Recent results on and prospects for B to D(*) τ ν , τ ν and μ ν at Belle

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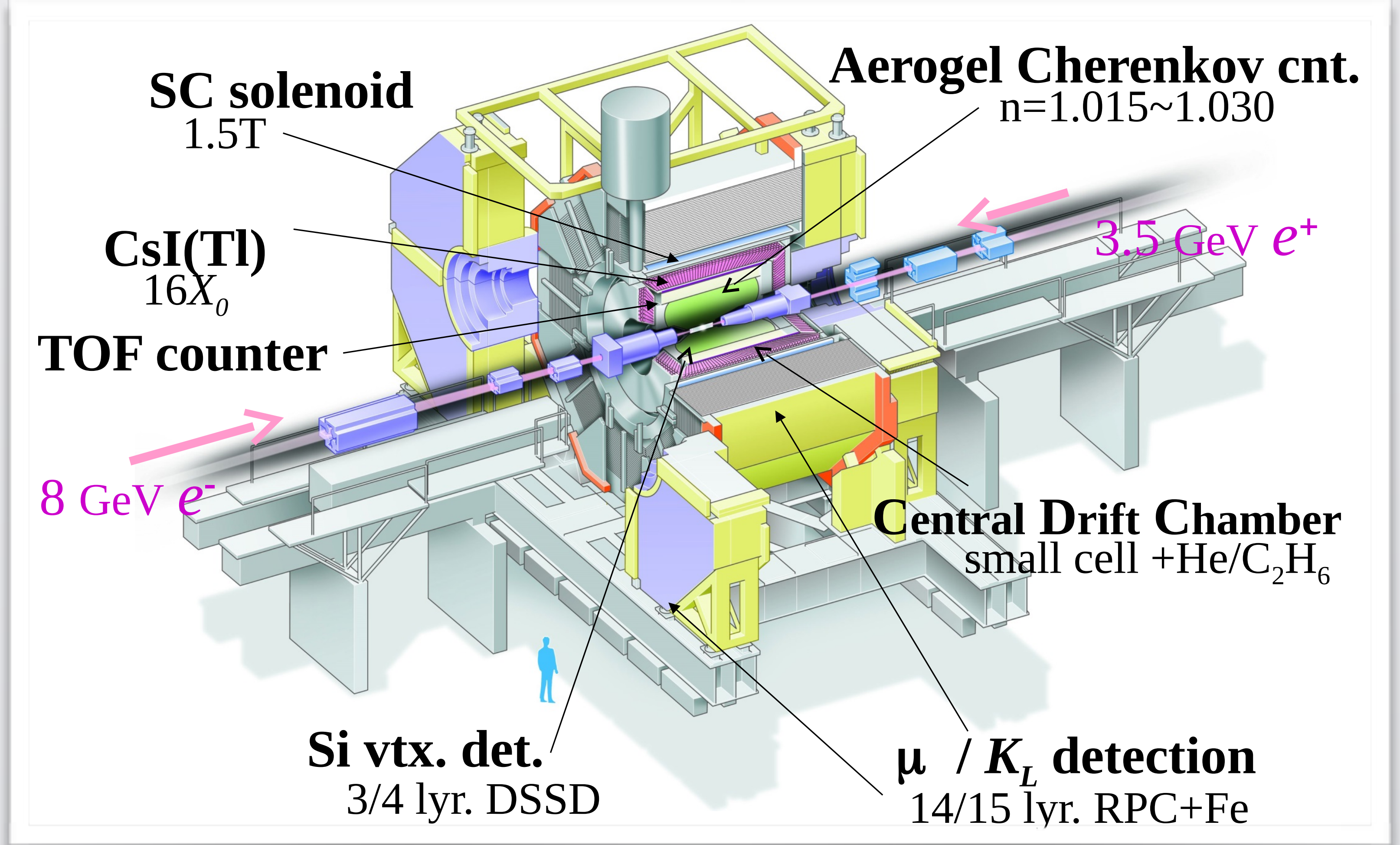
The Belle experiment (1998 - 2010)

- Asymmetric e^+e^- collider at KEK, Japan →

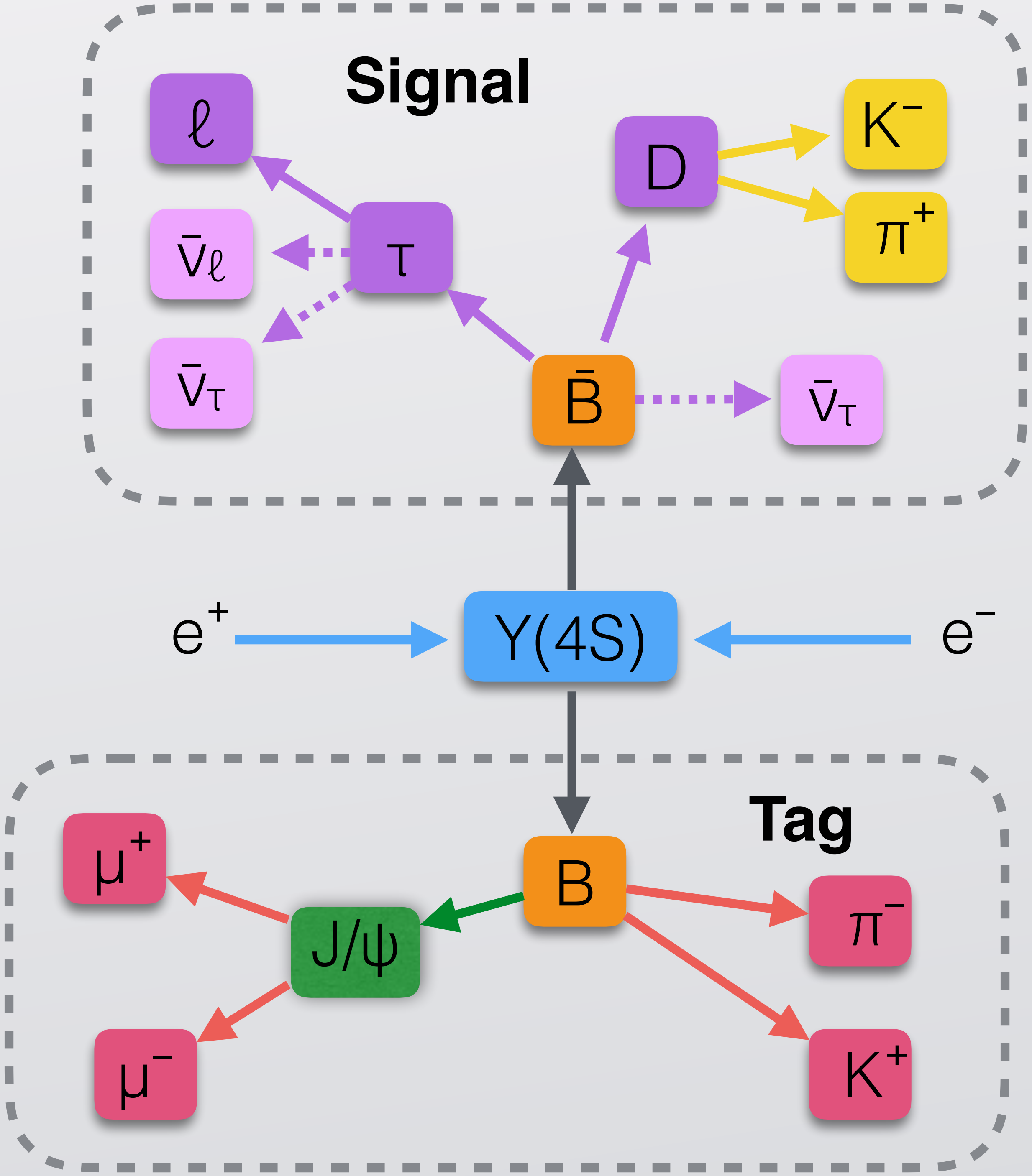
$$e^- e^+ \rightarrow \Upsilon(4S) \rightarrow b\bar{b}$$
$$\mathcal{B}(b\bar{b} \rightarrow B\bar{B}) \approx 0.96$$

- $m_{\Upsilon(4S)}$ = 10.58 GeV > 2 x m_B = 10.56 GeV ⟶ small momentum for B mesons
- B factory: 772 x 10^6 of $B\bar{B}$ pairs produced
- (~ 3 times higher continuum background from $\Upsilon(4S) \longrightarrow q\bar{q}$)



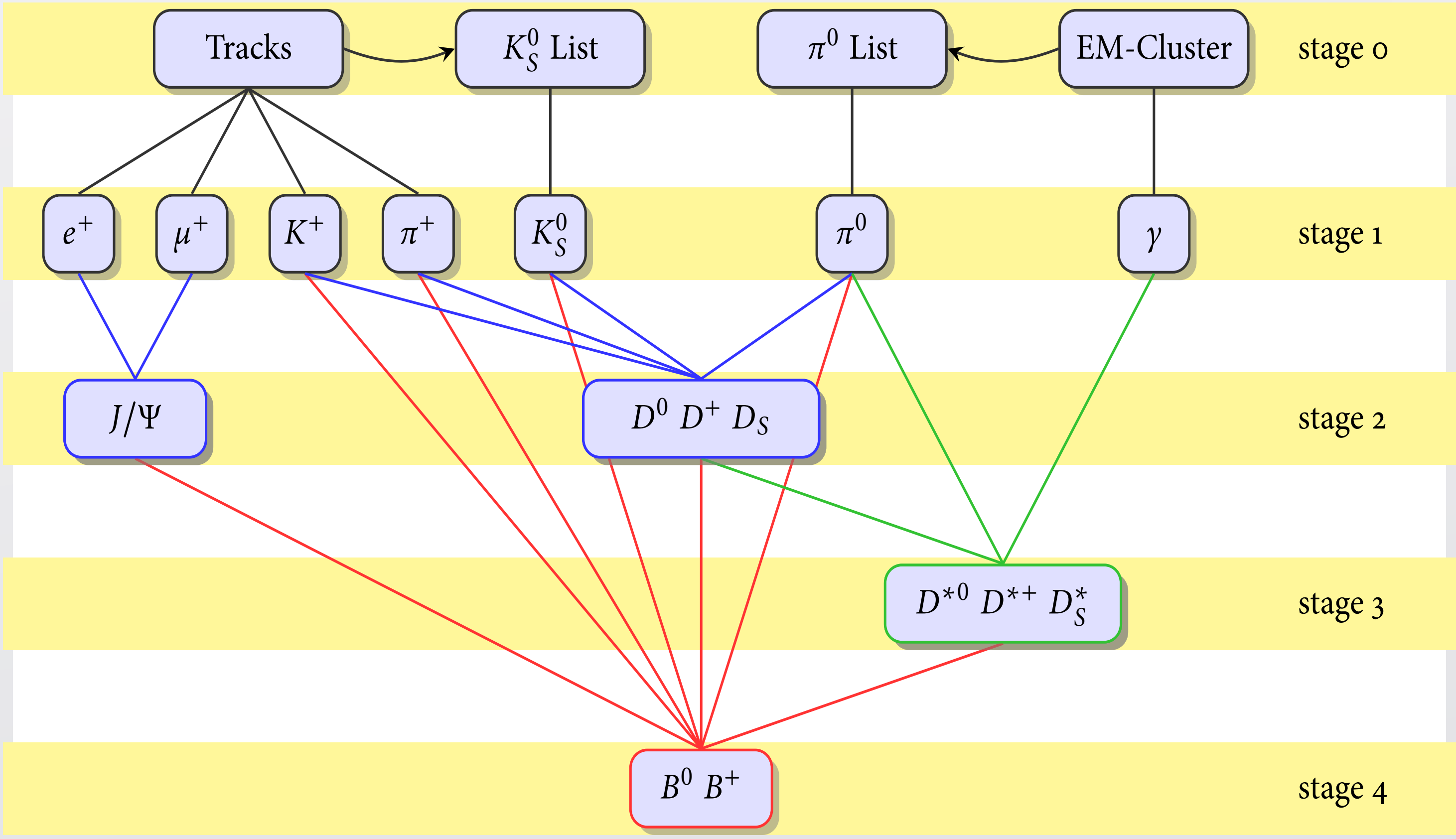
Tagging in Belle

- $\Upsilon(4S) \longrightarrow B\bar{B}$: very clean and well-known initial state
- Reconstruct one of the B mesons in the $\Upsilon(4S)$ event (**B tag**) to gather information about the B decay of interest
- Hadronic B decays:
  PRO: full B reconstruction, high purity
  CON: low efficiency
  ~2000 channels
- Semileptonic B decays:
  PRO: high efficiency
  CON: one missing neutrino, low purity
  ~100 channels



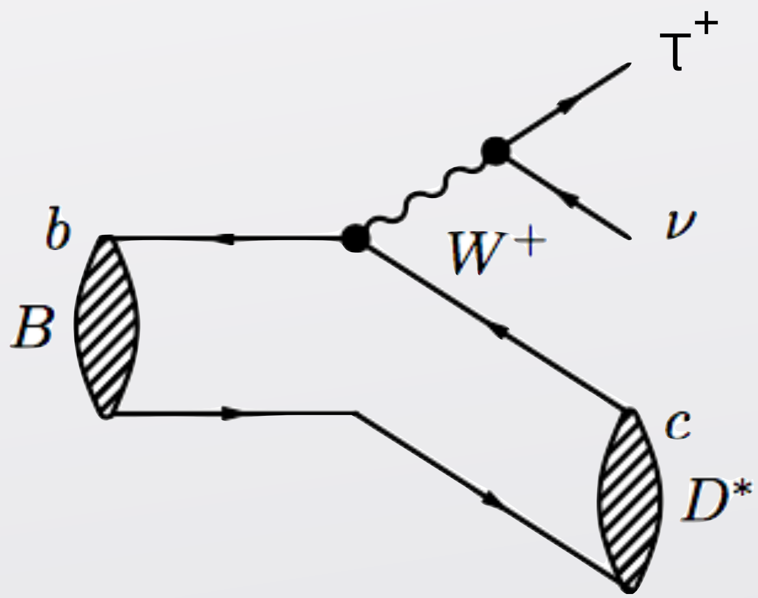
Tagging in Belle (FEI)

- 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

Interest of B ⟶ D(*) τ ν measurements



signal mode

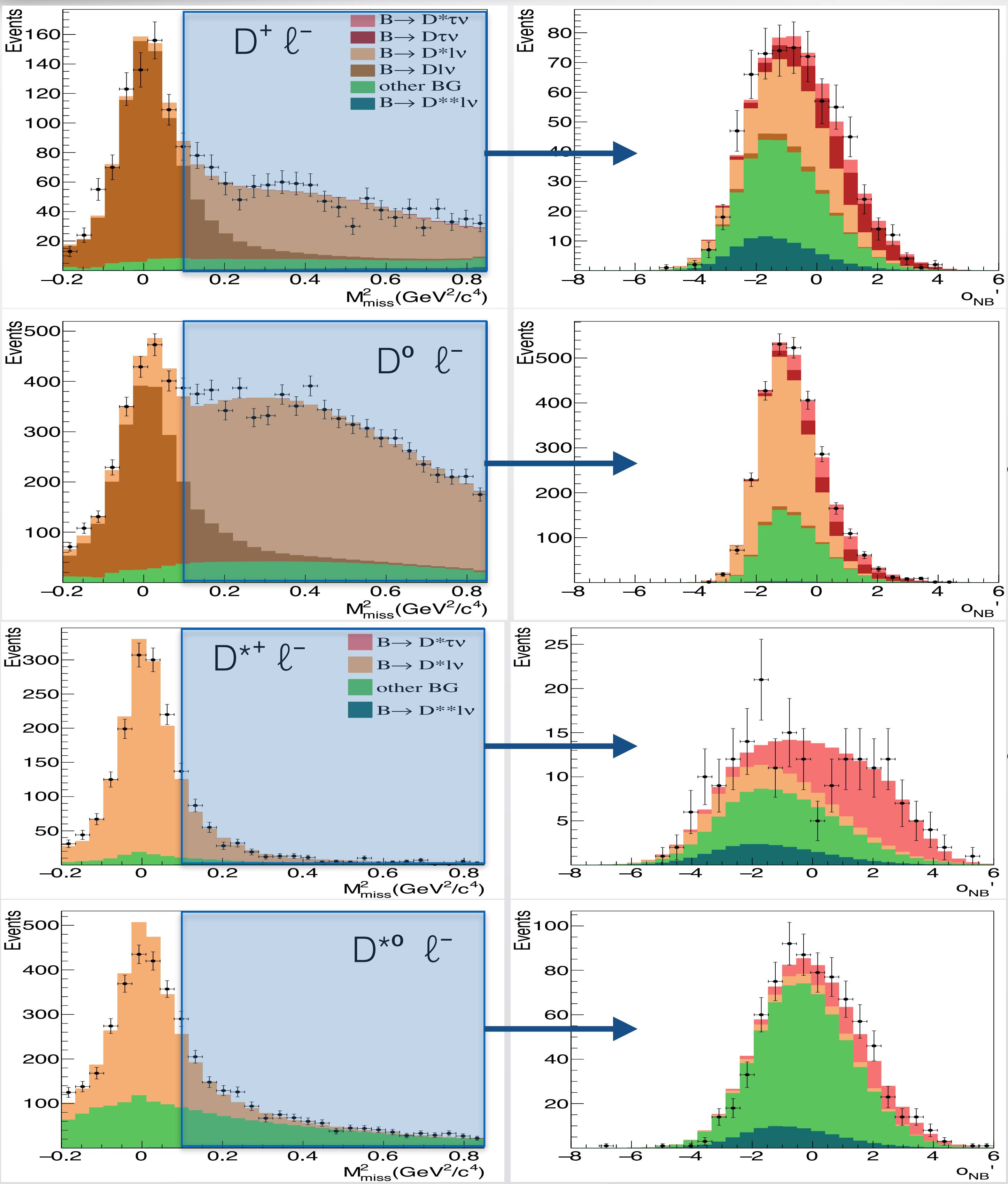
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu}_\ell)} \qquad \ell = (e, \mu)$$

normalization mode

- 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

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

PRD 92, 072014 (2015)



- Exploit leptonic τ decays
- Use m^2_{miss} to separate signal from normalization

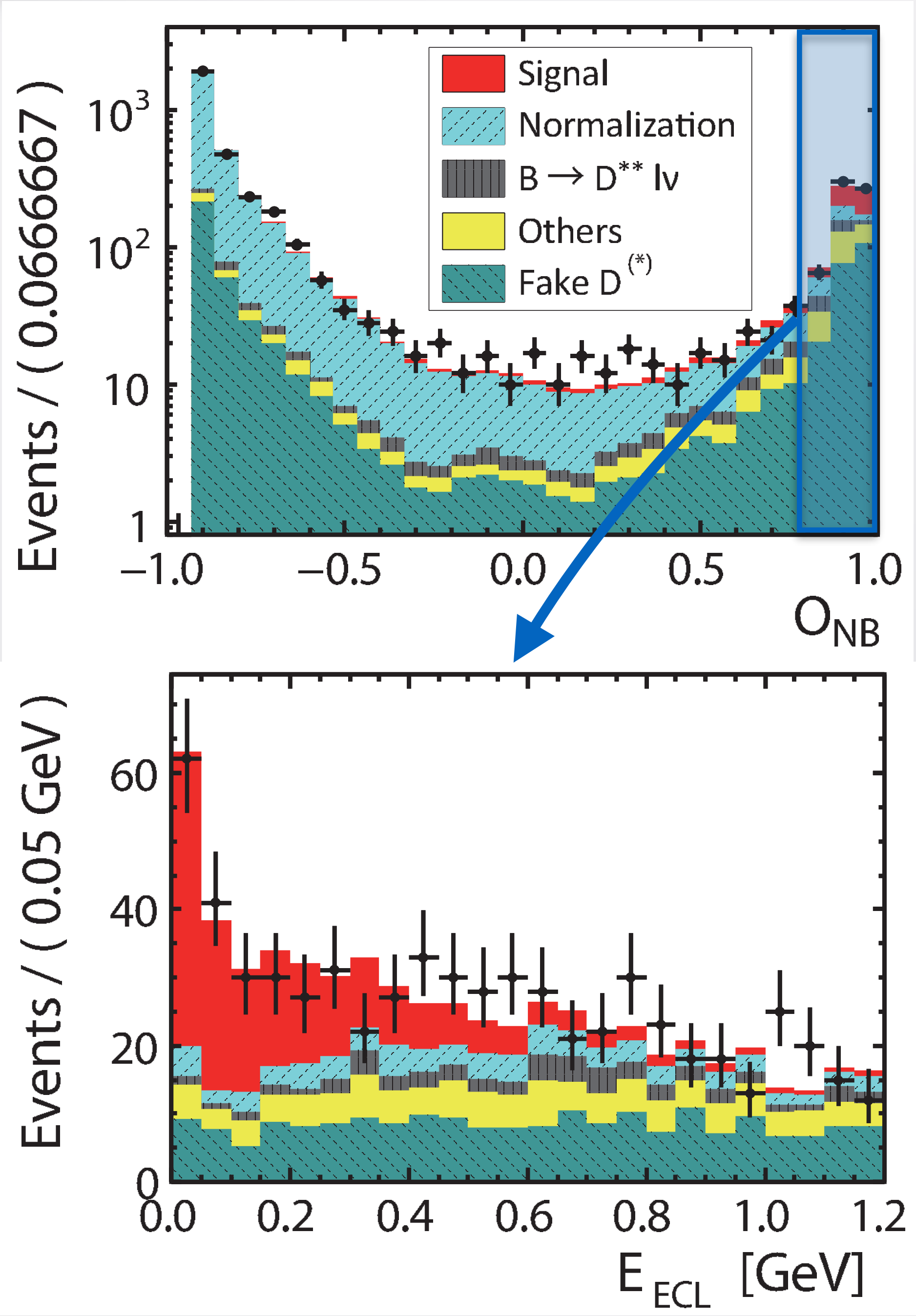
$$m^2_{miss} = p^2_\nu = (p_{e^+e^-} - p_{Btag} - p_{D^*\ell})^2$$

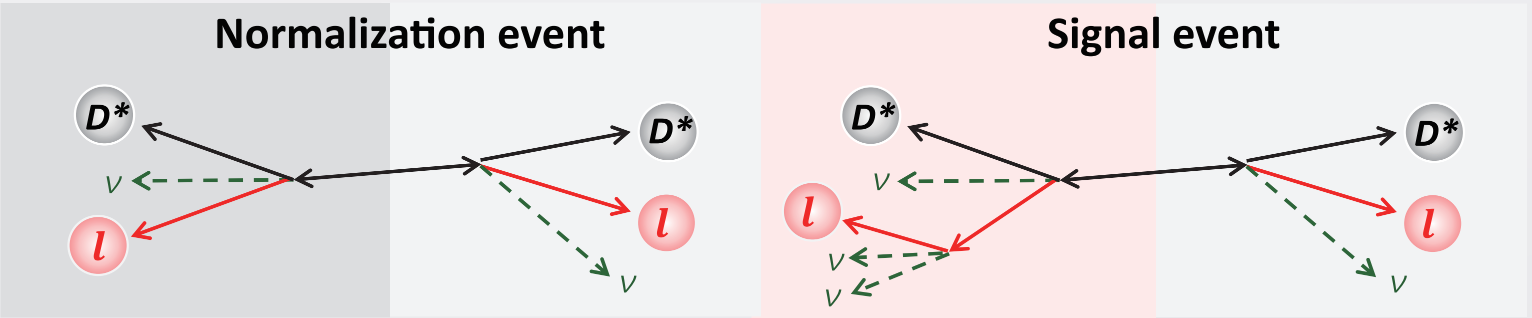
- Train signal MVA on high m^2_{miss} region, based on: E_{ECL} , p^*_ℓ , m^2_{miss} and others
- D ℓ modes with higher background levels due to "feed-down" from B ⟶(D* ⟶ D π_{slow}) ℓ ν

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

R(D*), semileptonic tag at Belle

PRD 94, 072007 (2016)





- Tag channels: $B^0 \longrightarrow D^{*-}\ \ell^+\ \nu_\ell$ (same as normalization)
- Discriminate between signal and normalization 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}

$$\cos\theta_{BY} = \frac{2E_B E_Y - m_B^2 - m_Y^2}{2p_B p_Y}$$

where $B \longrightarrow Y\nu$ (e.g. $Y = D^*\ell$)

R(D*) = 0.302 ± 0.030 ± 0.011

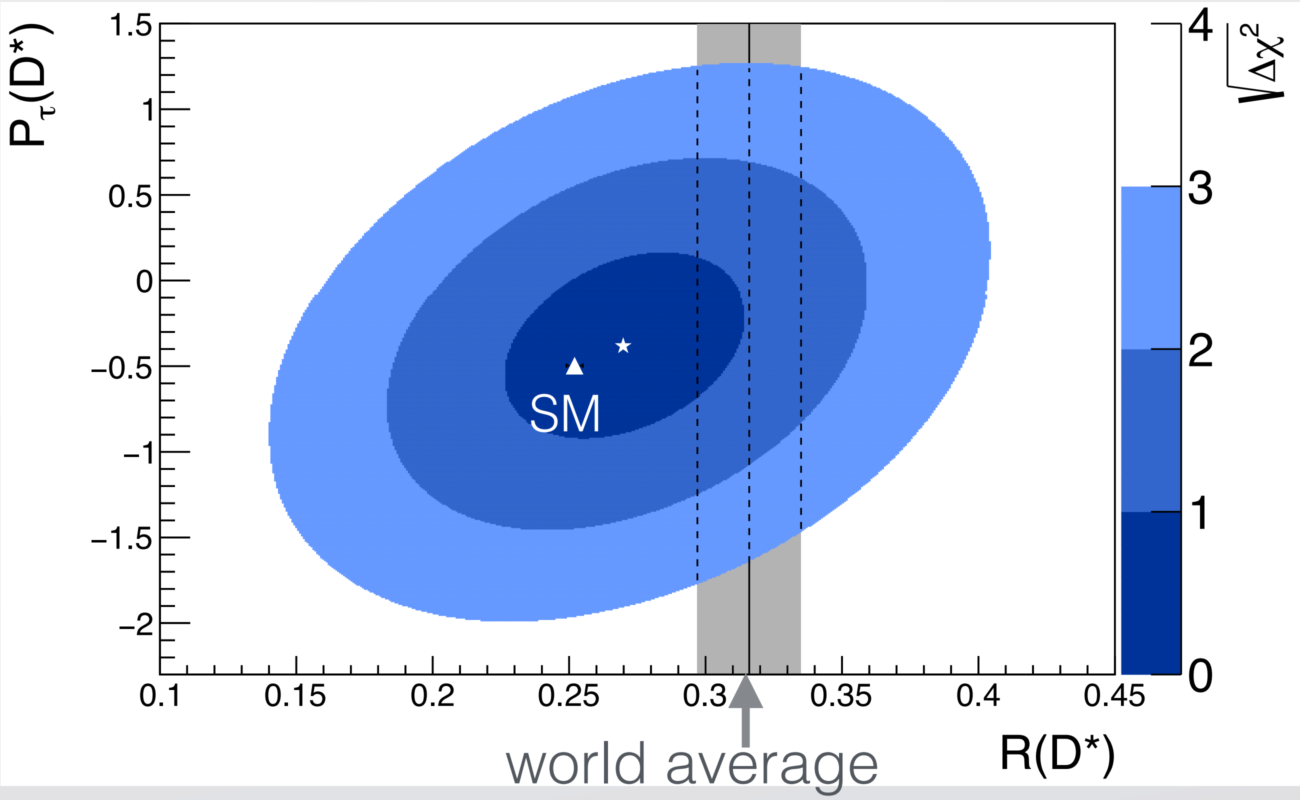
R(D*), hadronic tag and τ polarisation at Belle

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

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

PRL 118, 211801 (2017)

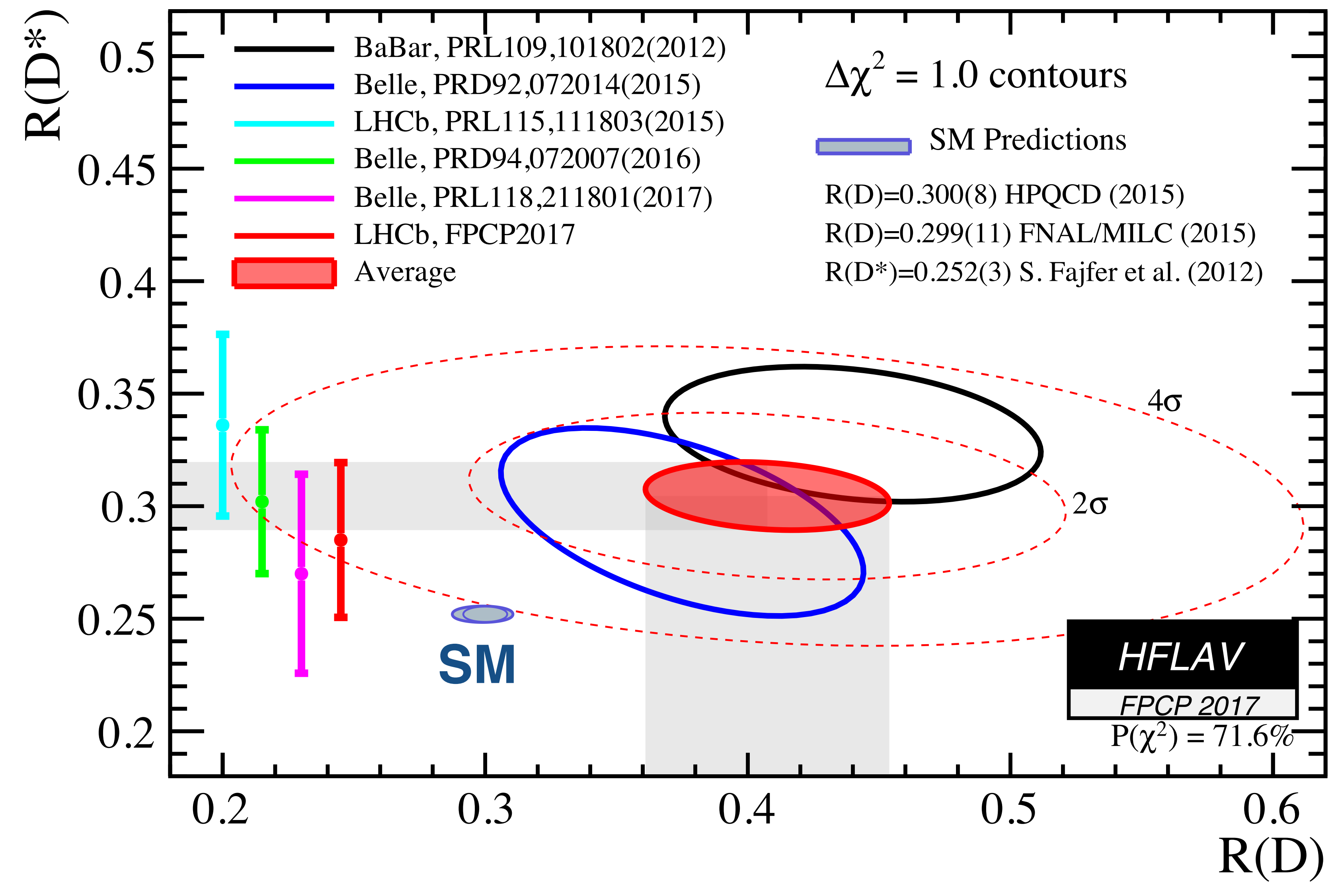
- The τ polarisation depend on the mediator ⟶ sensitive to NP
- Two-body τ decays (τ ⟶ π ν , ϱ ν) used to measure the τ polarisation
- New independent measurement of R(D*)



$$R(D^*) = 0.270 \pm 0.035^{+0.028}_{-0.025}$$
$$P_\tau(D^*) = -0.38 \pm 0.51^{+0.21}_{-0.16}$$

Consistent with SM

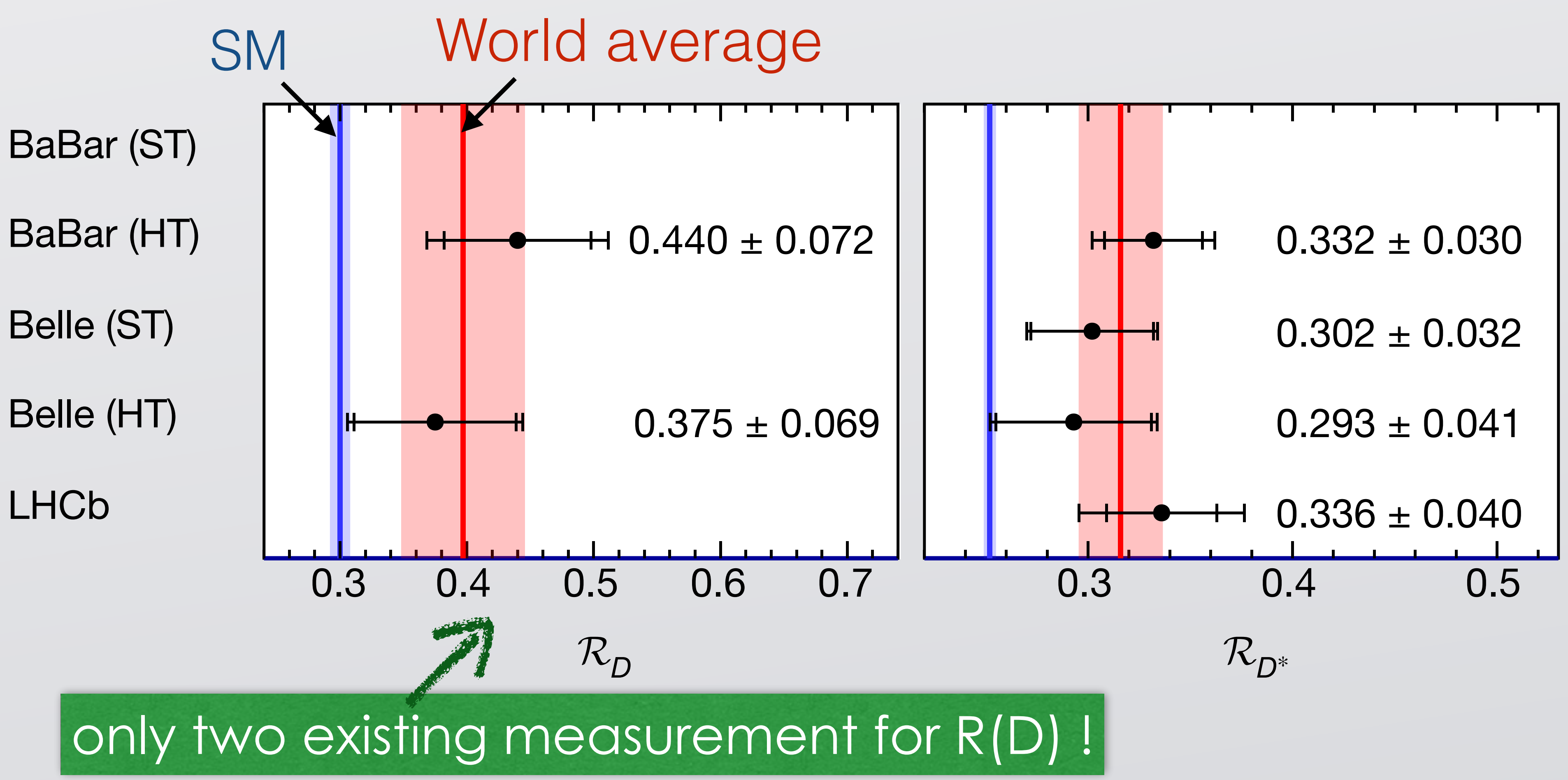
R(D(*)): experiments vs theory



- Babar, Belle and LHCB results point to a **~4σ** discrepancy between SM predictions and experimental results

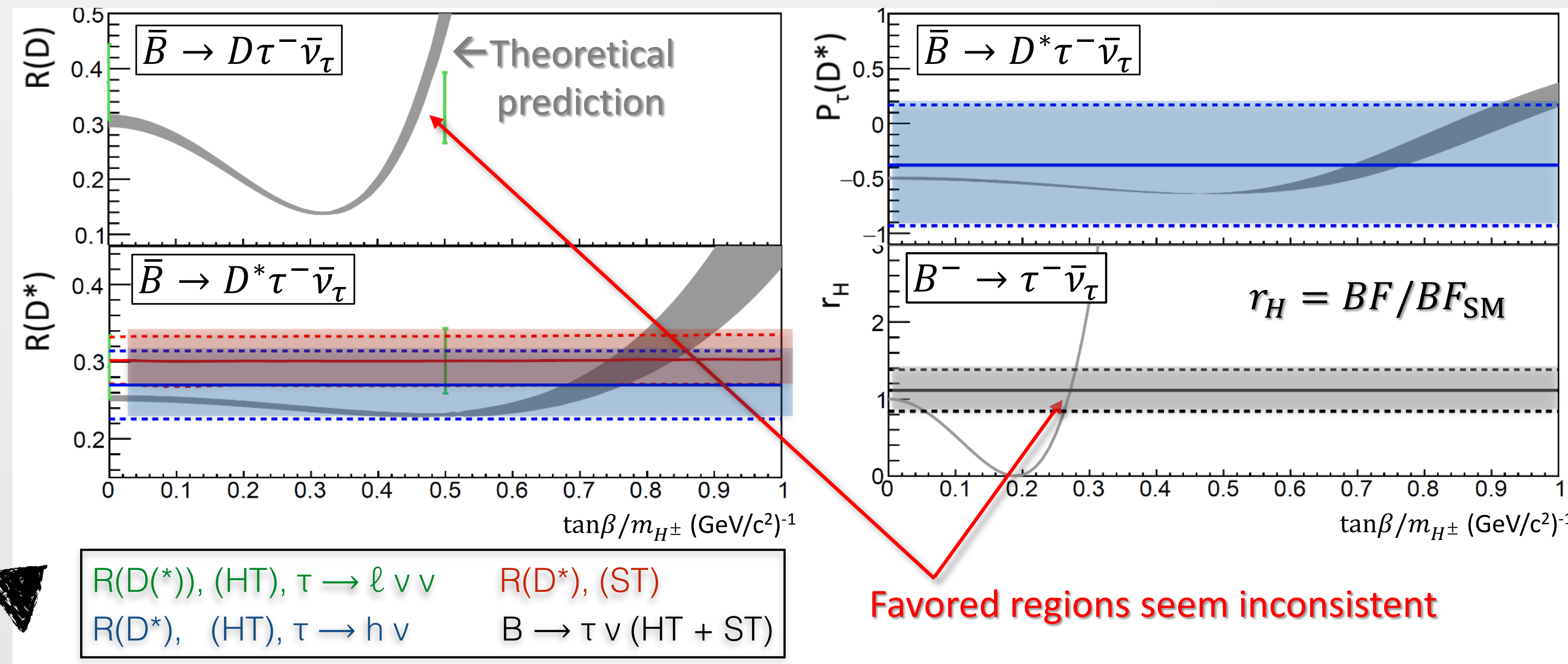
Prospects for B ⟶ D(*) τ ν at Belle

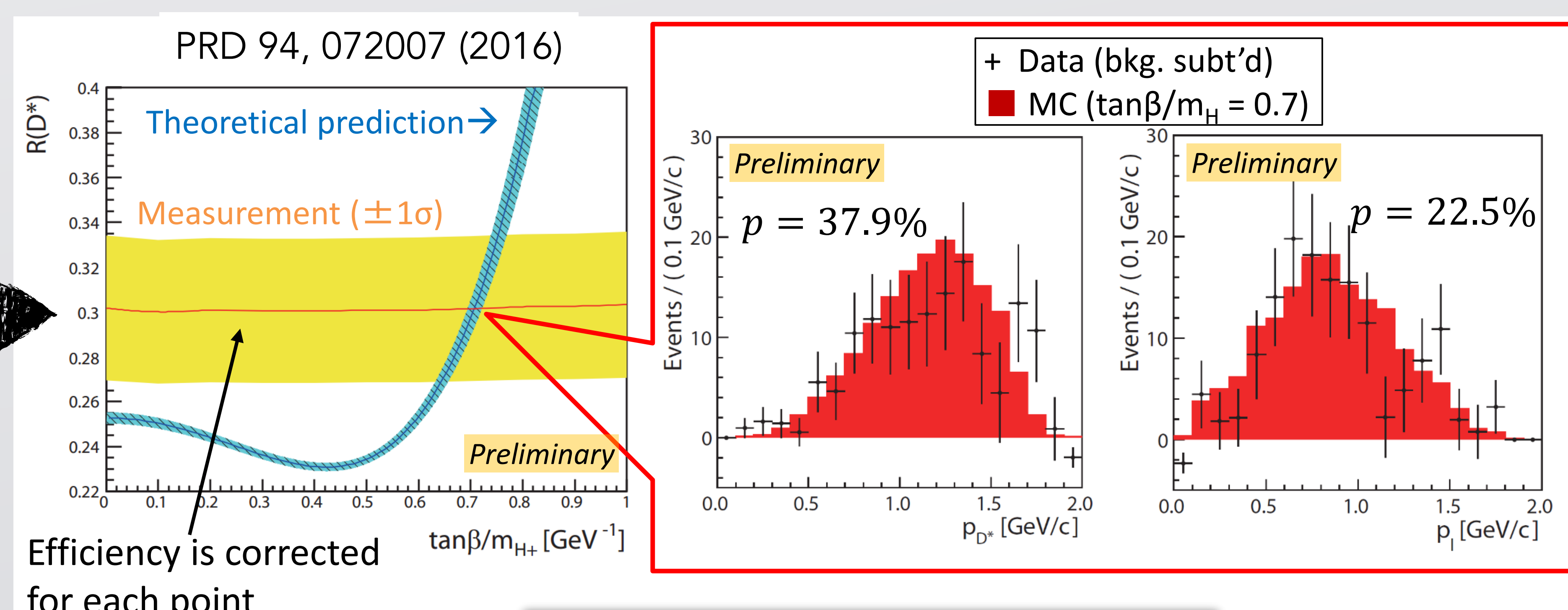
- Ongoing new simultaneous measurement of R(D) and R(D*)
- Semileptonic tag with modes B ⟶ D(*) ℓ ν + D(*) π ℓ ν
- Exploits improved tagging algorithm (FEI) with high efficiency



Theoretical interpretation of results

- Belle has produced comparisons of experimental results with NP models
- Focus on Type II - 2HDM:
- What value of tanβ/m_H favours the experimental results ?
- Do measured kinematic distributions (p_D or q^2, p^*_ℓ) match the NP ones ?



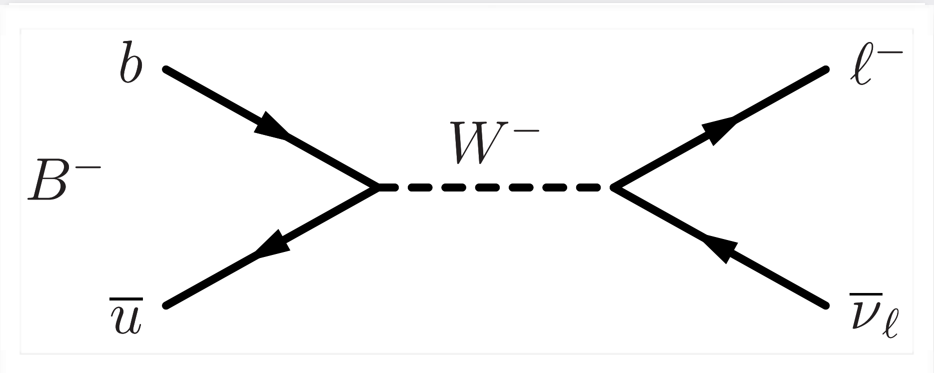


slides from S. Hirose, Moriond 2017

Interest of B ⟶ τ ν, μ ν measurements

$$\mathcal{B}(B \to \ell\nu) = \frac{G_F^2\, m_B^2\, m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right) f_B^2\, |V_{ub}|^2$$

helicity suppression



$$\mathcal{B}(B \to e\nu) \ll \mathcal{B}(B \to \mu\nu) \ll \mathcal{B}(B \to \tau\nu)$$

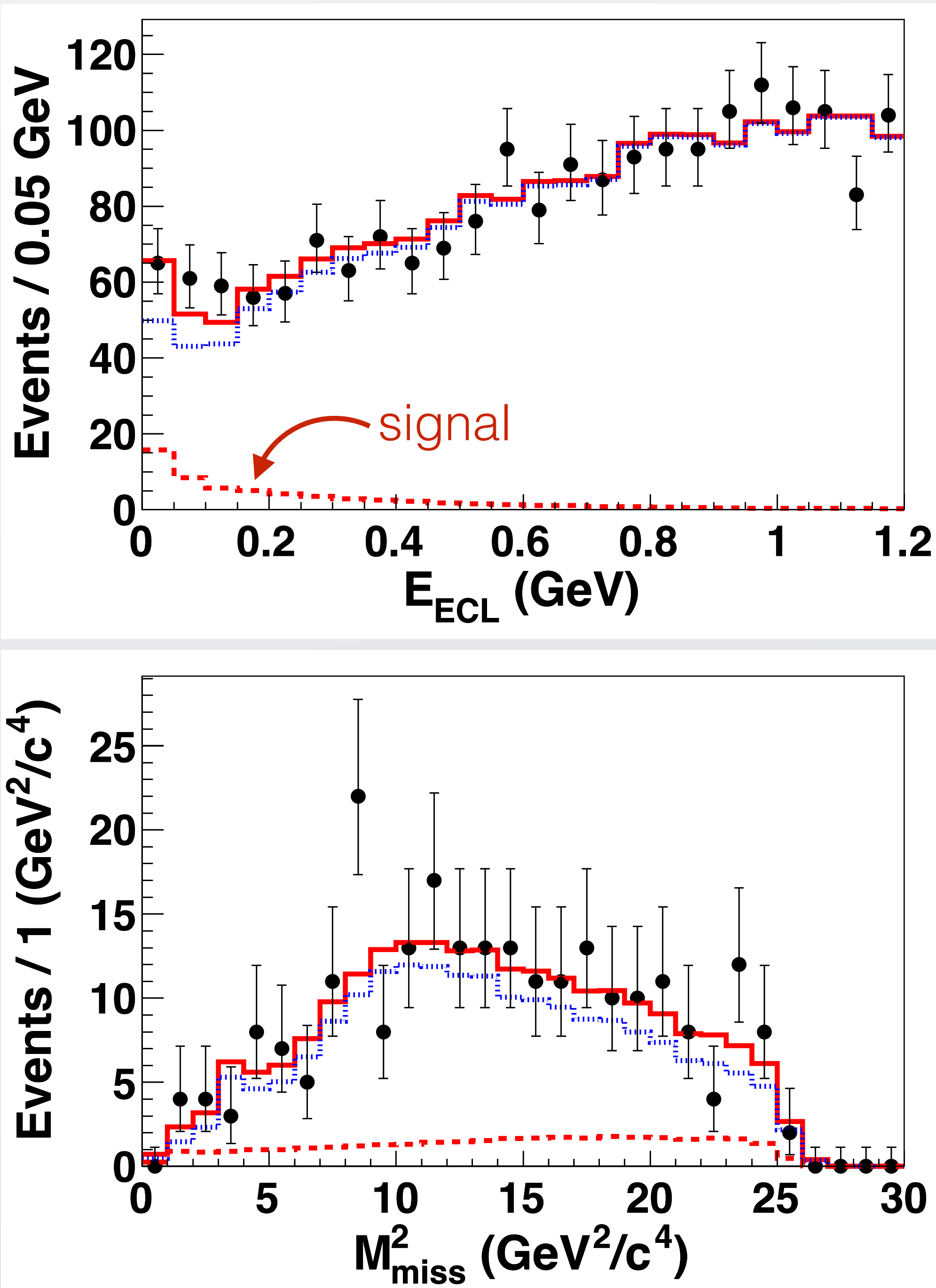
~ B_τ / 10^7	~ B_τ / 220	B_τ (~10^{-4})
N_{MC} ~ 10^{-2}	N_{MC} ~ 300	N_{MC} ~ 67000

- V_{ub}, quite small decay rates
- Leptonic decay, small theoretical uncertainties
- B ⟶ τ ν, measurable, good probe for 2HDM
- B ⟶ μ ν is barely measurable
- B ⟶ e ν is out of experimental reach

⟶ search NP effects

B ⟶ τ ν, hadronic tag at Belle

PRL 110, 131801 (2013)

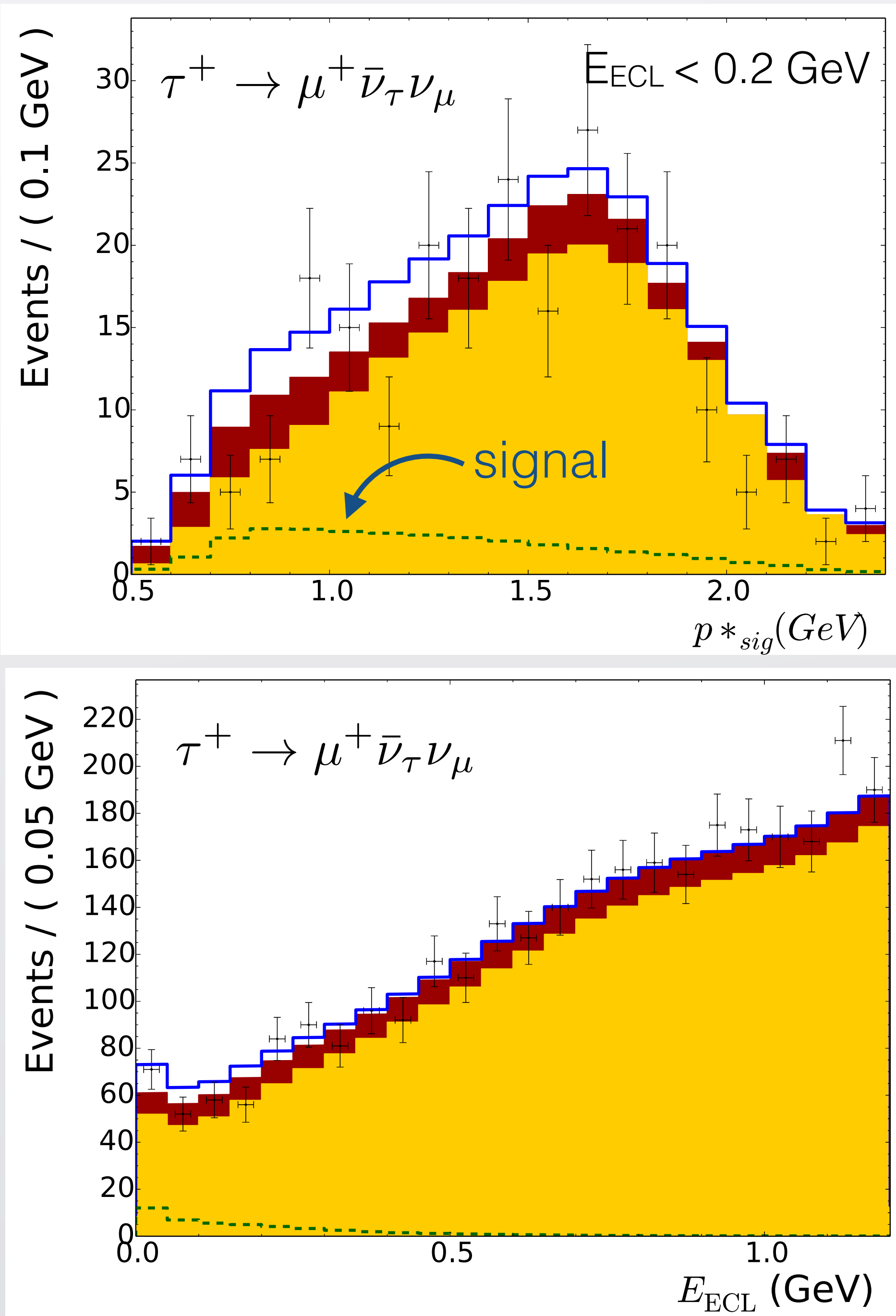


- More than one neutrino, gain information from Btag
- τ channels (total Br ~ 72 %):
  - ℓ ν ν , π ν, π π^o ν
- Signal yield extracted from a 2D fit to E_{ECL} and m^2_{miss}
- Signal yield: $62^{+23}_{-22}(\text{stat}) \pm 6(\text{syst})$
- Signal significance: 3σ
- Statistically dominated

$$\mathcal{B}(B \to \tau\nu) = [0.72^{+0.27}_{-0.25}(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-4}$$

B ⟶ τ ν, semileptonic tag at Belle

CKM 2014 proceedings

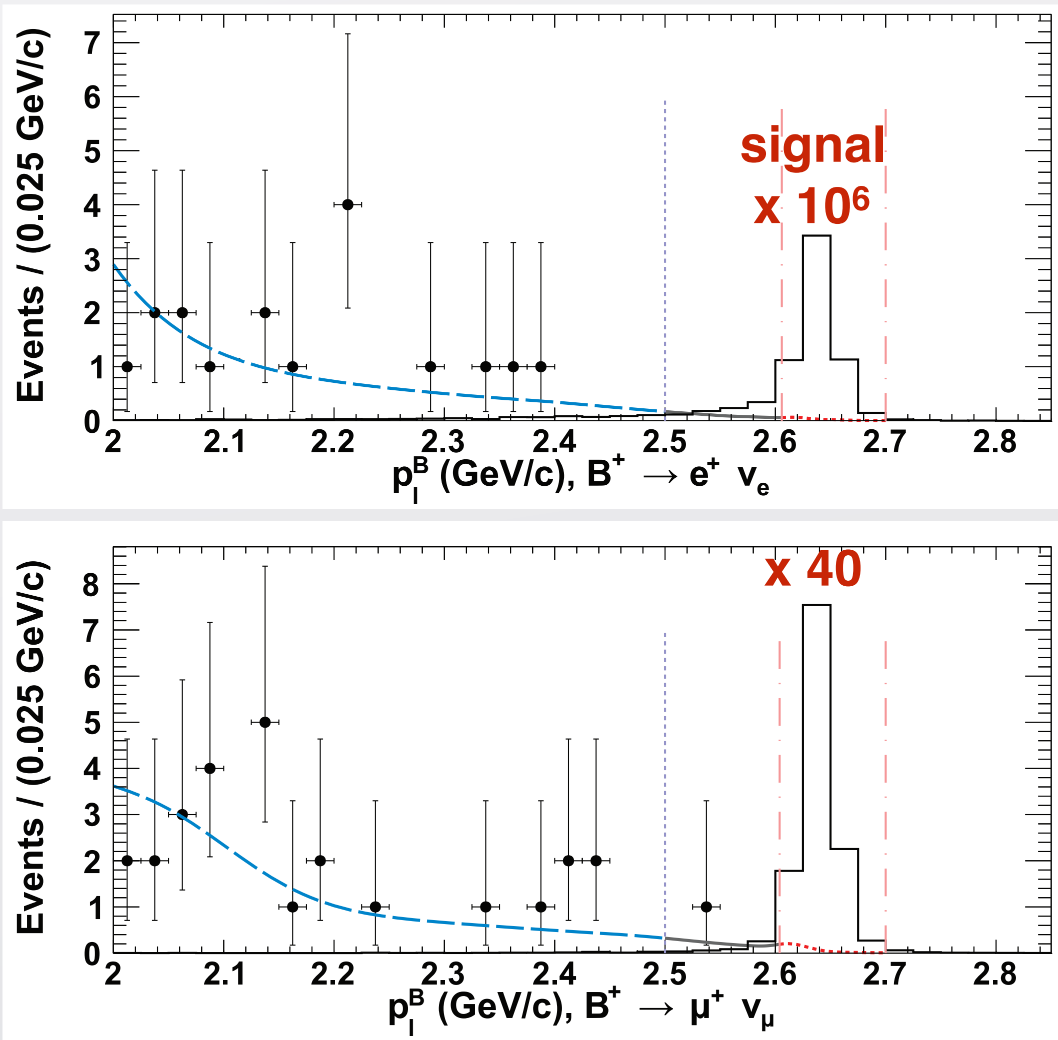


- Same τ decay channels as hadronic tag study
- Tag channels:
  - $B^+ \longrightarrow D(*)^o\ \ell^+ \nu_\ell$ (ℓ = e,μ)
  - Use a MVA for tag selection
- Signal yield extracted through 2D fit to p^*_ℓ and E_{ECL}
- Signal yield: 220 ± 50
- Signal significance: 3.8σ

$$\mathcal{B}(B \to \tau\nu) = [1.25 \pm +0.28(\mathrm{stat}) \pm 0.27(\mathrm{syst})] \times 10^{-4}$$

B ⟶ μ ν, hadronic tag at Belle

PRD 91, 052016 (2015)



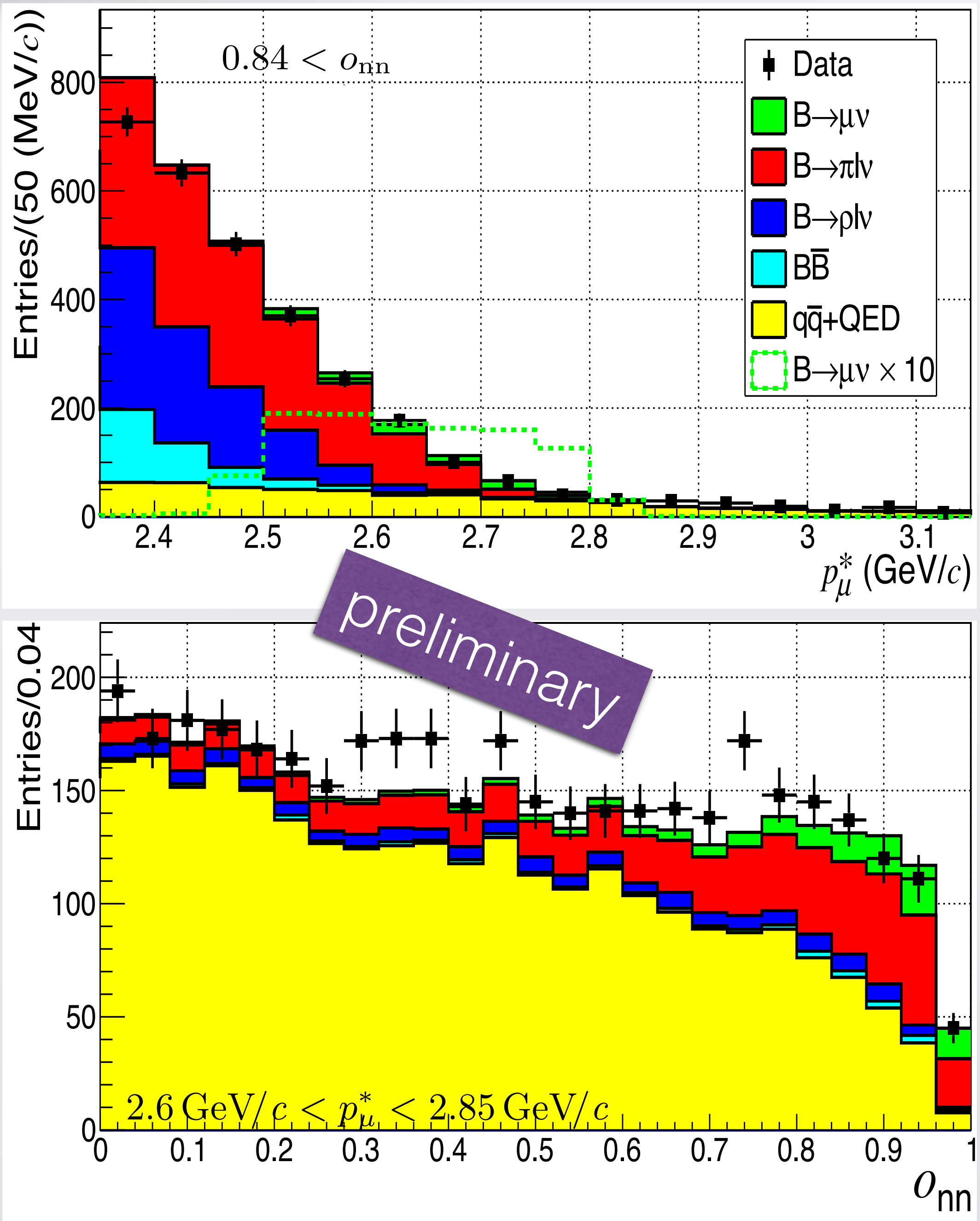
$$\mathcal{B}(B \to \mu\nu) < 2.7 \times 10^{-6}$$

- Predicted: $\mathcal{B} \approx 4 \times 10^{-7}$
- Two body decay, mono energetic lepton in B rest-frame with momentum with $p = m_B/2 = 2.6$ GeV
- With an hadronic tag only one neutrino in the event, can use $m^2_{miss} \sim 0$
- Reconstruction of B tag provides high resolution for B signal

B ⟶ μ ν, untagged at Belle

NEW

S.Falke @ EPS 2017



$$M_{bc} = \sqrt{E^2_{\rm beam}/c^4 - |\sum_i \vec{\mathbf{p}}^*_i/c|^2}$$

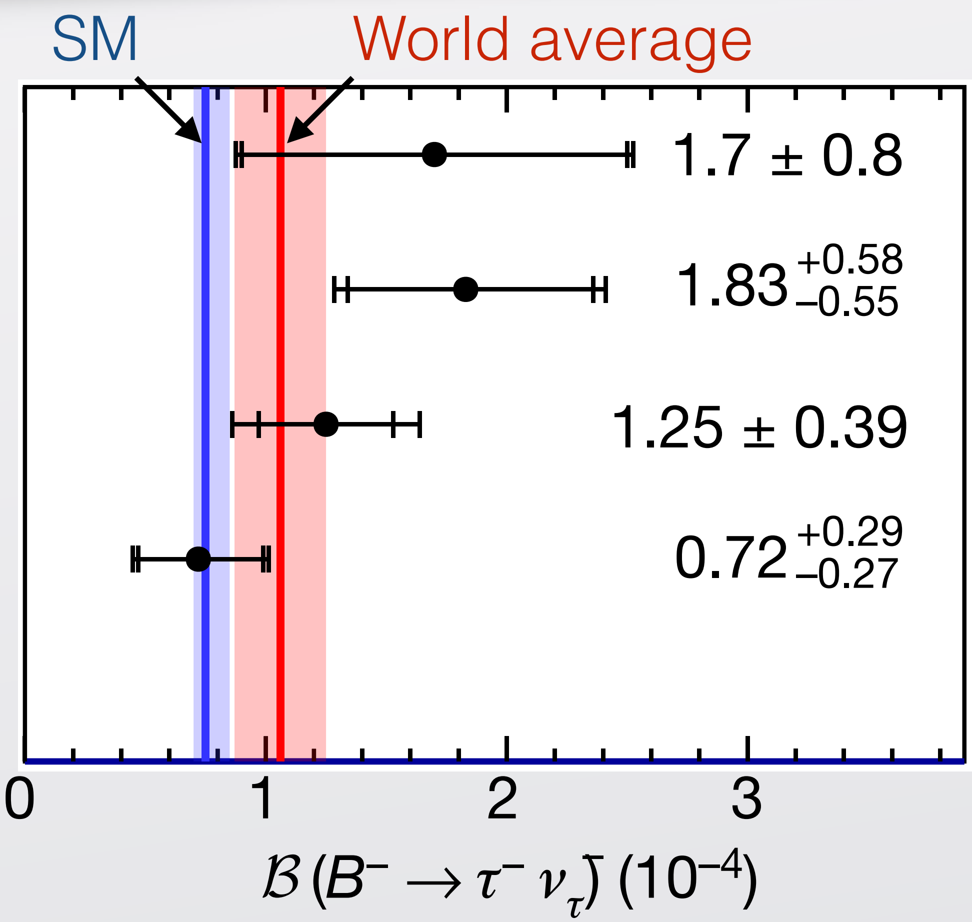
$$E_B = \sum_i \sqrt{(m_i c^2)^2 + |\vec{\mathbf{p}}^*_i c|^2},$$

- First measurement of branching fraction
  - Untagged: select B companion using M_{bc} and E_B cuts
- Use neural network to discriminate signal from background (14 input parameters)
- Signal extracted from 2D fit to p^*_μ and O_{nn}
- Signal significance: 2.4σ

B(B ⟶ μ ν) = (6.46 ± 2.22 ± 1.60) x 10^{-7}

Compatible with SM

Overview of B ⟶ τ ν, μ ν results



- Total significance is 5σ
- Statistically limited results
- Belle II will significantly improve this measurement with more statistics

	∫ L dt (fb^{-1})	B ⟶ μ ν , upper limit (90% CL)
Belle (no tag)	253	1.7×10^{-6}
BABAR (no tag)	426	1.0×10^{-6}
BABAR (ST)	418	8×10^{-6}
BABAR (HT)	342	5.2×10^{-6}
BELLE (HT)	711	2.7×10^{-6}
HFAG average		1.0×10^{-6}
Belle (no tag)	711	$(6.46 \pm 2.22 \pm 1.60) \times 10^{-7}$

⟵ **branching ratio**

- First branching measurement from Belle this year (significance 2.4σ)
- Wait for Belle II for improved results

Conclusion

- At Belle, 772×10^6 $B\bar{B}$ pairs produced in the clean Υ(4S) environment are analysed to produce precise measurements of rare SM processes

- **R(D(*))**: long-standing 4σ discrepancy between SM and experimental results

    - A new simultaneous measurement of R(D) and R(D*) from Belle is ongoing, with a new improved tag method

- Follow the next talk for Belle II prospects !

- **B ⟶ τ ν** : Measurements provide a 5σ signal significance, agreement with SM

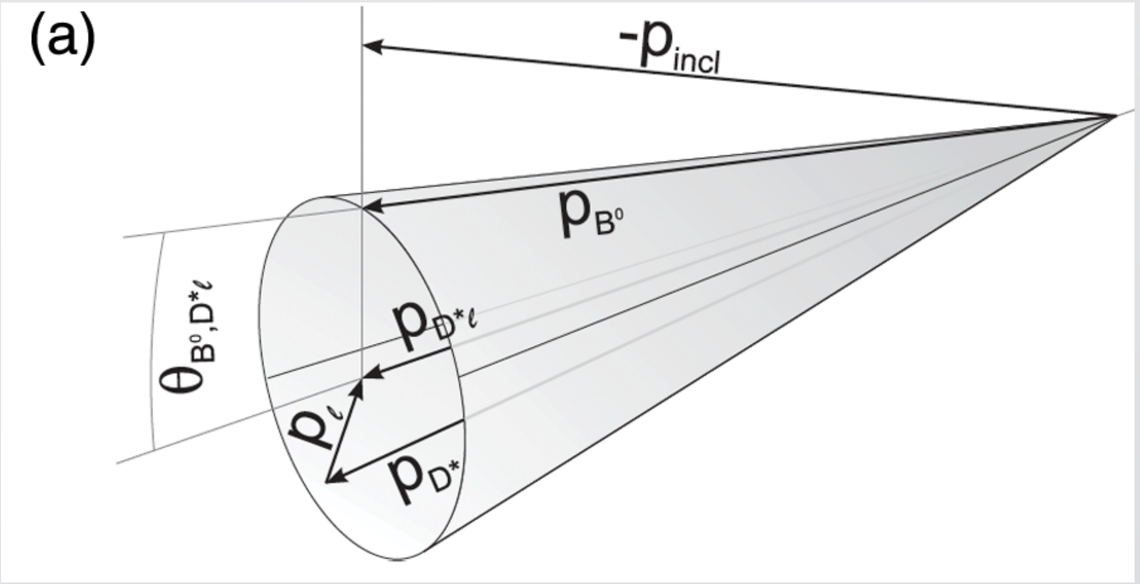
- **B ⟶ μ ν**: Belle preliminary result for first branching measurement, 2.4σ signal significance and compatible with SM

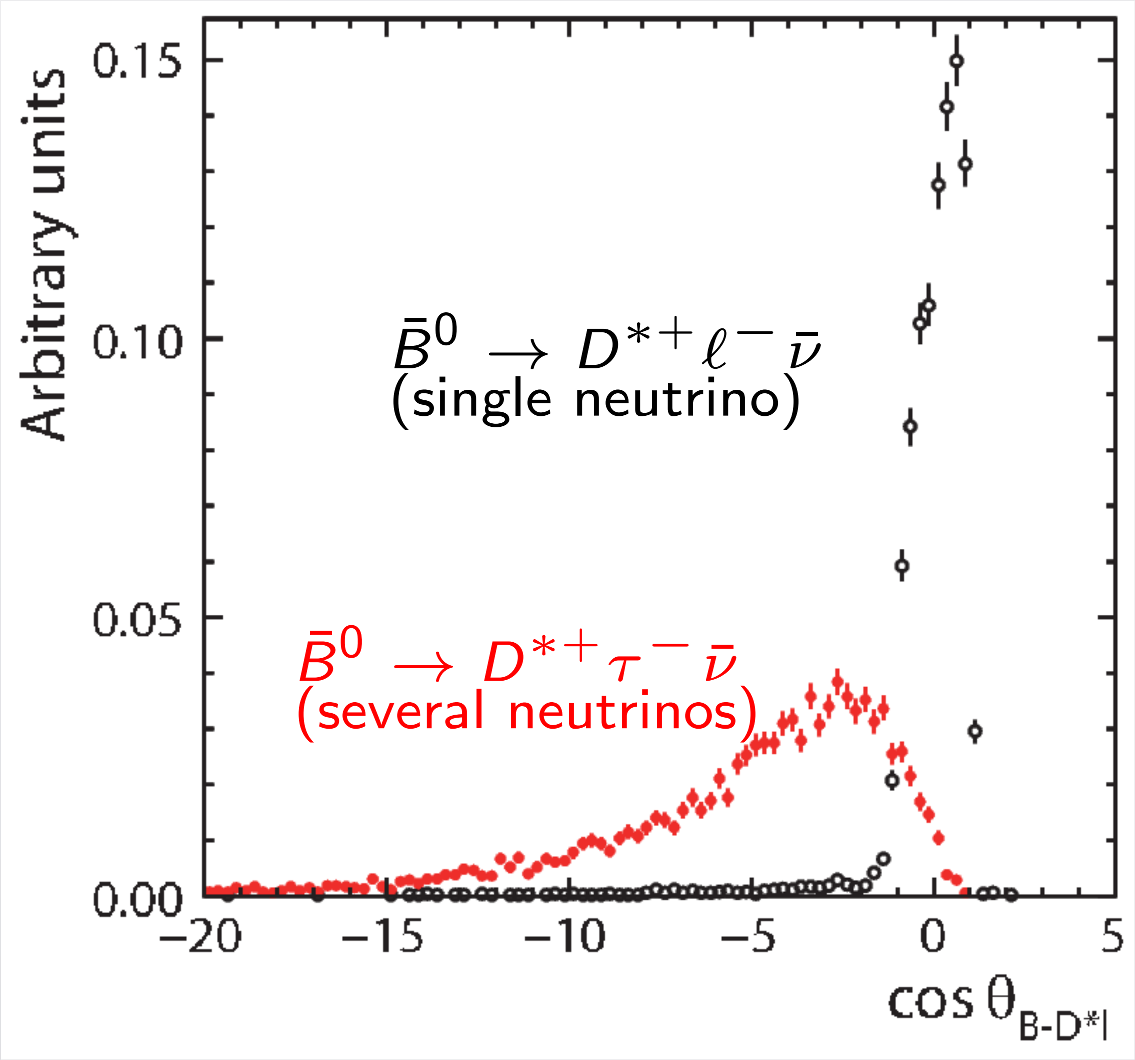
- Back-up

$\cos\theta_{BY}$

$$
\begin{aligned}
P_\nu^2 &= 0 \\
&= (P_B - P_Y)^2 \\
&= m_B^2 + m_Y^2 - 2(E_B E_Y - p_B p_Y \cos\theta_{BY})
\end{aligned}
$$

$$\Rightarrow \cos\theta_{BY} = \frac{2E_B E_Y - m_B^2 - m_Y^2}{2 p_B p_Y}.$$





Systematic uncertainties, R(D(*)), HT

	$R(D)$ [%]	$R(D^*)$ [%]	Correlation
$D^{(*(*))}\ell\nu$ shapes	4.2	1.5	0.04
D^{**} composition	1.3	3.0	-0.63
Fake D yield	0.5	0.3	0.13
Fake ℓ yield	0.5	0.6	-0.66
D_s yield	0.1	0.1	-0.85
Rest yield	0.1	0.0	-0.70
Efficiency ratio f^{D^+}	2.5	0.7	-0.98
Efficiency ratio f^{D^0}	1.8	0.4	0.86
Efficiency ratio $f_{\rm eff}^{D^{*+}}$	1.3	2.5	-0.99
Efficiency ratio $f_{\rm eff}^{D^{*0}}$	0.7	1.1	0.94
CF double ratio g^+	2.2	2.0	-1.00
CF double ratio g^0	1.7	1.0	-1.00
Efficiency ratio $f_{\rm wc}$	0.0	0.0	0.84
$M_{\rm miss}^2$ shape	0.6	1.0	0.00
$o'_{\rm NB}$ shape	3.2	0.8	0.00
Lepton PID efficiency	0.5	0.5	1.00
Total	7.1	5.2	-0.32

Systematic uncertainies, R(D*), ST

	$\mathcal{R}(D^*)$ [%]		
Sources	$\ell^{\rm sig} = e, \mu$	$\ell^{\rm sig} = e$	$\ell^{\rm sig} = \mu$
MC size for each PDF shape	2.2	2.5	3.9
PDF shape of the normalization in $\cos\theta_{B\text{-}D^*\ell}$	$^{+1.1}_{-0.0}$	$^{+2.1}_{-0.0}$	$^{+2.8}_{-0.0}$
PDF shape of $B \to D^{**}\ell\nu_\ell$	$^{+1.0}_{-1.7}$	$^{+0.7}_{-1.3}$	$^{+2.2}_{-3.3}$
PDF shape and yields of fake $D^{(*)}$	1.4	1.6	1.6
PDF shape and yields of $B \to X_c D^*$	1.1	1.2	1.1
Reconstruction efficiency ratio $\varepsilon_{\rm norm}/\varepsilon_{\rm sig}$	1.2	1.5	1.9
Modeling of semileptonic decay	0.2	0.2	0.3
$\mathcal{B}(\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau)$	0.2	0.2	0.2
Total systematic uncertainty	$^{+3.4}_{-3.5}$	$^{+4.1}_{-3.7}$	$^{+5.9}_{-5.8}$

Systematic uncertainies, R(D*) and τ polarisation

Source	rel. uncertainty on $\mathcal{R}(D^*)$	uncertainty on $P_\tau(D^*)$
Hadronic B decay composition	$^{+7.7}_{-6.9}\%$	$^{+0.13}_{-0.10}$
MC stat. for PDF construction	$^{+4.0}_{-2.8}\%$	$^{+0.15}_{-0.11}$
Semileptonic B decays	$\pm3.5\%$	±0.05
Fake D^* background	$\pm3.4\%$	0.02
Other	$\pm2.2\%$	±0.03