Belle II

Belle II Status and 1st Results

including a few recent highlights from Belle

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Yonsei University

XLVII IMFP, Jun.3 - 8, Aranjuez, Spain

Menu

- *Intro.*
- *the Past of Glory*
- *the Present with Wonder*
- *the Future for Excitement*
- *Epilogue*

Belle II vs. LHCb

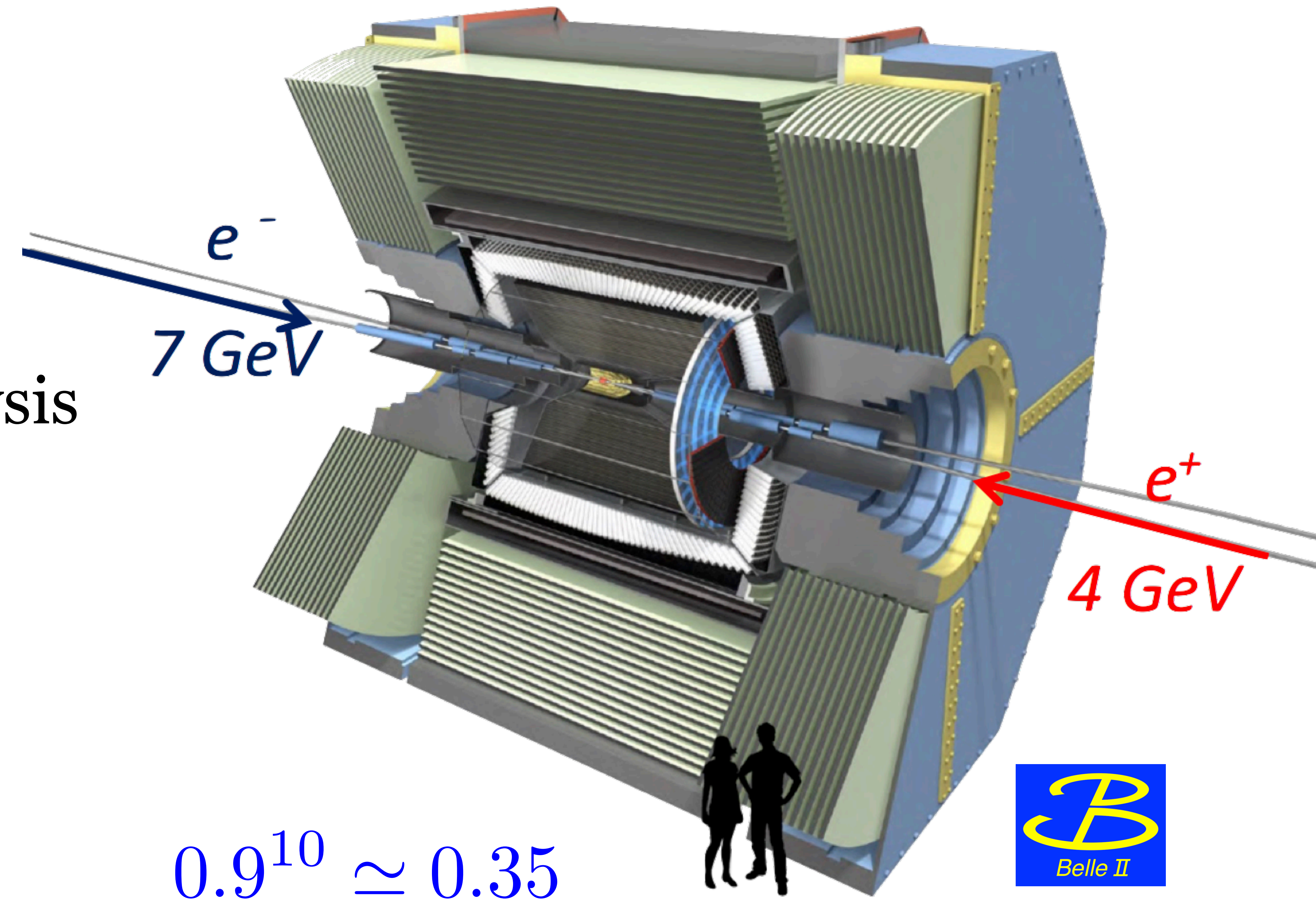
- **LHCb**
  - ultra-high-statistics sample of B and B_s in all-charged modes
  - heavy excited b-hadrons are accessible
  - (*previous lecture by Dr. Oyanguren*)
- **Belle II**
  - unique for final states with neutrinos or multiple photons (i.e. π^0), and inclusive analyses (e.g. $B \rightarrow X_s\,\gamma$)
  - also a good place to study charm, $\tau^+\tau^-$, $\Upsilon(nS)$
  - ***hermeticity*** is a great plus, too!

Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CP Violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\bar{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\bar{\nu})$ $[10^{-6}]$	***	20%	Belle II
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03	Belle II
$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	***	4	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-10}]$	***	< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3	Belle II/LHCb

from "The Belle II Physics Book", arXiv:1808.10567.

Strengths of Belle (II)

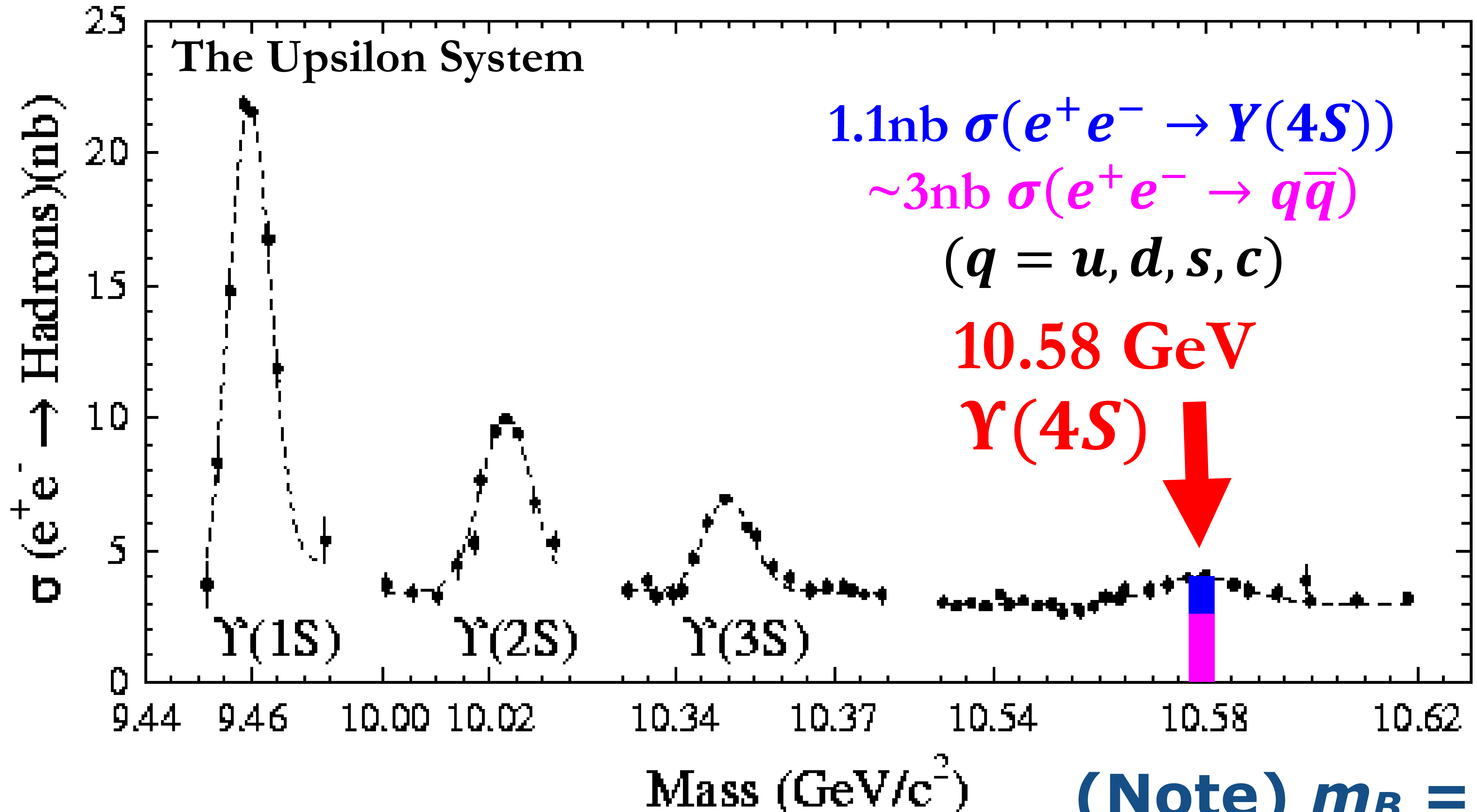
- **Full reconstruction of B**
  - ＊ missing (E,p) analysis
  - ＊ inclusive measurements
- **Hermeticity**
  - ＊ minimal trigger for, e.g. Dalitz analysis
  - ＊ precision τ measurements
- **Neutral particles**
  - ＊ and for η, η', ρ^+, etc.
- *other notable features*
  - ＊ good PID for both $\mu^\pm$ and $e^\pm$
  - ＊ high flavor-tagging efficiency
    - (×15 better than LHC)



$0.9^{10} \simeq 0.35$

- Belle II covering ≳90% of 4π
- ⟨N(track)⟩ ~ 10 per event

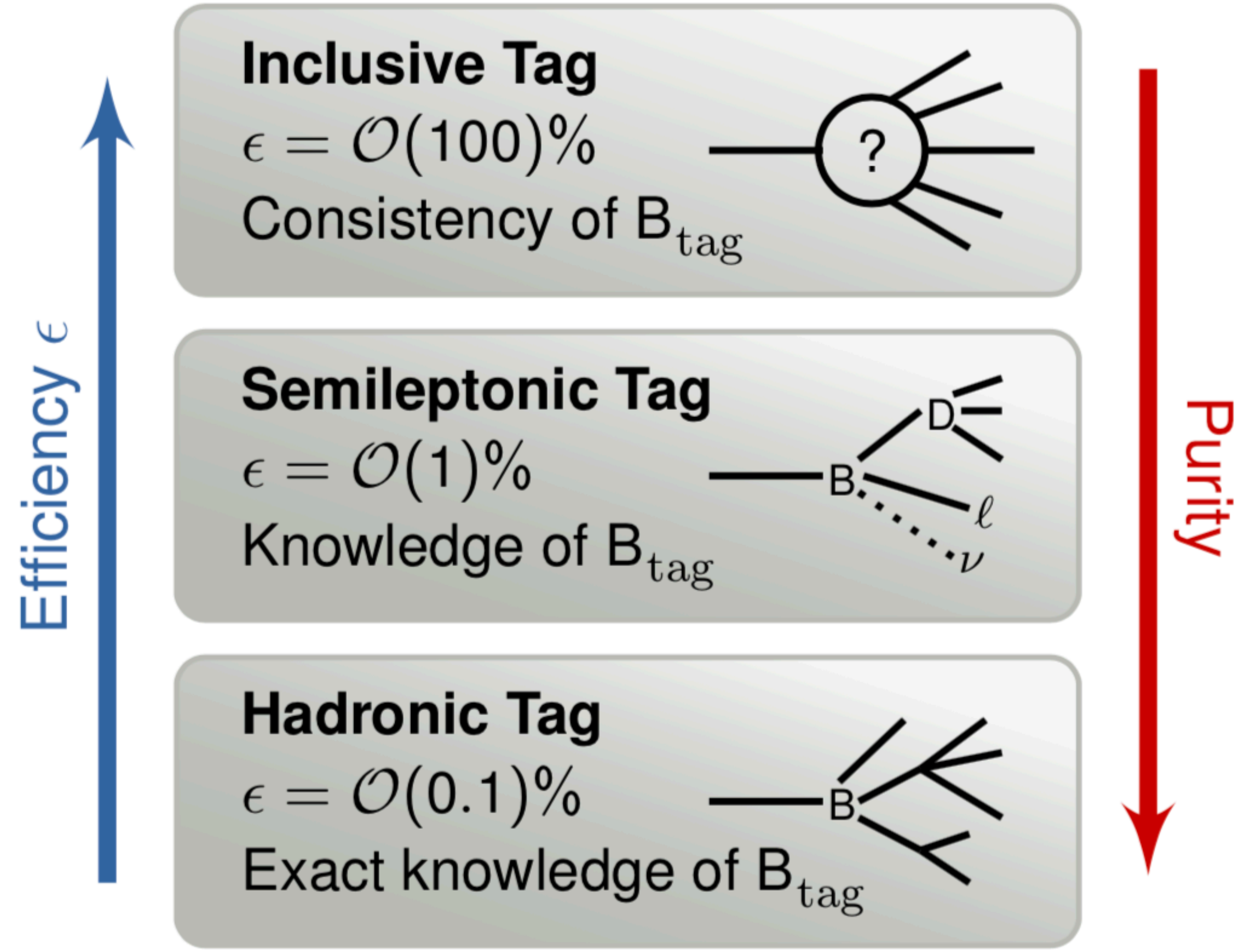
$e^+e^- \to \Upsilon(4S)$ as a B-factory

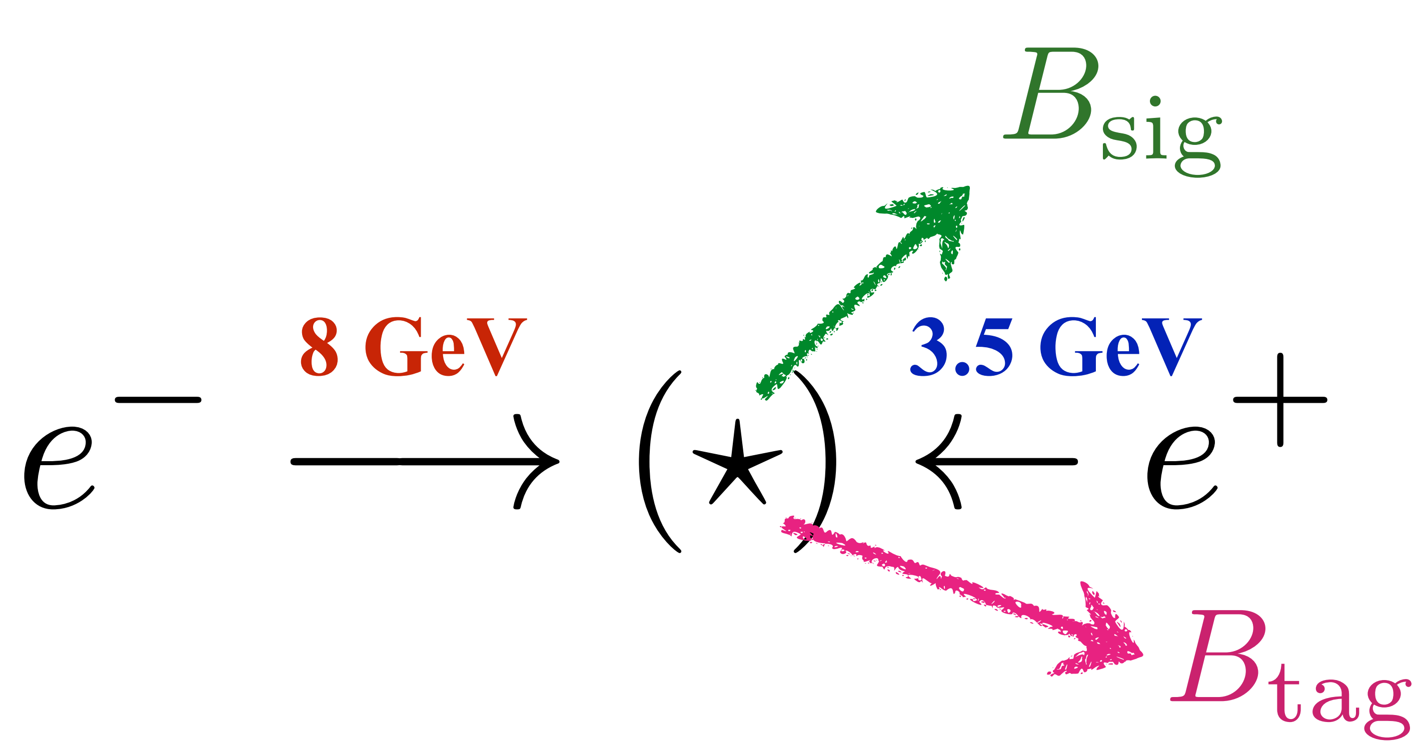


(Note) m_B = 5.28 GeV

- $\mathcal{B}(\Upsilon(4S) \to B\bar{B}) > 96\%$, with $p_B^{CM} \sim 0.35$ GeV/c
- nothing else but $B\bar{B}$ in the final state
  $\therefore$ if we know $(E, \vec{p})$ of one B, the other B is also constrained

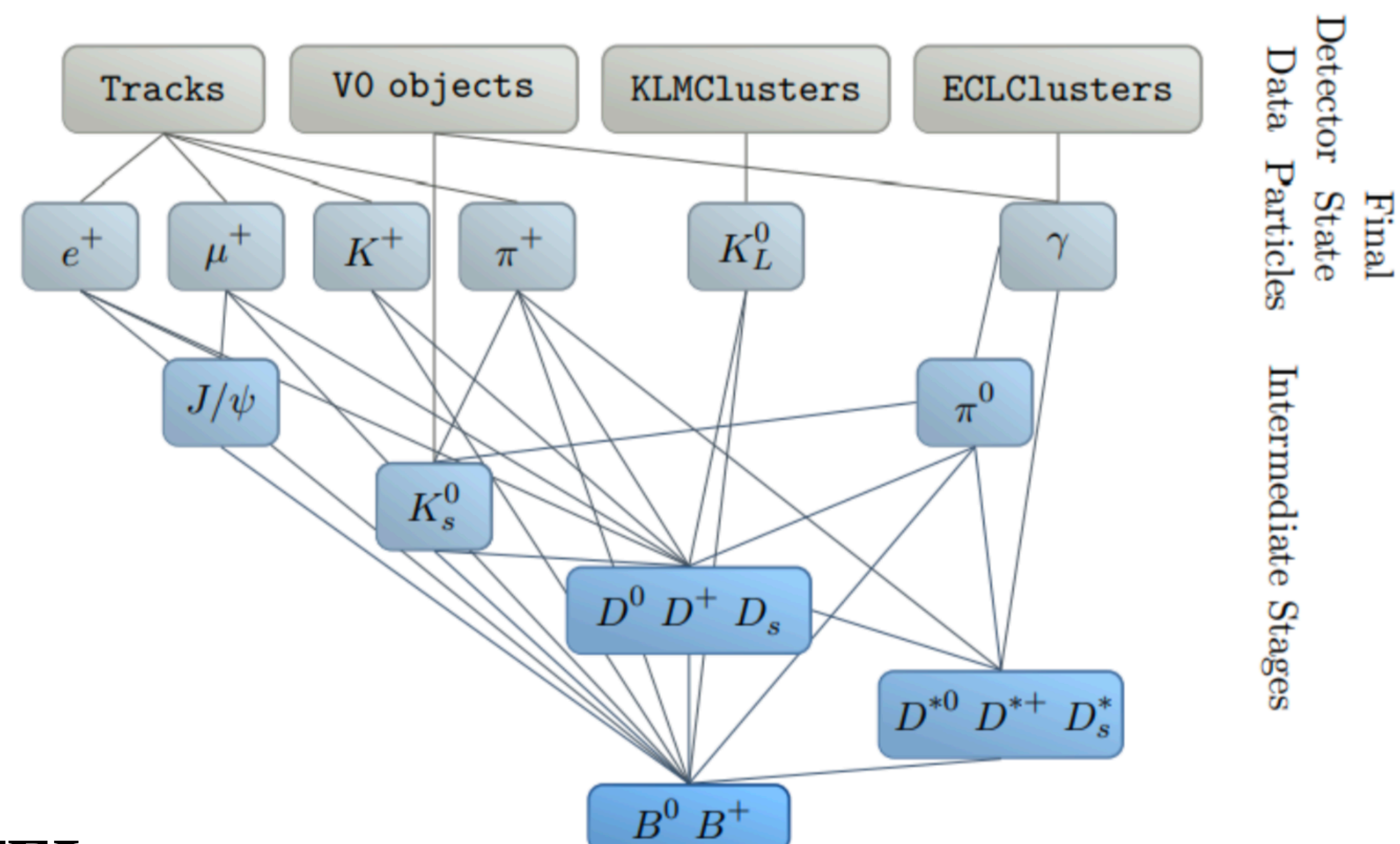
B-tagging and FEI





Exclusive Tagging:
The Full Event Interpretation (FEI)

Keck, T., et al. Comput Softw Big Sci (2019)



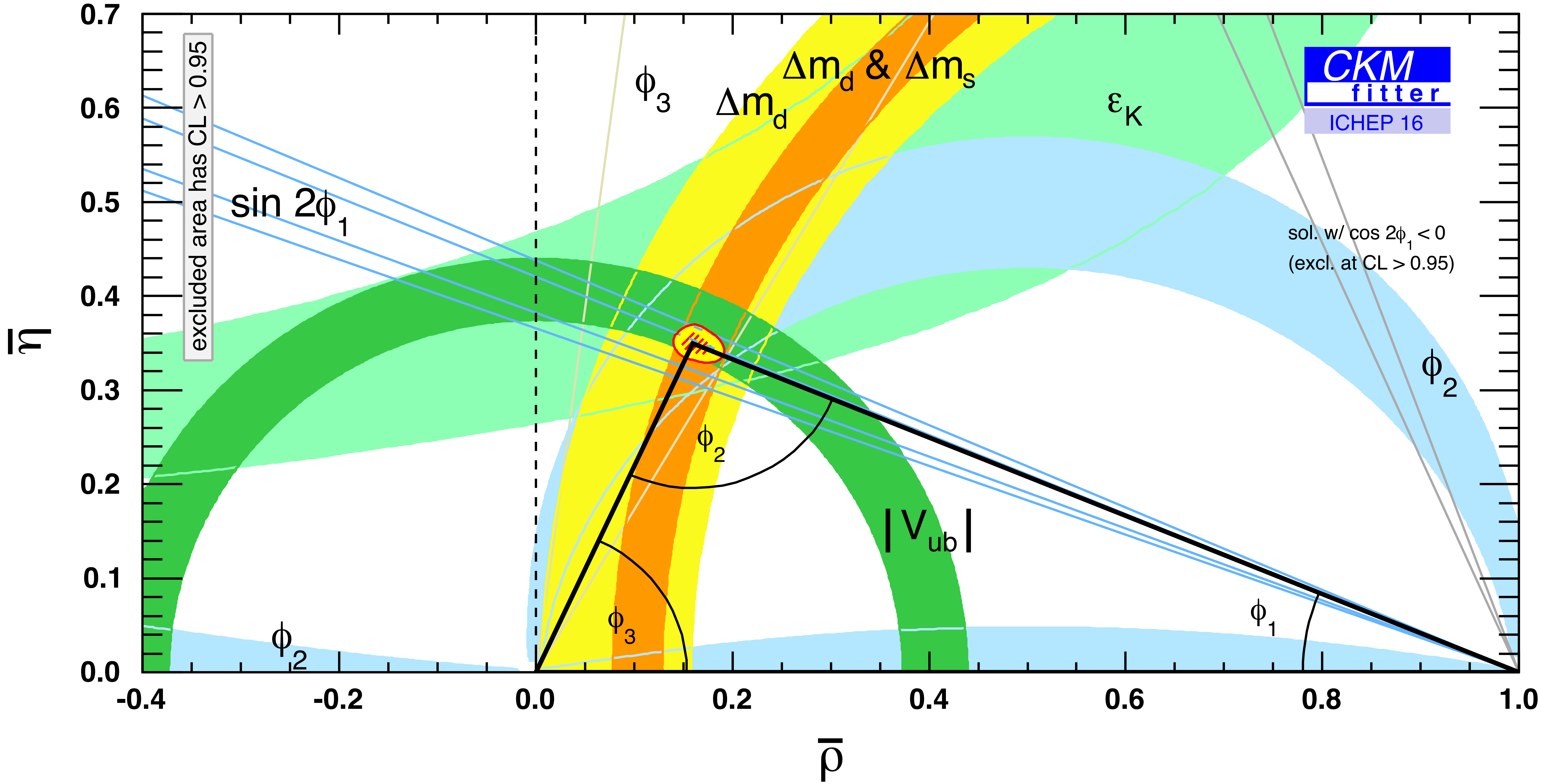
FEI

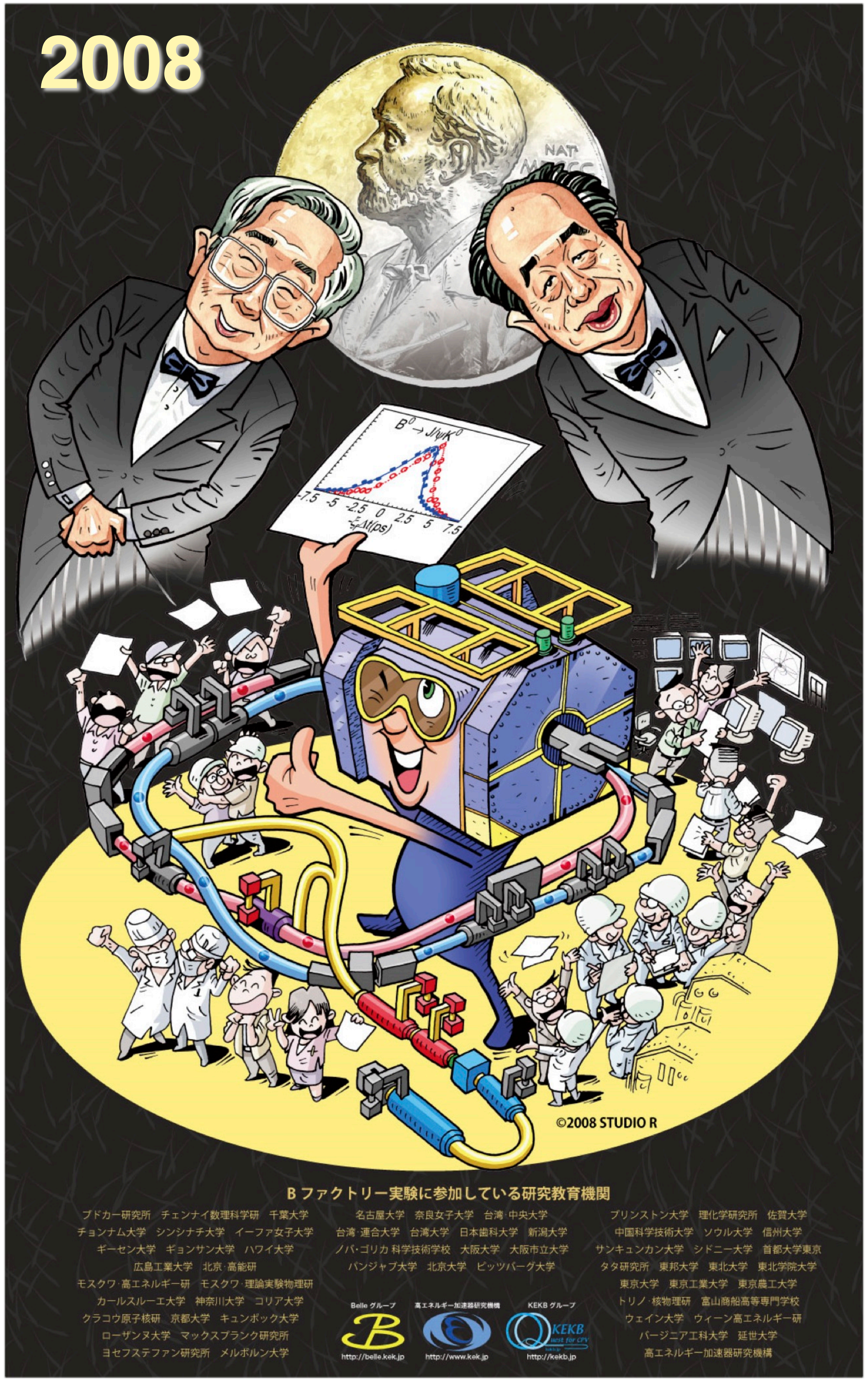
- the most evolved version of B-tagging S/W
- developed for Belle II; used in several Belle studies
  - O(200) decay chains with BDT trained for each
  - O(10k) decay chains in 6 stages
  - ×3 high MC efficiency than existing Belle algorithm

the Past

of Glory

The CKM Unitarity Triangle





Belle (and BaBar, too) achievements include:

- CPV, CKM, and rare decays of B mesons (and B_s, too)
- Mixing, CP, and spectroscopy of charmed hadrons
- Quarkonium spectroscopy and discovery of (*many*) exotic states, e.g. $X(3872)$, $Z_c(4430)^+$
- Studies of τ and 2γ

the Present

with Wonder

Nature, 2017/06/08

REVIEW

doi:10.1038/nature22346

A challenge to lepton universality in *B*-meson decays

Gregory Ciezarek[1], Manuel Franco Sevilla[2], Brian Hamilton[3], Robert Kowalewski[4], Thomas Kuhr[5], Vera Lüth[6] & Yutaro Sato[7]

One of the key assumptions of the standard model of particle physics is that the interactions of the charged leptons, namely electrons, muons and taus, differ only because of their different masses. Whereas precision tests comparing processes

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2 Accelerators Find Particles That May Break Known Laws of Physics

The LHC and the Belle experime
Model of particle physics, confirr

By Clara Moskowitz | September 9, 2

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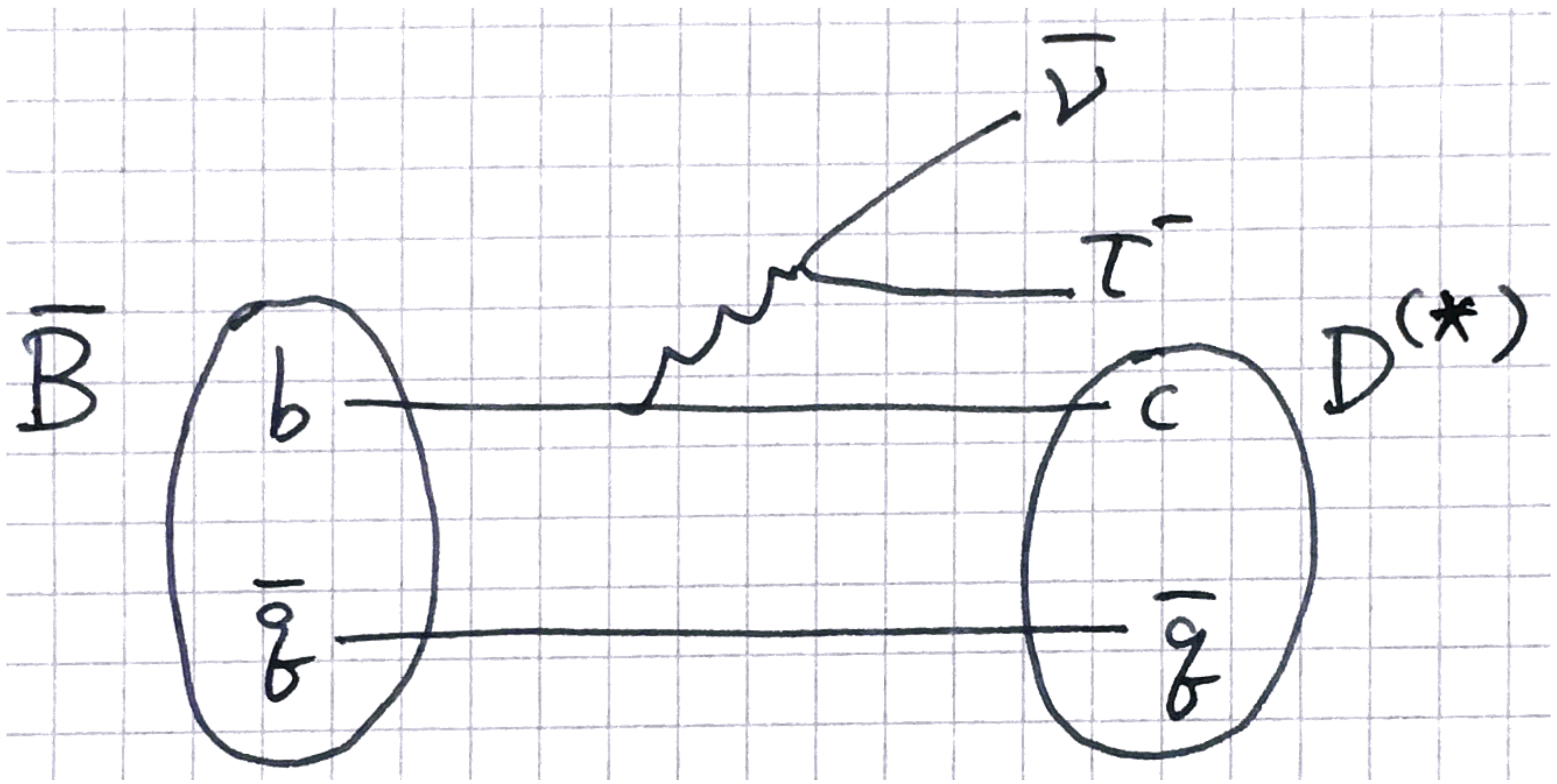
Democracy suffers a blow—in particle physics

Three independent B-meson experiments suggest that the charged leptons may not be so equal after all.

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



$$\mathcal{R}(D) \equiv \frac{\mathcal{B}(B \to D\,\tau^+\nu)}{\mathcal{B}(B \to D\,\ell^+\nu)}$$

$$\mathcal{R}(D^*) \equiv \frac{\mathcal{B}(B \to D^*\tau^+\nu)}{\mathcal{B}(B \to D^*\ell^+\nu)}$$

where $\ell = e,\ \mu$

- $m_\tau \gg m_e, m_\mu$ ∴ B ➔ D^* τ ν can be more sensitive to NP, e.g. from H^+
- ∃ hints (from BaBar, Belle, LHCb) for deviations of *R*(*D*), *R*(D^*) from SM; **LUV?**
- B ➔ D^* τ ν was first observed by Belle

PRL **99,** 191807 (2007) PHYSICAL REVIEW LETTERS week ending 9 NOVEMBER 2007

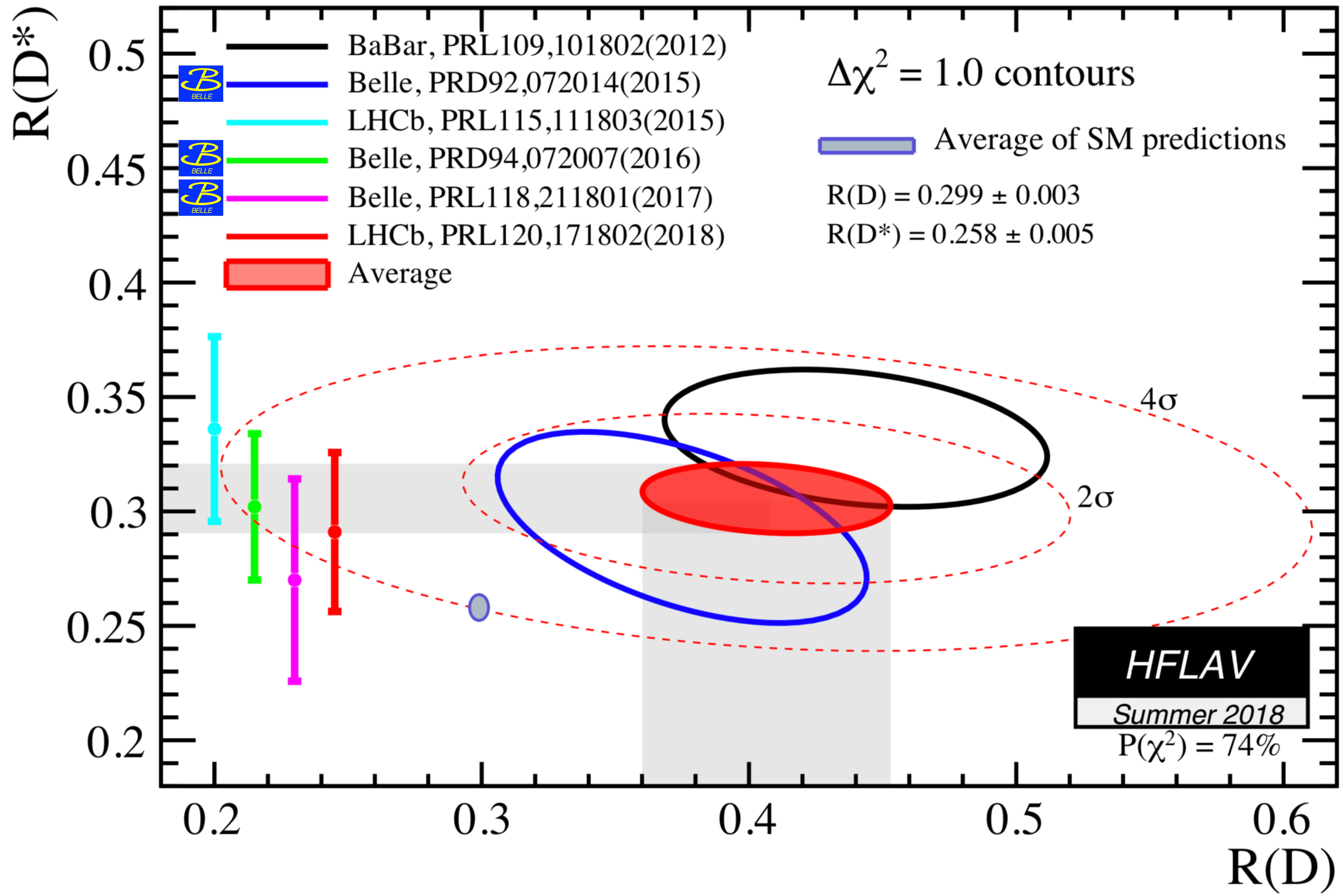
Observation of $B^0 \to D^{*-}\tau^+\nu_\tau$ Decay at Belle

A. Matyja,[27] M. Rozanska,[27] I. Adachi,[8] H. Aihara,[41] V. Aulchenko,[1] T. Aushev,[18,13] S. Bahinipati,[3] A. M. Bakich,[37]
V. Balagura,[13] E. Barberio,[21] I. Bedny,[1] V. Bhardwaj,[33] U. Bitenc,[14] A. Bondar,[1] A. Bozek,[27] M. Bračko,[20,14]

Reminder

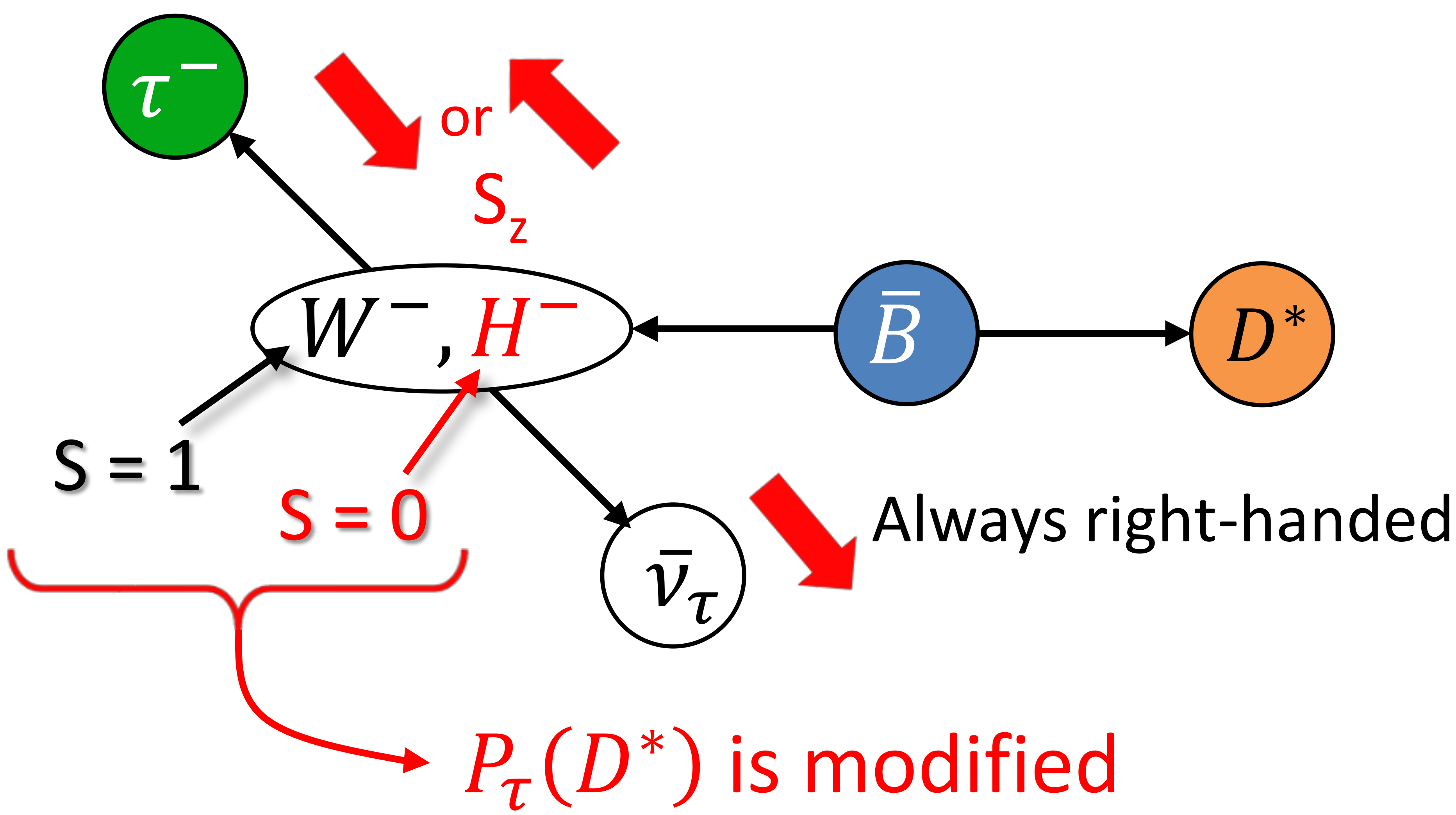
Puzzles of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$

as of 2018



Polarizations in $B \to D^* \tau \nu$

- $R(D^{(*)})$ deviations from SM (by ~3.8σ as of 2018) motivates further study
- Detailed kinematic information of the final-state particles, e.g. angular observables, can provide a good clue for NP signature (*if there is any*!)



$$\mathcal{P}_\tau^{\rm SM} = -0.497 \pm 0.014$$

by M. Tanaka & R. Watanabe, PRD 87, 034028 (2013)

- In 2017, Belle has reported world-first measurement of P_τ in B ➔ D* τν

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

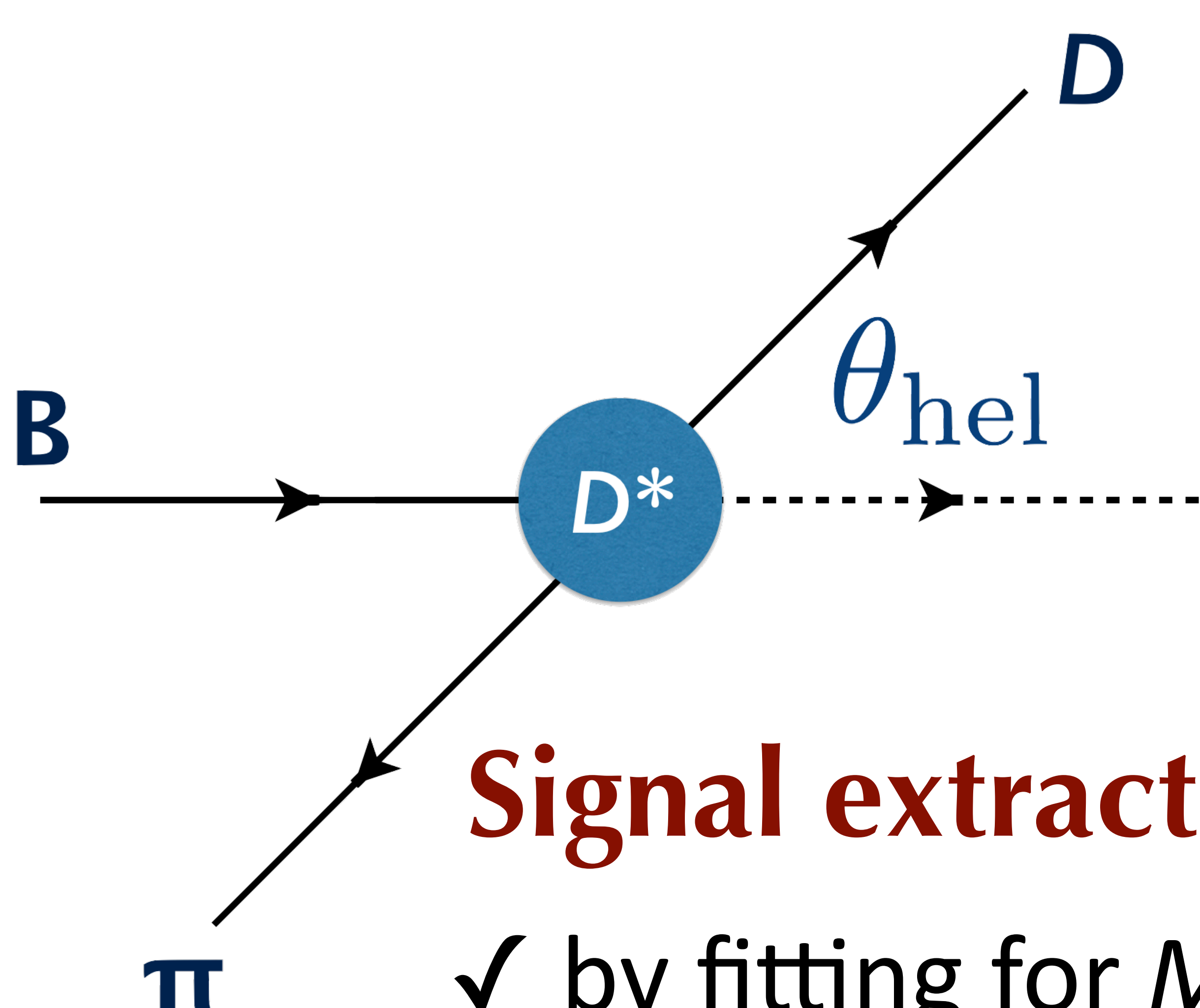
New in 2019

D^* polarization in $B \to D^* \tau \nu$

- D^* polarization (P_{D^*}) will give yet another clue about NP signature
- Belle measures P_{D^*}
  - ✓ reconstruct signal B in $\tau \to \ell \nu \nu$ and $\tau \to \pi \nu$ modes
  - ✓ then require kinematic consistency on the accompanying B ($B_{\rm tag}$) inclusively (a la 2007 PRL)

$M_{\rm tag} > 5.2$ GeV

$-0.30 < \Delta E_{\rm tag} < +0.05$ GeV



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

$F_L^{D^*}$ = the fraction of longitudinal polarization of D*

SM: 0.54 (0.53)

by covariant quark model (heavy quark limit)

Signal extraction

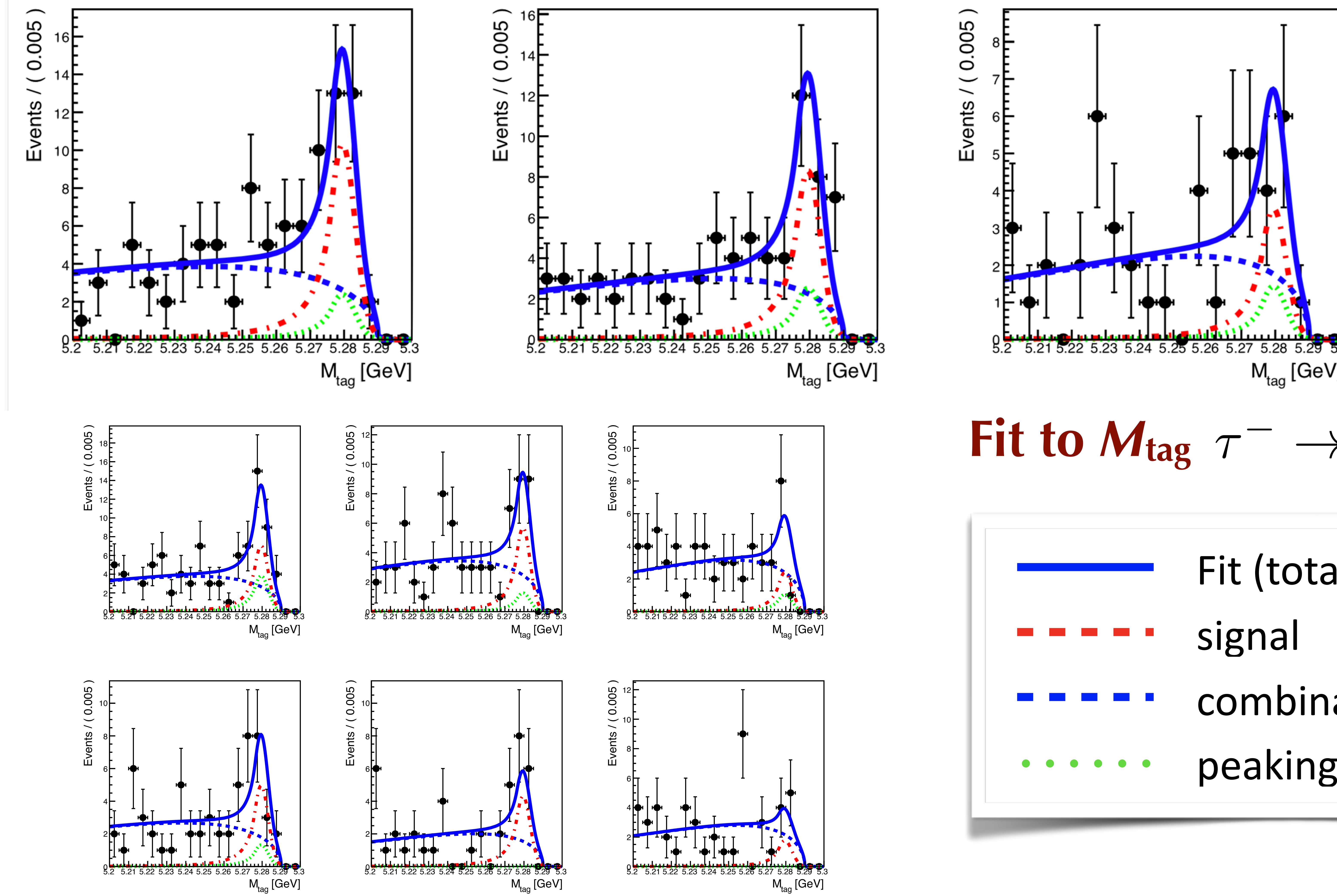
- ✓ by fitting for $M_{\rm tag}$ in three equal bins in $\cos\theta_{\rm hel}$
- ✓ The procedure is checked by "measuring" $F_L^{D^*}(B^0 \to D^{*-} e^+ \nu) = 0.56 \pm 0.02$

New in 2019

preliminary, arXiv:1903.03102 [hep-ex]

D^* polarization in $B \to D^* \tau \nu$

$-1.0 \leq \cos\theta_{\text{hel}} < -0.67$ | $-0.67 \leq \cos\theta_{\text{hel}} < -0.33$ | $-0.33 \leq \cos\theta_{\text{hel}} < 0$

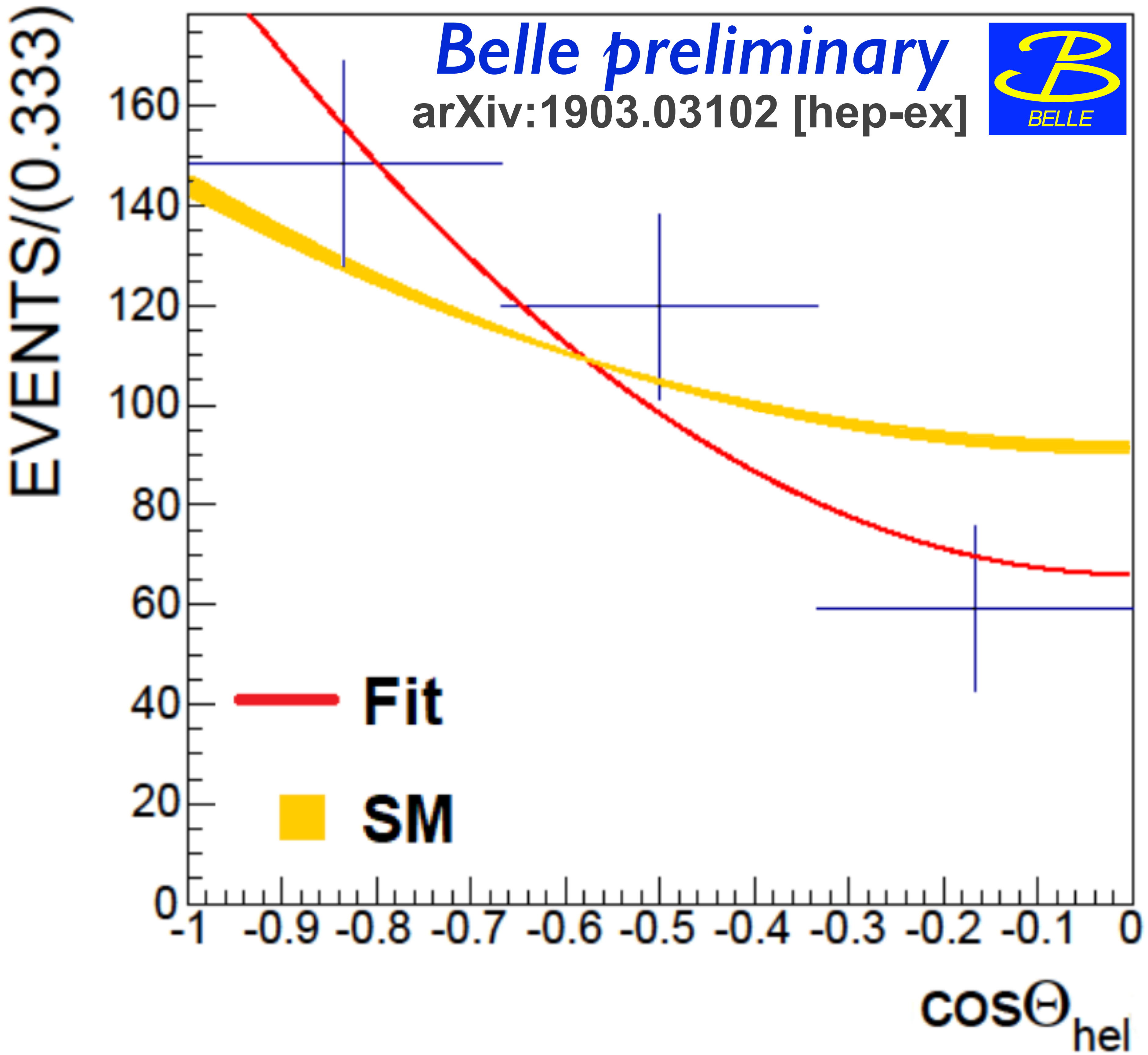


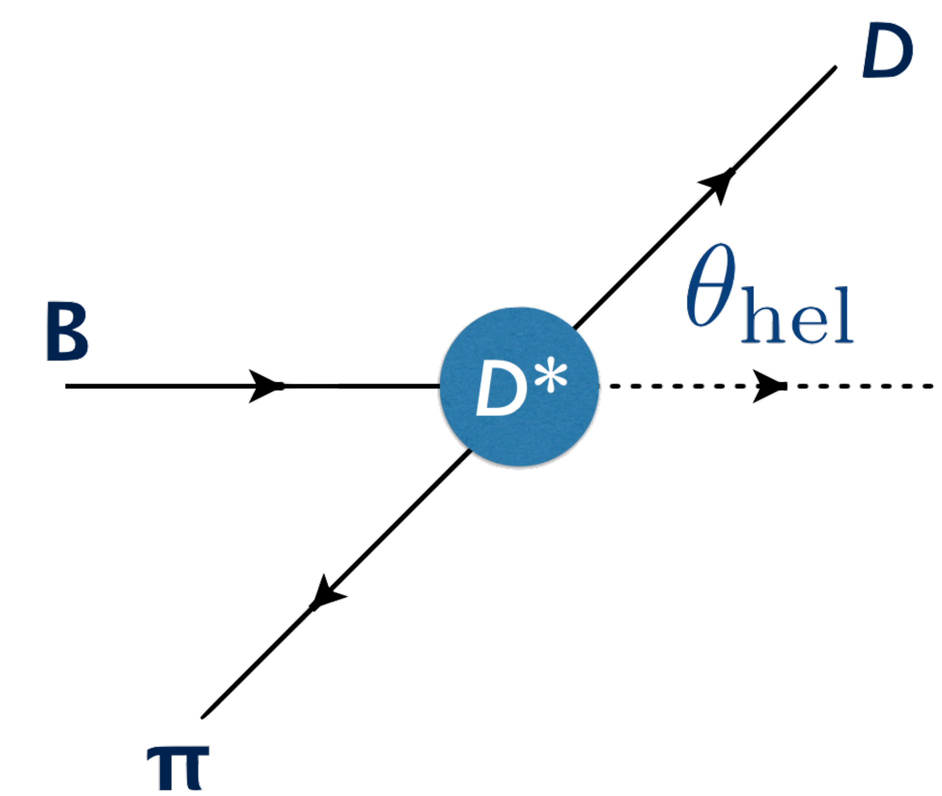
$D \to K\pi$ (top)
$D \to K\pi\pi^0$ (middle)
$D \to K3\pi$ (bottom)

Fit to M_{tag} $\tau^- \to e^- \nu\bar{\nu}$ mode

- Fit (total)
- signal
- combinatorial bkgd.
- peaking bkgd.

D^* polarization in $B \to D^*\tau\nu$





$$F_{\rm L}^{D^*} = 0.60 \pm 0.08 \pm 0.04$$

$$\left(F_{\rm L}^{D^*}\right)_{\rm SM} = 0.457 \pm 0.010$$

Huang, Li, Lu, Ali Paracha, and Wang
Phys. Rev. D **98**, 095018 (2018)

The measured $\cos\theta_{\rm hel}$ distribution in $B^0 \to D^{*-}\tau^+\nu_\tau$ decays (data points with statistical errors).

R(D) & R(D) before March 2019*

Experiment	Tag method	τ mode	**R(D)**	R(D*)
Babar '12	Hadronic	ℓ ν ν	**0.440 ± 0.058 ± 0.042**	0.332 ± 0.024 ± 0.018
Belle '15	Hadronic	ℓ ν ν	**0.375 ± 0.064 ± 0.026**	0.293 ± 0.038 ± 0.015
LHCb '15	-	ℓ ν ν	**-**	0.336 ± 0.027 ± 0.030
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 '18	-	π π π ν	**-**	0.291 ± 0.019 ± 0.029
Average	-	-	**0.407 ± 0.039 ± 0.024**	0.306 ± 0.013 ± 0.007
SM			**0.299 ± 0.003**	0.258 ± 0.005

New in 2019

preliminary arXiv:1904.08794 [hep-ex]

$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with SL tagging

Features

- update of the Belle's SL-tagged analysis **Phys. Rev. D 94, 072007 (2016)**
  - ✓ $R(D^*)$ only ⇒ $R(D)$ and $R(D^*)$, simultaneously
  - ✓ for $R(D^*)$, B^0 only ⇒ B^0 and B^+
  - ✓ improved tagging (FEI, a Belle II s/w)
- on the tag-side, exploit the observable
  - ✓ $\cos\theta_{B,D^{(*)}\ell}$ = angle between B and $D^{(*)}\ell$ in $\Upsilon(4S)$ frame

$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E_{\mathrm{beam}}E_{D^{(*)}\ell} - m_B^2 - m_{D^{(*)}\ell}^2}{2|p_B||p_{D^{(*)}\ell}|}$$

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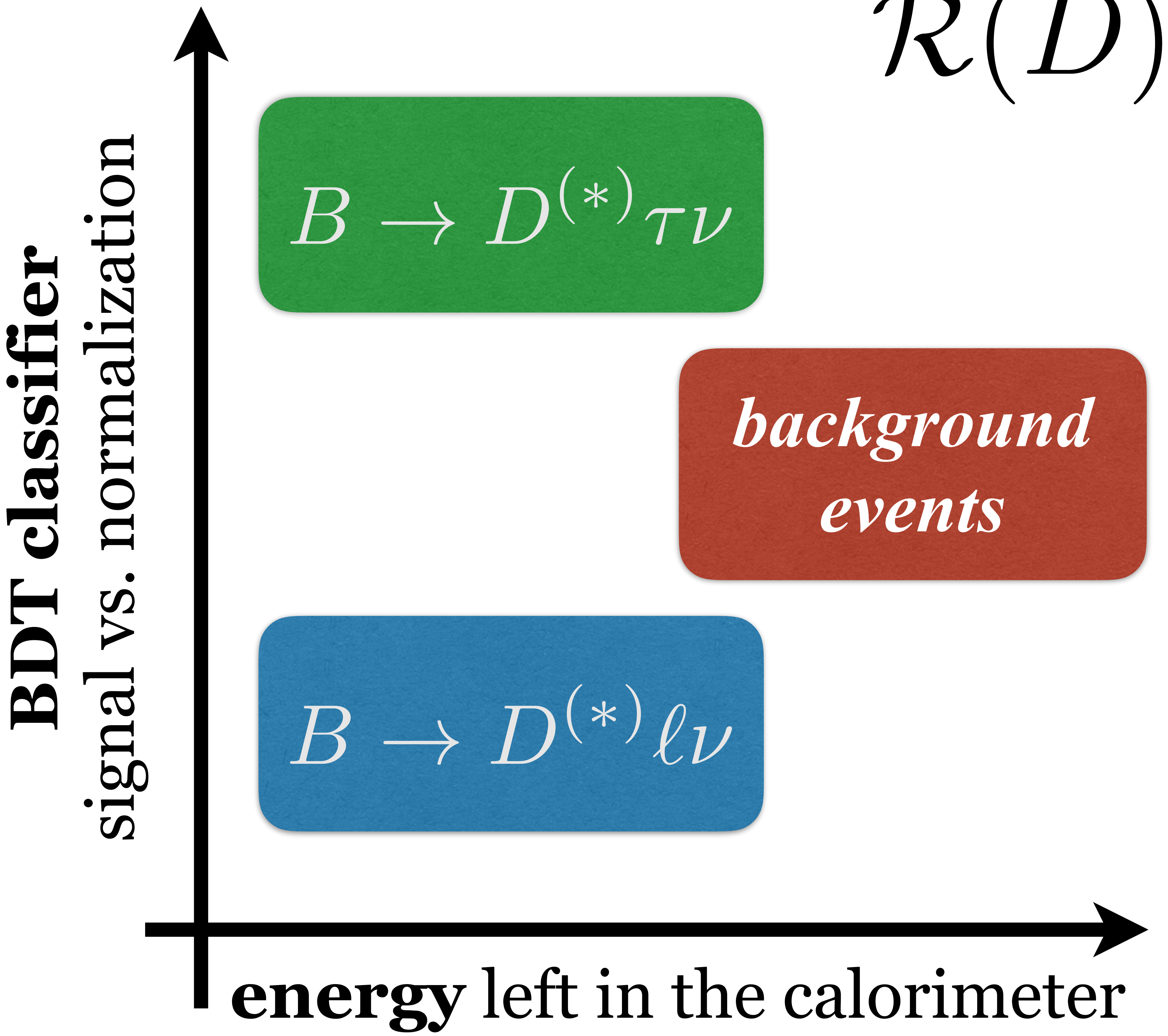
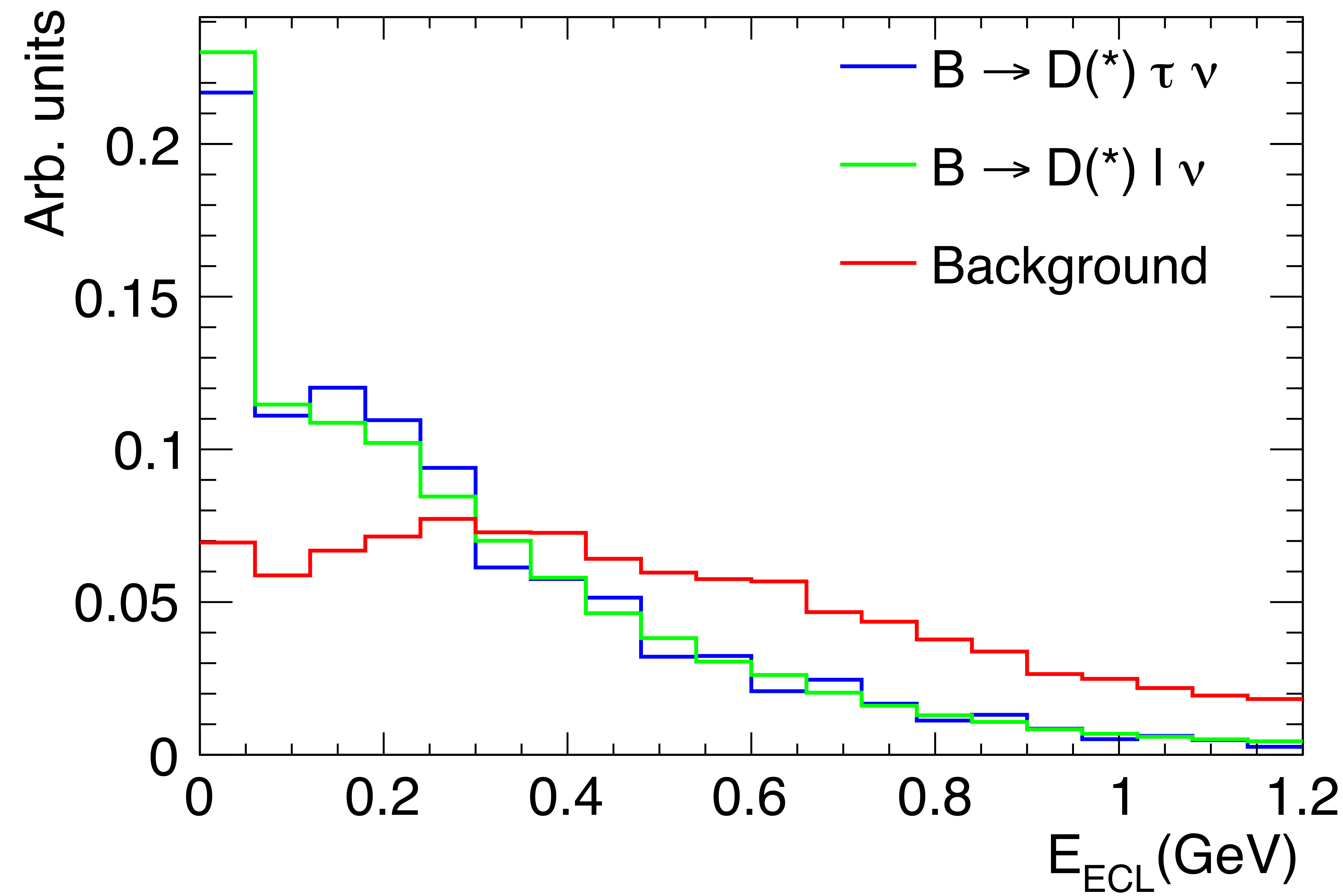
$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with SL tagging





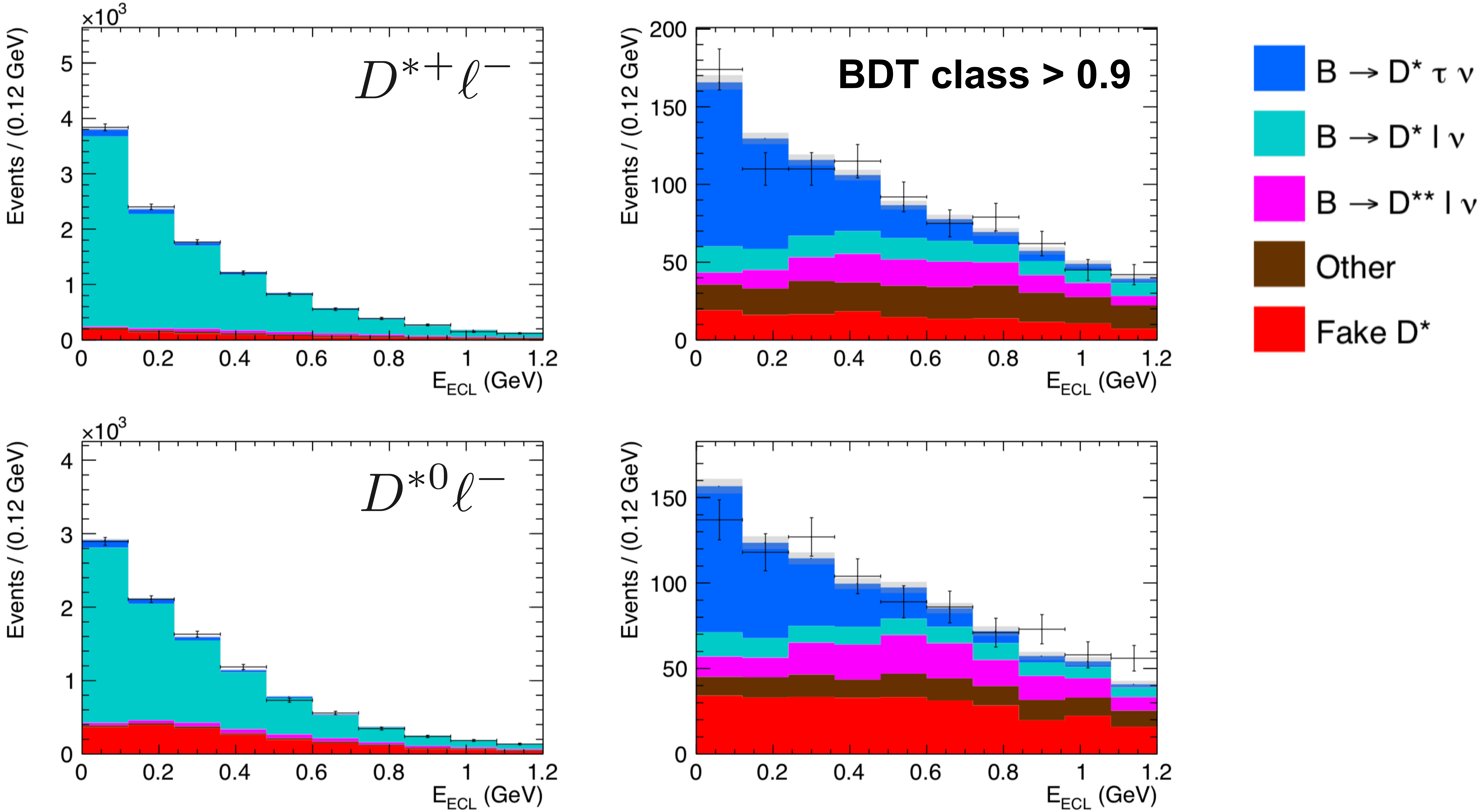
- E_{ECL} to suppress generic background
- BDT classifier to distinguish **Signal** from **$D^{(*)}\ell\nu$**
  - ✓ based on XGBoost package
  - ✓ uses m^2(miss), E(vis), cos θ(B,$D^{(*)}\ell$)
- 2D fit to (BDT class, E_{ECL})

E_{ECL} = extra energy left in the EM calorimeter

New in 2019

preliminary **arXiv:1904.08794 [hep-ex]**

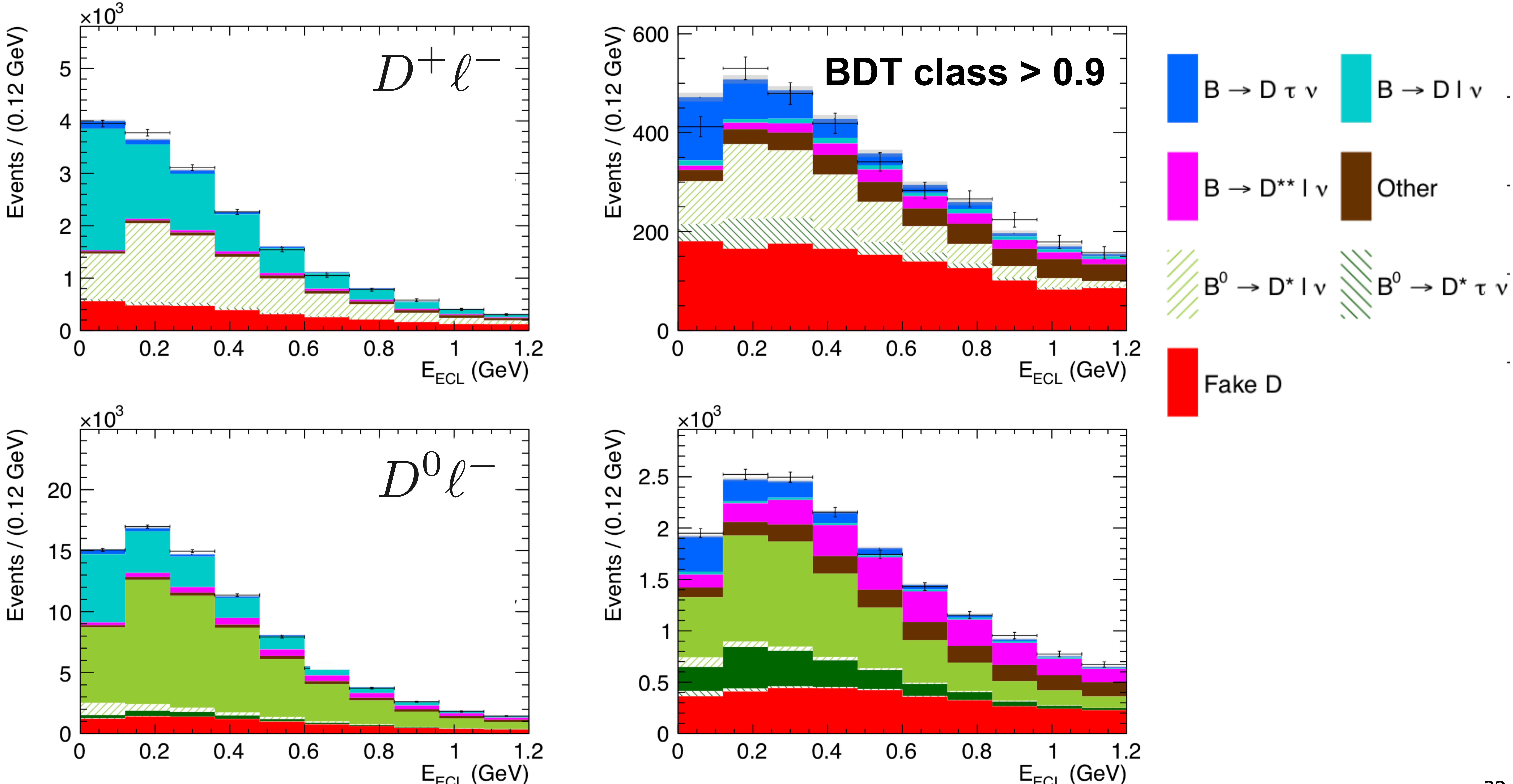
$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with SL tagging



New in 2019

preliminary **arXiv:1904.08794 [hep-ex]**

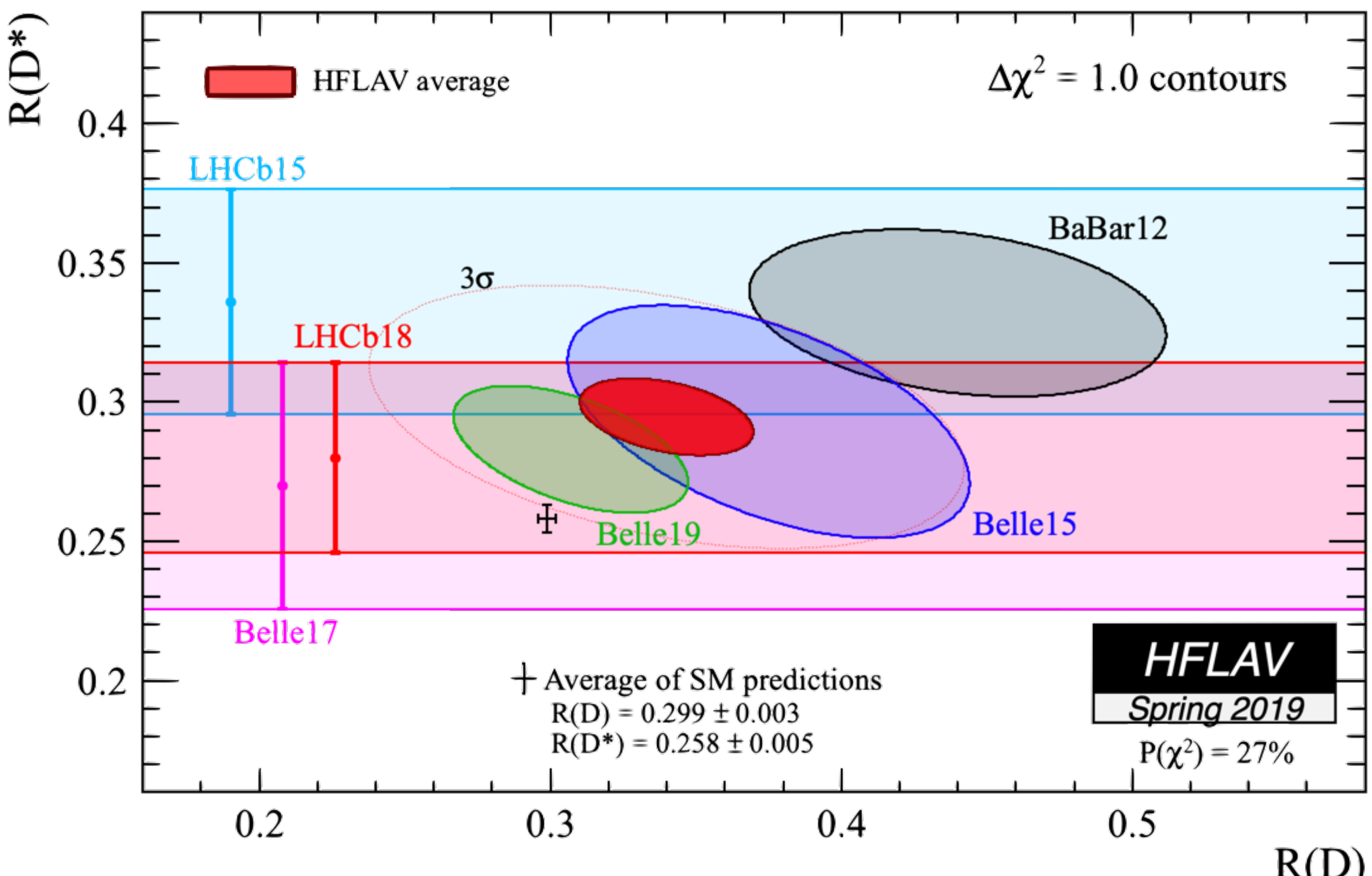
$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with SL tagging



Experiment	Tag method	τ mode	**R(D)**	R(D*)	
Babar '12	Hadronic	ℓ ν ν	**0.440 ± 0.058 ± 0.042**	0.332 ± 0.024 ± 0.018	
Belle '15	Hadronic	ℓ ν ν	**0.375 ± 0.064 ± 0.026**	0.293 ± 0.038 ± 0.015	
LHCb '15	-	ℓ ν ν	**-**	0.336 ± 0.027 ± 0.030	
Belle '16	Semileptonic	ℓ ν ν	-	0.302 ± 0.030 ± 0.011	B^0
Belle '17	Hadronic	π ν, ρ ν	**-**	0.270 ± 0.035 ± 0.027	
LHCb '18	-	π π π ν	**-**	0.291 ± 0.019 ± 0.029	
Belle '19 *preliminary*	**Semileptonic**	**ℓ ν ν**	**0.307 ± 0.037 ± 0.016**	**0.283 ± 0.018 ± 0.014**	B^0, B^+
Average (2018)	-	-	*0.407 ± 0.039 ± 0.024*	*0.306 ± 0.013 ± 0.007*	
Average (2019)	**-**	**-**	**0.340 ± 0.027 ± 0.013**	**0.295 ± 0.011 ± 0.008**	
SM			0.299 ± 0.003	0.258 ± 0.005	

averages from HFLAV

$\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ updated



$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

Belle, SL-tag (2019)

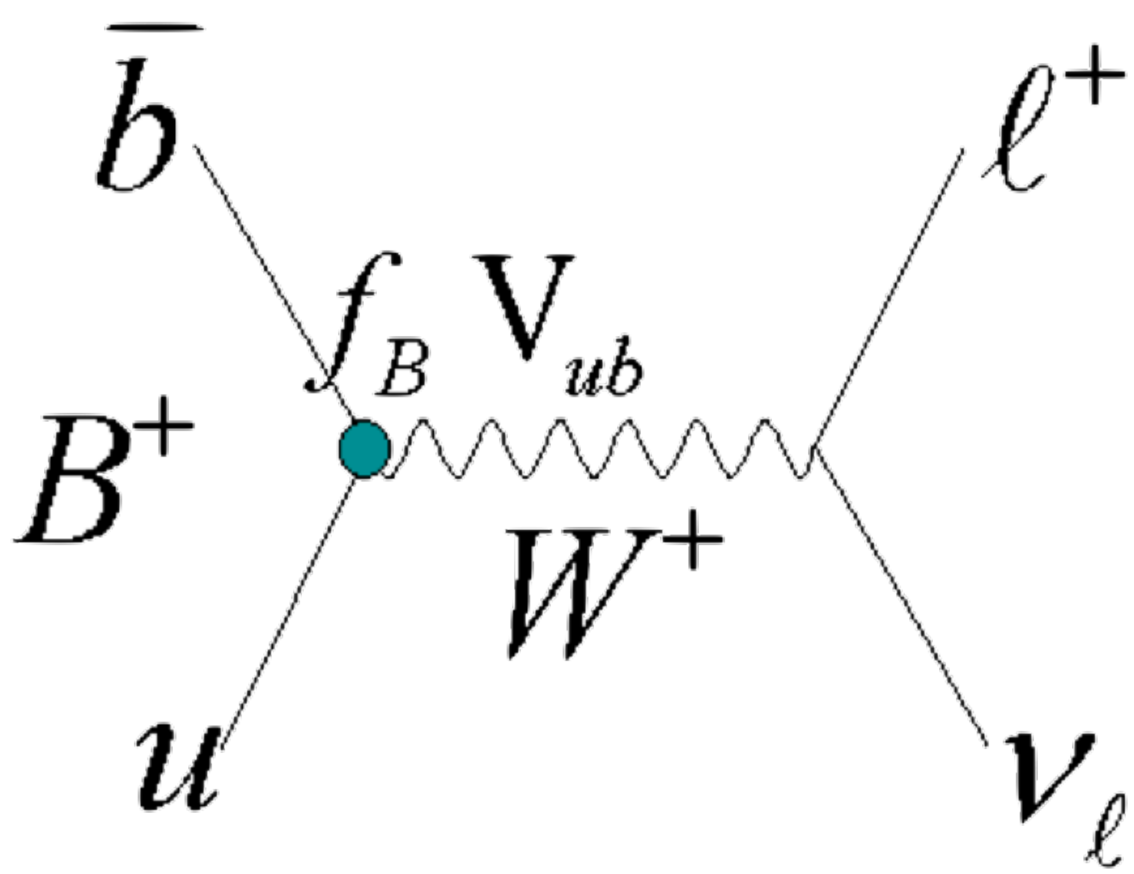
preliminary

arXiv:1904.08794 [hep-ex]

- Most precise $R(D)$, $R(D^*)$ to date
- First $R(D)$ with SL-tag
- 1.2σ from SM

- Belle average, now within 2σ from SM
- World average — tension with SM, now 3.1σ (was 3.8σ)

For a clean test of lepton universality



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

$$\frac{\Gamma(B^+ \to \ell^+ \nu)}{\Gamma(B^+ \to \tau^+ \nu)} = f(m_\ell^2, m_\tau^2)$$

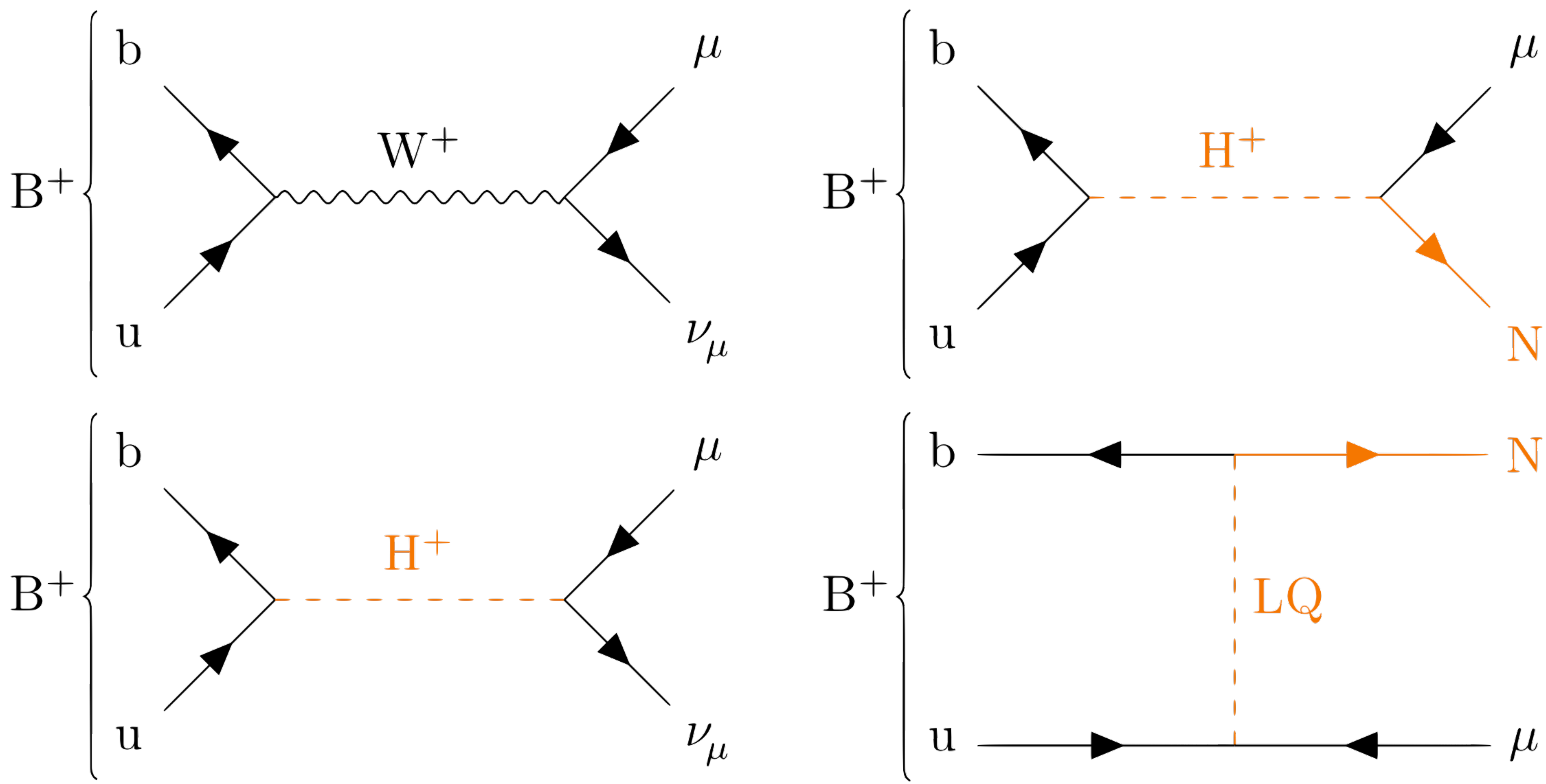
and all other parameters cancel!

- Belle has measured *B* ➔ $e^+ \nu$, $\mu^+ \nu$ with both inclusive tag and hadronic tag and updated *B* ➔ $\mu^+ \nu$ with inclusive tagging

PRL 121, 031801 (2018)

$$\mathcal{B}(B^+ \to \mu^+ \nu) = (6.46 \pm 2.22 \pm 1.60) \times 10^{-7}$$
$$\in [2.9, 10.7] \times 10^{-7} \text{ @ 90\% C.L.}$$

SM and NP diagrams for $B^+ \rightarrow \mu^+\nu$



N = unknown neutral fermion (e.g. a sterile ν)

New in 2019

$B^+ \to \mu^+\nu$ and $B^+ \to \mu^+ N$

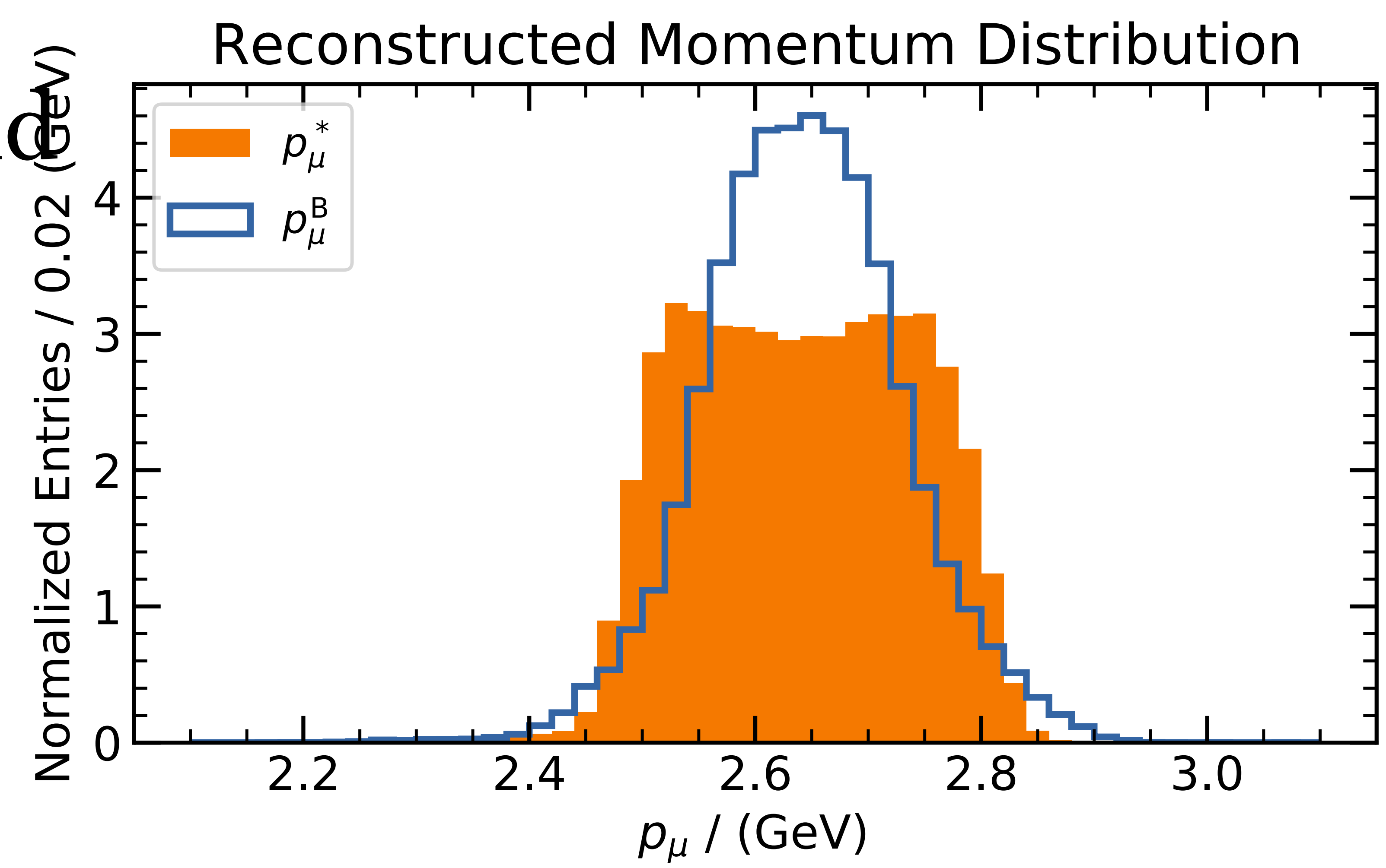
Preliminary

Features

- use inclusive B tagging to maximize signal selection efficiency ($\Leftarrow$ $BF_{SM} \sim 4 \times 10^{-7}$)
- an improved search over Belle's PRL 2018
  - ✓ modeling of $b \to u \ell \nu$ and continuum background
- carry out the analysis in the signal B rest frame
  - ✓ $p_\mu^B = 2.64$ GeV
  - ✓ achieve better resolution and sensitivity than using p_μ^* (CM frame)
    $\Leftarrow$ tag-side momentum is calibrated by using MC

$$\mathbf{p}_{\rm sig} = -\mathbf{p}^*_{\rm tag,cal}$$

  - ✓ sensitive to $B^+ \to \mu^+ N$ search, for $m_N \in [0, 1.5)$ GeV
    N = unknown neutral fermion (e.g. a sterile ν)



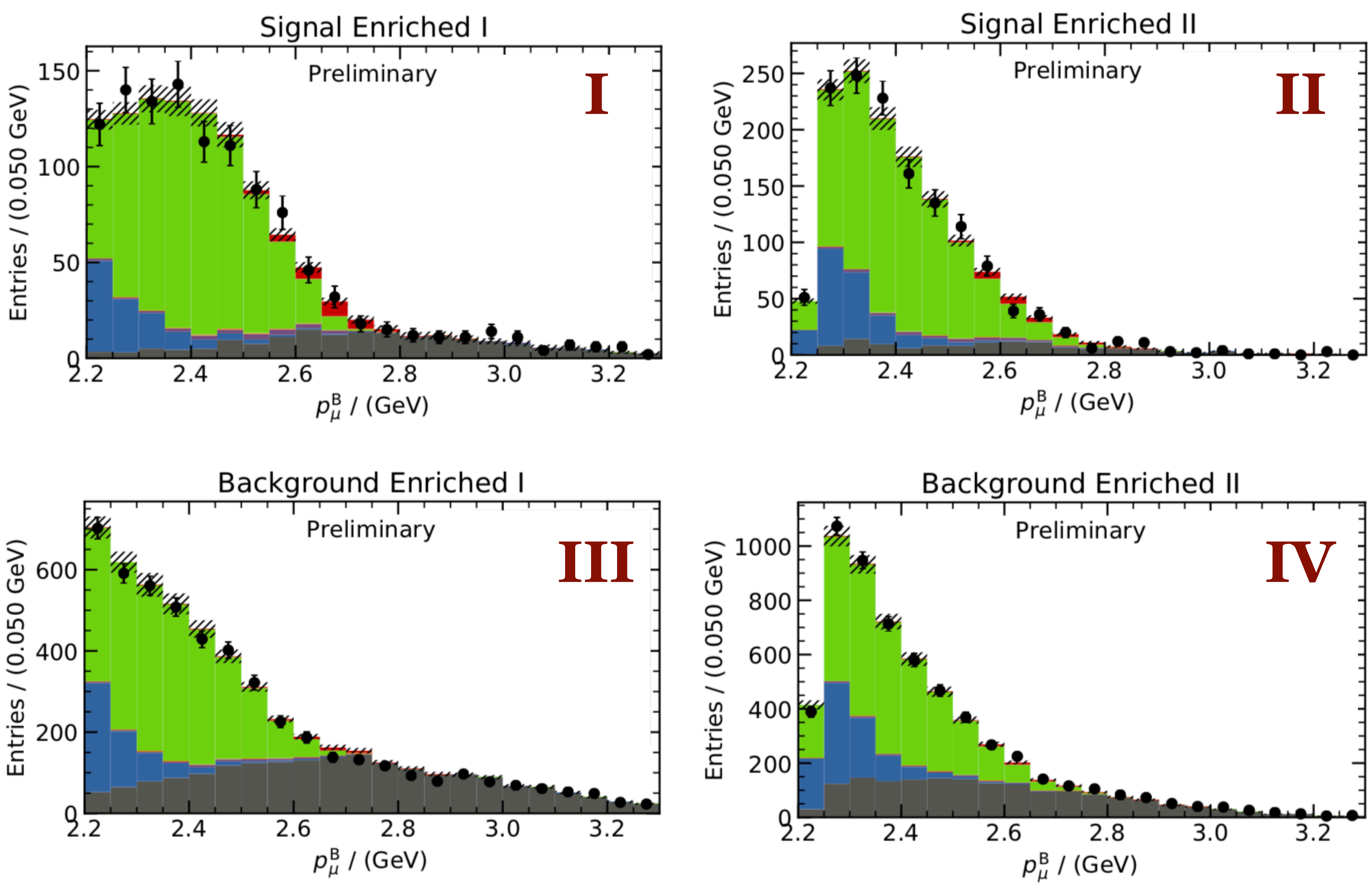
New in 2019

Preliminary

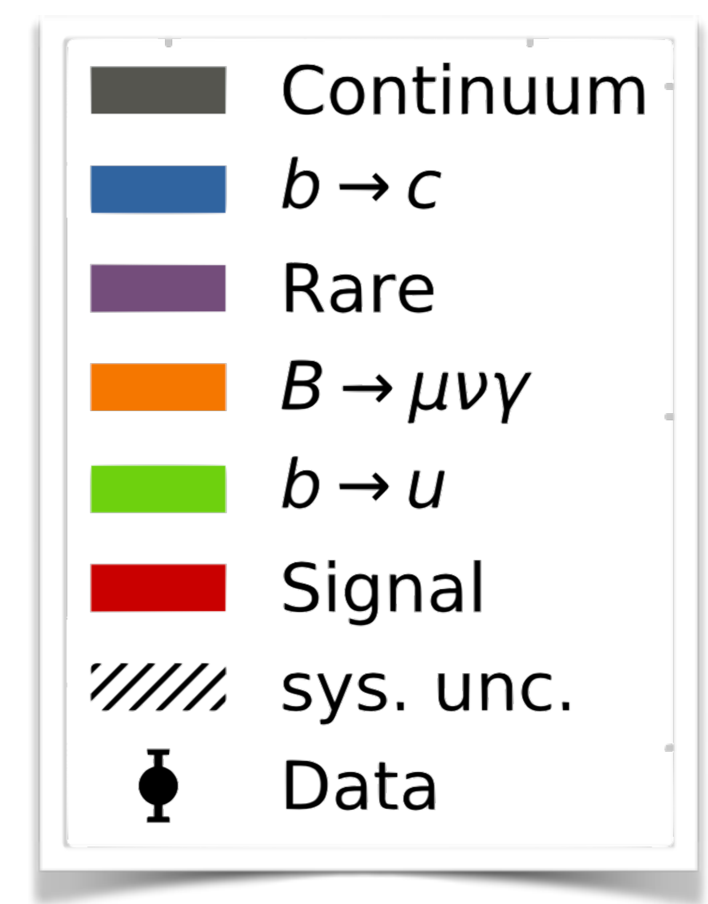
$B^+ \to \mu^+\nu$ and $B^+ \to \mu^+N$

Signal extraction

✓ by binned max. likelihood fit to p_μ^B in kinematic/BDT categories



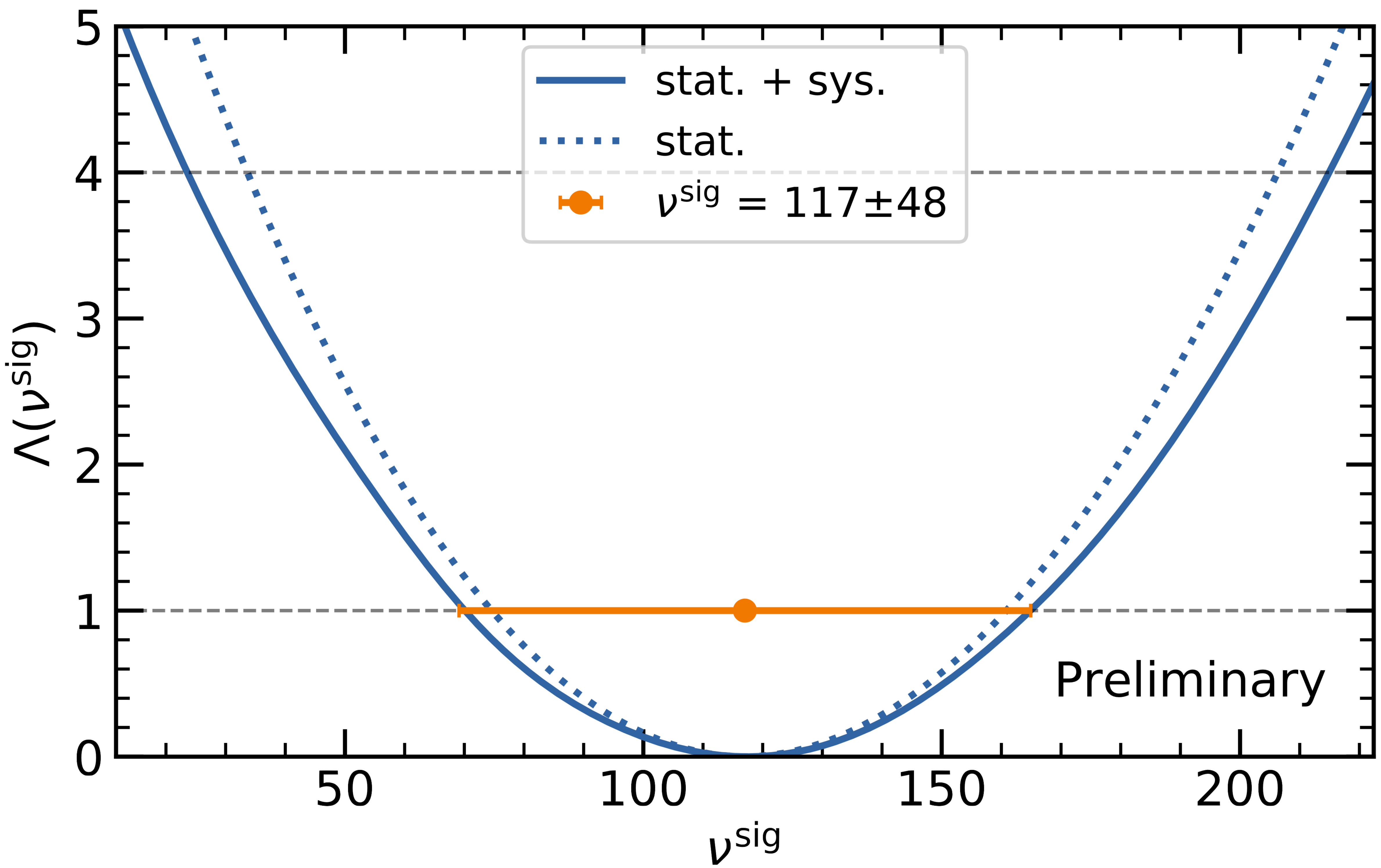
Category	C_{out}	$\cos\Theta_{B\mu}$
I	[0.98,1.00)	[-0.13,1.00)
II	[0.98,1.00)	[-1.00,-0.13)
III	[0.93,0.98)	[0.04,1.00)
IV	[0.93,0.98)	[-1.00,0.04)



New in 2019

Preliminary

$B^+ \to \mu^+\nu$ Results



- $\mathcal{B}(B^+ \to \mu^+\nu) = (5.3 \pm 2.0 \pm 0.9) \times 10^{-7}$ @ 2.8σ

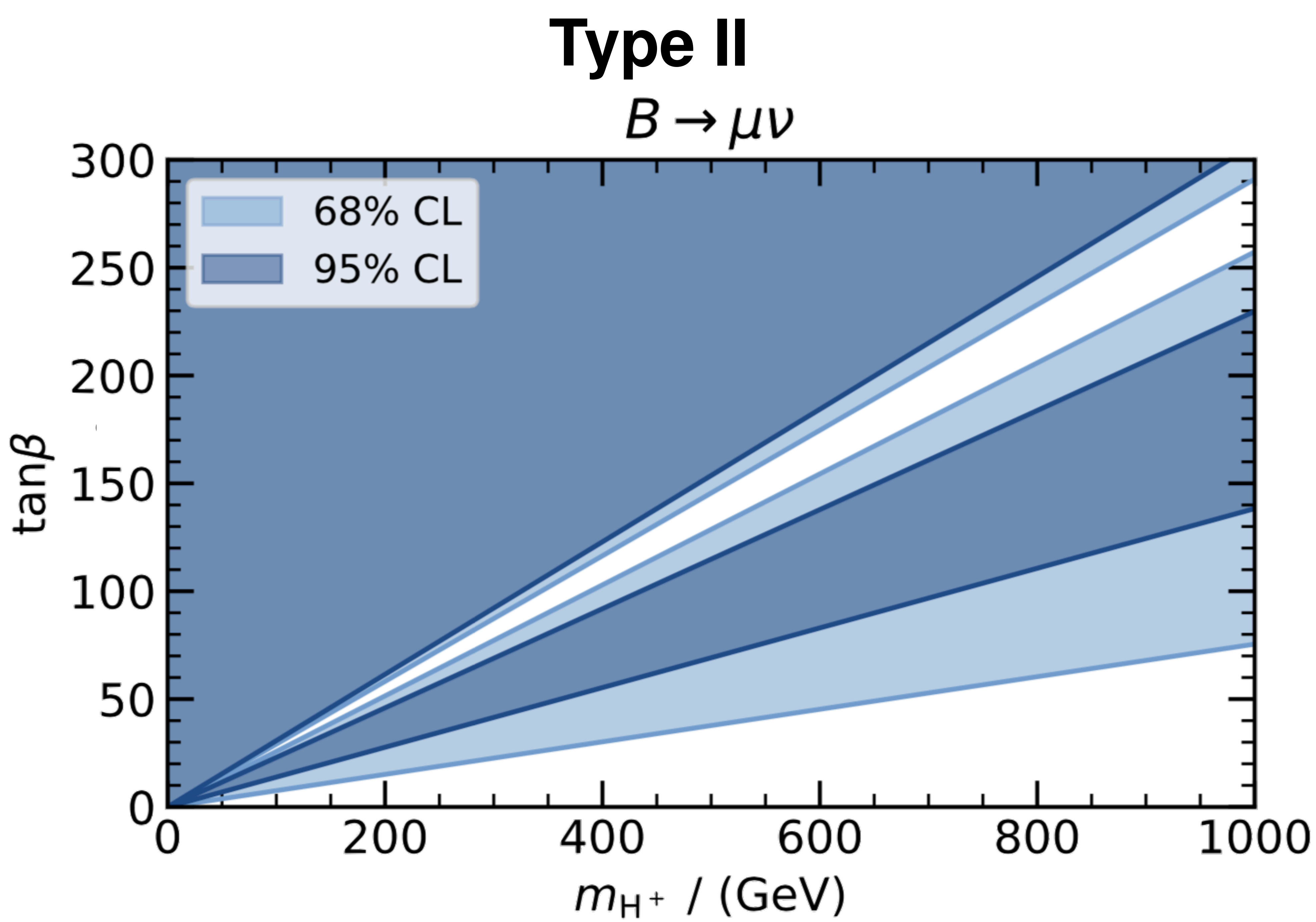
$\mathcal{B}(B^+ \to \mu^+\nu) < 8.6 \times 10^{-7}$ **Frequentist**

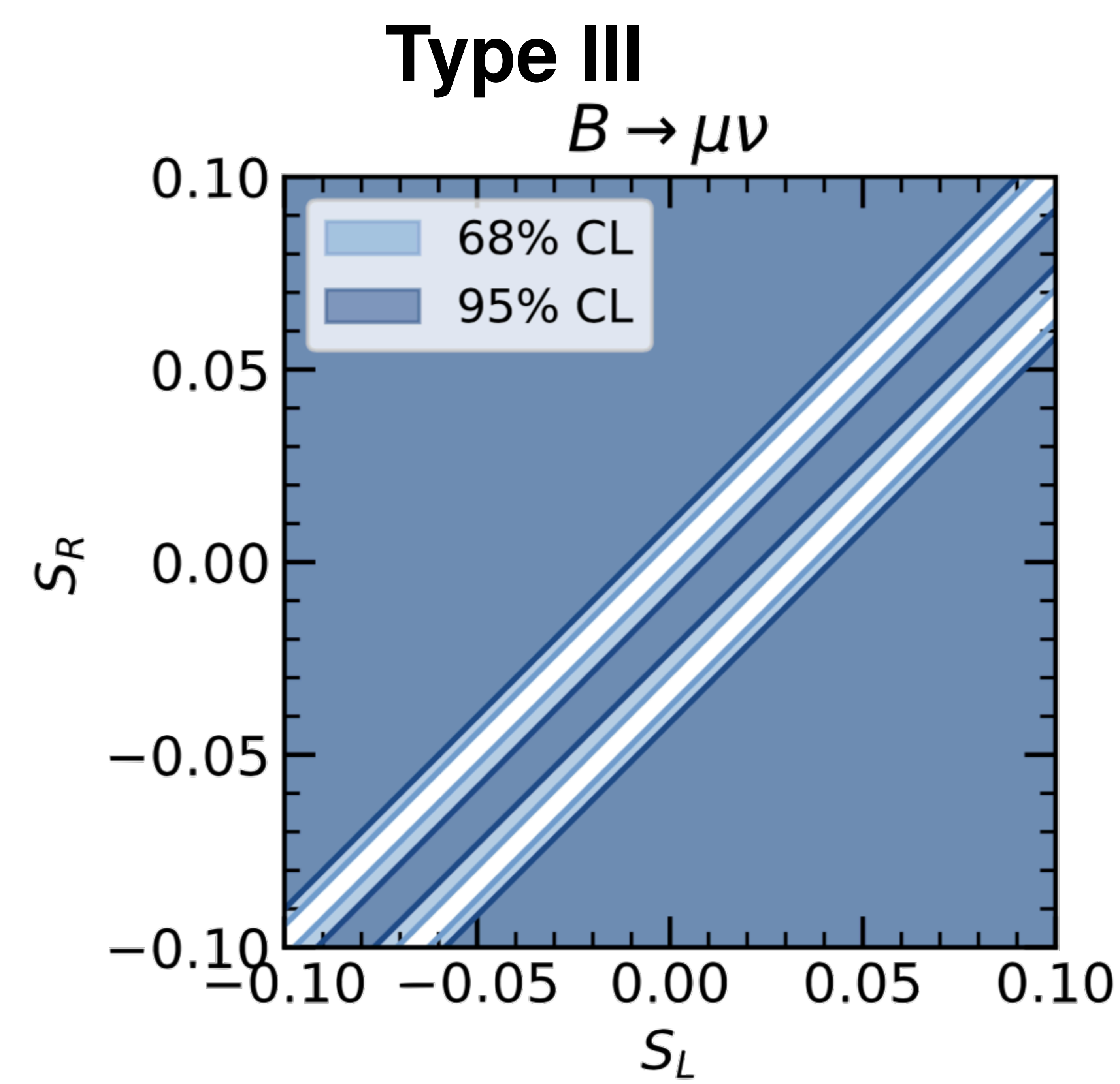
$< 8.9 \times 10^{-7}$ **Bayesian**

New in 2019

Preliminary

$B^+ \to \mu^+\nu$ Interpretation with NP (2HDM) scenarios





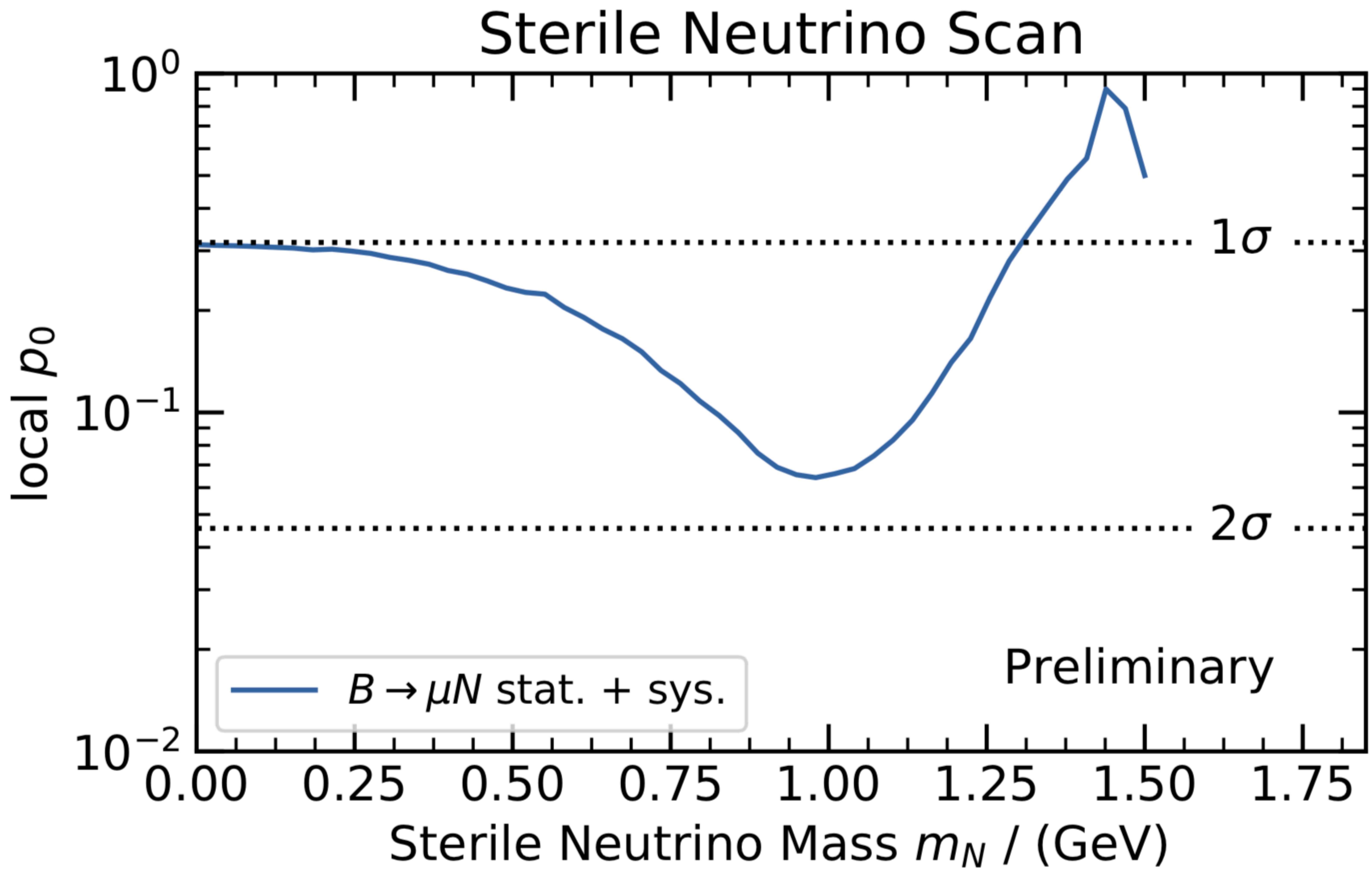
$$\mathcal{B}(\mathrm{B} \to \ell\nu_\ell) = \mathcal{B}^{\mathrm{SM}} \times \left| 1 - \frac{m_{\mathrm{B}}^2 \tan^2\beta}{m_{\mathrm{H}^+}^2} \right|^2$$

$$\mathcal{B}(\mathrm{B} \to \ell\nu_\ell) = \mathcal{B}^{\mathrm{SM}} \times \left| 1 + \frac{m_{\mathrm{B}}^2}{m_{\mathrm{b}}\, m_\ell} \frac{C_{\mathrm{R}} - C_{\mathrm{L}}}{C_{\mathrm{SM}}} \right|^2$$

New in 2019

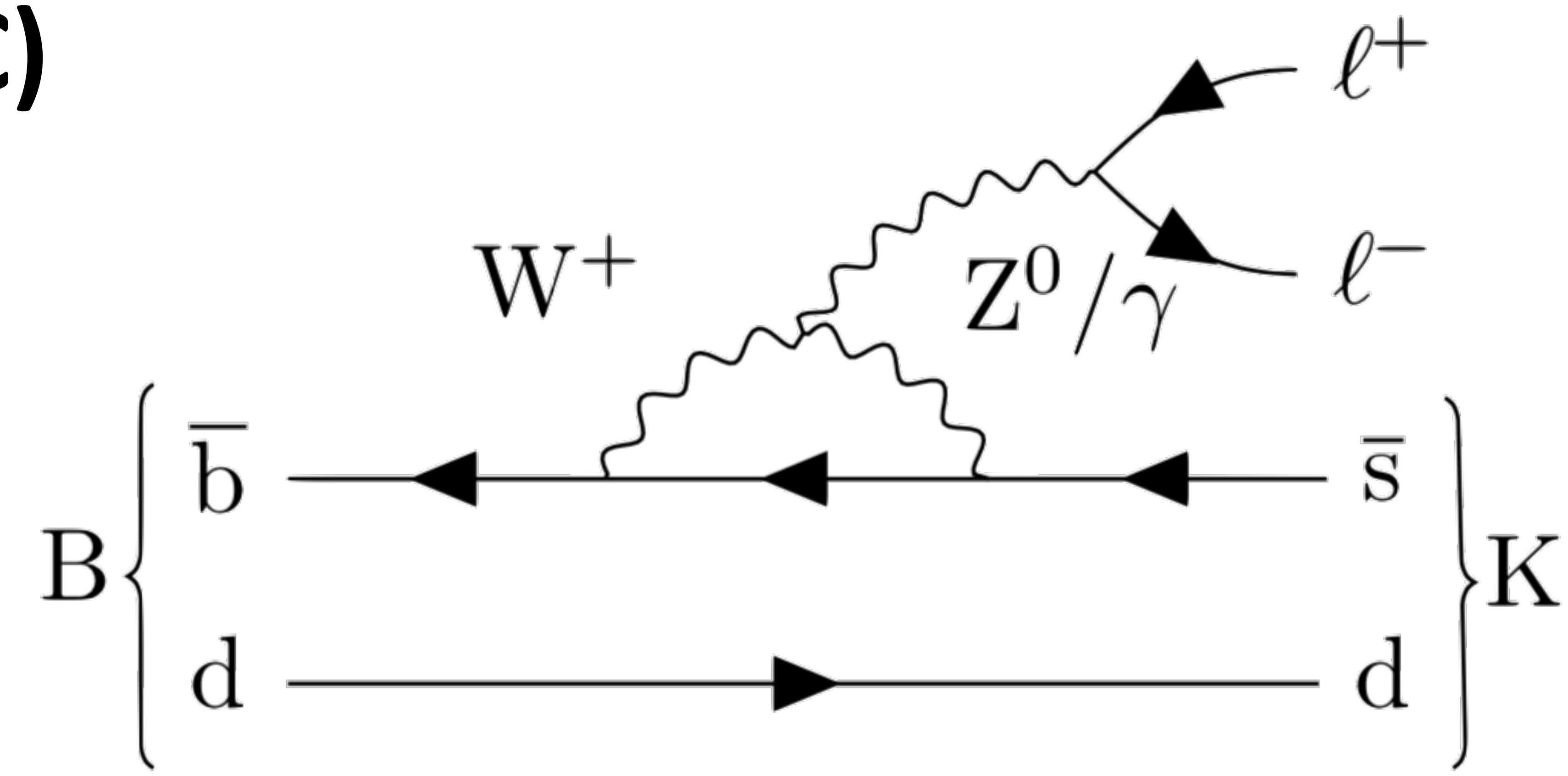
$B^+ \to \mu^+\nu$ and $B^+ \to \mu^+N$

Preliminary

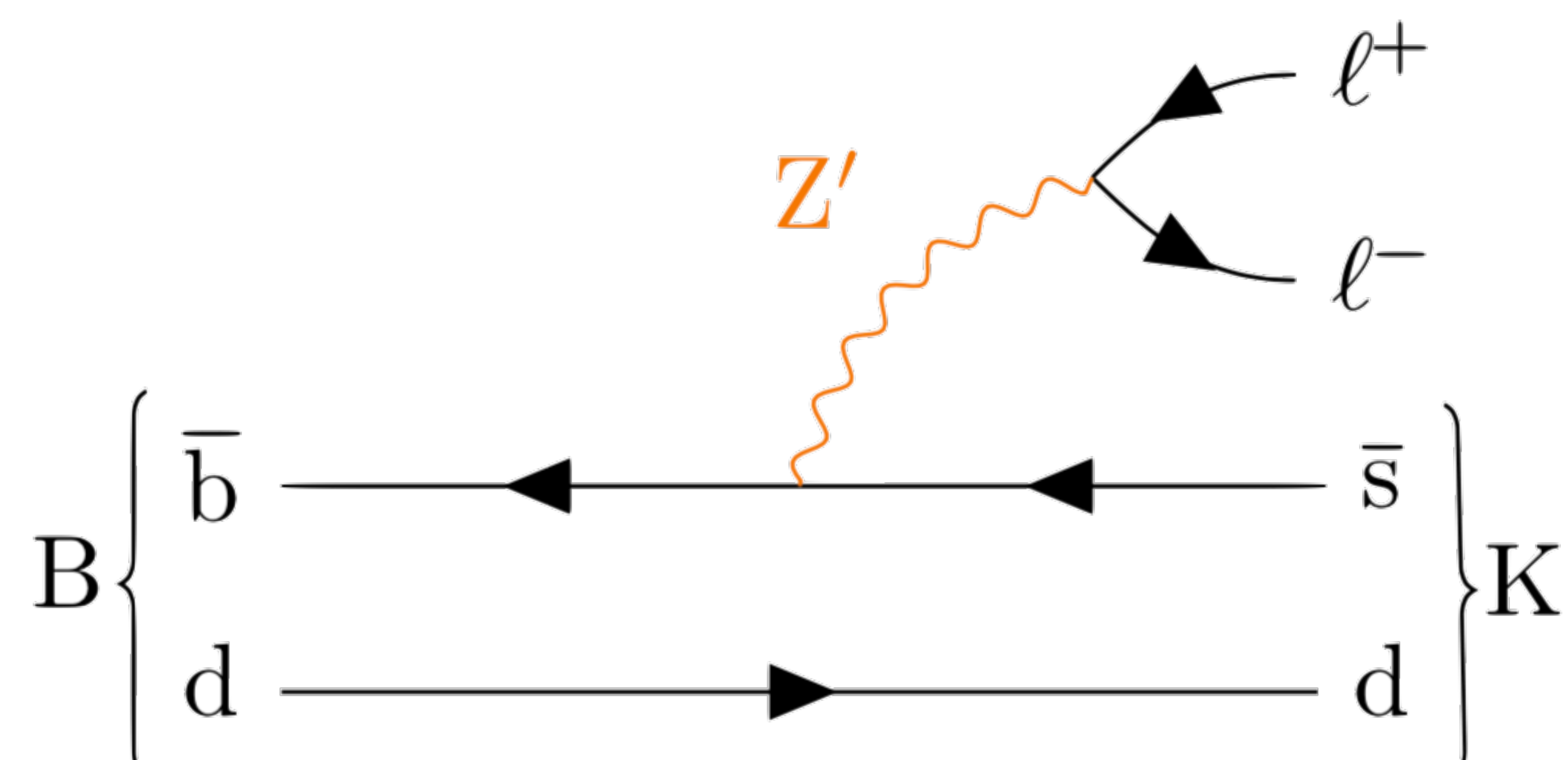


a few words on $B \to K^{(*)}\ell^+\ell^-$

- **Flavor-Changing Neutral Current (FCNC)**
  - *forbidden at tree level in SM*
  - but appears via EW penguin loop or box diagrams
  - sensitive to New Physics



- **Rich structure to probe NP**
  - q^2, angular distributions
  - asymmetries



- **and a testing ground for Lepton Flavor Universality (LFU)**
  $R_{K^{(*)}}$ anomaly

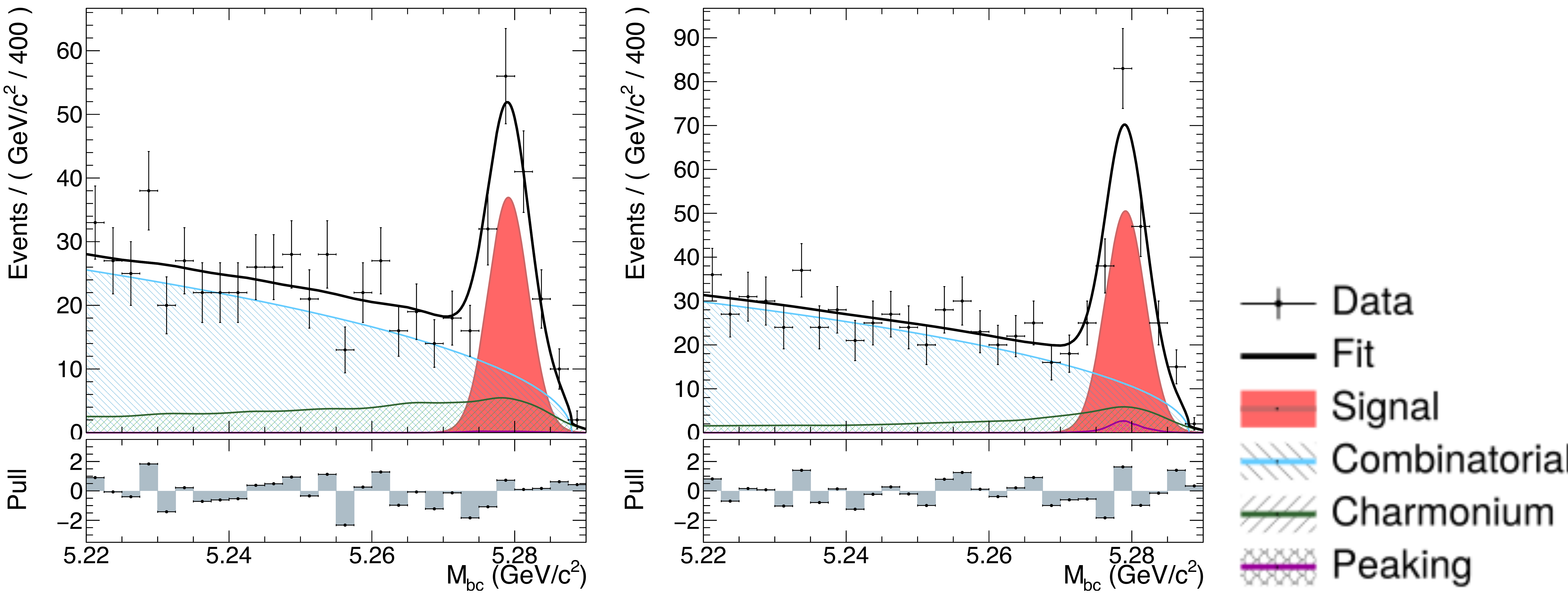
Belle's legacy on EWP

- First observation of $B \to K\ell^+\ell^-$ PRL **88**, 021801 (2002)
- First observation of $B \to K^*\ell^+\ell^-$ PRL **91**, 261601 (2003)
- First observation of $B \to X_s\ell^+\ell^-$ PRL **90**, 021801 (2003)
- First measurement of A_{FB} of $B \to K^*\ell^+\ell^-$ PRL **96**, 251801 (2006)

- First observations of several radiative modes, $\phi K\gamma$, $K_1\gamma$, etc.
- First observation of $B \to (\rho,\omega)\gamma$ PRL **96**, 221601 (2006)
- Most precise measurement of $B \to X_s\gamma$ covering the widest E_γ range PRL **103**, 241801 (2009)
- *and many more published results*

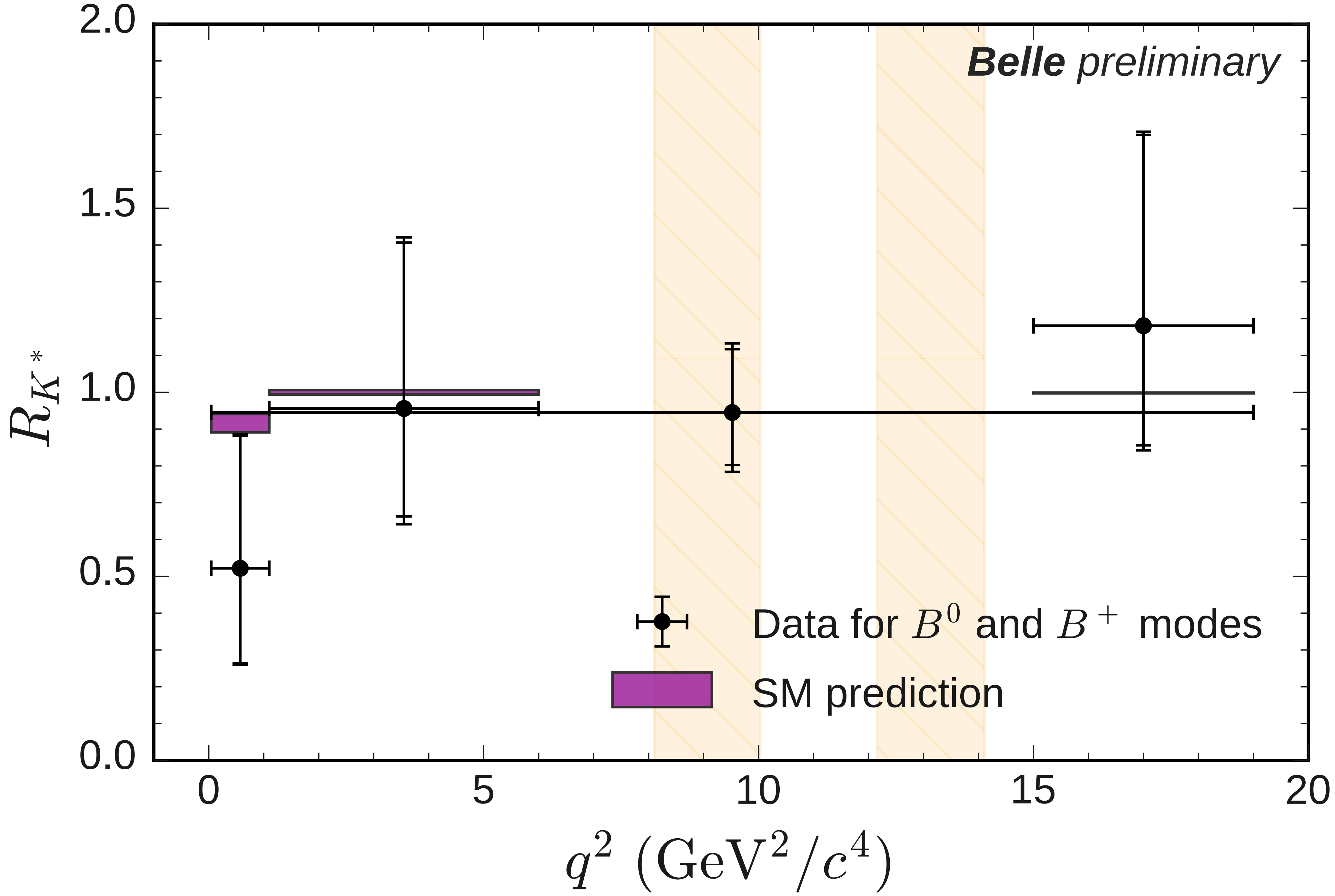
R_{K^*} from Belle

- Use both B^0 and B^+ modes
  - K^* modes: $K^+\pi^-,\ K^+\pi^0,\ K_S^0\pi^+$

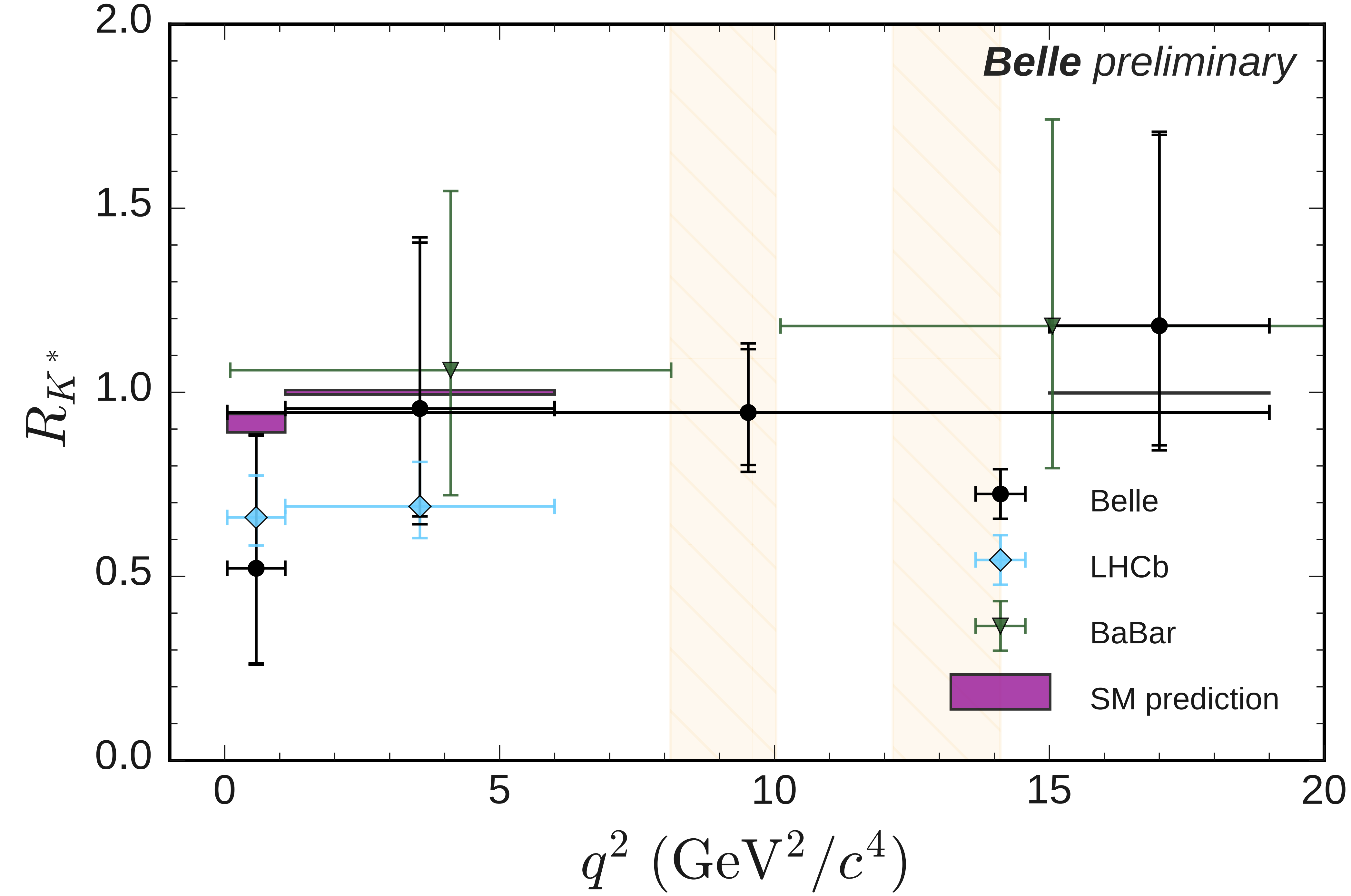


- example fit for $q^2 > 0.045\ \mathrm{GeV}^2$
- $103.0^{+13.4}_{-12.7}$ $(139.0^{+16.0}_{-15.4})$ events in the e (μ) modes

R_{K^*} (Belle)



R_{K^*} (all)



PHYS. REV. D **99**, 032012 (2019)

BELLE

$B \to X_s \gamma$ inclusive **motivations**

- $B \to X_s\gamma$ has played a powerful probe to search for NP in a loop

  $\mathcal{B}(B \to X_s\gamma) \Rightarrow$ strong constraint on NP, e.g. lower limit on $m(H^+)$

- Theory error on $\mathcal{B}(B \to X_s\gamma)$ (currently $\approx 7\%$)

  crucial to reduce it for Belle II test of NP in $B \to X_s\gamma$

- Resolved photon contribution is a significant portion of theory error via non-perturbative effects

  and depends on the spectator quark, hence related to isospin asymmetry

$$\frac{\mathcal{B}^{78}_{\mathrm{RP}}}{\mathcal{B}} \simeq -\frac{(1 \pm 0.3)}{3}\Delta_{0-} \qquad \Delta A_{CP} \approx 0.12\left(\frac{\tilde{\Lambda}_{78}}{100\ \mathrm{MeV}}\right)\mathrm{Im}\left(\frac{C_8}{C_7}\right)$$

null expected in SM;
sensitive to NP (e.g. SUSY)

- To measure Δ_{0-}, A_{CP}, and ΔA_{CP} of inclusive $B \to X_s\gamma$,

  $\Rightarrow$ "sum of the exclusive modes"

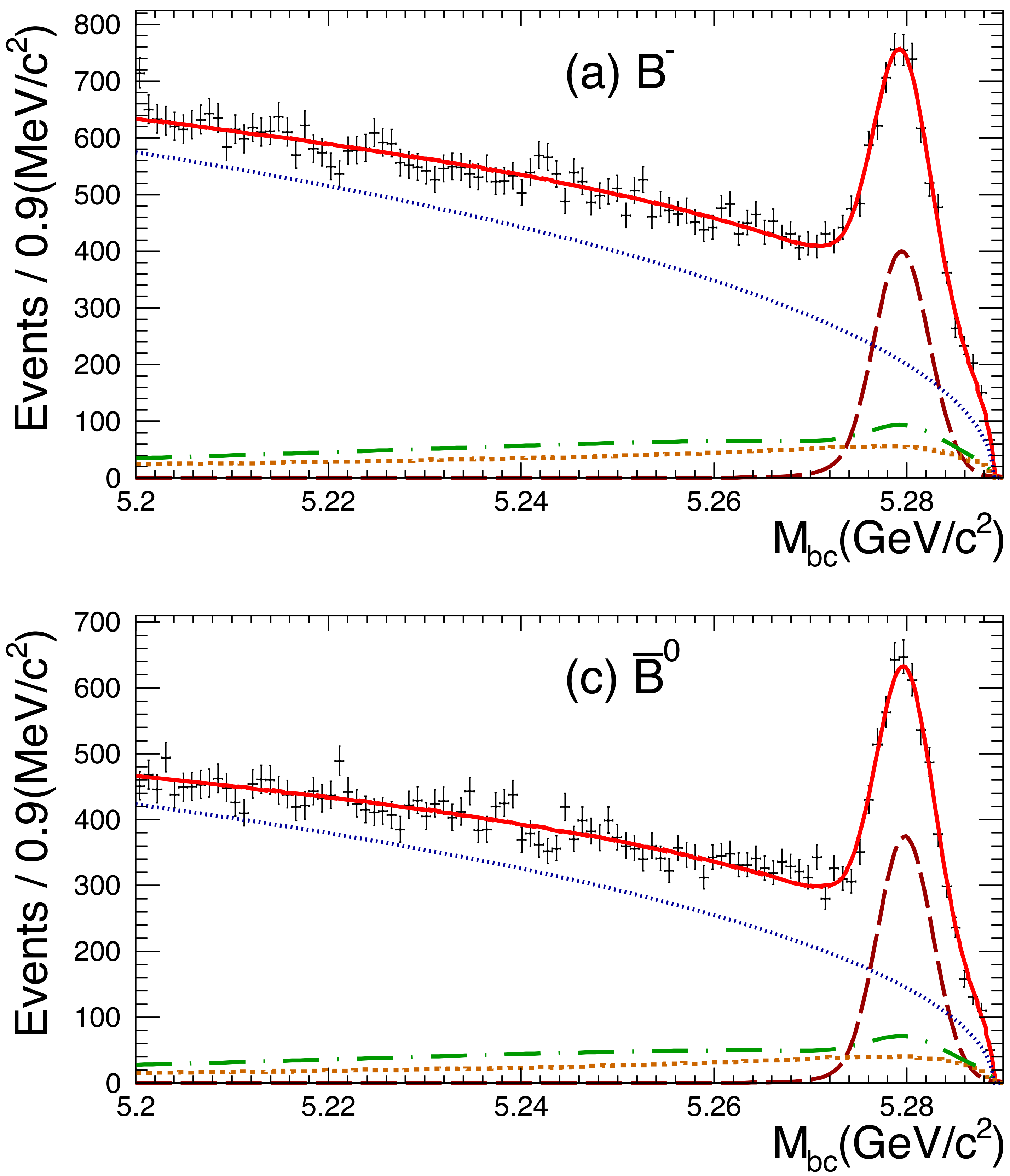
Final states for "sum of exclusives"

Mode ID	Final state	Mode ID	Final state
1	$K^+\pi^-$	20	$K_S^0\pi^+\pi^0\pi^0$
2	$K_S^0\pi^+$	21	$K^+\pi^+\pi^-\pi^0\pi^0$
3	$K^+\pi^0$	22*	$K_S^0\pi^+\pi^-\pi^0\pi^0$
4*	$K_S^0\pi^0$	23	$K^+\eta$
5	$K^+\pi^+\pi^-$	24*	$K_S^0\eta$
6*	$K_S^0\pi^+\pi^-$	25	$K^+\eta\pi^-$
7	$K^+\pi^-\pi^0$	26	$K_S^0\eta\pi^+$
8	$K_S^0\pi^+\pi^0$	27	$K^+\eta\pi^0$
9	$K^+\pi^+\pi^-\pi^-$	28*	$K_S^0\eta\pi^0$
10	$K_S^0\pi^+\pi^+\pi^-$	29	$K^+\eta\pi^+\pi^-$

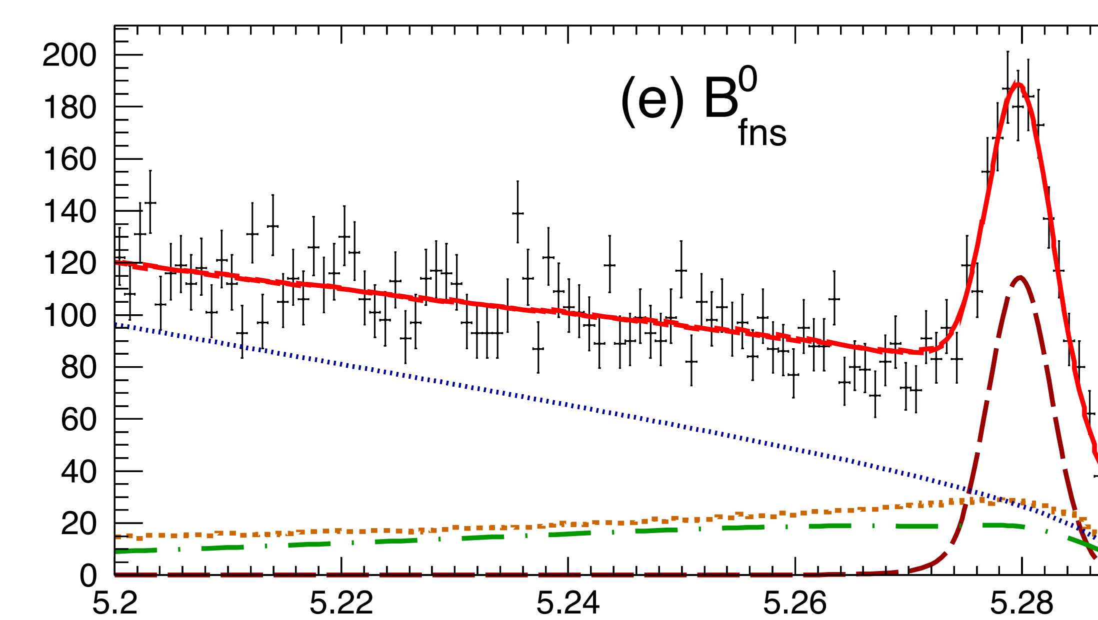
Mode ID	Final state	Mode ID	Final state
11	$K^+\pi^+\pi^-\pi^0$	30*	$K_S^0\eta\pi^+\pi^-$
12*	$K_S^0\pi^+\pi^-\pi^0$	31	$K^+\eta\pi^-\pi^0$
13	$K^+\pi^+\pi^+\pi^-\pi^-$	32	$K_S^0\eta\pi^+\pi^0$
14*	$K_S^0\pi^+\pi^+\pi^-\pi^-$	33	$K^+K^+K^-$
15	$K^+\pi^+\pi^-\pi^-\pi^0$	34*	$K^+K^-K_S^0$
16	$K_S^0\pi^+\pi^+\pi^-\pi^0$	35	$K^+K^+K^-\pi^-$
17	$K^+\pi^0\pi^0$	36	$K^+K^-K_S^0\pi^+$
18*	$K_S^0\pi^0\pi^0$	37	$K^+K^+K^-\pi^0$
19	$K^+\pi^-\pi^0\pi^0$	38*	$K^+K^-K_S^0\pi^0$

PHYS. REV. D **99**, 032012 (2019)

$B \to X_s\gamma$ inclusive signal yields



Mode	N_S	ϵ [%]
B^-	3243 ± 85	2.21 ± 0.12
B^+	3074 ± 86	2.23 ± 0.12
$\bar{B}^0$	3038 ± 78	2.42 ± 0.14
B^0	3102 ± 79	2.46 ± 0.14
$B_{\rm fns}$	902 ± 42	0.375 ± 0.023

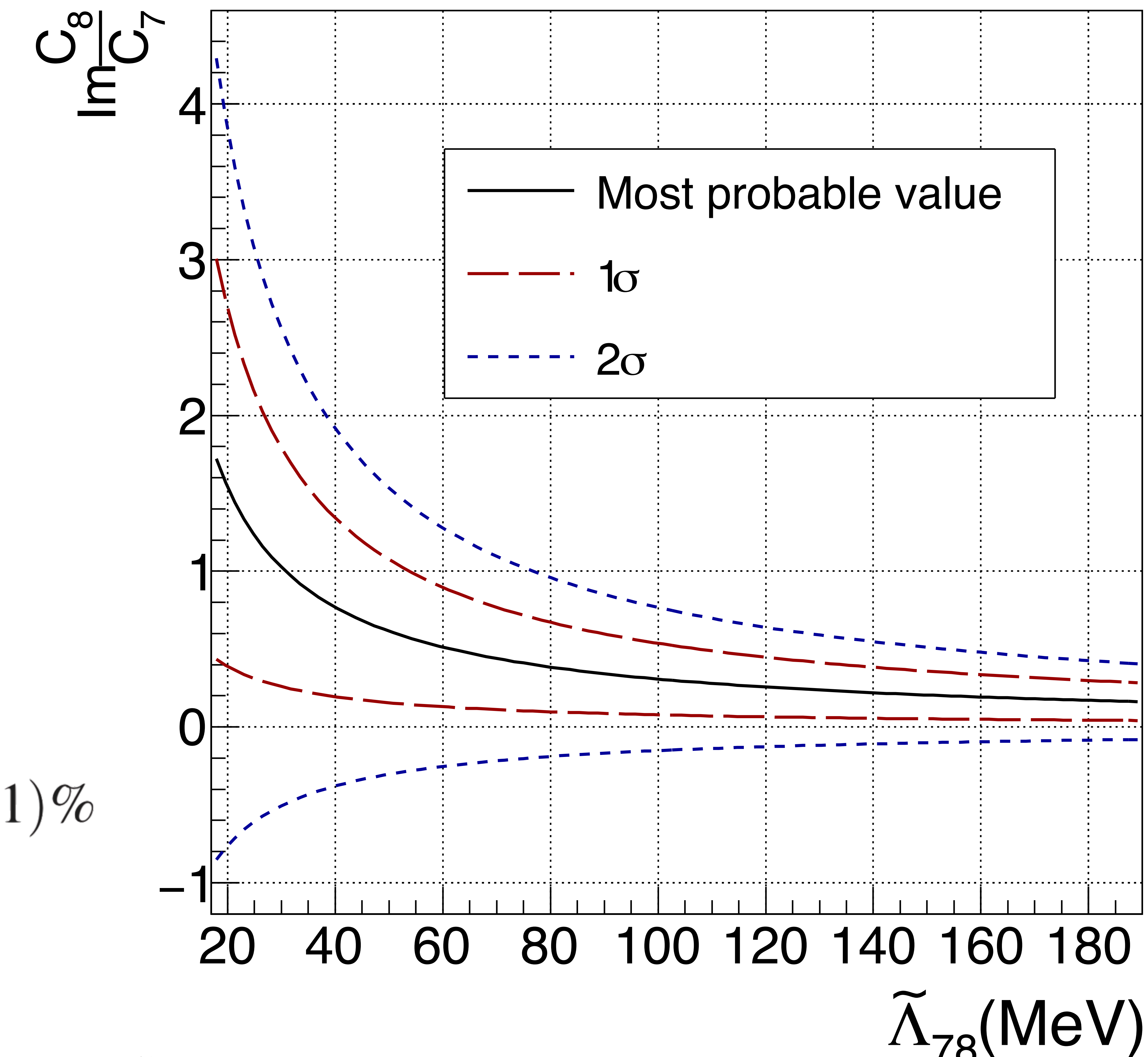


$B_{\rm fns}$ = flavor-non-specific neutral B

$B \to X_s\gamma$ inclusive Results

$$\Delta_{0-} = (-0.48 \pm 1.49 \pm 0.97 \pm 1.15)\%,$$
$$\Delta A_{CP} = (+3.69 \pm 2.65 \pm 0.76)\%,$$
$$A_{CP}^{\mathrm{C}} = (+2.75 \pm 1.84 \pm 0.32)\%,$$
$$A_{CP}^{\mathrm{N}} = (-0.94 \pm 1.74 \pm 0.47)\%,$$
$$A_{CP}^{\mathrm{tot}} = (+1.44 \pm 1.28 \pm 0.11)\%,$$
$$\bar{A}_{CP} = (+0.91 \pm 1.21 \pm 0.13)\%,$$

$$\frac{\mathcal{B}_{\mathrm{RP}}^{78}}{\mathcal{B}} \simeq (+0.16 \pm 0.50 \pm 0.32 \pm 0.38 \pm 0.05 \pm 0.21)\%$$



$$\frac{\mathcal{B}_{\mathrm{RP}}^{78}}{\mathcal{B}} \simeq -\frac{(1 \pm 0.3)}{3}\Delta_{0-} \qquad \Delta A_{CP} \approx 0.12\left(\frac{\tilde{\Lambda}_{78}}{100\ \mathrm{MeV}}\right)\mathrm{Im}\left(\frac{C_8}{C_7}\right)$$

the Future

for Excitement

Belle —> Belle II

still not solved

- CP violation from KM hypothesis is not large enough to explain the matter-antimatter asymmetry in our Universe

--> **We need New Physics!**

- The origin of the Flavor structure of Standard Model is totally unknown

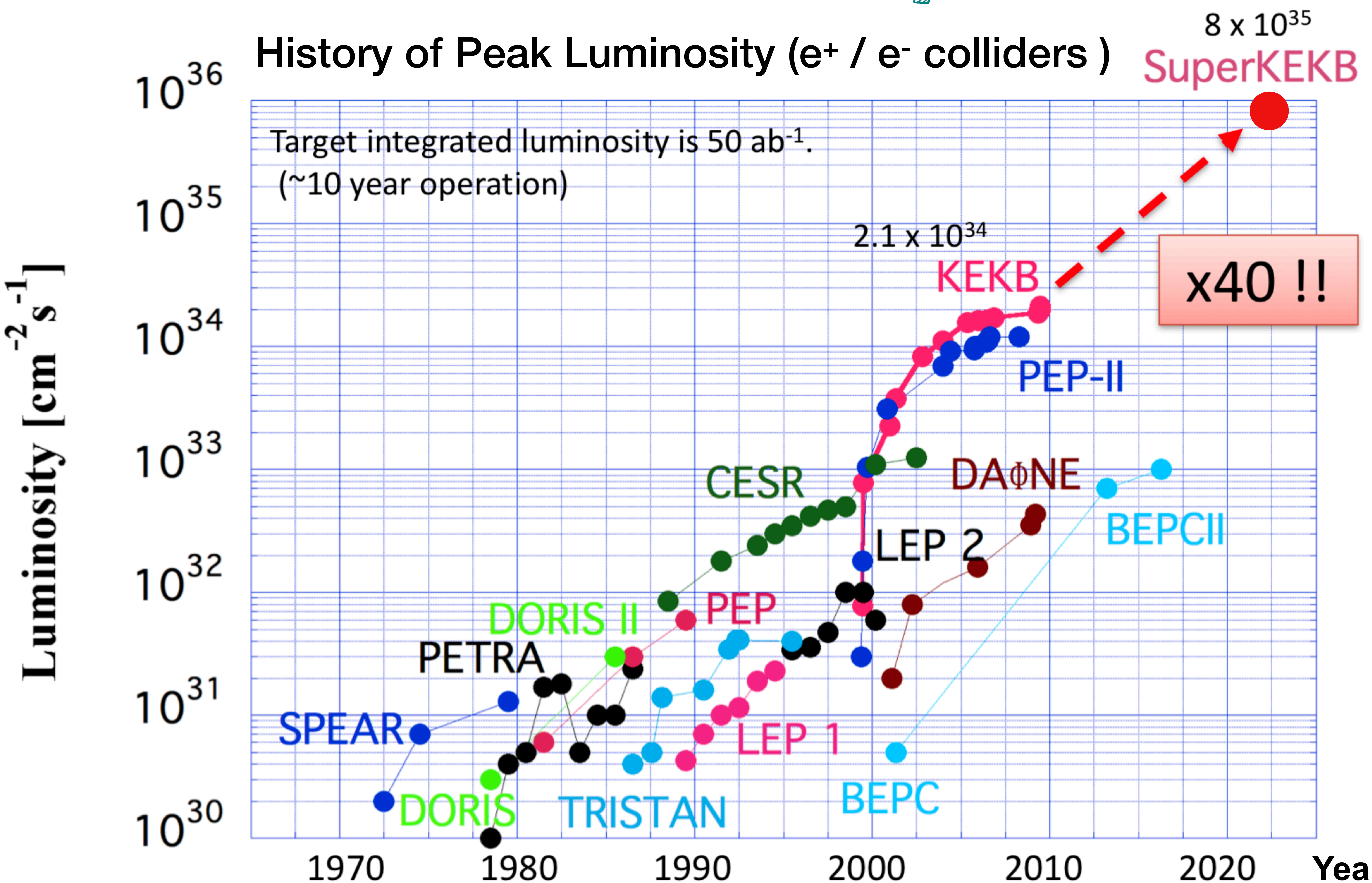
upgrade Belle —> Belle II

- KEKB is upgraded to SuperKEKB (x40 peak luminosity)
- aiming at x50 total data size
- Belle detector is also upgraded to Belle II

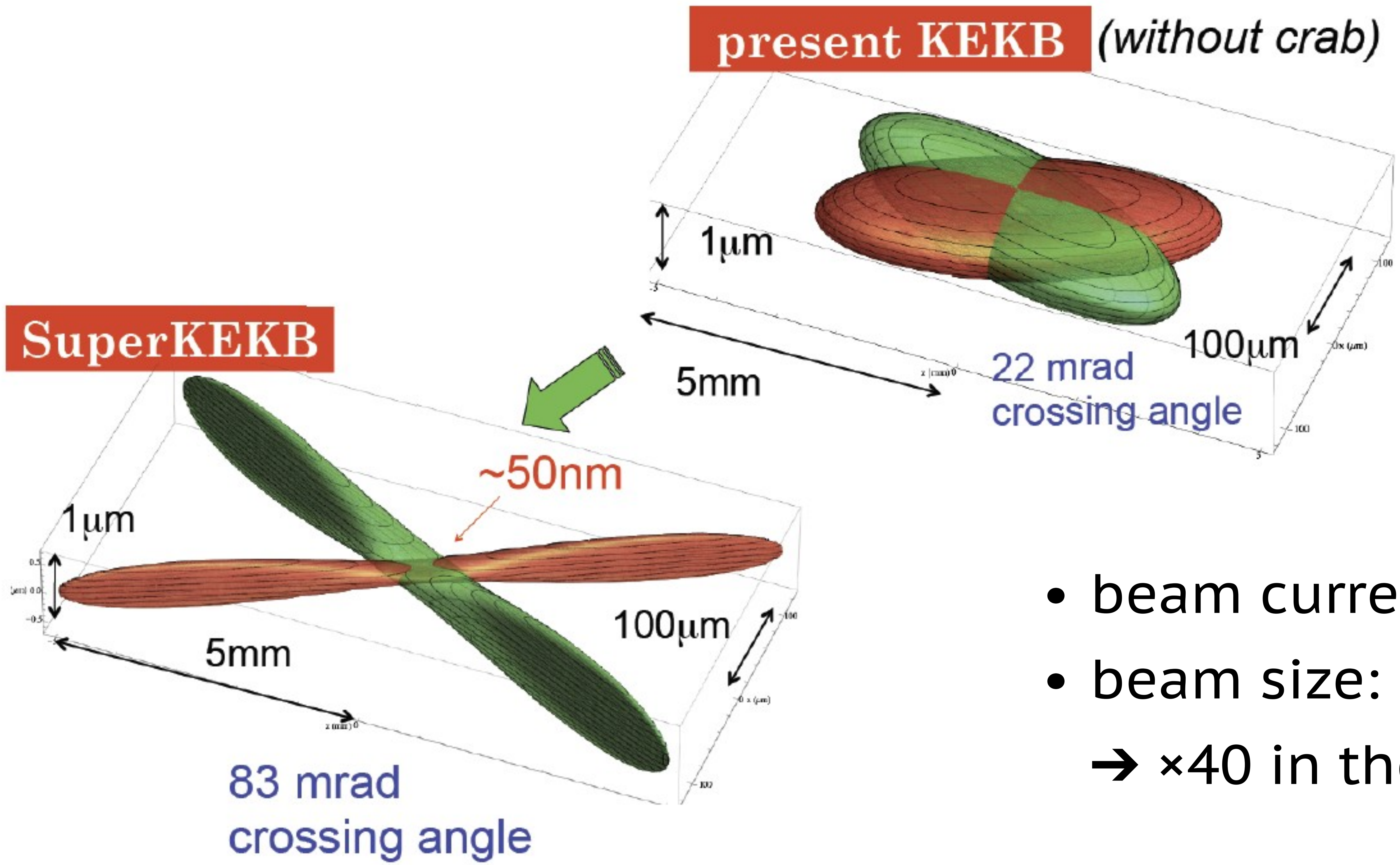
$$\mathcal{L}_{\text{peak}} = 8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

$$\int^{\text{goal}} \mathcal{L}\, dt = 50\ \text{ab}^{-1}$$

The next Luminosity Frontier



from KEKB to SuperKEKB

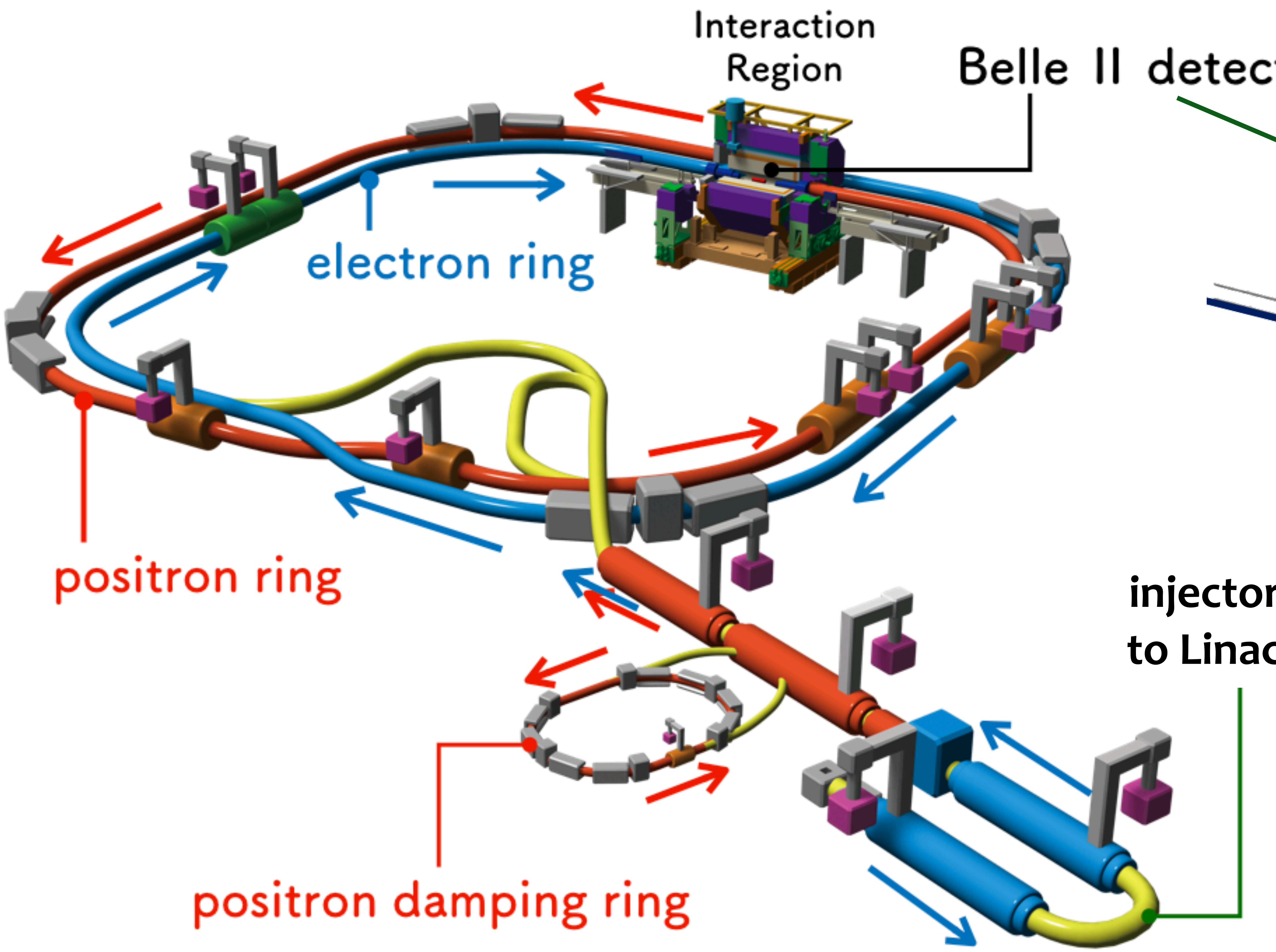


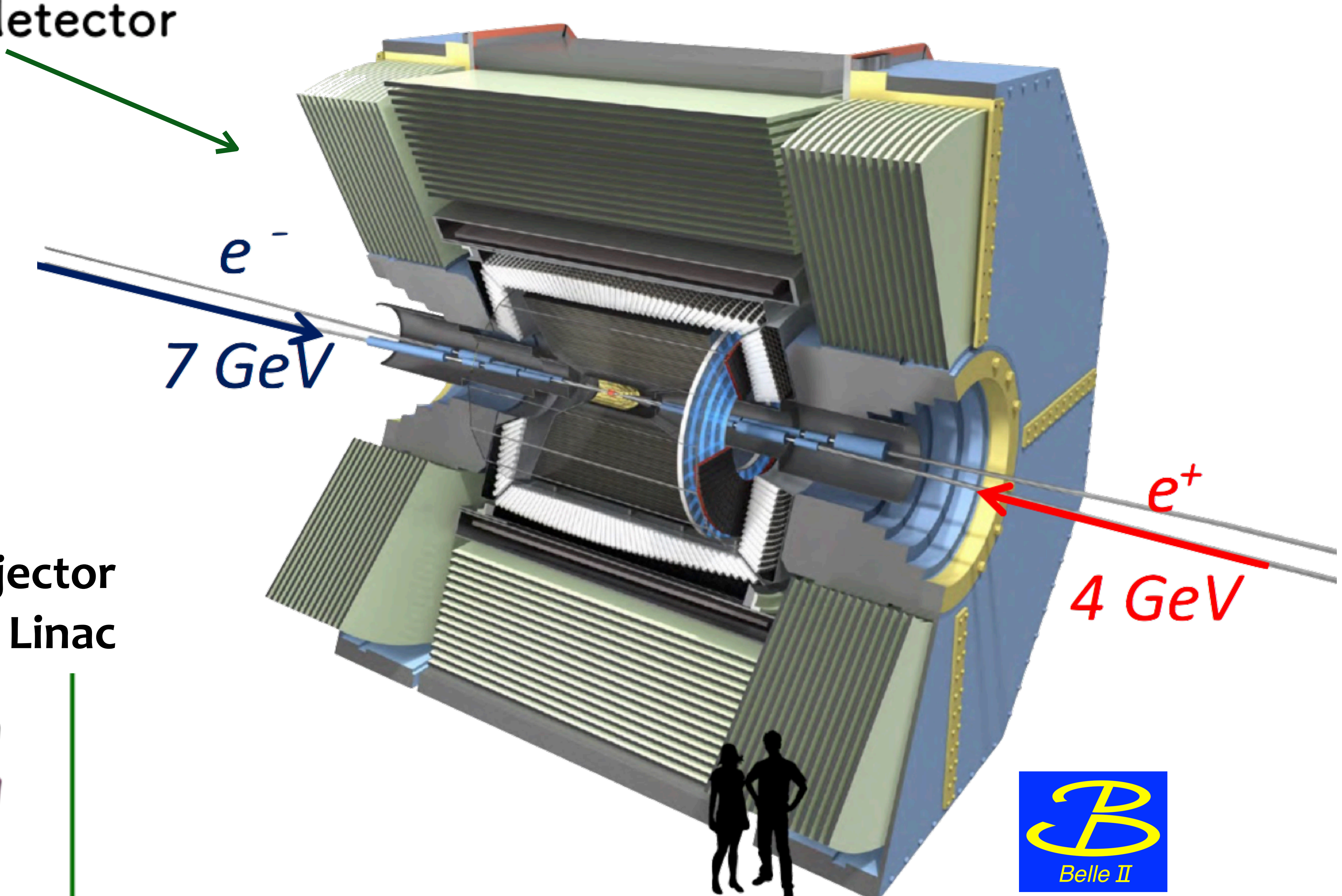
- beam current: ×2
- beam size: 1/20

  ➔ ×40 in the luminosity

SuperKEKB

Belle II

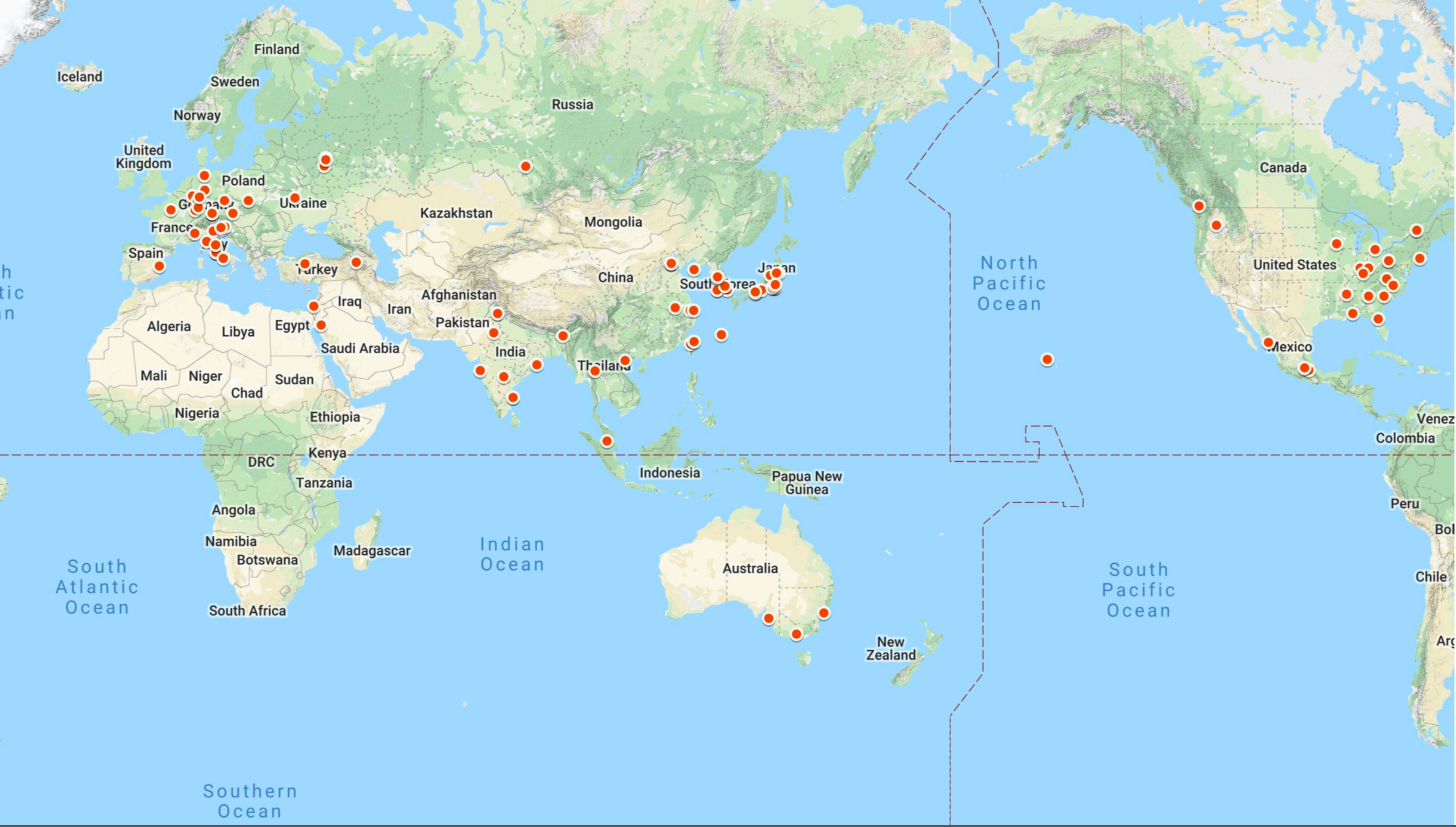




$$e^- \xrightarrow{7\text{ GeV}} (\star) \xleftarrow{4\text{ GeV}} e^+$$

$$\mathcal{L}_{\text{peak}} = 8 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$$

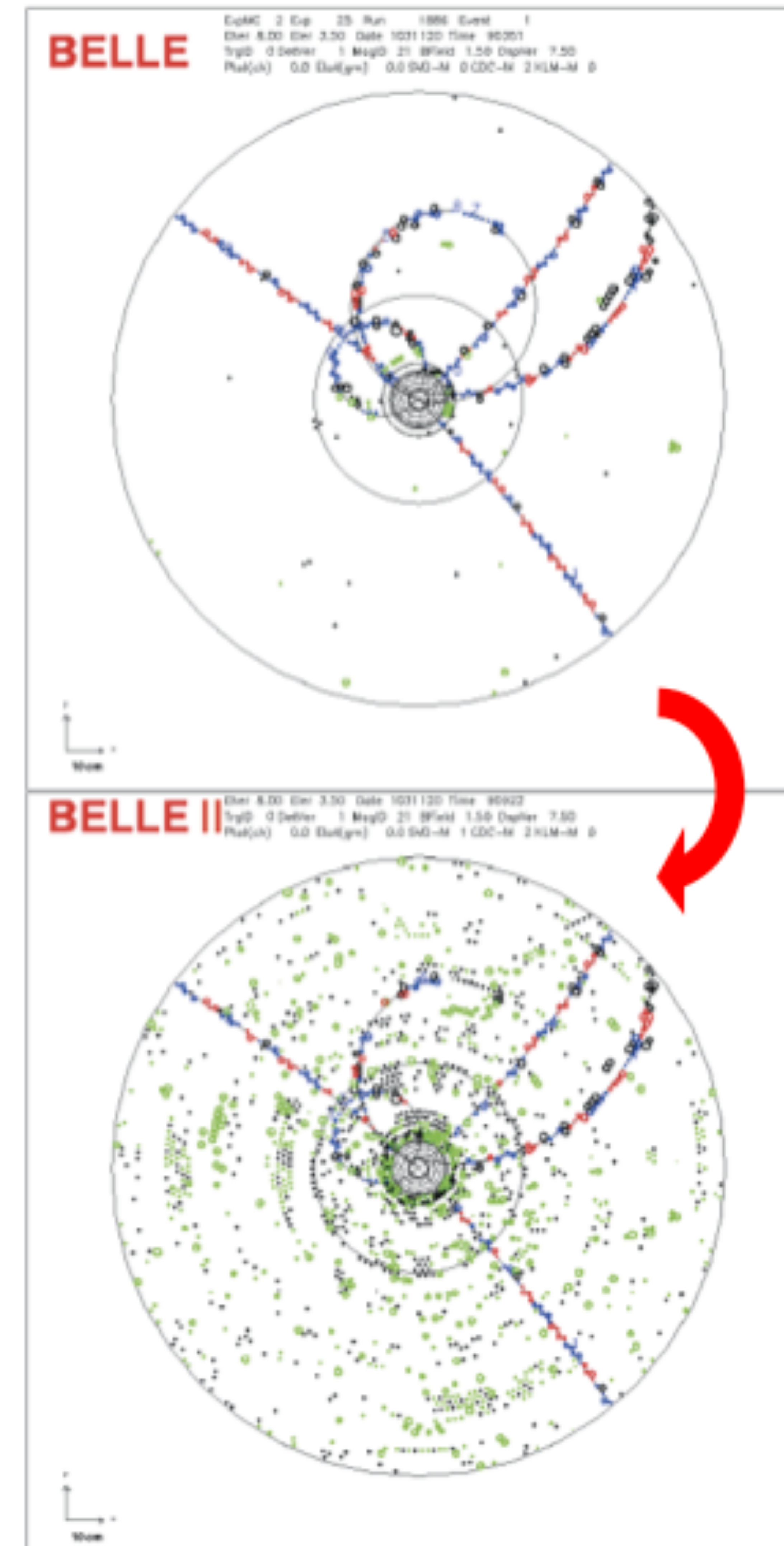
$$\int^{\text{goal}} \mathcal{L}\, dt = 50\ \text{ab}^{-1}$$



26 countries/regions, 112 institutions, ~971 collaborators

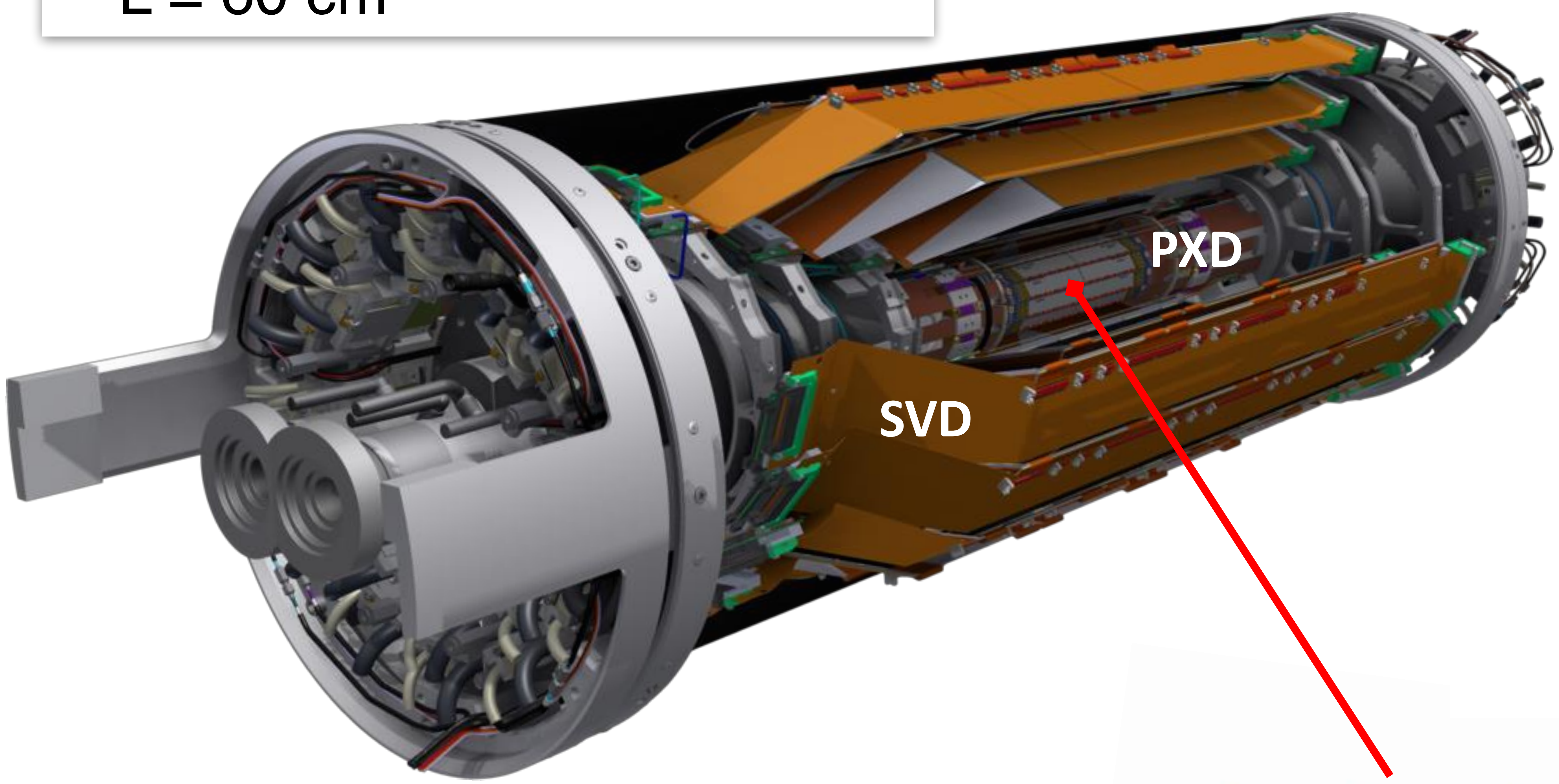
Challenges & responses for Belle II

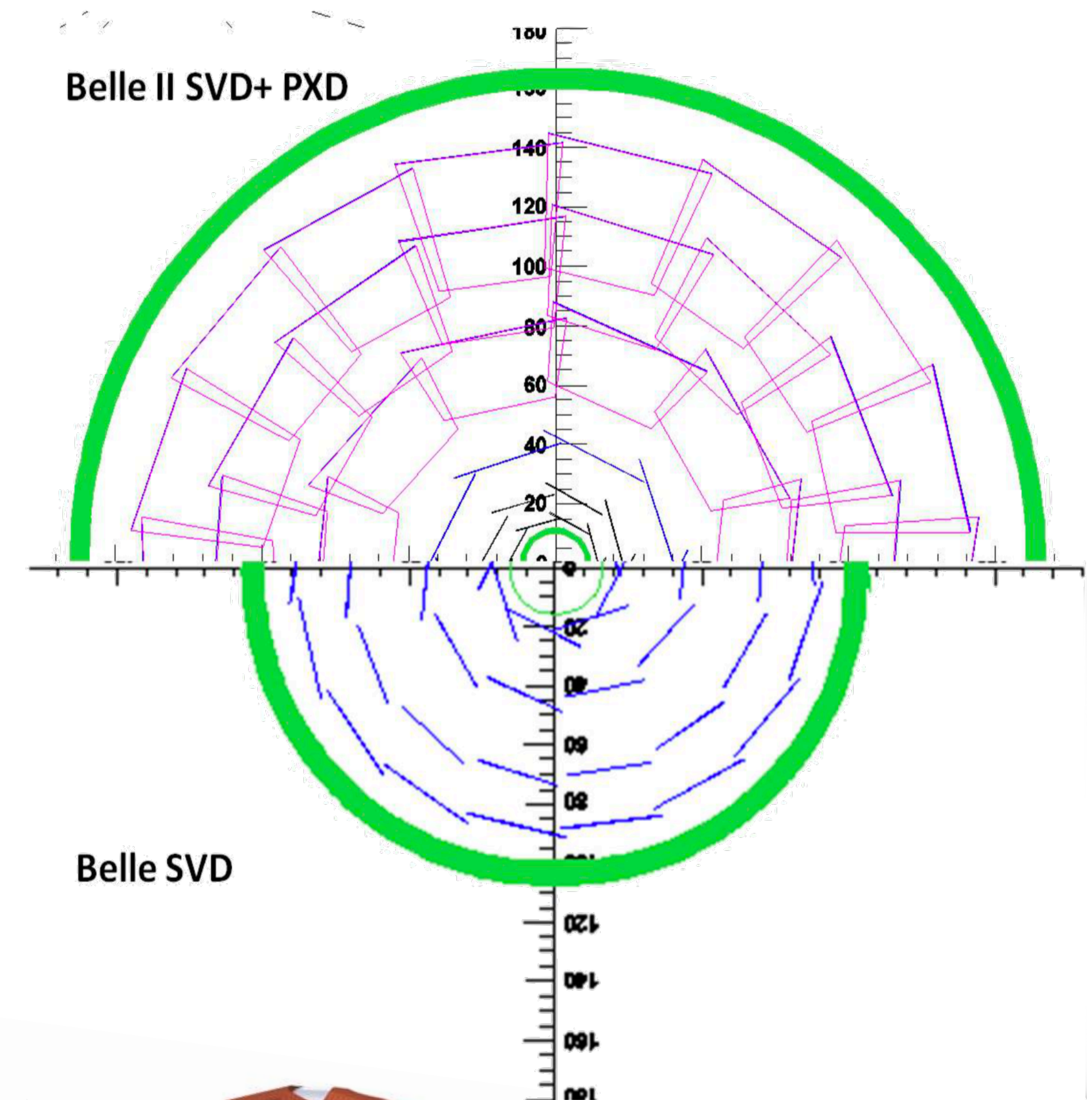
- Severe beam background
  - due to ×40 increase in L_{peak}
  - fine segmentation and fast readout ➔ reduce occupancy
  - replace detector components
- Some big changes
  - vertex: SVD (4 layers) ➔ **PXD (2) + SVD (4)**
  - hadron identification: binary Cherenkov ➔ **iTOP** ("imaging Time-of-Propagation")



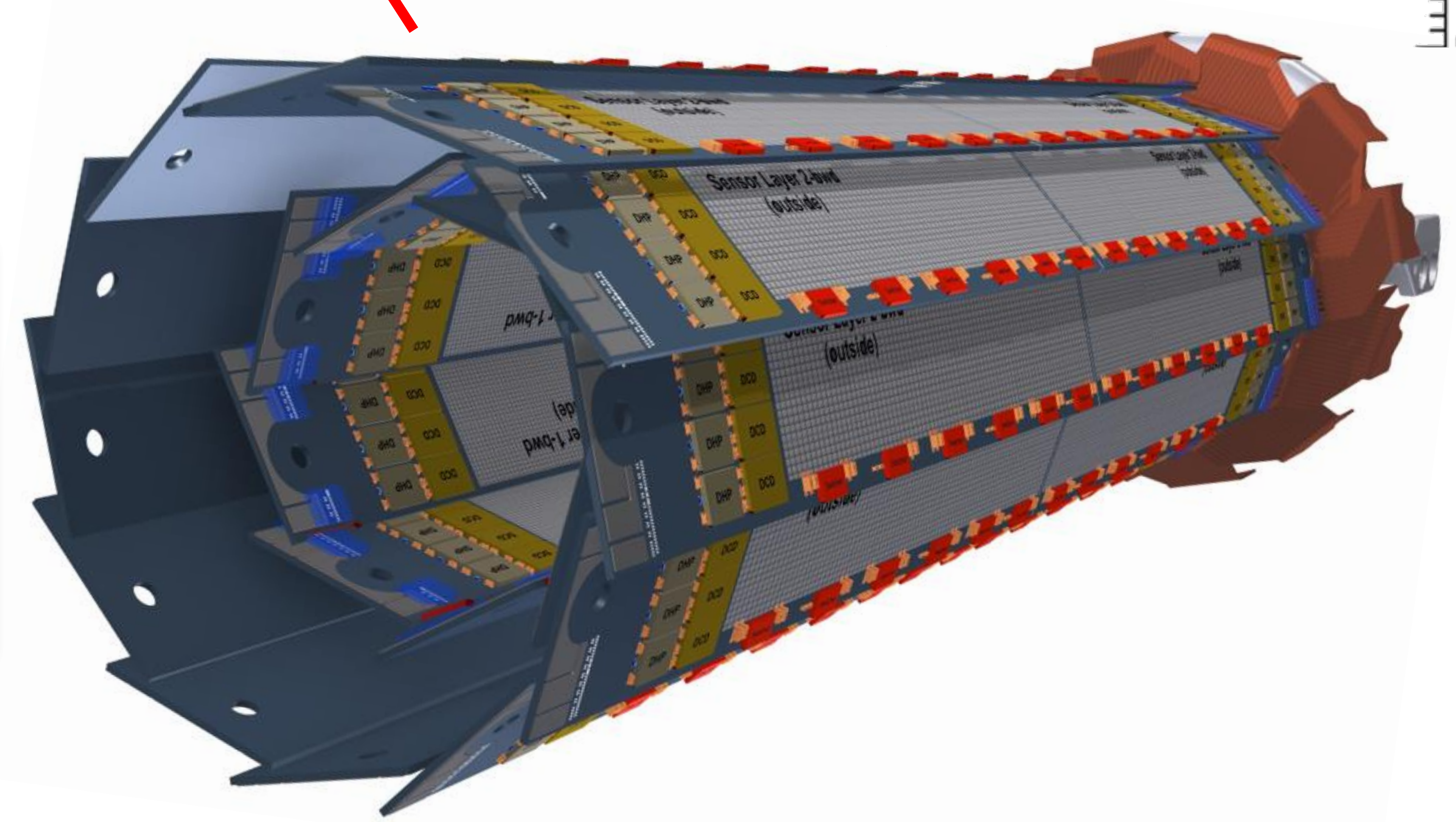
Vertexing for Belle II

SVD
- 4 layers of DSSD
- r = 3.8, 8.0, 11.5, 14.0 (cm)
- L = 60 cm





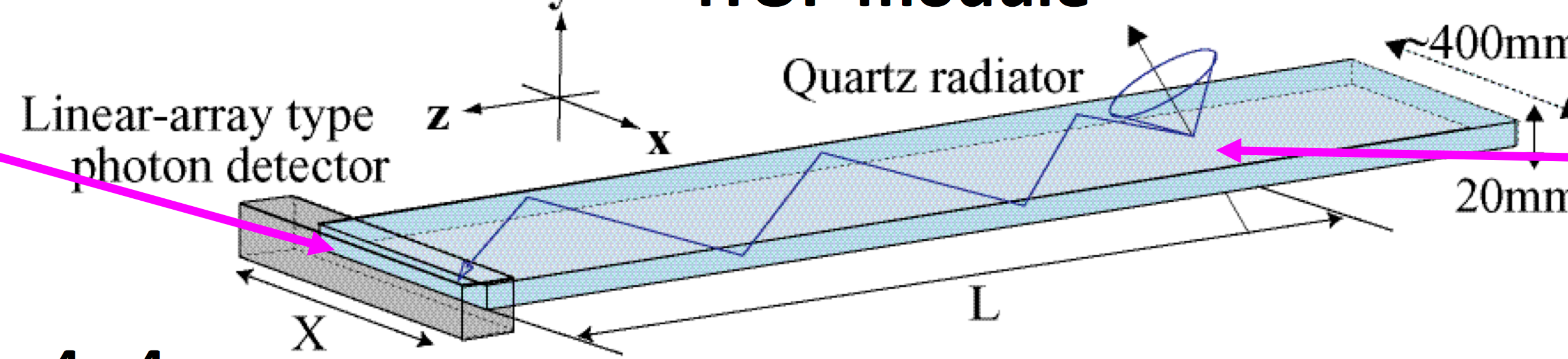
PXD (pixel detector)
- 2 layers of DEPFET
- r = 1.4, 2.2 (cm)
- L = 12 cm

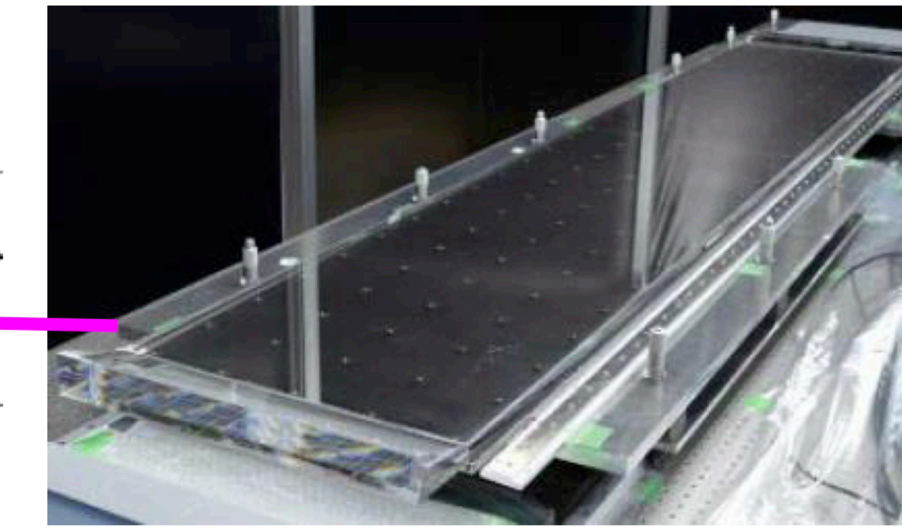


hadron ID for Belle II

512 Hamamatsu 4 x 4 MCP-PMT

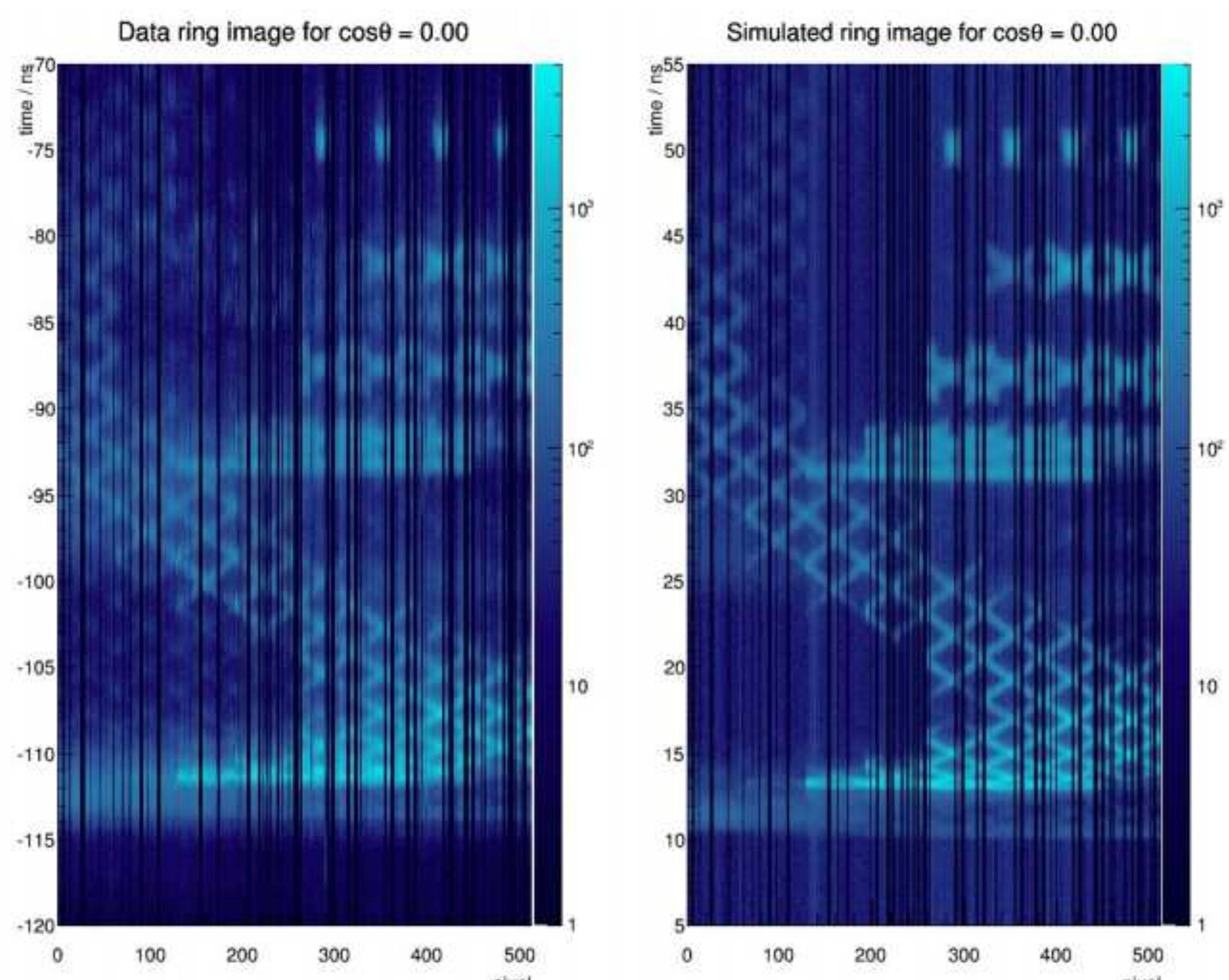
iTOP module





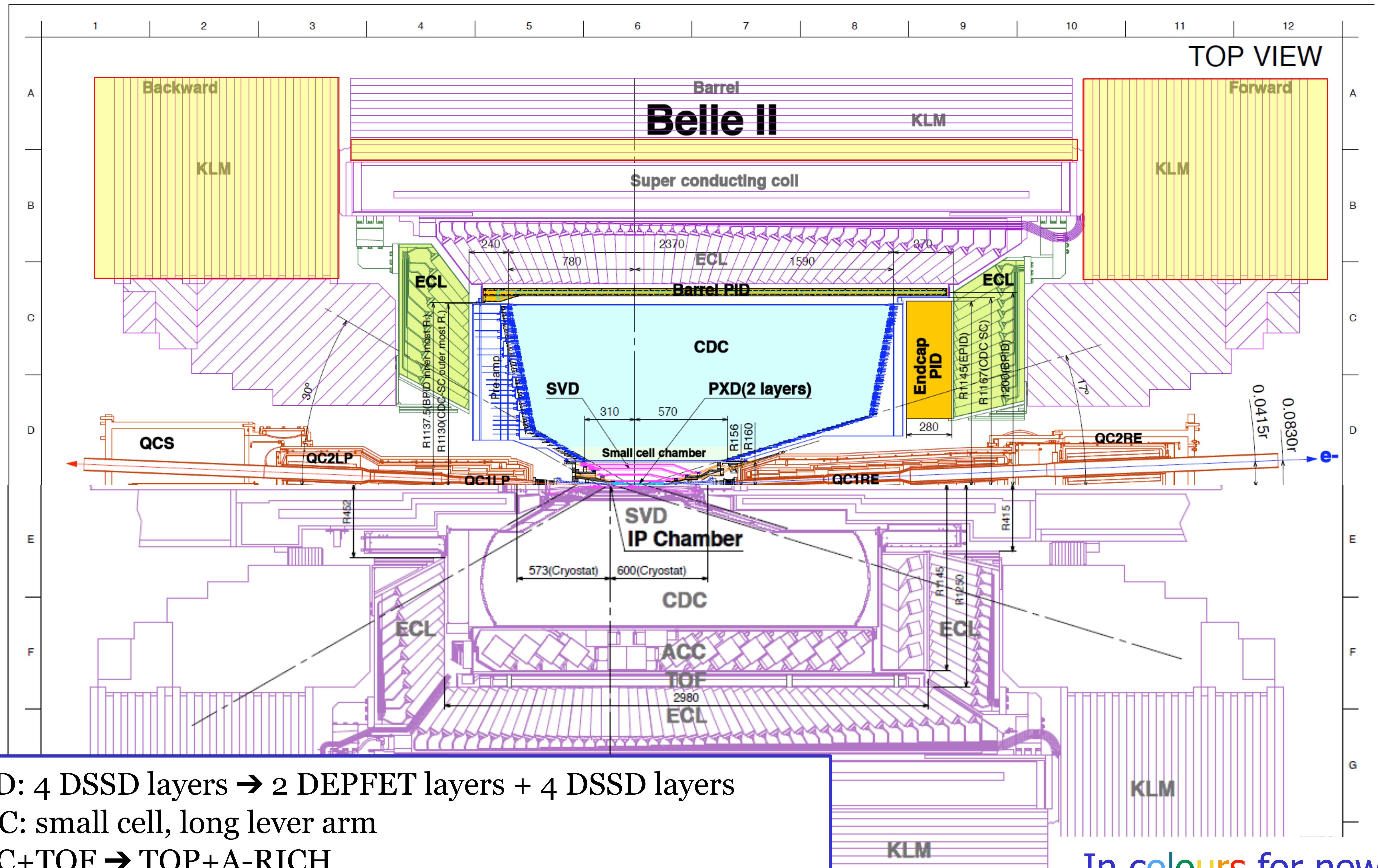
Quartz radiator

- high-quality quartz (O(100) reflections)
- flatness < 6.3 μm



Beam test (2013)

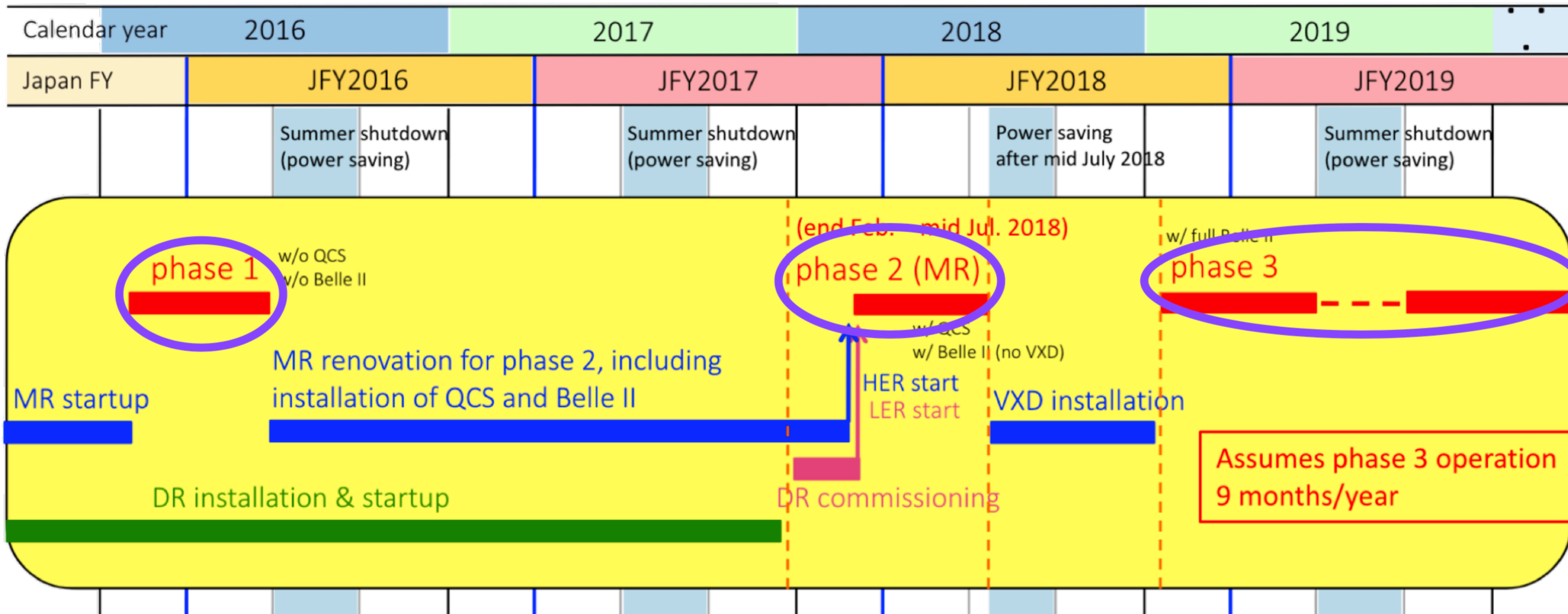
- 1.2 GeV/c e^+ beam at Spring-8
- normal incidence
- N(γ) ~ 30 for a single event
- image pattern matches w/ MC very well



SVD: 4 DSSD layers ➔ 2 DEPFET layers + 4 DSSD layers
CDC: small cell, long lever arm
ACC+TOF ➔ TOP+A-RICH
ECL: waveform sampling
KLM: RPC ➔ Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

In colours for new components

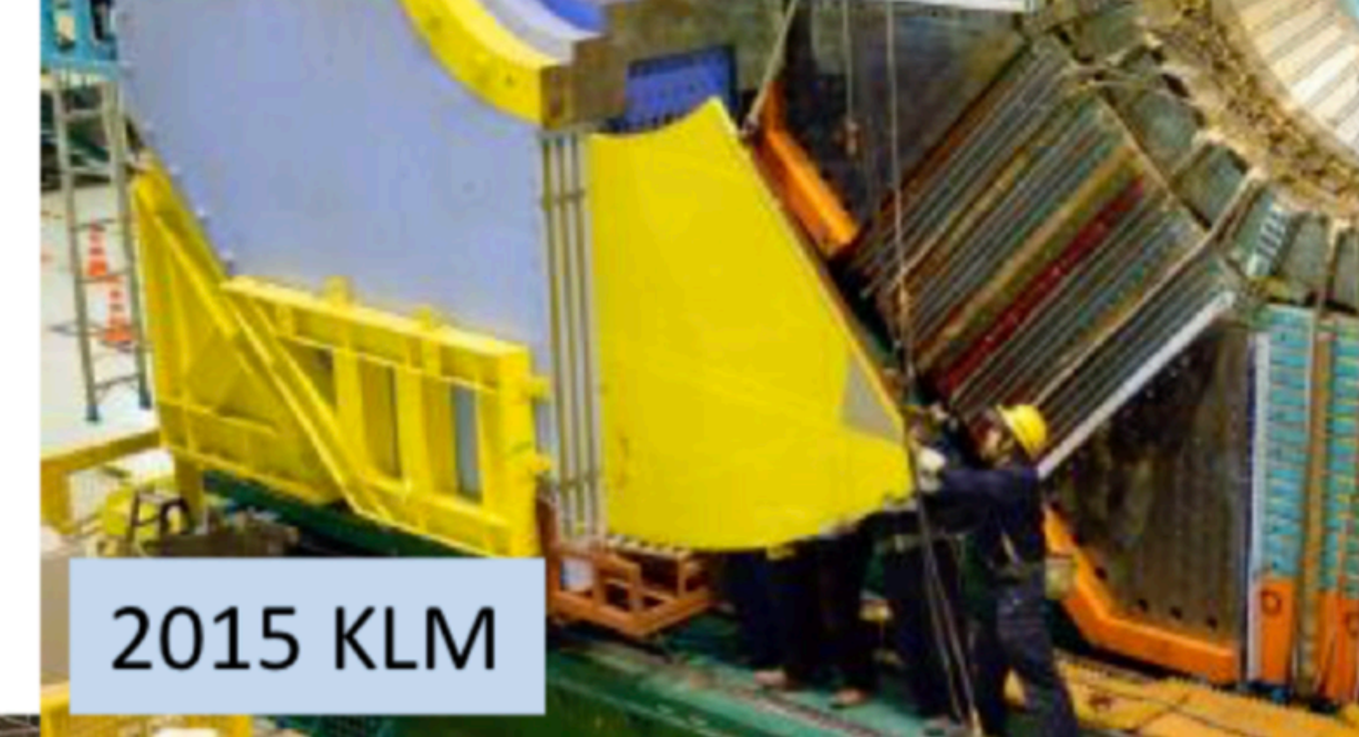
SuperKEKB/Belle II schedule



- **Phase 1**: single-beam background commissioning (w/o final focus, w/o Belle II)
- **Phase 2**: collision with final focus and Belle II (no VXD)
- **Phase 3**: collision with full Belle II (***since March 2019***)

Belle II

sub-detector installation

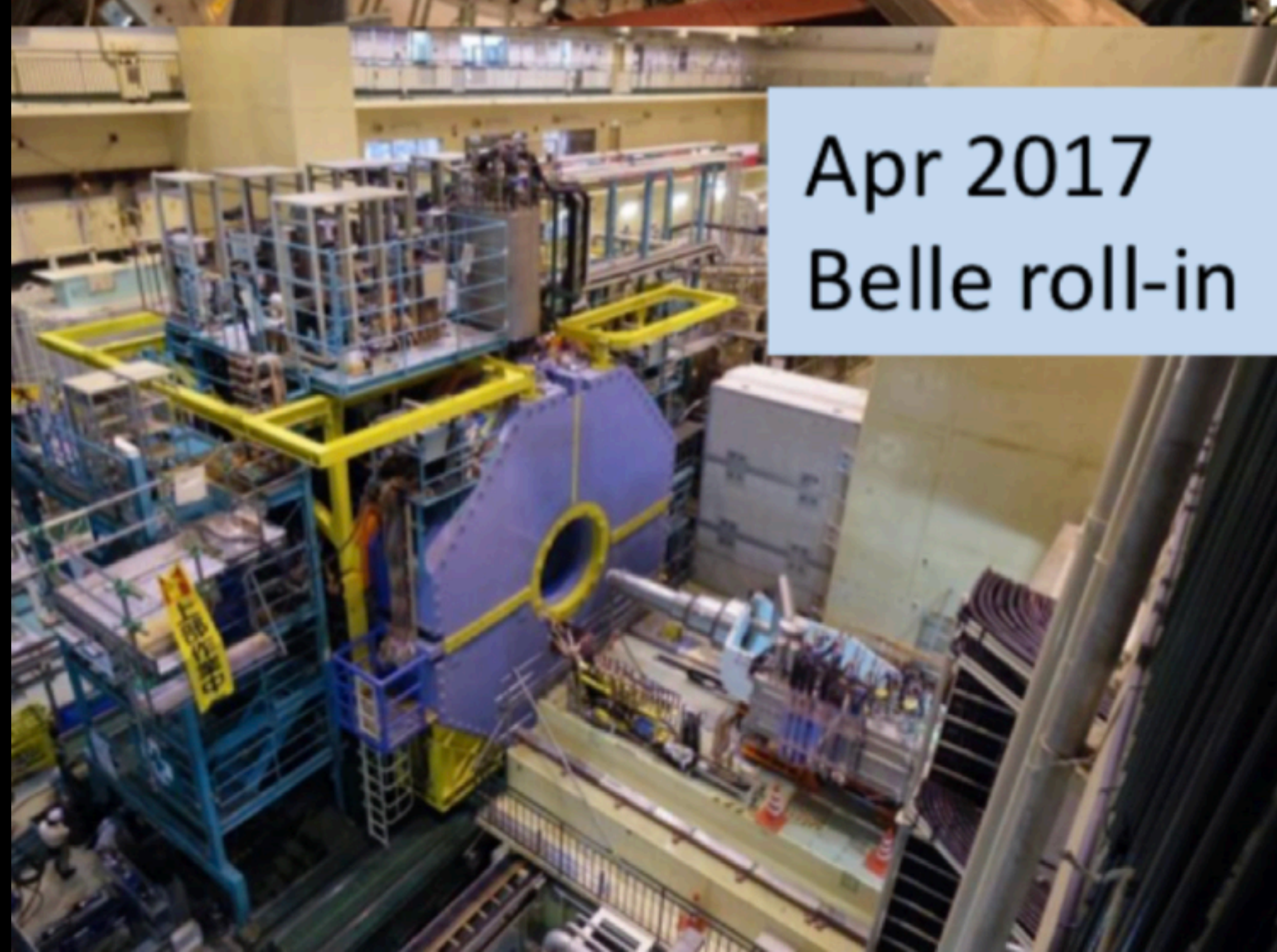


2015 KLM

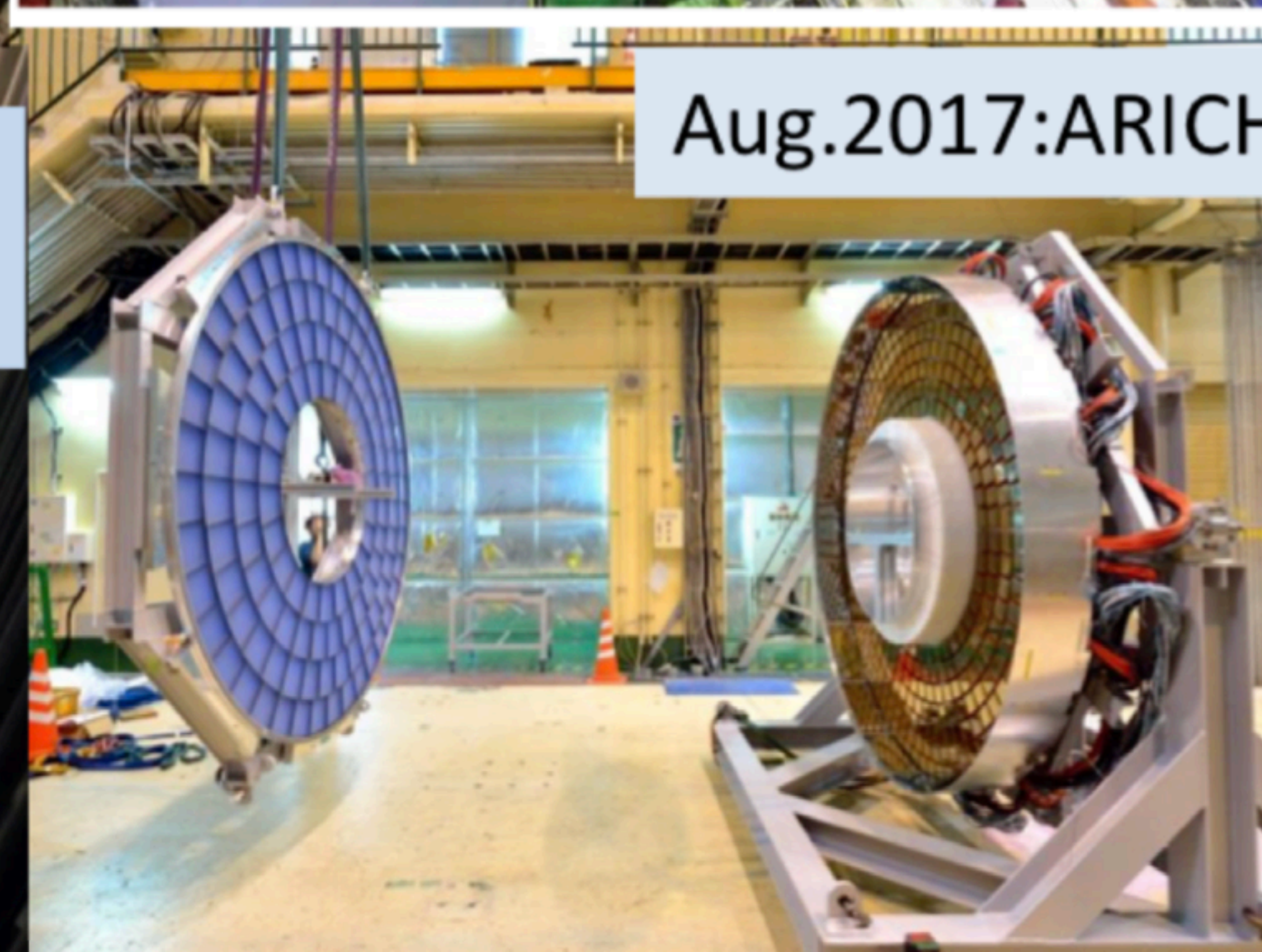
May 2016: TOP

Oct. 2016: CDC

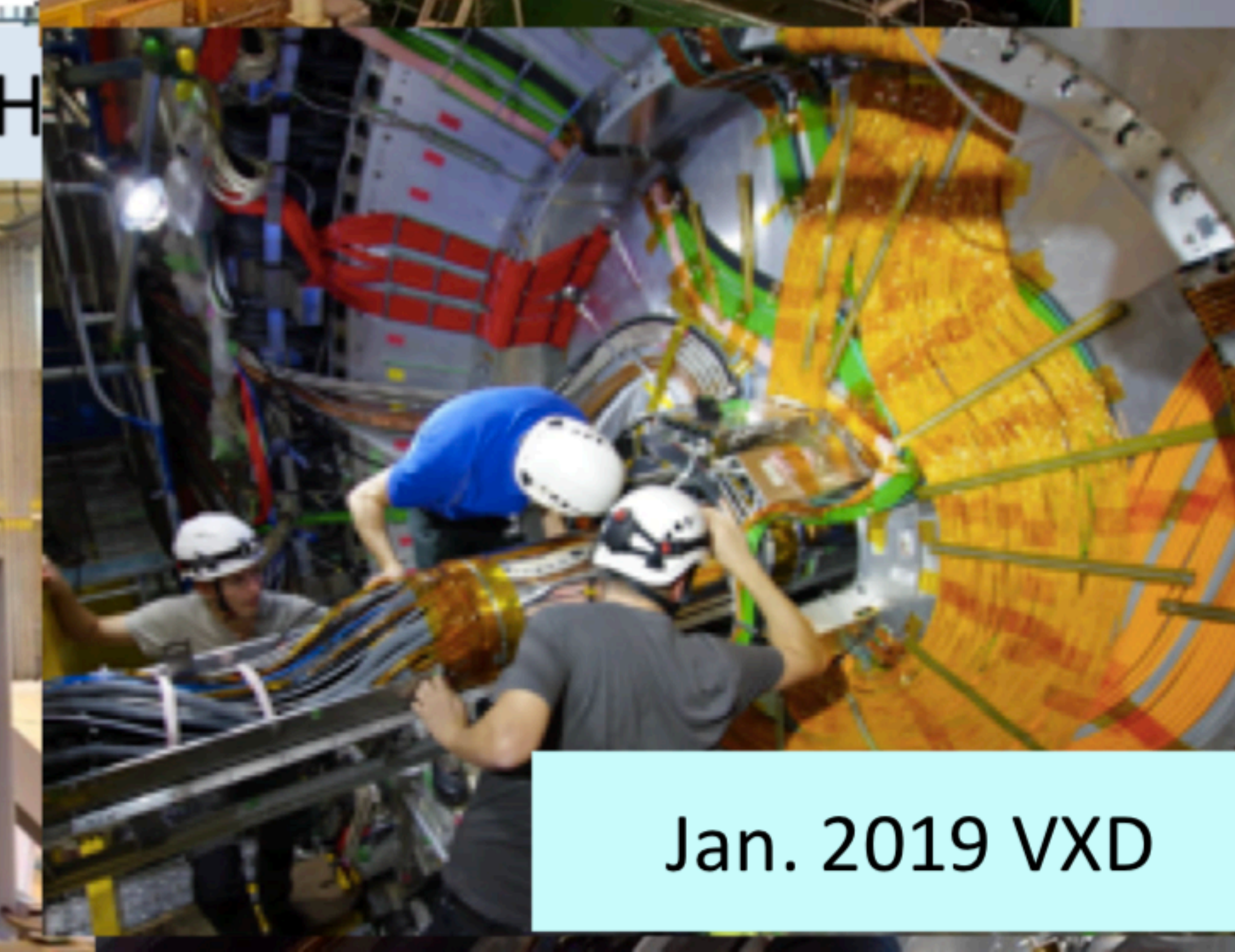
Jan. 2017 BWD ECL



Apr 2017
Belle roll-in



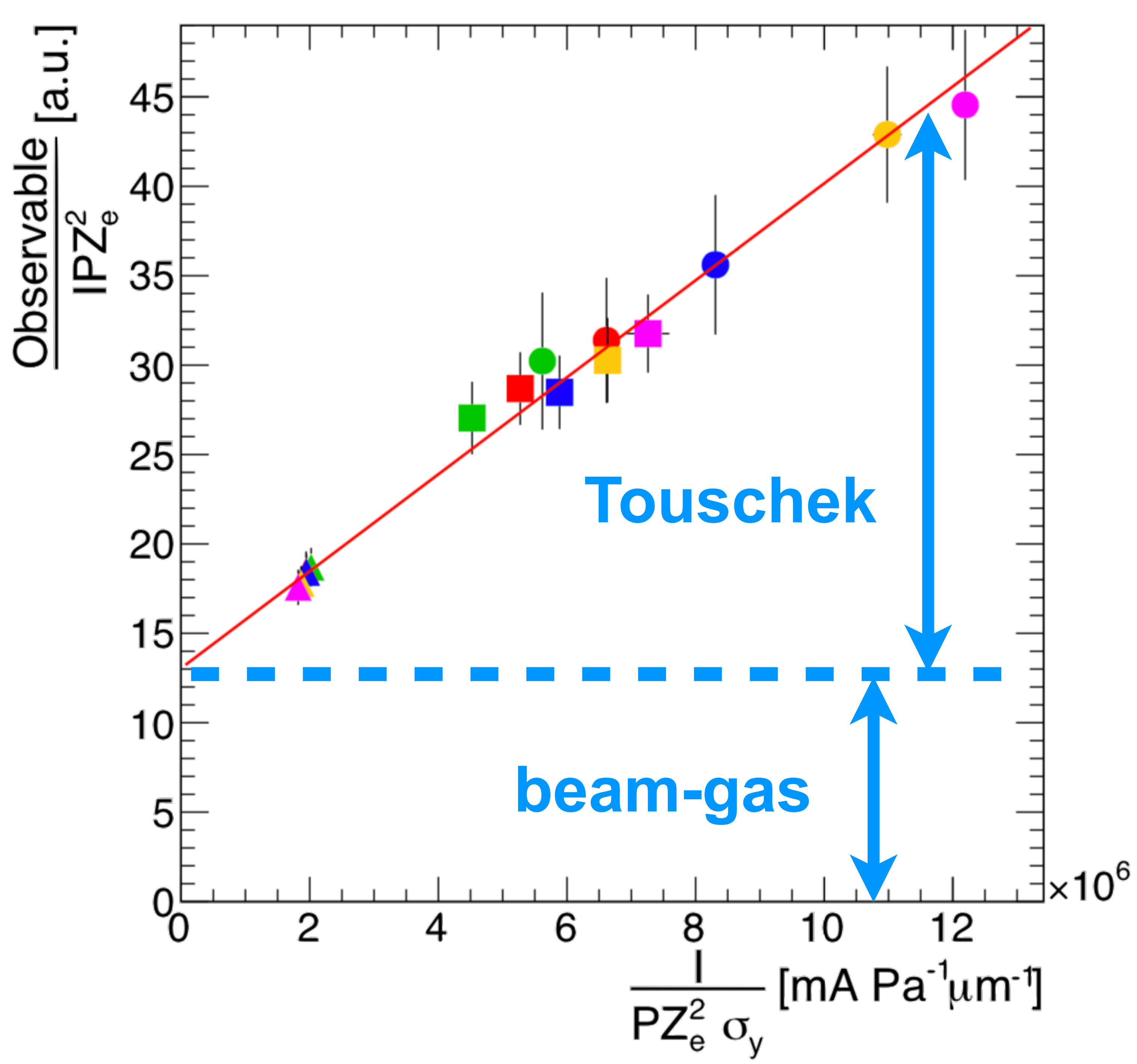
Aug.2017:ARICH

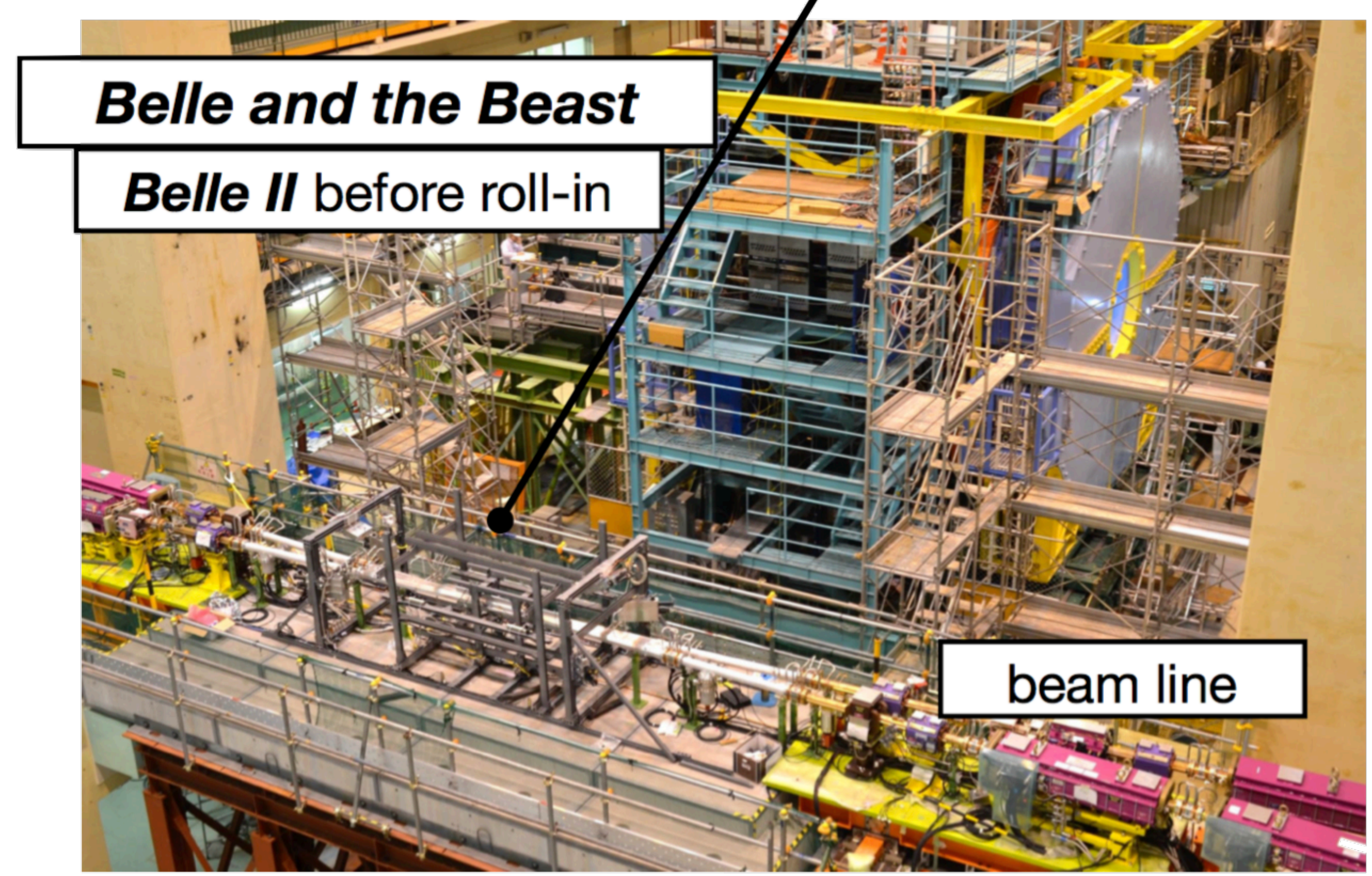


Jan. 2019 VXD

Belle II Phase 1 (Jan. - June, 2016)

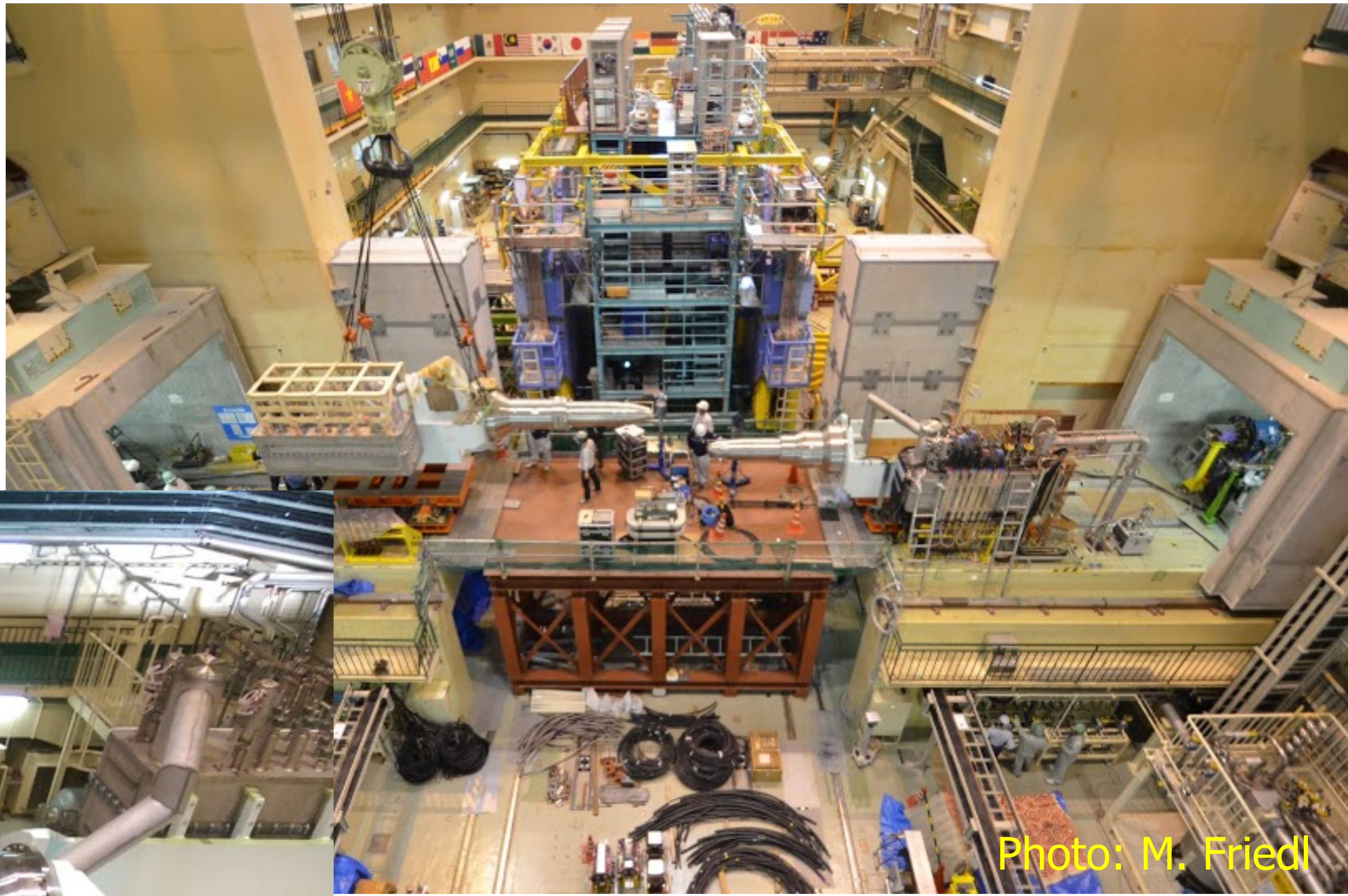
- single-beam background commissioning
- BEAST II, instead of Belle II
  - **B**eam **E**xorcism for **A ST**able Experiment II (diodes, TPC's, crystals)
- validation of Belle II beam background simulations



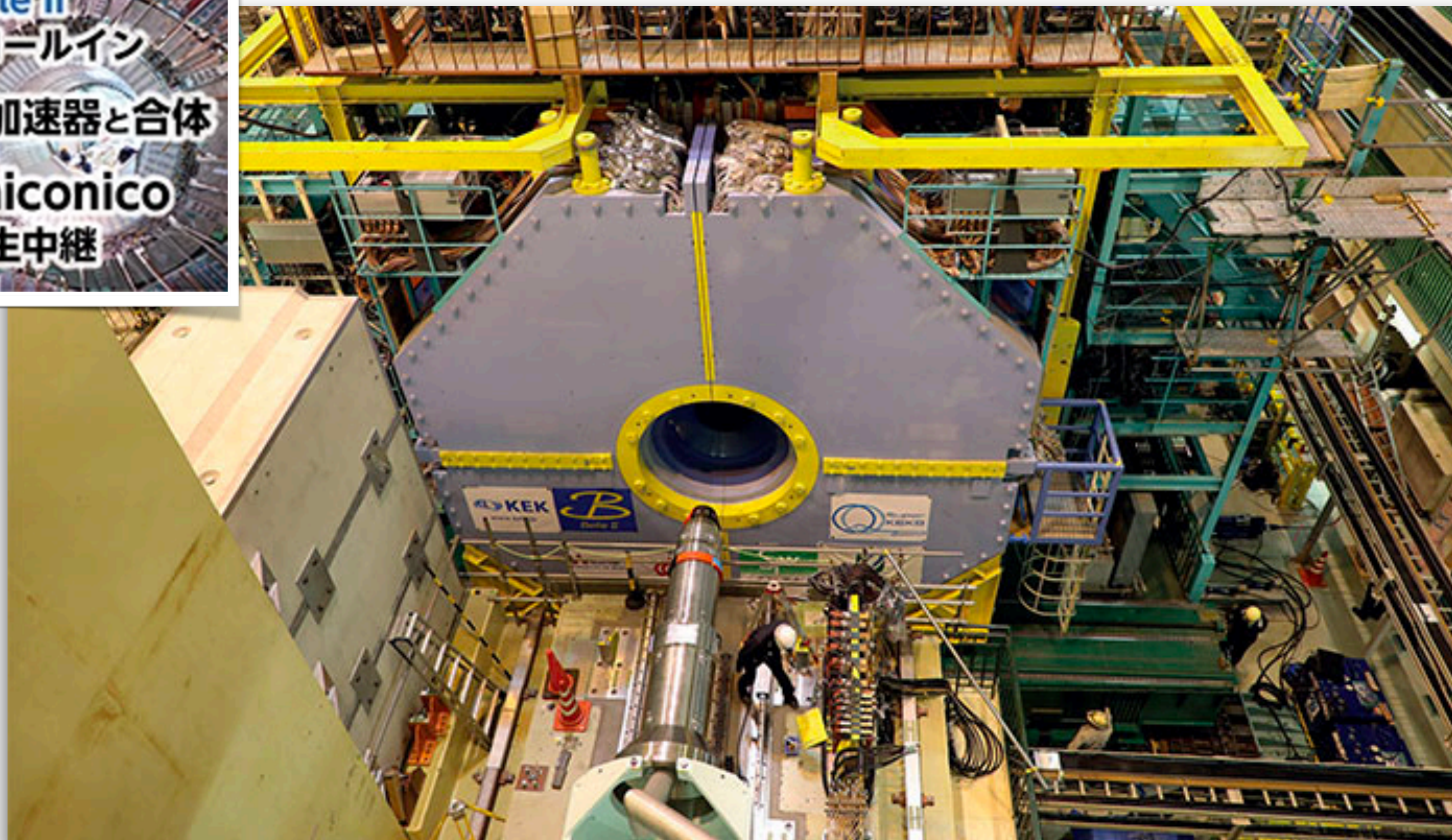


Final focus magnets

- Superconducting quadrupole magnets with 30+25 coils
- The final one delivered on Feb. 13, 2017



Belle II Roll-in (April, 2017)

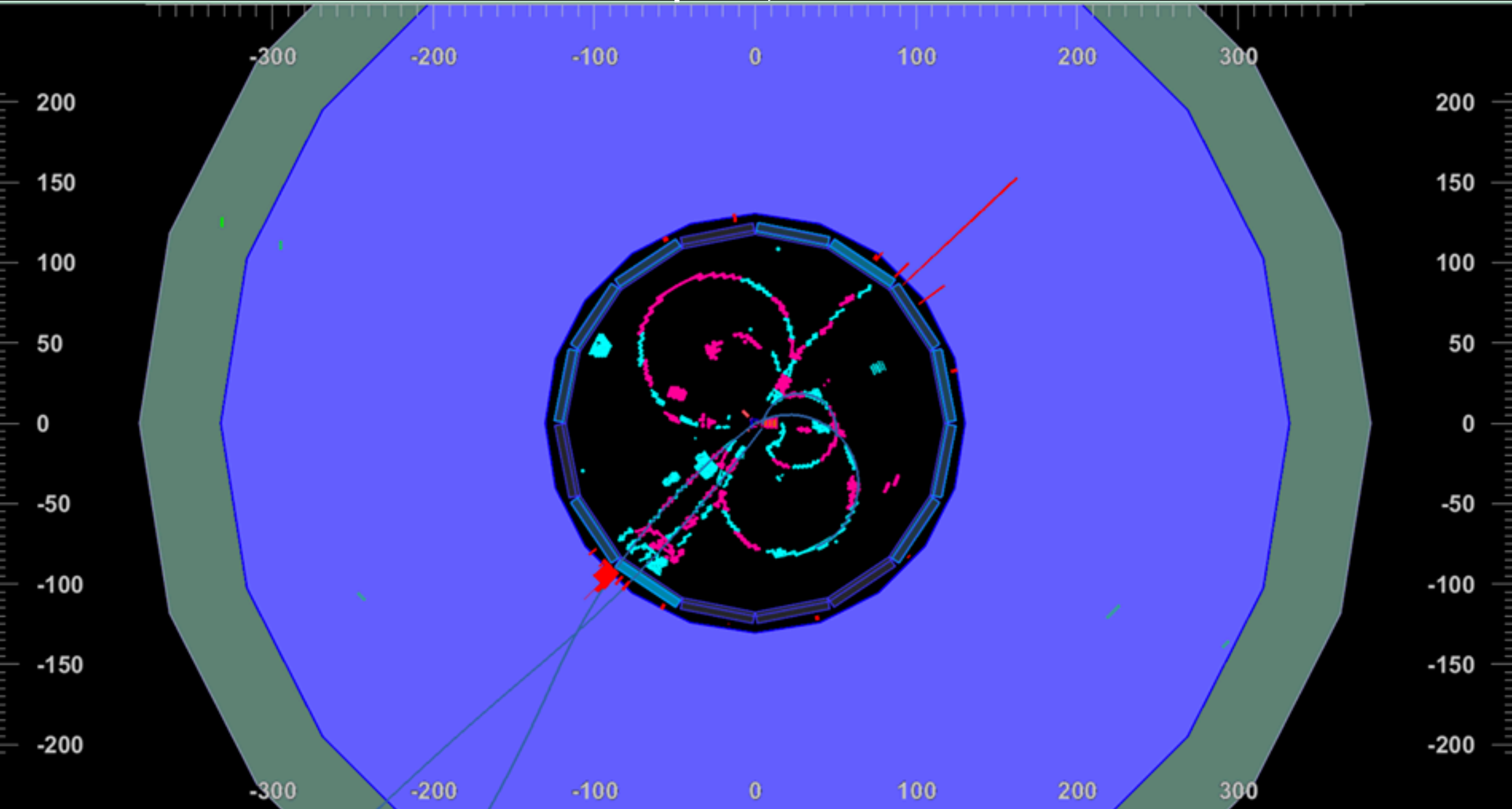


Belle II Phase 2 (Apr. - July, 2018)

Celebrating the first Belle II collision (Apr. 26, 2018)

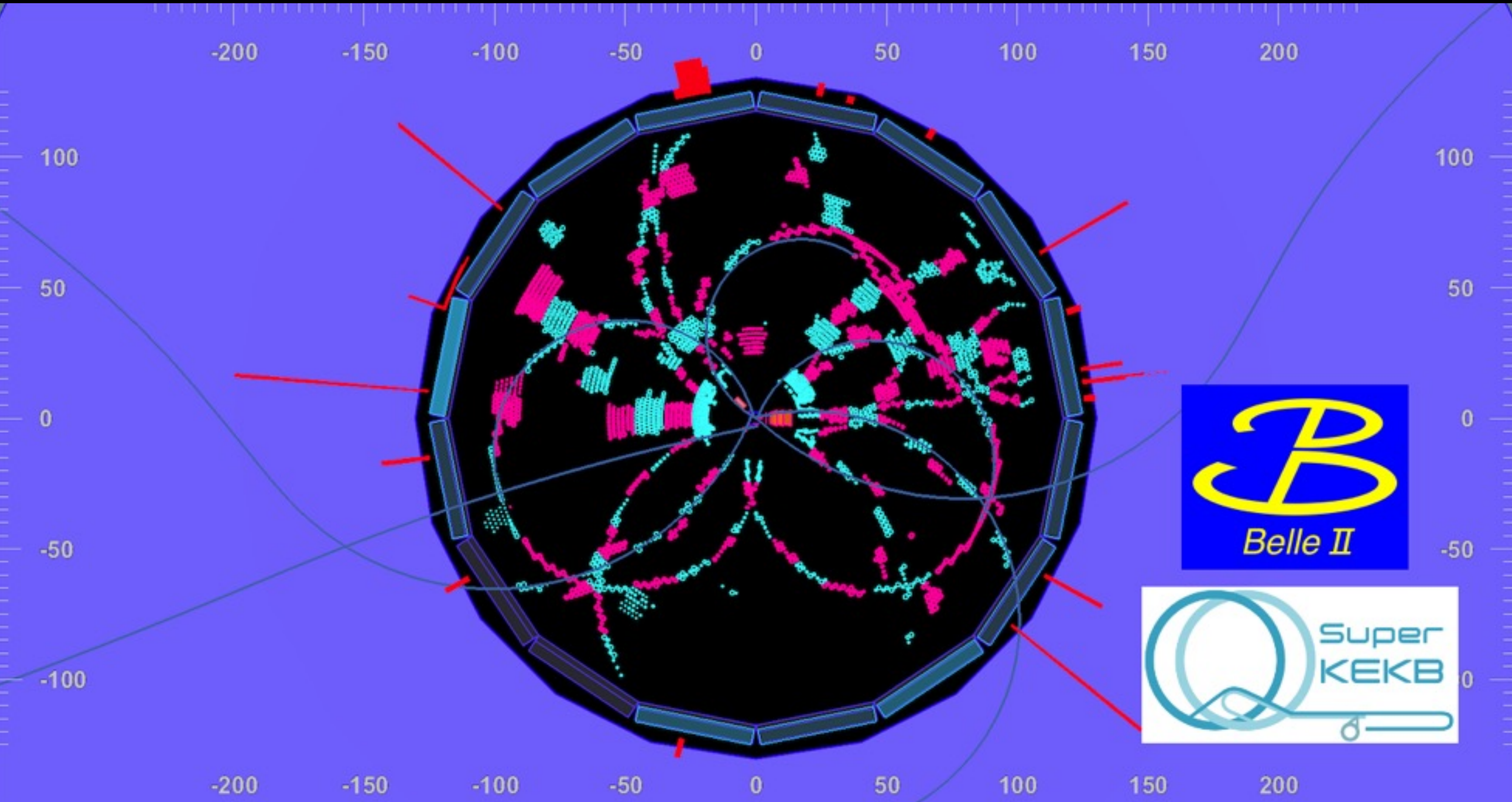
First collision event of SuperKEKB with Belle II

Apr. 26, 2018

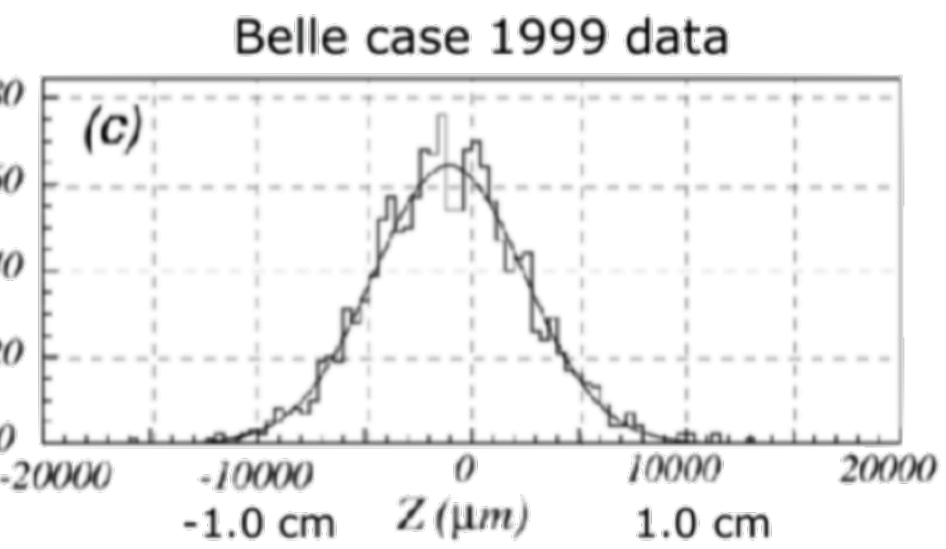


another event in that evening

Apr. 26, 2018

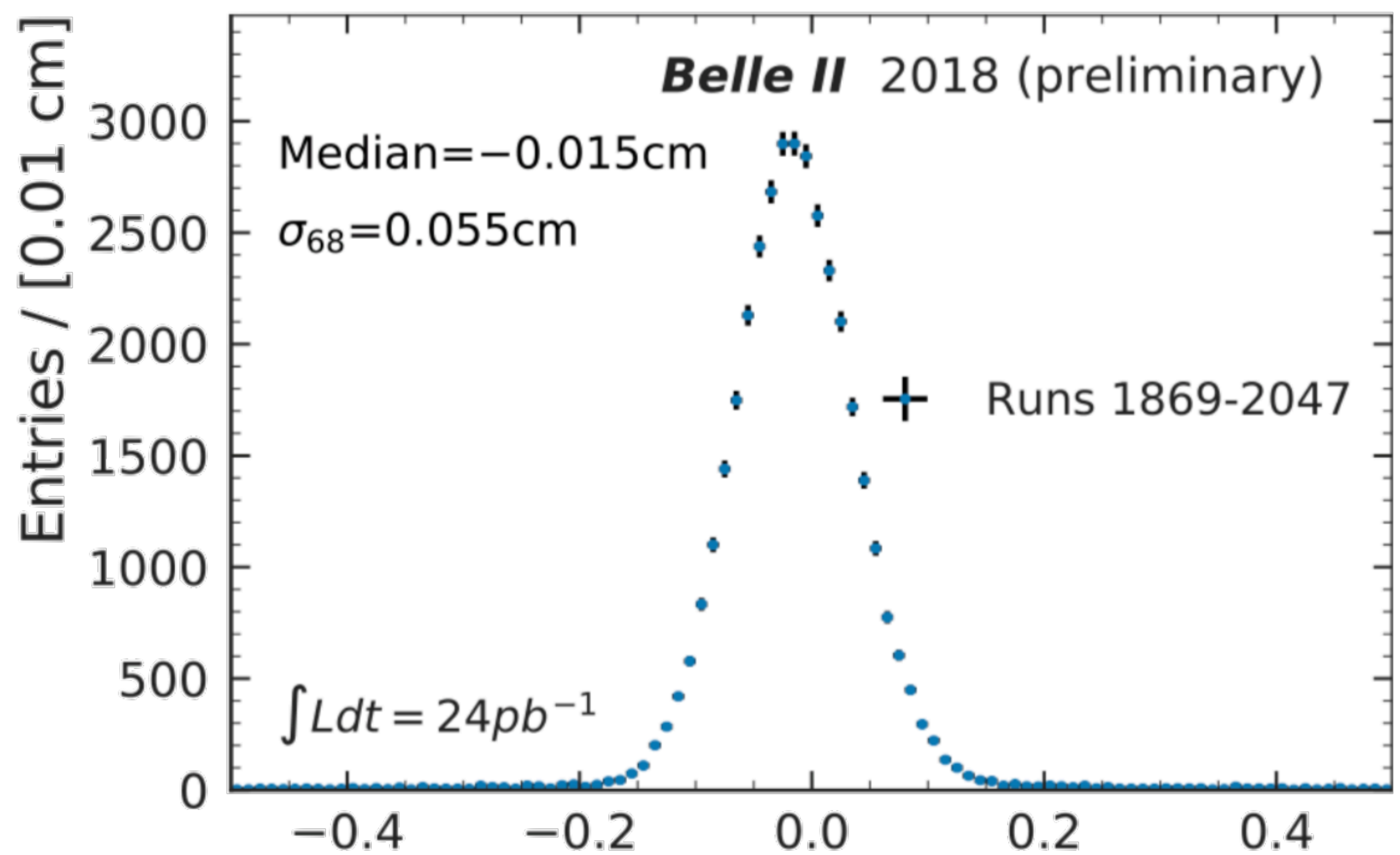


(Phase 2) beam profile

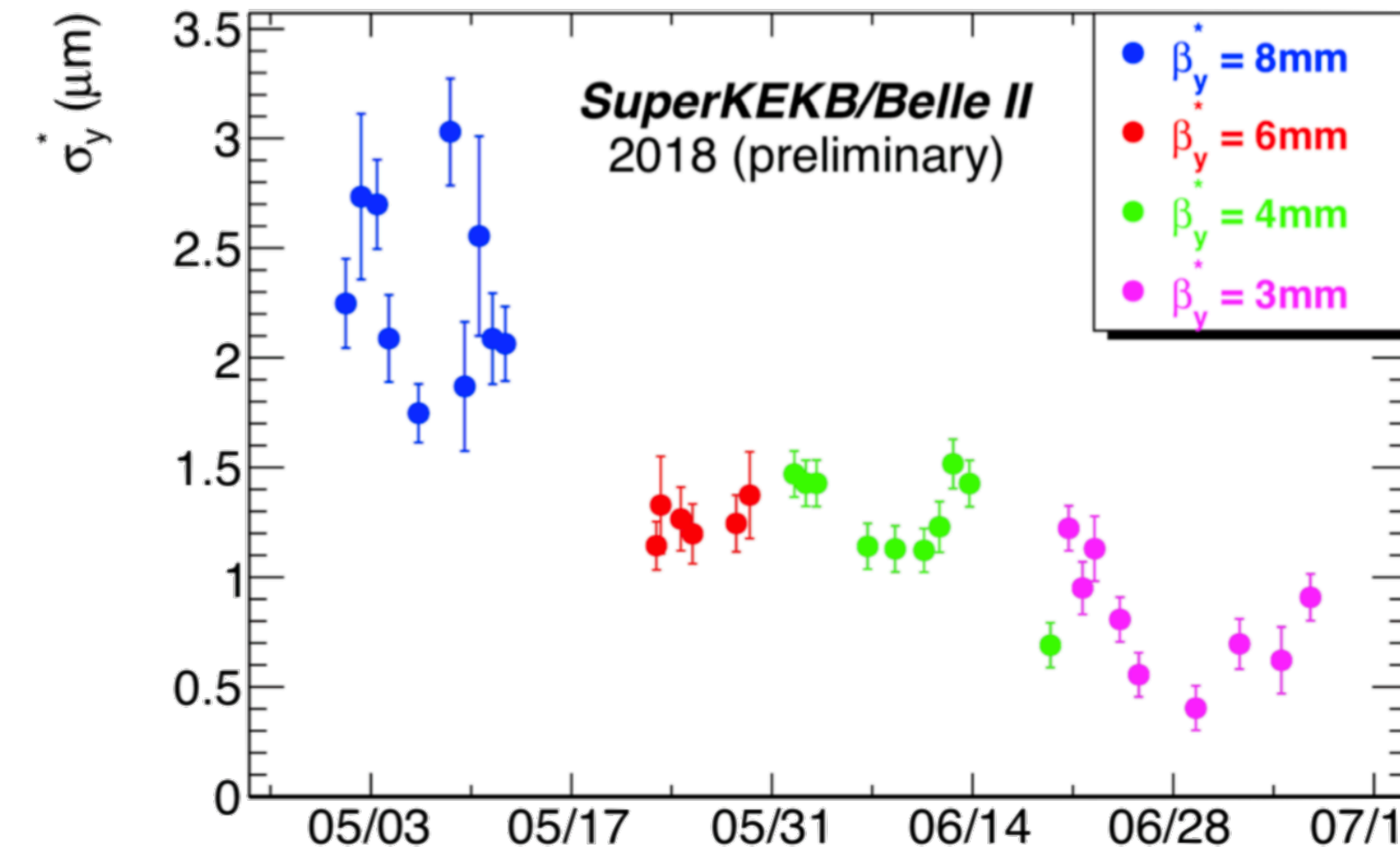


σ = 4.5 mm (KEKB)

nano-beam (SuperKEKB)



σ = 550 μm



- Nano-beam scheme is working!
- achieved

$$\beta_y^* = 3 \text{ mm}, \ \sigma_y = 400 \text{ nm}$$

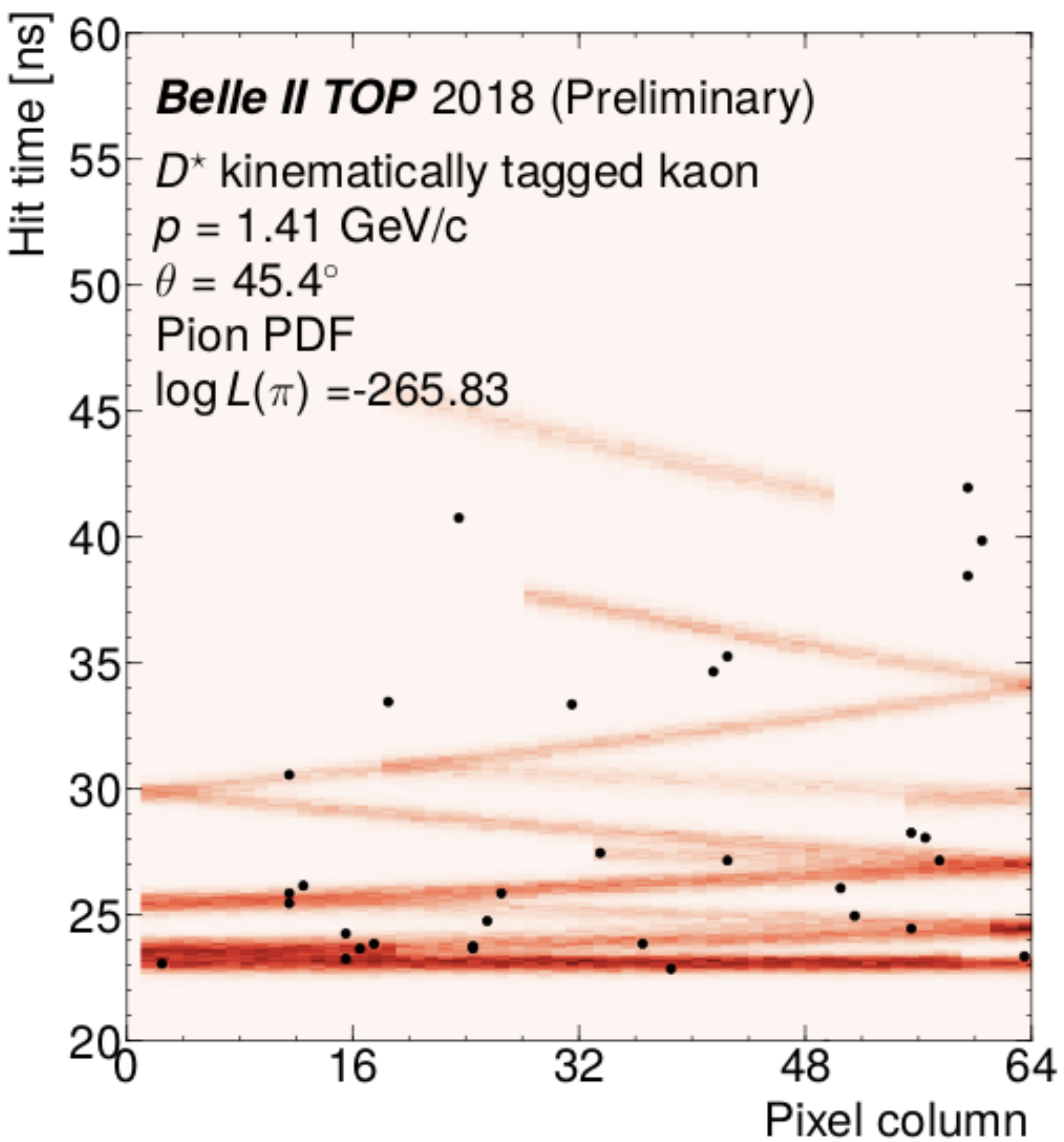
- Final goal:

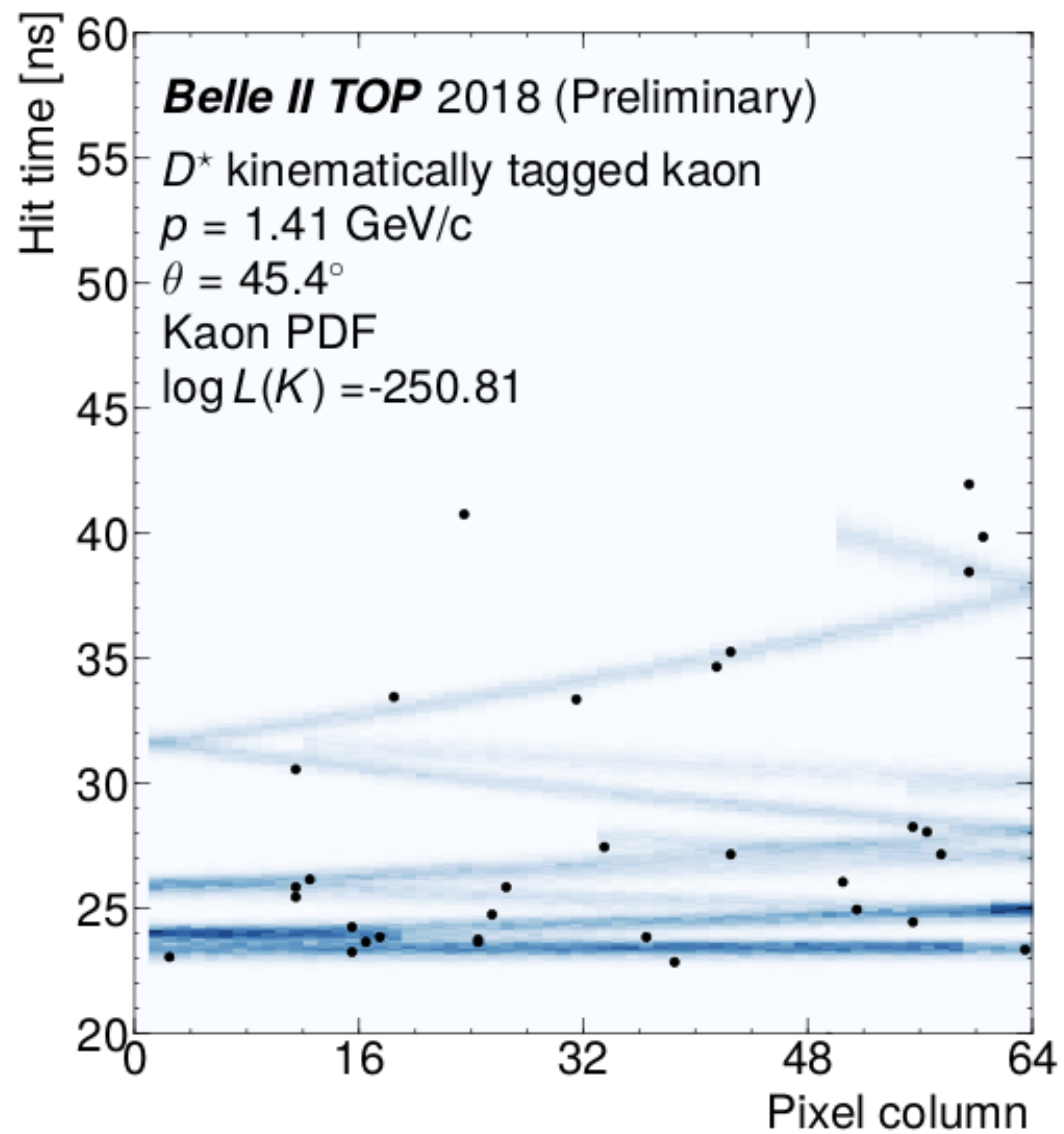
$$\beta_y^* = 0.3 \text{ mm}$$

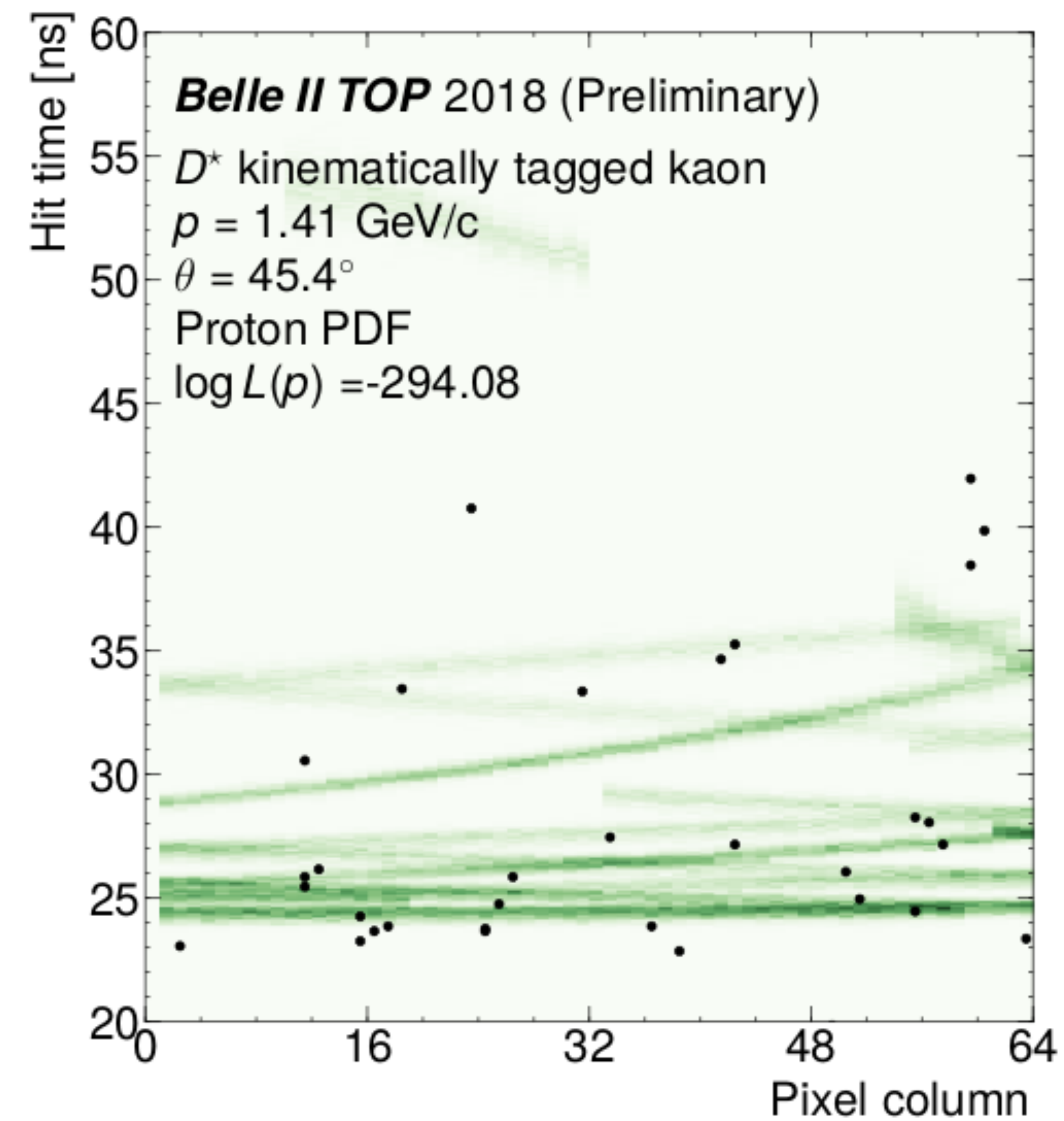
z vertex distribution

(Phase 2) iTop performance

Phase 2 (2018) data



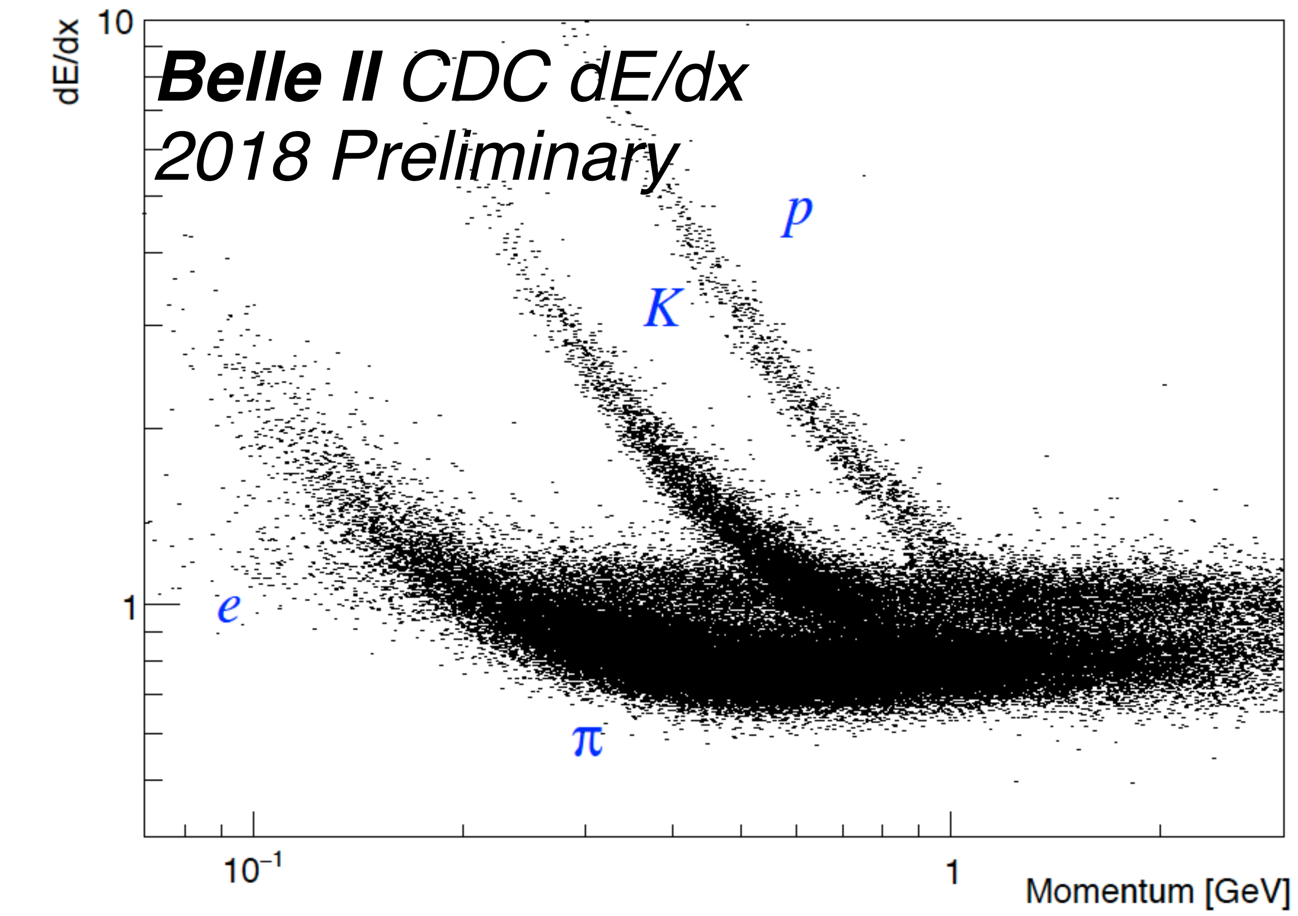




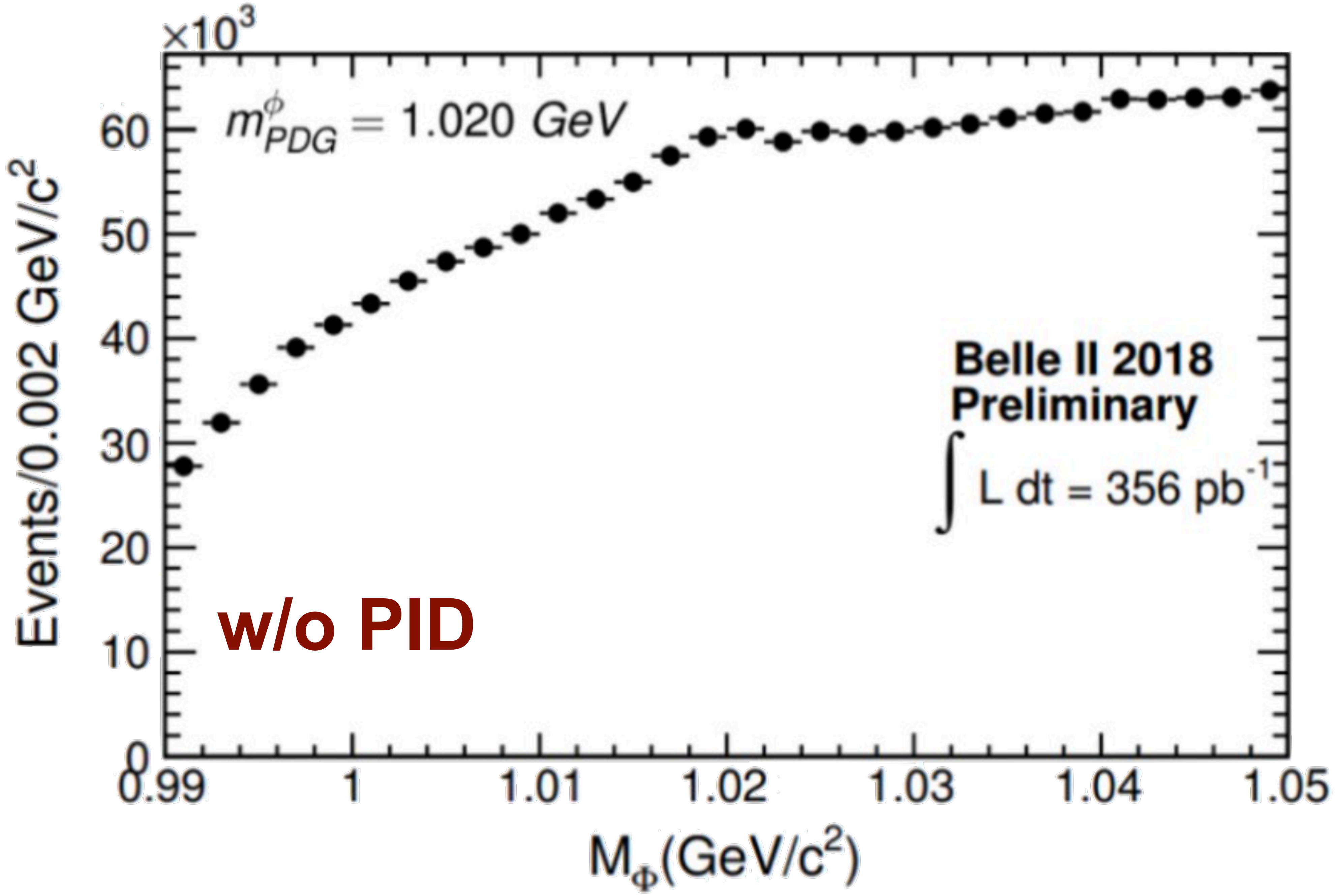
mapping of Cherenkov ring for D*-tagged Kaon track

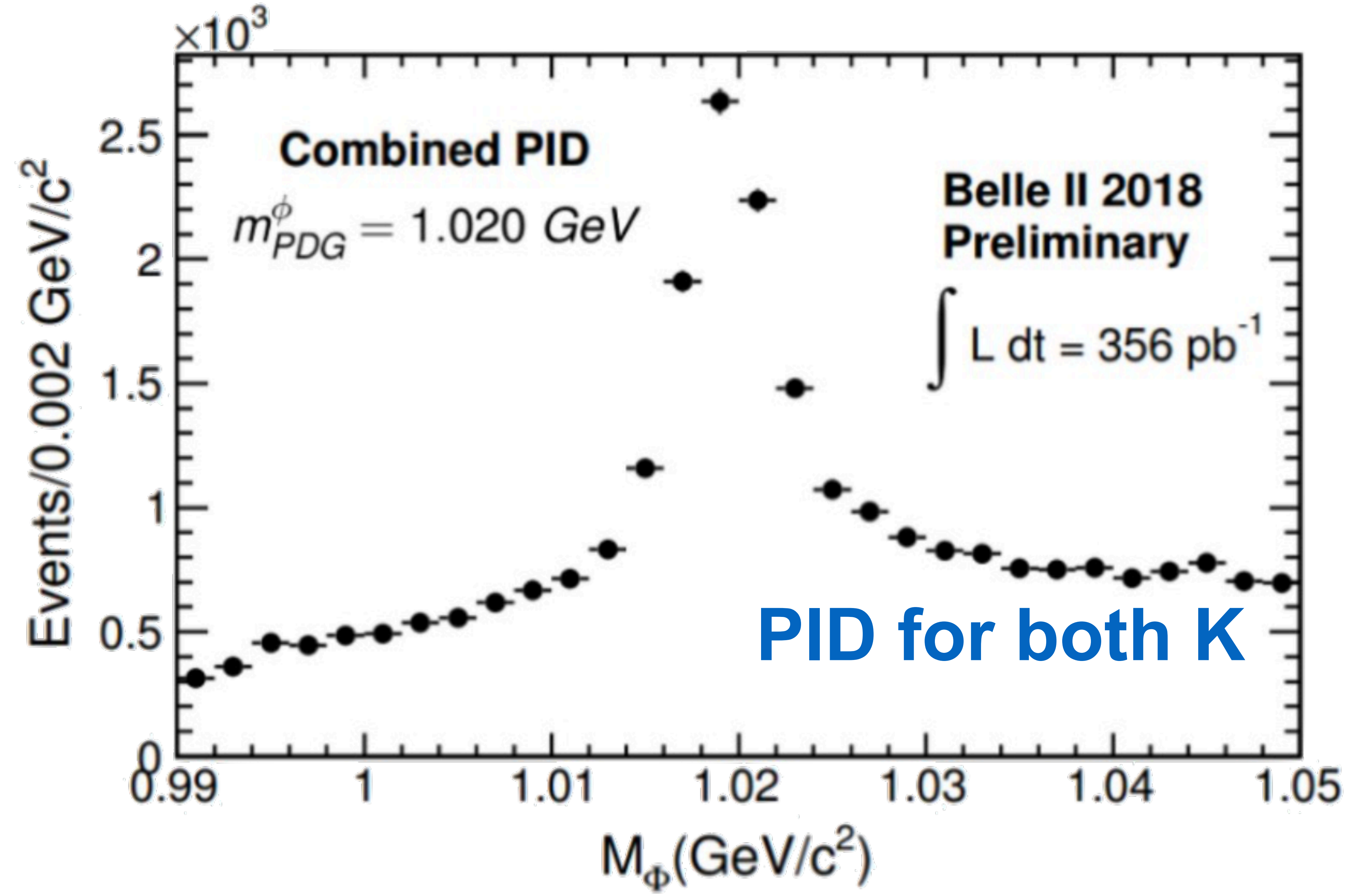
$$D^{*+} \to D^0 \pi_s^+ \ (D^0 \to K^- \pi^+)$$

(Phase 2) Particle ID



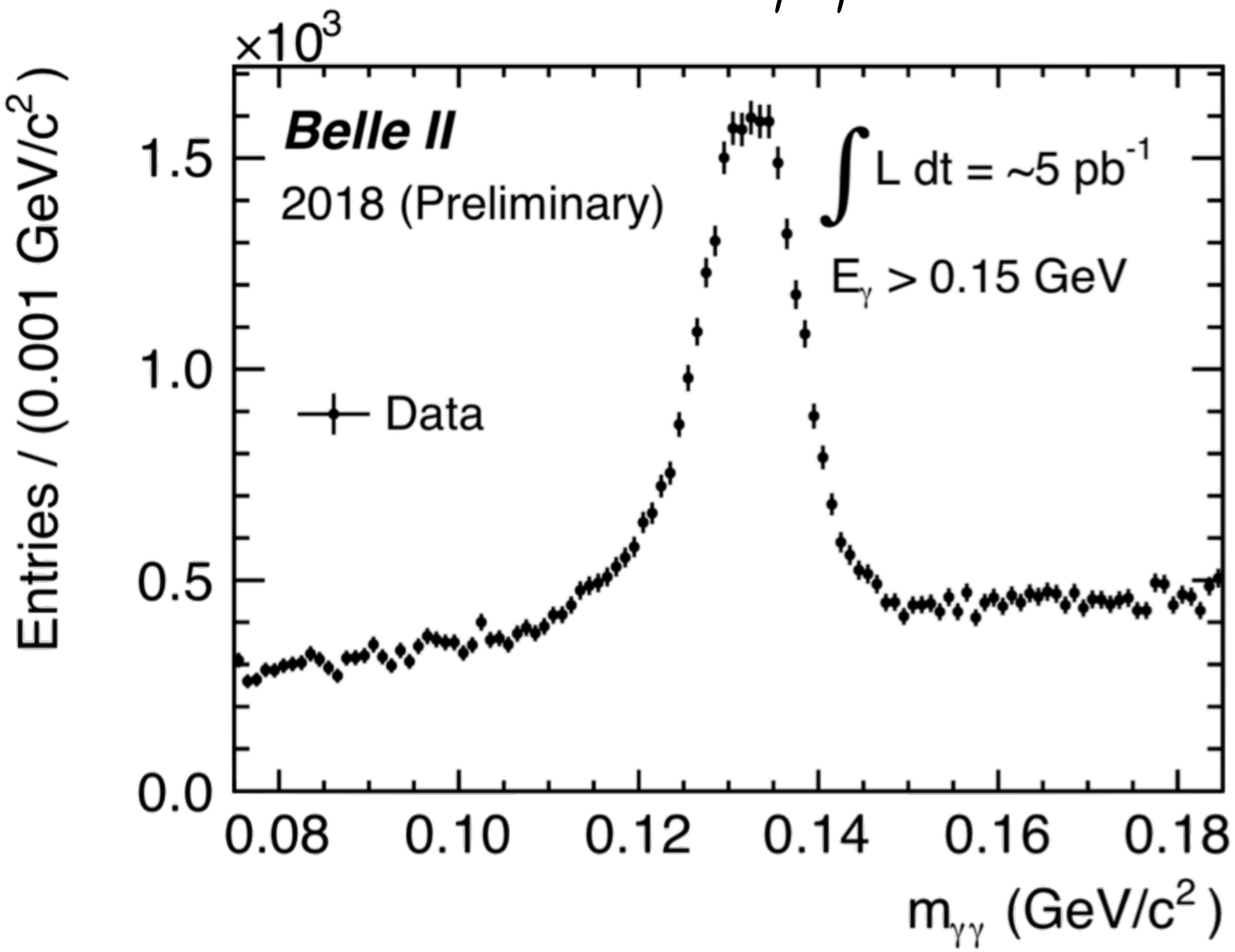
$$\phi \to K^+ K^-$$



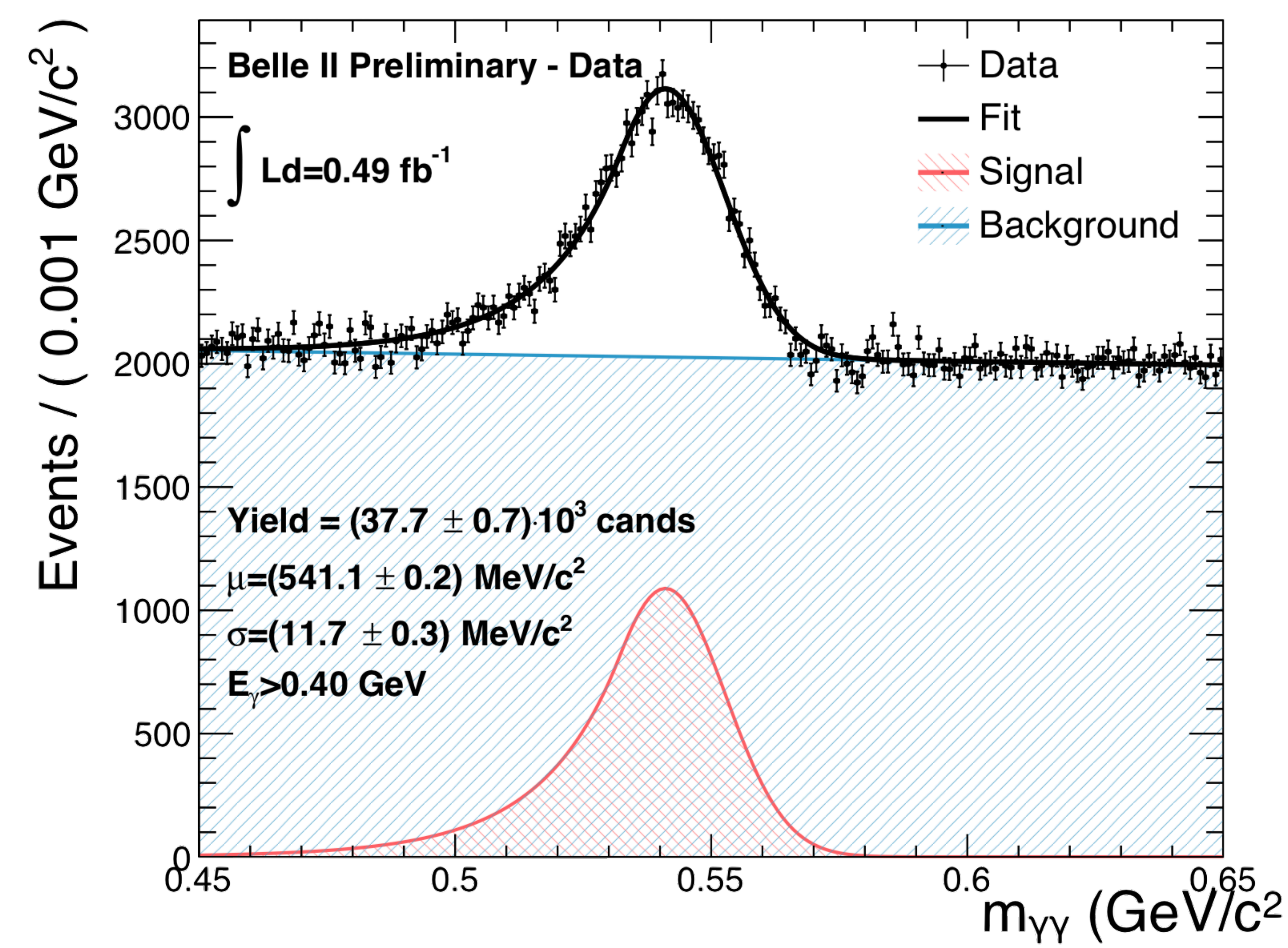


(Phase 2) photon reconstruction

$\pi^0 \to \gamma\gamma$

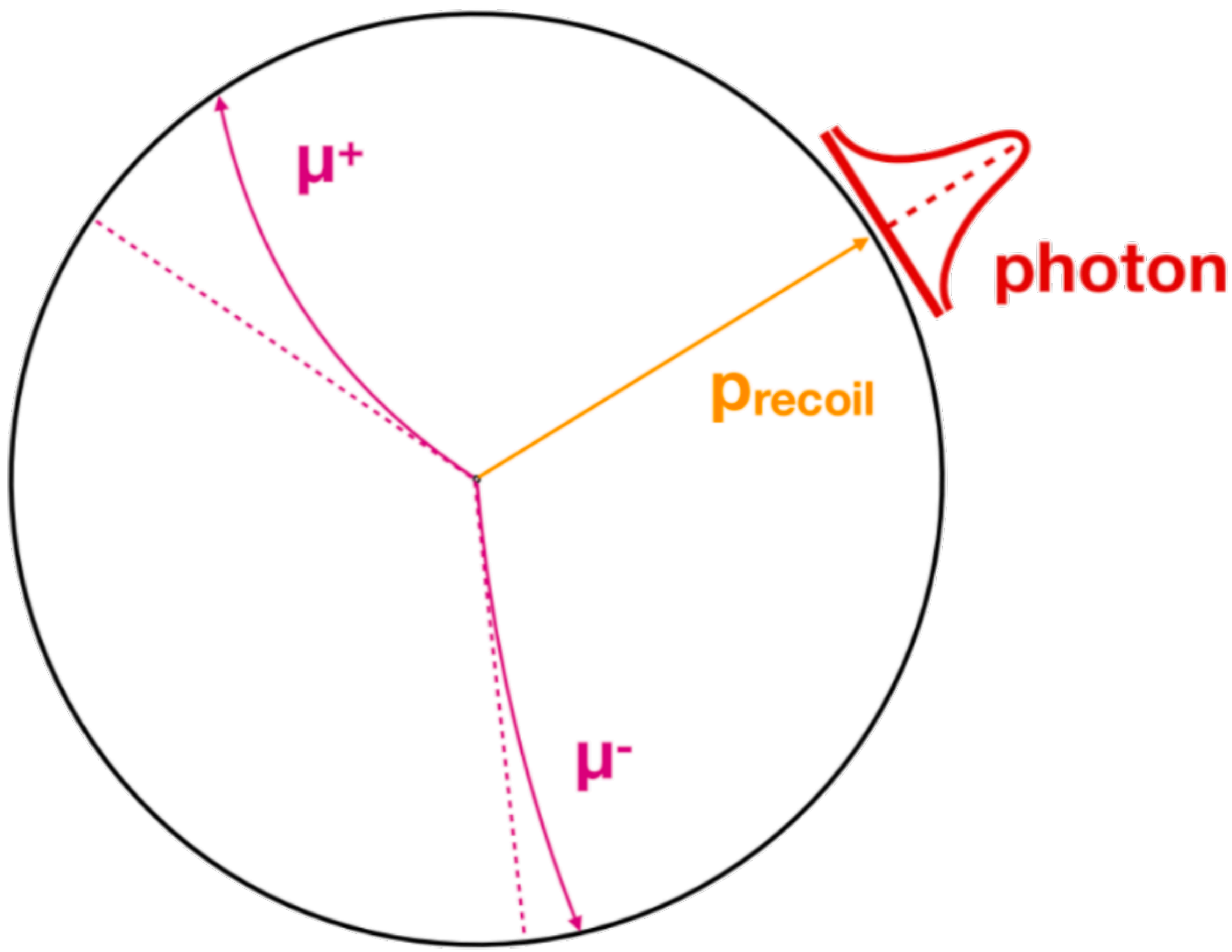


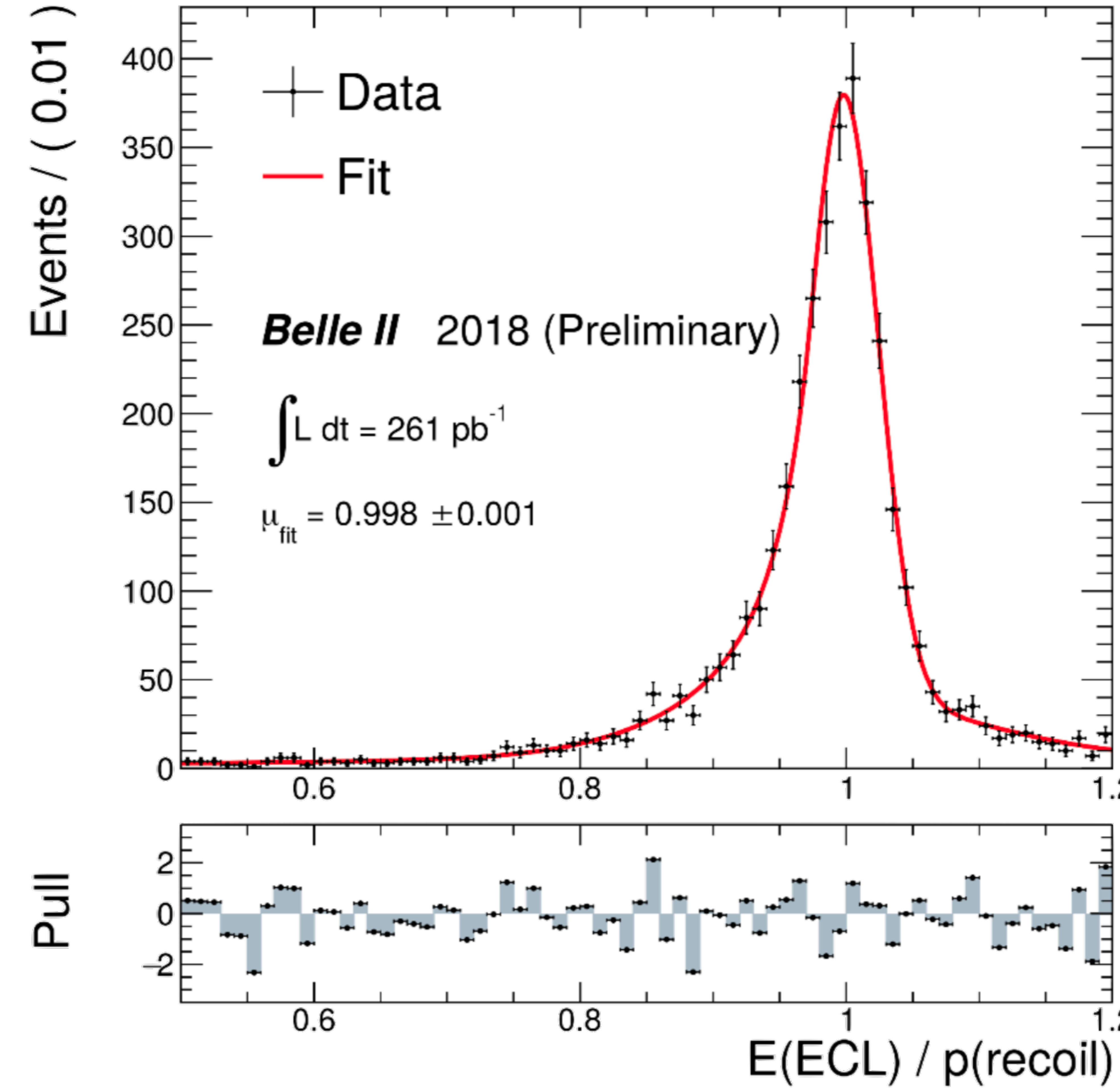
$\eta \to \gamma\gamma$



(Phase 2) photon reconstruction

$$e^+e^- \to \mu^+\mu^-\gamma$$



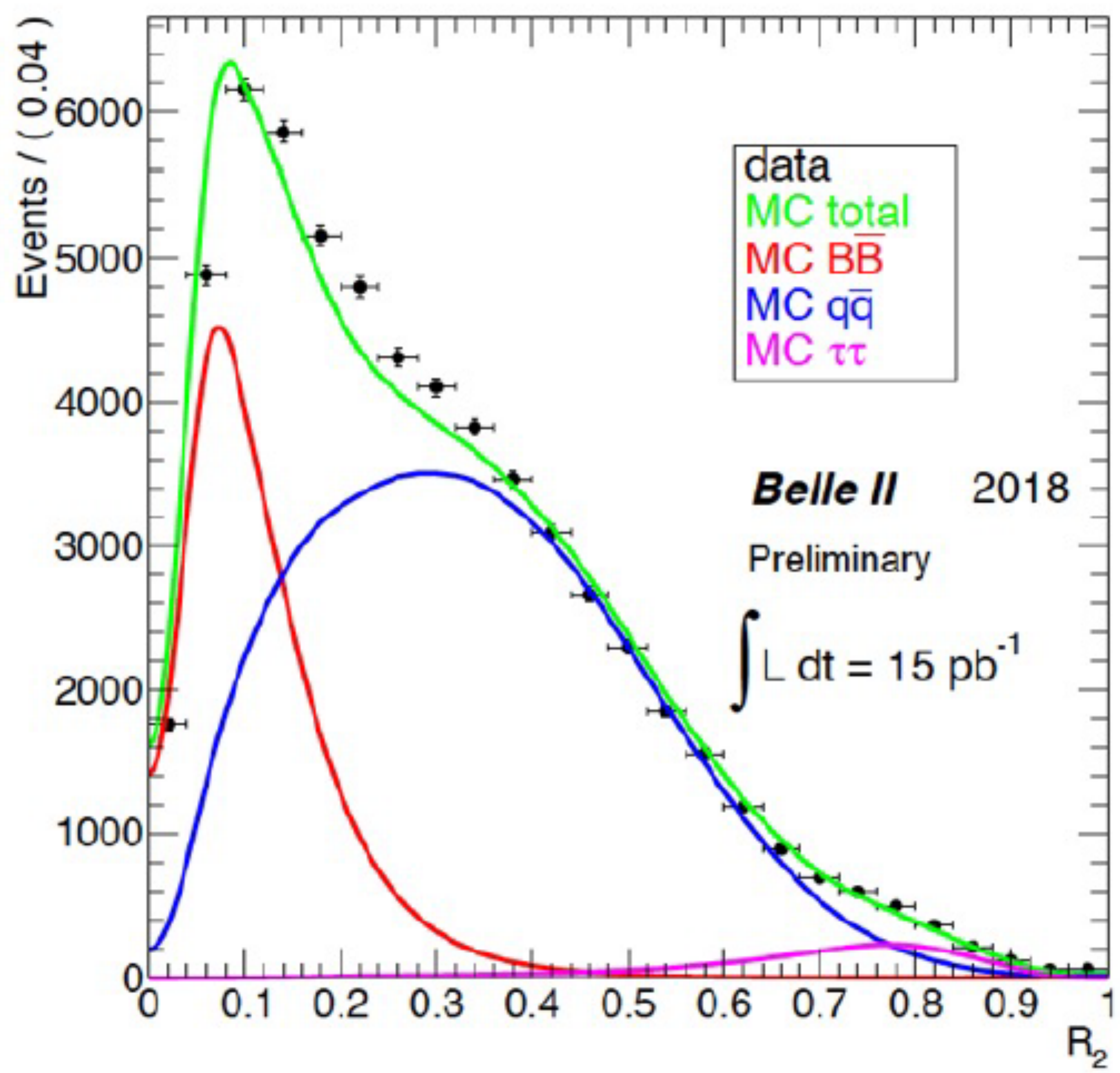


⇒ Ready for dark matter searches (single or triple γ triggers)

$$e^+e^- \to \gamma X \to \gamma(\gamma\gamma)$$

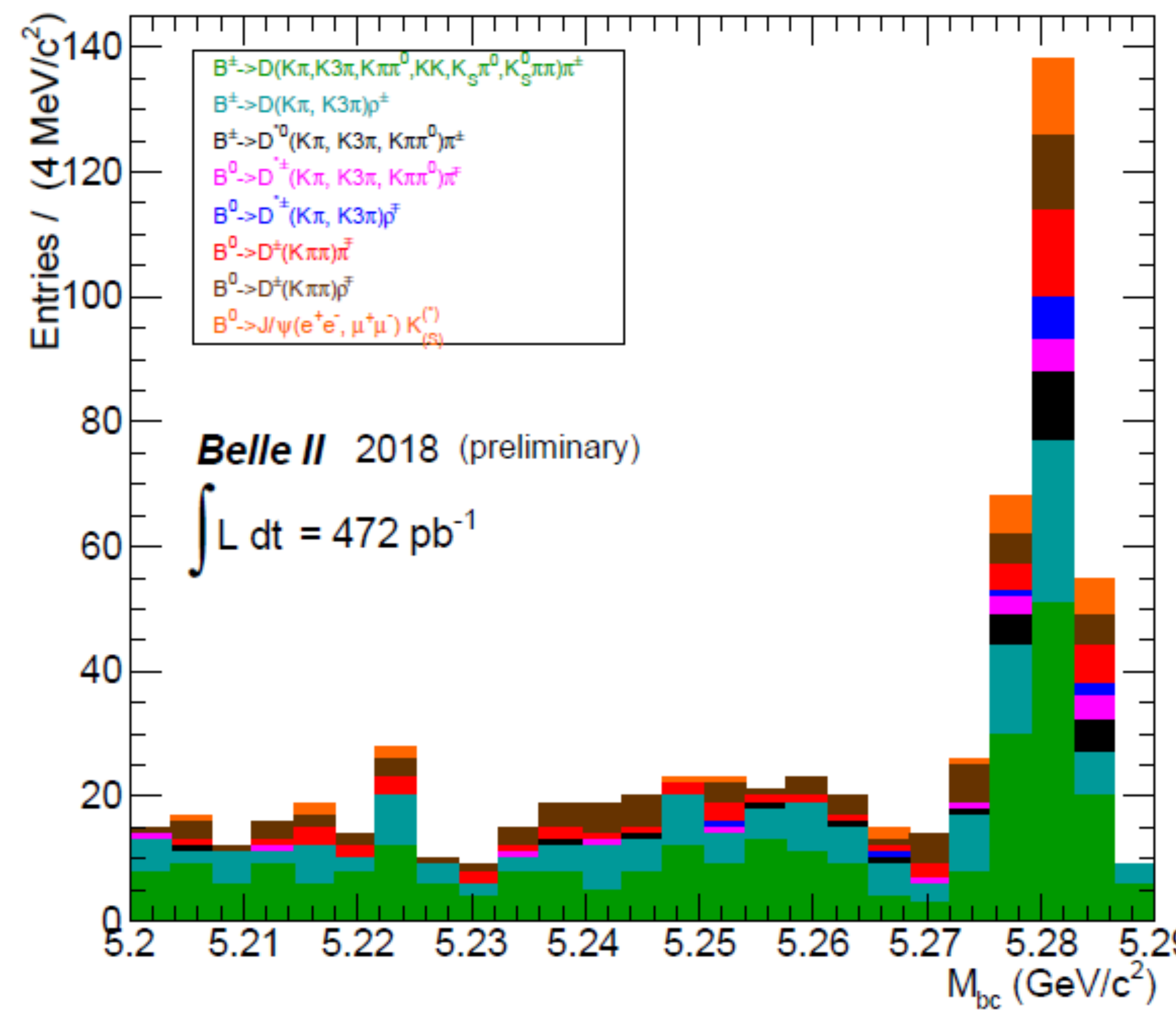
(Phase 2) Re-discovery of B mesons

Event Shape Distributionn (Fox-Wolfram R2)



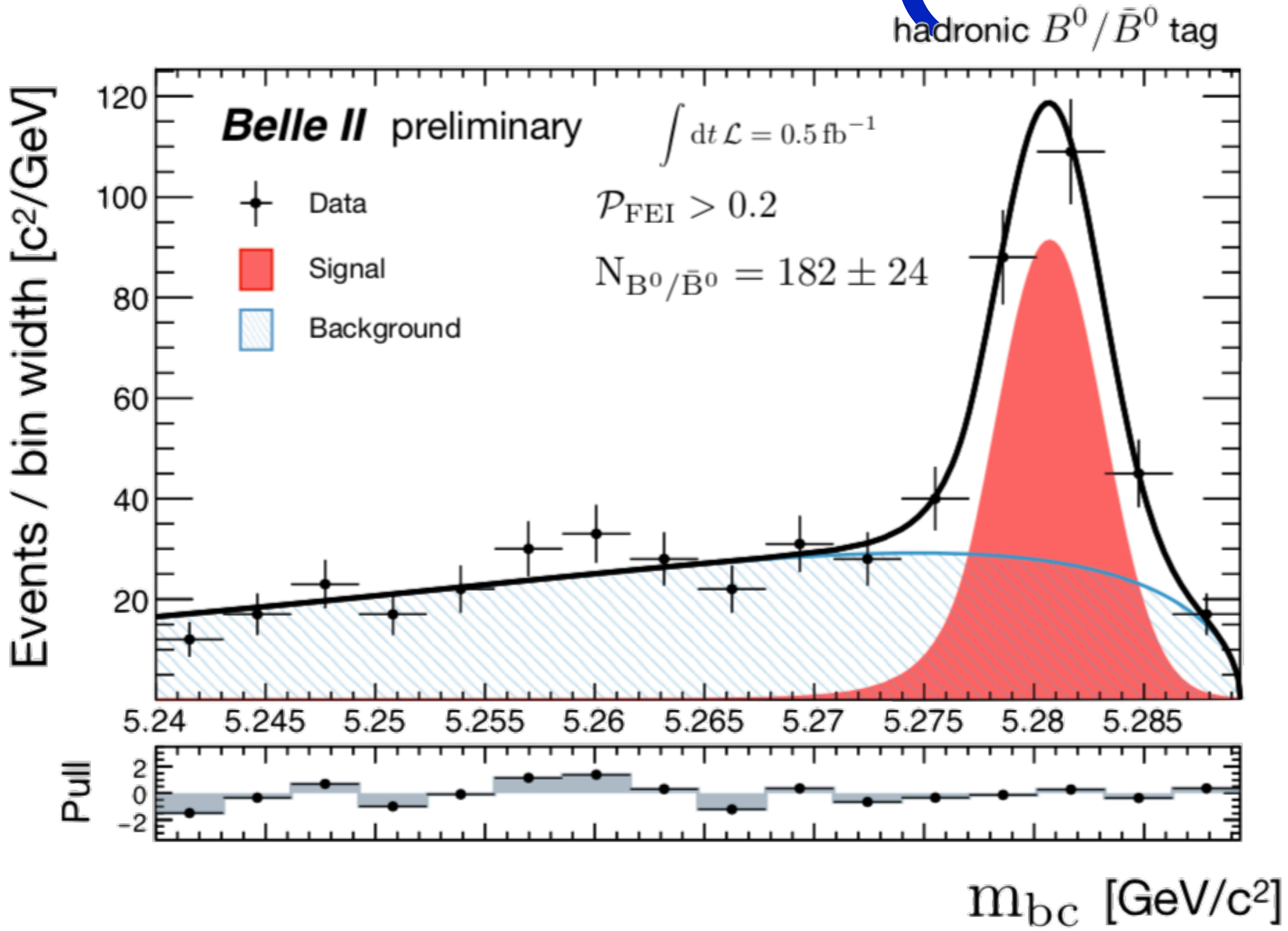
Spherical R2 Jet-like

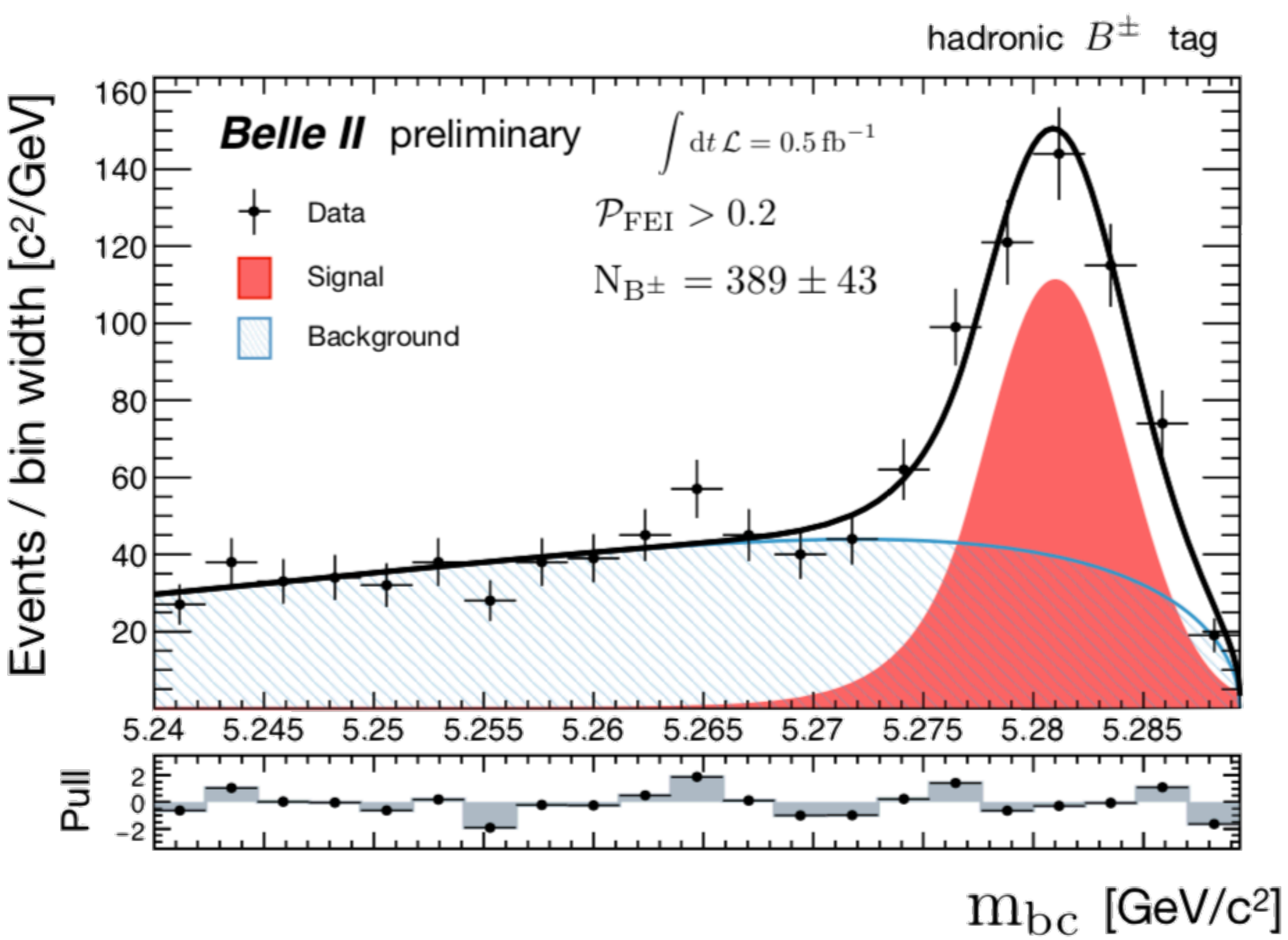
$$M_{\rm bc} = \sqrt{(E_{\rm CM}/2)^2 - p_B^2}$$



- Clearly observed the excess of $B\bar{B}$ events in early phase 2 Data
- "Rediscovered" reconstructed B mesons.
  Full reconstruction analysis chain is working well.

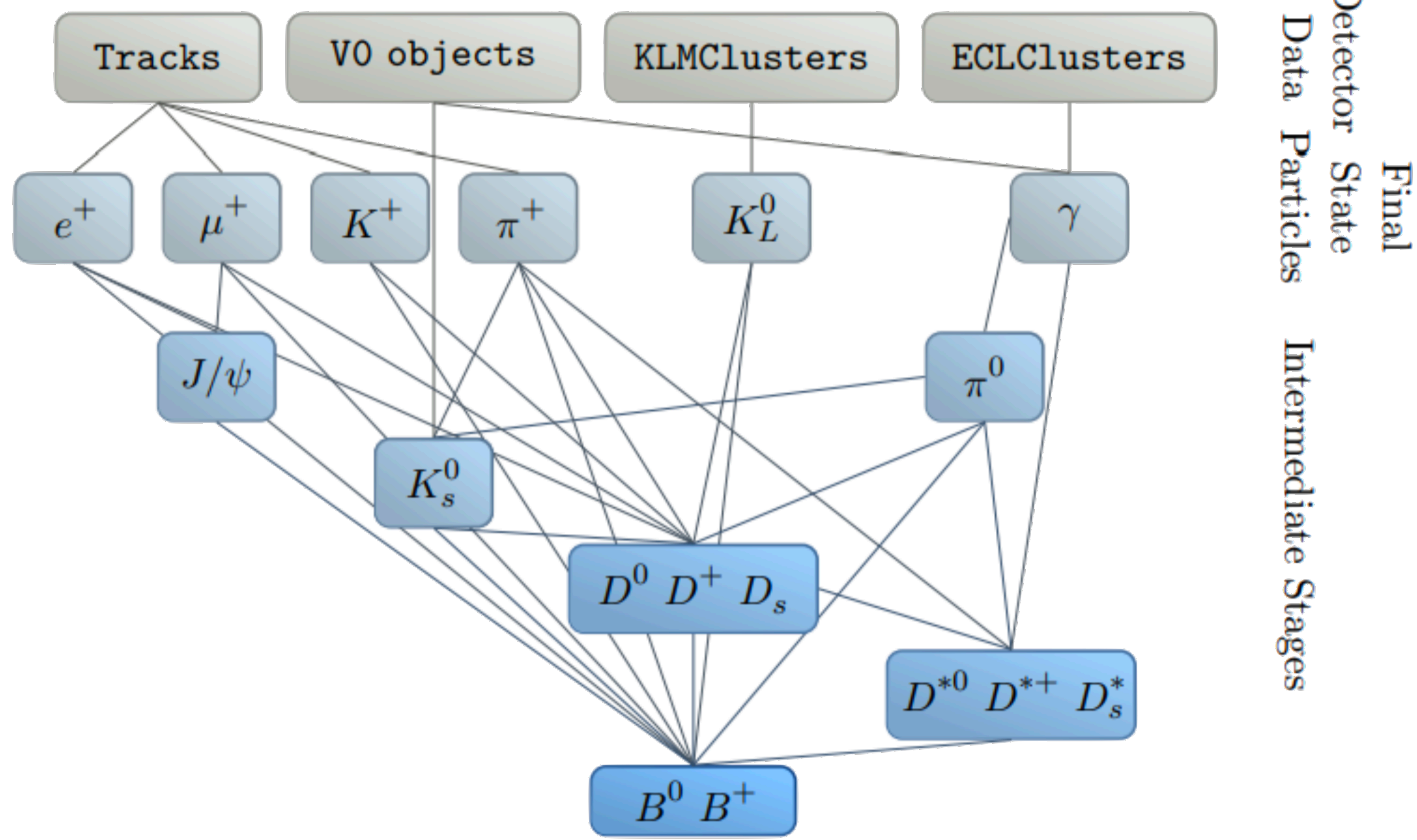
(Phase 2) Exclusive B-tagging





Full Event Interpretation (FEI)

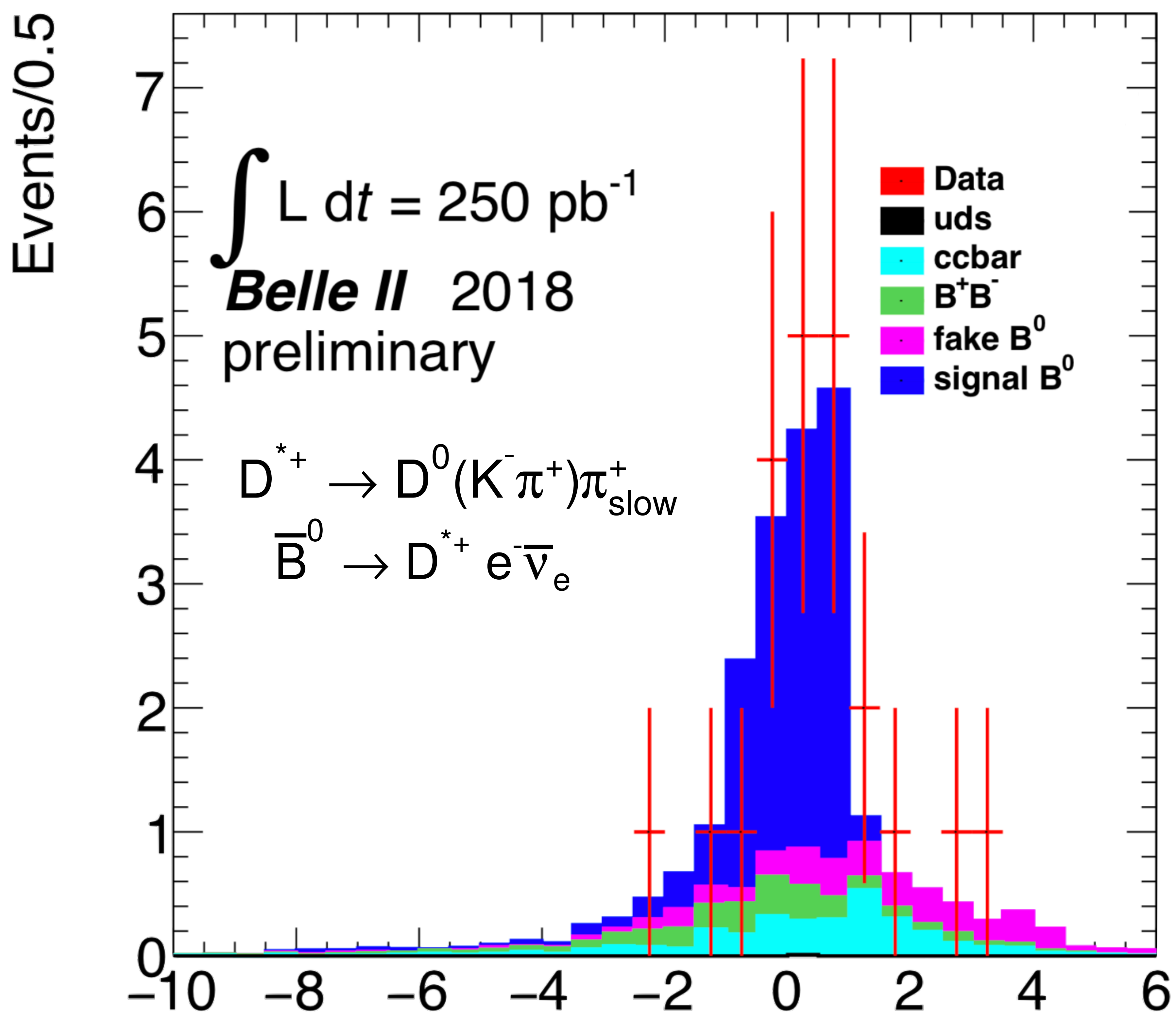
T. Keck et al., Comp. Softw. Big Sci. 3:6 (2019)



- O(200) decay chains with BDT trained for each
- O(10k) decay chains in 6 stages
- ×3 high MC efficiency than existing Belle algorithm

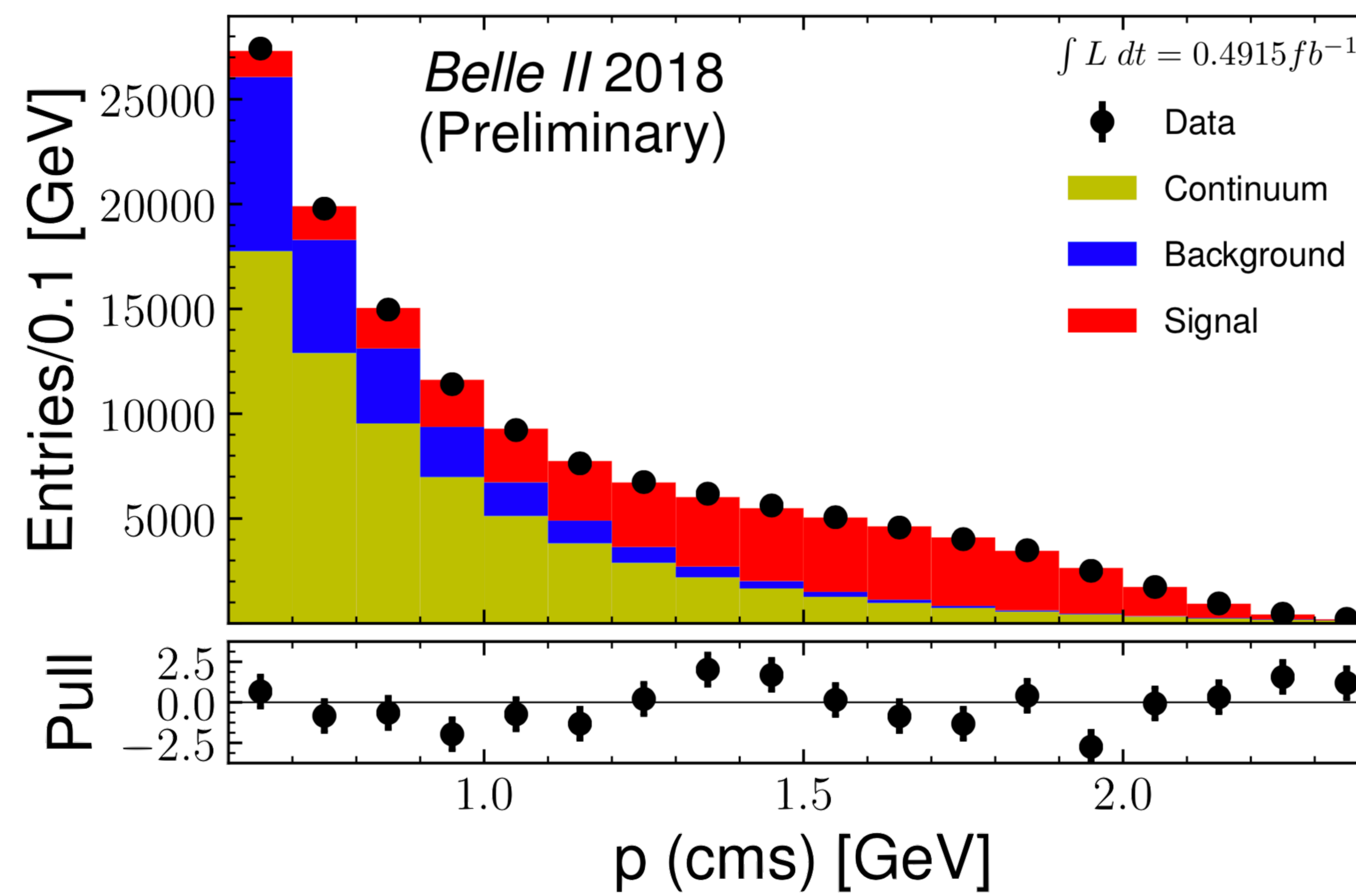
(Phase 2) Semileptonic B decay results

$\overline{B}^0 \to D^{*+} e^- \overline{\nu}_e$ (untagged)



$$\cos\theta_{BY} = \frac{2E_B^* E_Y^* - M_B^2 - M_Y^2}{2p_B^* p_Y^*}$$

$B \to X e^{\pm} \nu$ (inclusive)



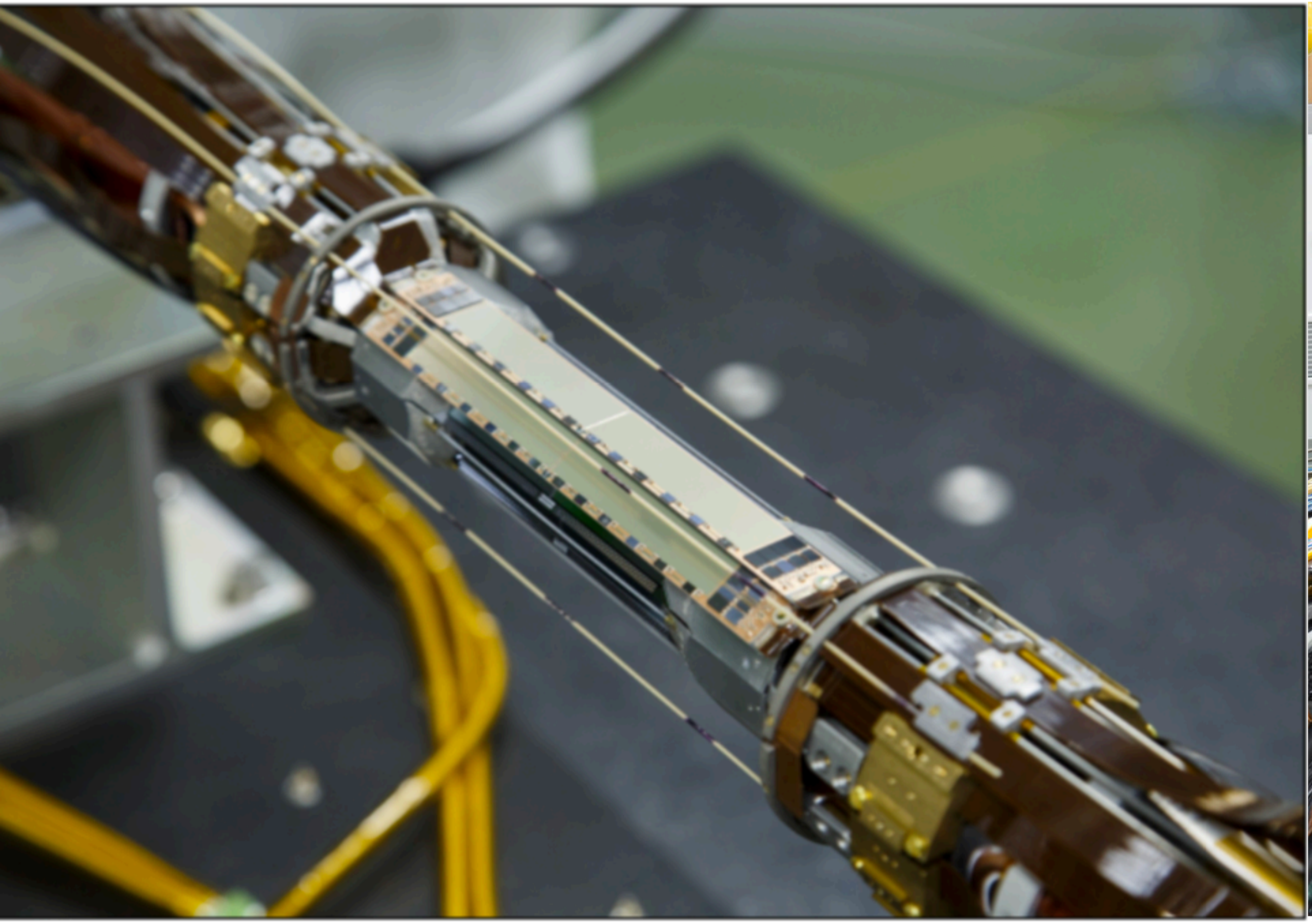
Observed (expected)
42191 ± 304 (40209 ± 200)
signal events

Belle II Phase 3

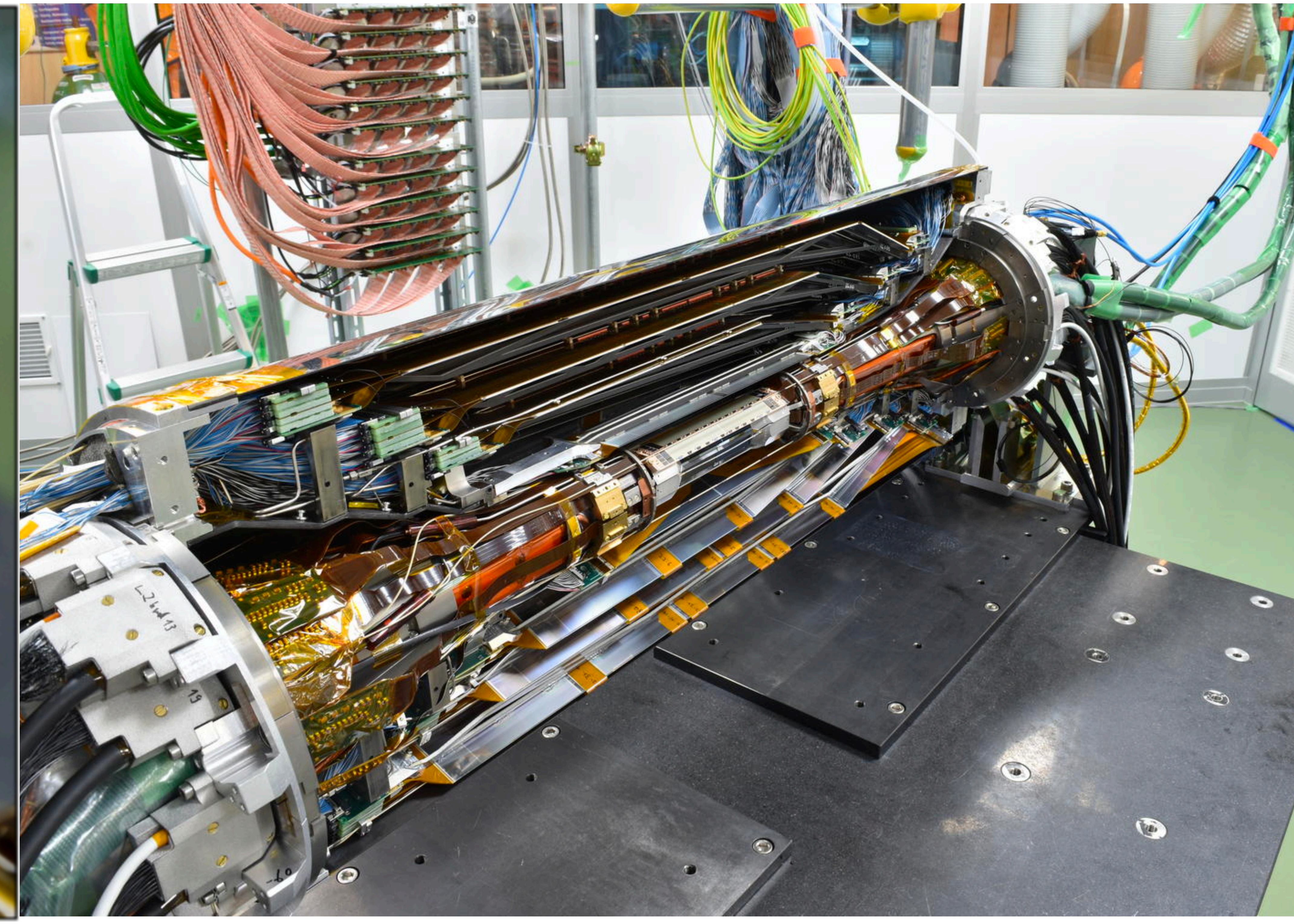
$\mathcal{L}_{\text{peak}} \sim 4 \times 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$ w/ Belle II running

$\int \mathcal{L}\, dt \sim 3\ \text{fb}^{-1}$

Belle II Phase 3



PXD mounted on beam pipe

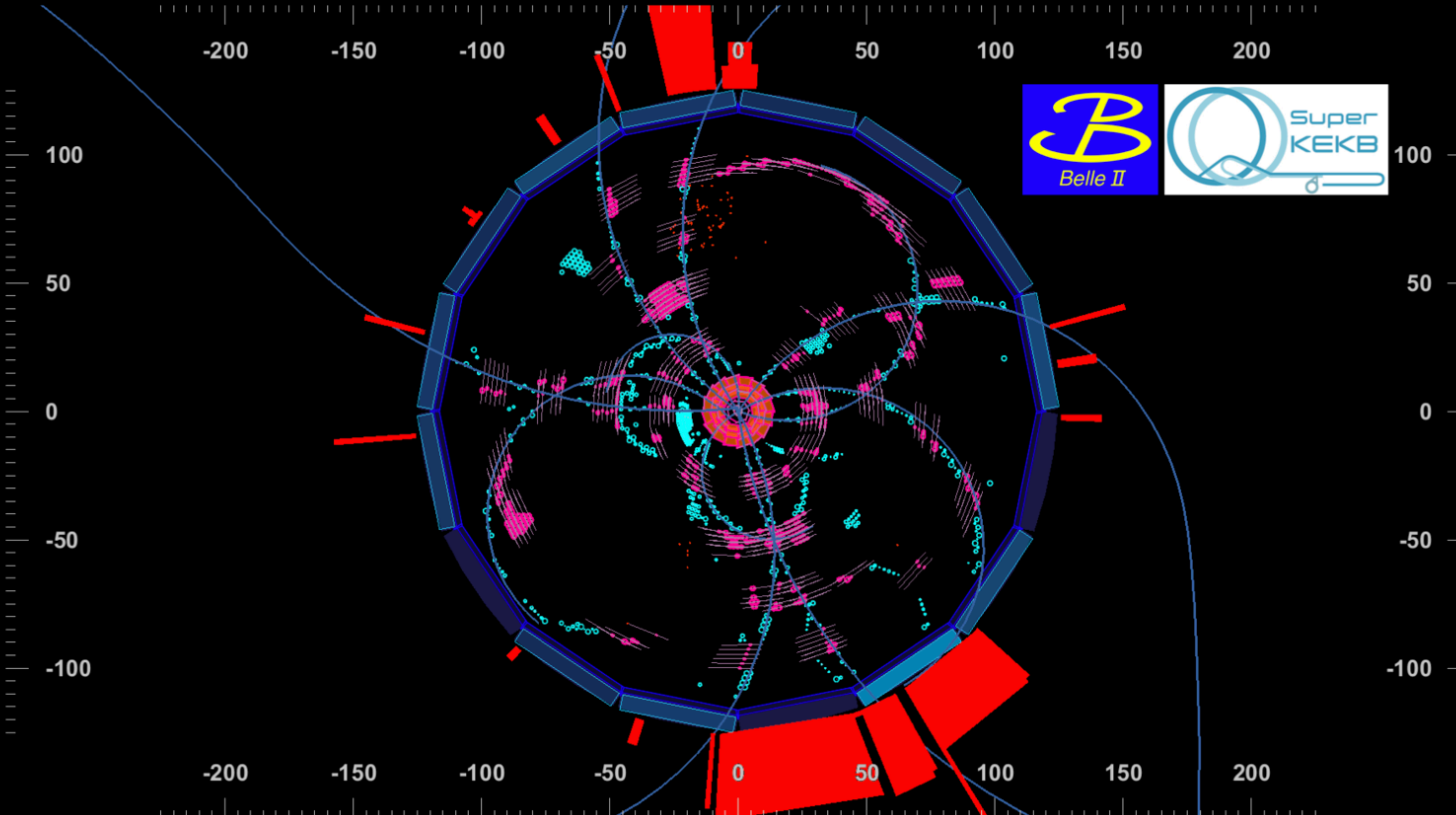


PXD combined with 1/2 of SVD

full PXD operation (with 2 layers) scheduled for 2020

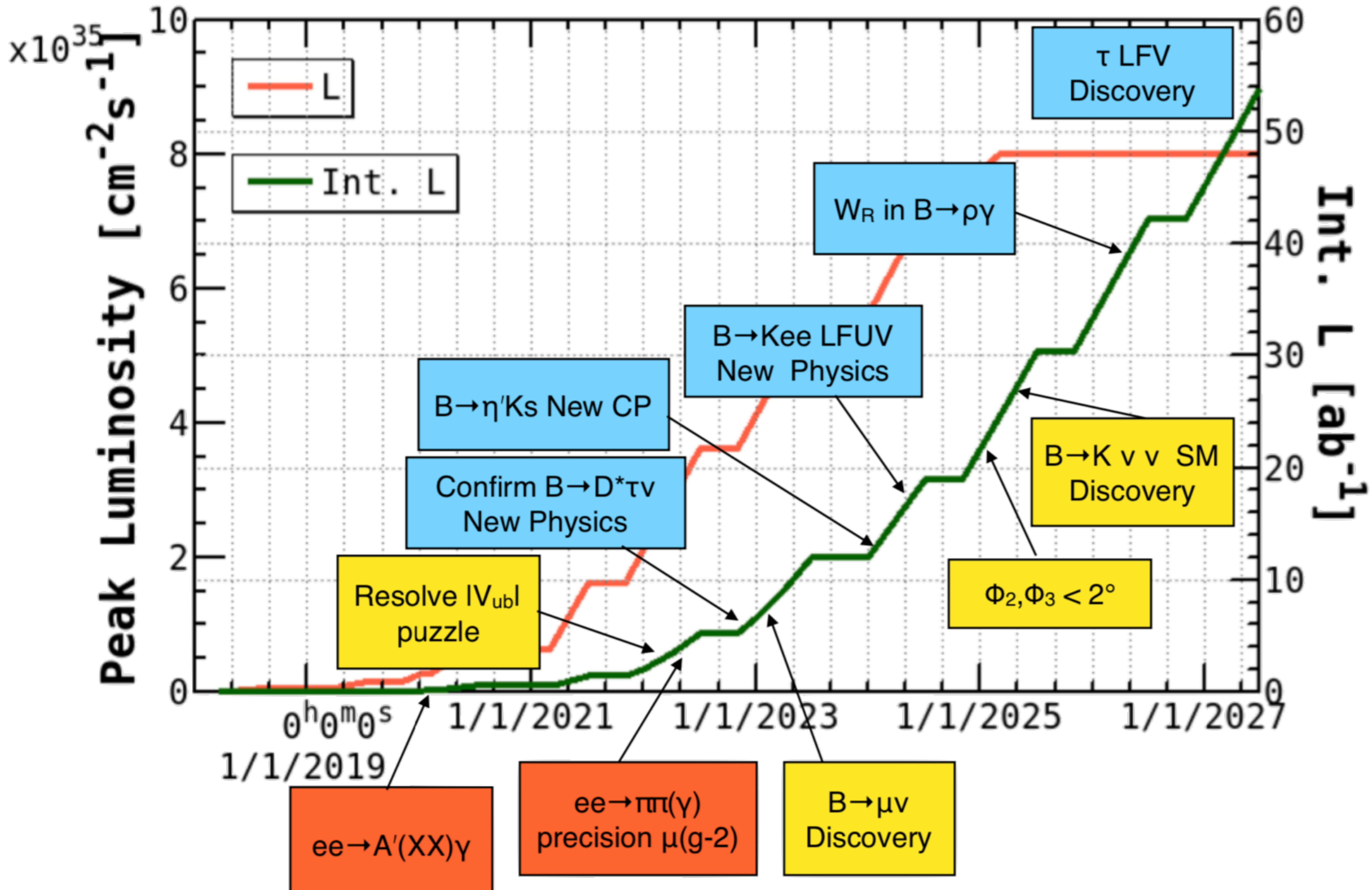
First BB-like event in the Belle II Phase 3 run

2019.3.25



Summary

- Belle II physics run (Phase 3) has started on Mar.25, 2019.
- Belle II is ready to open a new era of flavor physics.

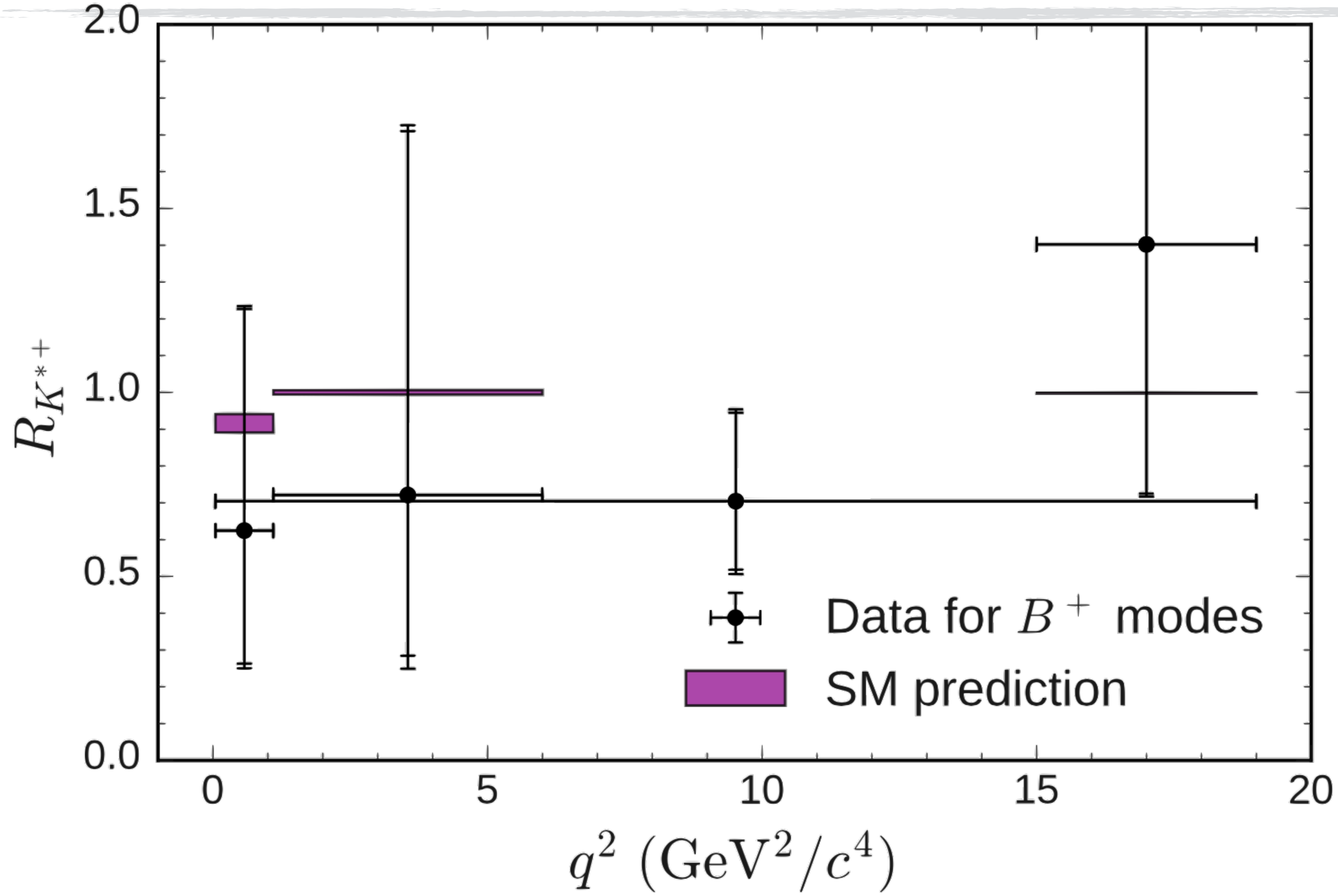


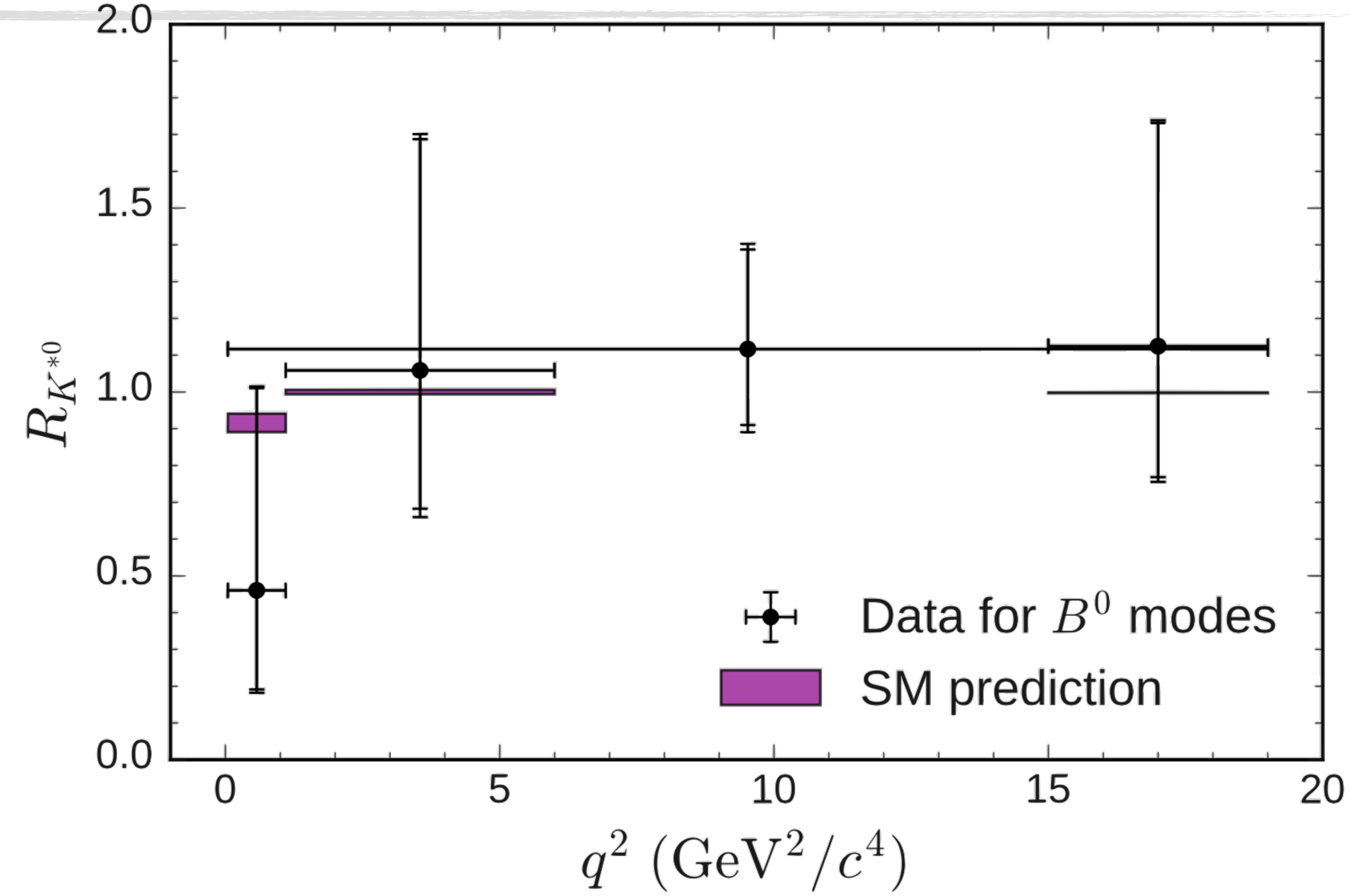

I have no idea what ERFCI stands for... is it a satellite or a metric?
30 slides in 10 minutes... is that a joke?
Hmmmmmm... I really need to make a dentist appointment.
Huh. I wonder if I should calculate the r² value?
This coffee is delicious.
I'm lost.

Thank you!

Back-up

R_{K^*} from Belle

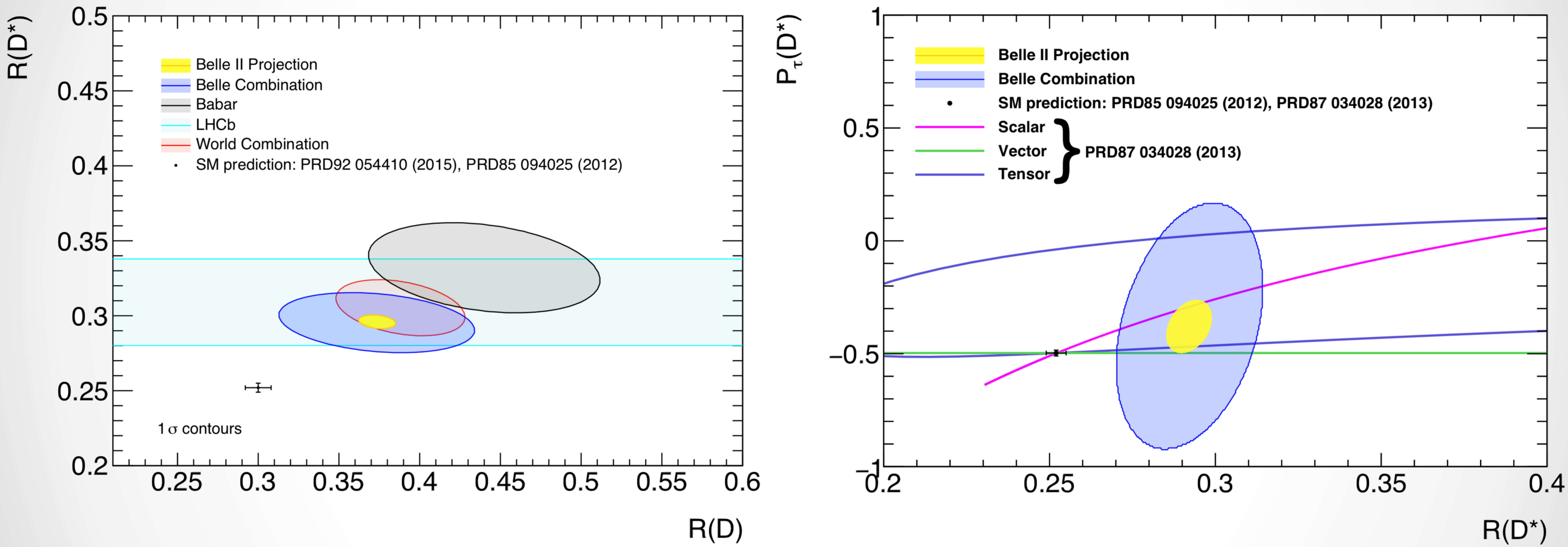




q^2 in GeV^2/c^4	All modes	B^0 modes	B^+ modes
$[0.045, 1.1]$	$0.52^{+0.36}_{-0.26} \pm 0.05$	$0.46^{+0.55}_{-0.27} \pm 0.07$	$0.62^{+0.60}_{-0.36} \pm 0.10$
$[1.1, 6]$	$0.96^{+0.45}_{-0.29} \pm 0.11$	$1.06^{+0.63}_{-0.38} \pm 0.13$	$0.72^{+0.99}_{-0.44} \pm 0.18$
$[0.1, 8]$	$0.90^{+0.27}_{-0.21} \pm 0.10$	$0.86^{+0.33}_{-0.24} \pm 0.08$	$0.96^{+0.56}_{-0.35} \pm 0.14$
$[15, 19]$	$1.18^{+0.52}_{-0.32} \pm 0.10$	$1.12^{+0.61}_{-0.36} \pm 0.10$	$1.40^{+1.99}_{-0.68} \pm 0.11$
$[0.045,]$	$0.94^{+0.17}_{-0.14} \pm 0.08$	$1.12^{+0.27}_{-0.21} \pm 0.09$	$0.70^{+0.24}_{-0.19} \pm 0.07$

- all measured values are consistent with SM and other recent measurements
- First $R(K^*)$ from B^+

Belle II prospects for $B \to D^* \tau \nu$



Plots are from “The Belle II Physics Book”, arXiv:1808.10567.

New in 2019

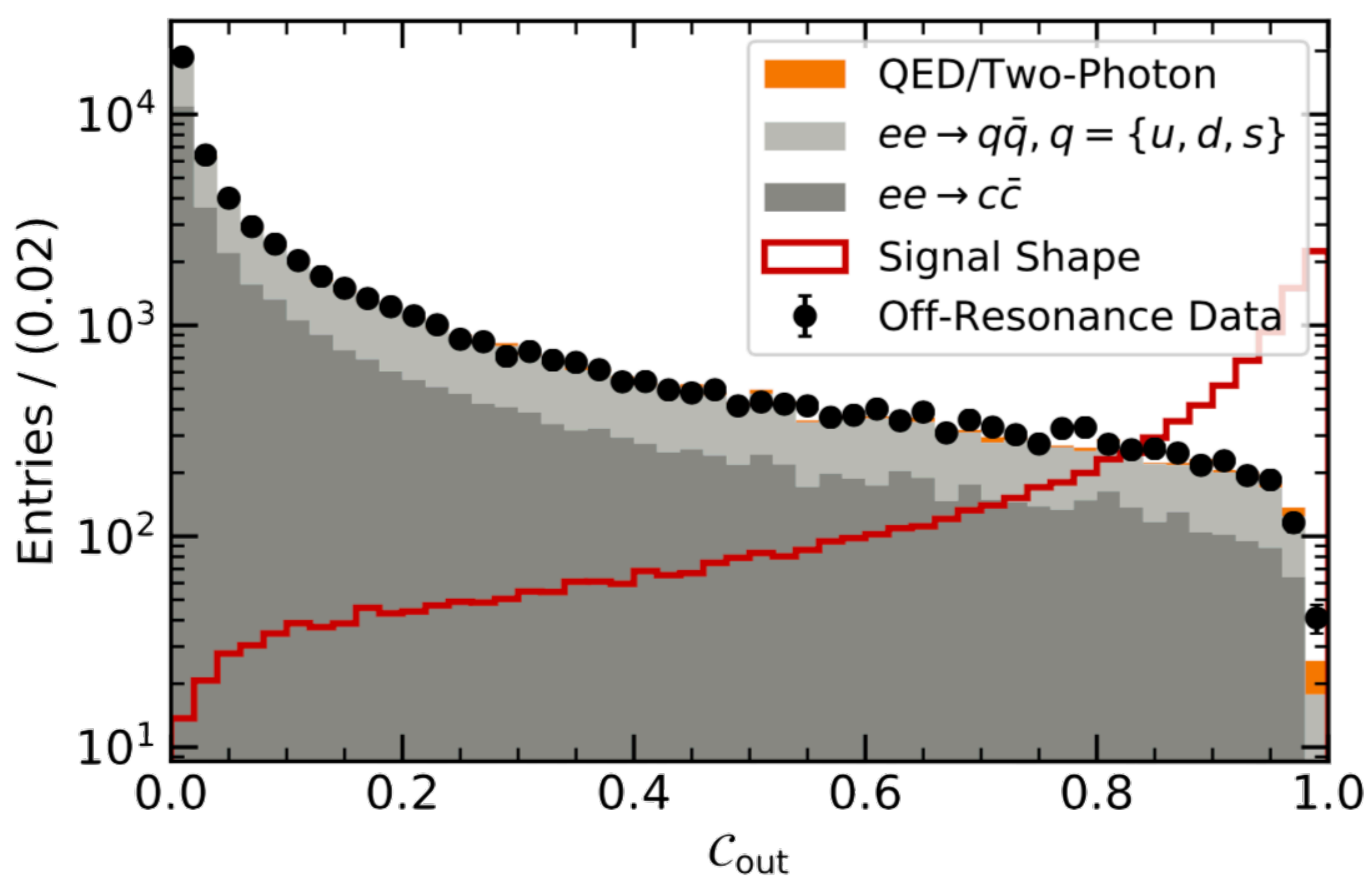
Preliminary

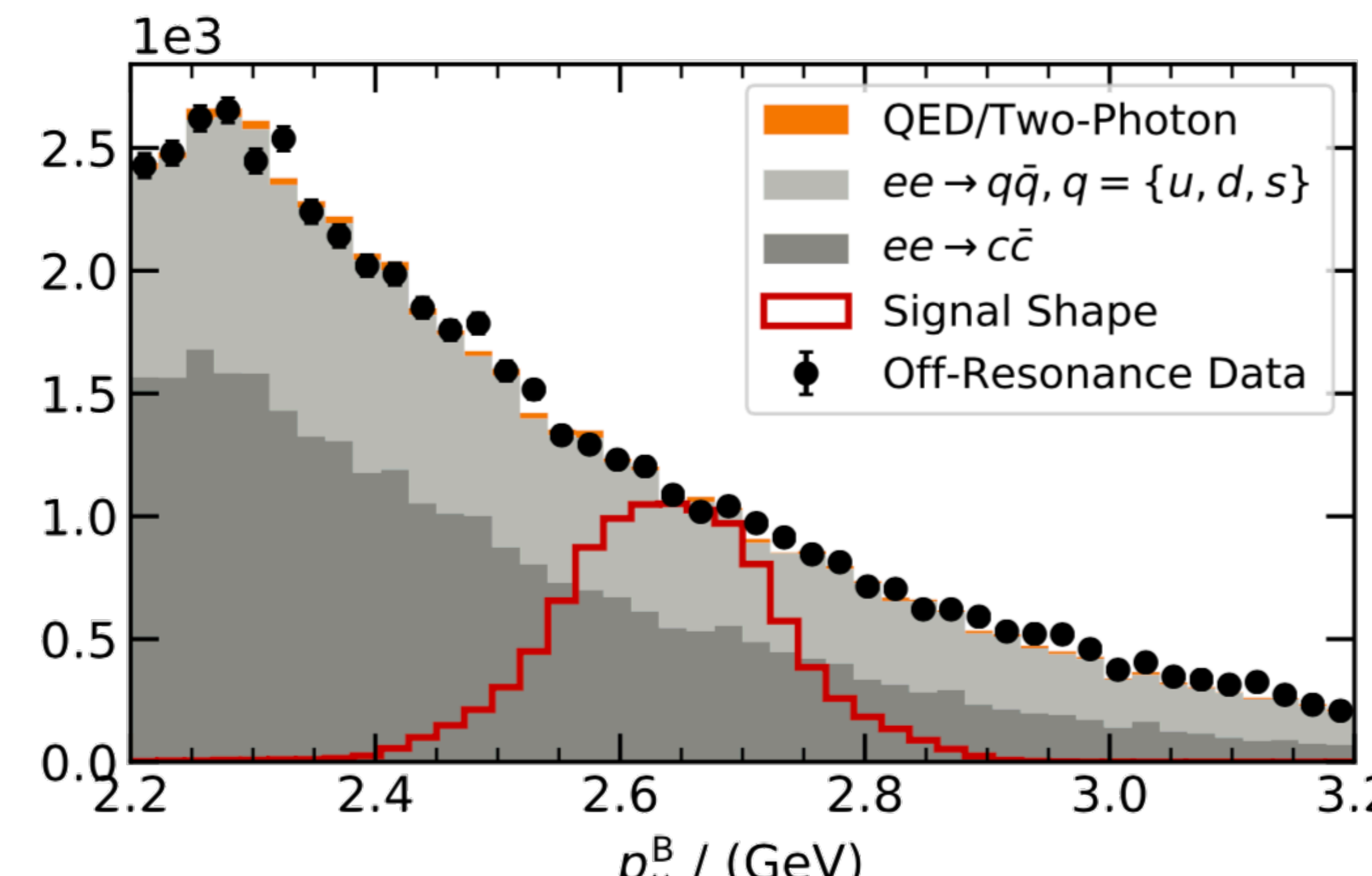
$B^+ \to \mu^+\nu$ and $B^+ \to \mu^+ N$

Signal extraction

✓ by binned max. likelihood fit to p_μ^B in kinematic/BDT categories

Category	C_{out}	$\cos\Theta_{B\mu}$	Signal Efficiency
I	[0.98,1.00)	[-0.13,1.00)	6.5 %
II	[0.98,1.00)	[-1.00,-0.13)	5.9 %
III	[0.93,0.98)	[0.04,1.00)	7.1 %
IV	[0.93,0.98)	[-1.00,0.04)	8.3 %





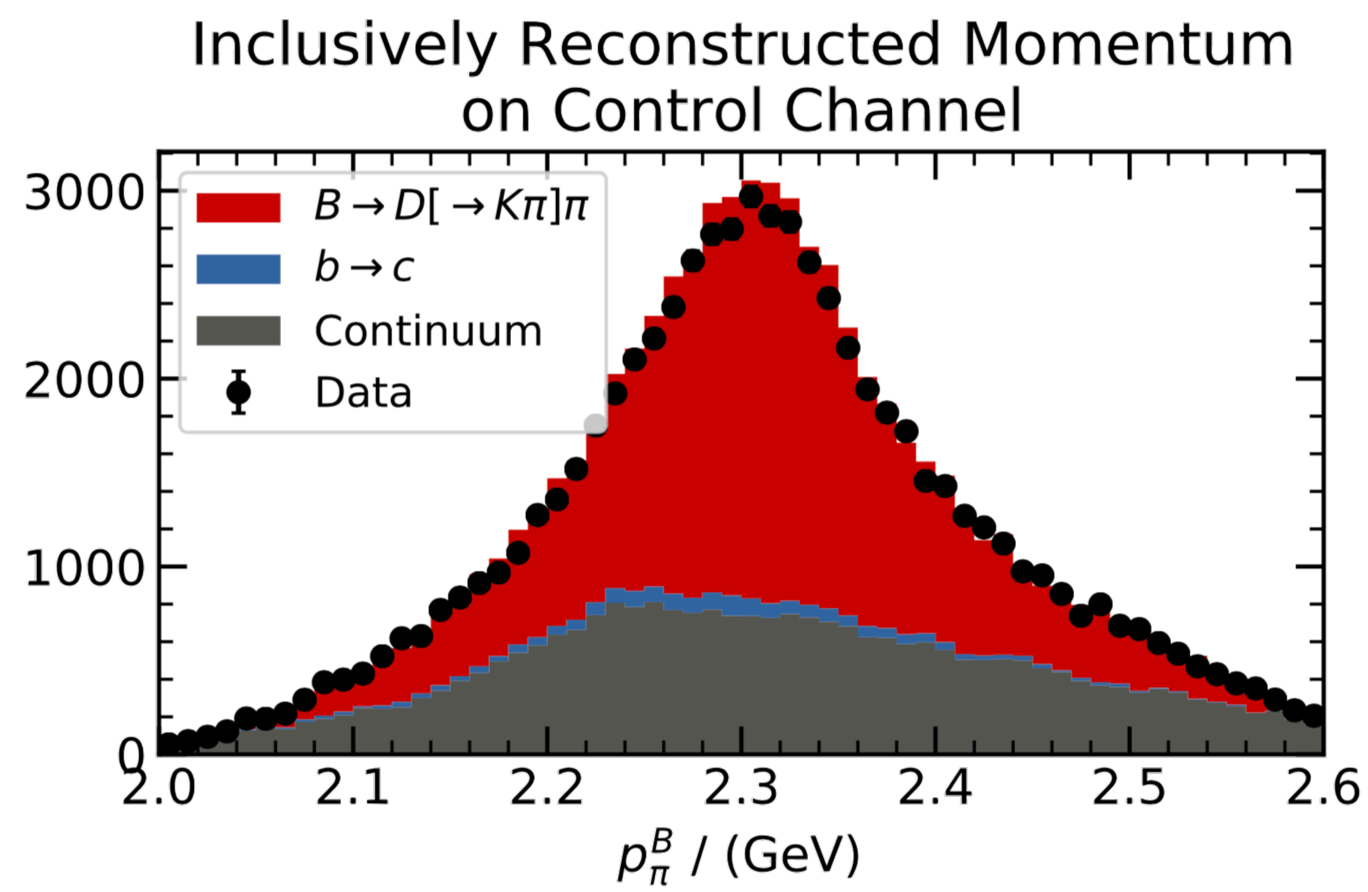
New in 2019

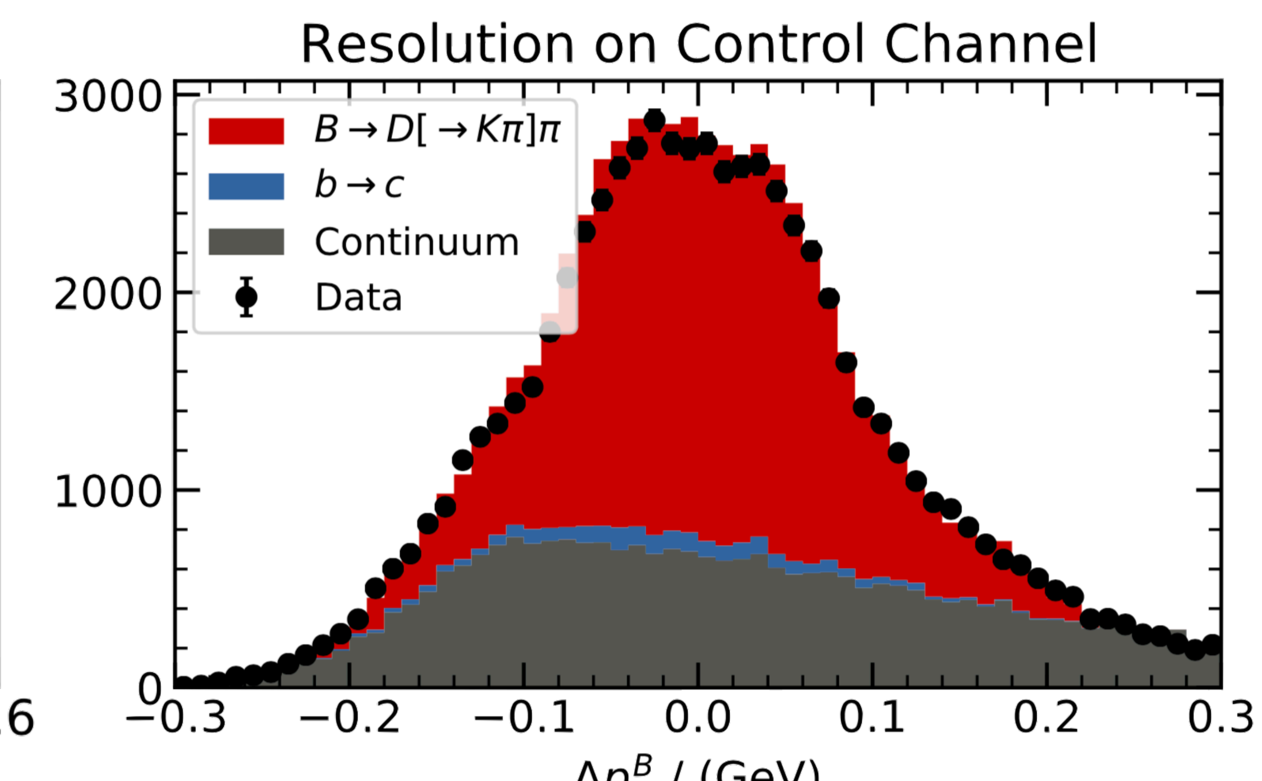
$B^+ \to \mu^+\nu$ and $B^+ \to \mu^+ N$

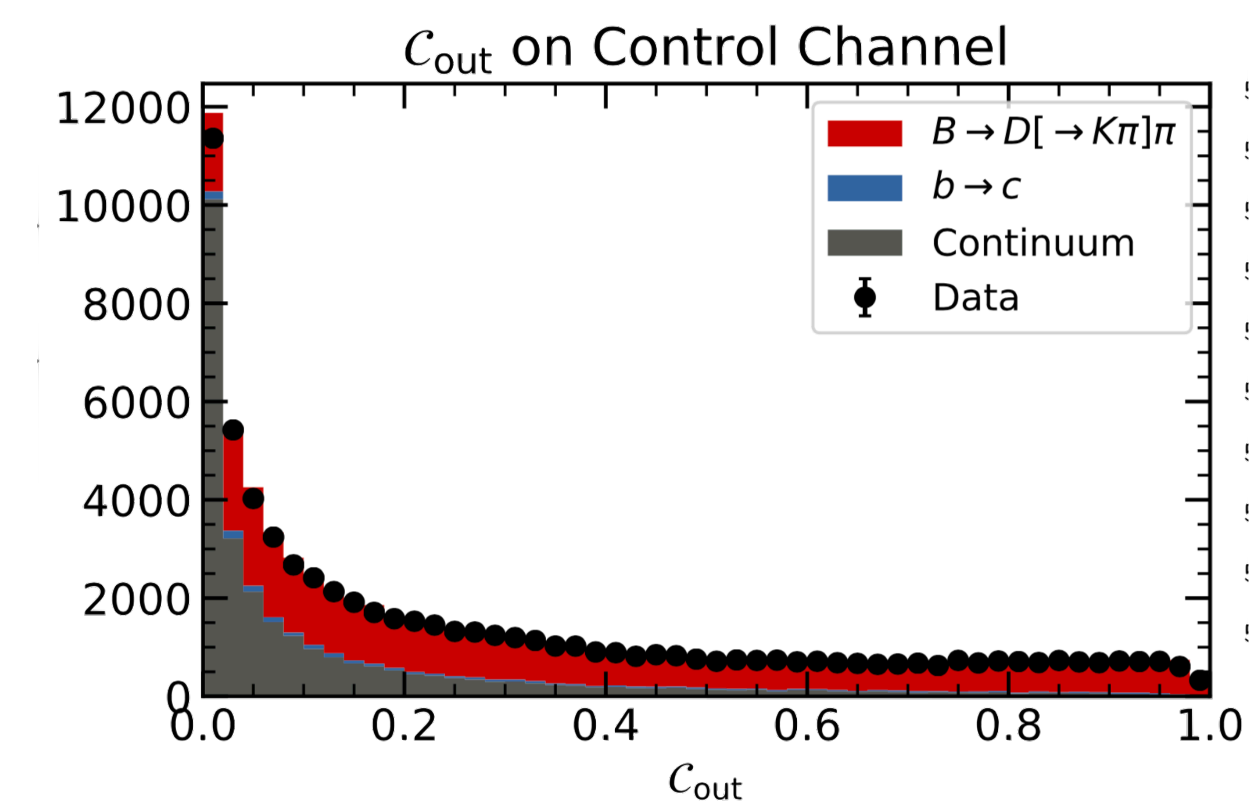
Preliminary

Signal extraction

- ✓ The procedure is validated by measuring $B^+ \to \overline{D}^0 \pi^+$
- ✓ Clean sample is reconstructed and selected by M_{bc}, $|\Delta E|$
- ✓ Prompt π^+ is treated as the signal μ^+
- ✓ Check Data vs. MC for p_μ^B, Δp_μ^B, $\mathcal{C}_{\mathrm{out}}$





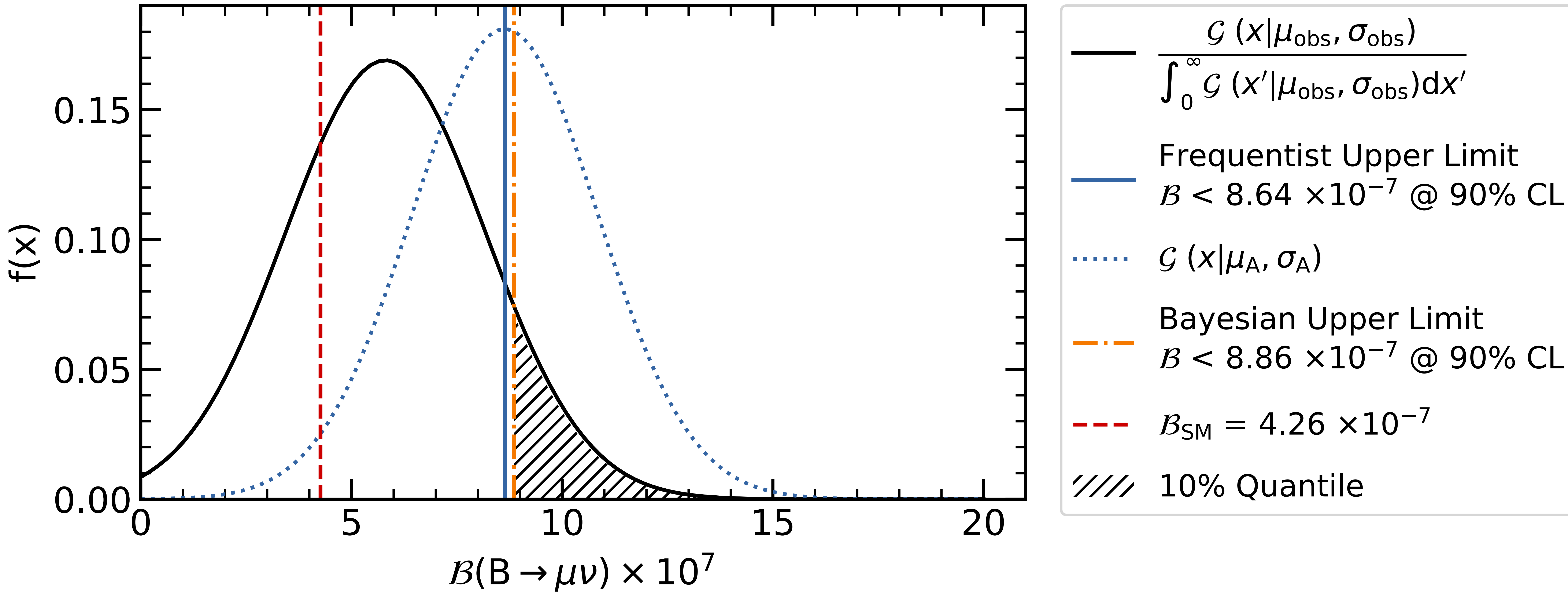


$$\Delta p_\mu^B = 0.11\ \mathrm{GeV}$$

New in 2019

Preliminary

$B^+ \rightarrow \mu^+\nu$ Results

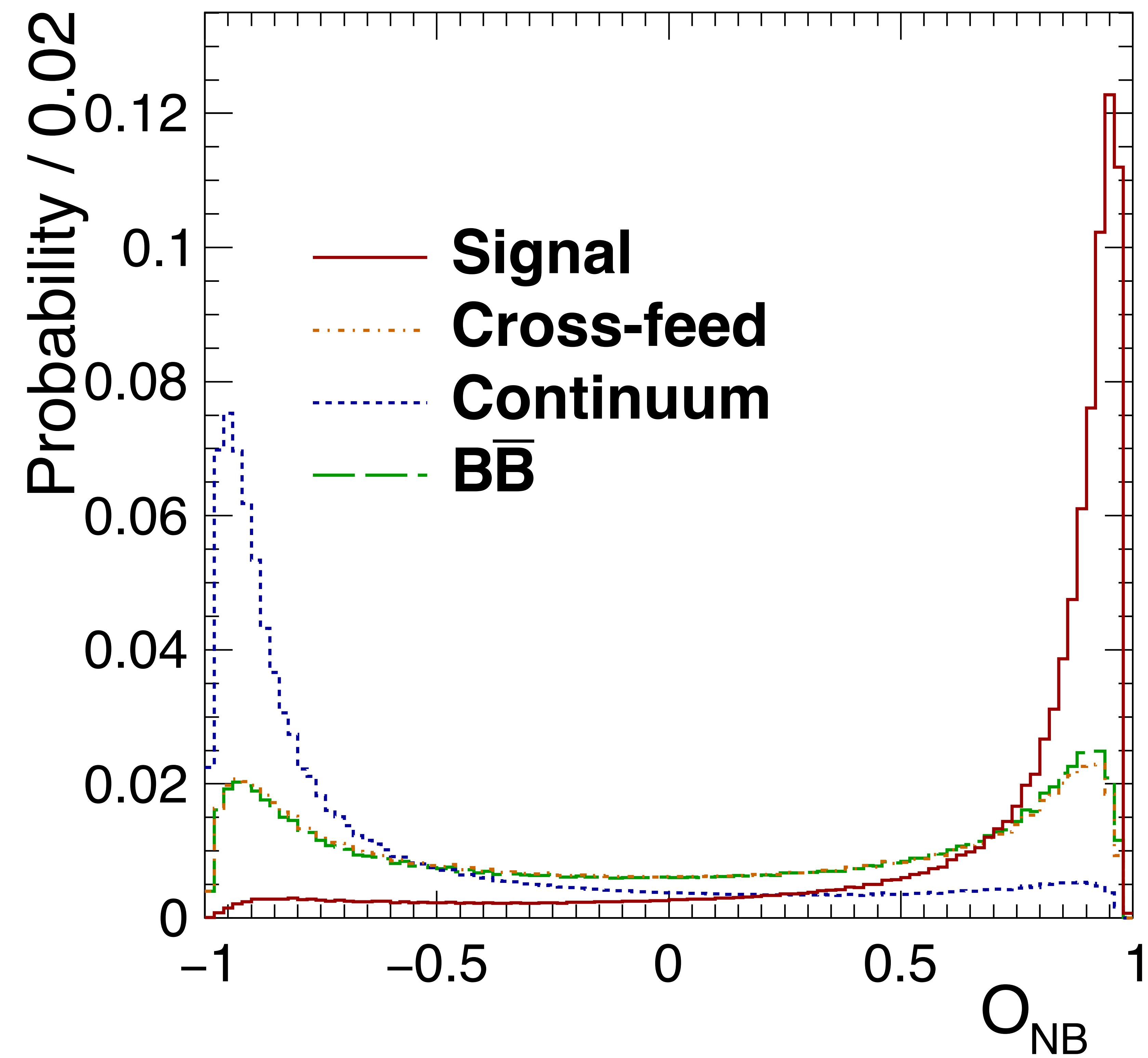


$\mathcal{B}(B^+ \to \mu^+\nu) < 8.6 \times 10^{-7}$ **Frequentist**

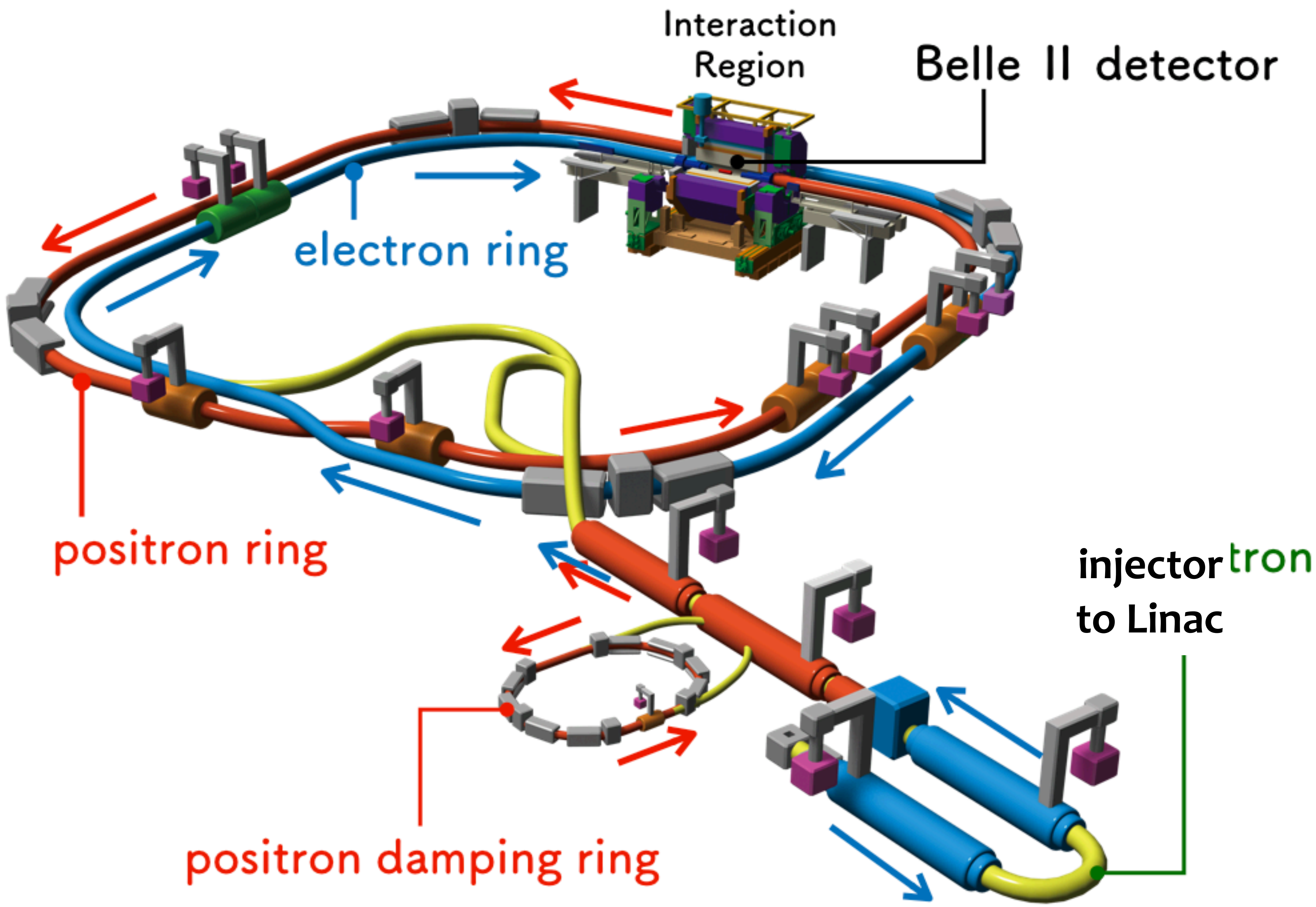
$< 8.9 \times 10^{-7}$ **Bayesian**

$B \to X_s\gamma$ inclusive backgrounds

- Two dominant sources
  - * $e^+e^- \to q\bar{q}$ continuum
  - * $B \to D^{(*)}\rho^+$
- Suppression by
  - * artificial NN (signal vs. $q\bar{q}$)
  - * D veto



SuperKEKB upgrade



- new e+ ring vacuum chamber (3km; commissioned 2016)
- new e+ damping ring (commissioned 2018)
- new superconducting final focus (commissioned 2018)

$$e^- \xrightarrow{7\ \text{GeV}} (\star) \xleftarrow{4\ \text{GeV}} e^+$$