Searches for New Physics using semileptonic $B^0 \to D^* \ell \nu_\ell$ decays at LHCb

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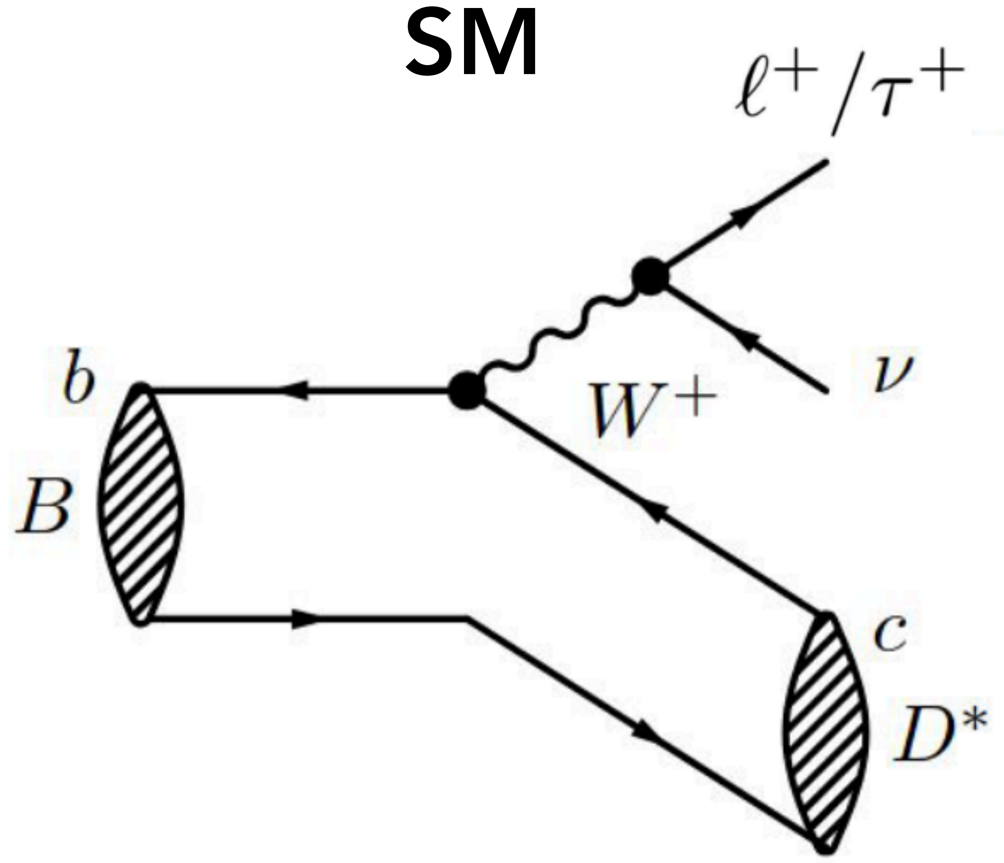
Tree-level $b \to c\ell\nu$ transitions

Semileptonic $b \to c\ell\nu$ transition are clean channels from theoretical point of view

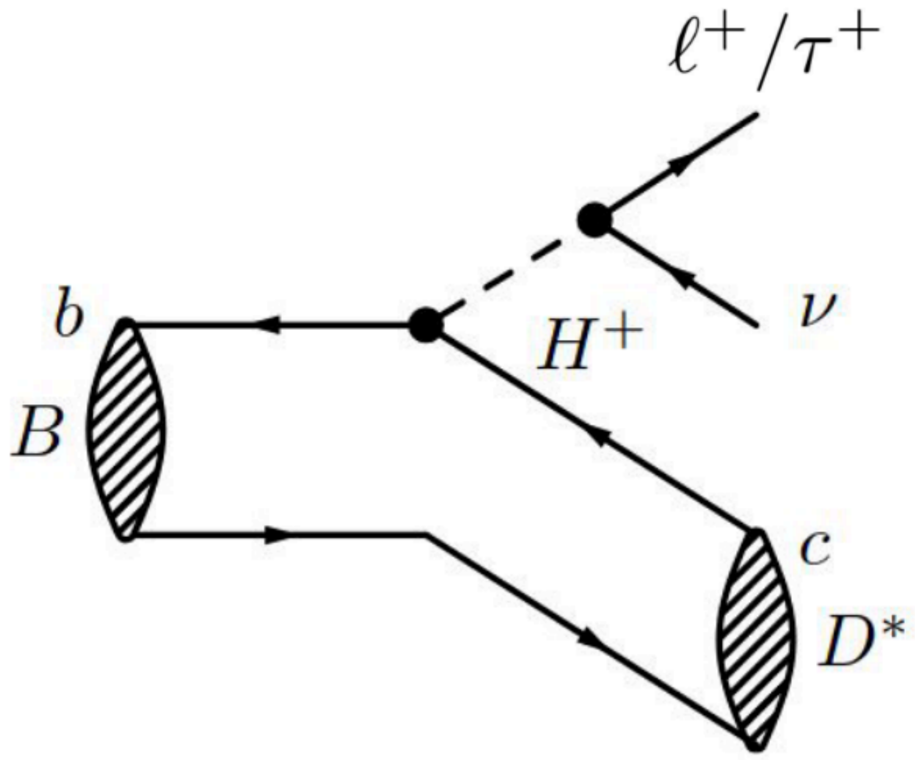
- Powerful **tests of the Standard Model (SM)** and **probe for New Physics (NP)** effects!
  - ✦ Measurements of $|V_{cb}|$ → see Aloïs' talk
  - ✦ Tests of **L**epton **F**lavour **U**niversality (LFU)
  - ✦ **Study the kinematics of the final state particles: angular analyses!**

SM

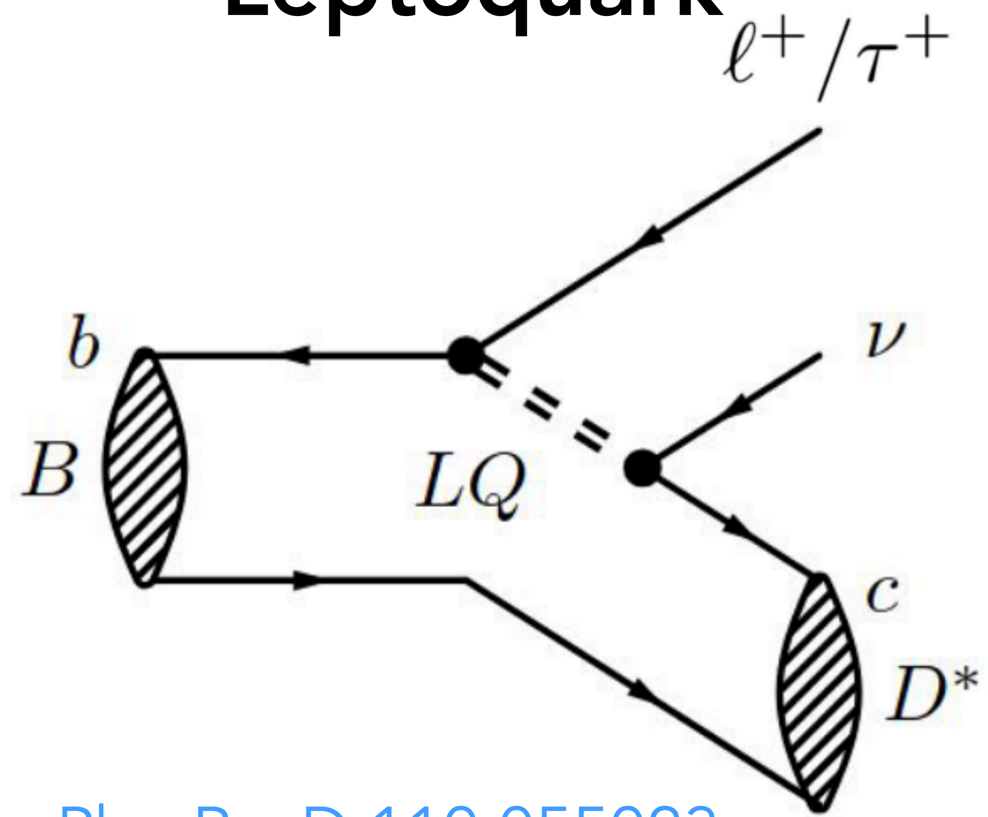


Some tree-level NP contributions that can appear in semileptonic decays:

Two Higgs Doublet



Leptoquark

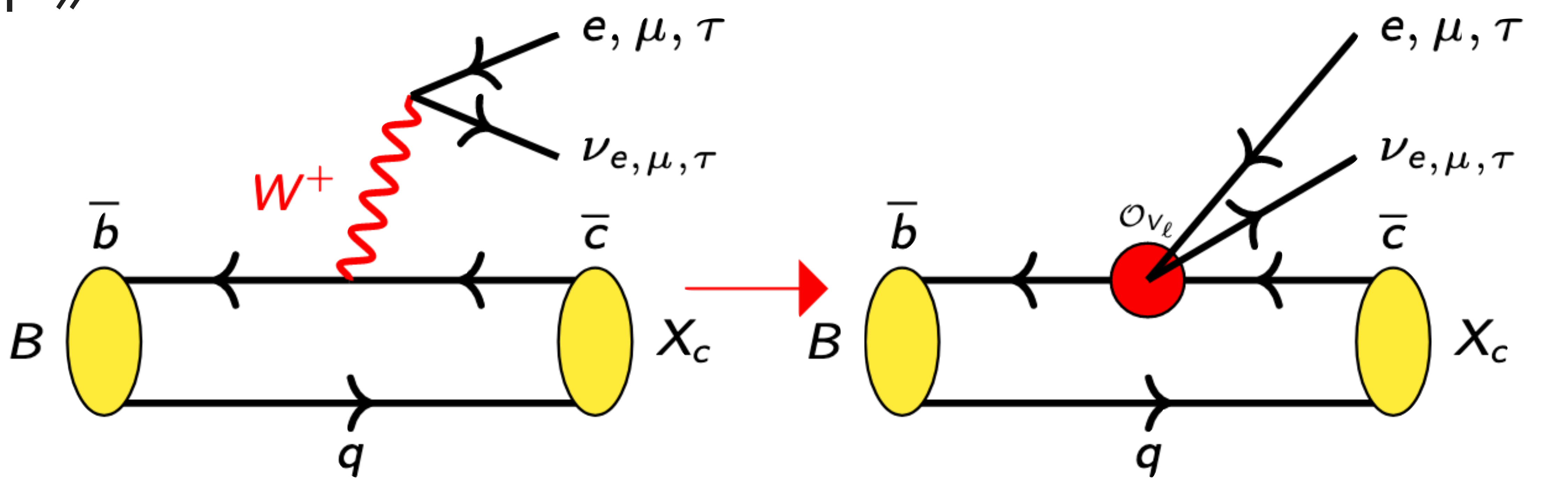


PhysRevD.110.055023

New Physics Framework: Effective Field Theory (EFT)

- SM can be described as a **low-energy approximation** of a heavier NP theory (with scale $\Lambda \gg m_W$) —> « SMEFT » approximation

$$\mathscr{L}_{eff}(b \to c\ell\nu) = \frac{4G_F}{\sqrt{2}} V_{cb}(\mathcal{O}_{SM} + \sum_i C_i \mathcal{O}_i)$$



- In $b \to c\ell\nu$ transitions, most general effective Lagrangian (dim 6):

$$\mathcal{L}_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb}\{\left[(1 + C_{V_L})P_L + C_{V_R} P_R\right]\gamma_\mu P_L + \left[C_S + C_P \gamma^5\right] P_L + C_T \sigma^{\mu\nu} P_L \sigma_{\mu\nu} P_L + h.c.\}$$

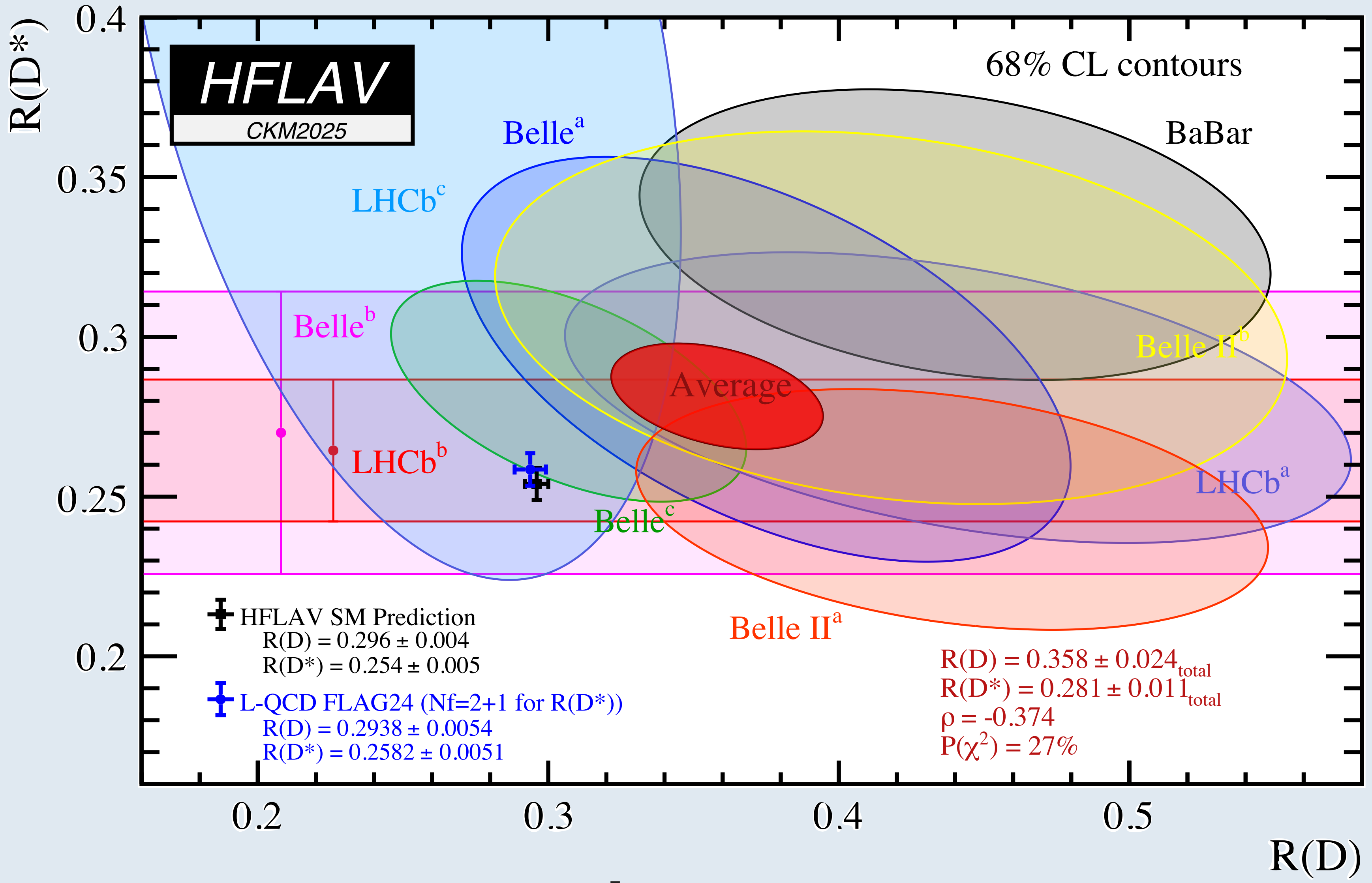
- C_{V_L}, C_{V_R}, C_S, C_P, C_T are **complex NP couplings** ($\equiv 0$ in SM), called **Wilson Coefficients**
- Different **NP models** (H+, LQ, . . .) ⇒ different **combinations of couplings**

How to test for NP experimentally?

Lepton Flavour Universality - ratio tests

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)} \qquad \ell = e, \mu$$

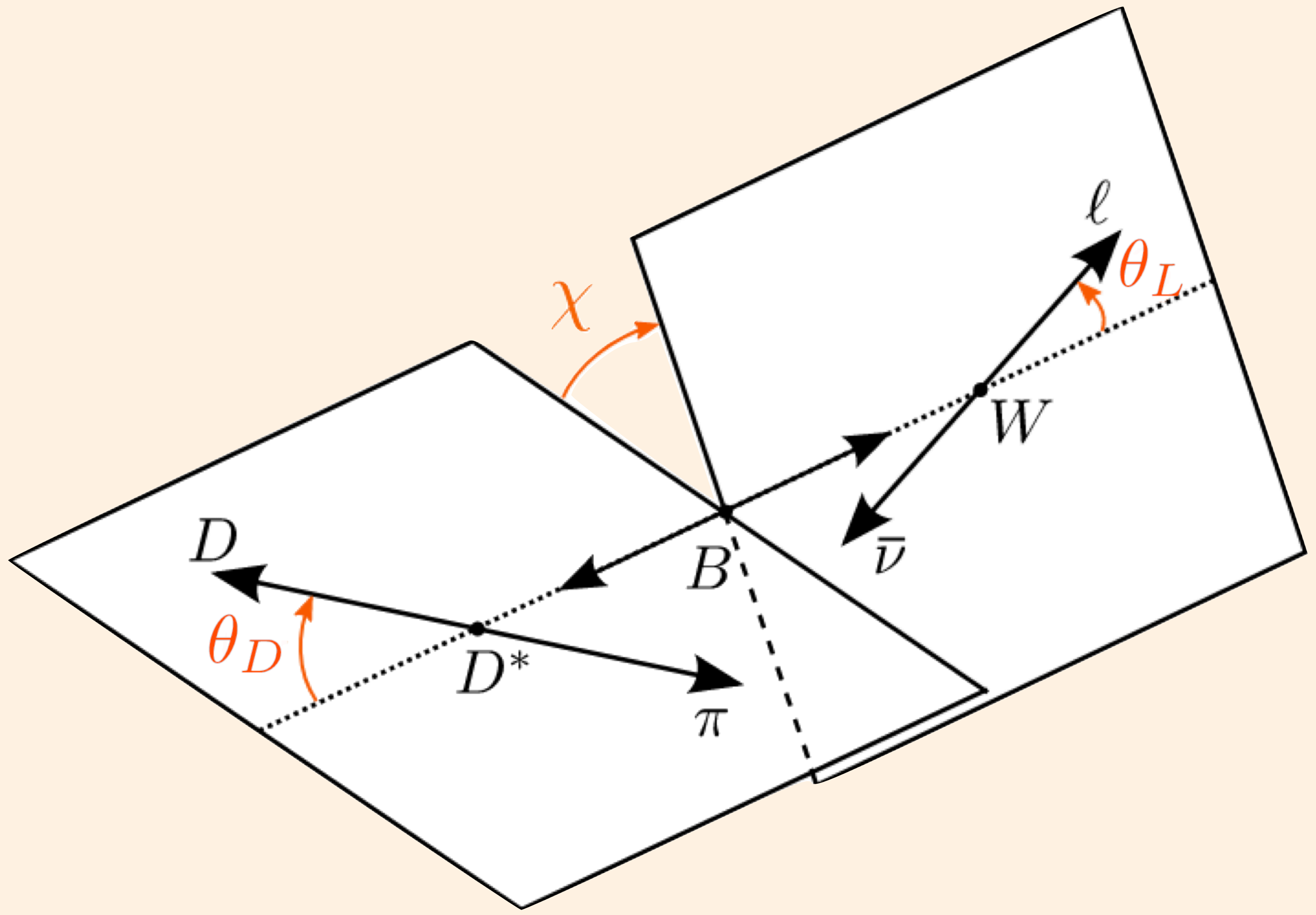
Link to 2025 HFLAV average



3.8σ tension between measurements and theory predictions!

Angular analyses

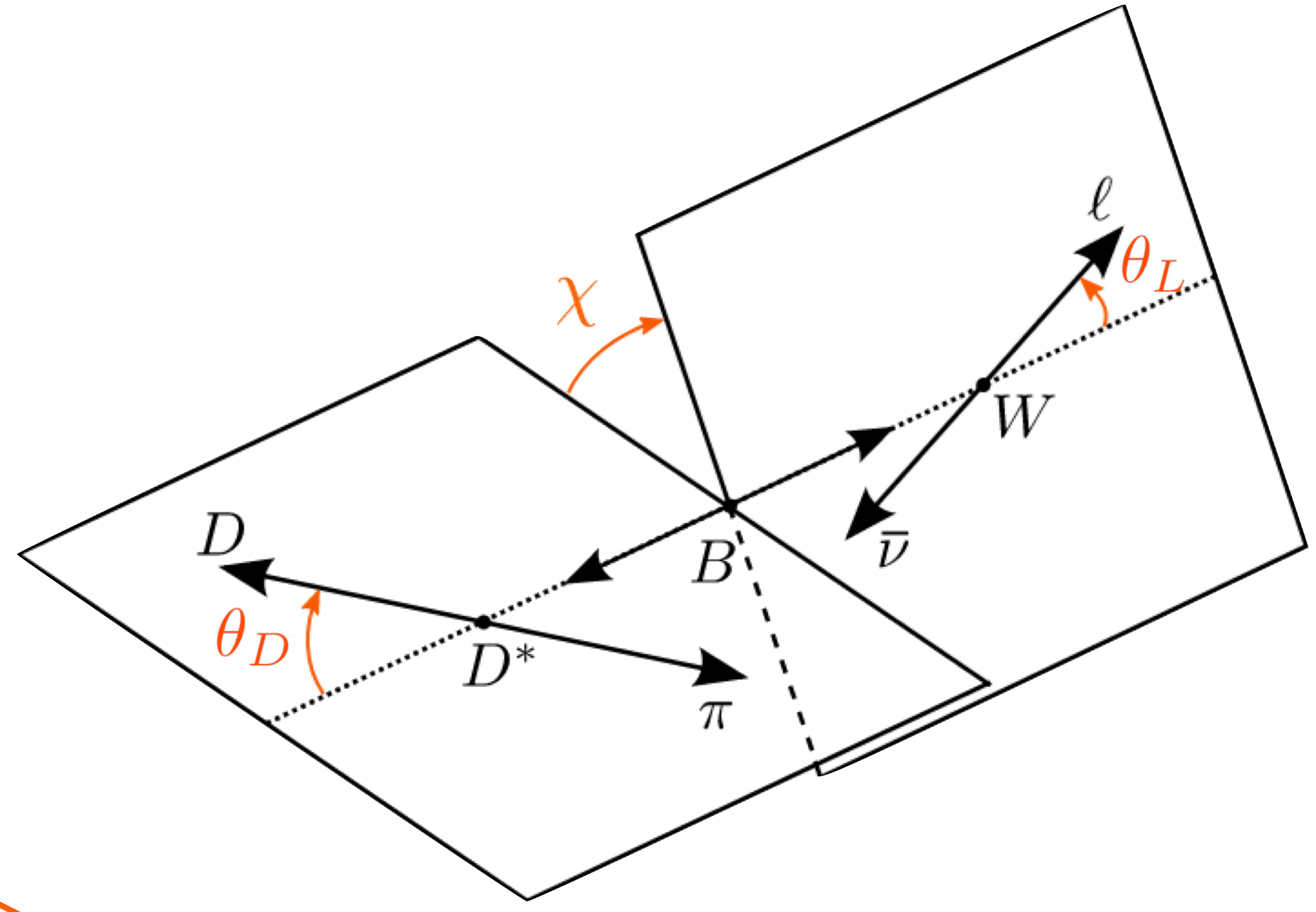
NP operators influence the angular distributions of the helicity angles



Angular observables as a probe of NP

Angular decay rate for $B \to D^*(D^0\pi)\ell\nu$:

$$\frac{d^4\Gamma}{d\cos\theta_D \, d\cos\theta_L \, d\chi \, dq^2} \propto \sum_X J_X(q^2) \cdot f_X(\cos\theta_D, \cos\theta_L, \chi)$$



Fixed functions of the angles

Angular coefficients, encapsulate:

1. Hadronic interaction (Form Factors)
2. **Wilson Coefficients (NP!)**

Transferred 4-momentum squared

$$q^2 = (p_{B^0} - p_{D^*})^2$$

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$$\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_D \mathrm{d}\cos\theta_L \mathrm{d}\chi \mathrm{d}q^2} = \frac{2G_F^2\eta_{EW}^2|V_{cb}|^2 m_B^2 m_{D^*}}{2\pi^4}$$

$$\times \left(J_{1c}(q^2)\cos^2\theta_D + J_{1s}(q^2)\sin^2\theta_D\right.$$
$$+ \left[J_{2c}(q^2)\cos^2\theta_D + J_{2s}(q^2)\sin^2\theta_D\right]\cos 2\theta_L$$
$$+ \left[J_{6c}(q^2)\cos^2\theta_D + J_{6s}(q^2)\sin^2\theta_D\right]\cos\theta_L$$
$$+ \left[J_3(q^2)\cos 2\chi + J_9(q^2)\sin 2\chi\right]\sin^2\theta_L\sin^2\theta_D$$
$$+ \left[J_4(q^2)\cos\chi + J_8(q^2)\sin\chi\right]\sin 2\theta_L\sin 2\theta_D$$
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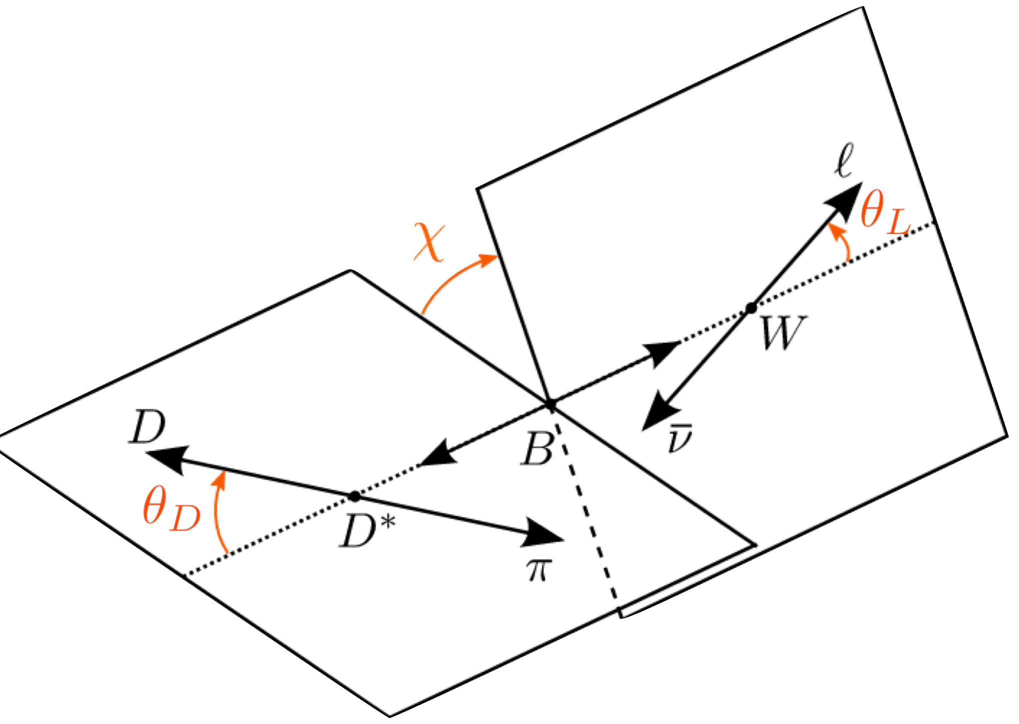

$q^2 = (p_{B^0} - p_{D^*})^2$

12 J_X coefficients

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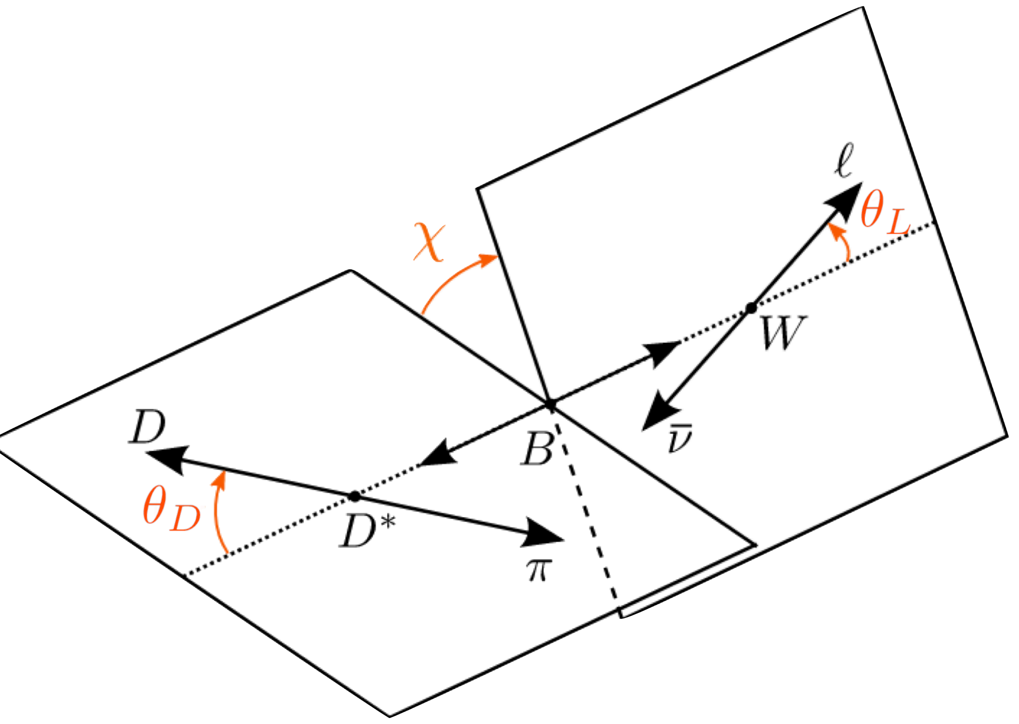
\end{aligned}$$



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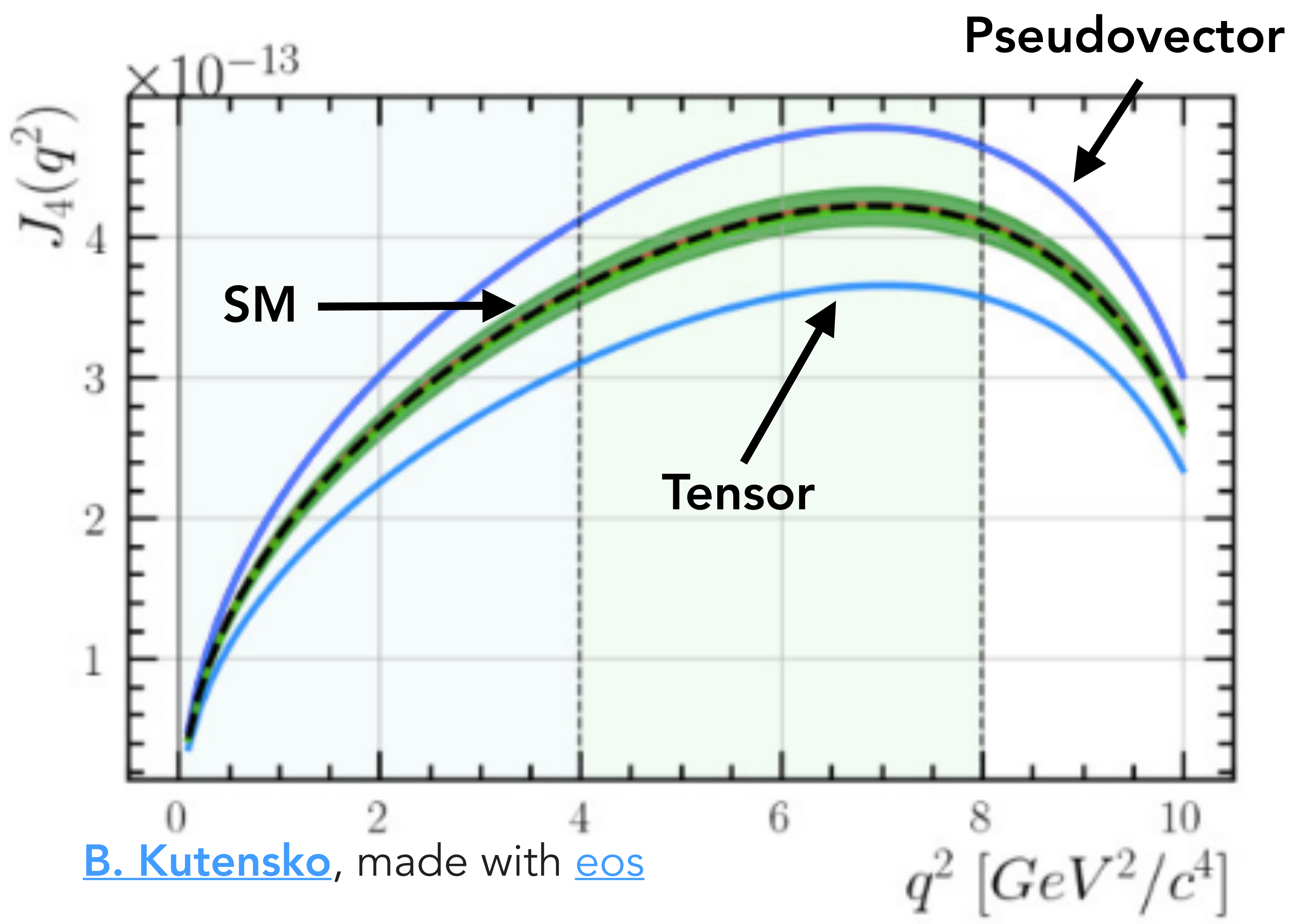

B. Kutensko, made with eos

Studying the J_X at different q^2 values allows to identify different NP contributions!

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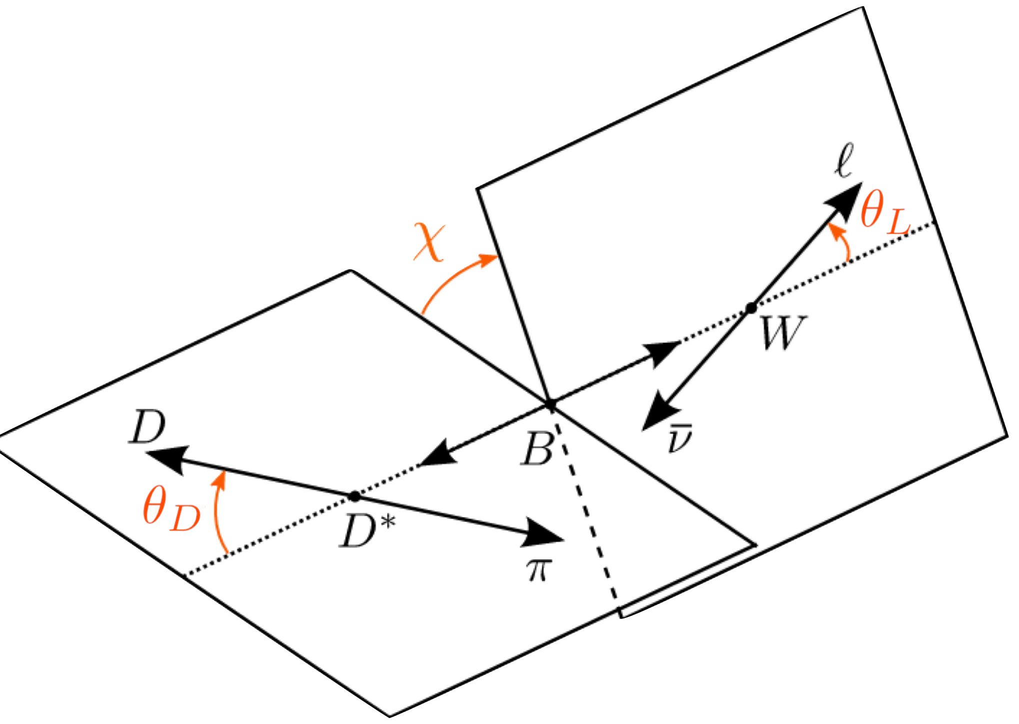

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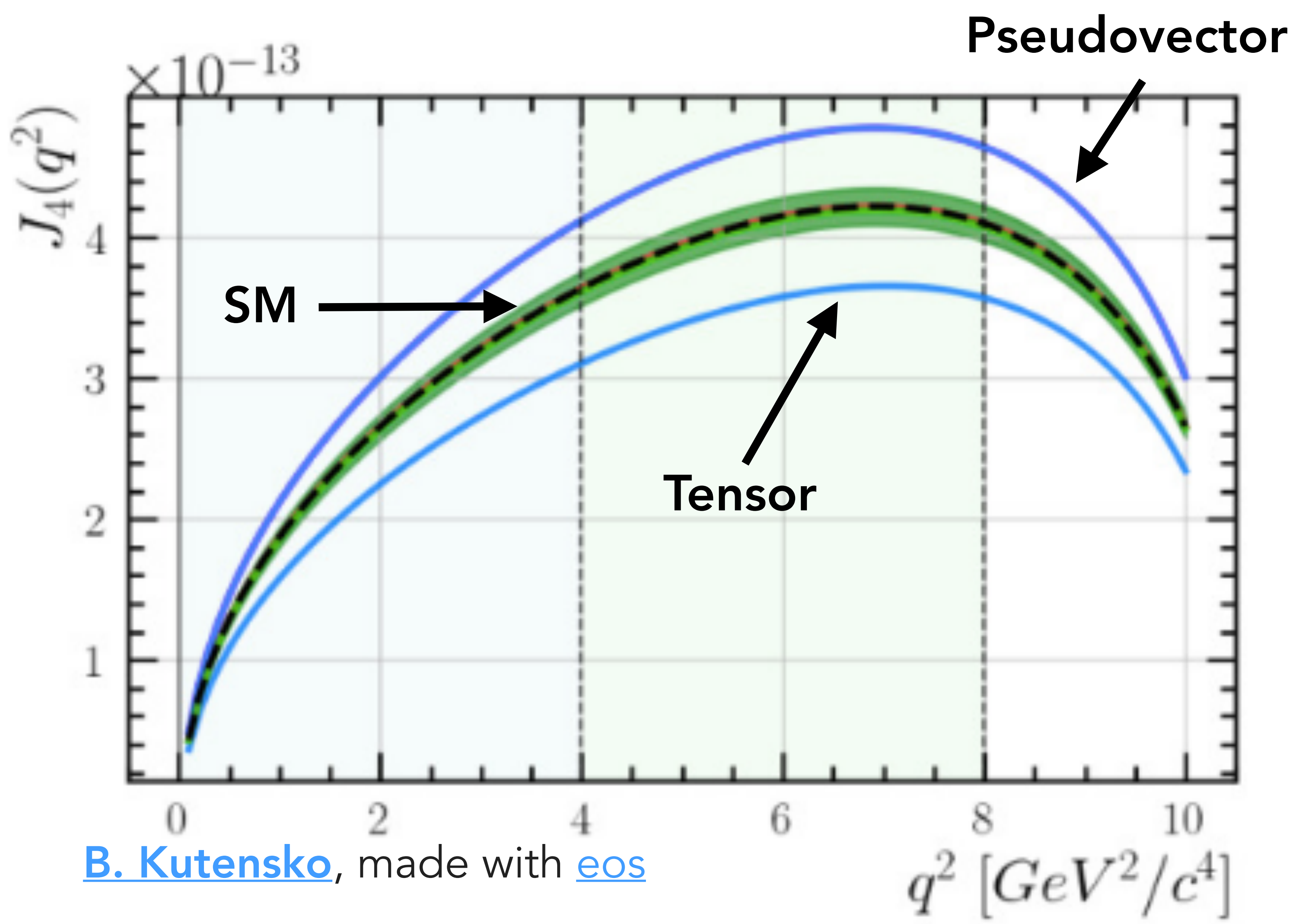
12 J_X coefficients



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Studying the J_X at different q^2 values allows to identify different NP contributions!

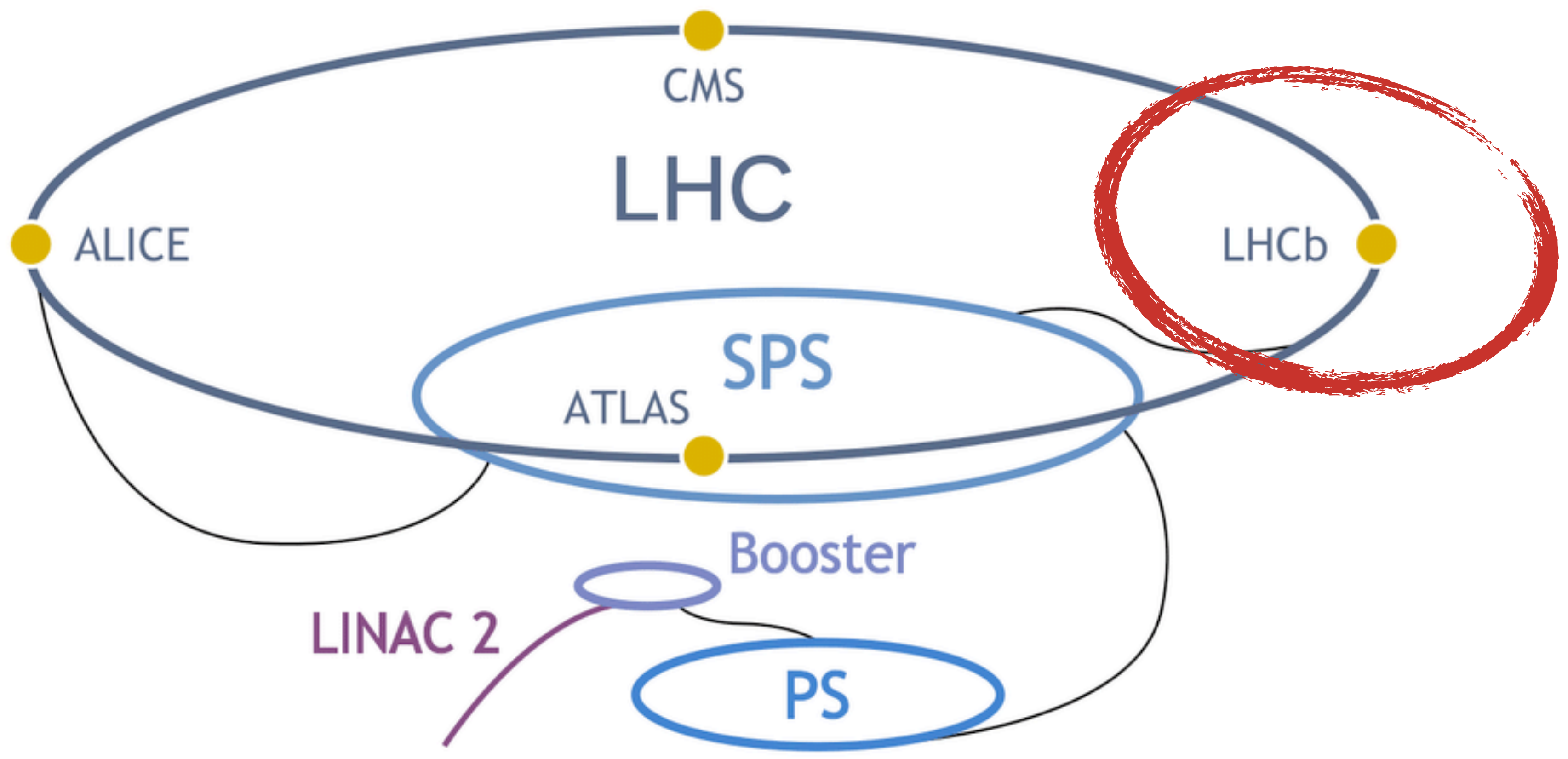
The goal of our analyses is to measure these 12 J_X coefficients in bins of q^2

The LHCb Experiment at the LHC

Exploits **proton-proton** collisions from the Large Hadron Collider (LHC) at CERN with

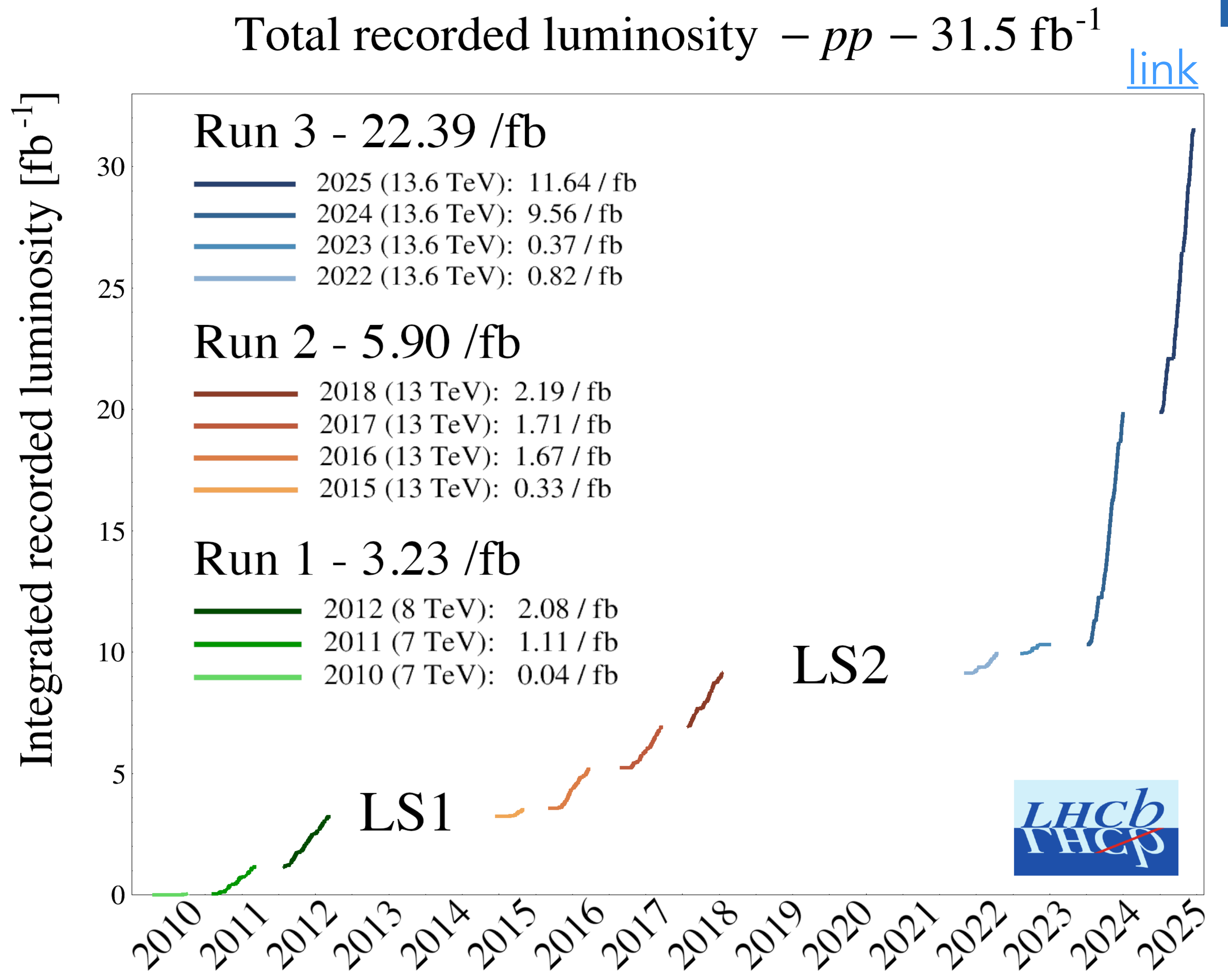
$\sqrt{s} = 13$ TeV **(Run 2)**,

$\sqrt{s} = 13.6$ TeV **(Run 3)**



Proton injection

link



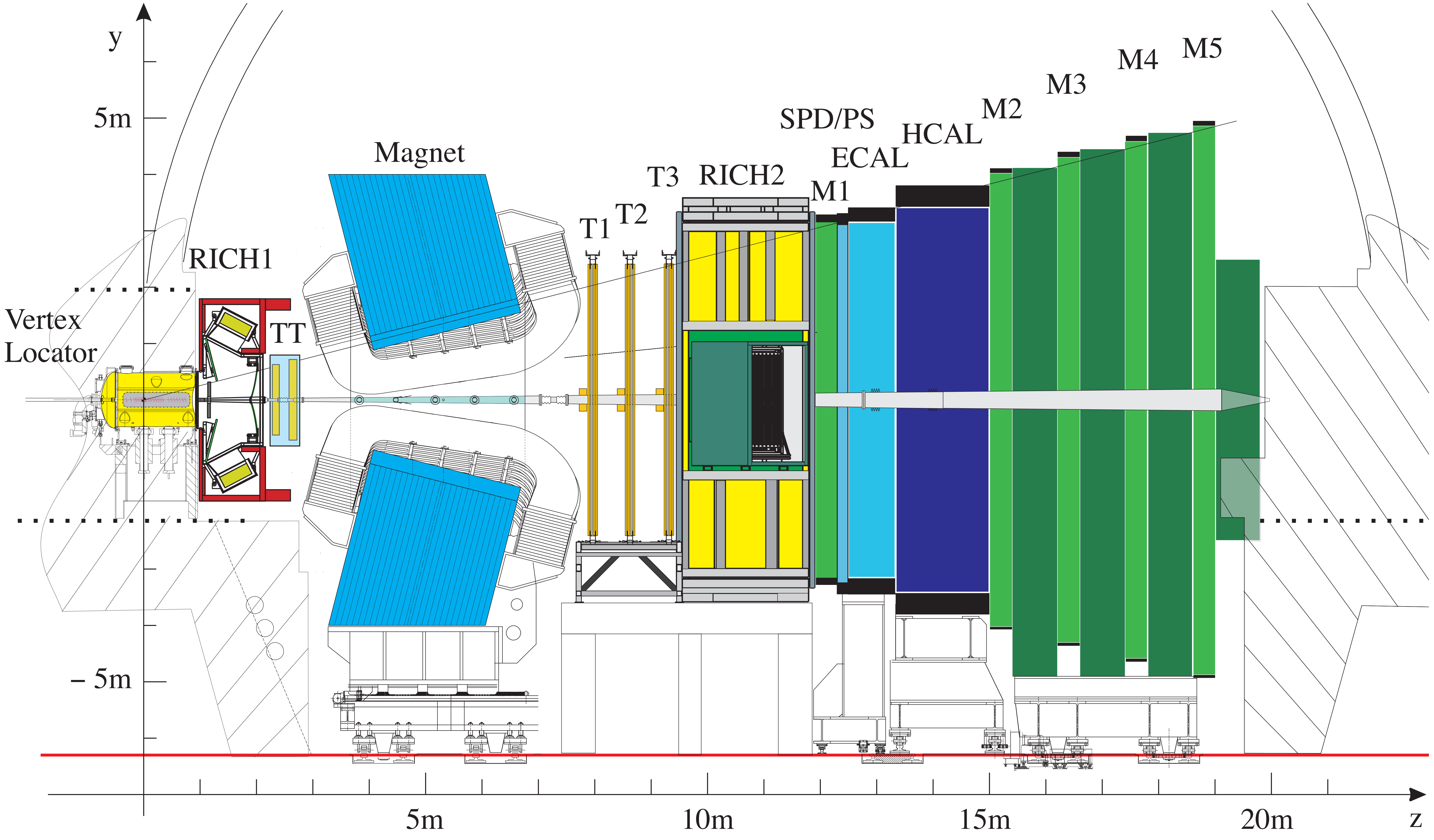
Run 1 **Run 2** → **Run 3**

Major Detector Upgrade!

$\times 5$ **instantaneous luminosity**

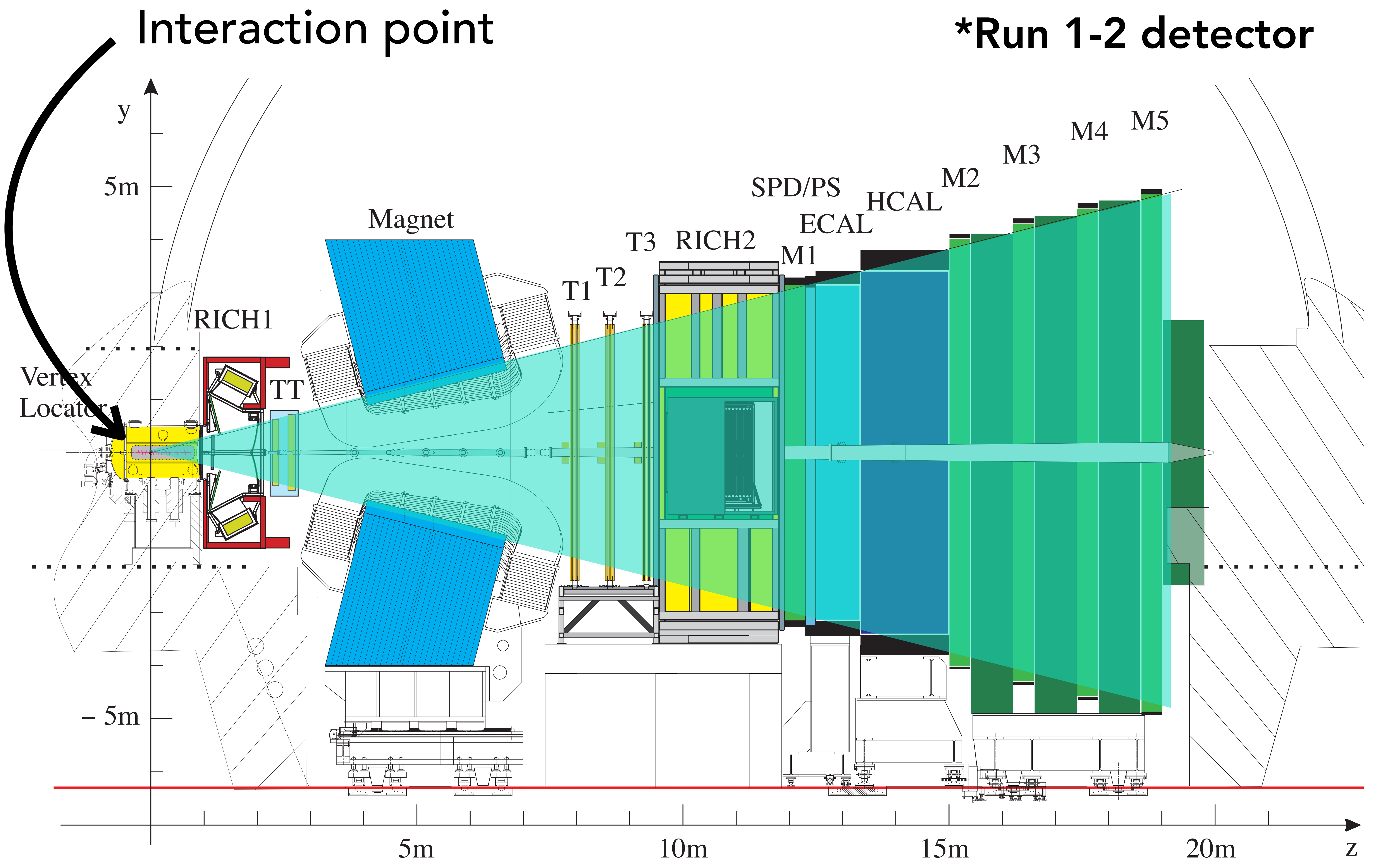
The LHCb Experiment at the LHC

***Run 1-2 detector**



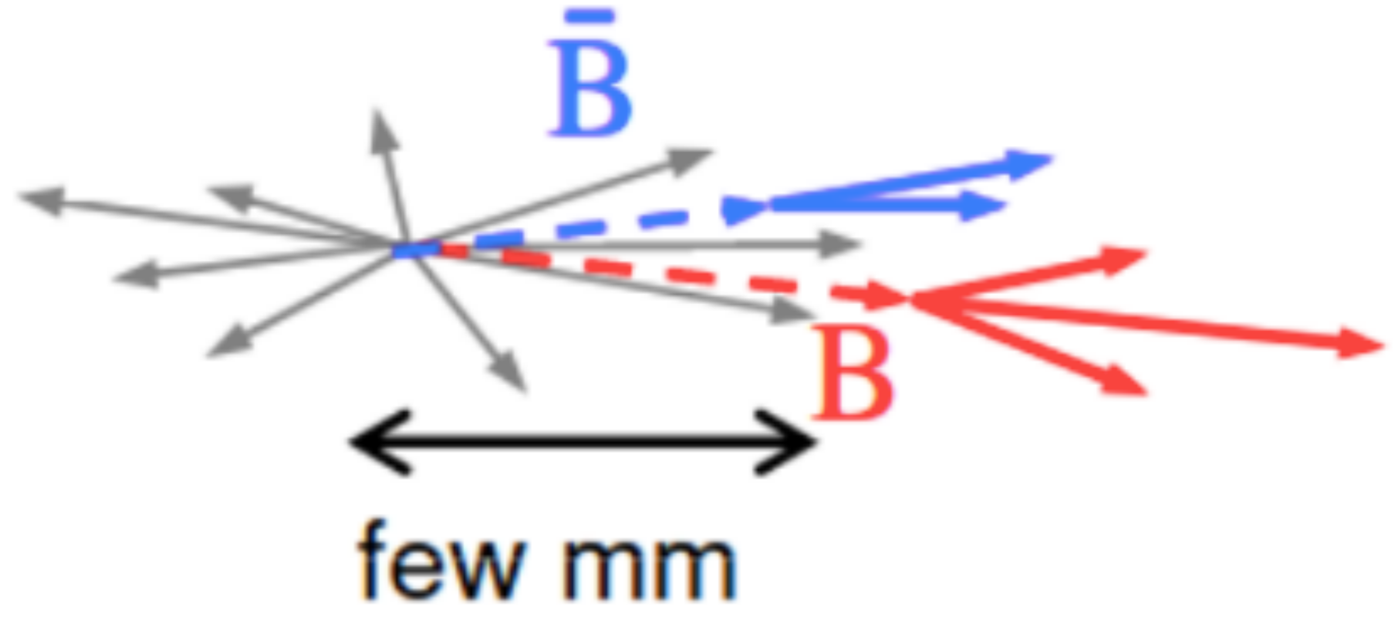
The LHCb Experiment at the LHC

- Forward arm spectrometer covering $2 < \eta < 5$
  - **Optimised for $pp \to b\bar{b}X$ events**

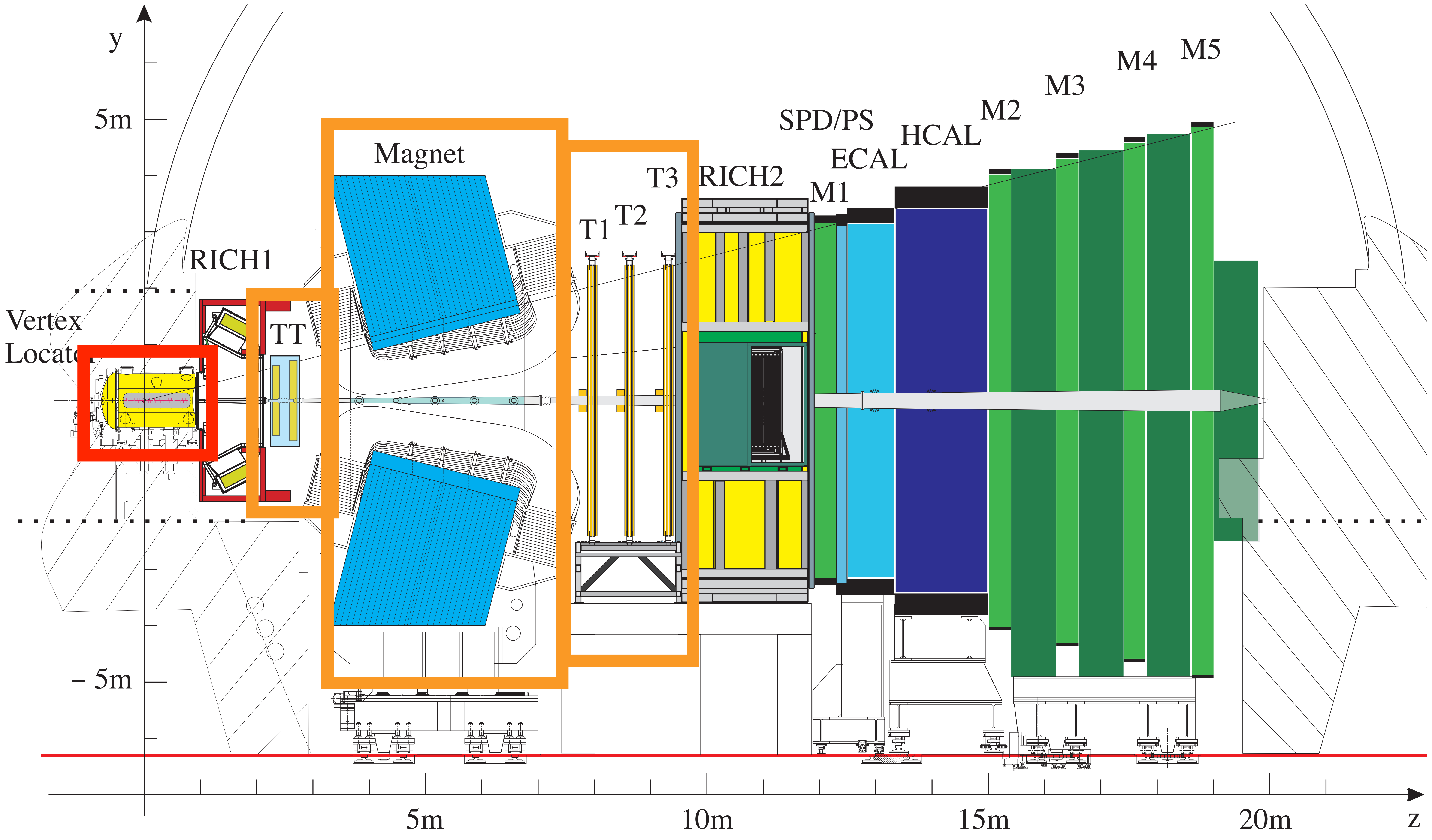


The LHCb Experiment at the LHC

- Forward arm spectrometer covering $2 < \eta < 5$
  - Optimised for $pp \to b\bar{b}X$ events
- **Tracking system**
  - **Excellent vertex reconstruction**



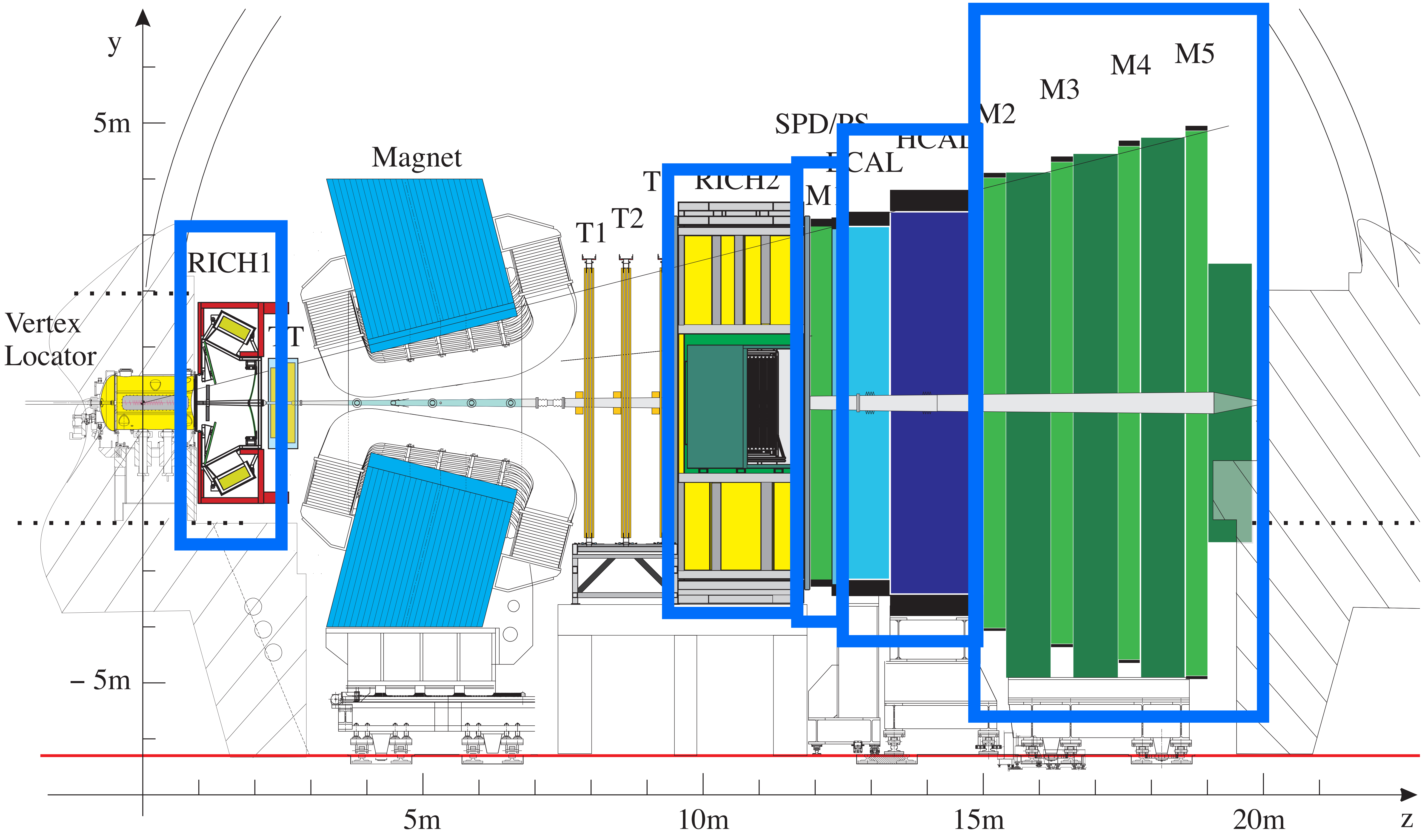
*Run 1-2 detector



The LHCb Experiment at the LHC

- Forward arm spectrometer covering $2 < \eta < 5$
  - Optimised for $pp \to b\bar{b}X$ events
- Tracking system
  - Excellent vertex reconstruction
- **Hadron PID** with 2 RICH detectors, **electron and muon PID** with ECAL/Muon chambers

***Run 1-2 detector**



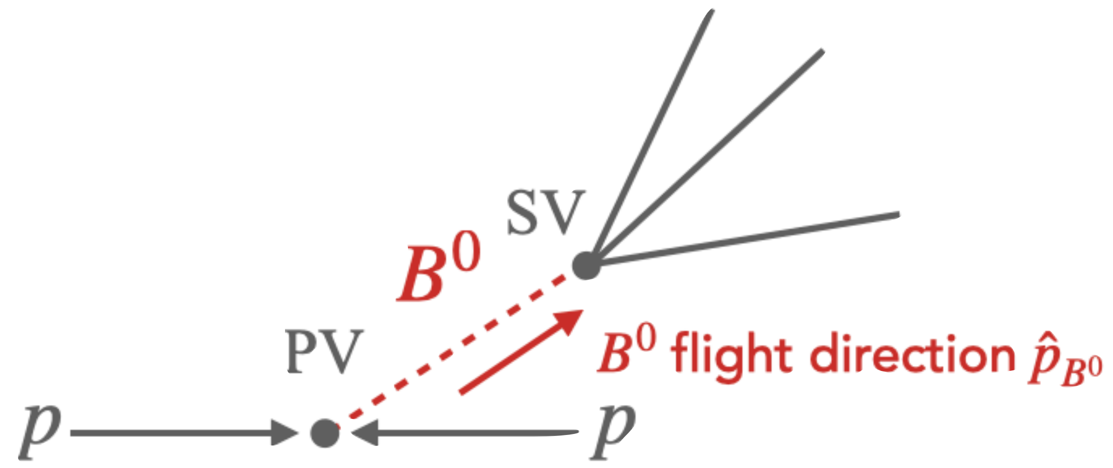
Angular analyses with $B^0 \to D^* \ell \nu$ decays

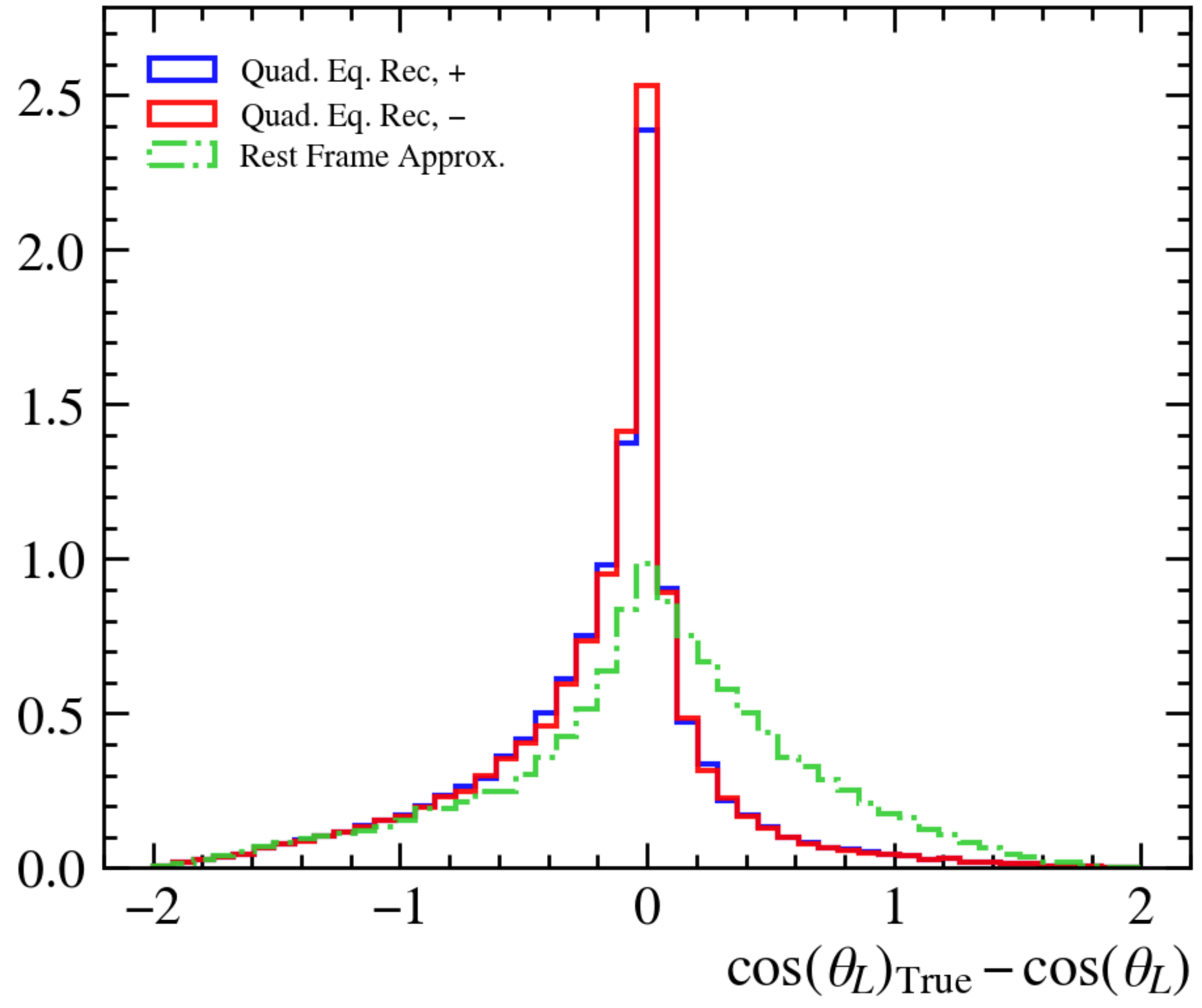
Semileptonic challenges at LHCb (1)

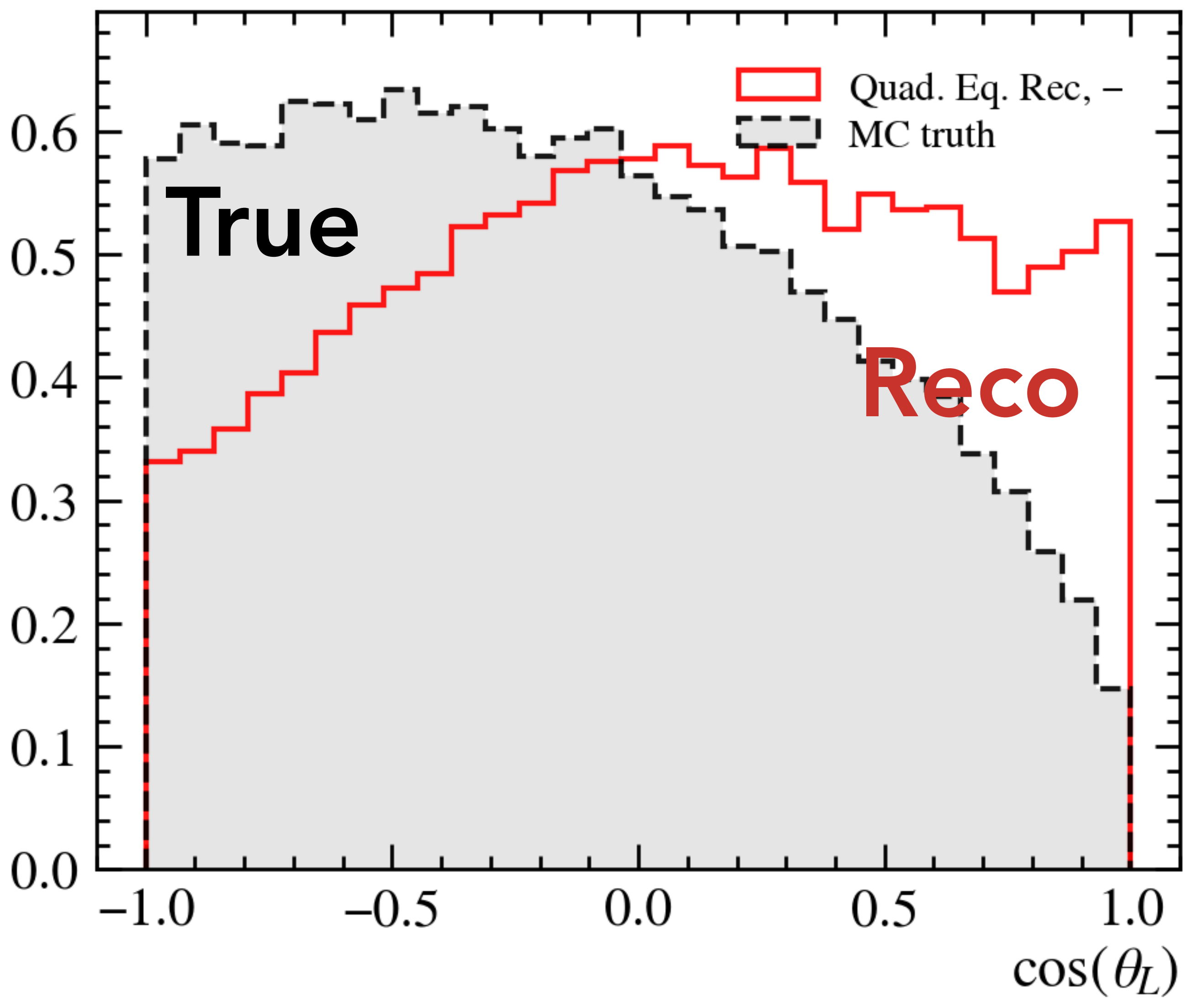
Neutrinos are not reconstructed at LHCb

- No final state invariant mass peak to fit → **binned template fits** instead of parametric fit
- Need to **approximate** the B^0/ν momentum:
  1. Rest Frame Approximation
  2. Solve kinematic equation
     - yields 2 solutions ± (quadratic eq.)

Use B^0 flight direction, reconstructed thanks to the VELO







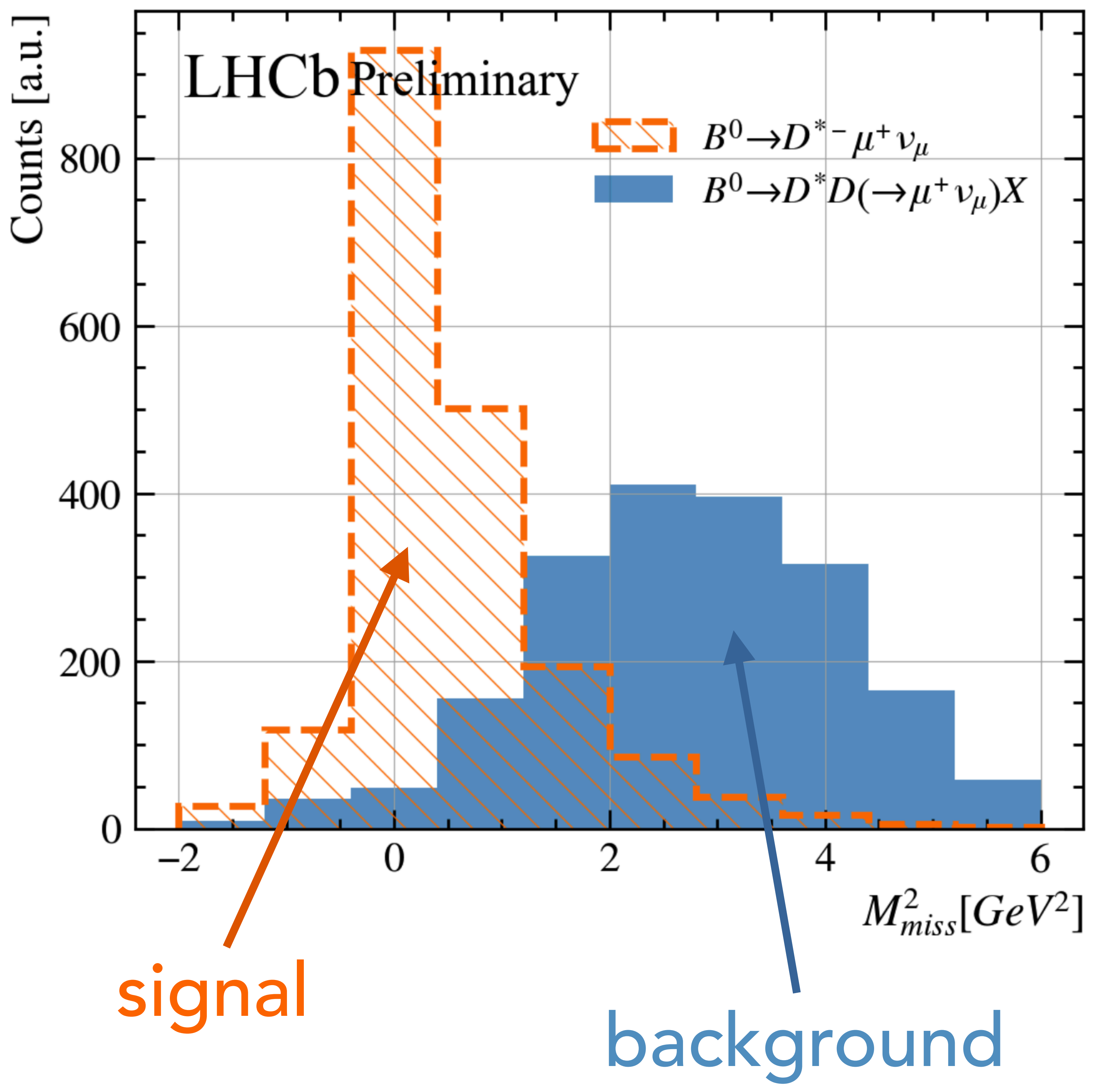
Large **resolution effects**!

This causes **bin migration between true space and reconstructed space**

Semileptonic challenges at LHCb (2)

Lots of **background** sources:

- $B^0 \to D^{**}(\to D^*X)\ell\nu$: decays with a higher excited D state (admixture of $D_0^*(2300)$, $D_1(2420)$, $D_1(2430)$, etc.)
- $B^0 \to D^*D(\to \ell\nu)X$: double-charm meson decay
- Mis-identified final state into ℓ
  - Use $m^2_{miss} = (p_{B^0} - p_{D*} - p_\ell)^2$ as a discriminating variable



Template-building (signal & background) needs a lot of **statistics from Monte-Carlo simulation**

- Large source of **systematic uncertainty**
- MC is generated with a **chosen model** → model-dependence

Fit methods overview

To deal with **resolution** and **kinematic-dependent detector efficiency** effects, multiple ways of fitting are developed:

- **Folding:** Multiply the binned PDF by a **response matrix**
  - Map the PDF from true space to reconstructed space
- **Unfolding:** Perform the fit on **unfolded** data (unfold with response matrix)
  - Map the reconstructed data into true space
- **Reweighting:** Construct a binned PDF using weights that account for **event migration** in angular space
  - Build templates accounting for reconstruction effects

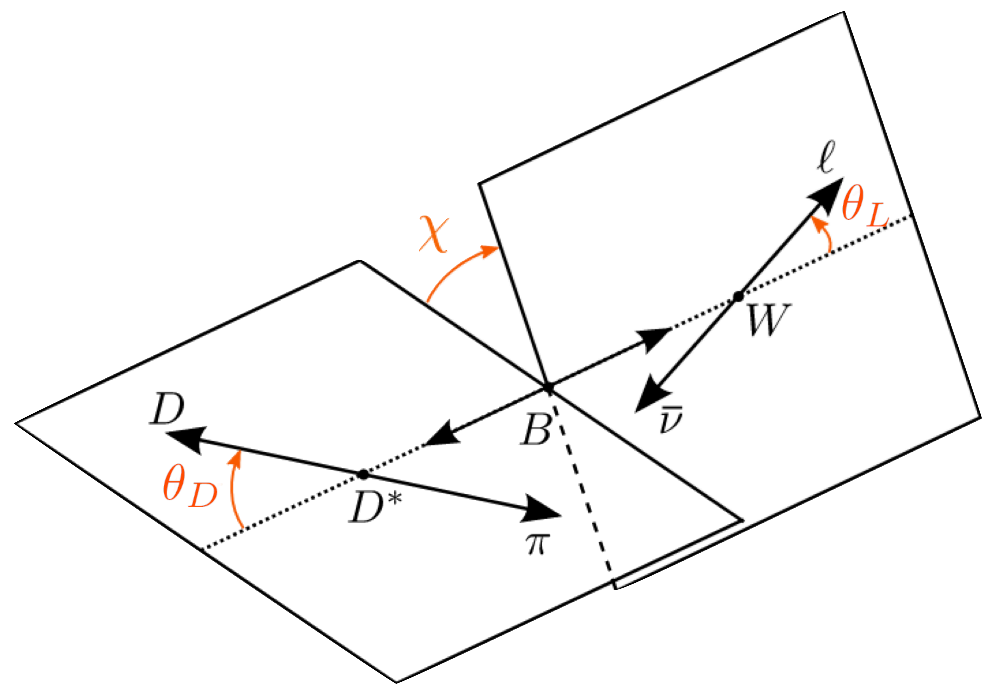
Response matrix:

$$R_{ij} = P(\text{reco bin } R_i \,|\, \text{true bin } T_j)$$

Built with MC sample!

All 3 methods have some degree of model dependence and suffer from limited MC statistics

Analyses status



$m^2_{miss} = (p_{B^0} - p_{D^*} - p_\ell)^2$

$q^2 = (p_{B^0} - p_{D^*})^2$

We have 2 angular analyses ongoing in our group:

Run 2 dataset

Decay: $B^0 \rightarrow D^*\mu\nu_\mu$ and $B^0 \rightarrow D^*e\nu_e$

Goal: Measure 12 J_X coefficients in two q^2 bins, test LFU with e-μ

Method: 4D template fit (« reweighting » approach)

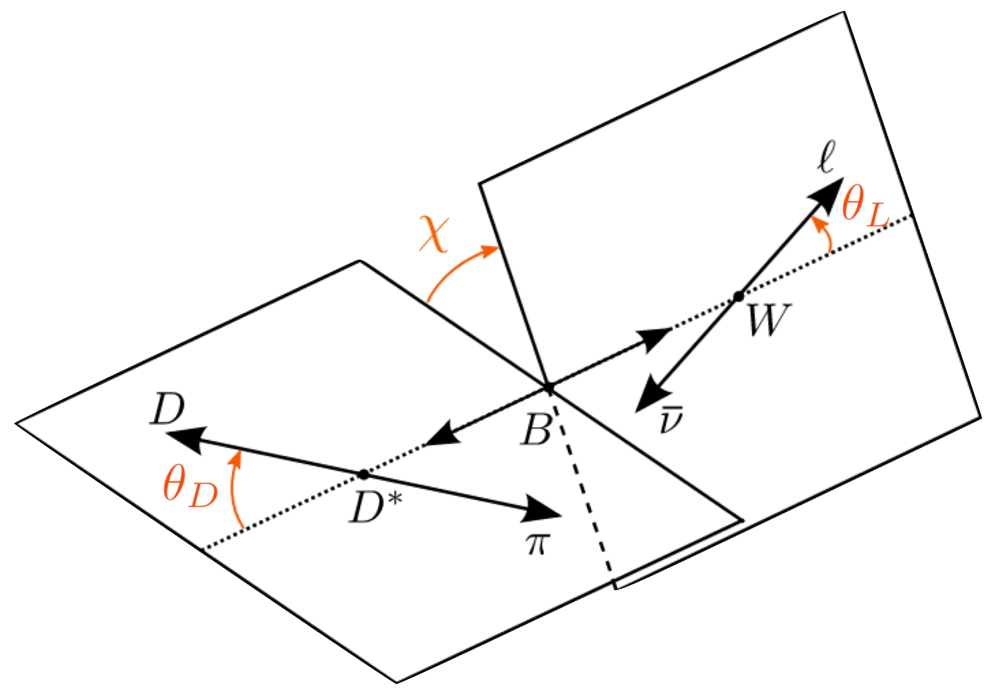
Run 3 dataset

Decay: $B^0 \rightarrow D^*e\nu_e$

Goal: Measure 12 J_X coefficients in several (tbd) q^2 bins

Method: tbd

Analyses status



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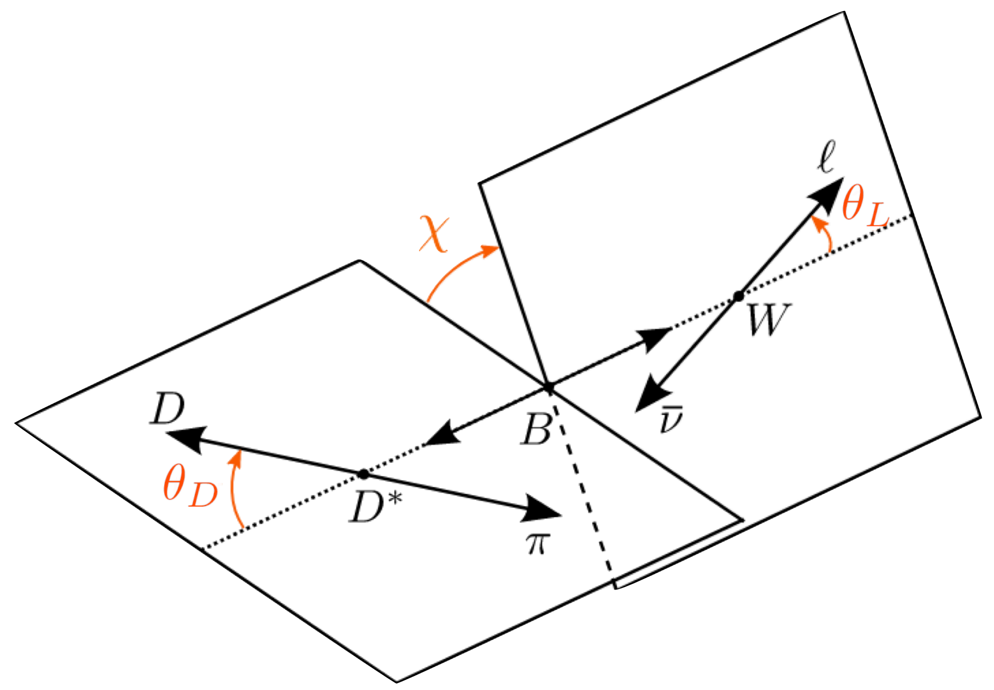
→ also measuring $R(D^*)_{\tau/e}$ with same dataset (and $\tau \to e\nu_e\nu_\tau$)

Analyses status



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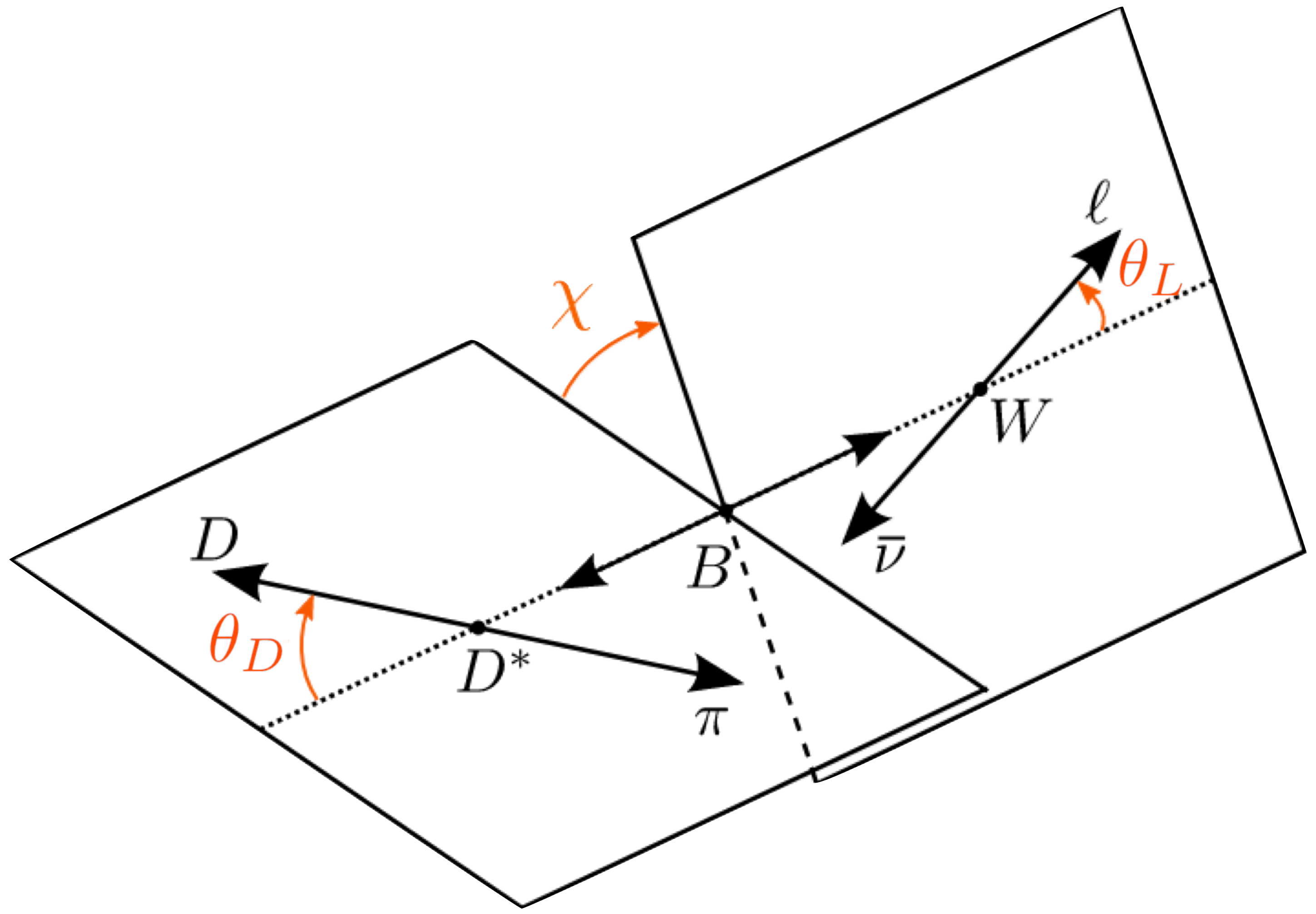
Goal: Measure 12 J_X coefficients in several (tbd) q^2 bins

Method: tbd

→ also measuring $R(D^*)_{\tau/e}$ with same dataset (and $\tau \to e \nu_e \nu_\tau$)

Run 2 strategy

Goal: extract the 12 J_X coefficients for $\ell = e, \mu$ in 2 q^2 bins with Run 2 data



Method: **4D template fit** in the **3 helicity angles** $\cos(\theta_D)$, $\cos(\theta_L)$, χ and the reconstructed « **missing mass squared** » m^2_{miss}

- m^2_{miss} used to **disentangle signal and background**
- Templates built mostly from **Monte Carlo simulation**, some data-driven (*eg* mis-identified leptonic final state)

$$q^2 = (p_{B^0} - p_{D^*})^2$$

$$m^2_{miss} = (p_{B^0} - p_{D^*} - p_\ell)^2$$

Template fit - Run 2

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Strategy: Include all detector **efficiencies** and **resolution** effects directly **in the signal templates**

Pros:

+ Model-independent*
+ No need to unfold the results to apply the detector effects

Cons:

- The q^2 resolution still needs to be corrected through the response matrix $R_{ij} \rightarrow$ model dependence

Integrate the decay rate over a q^2 range, define $I_X = \int J_X(q^2) dq^2$:

$$\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_D \mathrm{d}\cos\theta_L \mathrm{d}\chi} \propto \sum_X I_X \cdot f_X(\cos\theta_D, \cos\theta_L, \chi)$$

Unbinned angular function

$$\rightarrow \sum_X I_X \cdot h_X(\cos\theta_D, \cos\theta_L, \chi)$$

Binned angular template

Template fit - Run 2

Normalisation of I_{1c} | Signal templates

$$\mathrm{PDF}(\theta_D,\theta_L,\chi) = \left[\frac{1}{3}(4-6I_{1s}+I_{2c}+2I_{2s})h_{1_c} + \sum_X I_X h_X\right] \times f_{\mathrm{sig}} + \sum_{\mathrm{backgrounds}} f_{\mathrm{bkg}} \times h_{\mathrm{bkg}}$$

Fractions of dataset

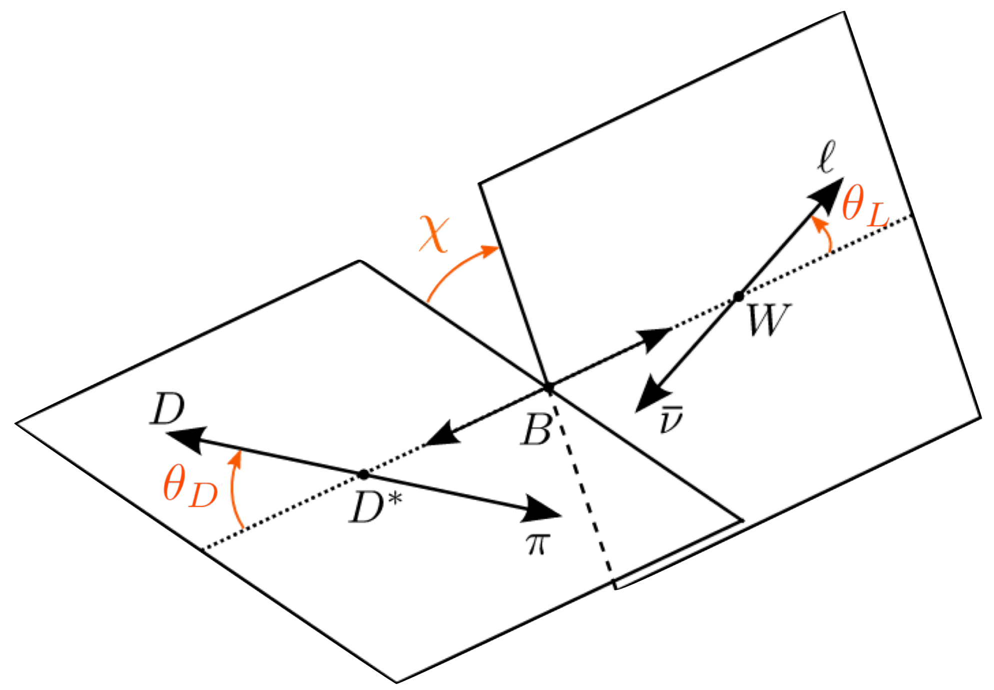
Background templates

- Extract 11 I_X from the fit, 1 constrained from total decay rate
- I_X coefficients are blinded by a random scaling + random shift
- Templates are fixed shapes
- Fractions: 10 free parameters, 2 fixed

Template fit procedure has been **validated** and **blinded I_X coefficients extracted**

Systematic uncertainties are almost done

Analyses status



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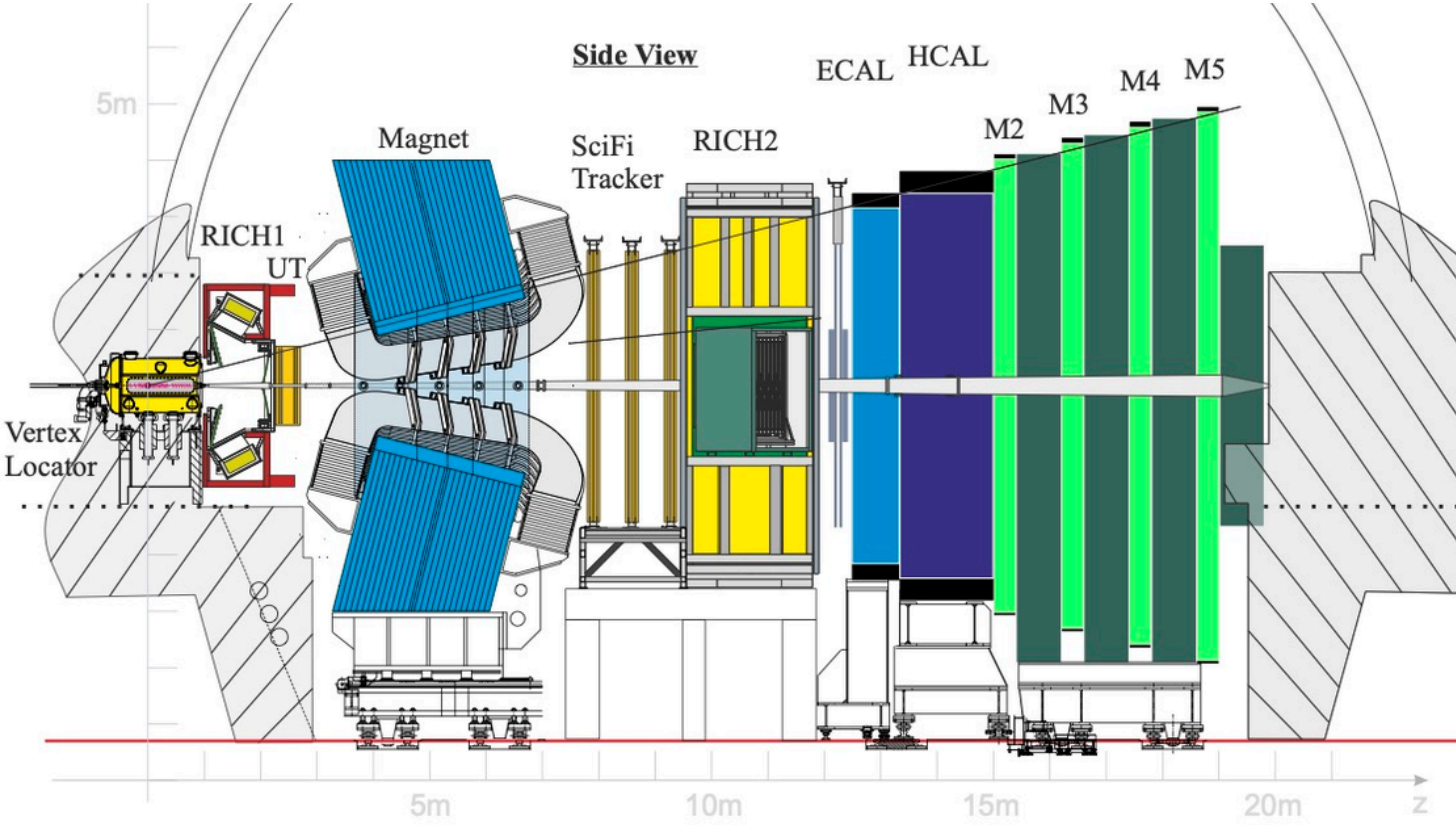
The LHCb Detector Upgrade I

Run 3 Upgrade:

- ✦ Changed all trackers,
- ✦ Replaced all readout electronics,
- ✦ Changed to fully software trigger (compared to hardware + software trigger in Run 1-2)
  - ▸ Improves greatly triggering on decays with electrons!
- ✦ Already collected $\sim 21\ \text{fb}^{-1}\ pp$ data (~2.5× more than Run 1+2)

We expect ~7× more statistics!

*Run 3 detector



Run 3 analysis status

- We are working on **improving the template fit procedure** in order to minimise the model dependence
  - Thorough study using large MC samples generated with RapidSim
  - Aim to compare the **different fitting methods** (folding, unfolding, reweighting) with different q^2 binning
- Ongoing work with a « Fast MC » will help **reduce the systematic** uncertainty linked to **limited MC statistics**

Great improvement over Run 2 analysis is expected!

Conclusion and prospects

- **Long-standing tension in R(D)-R(D*)** measurements encourages searches in semileptonic $b \to c\ell\nu$ transitions
- The 12 I_X angular coefficients are being measured with different leptonic final state to **probe potential NP** contributions:
  - Run 2 analysis being **finalised**,
  - Run 3 analysis **ongoing** with increased statistics and expecting reduced systematic uncertainties

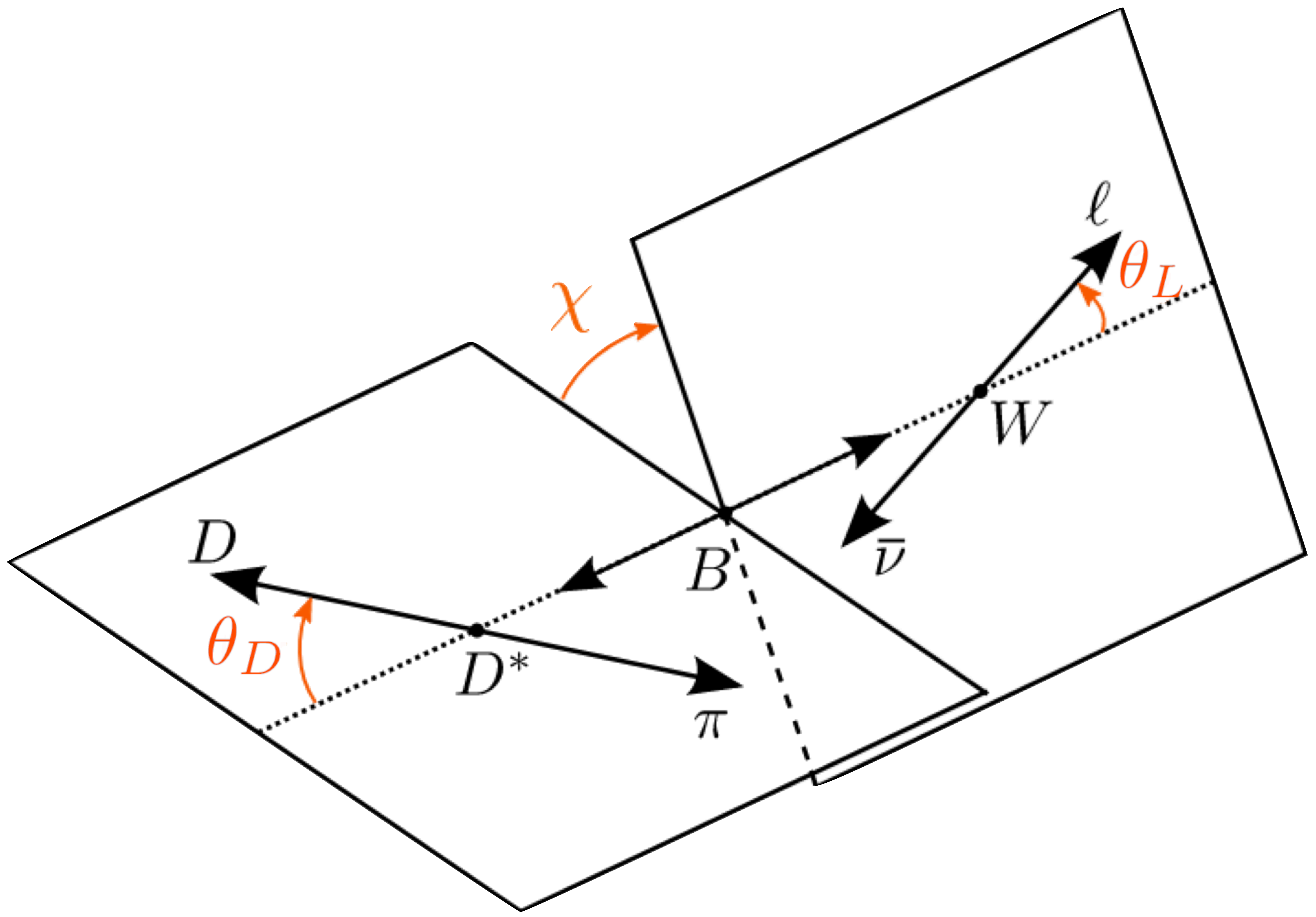
Thank you for your attention!

Email: lea.dreyfus@cern.ch
CERN Mattermost: @drlea

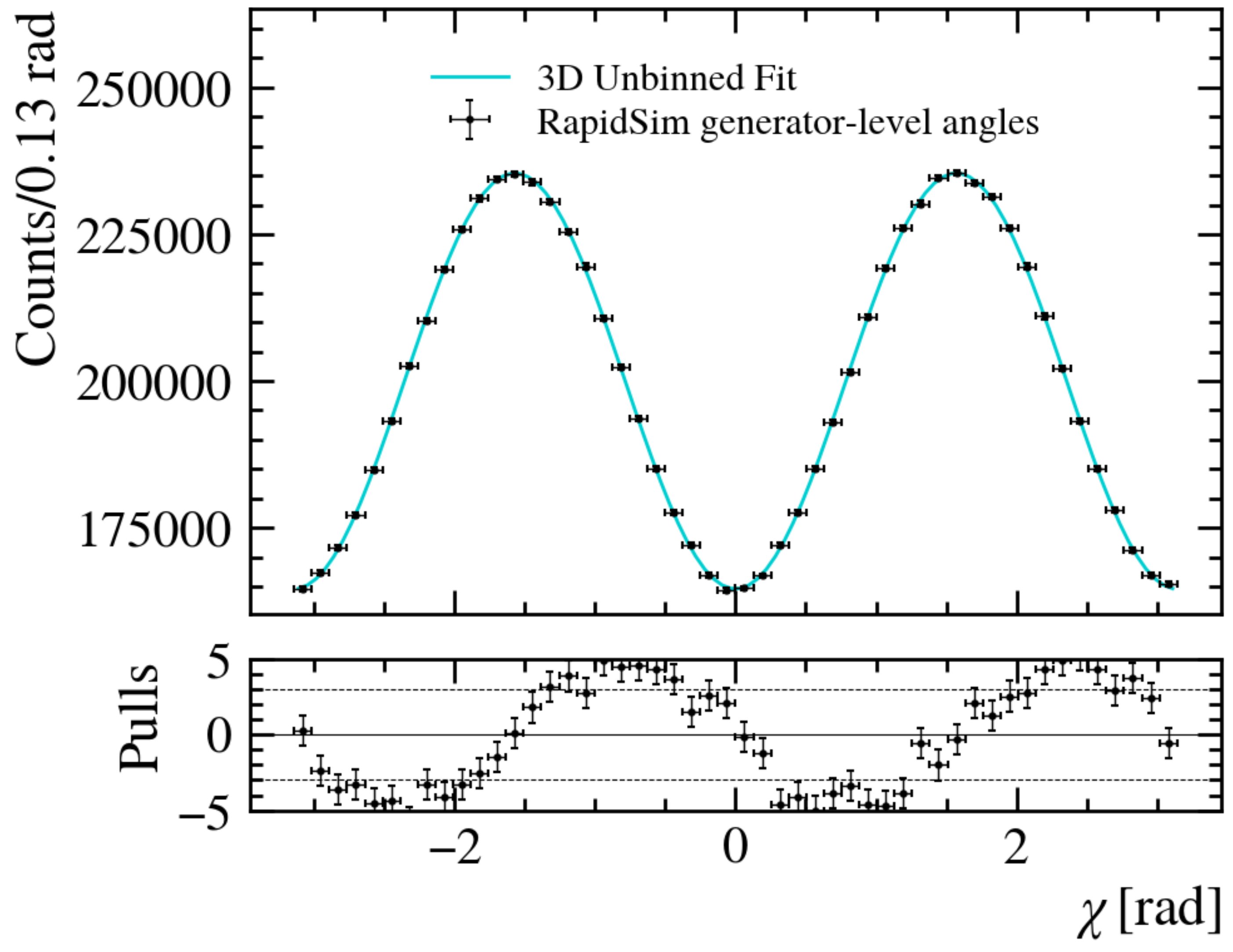
Backup slides

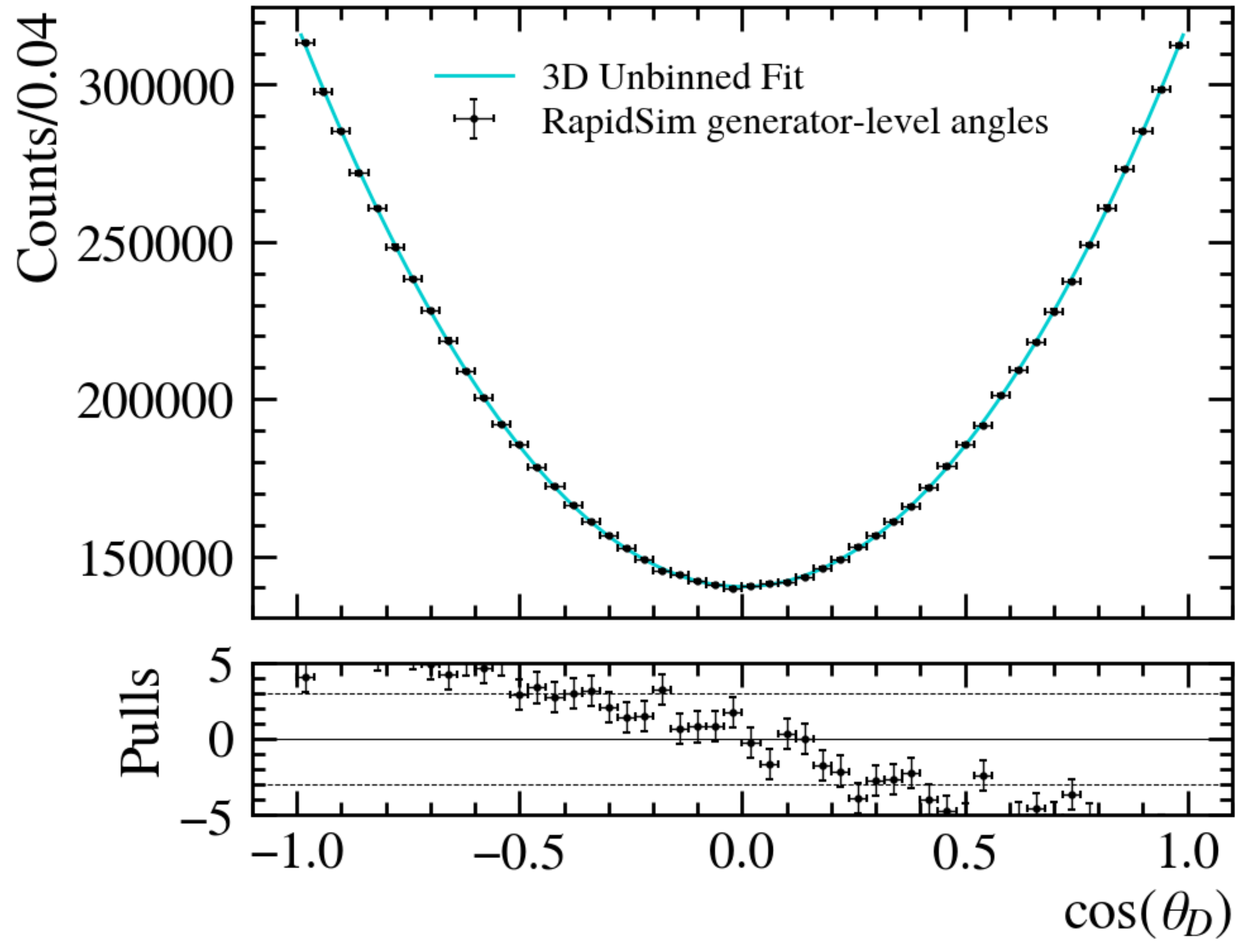
Angle definition

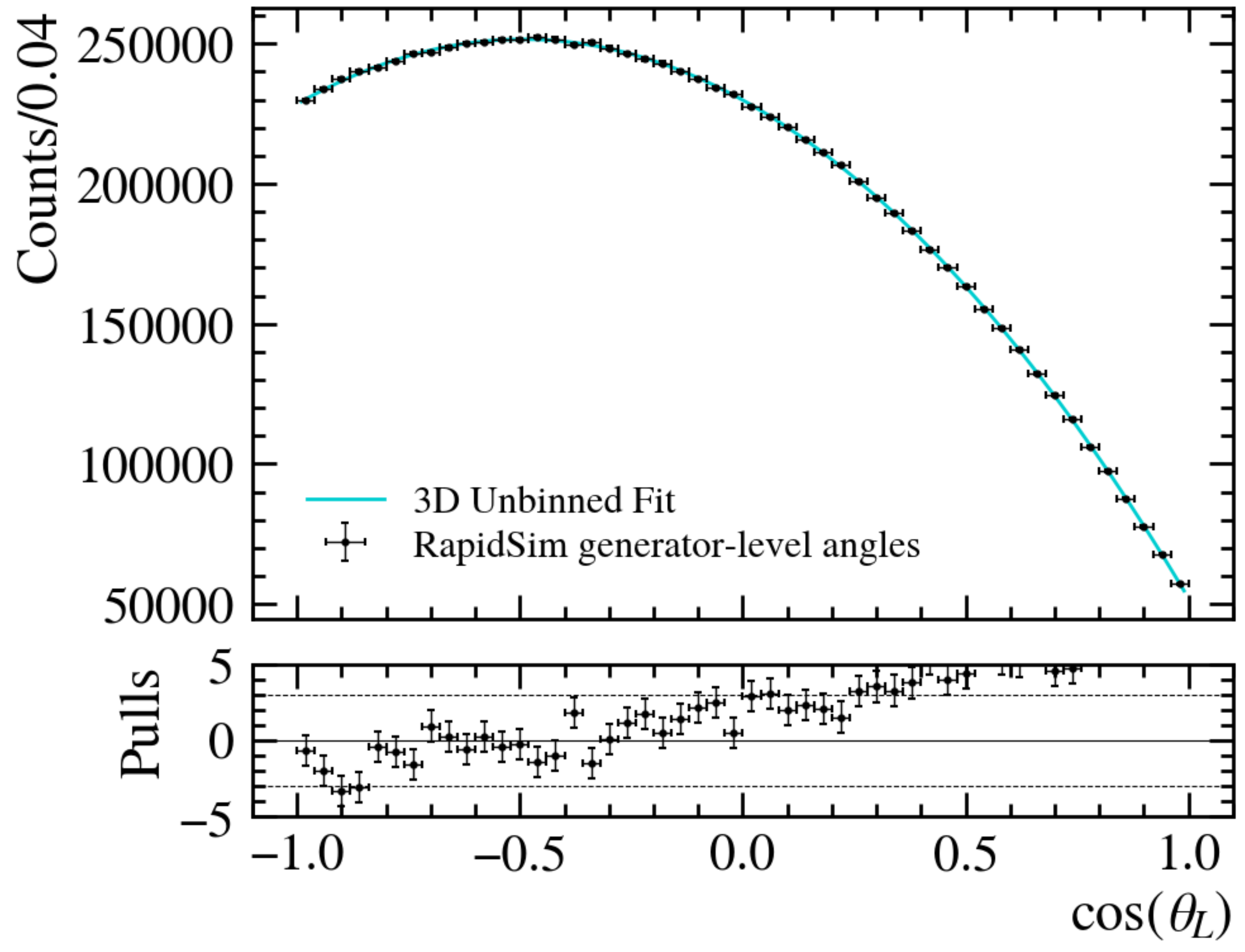
- θ_L: angle between the direction of the lepton and the direction opposite the B^0 hadron in the virtual W rest frame.
- θ_D: angle between the D^* child hadron and the direction opposite the B^0 hadron in the D^* rest frame.
- χ: the angle between the plane formed by the D^* decay and the W decay, defined in the B^0 meson rest frame



Generator-level angles and fit to decay rate







Run 2 conditions RapidSim sample $B^0 \to D^* e\nu$, 10M events, fit the 3D decay rate integrated over the whole q^2 range

Extract 11 out of the 12 coefficients, I_{1c} constrained with

$$\Gamma = \frac{1}{4}(3I_{1c} + 6I_{1s} - I_{2c} - 2I_{2s}) = 1\,,$$

Fit results:

name	value (rounded)	hesse	at limit
I1s	0.350739	+/- 0.00017	False
I2c	-0.531814	+/- 0.00037	False
I2s	0.116519	+/- 0.00026	False
I6c	-0.000309983	+/- 0.00037	False
I6s	-0.293781	+/- 0.00028	False
I3	-0.176987	+/- 0.00025	False
I4	-0.30759	+/- 0.00025	False
I5	0.237602	+/- 0.00026	False
I7	2.11921e-05	+/- 0.00034	False
I8	-0.000139842	+/- 0.00034	False
I9	1.01578e-05	+/- 0.00027	False

This is just to give an idea of the true distributions :)

More angular observable (1) arXiv:1907.02257

- Integrate the decay rate on one or several angles:

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_D d\cos\theta_\ell d\chi} = \frac{9}{32\pi}\Big\{ I_{1c}\cos^2\theta_D + I_{1s}\sin^2\theta_D + \left[I_{2c}\cos^2\theta_D + I_{2s}\sin^2\theta_D\right]\cos 2\theta_\ell + \left[I_{6c}\cos^2\theta_D + I_{6s}\sin^2\theta_D\right]\cos\theta_\ell + \left[I_3\cos 2\chi + I_9\sin 2\chi\right]\sin^2\theta_\ell\sin^2\theta_D + \left[I_4\cos\chi + I_8\sin\chi\right]\sin 2\theta_\ell\sin 2\theta_D + \left[I_5\cos\chi + I_7\sin\chi\right]\sin\theta_\ell\sin 2\theta_D \Big\},$$

- θ_ℓ distribution :

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} = a_{\theta_\ell}(q^2) + b_{\theta_\ell}(q^2)\cos\theta_\ell + c_{\theta_\ell}(q^2)\cos^2\theta_\ell\,,$$

$$a_{\theta_\ell}(q^2) = \frac{3}{8}\left(I_{1c} + 2I_{1s} - I_{2c} - 2I_{2s}\right)\,,$$

$$b_{\theta_\ell}(q^2) = \frac{3}{8}\left(I_{6c} + 2I_{6s}\right)\,,$$

$$c_{\theta_\ell}(q^2) = \frac{3}{4}\left(I_{2c} + 2I_{2s}\right)\,.$$

- θ_D distribution :

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D\,,$$

$$a_{\theta_D}(q^2) = \frac{3}{8}\left(3I_{1s} - I_{2s}\right)\,,$$

$$c_{\theta_D}(q^2) = \frac{3}{8}\left(3I_{1c} - 3I_{1s} - I_{2c} + I_{2s}\right)\,.$$

- χ distribution :

$$\frac{d^2\Gamma}{dq^2 d\chi} = a_\chi(q^2) + c^c_\chi(q^2)\cos 2\chi + c^s_\chi(q^2)\sin 2\chi\,,$$

$$a_\chi(q^2) = \frac{1}{8\pi}\left(3I_{1c} + 6I_{1s} - I_{2c} - 2I_{2s}\right)$$

$$c^c_\chi(q^2) = \frac{1}{2\pi}I_3\,,$$

$$c^s_\chi(q^2) = \frac{1}{2\pi}I_9\,.$$

More angular observable (2)

arXiv:1907.02257

- From the previously defined terms, define:

  - Differential decay rate

$$\frac{d\Gamma}{dq^2} = \frac{1}{4}\left(3I_{1c} + 6I_{1s} - I_{2c} - 2I_{2s}\right) ,$$

  - Forward-backward asymmetry

$$\mathcal{A}_{\rm FB}(q^2) = \frac{b_{\theta_\ell}(q^2)}{d\Gamma/dq^2} = \frac{3}{8}\frac{(I_{6c} + 2I_{6s})}{d\Gamma/dq^2} ,$$

  - D^* polarization fraction

$$F_L^{D^*}(q^2) = \frac{1}{2}\frac{3I_{1c} - I_{2c}}{3\left(I_{1c} + I_{1s}\right) - I_{2c} - I_{2s}} .$$

Sensitivity of observables to New Physics models

Table 1 The dependence of angular observables on combinations of Wilson coefficients. An entry of ✓ denotes the presence of this combination. An entry of m^n denotes the presence of this term, but with kinematic lepton-mass suppression $\propto (m_\ell/\sqrt{q^2})^n$ $(n = 1, 2)$. The "num(·)" indicates that only the dependence of the numerator of this observable is given. The V_i^a have been introduced in Ref. [30]

Observable	$\lvert C_A\rvert^2$	$\lvert C_V\rvert^2$	$\lvert C_P\rvert^2$	$\lvert C_T\rvert^2$	$\mathrm{Re}(C_A C_V^*)$	$\mathrm{Re}(C_A C_P^*)$	$\mathrm{Re}(C_A C_T^*)$	$\mathrm{Re}(C_V C_P^*)$	$\mathrm{Re}(C_V C_T^*)$	$\mathrm{Re}(C_P C_T^*)$
$J_{1c} = V_1^0$	✓	–	✓	✓	–	(m)	(m)	–	–	–
$J_{1s} = V_1^T$	✓	✓	–	✓	–	–	(m)	–	(m)	–
$J_{2c} = V_2^0$	✓	–	–	✓	–	–	–	–	–	–
$J_{2s} = V_2^T$	✓	✓	–	✓	–	–	–	–	–	–
$J_3 = V_4^T$	✓	✓	–	✓	–	–	–	–	–	–
$J_4 = V_1^{0T}$	✓	–	–	✓	–	–	–	–	–	–
$J_5 = V_2^{0T}$	(m^2)	–	–	(m^2)	✓	(m)	(m)	–	(m)	✓
$J_{6c} = V_3^0$	(m^2)	–	–	–	–	(m)	(m)	–	–	✓
$J_{6s} = V_3^T$	–	–	–	(m^2)	✓	–	(m)	–	(m)	–
$d\Gamma/dq^2$	✓	✓	✓	✓	–	(m)	(m)	–	(m)	–
num(A_{FB})	(m^2)	–	–	(m^2)	✓	(m)	(m)	–	(m)	✓
num(F_L)	✓	–	✓	✓	–	(m)	(m)	–	–	–
num(F_L-1/3)	✓	✓	✓	✓	–	(m)	(m)	–	(m)	–
num($\widetilde{F}_L$)	✓	(m^2)	✓	✓	–	(m)	(m)	–	(m)	–
num($\widetilde{F}_L$-1/3)	✓	✓	–	✓	–	–	–	–	–	–
num(S_3)	✓	✓	–	✓	–	–	–	–	–	–
Observable	–	–	–	–	$\mathrm{Im}(C_A C_V^*)$	$\mathrm{Im}(C_A C_P^*)$	$\mathrm{Im}(C_A C_T^*)$	$\mathrm{Im}(C_V C_P^*)$	$\mathrm{Im}(C_V C_T^*)$	$\mathrm{Im}(C_P C_T^*)$
$J_7 = V_3^{0T}$					(m^2)	–	(m)	(m)	–	✓
$J_8 = V_4^{0T}$					✓	–	–	–	–	–
$J_9 = V_5^T$					✓	–	–	–	–	–

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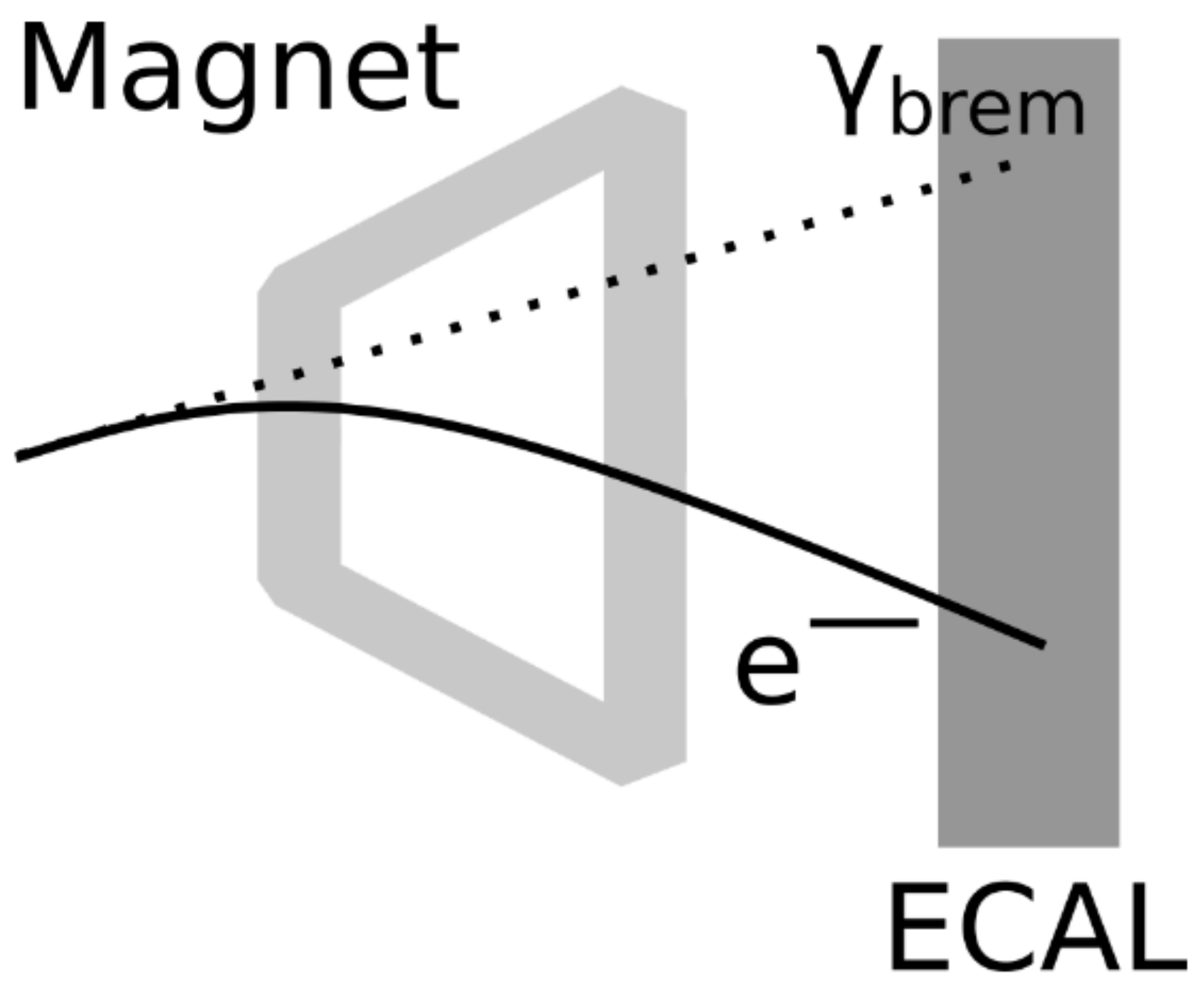
Bremsstrahlung recovery for electrons

- Bremsstrahlung (« brem ») mainly from interaction with detector material
- Energy loss $\propto E/m^2 \rightarrow$ mostly affects electrons
- If a photon is emitted **before the magnet**, the momentum measurement is **biased**
  - Recovery procedure: find the brem photon by extrapolating the track, add the energy back to electron
  - **Photon recovery efficiency ~60% (run 2)**
- Electrons are categorised into:
  - ✦ **With brem photon**
  - ✦ **No brem photon**



Both samples require different treatment for the background suppression, MC corrections, templates, etc

Kinematic reconstruction (1)

Two methods to reconstruct the missing momentum from the neutrino:

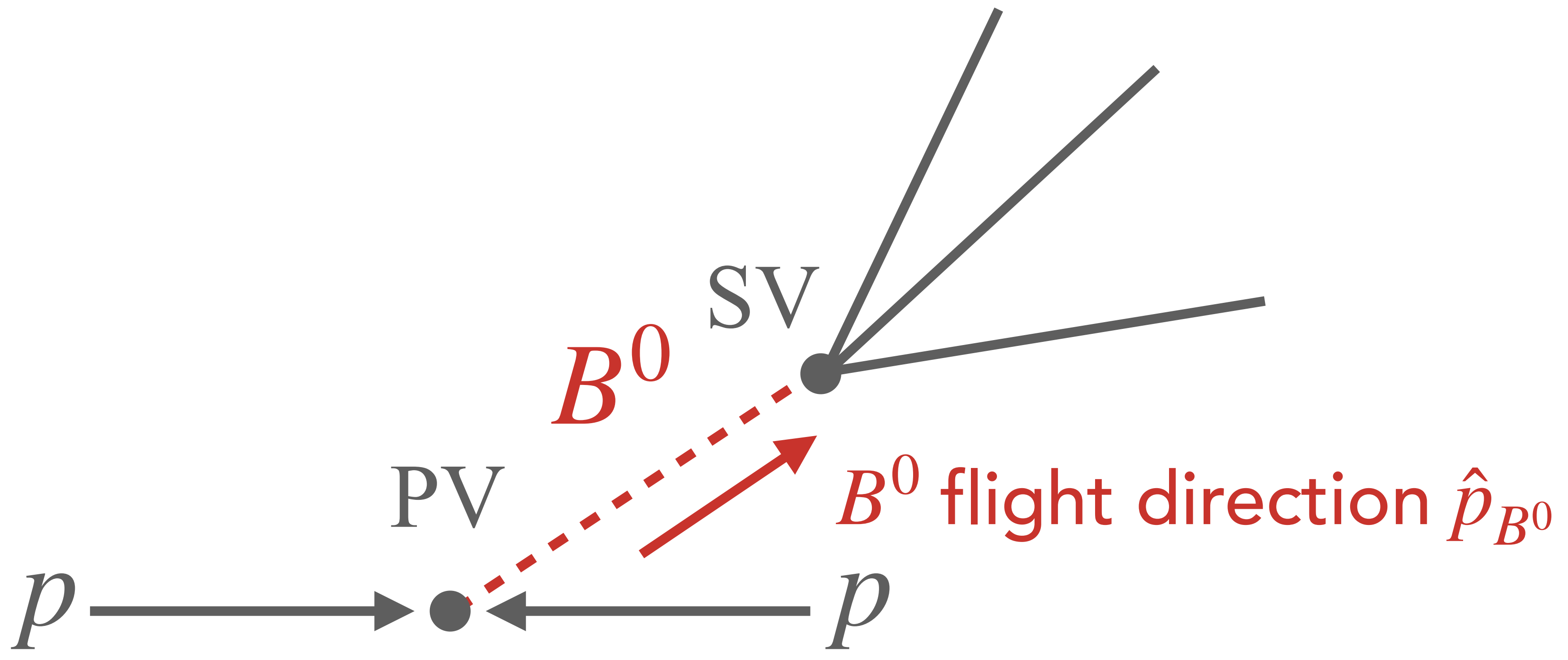
Rest Frame Approximation

Exploits high boost of the B^0:

The longitudinal component of p_{B^0} is approximated with boost of the visible final state

$$p^z_{B^0} = \frac{m_{B^0}}{m_{D^*\ell}} p^z_{D^*\ell}$$

$$|p_{B^0}| = \frac{m_{B^0}}{m_{D^*\ell}} p^z_{D^*\ell} \sqrt{1 + \tan^2(\theta)}$$



Get B^0 flight direction from the excellent PV and SV reconstruction in the VELO

Kinematic reconstruction (2)

Two methods to reconstruct the missing momentum from the neutrino:

Quadratic Equation solving:

Solve the eq. of motion for p_ν, assume $m_\nu = 0$

→ reconstructs p_{B^0} up to a twofold ambiguity

Work in a basis || and ⊥ to B^0 momentum

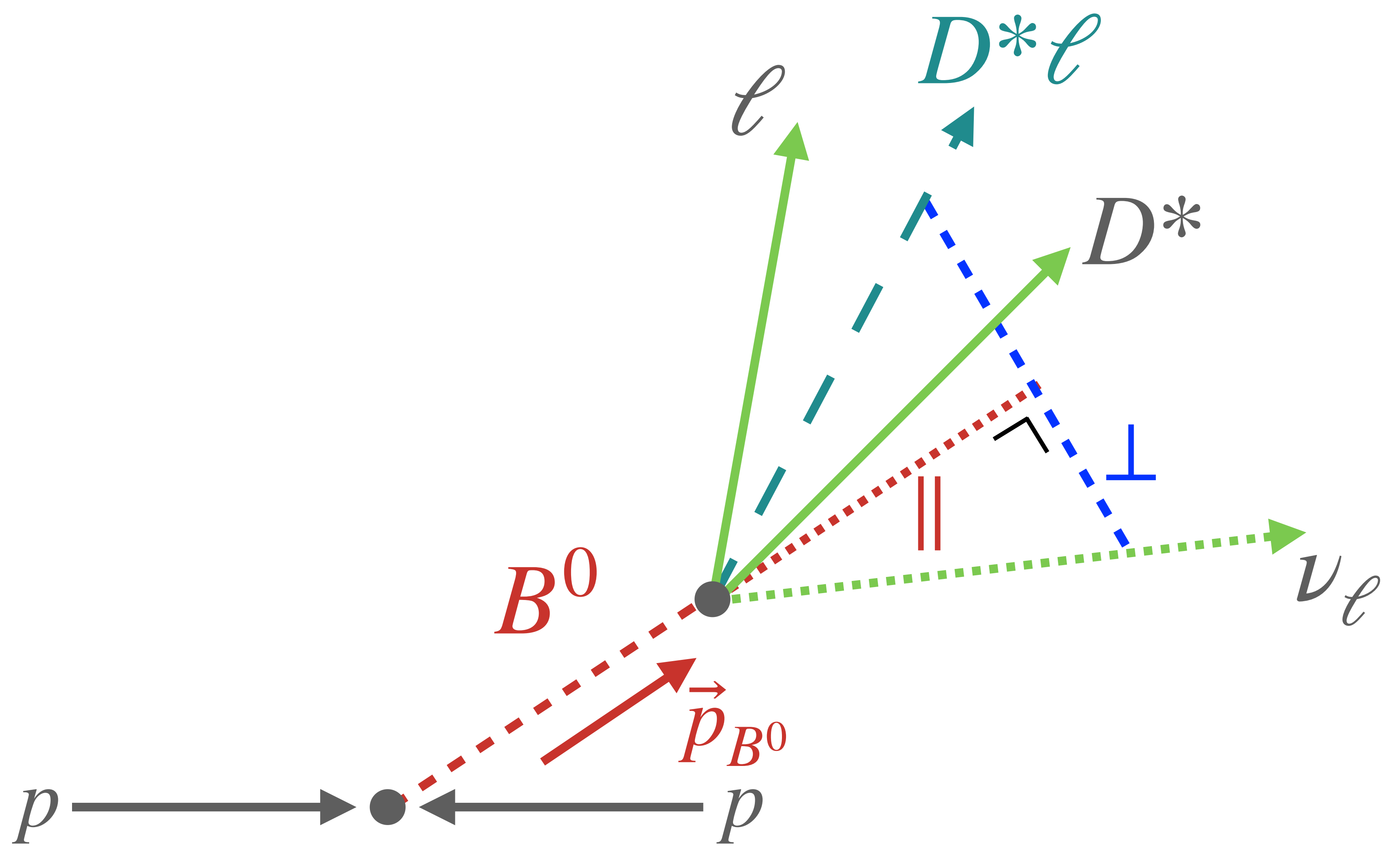
$$\boldsymbol{p}_{B^0} = (|\boldsymbol{p}_{B^0}|,\ 0),$$
$$\boldsymbol{p}_{D^*\ell} = (p^{\parallel}_{D^*\ell},\ p^{\perp}_{D^*\ell}),$$
$$\boldsymbol{p}_{\nu} = (p^{\parallel}_{\nu},\ p^{\perp}_{\nu}).$$

Solve, get:

$$|p_{B^0}| = p^{\parallel}_{D^*\ell} - a \pm \sqrt{r}$$

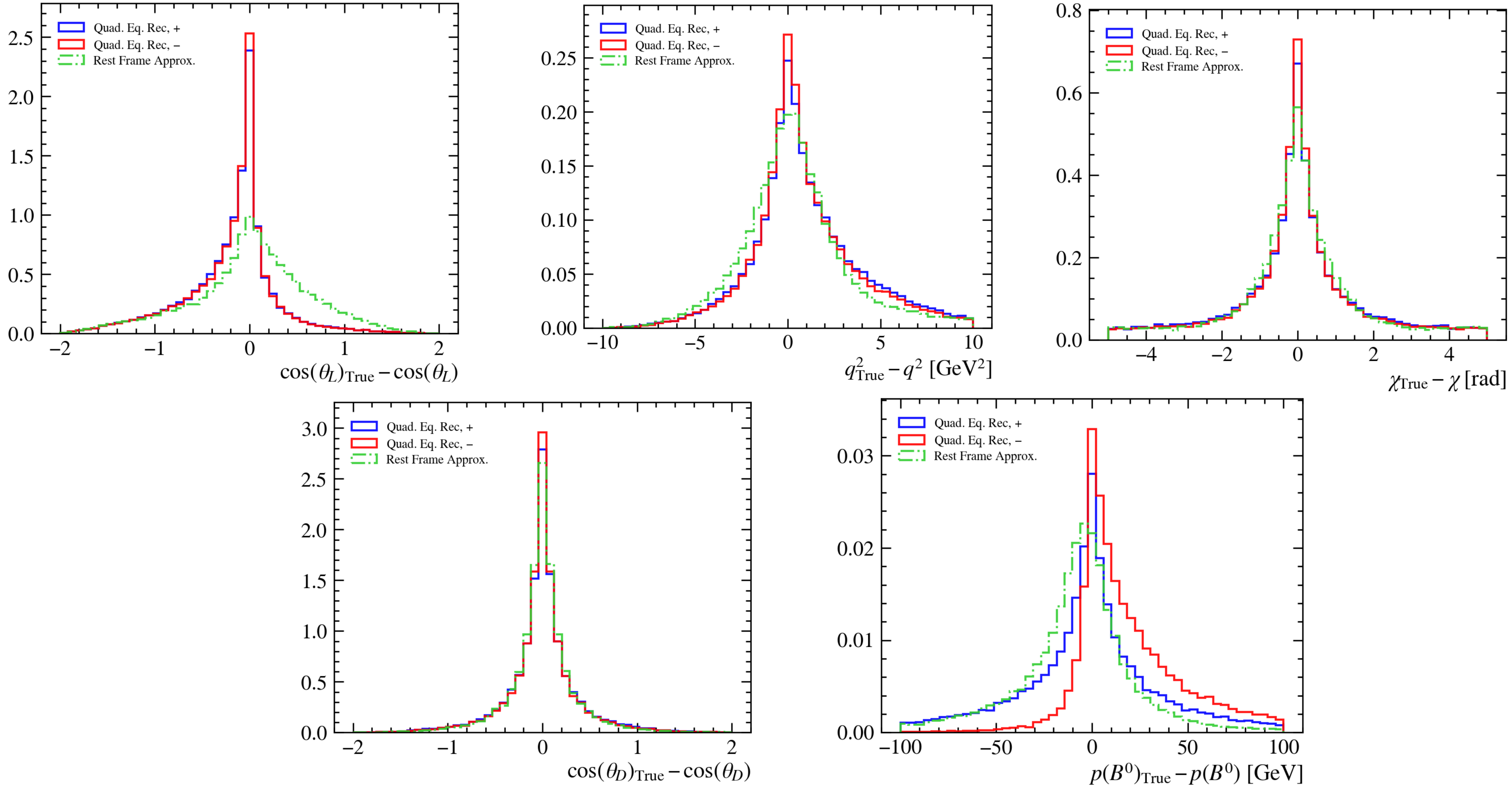
$$a = \frac{p^{\parallel}_{D^*\ell}\left(m^2_{B^0} - m^2_{D^*\ell} - 2(p^{\perp}_{D^*\ell})^2\right)^2}{2\left((p^{\parallel}_{D^*\ell})^2 - E^2_{D^*\ell}\right)}$$

$$r = \frac{E^2_{D^*\ell}\left[m^2_{B^0} - m^2_{D^*\ell} - 2(p^{\perp}_{D^*\ell})^2\right]^2}{4\left((p^{\parallel}_{D^*\ell})^2 - E^2_{D^*\ell}\right)^2} + \frac{E^2_{D^*\ell}(p^{\perp}_{D^*\ell})^2}{\left((p^{\parallel}_{D^*\ell})^2 - E^2_{D^*\ell}\right)}$$



Kinematic reconstruction (3)

Resolutions on the analysis variables (using Run 2 conditions RapidSim sample):



Template fit Run 2 - fit validation with Bootstrapping

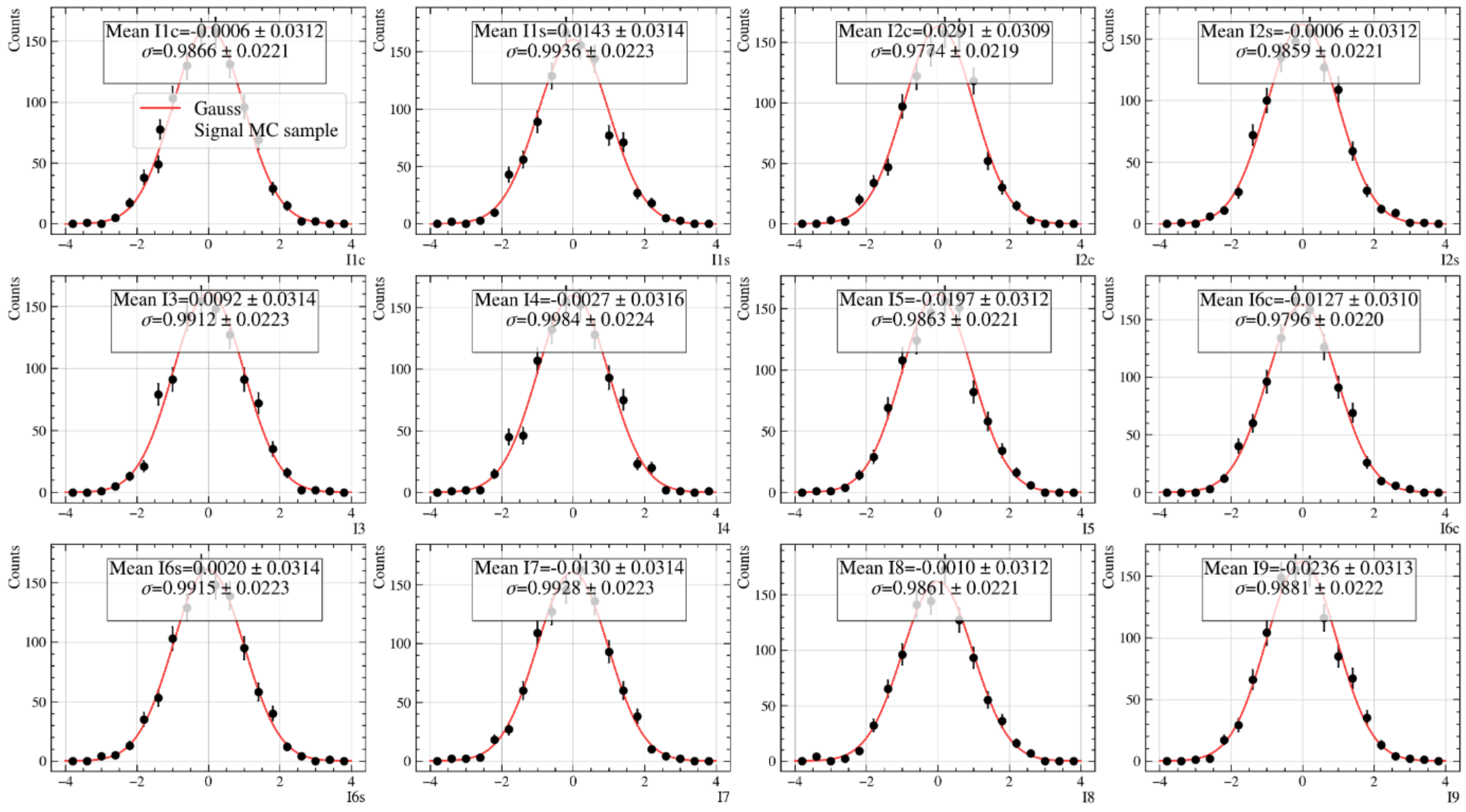
The fit is validated on bootstrapped SM signal + background sample

Template fit is iterated 1000 times

Pulls follow a gaussian distribution with $\mu = 0$ and $\sigma = 1$

▶ **Fit is robust and unbiased**

Pull distribution between true and fitted I_X for $B \to D^{*}e\nu$



Fit methods comparison - preliminary results