Belle II Opportunities in Rare *B*-decays with Invisible Particles

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on behalf of the Belle II collaboration

Flavor at the Crossroads
MITP, Germany
25.04.2022

Bundesministerium für Bildung und Forschung

Belle II

KIT Karlsruher Institut für Technologie

ETP Institut für Experimentelle Teilchenphysik

Outline

SuperKEKB

Belle II Detector + Performance

Current Luminosity + Prospects

General remarks for rare B-decays with invisible particles

Channels with missing energy

$B^+ \to K^+ \nu \bar{\nu}$

$B \to K \tau \tau$

$B^+ \to K^+ \tau^+ \mu^-$

$B^+ \to K^+ a(\to \text{invisible})$

SM | *BSM*

Fully reconstructed channels

$\mathcal{B}(B \to K^{(*)} l^+ l^-)$
$R(K^{(*)})$

$B^+ \to K^+ S(\to x^+ x^-)$

SM | *BSM*

Invisible particles: neutrinos/other undetectable particles

$b \to sll$ transitions

Other Belle II talks @ this workshop

Latest results and prospects: Talk by Gagan last Tuesday

Prospects of |Vub|: Talk by Tommy this Thursday

SuperKEKB

Energy asymmetric e^+e^--collider @ $\sqrt{s} = 10.58$ GeV

- $\sqrt{s} = 10.58$ GeV $\leftrightarrow \Upsilon(4S)$ resonance
- $\Upsilon(4S) \to B\bar{B}$ + nothing else with $\mathscr{B} > 96\,\%$

$\rightarrow$ clean B sample **(on-resonance)**

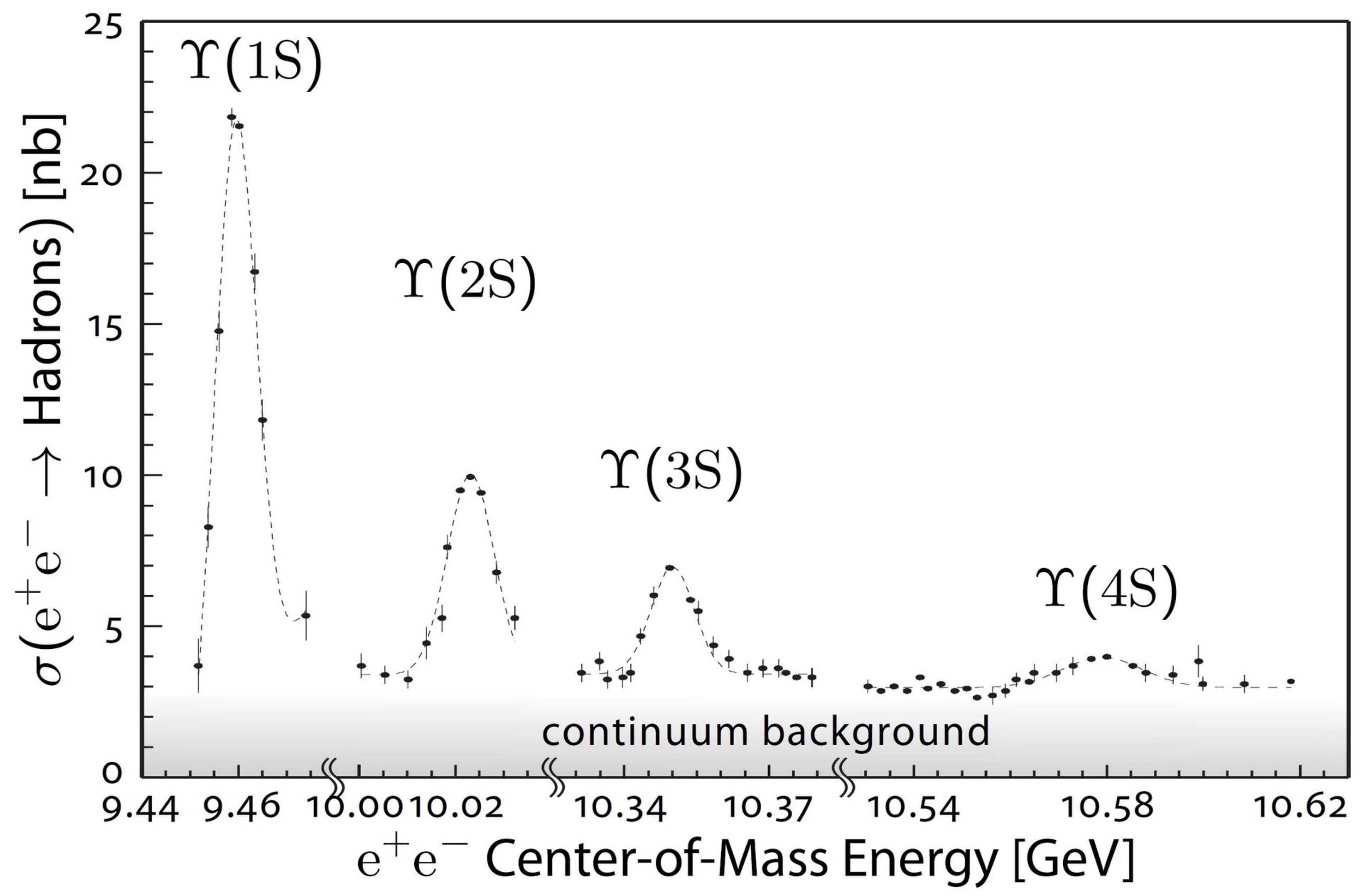
- @60 MeV below $\Upsilon(4S)$ resonance:

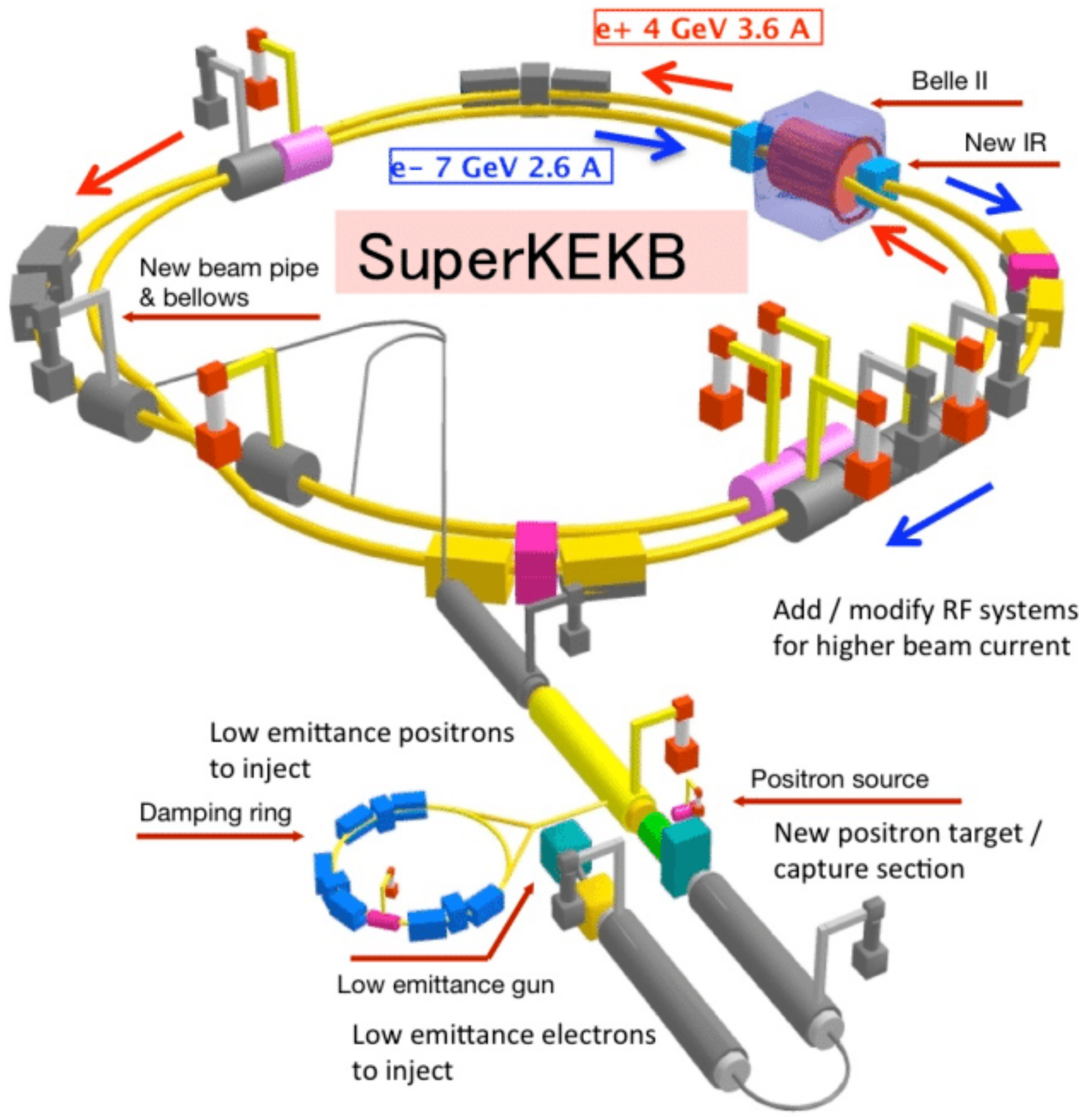
$\rightarrow$ control sample to constrain continuum backgrounds

$e^+e^- \to q\bar{q}$, where $q = (u, d, s, c)$ **(off-resonance)**

With **nano-beam scheme** and **upgraded rings SuperKEKB** aims to reach **30 × higher $\mathscr{L}_{inst}$** than **KEKB** at cost of **$\mathcal{O}(10)$ ×** higher backgrounds

- x 1.5 currents
- x 1/20 vertical beam size





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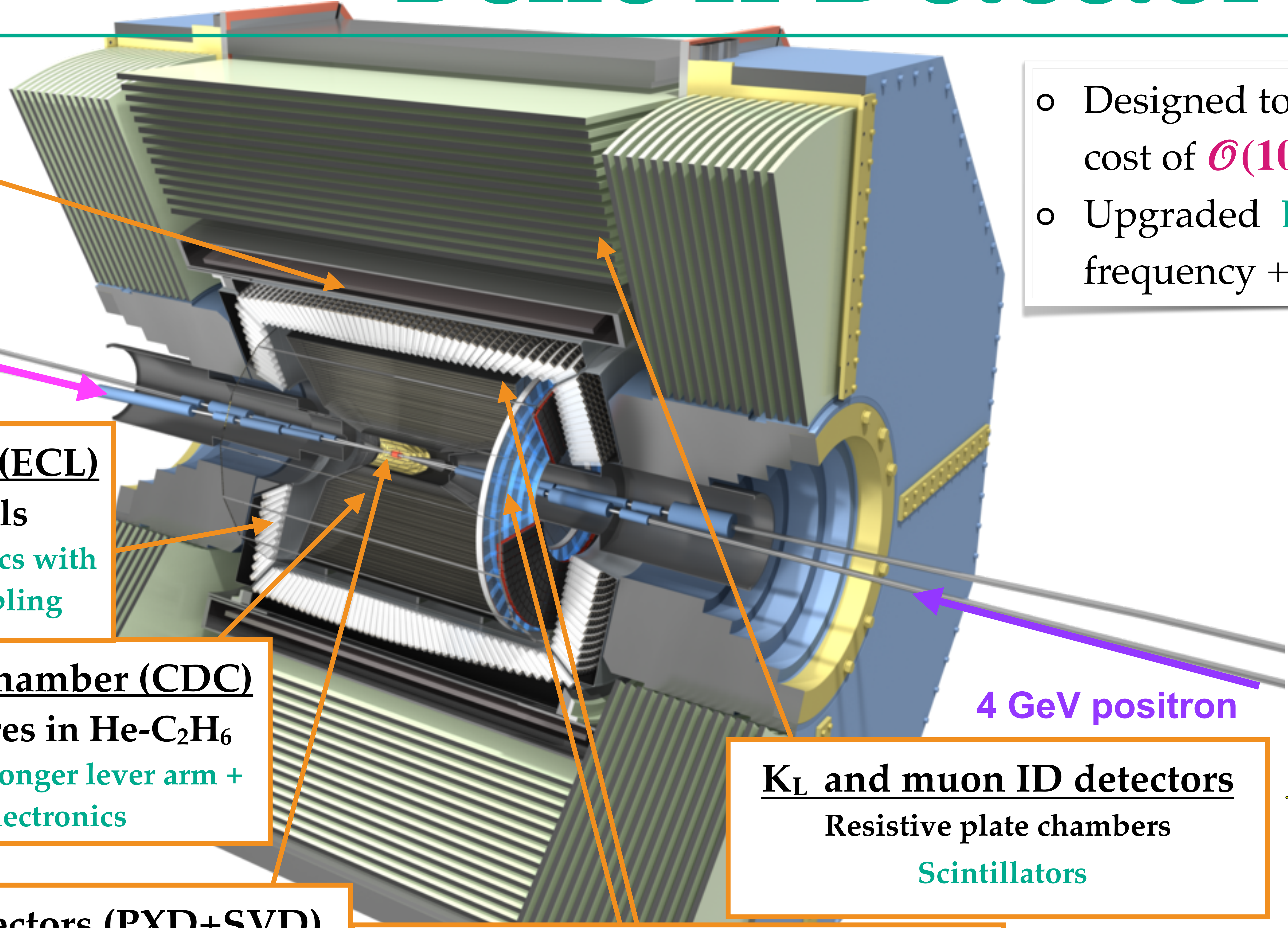
Belle II Detector



Magnet
1.5 Ts

EM Calorimeter (ECL)
CsI(TI) crystals
Updated electronics with waveform sampling

Central Drift Chamber (CDC)
14336 sense wires in He-C_2H_6
Smaller cells + longer lever arm + faster electronics

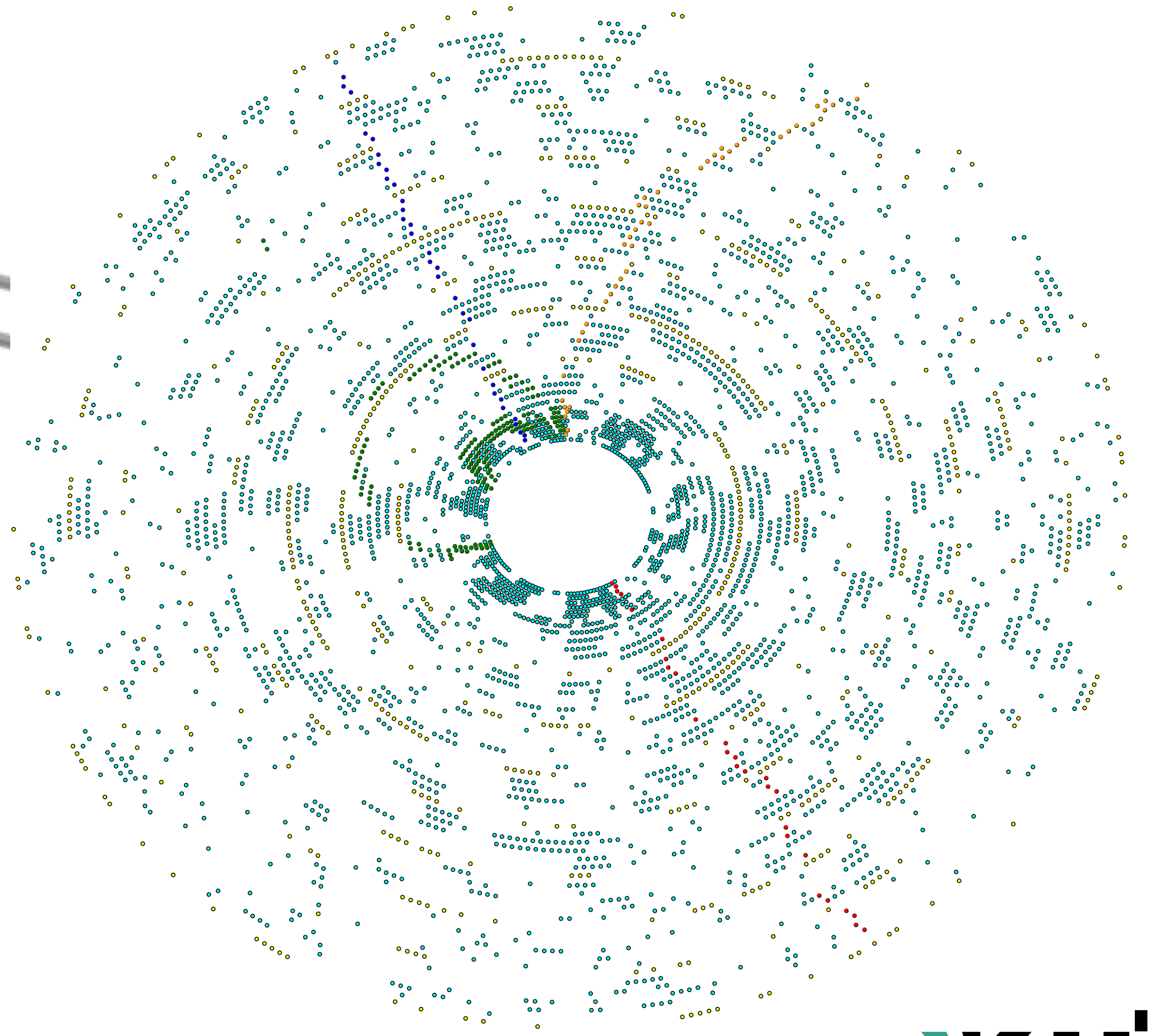
Vertex detectors (PXD+SVD)
2 pixel layers (DEPFET)
4 layers of silicon microstrip layers

Charged PID detectors
Time of propagation counter (TOP) (barrel)
Aerogel Cerenkov detector (ARICH) (forward)

K_L and muon ID detectors
Resistive plate chambers
Scintillators

- Designed to give **similar or better performance** at cost of $\mathcal{O}(10)\times$ higher backgrounds
- Upgraded **DAQ and trigger** (higher readout frequency + low multiplicity channels)

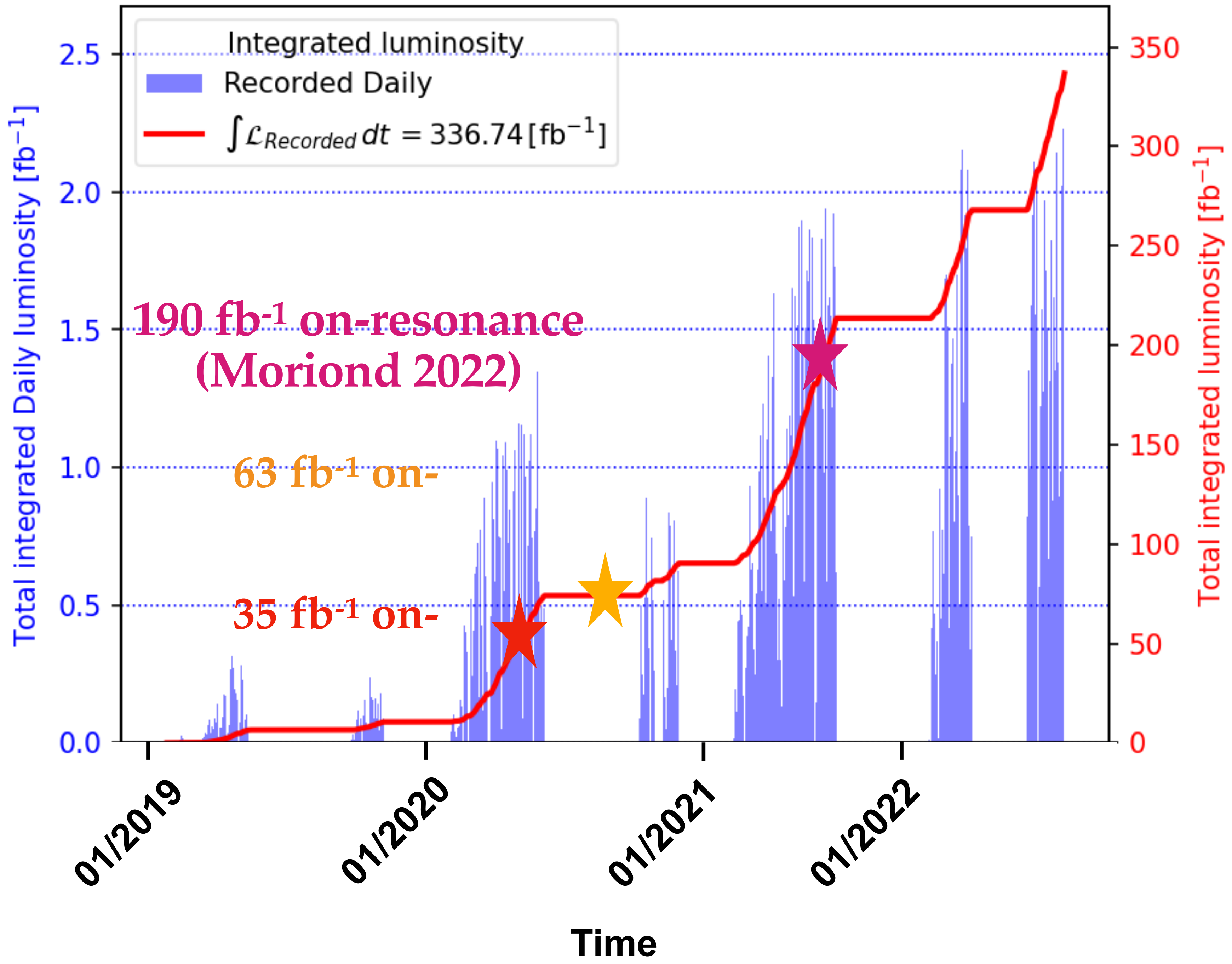
Simulated $e^+e^- \to \mu^+\mu^-$ event with high luminosity backgrounds (CDC view)

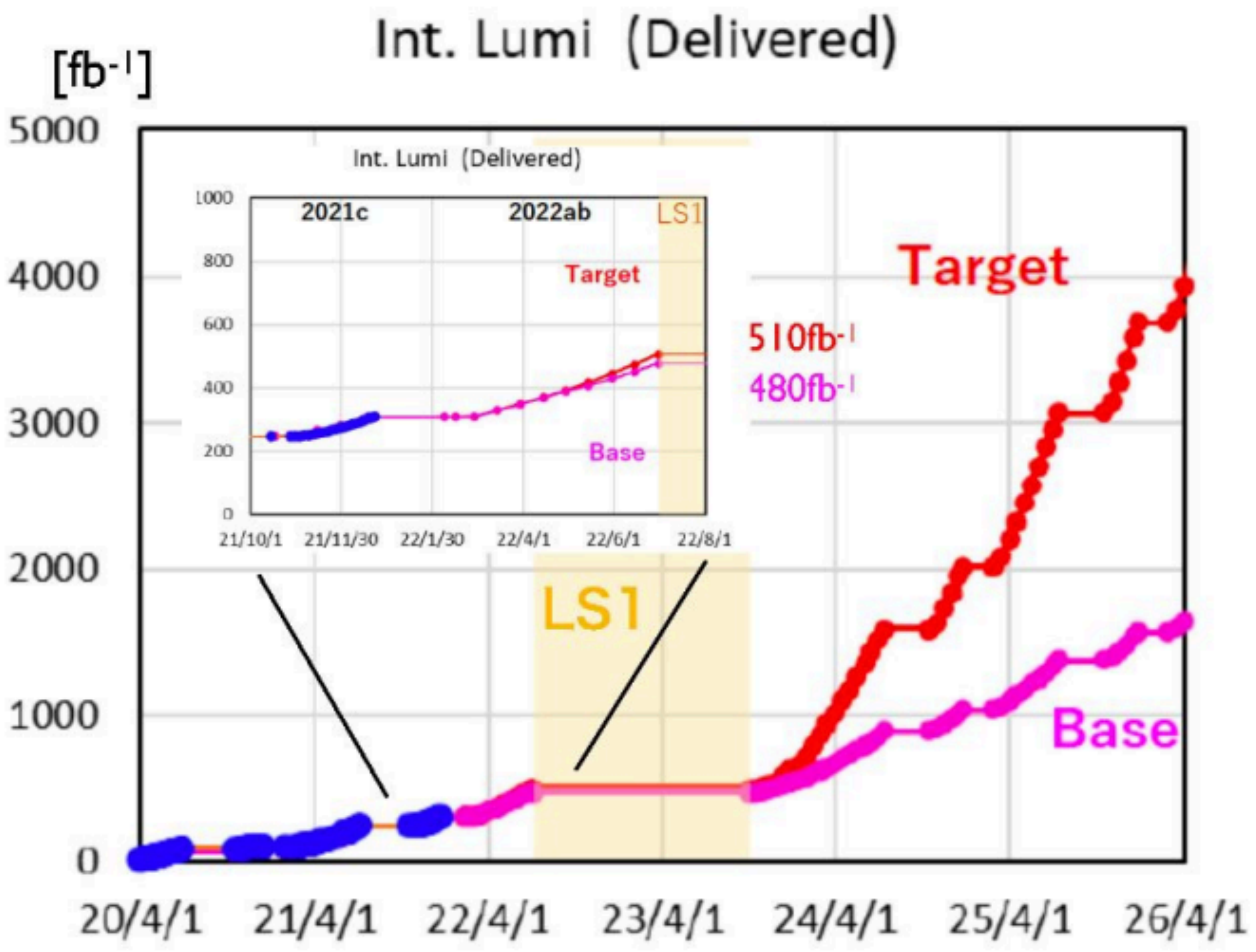


Luminosity

Status

- Collected ~ **330 fb^{-1}** since April 2019 (~1/2 Belle)
- Slower luminosity accumulation, but with ~ 90 % data-taking efficiency
- **Record-breaking $\mathscr{L}_{inst}$ 3.8 × 10^{34} cm^{-2} s^{-1}**
- **Highest daily integrated luminosity: 2.2 fb^{-1}**





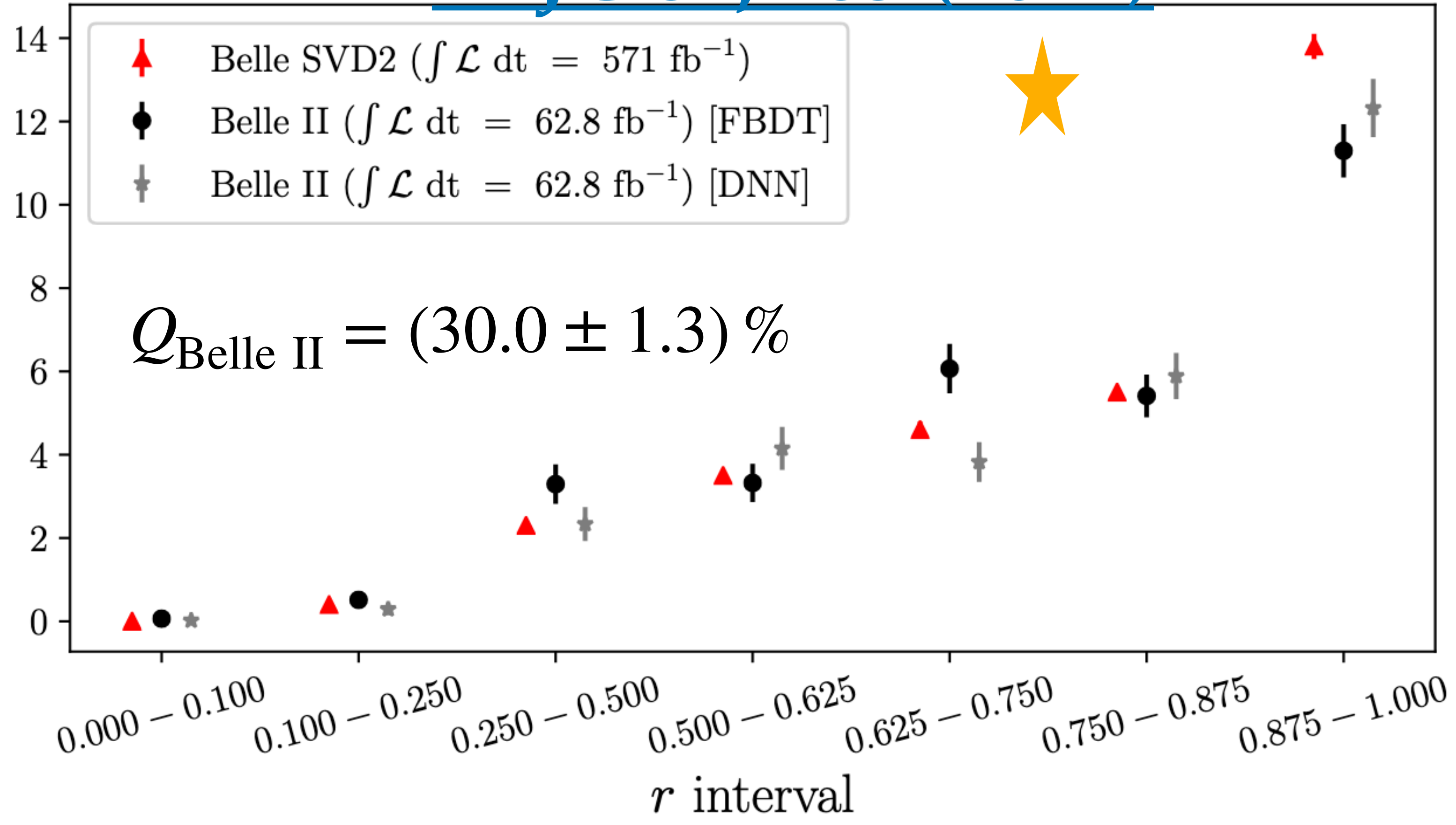
Prospects

- **Short-term plan**: long shutdown (LS1) in 2022
  - full PXD installation → important to maintain good vertex resolution at high luminosity
  - Replacement of 50% of barrel TOP PMTs to maintain good particle identification
- **Long-term plan**: LS2, final goal: $\mathscr{L}_{int}$ = 50 ab^{-1}

Performance

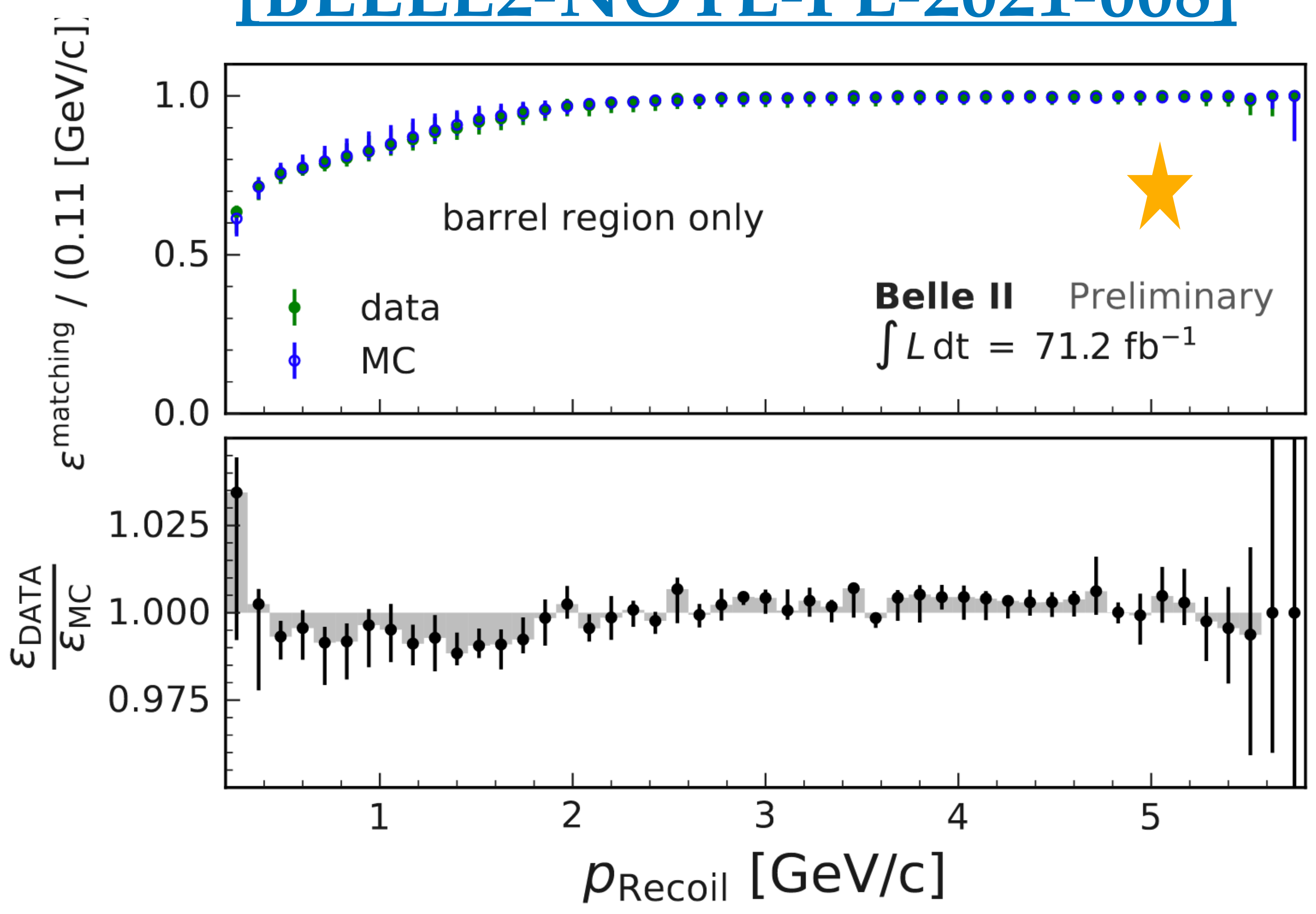
Good flavour tagger performance

[EPJC 82, 283 (2022)](#)



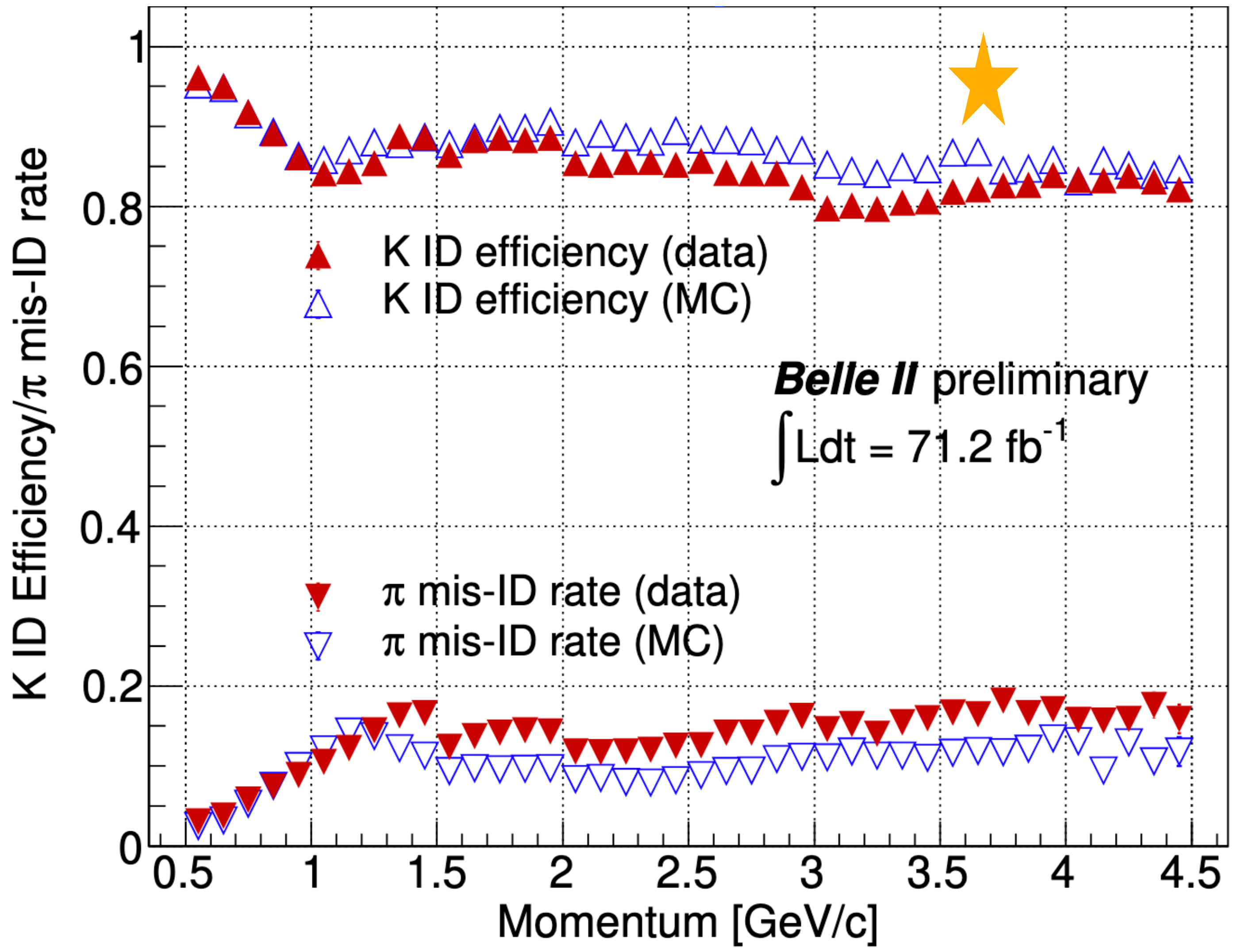
High photon matching efficiency

[BELLE2-NOTE-PL-2021-008]

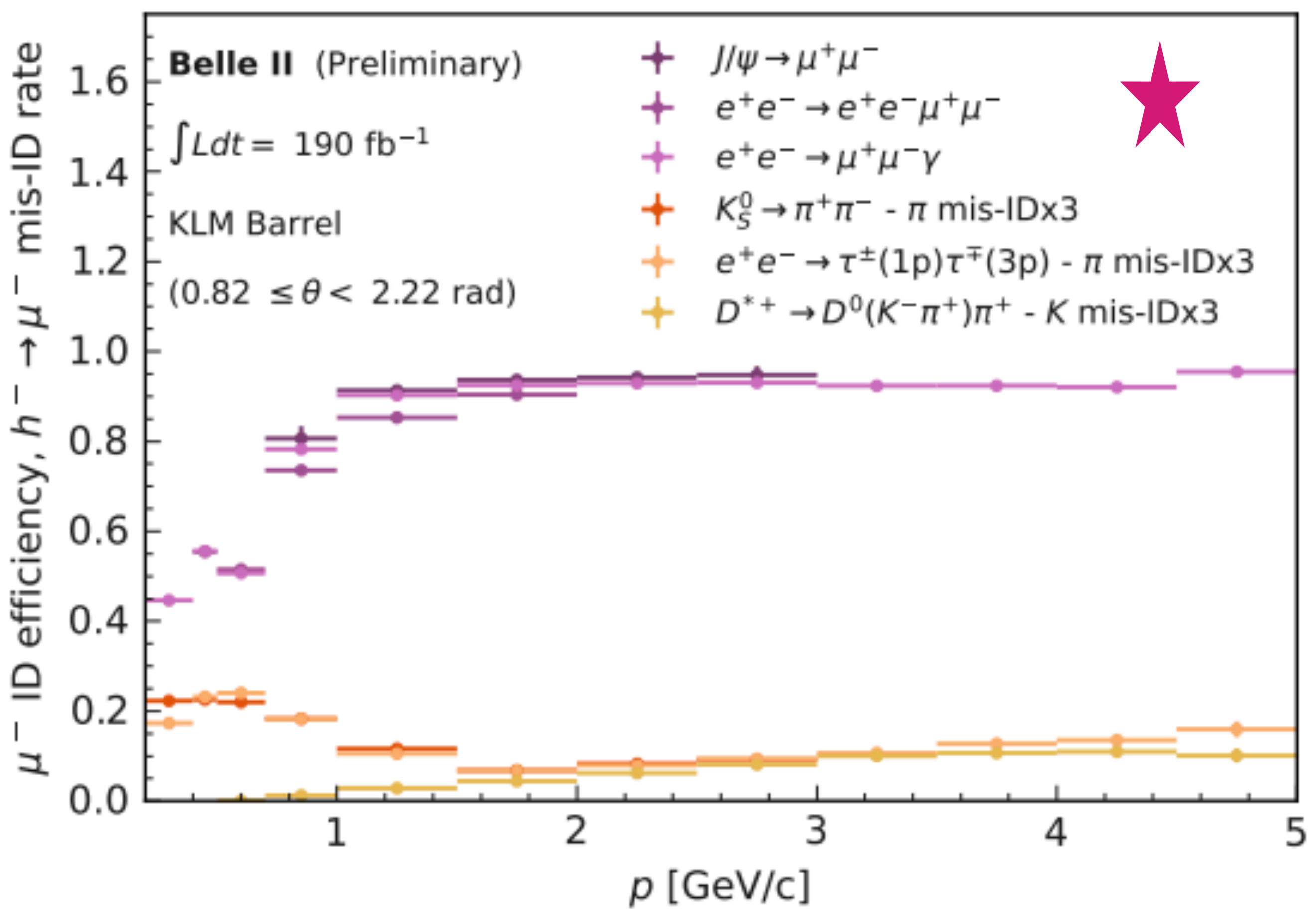


Good particle identification

[BELLE2-NOTE-PL-2020-024]

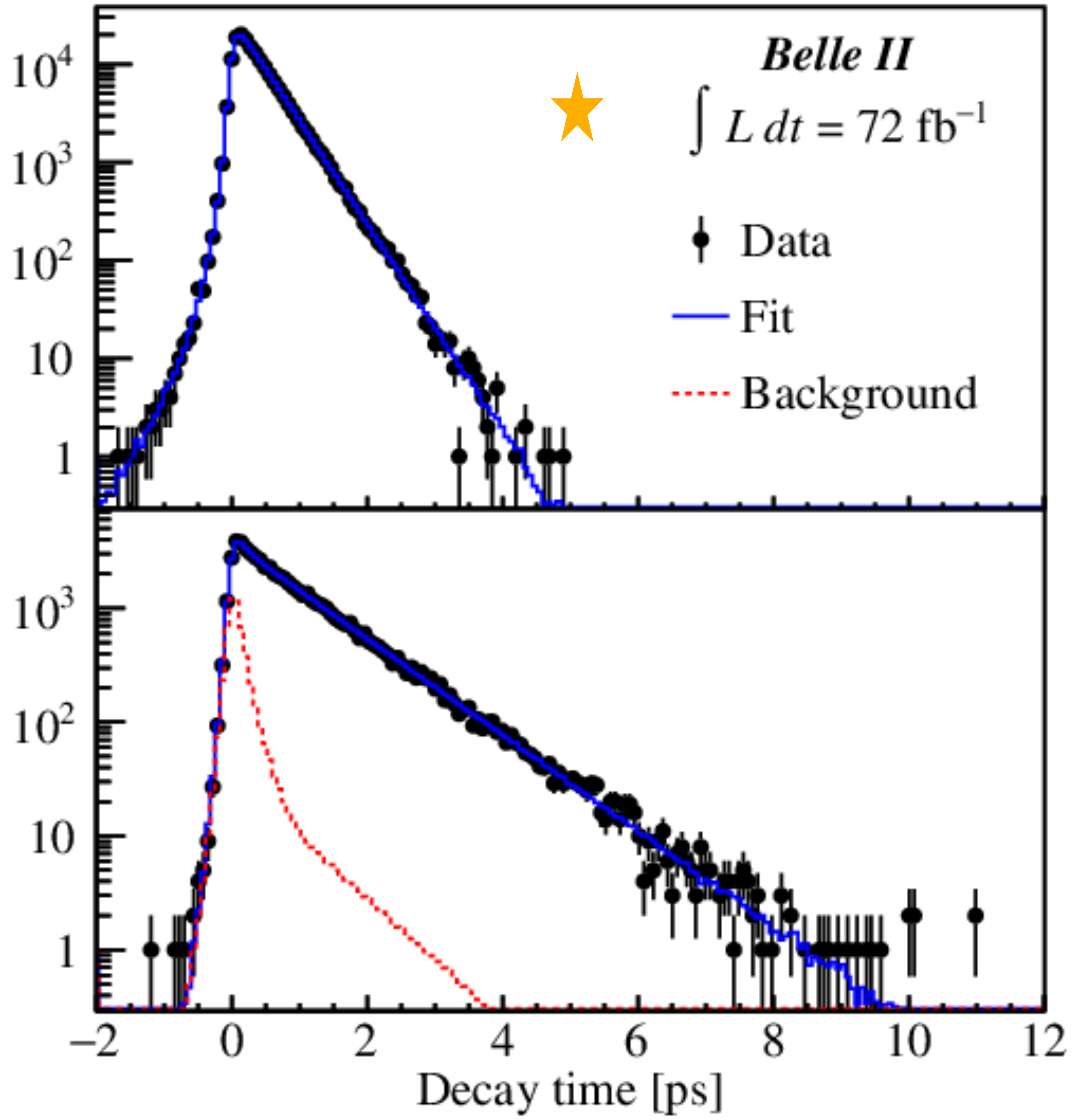


[BELLE2-NOTE-PL-2022-003]



Most precise measurement of D lifetimes

[PRL 127, 211801 (2021)](#)



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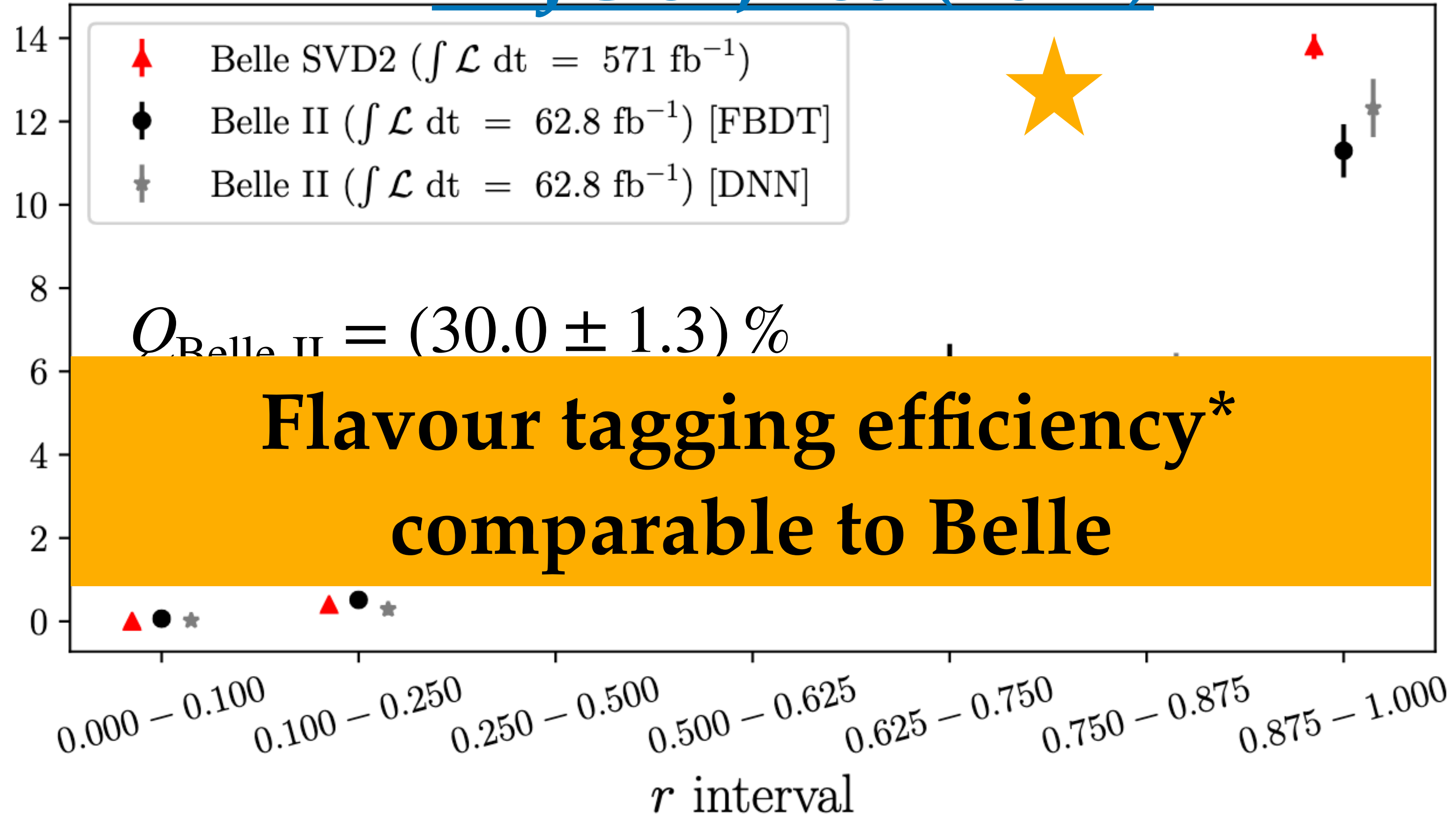
Performance

Good flavour tagger performance

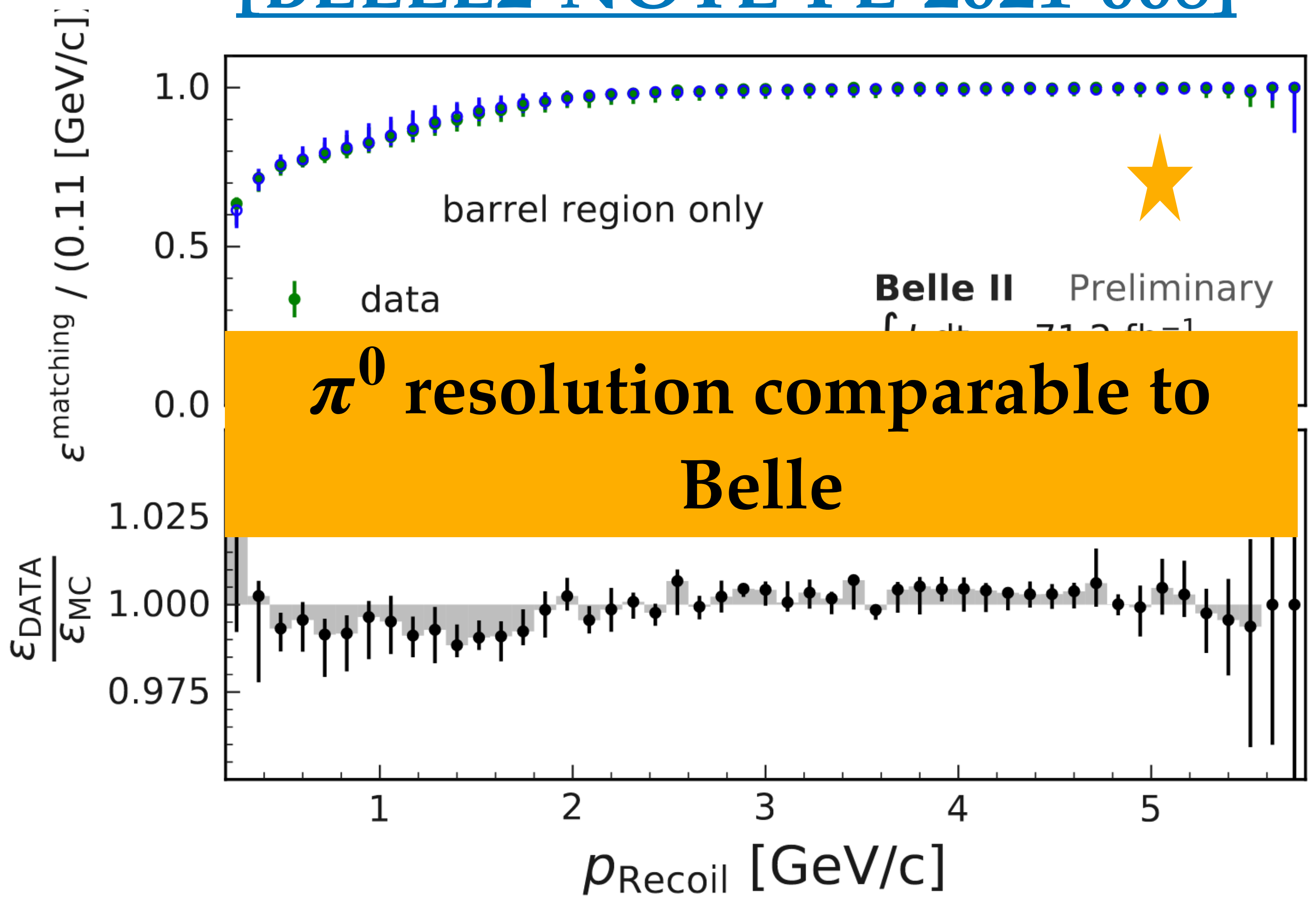
EPJC 82, 283 (2022)



Flavour tagging efficiency* comparable to Belle

High photon matching efficiency

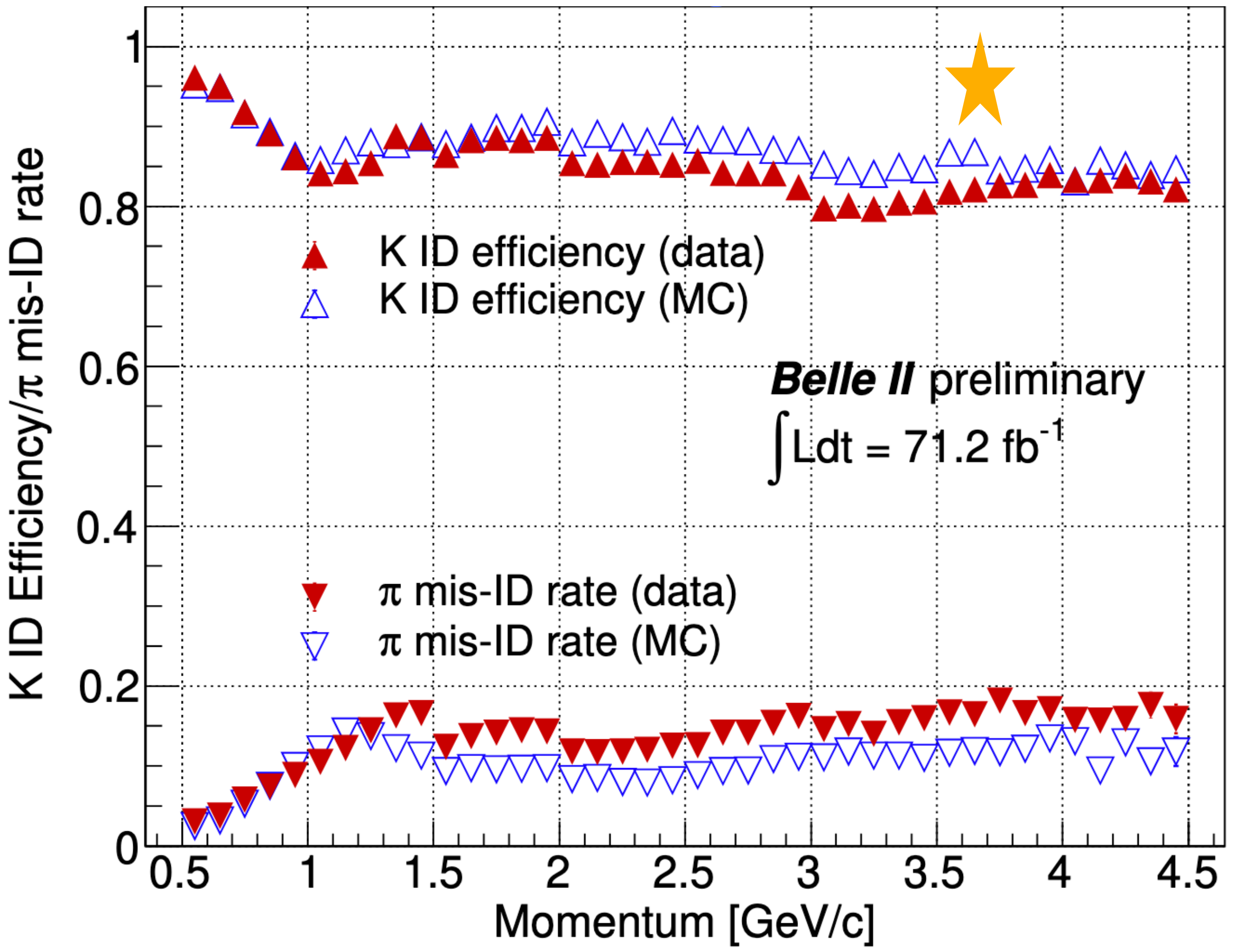
[BELLE2-NOTE-PL-2021-008]



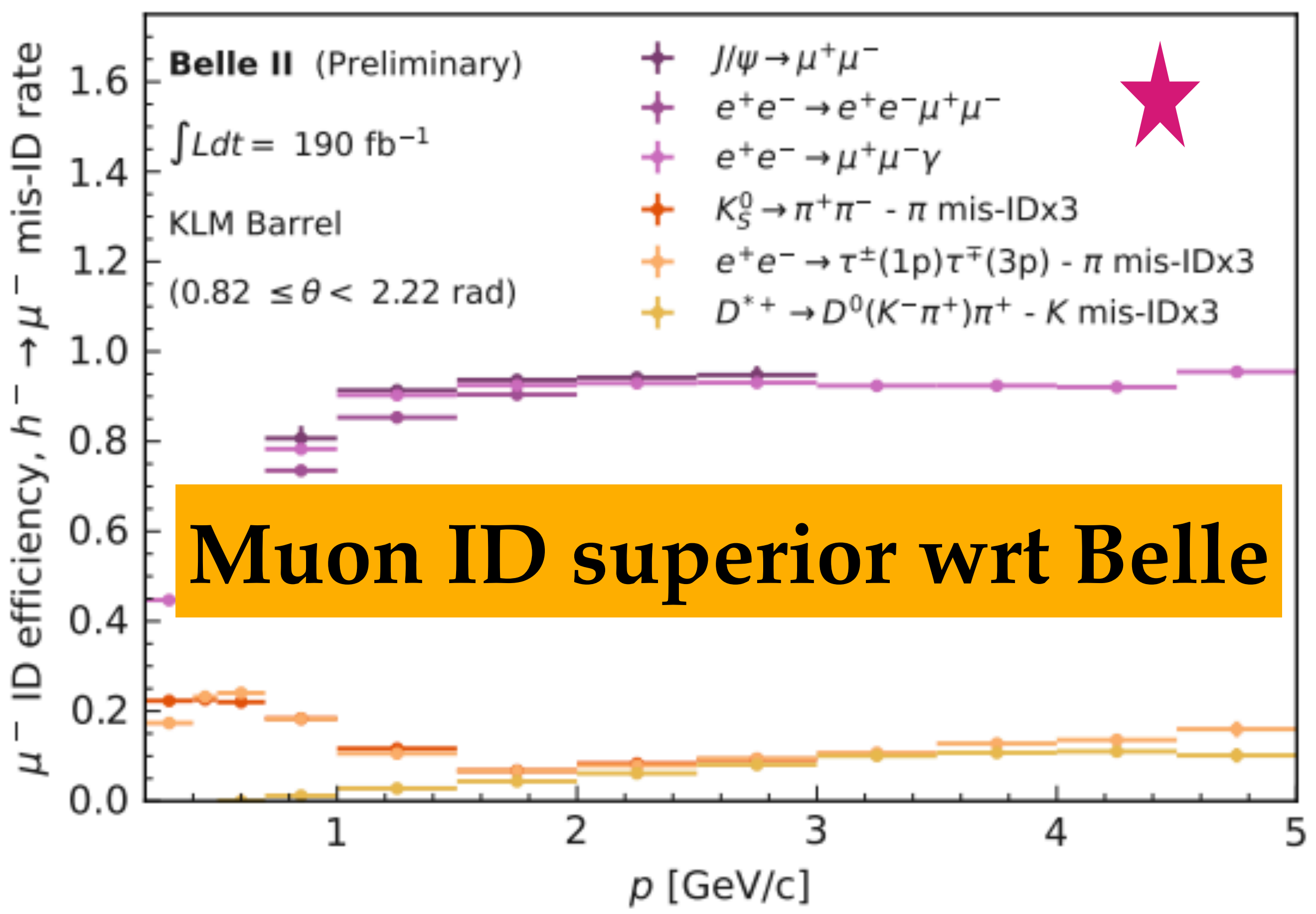
π^0 resolution comparable to Belle

Good particle identification

[BELLE2-NOTE-PL-2020-024]



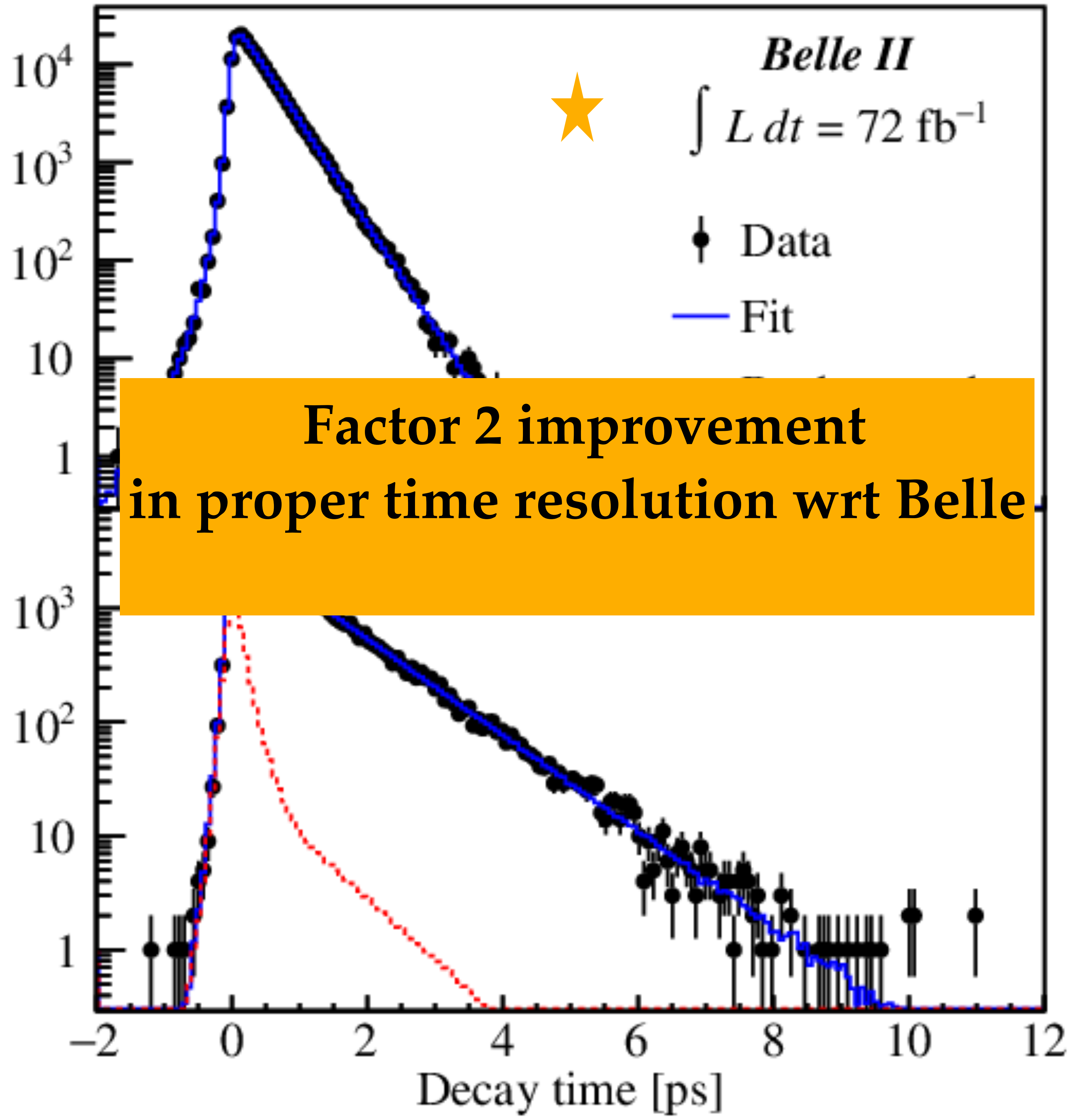
[BELLE2-NOTE-PL-2022-003]



Muon ID superior wrt Belle

Most precise measurement of D lifetimes

PRL 127, 211801 (2021)

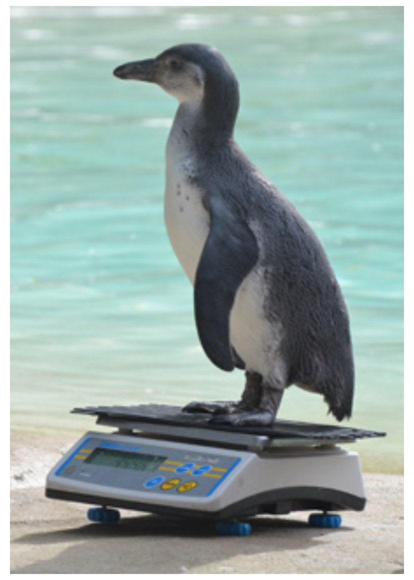


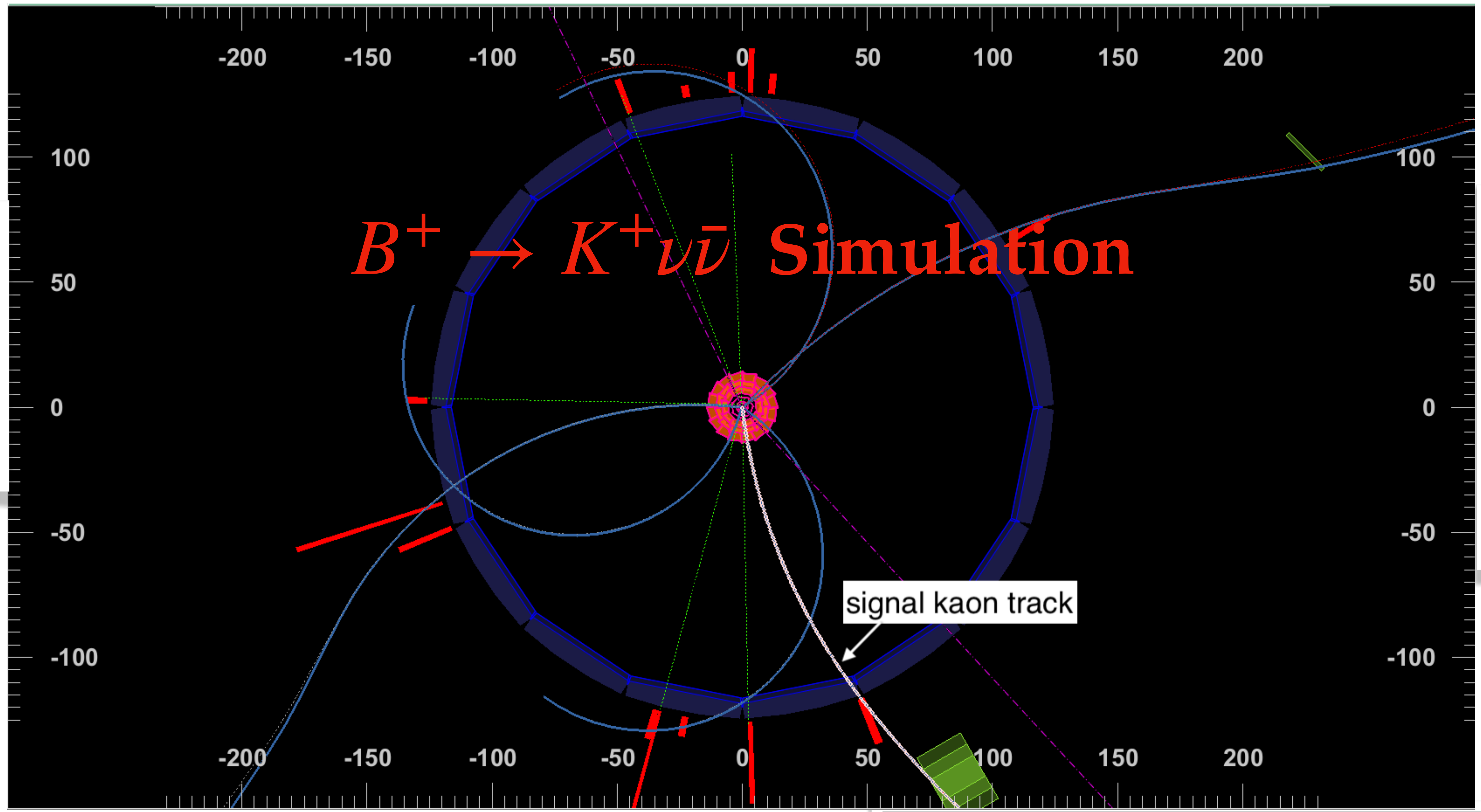
Factor 2 improvement in proper time resolution wrt Belle

*tagging power indicating the statistical precision of the sample; $\epsilon_{tag}(1-2\omega)^2$

Key Ingredients

Rare B-decay with invisible particle(s) has usually significant missing energy





Belle II Detector
- Hermetic
- Good Performance

Belle II Event
- Cleaner Environment
- Known Initial State Kinematics

Challenges of rare B-decays
- B-reconstruction: vertexing/tracking
- Good MC modelling (include rare backgrounds)

+

Challenges of channels with invisible particles
- Understanding of the neutral objects (π^0, K_L, K_s, n, γ)
- Reconstruction approach

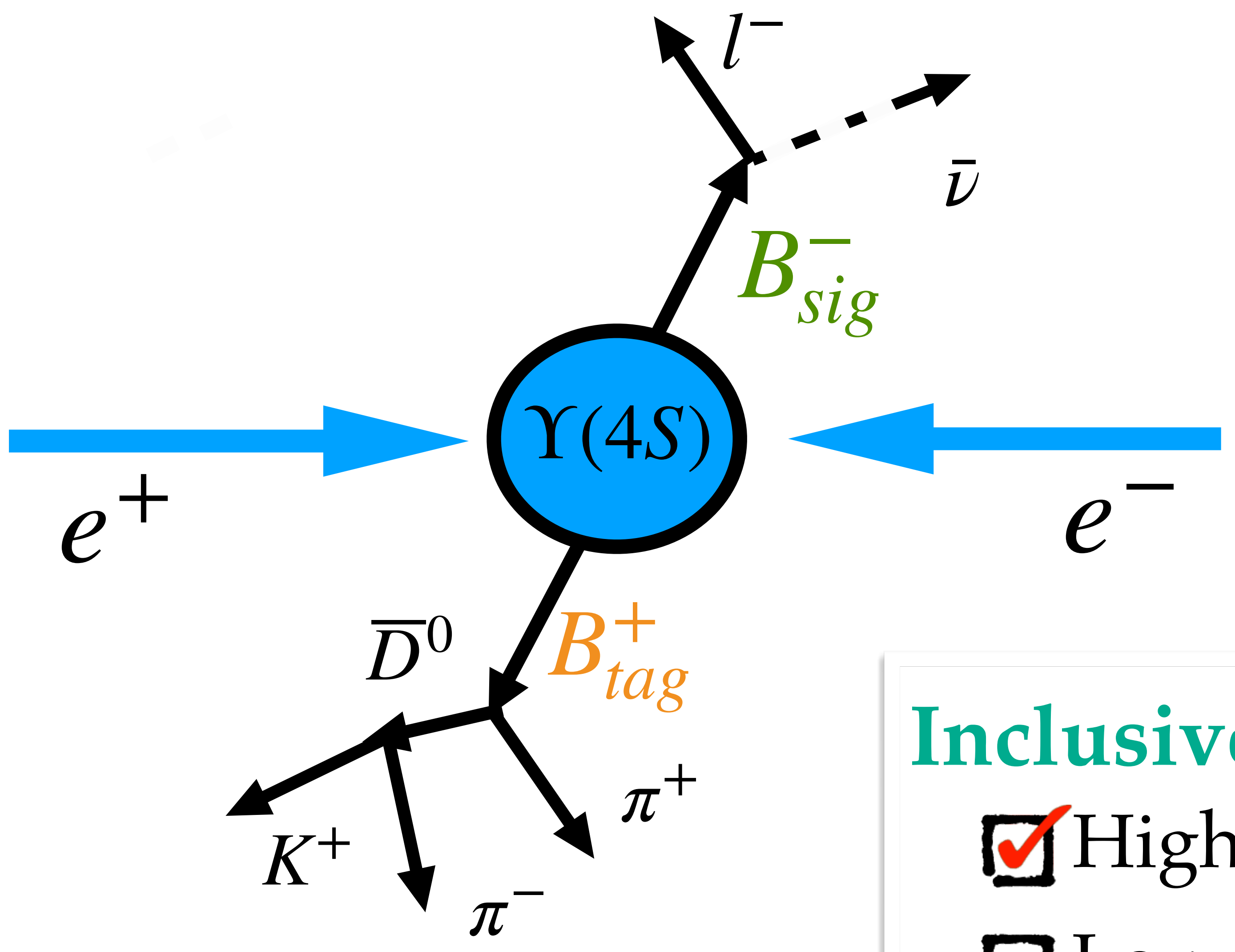
Reconstruction

Tagged Approach:

1. step: B^{+}_{tag} reconstruction in its **semileptonic (SL)** or **hadronic (HAD)** decay chain

2. step: B^{-}_{sig} reconstruction

- Flavour constraint: $B^{+}_{tag} \rightarrow B^{-}_{sig}$
- Kinematically constrained system with hadronic B^{+}_{tag} : $\vec{p}_{\bar{\nu}} + \vec{p}_{l^-} = \vec{p}_{e^+e^-} - \vec{p}_{B^-_{tag}}$



Inclusive Tagging Approach:

1. step: B^{-}_{sig} reconstruction

2. step: Constrain the rest of the event

Tagged Approach:

- ☑ Higher intrinsic background rejection
- ☑ Better resolution → analytical fits
- ☐ Lower signal efficiency (<1%)
- ☐ Systematics (B^{+}_{tag})

Inclusive Tagging Approach:

- ☑ Higher signal efficiency
- ☐ Lower intrinsic background rejection
- ☐ Worse resolution → binned fits

Other Approaches:

- ☐ ‘Semi-inclusive’ tagging
- ☐ Charm tagging

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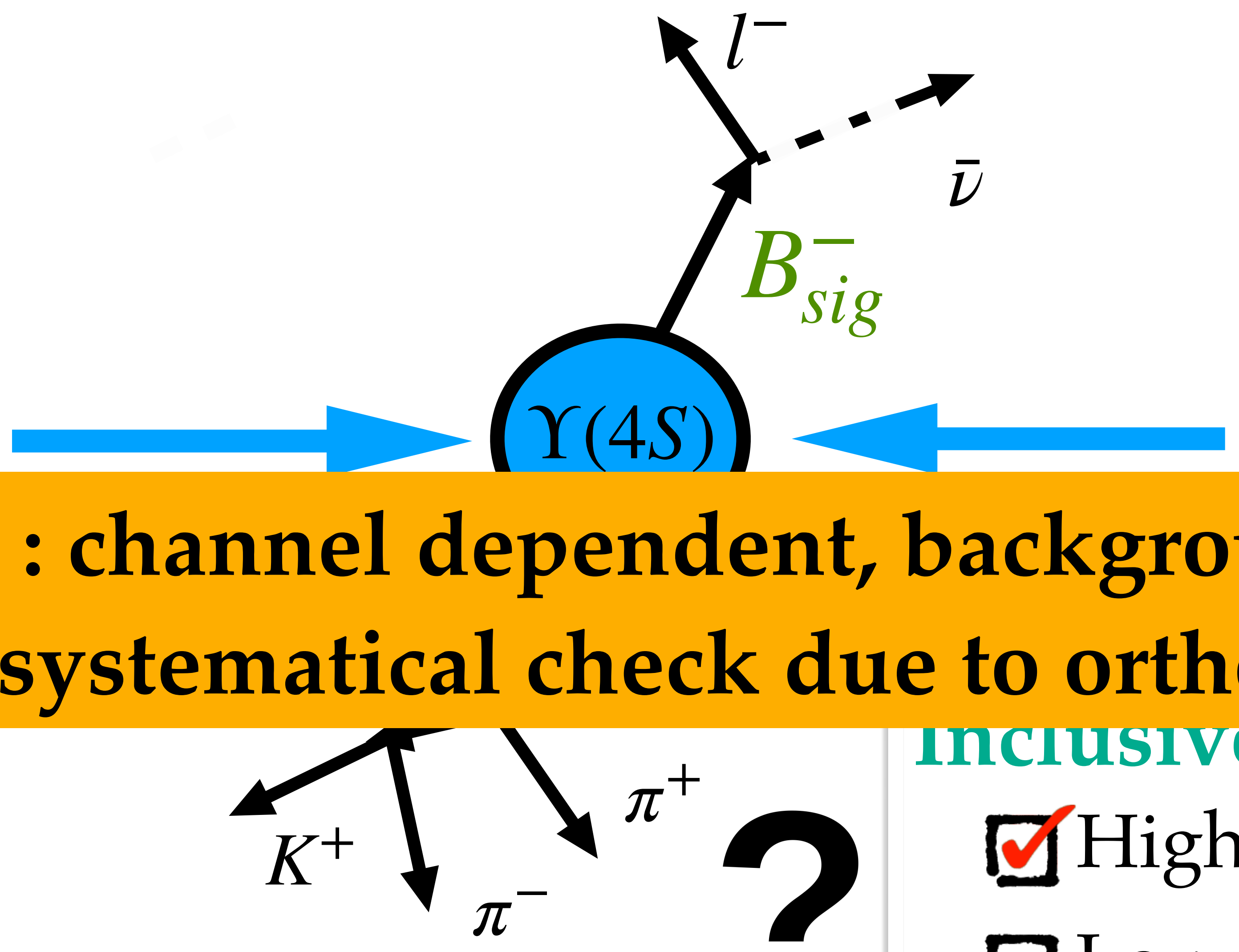
Reconstruction

Tagged Approach:

1. step: B^-_{tag} reconstruction in its **semileptonic (SL)** or **hadronic (HAD)** decay chain

2. step: B^-_{sig} re

- Flavour
- Kinematically constrained system with hadronic B^-_{tag} : $\vec{p}_{\bar{\nu}} + \vec{p}_{l^-} = \vec{p}_{e^+e^-} - \vec{p}_{B^-_{tag}}$



Inclusive Tagging Approach:

1. step: B^-_{sig} reconstruction

2. step: Constrain the rest of the event

Best sensitivity : channel dependent, background dependent

Use of different approaches : systematical check due to orthogonality, combination savvy

Inclusive Tagging Approach:

- [x] Higher signal efficiency
- [ ] Lower intrinsic background rejection
- [ ] Worse resolution → binned fits

?

Rare B-decay with missing energy

Tagged Approach:

- [x] Higher intrinsic background rejection
- [x] Better resolution → analytical fits
- [ ] Lower signal efficiency (<1%)
- [ ] Systematics (B^-_{tag})

?

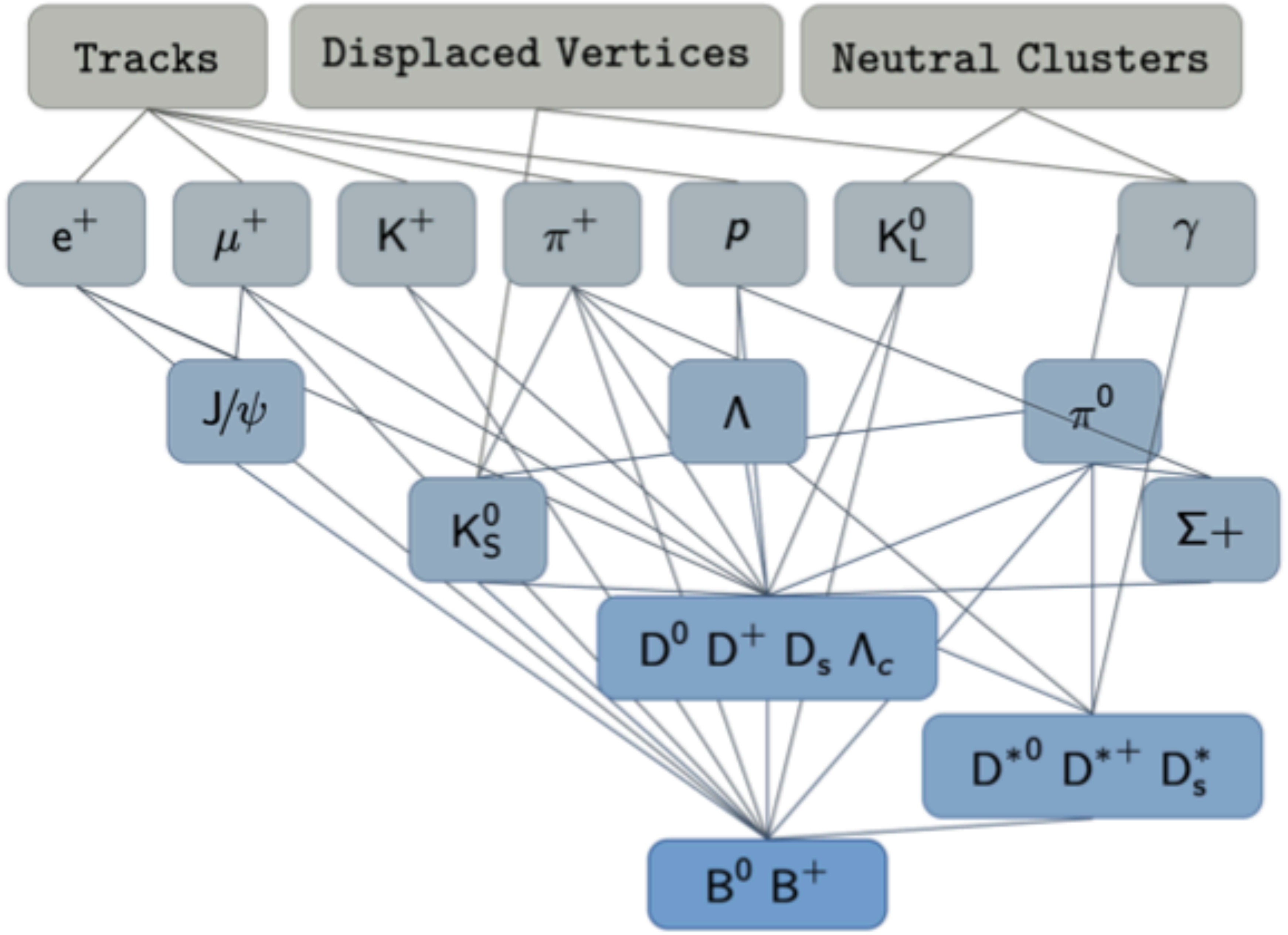
?

Other Approaches:

- [ ] 'Semi-inclusive' tagging
- [ ] Charm tagging

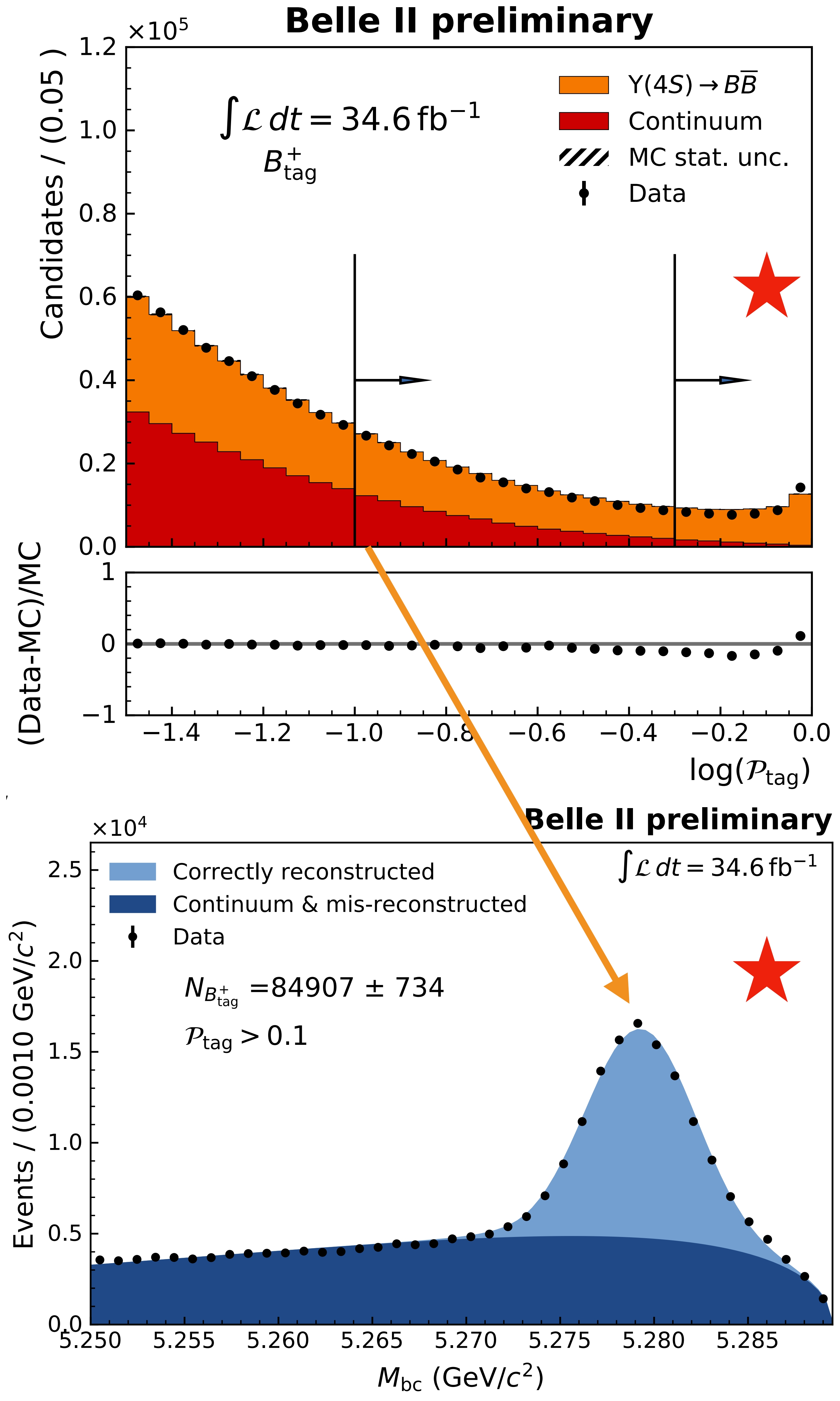
Full Event Interpretation (FEI)

FEI is an MVA tagging algorithm which reconstructs with with 200 BDTs ~ 10000 decay chains



[Comput. Softw. Big. Sci. (2019) 3: 6]

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
N of correct B_{tag} per 1 fb^{-1} in Belle (FEI)	8350/5060	19800/22440



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

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Full Event Interpretation (FEI)

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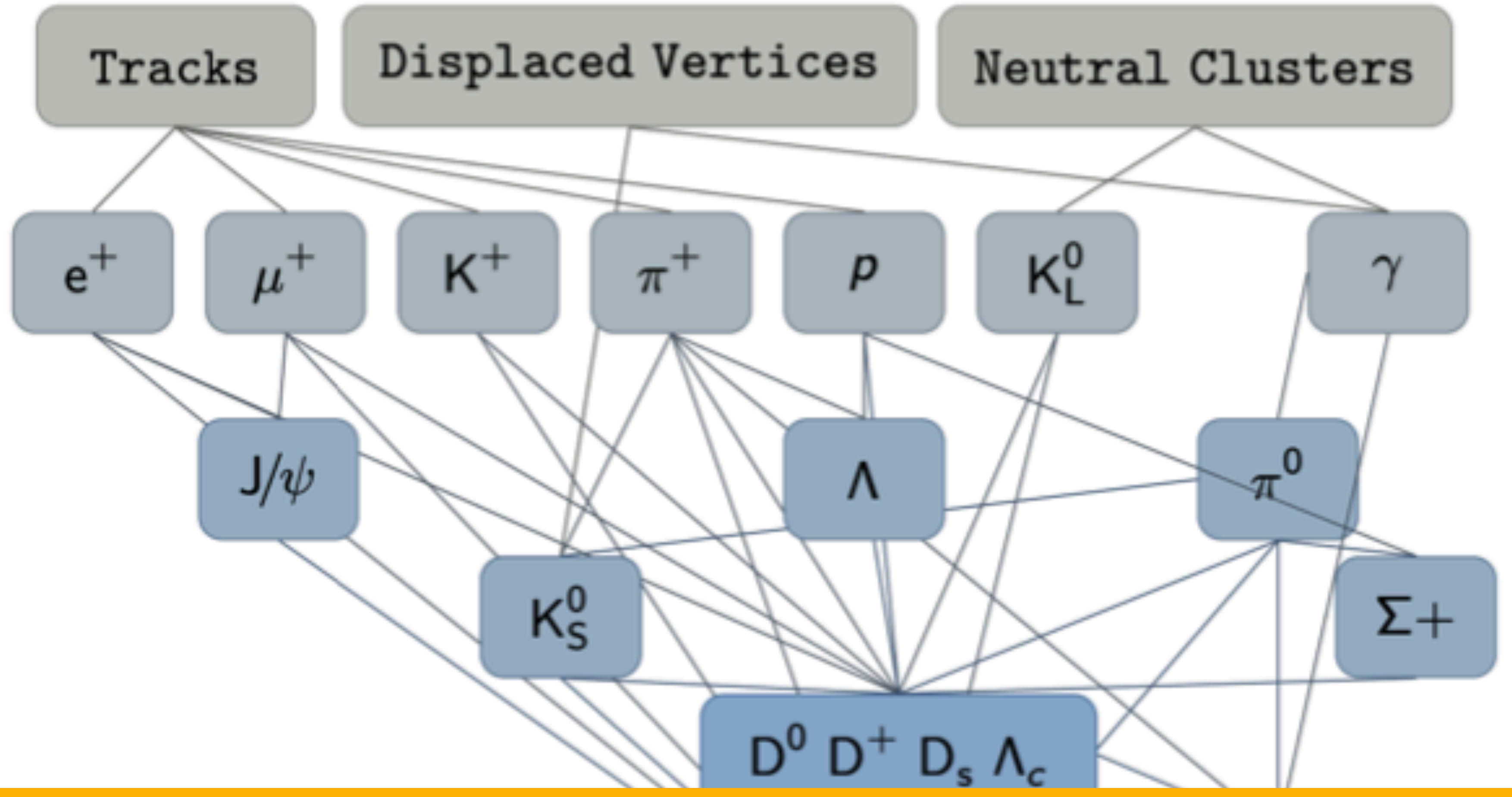

In Belle, FEI achieves up x 2 higher reconstruction efficiency compared to predecessor tagging algorithm
→ Belle II expects improvements

[Comput. Softw. Big. Sci. (2019) 3: 6]

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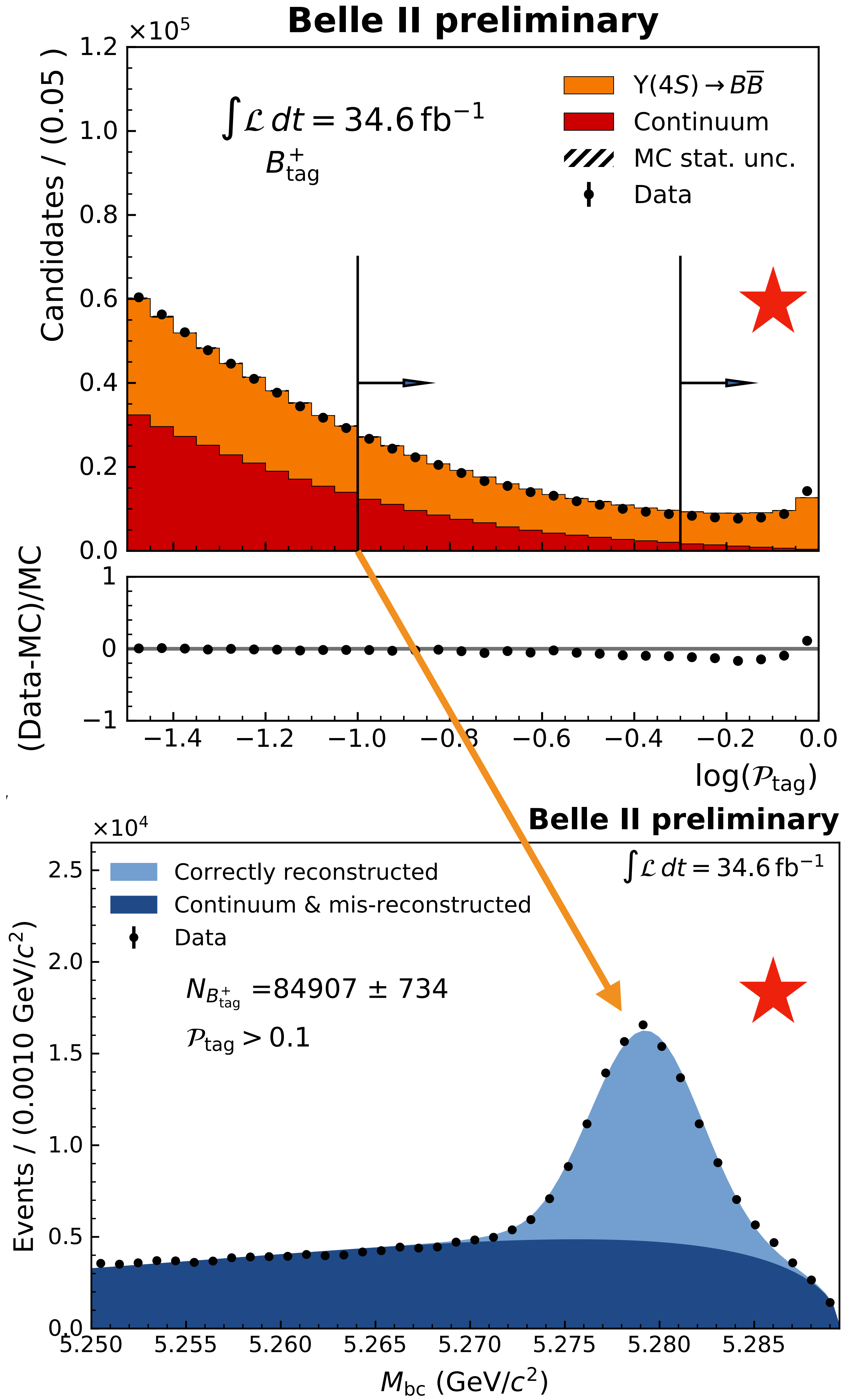

$$M_{bc} = \sqrt{E_{beam}^2 - |\vec{p_B}|^2}$$

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Neutral Particles

To take advantage of the 'clean event' need to reconstruct every particle possible!

π^0, K_L, K_s, n, γ

- γ = cluster in ECL that are not associated to a track
- K_L, n = cluster in KLM and ECL that is not associated to a track
- $\pi^0 = \gamma\gamma$
- $K_s = \pi^+\pi^-$ or $\pi^0\pi^0$

Background Rejection

- Large fraction of B-decay products have π^0 in its decay chain
- If K_L, n's interact with atomic nuclei in ECL and KLM, then need to devise vetos

Signal Identification

- If signal has π^0, K_s : need to have high reconstruction efficiency and good resolution

ROE / Tagged Reconstruction

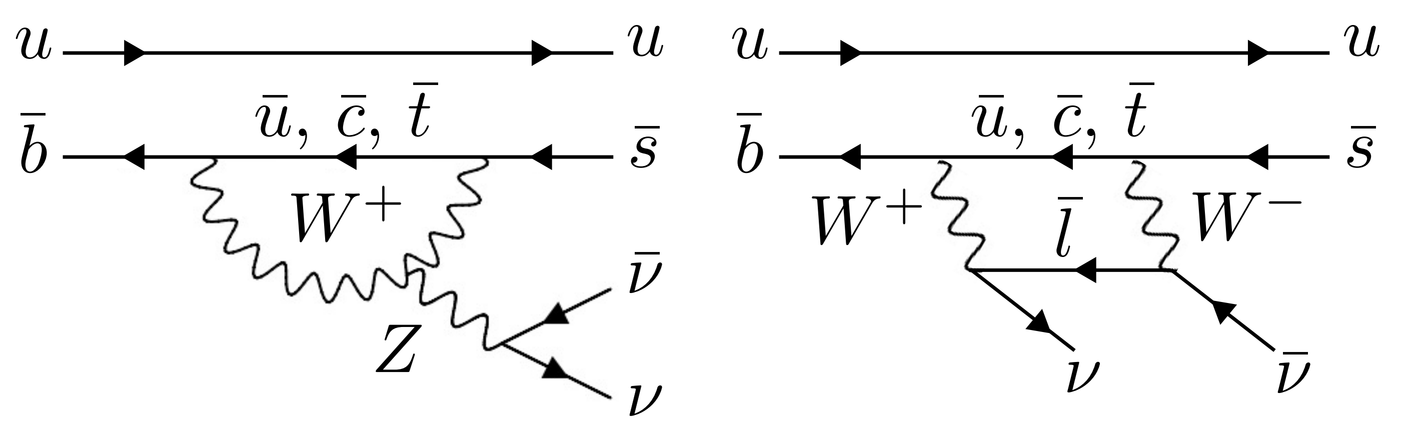
- Missing energy related variables (all particles that are not associated to signal/and B_{tag}) often used as discriminating variables/fitting variables
- If K_L, n's do not interact with atomic nuclei in ECL and KLM, potential fakes for invisible particles

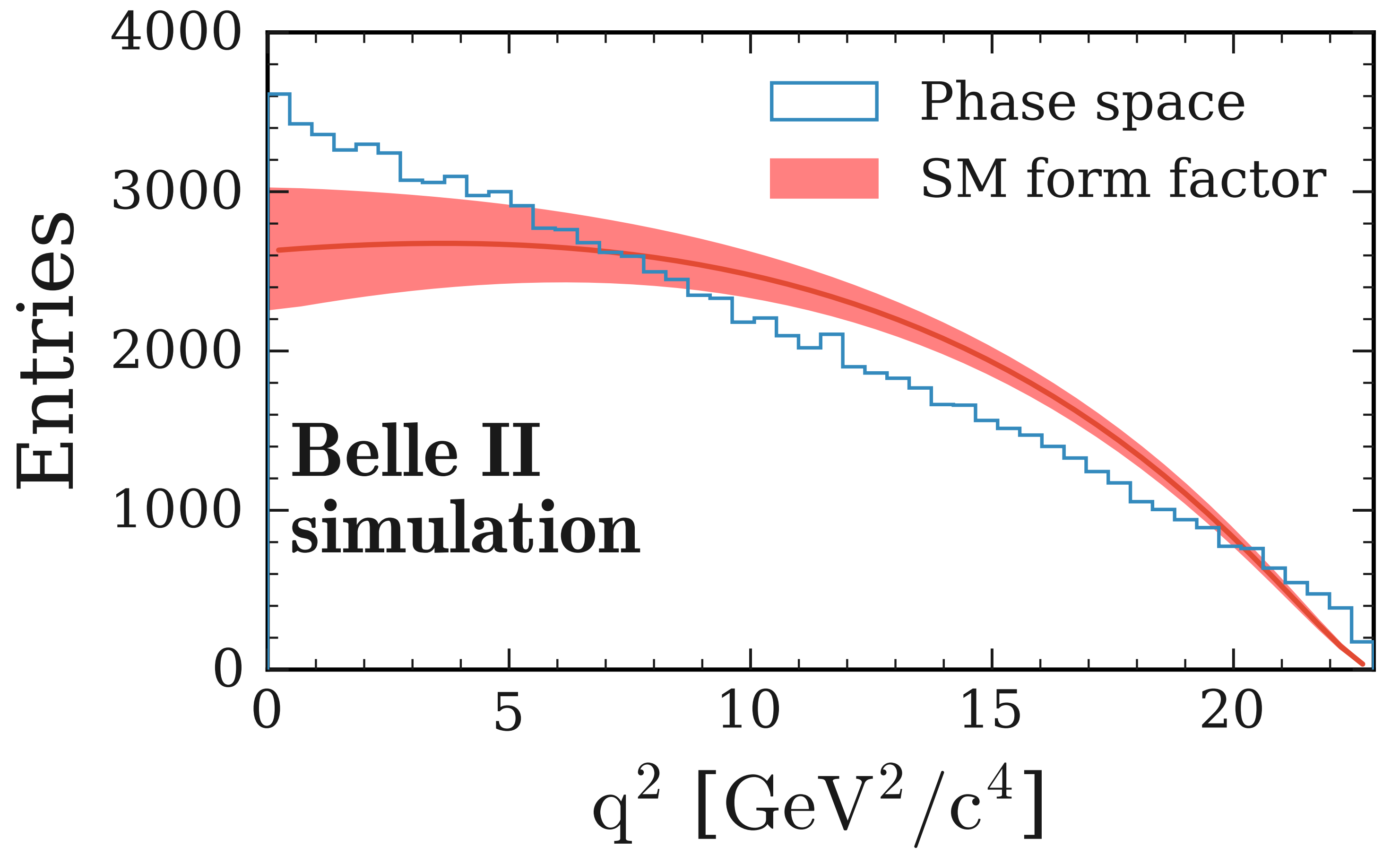
Channels with missing energy

Search for $B^+ \to K^+\nu\bar{\nu}$ [PRL 127, 181802 (2021)] ★

SM theory

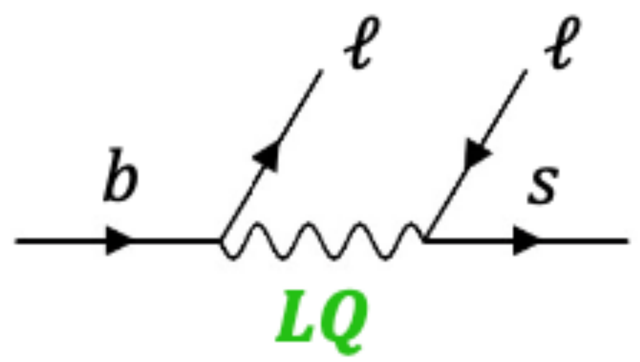
- FCNC transition heavily suppressed in SM
- Does not suffer from charm-loop contributions $\rightarrow$ clean SM computation
- $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$ [arxiv:606.00916]
- SM $q^2(\nu\bar{\nu})$ taken from [arXiv:1409.4557]
- Complimentary to other $b \to sll$ transitions

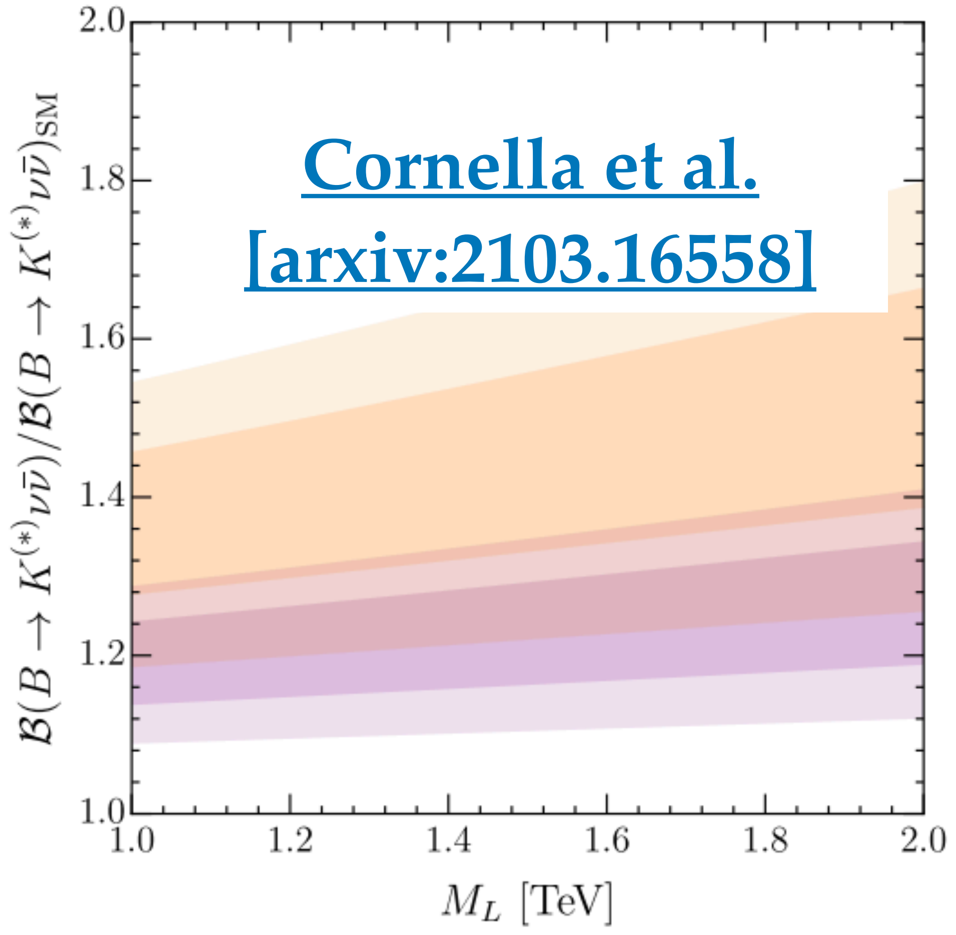




Possible BSM enhancements

- Axions [PRD 102, 015023 (2020)]
- Dark Matter candidates [PRD 101, 095006 (2020)]
- Z' [PL B 821 (2021) 136607]
- Leptoquarks [PRD 98, 055003 (2018)]



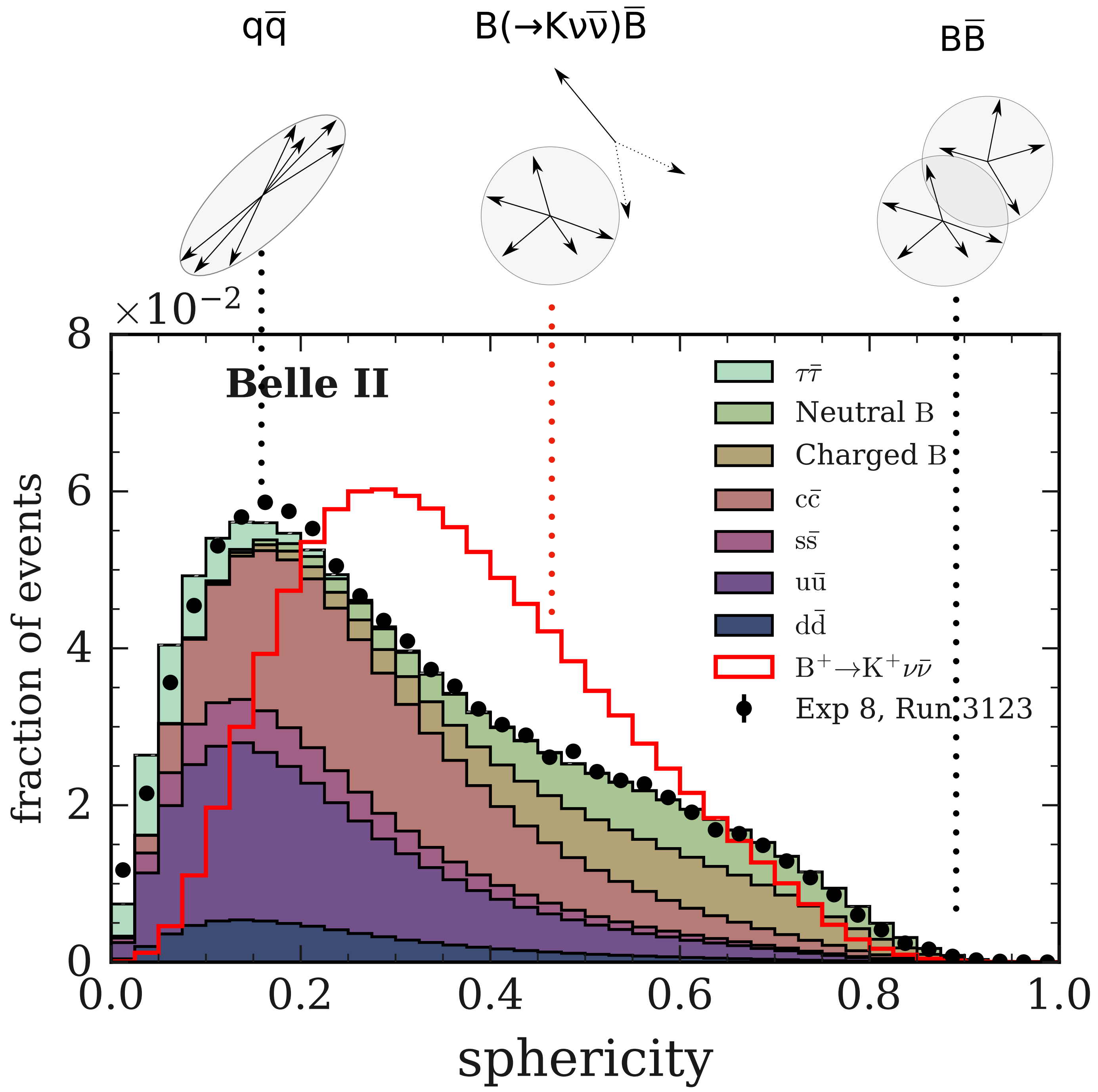


Consistent with $R(D^{(*)})$ and $b \to s\mu\mu$ anomalies

Search for $B^+ \to K^+ \nu \bar{\nu}$ [PRL 127, 181802 (2021)]

Strategy

1. Reconstruct signal: highest-p_T track in the event with at least 1 PXD hit
2. Reconstruct remaining tracks and clusters in the event
3. Minimise the background contamination with two nested BDTs using 51 variables: event topology, missing energy, vertex separation, signal kinematics)

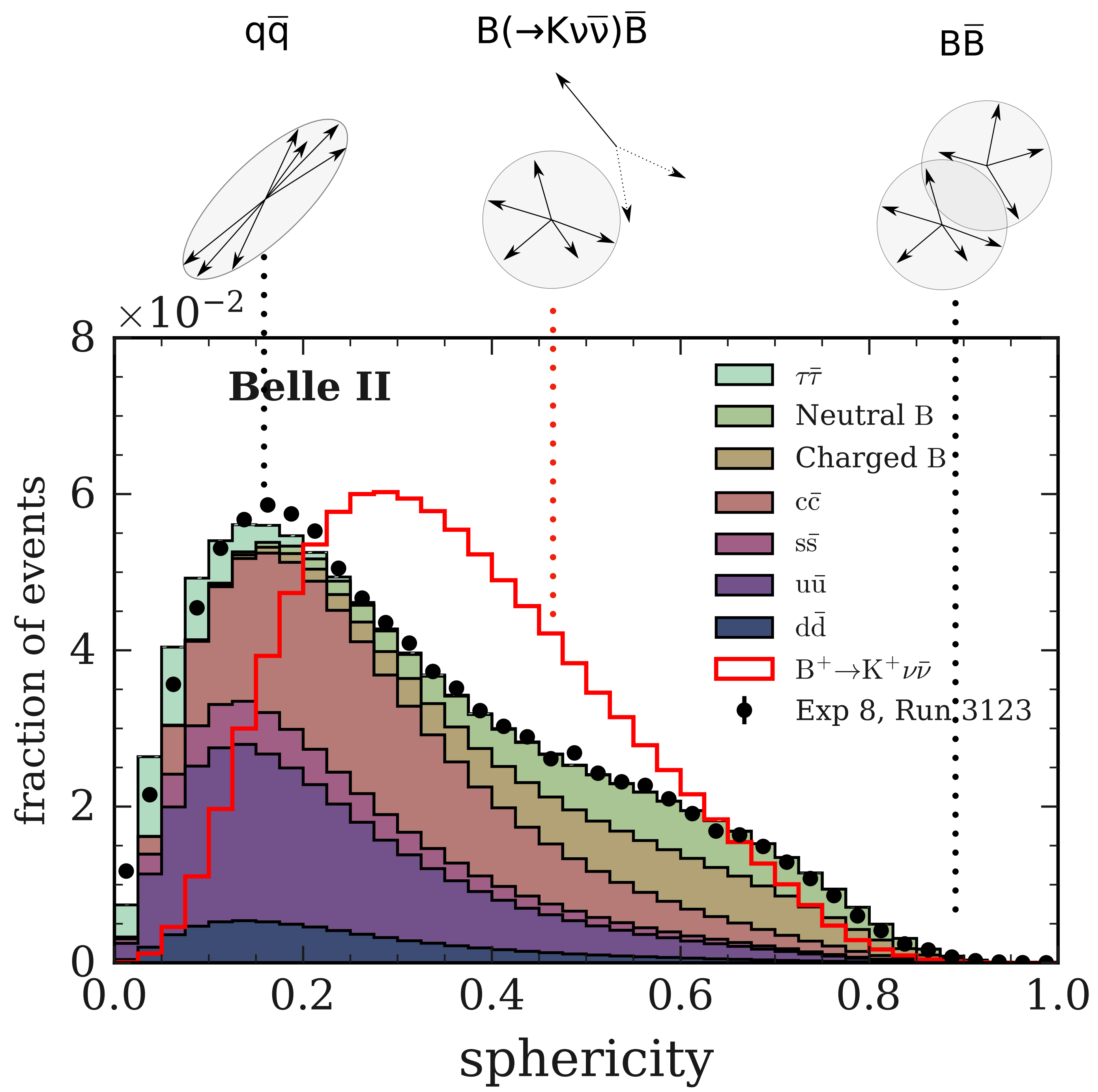


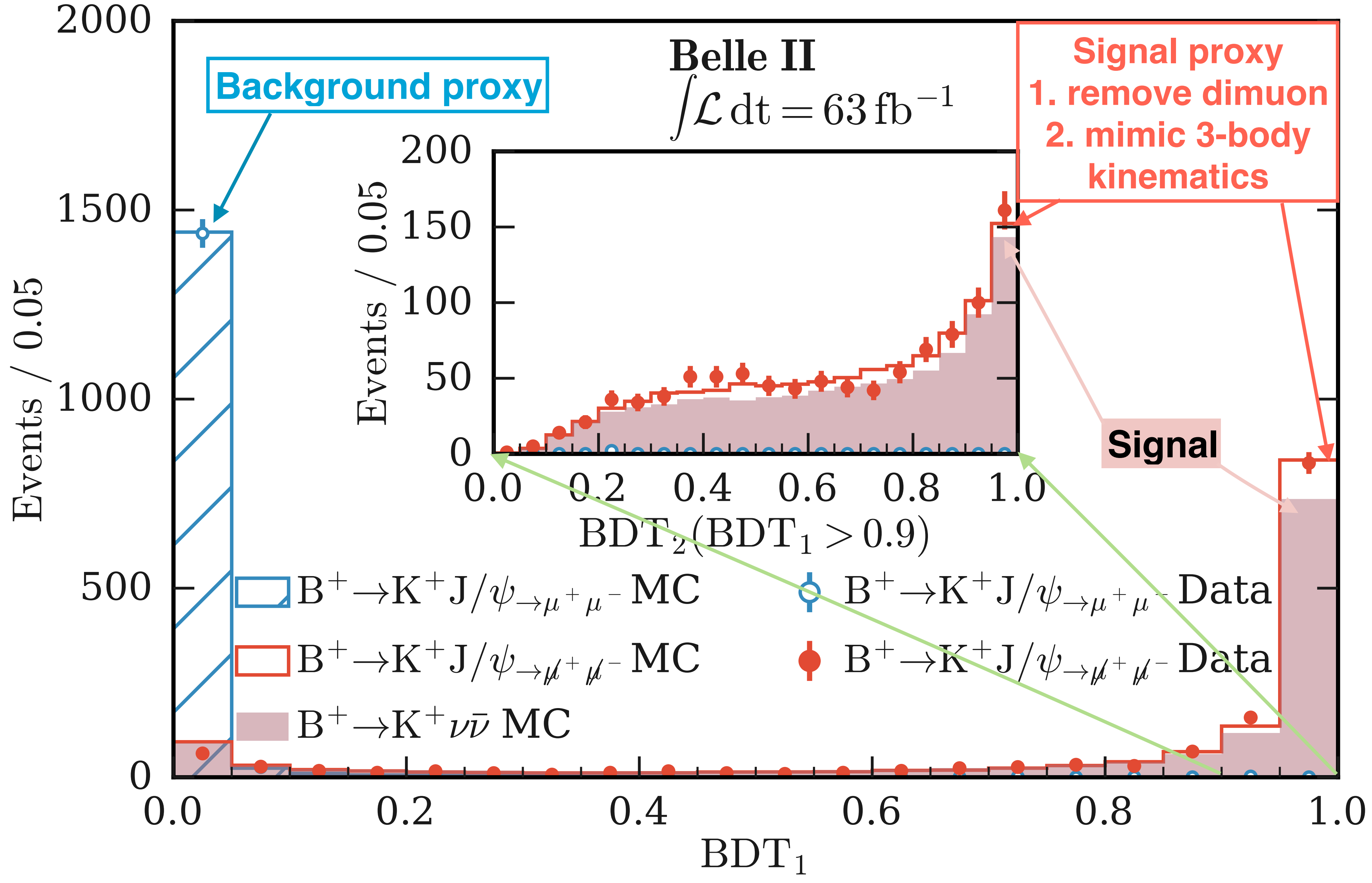
With only 1/10 $\mathscr{L}_{int}$ inclusive tagging approach achieved 20 × higher signal efficiency (~ 4%) compared to tagged reconstruction approach of previous experiments

Search for $B^+ \to K^+\nu\bar{\nu}$ [PRL 127, 181802 (2021)] ★

Strategy

1. Reconstruct signal: highest-p_T track in the event with at least 1 PXD hit
2. Reconstruct remaining tracks and clusters in the event
3. Minimise the background contamination with two nested BDTs using 51 variables: event topology, missing energy, vertex separation, signal kinematics)
4. **Validation with control channel $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$**





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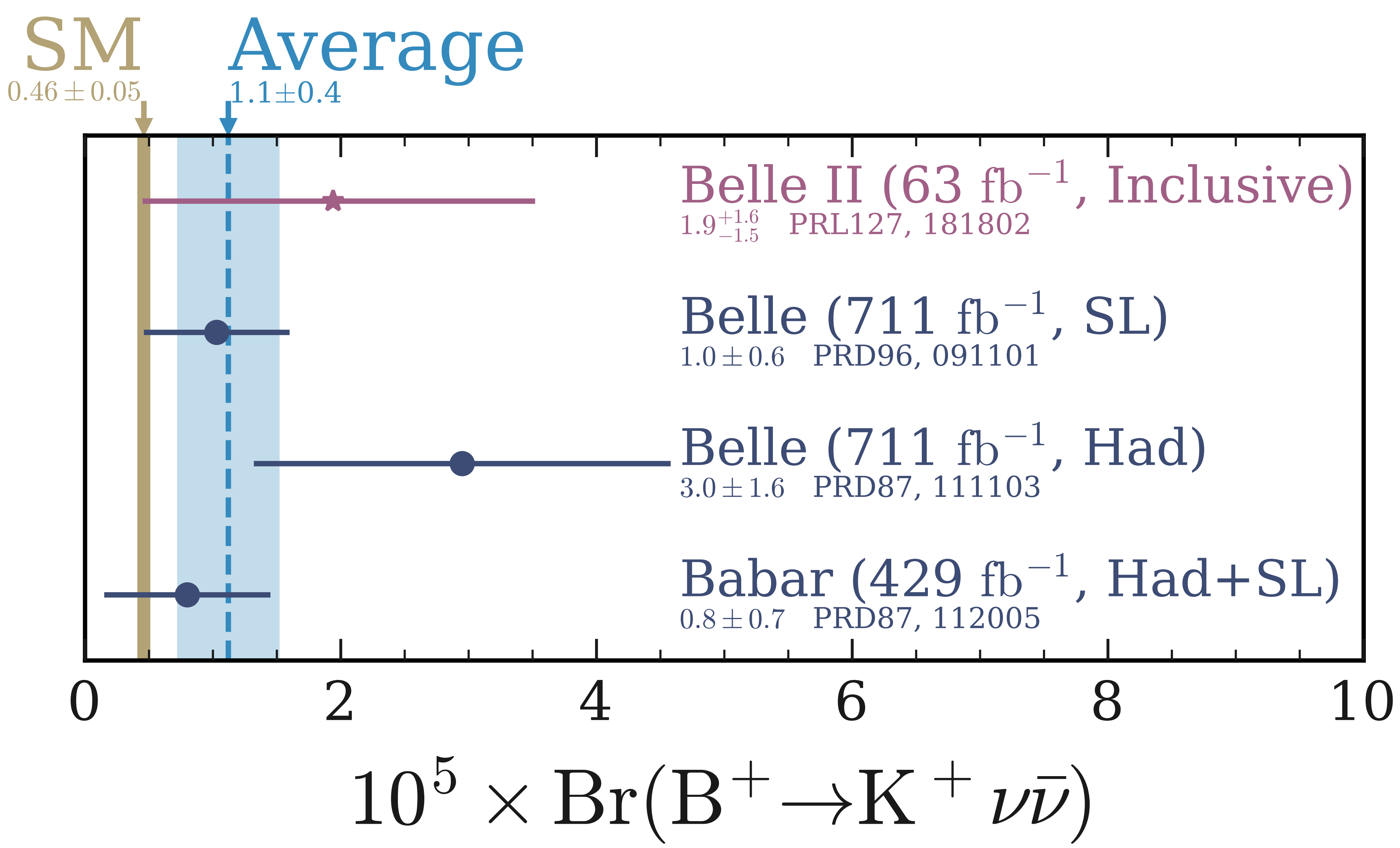
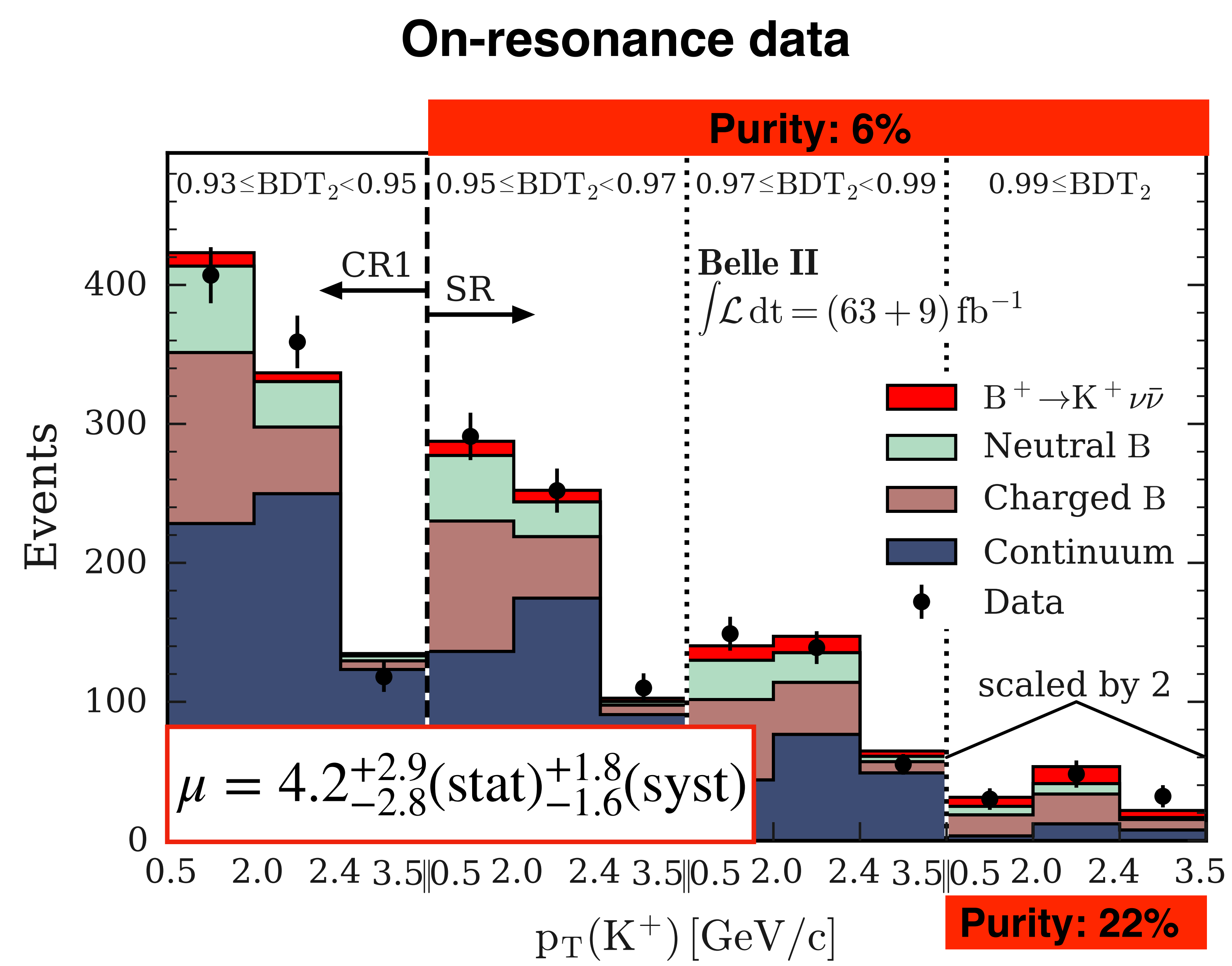
Search for $B^+ \to K^+\nu\bar{\nu}$ [PRL 127, 181802 (2021)] ★

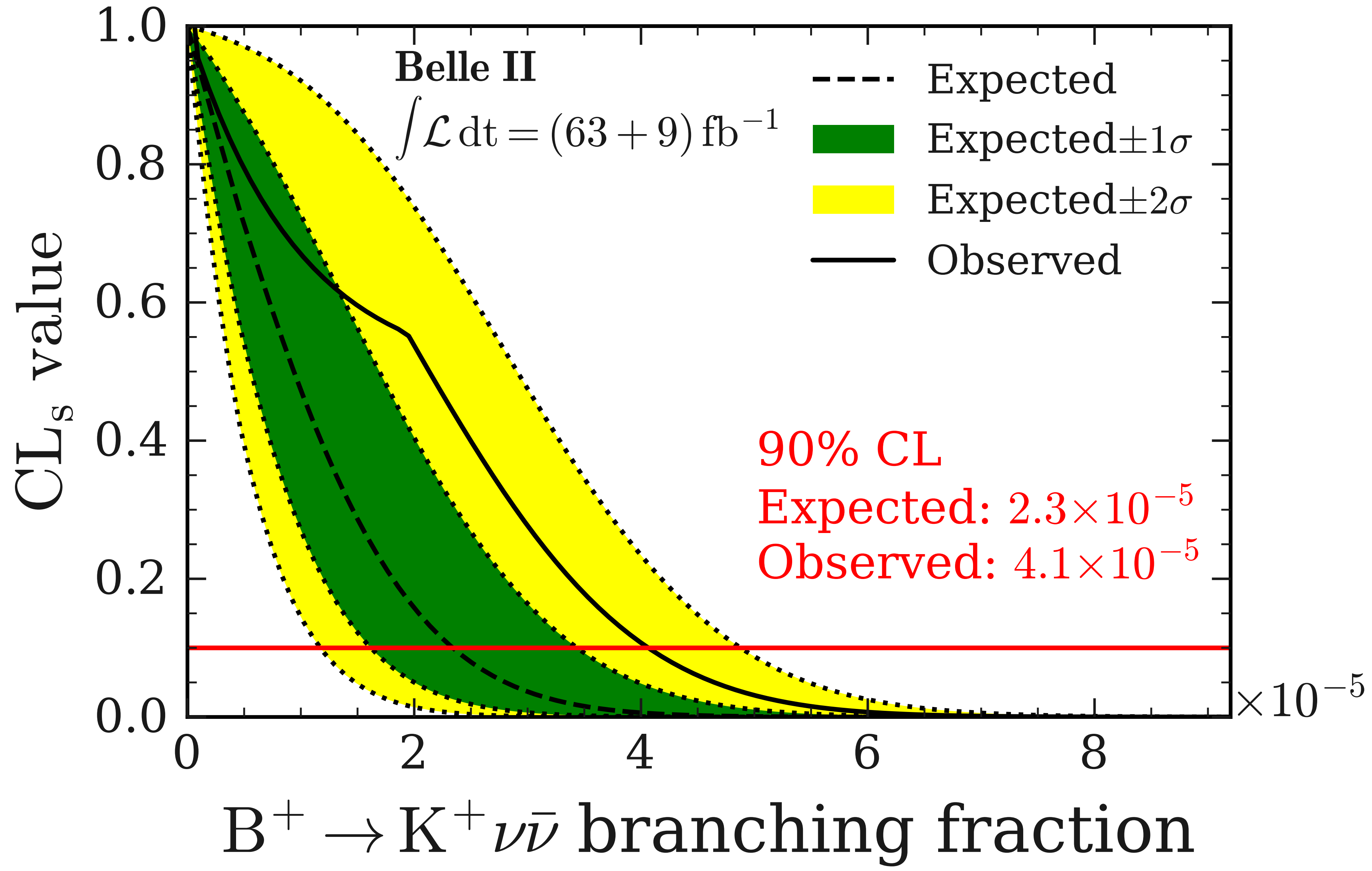
Results

- Binned simultaneous ML fit to $p_T(K^+) \times \mathrm{BDT}_2$ to extract signal strength μ (1μ = SM $\mathscr{B} = 4.6 \times 10^{-6}$)
- No significant signal is observed, limit of 4.1×10^{-5} @ 90 C.L.
  → competitive with *only* 63 fb^{-1}
- Inclusive tag approach shows the best performance



BSM $B^+ \to K^+\nu\bar{\nu}$ already with 1 ab^{-1}





Search for $B^+ \to K^+ \nu\bar{\nu}$ [PRL 127, 181802 (2021)] ★

Prospects in Belle II

- **Physics:** similar channels, inclusive measurement X_s, measurement of F_L
- **Faster observation:** reducing biggest systematics, combined measurement using all the tagging approaches

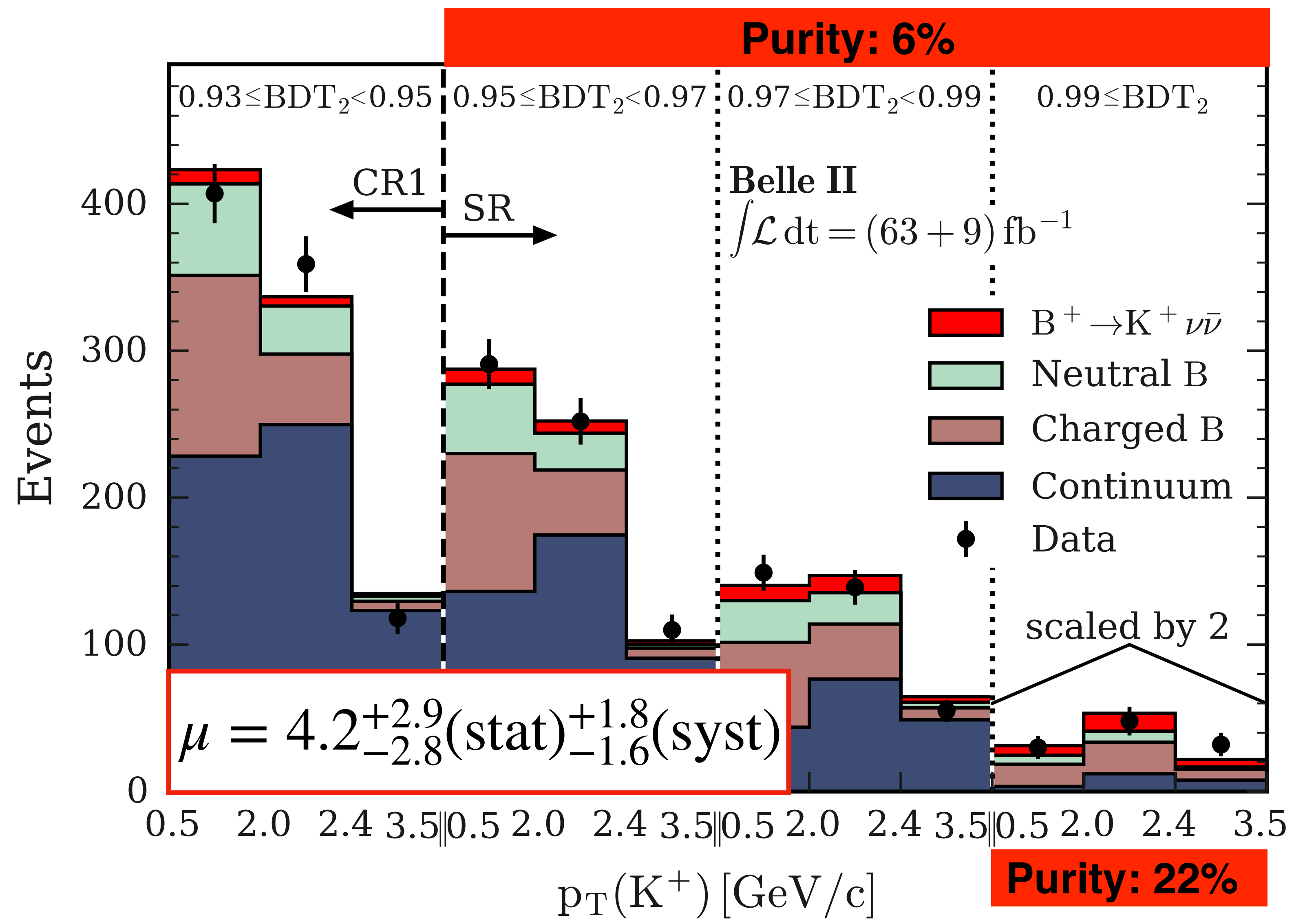
Belle II snowmass paper : 2 scenarios baseline (improved)

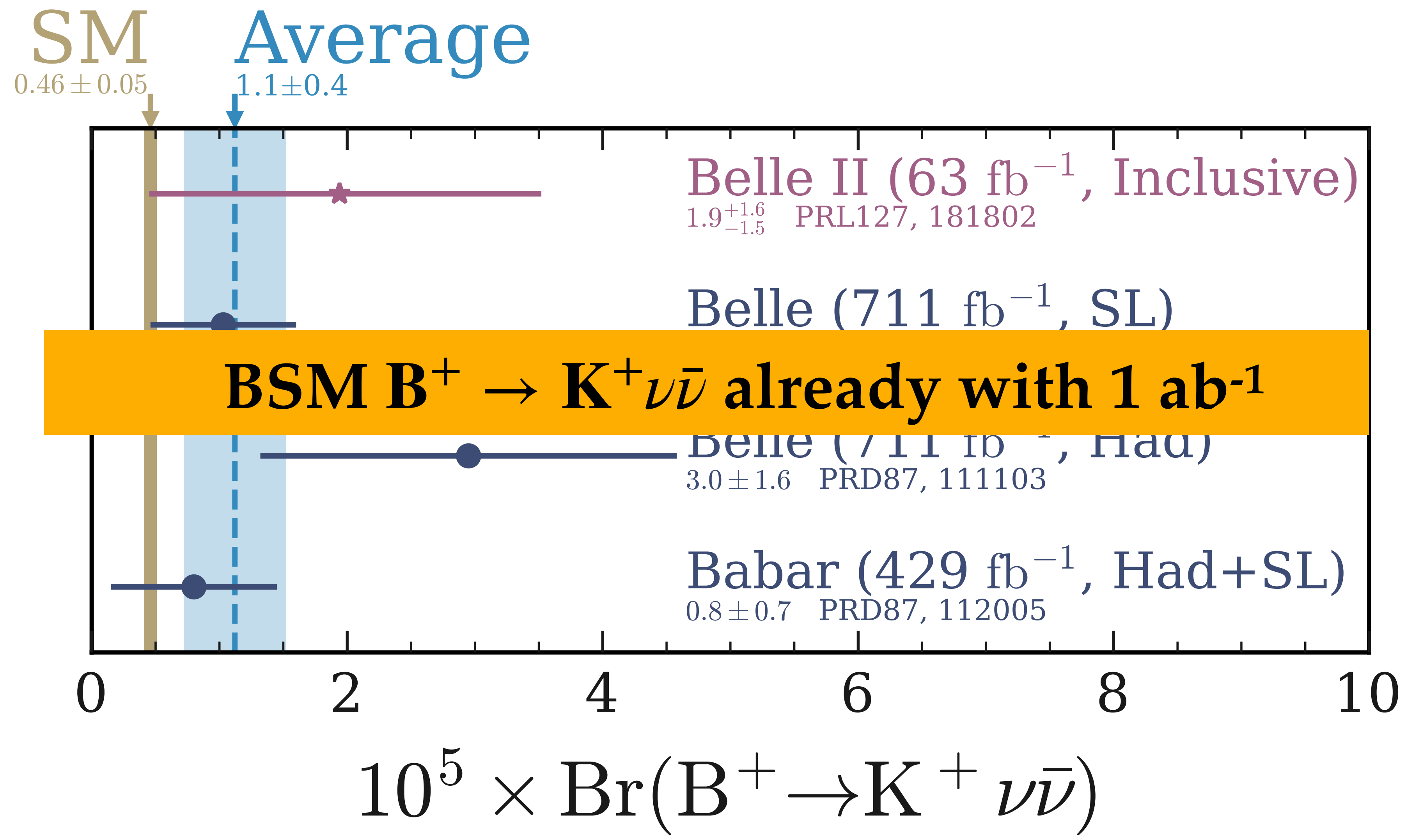
Uncertainties on the signal strength μ

Decay	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 ab^{-1}
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K^0_S\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \to K^{*0}\nu\bar{\nu}$	1.08 (0.72)	0.60 (0.40)	0.49 (0.33)	0.34 (0.23)

3σ (5σ) sigma for SM $B^+ \to K^+\nu\bar{\nu}$ with 5 fb^{-1}

On-resonance data

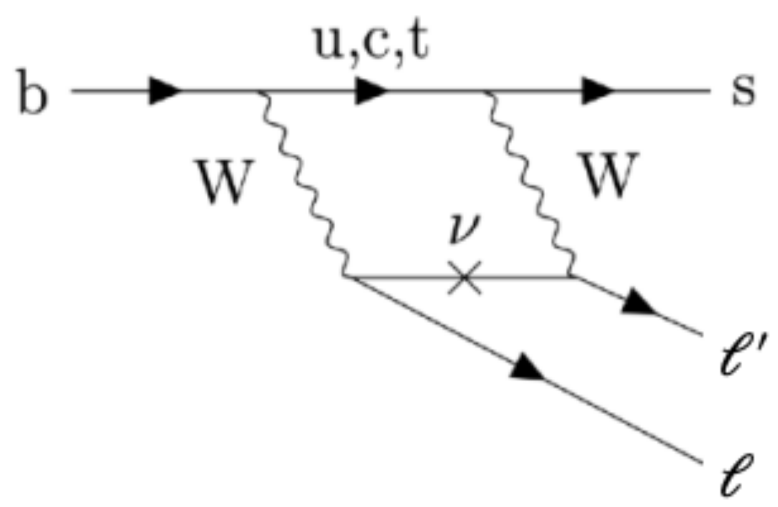


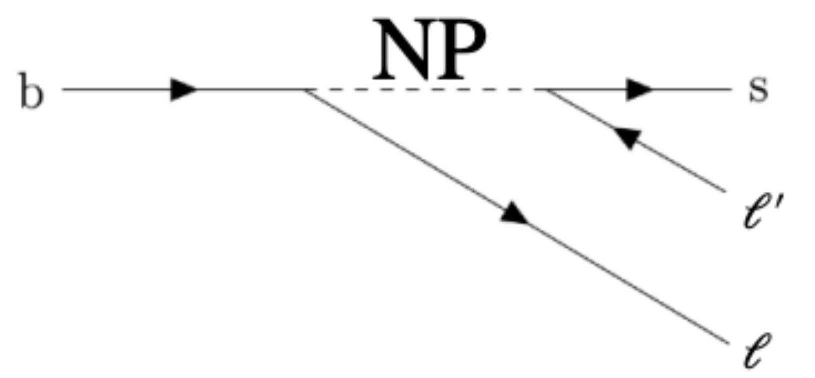


BSM $B^+ \to K^+\nu\bar{\nu}$ already with 1 ab^{-1}

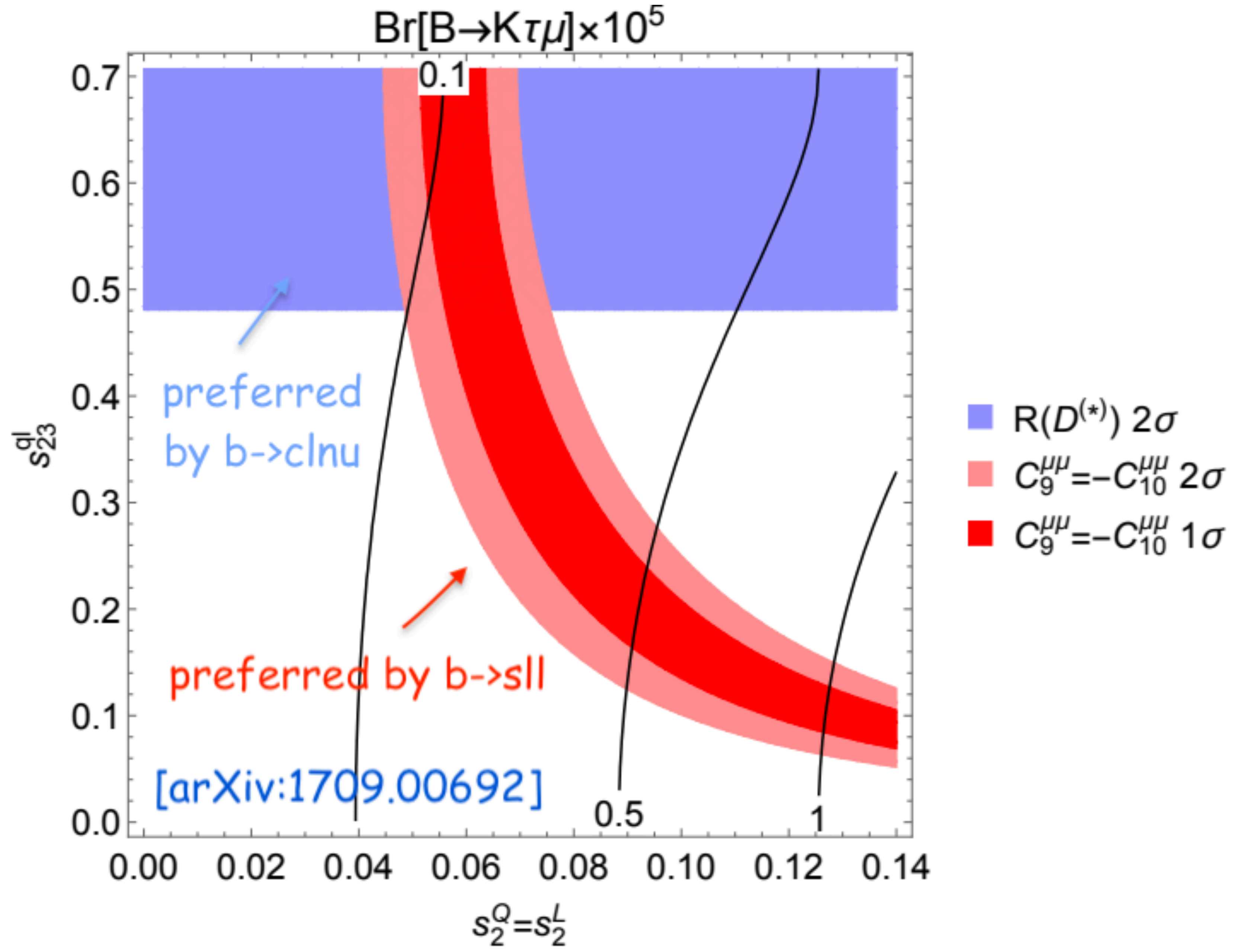
Search for $B^+ \to K^+\tau\, l$

Motivation:
- LFV decays are strongly suppressed in SM (can only occur via neutrino mixing)





BSM:
- Hints for LFU violation in $b \to sll$ and $b \to cl\nu$
- If LFU is violated, then BSM extensions predict that rates for LFV decays are enhanced (even more for 3rd generation leptons) → up to ~10^{-5}
- BSM models: Leptoquarks [arxiv:1709.00692], Z′, W', …



Current Bounds:
- Best limits set by BaBar (hadronic tag) and LHCb

	Mode	90% C.L. U.L. BABAR	90% C.L. U.L. LHCb
OS	$B^+ \to K^+\tau^+\mu^-$	2.8×10^{-5}	3.9×10^{-5}
SS	$B^+ \to K^+\tau^-\mu^+$	4.5×10^{-5}	
	$B^+ \to K^+\tau^+e^-$	1.5×10^{-5}	
	$B^+ \to K^+\tau^-e^+$	4.3×10^{-5}	

Belle II can:
- study different sign combinations
- with different tagging approaches including semi-inclusive tagging, charm tagging …

Search for $B \to K^{(*)}\tau\tau$

Motivation:
- FCNC transition involving 3rd generation leptons
- SM $\mathscr{B}(B \to K(*)\tau\tau) \sim 10^{-7}$

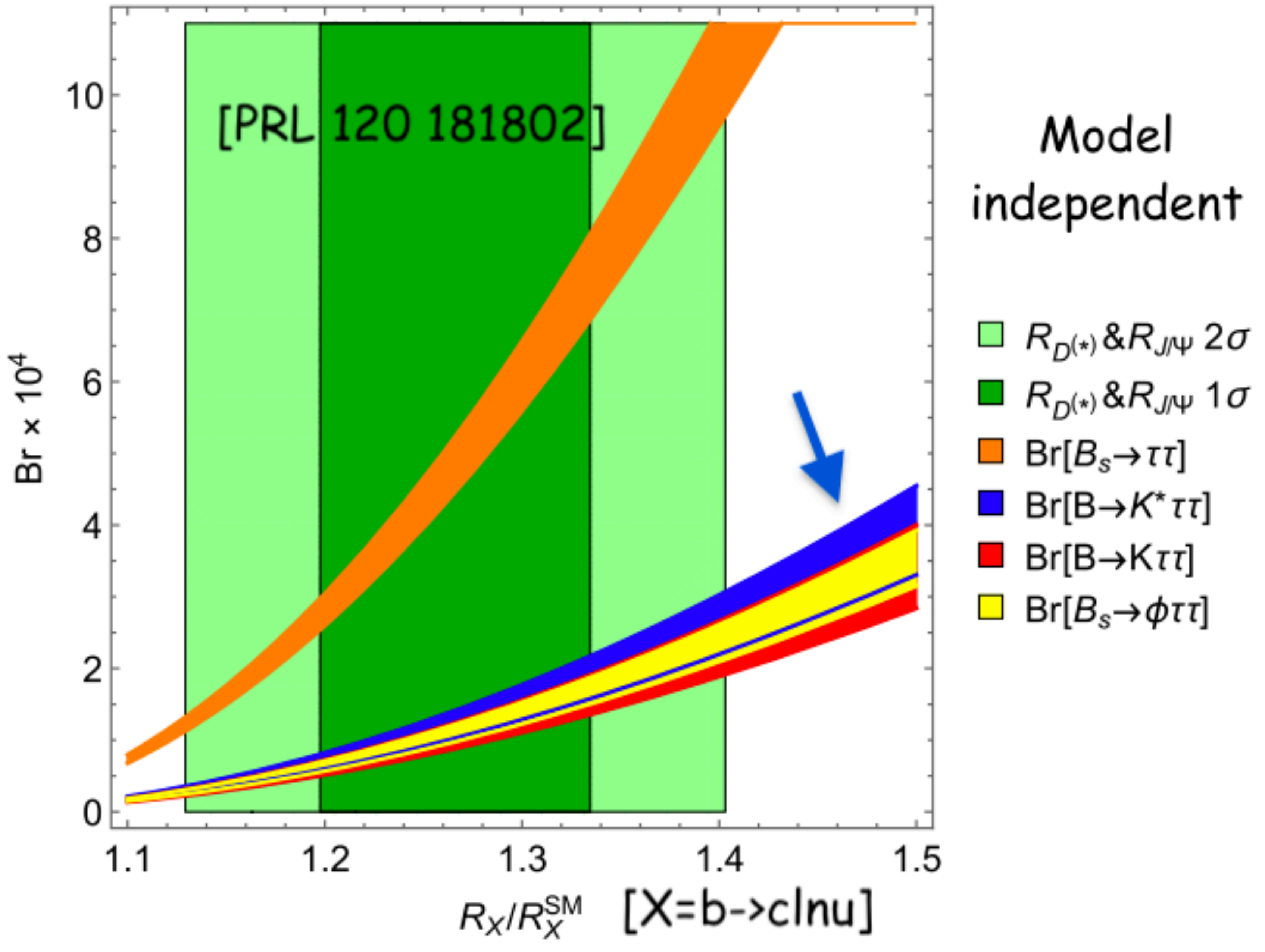
BSM:
- Rate enhanced by NP models (especially those coupling only to 3rd generation / with coupling ∝ particle mass)

Current Bounds:
- Belle $\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) < 2.0 \times 10^{-3}$ @ 90 % C.L. [arxiv:2110.03871]
- Babar $\mathscr{B}(B^+ \to K^+\tau^+\tau^-) < 2.3 \times 10^{-3}$ @ 90 % C.L. [PRL 118, 031802 (2017)]

Belle II can:
- exploit different tagging approaches
- include more τ decay modes (improved scenario)
- measure other channels K^{*+}

Belle II snowmass paper

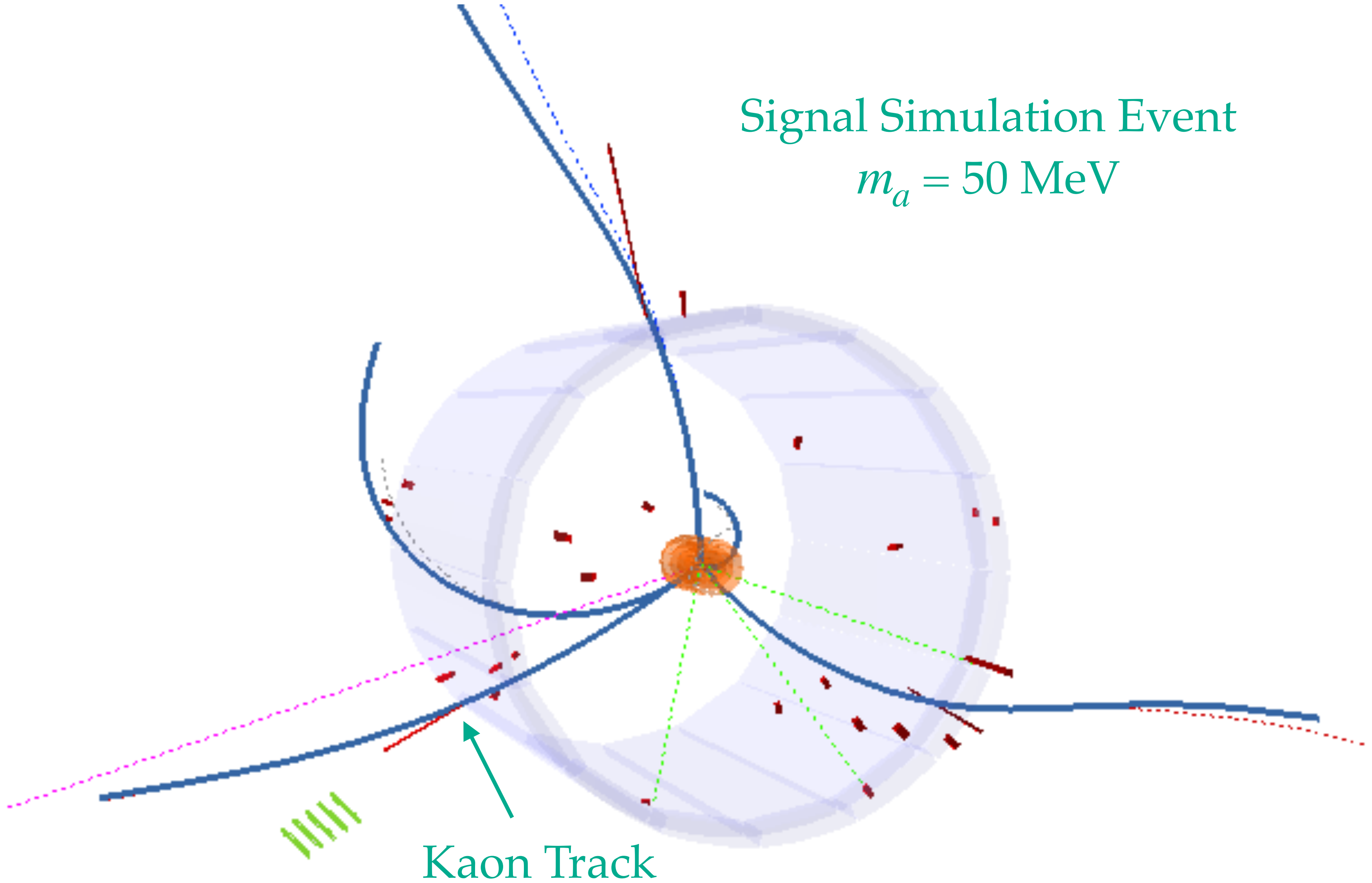
	$\mathcal{B}(B^0 \to K^{*0}\tau\tau)$ (had tag)	
ab^{-1}	"Baseline" scenario	"Improved" scenario
1	$< 3.2 \times 10^{-3}$	$< 1.2 \times 10^{-3}$
5	$< 2.0 \times 10^{-3}$	$< 6.8 \times 10^{-4}$
10	$< 1.8 \times 10^{-3}$	$< 6.5 \times 10^{-4}$
50	$< 1.6 \times 10^{-3}$	$< 5.3 \times 10^{-4}$



Search for $B^+ \to K^+ a$ (ALP)

BSM scenarios of $B^+ \to K^+ \nu\bar{\nu}$: **new mediators (a)**

- **a** (= dark scalar or **ALP**) decaying invisibly → very similar to the search for $B^+ \to K^+ \nu\bar{\nu}$
- **main experimental difference: two-body vs three-body kinematics**



ALP model from [arxiv: 2201.06580]

$$\mathcal{B}(B^+ \to K^+ a) = 0.25\left(c_{ff}(\Lambda) + 0.0032\, c_{WW}(\Lambda)\right)^2 \frac{f_0^2(m_a^2)}{f_0^2(0)} \frac{\lambda^{1/2}(m_B^2, m_K^2, m_a^2)}{m_B^2 - m_K^2}.$$

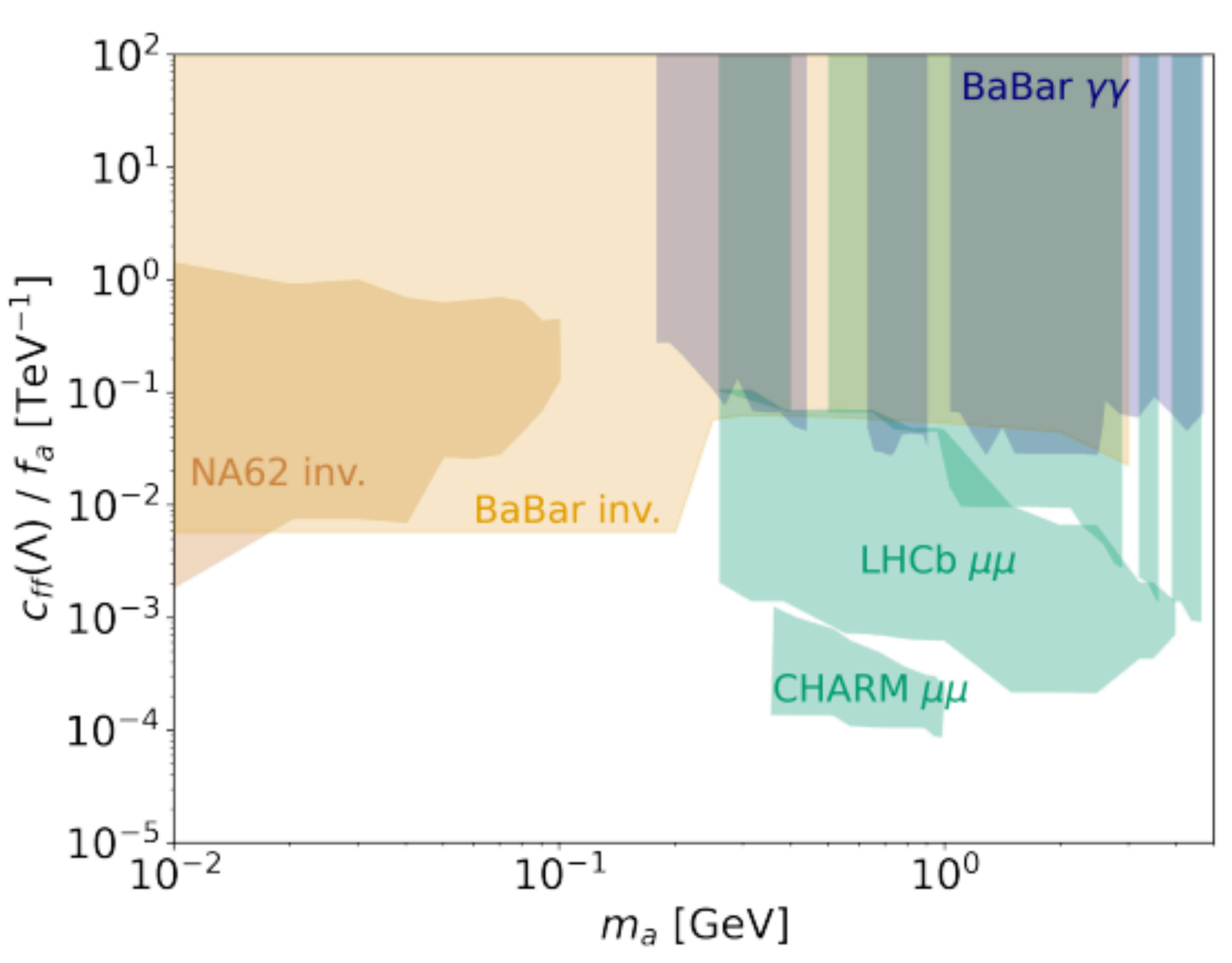
"c_{ff}" : ALP coupling to fermions

"c_{WW}" : ALP coupling to gauge bosons

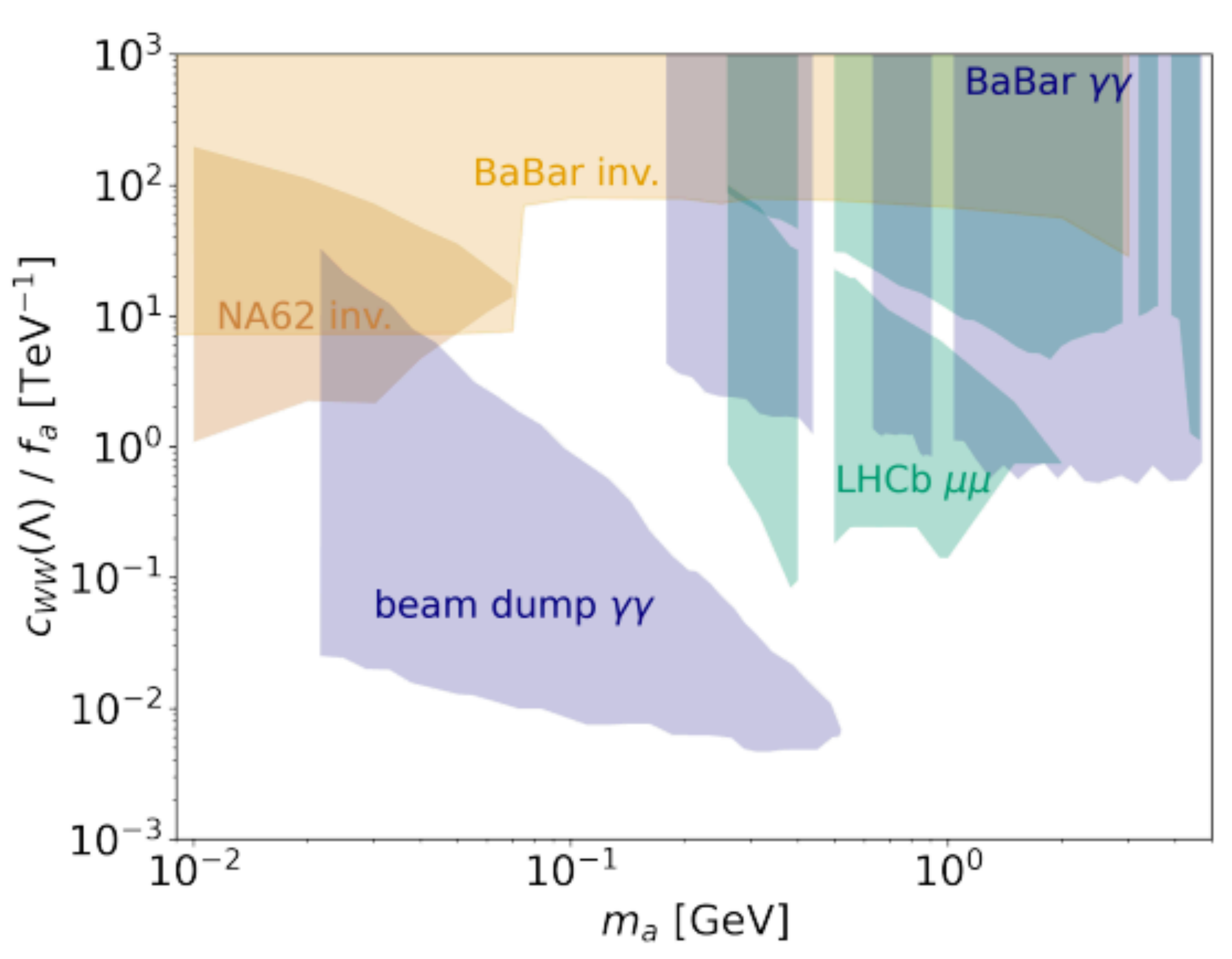
$\lambda(a,b,c) = a^2 + b^2 + c^2 - 2(ab + ac + bc)$

f_0 = scalar FF

Current bounds:



$c_{ff}(\Lambda)/f_a \lesssim (10^{-3} - 10^{-2})$ TeV^{-1},



$c_{WW}(\Lambda)/f_a \lesssim (10^{-2} - 1)$ TeV^{-1}

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Search for $B^+ \to K^+ a$ (ALP)

BSM scenarios of $B^+ \to K^+ \nu\bar{\nu}$: **new mediators (a)**

- **a** (= dark scalar or **ALP**) decaying invisibly → very similar to the search for $B^+ \to K^+ \nu\bar{\nu}$
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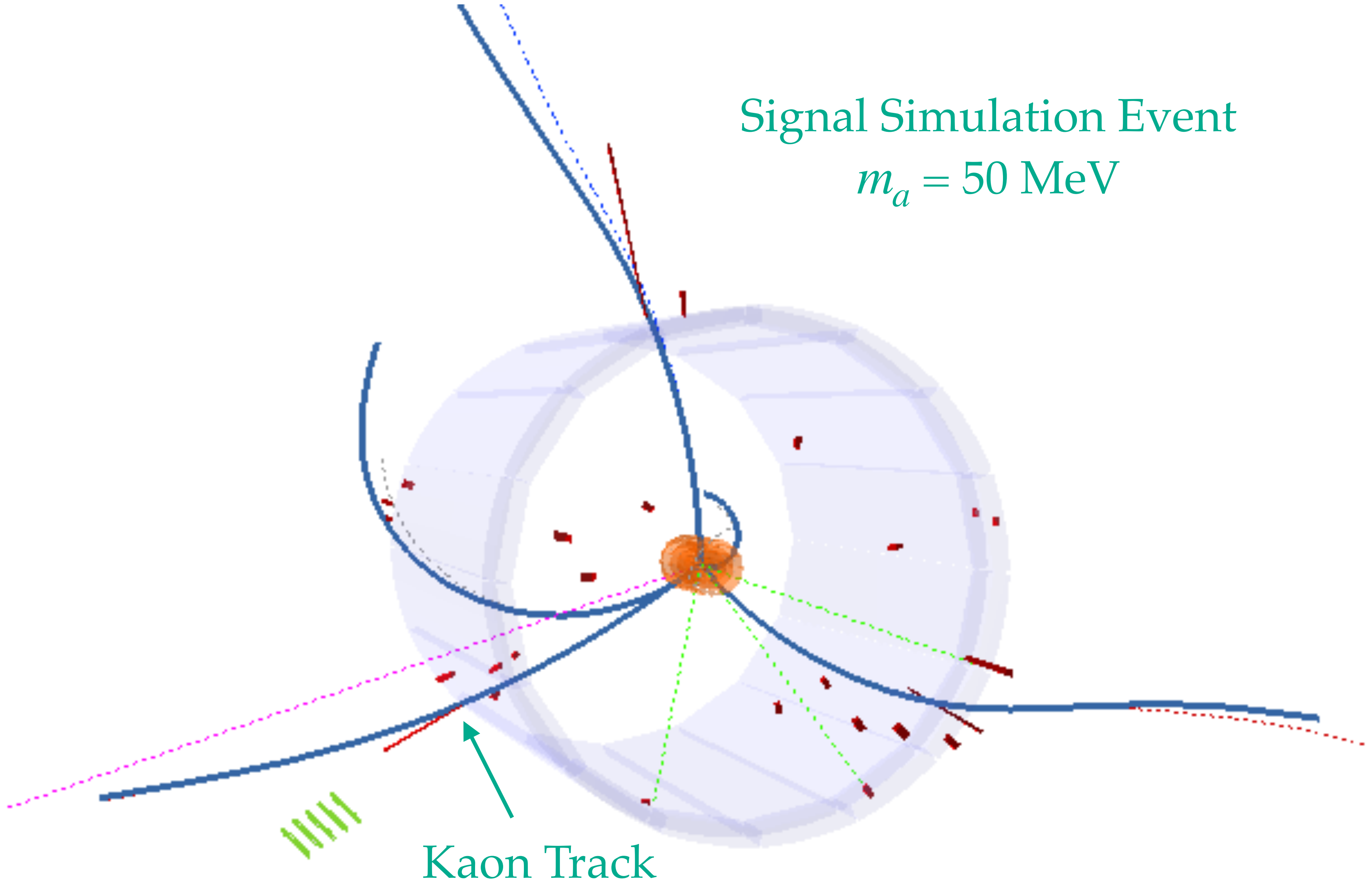

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"c_{ff}" : ALP coupling to fermions

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$\lambda(a,b,c) = a^2 + b^2 + c^2 - 2(ab + ac + bc)$

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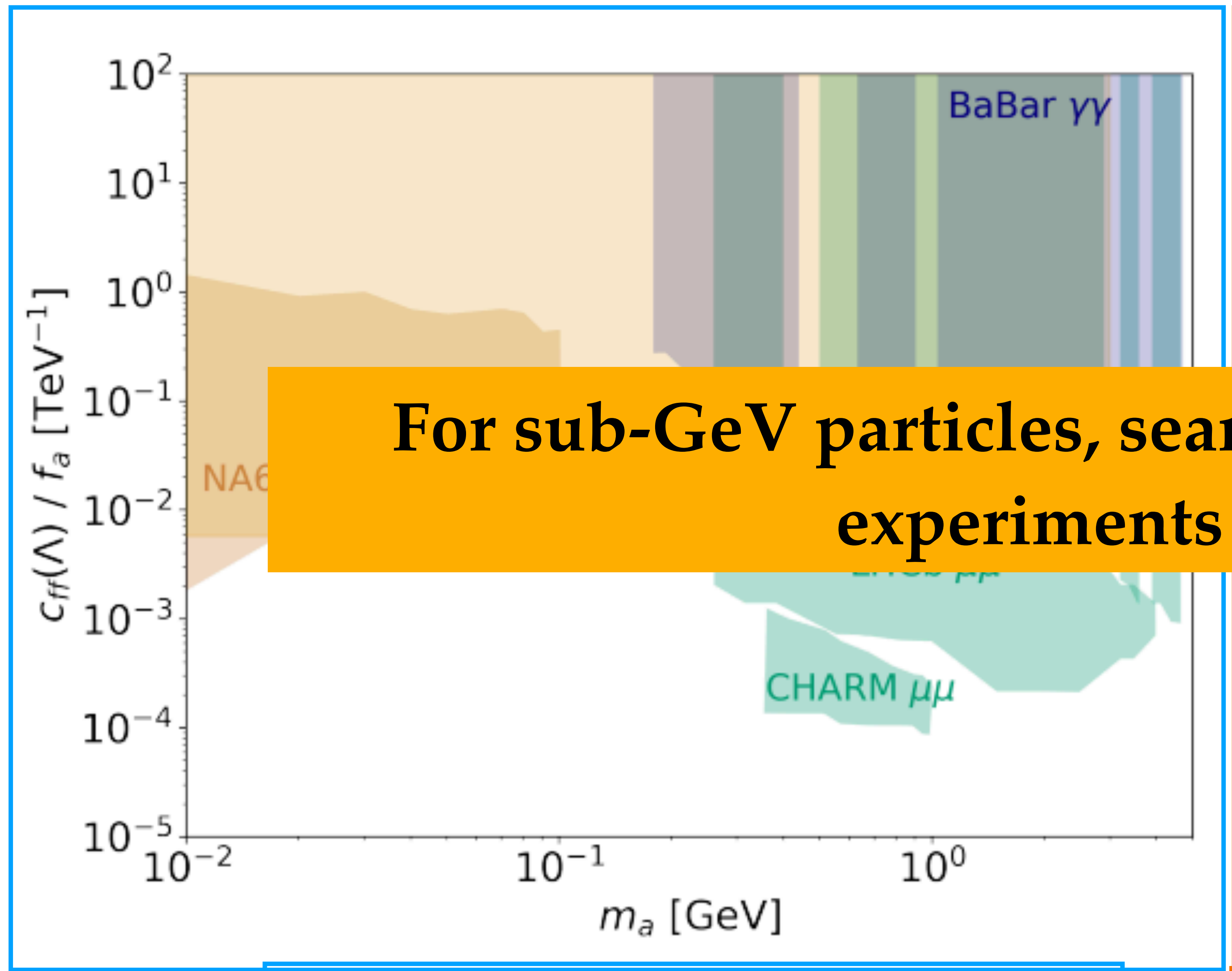
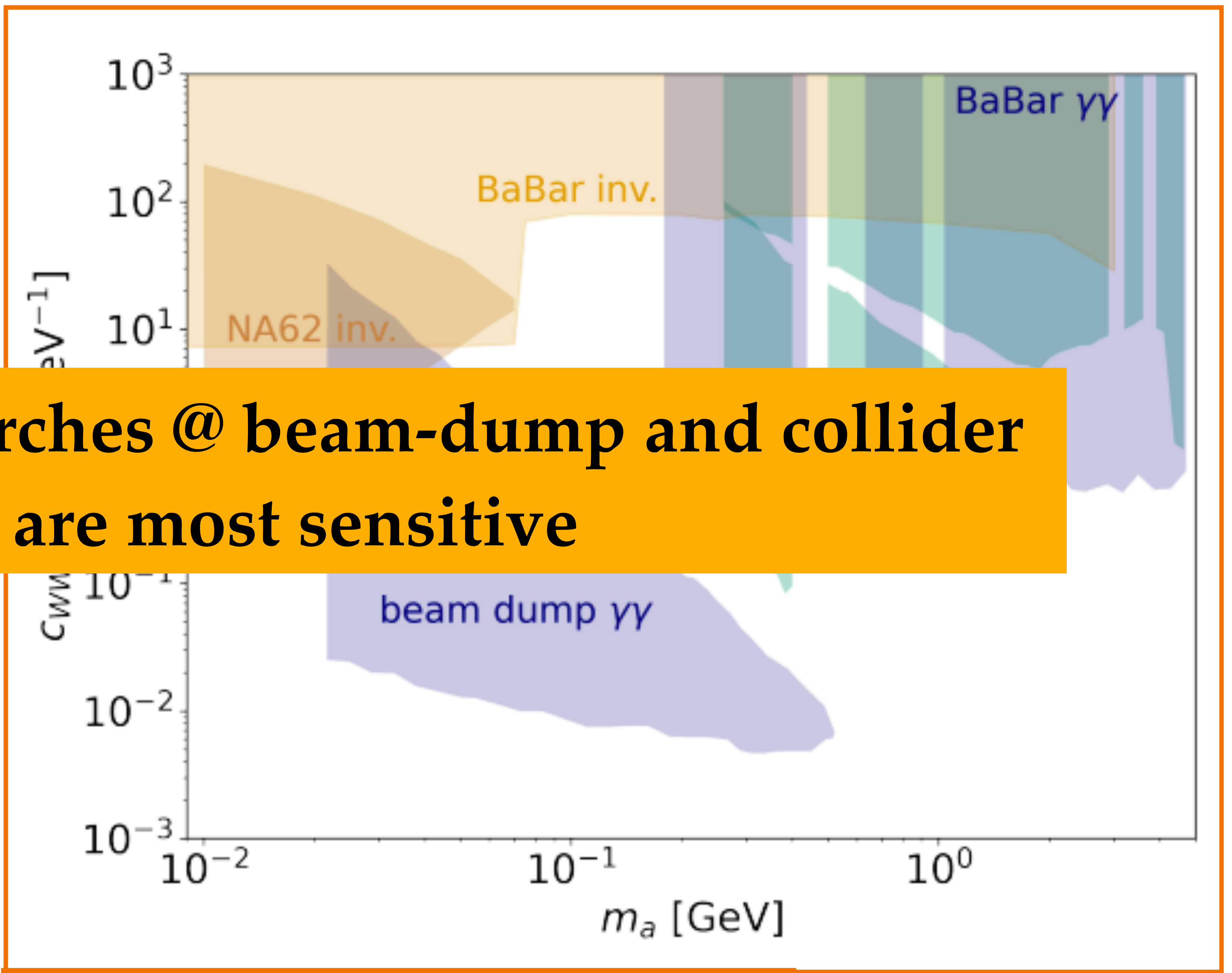
Current bounds:





For sub-GeV particles, searches @ beam-dump and collider experiments are most sensitive

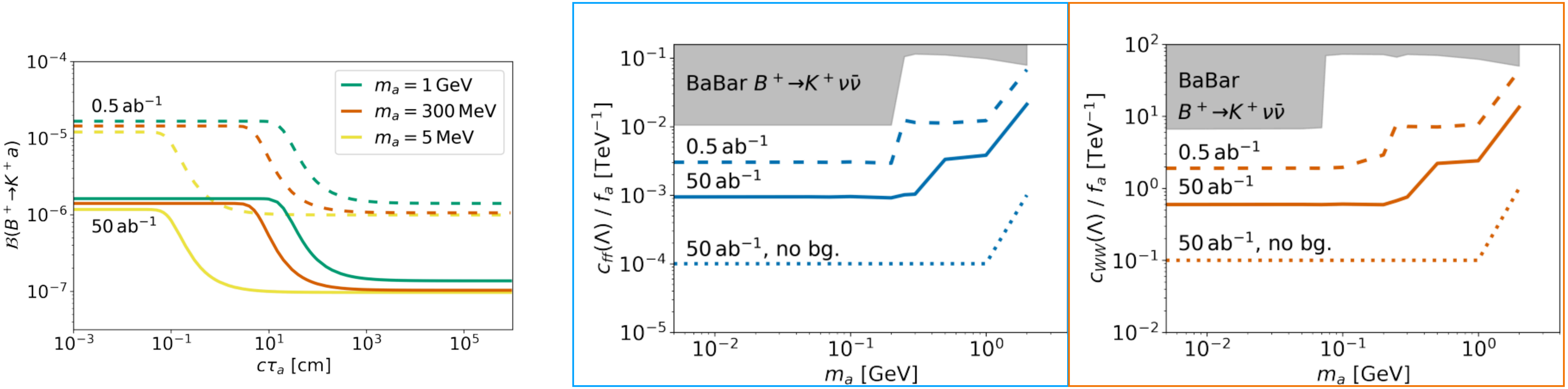
$c_{ff}(\Lambda)/f_a \lesssim (10^{-3} - 10^{-2})\ \mathrm{TeV}^{-1}$, $c_{WW}(\Lambda)/f_a \lesssim (10^{-2} - 1)\ \mathrm{TeV}^{-1}$

Search for $B^+ \to K^+ a$ (ALP): Sensitivity

[arxiv: 2201.06580]

Simplified sensitivity study probing different m_A scenarios for m_A in [5 MeV, 4 GeV]

- **With 0.5 ab⁻¹** limit on $\mathcal{B}(B^+ \to K^+ a) < 10^{-5}$ @ 90 CL → **expected an order of magnitude improvement**
- **With 50 ab⁻¹** limit on $\mathcal{B}(B^+ \to K^+ a) < 10^{-7}$ @ 90 CL → **expected two orders of magnitude improvement**



Belle II near-term plans

- Compare sensitivity of inclusive tagged vs hadronic tagged reconstruction approach for $B^+ \to K^+ a$
- Adapt inclusive tag to favour two-body kinematics
- Perform search for $B^+ \to K^+ a$ / $B \to K^* a$ with pre-shutdown dataset (0.5 ab⁻¹)

Fully reconstructed channels

Towards $b \to sll$ LFU : $R(K^{(*)})$

3.1 σ evidence of LFUV in R(K) reported by LHCb

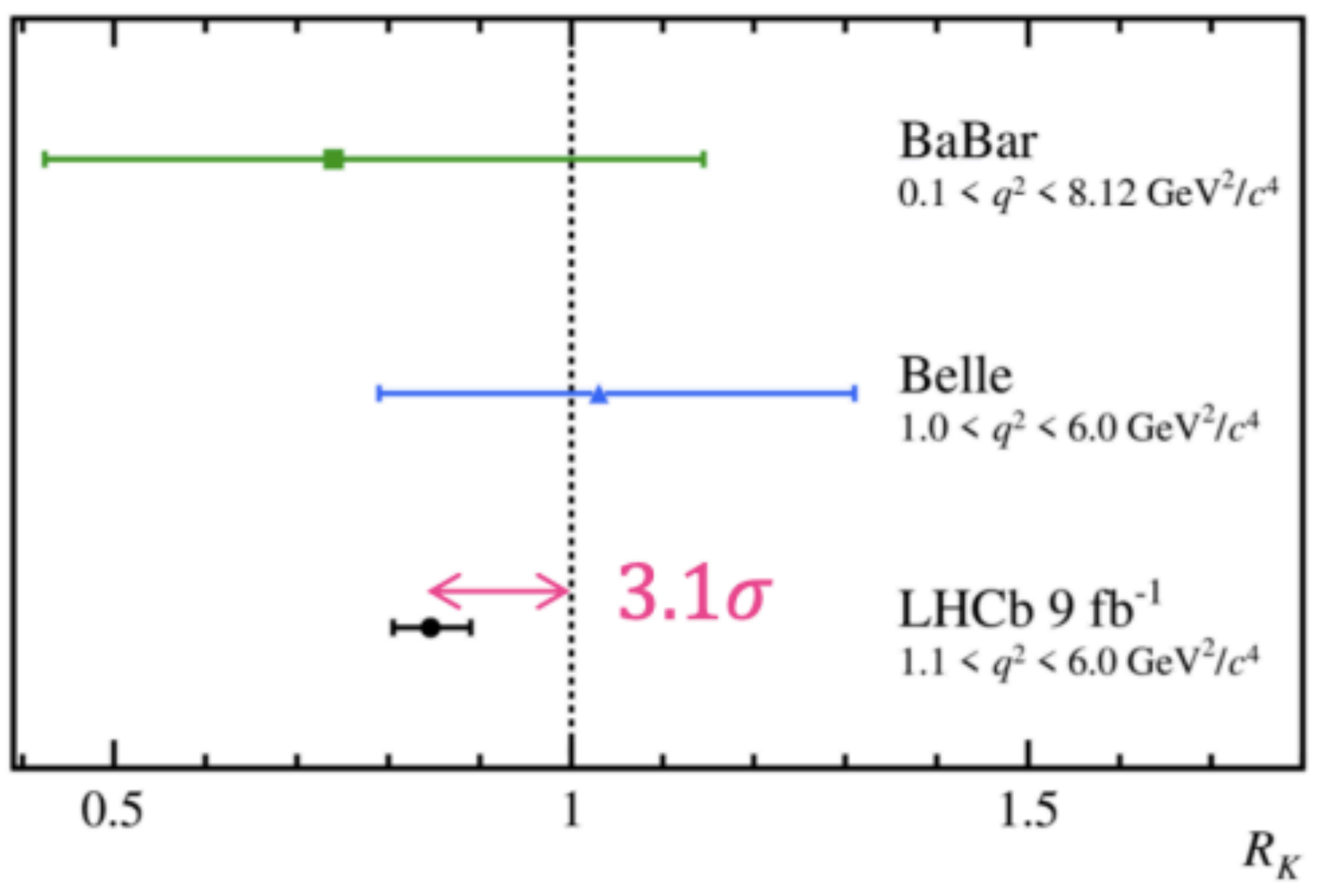
SM

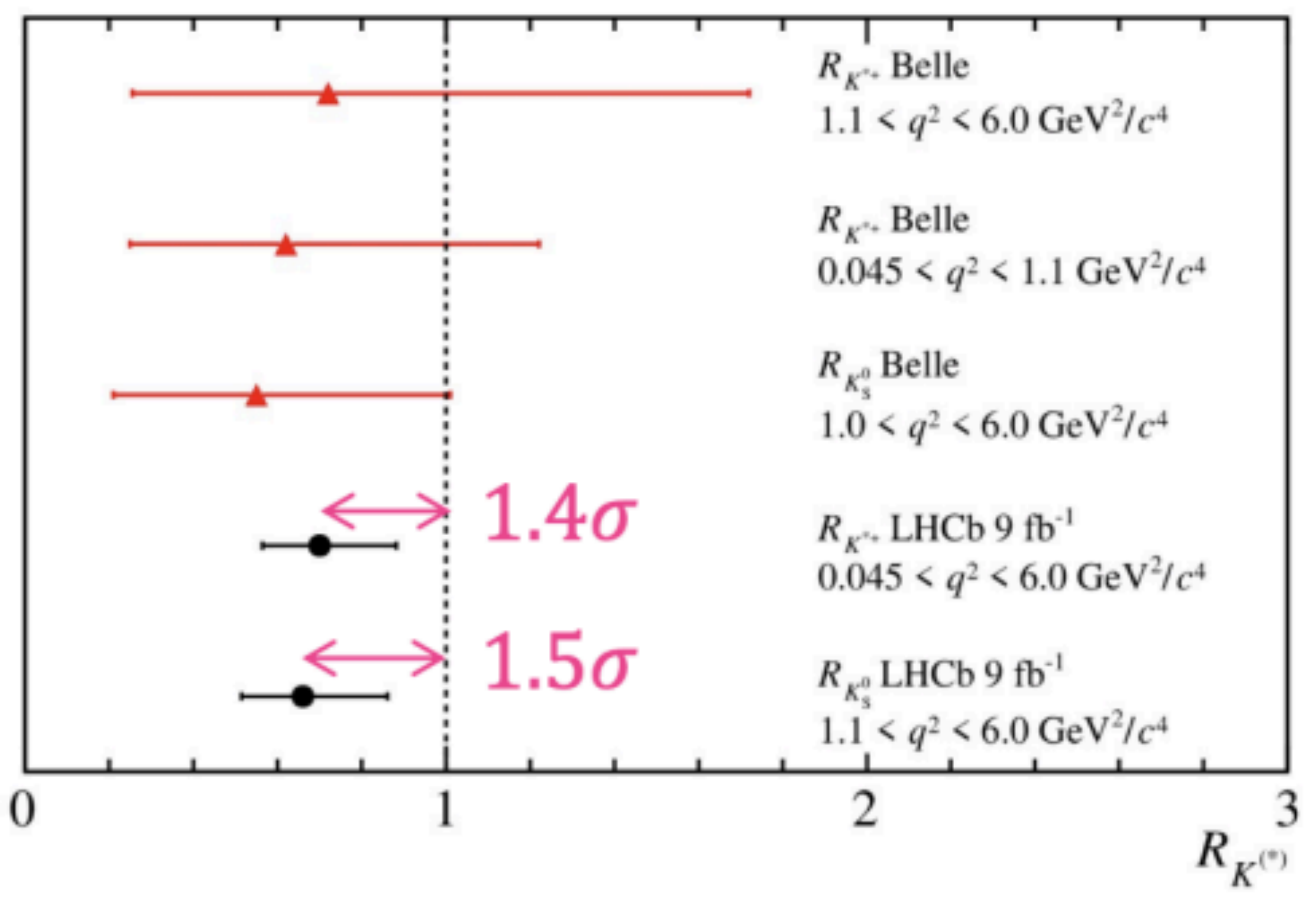
$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} = 1 \pm \mathcal{O}(10^{-2})$$

$q^2 \in [1(1.1), 6]$ for $R(K^{(*)})$

JHEP 2018, 93 (2018)

arXiv:2103.11769, arXiv:2110.09501



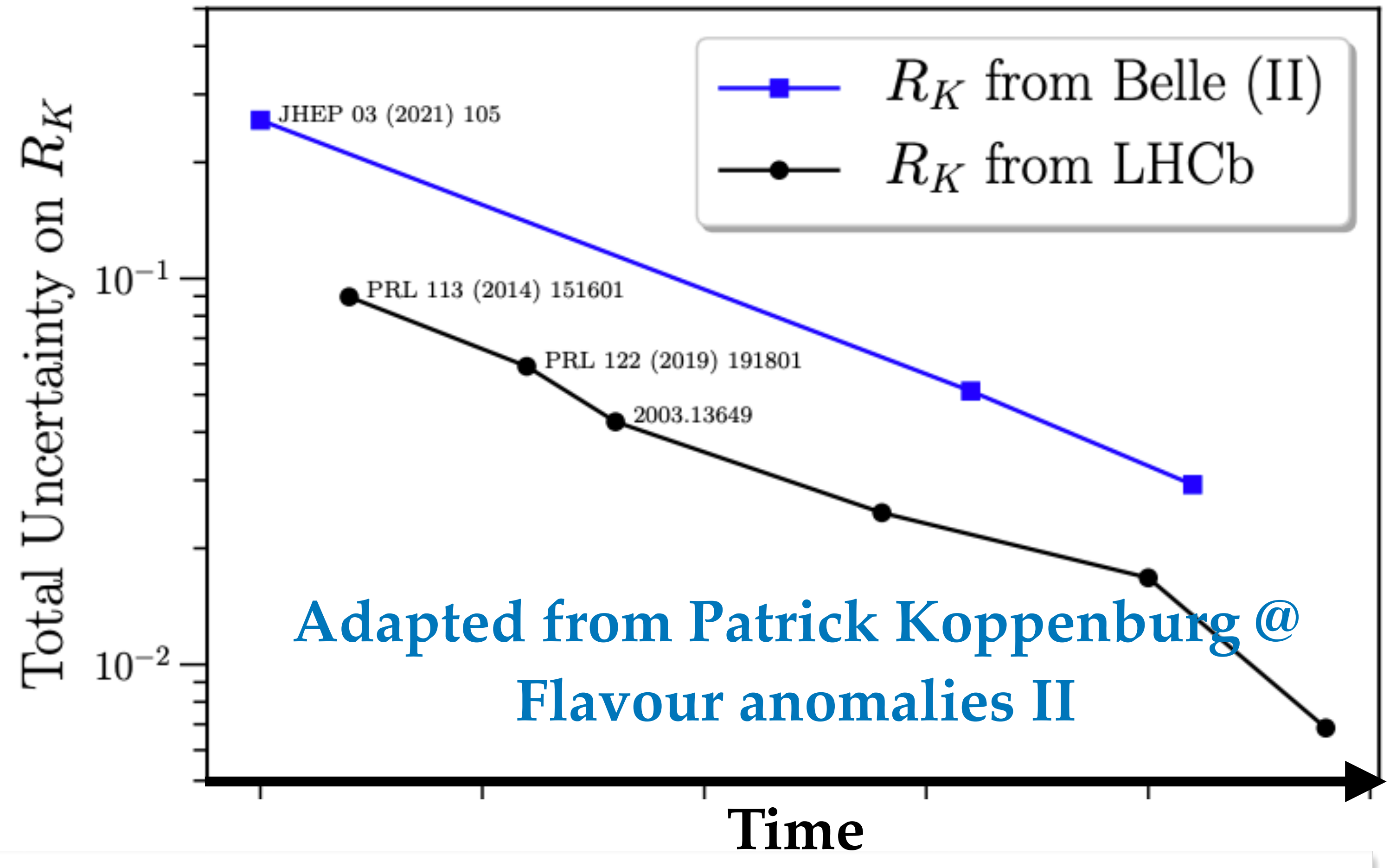


$R(K^{(*)})$ in Belle II

- Statistically limited for foreseeable future
- Then leading systematics due to lepton ID~0.4%

Belle II can:

- Provide independent check of $R(K^{(*)})$ with at least 5 ab^{-1}
- Measure $R(X_s)$
- Measure absolute $\mathscr{B}$ for electron and muon separately (constraint on Wilson coefficient C9)



But LHCb will always be ahead in precision for $R(K^{(*)})$ given LHC's and SuperKEKB's luminosity plans

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Towards $b \to sll$ LFU : $R(K^{(*)})$

3.1 σ evidence of LFUV in R(K) reported by LHCb

SM

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} = 1 \pm \mathcal{O}(10^{-2})$$

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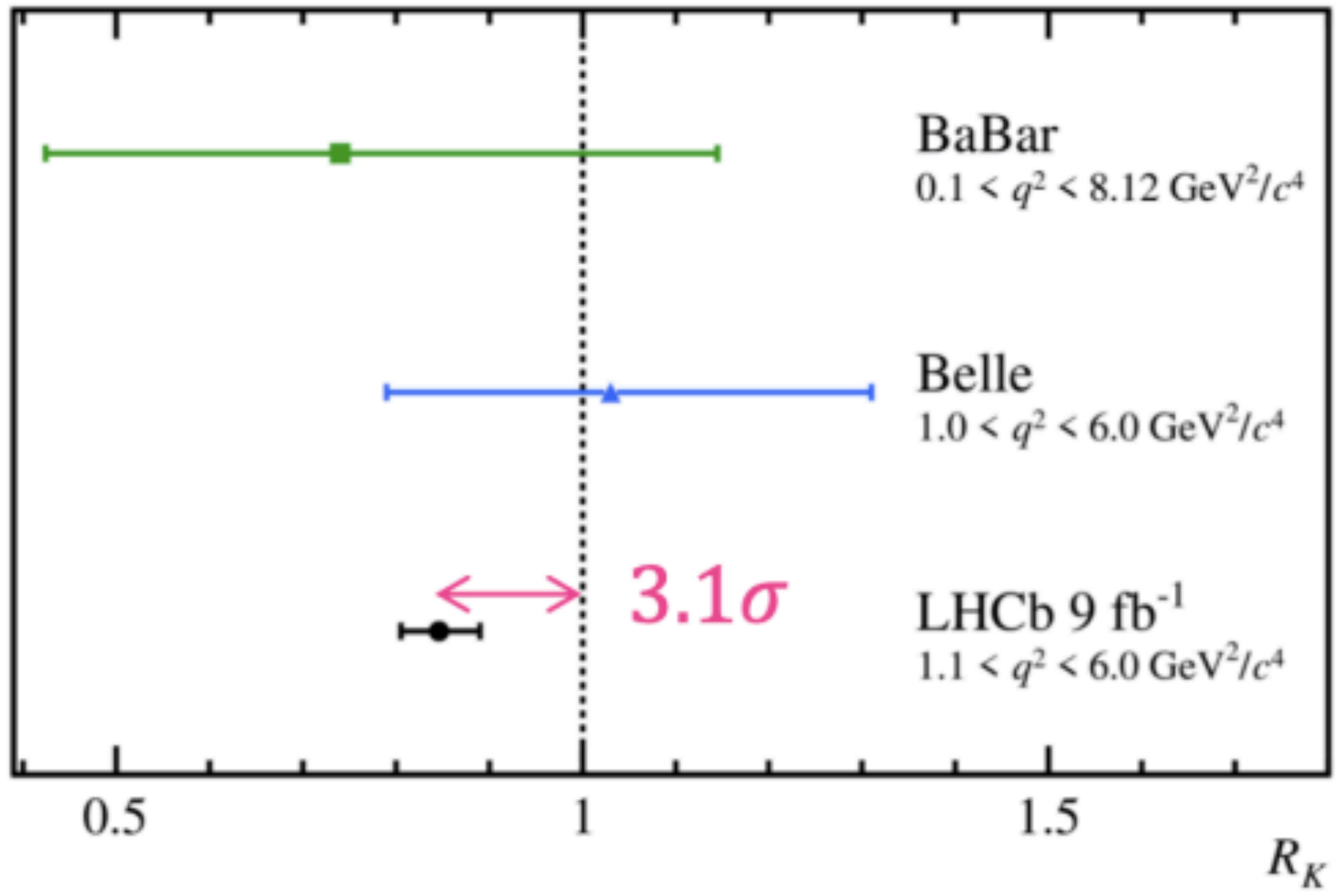
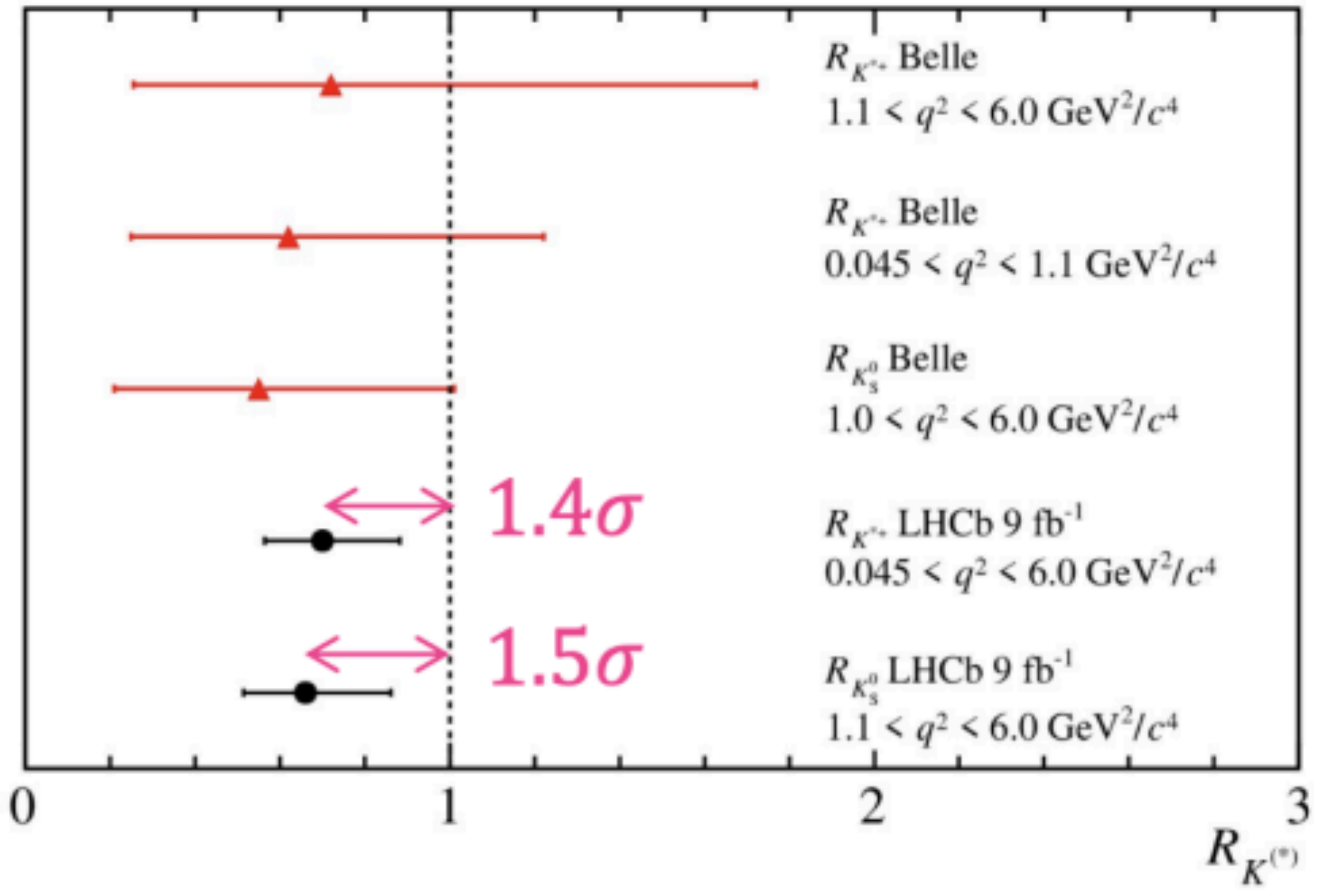
JHEP 2018, 93 (2018)



arXiv:2103.11769, arXiv:2110.09501

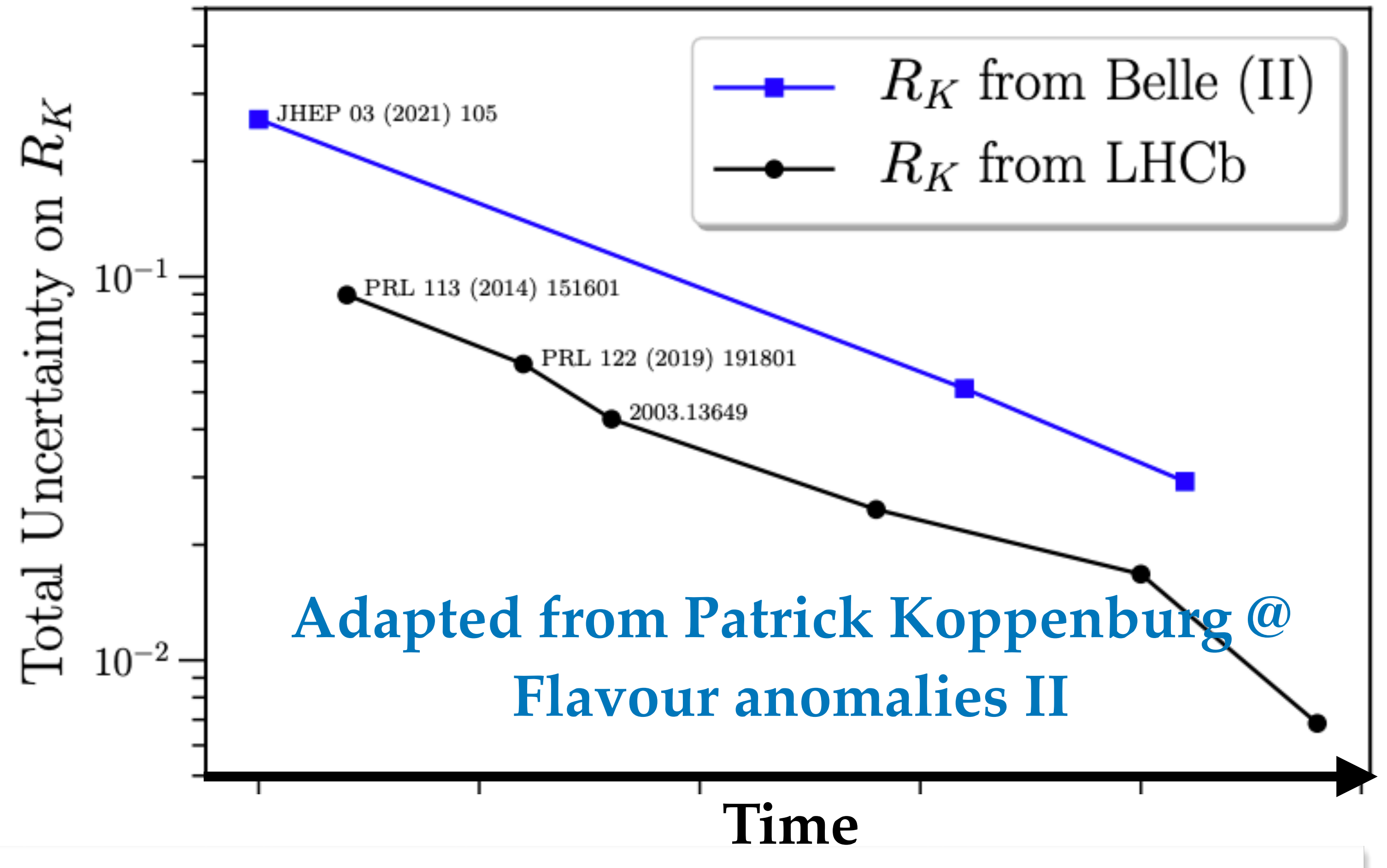


$R(K^{(*)})$ in Belle II

- Statistically limited for foreseeable future
- Then leading systematics due to lepton ID~0.4%
-

Belle II can:

- Provide independent check of $R(K^{(*)})$ with at least 5 ab-1
- Measure $R(X_s)$
- Measure absolute $\mathscr{B}$ for electron and muon separately (constraint on Wilson coefficient C9)



Adapted from Patrick Koppenburg @ Flavour anomalies II

But LHCb will always be ahead in precision for $R(K^{(*)})$ given LHC's and SuperKEKB's luminosity plans

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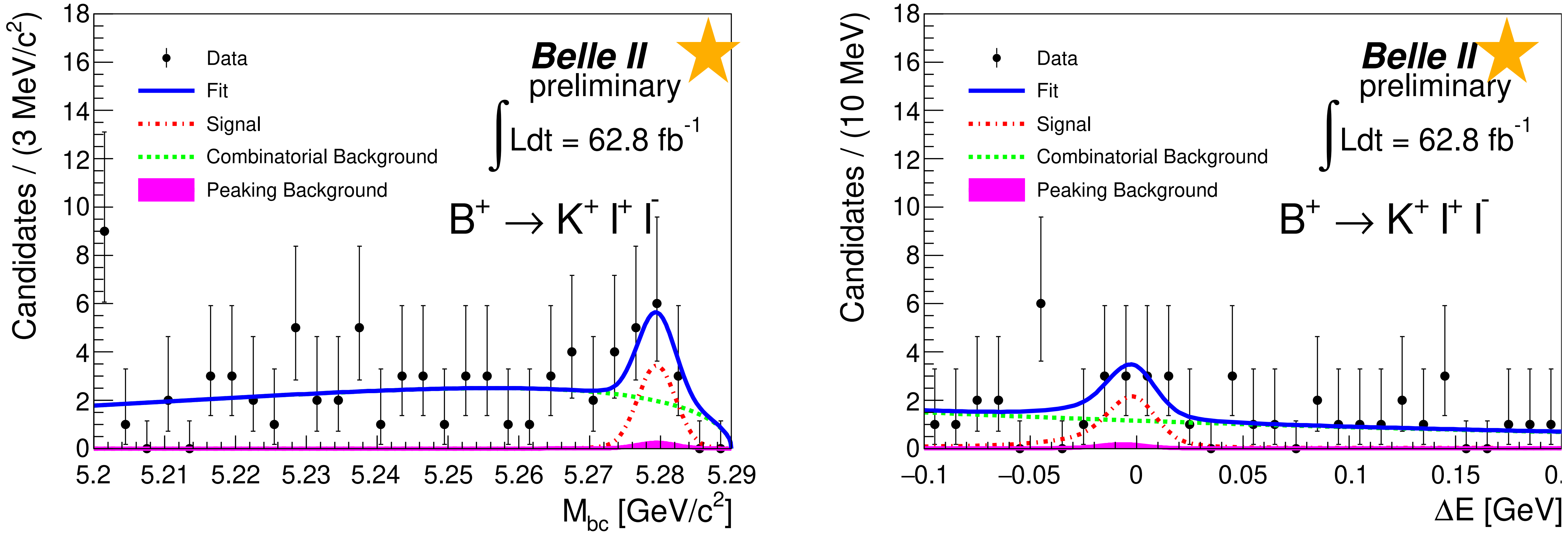
Study of $B \to K(*)ll$

Signal extraction with simultaneous ML fit to M_{bc} and ΔE

Fit projections for $B^+ \to K^+ll$

[BELLE2-NOTE-PL-2021-005]



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

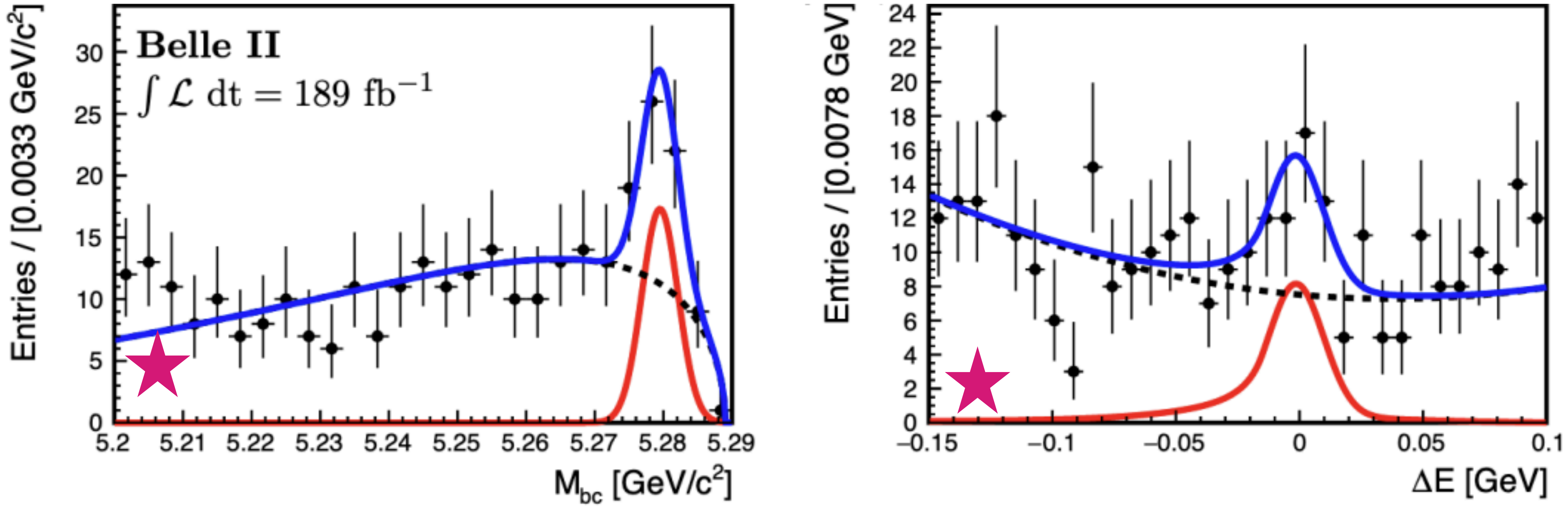
$$\Delta E = E_B - E_{beam}$$

Result

- $N_{sig} = 8.6^{+4.3}_{-3.9}(\text{stat}) \pm 0.4(\text{syst}) \rightarrow$ hint for $B^+ \to K^+ll$

Fit projections for $B \to K^*ll$

($K^* \to K^+\pi^-, K^+\pi^0, K_s^0\pi^+$)



Results

$$\mathcal{B}(B \to K^*\mu\mu) = (1.19 \pm 0.31 \pm^{+0.08}_{-0.07}) \times 10^{-6},$$
$$\mathcal{B}(B \to K^*ee) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6},$$
$$\mathcal{B}(B \to K^*\ell\ell) = (1.25 \pm 0.30 \pm^{+0.08}_{-0.07}) \times 10^{-6},$$

PDG averages

$(1.06 \pm 0.09) \times 10^{-6}$

$(1.19 \pm 0.20) \times 10^{-6}$

$(1.05 \pm 0.10) \times 10^{-6}$

Electron channel expected to become competitive already with 1 ab^{-1}

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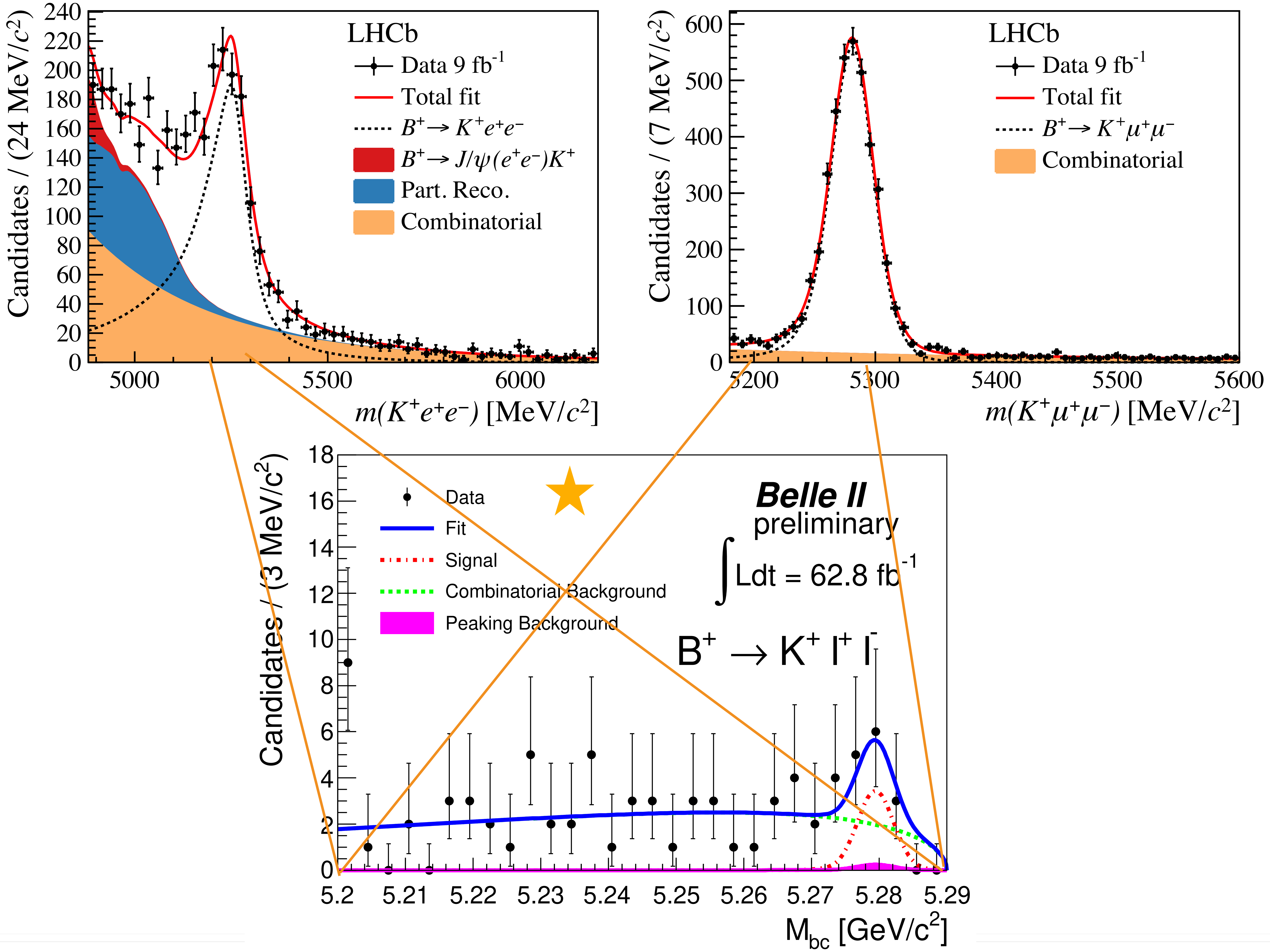
$R(K)$: Belle II vs LHCb (Aside)

[Nature Physics volume 18, pages 277–282 (2022)]



Three differing aspects to consider: efficiency, statistics and resolution

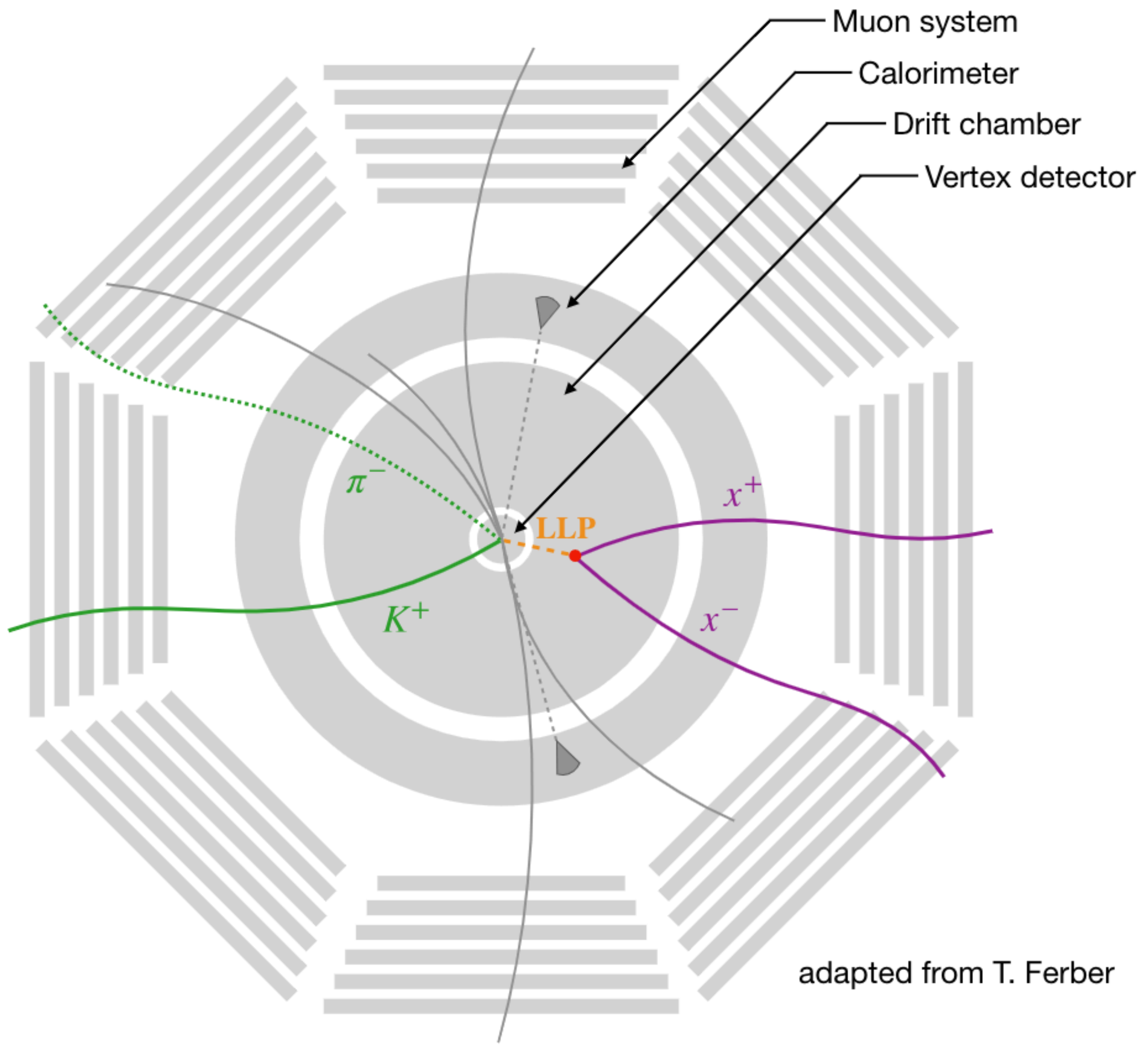
	Belle II	LHCb
Signal	K^+, K_s	K^+
Same $B^+\to K^+e^+e^-$ Efficiency	1 ab^{-1}	1 fb^{-1}
$B^+\to K^+\mu^+\mu^-$ Efficiency	30 % (Belle) [JHEP 03 (2021) 105]	~5 %
$B^+\to K^+e^+e^-$ Efficiency	30 % (Belle) [JHEP 03 (2021) 105]	<5% Lower due to tracking and trigger
High q^2 bin	Accessible	Hard
Kinematic vertex constraint	M_{bc}	Pointing to PV

Electrons (and muons) in Belle II have better resolution result of kinematic vertex constraints + Bremsstrahlung effects

Search for $B \to K^{(*)}S$ (LLP)

Search for $B \to K^{(*)}$ S

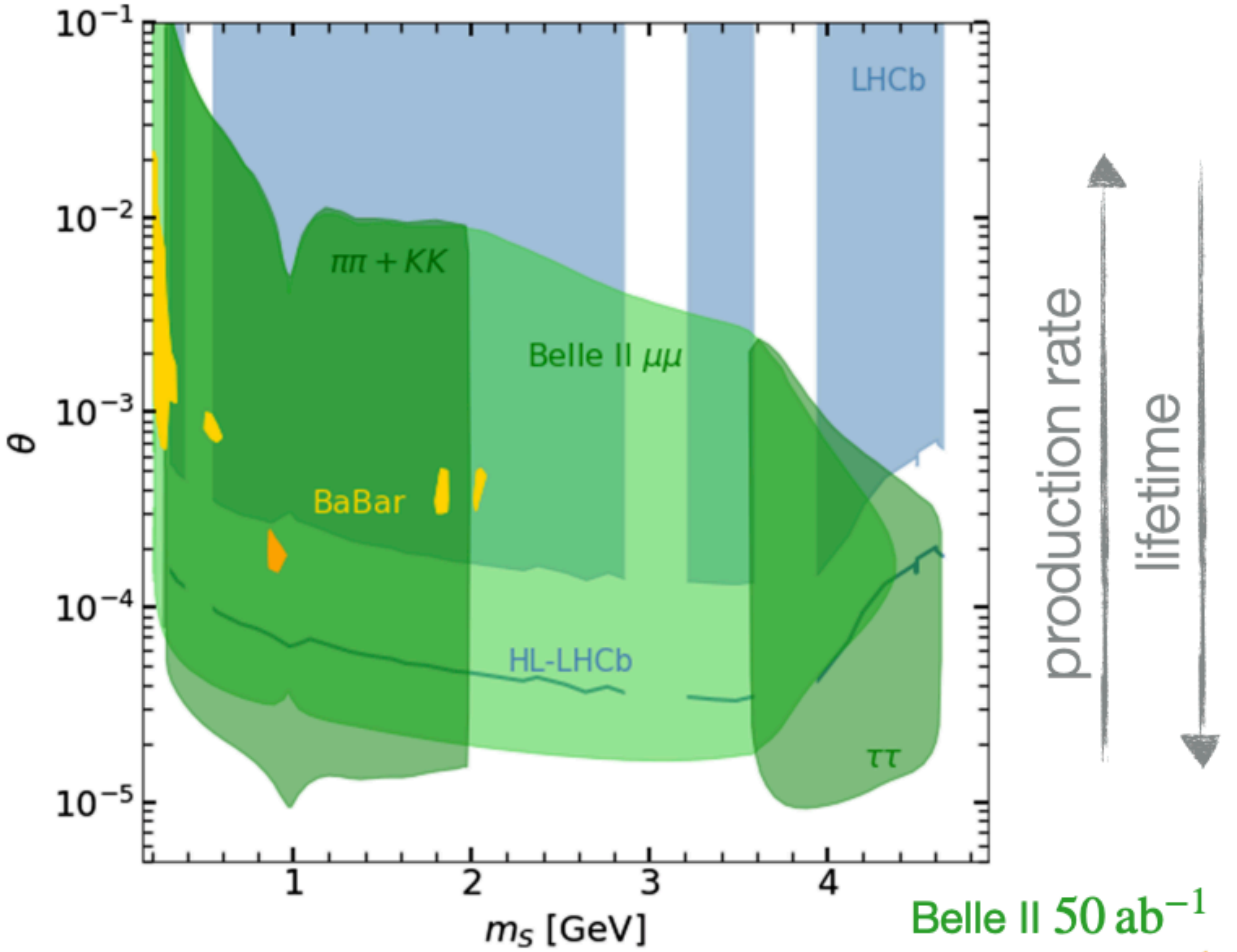
- S (= long-lived scalar particle = LLP) that decays visibly into pair of charged particles $x^+, x^-, x \in (e, \mu, \pi, K)$
- Bump hunt in the LLP invariant mass
- Separately for $x \in (e, \mu, \pi, K)$
- Separately for different lifetimes



adapted from T. Ferber

Current bounds and predictions

A. Filimonova, R. Schäfer, S. Westhoff



Belle II 50 ab^{-1}
BaBar 489 fb^{-1}
LHCb 3 fb^{-1}

Phys. Rev. D 101, 095006 (2020)

Prediction does not contain e^+e^- channel

Conclusion

Belle II

- is accumulating high quality data
- is well suited to study rare B-decays with (multiple) invisible particles
- has unique reach for light DM
- will provide competitive and independent checks of $b \to sll$ channels where anomalies were reported (electron modes)

Rare B-decays with invisible particles are challenging but fun!

- heavily suppressed in SM, but BSM models can enhance observables such as $\mathscr{B}$ significantly
- once the $\mathscr{B}$ of these channels are measured, start the theoretically cleaner precision measurements (angular variables, LFU tests)

Belle II made its first footprint

- search for $B^+ \to K^+\nu\bar{\nu}$ = first Belle II B-physics paper employing novel inclusive tagging approach
  sets highly competitive limit with "only" 1/10 of previous B-factory dataset

But what about?

- Other missing energy modes (eg. $B \to l\nu, B \to l\nu\gamma$), $b \to d$ transitions (e.g $B \to \pi\nu\nu$)
- Other LFV channels: e.g $B \to K\mu e, B \to K^*\mu e$
- DM: other DM candidates, other signatures (e.g $B \to Ka(\to \gamma\gamma)$)

NEXT TIME!

BACKUP

Other Belle II highlights (Moriond 2022)

Towards $sin(2\beta)$

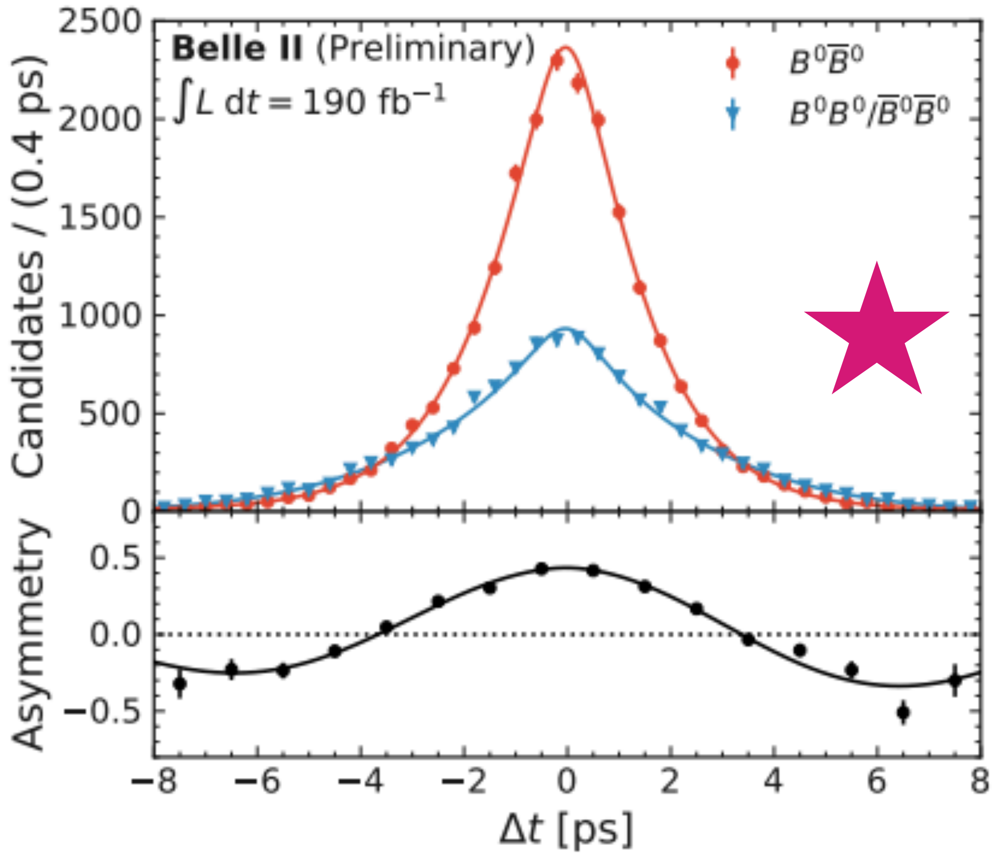
- Mixing and lifetime measurement → not yet competitive but will provide $\sin(2\beta)$
- $B^0 \to K_s^0\pi^0 \to$ unique to Belle II

Result compatible with world average:

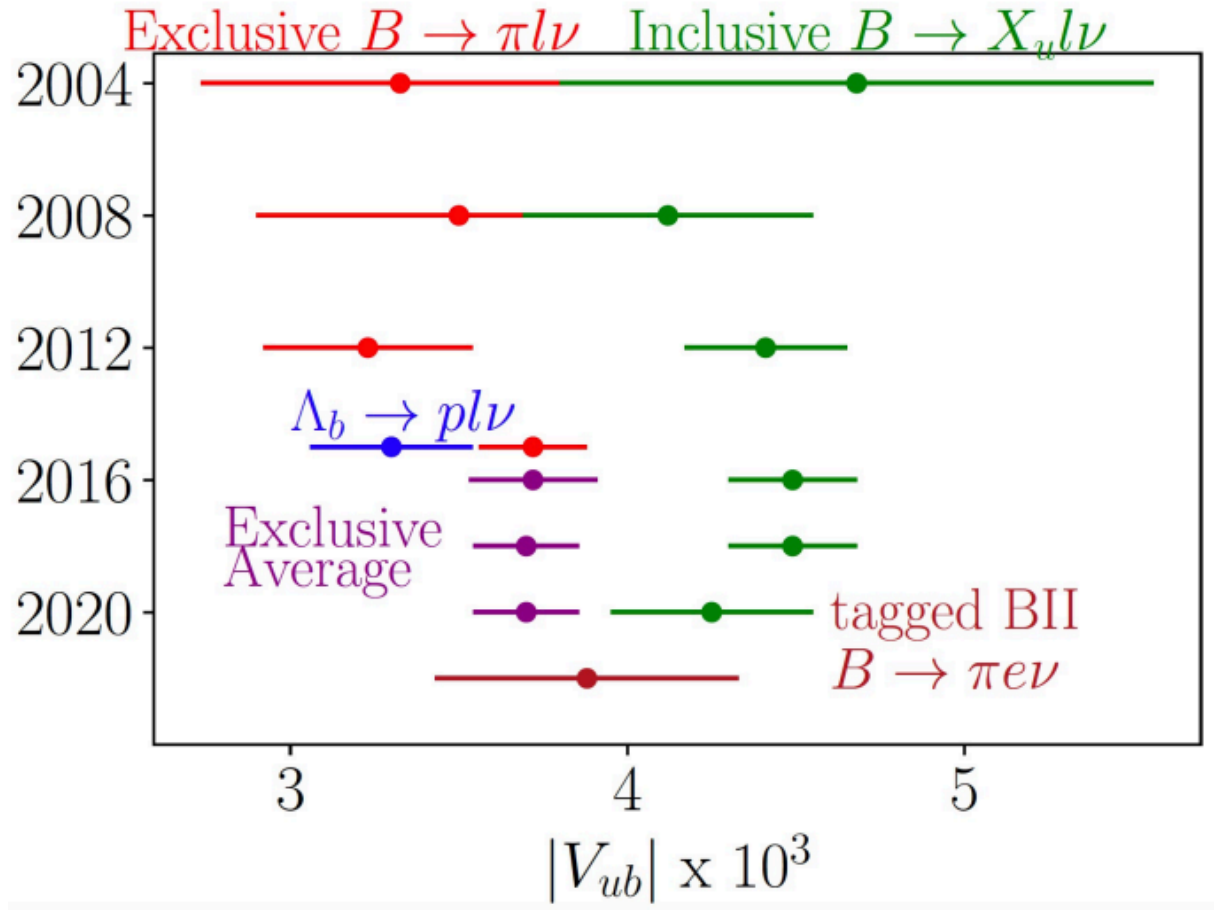
$$\tau_{B^0} = 1.499 \pm 0.013\,(\text{stat.}) \pm 0.008\,(\text{syst.})\ \text{ps},$$
$$\Delta m_d = 0.516 \pm 0.008\,(\text{stat.}) \pm 0.005\,(\text{syst.})\ \text{ps}^{-1}.$$

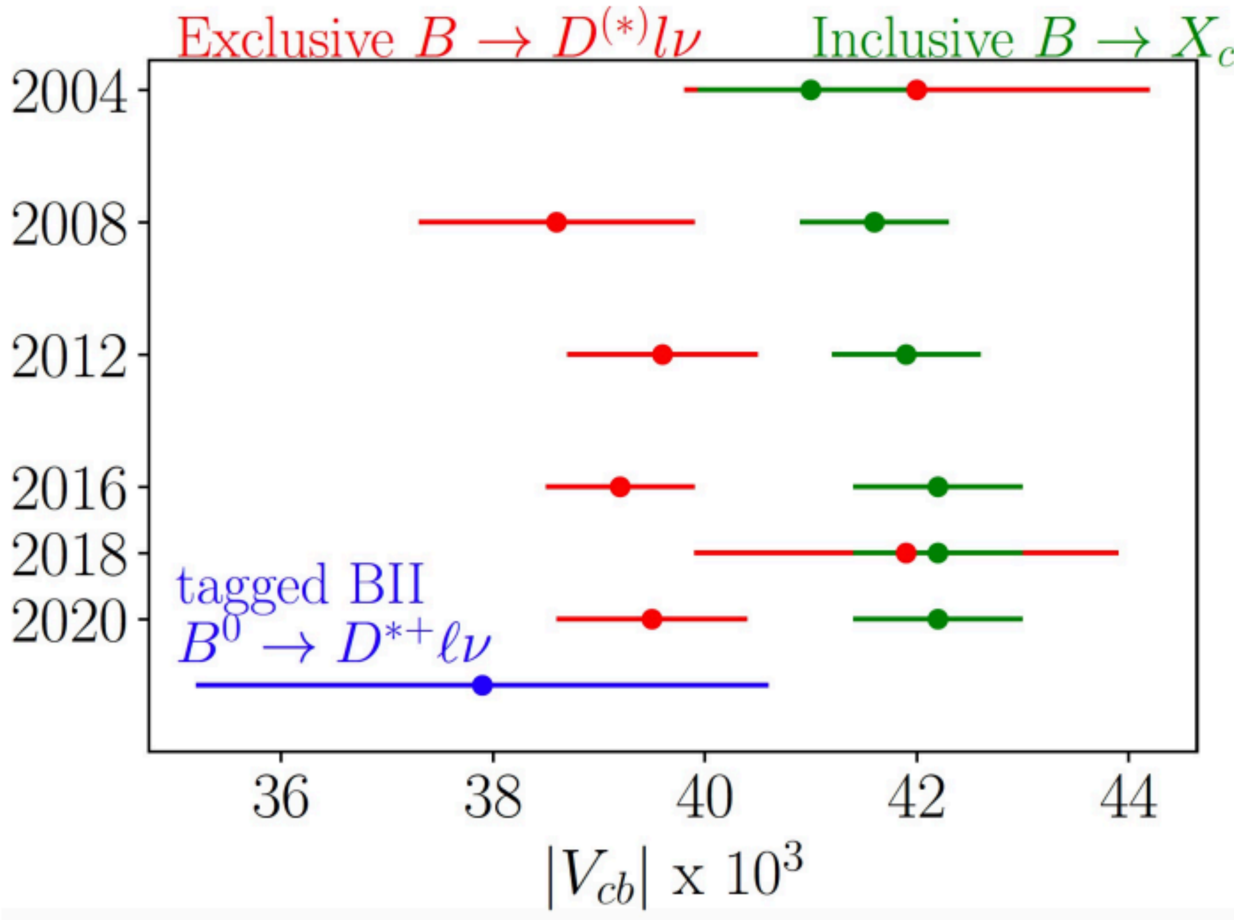
Compared to Belle and BaBar's best measurement:

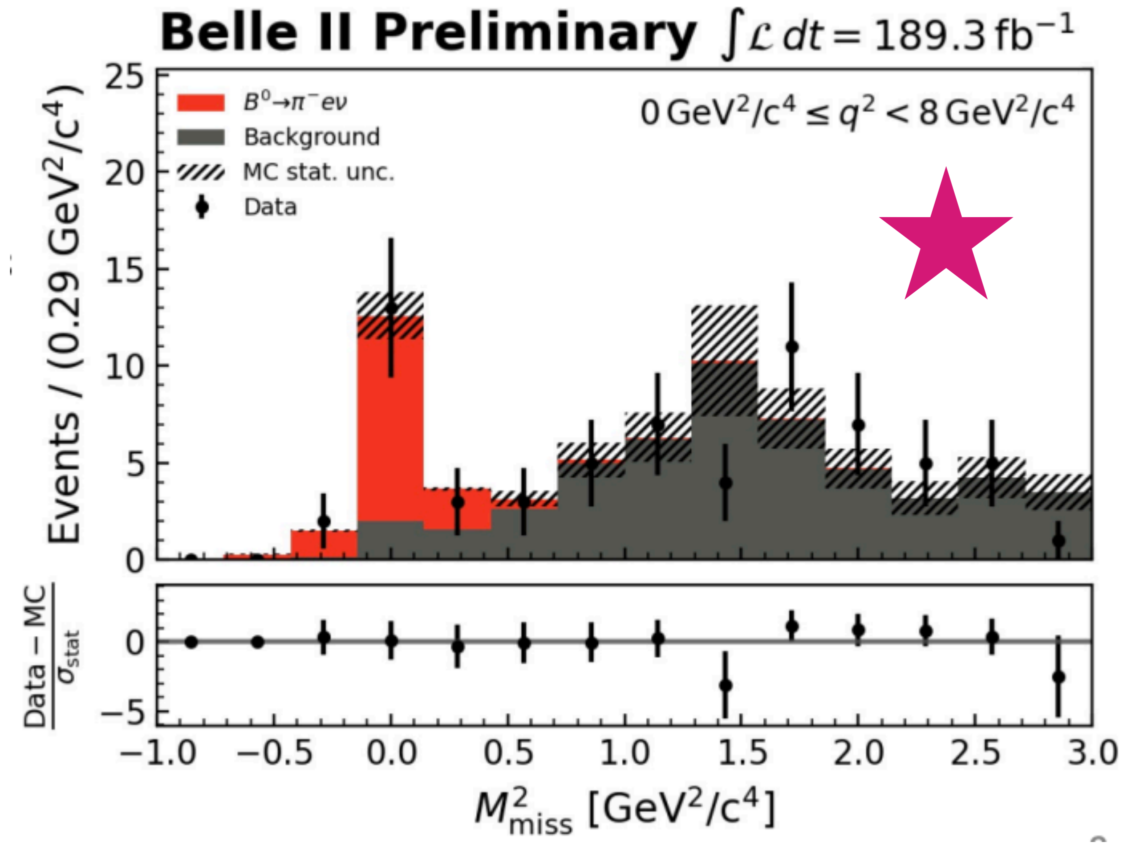
- Slightly worse stat. uncertainty because not using $B^0 \to D^{*-}\ell^+\nu$ modes yet.
- better alignment and background systematics.
- comparable resolution modelling systematics.



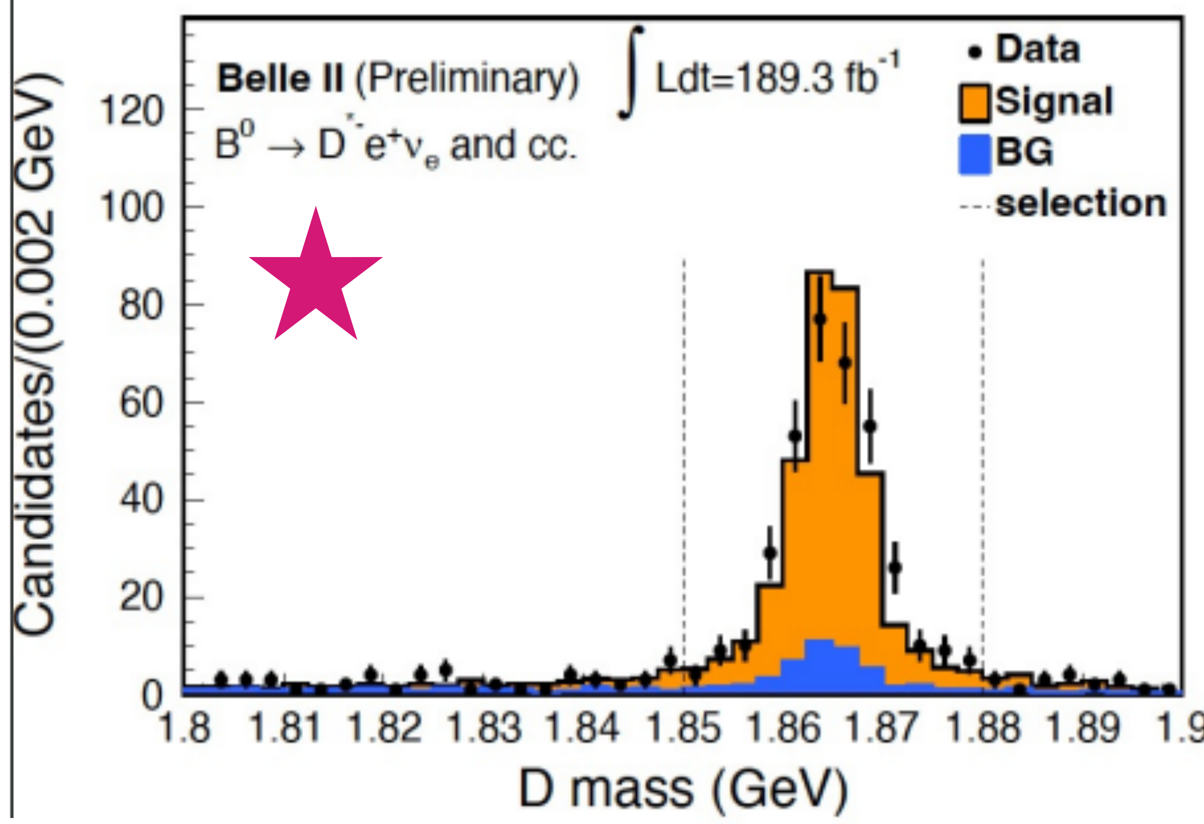
|Vub|/|Vcb| puzzles

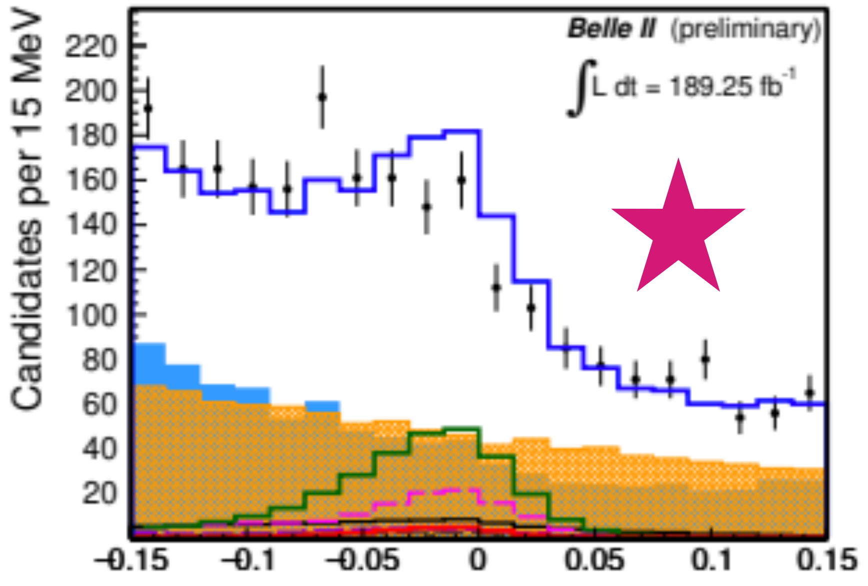






$$M^2_{\text{miss}} = \left(p_{e^+e^-} - p_{B_{\text{tag}}} - p_e - p_\pi\right)^2$$





$$\Delta E = E_B^* - E_{\text{beam}}^*\ [\text{GeV}]$$

Towards CKM angle α

Result compatible with previous measurements:

$$A_{CP} = -0.069 \pm 0.068\,(\text{stat.}) \pm 0.060\,(\text{syst.})$$
$$\mathcal{B}(B^+ \to \rho^+\rho^0) = (23.2^{+2.2}_{-2.1}\,(\text{stat.}) \pm 2.7\,(\text{syst.})) \times 10^{-6}$$
$$f_L = 0.943^{+0.035}_{-0.033}\,(\text{stat.}) \pm 0.027\,(\text{syst.})$$

World average: $A_{CP} = -0.05 \pm 0.05$

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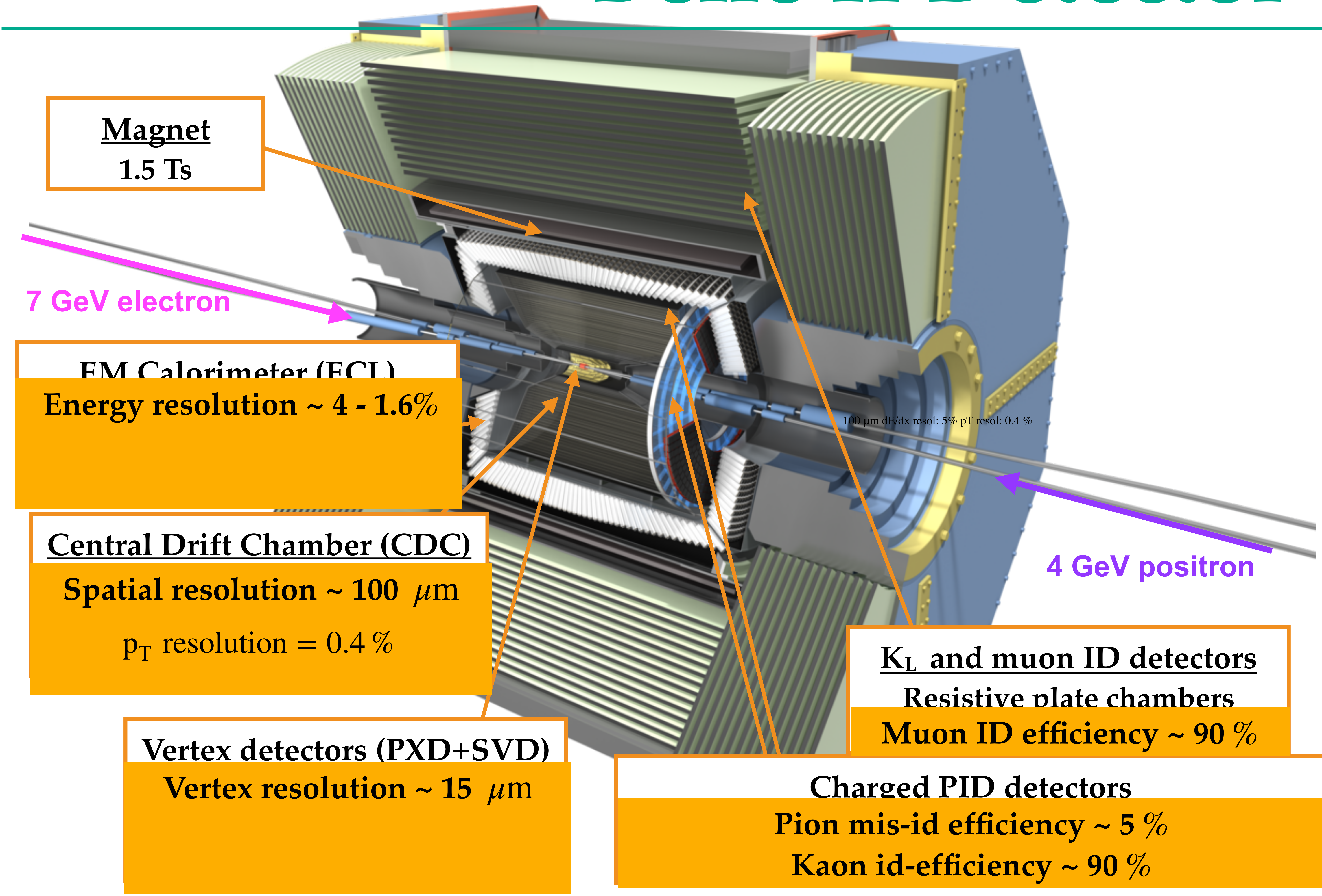
Belle II Detector



Search for $B^+ \to K^+\tau\, l$ (Aside)

Hadronic FEI tagging

- $\tau \to \pi/\rho/e/\mu$ decays
- $l = \{e, \mu\}$
- Fit to m_τ distributions

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

$E_B^* = E^*_{beam}$

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

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

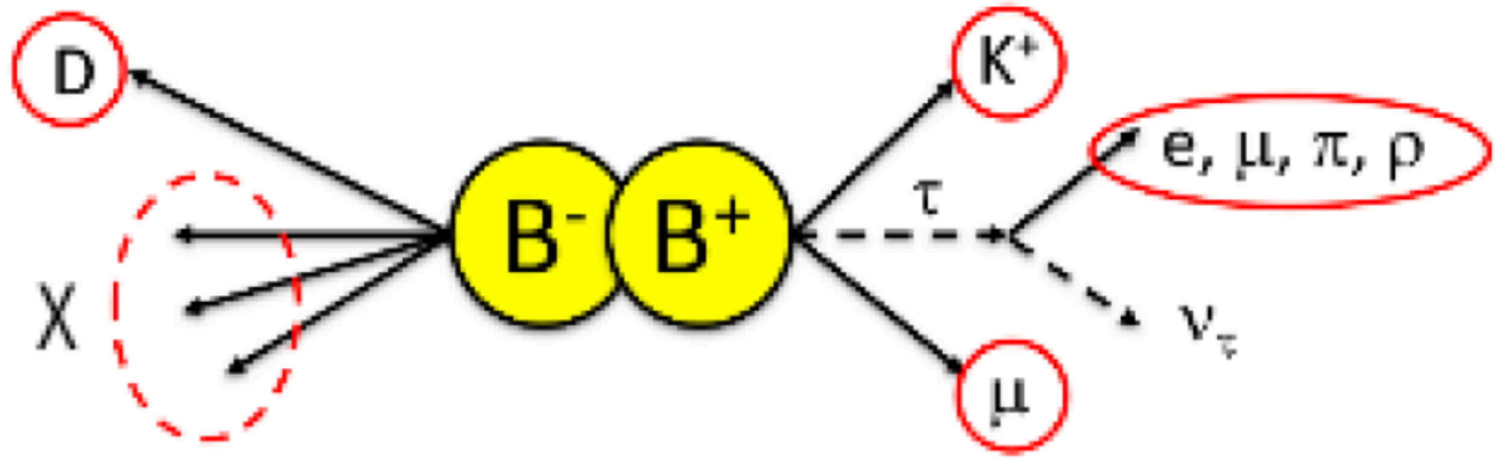
- Control samples:
  - $B^+ \to D^-(\to K^+\pi^-\pi^-)\pi^+\pi^+$,
  - $B^+ \to J/\psi(\to \ell\ell)K^+$

Semileptonic FEI tagging

- Recoil mass still peaks at m_τ but the resolution is a factor ~2-3 worse
- High efficiency but worse resolution

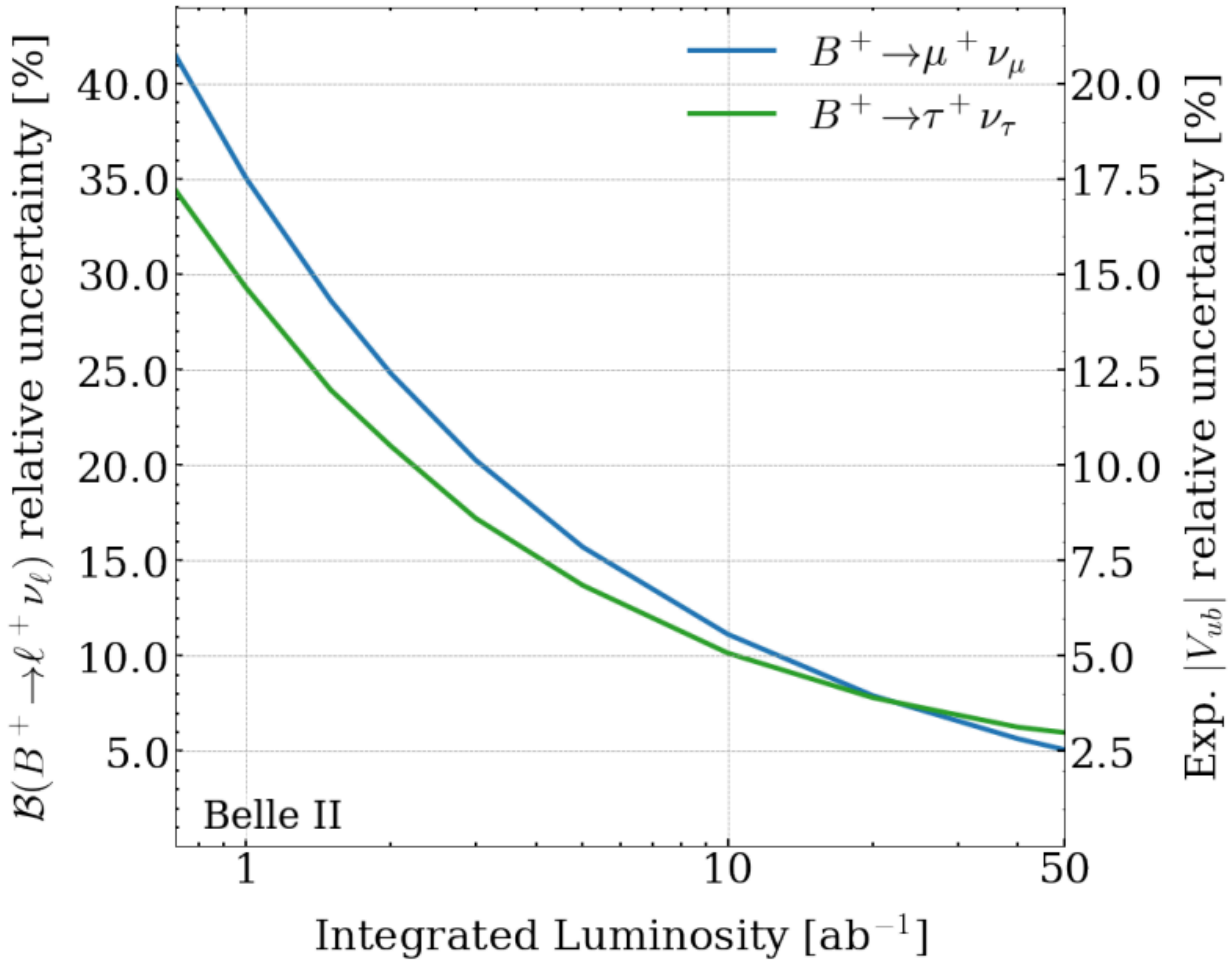
Other tagging approaches

- Measure $\mathscr{B}(B^+ \to K^+\tau\, l)$ exploiting high $\mathscr{B}$ of $B^- \to \overline{D}^0 X = 79 \pm 4\,\%$
  - Reconstruct B_{tag} D^0
  - Reconstruct signal's K and l, and τ
  - D^0X provides the tag-side
- Fit also to m_τ



$B \to l\,\nu$

Belle II snowmass paper



$B \to \tau\nu_\tau$, $B \to \mu\nu_\mu$, and $B \to e\nu_e$

1×10^{-4}, 4×10^{-7} and 9×10^{-12} in the SM

$\mathcal{B}(B \to \tau\nu_\tau) = (1.06 \pm 0.19) \times 10^{-4}$ and $\mathcal{B}(B \to \mu\nu_\mu) < 8.6 \times 10^{-7}$ and $\mathcal{B}(B \to e\nu_e) < 9.8 \times 10^{-7}$ at 90% confidence level