Prospects on angular analysis at LHCb

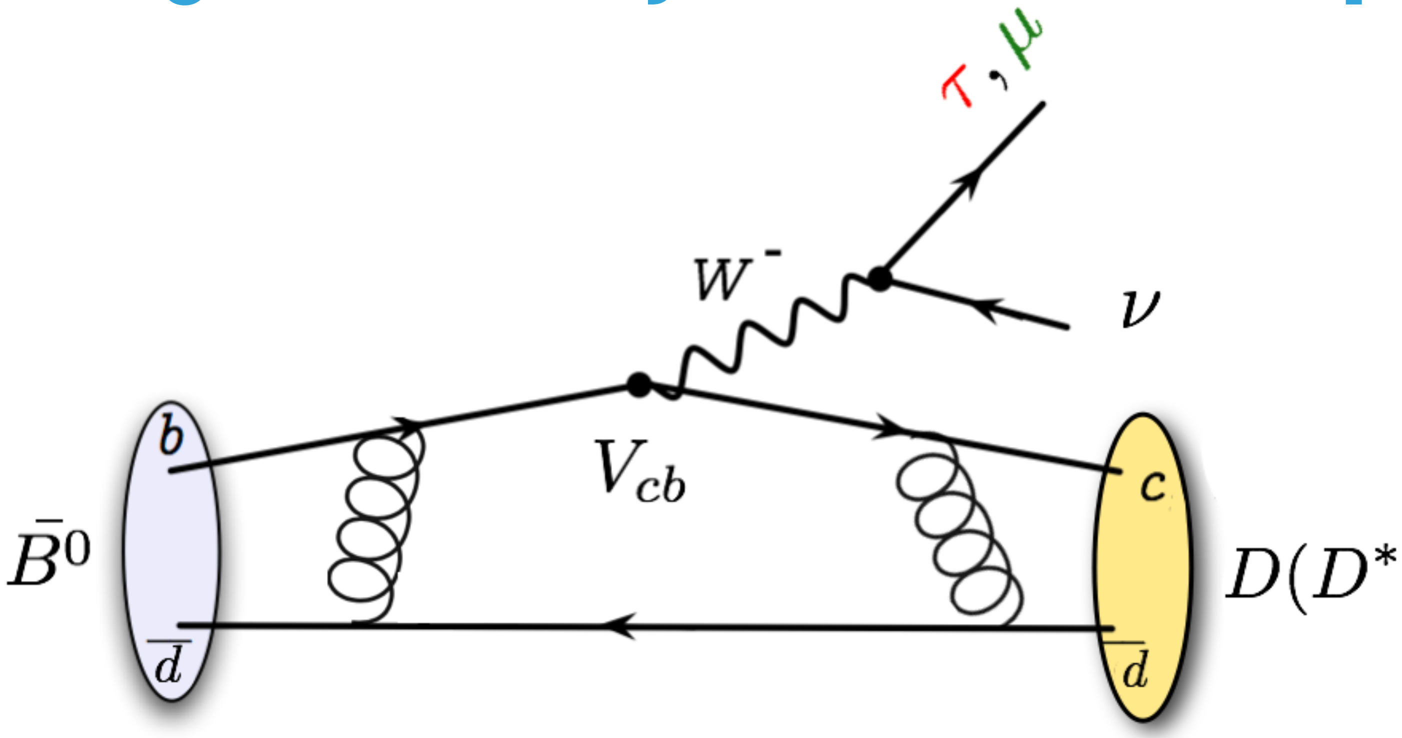
Lucia Grillo

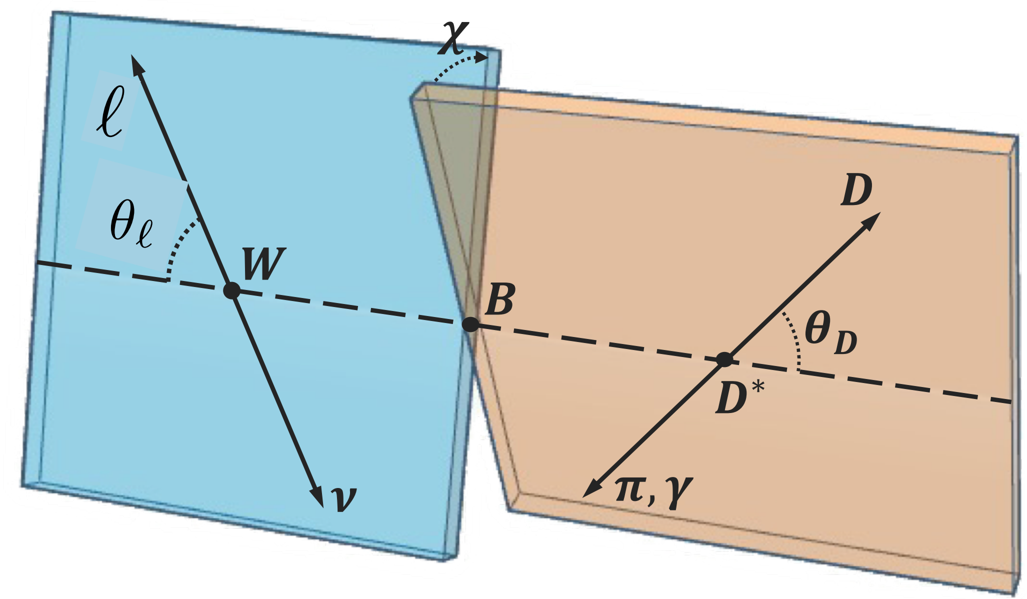
with input from Biljana Mitreska, Greg Ciezarek, and others

Open LHCb workshop on semileptonic exclusive b→c decays

12-14 April 2023

Angular analyses of semileptonic b-hadron decays



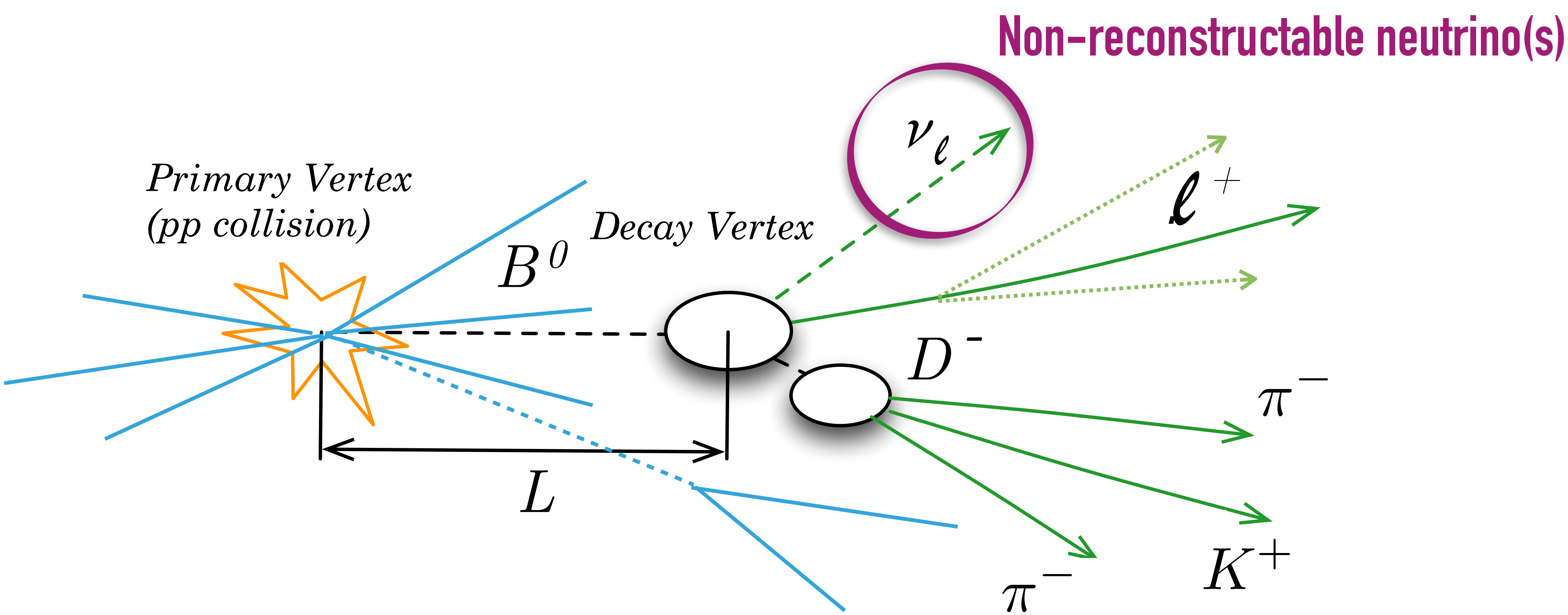


$$\frac{d^4(B^0 \to D^* \ell^+ \nu_\ell)}{dq^2 d\cos^2\theta_\ell d\cos\theta_{D^*} d\chi} \propto |V_{cb}|^2 \sum_i \mathcal{H}_i(q^2) f_i(\theta_\ell, \theta_{D^*}, \chi)$$

↑ (Electroweak) couplings + QCD encompassed by Form Factors

- Helicity angles distributions (and derived observables) are sensitive to New Physics contributions and hadronic interactions (Form Factors)
- Angular analyses: New Physics searches, complementary to Lepton Universality tests
- Hadronic Form Factors measurements
- In this talk: latest results and ongoing $H_b \to H_c \ell \nu$ studies at LHCb

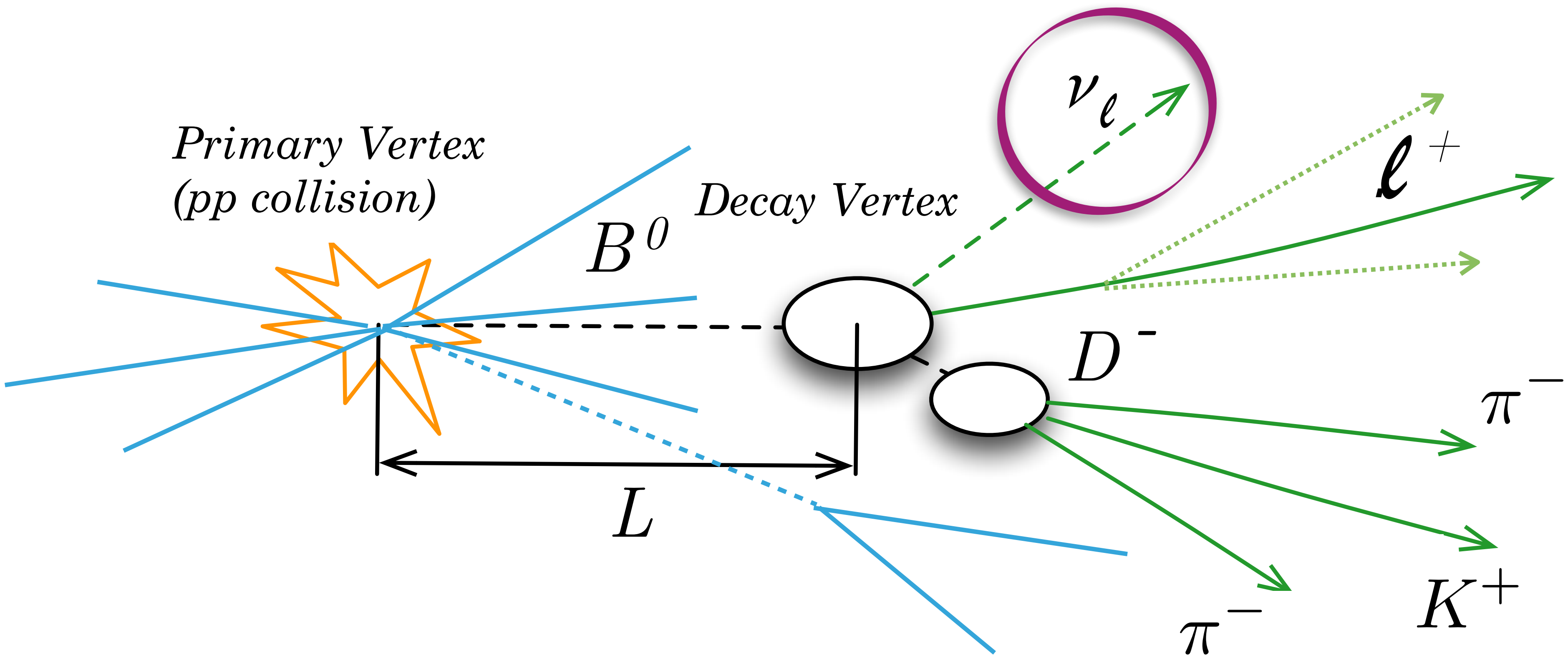
Semileptonic decays @LHCb



- **Partial reconstruction → unconstrained kinematics:** (with a single missing particle we can solve for the missing 3-momentum, with a quadratic ambiguity)
- **Partial reconstruction → large backgrounds:** need to fully exploit vertex topology information, track isolation, available kinematic information
- **Millions of signal candidates already collected**
- **All b-hadron species you can dream of -** Not included in this talk: other exclusive decays (baryons: complementary spin-structure) !

A word about the leptons

Non-reconstructable neutrino(s)



τ decay mode	BR[%]
$\tau \to \mu\bar{\nu}\nu$	17.39±0.0
$\tau \to e\bar{\nu}\nu$	17.82±0.0
$\tau \to 3\pi\nu$	9.31±0.05
$\tau \to 3\pi\pi^0\nu$	4.62±0.05
$\tau \to \pi\nu$	18.82±0.0
$\tau \to \rho\nu$	25.49±0.9

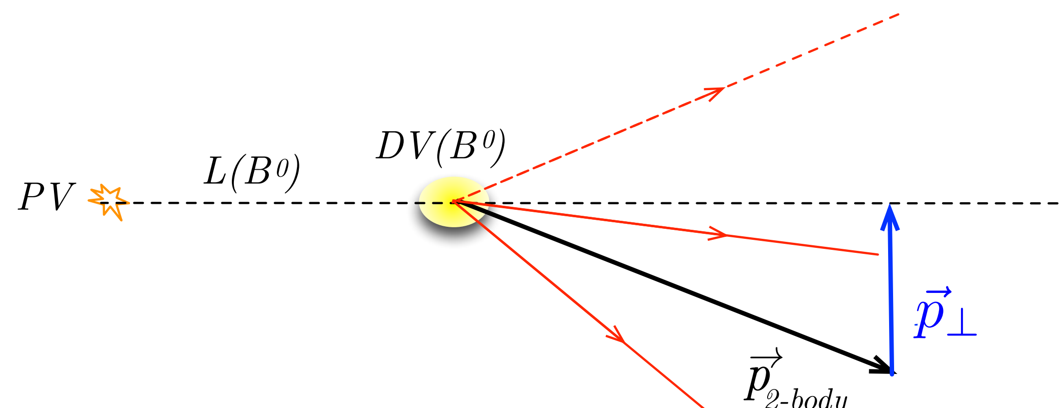
- **Muons:** easier to detect, semi-muonic samples are fairly clean
- **Taus @LHCb:** muonic decay (direct comparison with Hb→Hcμν) or hadronic (3-prong) decay: better constrained kinematics using the tau decay verses
- **Electrons @LHCb:** fewer electrons than muons (lower selection efficiency) and with worse resolution (Bremsstrahlung) - but less noticeable once you have already unconstrained kinematics

On-going efforts using all leptons!

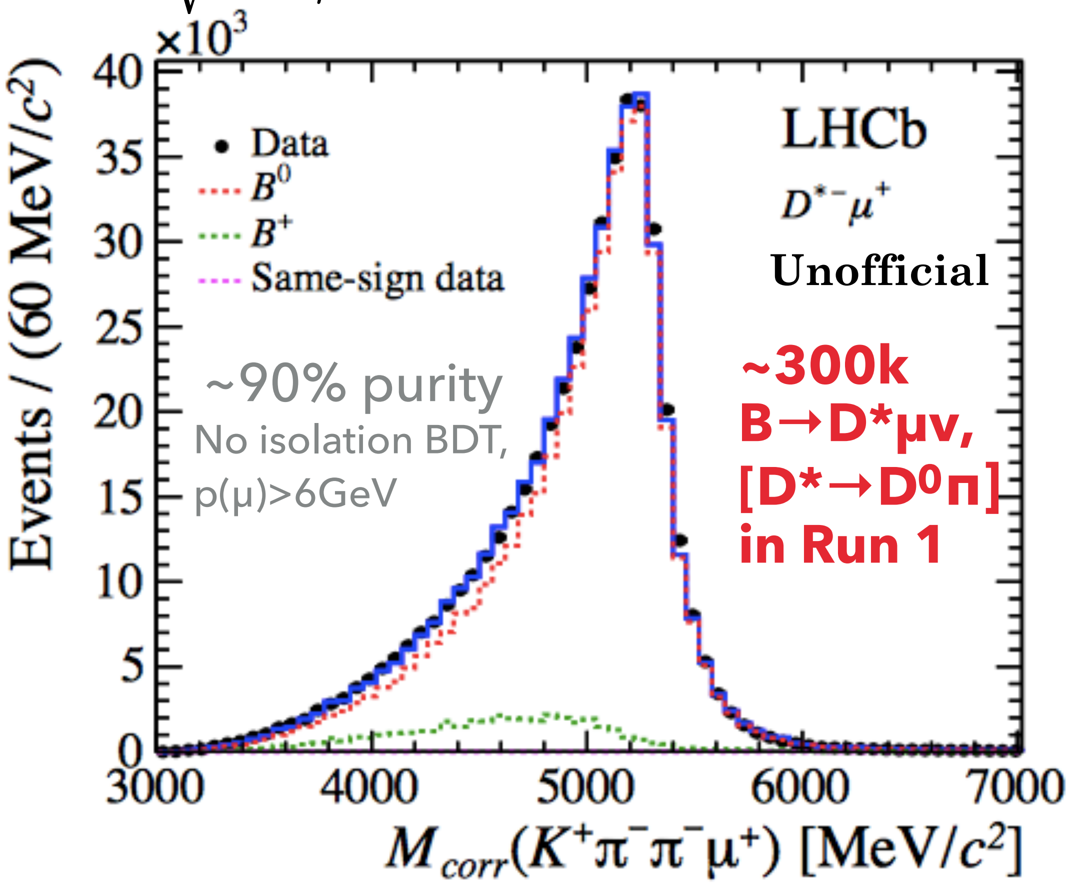
Backgrounds

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

- Analyses with muons: signal dominated

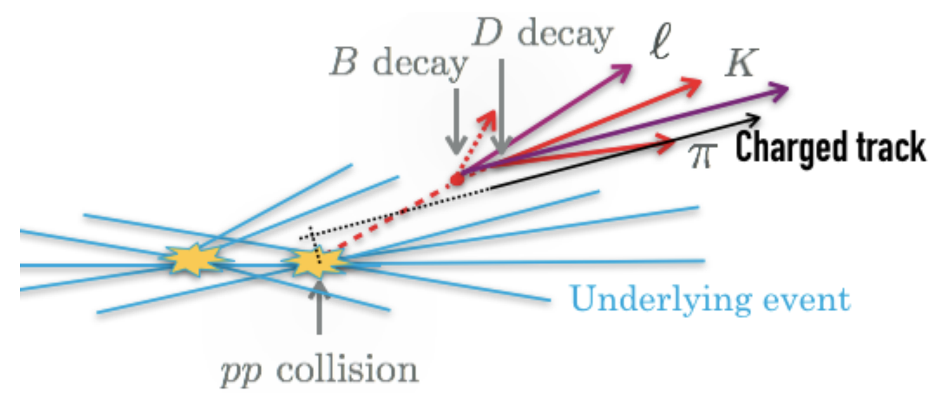


$$M_{corr} = \sqrt{M^2_{D\mu} + |p_\perp|^2} + |p_\perp|$$

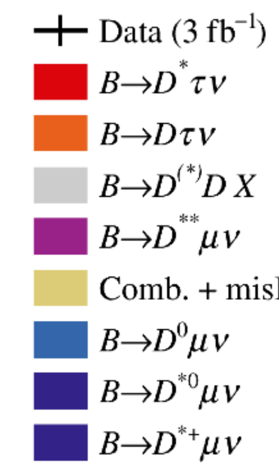


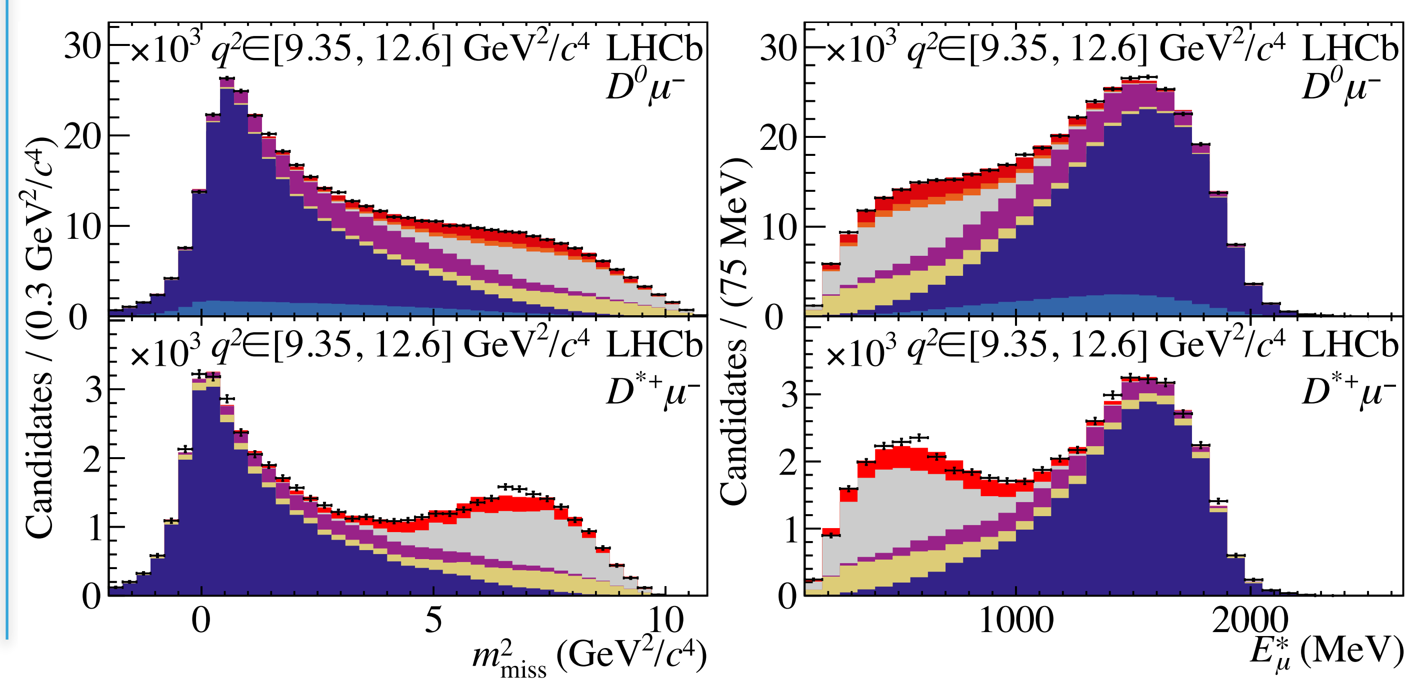
$B^0 \to D^{(*)}\tau\nu$

- Analyses with taus: background dominated
- Essential use of track isolation and control regions to describe the sample composition



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





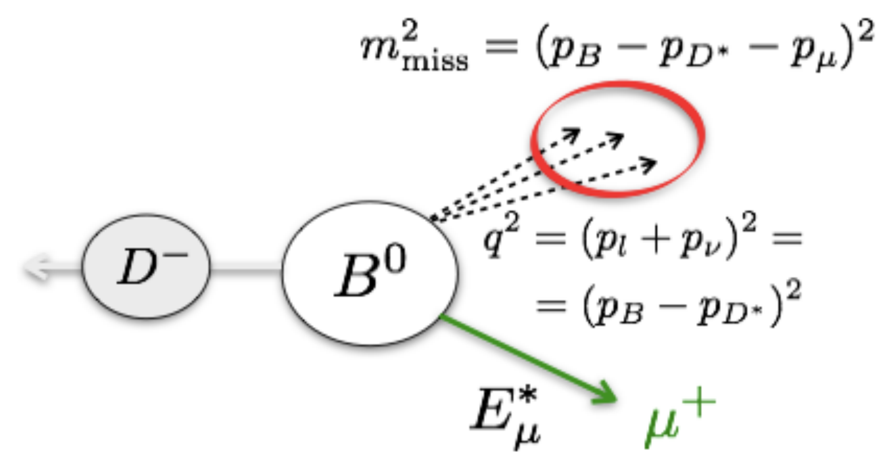
Remember Greg's talk

LHCb-PAPER-2022-039

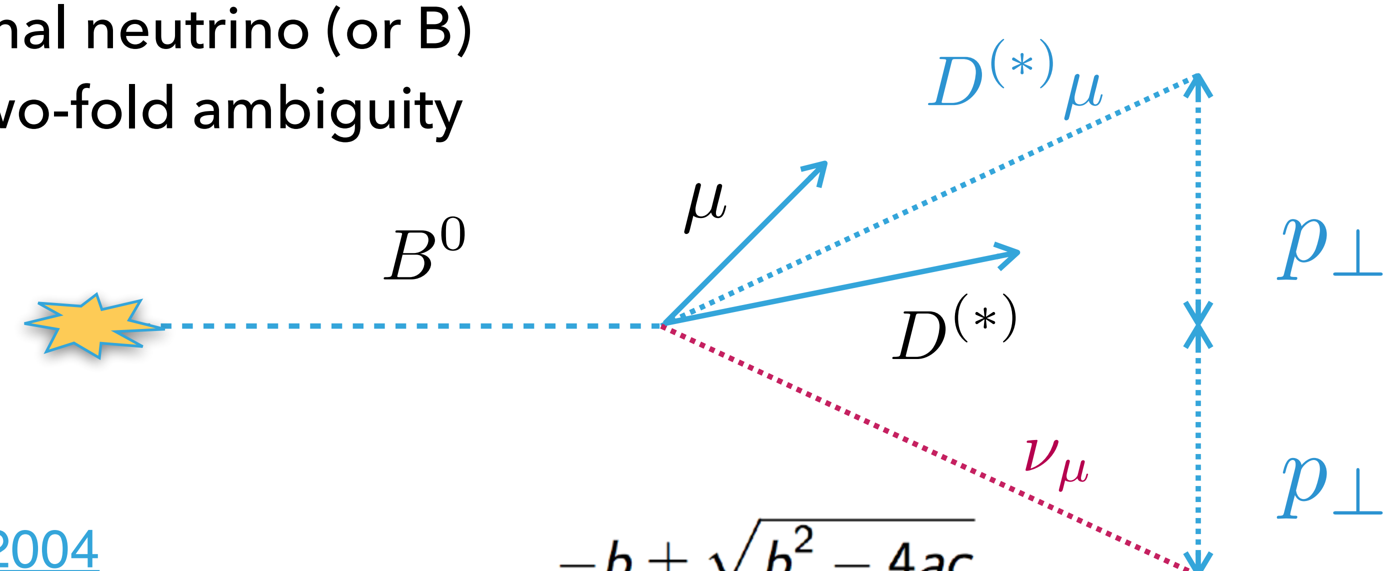
Partial reconstruction

- With more than one missing neutrino:
  B rest frame approximation

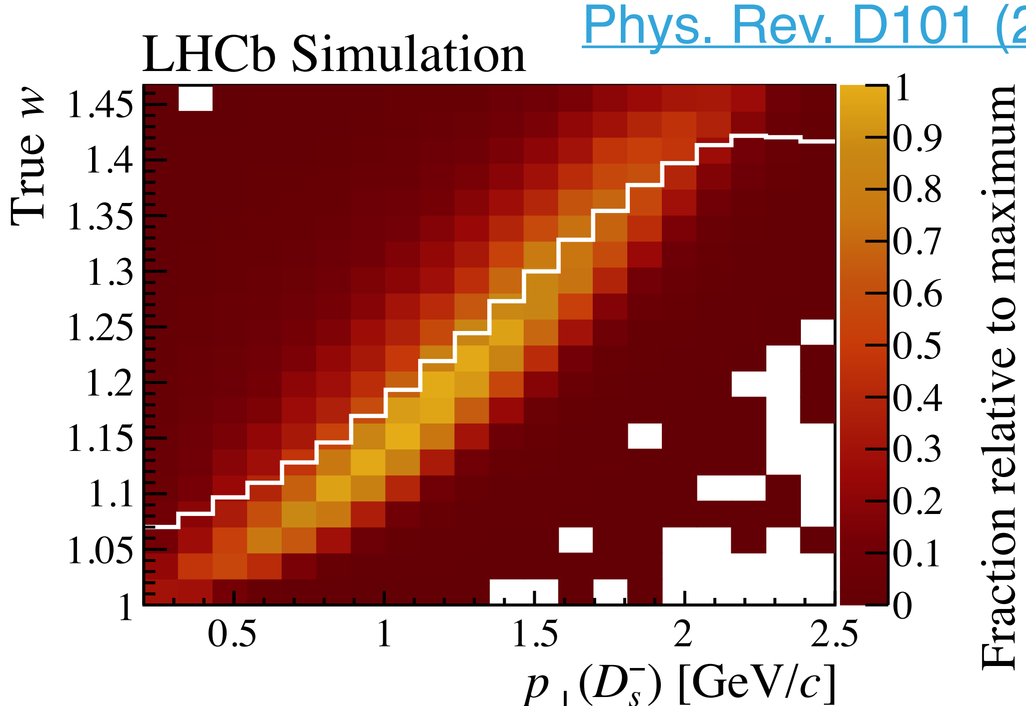
$$(\gamma\beta_z)_B = (\gamma\beta_z)_{D^*\mu} \Longrightarrow (p_z)_B = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$



- With only one missing particle: **longitudinal neutrino (or B) momentum component known up to a two-fold ambiguity**
  - Pick one solution randomly
  - Use linear regression prediction
    [G. Ciezarek et. al, JHEP 2 (2017) 021]
  - Use a proxy variable



[Phys. Rev. D101 (2020) 072004]



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

$$a = |2p_{\parallel,X_\mu} m_{X_\mu}|^2,$$

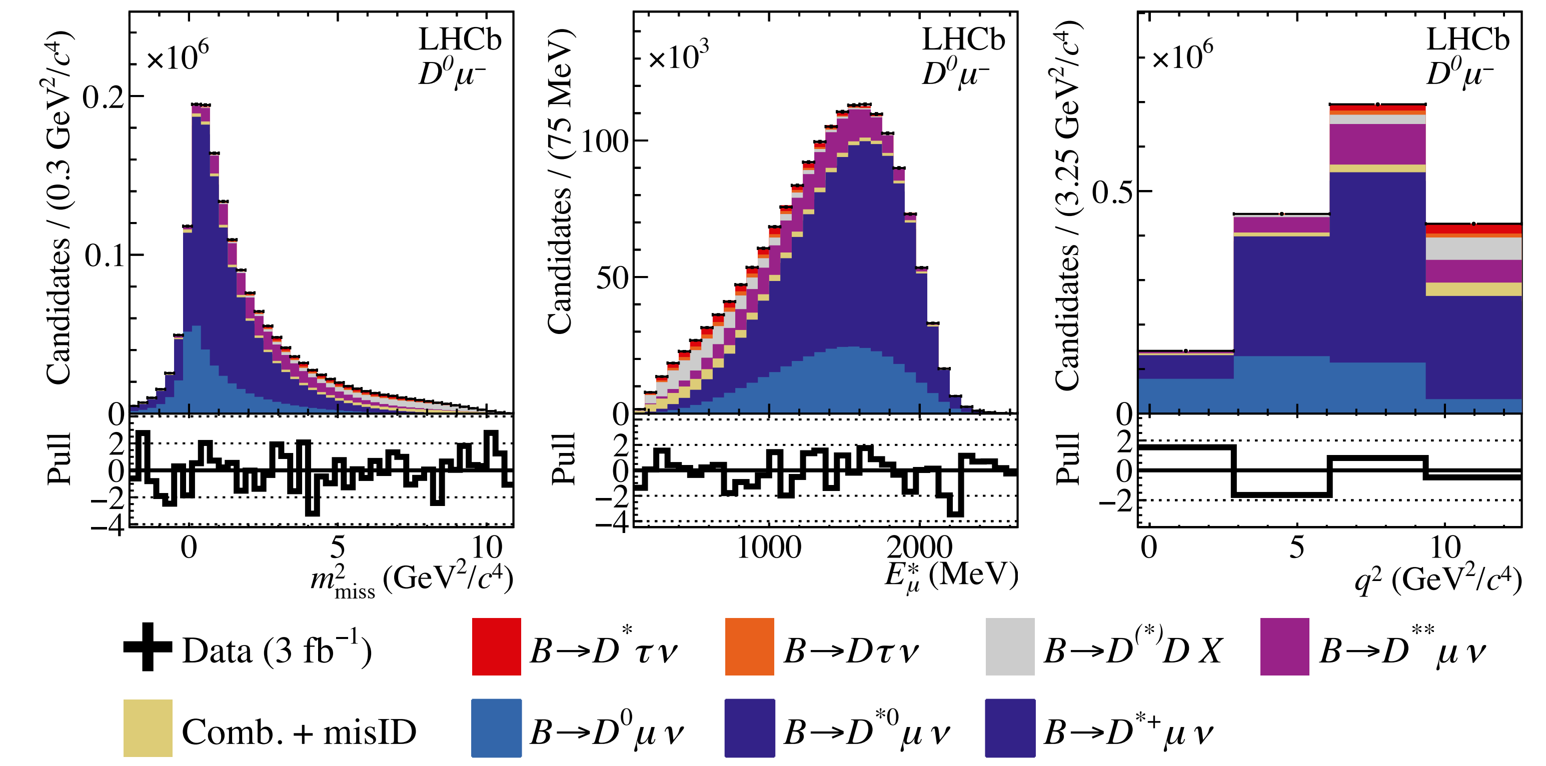
$$b = 4p_{\parallel,X_\mu}(2p_\perp p_{\parallel,,X_\mu} - m^2_{miss}),$$

$$c = 4p^2_\perp(p^2_{\parallel,X_\mu} + m^2_{\mathrm{B}^0}) - |m^2_{miss}|^2,$$

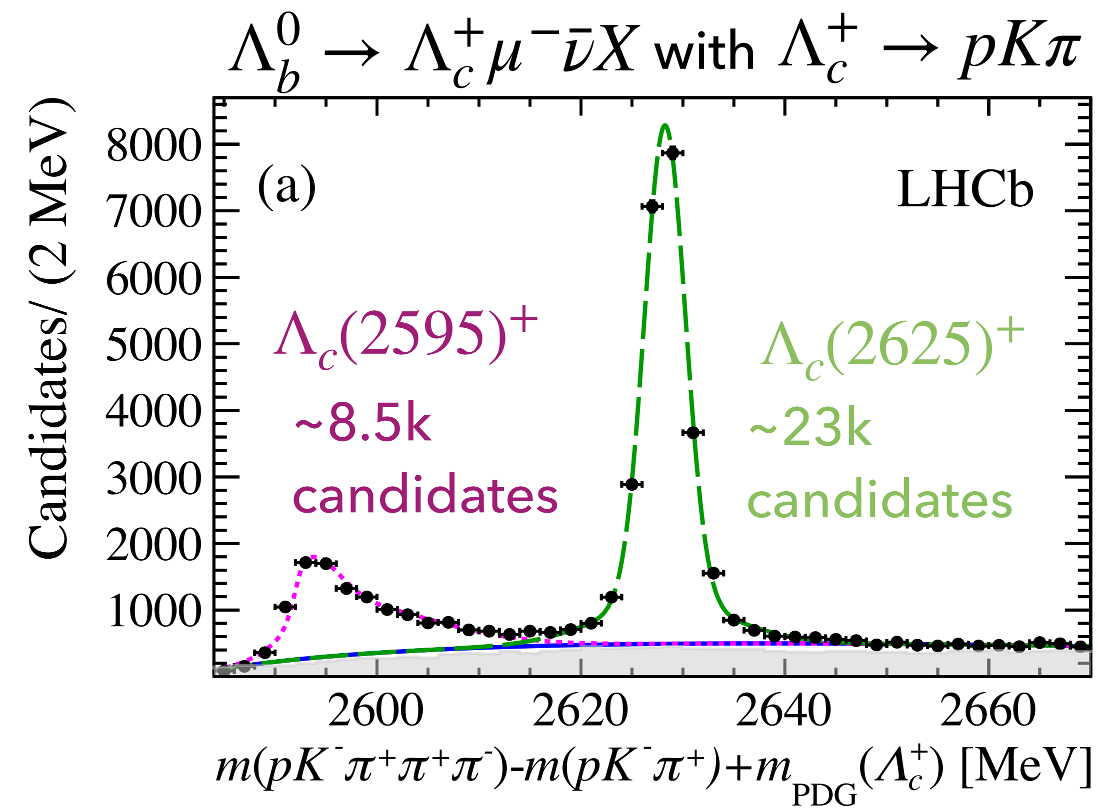
$$m^2_{miss} = m^2_{\mathrm{B}^0} - m^2_{X_\mu}.$$

Large samples & a variety of decay modes

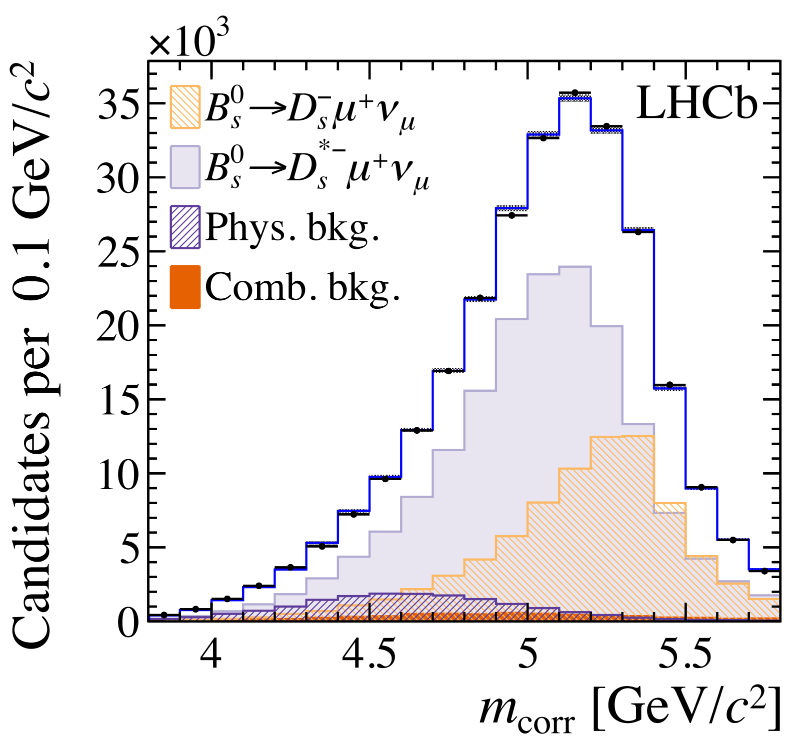
LHCb-PAPER-2022-039



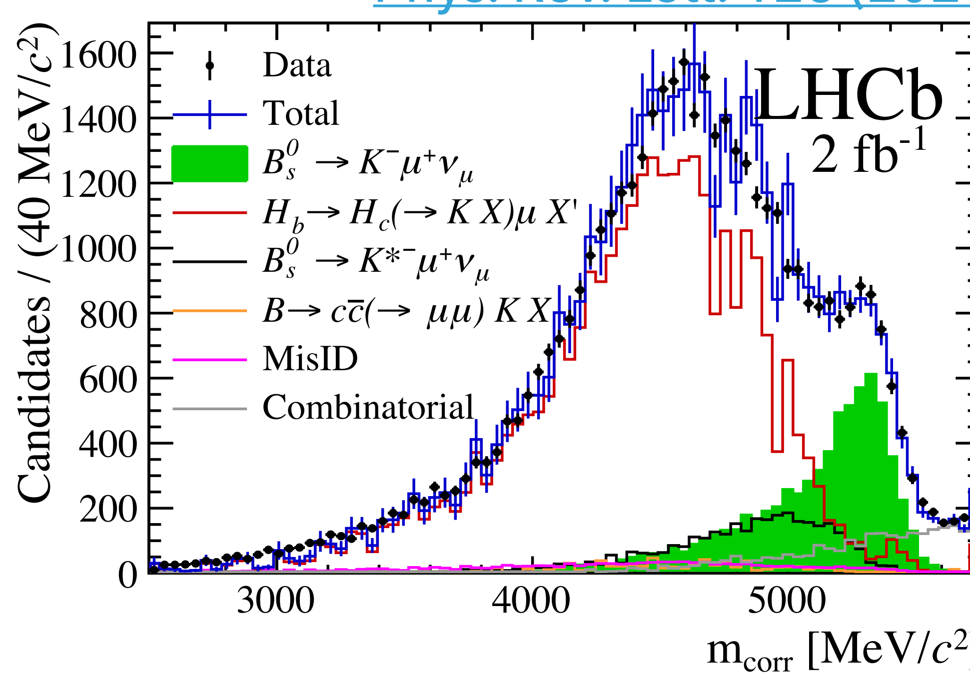
Phys. Rev. D96 (2017) 112005



Phys. Rev. D101 (2020) 072004



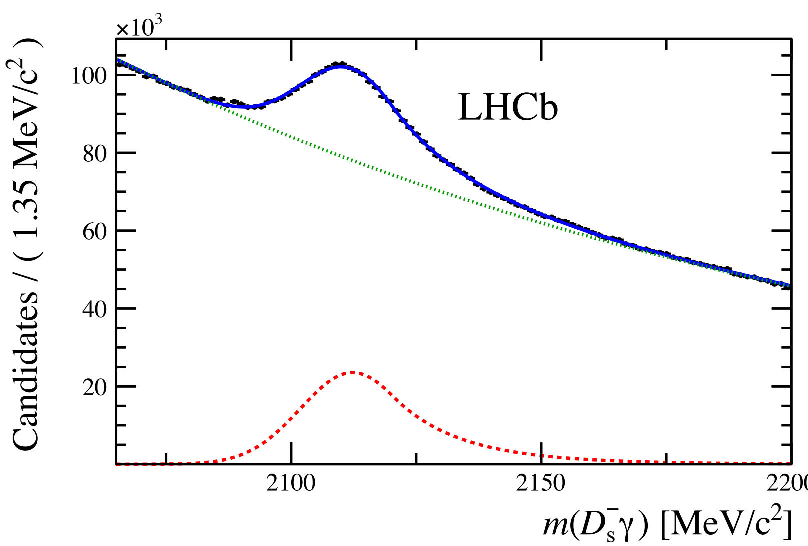
Phys. Rev. Lett. 126 (2021) 081804



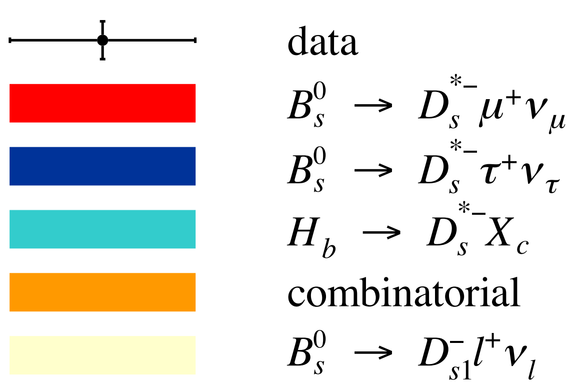
- Run-II: ~x4 Run-I considering luminosity and cross-section x gain in selection efficiencies (sample/ selection dependent)

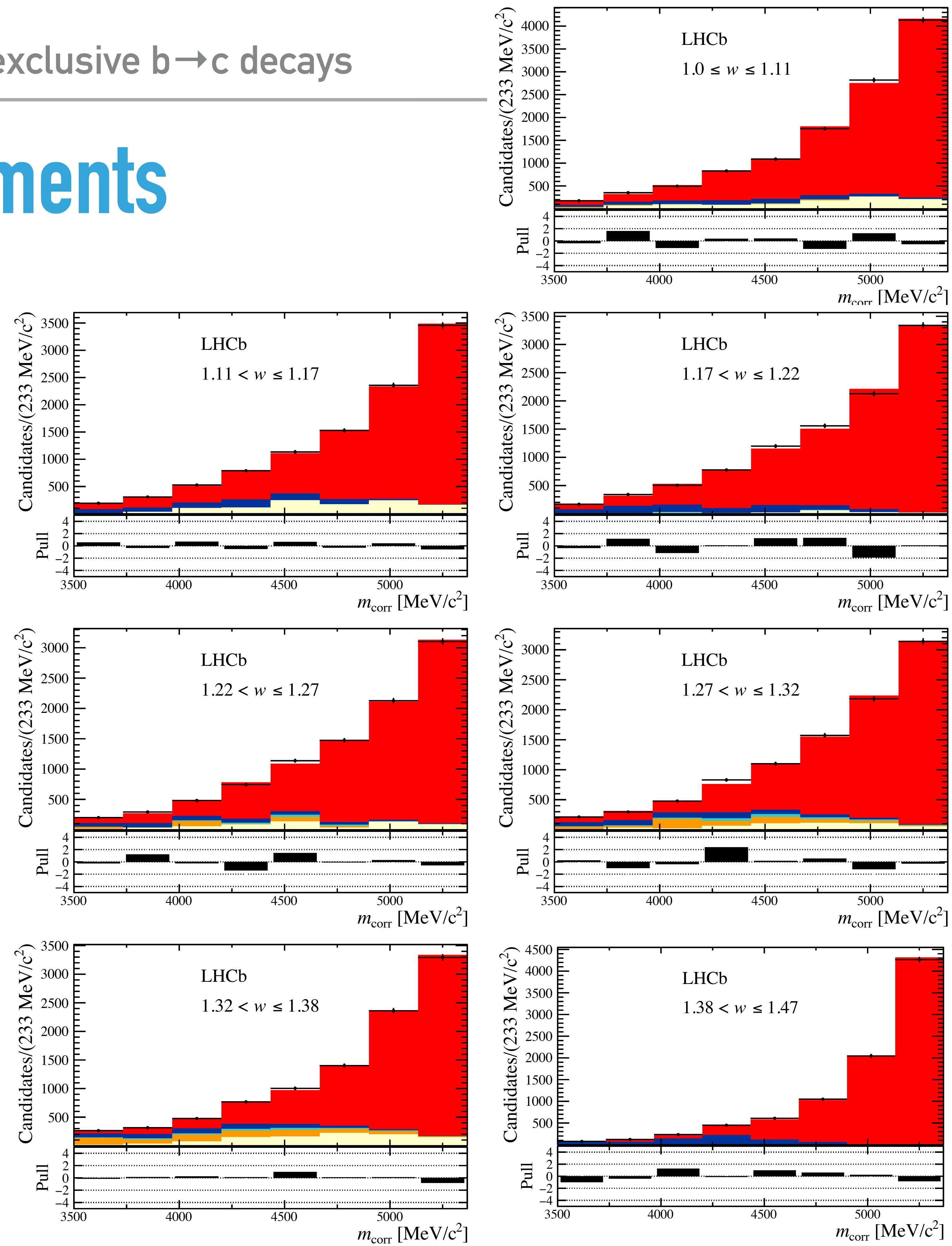
Differential measurements

- 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 $w = v_{B_s^0} \cdot v_{D_s^{*-}}$





[JHEP 12 (2020) 144]

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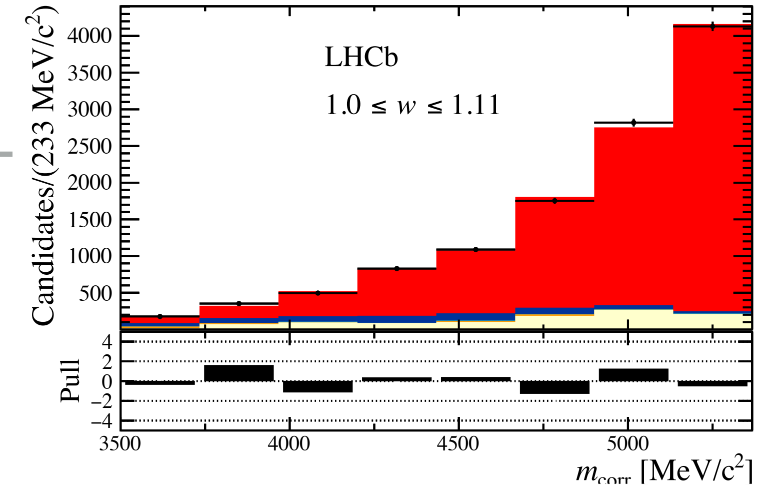

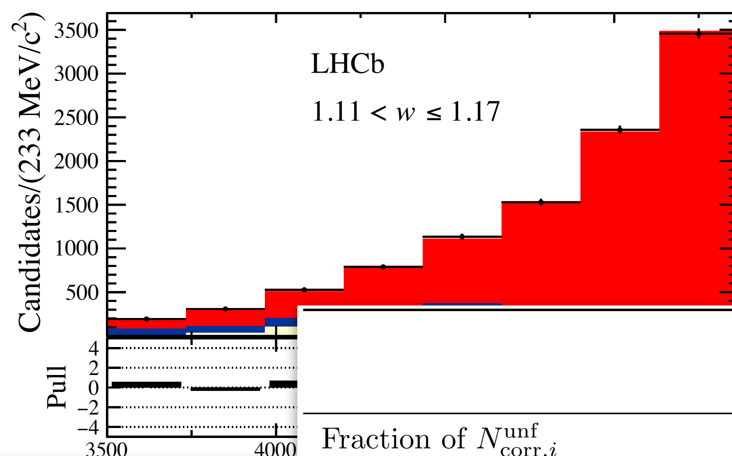

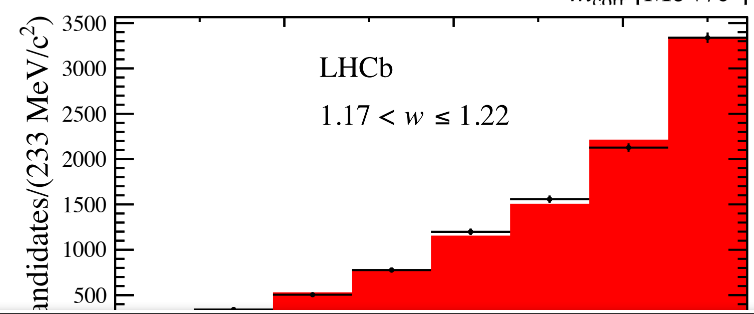

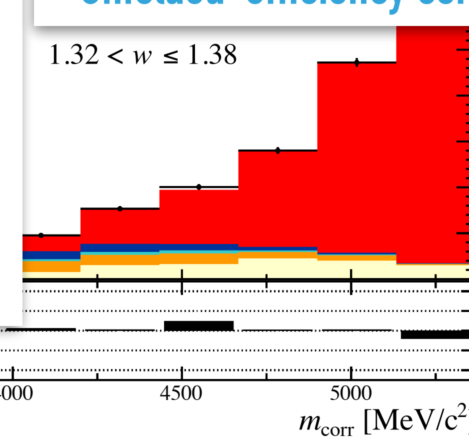

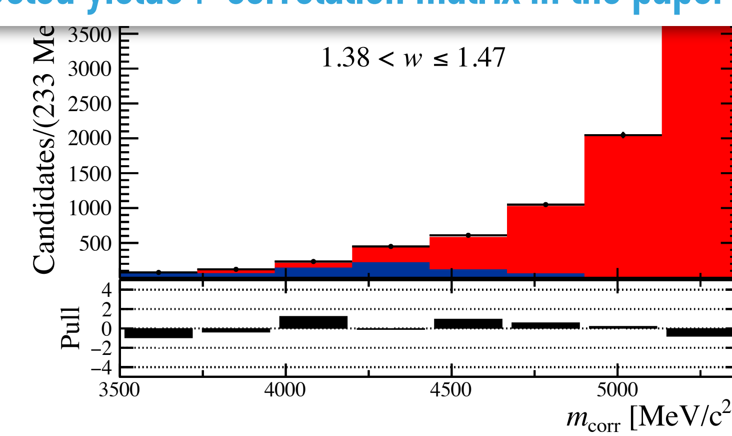

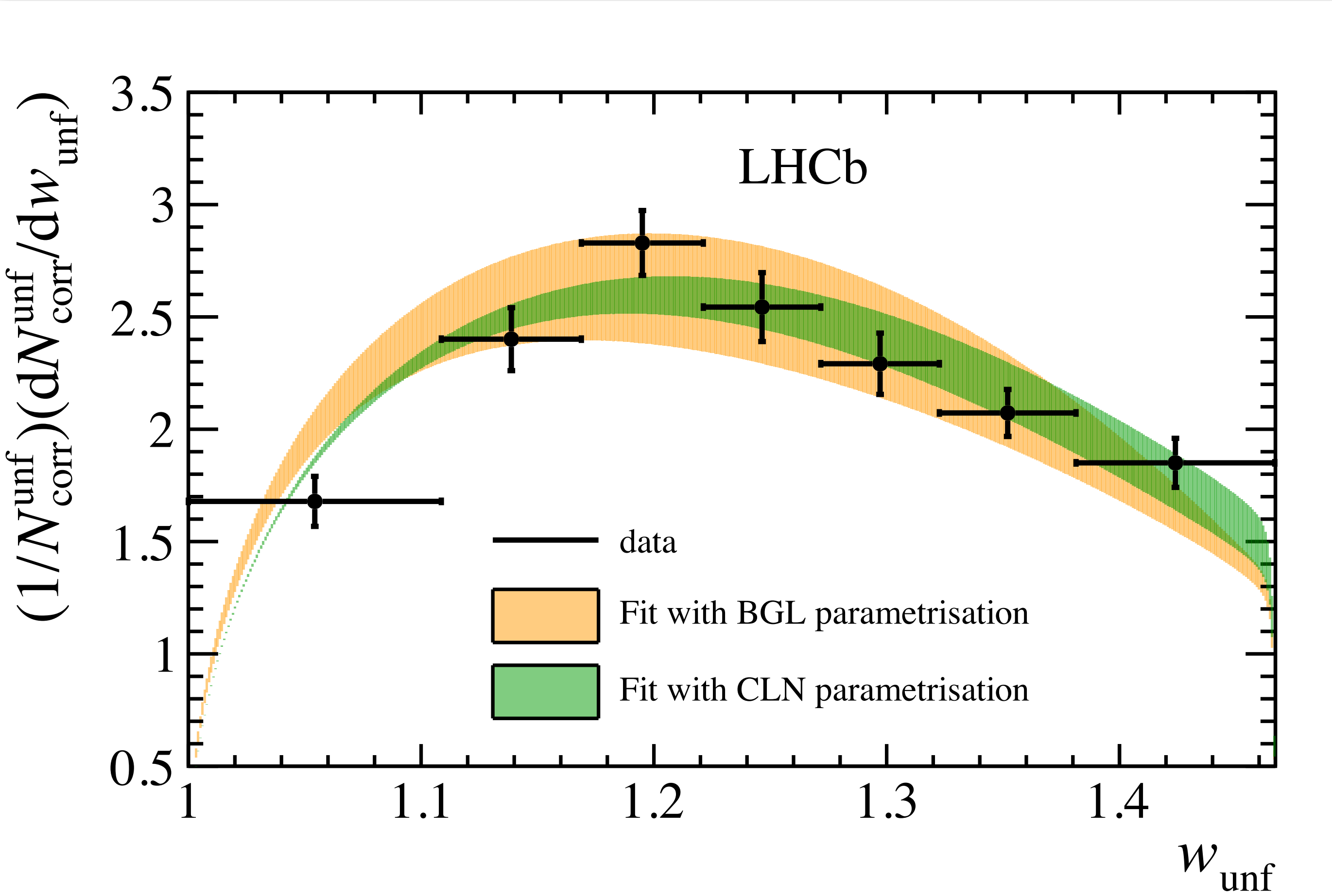

	w bin						
	1	2	3	4	5	6	7
Fraction of $N^{\rm unf}_{{\rm corr},i}$	0.183	0.144	0.148	0.128	0.117	0.122	0.158
Uncertainties (%)							
Simulation sample size	3.5	3.0	2.8	3.1	3.4	3.0	3.7
Sample sizes for effs and corrections	3.6	3.2	3.0	2.8	2.8	2.7	2.8
SVD unfolding regularisation	0.5	0.5	0.1	0.7	1.2	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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Hadronic Form Factors measurements

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

BGL

$$r = m_{D_s^*}/m_{B_s^0}$$

$$z(w) = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

$$H_0 = \frac{\mathcal{F}_1(w)}{m_{B_s^0}\sqrt{1 + r^2 + 2wr}}$$

$$H_\pm = f(w) \mp m_{B_s^0} m_{D_s^*} \sqrt{w^2 - 1}\, g(w)$$

$$H_t = m_{B_s^0} \frac{\sqrt{r}(1+r)\sqrt{w^2-1}}{\sqrt{1 + r^2 - 2wr}} \mathcal{F}_2(w)$$

$$f(z) = \frac{1}{P_{1^+}(z)\phi_f(z)} \sum_{n=0}^{\infty} a_n^f z^n$$

$$g(z) = \frac{1}{P_{1^-}(z)\phi_g(z)} \sum_{n=0}^{\infty} a_n^g z^n$$

$$\mathcal{F}_1(z) = \frac{1}{P_{1^+}(z)\phi_{\mathcal{F}_1}(z)} \sum_{n=0}^{\infty} a_n^{\mathcal{F}_1} z^n$$

$$\mathcal{F}_2(z) = \frac{\sqrt{r}}{(1+r)P_{0^-}(z)\phi_{\mathcal{F}_2}(z)} \sum_{n=0}^{\infty} a_n^{\mathcal{F}_2} z^n$$

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- 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 $w = v_{B_s^0} \cdot v_{D_s^{*-}}$

CLN fit	
Unfolded fit	$\rho^2 = 1.16 \pm 0.05 \pm 0.07$
Unfolded fit with massless leptons	$\rho^2 = 1.17 \pm 0.05 \pm 0.07$
Folded fit	$\rho^2 = 1.14 \pm 0.04 \pm 0.07$
BGL fit	
Unfolded fit	$a_1^f = -0.005 \pm 0.034 \pm 0.046$ $a_2^f = 1.00^{+0.00}_{-0.19}{}^{+0.00}_{-0.38}$
Folded fit	$a_1^f = 0.039 \pm 0.029 \pm 0.046$ $a_2^f = 1.00^{+0.00}_{-0.13}{}^{+0.00}_{-0.34}$

Hadronic Form Factors measurements

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Folded fit	$a_1^f = 0.039 \pm 0.029 \pm 0.046$ $a_2^f = 1.00^{+0.00}_{-0.13}{}^{+0.00}_{-0.34}$

Already a few analyses sensitive to hadronic FF parameters

- First measurement of $|V_{cb}|$ using $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$
  - Measure rate relative to $B^0 \to D^{(*)-}\mu^+\nu_\mu$
  - Requires external inputs for $|V_{cb}|$
  - Measurement of decay rate as a function of $p_\perp(D_s^-)$, proxy for q^2 or recoil w ($D_s^{(*)-}$ energy in the B_s^0 rest frame)

More details in Ricardo's talk

Parameter	Value
$\lvert V_{cb}\rvert$ $[10^{-3}]$	42.3 ± 0.8 (stat) ± 1.2 (ext)
$\mathcal{G}(0)$	1.097 ± 0.034 (stat) ± 0.001 (ext)
d_1	-0.017 ± 0.007 (stat) ± 0.001 (ext)
d_2	-0.26 ± 0.05 (stat) ± 0.00 (ext)
b_1 a_1^f	-0.06 ± 0.07 (stat) ± 0.01 (ext)
a_0 a_0^g	0.037 ± 0.009 (stat) ± 0.001 (ext)
a_1 a_1^g	0.28 ± 0.26 (stat) ± 0.08 (ext)
c_1 $a_1^{\mathcal{F}_1}$	0.0031 ± 0.0022 (stat) ± 0.0006 (ext)

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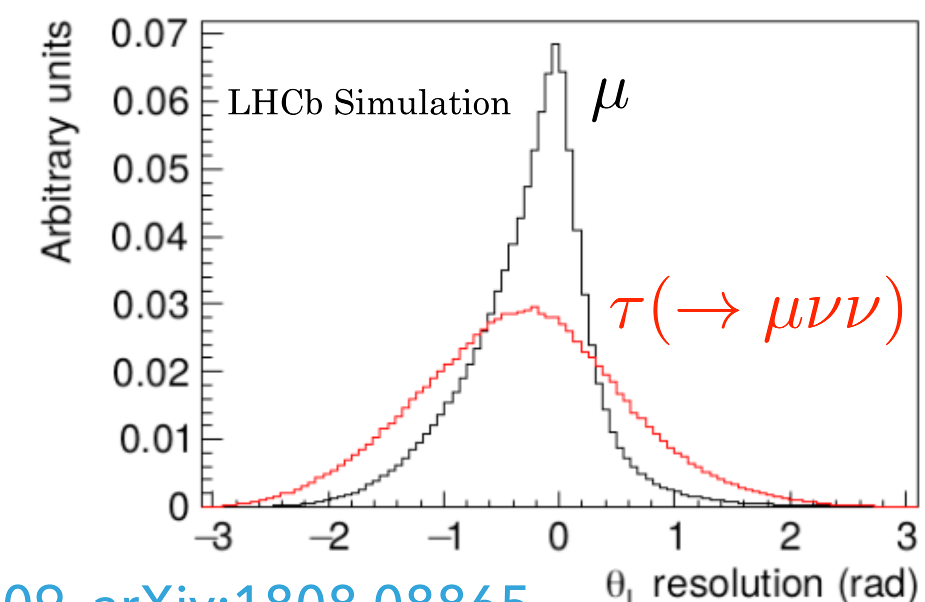
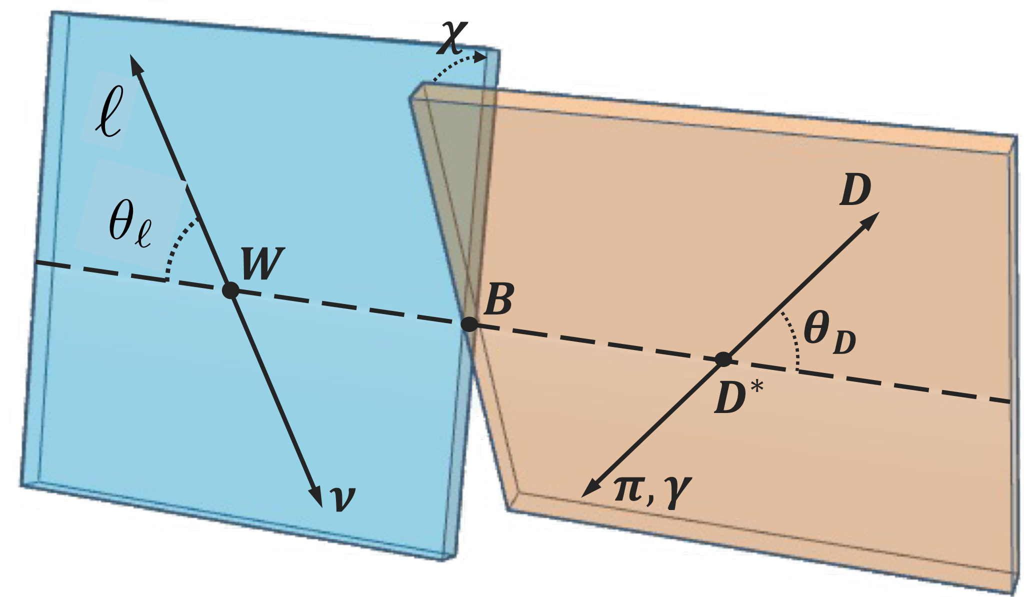
- Sensitivity to hadronic form factors also from many more measurements, e.g. LFU ratios (dedicated measurements being worked on) LHCb-PAPER-2022-039

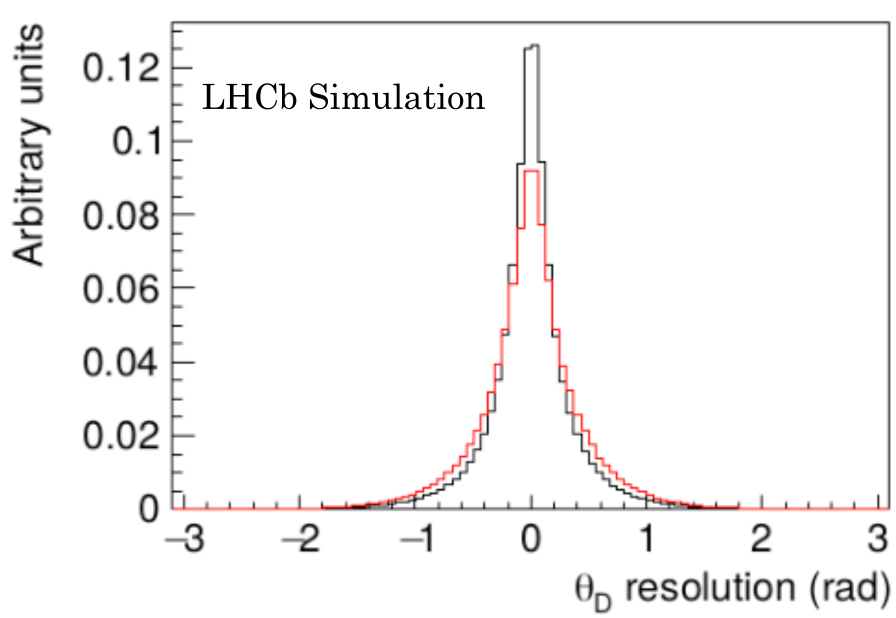
Expanding differential measurements

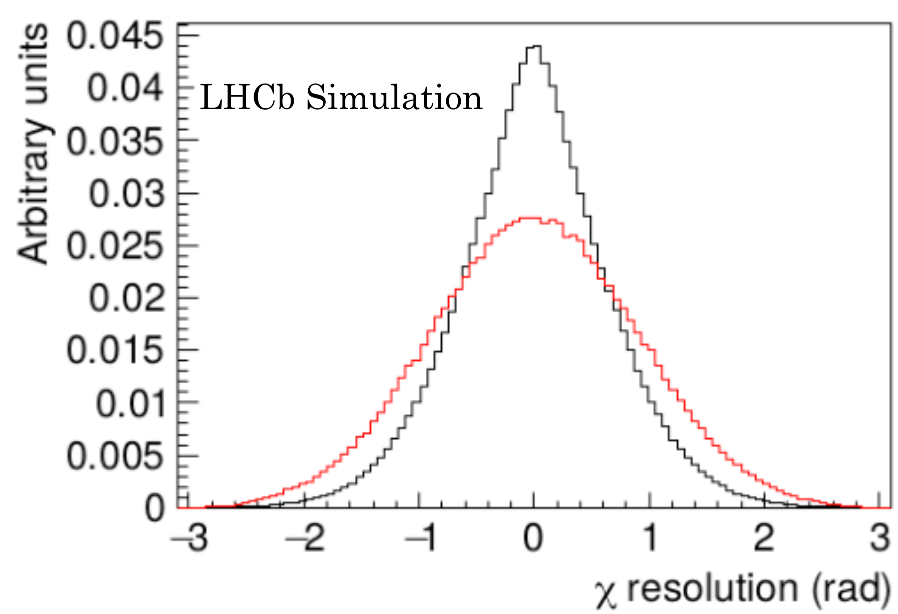
- Fully differential decay rate - in q^2 (or w) and helicity angles
- Resolutions (worst case: rest frame approximation)





LHCB-PUB-2018-009, arXiv:1808.08865

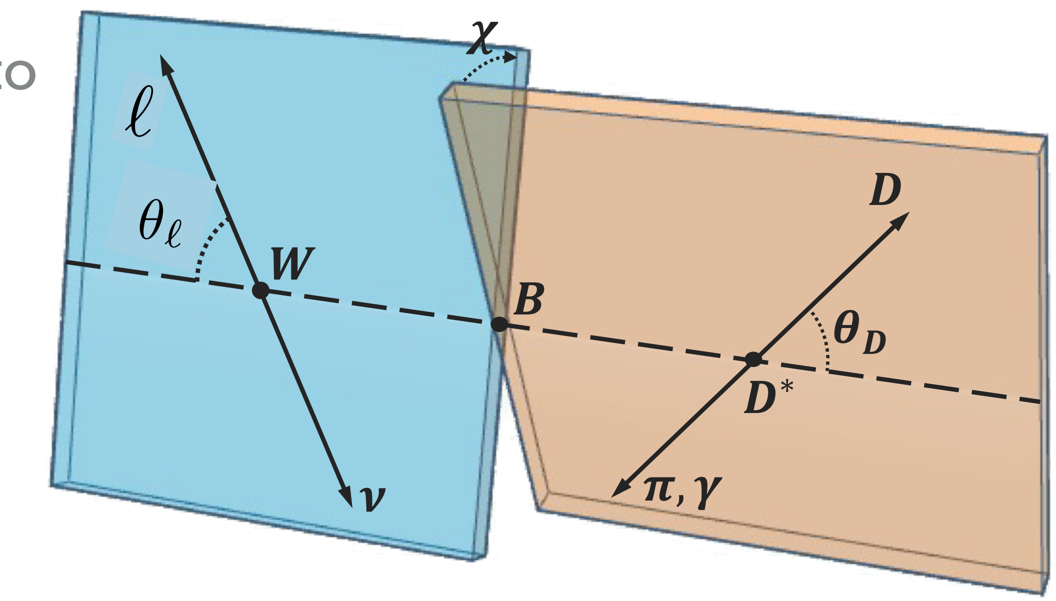


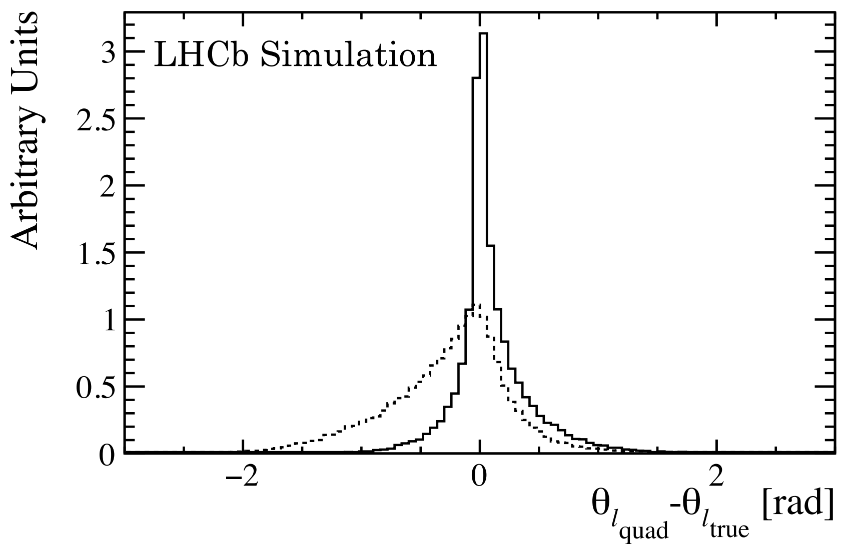


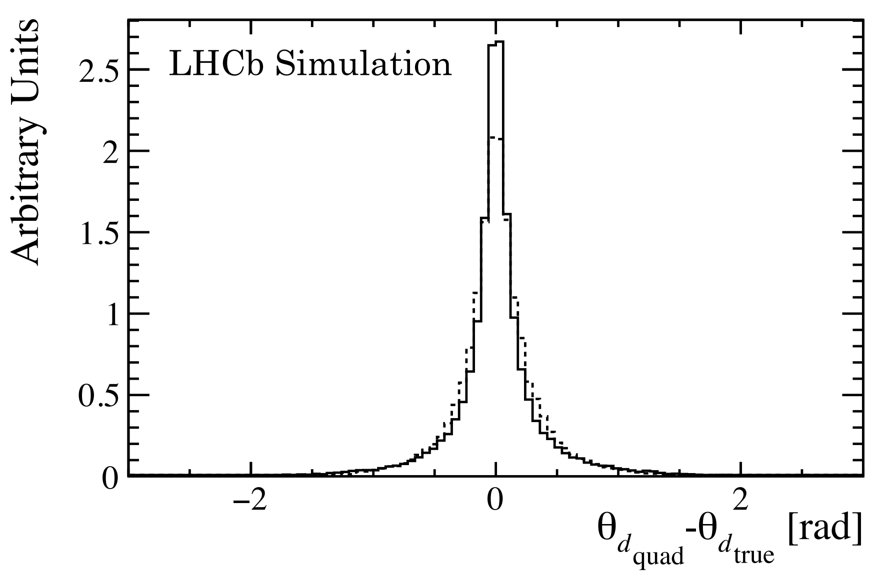
Resolutions to be modelled, but good sensitivity with large datasets!

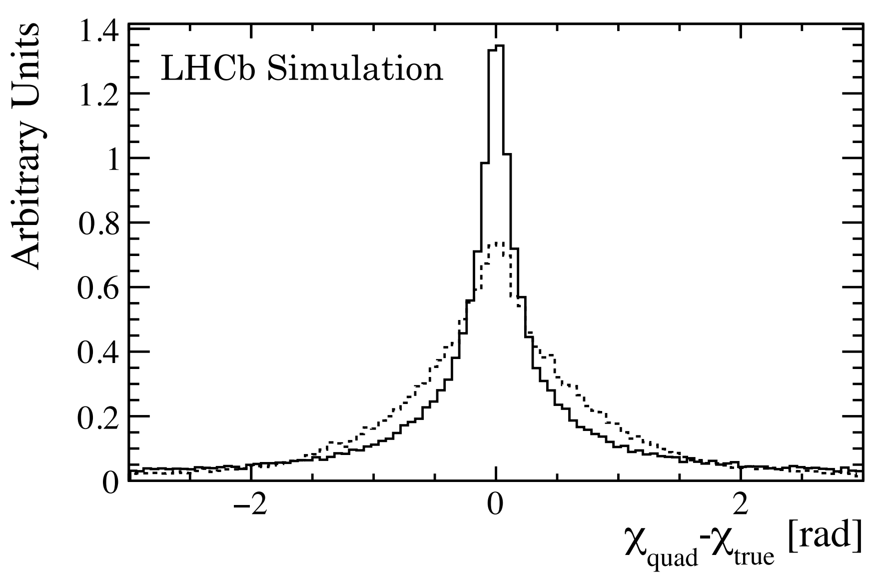
Expanding differential measurements

- $B^0 \to D^* \mu\nu$ decays
- Solution of quadratic equation (solid) compared to B rest frame approximation (dashed)





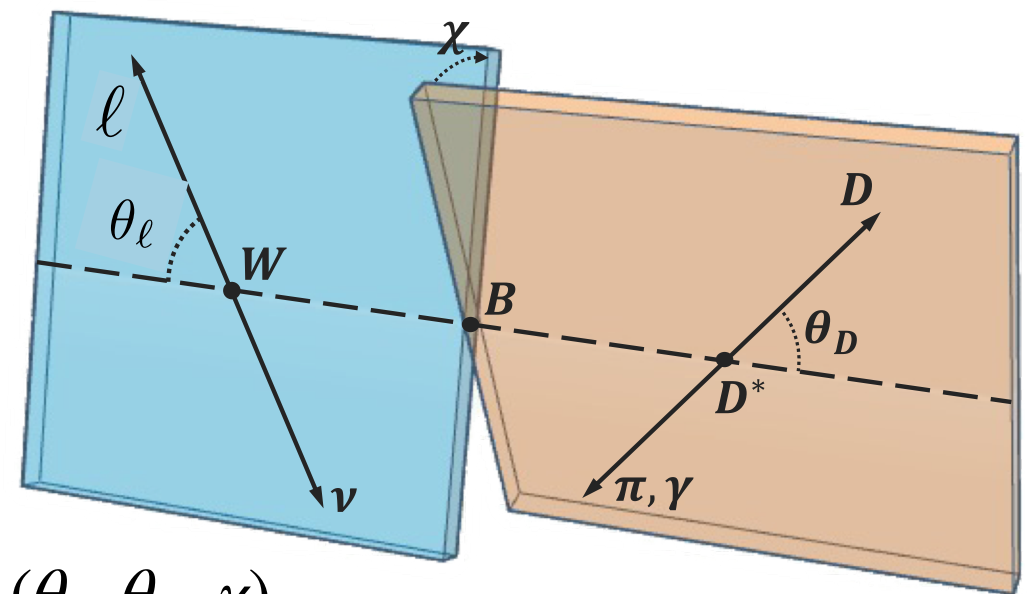




Let's start from the muons, considerably easier test bench for the analyses (kinematic constraints, backgrounds, statistics)

Expanding differential measurements

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



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

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	$-\sin 2\theta_D\sin\theta_\mu(1+\cos\theta_\mu)\cos\chi$	$2\sin 2\theta_D\sin\theta_\mu(1+\cos\theta_\mu)\cos\chi$

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- 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
- Measuring the 12 angular coefficients (integrating in q^2) currently pursued for B→D*lv…

Angular coefficients and CP violating observables

V. Dedu and A. Poluektov, arXiv:2304.00966

$$\frac{d\Gamma(B \to D^{*}\ell\nu)}{dw d\cos\theta_\ell d\cos\theta_d d\chi} = (P_{\text{even}} + P_{\text{odd}})$$

- $P_{\text{odd}} \equiv 0$ in SM, but can have non-zero terms in NP:

Amplitude term	Coupling	Angular function
$\text{Im}(\mathcal{A}_\perp \mathcal{A}_0^*)$	$\text{Im}[(1+g_L+g_R)(1+g_L-g_R)^*]$	$-\sqrt{2}\sin 2\theta_\ell \sin 2\theta_D \sin\chi$
$\text{Im}(\mathcal{A}_\parallel \mathcal{A}_\perp^*)$	$\text{Im}[(1+g_L-g_R)(1+g_L+g_R)^*]$	$2\sin^2\theta_\ell \sin^2\theta_D \sin 2\chi$
$\text{Im}(\mathcal{A}_{SP} \mathcal{A}_{\perp,T}^*)$	$\text{Im}(g_P g_T^*)$	$-8\sqrt{2}\sin\theta_\ell \sin 2\theta_D \sin\chi$
$\text{Im}(\mathcal{A}_0 \mathcal{A}_\parallel^*)$	$\text{Im}[(1+g_L-g_R)(1+g_L+g_R)^*]$	$-2\sqrt{2}\sin\theta_\ell \sin 2\theta_D \sin\chi$

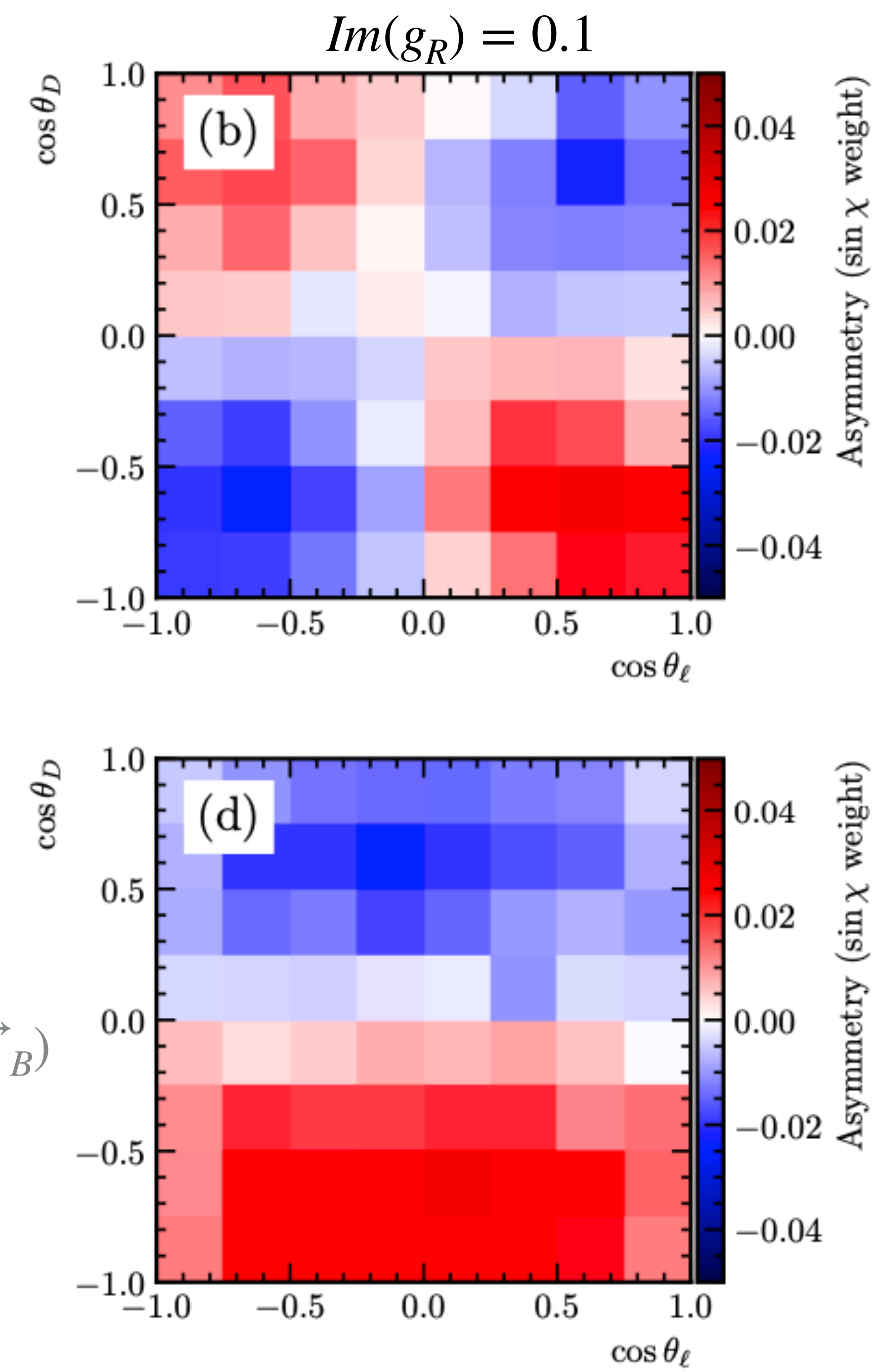
Right-handed vector

Interference of pseudo scalar and tensor currents

- Express sinχ using the momenta of reconstructible decay products and B momentum estimate for quadratic eq.

$$\sin\chi = S_1 \cdot (\vec{p}_\pi, \vec{p}_\mu, \vec{p}_D) + S_2 \cdot (\vec{p}_B, \vec{p}_\mu, \vec{p}_D) + S_3 \cdot (\vec{p}_\pi, \vec{p}_B, \vec{p}_D) + S_4 \cdot (\vec{p}_\pi, \vec{p}_\mu, \vec{p}_B)$$

- sinχ is P-odd and can be used as per-event weight to cancel out the P-even contribution in data



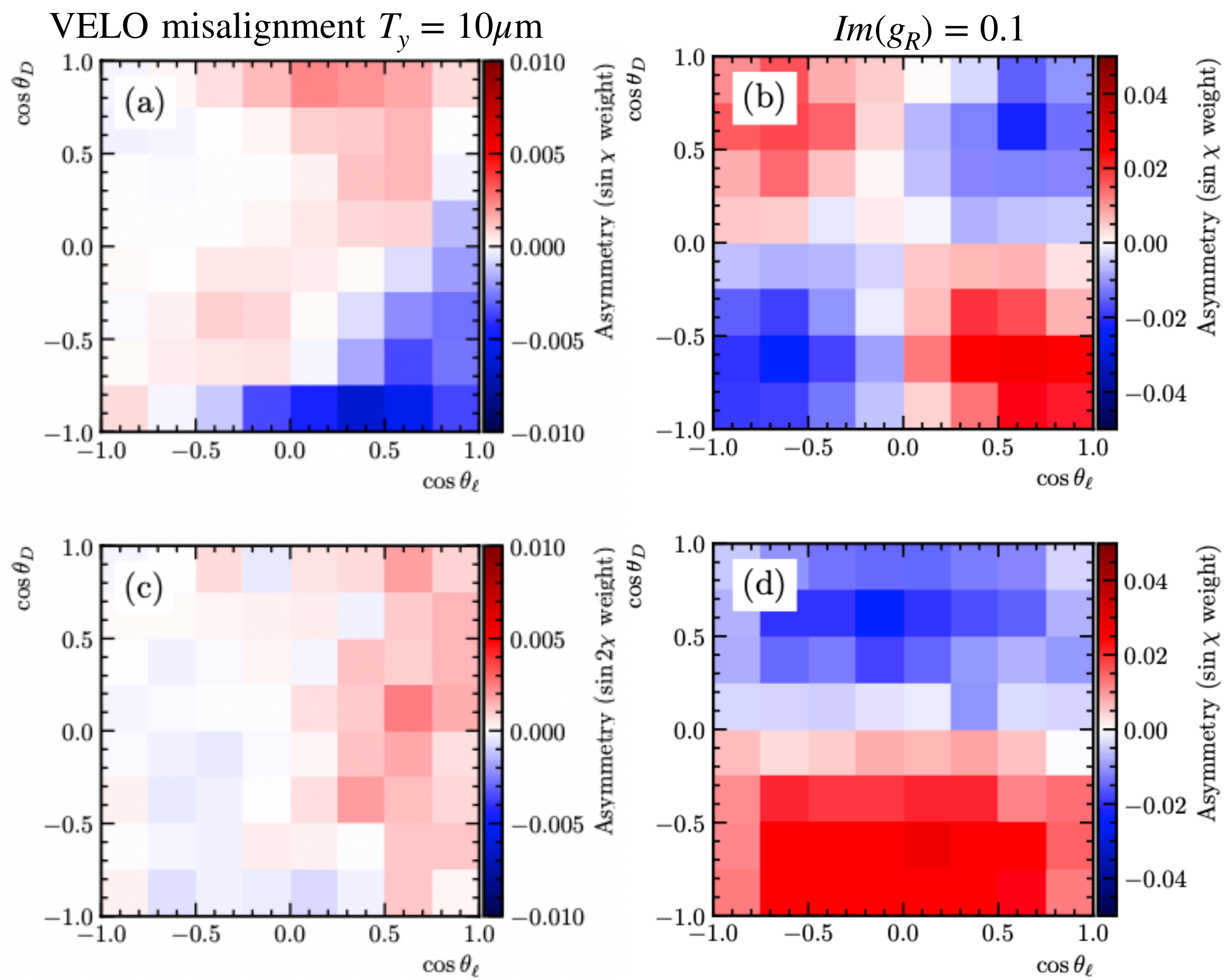
Angular coefficients and CP violating observables

V. Dedu and A. Poluektov, arXiv:2304.00966

$$\frac{d\Gamma(B \to D^{*}\ell\nu)}{dw\,d\cos\theta_\ell\,d\cos\theta_d\,d\chi} = (P_{\text{even}} + P_{\text{odd}})$$

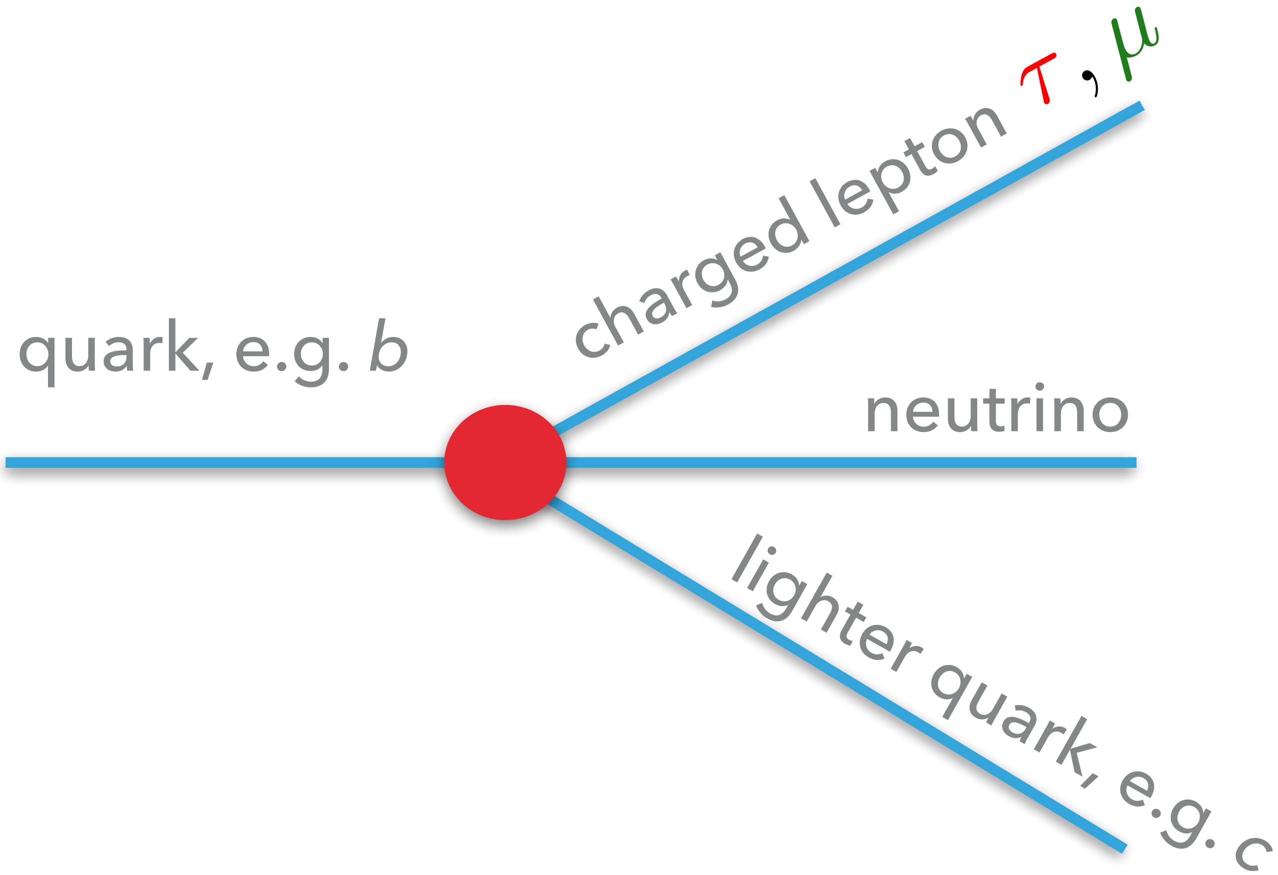
- Dedicated analysis optimised for CPV observables
- Statistical sensitivity with Run1+2 $B^0 \to D^{*}\mu\nu$ sample :~1% for Im(gR), 0.1% Im(gPgT*)
- A number of possible systematic uncertainties estimated: double-charm and D** backgrounds, detection asymmetry and detector misalignment

More in Anton's talk



EFT: Modelling New Physics (and hadronic) effects

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



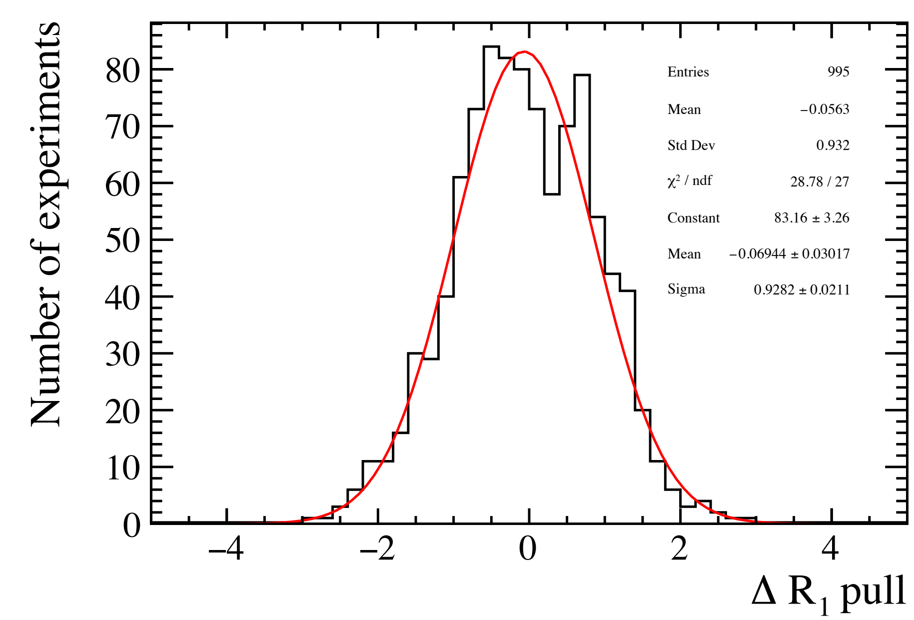
Wilson coefficients

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

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

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)



More in Patrick's talk

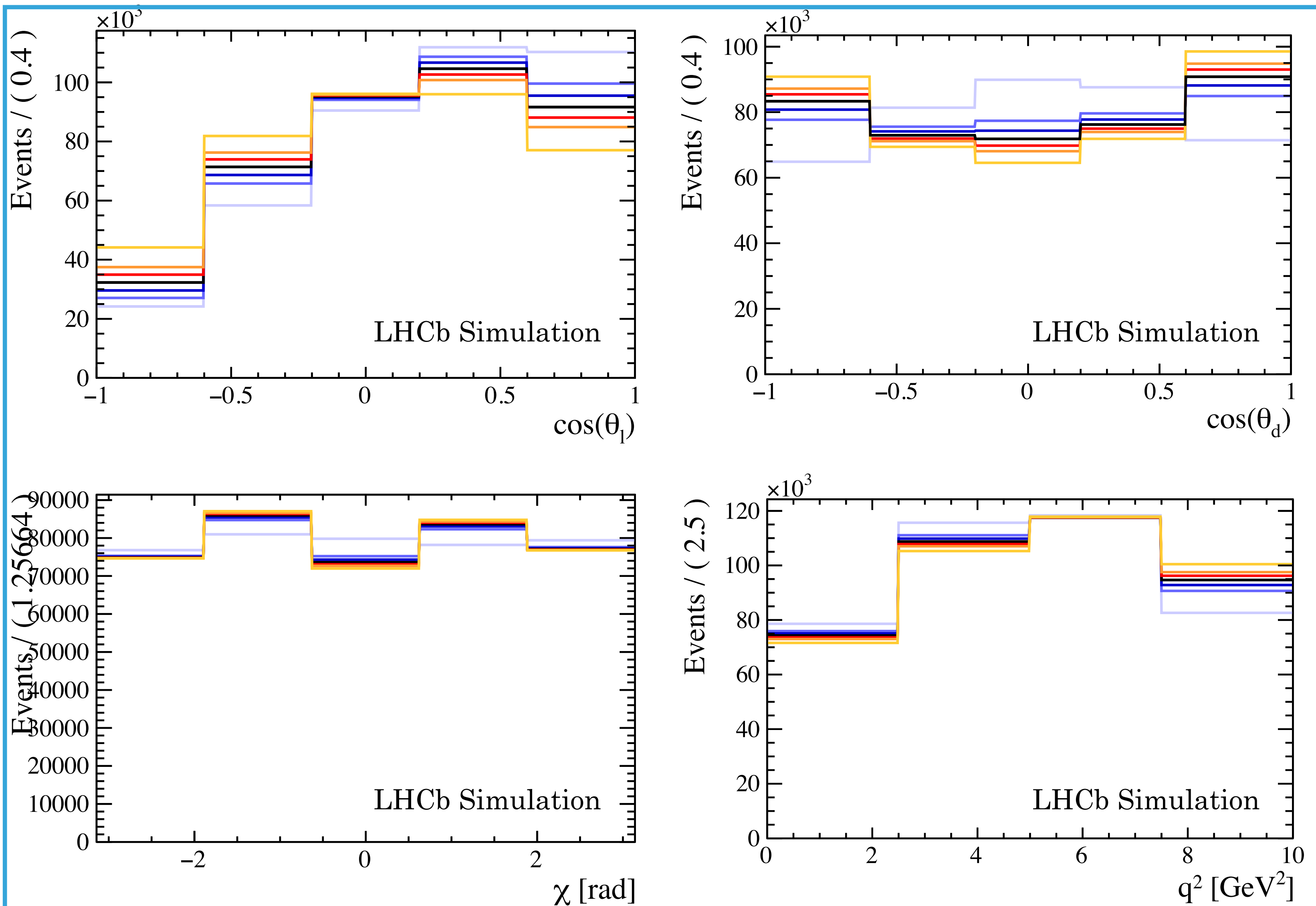
$B^0 \to D^{(*)}\mu\nu$

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

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

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

Ongoing angular analyses

- Different strategies considered:
- Measure directly Wilson Coefficients
- Measure angular coefficients (depend on amplitudes - q^2 dependence) which relate to the Wilson Coefficients

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_d d\cos\theta_\ell d\chi} \propto I_{1c}\cos^2\theta_d + I_{1s}\sin^2\theta_d + \left[I_{2c}\cos^2\theta_d + I_{2s}\sin^2\theta_d\right]\cos 2\theta_\ell + \left[I_{6c}\cos^2\theta_d + I_{6s}\sin^2\theta_d\right]\cos\theta_\ell + \left[I_3\cos 2\chi + I_9\sin 2\chi\right]\sin^2\theta_\ell\sin^2\theta_d + \left[I_4\cos\chi + I_8\sin\chi\right]\sin 2\theta_\ell\sin 2\theta_d + \left[I_5\cos\chi + I_7\sin\chi\right]\sin\theta_L\sin 2\theta_d$$

- CP-violating observables

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

SM

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

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	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	$\chi_R^S\lambda_R^S$	$[\bar{c}\chi_R^S P_R b][\bar{\ell}\lambda_R^S P_R\nu]$
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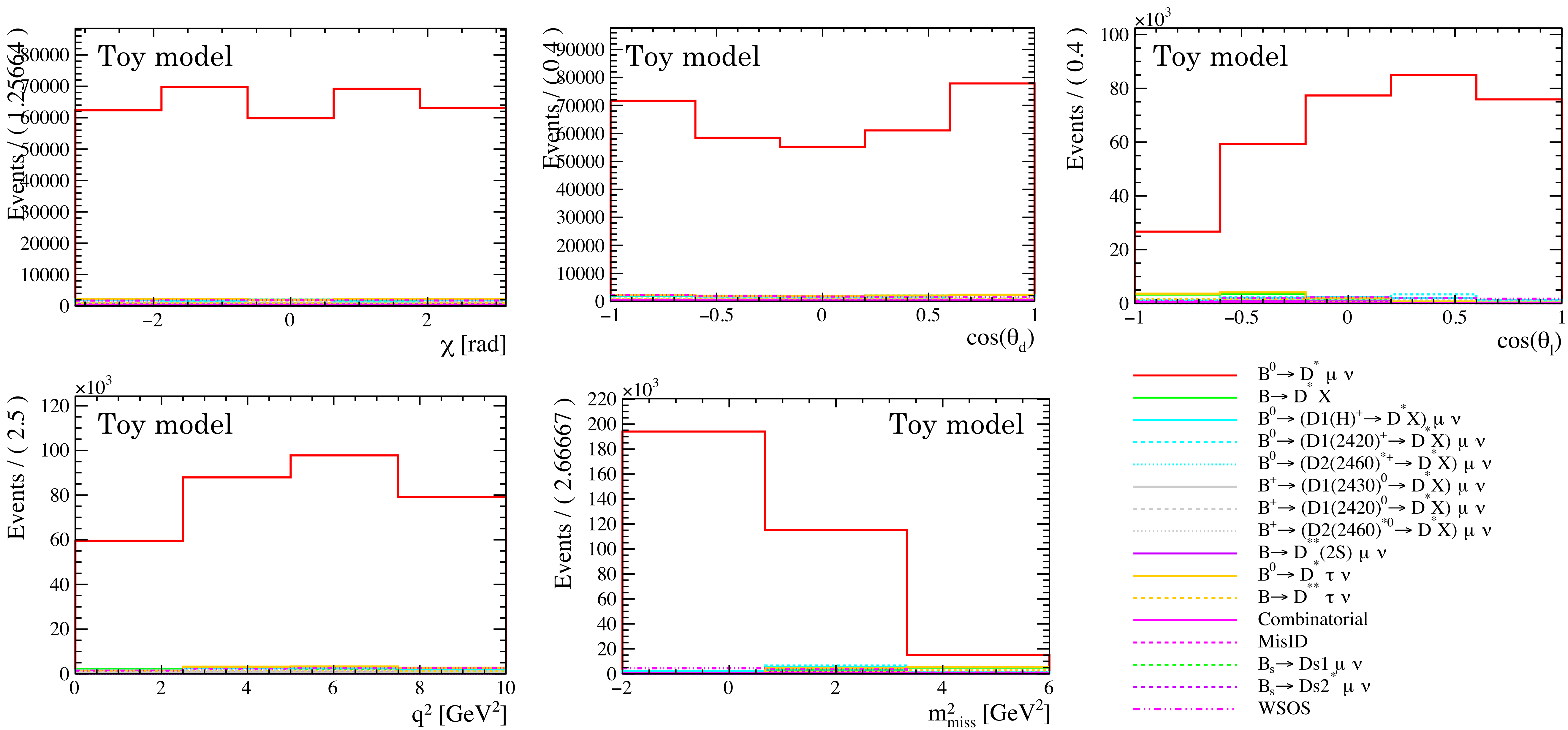
	T_qRlR	$\chi_R^T\lambda_R^T$	$[\bar{c}\chi_R^T\sigma^{\mu\nu}P_R b][\bar{\ell}\lambda_R^T\sigma_{\mu\nu}P_R\nu]$

Hammer Manual

An angular analysis of $B^0 \to D^{(*)}\mu\nu$

- **Extract directly Wilson Coefficients and FF parameters** from fit to data
- **Shape analysis only** - no attempt to measure $|V_{cb}|$, lose sensitivity to yield changes
- To be considered also as benchmark study/measurement



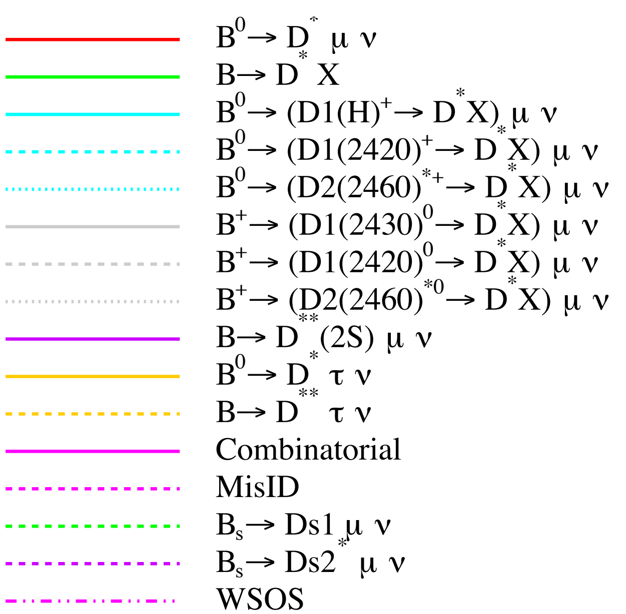
An angular analysis of $B^0 \to D^{(*)}\mu\nu$

- **Extract directly Wilson Coefficients and FF parameters** from fit to data
- **Shape analysis only** - no attempt to measure $|V_{cb}|$, lose sensitivity to yield changes
- To be considered also as benchmark study/measurement

- B→D**μν description using BLR parametrisation (arxiv:1711.03110, Phys. Rev. D 95, 014022 (2017)) and parameter values from R(D) vs R(D*)

- Despite the small contribution, care needed to choose B→D*τν model (and evaluating impact of the choice)

- Data-driven techniques when possible (background from mis-identified particles, random track combinations)



Hadronic Form Factors with full angular analysis

- SM fits: using CLN (Nuclear Physics B 530 (1998) 153-181) , BGL (Phys.Rev. D56 (1997) 6895-6911) and BLPR parametrisations

BGL

$$f(z) = \frac{1}{P_{1^+}(z)\phi_f(z)} \sum_{n=0}^{\infty} b_n z^n \qquad \mathcal{F}_1(z) = \frac{1}{P_{1^+}(z)\phi_{\mathcal{F}_1}(z)} \sum_{n=0}^{\infty} c_n z^n$$

$$g(z) = \frac{1}{P_{1^-}(z)\phi_g(z)} \sum_{n=0}^{\infty} a_n z^n \qquad \mathcal{F}_2(z) = \frac{1}{P_{0^-}(z)\phi_{\mathcal{F}_2}(z)} \sum_{n=0}^{\infty} d_n z^n$$

- Statistical precision comparable (Run1 only) to latest B-factory measurements (Phys. Rev. D 100, 052007 (2019), Phys. Rev. Lett. 123, 091801 (2019)), and increased (as expected) wrt LHCb R(D*) measurement on same dataset

Parameter	Expected sensitivity (stat) with Run1 dataset statistics
Δa0	6E-05
Δa1	5E-03
Δa2	8E-02
Δb1	6E-04
Δb2	1E-02
Δc1	8E-05
Δc2	1E-03
Δd0	1E-02
Δd1	3E-01

CLN

Parameter	Expected sensitivity (stat) with Run1 dataset
ΔR1	1.5E-02
ΔR2	1.3E-02
ΔR0	1,7E-01
Δρ^2	1.8E-02

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Hadronic Form Factors with full angular analysis

- Using **BLPR** parametrisation for New Physics (and possibly SM) fits
- Incorporates HQET predictions that relate the FFs for NP matrix elements to the SM ones
- Calculations by F. Bernlochner *et. al.* Phys. Rev. D 95, 115008 (2017) , using both the leading and $\mathcal{O}(\Lambda_{QCD}/m_b)$ sub-leading Isgur-Wise function - starting values for fit parameters from fit in Phys. Rev. D 95, 115008 (2017) without any experimental inputs
- Intended approach (at least from HAMMER) was SM fit to B→D*μν and use FF HQET parameters as input for NP fit to B→D*τν
- High statistics B→D*μν analysis still useful - need for BGL and/or also some more general parametrisation (in HAMMER would be great!)

Parameter	Starting value	Expected sensitivity (stat)* with Run1 dataset statistics
$\bar{\rho}_*^2$	1.24+/-0.08	O(0.1)
$\hat{\chi_2}(1)$	-0.06+/-0.02	O(0.1)
$\hat{\chi_2}'(1)$	0.0+/-0.02	0.3
$\hat{\chi_3}'(1)$	0.05+/-0.02	0.9*
$\eta(1)$	0.30+/-0.04	0.1
$\eta'(1)$	-0.05+/-0.10	0.5
V_{20}	75	$\mathcal{O}(10^2)$

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* changes depending on NP scenario

* large correlation between Δχ3 and Δρ^2

New Physics Wilson Coefficients

- Ideally no assumption about the NP structure (Eur. Phys. J. C 80, 883 (2020))
- In practice easier searches for specific NP models (e.g. Bhattacharya *et. al.* JHEP 05 (2019) 191)
- Studied different NP scenarios (plan to report fit results for each)

WC floating in fit \ Expected (stat - Run1) uncertainty on WC	VqRlL	VqLlL	SqRlL (SqLlL)	TqLlL
VqRlL	$\mathcal{Im}\ \mathcal{O}(10^{-2})$ $\mathcal{Re}\ \mathcal{O}(10^{-2})$			
VqLlL		$\mathcal{Im}\ \mathcal{O}(10^{-1})$ $\mathcal{Re}$ —		
SqRlL (SqLlL)			$\mathcal{Im}\ \mathcal{O}(10^{-1})$ $\mathcal{Re}\ \mathcal{O}(10^{-1})$	
TqLlL				$\mathcal{Im}\ \mathcal{O}(10^{-3})$ $\mathcal{Re}\ \mathcal{O}(10^{-3})$
VqRlL+VqLlL+ SqRlL+ TqLlL	$\mathcal{Im}\ \mathcal{O}(10^{-2})$ $\mathcal{Re}\ \mathcal{O}(10^{-2})$	$\mathcal{Im}\ \mathcal{O}(10^{0})$ $\mathcal{Re}$ —	$\mathcal{Im}\ \mathcal{O}(10^{-1})$ $\mathcal{Re}\ \mathcal{O}(10^{-1})$	$\mathcal{Im}\ \mathcal{O}(10^{-3})$ $\mathcal{Re}\ \mathcal{O}(10^{-2})$

Uncertainties increase, generally within same order of magnitude, fits less stable →

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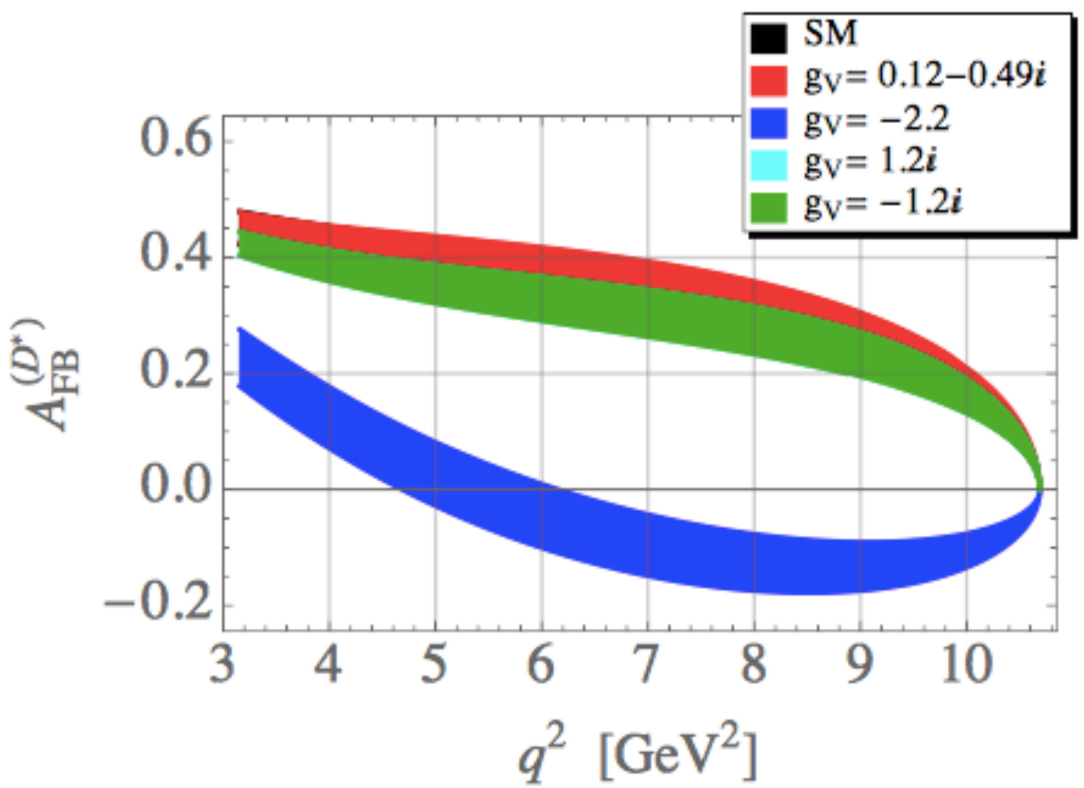
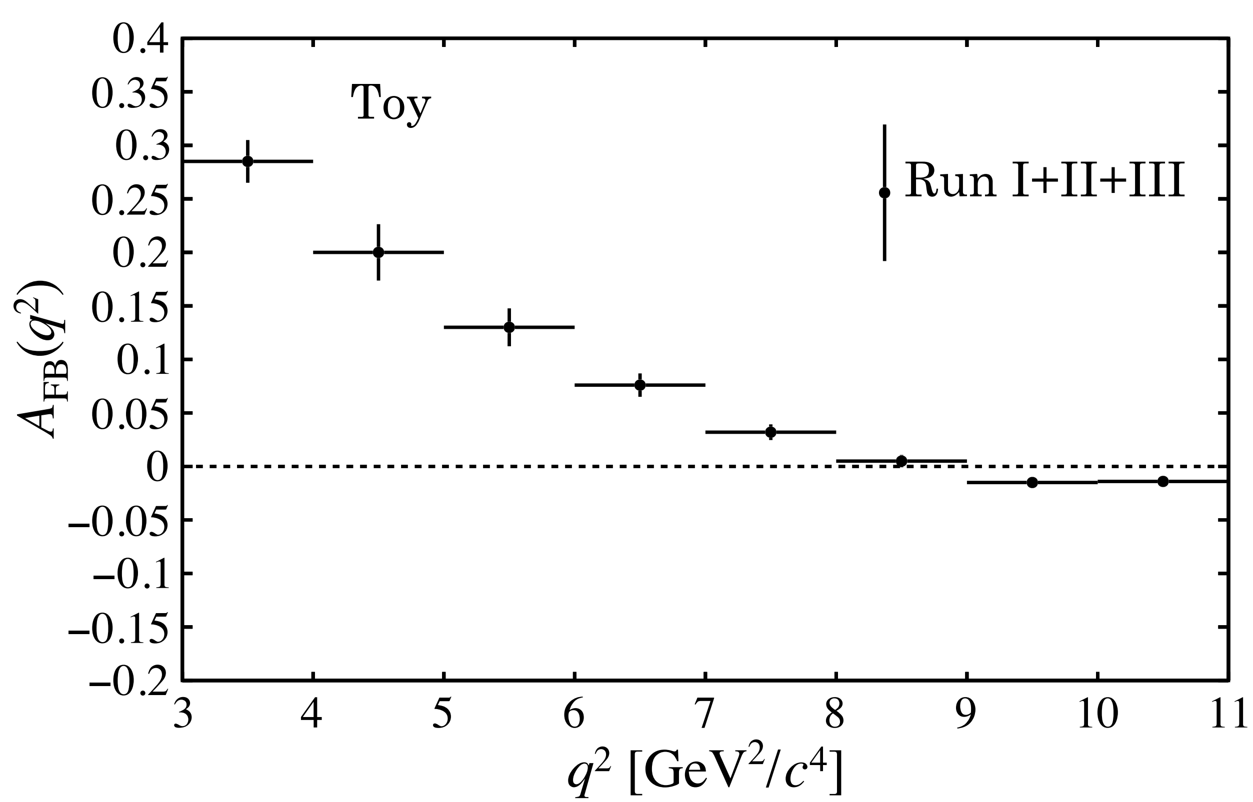
$B^0 \to D^{(*)}\tau\nu$

- Ideally shape + rate analysis, i.e. R(D) vs R(D*) determination simultaneous to WC
- Sensitivity studies need to include the full set of (at times poorly known) backgrounds

- Additional observables can be used to constrain NP contributions - while preparing/in addition to simultaneous R(D) vs R(D*) and angular analyses (e.g. longitudinal D* polarisation, measured by Belle $F_L^{D^*} = 0.60 \pm 0.08(\mathrm{stat}) \pm 0.04(\mathrm{syst})$ arXiv:1903.03102, …)



Becirevic *et.al.* arXiv:1602.03030



Well advanced: D* polarisation and angular coefficient analyses

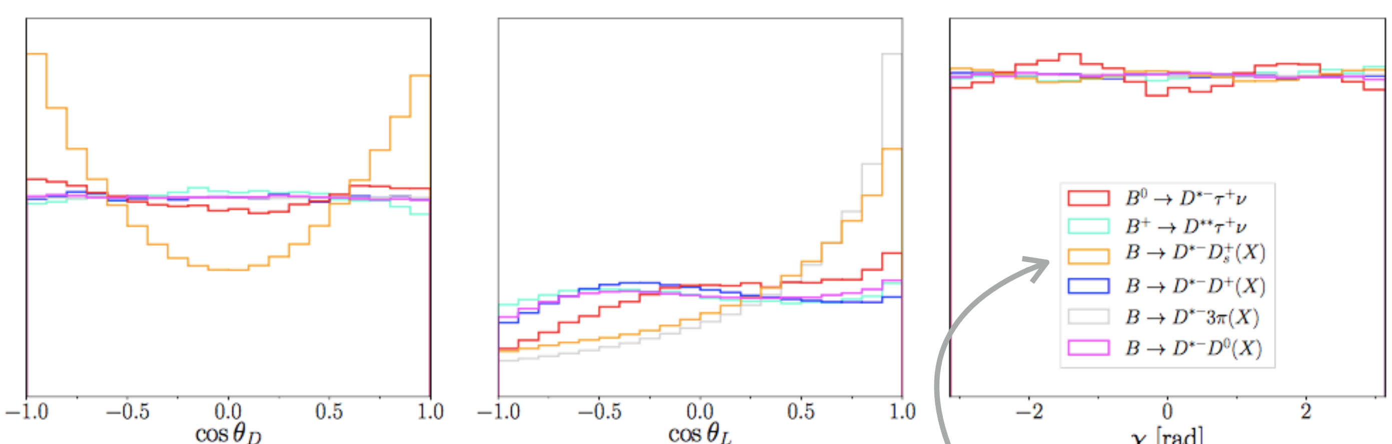
$B^0 \to D^{(*)}\tau\nu$

- Ideally shape + rate analysis, i.e. R(D) vs R(D*) determination simultaneous to WC
- Sensitivity studies need to include the full set of (at times poorly known) backgrounds
- Better angular resolutions when using 3-prong hadronic tau decays

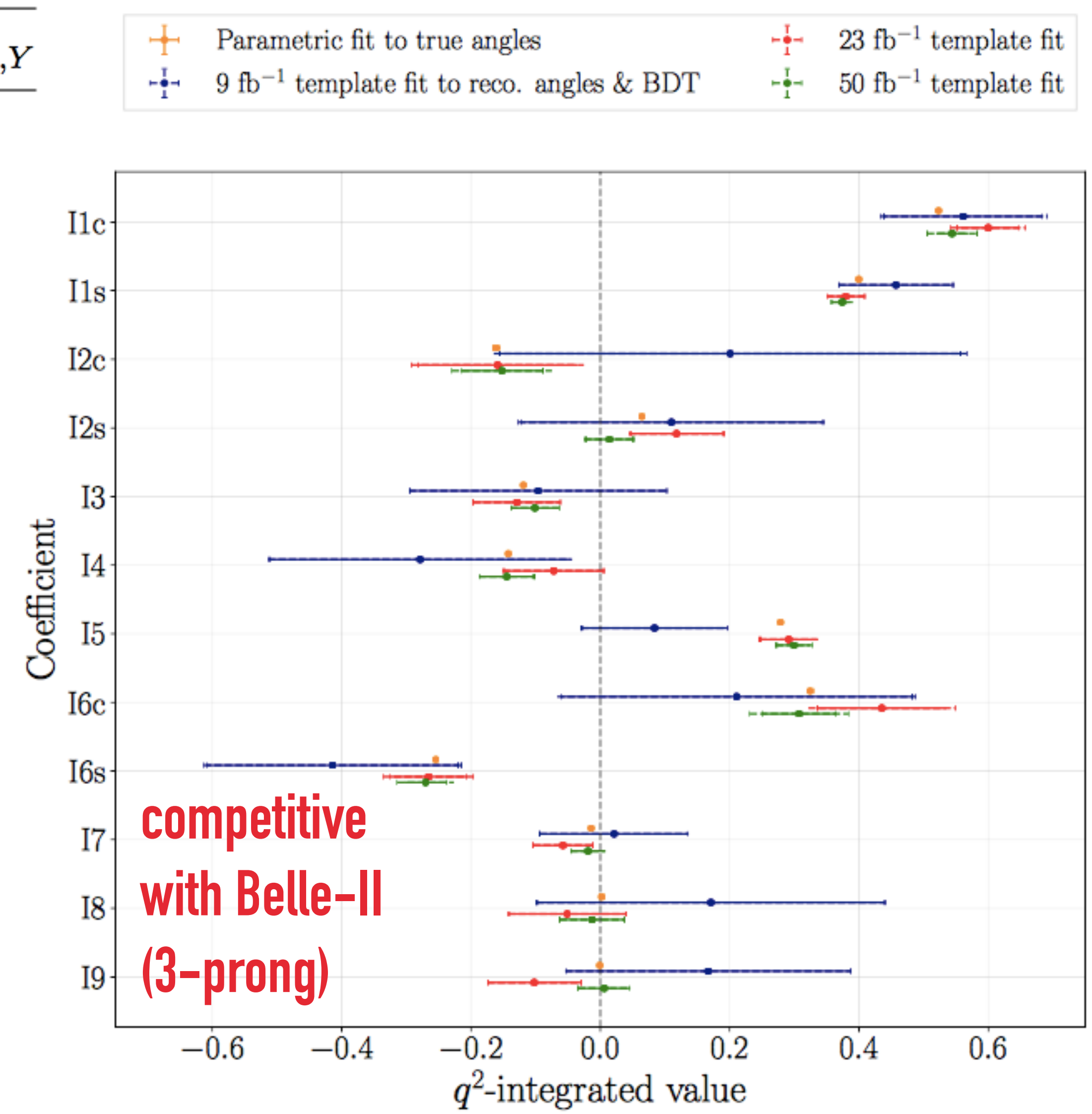
D. Hill et.al., JHEP 11 (2019) 133

$$|\vec{p}_{B^0}| = \frac{(m_Y^2 + m_{B^0}^2)|\vec{p}_Y|\cos\theta_{B^0,Y} \pm E_Y\sqrt{(m_{B^0}^2 - m_Y^2)^2 - 4m_{B^0}^2|\vec{p}_Y|^2\sin^2\theta_{B^0,Y}}}{2(E_Y^2 - |\vec{p}_Y|^2\cos^2\theta_{B^0,Y})}$$

$Y = D^{*-}\tau^+$, estimated up to a two-fold ambiguity



JHEP 06 (2021) 177



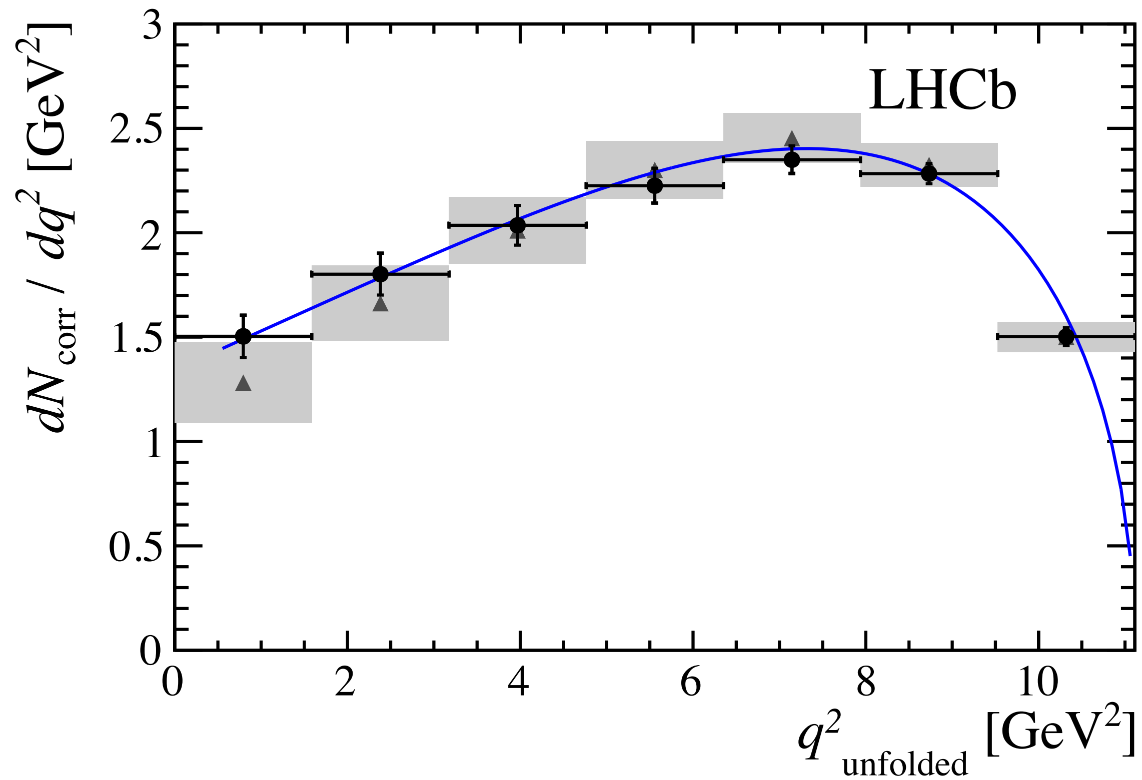
- Lower statistics than muonic decays samples, large backgrounds, external inputs needed for R(D), R(D*)

Baryons: $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}$

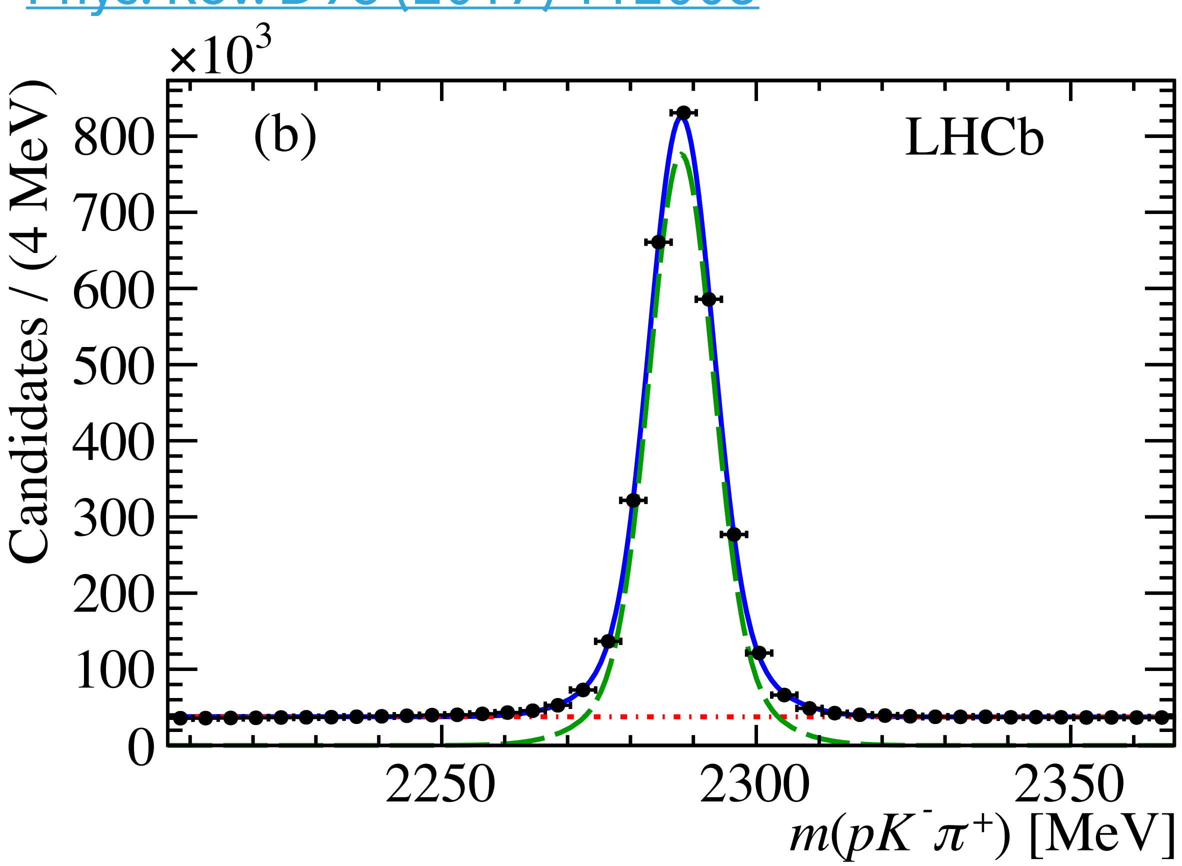
- Probing baryonic decays - different spin structure
- Measurement of the shape of the differential decay rate using Run-I dataset
- Low background level and smooth acceptance across decay variables

Lattice Phys. Rev. D92 (2015) 034503 (grey band)

Unfolded data distribution described by single form factor fit (blue line)



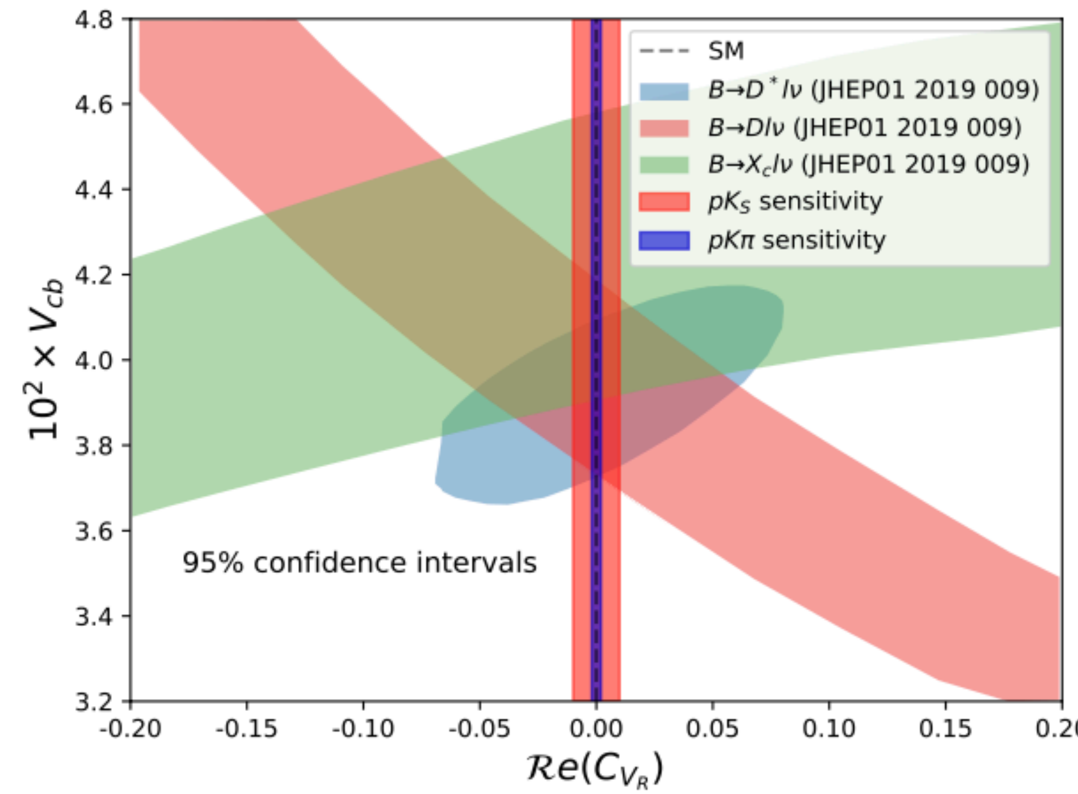
Phys. Rev. D96 (2017) 112005

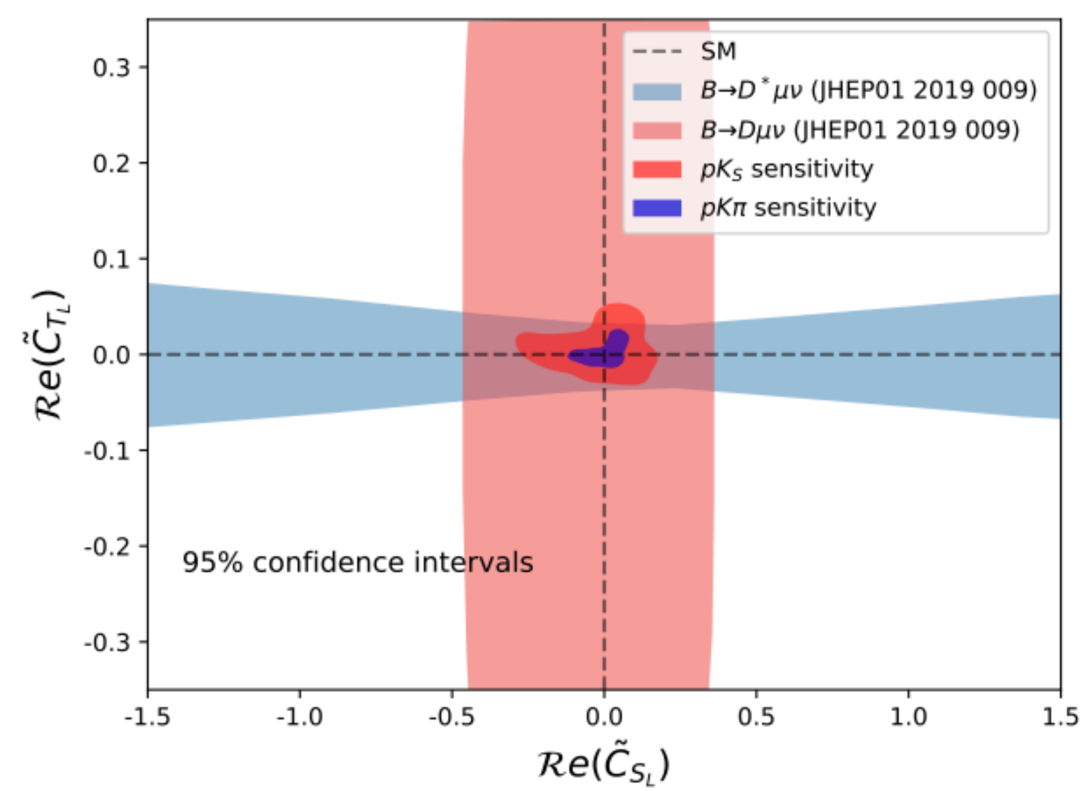


Final state	Yield
$\Lambda_c(2595)^+\mu^-\bar{\nu}_\mu$	8569 ± 144
$\Lambda_c(2625)^+\mu^-\bar{\nu}_\mu$	22965 ± 266
$\Lambda_c(2765)^+\mu^-\bar{\nu}_\mu$	2975 ± 225
$\Lambda_c(2880)^+\mu^-\bar{\nu}_\mu$	1602 ± 95
$\Lambda_c^+\mu^-\bar{\nu}_\mu X$	$(2.74\pm0.02)\times10^6$

Baryons: $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}$

- Study of the sensitivity with collected samples to Real NP Wilson Coefficients for decays with zero and non-zero Λb polarisation
- 2D Fits to q^2 and cosθμ for zero polarisation case
- Sensitivity compared to global fits to B→D(*)lν (M. Jung, D.M. Straub, JHEP 01 (2019) 009)





Free parameters	pK_S^0 case	$pK^-\pi^+$ case
C_{V_R}	0.005	0.001
C_{S_R}	0.046	0.018
C_{T_L}	0.020	0.007
C_{S_L}	0.091	0.039
$P_{\Lambda_b^0}$	0.13	–
$\alpha_{\Lambda_c^+}$	0.003	–

M. Ferrillo et. al., JHEP 12 (2019) 148

Summary

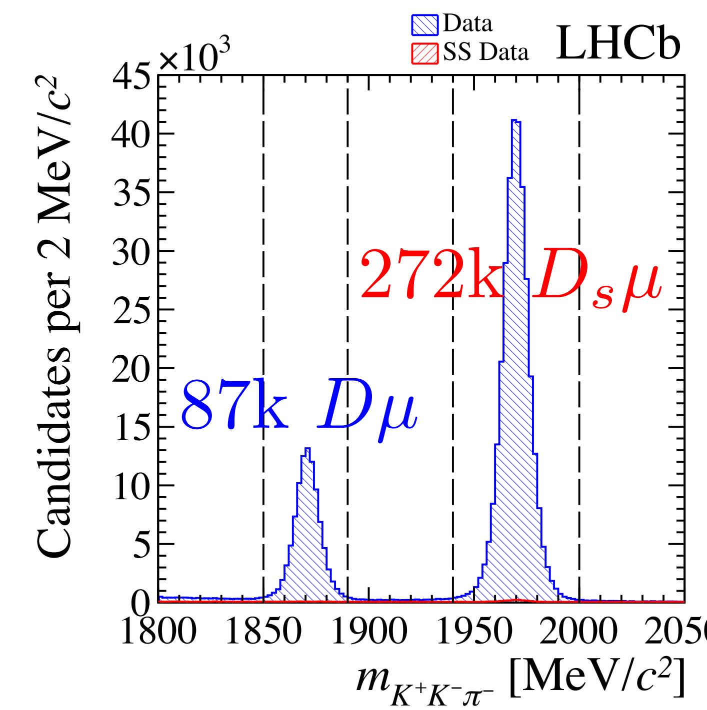
- Angular analyses of SL decays are possible at LHCb …
- … with different challenges with respect to the B factories
- Started developing these analyses mainly from the semi-muonic decays
- More leptons, observables, b-hadrons and decay modes to come!

Back-up

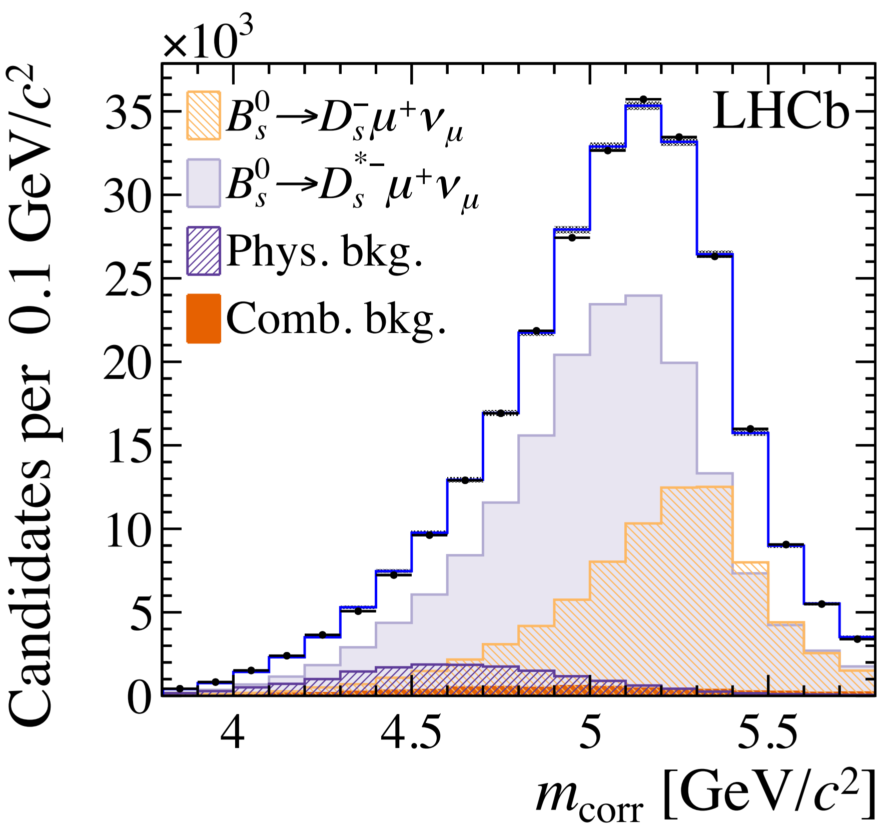
Hadronic Form Factors measurements and $|V_{cb}|$

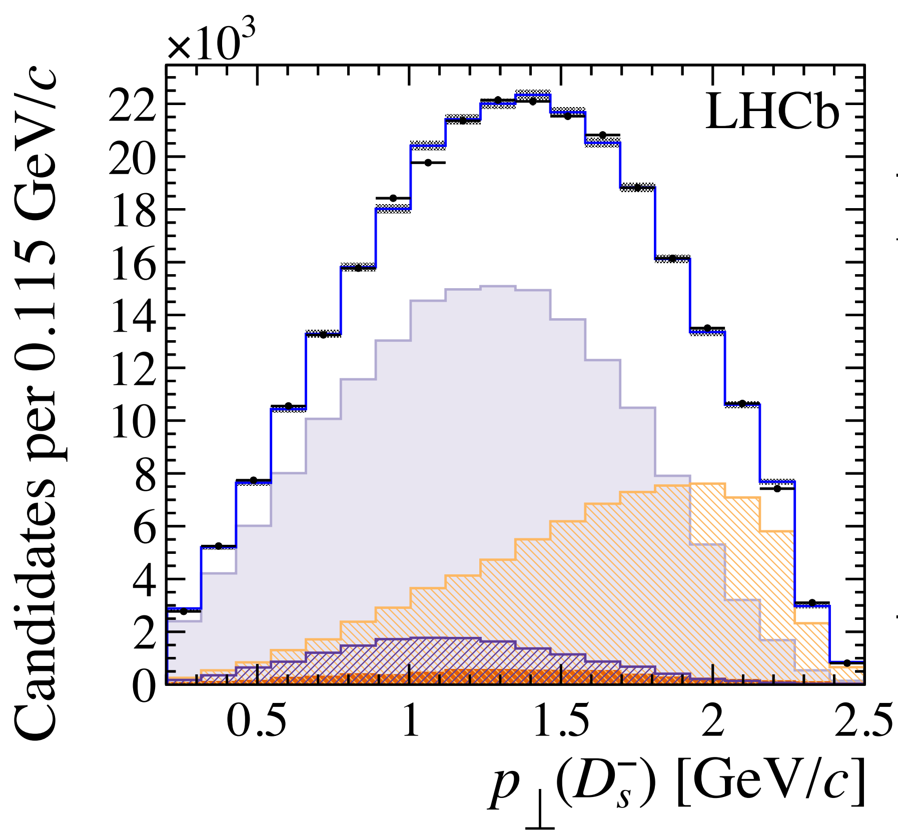
- First measurement of $|V_{cb}|$ using $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$
  - Measure rate relative to $B^0 \to D^{(*)-}\mu^+\nu_\mu$
  - Requires external inputs for $|V_{cb}|$
  - Measurement of decay rate as a function of $p_\perp(D_s^-)$, proxy for q^2 or recoil w ($D_s^{(*)-}$ energy in the B_s^0 rest frame)

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



Phys. Rev. D101 (2020) 072004



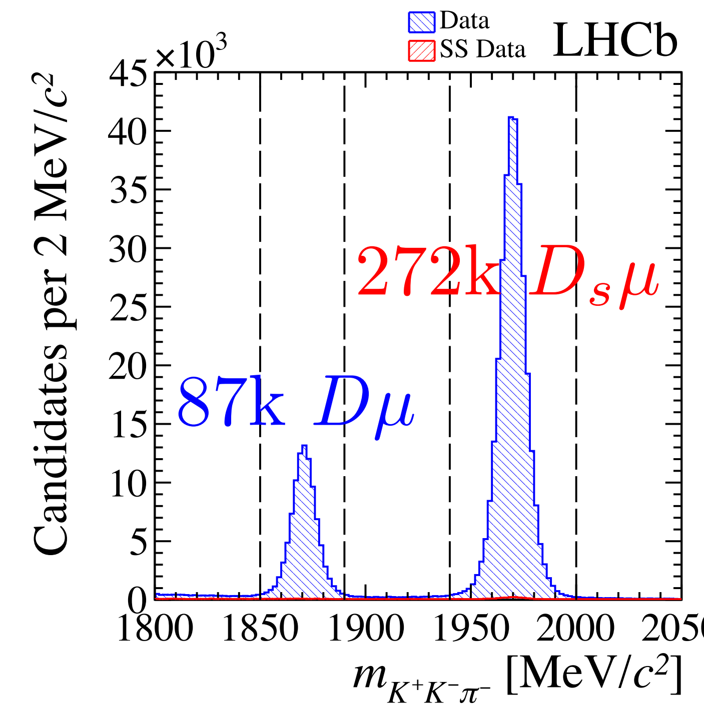


BGL

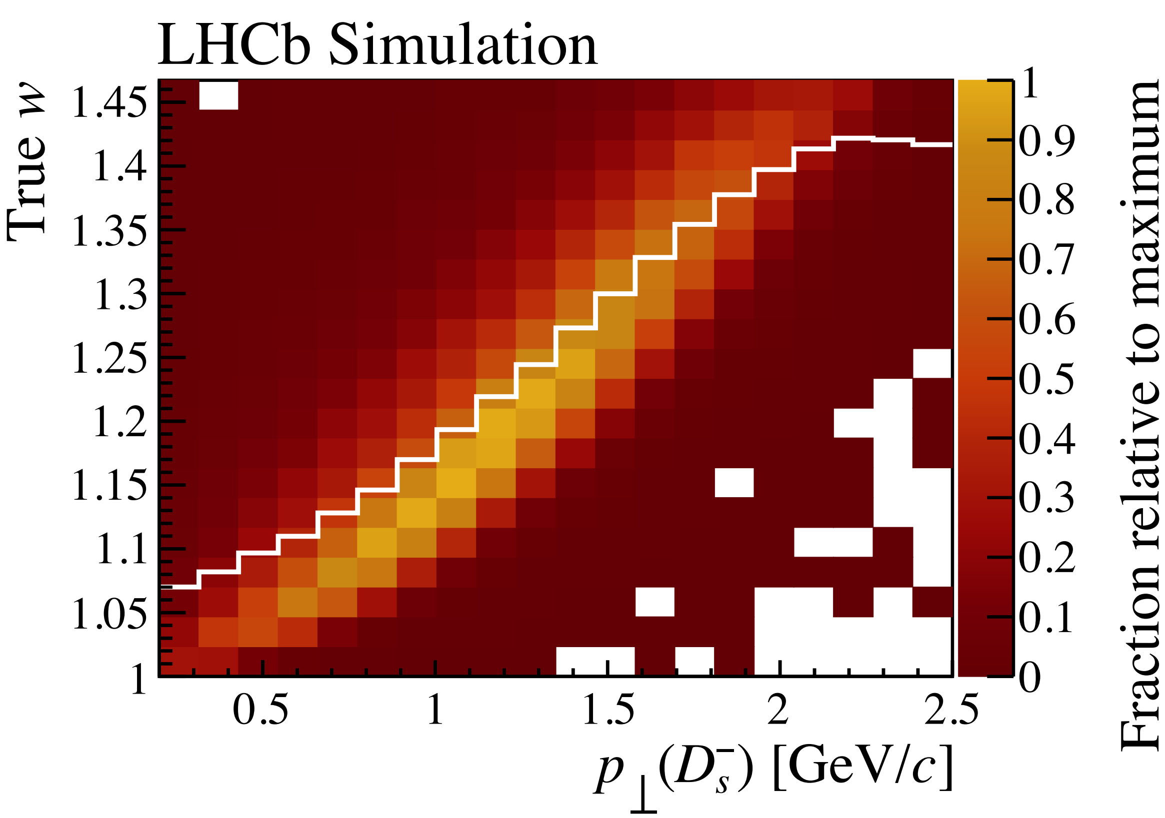
Parameter		Value				
$\lvert V_{cb}\rvert$ $[10^{-3}]$		42.3	$\pm$ 0.8	(stat)	$\pm$ 1.2	(ext)
$\mathcal{G}(0)$		1.097	$\pm$ 0.034	(stat)	$\pm$ 0.001	(ext)
d_1		-0.017	$\pm$ 0.007	(stat)	$\pm$ 0.001	(ext)
d_2		-0.26	$\pm$ 0.05	(stat)	$\pm$ 0.00	(ext)
b_1	a_1^f	-0.06	$\pm$ 0.07	(stat)	$\pm$ 0.01	(ext)
a_0	a_0^g	0.037	$\pm$ 0.009	(stat)	$\pm$ 0.001	(ext)
a_1	a_1^g	0.28	$\pm$ 0.26	(stat)	$\pm$ 0.08	(ext)
c_1	$a_1^{\mathcal{F}_1}$	0.0031	$\pm$ 0.0022	(stat)	$\pm$ 0.0006	(ext)

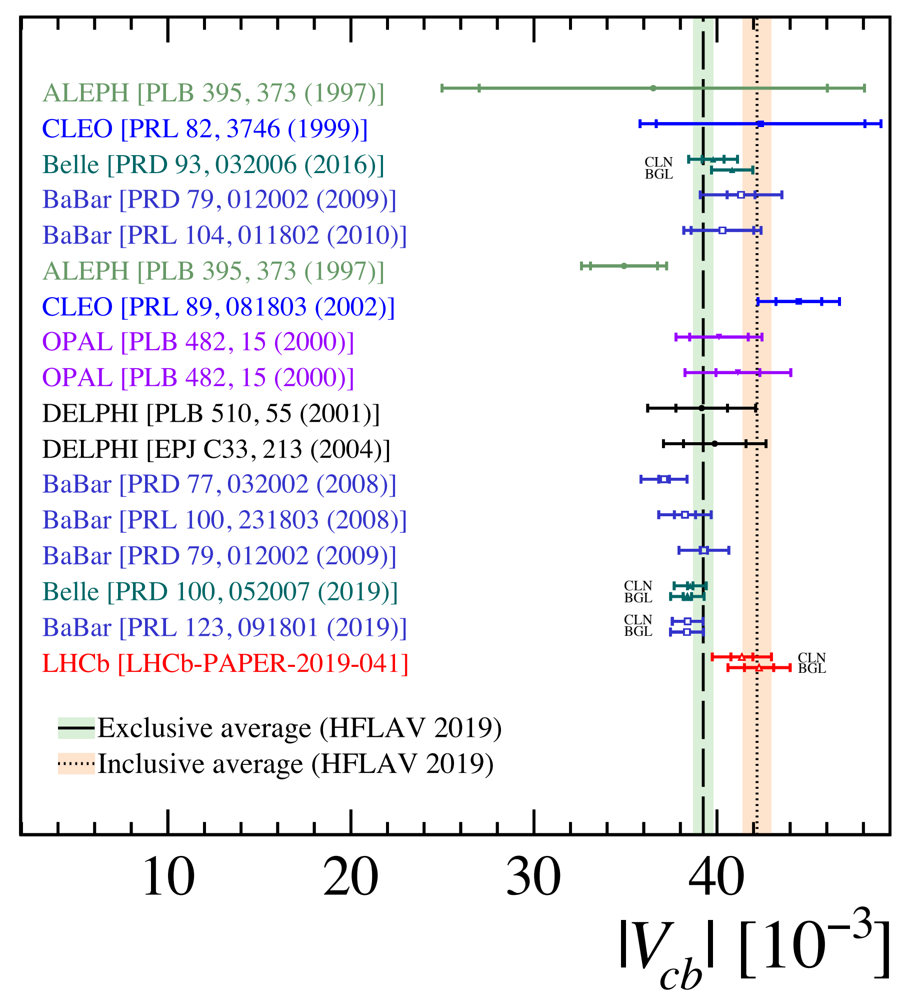
Measurements of $|V_{cb}|$ and hadronic form factors

- First measurement of $|V_{cb}|$ using $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$
  - Measure rate relative to $B^0 \to D^{(*)-}\mu^+\nu_\mu$
  - Requires external inputs for $|V_{cb}|$
  - Measurement of decay rate as a function of $p_\perp(D_s^-)$, proxy for q^2 or recoil w ($D_s^{(*)-}$ energy in the B_s^0 rest frame)



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





Two FF parametrisations - **consistent**

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