New physics searches with angular analyses of b-hadron decays

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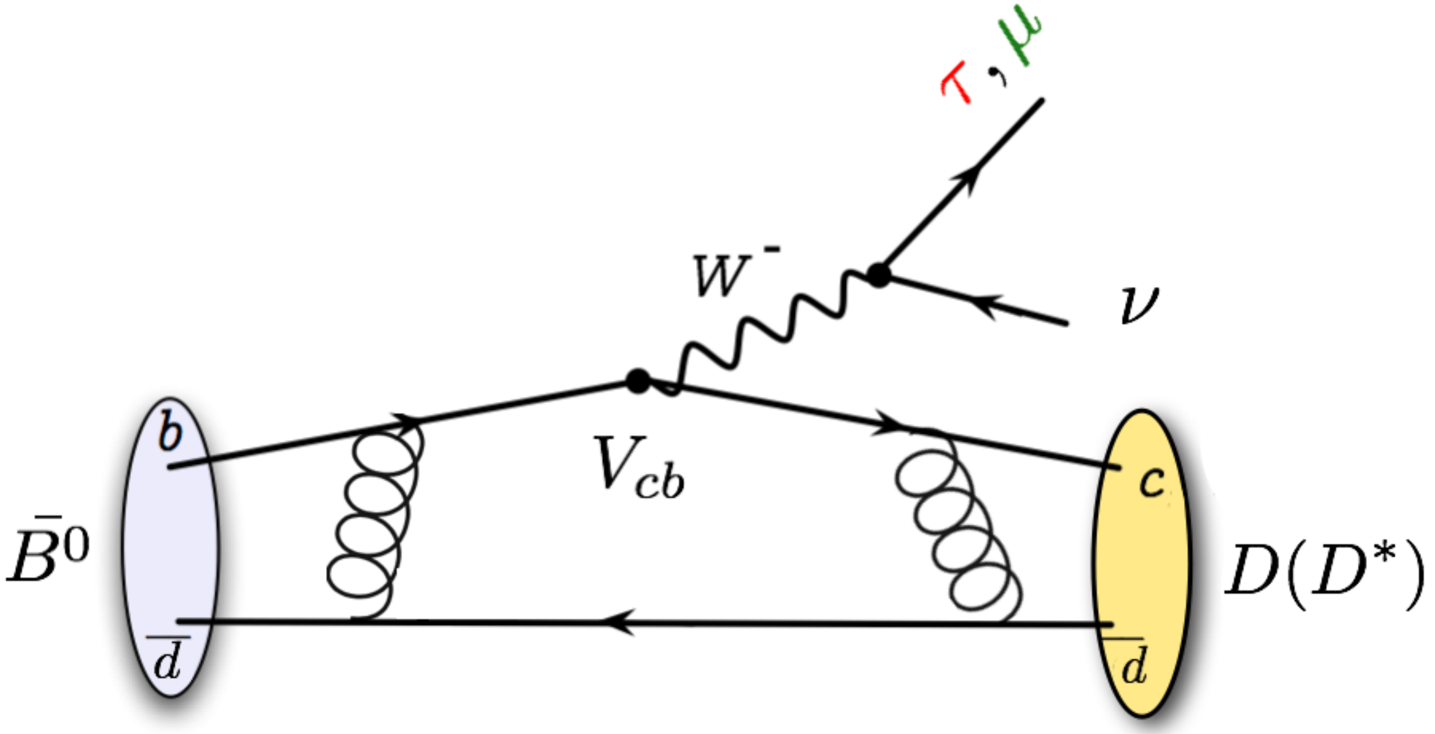
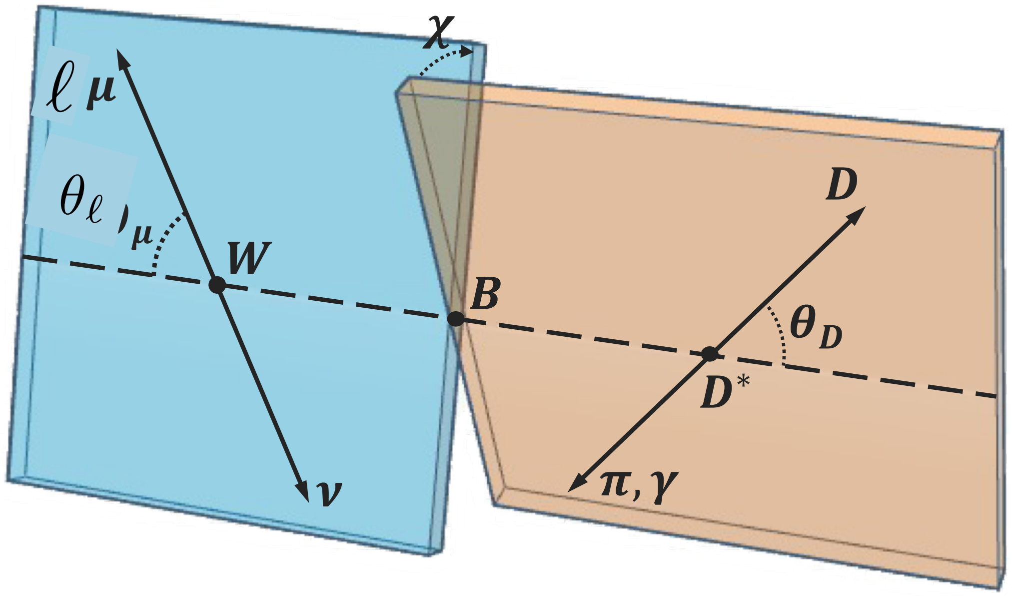
with input from Greg Ciezarek, Biljana Mitreska, Hasret Nur, Marcello Rotondo, and others

Challenges of semileptonic b-hadron decays

25 September 2024

Differential measurements of b-hadron decays





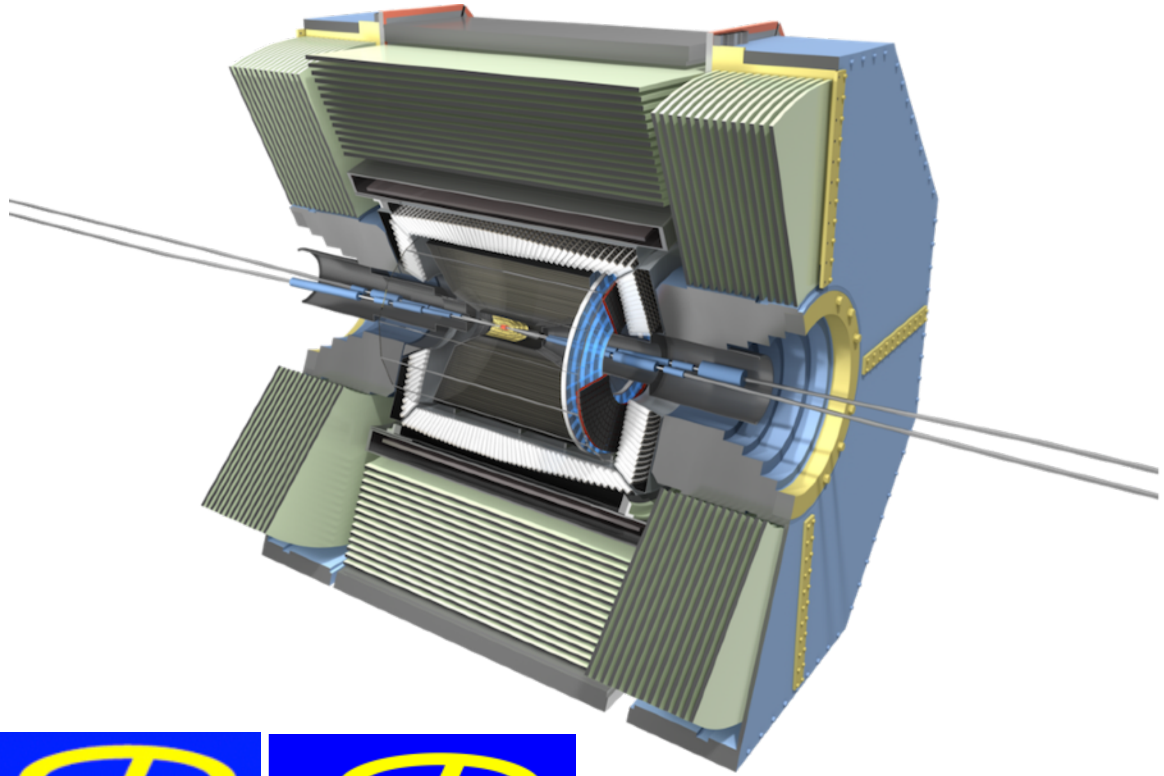
$$\frac{d^4(B^0 \to D^* \ell^+ \nu_\ell)}{dq^2 d\cos^2\theta_\ell d\cos\theta_{D^*} d\chi} \propto |V_{cb}|^2 \sum_i \underset{\uparrow}{\mathcal{H}_i}(q^2) f_i(\theta_\ell, \theta_{D^*}, \chi)$$

(Electroweak) couplings + **QCD** encompassed by Form Factors

Sensitive to New Physics

- 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

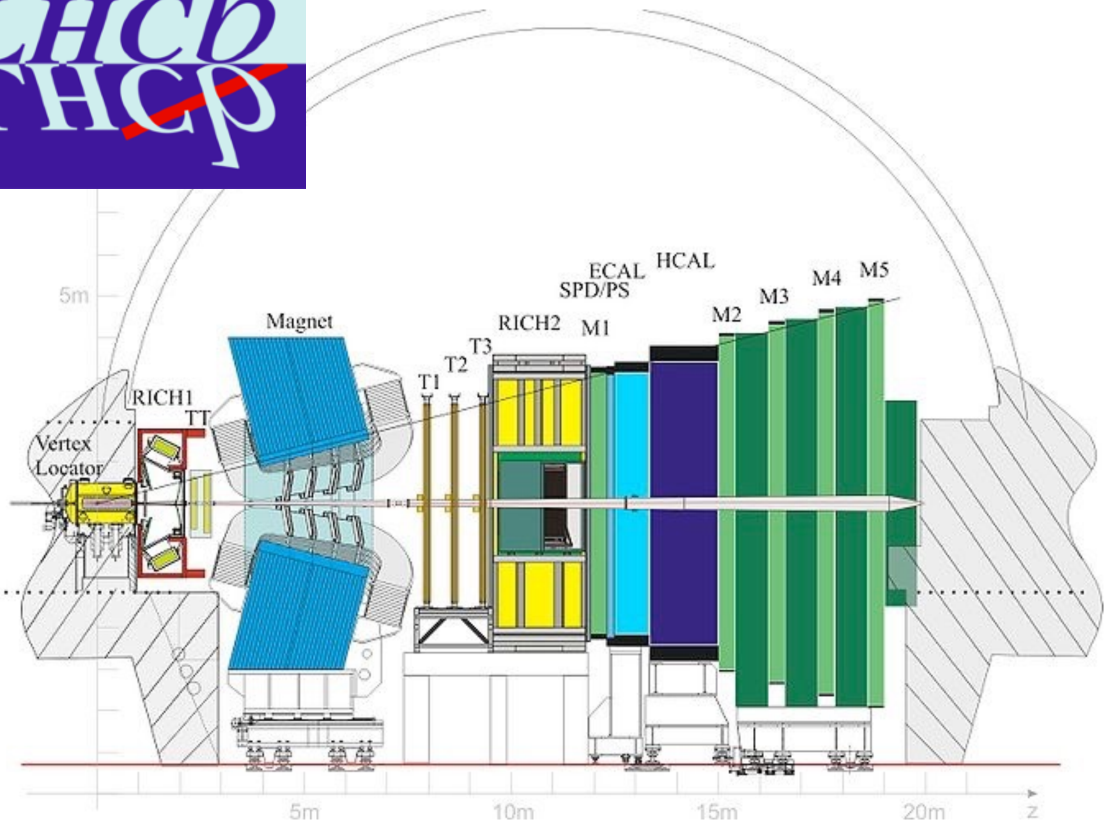
Experimental datasets



BELLE Belle II

- Constrained kinematics
- Cleaner environment
- Electrons as good as muons

LHCb

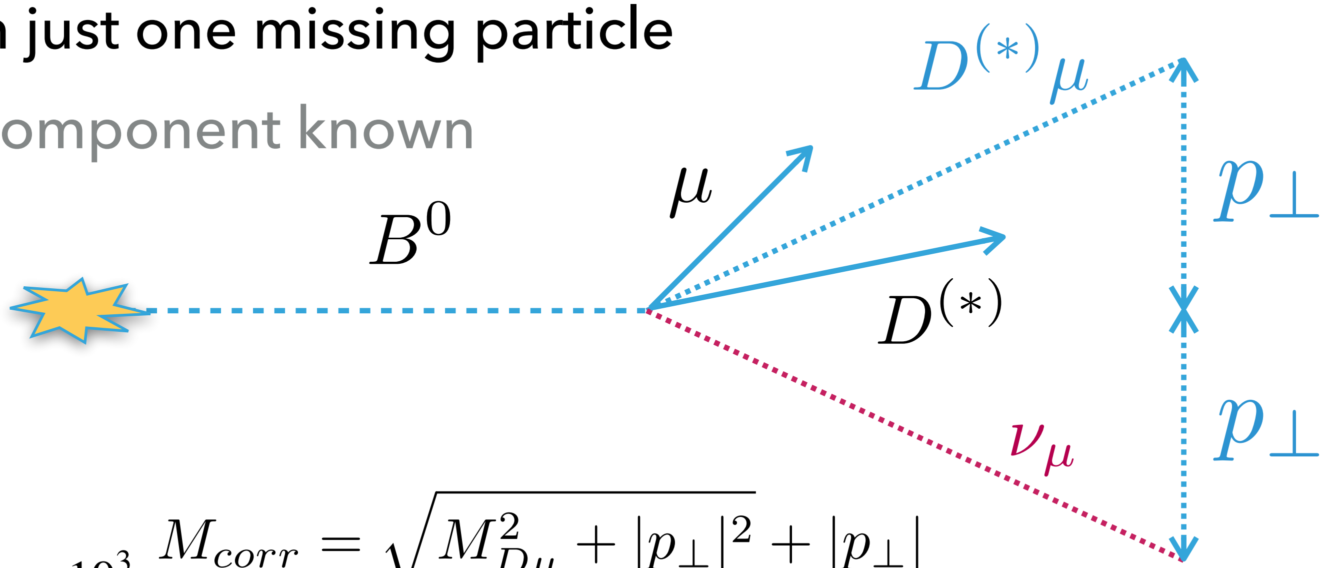


- Unconstrained kinematics
- Different background composition (hadron collision environment, partial reconstruction etc)
- Larger boost
- Unprecedentedly sized samples
- Full suite of hadron species available

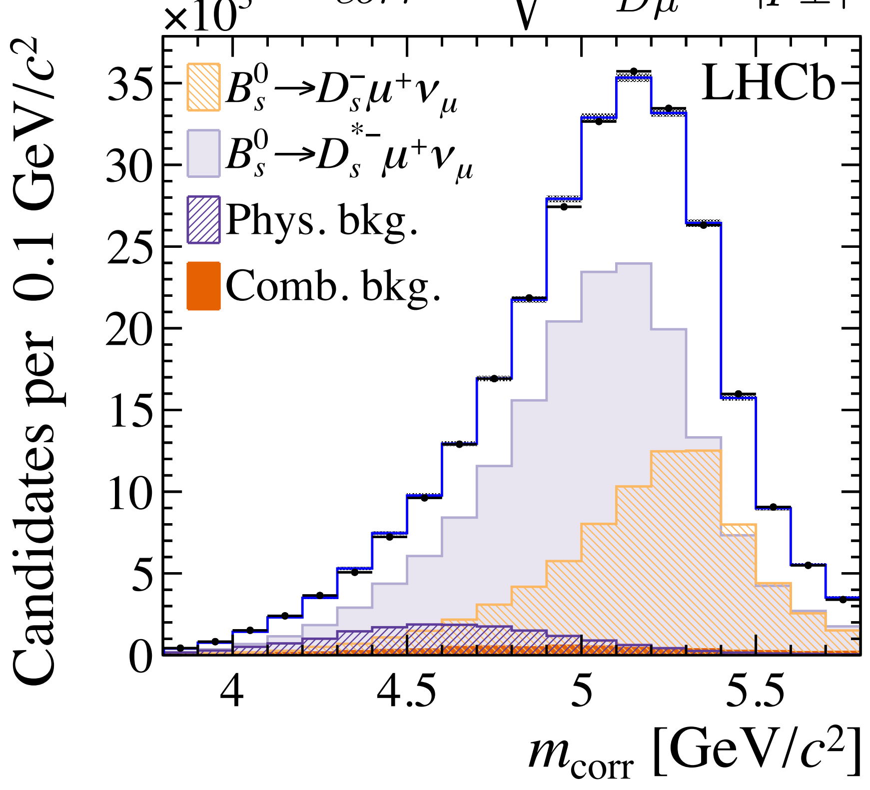
Focus on LHCb B meson analyses (see Anna's talk for baryons)

Light leptons

- At LHCb muons are clearly easier (results with light leptons so far use muons)
    - Fewer electrons than muons @LHCb with worse resolution, but less noticeable with unconstrained kinematics
- Partial reconstruction, but good options with just 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
        - Used proxy variable(s) (e.g. Phys. Rev. D101 (2020) 072004)



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



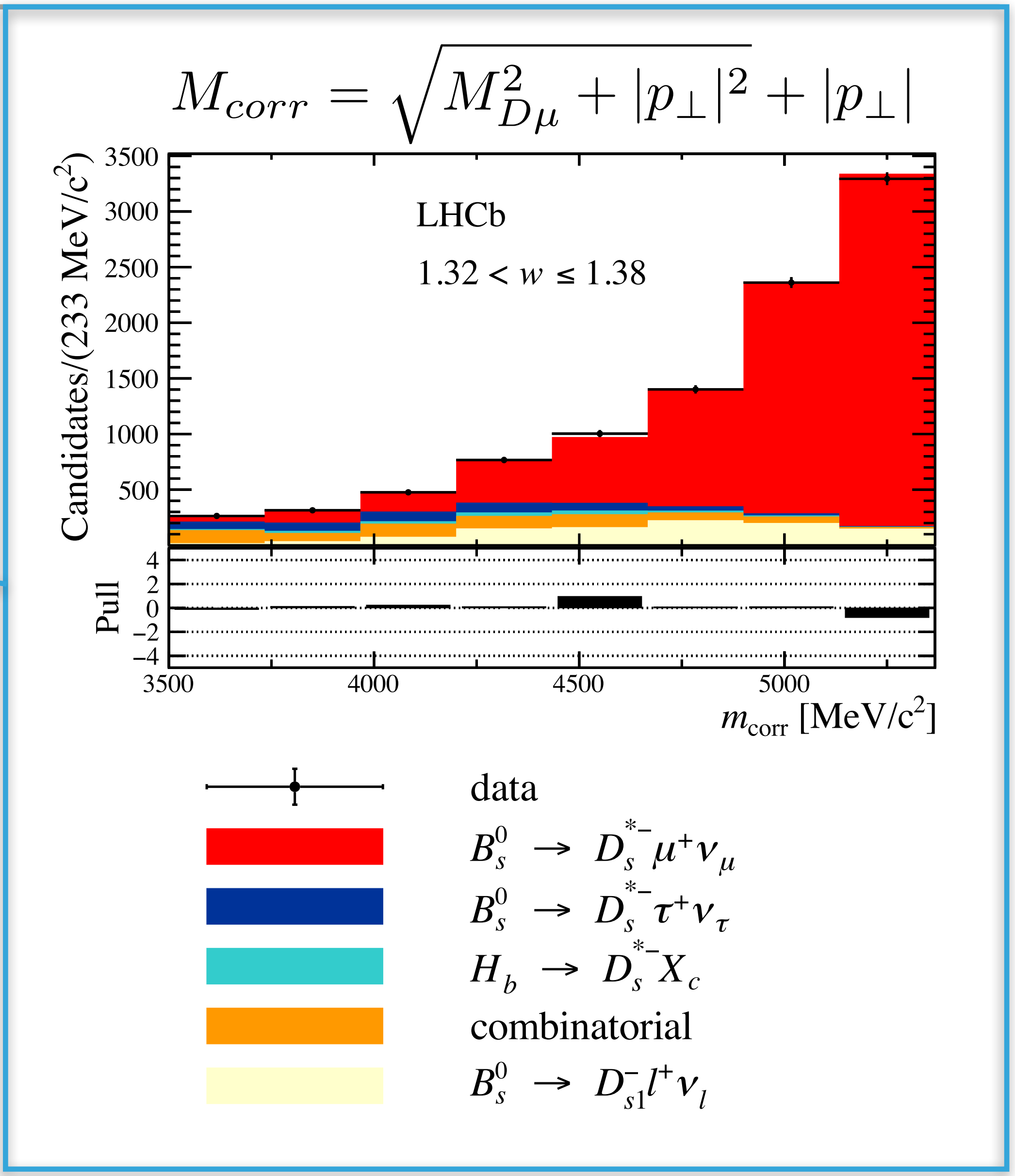
Phys. Rev. D101 (2020) 072004

- Samples are signal dominated

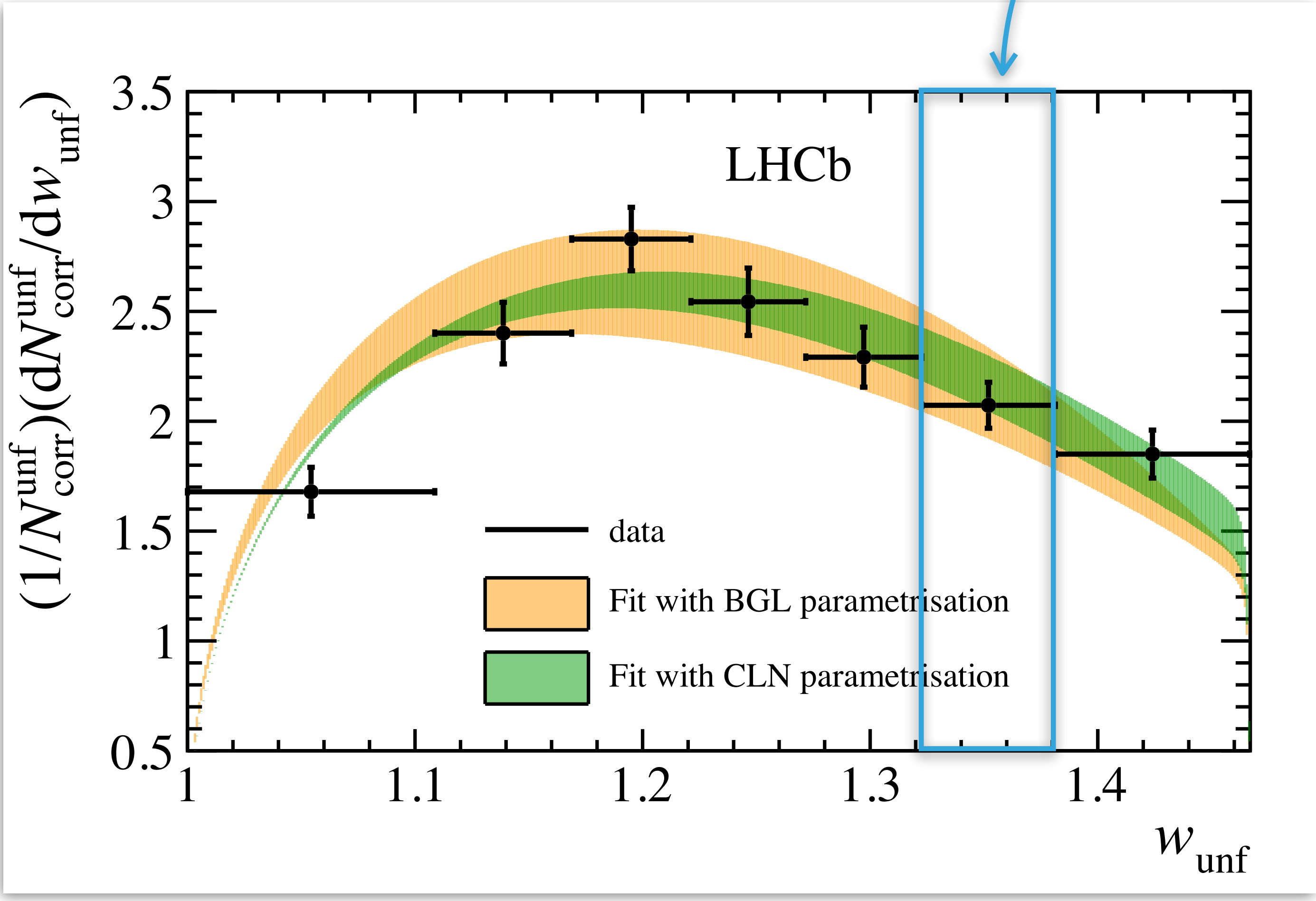
Light leptons: shape & hadronic form factors measurements

JHEP 12 (2020) 144

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



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



Unfolded efficiency corrected yields+ correlation matrix in the paper

Light leptons: shape & hadronic form factors measurements

JHEP 12 (2020) 144

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

Already a few analyses sensitive to hadronic FF parameters

Phys. Rev. D101 (2020) 072004

- 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)

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)

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

Tau leptons

- **Partial reconstruction → large backgrounds:**
  need to fully exploit vertex topology information, track isolation, available kinematic information

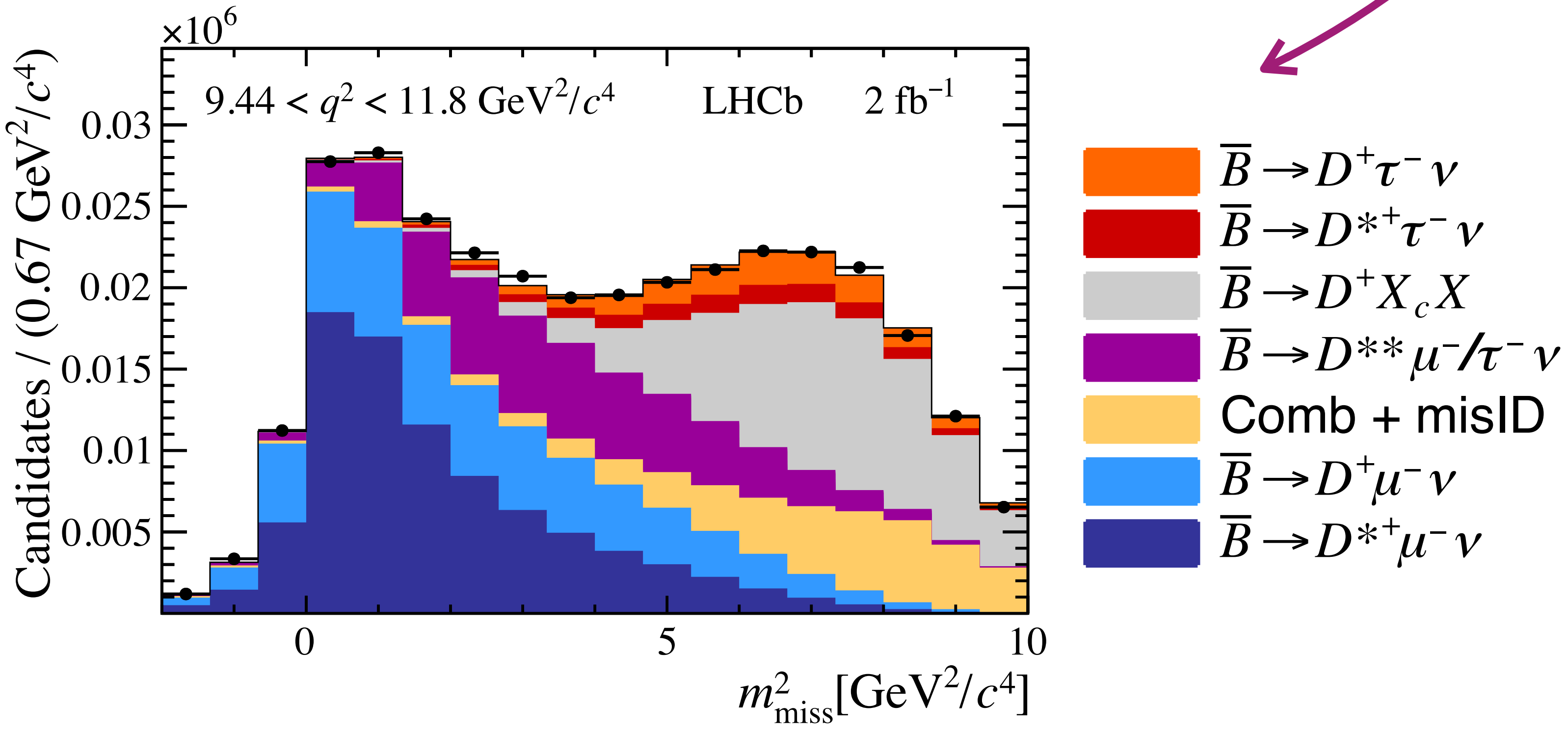
- With three missing neutrinos: **B rest frame approximation**

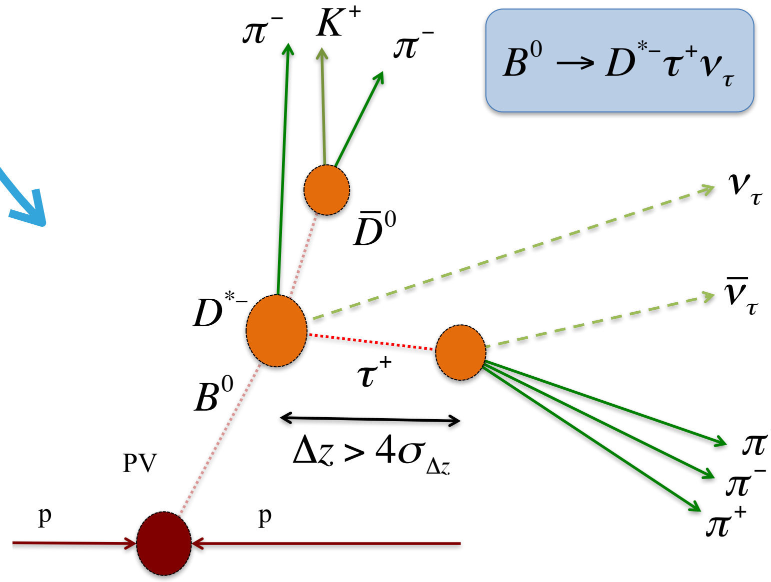
$$(\gamma\beta_z)_B = (\gamma\beta_z)_{D^*\mu} \Longrightarrow (p_z)_B = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$

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

LHCb-PAPER-2024-007

$$m^2_{\text{miss}} = (P_B - P_D - P_\mu)^2$$





Fit to background-enriched regions essential to control backgrounds

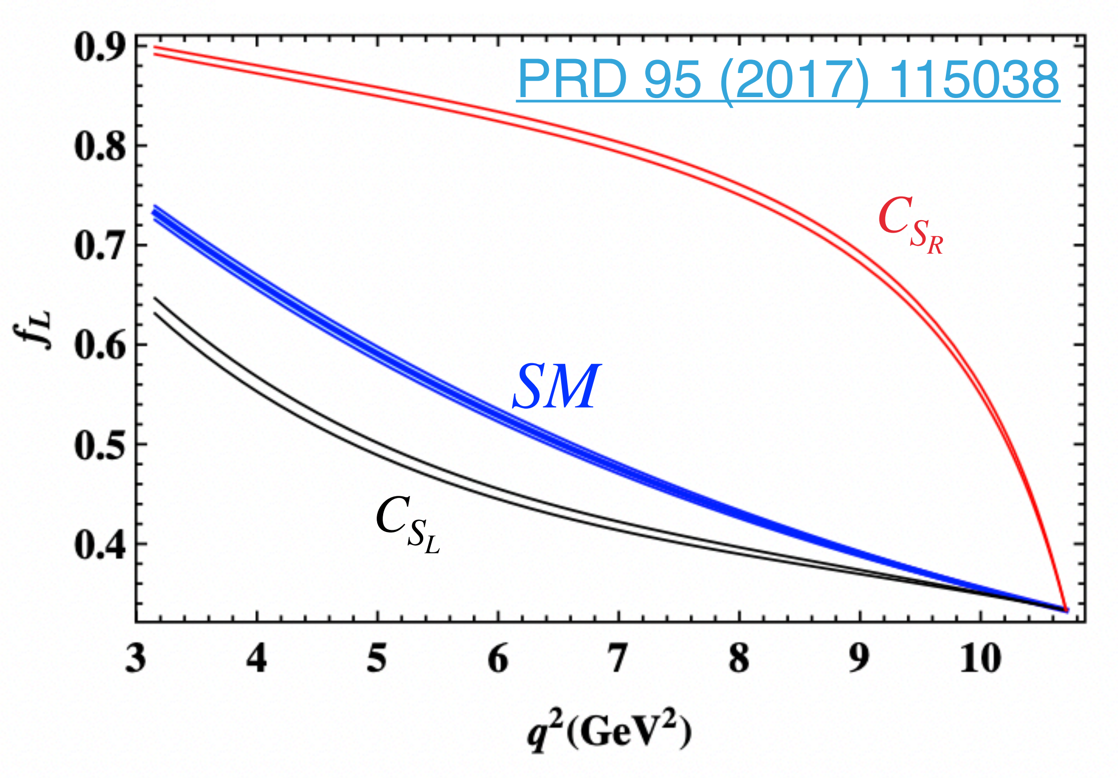
Can take advantage of the more constrained kinematics and tau decay vertex

D* polarisation fraction

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = \underset{\substack{\uparrow \\ \text{Unpolarised}}}{\boxed{a_{\theta_D}(q^2)}} + \underset{\substack{\uparrow \\ \text{Polarised}}}{\boxed{c_{\theta_D}(q^2)}}\cos^2\theta_D$$

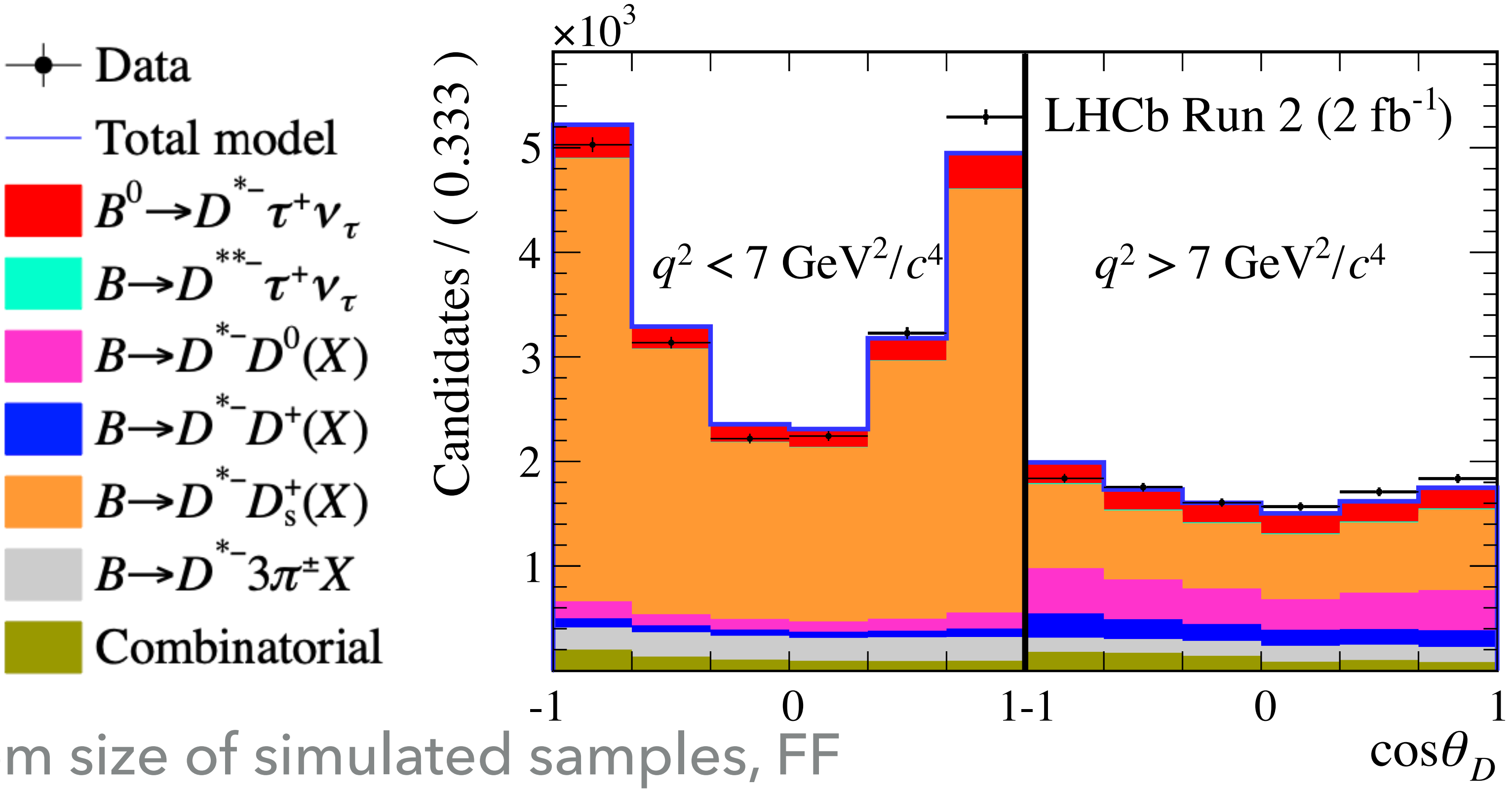
$$F_L^{D^*} = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$$

The presence of new mediators impacts the polarisation fraction



PRD 95 (2017) 115038

- Run1 + partial Run2 (5fb^{-1}), hadronic τ decay
  - Background treatment similar to $R(D^*)$ analysis (PRD 108, 012018)
  - 4D-binned templated fit to τ decay time, anti-D_s BDT output, $\cos\theta_D$ and $q^2 (q^2 \lessgtr 7\text{GeV}^2/\text{c}^4)$
  - 2 signal components: polarised & unpolarised



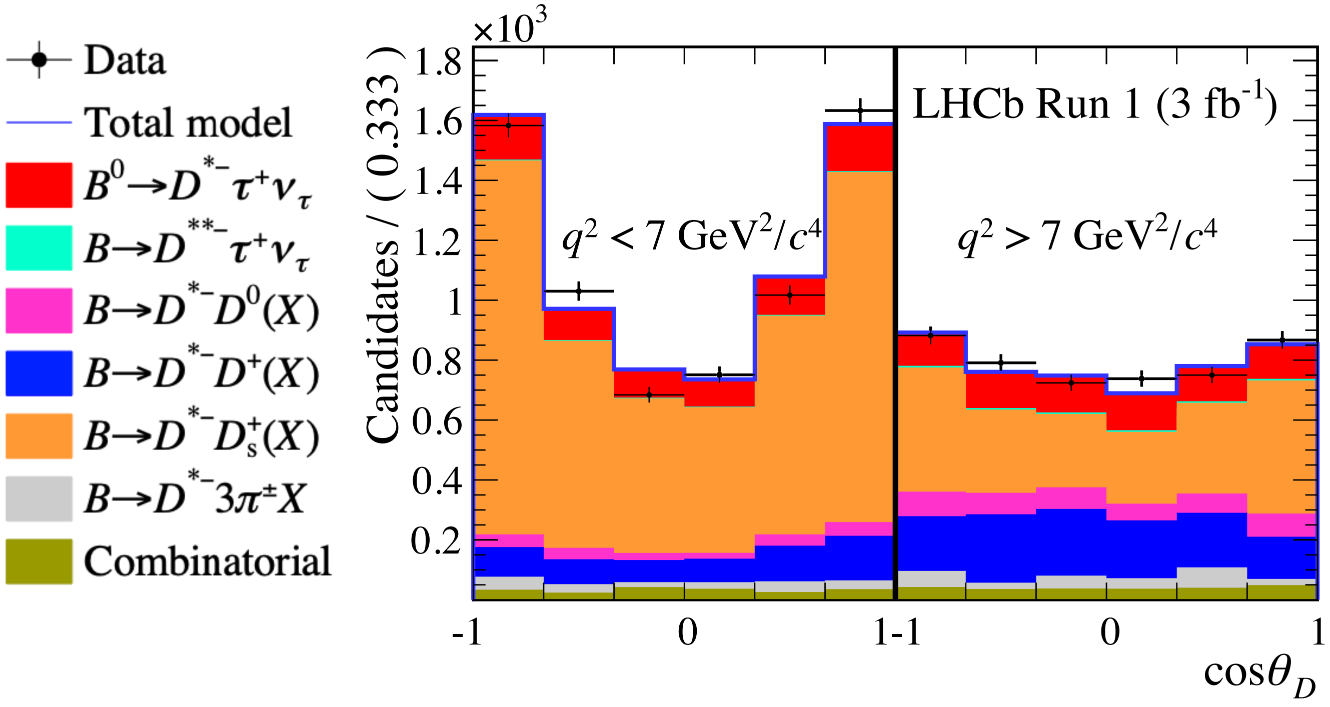
  - Main systematic uncertainties from size of simulated samples, FF parameterisation and double-charm background modelling.

D* polarisation fraction

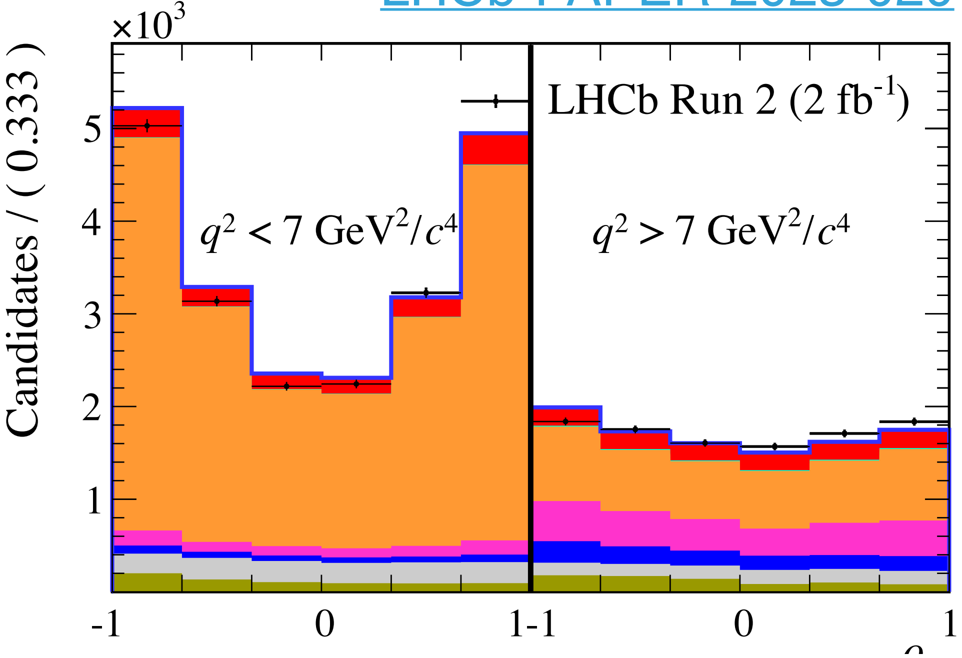
$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = \underbrace{\boxed{a_{\theta_D}(q^2)}}_{\uparrow\ \text{Unpolarised}} + \underbrace{\boxed{c_{\theta_D}(q^2)}}_{\uparrow\ \text{Polarised}}\cos^2\theta_D$$

$$F_L^{D^*} = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$$

$$F_L^{D^*}(q^2 < 7\mathrm{GeV}^2/\mathrm{c}^4) = 0.51 \pm 0.07(\mathrm{stat}) \pm 0.03(\mathrm{syst})$$
$$F_L^{D^*}(q^2 > 7\mathrm{GeV}^2/\mathrm{c}^4) = 0.35 \pm 0.08(\mathrm{stat}) \pm 0.02(\mathrm{syst})$$
$$F_L^{D^*}(\text{whole } q^2 \text{ range}) = 0.43 \pm 0.06(\mathrm{stat}) \pm 0.03(\mathrm{syst})$$



[LHCb-PAPER-2023-020]

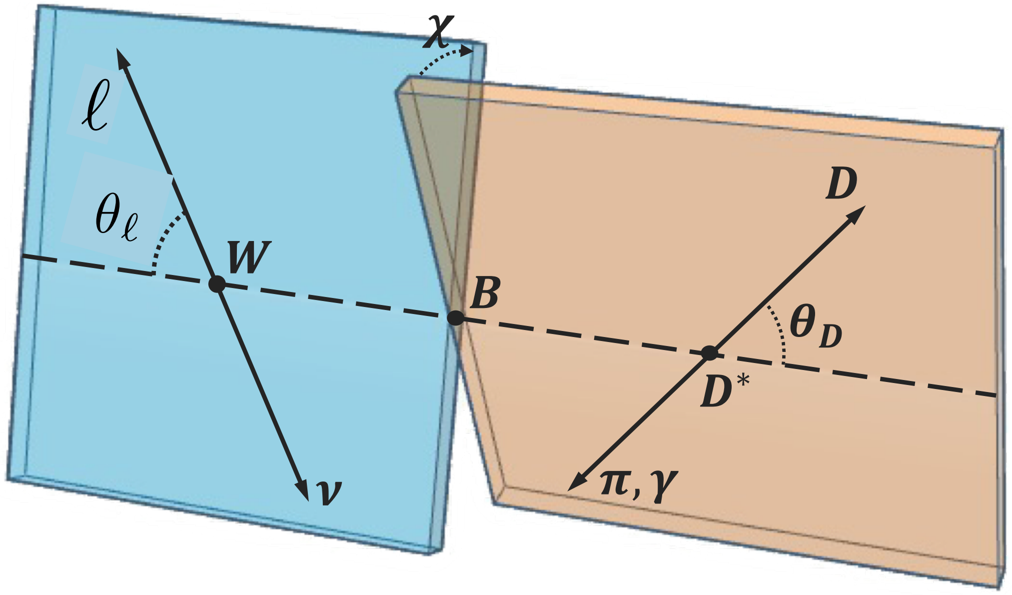


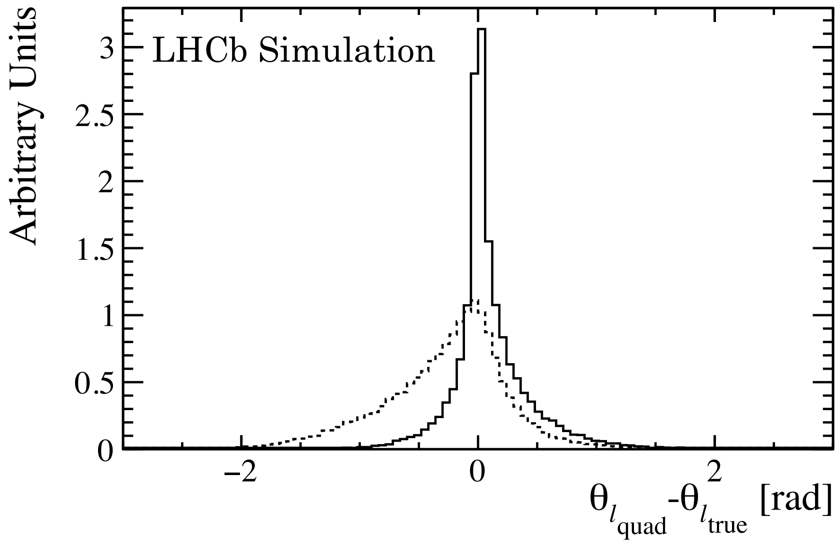
Run 2 samples a factor 4–12 larger than Run 1 (depending on sample & selection)

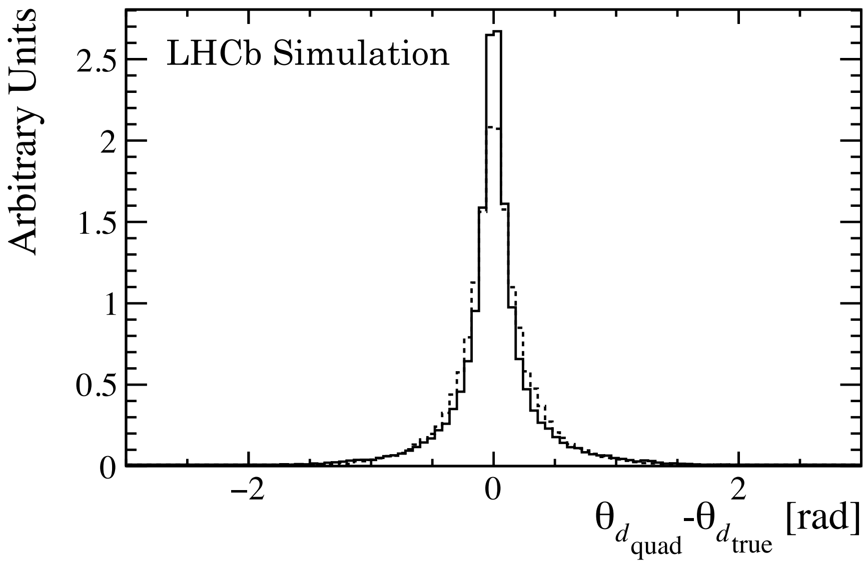
- Compatible with previous Belle result:
  $F_L^{D^*} = 0.60 \pm 0.08(\mathrm{stat}) \pm 0.04(\mathrm{syst})$
  ([arXiv:1903.03102])
- Compatible with SM predictions:
  $F_L^{D^*} = 0.441 \pm 0.006$ [PRD 98 (2018) 095018]
  $F_L^{D^*} = 0.457 \pm 0.010$ [Eur. Phys. J. C 79, 268 (2019)]
  $F_L^{D^*} = 0.467 \pm 0.009$ [Eur. Phys. J. C 80, 347 (2020)]
  $F_L^{D^*} = 0.422 \pm 0.010$ [arXiv:2310.03680]
  $F_L^{D^*}(q^2 < 7\mathrm{GeV}^2/\mathrm{c}^4) = 0.51 \pm 0.07(\mathrm{stat}) \pm 0.03(\mathrm{syst})$
  $F_L^{D^*}(q^2 > 7\mathrm{GeV}^2/\mathrm{c}^4) = 0.51 \pm 0.07(\mathrm{stat}) \pm 0.03(\mathrm{syst})$ [arXiv:2310.03680]

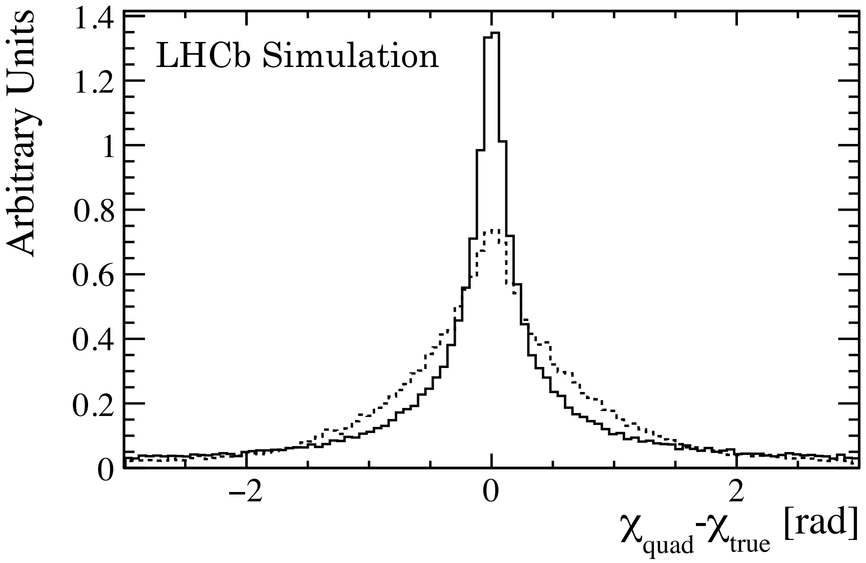
Extending differential measurements: decay angles

- Natural extension: describe the fully differential decay rate
- $B^0 \rightarrow D^* \mu\nu$ decays
- Solution of quadratic equation (solid) compared to B rest frame approximation (dashed)



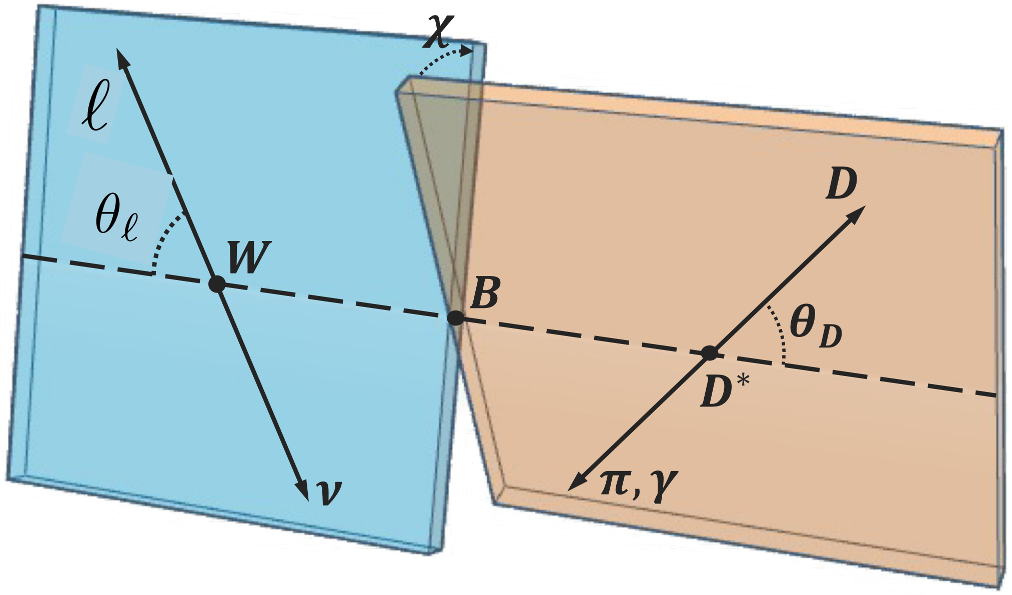


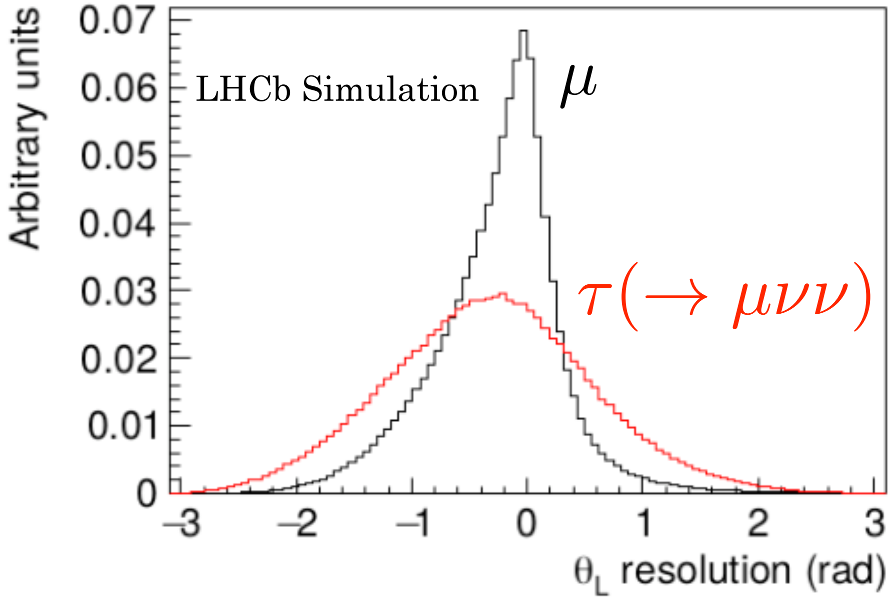


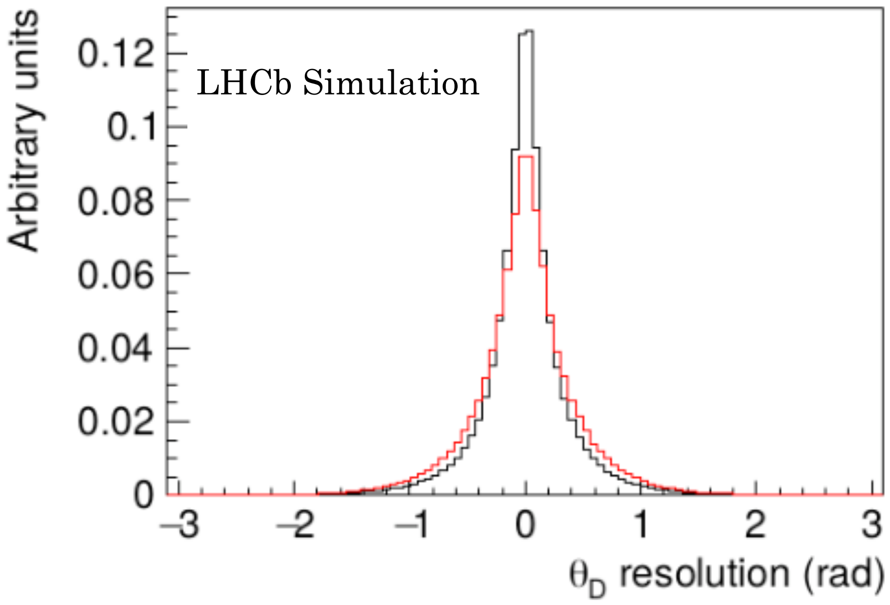


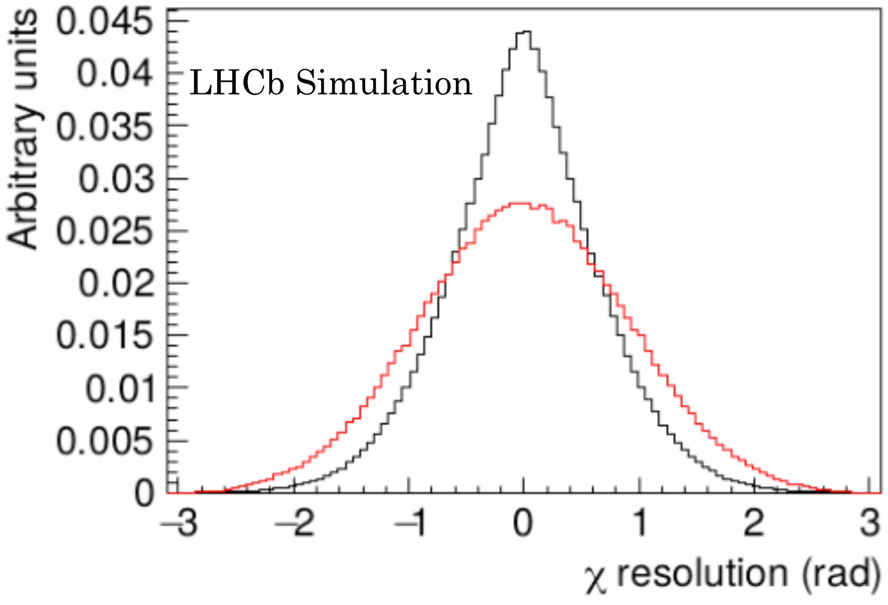
Extending differential measurements: decay angles

- Natural extension: describe the fully differential decay rate
- $B^0 \rightarrow D^* \tau \nu$ decays
- Angular resolutions (worst case: B rest frame approximation, τ leptons)







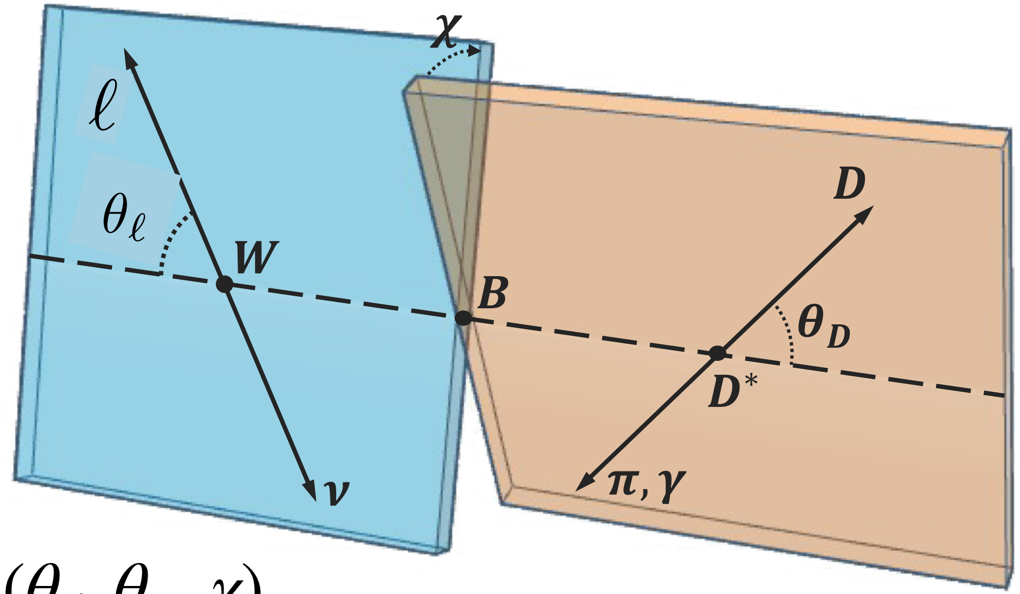


LHCB-PUB-2018-009, arXiv:1808.08865

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

Angular Coefficients

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



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

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

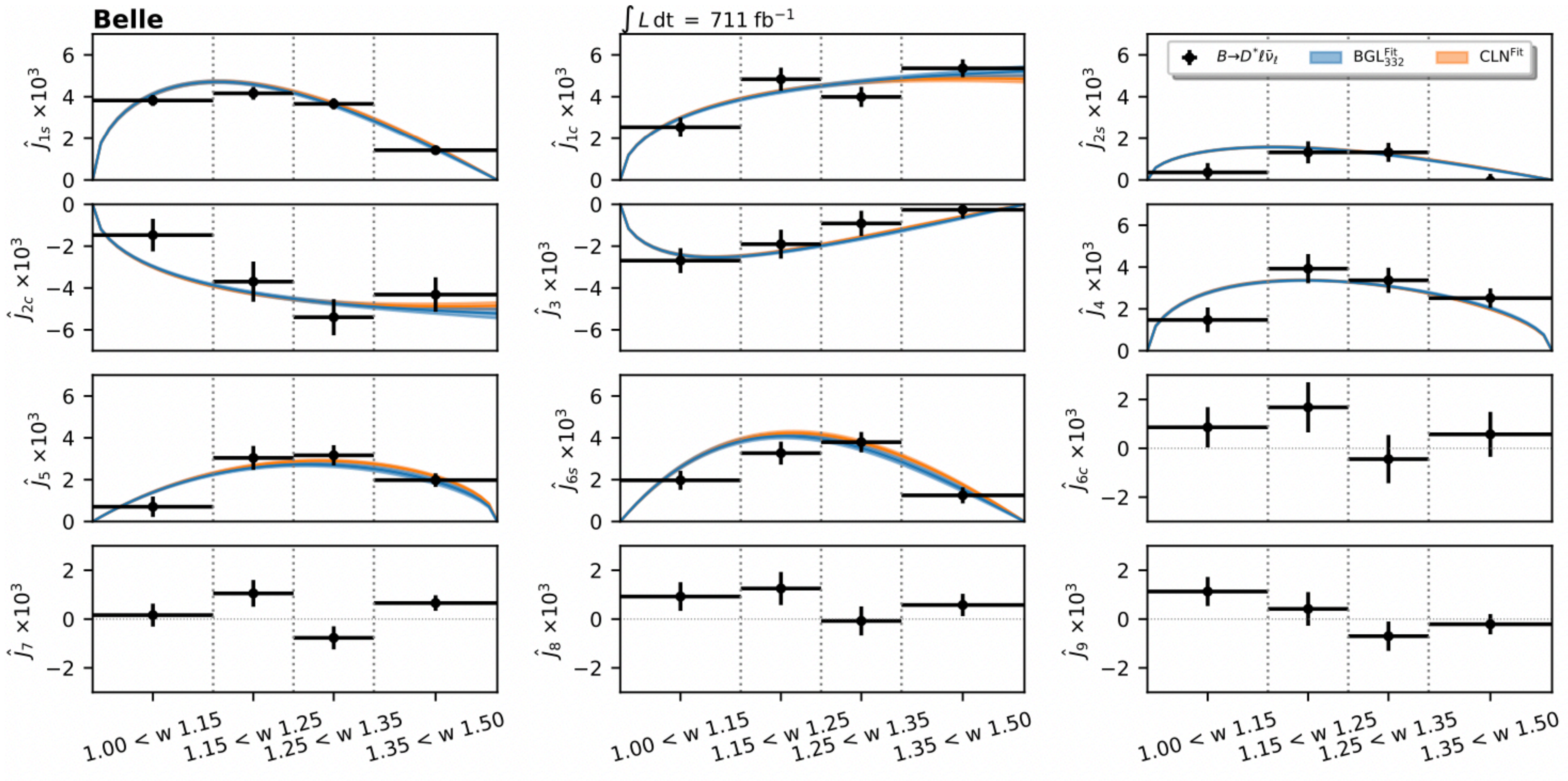
Phys. Rev. D101 (2020) 072004

- Full description using the possible three helicity states of the D* - measuring the angular coefficients does not separate hadronic and NP effects, but also doesn't make assumptions
- Measuring the 12 angular coefficients (ok to integrate in q^2 ? - or w - D. Hill et.al., JHEP 11 (2019) 133)
- Ongoing measurements of $B^0 \to D^*\ell\nu$ and $B_s^0 \to D_s^*\ell\nu$

Angular Coefficients

- Measurement of the angular coefficients of $B \to D^* \ell \nu$ using the full Bell dataset and hadronic B tagging, including both charged and neutral B mesons

- The signal yield in bins of the angles, w and decay mode is determined using the $M^2_{\text{miss}} = (p_{e+e-} - p_{\text{tag}} - p_{D^*} - p_\ell)^2$



$$\Delta X = X^\mu - X^e$$

Observable	χ^2 / ndf	p-value
ΔA_{FB}	1.7 / 4	0.79
$\Delta F_{\text{L}}(D^*)$	2.3 / 4	0.67
$\Delta \hat{J}_{1s}$	5.3 / 4	0.26
$\Delta \hat{J}_{1c}$	4.2 / 4	0.38
$\Delta \hat{J}_{2s}$	4.6 / 4	0.33
$\Delta \hat{J}_{2c}$	5.0 / 4	0.28
$\Delta \hat{J}_3$	7.4 / 4	0.12
$\Delta \hat{J}_4$	2.5 / 4	0.64
$\Delta \hat{J}_5$	4.8 / 4	0.31
$\Delta \hat{J}_{6s}$	2.1 / 4	0.72
$\Delta \hat{J}_{6c}$	1.1 / 4	0.89
$\Delta \hat{J}_7$	1.6 / 4	0.81
$\Delta \hat{J}_8$	3.3 / 4	0.51
$\Delta \hat{J}_9$	4.6 / 4	0.33
$\Delta \hat{J}_i$	41 / 48	0.76

arXiv:2310.20286

$$\boxed{|V_{cb}| = (41.0 \pm 0.3(\text{stat}) \pm 0.4(\text{syst}) \pm 0.5(\text{theo})) \times 10^{-3}}$$

- In agreement with previous analysis (PRD 108(2023) 012002) and HFLAV inclusive, no deviation from SM in LFU tests

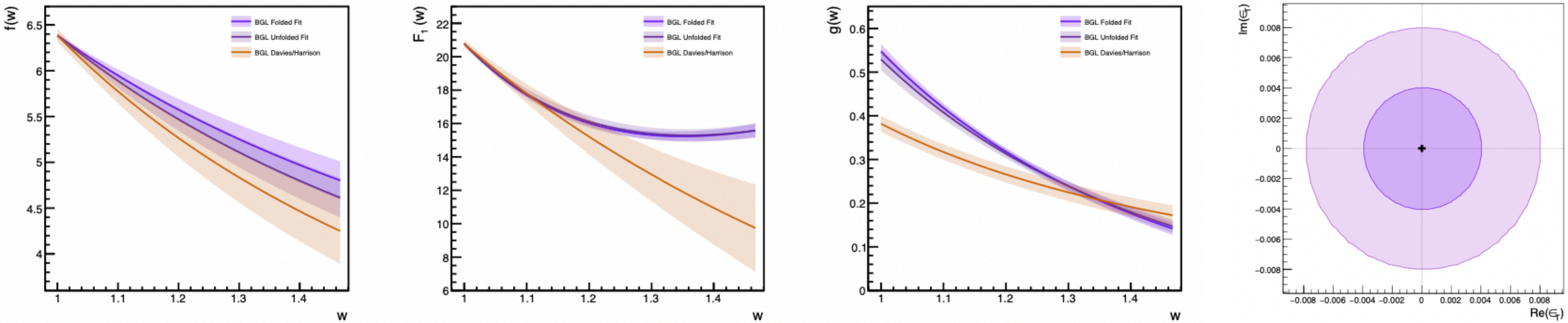
More in Markus' talk

Angular Coefficients: $B_s^0 \rightarrow D_s^* \mu \nu$ F. Manganella's thesis, courtesy M. Rotondo

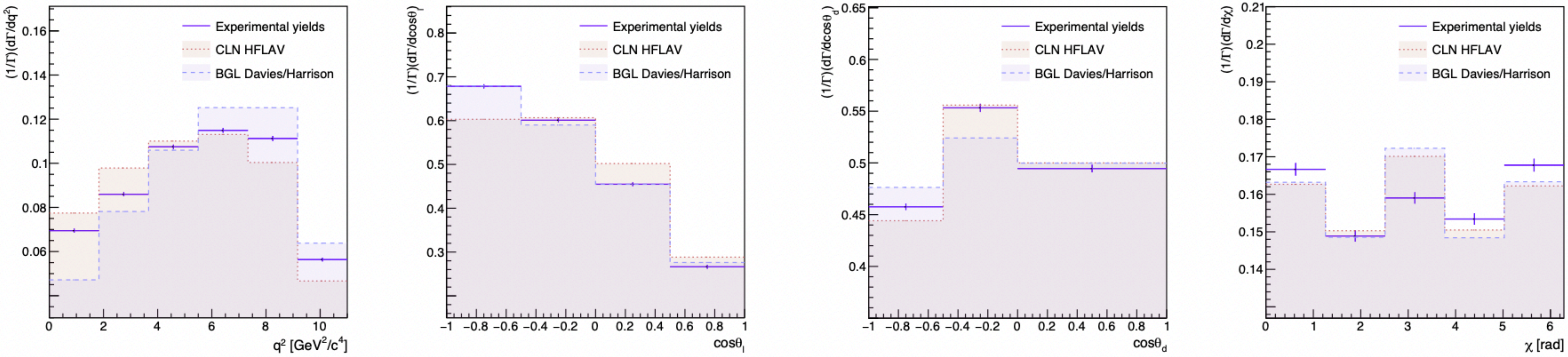
- Building upon JHEP 12 (2020) 144 : binned folded and unfolded fit over 4-d space. Fully differential decay rate:

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_l d\cos\theta_d d\chi} \propto \sum_i I_i(q^2) k_i(\theta_\ell, \theta_D, \chi)$$

- Use CLN and BGL to parametrise $I_i(q^2)$ expressions, modify $I_i(q^2) \rightarrow I_i(q^2, \epsilon_{NP})$ to include a New Physics coupling constant



Unfolded distributions



- Tension (similar with Belle J. Harrison, C.T.H. Davies, arXiv:2304.03137 but different binning)

Additional ideas: CPV observables

V. Dedu and A. Poluektov, arXiv:2304.00966

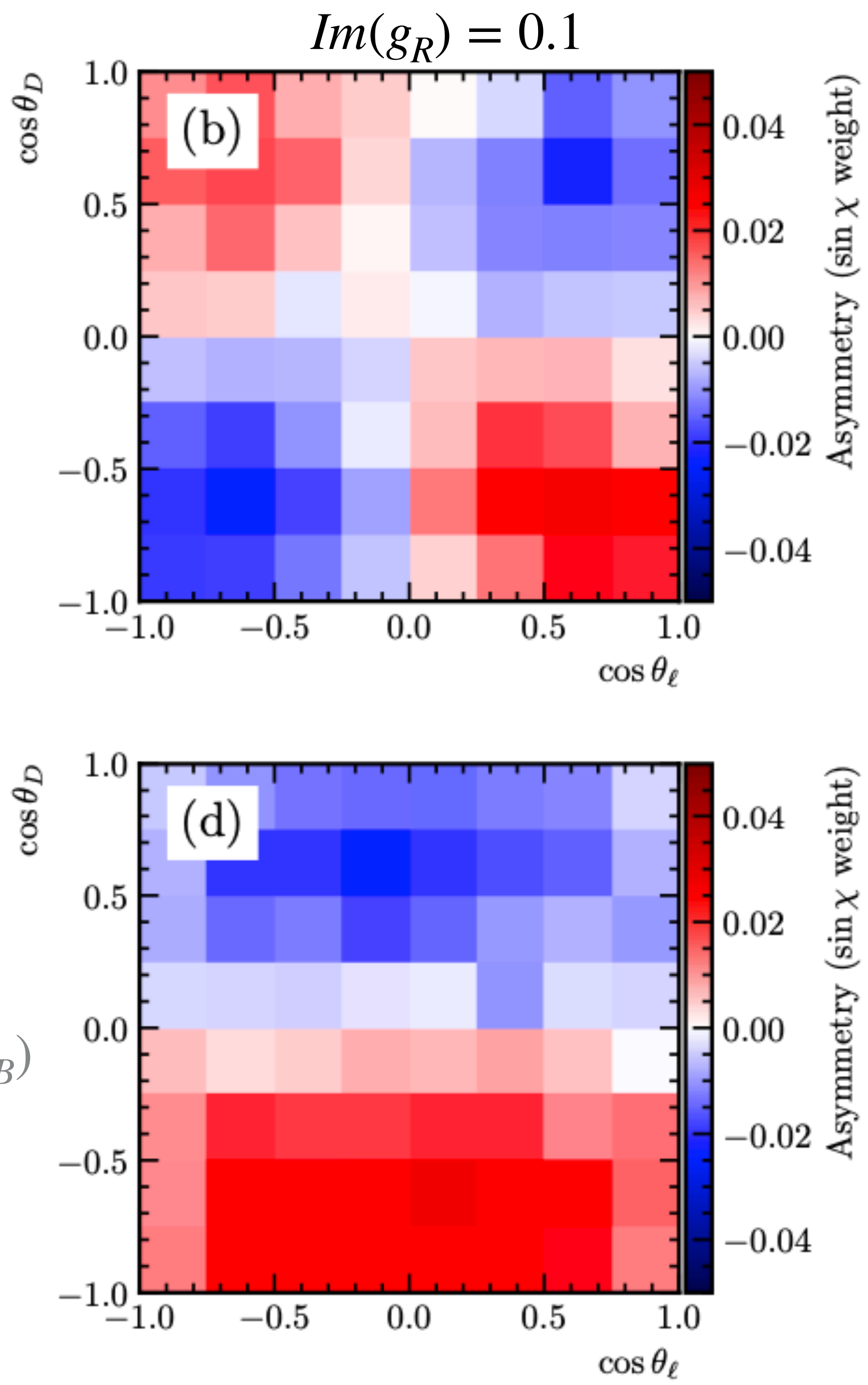
$$\frac{d\Gamma(B \to D^*\ell\nu)}{dw d\cos\theta_\ell d\cos\theta_d d\chi} = (P_{\text{even}} + P_{\text{odd}})$$

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

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

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.

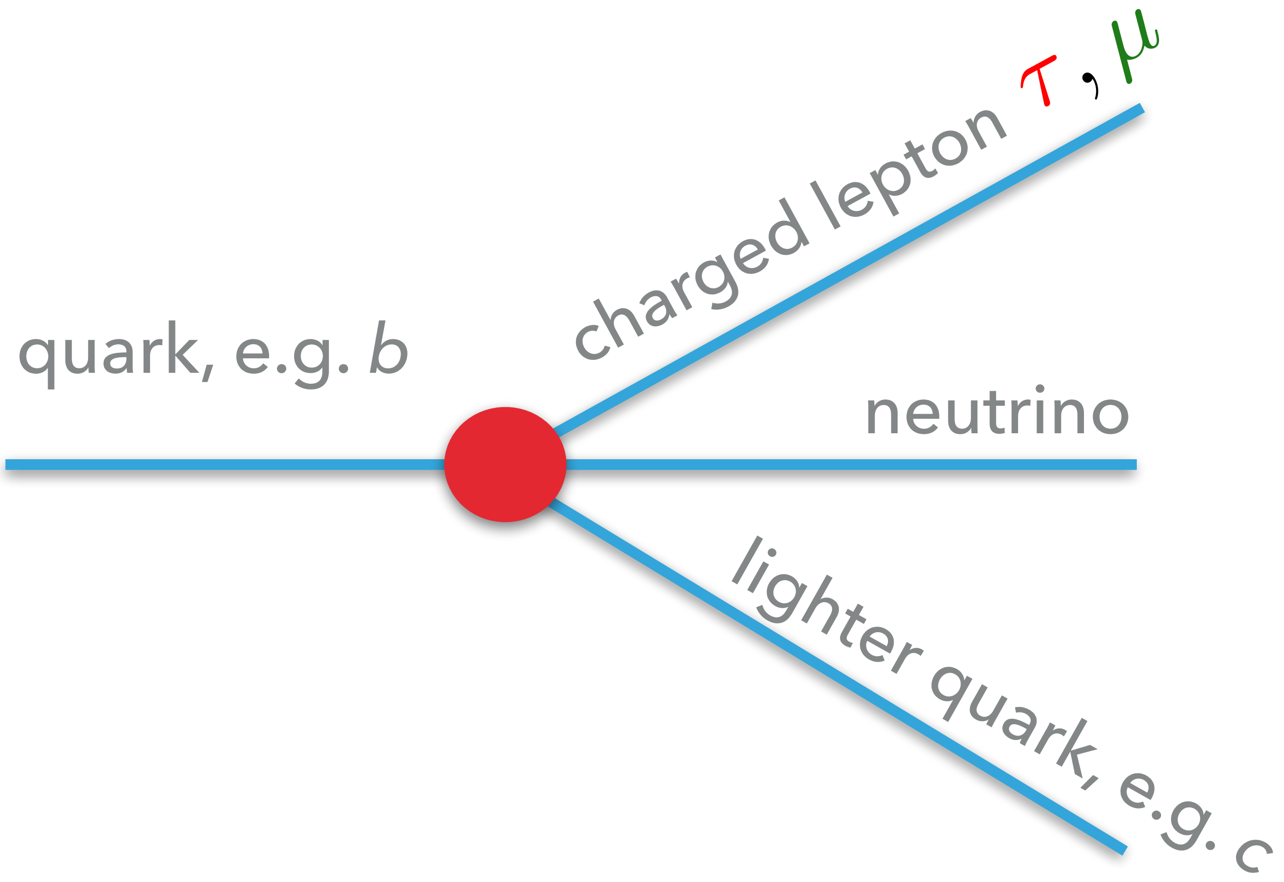
$$\sin\chi = S_1 \cdot (\vec{p}_\pi, \vec{p}_\mu, \vec{p}_D) + S_2 \cdot (\vec{p}_B, \vec{p}_\mu, \vec{p}_D) + S_3 \cdot (\vec{p}_\pi, \vec{p}_B, \vec{p}_D) + S_4 \cdot (\vec{p}_\pi, \vec{p}_\mu, \vec{p}_B)$$

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

- On going dedicated analysis optimised for CPV observables

New Physics Wilson Coefficients

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



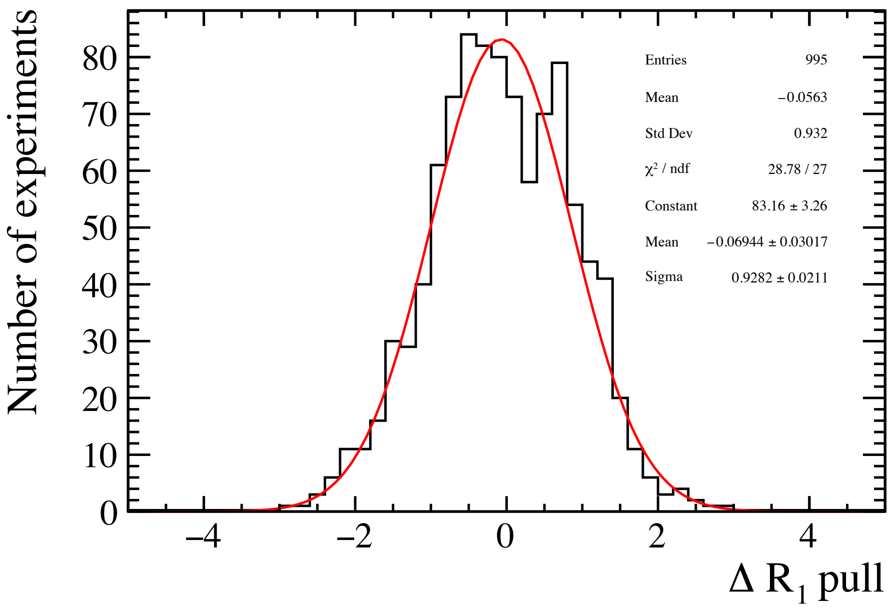
Wilson coefficients

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

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

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)



Exploiting angular observables

- Measuring $B^0 \to D^*\mu\nu$ as benchmark
- Aim: extend $R(D)$ vs $R(D^*)$ measurement to include angular variables and with NP WC in signal parametrisation

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

SM

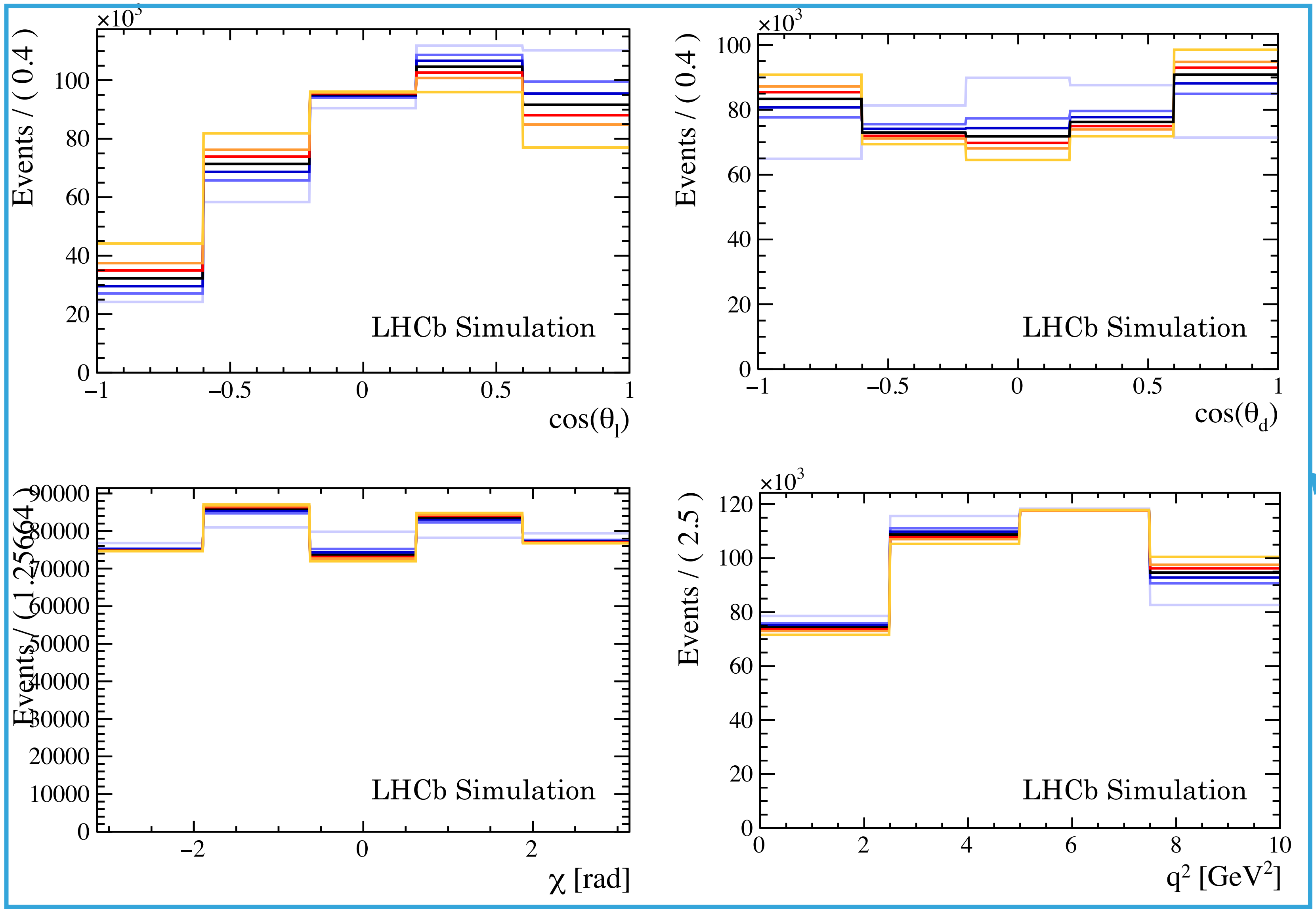
$$= \frac{G_F}{\sqrt{2}} V_{cb} \Big[(1 + g_V)\bar{c}\gamma_\mu b + (-1 + g_A)\bar{c}\gamma_\mu\gamma_5 b$$

$$+ g_S i\partial_\mu(\bar{c}b) + g_P i\partial_\mu(\bar{c}\gamma_5 b)$$

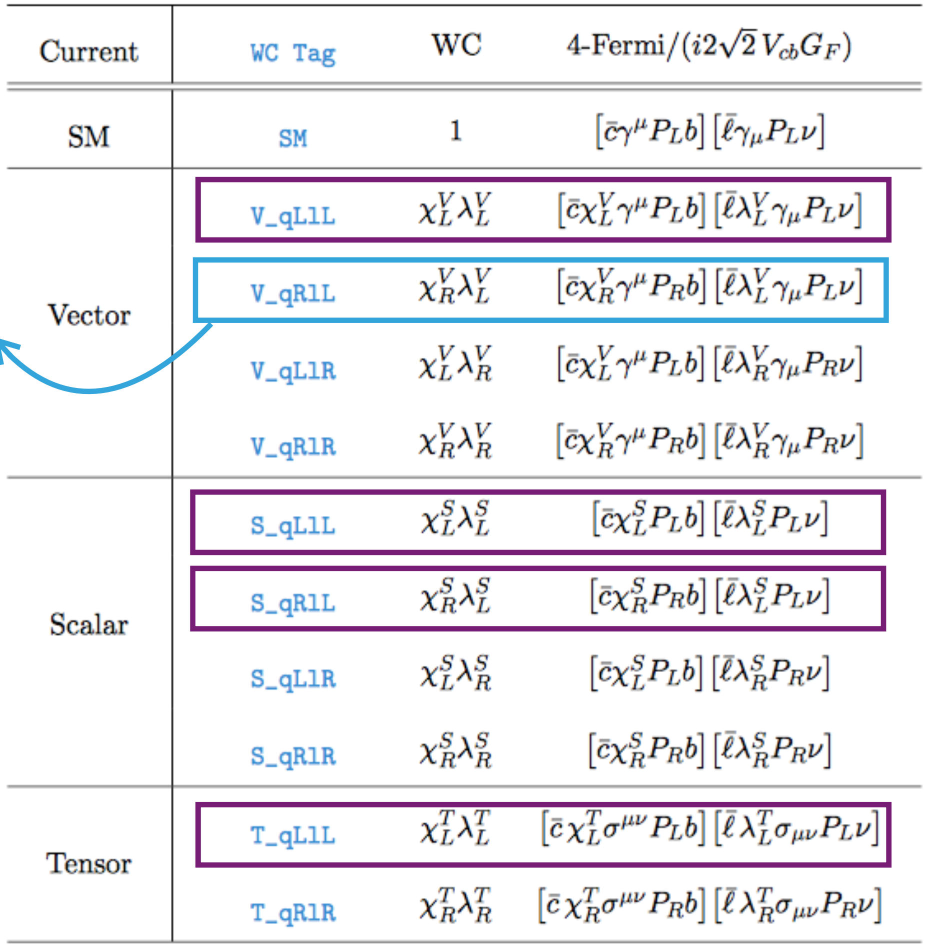
$$+ g_T i\partial^\nu(\bar{c}i\sigma_{\mu\nu}b) + g_{T5} i\partial^\nu(\bar{c}i\sigma_{\mu\nu}\gamma_5 b) \Big]$$

$$\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell + h.c.$$

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



$B^0 \to D^*\mu\nu$

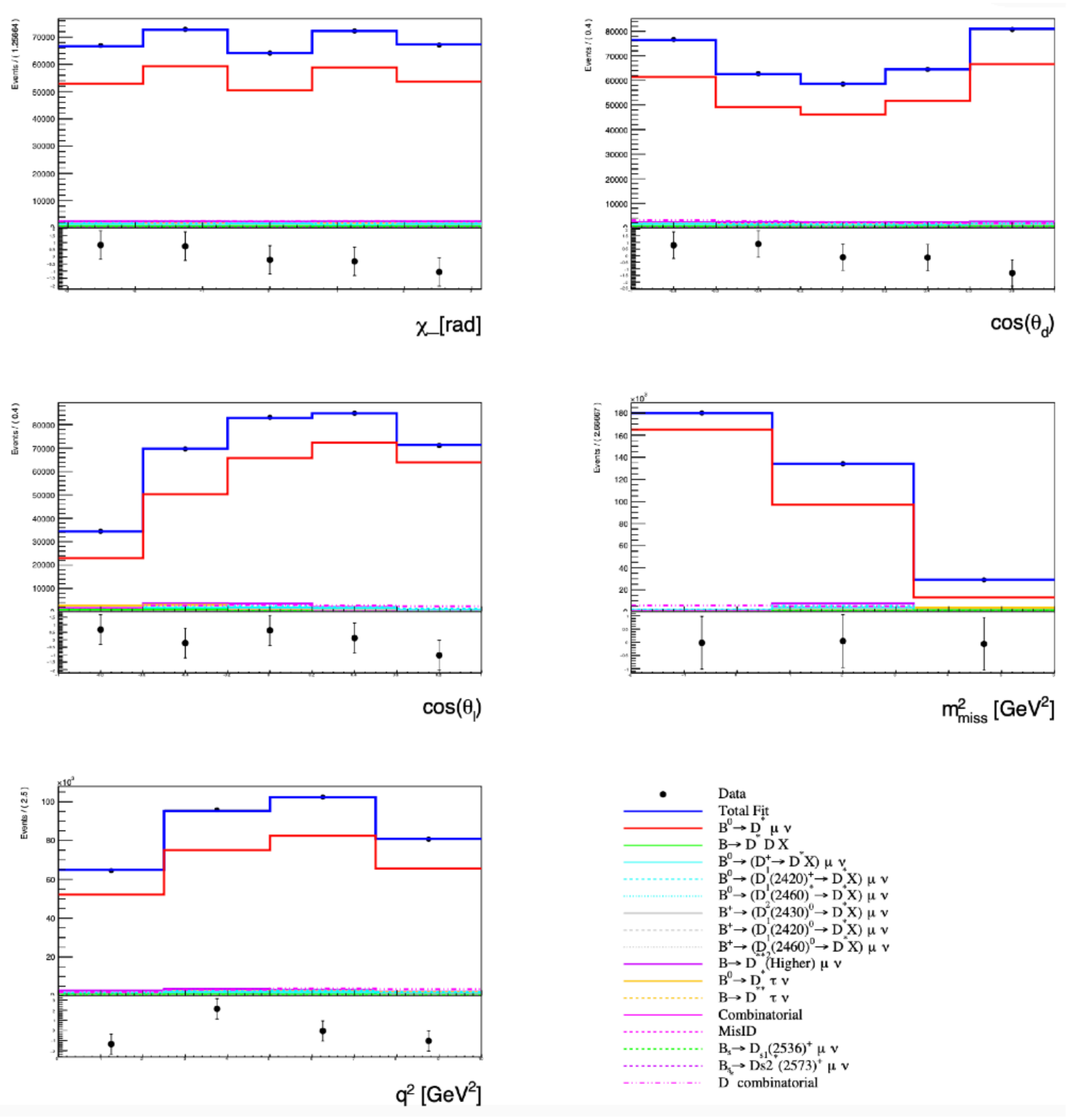


Current	WC Tag	WC	4-Fermi/$(i2\sqrt{2}\,V_{cb}G_F)$
SM	SM	1	$[\bar{c}\gamma^\mu P_L b]\,[\bar{\ell}\gamma_\mu P_L \nu]$
Vector	V_qL1L	$\chi^V_L\lambda^V_L$	$[\bar{c}\chi^V_L\gamma^\mu P_L b]\,[\bar{\ell}\lambda^V_L\gamma_\mu P_L \nu]$
	V_qR1L	$\chi^V_R\lambda^V_L$	$[\bar{c}\chi^V_R\gamma^\mu P_R b]\,[\bar{\ell}\lambda^V_L\gamma_\mu P_L \nu]$
	V_qL1R	$\chi^V_L\lambda^V_R$	$[\bar{c}\chi^V_L\gamma^\mu P_L b]\,[\bar{\ell}\lambda^V_R\gamma_\mu P_R \nu]$
	V_qR1R	$\chi^V_R\lambda^V_R$	$[\bar{c}\chi^V_R\gamma^\mu P_R b]\,[\bar{\ell}\lambda^V_R\gamma_\mu P_R \nu]$
Scalar	S_qL1L	$\chi^S_L\lambda^S_L$	$[\bar{c}\chi^S_L P_L b]\,[\bar{\ell}\lambda^S_L P_L \nu]$
	S_qR1L	$\chi^S_R\lambda^S_L$	$[\bar{c}\chi^S_R P_R b]\,[\bar{\ell}\lambda^S_L P_L \nu]$
	S_qL1R	$\chi^S_L\lambda^S_R$	$[\bar{c}\chi^S_L P_L b]\,[\bar{\ell}\lambda^S_R P_R \nu]$
	S_qR1R	$\chi^S_R\lambda^S_R$	$[\bar{c}\chi^S_R P_R b]\,[\bar{\ell}\lambda^S_R P_R \nu]$
Tensor	T_qL1L	$\chi^T_L\lambda^T_L$	$[\bar{c}\chi^T_L\sigma^{\mu\nu} P_L b]\,[\bar{\ell}\lambda^T_L\sigma_{\mu\nu} P_L \nu]$
	T_qR1R	$\chi^T_R\lambda^T_R$	$[\bar{c}\chi^T_R\sigma^{\mu\nu} P_R b]\,[\bar{\ell}\lambda^T_R\sigma_{\mu\nu} P_R \nu]$

Hammer Manual

Exploiting angular observables: $B^0 \to D^* \mu \nu$

- **Extract directly Wilson Coefficients and FF parameters** from fit to data
- **Shape analysis** - no attempt to measure $|V_{cb}|$
- SM fits: CLN (Nuclear Physics B 530 (1998) 153-181) , BGL (Phys.Rev. D56 (1997) 6895-6911) and BLPR parametrisation for hadronic FF
- NP fits: **BLPR** parametrisation (F. Bernlochner et. al. Phys. Rev. D 95, 115008 (2017))
- High statistics $B^0 \to D^* \mu \nu$ sample(s), could fit for hadronic FF parameters and NP WC at the same time, if correlations allow
- First sensitivity estimates B. Mitreska CERN-THESIS-2022-105



Example of fit projection for single pseudo-experiment, courtesy H. Nur

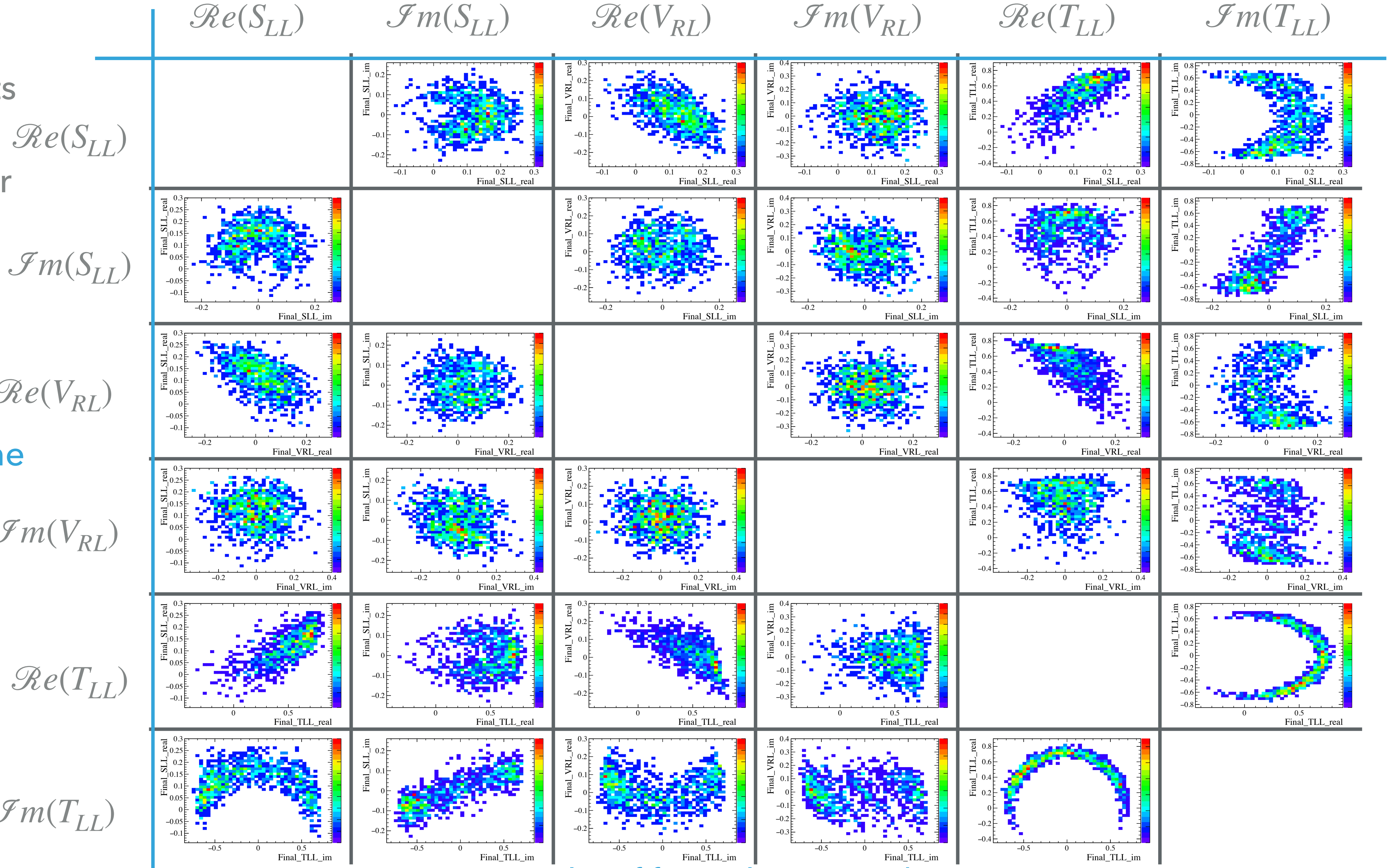
Exploiting angular observables: $B^0 \to D^* \mu \nu$

- Ideally no assumption about the NP structure (Eur. Phys. J. C 80, 883 (2020))
- In practice easier to search for specific NP models (e.g. Bhattacharya *et. al.* JHEP 05 (2019) 191) or allowing one NP WC at a time

Pseudo-experiments generated with NP components (0.5 for Real and Imaginary parts)

No observable to gain sensitivity to the imaginary parts

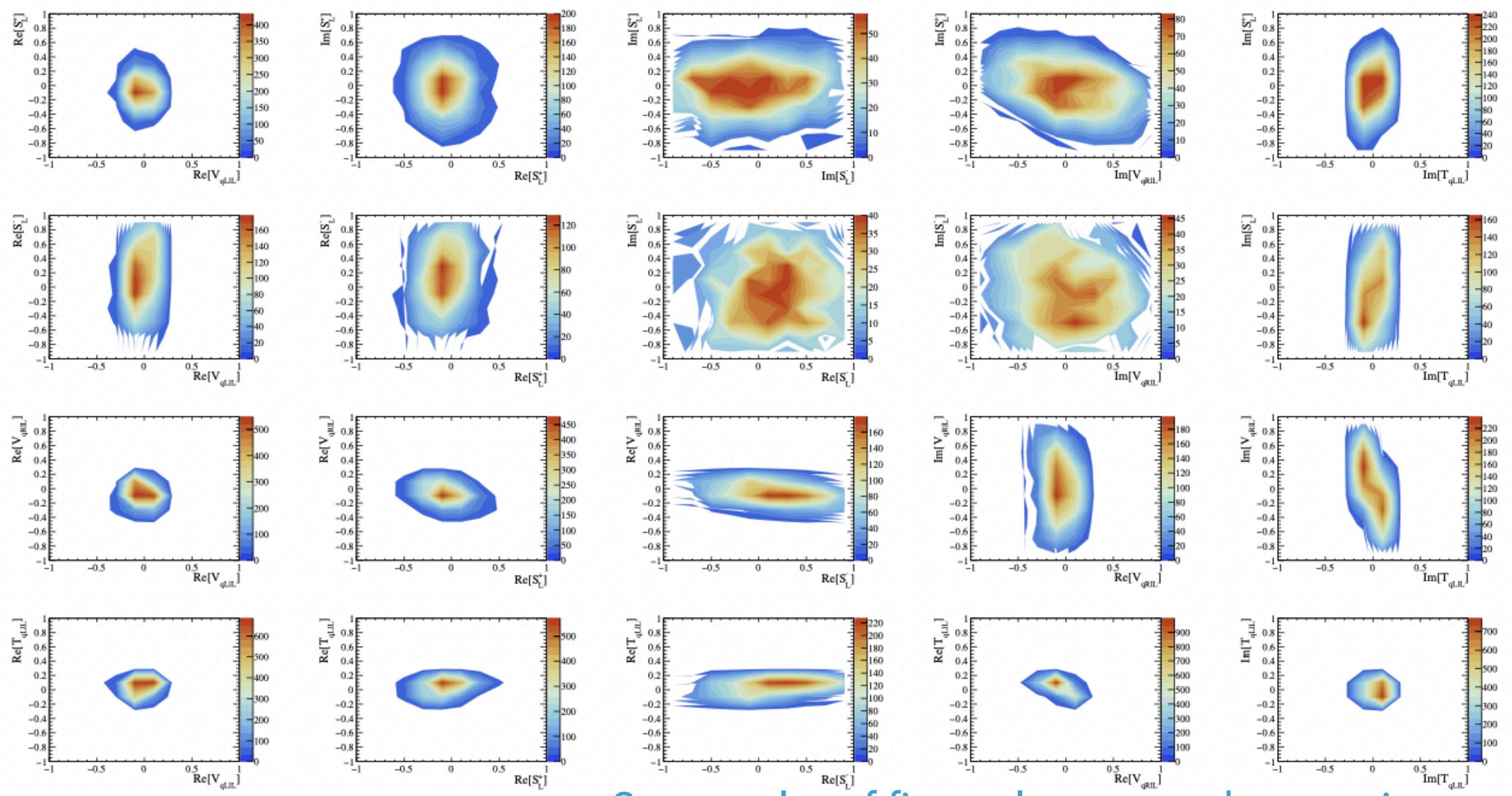
Unbiased well-behaved fit to the real parts of NP WC, need to see how to present the results for the most general case



Scatter plot of fit results to pseudo-experiments, courtesy H. Nur

Even before adding angular observables

- Expanding on $R(D^{+})$ vs $R(D^{*+})$ measurement (LHCb-PAPER-2024-007)
- Modify signal and normalisation models to include NP contributions
- Pseudo-experiments study: no NP assumed in muon modes, NP assumed left-handed $(V_{LR} = V_{RR} = S_{LR} = S_{RR} = T_{RR} = 0)$, $S_L^{+} = \dfrac{S_{LL} + S_{RL}}{2}$, $S_L^{-} = \dfrac{S_{LL} - S_{RL}}{2}$
- Confirmed no significant difference when floating or fixing FF (BLPR) parameters and some sensitivity to NP Wilson Coefficients [preliminary study to be followed up]



Scatter plot of fit results to pseudo-experiments

S. Meloni CERN-THESIS-2021-266

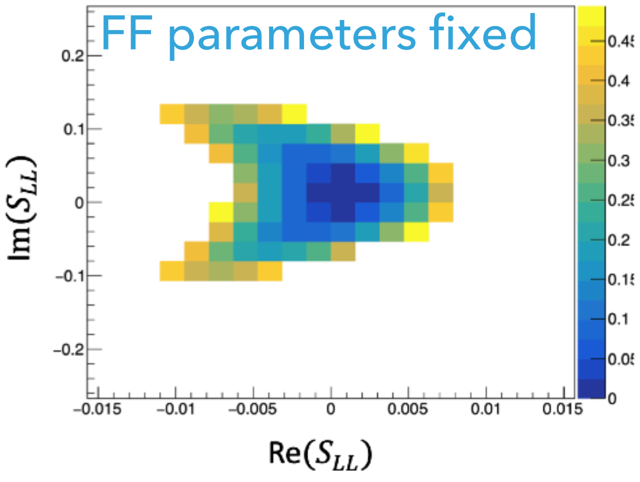
Conclusions

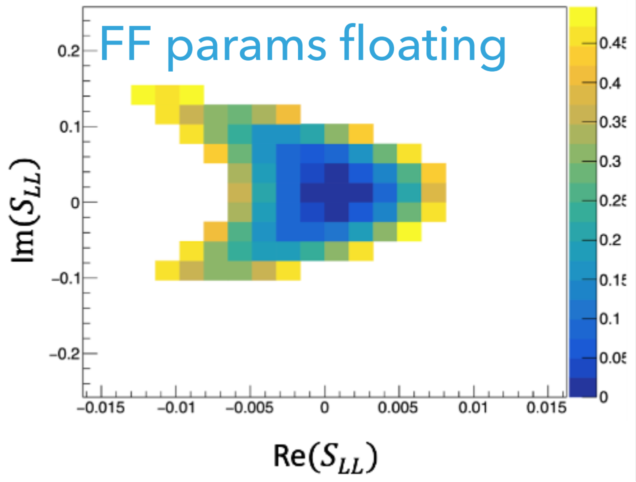
- First differential decay rate measurements of semileptonic decays performed also at LHCb
- Different advantages and challenges wrt measurements performed at the b-factories: essential to take advantage of the complementarity
- Work on-going to perform angular analyses using different approaches
- Not many results today… stay tuned!

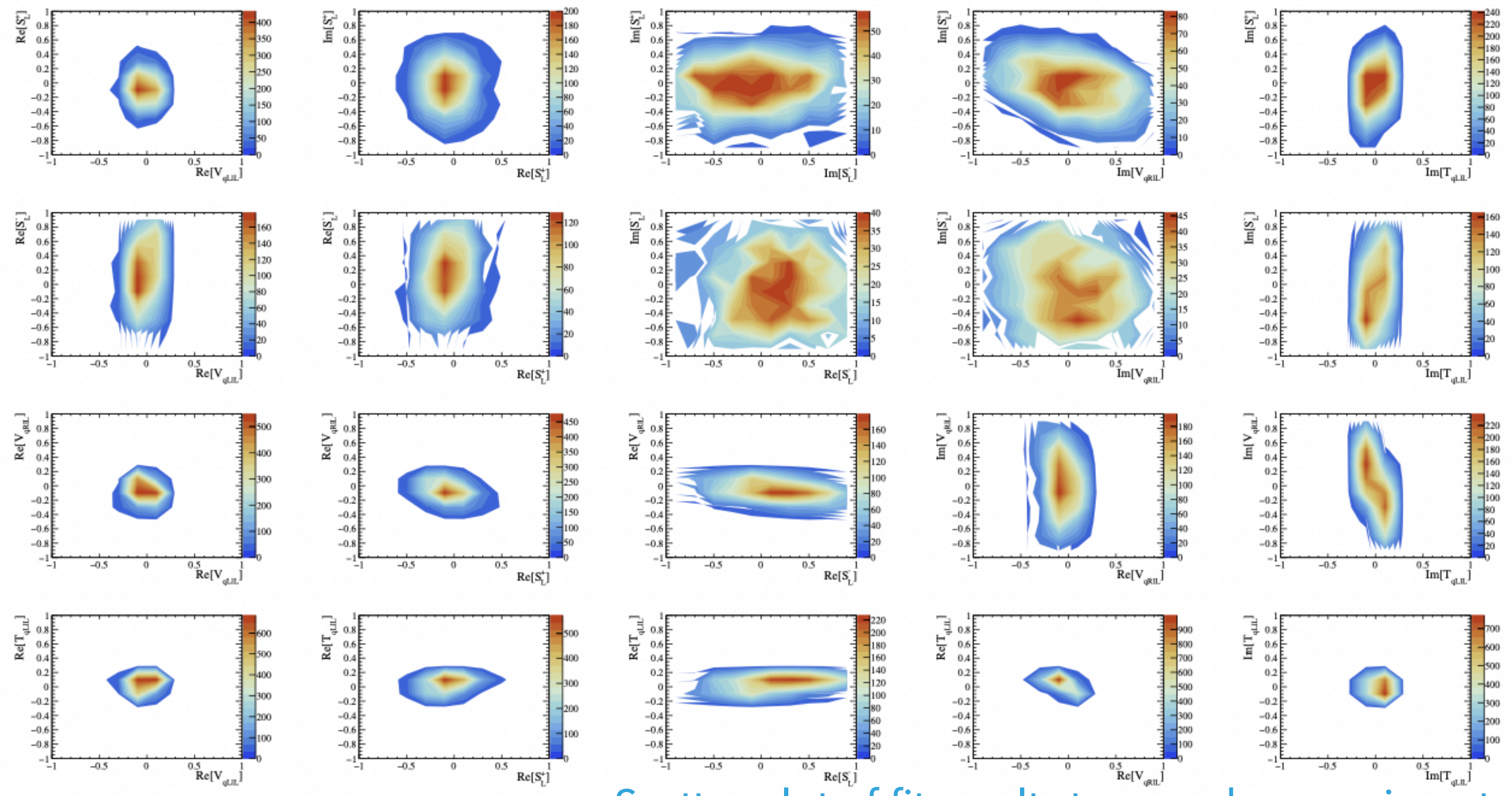
Backup

Even before adding angular observables

- Expanding on $R(D^+)$ vs $R(D^{*+})$ measurement (LHCb-PAPER-2024-007)
- Modify signal and normalisation models to include NP contributions
- Pseudo-experiments study: no NP assumed in muon modes, NP assumed left-handed $(V_{LR} = V_{RR} = S_{LR} = S_{RR} = T_{RR} = 0)$, $S_L^+ = \dfrac{S_{LL} + S_{RL}}{2}$, $S_L^- = \dfrac{S_{LL} - S_{RL}}{2}$
- Confirmed no significant difference when floating or fixing FF (BLPR) parameters and some sensitivity to NP Wilson Coefficients [preliminary study to be followed up]







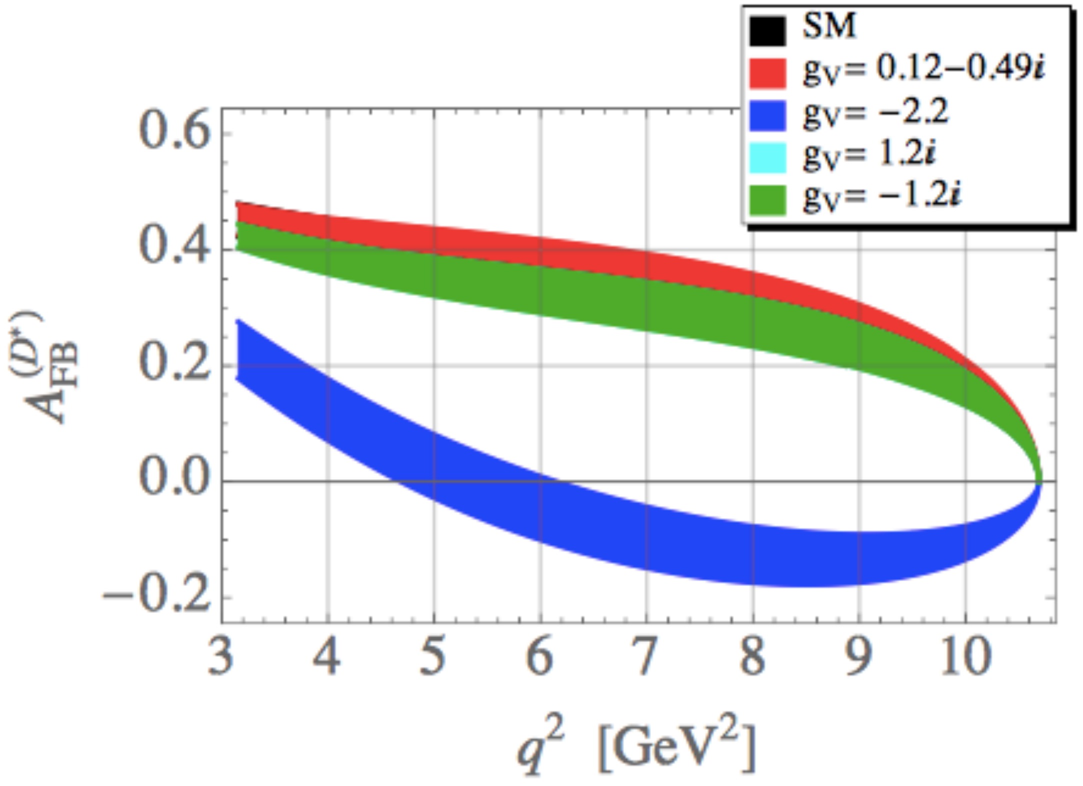
Scatter plot of fit results to pseudo-experiments

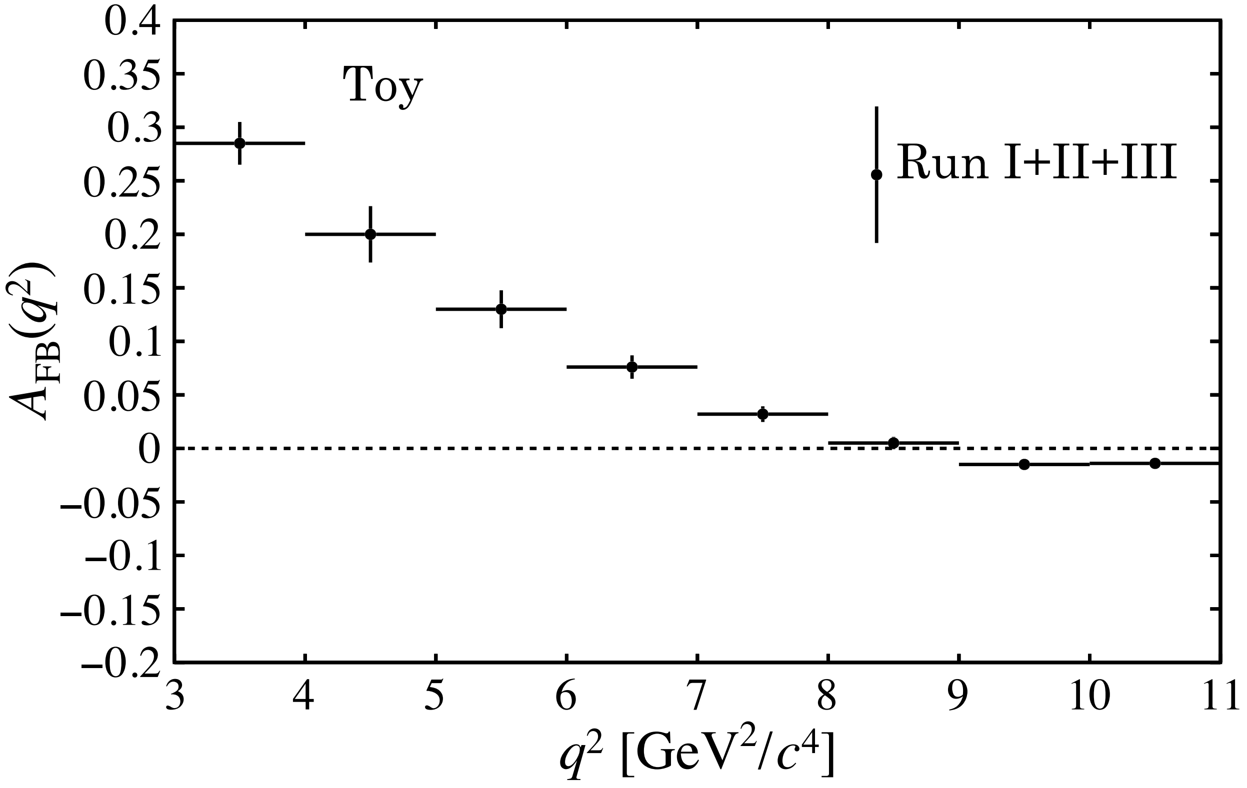
S. Meloni CERN-THESIS-2021-266

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

- 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

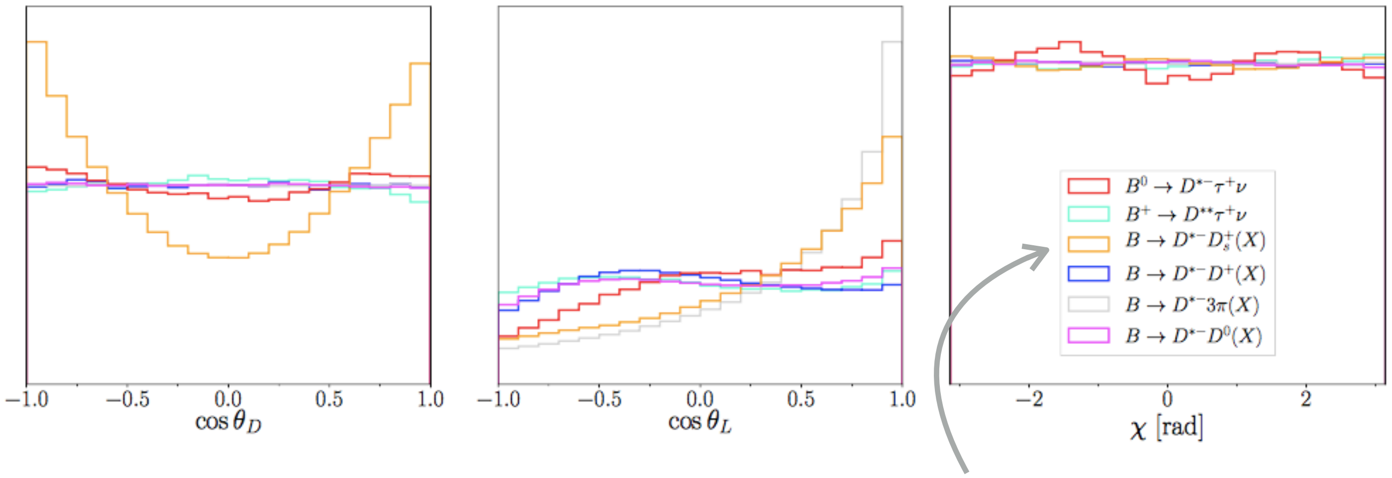
$B^0 \to D^{(*)}\tau\nu$

- 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

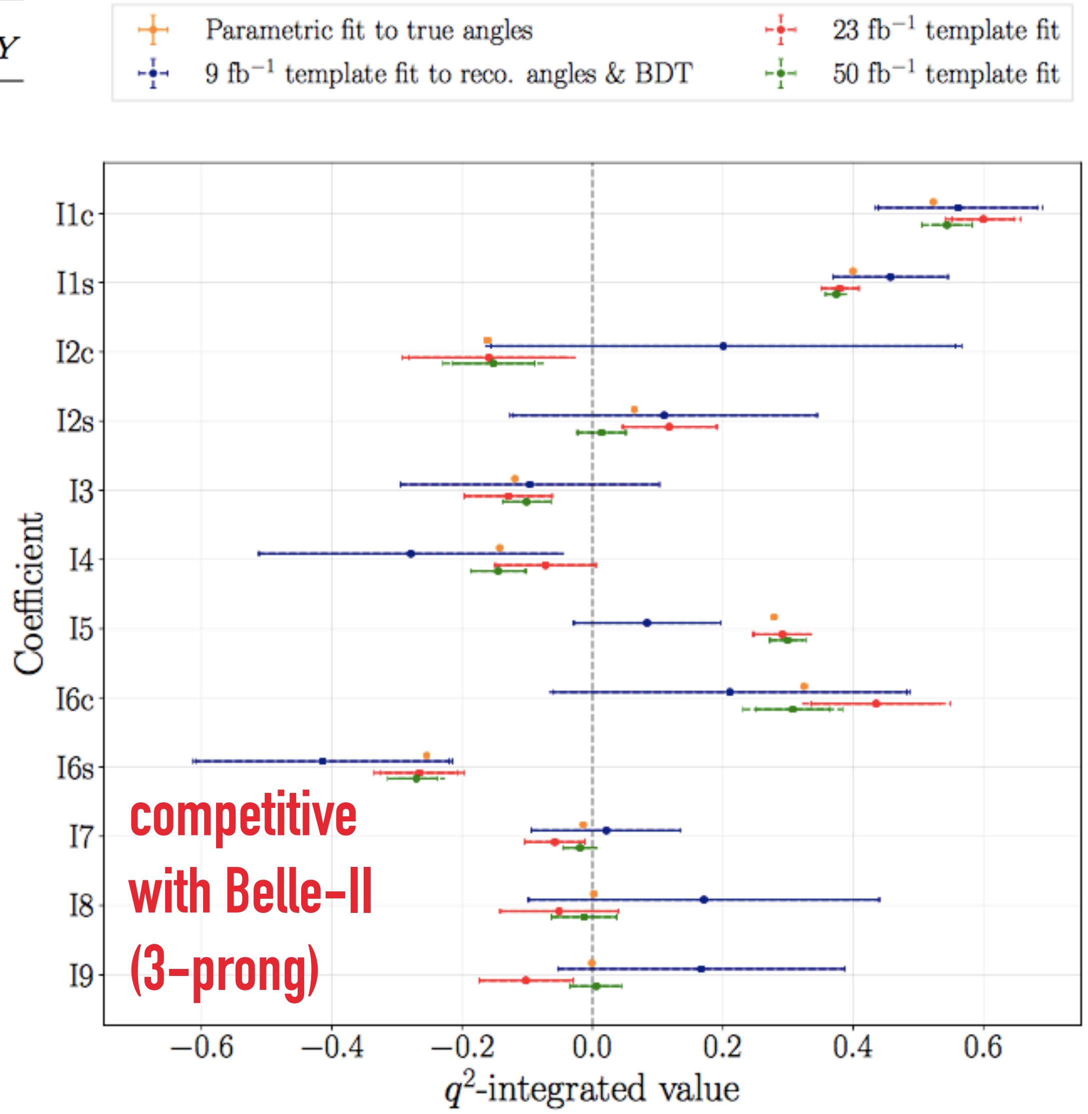
D. Hill et.al., JHEP 11 (2019) 133

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

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



JHEP 06 (2021) 177



competitive with Belle-II (3-prong)

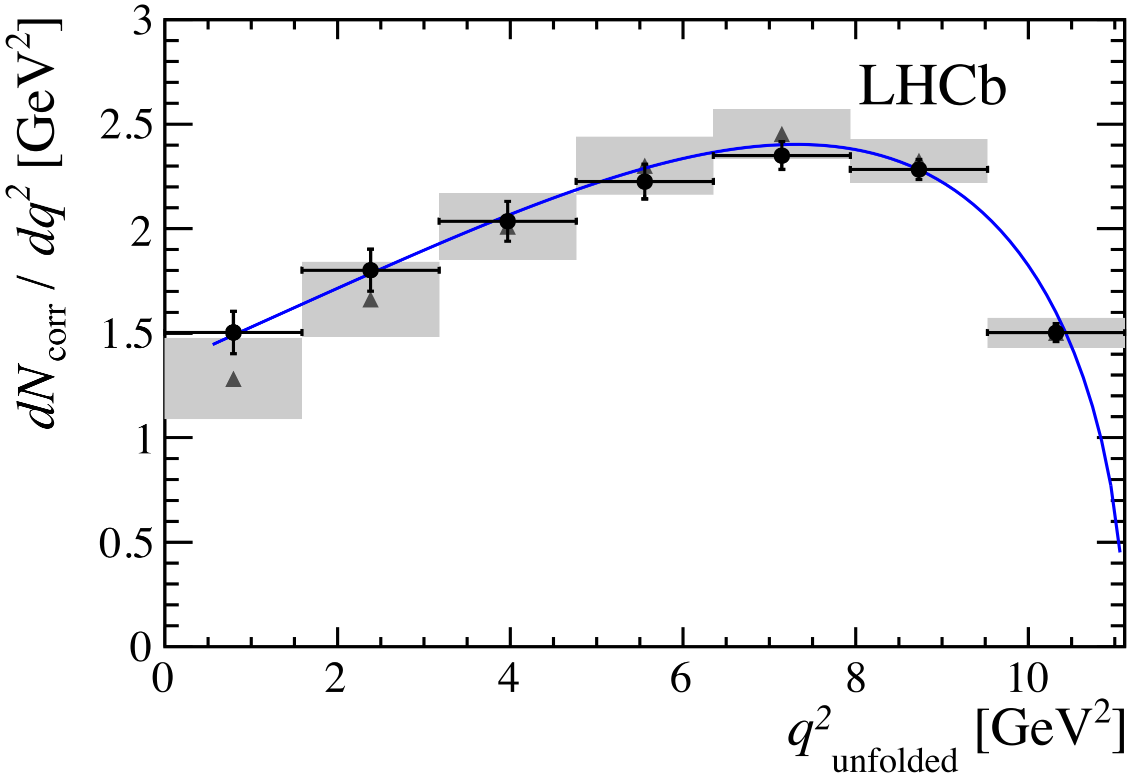
- Lower statistics than muonic decays samples, large backgrounds, external inputs needed for R(D), R(D*)

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

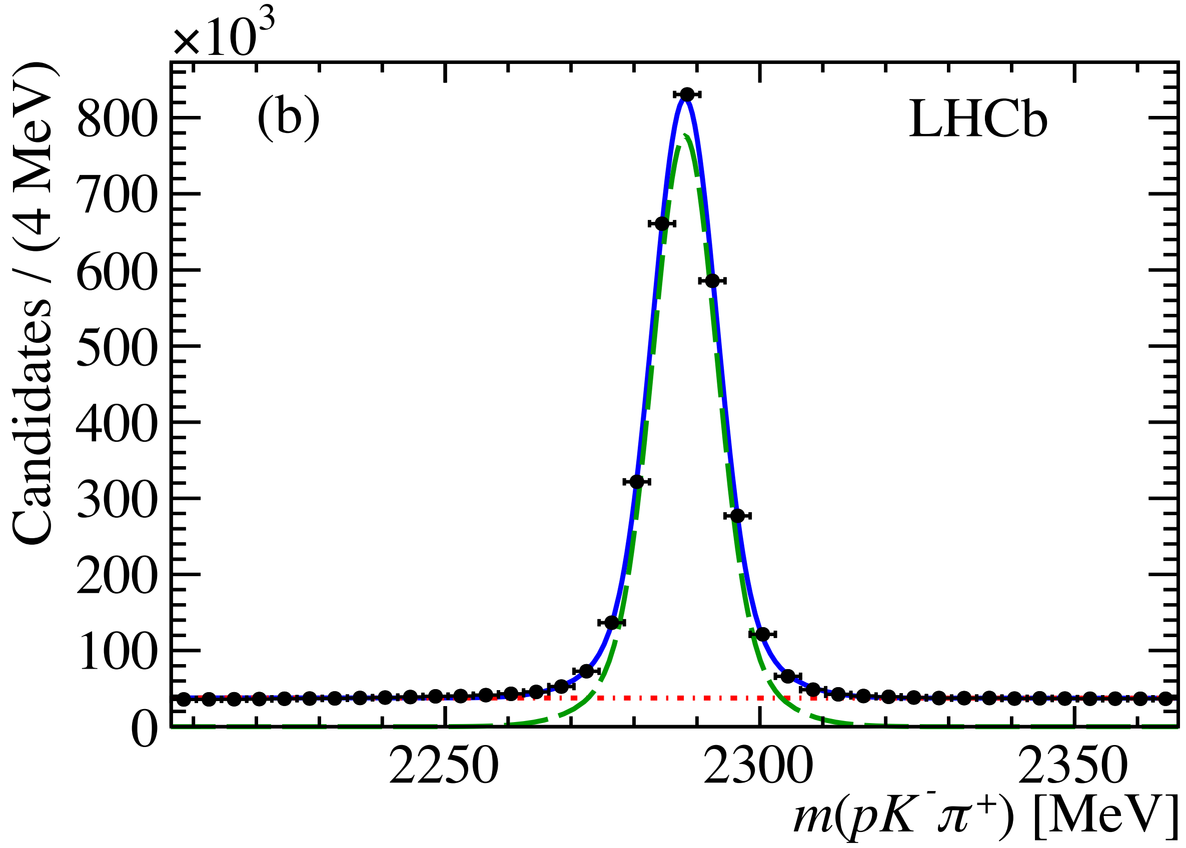
- Probing baryonic decays - different spin structure
- Measurement of the shape of the differential decay rate using Run-I dataset
- Low background level and smooth acceptance across decay variables

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

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



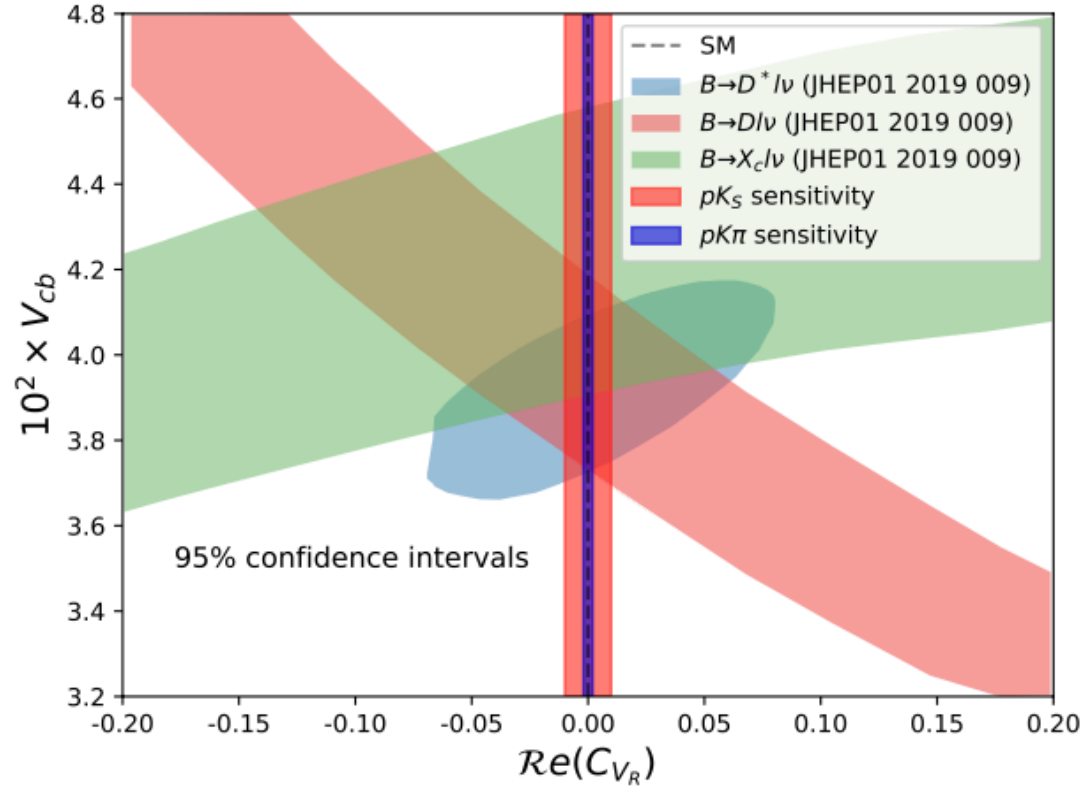
Phys. Rev. D96 (2017) 112005

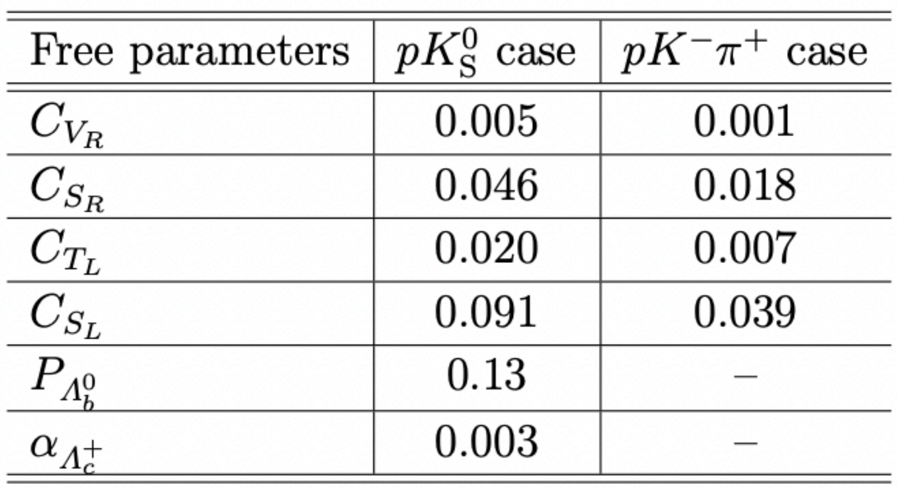


Final state	Yield
$\Lambda_c(2595)^+\mu^-\overline{\nu}_\mu$	8569 ± 144
$\Lambda_c(2625)^+\mu^-\overline{\nu}_\mu$	22965 ± 266
$\Lambda_c(2765)^+\mu^-\overline{\nu}_\mu$	2975 ± 225
$\Lambda_c(2880)^+\mu^-\overline{\nu}_\mu$	1602 ± 95
$\Lambda_c^+\mu^-\overline{\nu}_\mu X$	$(2.74\pm0.02)\times10^6$

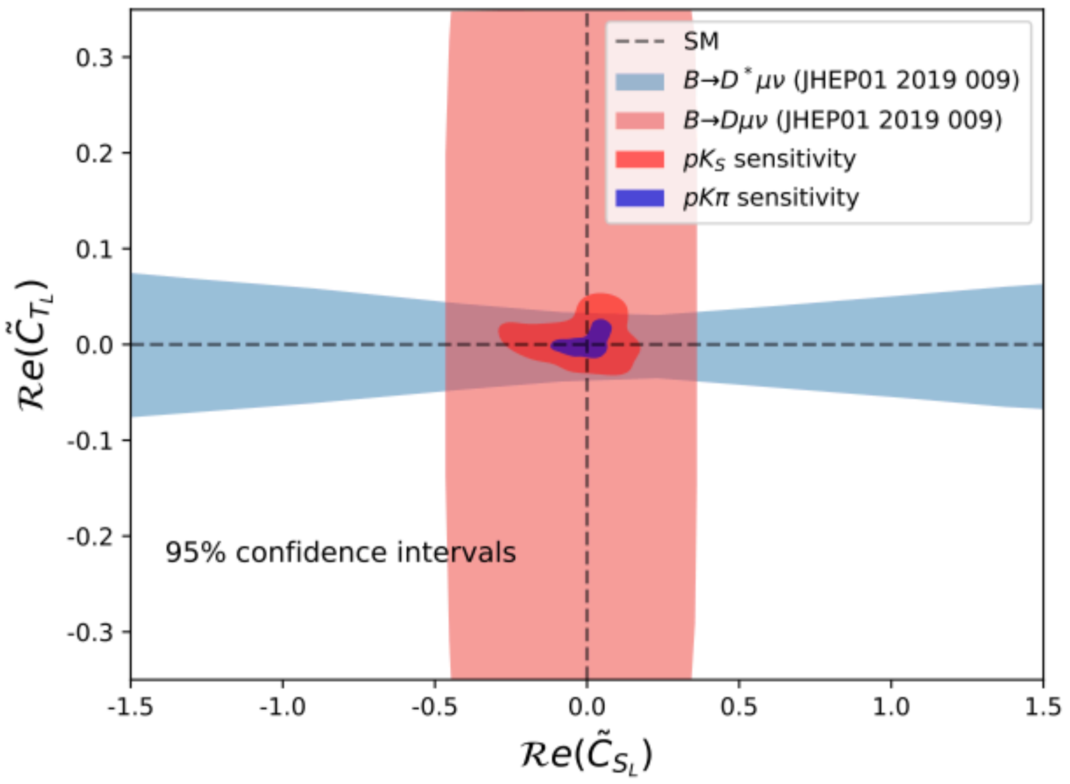
Baryons: $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}$

- 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	–



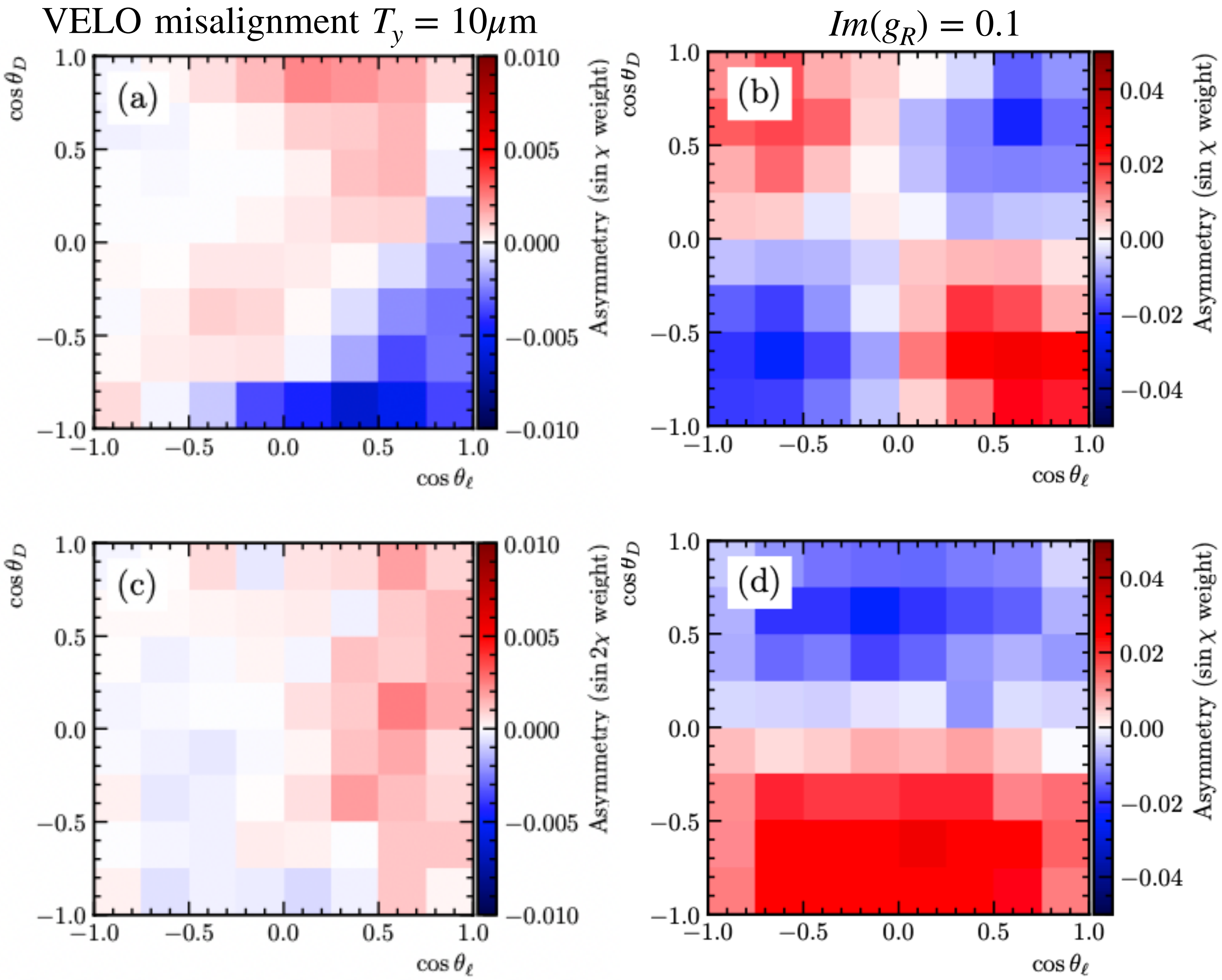
M. Ferrillo et. al., JHEP 12 (2019) 148

Additional ideas: CPV observables

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

V. Dedu and A. Poluektov, arXiv:2304.00966

- 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

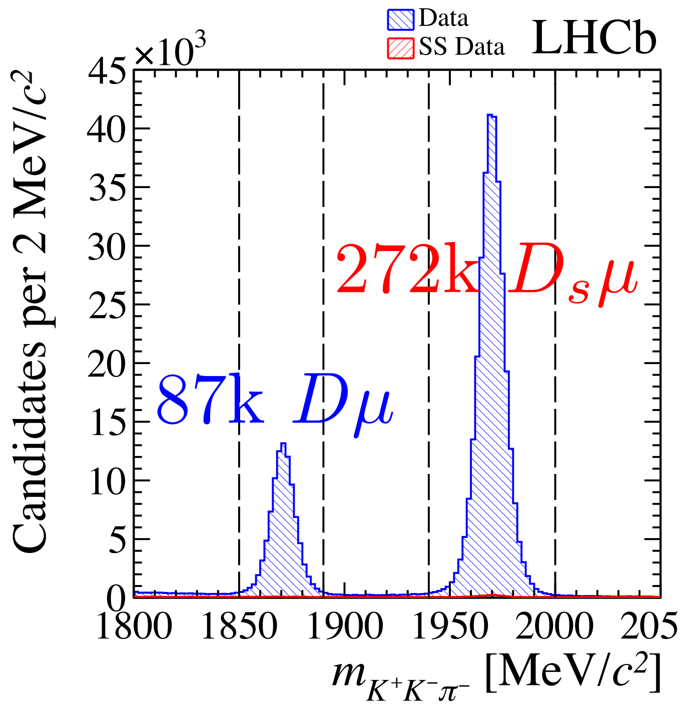


VELO misalignment $T_y = 10\mu m$

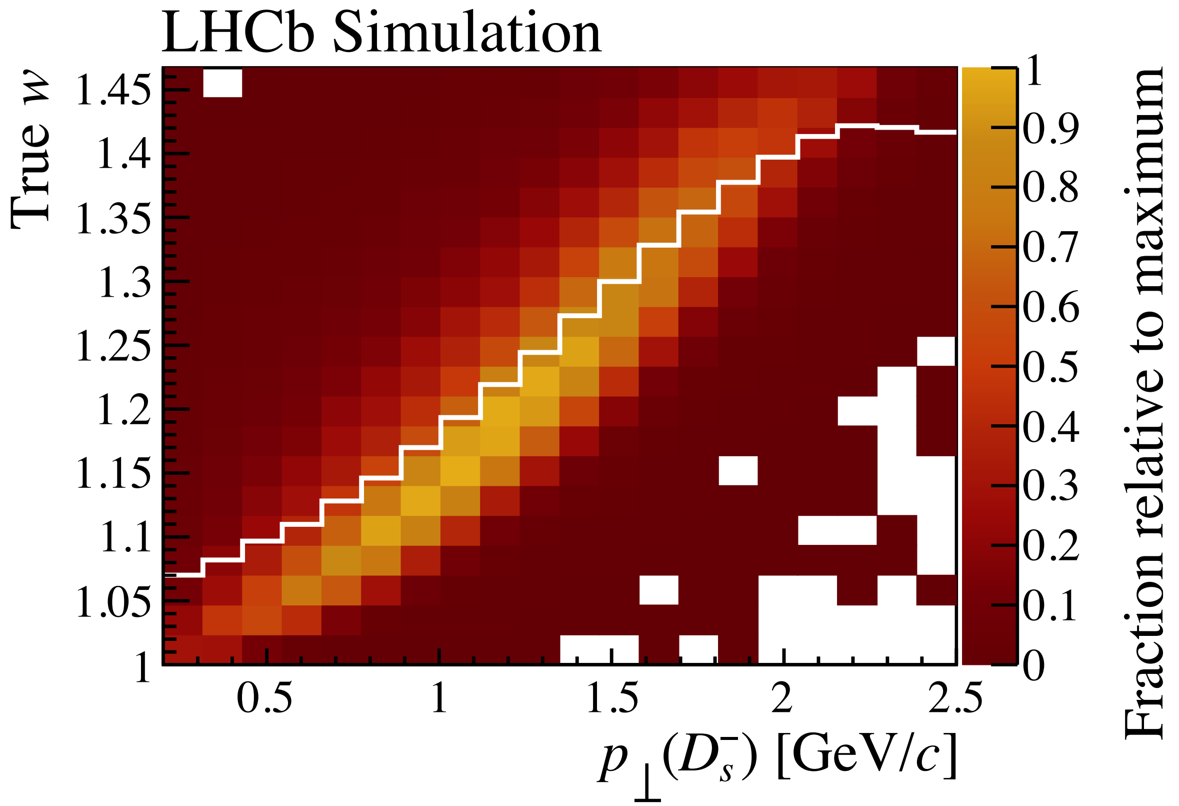
$Im(g_R) = 0.1$

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

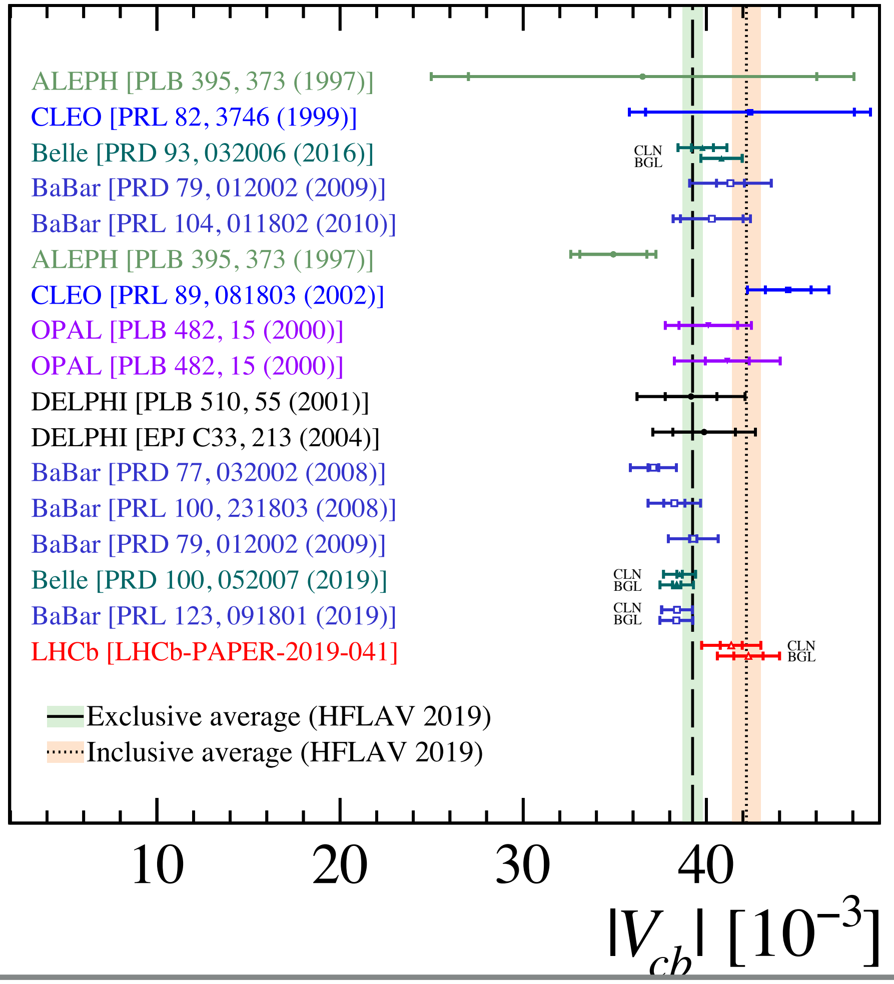
- First measurement of $|V_{cb}|$ using $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$
  - Measure rate relative to $B^0 \to D^{(*)-}\mu^+\nu_\mu$
  - Requires external inputs for $|V_{cb}|$
  - Measurement of decay rate as a function of $p_\perp(D_s^-)$, proxy for q^2 or recoil w ($D_s^{(*)-}$ energy in the B_s^0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



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



Phys. Rev. D101 (2020) 072004



Two FF parametrisations - **consistent**