$B^0 \to D^{(*)}\ell\nu$ Angular Analysis at LHCb

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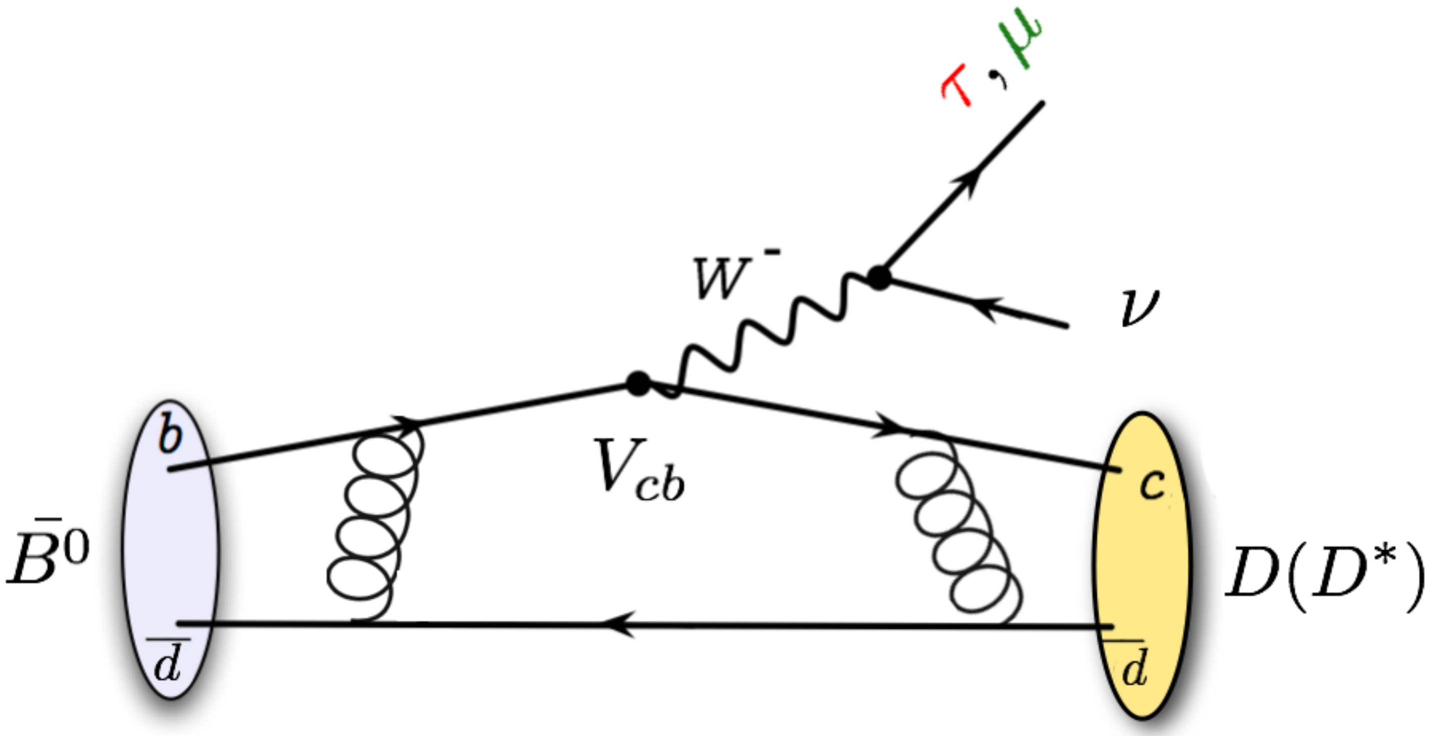
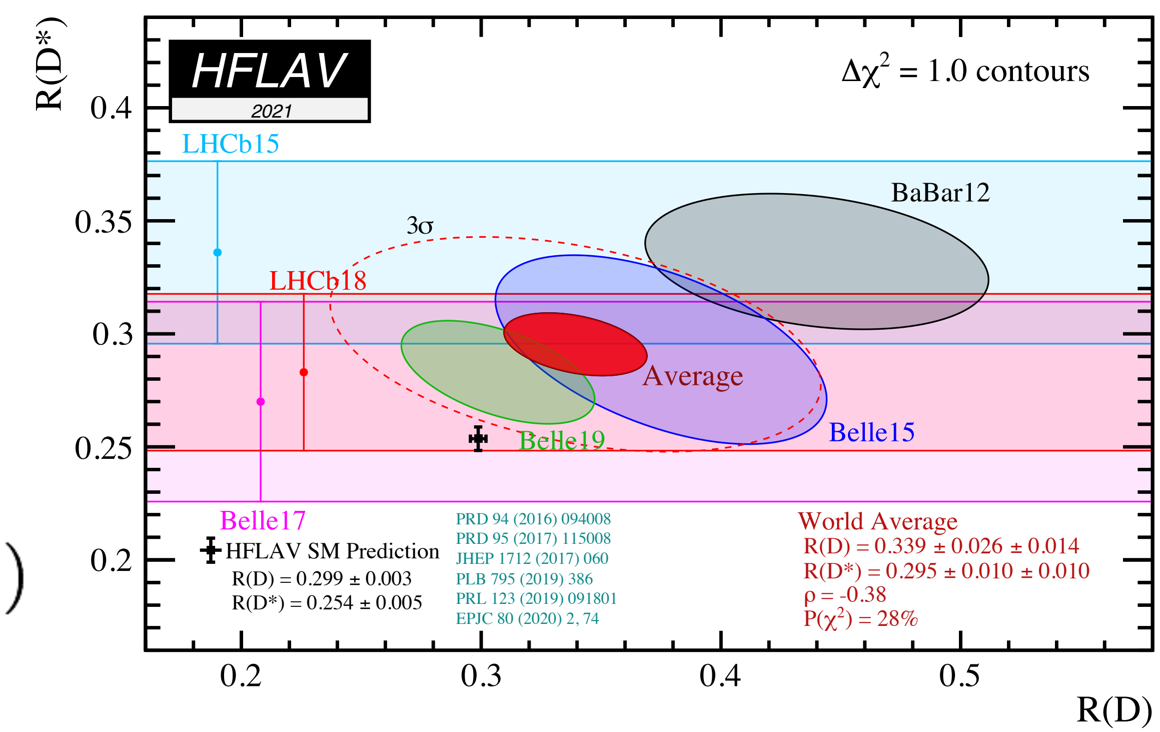
with input from Biljana Mitreska, Greg Ciezarek, Marco Gersabeck, Marcello Rotondo

Challenges in Semileptonic B decays 19-23/04/2022

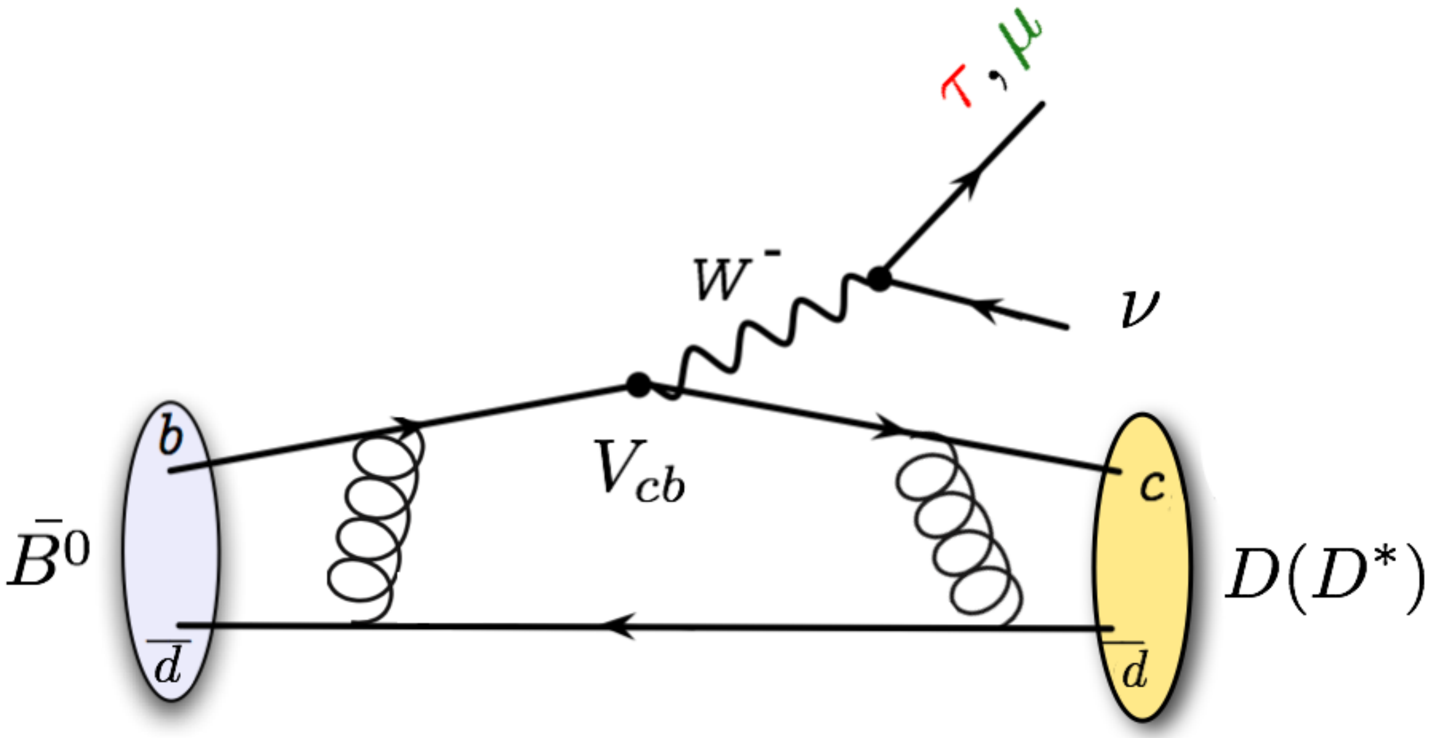
Angular analyses of semileptonic B decays

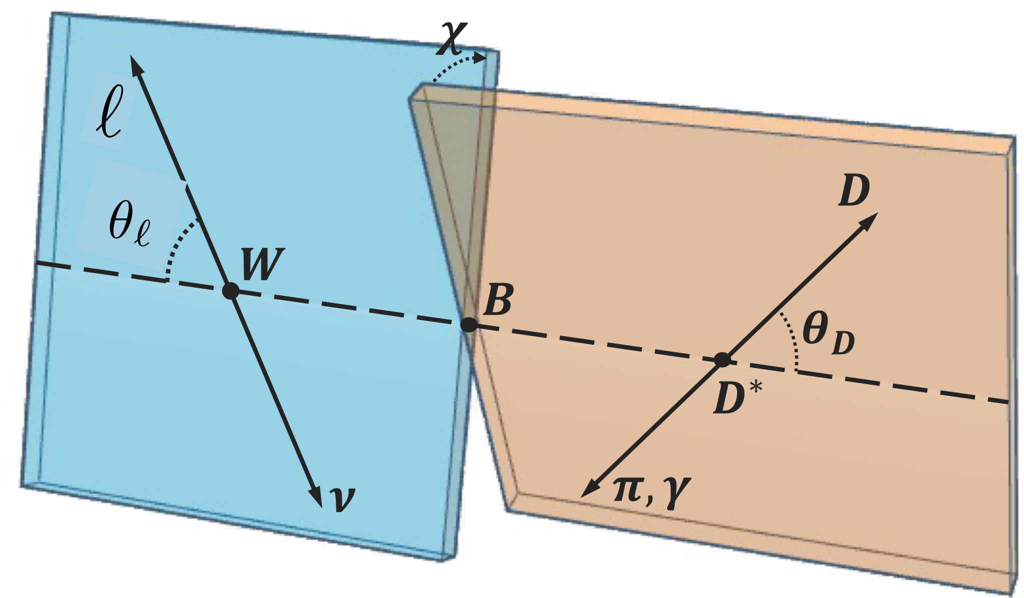




- New Physics searches, complementary to Lepton Universality tests
- Hadronic Form Factors measurements
- In this talk: ongoing $B^0 \to D^{(*)}\ell\nu$ studies at LHCb

Semileptonic decays





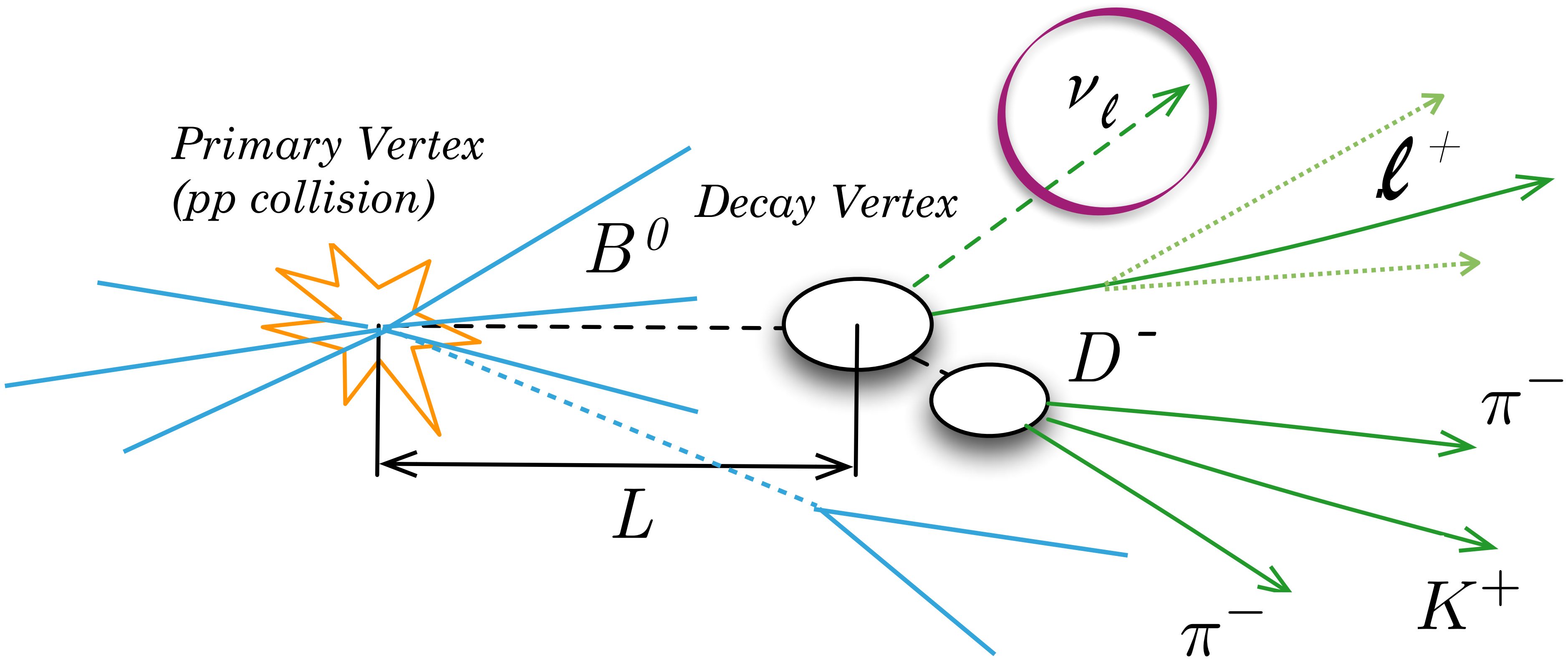
$$\frac{d^4(B^0 \to D^* \ell^+ \nu_\ell)}{dq^2 d\cos^2\theta_\ell d\cos\theta_{D^*} d\chi} \propto |V_{cb}|^2 \sum_i \mathcal{H}_i(q^2) f_i(\theta_\ell, \theta_{D^*}, \chi)$$

(Electroweak) couplings + QCD encompassed by Form Factors

- Helicity angles distributions (and derived observables) are sensitive to New Physics contributions and hadronic interactions (Form Factors)

Semileptonic decays @LHCb

Non-reconstructable neutrino(s)



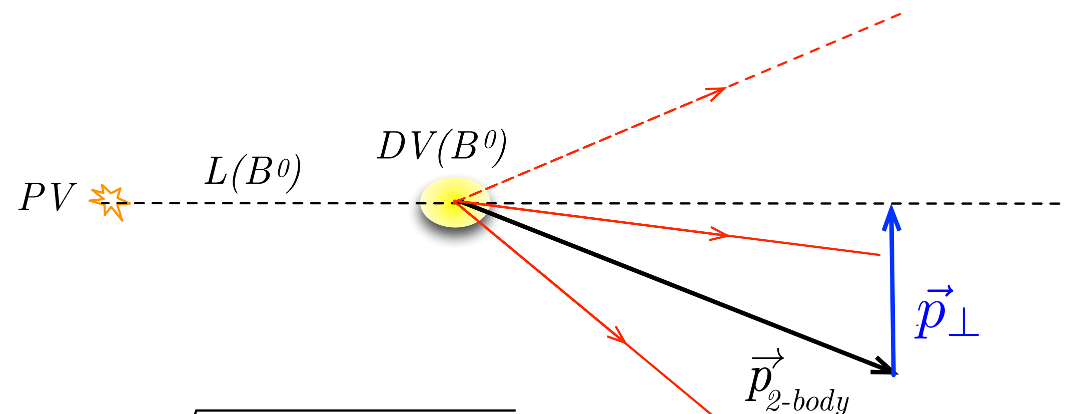
τ decay mode	BR[%]
$\tau \to \mu\bar{\nu}\nu$	17.39±0.0
$\tau \to e\bar{\nu}\nu$	17.82±0.0
$\tau \to 3\pi\nu$	9.31±0.05
$\tau \to 3\pi\pi^0\nu$	4.62±0.05
$\tau \to \pi\nu$	18.82±0.0
$\tau \to \rho\nu$	25.49±0.9

- 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) !

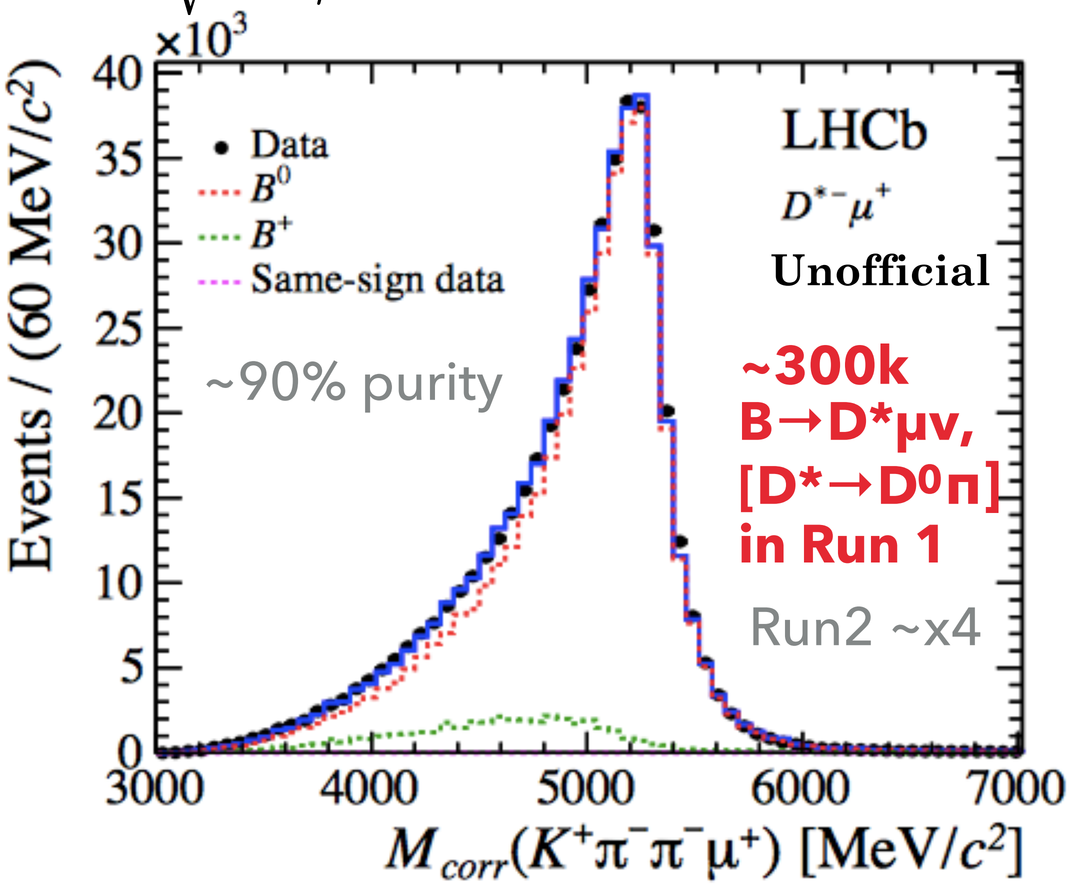
Backgrounds

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

- Analyses with muons: signal dominated

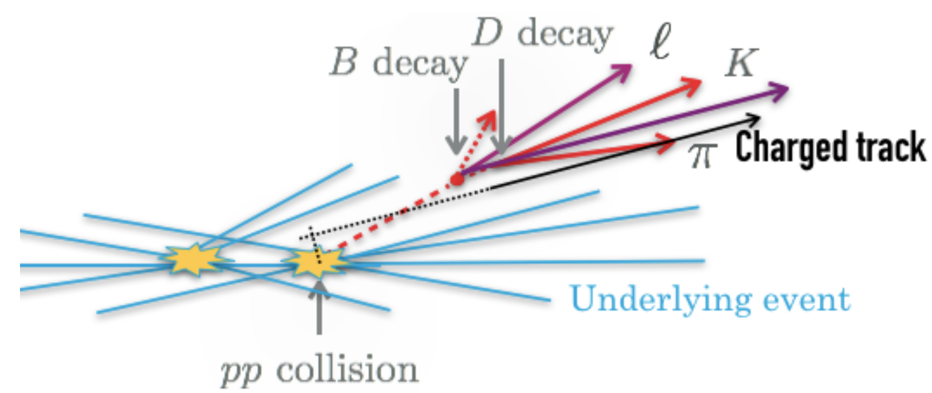


$$M_{corr} = \sqrt{M_{D\mu}^2 + |p_\perp|^2} + |p_\perp|$$

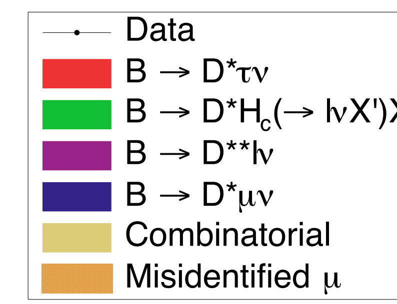


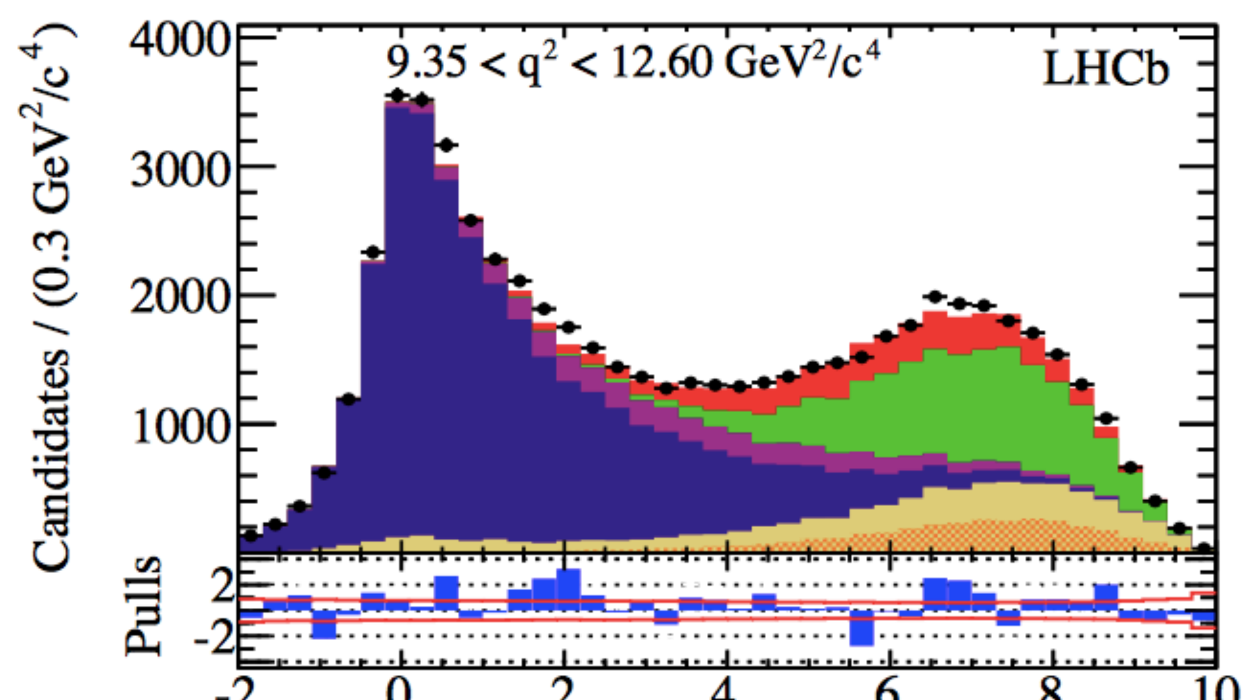
$B^0 \to D^{(*)}\tau\nu$

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



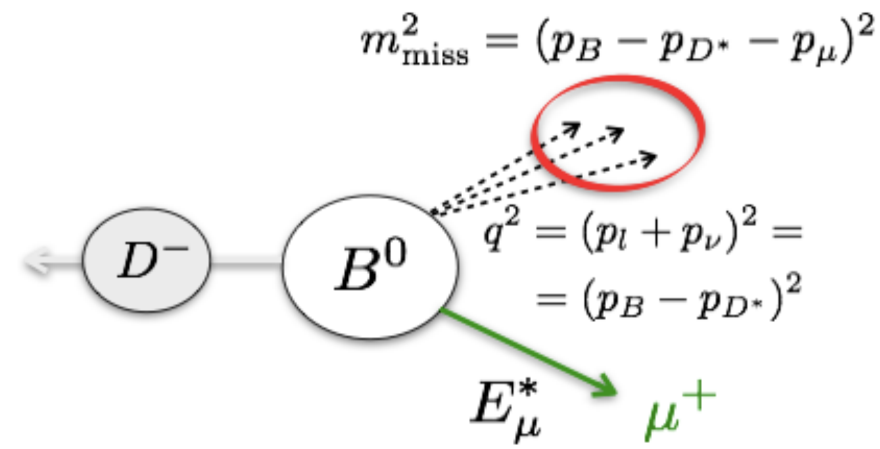
$$m^2_{\mathrm{miss}} = (p_B - p_{D^*} - p_\mu)^2$$





Phys. Rev. Lett. 115, 111803 (2015)

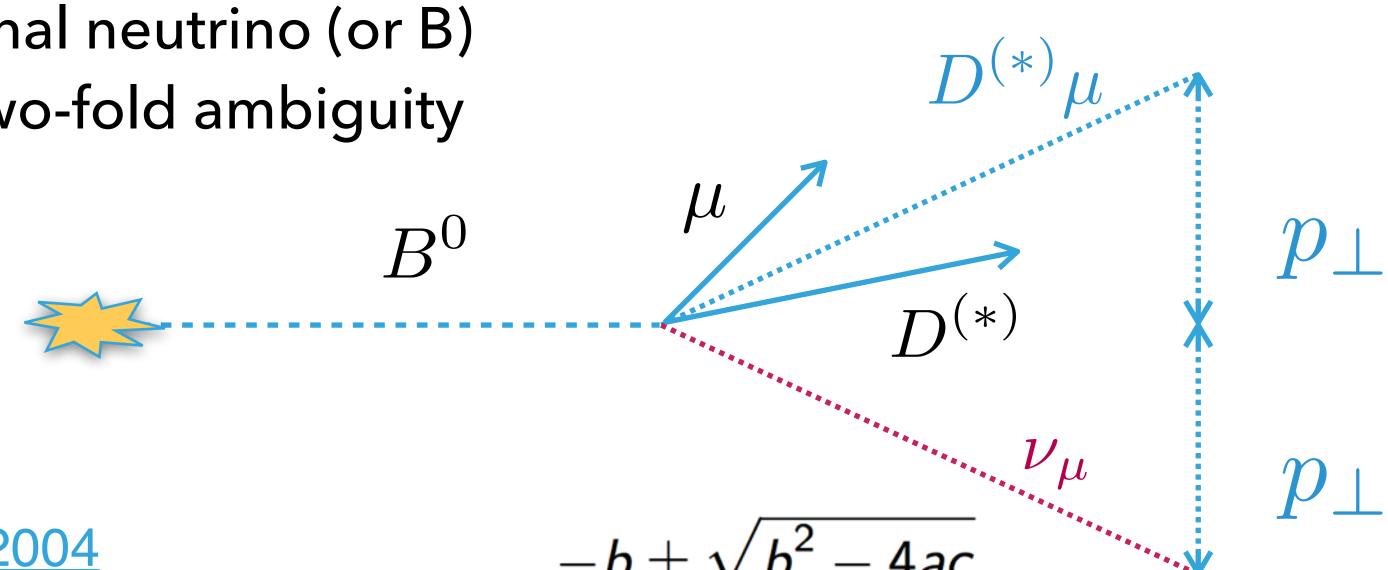
Partial reconstruction



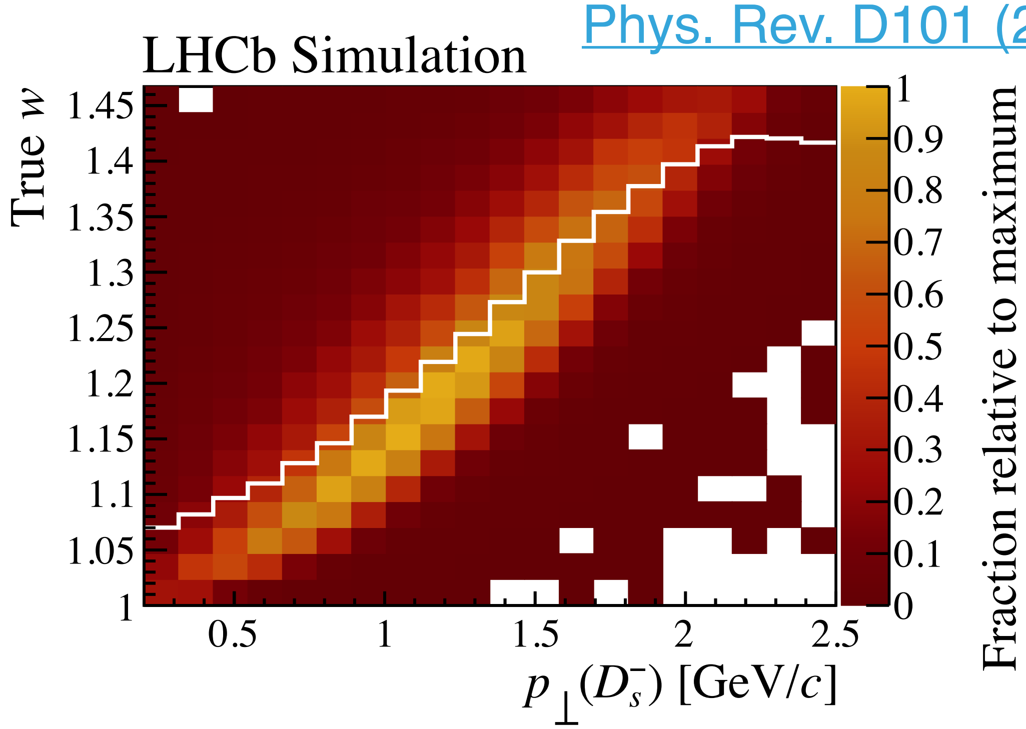
- With more than one missing neutrino:
  B rest frame approximation

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

- 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
    [JHEP 2 (2017) 021]
  - Use a proxy variable



[Phys. Rev. D101 (2020) 072004]



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

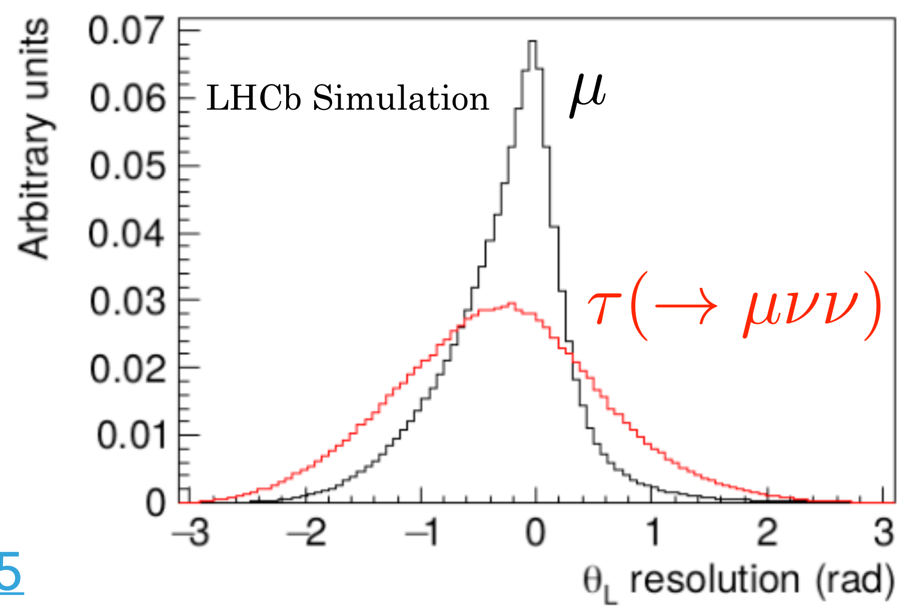
$$a = |2p_{\parallel,X_\mu} m_{X_\mu}|^2,$$

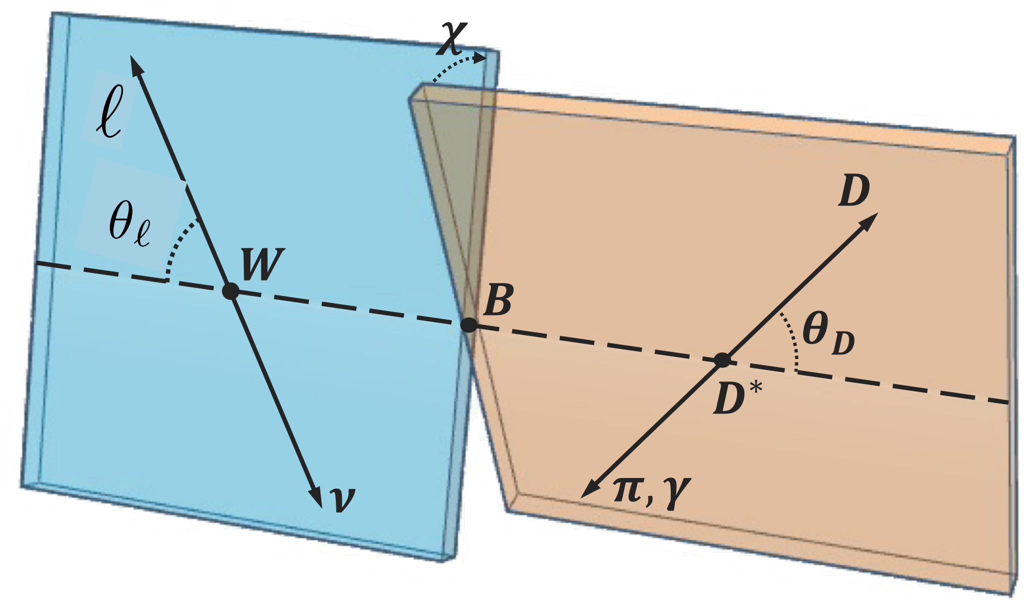
$$b = 4p_{\parallel,X_\mu}(2p_\perp p_{\parallel,,X_\mu} - m^2_{miss}),$$

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

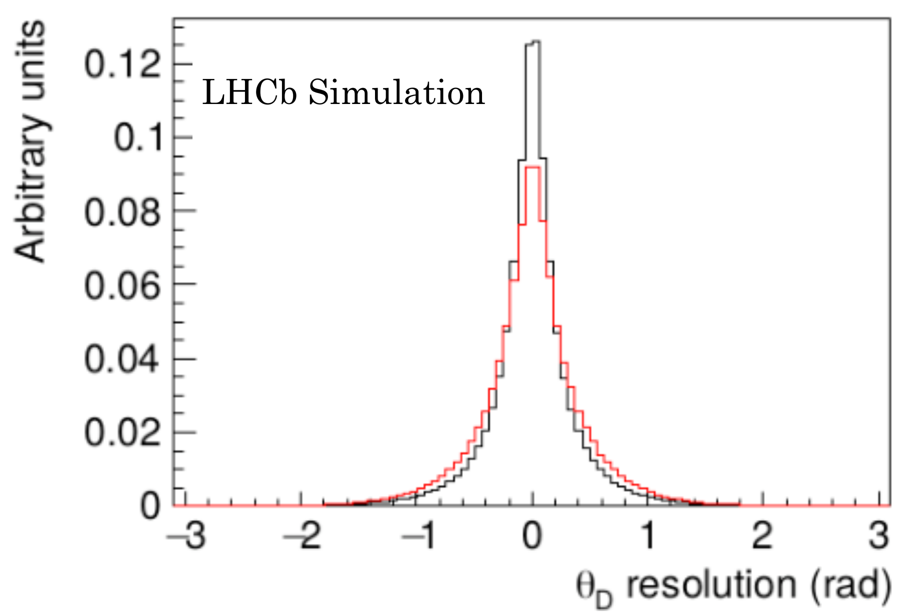
$$m^2_{miss} = m^2_{\rm B^0} - m^2_{X_\mu}.$$

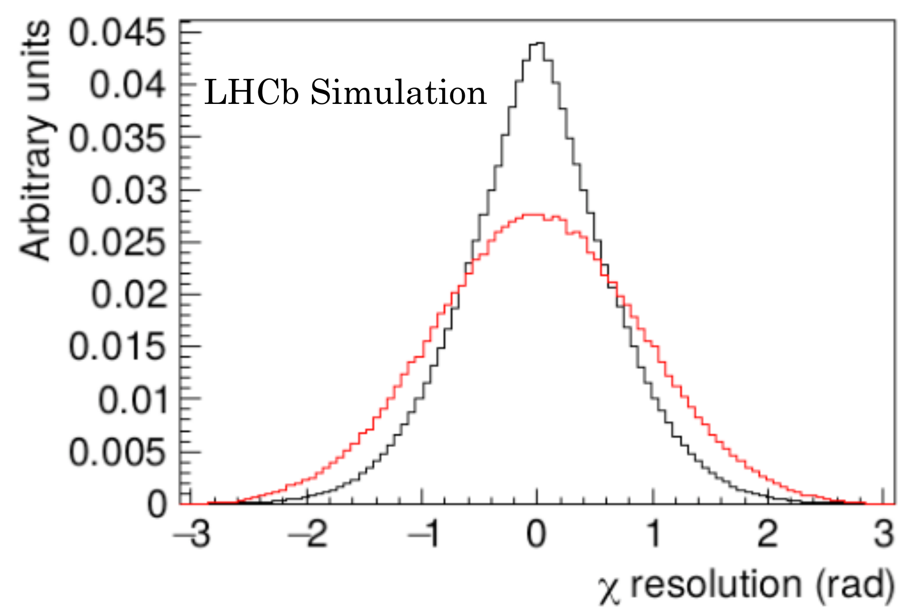
Differential measurements





[arXiv:1808.08865](https://arxiv.org/abs/1808.08865)



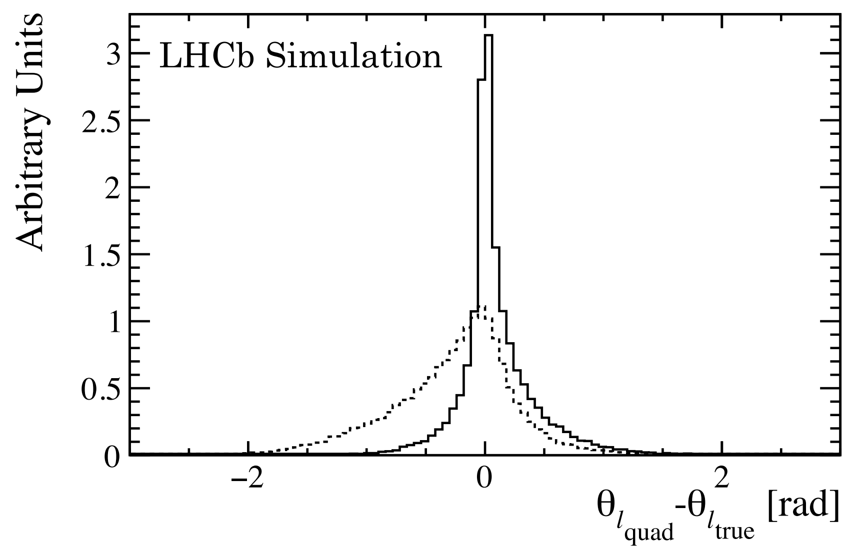


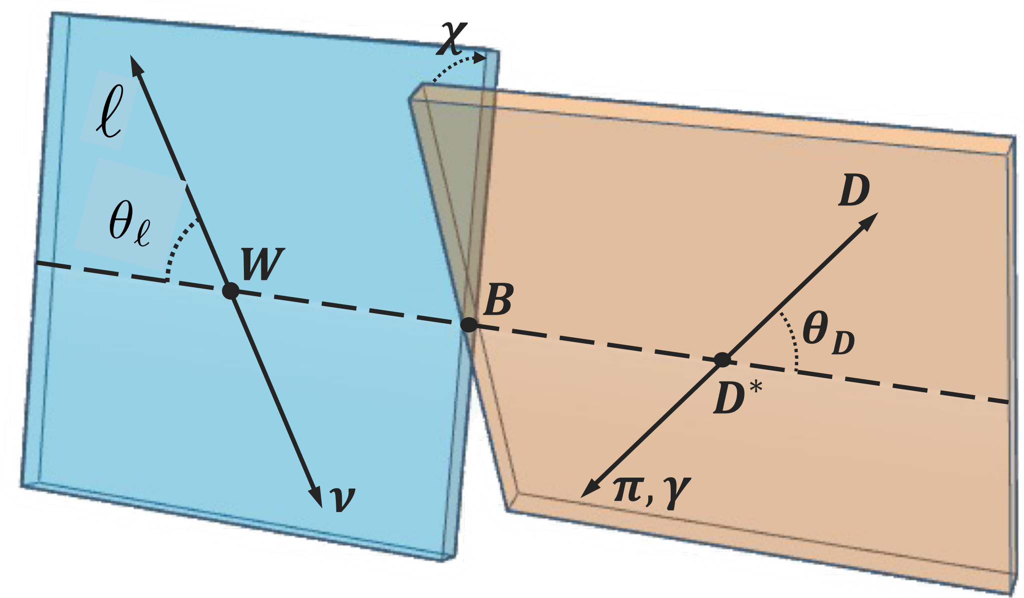
Resolutions to be modelled, but good sensitivity with large datasets!

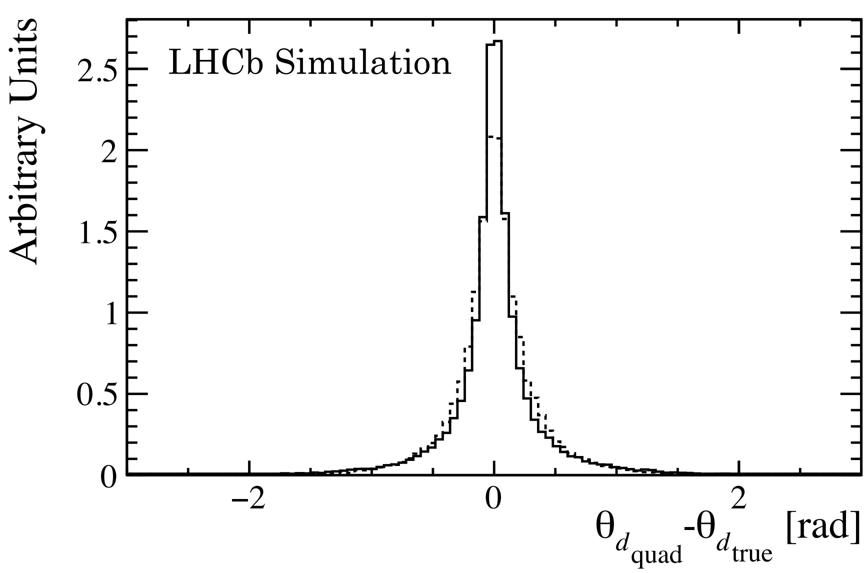
- Helicity angles distributions (and derived observables) are sensitive to New Physics contributions and hadronic interactions (Form Factors)

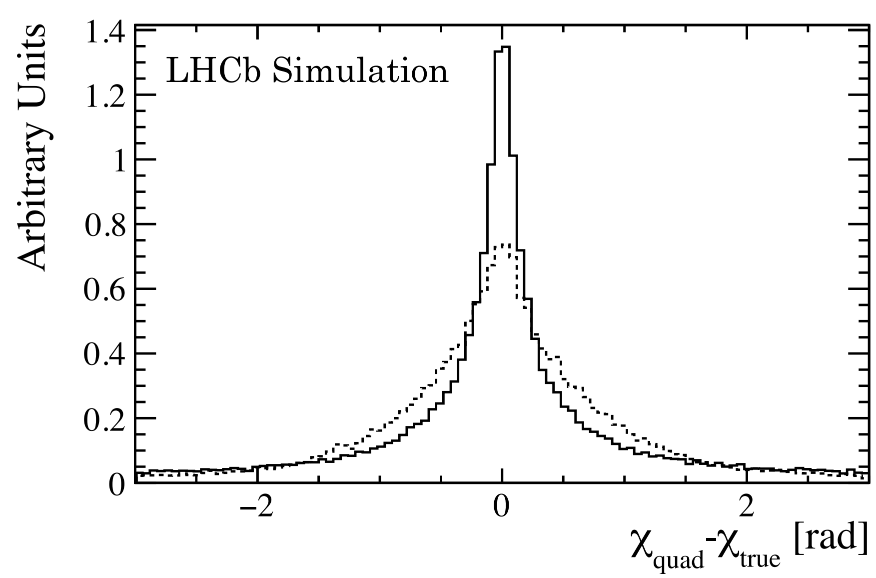
Differential measurements

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



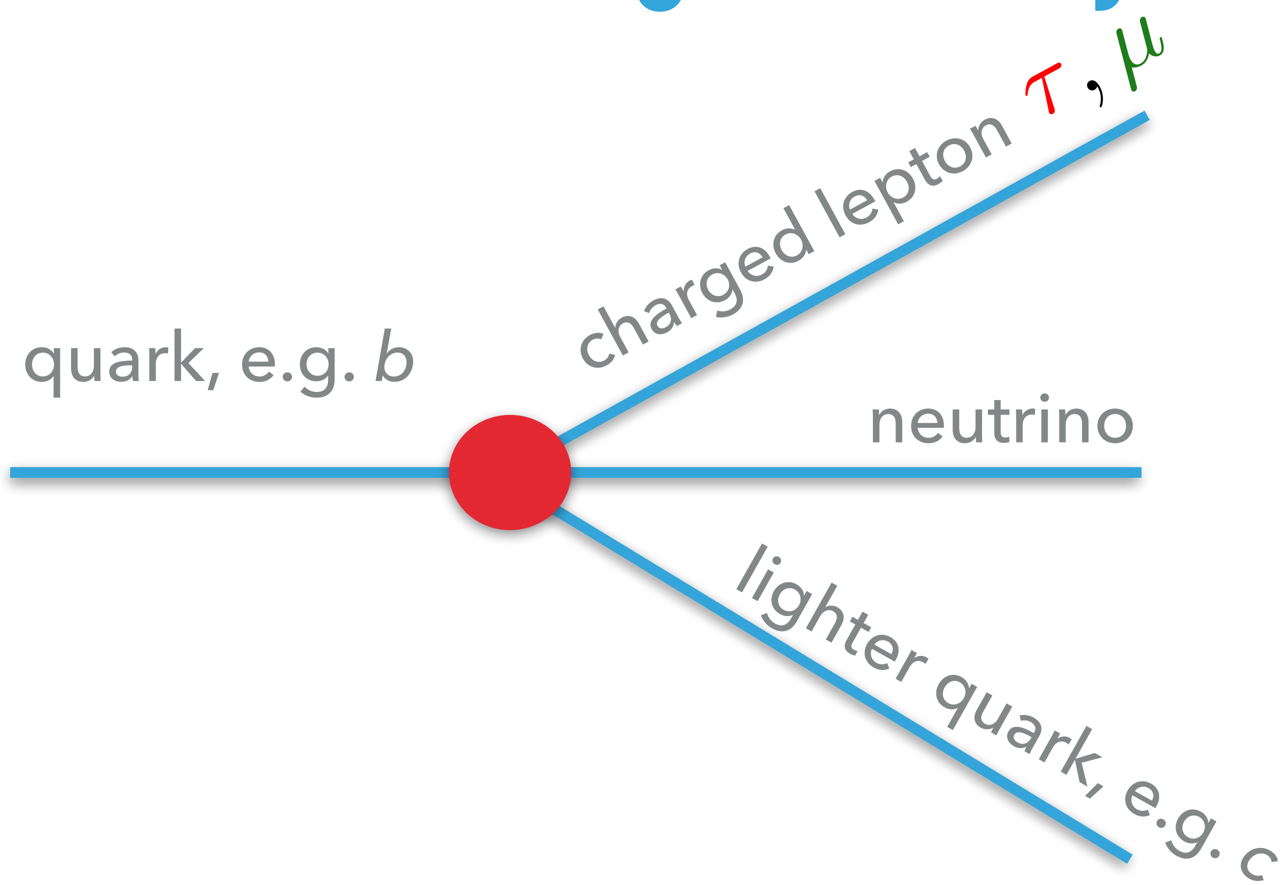






- Helicity angles distributions (and derived observables) are sensitive to New Physics contributions and hadronic interactions (Form Factors)

EFT: Modelling New Physics (and hadronic) effects



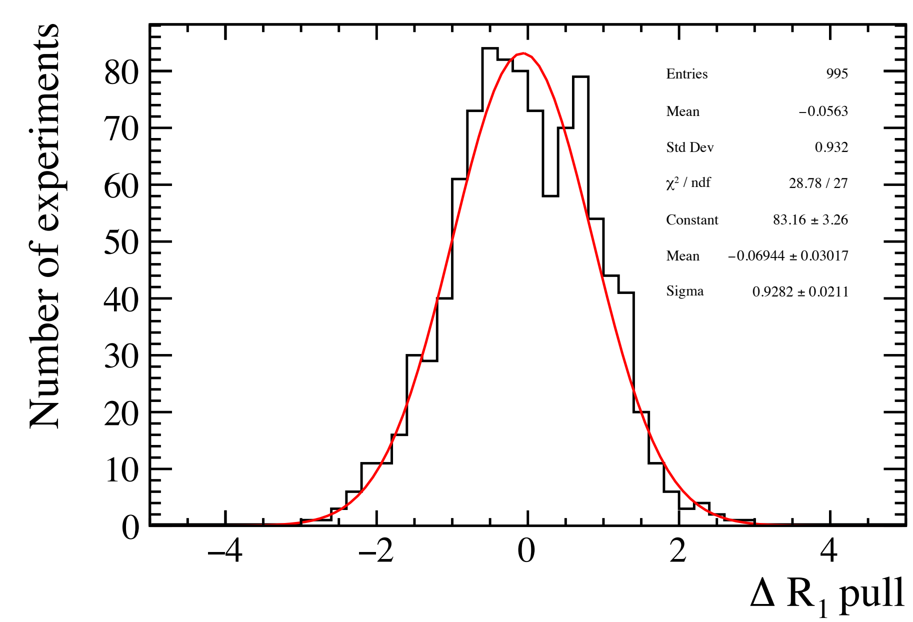
Wilson coefficients

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

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

Effective operators

- [HAMMER](#) tool (Bernlochner, Duell, Ligeti, Papucci, 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 ([arXiv:2007.12605](#))



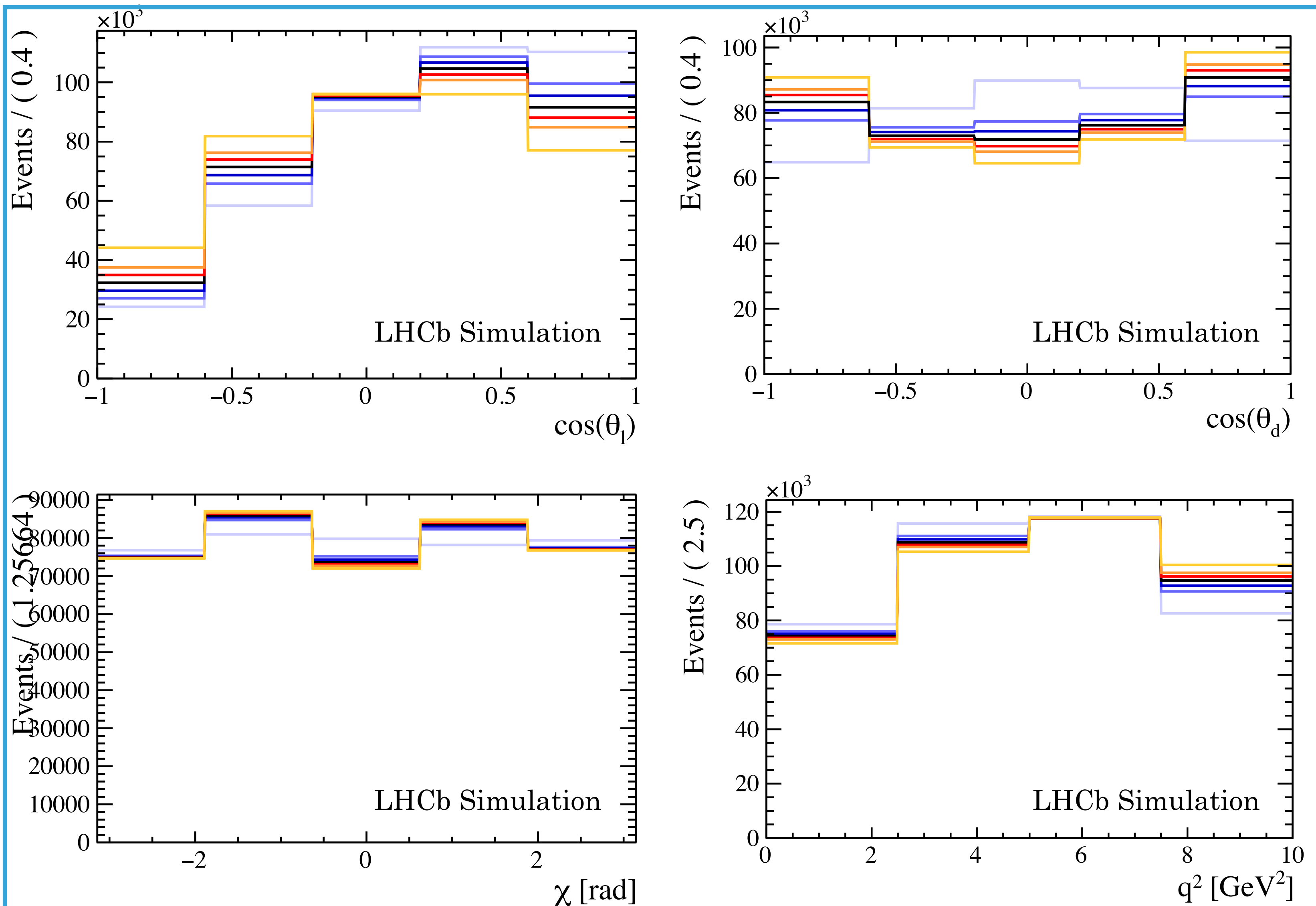
$B^0 \to D^{(*)}\mu\nu$

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

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

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

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

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

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

SM

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

Current	WC Tag	WC	4-Fermi/$(i2\sqrt{2}V_{cb}G_F)$
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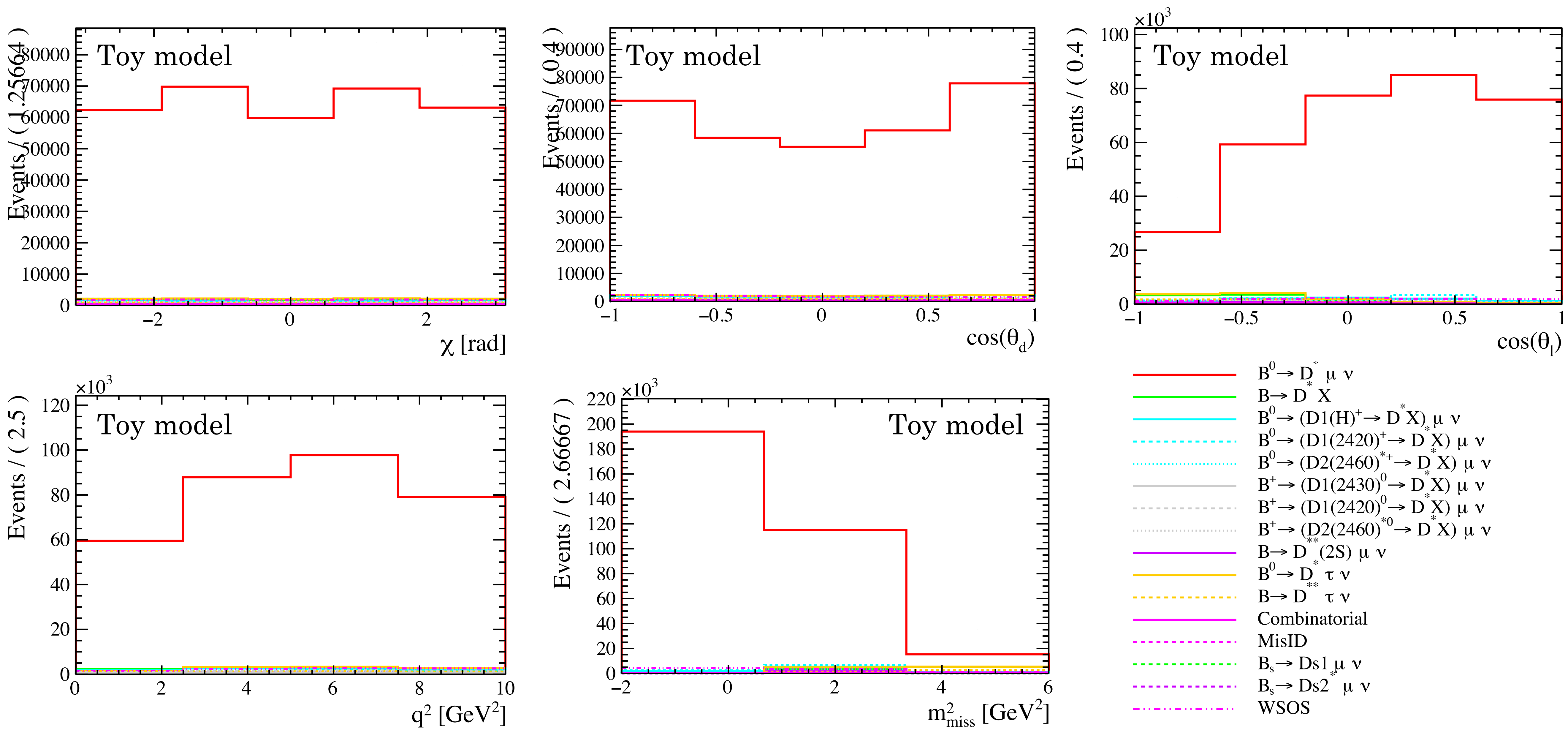
Vector	V_qLlL	$\chi_L^V\lambda_L^V$	$[\bar{c}\chi_L^V\gamma^\mu P_L b][\bar{\ell}\lambda_L^V\gamma_\mu P_L\nu]$
	V_qRlL	$\chi_R^V\lambda_L^V$	$[\bar{c}\chi_R^V\gamma^\mu P_R b][\bar{\ell}\lambda_L^V\gamma_\mu P_L\nu]$
	V_qLlR	$\chi_L^V\lambda_R^V$	$[\bar{c}\chi_L^V\gamma^\mu P_L b][\bar{\ell}\lambda_R^V\gamma_\mu P_R\nu]$
	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

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



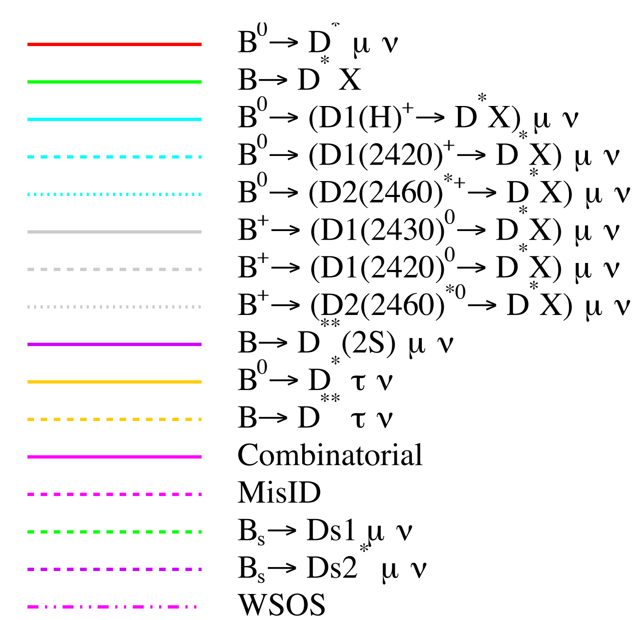
An angular analysis of $B^0 \to D^{(*)}\mu\nu$

- **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

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

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2|V_{cb}|^2}{192\pi^3 M^3}\frac{k}{q^5}(q^2-m_l^2)^2$$
$$= \left[(2q^2+m_l^2)(2q^2|f|^2+|\mathcal{F}_1|^2+2k^2q^4|g|^2)+3m_l^2k^2q^2|\mathcal{F}_2|^2\right]$$

$$F(q^2) = \frac{1}{P(q^2)\phi(q^2;t_0)}\sum_n a_n z(q^2;t_0)^n$$

- 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

CLN

Parameter	Expected sensitivity (stat) with Run1 dataset
ΔR1	1.42E-02
ΔR2	1.20E-02
Δρ^2	1.70E-02

BGL

Parameter	Expected sensitivity (stat) with Run1 dataset statistics
Δa0	6E-05
Δa1	4E-03
Δa2	8E-02
Δb1	6E-04
Δb2	1E-02
Δc1	7E-05
Δc2	1E-03
Δd0	9E-04

Hadronic Form Factors

- Using **BLPR** parametrisation for SM and NP fits
- Incorporates HQET predictions that relate the FFs for NP matrix elements to the SM ones
- Calculations by 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 CLN + NP in HAMMER
- Need to see how to present the results (e.g. NP+Hadr ? etc)

Parameter	Starting value	Expected sensitivity (stat)* with Run1 dataset statistics
$\bar{\rho}_*^2$	1.24+/-0.08	0.02-0.08
$\hat{\chi_2}(1)$	-0.06+/-0.02	O(0.1)
$\hat{\chi_2}'(1)$	0.0+/-0.02	0.2-1.0
$\hat{\chi_3}'(1)$	0.05+/-0.02	fixed *
$\eta(1)$	0.30+/-0.04	0.1-0.2
$\eta'(1)$	-0.05+/-0.10	~1
V_{20}	7.5	1-10

* depending on different NP scenario

* large correlation between Δχ3 and Δρ^2

New Physics Wilson Coefficients

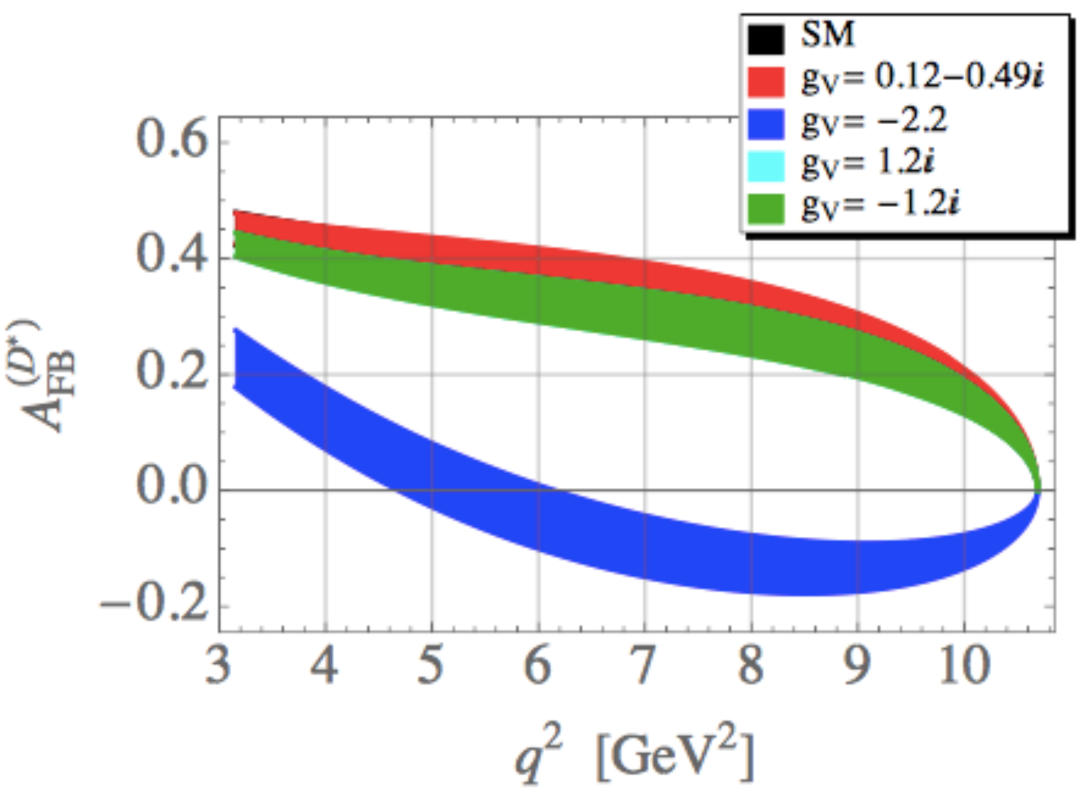
- Ideally no assumption about the NP structure (Eur. Phys. J. C 80, 883 (2020))
- In practice easier searches for specific NP models (e.g. Bhattacharya *et. al.* JHEP 05 (2019) 191)
- Studied different NP scenarios (plan to report fit results for each)

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)			$\mathcal{Im}\ \mathcal{O}(10^{-1})$ $\mathcal{Re}\ \mathcal{O}(10^{-2})$	
TqLlL				$\mathcal{Im}\ \mathcal{O}(10^{-3})$ $\mathcal{Re}\ \mathcal{O}(10^{-3})$
VqRlL+VqLlL+ SqRlL+ TqLlL	$\mathcal{Im}\ \mathcal{O}(10^{-2})$ $\mathcal{Re}\ \mathcal{O}(10^{-2})$	$\mathcal{Im}\ \mathcal{O}(10^{-1})$ $\mathcal{Re}$ —	$\mathcal{Im}\ \mathcal{O}(10^{-1})$ $\mathcal{Re}\ \mathcal{O}(10^{-1})$	$\mathcal{Im}\ \mathcal{O}(10^{-3})$ $\mathcal{Re}\ \mathcal{O}(10^{-3})$

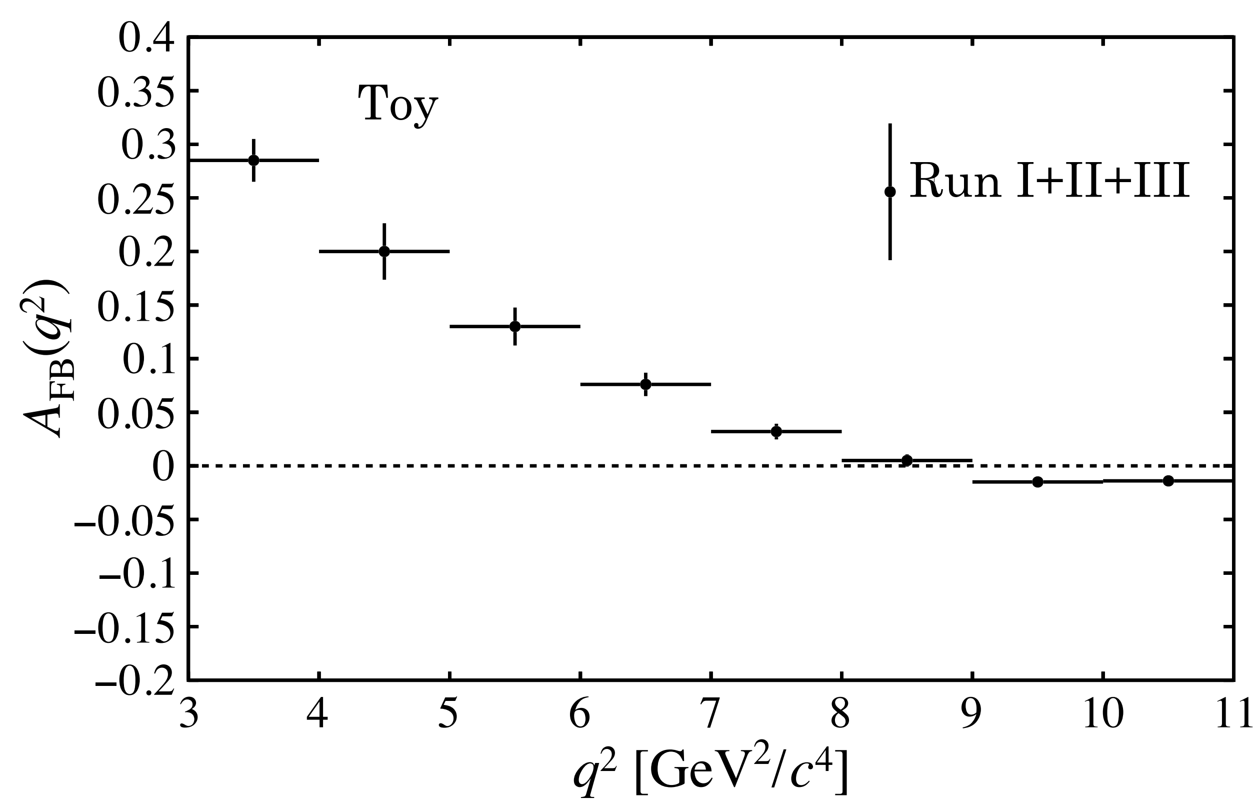
Uncertainties increase, generally within same order of magnitude, fits less stable → (last row)

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

- 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. 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



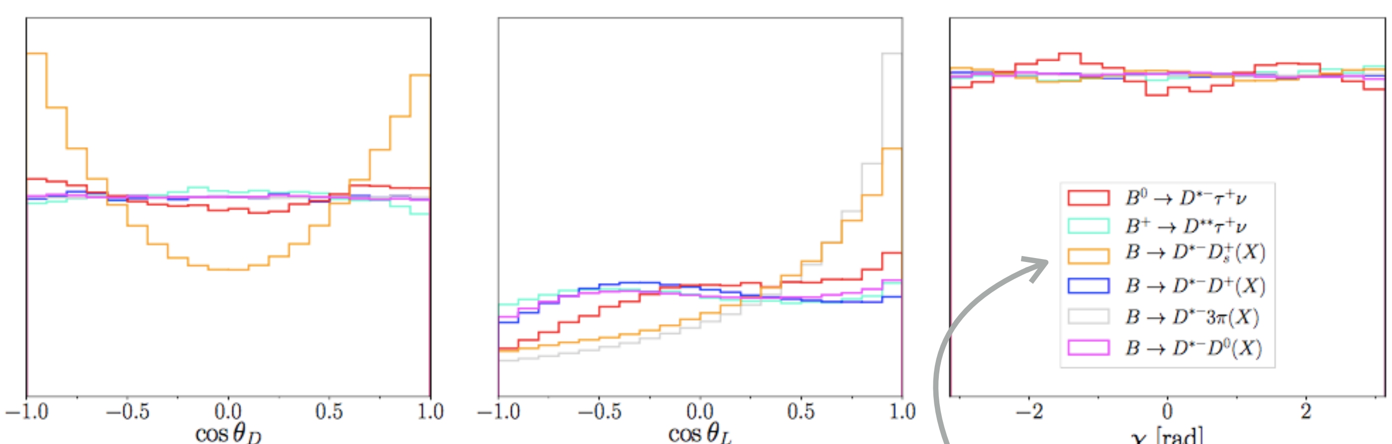
$B^0 \to D^{(*)}\tau\nu$

- 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

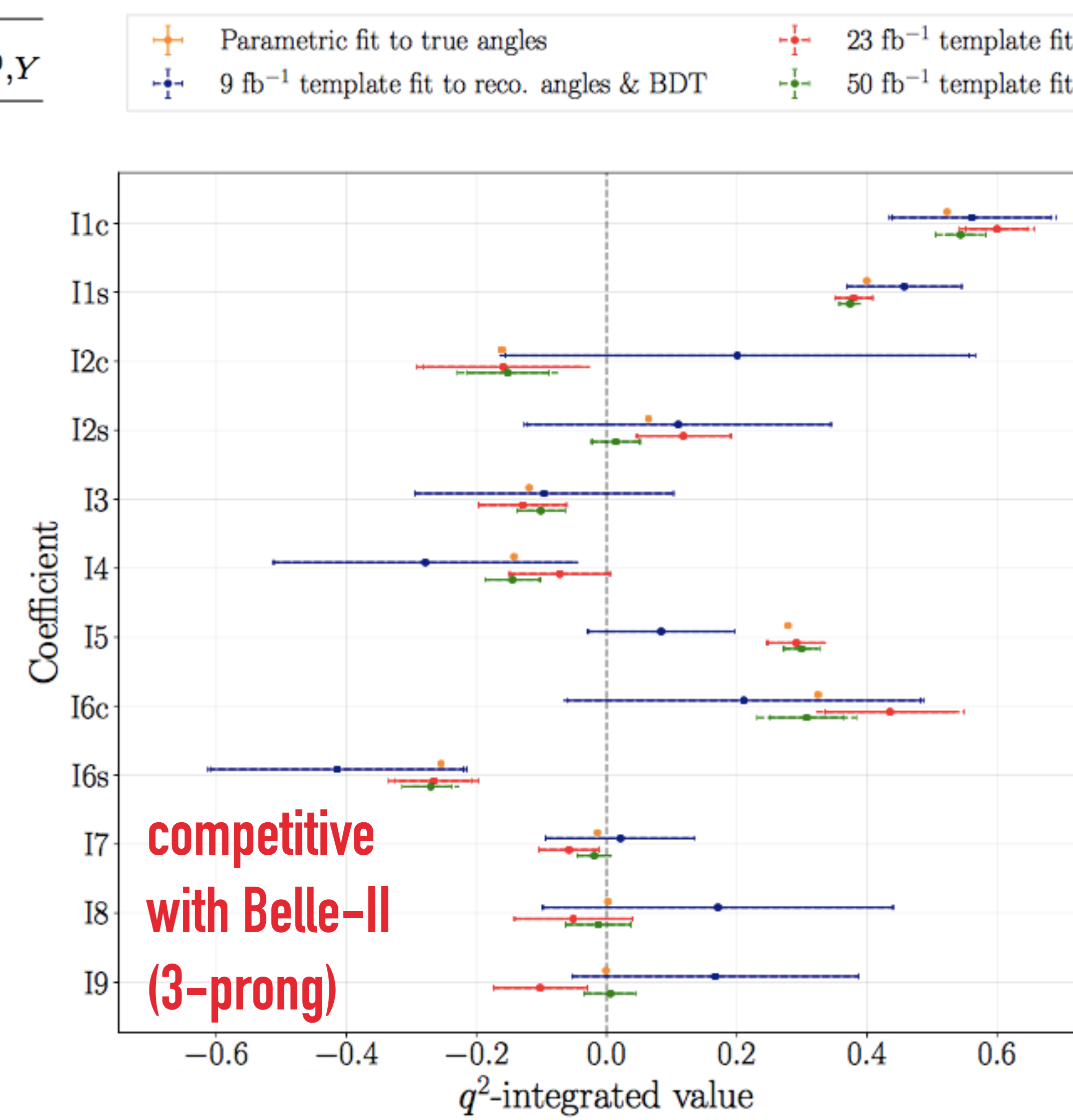
JHEP 11 (2019) 133

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

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



JHEP 06 (2021) 177



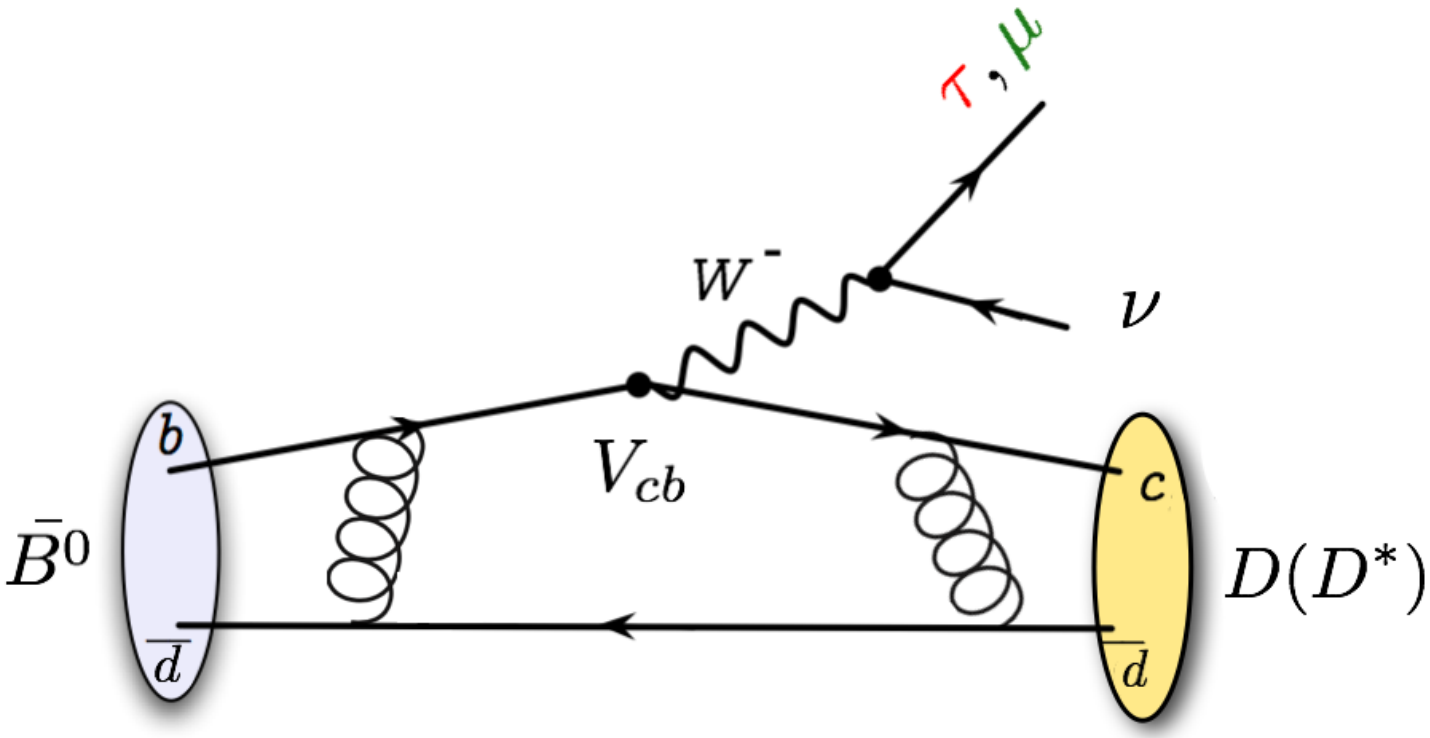
- Lower statistics than muonic decays samples, large backgrounds, external inputs needed for R(D), R(D*)

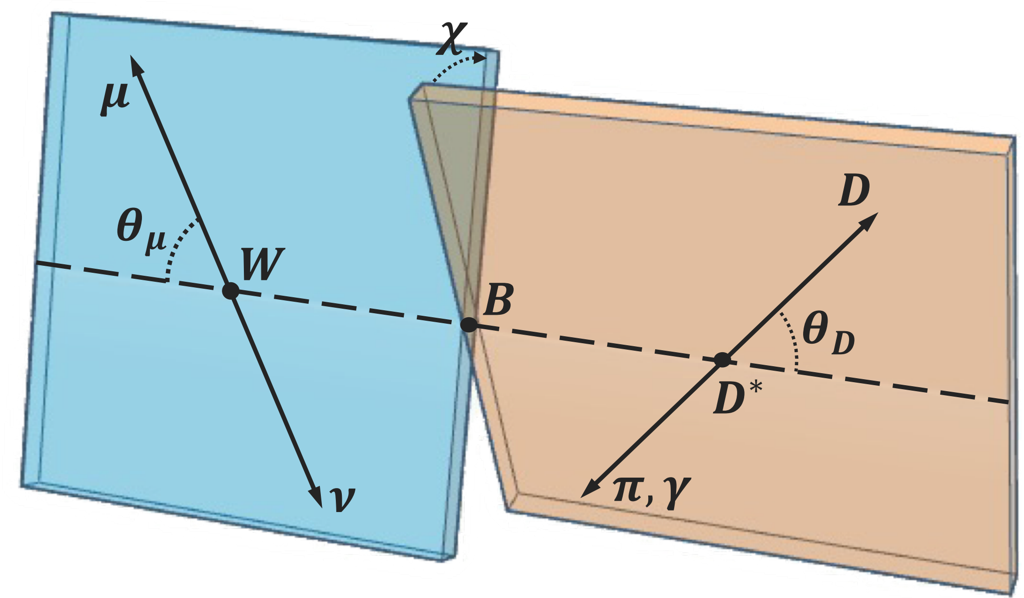
Summary

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

Back-up

Semileptonic decays





Electroweak + phase space

Differential decay rate

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

$$\times \left[(|H_+|^2 + |H_+|^2 + |H_0|^2) \left(1 - \frac{m_\mu^2}{2q^2}\right) + \frac{3}{2} \frac{m_\mu^2}{q^2} |H_t|^2 \right]$$

*considering lepton mass

Helicity amplitudes

QCD component encompassed by form factors