Current trends in flavour physics

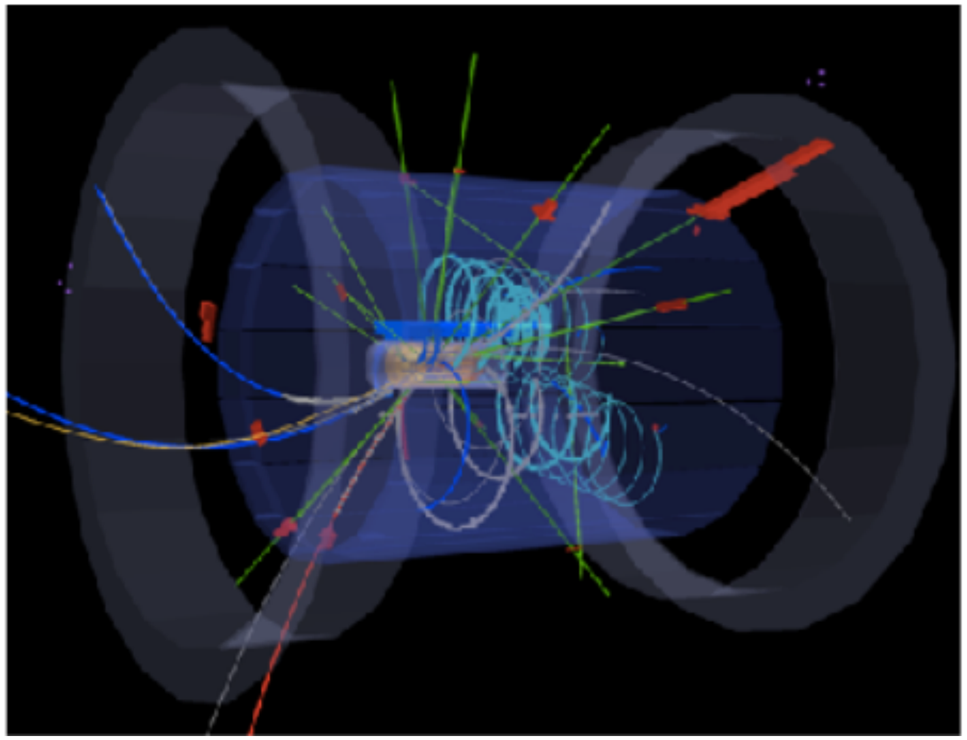
Status and perspective of measuring the leptonic and semileptonic decays at Belle and Belle II

Anže Zupanc
Jožef Stefan Institute and
Faculty of Mathematics and Physics, University of Ljubljana

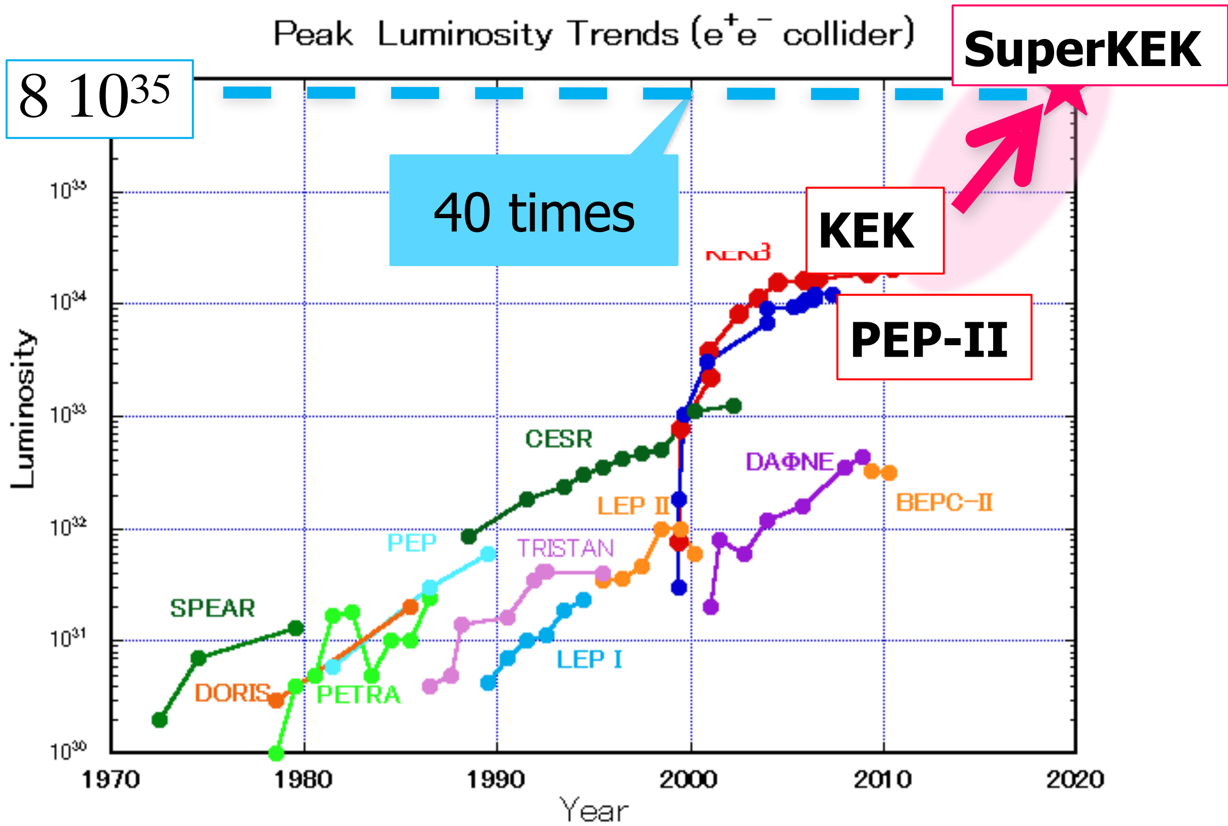
Outline

- *Belle and Belle II*
  - Experimental techniques for studies of modes with missing energy
- *Leptonic decays*
  - $B \to \tau\nu$, $B \to \mu\nu$
- *Charmless semileptonic decays*
  - Exclusive $B \to \pi l\nu$ and $B_s \to Kl\nu$
- *Semitauonic decays*
  - $B \to D^{(\star)}\tau\nu$
  - Measurements of rates ($R(D)$, $R(D^\star)$), τ and $D^\star$ polarisation ($P(\tau)$, $P(D^\star)$), lepton momentum spectrum, q^2 spectrum

Belle II at SuperKEKB

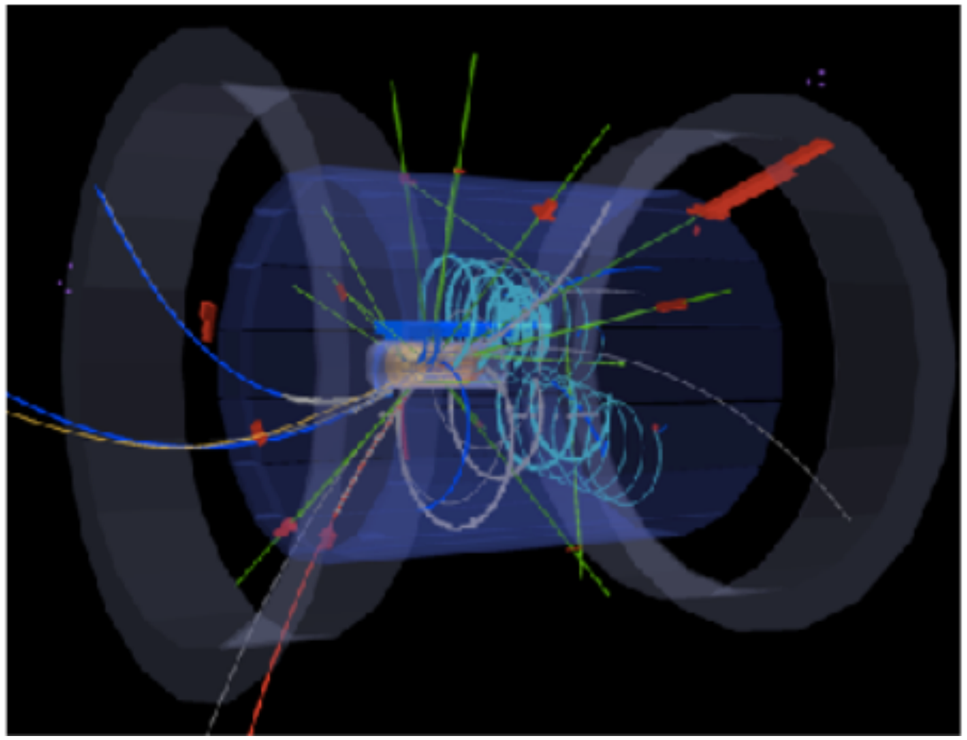


- *Belle at KEKB*
  - accumulated $1ab^{-1}$ at or near Y(4S)
- *Belle II at SuperKEKB*
  - *40-fold increase in luminosity over KEKB*
  - *collect 50 ab^{-1} by 2025*
  - *All sub-detectors are upgraded except for the ECL crystals and part of the barrel KLM*
  - *expect similar or better performance compared to that achieved at Belle despite much higher background levels*

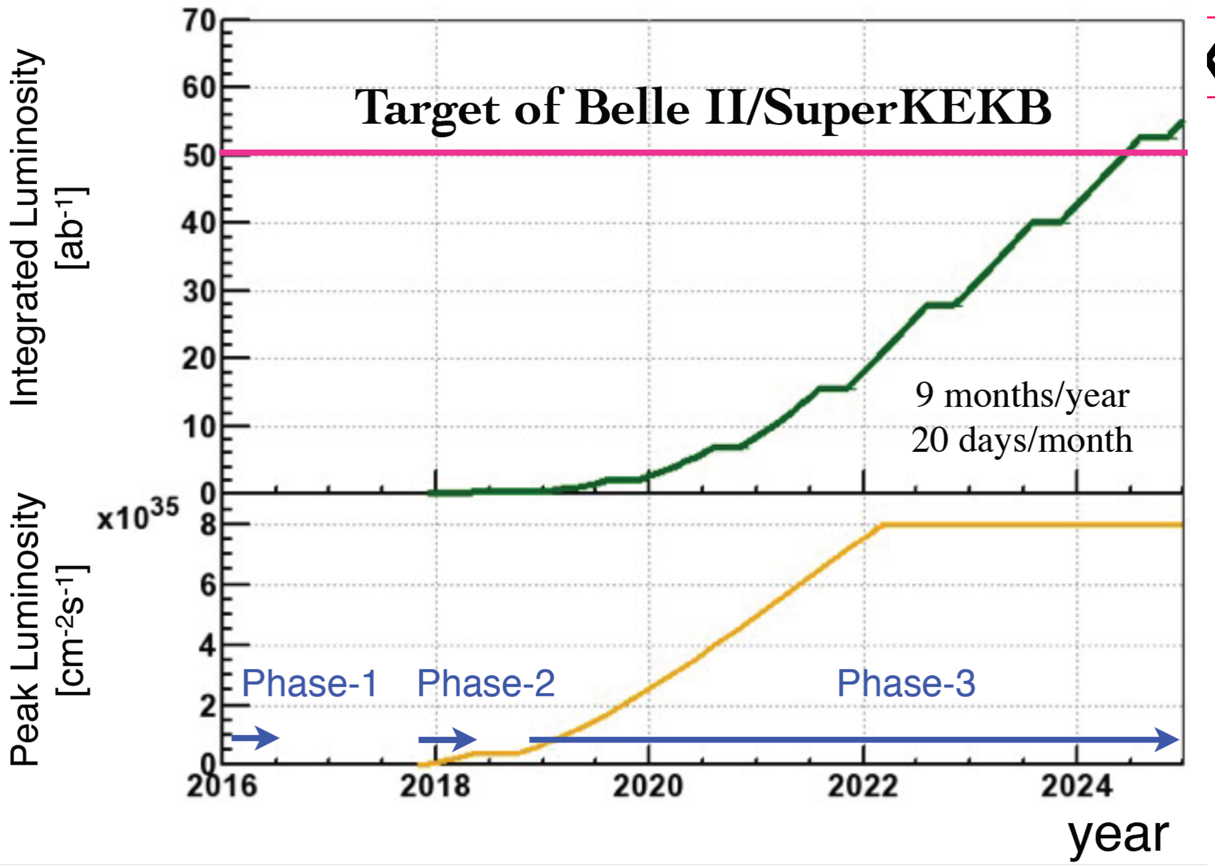


Belle II at SuperKEKB

- *Belle at KEKB*
  - accumulated 1ab^{-1} at or near Y(4S)
- *Belle II at SuperKEKB*
  - *40-fold increase in luminosity over KEKB*
  - *collect 50 ab^{-1} by 2025*
  - *All sub-detectors are upgraded except for the ECL crystals and part of the barrel KLM*
  - *expect similar or better performance compared to that achieved at Belle despite much higher background levels*



SuperKEKB luminosity projection



Measurement techniques

B-factories

- multiple neutrinos prevent to fully measure/determine the decay’s kinematics from the decay products alone
- exploit unique experimental setup
  - detector hermetically encloses the interaction point
  - knowledge of initial state and known production process

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B_{\text{comp}}\overline{B}_{\text{sig}}$$

The companion *B* meson reconstruction

- **Hadronic**: *sum of exclusive hadronic decays*

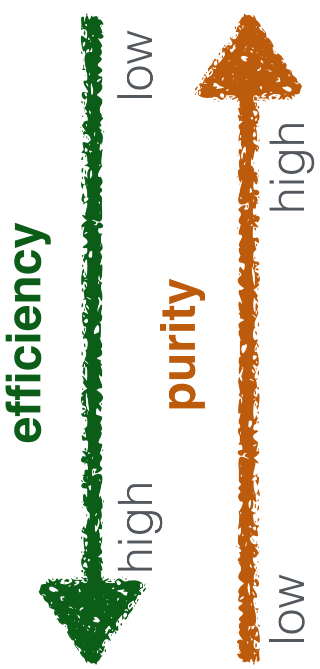
$$B \rightarrow \overline{D}^{(*)} n\pi,\ \overline{D}^{(*)} D^{(*)} K,\ \overline{D}_s^{(*)} D^{(*)},\ J/\psi K n\pi$$

- **Semi-leptonic**: *sum of exclusive semi-leptonic decays*

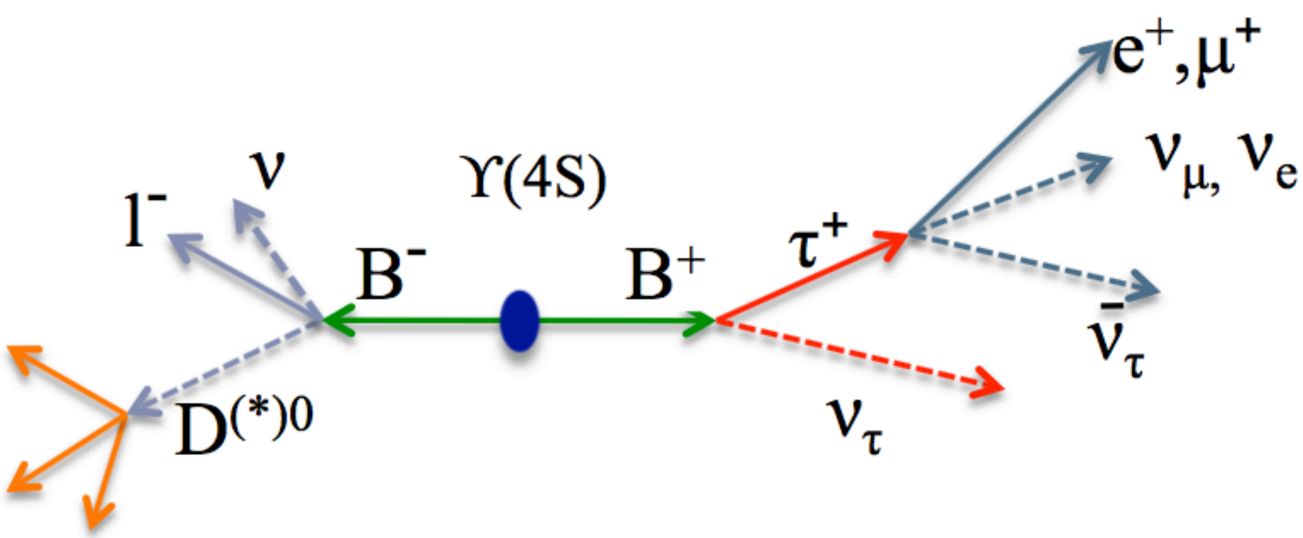
$$B \rightarrow \overline{D}^{(*)} \ell \nu_\ell$$

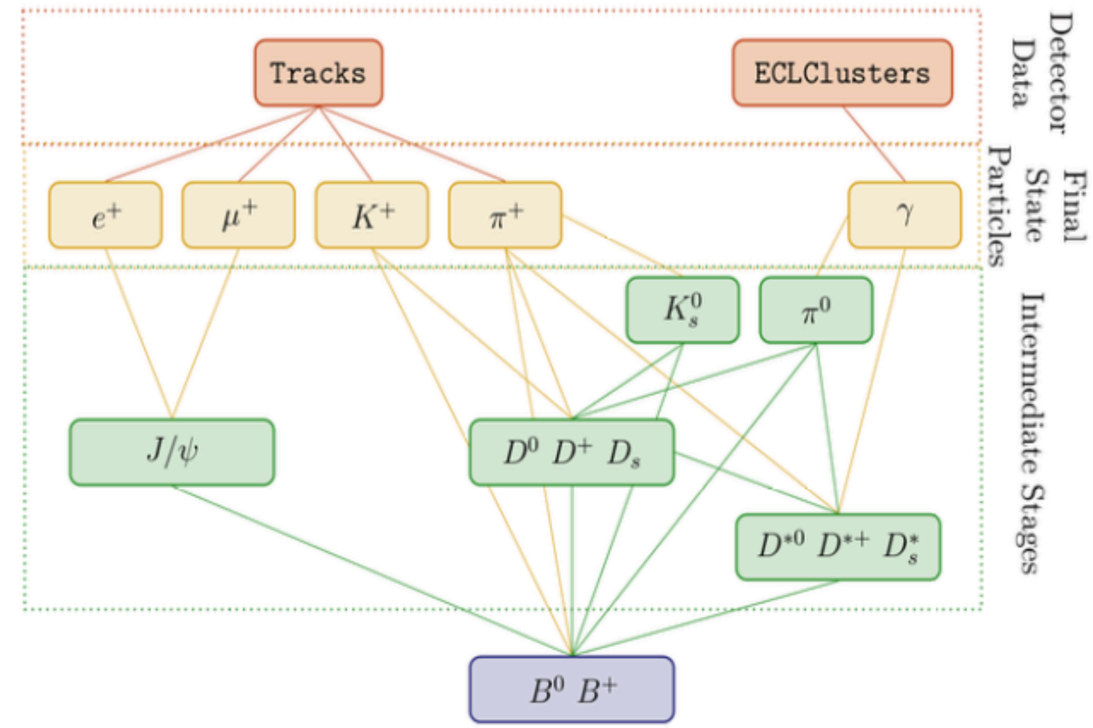
- ***Untagged/Inclusive***: *sum all tracks/clusters in the detector not used for B_{sig} reconstruction*

provides $p(B_{sig})$



Hadronic and Semileptonic B_{comp} reconstruction at Belle II



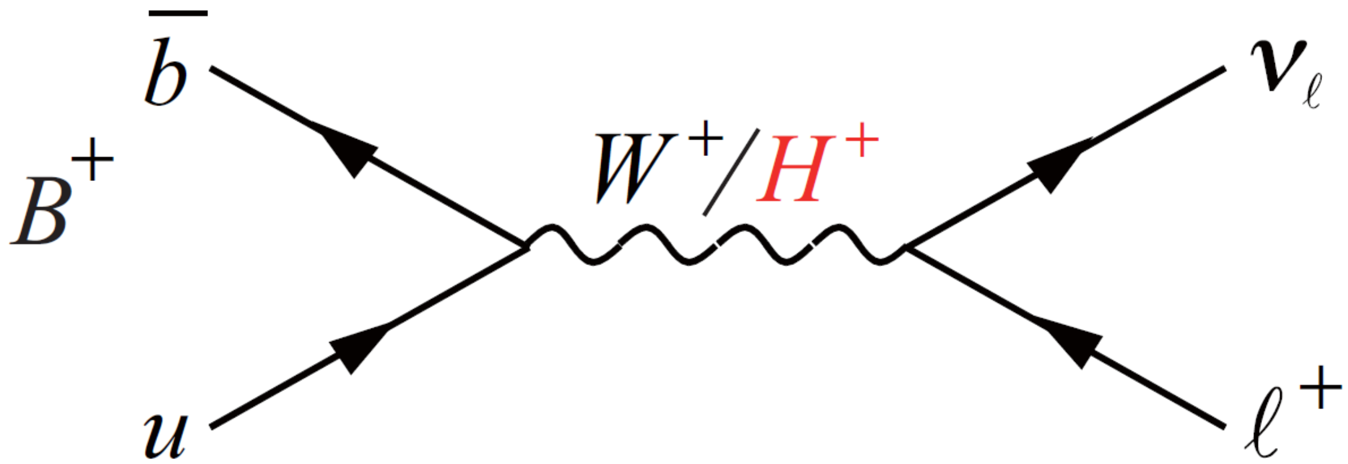


- Input variables used to train the multivariate classifiers:
  - PID, tracks momenta, impact parameters (charged FS particles);
  - cluster info, energy and direction (photons);
  - invariant mass, angle between photons, energy and direction (π^0);
  - released energy, invariant mass, daughter momenta and vertex quality ($D^{(*)}_{(s)}$, J/ψ);
  - the same as previous step plus vertex position, ΔE (B);
  - additionally, for each particle the classifier output of the daughters are also used as discriminating variables.

Improvement close to factor of 2 compared to performance of algorithm used at Belle seen in Belle II MC.

Leptonic decays: B → τν

Can be mediated by NP, for example charged Higgs (2HDM):

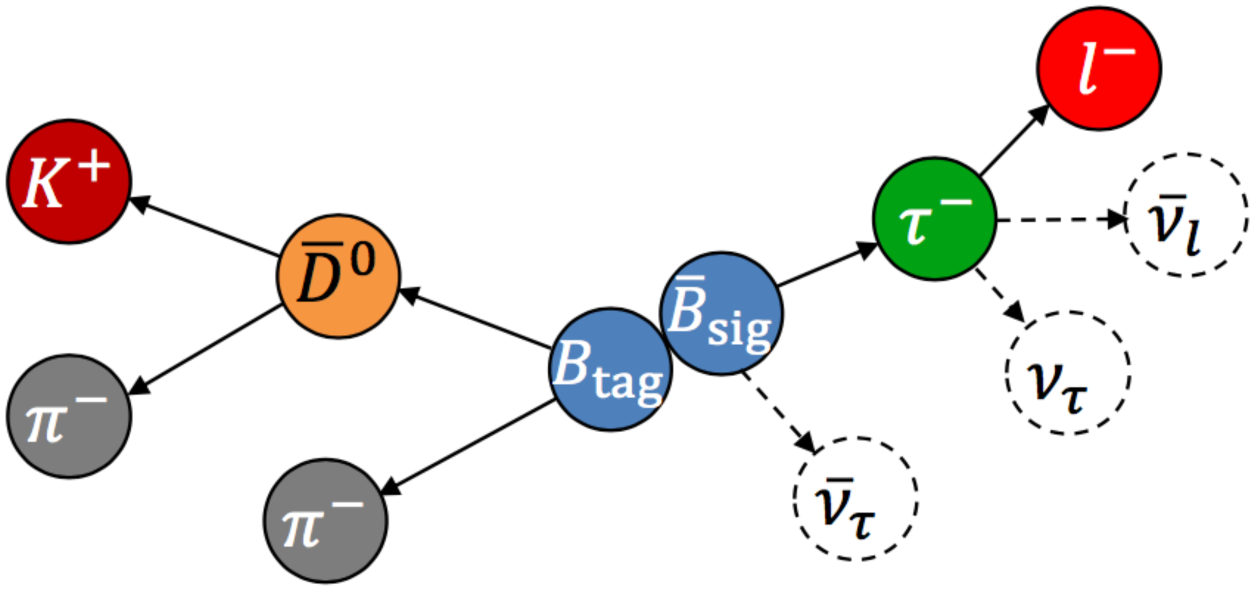


- any new physics contribution will modify the decay rate by some factor

$$\mathcal{B}(B \to \tau\nu) = \underbrace{\overbrace{\frac{G_F^2}{8\pi}\tau_B f_B^2 |V_{ub}|^2 m_B^3 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \left(\frac{m_\tau}{m_B}\right)^2}^{SM}}_{\equiv \mathcal{B}^{SM}} \times \underbrace{\overbrace{\left(1 - m_B^2 \frac{\tan^2\beta}{m_{H^\pm}^2}\right)^2}^{2HDM(TypeII)}}_{\equiv r_H}$$

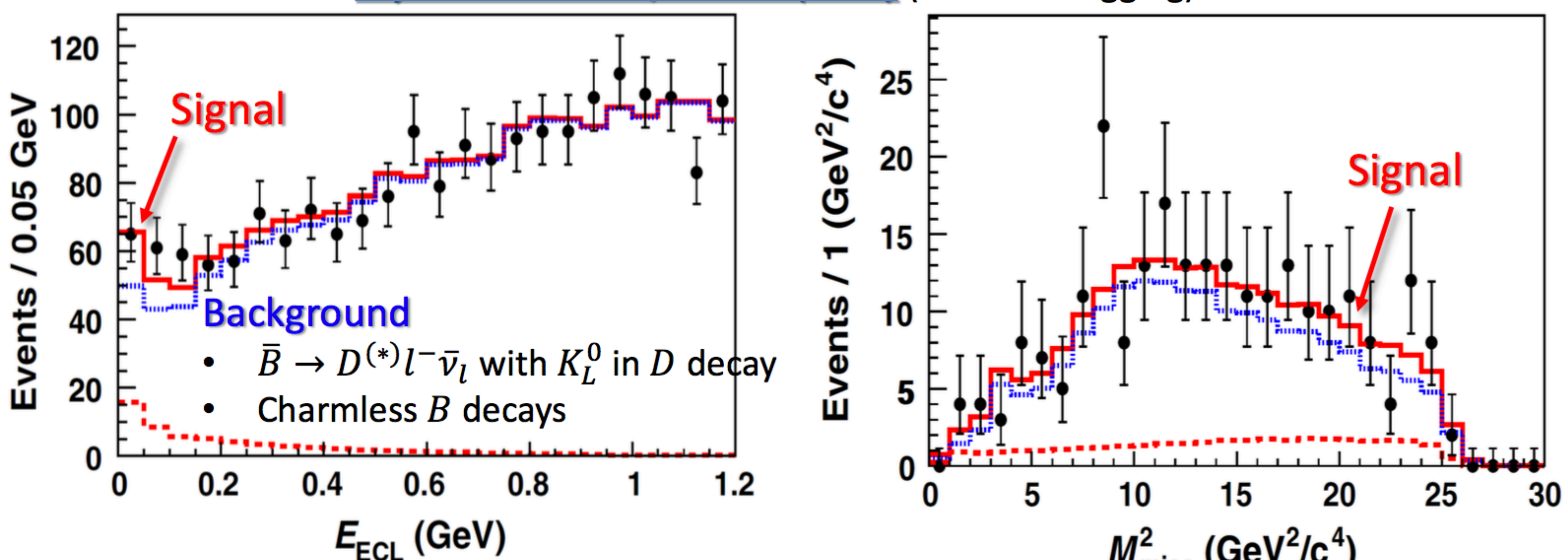
- Belle performed measurement of these decays using hadronic (PRL110, 131801) and semileptonic (PRD92,051102(R)) reconstruction of Btag

Leptonic decays: B → τν



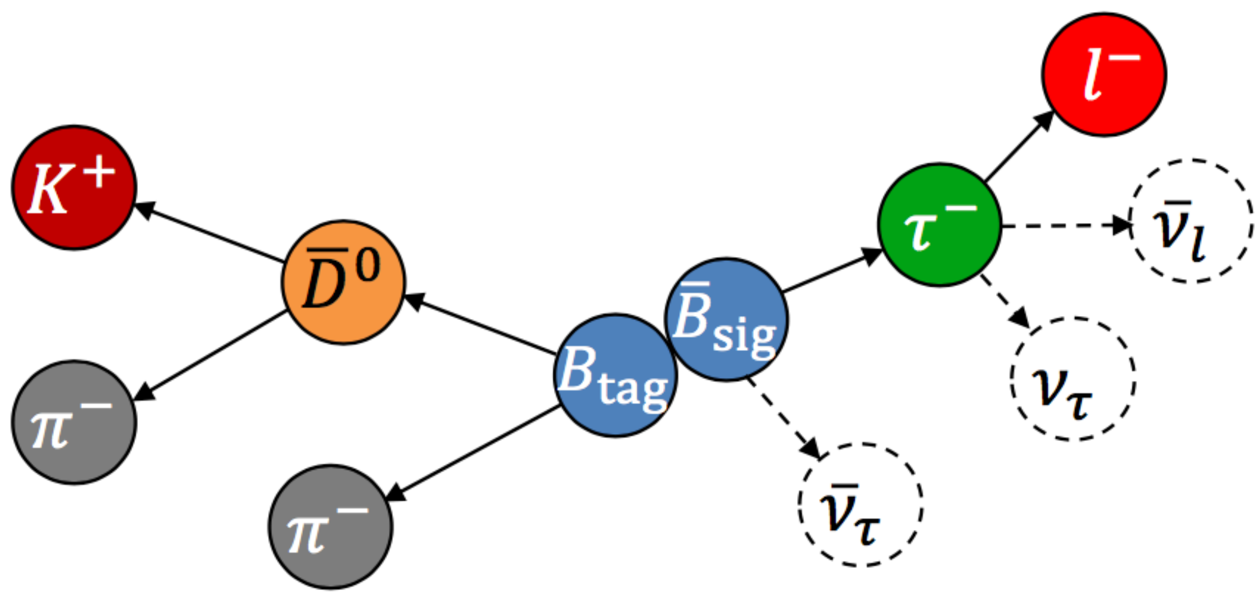
- τ reconstructed in decays to eνν, μνν, πν, and ρν (~70% of all τ decays)
- signal extracted from 2D (E_{ECL}, M_{miss}^2 or p_l) fit

Phys. Rev. Lett. 110, 131801 (2013) (Hadronic tagging)

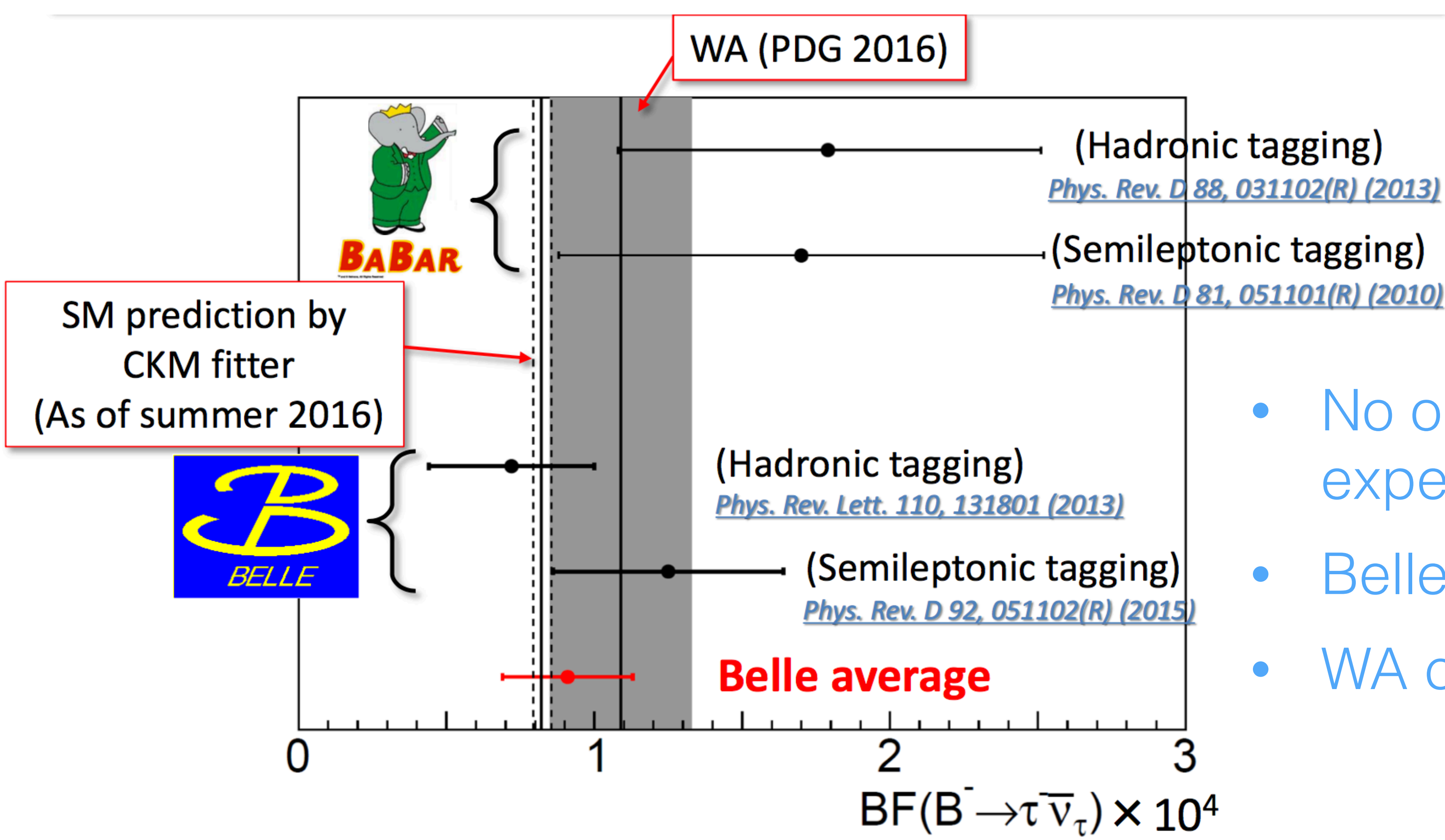


In the SL tagging analysis, p_l is used instead

Leptonic decays: B → τν



- τ reconstructed in decays to eνν, μνν, πν, and ρν (~70% of all τ decays)
- signal extracted from 2D (E_{ECL}, M_{miss}^2 or p_l) fit



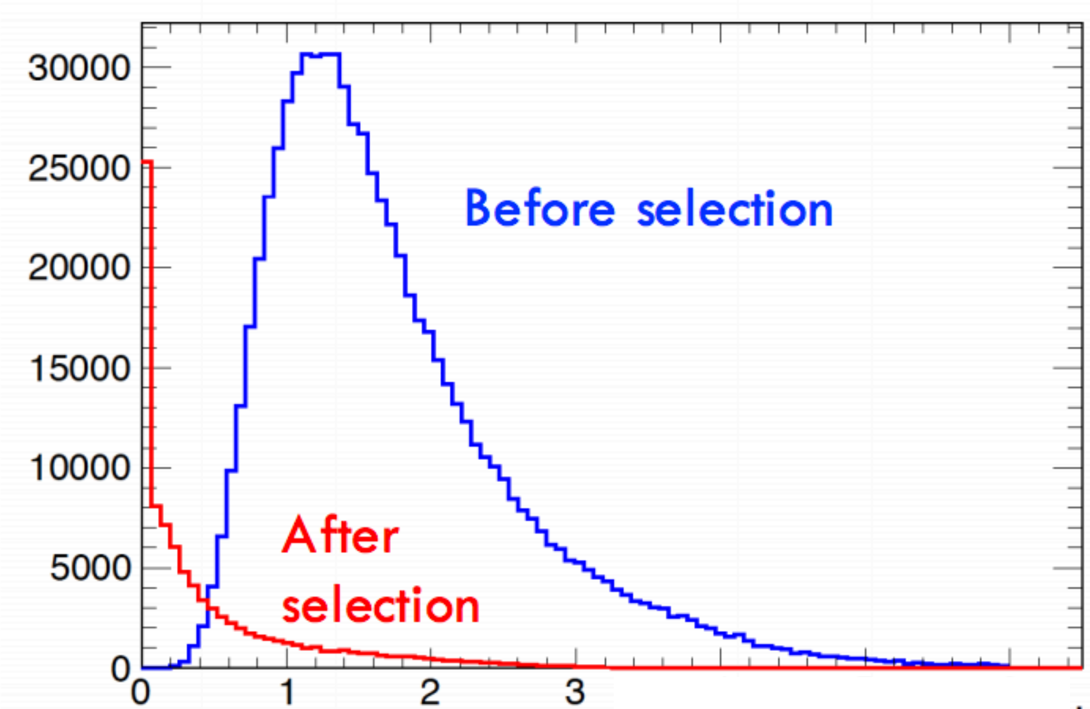
- No observation yet at single experiment
- Belle average has 4.0σ significance
- WA consistent with SM

Leptonic decays: $B \to \tau\nu$ Sensitivity study at Belle II

Benchmark mode to test of detector performance:

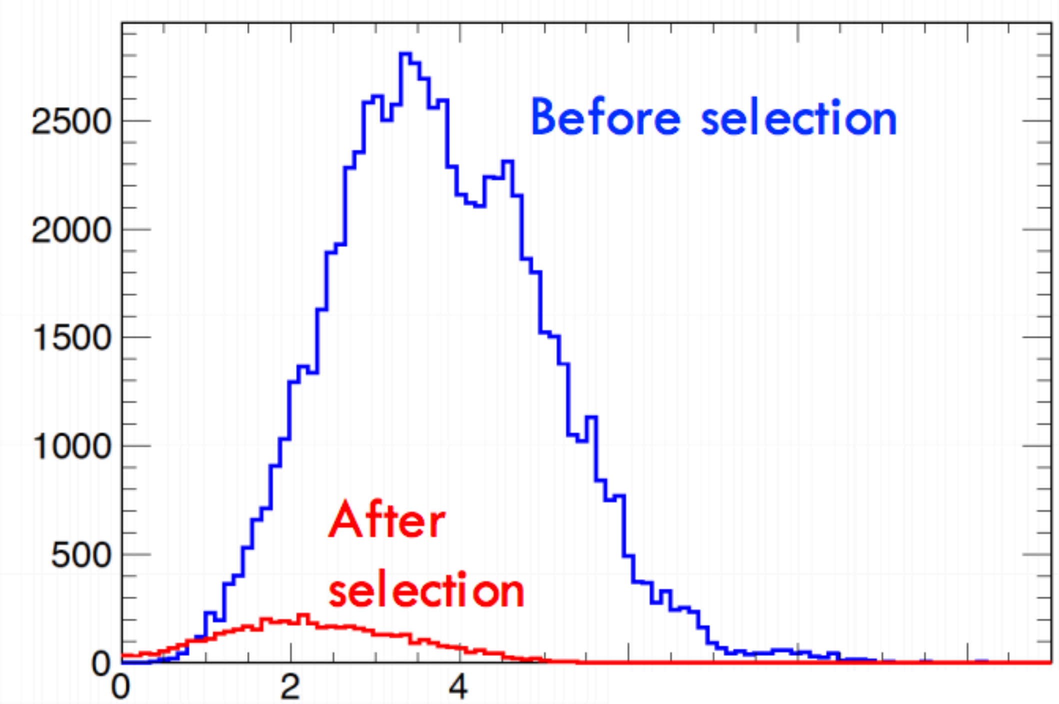
1. Btag reconstruction efficiency
2. Extra energy in the calorimeter resolution
   - Beam background energy deposits in ECL much higher in Belle II compared to Belle, however selection based on cluster's energy, timing, shape effectively rejects them.

signal $B \to \tau\nu$



E_{ECL}

B^+B^- bkg

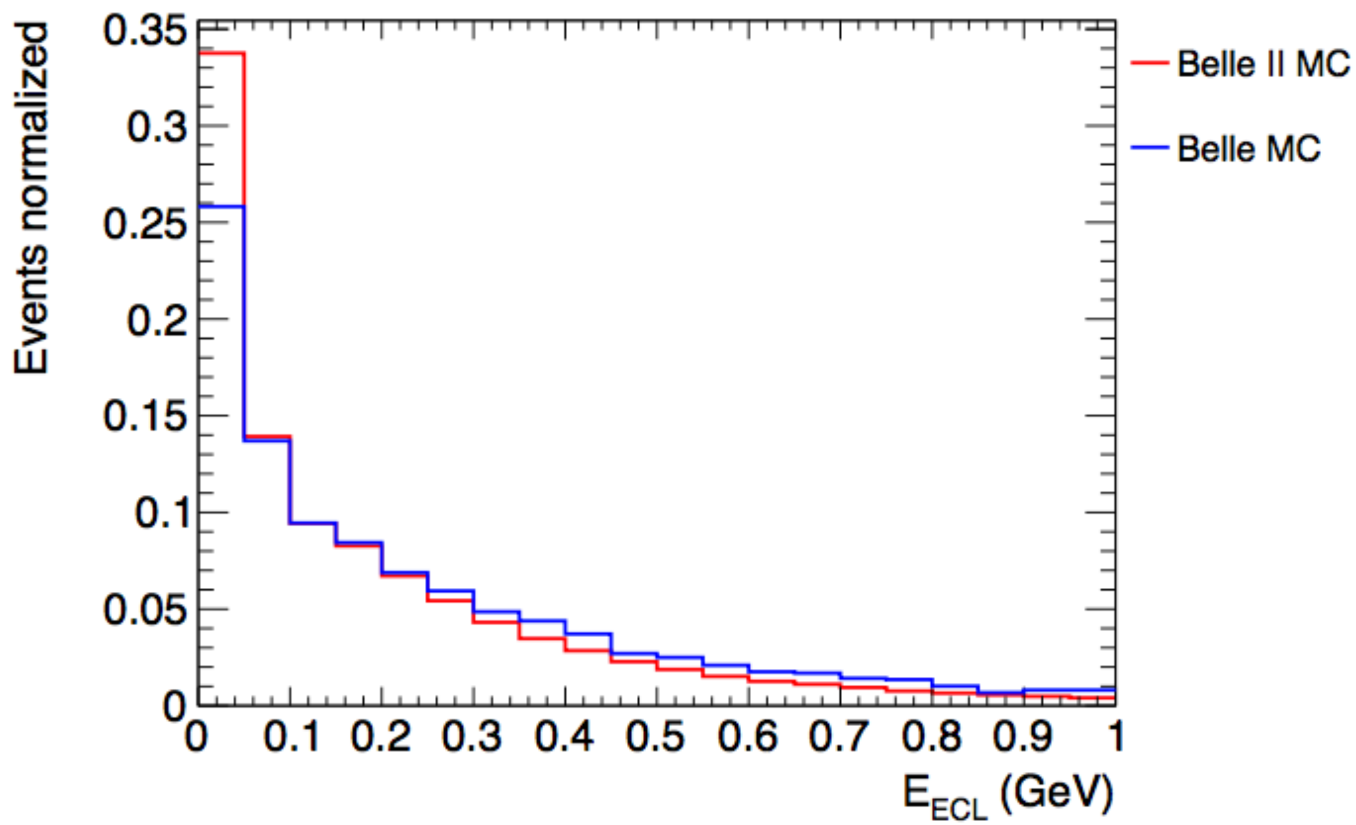


E_{ECL}

Leptonic decays: $B \to \tau\nu$ Sensitivity study at Belle II

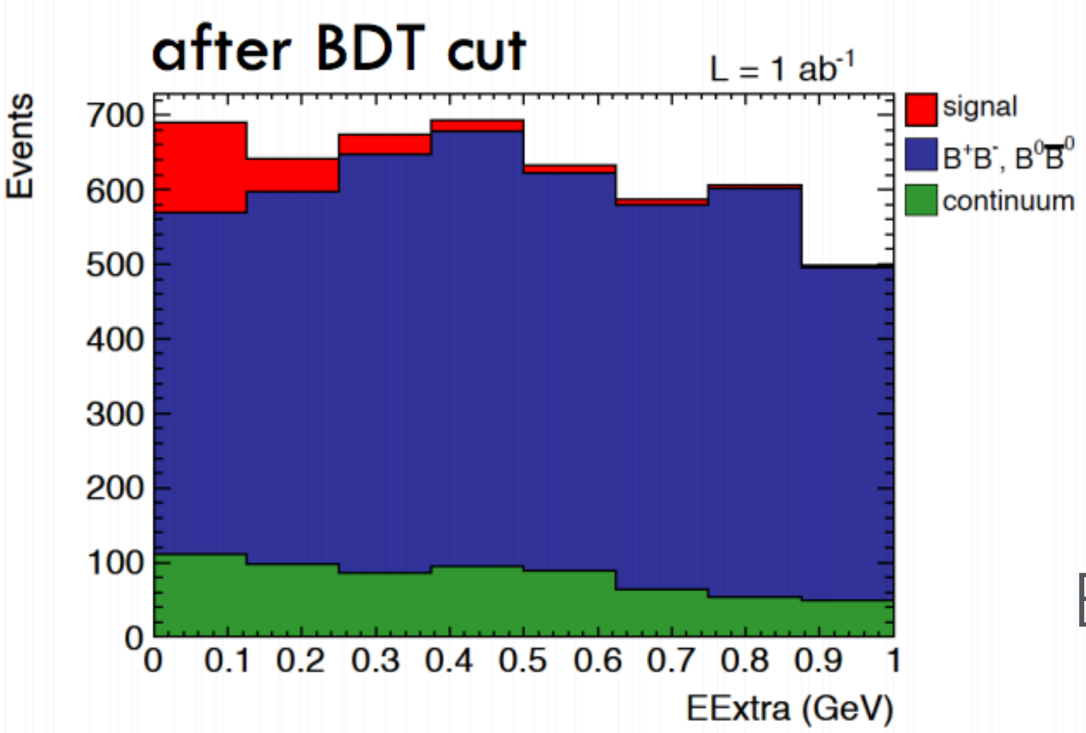
Benchmark mode to test of detector performance:

1. Btag reconstruction efficiency
2. Extra energy in the calorimeter resolution
   - Beam background energy deposits in ECL much higher in Belle II compared to Belle, however selection based on cluster's energy, timing, shape effectively rejects them.



E_{ECL}

Leptonic decays: B → τν
Belle II prospects



E_{extra} < 1 GeV	Babar PRD 88, 031102 (2013)	Belle PRL 110, 131801 (2013)	Belle II (this study)
Signal Efficiency (‰)	**0.72**	**1.1**	**1.6**

Expected Belle II sensitivity @ 1 ab^{-1}: **~30%**

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (0.83 \pm 0.22) \times 10^{-4}$$

[NB: No KL veto applied in the study; 1D fit only;
Only hadronic reconstruction of the companion B;]

Guess-estimate of systematics

Integrated Luminosity (ab^{-1})	1	5	50
statistical uncertainty (%)	29.2	13.0	4.1
systematic uncertainty (%)	12.6	6.8	4.6
total uncertainty (%)	31.6	14.7	6.2

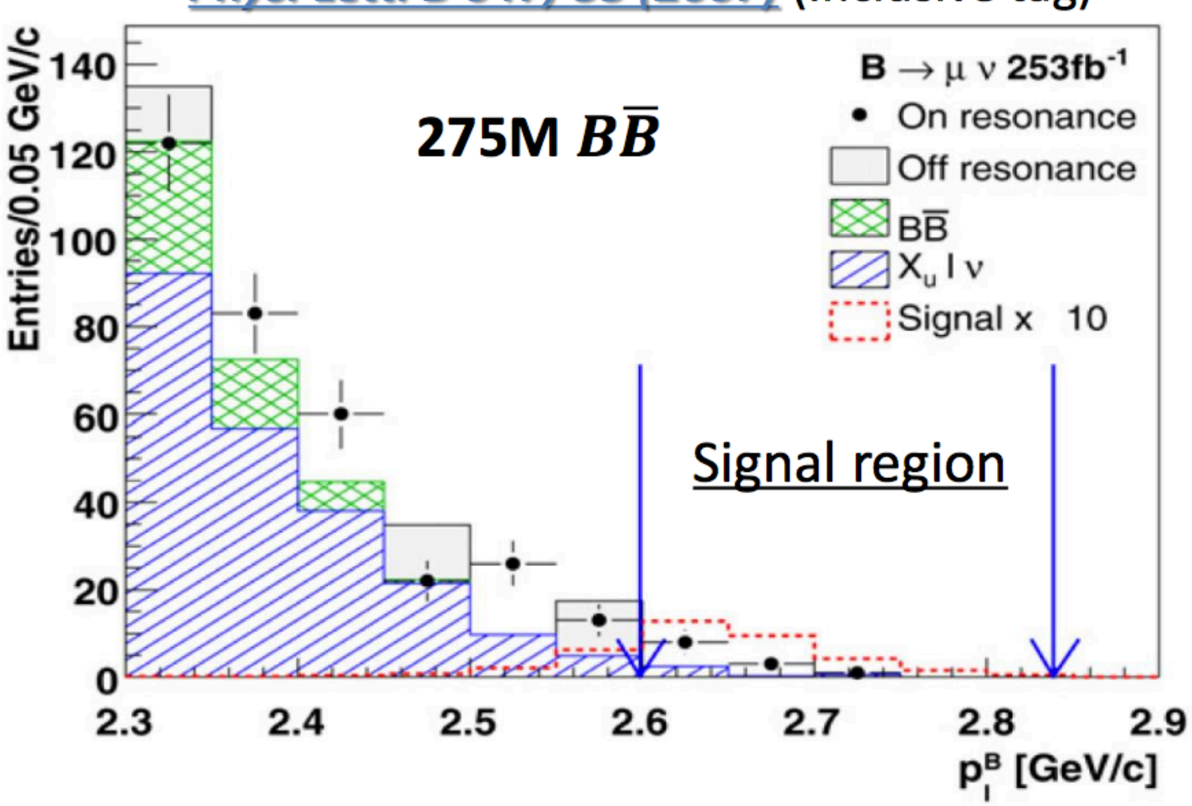
- A lot of sources of systematic scale with luminosity (sig./bkg. PDF), tagging efficiency;
- Peaking backgrounds will have to be measured more precisely

Leptonic decays: B → μν

- 2-body decay ☞ monochromatic muons in B rest frame
  - measurement can be performed without exclusive reconstruction of the companion B meson (higher efficiency)

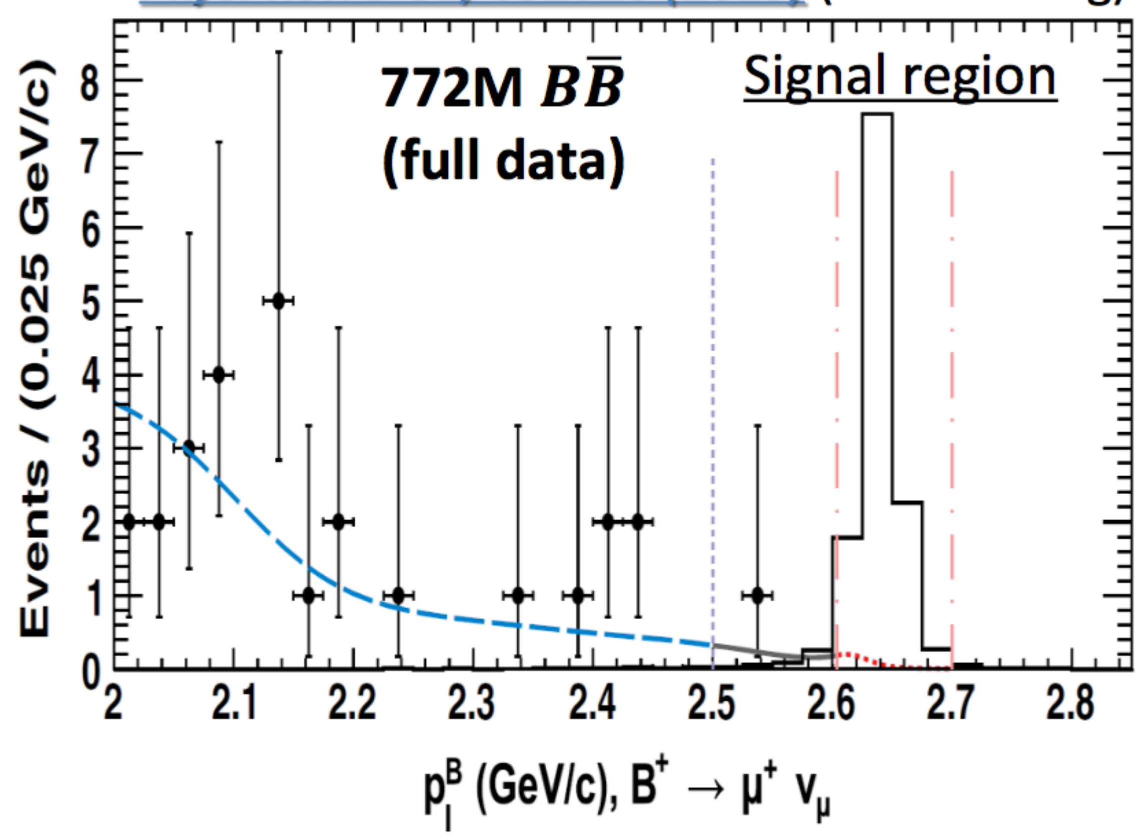
$$\mathcal{B}(B \to \mu\nu)^{\rm SM} = (3.7 \pm 0.5) \times 10^{-7}$$

Phys. Lett. B 647, 88 (2007) (Inclusive tag)



Advantage: better efficiency (~3%)

Phys. Rev. D 91, 052016 (2015) (Hadronic tag)

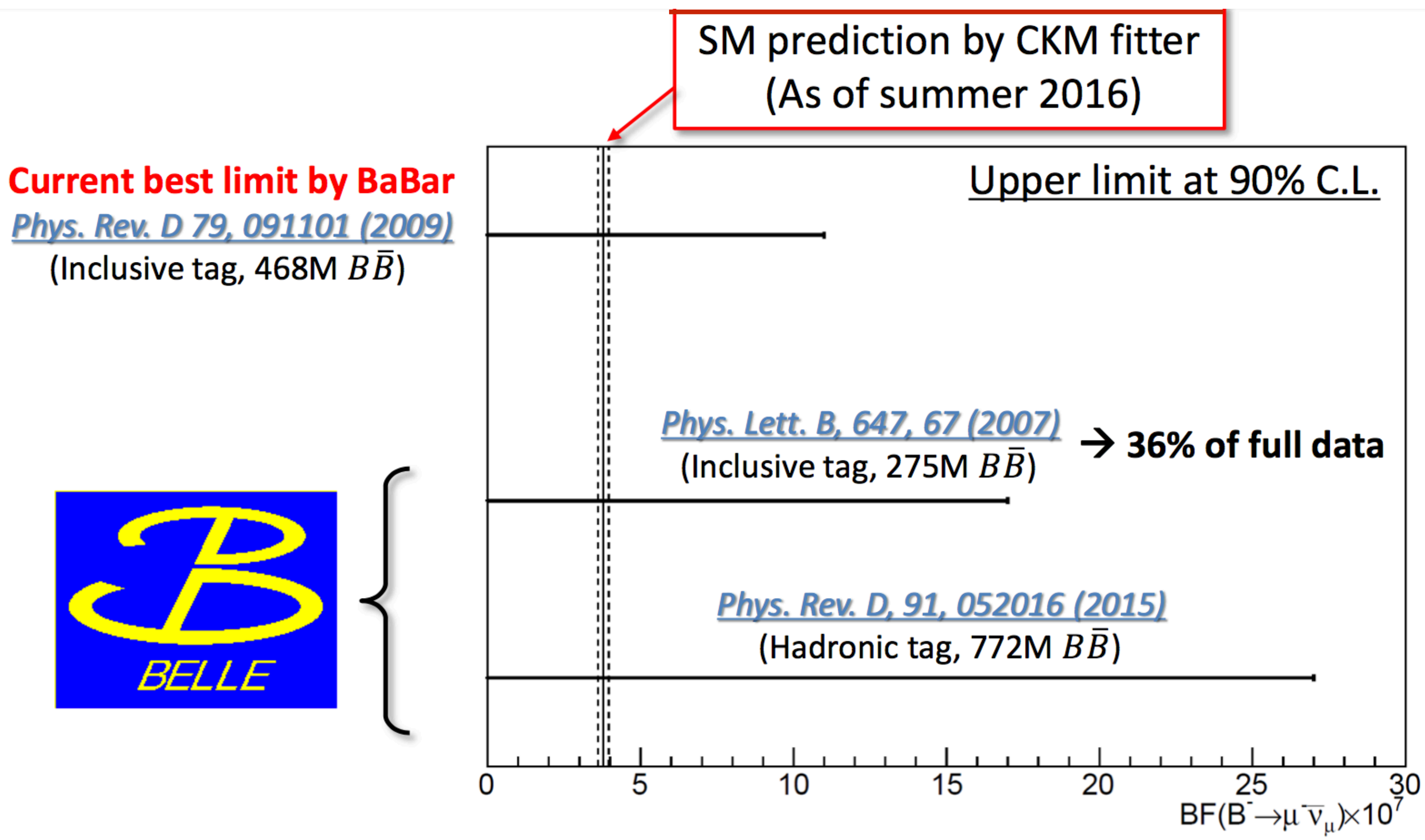


Advantage: better resolution

Leptonic decays: B → μν

- 2-body decay ☞ monochromatic muons in B rest frame
  - measurement can be performed without exclusive reconstruction of the companion B meson (higher efficiency)

$$\mathcal{B}(B \to \mu\nu)^{\rm SM} = (3.7 \pm 0.5) \times 10^{-7}$$



- Upper limits approaching SM expectation
- Inclusive tag analysis with the full Belle data sample is ongoing
- Belle II expectations are:
  - *observation at SM level with 5 ab^{-1}*
  - *$\sigma Br/Br$ ~7% at 50 ab^{-1}*

$$R^{\mu\tau} = \frac{\mathcal{B}(B \to \mu\nu)}{\mathcal{B}(B \to \tau\nu)}$$ (theory free LFUV test)

Charmless SL decays: $B \to \pi l \nu$

A way to measure $|V_{ub}|$:

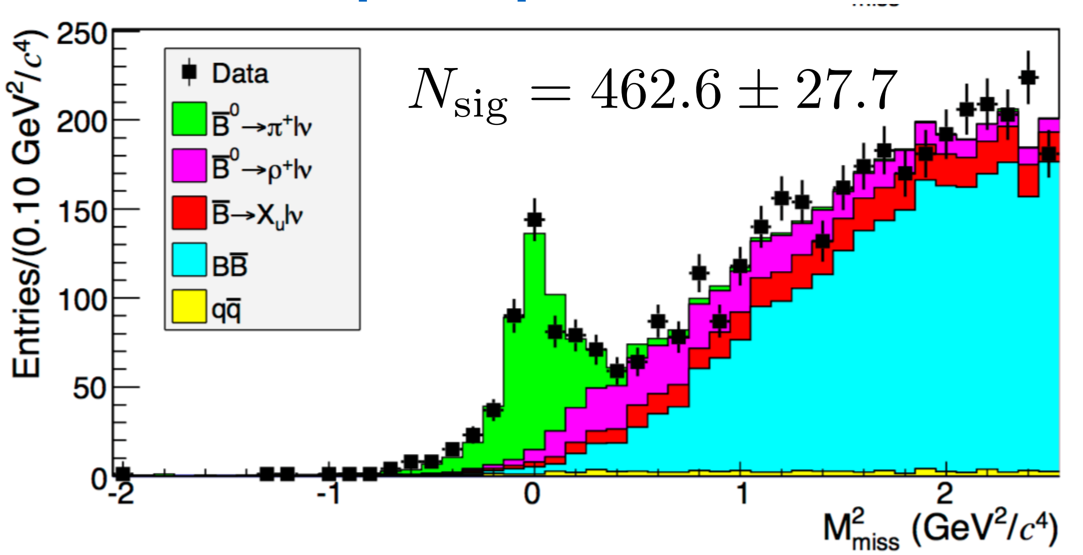
$$\frac{d\mathcal{B}(B \to \pi \ell \nu)}{dq^2} = |V_{ub}|^2 \frac{G_F^2 \tau_B}{24\pi^3} p_\pi^3 |f_+^{B\pi}(q^2)|^2$$

(exp.) (theory; LQCD)

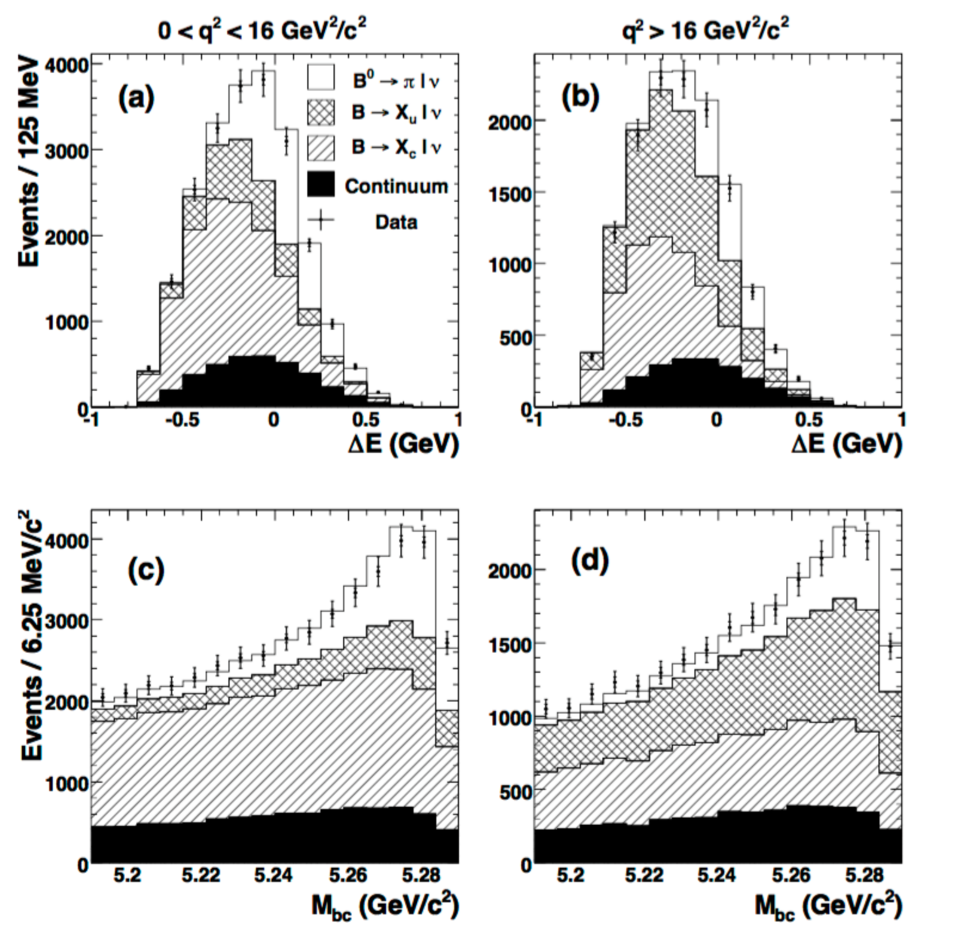
1. Tagged measurements
   - one of the two B mesons fully reconstructed in hadronic decay modes
   - *low efficiency (few 10^{-3})*
   - *high purity* and *good q^2 resolution (~ 0.25 GeV^2)*
   - *dominant source of systematic error -> Btag efficiency calibration*

2. Untagged measurements
   - neutrino 4-momentum inferred from missing energy and missing momentum of in the whole event
   - *high efficiency (~ 10^{-1})*
   - *low purity* and *bad q2 resolution (~ 0.50 GeV^2)*
   - *dominant source of systematic error -> continuum q^2 dependence + detector induced (tracking, PID)*

Belle [711 fb^{-1}] PRD88 032005

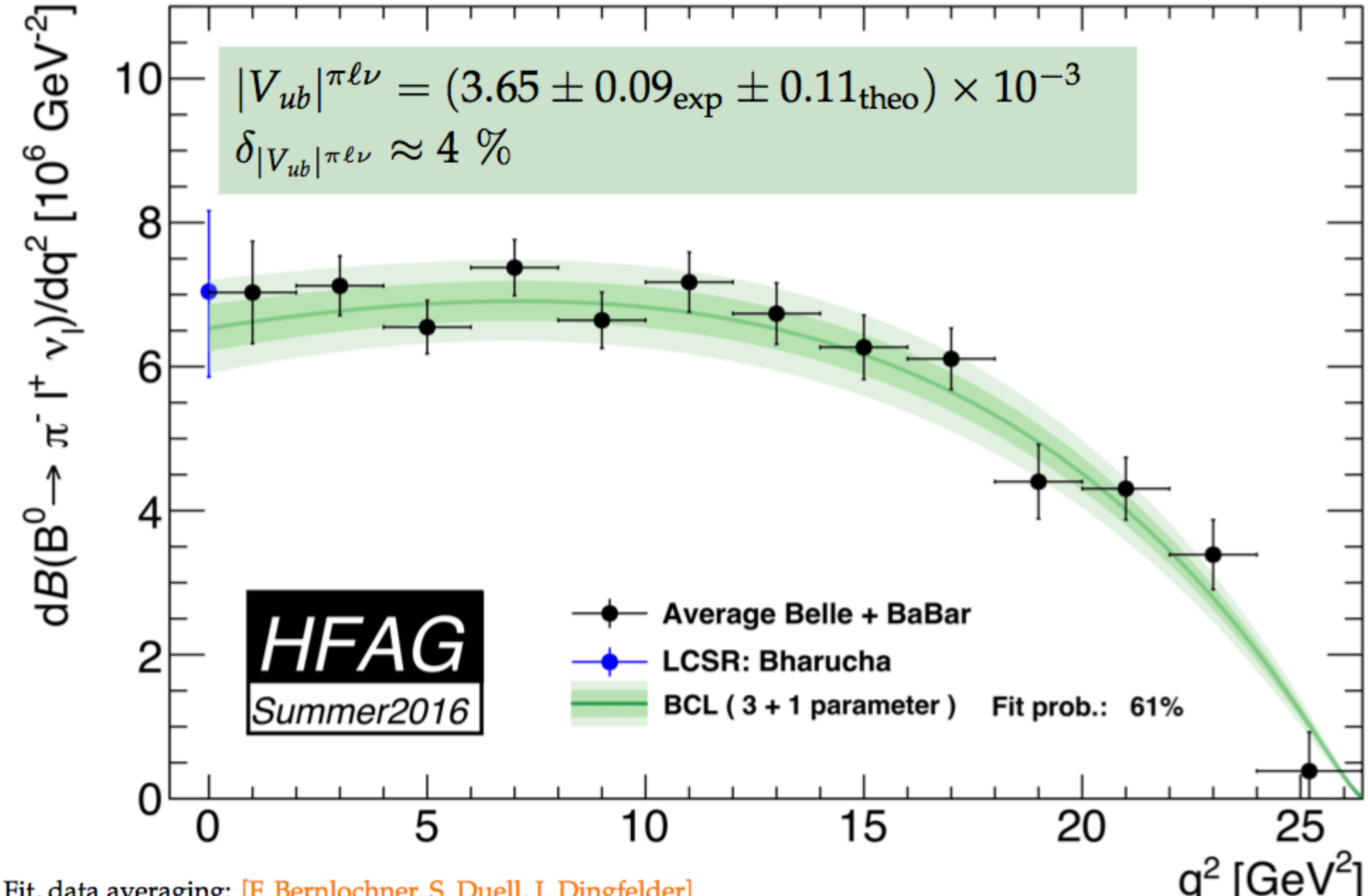


Belle [605 fb^{-1}] PRD83 071101



$N_{\rm sig} = 21486 \pm 548$

Charmless SL decays: $B \to \pi l \nu$

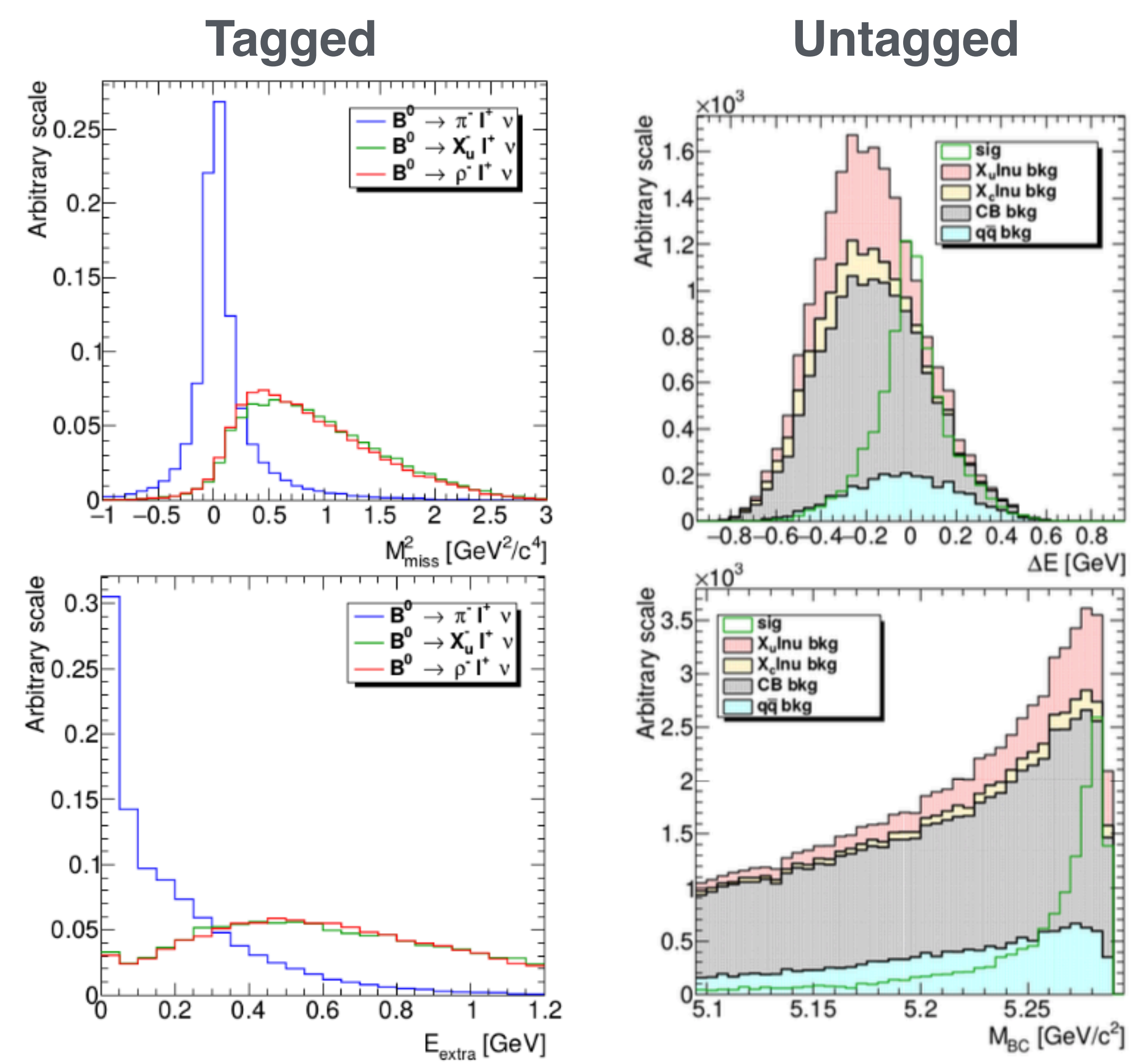


Fit, data averaging: [F. Bernlochner, S. Duell, J. Dingfelder]
LQCD averaging: [FLAG-3 review (arXiv:1607.00299)]
LQCD: [Fermilab/MILC, Phys.Rev. D92 (2015) no.1, 014024]
LQCD: [RBC/UKQCD, Phys.Rev. D91 (2015) no.7, 074510]
LCSR: [A. Bharucha, JHEP 1205 (2012) 092]

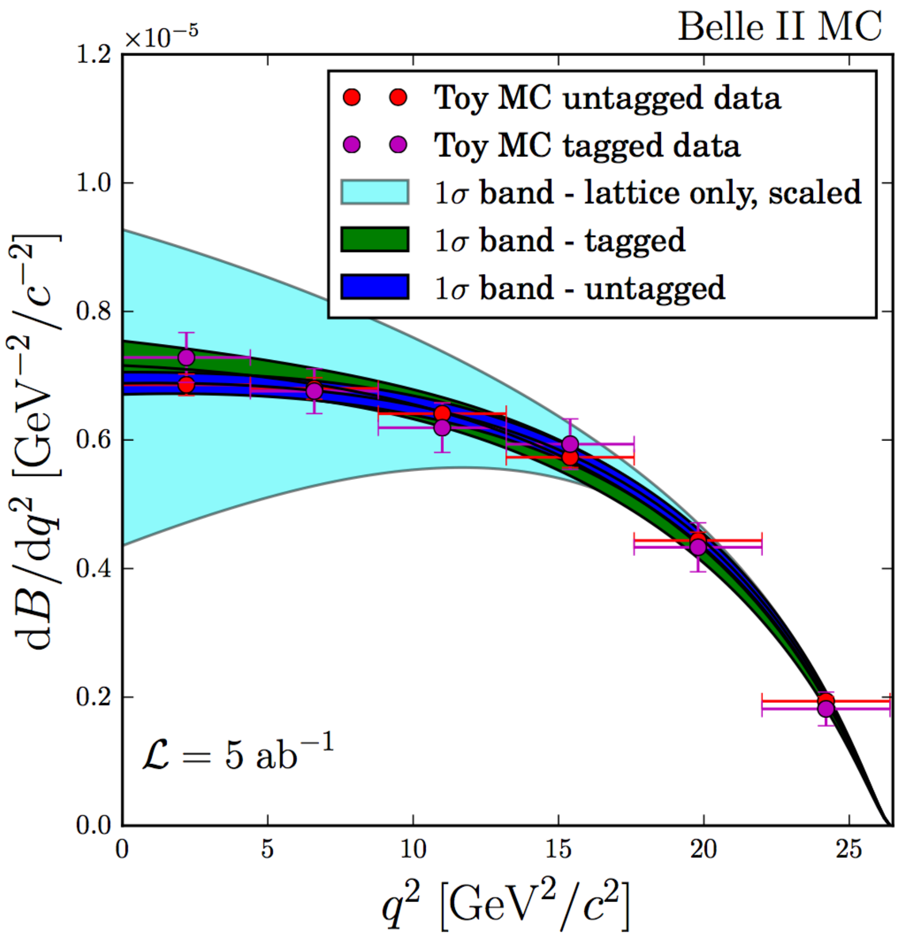
Experimental and theory errors commensurate

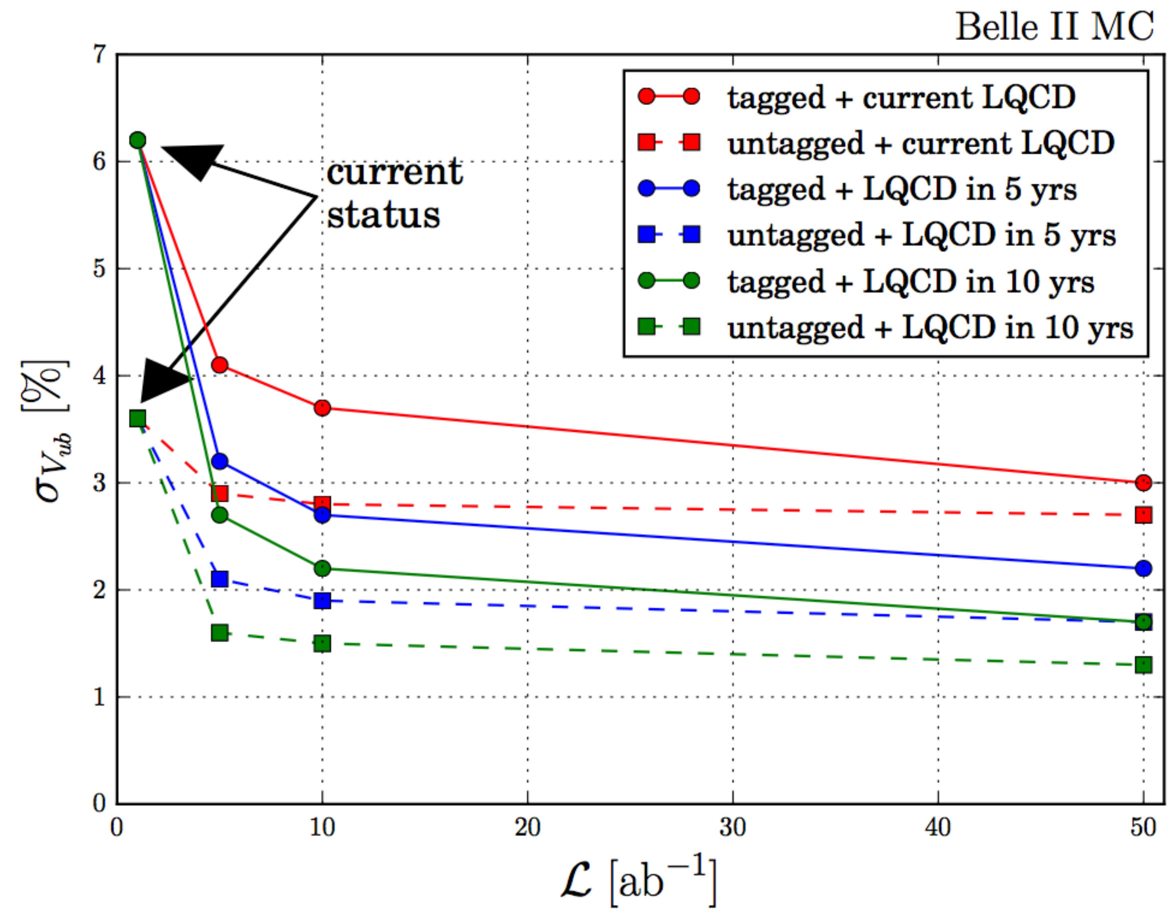
Charmless SL decays: B → πlν Belle II prospects

- both tagged and untagged measurements report significant improvement in reconstruction efficiencies (up to x2)
- measurements will be systematically limited at Belle II statistics
  - guess-estimated from Belle
  - largest irreducible systematics will be tagging efficiency in tagged measurement and FFs of background in untagged measurement



Charmless SL decays: B → πlν
Belle II + LQCD prospects



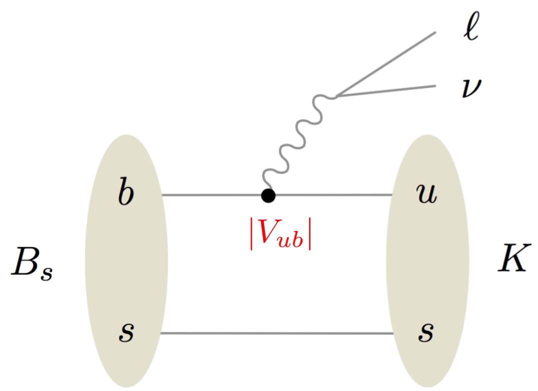


LQCD forecasts: [A. Kronfeld, T. Kaneko, S. Simula]

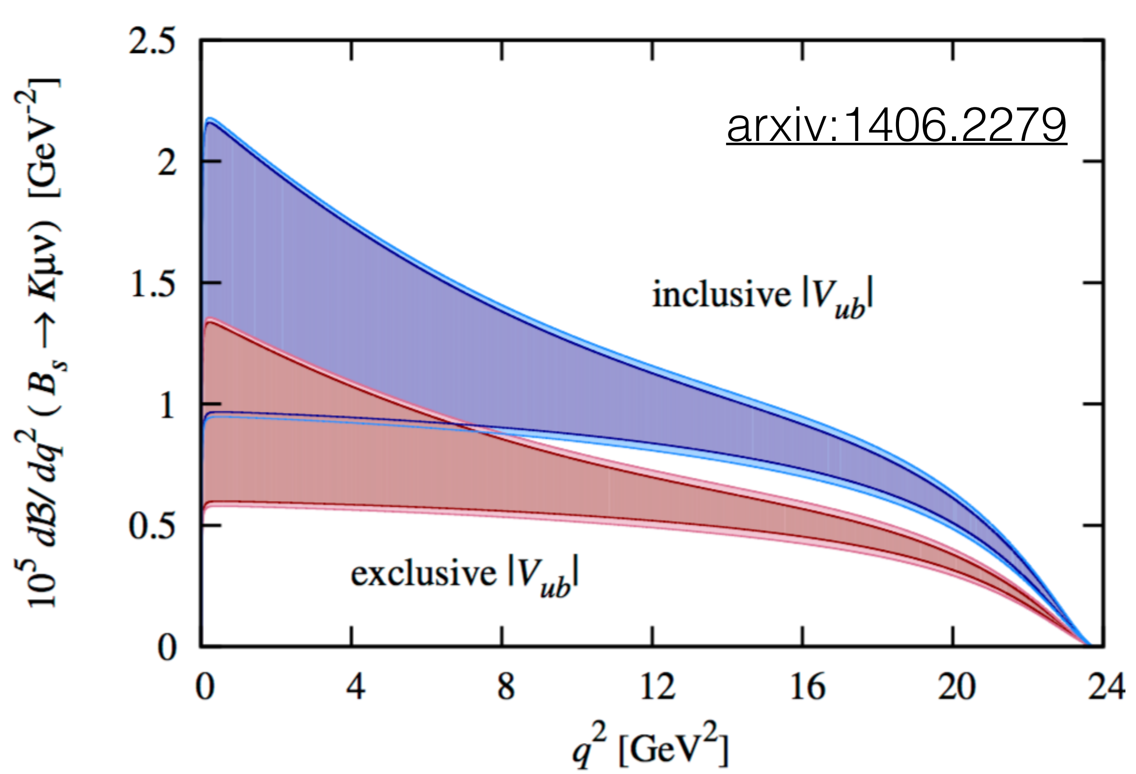
Below 2% precision on $|V_{ub}|$ reachable assuming x2 (x5) reduction of LQCD uncertainties in 5 (10) years and new experimental input from Belle II.

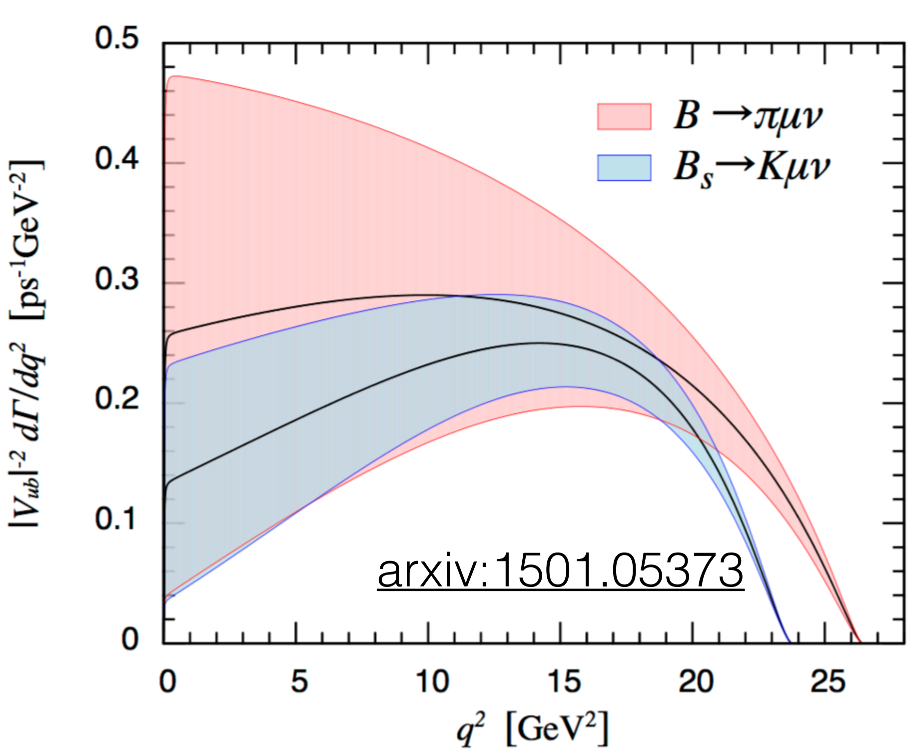
Charmless SL decays: $B_s \to K l \nu$

- provides an alternative exclusive semileptonic determination of |Vub|
- Lattice QCD calculations of form factors became available in last couple of years



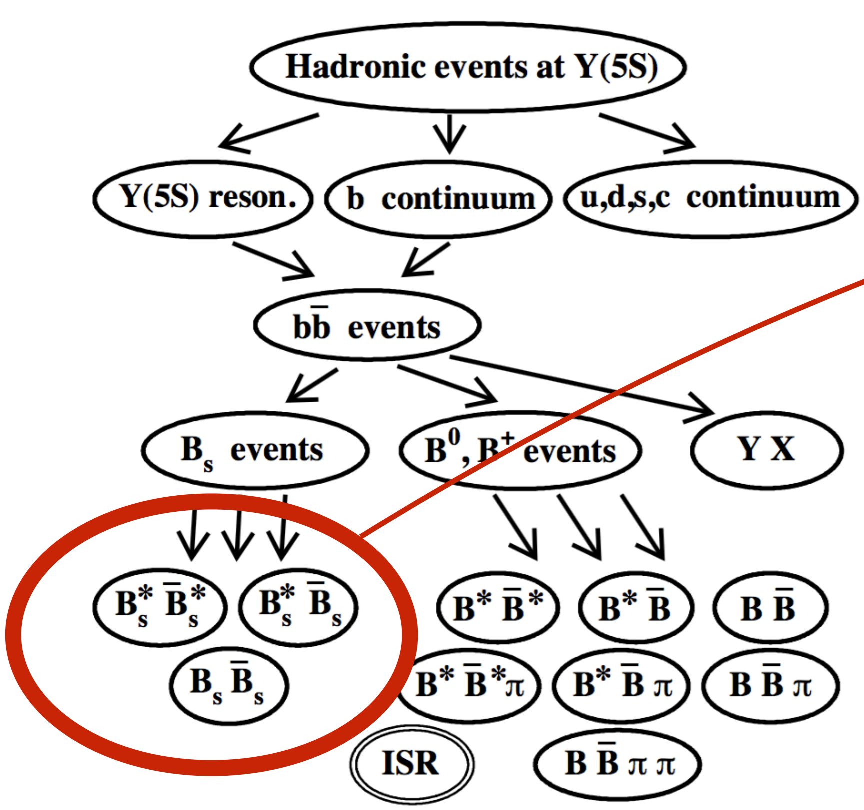
$$\frac{d\mathcal{B}(B_s \to K\ell\nu)}{dq^2} = \tau_{B_s} \frac{G_F^2 |\mathbf{p}_K|^3}{24\pi^3} |V_{ub}|^2 \; |f_+|^2 + \mathcal{O}\left(\frac{m_\ell^2}{q^2}\right)$$





Charmless SL decays: $B_s \to K l \nu$

- *How well can we measure $dBr(B_s \to K l \nu)/dq^2$ at Belle II?*
- This measurement was not yet performed at the B-factories
  - cannot extrapolate existing measurements
- Perform (untagged) study on simulated data to get reasonable estimations

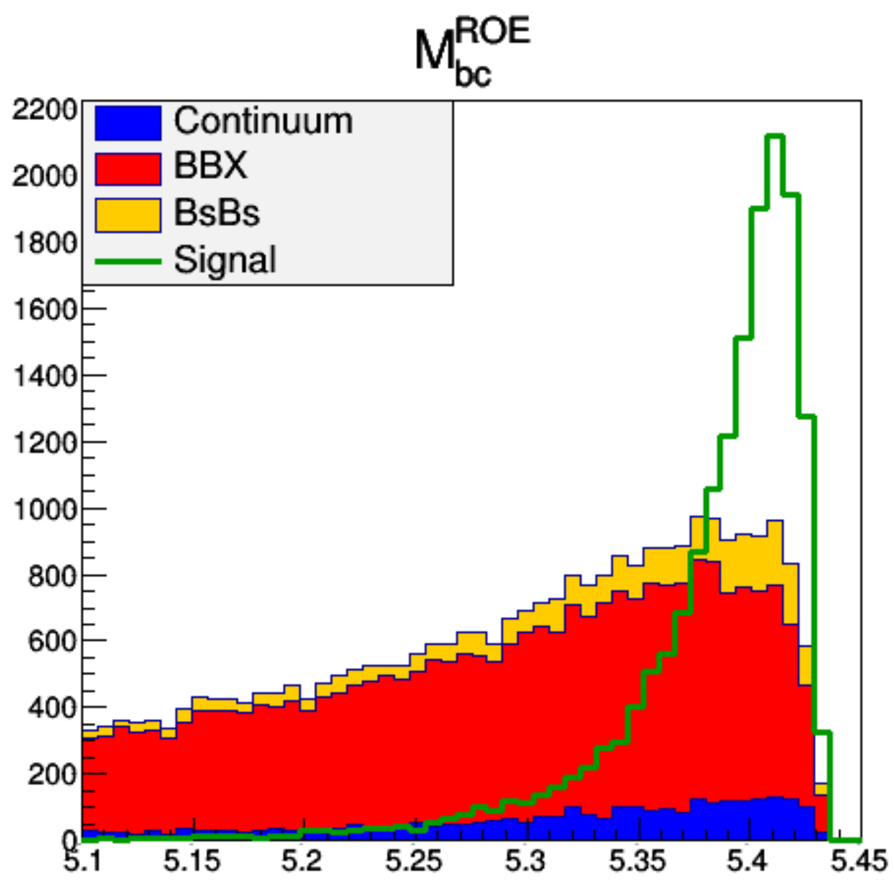


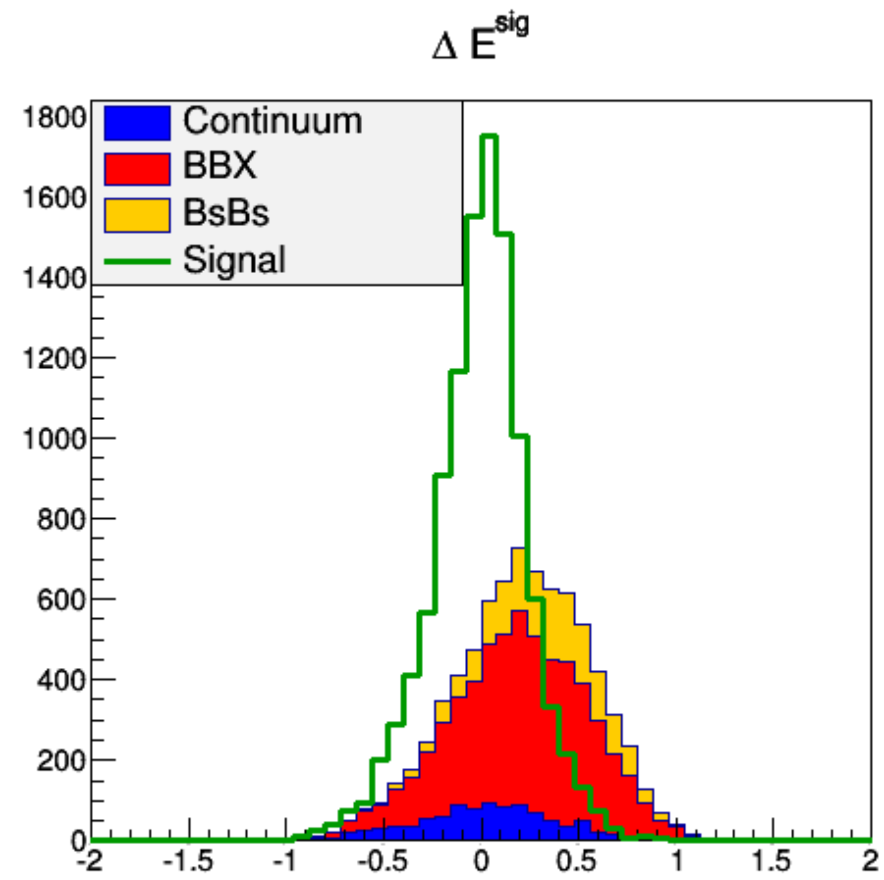
Channel	% / $b\bar{b}$ event	% / B_s^0 event
All B_s^0 events	$19.5^{+3.0}_{-2.3}$	
$B_s^{*0}\bar{B}_s^{*0}$		$90.1^{+3.8}_{-4.0} \pm 0.2$
$B_s^{*0}\bar{B}_s^0 + B_s^0\bar{B}_s^{*0}$		$7.3^{+3.3}_{-3.0} \pm 0.1$
$B_s^0\bar{B}_s^0$		$2.6^{+2.6}_{-2.5}$
All B events	$73.7 \pm 3.2 \pm 5.1$	
B^+ mesons	$72.1^{+3.9}_{-3.8} \pm 5.0$	
B^0 mesons	$77.0^{+5.8}_{-5.6} \pm 6.1$	
$B\bar{B}$	$5.5^{+1.0}_{-0.9} \pm 0.4$	
$B\bar{B}^* + B^*\bar{B}$	$13.7 \pm 1.3 \pm 1.1$	
$B^*\bar{B}^*$	$37.5^{+2.1}_{-1.9} \pm 3.0$	
$B\bar{B}\pi$	$0.0 \pm 1.2 \pm 0.3$	
$B\bar{B}^*\pi + B^*\bar{B}\pi$	$7.3^{+2.3}_{-2.1} \pm 0.8$	
$B^*\bar{B}^*\pi$	$1.0^{+1.4}_{-1.3} \pm 0.4$	
ISR to final B	$9.2^{+3.0}_{-2.8} \pm 1.0$	

Only every 5th b<u>b</u> event at Y(5S) produces B_sB_s-pairs!

$$N(B_s^0) = 2 \times \mathcal{L}_{\text{int}} \times \sigma_{b\bar{b}} \times f_s \qquad \sigma_{b\bar{b}} = (0.340 \pm 0.016)\ \text{nb}$$

Charmless SL decays: $B_s \to Kl\nu$





- Signal efficiency and background rejection confirmed to be similar to that achieved $B \to \pi l\nu$
- 3000 Klnu signal events in $1ab^{-1}$ @ Y(5S)

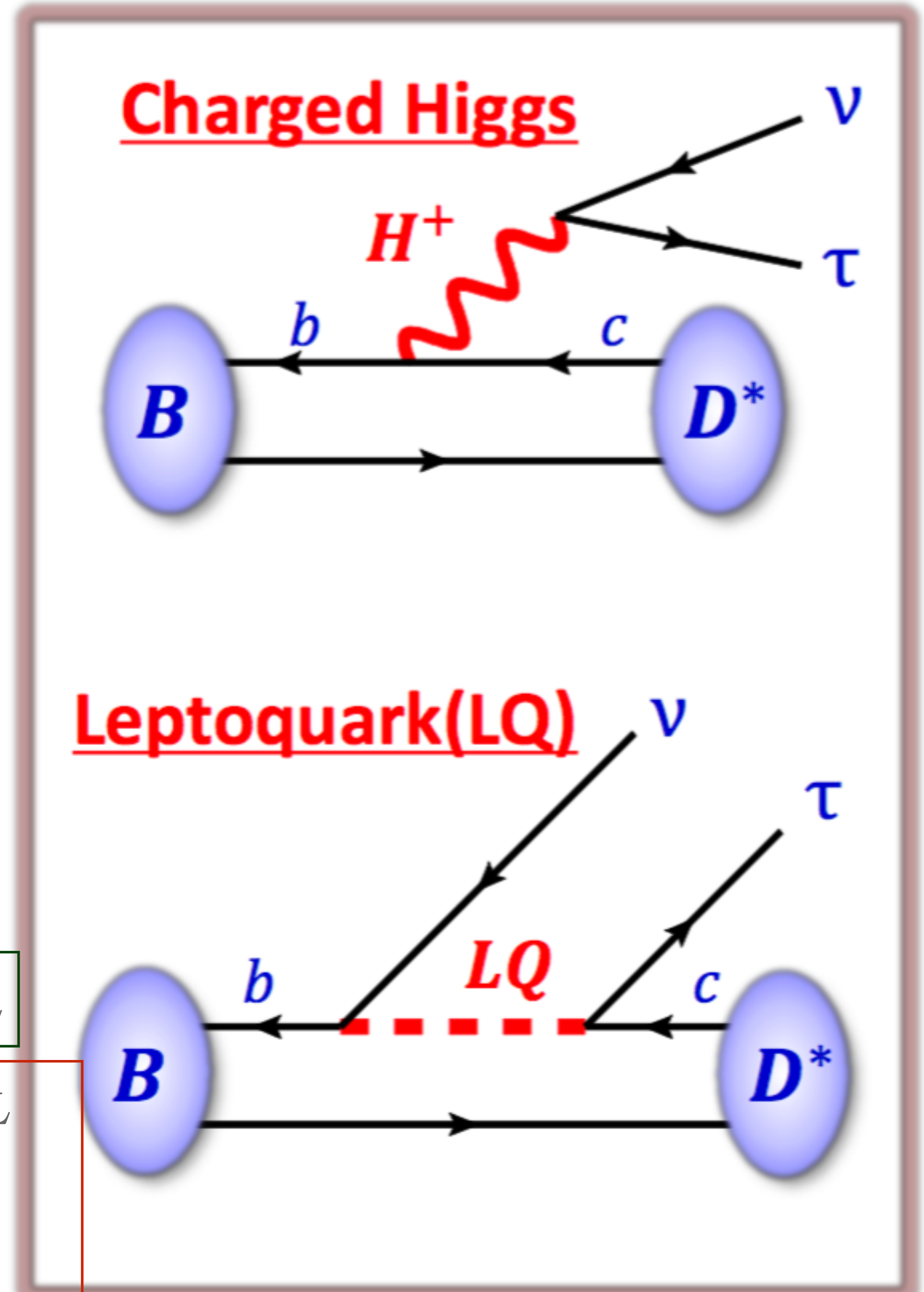
Measurement of $B_s \to Kl\nu$ sample at Belle II possible, but not competitive to $B \to \pi l\nu$. Interesting x-check nonetheless, if Belle II collects large amount of collisions at Y(5S).

Semitauonic decays: Motivation

Semi-tauonic *B* decays are sensitive probes of New Physics. NP could impact:

- Branching fraction
- tau, D* polarisations
- Properties of NP can be inferred also by looking at various kinematic properties of the decay (momenta, …)

NP effects can be different for D and D modes.*



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

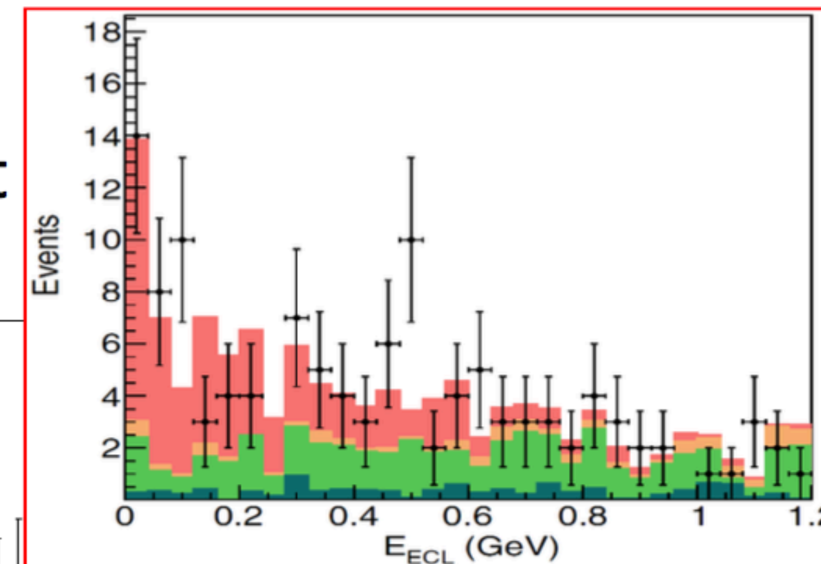
$-\mathcal{L}_{\rm eff} = 2\sqrt{2}G_F V_{cb}(1+C_{V_1})\mathcal{O}_{V_1}$	SM	$\mathcal{O}_{V_1} = \bar{c}_L\gamma^\mu b_L\,\bar{\tau}_L\gamma_\mu\nu_L$
$+C_{V_2}\mathcal{O}_{V_2}$	RH-current	$\mathcal{O}_{V_2} = \bar{c}_R\gamma^\mu b_R\,\bar{\tau}_L\gamma_\mu\nu_L$
$+C_{S_1}\mathcal{O}_{S_1}$	2HDM (Type-II)	$\mathcal{O}_{S_1} = \bar{c}_L b_R\,\bar{\tau}_R\nu_L$
$+C_{S_2}\mathcal{O}_{S_2}$	2HDM	$\mathcal{O}_{S_2} = \bar{c}_R b_L\,\bar{\tau}_R\nu_L$
$+C_T\mathcal{O}_T$	Tensor	$\mathcal{O}_T = \bar{c}_R\sigma^{\mu\nu} b_L\,\bar{\tau}_R\sigma_{\mu\nu}\nu_L$

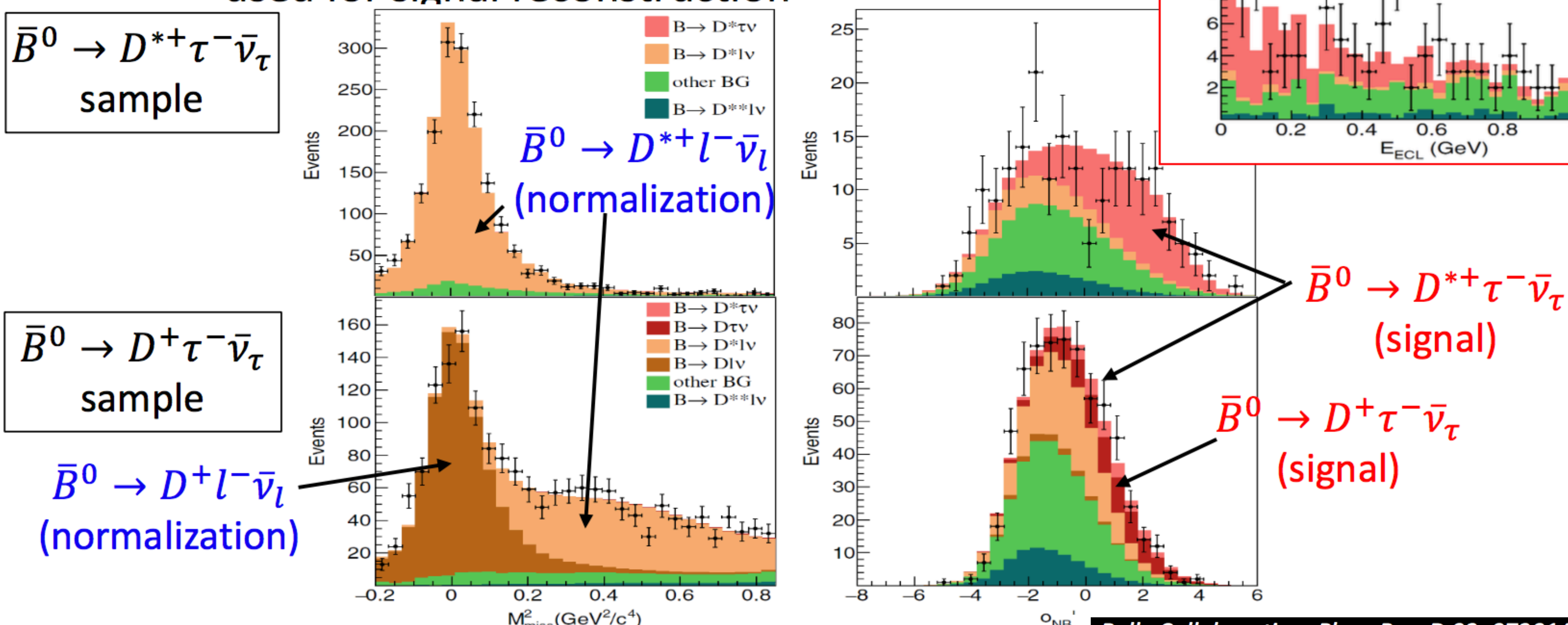
Semitauonic decays: Status

Experiment	Mode	Technique	Observables
BaBar [PRL109, 101802; PRD88, 072012]	$B \to \overline{D}^{(*)}\tau\nu_\tau$ $\tau \to \ell\overline{\nu}_\ell\nu_\tau$	Hadronic	R(D), R(D*), q^2
Belle [PRL99,191807; PRD82,072005;]	$B \to \overline{D}^{(*)}\tau\nu_\tau$ $\tau \to \ell\overline{\nu}_\ell\nu_\tau$	Inclusive	Br
Belle [PRD92,072014]	$B \to \overline{D}^{(*)}\tau\nu_\tau$ $\tau \to \ell\overline{\nu}_\ell\nu_\tau$	Hadronic	R(D), R(D*), q^2, $\lvert p_l^*\rvert$
Belle [PRD94, 072007]	$B^0 \to D^{*-}\tau\nu_\tau$ $\tau \to \ell\overline{\nu}_\ell\nu_\tau$	Semi-leptonic	R(D*), $\lvert p^*_l\rvert$, $\lvert p^*_{D^*}\rvert$
Belle [arXiv:1608.06391]	$B \to \overline{D}^{*}\tau\nu_\tau$ $\tau \to \pi\nu_\tau,\ \rho\nu_\tau$	Hadronic	R(D*), P_τ
LHCb [PRL115,111803]	$B^0 \to D^{*-}\tau\nu_\tau$ $\tau \to \mu\overline{\nu}_\mu\nu_\tau$		R(D*)

(Hadronic tag, Leptonic tau decay)

- M^2_{miss} to measure $\bar{B} \to D^{(*)} l^- \bar{\nu}_l$
  - $M^2_{\text{miss}} = \left(p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^{(*)}} - p_l\right)^2$ → 0 GeV^2/c^4
- (Transformed) neural network output ($O_{\text{NB}}{}'$) to measure $\bar{B} \to D^{(*)} \tau^- \bar{\nu}_\tau$
  - Powerful variable is E_{ECL}: sum of ECL energy not used for signal reconstruction



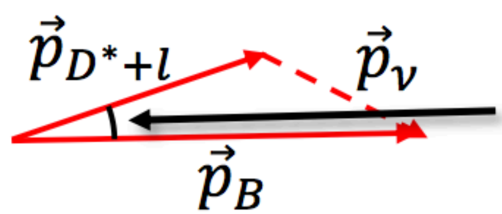


Belle Collaboration, Phys. Rev. D 92, 072014 (2015)

(SL tag, Leptonic tau decay)

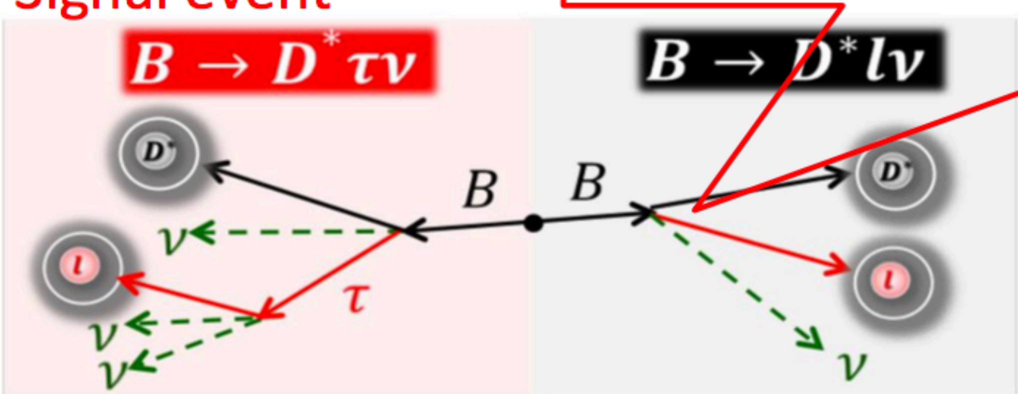
- Independent analysis of the previous $R(D^{(*)})$ measurement
- More background due to a ν in $\bar{B}_{\text{tag}} \to D^{(*)} l^- \bar{\nu}_l$

  →Focus on $\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau$
- Signal/normalization separation based on smaller $\cos\theta_{B-D^*l}$

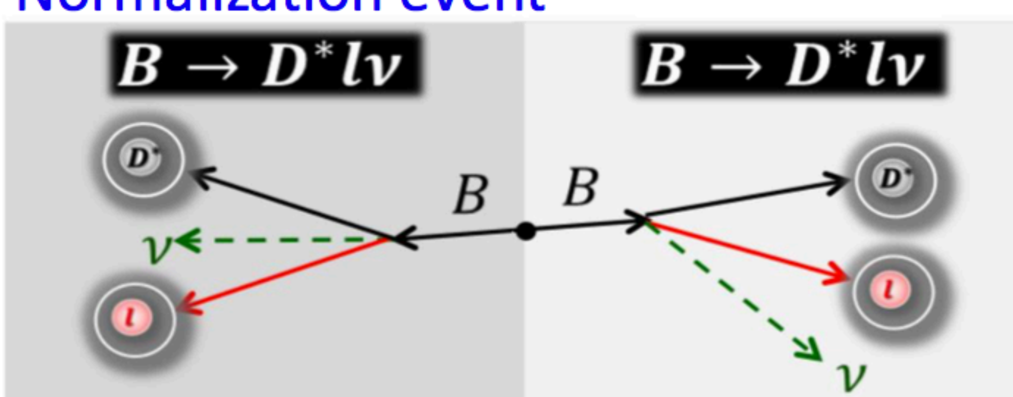


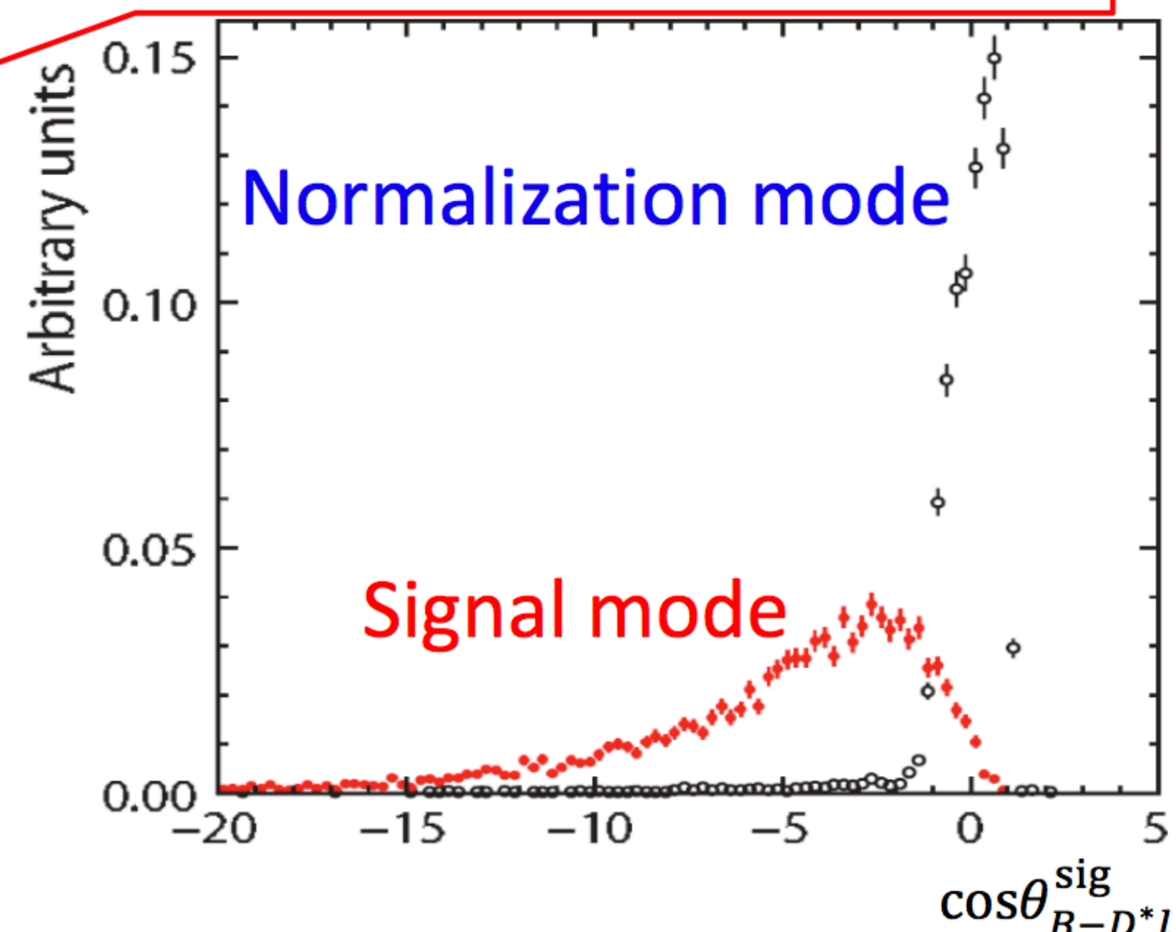
$$\cos\theta_{B-D^*l} = \frac{E^*_{\text{beam}} E^*_{D^*l} - m_B^2 - m_{D^*l}^2}{2|p^*_{\text{beam}}||p^*_{D^*l}|}$$

Signal event



Normalization event





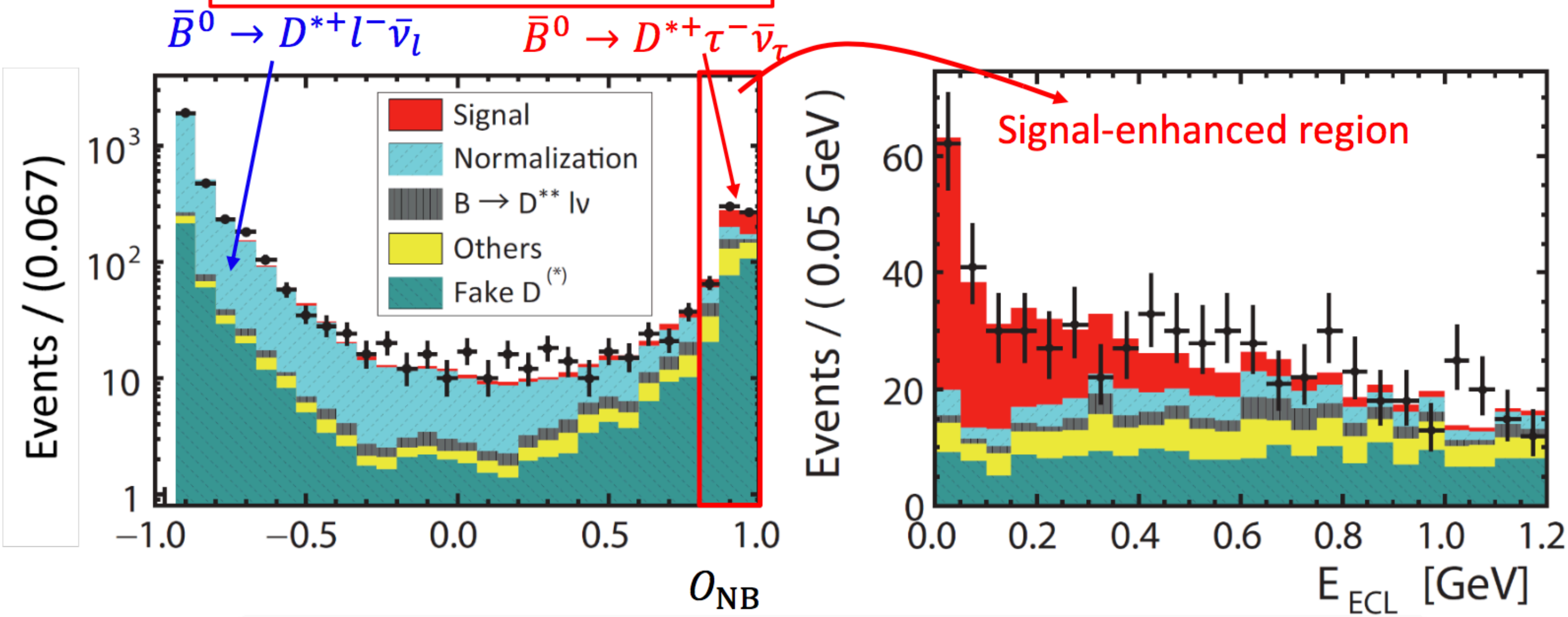
Belle Collaboration, Phys. Rev. D 94, 072007 (2016)

(SL tag, Leptonic tau decay)

- Two-dimensional fit to neural network output (O_{NB}) and E_{ECL}

- $\cos\theta^{\mathrm{sig}}_{B-D^{*}l}$
- M^{2}_{miss}
- Total energy of $B_{\mathrm{tag}} + B_{\mathrm{sig}}$

Summed energy, not used for the event reconstruction



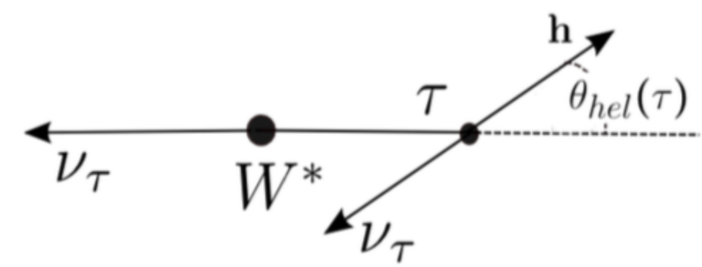
$$R(D^*) = 0.302 \pm 0.030\ (\mathrm{stat.}) \pm 0.011 (\mathrm{syst.})$$

Belle Collaboration, Phys. Rev. D 94, 072007 (2016)

Tau Polarimeters (hadronic decays)

- $\cos\theta_{hel}(\tau)$ distribution in (quasi)2-body decays $\tau \to M\nu_\tau$
- τ polarization measurment based on $\cos\theta_{hel}(\tau)$ distribution:

$$\frac{d\Gamma}{d\cos\theta_{hel}(\tau)} \sim \frac{1}{2}(1 + \alpha P_\tau \cos\theta_{hel}(\tau))$$



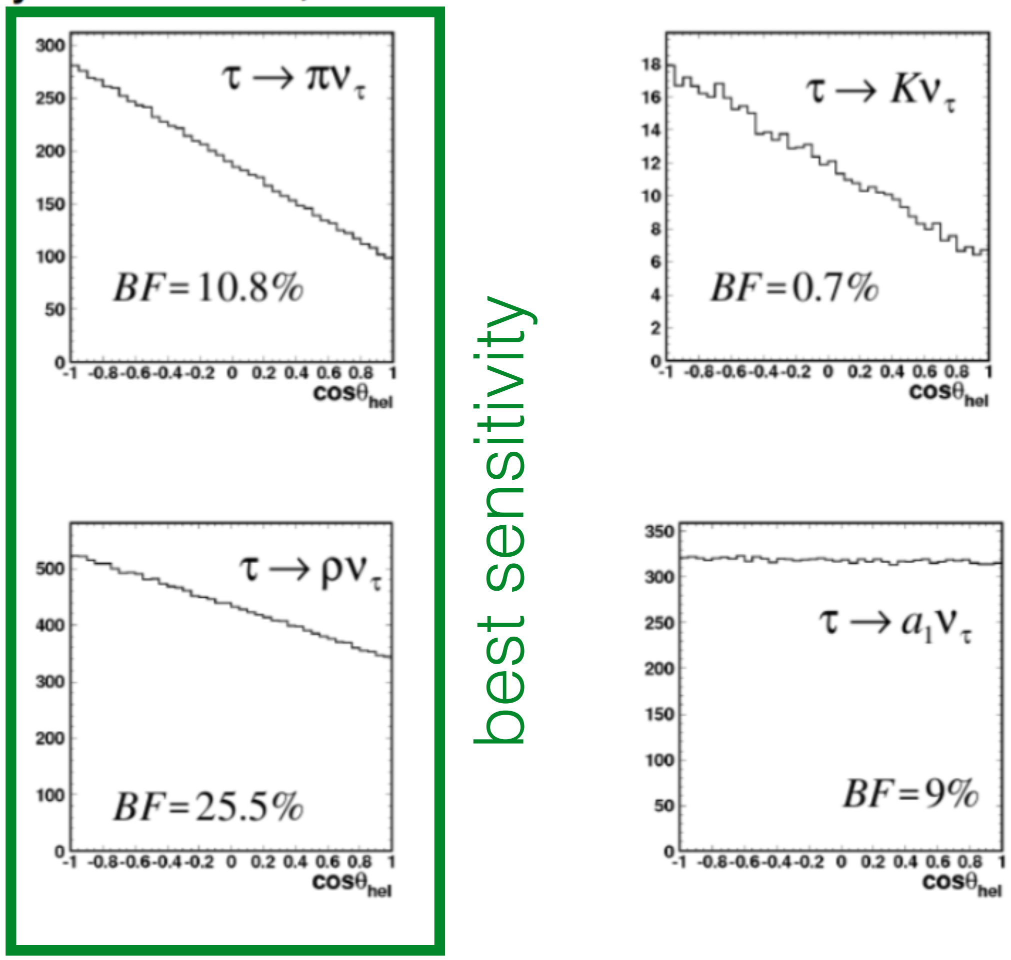
- **SM: $P_\tau \approx$ -0.5**
- leptonic τ decays not useful;

for $J_M = 0$

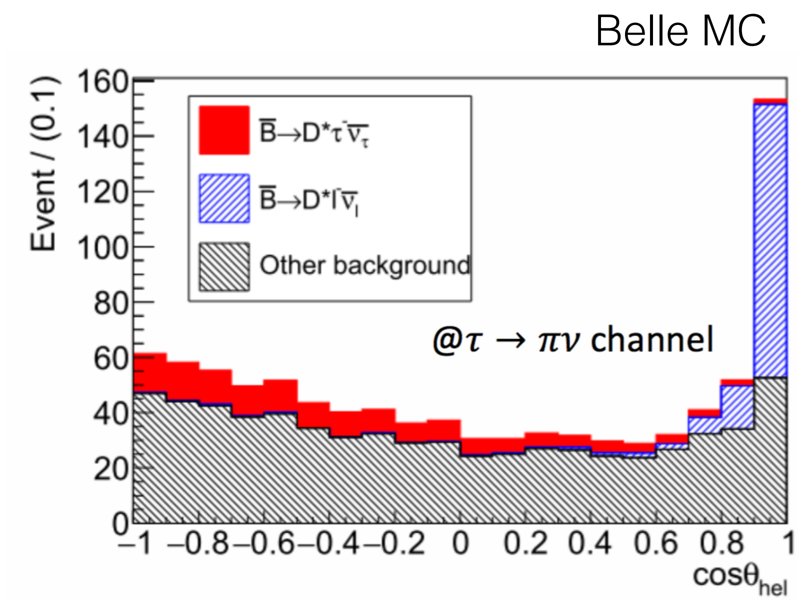
$\alpha = 1$

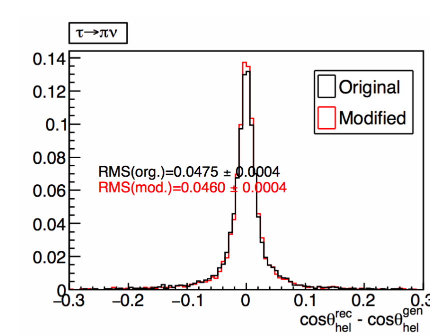
for $J_M = 1$

$$\alpha = \frac{m_\tau^2 - m_M^2}{m_\tau^2 + m_M^2}$$



$\alpha = 0.45$ for $\tau \to \rho\nu$ $\alpha = 0.12$ for $\tau \to a_1\nu$



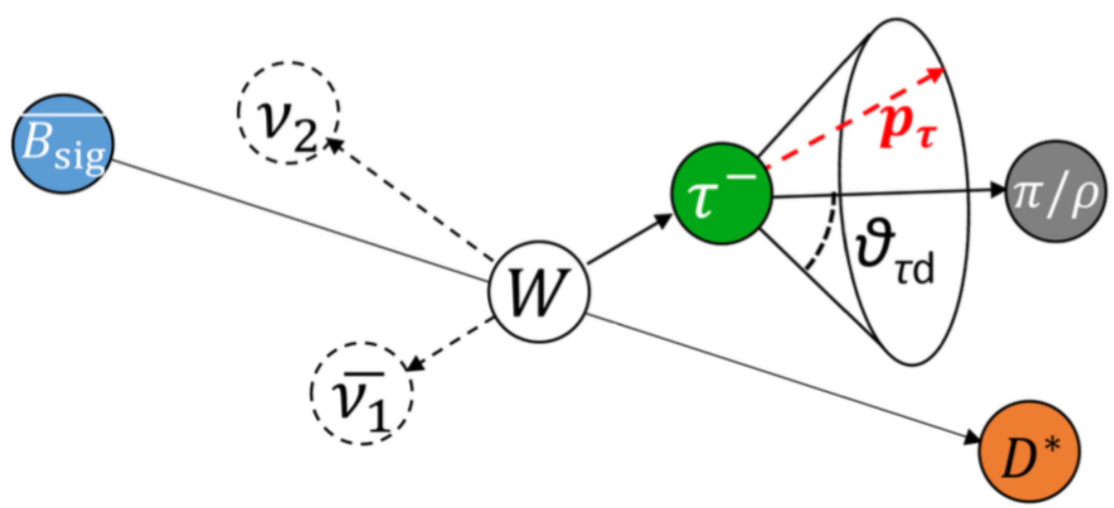


Tau Polarimeters (hadronic decays)

Experimental challenges:

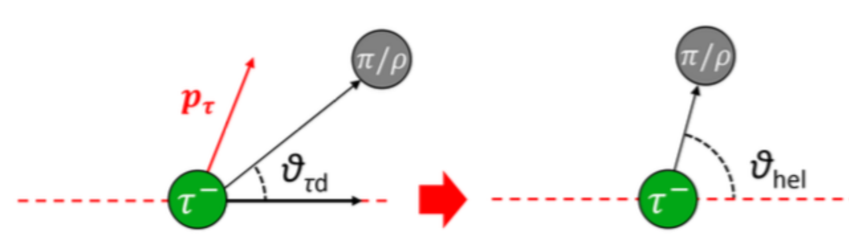
- due to multiple neutrinos in the final state the tau momentum can not be completely determined
- go to W rest frame, where $p_W = p_{Bsig} - p_{D^*} = 0$
- in W rest frame the tau and neutrino from B decay are back-to-back, therefore:
    - magnitude of tau momentum ($|p_\tau|$) can be determined $|\vec{p}_\tau| = \frac{q^2 - m_\tau^2/c^2}{2\sqrt{q^2}}$
    - direction of the tau momentum is constrained to lie on the cone around the hadron daughter momentum

$$\cos\theta_{\tau d} = \frac{2E_\tau E_{\mathrm{da}} - m_\tau^2 - m_{\mathrm{da}}^2}{2|\boldsymbol{p}_\tau||\boldsymbol{p}_{\mathrm{da}}|}$$



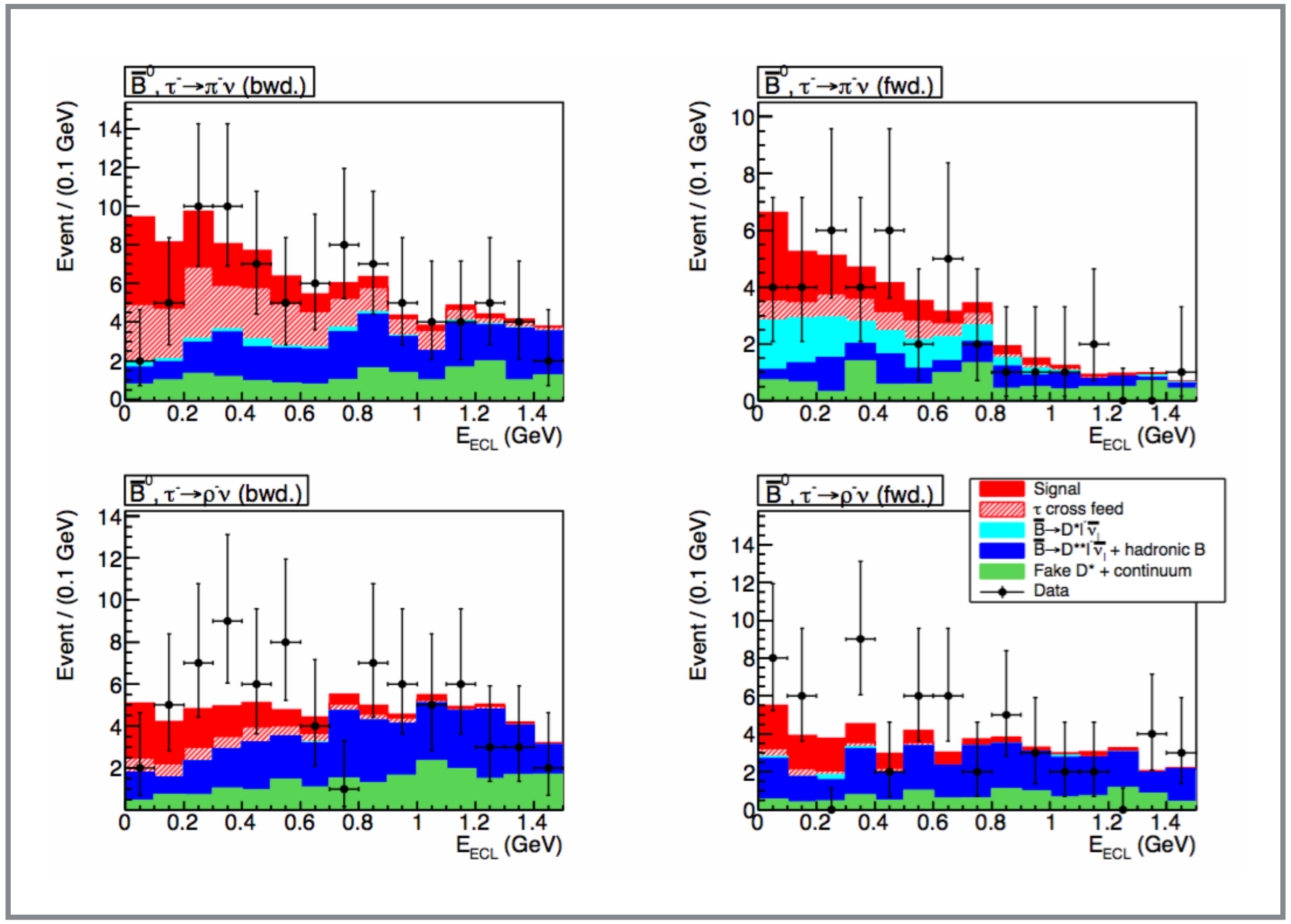
Decay kinematics of the $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$ decay in the W rest frame

Boost in arbitrary direction on the cone to get into the tau rest frame

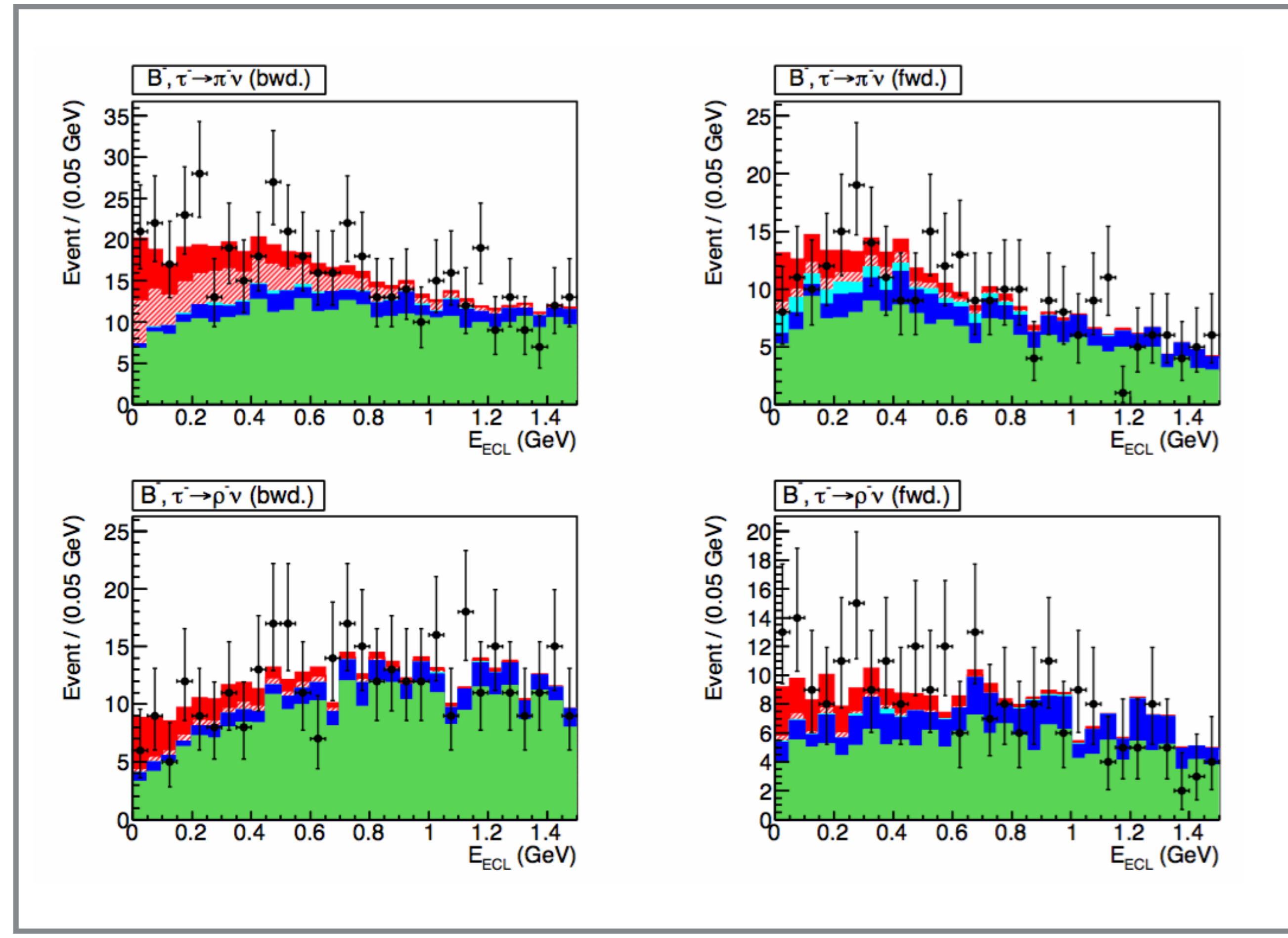


(Hadronic tag, Hadronic tag decay)

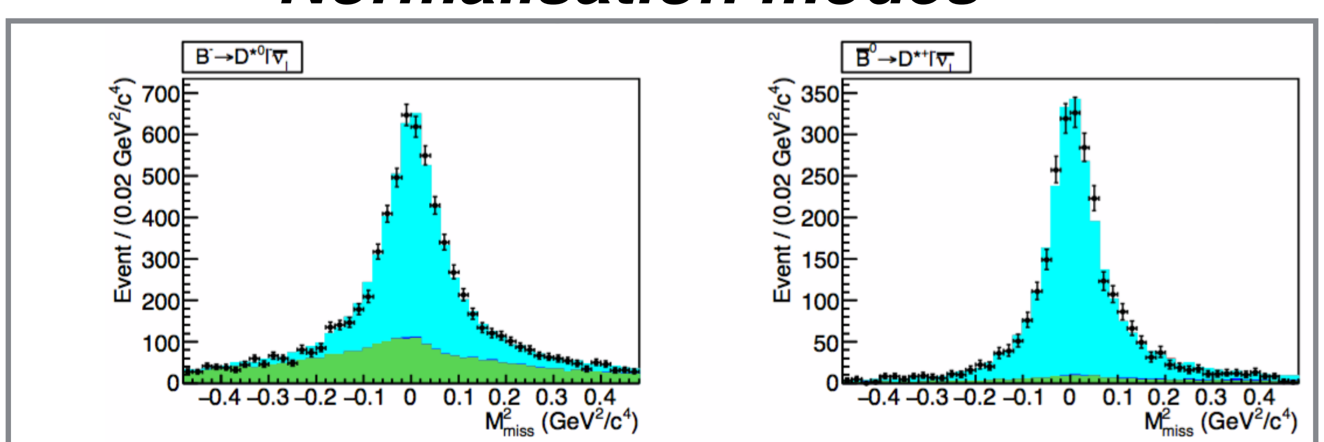
Backward



Forward



Normalisation modes

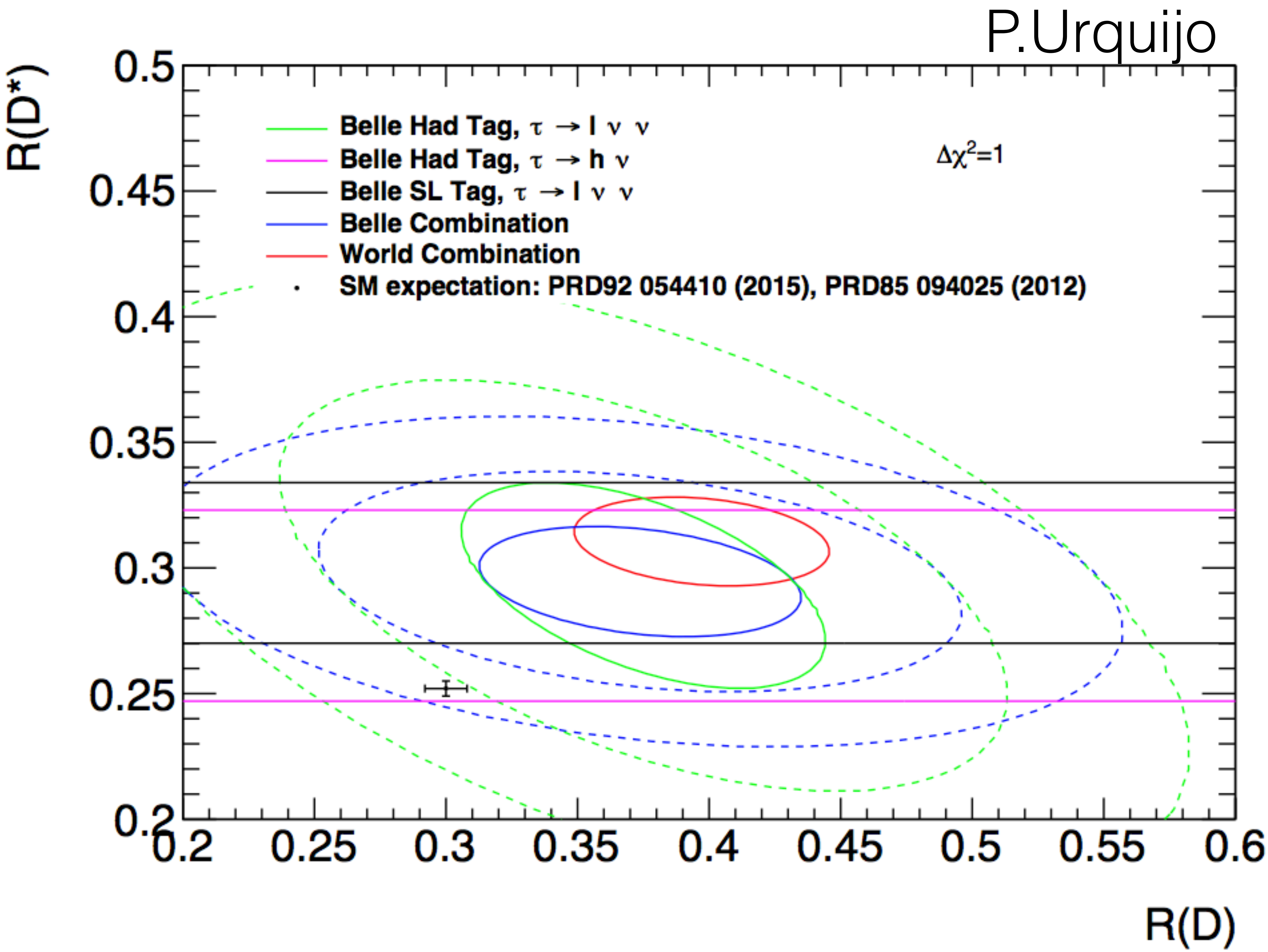


Signal extracted in two bins of helicity angle

$$R(D^*) = 0.276 \pm 0.034(\text{stat.})^{+0.029}_{-0.026}(\text{syst.}),$$

$$P_\tau = -0.44 \pm 0.47(\text{stat.})^{+0.20}_{-0.17}(\text{syst.}).$$

Semitauonic decays: Belle and World Average



Systematic errors

BaBar@Hadronic(τ→l)

Source of uncertainty	(%) $\mathcal{R}(D)$	$\mathcal{R}(D^*)$
Additive uncertainties		
PDFs		
MC statistics	4.4	2.0
$B \to D^{(*)}(\tau^-/\ell^-)\bar{\nu}$ FFs	0.2	0.2
$D^{**} \to D^{(*)}(\pi^0/\pi^\pm)$	0.7	0.5
$\mathcal{B}(\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell)$	0.8	0.3
$\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)$	1.8	1.7
$D^{**} \to D^{(*)}\pi\pi$	2.1	2.6
Cross-feed constraints		
MC statistics	2.4	1.5
$f_{D^{**}}$	5.0	2.0
Feed-up/feed-down	1.3	0.4
Isospin constraints	1.2	0.3
Fixed backgrounds		
MC statistics	3.1	1.5
Efficiency corrections	3.9	2.3
Multiplicative uncertainties		
MC statistics	1.8	1.2
$B \to D^{(*)}(\tau^-/\ell^-)\bar{\nu}$ FFs	1.6	0.4
Lepton PID	0.6	0.6
$\pi^0/\pi^\pm$ from $D^* \to D\pi$	0.1	0.1
Detection/Reconstruction	0.7	0.7
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.2	0.2
Total syst. uncertainty	9.6	5.5
Total stat. uncertainty	13.1	7.1
Total uncertainty	16.2	9.0

Belle@Semileptonic(τ→l)

Sources	$\mathcal{R}(D^*)$ [%] $\ell^{\rm sig} = e, \mu$
MC size for each PDF shape	2.2
PDF shape of the normalization in $\cos\theta_{B\text{-}D^*\ell}$	$^{+1.1}_{-0.0}$
PDF shape of $B \to D^{**}\ell\nu_\ell$	$^{+1.0}_{-1.7}$
PDF shape and yields of fake $D^{(*)}$	1.4
PDF shape and yields of $B \to X_c D^*$	1.1
Reconstruction efficiency ratio $\varepsilon_{\rm norm}/\varepsilon_{\rm sig}$	1.2
Modeling of semileptonic decay	0.2
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.2
Total systematic uncertainty	$^{+3.4}_{-3.5}$

Scales with MC statistics

Scales with DATA statistics

Theory/External

Irreducible
Requires additional studies

Belle@Hadronic(τ→h)

Source	$R(D^*)$	P_τ
Hadronic B composition	$^{+7.8\%}_{-6.9\%}$	$^{+0.14}_{-0.11}$
MC statistics for each PDF shape	$^{+3.5\%}_{-2.8\%}$	$^{+0.13}_{-0.11}$
Fake D^* PDF shape	3.0%	0.010
Fake D^* yield	1.7%	0.016
$\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell$	2.1%	0.051
$\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau$	1.1%	0.003
$\bar{B} \to D^*\ell^-\bar{\nu}_\ell$	2.4%	0.008
τ daughter and ℓ^- efficiency	2.1%	0.018
MC statistics for efficiency calculation	1.0%	0.018
EvtGen decay model	$^{+0.8\%}_{-0.0\%}$	$^{+0.016}_{-0.000}$
Fit bias	0.3%	0.008
$\mathcal{B}(\tau^- \to \pi^-\nu_\tau)$ and $\mathcal{B}(\tau^- \to \rho^-\nu_\tau)$	0.3%	0.002
P_τ correction function	0.1%	0.018
Common sources		
Tagging efficiency correction	1.4%	0.014
D^* reconstruction	1.3%	0.007
D sub-decay branching fractions	0.7%	0.005
Number of $B\bar{B}$	0.4%	0.005
Total systematic uncertainty	$^{+10.4\%}_{-9.5\%}$	$^{+0.20}_{-0.17}$

Belle II prospects

- At least 3 independent measurements of R(D*) with similar statistical and systematic uncertainties
  - **5 ab^{-1}: 2% (stat.) ± 2% (syst.)**
  - **50 ab^{-1}: 1% (stat.) ± 2% (syst.)**

$$R(D^*)$$

- At least 1 measurement of R(D)
  - **5 ab^{-1}: 5% (stat.) ± 3% (syst.)**
  - **50 ab^{-1}: 2% (stat.) ± 3% (syst.)**

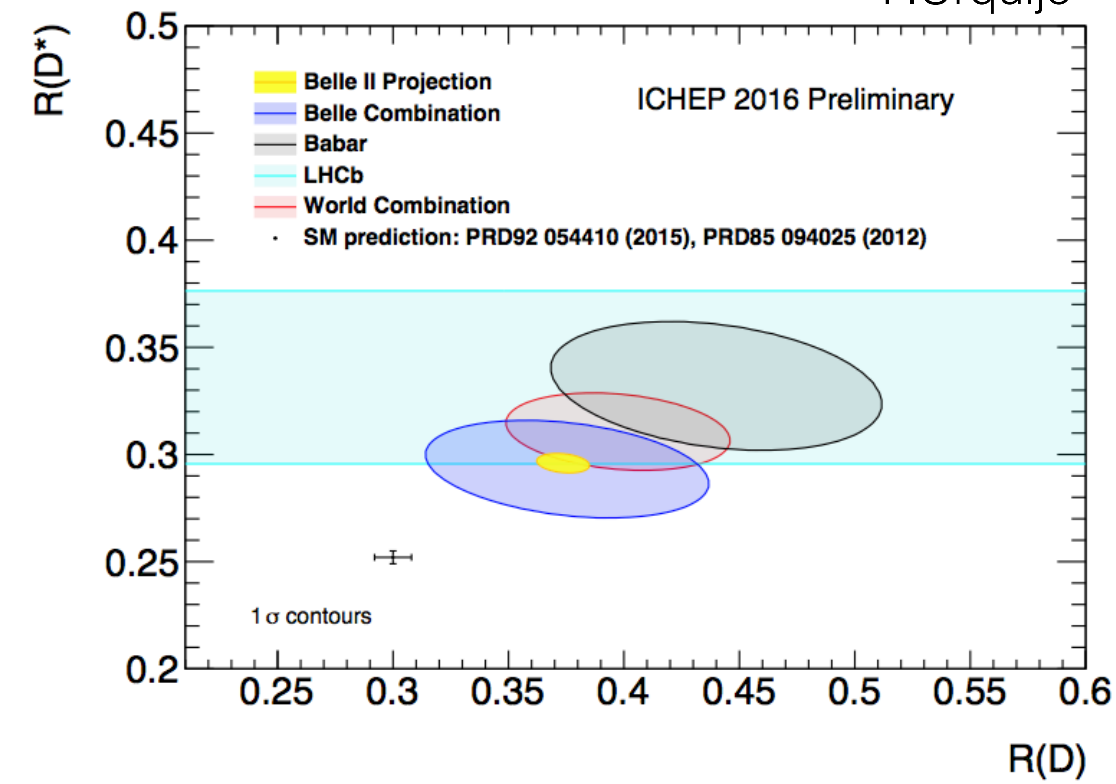
$$R(D)$$

- At least 1 measurement of P_τ
  - **50 ab^{-1}: ± 0.11 (total)**

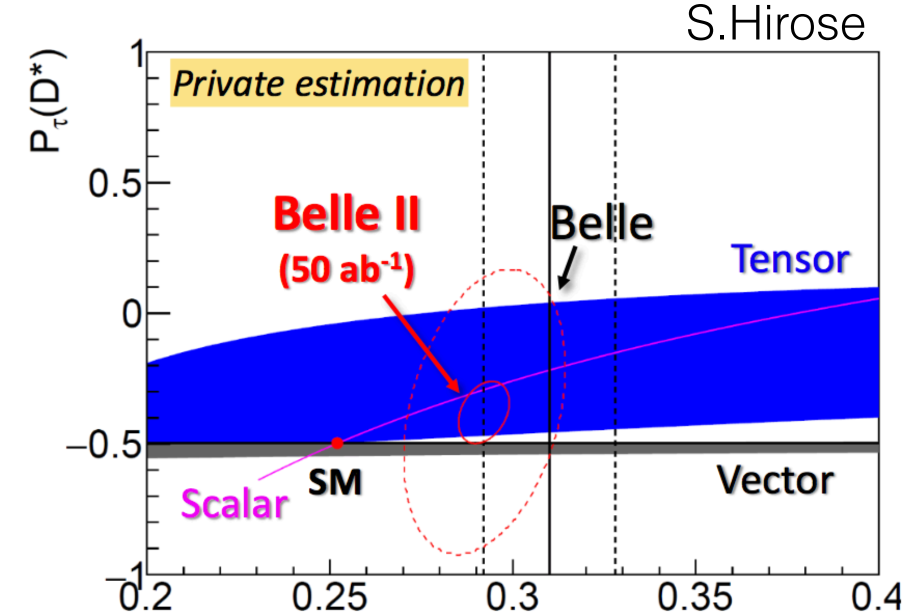
$$P_\tau$$

- D* polarisation measurement is also possible
- And measurements of various kinematic spectra

P.Urquijo



S.Hirose

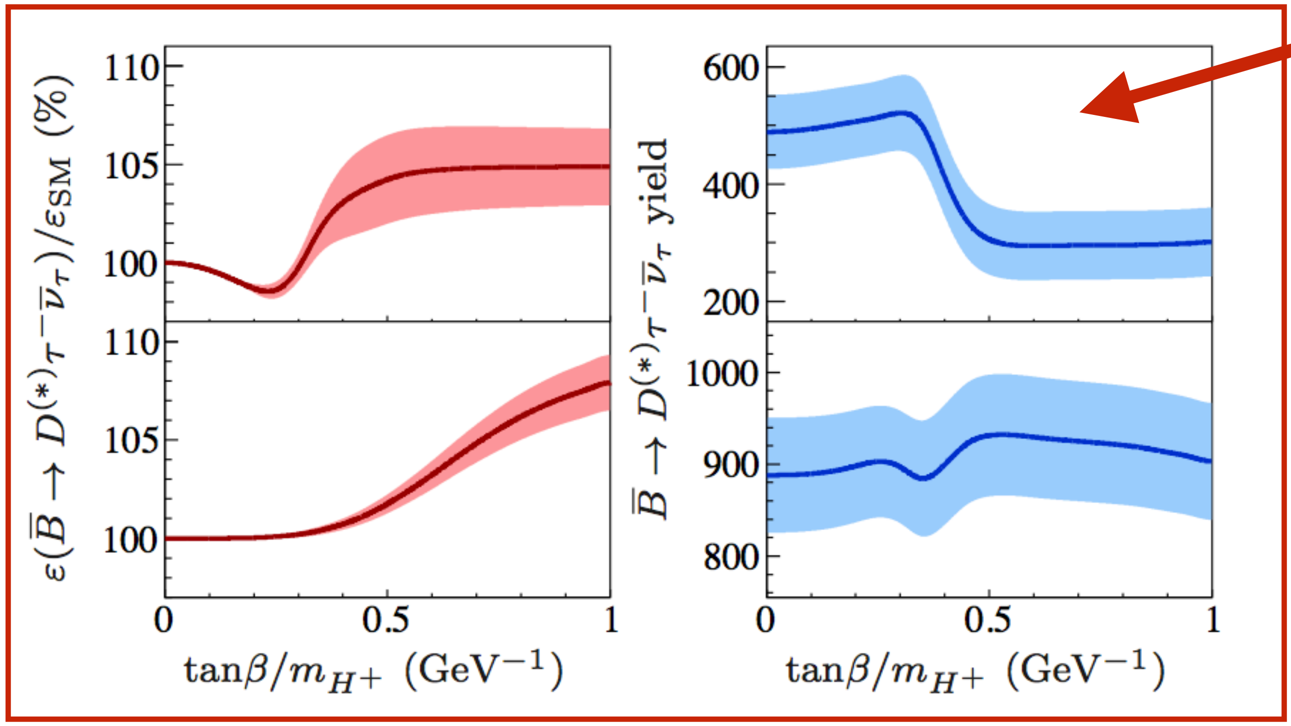


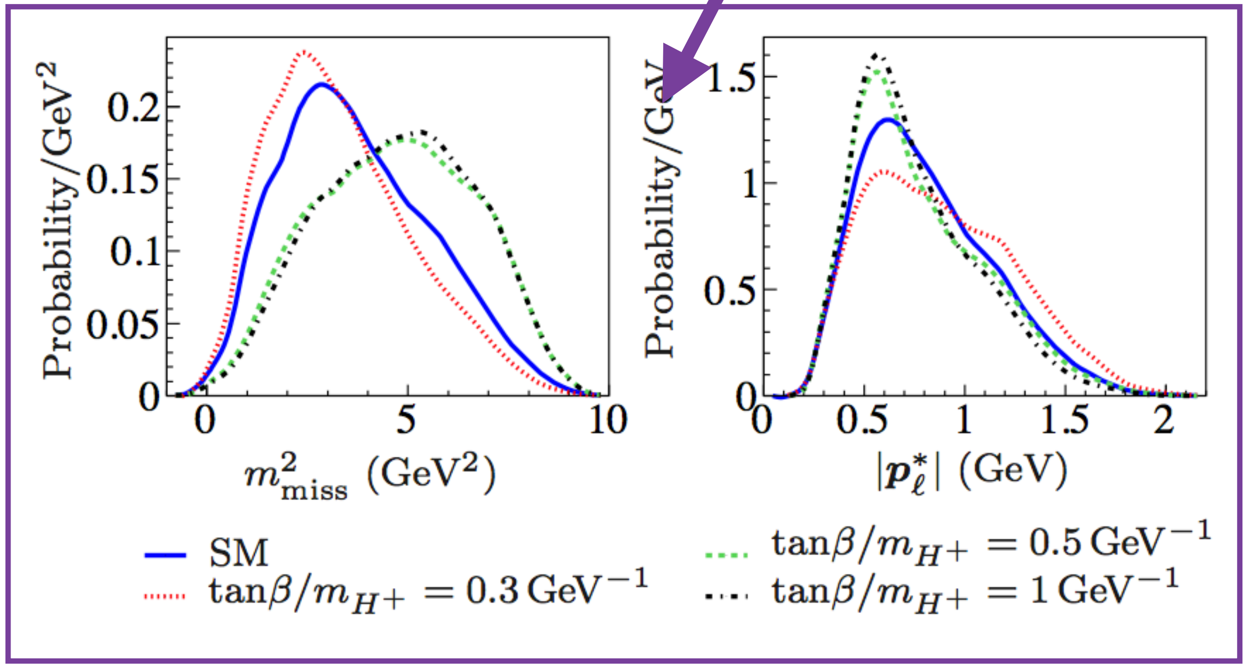
Theoretical calculation based on M. Tanaka and R. Watanabe, Phys. Rev. D 87, 034028 (2013)

New Physics contributions? $R(D^{(*)})$

Model dependent analysis (type-II 2HDM)

- kinematics of the decays depend on NP model and its free parameters
  - difference in kinematics → difference in efficiency and fitted distributions



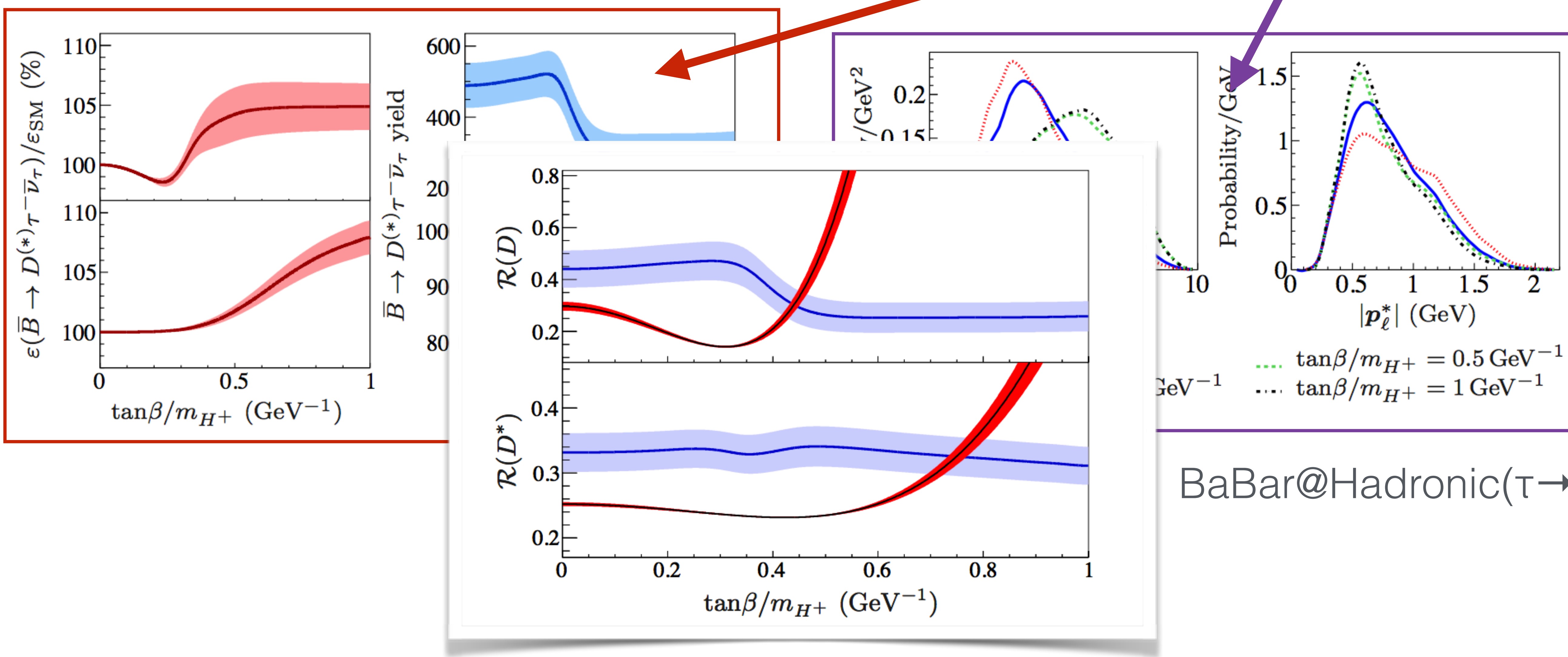


BaBar@Hadronic(τ→l)

New Physics contributions? $R(D^{(*)})$

Model dependent analysis (type-II 2HDM)

- kinematics of the decays depend on NP model and its free parameters
  - difference in kinematics → difference in efficiency and fitted distributions

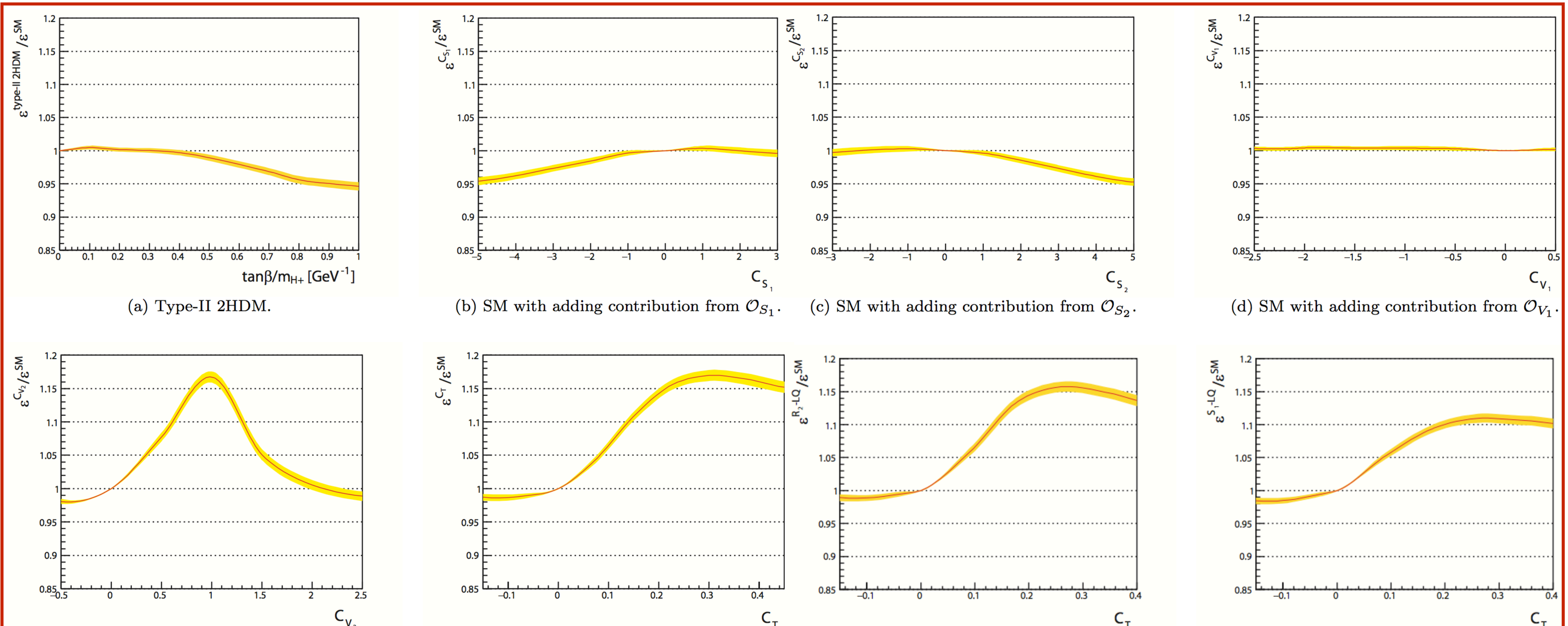


BaBar@Hadronic(τ→l)

New Physics contributions? $R(D^{(*)})$

Model independent analysis

- examine the impact of each operator
  - difference in kinematics → difference in efficiency and fitted distributions



(a) Type-II 2HDM.

(b) SM with adding contribution from $\mathcal{O}_{S_1}$.

(c) SM with adding contribution from $\mathcal{O}_{S_2}$.

(d) SM with adding contribution from $\mathcal{O}_{V_1}$.

(e) SM with adding contribution from $\mathcal{O}_{V_2}$.

(f) SM with adding contribution from $\mathcal{O}_T$.

(g) R_2-type leptoquark model.

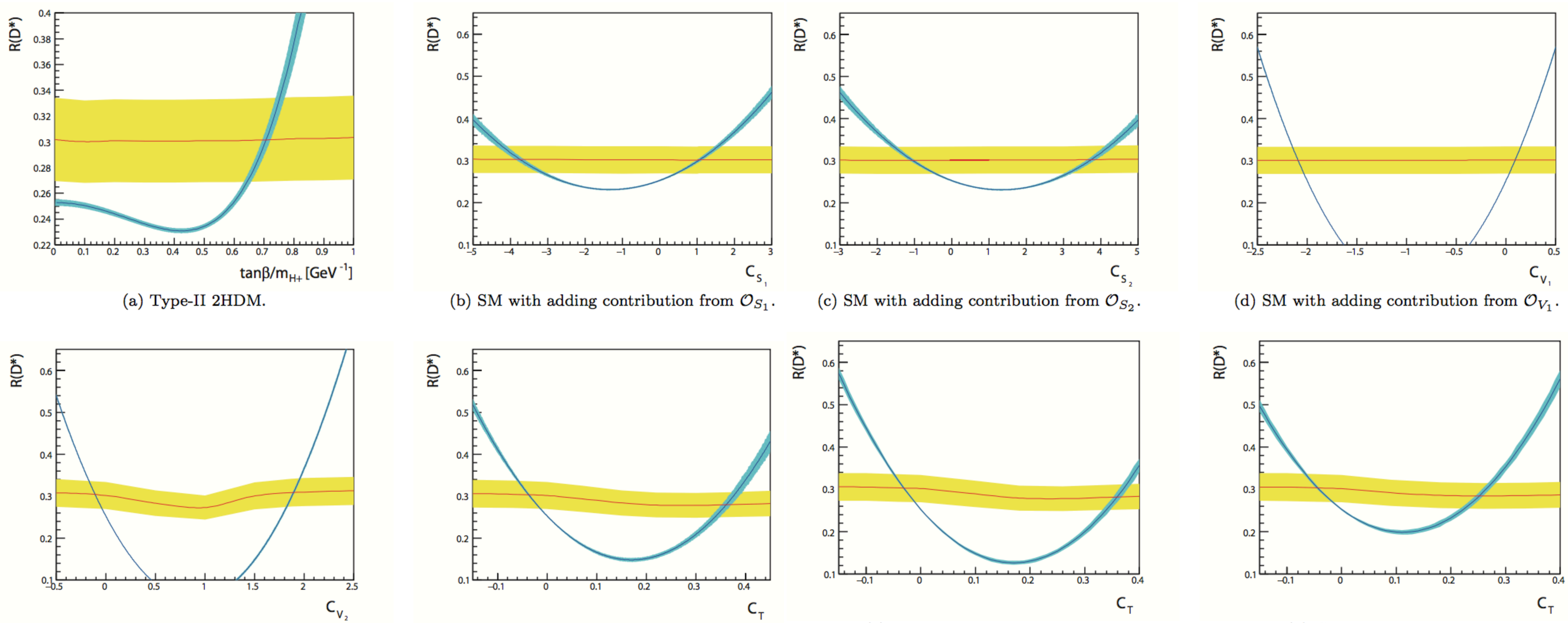
(h) S_1-type leptoquark model.

2

New Physics contributions? $R(D^{(*)})$

Model independent analysis

- examine the impact of each operator
  - difference in kinematics → difference in efficiency and fitted distributions



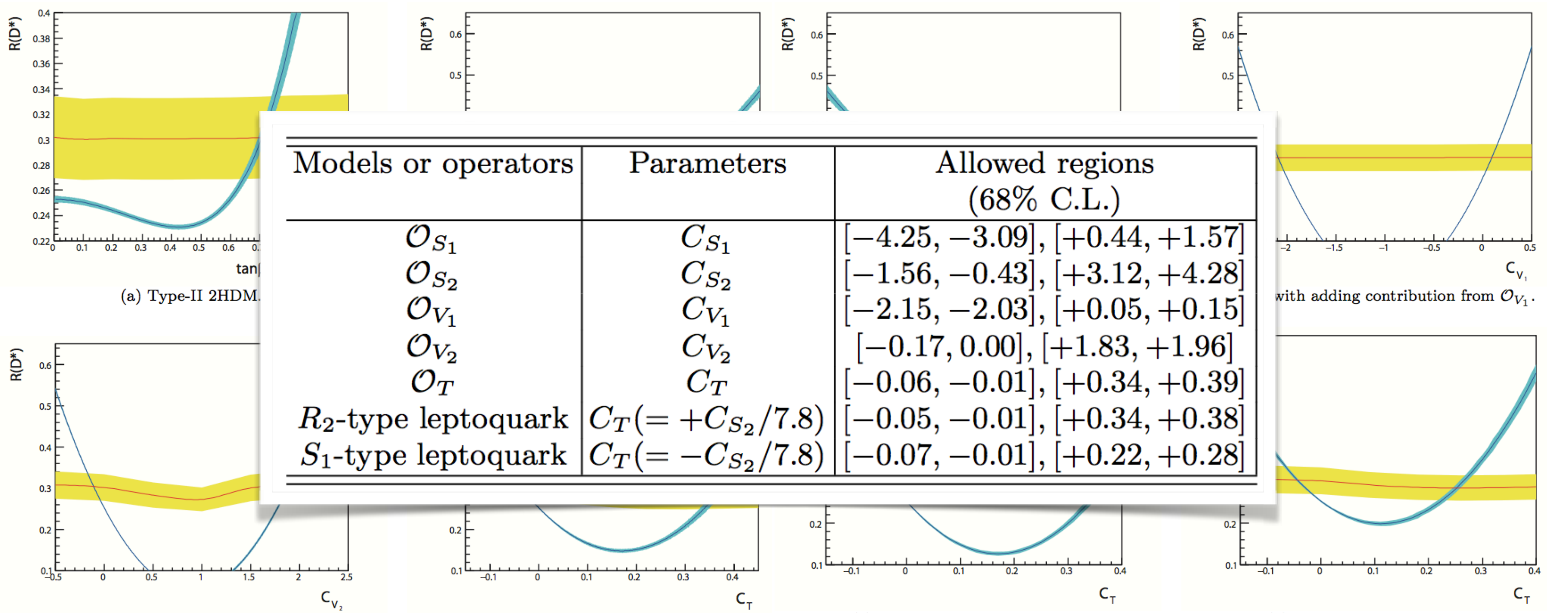
(a) Type-II 2HDM.
(b) SM with adding contribution from $\mathcal{O}_{S_1}$.
(c) SM with adding contribution from $\mathcal{O}_{S_2}$.
(d) SM with adding contribution from $\mathcal{O}_{V_1}$.
(e) SM with adding contribution from $\mathcal{O}_{V_2}$.
(f) SM with adding contribution from $\mathcal{O}_{T}$.
(g) R_2-type leptoquark model.
(h) S_1-type leptoquark model.

3

New Physics contributions? $R(D^{(*)})$

Model independent analysis

- examine the impact of each operator
  - difference in kinematics → difference in efficiency and fitted distributions



(a) Type-II 2HDM.

with adding contribution from $\mathcal{O}_{V_1}$.

(e) SM with adding contribution from $\mathcal{O}_{V_2}$.

(f) SM with adding contribution from $\mathcal{O}_T$.

(g) R_2-type leptoquark model.

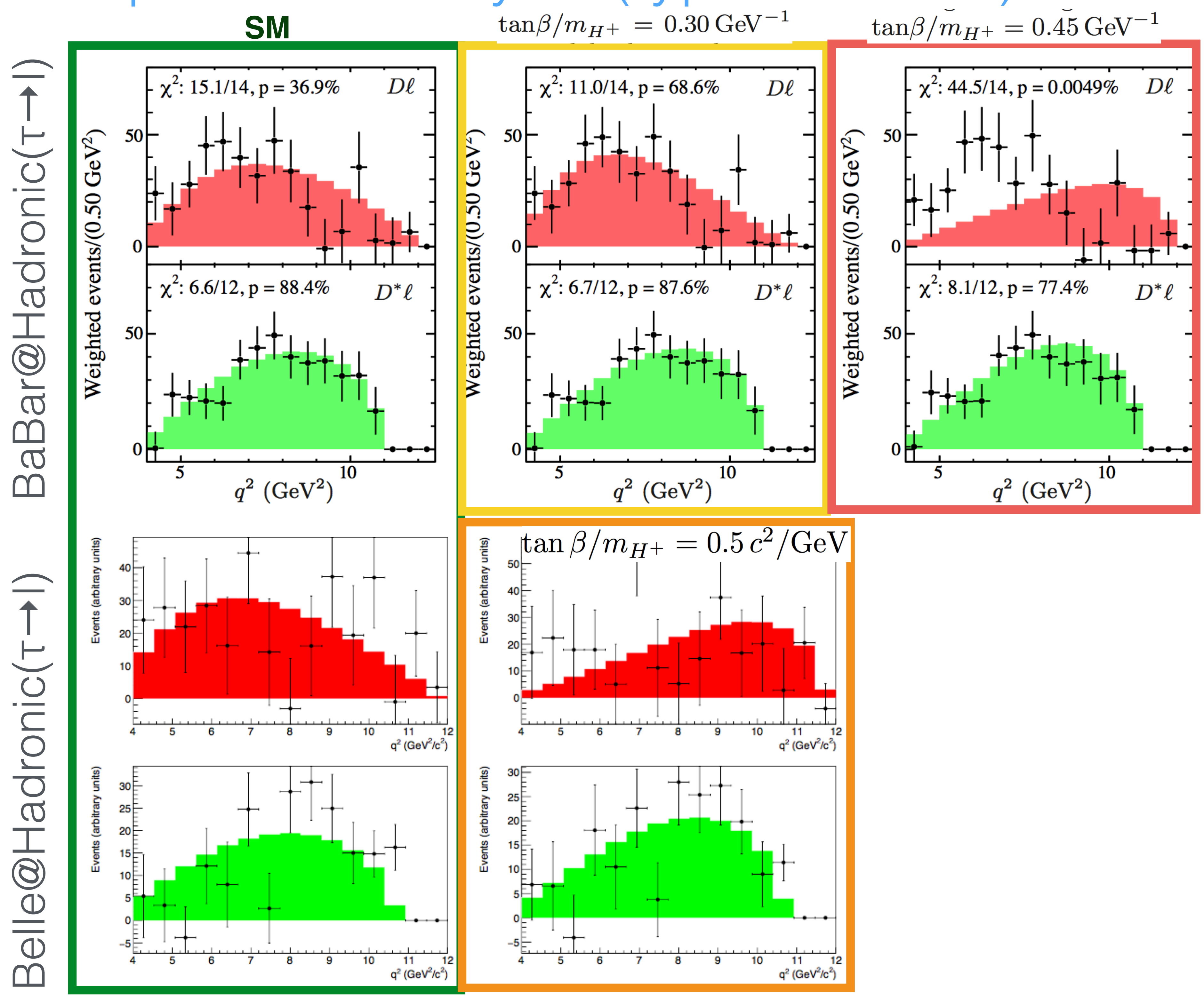
(h) S_1-type leptoquark model.

3

Models or operators	Parameters	Allowed regions (68% C.L.)
$\mathcal{O}_{S_1}$	C_{S_1}	$[-4.25, -3.09]$, $[+0.44, +1.57]$
$\mathcal{O}_{S_2}$	C_{S_2}	$[-1.56, -0.43]$, $[+3.12, +4.28]$
$\mathcal{O}_{V_1}$	C_{V_1}	$[-2.15, -2.03]$, $[+0.05, +0.15]$
$\mathcal{O}_{V_2}$	C_{V_2}	$[-0.17, 0.00]$, $[+1.83, +1.96]$
$\mathcal{O}_T$	C_T	$[-0.06, -0.01]$, $[+0.34, +0.39]$
R_2-type leptoquark	$C_T(= +C_{S_2}/7.8)$	$[-0.05, -0.01]$, $[+0.34, +0.38]$
S_1-type leptoquark	$C_T(= -C_{S_2}/7.8)$	$[-0.07, -0.01]$, $[+0.22, +0.28]$

New Physics contributions? q^2

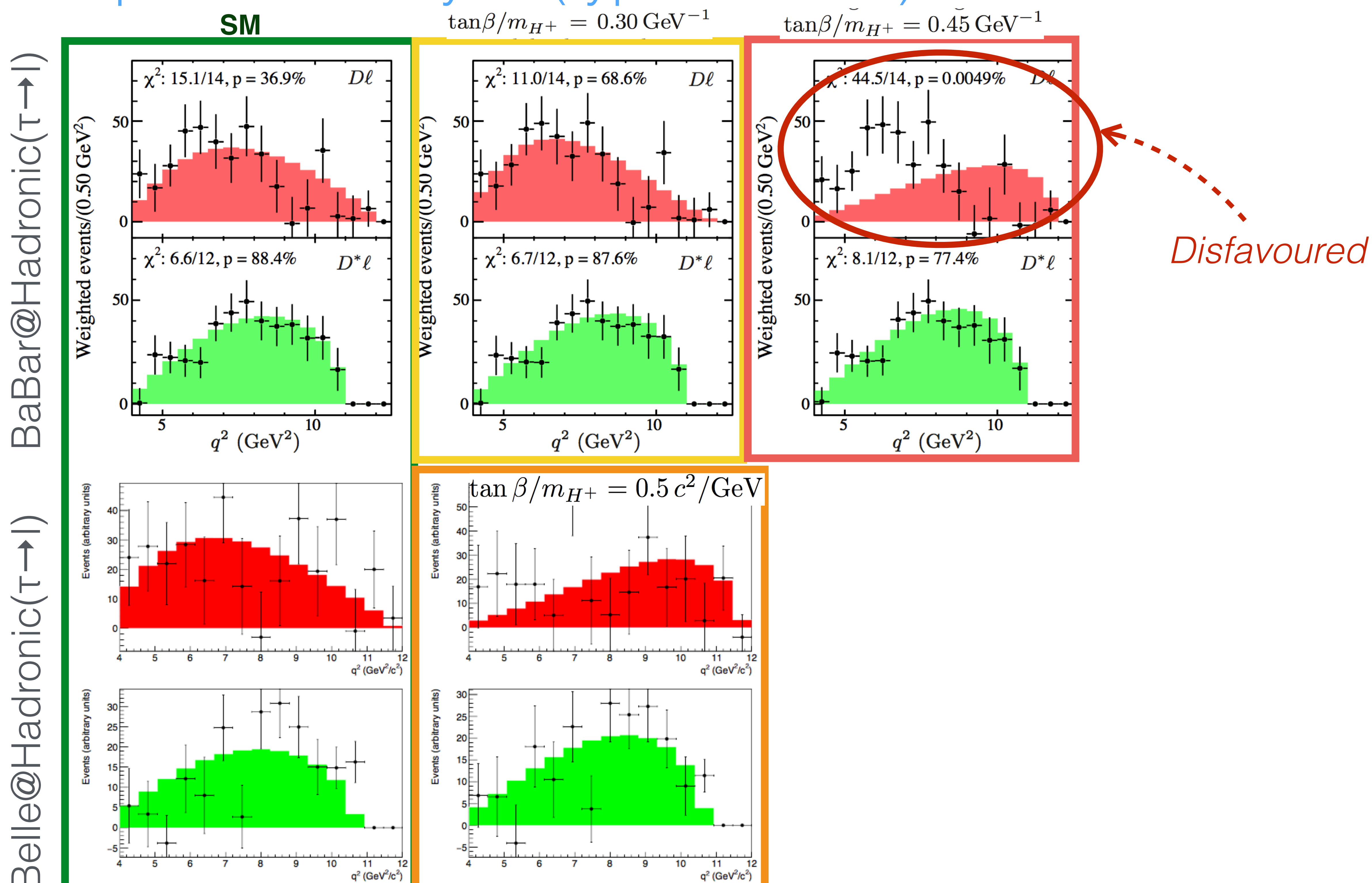
Model dependent analysis (type-II 2HDM)



New Physics contributions?

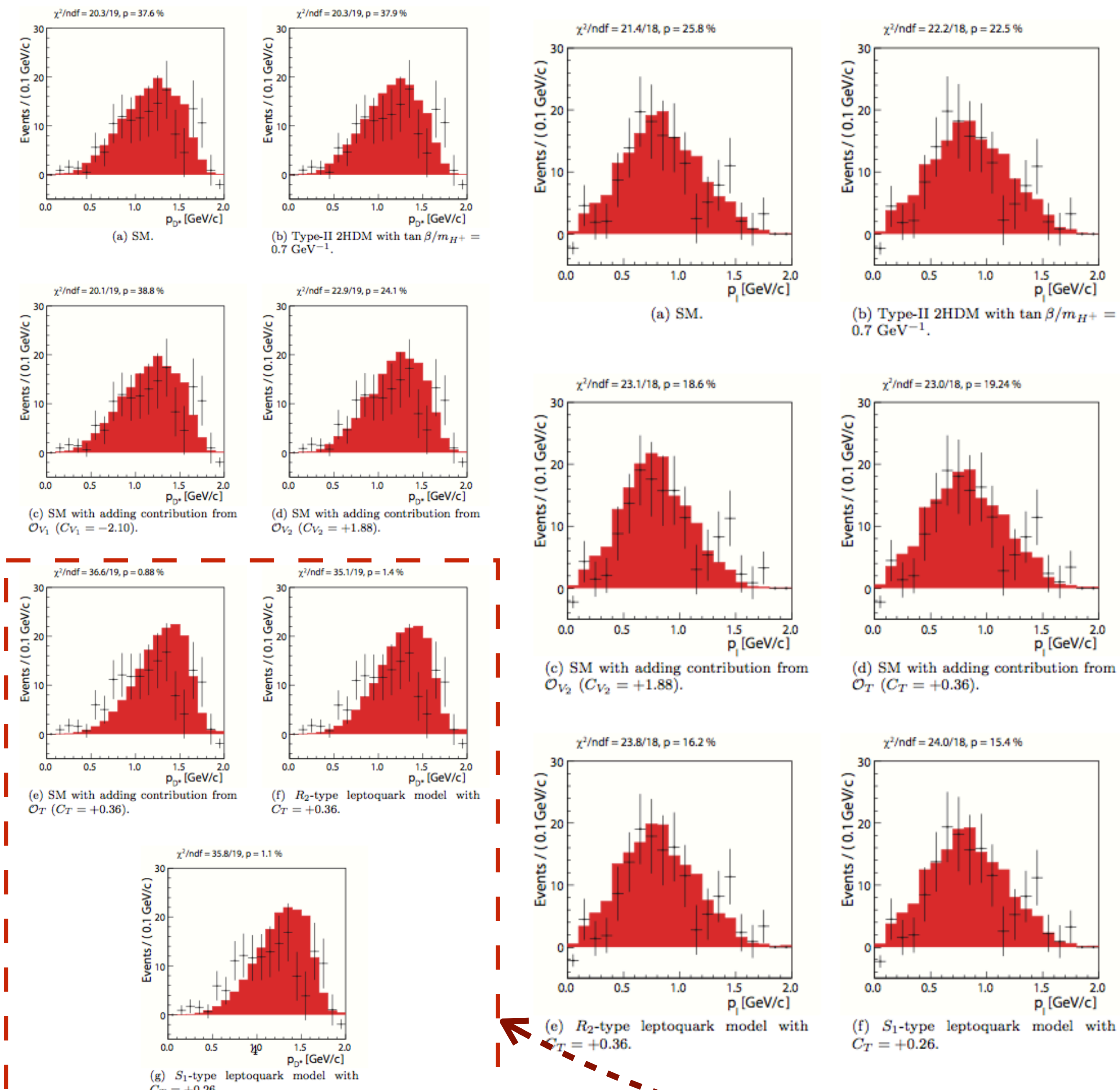
q^2

Model dependent analysis (type-II 2HDM)



New Physics contributions? $|p^*_\ell|, \ |p^*_{D^*}|$

Model independent analysis



Belle@Semileptonic(τ→l)

Model or operator	Parameter	p values [%]	
		p_{D^*}	p_ℓ
SM		37.6	25.8
Type-II 2HDM	$\frac{\tan\beta}{m_{H^+}} = 0.7\ \mathrm{GeV}^{-1}$	37.9	22.5
$\mathcal{O}_{V_2}$	$C_{V_2} = +1.88$	24.1	18.6
$\mathcal{O}_T$	$C_T = +0.36$	0.9	19.2
R_2-type leptoquark model	$C_T = +0.36$	1.4	16.2
S_1-type leptoquark model	$C_T = +0.26$	1.1	15.4

Large additional contributions from tensor operator or R2-(S1)-type leptoquark models are disfavoured.

Conclusions

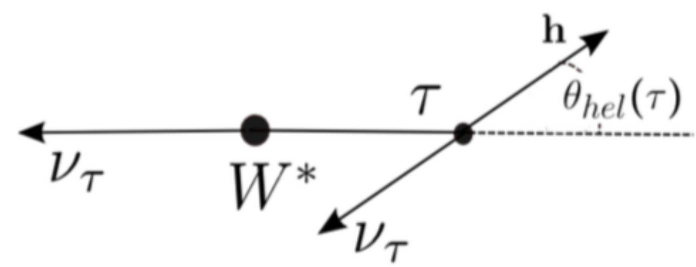
- B-factories are excellent laboratory for studies of leptonic and semileptonic B (and D) decays
- Large Belle II data sample will help to disentangle the discrepancies wrt. SM predictions seen in $b \to c\tau\nu$ decays
    - but will require a lot of additional work ($B \to D^{**}l\nu$)

Most of the material and Belle II projections are found in *Belle II Theory Interface Platform* report (in preparation)

Tau Polarimeters (hadronic decays)

- $\cos\theta_{hel}(\tau)$ distribution in (quasi)2-body decays $\tau \to M\nu_\tau$
- τ polarization measurment based on $\cos\theta_{hel}(\tau)$ distribution:

$$\frac{d\Gamma}{d\cos\theta_{hel}(\tau)} \sim \frac{1}{2}(1 + \alpha P_\tau \cos\theta_{hel}(\tau))$$



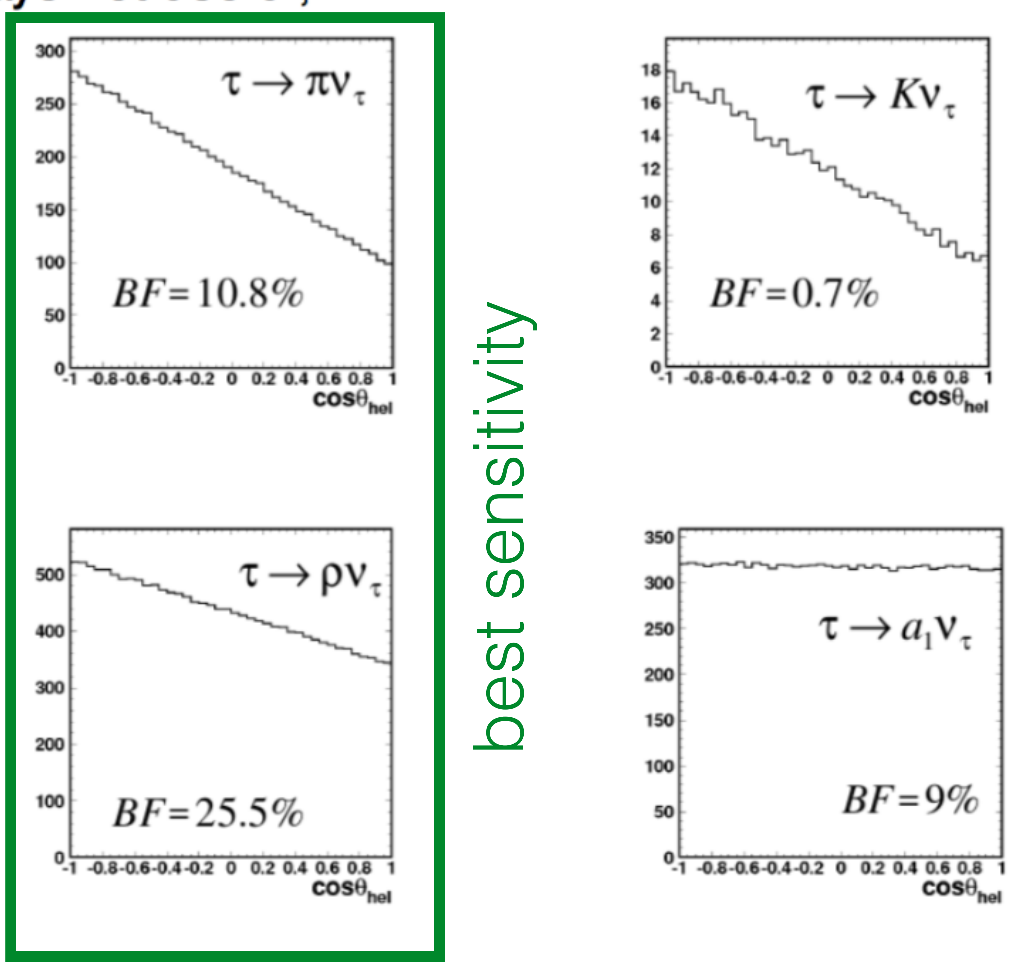
- **SM: $P_\tau \approx$ -0.5**
- leptonic τ decays not useful;

for $J_M = 0$

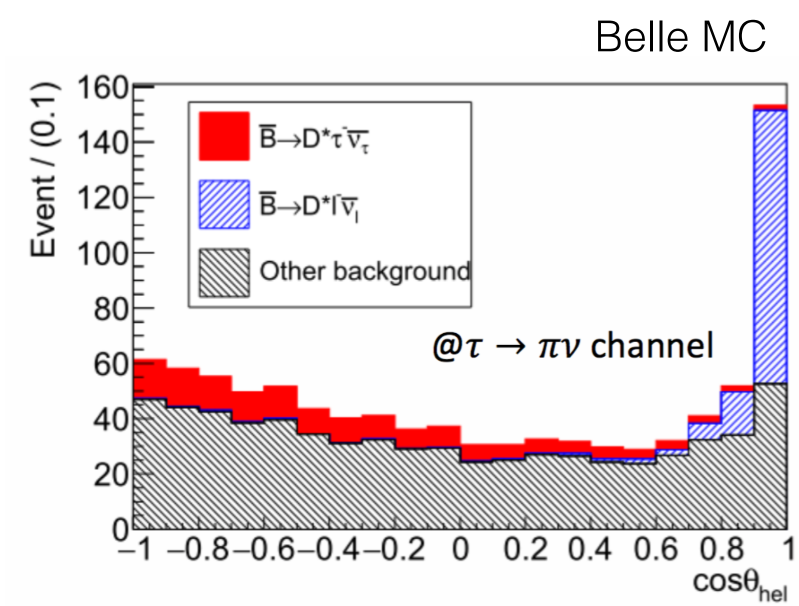
$\alpha = 1$

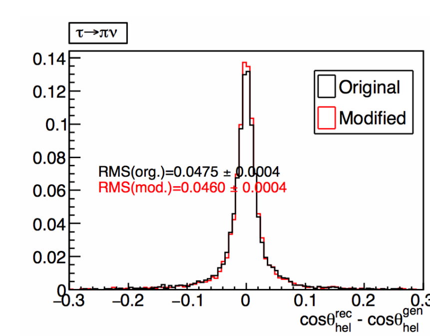
for $J_M = 1$

$$\alpha = \frac{m_\tau^2 - m_M^2}{m_\tau^2 + m_M^2}$$



$\alpha = 0.45$ for $\tau \to \rho\nu$ $\alpha = 0.12$ for $\tau \to a_1\nu$



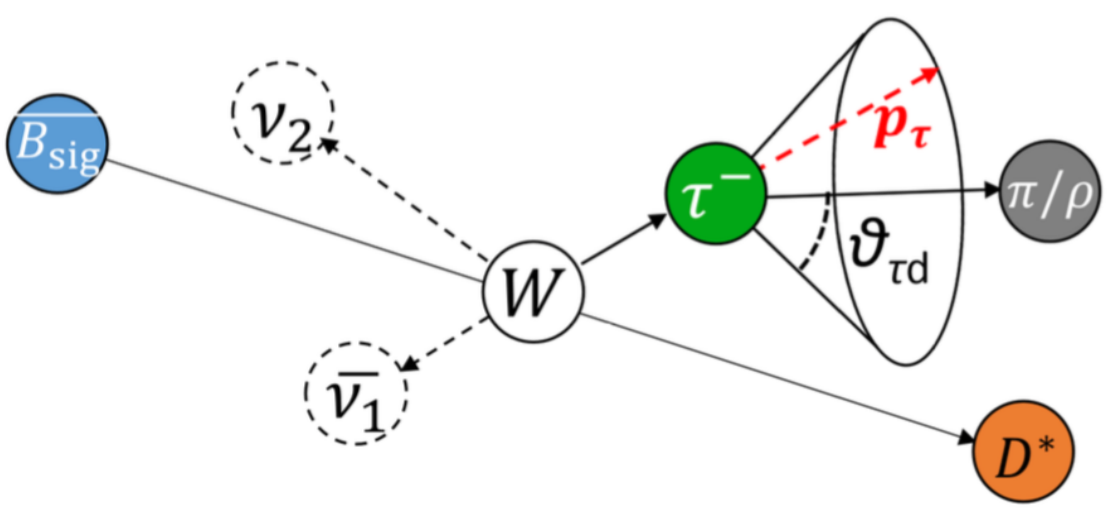


Tau Polarimeters (hadronic decays)

Experimental challenges:

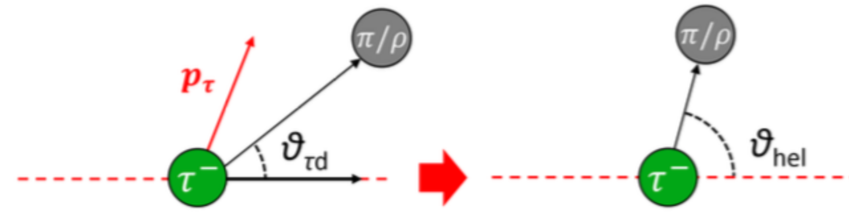
- due to multiple neutrinos in the final state the tau momentum can not be completely determined
- go to W rest frame, where $p_W = p_{Bsig} - p_{D^*} = 0$
- in W rest frame the tau and neutrino from B decay are back-to-back, therefore:
  - magnitude of tau momentum ($|p_\tau|$) can be determined $|\vec{p}_\tau| = \frac{q^2 - m_\tau^2/c^2}{2\sqrt{q^2}}$
  - direction of the tau momentum is constrained to lie on the cone around the hadron daughter momentum

$$\cos\theta_{\tau d} = \frac{2E_\tau E_{\mathrm{da}} - m_\tau^2 - m_{\mathrm{da}}^2}{2|\boldsymbol{p}_\tau||\boldsymbol{p}_{\mathrm{da}}|}$$



Decay kinematics of the $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$ decay in the W rest frame

Boost in arbitrary direction on the cone to get into the tau rest frame



Semitauonic decays: Observables (I)

Ratio of branching fractions

$$R_{D^{(*)}} := \frac{\mathcal{B}(\bar{B} \to D^{(*)} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)} \ell^- \bar{\nu}_\ell)}$$

- benefits from cancelations
  - Vcb
  - hadronic matrix elements (theory)
  - experimental systematics

SM prediction

$$R(D) = 0.300 \pm 0.008$$

H. Na et al., Phys.Rev.D 92, 054410 (2015)

$$R(D^*) = 0.252 \pm 0.003$$

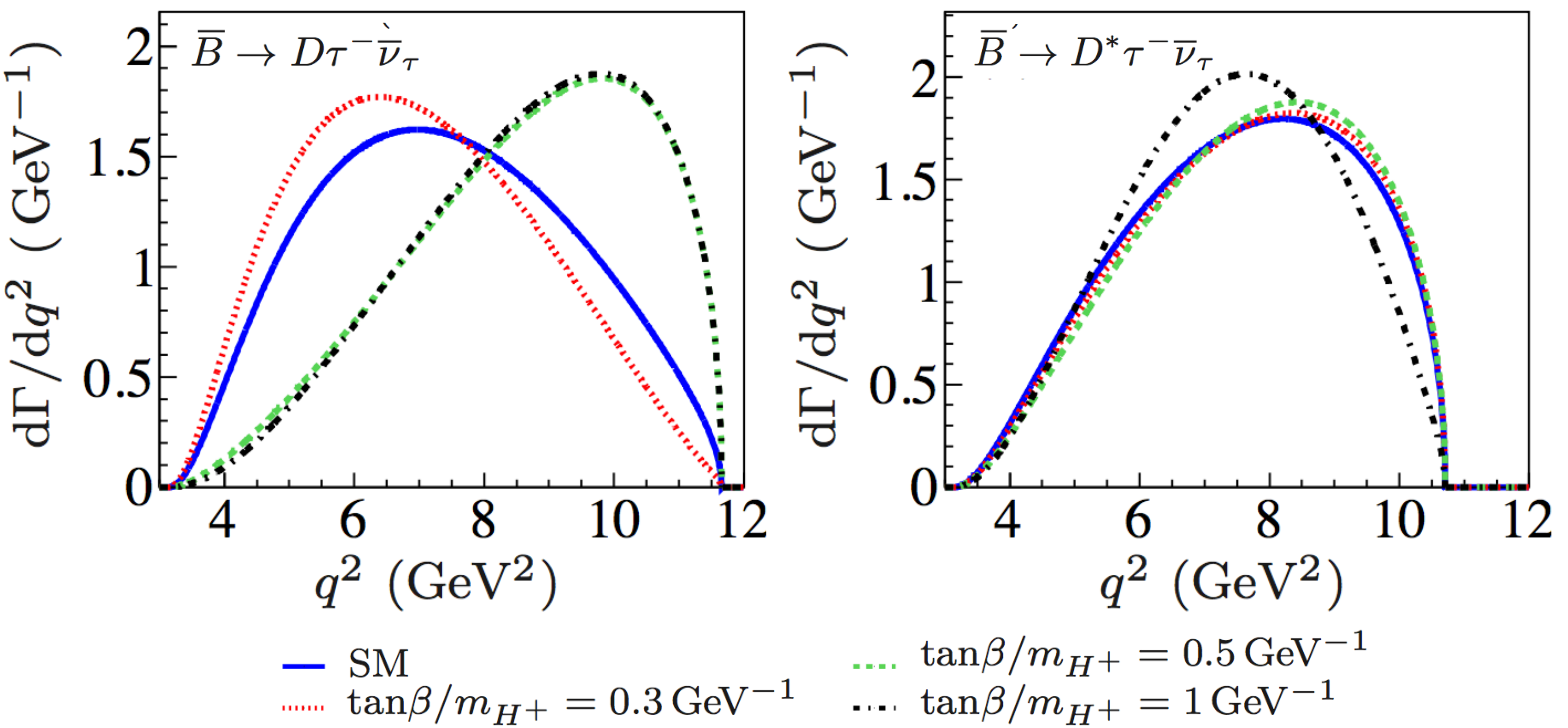
S.Fajfer, J.F.Kamenik, and I.Nisandzic, Phys.Rev.D85(2012) 094025

Semitauonic decays: Observables (II)

Kinematics of the decay

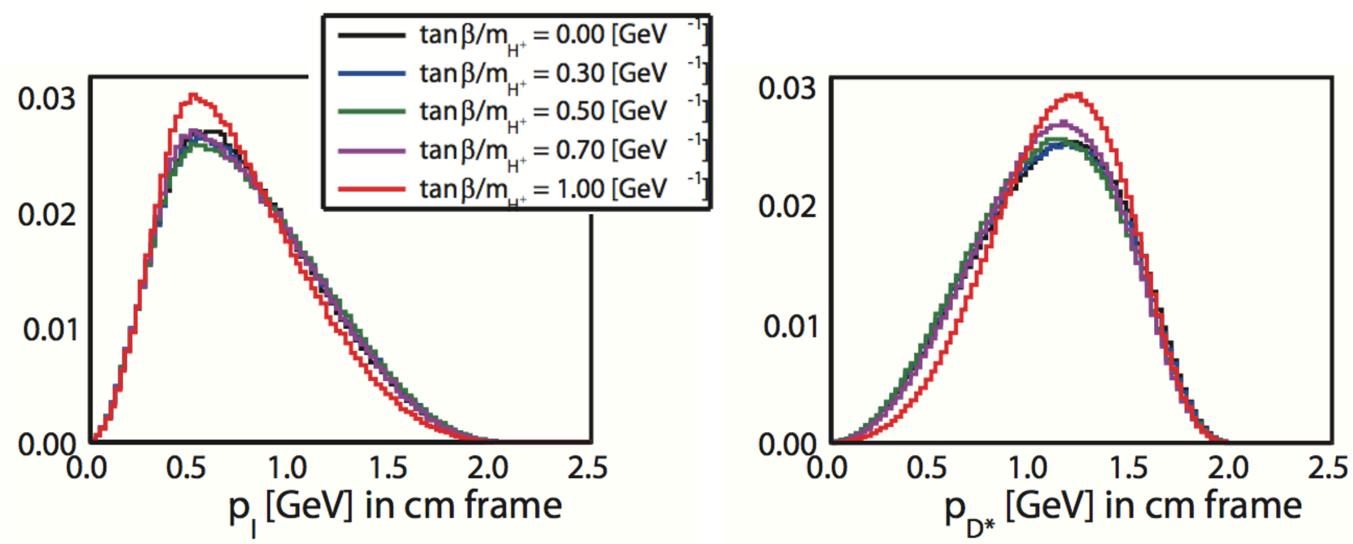
$$q^2 = (p_\tau + p_\nu)^2$$

SM and 2HDM predictions of q^2

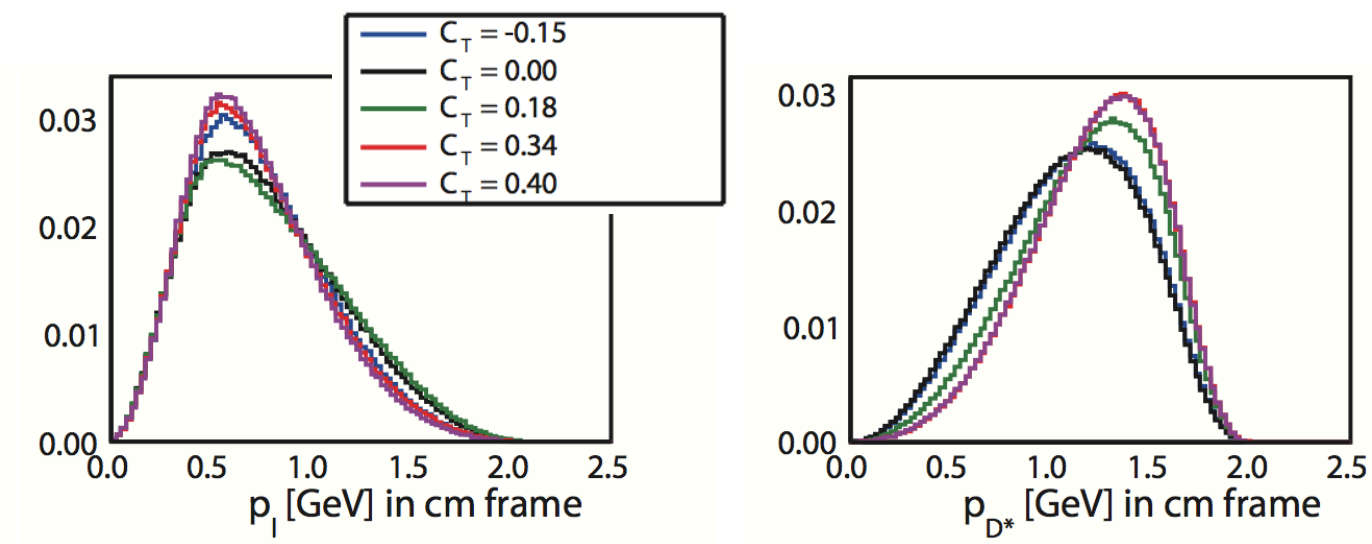


Semitauonic decays: Observables (III)

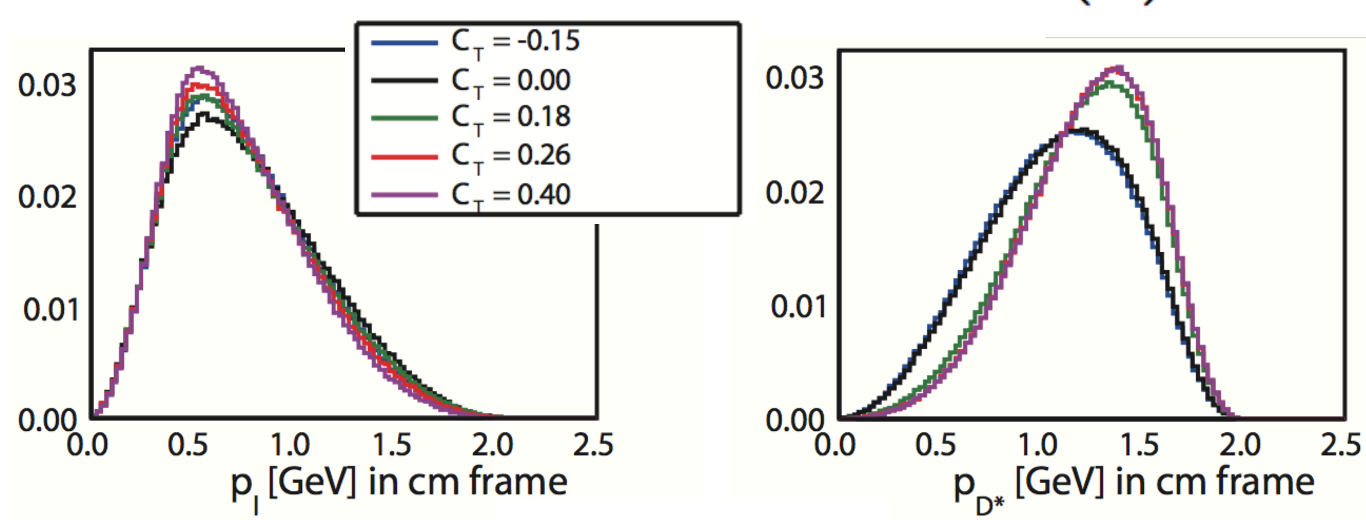
Kinematics of the decay $\quad p^*_{\ell(\tau)},\ p^*_{D^*}$



(a) Type-II 2HDM.



(b) R_2-LQ.

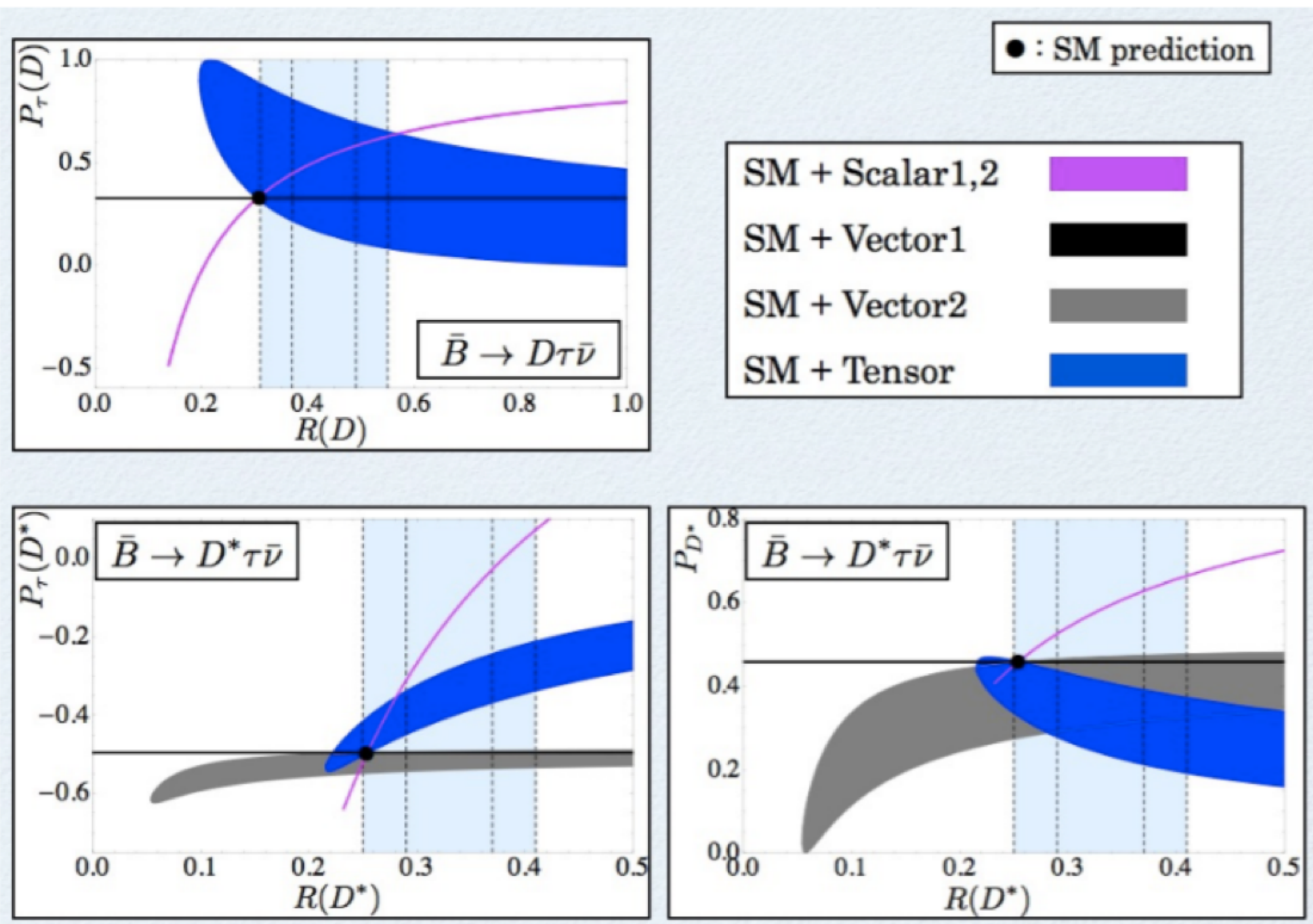


(c) S_1-LQ.

Semitauonic decays: Observables (IV)

Tau polarisation

Examples of correlations between τ and D^* polarization and BF ratio (R(D$^{(*)}$));



$$P_\tau = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

$\Gamma^\pm$ denotes the decay rate of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ with a τ helicity of $\pm 1/2$.

SM prediction

$P_\tau = 0.325 \pm 0.009$ for $\bar{B} \to D\tau^-\bar{\nu}_\tau$

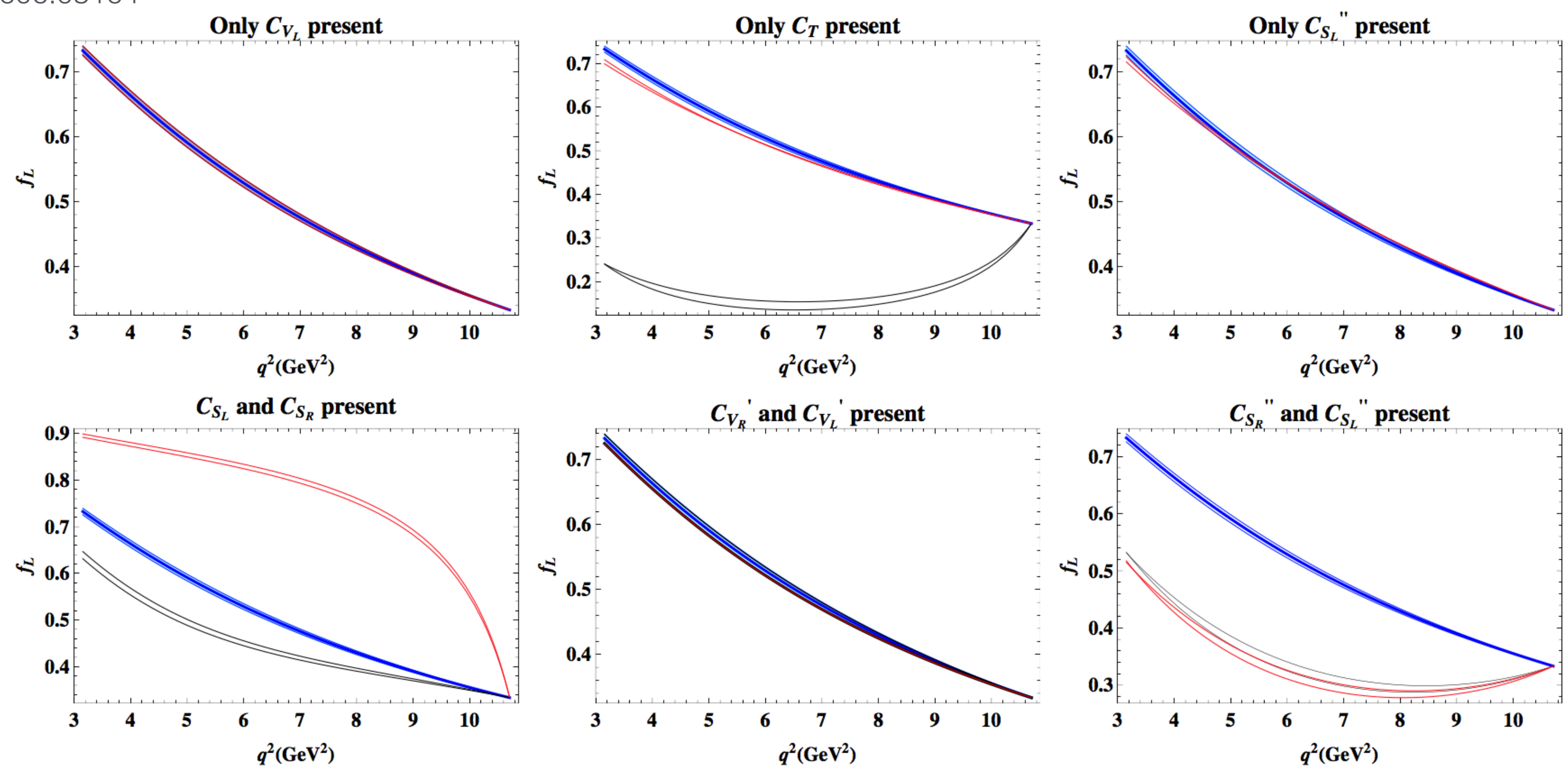
$P_\tau = -0.497 \pm 0.013$ for $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$

M.Tanaka, R.Watanabe Phys. Rev. D87 (2013), 034028

Semitauonic decays: Observables (V)

D^* polarisation fraction in $\overline{B} \to D^* \tau^- \overline{\nu}_\tau$ $\quad f_L(q^2)$

arxiv:1606.03164



SM contributions in all plots shown in BLUE, red and black show SM + various NP