実験: b→cτν

2026/9/2

KEK 古賀太一朗

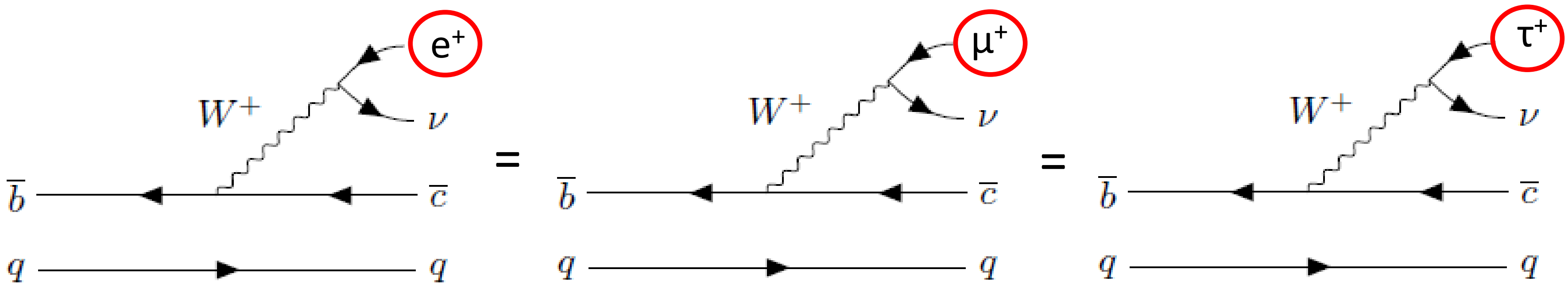
Contents

- $b \to c\tau\nu$ result and expected sensitivity
  -mainly about Belle II

- Measurements:
  - -$R(D^{(*)})$: Ratios of $BR(B \to c\tau\nu)/BR(B \to ce\nu,\ B \to c\mu\nu)$
  - -$P_\tau(D^*)$: τ polarization
  - -$F_L\,(D^{(*)})$: D^* polarization
  - -$R(X)$,$R(J/\psi)$,$R(\Lambda_c^+)$

b→cτν

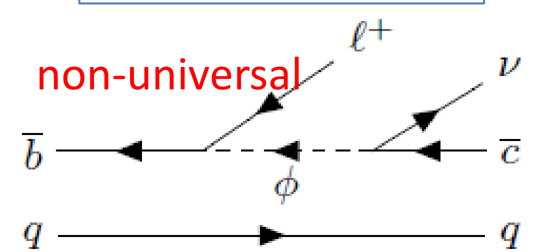
- SM expects lepton coupling to EW gauge bosons to be flavor-universal (lepton flavor universality, LFU)



Branching ratio (BR)~10% BR ~10% BR~3% (lepton mass difference)

- B meson is a good prove to test LFU to search for new physics
  - -O(10GeV), 3 flavor(e, μ, τ) can be tested at same time
  - -LFU between e and μ is well (~1% level) tested
  - -LFU between τ and ℓ(e,μ): main topic today

new physics



Experimental observables

- R: ratio of BR(b→cτν) and BR(b→ceν, cμν)
  -cancel systematics by taking ratio

$$\mathcal{R}(D) = \frac{\mathcal{B}(B \to D\tau\nu_\tau)}{\mathcal{B}(B \to D\ell\nu_\ell)}$$

ℓ=e,μ

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

他にもR(X),R(J/ψ),R(Λ_c^+) もあるが今回はスキップ

- τ polarization ($P_\tau(D^*)$) and D* polarization ($F_L(D^{(*)})$) in B→D*τν decay

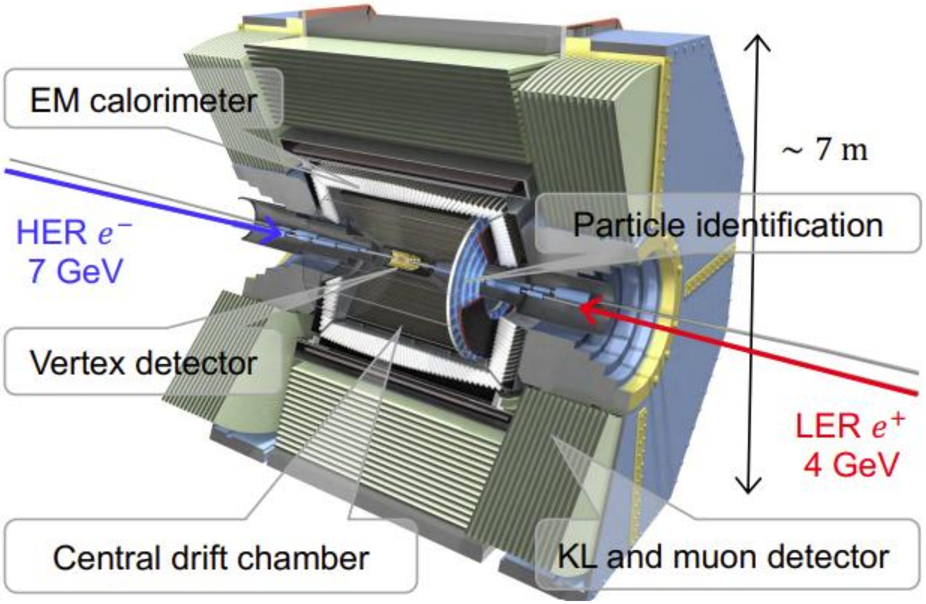
$$P_\tau(D^{(*)}) = [\Gamma^+(D^{(*)}) - \Gamma^-(D^{(*)})]/[\Gamma^+(D^{(*)}) + \Gamma^-(D^{(*)})]$$

+−: τ helicity of $\pm 1/2$.

Belle II

- Belle II at SuperKEKB: on-threshold $\bar{B}B$ production from $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$, reconstructed with hermetic detector

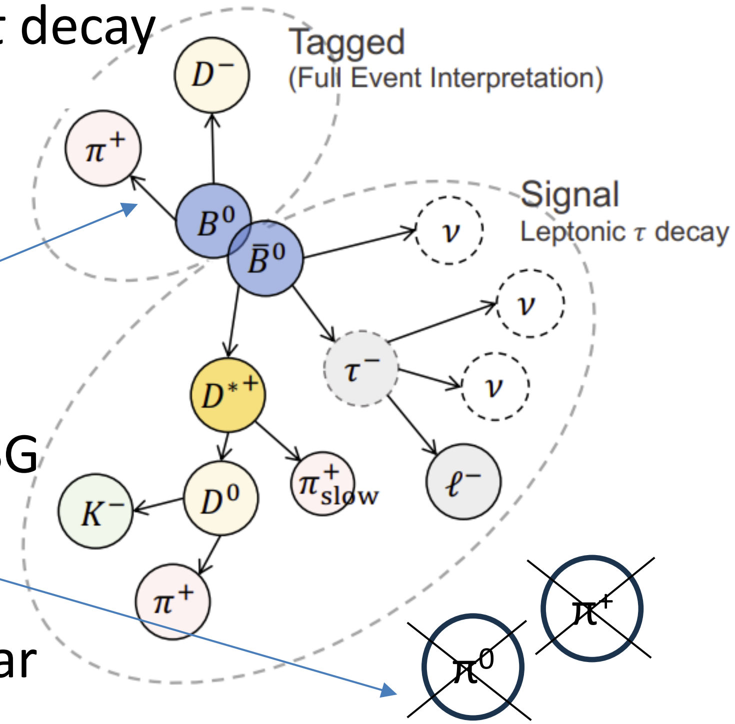
- Belle II Feature:
  - **-clean background environment**
  - **-known initial beam state**
  - -particle identification of e,μ,π,K
  - **-neutral particle detection**
  - -achieved luminosity of $5.3 \times 10^{34}\ cm^2 s^{-1}$ integrated luminosity of **$808 fb^{-1}$** @Υ(4S)



- Best experiment to measure b→cτν
  - -τ immediately decays to one or multiple neutrino(s) (τ→μνν, τ→πν etc.)
  - -all Belle II features are suitable for measurement with missing neutrino(s)

Analysis concept for B→D$^{(*)}$τν

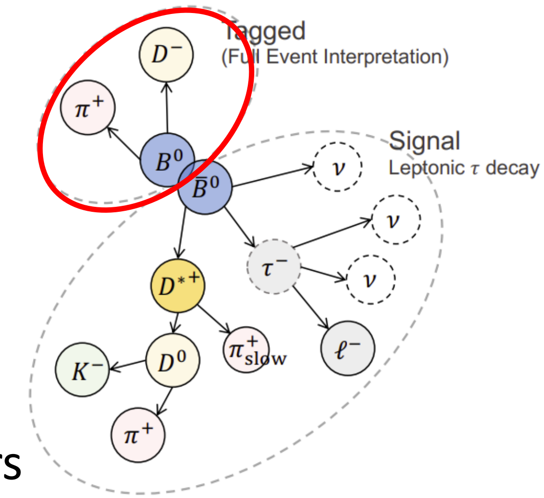
- Reconstruct $B \to D^* \tau \nu_\tau$ $B \to D^* \ell \nu_\ell$
  - -leptonic/hadronic B decay, leptonic/hadronic τ decay
- Challenge: neutrino(s) in final state
  - -Fully reconstruct partner B meson (tagging) to measure missing neutrino masses
  - -No remained particles except for BB to reject BG
  - -Major BG: B→D**ℓν, hadronic B decay
    - -D** Branching ratio is not measured well so far



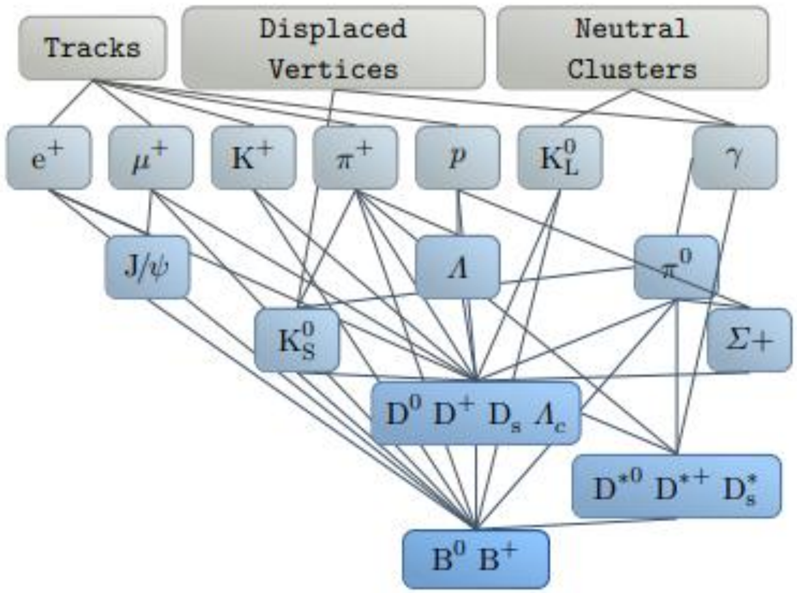
- Cancel theoretical and experimental systematics error by taking ratio of B→D*τν and B→D*ℓν

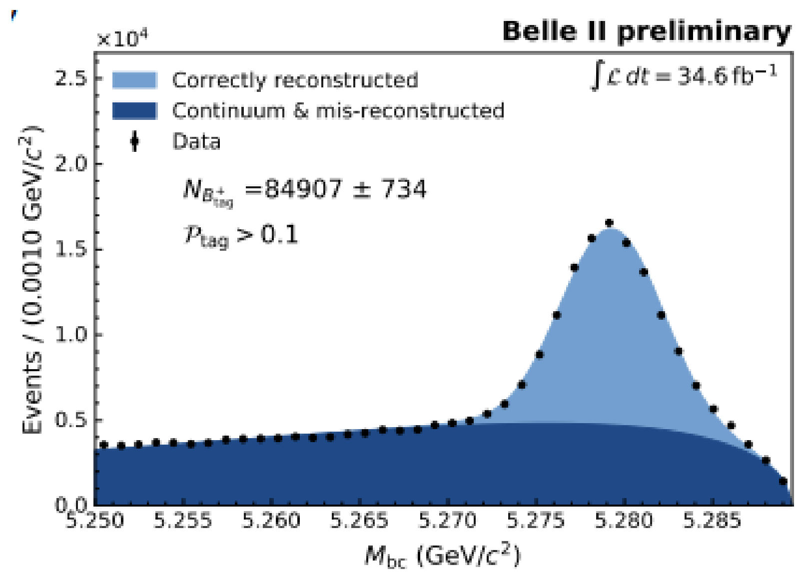
B_{tag} reconstruction

- Reconstruct hadronic B_{tag} decays
  -a few tens kind of decay modes



- Optimize selection criteria by using machine learning algorithm (Full Event Interpretation, FEI)
  - -Multivariate classifier to estimate B_{tag} probability
  - input: vertex, momentum, particle identification of daughters

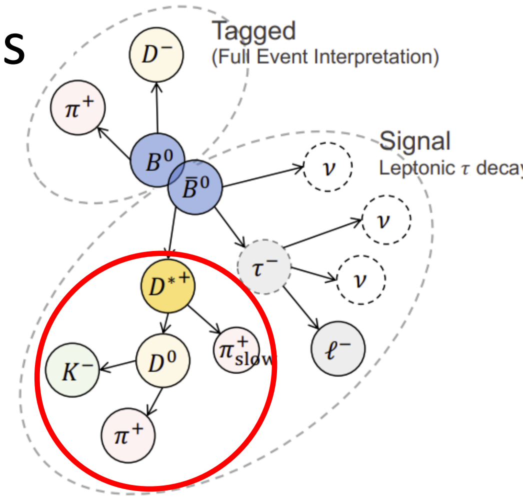




$$M_{bc} = \sqrt{E_{beam}^2 - (p_{tag}^{CM})^2}$$

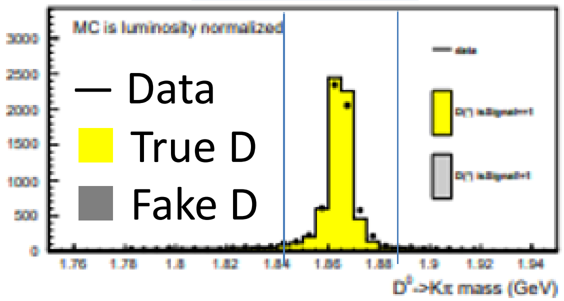
D, D* reconstruction

- Use most of D(*) decays with large branching ratios
  - -7 kind of D^0, D^+ decays
  - -4 kind of D^* decays

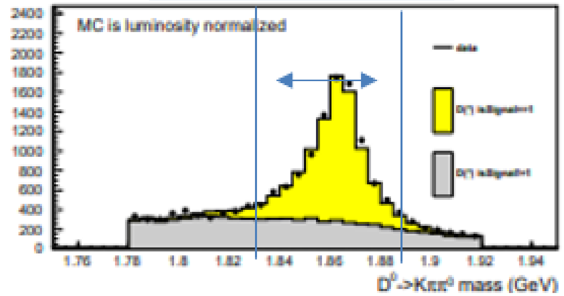


#Events

$D^0 \to K\pi$

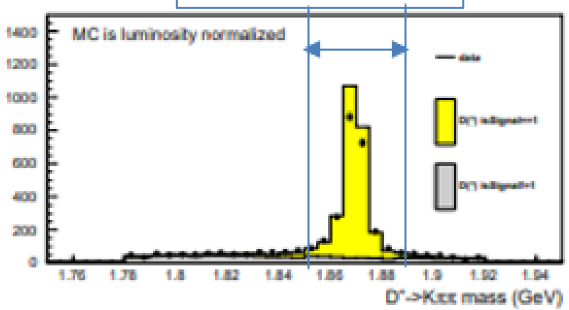


$D^0 \to K\pi\pi^0$



invariant mass of D(GeV)

$D^+ \to K\pi\pi$



$D^+ \to K_s\pi\pi^0$

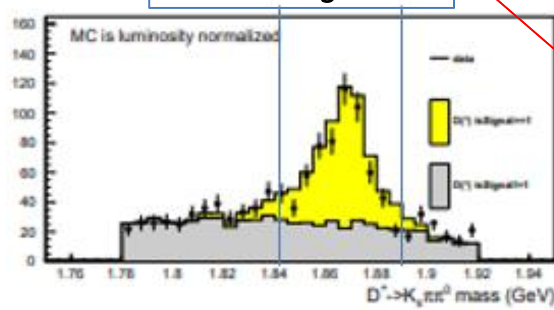


Table 3.2: List of reconstructed D^0 decay modes.

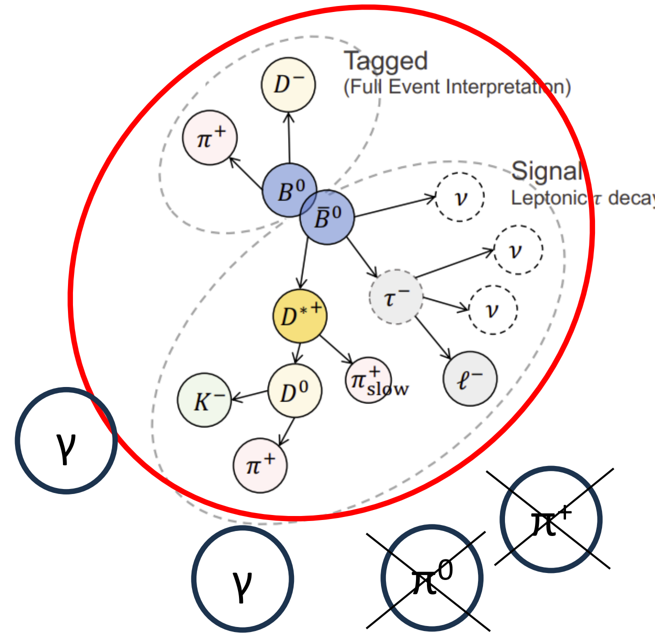
Decay	Branching ratio on PDG
$D^0 \to K^-\pi^+\pi^0$	(14.4 ±0.50)%
$D^0 \to K^-\pi^+\pi^-\pi^+$	(8.23 ±0.14)%
$D^0 \to K^0_S\pi^+\pi^-\pi^0$	(5.20 ±0.60)%
$D^0 \to K^-\pi^+$	(3.95 ±0.03)%
$D^0 \to K^0_S\pi^+\pi^-$	(2.80 ±0.18)%
$D^0 \to K^0_S\pi^0$	(1.24 ±0.02)%
$D^0 \to K^-K^+$	(0.41 ±0.01)%

Decay	Branching ratio on PDG
$D^+ \to K^-\pi^+\pi^+$	(9.38 ±0.16)%
$D^+ \to K^0_S\pi^+\pi^0$	(7.36 ±0.21)%
$D^+ \to K^-\pi^+\pi^+\pi^0$	(6.25 ±0.18)%
$D^+ \to K^0_S\pi^+\pi^-\pi^+$	(3.10 ±0.09)%
$D^+ \to K^0_S\pi^+$	(1.56 ±0.03)%
$D^+ \to K^-K^+\pi^+$	(0.968 ±0.018)%
$D^+ \to K^0_S K^+$	(0.304 ± 0.01)%

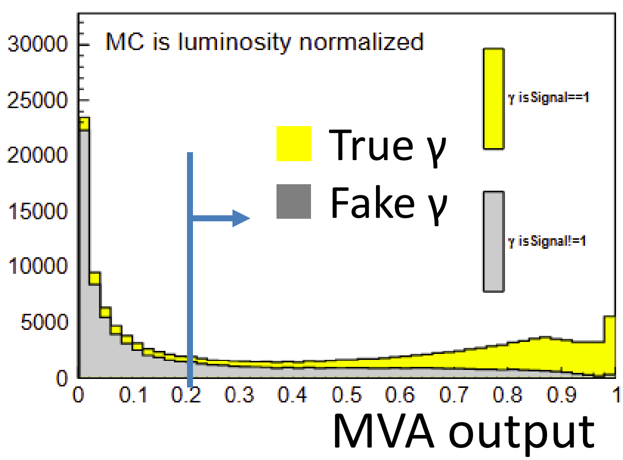
gray: newly added

Υ(4S) reconstruction

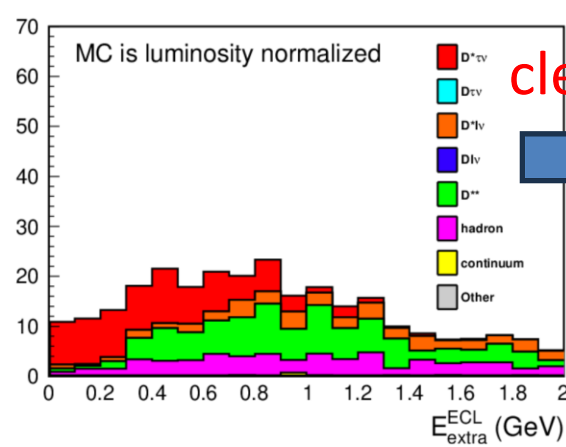
- Combine B_{tag}, D*, ℓ to reconstruct Υ(4S)
  - $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$
- Require no remained charged particle, π^0
  - to reject background from B→D**ℓν etc.
- Machine learning is used to reject fake γ (energy deposit from hadron, hadronic split-off) to calculate sum of γ energy at rest of events (E_{ECL})



fake photon MVA

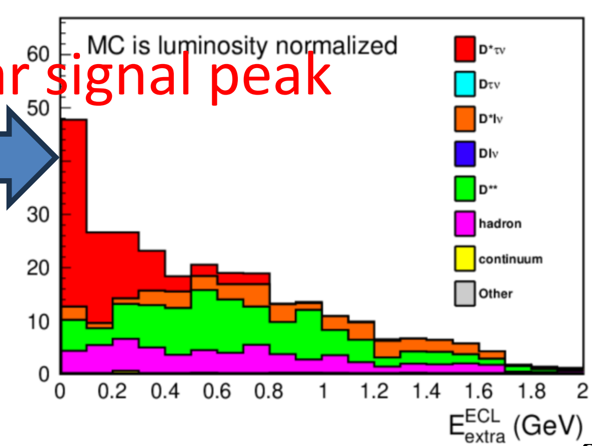


E_{ECL} without MVA



clear signal peak

E_{ECL} with MVA



Three $R(D^{(*)})$ analysis results from Belle II

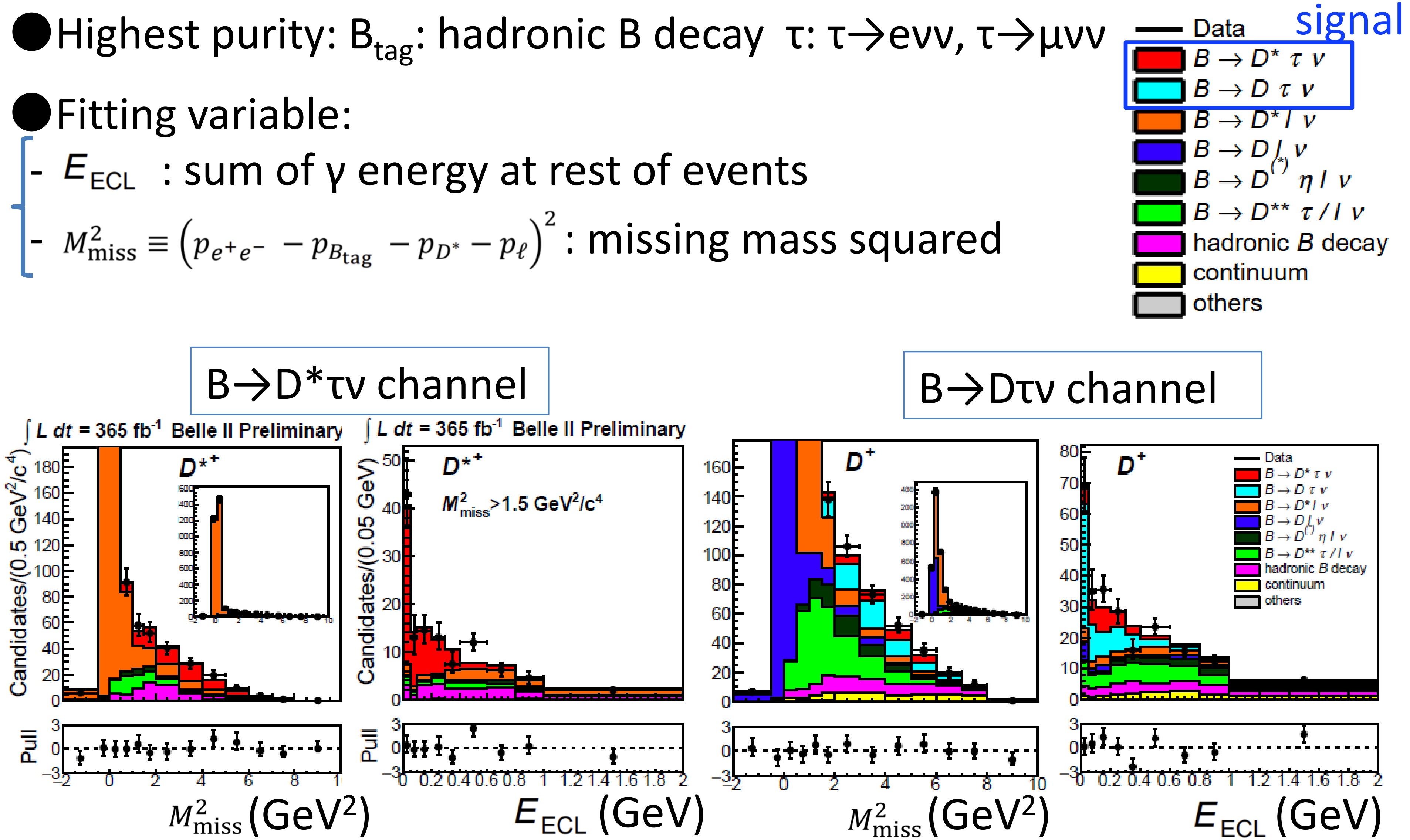
- Three results with different B_{tag}, tau decay mode @365fb^{-1}
  -statistically independent results

	year	dataset	B_{tag} mode	tau decay	observable
①	2025	365fb^{-1}	hadronic	$\tau \to e\nu\nu$ $\tau \to \mu\nu\nu$	$R(D^{(*)})$
②	2025	365fb^{-1}	semileptonic	$\tau \to e\nu\nu$ $\tau \to \mu\nu\nu$	$R(D^{(*)+})$
③	2026	365fb^{-1}	hadronic	$\tau \to \pi\nu$ $\tau \to \rho\nu$	$R(D^{*})$, $P_{\tau}(D^{*})$

higher purity, lower statistics
lower purity, higher statistics
lower purity

① R(D$^{(*)}$) with hadronic tag, leptonic tau decay

- Highest purity: B_{tag}: hadronic B decay τ: τ→eνν, τ→μνν
- Fitting variable:
  - E_{ECL} : sum of γ energy at rest of events
  - $M^2_{miss} \equiv \left(p_{e^+e^-} - p_{B_{tag}} - p_{D^*} - p_\ell\right)^2$: missing mass squared



① R(D$^{(*)}$) with hadronic tag, leptonic tau decay

● Breakdown of systematics error

-Dominant systematics is MC statistics (-_-;)
-Second dominant is gap-mode (explained later)

②,③ is similar situation

Source	$R(D^*)$	$R(D)$	ρ
Simulation sample size	4.8%	8.4%	−0.44
gap-mode branching fraction	2.7%	3.1%	0.00
$B \to D^{**}\tau^-/(\ell^-)\bar{\nu}_\ell$ branching fractions	0.3%	1.3%	0.25
Hadronic B decay branching fractions	1.6%	1.5%	−0.26
Form factors	0.5%	0.9%	−0.70
Fraction of misreconstructed $D^{(*)}$	0.5%	1.2%	0.00
Continuum background	2.4%	2.1%	0.93
Fit biases	0.3%	1.2%	0.00
Low-momentum π^0, γ efficiency	2.2%	2.4%	0.99
Other efficiency corrections	0.7%	1.4%	0.92
B-tagging efficiency of data	0.9%	1.8%	−1.00
B-tagging efficiency of $B \to D\tau\nu$	0.1%	1.8%	1.00
M^2_{miss} resolution	0.5%	0.8%	0.48
Total systematic uncertainty	6.7%	10.3%	−0.20
Statistical uncertainty	7.9%	12.5%	−0.40

● Result:

$$R(D^*) = 0.242 \pm 0.019(\text{stat}) \pm 0.016(\text{syst}),$$
$$R(D) = 0.439 \pm 0.055(\text{stat}) \pm 0.046(\text{syst})$$

most precise result by Belle II

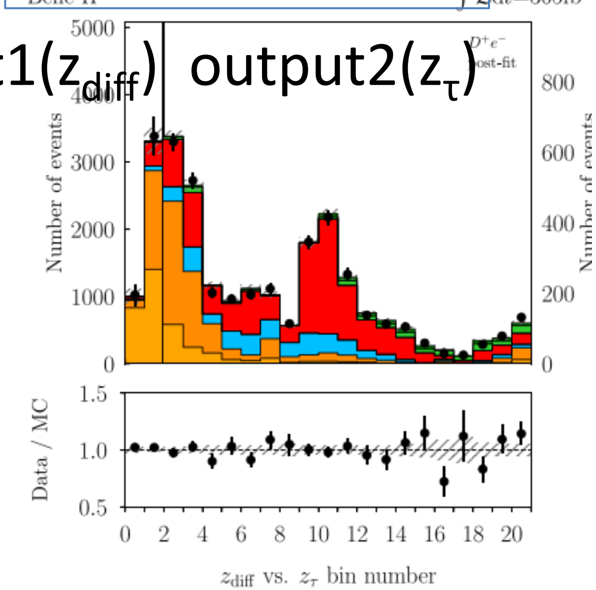
② $R(D^{+(*)})$ with semileptonic tag, leptonic tau decay

- B_{tag}: semileptonic B decay τ: τ→eνν, τ→μνν
  - B_{tag} momentum can not be measured due to missing neutrino → MVA
- Fitting variable: 2D fitting of MVA outputs

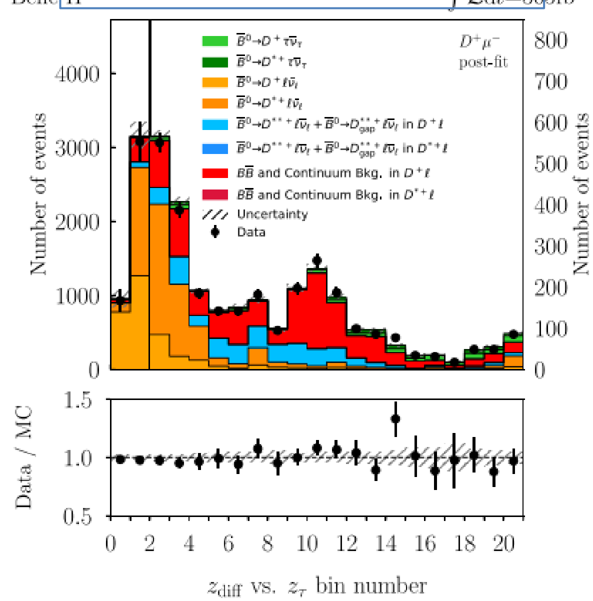
input to MVA	meaning	importance
$\cos\theta_{BY}^{sig}$	$\cos\theta_{BY}$ of signal B	1
E_{ECL}	sum of γ energy at rest of events	2
$\cos^2\phi_B$	angle estimated from $\cos\theta_{BY}^{sig}$, $\cos\theta_{BY}^{tag}$, Y^{sig}, Y^{tag}	3
p^*_D	$D^{(*)}$ momentum at CMS frame	4
p^*_ℓ	signal ℓ momentum at CMS frame	5

B→D*+τν channel

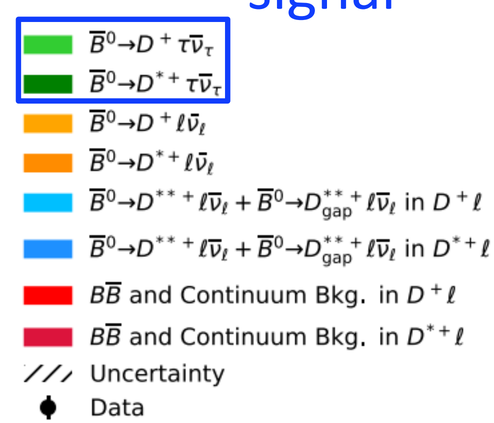
output1(z_{diff}) output2(z_τ)



B→D⁺τν channel



signal

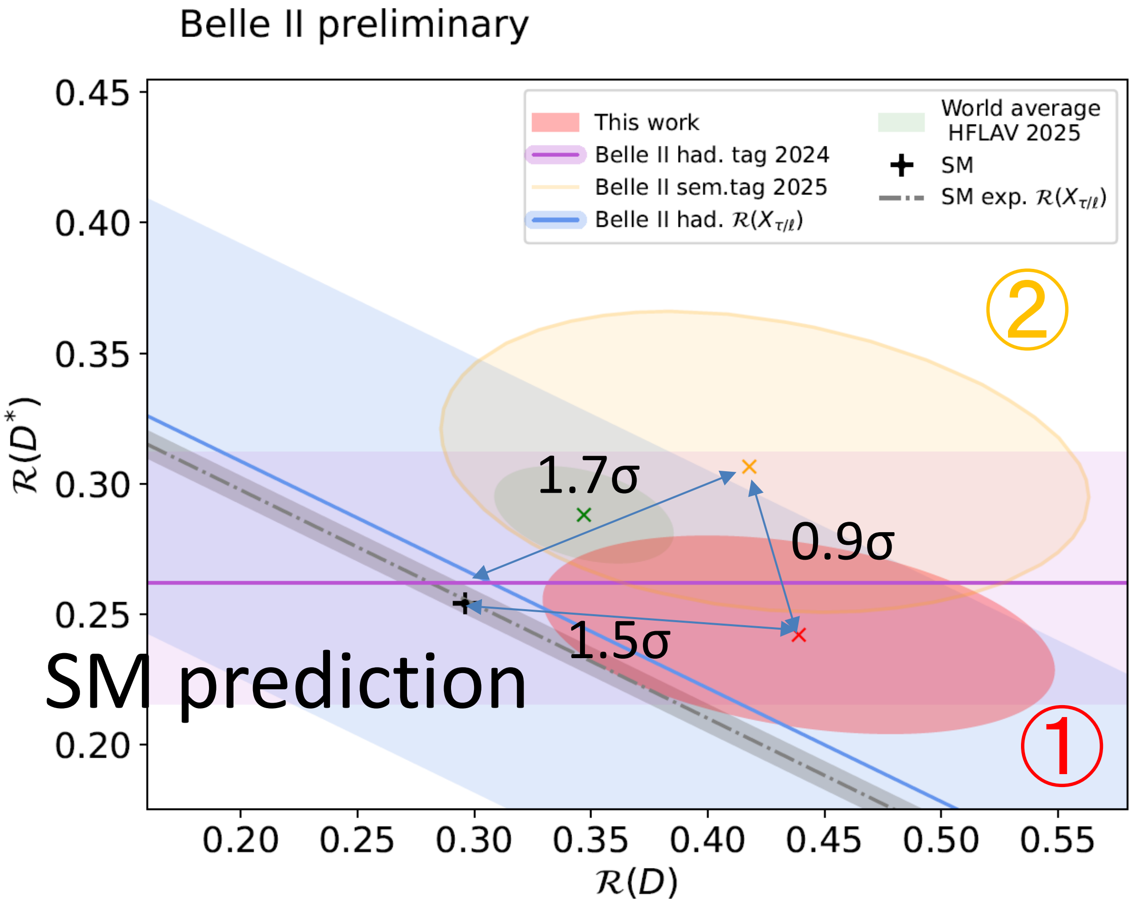


Result of ① and ②

-① hadronic tag is consistent with SM by 1.5σ

-② semileptonic tag is consistent with SM by 1.7σ

-① and ② are consistent by 0.9σ in each other



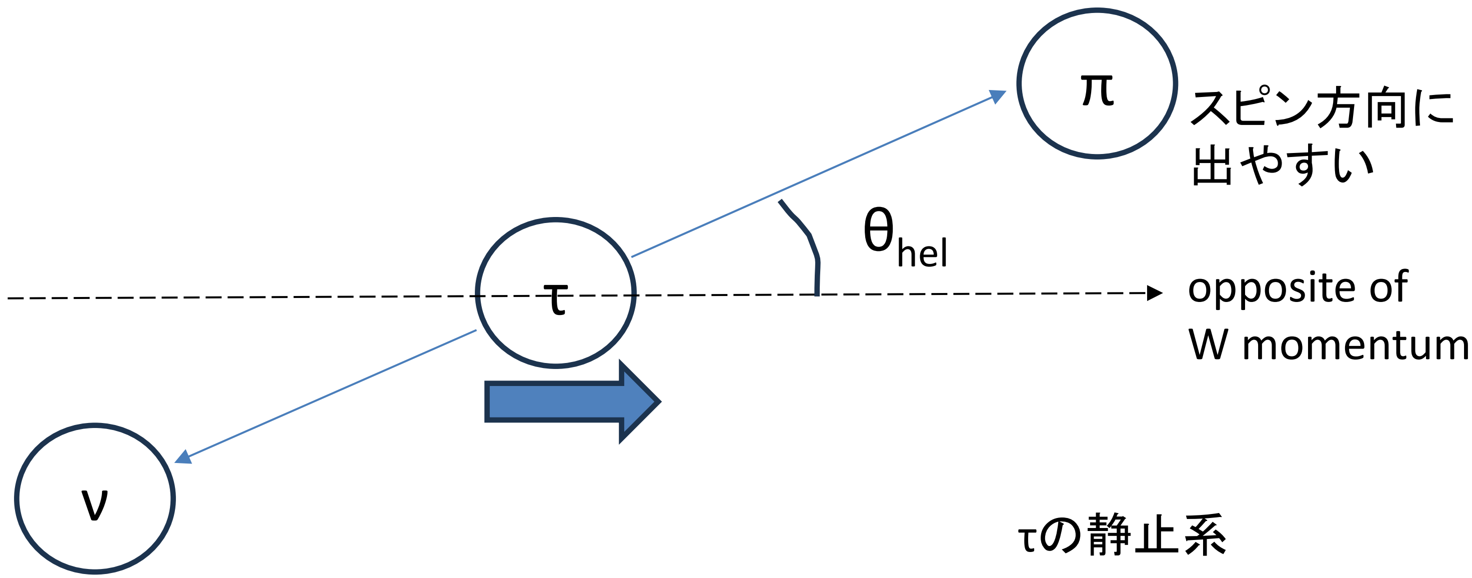
B→D(*)τν 偏極度測定

-新物理のモデルの中には、D*やτの偏極度に影響を与えるものがある

+ー: τ helicity of $\pm 1/2$.

-τの偏極度: $P_\tau(D^{(*)}) = [\Gamma^+(D^{(*)}) - \Gamma^-(D^{(*)})]/[\Gamma^+(D^{(*)}) + \Gamma^-(D^{(*)})]$

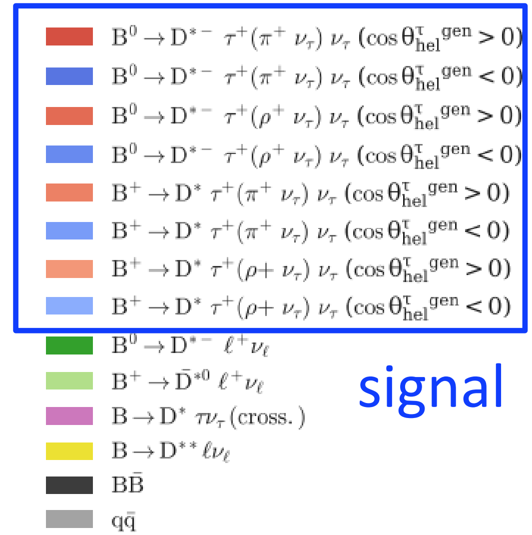
-微分崩壊分岐比: $\frac{1}{\Gamma(D^{(*)})}\frac{d\Gamma(D^{(*)})}{d\cos\theta_{hel}} = \frac{1}{2}\left[1 + \alpha P_\tau(D^{(*)})\cos\theta_{hel}\right]$



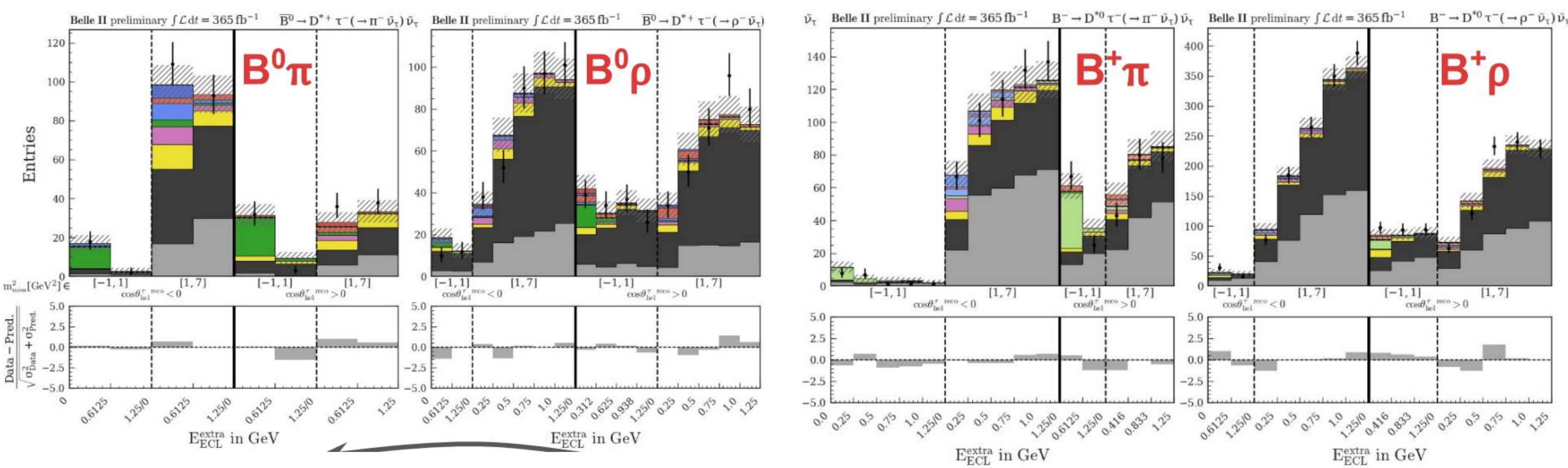
-τ→ℓννでは2個ニュートリノがありスピンの情報が損失するため、
τ→πν、ρνが用いられる. ただしBG大.

③ R(D$^{(*)}$) with hadronic tag, hadronic tau decay

- low purity, low stat. B_{tag}: hadronic B decay τ: $\tau\to\pi\nu$, $\tau\to\rho\nu$ ($\rho^-\to\pi^-\pi^0$)
- Fitting variable: E_{ECL} , M^2_{miss} , $\cos\theta^\tau_{hel}$
  - M^2_{miss} :<1, >1GeV^{2}の2bin
  - $\cos\theta^\tau_{hel}$:<0, >0の2bin
- dominant BG: B→ D*+ hadron, B→D*D$_{(s)}$(K)
  - evaluation by sideband



signal



Result of ③

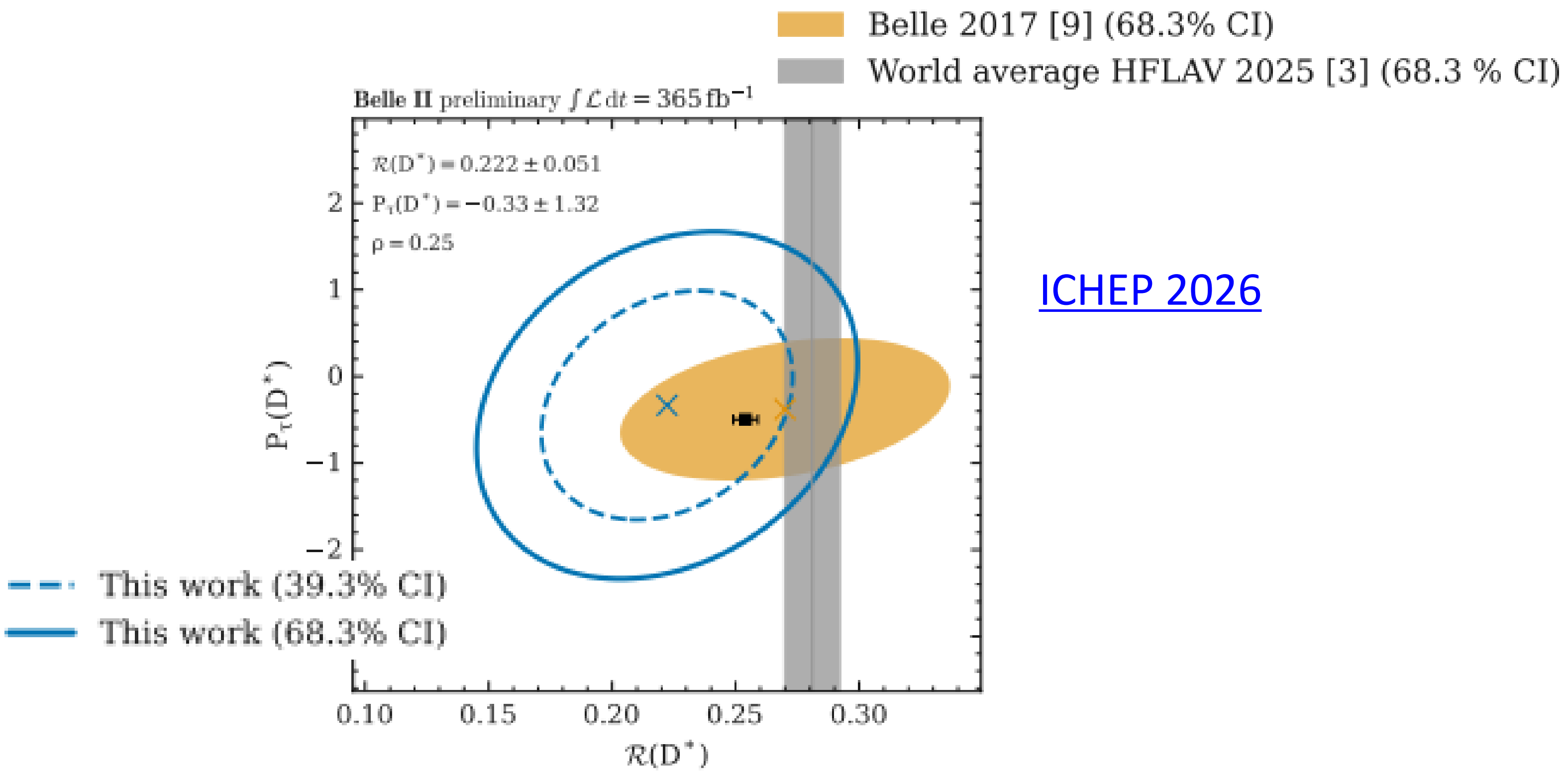
R(D*) is not so precise

- Result:

$$\mathcal{R}(D^*) = 0.222 \pm 0.041\ (\text{stat}) \pm 0.030\ (\text{syst})$$
$$P_\tau(D^*) = -0.33 \pm 1.15\ (\text{stat}) \pm 0.65\ (\text{syst})$$

first polarization result from Belle II

- Consistent with SM by 0.68σ



ICHEP 2026

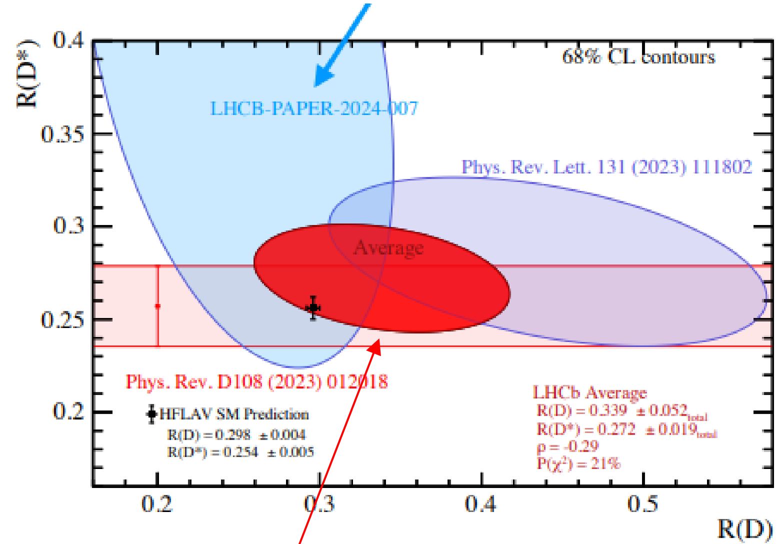
Results from LHC, Babar

R(D(*)) by LHCb

-LHCbから3つの測定 (R(J/ψ),R(Λ_c^+) も)

-D^0 or D^+, τの崩壊モード, fit変数が異なる

-LHCb[b]はB→D*πππとの比をとって誤差削減.



-どの測定も系統誤差が支配的

-BG, MC stat., form factor. 今後は？

-LHCb の結果のみだと、SMと68%CLでコンシステント

paper	D崩壊	τ崩壊	dataset	fit variable	R(D*) ±stat±syst.	R(D) ±stat±syst.
LHCb[a] 2023	D^0→Kπ	τ→μνν	RUN1 3fb^{-1}	M_{miss}^2, E^*_ℓ, q^2	0.281 ± 0.018 ± 0.024	0.441 ± 0.060 ± 0.066
LHCb[b] 2023	D^0→Kπ	τ→πππ(π0)ν	RUN1 3fb^{-1}	M_{miss}^2, tau decay time, BDT	0.247 ±0.015 ±0.015±0.012	--
LHCb[c] 2024	D^+→Kππ	τ→μνν	RUN2 2fb^{-1}	M_{miss}^2, E^*_ℓ, q^2	0.402 ± 0.081 ± 0.085	0.249 ± 0.043 ± 0.047

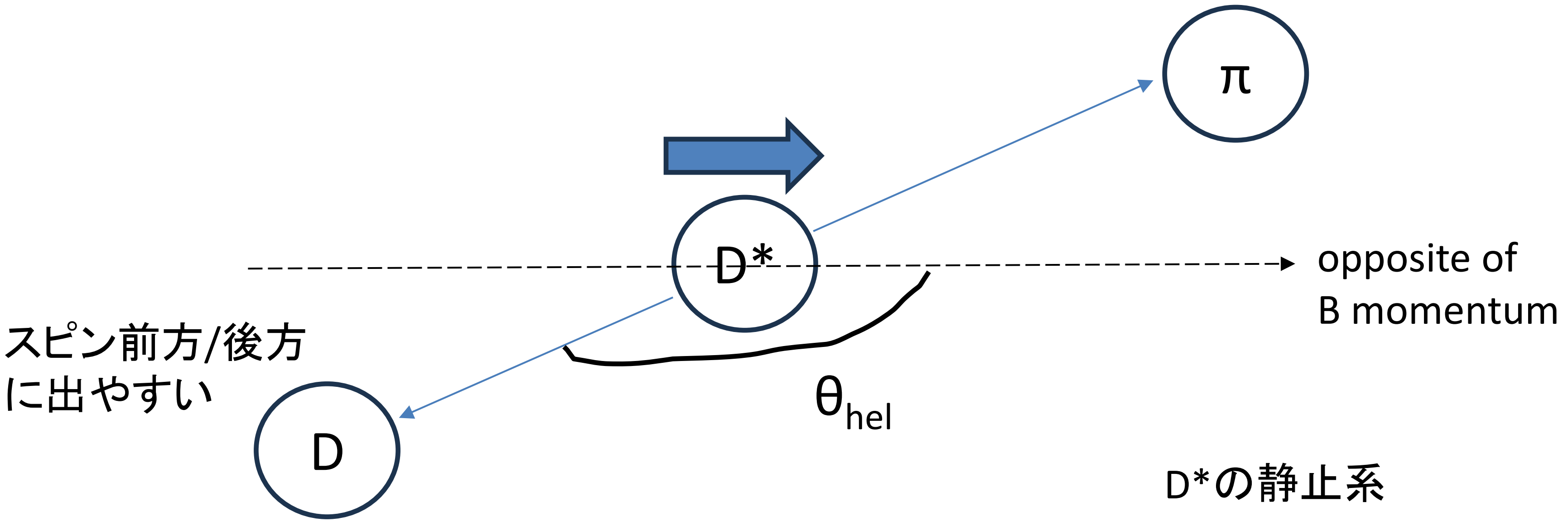
external BR

-LHCb[b] 2023 BDT: neutral particles around 3π to identify BG from 3π system from Ds+ decays

B→D*τν　D*偏極度測定

-D(*) longitudinal polarization: $F^{D^*}_L$

-微分崩壊分岐比: $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}} = \frac{3}{4}(2F_L^{D^*}\cos^2\theta_{\rm hel} + (1 - F_L^{D^*})\sin^2\theta_{\rm hel})$



$B \to D^* \tau \nu$　D^*偏極度測定 @LHCb

-LHCb run1 + partial run2 ($5 fb^{-1}$) を使った解析

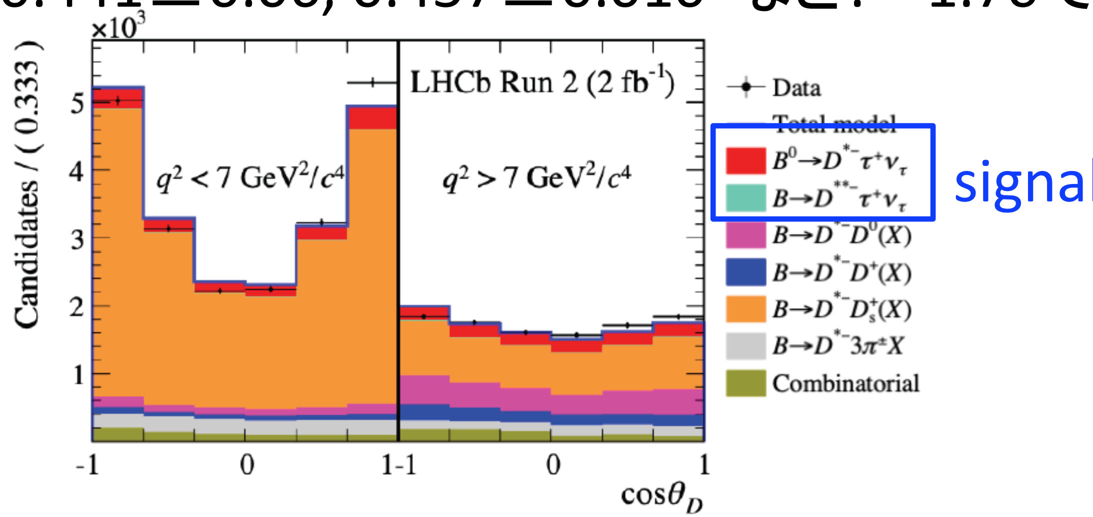
-LHCb[b] 2023 のR(D*)解析を拡張: $\cos\theta_{hel}$をフィット変数に追加

arxiv.2311.05224

Measured values of $F_L^{D^*}$:

$$q^2 < 7\,\mathrm{GeV}^2/c^4 \;:\; 0.51 \pm 0.07\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})$$
$$q^2 > 7\,\mathrm{GeV}^2/c^4 \;:\; 0.35 \pm 0.08\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})$$
$$q^2 \text{ whole range} :\; 0.43 \pm 0.06\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})$$

SM model: $F^{D^*}_L = 0.441 \pm 0.06,\ 0.457 \pm 0.010$ など. ~1.7σで一致.



-Belle IIでも同様のD*偏極度測定は可能(現在進行中)

R(D$^{(*)}$) semileptonic tag by Babar

-R(D$^{(*)}$) measurement with semileptonic tag by Babar @426fb^{-1}
has been available as doctor thesis, but not published since 2022

-Presentation at 2026 Moriond and 2025 workshop

- -"Journal paper in preparation: submission anticipated over next few month"
- -very roughly say, analysis method is similar to semileptonic tag @ Belle II

New preliminary BABAR results, using its full dataset

$$R(D) = 0.316 \pm 0.062\,(\text{stat}) \pm 0.019\,(\text{syst})$$

$$R(D^*) = 0.226 \pm 0.022\,(\text{stat}) \pm 0.012\,(\text{syst})$$

$$\rho = -0.82$$

→ Consistent with SM expectations at ~1.5 σ

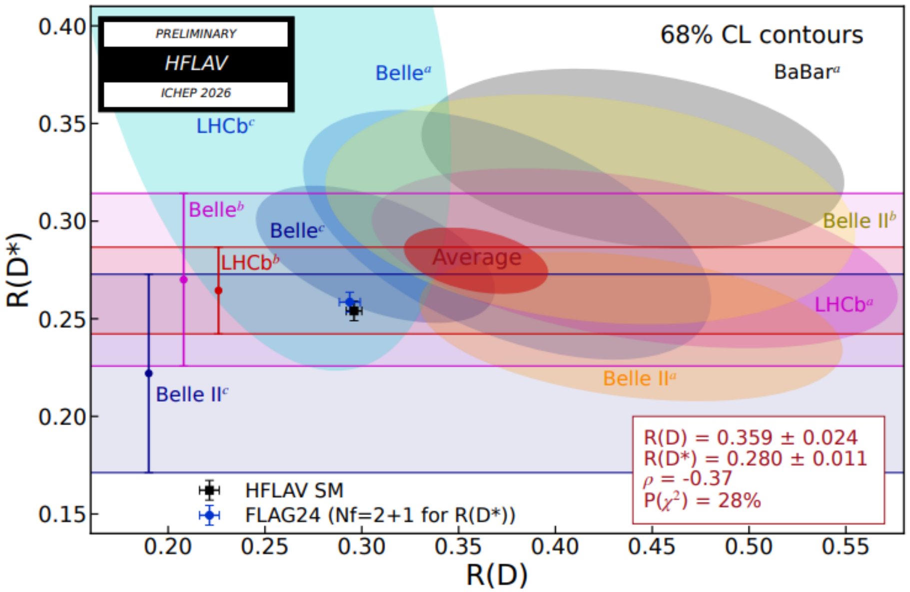
→ New world average consistent with SM expectations at 2 σ

Global average

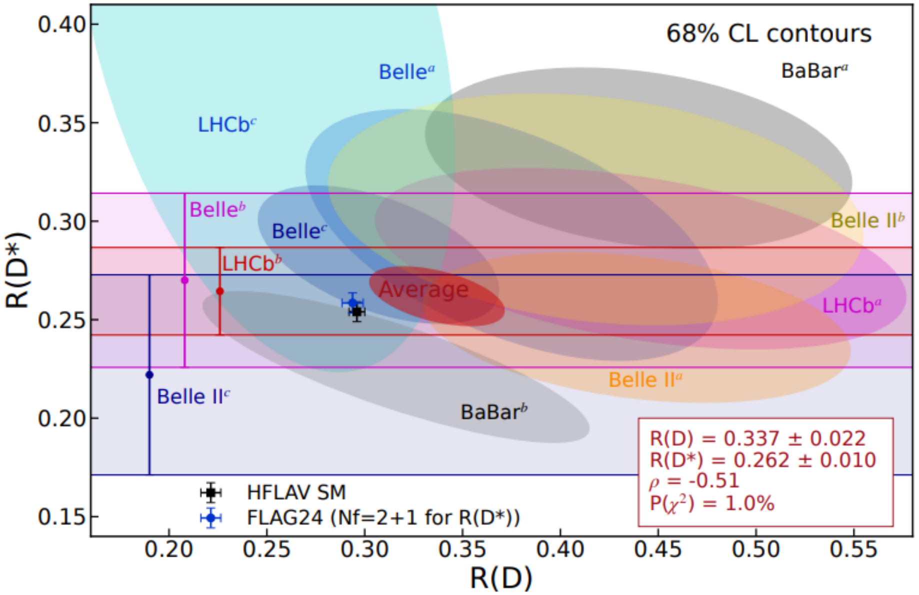
-Global average is 3.7σ (2.0σ) different from SM prediction without (with) Babar 2026 Moriond

-Consistency between experiments ($P(\chi^2)$=1.0%) is low with Babar.

3.7σ without Babar 2026 Moriond



2.0σ with Babar 2026 Moriond



https://hflav-eos.web.cern.ch/hflav-eos/semi/ichep26/html/RDsDsstar/RDRDs.html

Belle II prospect

future Belle II sensitivity

-At present analysis, major error sources are statistic and MC statistics.
Sensitivity will improve by increasing them.

-Present precision

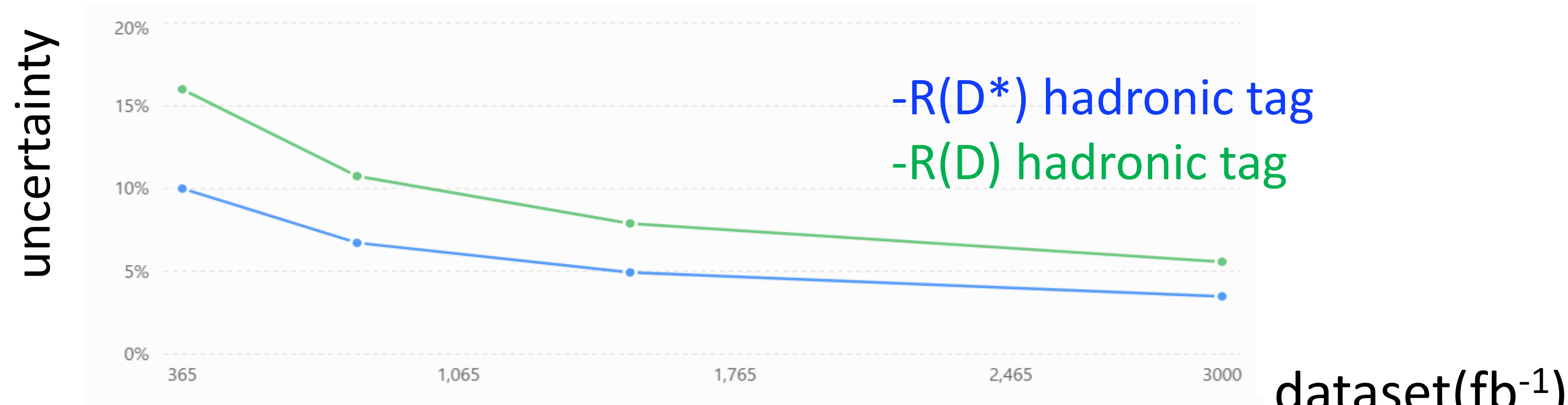
analysis	year	dataset	tag	τ decay	precision (stat.+sys.)
①	2025	$365fb^{-1}$	hadronic	hadronic	$R(D^*)$:10% $R(D)$:16%
②	2025	$365fb^{-1}$	semileptonic	leptonic	$R(D^*)$:13% $R(D)$:22%
③	2026	$365fb^{-1}$	hadronic	hadronic	$R(D^*)$:23% $P_\tau(D^*)$: ± 1.3

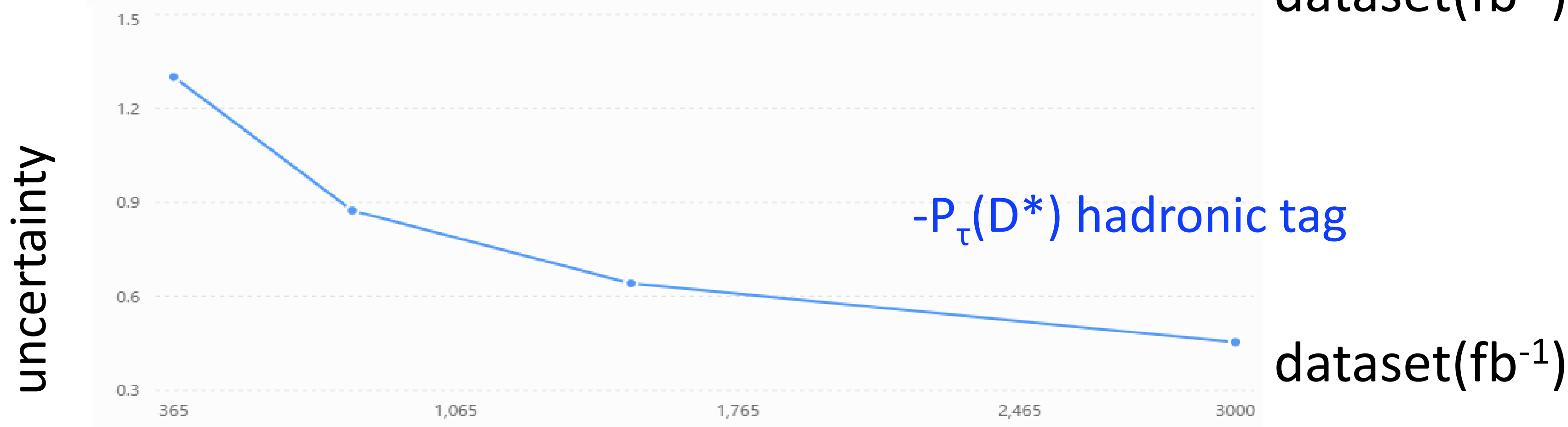
-Near future sensitivity with $808fb^{-1}$
(※my private number by hand calculation, just scaling √(808/365))

	year	dataset	tag	τ decay	sensitivity
①	2027-28	$808fb^{-1}$	hadronic	hadronic	$R(D^*)$:7% $R(D)$:11%, q^2, $F_L(D^*)$
②	2027-28	$808fb^{-1}$	semileptonic	leptonic	$R(D^*)$:9% $R(D)$:15%
③	2027-28	$808fb^{-1}$	hadronic	leptonic	$R(D^*)$:23% $P_\tau(D^*)$: ± 0.90
④	?	?	inclusive	leptonic	$R(D^*)$:? % $F_L(D^*)$: ?

future Belle II sensitivity

-More future sensitivity
(※my private number by hand calculation, just scaling √N)





-I personally think more improvement of analysis method is possible
 -ML for hadronic tag, add more D(*) channels for semileptonic tag, partial reconstruction of B_{tag}, combined analysis of all analysis, etc..

new measurement: q^2 dependent R(D$^{(*)}$)

-new physics can change q2 distribution of R(D$^{(*)}$) Phys. Rev. D 91, 114028

$$R_D(q^2) \equiv \frac{d\mathcal{B}(\bar{B} \to D\tau\bar{\nu})/dq^2}{d\mathcal{B}(\bar{B} \to D\ell\bar{\nu})/dq^2} \frac{\lambda_D(q^2)}{(m_B^2 - m_D^2)^2} \left(1 - \frac{m_\tau^2}{q^2}\right)^{-2},$$

$$R_{D^*}(q^2) \equiv \frac{d\mathcal{B}(\bar{B} \to D^*\tau\bar{\nu})/dq^2}{d\mathcal{B}(\bar{B} \to D^*\ell\bar{\nu})/dq^2} \left(1 - \frac{m_\tau^2}{q^2}\right)^{-2}. \quad (8)$$

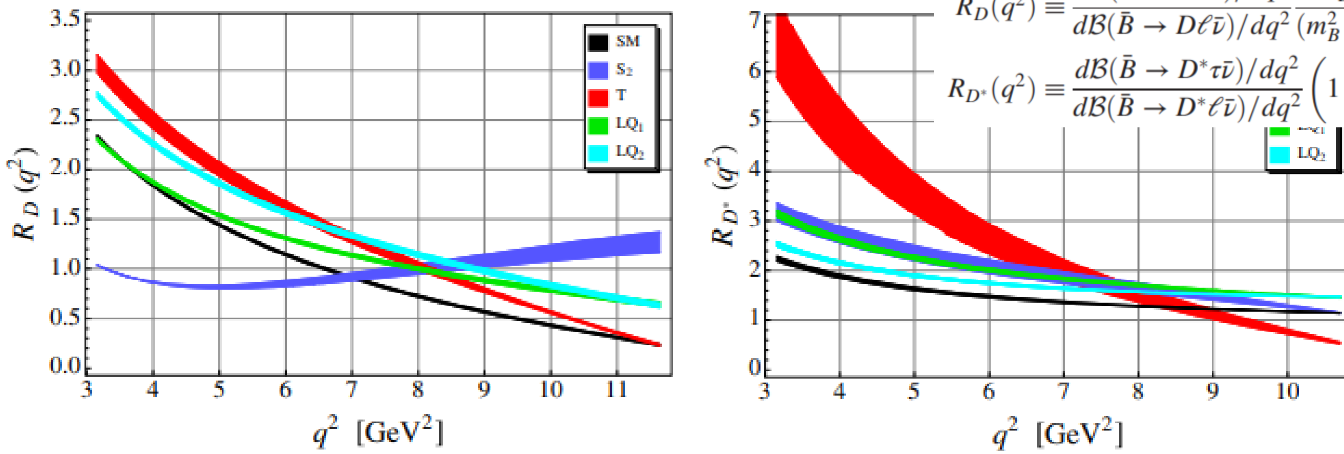


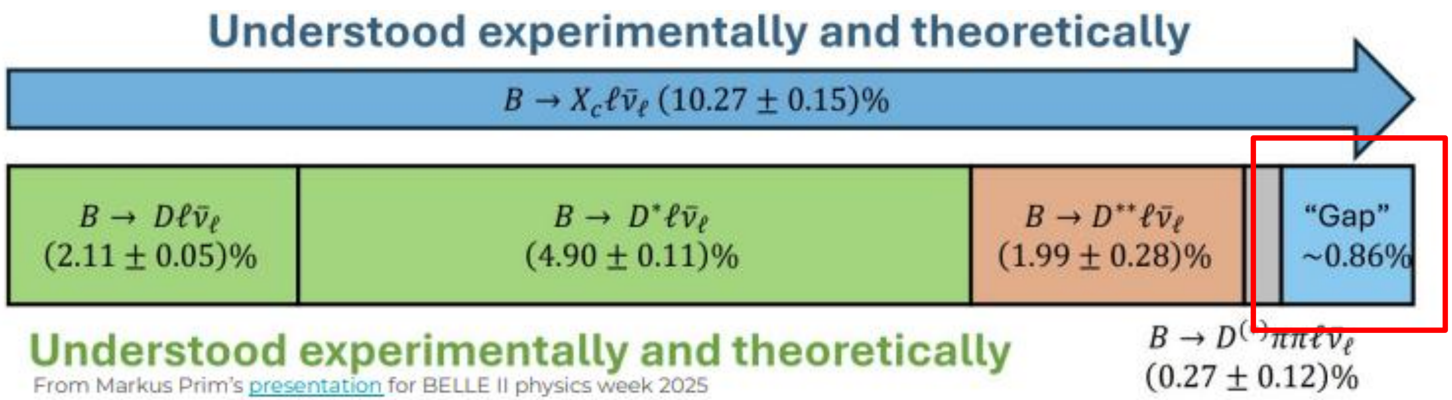
FIG. 4 (color online). The $R_{D^{(*)}}(q^2)$ distributions, predicted in the SM (black) and various NP scenarios listed in Sec. II: S_2 (blue), T (red), LQ_1 (green), and LQ_2 (cyan). The width of each curve is due to the theoretical errors in the hadronic form factor parameters.

-Analysis of q^2 dependent R(D$^{(*)}$) is on-going at Belle II

-targeting 2027-2028

new measurement: B→D$^{(*)}$ηℓν

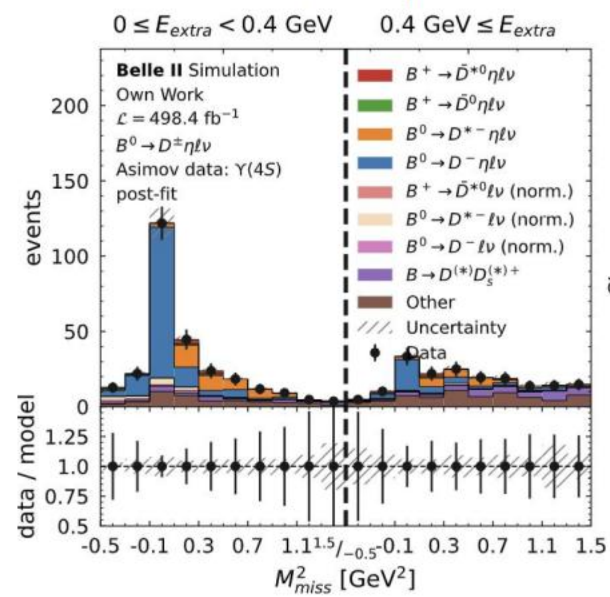
- Next leading systematics is modeling of gap mode in B→Xℓν
  - -~0.86% unmeasured decay
  - -for now, we are using B→D$^{(*)}$ηℓν to model it



- We are measuring BR(B→D$^{(*)}$ηℓν)
  - -targeting winter 2026
  - -expected Asimov sensitivity is ~0.1%

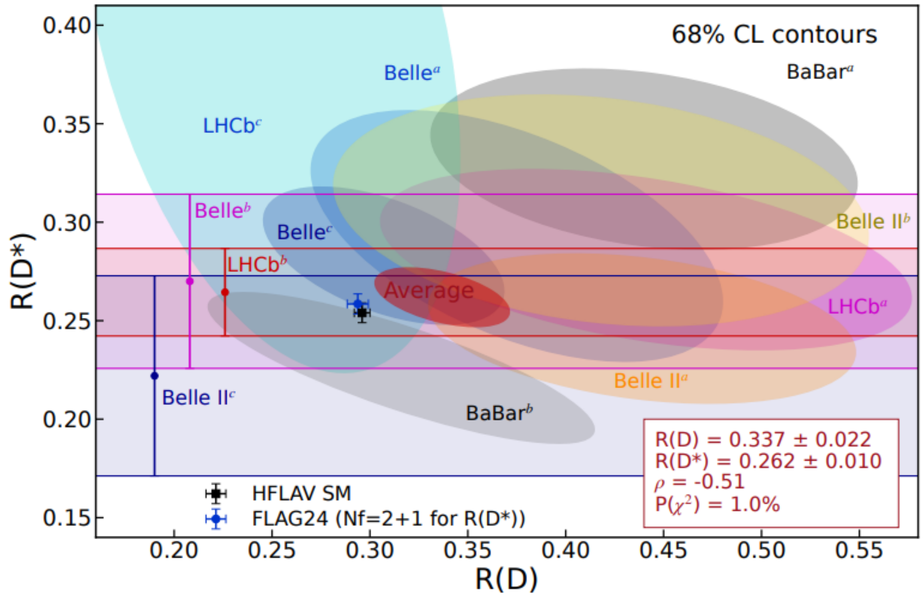
$$\mathcal{B}(B^0 \to D^\pm \eta \ell \nu) = (0.88 \pm 0.10_{\text{stat.}})\%$$
$$\mathcal{B}(B^0 \to D^{*\pm} \eta \ell \nu) = (0.88 \pm 0.11_{\text{stat.}})\%$$
$$\mathcal{B}(B^\pm \to D^0 \eta \ell \nu) = (0.92 \pm 0.08_{\text{stat.}})\%$$
$$\mathcal{B}(B^\pm \to D^{*0} \eta \ell \nu) = (0.92 \pm 0.09_{\text{stat.}})\%$$

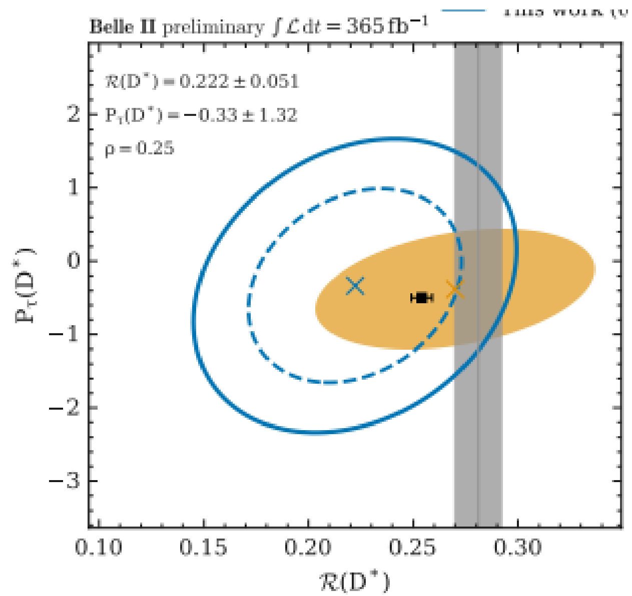
Full Gap [slide at last JPS]



Summary

● Measurement of b→cτν: result of $R(D^{(*)})$, $P_\tau(D^*)$

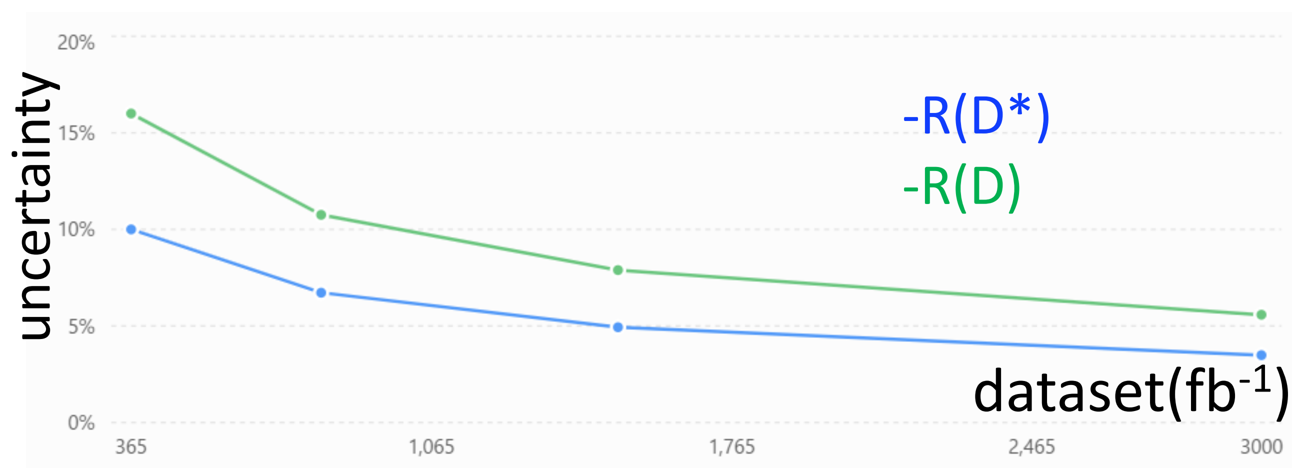




● Expected sensitivity by Belle II in future

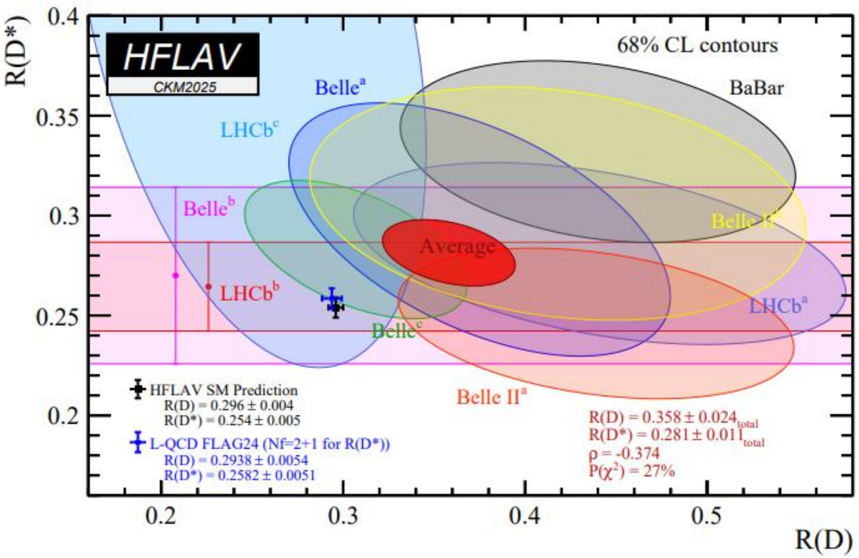
-q^2 dependence

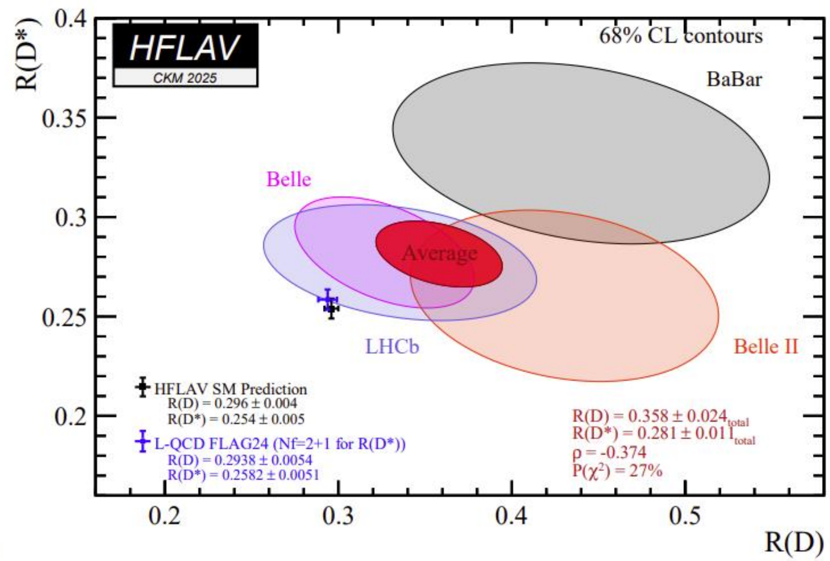
-$B \to D^{(*)}\eta\ell\nu$



backup

R(D(*)) 測定状況 2025





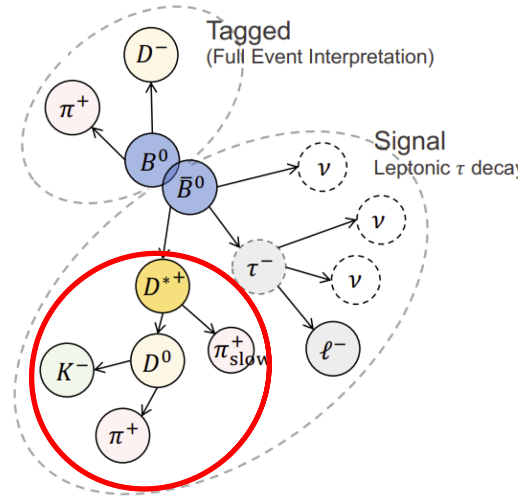
paper	tag手法	τ崩壊	#BB events	R(D*), R(D)
Babar 2012	hadronic	leptonic	471×10^6	0.332 ± 0.024 ± 0.018, 0.440 ± 0.058 ± 0.042 (灰色)
Belle^a 2015	hadronic	leptonic	772×10^6	0.293 ± 0.038 ± 0.015, 0.375 ± 0.064 ± 0.026 (青)
Belle^b 2017	hadronic	hadronic	772×10^6	$0.270 \pm 0.035 ^{+0.028}_{-0.025}$ (ピンク 棒線)
Belle^c 2020	semileptonic	leptonic	772×10^6	0.283 ± 0.018 ± 0.014, 0.307 ± 0.037 ± 0.016 (緑)
Belle II^a 2025	semileptonic	leptonic	387×10^6	0.306 ± 0.034 ± 0.018, 0.418 ± 0.074 ± 0.051 (黄色)
Belle II^b 2025	hadronic	leptonic	387×10^6	0.242 ± 0.019 ± 0.016, 0.439 ± 0.055 ± 0.046 (赤)

paper	D崩壊	τ崩壊	dataset	R(D*), R(D)
LHCb^a 2023	$D^0 \to K\pi$	leptonic(μνν)	RUN1 $3fb^{-1}$	0.281 ± 0.018 ± 0.024, 0.441 ± 0.060 ± 0.066 (紫)
LHCb^b 2023	$D^0 \to K\pi$	$\tau \to \pi\pi\pi(\pi 0)\nu$	RUN1 $3fb^{-1}$	0.267 ± 0.012 ± 0.019 (赤 棒線)
LHCb^c 2024	$D^+ \to K\pi\pi$	leptonic(μνν)	RUN2 $2fb^{-1}$	0.402 ± 0.081 ± 0.085, 0.249 ± 0.043 ± 0.047 (水色)

D, D* reconstruction

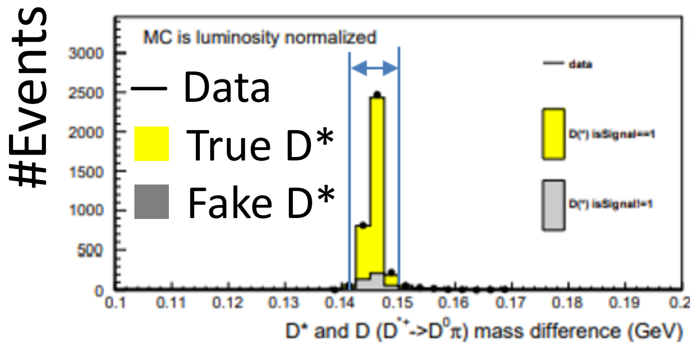
-Use most of D(*) decays with large branching ratios

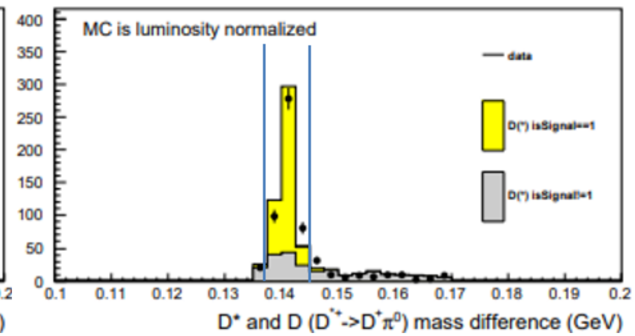
-4 kind of D* decays



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

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

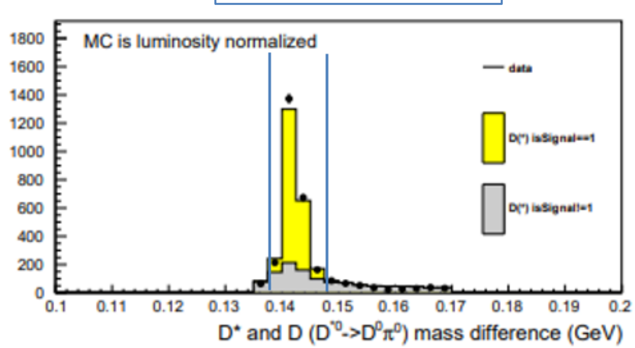


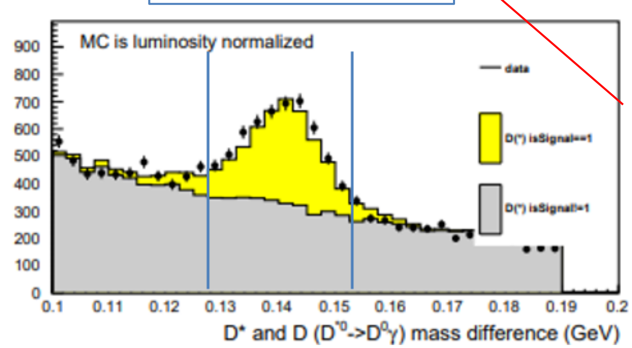


mass difference of D* and D(GeV)

$D^{*0} \to D^0\pi^0$

$D^{*0} \to D^0\gamma$





Decay	Branching ratio on PDG
$D^{*+} \to D^0\pi^+$	$(67.7 \pm 0.5)\%$
$D^{*+} \to D^+\pi^0$	$(30.7 \pm 0.5)\%$
$D^{*0} \to D^0\pi^0$	$(64.7 \pm 0.9)\%$
$D^{*0} \to D^0\gamma$	$(35.3 \pm 0.9)\%$

gray: newly added

Babar, Belle, Belle II experiments

-on-threshold BB production from $e^+e^- \rightarrow Y(4S) \rightarrow B\bar{B}$

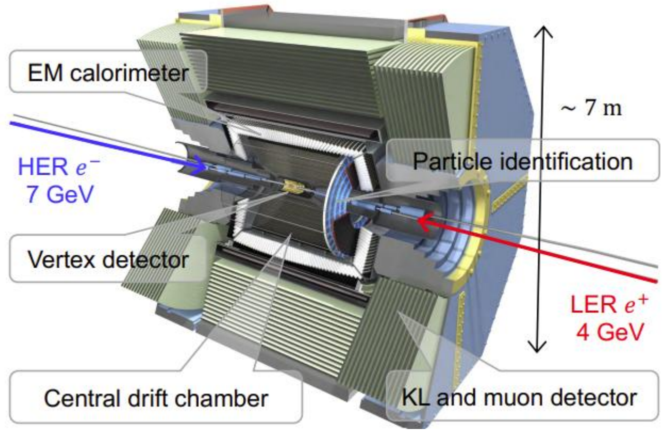
-nearly 4π coverage with excellent PID

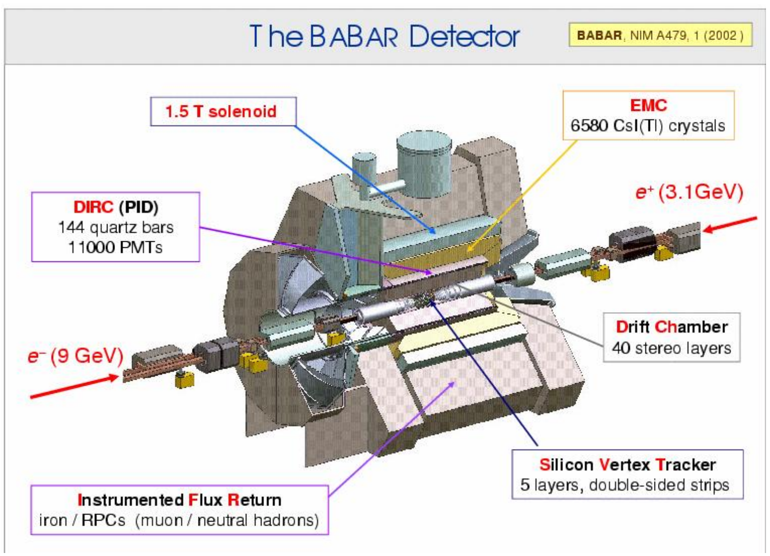
-clean background environment

-known initial beam state

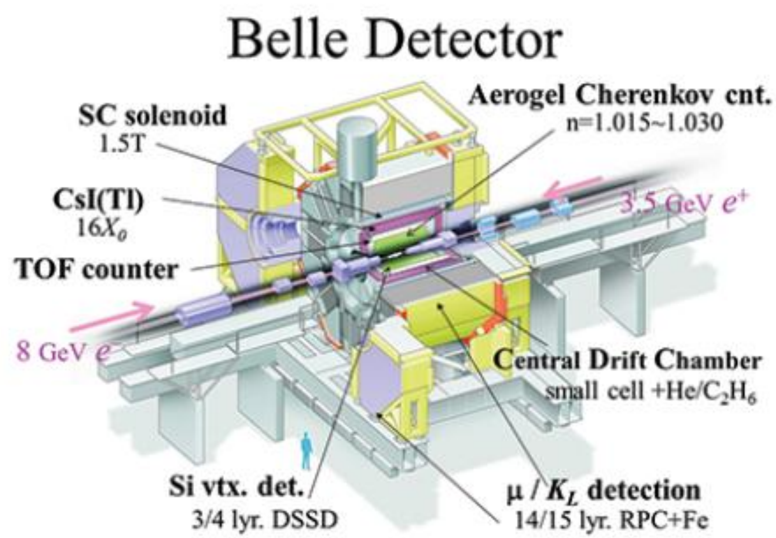
-number of BB events for analysis: $O(10^8)$

471×10^6 (Babar), 772×10^6(Belle), 198×10^6 (Belle II)





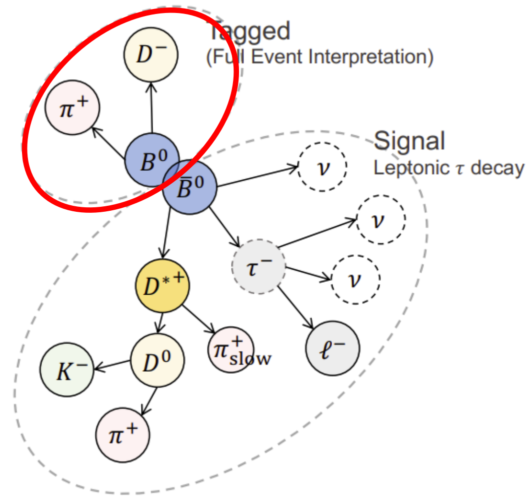
https://www.ippp.dur.ac.uk/~krauss/Lectures/QuarksLeptons/Detector/Typical_Detector.html



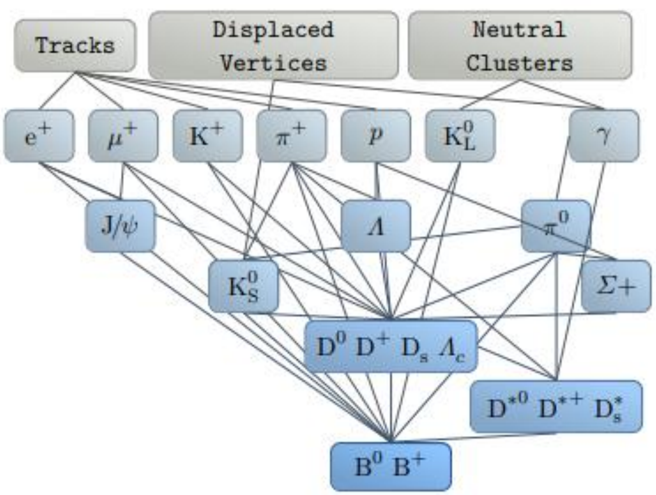
https://ihepa.phys.ufl.edu/the-belle-and-belle-ii-experiments-at-kekb/

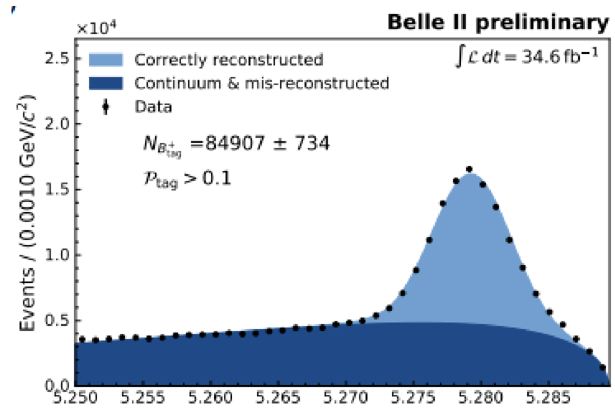
B_{tag}再構成 @Belle II

-ハドロン崩壊するB_{tag}を再構成
 -崩壊の種類が多く(数十)、1つ1つ最適化するのは大変



-Belle II: Full Event Interpretation (FEI)アルゴリズム
 -荷電粒子飛跡、中性クラスターを総当たりで組み合わせ
 -Multivariate classifierでBの信号確率を計算
 学習の入力情報: 娘粒子の生成点, 運動量, 粒子識別





$$M_{bc} = \sqrt{E^2_{beam} - (p^{CM}_{tag})^2}$$

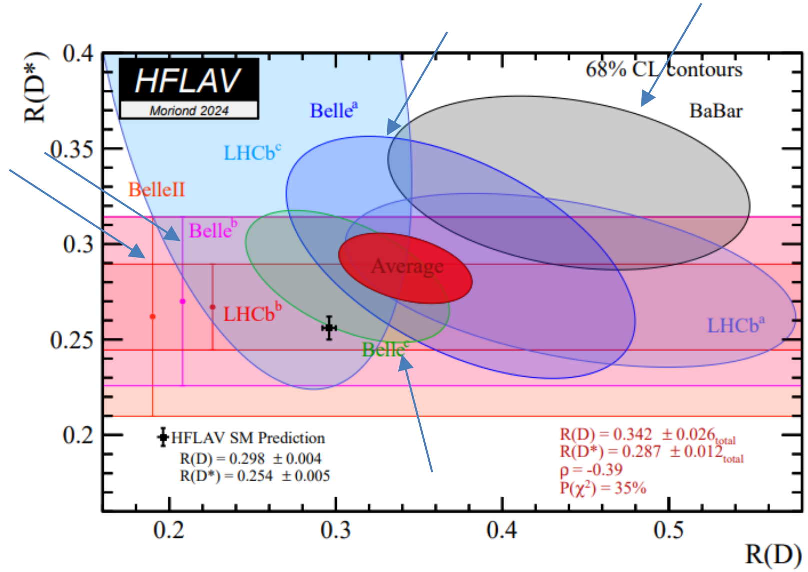
-B_{tag}に対する検出効率 ~0.27%, purity ~15%
 -Belleより約2倍検出効率が向上

ハドロン崩壊分岐比
が小さいため　統計勝負

R(D(*)) 測定 @Belle, Babar

- 基本的な測定手法はBelle IIと同様
  - tag手法, fit変数などが異なる

- どの測定も統計誤差が支配的
  - 今後Belle IIで改善が見込まれる



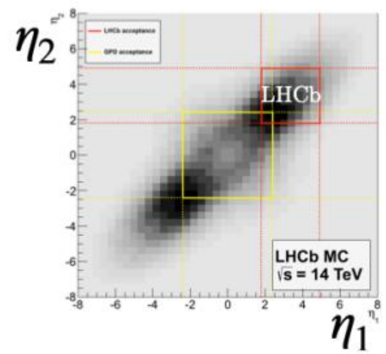
paper	tag手法	τ崩壊	#BB events	fit variable	Reconstructed decay mode	R(D*) ±stat±syst.	R(D) ±stat±syst.
Babar 2012	hadronic	τ→eνν,τ→μνν	471×10^6	M_{miss}^2, p^*_ℓ	B→D*ℓν, B→Dℓν	0.332 ± 0.024 ± 0.018	0.440±0.058 ±0.042
Belle[a] 2015	hadronic	τ→eνν,τ→μνν	772×10^6	M_{miss}^2, MVA	B→D*ℓν, B→Dℓν	0.293 ± 0.038 ± 0.015	0.375 ± 0.064 ± 0.026
Belle[b] 2017	hadronic	τ→πν,τ→ρν	772×10^6	M_{miss}^2, E_{ECL}^{extra}	B→D*ℓν	0.270 ± 0.035 ±0.028	
Belle[c] 2020	semileptonic	τ→eνν,τ→μνν	772×10^6	MVA, E_{ECL}^{extra}	B→D*ℓν, B→Dℓν	0.283 ± 0.018 ± 0.014	0.307 ± 0.037 ± 0.016
Belle II 2023	hadronic	τ→eνν,τ→μνν	198×10^6	M_{miss}^2, E_{ECL}^{extra}	B→D*ℓν	0.267 ± 0.041 ± 0.033	

- p^*_ℓ: Bの静止系でのレプトン運動量
- Belle2015 MVA: カロリメータ残存エネルギー(E_{ECL}^{extra}),M_{miss}^2, q_2, p^*_ℓ, #π0 in ROE, $\cos\theta_{YD*}$
- Belle2020 MVA: M_{miss}^2, カロリメータ再構成エネルギー, $\cos\theta_{B,D^*\ell}$

LHCb experiment

-LHCb: $b\bar{b}$ production with pp collision at 7,8,13 TeV

Forward spectrometer $2 < \eta < 5$

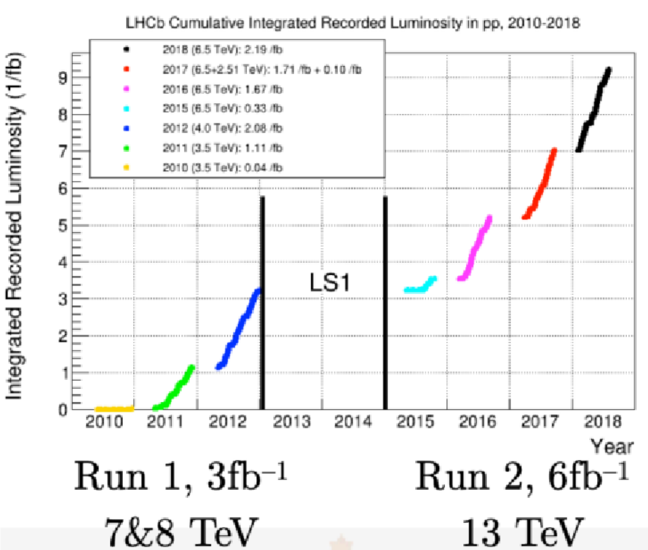


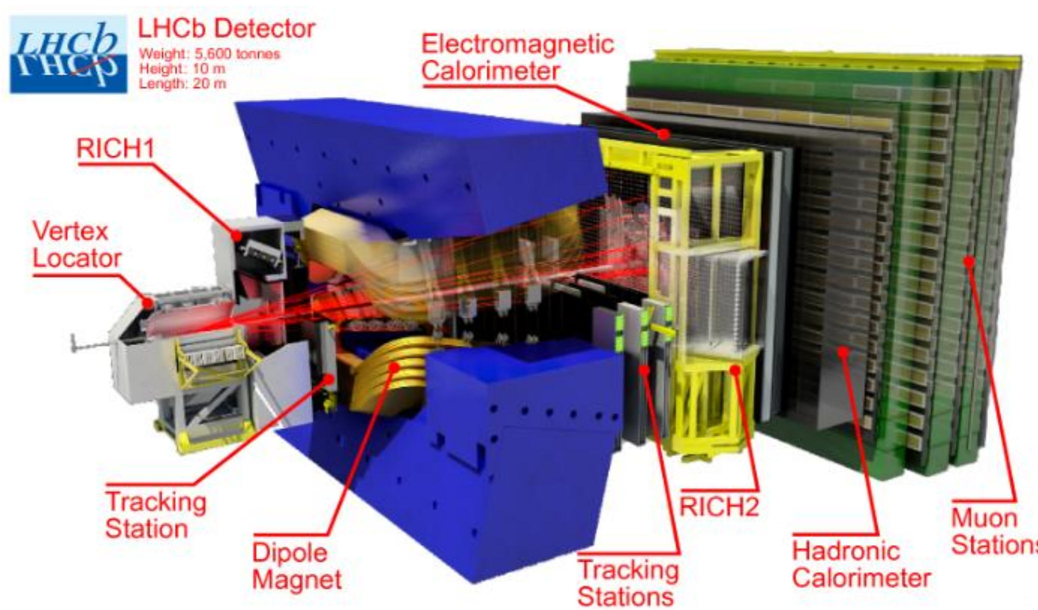
-large bb cross section: ~200µb

-large B momentum: p_B ~ 80GeV

-Run 1+2: ~9fb^{-1} of pp collisions

arxiv.2105.12668, [ICHEP 2024]





R(D(*)) 測定手法 @LHCb

-Reconstruct $B \to D^* \tau \nu_\tau$ $B \to D^* \ell \nu_\ell$

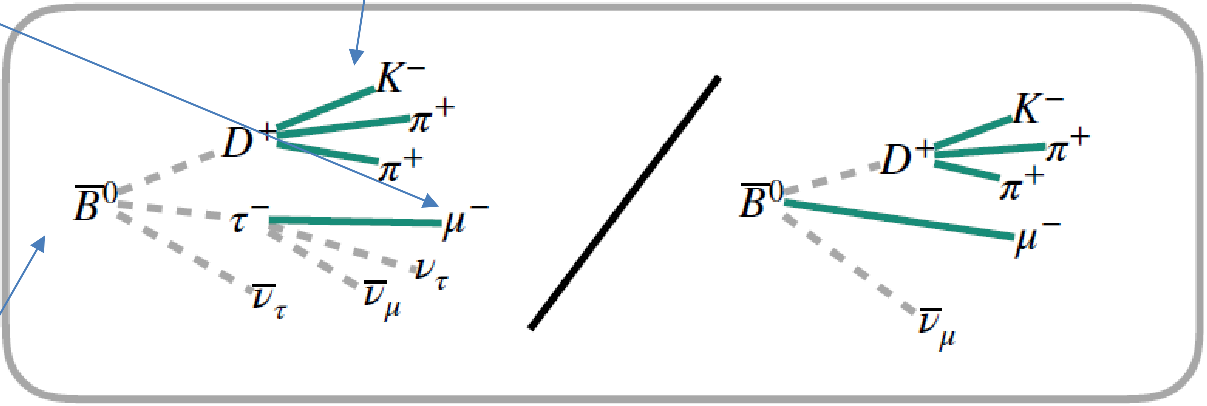
-leptonic τ decay and/or hadronic τ decay

-use D^0->Kπ or D^+->Kππ (cleanest D decay) to reduce BG.

-use muon only (not electron)

R(D*)cern seminar

R(D⁺) =



-Challenge: multiple neutrinos in final state

-No use of Btag. Estimate B momentum from visible particles approximately.

-Check remained particles to estimate background

-Major BG: B→D**ℓν, B→D*D(→μX)X, combinatorial, misidentified, ..

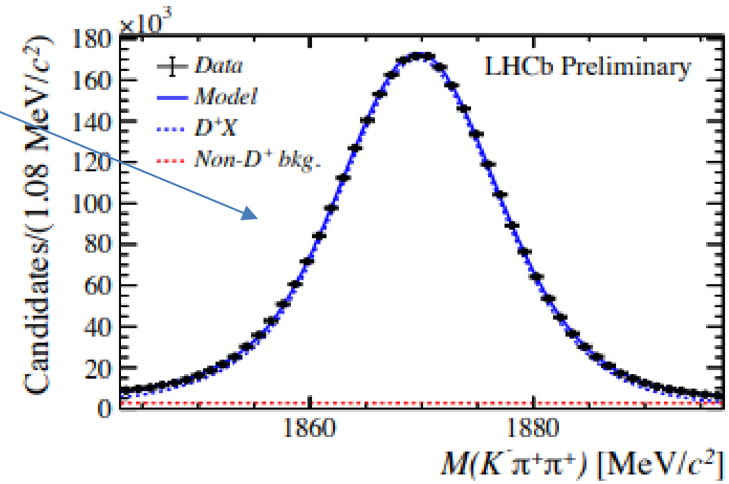
-amount of BG is larger than Babar, Belle in general

-Cancel many systematics error by taking ratio of B→D*τν and B→D*ℓν

B 再構成 @LHCb

ICHEP slide

- -D→Kππ or D→Kπを再構成
  - -vertexのBDTでB decayかどうか判断
  - -π0/γ があればBDTでD*と区別



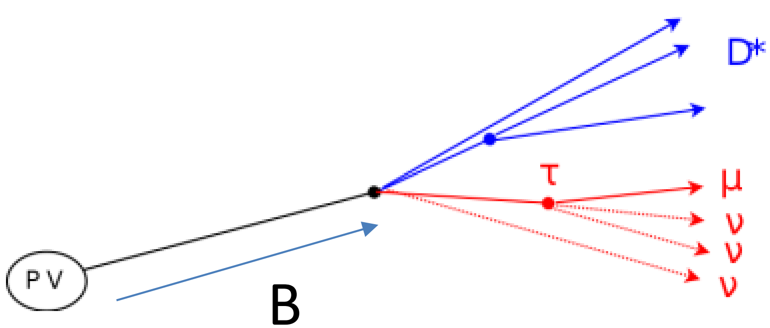
-D(*),μでBを再構成. Bの運動量概算.

$(p_B)_z = (m_B/m_{\mathrm{reco}})(p_{\mathrm{reco}})_z$ (z:ビーム軸)

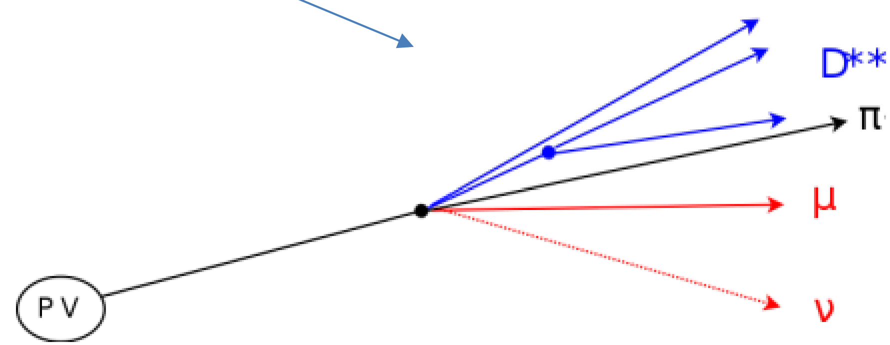
-残った飛跡の 本数で場合分け

(0本:信号, 1本以上: バックグラウンド)

$\overline{B}^0 \rightarrow D^{*+}\tau^-\overline{\nu}_\tau$



バックグラウンド

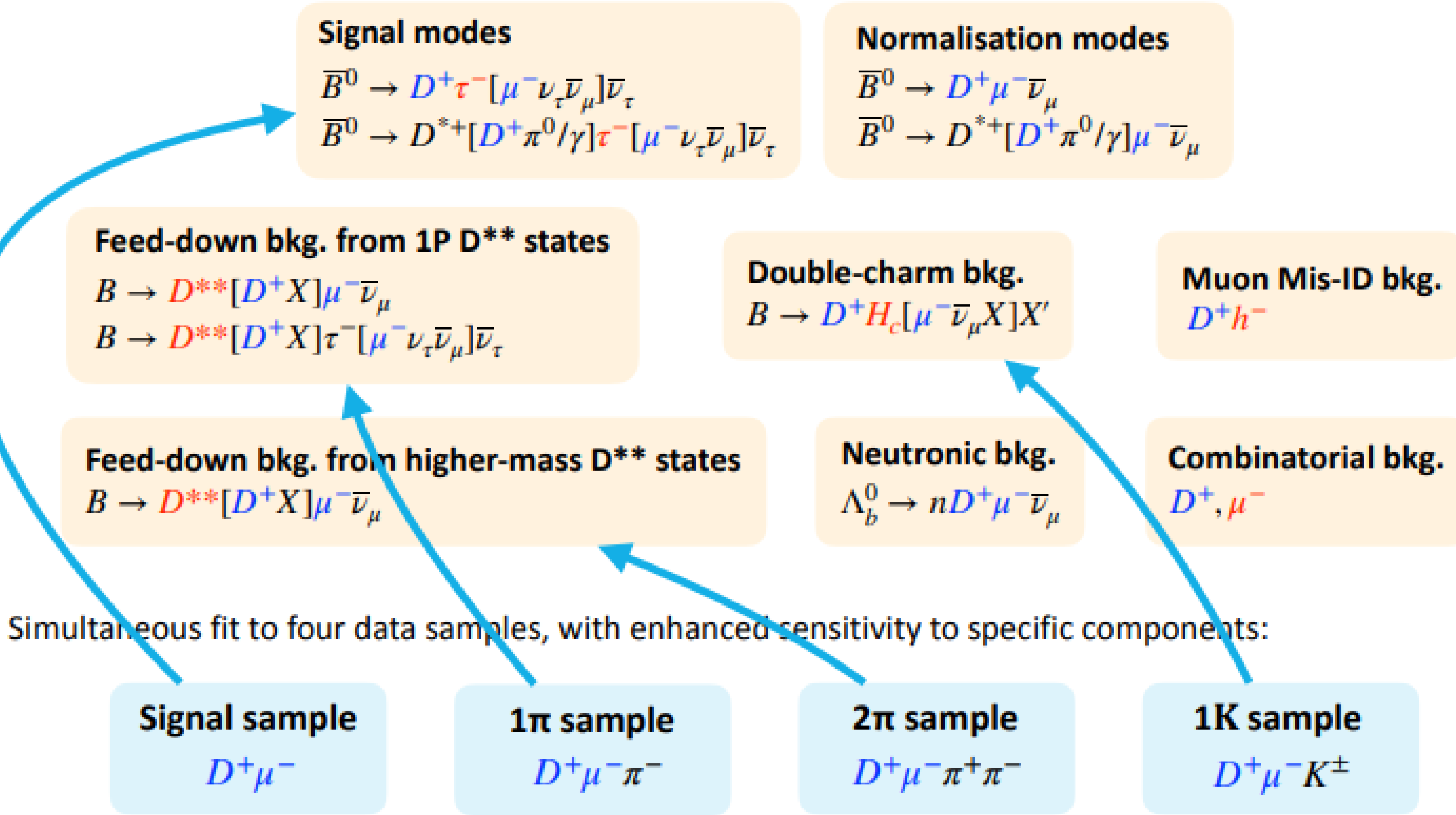


R(D(*)) fit @LHCb

ICHEP slide

-(M_{miss}^2, E_μ^* (Bの静止系でのμエネルギー), $q^2=(p_B-p_D)^2$)で3次元フィット

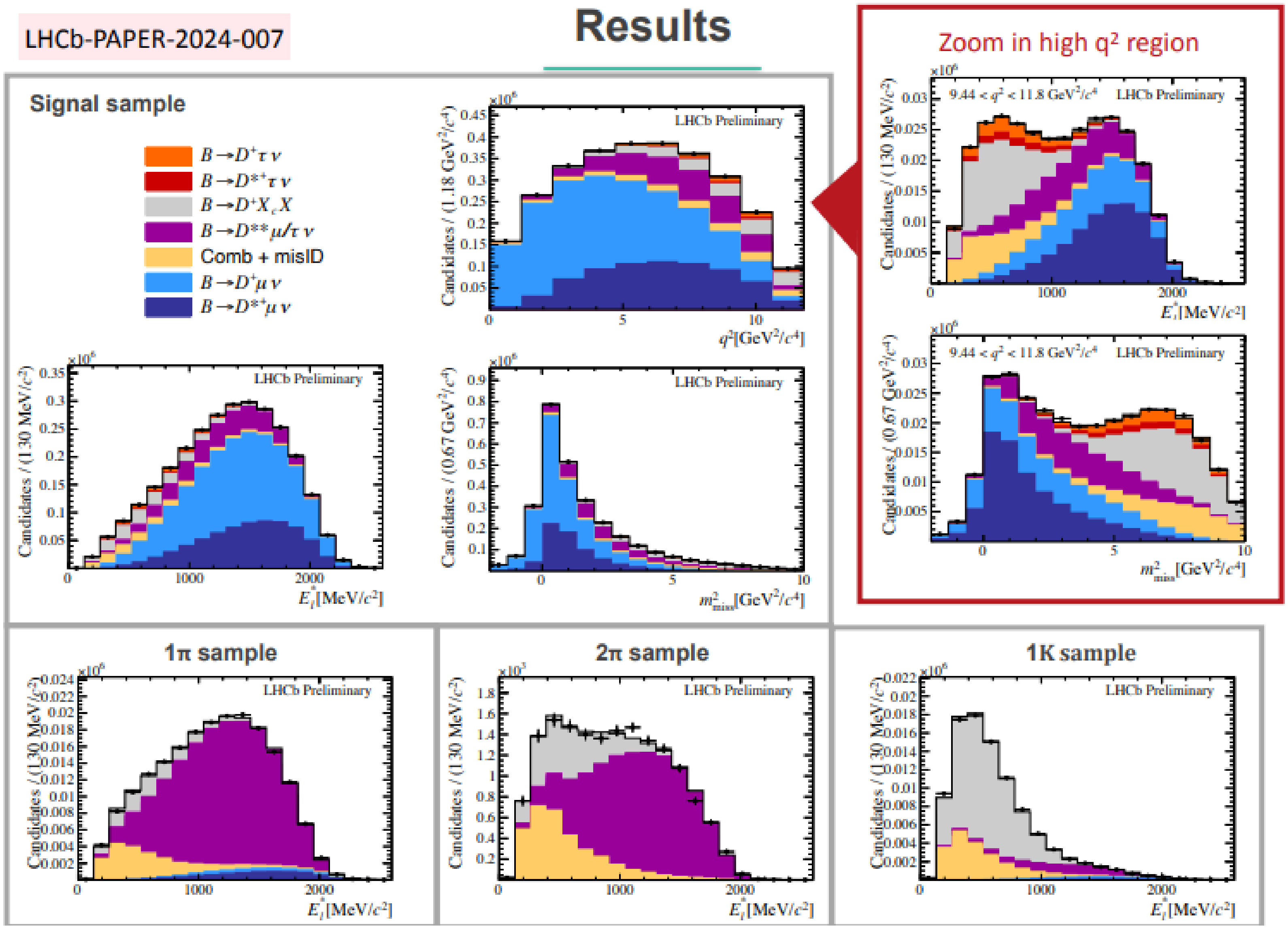
-残飛跡数=1本, 2本のサンプルも同時フィットしてバックグラウンド見積



R(D(*)) result @LHCb

ICHEP slide

-(M_{miss}^2, E_μ^* (Bの静止系でのμエネルギー), $q^2=(p_B-p_D)^2$)で3次元フィット

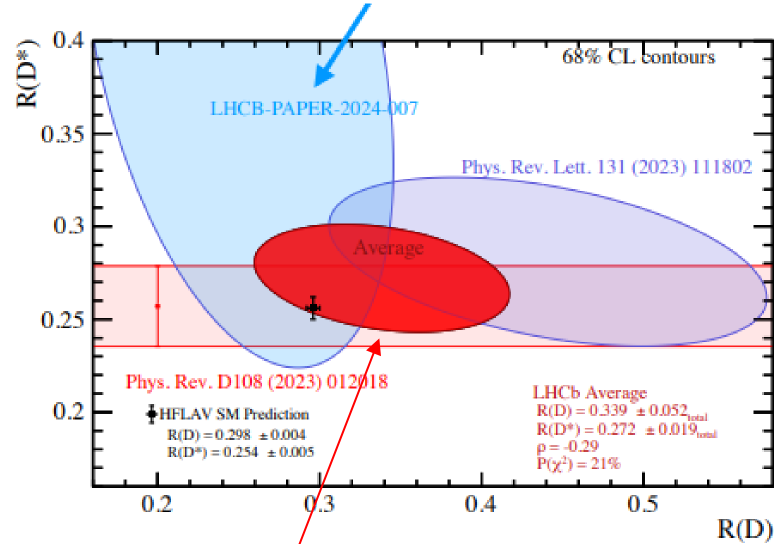


R(D(*)) 結果 @LHCb

-LHCbから3つの測定 (R(J/ψ),R(Λ_c^+) も)

-D^0 or D^+, τの崩壊モード, fit変数が異なる

-LHCb[b]はB→D*πππとの比をとって誤差削減.



-どの測定も系統誤差が支配的

-BG, MC stat., form factor. 今後は？

-LHCb の結果のみだと、SMと68%CLでコンシステント

paper	D崩壊	τ崩壊	dataset	fit variable	R(D*) ±stat±syst.	R(D) ±stat±syst.
LHCb[a] 2023	D^0→Kπ	τ→μνν	RUN1 $3fb^{-1}$	M_{miss}^2, E^*_ℓ, q^2	0.281 ± 0.018 ± 0.024	0.441 ± 0.060 ± 0.066
LHCb[b] 2023	D^0→Kπ	τ→πππ(π0)ν	RUN1 $3fb^{-1}$	M_{miss}^2, tau decay time, BDT	0.247 ±0.015 ±0.015±0.012	--
LHCb[c] 2024	D^+→Kππ	τ→μνν	RUN2 $2fb^{-1}$	M_{miss}^2, E^*_ℓ, q^2	0.402 ± 0.081 ± 0.085	0.249 ± 0.043 ± 0.047

external BR

-LHCb[b] 2023 BDT: neutral particles around 3π to identify BG from 3π system from Ds+ decays

Inclusive measurement of R(X) @Belle II

-The first measurement of $R(X) = \dfrac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$ at B factory, 189fb^{-1}

-inclusive: complementary to exclusive analyses of R(D*)

-one of unique and high-profile goals of BelleII

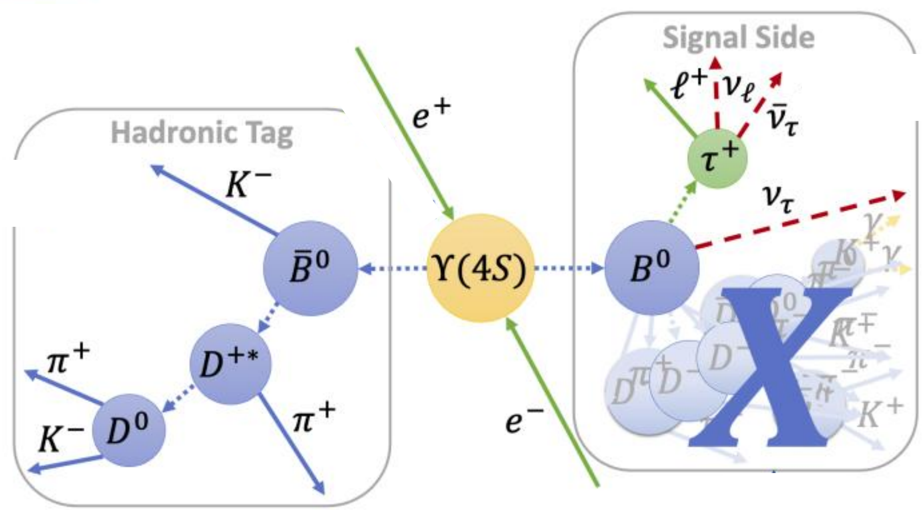
-Reconstruct $B \to X\tau\nu_\tau$, $B \to X\ell\nu_\ell$

-B_{tag}: Hadronic tag

-B_{sig}: Leptonic τ decays of $\tau \to e\bar{\nu}_e\nu_\tau / \mu\bar{\nu}_\mu\nu_\tau$

e(μ) momentum^{lab} > 0.5(0.7) GeV

Any other particles in final state (X)



-Challenge: large BG and modeling of many decay channels

-correct understanding of PDF shapes and background yields:

PDF shapes are calibrated in side-band by using X mass distribution

R(X) signal extraction

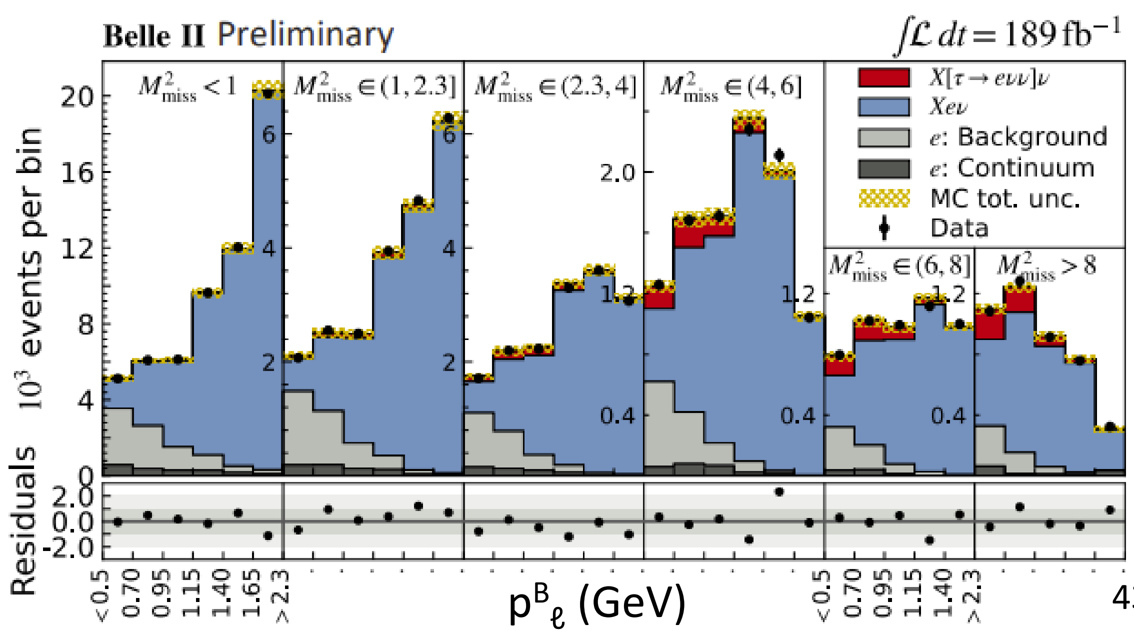
-Two-dimensional binned likelihood is used to extract $N_{B\to X\tau\nu}$, $N_{B\to X\ell\nu}$

- p^B_ℓ : lepton momentum in B rest frame
- $M^2_{\rm miss}$: missing mass of un-detected particles

-Templates for fitting

- -Xτν, Xℓν
- -Continuum with off-resonant data constraint
- -Background from fake and secondaries leptons

-Post fit distributions show good data/MC agreement, including BG dominant bin:



R(X) Result

-The first results of $R(X) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$ at B factory:

PRL 132,211804(2024)

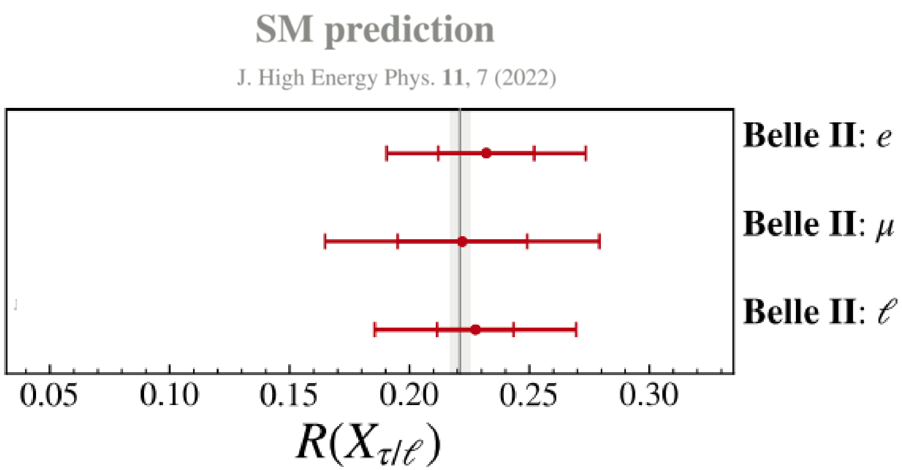
$R(X_{\tau/\ell}) = 0.228 \pm 0.016(\text{stat.}) \pm 0.036(\text{syst.})$

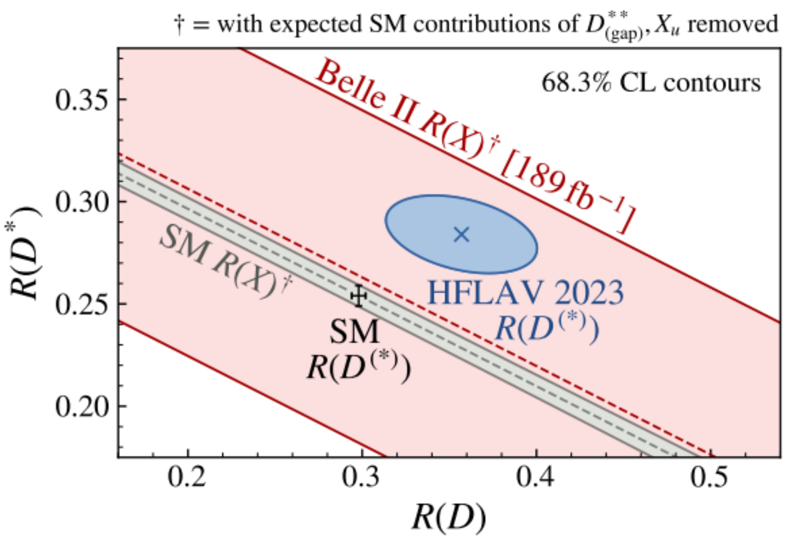
-e only: $R(X_{\tau/\mu}) = 0.232 \pm 0.020(\text{stat.}) \pm 0.037(\text{syst.})$

-μ only: $R(X_{\tau/e}) = 0.228 \pm 0.027(\text{stat.}) \pm 0.050(\text{syst.})$

Major systematics: MC statistics, PDF shape, BR of $B \to D^{**}\ell\nu$

-Consistent with SM prediction and R(D(*)) measurements





B→D*τν τ偏極度測定 @Belle II

-Belle[b] 2017 でR(D*)とP_τ(D*)を測定

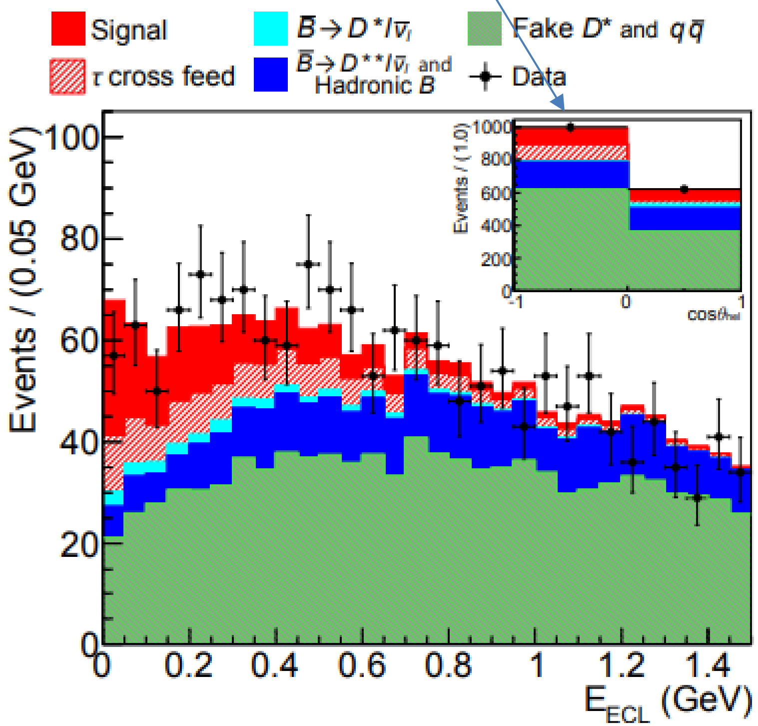
-測定手順はR(D*)と同様

-ただし $\cos\theta_{hel}$の正負(forward, backward)にビンを分けて同時フィット

-測定結果:

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

SM prediction: P_τ(D*) = -0.497±0.013
と誤差の範囲で一致. ただし誤差は大きい



B→D*τν　D*偏極度測定 @Belle

-Belleでの772×10^6 BB pairを使った微分崩壊分岐比の解析

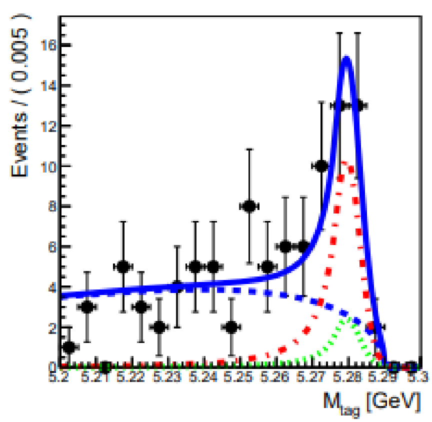
-統計を重視するため(?)、解析手法がこれまでに述べた解析と異なる

- -τ→ℓνν, πν 両方使用
- -B_{tag}の再構成をカットベースで緩く行う→統計増
- -B→D*τνをカットベースでエンハンス（ $X_{miss}=(E_{miss} - |p_{D*}+p_{d\tau}|)/\sqrt{(E_{beam}^2-m_B^2)}$ ）
- -B_{tag}の質量をcosθごとにフィットして微分断面積を算出

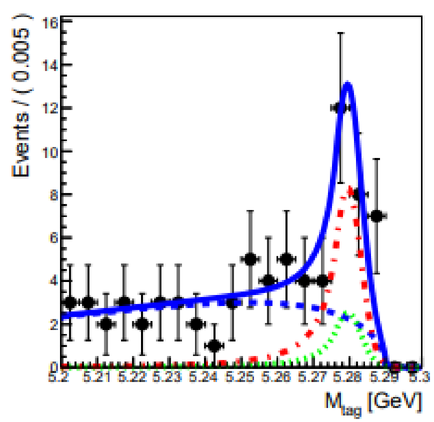
arxiv.1903.03102

B→D*τν (D*→πD, D→Kπ, τ→eνν)の例

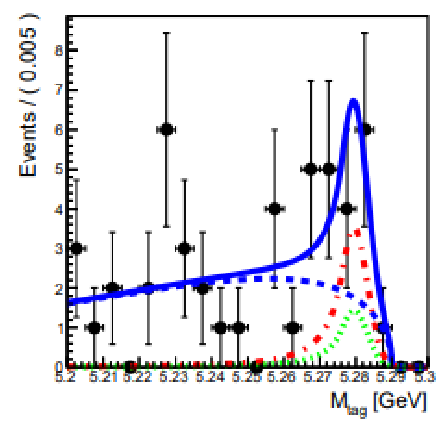
$-1<\cos\theta_{hel}<0.67$



$-0.67<\cos\theta_{hel}<-0.33$



$-0.33<\cos\theta_{hel}<0$



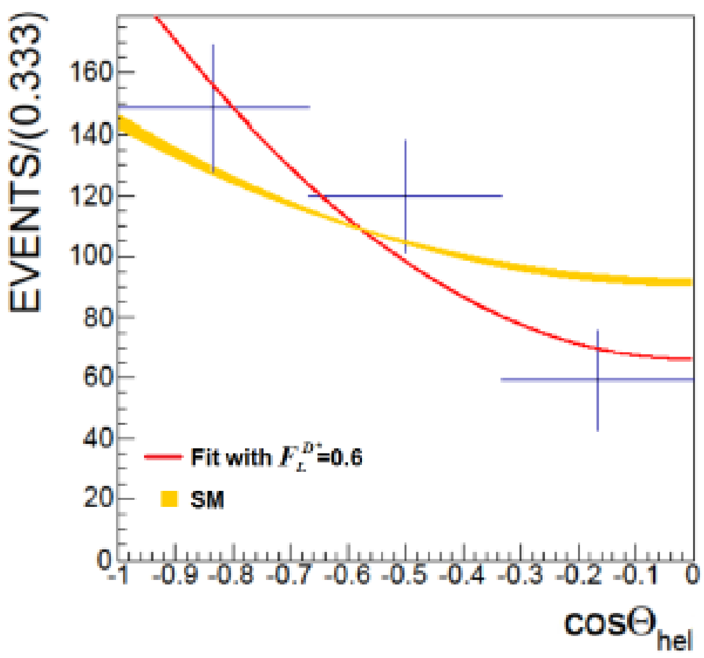
B→D*τν　D*偏極度測定 @Belle

-Belleでの772×10^6 BB pairを使った微分崩壊分岐比の解析

-微分崩壊分岐比より$F^{D^*}_L$をfit:

$$F^{D^*}_L = 0.60 \pm 0.08(\text{stat.}) \pm 0.04(\text{sys.})$$

SM model: $F^{D^*}_L = 0.441 \pm 0.06$, 0.457 ± 0.010 など. ~1.7σで一致.



arxiv.1903.03102