Search for $B^+ \to K^+\nu\bar{\nu}$ decays

[PRL 127, 181802 (2021)]

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Seminar
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Bundesministerium
für Bildung
und Forschung

Belle II

Karlsruher Institut für Technologie

Institut für Experimentelle Teilchenphysik

Outline

SuperKEKB

Belle II
+
Performance

Luminosity

Rare B-decays with neutrinos at Belle II

(Theoretical) Motivations

Search for $B^+ \to K^+ \nu \bar{\nu}$ decays with inclusive tagging

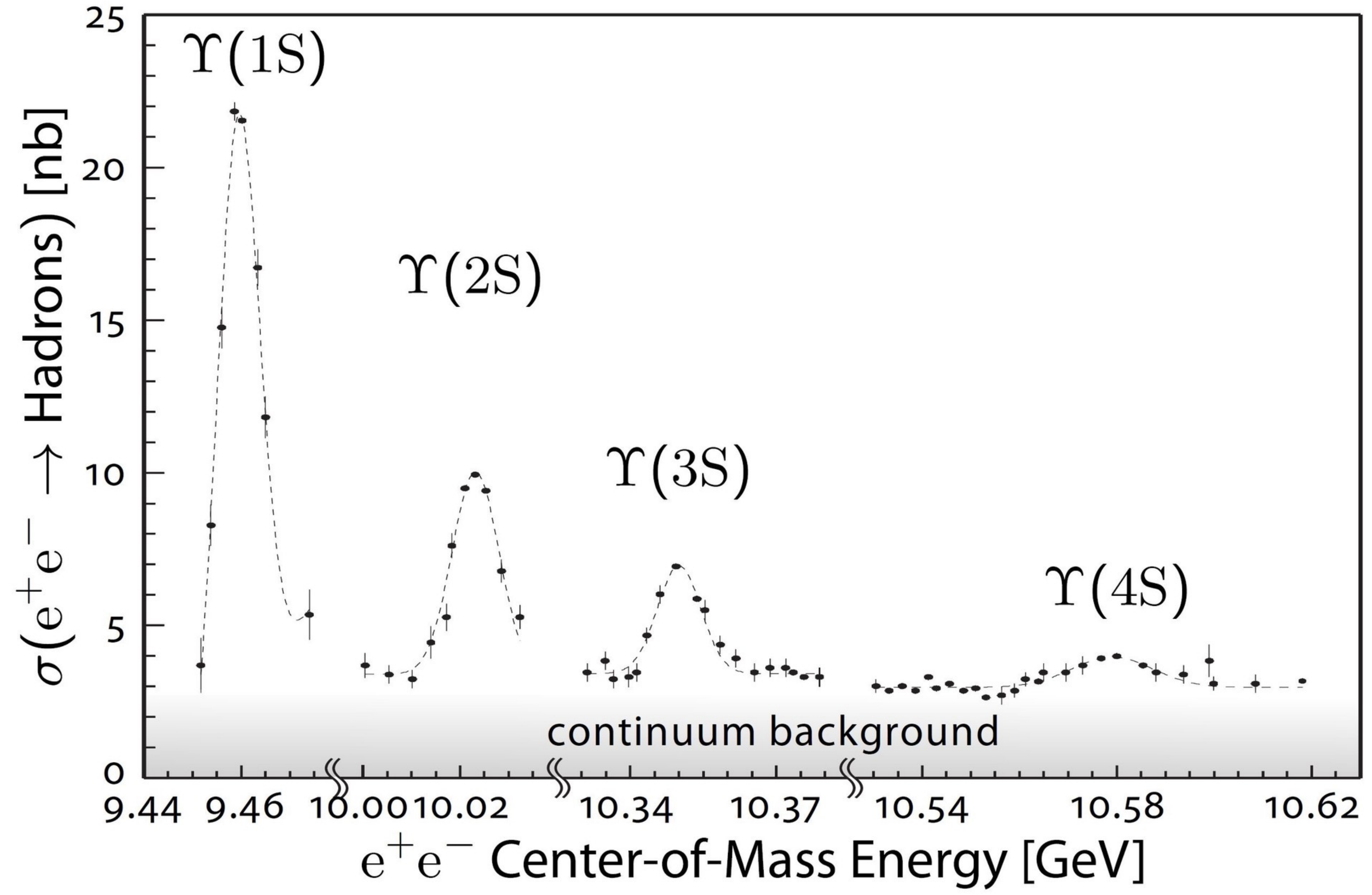
[PRL 127, 181802 (2021)]

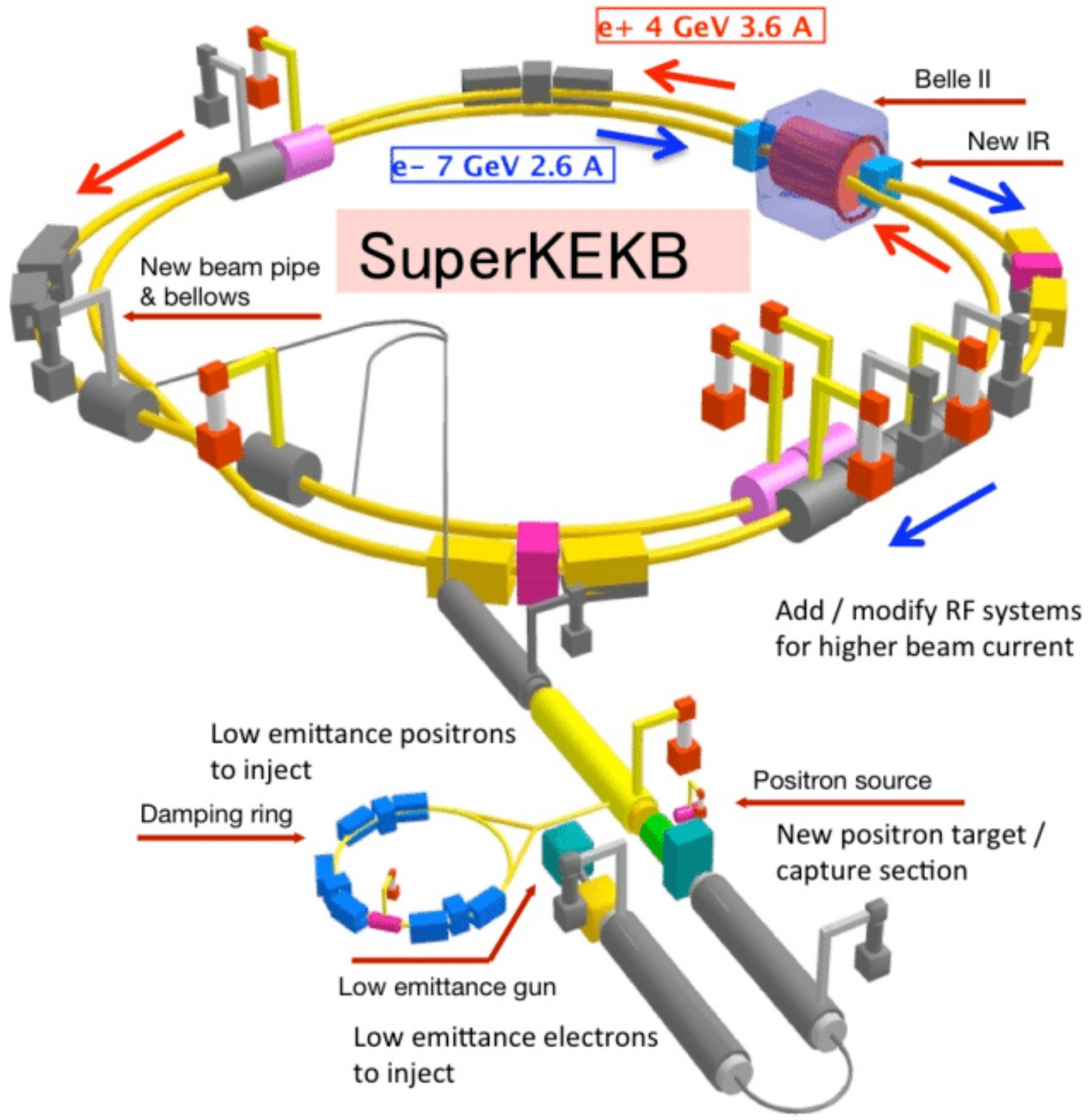
Prospects

SuperKEKB

Energy asymmetric e^+e^--collider in Tsukuba, Japan

- $\sqrt{s} = 10.58$ GeV$\rightarrow$ ($\Upsilon(4S) \rightarrow B\bar{B}$) + nothing w/ $\mathscr{B} > 96\,\%$
  $\rightarrow$ clean B sample **(on-resonance)**
- $\sqrt{s} = 10.52$ GeV $\rightarrow$ control sample to constrain continuum backgrounds $e^+e^- \rightarrow q\bar{q}$, where $q = (u, d, s, c)$ **(off-resonance)**
- Other $\sqrt{s}$
- Operating with continuous injection scheme





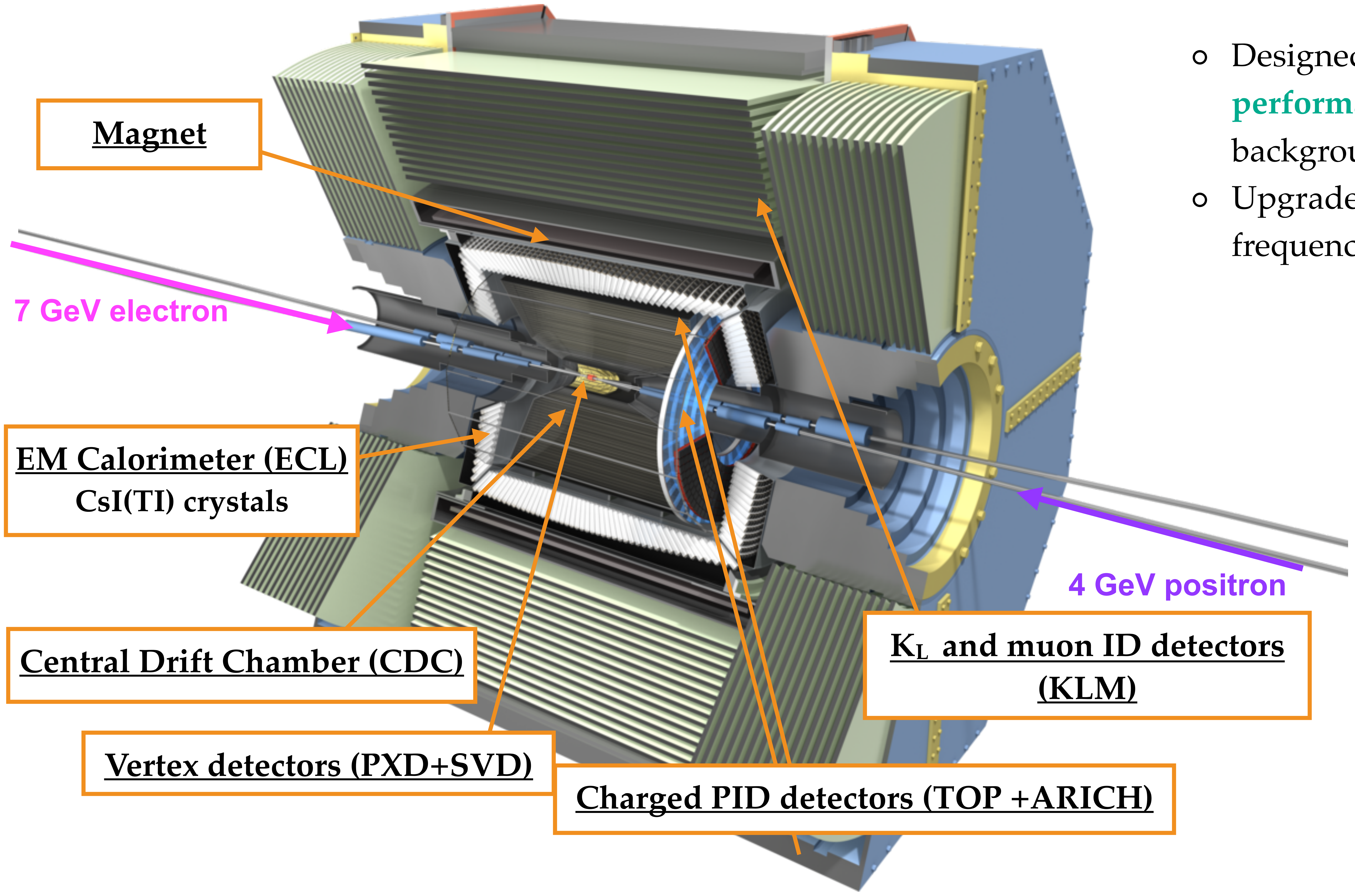
SuperKEKB in not only a *B*-factory

- τ and c pairs have high cross-section at $\sqrt{s} = 10.58$ GeV

Comparison to KEKB

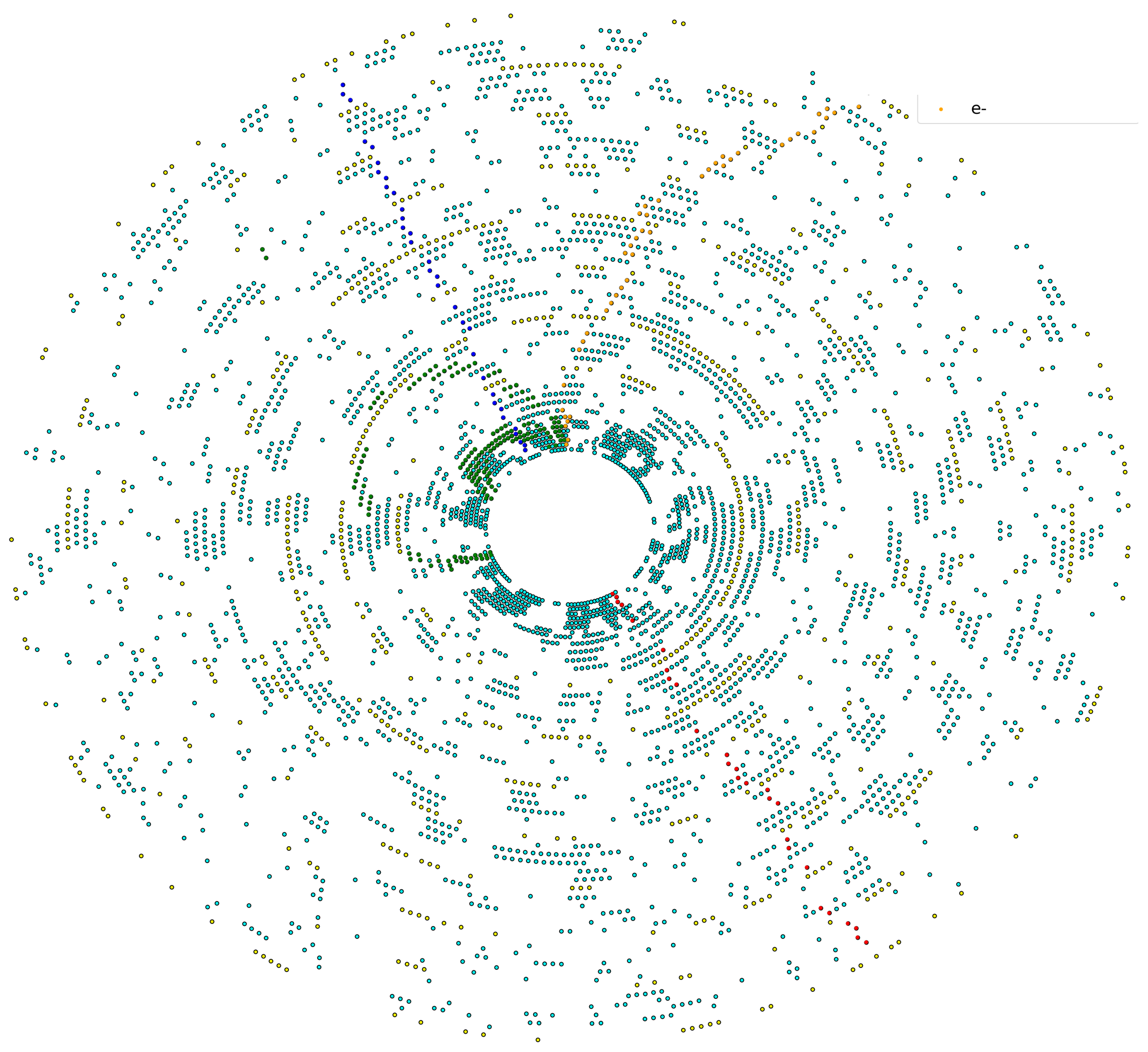
- With nano-beam scheme and upgraded rings SuperKEKB aims to reach $30 \times \mathscr{L}_{inst}$ higher at cost of $\mathcal{O}(10) \times$ higher backgrounds:
  - x 1.5 currents
  - x 1/20 vertical beam size

Belle II Detector



- 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)

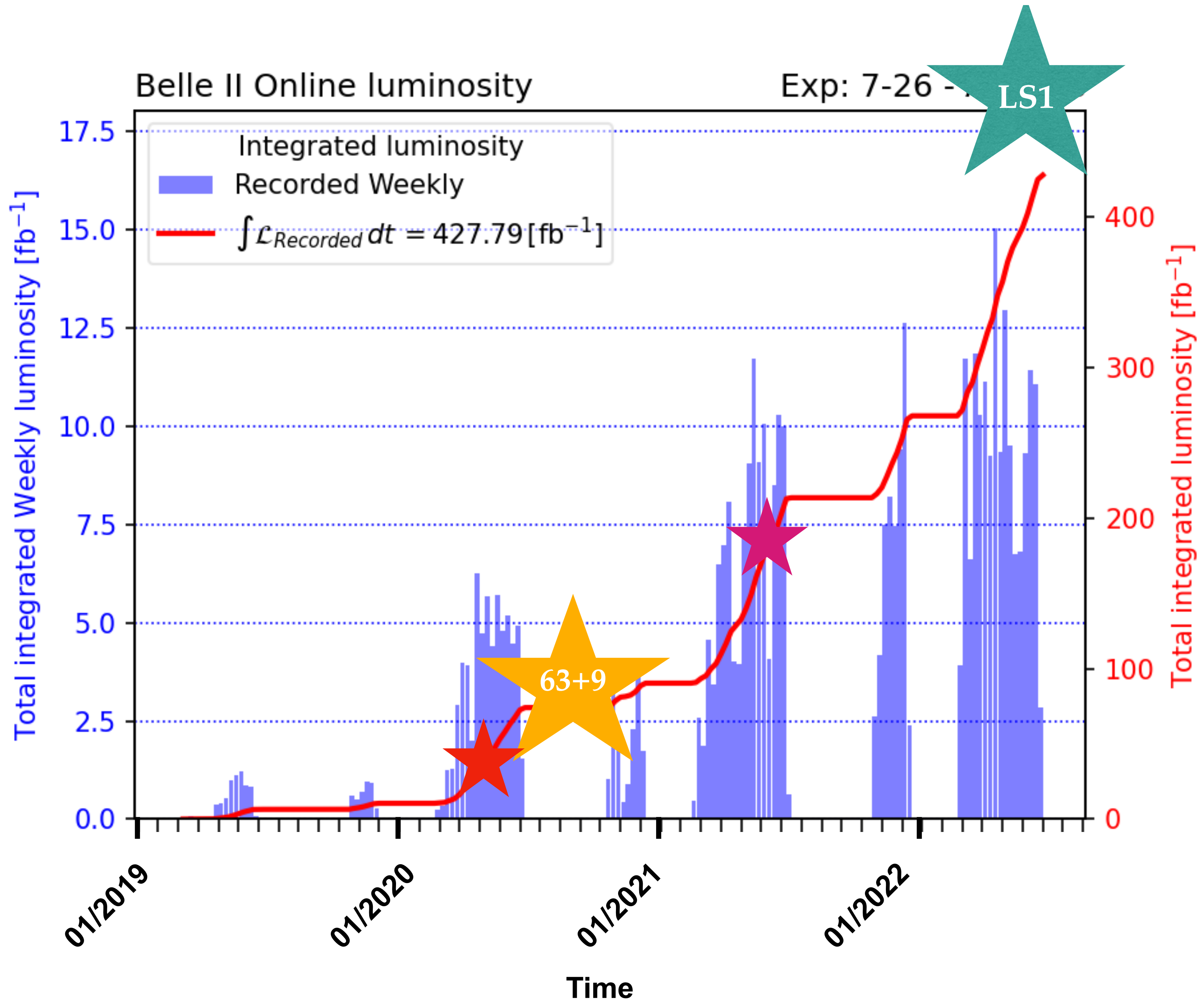
Simulated $e^+e^- \to \mu^+\mu^-$ event with high luminosity backgrounds (CDC x-y view)

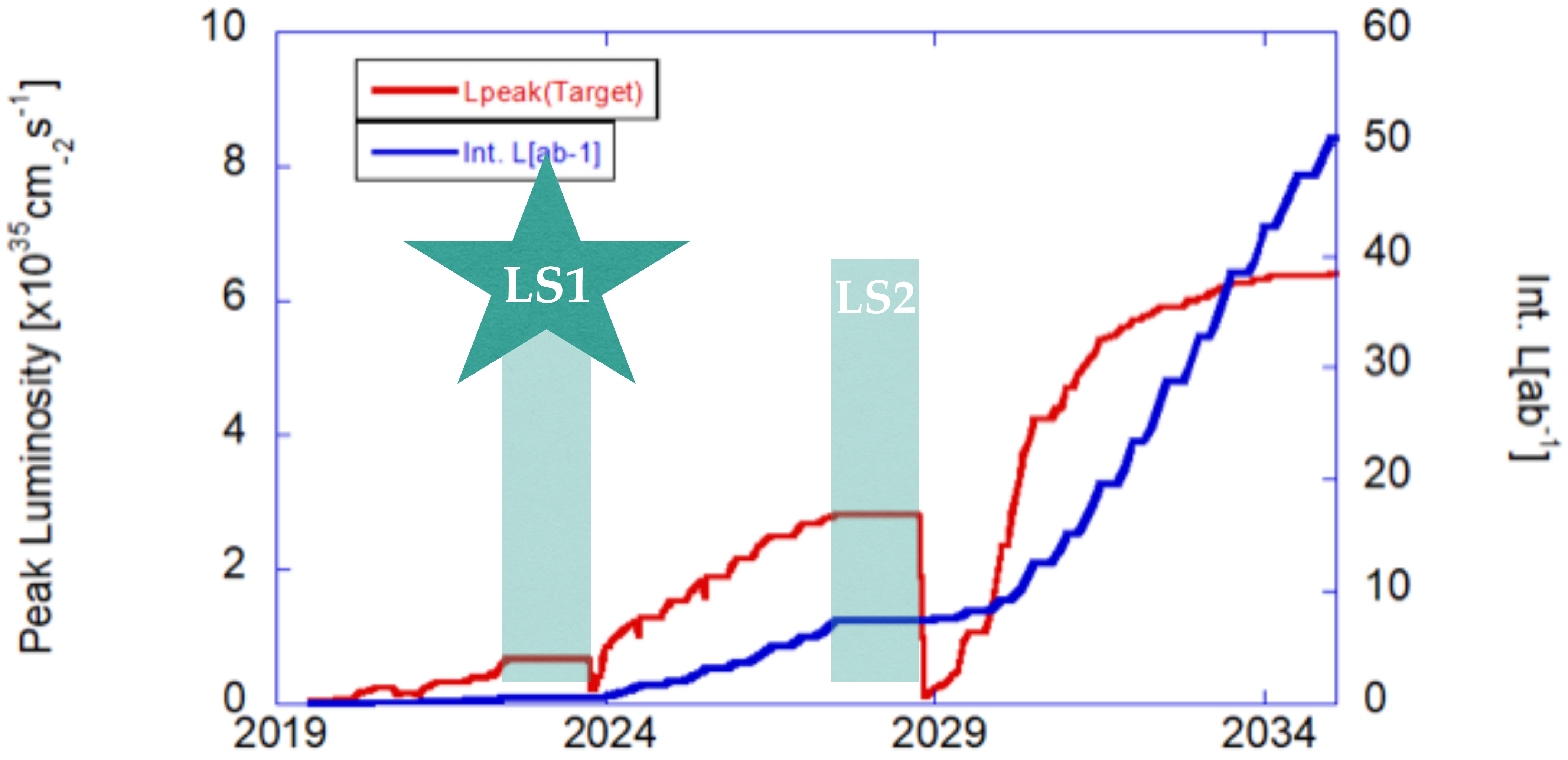


Luminosity

Status

- **363 fb^{-1} (on-resonance) → (~1/2 Belle, ~ BaBar)**
- **42 fb^{-1} (off-resonance)**
- ~ 90 % data-taking efficiency
- **Record-breaking $\mathscr{L}_{inst}$ = 4.7 × 10^{34} cm^{-2} s^{-1}**
- **Highest daily integrated luminosity: 2.5 fb^{-1}**





Prospects

- **Short-term plan**:
  - Now in long shutdown (LS1) until end of 2023:
    - Full PXD installation
    - New beampipe
    - Replacement of defect CDC readout boards
    - Replacement of 50% of barrel TOP PMTs
- **Long-term plan**: LS2, final goal: $\mathscr{L}_{int}$ = 50 ab^{-1}

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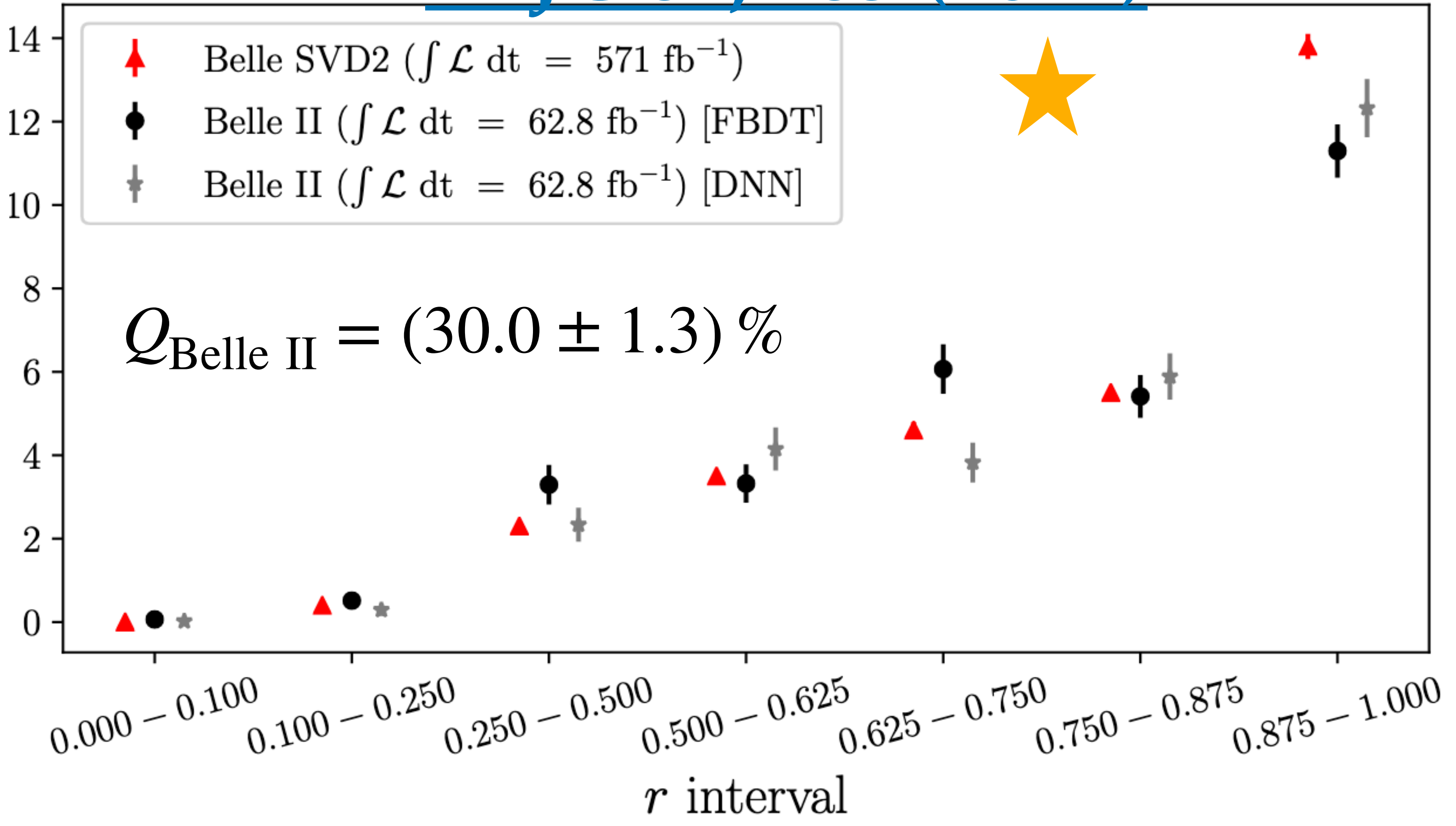
Performance

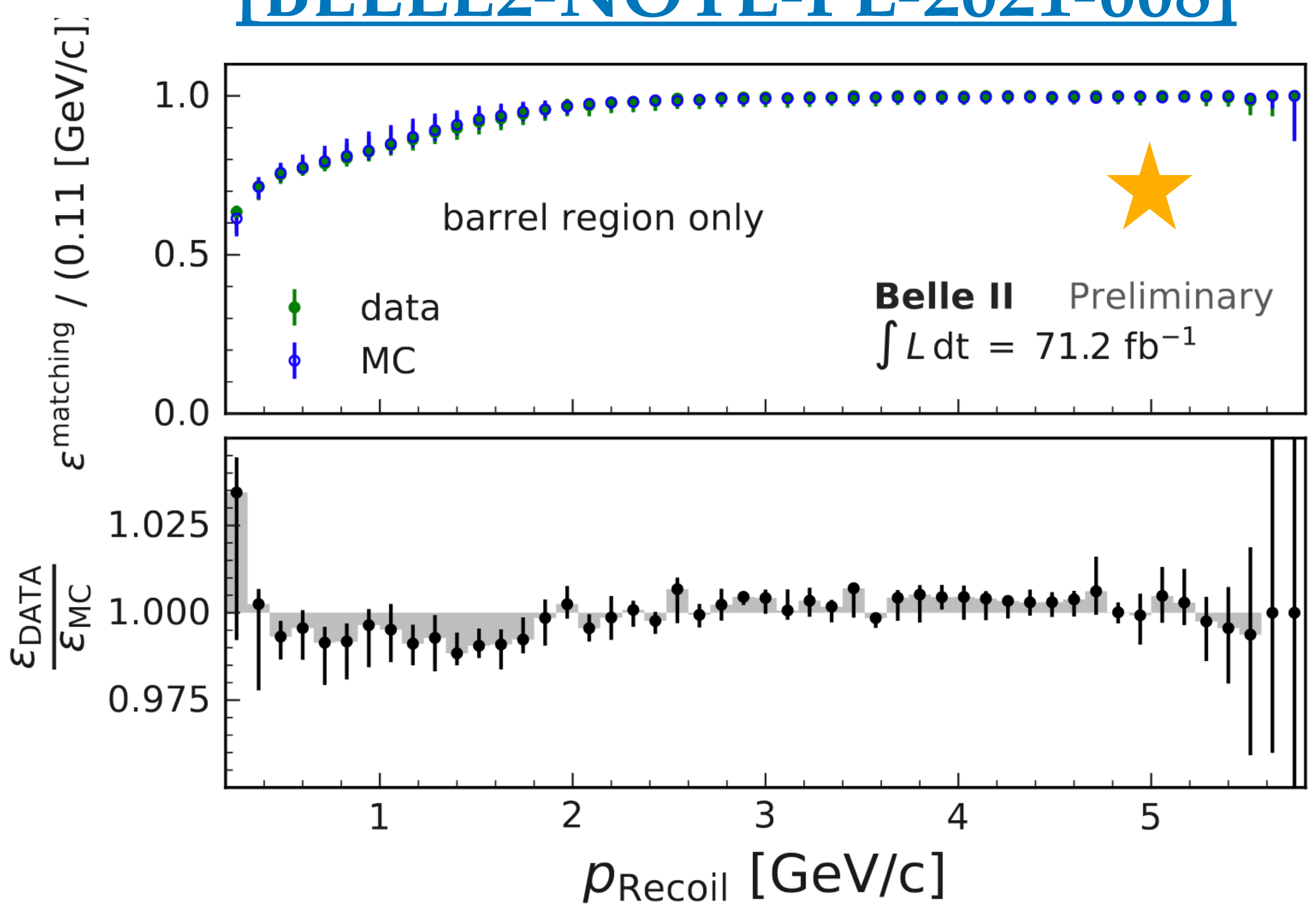
Good flavour tagger performance

EPJC 82, 283 (2022)



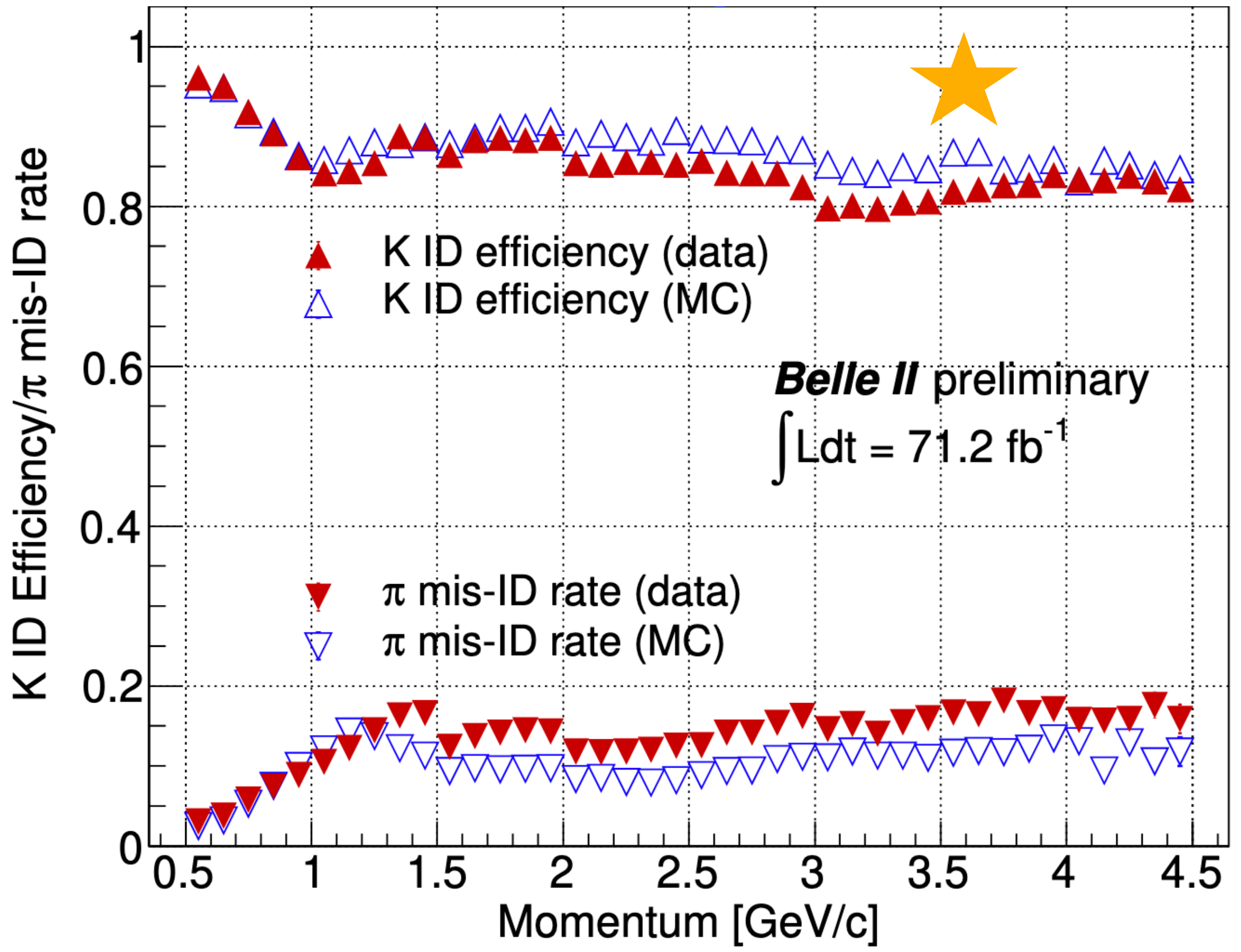
High photon matching efficiency

[BELLE2-NOTE-PL-2021-008]

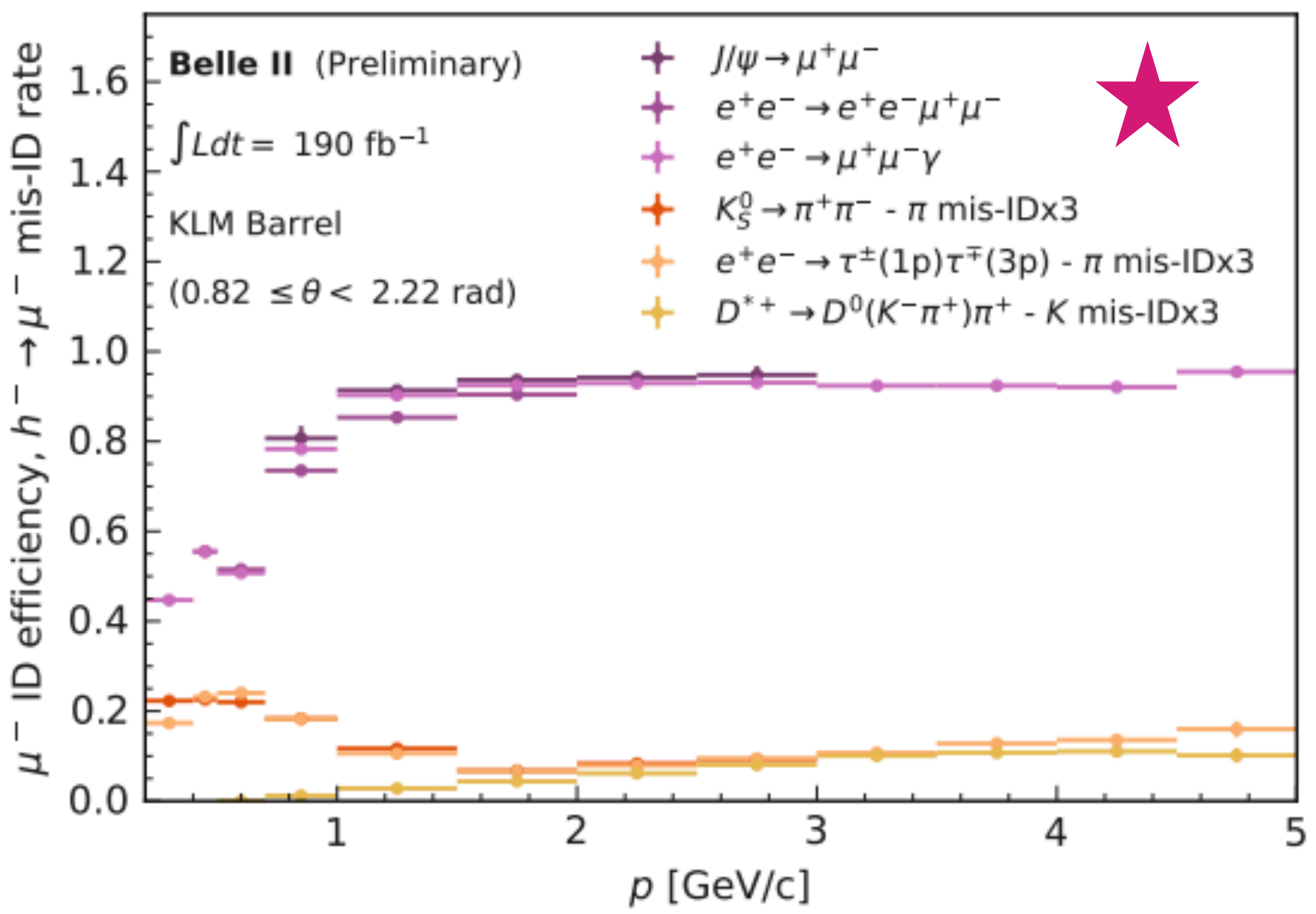


Good particle identification

[BELLE2-NOTE-PL-2020-024]

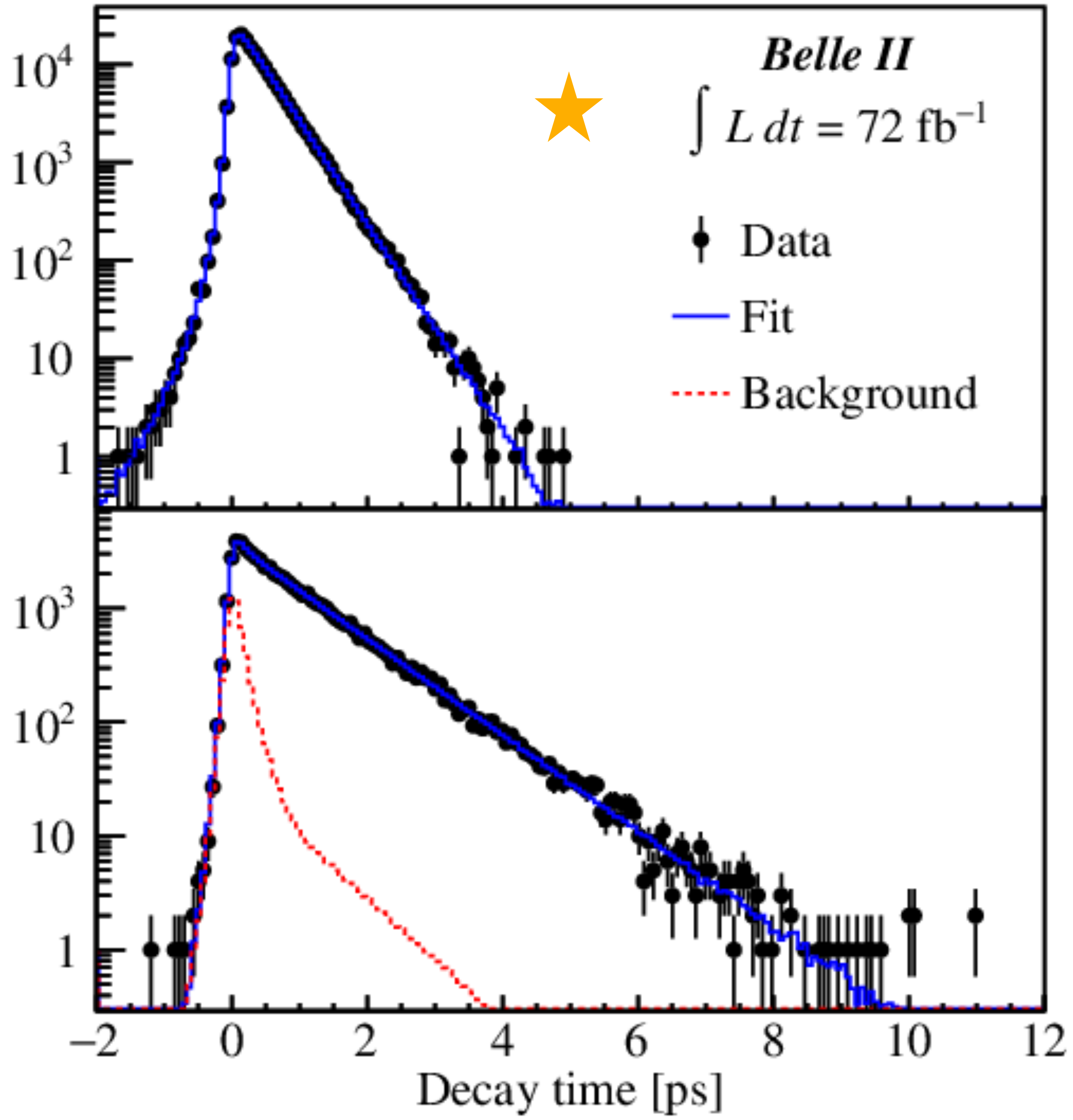


[BELLE2-NOTE-PL-2022-003]



Most precise measurement of *D* lifetimes

PRL 127, 211801 (2021)

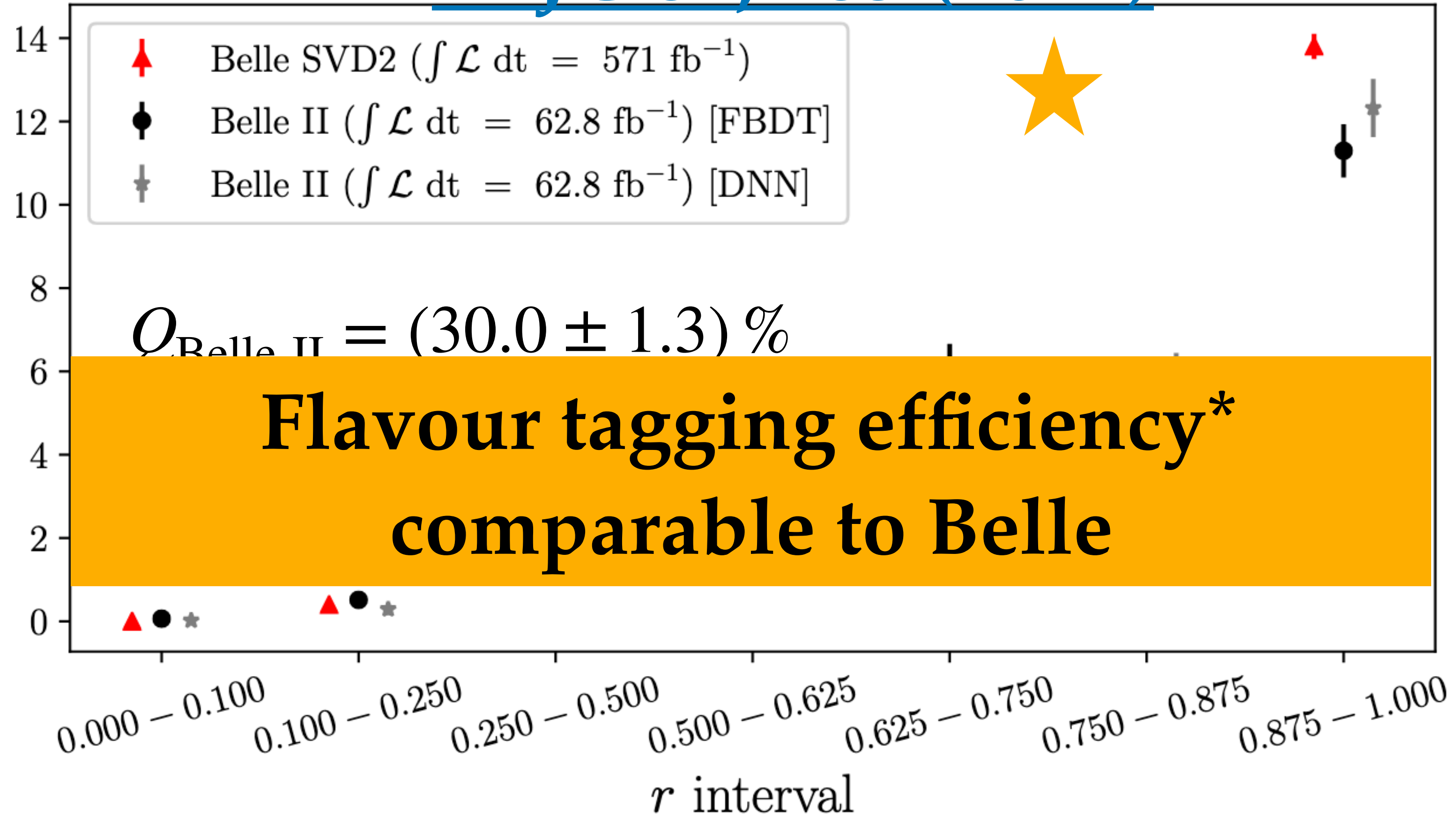


*tagging power indicating the statistical precision of the sample = $\epsilon_{tag}(1-2\omega)^2$

Performance

Good flavour tagger performance

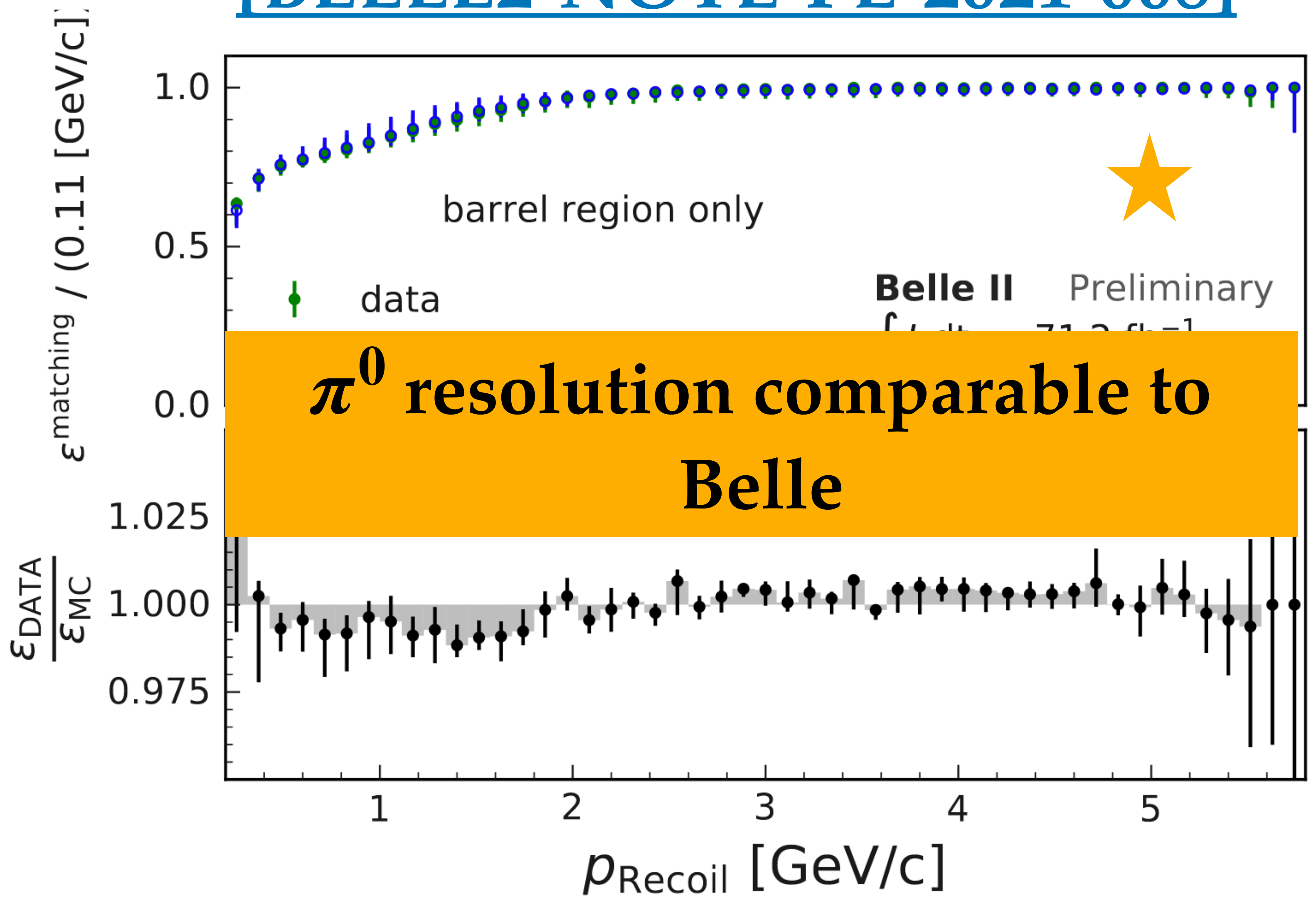
[EPJC 82, 283 (2022)]



Flavour tagging efficiency* comparable to Belle

High photon matching efficiency

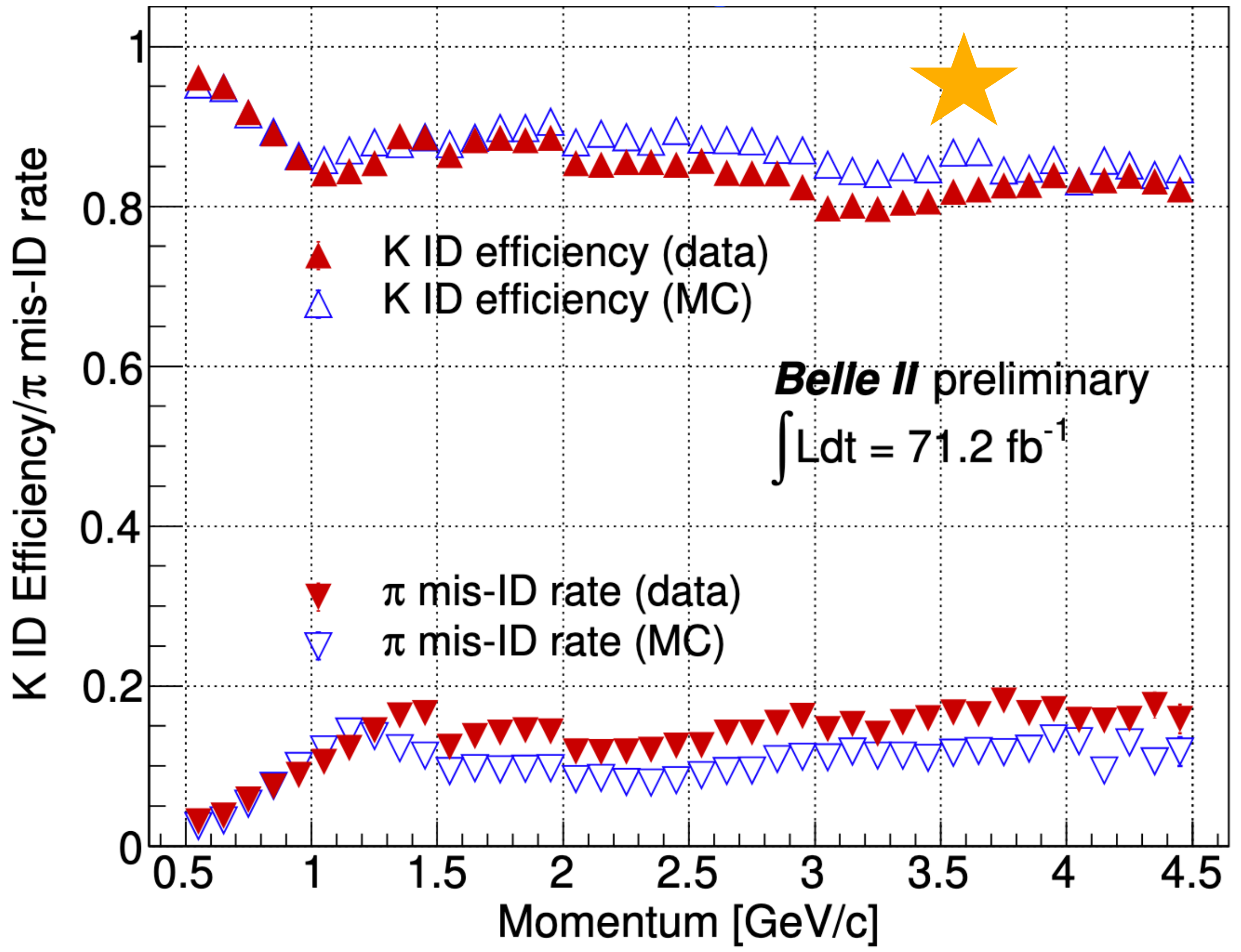
[BELLE2-NOTE-PL-2021-008]



π^0 resolution comparable to Belle

Good particle identification

[BELLE2-NOTE-PL-2020-024]



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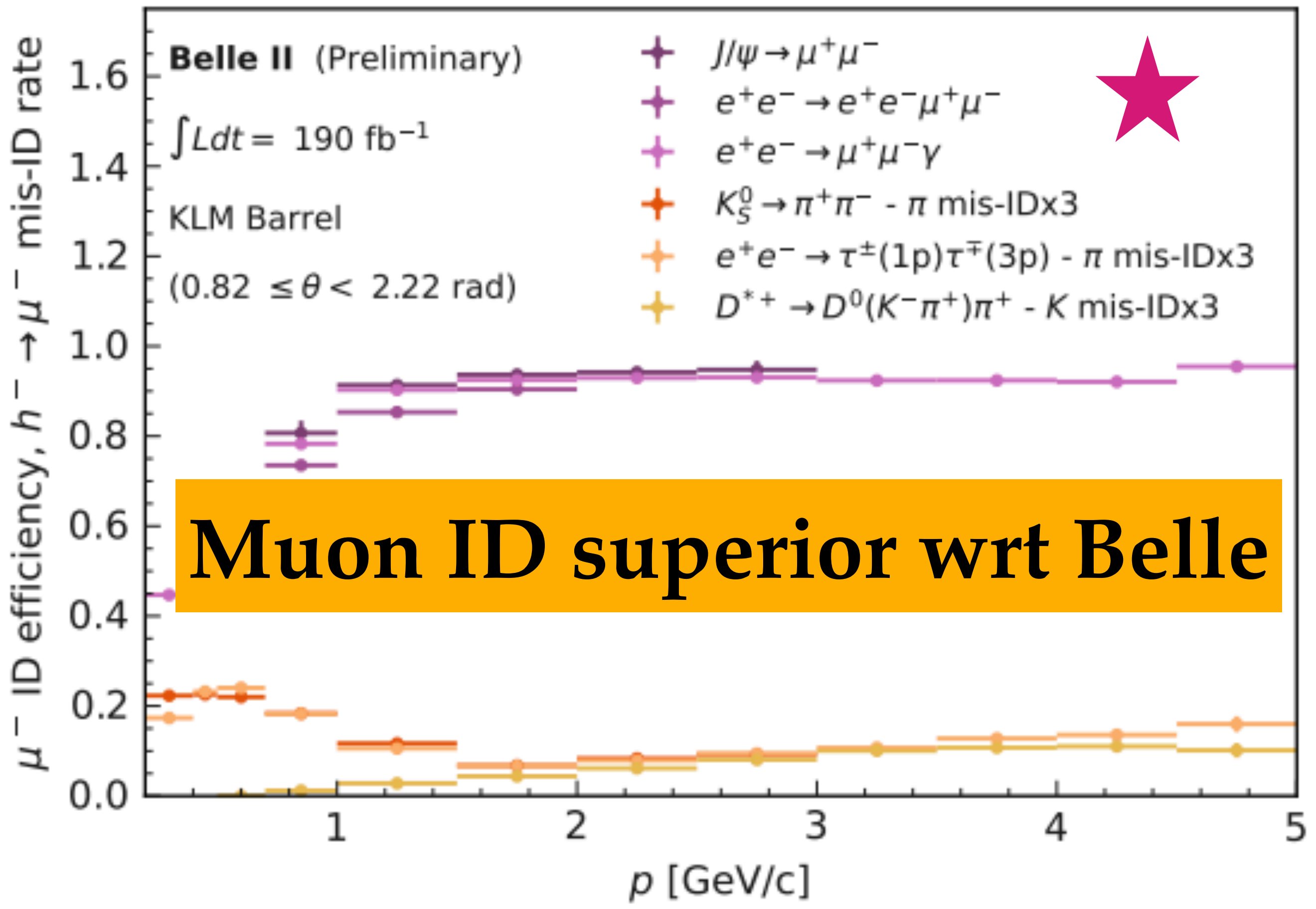
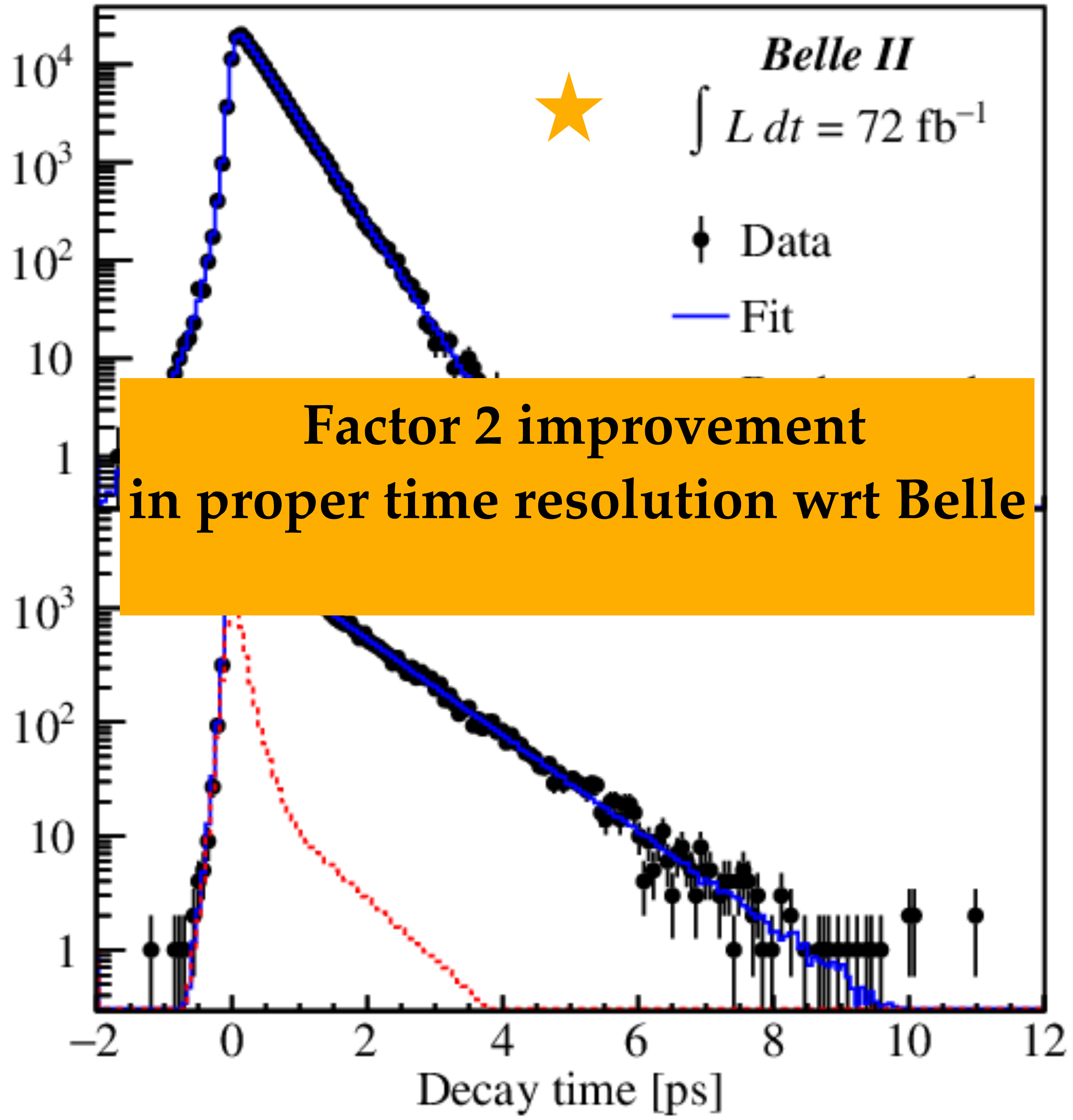


Muon ID superior wrt Belle

Most precise measurement of *D* lifetimes

[PRL 127, 211801 (2021)]

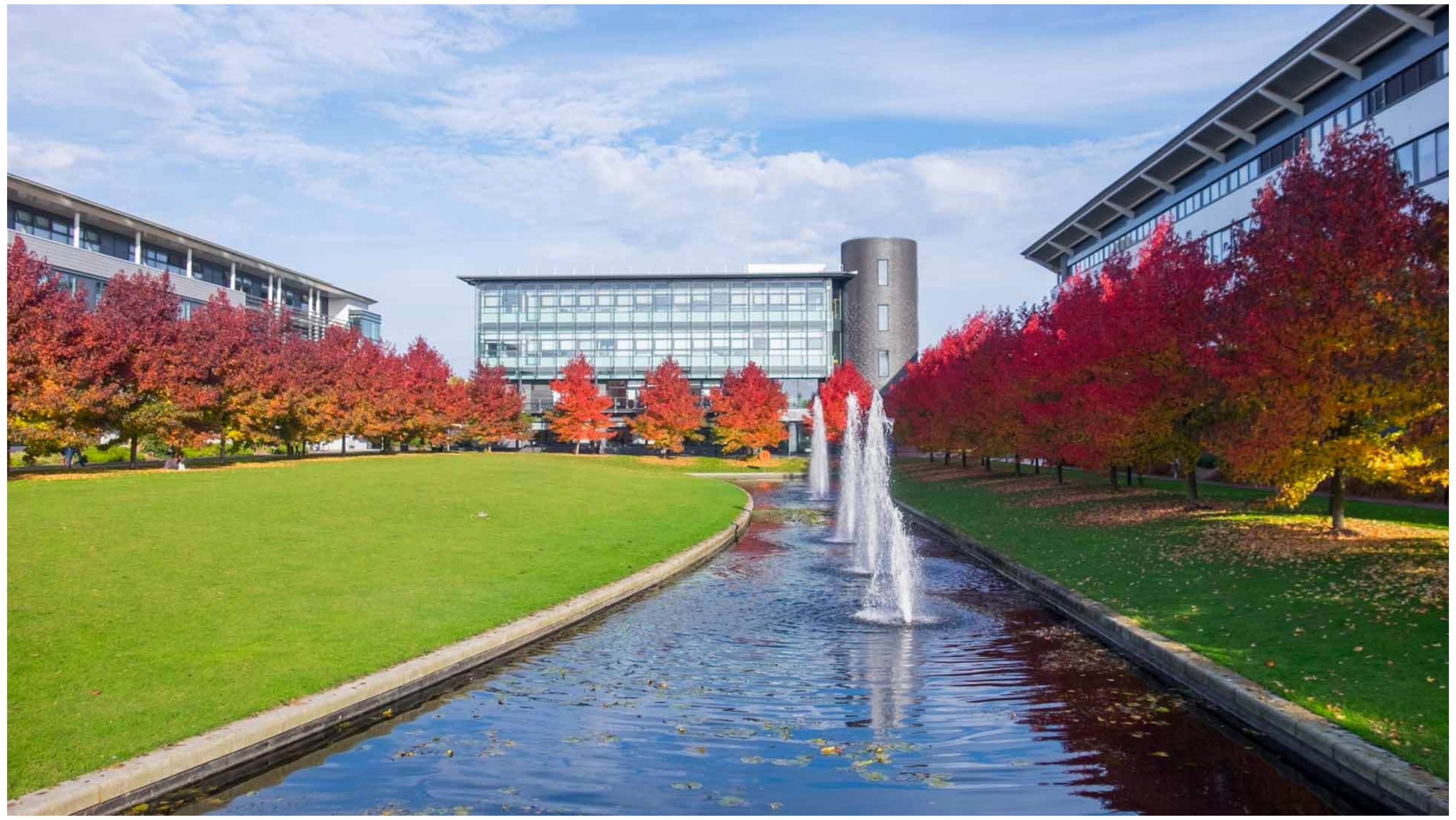


Factor 2 improvement in proper time resolution wrt Belle

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

Rare *B*-decays with neutrinos at Belle II

Zeeman Building, Warwick University, UK



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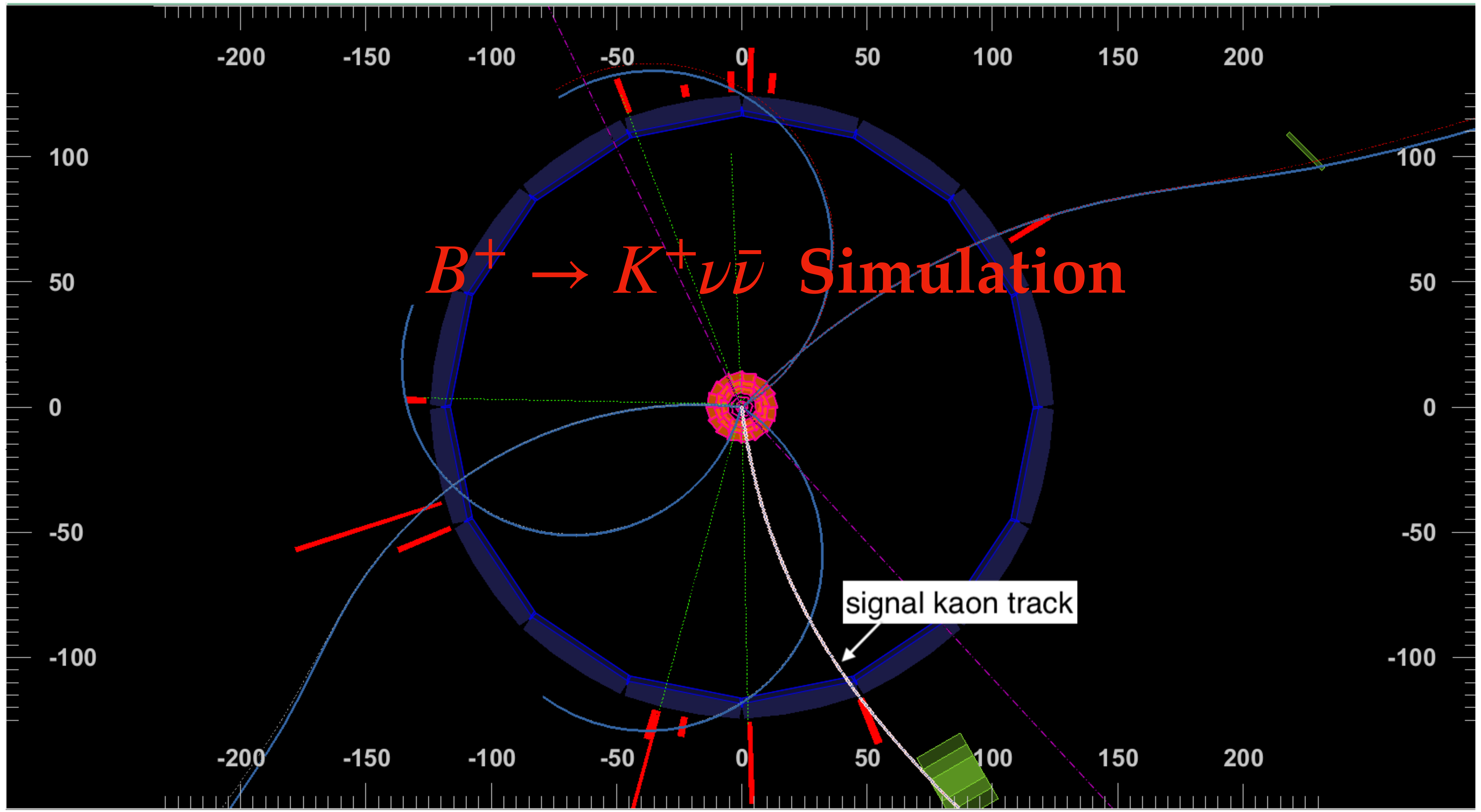
Key ingredients



Belle II:

- Hermetic detector with good performance

Belle II Event:

- Cleaner environment (wrt LHCb)
- Known initial state kinematics

Challenges of rare B-decays

- High reconstruction efficiency
- Good MC modelling

+

Challenges of channels with neutrinos

- Good understanding of the neutral objects (π^0, K_L, K_s^0, n, γ)
- Choice of reconstruction approach

Reconstruction

Exclusive Tagging Approach:

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

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

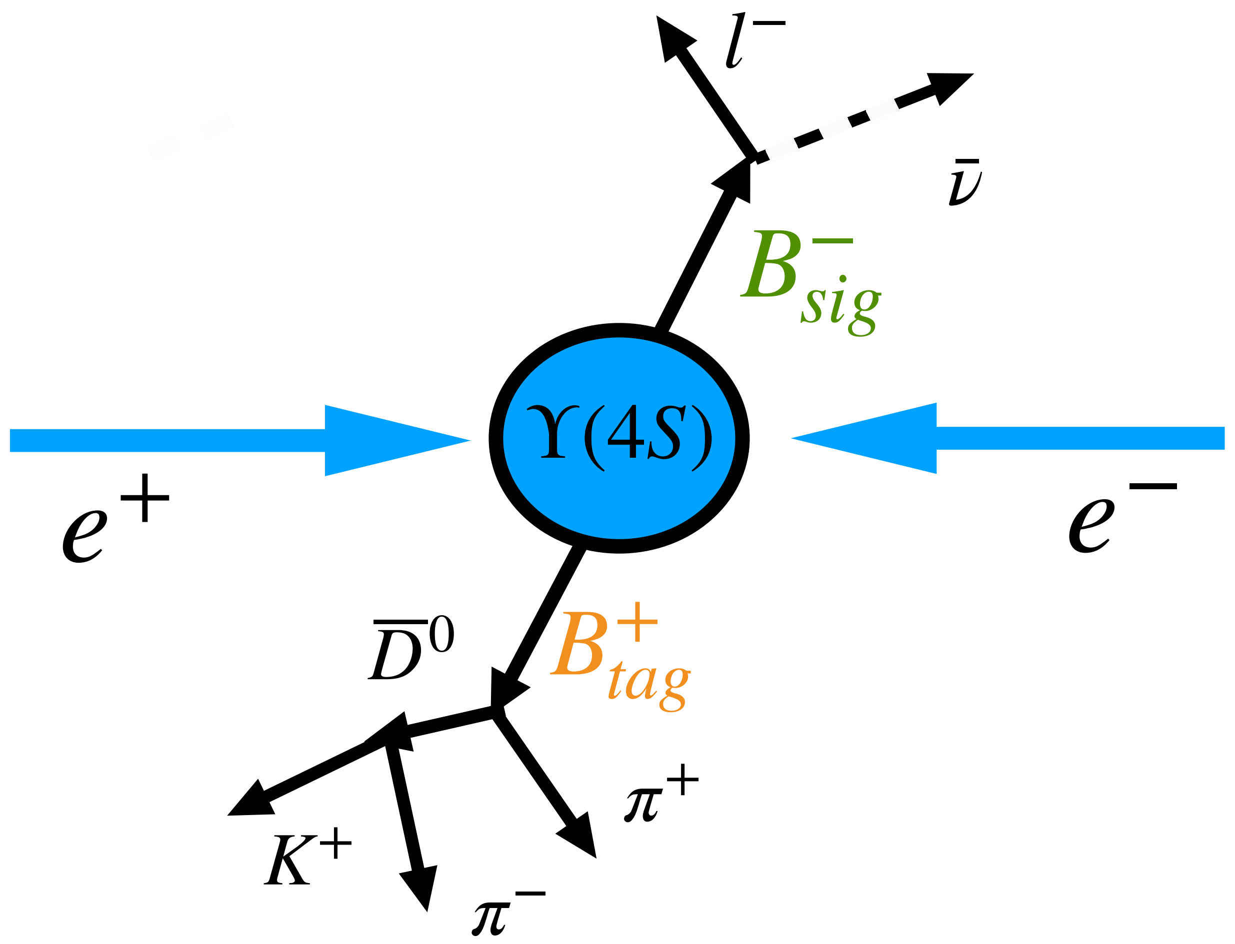
- Flavour constraint: $B^+_{tag} \rightarrow B^-_{sig}$
- Kinematically constrained system with hadronic B^+_{tag} : $\vec{p}_{\bar{\nu}} + \vec{p}_{l^-} = \vec{p}_{e^+e^-} - \vec{p}_{B^-_{tag}}$

☑ Higher intrinsic background rejection

☑ Better resolution → analytical fits

☐ Lower signal efficiency (<1%)
HAD (~ 0.04%) SL (~0.2%)

☐ Systematics (B^+_{tag})



Inclusive Tagging Approach:

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

2. step: Constrain the rest of the event

☑ Higher signal efficiency

☐ Lower intrinsic background rejection

☐ Worse resolution → binned fits

Other Approaches:

- 'Semi-inclusive' tagging
- Charm tagging

Reconstruction

Exclusive Tagging Approach:

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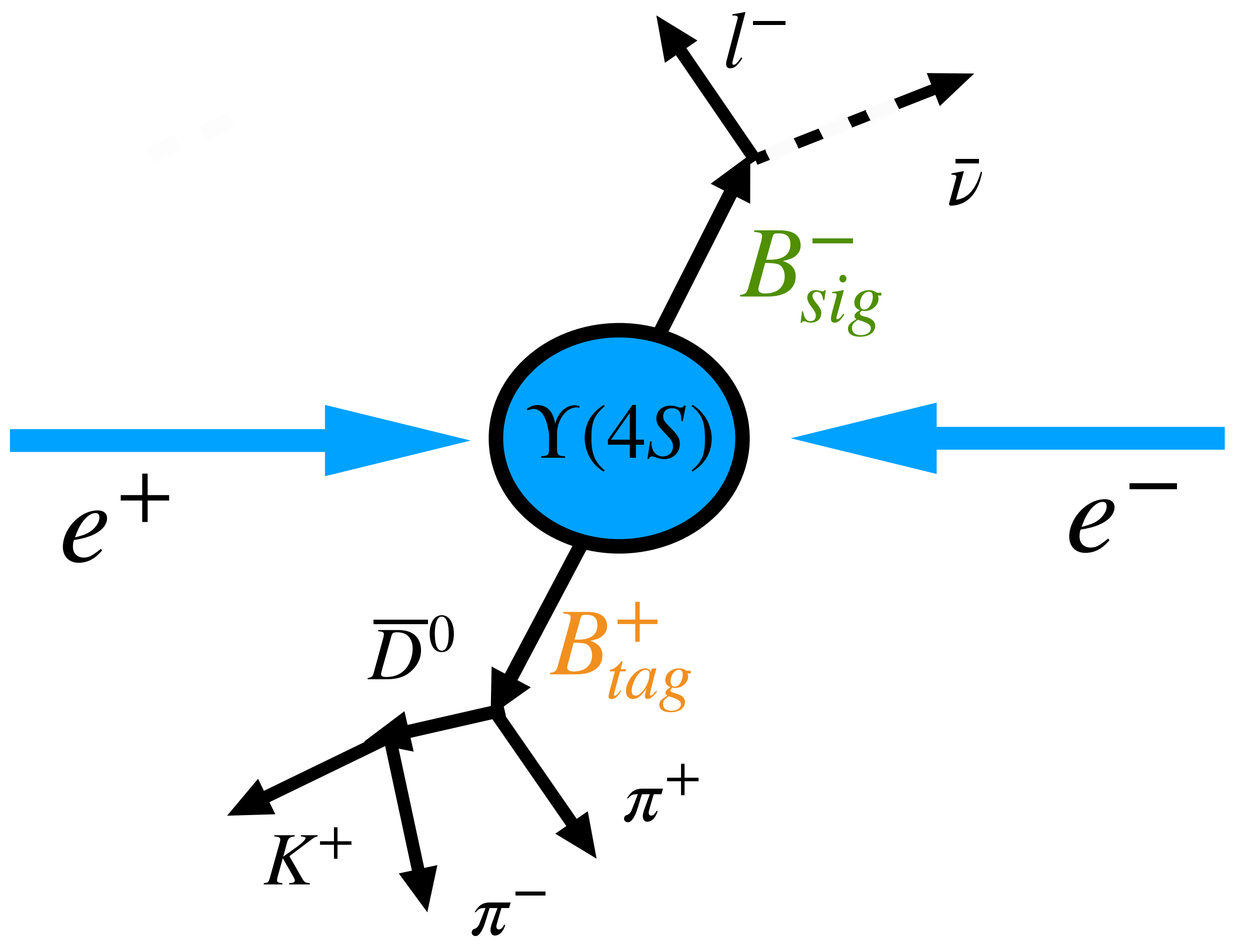
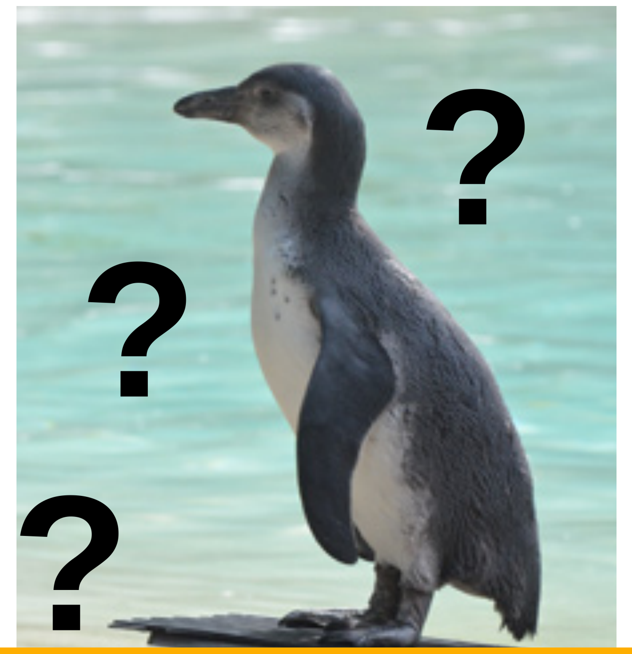


Rare B-decay with neutrinos



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

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☑ Higher signal efficiency

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Other Approaches:

- 'Semi-inclusive' tagging
- Charm tagging

Best sensitivity : channel dependent, background dependent

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

Blackett Laboratory, Imperial College London, UK

(Theoretical) Motivations

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Anomalies in $b \to sll$ transition

Exclusive $b \to sl^+l^-$ measurements:

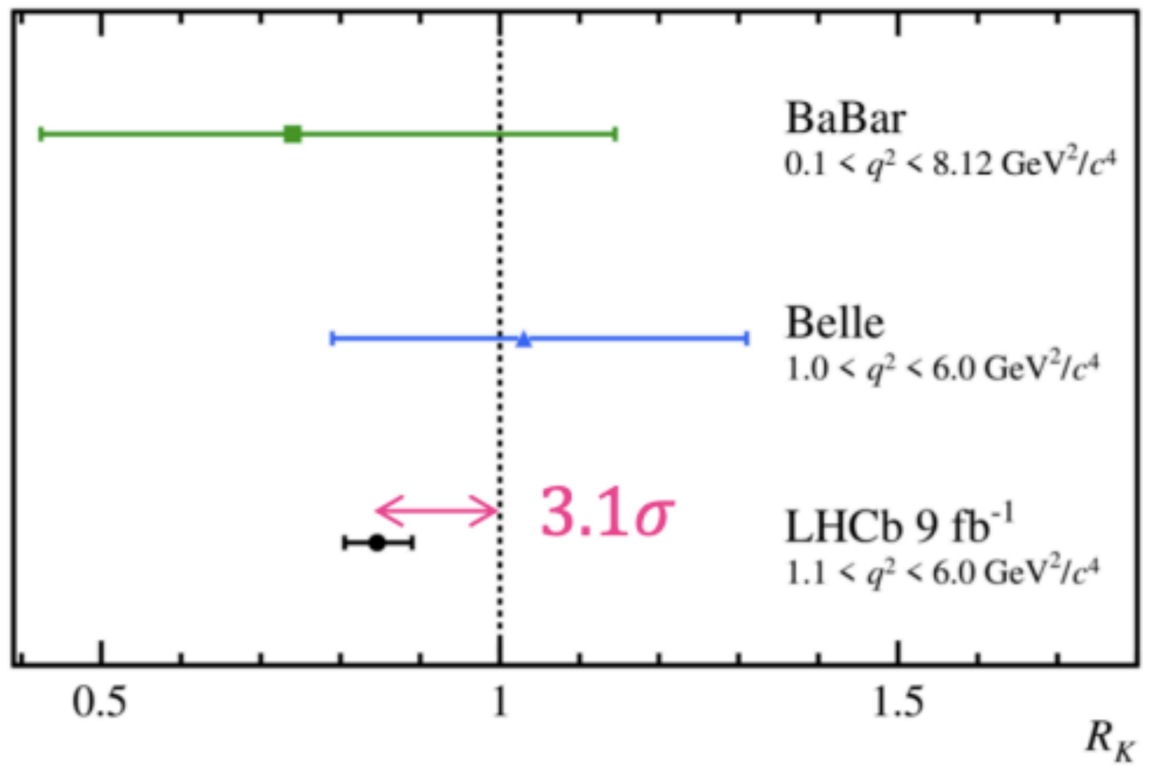
- Single measurement: 3.1 σ evidence of lepton flavour universality violation in $R(K)$
- Tensions also measured in angular observables of $B \to K^*\mu^+\mu^-$
- Global fits with prefer non-zero NP Wilson coefficients* C9 and/or C10 at > 4σ

SM

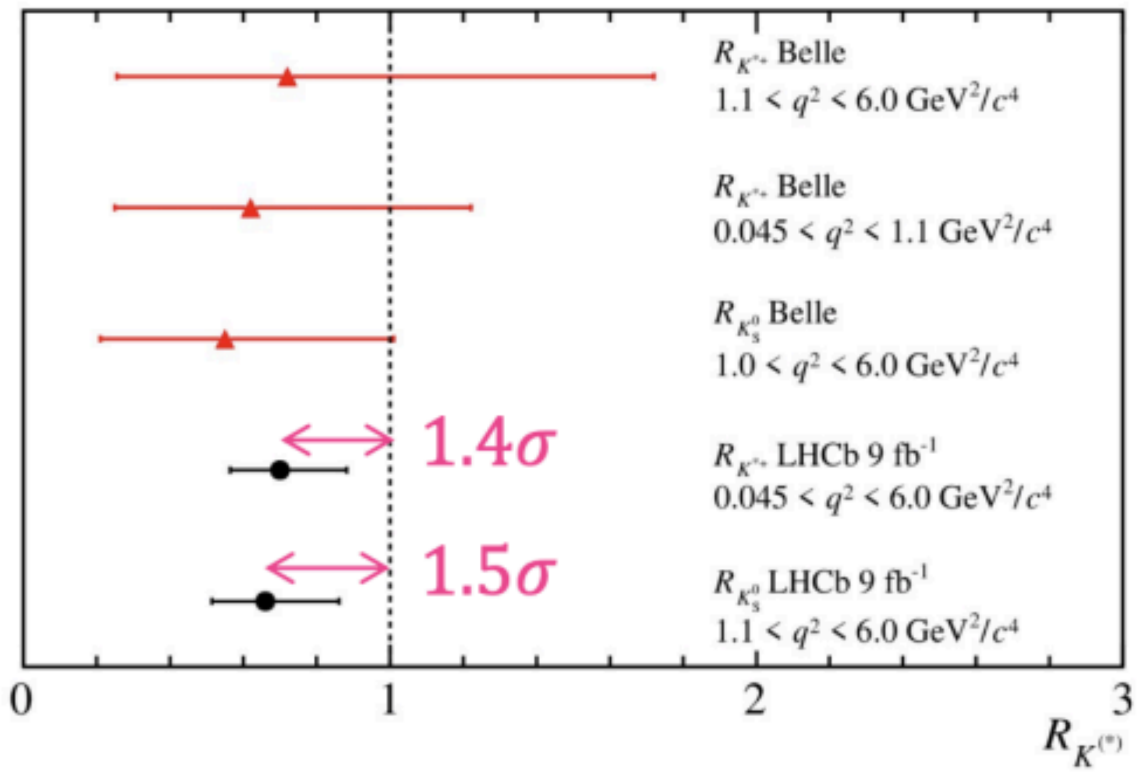
$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} = 1 \pm \mathcal{O}(10^{-2})$$

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

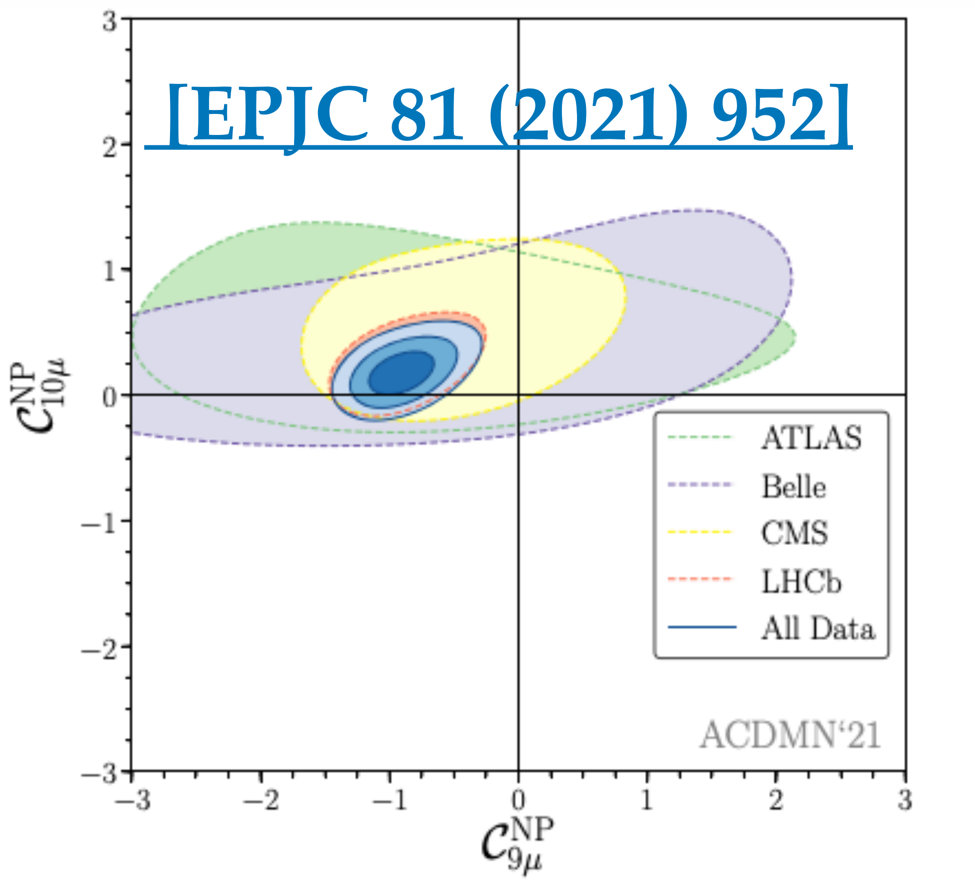
JHEP 2018, 93 (2018)



arXiv:2103.11769, arXiv:2110.09501



[EPJC 81 (2021) 952]



Complementarity of $b \to sl^+l^-$ and $b \to s\nu\bar{\nu}$ transitions:

- In SM governed by the same form factors, but in $b \to s\nu\bar{\nu}$ absence of photon exchange → theoretically cleaner
- In SM neutrinos and left-handed charged leptons are related by $SU(2)_L$ symmetry → within SM-EFT formalism $b \to sl^+l^-$ and $b \to s\nu\bar{\nu}$ share Wilson coefficients

*In EFTs, the heavier degrees of freedom (i.e the loop) can be integrated out and replaced with an effective coupling known as Wilson coefficient C_j

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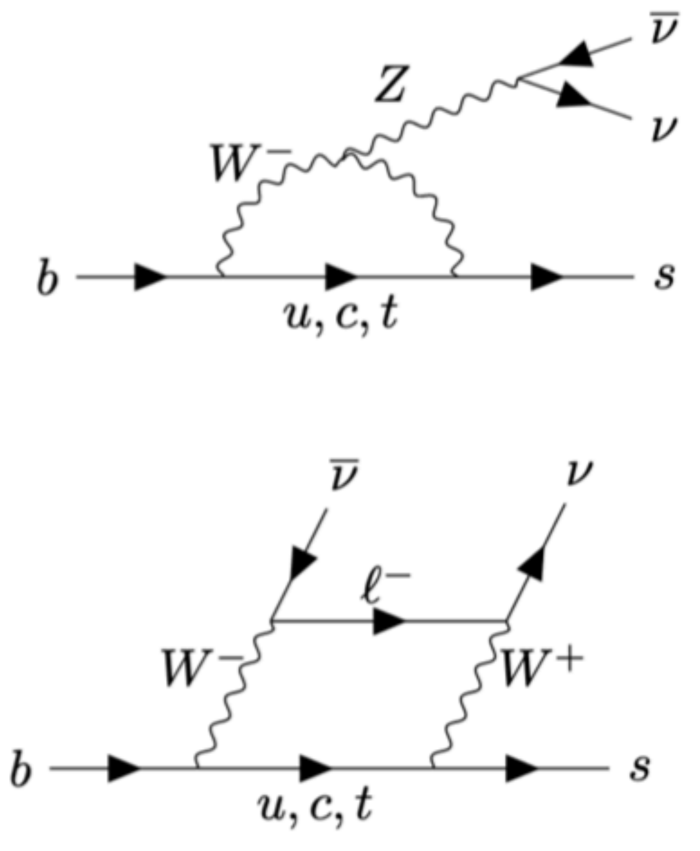
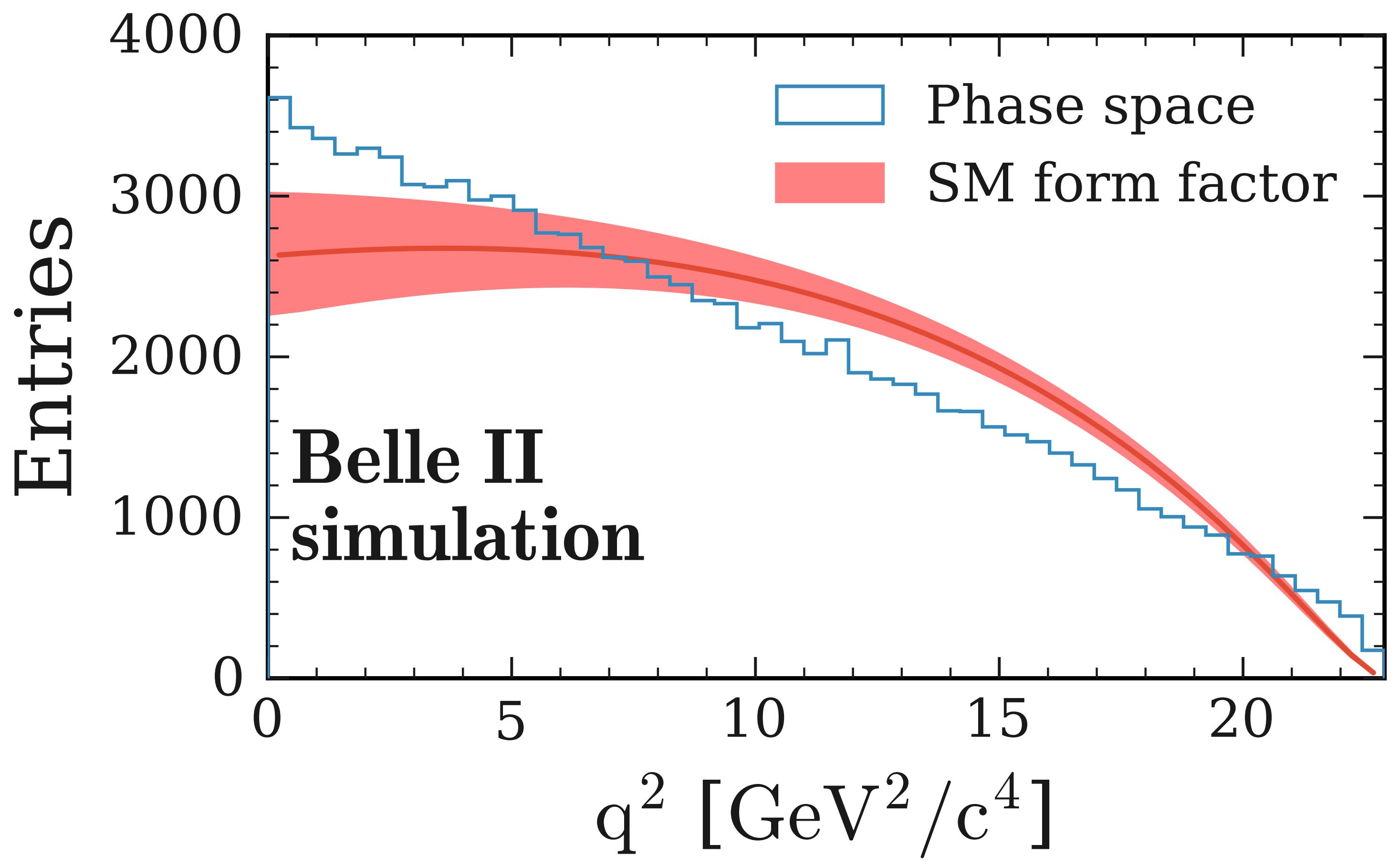
SM and BSM extensions

$B \to K^{(*)}\nu\bar{\nu}$ decays in SM

- FCNC transitions heavily suppressed in SM
- Observables : $\dfrac{d\mathscr{B}(B \to K\nu\bar{\nu})}{dq^2}$, $\dfrac{d\mathscr{B}(B \to K^*\nu\bar{\nu})}{dq^2}$, $F_L(q^2)$,

  where $q^2 = M^2(\nu\bar{\nu})$



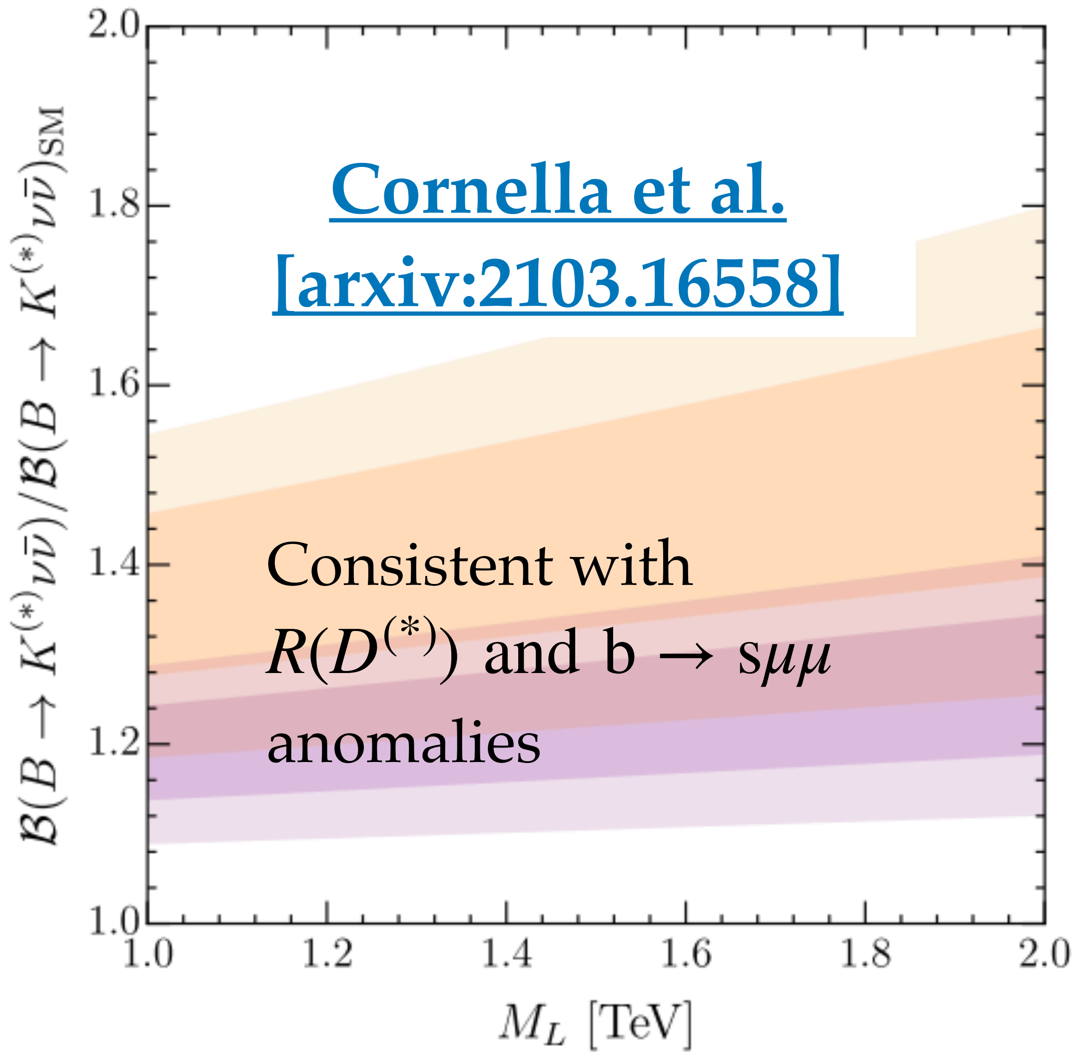


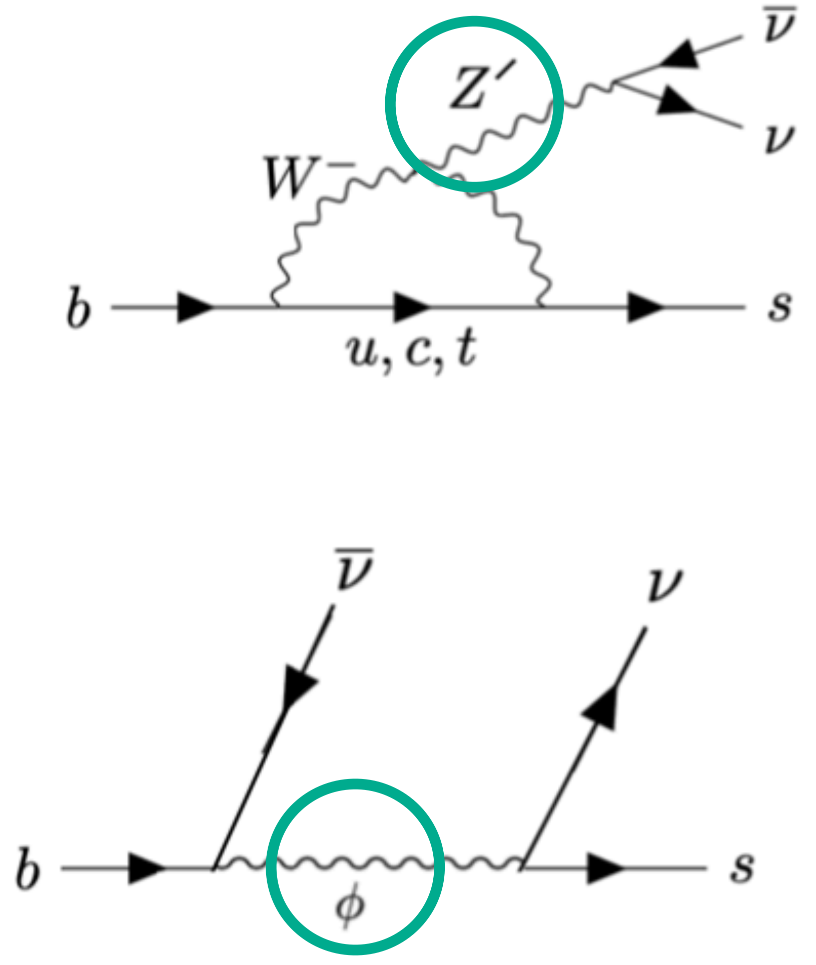
$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})$ in SM

- $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$ [arxiv:606.00916]
- SM $q^2(\nu\bar{\nu})$ taken from [arXiv:1409.4557]

Possible BSM extensions

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





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$B^+ \to K^+\nu\bar{\nu}$: experimental status

All previous measurements with exclusive tagging approach:

- Best limit set by BaBar in 2013
- Limit $\sim$ 10 higher than SM $\mathscr{B}(B^+ \to K^+\nu\bar{\nu})$
- One of the Belle II's golden channel

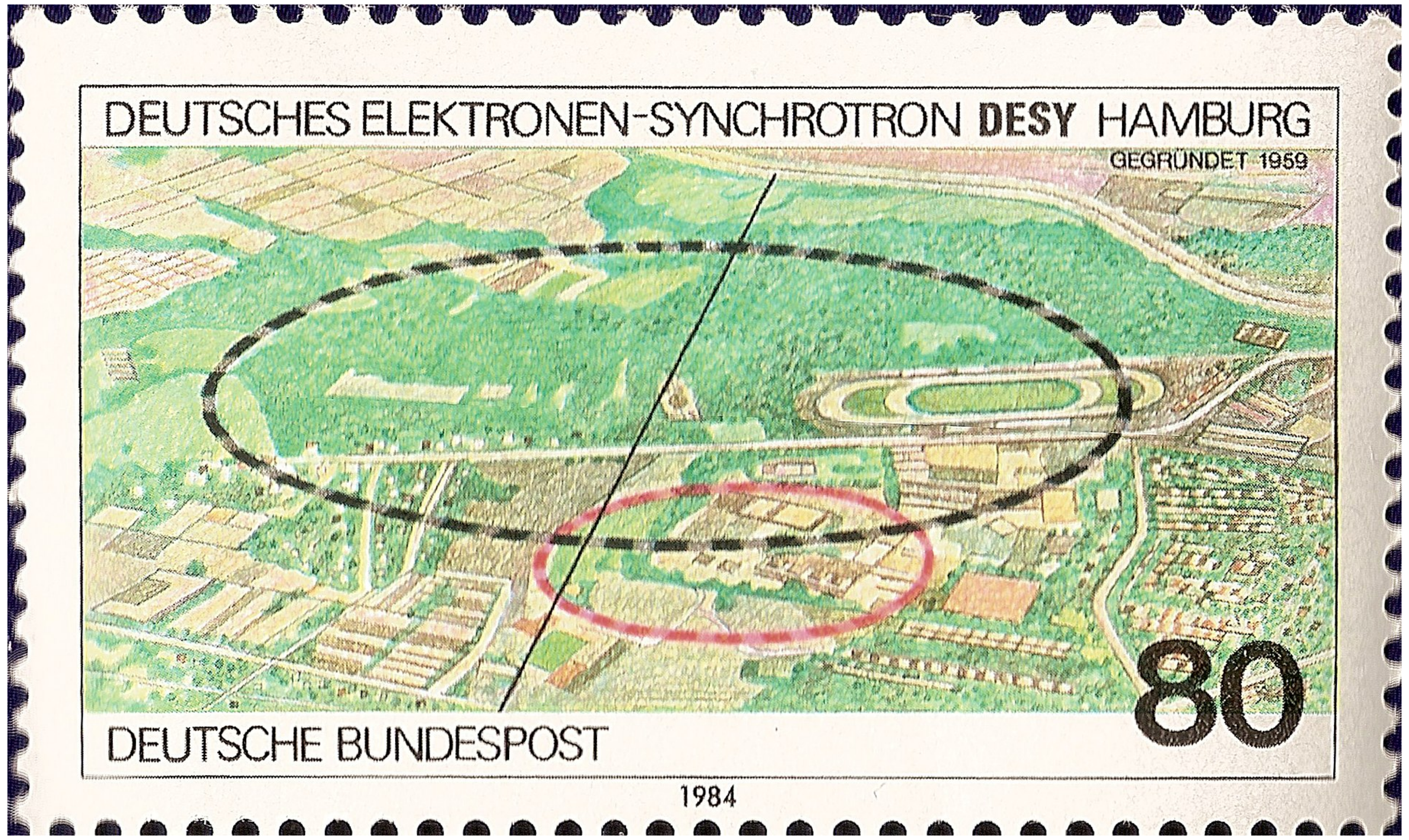
Experiment	Year	Observed limit on BR$(B^+ \to K^+\nu\bar{\nu})$	Approach	Data [fb^{-1}]
BABAR	**2013**	$< 1.6 \times 10^{-5}$ **[Phys.Rev.D87,112005]**	**SL + Had tagging**	429
Belle	**2013**	$< 5.5 \times 10^{-5}$ **[Phys.Rev.D87,111103(R)]**	**Had tagging**	711
Belle	**2017**	$< 1.9 \times 10^{-5}$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

Backgrounds

- Beam-backgrounds
- Luminosity Backgrounds
- Continuum Backgrounds
- B-backgrounds

Search for $B^+ \to K^+ \nu\bar{\nu}$ decays with inclusive tagging

[PRL 127, 181802 (2021)]



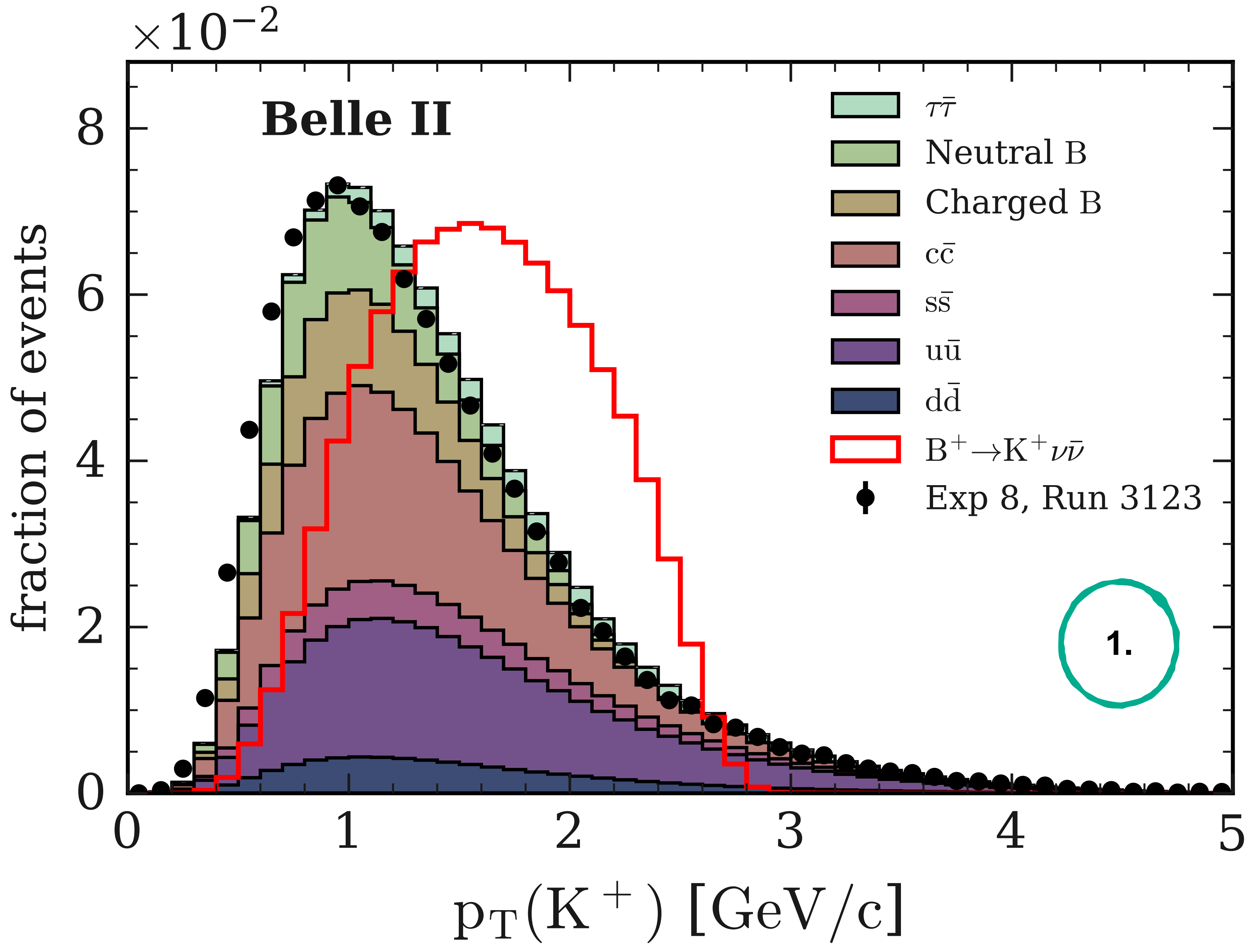
DESY stamp for 25th anniversary, Germany

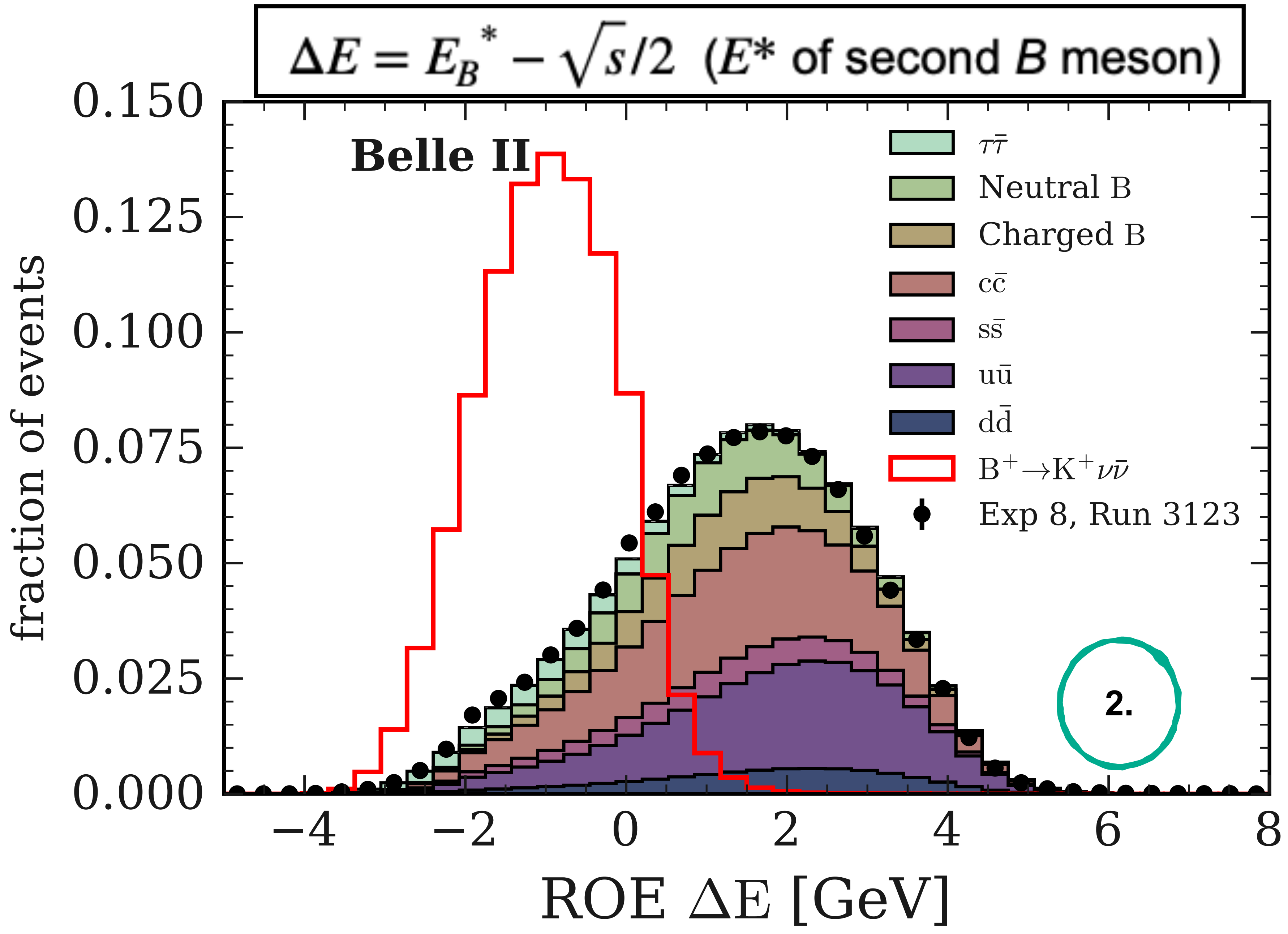
Inclusive tag

[PRL 127, 181802 (2021)] ★

Inclusive tag exploits distinct signal kinematics

1. Reconstruct signal by selecting highest-p_T track in the event
2. Reconstruct remaining tracks and clusters in the event (ROE)*





Main Backgrounds

- Beam-backgrounds
- Luminosity Backgrounds
- **Continuum Backgrounds**
- ***B*-backgrounds**

*Preselection:

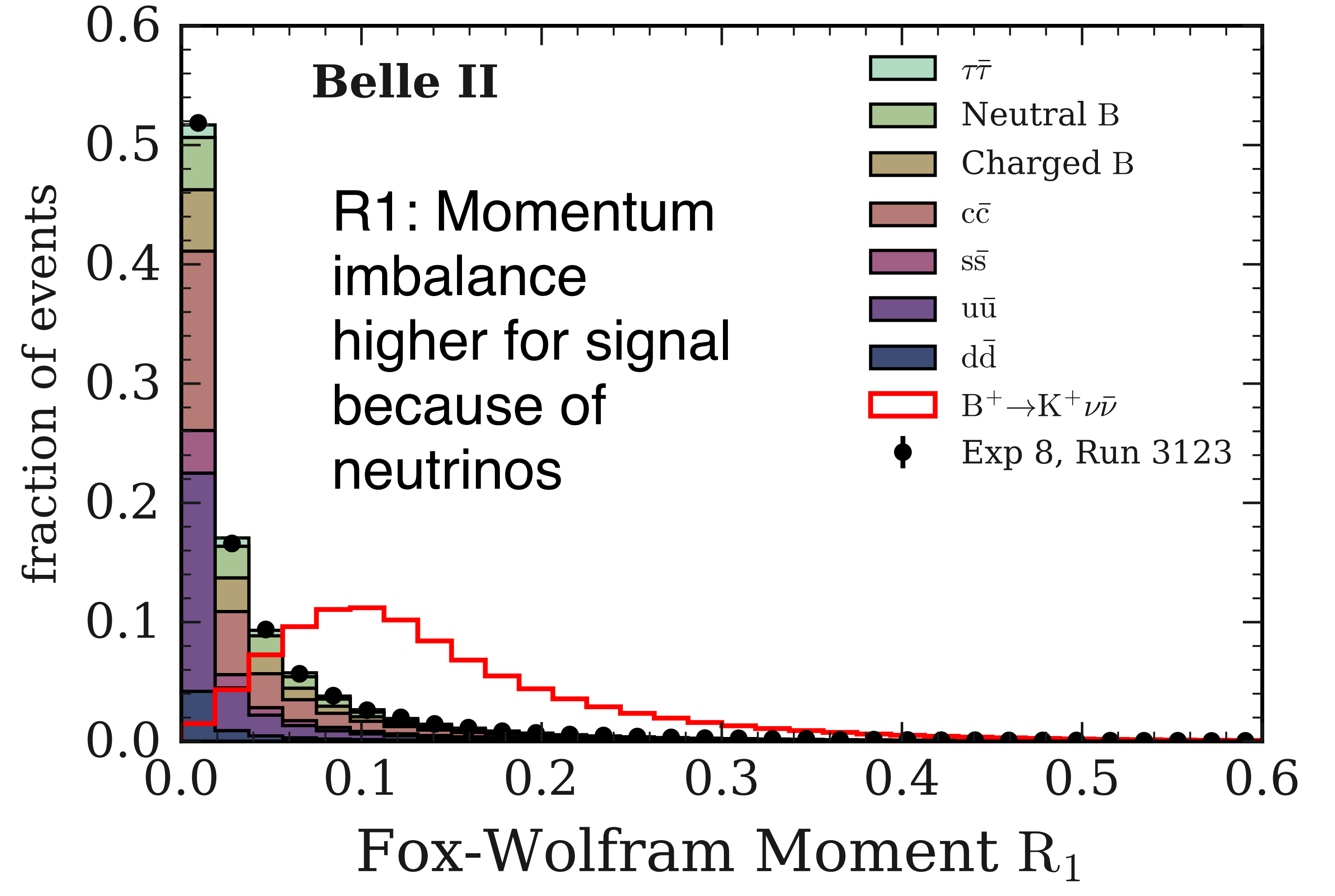
- Tracks:
  - $p_T > 0.1$ GeV/c
  - $\theta \in$ CDC,
  - $|dr| < 0.5$cm
  - $|dz| < 3.0$cm,
  - $E < 5.5$GeV
- Clusters:
  - $E > 0.1$ GeV/c
  - $\theta \in$CDC
  - $E < 5.5$ GeV

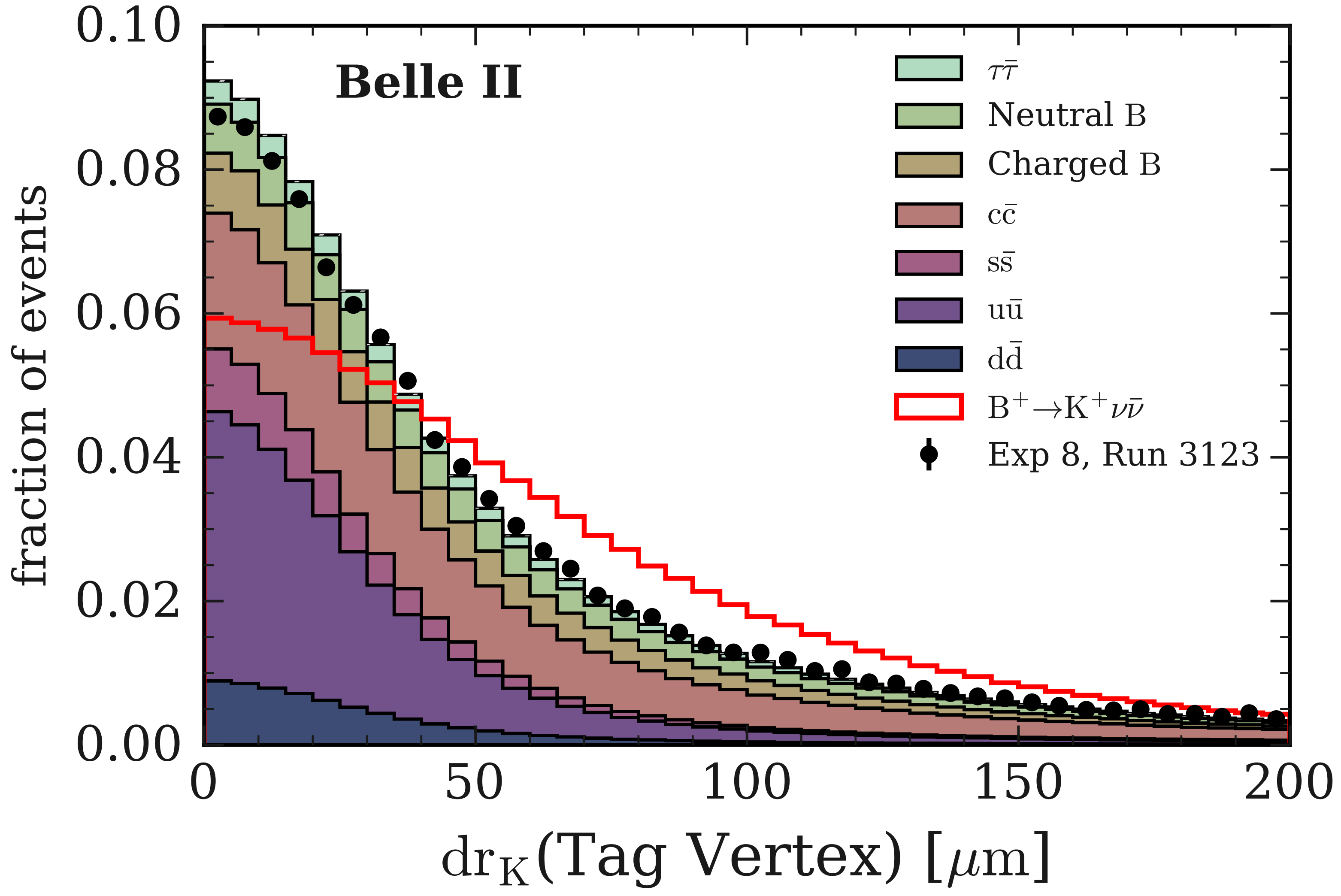
Discriminating variables

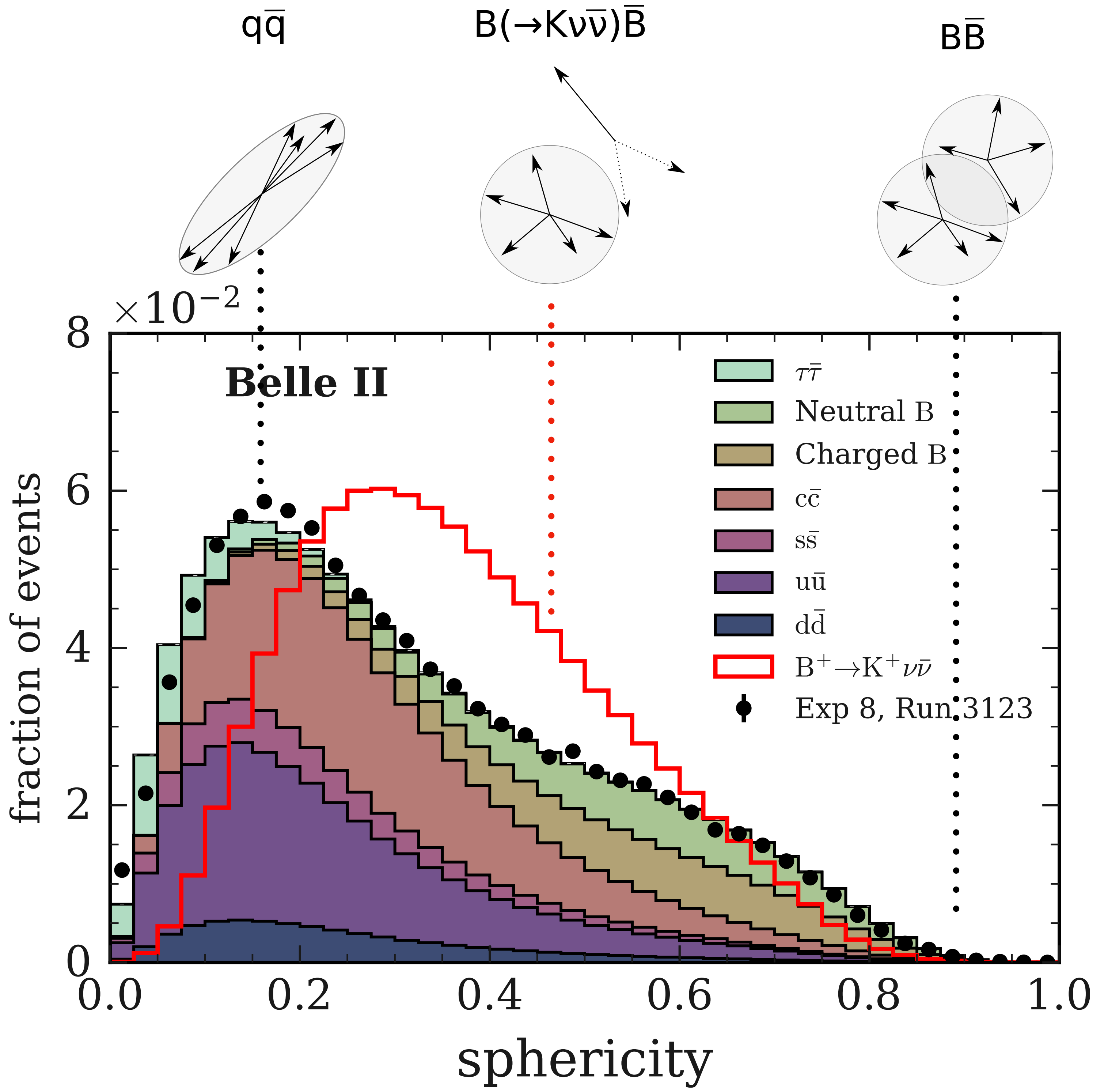
[PRL 127, 181802 (2021)] ★

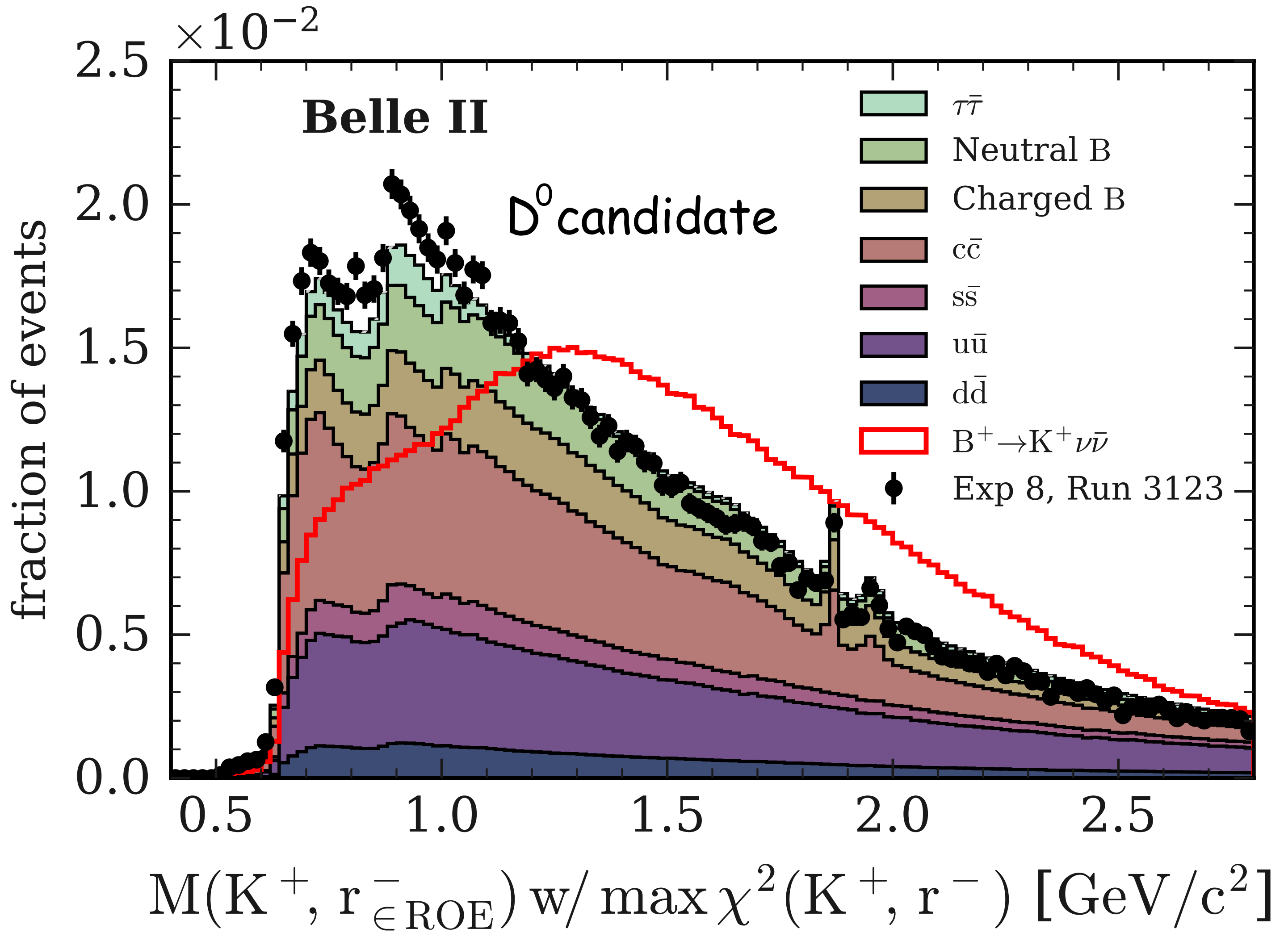
3. Construct >100 discriminating variables

- event topology
- missing energy
- vertex separation
- signal kinematics
- 2/3 track vertices….







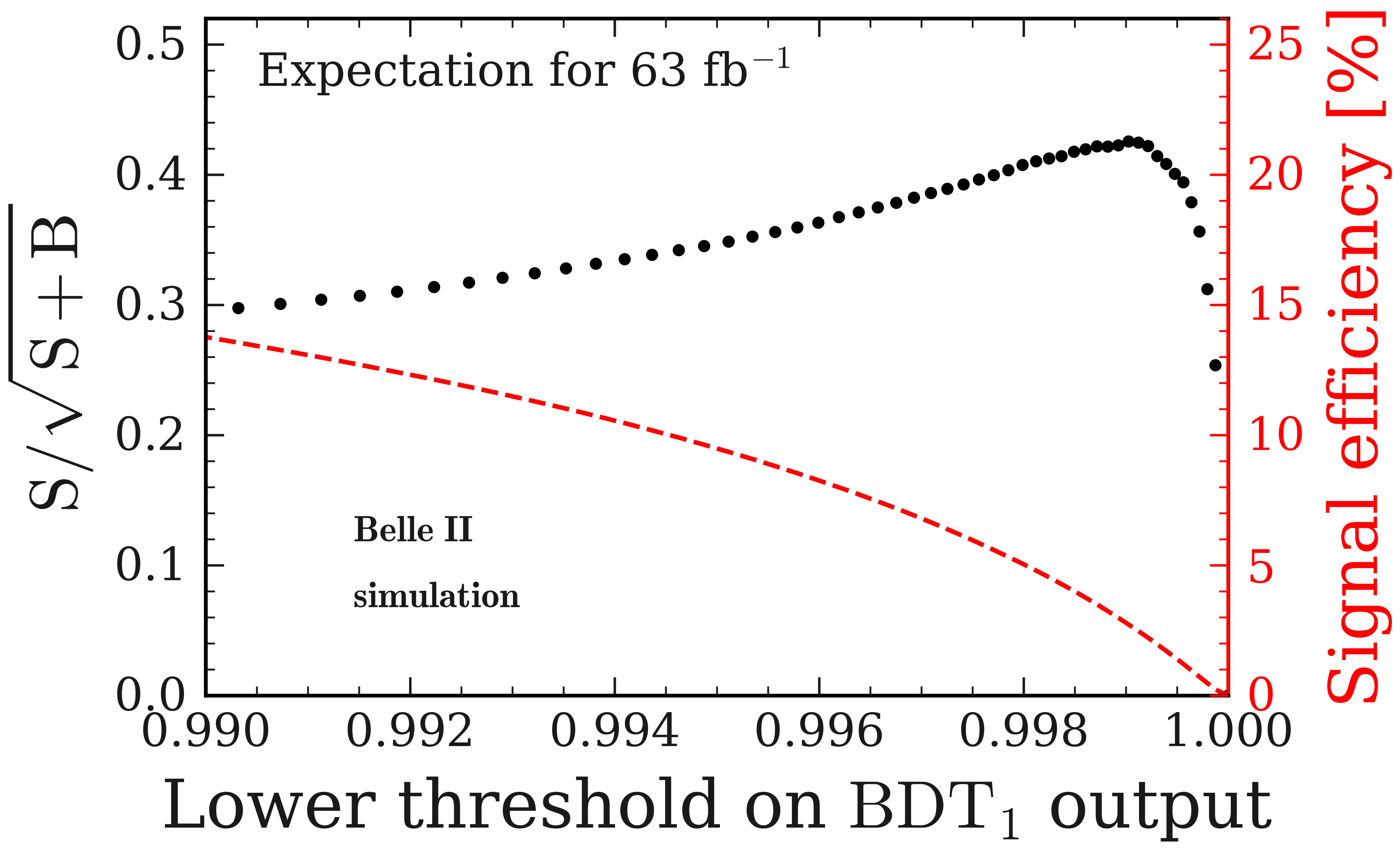


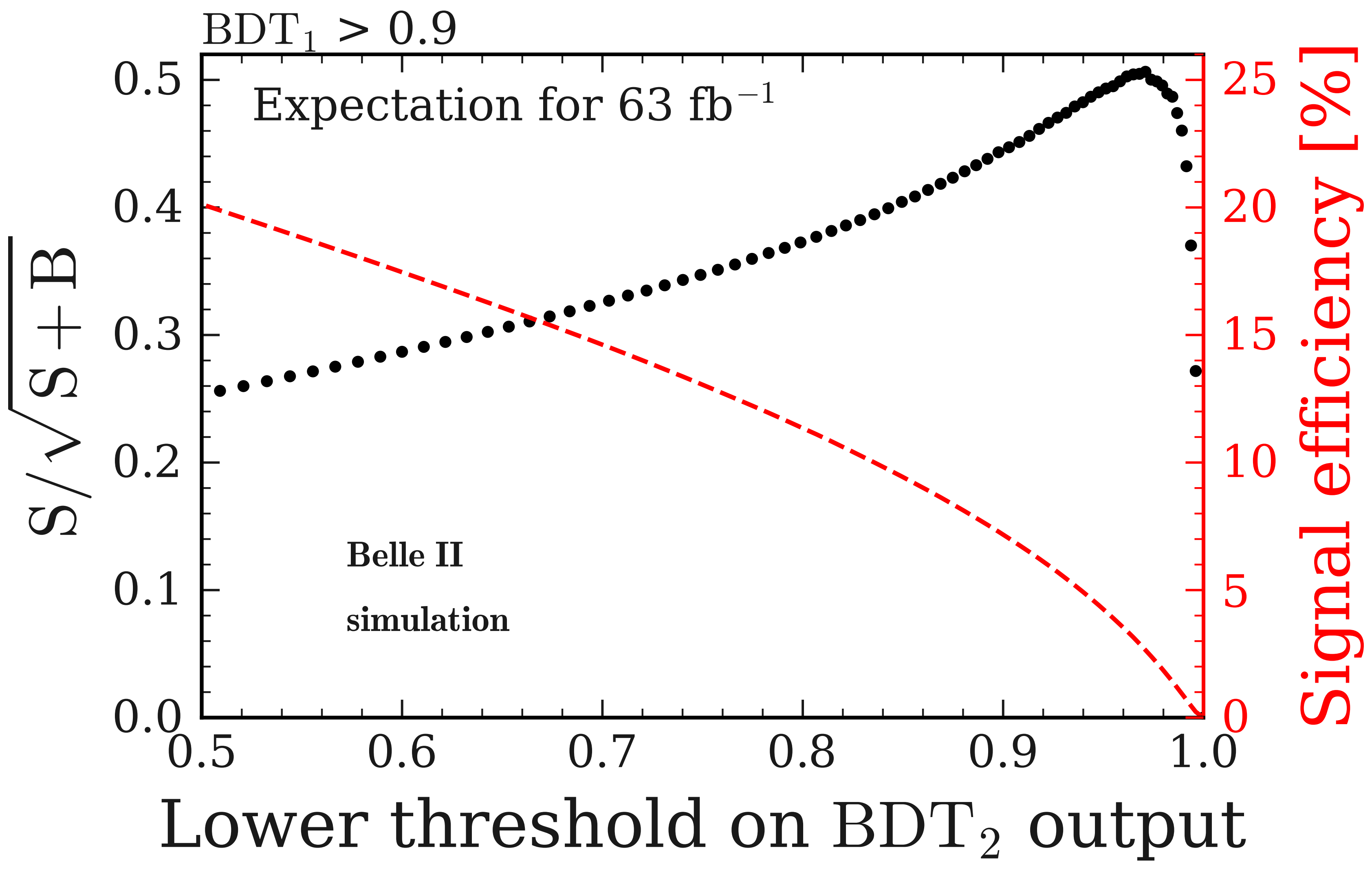
Nested BDTs

[PRL 127, 181802 (2021)] ★

4. Minimise the background contamination with two nested BDTs using 51 input variables

- 51 variables : good data/MC modelling and w/o loss of performance
- BDT_1 trained on the chosen 51 variables on ~ 10^6 events for all types of backgrounds and signal
- BDT_2 is trained with the same set of variables **but only on events with $BDT_1 > 0.9$** (~ 28% ε_{sig})
- **Boosting of statistics in signal region → improvement of signal purity of 35% @ 4% ε_{sig}**



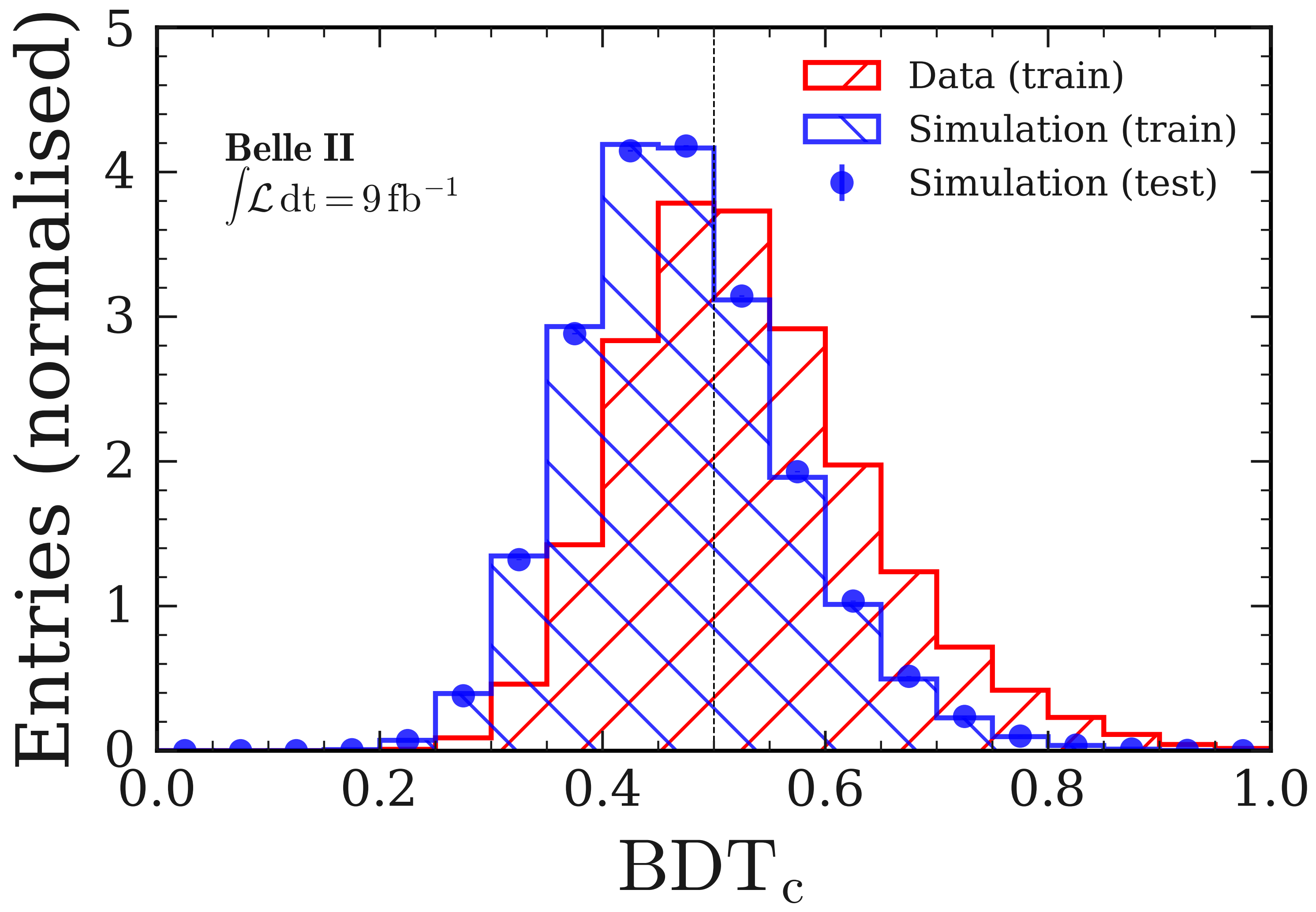


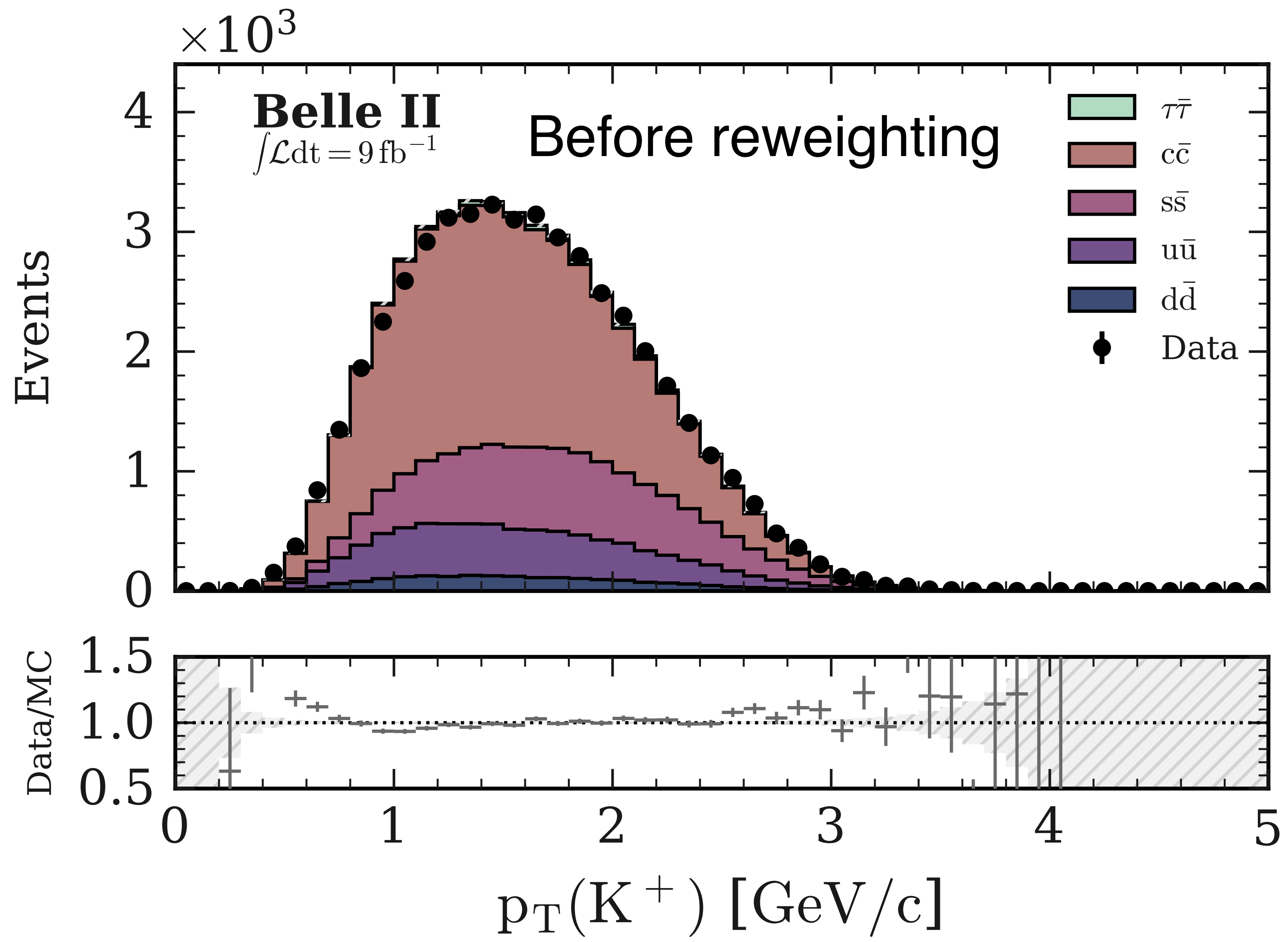
Improvement of Continuum Modelling

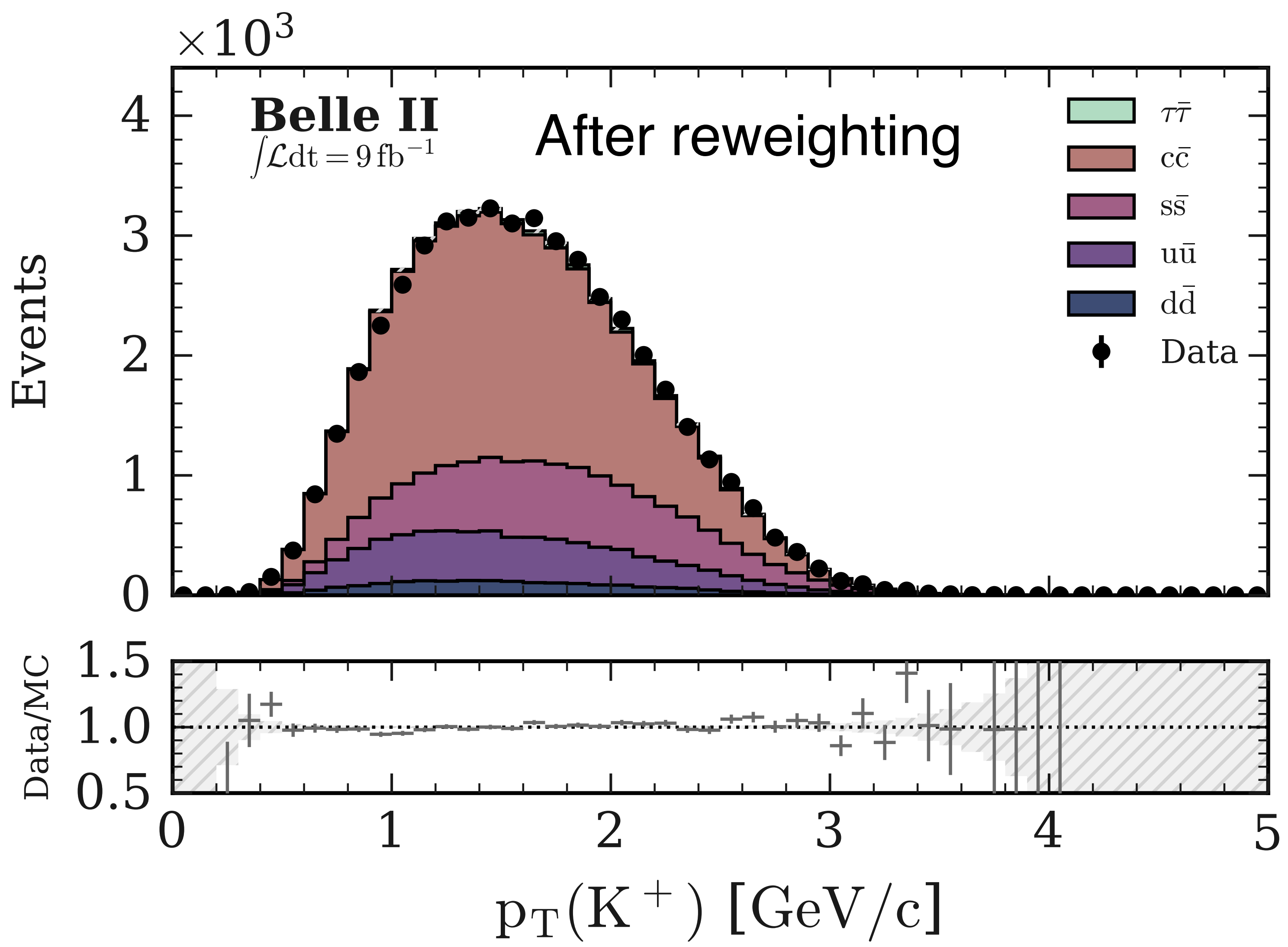
[PRL 127, 181802 (2021)] ★

5. Improve continuum modelling

- Additional BDT_c is trained on events with $BDT_1 > 0.9$ in order to correct mis-modelling of continuum simulation:
  - **Signal = off-resonance data** , **background = continuum simulation**
  - **Continuum simulation** events are reweighted with $\frac{p}{1-p}$, where $p = BDT_c$ output
  - After reweighting significant improvement for all input variables
  - Method taken from J. Phys.: Conf. Ser. 368 012028:







Validation I

[PRL 127, 181802 (2021)] ★

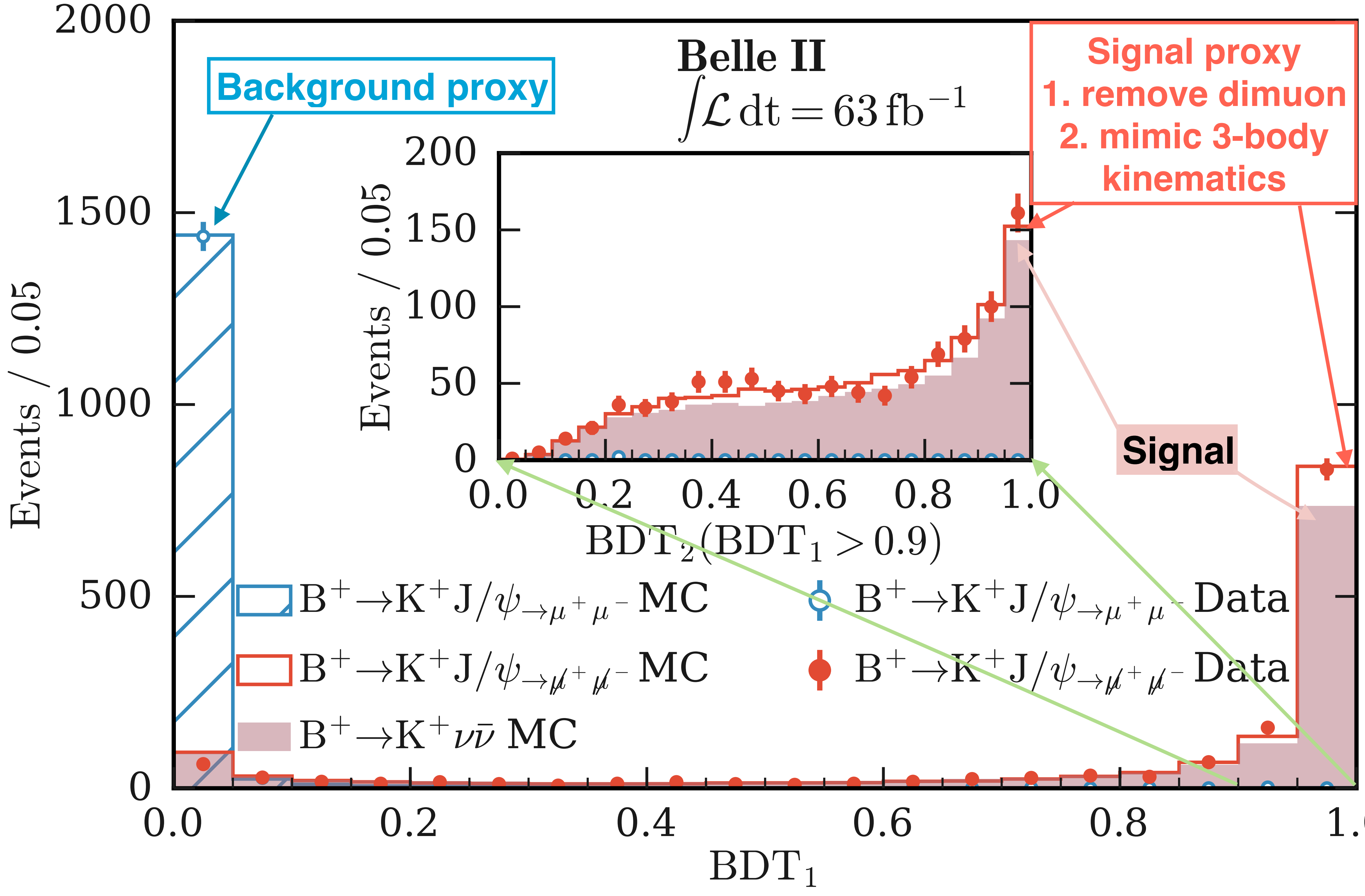
6. Validation with control channel $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$

- Used because of high $\mathscr{B}$ and clean signature
- Validation for both **signal** and ***B*-backgrounds**!
- Excellent agreement → **for BDT₂ > 0.95**

  data/MC=1.06 ±0 .10

Signal-like $B^+ \to J/\psi(\to \mu^+\mu^-)K^+ = B^+ \to J/\psi(\to \not{\mu}^+\not{\mu}^-)K^+$

1. Reconstruct $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$
2. Ignore dimuon from J/ψ to mimic missing energy
3. Replace four-momenta of K^+ by that of the signal to mimic 3-body kinematics

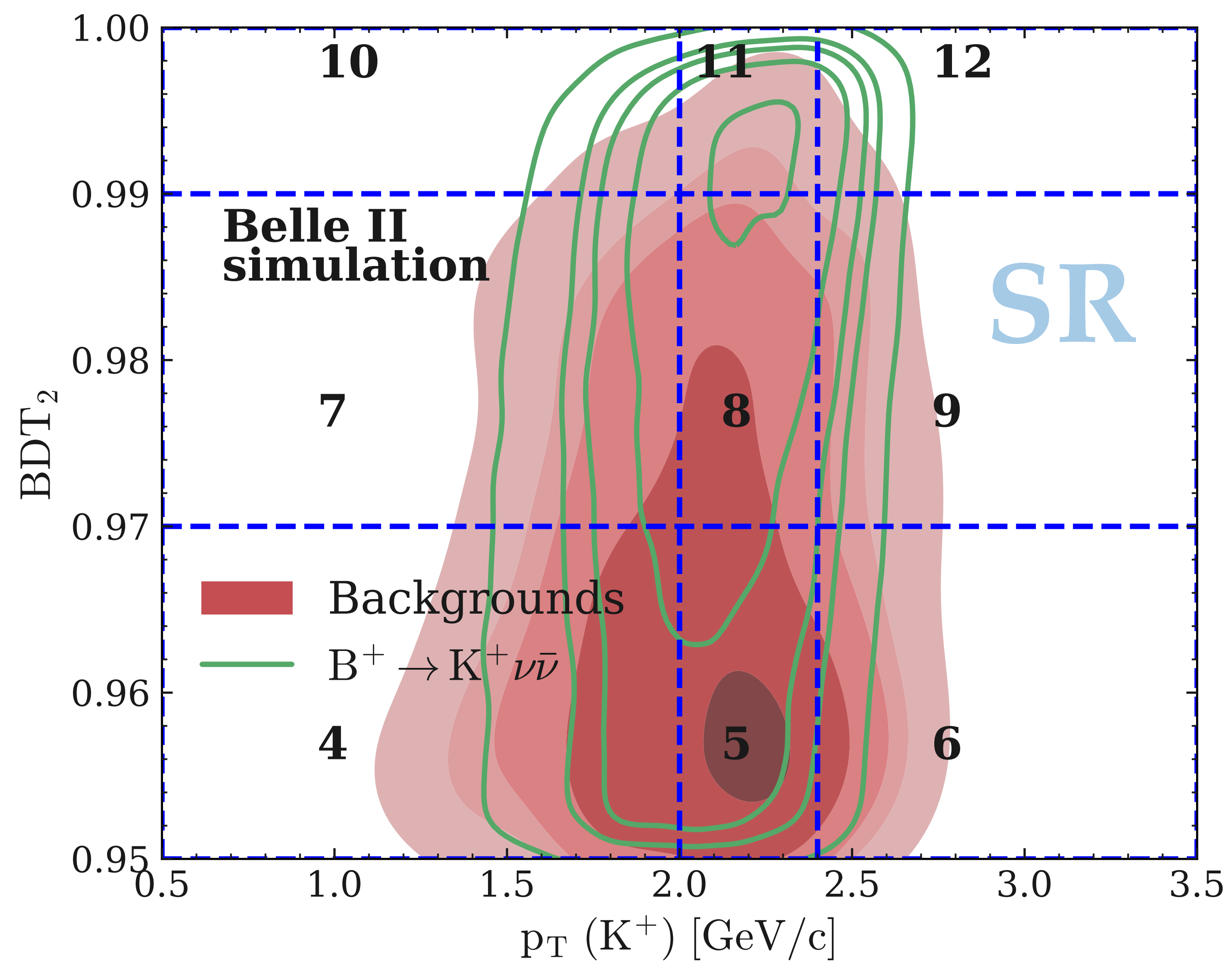


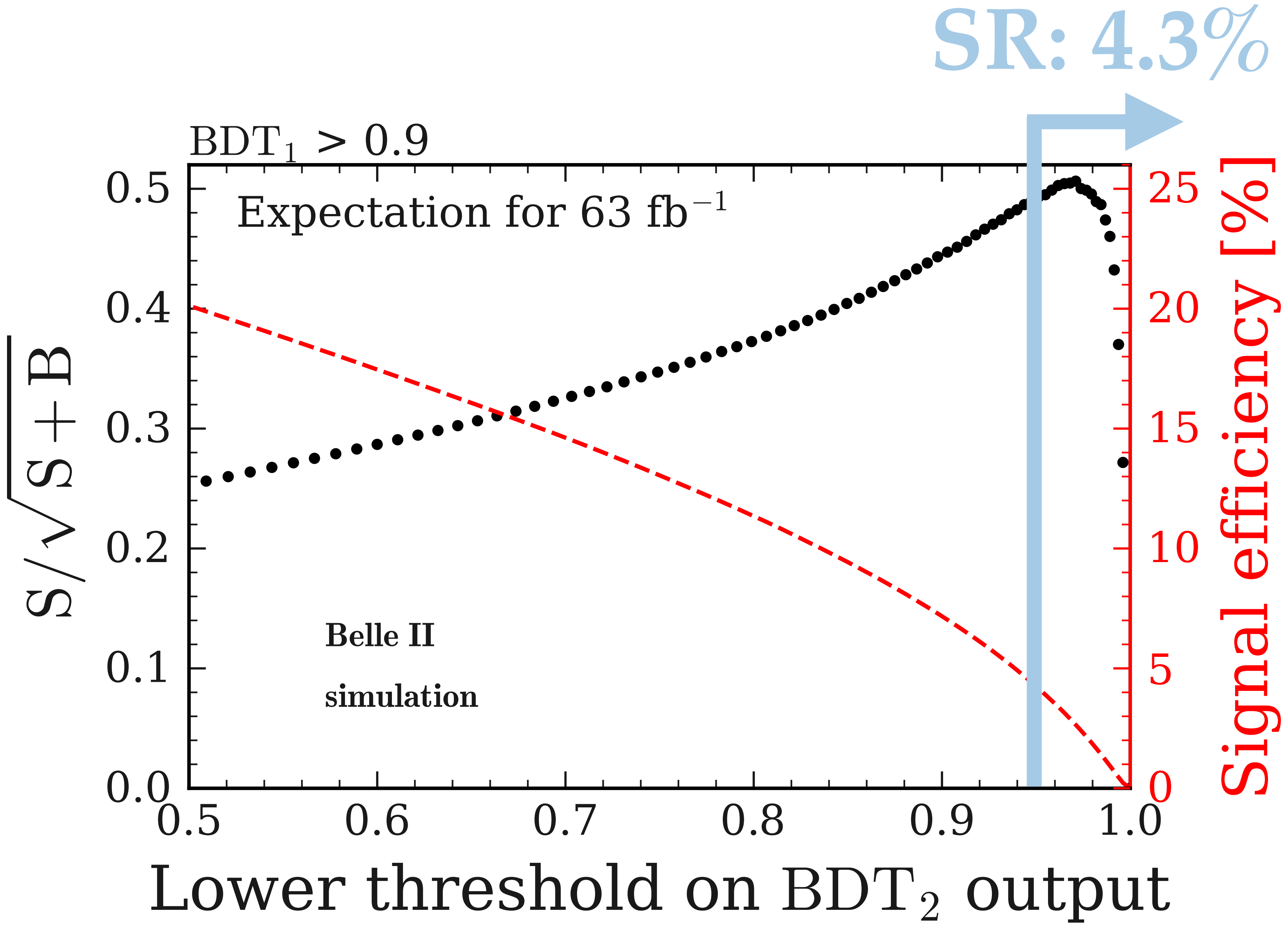
Fit region

[PRL 127, 181802 (2021)] ★

7. Fitting variables and measurement region selection

- Identify signal region (SR) with BDT2 output at maximum FOM
- Bin further in 2D : $p_T(K) \times \mathrm{BDT}_2$ to maximise sensitivity
- Fit region = 24 bins in $p_T(K) \times \mathrm{BDT}_2$
  - 12 bins (on-resonance)
  - 12 bins (off-resonance)





Region	2D Bin Boundary Definition	Physics Processes	$\sqrt{s}$
Signal Region (SR)	$p_T(K^+) \in [0.5, 2.0, 2.4, 3.5]$ GeV/c $\mathrm{BDT}_2 \in [0.95, 0.97, 0.99, 1.0]$	signal + all backgrounds	$\Upsilon(4S)$
Control Region 1 (CR1)	$p_T(K^+) \in [0.5, 2.0, 2.4, 3.5]$ GeV/c $\mathrm{BDT}_2 \in [0.93, 0.95]$	signal + all backgrounds	$\Upsilon(4S)$
Control Region 2 (CR2)	$p_T(K^+) \in [0.5, 2.0, 2.4, 3.5]$ GeV/c $\mathrm{BDT}_2 \in [0.95, 0.97, 0.99, 1.0]$	continuum backgrounds	off-resonance (-60 MeV/c^2)
Control Region 3 (CR3)	$p_T(K^+) \in [0.5, 2.0, 2.4, 3.5]$ GeV/c $\mathrm{BDT}_2 \in [0.93, 0.95]$	continuum backgrounds	off-resonance (-60 MeV/c^2)

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

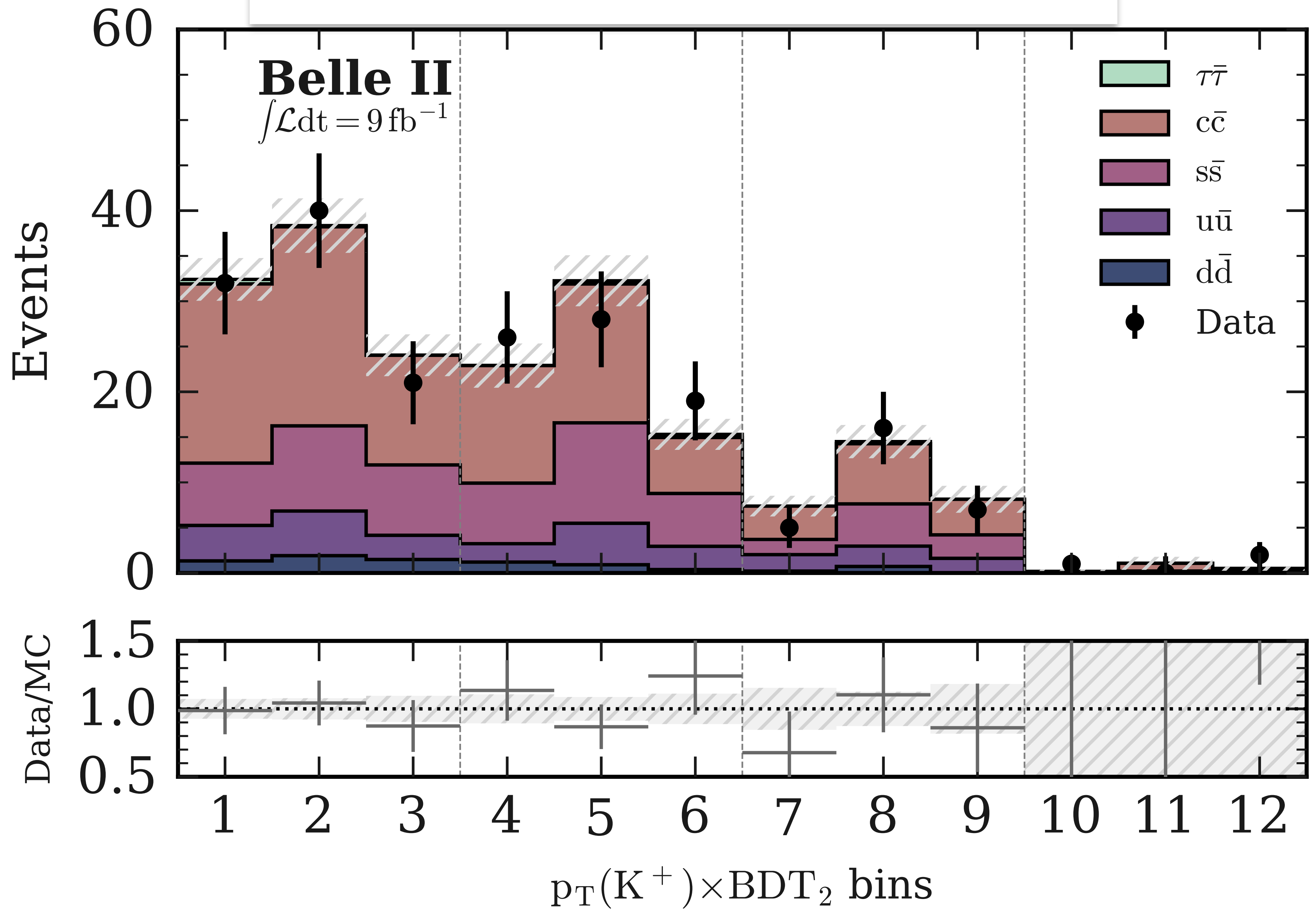
Validation II

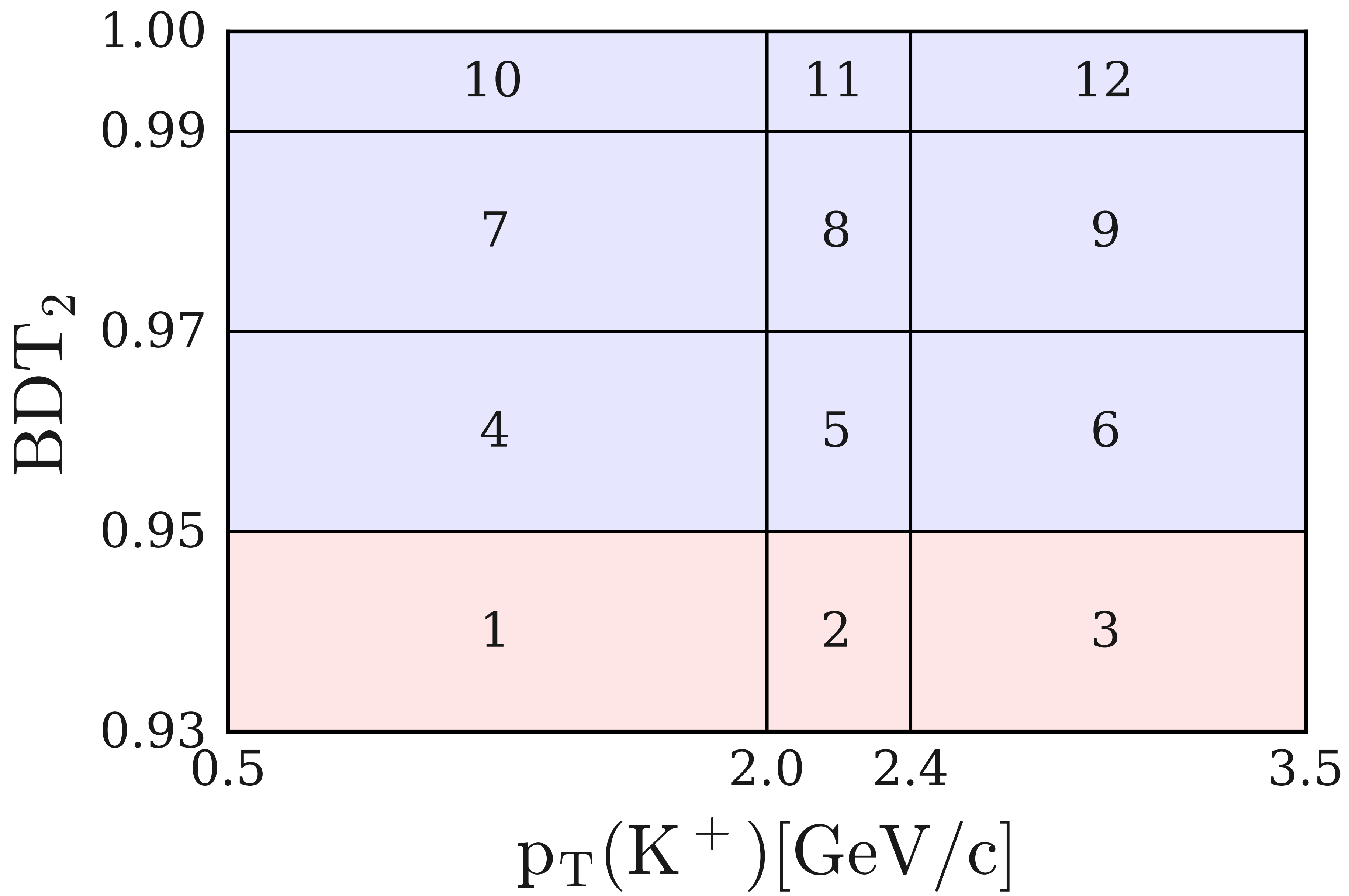
[PRL 127, 181802 (2021)] ★

8. Validation between off-resonance data and continuum simulation in fitting variables $p_T(K) \times \mathrm{BDT}_2$

- Very good agreement in shape
- Large normalisation discrepancy: **Data/MC =1.40 ± 0.12**

CR2 + CR3





Statistical model

[PRL 127, 181802 (2021)] ★

9. Set-up binned fit using HistFactory statistical model

- Likelihood based on HistFactory formalism implemented with pyhf + cross-check with sghf: simplified Gaussian model
  - Signal and background templates from MC
  - Separate templates for all backgrounds: mixed B, charged B, $c\bar{c}$, $u\bar{u}$, $s\bar{s}$, $d\bar{d}$, $\tau^-\tau^+$
  - All systematics included via nuisance parameters:
    - background normalisation uncertainty
    - tracking inefficiency
    - neutral energy mis-calibration for photons
    - neutral energy mis-calibration for unmatched photons
    - uncertainty on PID correction due to limited statistics
    - uncertainty on branching fractions of leading background processes
    - uncertainty on SM form factor
  - **Total number of fit parameters:**
    - 175 nuisance parameters ϕ
    - 1 parameter of interest (signal strength=μ)
    - **1 μ = SM $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$**

$$f(n, a \,|\, \eta, \chi) = \prod_{r \in \text{regions}} \prod_{b \in \text{bins}} \text{Pois}(n_{rb} \,|\, \nu_{rb}(\eta, \chi)) \prod_{\chi} c_\chi(a_\chi \,|\, \chi)$$

Simultaneous measurements of multiple regions

Constraints

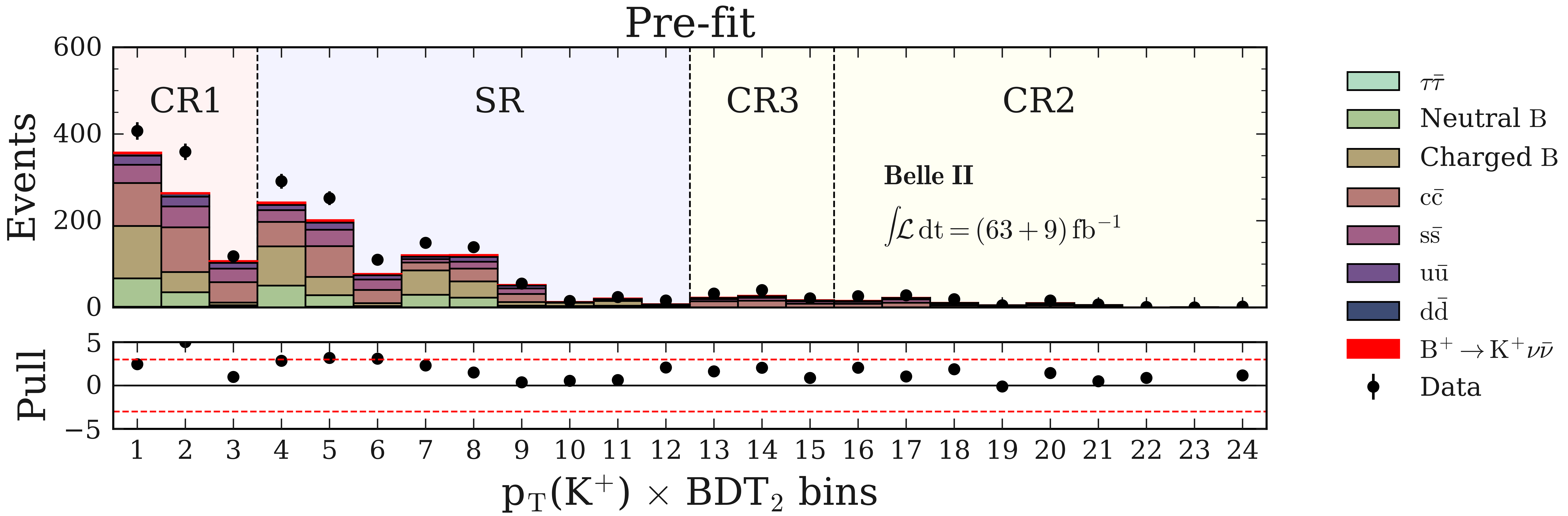
η = parameter of interest
χ = nuisance parameters

Statistical model

[PRL 127, 181802 (2021)] ★

9. Set-up binned fit using HistFactory statistical model

- Likelihood based on HistFactory formalism implemented with pyhf + cross-check with sghf: simplified Gaussian model
  - Signal and background templates from MC

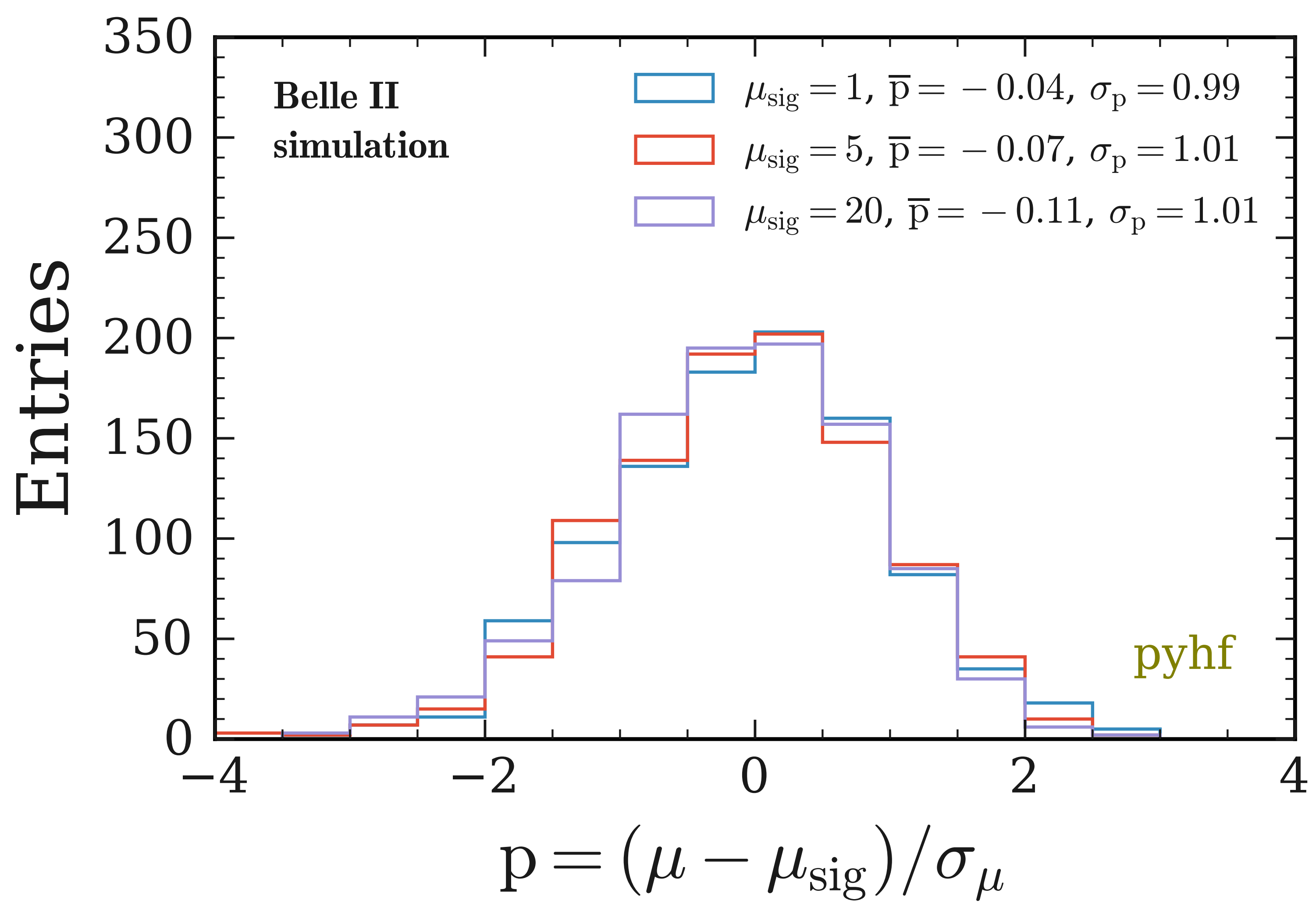


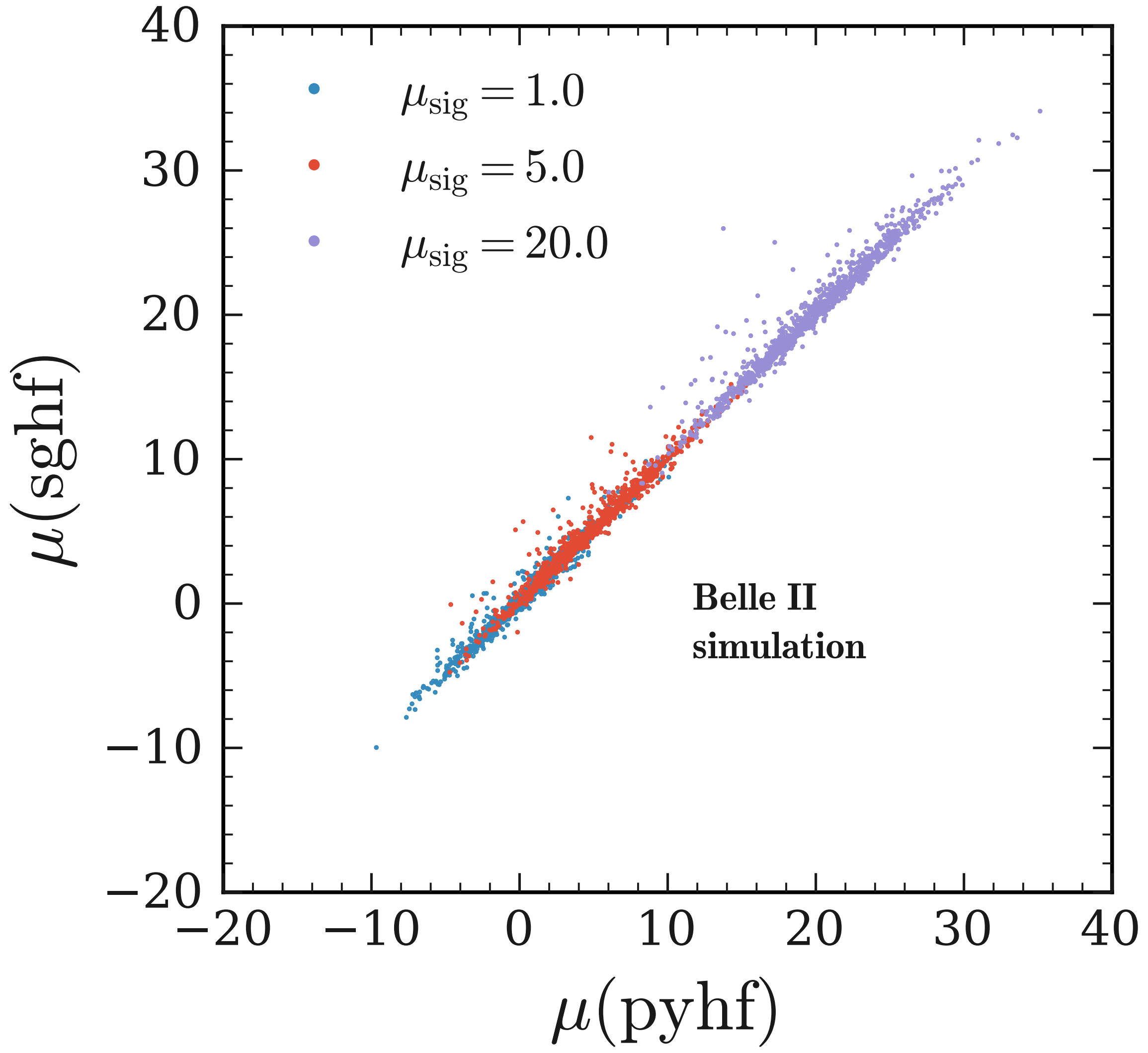
Fit validation

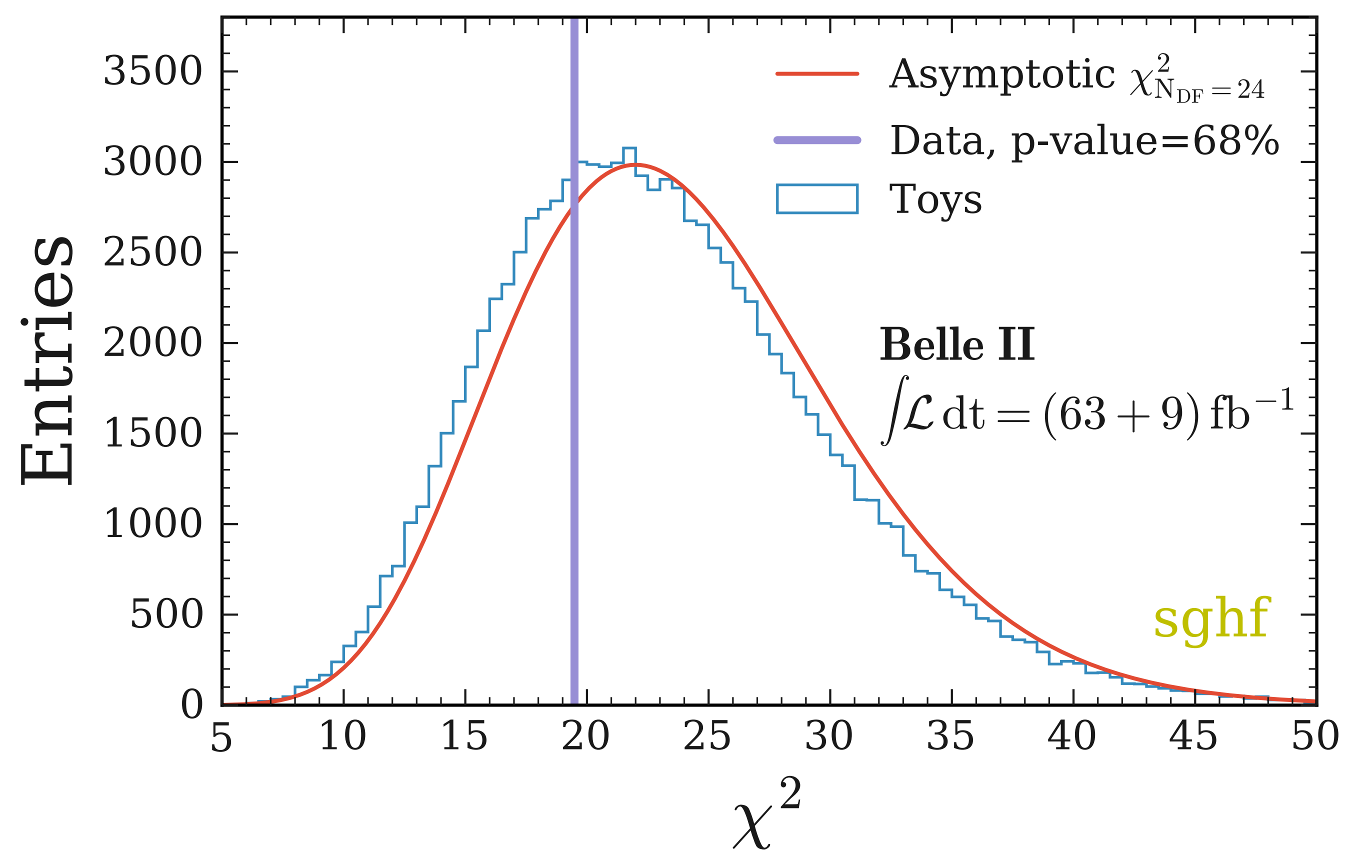
[PRL 127, 181802 (2021)] ★

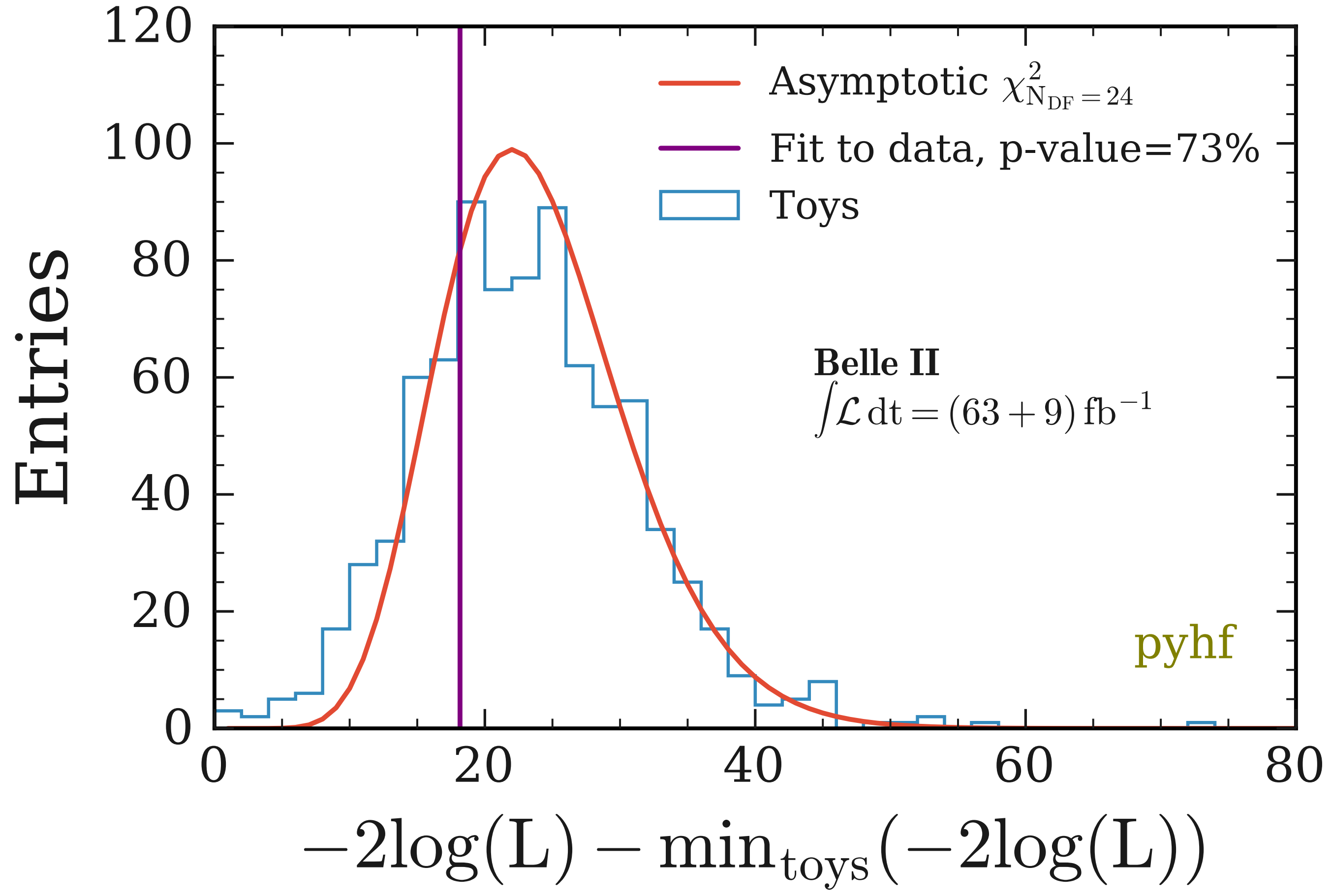
10. Perform Fit Bias Check

- Used because of high $\mathscr{B}$ and clean signature
- Generate toys with signal strength μ = 1, 5, 20 and check pulls $= \dfrac{\mu_{fit} - \mu_{inj}}{\sigma_\mu}$
- Results: 0 bias, expected μ recovered, very good agreement between pyhf and sghf









11. Check Data-Model Compatibility

- Generate toys and check fit quality
- Results: p-value shows good data model compatibility for both pyhf and sghf

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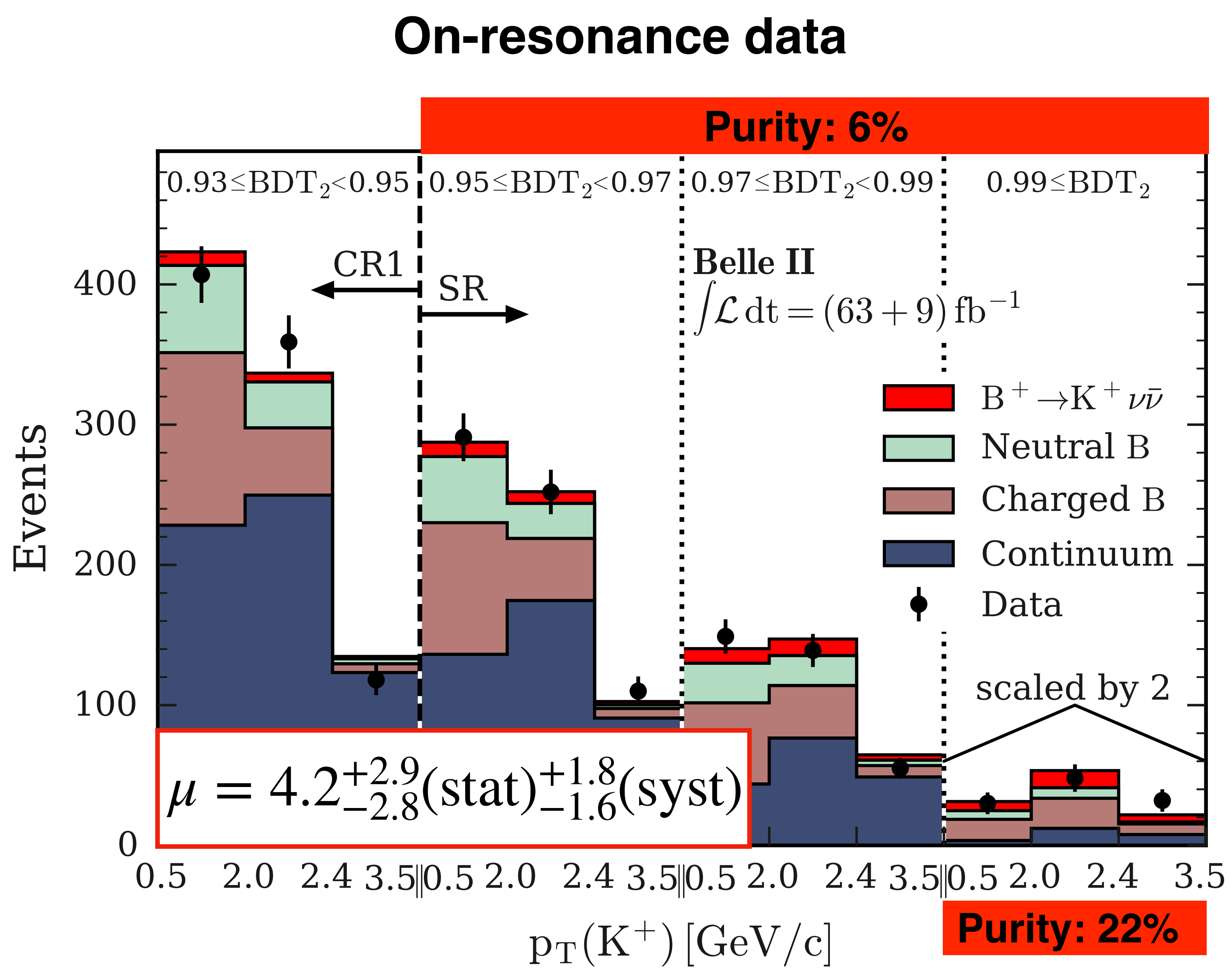
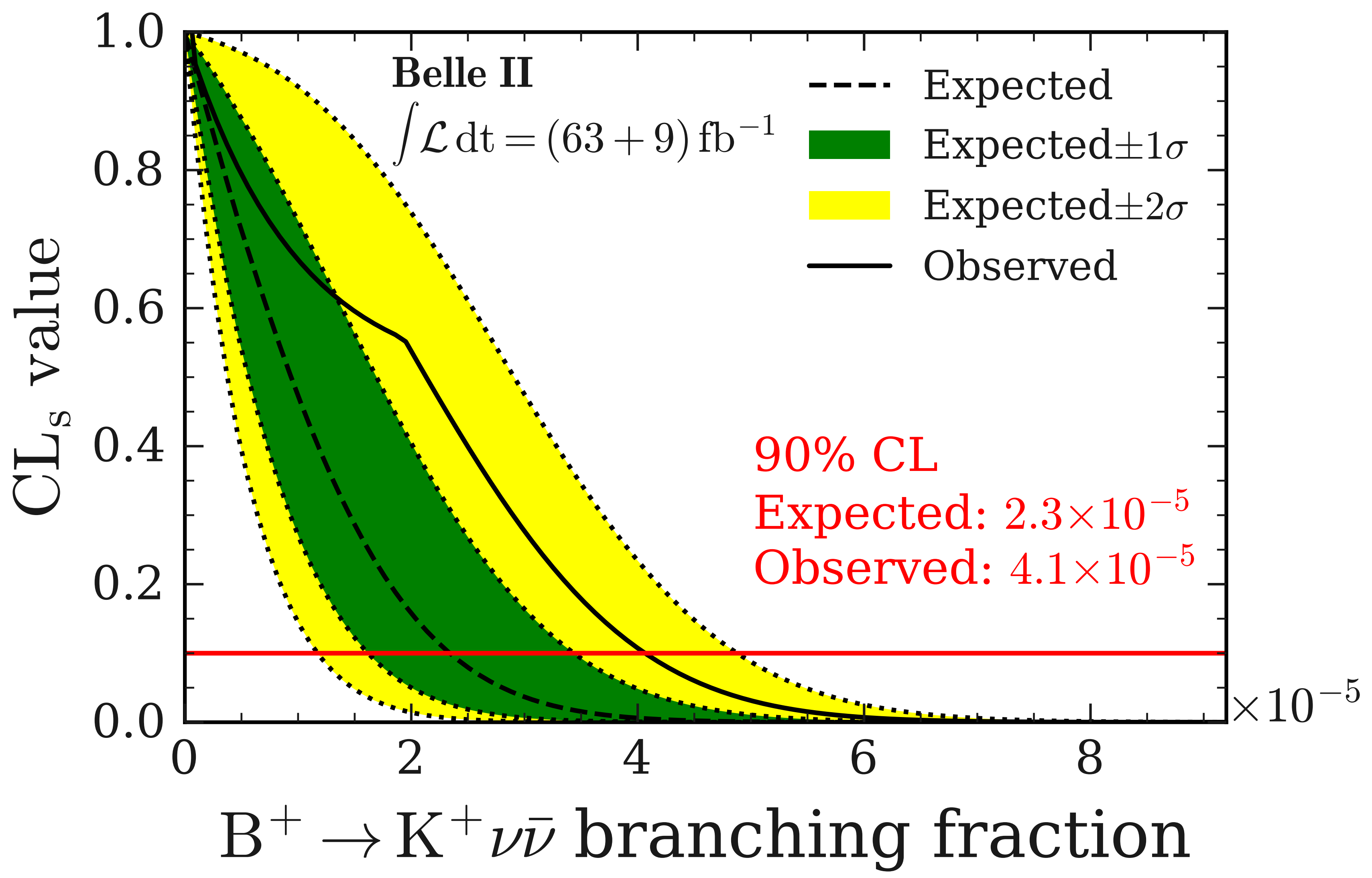
Fit results

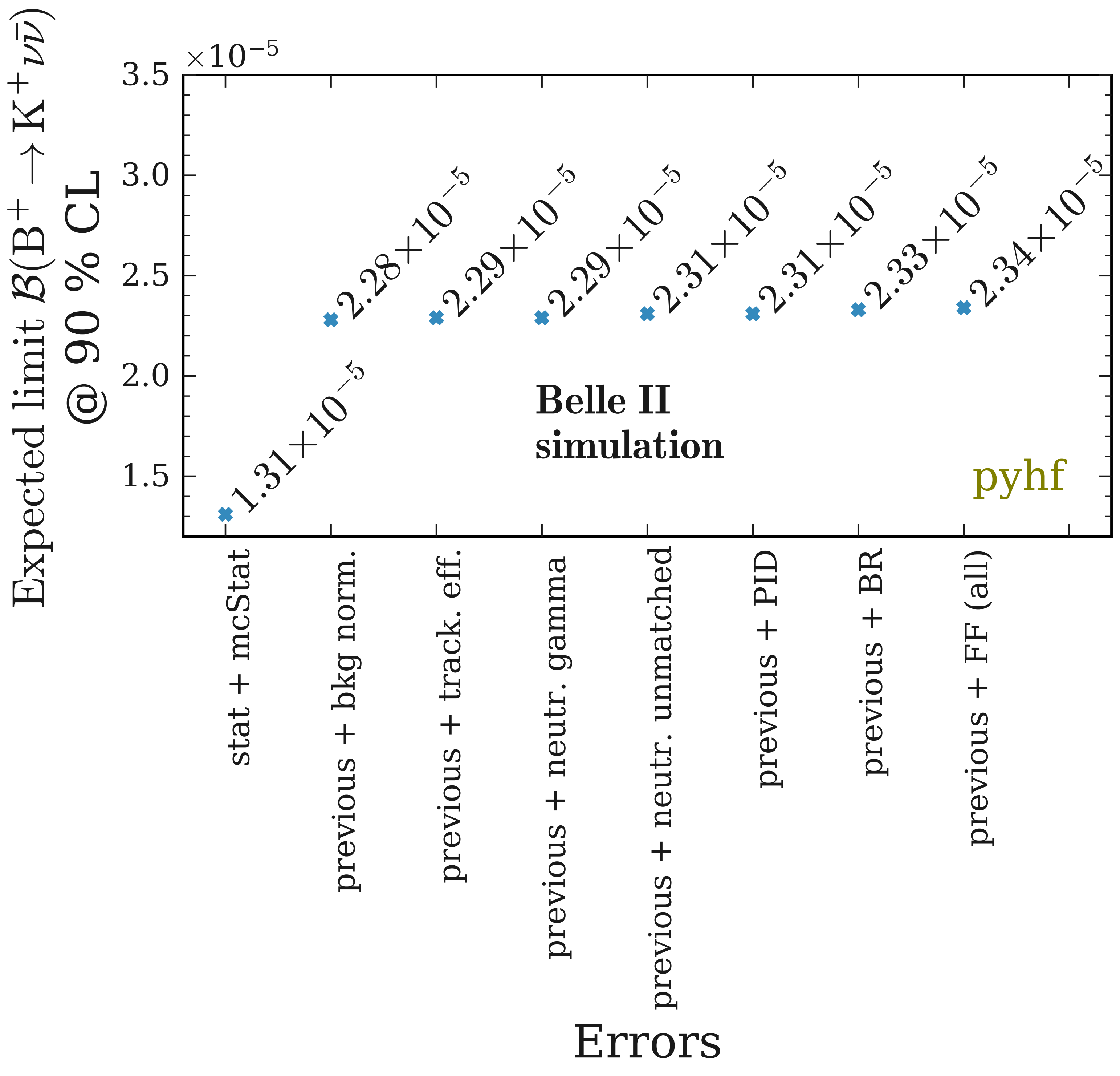
[PRL 127, 181802 (2021)] ★

12. Perform simultaneous ML fit to $p_T(K^+) \times \mathrm{BDT}_2$ to extract signal strength μ

- $\boldsymbol{\mu = 4.2^{+2.9}_{-2.8}(\mathrm{stat})^{+1.8}_{-1.6}(\mathrm{syst}) = 4.2^{+3.4}_{-3.2}}$ → no significant signal is observed
- Limit of 4.1×10^{-5} @ 90 C.L. → competitive with *only* 63 fb^{-1}
- Leading systematic: background normalisation

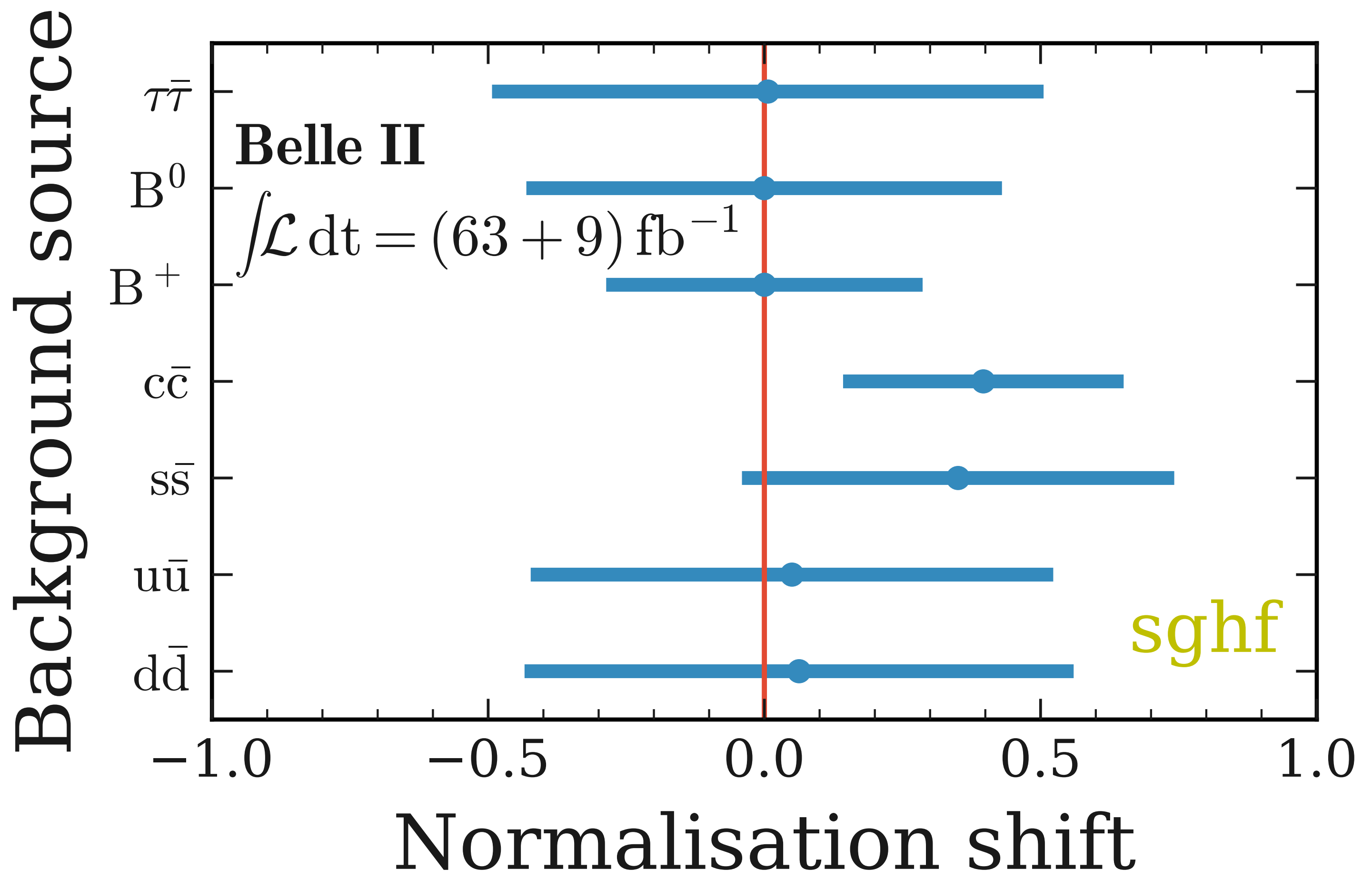


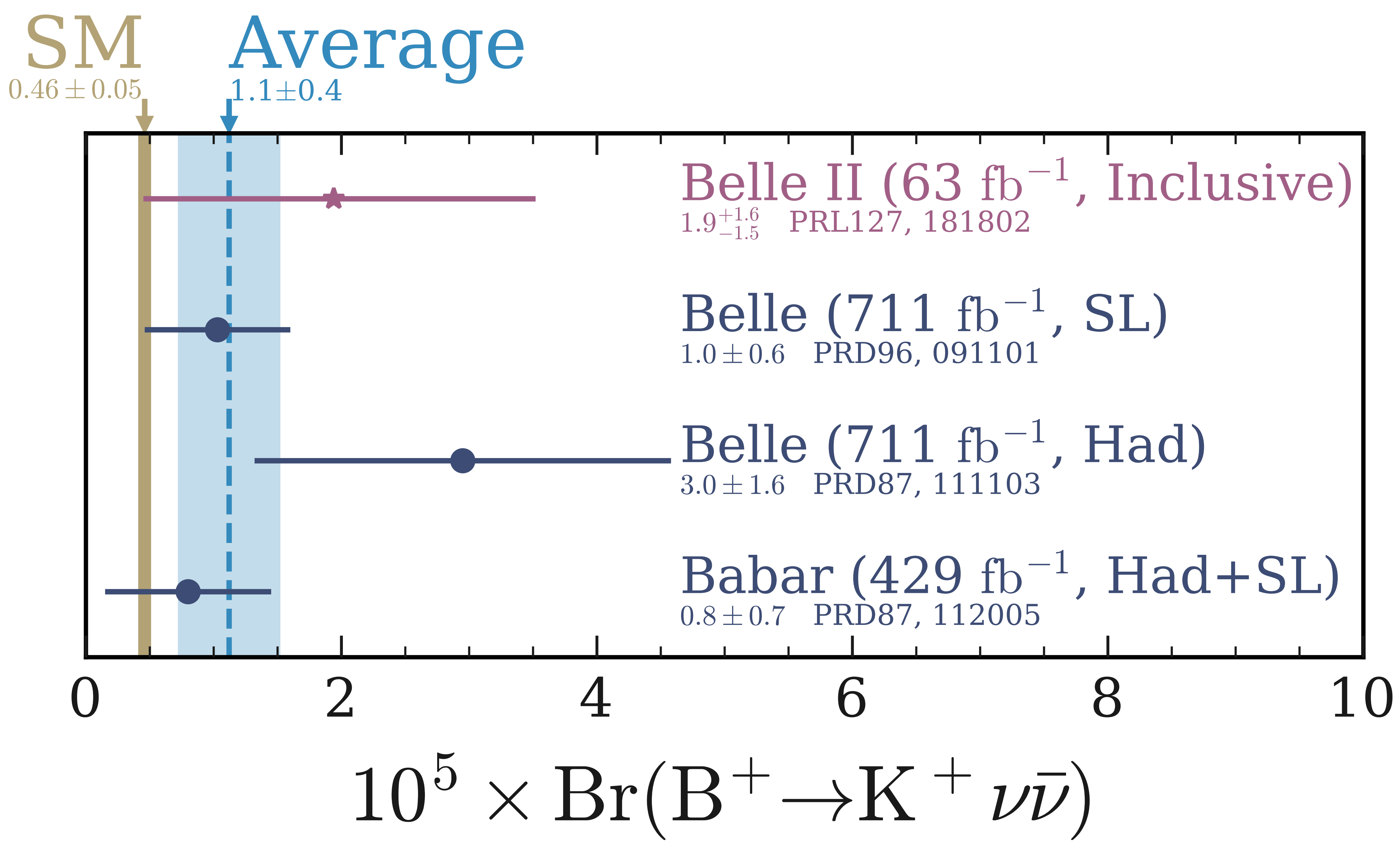


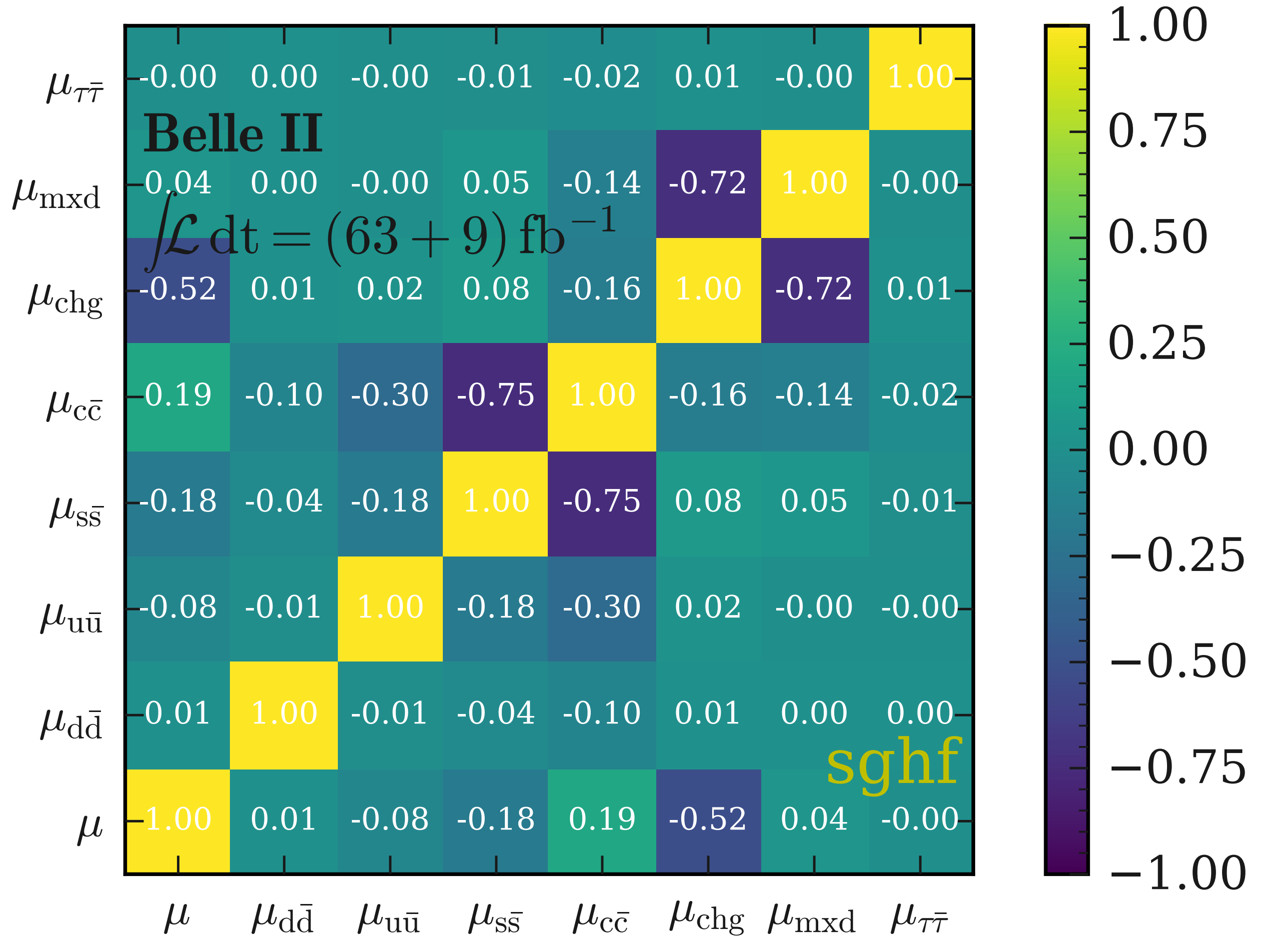


What we learnt from fit? [PRL 127, 181802 (2021)]

1. $c\bar{c}$, $s\bar{s}$ continuum backgrounds are pulled up by 40%
2. Inclusive tag approach shows the best performance
    1. 3.5 better than HAD tag
    2. 20% better than SL Belle tag
    3. 10% better than HAD and SL tag
3. BSM $B^+ \to K^+\nu\bar{\nu}$ already with 1 ab^{-1}







Prospects

Hochhaus, KIT, Germany

Karlsruher Institut für Technologie

Prospects in Belle II

[PRL 127, 181802 (2021)] ★

Belle II snowmass paper : 2 scenarios baseline (improved*)

Uncertainties on the signal strength μ

Decay	$1\,\text{ab}^{-1}$	$5\,\text{ab}^{-1}$	$10\,\text{ab}^{-1}$	$50\,\text{ab}^{-1}$
$B^+ \to K^+\nu\bar{\nu}$	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) for SM $B^+ \to K^+\nu\bar{\nu}$ with 5 ab^{-1}

We are here

↓

Measurements : Limit → $\mathscr{B}$ → Angular Observables → Ratios

Prospects in Belle II

- **What we want to measure:**
  - Other channels
  - Differential measurements
  - Inclusive measurement X_s
  - Measurement of F_L
  - BSM measurements
- **How to get there faster?**
  - Reduce biggest systematics
  - Combine all tagging approaches
  - Combining more channels

*The "improved" scenario assumes a 50% increase in signal efficiency for the same background level

Re-(interpretations)

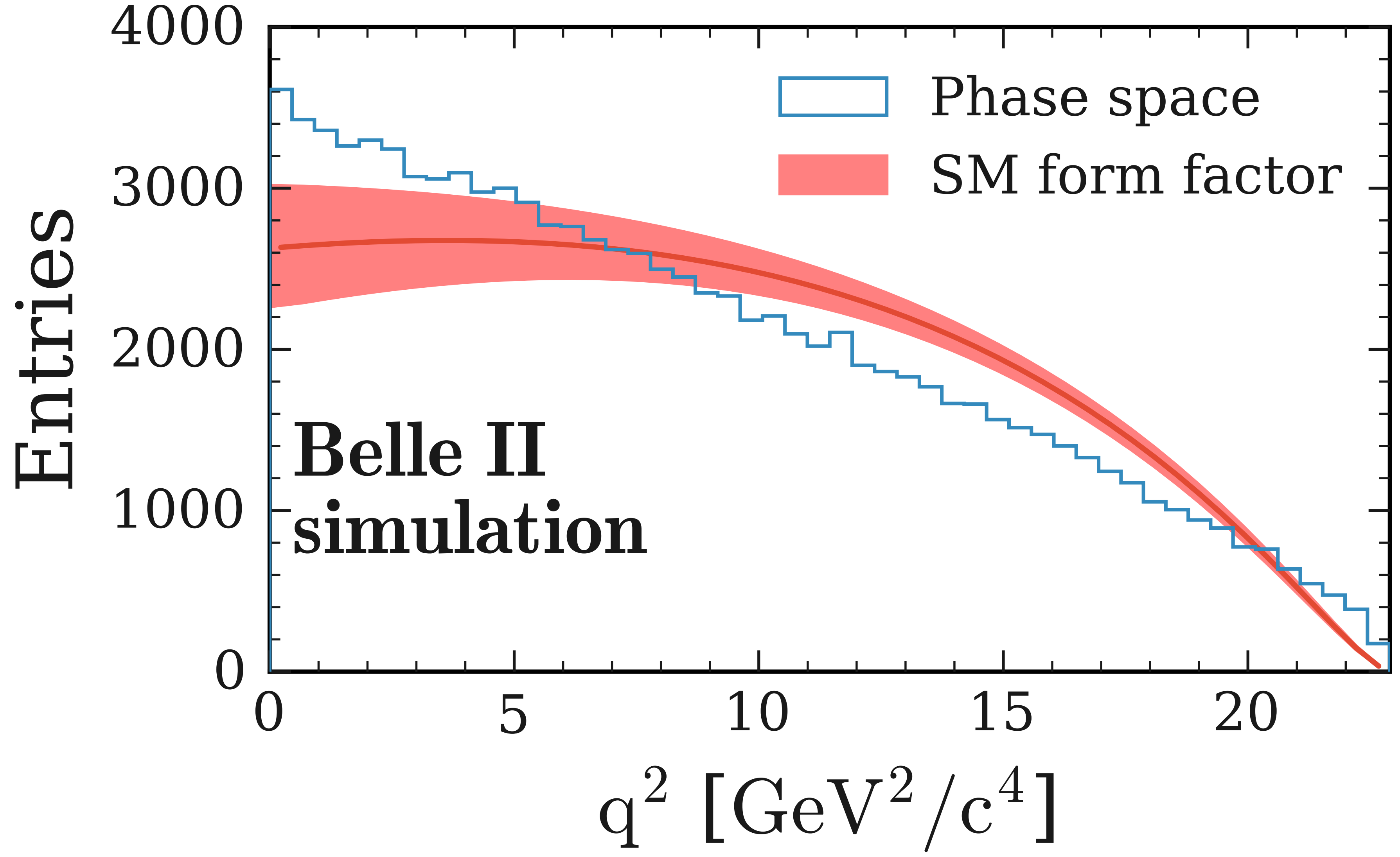
[PRL 127, 181802 (2021)] ★

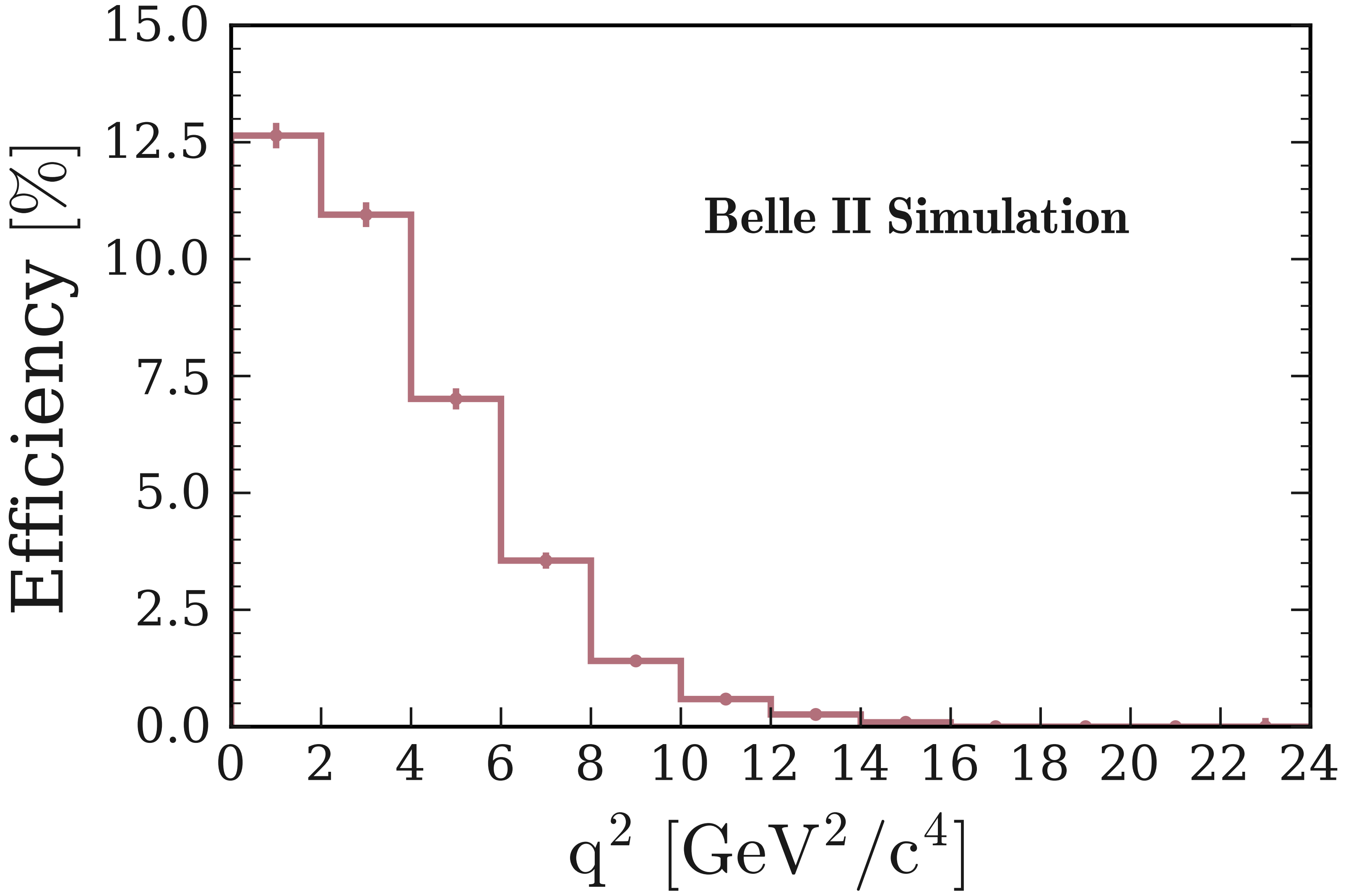
Partial reinterpretation can be done as Belle II publishes ϵ_{sig} as a function of q^2:

- Reminder: default signal model → PHSP model with SM form factor reweighting **[arXiv:1409.4557]**
- At low q^2 maximum signal efficiency of 13%
- No sensitivity for $q^2 > 16$ GeV^2/c^2
- All public plots at HEPData

For full re-(interpretation):

- Provide full likelihood





Conclusion

Belle II

- is accumulating high quality data
- is well suited to study rare B-decays with (multiple) neutrinos
- will provide competitive and independent checks of $b \to sll$ channels where anomalies were reported

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 tagging	429
Belle	2013	$< 5.5 \times 10^{-5}$ [Phys.Rev.D87,111103(R)]	Had tagging	711
Belle	2017	$< 1.9 \times 10^{-5}$ [Phys.Rev.D96,091101(R)]	SL tagging	711
Belle II	2021	$< 4.1 \times 10^{-5}$	Inclusive tagging	63

Rare B-decays with neutrinos are challenging but fun!

- $b \to sll$ transitions are heavily suppressed in SM
- BSM can change this
- Next stop is measurement of $\mathscr{B}$

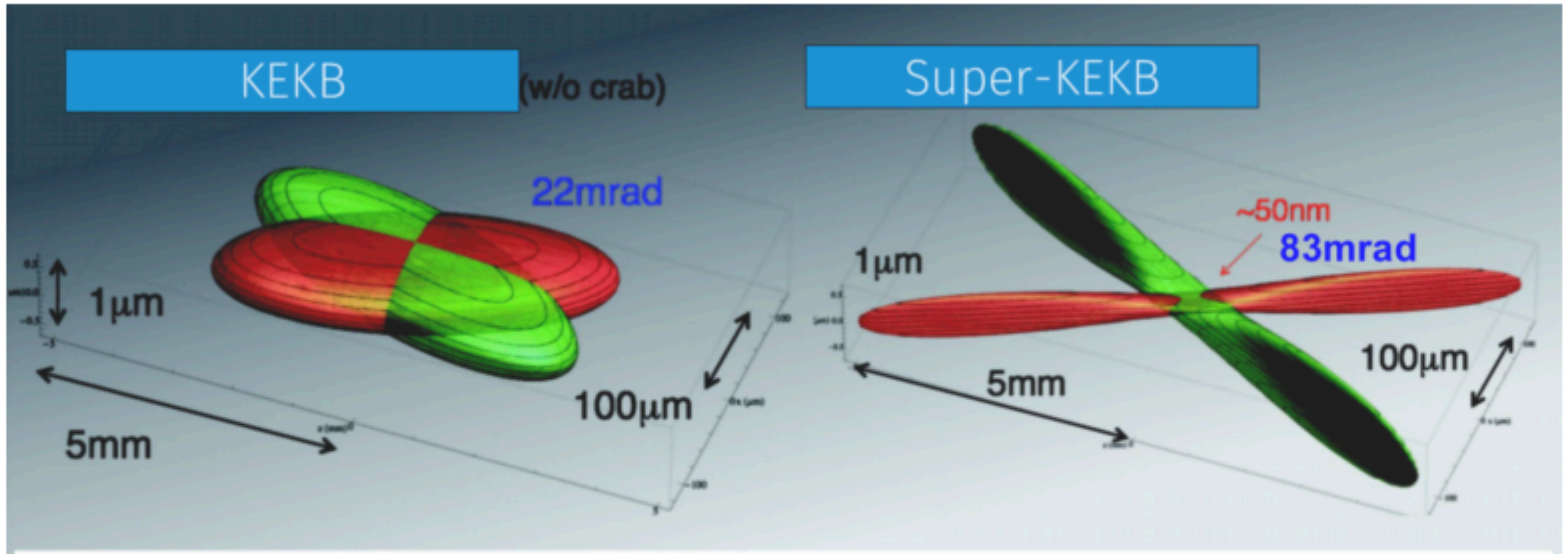
Belle II made its first footprint with search for $B^+ \to K^+ \nu\bar{\nu}$ decays

- first Belle II B-physics paper
- employing novel inclusive tagging approach
- highly competitive limit with "only" 1/10 of previous B-factory dataset

Backup

Globe, CERN, Geneva, Switzerland

SuperKEKB vs KEKB



	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

factor 20 factor 2-3

	KEKB		**SuperKEKB (Juni 2022)**		SuperKEKB Ziel	
	LER	HER	**LER**	**HER**	LER	HER
Energie [GeV]	3.5	8	**4**	**7**	4	7
#Bunches	1584		**2249**		1800	
β^*_x/β^*_y [mm]	1200/5.9	1200/5.9	**80/1.0**	**60/1.0**	32/0.27	25/0.3
I [A]	1.64	1.19	**1.46**	**1.15**	2.8	2.0
Luminosität [10^{34} $cm^{-2}s^{-1}$]	2.1		**4.65 (Rekord!)**		60	
Int. Luminosität [ab^{-1}]	1		**0.43**		50	

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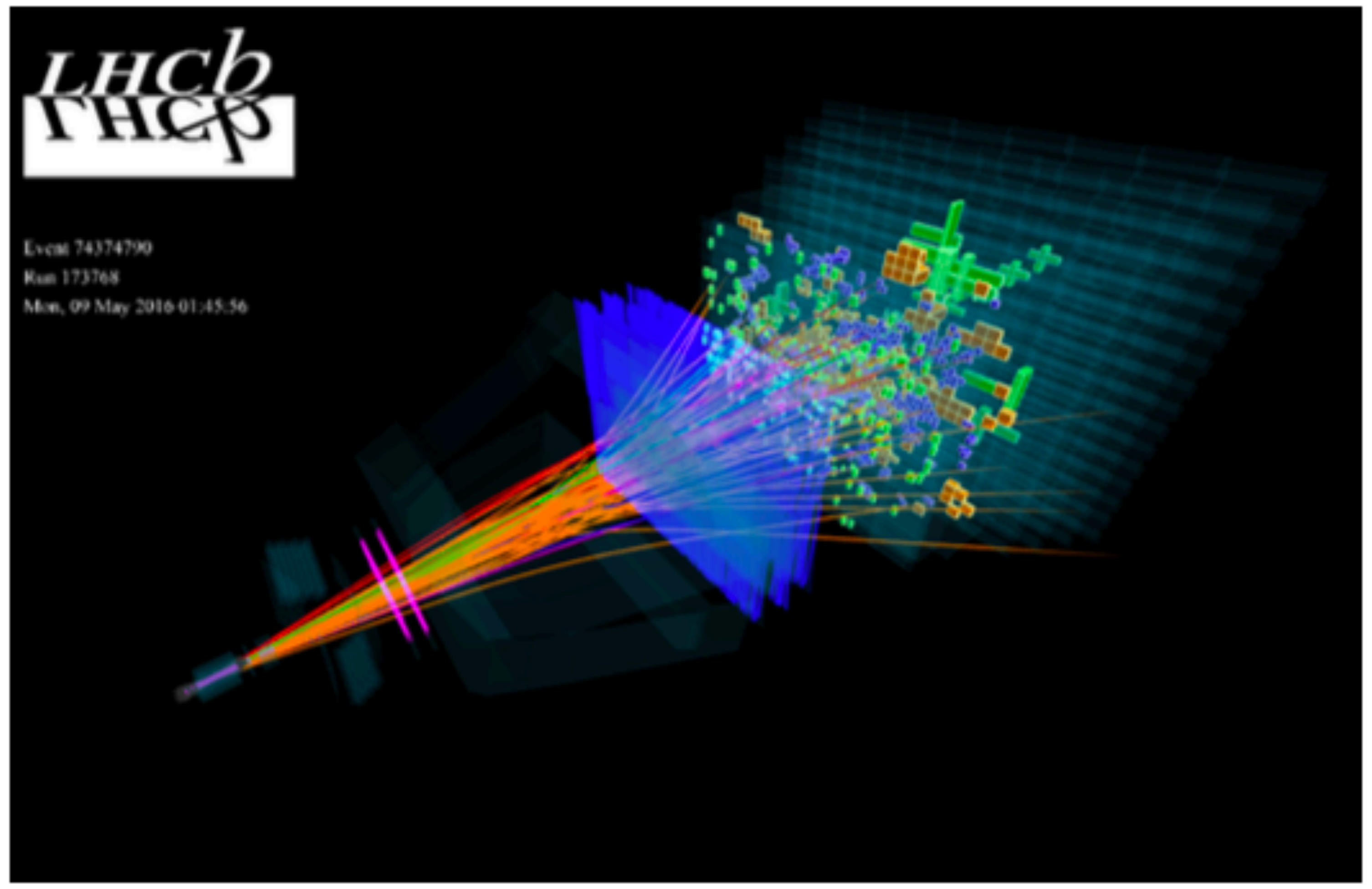
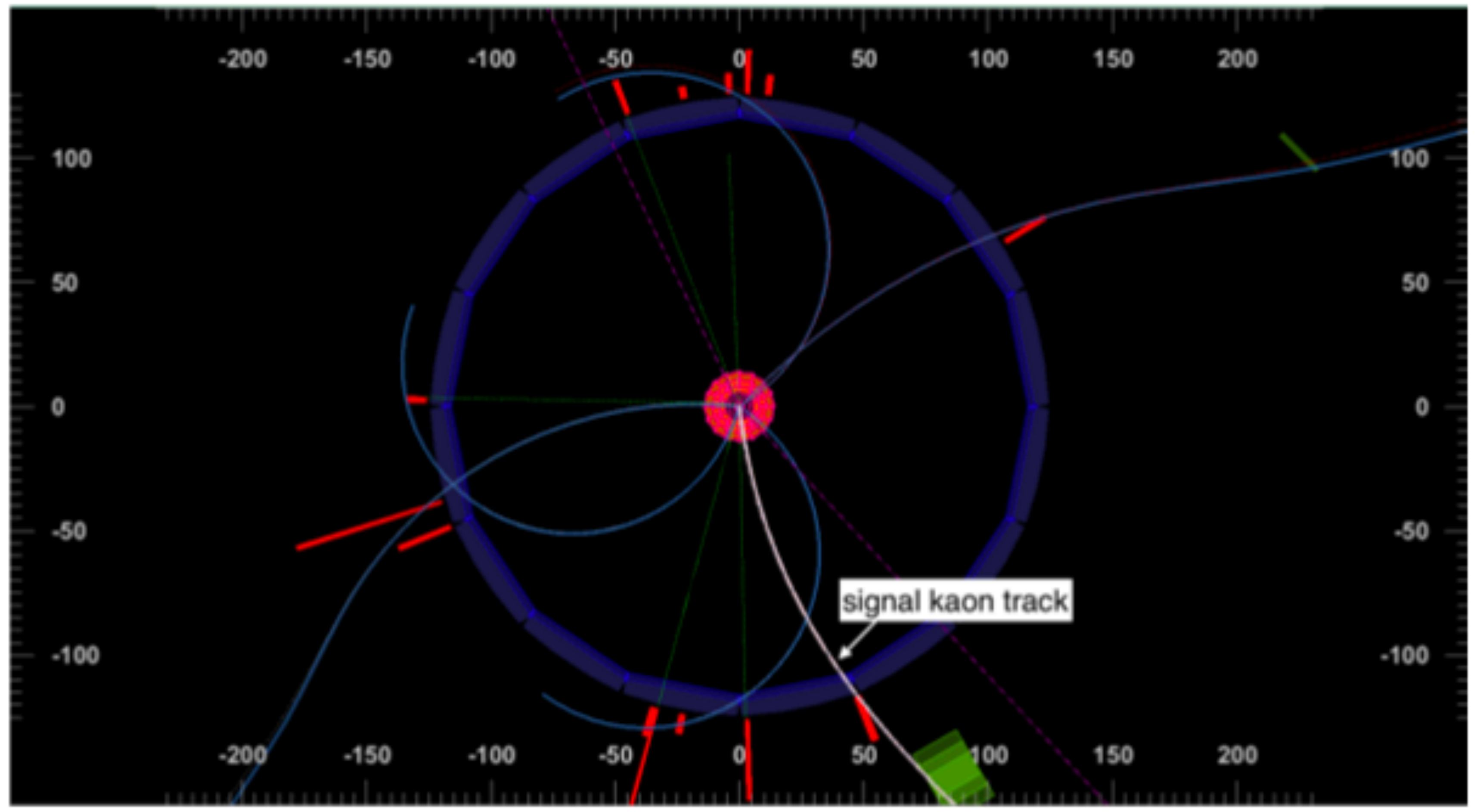
Belle II vs LHCb

LHCb	Belle II
single-arm detector longitudinal momentum of B not known	hermetic detector known initial state kinematics pro @ neutral object reconstruction (photon, K_L)





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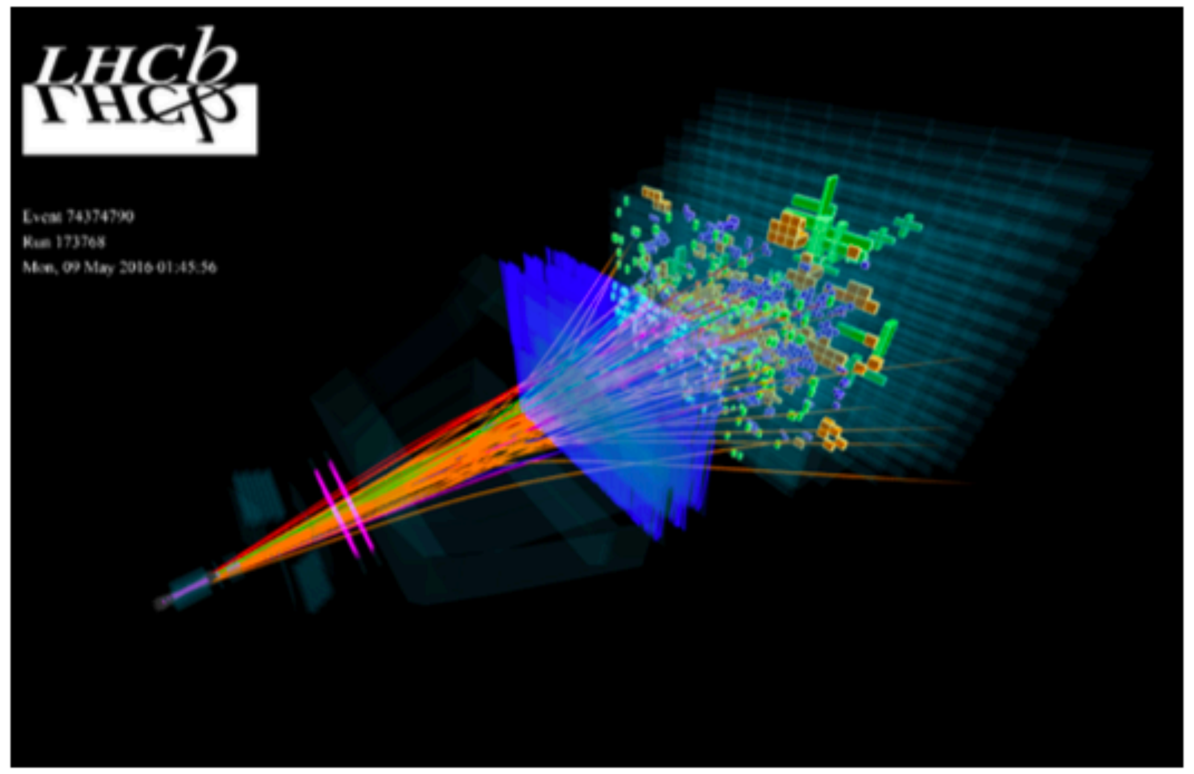
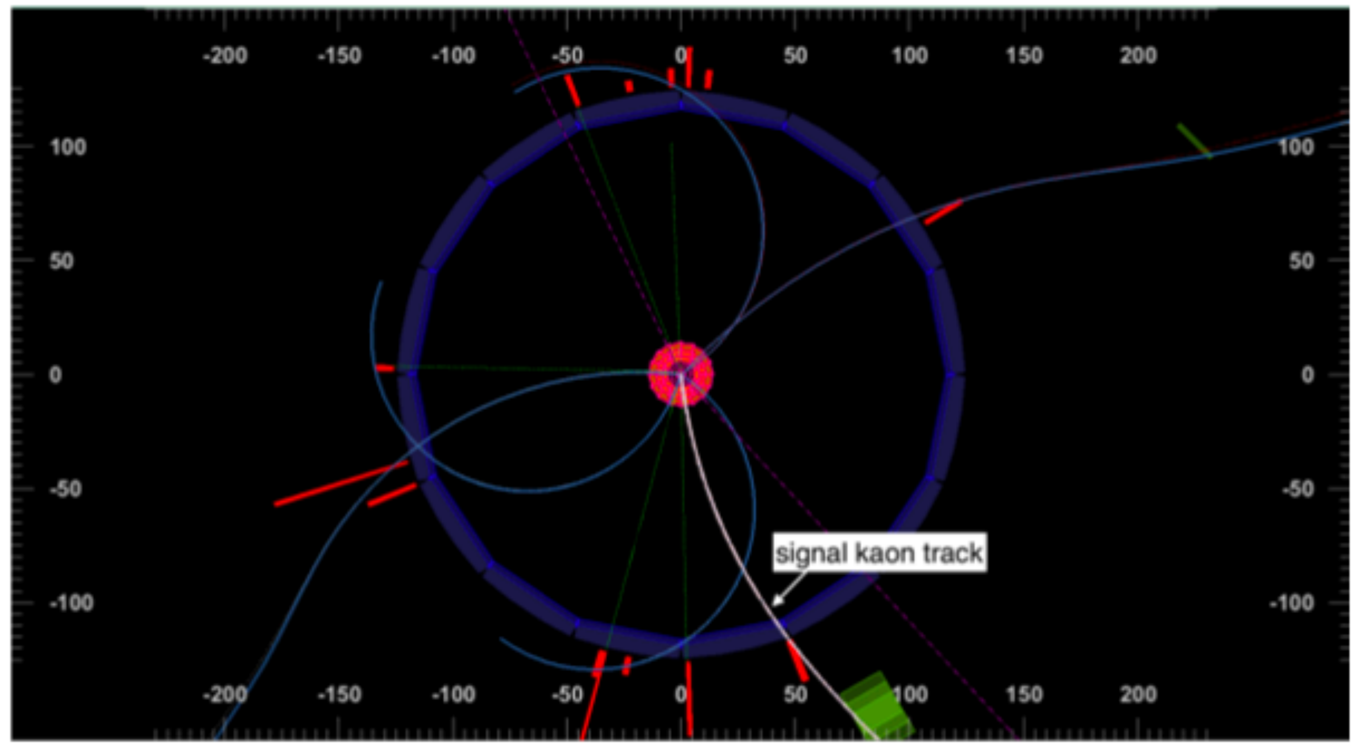
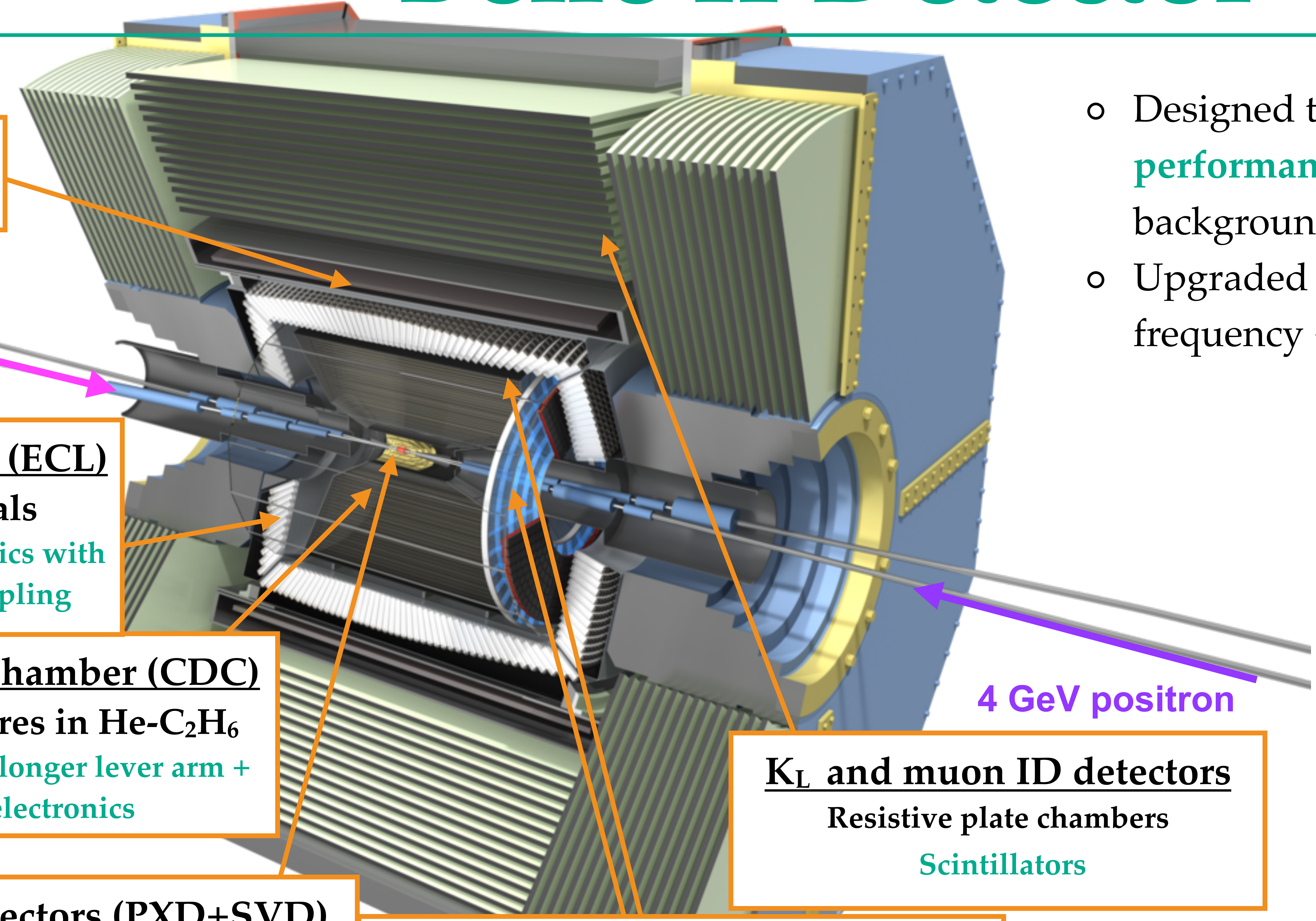




LHC	SuperKEKB
pp-collisions b-quarks produced by gluon fusion all b-hadrons species (B_d, B_s, B_c, b-baryon) highly boosted topology $\sigma_{bb} = 100\ \mu$b different backgrounds (N/S = 1000)	e^+e^- energy asymmetric collisions $B\bar{B}$ produced from $\Upsilon(4S)$ exclusive $B\bar{B}$ production asymmetric beam energy $\rightarrow$ boost $\sigma_{bb} = 1.1$ nb B-backgrounds, continuum backgrounds + QED (N/S=4)
1 fb^{-1}	1 ab^{-1}

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

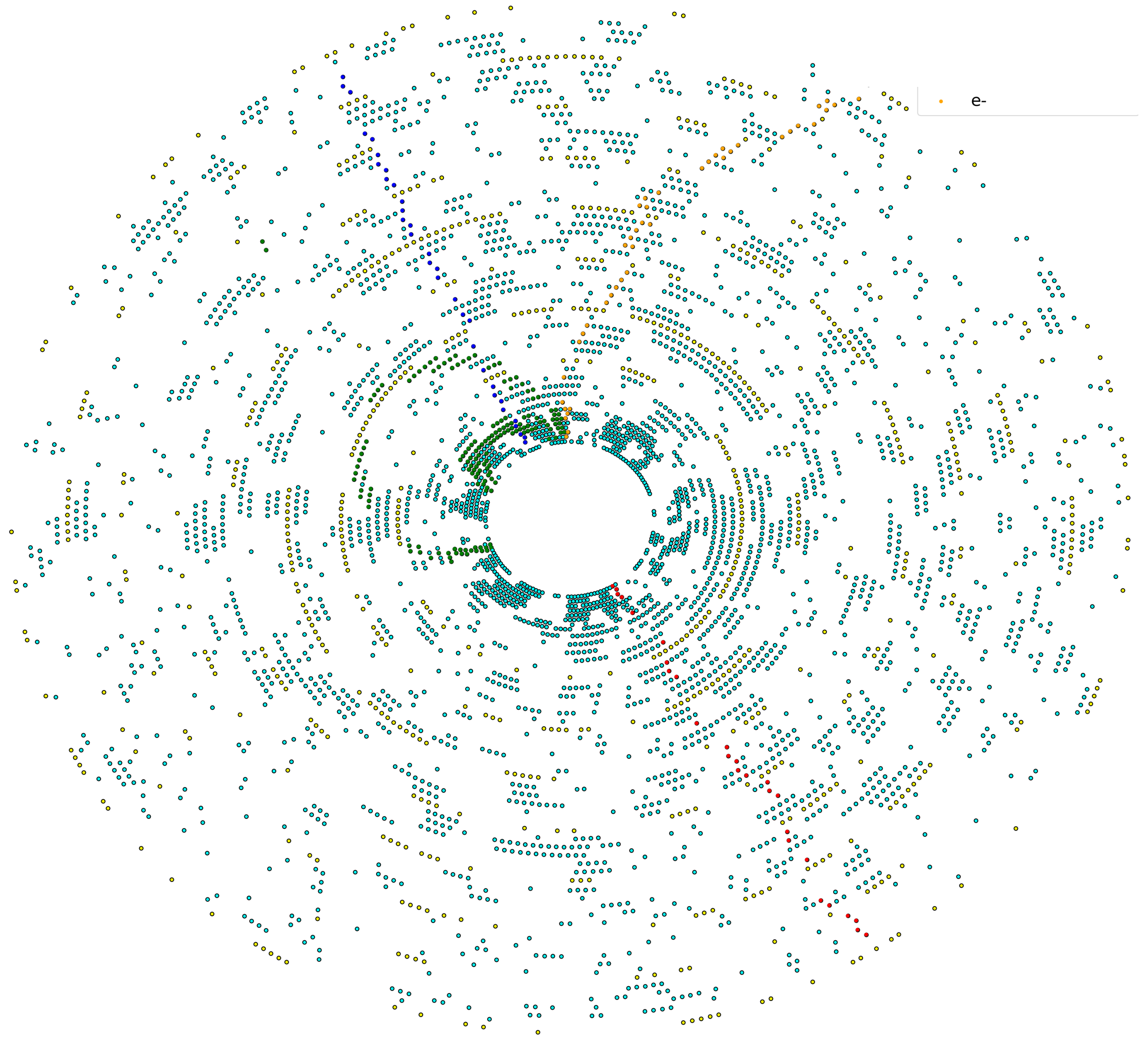
Vertex detectors (PXD+SVD)
2 pixel layers (DEPFET)
4 layers of silicon microstrip layers

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

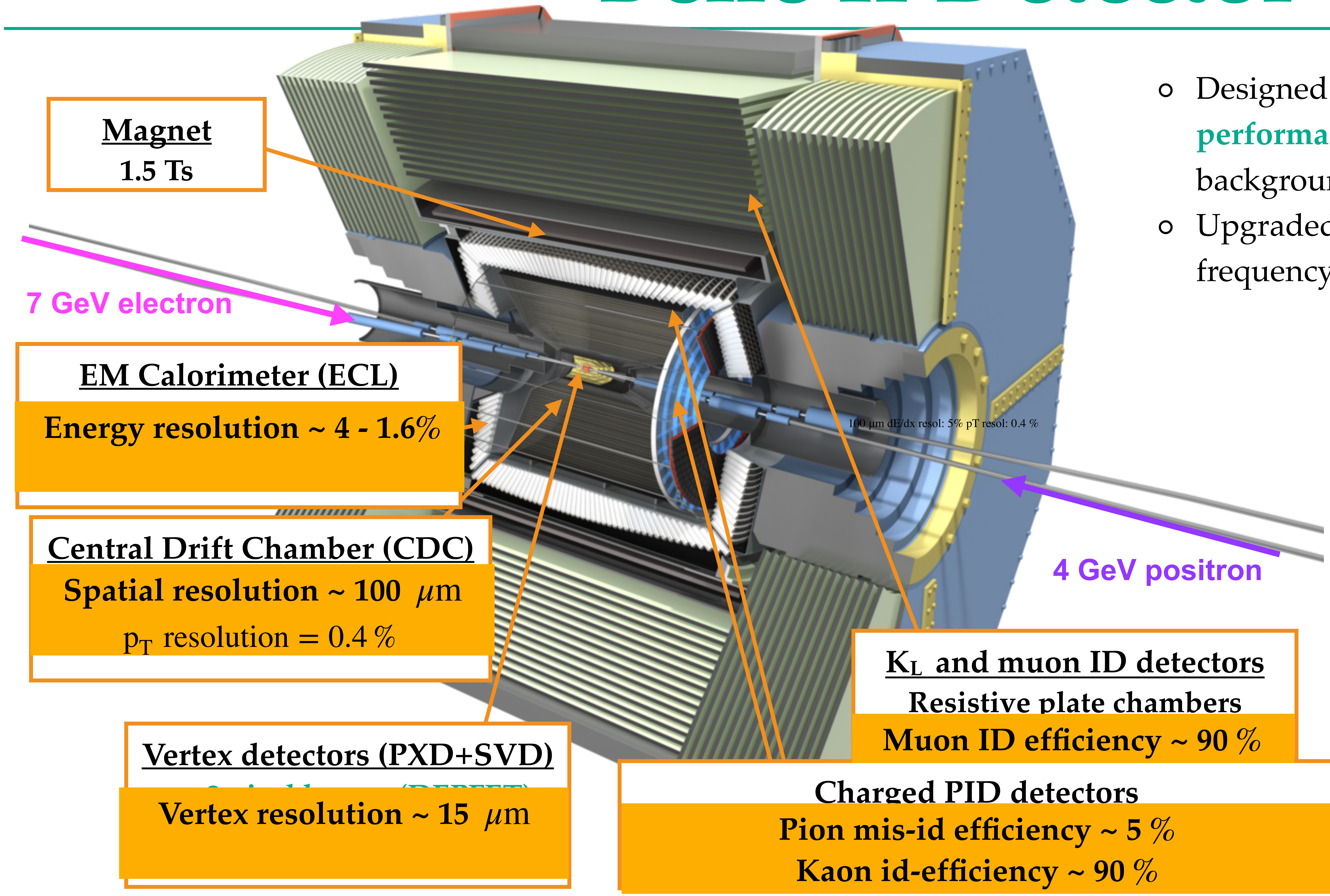
K_L and muon ID detectors
Resistive plate chambers
Scintillators

- 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 x-y view)



Belle II Detector



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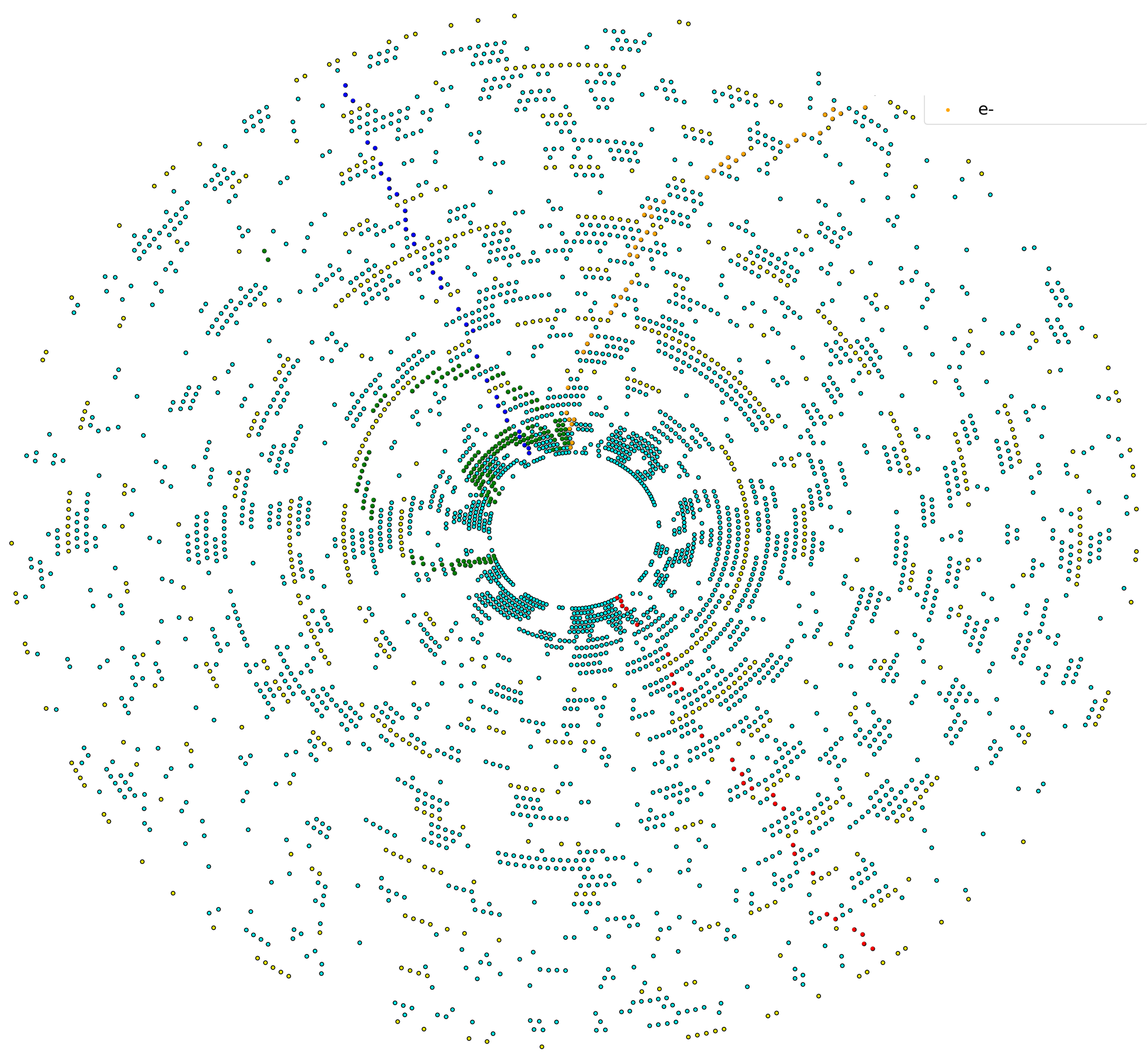


Experimental Summary

Observable	SM expectation	Experiment	Observed 90% CL	Reconstruction approach	Data [fb^{-1}]
$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})$	$(4.6 \pm 0.5) \times 10^{-6}$ [17]	Belle II	$< 4.1 \times 10^{-5}$	Inclusive tag **[SS21a]**	63
		BaBar	$< 1.6 \times 10^{-5}$	SL and HAD tag [12]	429
		Belle	$< 5.5 \times 10^{-5}$	Hadronic tag [11]	711
		Belle	$< 1.9 \times 10^{-5}$	Semileptonic tag [10]	711
$\mathcal{B}(B^0 \to K_s^0 \nu\bar{\nu})$	$(4.3 \pm 0.5) \times 10^{-6}$ [17]	BaBar	$< 4.9 \times 10^{-5}$	SL and HAD tag [12]	429
$\mathcal{B}(B^0 \to K_s^0 \nu\bar{\nu})$		Belle	$< 9.7 \times 10^{-5}$	Hadronic tag [11]	711
$\mathcal{B}(B^0 \to K_s^0 \nu\bar{\nu})$		Belle	$< 1.3 \times 10^{-5}$	Semileptonic tag [10]	711
$\mathcal{B}(B^+ \to K^{*+} \nu\bar{\nu})$	$(8.4 \pm 1.5) \times 10^{-6}$ [17]	BaBar	$< 6.3 \times 10^{-5}$	SL and HAD tag [12]	429
$\mathcal{B}(B^+ \to K^{*+} \nu\bar{\nu})$		Belle	$< 4.0 \times 10^{-5}$	Hadronic tag [11]	711
$\mathcal{B}(B^+ \to K^{*+} \nu\bar{\nu})$		Belle	$< 6.1 \times 10^{-5}$	Semileptonic tag [10]	711
$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})$	$(7.8 \pm 1.4) \times 10^{-6}$ [17]	BaBar	$< 12.0 \times 10^{-5}$	SL and HAD tag [12]	429
$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})$		Belle	$< 5.5 \times 10^{-5}$	Hadronic tag [11]	711
$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})$		Belle	$< 1.8 \times 10^{-5}$	Semileptonic tag [10]	711

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

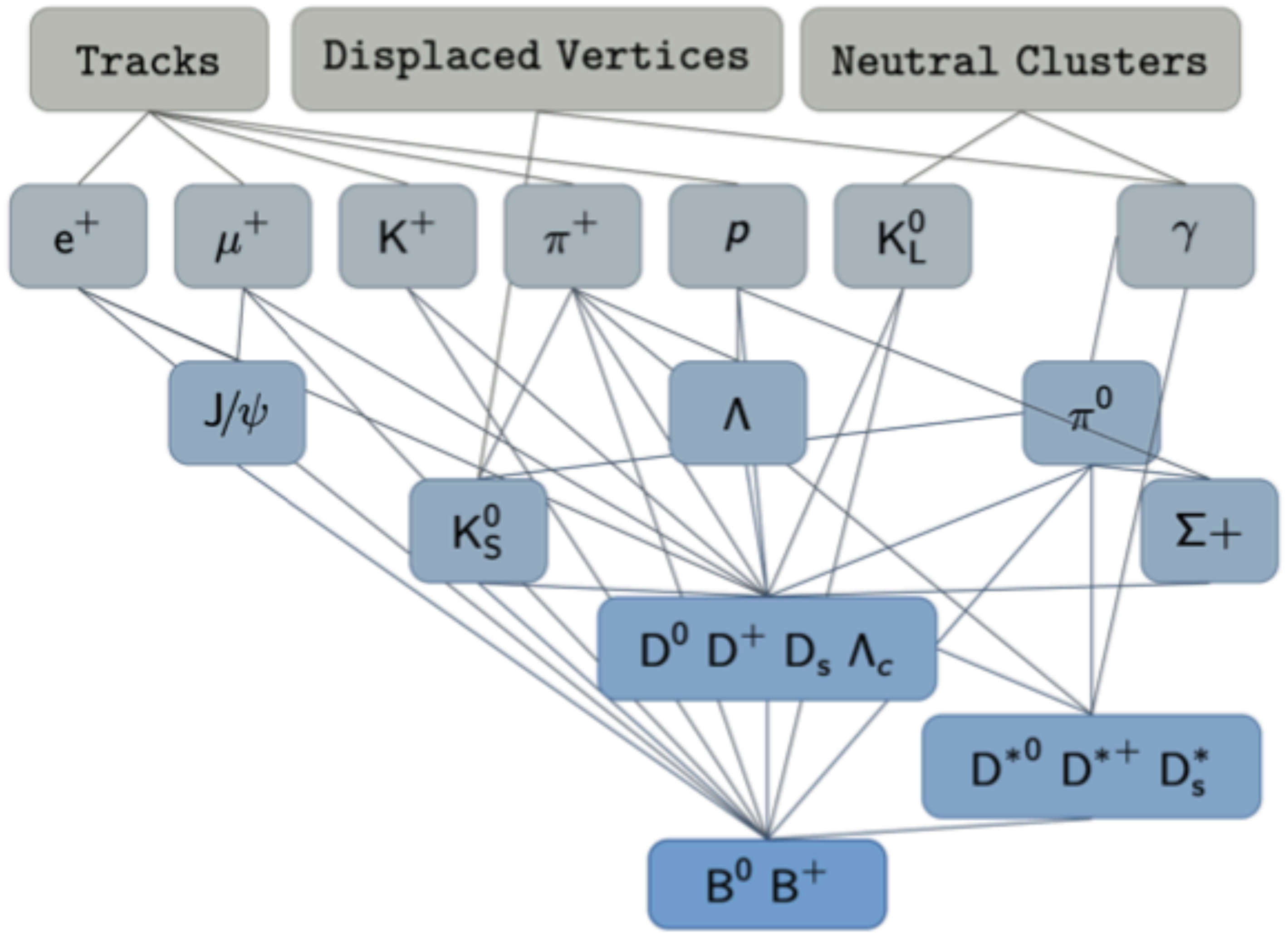
- If signal has π^0, K_s : need to have high reconstruction efficiency and good resolution

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

Full Event Interpretation (FEI)

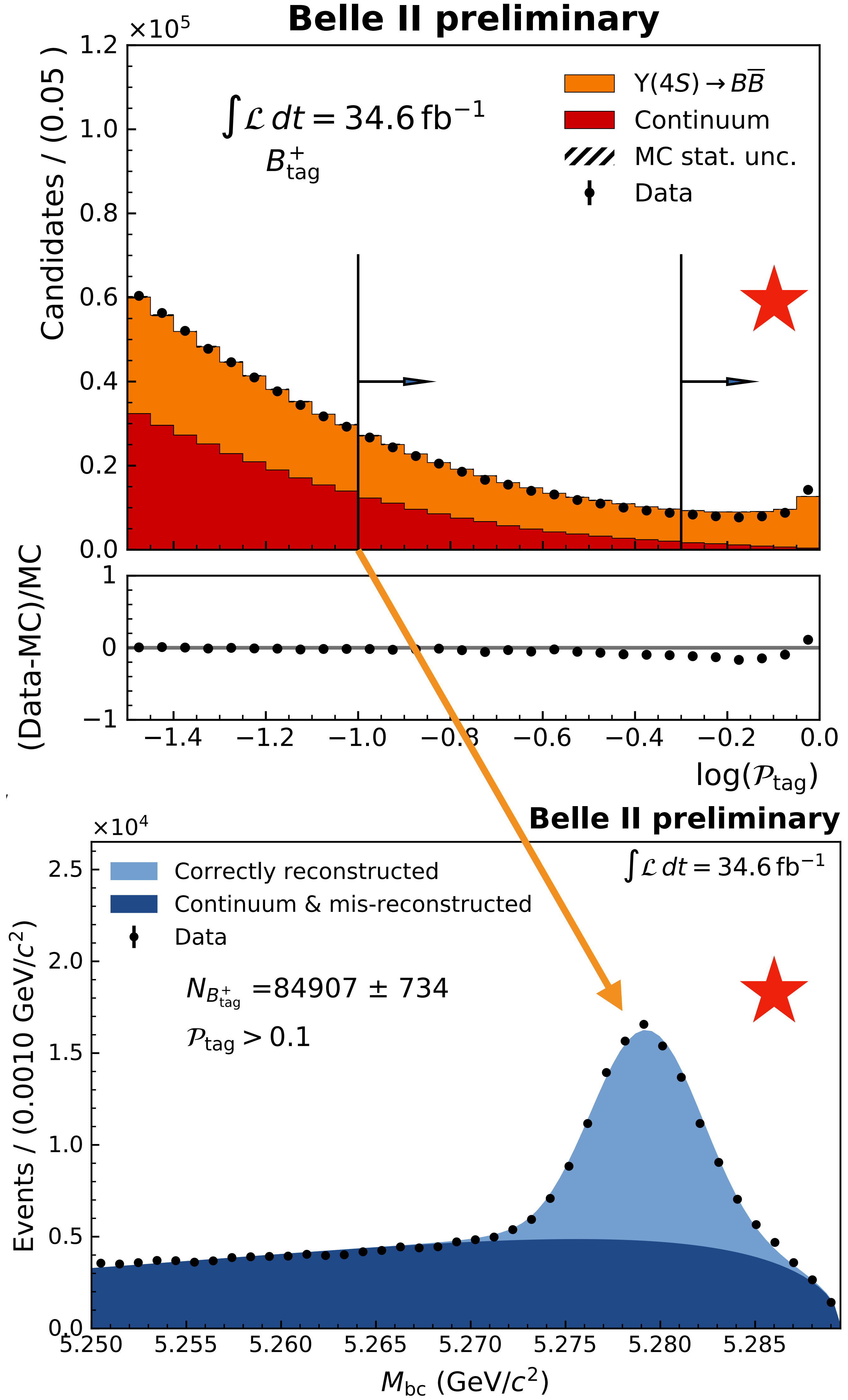
FEI is an MVA tagging algorithm which reconstructs with 200 BDTs ~ 10000 decay chains



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

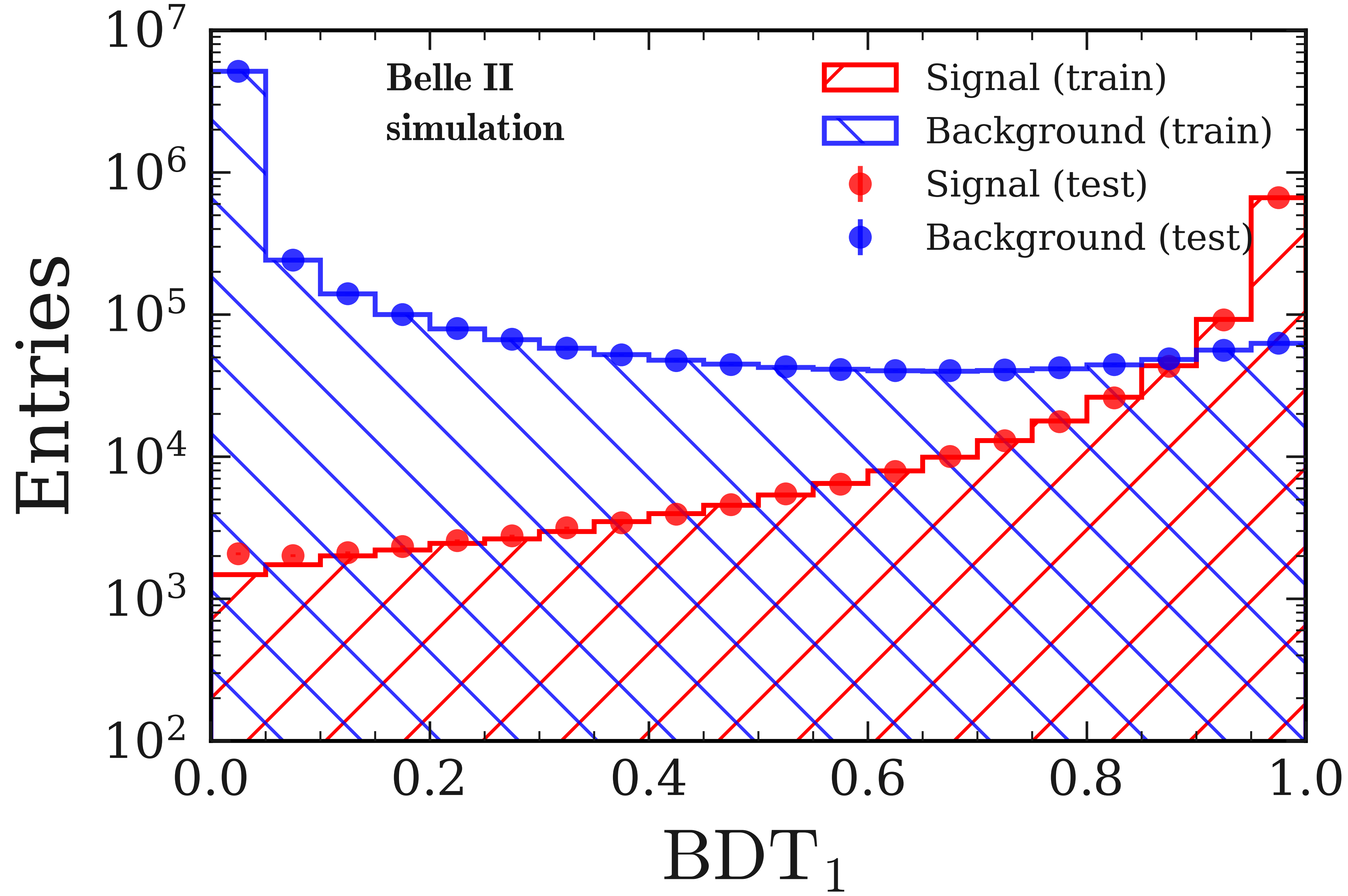
MC tag-side efficiency @10% purity	Had. B^+/B^0 [%]	SL. B^+/B^0 [%]
Full Reconstruction Belle	0.28/0.18	0.67/0.63
FEI Belle	0.76/0.46	1.80/2.04
N of correct B_{tag} per 1 fb^{-1} in Belle (FEI)	8350/5060	19800/22440

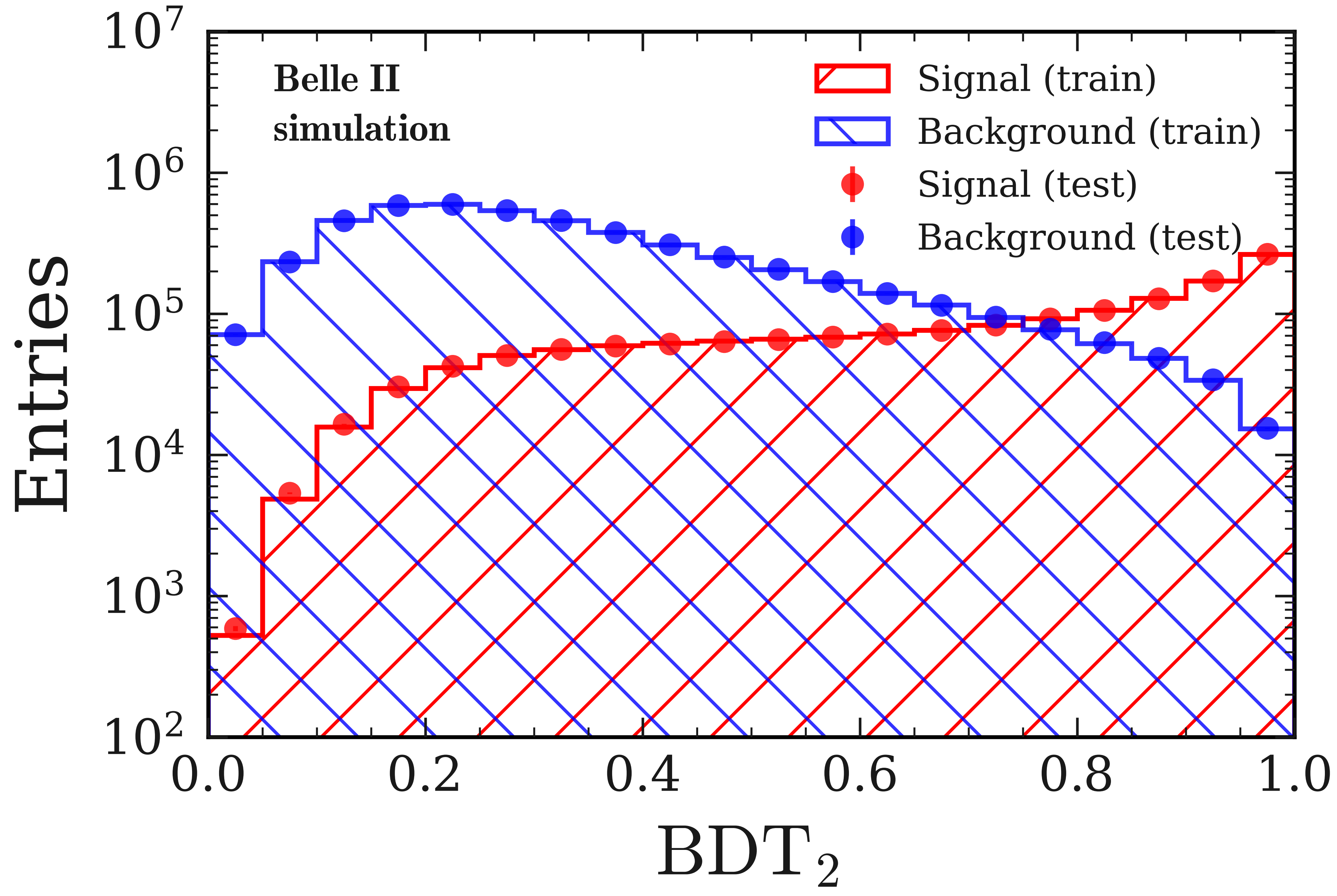
In Belle, FEI achieves up x 2 higher reconstruction efficiency → Belle II expects improvements



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

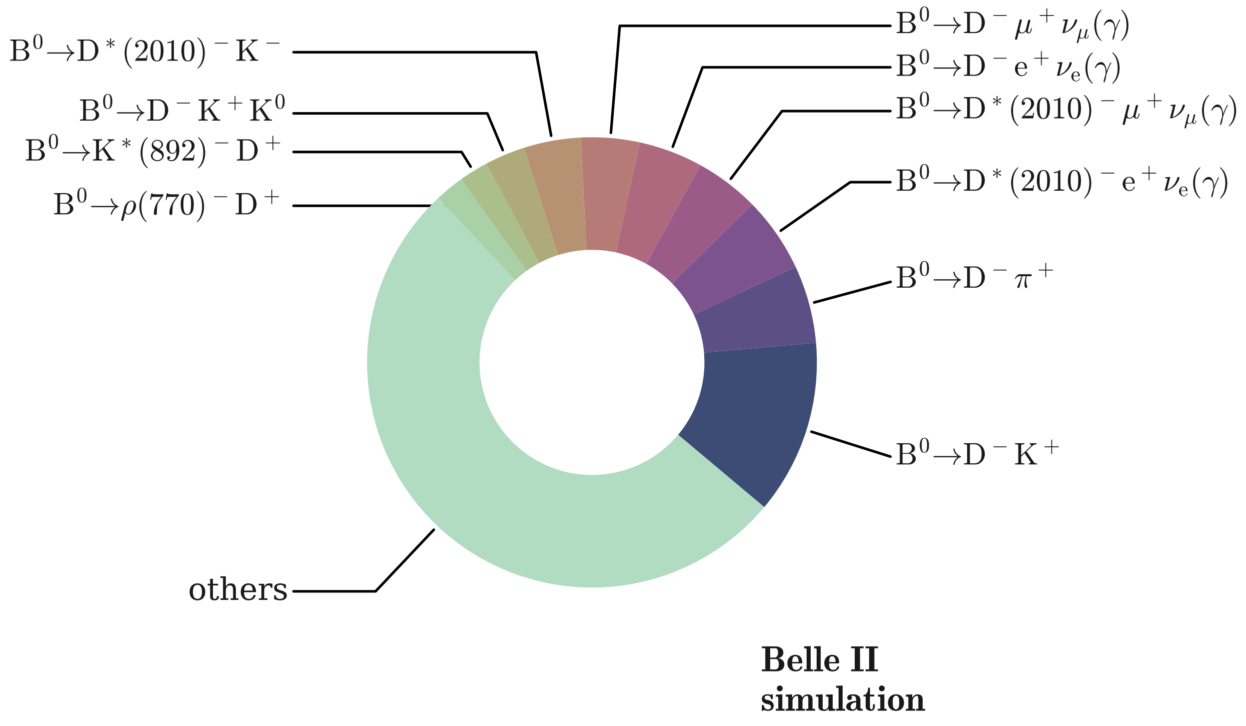
Overtraining



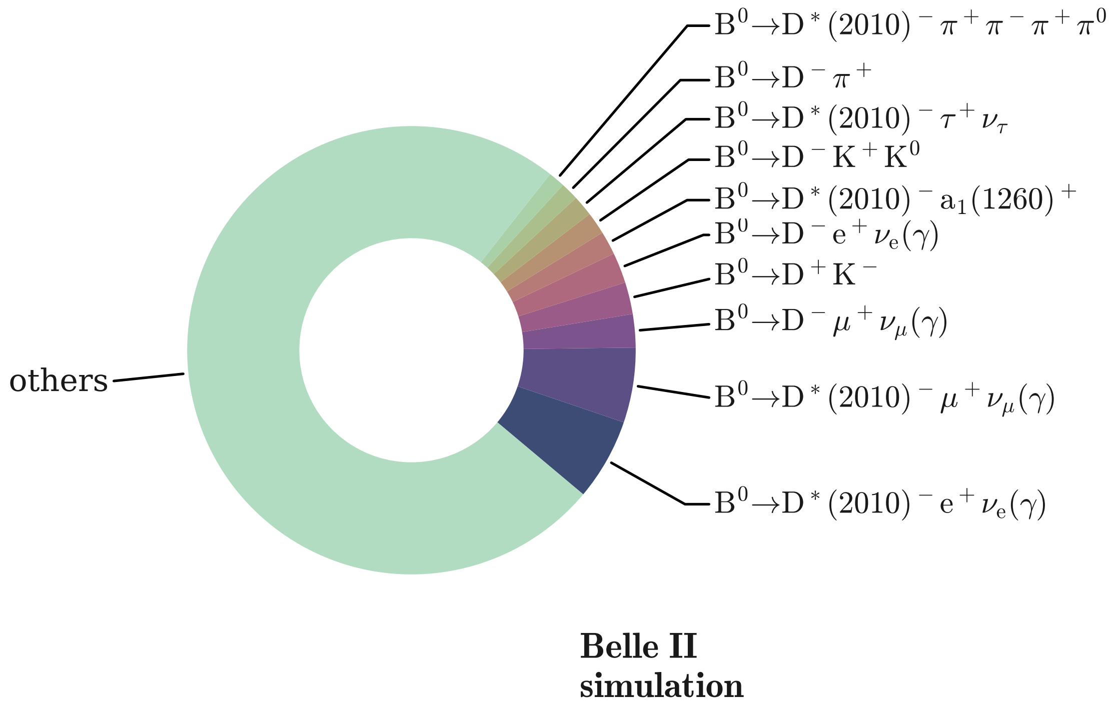


Background Composition In SR

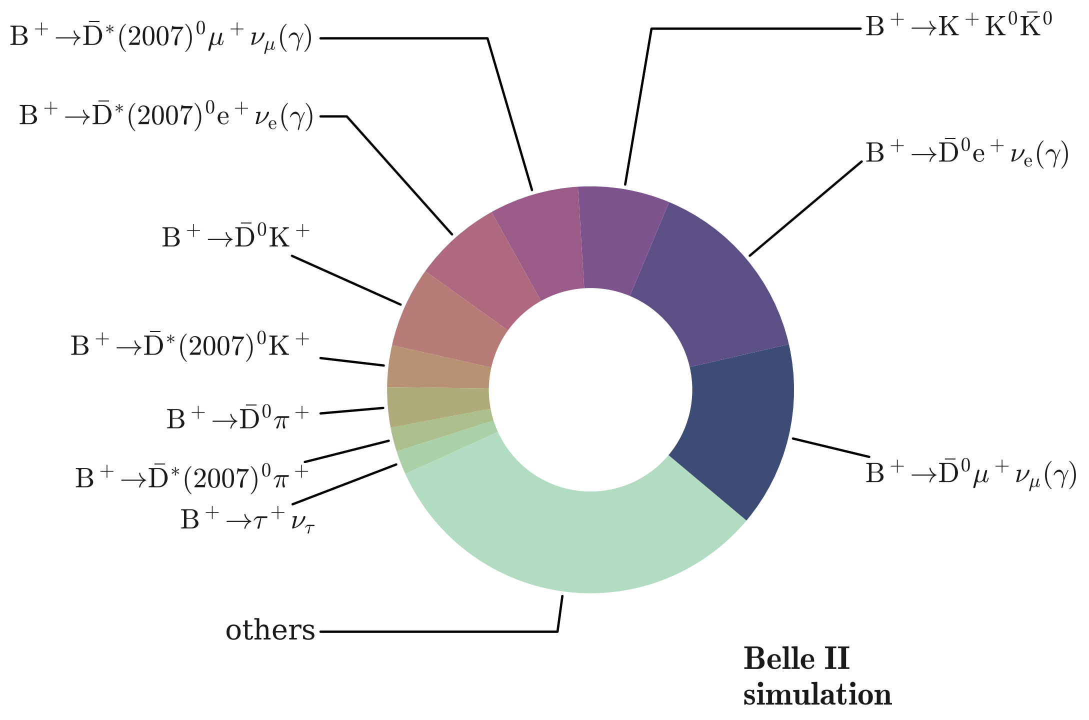
- $B^0\bar{B}^0$ signal side:



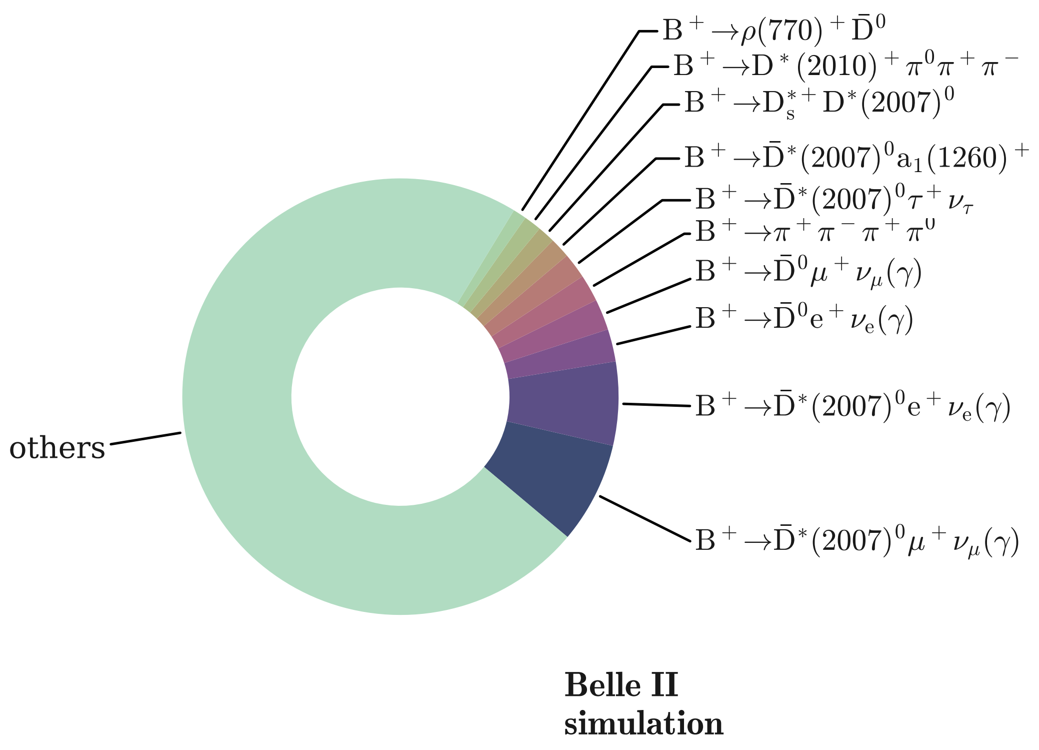
- $B^0\bar{B}^0$ tag side:



- B^+B^- signal side:



- $B^+\bar{B}^-$ tag side:



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BDT Variable Ranking

Variable
foxWolframR1
B_sig_KSFWVariables_hso22
B_sig_KSFWVariables_hso20
B_sig_roeDeltae_ipMask
B_sig_weMissM2_ipMask_0
sphericity
foxWolframR3
nTracksCleanedPlusNGammasCleaned
TagVpVal
harmonicMomentThrust0
B_sig_KSFWVariables_hoo0

Future Ideas - Sharing of the Systematics

Status:

- **Next iteration of analysis expects new channels ($B^+ \to K^{*+}\nu\bar{\nu}$, $B \to K^*\nu\bar{\nu}$, $B^0 \to K_s^0\nu\bar{\nu}$)**
- **Can perform simultaneous fit to all channels**
  - **Main advantage: could share the systematics**
  - **Main disadvantage: how to account for partial correlations/shared statistical errors properly?**

	Scalar	Scalar	Axial Vector	Axial Vector
Signal	K^+	K_s	K^*	K^{*+}
Background normalisation				
Tracking inefficiency				
Neutral Energy Miscalibration				
PID				
BR uncertainty				
FF uncertainty				

Same color = could be shared between the channels?

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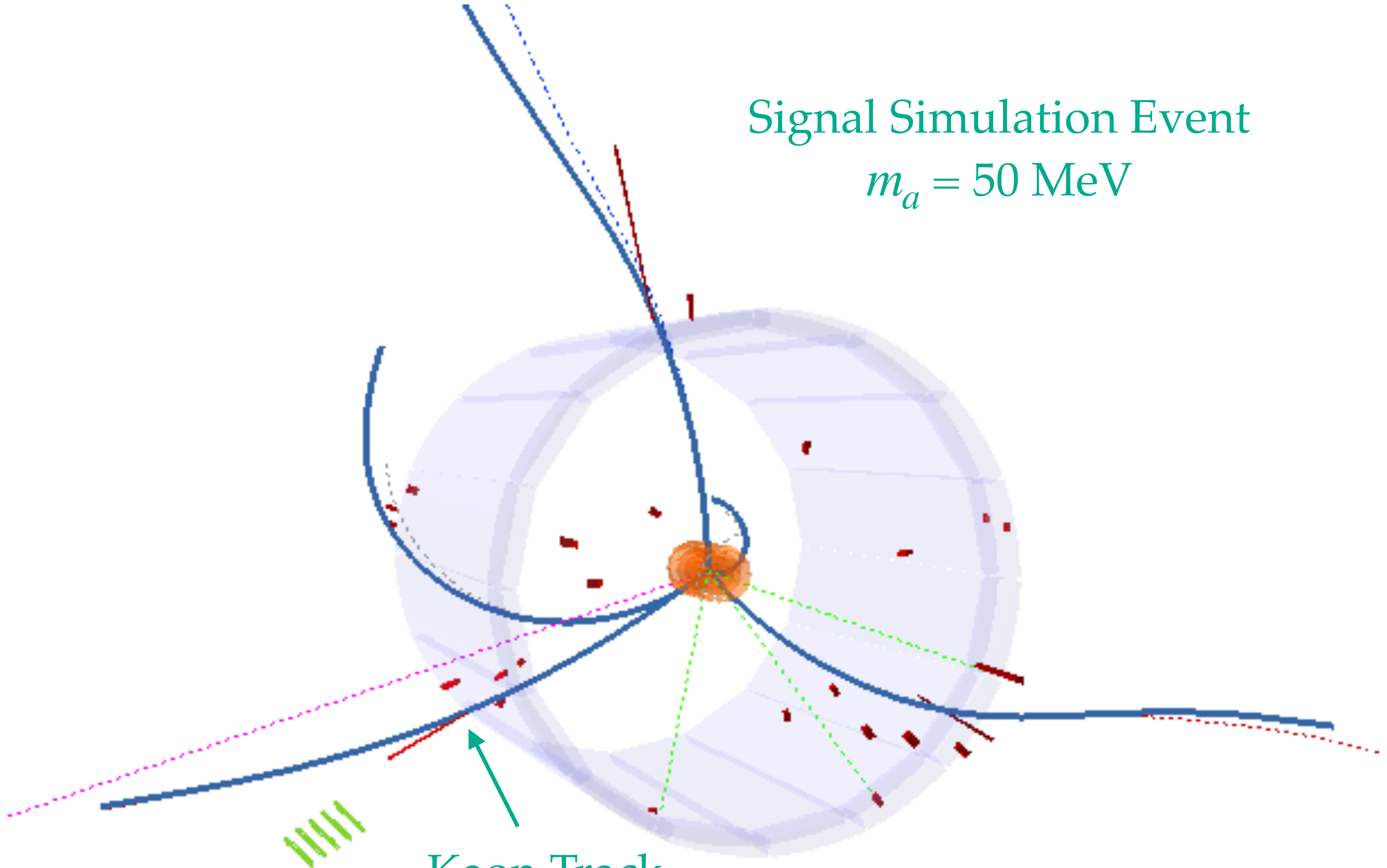
Search for $B^+ \to K^+ a$ (ALP)

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 $B^+ \to K^+ \nu\bar{\nu}$
- **main experimental difference: two-body vs three-body kinematics**



ALP model from [arxiv: 2201.06580]

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

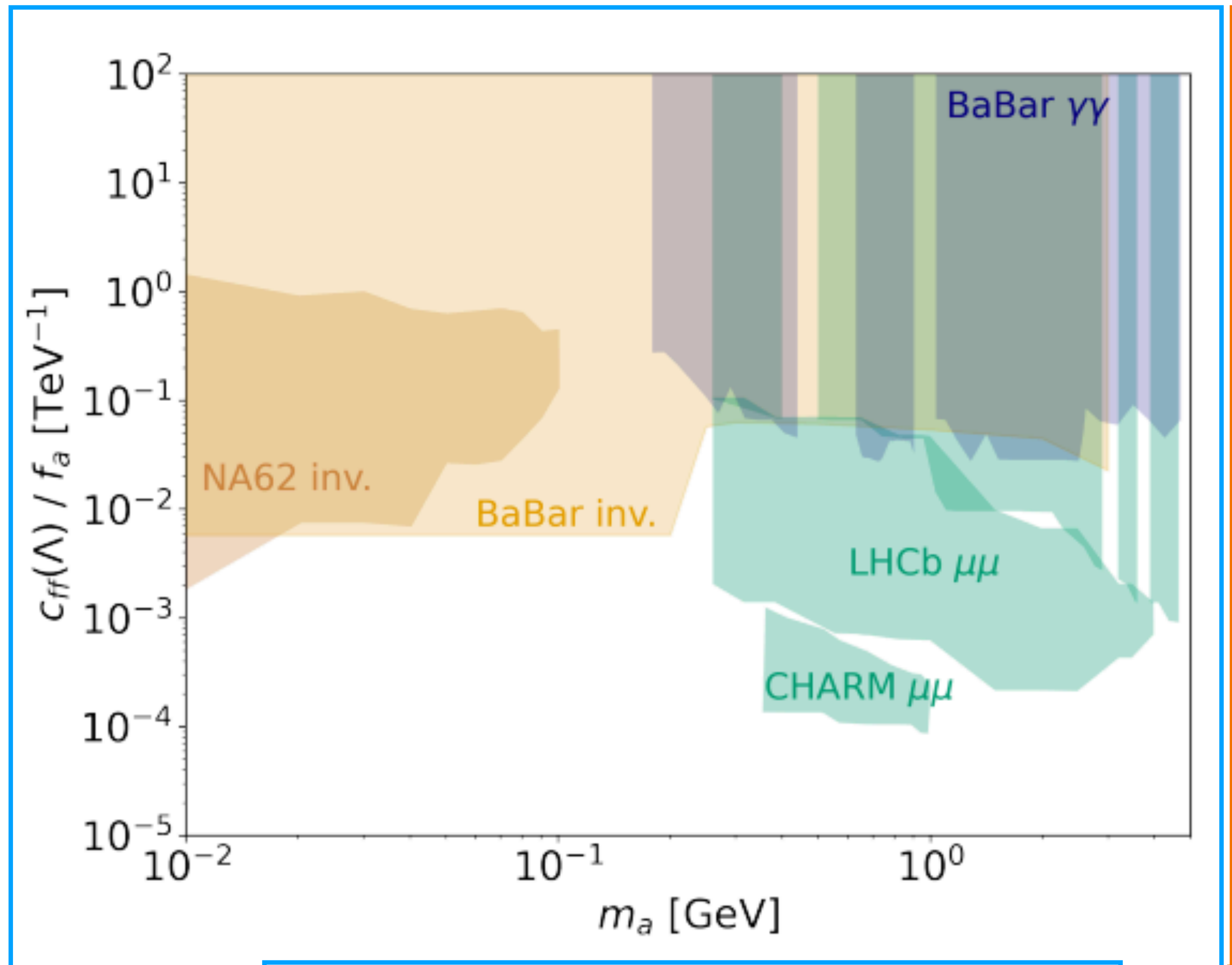
"c_{ff}" : ALP coupling to fermions

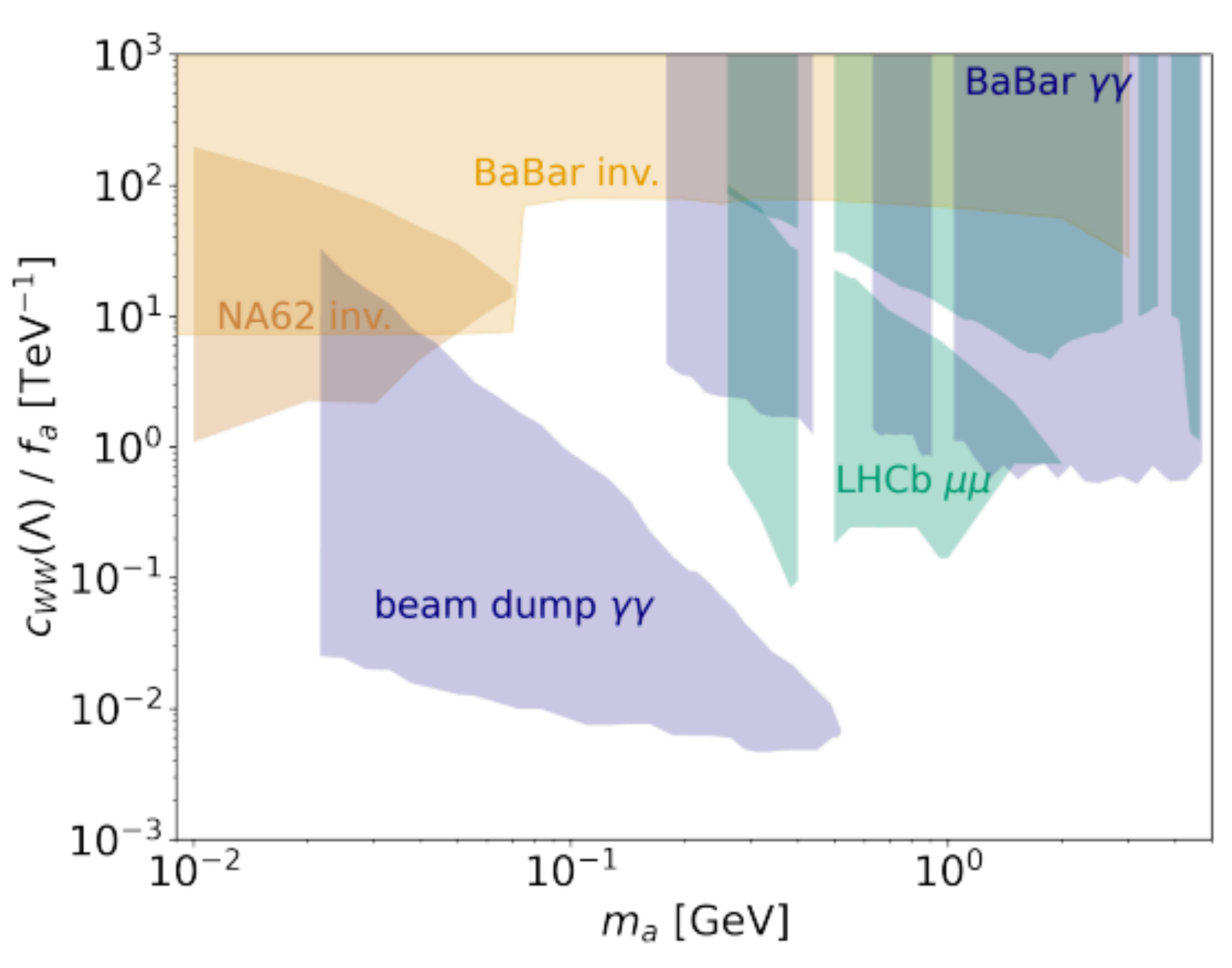
f_0 = scalar FF

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

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

Current bounds:





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

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

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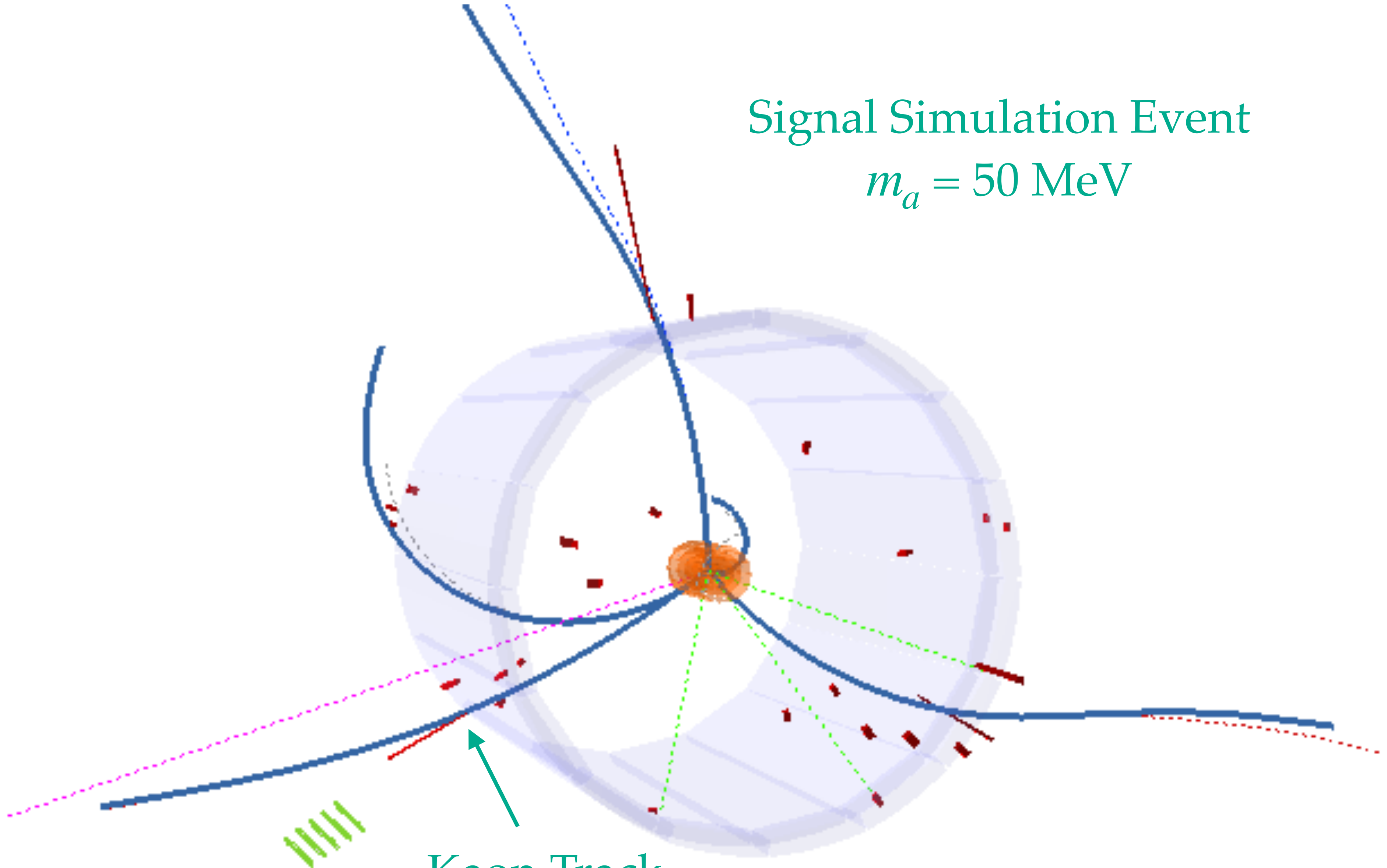

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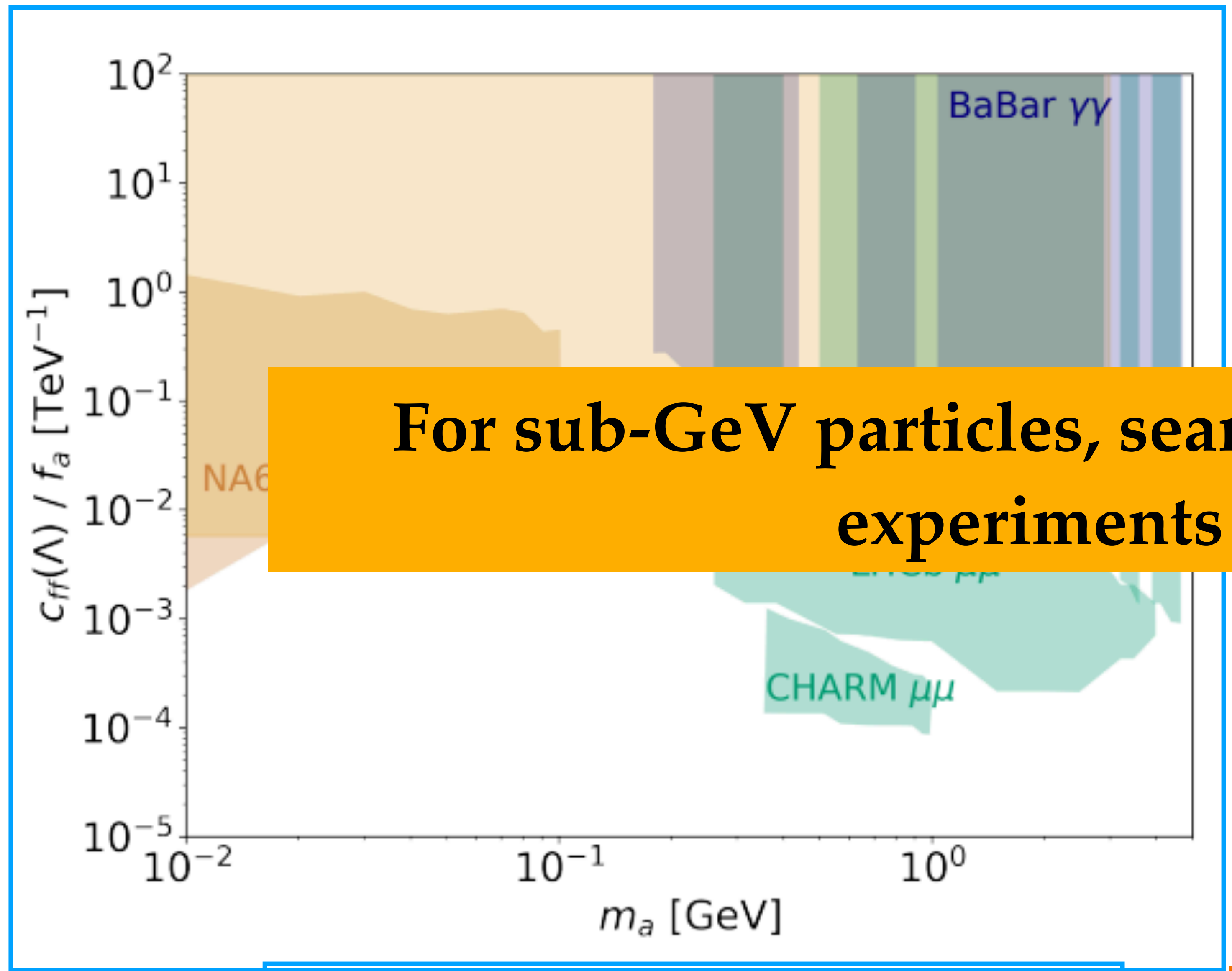
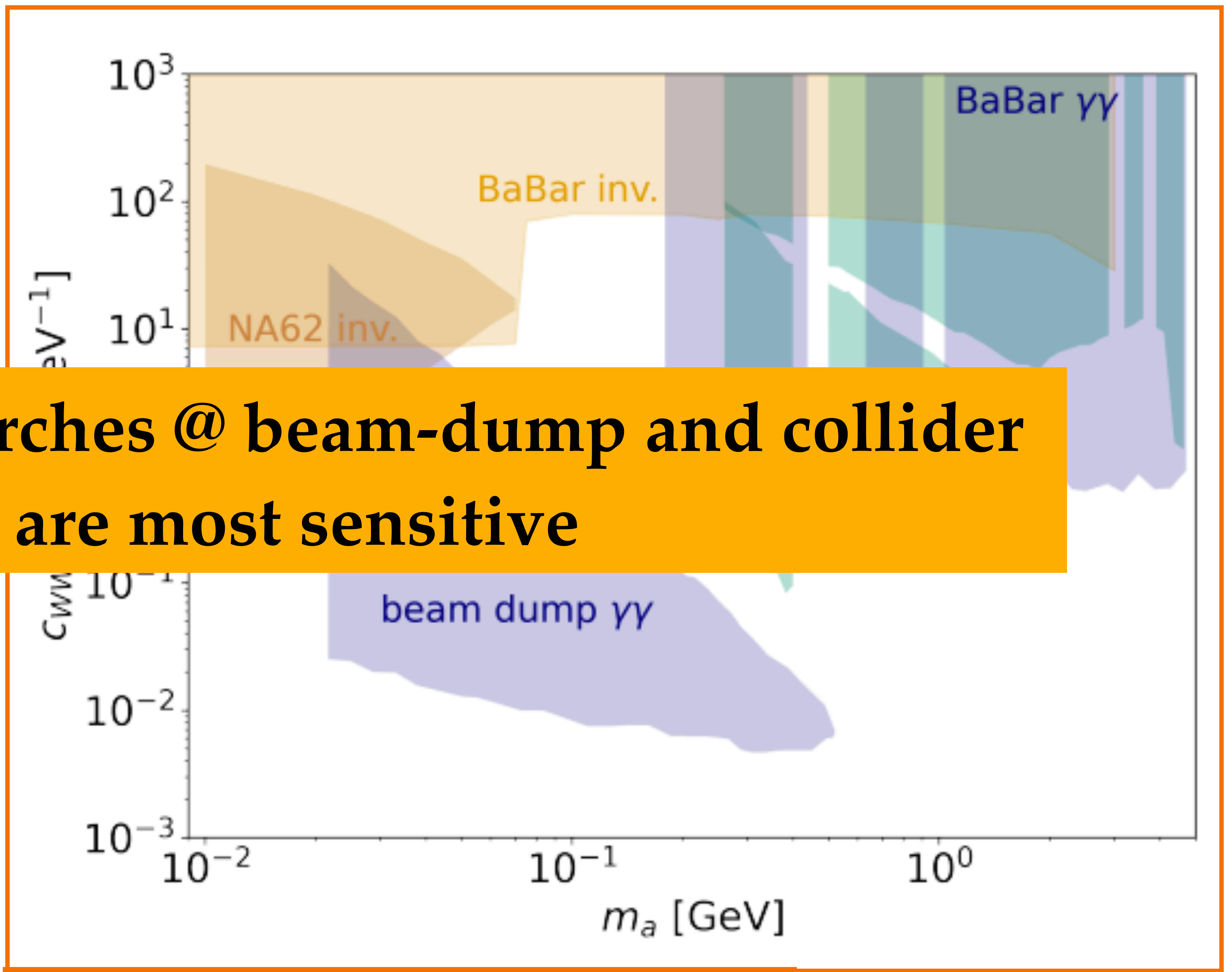




For sub-GeV particles, searches @ beam-dump and collider experiments are most sensitive

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

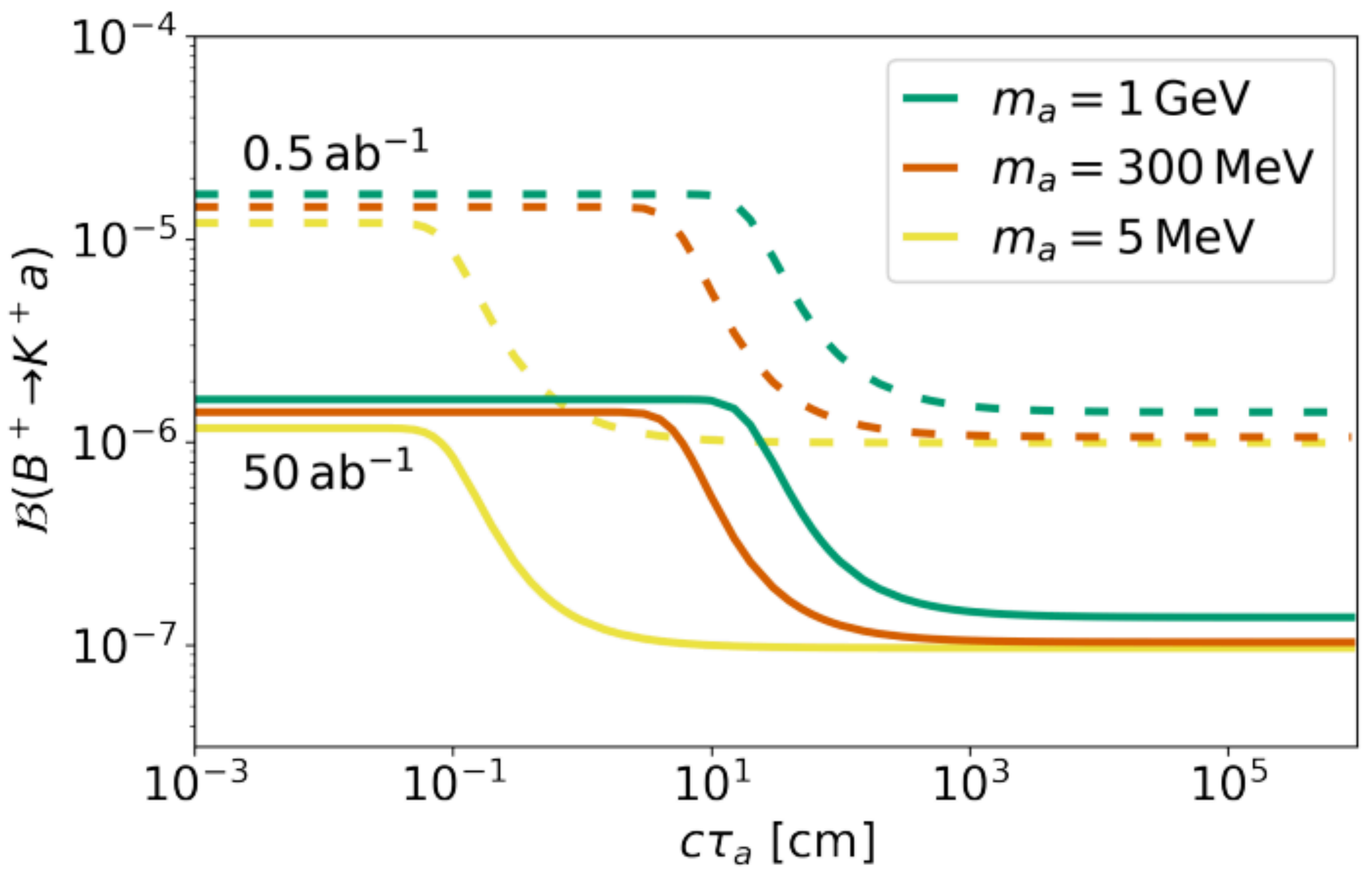
$c_{WW}(\Lambda)/f_a \lesssim (10^{-2} - 1)$ TeV^{-1}

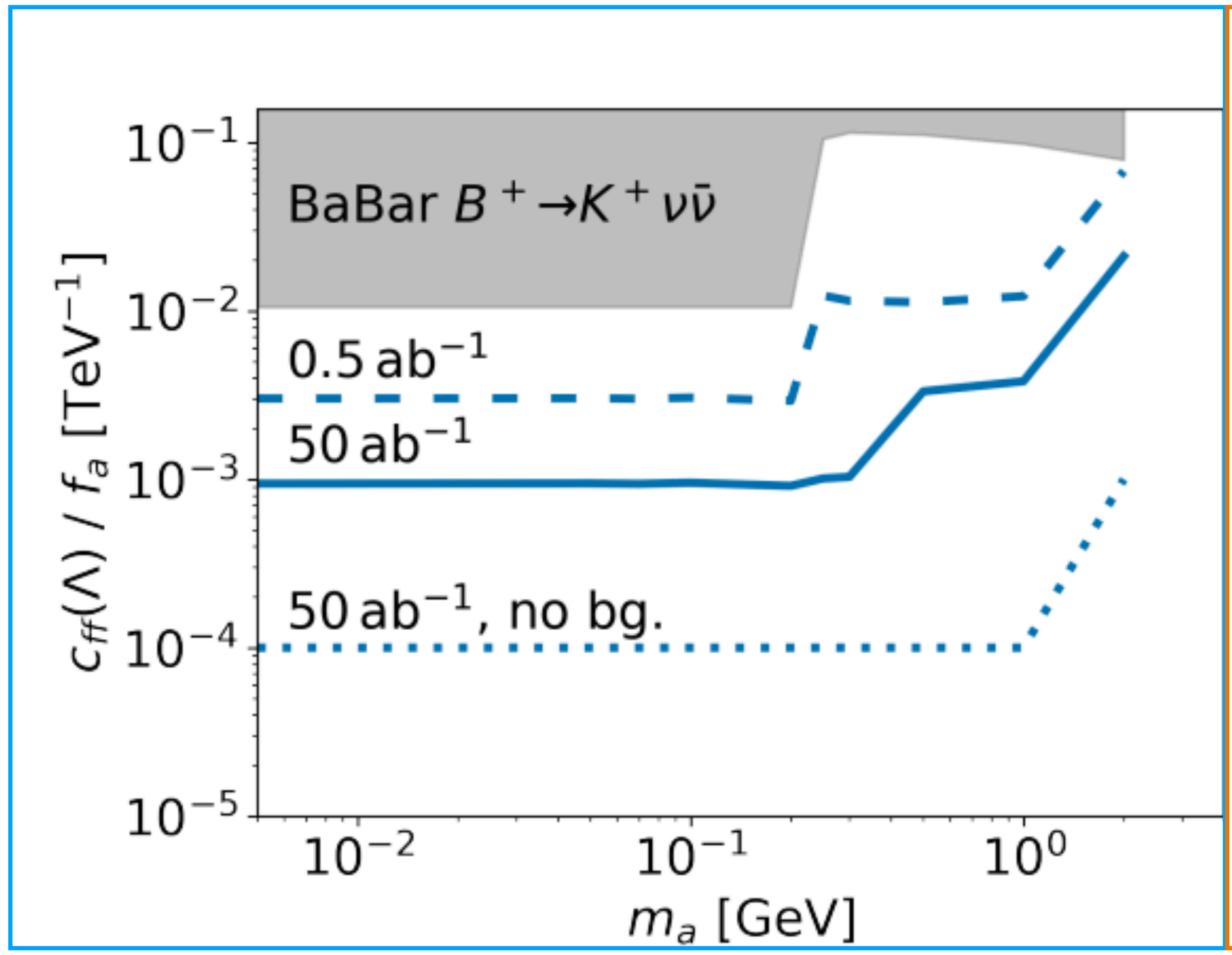
Search for $B^+ \to K^+ a$ (ALP): Sensitivity

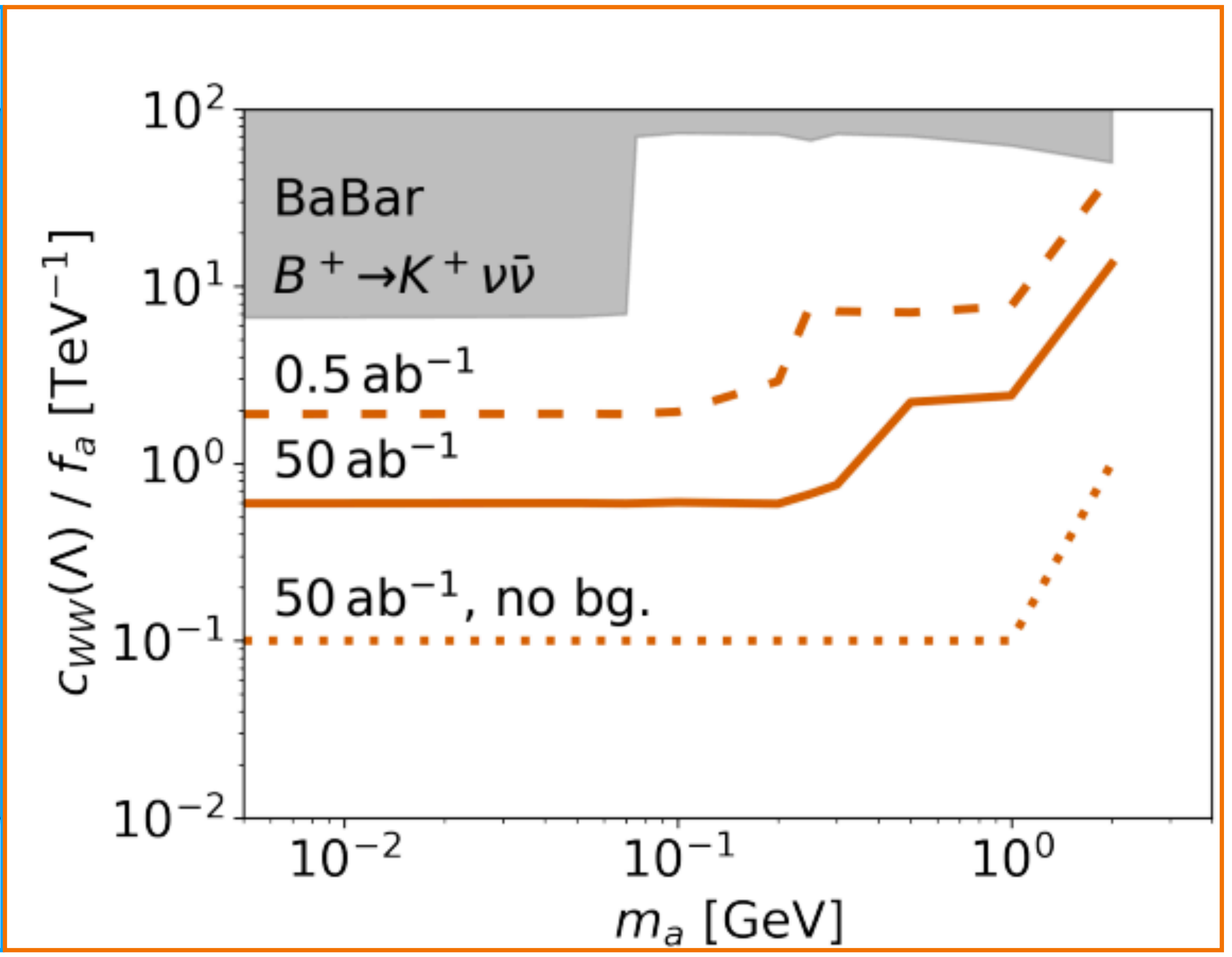
[arxiv: 2201.06580]

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

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

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

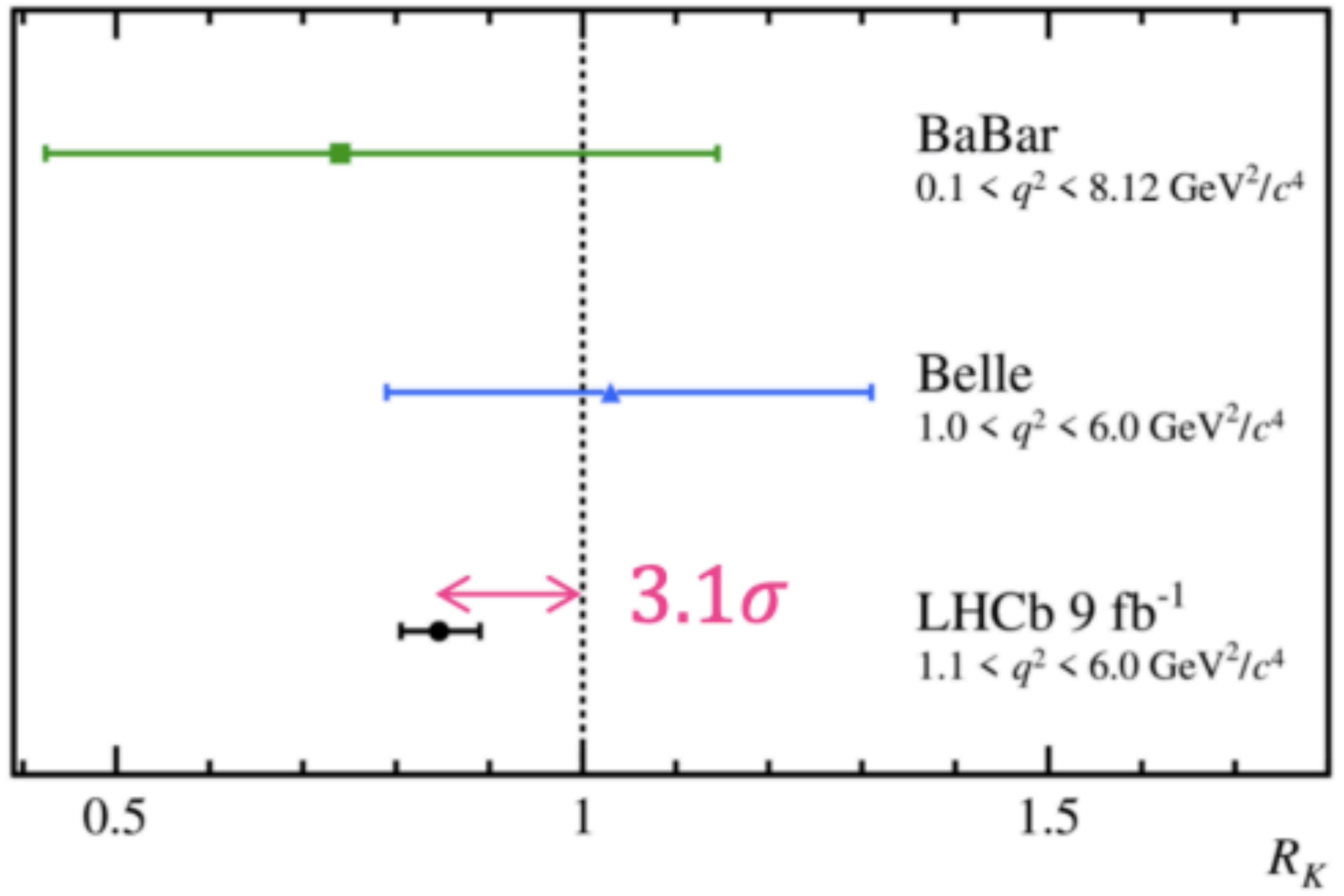
3.1 σ evidence of LFUV in R(K) reported by LHCb

SM

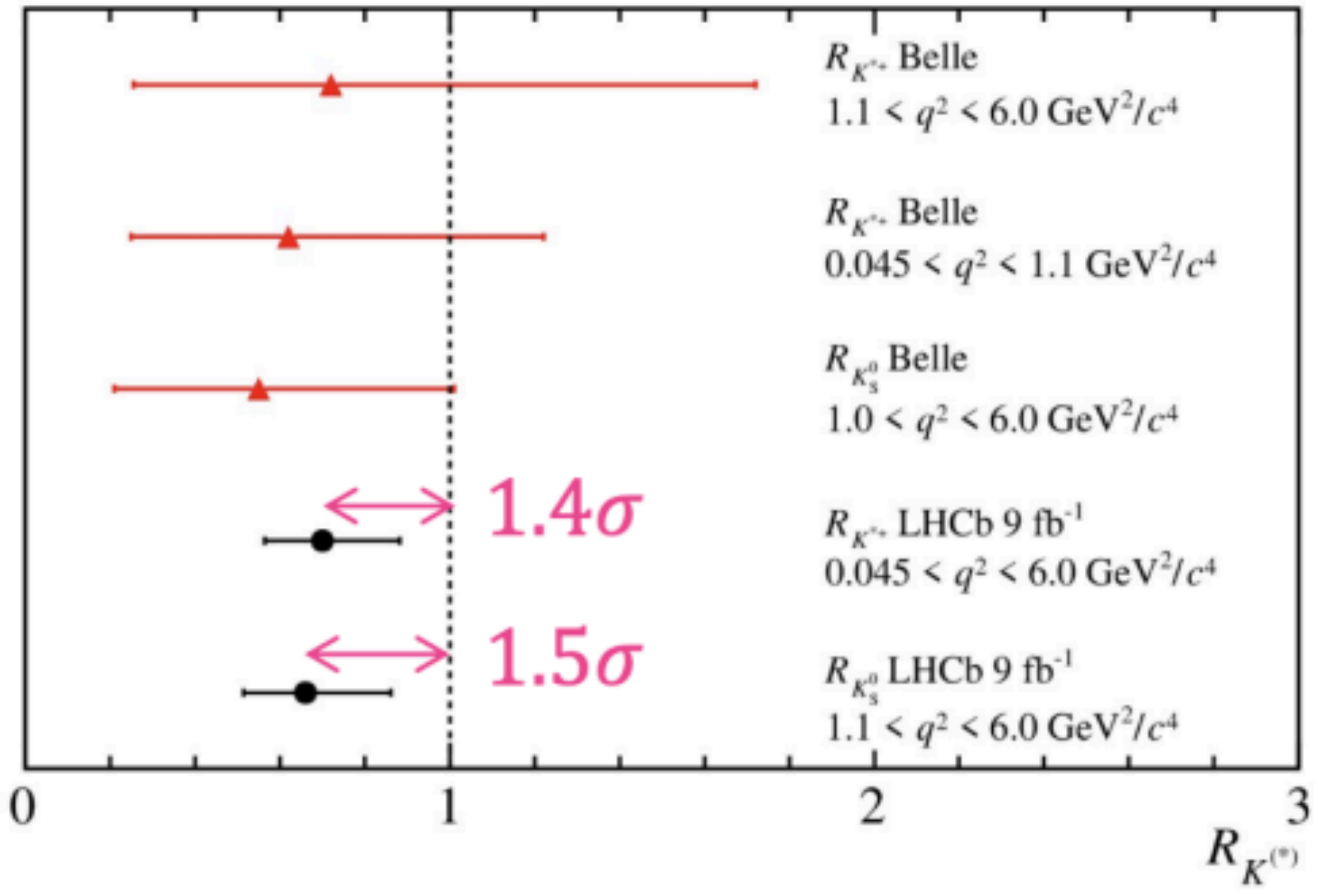
$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} = 1 \pm \mathcal{O}(10^{-2})$$

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

JHEP 2018, 93 (2018)



arXiv:2103.11769, arXiv:2110.09501

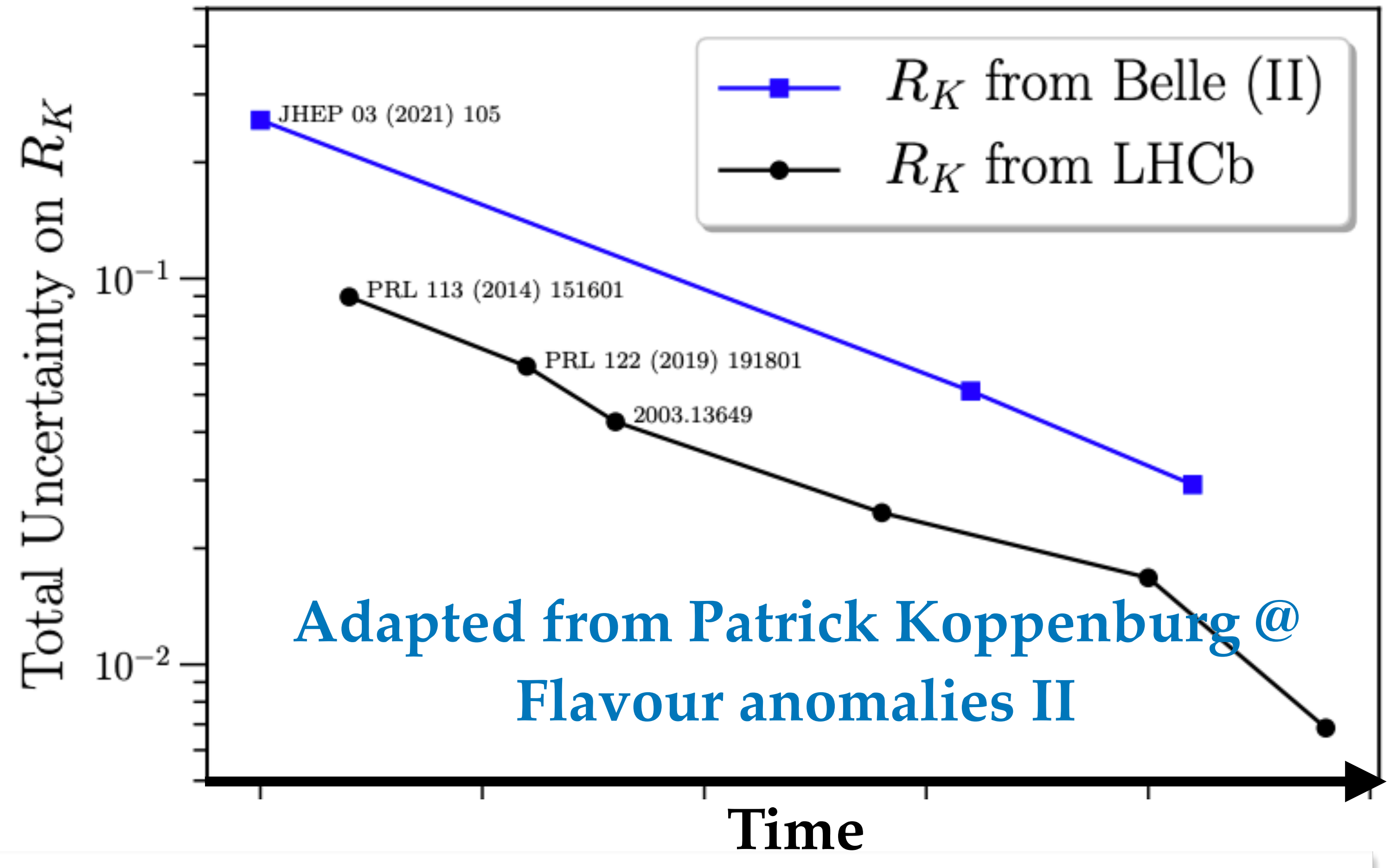


$R(K^{(*)})$ in Belle II

- 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 $\mathcal{B}$ 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

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

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JHEP 2018, 93 (2018)

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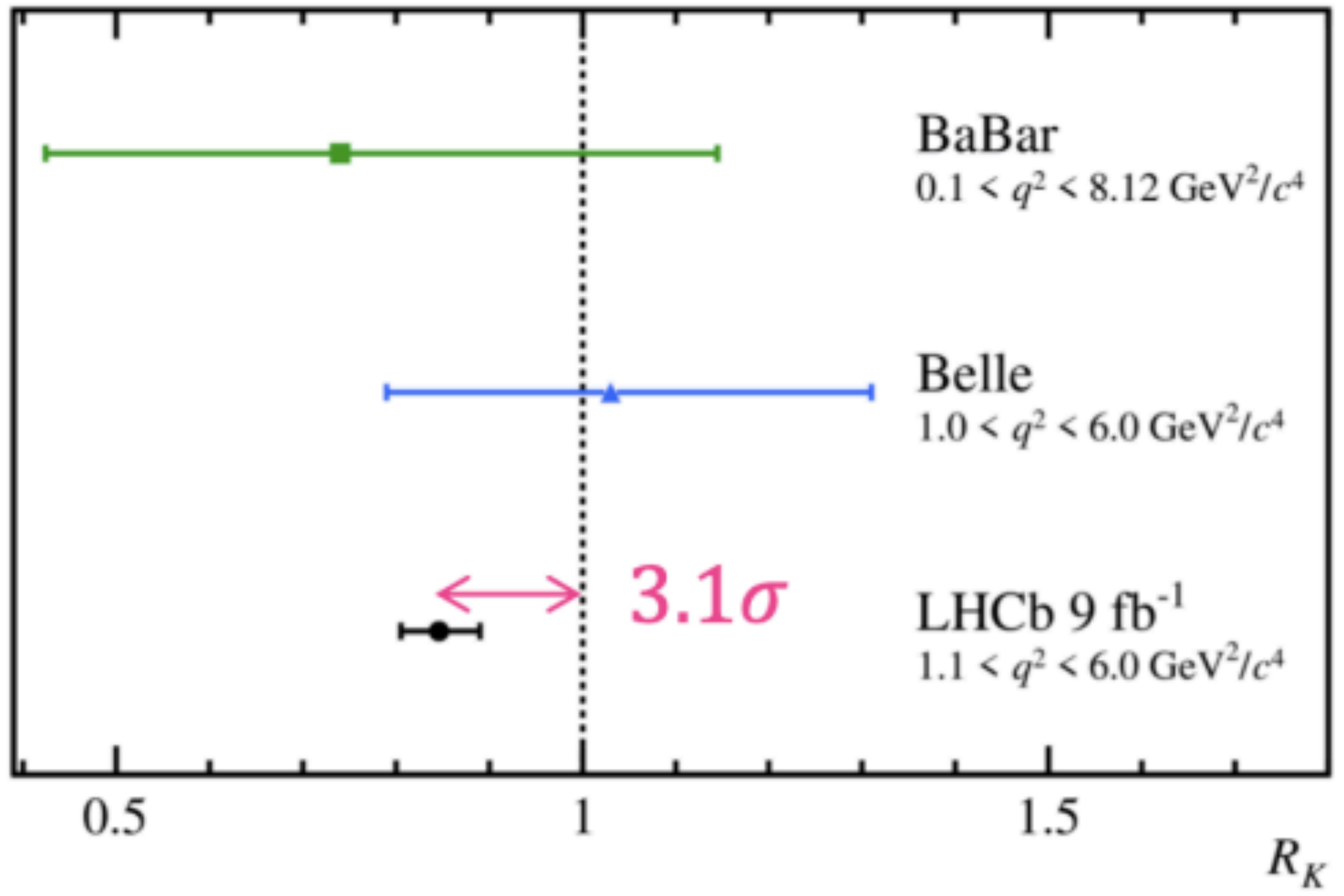

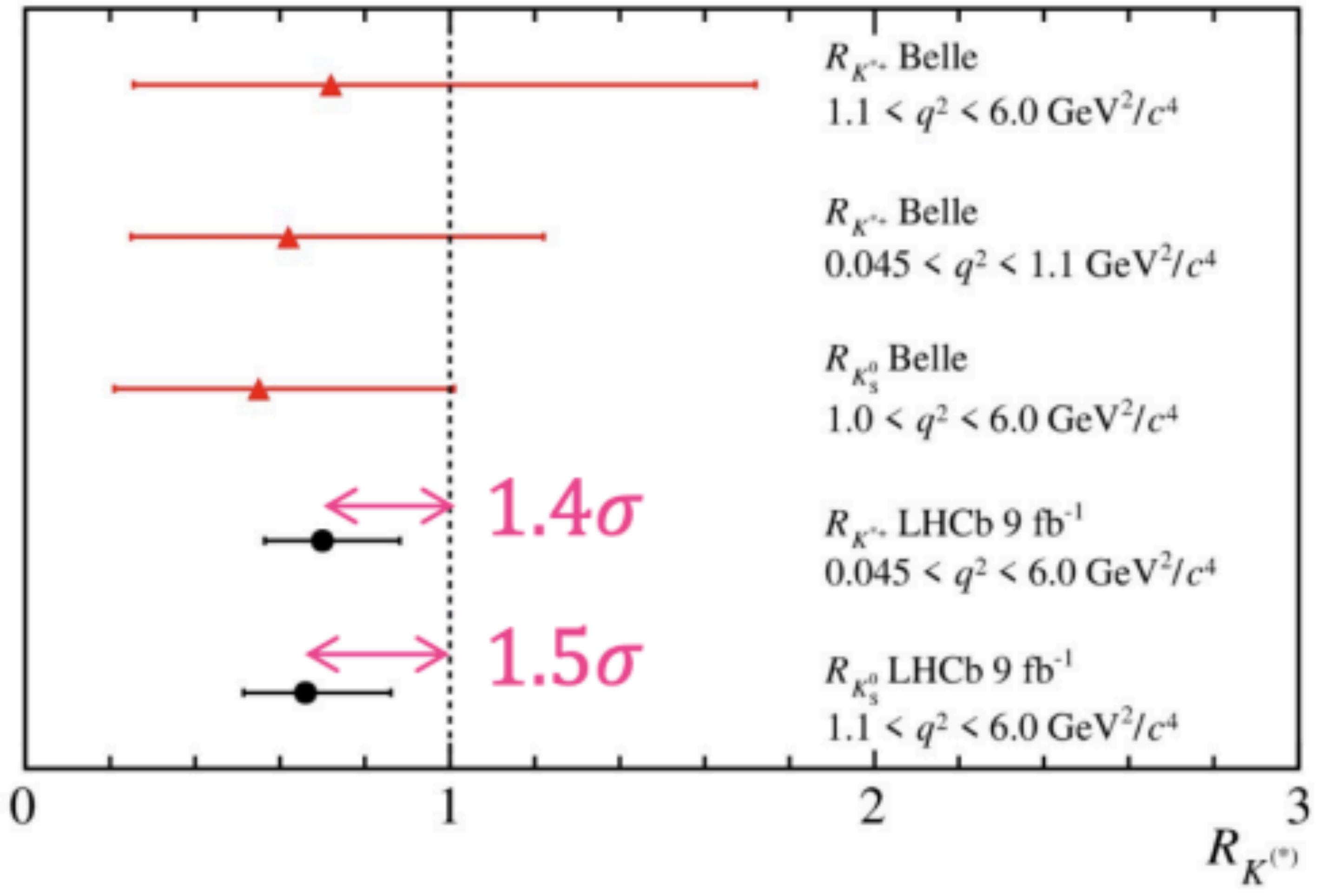

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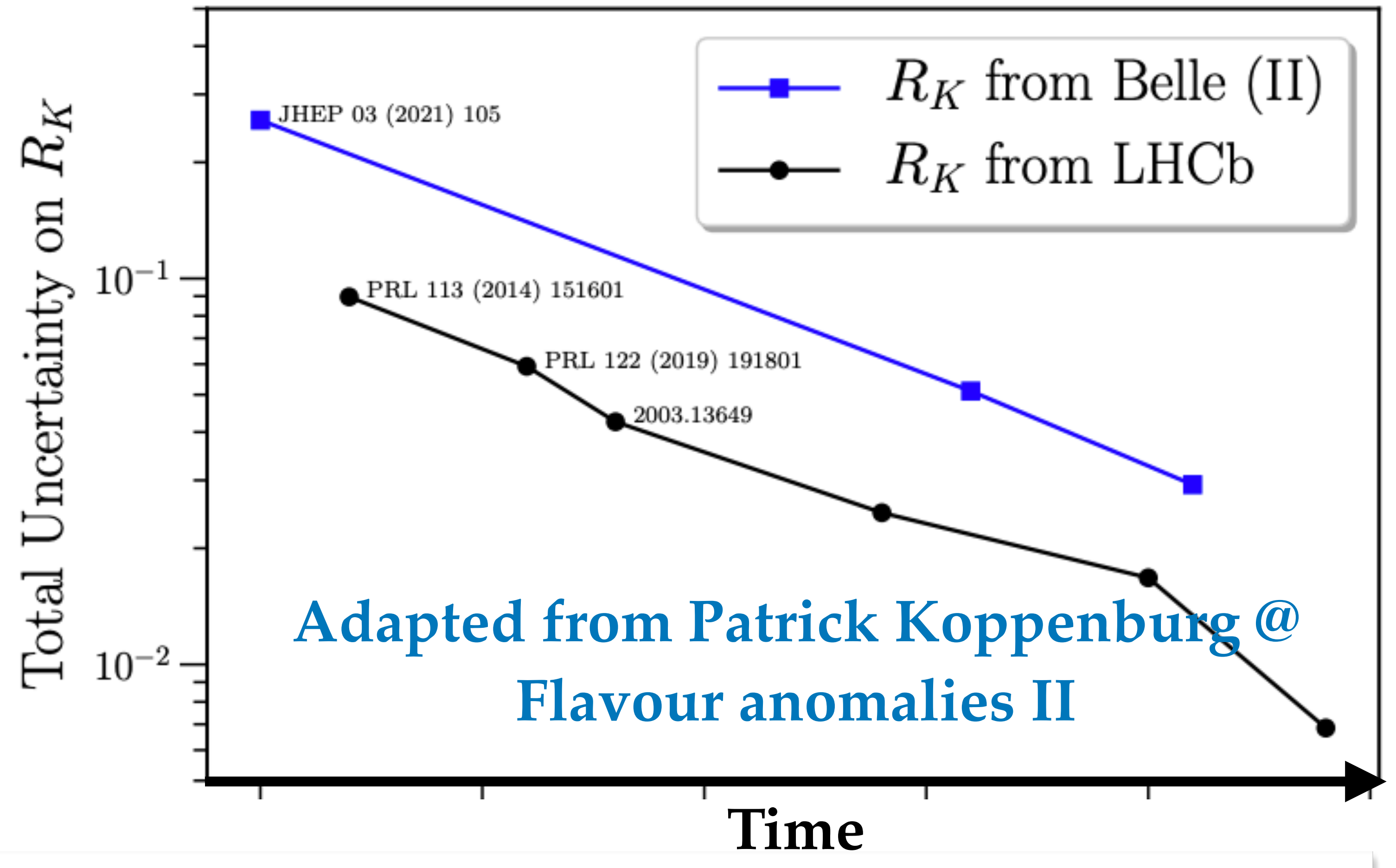

Adapted from Patrick Koppenburg @ Flavour anomalies II

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

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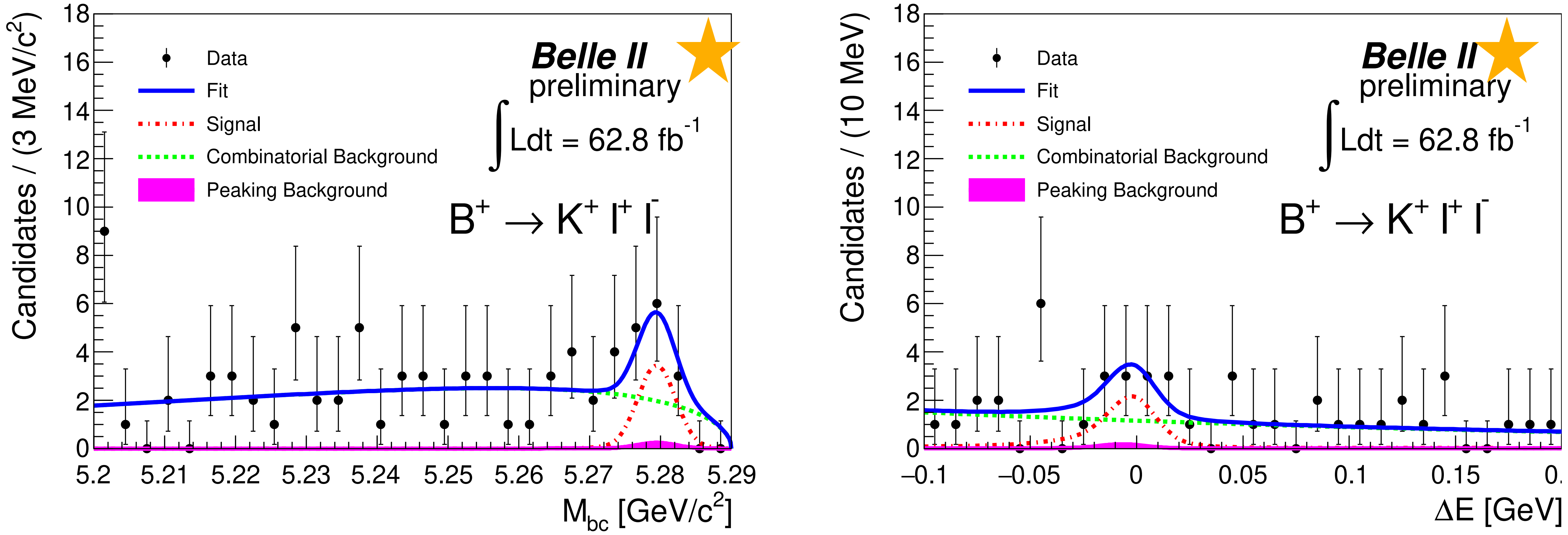
Study of $B \to K(*)ll$

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

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

[BELLE2-NOTE-PL-2021-005]



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

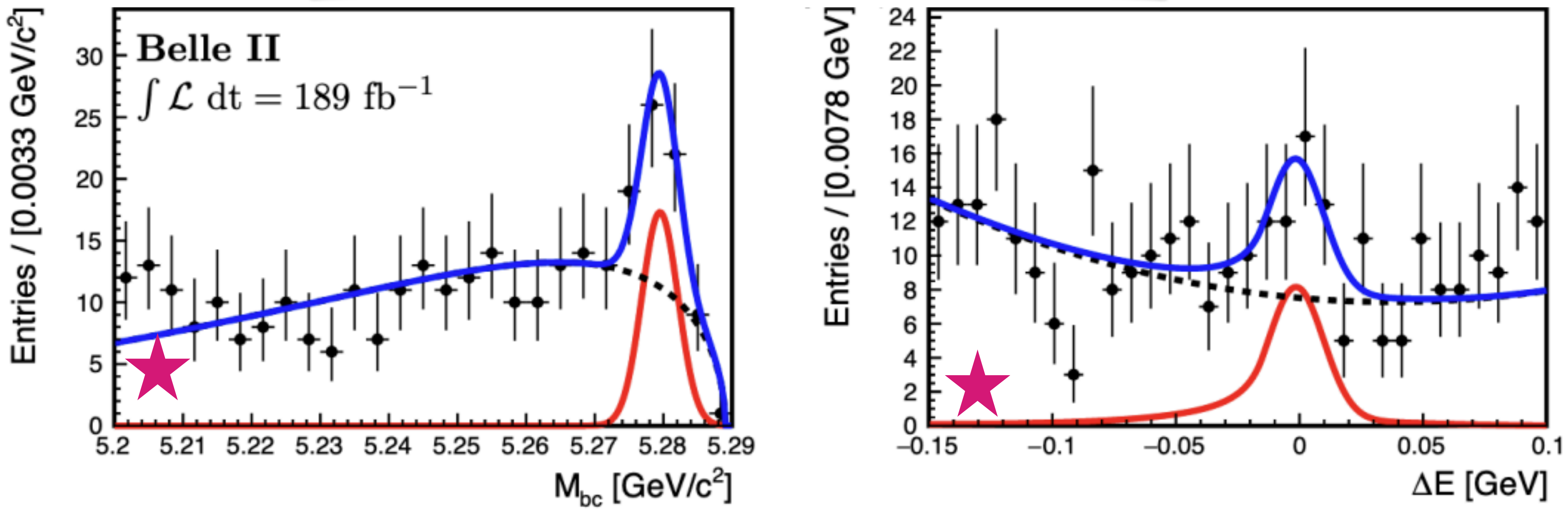
$$\Delta E = E_B - E_{beam}$$

Result

- $N_{sig} = 8.6^{+4.3}_{-3.9}(\text{stat}) \pm 0.4(\text{syst}) \to$ 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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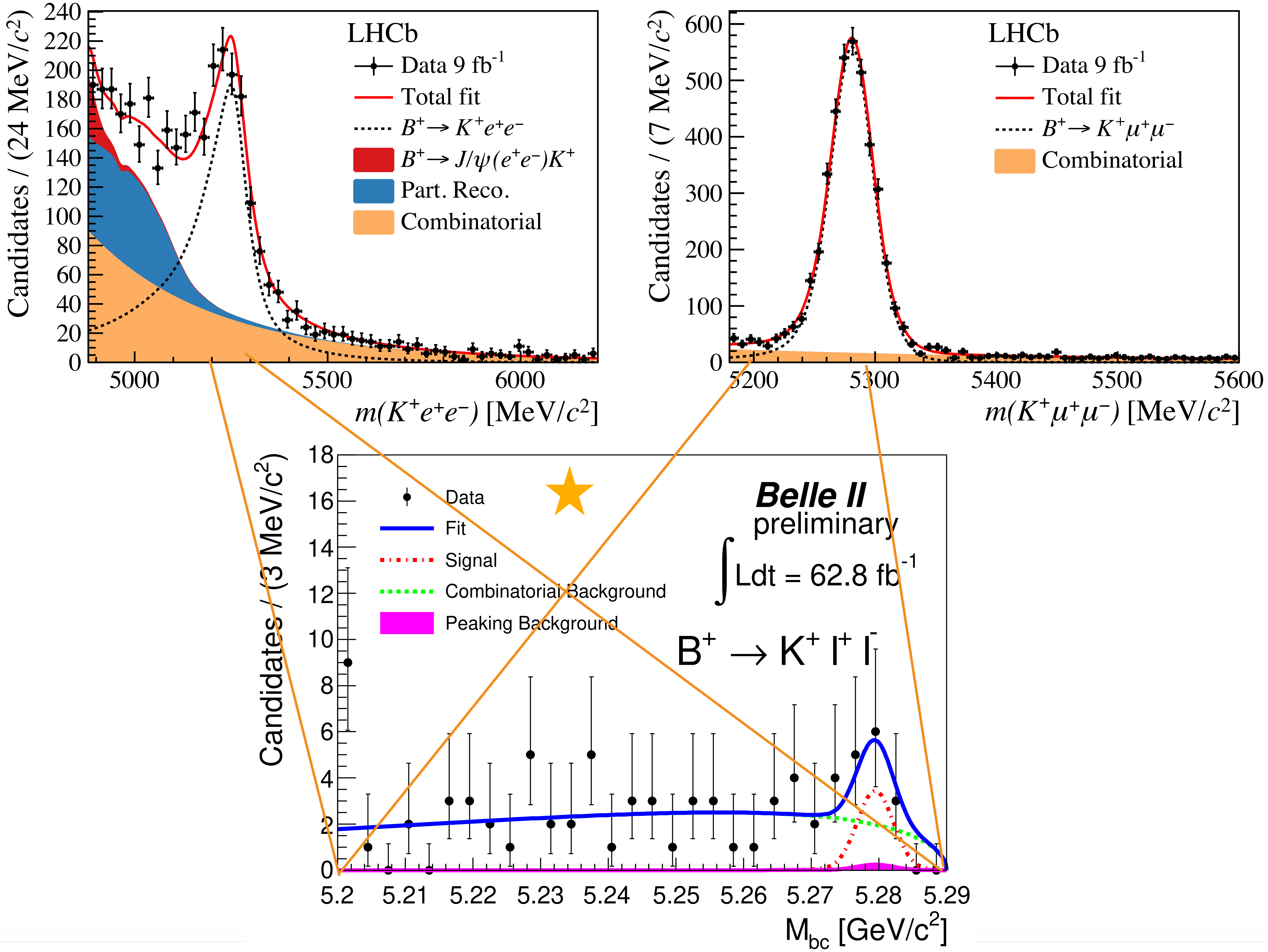
$R(K)$: Belle II vs LHCb (Aside)

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



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

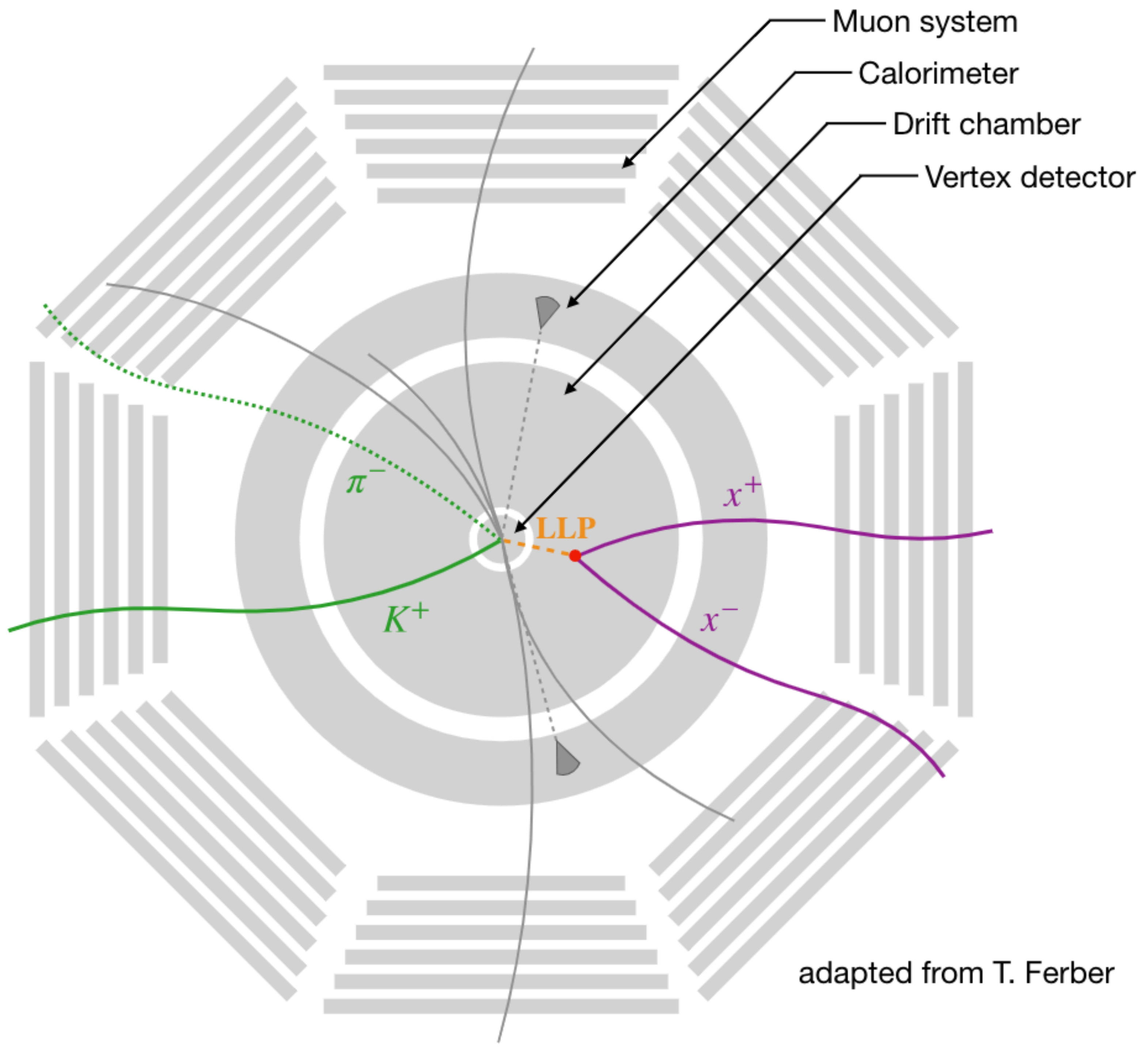
Three differing aspects to consider:
efficiency, statistics and resolution

	Belle II	LHCb
Signal	K⁺, K_s	K⁺
Same	1 ab⁻¹	1 fb⁻¹
$B^+ \to K^+e^+e^-$ Efficiency		
$B^+ \to K^+\mu^+\mu^-$ 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 q² bin	Accessible	Hard
Kinematic vertex constraint	M_{bc}	Pointing to PV

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

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

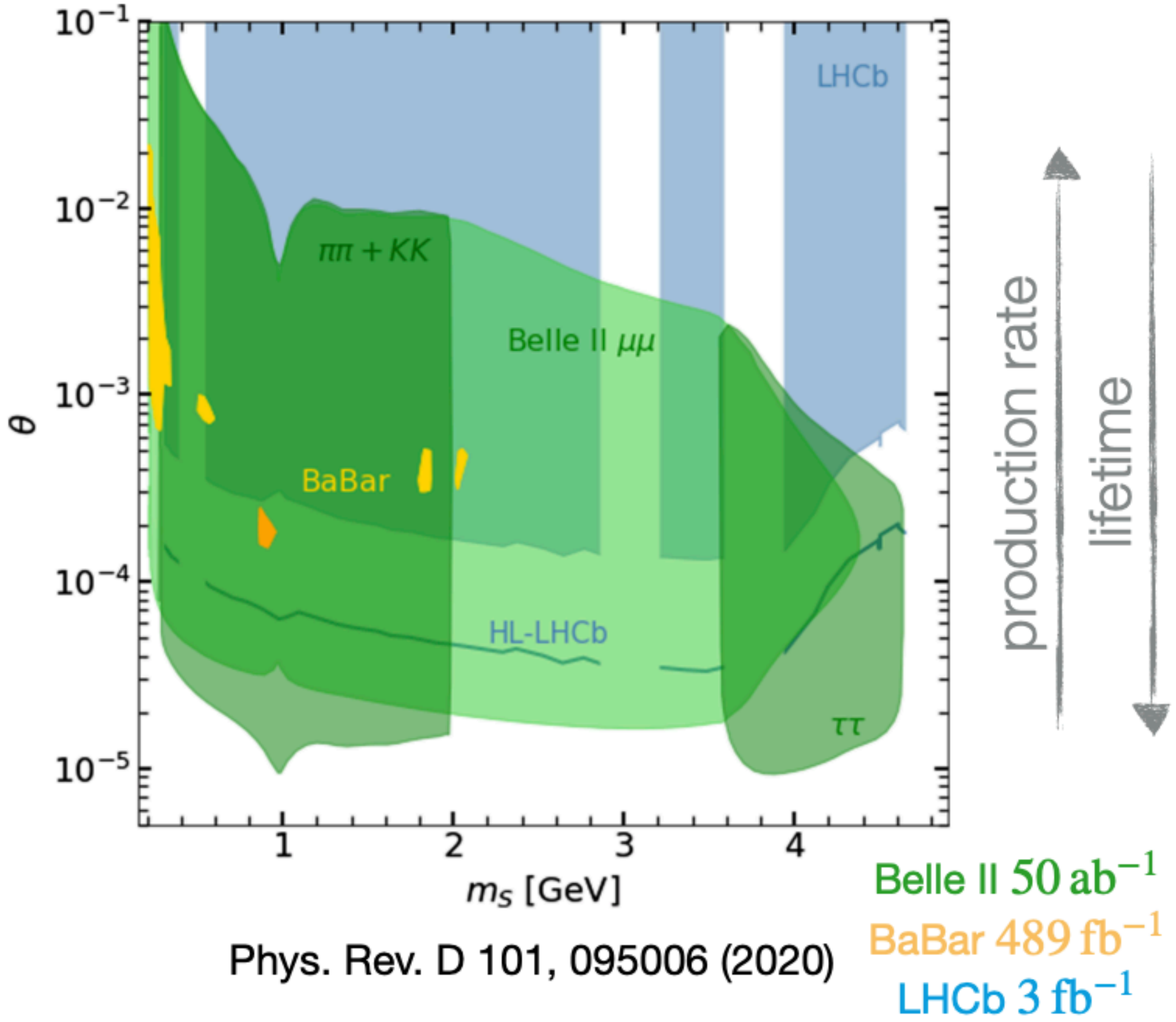
- **S (= long-lived scalar particle = LLP)** that decays visibly into pair of charged particles $x^+, x^-, x \in (e, \mu, \pi, K)$
- Bump hunt in the LLP invariant mass
- Separately for $x \in (e, \mu, \pi, K)$
- Separately for different lifetimes



adapted from T. Ferber

Current bounds and predictions

A. Filimonova, R. Schäfer, S. Westhoff



Phys. Rev. D 101, 095006 (2020)

Prediction does not contain e^+e^- channel

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

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

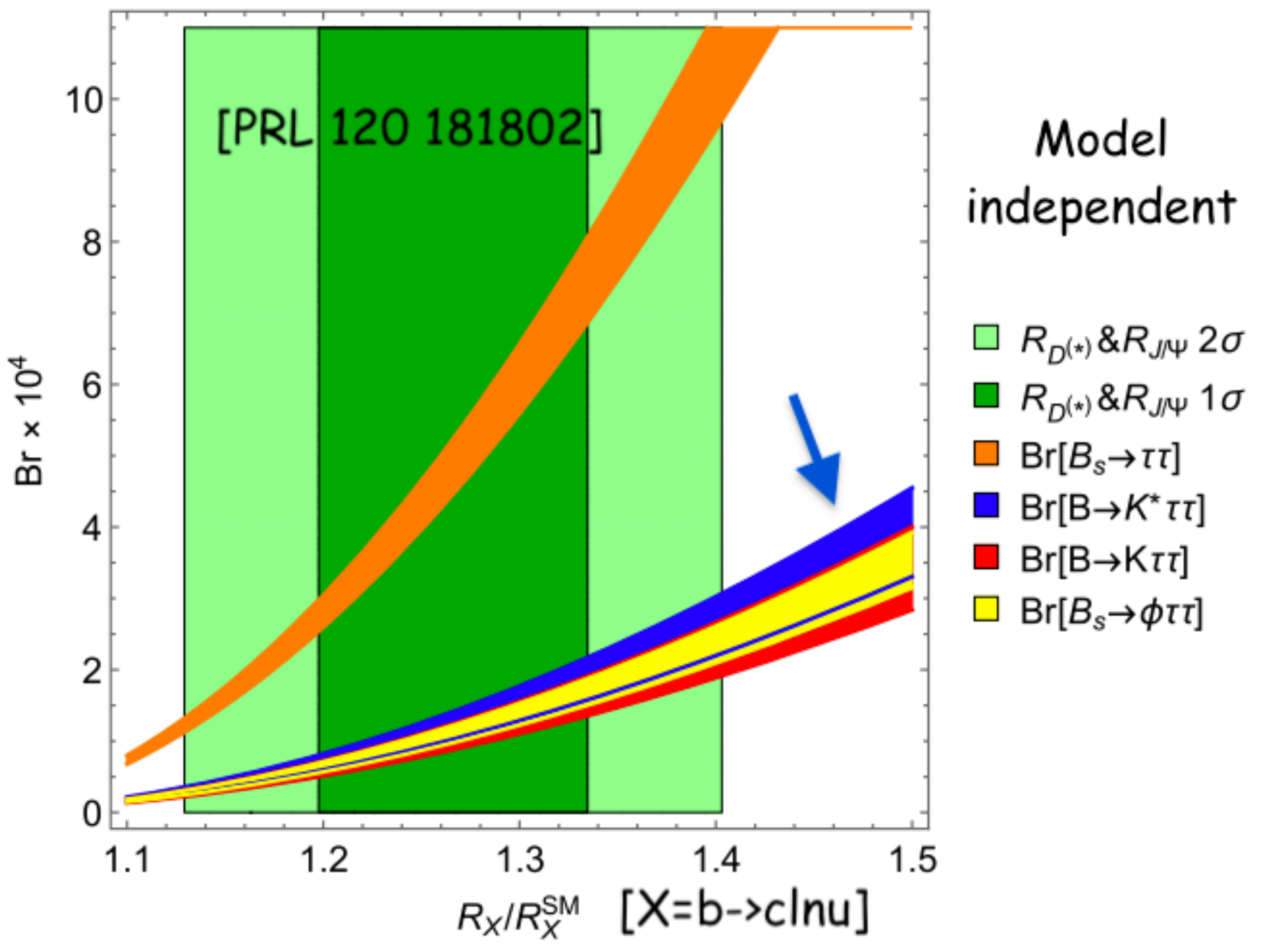
BSM:
- Rate enhanced by NP models (especially those coupling only to 3rd generation / with coupling ∝ particle mass)

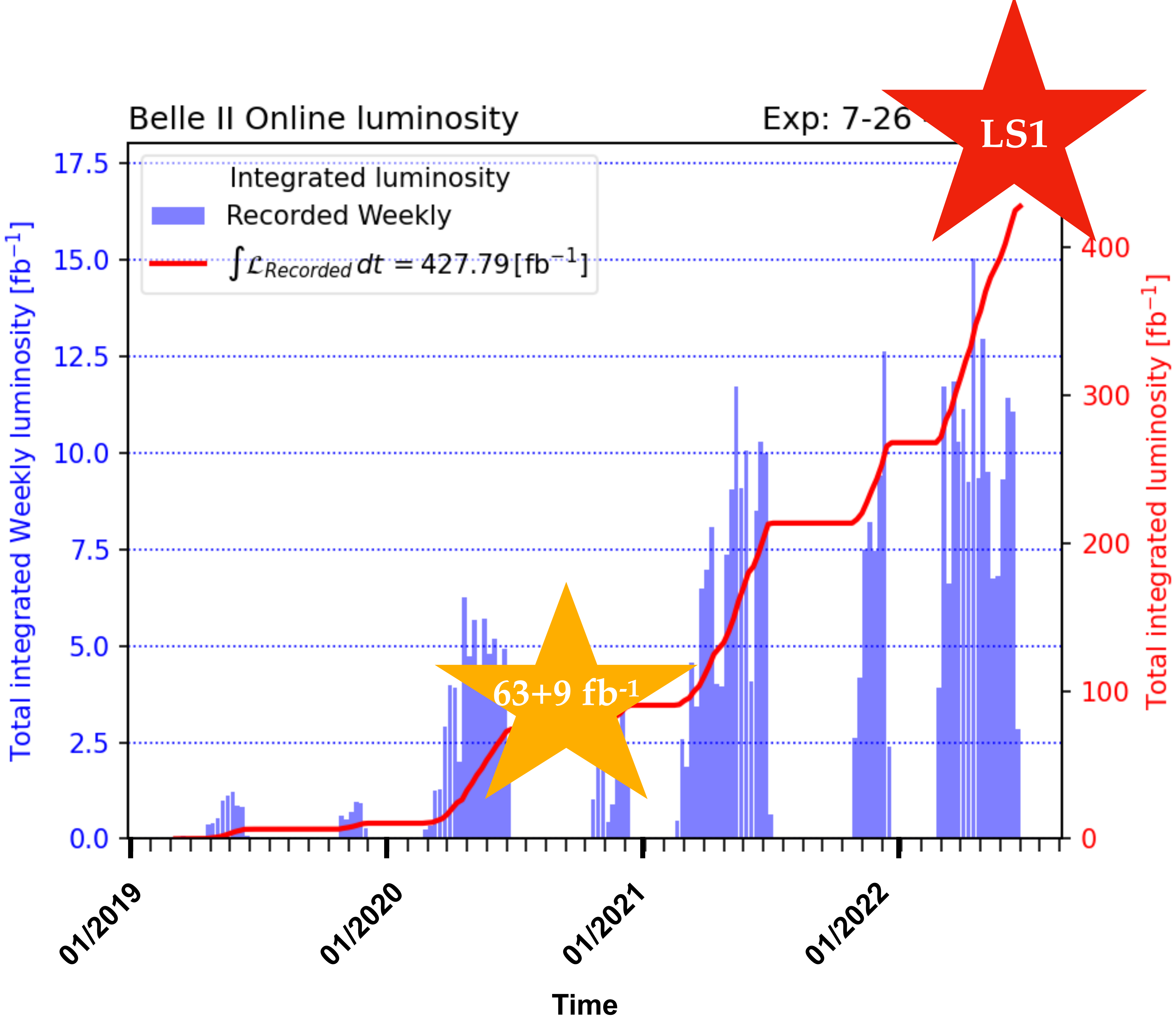
Current Bounds:
- Belle $\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) < 2.0 \times 10^{-3}$ @ 90 % C.L. [arxiv:2110.03871]
- Babar $\mathscr{B}(B^+ \to K^+\tau^+\tau^-) < 2.3 \times 10^{-3}$ @ 90 % C.L. [PRL 118, 031802 (2017)]

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	$< 1.6 \times 10^{-3}$	$< 5.3 \times 10^{-4}$





Two scenarios are considered, which are similar for all except the \BKSpnn decay. The "baseline" scenario assumes no further improvements. The "improved" scenario assumes a 50\% increase in signal efficiency for the same background level, an advance that current studies indicate to be achievable by various means including combination with semileptonic and hadronic reconstruction of the partner B meson. For the \BKSpnn decay, we assume 20\% and 70\% improvements for the baseline and improved scenarios, respectively, since Ref.~\cite{Belle-II:2021rof} relied on the $\Kstarp \to \Kp \piz$ sub-decay only. The projections are in ~\autoref{tab:b2knnbase}. {\bf Belle~II is the only experiment capable of exploring these key channels that disclose a vast and uncharted region of SM and non-SM dynamics.} For example, with just 5\invab of integrated luminosity, the \BKpnn analysis is sensitive to the SM rate at 3σ (5σ) level for the baseline (improved) scenarios.