Flavour physics with electroweak-penguin and semileptonic decays at Belle and Belle II

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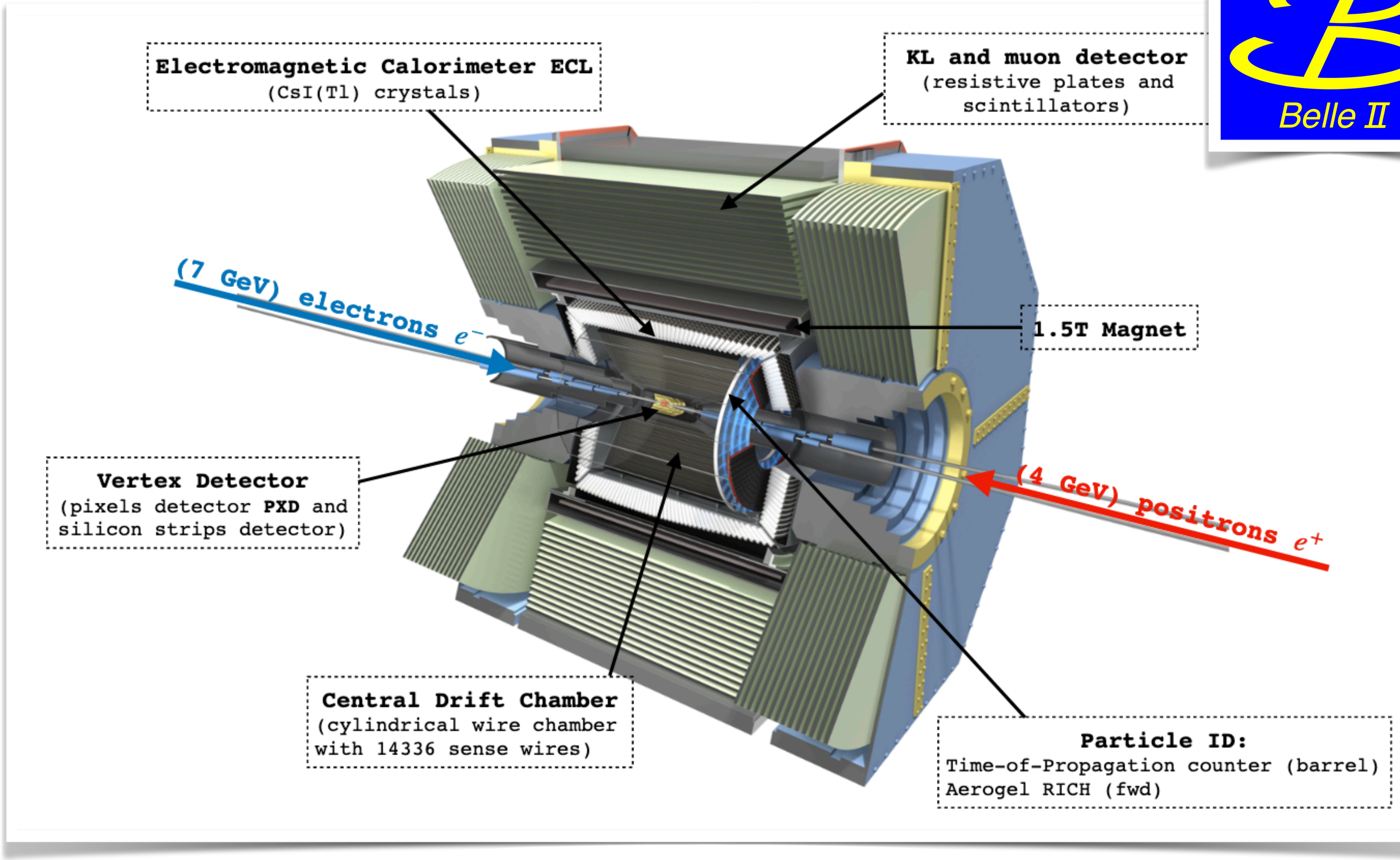
Belle and Belle II experiments

- **Belle @ KEKB**:
  - one of the first generation B factories, **771 x 10⁶ $B\bar{B}$** pairs collected in ~ 10 years of data taking
  - experiment goal: measurement of **CP violation in B meson system but they did much more**
- **Belle II @ SUPERKEKB**:
  - from KEKB to SuperKEKB: aim to collect **50 ab^{-1}** (~50x Belle) by 2031 reaching **~60 x 10^{34} cm^{-2} s^{-1}** (~30x KEKB)
  - Upgrade of Belle detector: similar or better performances wrt Belle in much higher machine background/event rate environments
  - Total integrated luminosity as of today: **213 fb^{-1}** , >120 fb^{-1} in February-June 2021
  - Current **world record instantaneous luminosity** = 3.1×10^{34} cm^{-2} s^{-1} (KEKB world record: 2.1×10^{34} cm^{-2} s^{-1})



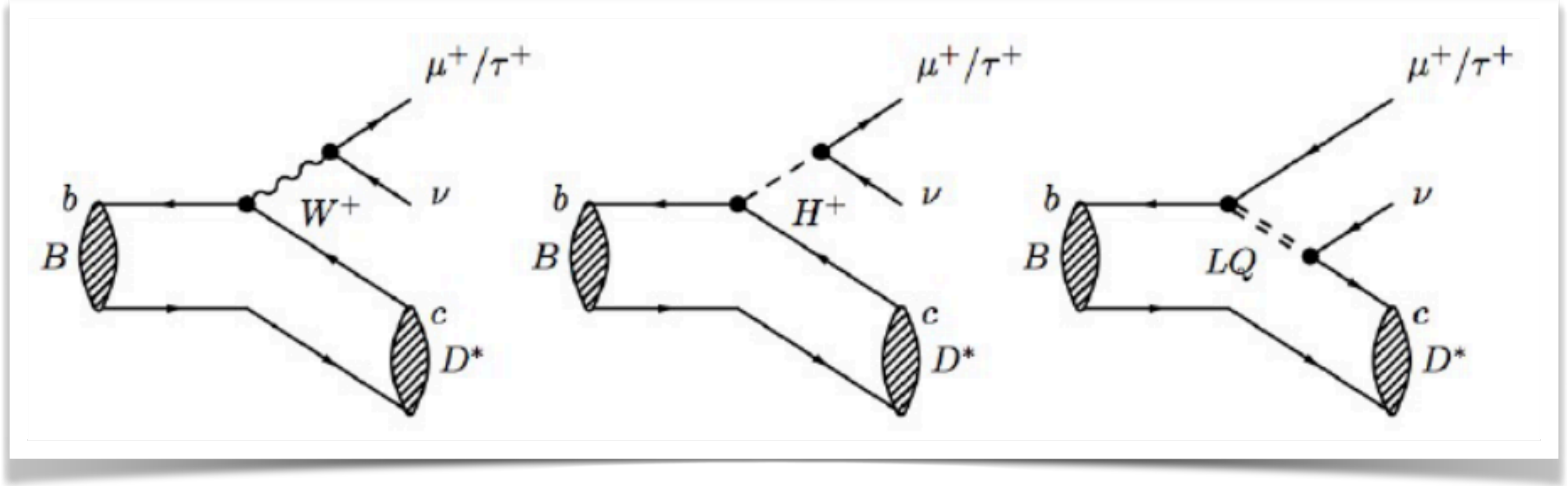
Semileptonic and electroweak penguin decays at Belle II

- Large Belle II dataset will allow to continuing investigating the flavour sector, in a complementary way wrt other experiments

- Electroweak and semileptonic B decays are among the **golden channels** of Belle II physics program.

New Physics searches in tree and penguin+box -mediated processes

e.g.

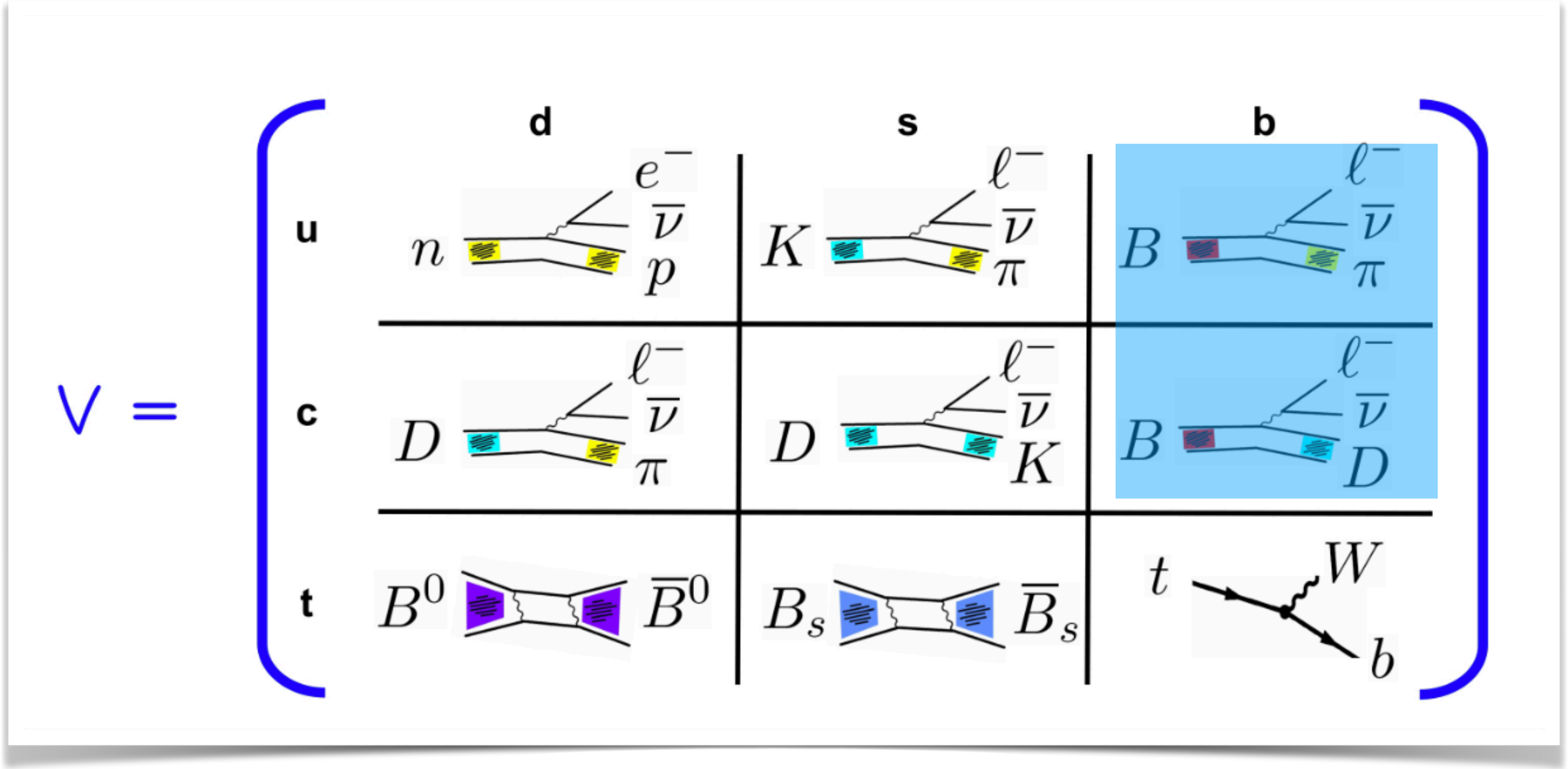


Indirect New Physics (NP) searches: non standard particles as decay mediators

Direct NP searches: new sources of missing energy (b→s $\upsilon\bar{\upsilon}$)

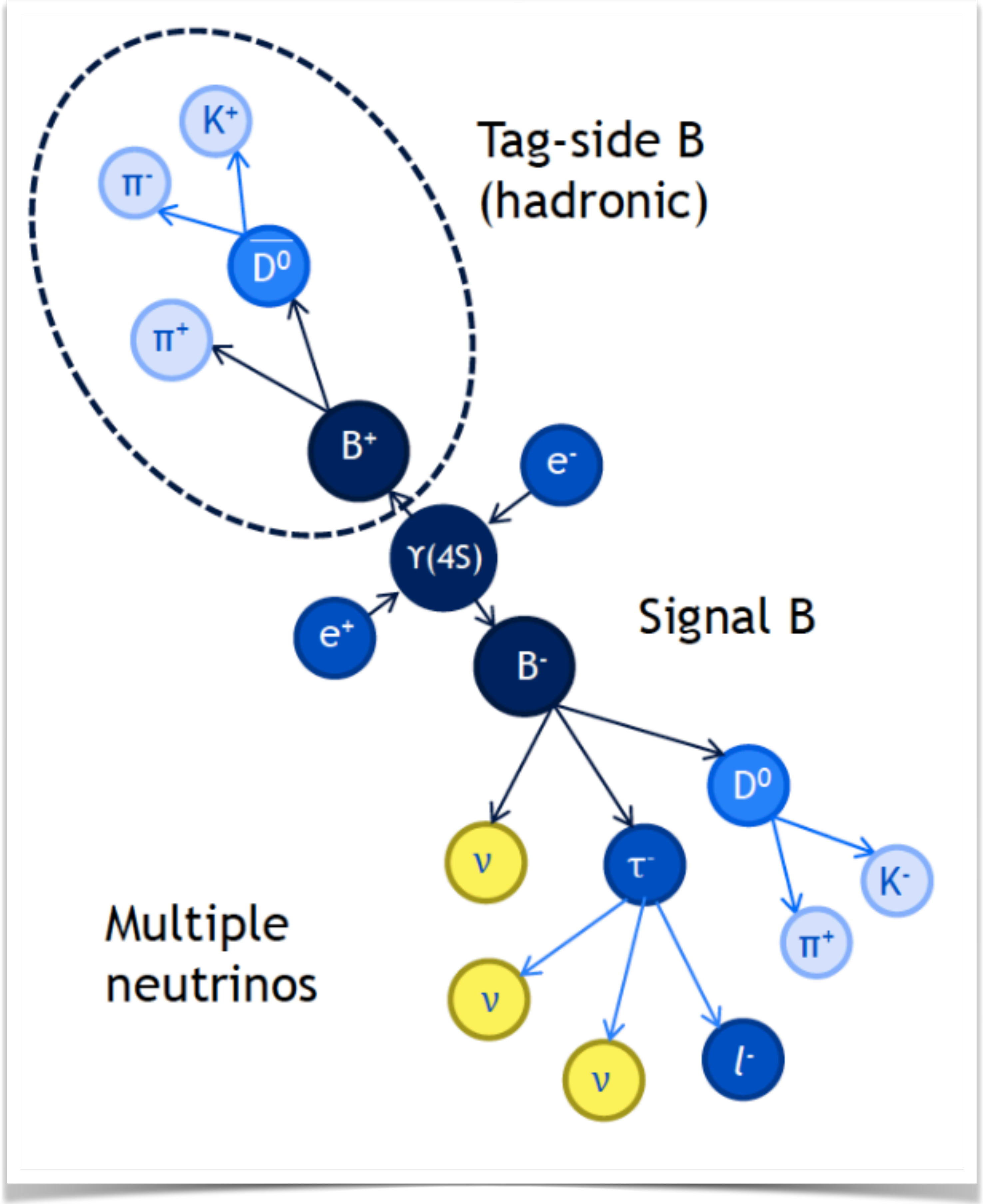
[will mainly focus on this]

CKM metrology from b→u/c $\ell\,\upsilon$ decays

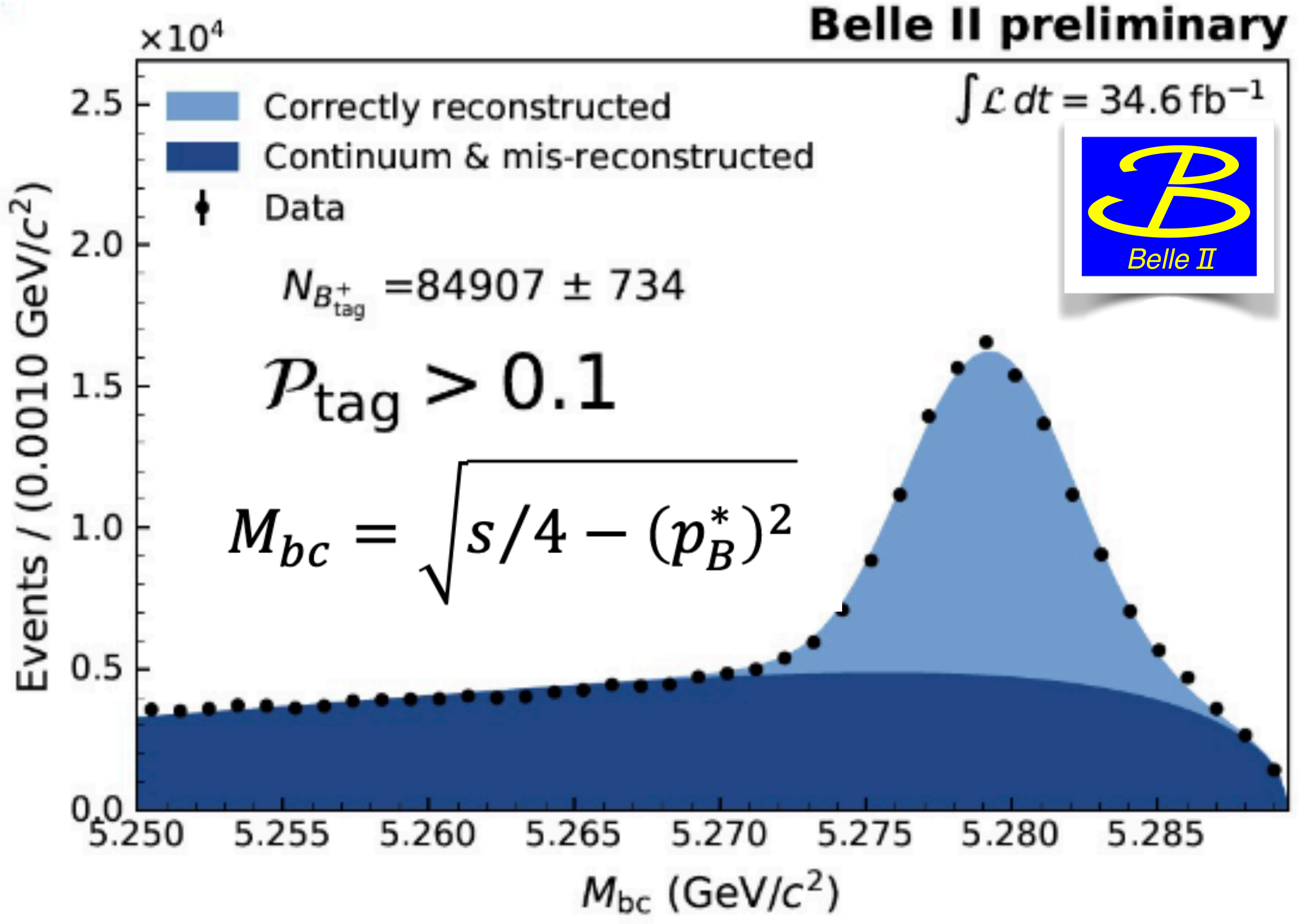


B meson pair reconstruction: Tagged analisys

- Reconstruct one B in the event (B_{tag}) and constraint the kinematic of the other B (B_{sig})
- B_{tag} reconstruction with **Full Event Interpretation** (FEI): multivariate algorithm with hierarchical approach to reconstruct O(200) **hadronic** and **semileptonic** decay channels
- B_{sig} reconstruction: once the B_{tag} has been reconstructed, search for the signal signature in the rest of the event
- Knowing the initial energy, the missing energy associated to the **neutrinos** can be computed



BELLE2-NOTE-PL-2020-002

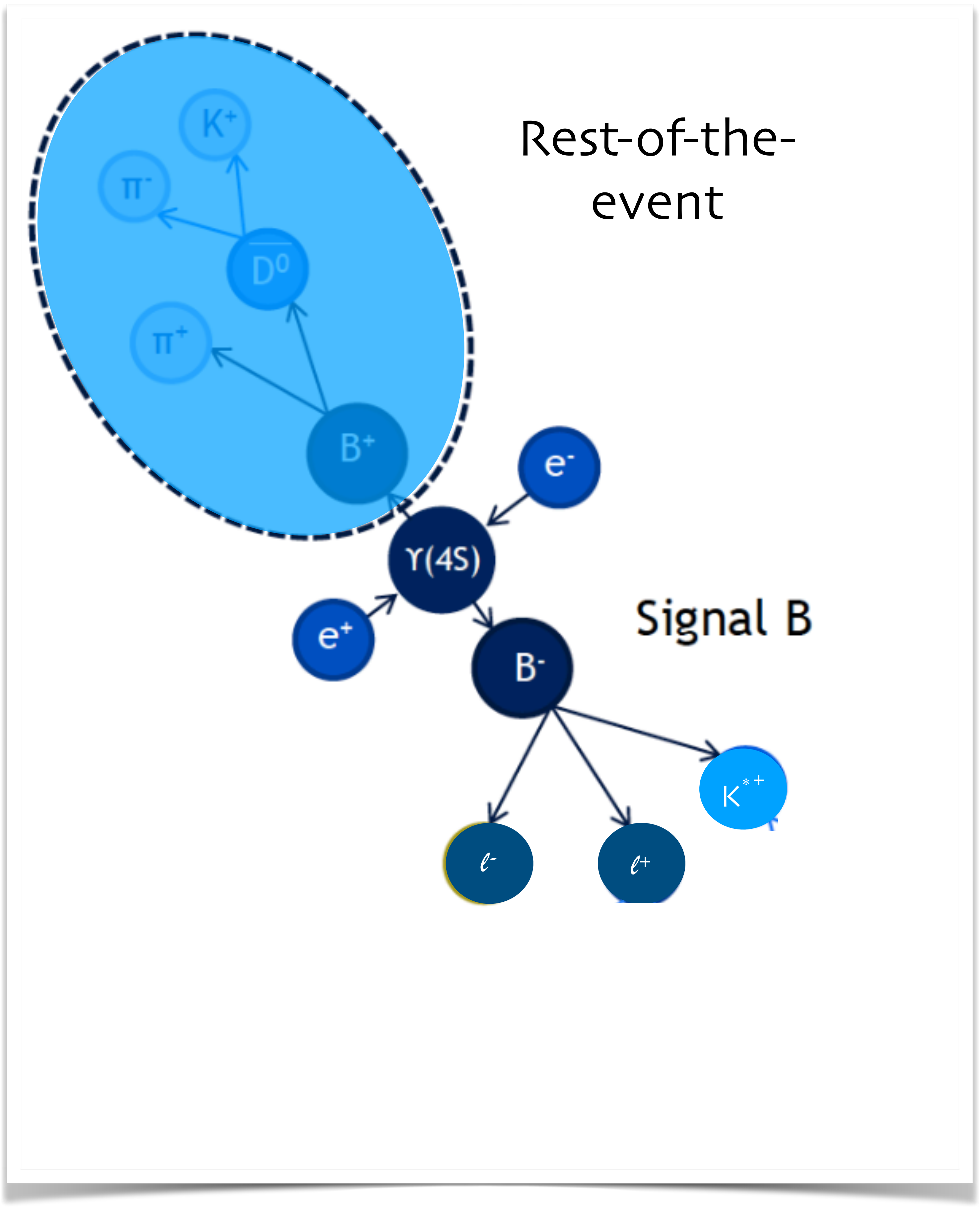


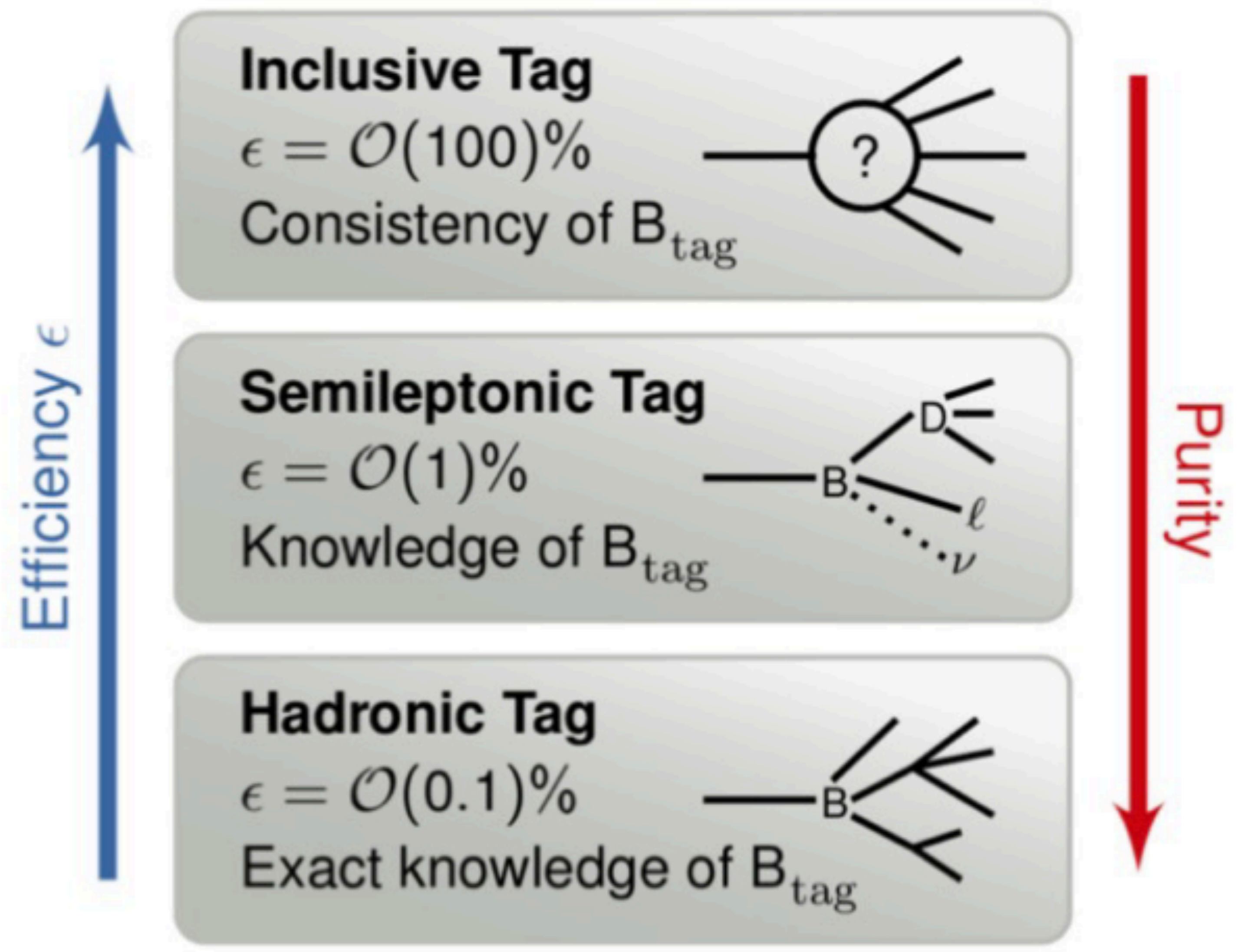
Hadronic FEI

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

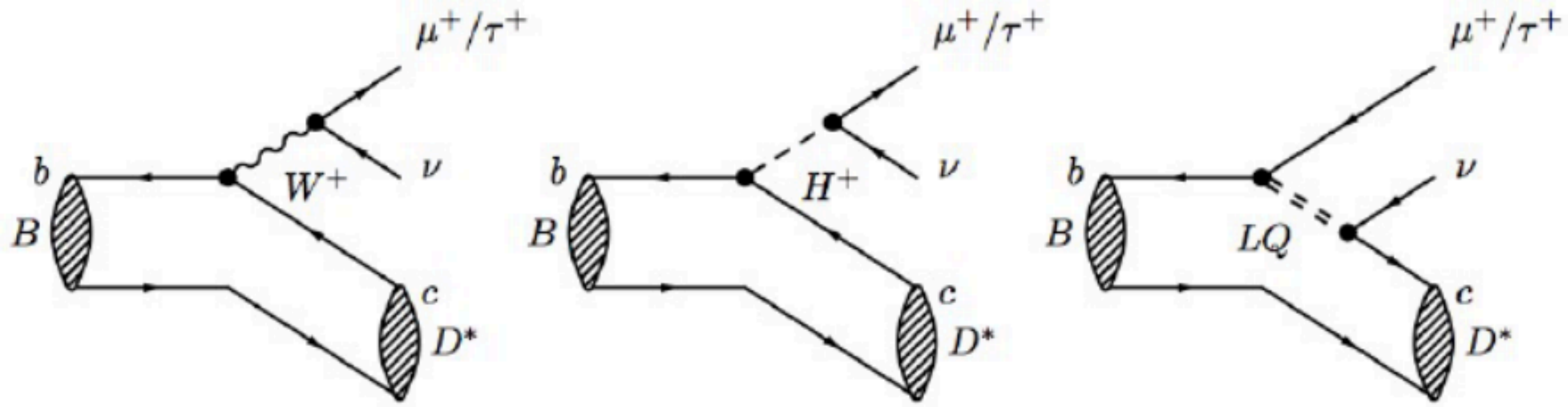
B meson pair reconstruction: Untagged analysis

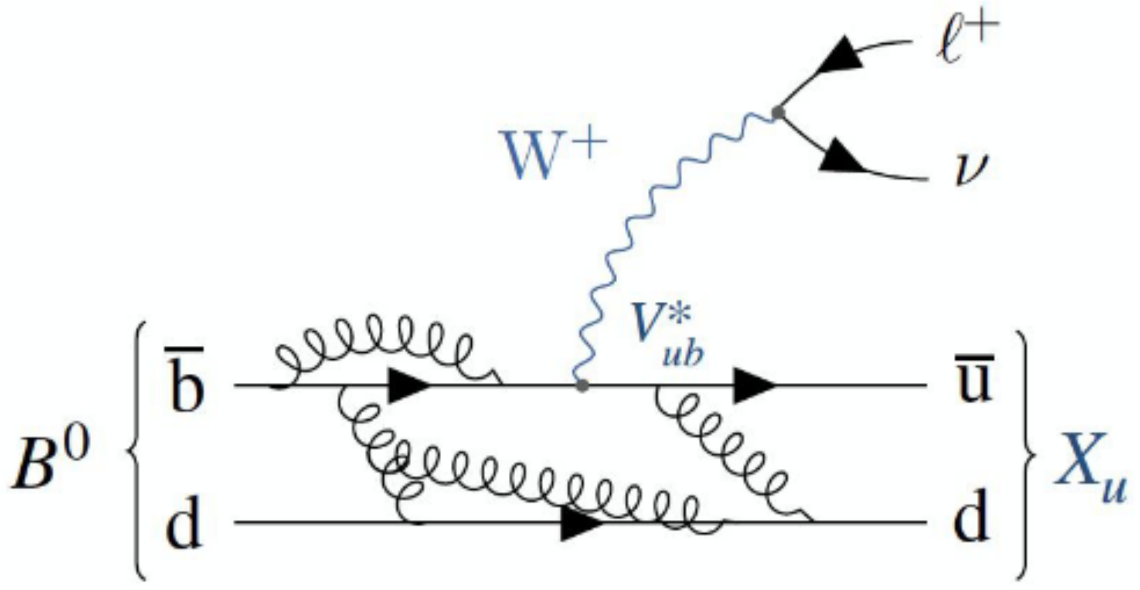
- Search for the final state particles consistent with the signature (and eventually constraint the kinematic of the rest of the event)
  - **exclusive B_{sig}** reconstruction: all final state particles are reconstructed (e.g $B^+ \to K^+ \ell^+ \ell^-$), can apply kinematic constraint to ROE that should be compatible with a B meson
  - **inclusive B_{sig}** reconstruction: one/few final state particle(s) are reconstructed (e.g. $B \to X_s^* \gamma$), the ROE is the other B in the event + what is left from signal reconstruction





Semileptonic decays





$b \to c\ell\nu$: latest Belle $R(D^{(*)})$ measurement

- Sensitive probes for New Physics (leptoquarks, two Higgs doublets etc.) which could impact **lepton flavour universality ratios**:

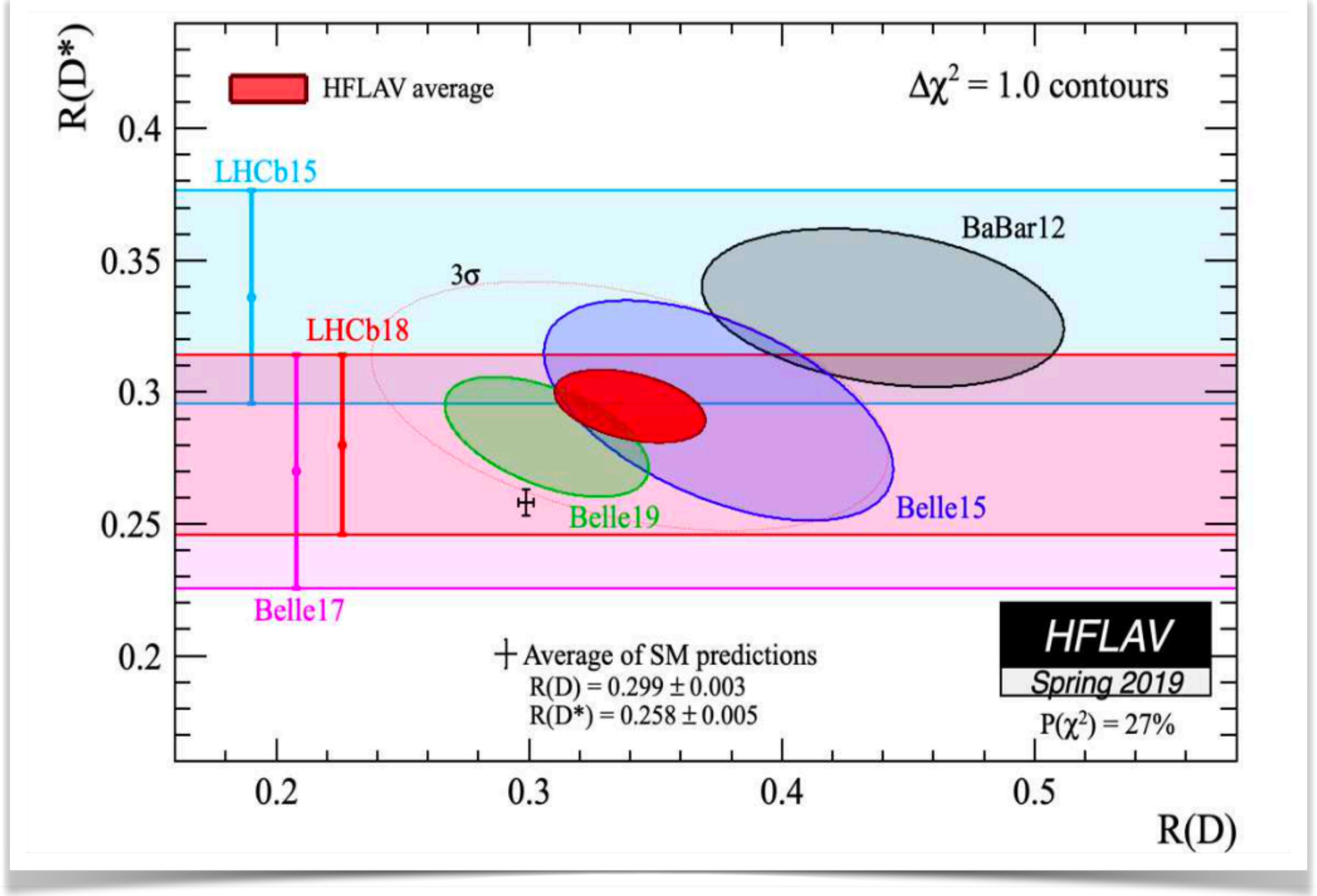
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

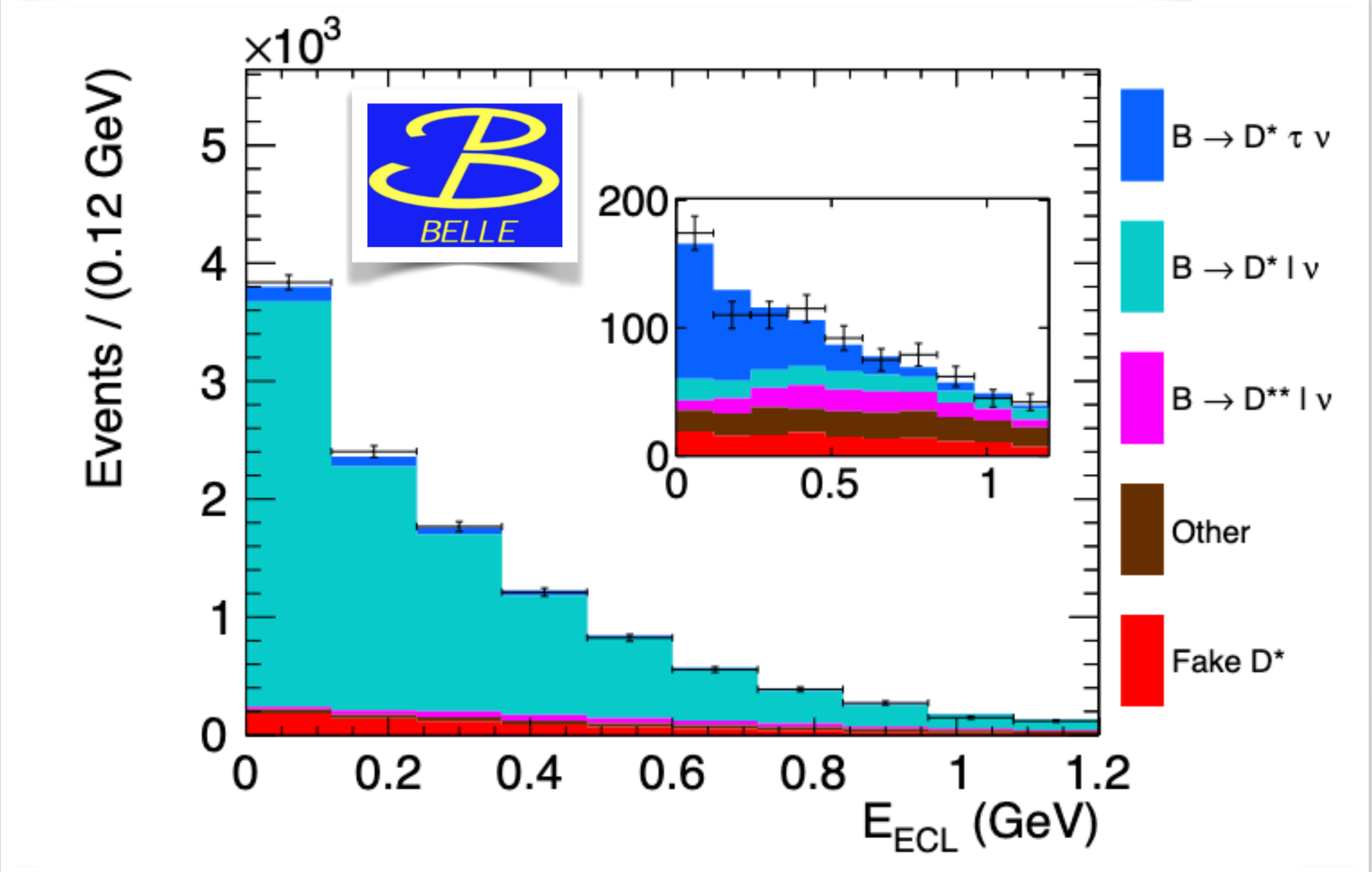
(where $\ell = e$ and μ)

- **Belle analysis** (711 fb^{-1})
  - Tag side reconstructed with Semileptonic FEI, τ in purely leptonic modes
  - Signal extracted from 2D fit to BDT output 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
  - **Most precise measurements** reported to date

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

HFLAV average: 3.1σ excess over SM (D and D* combined)





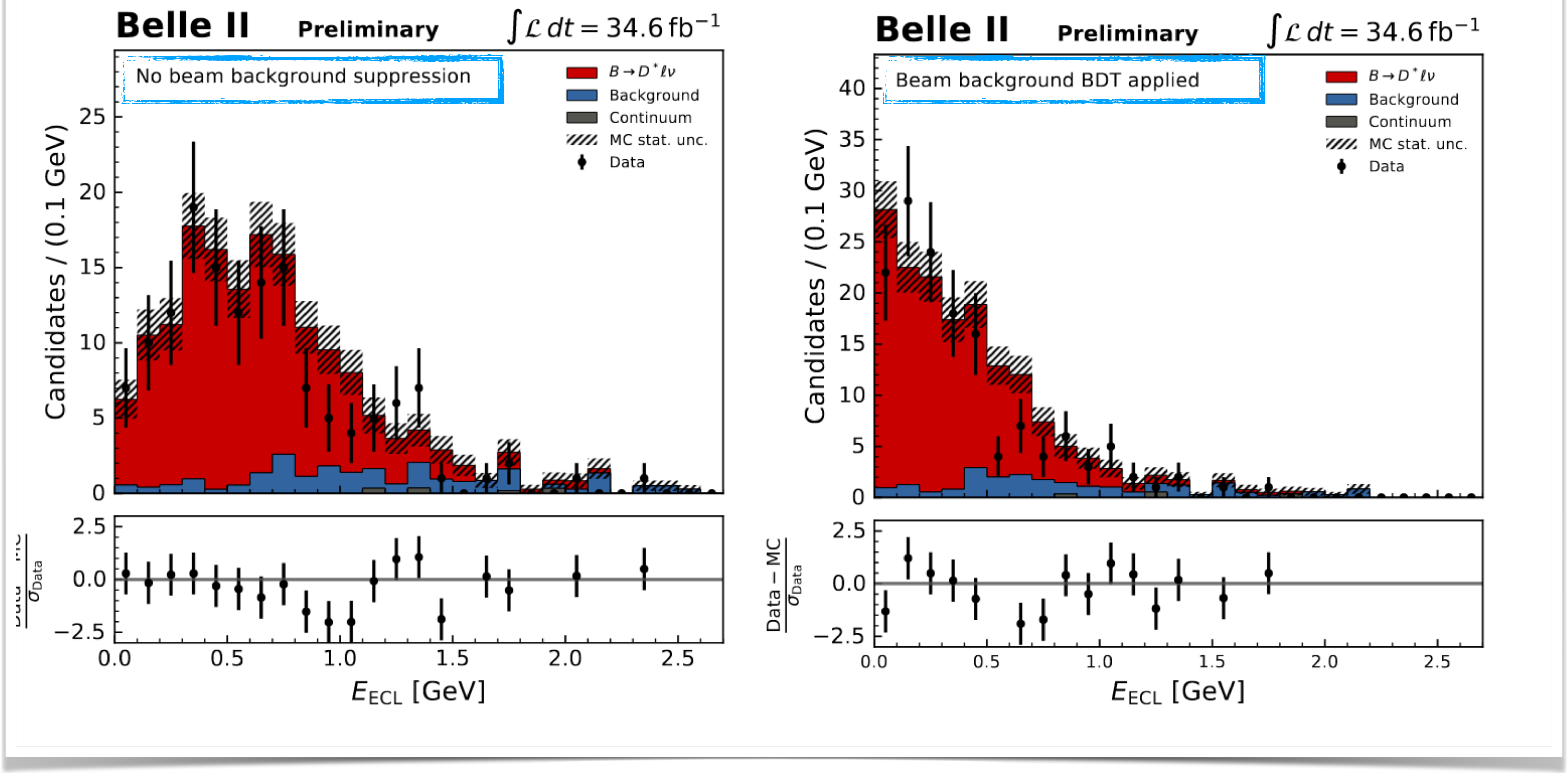
Belle coll., Phys.Rev.Lett. 124 (2020) 16, 161803

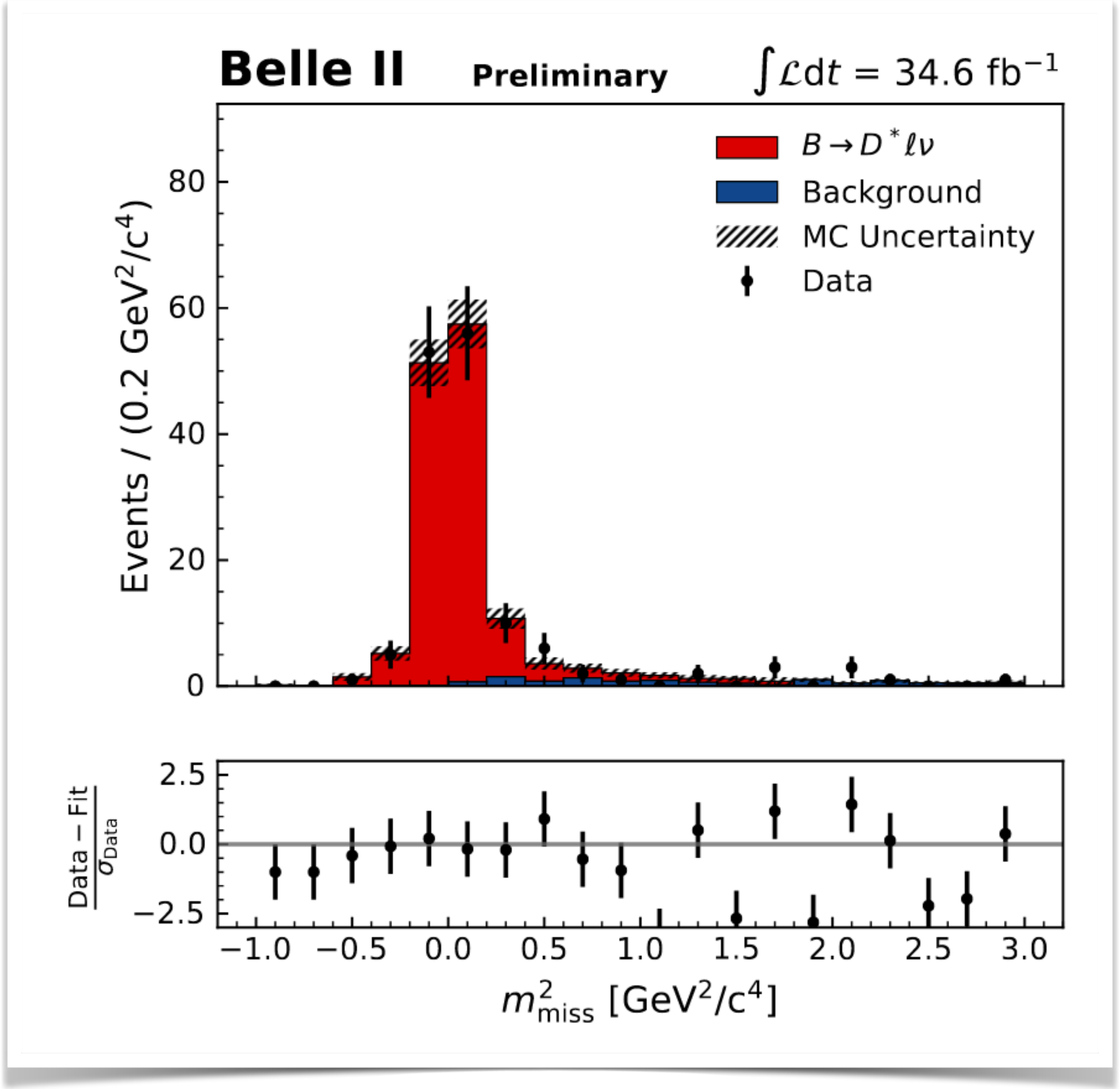
b→cℓν: toward R(D(*)) Belle II measurement (II)

- Measurement of **normalisation channel** with 34.6 fb^{-1} using hadronic **FEI**

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

Dedicated Belle II studies to **improve E_{ECL} reconstruction**



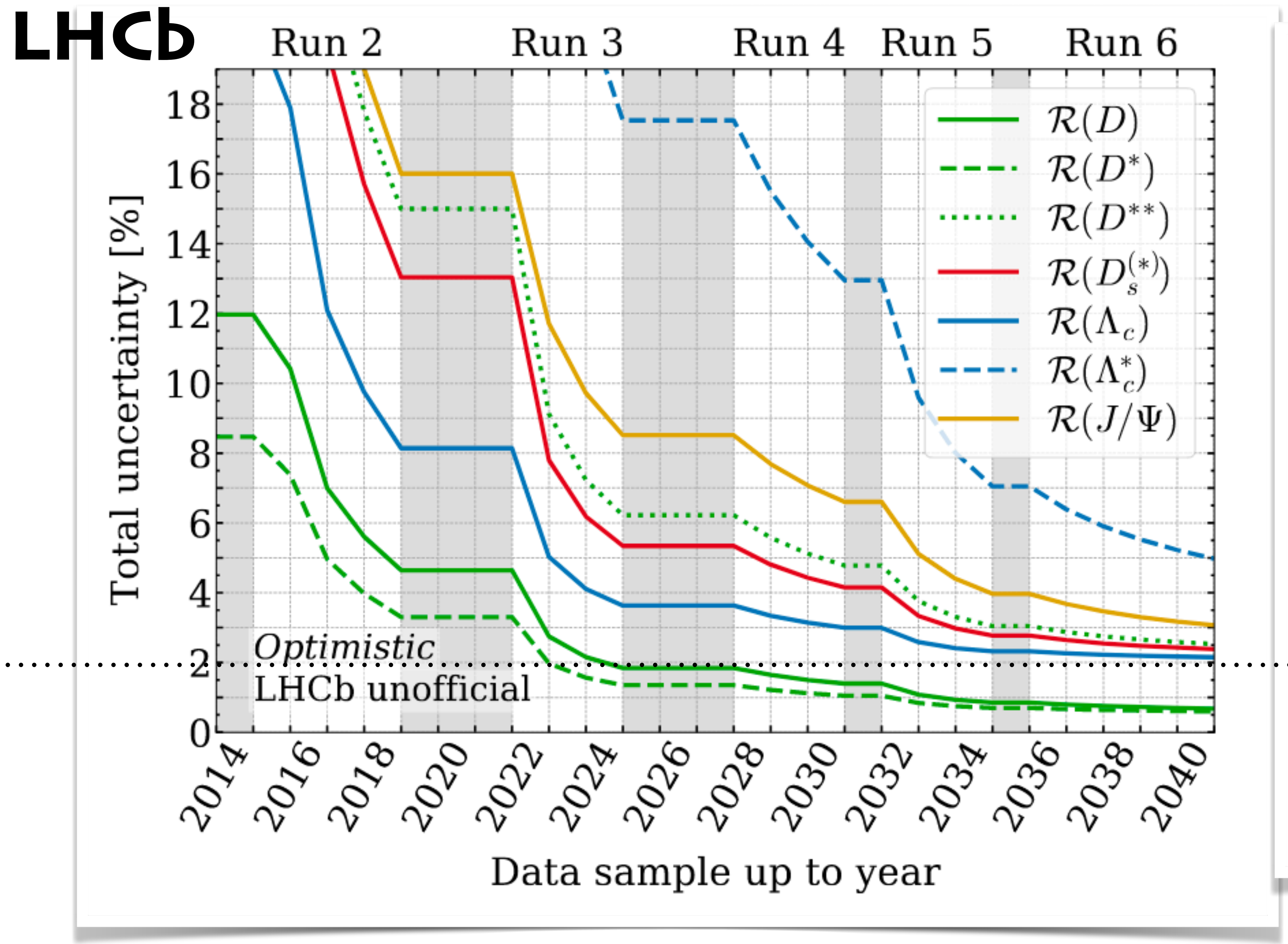


$$\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_l) = \left(4.51 \pm 0.41_{\text{stat}} \pm 0.27_{\text{syst}} \pm 0.45_{\pi_s}\right)\%$$

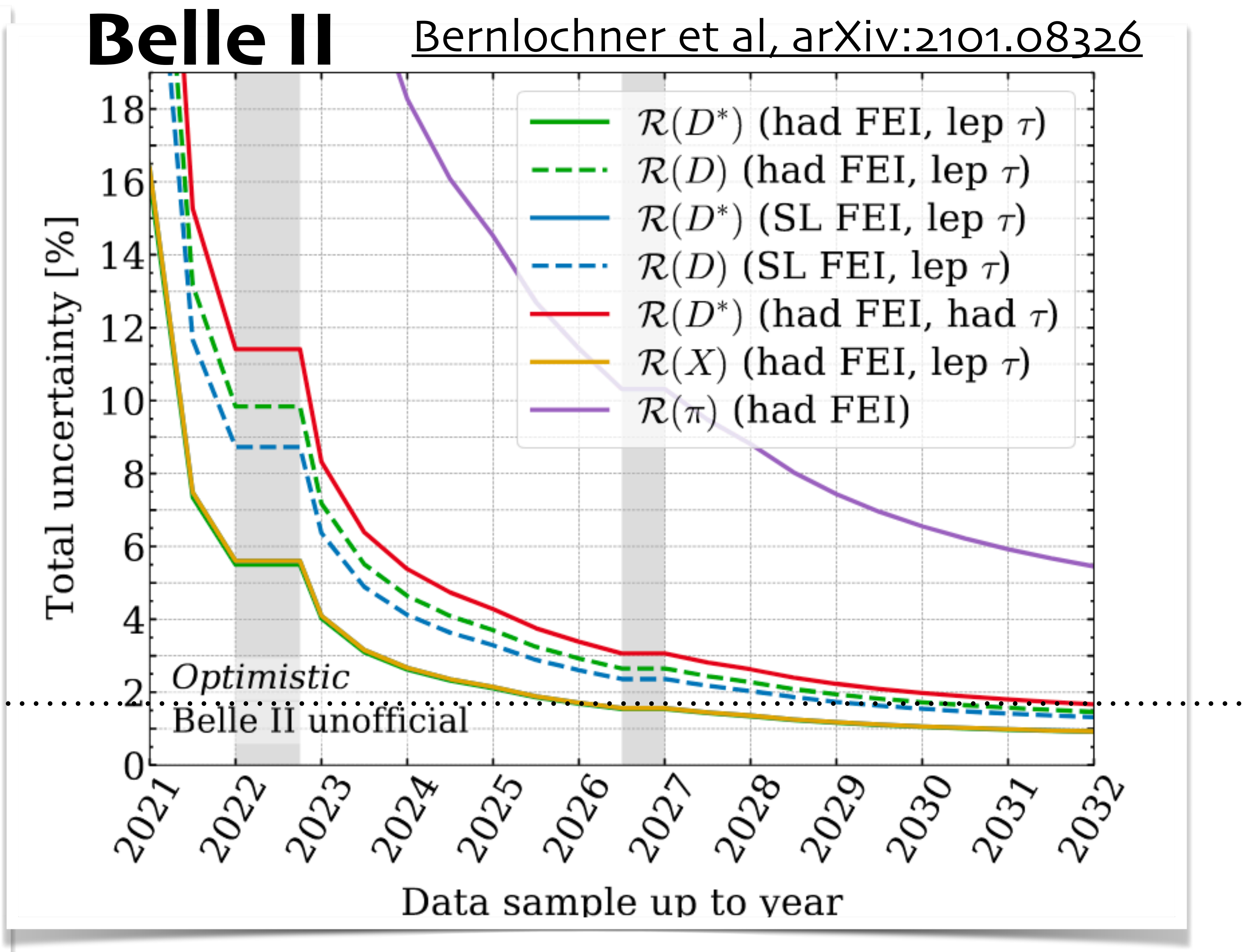
In agreement with world average

main systematic from soft π reconstruction, will improved in the future with auxiliary measurements

$b \to c\ell\nu$: R(D$^{(*)}$) perspectives at Belle II

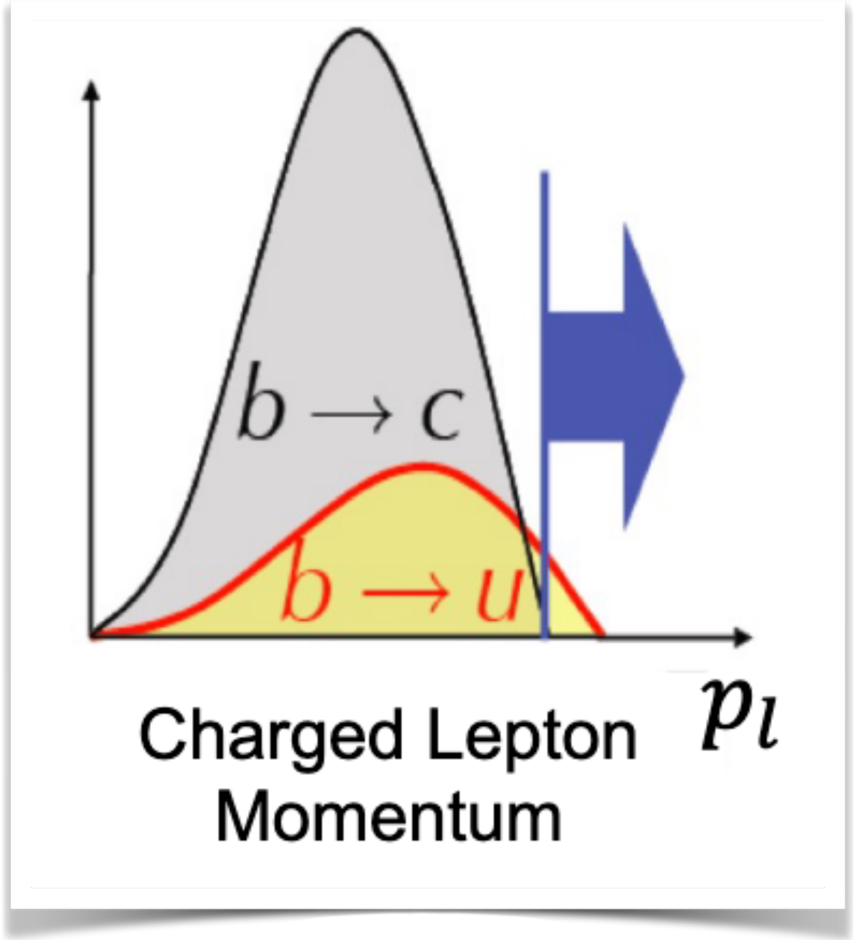


Bernlochner et al, arXiv:2101.08326



- Plethora 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 Belle II data

b→uℓν: new Belle measurements

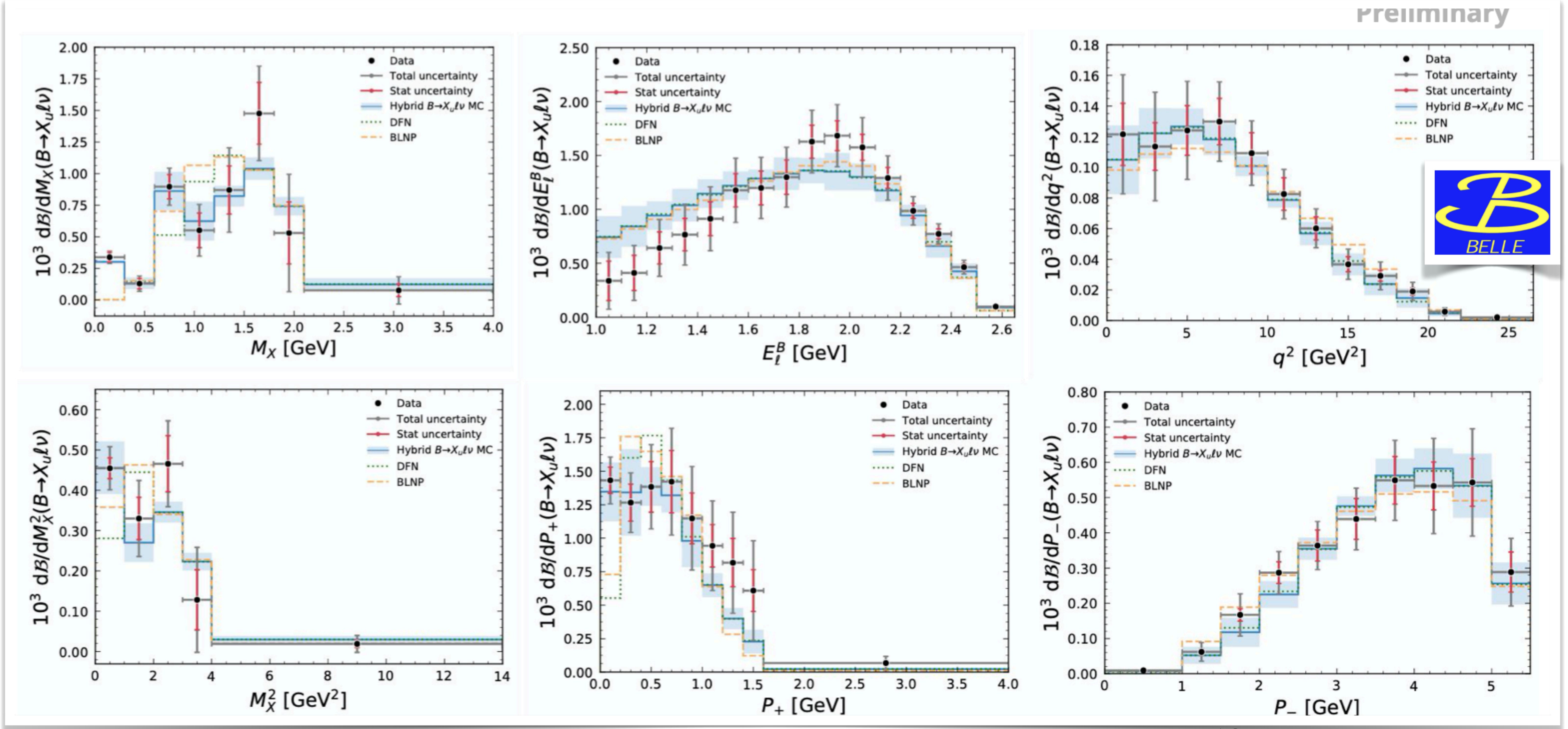


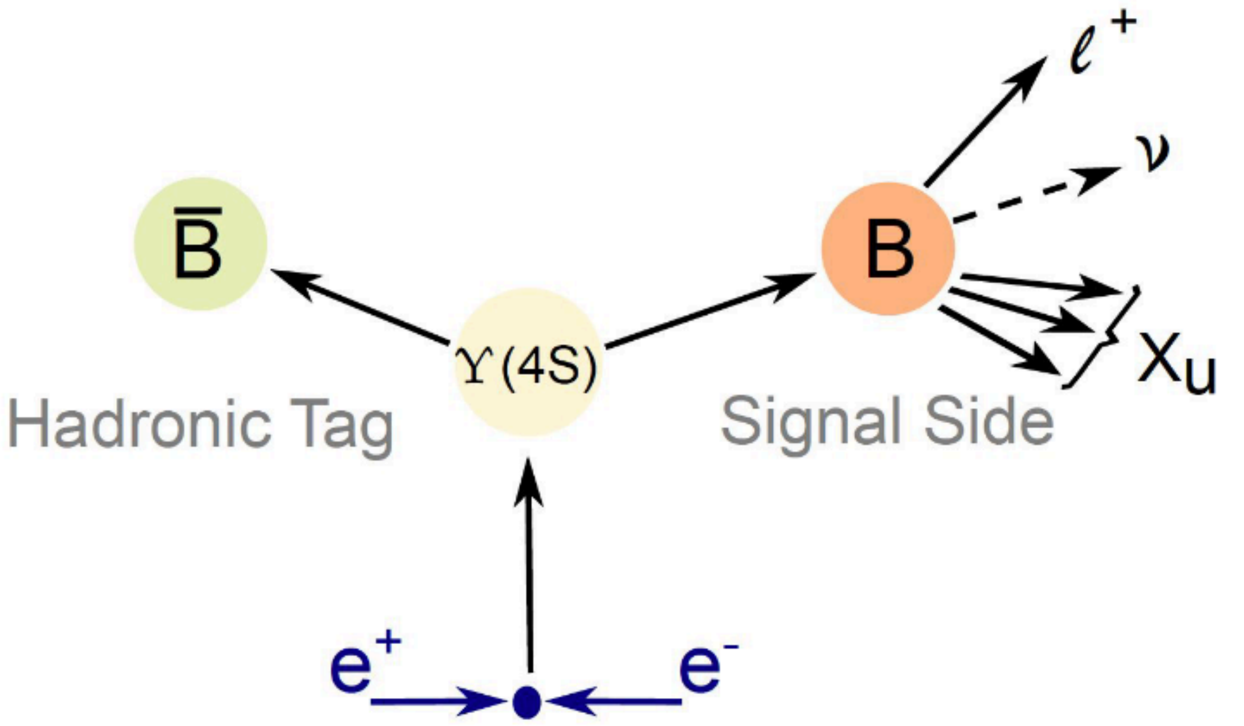
- Challenging due to $B \to X_c \ell \nu$ contamination: clear separation through kinematic variables, e.g. lepton momentum endpoint or low M_X

- Full Reconstruction of hadronic B_{tag} (NIM A 654, 432-440 (2011))

- Inclusive measurement: measure the 6 kinematic variables in the phase space of E_B > 1 GeV

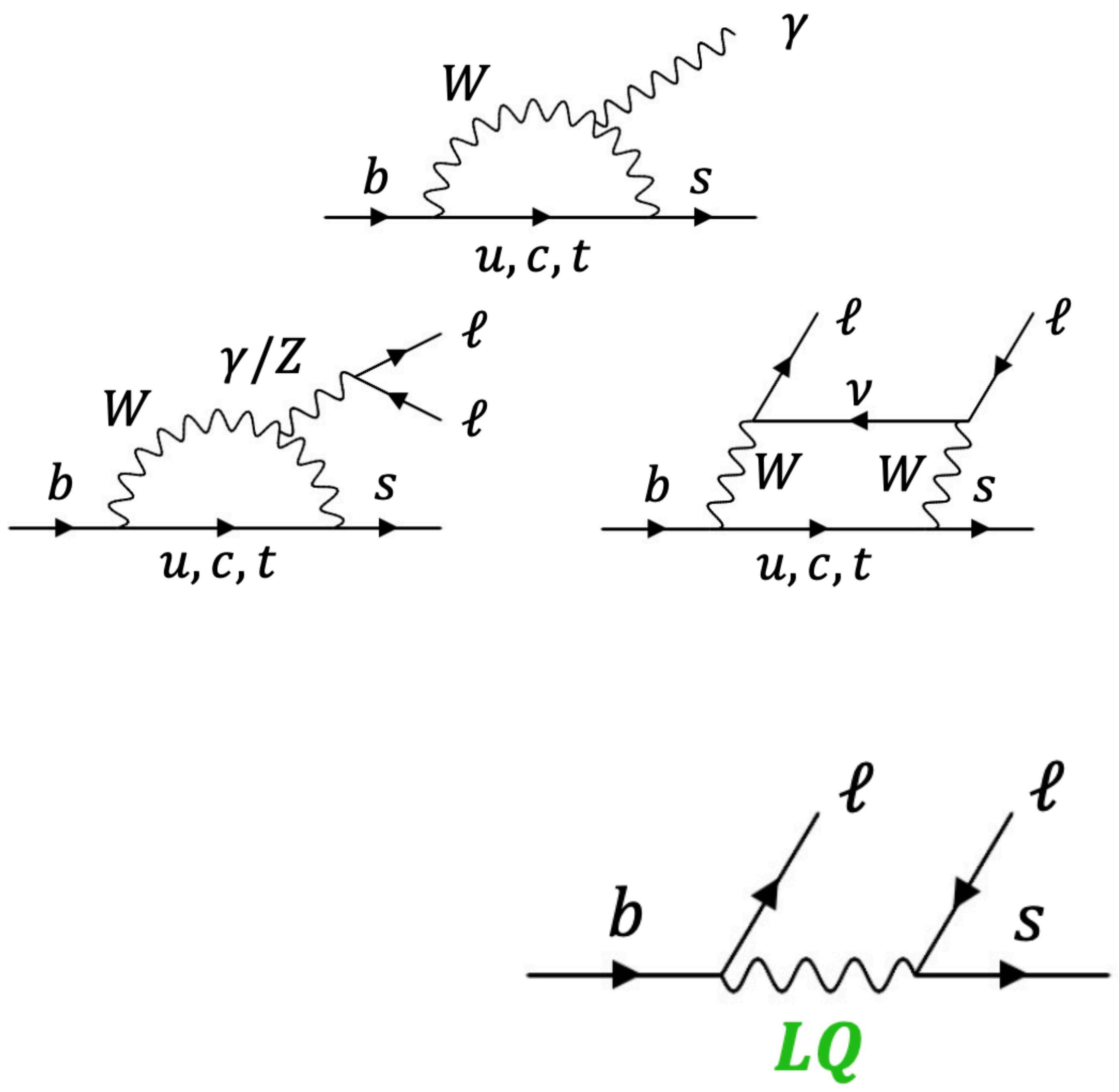
q^2, E_l^B, M_X, M_X^2, P_+, P_- (light-cone momenta: $P_\pm = E_X \mp |p_X|$)





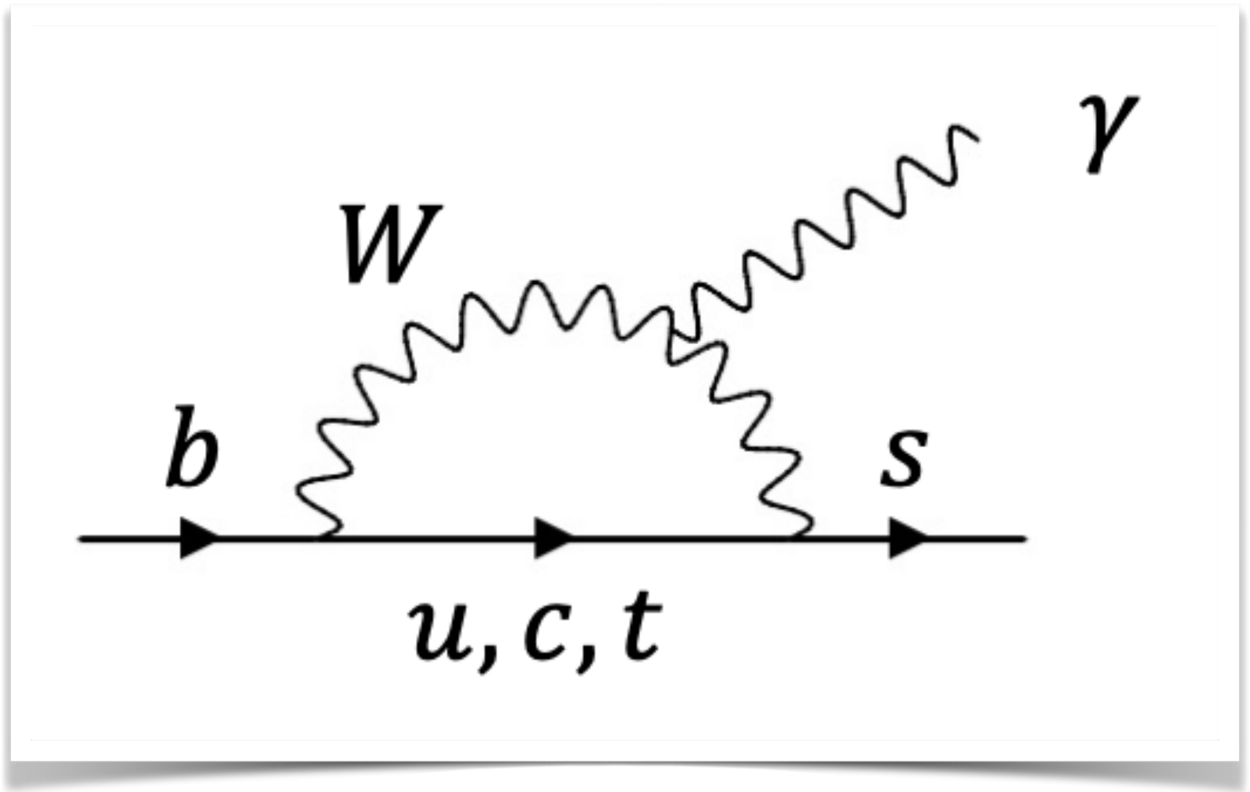
Necessary input for future **model-independent determinations** of $|V_{ub}|$

Radiative and Electroweak penguin decays

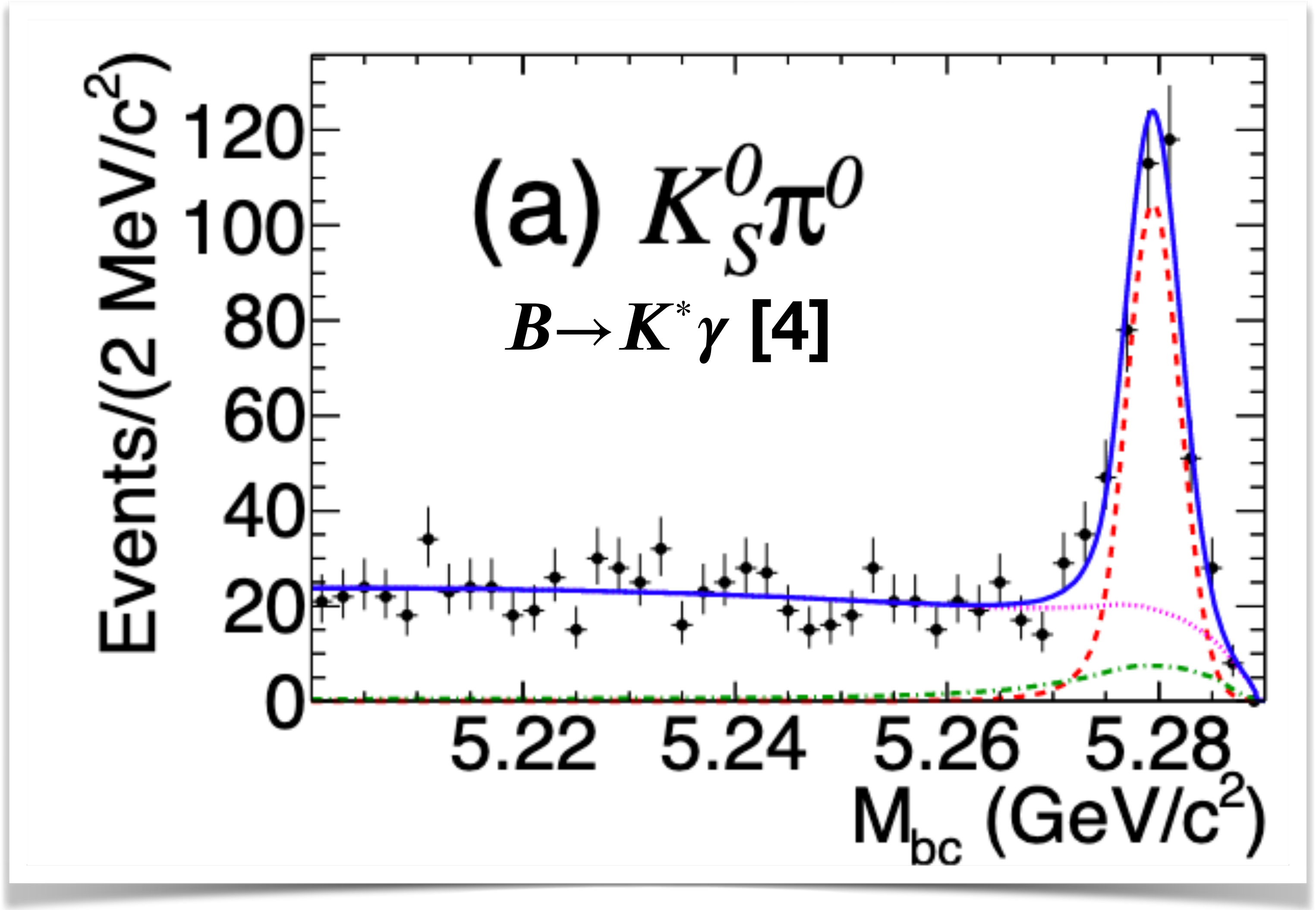


$b\to s\gamma$ state of the art

- $b\to s\gamma$ transitions excellent probe for physics beyond the Standard Model
  - BF ~ 10^{-5}, large uncertainty in the exclusive measurements due to form factors, which cancels in CP and isospin asymmetries (ratios of rates)
- State of the art, best measurements from **Belle**:



	$B\to K^*\gamma$	$B\to X_s\gamma$
BF precision	3% **[4]**	10-12% **[2]** , **[3]**
A_{CP}	consistent with zero and SM predictions **[1]** , **[4]**	
Δ_{0-}	first evidence for isospin violation @ 3.1σ **[4]**	consistent with zero **[1]**



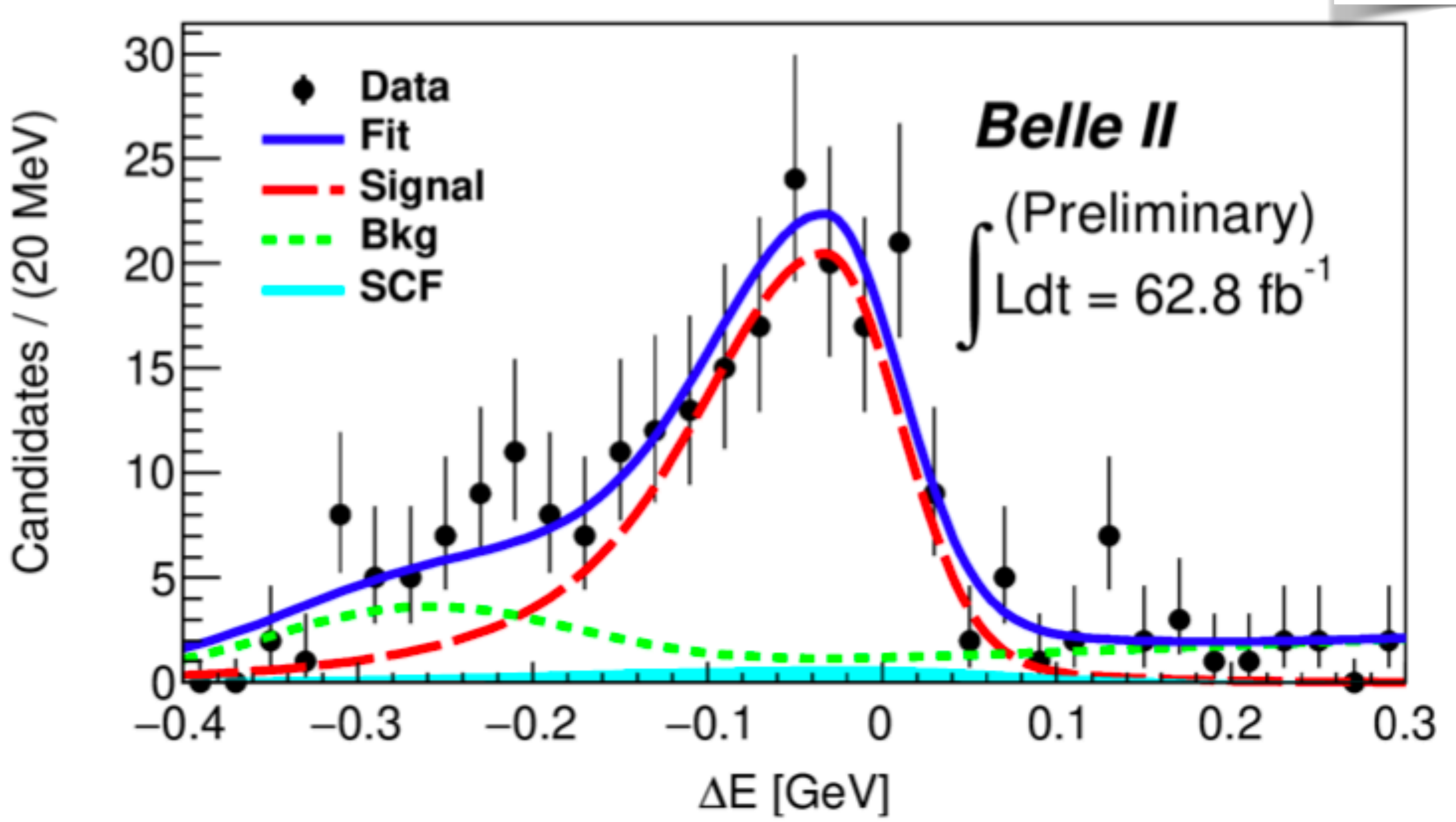
- Can be improved with the larger data set by Belle II in future

[1] Phys. Rev. D 99, 032012 (2019), 711 fb^{-1}, **[2]** *Phys.Rev.D* 91 (2015) 5, 052004, 711 fb^{-1}, **[3]** PRL 103, 241801 (2009), 605 fb^{-1}, **[4]** Phys. Rev. Lett. 119, 191802 (2017), 711 fb^{-1}

b→sγ: first results at Belle II (I)

- $B \to K^{*}\gamma$ branching fraction measurement, with 63 fb^{-1}
  - full reconstruction of the decay chain: charged and neutral K* + high energy photon
- Measured BR **consistent** with **world average** values at 1-2 σ
  - CP and isospin asymmetry measurement foreseen in the next iterations of the analysis

$$\Delta E = E_B^{\mathrm{CM-frame}} - \sqrt{s}/2$$



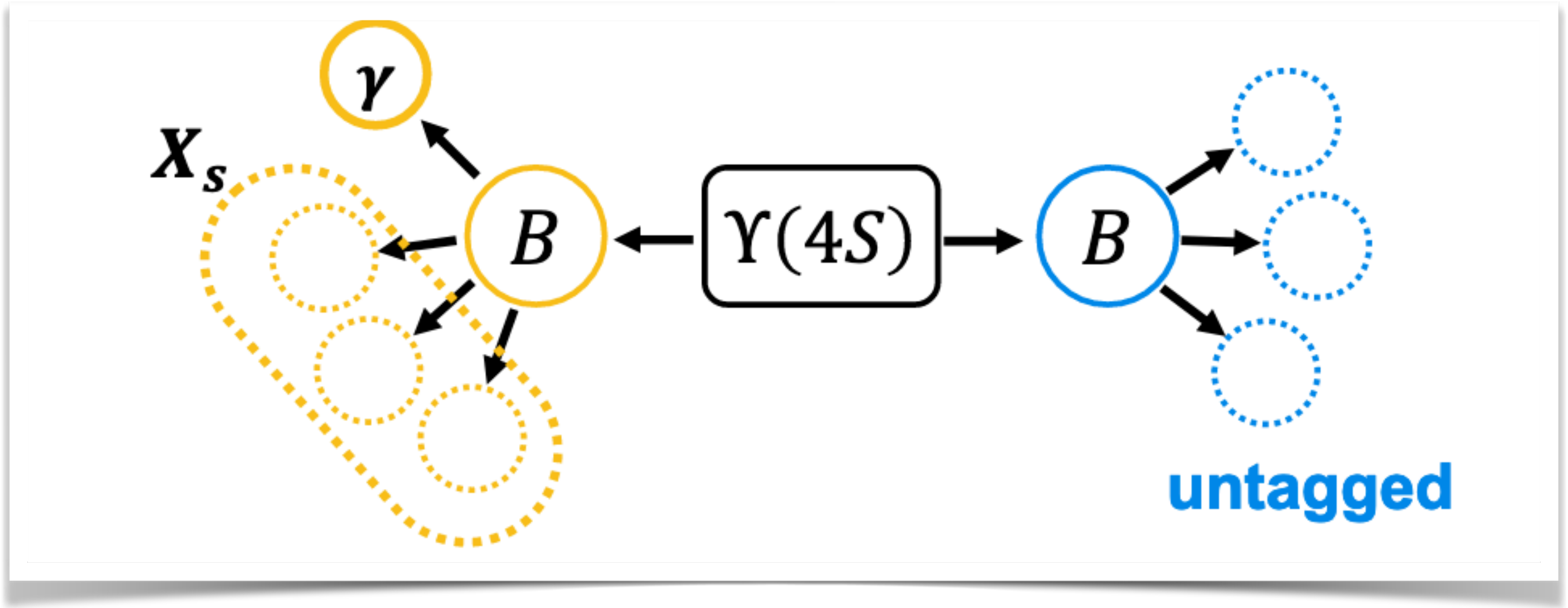
(c) $B^+ \to K^{*+}[K^+\pi^0]\gamma$

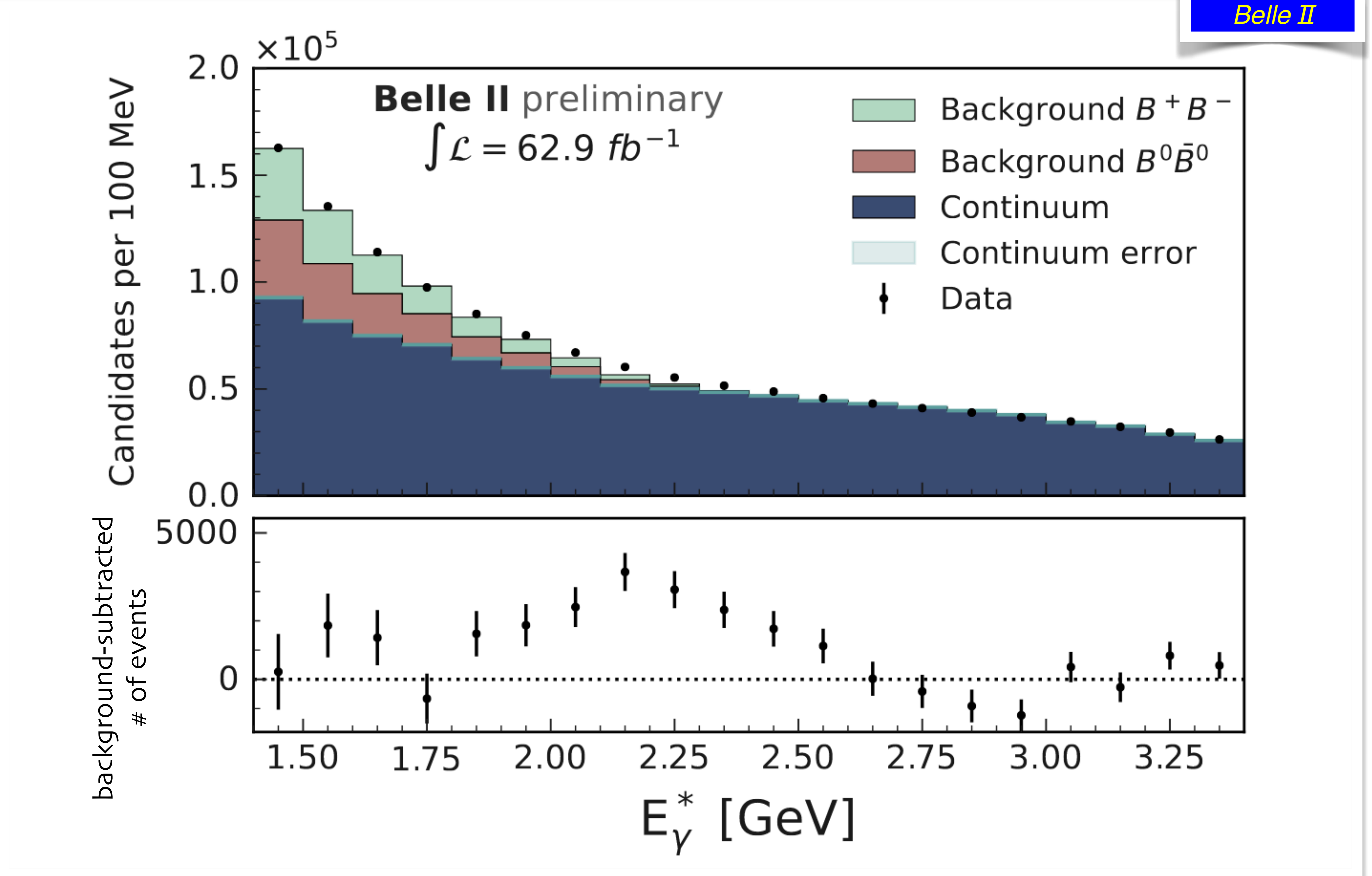
Mode	Br (fit) x10^{-5}
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	$4.5 \pm 0.3(\mathrm{stat}) \pm 0.2(\mathrm{syst})$
$B^0 \to K^{*0}[K_S^0\pi^0]\gamma$	$4.4 \pm 0.9(\mathrm{stat}) \pm 0.6(\mathrm{syst})$
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	$5.0 \pm 0.5(\mathrm{stat}) \pm 0.4(\mathrm{syst})$
$B^+ \to K^{*+}[K_S^0\pi^+]\gamma$	$5.4 \pm 0.6(\mathrm{stat}) \pm 0.4(\mathrm{syst})$

b→sγ: first results at Belle II (II)

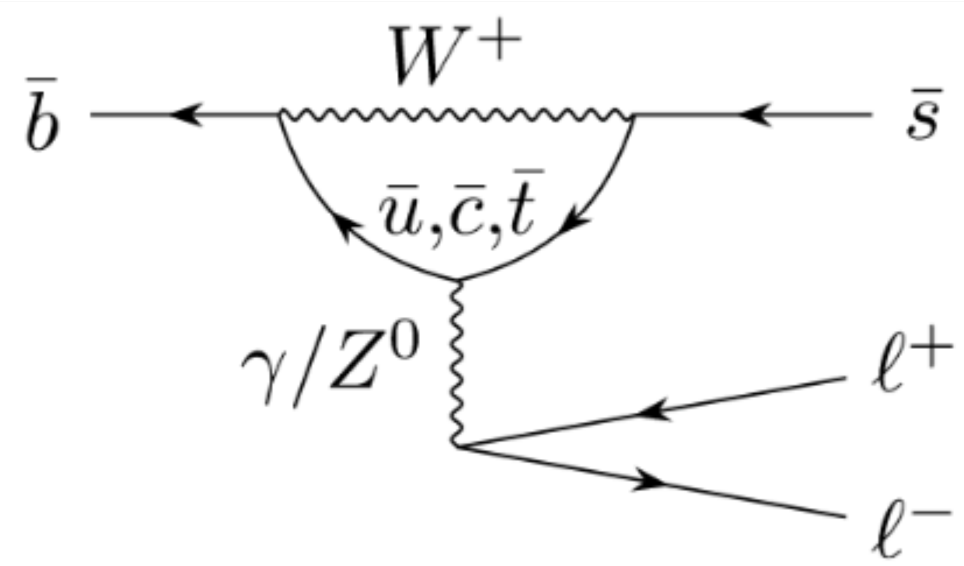
- $B \to X_s \gamma$ with untagged method, 63 fb^{-1}
    - Reconstruct only high energy γ from signal side, monochromatic particle is expected

- Extract signal from photon energy spectrum
- **Excess** visible in the expected signal region

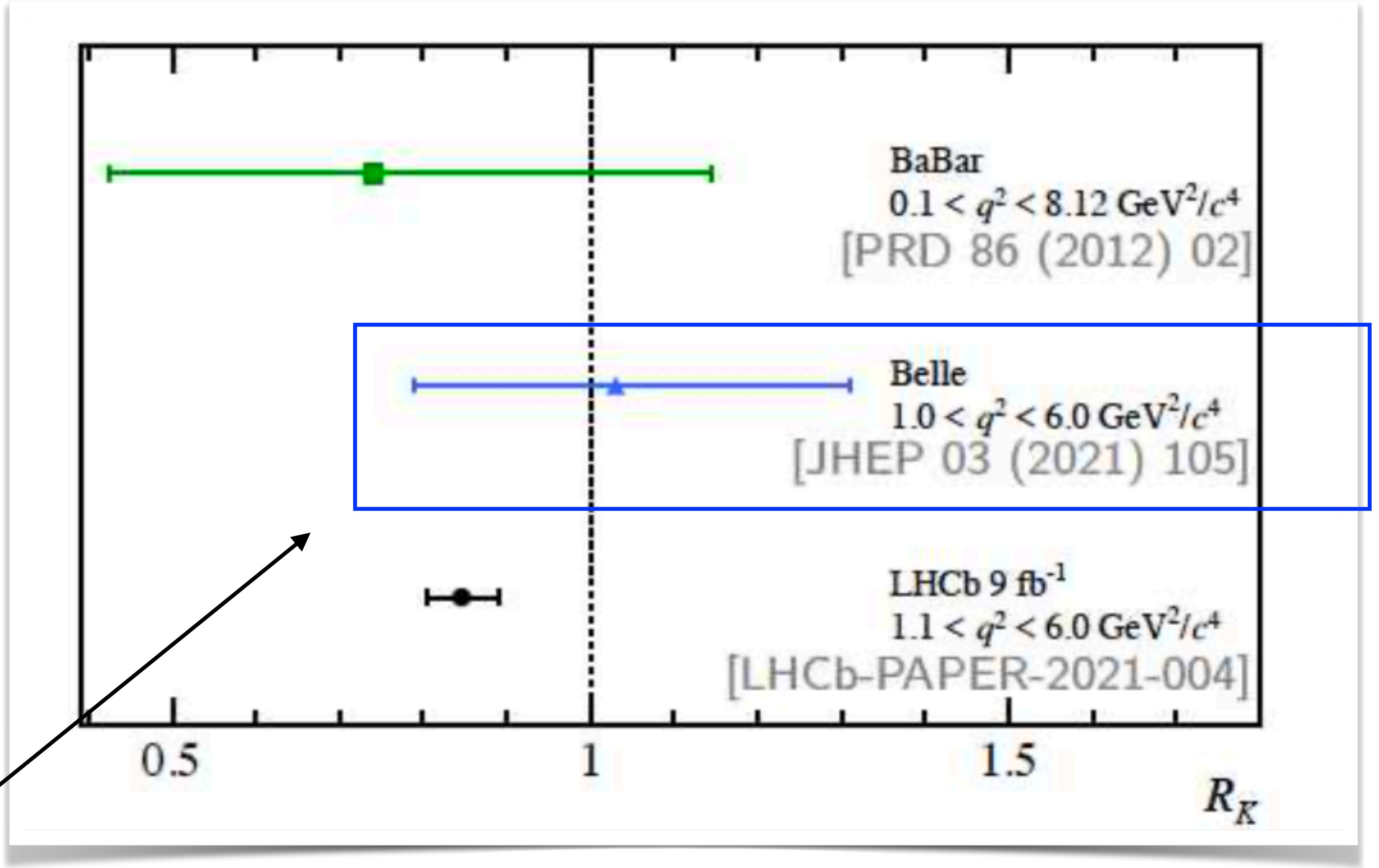




$B \to K^{(*)}ll$: $R(K^{(*)})$ status of the art

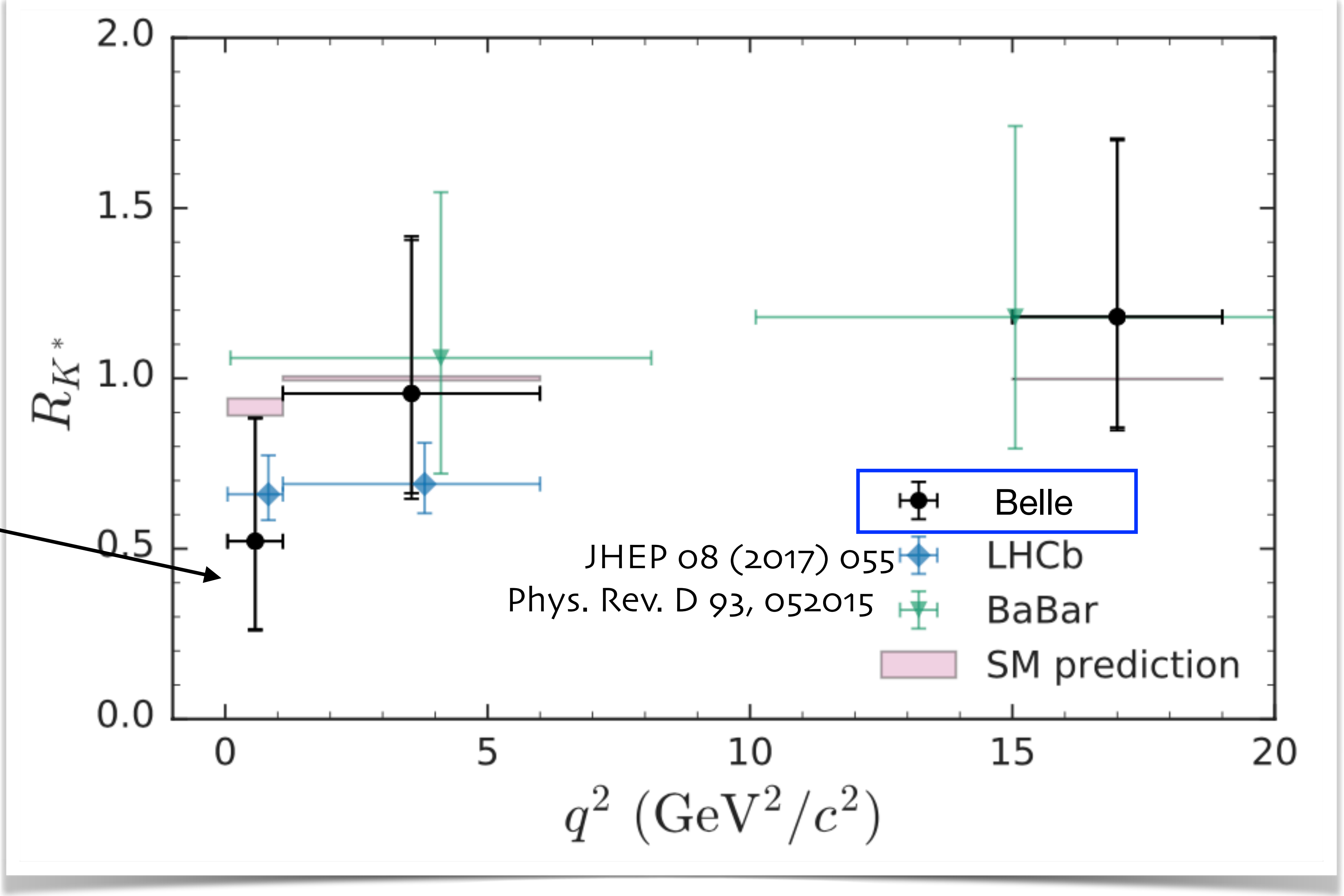


$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$



- Evidence of lepton universality violation on $B^+ \to K^+ l^+ l^-$ from LHCb (arXiv:2103.11769) at 3.1σ level

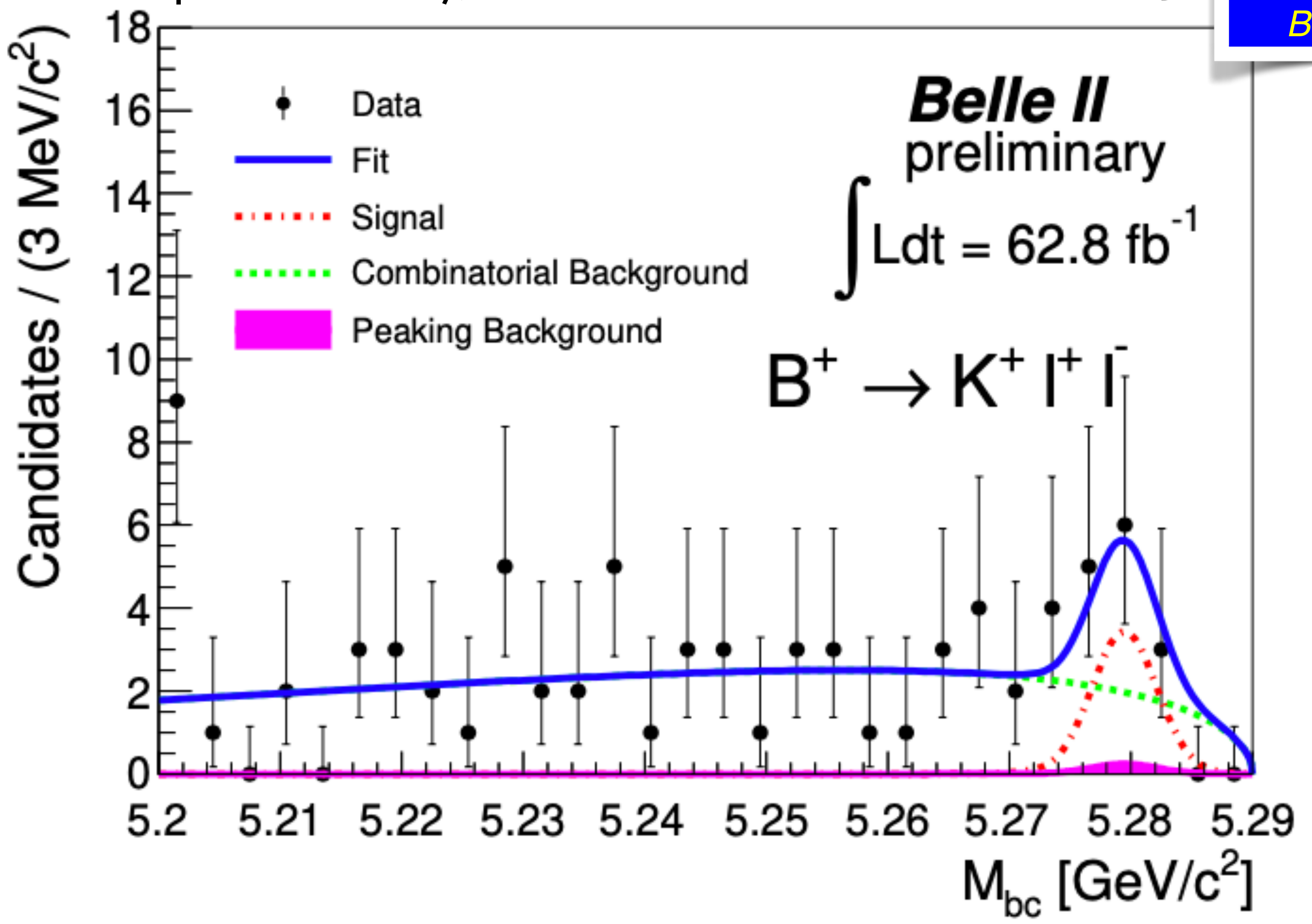
- **Belle** measurements on full dataset (711 fb^{-1}):
  - **R(K)** measured in q^2 bins, in agreement with SM expectations
  - **R(K*)** measurement, charged ratio never measured before
    Belle, PRL 126, 161801 (2021)
  - Statistically limited



$B \to K^{(*)}ll$: status and perspectives at Belle II

- Search for $B^+ \to K^+ \ell^+ \ell^-$ with 63 fb^{-1} of Belle Data
    - rehearsing analysis using $B^+ \to J/\psi\,(\ell^+\ell^-)K^+$ control sample (same final state but large BR)
- Signal yield extracted from 2D fit to M_{bc} and ΔE, **2.7σ significance**
    - $N_{sig} = 8.6^{+4.3}_{-3.9}(\text{stat}) \pm 0.4(\text{syst})$

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



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

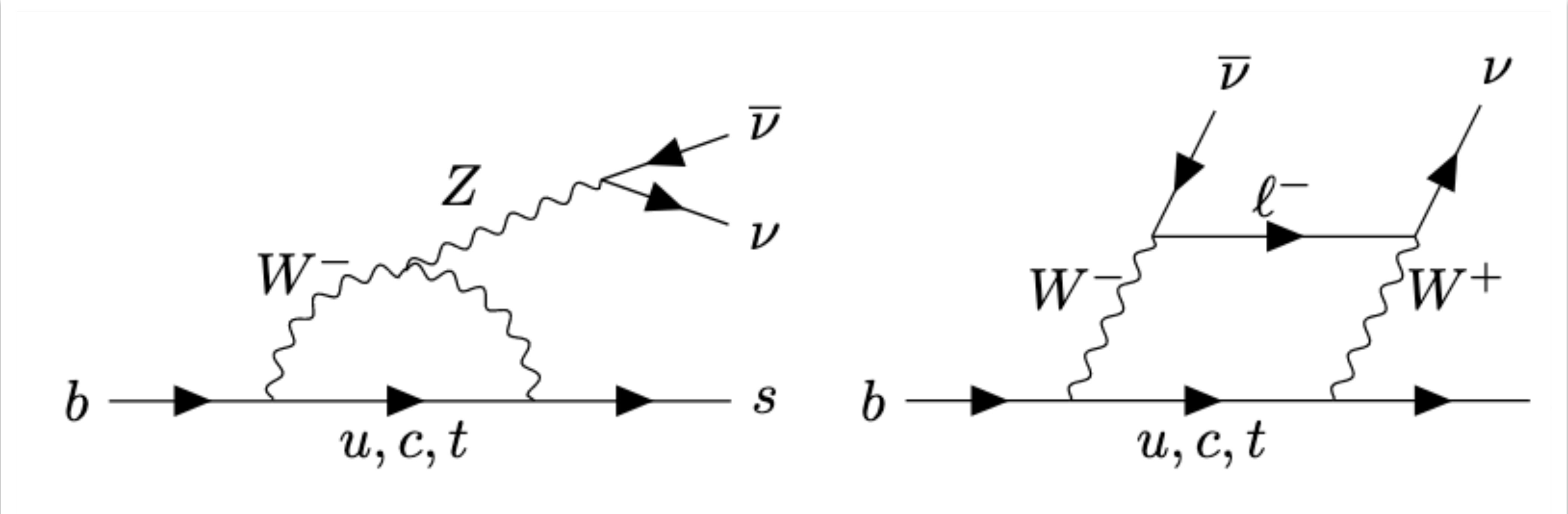
- Long term perspectives for **R(K$^{(*)}$)**:
    - LHCb with full luminosity (~2035, 300fb^{-1}) is expected to have better precision in the low q^2 wrt to full Belle II data sample
    - In the high q^2 Belle II precision will reach **few %** level

$b \to s\nu\bar{\nu}$: state of the art prior to Moriond2021

- SM predictions:

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

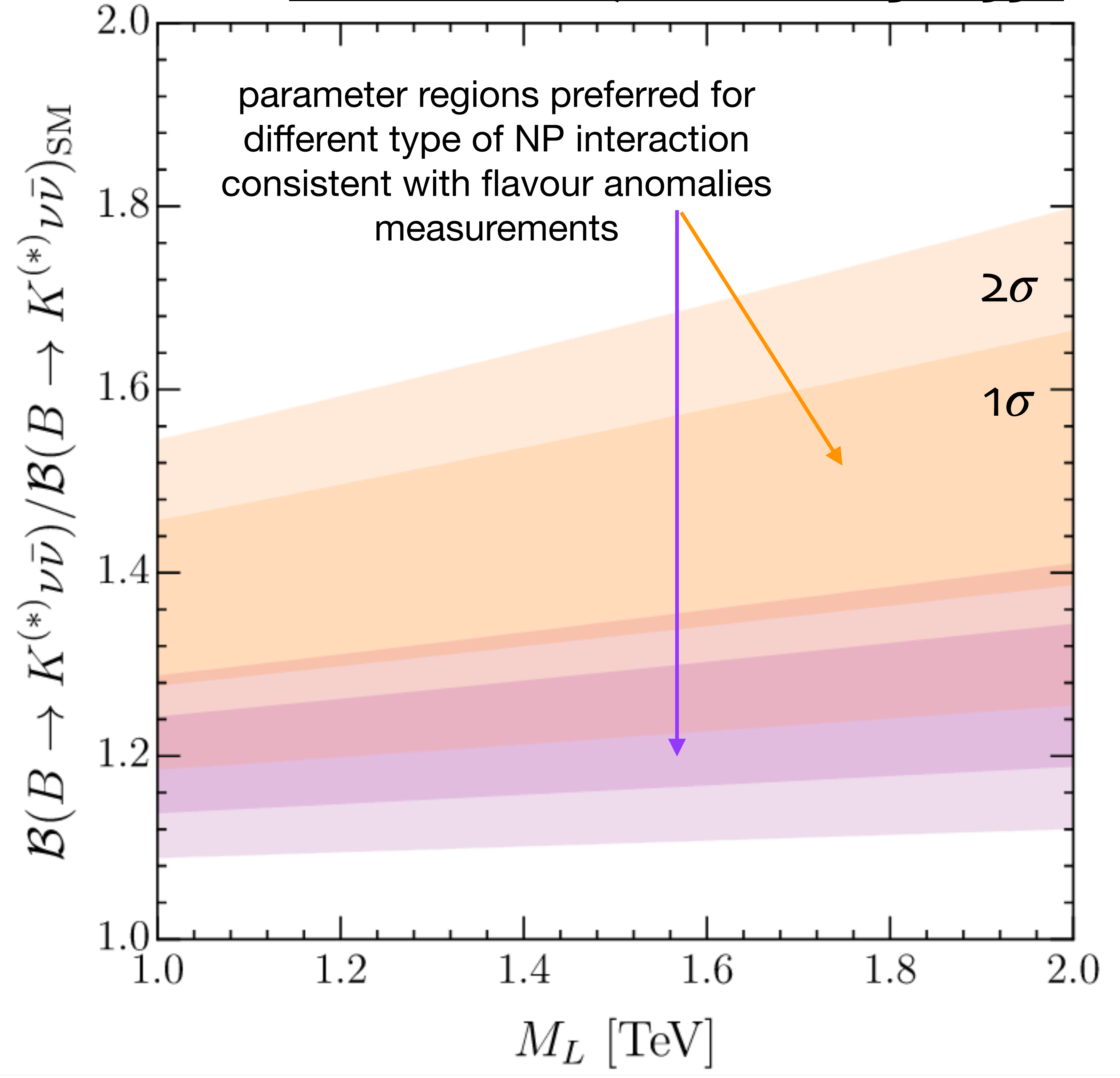
$$\mathrm{BR}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{SM}} = (4.6 \pm 0.5) \times 10^{-6}\,,$$
$$\mathrm{BR}(B^+ \to K^{*+}\nu\bar{\nu})_{\mathrm{SM}} = (8.4 \pm 1.5) \times 10^{-6}\,,$$



(a) Penguin diagram (b) Box diagram

- Possible enhancement in NP scenarios, e.g. Leptoquark models explaining flavour anomalies →

Cornella et al, arXiv:2103.16558



- BaBar and Belle key ingredient: **hadronic** and **semileptonic tag** side reconstruction

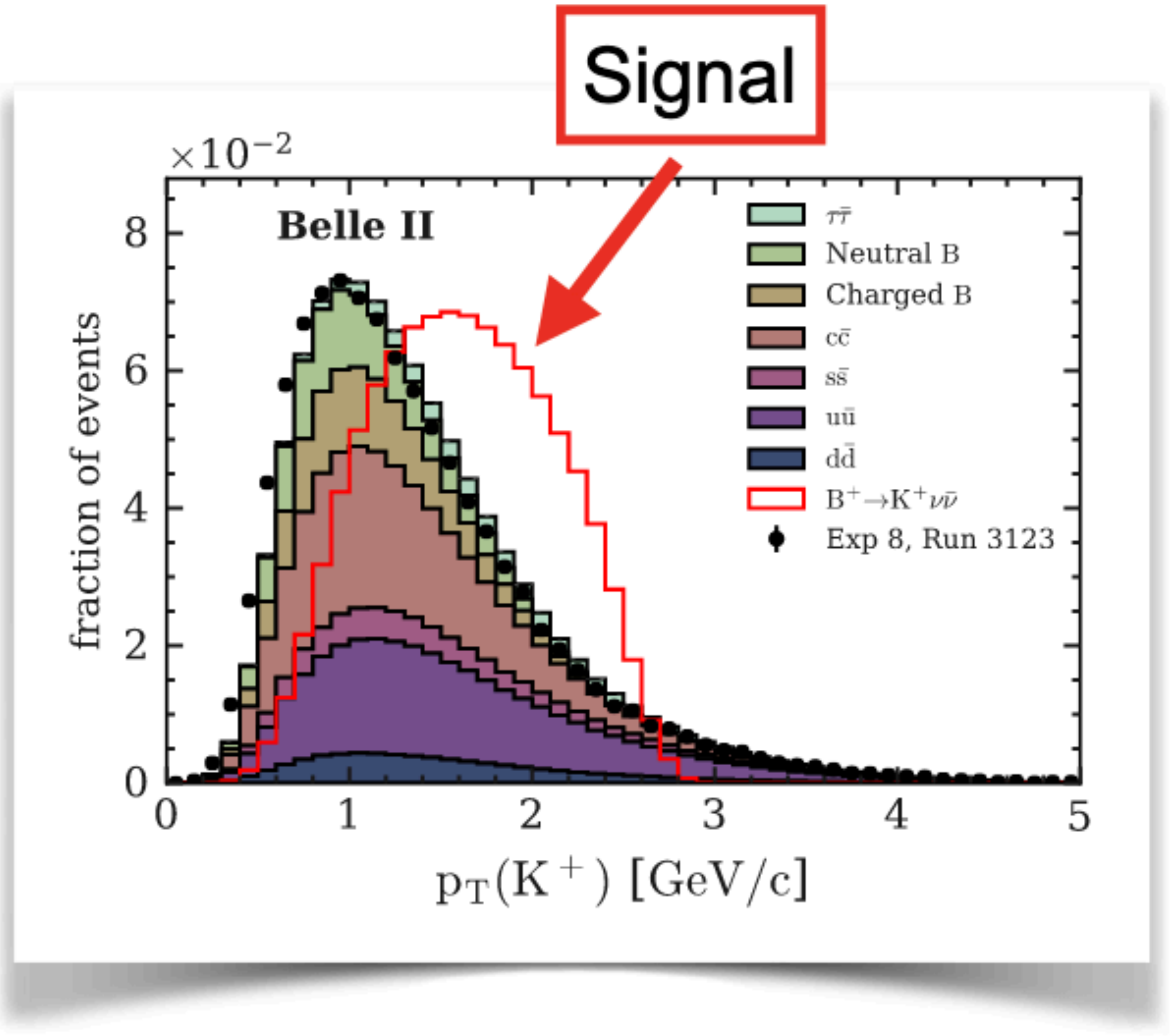
	UL @ 90% CL (10^{-5})	**Ref**
$B^+ \to K^+ \nu\bar{\nu}$	1.6	BaBar, HAD+SL TAG, 429 fb^{-1}
$B^+ \to K^{*+} \nu\bar{\nu}$	4.0	Belle, HAD TAG, 711 fb-1
$B^0 \to K^0 \nu\bar{\nu}$	2.6	Belle, SL TAG, 711 fb-1
$B^0 \to K^{*0} \nu\bar{\nu}$	1.8	Belle, SL TAG, 711 fb-1

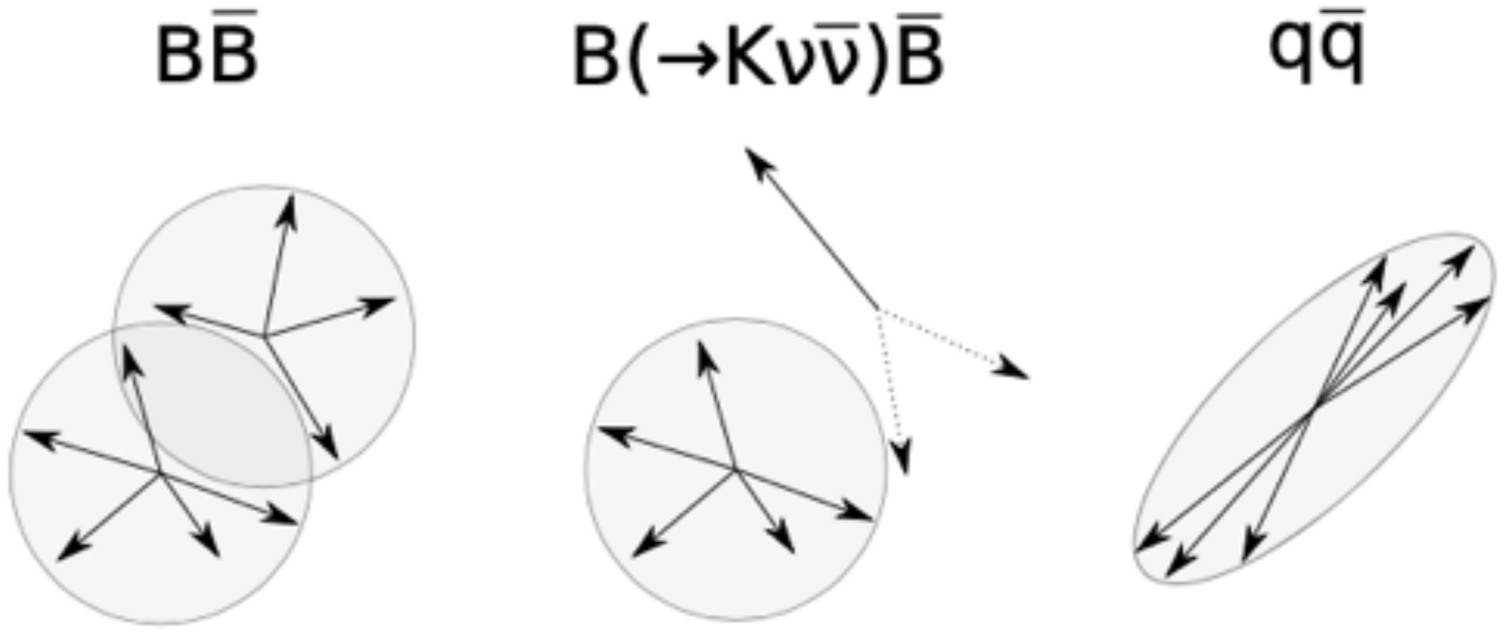
$B^+ \to K^+ \nu \bar{\nu}$ measurement @ Belle II (I)

Belle II coll., arXiv:2104.12624
submitted to journal

NOVEL INCLUSIVE APPROACH on 63 fb^{-1} of Belle II data:

- Signal kaon = highest p_T track →
- Associate all other tracks and clusters to other B in the event
- Use multivariate approach (2 BDTs in cascade) based on kinematics, event shape and vertexing variables to suppress background
- **Signal efficiency** ~ **4.3 %** (SM signal)

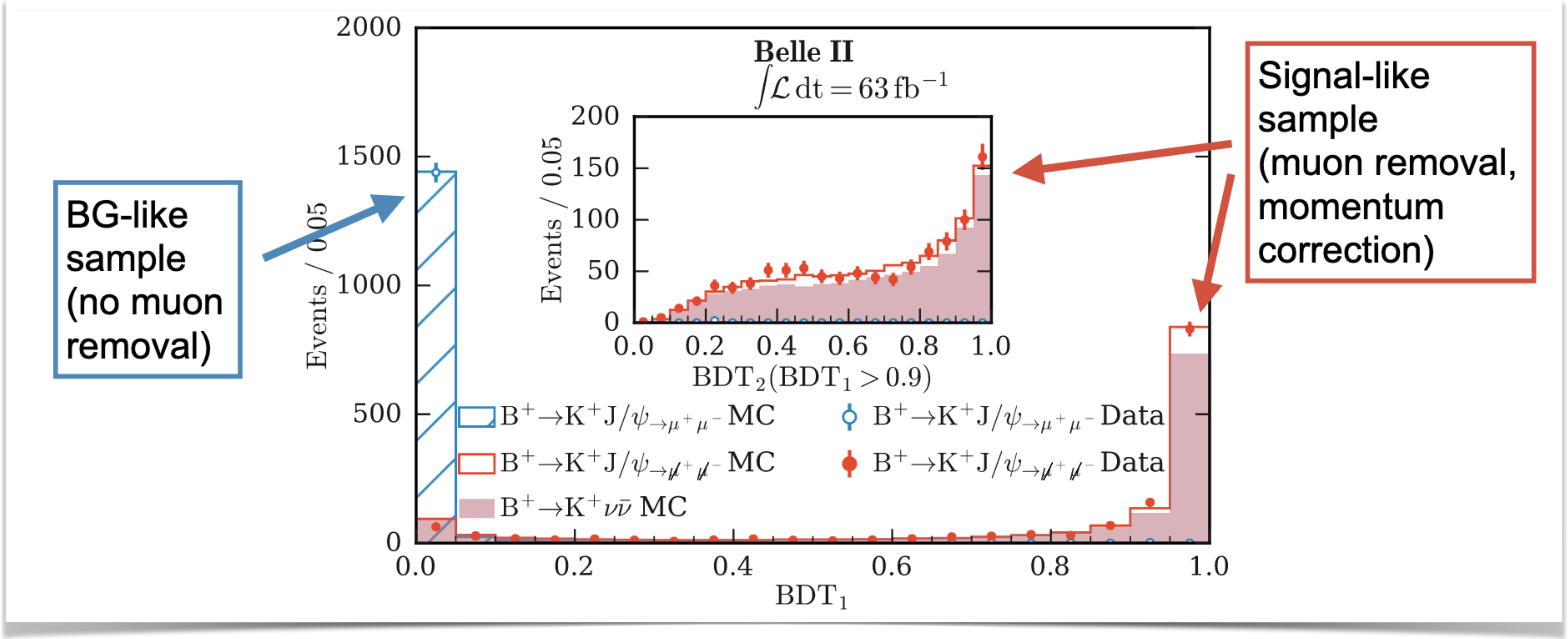




$B^+ \to K^+ \nu\bar{\nu}$ measurement @ Belle II (II)

Belle II coll., arXiv:2104.12624
submitted to journal

- Check data-simulation agreement in BDTs output using $B^+ \to J/\psi(\mu^+\mu^-)K^+$ control sample
- **Data/MC ratio in fit region**: 1.06 ± 0.10

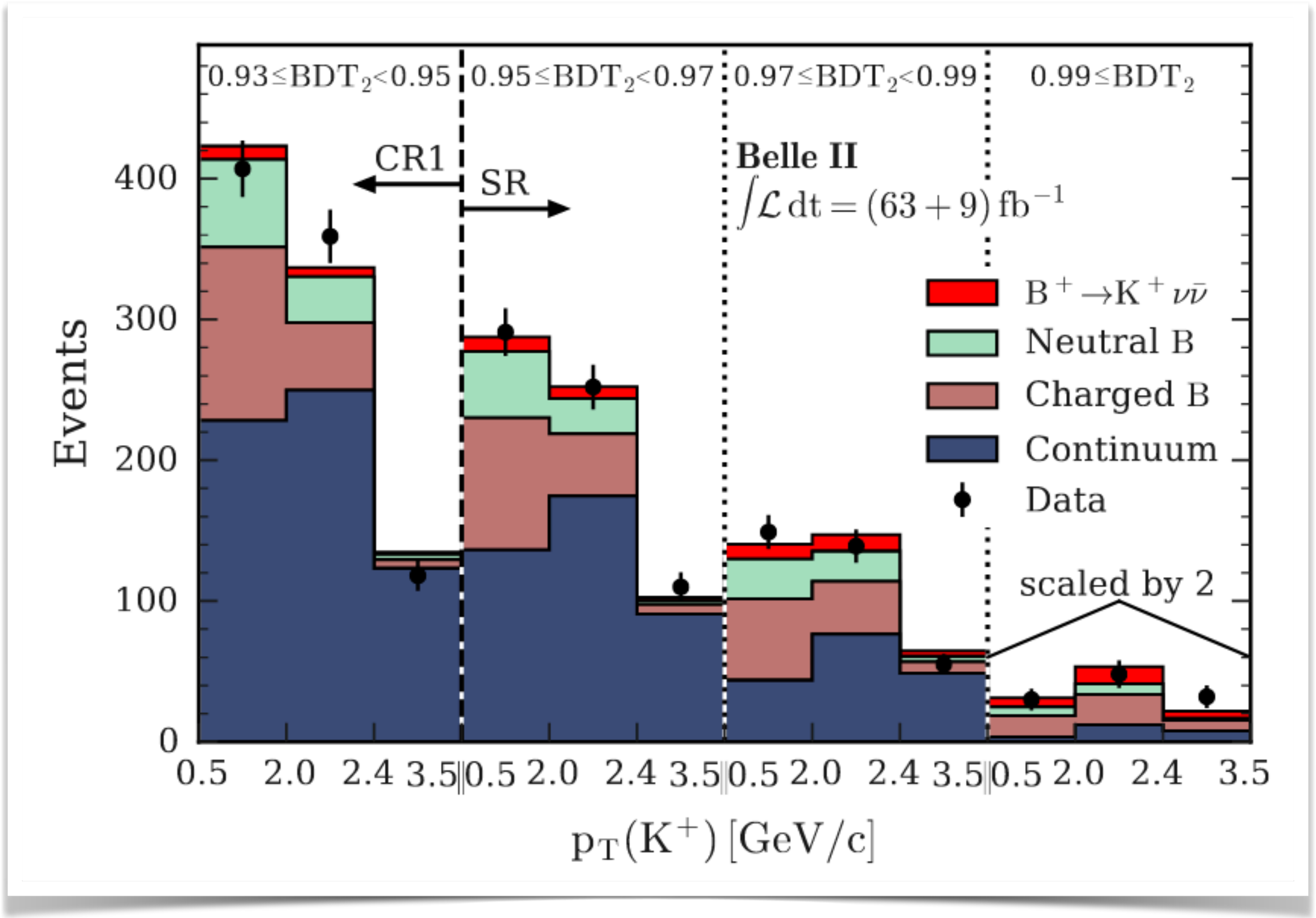


- Extract signal from simultaneous maximum likelihood fit to on-resonance + off- resonance data (taken 60MeV below $\Upsilon(4S)$ resonance) in bins of $p_T(K^+)$ and second BDT (BDT_2):

Signal strength:

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

- consistent with SM exp (μ=1) at 1 σ
- consistent with background-only hypothesis at 1.3 σ



- Leading systematics: **background normalisation** uncertainty can be also reduced with increasing statistics

$B^+ \to K^+ \nu\bar{\nu}$ measurement @ Belle II (III)

Belle II coll., arXiv:2104.12624
submitted to journal

- No evidence for signal, upper limit on BR using CLs method (assuming SM signal)

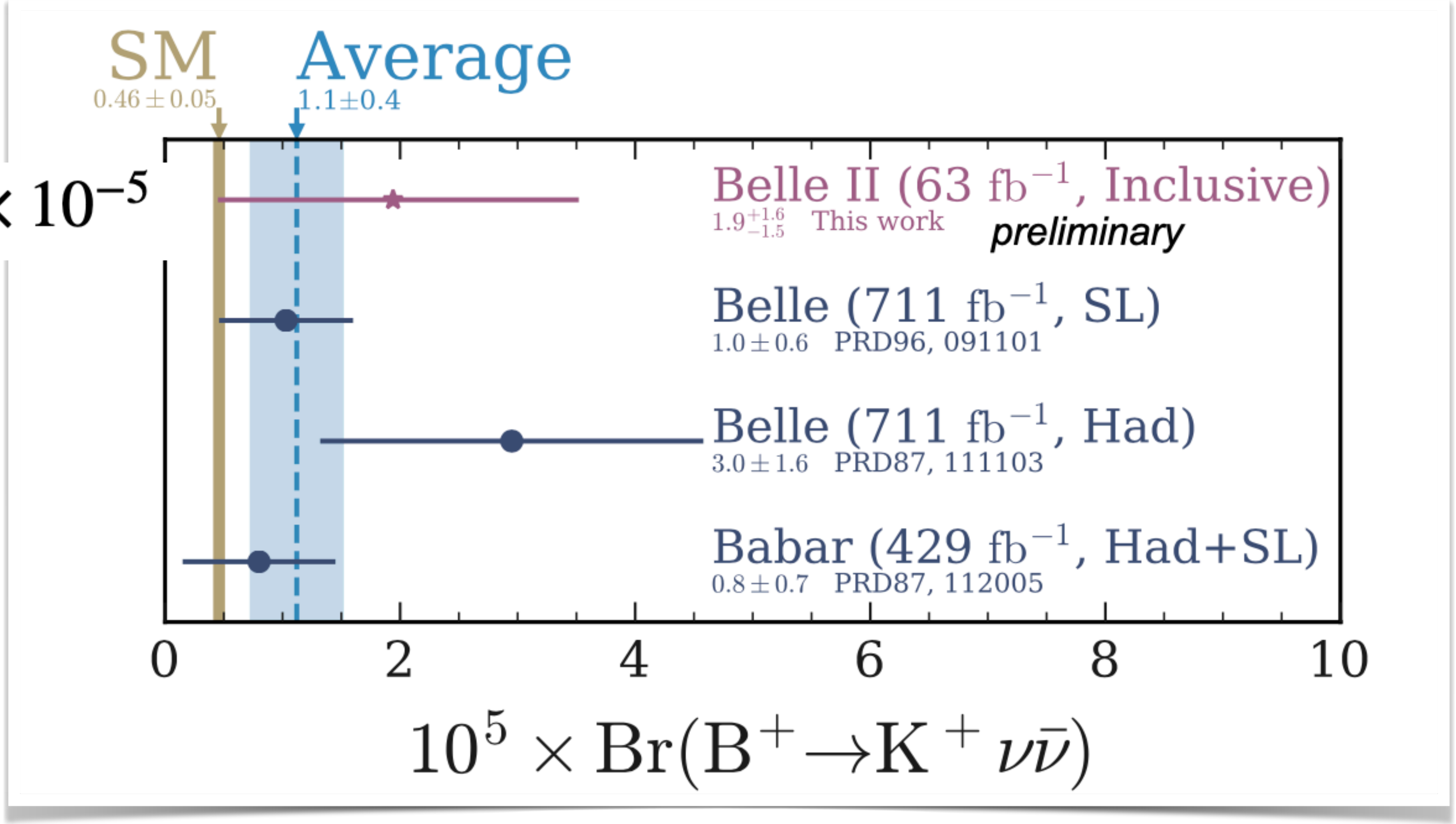
$$\mathscr{B}(B^\pm \to K^\pm \nu\bar{\nu}) < (4.1 \pm 0.5) \times 10^{-5} \ @ \ 90\,\%\,\mathrm{CL}$$

- Comparing theory and experiments:

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

  - When converted to the same luminosity, **our measurement is better*) than semi-leptonic tagging by 10-20%**
  - … **and than hadronic tagging by a factor 3.5!**

*) assuming the total uncertainty on the branching-fraction scales with $1/\sqrt{L}$



- Room for **improvement** in K^+ channel, application of inclusive method to **other channels** in progress

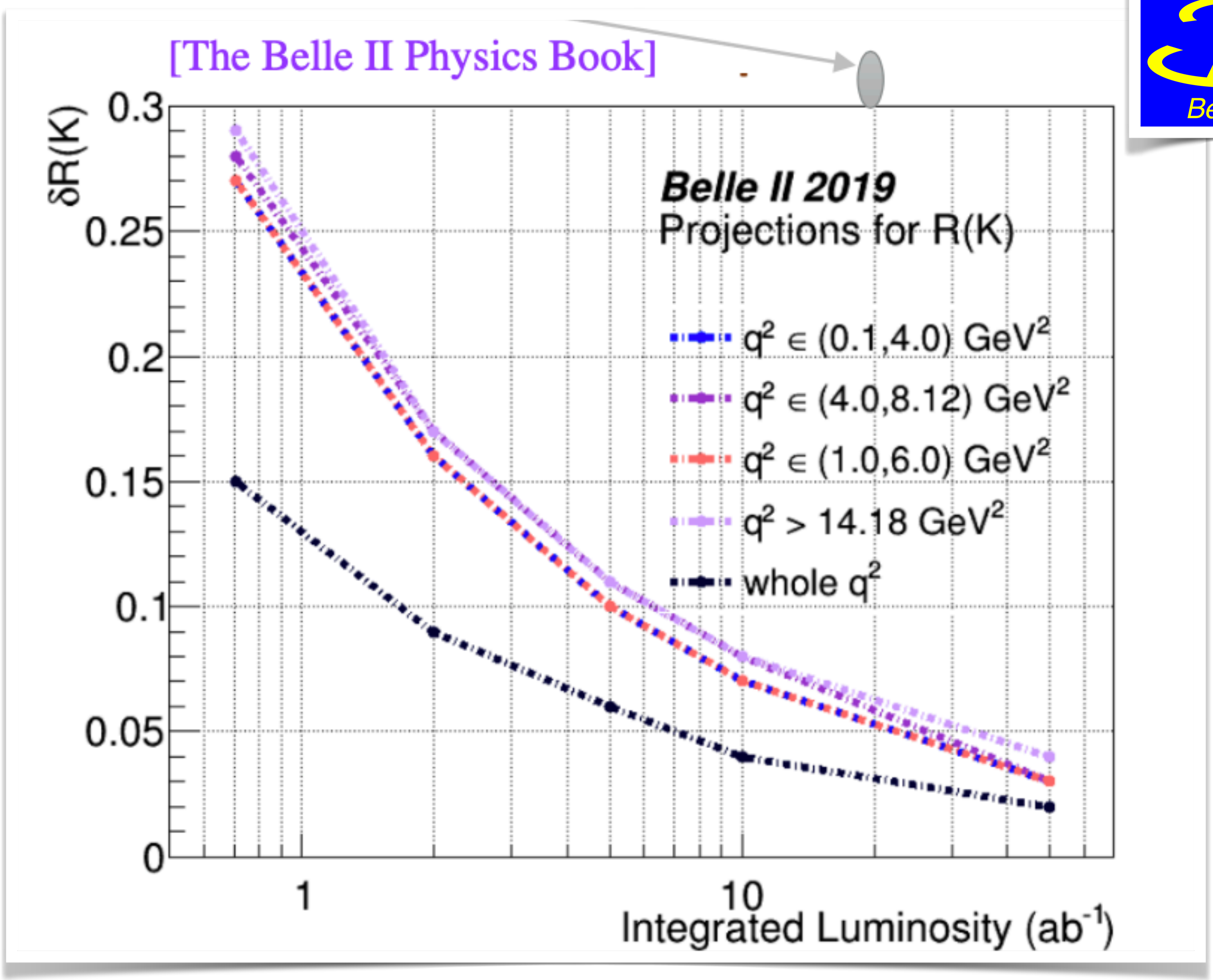
Conclusions

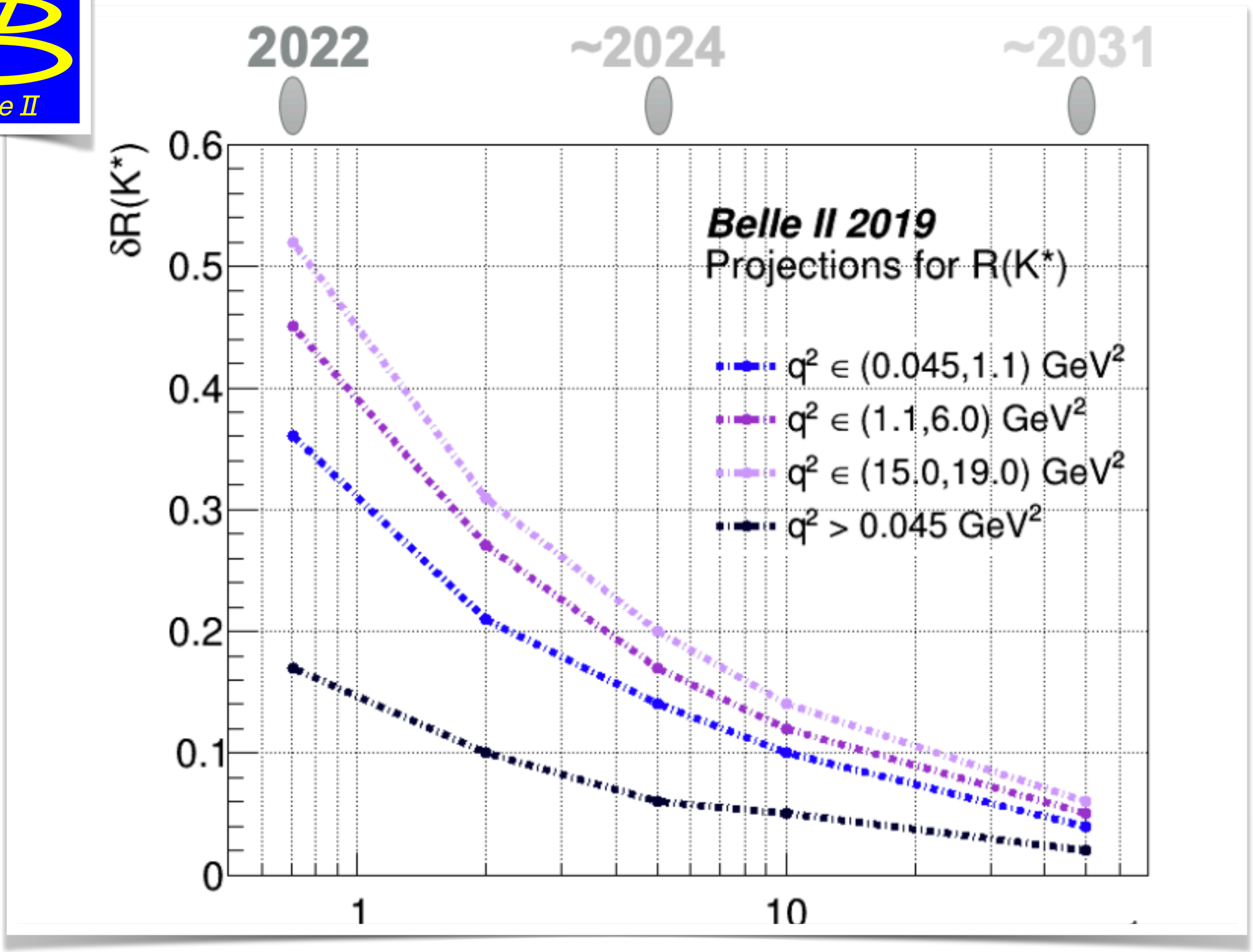
- **Belle** is still producing interesting results, moreover the accumulated knowledge on MC modelling, analysis techniques, etc. will be beneficial for future measurements by e.g. Belle II or LHCb
- SuperKEKB has set a new world record in instantaneous luminosity of **3.1×10^{34} cm^{-2} s^{-1}** and is entering the regime of a "**Super B factory**"
  - plan to record **50 ab^{-1}**, 30x Belle dataset, by **2031**
- As proven by performed measurements in agreement with world averages, **Belle II** detector is performing very well
- In the SL and EWP sector:
  - **complementarity** with LHCb
  - preliminary results on channels of interest and competitive measurements based on **new analysis technique**
    - **$B^+ \to K^+ \upsilon\bar{\upsilon}$ inclusive measurement** in the same ballpark wrt Belle and BaBar ones with **~1/10 Belle statistics**
- Belle II is starting playing a role in understanding the **flavour physics puzzle**.

Extra slides

$B \to K^{(*)}ll$: Belle II perspectives

The Belle II Physics Book, PETP 2019, 123C01 (2019)





- LHCb with full luminosity (~2035, 300fb^{-1}) is expected to have better precision in the low q^2 wrt to full Belle II data sample,
- In the high q^2 Belle II precision at **few %** level

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%	–
$Br(\tau \to e\gamma)$	$<120\times10^{-9}$	–	$<40\times10^{-9}$	$<12\times10^{-9}$	–	$<5\times10^{-9}$	–
$Br(\tau \to \mu\mu\mu)$	$<21\times10^{-9}$	$<46\times10^{-9}$	$<3\times10^{-9}$	$<3\times10^{-9}$	$<16\times10^{-9}$	$<0.3\times10^{-9}$	$<5\times10^{-9}$

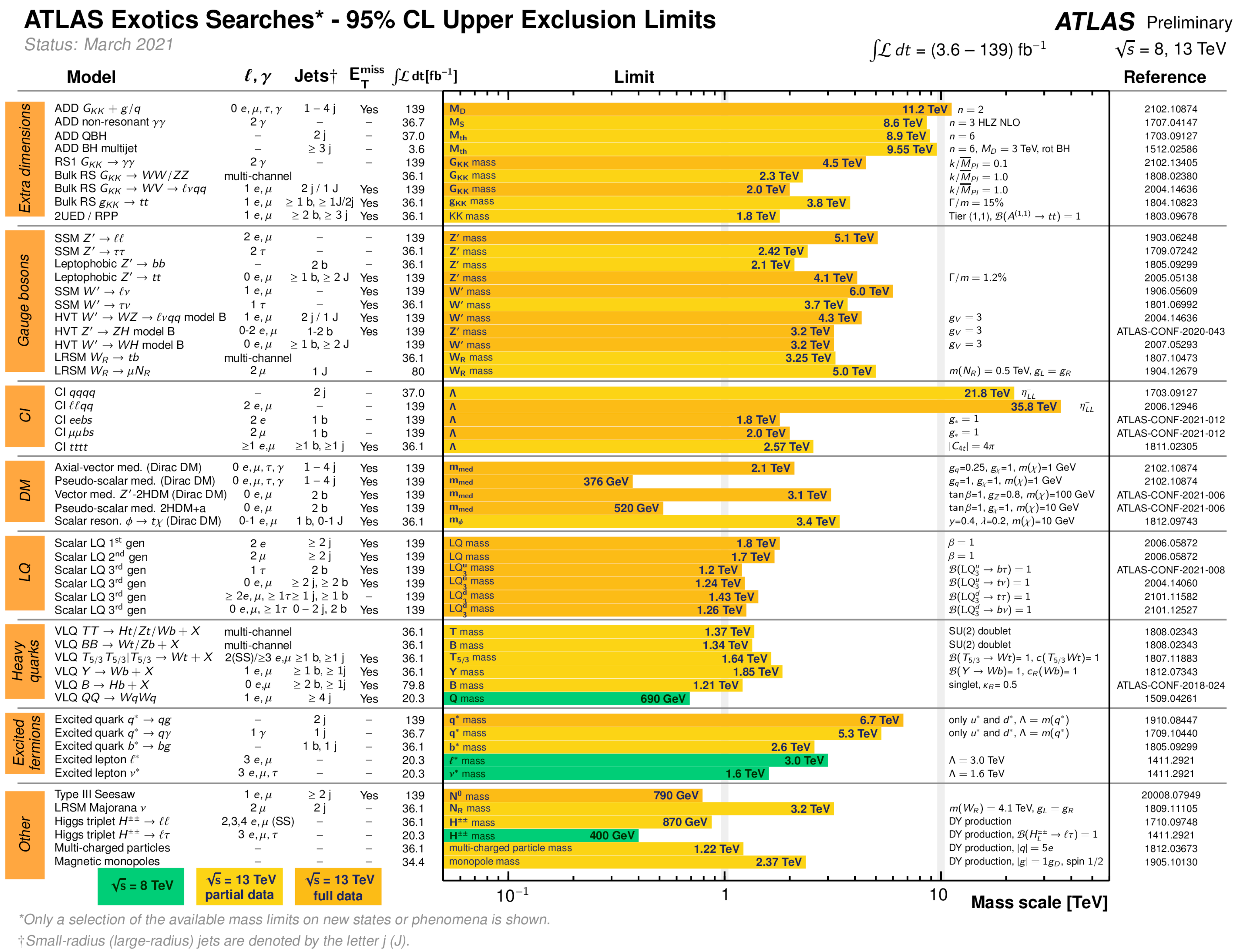
Results on other D & τ modes expected

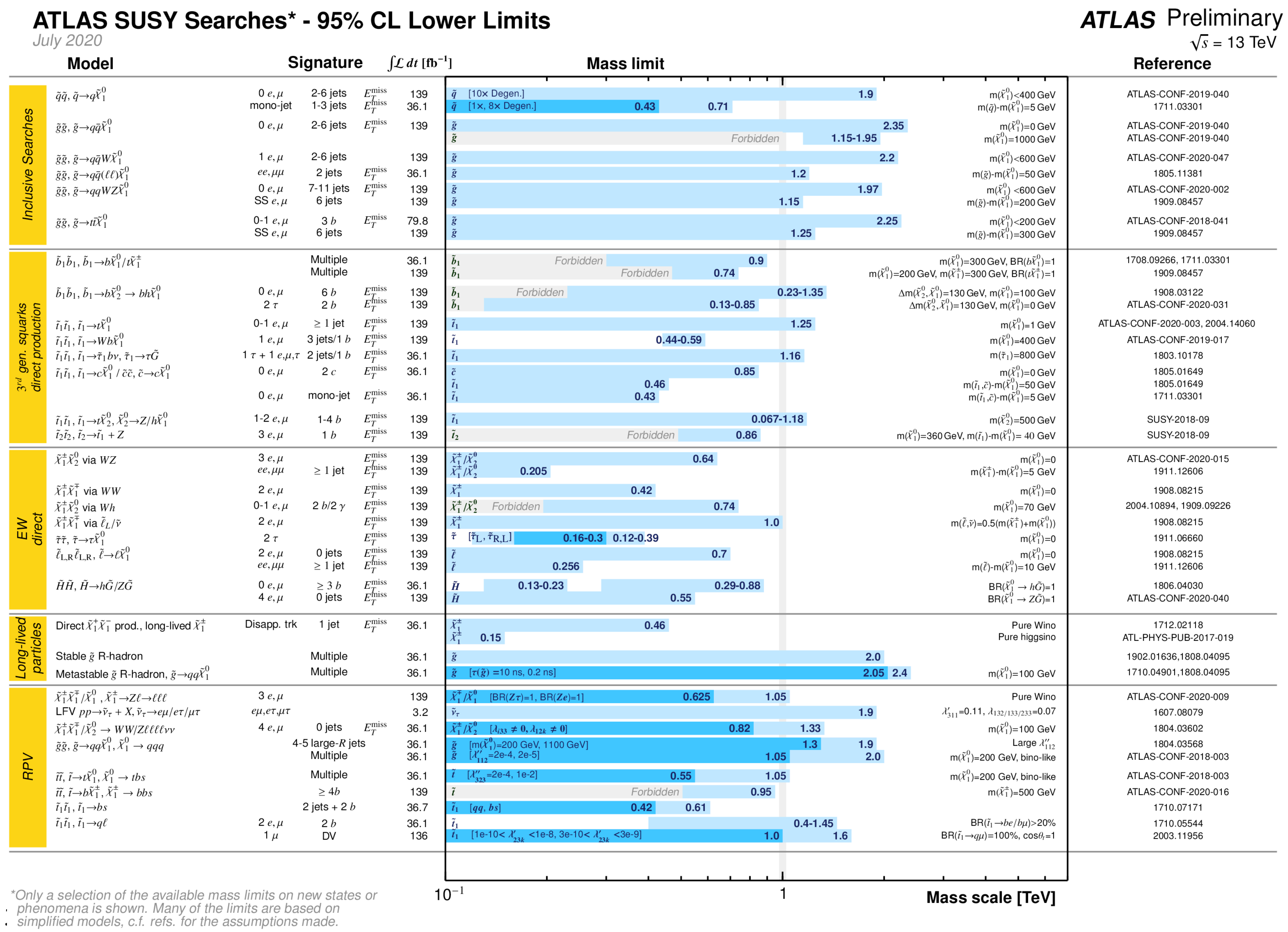
○ *Possible in similar channels, lower precision*
– *Not competitive.*

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





E_{ECL} clean up in $B \to D^* \ell \nu$ Belle II analysis

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

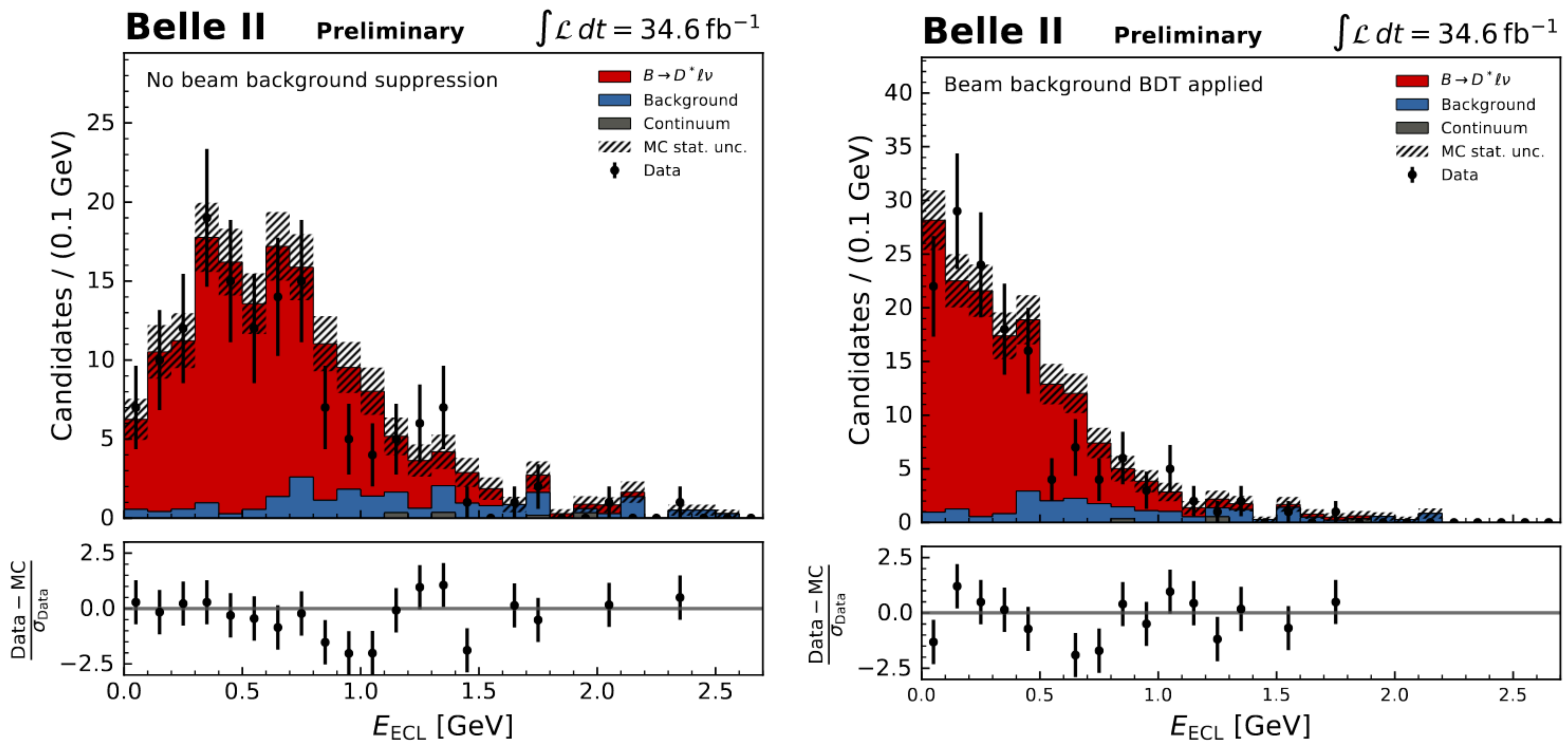


FIG. 3. Two versions of E_{ECL} are shown: (left) is the version applying detector region dependent energy selection criteria, (right) shows the impact of using a BDT to identify neutral energy depositions from beam background processes. It is based on shower shape variables and the detector region of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