Study of Semitauonic B-meson Decays at Belle/Belle II Experiments

Students’ seminar | Krakow School of Interdisciplinary PhD Studies

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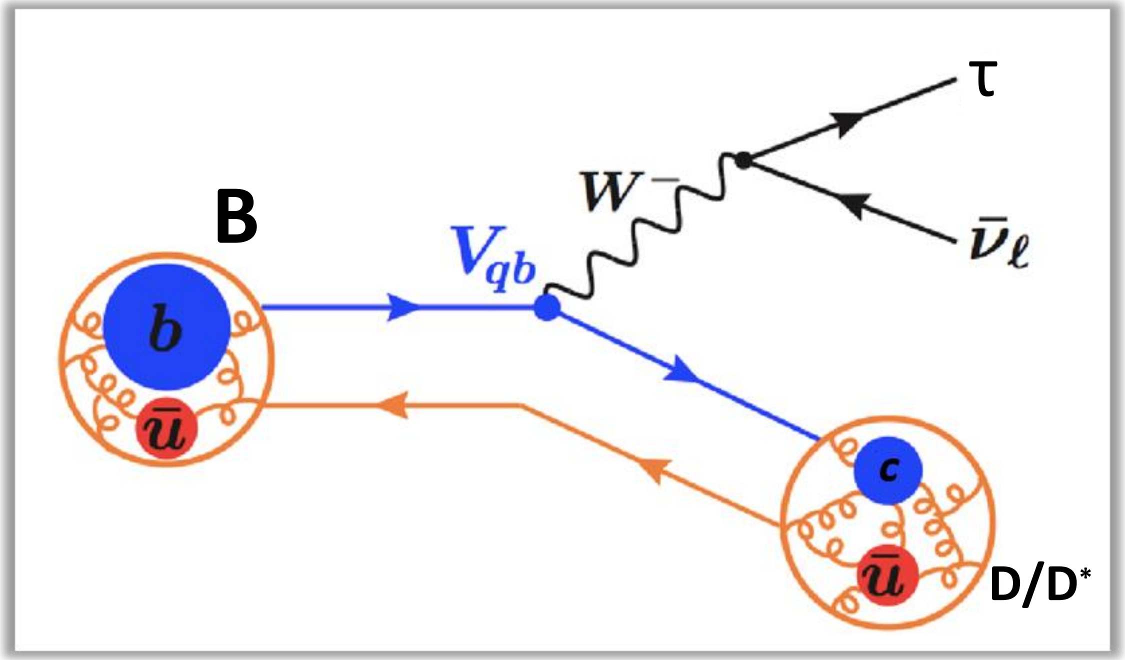
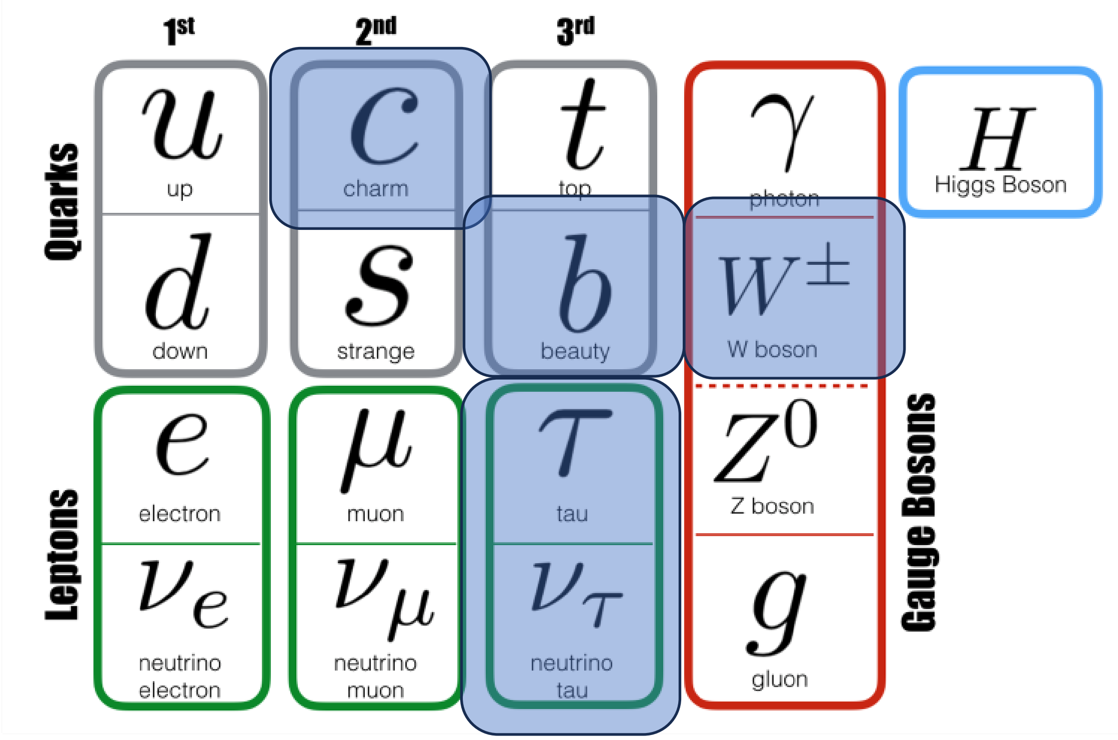
Outline

- Introduction & Motivation
- Belle (II) experiments
- Methodology
- Results
- Summary





Decays of B mesons to D/D* mesons:

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

$\tau \rightarrow h\nu$, or $l\, \nu\nu$

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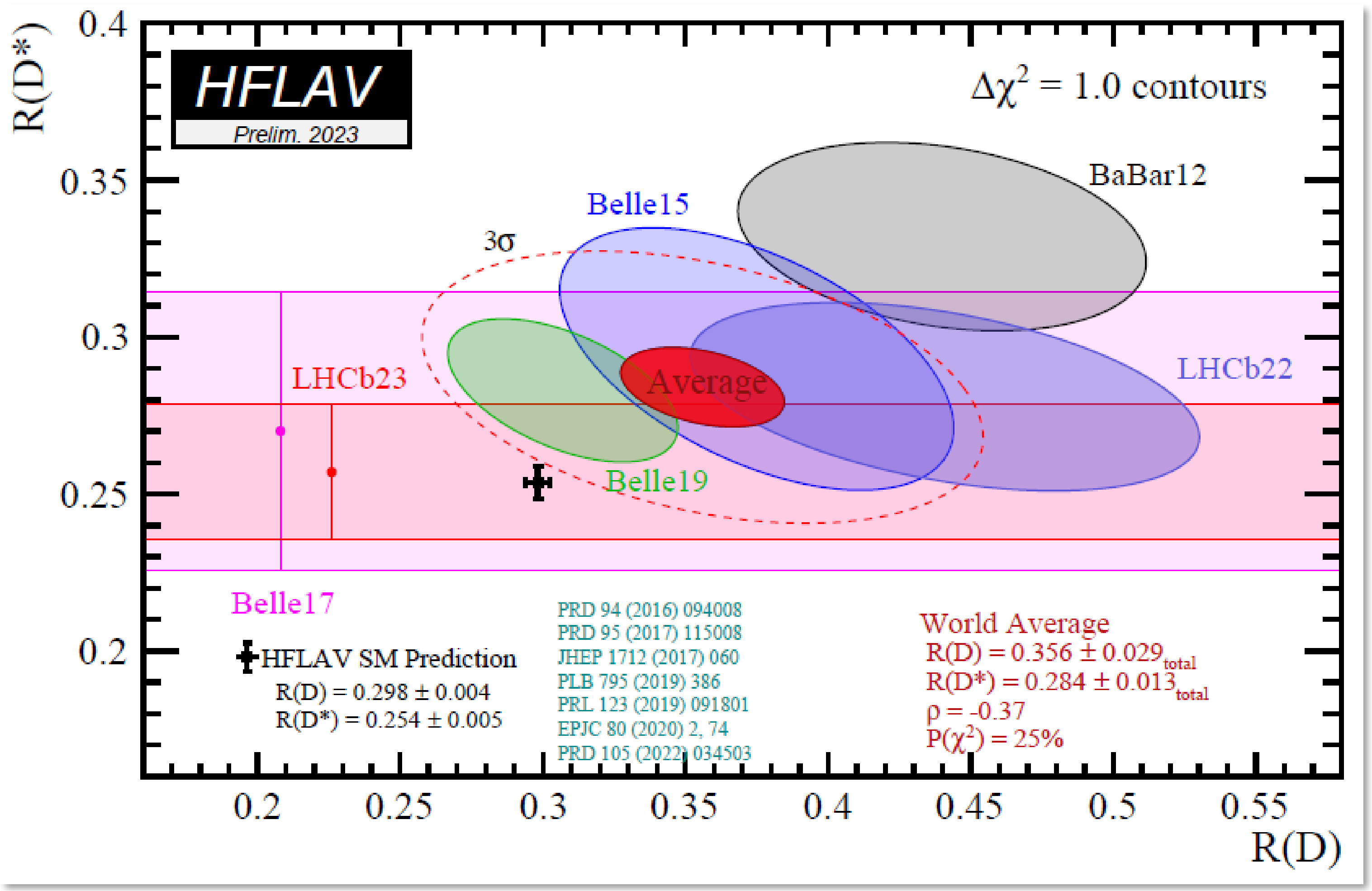
- Sensitive to new physics amplitudes
- Large numer of observables
- Good theoretical tools, precise predictions
- Experimentally challenging



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

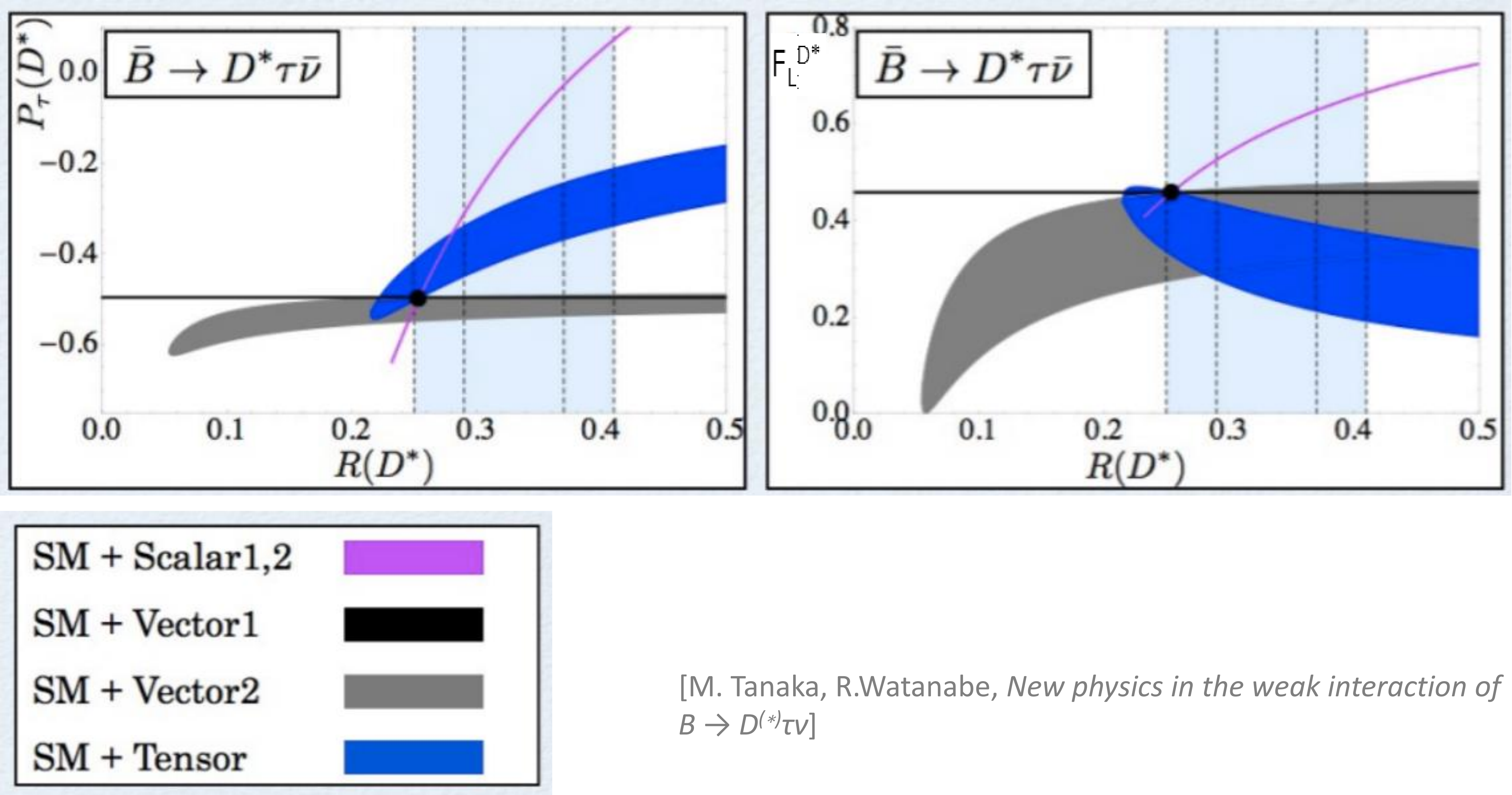
Standard Model prediction:

$R(D^*)^{SM} = 0.254 \pm 005$
$R(D)^{SM} = 0.298 \pm 0.004$

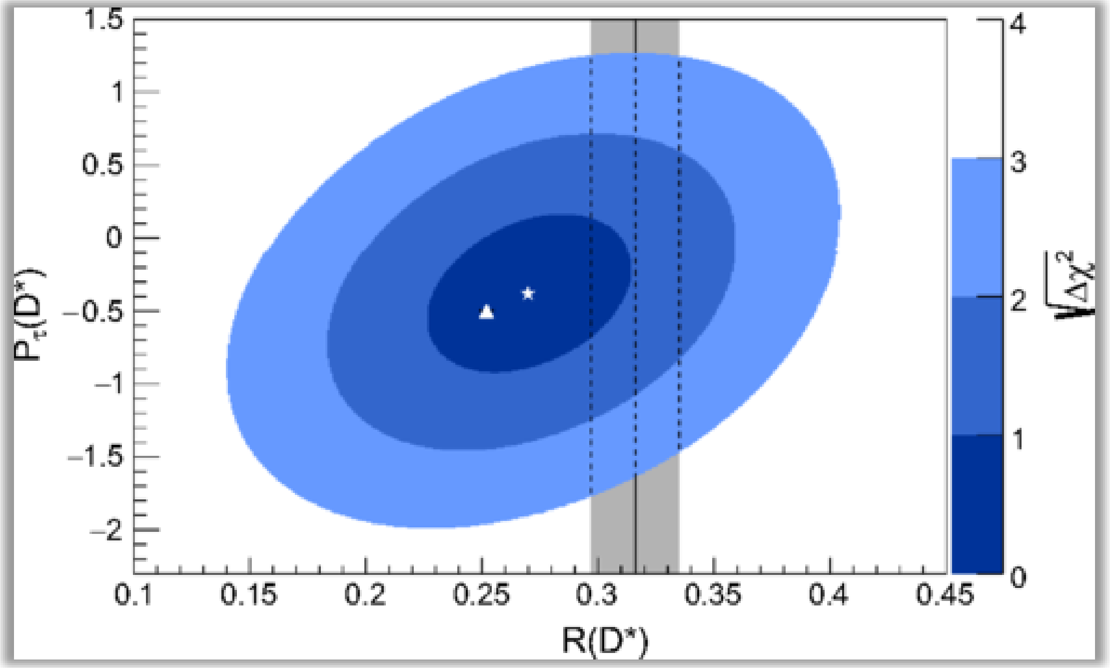
Experimental average:

$R(D^*) = 0.284 \pm 0.013$
$R(D) = 0.356 \pm 0.029$

Combined R(D) and R(D*) measurements in tension (~3σ) with the Standard Model prediction



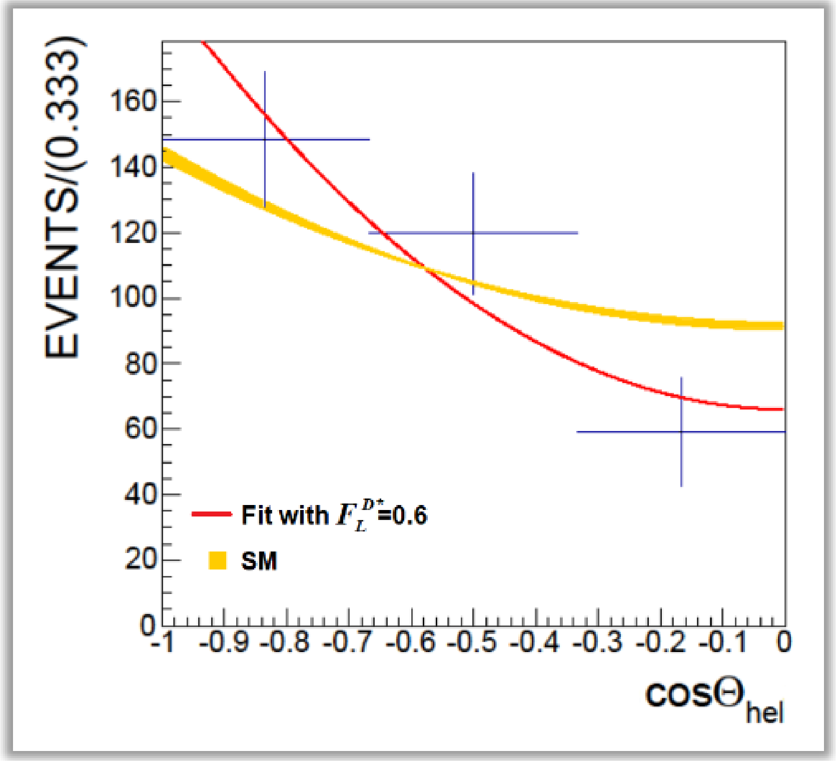
[M. Tanaka, R.Watanabe, *New physics in the weak interaction of $B \to D^{(*)}\tau\nu$*]



R(D*) = 0.270 ± 0.035 (stat) ± 0.030 (syst)
P_τ = -0.38 ± 0.51 (stat) ± 0.20 (syst)

Combined R(D*) and P_τ result consistent with the SM prediction within 0.6σ

[PRL118, 211801 (2017) PRD97, 012004 (2018)]



F_L^{D*}= 0.60 ± 0.08 (stat) ± 0.04 (syst)

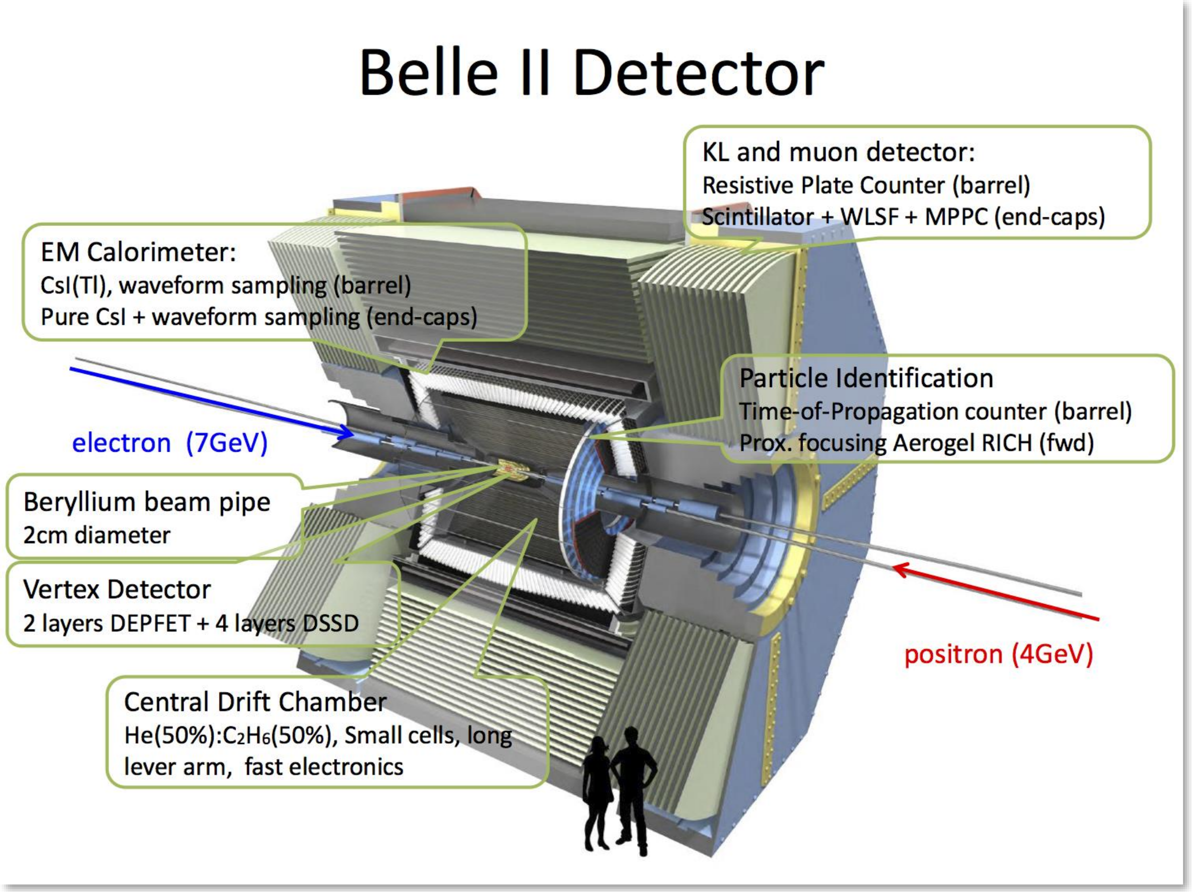
Consistent with SM prediction within 1.5σ

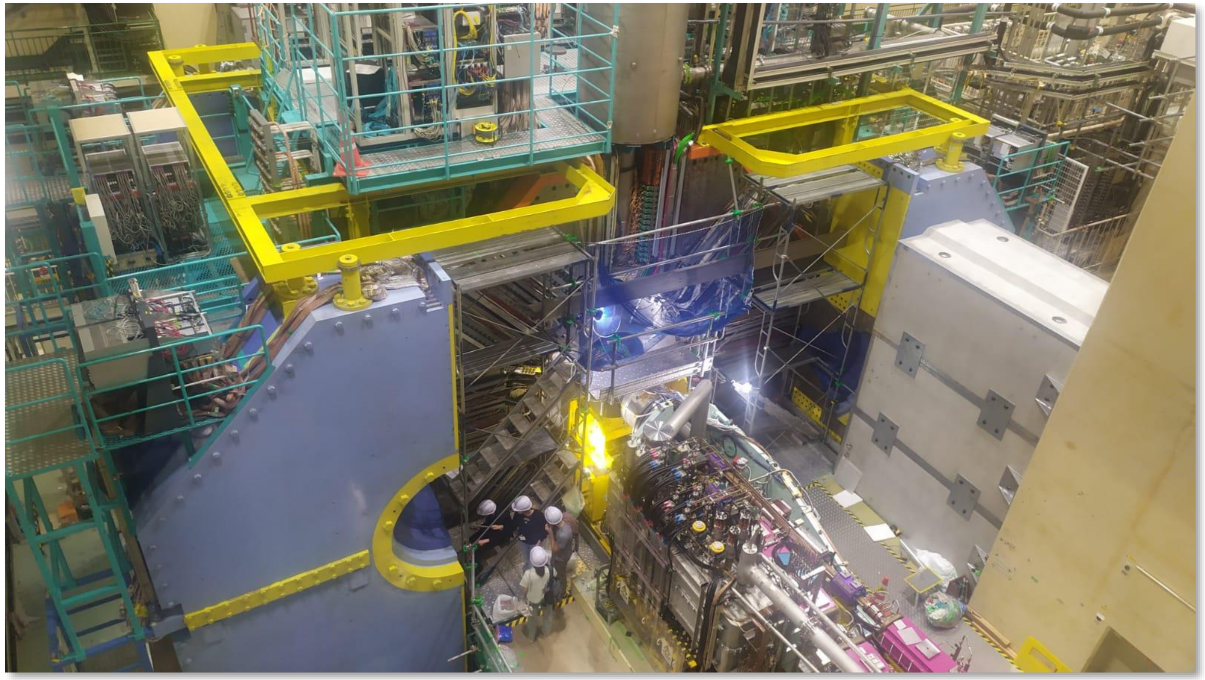
[Belle Collab. 1903.03102 [hep-ex] (2019)]

II Belle (II) Experiment

The Belle II experiment:

- a particle physics experiment designed to study the properties of B mesons
- operates at the SuperKEKB accelerator complex at KEK in Tsukuba, Japan
- successor to the Belle Experiment, that operated in 1999-2010.





Multifunctional detection system composed of different types of sub-detectors:

- Particle identification
- Track reconstruction
- Vertexing

On-resonance B-meson pair production

$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

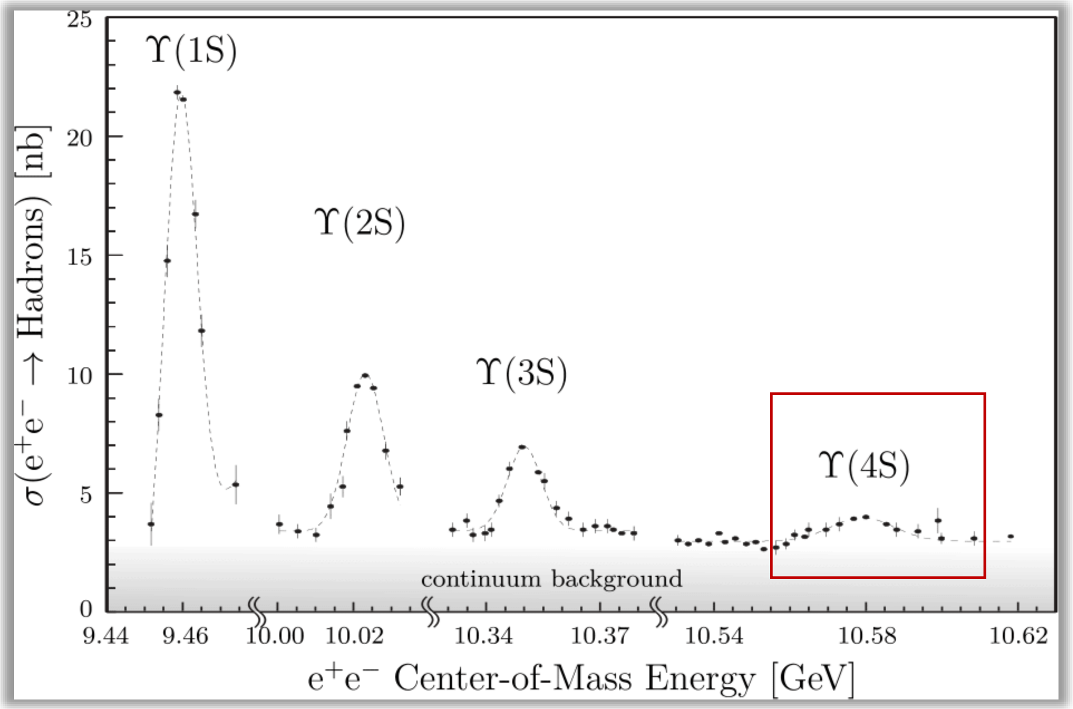
Beam energies precisely tunned to $\Upsilon(4S)$ mass:

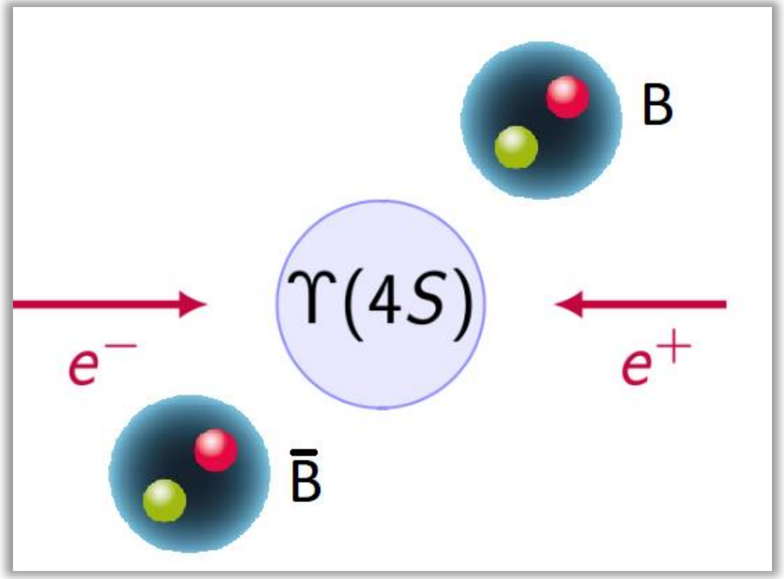
$$\sqrt{s} = E_{e+} + \mathrm{E}_{e-} = M_{\Upsilon(4S)}$$

Kinematical constraints

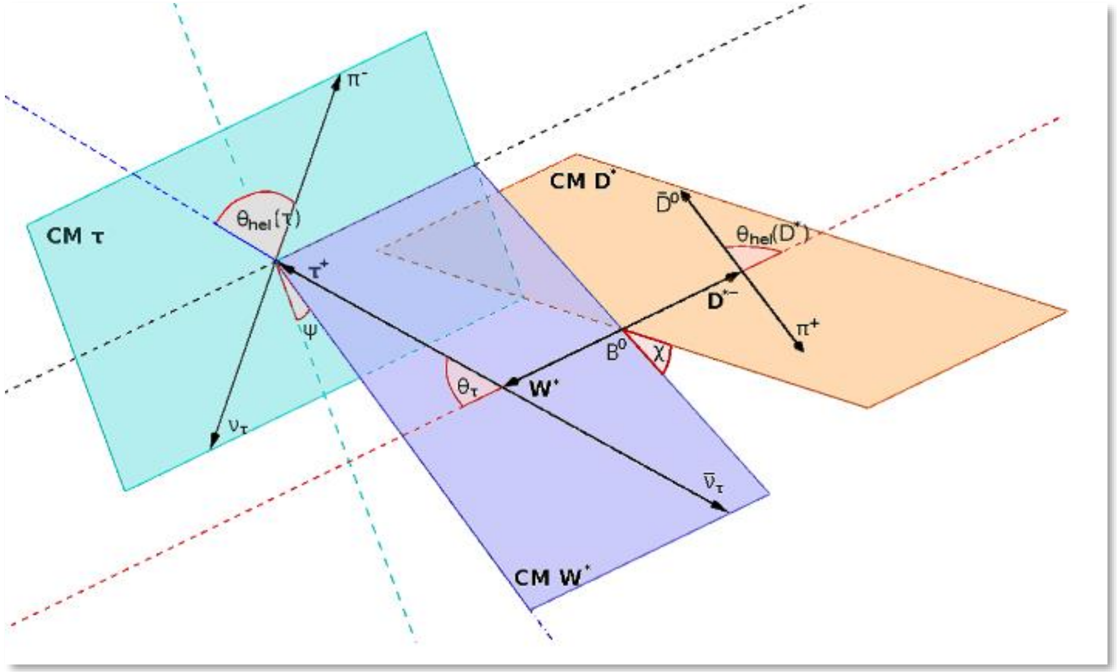
Momentum conservation in two-body $\Upsilon(4S)$ decay:

$$\vec{p}_B(sig) = -\vec{p}_B(tag)$$





III Analysis strategy: kinematic variables



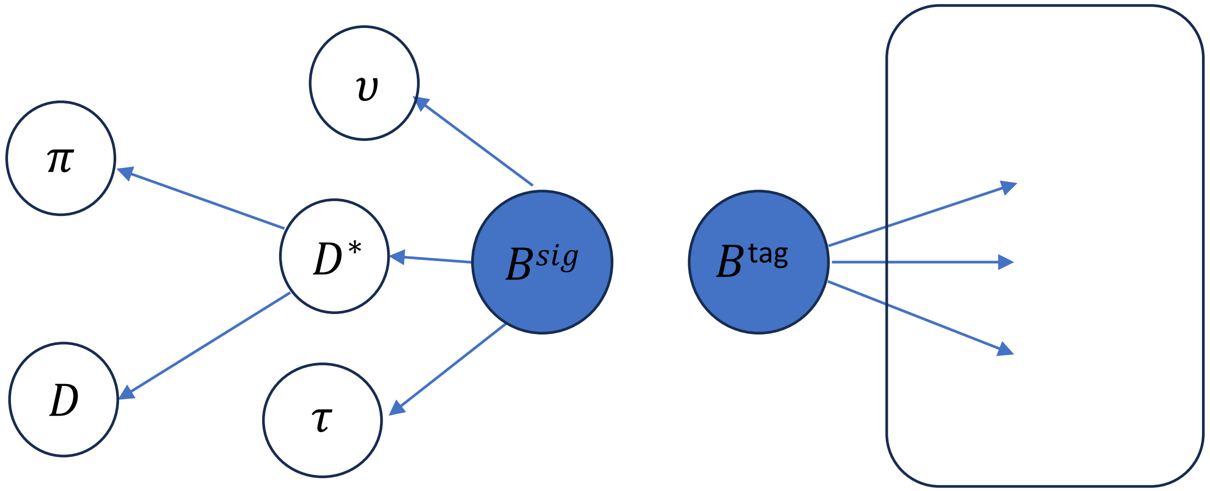
Kinematic variables available experimentally at B factories:

$q^2 = (p_B - p_{D^*})^2$	Four-momentum transfer squared
$\theta_{hel}(D^*)$	Angle between D-meson and B-meson in D* rest frame

We need signal B-meson momentum $\vec{p}_B(sig)$ to reconstruct these.

D* polarisation can be extracted from experimental data:

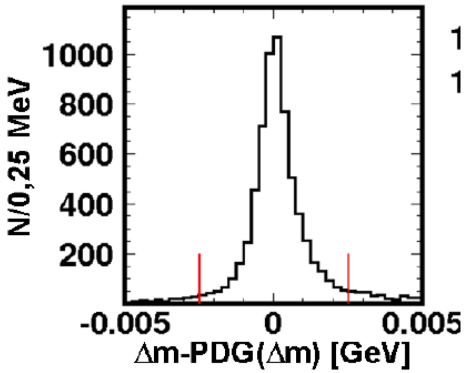
$$\frac{1}{\Gamma}\frac{d\Gamma}{dcos\theta_{hel}(D^*)} = \frac{3}{4}(2F_L^{D^*}\cos^2\theta_{hel}(D^*) + (1 - F_L^{D^*})sin^2\theta_{hel}(D^*)]$$

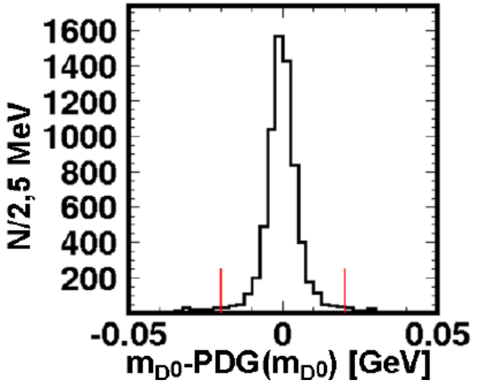


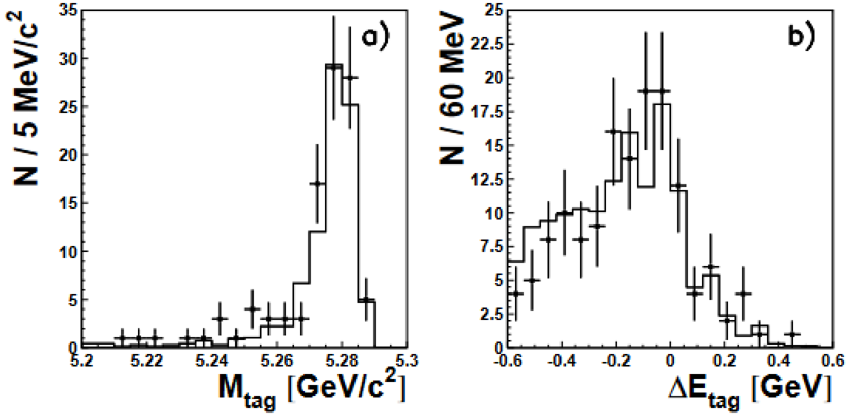
$$\vec{p}_B(sig) = -\vec{p}_B(tag)$$

1 **Reconstruct Bsig candidates**
A clean signature from {D*, ℓ/h} pairs

2 **Combine remaining tracks and clusters to form Btag candidate**
Use beam-constrained variables to identify correct candidates



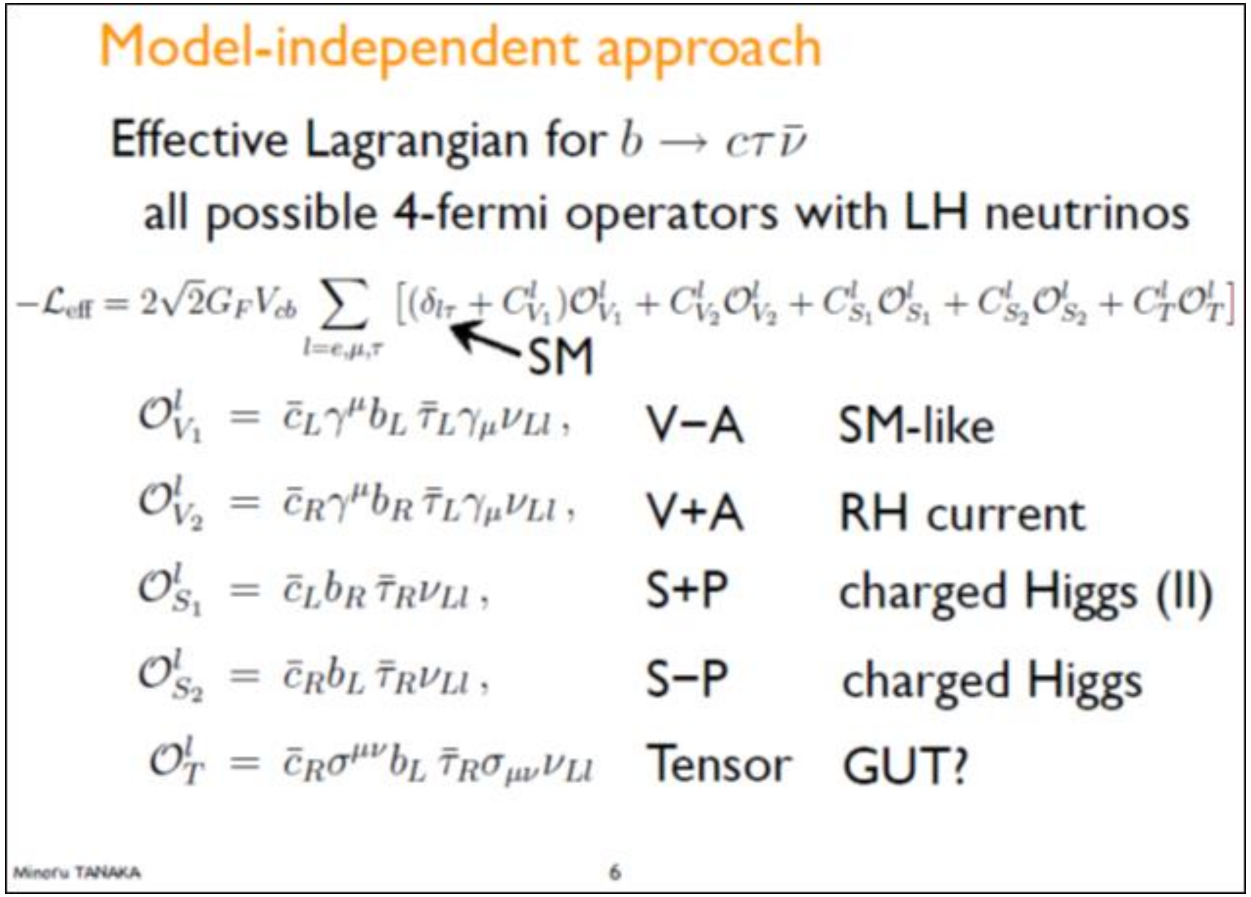




$$M_{tag} = \sqrt{E_{beam}^2 - p_{tag}^2}$$

$$\Delta E_{tag} = E_{tag} - E_{beam}$$

[A. Matyja et al., *Observation of $B^0 \to D^{*-}\tau^+\nu\tau$ decay at Belle*]



Model-independent approach

Effective Lagrangian for $b \to c\tau\bar{\nu}$

all possible 4-fermi operators with LH neutrinos

$$-\mathcal{L}_{\rm eff} = 2\sqrt{2}G_F V_{cb} \sum_{l=e,\mu,\tau} [(\delta_{l\tau} + C^l_{V_1})\mathcal{O}^l_{V_1} + C^l_{V_2}\mathcal{O}^l_{V_2} + C^l_{S_1}\mathcal{O}^l_{S_1} + C^l_{S_2}\mathcal{O}^l_{S_2} + C^l_T\mathcal{O}^l_T]$$

← SM

$\mathcal{O}^l_{V_1} = \bar{c}_L\gamma^\mu b_L\,\bar{\tau}_L\gamma_\mu\nu_{Ll}$,	V−A	SM-like
$\mathcal{O}^l_{V_2} = \bar{c}_R\gamma^\mu b_R\,\bar{\tau}_L\gamma_\mu\nu_{Ll}$,	V+A	RH current
$\mathcal{O}^l_{S_1} = \bar{c}_L b_R\,\bar{\tau}_R\nu_{Ll}$,	S+P	charged Higgs (II)
$\mathcal{O}^l_{S_2} = \bar{c}_R b_L\,\bar{\tau}_R\nu_{Ll}$,	S−P	charged Higgs
$\mathcal{O}^l_T = \bar{c}_R\sigma^{\mu\nu}b_L\,\bar{\tau}_R\sigma_{\mu\nu}\nu_{Ll}$	Tensor	GUT?

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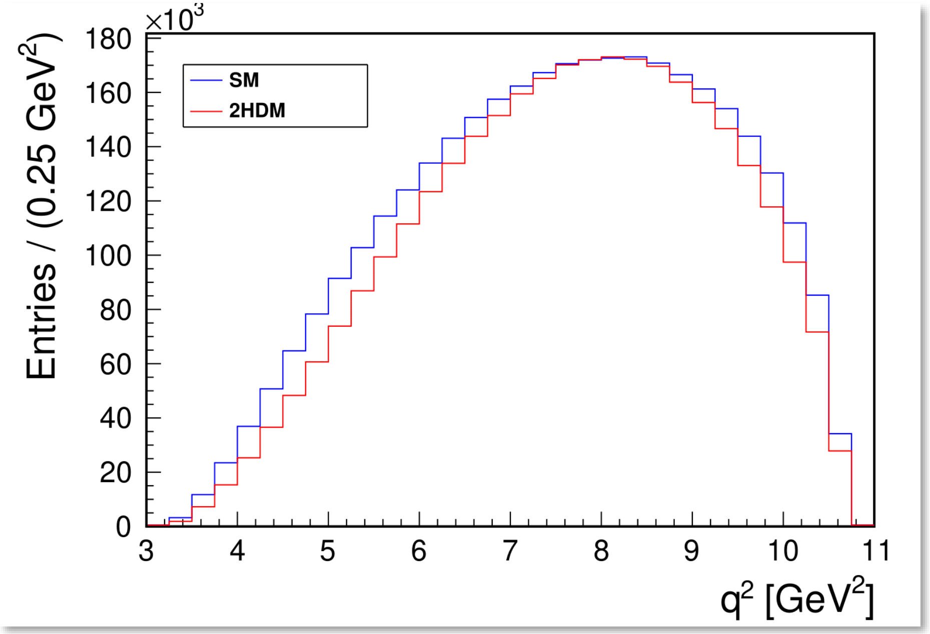
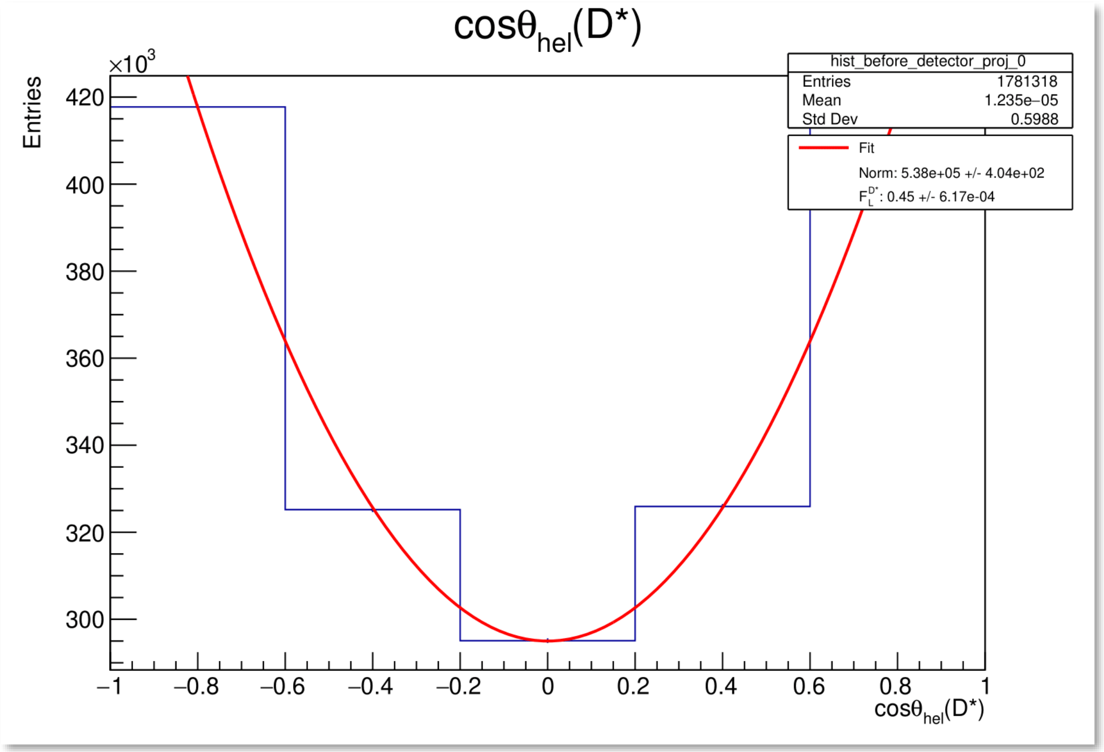
Generated samples:

- Standard Model: $C_i = 0$
- 2HDM: C_{S1}=-3.7

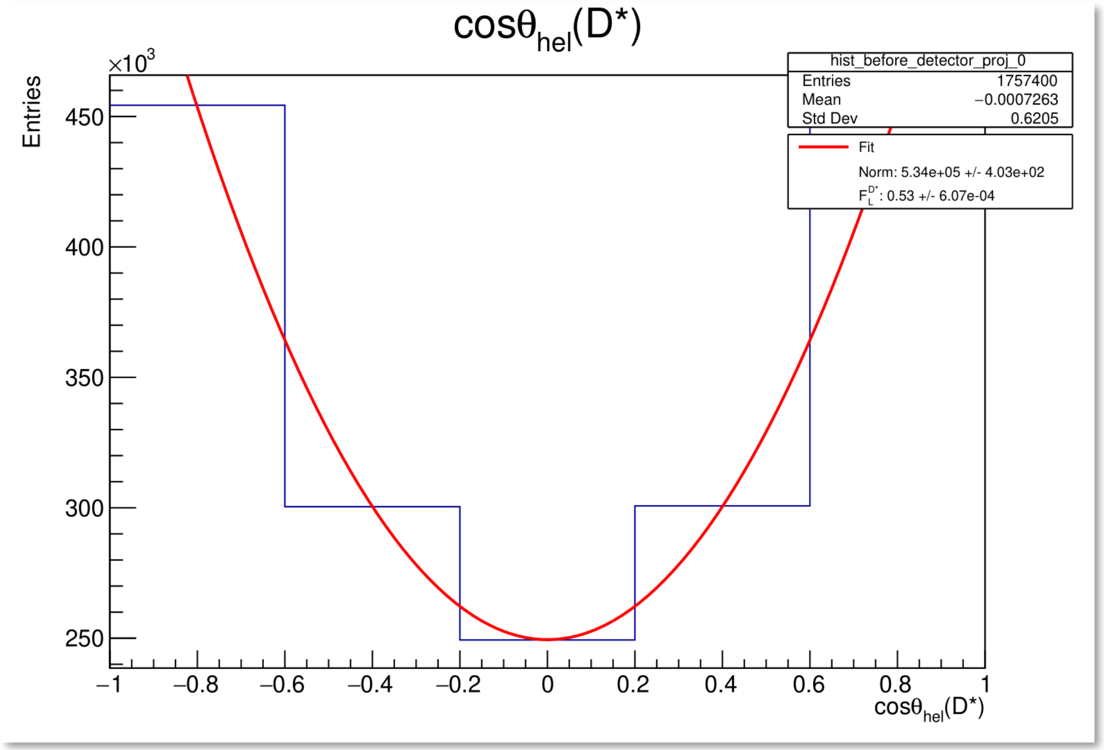


Calculations from: [M. Tanaka, R. Watanabe. Phys. Rev. D 87, 034028]

$\cos\theta_{hel}(D*)$ (SM)



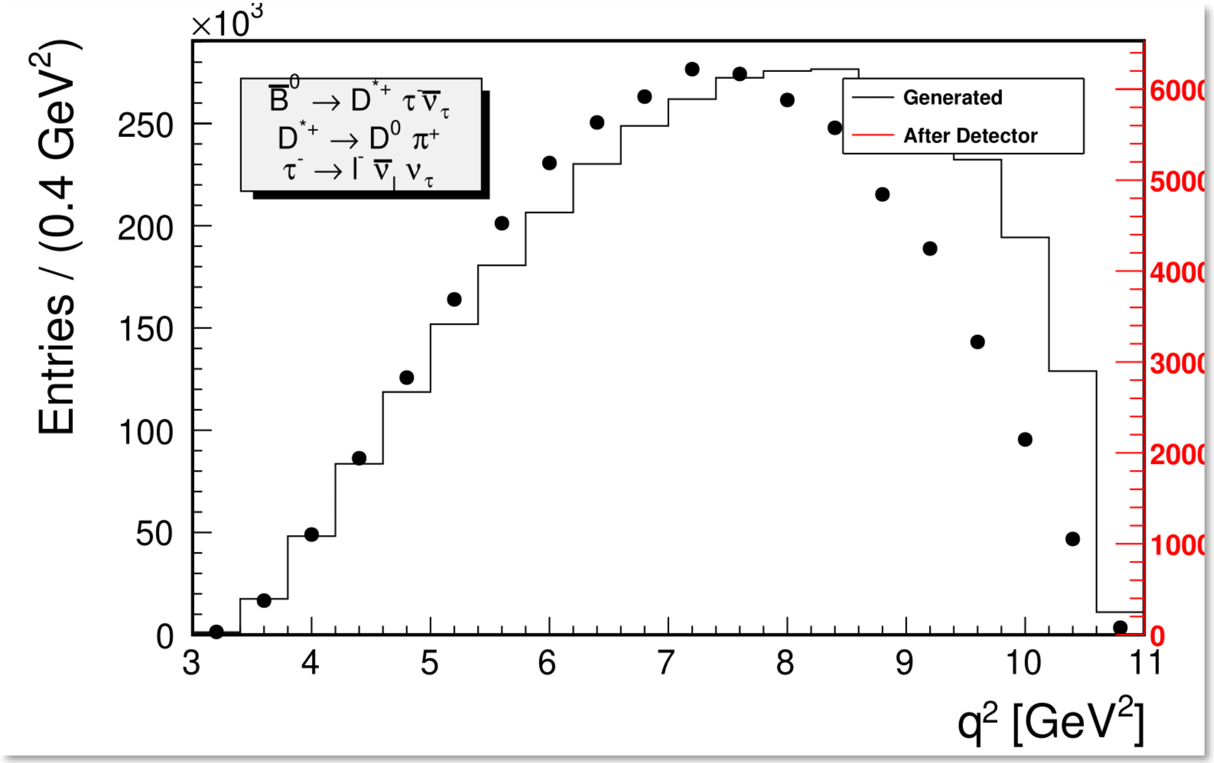
$\cos\theta_{hel}(D*)$ (2HDM)

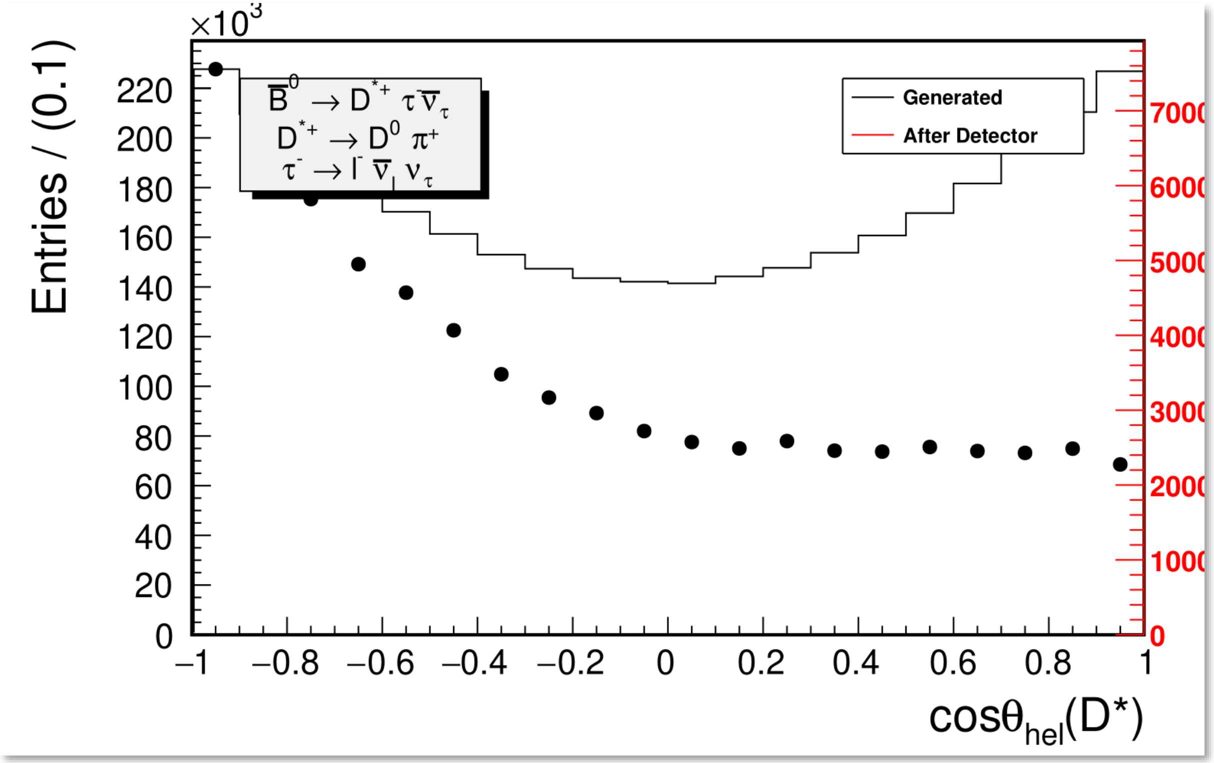


Generated $\cos\theta_{hel}(D^*)$ distributions for two models: SM and 2HDM:

- $F_L(D^*)_{SM} = 0.45$
- $F_L(D^*)_{2HDM} = 0.53$

IV Results: acceptance effects





Generated (solid line) vs. reconstructed (points) q2 and $\cos\theta_{hel}(D^*)$ distributions for Belle geometry, assuming Standard Model decay dynamics.

Decay channel:

$B^0 \rightarrow D^{*+}\tau^-\nu_\tau$

$D^{*+} \rightarrow D^0\pi^+$

$\tau^- \rightarrow \ell^-\nu_\ell\nu_\tau$

IV Results: efficiency map

Pick four variables that characterize the decay and can be reconstructed experimentally. Construct 4D histograms (generated and reconstructed) in these variables:

- $\cos\theta_{hel}(D^*)$ – cosine helicity angle D*
- q^2 – four-momentum transfer squared
- Ed - normalized τ daughter energy
- $\cos\theta_d$ – τ daughter polar angle

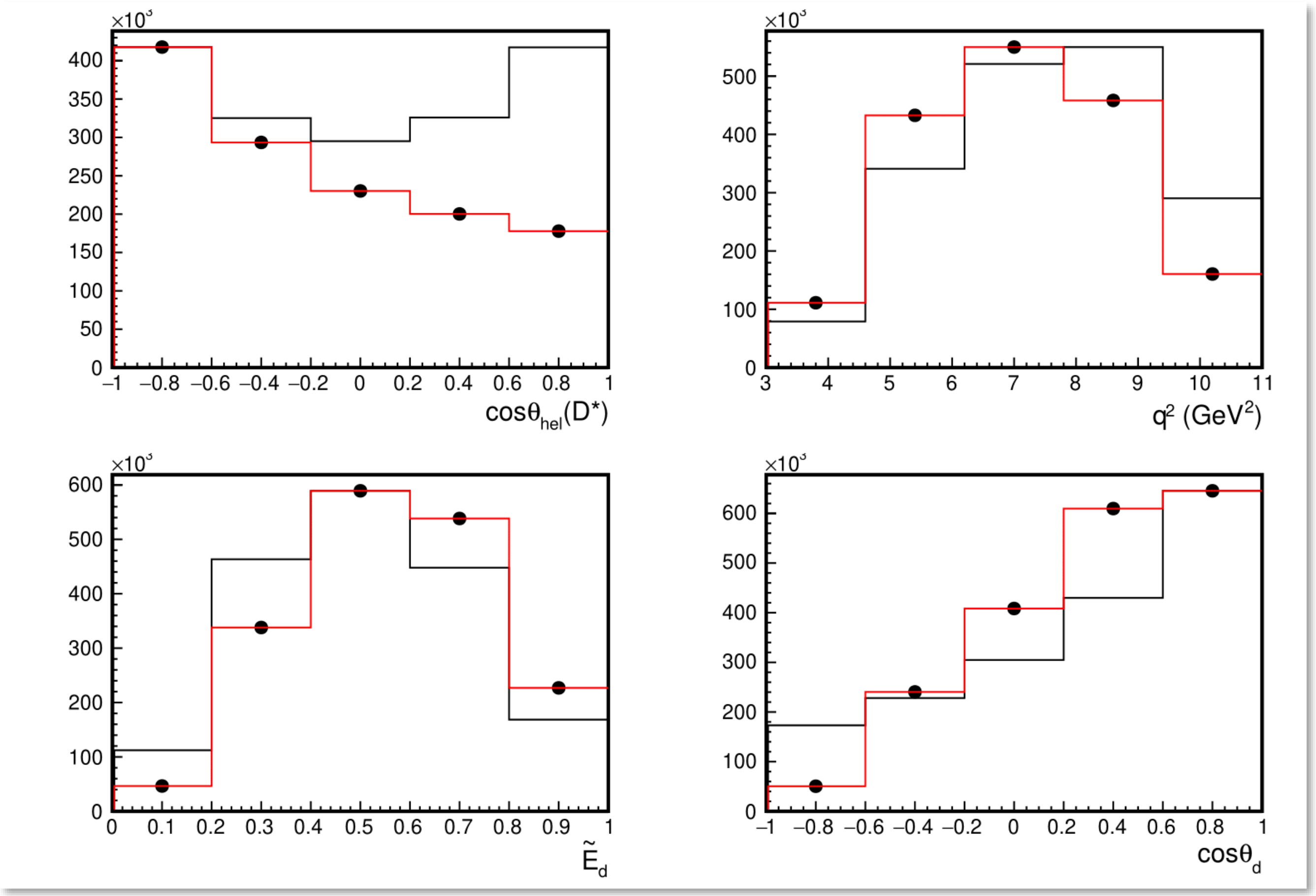


Fig. 1D projections of 4D histograms: generated (black) and reconstructed (red)

Create a 4D efficiency map by dividing reconstructed histograms by generated ones:

$$w_{ijkl} = \frac{N^{rec}_{ijkl}}{N^{gen}_{ijkl}} \frac{N^{gen}_{total}}{N^{rec}_{total}}$$

- N_{ijkl} – numer of events per bin
- N_{tot} – total numer of events

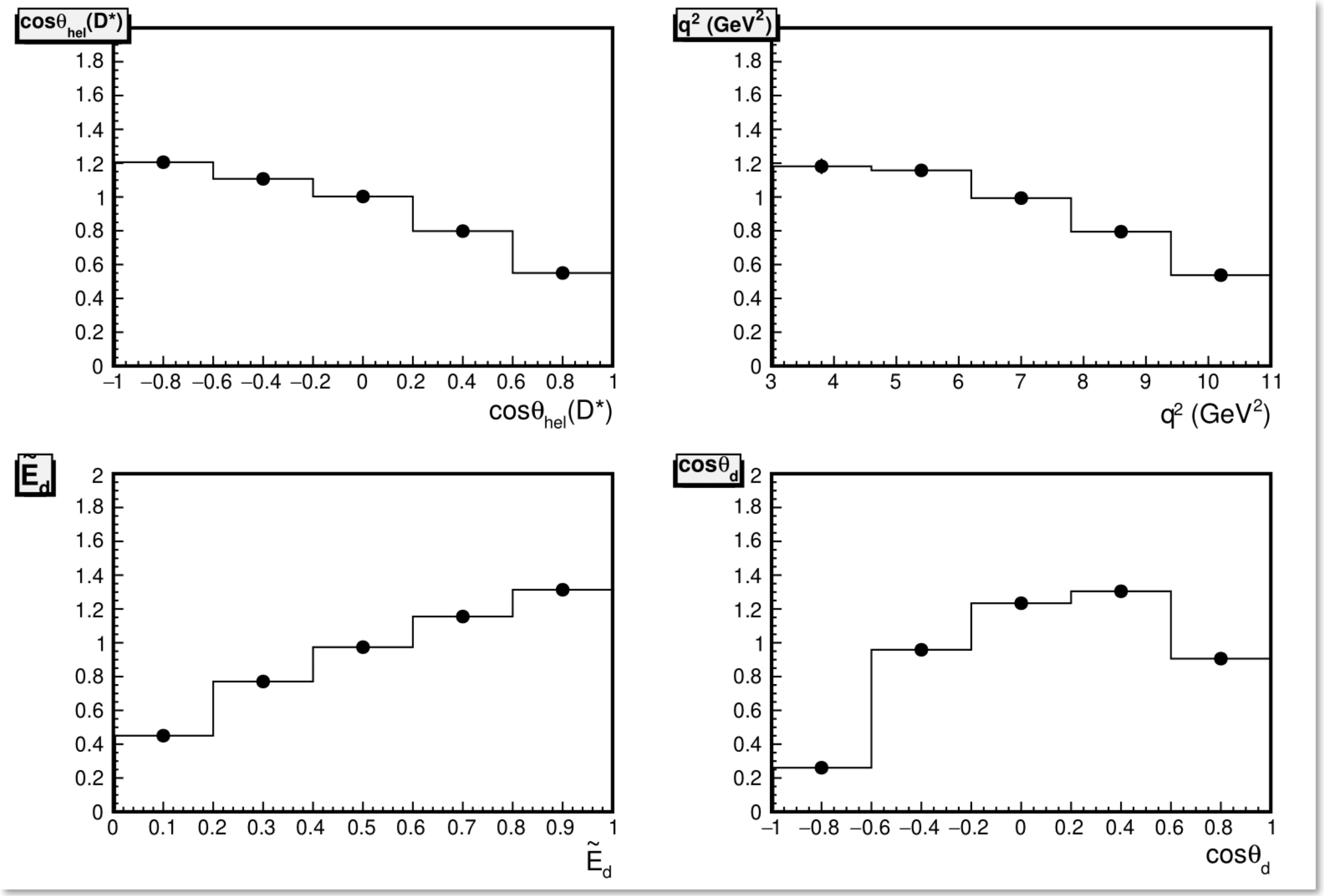


Fig. 1D projections of 4D efficiency map

Reweight reconstructed distributions using w_{ijkl} to recover generated observables

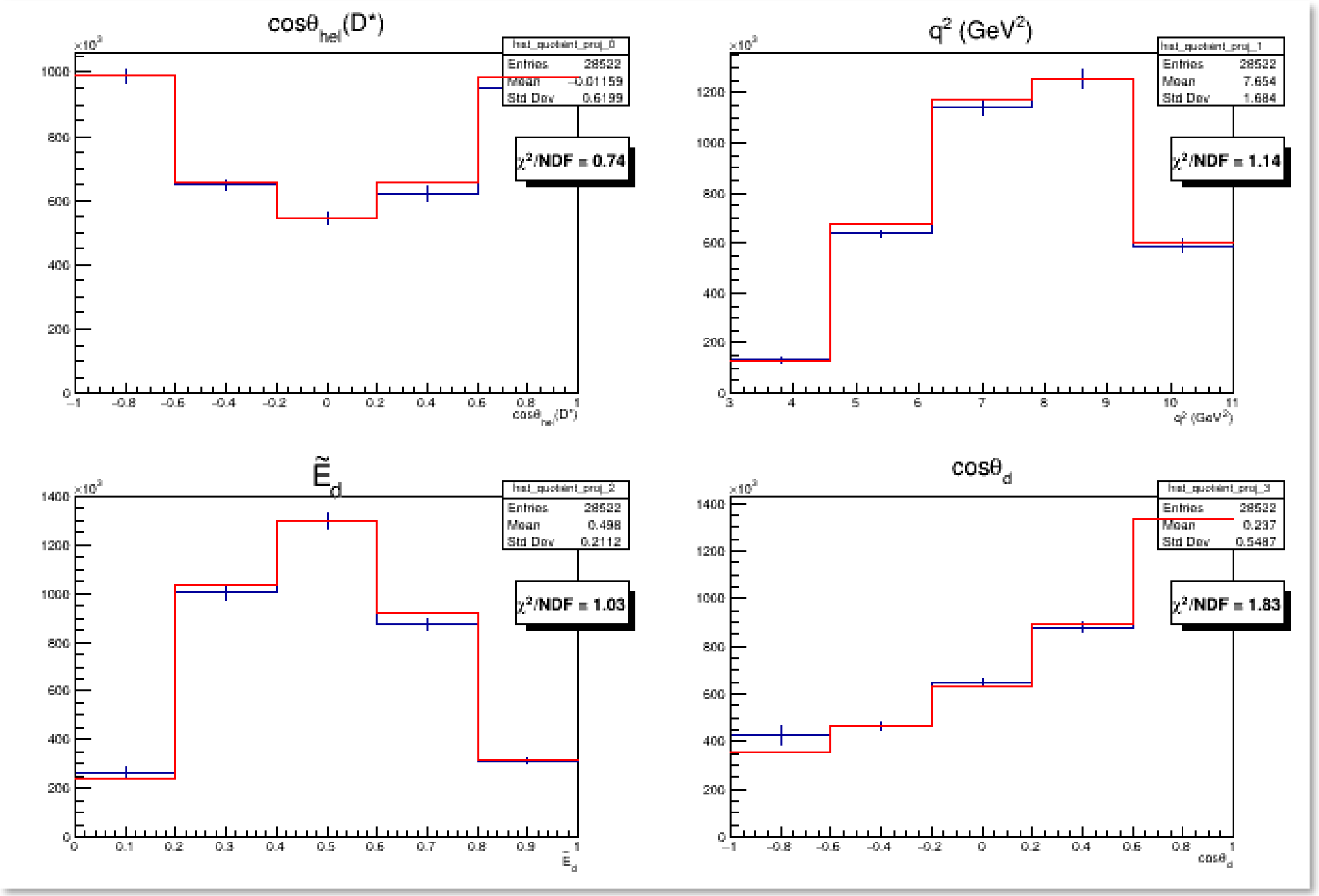


Fig. Generated (red) and reconstructed + reweghted distributions (blue). Plots made on independent sample generated with non-SM decay dynamics (2HDM)

So far detector resolution not considered in the analysis (true Monte-Carlo kinematics used for reconstructed events)

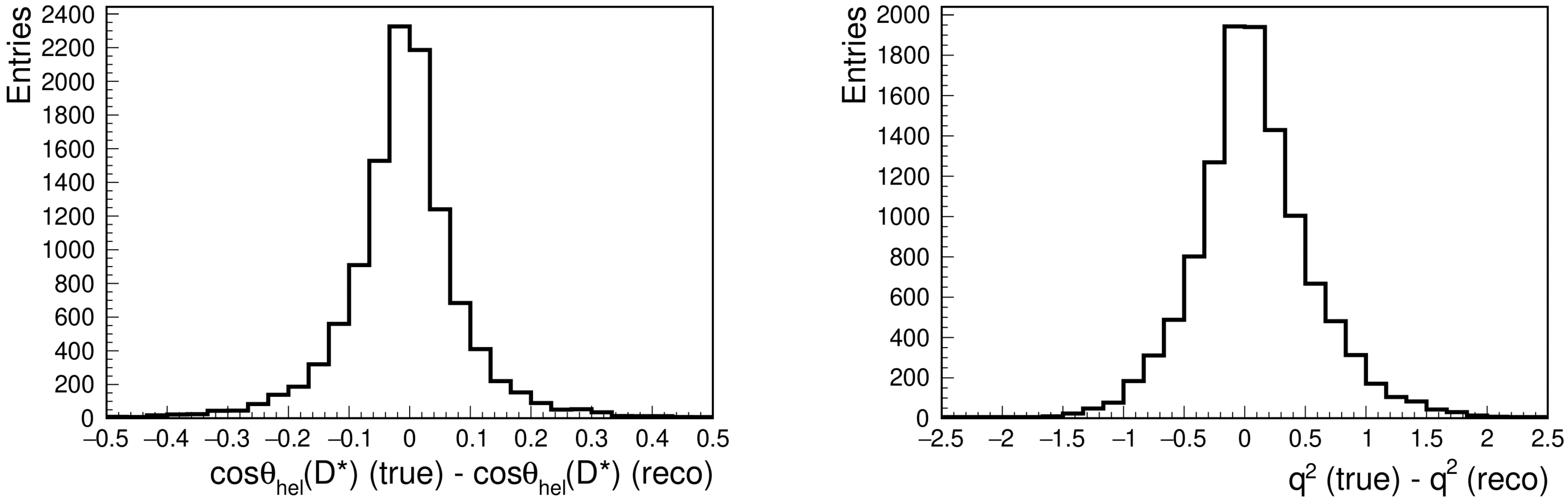


Fig. Distributions (true - reconstructed) of q^2 and $\cos\theta_{hel}(D^*)$. Plot generated for Belle geometry, with Standard Model decay dynamics. Mtag > 5.27GeV.

V Summary

- Semitauonic B-meson decays are rich in observables experimentally accessible at B Factories
- Combined analysis of observables such as R(D*), F_L^{D*} can increase our understanding about the dynamics of the decay
- Using data from Belle and the ongoing Belle II experiment we can improve the sensitivity of previous measurements