Exclusive B decays with τ's @ Belle II

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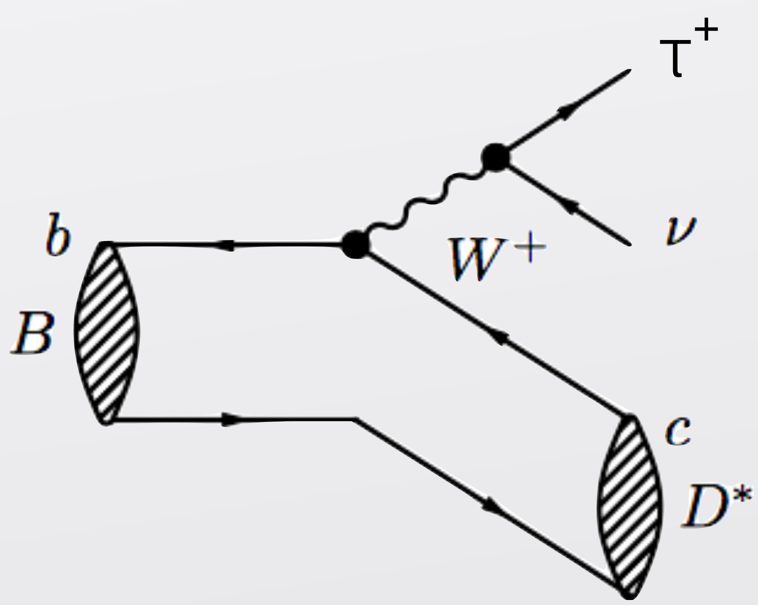
Challenges in Semileptonic B Decays

MITP - 10/04/2018

Outline

- Analysis strategies at B factories
- Recent measurements
- Systematics overview
- Reconstruction methods @ Belle II
- Naive prospects @ Belle II
- New physics probes

Motivation for B ⟶ D(*) τ ν measurements



$$\mathcal{R}(D^{(*)}) = \frac{\overbrace{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu}_\tau)}^{\text{signal mode}}}{\underbrace{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu}_\ell)}_{\text{normalization mode}}} \qquad \ell = (e, \mu)$$

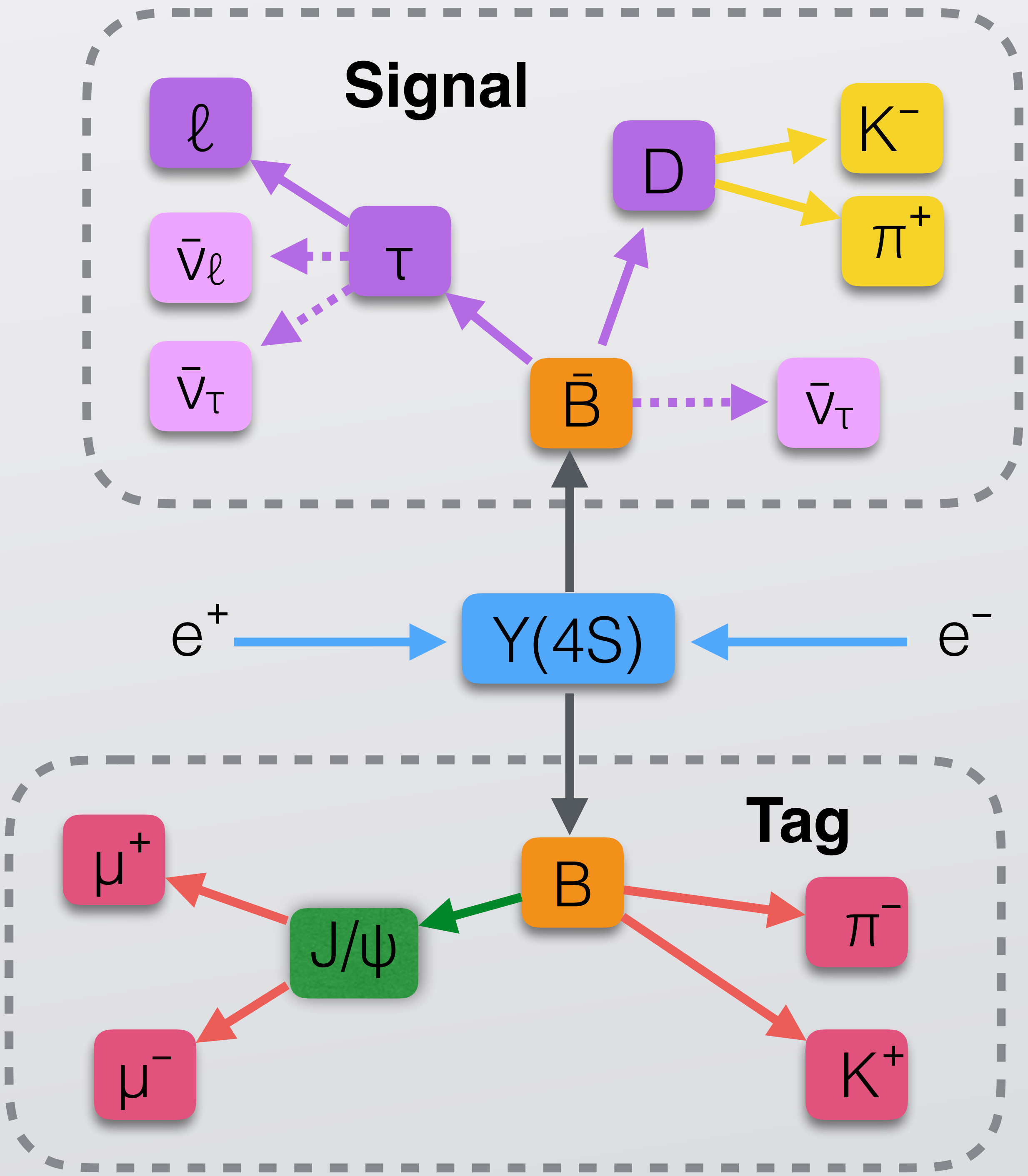
- W coupling to leptons is universal in the SM
- A charged Higgs would couple more strongly to the τ lepton and produce an enhancement in BR of B decays that involve a τ lepton
- Ratios R(D(*)) eliminate many sources of systematic errors for experimental measurements and theoretical predictions

Previous measurements

Experimen	Tag method	τ	R_D	R_{D^*}	ϱ
Belle 07*	Inclusive	e ν ν, π	0.38±0.11	0.34±0.08	-
Belle 10*	Inclusive	l ν ν, π			
Babar 12	Hadronic	l ν ν	0.440±0.058±0.042	0.332±0.024±0.018	-0.27
Belle 15	Hadronic	l ν ν	0.375±0.064±0.026	0.293±0.038±0.015	-0.32
Belle 16	Semileptonic	l ν ν	-	0.302±0.030±0.011	-
Belle 17	Hadronic	π ν, ϱ ν	-	0.270±0.035±0.027	-
LHCb 16	-	l ν ν	-	0.336±0.027±0.030	-
LHCb 17	-	π π π	-	0.285±0.019±0.029	-
Belle ave.	SL+Had	-	0.374±0.061	0.296±0.022	-0.29
HFAG	-	-	0.403±0.040±0.024	0.310±0.015±0.008	-0.23

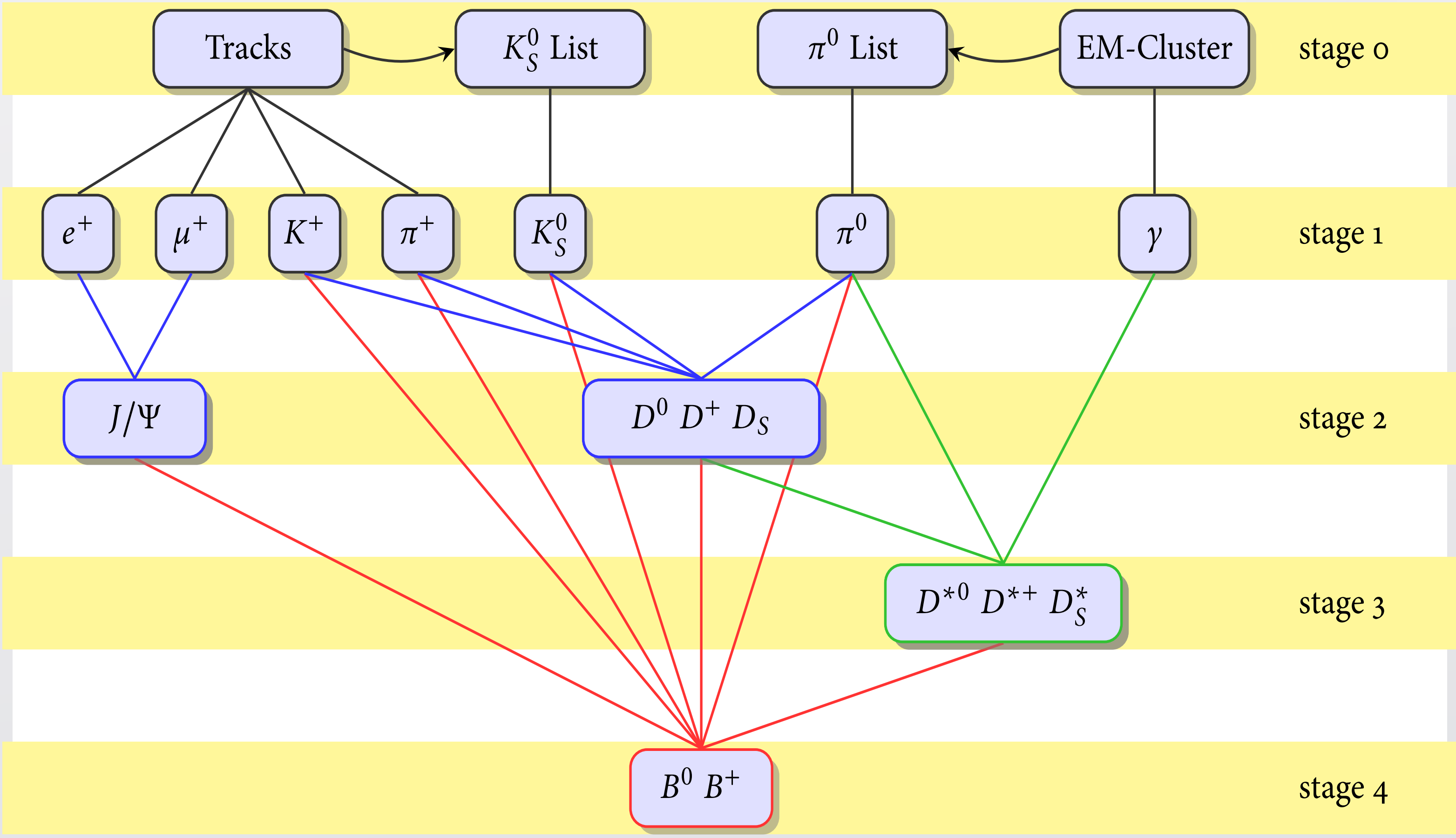
Tagging in Belle II

- e+e- ⟶ Υ(4S) ⟶ $B\bar{B}$: very clean and well-known initial state
- Reconstruct one of the B mesons in the Υ(4S) event (**B tag**) to gather information about the B decay of interest
- Hadronic B decays:
  PRO: full B reconstruction, high purity
  CON: low efficiency
  ~5000 channels
- Semileptonic B decays:
  PRO: high efficiency
  CON: one missing neutrino, low purity
  ~100 channels



Tagging in Belle II - Hadronic

- Tagging is done using a hierarchical multivariate analysis approach
- The B tag signal probability depends on the signal probabilities of all daughters
- The last tagging algorithm developed by Belle II (FEI) shows large improvement w.r.t previous methods
  - Can also be used on Belle data !



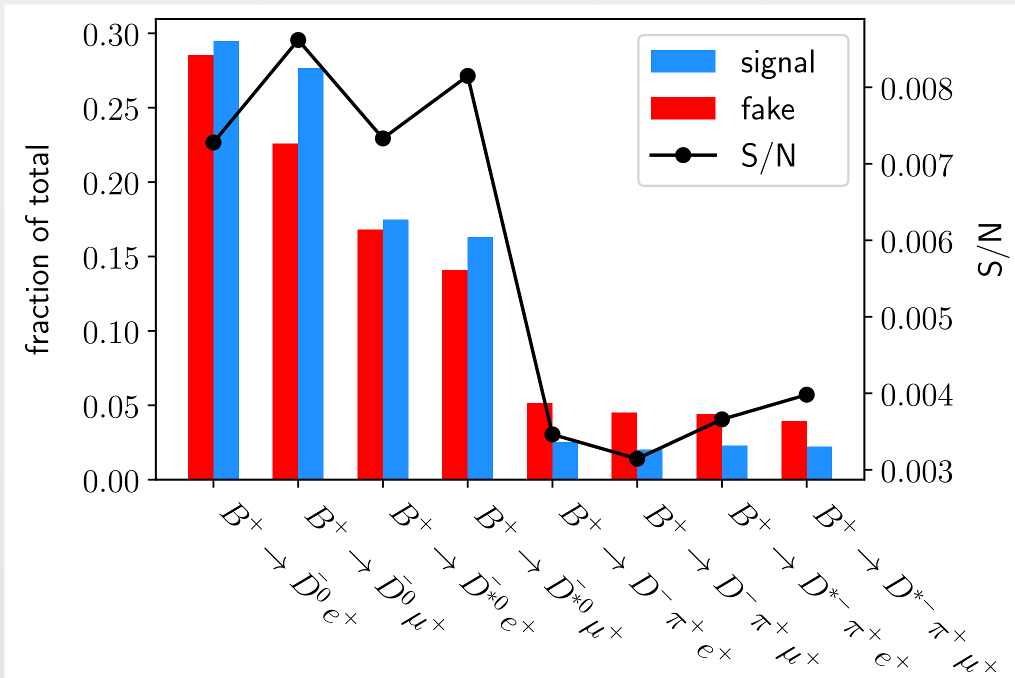
Algorithm	MVA type	Efficiency	Purity
NB (Belle)	NeuroBayes	0.2%	0.25%
FEI (Belle II)	FastBDT	0.5%	0.25%

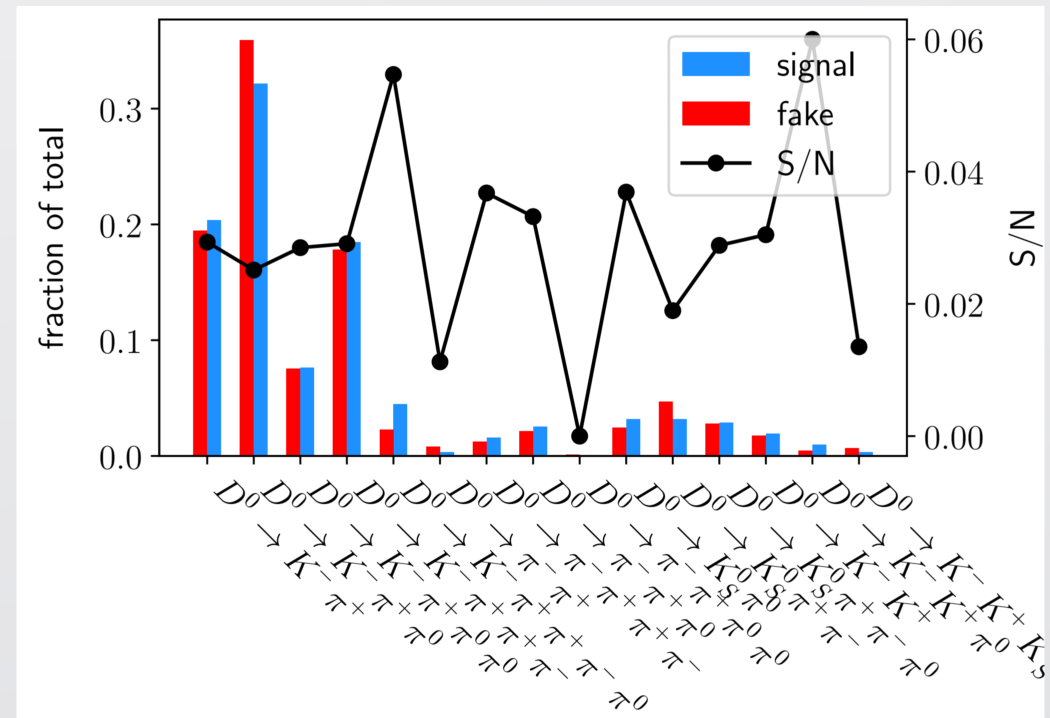
Tagging in Belle II - Semileptonic

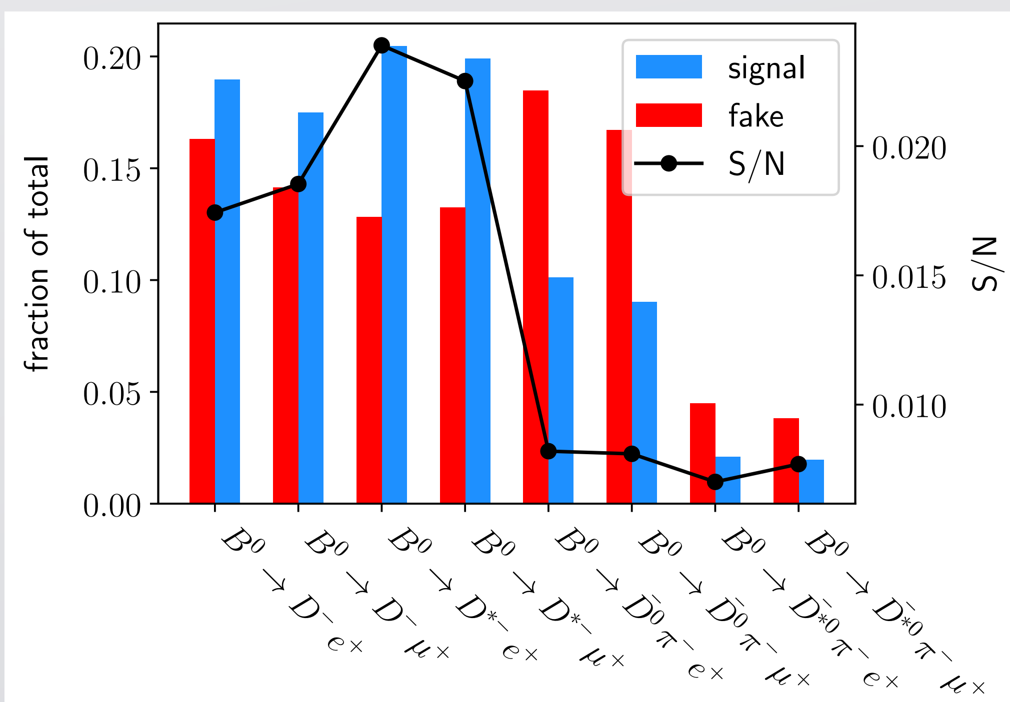
- In past measurement: cut-based
- Future measurements: **BDT-based (FEI)**

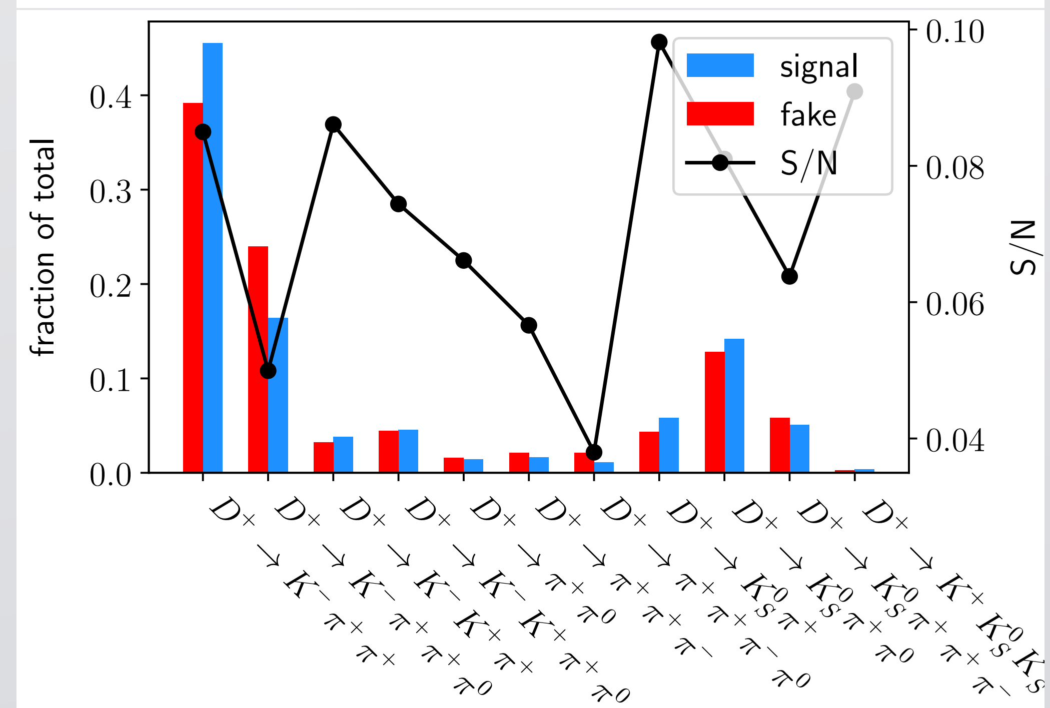
Algorithm	Experiment	B+	B0
FEI	Belle	1.80%	2.04%
FEI	Belle II	1.45%	1.94%

Belle MC (FEI)









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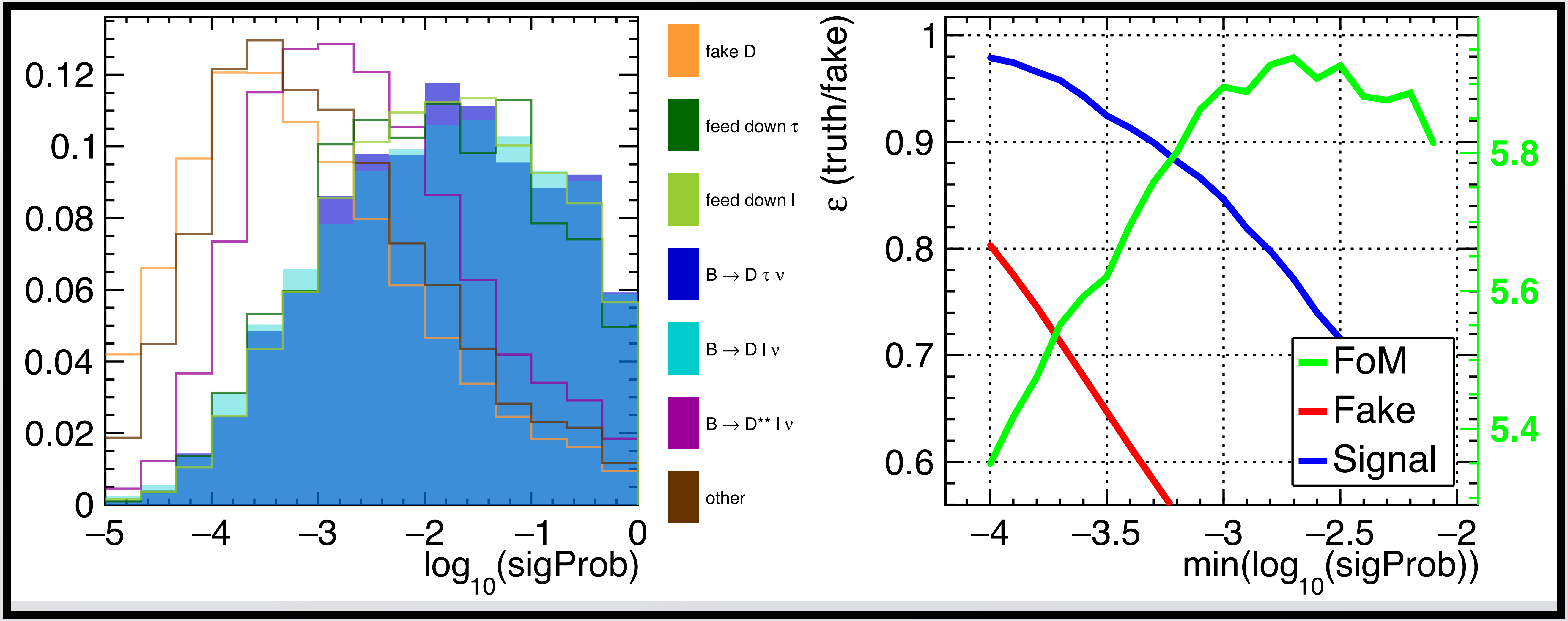
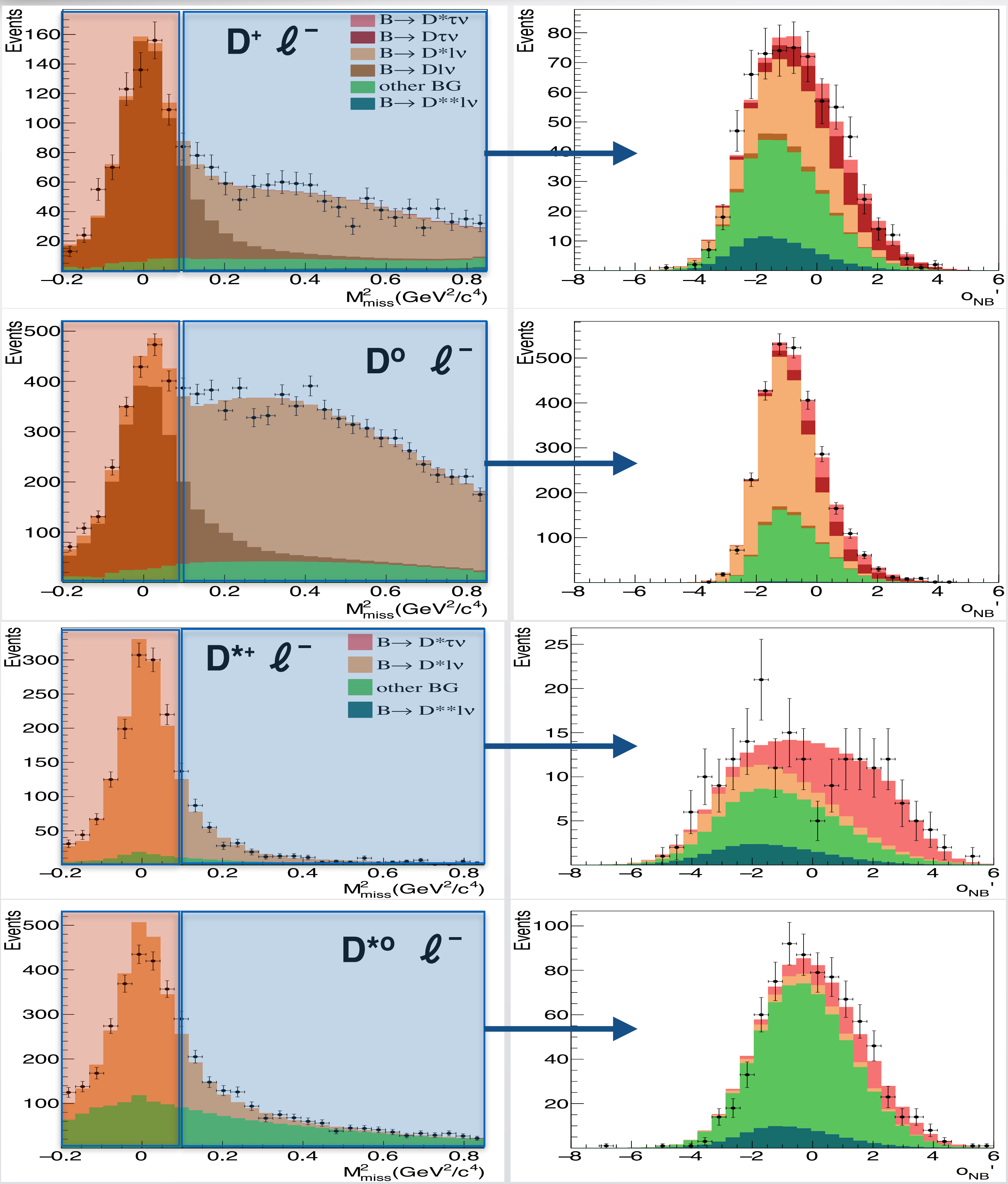


R(D(*)), hadronic tag at Belle

PRD 92, 072014 (2015)



- Leptonic τ decays
- Use m^2_{miss} to separate signal B → D(*) τ ν from normalization B → D(*) l ν

$$m^2_{miss} = p^2_\nu = (p_{e^+e^-} - p_{Btag} - p_{D^*\ell})^2$$

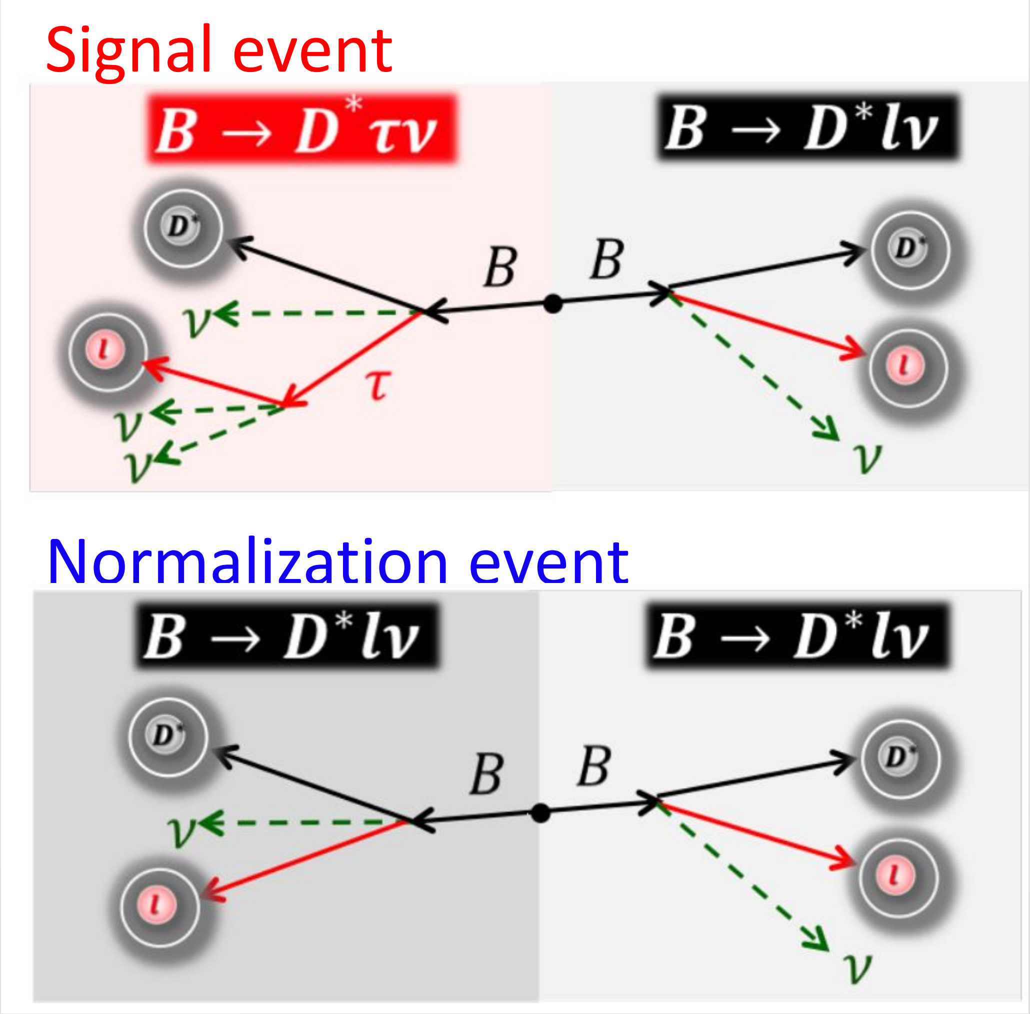
- Train and fit signal MVA(NB) on high m^2_{miss} region, based on: E_{ECL} , p^*_ℓ , m^2_{miss} and others
- D ℓ modes with higher background levels due to **"feed-down"** from B →(D* → D π_{slow}) ℓ ν

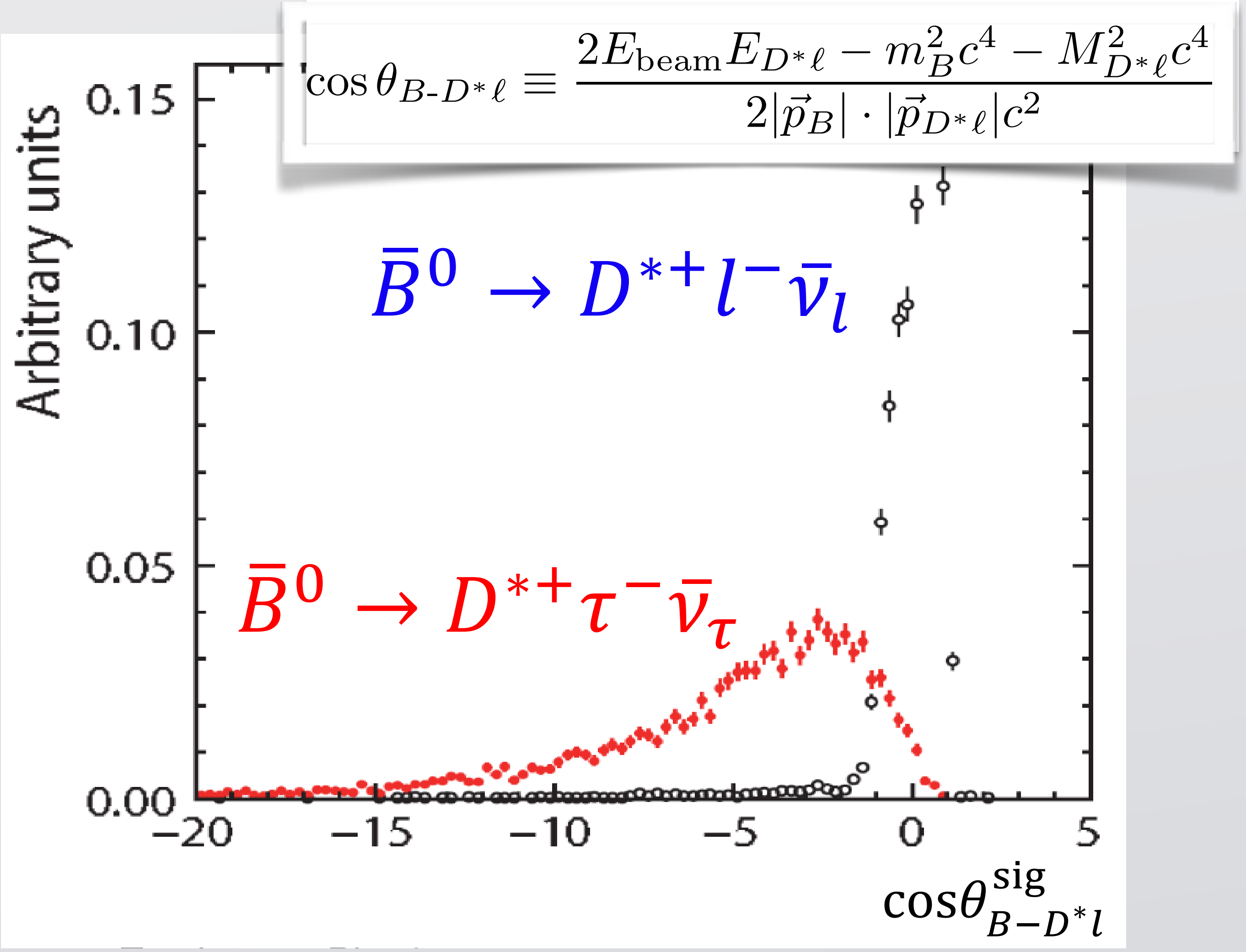
R(D) = 0.375 ± 0.064 ± 0.026
R(D*) = 0.293 ± 0.038 ± 0.015

R(D*), semileptonic tag at Belle

- Measure only the clean $B^o \longrightarrow D^{*+}\ l^-\ \nu$
- No MVA tagging algorithm, reject signal in tag by choosing $-1 < \cos\theta_{B,D^*l} < -1$
- Identity signal (normalization) as B candidate with lower (higher) $\cos\theta_{B,D^*l}$

PRD 94, 072007 (2016)





R(D*), semileptonic tag at Belle

signal
B ⟶ D(*) τ ν

normalization
B ⟶ D(*) l ν

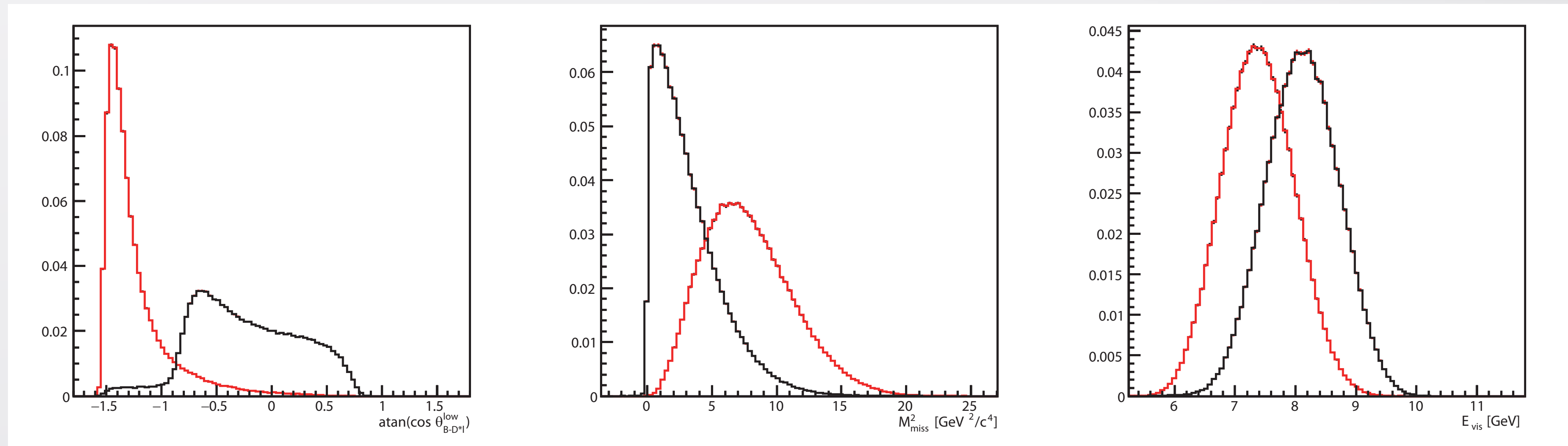
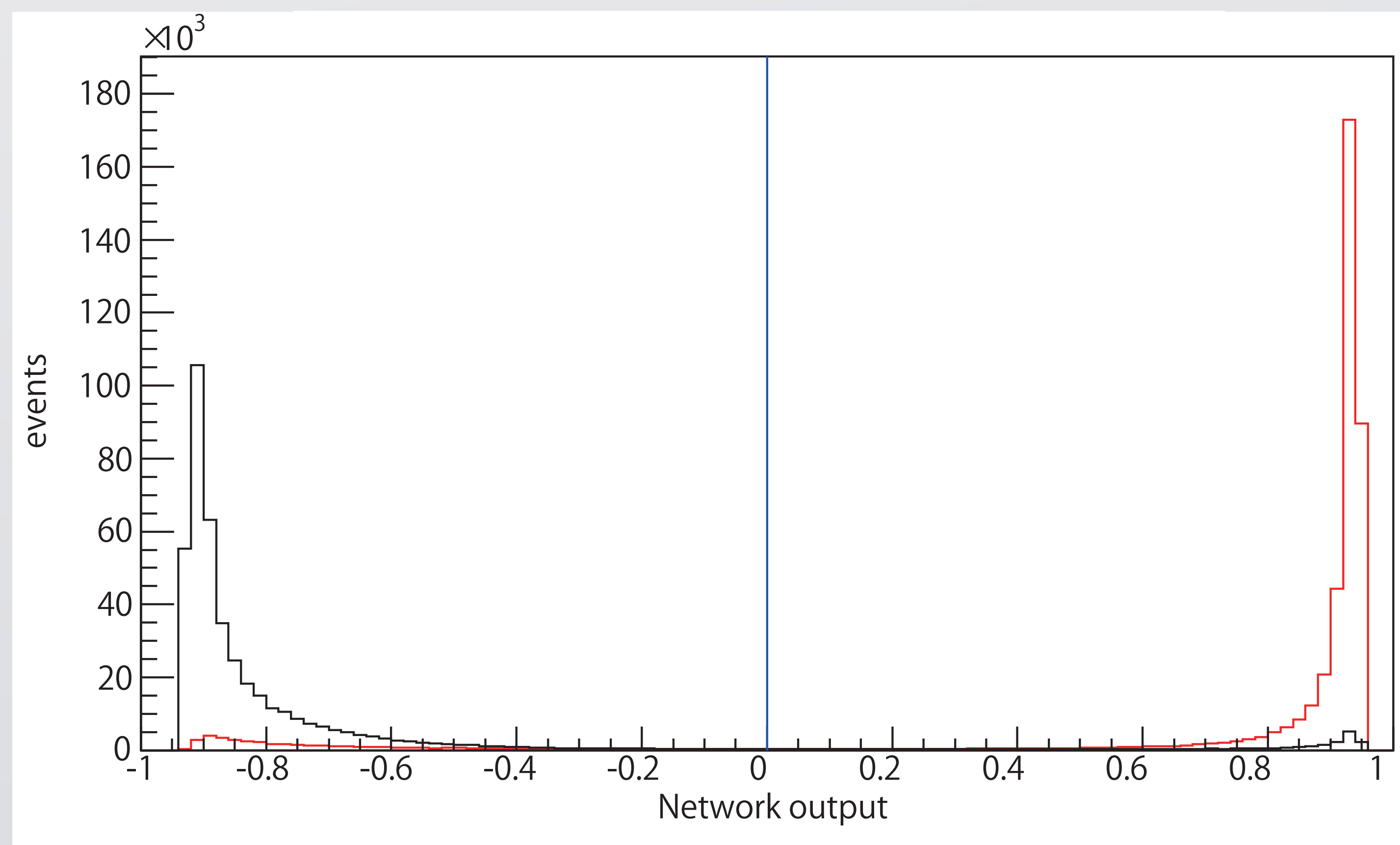
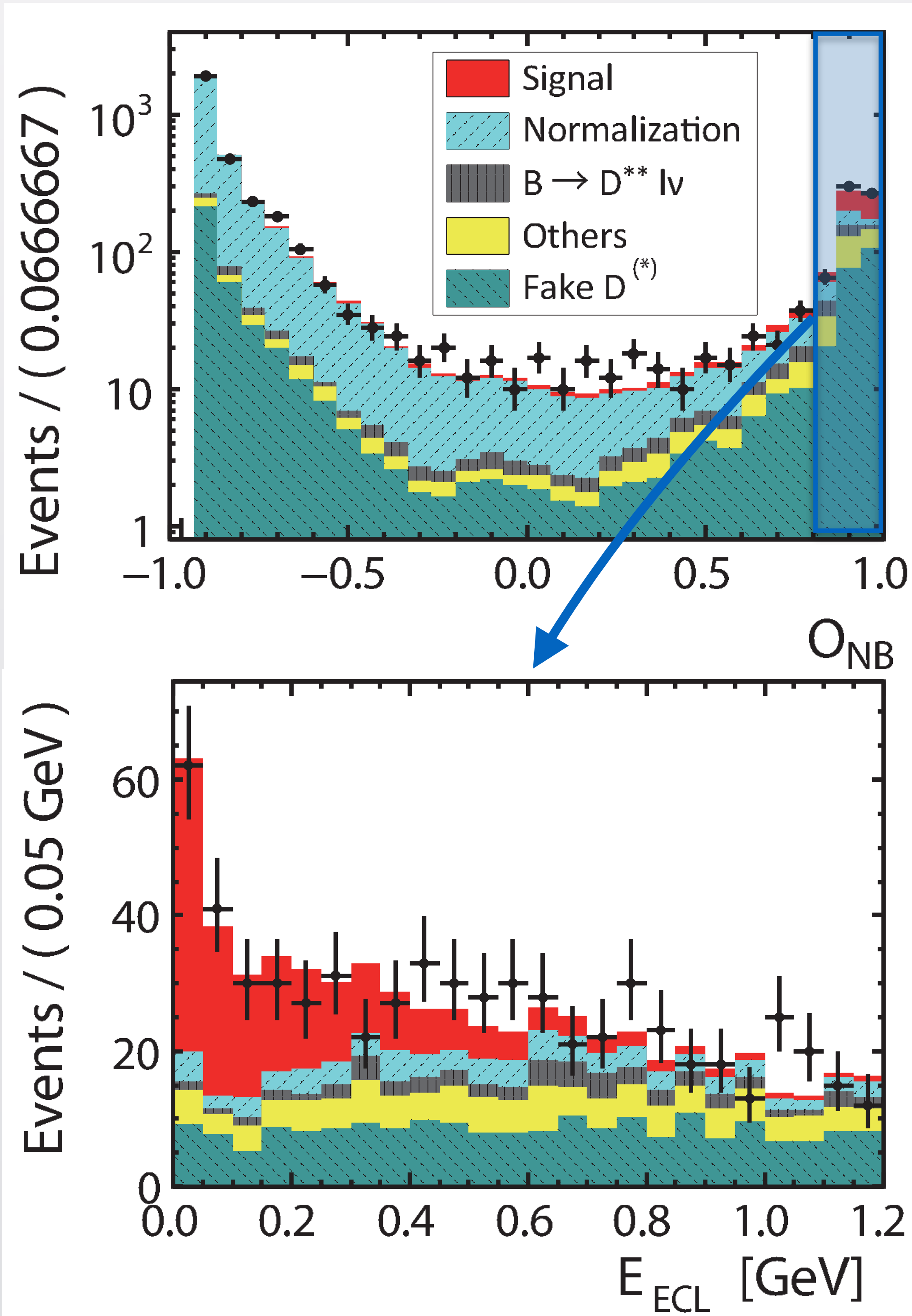


Figure 3.1: Distributions of the NeuroBayes input parameters for signal (red) and normalization (black) events : $\mathrm{atan}(\cos\theta^{\mathrm{low}}_{B\text{-}D^*\ell})$ (left), M^2_{miss} (center), E_{vis} (right). For visualization, arctan is used for $\cos\theta^{\mathrm{low}}_{B\text{-}D^*\ell}$ in this plot.



R(D*), semileptonic tag at Belle

PRD 94, 072007 (2016)



- Discriminate between signal B ⟶ D(*) τ ν and normalization B ⟶ D(*) l ν using MVA based on (m^2_{miss}, $\cos\theta_{BY}$, E_{Btag} + E_{Bsig})
- Signal extracted with fit to the 2D plane E_{ECL}-O_{NB}

$$\boxed{R(D^*) = 0.302 \pm 0.030 \pm 0.011}$$

Systematic errors

R(D*) - semileptonic tag (τ ⟶ l)

Sources	$\ell^{\rm sig} = e, \mu$
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	$^{+3.4}_{-3.5}$

R(D(*)) - hadronic tag (τ ⟶ l)

	$R(D)$ [%]	$R(D^*)$ [%]
$D^{(*(*))}\ell\nu$ shapes	4.2	1.5
D^{**} composition	1.3	3.0
Fake D yield	0.5	0.3
Fake ℓ yield	0.5	0.6
D_s yield	0.1	0.1
Rest yield	0.1	0.0
Efficiency ratio f^{D^+}	2.5	0.7
Efficiency ratio f^{D^0}	1.8	0.4
Efficiency ratio $f_{\rm eff}^{D^{*+}}$	1.3	2.5
Efficiency ratio $f_{\rm eff}^{D^{*0}}$	0.7	1.1
CF double ratio g^+	2.2	2.0
CF double ratio g^0	1.7	1.0
Efficiency ratio $f_{\rm wc}$	0.0	0.0
$M^2_{\rm miss}$ shape	0.6	1.0
$o'_{\rm NB}$ shape	3.2	0.8
Lepton PID efficiency	0.5	0.5
Total	7.1	5.2

- Dominated by:
  - B -> D** l nu uncertainty
  - MC statistics for PDFs
  - efficiency ratios (for R(D))

What can be improved

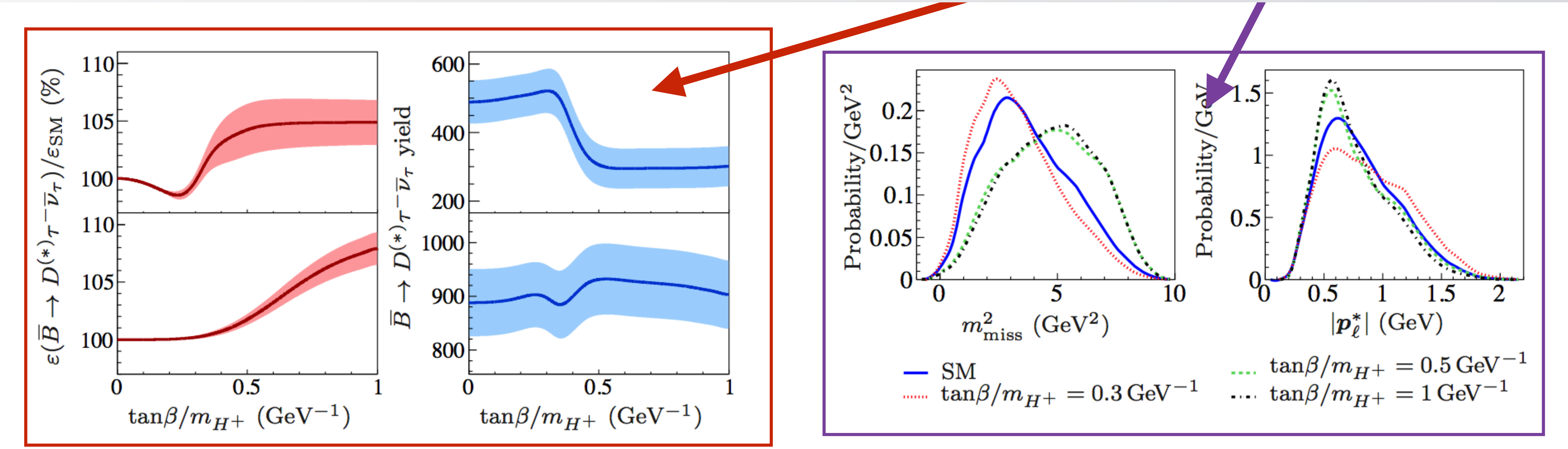
- Statistical uncertainty
  - Signal efficiency -> higher soft π efficiency, higher tag efficiency
  - Background rejection/ purity -> Better lep vs π PID at low p (tau-> l nu nu), better D(*) mass resolution, better treatment of missing/neutral particles in vertex fits for B/D(*) fake rejections

- Systematic uncertainty
  - Modelling of semileptonic B decays (form factors, branching ratios), especially **B ⟶ D** l nu**
  - MC statistics for PDFs
  - Detector modelling -> lepton ID efficiency and fake rate

New physics probes

Model dependent analysis (type-II 2HDM)

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



BaBar@Hadronic(τ→l)

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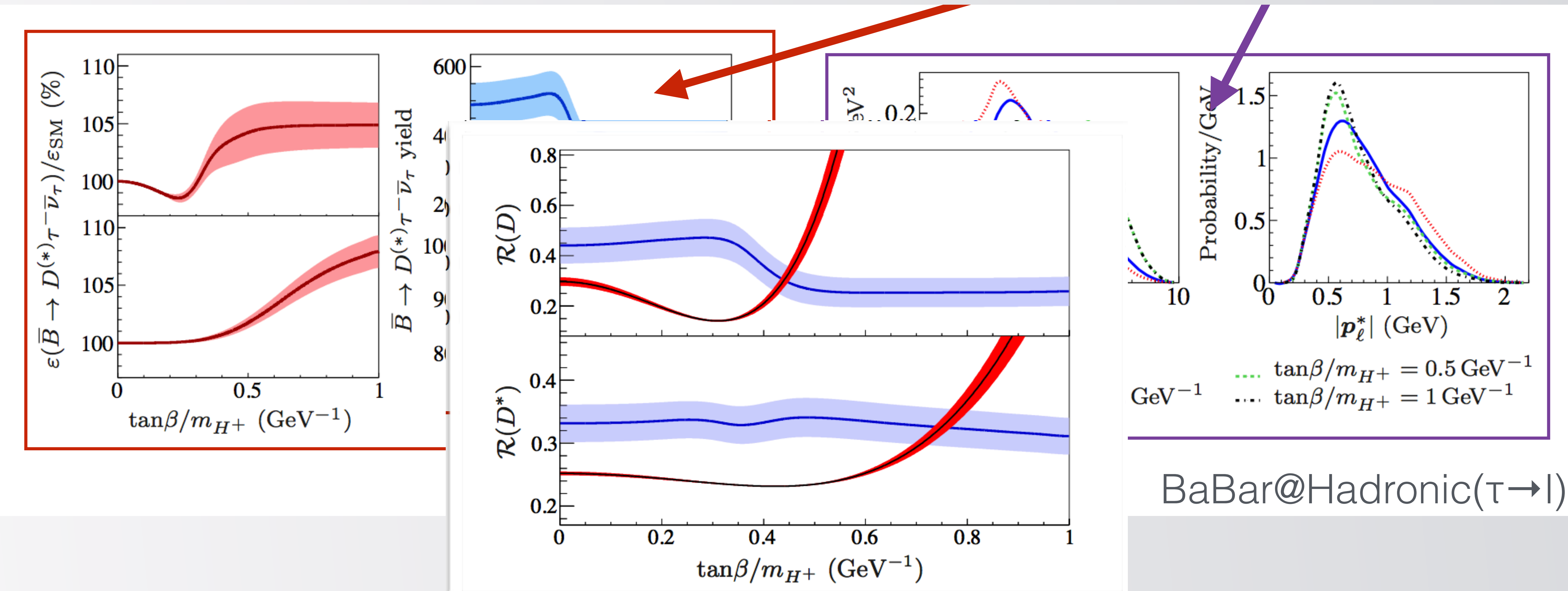
- different in kinematics ⟶ difference in **efficiency** and **fitted distributions**

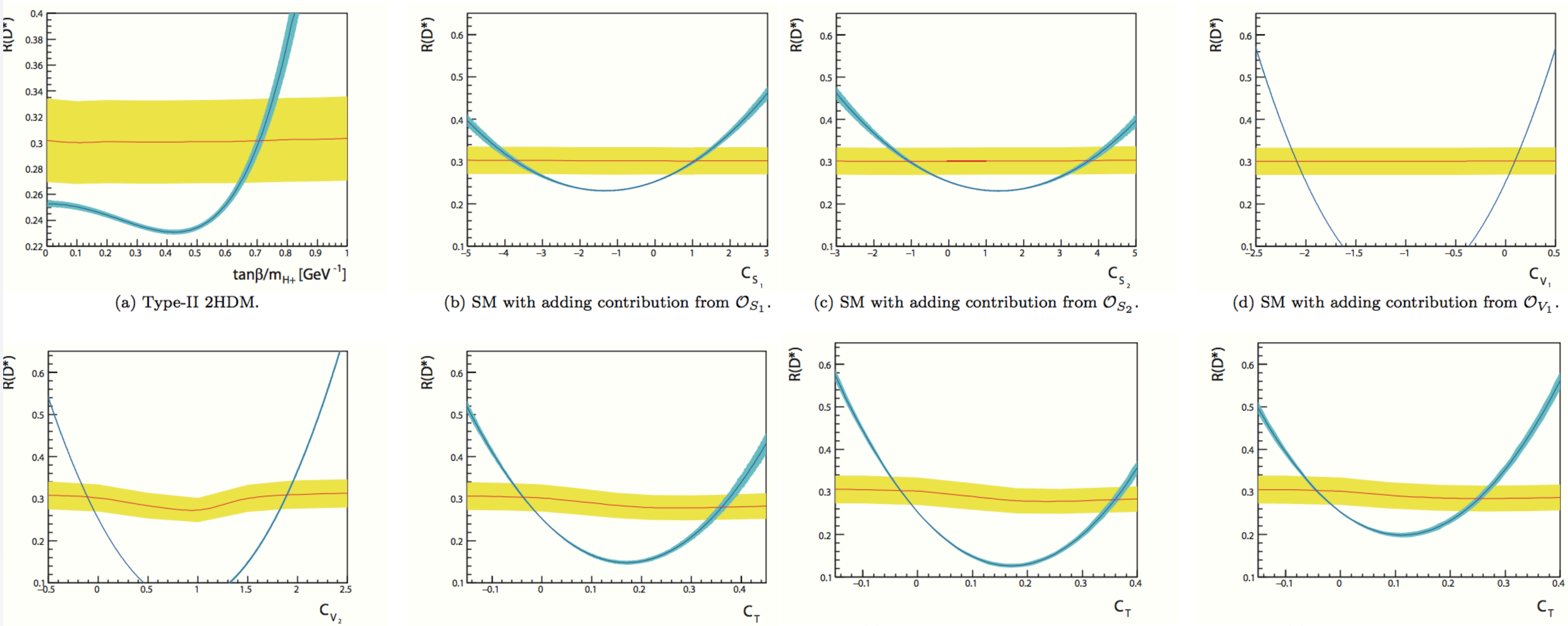


BaBar@Hadronic(τ→l)

New physics probes

Model independent analysis (type-II 2HDM)

- examine the impact of each operator



(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

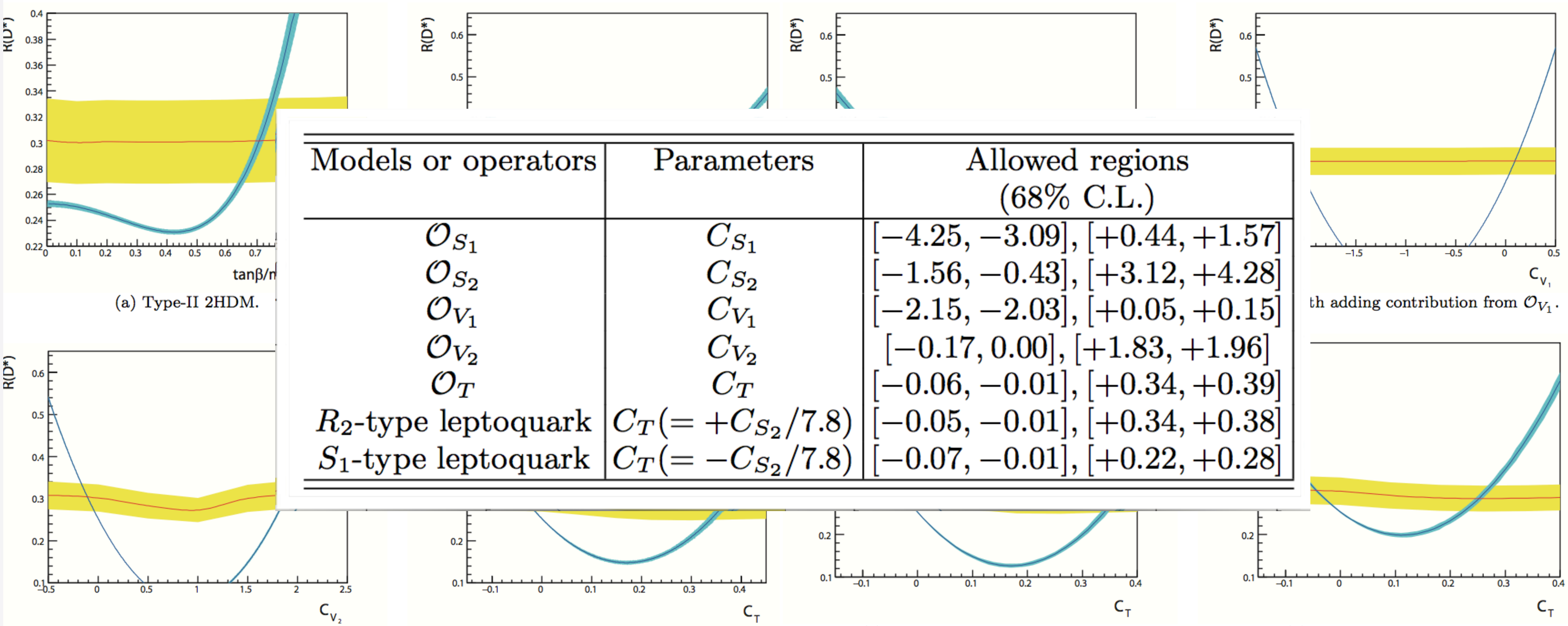
Belle@Semileptonic(τ→l)

New physics probes

Model independent analysis (type-II 2HDM)

- examine the impact of each operator

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	$C_T(= -C_{S_2}/7.8)$	$[-0.07, -0.01], [+0.22, +0.28]$



(a) Type-II 2HDM.

...th 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.

3

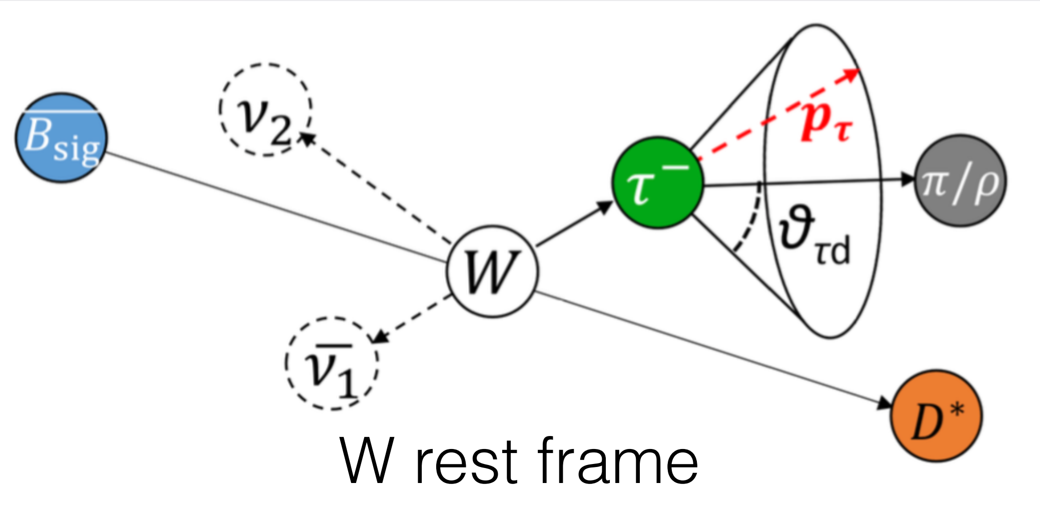
(h) S_1-type leptoquark model.

Belle@Semileptonic(τ→l)

R(D*), hadronic tag and τ polarisation at Belle

PRL 118, 211801 (2017)

- The τ polarisation depends on the mediator ⟶ sensitive to NP
- Two-body **hadronic τ** decays (τ ⟶ π ν , ρ ν) used to measure the τ polarisation
- New independent measurement of R(D*)

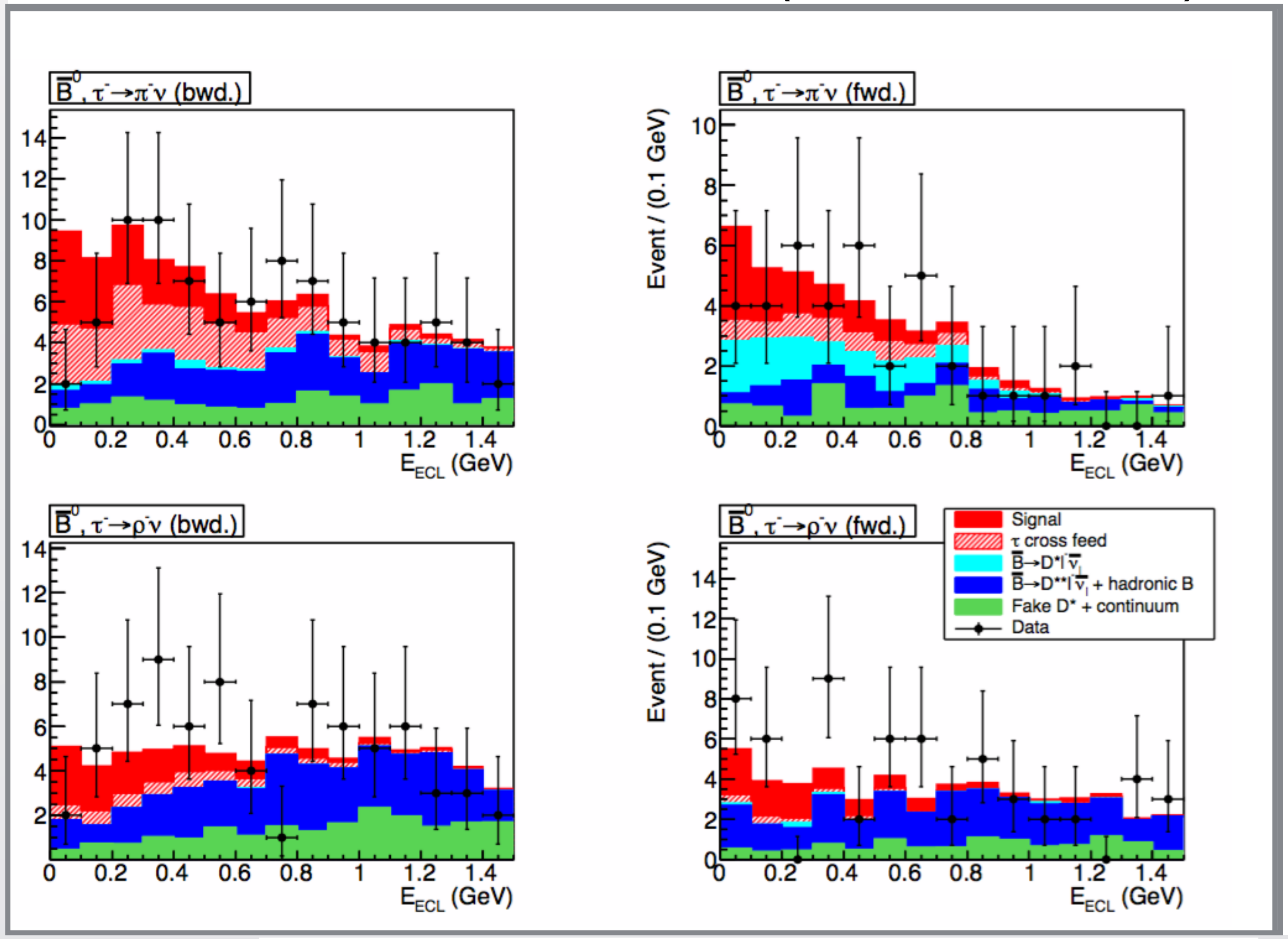


$$P_\tau(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

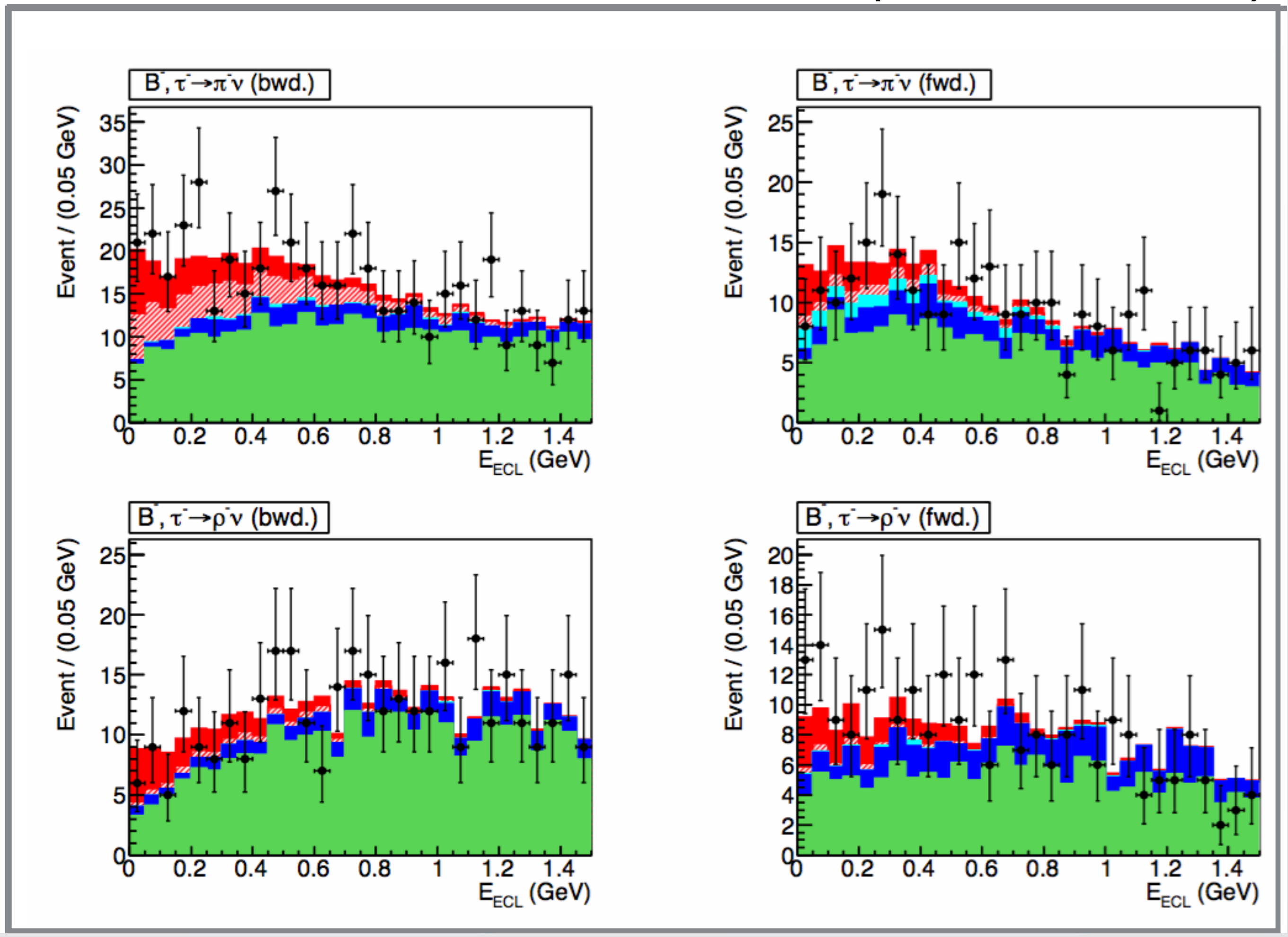
$\Gamma^\pm$ = decay rate of B ⟶ D* τ ν with helicity of ± 1/2

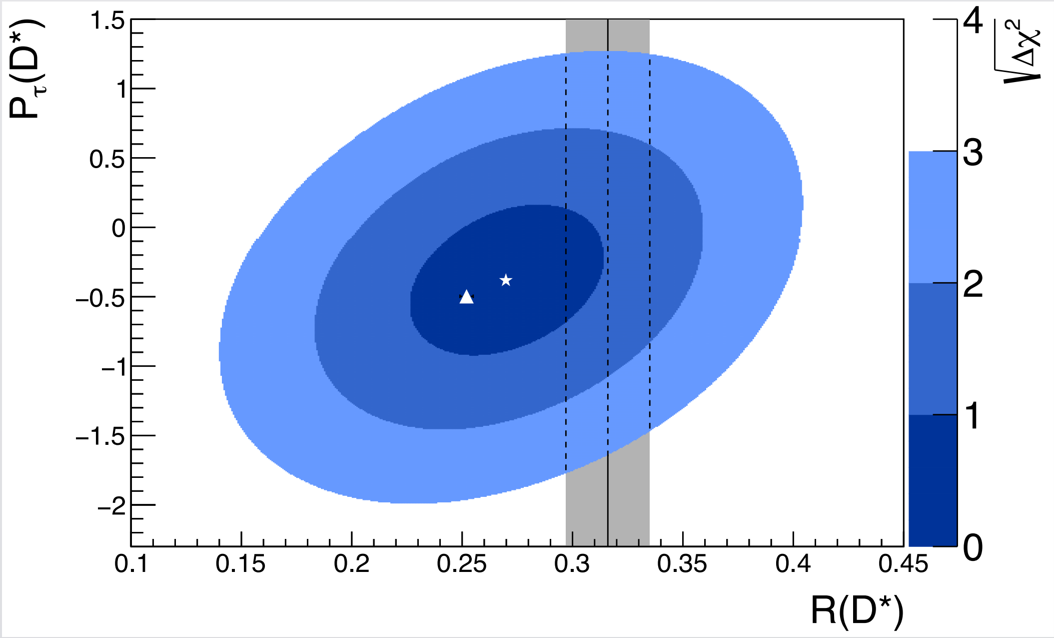
R(D*), hadronic tag and τ polarisation at Belle

Backward *($cos\theta_{hel} < 0$)*



Forward *($cos\theta_{hel} > 0$)*





$$R(D^*) = 0.270 \pm 0.035^{+0.028}_{-0.025}$$

$$P_\tau(D^*) = -0.38 \pm 0.51^{+0.21}_{-0.16}$$

Consistent with SM

Systematics (R(D*), polarisation with τ ⟶ h)

Source	$R(D^*)$	$P_\tau(D^*)$
Hadronic B composition	$^{+7.7\%}_{-6.9\%}$	$^{+0.134}_{-0.103}$
MC statistics for PDF shape	$^{+4.0\%}_{-2.8\%}$	$^{+0.146}_{-0.108}$
Fake D^*	3.4%	0.018
$\bar{B} \to D^{**}\ell^-\bar{\nu}_\ell$	2.4%	0.048
$\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau$	1.1%	0.001
$\bar{B} \to D^{*}\ell^-\bar{\nu}_\ell$	2.3%	0.007
τ daughter and ℓ^- efficiency	1.9%	0.019
MC statistics for efficiency estimation	1.0%	0.019
$\mathcal{B}(\tau^- \to \pi^-\nu_\tau, \rho^-\nu_\tau)$	0.3%	0.002
$P_\tau(D^*)$ correction function	0.0%	0.010
Common sources		
Tagging efficiency correction	1.6%	0.018
D^* reconstruction	1.4%	0.006
Branching fractions of the D meson	0.8%	0.007
Number of $B\bar{B}$ and $\mathcal{B}(\Upsilon(4S) \to B^+B^-$ or $B^0\bar{B}^0)$	0.5%	0.006
Total systematic uncertainty	$^{+10.4\%}_{-9.4\%}$	$^{+0.21}_{-0.16}$

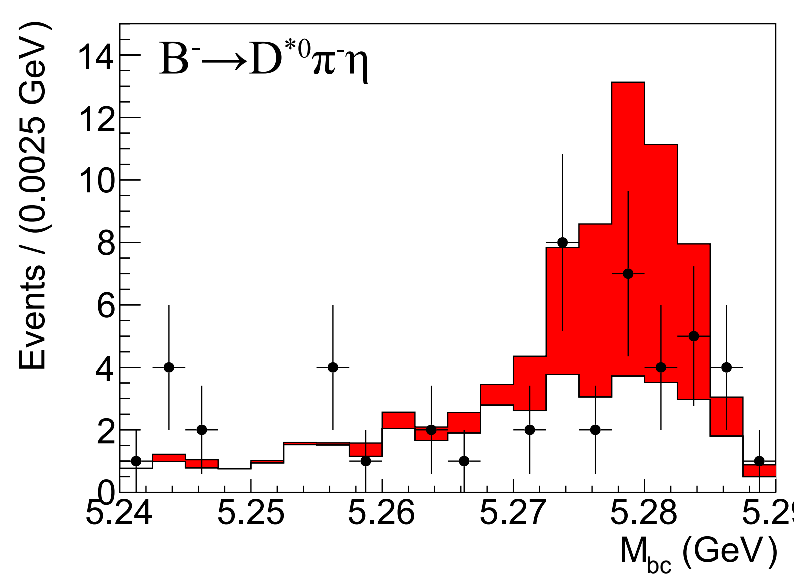


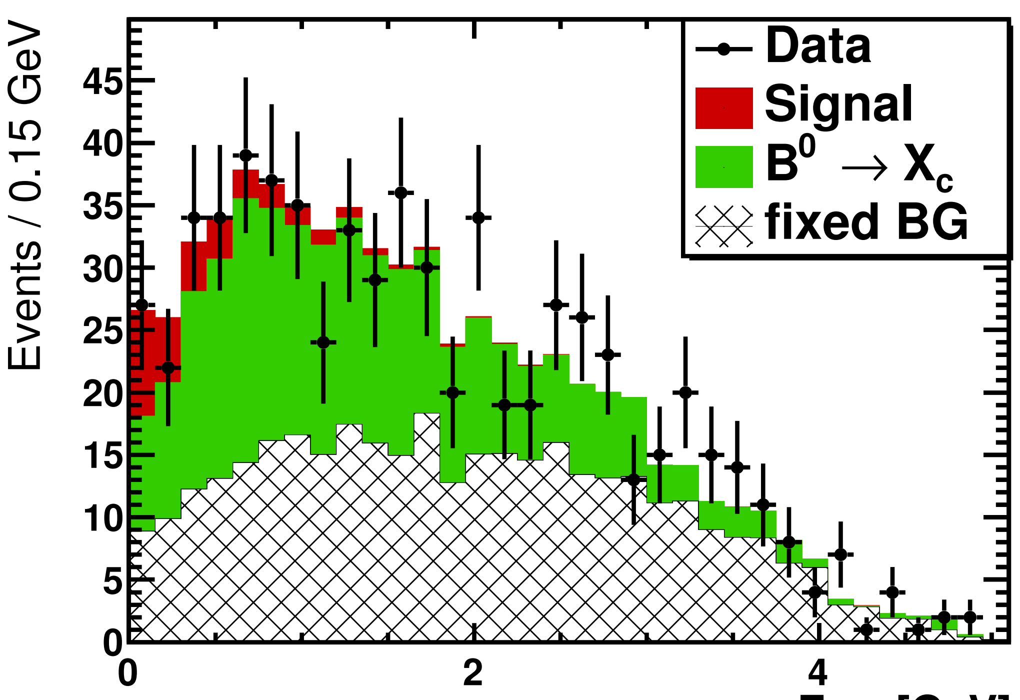
TABLE I. Calibration factors used to correct the hadronic B background rates in the MC simulation. The errors arise from the calibration sample statistics.

B decay mode	B^-	$\bar{B}^0$
$D^*\pi^-\pi^-\pi^+$	< 0.51	$0.62^{+0.67}_{-0.49}$
$D^*\pi^-\pi^-\pi^+\pi^0$	$0.31^{+0.43}_{-0.40}$	$0.59^{+0.45}_{-0.39}$
$D^*\pi^-\pi^-\pi^+\pi^0\pi^0$	$2.15^{+1.70}_{-1.60}$	$2.60^{+6.95}_{-2.24}$
$D^*\pi^-\pi^0$	$0.06^{+0.33}_{-0.28}$	< 0.47
$D^*\pi^-\pi^0\pi^0$	$0.09^{+1.04}_{-0.98}$	$1.63^{+0.74}_{-0.69}$
$D^*\pi^-\eta$	$0.24^{+0.21}_{-0.18}$	$0.15^{+0.16}_{-0.10}$
$D^*\pi^-\eta\pi^0$	$0.74^{+0.79}_{-0.75}$	$0.89^{+1.04}_{-0.88}$

$B \longrightarrow \pi\, \tau\, \nu$ at Belle

PRD 93, 032007 (2016)

- 72% of τ branching ratio ($\tau \longrightarrow l\, \nu\, \nu$, $\pi\, \nu$, $\varrho\, \nu$)
- Hadronic tag to constrain signal side
- Event selection through signal BDT, m^2_{miss} (reject $B \longrightarrow \pi\, l\, \nu$) and tag quality
- Extract signal through fit to E_{ECL} distribution



(b) $\tau \rightarrow \pi\nu$

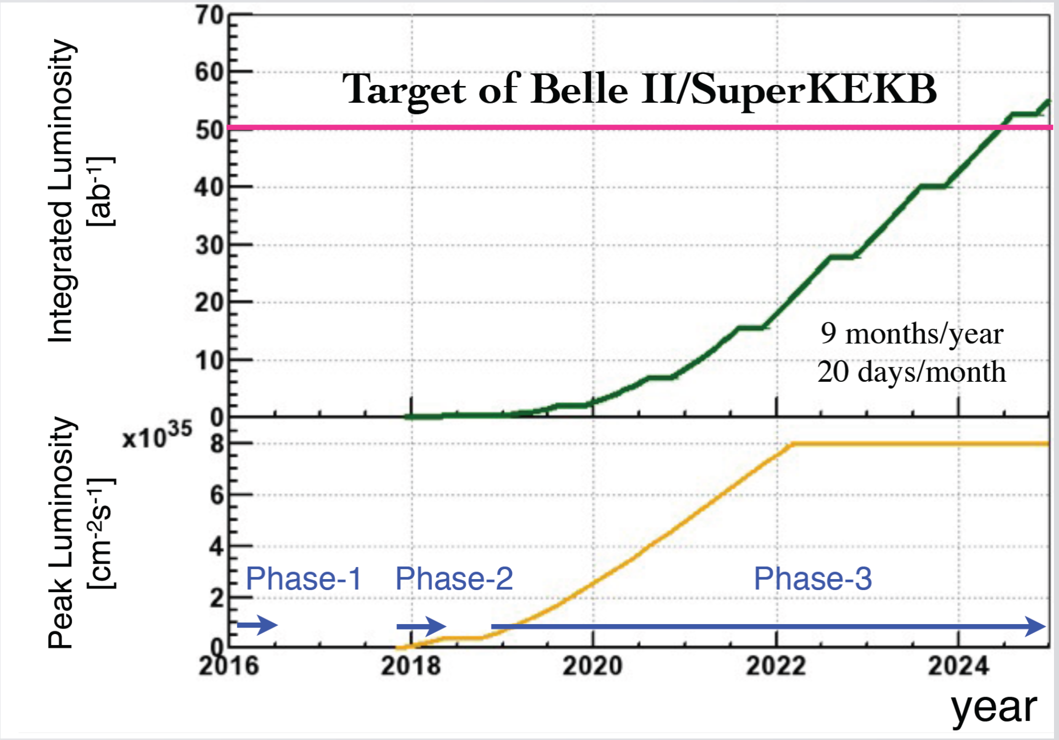
Source	Relative error (%)
Particle ID	2.4
Track efficiency	0.7
N($B\bar{B}$)	1.4
K_L veto	3.2
BG $\mathcal{B}$	2.8
Tagside	4.6
$\|V_{ub}\|$	2.8
Rare processes	2.0
$B \rightarrow X_u\tau\nu$	2.2
Background fit	0.2
Signal model	1.8
Total	8.3

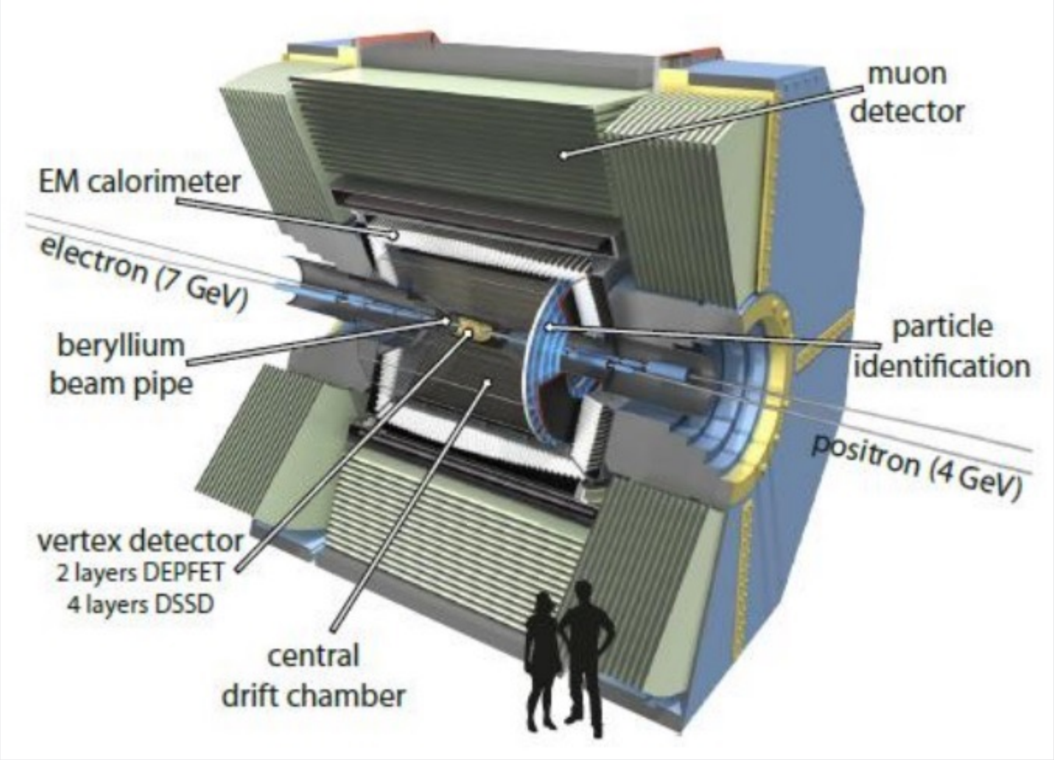
$\boxed{\text{90\% CL upper limit: BR} < 2.5 \times 10^{-4}}$

Agreement with SM

SuperKEKB and Belle II

- KEKB: accumulated **1 ab^{-1}** at Υ(4S)
- SuperKEKB:
  - 40-fold increase in luminosity over KEKB
  - collect **50 ab^{-1}** by 2025
- Belle II:
  - upgrade all sub detectors except for ECL and part of barrel KLM
  - expect similar/better performance w.r.t. Belle, despite much higher background levels

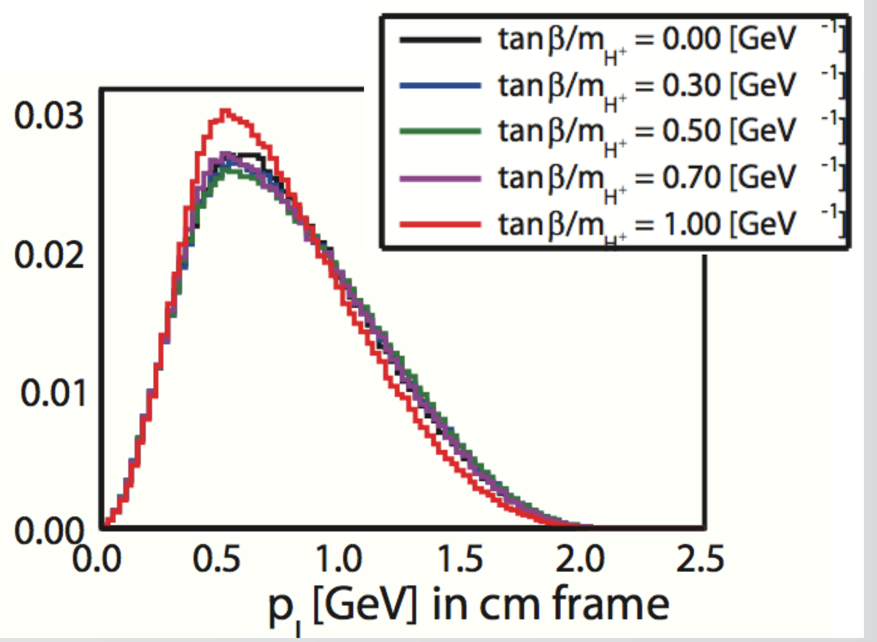




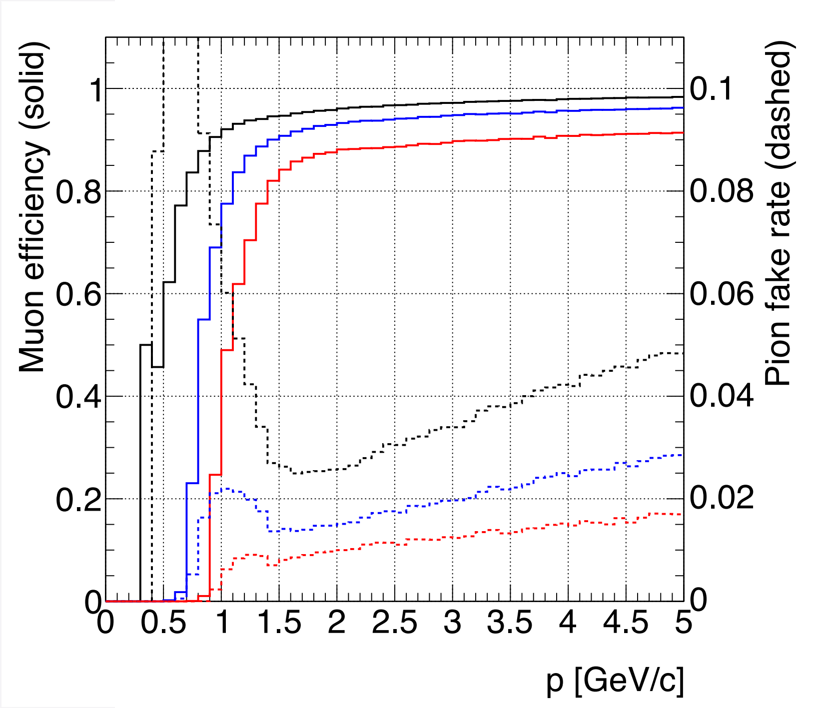
The Belle II detector

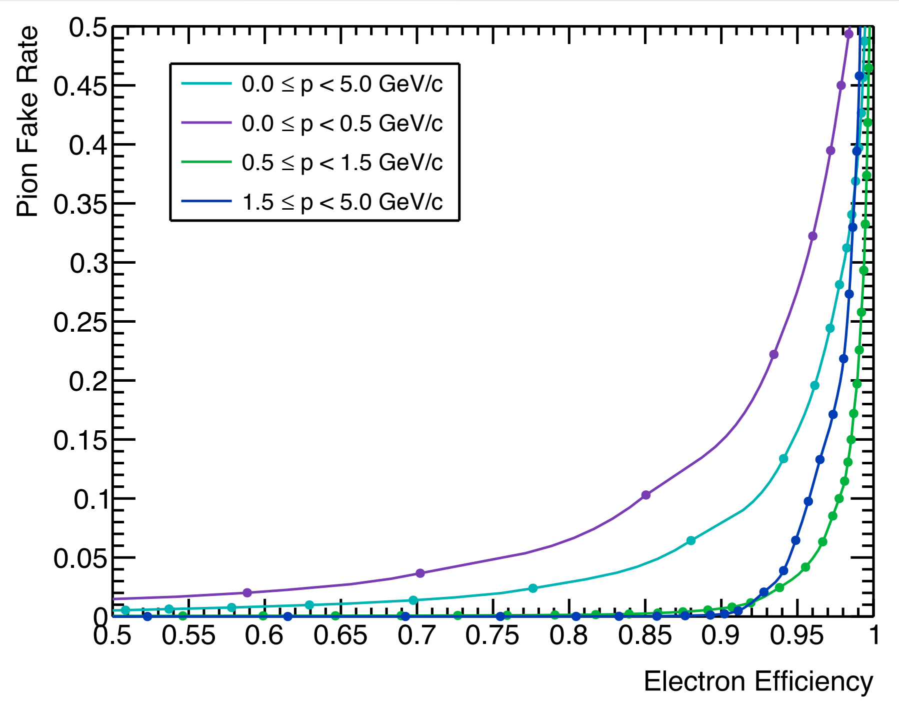
Lepton reconstruction @ Belle II

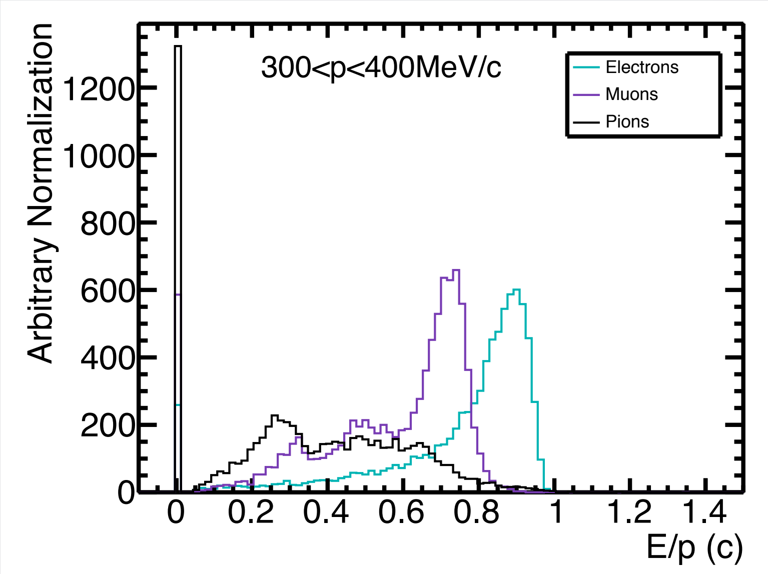
- e reconstruction based on CDC track + ECL cluster
- e from τ: low momentum $\longrightarrow$ low efficiency
- Small radius in B field doesn't reach ECL
- Only muons with p > 0.7 GeV are able to reach KLM and have good μ/π separation



- **Work in progress for improvements @ Belle II**

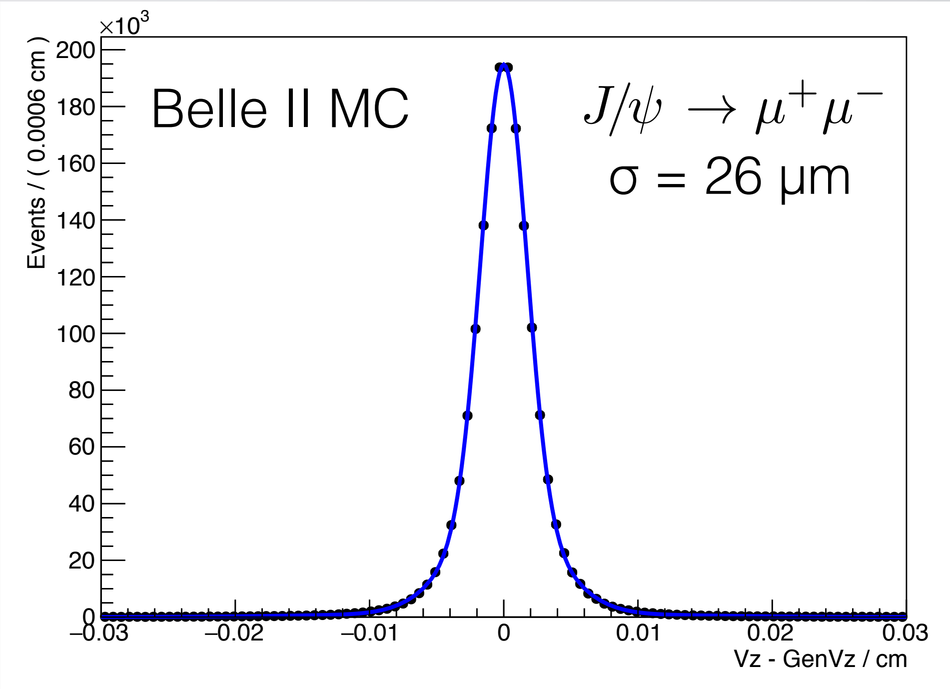


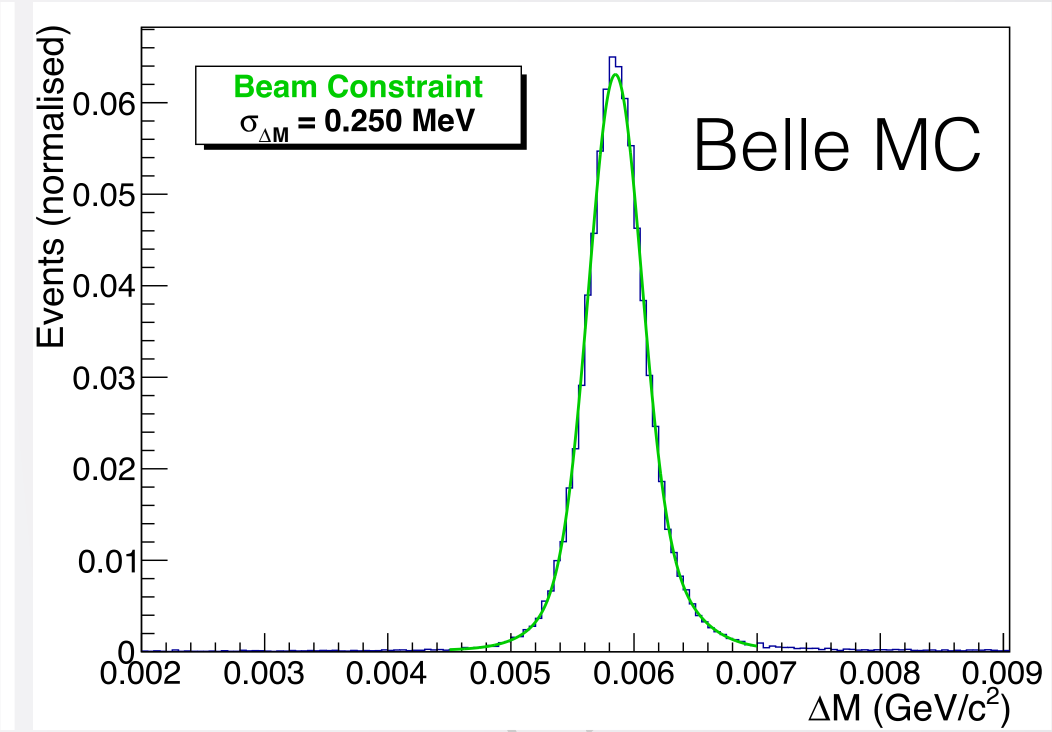


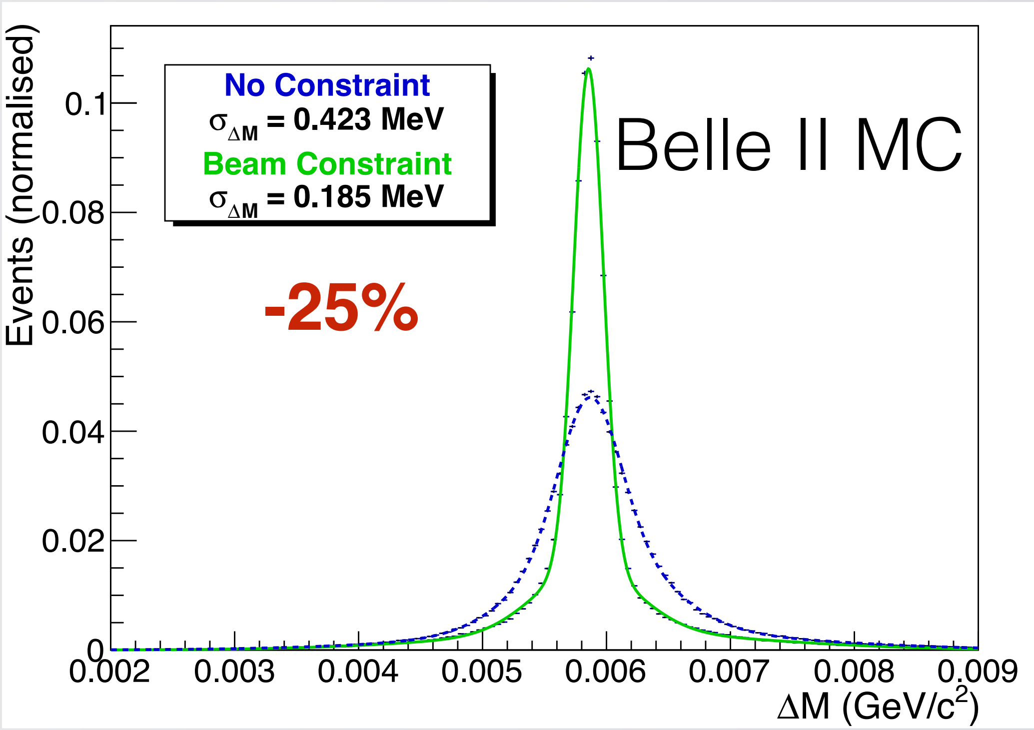


Vertex fitting @ Belle II

- **2x** improvement for vertex fitting, w.r.t. Belle
- Mass resolution is improved by vertex fit ⟶ D and D* selection (**-25%**)
- Under development: *TreeFitter*, helps with decay trees with π^{o}, K_S





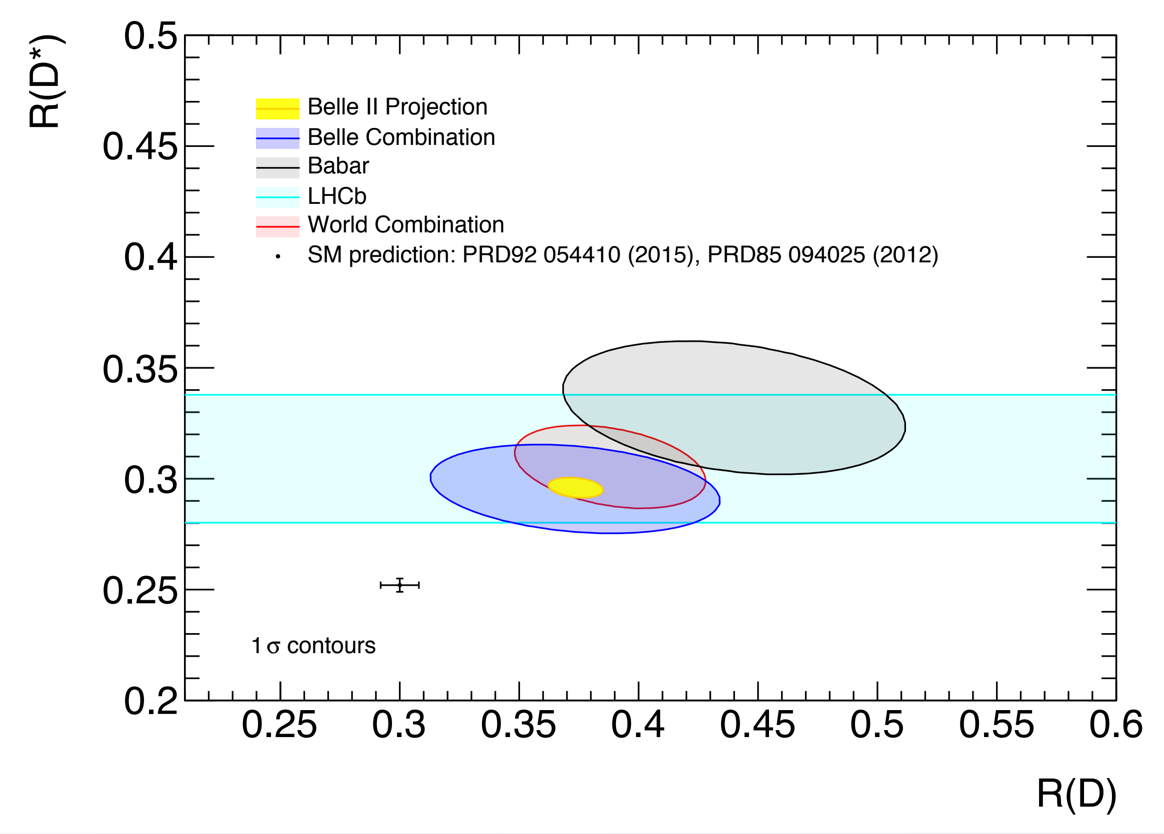


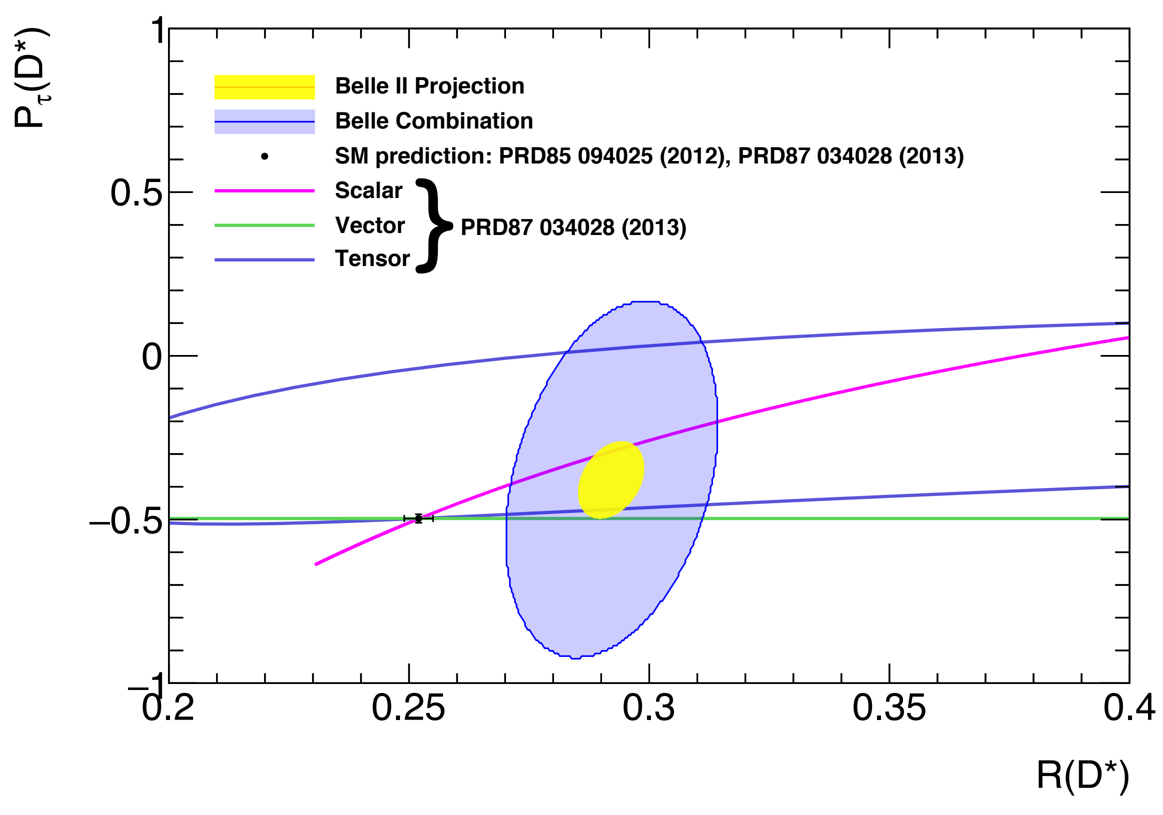
B ⟶ D(*) τ ν @ Belle II

- Current measurements are statistically limited
- Dominant systematics from:
  - MC statistics ⟶ larger at Belle II
  - limited knowledge of B ->D** l nu and B->D(*) Xc bkg ⟶ dedicated studies with large data sample at Belle II
- Study kinematic distributions, polarization

Errors @ Belle II

	5 ab^{-1}	50 ab^{-1}
R(D)	(6.0 +/- 3.9)%	(2.0 +/- 2.5)%
R(D*)	(3.0 +/- 2.5)%	(1.0 +/- 2.0)%
Pτ (D*)	0.18 +/- 0.08	0.06 +/- 0.04

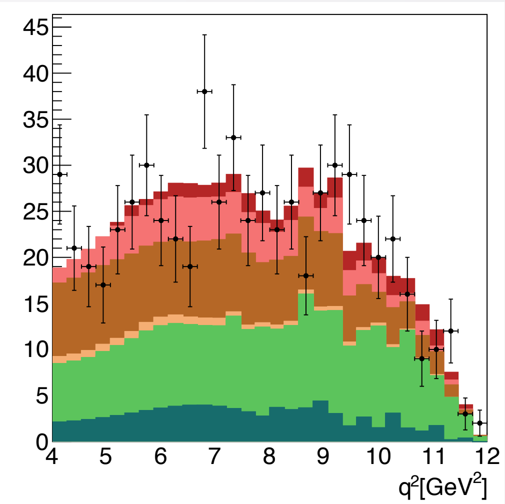


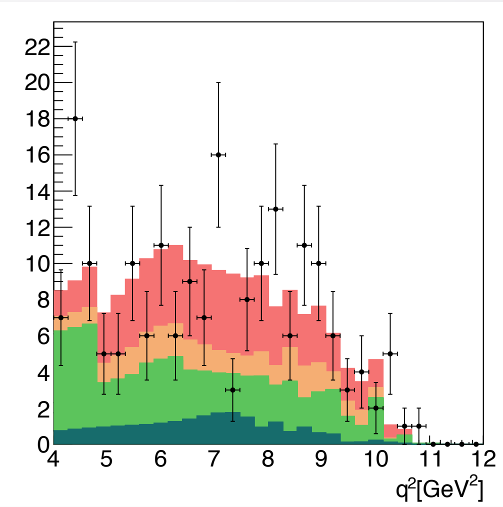


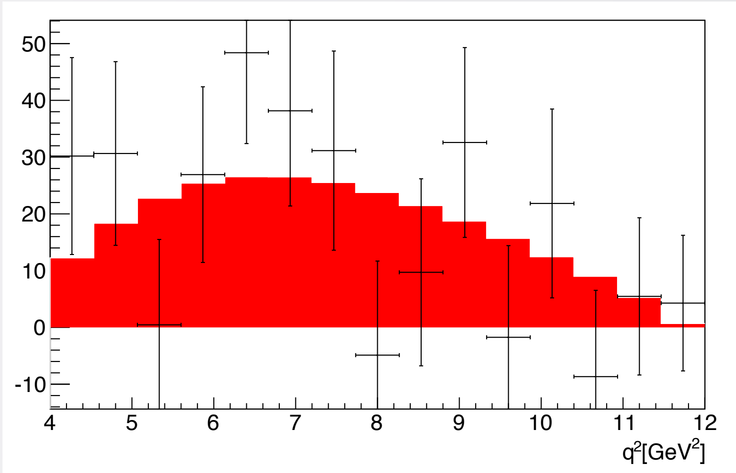
Differential measurements

- Currently very hard to compare signal observables due to limited statistics
- Expect improvement with Belle II luminosity

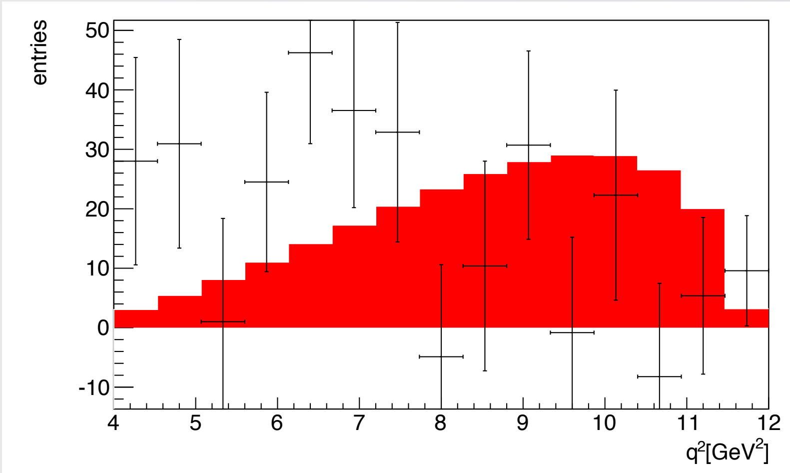
All events | **Background-subtracted (stat. error only)** | **Belle II @ 50 ab^{-1}**



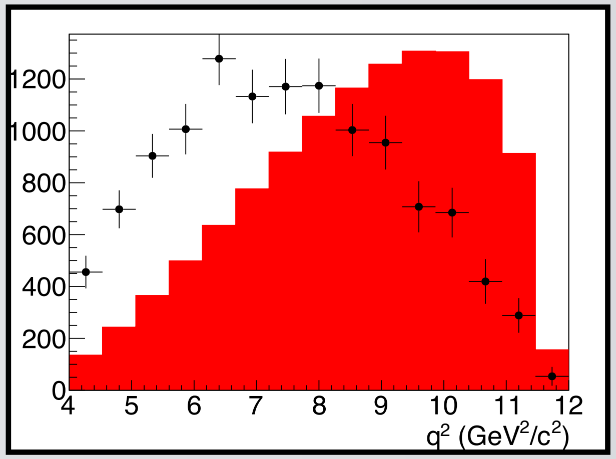


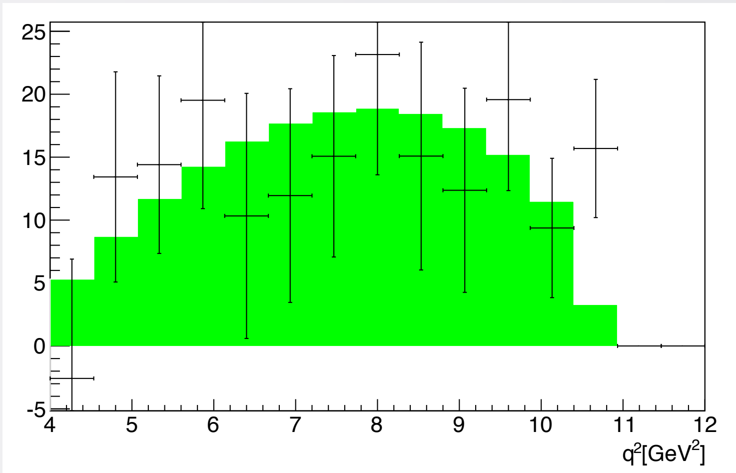


(a) $D\tau$ SM

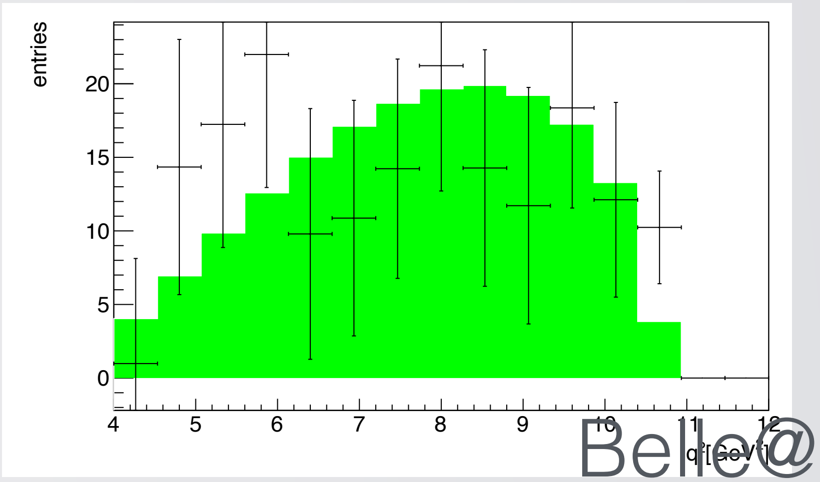


(b) $D\tau$ $\tan\beta/m_{H^+} = 0.5\,\mathrm{c}^2\,\mathrm{GeV}^{-1}$





(c) $D^*\tau$ SM



(d) $D^*\tau$ $\tan\beta/m_{H^+} = 0.5\,\mathrm{c}^2\,\mathrm{GeV}^{-1}$

Belle@Hadronic ($\tau \longrightarrow l$)

$B \longrightarrow \pi \tau \nu$ @ Belle II

- Both tagged and untagged measurements report significant improvement in reconstruction efficiency (~ 2x)
- Measurements will be systematically limited at Belle II statistics

$$R_\pi (5\ ab^{-1}) = 0.64 +/- 0.23$$

$$R_\pi (50\ ab^{-1}) = 0.64 +/- 0.09$$

Conclusion

- B factories have discovered anomalies in b ⟶ c tau nu, but also b ⟶ u tau nu can be probed for charged Higgs effects
- SuperKEKB will have a 40-fold increase in luminosity w.r.t. to KEKB, Belle II expects improvement for reconstruction hardware and software sides
- A new BDT-based tagging algorithm with higher efficiency will be used on Belle (II) data
- Lepton efficiency and pion background rejection, together with mass resolution for D(*) are key reconstruction topics
- Expect much higher statistics for observables that are fundamental to distinguish new physics