Lepton flavour universality and lepton flavour violation tests at Belle II

Elisa Manoni

Istituto Nazionale di Fisica Nucleare, Sezione di Perugia

"Interplay of quark and lepton flavour at Belle II and the LHC"

Institute of the Physics of the Universe , Aix-Marseille Université

July 3rd, 2021

S. Tanaka

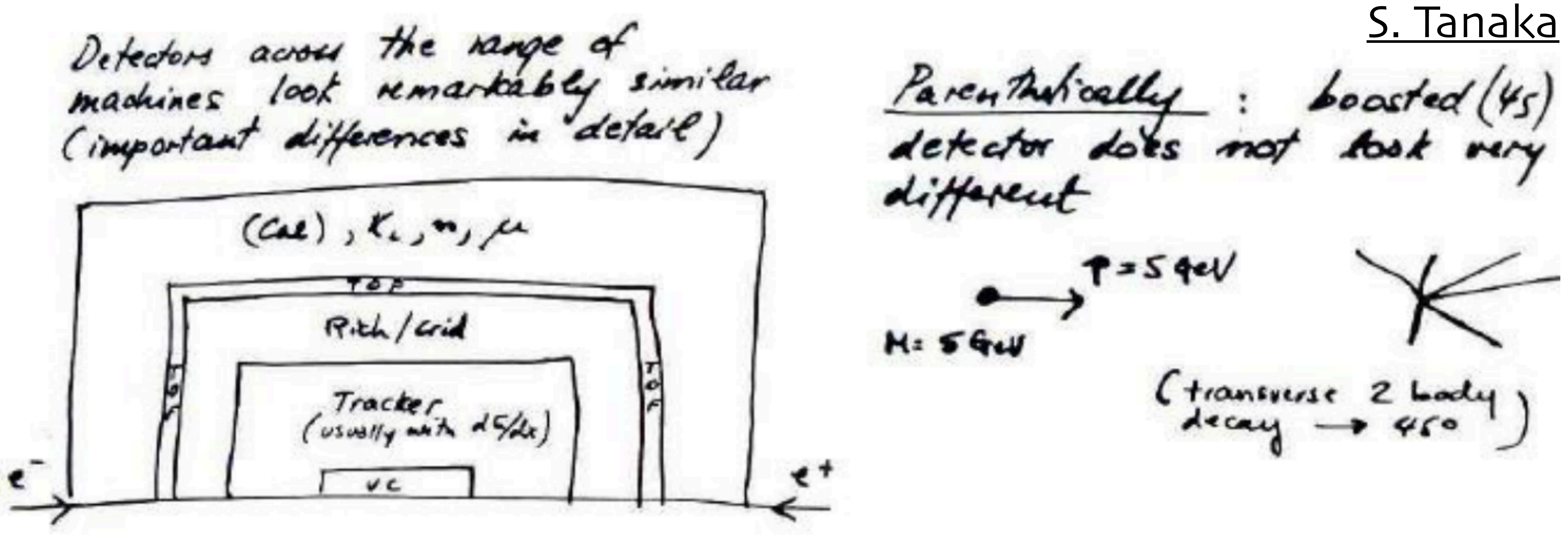


Figure 2: First presentation [17] of the boosted-$\Upsilon(4S)$ idea in 1987.

Standard Model is a working theory..

- Two examples:

..but not the ultimate one

- What's the origin of lepton and quark particle mass and mixing angle pattern?
- Why matter dominates ove anti-matter?
- What's the origin of dark matter?
- …….

..but not the ultimate one

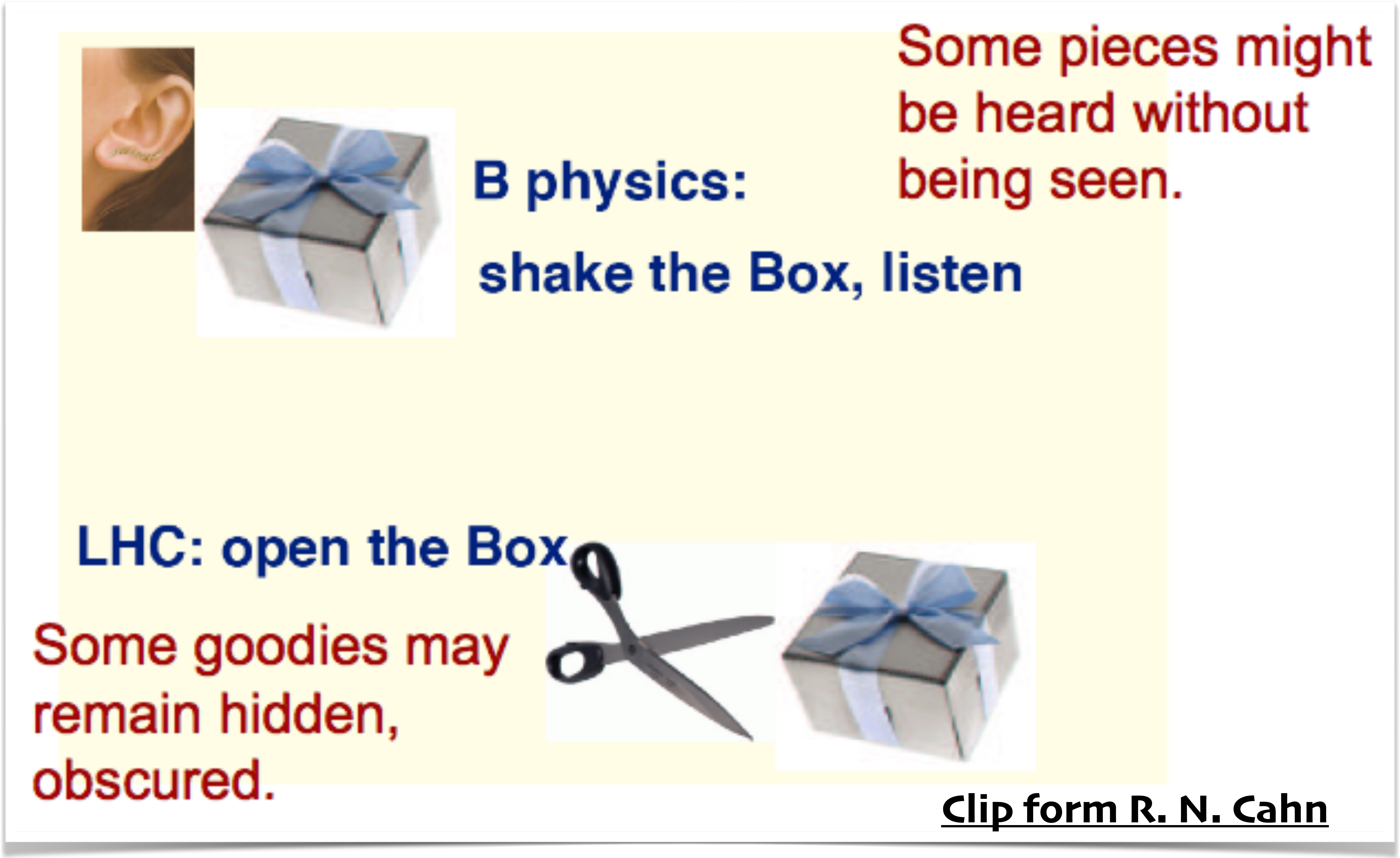
- What's t
  pattern?
- Why ma
- What's t
- ....

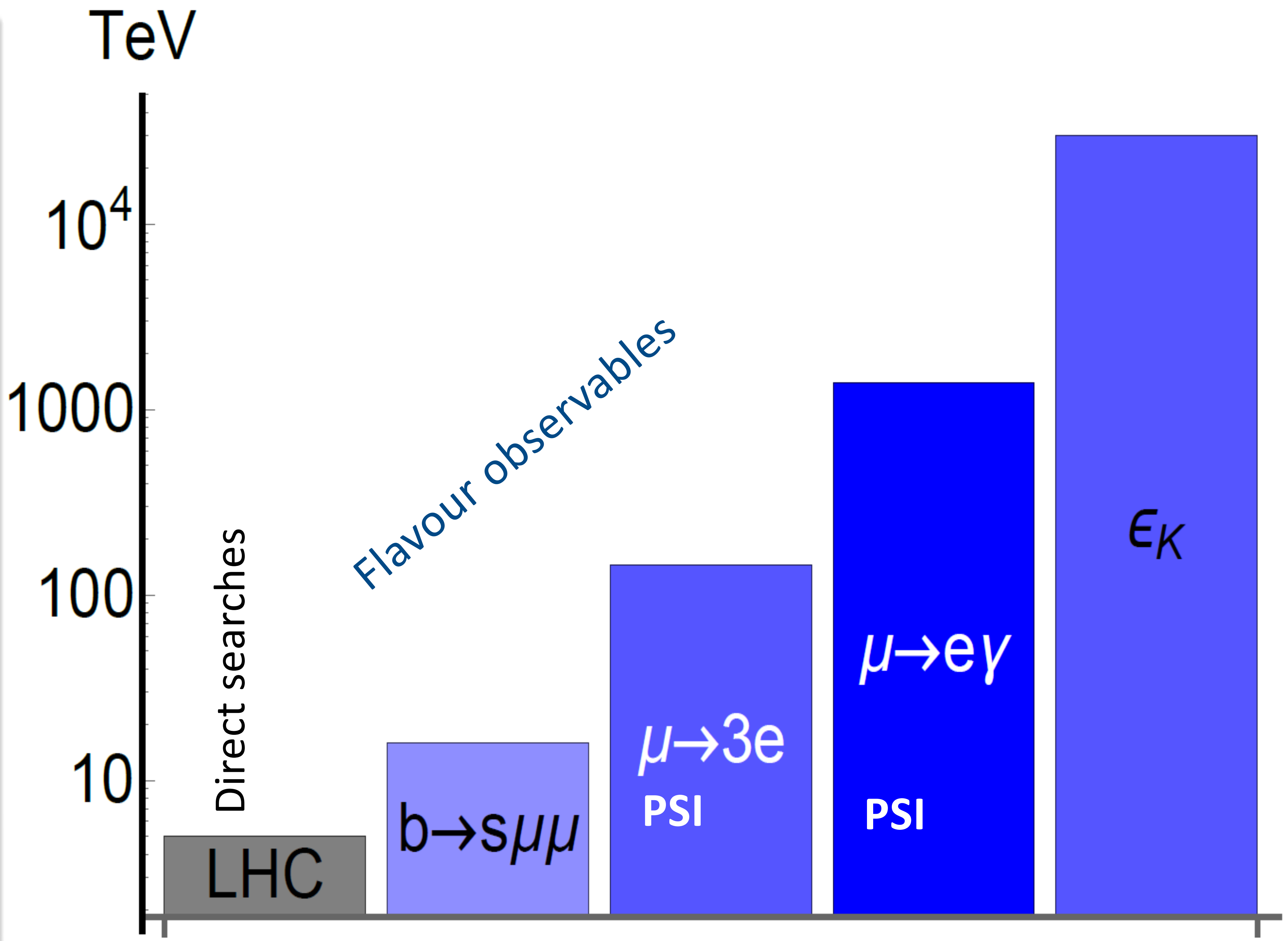
What's beyond?

- Theorists at work

- Experimentalist at work

The role of indirect searches



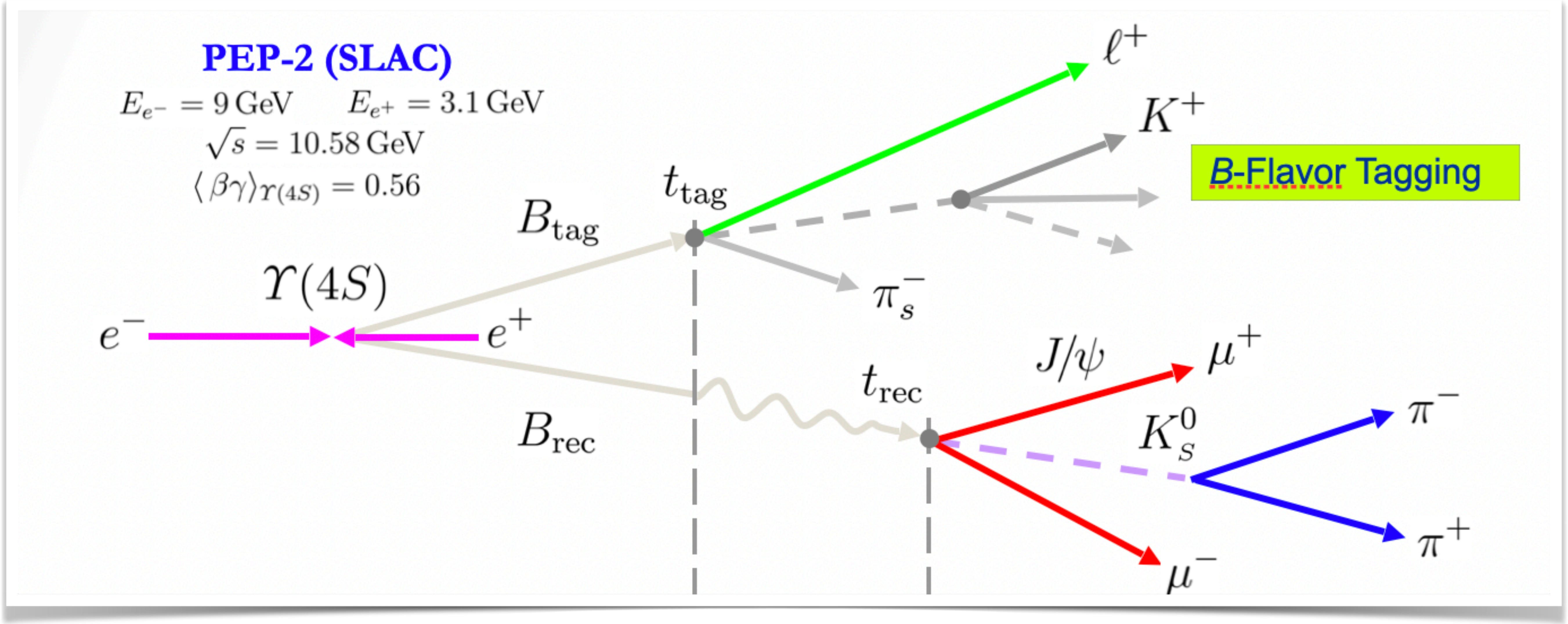


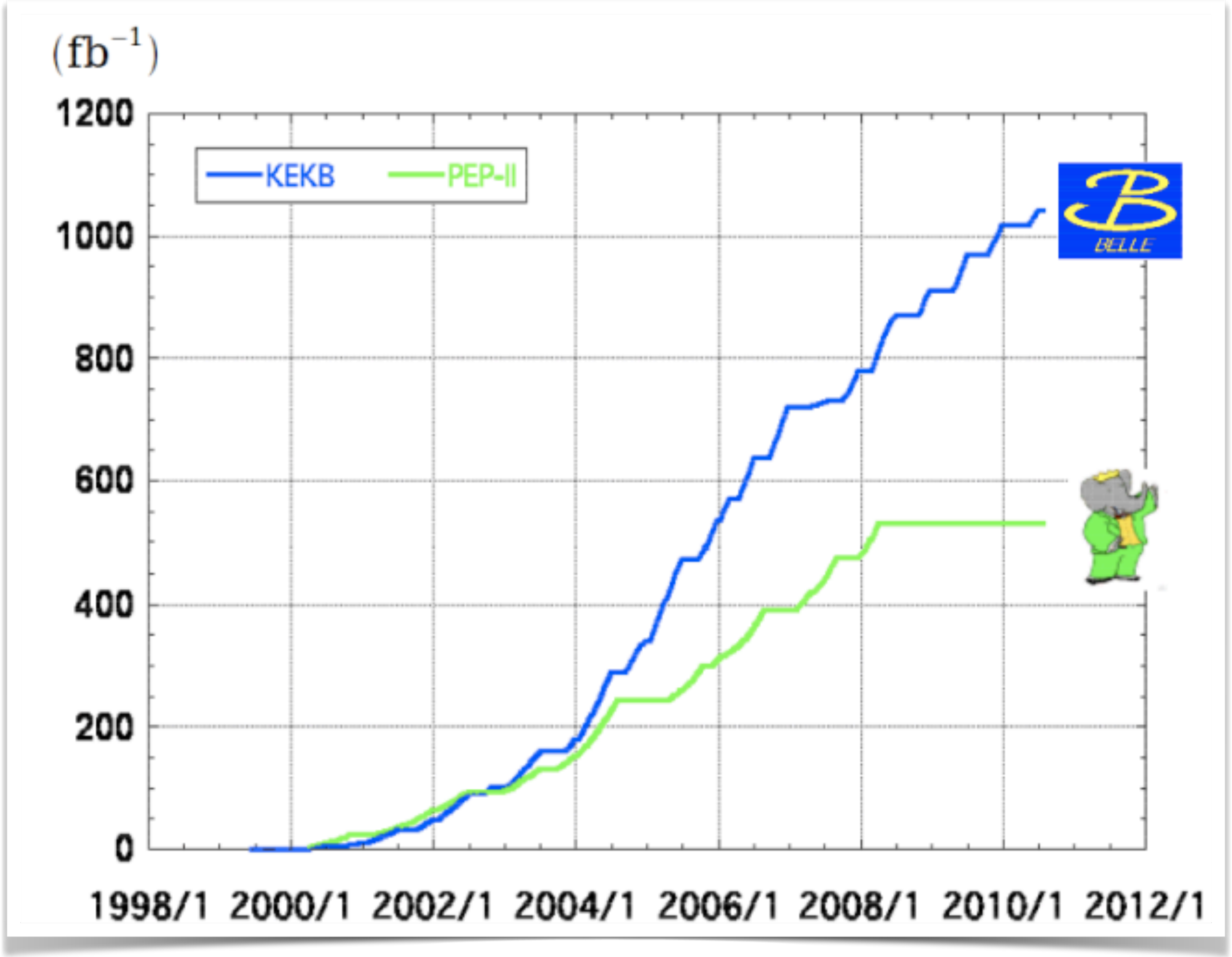
- Indirect searches allow to test higher NP energy scale, complementary to direct searches

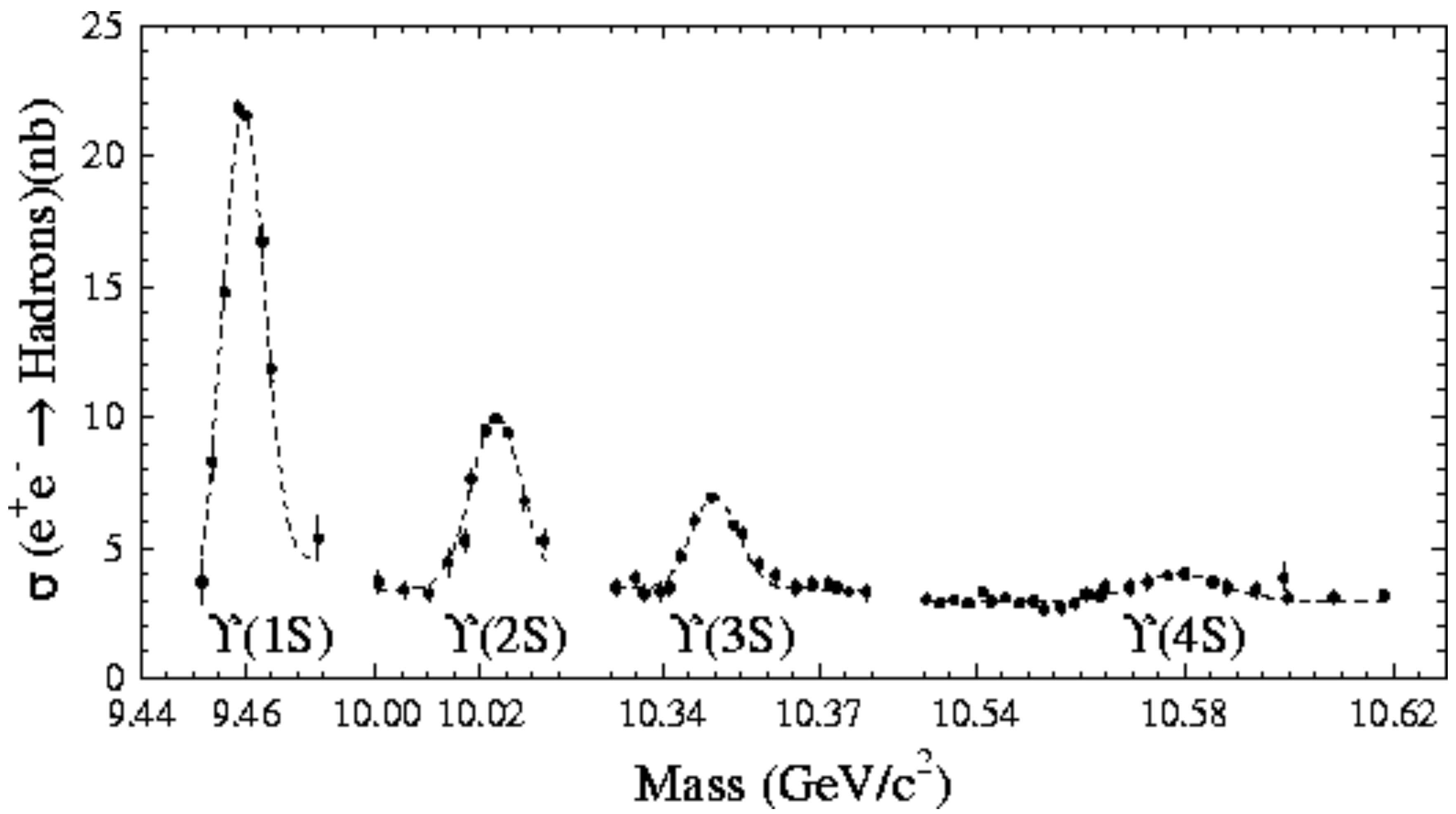
The long way to indirect searches @ at SuperB factory

First generation B factories: where and why

- Experiment @ first generation B factories: **BaBar** (USA) and **Belle** (JAPAN)
  - took data for about 10 years , collecting ~ 480 and 780 x 10^6 BB pairs, respectively
- Experiment goal: measurement of **CP violation in B meson system**



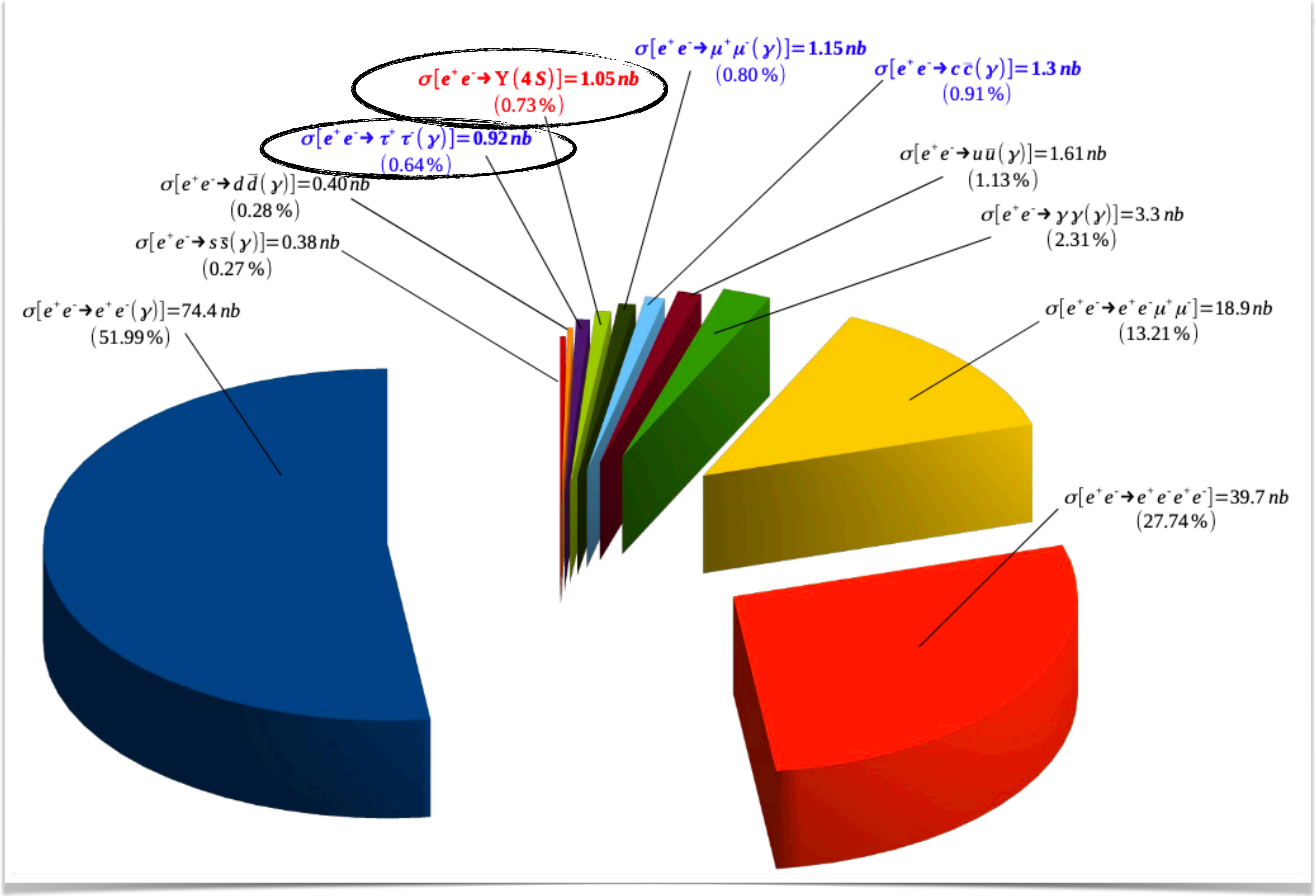




Fantastic performances of the accelerators, well beyond design values, e.g. KEKB peak luminosity (WR!): **2. 1 x 10^{34}cm^{-2}s^{-1}**

Much more than just CPV in B system (I)

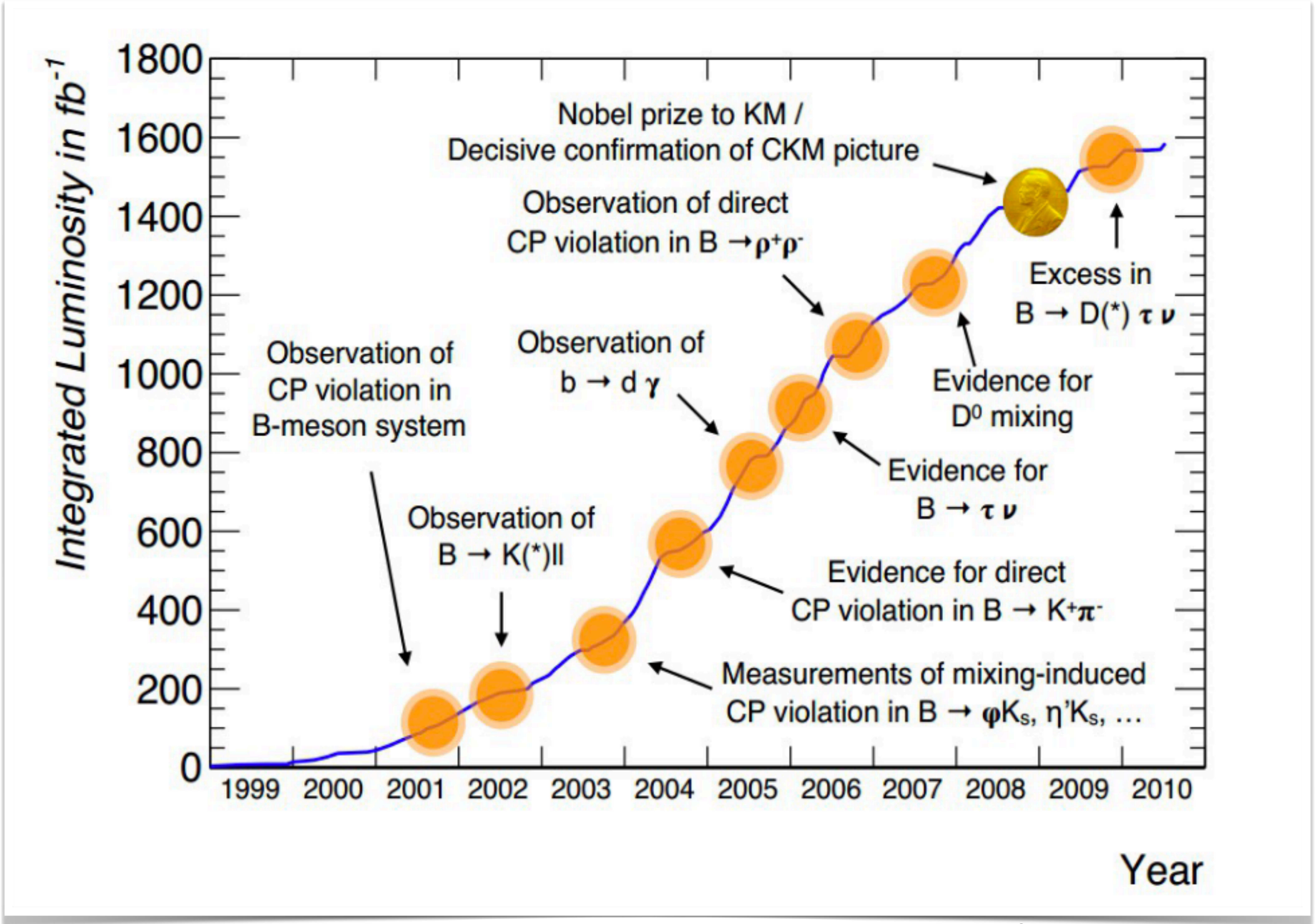
The BelleII Physics Book, PETP 2019, 123C01 (2019)

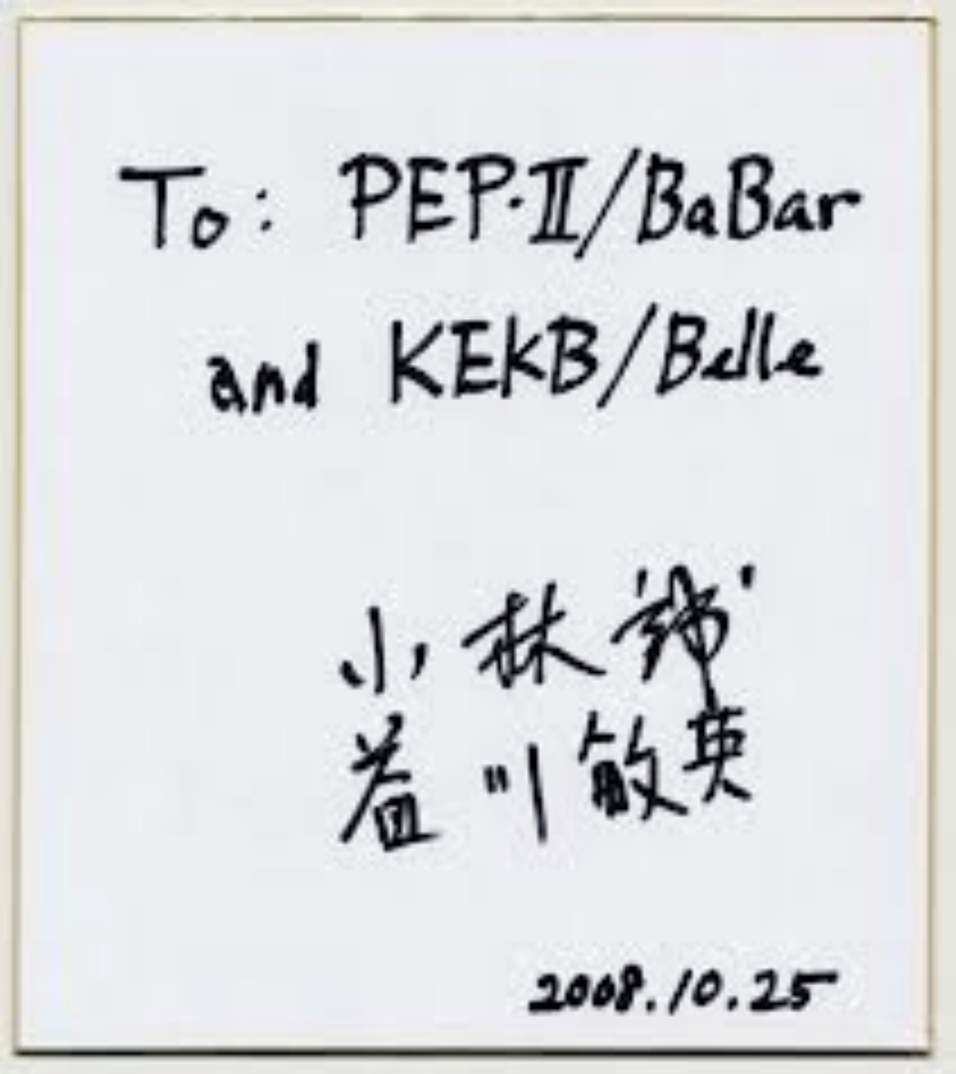


Physics process	Cross section [nb]
$\Upsilon(4S)$	1.110 ± 0.008
$u\bar{u}(\gamma)$	1.61
$d\bar{d}(\gamma)$	0.40
$s\bar{s}(\gamma)$	0.38
$c\bar{c}(\gamma)$	1.30
$e^+e^-(\gamma)$	300 ± 3 (MC stat.)
$e^+e^-(\gamma)$	74.4
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)
$\gamma\gamma(\gamma)$	3.30
$\mu^+\mu^-(\gamma)$	1.148
$\mu^+\mu^-(\gamma)$	0.831
$\mu^+\mu^-\gamma(\gamma)$	0.242
$\tau^+\tau^-(\gamma)$	0.919
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)

Much more than just CPV in B system (II)

- They did much more than just measuring CP violation






Makoto Kobayashi


Toshihide Maskawa

- The great success of BaBar and Belle led to the BelleII experiment

From B factories to SuperB factories: KEKB ➟ SuperKEKB

- Aim to collect **50ab⁻¹** (~50x Belle) by 2031 reaching **~60 x 10³⁴cm⁻²s⁻¹** (~30x KEKB)

- Can do this without using brute-force! Nano-beam scheme:

beam current

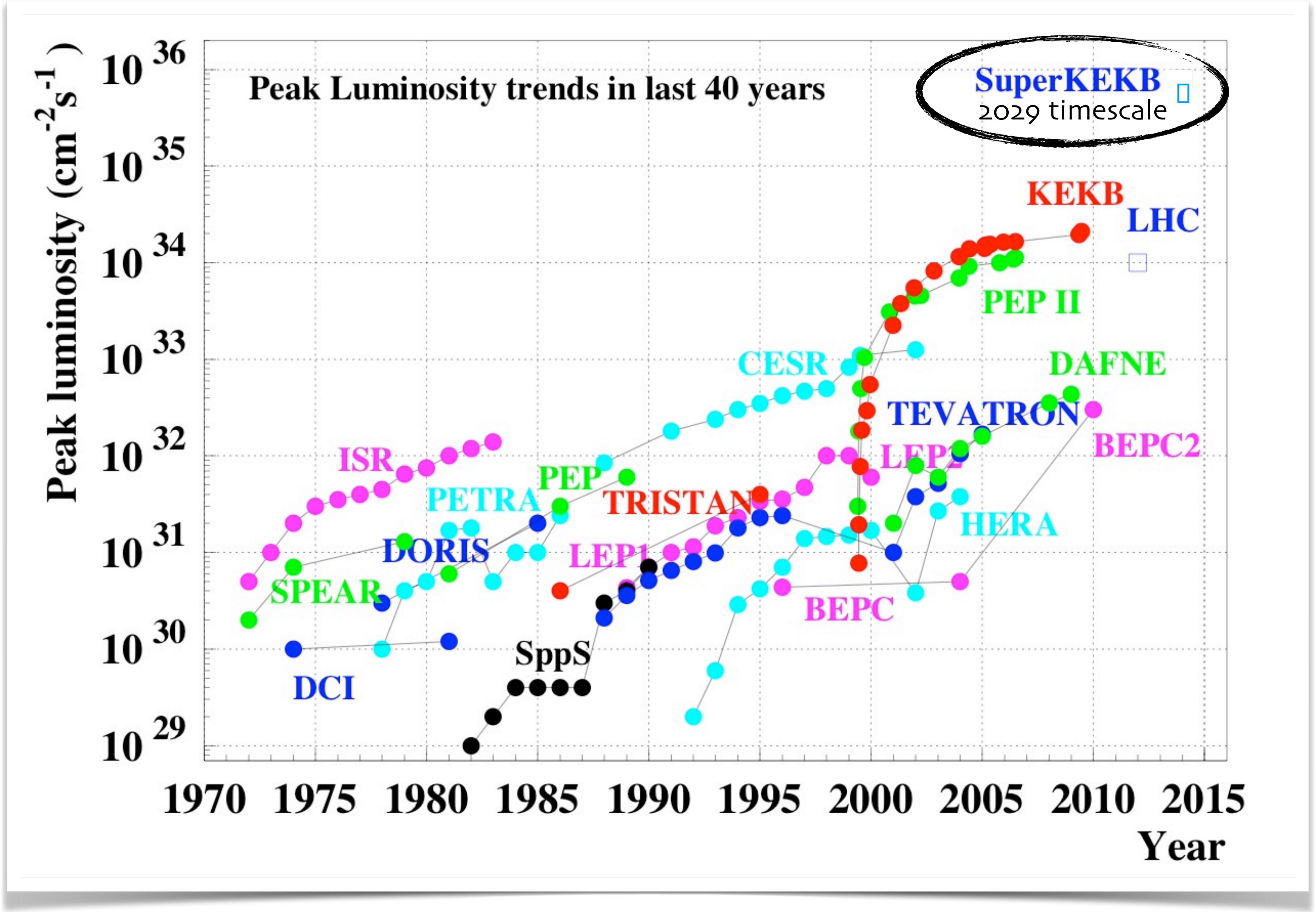
$$L = \frac{\gamma_{\pm}}{2 e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{y\pm}}{\beta_{y\pm}}\frac{R_L}{R_{\xi_y}}$$

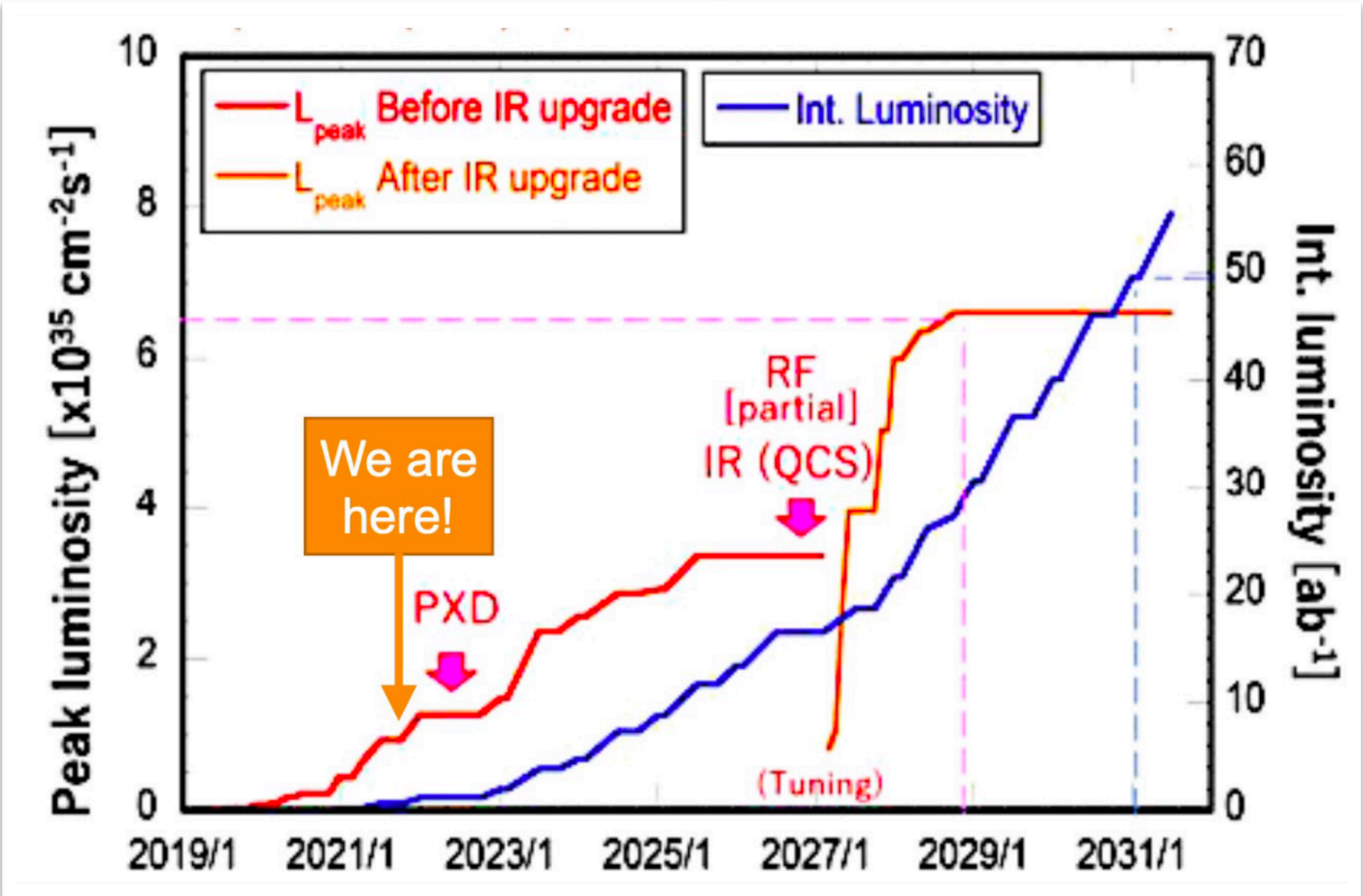
vertical beta function at IP

  - 20x smaller β^*_y

  - 1.5x higher currents

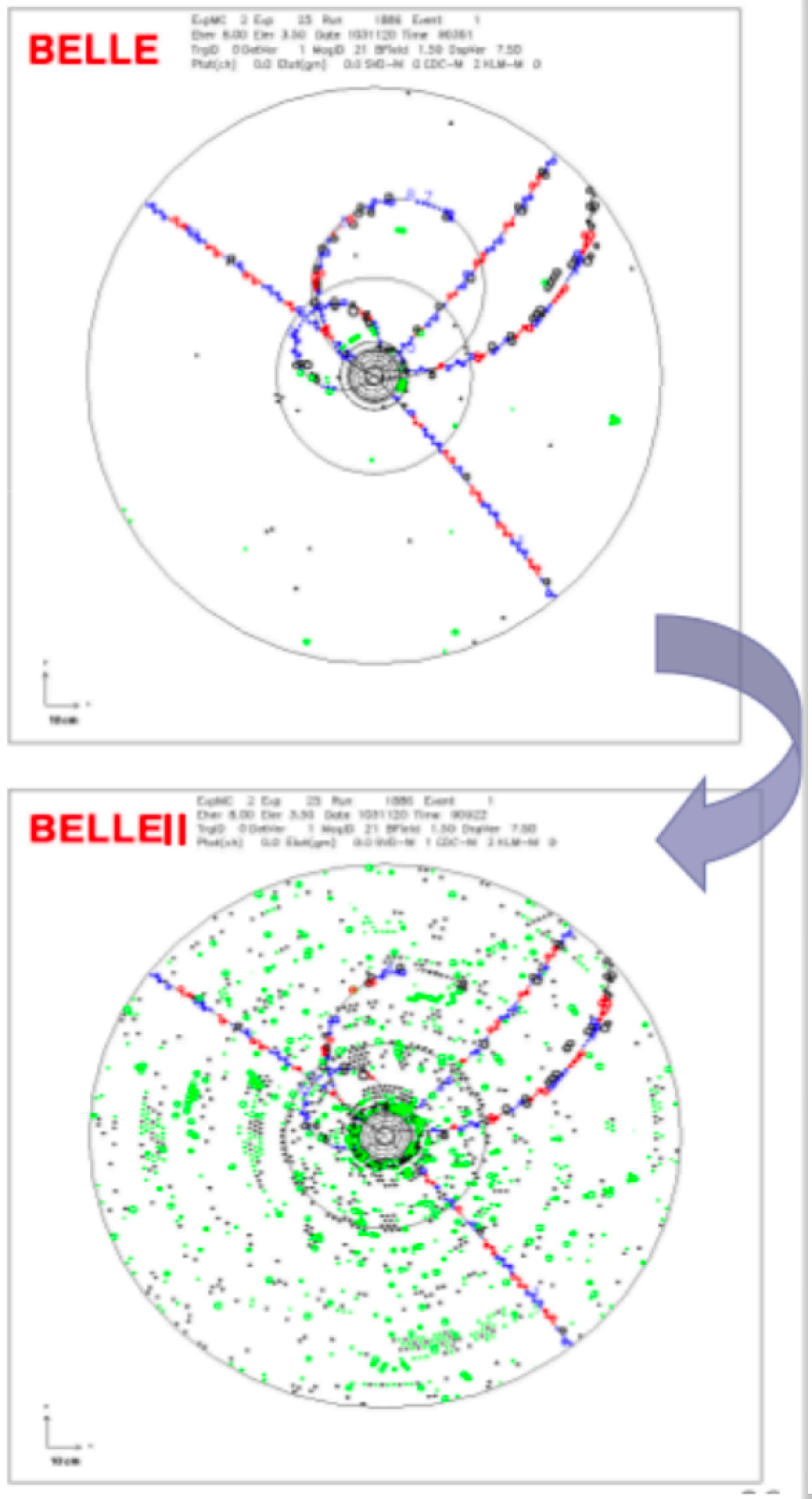
- price to be paid: higher "machine background"

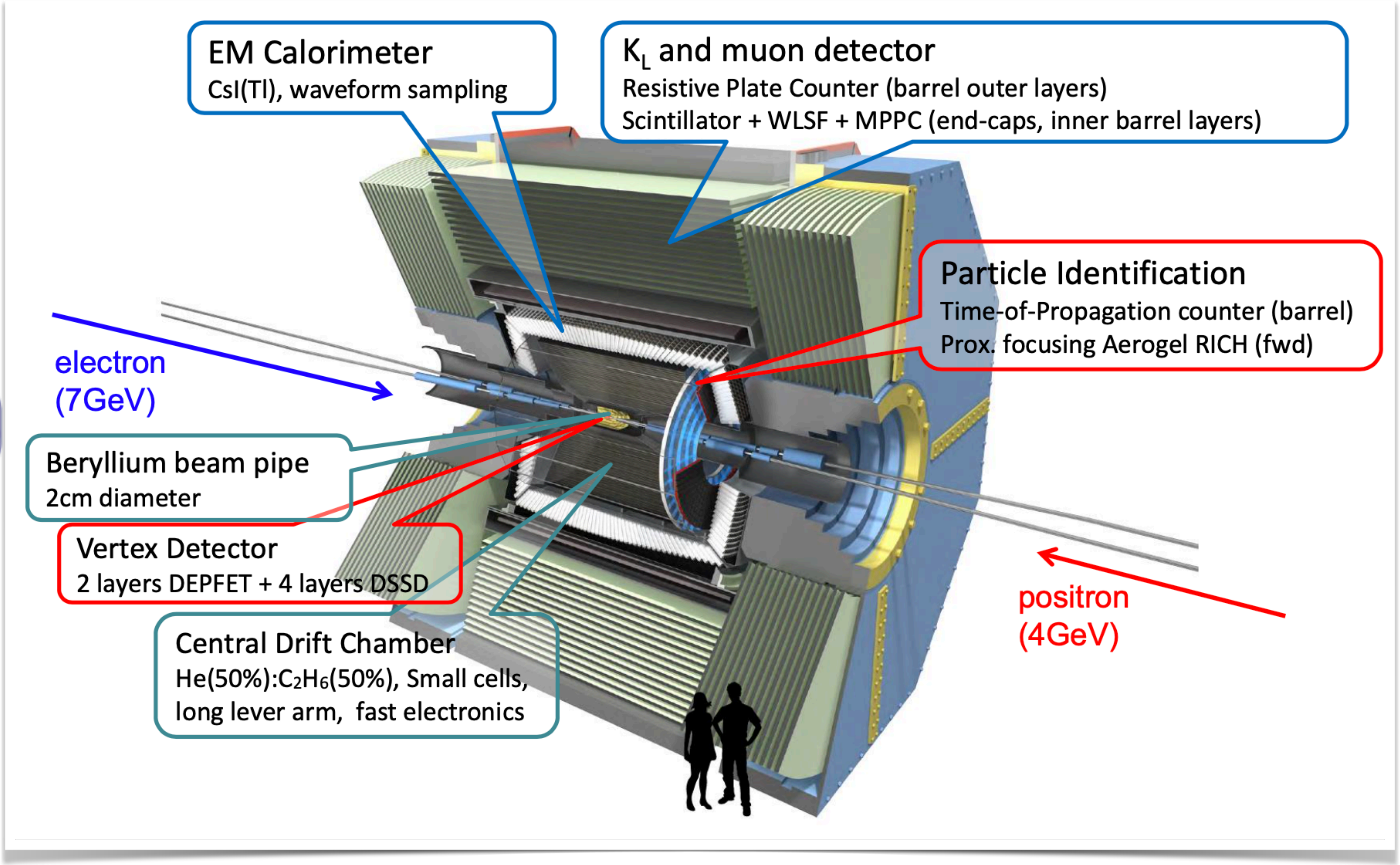




From Belle to BelleII

- Higher luminosity mean higher machine background: from Belle to BelleII detector to **maintain or improve detector performances**
- "Faster" and more rad hard sub-detectors





- To realise nano-beam scheme:

1. Lorentz boost factor reduced wrt Belle → higher detector **hermiticity**, important for searches with missing particles;
2. smaller beam pipe ⟶ vertex detector closer to IP, better **vertex resolution**

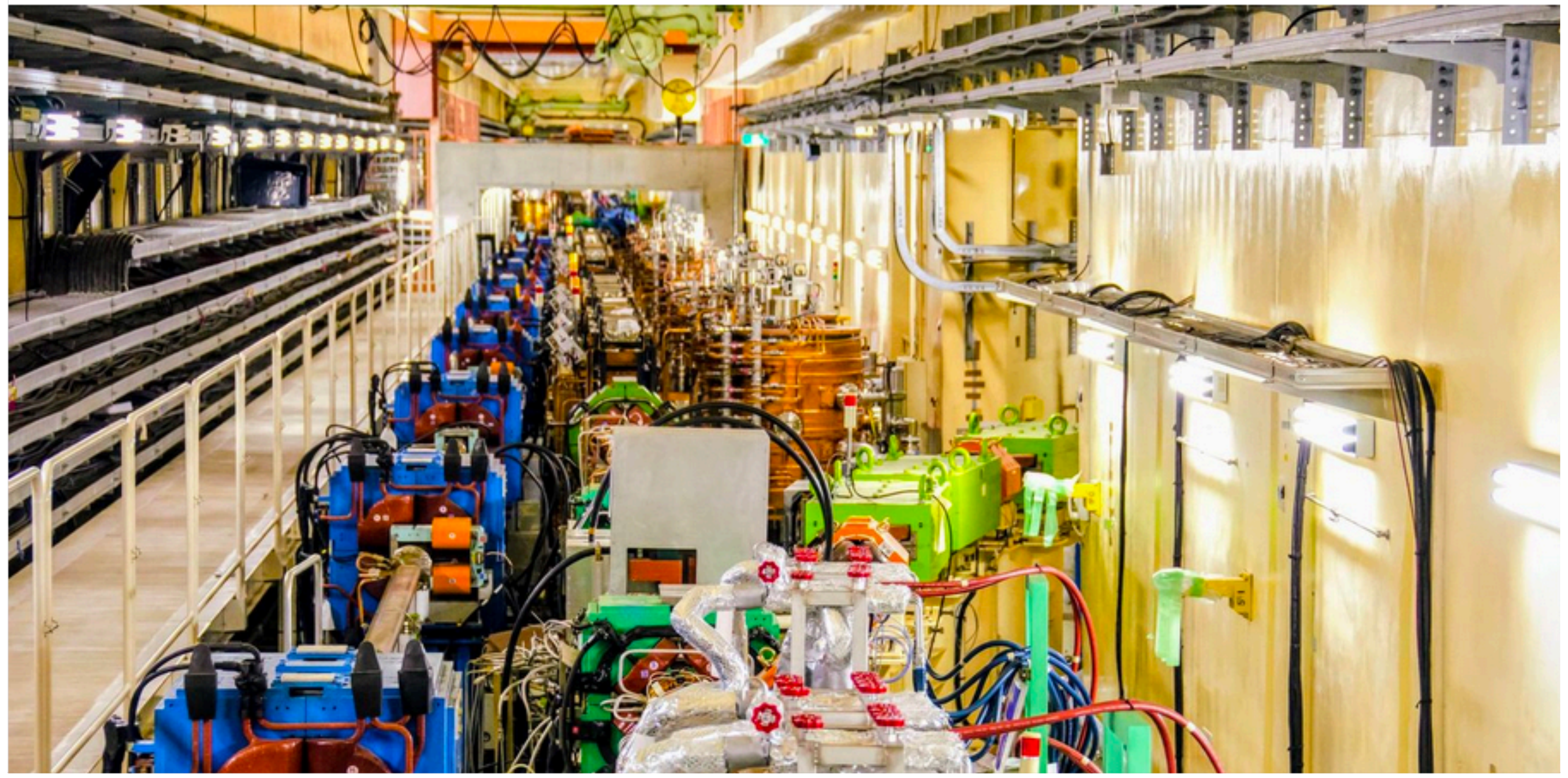
Belle II/SuperKEKB @ work

- BelleII is taking data since 2019, data taking continued amid COVID-19 pandemic

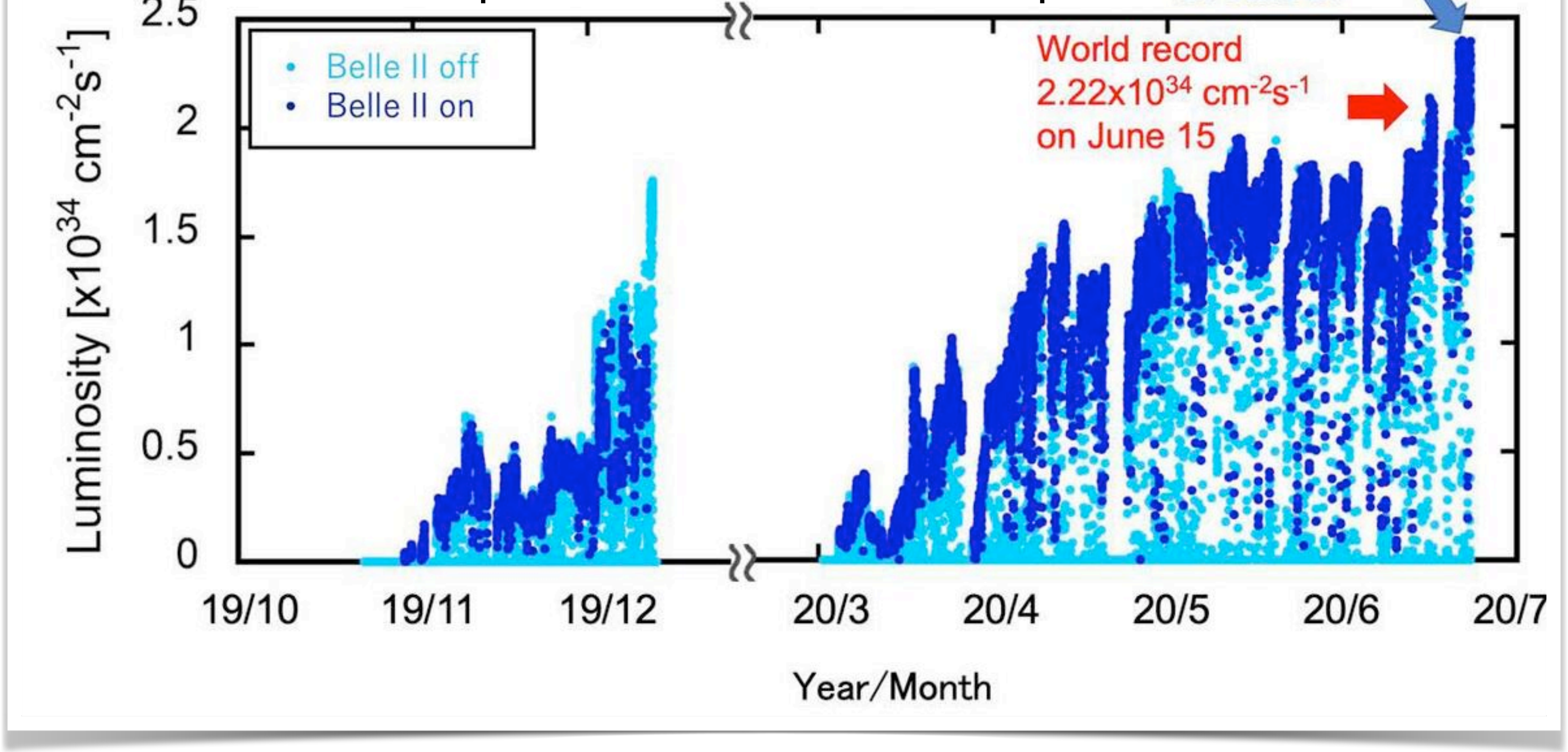
Belle II Collaboration
Ieri alle 09:15 ·

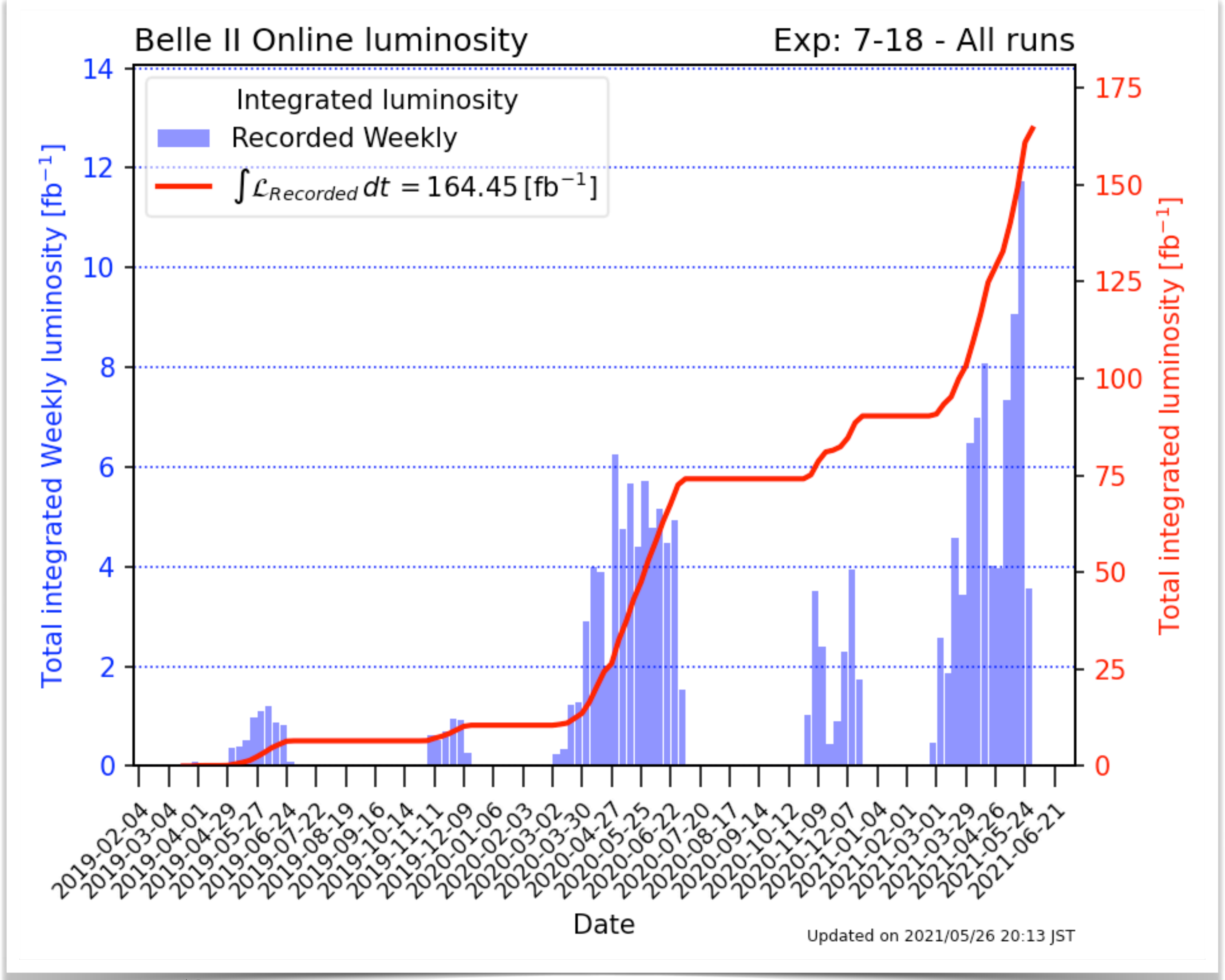
SuperKEKB reaches Super-B factory class performance levels!

Belle II@SuperKEKB has integrated 12 fb^{-1} of data in a week - a new world record! By comparison, during the best week at KEKB more than a decade ago, Belle integrated 8 fb^{-1}, while PEP-II Integrated 5 fb^{-1} for BaBar during its best week. Stay tuned as #Belle2@SuperKEKB aims for the long-standing world record of integrated luminosity per month while it accumulates a large data sample to hunt for New Physics in the flavor sector.



SuperKEKB world record press release

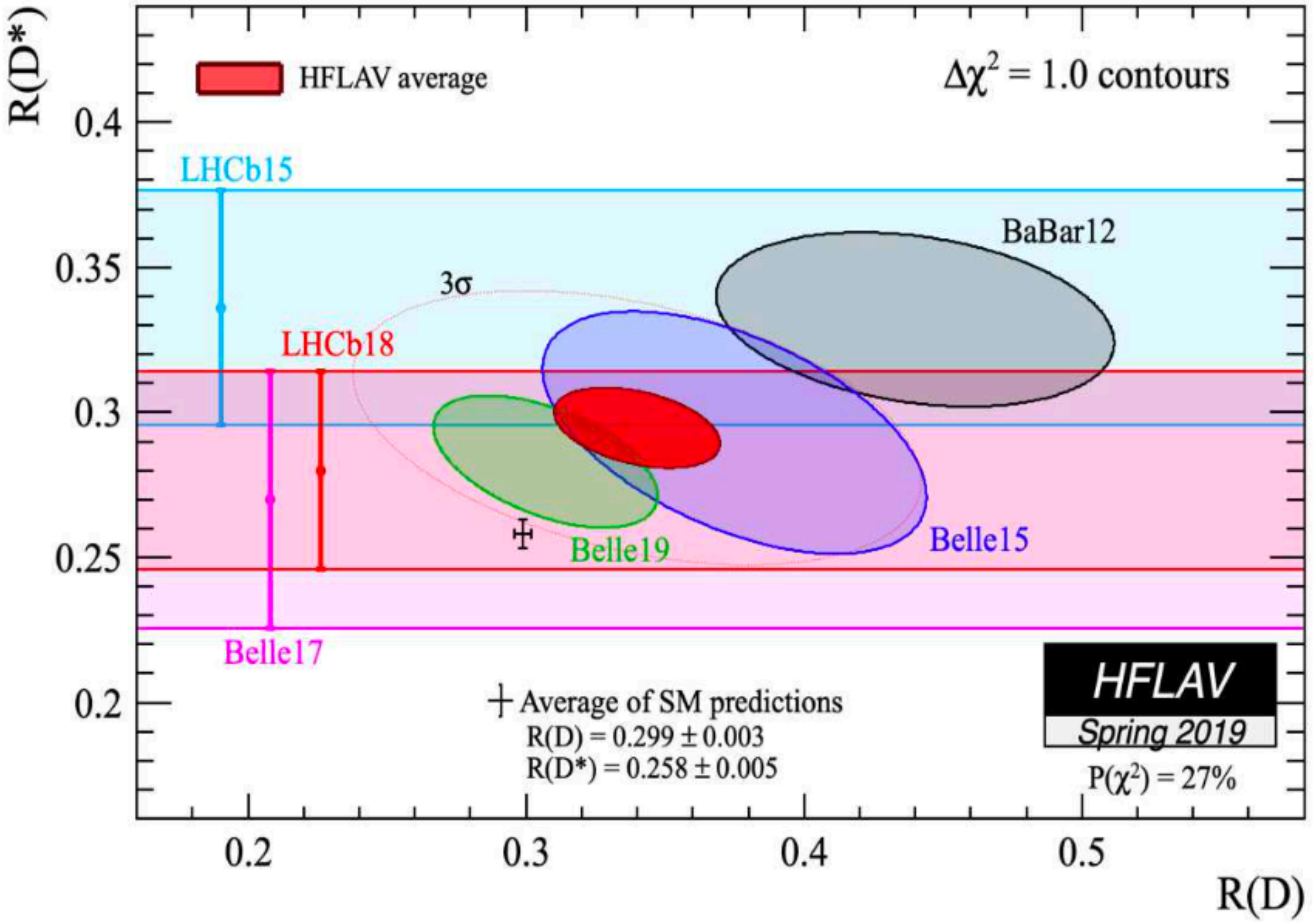


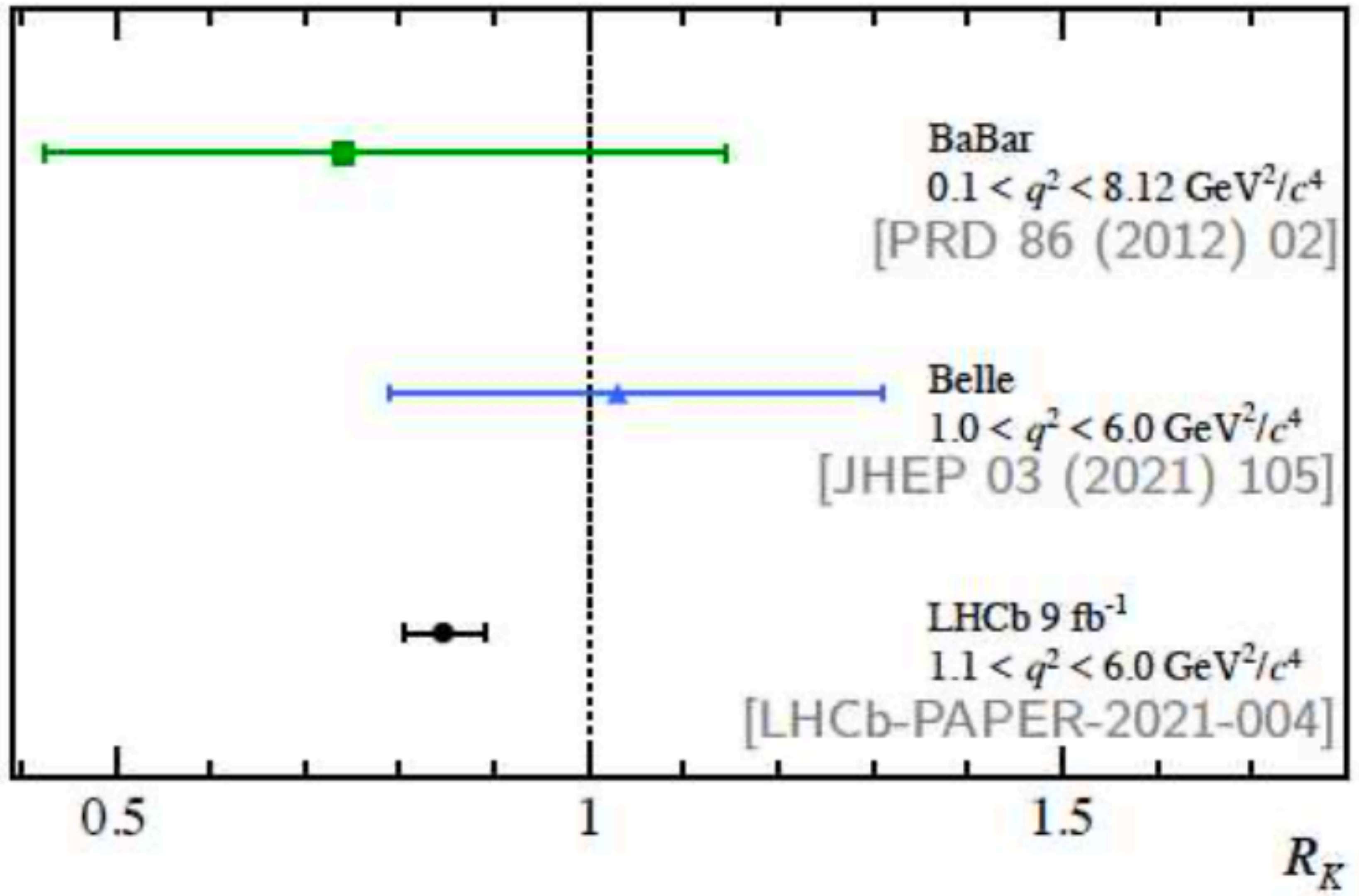


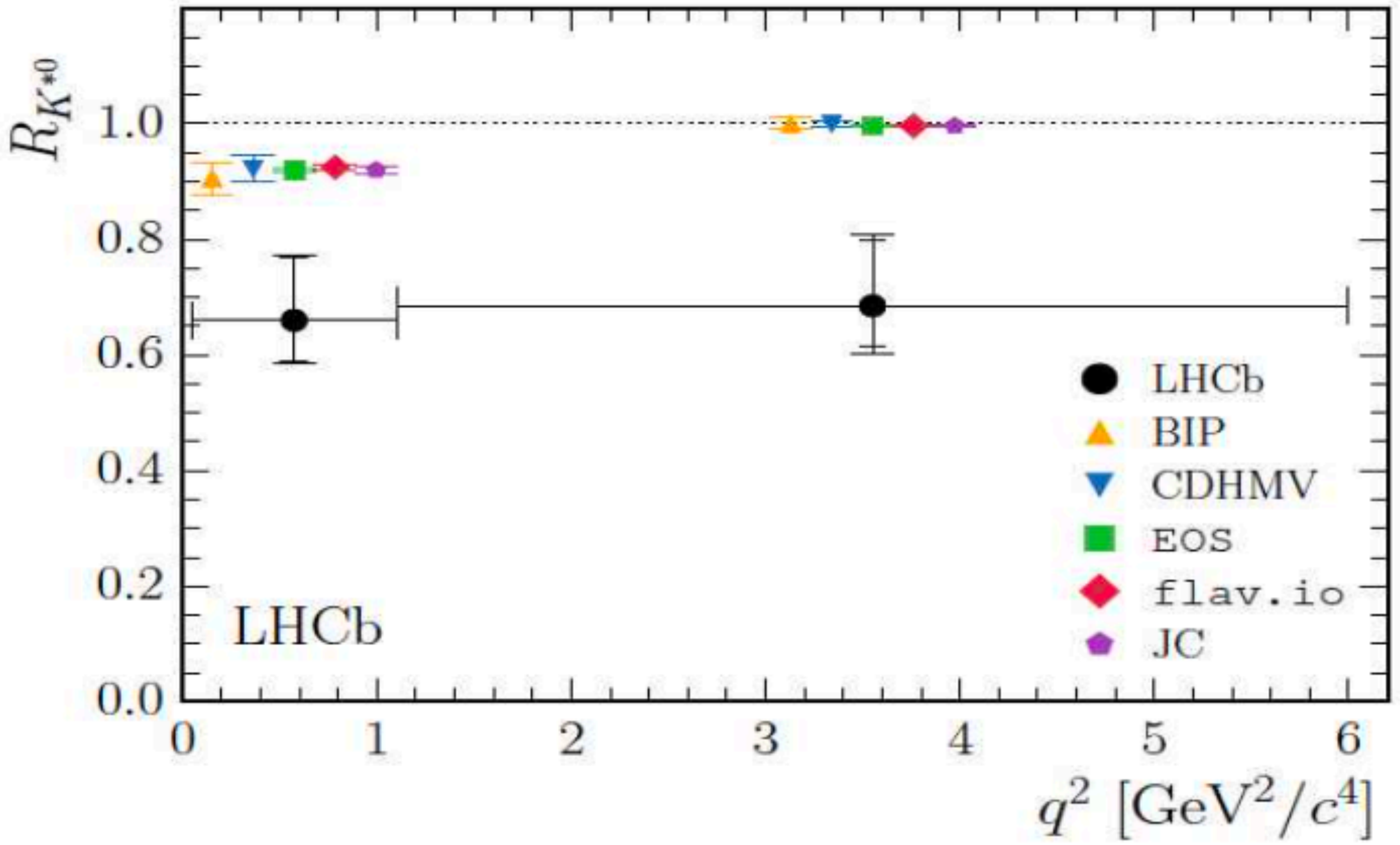
- Increasing peak luminosity: n spring 2021, exceeded 2.8 x 10^{34} cm^{-2} s^{-1}

Flavour anomalies in a nutshell

- Tension between experimental measurement and SM predictions in
  - b → c l υ
  - b → s ll



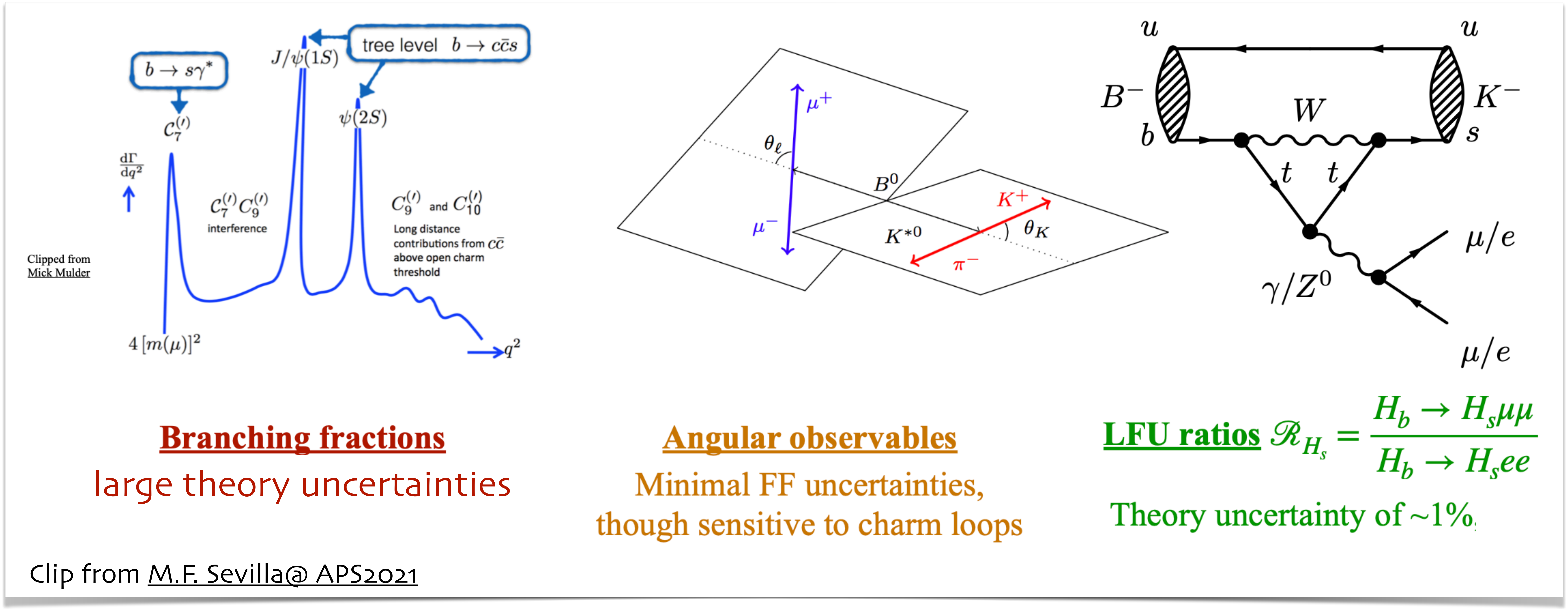




- What can BelleII say on these and other related modes?

$b \to sLL$

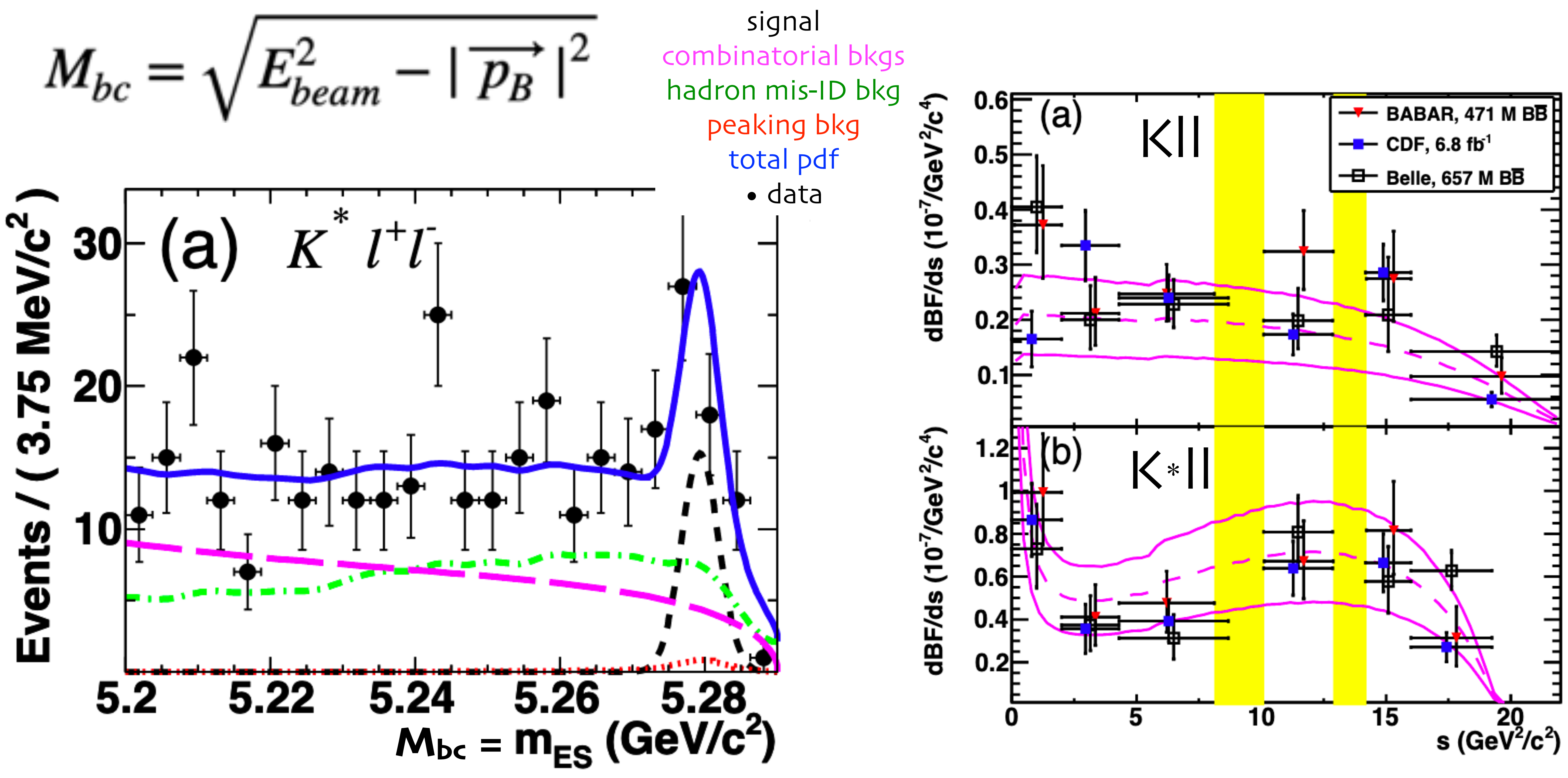
b→sll observables



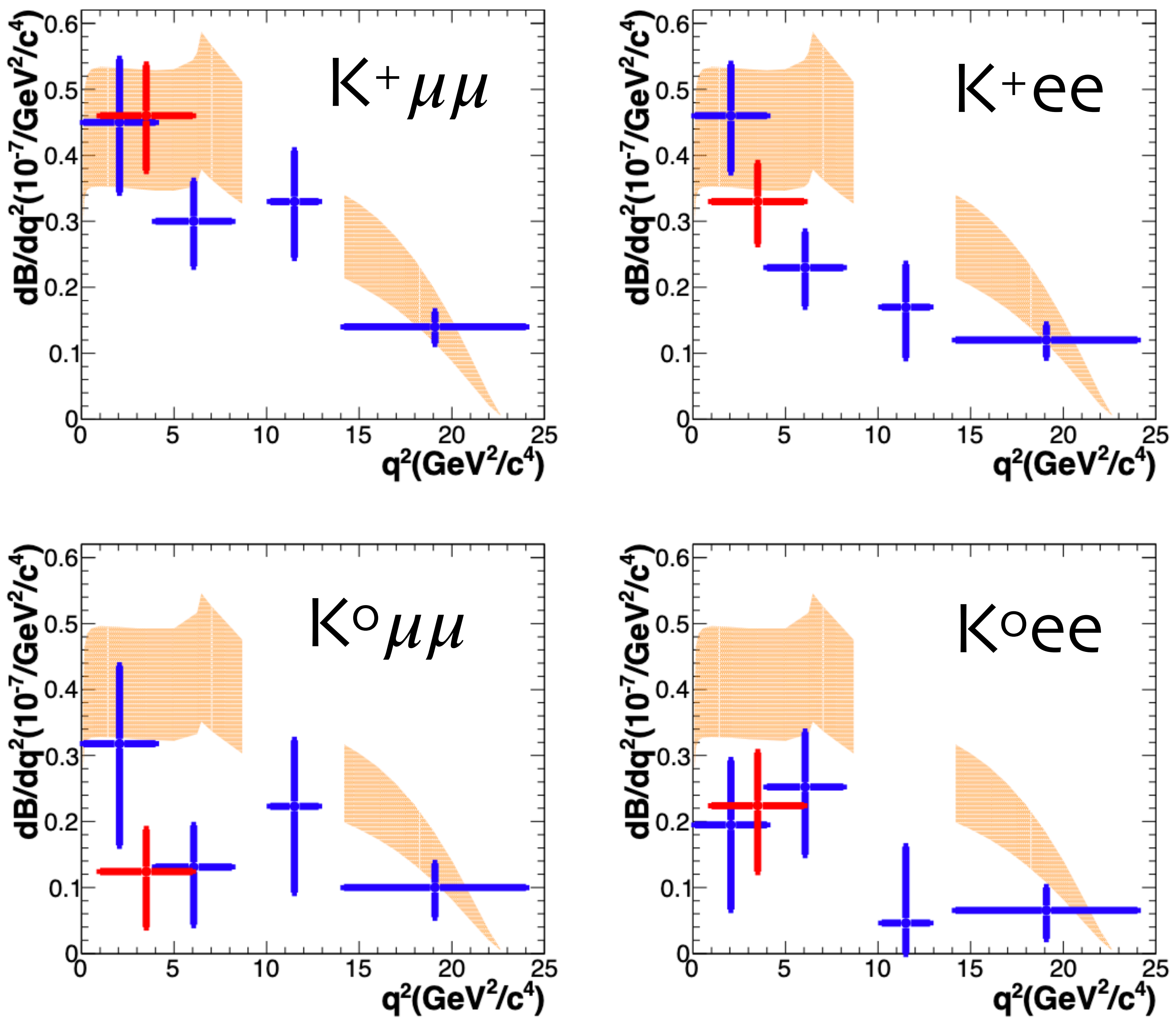
- Fully reconstructed final states, untagged analysis
- @ (super)B-factories, both charged and neutral $K^{(*)}$ modes are reconstructed
- Key ingredients: Lepton identification, hadron mis-identification (in particular μ-π)

Partial branching fractions from B factories

BaBar coll., PhysRevD.86.032012 (prior latest Belle measurement)



Belle coll., JHEP03(2021) 105 (latest Belle measurement)



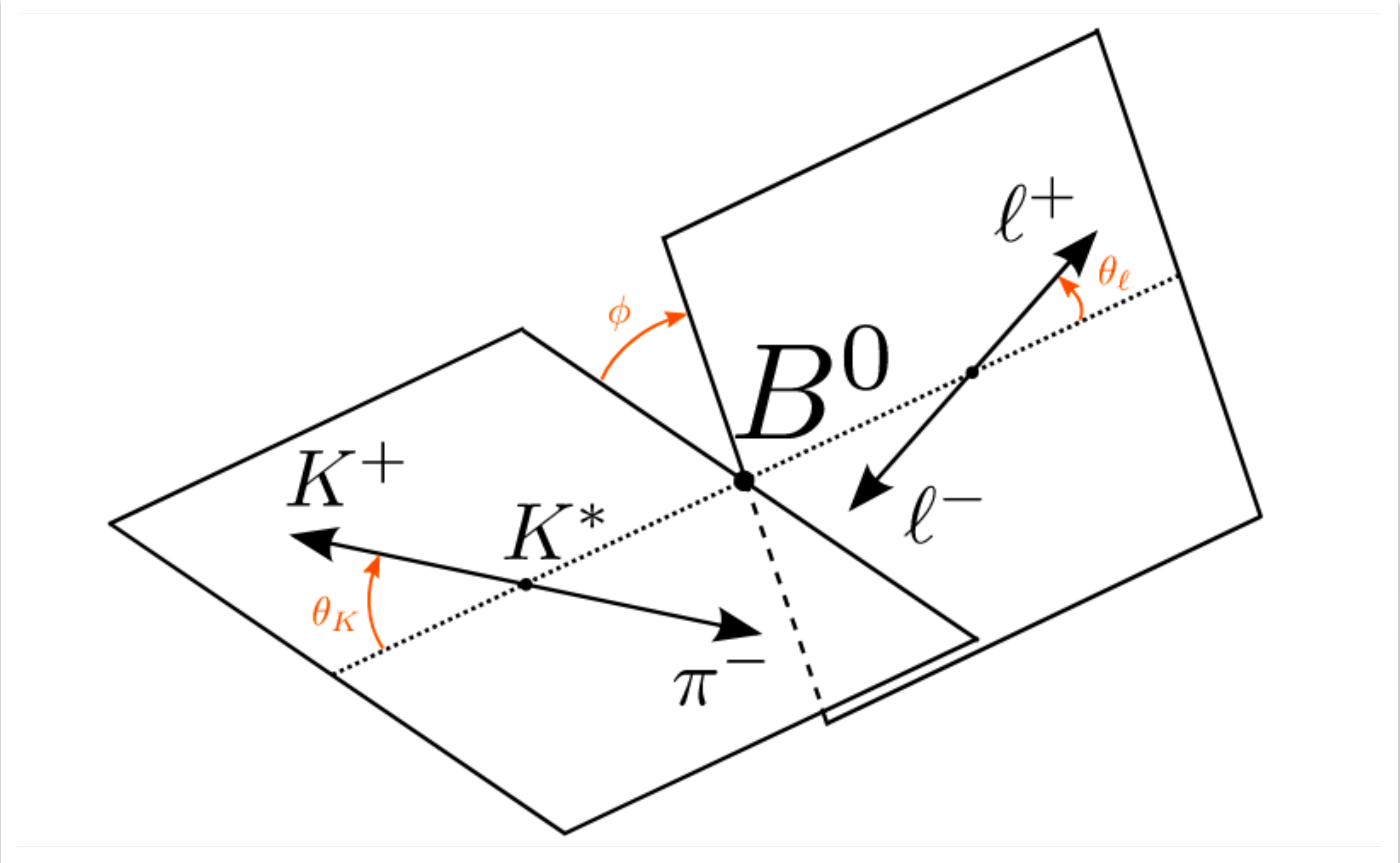
- Partial branching fractions measured by BaBar, Belle, and CDF
    - latest Belle measurement, performed separately for electron and muons
    - in agreement with SM expectations, large experimental errors, **statistically limited**

B→K*ll angular analysis from B factories

- Differential decay rate as a function of 3 angles:

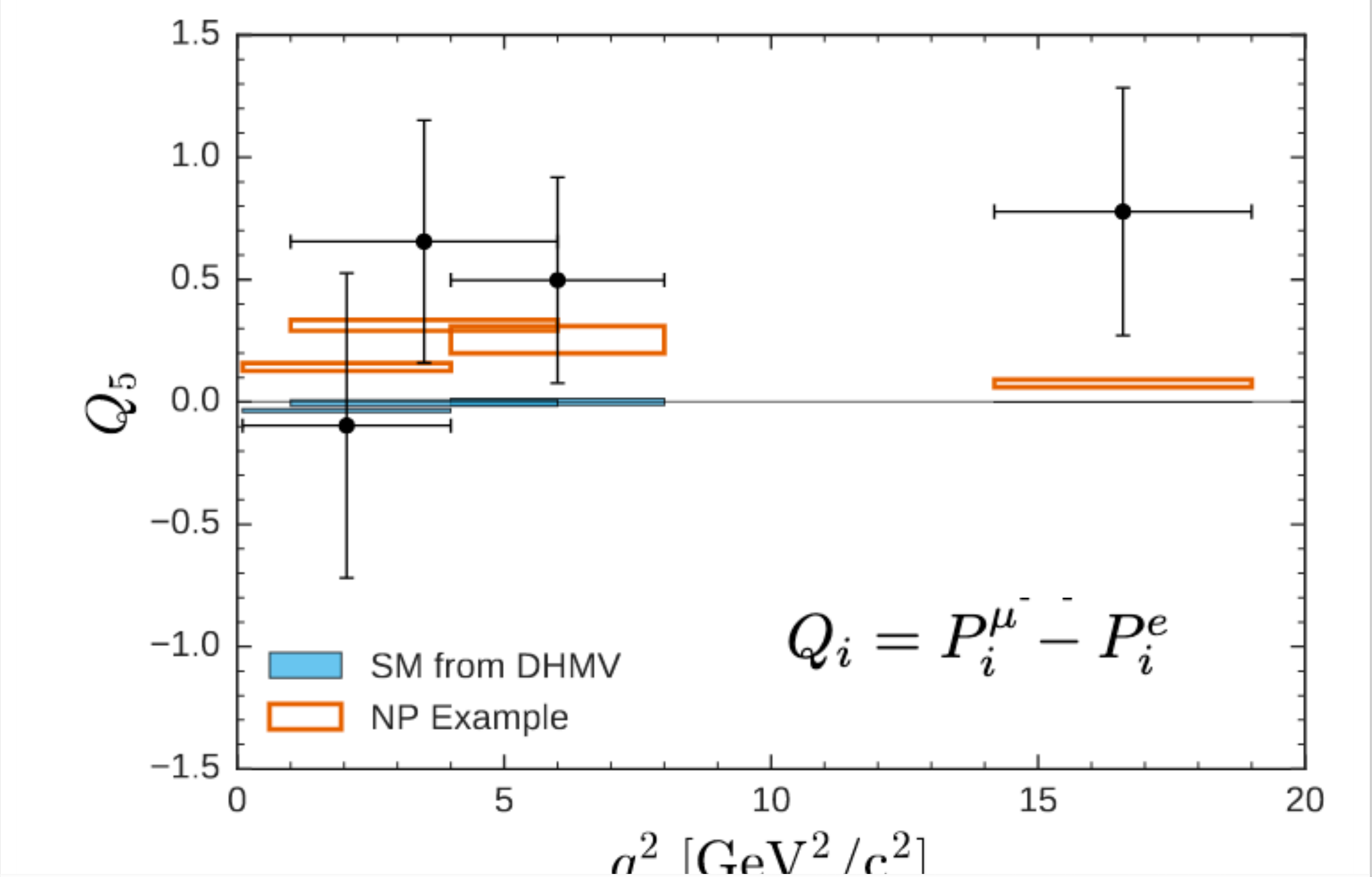
$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_L\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_L$$
$$-F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Big]$$

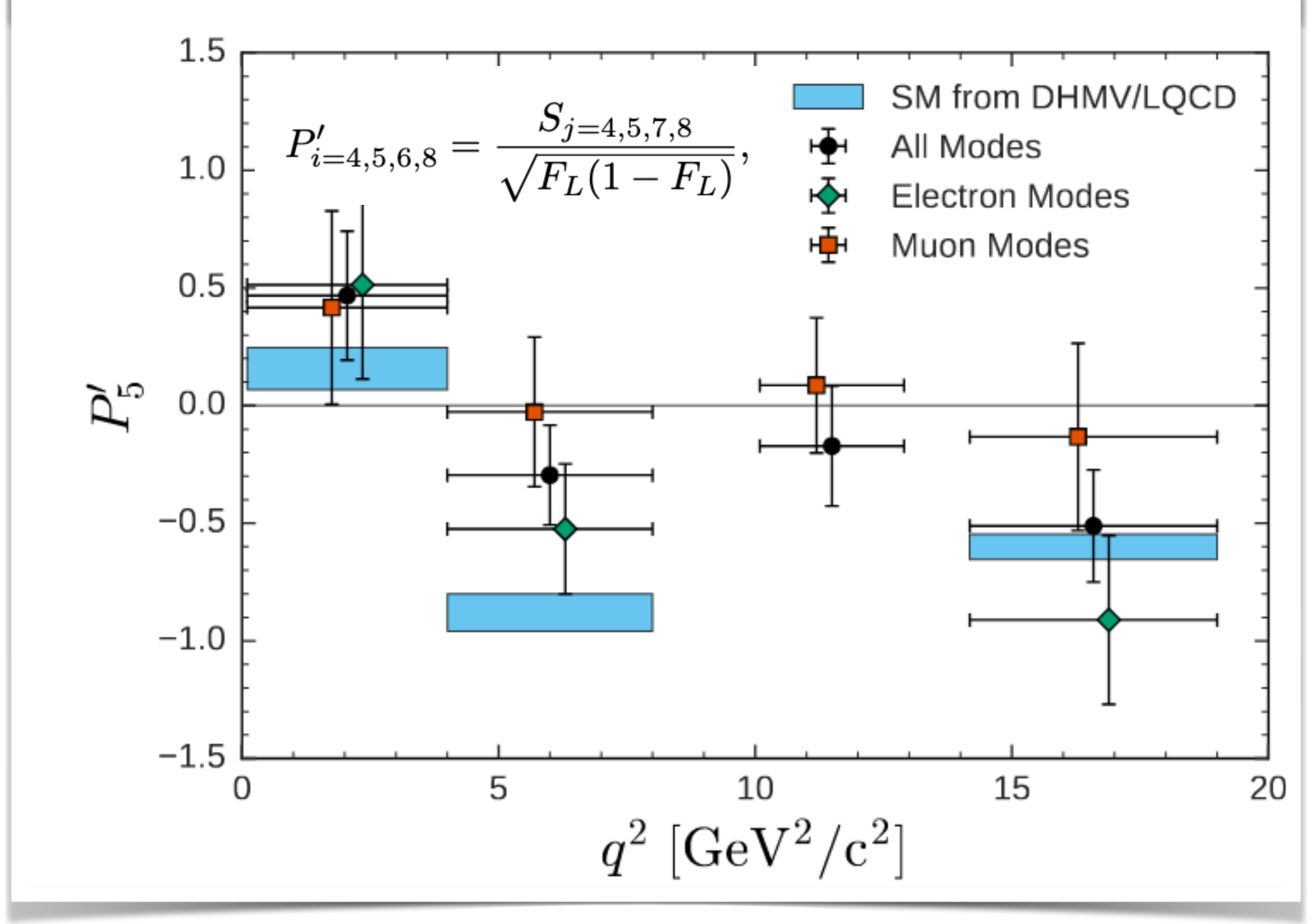
With a data transformation technique the dimension of the free parameters can be reduced to 4



- 2.6 σ discrepancy in muon channel for P5′ (uncertainty at the **50% level**, dominated by statistics)

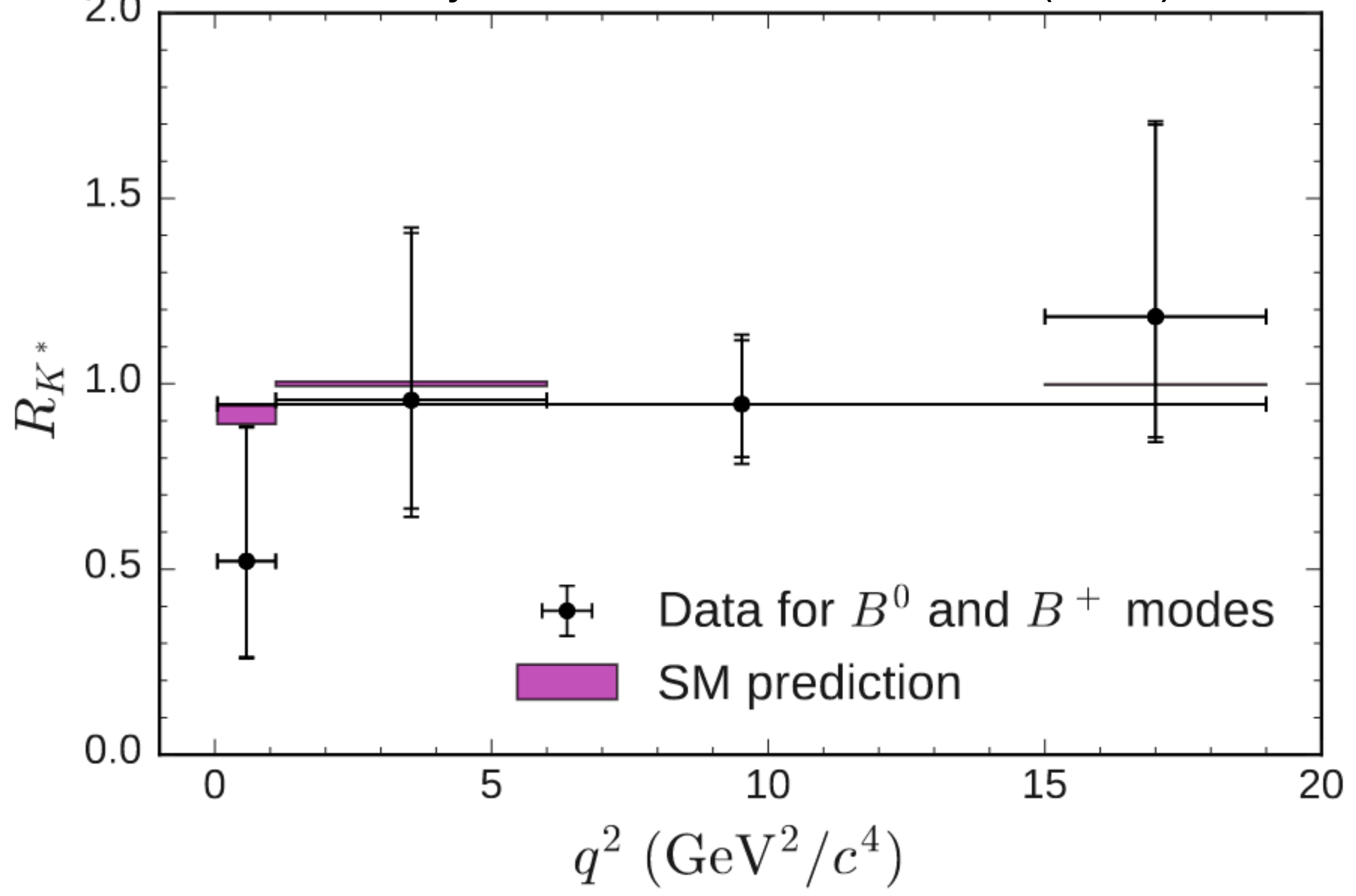
Belle coll., Phys.Rev.Lett. 118 (2017) 11, 111801



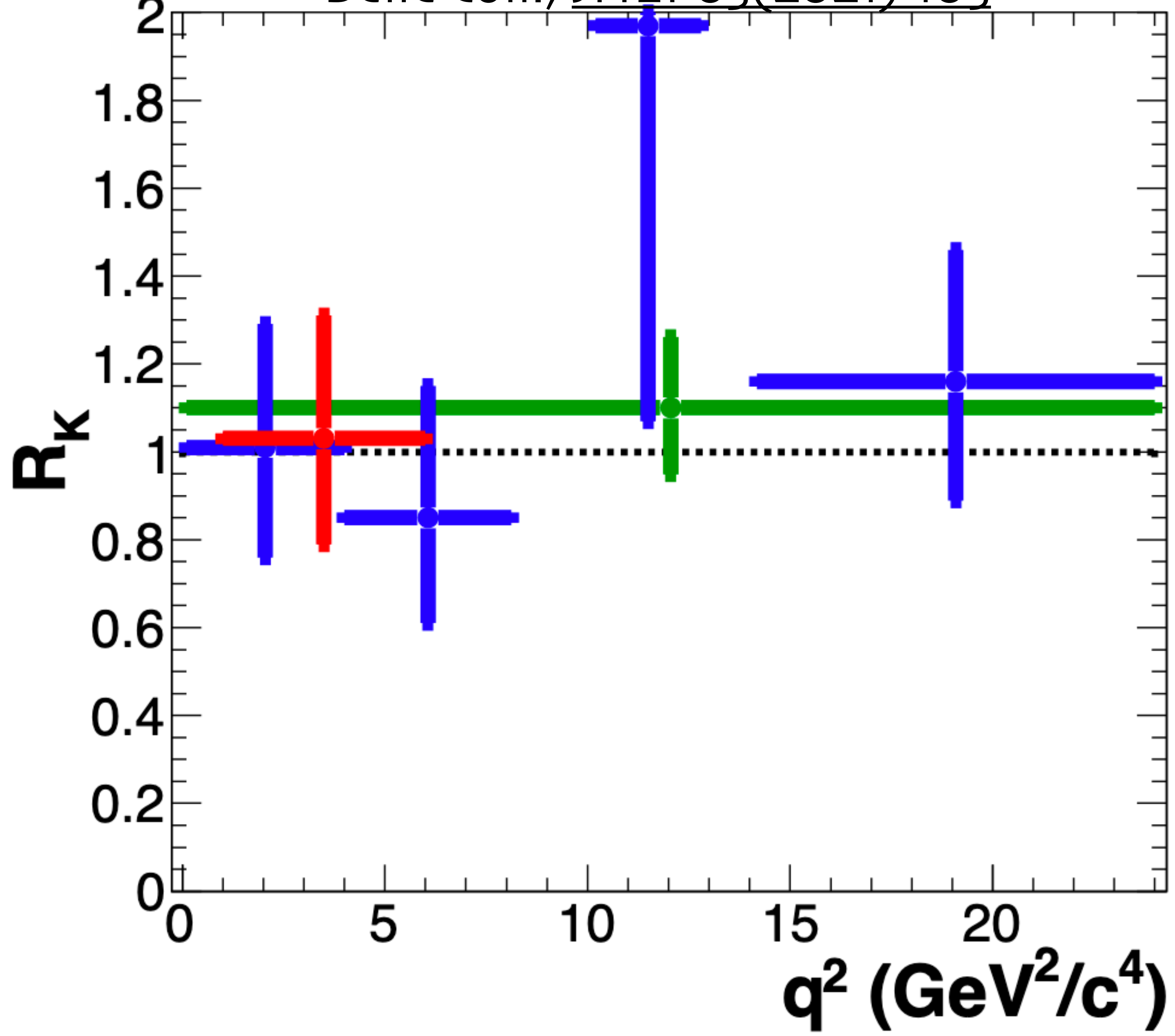


$R(K^{(*)})$: latest measurement from Belle

Belle coll., Phys. Rev. Lett. 126, 161801 (2021)



Belle coll., JHEP03(2021) 105



q^2 in GeV$^2/c^4$	All modes
$[0.045, 1.1]$	$0.52^{+0.36}_{-0.26} \pm 0.06$
$[1.1, 6]$	$0.96^{+0.45}_{-0.29} \pm 0.11$
$[0.1, 8]$	$0.90^{+0.27}_{-0.21} \pm 0.10$
$[15, 19]$	$1.18^{+0.52}_{-0.32} \pm 0.11$
$[0.045,]$	$0.94^{+0.17}_{-0.14} \pm 0.08$

- In agreement with SM expectations within errors
- Measurement **statistically** limited
- Main systematics from lepton ID efficiency and knowledge of peaking background

Toward BelleII measurements (I)

- BelleII performances, some examples: Hadron ID, Leptin ID, neutral reconstruction
  - good understanding of the detector
  - performances comparable to Belle/BaBar in higher machine background environment
  - improvements in algorithms and understanding of the detectors foreseen

BELLE2-NOTE-PL-2020-024

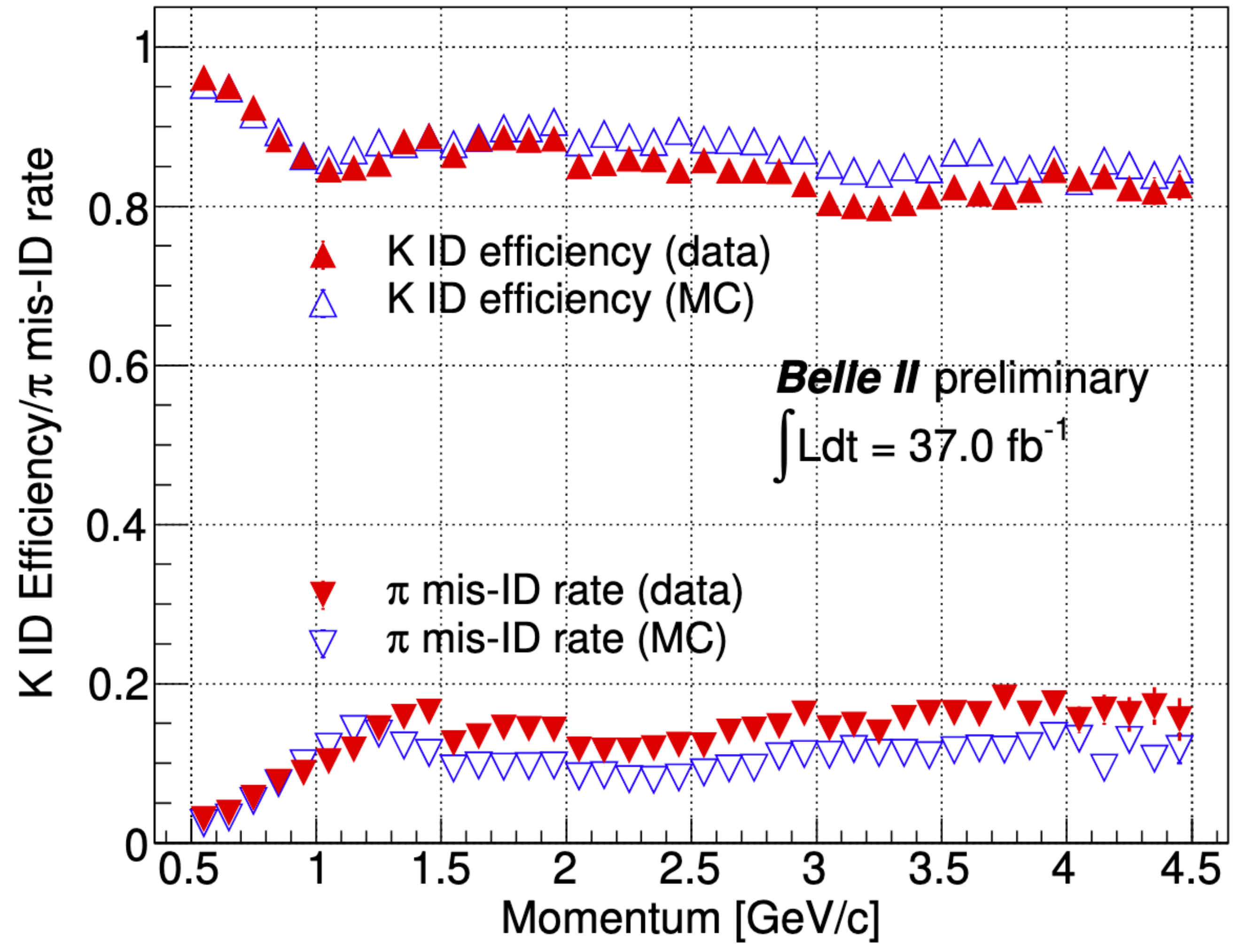


FIG. 4: Kaon efficiency and pion mis-ID rate for the PID criterion $\mathcal{R}_{K/\pi} > 0.5$ using the decay $D^{*+} \to D^0[K^-\pi^+]\pi^+$ in the bins of laboratory frame momentum of the tracks.

BELLE2-NOTE-PL-2019-019

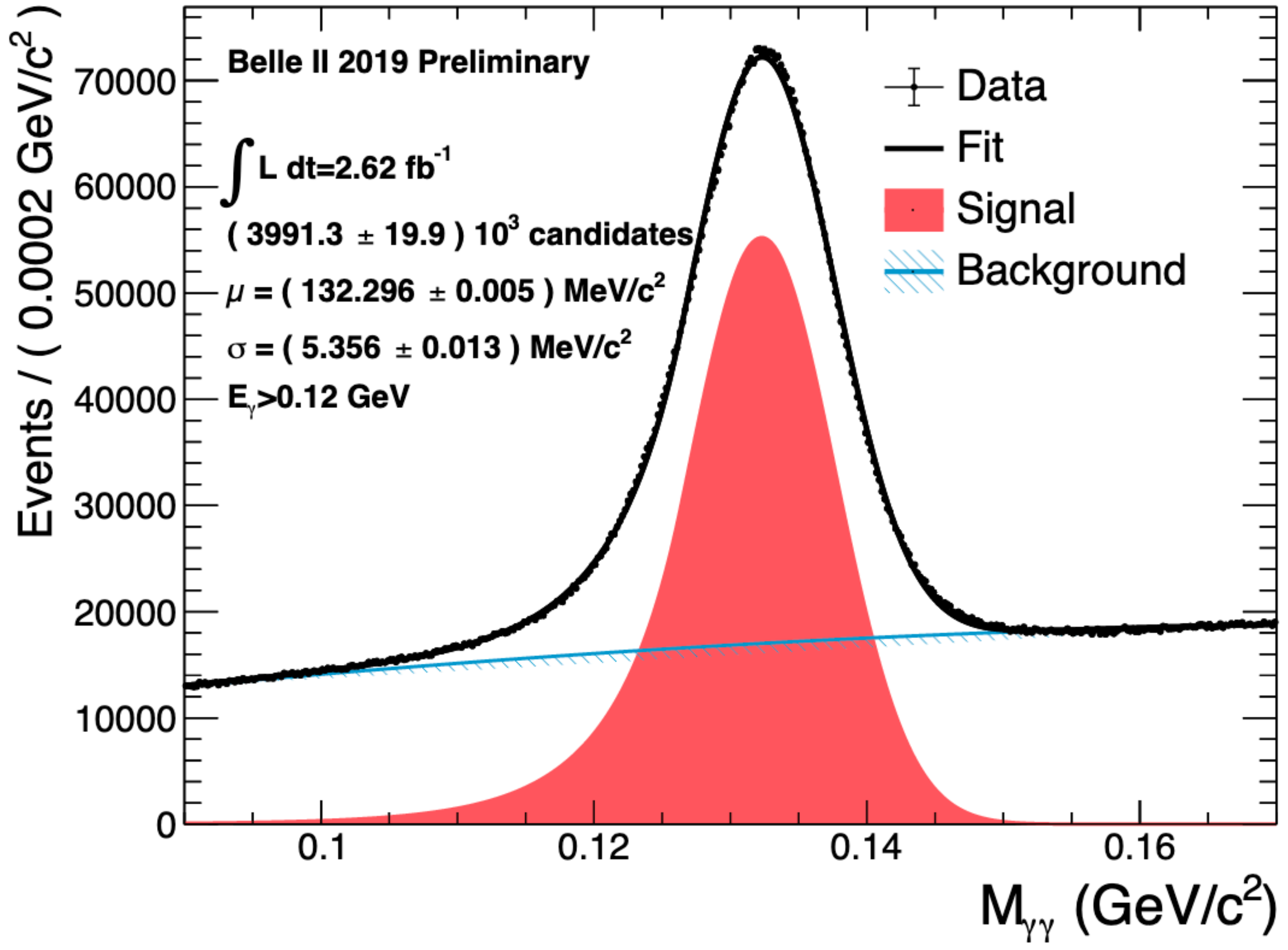


FIG. 1: Invariant mass of $\gamma\gamma$ for data phase III. The functions superimposed are the result of a binned ML fit to the data using as signal a Crystal Ball plus a Gauss (with the same mean) and a first order polynomial for background. A clear peak for the decay $\pi^0 \to \gamma\gamma$ is visible. Data corresponds to an integrated luminosity of 2.62 fb^{-1} (proc9 hadron skim). The selection criteria are $E_\gamma > 120$ MeV, $E_9/E_{21} > 0.9$, $N_{hits} > 1.5$.

BELLE2-NOTE-PL-2020-027

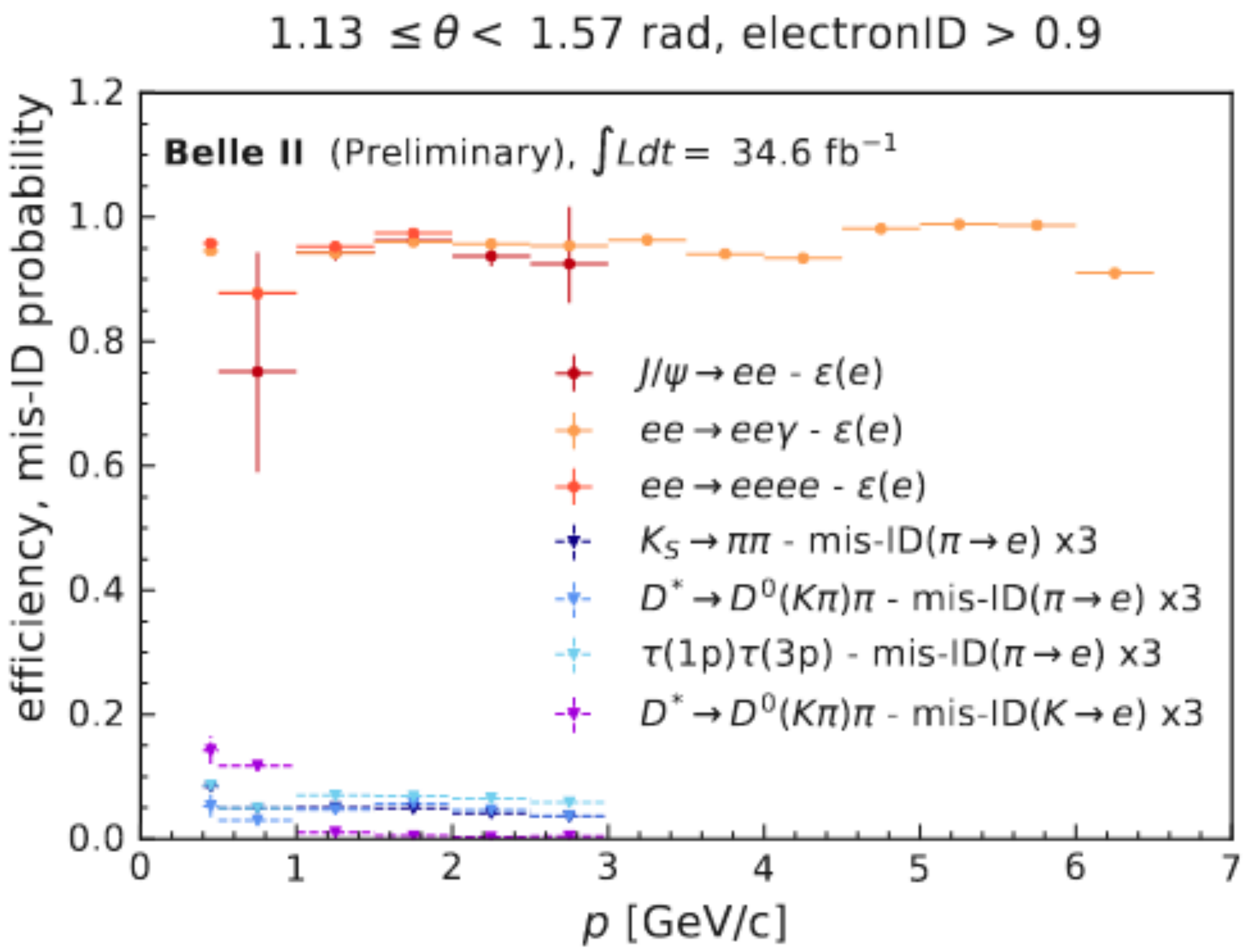
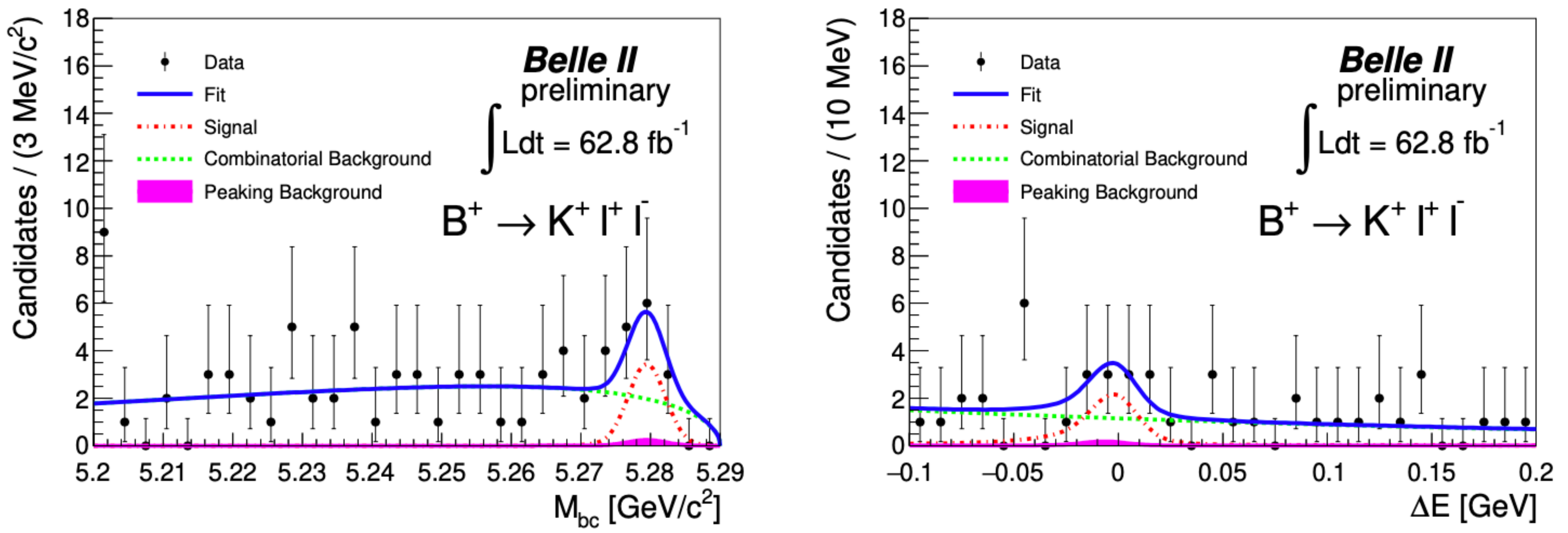


FIG. 10: Example ECL barrel bin for **electronID** with all measurements, efficiencies and hadron-lepton mis-identification rates overlaid. Note that the mis-identification rate has been inflated by a factor 3 for illustration purposes.

Toward BelleII measurements (II)

- Rediscovery of **$B^+ \to K^+ l^+ l^-$**, more on $b \to sll$ to come in the next months
- Signal yield extracted from 2D fit to M_{bc} and ΔE, 2.7 σ significance
    - Nsig = $8.6^{+4.3}_{-3.9}(\text{stat}) \pm 0.4(\text{syst})$

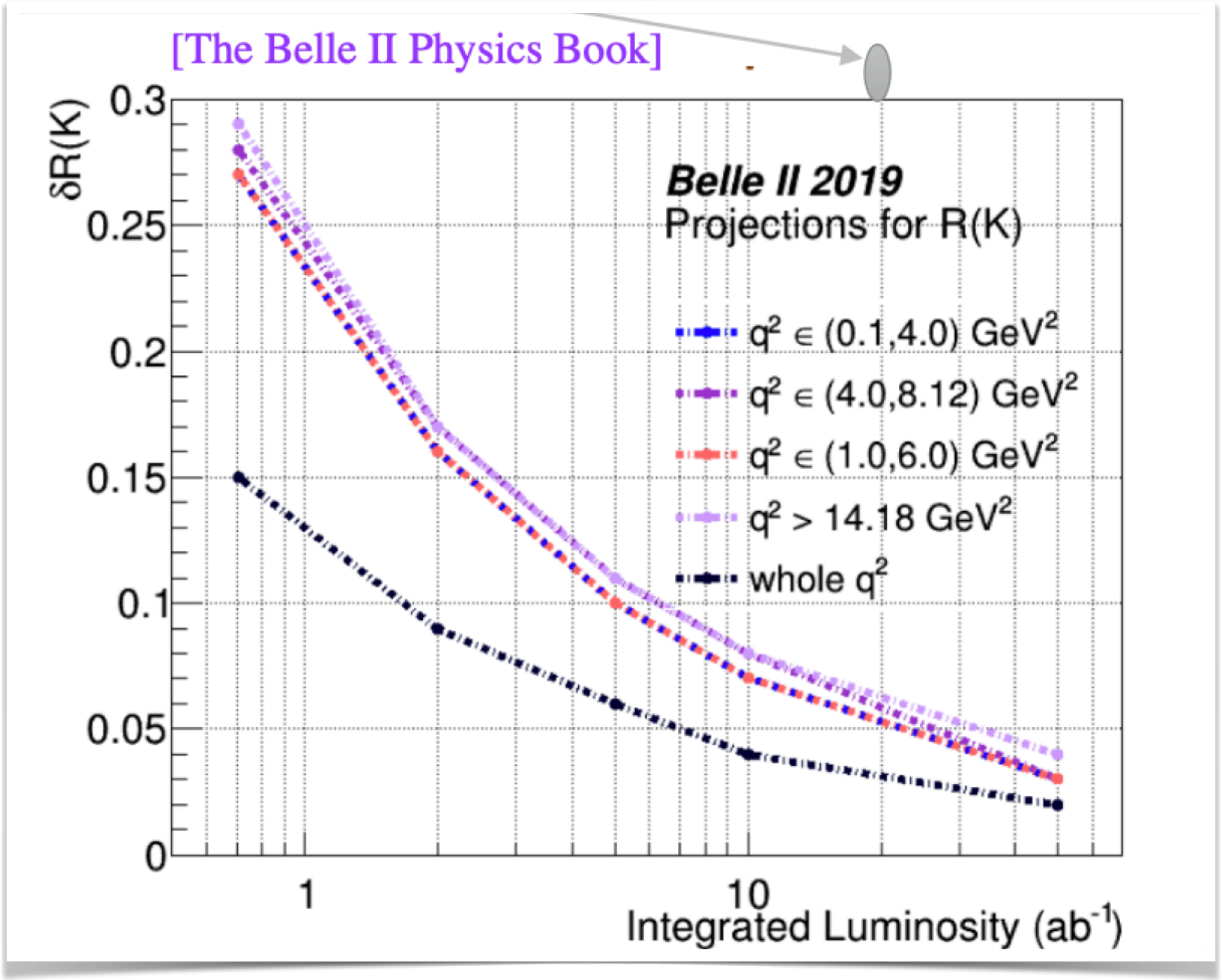
Belle II preliminary, BELLE2-NOTE-PL-2021-005

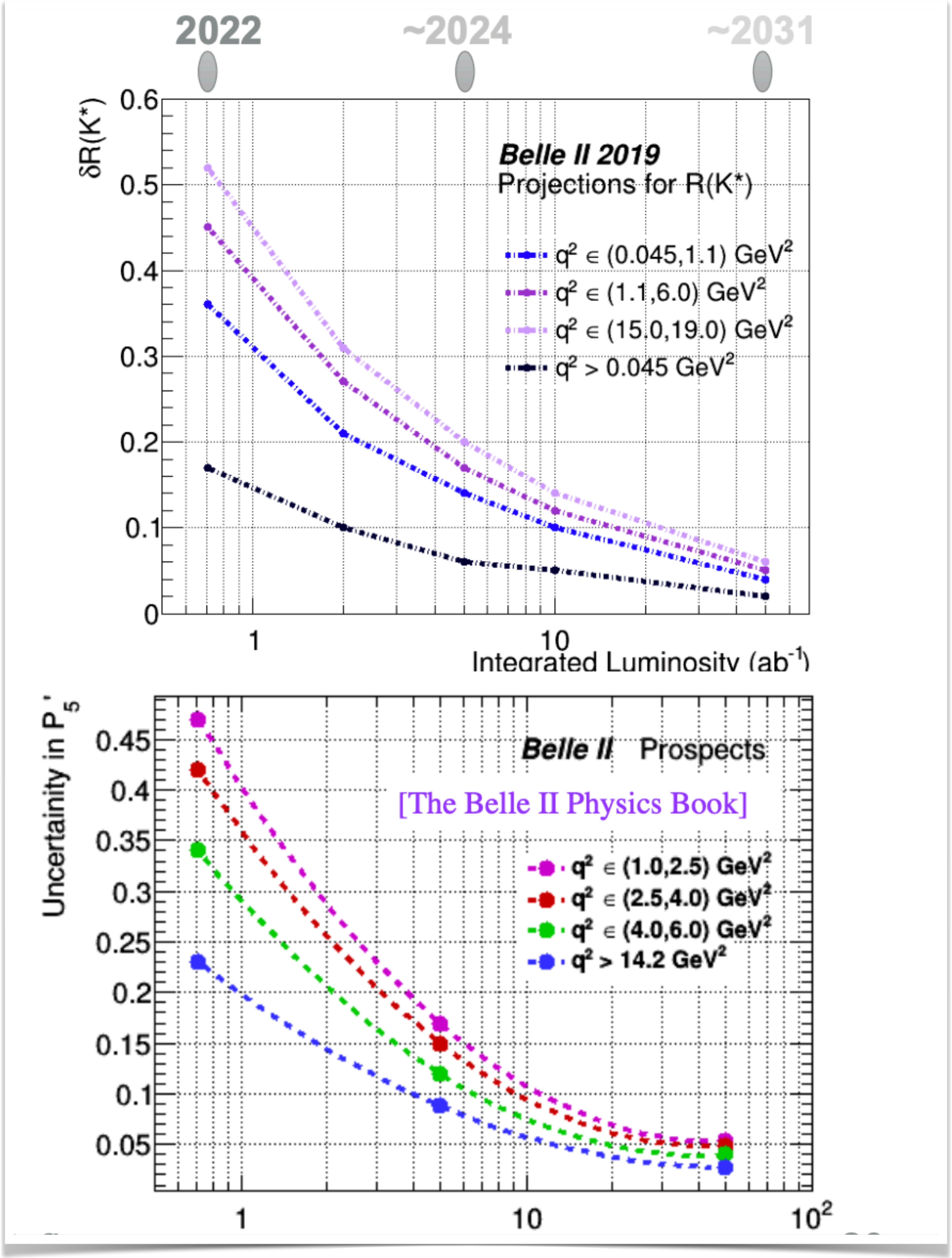


$$M_{bc} = \sqrt{E_{beam}^2 - |\overrightarrow{p_B}|^2}$$

$$\Delta E = E_B - E_{beam}$$

BelleII perspectives





- **R(K(*))**: LHCb with full luminosity (~2035, 300fb^{-1}) will have better precision in the low q^2 wrt to full BelleII data sample, in the high q^2 BelleII precision et **few %** level

- **P'5**: will be studied in both e and μ channel at BelleII, **few %** level precision expected with full BelleII statistics

The BelleII Physics Book, PETP 2019, 123C01 (2019)

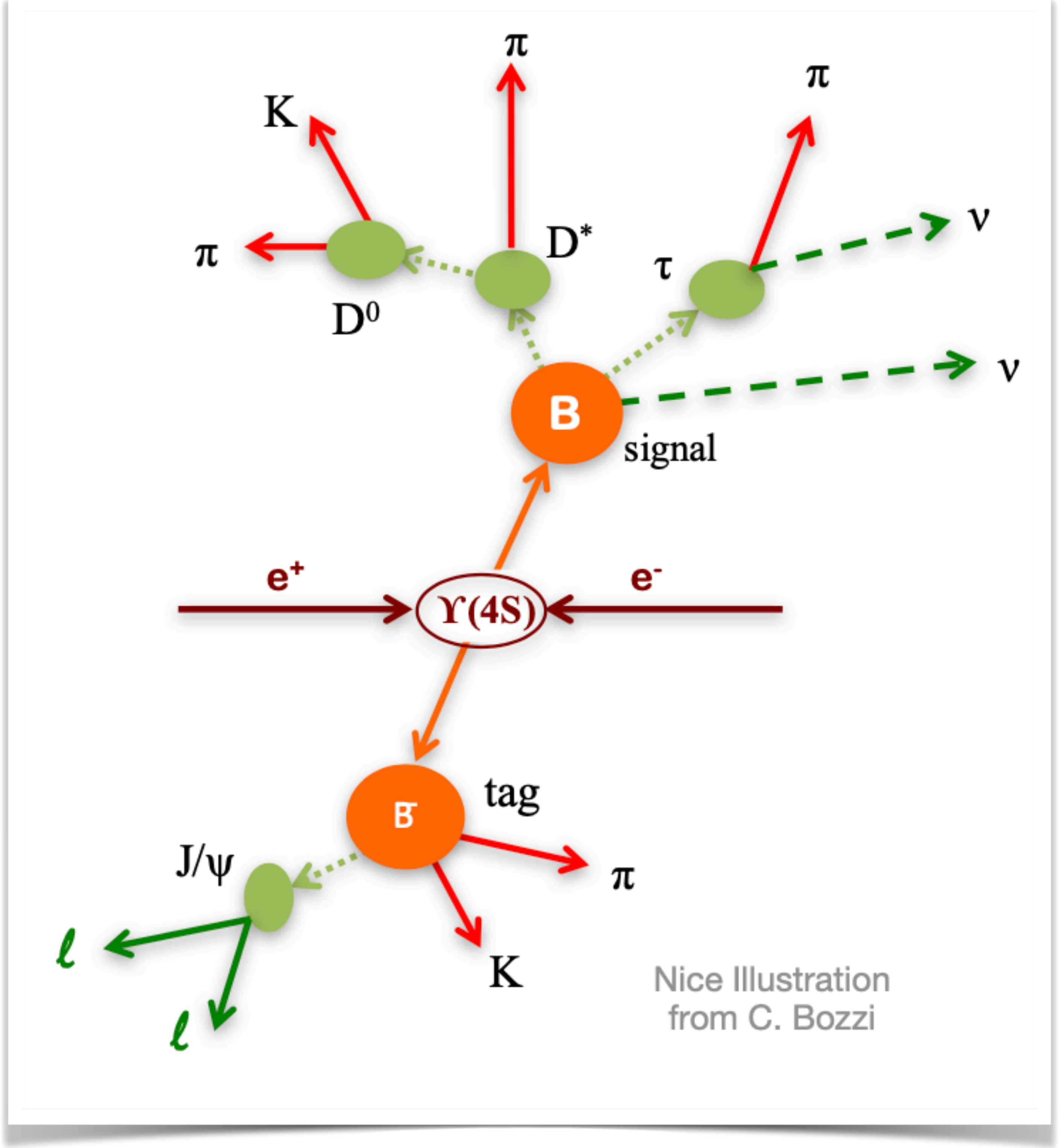
b → cℓν

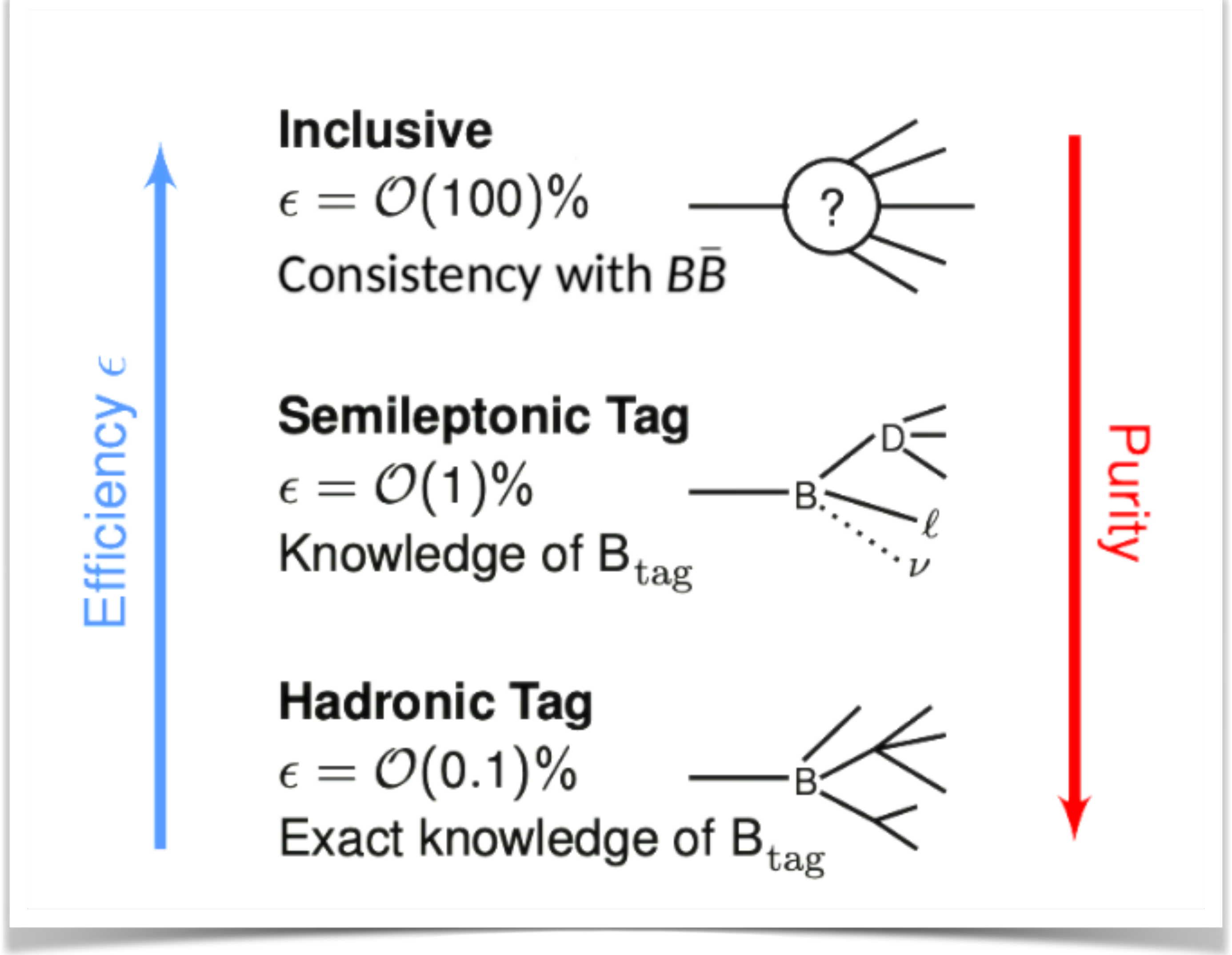
R(D(*)): analysis strategy

- Measurable:

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

- Search for final states involving neutrinos, two key elements
- One of the KEYS of measurement @ B-factories:
  - beam energy completely transferred to BB pair: $e^+e^- \to \Upsilon(4S) \to BB$
  - exploit (almost) **full reconstruction of one of the B** and look for signal or normalisation signature in the rest of the event
  - can compute momentum associated to **missing** particles, e.g. $p_{miss} = p_{e+e-} - p_{Btag} - p_{D^*} - p_\pi$





R(D(*)): latest Belle measurement

- Tag side reconstructed in semileptonic final state
- τ reconstructed in purely leptonic modes
- Signal extracted from 2D fit to BDT and E_{ECL}:
  - **E_{ECL}**=neutral energy deposited in the calorimeter not associated to signal nor to tag side, key ingredient in analysis with missing energy

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

Most precise measurement to date

Belle coll., Phys.Rev.Lett. 124 (2020)

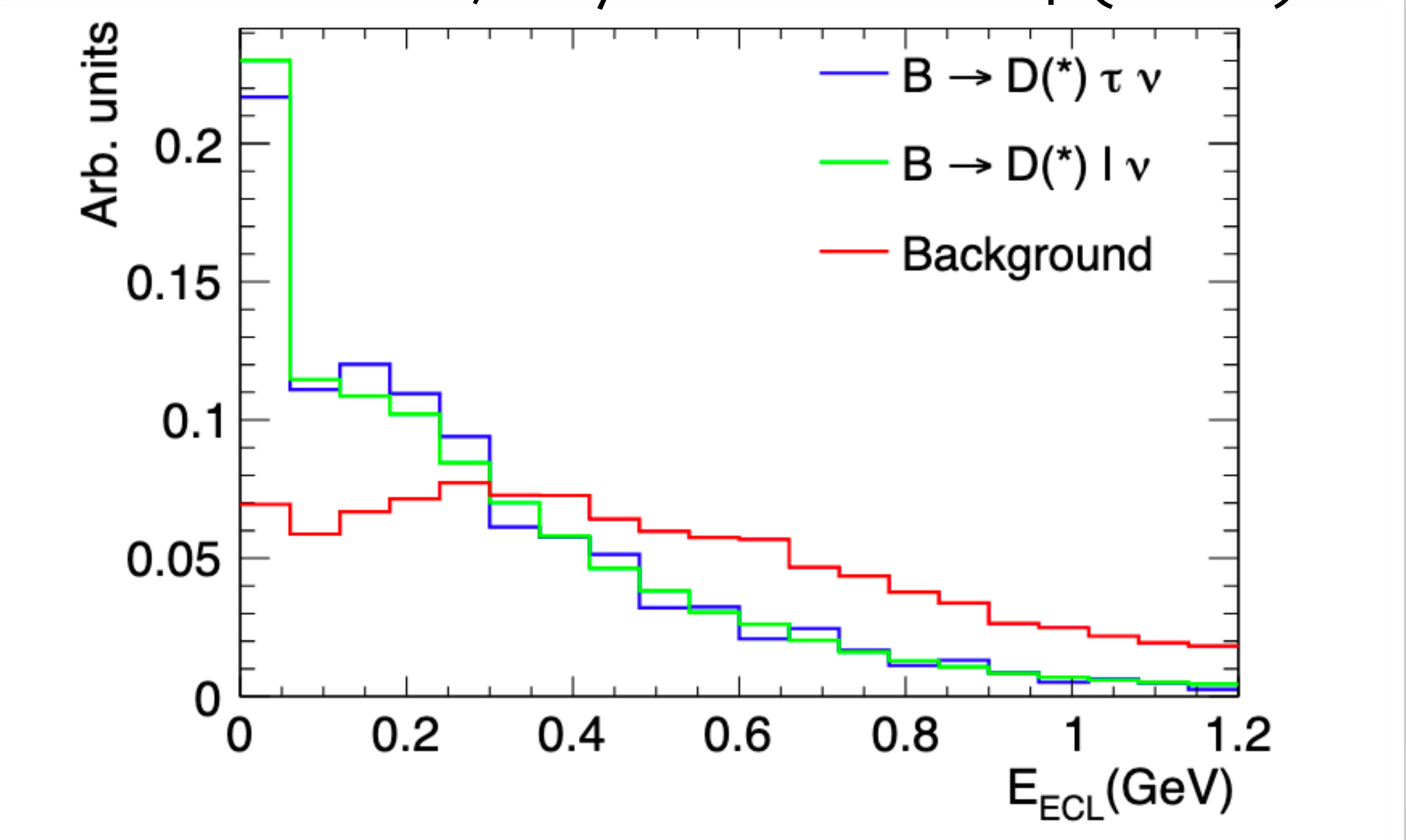
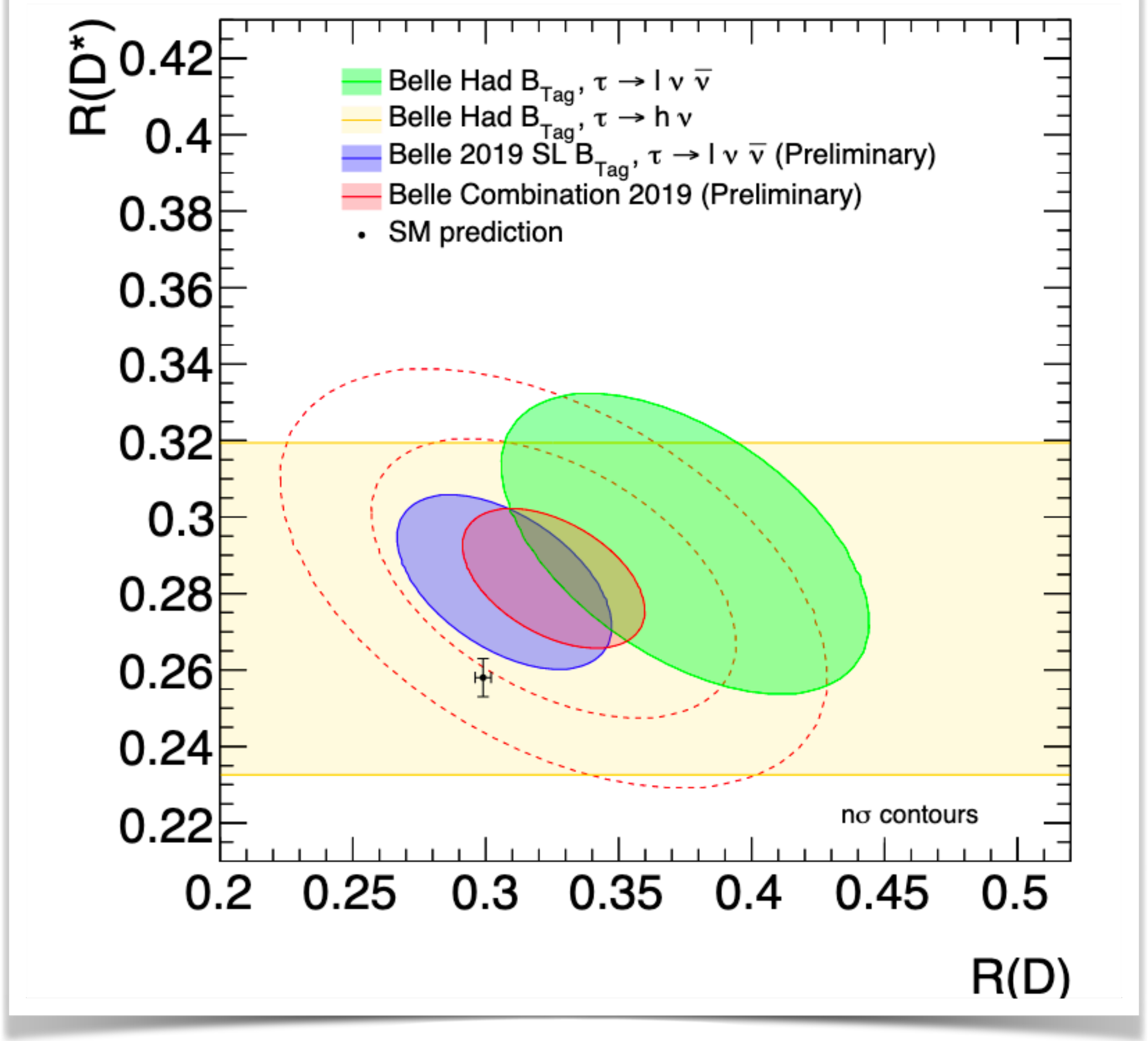


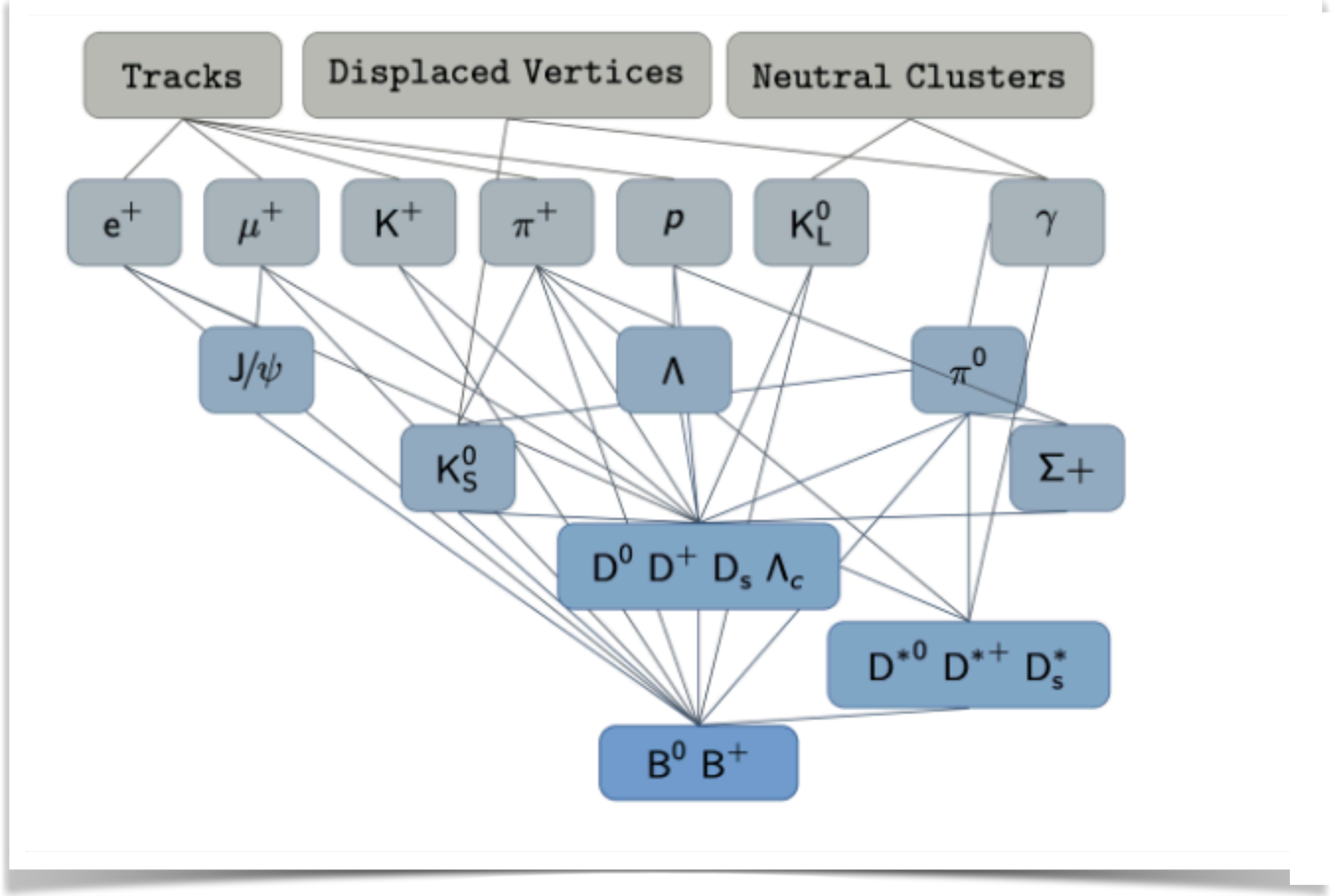
FIG. 1. E_{ECL} distributions for the signal, normalization, and background taken from MC simulation. The distributions for all decay modes are summed together and normalized to unity.

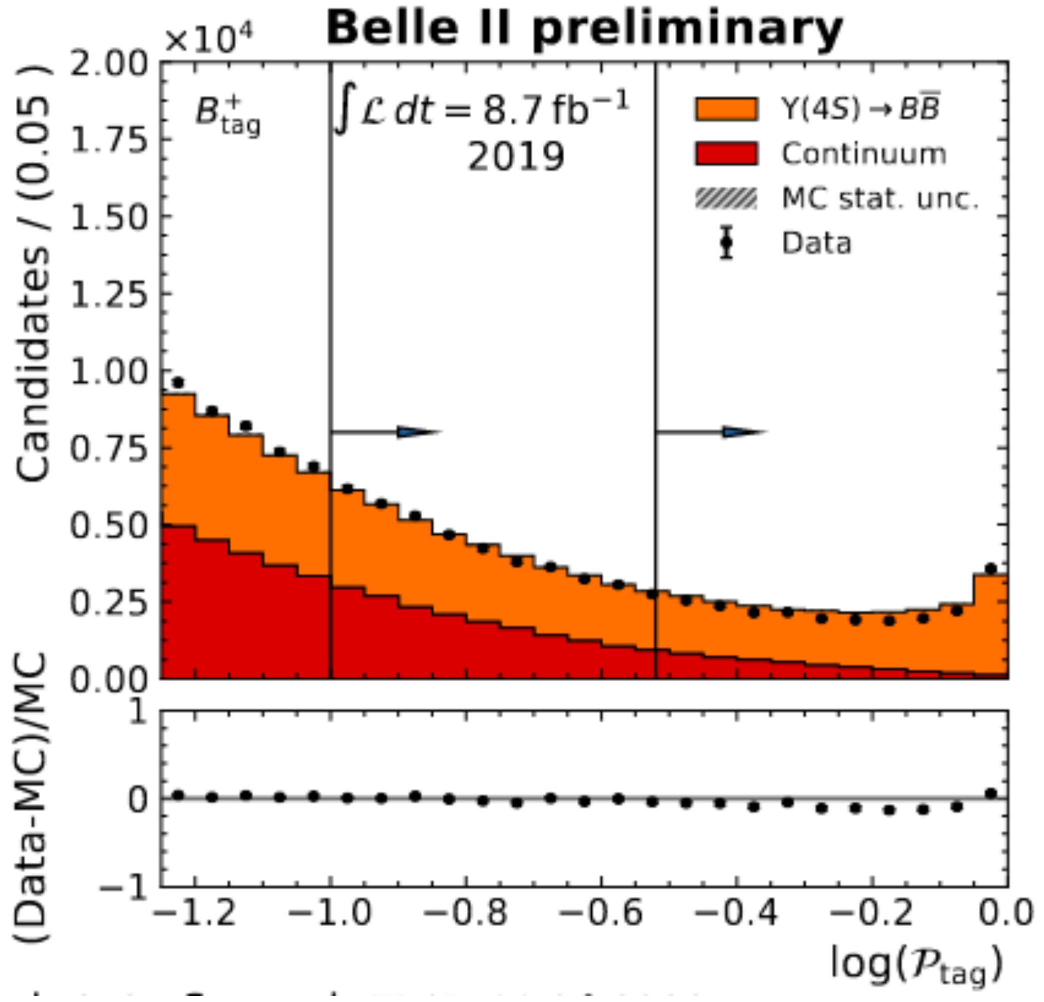


R(D(*)): toward Belle II measurement (I)

BELLE2-NOTE-PL-2020-002

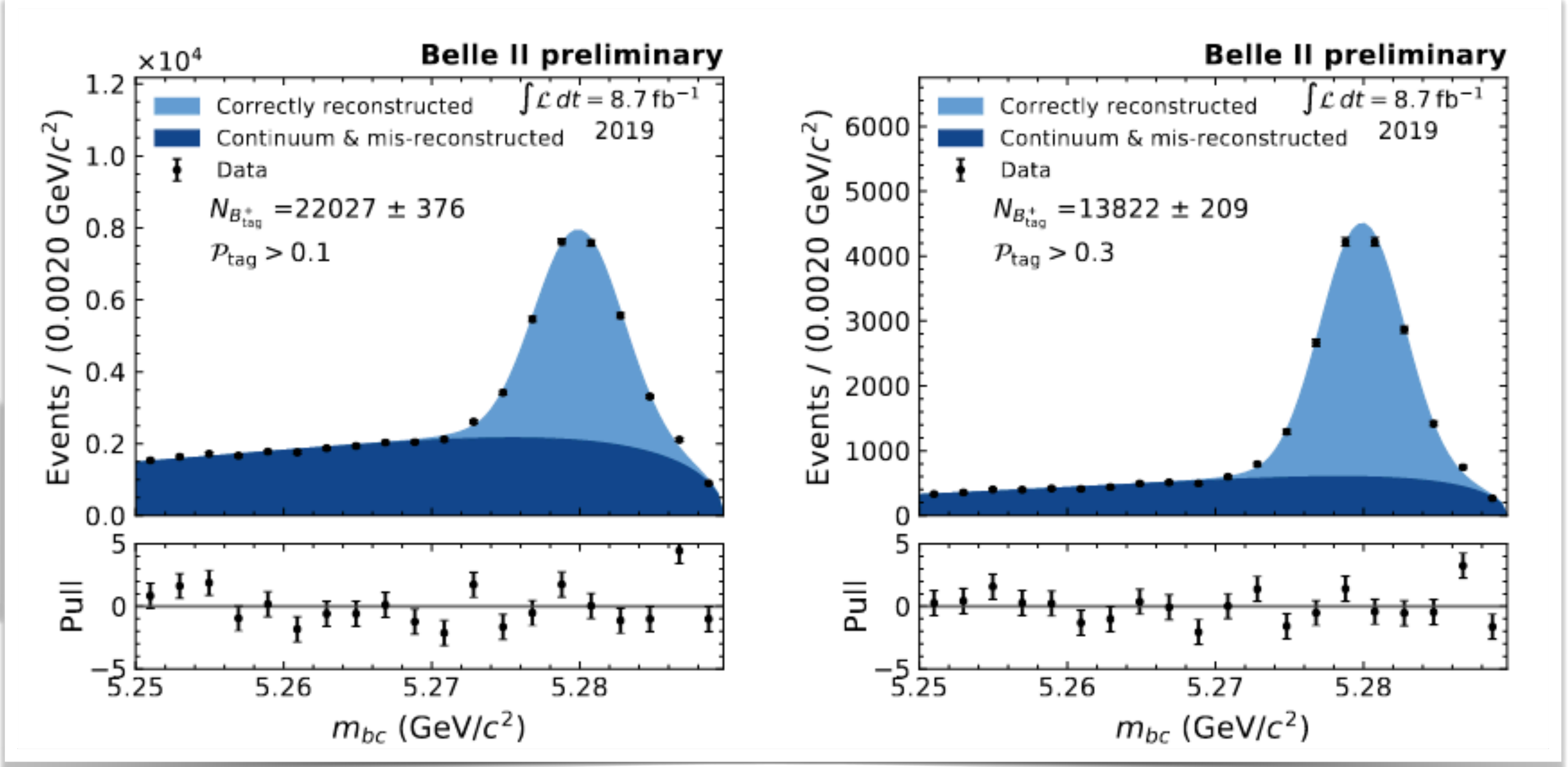
- Tag side reconstruction with **Full Event Interpretation** (FEI) (Keck et al., Comp. Soft. Big Sci. (2019) 3:6)
  - Multivariate tagging algorithm optimised for BelleII, successor of Belle Full Reconstruction (Feindt et al. Nucl.Instrum.Meth.A 654 (2011) 432-440), can be applied to Belle data
  - hierarchical approach to reconstruct O(200) decay channels via O(10⁴) decay chains





MC tag-side efficiency @10% purity	Had. B^+/B^0 [%]	SL. B^+/B^0 [%]
Full Reconstruction Belle	0.28/0.18	0.67/0.63
FEI Belle	0.76/0.46	1.80/2.04

P. Urquijo (BelleII), FPCP2020



R(D(*)): toward Belle II measurement (II)

- Rediscovery of **normalisation channel** using hadronic **FEI**

Belle coll.,BELLE2-CONF-PH-2020-009

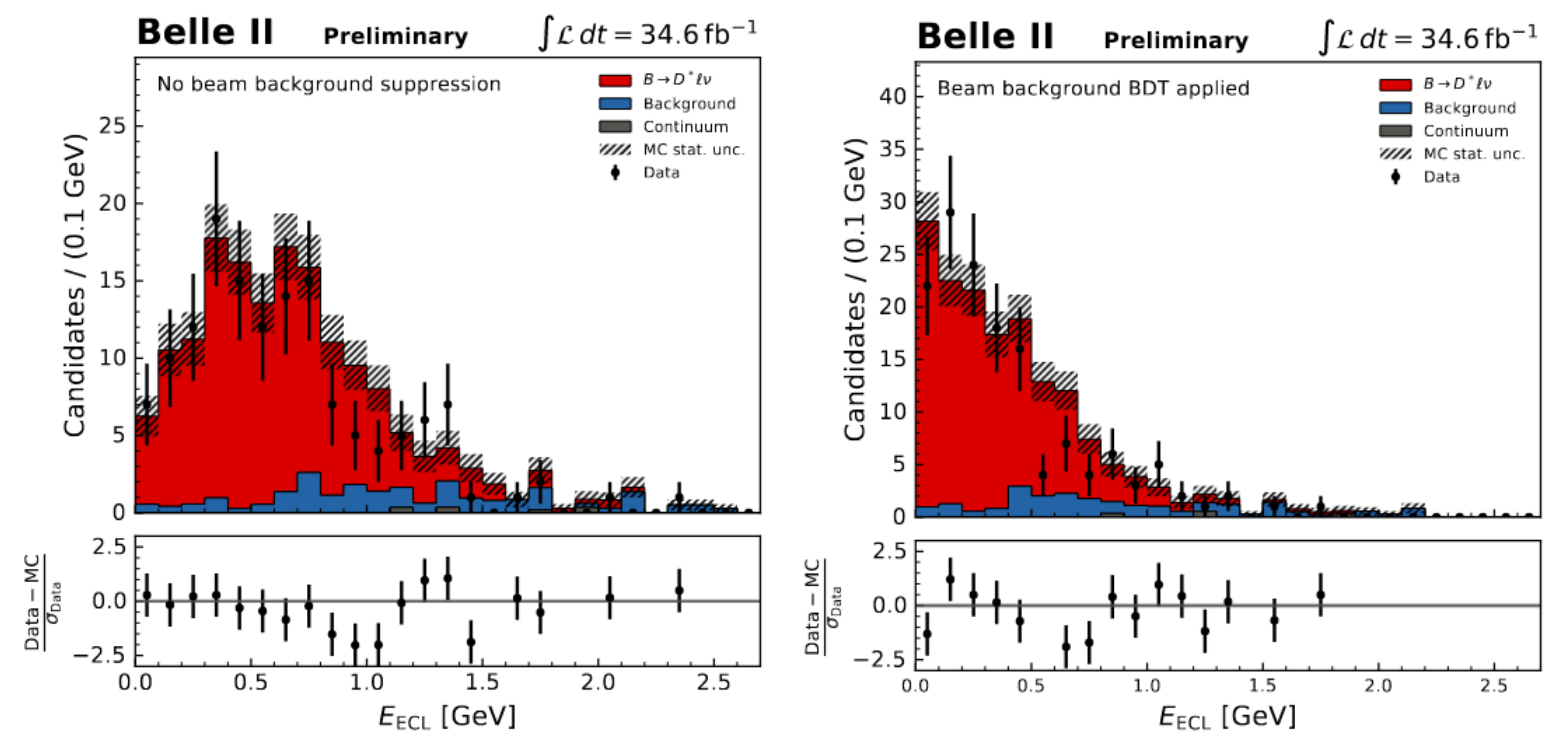


FIG. 3. Two versions of E_ECL are shown: (left) is the version applying detector region dependent energy selection criteria, (right) shows the impact of using a BDT to identify neutral energy depositions from beam background processes. It is based on shower shape variables and the detector region of the reconstructed neutral cluster.

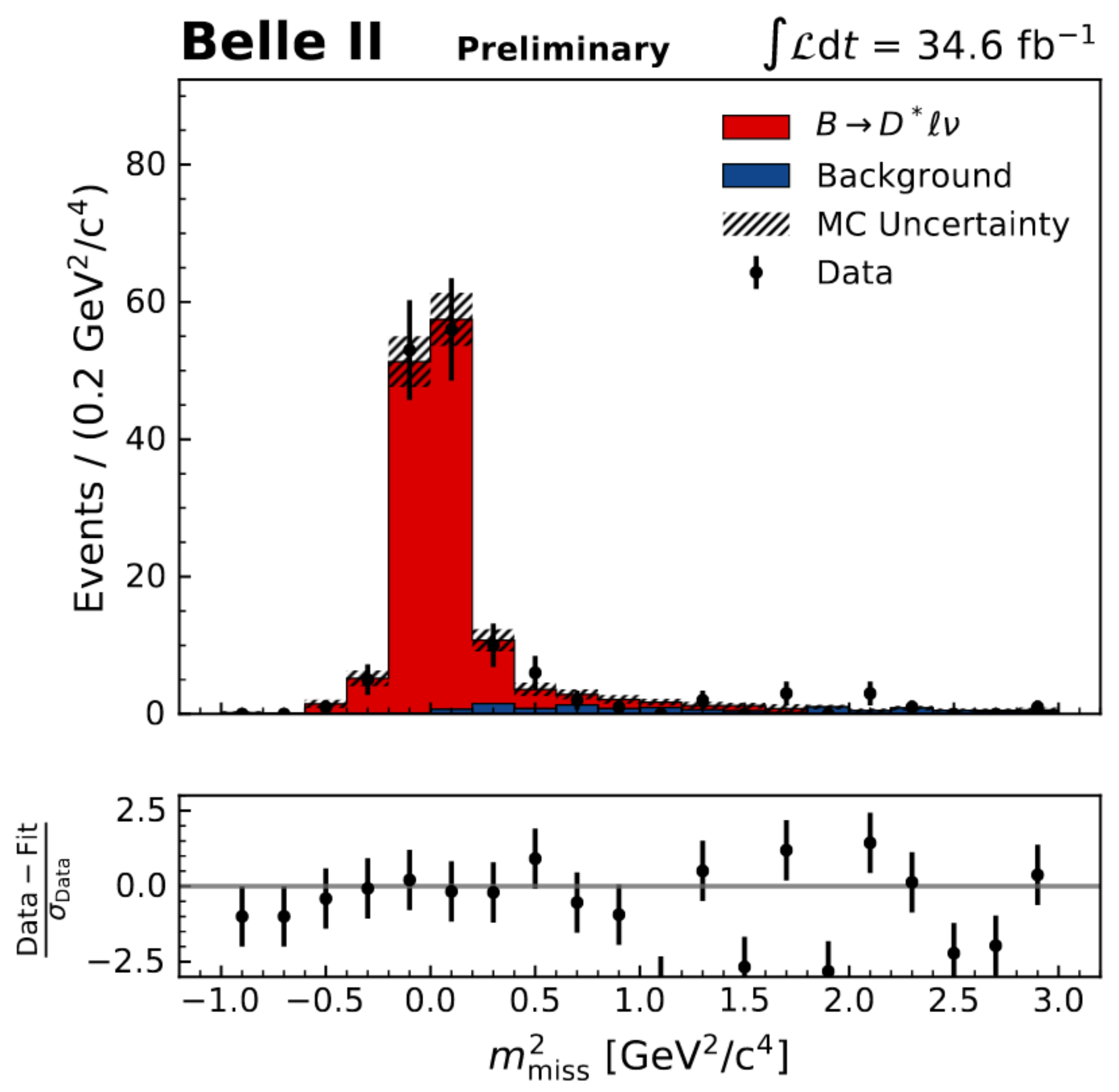
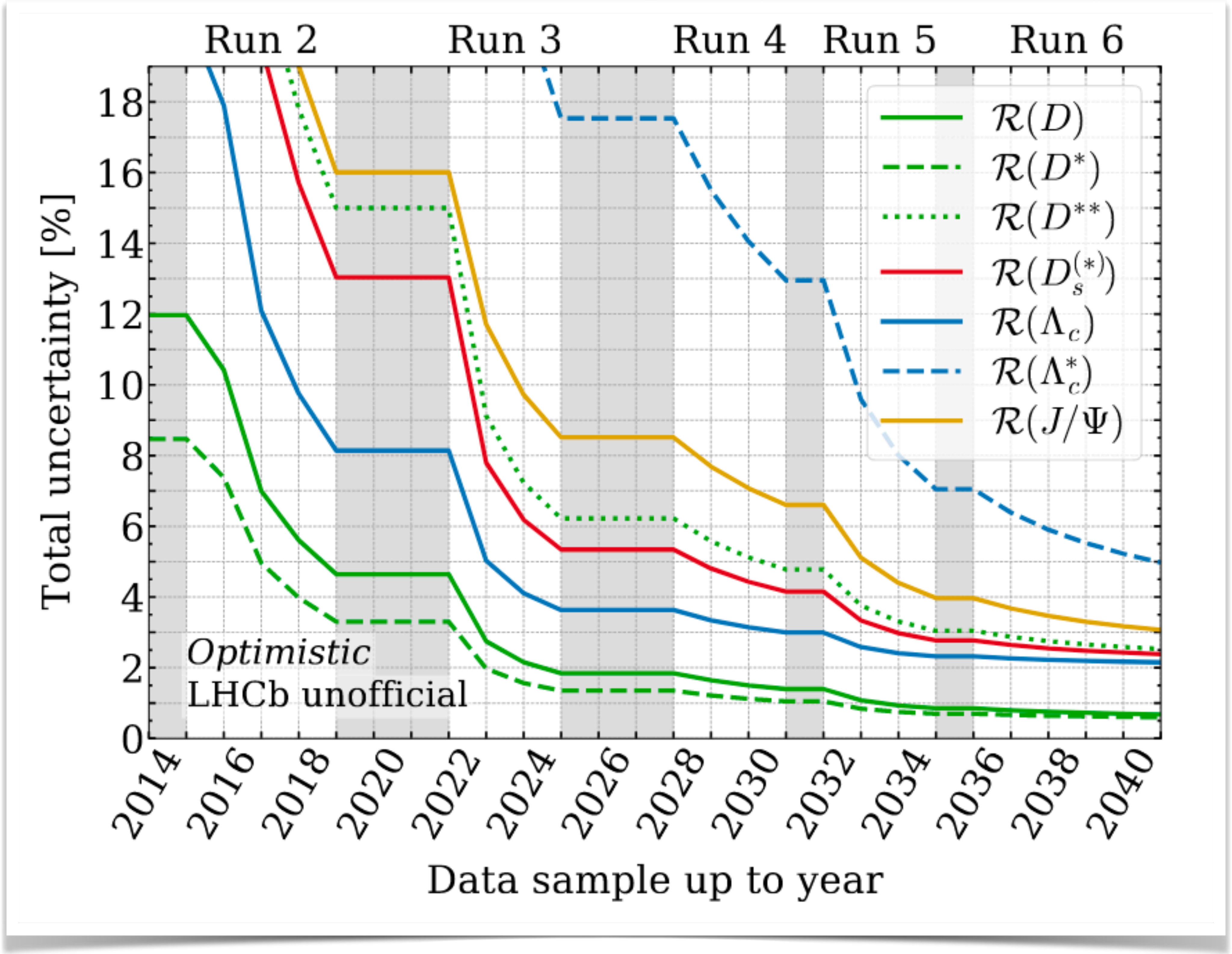


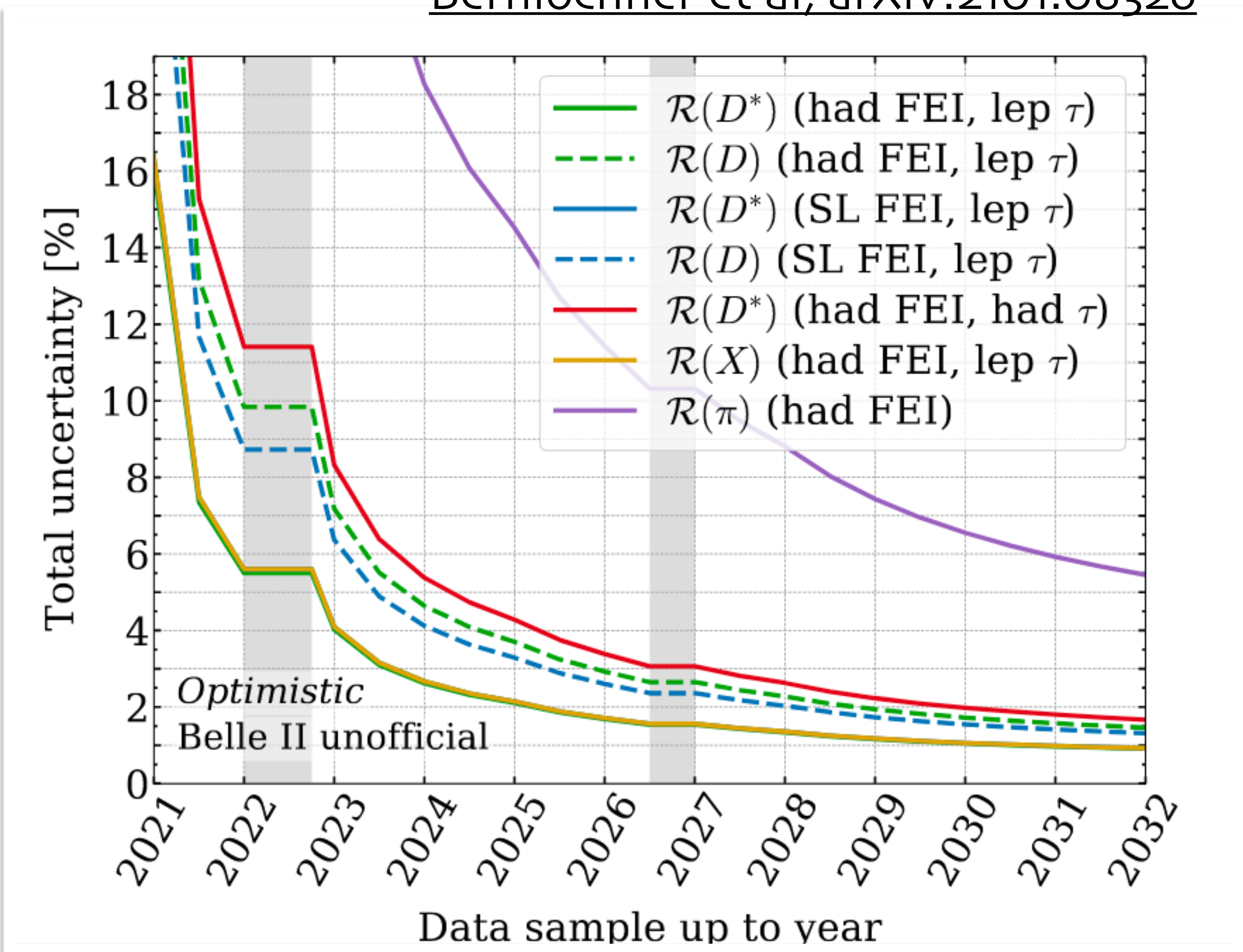
FIG. 2. The post-fit m^2_miss distribution is shown.

$$\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_l) = \left(4.51 \pm 0.41_\text{stat} \pm 0.27_\text{syst} \pm 0.45_{\pi_s}\right)\,\%$$

R(D(*)): perspectives at BelleII



Bernlochner et al, arXiv:2101.08326



- Pletora of τ/l **ratio** measurements from LHCb and Belle
- On **R(D(*))**, **(sub)-%** level precision can be reached
- @ Belle, one of the dominant systematics from D** background, can be studied in more detail with BelleII data

Table 49: Composition of the systematic uncertainty in each Belle analysis. Relative uncertainties in percent are shown. The analysis method and the τ decay mode are indicated in the parentheses; their meaning is explained in the caption of Table 48.

Source	Belle (Had, ℓ^-) R_D	Belle (Had, ℓ^-) R_{D^*}	Belle (SL, ℓ^-) R_{D^*}	Belle (Had, h^-) R_{D^*}
MC statistics	4.4%	3.6%	2.5%	$^{+4.0}_{-2.9}$%
$B \to D^{**}\ell\nu_\ell$	4.4%	3.4%	$^{+1.0}_{-1.7}$%	2.3%
Hadronic B	0.1%	0.1%	1.1%	$^{+7.3}_{-6.5}$%
Other sources	3.4%	1.6%	$^{+1.8}_{-1.4}$%	5.0%
Total	7.1%	5.2%	$^{+3.4}_{-3.5}$%	$^{+10.0}_{-9.0}$%

Looking for other NP hints in B and τ decays

NP models explaining LFU violation

- G. Isidori @ Beyond the anomalies II

G. Isidori – B-physics anomalies: facts, hopes, dreams, & worries *Beyond the anomalies II – Durham, Apr. 2021*

▶ ***From EFT to simplified models***

Beside direct searches, an essential role is still played by low-energy observables → many visible BSM effects expected, by consistency, virtually in all models addressing the anomalies

Main message: "super-reach" program for LHCb & Belle-II and other low-energy facilities. This program is essential to confirm/disproof the picture and, if confirmed..., to determine the flavor structure of the new sector.

I. EFT-based (model-independent) correlations on a large class of semi-leptonic processes

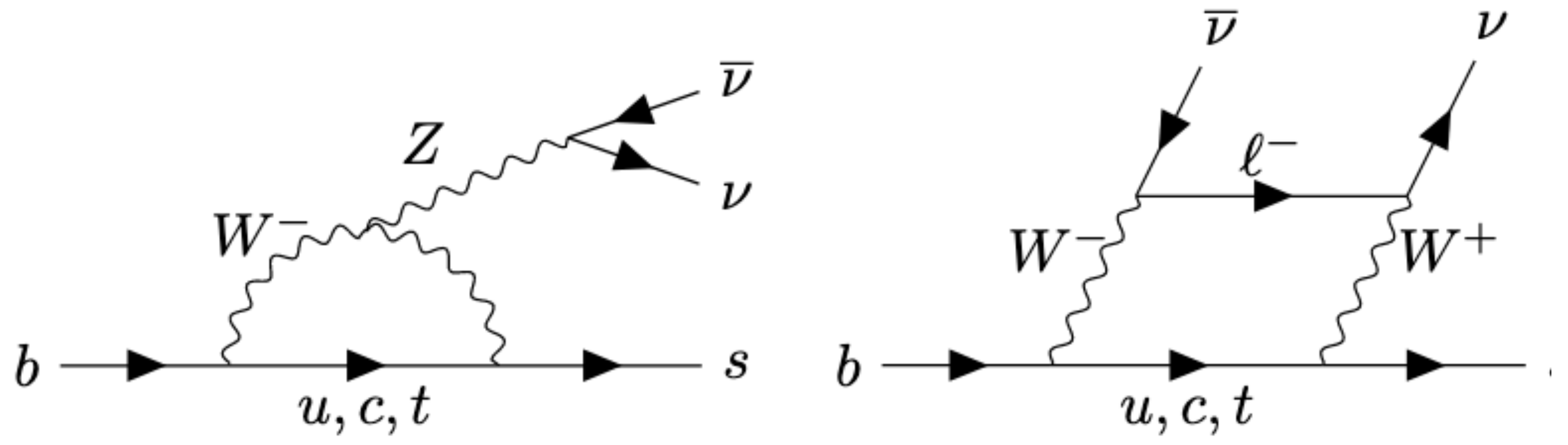
[$b \to d\ \mu\mu$, $b \to s\ \tau\tau$, $b \to s\ \tau\mu$, $b \to u\ \tau\nu$, ...]

II. Model-dependent correlations for UV-sensitive observables

[$\Delta F=2$, $b \to s\ \nu\nu$, $\tau \to \mu\gamma$, $\tau \to 3\mu$, $\mu N \to eN$, ...]

B→K(*)$\nu\nu$: state of the art prior Moriond2021

- b→s transition with neutral leptons in the final state
- SM predictions:



(a) Penguin diagram (b) Box diagram

T. Blake,, et al, Prog. Part.Nucl. Phys.92, 50 (2017)

$$\mathrm{BR}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{SM}} = (4.6 \pm 0.5) \times 10^{-6}\,,$$
$$\mathrm{BR}(B^+ \to K^{*+}\nu\bar{\nu})_{\mathrm{SM}} = (8.4 \pm 1.5) \times 10^{-6}\,,$$
$$F_L^{\mathrm{SM}} = 0.47 \pm 0.03\,,$$ Buras et al, JHEP 02 184 (2015)

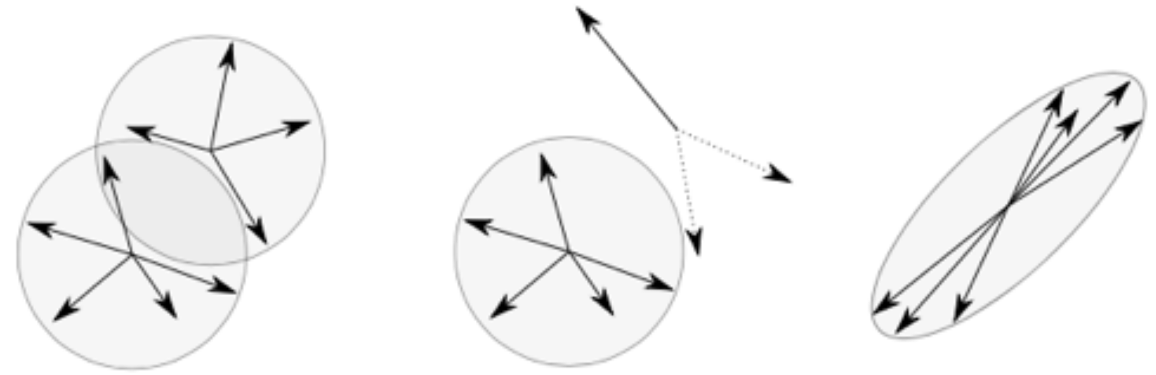
- BaBar and Belle key ingredients: **tag side** reconstruction in hadronic and semi-leptonic modes, usage of **event shape** variables to reduce contributions from $e^+e^-\to qq$ events and **extra neutral energy** deposited in the calorimeter

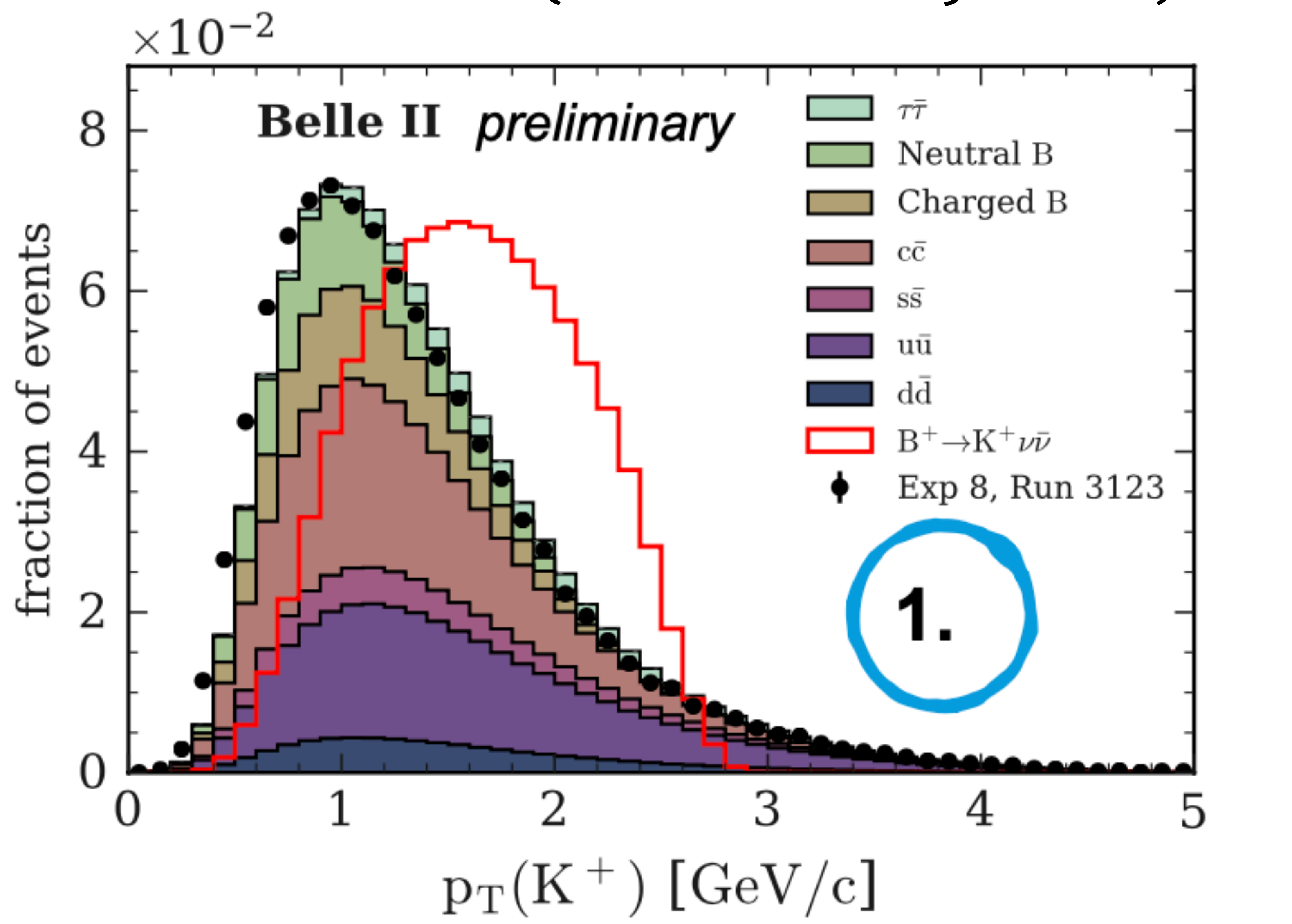
	UL @ 90% CL (10^{-5})	**Ref**
$B^+\to K^+\nu\nu$	1.6	BaBar, HAD+SL TAG, 429 fb^{-1}
$B^+\to K^{*+}\nu\nu$	4.0	Belle, HAD TAG, 711 fb-1
$B^0\to K^0\nu\nu$	2.6	Belle, SL TAG, 711 fb-1
$B^0\to K^{*0}\nu\nu$	1.8	Belle, SL TAG, 711 fb-1

$B^+ \to K^+\nu\nu$ measurement @ BelleII (I)

BelleII coll., arXiv:2104.12624
(submitted to journal)

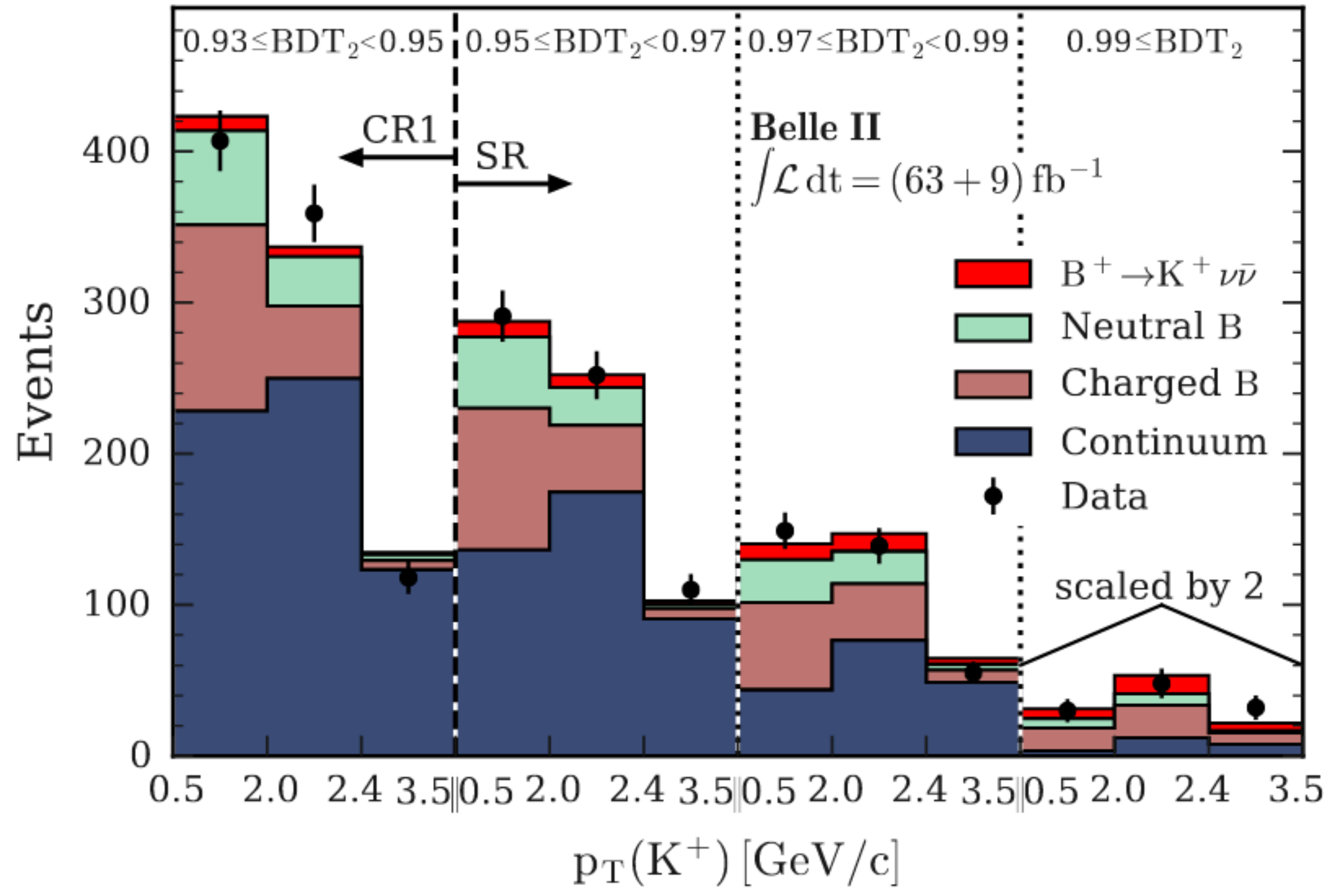
- **NOVEL INCLUSIVE APPROACH**:
  - signal kaon = highest pt track
  - associate all other tracks and clusters to rest of the event
  - use multivariate approach based on kinematics, event shape and vertexing variables to suppress background
  - extract signal from binned simultaneous ML fit to on-resonance + off- resonance data





$$\text{Measured signal strength } \mu = 4.2^{+2.9}_{-2.8}(\text{stat})^{+1.8}_{-1.6}(\text{syst})$$

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = 1.9^{+1.6}_{-1.5} \times 10^{-5}$$

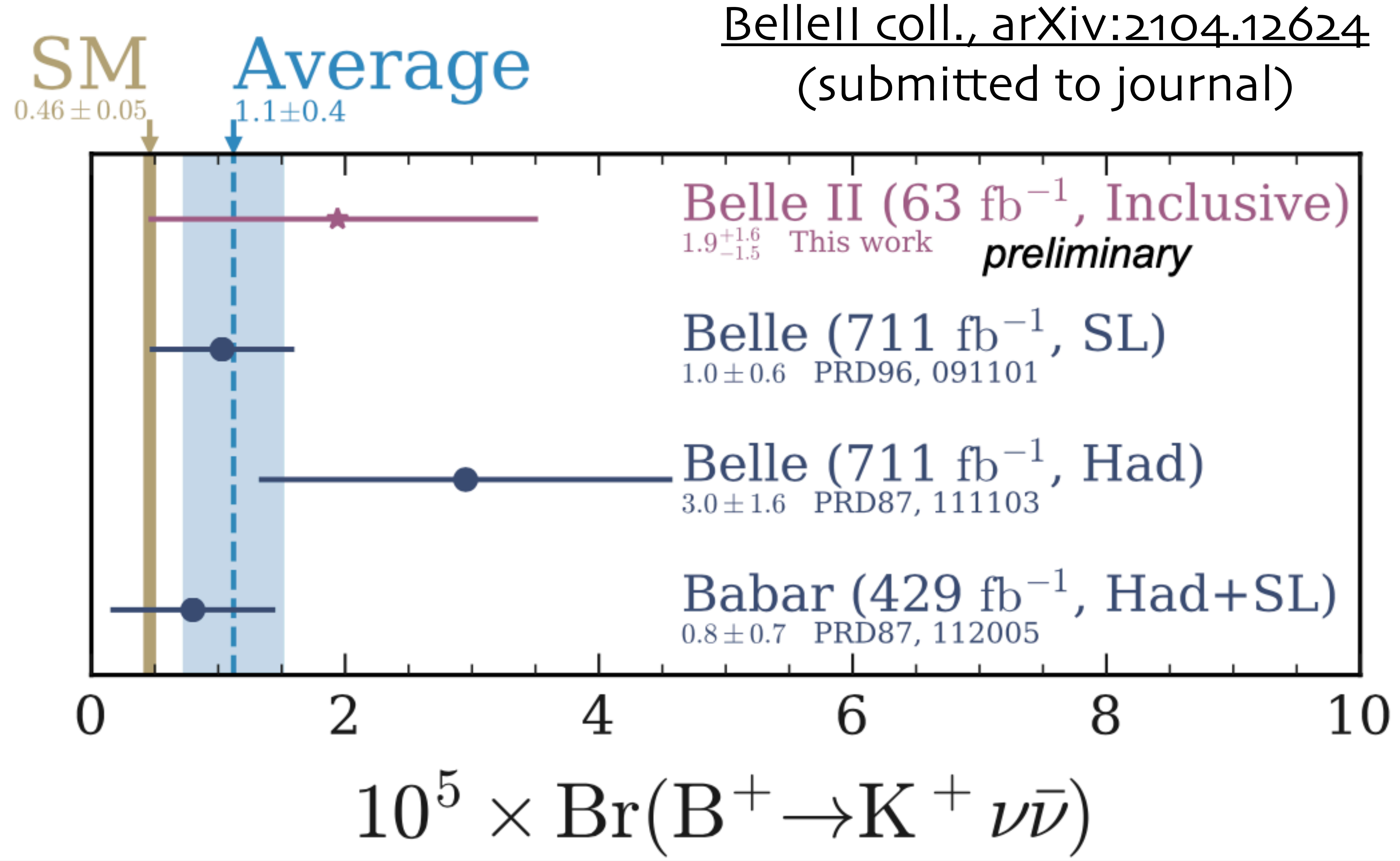


$B^+ \to K^+ \nu\nu$ measurement @ BelleII (II)

- Leading systematics: background normalisation uncertainty can be also reduced with increasing statistics
- Room for **improvement** in K^+ channel
- Application of inclusive method to **other channels** under study

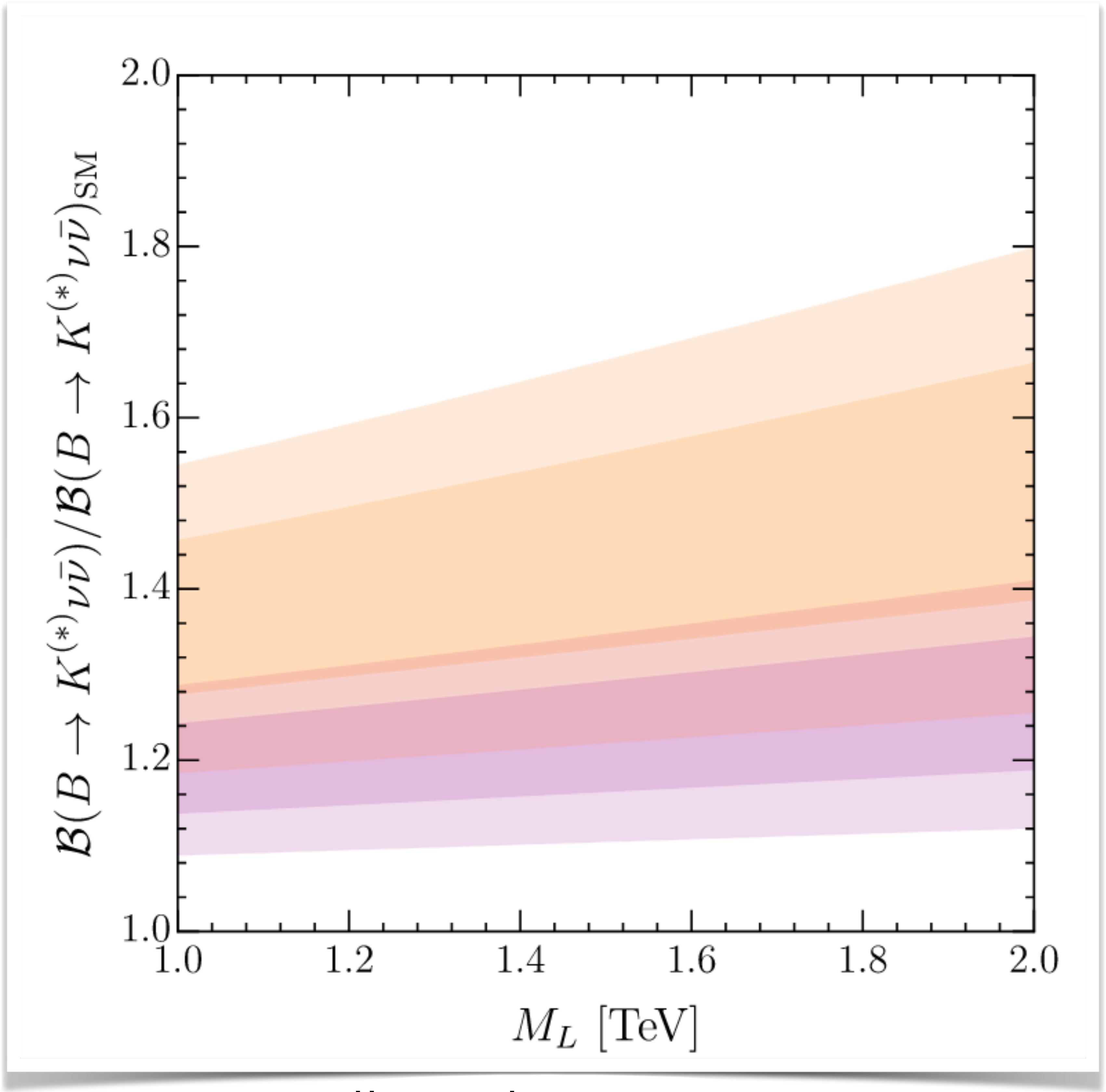
Experiment	Year	Observed limit on $BR(B^+ \to K^+ \nu\bar{\nu})$	Approach	Data $[fb^{-1}]$
BABAR	**2013**	$< 1.6 \times 10^{-5}$ [Phys.Rev.D87,112005]	SL + Had tag	429
Belle	**2013**	$< 5.5 \times 10^{-5}$ [Phys.Rev.D87,111103(R)]	Had tag	711
Belle	**2017**	$< 1.9 \times 10^{-5}$ [Phys.Rev.D96,091101(R)]	SL tag	711
Belle II *preliminary*	**2021**	$< 4.1 \times 10^{-5}$	Inclusive tag	63

BelleII coll., arXiv:2104.12624 (submitted to journal)



B→K(*)νν @ Belle II perspectives

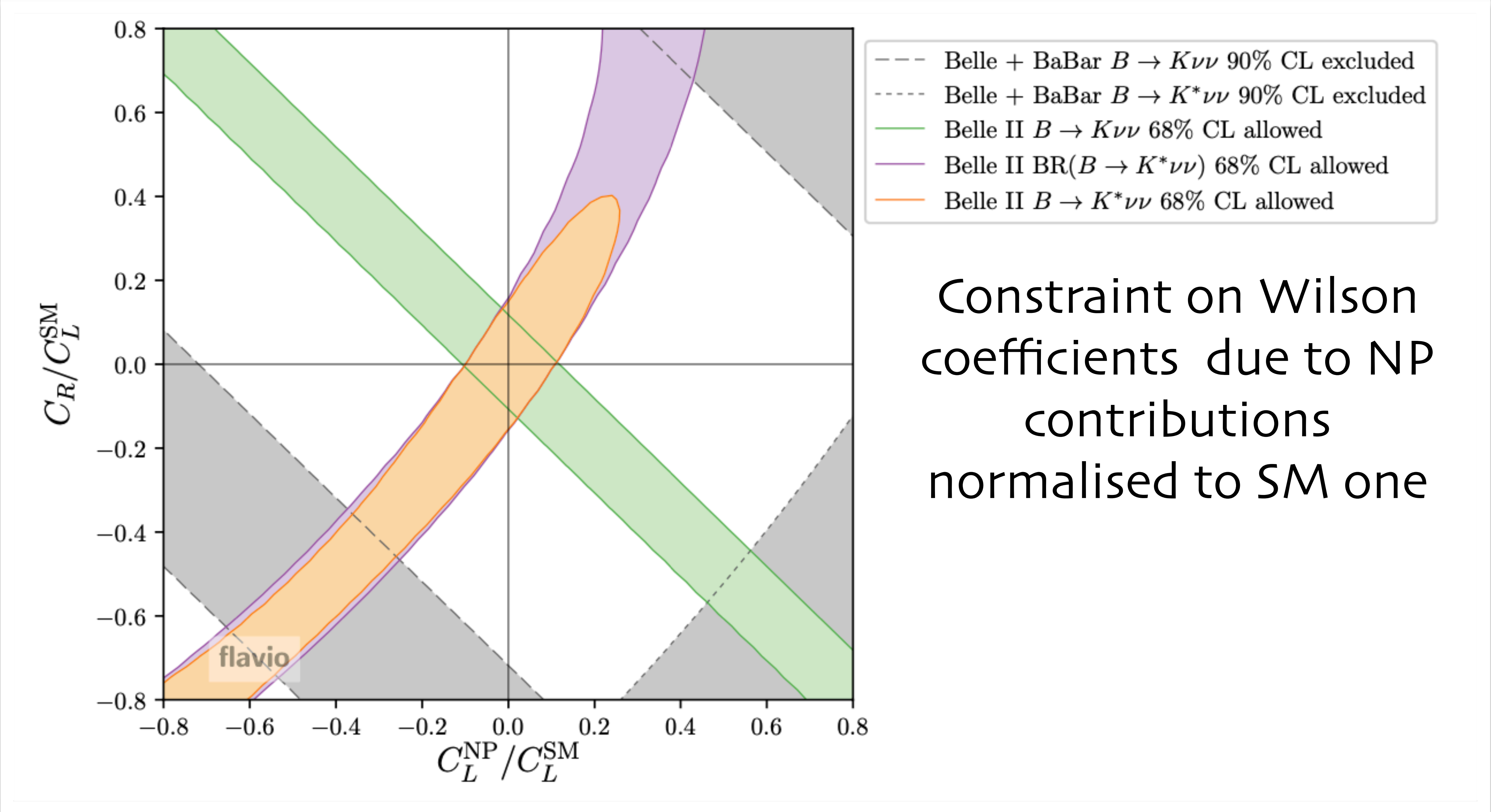
- Extrapolation done on **tagged analysis** only
- To be updated with most recent simulations and adding inclusive analysis



Cornella et al, arXiv:2103.16558

The BelleII Physics Book, PETP 2019, 123C01 (2019)

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+\nu\bar{\nu})$	< 450%	30%	11%
$\mathrm{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	< 180%	26%	9.6%
$\mathrm{Br}(B^+ \to K^{*+}\nu\bar{\nu})$	< 420%	25%	9.3%
$F_L(B^0 \to K^{*0}\nu\bar{\nu})$	–	–	0.079
$F_L(B^+ \to K^{*+}\nu\bar{\nu})$	–	–	0.077



Constraint on Wilson coefficients due to NP contributions normalised to SM one

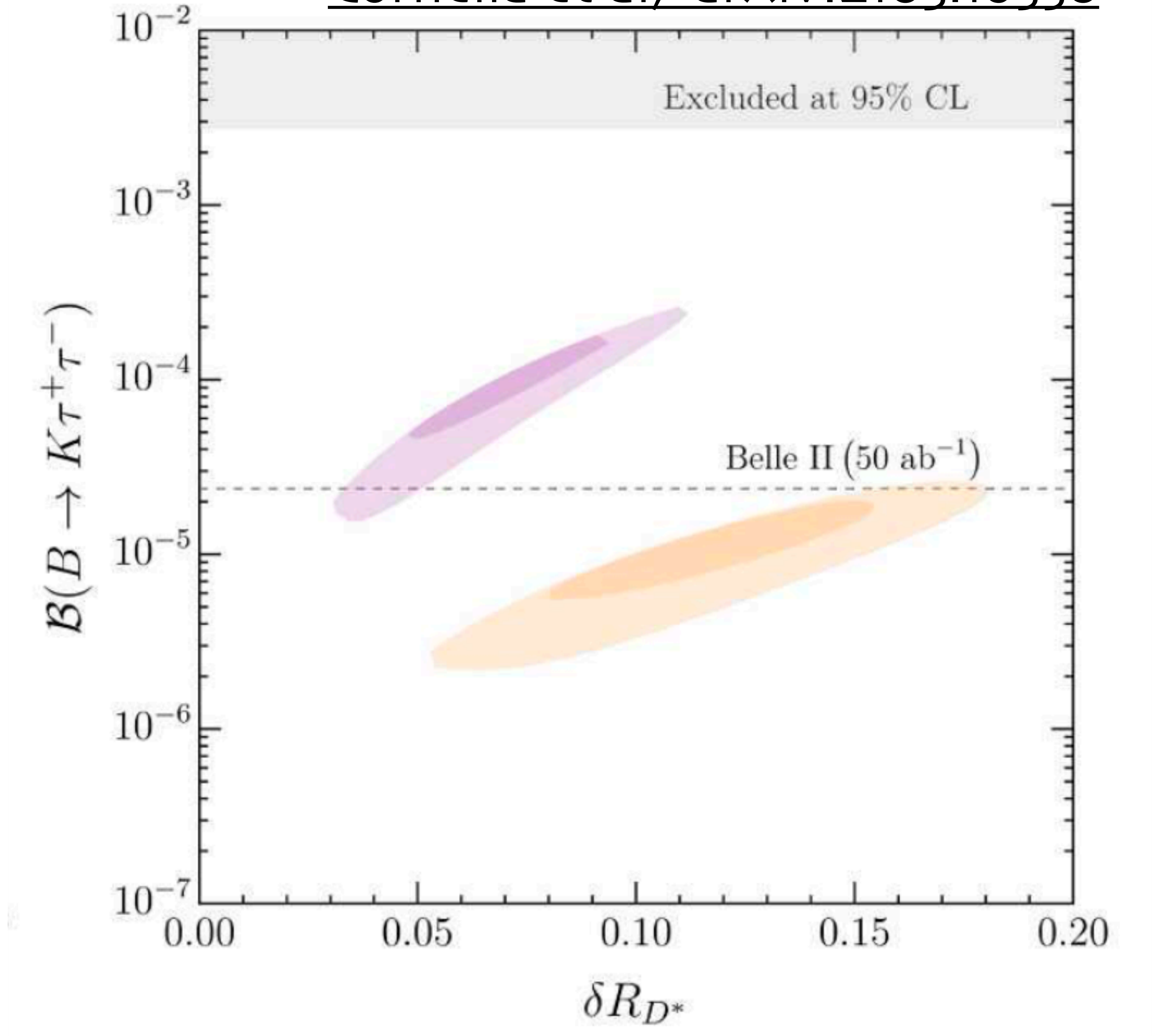
$B \to K^{(*)}\tau\tau/\tau l$

- $b \to s\tau\tau/\tau l$ can be **enhanced** in NP models explains B-anomalies
  - **LFV** decay prohibited in the SM, expectation for $s\tau\tau$ final state:

$$B(B^+ \to K^+ \tau^+ \tau^-)_{SM} = (1.22 \pm 0.10)\, 10^{-7}$$
$$B(B^0 \to K^0 \tau^+ \tau^-)_{SM} = (1.13 \pm 0.09)\, 10^{-7}$$
$$B(B^+ \to K^{*+} \tau^+ \tau^-)_{SM} = (0.99 \pm 0.12)\, 10^{-7}$$
$$B(B^0 \to K^{*0} \tau^+ \tau^-)_{SM} = (0.91 \pm 0.11)\, 10^{-7}$$

- Usually searched for with **HAD** or **SL tagging** method
- State of the art and Belle II projections (K^* modes also feasible)

Cornella et al, arXiv:2103.16558



LHCb: [JHEP 06 (2020) 129]

$$\mathcal{B}(B^+ \to K^+\tau\mu) < 3.9 \times 10^{-5}$$

BaBar: [Phys.Rev.D 86 (2012) 012004]

Mode	$\mathcal{B}(B \to h\tau\ell)(\times 10^{-5})$ Central value	90% C.L. UL
$B^+ \to K^+\tau\mu$	$0.0^{+2.7}_{-1.4}$	<4.8
$B^+ \to K^+\tau e$	$-0.6^{+1.7}_{-1.4}$	<3.0
$B^+ \to \pi^+\tau\mu$	$0.5^{+3.8}_{-3.2}$	<7.2
$B^+ \to \pi^+\tau e$	$2.3^{+2.8}_{-1.7}$	<7.5

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B^+ \to K^+\tau^+\tau^-) \cdot 10^5$	< 32	< 6.5	< 2.0
$Br(B^0 \to \tau^+\tau^-) \cdot 10^5$	< 140	< 30	< 9.6
$Br(B_s^0 \to \tau^+\tau^-) \cdot 10^4$	< 70	< 8.1	–
$Br(B^+ \to K^+\tau^\pm e^\mp) \cdot 10^6$	–	–	< 2.1
$Br(B^+ \to K^+\tau^\pm \mu^\mp) \cdot 10^6$	–	–	< 3.3
$Br(B^0 \to \tau^\pm e^\mp) \cdot 10^5$	–	–	< 1.6
$Br(B^0 \to \tau^\pm \mu^\mp) \cdot 10^5$	–	–	< 1.3

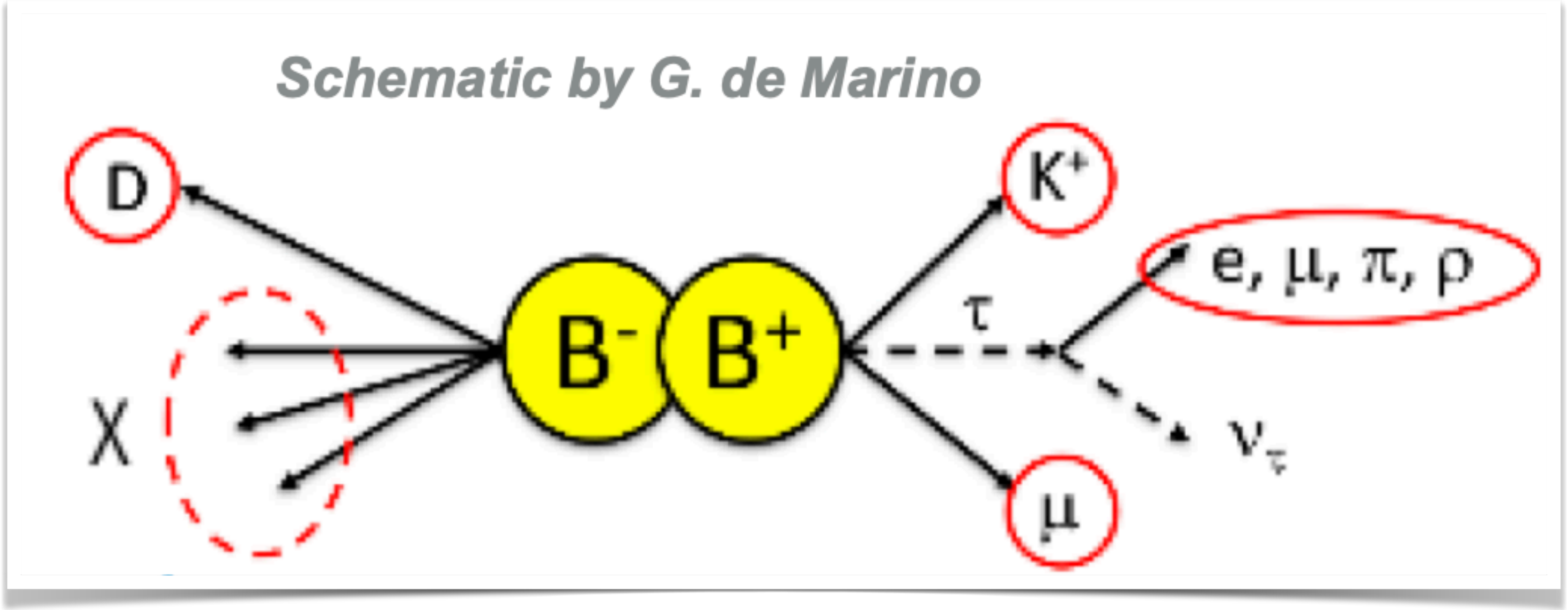
The BelleII Physics Book, PETP 2019, 123C01 (2019)

$B \to K^{(*)}\tau\tau/\tau l$

- New idea to measure $\mathcal{B}(B^+ \to K^+\tau l)$: **semi-inclusive tagging**

- Exploit high BF of $B^- \to D^0X$: 79±4%

- Reconstruct tag D^0 and signal's K and l, and τ



- D^0X provides the tag-side

- Fit $$m_\tau^2 = m_B^2 + m_{Kl}^2 - 2(E_B^* E_{Kl}^* - |\vec{p}^*_{B_{sig}}||\vec{p}^*_{Kl}|\cos\theta)$$

  $E_B^* = E^*_{beam}$, $|\vec{p}^*_{B_{sig}}| = \sqrt{(E^*_{beam})^2 - m_B^2}$

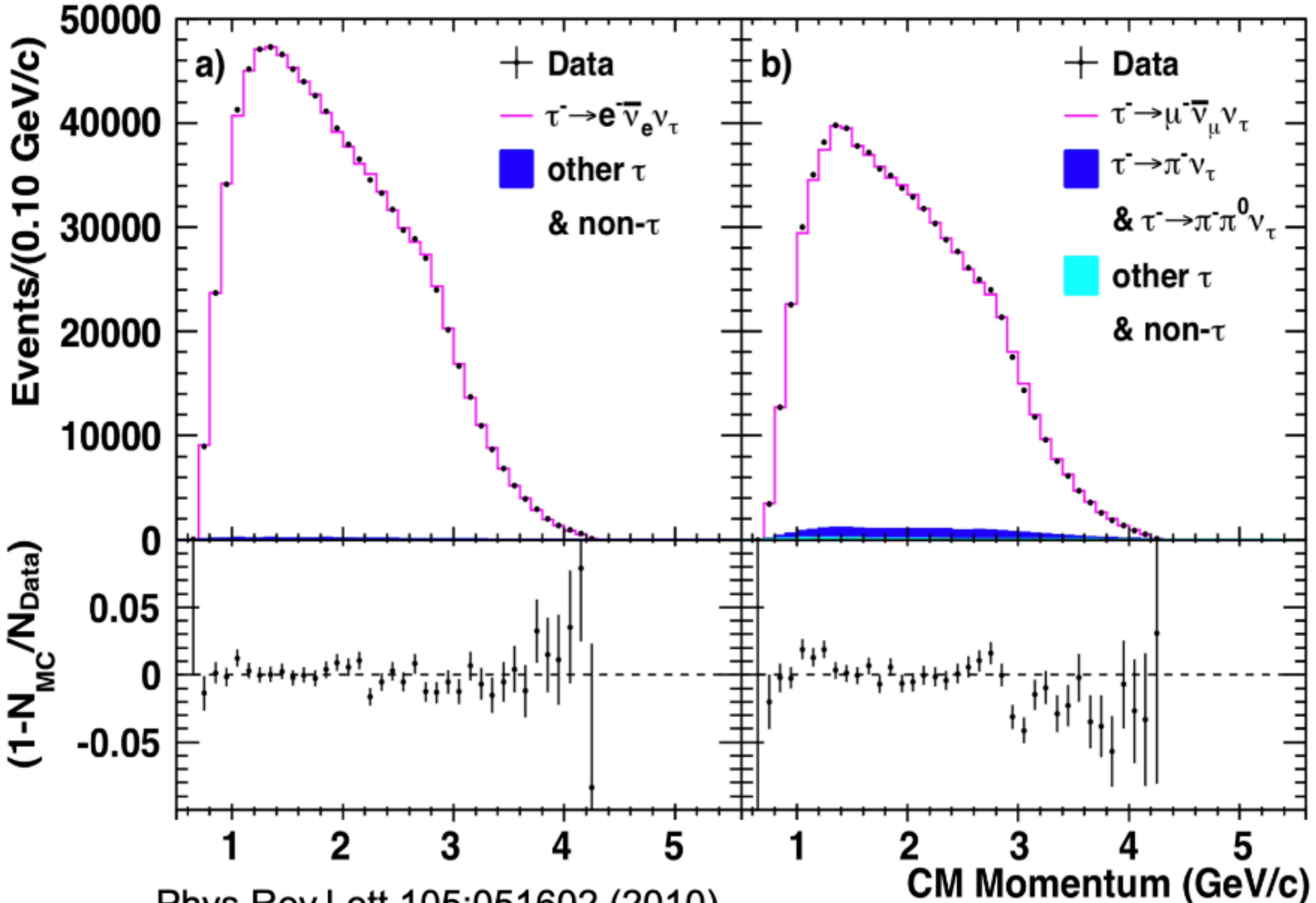
  θ angle between $\vec{p}^*_{B_{sig}}$ $(= -\vec{p}^*_{B_{tag}})$ and $\vec{p}^*_K$

- Work in progress, can be also applied to other missing energy modes.

LFUV in tau decays

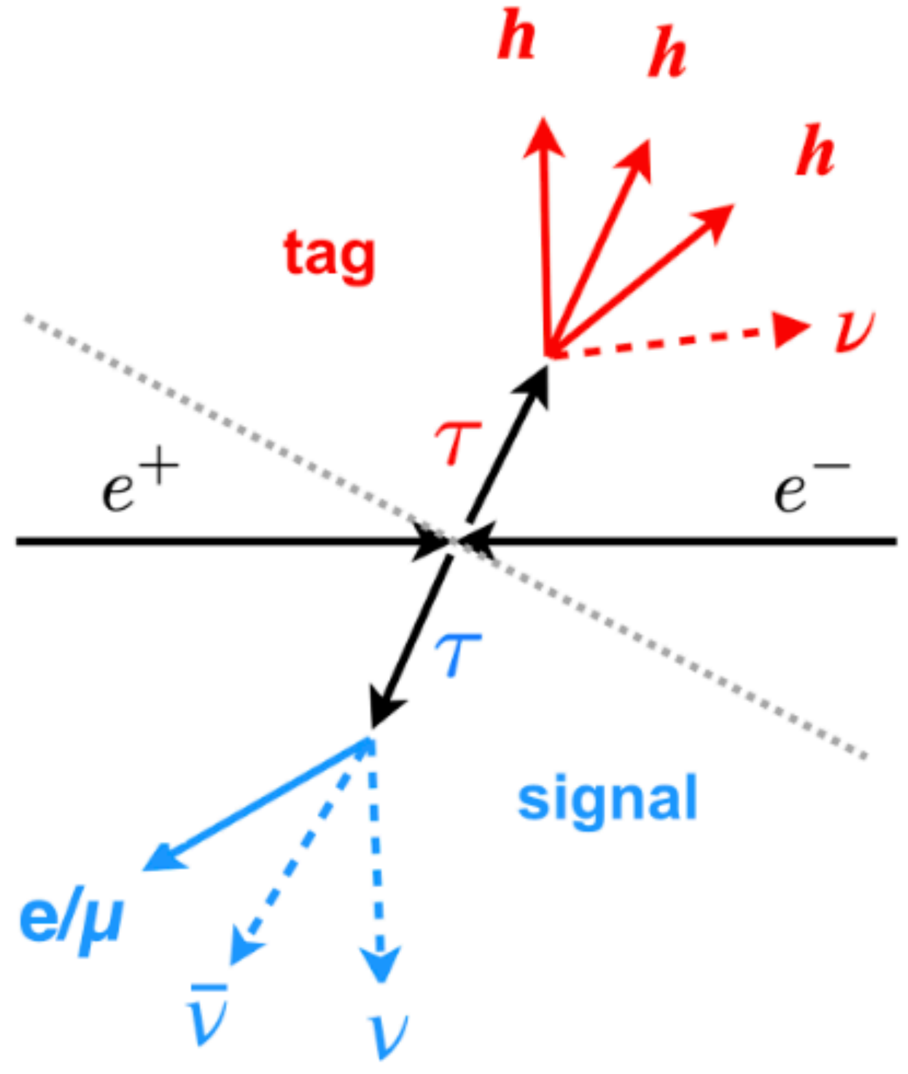
- LFU can be tested also in τ system

$$R_\mu \equiv \frac{\mathcal{B}(\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \overline{\nu}_e \nu_\tau)}$$ = 0.9796 ± 0.0016 (stat) ± 0.0036 (sys)



Phys.Rev.Lett.105:051602 (2010)

	μ
N^D	731102
Purity	97.3%
Total Efficiency	0.485%
Particle ID Efficiency	74.5%
Systematic uncertainties:	
Particle ID	0.32
Detector response	0.08
Backgrounds	0.08
Trigger	0.10
$\pi^-\pi^-\pi^+$ modelling	0.01
Radiation	0.04
$\mathcal{B}(\tau^- \to \pi^-\pi^-\pi^+\nu_\tau)$	0.05
$\mathcal{L}\sigma_{e^+e^-\to\tau^+\tau^-}$	0.02
Total [%]	0.36

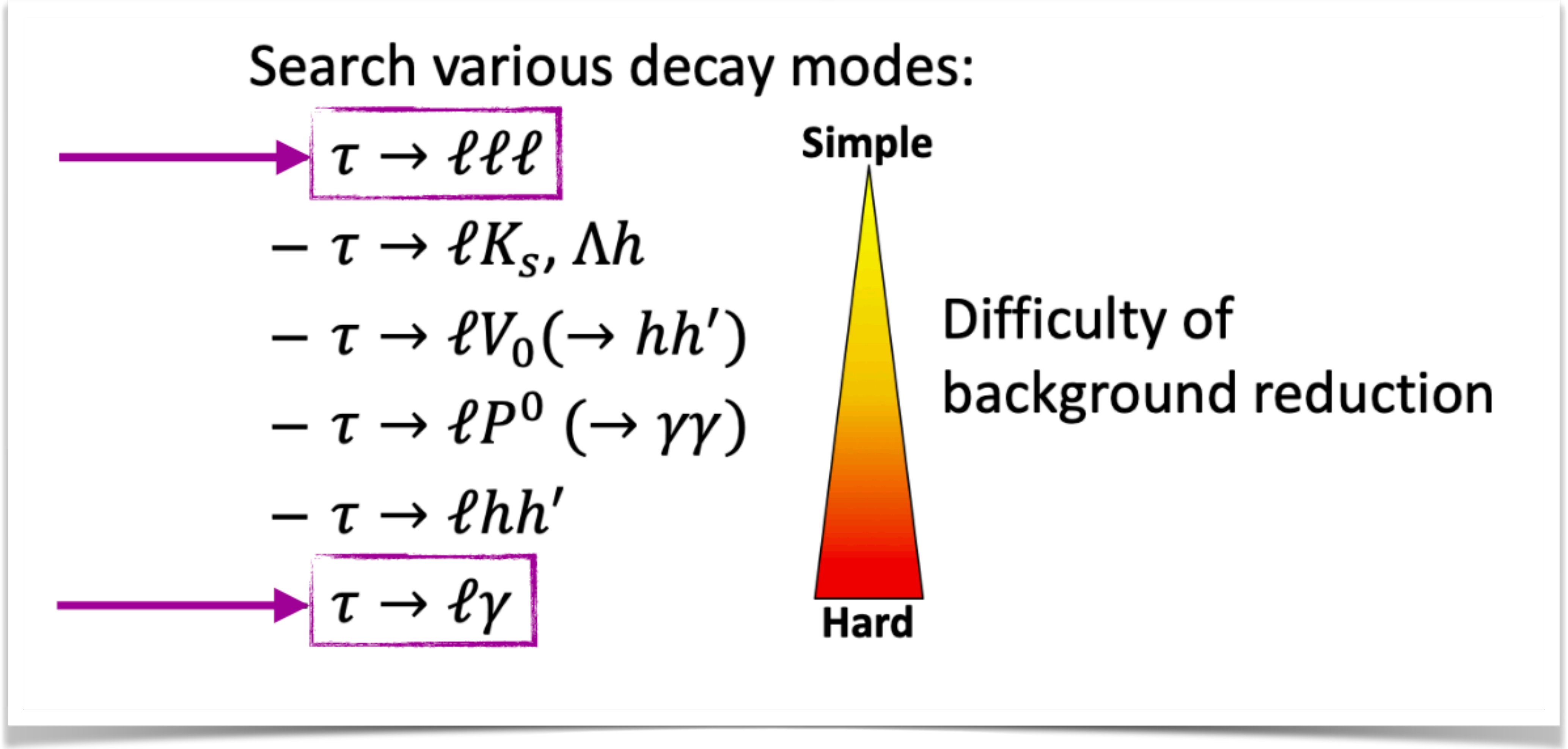


@ BelleII:

- syst due to PID correction is partially statistical in origin
- trigger studies ongoing
- preliminary sensitivity studies indicate a higher efficiency can be obtained wrt BaBar
- Work hard to **improve systematics** and add **tagging** modes to have a competitive measurement with stat < BaBar

LFV in τ decays (I)

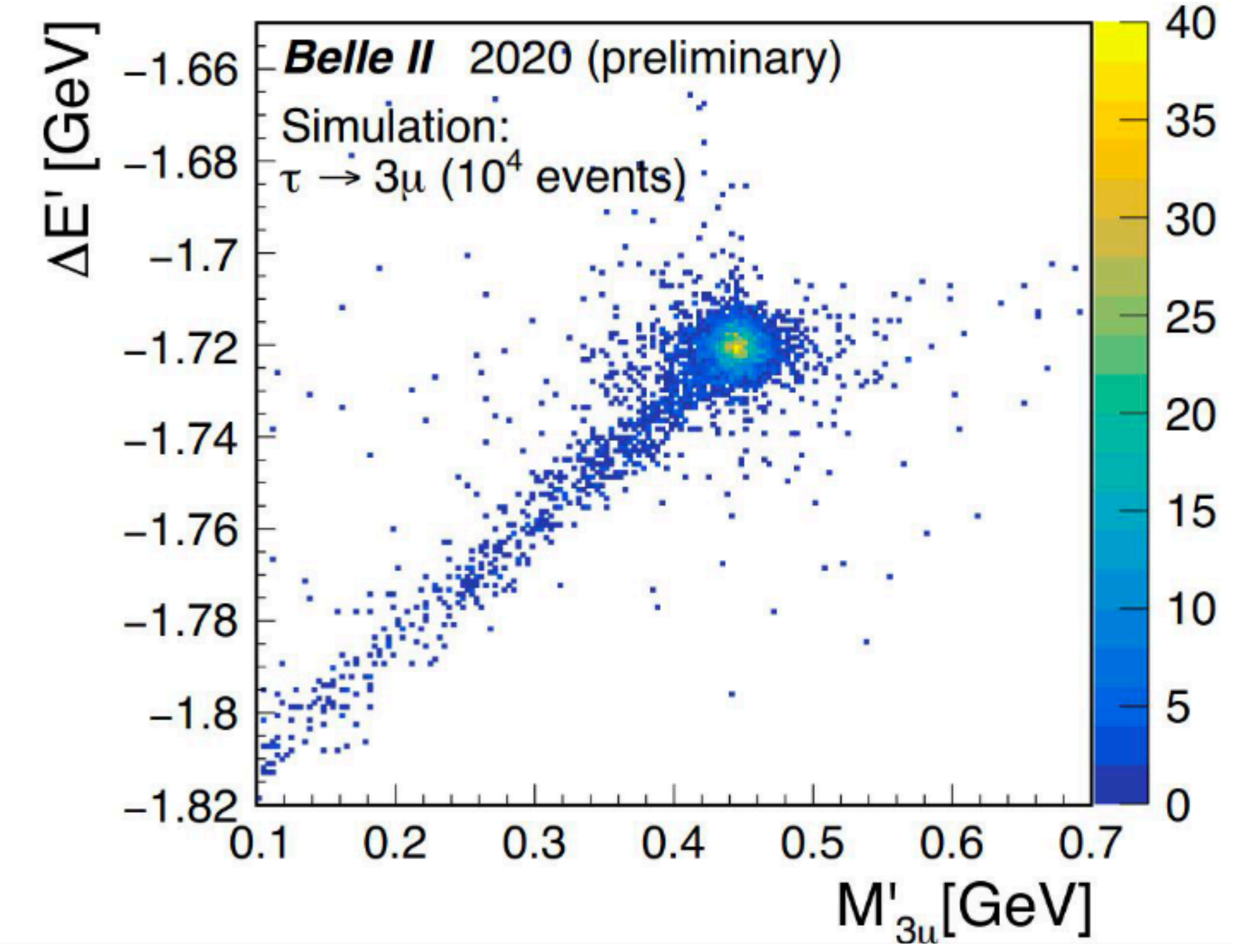
- τ system is also ideal to search for LFV processes where NP can enter at tree or loop level
- Many modes to be studied →
- Fully reconstructed final states, extract signal using 2 main variables: $\mathbf{M}_\tau$ and $\mathbf{\Delta E} = E_\tau - E_{beam}$ (primed quantities: rotation to reduce correlation among the two variables)



- **3**μ final state, almost background free
- irreducible background in $\mu\gamma$

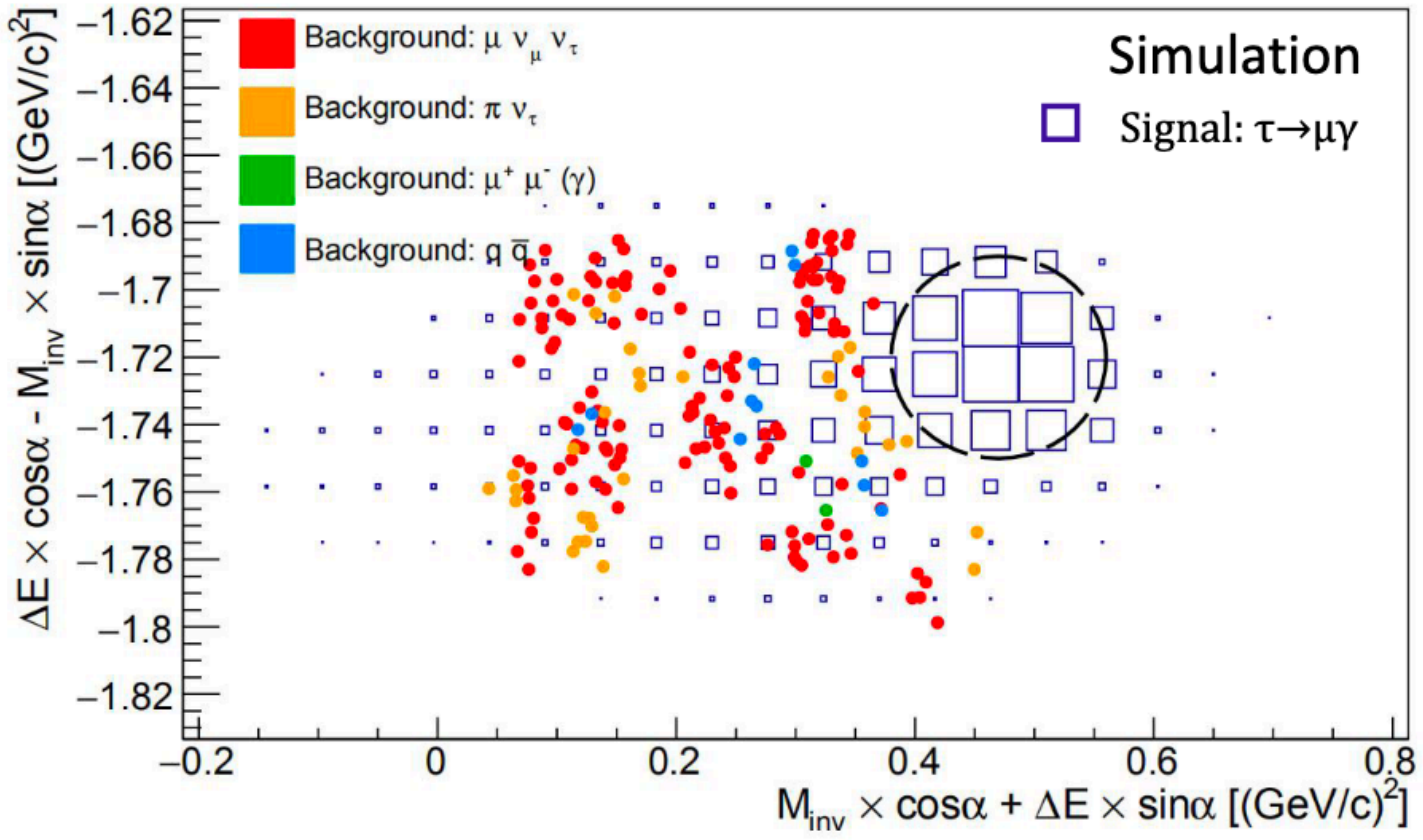
M. Martini (BelleII), Bormio 2019

Rotated signal region ($\tau \to 3\mu$, signal events only)



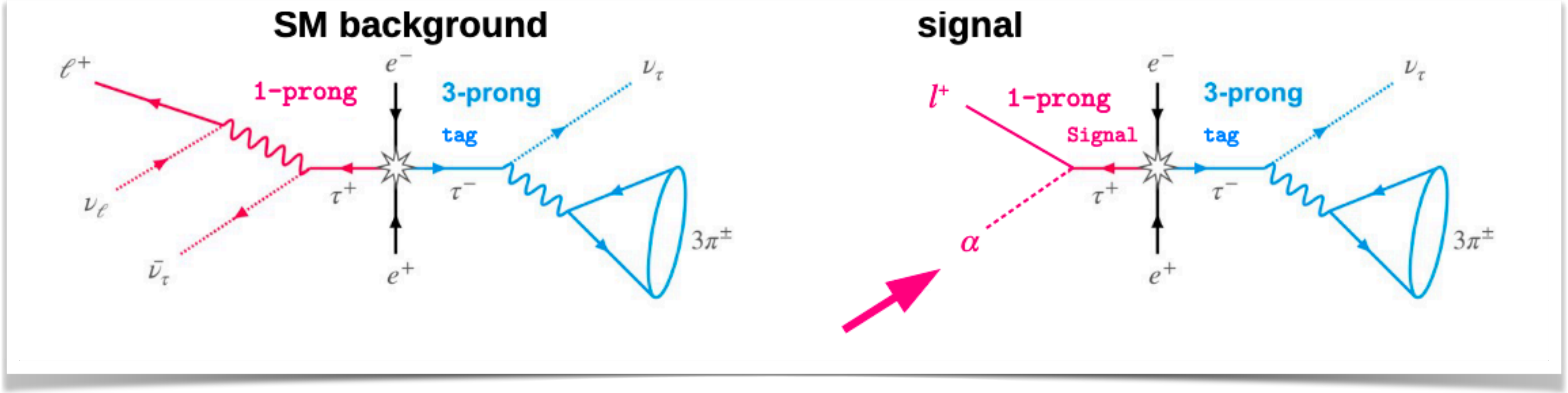
The BelleII Physics Book, PETP 2019, 123C01 (2019)

Rotated signal region ($\tau \to \mu\gamma$)



LFV in τ decays (II)

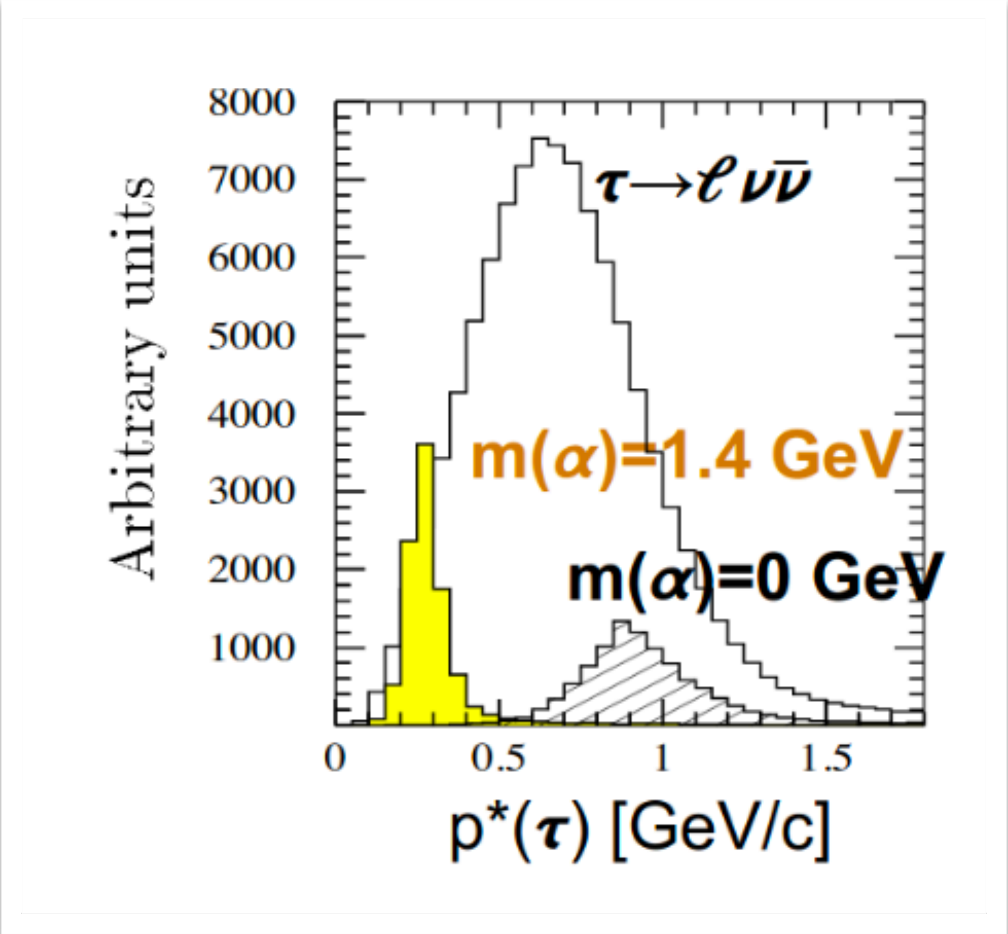
- Search for $\tau \to \mathbf{l}\alpha$, α being an invisible particle



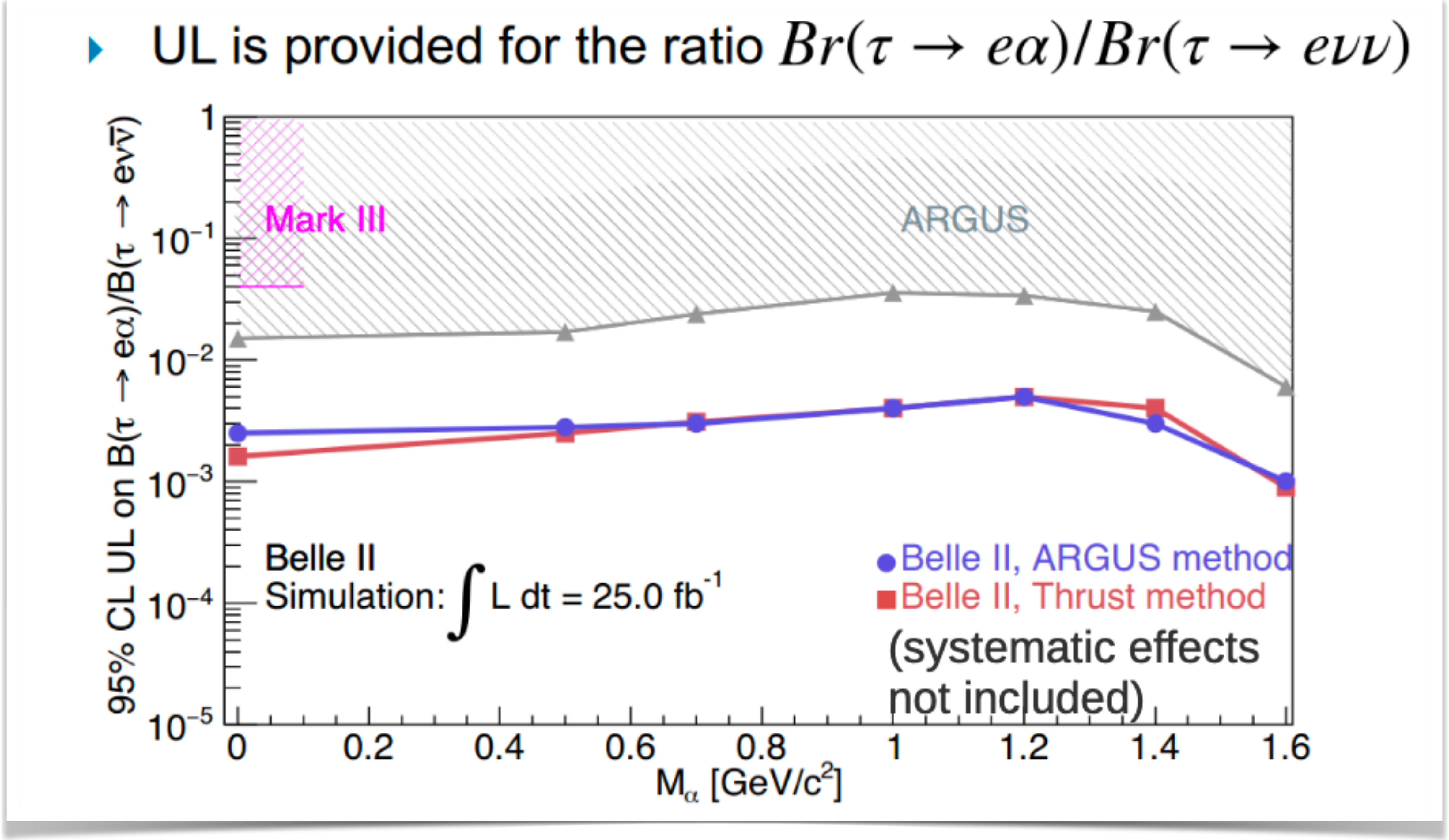
- Signal manifests as a peak in the τ momentum in pseudo-rest frame:
  - τ boost not known, approximate it using 3-prong momentum (ARGUS method) or thrust direction

$$\vec{T} = max \left(\frac{\sum_i \vec{p}_i \hat{T}}{|p_i|} \right)$$

- $\tau \to e\upsilon\upsilon$ irreducible background.

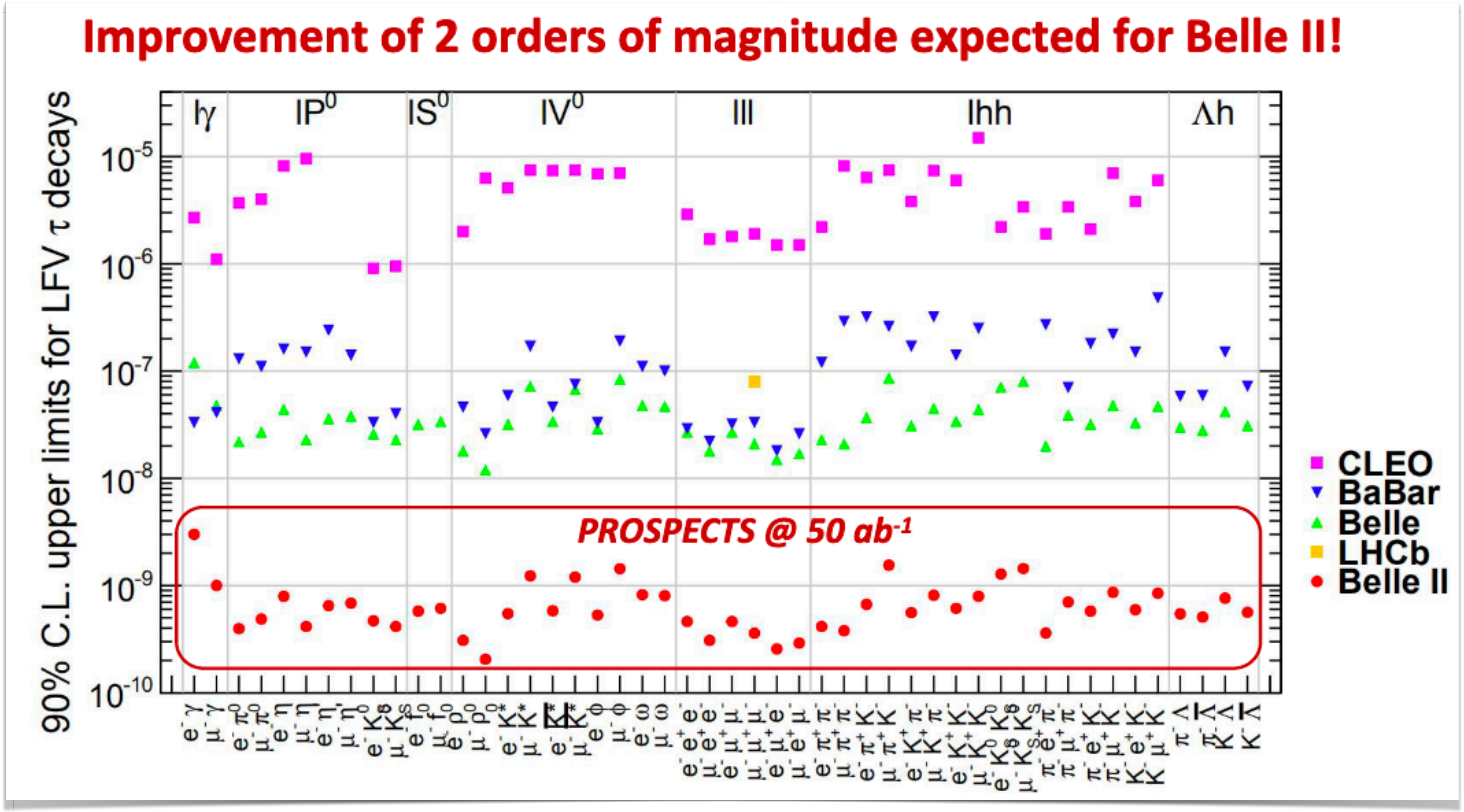


Argus coll., Z.Phys. C68 (1995) 25-2



BELLE2-NOTE-PL-2020-018

Overview of BelleII potential in LFV in τ decays



The BelleII Physics Book, PETP 2019, 123C01 (2019)

Summary and conclusions

- **LFU anomalies growing** since 2012: exciting times to explore flavour physics as playground for beyond standard model searches

- **Belle II** has started taking data in 2019 and foresees to collect **50ab^{-1}** by **2031**

  - **Accelerators** and **detector** are performing well, improvements foreseen in reconstruction performances thanks to what we are learning while the experiment is running

  - **Will play a major role in the flavour sector with strong interplay with LHCb**

Belle II
Higher sensitivity to decays with photons and neutrinos (e.g. $B \to K\nu\nu$, $\mu\nu$), inclusive decays, time dependent CPV in B_d, τ physics.

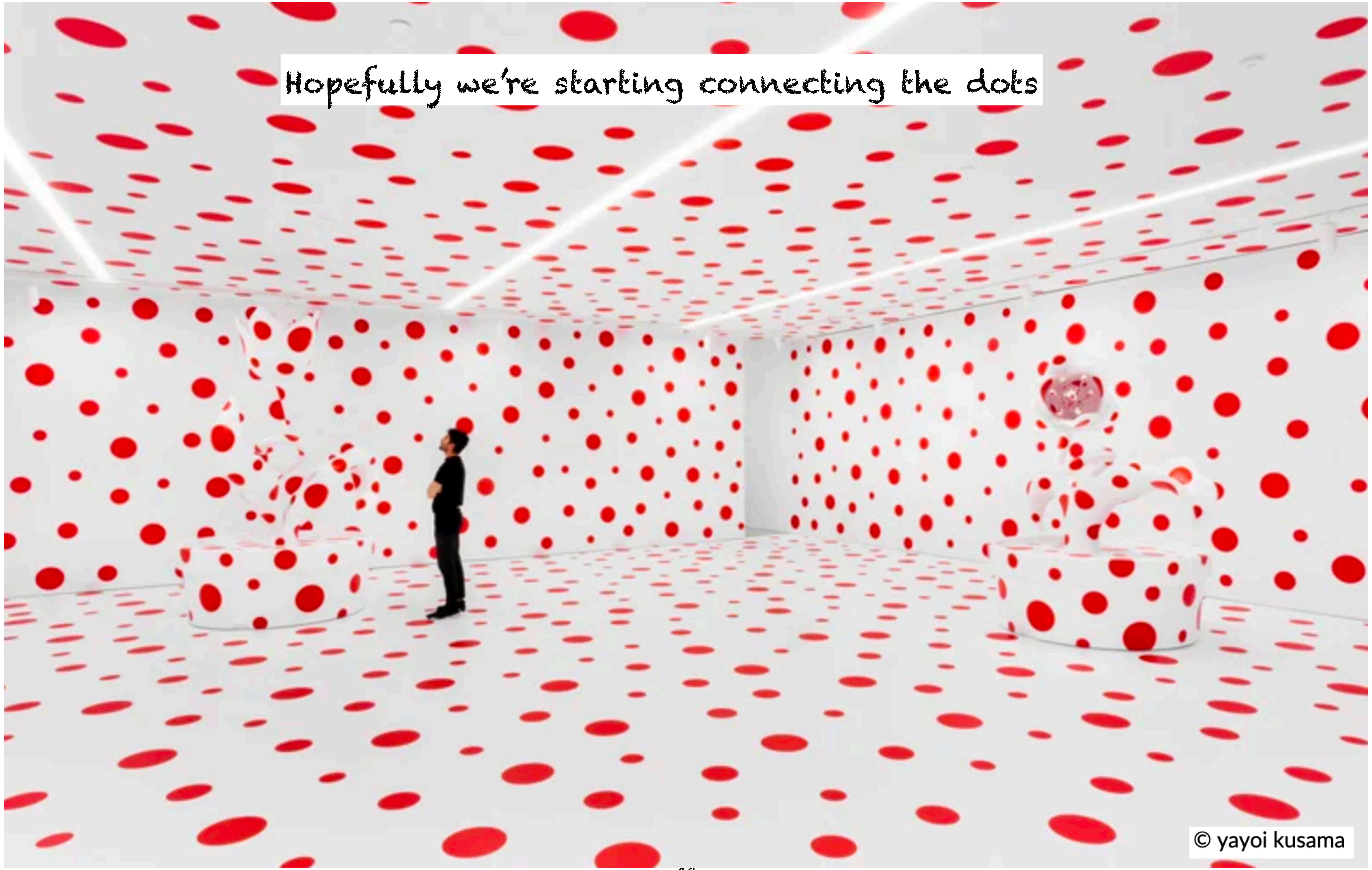
LHCb
Higher production rates for ultra rare B, D, & K decays, access to all b-hadron flavours (e.g. Λ_b), high boost for fast B_s oscillations.

Overlap in various key areas to verify discoveries.

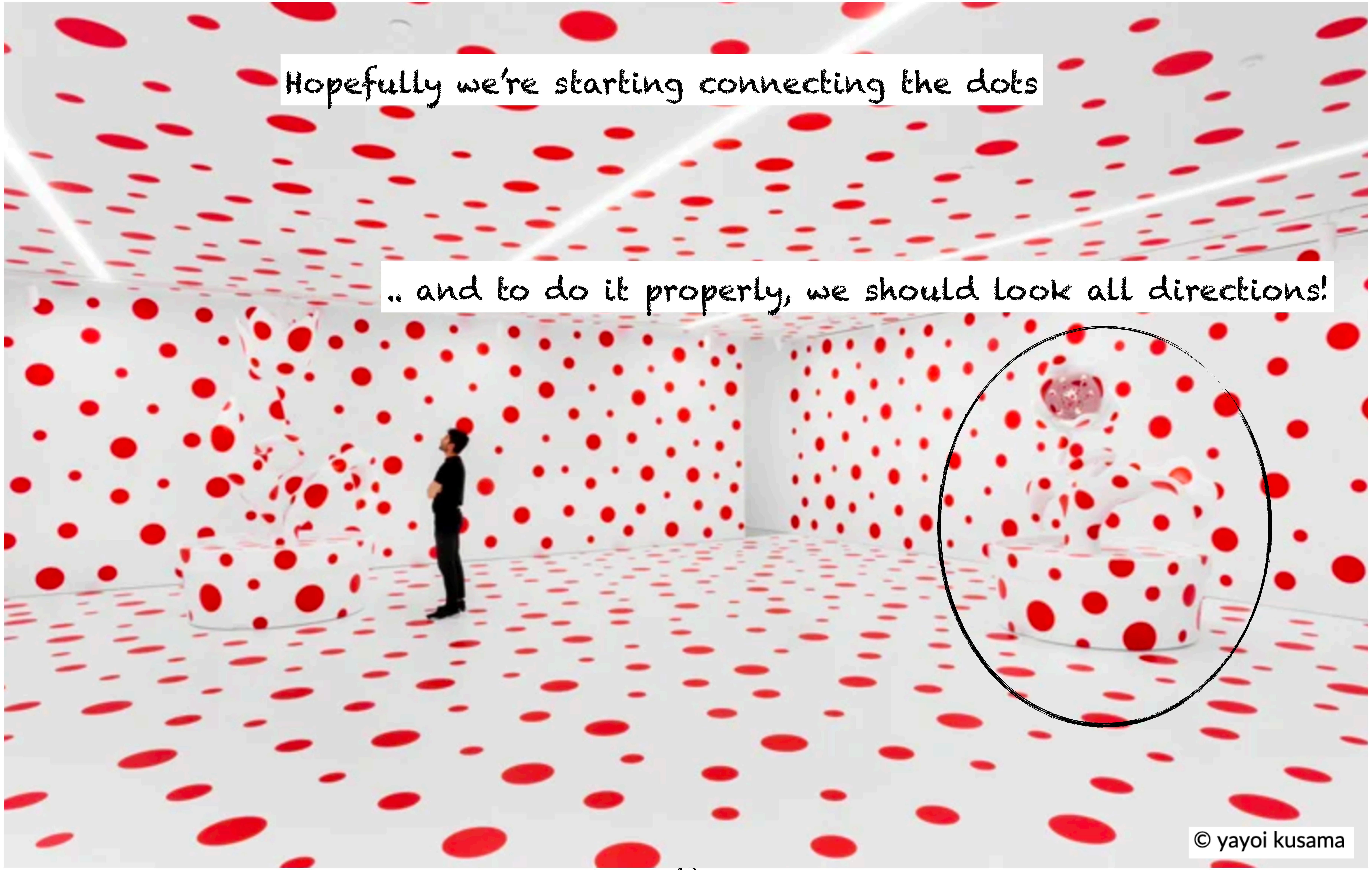
Upgrades
Most key channels will be stats. limited (not theory or syst.).
LHCb scheduled major upgrades during LS3 and LS4.
Belle II formulating a 250 ab^{-1} upgrade program post 2028.

P. Urquijo (BelleII), FPCP2020

Summary and conclusions



Summary and conclusions



extra slides

Belle II - LHCb Comparison

+ Important contributions on B and D flavour physics from ATLAS, CMS, BESIII.

Belle II
Higher sensitivity to decays with photons and neutrinos (e.g. $B\to K\nu\nu$, $\mu\nu$), inclusive decays, time dependent CPV in B_d, τ physics.

LHCb
Higher production rates for ultra rare B, D, & K decays, access to all b-hadron flavours (e.g. Λ_b), high boost for fast B_s oscillations.

Overlap in various key areas to verify discoveries.

Upgrades
Most key channels will be stats. limited (not theory or syst.).
LHCb scheduled major upgrades during LS3 and LS4.
Belle II formulating a 250 ab^{-1} upgrade program post 2028.

Observable	Current Belle/ Babar	2019 LHCb	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})	LHCb (23 fb^{-1})	Belle II Upgrade (250 ab^{-1})	LHCb upgrade II (300 fb^{-1})
CKM precision, new physics in CP Violation							
$\sin 2\beta/\varphi_1$ ($B\to J/\psi K_S$)	0.03	0.04	0.012	0.005	0.011	0.002	0.003
γ/φ_3	13°	5.4°	4.7°	1.5°	1.5°	0.4°	0.4°
α/φ_2	4°	–	2	0.6°	–	0.3°	–
$\lvert V_{ub}\rvert$ (Belle) or $\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ (LHCb)	4.5%	6%	2%	1%	3%	<1%	1%
φ_s	–	49 mrad	–	–	14 mrad	–	4 mrad
$S_{CP}(B\to\eta' K_S$, gluonic penguin)	0.08	○	0.03	0.015	○	0.007	○
$A_{CP}(B\to K_S\pi^0)$	0.15	–	0.07	0.04	–	0.02	–
New physics in radiative & EW Penguins, LFUV							
$S_{CP}(B_d\to K^*\gamma)$	0.32	○	0.11	0.035	○	0.015	○
$R(B\to K^* l^+ l^-)$ ($1<q^2<6$ GeV^2/c^2)	0.24	0.1	0.09	0.03	0.03	0.01	0.01
$R(B\to D^*\tau\nu)$	6%	10%	3%	1.5%	3%	<1%	1%
$Br(B\to\tau\nu)$, $Br(B\to K^*\nu\nu)$	24%, –	–	9%, 25%	4%, 9%	–	1.7%, 4%	–
$Br(B_d\to\mu\mu)$	–	90%	–	–	34%	–	10%
Charm and τ							
$\Delta A_{CP}(KK-\pi\pi)$	–	8.5×10^{-4}	–	5.4×10^{-4}	1.7×10^{-4}	2×10^{-4}	0.3×10^{-4}
$A_{CP}(D\to\pi^+\pi^0)$	1.2%	–	0.5%	0.2%	–	0.1%	–
$Br(\tau\to e\gamma)$	$<120\times10^{-9}$	–	$<40\times10^{-9}$	$<12\times10^{-9}$	–	$<5\times10^{-9}$	–
$Br(\tau\to\mu\mu\mu)$	$<21\times10^{-9}$	$<46\times10^{-9}$	$<3\times10^{-9}$	$<3\times10^{-9}$	$<16\times10^{-9}$	$<0.3\times10^{-9}$	$<5\times10^{-9}$

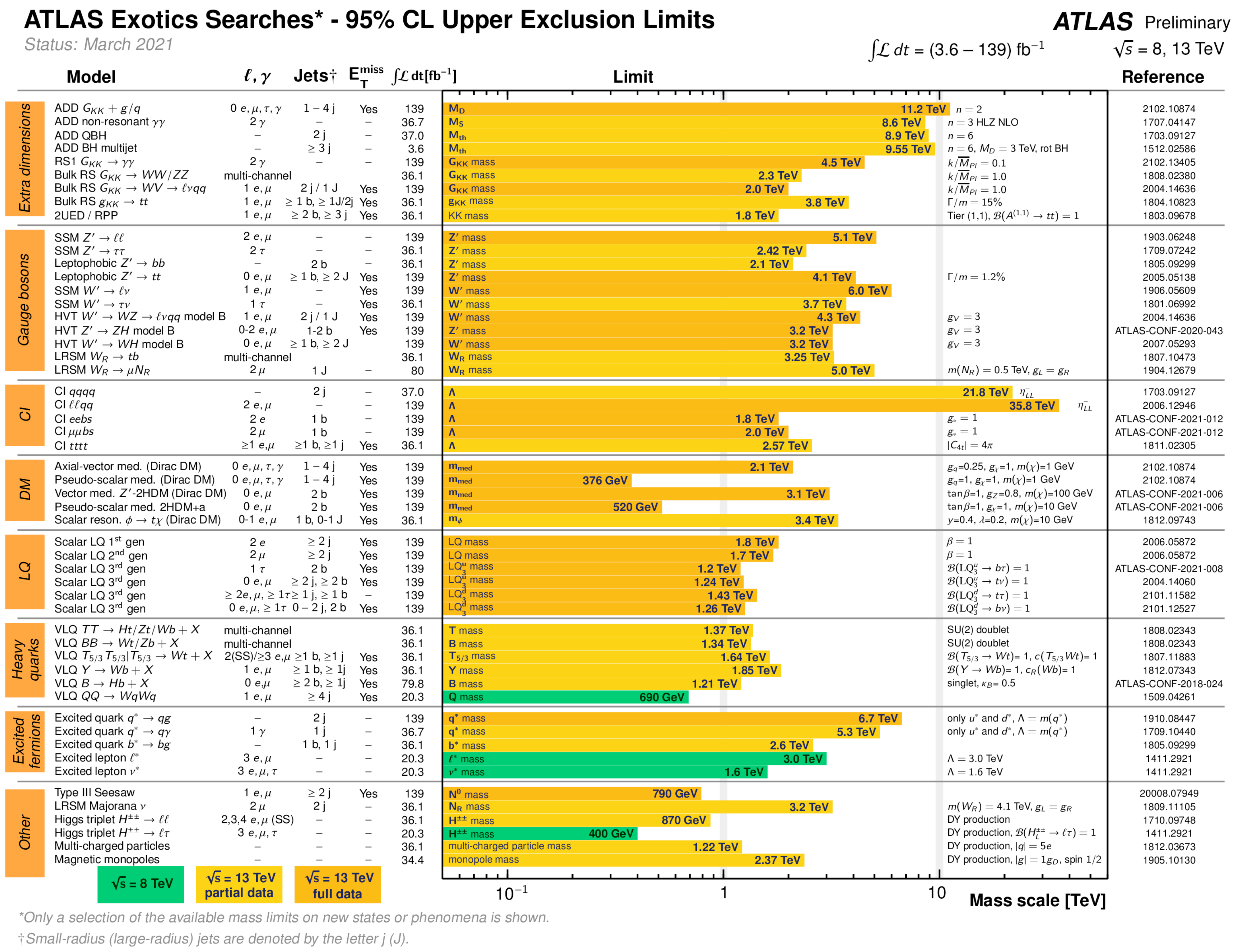
Results on other D & τ modes expected

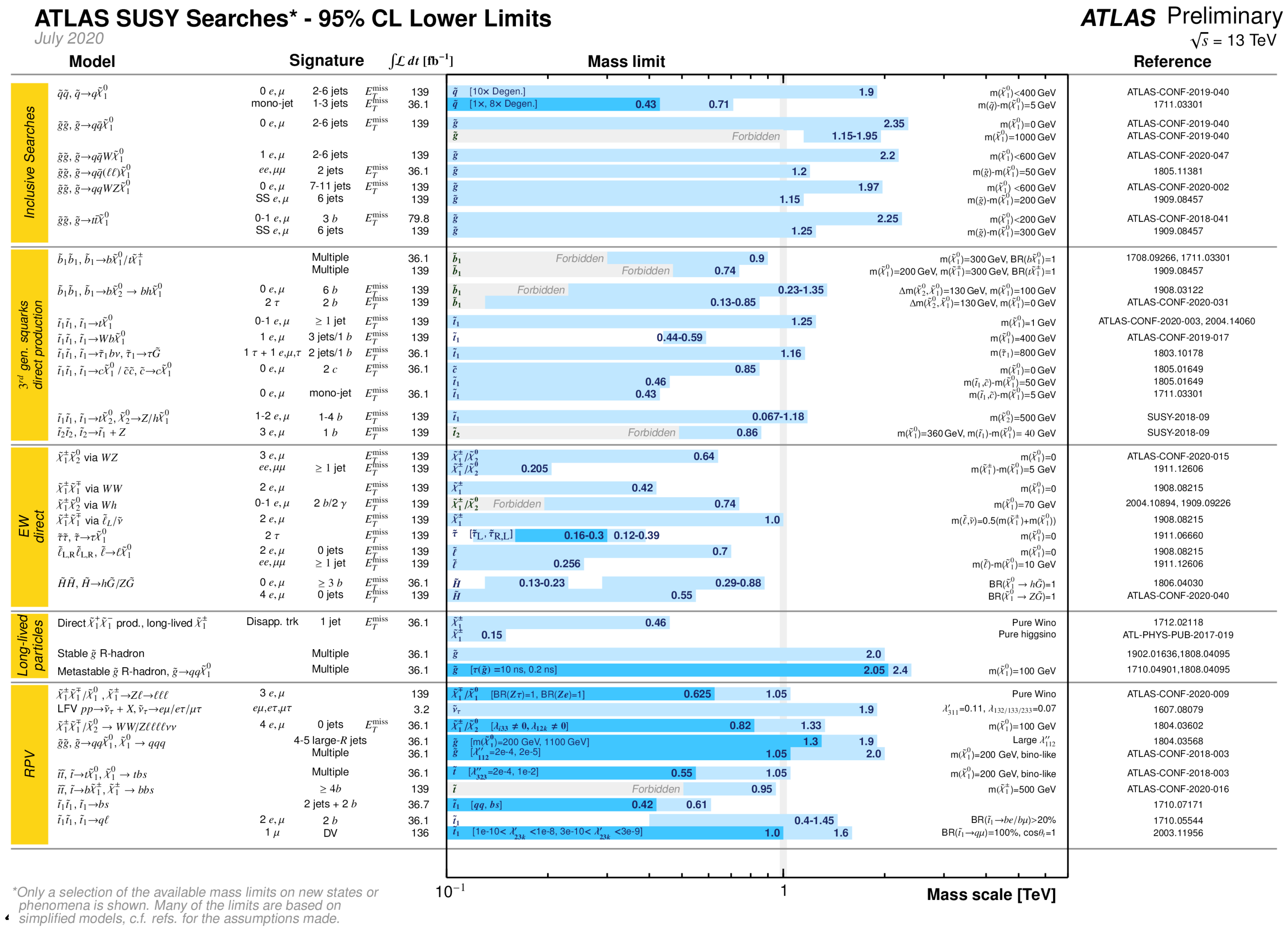
○ Possible in similar channels, lower precision
– Not competitive.

arXiv: 1808.08865 (Physics case for LHCb upgrade II), PTEP 2019 (2019) 12, 123C01 (Belle II Physics Book)

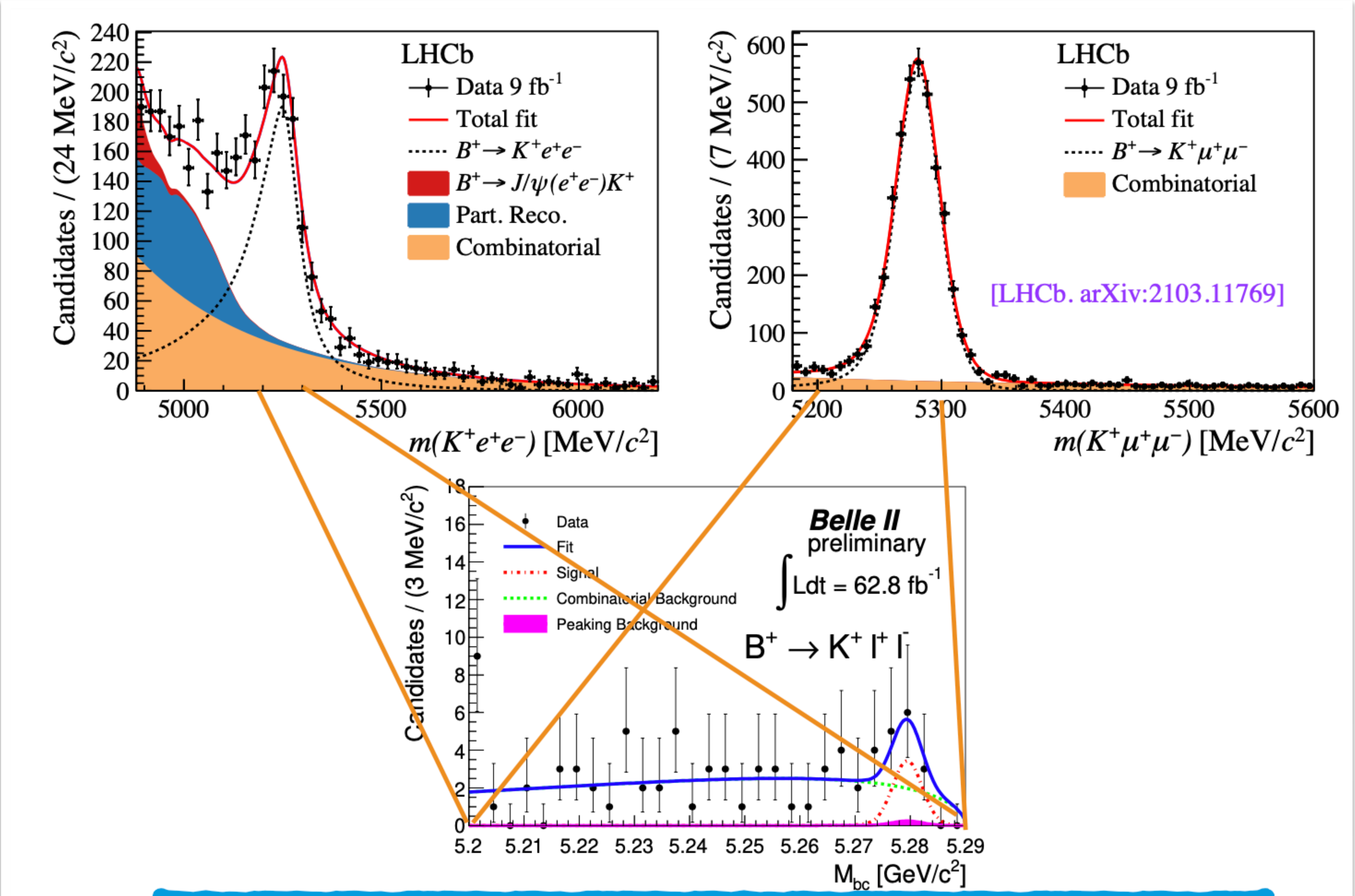
Indirect searches: ATLAS

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-009/fig_01.png
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2020-020/fig_23.png





R(K)



Electrons (and muons) in Belle II have better resolution thanks to M_{bc}