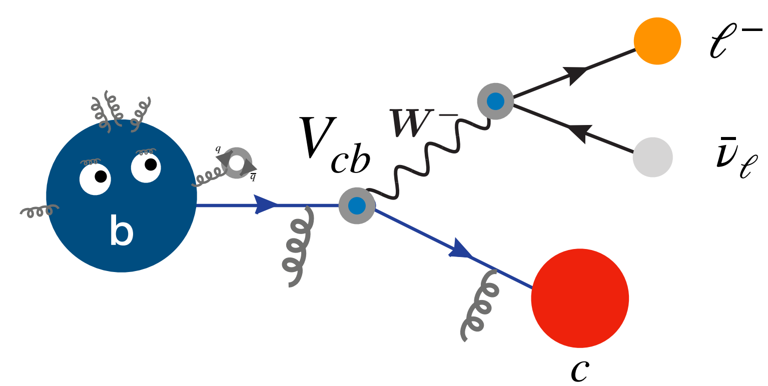
Rough Tour Guide for today

1. Exclusive $B \to D^{(*,**)}\ell\bar{\nu}_\ell$ Measurements with $\ell = e, \mu$



2. Inclusive $B \to X_c\ell\bar{\nu}_\ell$ Measurements with $\ell = e, \mu$



3. Ratio measurements with τ

Signal

$$R = \frac{b \to q\,\tau\bar{\nu}_\tau}{b \to q\,\ell\bar{\nu}_\ell}$$

Normalization

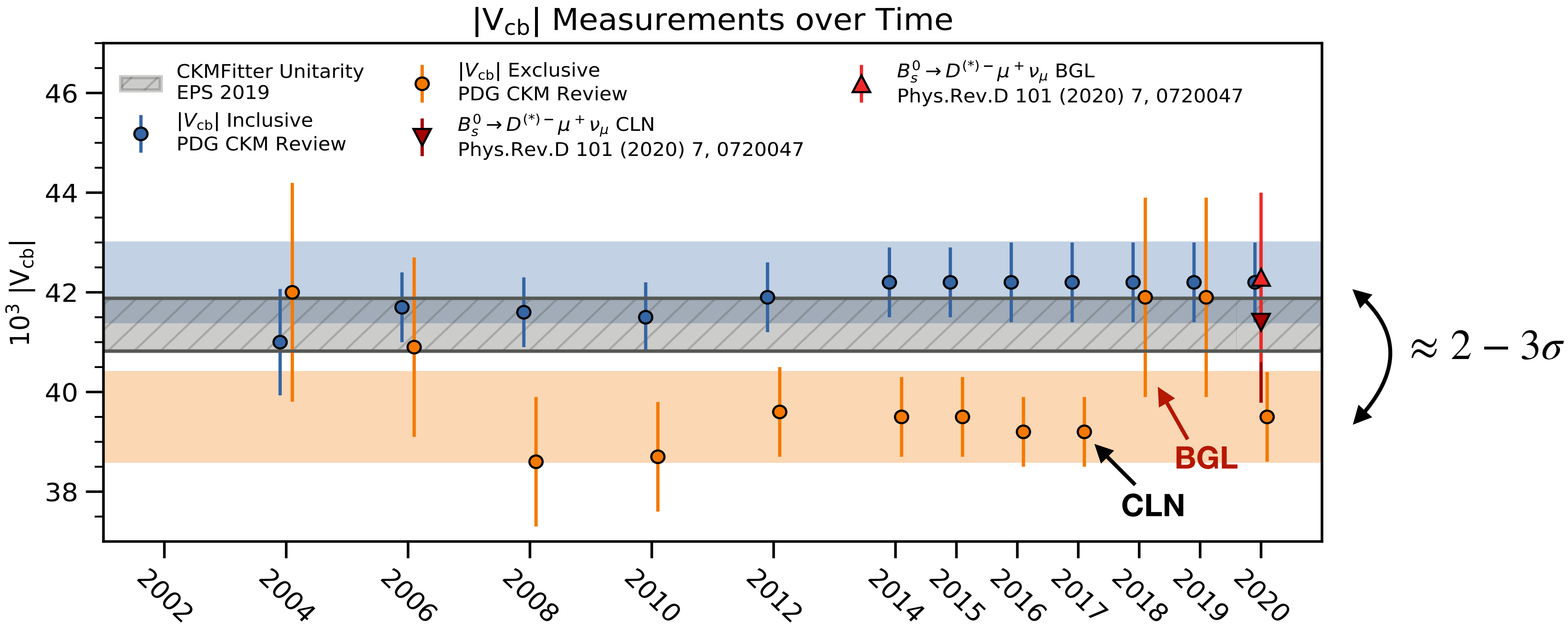
$\ell = e, \mu$

Backdrop of Inclusive *vs.* Exclusive

$|V_{cb}|$

Inclusive

Exclusive



CLN

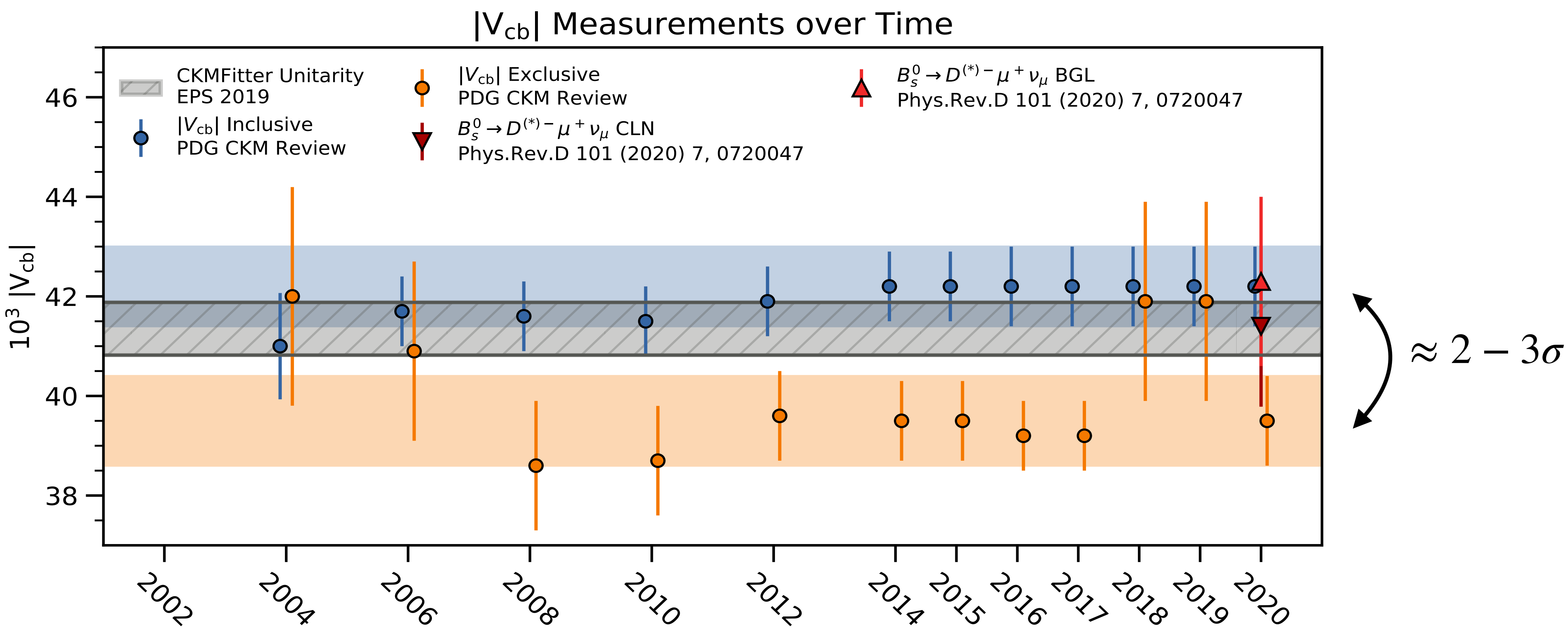
Experiment	eta_{EW} F(1) $|V_{cb}|$ (rescaled) [10^{-3}]	rho^2 (rescaled)	Correlation (stat/syst/total)	Parameters	Remarks
ALEPH	31.38 +/- 1.80 +/- 1.24	0.488 +/- 0.226 +/- 0.146	0.94/0.69/0.86	input parameters	Phys.Lett.B395:373-387,1997
CLEO	40.16 +/- 1.24 +/- 1.54	1.363 +/- 0.084 +/-0.087	0.87/0.90/0.89	input parameters	Phys.Rev.Lett.89:081803,2002
OPAL excl	36.20 +/- 1.58 +/- 1.47	1.198 +/- 0.206 +/- 0.153	0.95/0.48/0.75	input parameters	Phys.Lett.B482:15-30,2000
OPAL partial reco	37.44 +/- 1.20 +/- 2.32	1.090 +/- 0.137 +/- 0.297	0.77/0.79/0.79	input parameters	Phys.Lett.B482:15-30,2000
DELPHI partial reco	35.52 +/- 1.41 +/- 2.29	1.139 +/- 0.123 +/- 0.382	0.94/0.68/0.71	input parameters	Phys.Lett.B510:55-74,2001
DELPHI excl	35.87 +/- 1.69 +/- 1.95	1.070 +/- 0.141 +/- 0.153	0.89/0.81/0.84	input parameters	Eur.Phys.J.C33:213-232,2004
BELLE	34.82 +/- 0.15 +/- 0.55	1.106 +/- 0.031 +/- 0.008	0.66/-0.30/0.09	input parameters	Submitted to Phys.Rev.D82
BABAR excl	33.77 +/- 0.29 +/- 0.97	1.182 +/- 0.048 +/- 0.029	0.27/0.02/0.08	input parameters	Phys.Rev.D77:032002,2008
BABAR D*0	34.55 +/- 0.58 +/- 1.06	1.124 +/- 0.058 +/- 0.053	0.90/0.48/0.60	input parameters	Phys.Rev.Lett.100:231803,2008
BABAR global fit	35.45 +/- 0.20 +/- 1.08	1.171 +/- 0.019 +/- 0.060	0.38/0.87/0.84	input parameters	Phys.Rev.D79:012002,2009
Average	**35.00 +/- 0.11 +/- 0.34**	**1.121 +/- 0.014 +/- 0.019**	**0.50/0.33/0.34**	**chi2/dof = 42.2/23 (CL = 0.009)**	eps 1 pdf 1 eps 2 pdf 2

Backdrop of Inclusive *vs.* Exclusive

$|V_{cb}|$

Inclusive

Exclusive



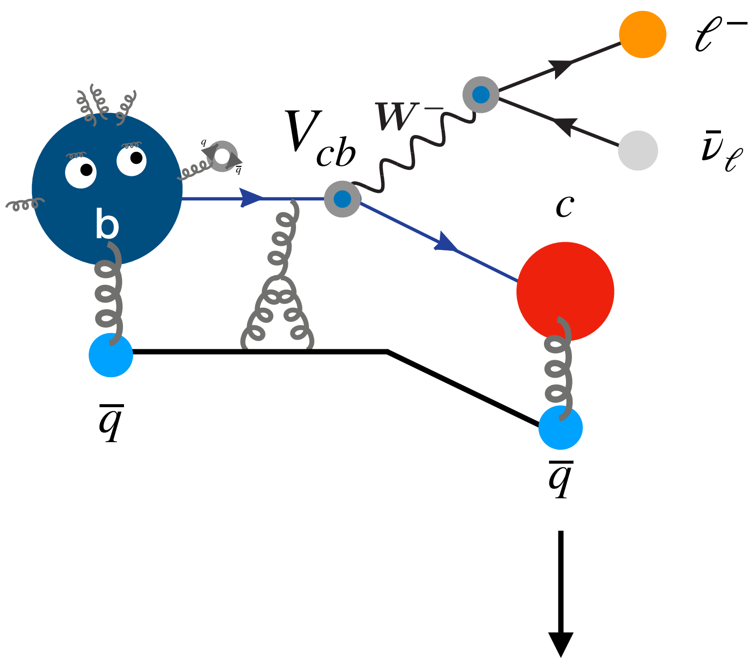
$|V_{cb}|$ & HQE / form factor parameters are important input for:

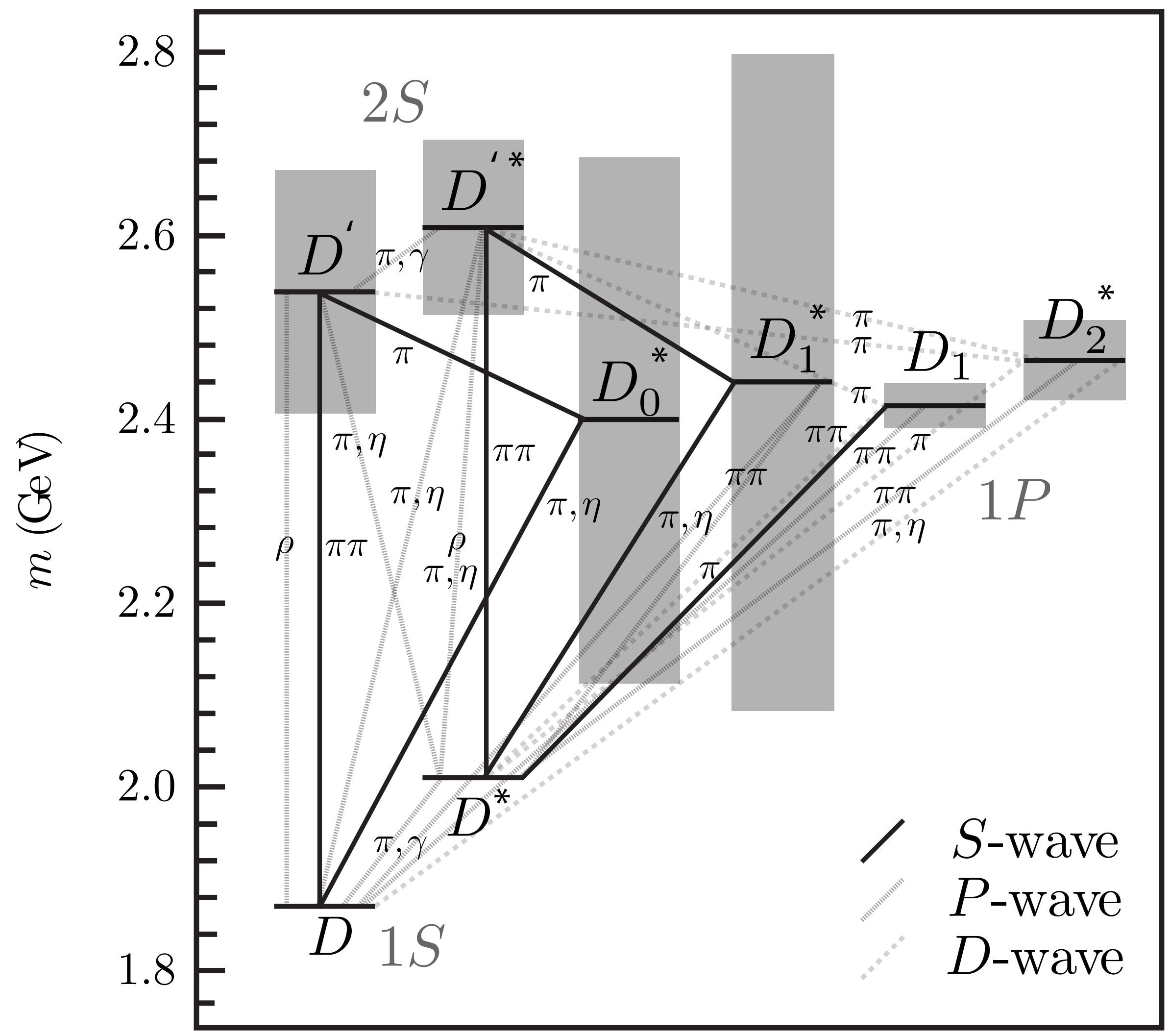
- CKM UT Fit (& search for NP)
- Prediction of SM processes (e.g. SL decays with τ, $B_{(s)} \to \mu\mu$, …)
- Modelling of backgrounds for $b \to u\ell\bar{\nu}_\ell$ & $|V_{ub}|$

…

1. Exclusive

Overview





Mesons containing a heavy quark Q are made up of a heavy quark and a light antiquark $\bar{q}$ (and gluons and $q\bar{q}$ pairs)

2 L = 0 ground states: D/D^*

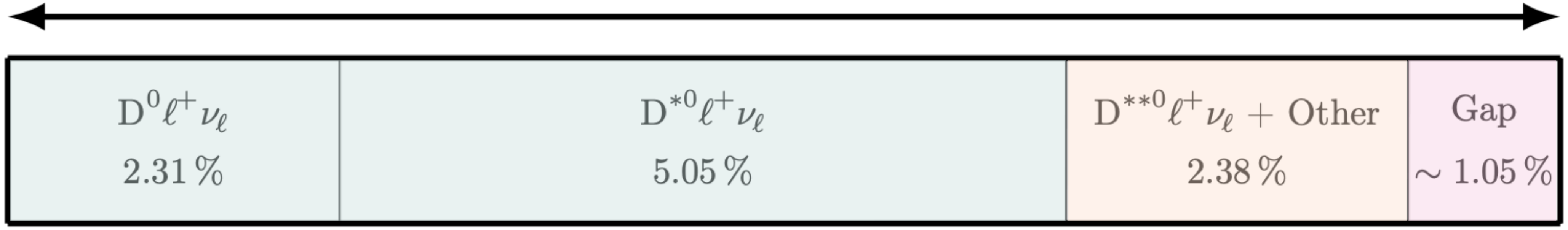
4 L = 1 ground states: D_0, D_1', D_1, D_2

(or sometimes D_0^*, D_1^*, D_1, D_2^* or just D^{**})

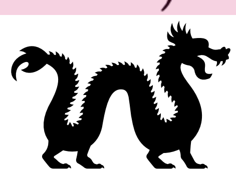
D/D^* saturate **~75%** of the inclusive $B \to X_c \ell \bar{\nu}_\ell$ rate and are the **principal route** to V_{cb}

D^{**} saturate **~15%** of the inclusive $B \to X_c \ell \bar{\nu}_\ell$ rate, mostly are perceived as background

$$\mathcal{B}(\mathrm{B}^+ \to X_c^0 \ell^+ \nu_\ell) \approx 10.79\,\%$$



Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell^+\,\nu_\ell$	$(6.6 \pm 0.1) \times 10^{-3}$	$(6.2 \pm 0.1) \times 10^{-3}$
$B \to D_2^*\,\ell^+\,\nu_\ell$	$(2.9 \pm 0.3) \times 10^{-3}$	$(2.7 \pm 0.3) \times 10^{-3}$
$B \to D_0^*\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.8) \times 10^{-3}$	$(3.9 \pm 0.7) \times 10^{-3}$
$B \to D_1'\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.9) \times 10^{-3}$	$(3.9 \pm 0.8) \times 10^{-3}$
$B \to D\pi\pi\,\ell^+\,\nu_\ell$	$(0.6 \pm 0.9) \times 10^{-3}$	$(0.6 \pm 0.9) \times 10^{-3}$
$B \to D^*\pi\pi\,\ell^+\,\nu_\ell$	$(2.2 \pm 1.0) \times 10^{-3}$	$(2.0 \pm 1.0) \times 10^{-3}$
$B \to X_c \ell \nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$



Fairly well known. Some iso-spin tension.

Broad states based on 3 measurements. (BaBar, Belle, DELPHI)

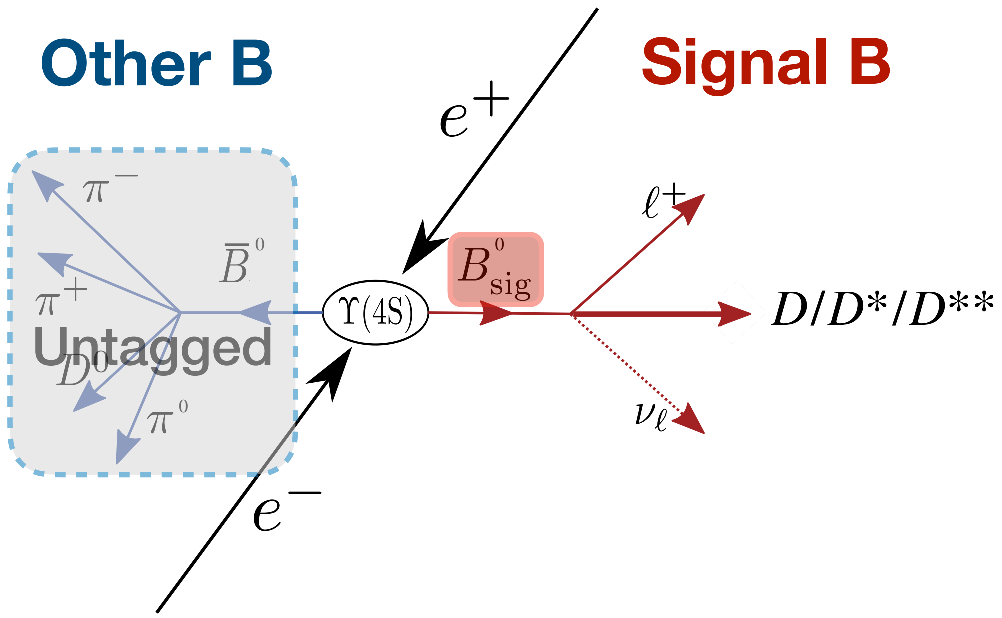
Some hints from the BaBar result.

New result from Belle soon

Image credit: F. Metzner

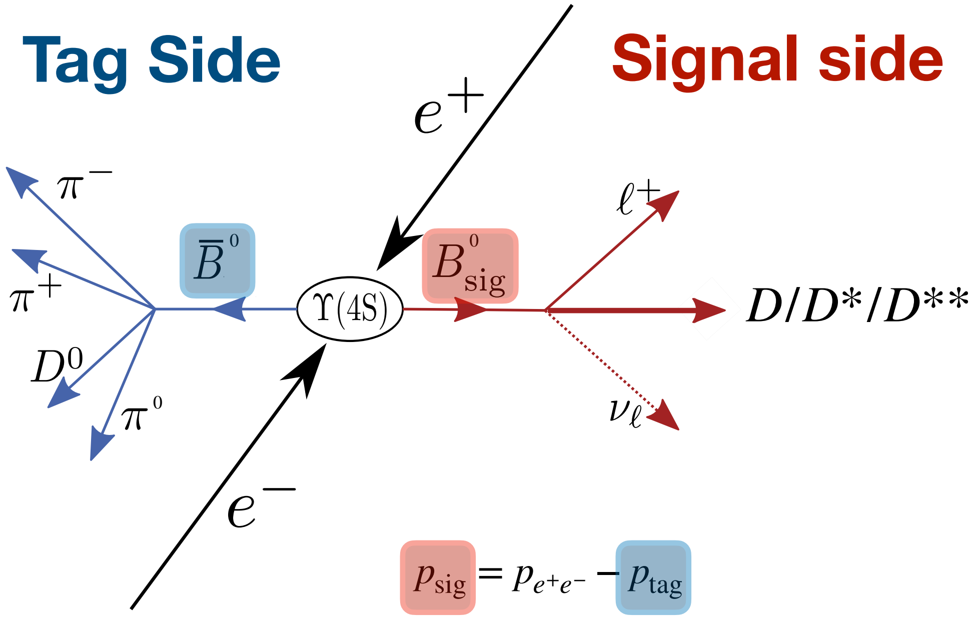
Slide: R. Van Tonder

Measurement Strategies (e^+e^- B-Factory)



+ Very high efficiency
+ Measurement of absolute branching fractions straightforward (depends on total # of $N_{B\bar{B}}$, understanding efficiencies)

- Less experimental control, e.g. more background from $e^+e^+ \rightarrow q\bar{q}$
- Cannot directly access signal B rest frame, need tricks



+ High degree of experimental control, e.g. can identify all final state particles with either the signal or the tag side
+ If hadronic modes for tagging are used, can reconstruct B rest frame

- Understanding efficiencies is difficult
- Low efficiency reduces the effective statistical power

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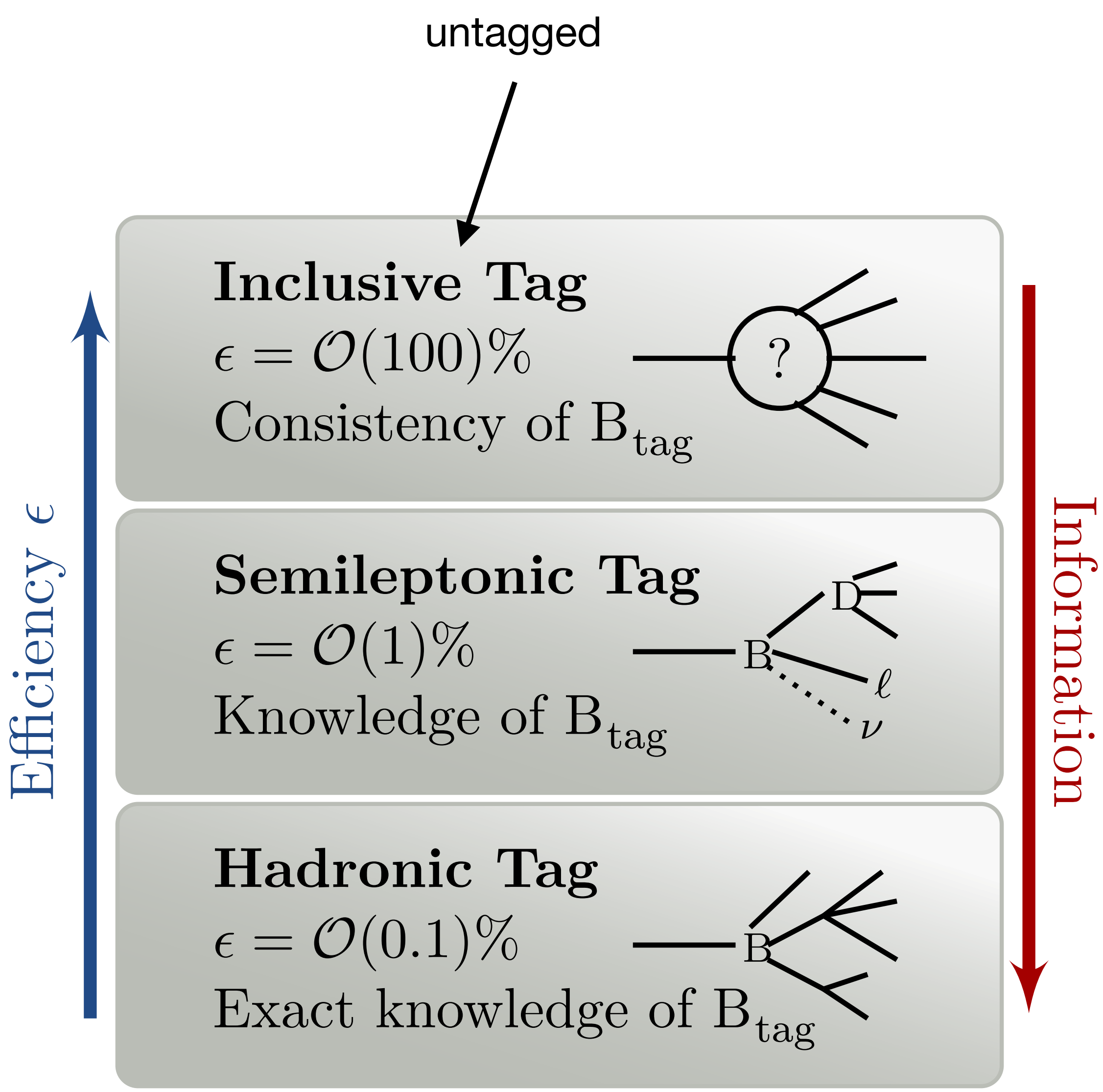

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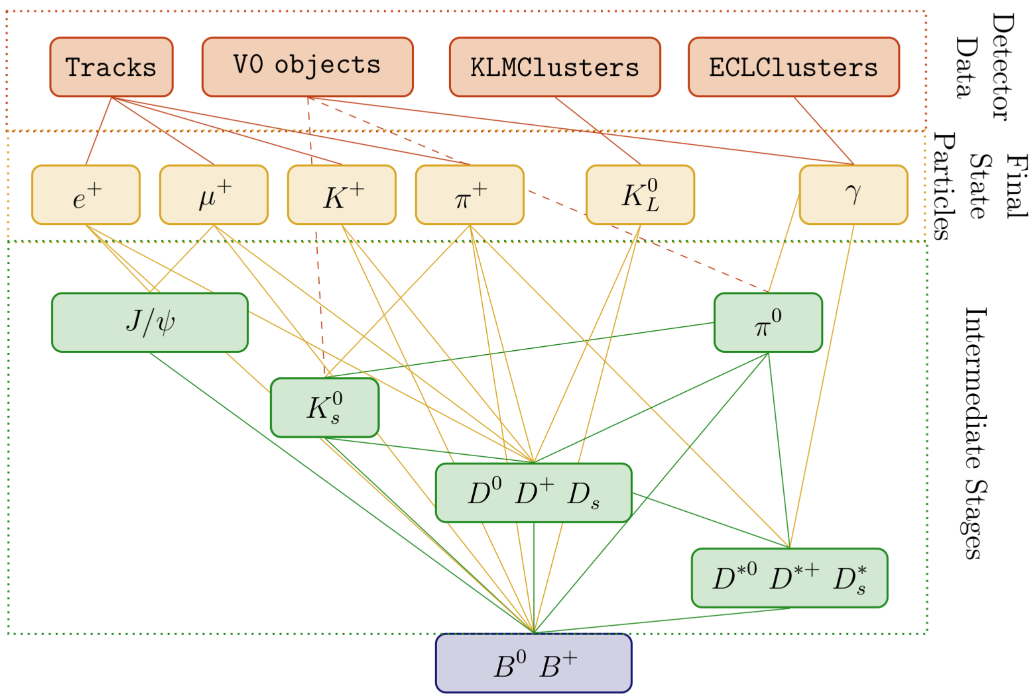
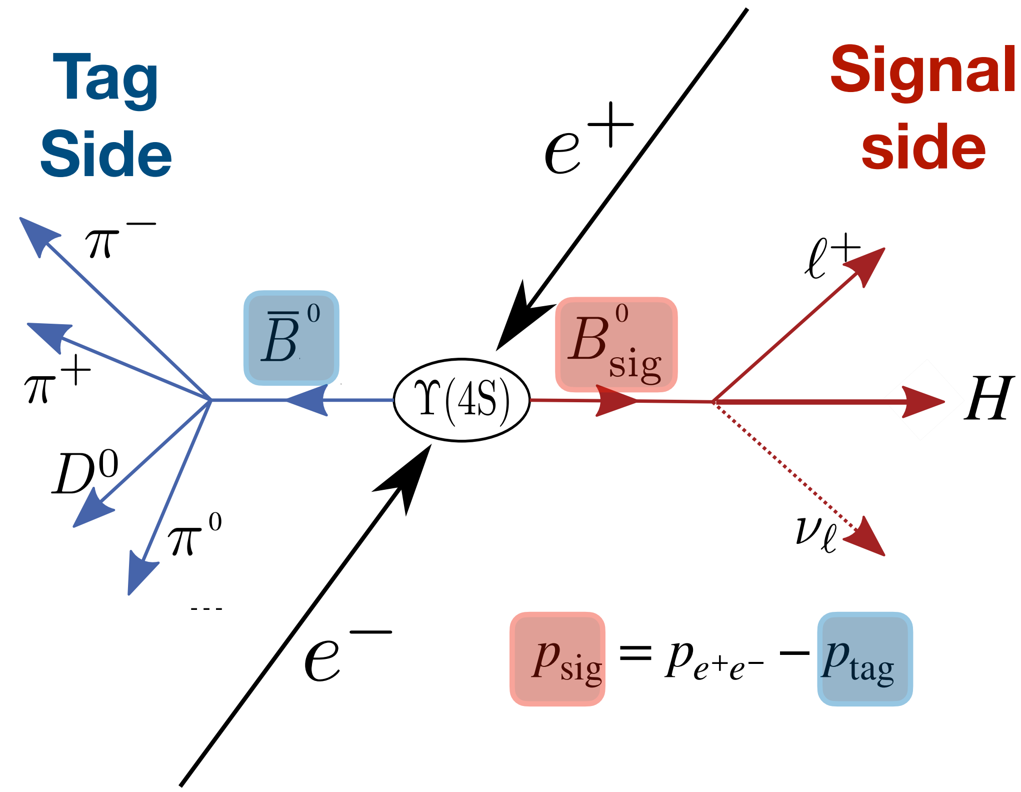
Tagging in a nutshell





Candidates reconstructed with **hierarchical** approach via e.g. **neural networks (FR) or boosted decision trees (FEI)**

Over 10'000 decay cascades with an **efficiency** of **0.28% / 0.18%** for $B^\pm$ and $B^0/\bar{B}^0$

E.g. train a classifier to identify correctly reconstructed electron candidates:

Input variables: all four momenta & particle identification scores

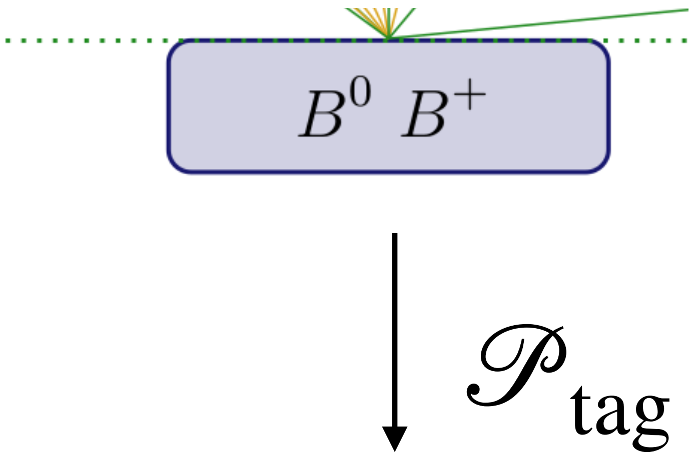
Output: Score $\mathcal{O}_e$

Apply mild selection on $\mathcal{O}_e$ to reduce # of candidate particles

Then train a classifier to identify correctly reconstructed J/ψ candidates

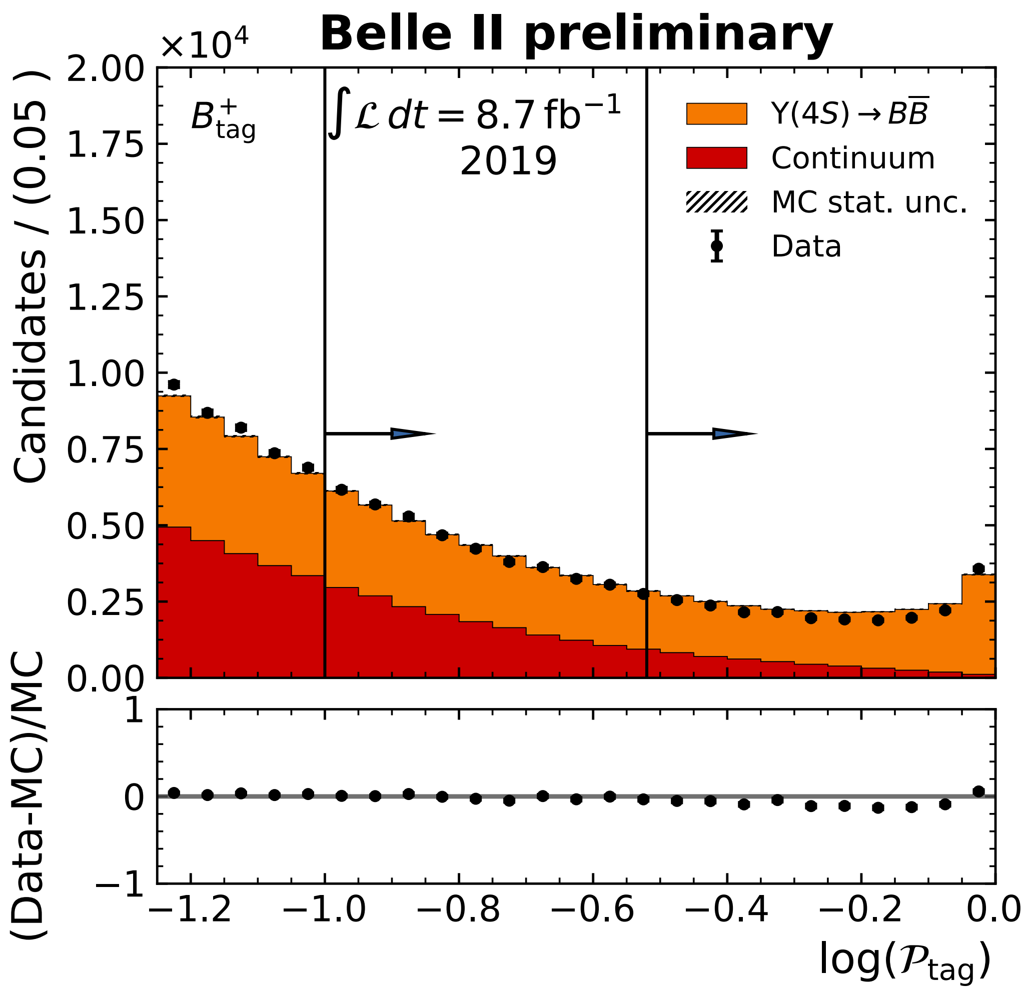
Input variables: all four momenta and output scores of previous layer

Output variable: $\mathcal{O}_{J/\psi}$ [...]



$\mathscr{P}_{\text{tag}}$ =

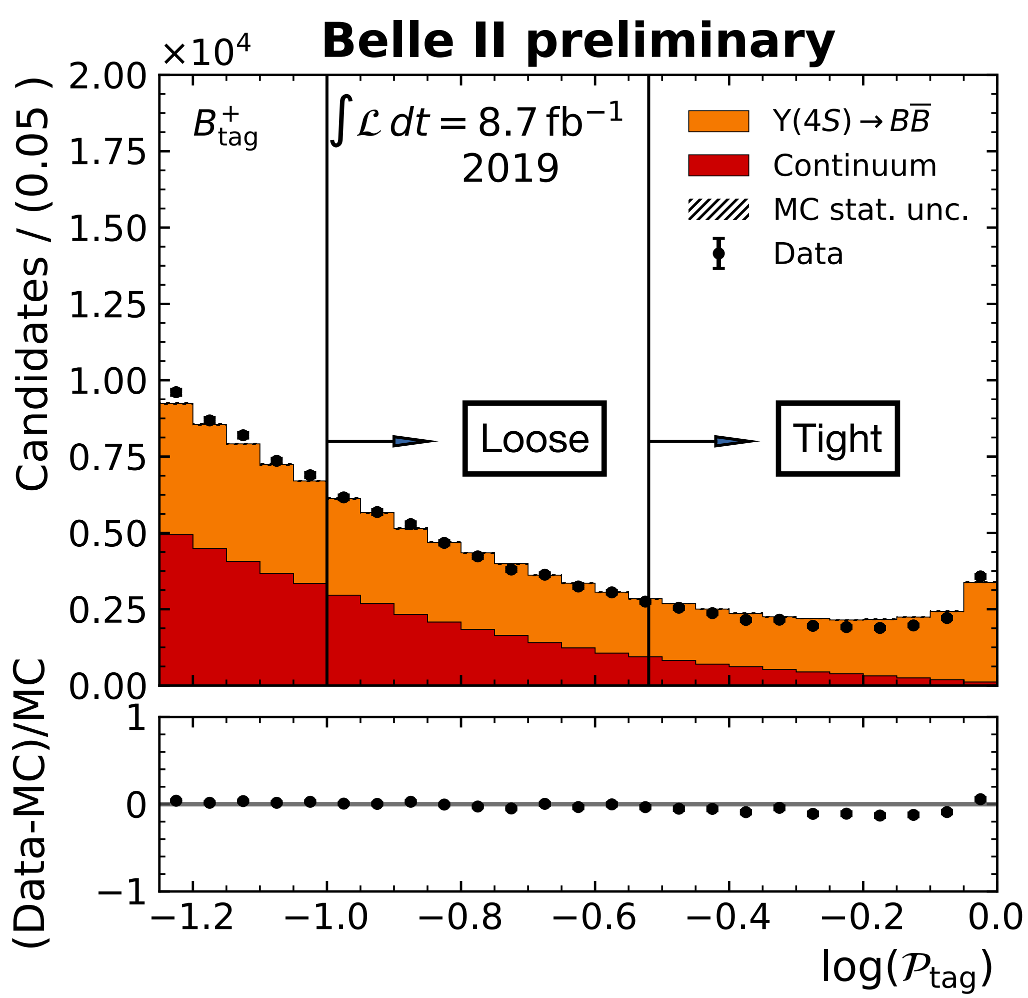
Output classifier = Measure of how well we reconstructed the B-Meson decay



beam constrained mass

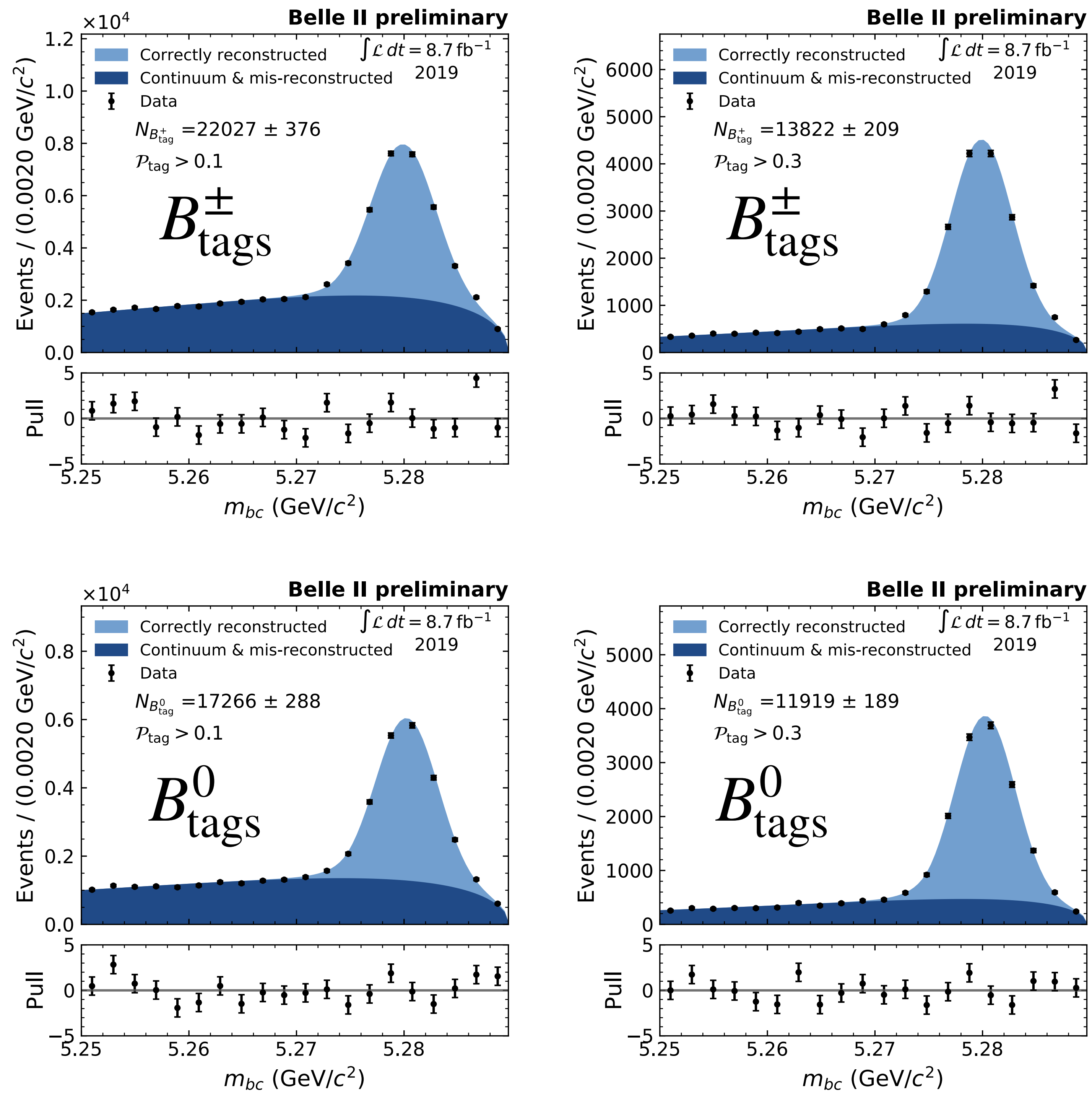
ca. 5.279 GeV

$$m_{bc} = \sqrt{E_{\mathrm{beam}}^2/4 - |\vec{p}_{B_{\mathrm{tag}}}|^2} \simeq m_B$$

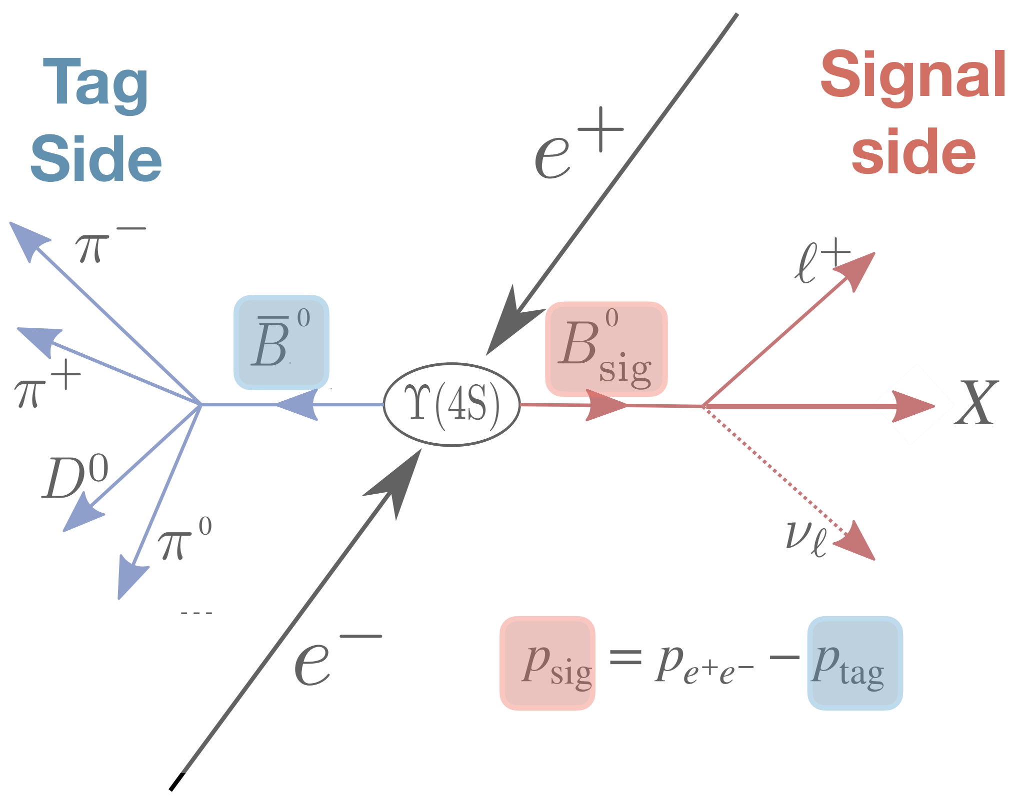


Loose Selection

Tight Selection



Efficiency can be calibrated, but this has caveats



Why is the efficiency different? Use 10'000 different decays, use uncalibrated detector information, line-shapes differ in simulation

$\rightarrow$ all aggregated in $\mathscr{P}_{tag}$

<u>Strategy</u>: use a well measured process, add it to your MC with its measured BF and compare

$$\frac{N^{Data}_{X\ell\bar{\nu}_\ell}}{N^{MC}_{X\ell\bar{\nu}_\ell}}$$

Belle II Collaboration, BELLE2-CONF-PH-2020-005, [arXiv:2008.06096]

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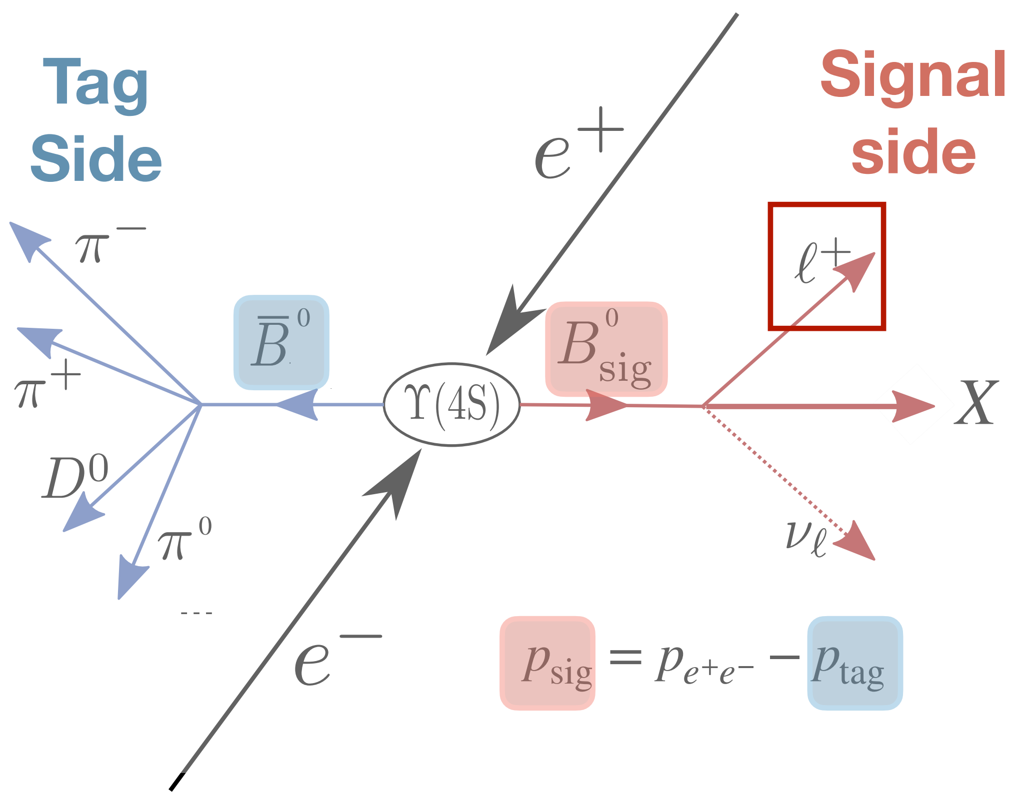

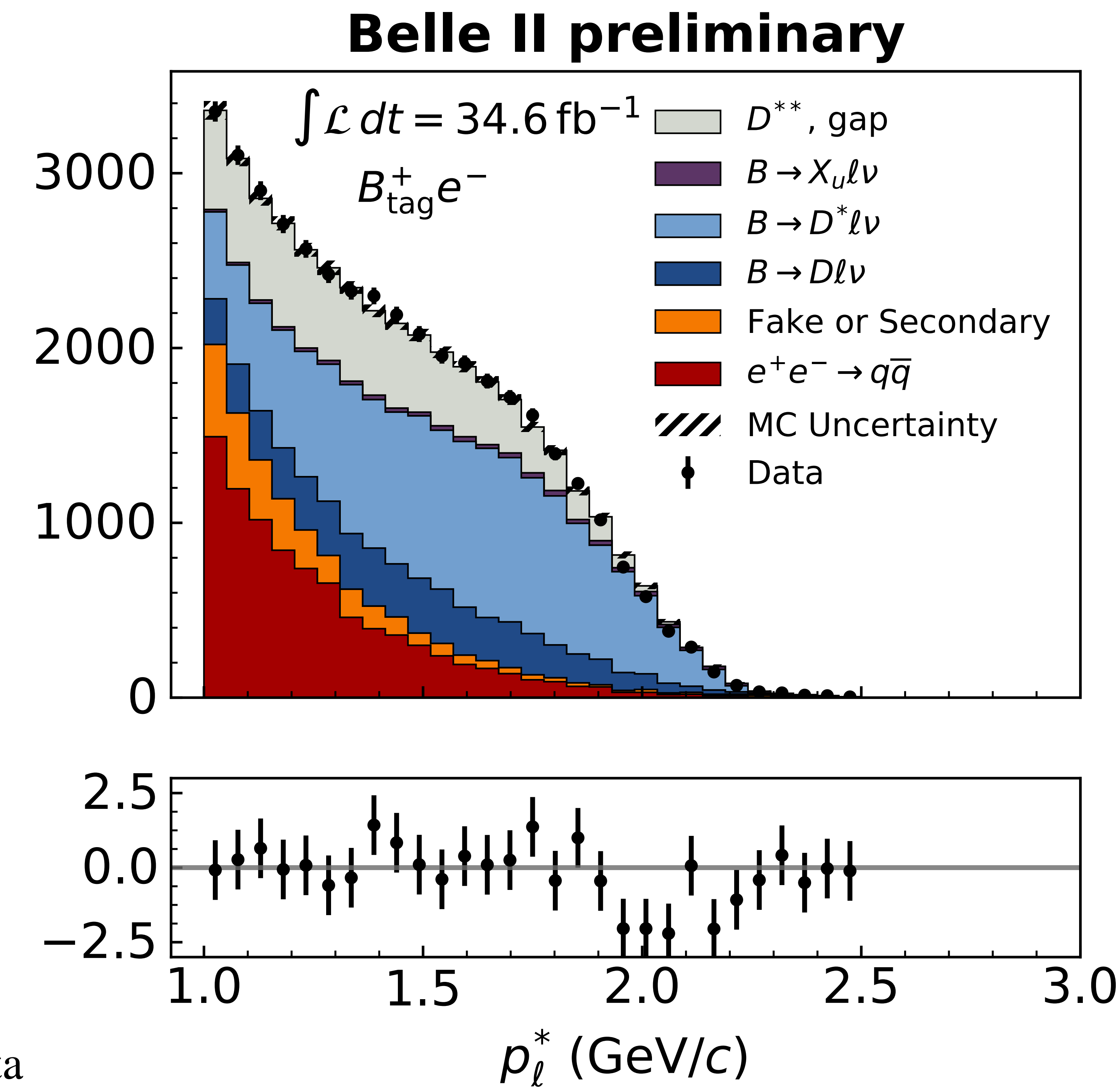

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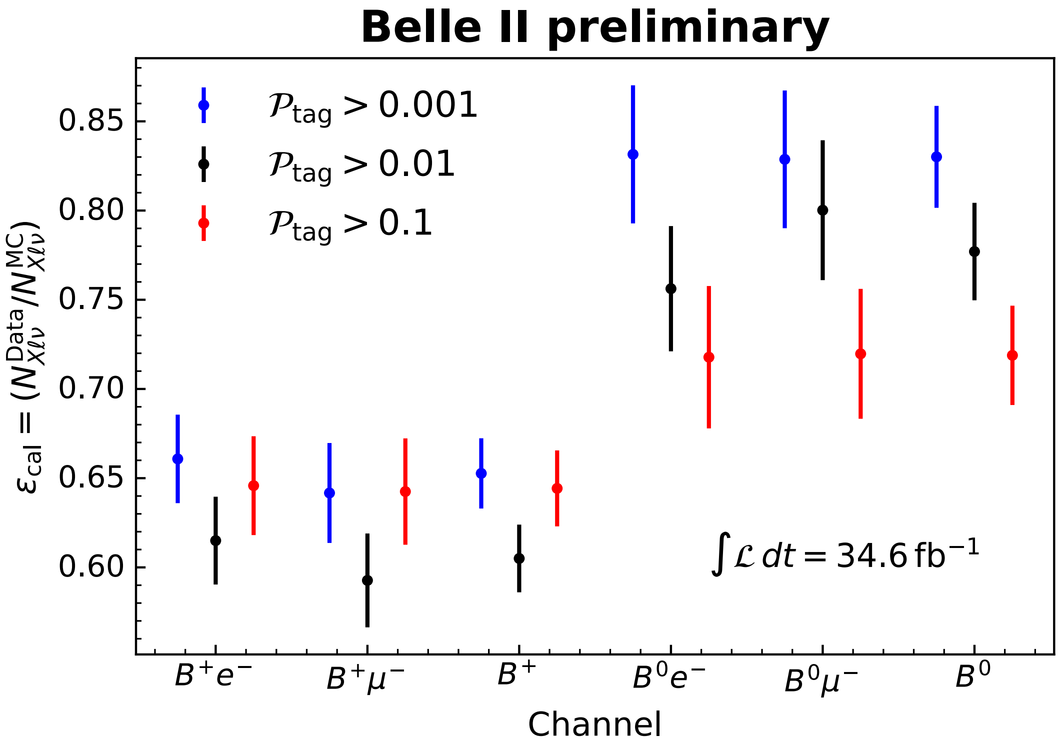
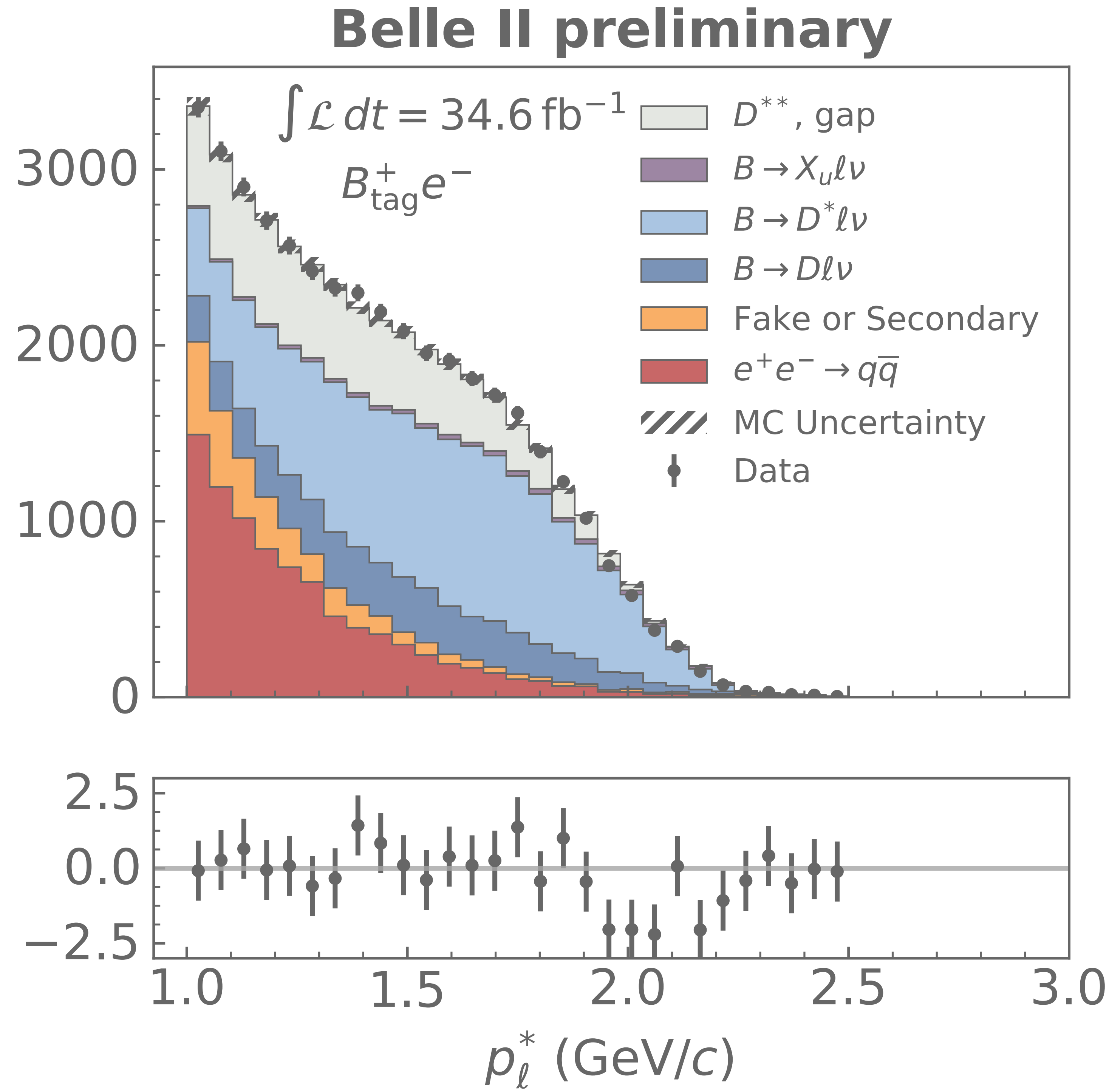
Efficiency Calibration

$$\epsilon_{\mathrm{cal}} = \frac{N^{\mathrm{Data}}_{X\ell\bar{\nu}_\ell}}{N^{\mathrm{MC}}_{X\ell\bar{\nu}_\ell}}$$





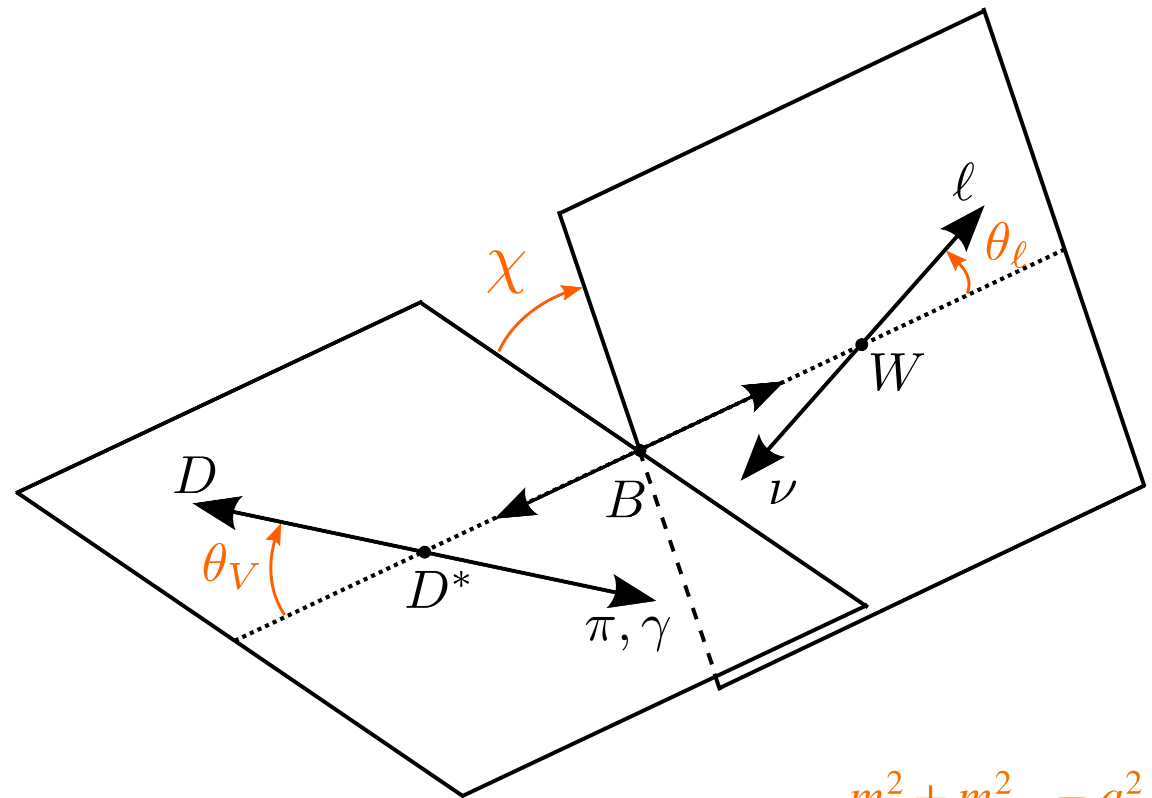
B^+		
$\mathcal{P}_{\mathrm{tag}} >$	ϵ	uncertainty [%]
0.001	0.65 ± 0.02	3.0
0.01	0.61 ± 0.02	3.1
0.1	0.64 ± 0.02	3.3

B^0		
$\mathcal{P}_{\mathrm{tag}} >$	ϵ	uncertainty [%]
0.001	0.83 ± 0.03	3.4
0.01	0.78 ± 0.03	3.5
0.1	0.72 ± 0.03	3.9

Tagged measurements of $B \to D^{(*)}\ell\bar{\nu}_\ell$

Target B^0 and B^+ and reconstruct D in many modes :

$D^+ \to K^-\pi^+\pi^+$, $D^+ \to K^-\pi^+\pi^+\pi^0$, $D^+ \to K^-\pi^+\pi^+\pi^+\pi^-$, $D^+ \to K_S^0\pi^+$, $D^+ \to K_S^0\pi^+\pi^0$, $D^+ \to K_S^0\pi^+\pi^+\pi^-$, $D^+ \to K_S^0K^+$, $D^+ \to K^+K^-\pi^+$, $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^0$, $D^0 \to K^-\pi^+\pi^+\pi^-$, $D^0 \to K^-\pi^+\pi^+\pi^-\pi^0$, $D^0 \to K_S^0\pi^0$, $D^0 \to K_S^0\pi^+\pi^-$, $D^0 \to K_S^0\pi^+\pi^-\pi^0$, and $D^0 \to K^-K^+$.

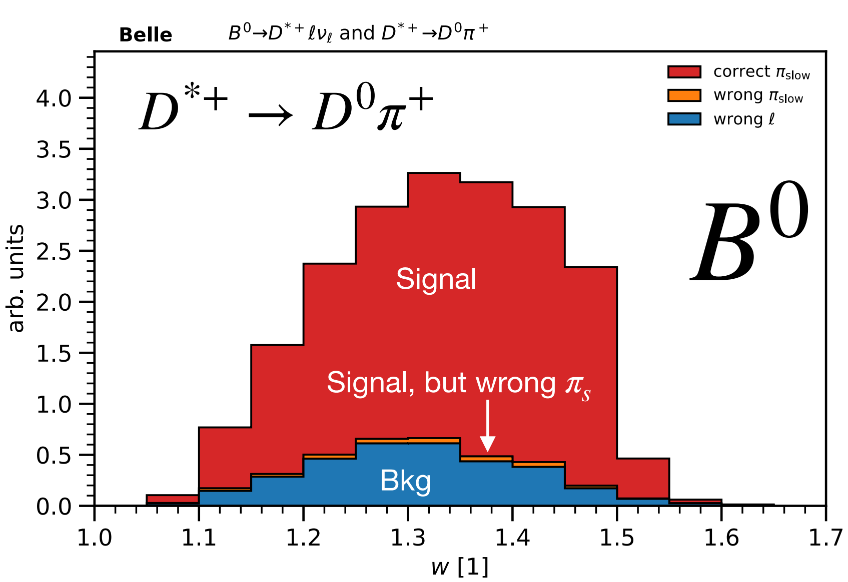


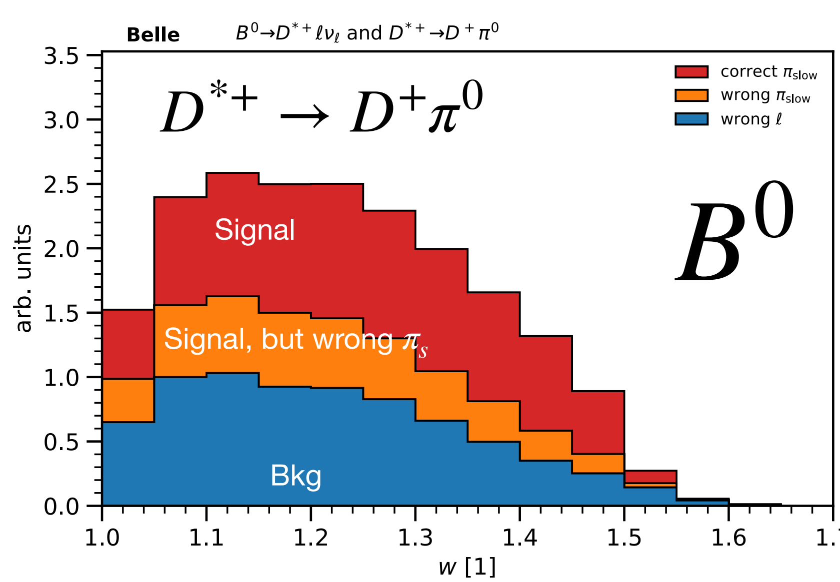
Reconstruct $D^{*+} \to D^0\pi^+, D^{*+} \to D^+\pi^0, D^{*0} \to D^0\pi^0$

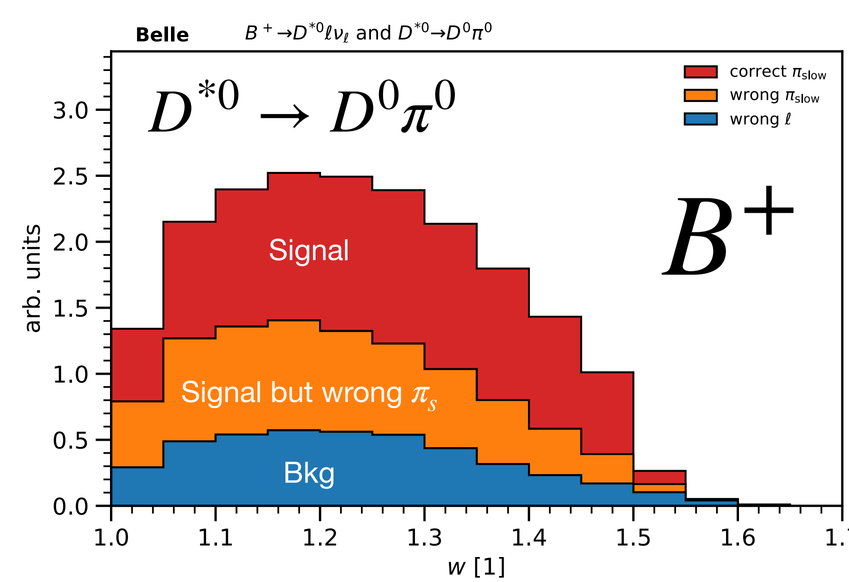
In principle also can do $D^{*0} \to D^0\gamma$, but has different Lorentz structure & angular distributions

Tagged measurement can directly reconstruct **B rest frame** & access $\{w, \cos\theta_\ell, \cos\theta_V, \chi\}$

$$w = v_B \cdot v_{D^{(*)}} = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2 m_B m_{D^{(*)}}}$$





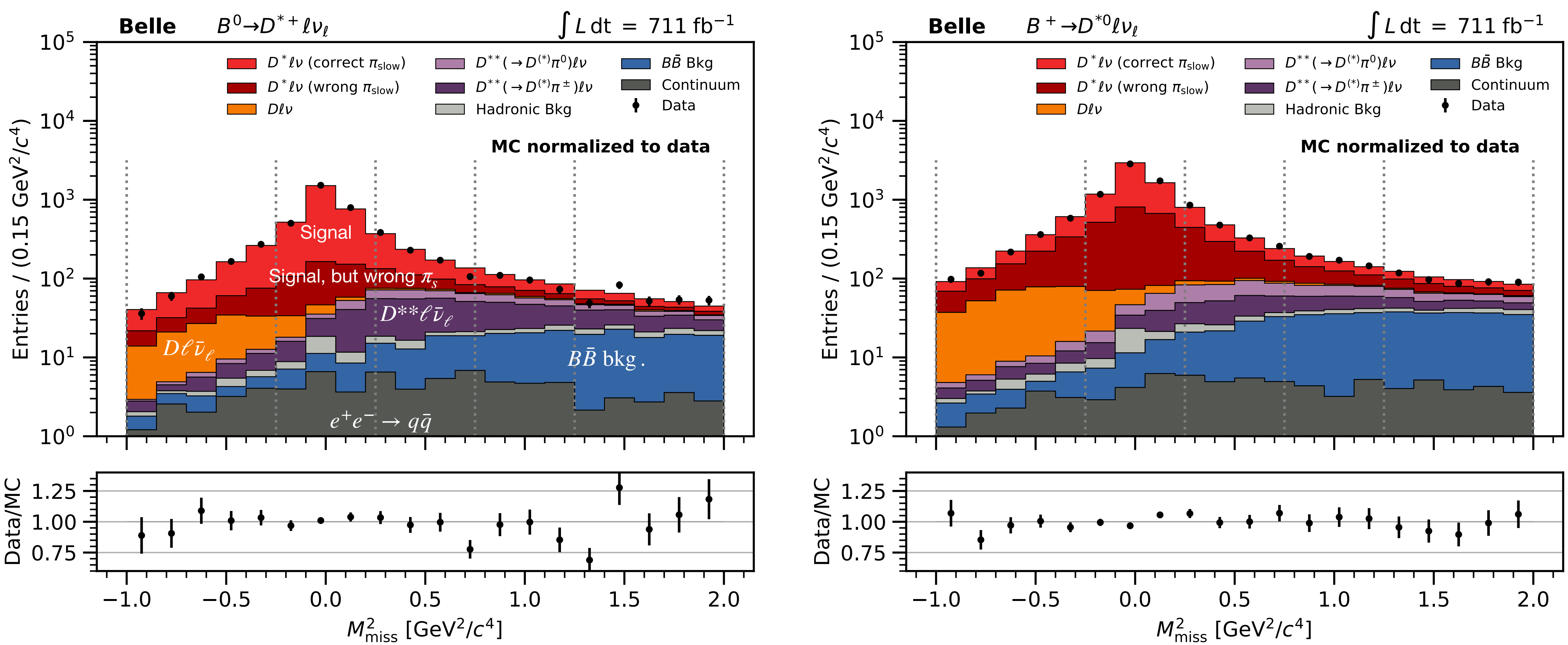


Background subtraction

Need to subtract residual **background** contributions:

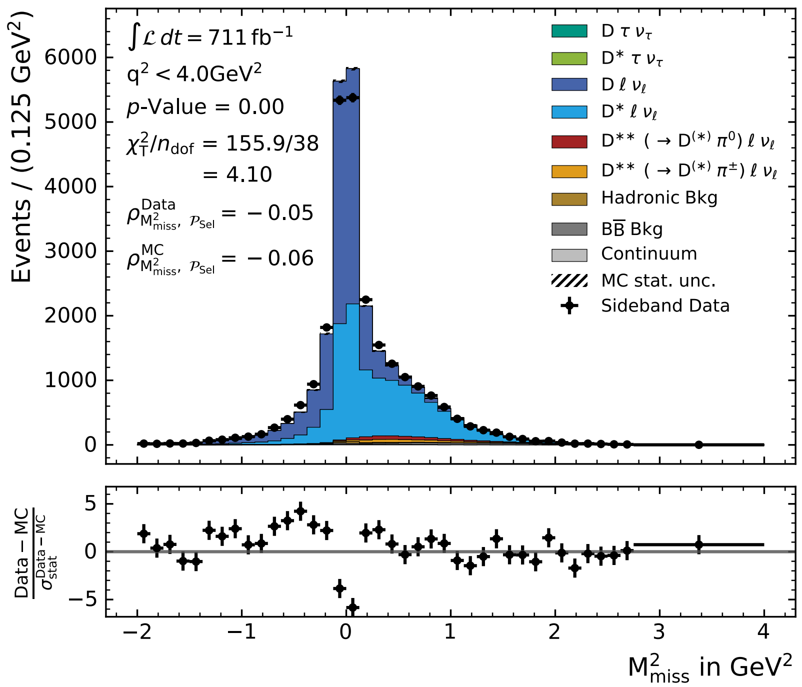
- From other SL decays ($B \to D^{**}\ell\bar{\nu}_\ell$ or $B \to D\ell\bar{\nu}_\ell$)
- From other B decays (with fake or real leptons)
- From Continuum ($e^+e^- \to q\bar{q}$)

Use: $0 = m_\nu^2 \simeq M_{\text{miss}}^2 = (E_{\text{miss}}, \mathbf{p}_{\text{miss}})^2 = (p_B - p_{D*} - p_\ell)^2$ or $U = E_{\text{miss}} - |\mathbf{p}_{\text{miss}}|$



MC modelling of M^2_{miss} challenging

Need to apply additional smearing to match actual resolution



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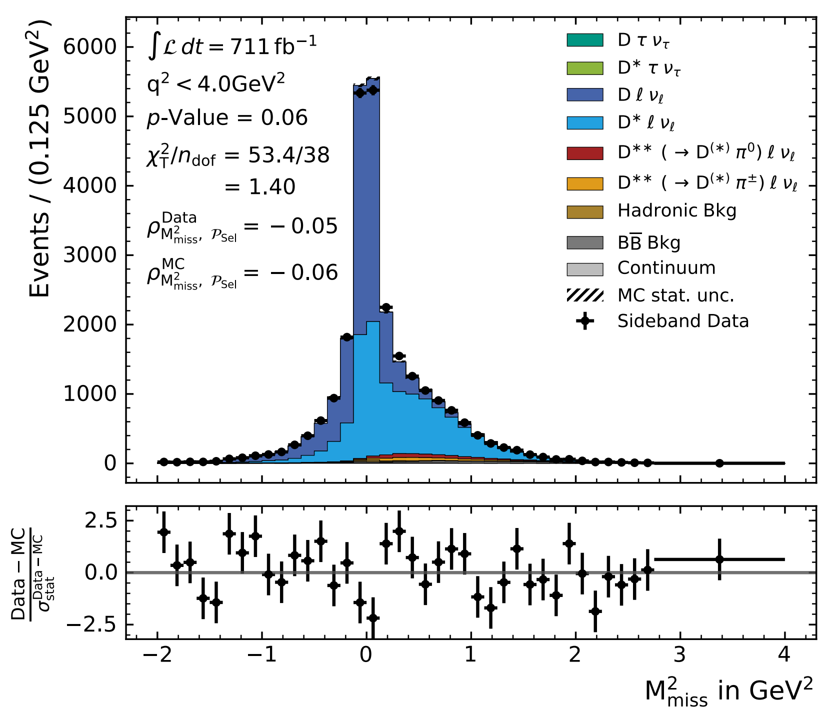
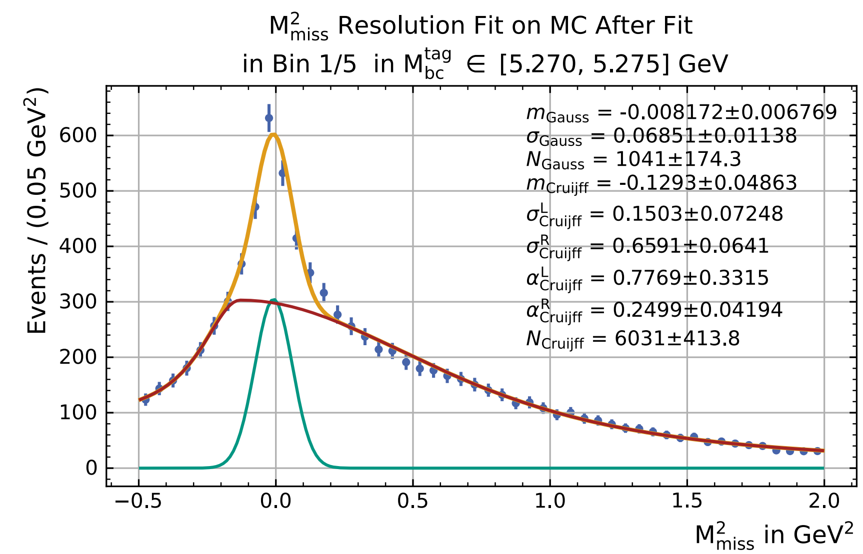


Use an appropriate smearing function

(e.g. asymmetric Laplace distribution and as a function of m_{bc})

$$f_{\mathrm{AL}}(x; m, \lambda, \kappa) = \frac{\lambda}{\kappa + 1/\kappa} \begin{cases} \exp\left((\lambda/\kappa)(x-m)\right) & \text{if } x < m, \\ \exp(-\lambda\kappa(x-m)) & \text{if } x \geq m, \end{cases}$$



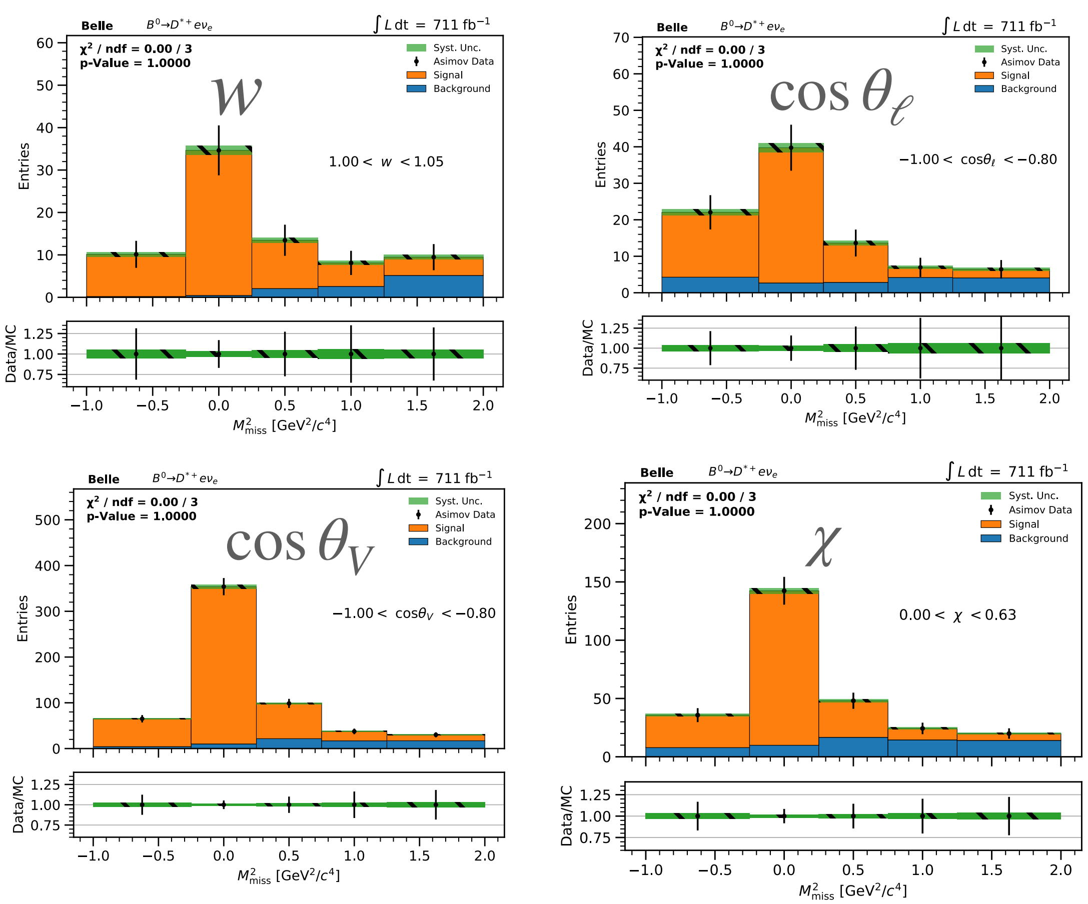
Fit in Bins of $\{w, \cos\theta_\ell, \cos\theta_V, \chi\}$

E.g. Can use **binned likelihood** fit to **1D distributions**
(good to use coarse binning to reduce modelling dependence (Bkg shape, resolution))

4D fit also possible; but binned approach suffers from course of dimensionality

→ **better unbinned (but then need to worry about efficiency & migrations)**

Example **1D fits** to MC (Asimov fits)



Best approach: use folding to extract relevant information

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta^*\, d\cos\theta_\ell\, d\chi} = \frac{9}{32\pi}\left[\left(I_1^s \sin^2\theta^* + I_1^c \cos^2\theta^*\right) + \left(I_2^s \sin^2\theta^* + I_2^c \cos^2\theta^*\right)\cos 2\theta_\ell \right.$$
$$+ I_3 \sin^2\theta^* \sin^2\theta_\ell \cos 2\chi + I_4 \sin 2\theta^* \sin 2\theta_\ell \cos\chi + I_5 \sin 2\theta^* \sin\theta_\ell \cos\chi$$
$$+ \left(I_6^c \cos^2\theta^* + I_6^s \sin^2\theta^*\right)\cos\theta_\ell + I_7 \sin 2\theta^* \sin\theta_\ell \sin\chi$$
$$\left. + I_8 \sin 2\theta^* \sin 2\theta_\ell \sin\chi + I_9 \sin^2\theta^* \sin^2\theta_\ell \sin 2\chi\right],$$

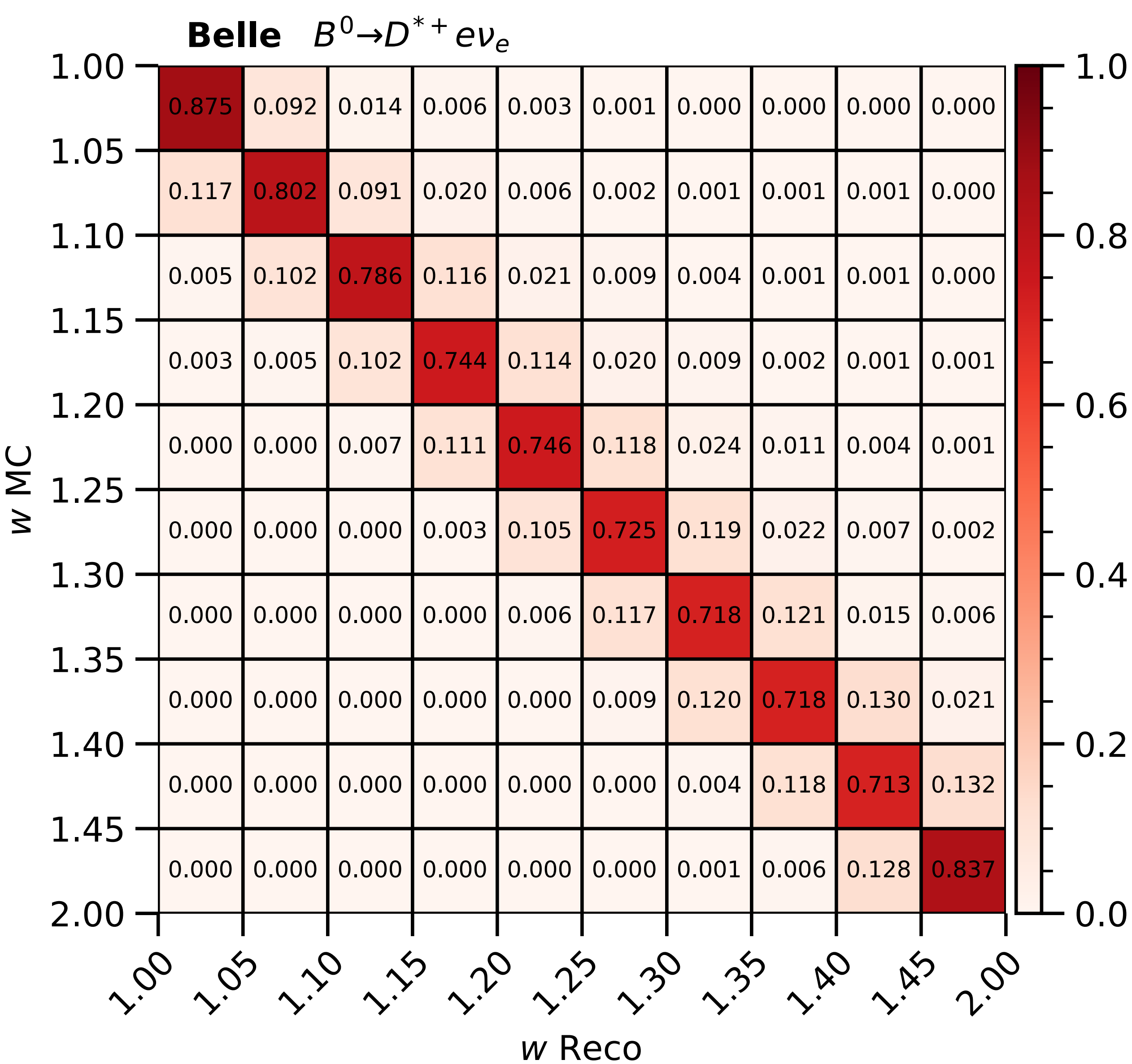
I.e. by building smart asymmetries, can project out the relevant 12 terms (integrated over a certain q^2 range)

Detector migrations

An event reconstructed in a given *bin i,* might not have had a “true” value corresponding to a *bin j*

Can be parametrized as a migration matrix:

$$\mathscr{M}_{ij} = \mathscr{P}(\text{reco. in bin } i \,|\, \text{true value in bin } j)$$



Can recover true values by “unfolding” determined yields, mapping $\text{reco} \to \text{true}$

Simplest version: migration matrix inversion

$$\mathbf{x}_{\text{true}} = \mathscr{M}_{ij}^{-1} \, \mathbf{x}_{\text{reco}}$$

Many approaches to dampen impact of increase in variance

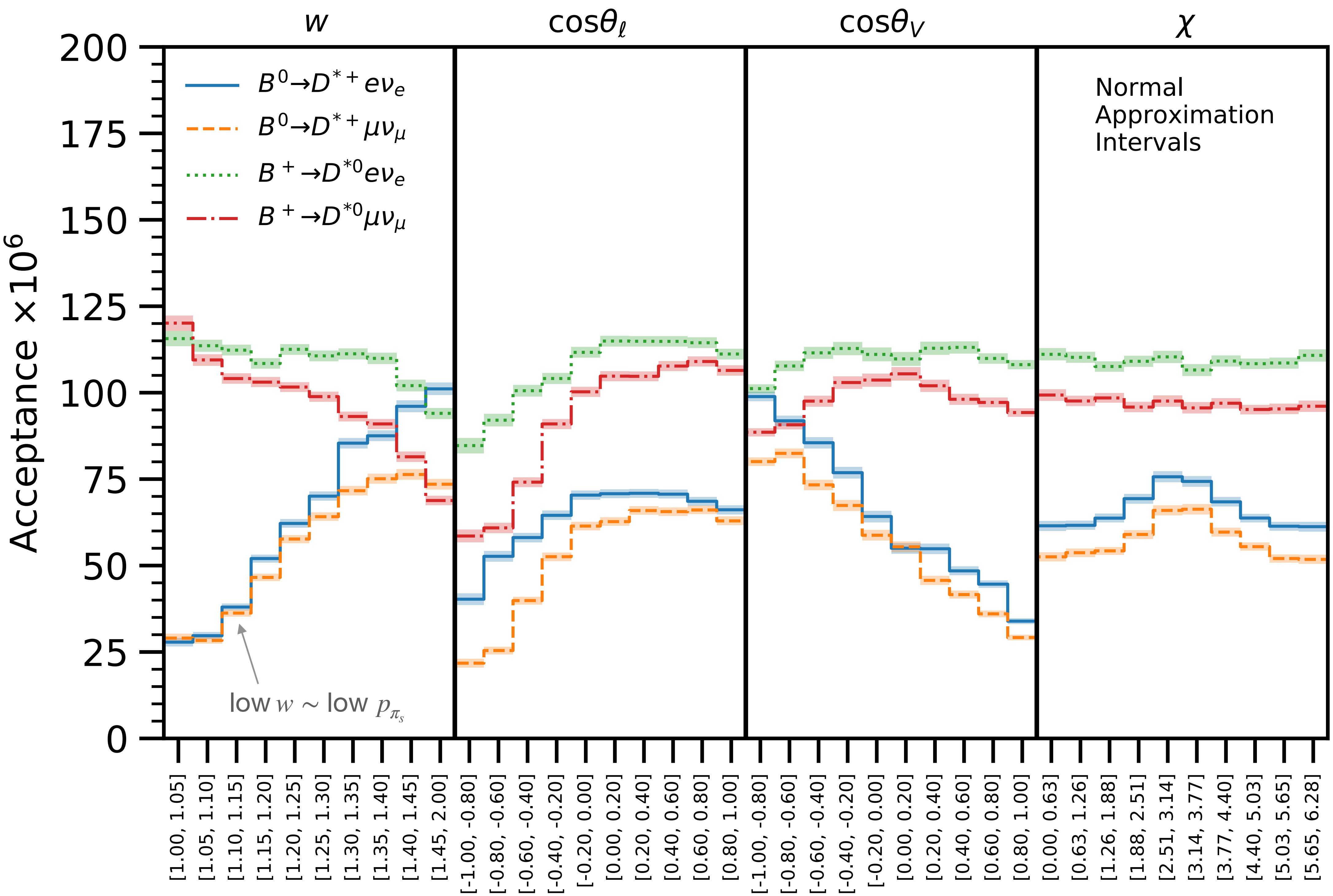
(mostly a problem with large migrations → true bin is then the sum of many reco bins with high weights)

or to reduce impact of MC prior

(here less an issue; but Bayesian unfolding can propagate the observed shape to MC to minimize model dependencies)

Acceptance × Efficiency

After migration effects are corrected, need to correct also for selection effects
(Acceptance x Efficiency)



A word on Efficiencies

Efficiencies can be are a large source of uncertainties

Two examples relevant for this:

- Lepton Identification Uncertainty

Often based on a global likelihood (or a multivariate classifier) using individual likelihoods (or input features) to calculate a score how likely the identified particle is an electron or a muon

Symbolically:

$$\mathscr{L} = \mathscr{L}_{\mathrm{CDC}} \times \mathscr{L}_{\mathrm{ECL}} \times \mathscr{L}_{\mathrm{TOP}} \times \mathscr{L}_{\mathrm{KLM}}$$

$\mathscr{L}_{\mathrm{CDC}}$: Ionization energy loss

$\mathscr{L}_{\mathrm{ECL}}$: $E/|\vec{p}\,|$

$\mathscr{L}_{\mathrm{TOP}}$: Information from Cherenkov light angles

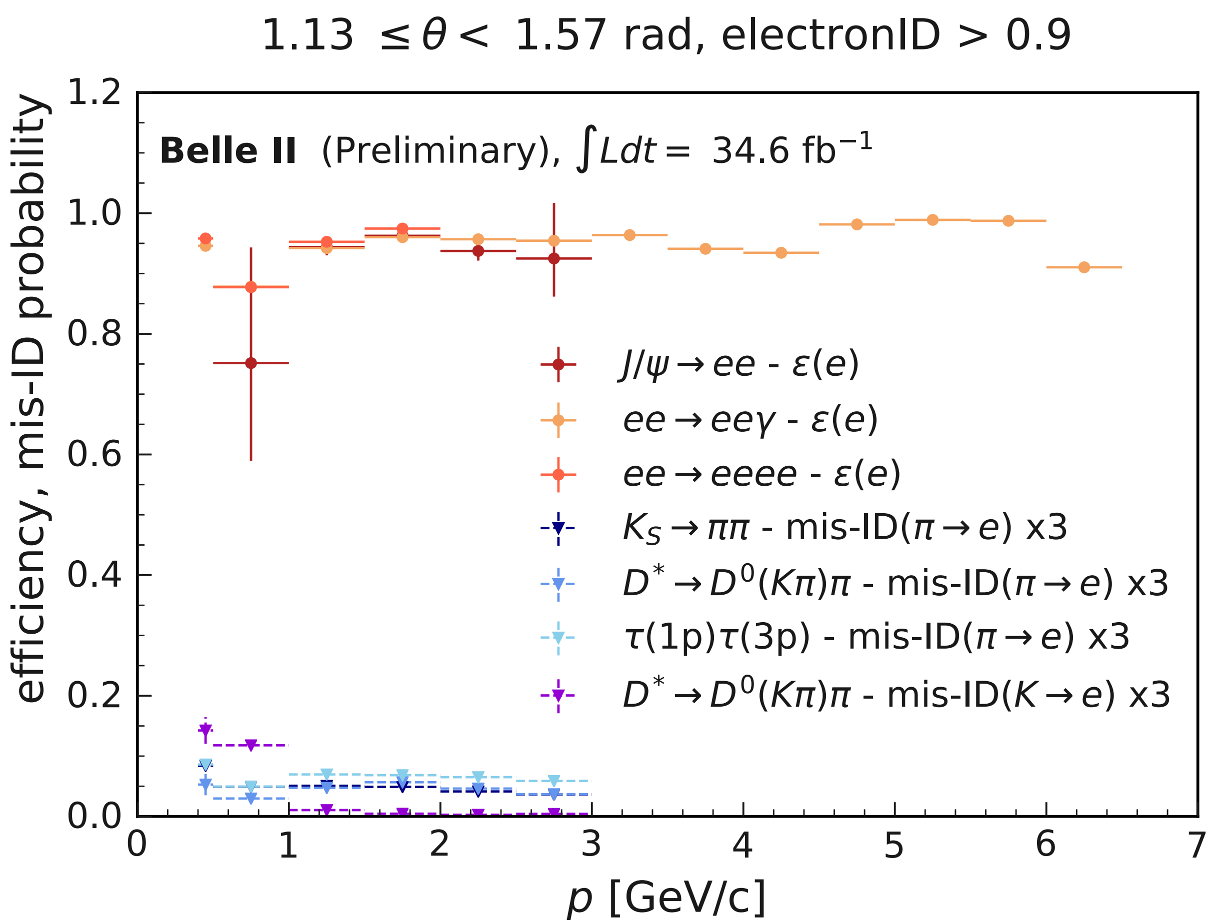
$\mathscr{L}_{\mathrm{KLM}}$: Matched KLM cluster hit?

Use clean physics sample to correct MC efficiencies and fake rates

E.g. $e^+e^- \to \mu\mu\gamma, e^+e^- \to e^+e^-\gamma, J/\psi \to \ell\ell, \ldots$

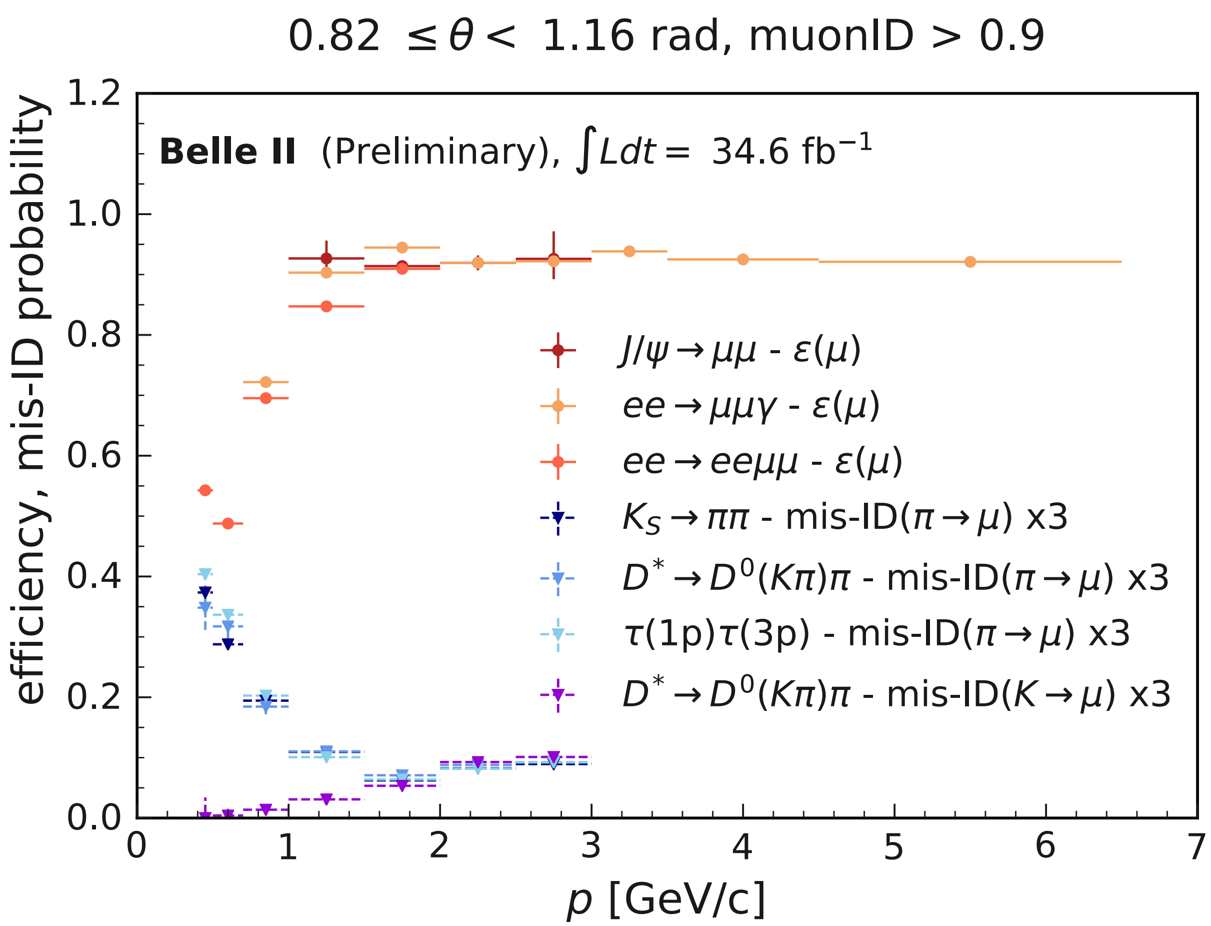
Construct likelihood ratio for Lepton ID: $\ell \mathrm{ID} = \mathscr{L}_e / [\mathscr{L}_e + \mathscr{L}_\mu + \mathscr{L}_\pi + \mathscr{L}_K + \mathscr{L}_p]$

Electrons



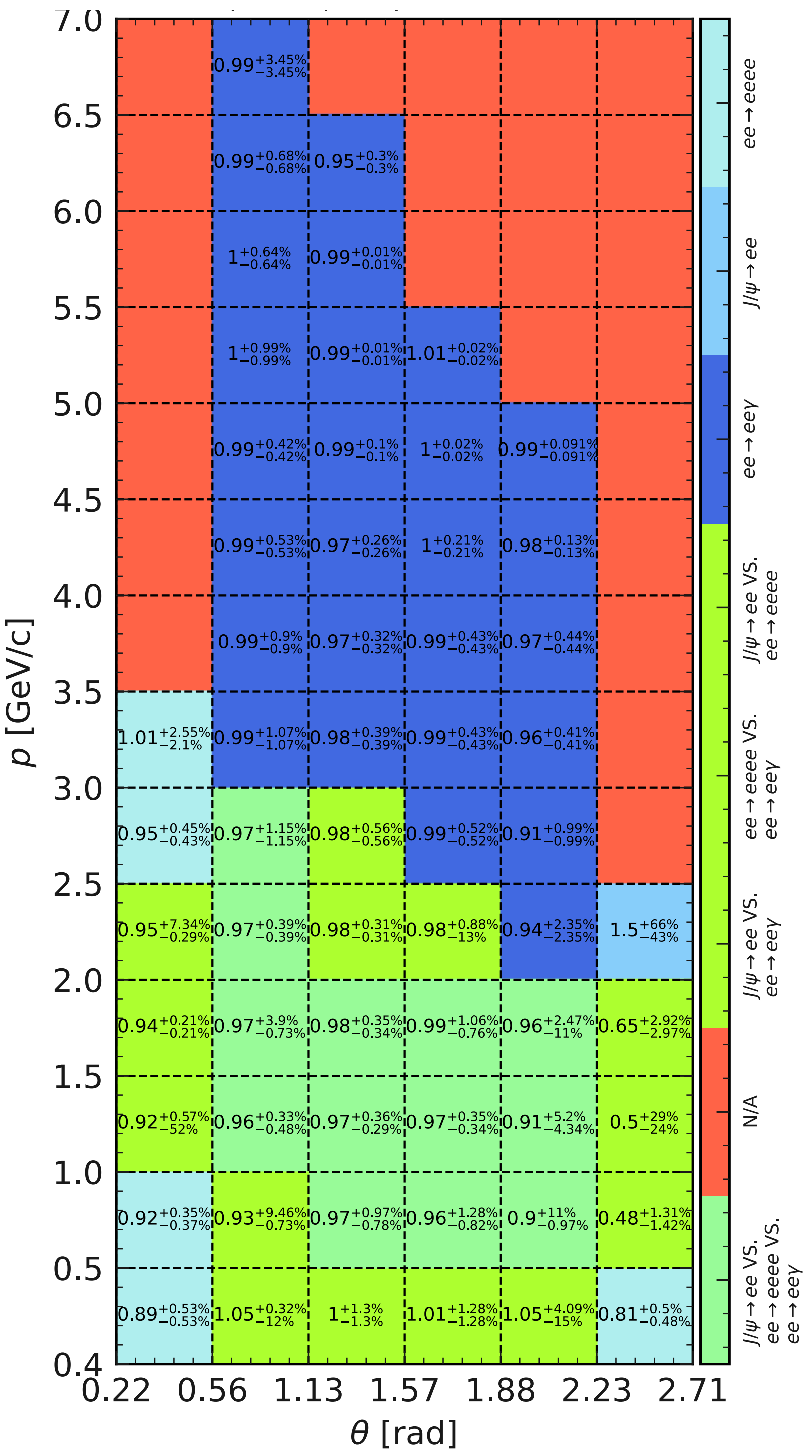
Momentum in lab frame

Muons



Construct correction tables of efficiency ratios $\dfrac{\epsilon_{\text{Data}}}{\epsilon_{\text{MC}}}$

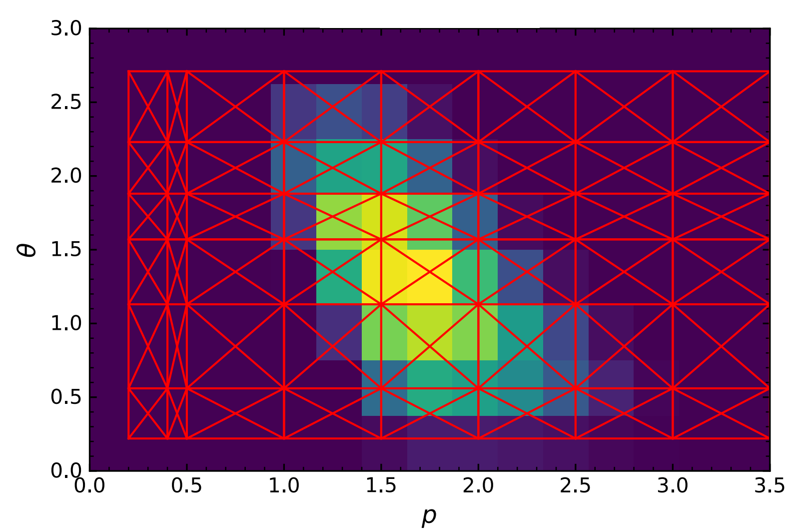
as a function of lab momentum and detector position (polar angle) to correct MC efficiencies



Precision limited by available control channel statistics (i.e. goes down by Lumi)

Non-closure between channels is added as extra uncertainty (limiting factor at very high luminosity)

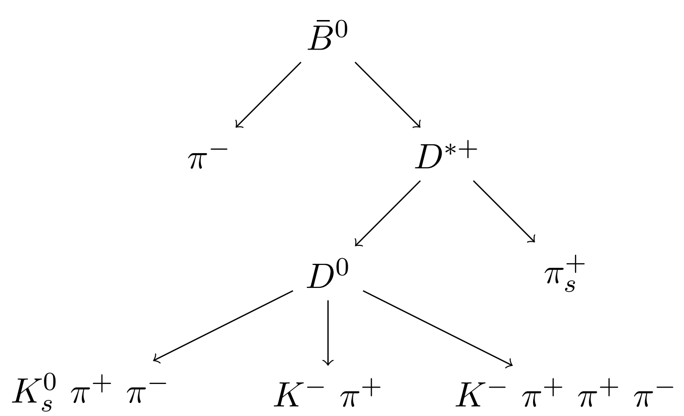
Coverage of control channels and signal are different, i.e. not all control channels have same relevance)



Second example:

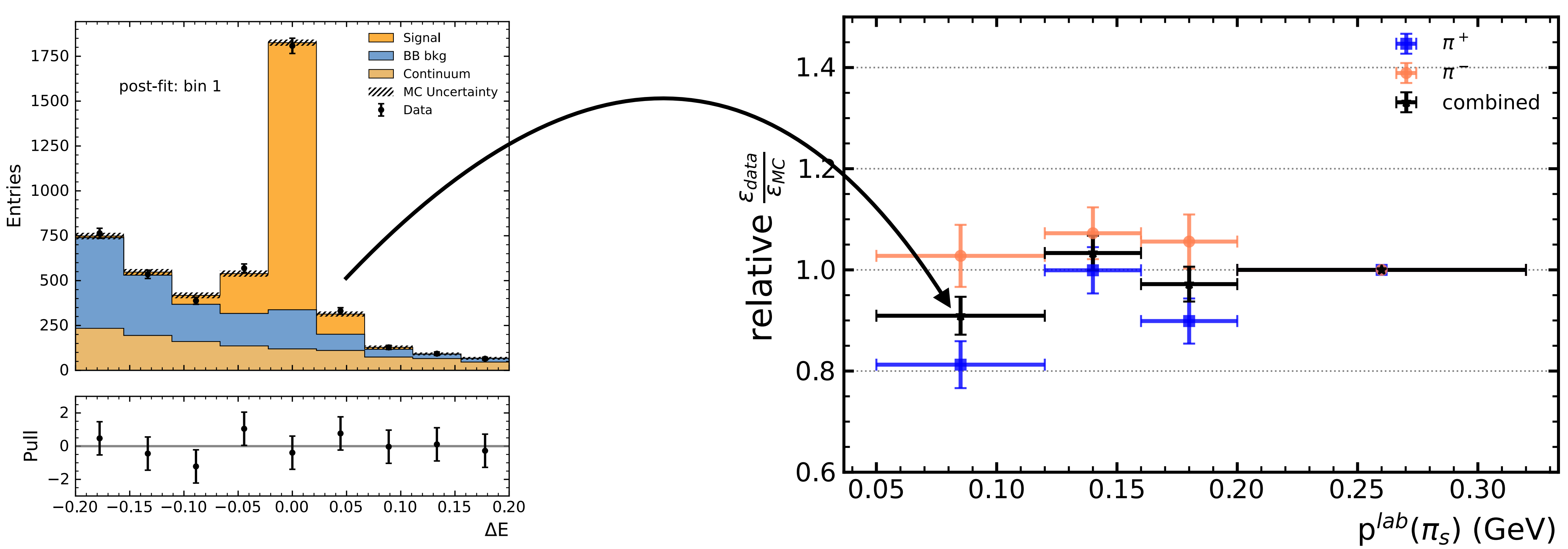
- Slow pion reconstruction efficiency

Also needs to be measured in data, e.g. via $B^0 \to D^{*+}\pi^-$ decays

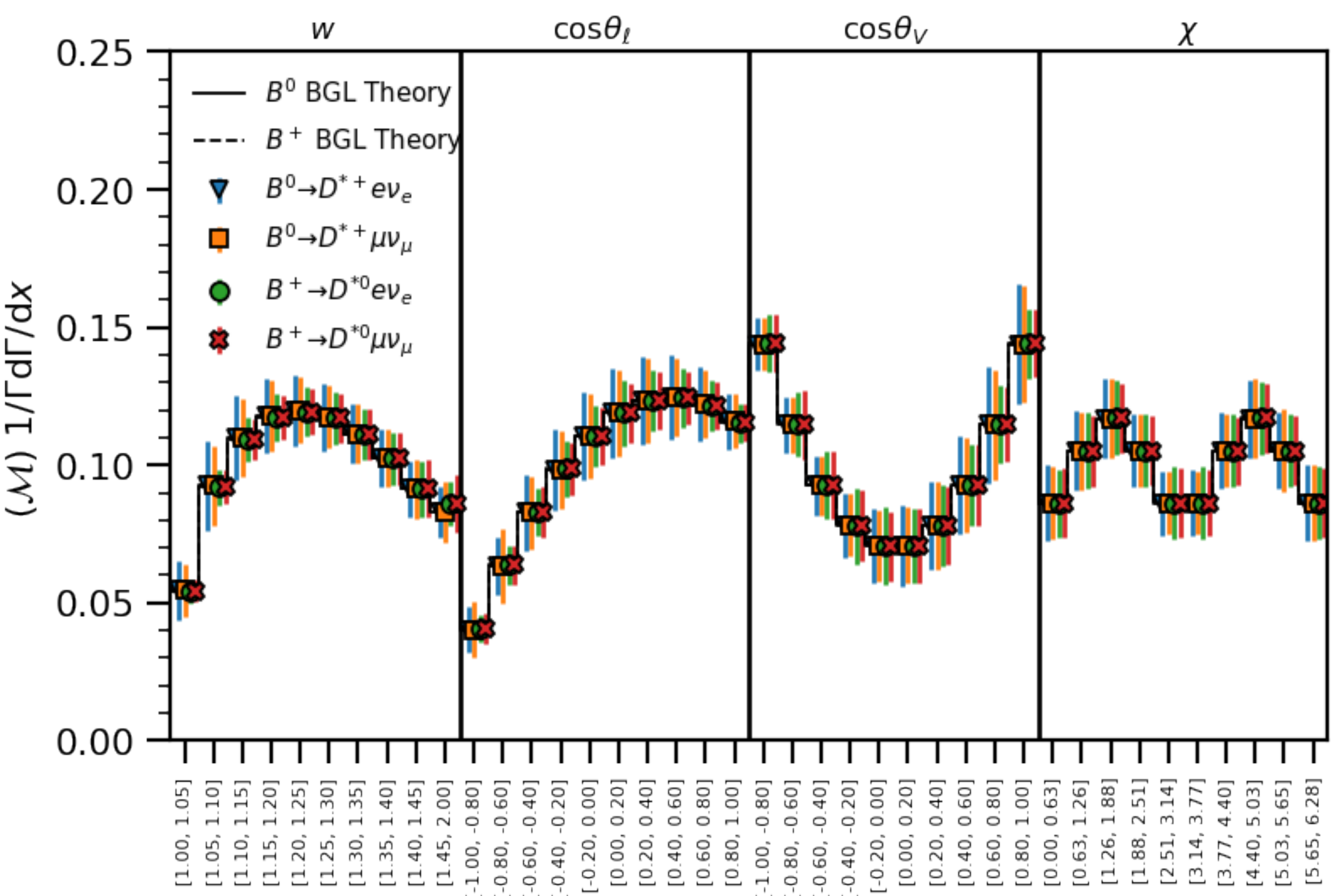


Extract signal in a fit to $\Delta E = \sqrt{s}/2 - E_B$ in bins of $p_{\pi_s}^{\text{lab}}$

Measure ratio efficiency ratio **relative** to high-momentum region of $p_{\pi_s}^{\text{lab}} > 200\,\text{MeV}$



The final result (MC)



Note how the different channels are complementary in different regions of phase-space

(e.g. B^+ has much better precision at low w than B^0, but both have equal precision at high w)

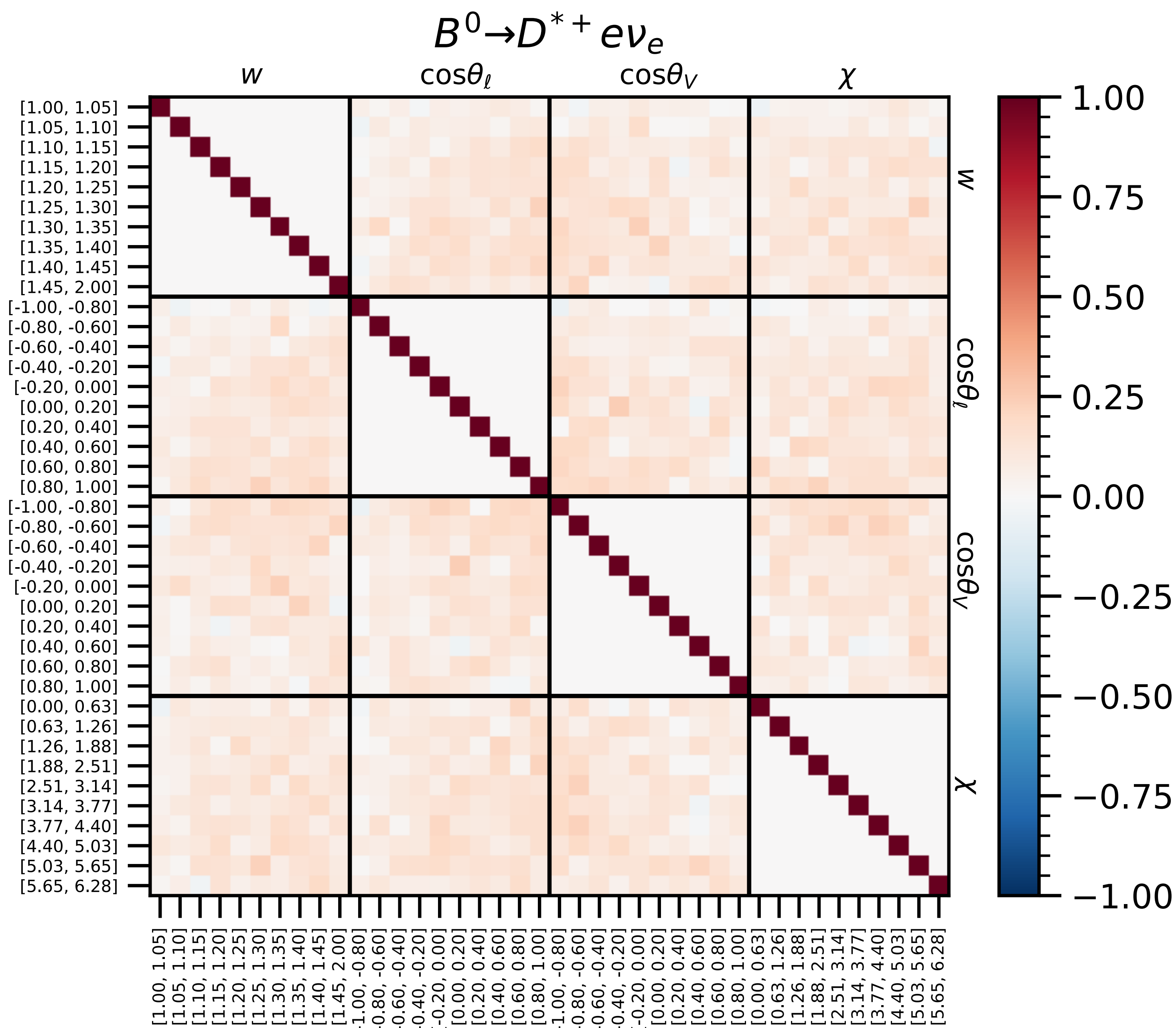
For a simultaneous analysis, need to determine correlations between different 1D projections → can be done using **boostrapping**

Very simple: create a replica of your data set by sampling with replacement

Repeat full analysis chain of 4 x1D measurement for **each replica**

Pearson correlator of replica sample provides estimator for statistical correlation between bins:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$



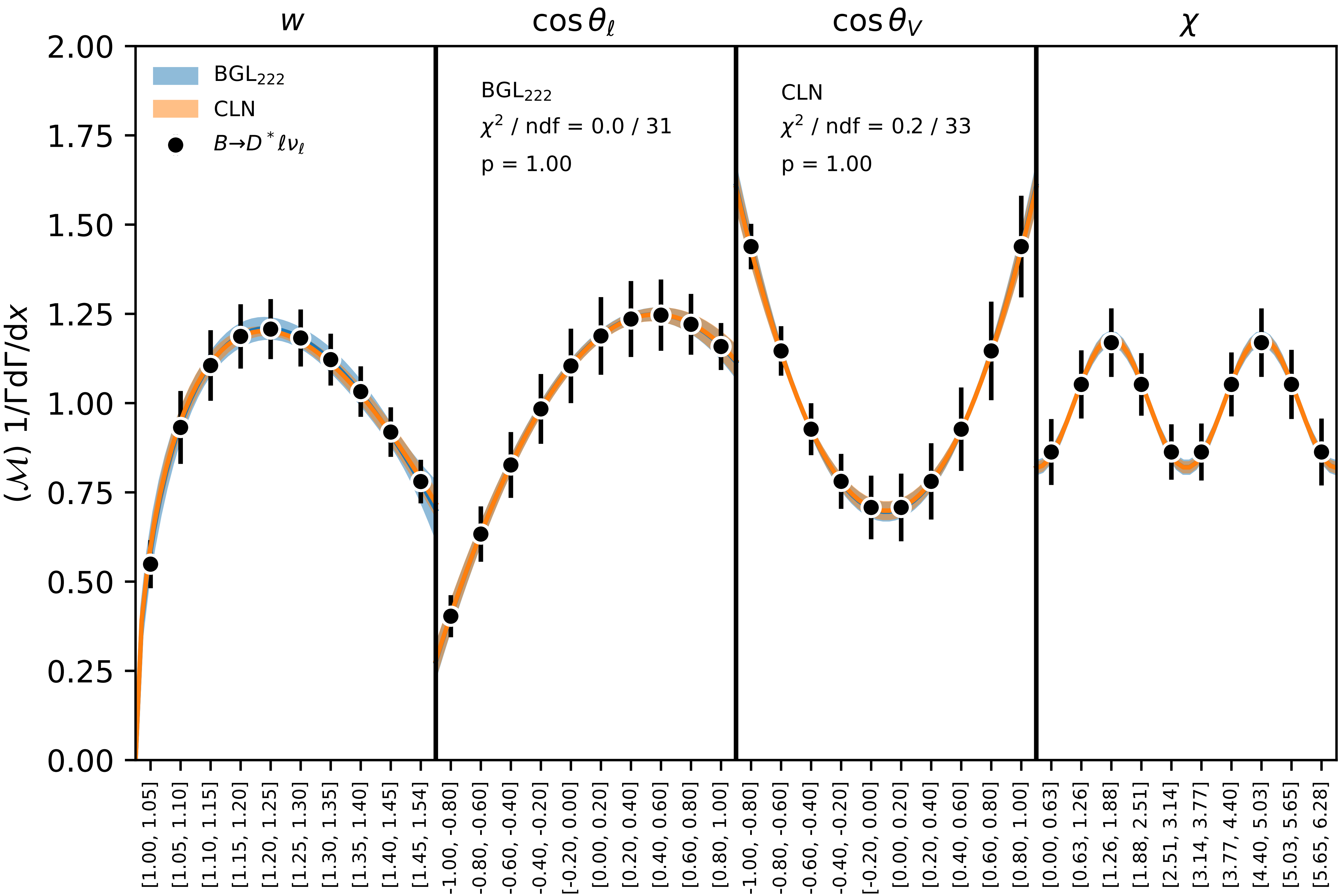
But since we measured projections of the same data, the effective **degrees of freedom** are not 40, but 37 (Jung, Van Dyk)

Best use of tagged data:

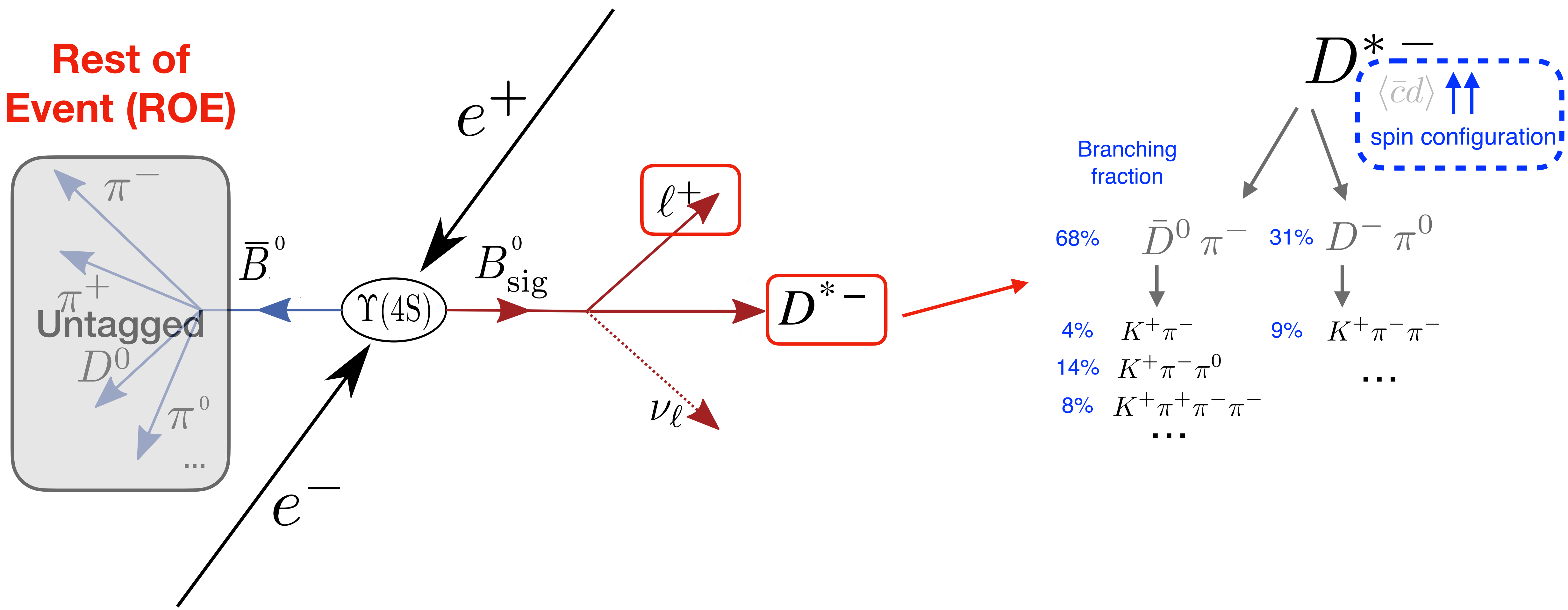
Fit normalized shapes (and if available total rate)

36 dof from shapes (4*9) and 1 from normalization

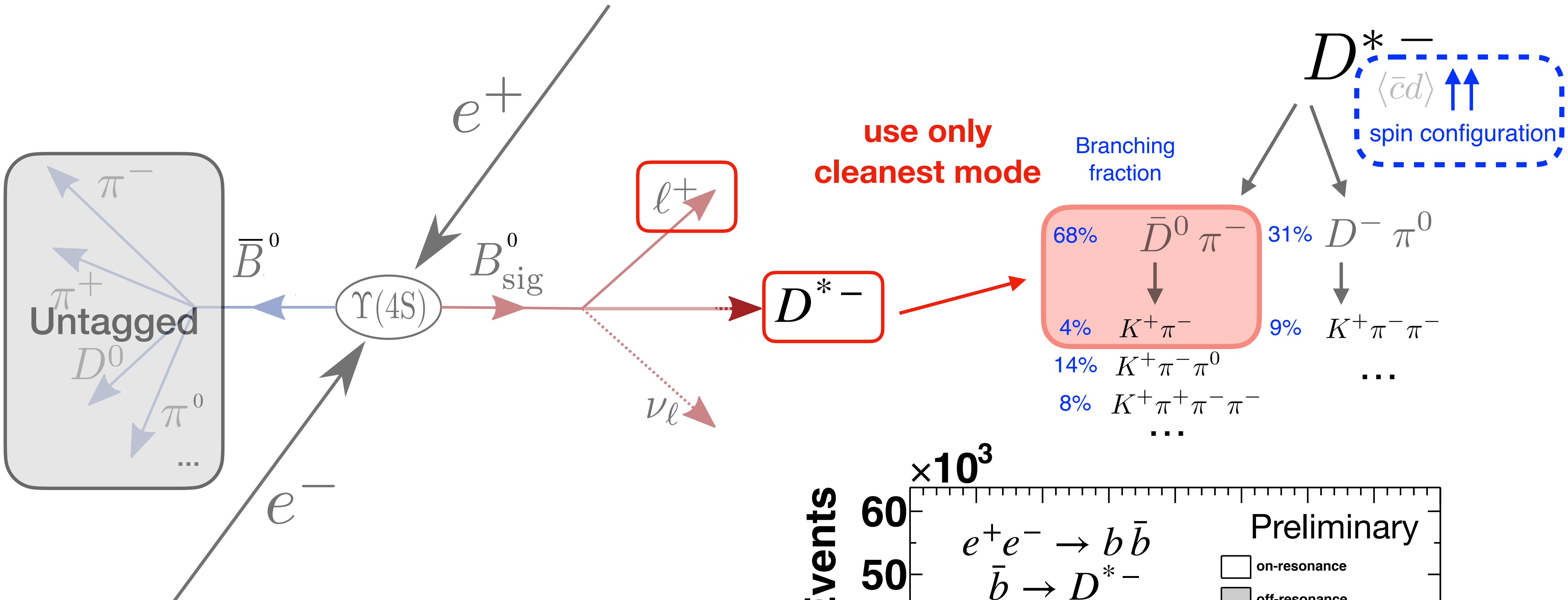
(Asimov again)

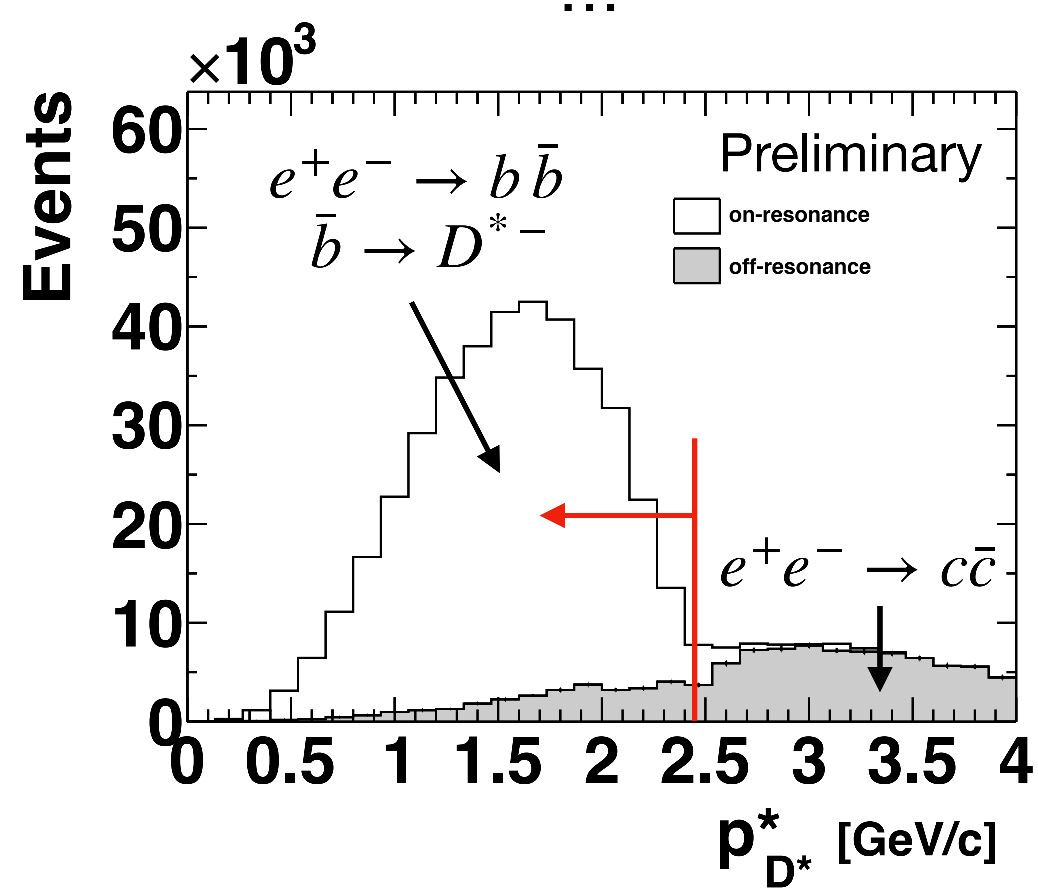


Untagged measurements of $B \to D^{(*)}\ell\bar{\nu}_\ell$

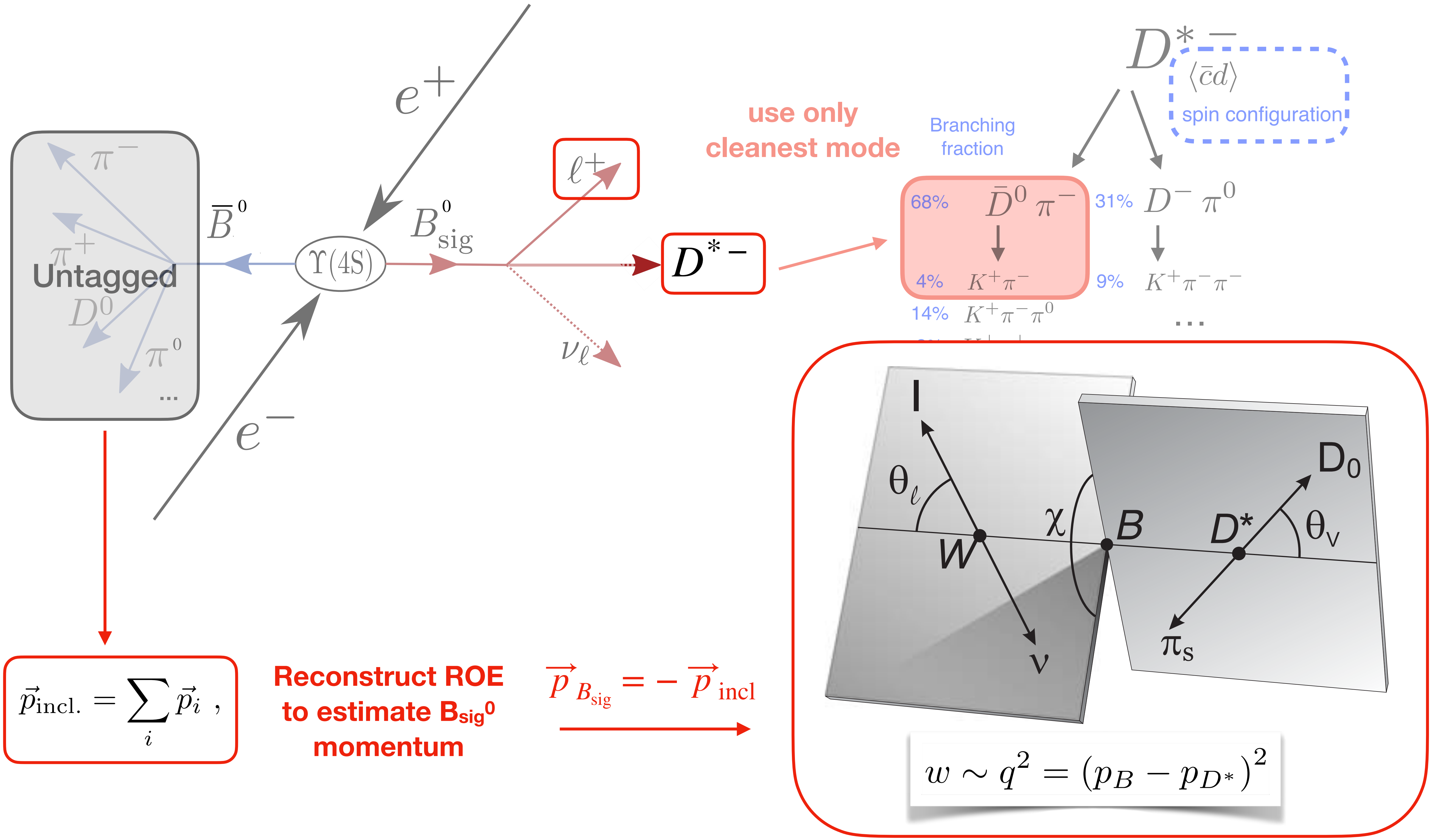


Untagged measurements of $B \to D^{(*)}\ell\bar{\nu}_\ell$



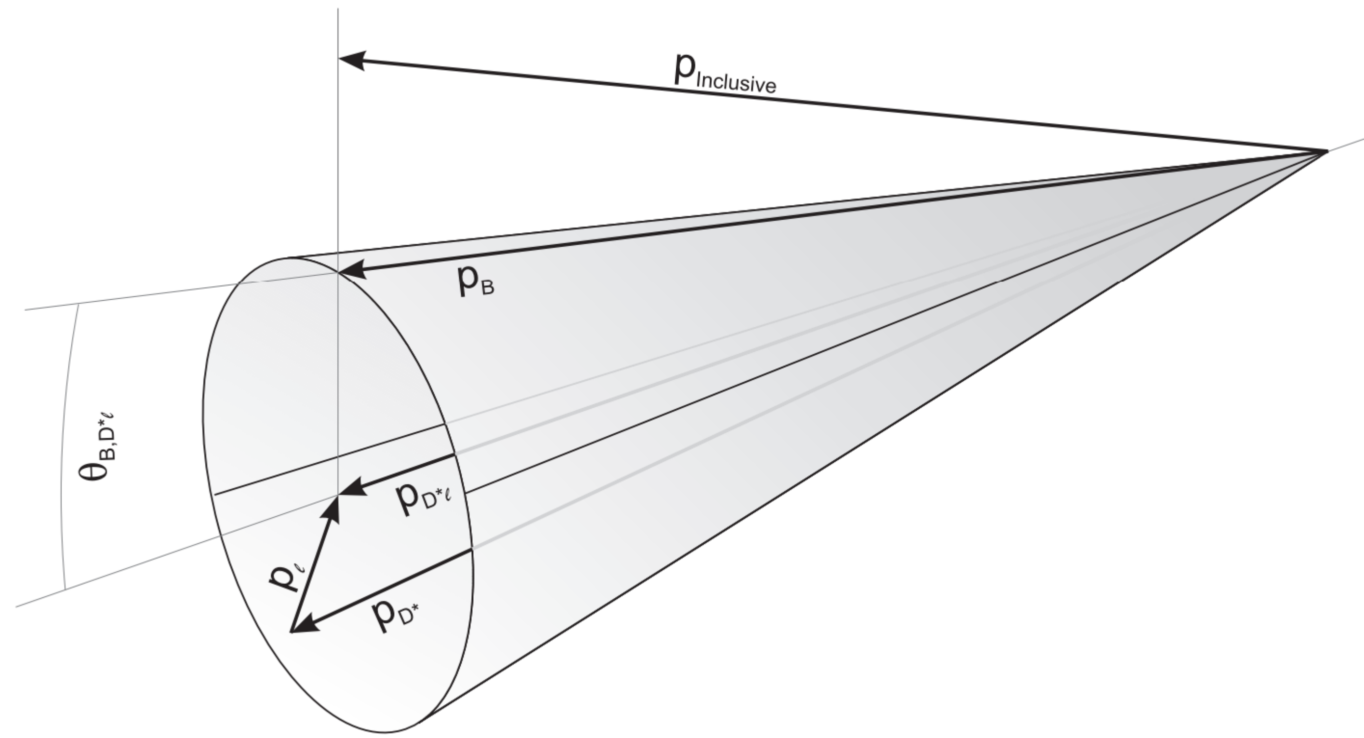


Untagged measurements of $B \to D^{(*)}\ell\bar{\nu}_\ell$



Alternative Reconstruction Methods

Can exploit that the B meson lies on a **cone**, whose opening angle is fully determined by properties of visible particles:



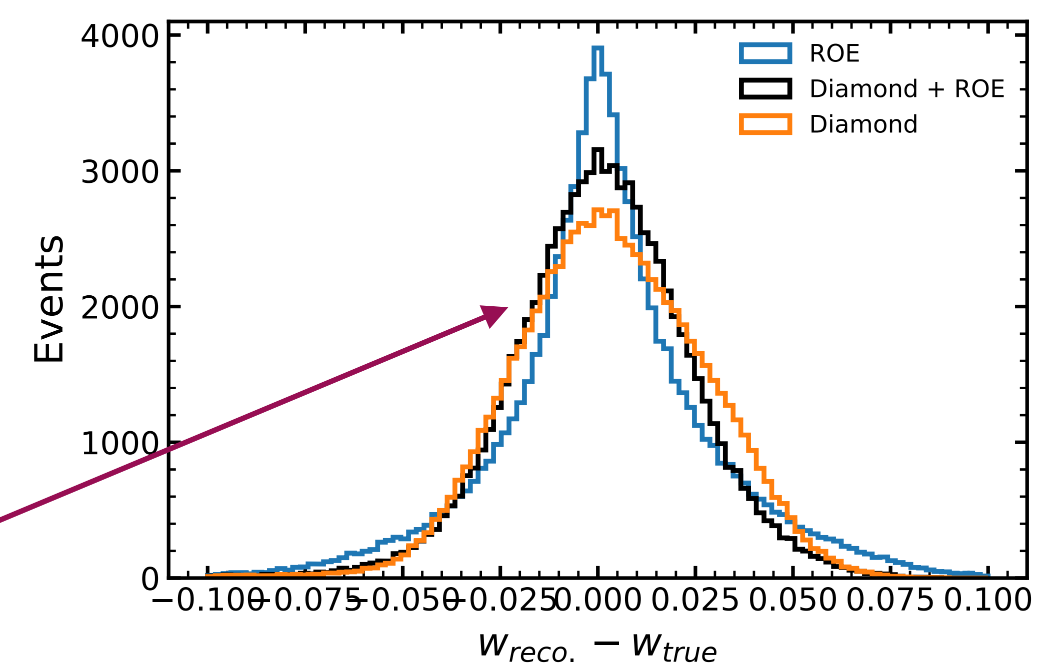
$$\cos\theta_{B,D^*\ell} = \frac{2E_B E_{D^*\ell} - m_B^2 - m_{D^*\ell}^2}{2\,|\mathbf{p}_B|\,|\mathbf{p}_{D\ell}|}$$

Can use this to estimate B meson direction building a weighted average on the cone

$$(E^B, p_B^x, p_B^y, p_B^z) = (\sqrt{s}/2, |\mathbf{p}_B|\sin\theta_{BY}\cos\phi, |\mathbf{p}_B|\sin\theta_{BY}\sin\phi, |\mathbf{p}_B|\cos\theta_{BY})$$

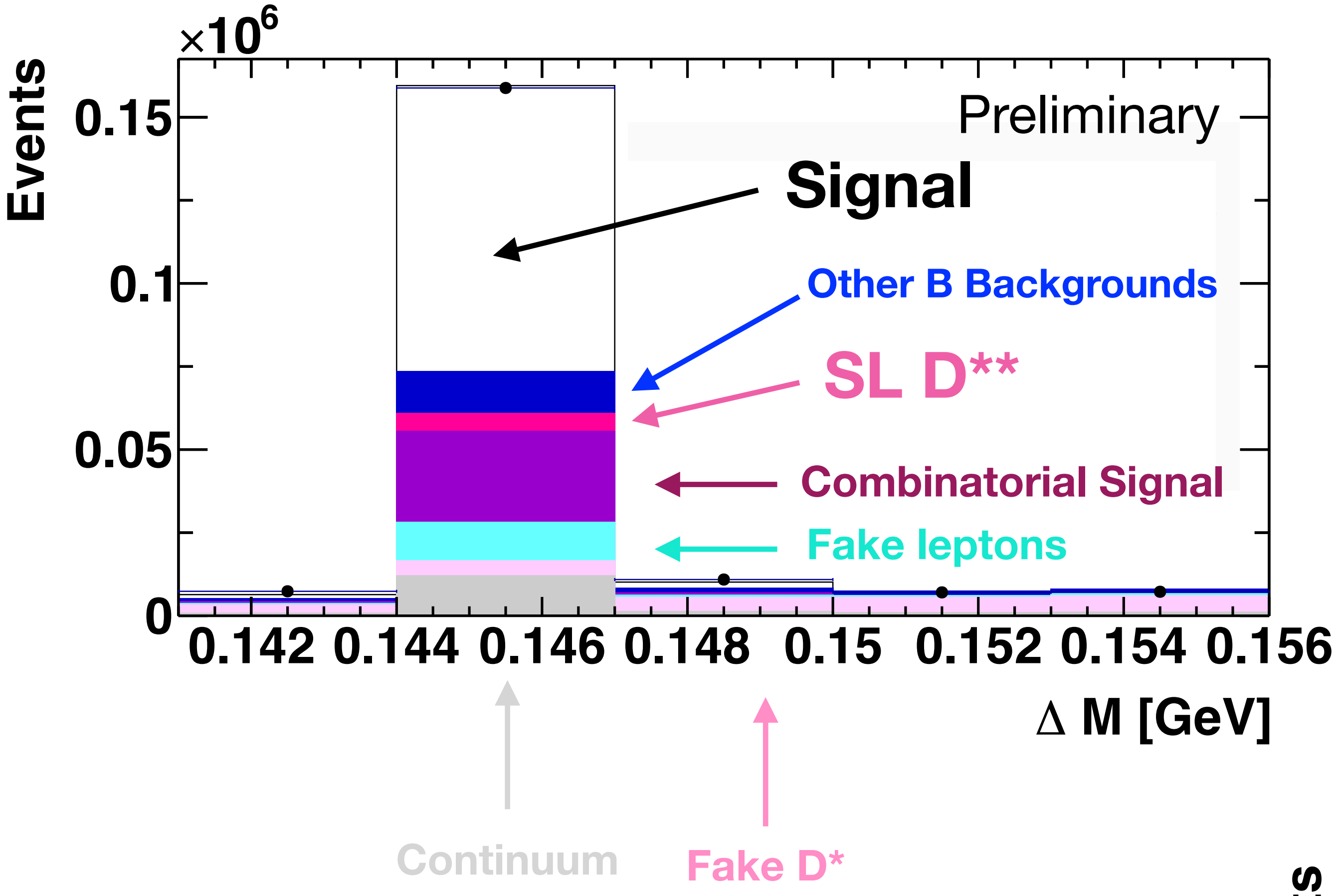
with weights according to $w_i = \sin^2\theta_i$ with θ denoting the polar angle

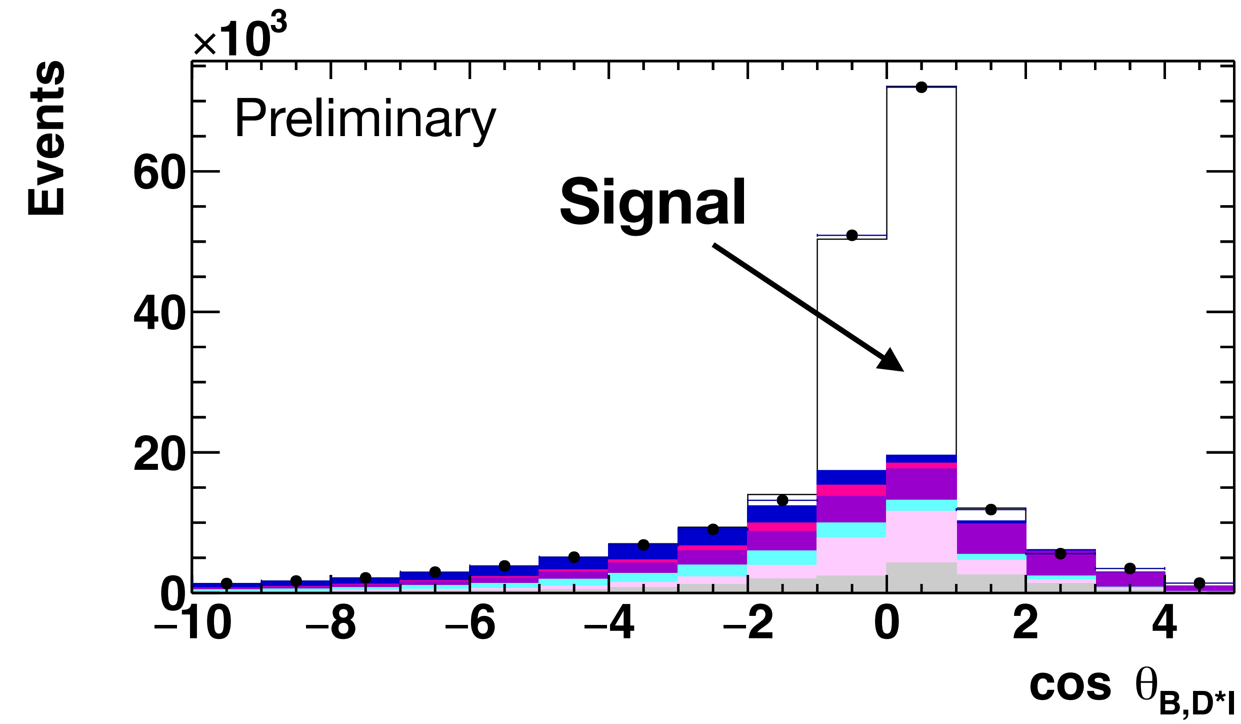
(following the angular distribution of $\Upsilon(4S) \to B\bar{B}$)

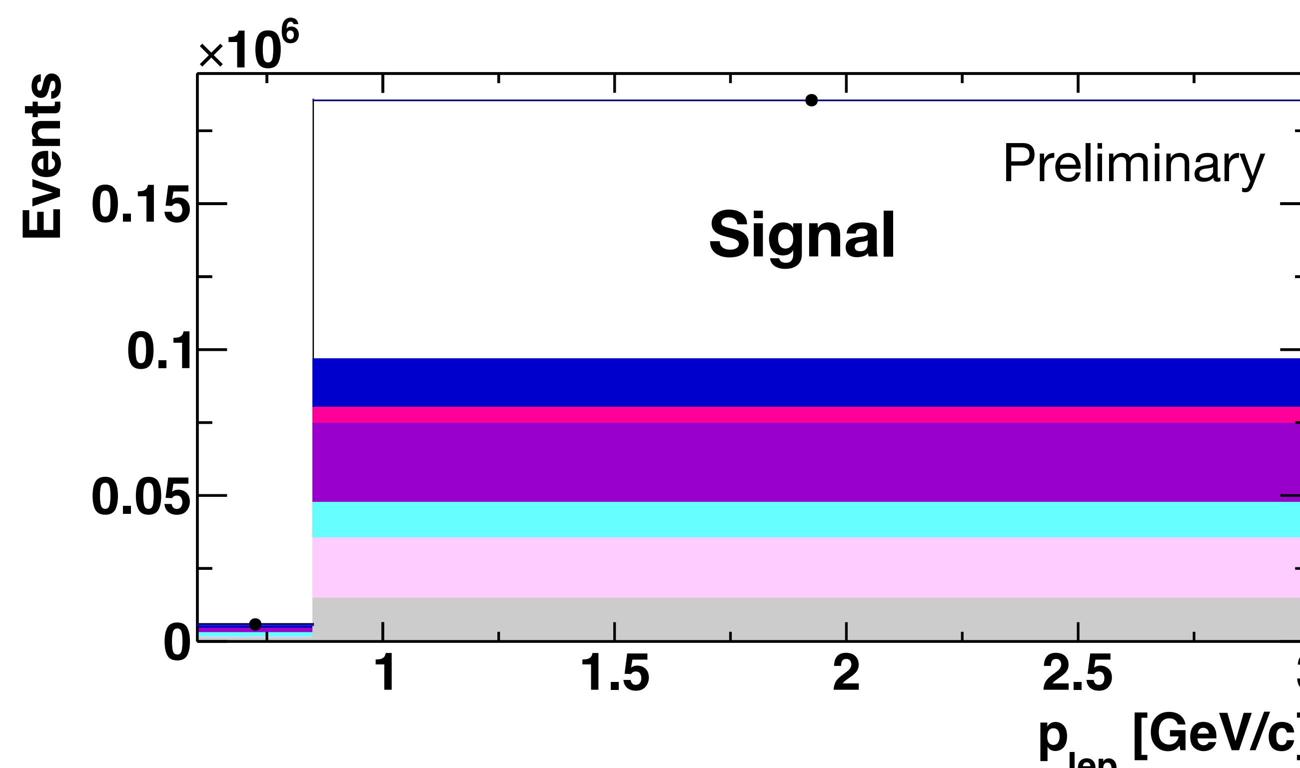


One can also **combine** both estimates

Background Subtraction







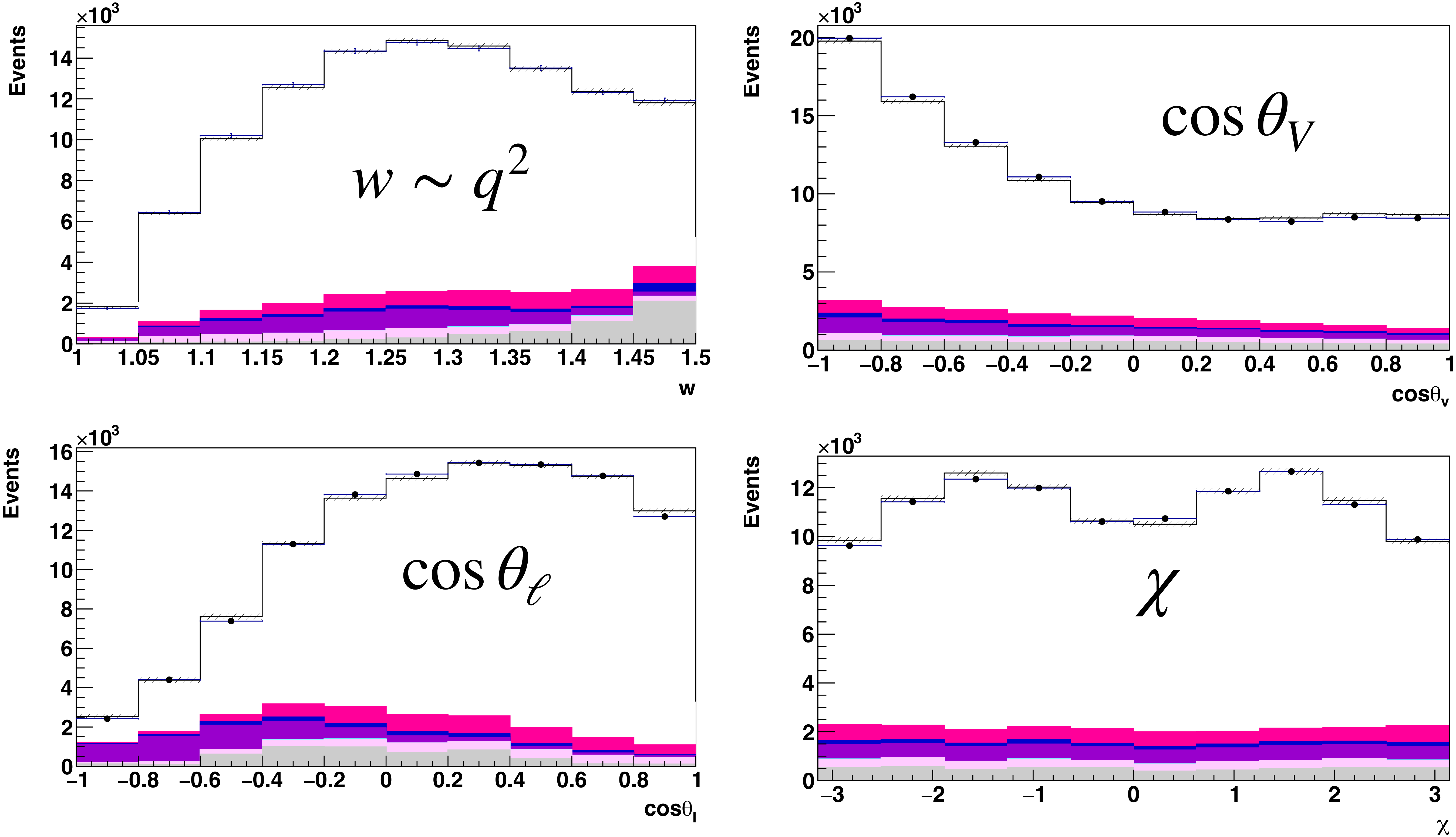
3 Variables used:

$$\Delta M = m_{D^*} - m_D$$

$$\cos\theta_{B,D^*\ell} = \frac{2E_B E_{D^*\ell} - m_B^2 - m_{D^*\ell}^2}{2|\vec{p}_B||\vec{p}_{D^*\ell}|}$$

$$p_{\text{lep}}$$

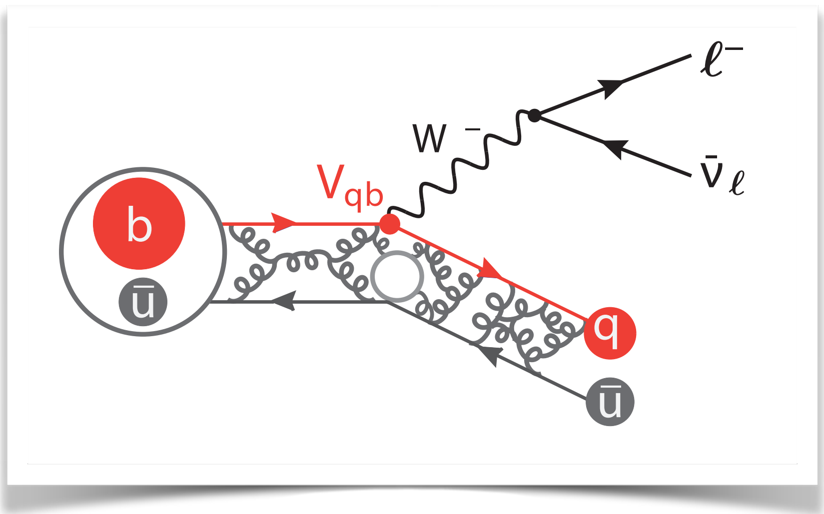
Kinematic Distributions



2. Inclusive

Florian Bernlochner (florian.bernlochner@uni-bonn.de)

Overview



Inclusive $|V_{cb}|$

$$\bar{B} \to X_c \, \ell \, \bar{\nu}_\ell$$

Operator Product Expansion (OPE)

$$\mathcal{B} = |V_{qb}|^2 \left[\Gamma(b \to q \, \ell \, \bar{\nu}_\ell) + 1/m_{c,b} + \alpha_s + \ldots \right]$$

Established approach: Use **spectral moments** (hadronic mass moments, lepton energy moments etc.) to determine non-perturbative matrix elements (ME) of OPE and extract $|V_{cb}|$

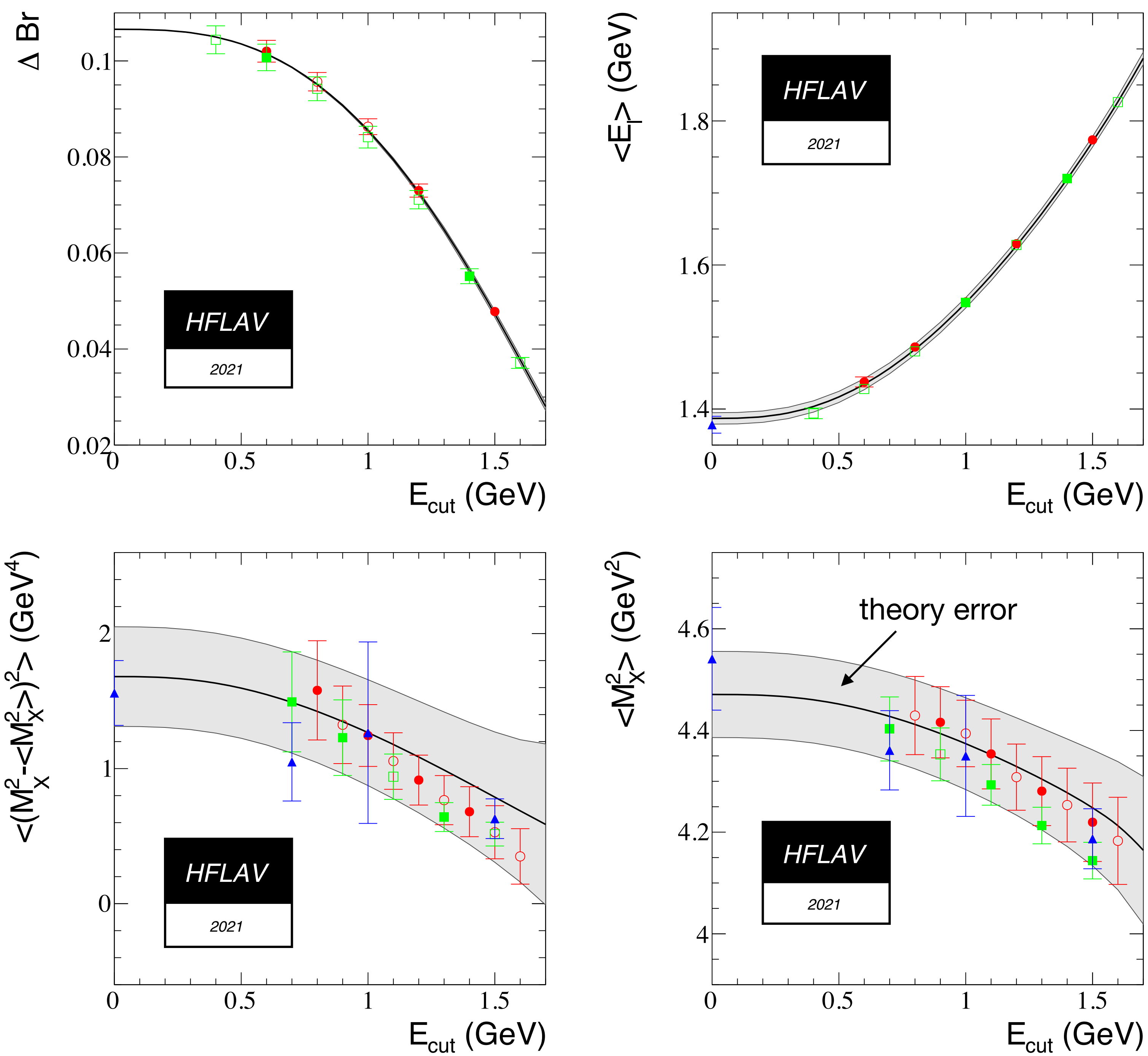
$$\mathrm{d}\Gamma = \mathrm{d}\Gamma_0 + \mathrm{d}\Gamma_{\mu_\pi} \frac{\mu_\pi^2}{m_b^2} + \mathrm{d}\Gamma_{\mu_G} \frac{\mu_G^2}{m_b^2} + \mathrm{d}\Gamma_{\rho_D} \frac{\rho_D^3}{m_b^3} + \mathrm{d}\Gamma_{\rho_{LS}} \frac{\rho_{LS}^3}{m_b^3} + \ldots$$

- $\mathrm{d}\Gamma_i$ are computed **perturbatively**
- The non-perturbative dynamics is enclosed into the HQE parameters: $\mu_\pi, \mu_G, \rho_D, \rho_{LS} \sim \langle B | \, \bar{b}_v iD^\mu \ldots iD^\nu \Gamma_{\mu\ldots\nu} b_v \, | B \rangle$
- HQE parameters are extracted from data.

Experiment	Hadron moments <M^n_X>	Lepton moments <E^n_l>	References
BaBar	n=2 c=0.9,1.1,1.3,1.5 n=4 c=0.8,1.0,1.2,1.4 n=6 c=0.9,1.3 [1]	n=0 c=0.6,1.2,1.5 n=1 c=0.6,0.8,1.0,1.2,1.5 n=2 c=0.6,1.0,1.5 n=3 c=0.8,1.2 [1,2]	[1] Phys.Rev. D81 (2010) 032003 [2] Phys.Rev. D69 (2004) 111104
Belle	n=2 c=0.7,1.1,1.3,1.5 n=4 c=0.7,0.9,1.3 [3]	n=0 c=0.6,1.4 n=1 c=1.0,1.4 n=2 c=0.6,1.4 n=3 c=0.8,1.2 [4]	[3] Phys.Rev. D75 (2007) 032005 [4] Phys.Rev. D75 (2007) 032001
CDF	n=2 c=0.7 n=4 c=0.7 [5]	.	[5] Phys.Rev. D71 (2005) 051103
CLEO	n=2 c=1.0,1.5 n=4 c=1.0,1.5 [6]	.	[6] Phys.Rev. D70 (2004) 032002
DELPHI	n=2 c=0.0 n=4 c=0.0 n=6 c=0.0 [7]	n=1 c=0.0 n=2 c=0.0 n=3 c=0.0 [7]	[7] Eur.Phys.J. C45 (2006) 35-59

Bad news: number of these matrix elements increases if one increases expansion in $1/m_{b,c}$

Spectral Moment Fit from HFLAV (Kinetic scheme)



χ^2-fit of the spectral moments, which **includes theory uncertainties and correlations** based on a fixed correlation model

Constrains $m_c^{1S} = 0.986 \pm 0.013\,\mathrm{GeV}$

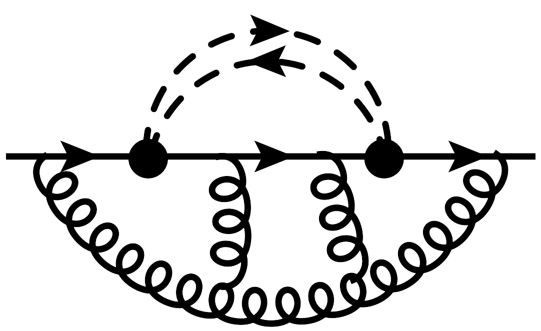
(Phys. Rev. D80 074010, 2009)

$Br(B \to X_c l\nu)$ (%)	$\lvert V_{cb} \rvert$ (10^{-3})
10.65 +/- 0.16	42.19 +/- 0.78

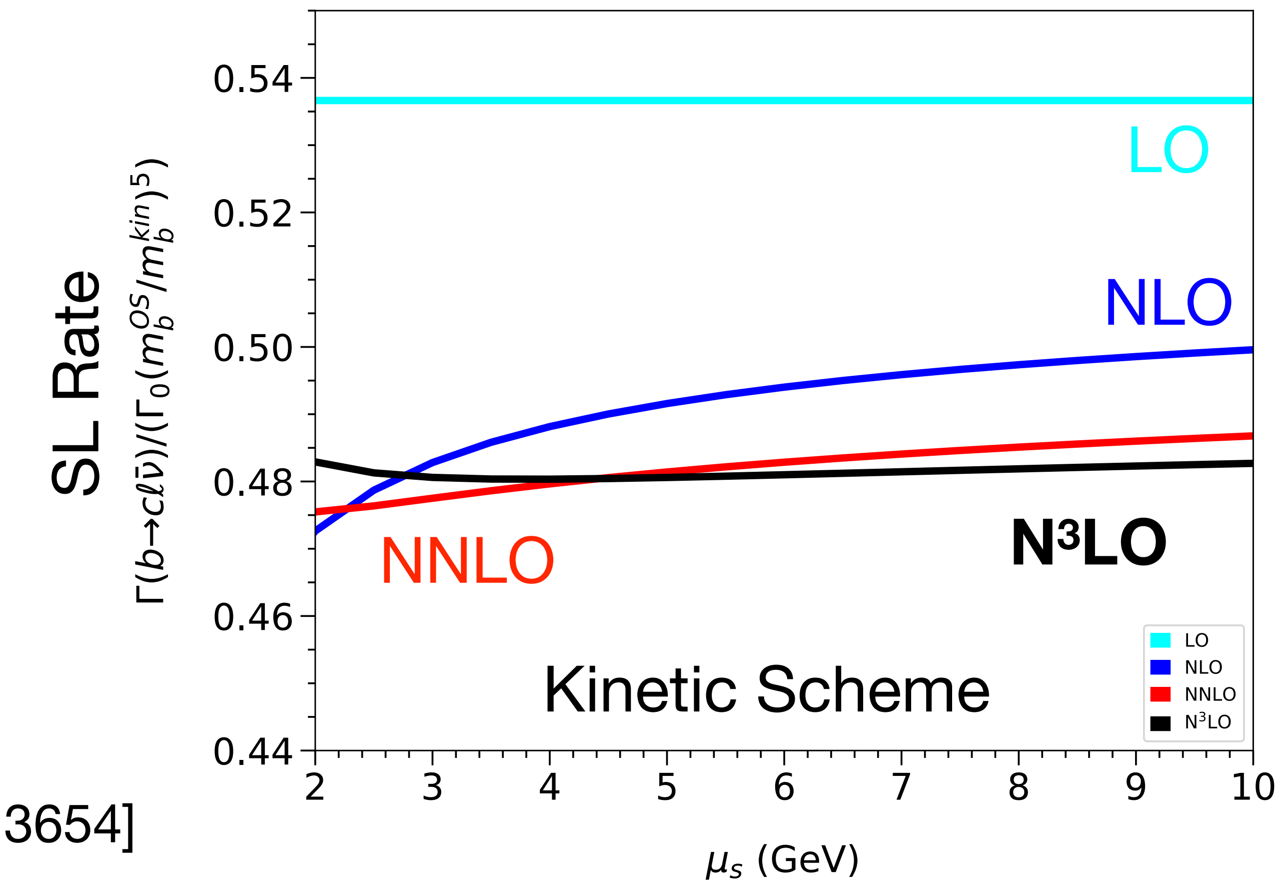
m_b^{kin} (GeV)	mu^2_{pi} (GeV^2)
4.554 +/- 0.018	0.464 +/- 0.076

State-of-the-art

Fantastic progress on the theory side:
semileptonic rate @ **N³LO**!



M. Fael, K. Schönwald, M. Steinhauser
[Phys.Rev.D 104 (2021) 1, 016003, arXiv:2011.13654]



Renormalization scale

Updated inclusive fit to $\langle E_\ell \rangle, \langle M_X \rangle$ moments:

$$|V_{cb}| = 42.16(30)_{th}(32)_{exp}(25)_{\Gamma}\ 10^{-3}$$

$$\Delta |V_{cb}| / |V_{cb}| = 1.2\,\%\,!$$

m_b^{kin}	$\overline{m}_c(2\mathrm{GeV})$	μ_π^2	ρ_D^3	$\mu_G^2(m_b)$	ρ_{LS}^3	$\mathrm{BR}_{c\ell\nu}$	$10^3\lvert V_{cb}\rvert$
4.573	1.092	0.477	0.185	0.306	-0.130	10.66	42.16
0.012	0.008	0.056	0.031	0.050	0.092	0.15	0.51
1	0.307	-0.141	0.047	0.612	-0.196	-0.064	-0.420
	1	0.018	-0.010	-0.162	0.048	0.028	0.061
		1	0.735	-0.054	0.067	0.172	0.429
			1	-0.157	-0.149	0.091	0.299
				1	0.001	0.013	-0.225
					1	-0.033	-0.005
						1	0.684
							1

M. Bordone, B. Capdevila, P. Gambino
[Phys.Lett.B 822 (2021) 136679, arXiv:2107.00604]

See also [Phys.Lett.B 829 (2022) 137068, 2202.01434] for very recent 1S fit finding $|V_{cb}| = (42.5 \pm 1.1) \times 10^{-3}$

$$\mathrm{d}\Gamma = \mathrm{d}\Gamma_0 + \mathrm{d}\Gamma_{\mu_\pi}\frac{\mu_\pi^2}{m_b^2} + \mathrm{d}\Gamma_{\mu_G}\frac{\mu_G^2}{m_b^2} + \mathrm{d}\Gamma_{\rho_D}\frac{\rho_D^3}{m_b^3} + \mathrm{d}\Gamma_{\rho_{LS}}\frac{\rho_{LS}^3}{m_b^3} + \dots$$

Bad news: number of these matrix elements increases if one increases expansion in $1/m_{b,c}$

Innovative idea from [JHEP 02 (2019) 177, arXiv:1812.07472]
(M. Fael, T. Mannel, K. Vos)

→ Number of ME reduce by exploiting **reparametrization invariance**, but **not true for every observable**

Spectral moments :

$v = p_B/m_B$

$$\langle M^n[w] \rangle = \int \mathrm{d}\Phi \, w^n(v, p_\ell, p_\nu) \, W^{\mu\nu} L_{\mu\nu}$$

$w = (m_B v - q)^2 \Rightarrow \langle M_X^n \rangle$ Moments — not RPI (depends on v)

$w = v \cdot p_\ell \Rightarrow \langle E_\ell^n \rangle$ Moments — not RPI (depends on v)

$w = q^2 \Rightarrow \langle (q^2)^n \rangle$ Moments — RPI! (does not depend on v)

$$\mathrm{d}\Gamma = \mathrm{d}\Gamma_0 + \mathrm{d}\Gamma_{\mu_\pi}\frac{\mu_\pi^2}{m_b^2} + \mathrm{d}\Gamma_{\mu_G}\frac{\mu_G^2}{m_b^2} + \mathrm{d}\Gamma_{\rho_D}\frac{\rho_D^3}{m_b^3} + \mathrm{d}\Gamma_{\rho_{LS}}\frac{\rho_{LS}^3}{m_b^3} + \ldots$$

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→ Number of ME reduce by exploiting **reparametrization invariance**, but **not true for every observable**

Measurements of q^2 **moments** of inclusive $B \to X_c \ell \bar{\nu}_\ell$ decays with hadronic tagging [PRD 104, 112011 (2021), arXiv:2109.01685]

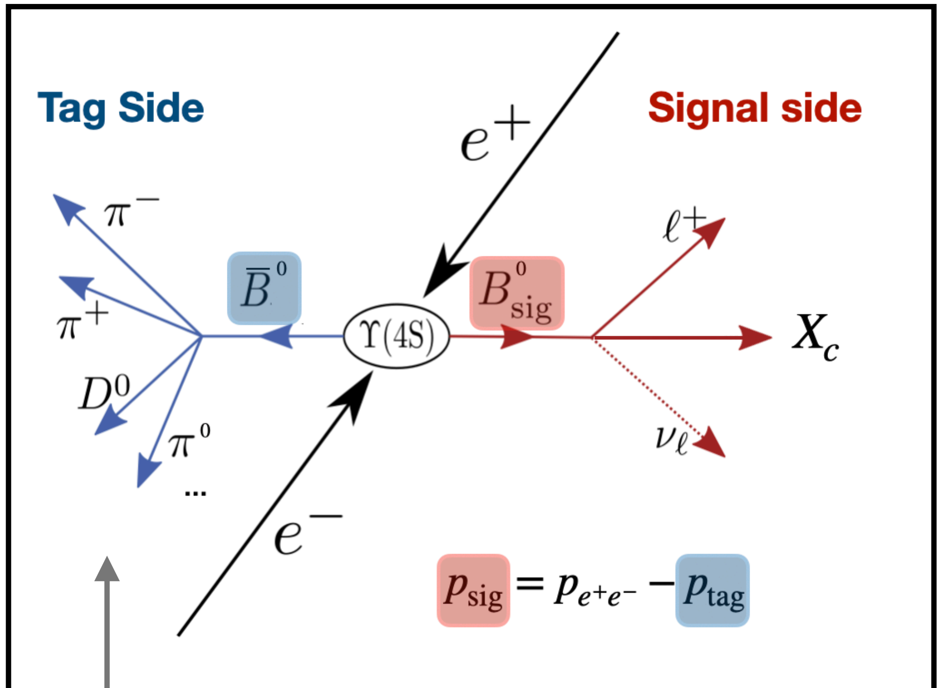
Belle

Measurements of Lepton **Mass squared moments** in inclusive $B \to X_c \ell \bar{\nu}_\ell$ Decays with the Belle II Experiment
[Under review by PRD, arXiv:2205.06372]

Belle II

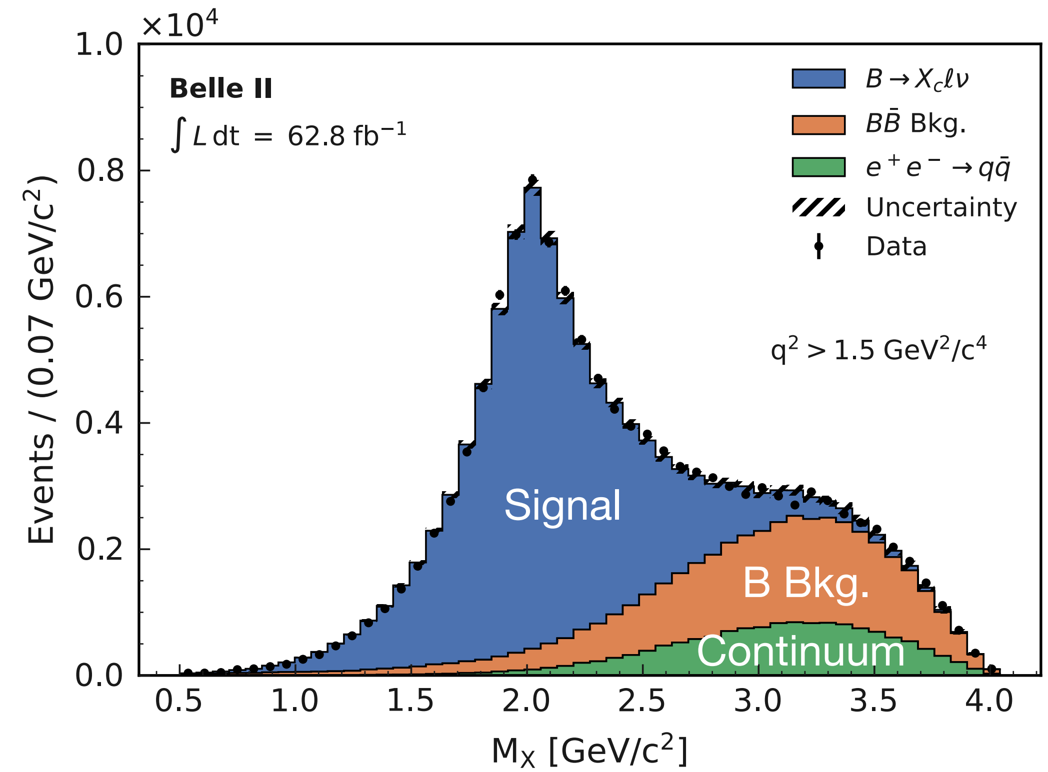
How to measure spectral moments

Key-technique: hadronic tagging



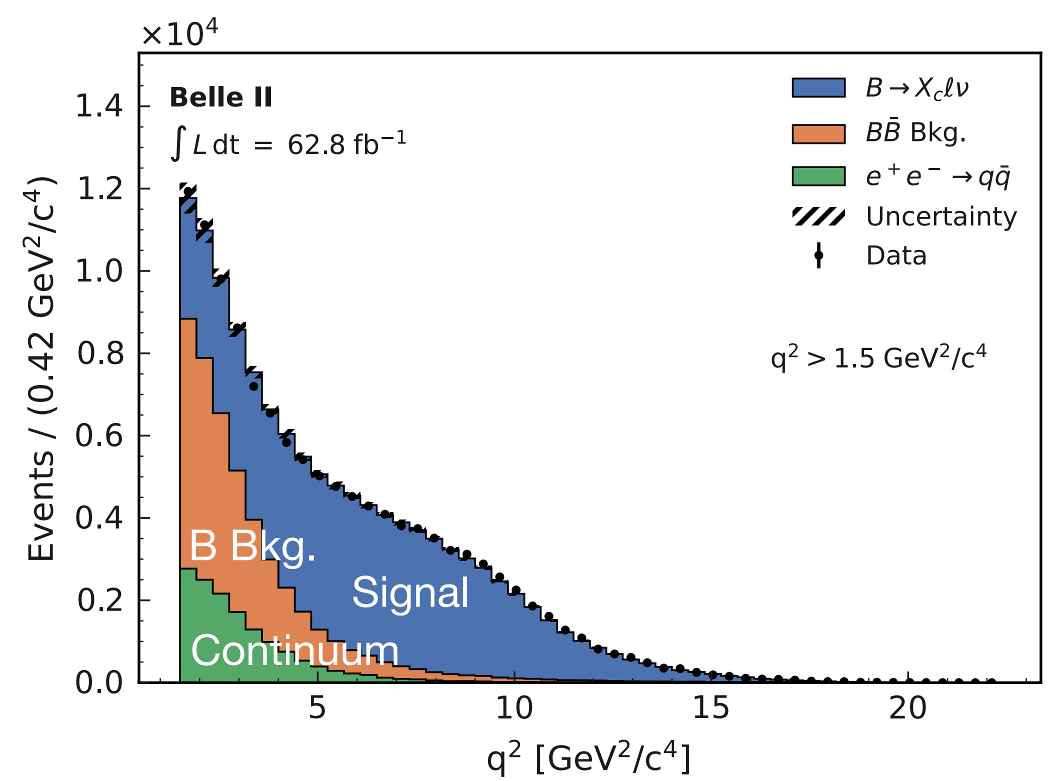
Can identify X$_c$ constituents

$$M_X = \sqrt{(p_{X_c})_\mu (p_{X_c})^\mu}$$



Hadronic Tagging
with **Belle II** algorithm (FEI)

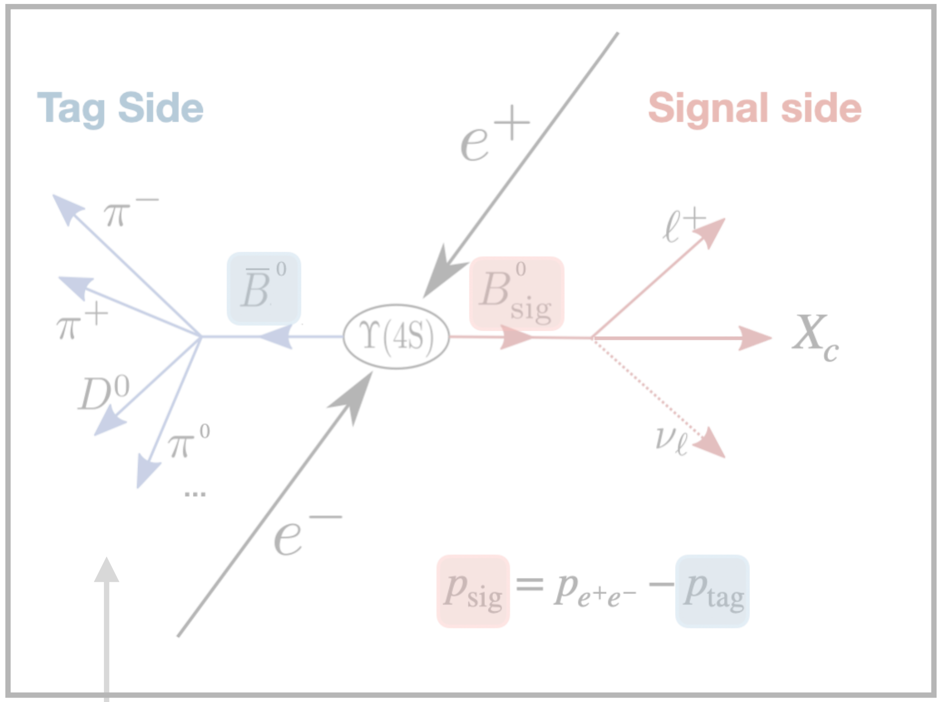
$$q^2 = \left(p_{sig} - p_{X_c}\right)^2$$



[Full Event Interpretation, T. Keck et al, Comp. Soft. Big. Sci 3 (2019), arXiv:1807.08680]

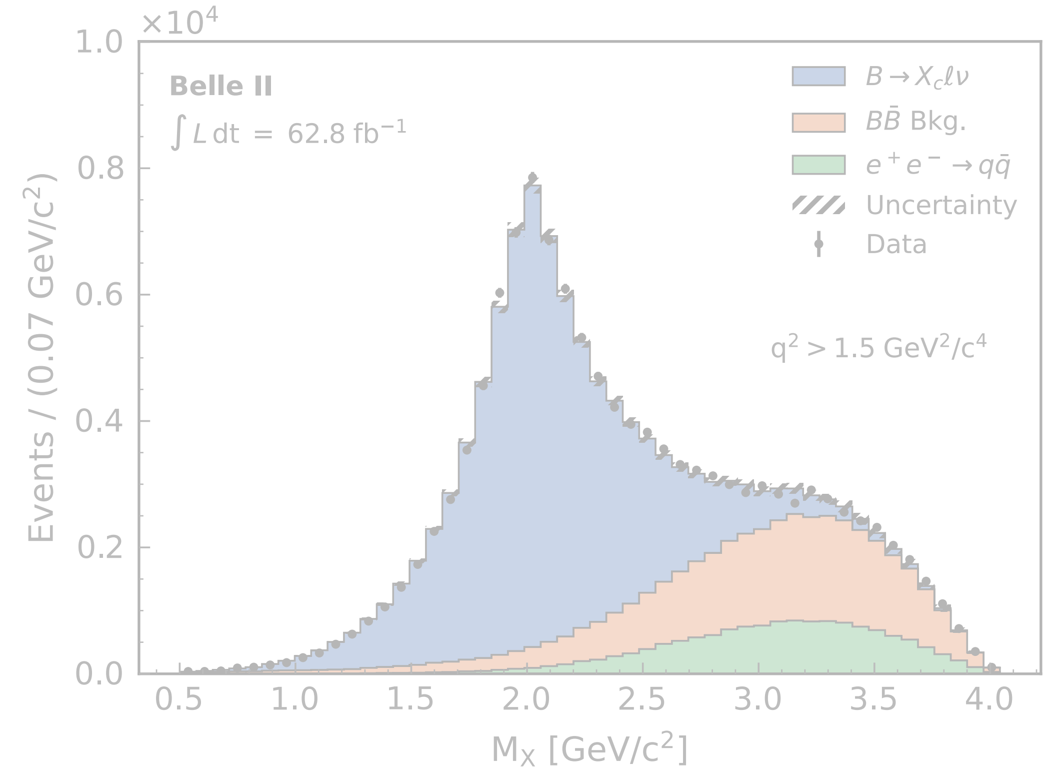
How to measure spectral moments

Key-technique: hadronic tagging



Can identify X_c constituents

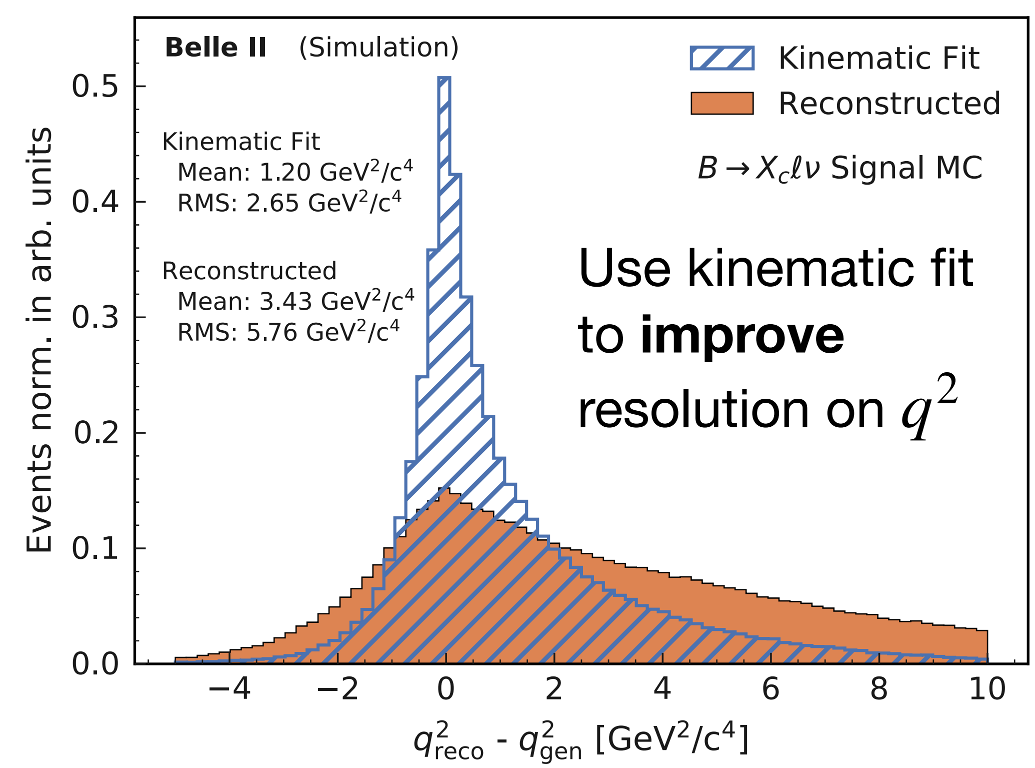
$$M_X = \sqrt{(p_{X_c})_\mu (p_{X_c})^\mu}$$



Improved Hadronic Tagging using **Belle II** algorithm (ca. 2 times more efficient)

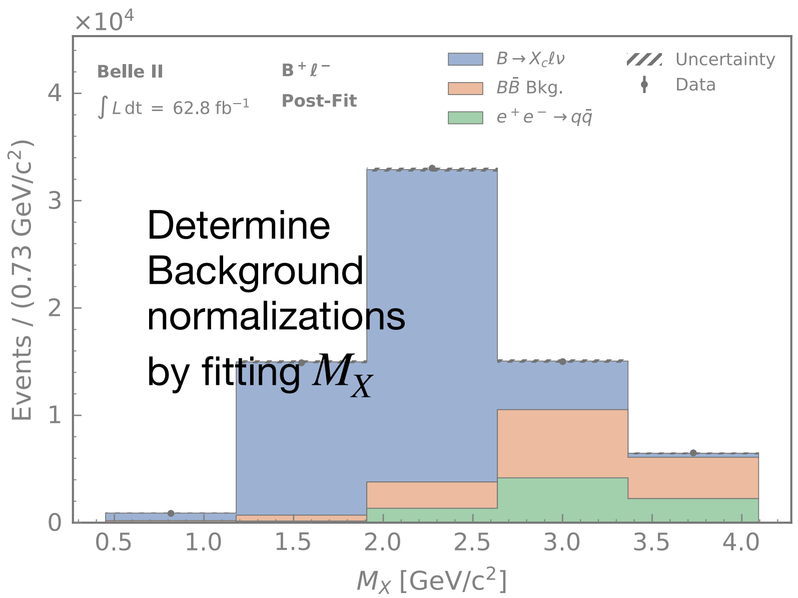
[Full Event Interpretation, T. Keck et al, Comp. Soft. Big. Sci 3 (2019), arXiv:1807.08680]

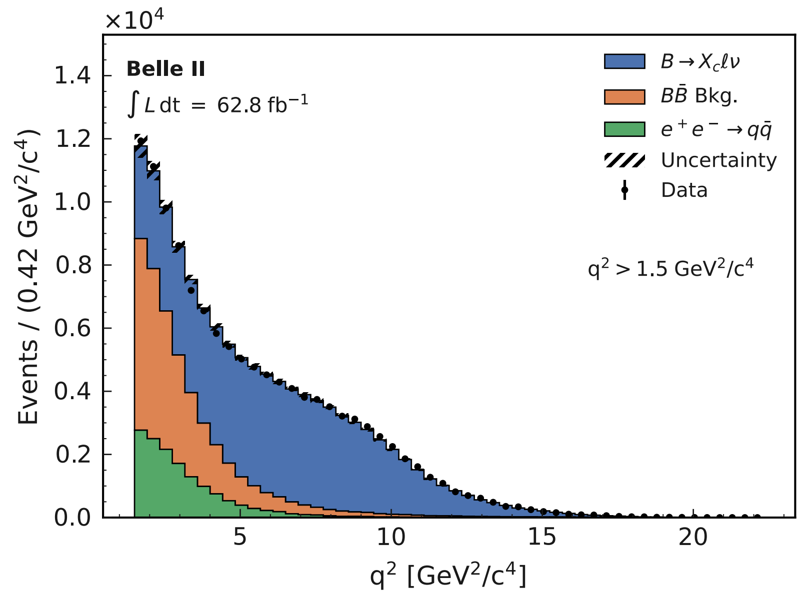
$$q^2 = \left(p_{\rm sig} - p_{X_c}\right)^2$$

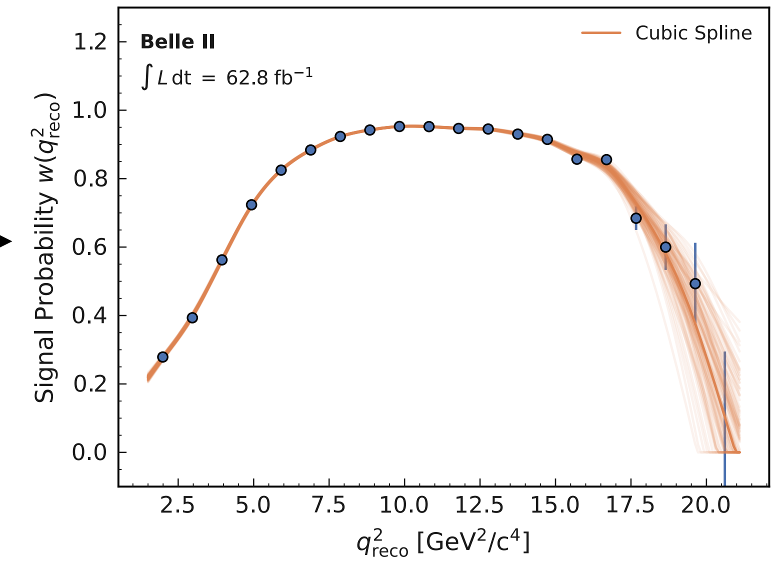


Use kinematic fit to **improve** resolution on q^2

Measurement in a nutshell







Step #1: Subtract Background

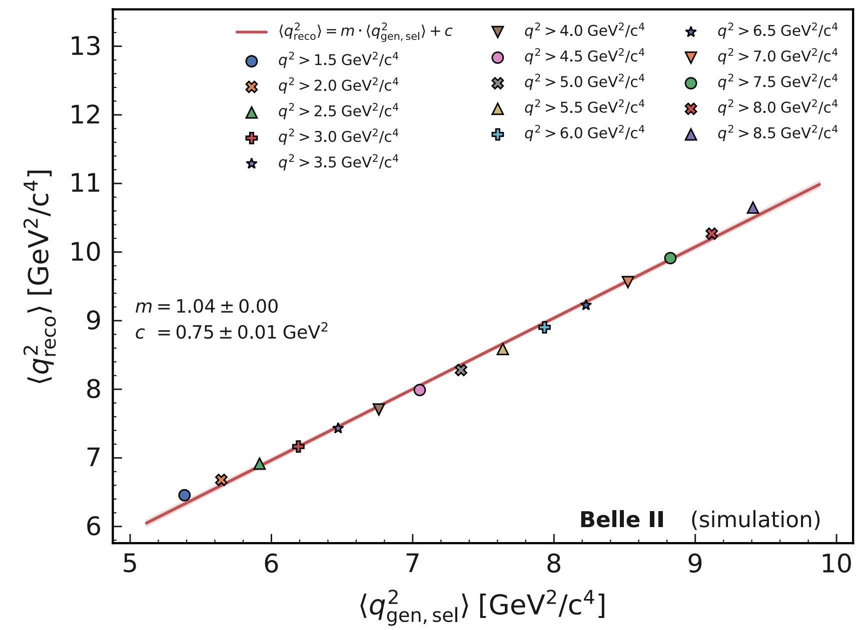
Event-wise **Master-formula**

$$\langle q^{2n} \rangle = \frac{\sum_i^{N_\mathrm{data}} w(q^2_\mathrm{reco,i}) \times q^{2n}_{\mathrm{calib},i}}{\sum_j^{N_\mathrm{data}} w(q^2_\mathrm{reco,j})} \times \mathcal{C}_\mathrm{calib} \times \mathcal{C}_\mathrm{gen} \, ,$$

Measurement in a nutshell

Exploit linear dependence between rec. & true moments

$$q^{2m}_{\mathrm{cal}\,i} = \left(q^{2m}_{\mathrm{reco}\,i} - c\right)/m$$



Step #1: Subtract Background

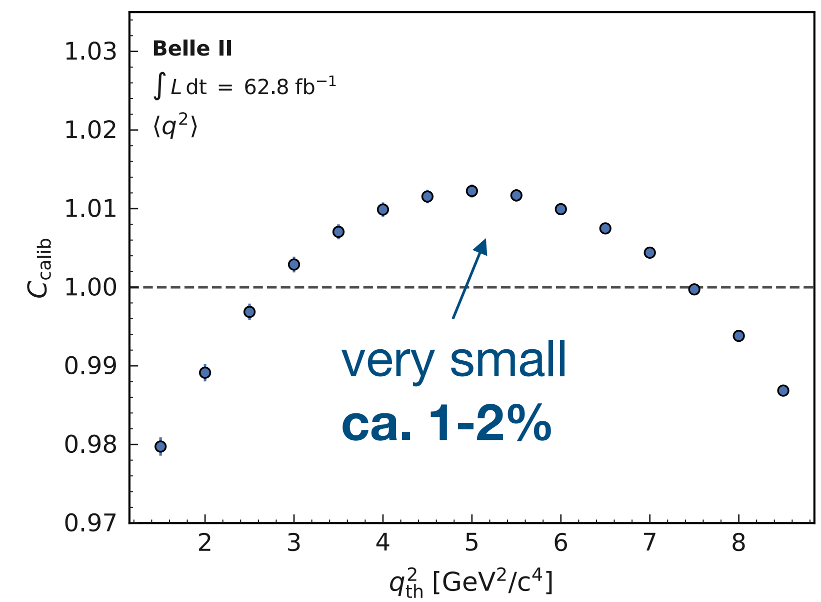
Step #2: Calibrate moment

Event-wise **Master-formula**

$$\langle q^{2n} \rangle = \frac{\sum_i^{N_{\mathrm{data}}} w(q^2_{\mathrm{reco,i}}) \times q^{2n}_{\mathrm{calib},i}}{\sum_j^{N_{\mathrm{data}}} w(q^2_{\mathrm{reco,j}})} \times \mathcal{C}_{\mathrm{calib}} \times \mathcal{C}_{\mathrm{gen}} \,,$$

Measurement in a nutshell

Very small deviation from linear behavior between reconstruct and true q^2



Step #1: Subtract Background

Step #2: Calibrate moment

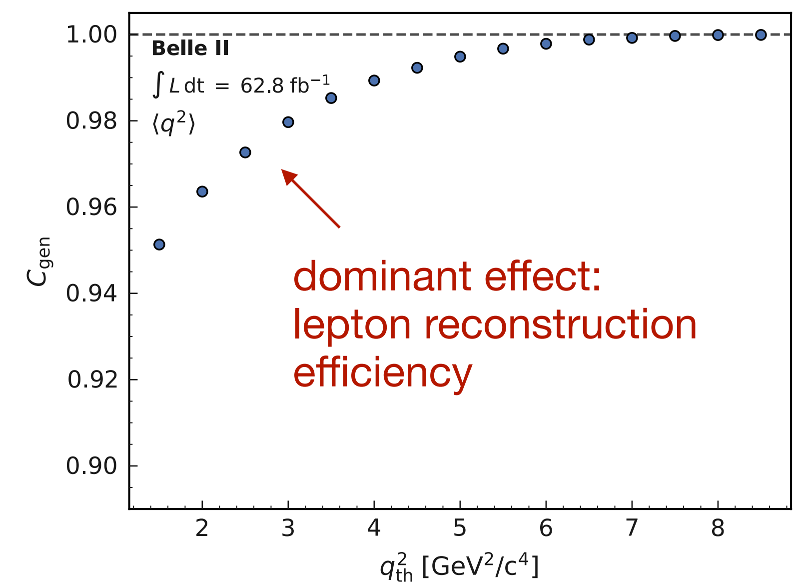
Event-wise **Master-formula**

$$\langle q^{2n} \rangle = \frac{\sum_i^{N_{\mathrm{data}}} w(q^2_{\mathrm{reco,i}}) \times q^{2n}_{\mathrm{calib},i}}{\sum_j^{N_{\mathrm{data}}} w(q^2_{\mathrm{reco,j}})} \times \mathcal{C}_{\mathrm{calib}} \times \mathcal{C}_{\mathrm{gen}} \,,$$

Step #3: If you fail, try again

Measurement in a nutshell

Account for efficiency & acceptance effects



Step #1: Subtract Background

Step #2: Calibrate moment

Event-wise **Master-formula**

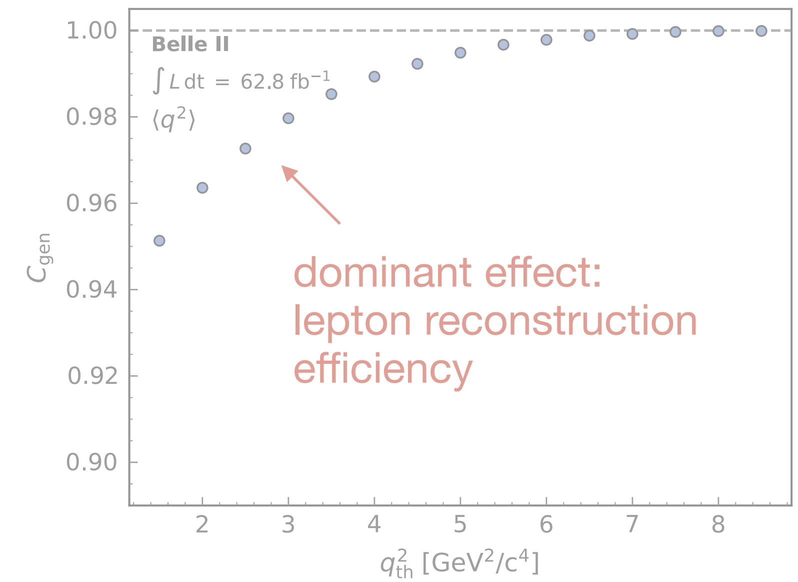
$$\langle q^{2n} \rangle = \frac{\sum_i^{N_{\rm data}} w(q^2_{\rm reco,i}) \times q^{2n}_{{\rm calib},i}}{\sum_j^{N_{\rm data}} w(q^2_{\rm reco,j})} \times \mathcal{C}_{\rm calib} \times \mathcal{C}_{\rm gen},$$

Step #3: If you fail, try again

Step #4: Correct for selection effects

Measurement in a nutshell

Account for efficiency & acceptance effects



Step #1: Subtract Background

Step #2: Calibrate moment

Event-wise **Master-formula**

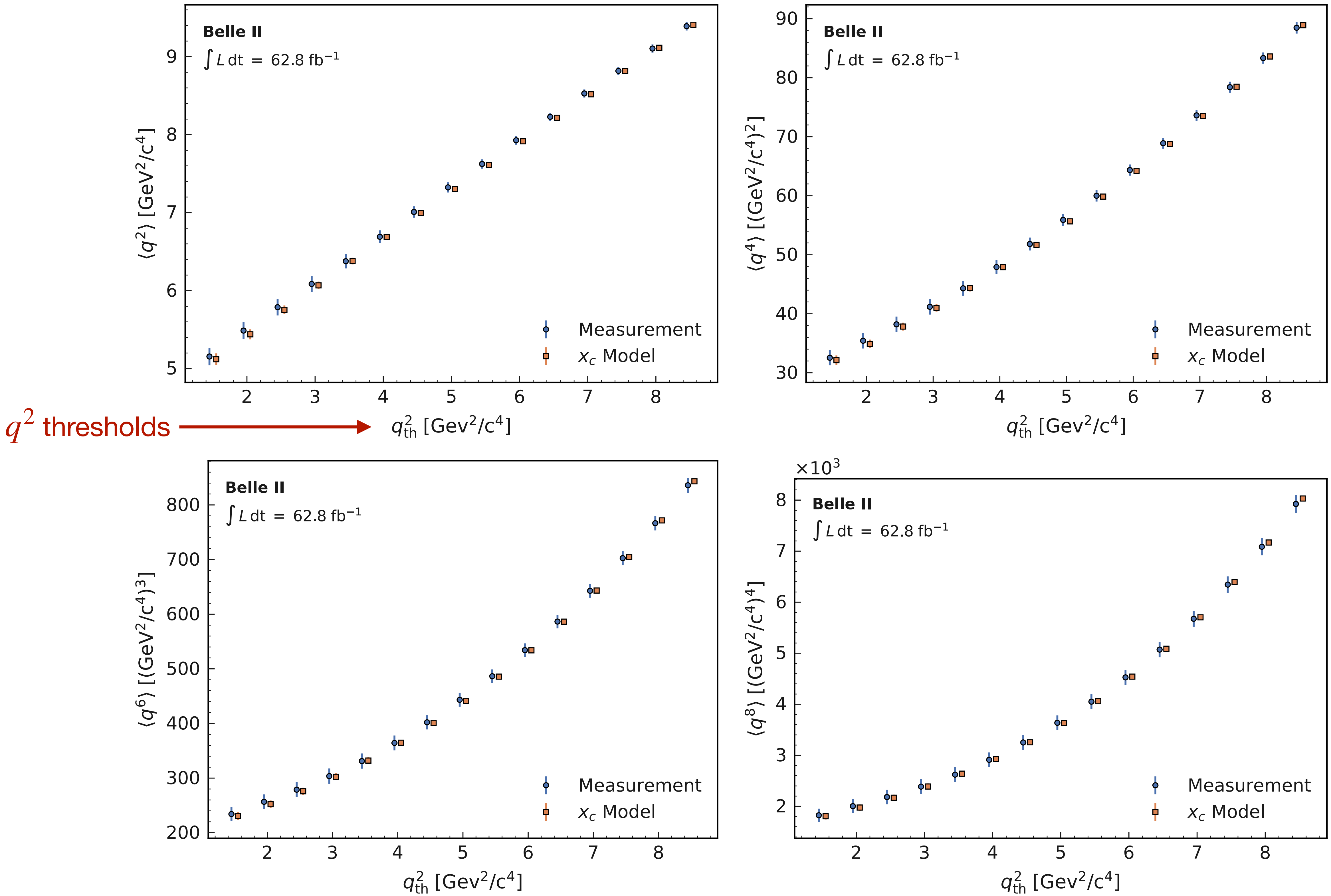
$$\langle q^{2n} \rangle = \frac{\sum_i^{N_{\mathrm{data}}} w(q^2_{\mathrm{reco,i}}) \times q^{2n}_{\mathrm{calib},i}}{\sum_j^{N_{\mathrm{data}}} w(q^2_{\mathrm{reco,j}})} \times \mathcal{C}_{\mathrm{calib}} \times \mathcal{C}_{\mathrm{gen}} \,,$$

Step #3: If you fail, try again

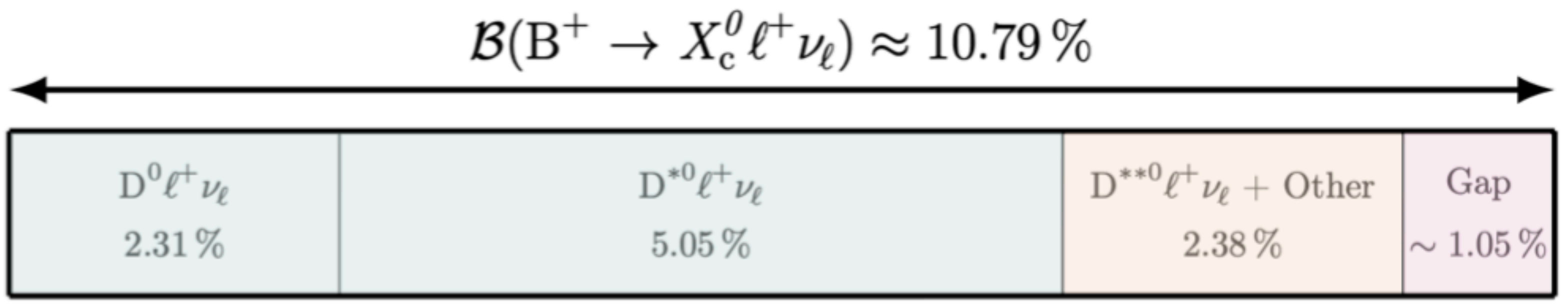
Step #4: Correct for selection effects

→ Repeat this for many different thresholds cuts q^2_{th}

Belle II q^2 spectral moments



Note: Measurements rely on MC



Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+ \nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+ \nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell^+ \nu_\ell$	$(6.6 \pm 0.1) \times 10^{-3}$	$(6.2 \pm 0.1) \times 10^{-3}$
$B \to D_2^*\,\ell^+ \nu_\ell$	$(2.9 \pm 0.3) \times 10^{-3}$	$(2.7 \pm 0.3) \times 10^{-3}$
$B \to D_0^*\,\ell^+ \nu_\ell$	$(4.2 \pm 0.8) \times 10^{-3}$	$(3.9 \pm 0.7) \times 10^{-3}$
$B \to D_1'\,\ell^+ \nu_\ell$	$(4.2 \pm 0.9) \times 10^{-3}$	$(3.9 \pm 0.8) \times 10^{-3}$
$B \to D\pi\pi\,\ell^+ \nu_\ell$	$(0.6 \pm 0.9) \times 10^{-3}$	$(0.6 \pm 0.9) \times 10^{-3}$
$B \to D^*\pi\pi\,\ell^+ \nu_\ell$	$(2.2 \pm 1.0) \times 10^{-3}$	$(2.0 \pm 1.0) \times 10^{-3}$
$B \to X_c \ell \nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$

→ Fairly well known. Some iso-spin tension.

→ Broad states based on 3 measurements. (BaBar, Belle, DELPHI)

→ Some hints from the BaBar result.

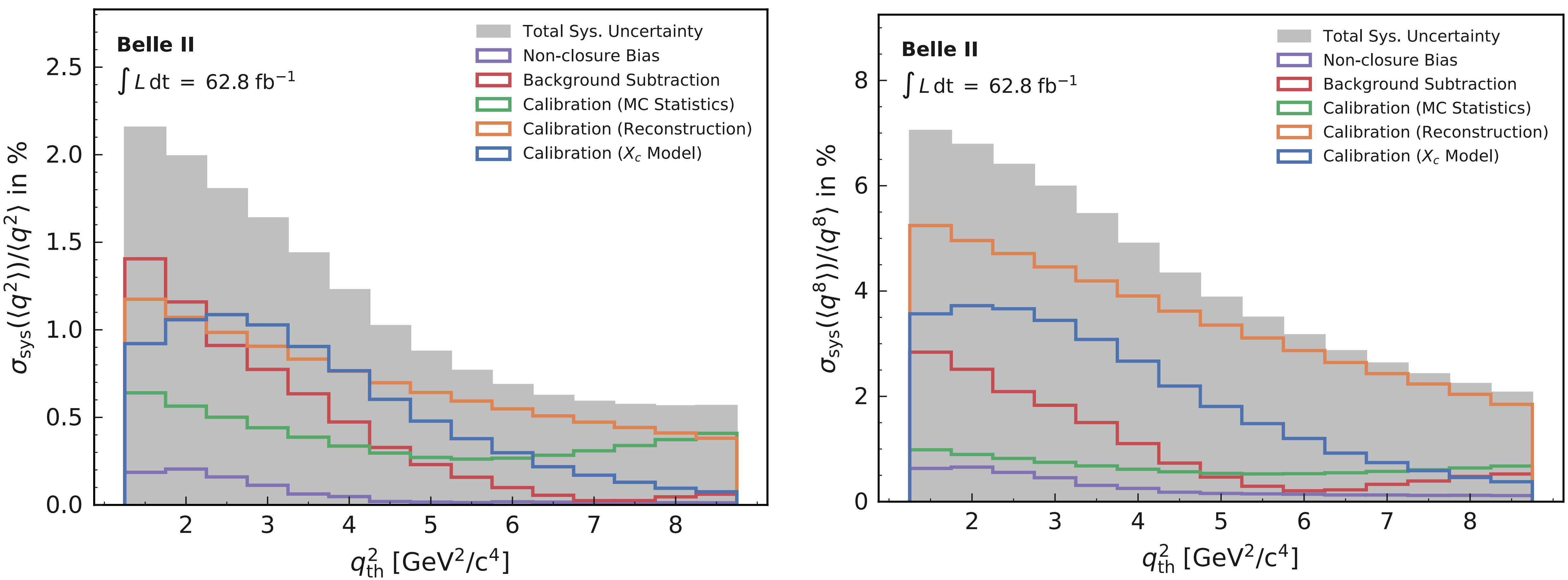
New result from Belle soon

Image credit: F. Metzner

Slide: R. Van Tonder

Belle II q^2 spectral moments

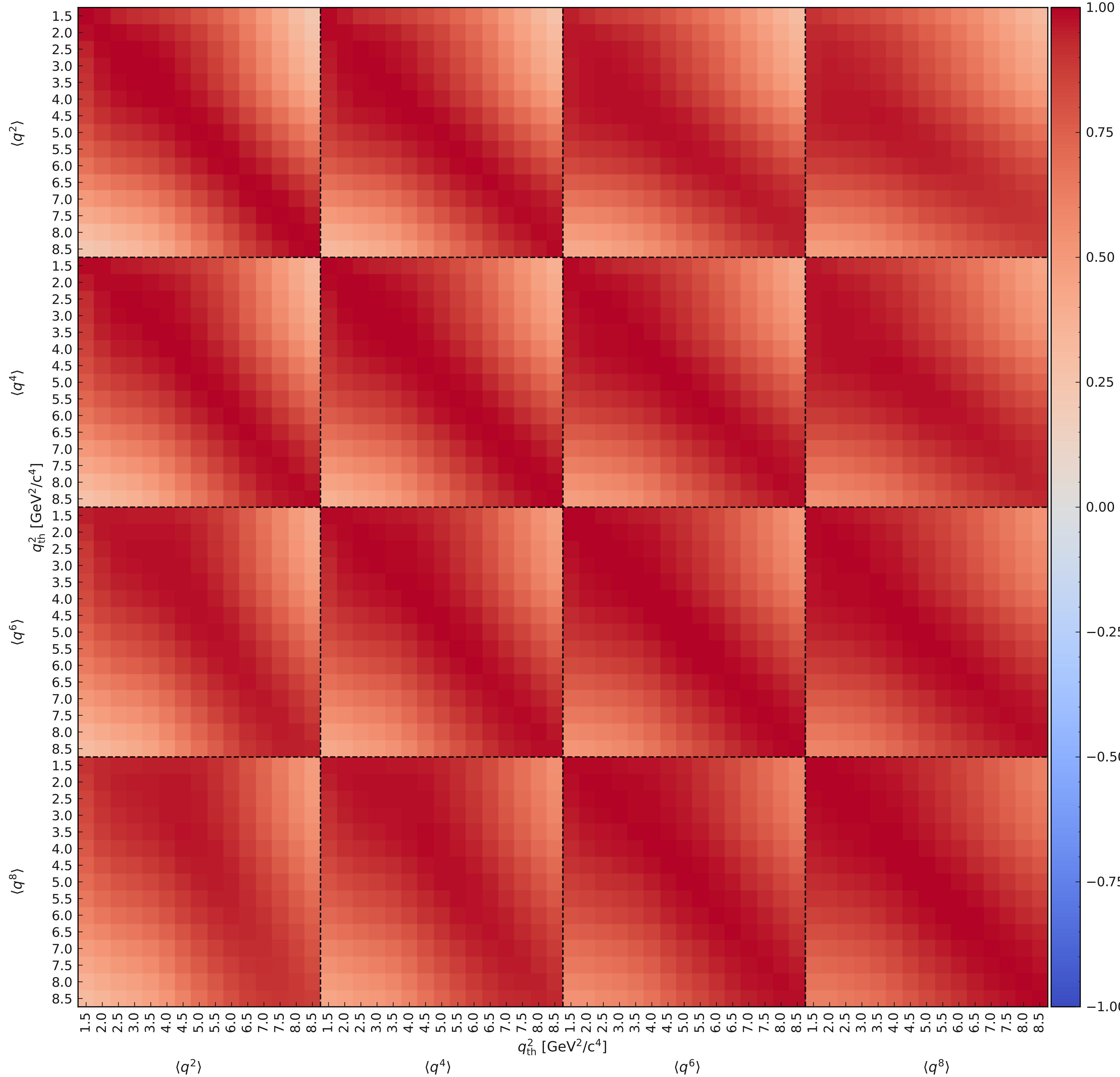
Largest uncertainty from reconstruction, background subtraction, X_c model



Belle II sensitivity similar to Belle already.

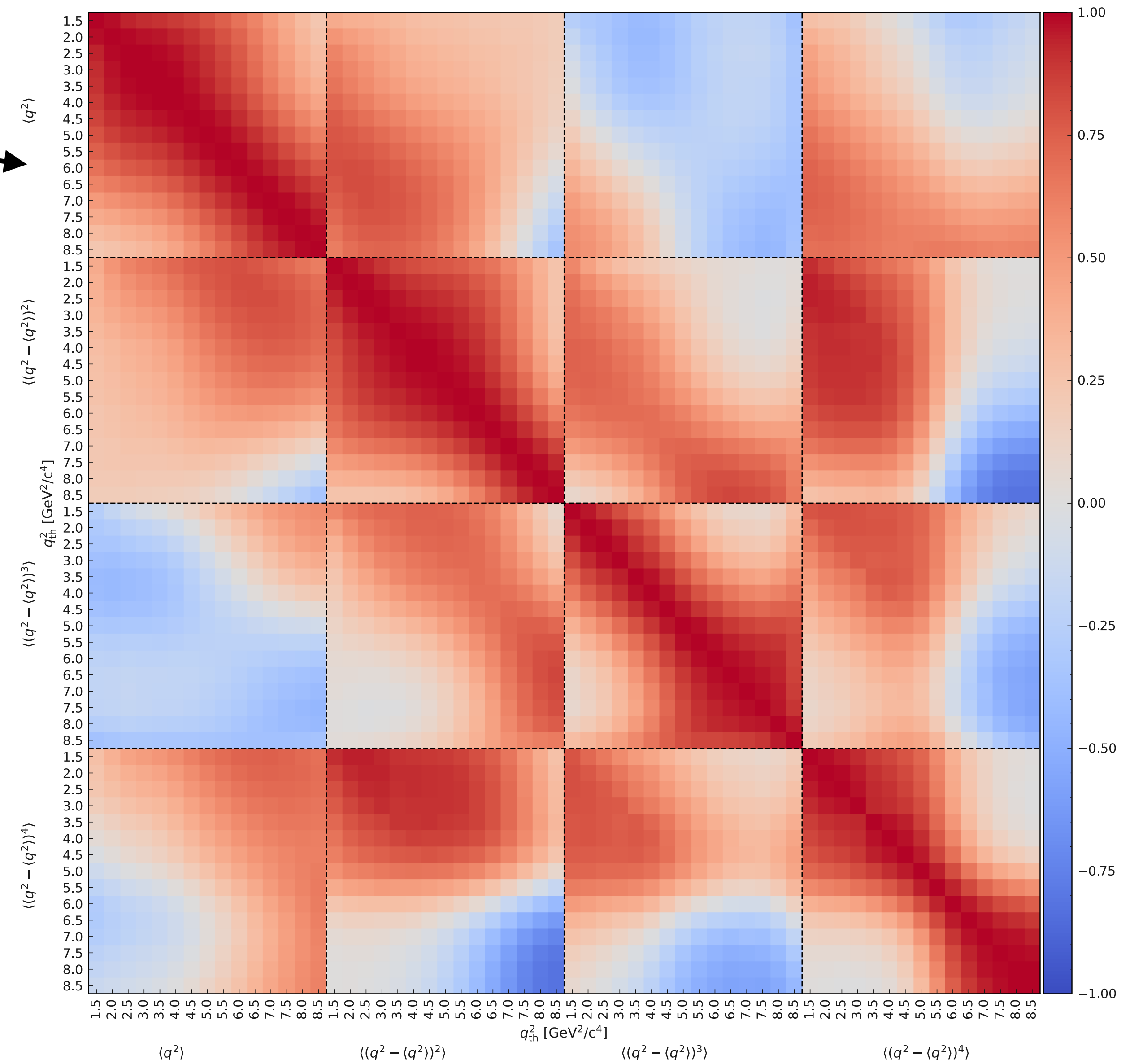
Statistical plus **systematic** correlations

fairly

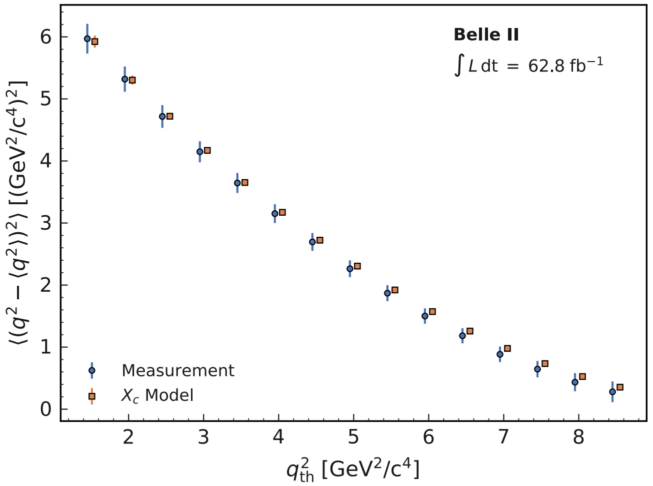


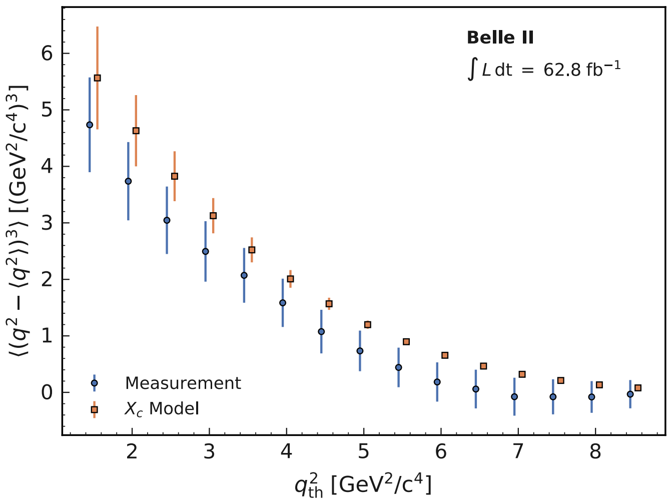
From moments to *central moments*

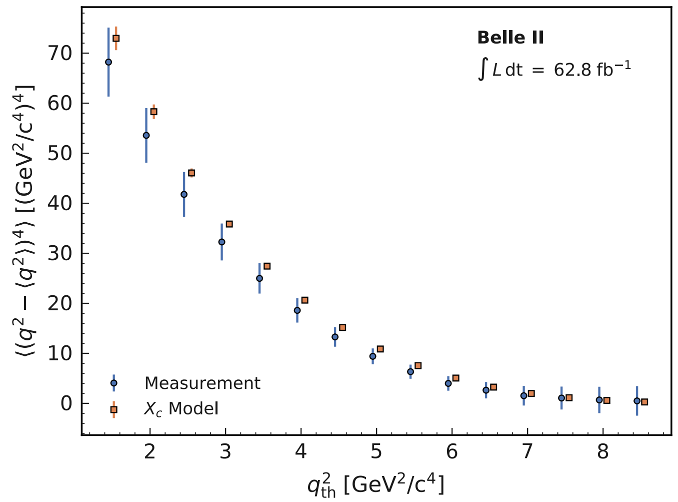
Central moments are **less** strongly correlated



$$\begin{pmatrix} \langle q^2 \rangle \\ \langle q^4 \rangle \\ \langle q^6 \rangle \\ \langle q^8 \rangle \end{pmatrix} \rightarrow \begin{pmatrix} \langle q^2 \rangle \\ \langle (q^2 - \langle q^2 \rangle)^2 \rangle \\ \langle (q^2 - \langle q^2 \rangle)^3 \rangle \\ \langle (q^2 - \langle q^2 \rangle)^4 \rangle \end{pmatrix}$$



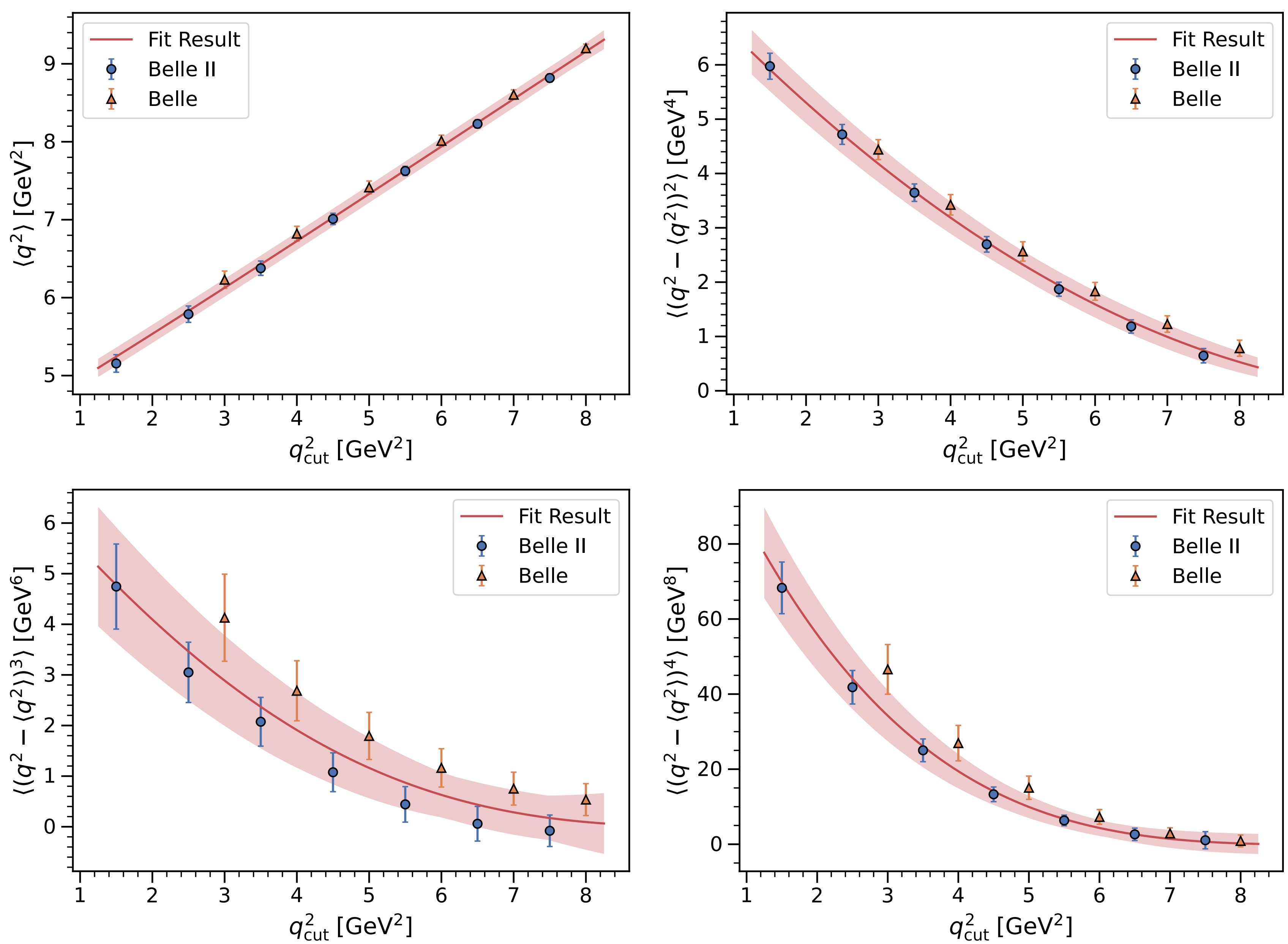




$|V_{cb}|$ from q^2 mom.

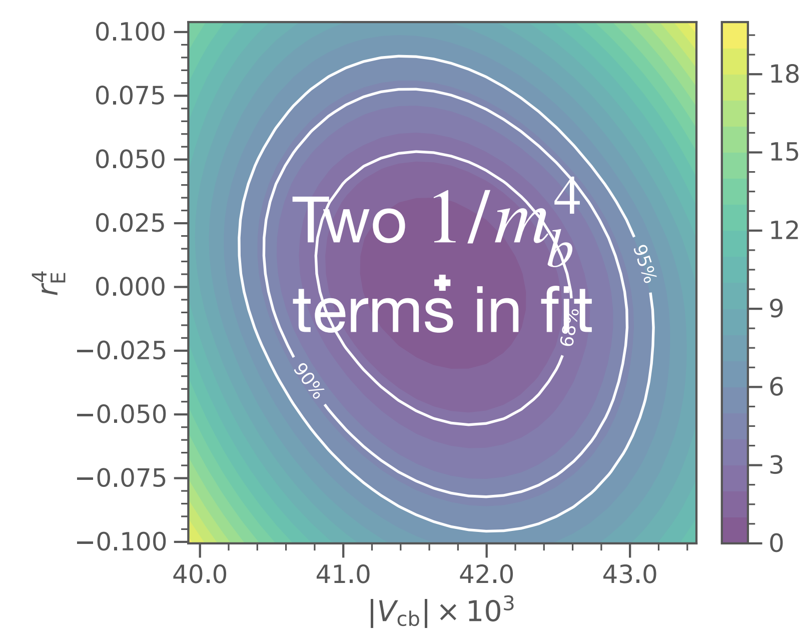
F. Bernlochner, M. Fael, K. Olschwesky, E. Persson, R. Van Tonder, K. Vos, M. Welsch [arXiv:2205.10274]

Extraction of $|V_{cb}|$ from q^2 moments:



Included corrections on the mom. predictions

$\langle (q^2)^n \rangle$	tree	α_s	α_s^2	α_s^3
Partonic	✓	✓		
μ_G^2	✓	✓		
ρ_D^3	✓	✓		
$1/m_b^4$	✓			



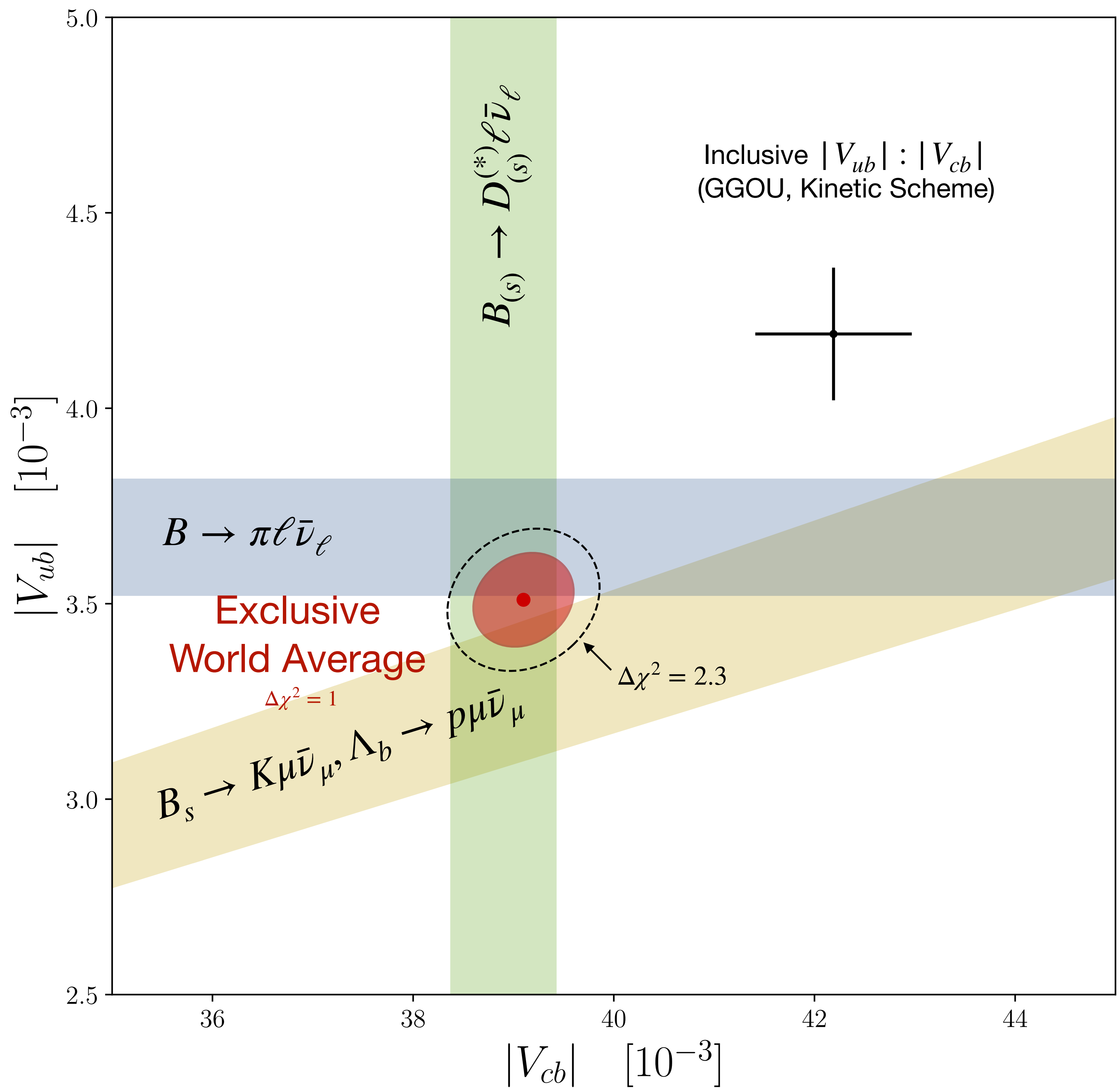
$$\rightarrow \quad |V_{cb}| = (41.69 \pm 0.59|_{\mathrm{fit}} \pm 0.23|_{\mathrm{h.o.}}) \cdot 10^{-3} = (41.69 \pm 0.63) \cdot 10^{-3}$$

Summary on $|V_{cb}|$

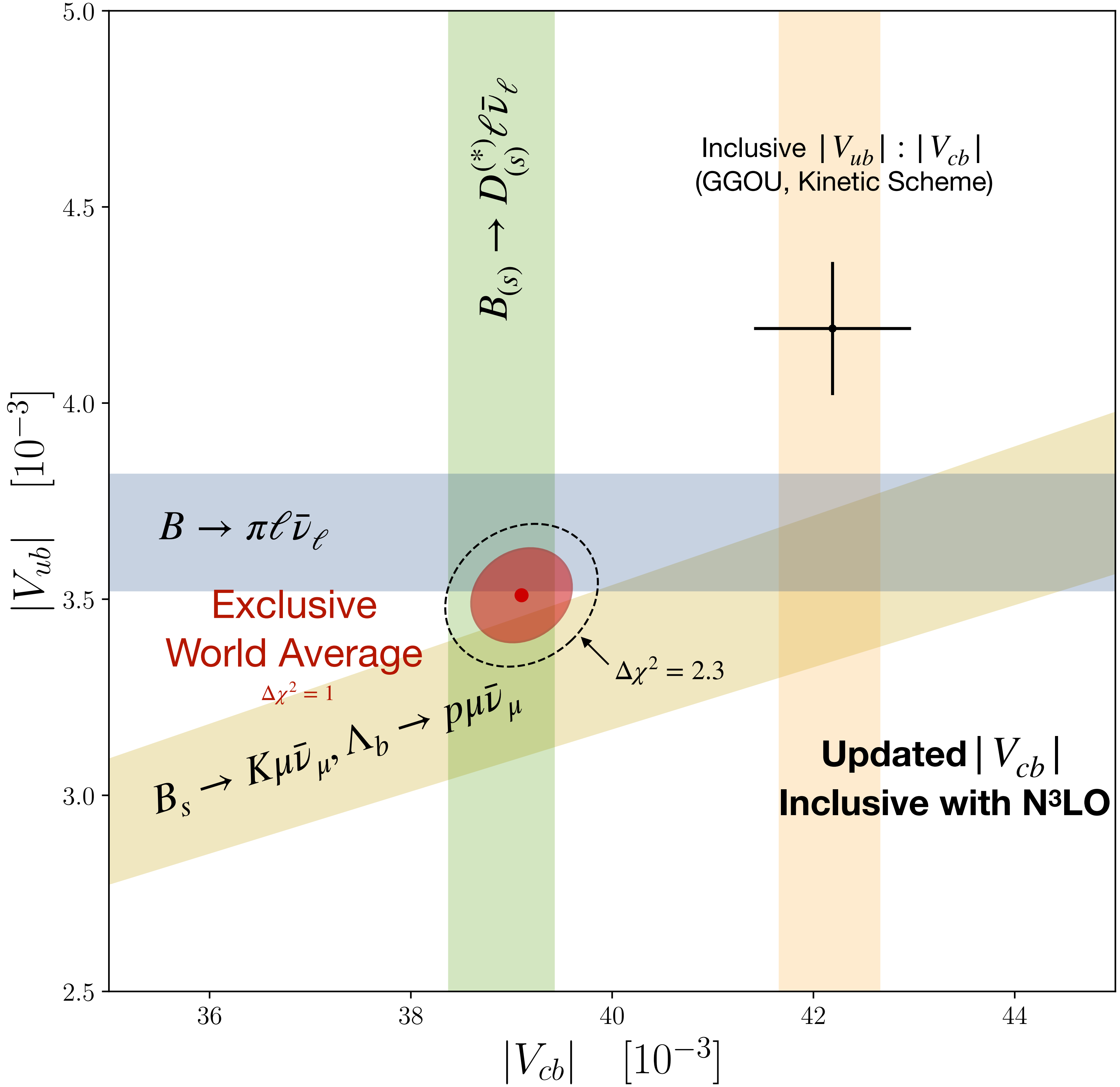
Florian Bernlochner (florian.bernlochner@uni-bonn.de)

Summary

Numbers from new HFLAV 2021 report

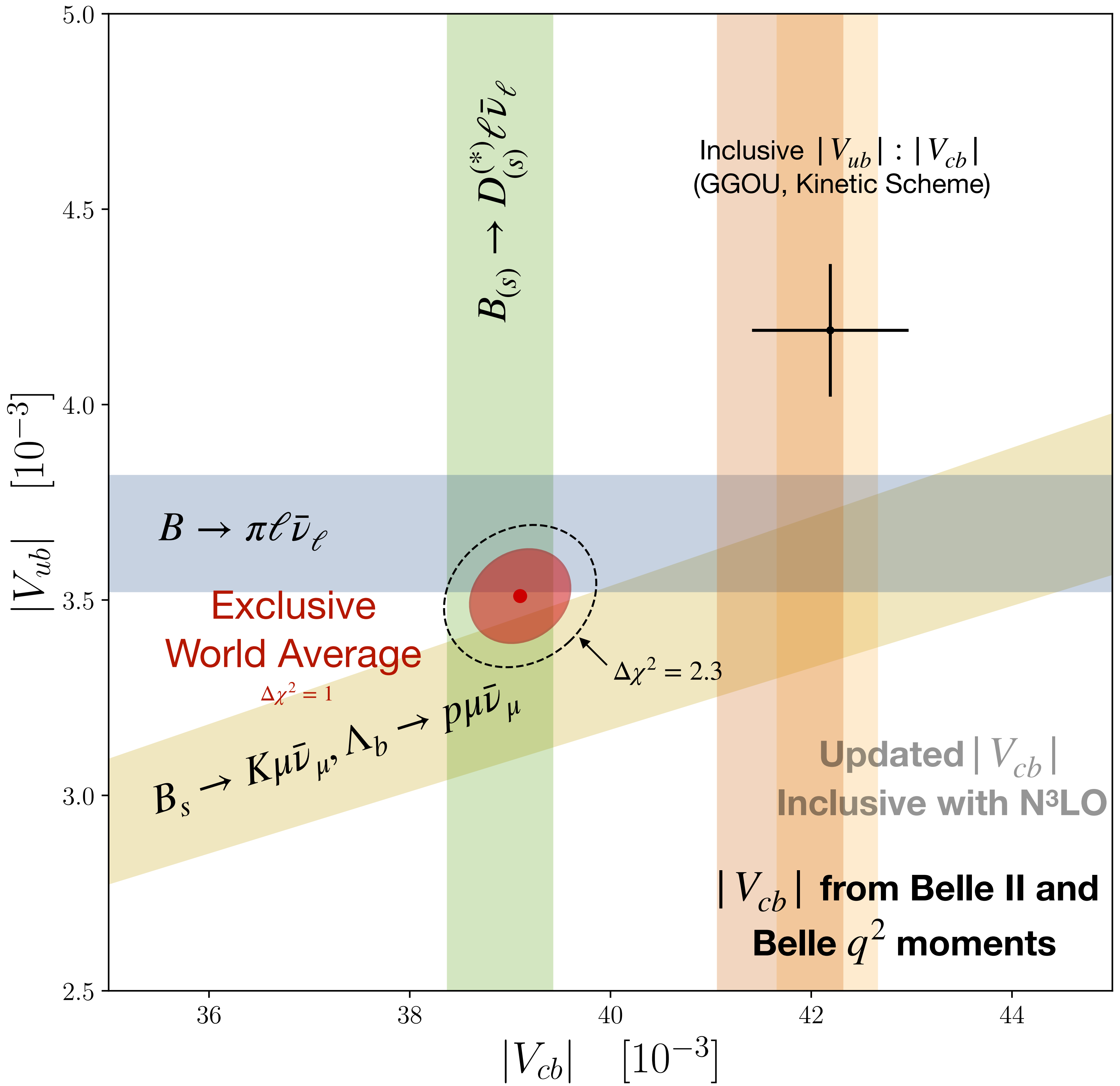


Summary



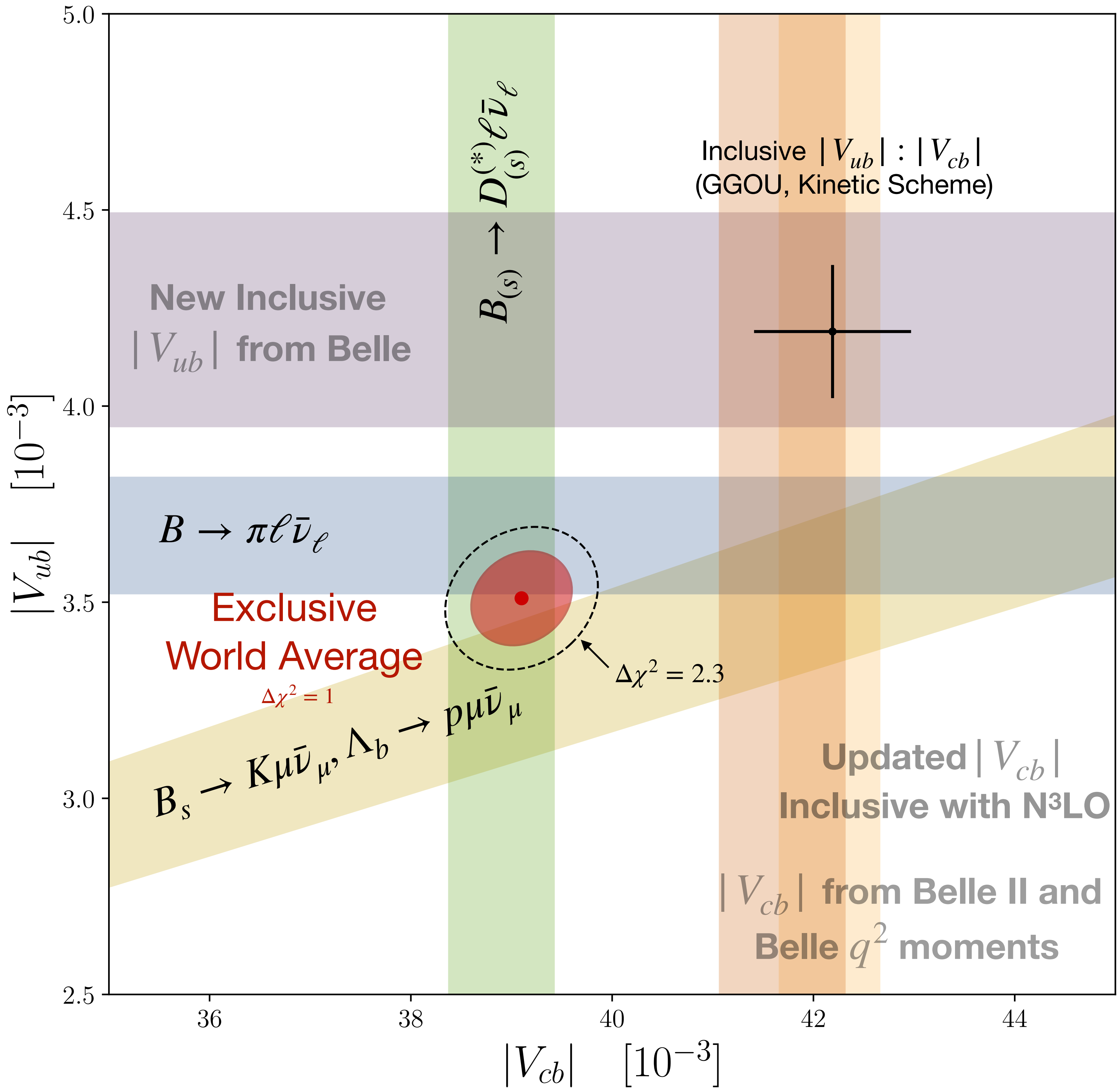
$B_{(s)} \to D^{(*)}_{(s)} \ell \bar{\nu}_\ell$
Inclusive $|V_{ub}|$: $|V_{cb}|$
(GGOU, Kinetic Scheme)
$B \to \pi \ell \bar{\nu}_\ell$
Exclusive
World Average
$\Delta\chi^2 = 1$
$\Delta\chi^2 = 2.3$
$B_s \to K\mu\bar{\nu}_\mu, \Lambda_b \to p\mu\bar{\nu}_\mu$
Updated $|V_{cb}|$
Inclusive with N³LO
$|V_{ub}|$ $[10^{-3}]$
$|V_{cb}|$ $[10^{-3}]$
5.0
4.5
4.0
3.5
3.0
2.5
36
38
40
42
44

Summary



5.0
4.5
4.0
3.5
3.0
2.5
36
38
40
42
44
$|V_{ub}|\quad[10^{-3}]$
$|V_{cb}|\quad[10^{-3}]$
$B_{(s)} \to D^{(*)}_{(s)}\ell\bar{\nu}_\ell$
Inclusive $|V_{ub}|:|V_{cb}|$
(GGOU, Kinetic Scheme)
$B \to \pi\ell\bar{\nu}_\ell$
Exclusive
World Average
$\Delta\chi^2 = 1$
$\Delta\chi^2 = 2.3$
$B_s \to K\mu\bar{\nu}_\mu, \Lambda_b \to p\mu\bar{\nu}_\mu$
Updated $|V_{cb}|$
Inclusive with N³LO
$|V_{cb}|$ from Belle II and
Belle q^2 moments

Summary



Inclusive $|V_{ub}| : |V_{cb}|$
(GGOU, Kinetic Scheme)
$B_{(s)} \to D_{(s)}^{(*)} \ell \bar{\nu}_\ell$
New Inclusive
$|V_{ub}|$ from Belle
$B \to \pi \ell \bar{\nu}_\ell$
Exclusive
World Average
$\Delta\chi^2 = 1$
$\Delta\chi^2 = 2.3$
$B_s \to K \mu \bar{\nu}_\mu, \Lambda_b \to p \mu \bar{\nu}_\mu$
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Inclusive with N³LO
$|V_{cb}|$ from Belle II and
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4.5
4.0
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40
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44
$|V_{ub}|$ $[10^{-3}]$
$|V_{cb}|$ $[10^{-3}]$

3. τ

Florian Bernlochner (florian.bernlochner@uni-bonn.de)

Measurement Strategies

Signal

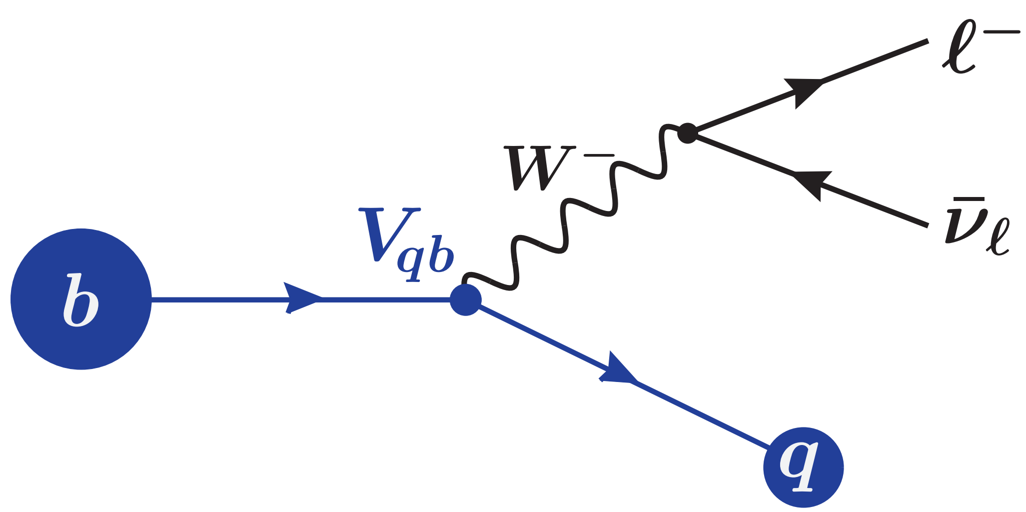
$$R = \frac{b \to q\,\tau\bar{\nu}_\tau}{b \to q\,\ell\bar{\nu}_\ell}$$

Normalization

$\ell = e, \mu$

1. Leptonic or Hadronic τ decays?

Some properties (e.g. τ **polarization**) readily **accessible** in **hadronic decays.**



2. Albeit not necessarily a rare decay of O(%) in BF, TRICKY to separate from normalisation and backgrounds

LHCb: **Isolation** criteria, **displacement** of τ, **kinematics**

B-Factories: Full reconstruction of event (**Tagging**), **matching topology, kinematics**

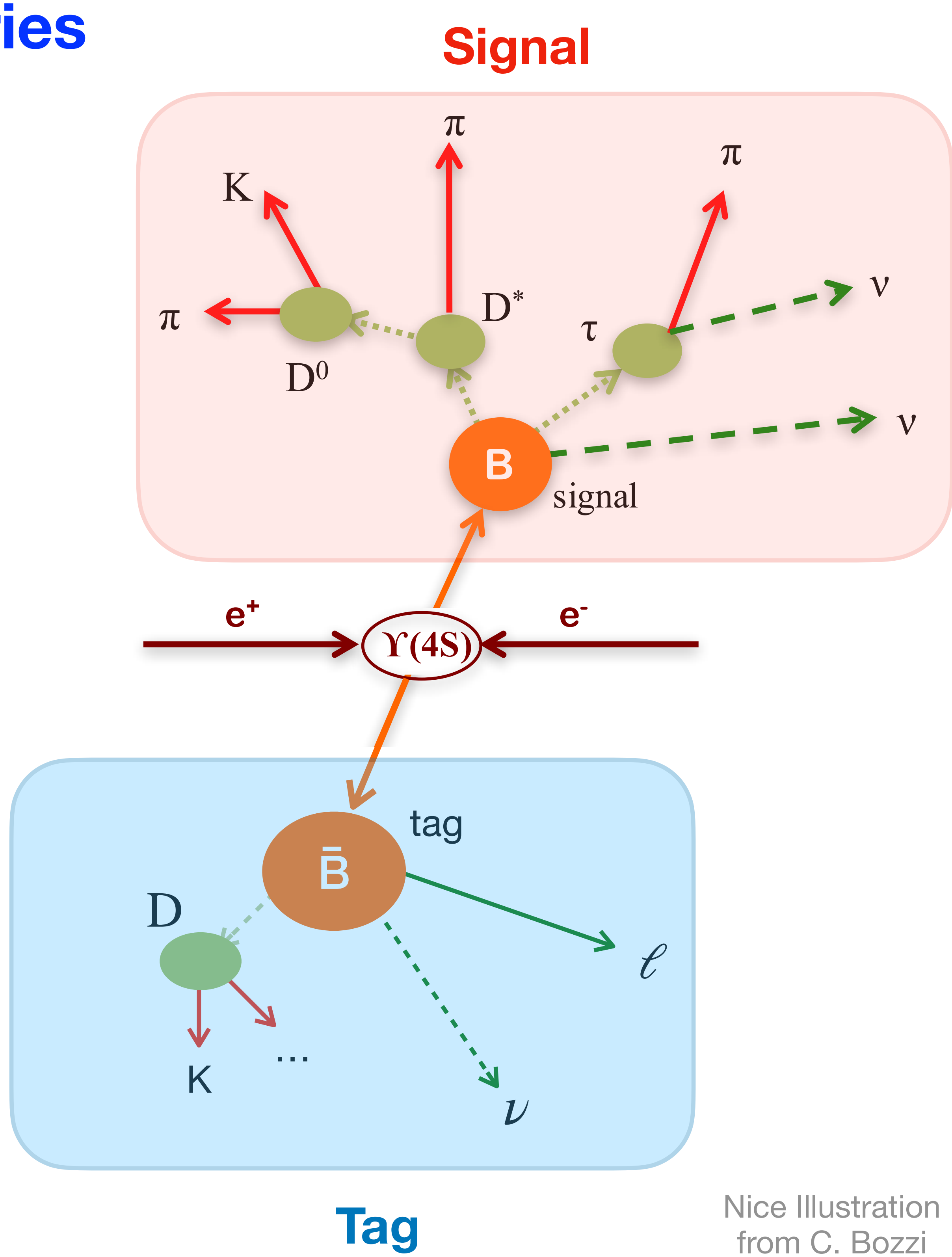
Measurement Strategies

3. Semileptonic decays at B-Factories

- e+/e- collision produces ***Y(4S)* → *BB̄***
- Fully reconstruct one of the two B-mesons ('tag') → **possible** to **assign all particles** to either signal or tag B
- **Missing four-momentum** (**neutrinos**) can be reconstructed with high precision

$$p_{\rm miss} = (p_{\rm beam} - p_{B{\rm tag}} - p_{D^{(*)}} - p_\ell)$$

✓ **Small efficiency (~0.2-0.4%) compensated by large integrated luminosity**



Nice Illustration from C. Bozzi

Measurement Strategies

4. Semileptonic decays at LHCb

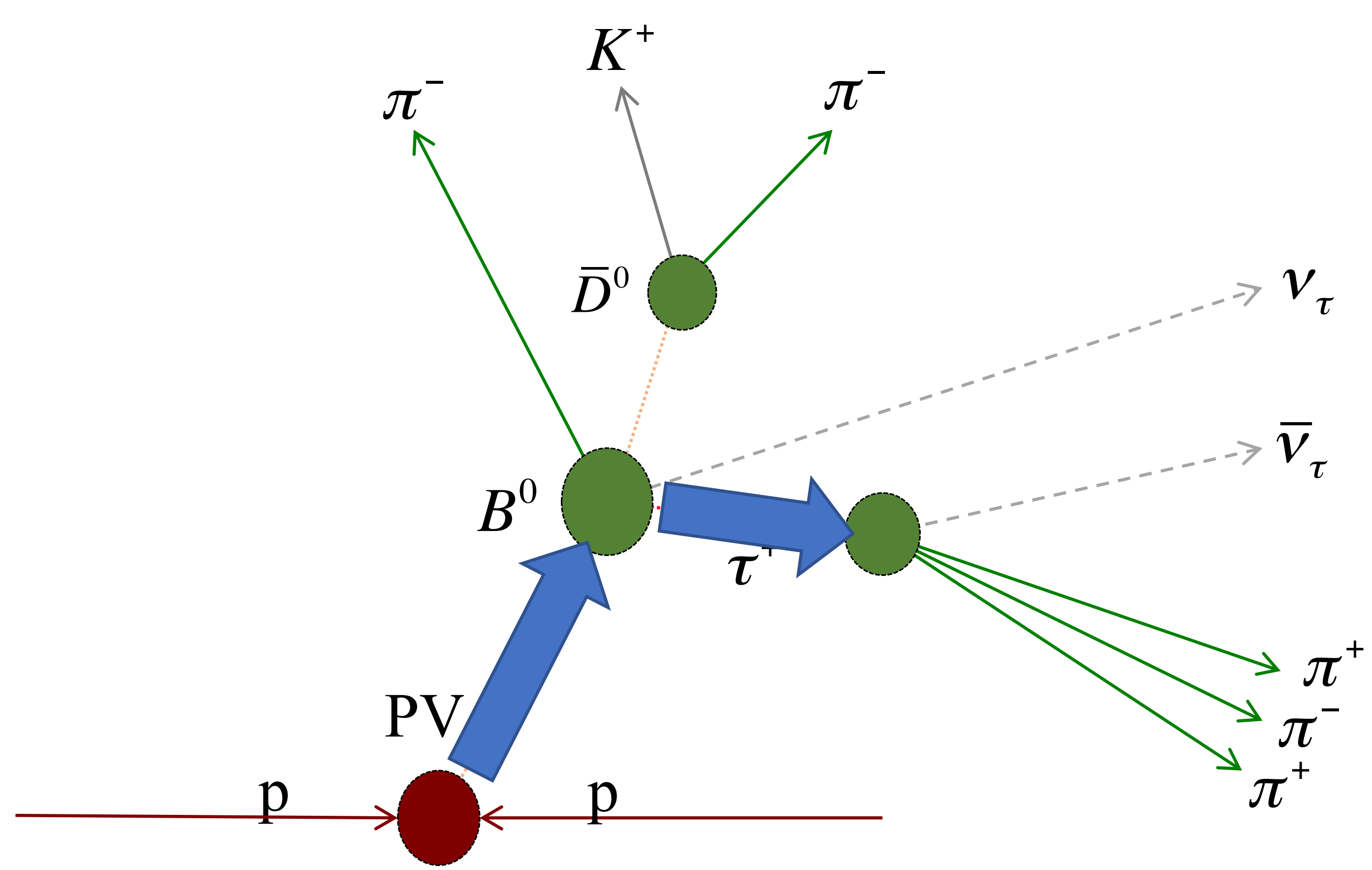
- No constraint from beam energy at a hadron machine, **but..**
- **Large Lorentz boost** with decay lengths in the range of **mm**

  ✓ **Well-separated decay vertices**

  ✓ **Momentum direction of decaying particle is well known**

- With known masses and other decay products can even **reconstruct four-momentum transfer squared q²** up to a two-fold ambiguity

$$q^2 = \left(p_{X_b} - p_{X_q}\right)^2$$



Nice Illustration from C. Bozzi

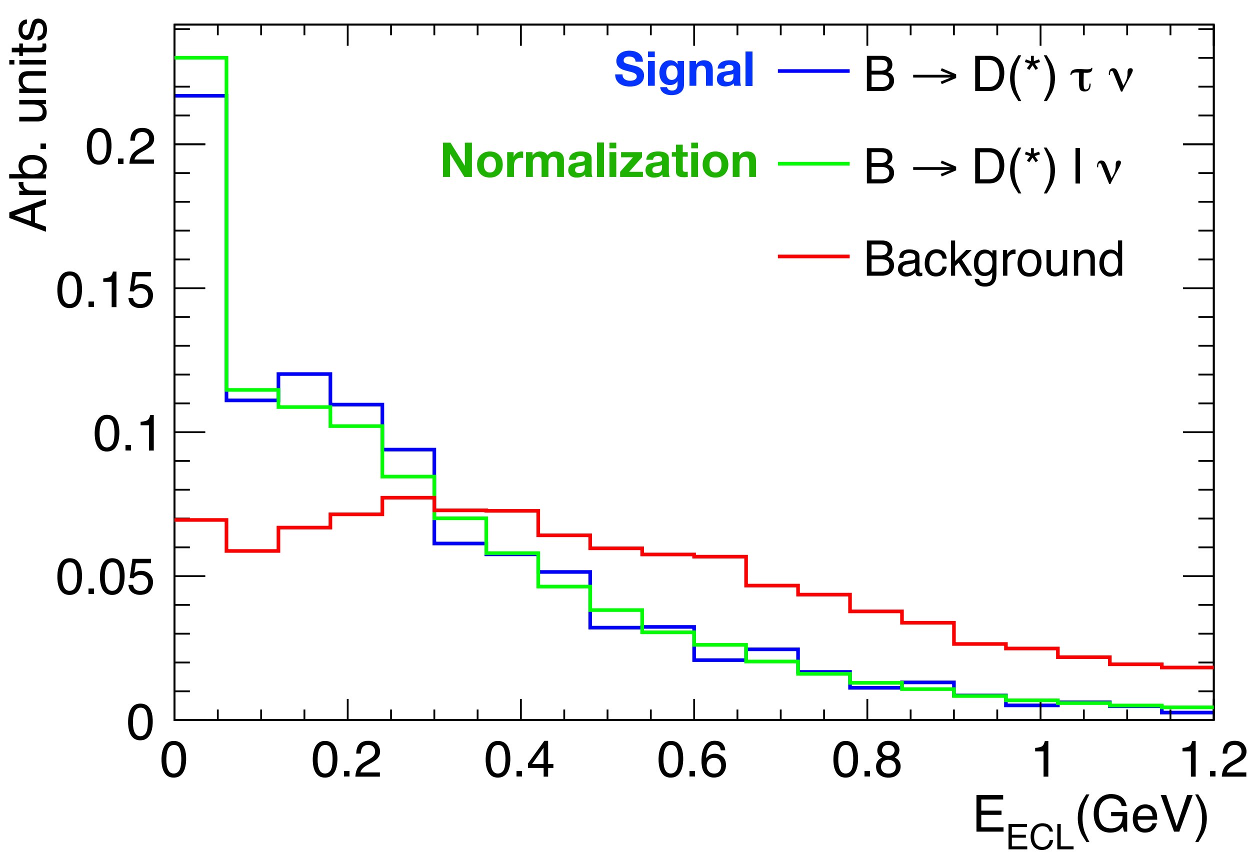
Even bit more complicated for leptonic tau decays

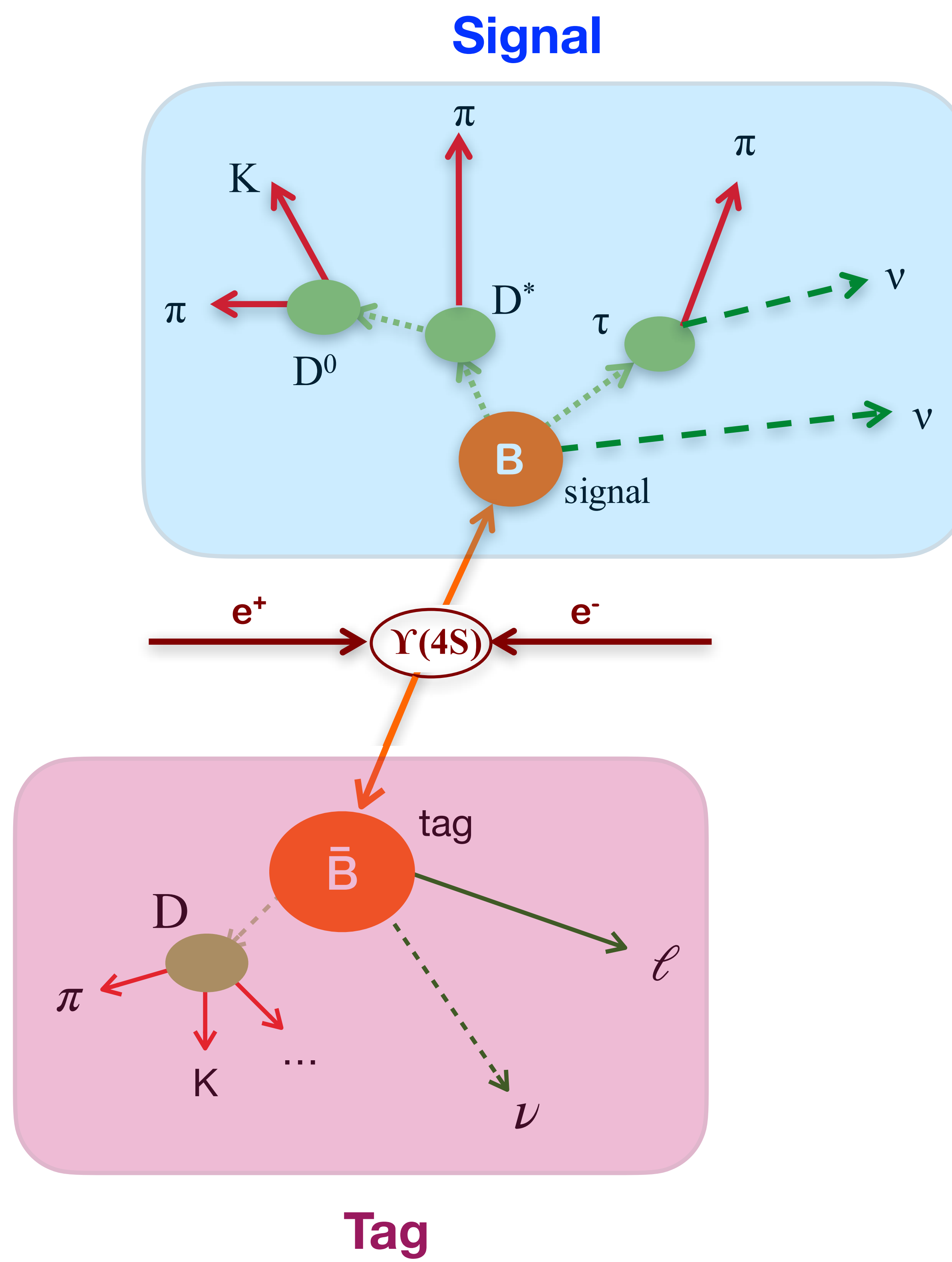
Latest $R(D^{(*)})$ from Belle

G. Caria et al (Belle),
Phys. Rev. Lett. 124, 161803, April 2020
[arXiv:1904.08794]

- Reconstruct one of the two B-mesons (‘tag’) in **semileptonic modes → possible to assign all particles in detector** to tag- & signal-side
- Demand Matching topology + **unassigned** energy in the calorimeter $E_{\rm ECL}$ to discriminate background from signal

$$E_{\rm extra} = E_{\rm ECL} = \sum_i E_i^{\gamma}$$

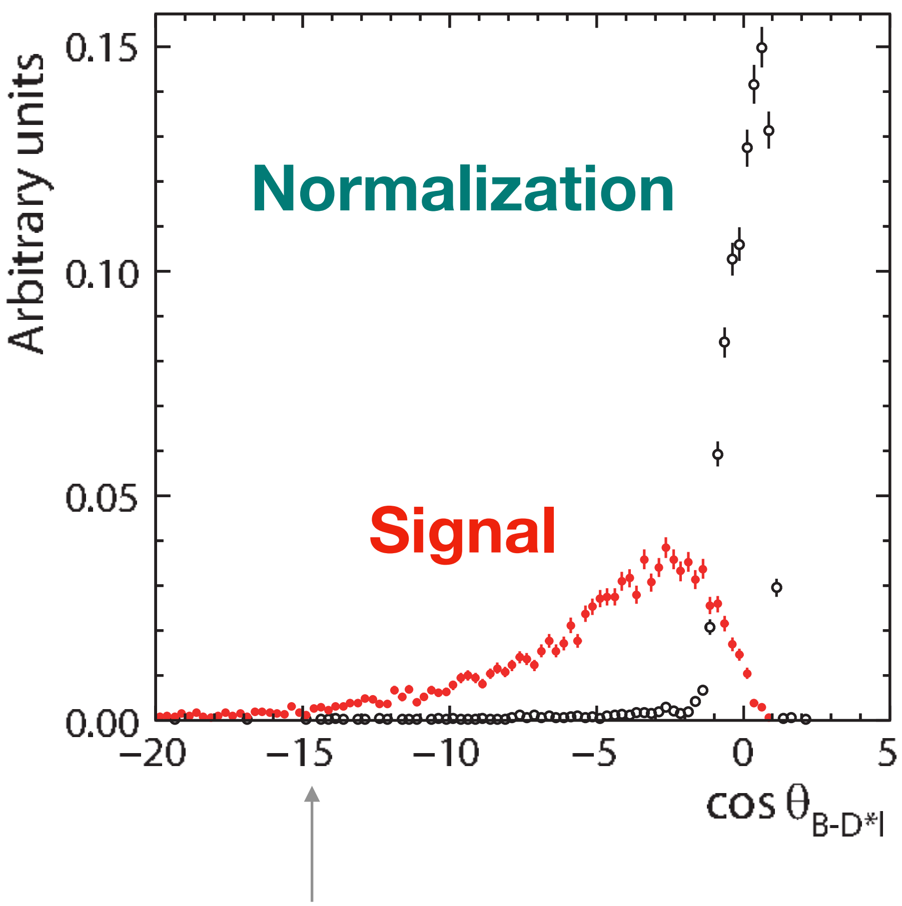


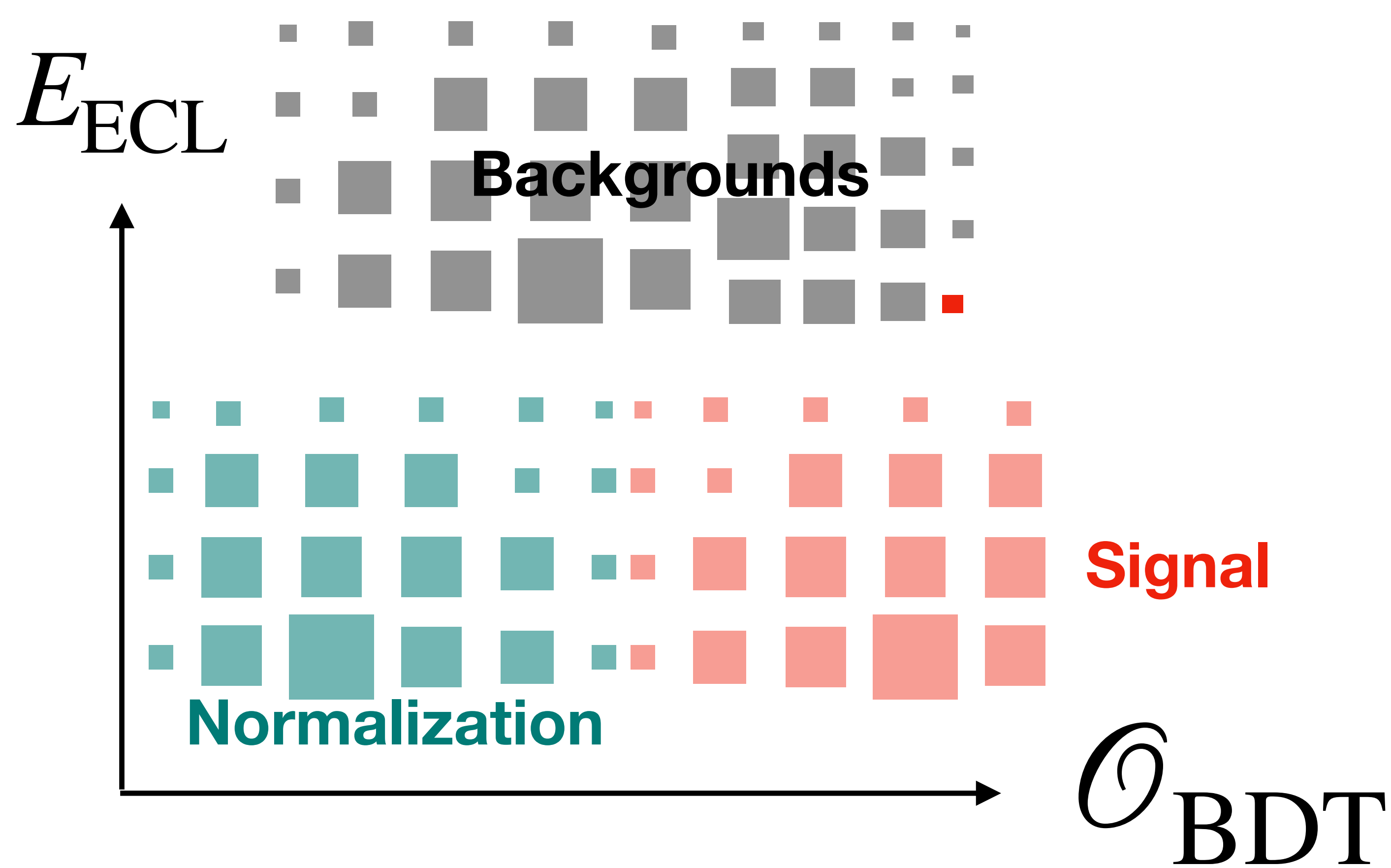


Separation of signal & normalization

- Use kinematic properties to separate $B \to D^{(*)}\tau\nu$ signal from $B \to D^{(*)}\ell\nu$ normalization

- Construct BDT with 3 variables: $\cos\theta_{B-D^{(*)}\ell}$, E_{vis}, $m^2_{miss} = p^2_{miss}$



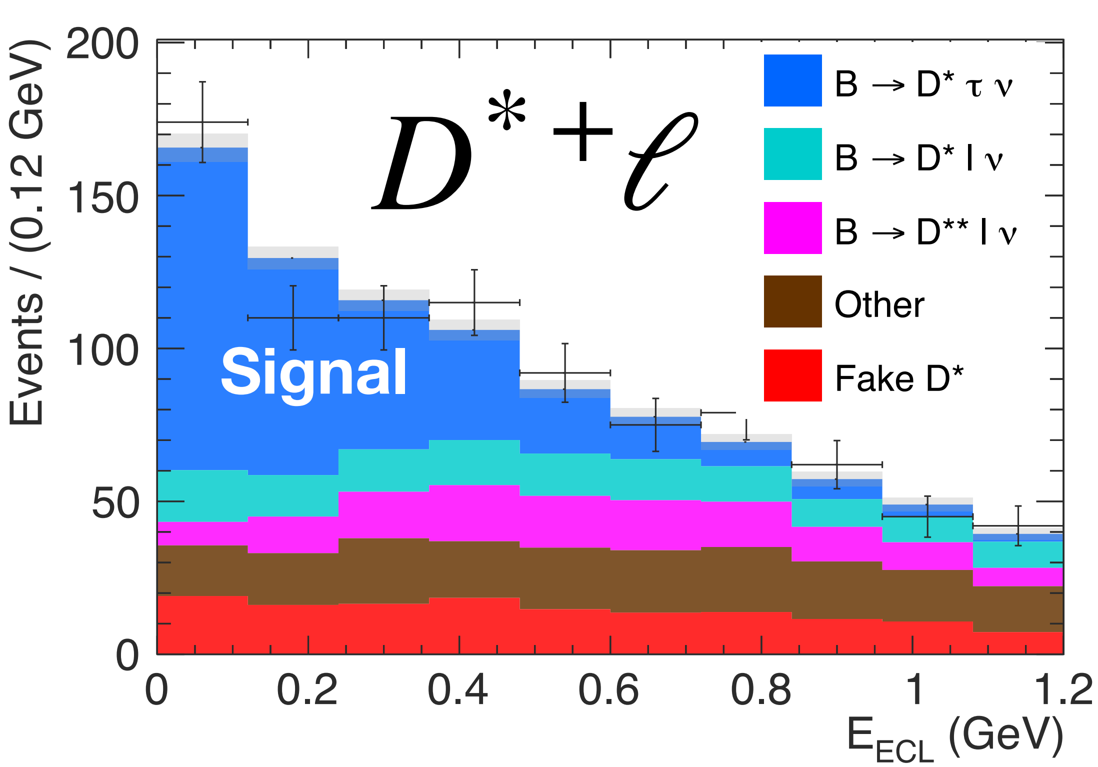


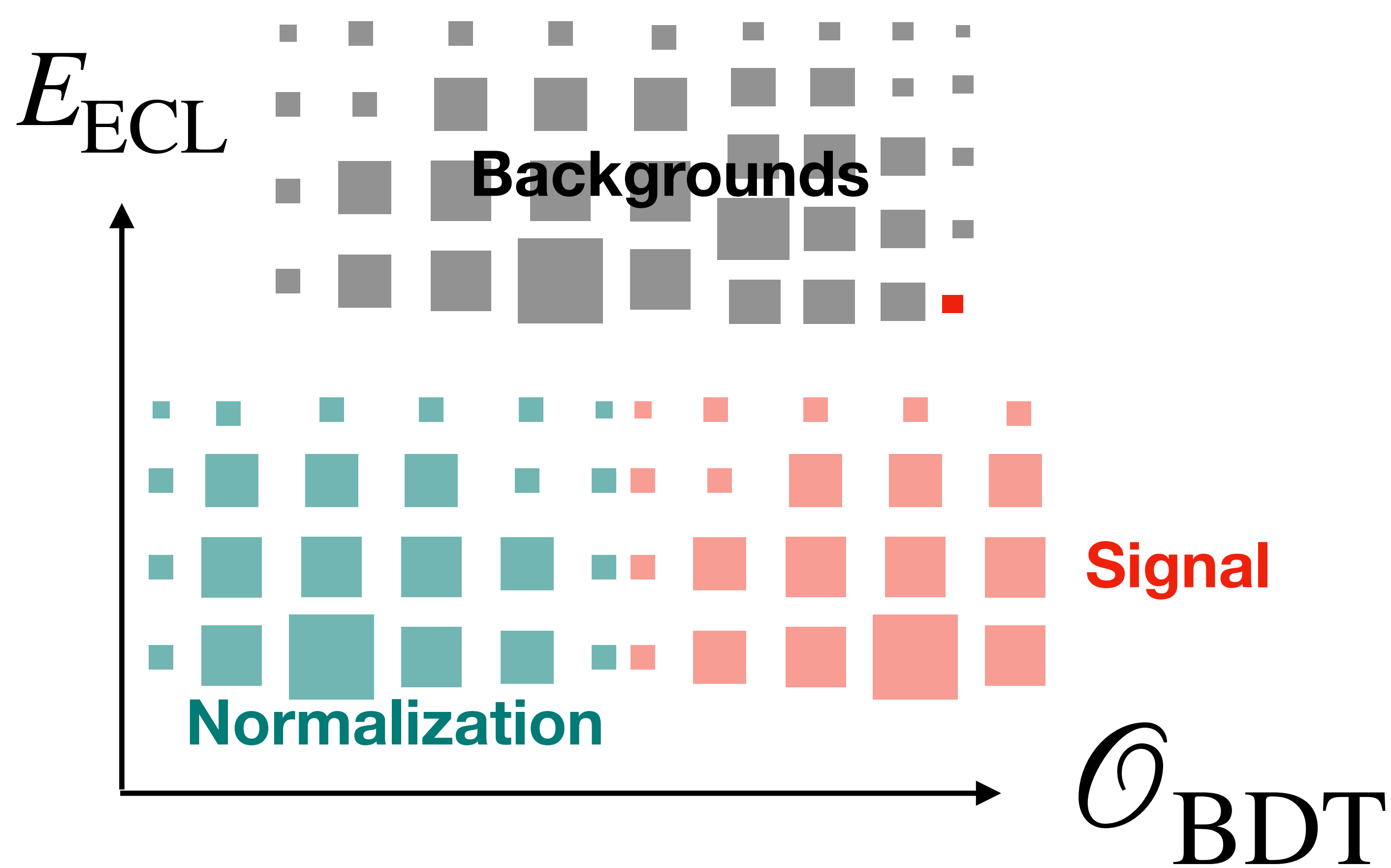
In case you are wondering how a cosine can be outside [-1,1]: it's because the reconstruction uses measured energies and the definition assumes only a single missing neutrino

Separation of signal & normalization

- Use kinematic properties to separate $B \to D^{(*)}\tau\nu$ signal from $B \to D^{(*)}\ell\nu$ normalization

- Construct BDT with 3 variables: $\cos\theta_{B-D^{(*)}\ell}$, E_{vis}, $m^2_{\text{miss}} = p^2_{\text{miss}}$



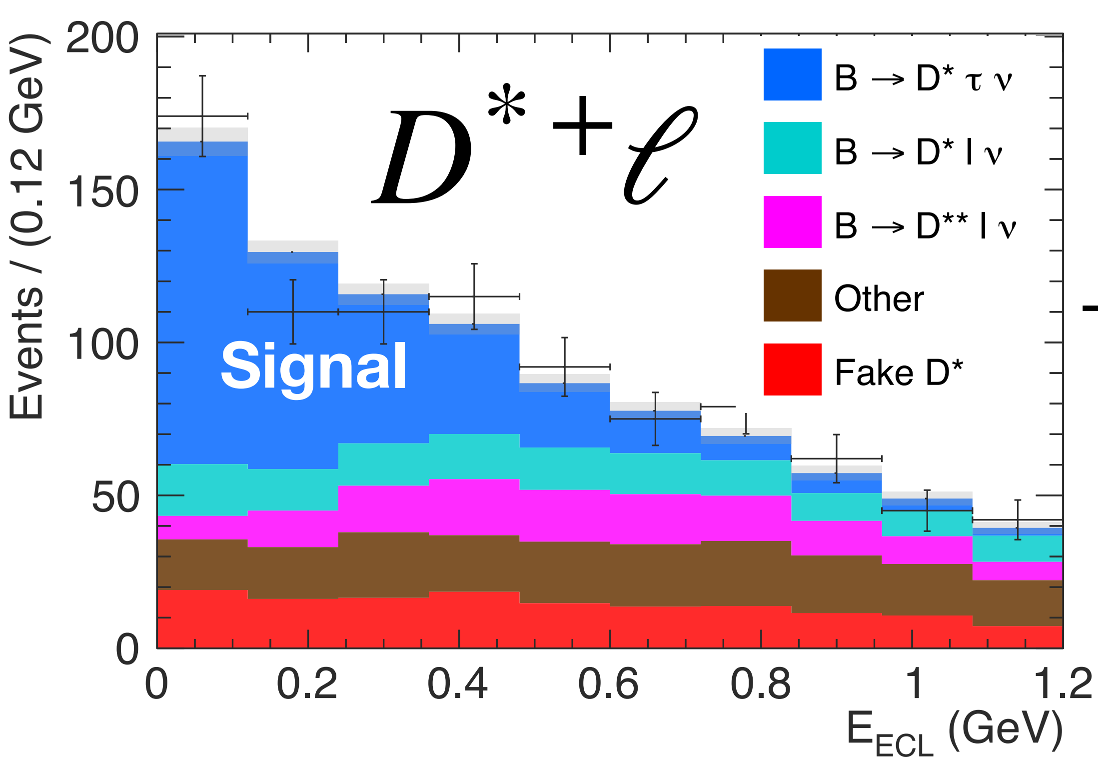


Signal-enriched selection with cut on $\mathcal{O}_{\text{BDT}}$

Separation of signal & normalization

- Use kinematic properties to separate $B \to D^{(*)}\tau\nu$ signal from $B \to D^{(*)}\ell\nu$ normalization

- Construct BDT with 3 variables: $\cos\theta_{B-D^{(*)}\ell}$, E_{vis}, $m^2_{\mathrm{miss}} = p^2_{\mathrm{miss}}$



Signal enriched selection with cut on $\mathcal{O}_{\mathrm{BDT}}$

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

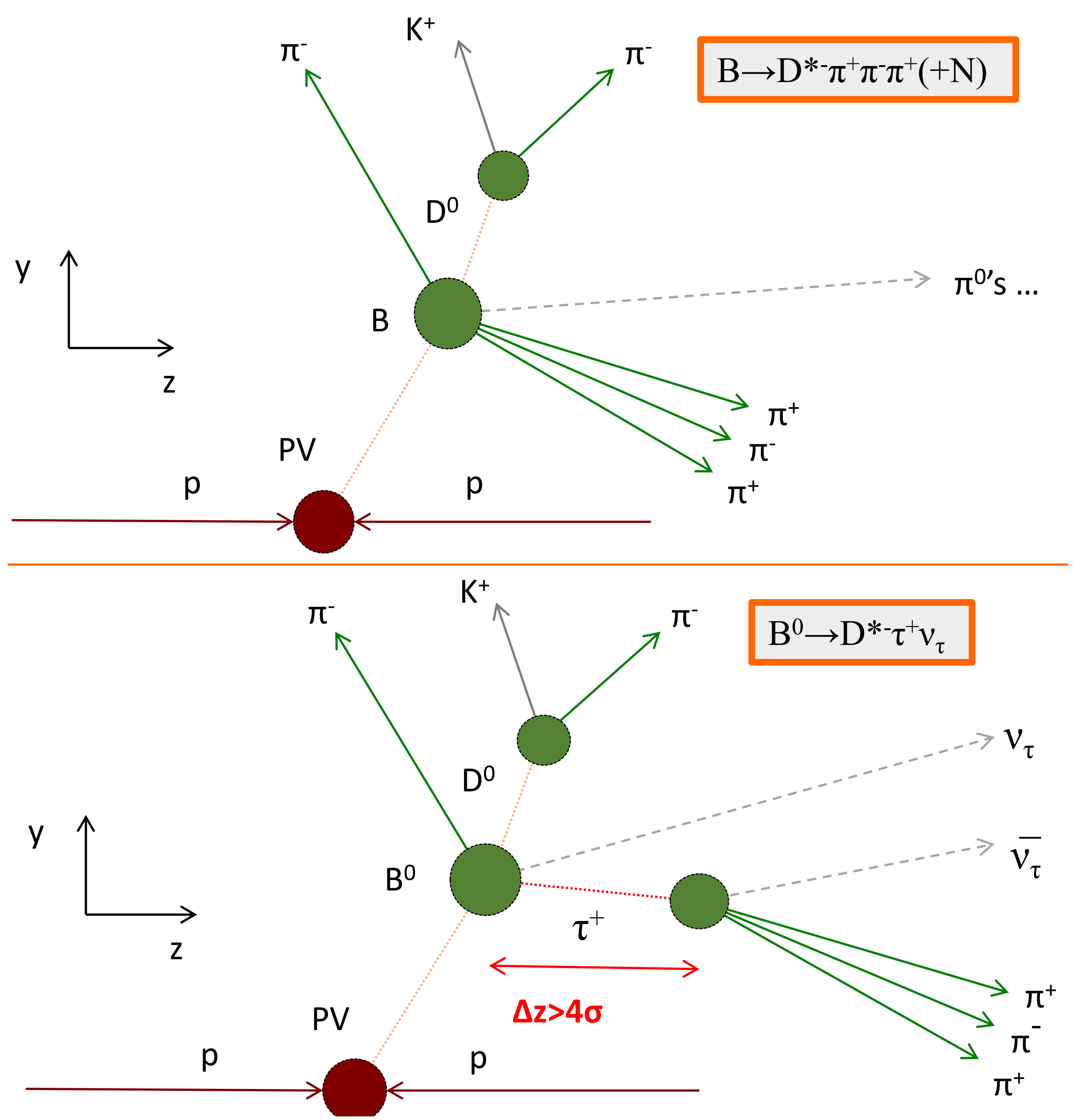
Most precise measurement to date

LHCb Measurement of $R(D^*)$

R. Aaij et al (LHCb),
Phys.Rev.Lett.120,171802 (2018) [arXiv:1708.08856]
Phys.Rev.D 97, 072013 (2018) [arXiv:1709.02505]

- Tau reconstructed via $\tau \to \pi^+\pi^+\pi^-(\pi^0)\nu$, only two neutrinos missing

Although a semileptonic decay is studied, nearly no background from $B \to D^* X\mu\nu$



- Main background: prompt **$X_b \to D^*\pi\pi\pi$ + neutrals**

BF ~ 100 times larger than signal, all pions are promptly produced

- Suppressed by requiring minimum distance between ***X_b & τ vertices (> 4 $\sigma_{\Delta z}$)***

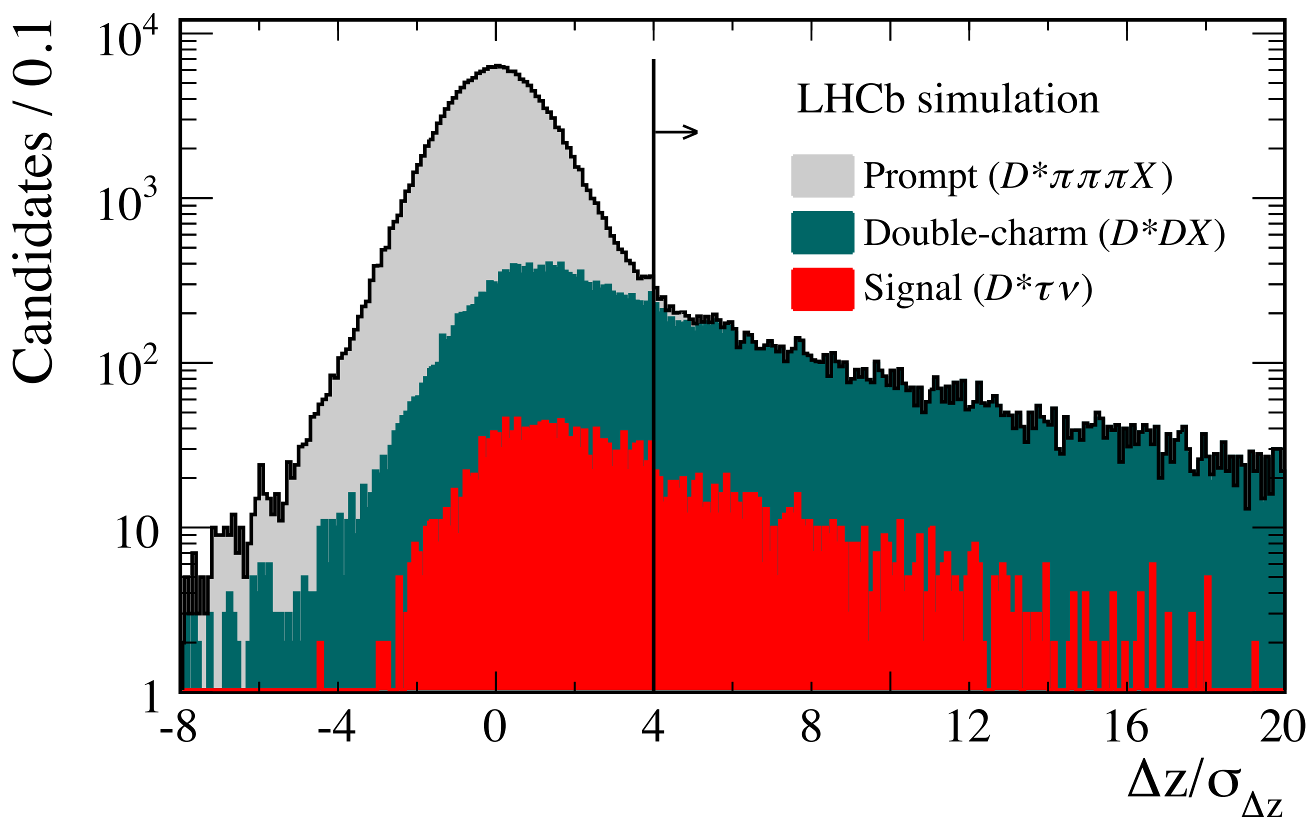
$\sigma_{\Delta z}$: resolution of vertices separation

- Reduces this background by three orders of magnitude

LHCb Measurement of $R(D^*)$

- Tau reconstructed via $\tau \to \pi^+\pi^+\pi^-(\pi^0)\nu$, only two neutrinos missing

Although a semileptonic decay is studied, nearly no background from $B \to D^* X\mu\nu$



- Main background: prompt **$X_b \to D^*\pi\pi\pi$ + neutrals**

BF ~ 100 times larger than signal, all pions are promptly produced

- Suppressed by requiring minimum distance between ***X_b & τ vertices (> 4 $\sigma_{\Delta z}$)***

$\sigma_{\Delta z}$: resolution of vertices separation

- Reduces this background by three orders of magnitude

- Remaining double charm bkgs:

$X_b \to D^{*-}D_s^+X$ ~ 10 x Signal

$X_b \to D^{*-}D^+X$ ~ 1 x Signal

$X_b \to D^{*-}D_{s0}^+X$ ~ 0.2 x Signal

LHCb Measurement of $R(D^*)$

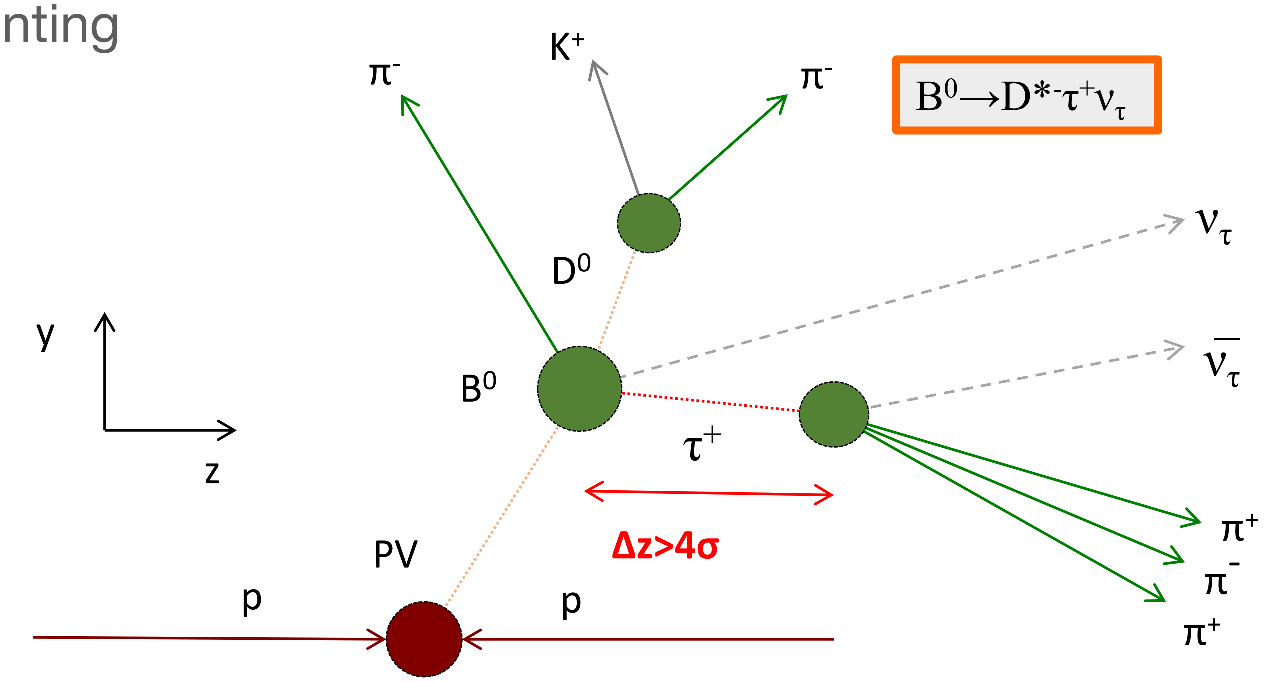
- Remaining backgrounds reduced via isolation & MVA

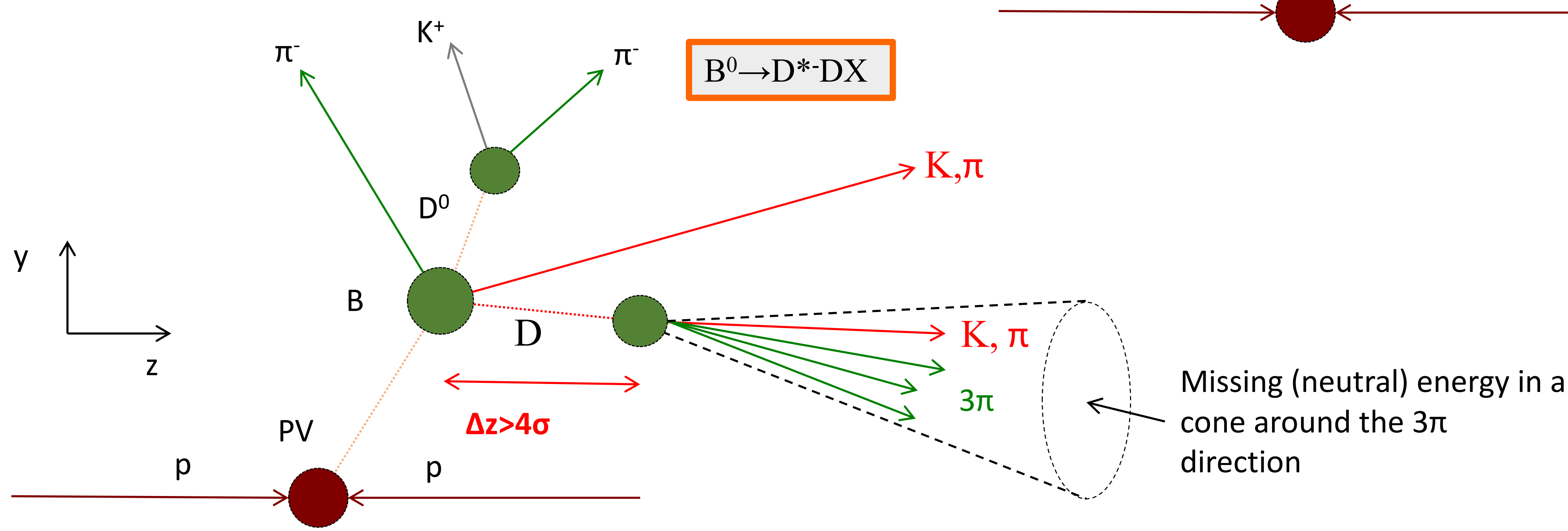
Require signal candidates to be well isolated

i.e. reject events with extra charged particles pointing to the B and/or τ

Events with additional neutral energy are suppressed with a MVA

More information about that in backup





LHCb Measurement of $R(D^*)$

- Extraction in **3D fit** to

  MVA : q^2 : τ decay time

  Invariant masses of 3π system
  Invariant mass of $D^*3\pi$ system
  Neutral isolation variables

  q^2 reconstructed with some tricks (more in backup)

  4 Bins 8 Bins 8 Bins

- Components:

1 Signal component for $\tau \to \pi^+\pi^+\pi^-(\pi^0)\nu$

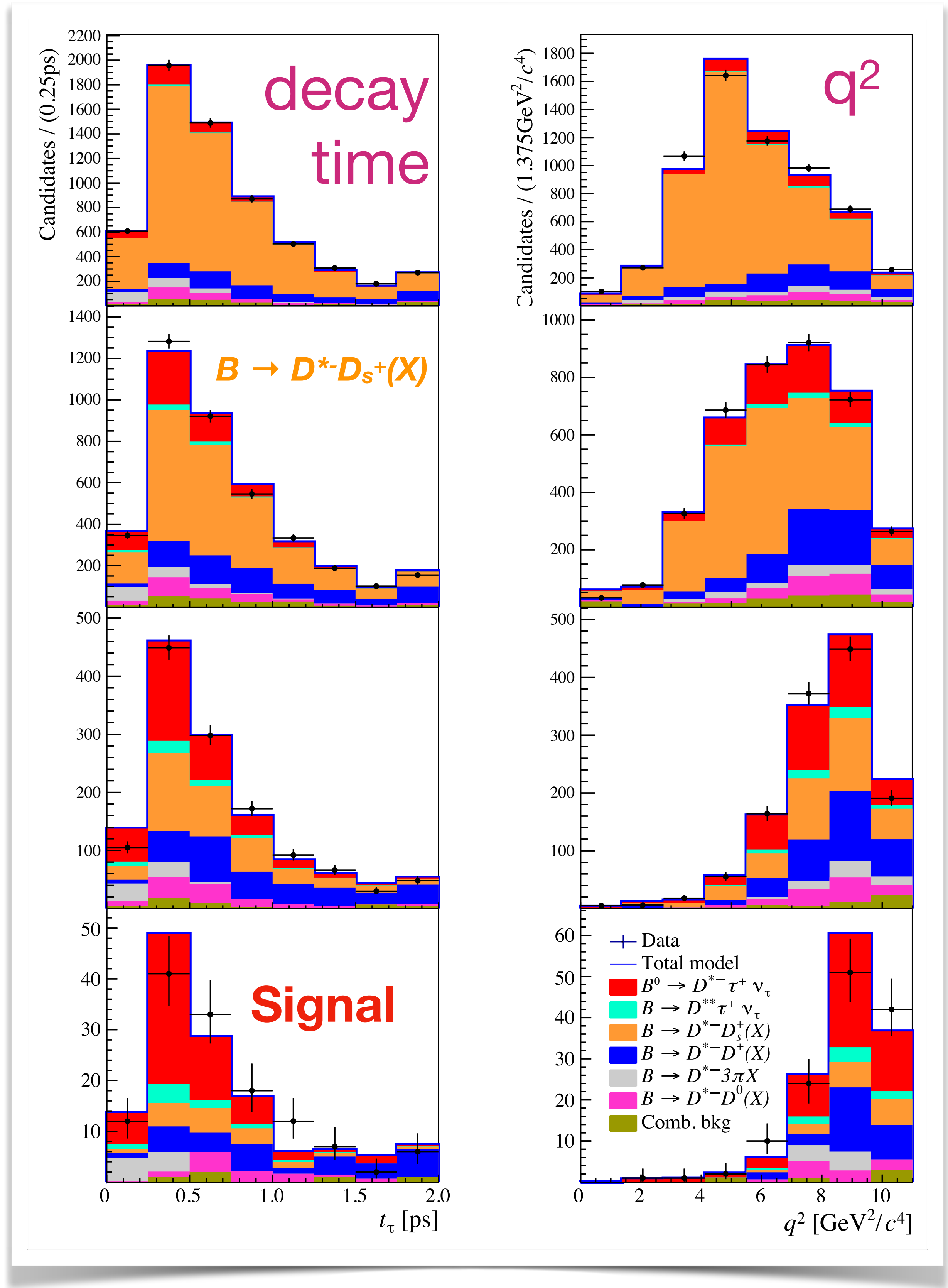
11 Background components

- ~ 1296 ± 86 Signal events
- Using normalization mode and light lepton BFs:

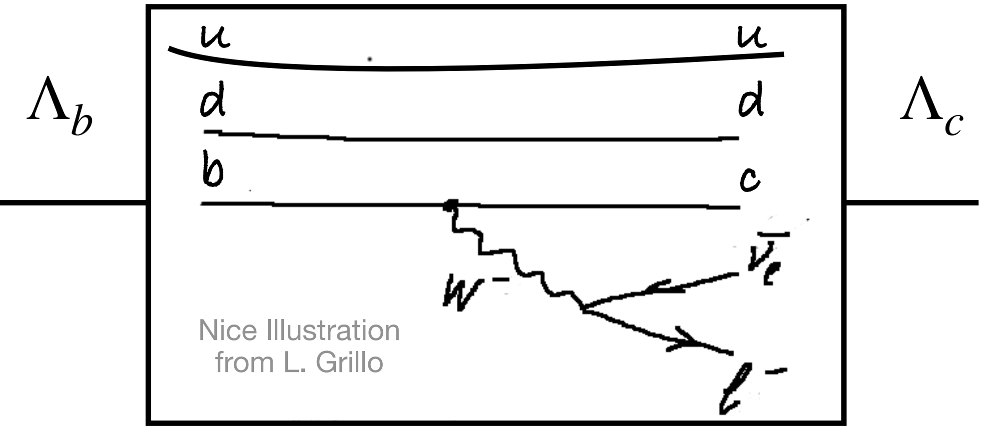
More information about normalization in backup

R(D*) = 0.286 ± 0.019 (stat) ± 0.025 (syst) ± 0.021 (norm)

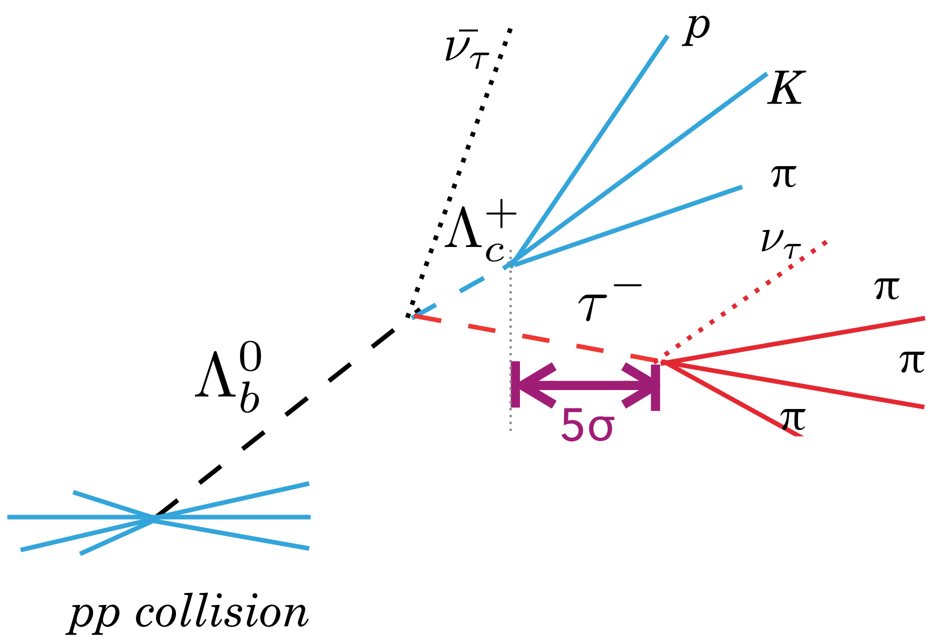
Purer MVA Selection

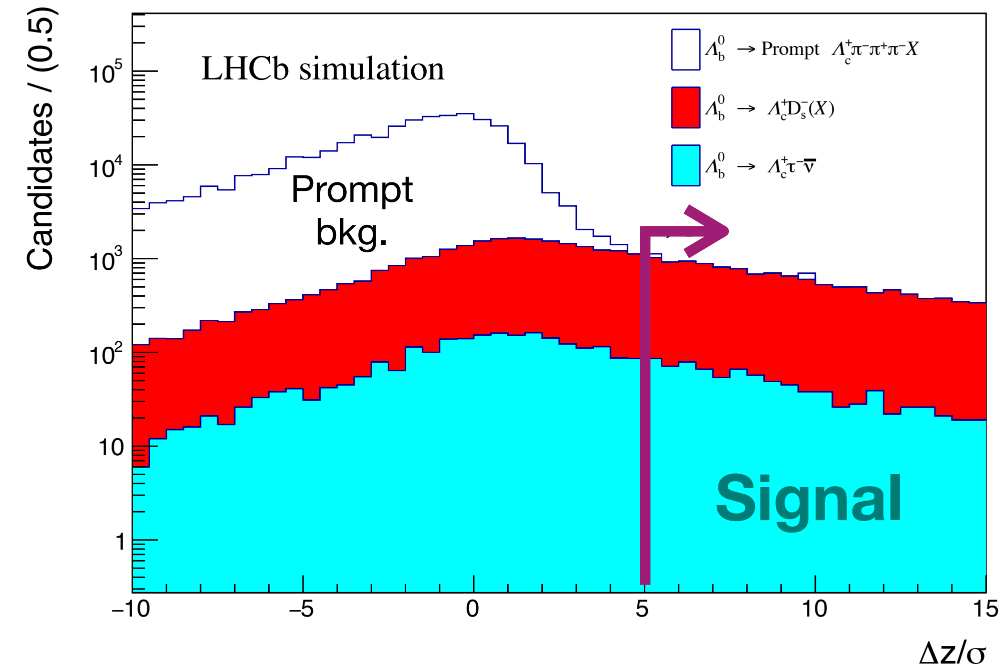


LHCb $R(\Lambda_c)$ Measurement



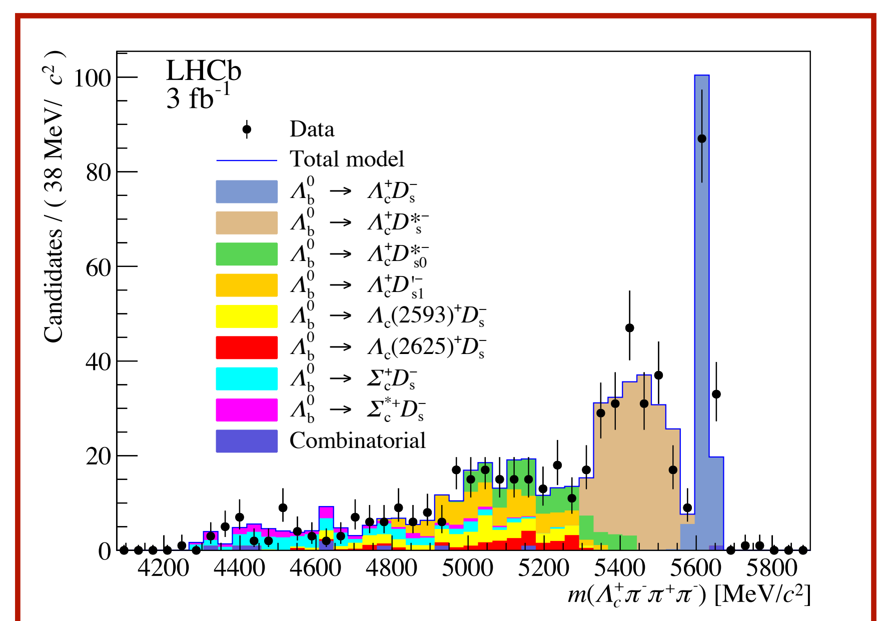
Same experimental Method: exploit vertex **separation**





Long-lived bkg. (D_s)

$m_{3\pi} \in [m_{D_s} - 45\,\mathrm{MeV}, m_{D_s} + 45\,\mathrm{MeV}]$



Bkg. composition constrained by fit to $m_{3\pi}$

Target **ratio**:

$$\mathcal{K}(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi)} = \frac{N_{sig}}{N_{norm}} \times \frac{\epsilon_{norm}}{\epsilon_{sig}} \times \frac{1}{\mathcal{B}(\tau^- \to 3\pi(\pi^0)\nu_\tau)}$$

- Extraction in **3D fit** to
  MVA : q^2 : τ decay time

Kinematic and angular information of 3π system, neutral energy in cone around 3π direction

$$N(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau) = 349 \pm 40$$
$$N(\Lambda_b^0 \to \Lambda_c^+ D_s^-(X)) = 2757 \pm 80$$

External input:

$$\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+ 3\pi) = (6.14 \pm 0.94) \times 10^{-3}$$

$$\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+ \tau \bar{\nu}_\tau) = (1.50 \pm 0.16 \pm 0.25 \pm 0.23)\,\%$$

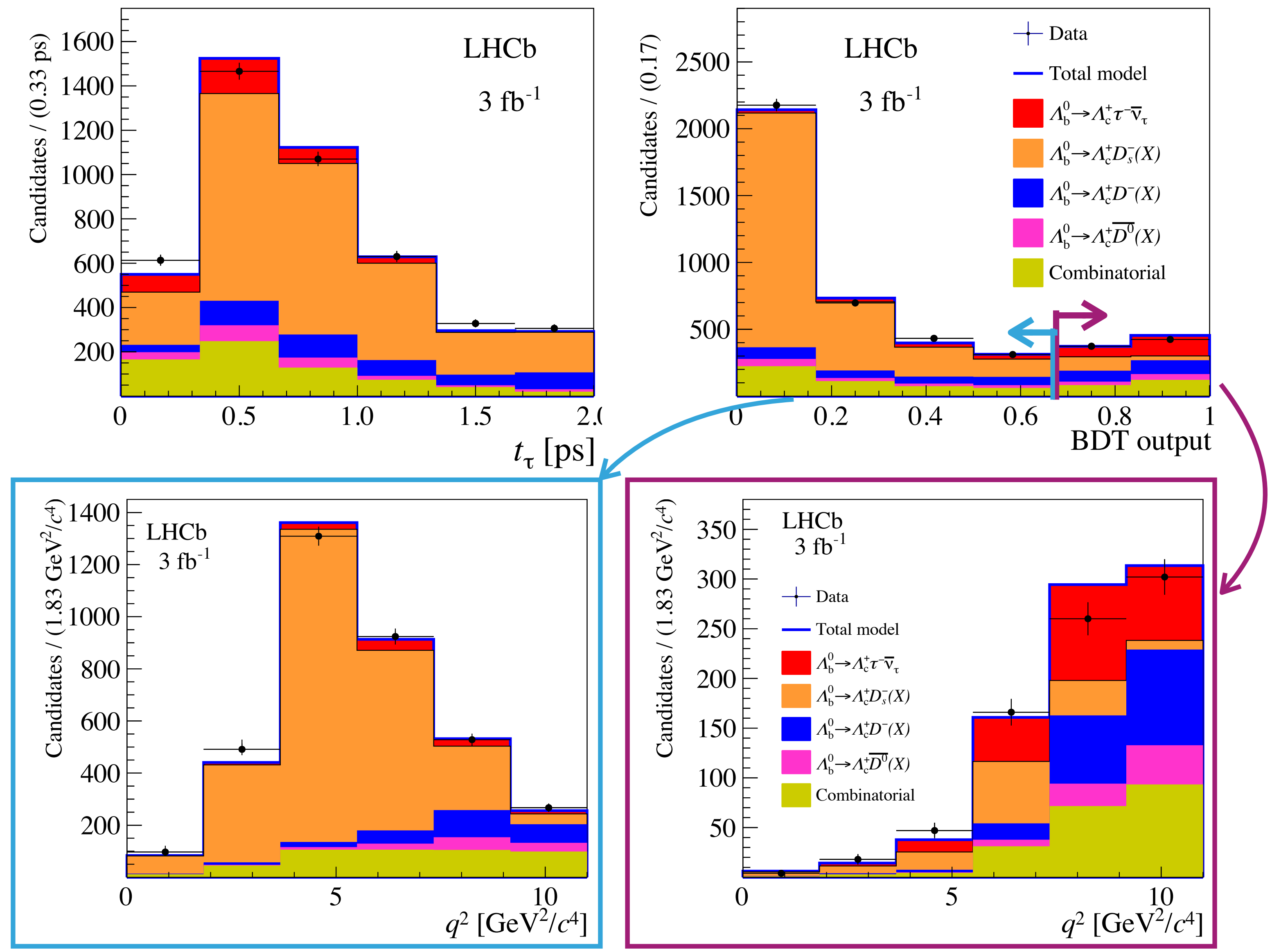
First observation with 6.1 σ !

More external input:

$$\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+ \mu \bar{\nu}_\mu) = (6.2 \pm 1.4)\,\%$$

$$R(\Lambda_c^+) = 0.242 \pm 0.026_{\text{stat}} \pm 0.040_{\text{syst}} \pm 0.059_{\text{ext}}$$

$$R(\Lambda_c^+) = 0.242 \pm 0.026_{\text{stat}} \pm 0.040_{\text{syst}} \pm 0.059_{\text{ext}}$$



Compatible with SM

$$R(\Lambda_c^+)_{\text{SM}} = 0.340 \pm 0.004$$

F. Bernlochner, Zoltan Ligeti, Dean J. Robinson, William L. Sutcliffe, [arXiv:1808.09464], [arXiv:1812.07593]

- Extraction in **3D fit** to

MVA : q^2 : τ decay time

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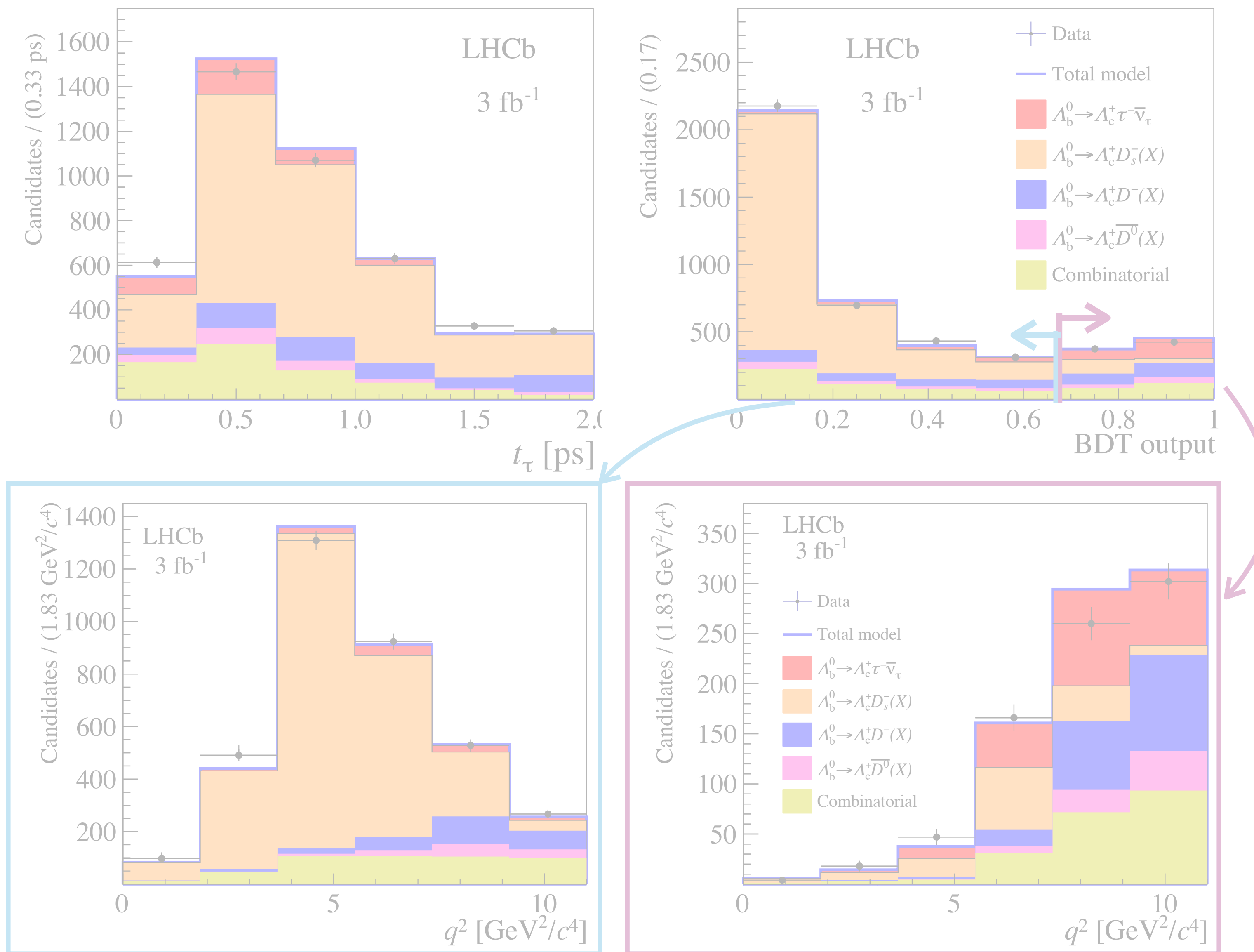
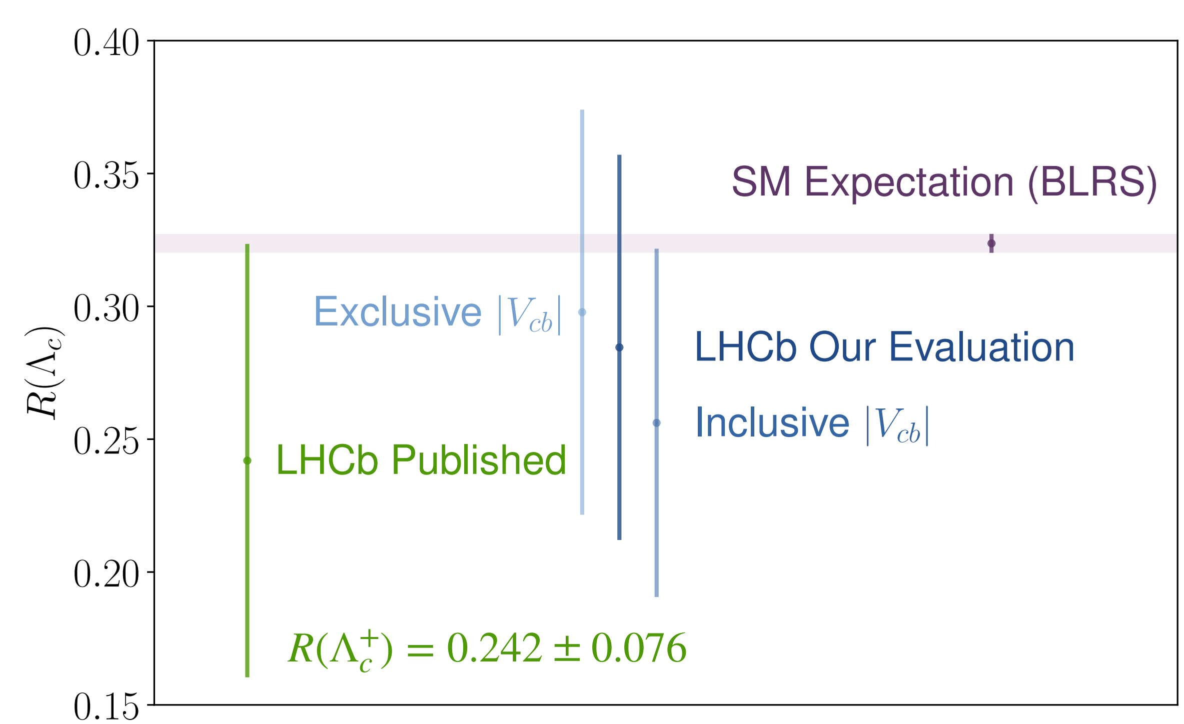


Can also use SM prediction for $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu \bar{\nu}_\mu)$ instead of LEP measurement

FB, Zoltan Ligeti, Michele Papucci, Dean Robinson, [arXiv:2206.11282 [hep-ph]]

$$R(\Lambda_c^+) = 0.285 \pm 0.073$$



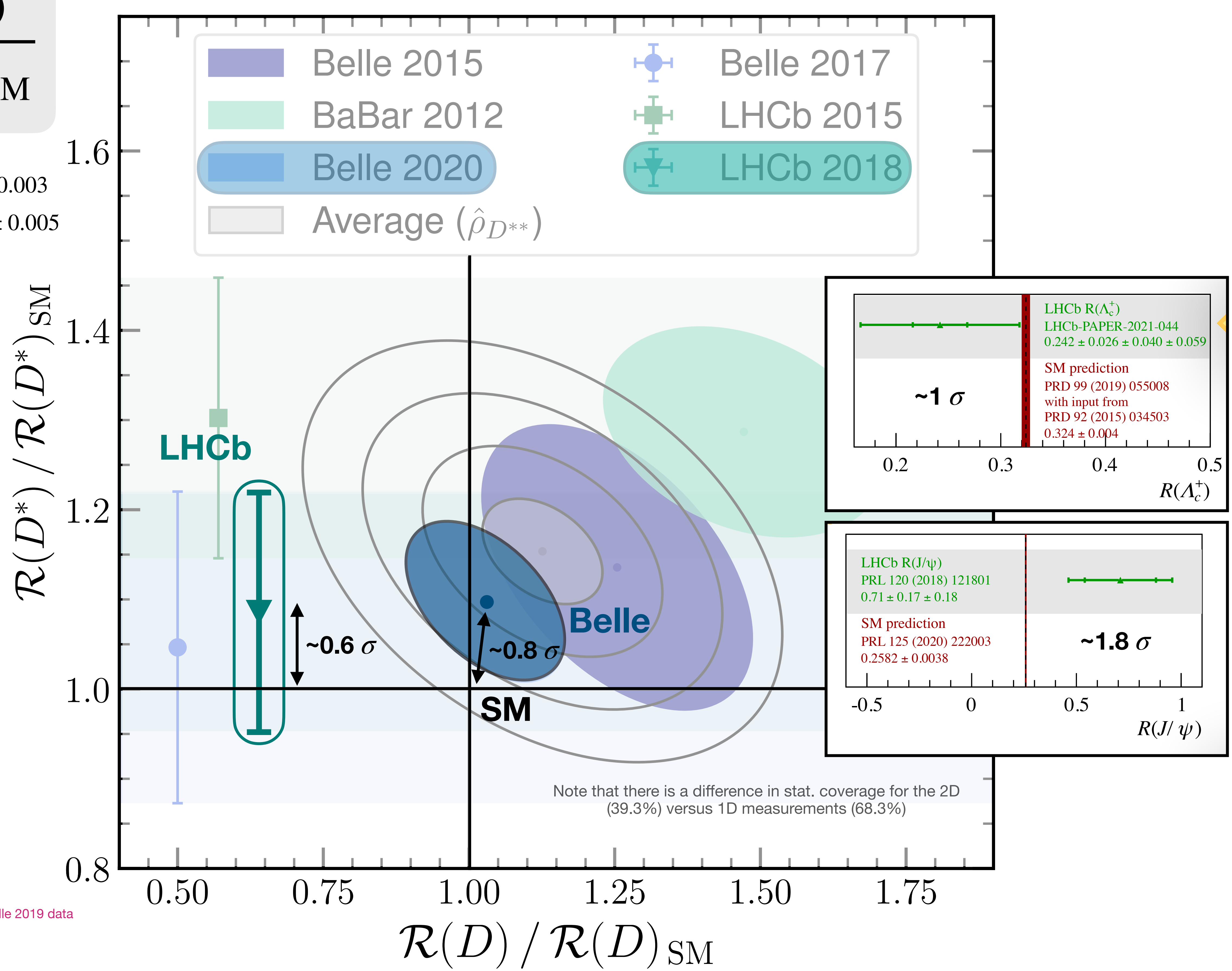
FB, M. Sevilla, D. Robinson, G. Wormser
[Rev. Mod. Phys. **94**, 015003,arXiv:2101.08326]

$$\frac{\mathscr{R}(D^{(*)})}{\mathscr{R}(D^{(*)})_{\rm SM}}$$

$\mathscr{R}(D)_{\rm SM} = 0.299 \pm 0.003$

$\mathscr{R}(D^*)_{\rm SM} = 0.258 \pm 0.005$

HFLAV arithmetic average of SM Calculations



More Recent SM Calculations:

BaBar B->D*
https://arxiv.org/abs/1903.10002
- R(D*)=0.253+-0.005

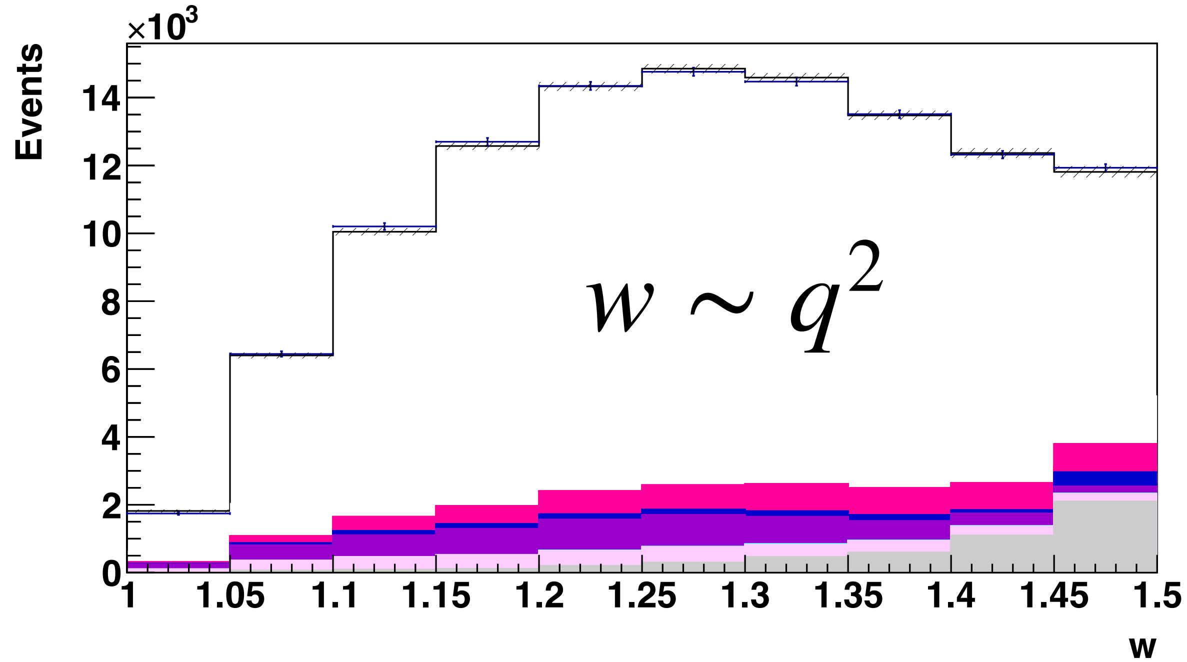
Gambino, Jung, Schacht using Belle 2019 data
https://arxiv.org/abs/1905.08209
- R(D*)=0.254 +0.007 -0.006

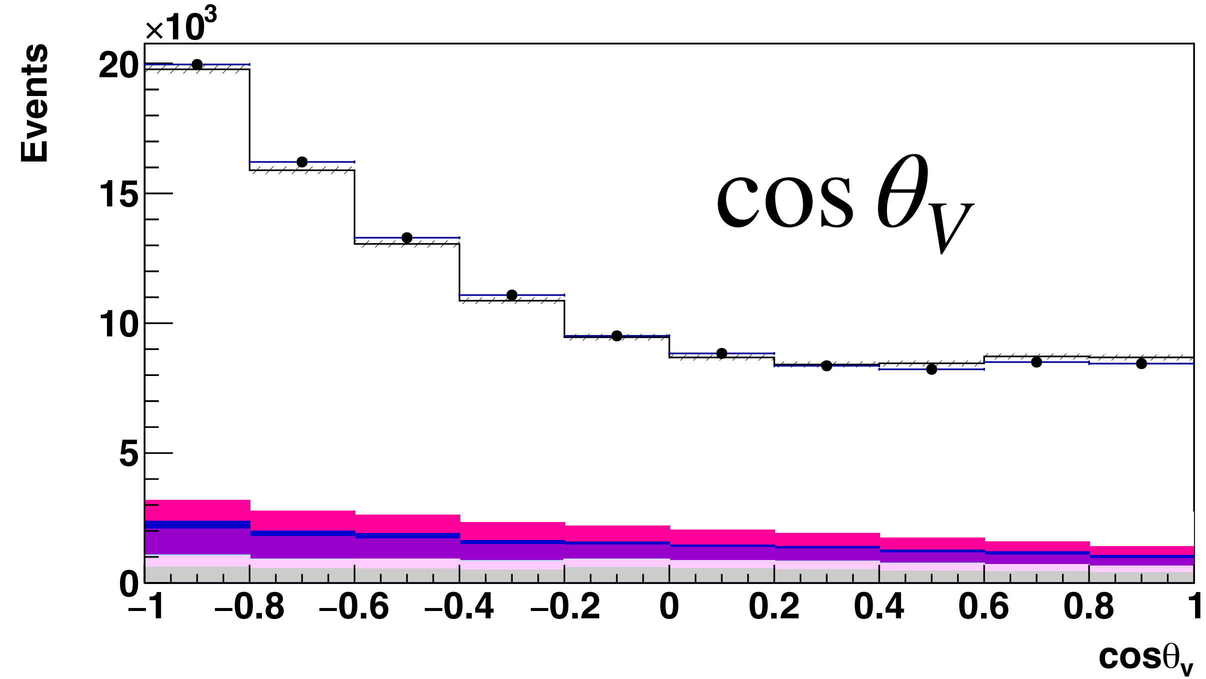
Bordone, Jung, van Dyk using Belle 2019 data
https://arxiv.org/abs/1908.09398
- RD=297+-0.003, RD*=0.250+-0.003

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

More Discussion Material

Florian Bernlochner (florian.bernlochner@uni-bonn.de)





Fit of 1D projections with correlations results in two very compatible values of $|V_{cb}|$ for CLN & BGL:

Caprini-Lellouch-Neubert Form Factors

$$|V_{cb}| = \left(38.4 \pm 0.2 \pm 0.6 \pm 0.6\right) \times 10^{-3}$$

Boyd-Grinstein-Lebed Form Factors

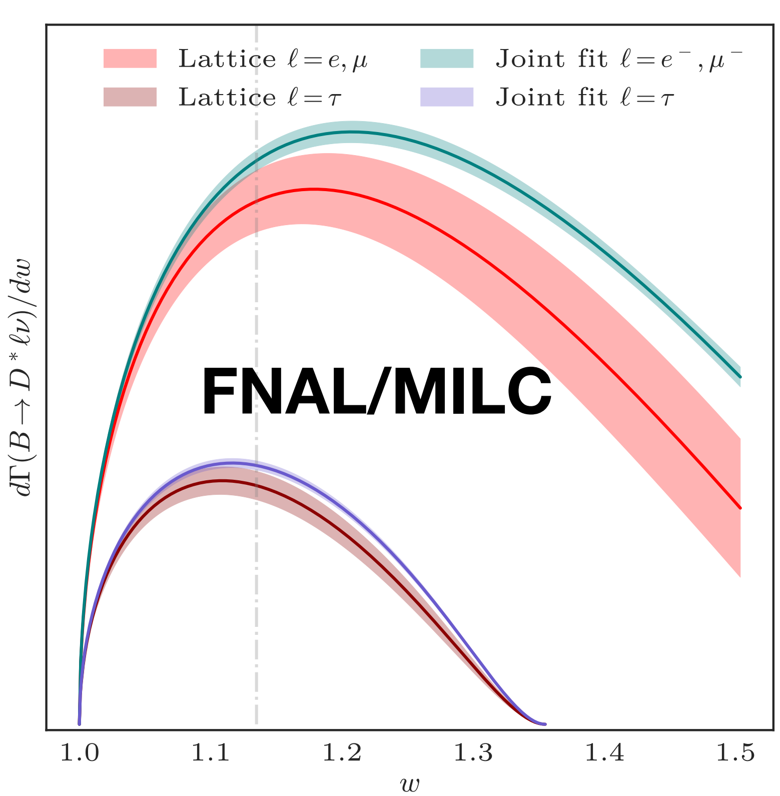
$$|V_{cb}| = \left(38.3 \pm 0.3 \pm 0.7 \pm 0.6\right) \times 10^{-3}$$

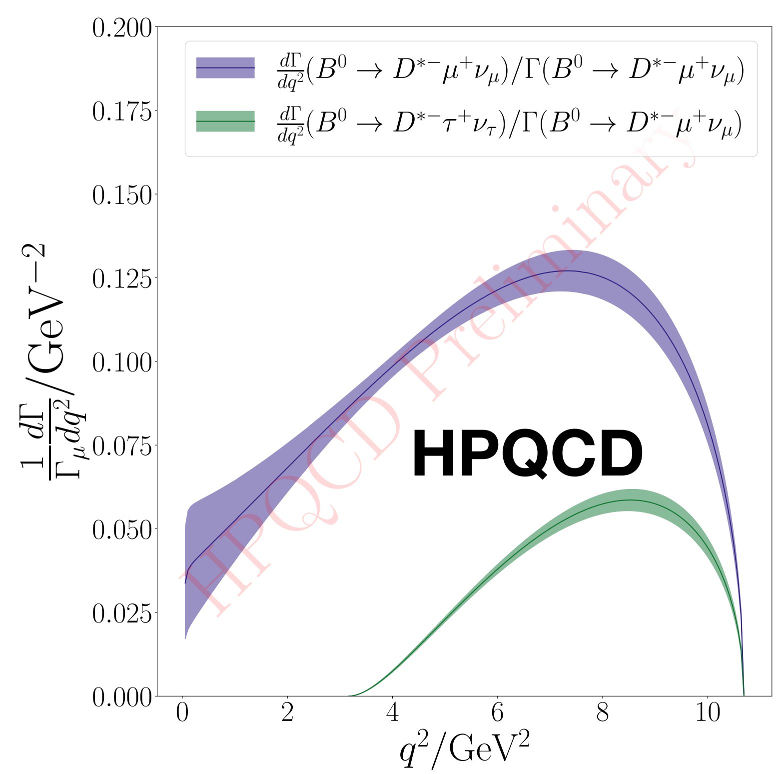
New Developments in exclusive $|V_{cb}|$

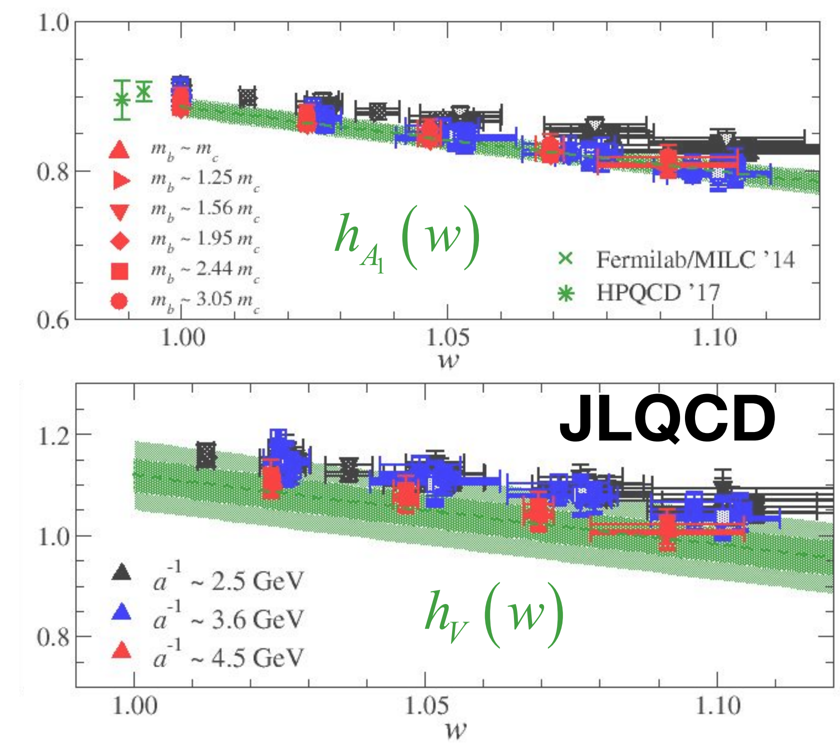
Very exciting times:

After more than 10 years in the making, we have first beyond zero recoil LQCD predictions beyond zero recoil for $B \to D^* \ell \bar{\nu}_\ell$:-)

One is finished, two are nearly finished:







A. Bazavov et al. [FNAL/MILC] [Under Review, arXiv:2105.14019]

Truncation Order

Martin will tell us more about form factors (FF) and how to determine from these distributions $|V_{cb}|$

One model independent way to parametrize FFs is the **BGL** parametrization (Boyd-Grinstein-Lebed, [arXiv:hep-ph/9705252])

$$g(z) = \frac{1}{P_g(z)\phi_g(z)} \sum_{n=0}^{N} a_n z^n, \qquad f(z) = \frac{1}{P_f(z)\phi_f(z)} \sum_{n=0}^{N} b_n z^n, \qquad \mathcal{F}_1(z) = \frac{1}{P_{\mathcal{F}_1}(z)\phi_{\mathcal{F}_1}(z)} \sum_{n=0}^{N} c_n z^n,$$

One Problem you face as an experimentalist: where do you truncate?

Truncate too soon:

- Model dependence in extracted result for $|V_{cb}|$?

Truncate too late:

- Unnecessarily increase variance on $|V_{cb}|$?

Is there an **ideal** truncation order?

Nested Hypothesis Tests or Saturation Constraints

This work
[arXiv:1902.09553, PRD100,013005 (2019)]

Use a **nested hypothesis test** to determine optimal truncation order

Challenge nested fits

$\mathbf{BGL}_{n_a,n_b,n_c}$ ↔ $\mathbf{BGL}_{n_a+1,n_b,n_c}$

$\mathbf{BGL}_{n_a,n_b,n_c}$ ↔ $\mathbf{BGL}_{n_a,n_b+1,n_c}$

$\mathbf{BGL}_{n_a,n_b,n_c}$ ↔ $\mathbf{BGL}_{n_a,n_b,n_c+1}$

Test statistics & Decision boundary

$$\Delta\chi^2 = \chi^2_N - \chi^2_{N+1} \qquad \Delta\chi^2 > 1$$

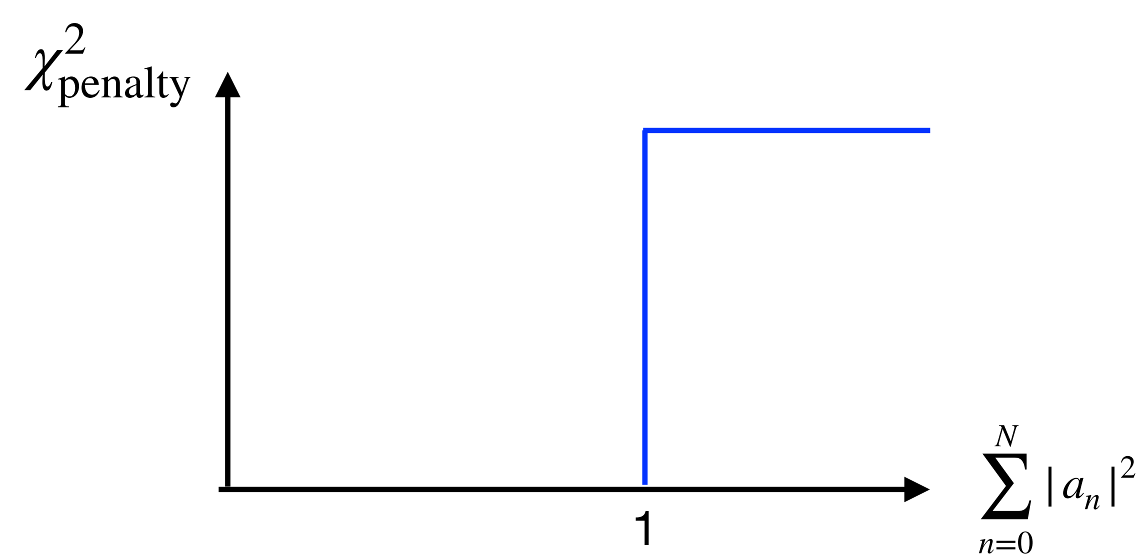
Distributed like a χ^2-distribution with 1 dof (Wilk's theorem)

Gambino, Jung, Schacht
[arXiv:1905.08209, PLB]

Constrain contributions from higher order coefficients using **unitarity bounds**

$$\sum_{n=0}^{N} |a_n|^2 \leq 1 \qquad \sum_{n=0}^{N} \left(|b_n|^2 + |c_n|^2 \right) \leq 1$$

e.g. $\chi^2 \to \chi^2 + \chi^2_{\text{penalty}}$



Nesting Procedure

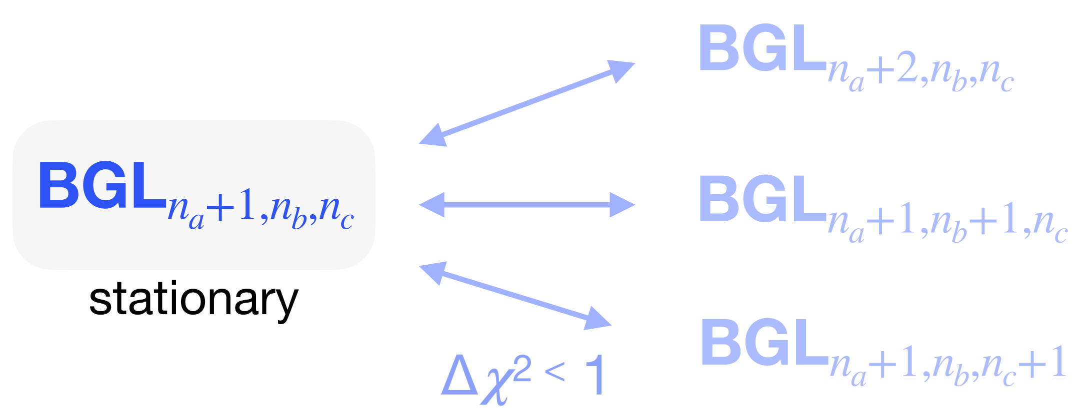
Steps:

1 Carry out nested fits with one parameter added

2 Accept descendant over parent fit, if $\Delta\chi^2 > 1$

3 Repeat 1 and 2 until you find **stationary** points

4 If multiple **stationary** points remain, choose the one with smallest N, then smallest χ^2



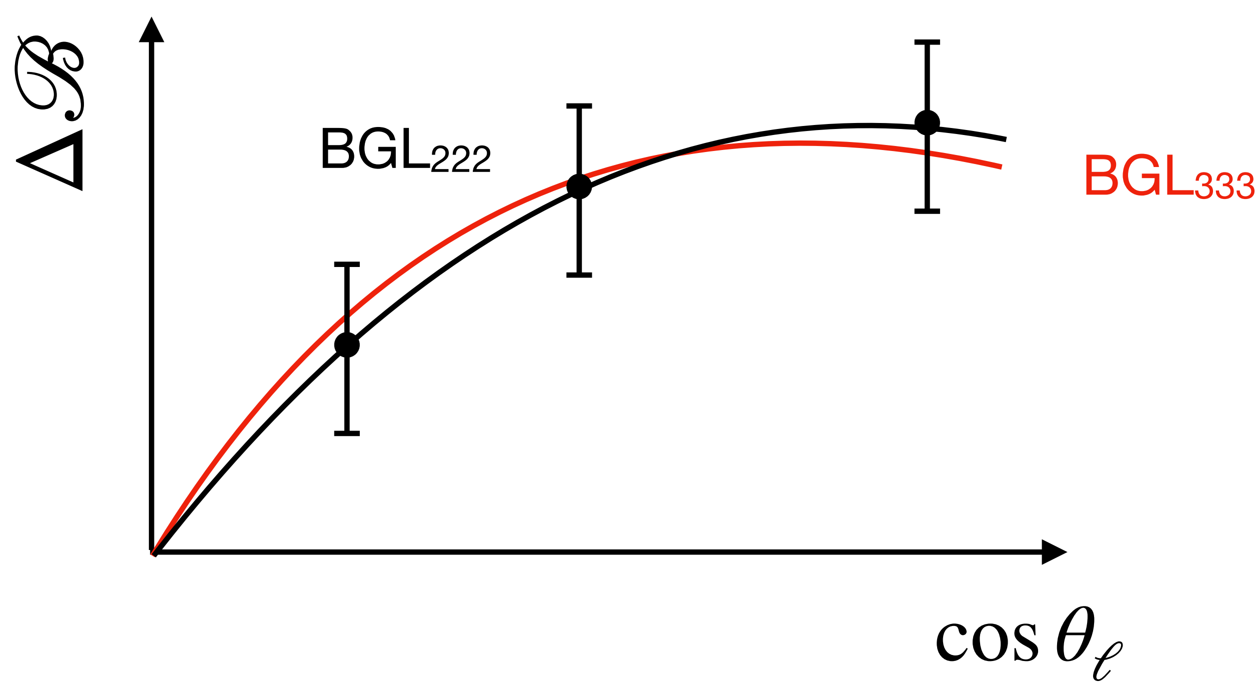
Toy study to illustrate possible bias

Use the central values of the **BGL_{222} fit** as a starting point to add **fine structure**

	'1-times'	'10-times'
Parameter	Value $\times\ 10^2$	Value $\times\ 10^2$
$\tilde{a}_2$	2.6954	26.954
$\tilde{b}_2$	-0.2040	-2.040
$\tilde{c}_3$	0.5350	5.350

Create a "true" higher order Hypothesis of order **BGL_{333}**

Has fine structure element the **current data cannot resolve**



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Toy Test

Produce **ensemble** of toy measurements using **untagged covariance** & **BGL_{333}** central values

↓

Each toy is fitted to build the descendant tree and carry out a **nested hypo. test** to select its preferred **$BGL n_a n_b n_c$**

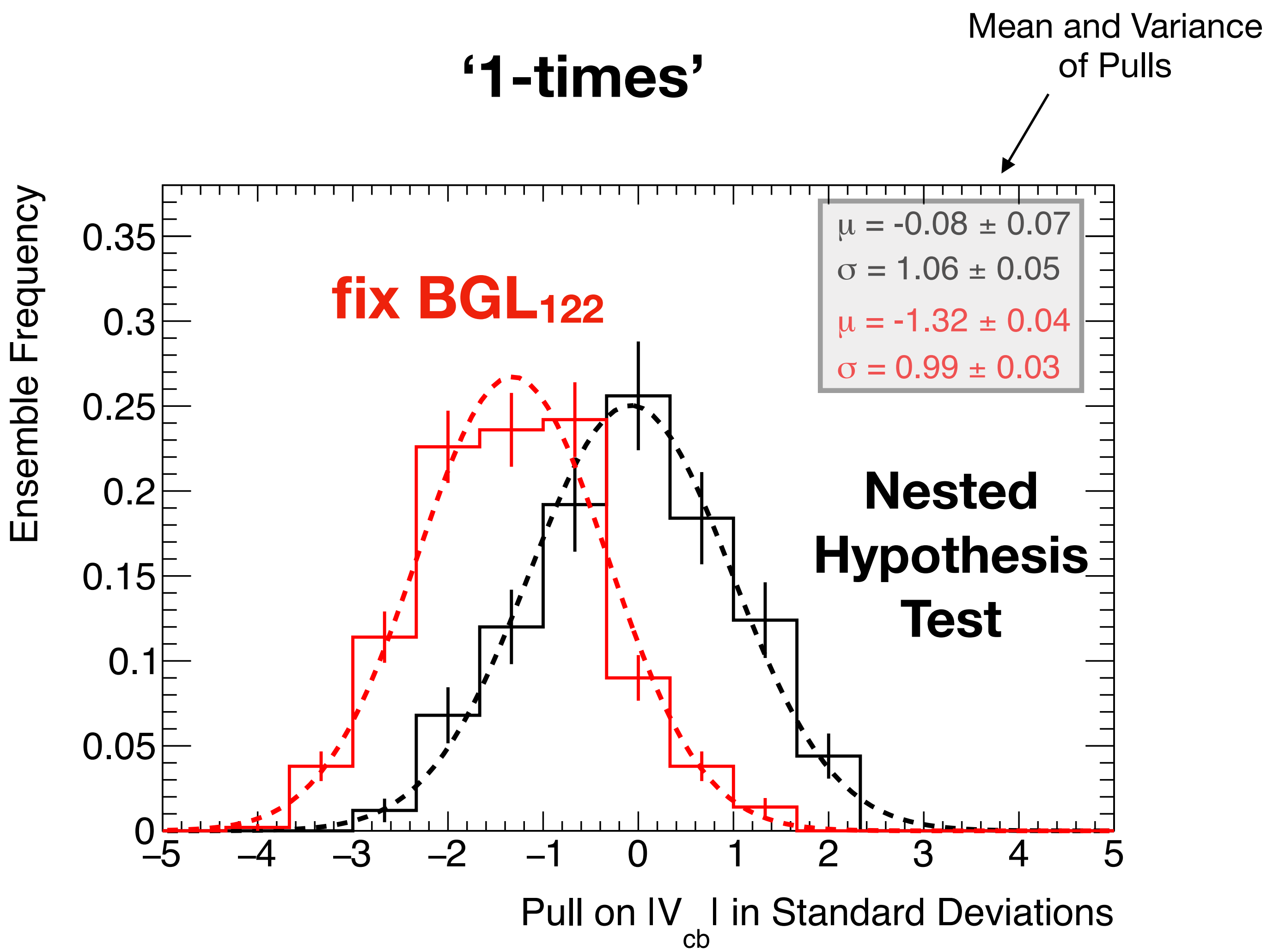
Construct Pulls

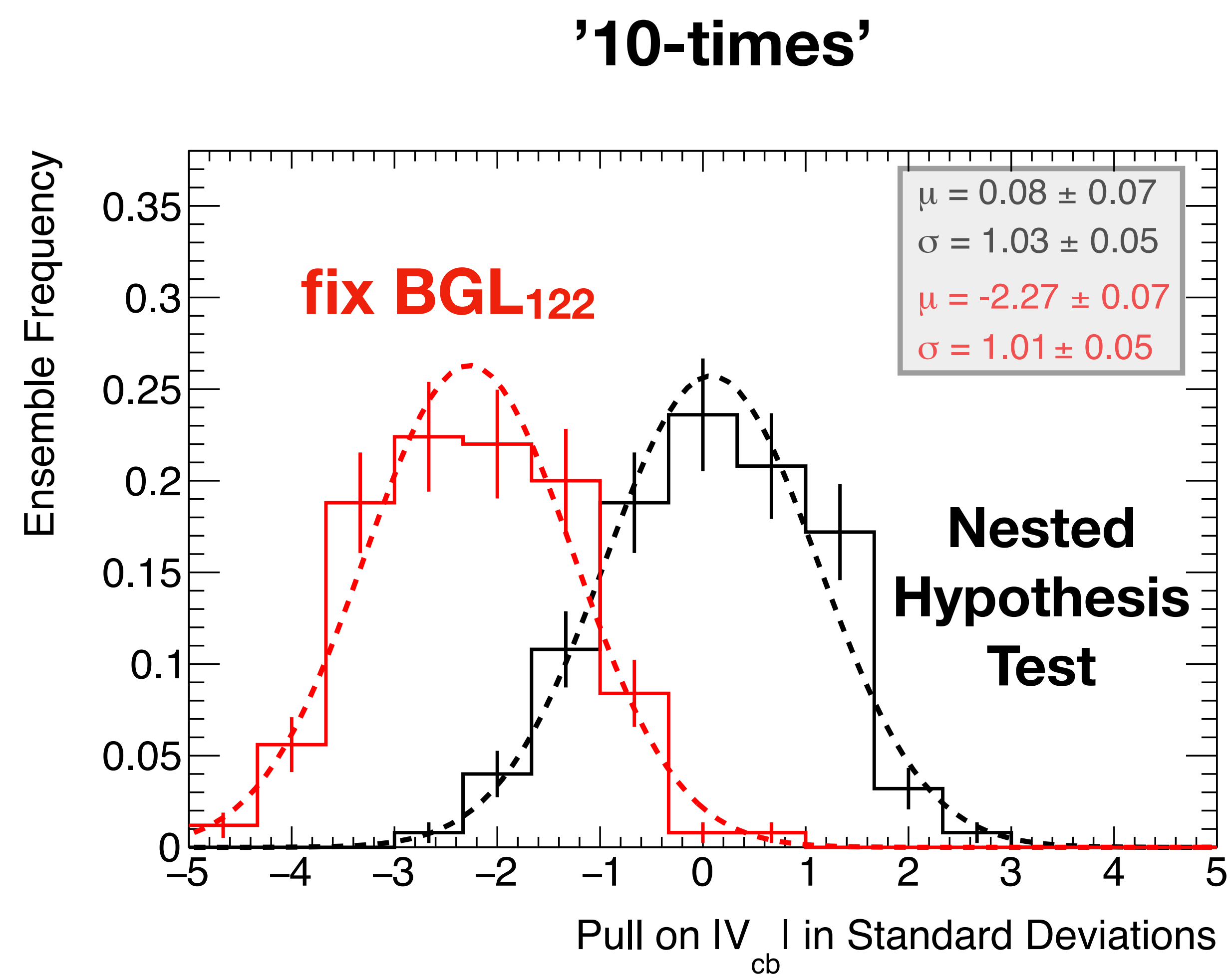
$$\textbf{Pull} = \frac{|V_{cb}|_{\textbf{true}} - |V_{cb}|_{\textbf{toy}}}{\Delta\, |V_{cb}|_{\textbf{toy}}}$$

As calculated from selected $BGL n_a n_b n_c$ fit of each toy

If methodology unbiased, should follow a standard normal distribution (mean 0, width 1)

Bias





→ Procedure produces **unbiased** $|V_{cb}|$ values, just picking a hypothesis (BGL_{122}) does not

Relative Frequency of selected Hypothesis:

	BGL_{122}	BGL_{212}	BGL_{221}	BGL_{222}	BGL_{223}	BGL_{232}	BGL_{322}	BGL_{233}	BGL_{323}	BGL_{332}	BGL_{333}
1-times	6%	0%	37%	27%	6%	6%	11%	0%	2%	4%	0.4%
10-times	0%	0%	8%	38%	14%	8%	16%	3%	4%	8%	1%

More on the Gap

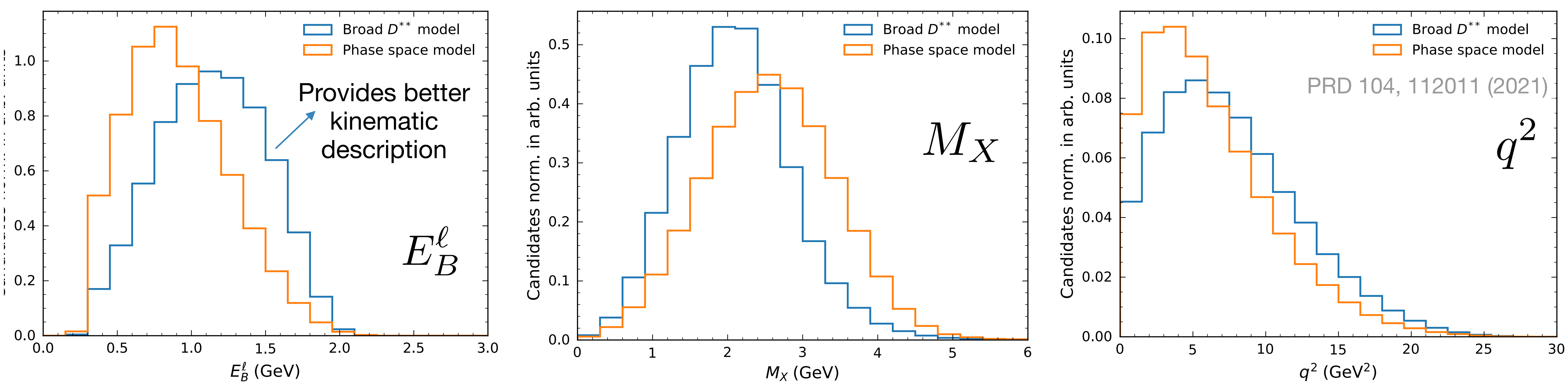
Model 1:
Equidistribution of all final state particles in phase space

Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell^+\,\nu_\ell$	$(6.6 \pm 0.1) \times 10^{-3}$	$(6.2 \pm 0.1) \times 10^{-3}$
$B \to D_2^*\,\ell^+\,\nu_\ell$	$(2.9 \pm 0.3) \times 10^{-3}$	$(2.7 \pm 0.3) \times 10^{-3}$
$B \to D_0^*\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.8) \times 10^{-3}$	$(3.9 \pm 0.7) \times 10^{-3}$
$B \to D_1'\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.9) \times 10^{-3}$	$(3.9 \pm 0.8) \times 10^{-3}$
$B \to D\pi\pi\,\ell^+\,\nu_\ell$	$(0.6 \pm 0.9) \times 10^{-3}$	$(0.6 \pm 0.9) \times 10^{-3}$
$B \to D^*\pi\pi\,\ell^+\,\nu_\ell$	$(2.2 \pm 1.0) \times 10^{-3}$	$(2.0 \pm 1.0) \times 10^{-3}$
$B \to D\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to D^*\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to X_c\ell\nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$

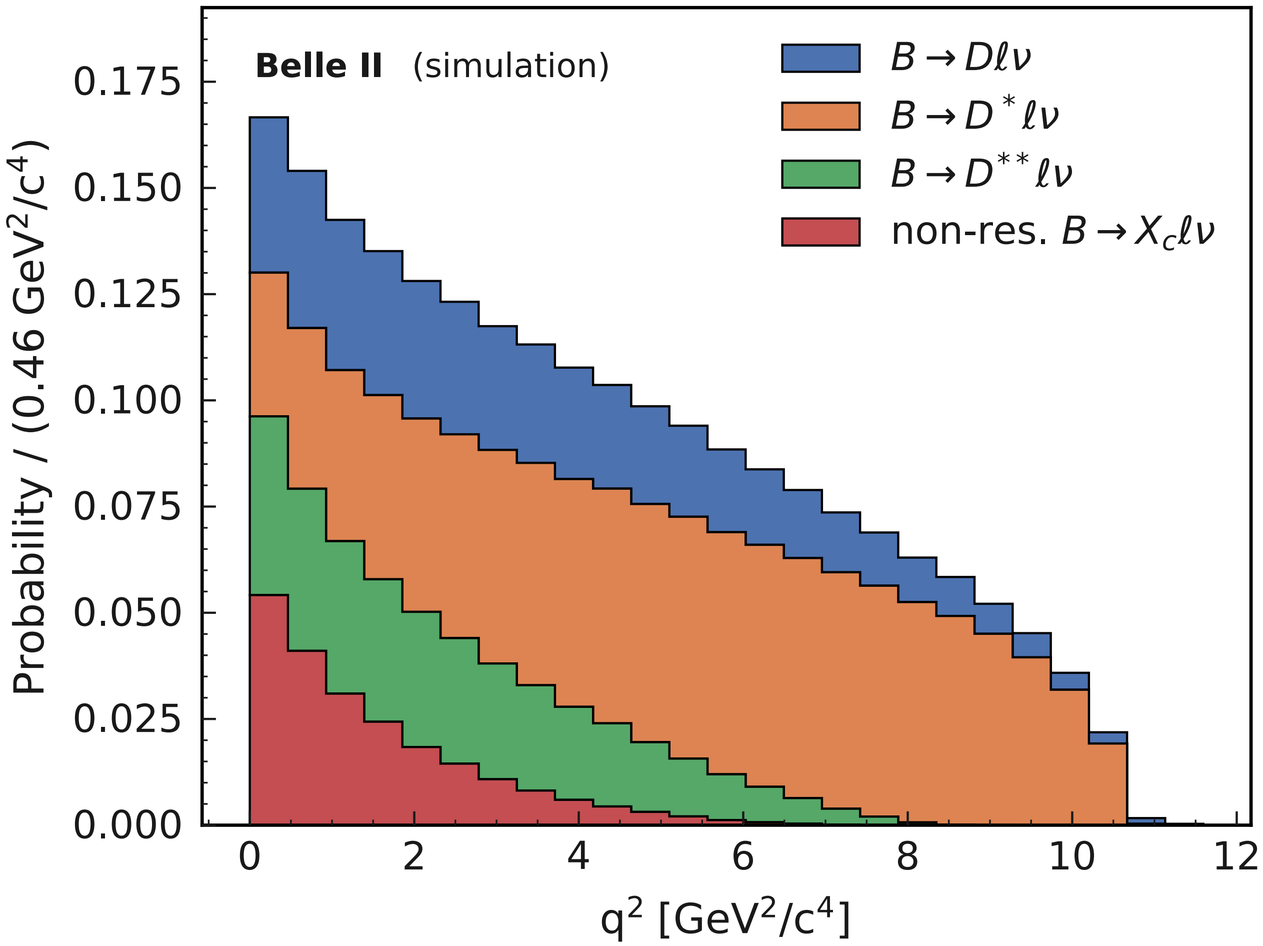
Model 2:
Decay via intermediate broad D^{**} state

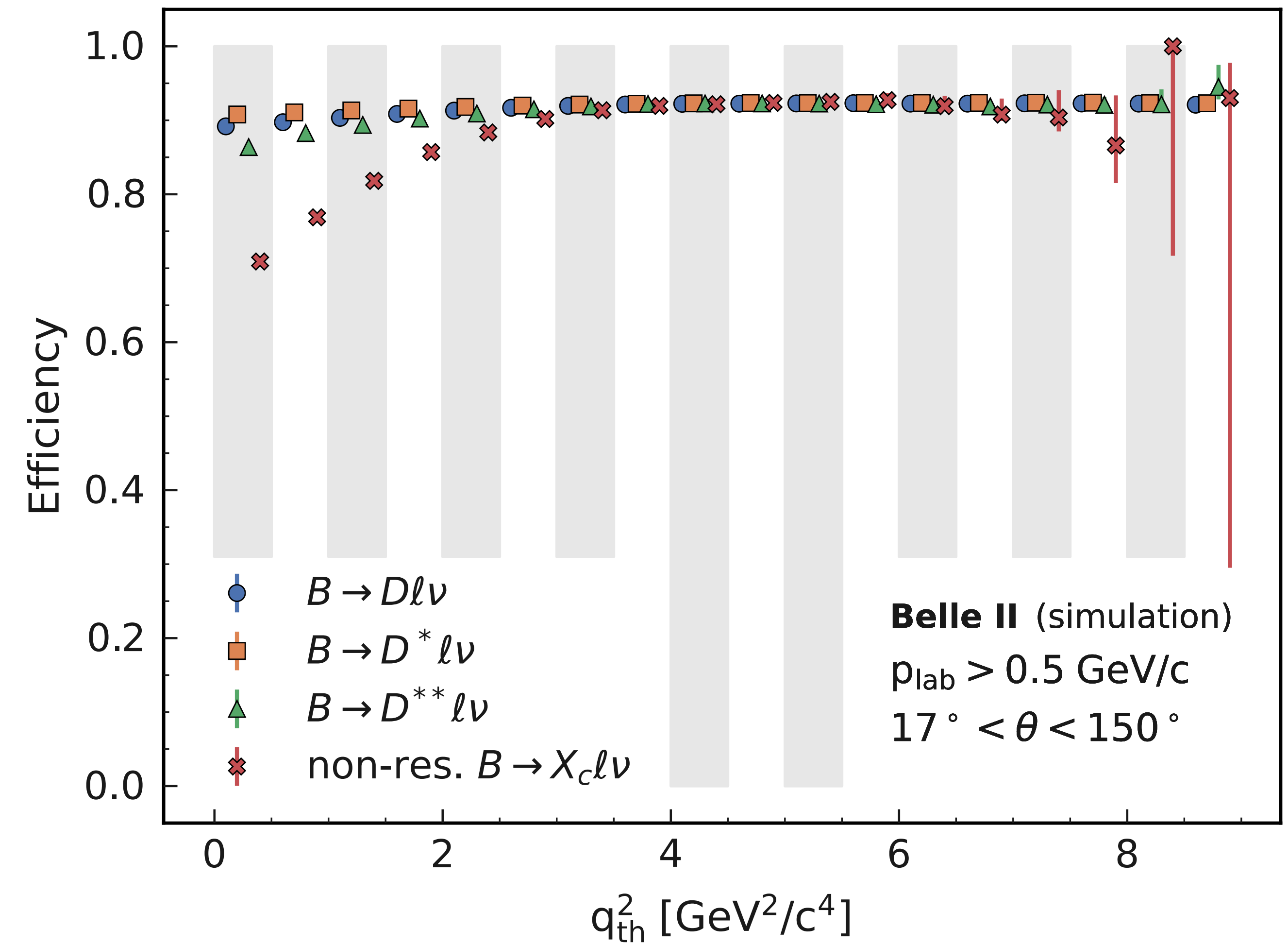
Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D_0^*\,\ell^+\,\nu_\ell$ $(\hookrightarrow D\pi\pi)$	$(0.03 \pm 0.03) \times 10^{-2}$	$(0.03 \pm 0.03) \times 10^{-2}$
$B \to D_1^*\,\ell^+\,\nu_\ell$ $(\hookrightarrow D\pi\pi)$	$(0.03 \pm 0.03) \times 10^{-2}$	$(0.03 \pm 0.03) \times 10^{-2}$
$B \to D_0^*\pi\pi\,\ell^+\,\nu_\ell$ $(\hookrightarrow D^*\pi\pi)$	$(0.108 \pm 0.051) \times 10^{-2}$	$(0.101 \pm 0.048) \times 10^{-2}$
$B \to D_1^*\pi\pi\,\ell^+\,\nu_\ell$ $(\hookrightarrow D^*\pi\pi)$	$(0.108 \pm 0.051) \times 10^{-2}$	$(0.101 \pm 0.048) \times 10^{-2}$
$B \to D_0^*\,\ell^+\,\nu_\ell$ $(\hookrightarrow D\eta)$	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$
$B \to D_1^*\,\ell^+\,\nu_\ell$ $(\hookrightarrow D^*\eta)$	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$

(Assign 100% BR uncertainty in systematics covariance matrix)



X_c Simulation

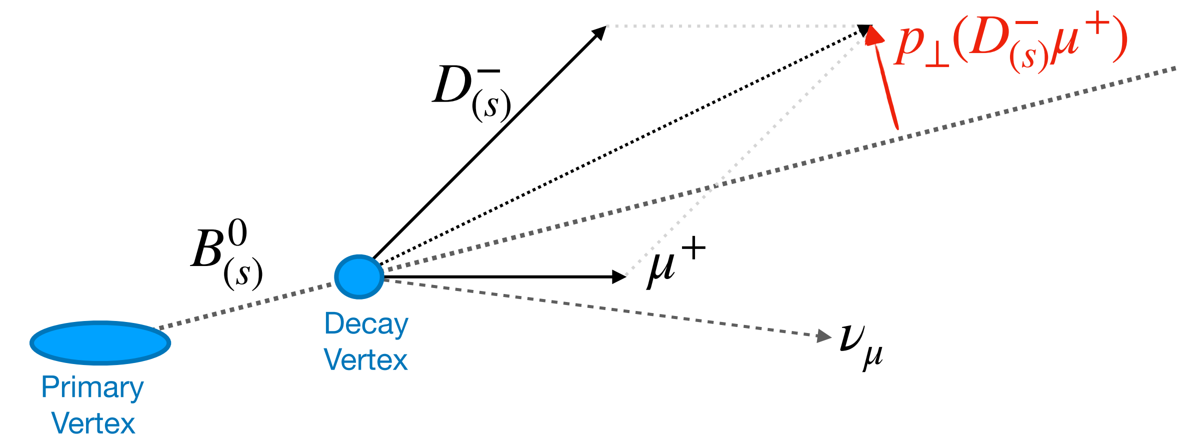




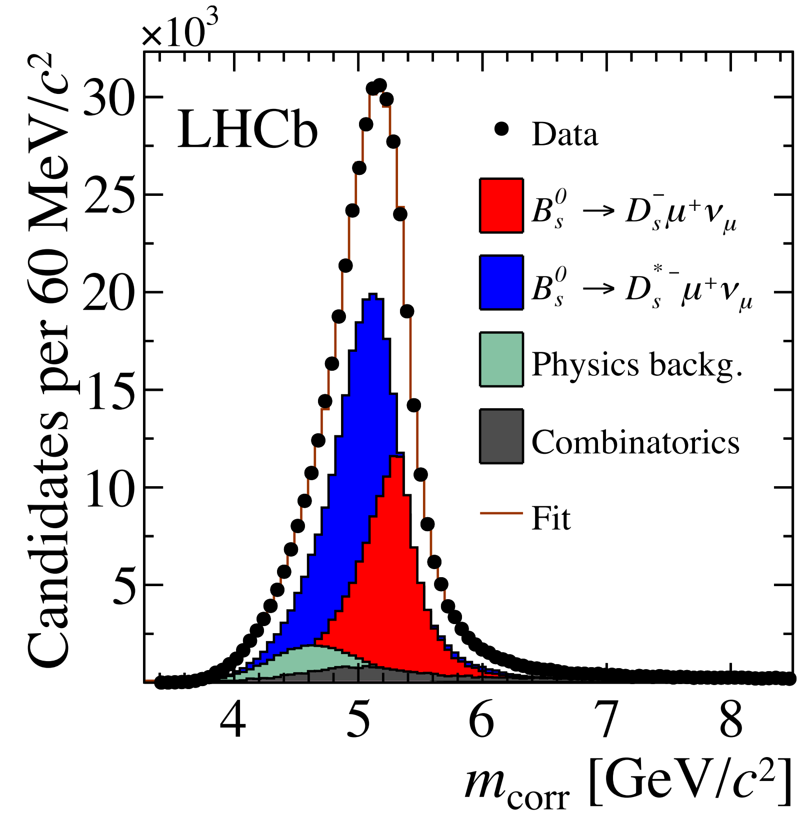
Measurement of $|V_{cb}|$ with $B_s \to D_s^{(*)}\mu\bar{\nu}_\mu$ decays

[Phys. Rev. D **101**, 072004, arXiv:2001.03225]

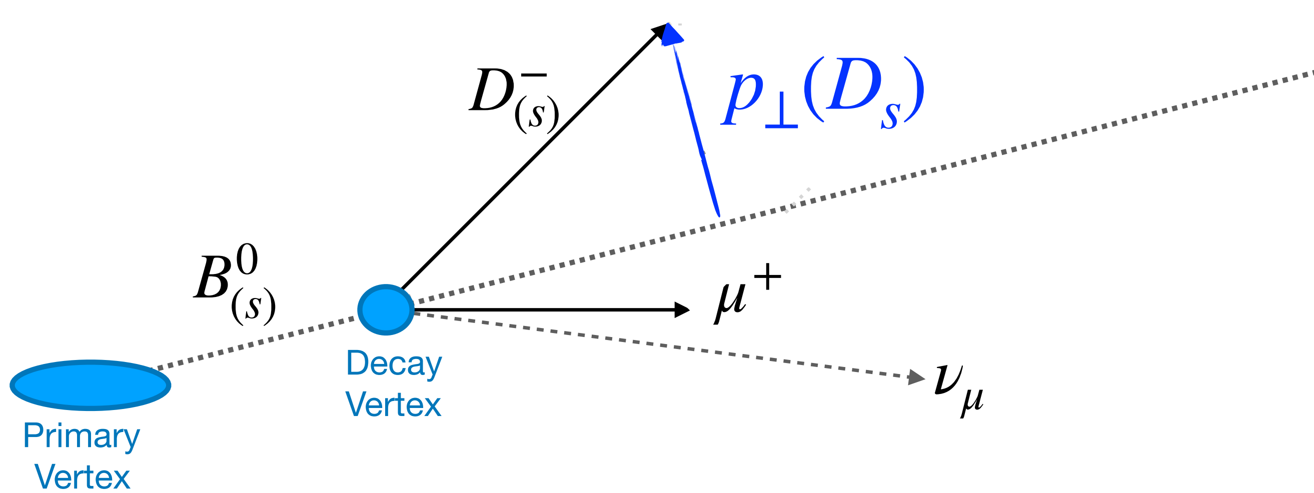
Leverage large **separation** of **decay vertex** from **primary vertex** to reconstruct B_s **flight direction**; reconstruct *corrected* mass m_{corr}:

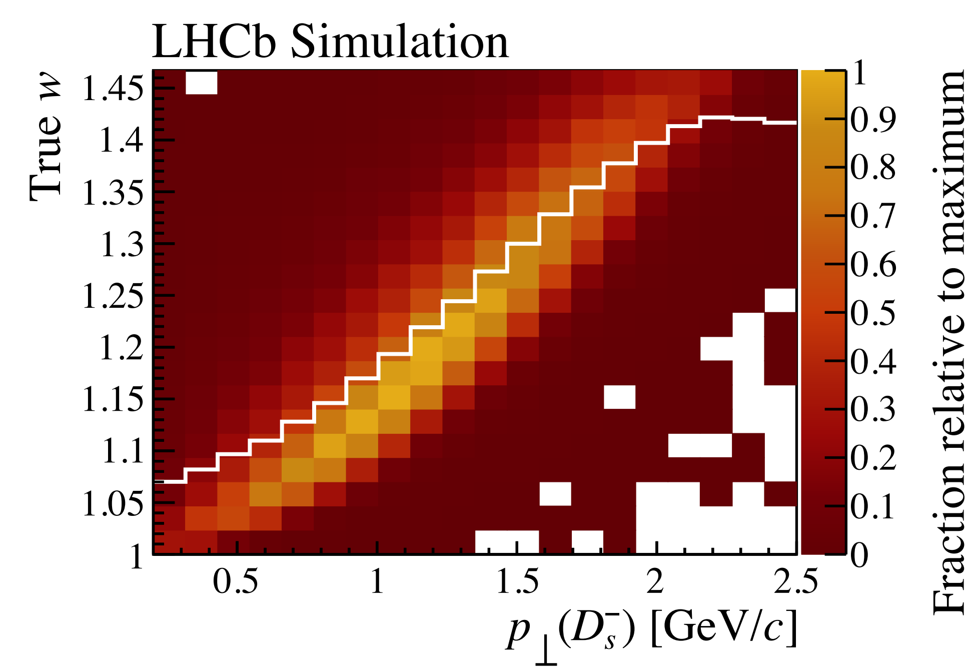


$$m_{corr} \equiv \sqrt{m^2(D_s^-\mu^+) + p_\perp^2(D_s^-\mu^+)} + p_\perp(D_s^-\mu^+)$$



Exploit $p_\perp(D_s)$ correlation with *w* to fit form factors

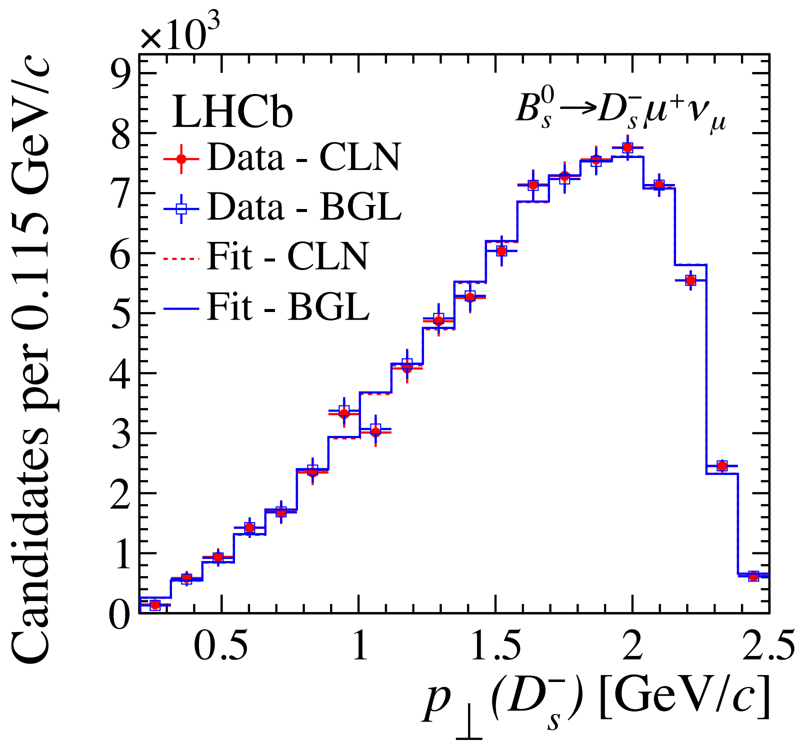


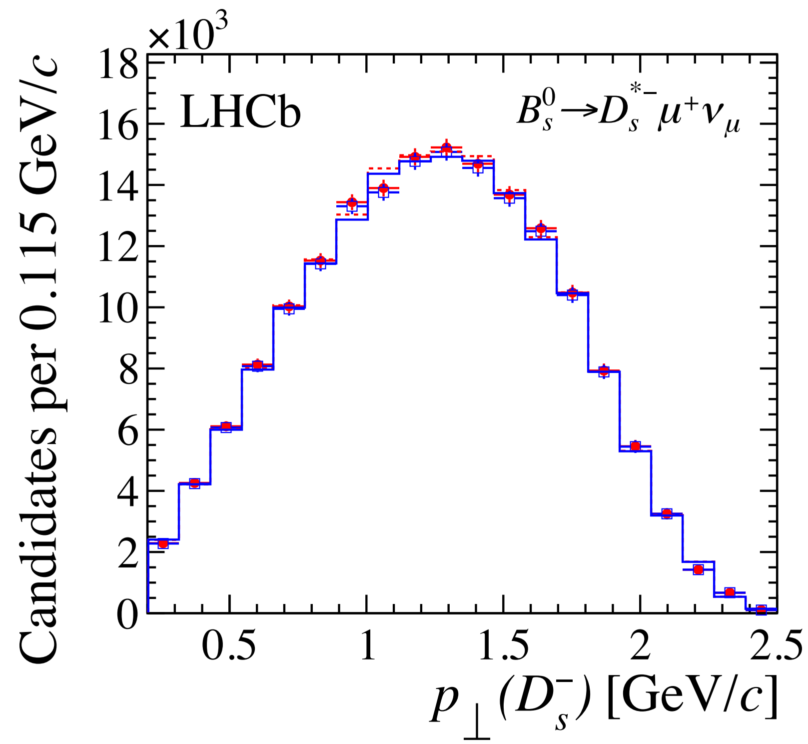


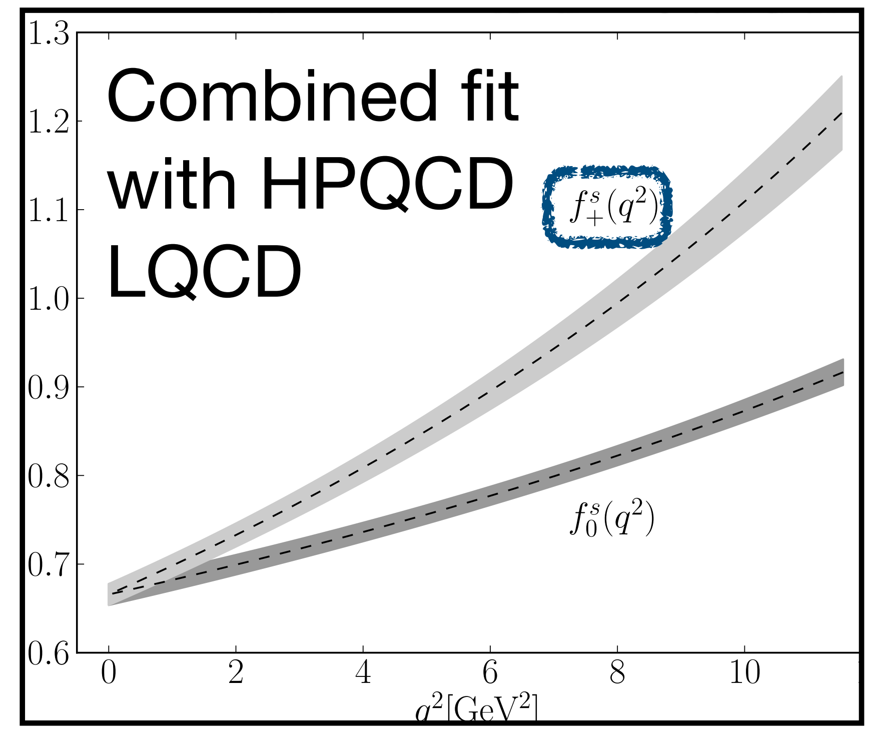
Measurement of $|V_{cb}|$ with $B_s \to D_s^{(*)}\mu\bar{\nu}_\mu$ decays

[Phys. Rev. D **101**, 072004, arXiv:2001.03225]

Background subtracted and **fitted** distributions:

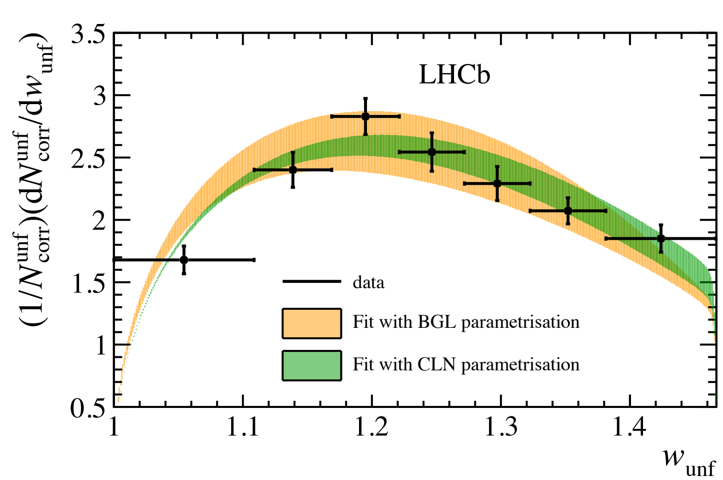






$\longrightarrow$ $|V_{cb}|_{\rm BGL} = (41.7 \pm 0.8({\rm stat}) \pm 0.9({\rm syst}) \pm 1.1({\rm ext})) \times 10^{-3}$

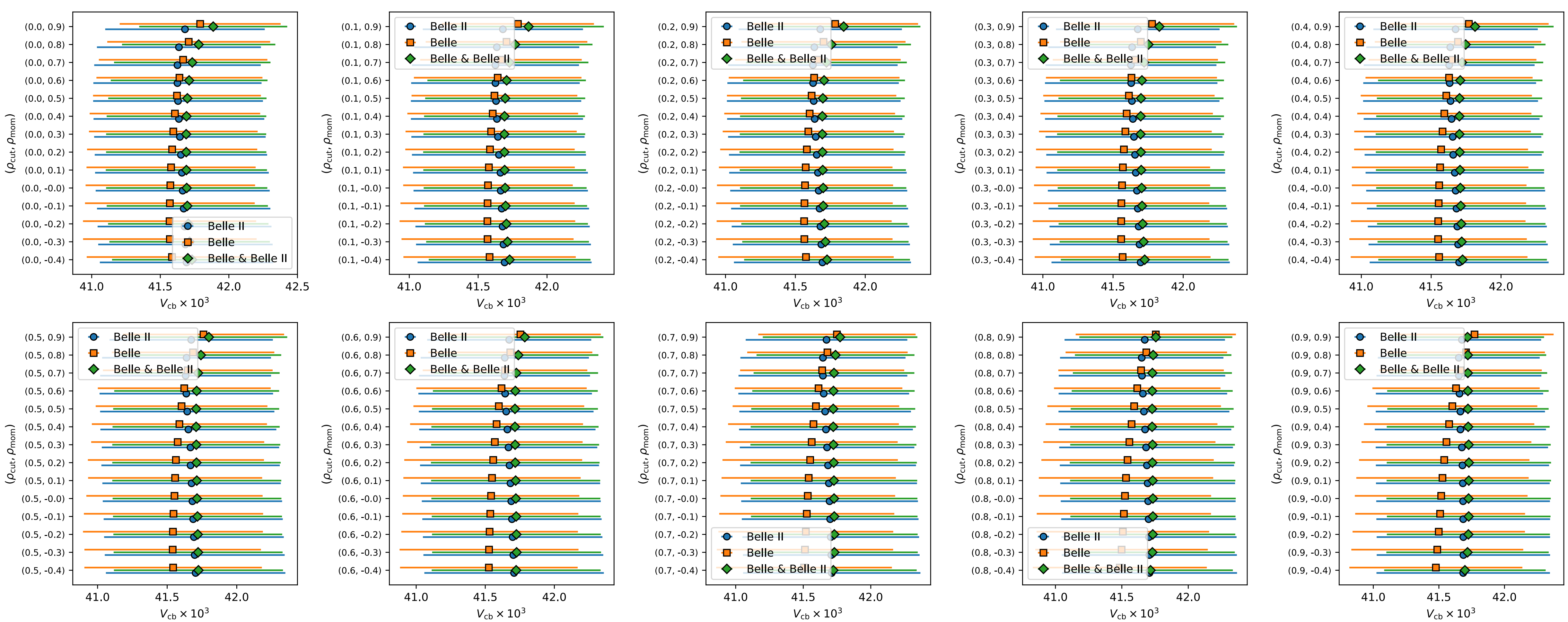
Also provide unfolded w spectrum for $B_s \to D_s^* \mu\bar{\nu}_\mu$



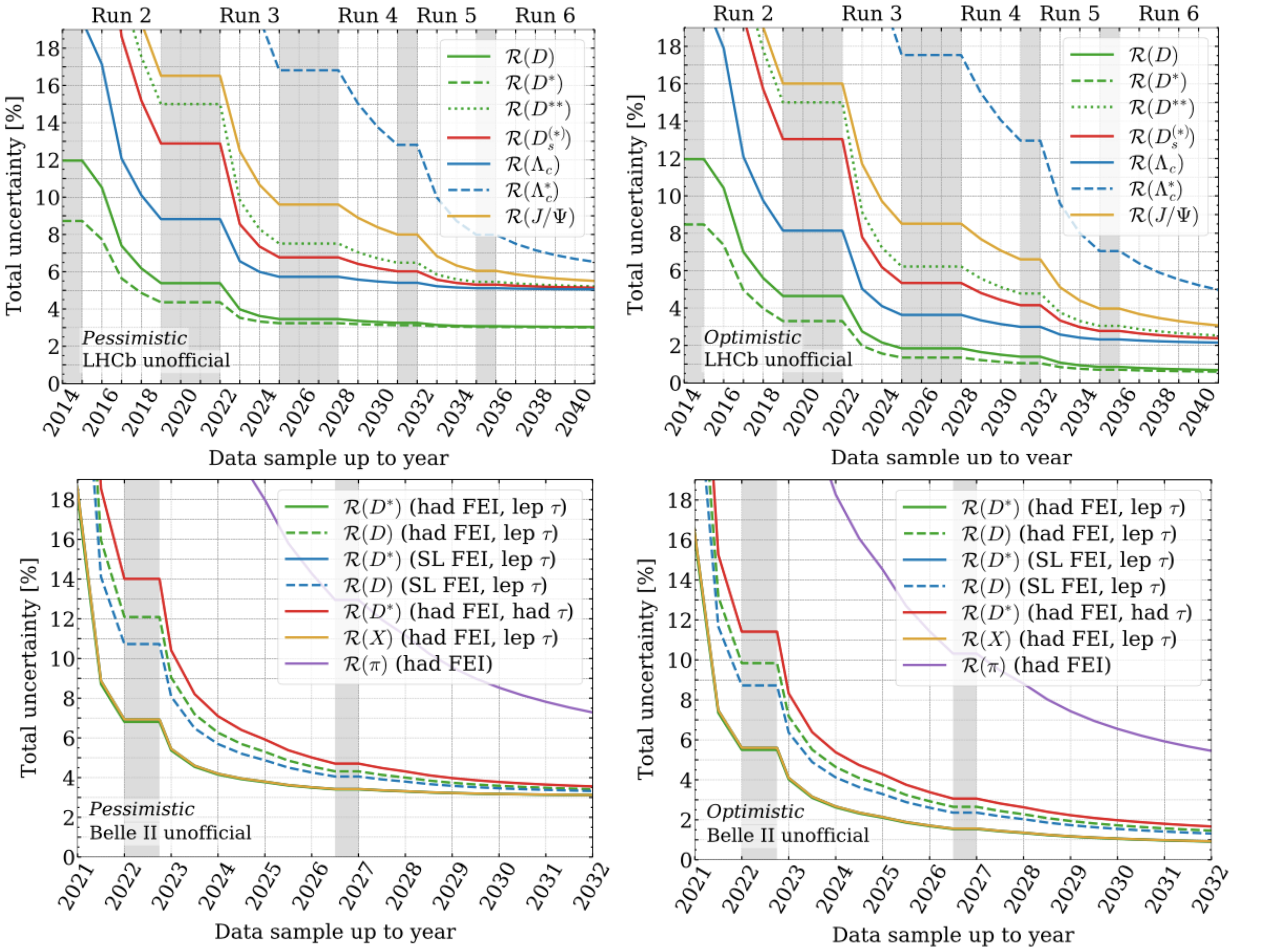
Theory Correlations in inclusive $|V_{cb}|$

$$\rho_n[q_n(q_A^2), q_n(q_B^2)] = \rho_{\mathrm{cut}}^x \quad \text{with} \quad x = \frac{|q_A^2 - q_B^2|}{0.5\,\mathrm{GeV}^2}.$$

$$\rho_{nm}[q_m(q_A^2), q_n(q_B^2)] = \mathrm{sign}(\rho_{\mathrm{mom}}) \cdot |\rho_{\mathrm{mom}}|^{|m-n|} \cdot \rho_n(q_n(q_A^2), q_n(q_B^2)).$$



FB, M. Sevilla, D. Robinson, G. Wormser
[Rev. Mod. Phys. **94**, 015003,arXiv:2101.08326]



Meet the "Measurement Matrix"

	Hadronic or inclusive tagging	SL tagging
Leptonic τ	✓	✓
Hadronic τ	✓	✗

$\otimes$ Polarisation

Belle:
Phys.Rev.Lett.118,211801 (2017)
Phys. Rev. D 97, 012004 (2018)
(D* had tag)

$\otimes$

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

$\otimes$

D	D^*	π

Polarisation

LHCb:
Phys.Rev.Lett.115,111803 (2015)
(D*, Leptonic τ)
Phys.Rev.D 97, 072013 (2018)
Phys.Rev.Lett.120,171802 (2018)
(D*, Hadronic τ)

Belle:
Phys.Rev.D 92, 072014 (2015)
(D/D* had tag, q^2)
Phys.Rev. D94,072007 (2016)
(D*, SL tag, p_{D^*}, p_l)

Belle:
Phys. Rev. D 93, 032007 (2016)
(π had tag)

BaBar:
Phys.Rev.Lett. 109,101802 (2012)
Phys.Rev.D 88, 072012 (2013)
(D/D* had tag, q^2)

Prel. Belle: https://arxiv.org/pdf/1901.06380.pdf (D*, incl. tagging)

& older work, e.g.

Belle:
Phys.Rev. D82 (2010) 072005
(D/D* incl. tag)

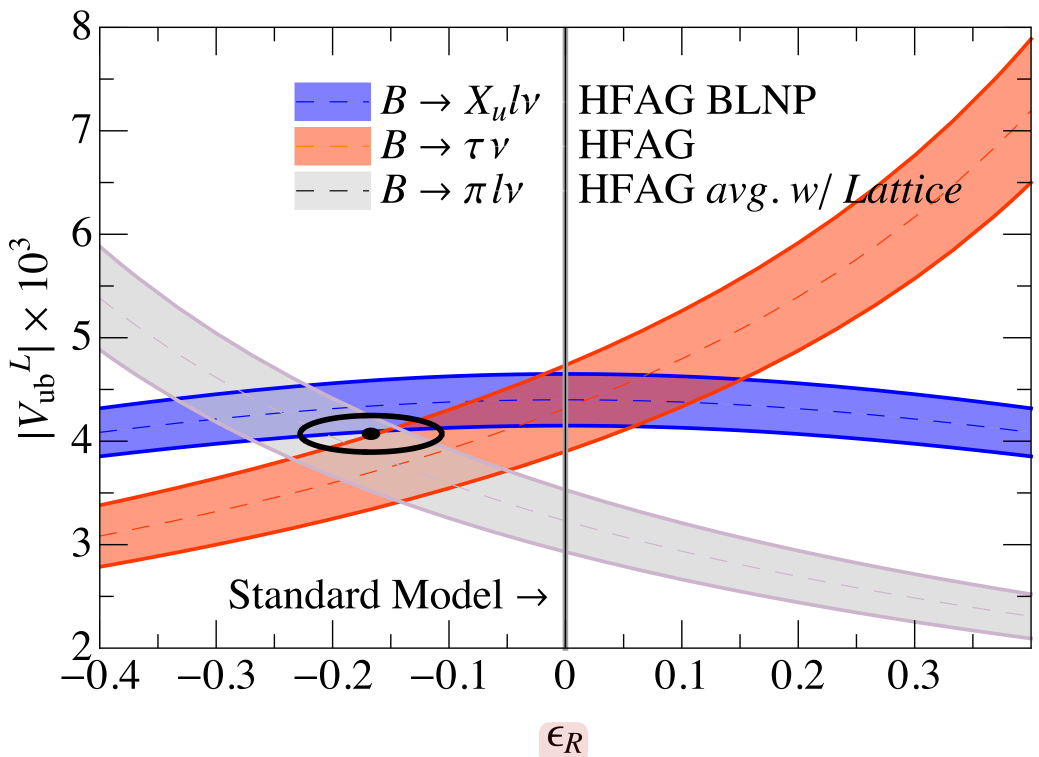
The two categories of measurements

1st Category

Measurements that have **no** or **trivial** or **negligible** dependence on parameter of interest

Example: **Right-handed currents** & $|V_{ub}|$

$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ub}^L \big(\bar{u}\gamma_\mu P_L b + \epsilon_R\, \bar{u}\gamma_\mu P_R b\big)\big(\bar{\nu}\gamma^\mu P_L \ell\big) + \text{h.c.},$$



Decay	$\lvert V_{ub}\rvert \times 10^3$	ϵ_R dependence
$B \to \pi\, \ell \bar{\nu}$	3.23 ± 0.30	$1 + \epsilon_R$
$B \to X_u \ell \bar{\nu}$	4.39 ± 0.21	$\sqrt{1 + \epsilon_R^2}$
$B \to \tau\, \bar{\nu}_\tau$	4.32 ± 0.42	$1 - \epsilon_R$

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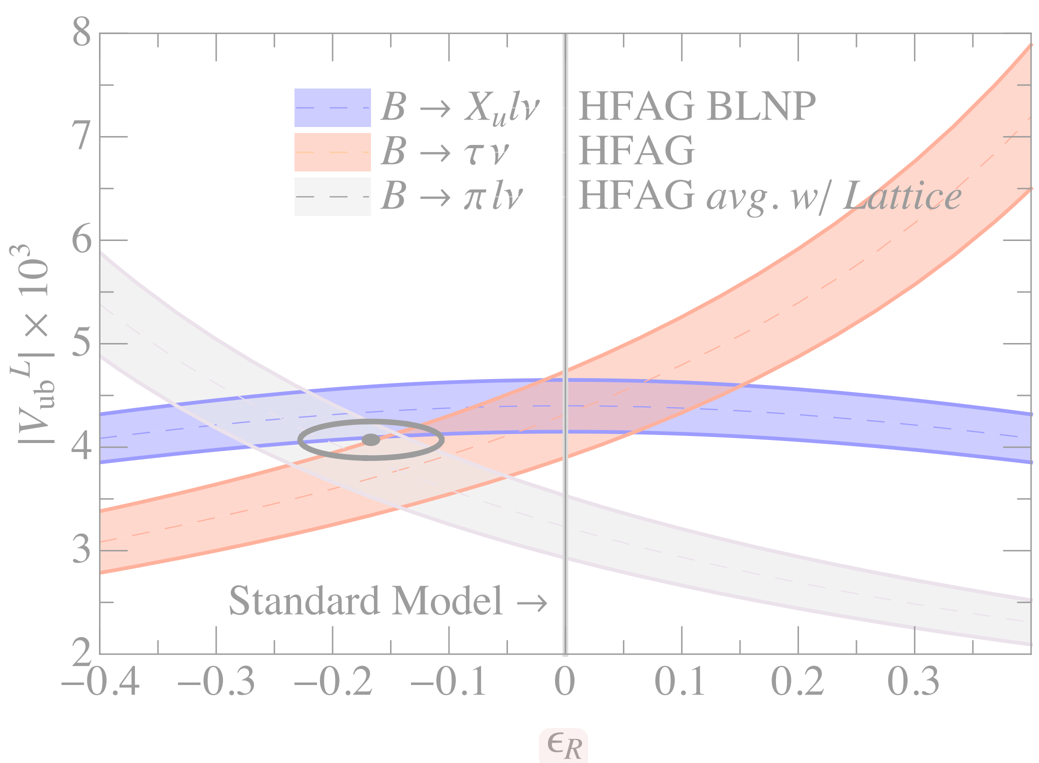

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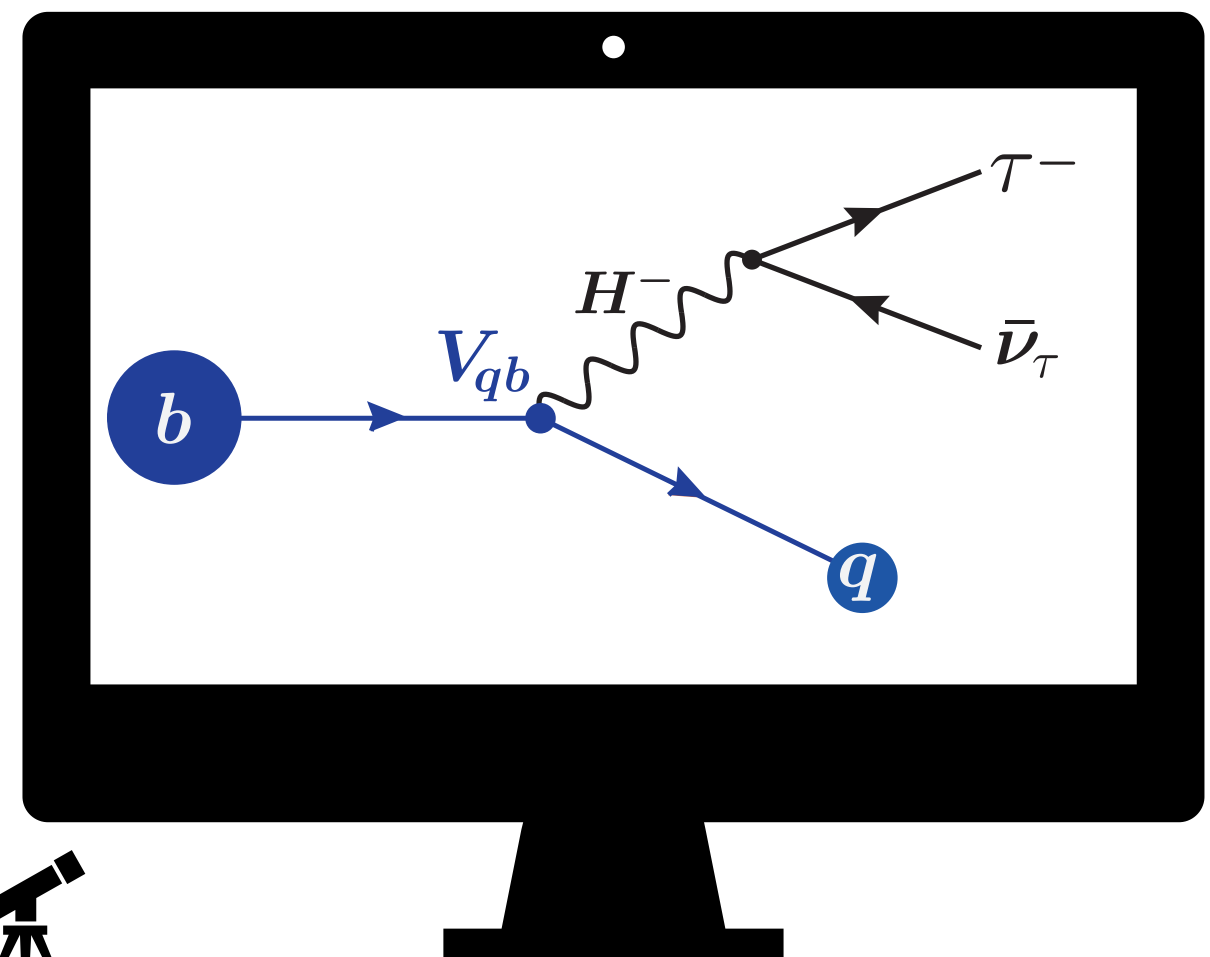
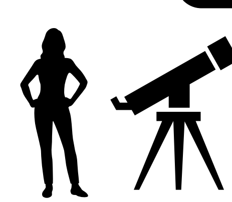
2nd Category

Measurements that have **non-trivial dependence** on parameter of interest / other params.





- Let's say you want to use the **measured** $R(D^{(*)})$ **ratios** to learn something about the anomaly and **your favorite model** that could explain it!

The two categories of measurements

1st Category

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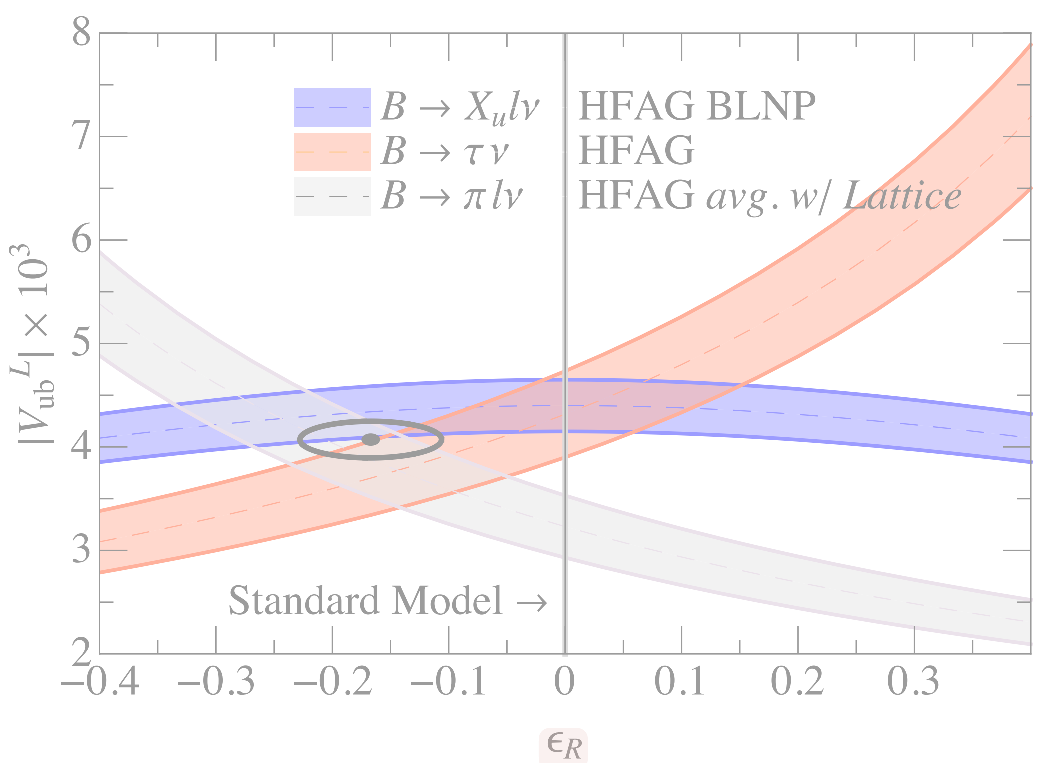

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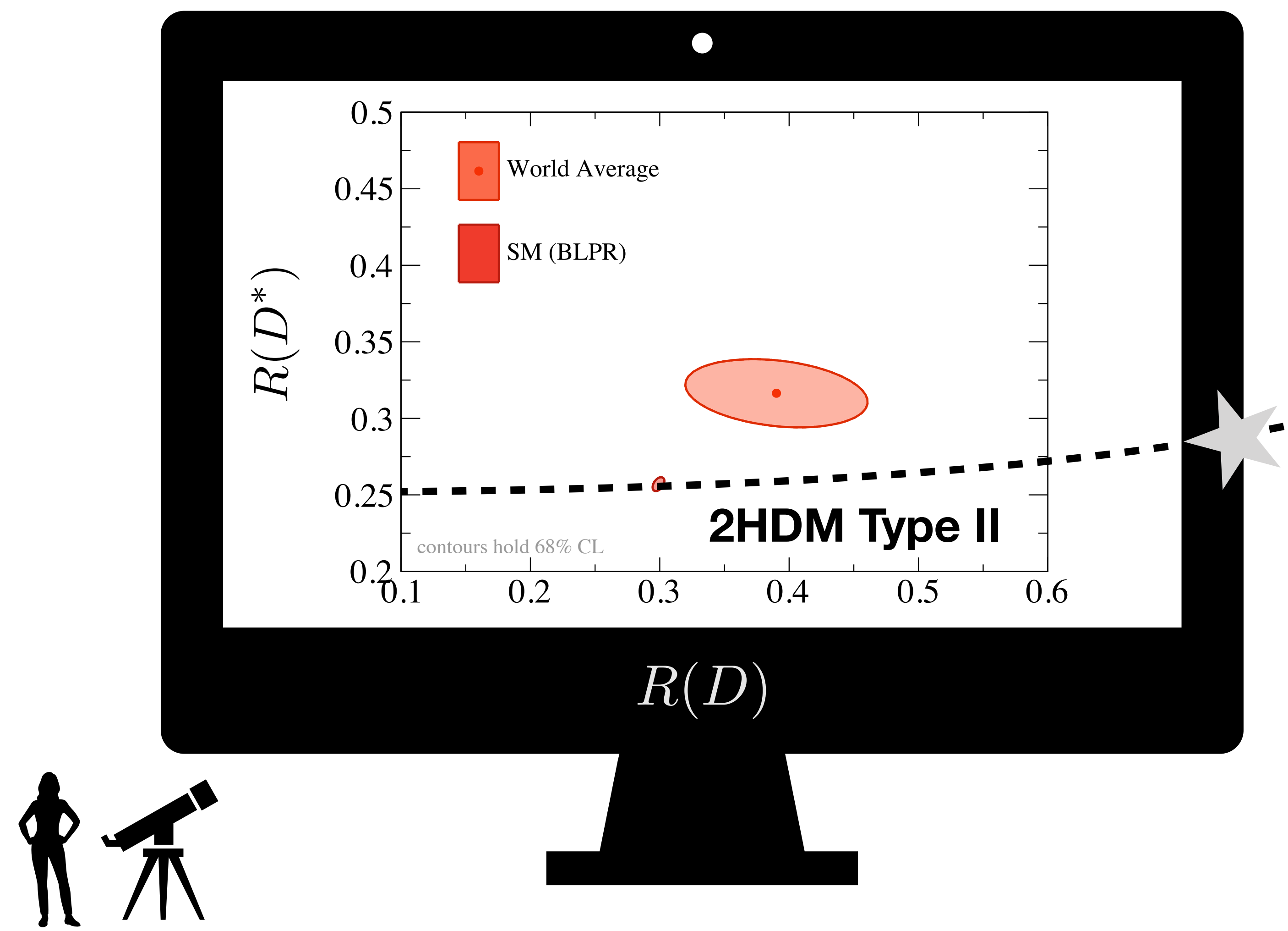
Measurements that have **non-trivial dependence** on parameter of interest / other params.



- Let's say you want to use the **measured** $R(D^{(*)})$ **ratios** to learn something about the anomaly and **your favorite model** that could explain it!

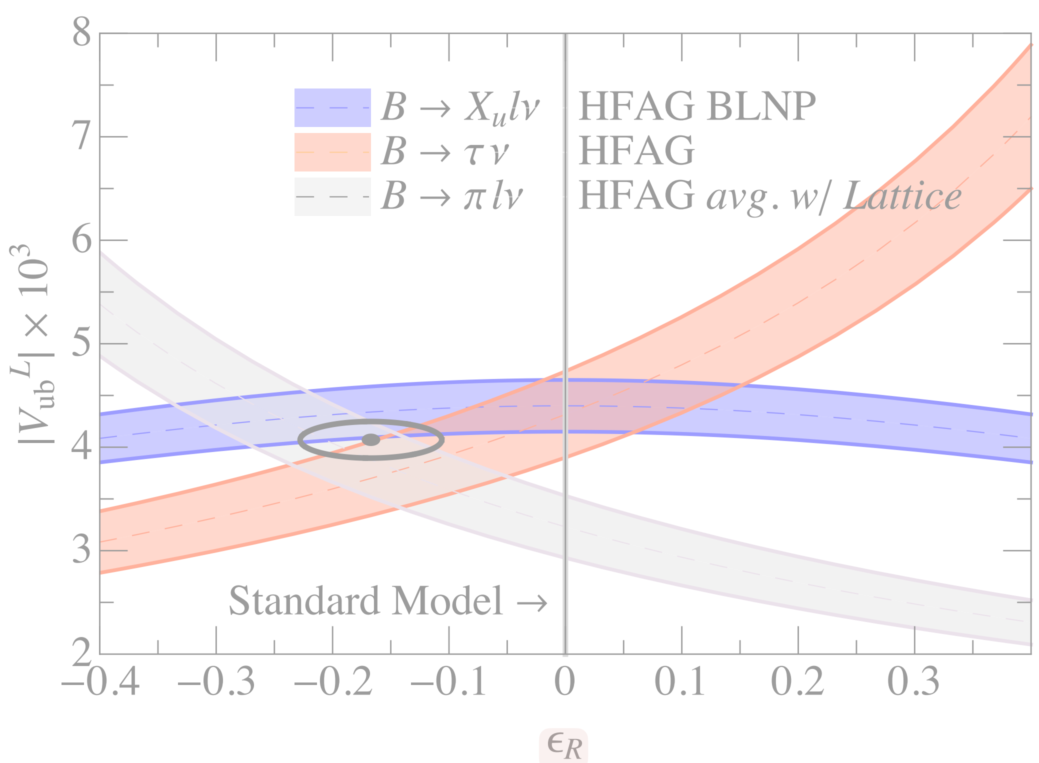
The two categories of measurements

1st Category

Measurements that have **no** or **trivial** or **negligible** dependence on parameter of interest

Example: **Right-handed currents** & | V_{ub} |

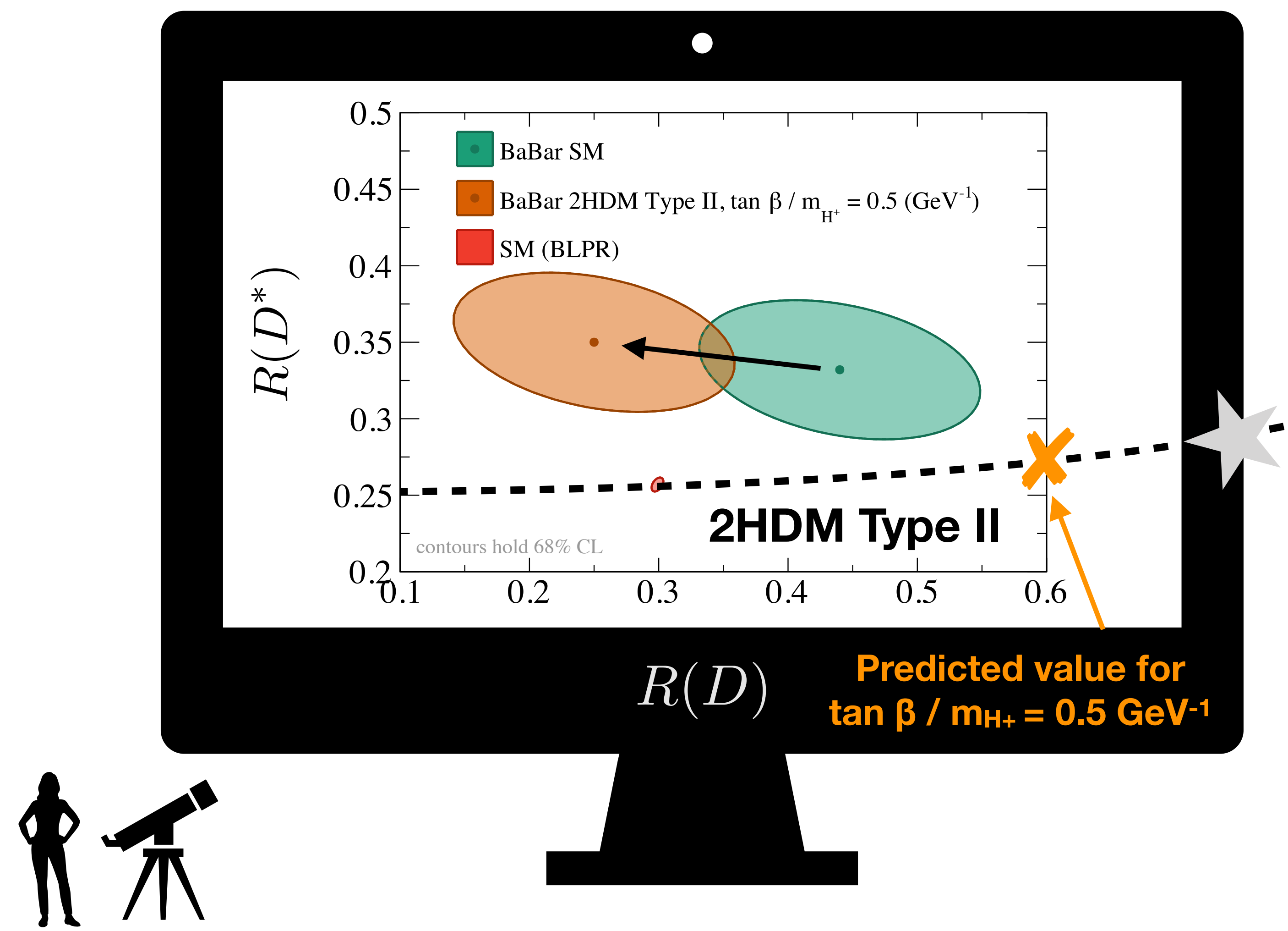
$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ub}^L \left(\bar u \gamma_\mu P_L b + \epsilon_R\, \bar u \gamma_\mu P_R b \right) \left(\bar \nu \gamma^\mu P_L \ell \right) + \text{h.c.},$$



Decay	$\lvert V_{ub}\rvert \times 10^3$	ϵ_R dependence
$B \to \pi \ell \bar\nu$	3.23 ± 0.30	$1 + \epsilon_R$
$B \to X_u \ell \bar\nu$	4.39 ± 0.21	$\sqrt{1+\epsilon_R^2}$
$B \to \tau \bar\nu_\tau$	4.32 ± 0.42	$1 - \epsilon_R$

2nd Category

Measurements that have **non-trivial dependence** on parameter of interest / other params.



- As it turns out, **not that easy** — the **measured points** themselves are **extracted assuming** the **SM** and kinematic distributions sensitive to the PoI are altering the measurement

NP Interpretation Strategies for $H_b \to H_c \tau \bar{\nu}$

What you can do today

#1

Just fit ratios, hope that **bias** is small with respect to the current precision

Frankly a perfectly sane strategy; after all the experiments do not provide any other information one could use and not all measurements might have such a strong dependence as e.g. BaBar

What we should allow you to do

#2

Fold your model into the MC simulation, directly confront the data

#3

Provide theorists with direct measurements of Wilson coefficients; these can be used to confront your favorite model

↓

Benefit: no biases, more sensitivity as shape of **all** kinematic distributions help distinguish between models

a fairly prominent problem

SciPost Physics — Submission

WORKING DRAFT

Publishing statistical models: Getting the most out of particle physics experiments

Kyle Cranmer[1*], Sabine Kraml[2‡], Harrison B. Prosper[3§] (editors), Philip Bechtle[4], Florian U. Bernlochner[4], Itay M. Bloch[5], Enzo Canonero[6], Marcin Chrzaszcz[7], Andrea Coccaro[8], Glen Cowan[9], Matthew Feickert[10], Nahuel Ferreiro Iachellini[11,12] Andrew Fowlie[13], Lukas Heinrich[14], Alexander Held[1], Thomas Kuhr[12,15], Anders Kvellestad[16], Maeve Madigan[17], Farvah Mahmoudi[14,18], Knut Dundas Morå[19], Mark S. Neubauer[10], Maurizio Pierini[14], Juan Rojo[8], Sezen Sekmen[21], Luca Silvestrini[22], Veronica Sanz[23,24], Giordon Stark[25], Riccardo Torre[8], Robert Thorne[26], Wolfgang Waltenberger[27], Nicholas Wardle[28], Jonas Wittbrodt[29]

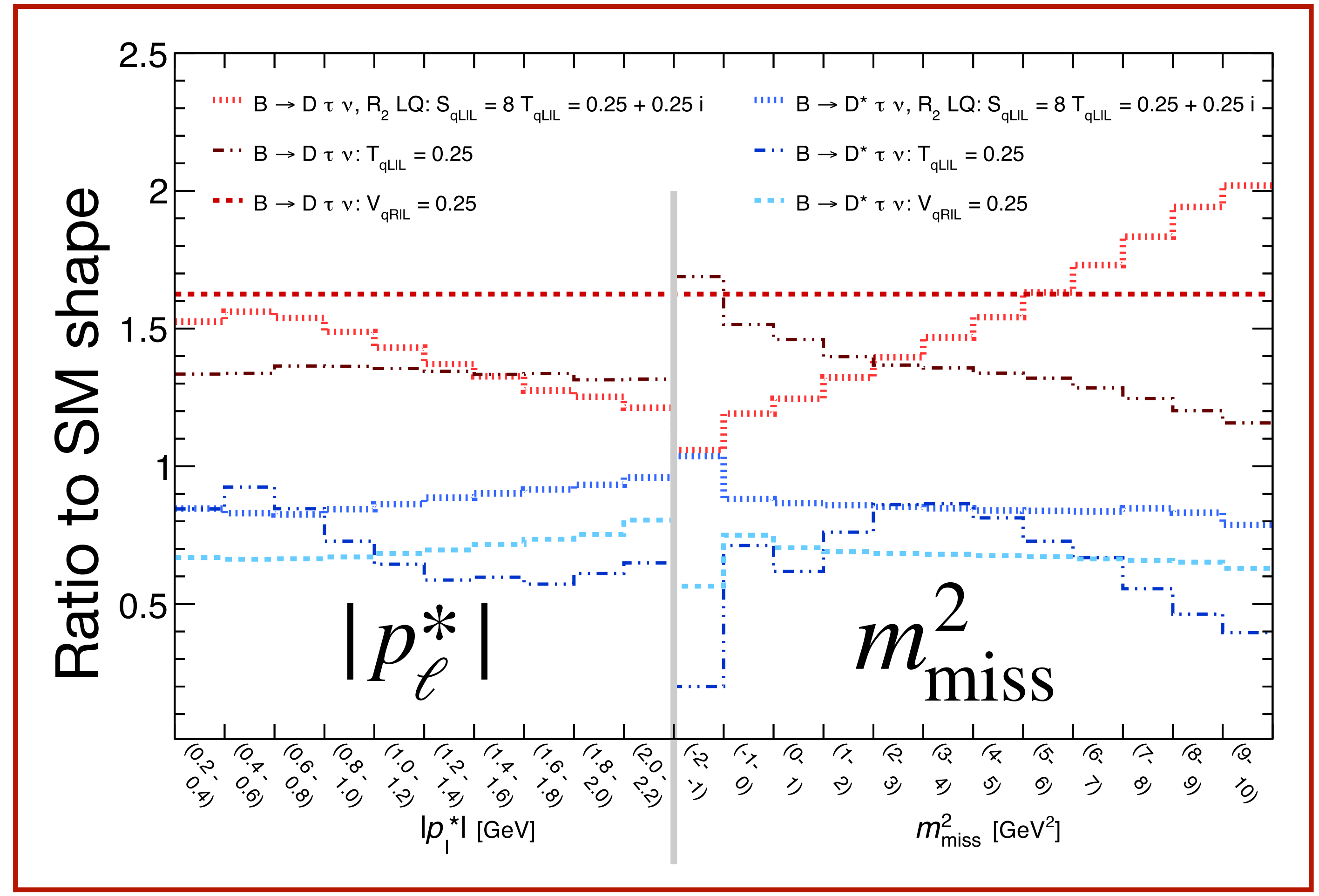
[to appear soon]

$b \to c\tau\bar{\nu}_\tau$

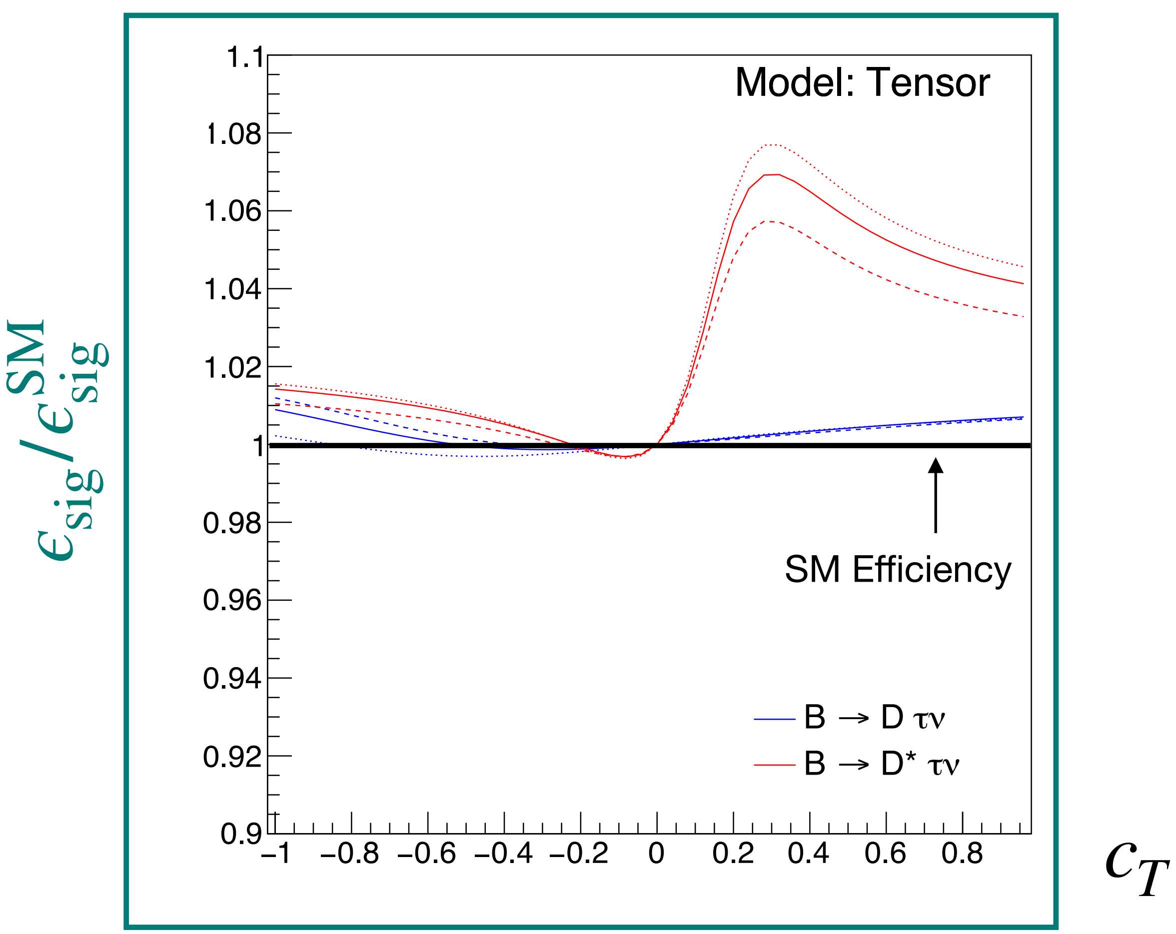
$\tau \to \ell\bar{\nu}_\ell\nu_\tau$

Use **kinematic** quantities (e.g. $|p^*_\ell|$, m^2_{miss}, q^2) to **subtract background**

$$\mathcal{R}(D^{(*)}) = \frac{N_{\text{sig}}}{N_{\text{norm}}} \times \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{sig}}}$$

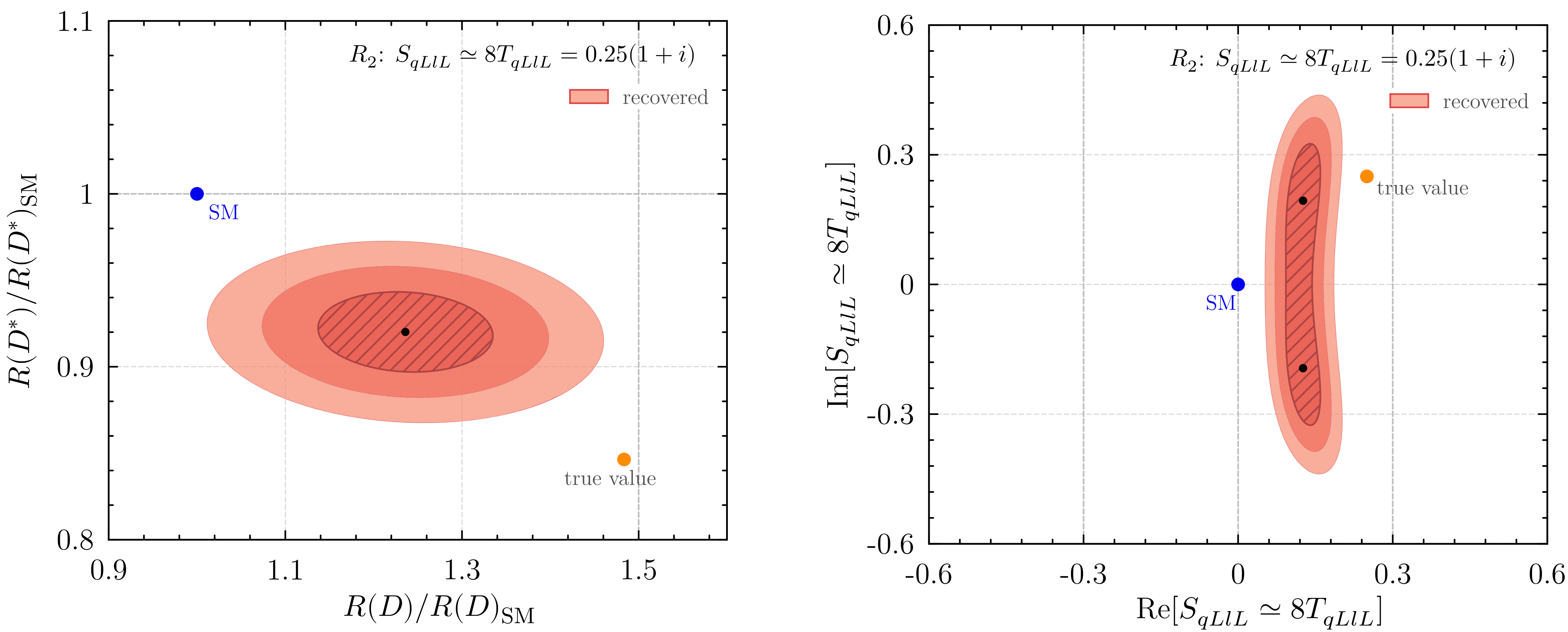


Assume **SM** acceptance x efficiency



Slightly dramatic example of what could happen

Produce fit shapes / eff. with some NP → Determine $\mathscr{R}(D^{(*)})$ using SM shapes / eff. → Determine NP couplings from measured $\mathscr{R}(D^{(*)})$



Note: the values were chosen intentionally not to reproduce the measured values to avoid the temptation to correct measured values..

HAMMER — a tool to correct $H_b \to H_c \tau \bar{\nu}$ to arbitrary NP

Challenge: Produce MC for each NP working point

- **Need** a **MC generator** that incorporates **all NP effects** and **modern form factors** (e.g. EvtGen does not)

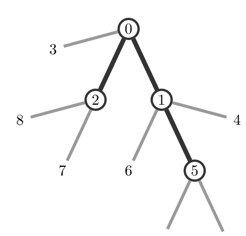
- **Very expensive**; MC statistics is already one of the largest systematic uncertainties on these measurements

HAMMER offers a solution to these problems

SM or Phase-space MC can be corrected to NP or FFs via ratio of event weights

$$r_I = \frac{d\Gamma_I^{\rm new}/d\mathcal{PS}}{d\Gamma_I^{\rm old}/d\mathcal{PS}} \,,$$

Helicity Amplitude Module for Matrix Element Reweighting



To correct angular distributions one needs to do this for all D* and τ decay products

$$\sum_{\alpha,i,\beta,j} c_\alpha c_\beta^\dagger F_i F_j^\dagger W_{\alpha i \beta j} \,,$$

encode hadronic form factors ($F_i F_j^\dagger$)

tensor that encodes amplitudes of given process ($W_{\alpha i \beta j}$)

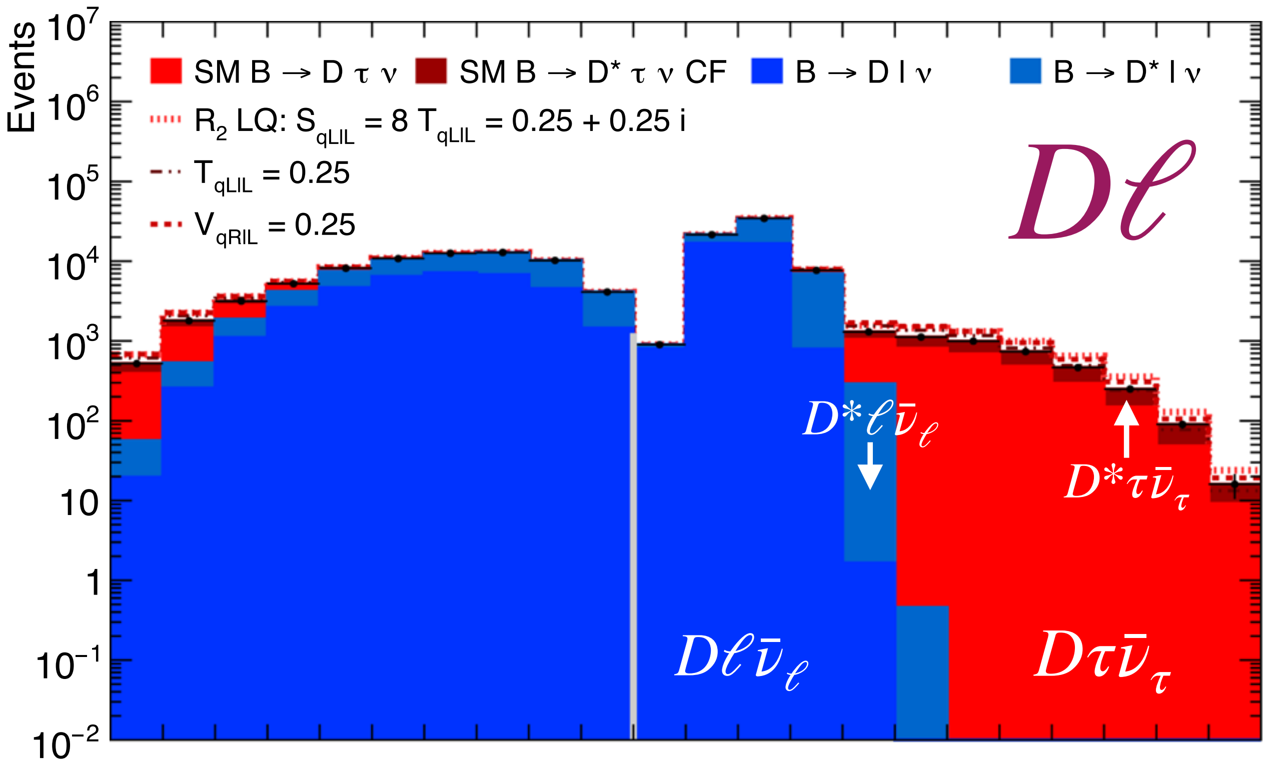
sum independent of Wilson coefficients c_α

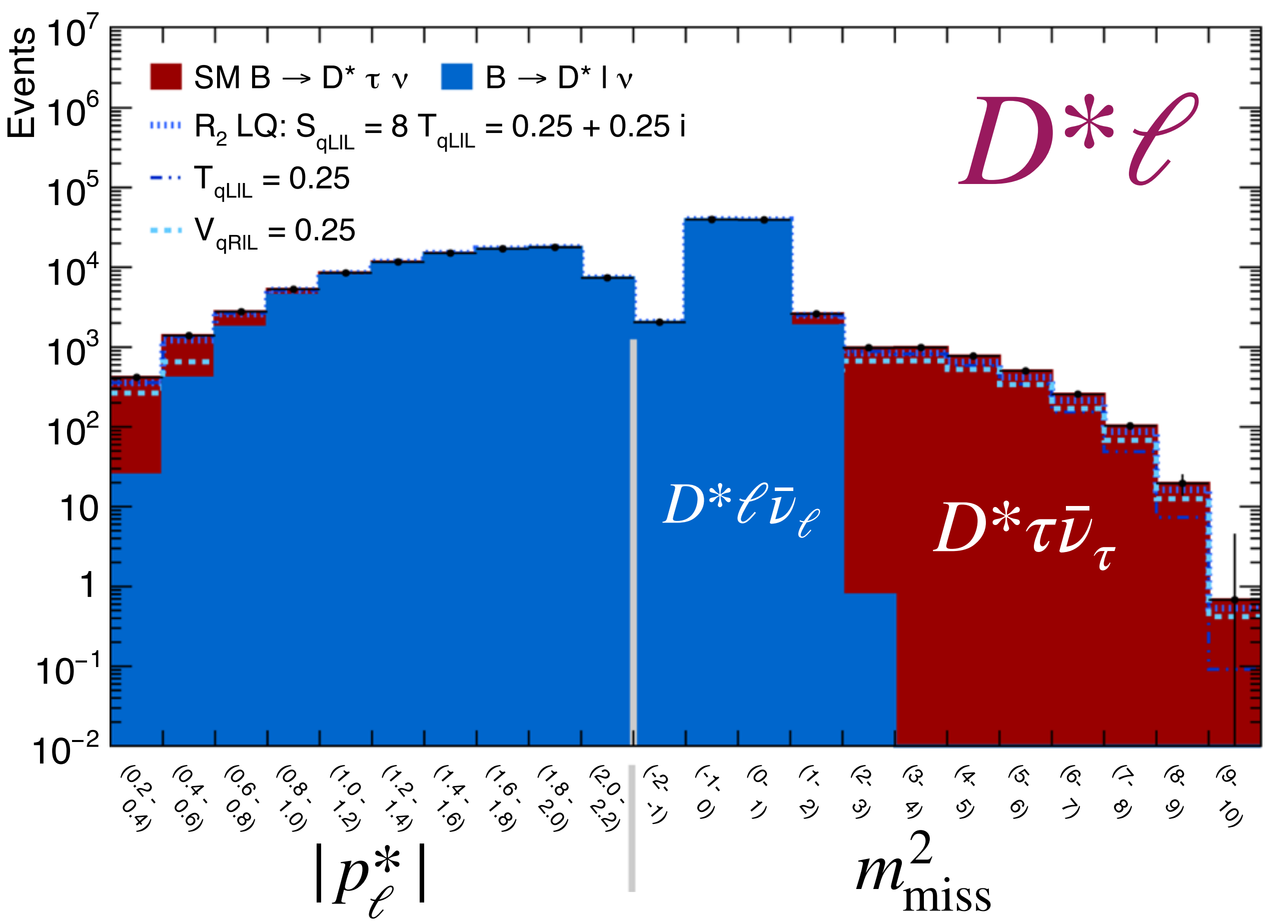
→ can exploit this to create **fast predictions**

https://hammer.physics.lbl.gov/

An illustrative Toy Example

FB, S. Duell, Z. Ligeti, M. Papucci, D. Robinson
Eur. Phys. J. C (2020) **80**: 883 [arXiv:2002:00020]

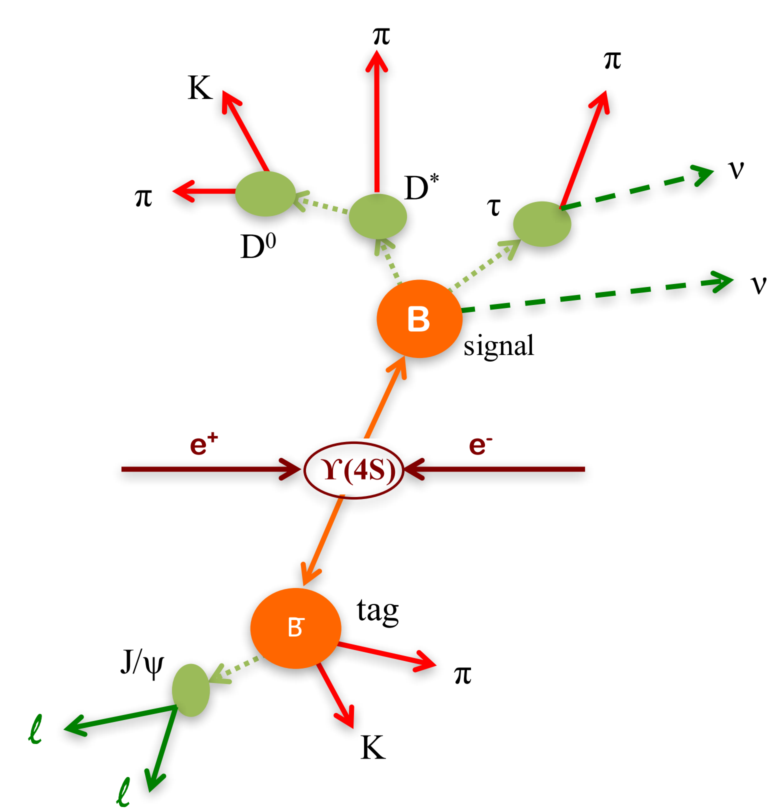




2 Categories: $D\ell, D^*\ell$

Binned 2D fit in $m^2_{\rm miss}$: $|p^*_\ell|$

Corresponds to a guestimate of how an analysis with 5/ab of Belle II data could look like in a single channel



A toy example