Systematics in Flavour Physics Analyses (rare decays)

Systematic Effects and Nuisance Parameters in Particle Physics Data Analyses

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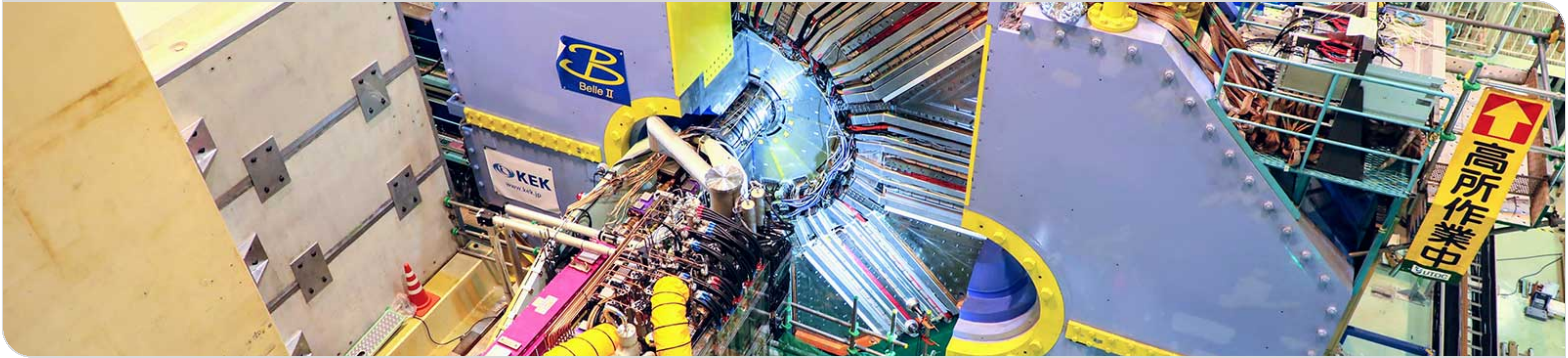
Slavomira Stefkova (KIT)

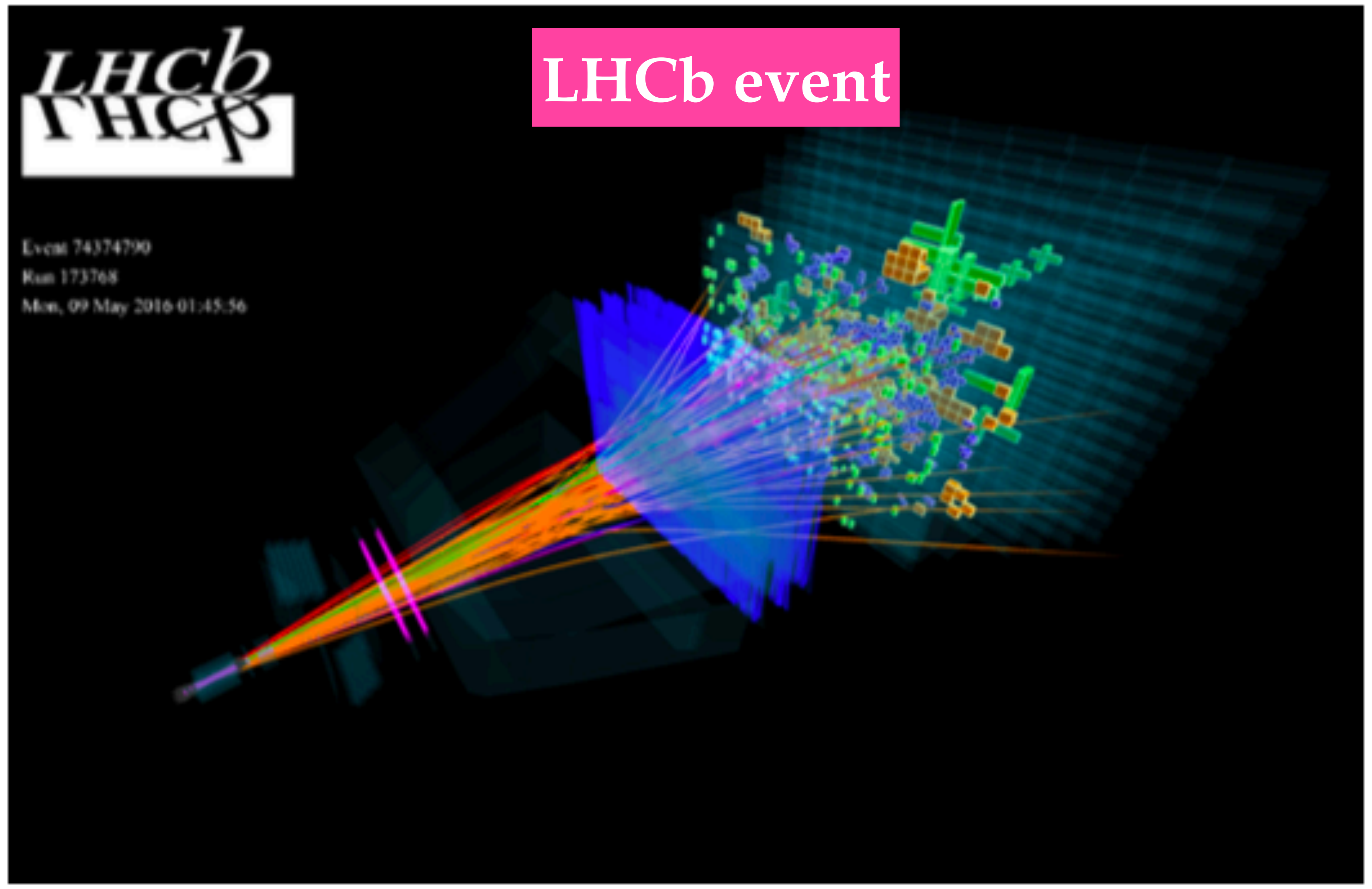
slavomira.stefkova@kit.edu

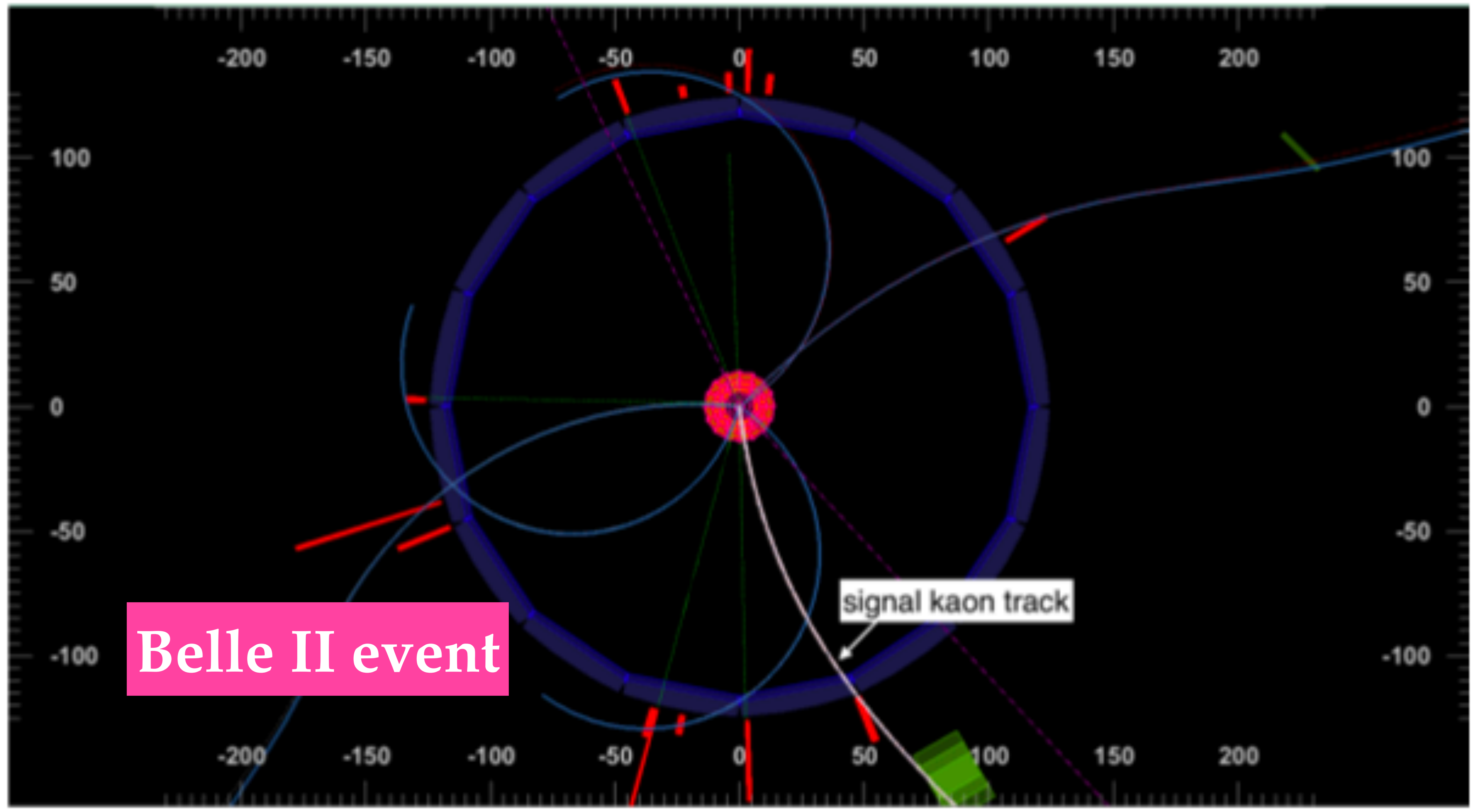


Flavour experiments in nutshell

Collider Flavour Physics: Belle II and LHCb

- Two active collider flavour physics experiments specialising in B-physics: **LHCb and Belle II**
- The **main differences** with respect to other ATLAS and CMS experiments:
  - Generally more sensitive to lower deposits: mass of B-meson ~ 5 GeV
  - The innermost detector has excellent vertex resolution close to IP

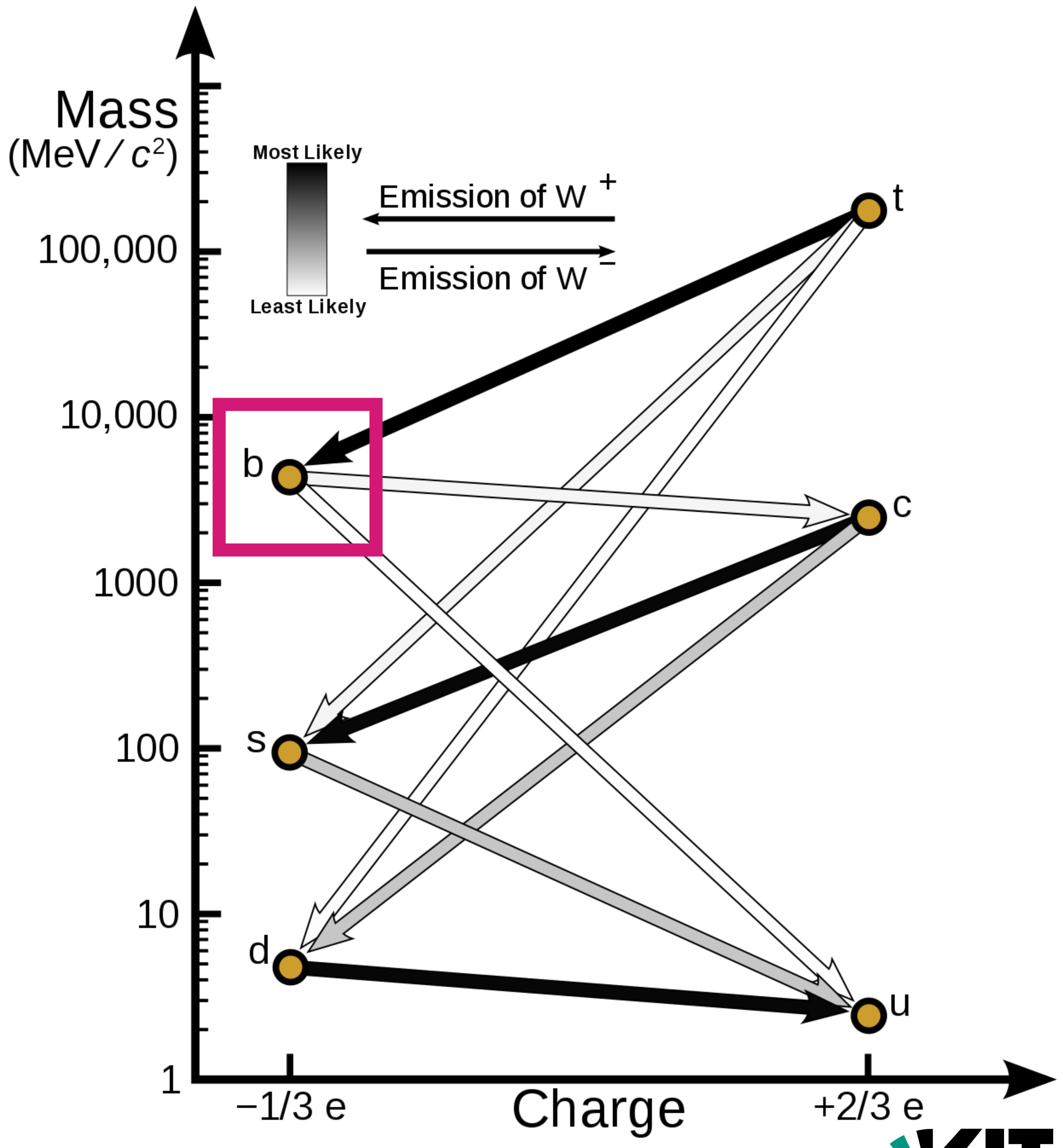




B-decays measurements (and others)

- *B*-decay is **abundant** or **rare** depending on the likelihood dictated by CKM matrix:
  - Precision measurements of CP violation (**rare and abundant**)
  - Indirect searches/measurements for NP in rare *B*-decays (**rare**)
  - Indirect searches for NP in semileptonic *B*-decays (**abundant**)
  - Spectroscopy of *B*-decays (**abundant**)

- Belle II and LHCb also well suited for measurements with
  - Decays involving c and τ
  - Direct searches for NP, e.g DM, mediators connected to DM, leptoquarks, Z', …..



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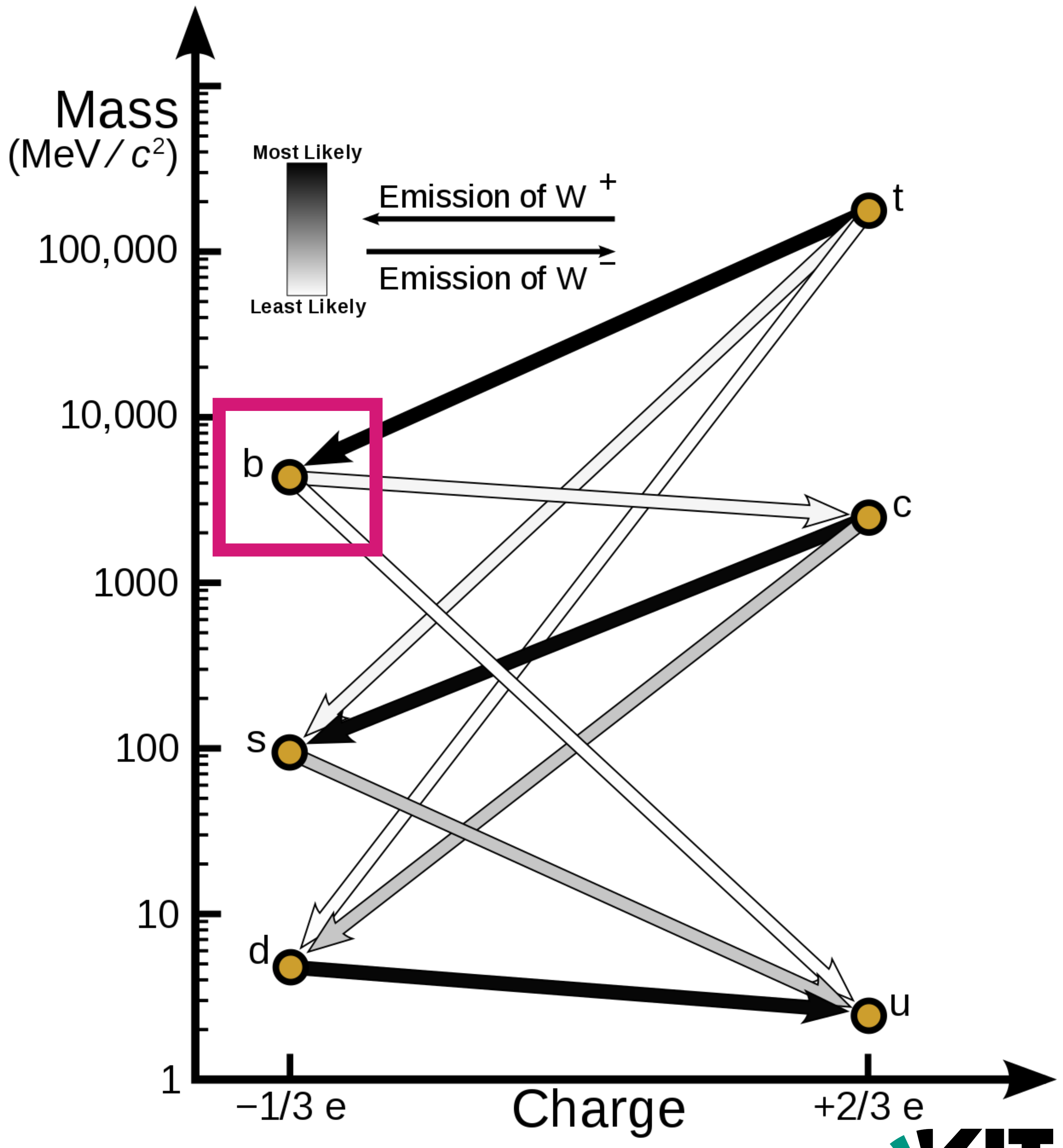
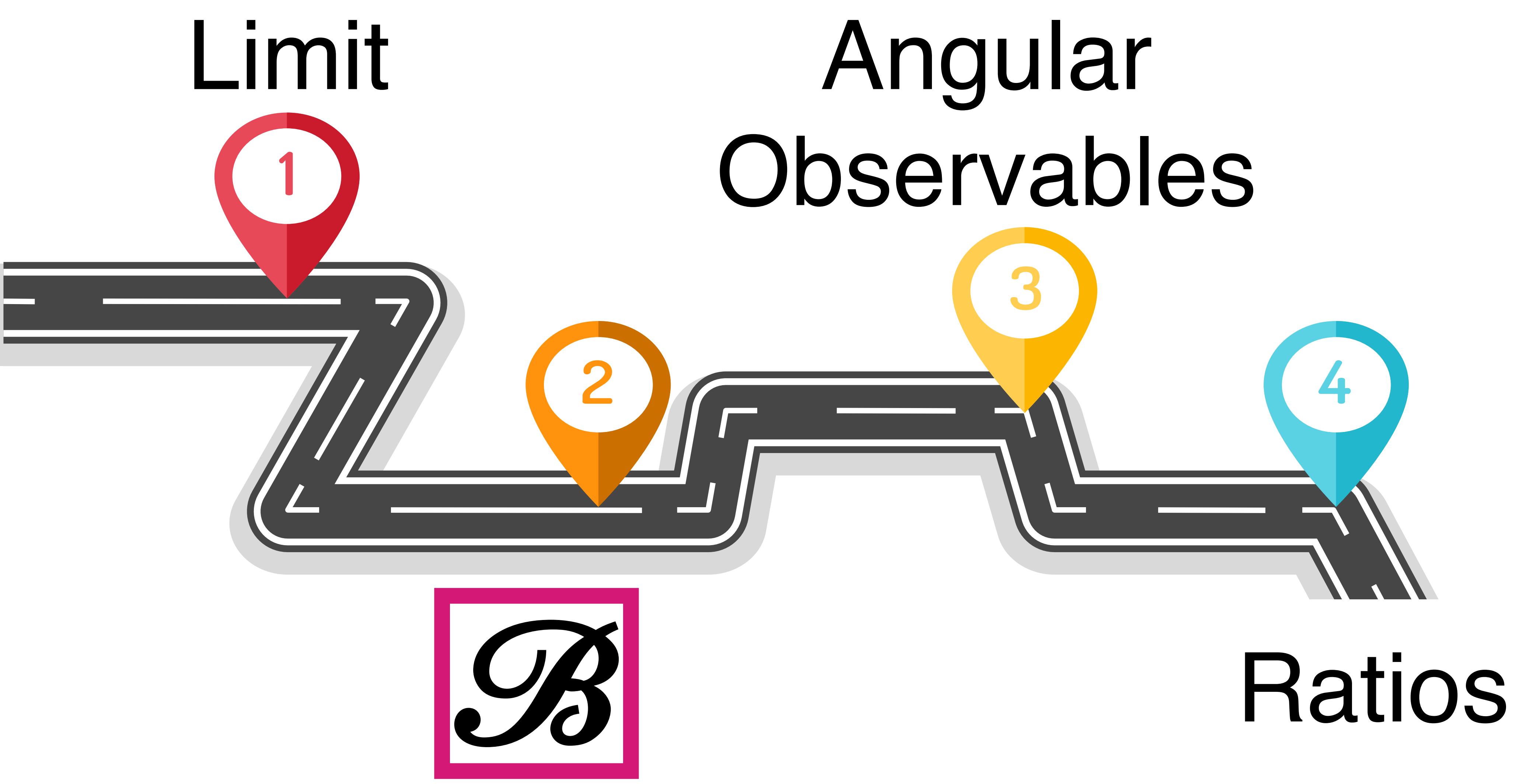


What do we measure in rare *B*-decays?



Theoretically cleaner →

Parameter of interests:

1. **$\mathscr{B}$ → 1 parameter of interest**

   Signal strength of the process (1 μ = SM expectation)

2. **Angular observables → several parameters of interest:**

   e.g: angular observables of $B \to K^{*0}\mu^+\mu^-$: P_5', F_L, A_{FB}

3. **Ratios → 2 parameters of interests**:

   e.g: signal strengths of two processes

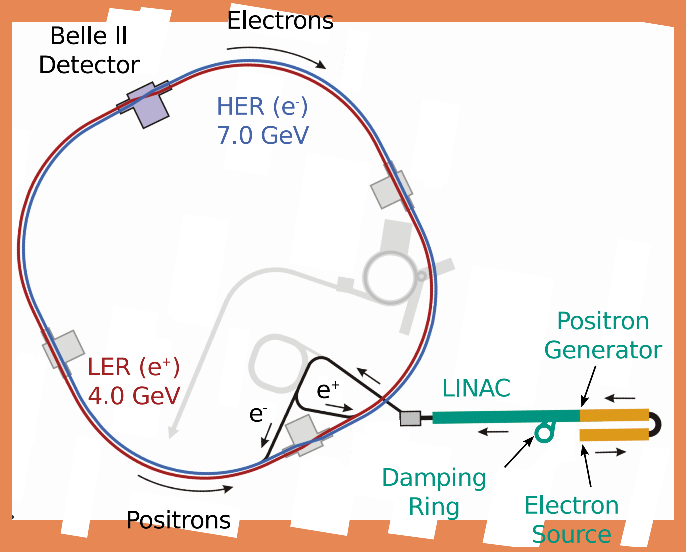
$$\frac{\mathscr{B}(B^+ \to K^+\mu^+\mu^-)}{\mathscr{B}(B^+ \to K^+e^+e^-)} = \frac{\epsilon(B^+ \to K^+e^+e^-)}{\epsilon(B^+ \to K^+\mu^+\mu^-)} \times \frac{N(K^+B^+ \to \mu^+\mu^-)}{N(B^+ \to K^+e^+e^-)}$$

How often does *B*-decay into the decay products?

rare → $\mathscr{B}$ **< 10^{-5}**

Types of Systematic Uncertainties

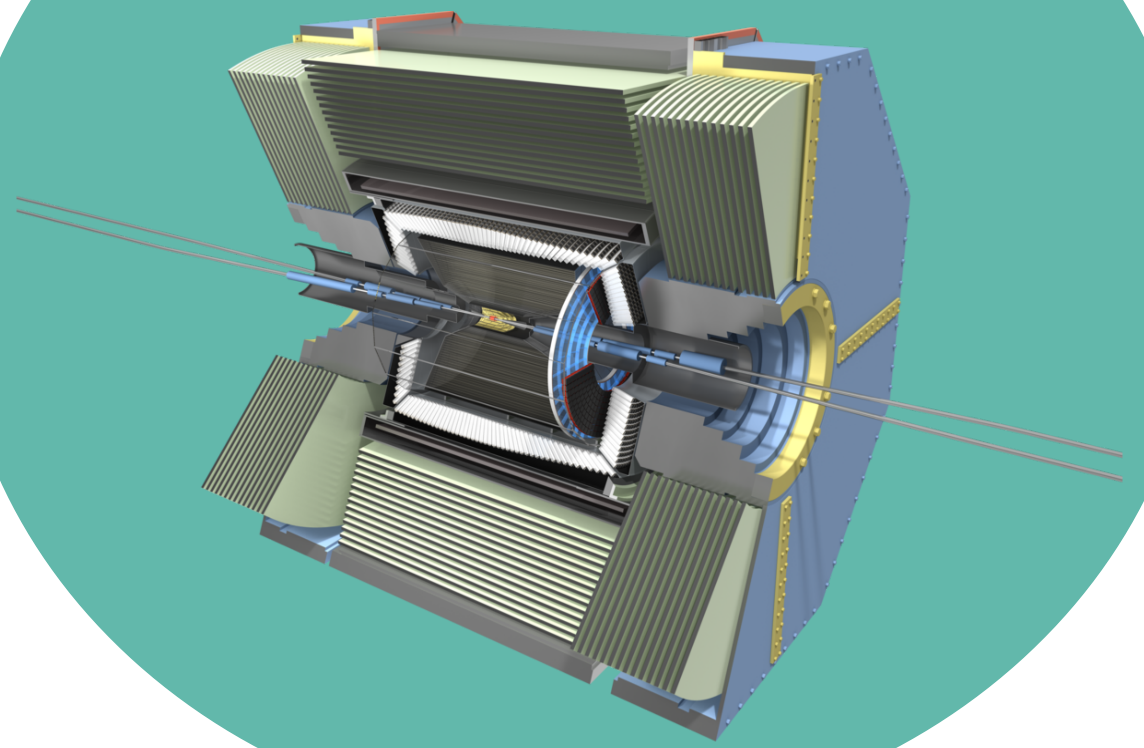
Accelerator



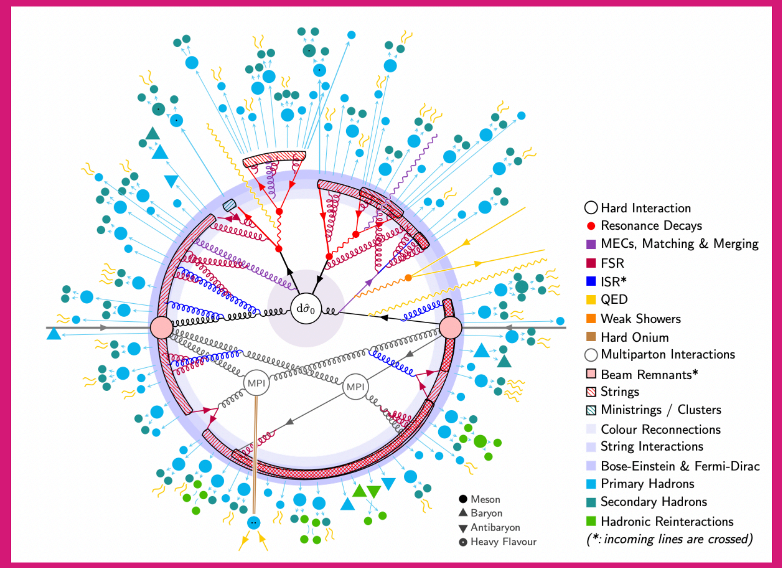
External Measurement

BESIII

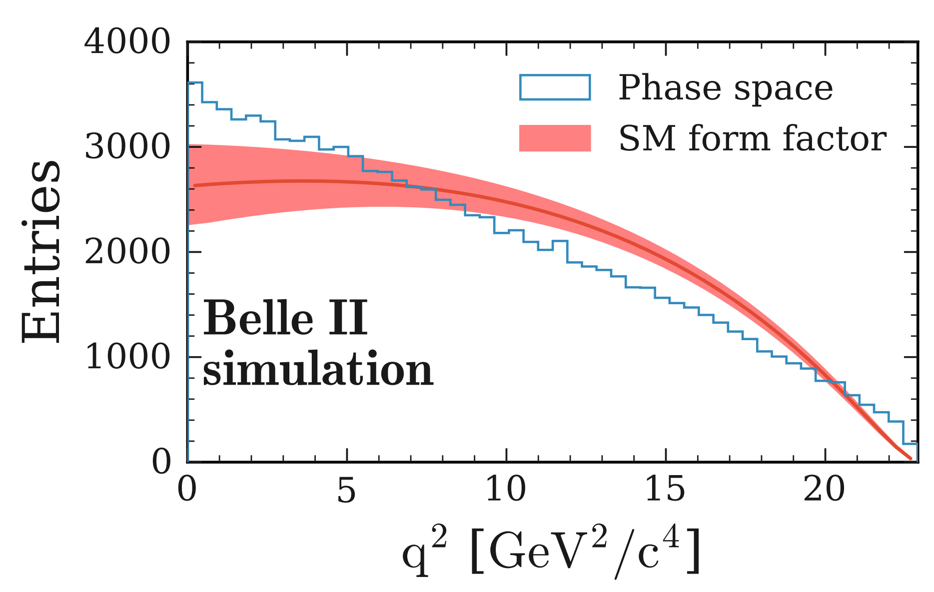
Detector



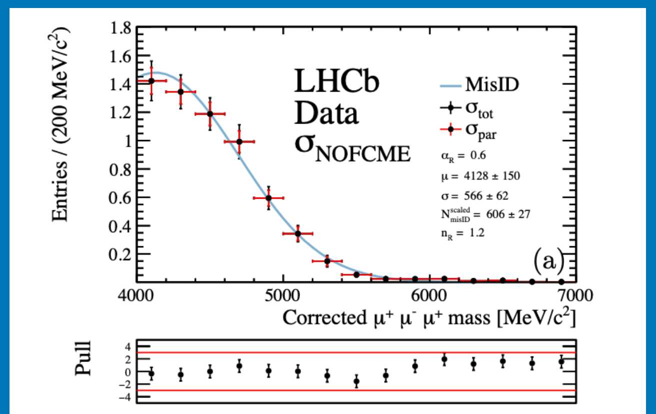
Simulation



Theory



Analysis Technique

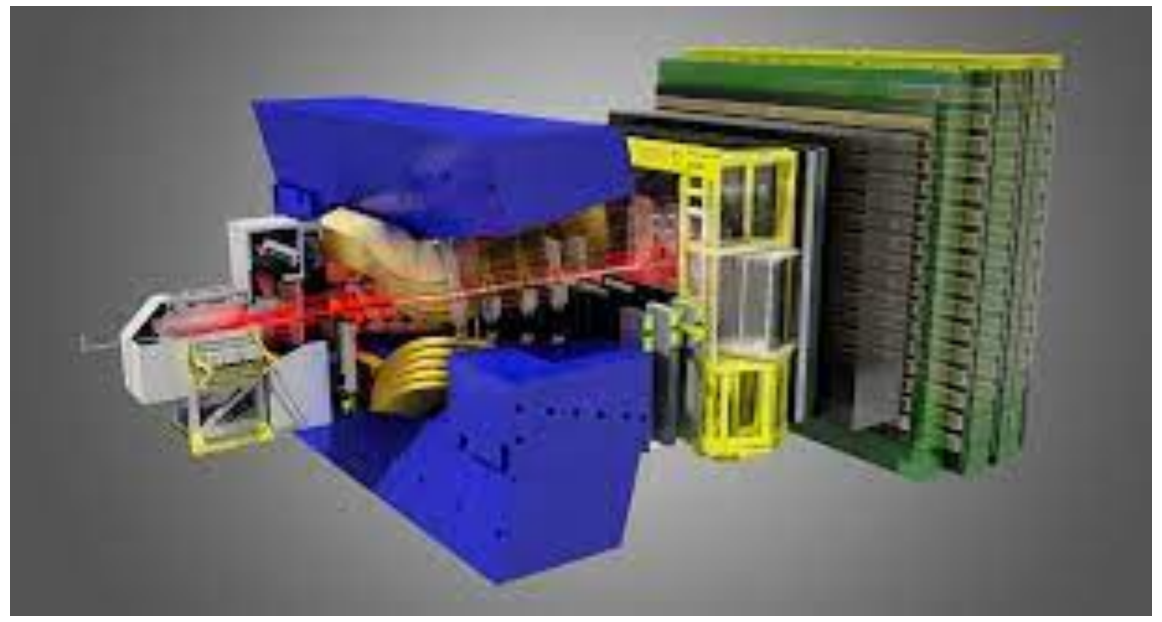


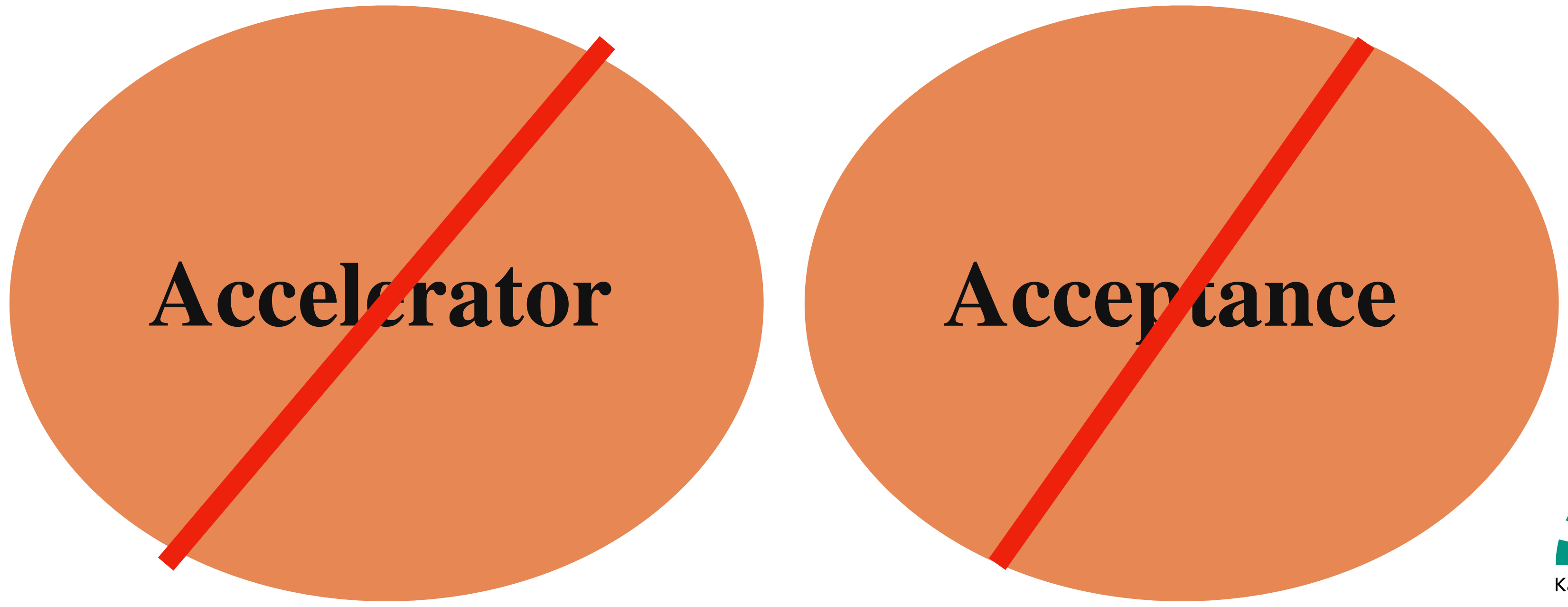
LHCb and Belle II: Measurement Style

For measuring $\mathscr{B}$ of rare B-decays **LHCb uses mostly relative** and **Belle II absolute approach**:

- $\mathscr{B}(B^+ \to \mu^+\mu^-\mu^+\nu) = \mathscr{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+) \times \dfrac{\epsilon(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}{\epsilon(B^+ \to \mu^+\mu^-\mu^+\nu)} \times \dfrac{N(B^+ \to \mu^+\mu^-\mu^+\nu)}{N(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}$
- $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = \dfrac{N(B^+ \to K^+\nu\bar{\nu})}{\epsilon(B^+ \to K^+\nu\bar{\nu})}$

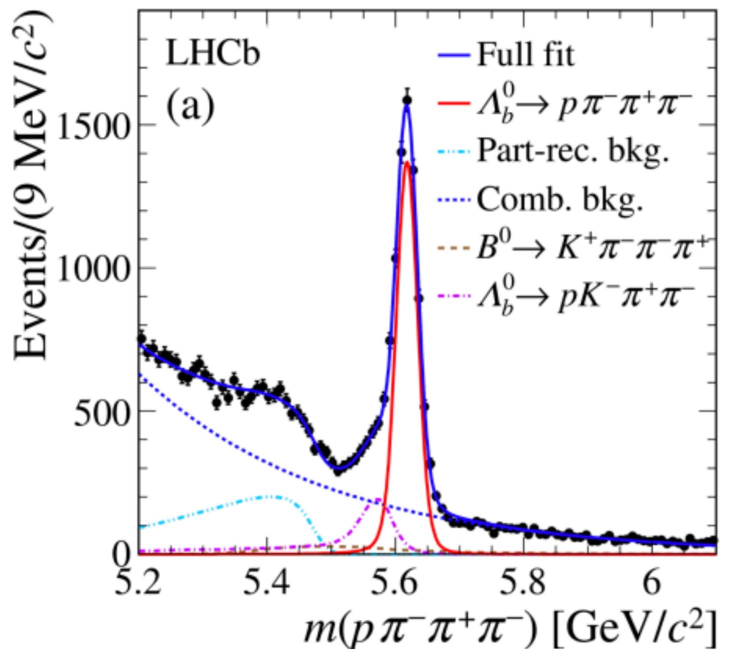
- Systematics need to be therefore derived either on the efficiencies or numbers of events in Belle II or on relative efficiencies and yields in LHCb:
  - Relative measurements cancel uncertainties due to accelerator and acceptance





Building models and fitting

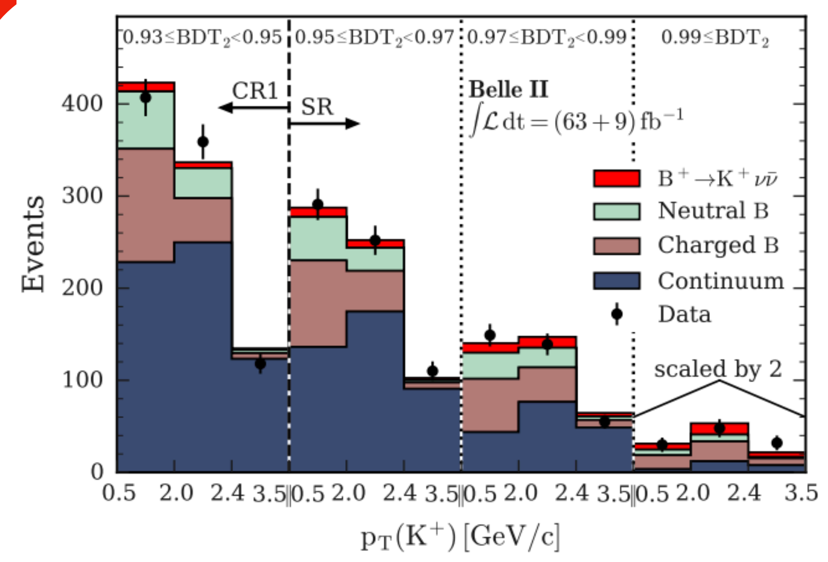
Unbinned



Per-event model

$$p(\{x_i\}\,|\,\theta) = \mathrm{Pois}(N\,|\,\theta)\prod_{i=0}^{N} p(x_i\,|\,\theta)$$

Binned



Step-wise per-event model

$$p(\{n_b\}\,|\,\theta) = \prod_b \mathrm{Pois}(n_b\,|\,\lambda(\theta)p(b\,|\,\theta)) = \prod_b \mathrm{Pois}(n_b\,|\,\lambda_b(\theta))$$

Model Description

Parametrised functions: (Crystal Balls, exponential, Gauss, …) Density Estimates (KDE)

Parametrised histograms

Fitting

Maximum Likelihood Fit systematics included as nuisances

Limit Setting

- Frequentist
  - Asymptotic
  - Toy-based
- Bayesian

Observation

- Significance

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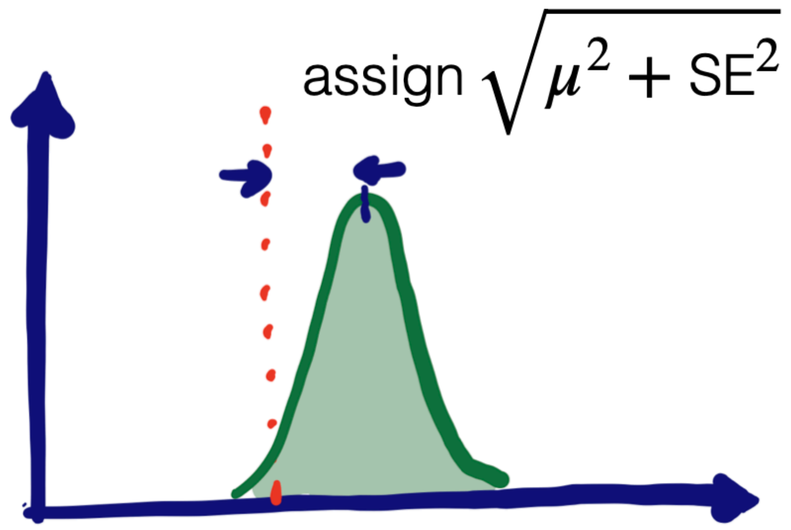
How do we get systematic variations?

→ Systematic uncertainties can affect shape, normalisation or both

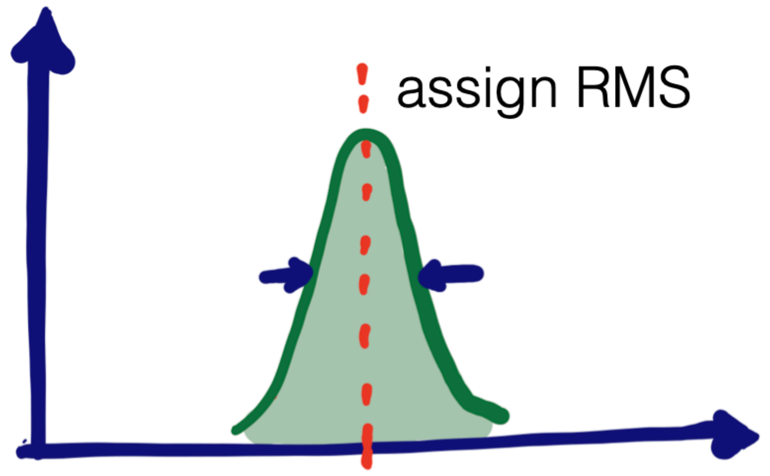
What samples do we use?

1. Alternative models (simulation)
2. Calibration samples (mixture of simulation and data)
3. Signal embedding (mixture of simulation and data)
4. (Orthogonal) data samples (data)



What methods do we use? [T.Blake (Phystat 2021)]:

1. Generate a large number of pseudo-experiments from a varied model and determine observables using the nominal model…(bootstrap method)
2. Repeat the determination of the observables in data using a different set of assumptions…(alternative method)



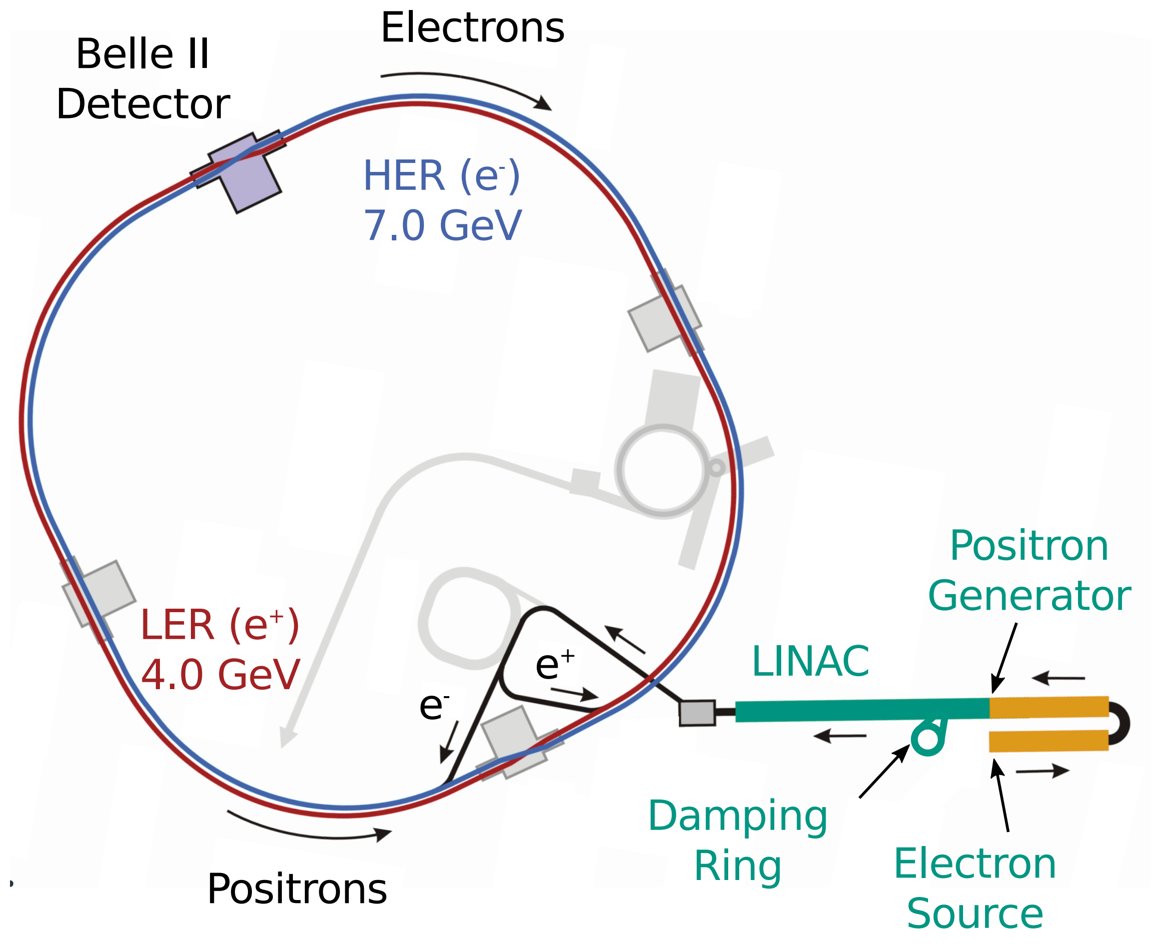
→ After evaluation of systematics we include them in a likelihood as constraints, aka penalty terms

Practical examples of systematics*

*mixture of good, bad and ugly

Systematic Uncertainties: Accelerator

Accelerator	$\mathscr{B}(B^+ \to K^+ \nu\bar{\nu})$ **(Belle II)**	$\mathscr{B}(B^+ \to \mu^+\mu^-\mu^+\nu)$ **(LHCb)**
Delivered Luminosity	Integrated Luminosity (Calibration)	
***B*-dataset**	Number of BB (Calibration)	

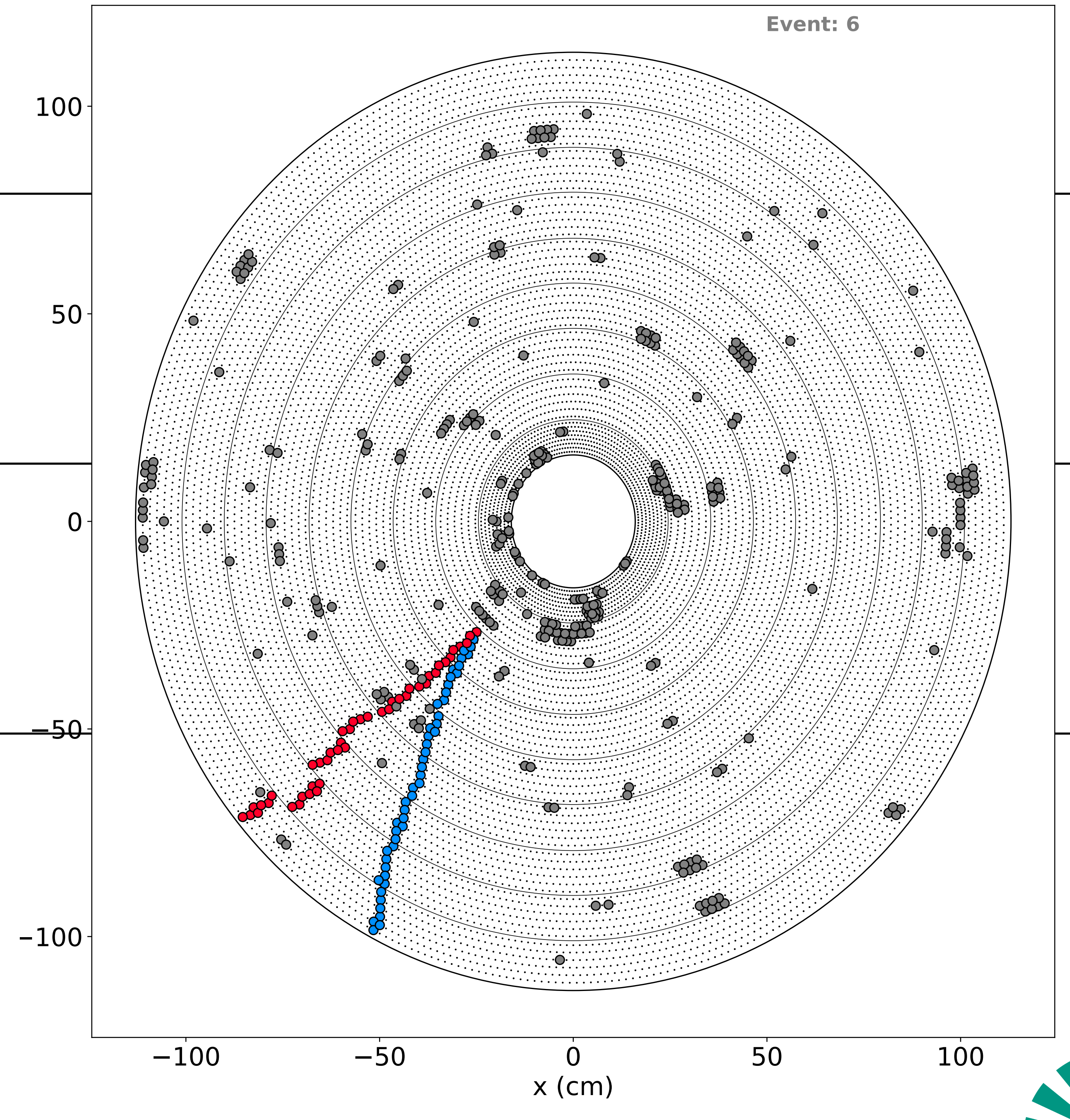


$\mathscr{B}(B^+ \to K^+ \nu\bar{\nu})$
[Phys. Rev. Lett. 127, 181802 (2021)]

$\mathscr{B}(B^+ \to \mu^+\mu^-\mu^+\nu)$
[Eur. Phys. J. C 79 (2019) 675]

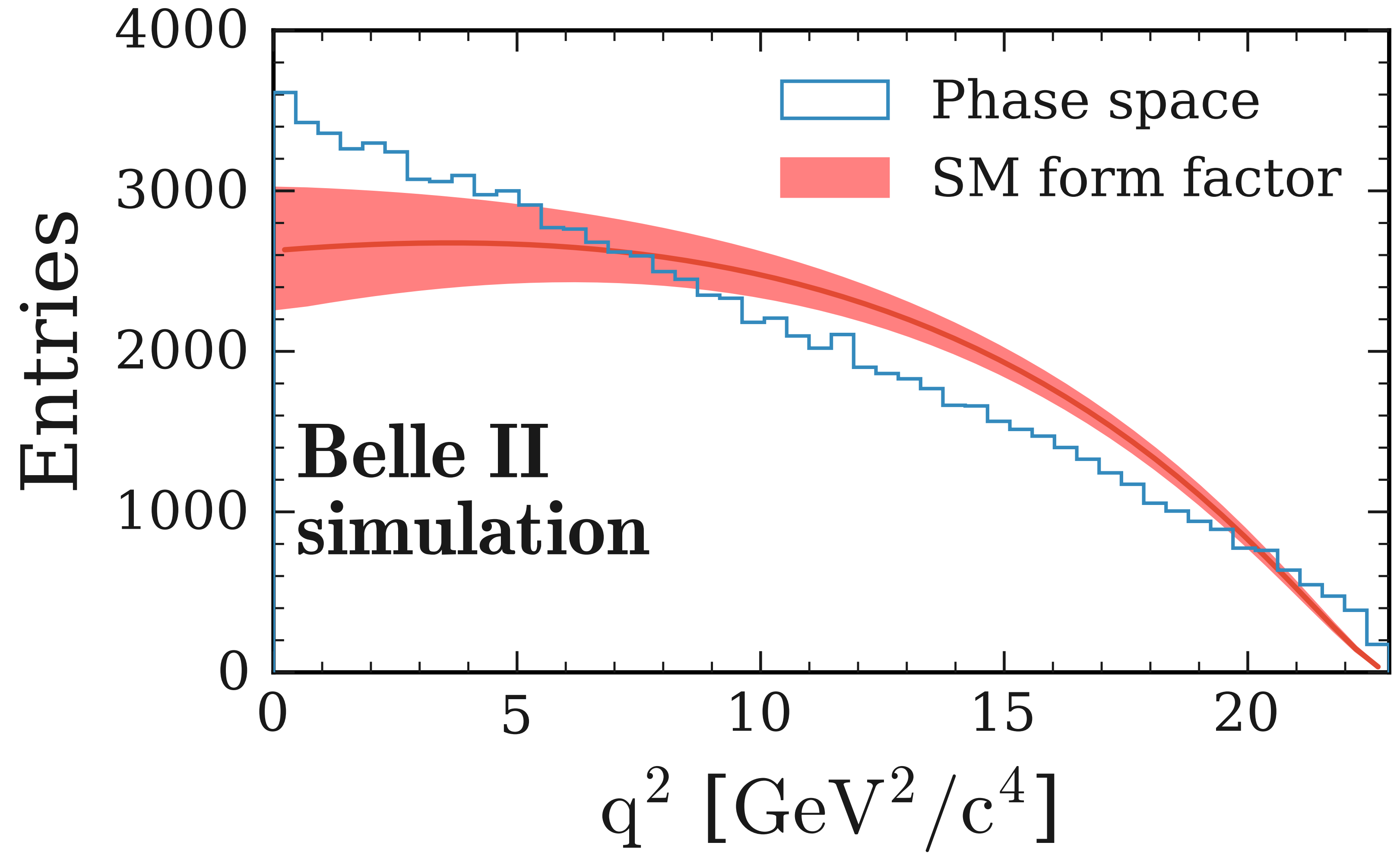
Systematic Uncertainties: Detector

Detector	$\mathscr{B}(B^+ \to K^+ \nu \bar{\nu})$ **(Belle II)**	$\mathscr{B}(B^+ \to \mu^+ \mu^- \mu^+ \nu)$ **(LHCb)**
Tracking of charged particles	Tracking efficiency (Calibration)	Tracking efficiency (Calibration)
Measurement of energy deposit (photons)	Uncertainty on the absolute energy for photons (0.5%) (Calibration)	
Measurement of energy deposit (others)	Uncertainty on the absolute energy for other clusters (5-10%) (Calibration)	
Particle Identification	Uncertainty on the PID corrections (Calibration)	



Systematic Uncertainties: Theory

Theory	$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})$ **(Belle II)**	$\mathscr{B}(B^+ \to \mu^+\mu^-\mu^+\nu)$ **(LHCb)**
Signal shape	Form Factor Uncertainty (theory model)	
Signal model		Signal Model (Alternative simulation model)



Systematic Uncertainties: Simulation

Simulation	$\mathscr{B}(B^+ \to K^+ \nu\bar{\nu})$ **(Belle II)**	$\mathscr{B}(B^+ \to \mu^+\mu^-\mu^+\nu)$ **(LHCb)**
***B*-production kinematics**		Kinematic reweighting (Calibration)
Uncertainty on background BF	Uncertainty on the BF of leading B-background (alternative models)	
Background normalisation	Continuum background (Orthogonal data sample)	
Missing background template		Modelling of $B^+ \to (D \to (\eta \to \mu\mu)\mu\nu)$ (alternative fitting model)

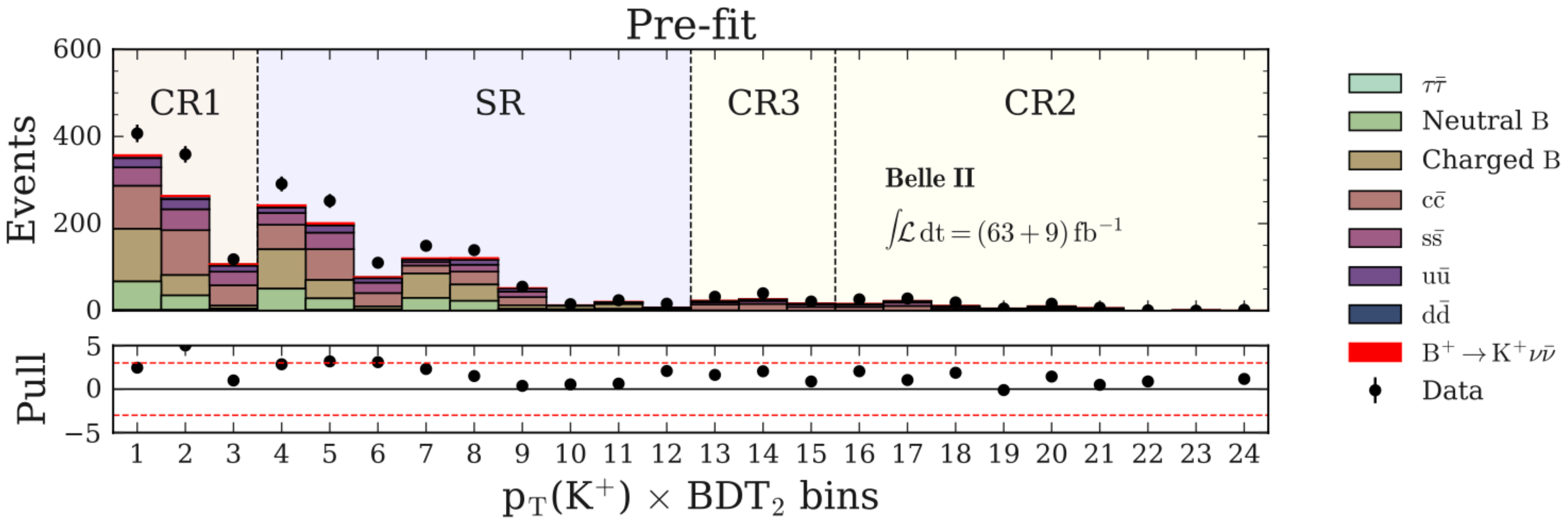
Systematic Uncertainties: Further Analysis

Further Analysis	$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})$ **(Belle II)**	$\mathscr{B}(B^+ \to \mu^+\mu^-\mu^+\nu)$ **(LHCb)**
Background shape		Background shape modelling (Alternative fitting model)
Fitting bias		Fitting bias (Alternative simulation models)

Methods: capturing correlations, assessing data-model compatibility

Few words about correlations…

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



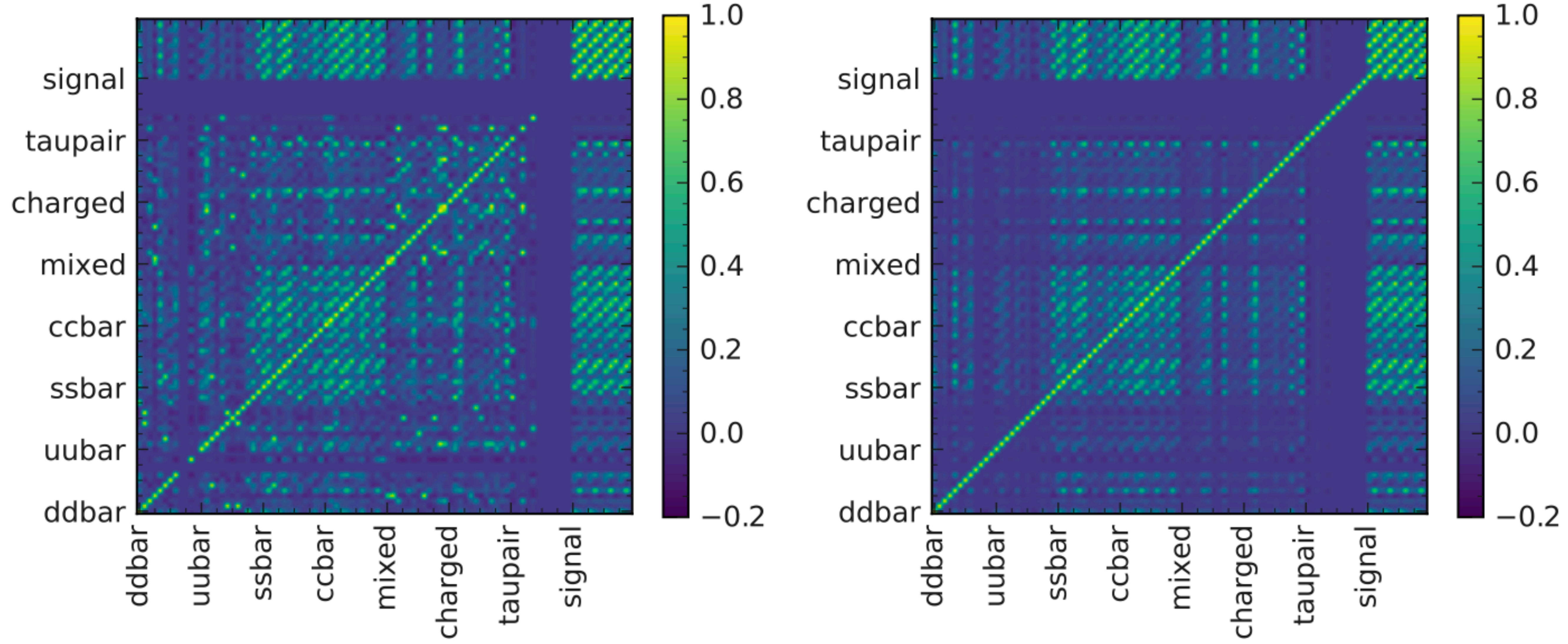
Correlated systematics (I)

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

Bootstrap

- PID (statistical error=σ), uncertainty on the branching fractions (measurement uncertainty=σ):
  - Non-trivial correlations PID corrections computed in bins of (p_T, θ)
  - Produce alternative simulations with bootstrap method: central values varied with lognormal(0, σ)
  - Reconstruct covariance matrix
  - Translation to nuisance parameters: SVD decomposition + leading eigenvectors as the nuisances

Full covariance



3 leading eigenvectors

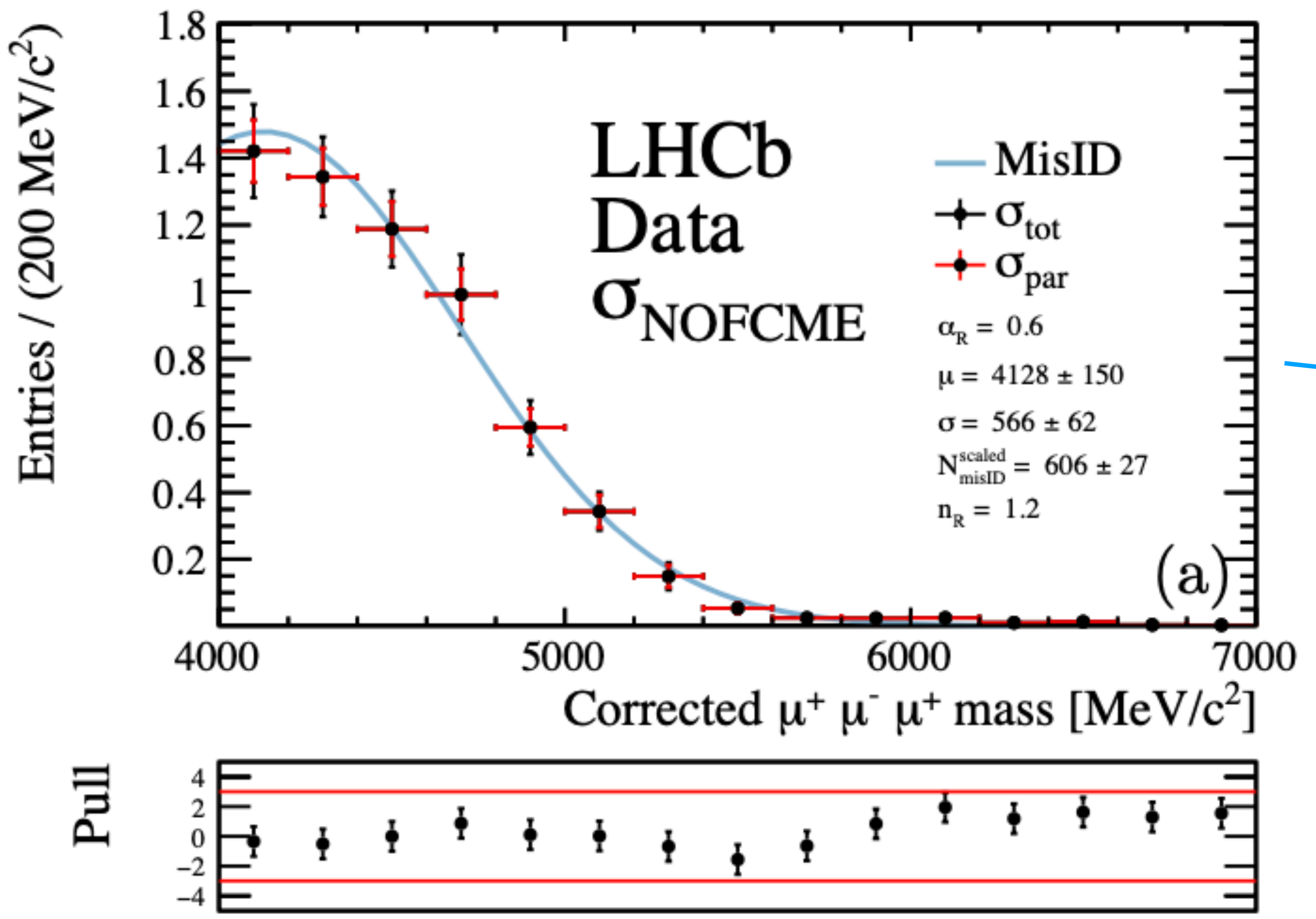
Correlated systematics (II)

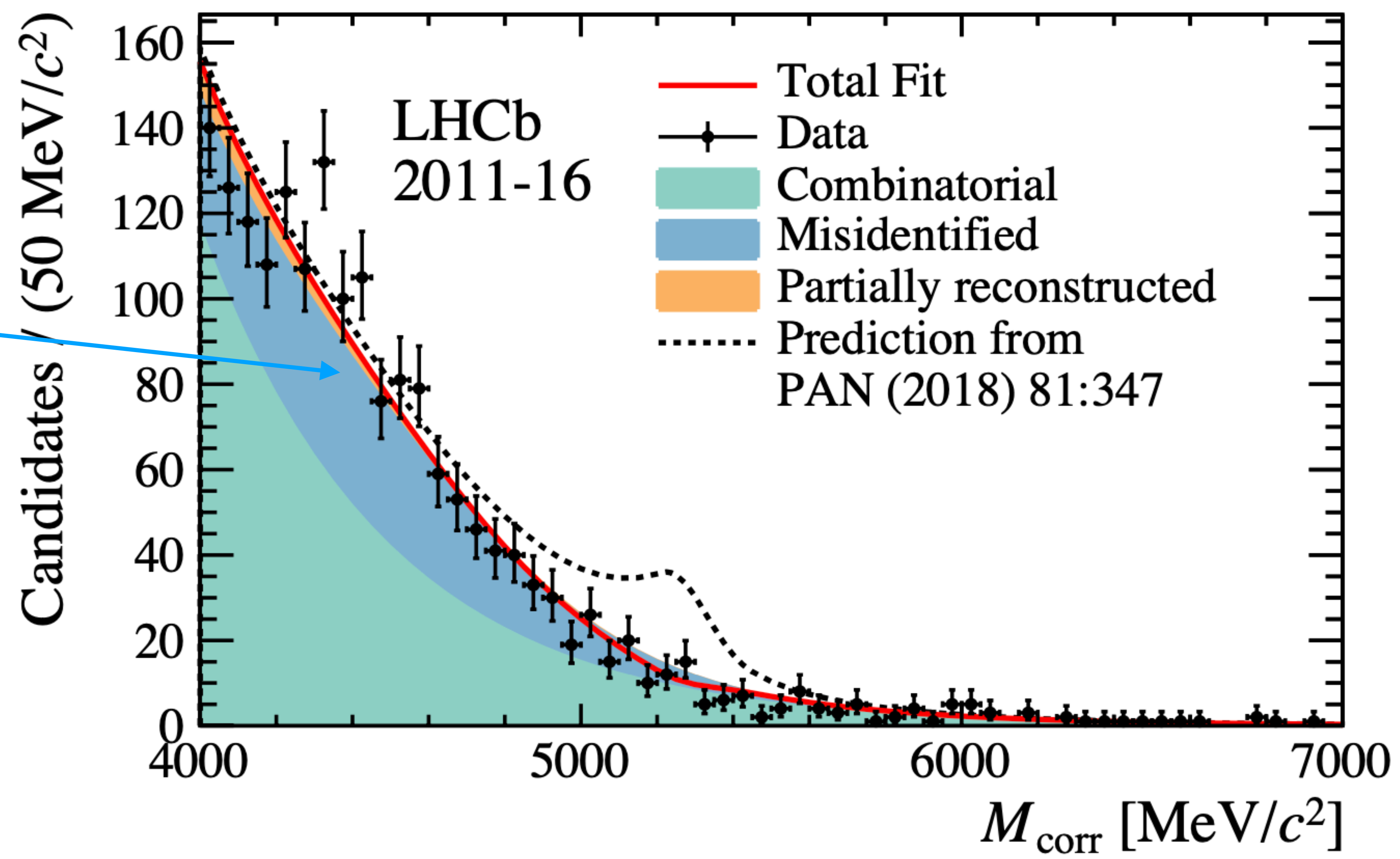
MVA-Gaussian

Data-driven estimate of a particular background:

- Fit to “sideband” data and then propagate the result of the fit together with the correlation to the main fit
- Using multivariate gaussian constraints to input or preserve the correlation of this systematics

Misidentified background

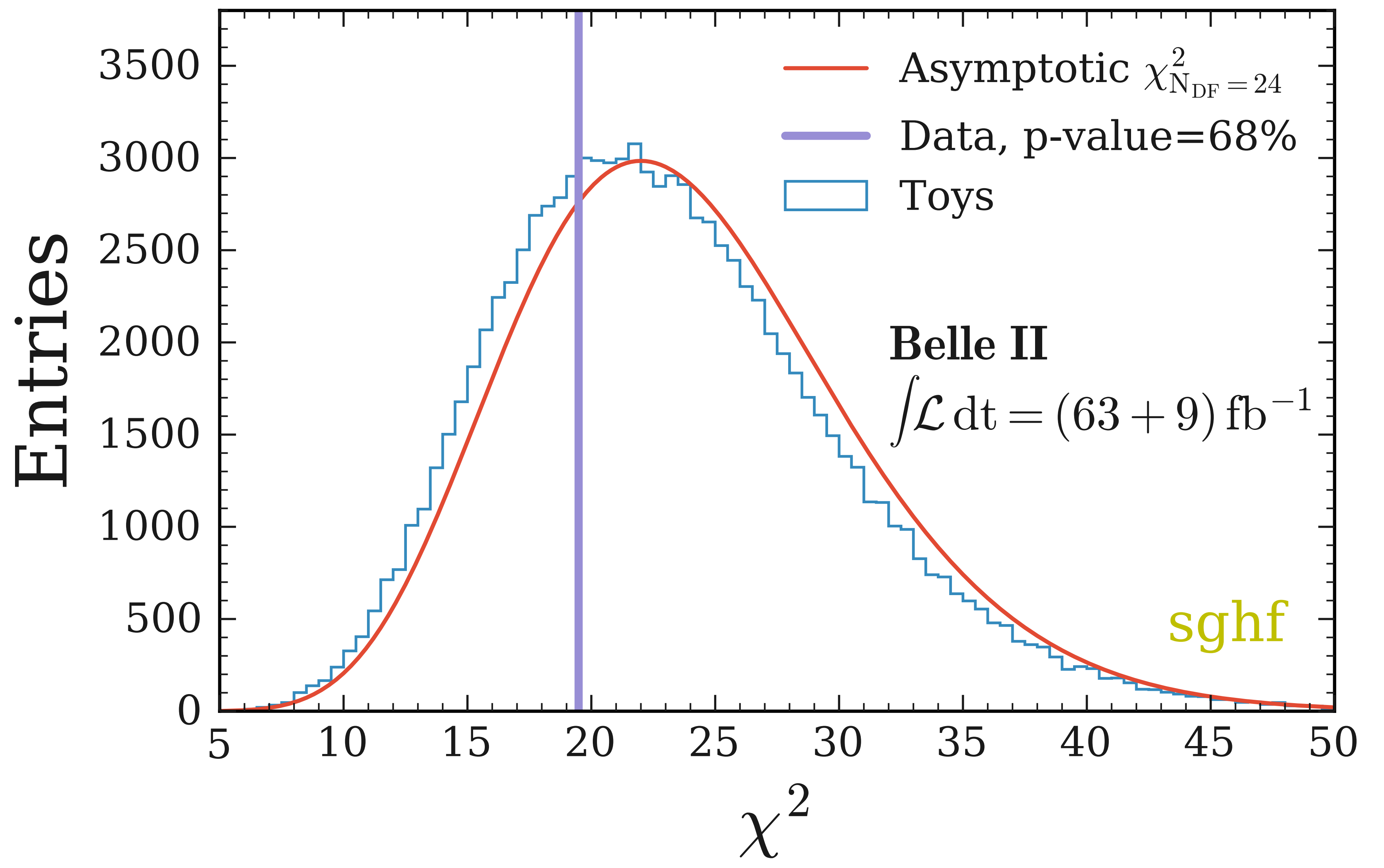


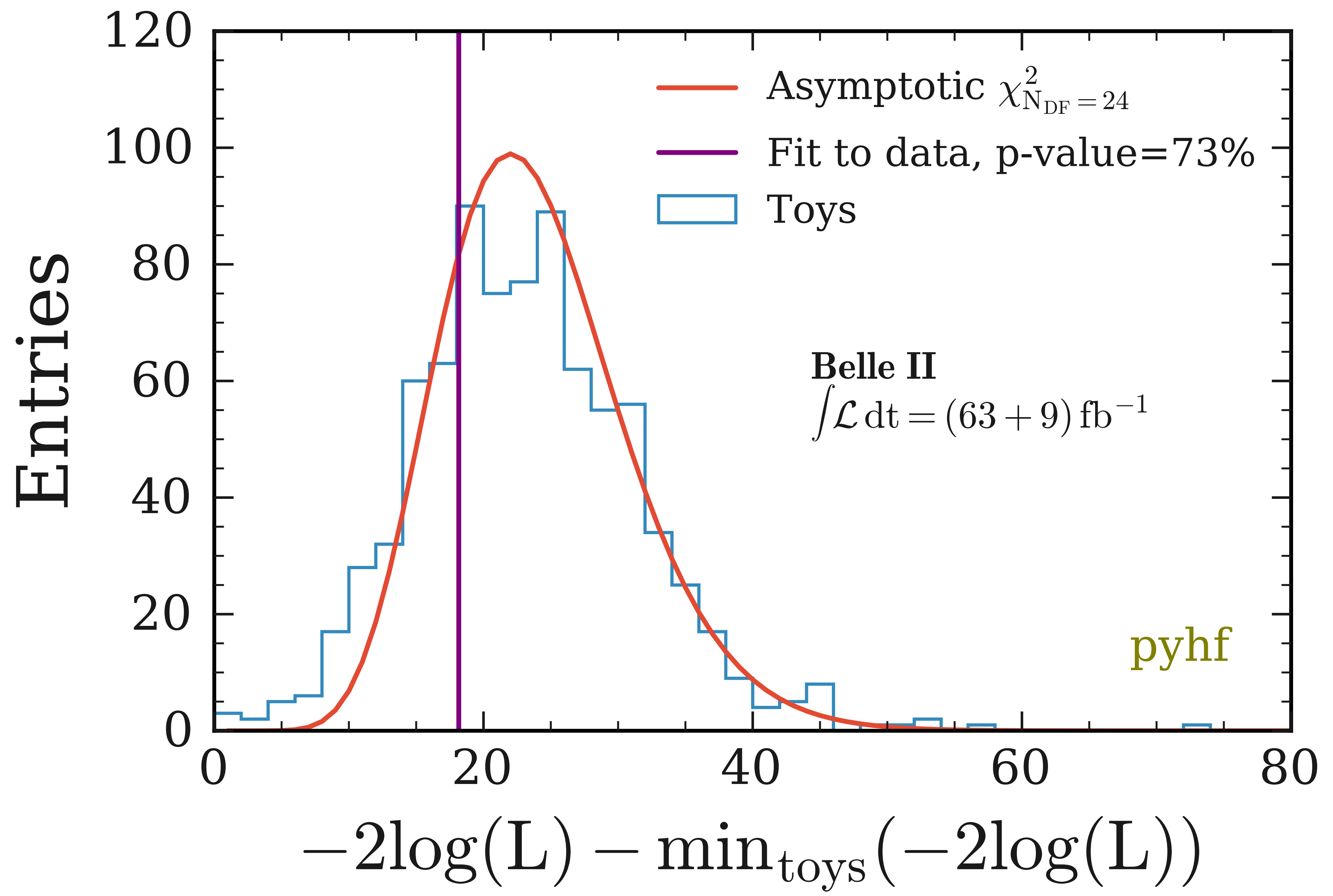


Data-model compatibility

Using toy-based method:

- The toys are generated using observed data counts based on Poisson statistics
- In order to avoid double counting of the fluctuations, the observed counts are subtracted from each toy and the expectation is added instead
- This way the toys are centered around the Asimov dataset which by construction has no fluctuations





Statistical modelling challenges in rare decays

Rare-decay searches/measurements

The main goal is to suppress the background as much as possible

- Low-statistics samples → trade-off between smoothness and fit stability
- Asymptotic conditions may not be necessarily satisfied

Control samples are not so easy to get by!

- Inflates the nuisances (if it does not make them basically unconstrained)

Rare signal decays can have as background decays that are also rare:

- Signal rare decays may have backgrounds that have never been measured and are not modelled

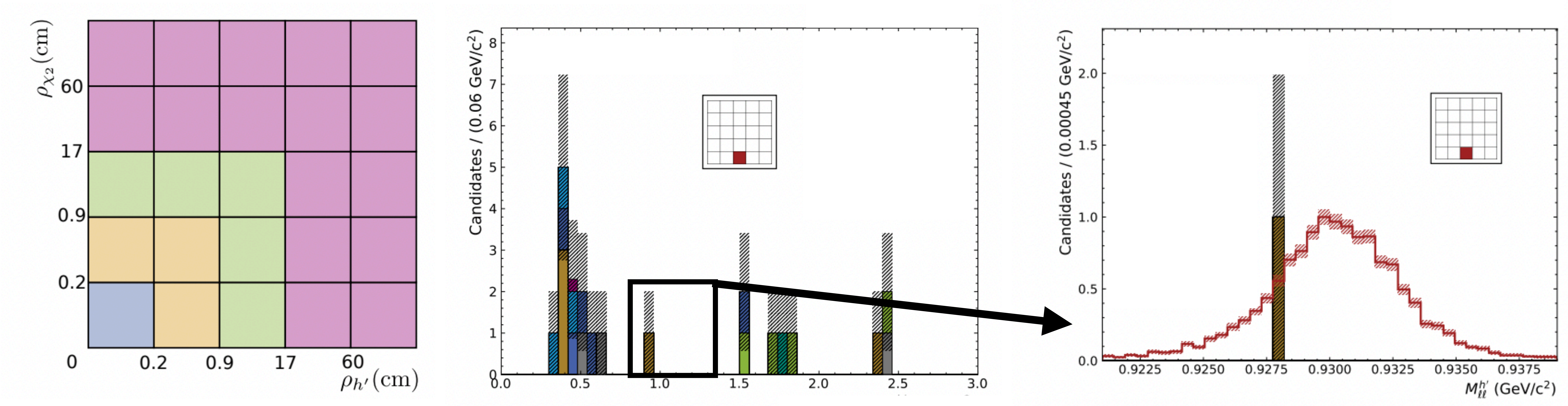
Calibration channels may not be necessarily very large

- (Not ultra rare decays) MC statistical error becomes prominent

Aside: DM searches

The main goal is to suppress the background as much as possible

- Very low-statistics samples → trade-off between smoothness and stability
- Asymptotic conditions may not be necessarily satisfied
- **If signal resolution very narrow sensitive to left-over events**



Conclusion

In this presentation I have summarised the

- Statistical modelling of for rare B-decay searches
- Shown examples of systematic uncertainties that are treated as nuisances
- Show examples of how correlated systematic are computed and propagated into the model
- Highlighted few problems with statistical modelling and propagation of nuisances relevant for rare decay searches and DM

Thank you!

Back-up

Systematic Uncertainties

Reconstruction	B+ -> K+ nu \bar{nu} (Belle II)	B+ ->mu+ mu- mu+ nu (LHCb)	
		Trigger efficiency	
	Tracking efficiency	Tracking effciency	

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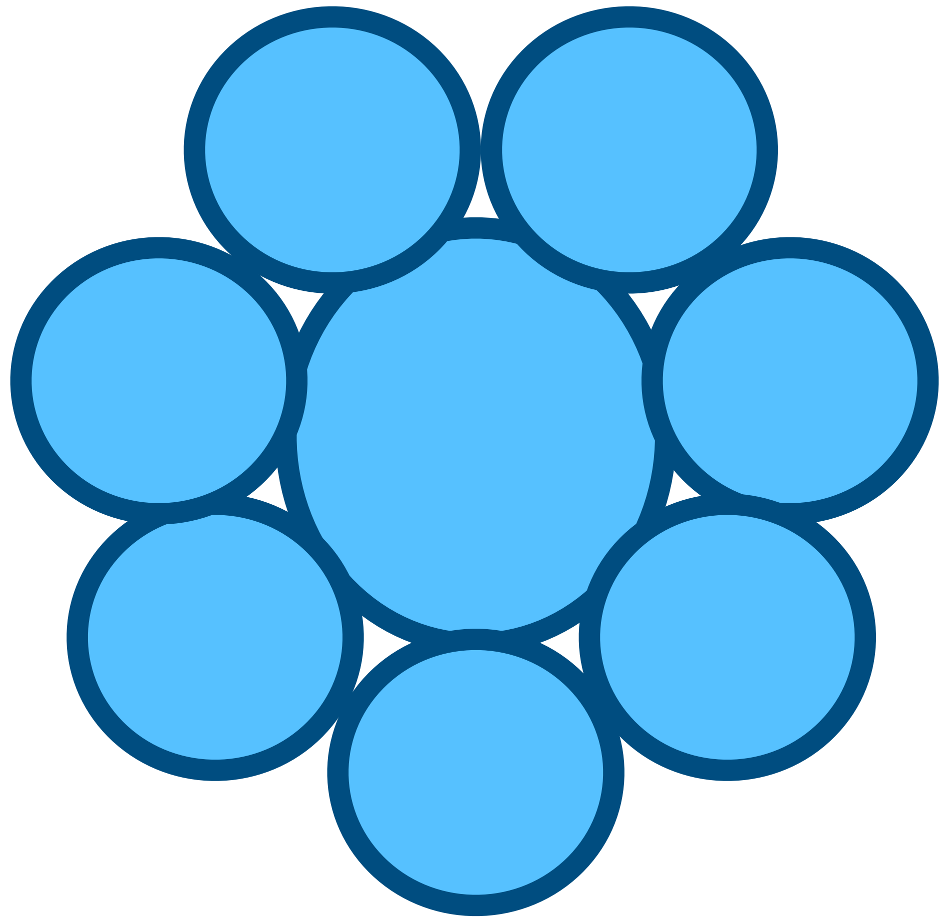
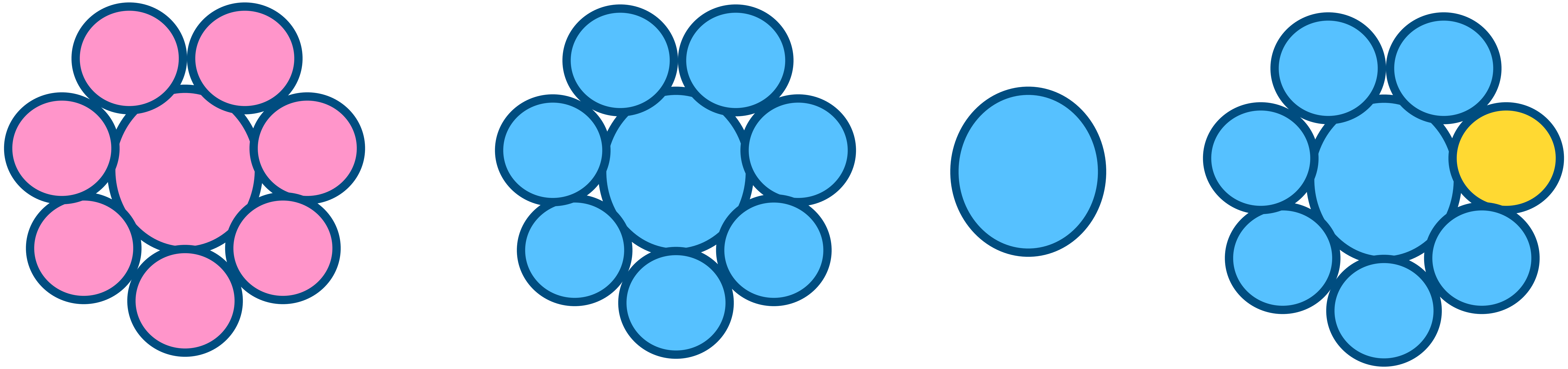
Systematic Uncertainties

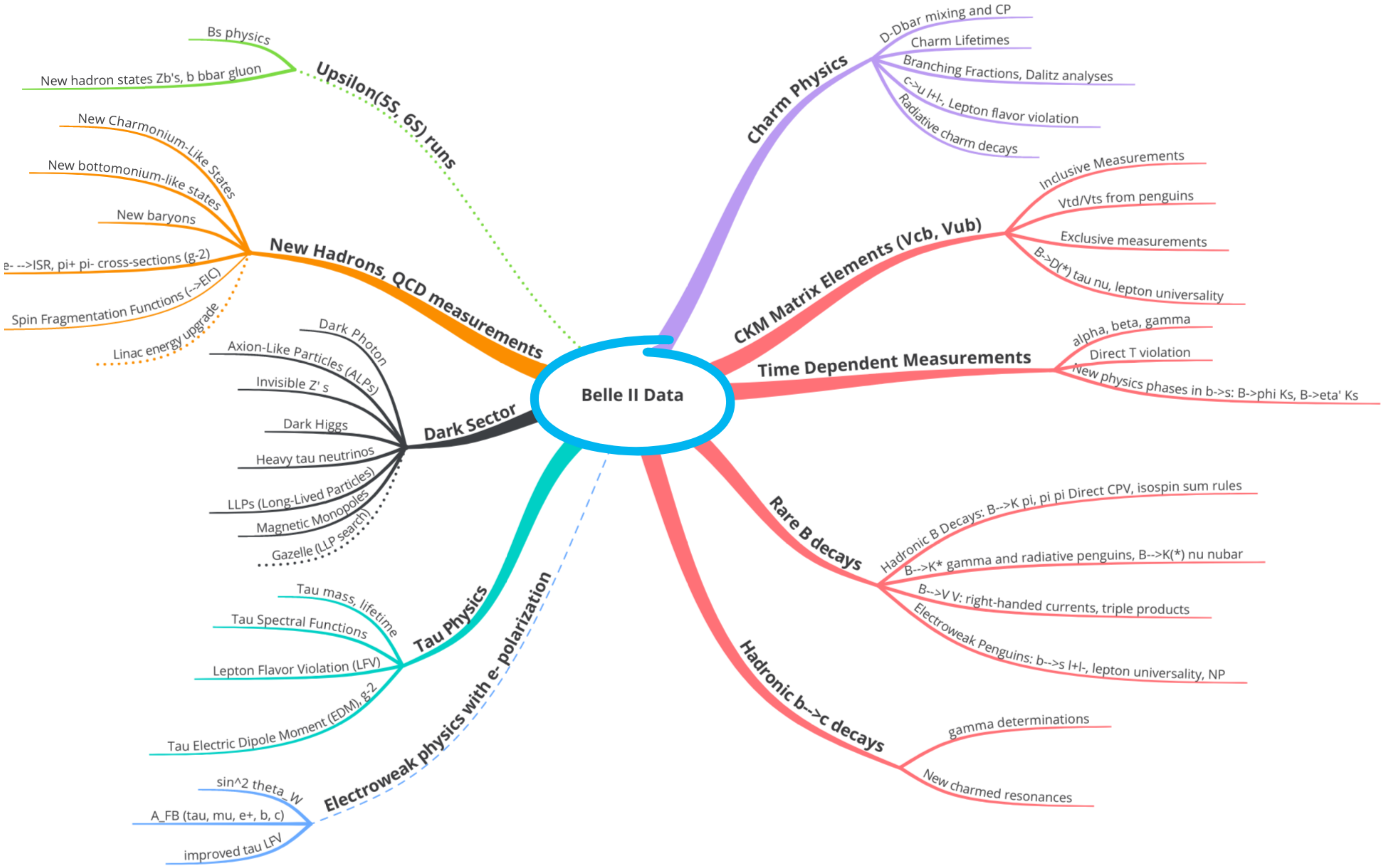
Further Analysis	B+ -> K+ nu \bar{nu} (Belle II)	B+ ->mu+ mu- mu+ nu (LHCb)	
		Trigger efficiency	
	Tracking efficiency	Tracking effciency	

When do we integrate systematics?

- When we know something in our analysis chain is maybe incorrect impacting on the measurement:
  1. Wrong → we apply corrections (known as calibrations)
  2. Uncertain → we do cross-checks:
     1. If passed with no major impact on the measurement → no action
     2. If major impact on the measurement → analysis is not robust
     3. If minor impact → **systematics and nuisance parameters**







Belle II Data
Upsilon(5S, 6S) runs
Bs physics
New hadron states Zb's, b bbar gluon
New Hadrons, QCD measurements
New Charmonium-Like States
New bottomonium-like states
New baryons
e- -->ISR, pi+ pi- cross-sections (g-2)
Spin Fragmentation Functions (-->EIC)
Linac energy upgrade
Dark Sector
Dark Photon
Axion-Like Particles (ALPs)
Invisible Z' s
Dark Higgs
Heavy tau neutrinos
LLPs (Long-Lived Particles)
Magnetic Monopoles
Gazelle (LLP search)
Tau Physics
Tau mass, lifetime
Tau Spectral Functions
Lepton Flavor Violation (LFV)
Tau Electric Dipole Moment (EDM), g-2
Electroweak physics with e- polarization
sin^2 theta_W
A_FB (tau, mu, e+, b, c)
improved tau LFV
Charm Physics
D-Dbar mixing and CP
Charm Lifetimes
Branching Fractions, Dalitz analyses
C-->u l+l-, Lepton flavor violation
Radiative charm decays
CKM Matrix Elements (Vcb, Vub)
Inclusive Measurements
Vtd/Vts from penguins
Exclusive measurements
B->D(*) tau nu, lepton universality
Time Dependent Measurements
alpha, beta, gamma
Direct T violation
New physics phases in b->s: B->phi Ks, B->eta' Ks
Rare B decays
Hadronic B Decays: B-->K pi, pi pi Direct CPV, isospin sum rules
B-->K* gamma and radiative penguins, B-->K(*) nu nubar
B-->V V: right-handed currents, triple products
Electroweak Penguins: b-->s l+l-, lepton universality, NP
Hadronic b-->c decays
gamma determinations
New charmed resonances

HistFactory Template

Modifiers and Constraints

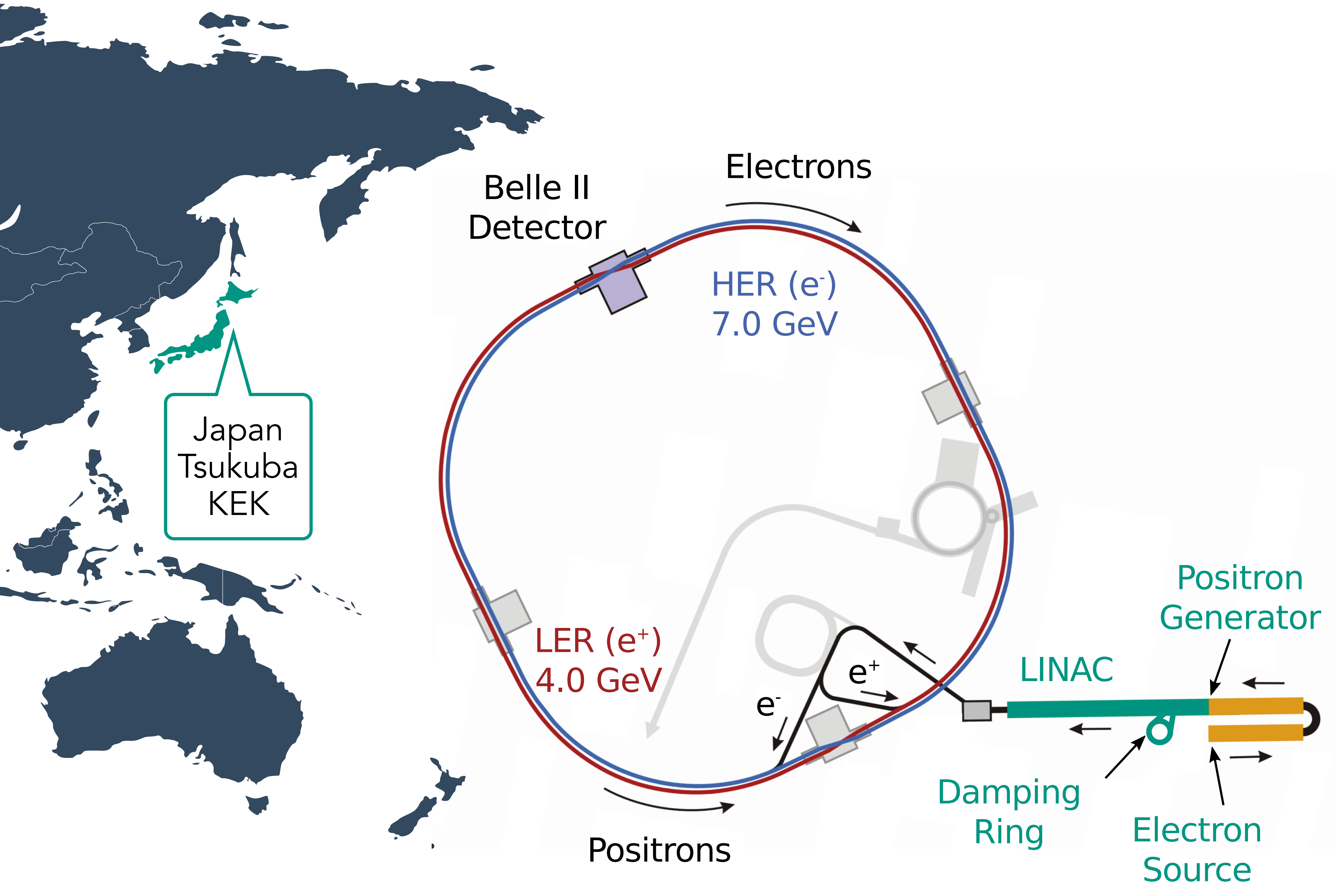
Description	Modification	Constraint Term c_χ	Input	Factor	"Data"
Uncorrelated Shape	$\kappa_{scb}(\gamma_b) = \gamma_b$	$\prod_b \mathrm{Pois}\left(r_b = \sigma_b^{-2} \middle\vert\, \rho_b = \sigma_b^{-2}\gamma_b\right)$	σ_b	Bin-wise	Per-bin
Correlated Shape	$\Delta_{scb}(\alpha) = f_p\left(\alpha \middle\vert\, \Delta_{scb,\alpha=-1}, \Delta_{scb,\alpha=1}\right)$	$\mathrm{Gaus}\left(a = 0 \middle\vert\, \alpha, \sigma = 1\right)$	$\Delta_{scb,\alpha=\pm 1}$	Global	Per-bin
Normalisation Unc.	$\kappa_{scb}(\alpha) = g_p\left(\alpha \middle\vert\, \kappa_{scb,\alpha=-1}, \kappa_{scb,\alpha=1}\right)$	$\mathrm{Gaus}\left(a = 0 \middle\vert\, \alpha, \sigma = 1\right)$	$\kappa_{scb,\alpha=\pm 1}$	Global	Per-sample
MC Stat. Uncertainty	$\kappa_{scb}(\gamma_b) = \gamma_b$	$\prod_b \mathrm{Gaus}\left(a_{\gamma_b} = 1 \middle\vert\, \gamma_b, \delta_b\right)$	$\delta_b^2 = \sum_s \delta_{sb}^2$	Bin-wise	Per-bin
Luminosity	$\kappa_{scb}(\lambda) = \lambda$	$\mathrm{Gaus}\left(l = \lambda_0 \middle\vert\, \lambda, \sigma_\lambda\right)$	$\lambda_0, \sigma_\lambda$	Global	Nothing
Normalisation	$\kappa_{scb}(\mu_b) = \mu_b$			Global	Nothing
Data-driven Shape	$\kappa_{scb}(\gamma_b) = \gamma_b$			Bin-wise	Nothing

- Correlated Shape: same source of uncertainty which has a different effect on the various sample shapes (e.g PID, tracking inefficiency, …)
- MC Stat. uncertainty: uncertainty due to the finite sample size of the datasets
- Luminosity especially useful if cross-section is to be measured

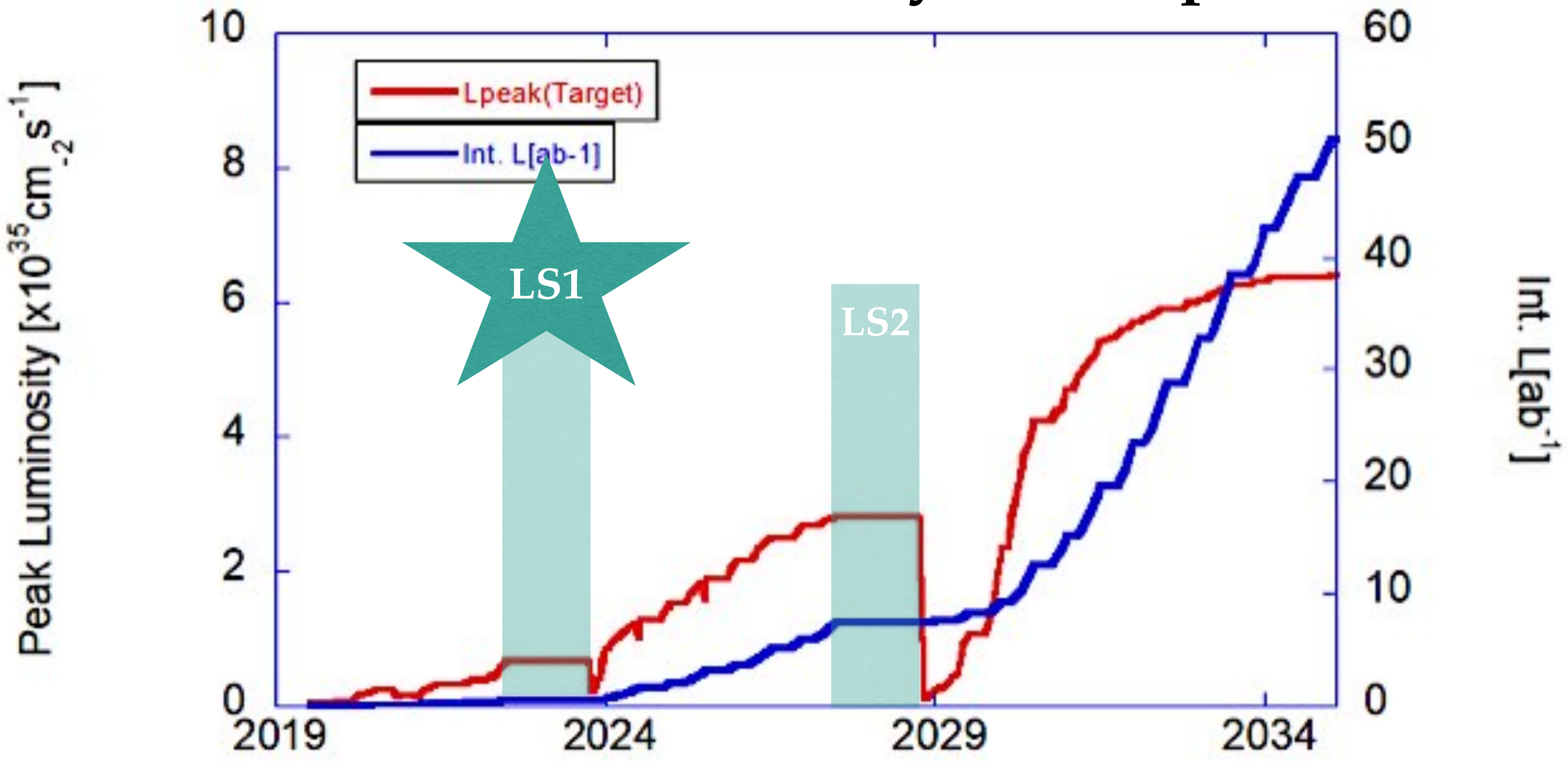
SuperKEKB

SuperKEKB operates nominally at $\sqrt{s}$ = 10.58 GeV

- $\Upsilon(4S) \to B\bar{B}$ in 96 %
- Currently 363 fb^{-1} ~ 390 mil. B-meson pairs
  - ~1/2 Belle, ~ BaBar
- Record-breaking $\mathscr{L}_{inst} = 4.7 \times 10^{34}\ cm^{-2}\, s^{-1}$



Belle II luminosity roadmap



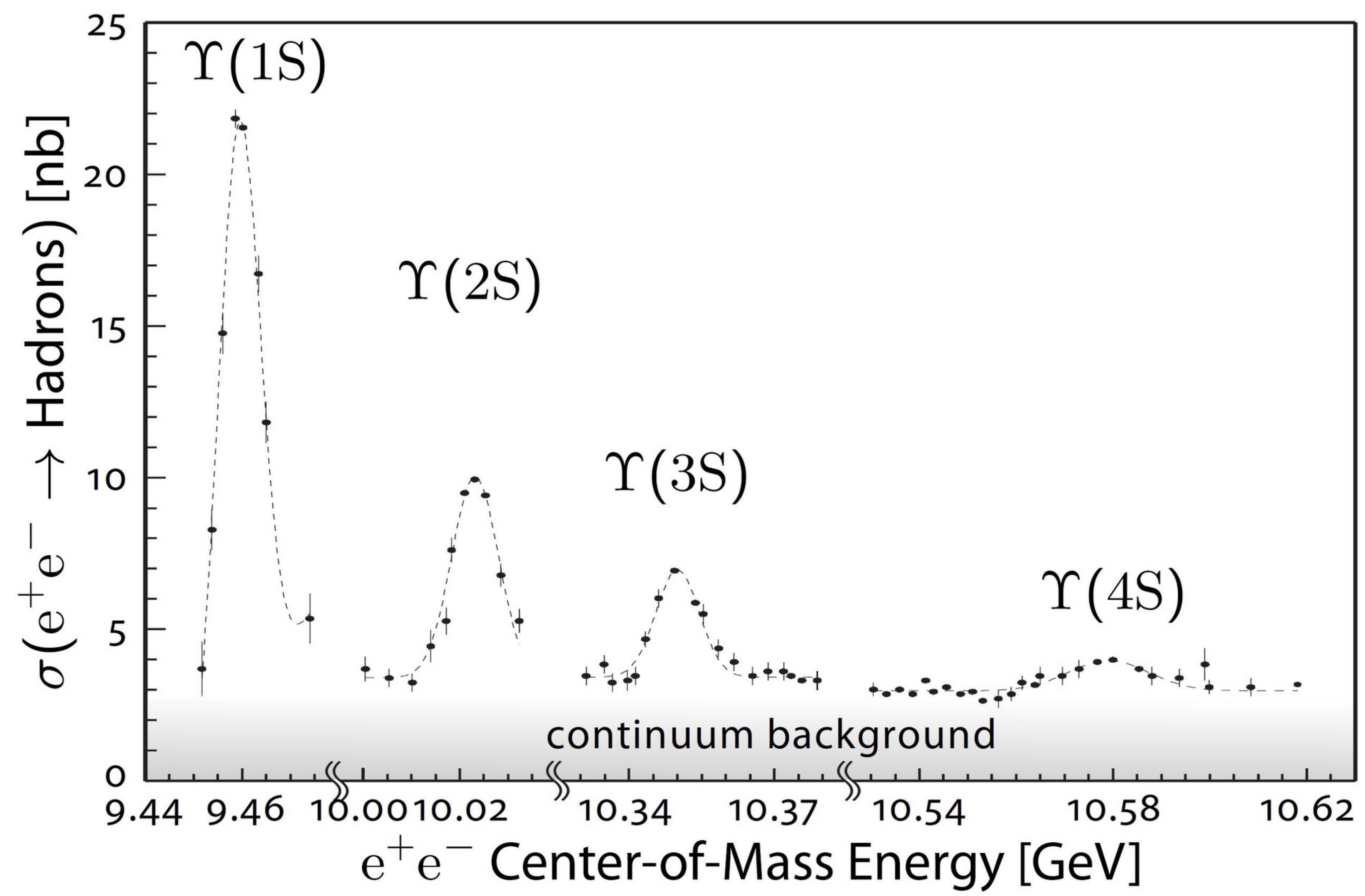
- Now in long shutdown **(LS1)** until this autumn
- **Final aim:** operate at **30 × higher $\mathscr{L}_{inst}$** than KEKB at a cost of **$\mathcal{O}$(10) × higher** backgrounds
- **Final luminosity goal: $\mathscr{L}_{int}$ = 50 ab^{-1}**

Backgrounds at e^+e^- Collider

Four types of backgrounds at e^+e^- colliders:

- **Continuum Backgrounds $e^+e^- \rightarrow q\bar{q}$, where $q \in (s, c, d, u)$ and $e^+e^- \rightarrow \tau\bar{\tau}$**
- ***B*-backgrounds**
  - **misidentified**
  - **mis-reconstructed**
  - **combinatorial**

Continuum backgrounds



$\sqrt{s} = 10.52$ GeV $\rightarrow$ control sample to constrain continuum backgrounds

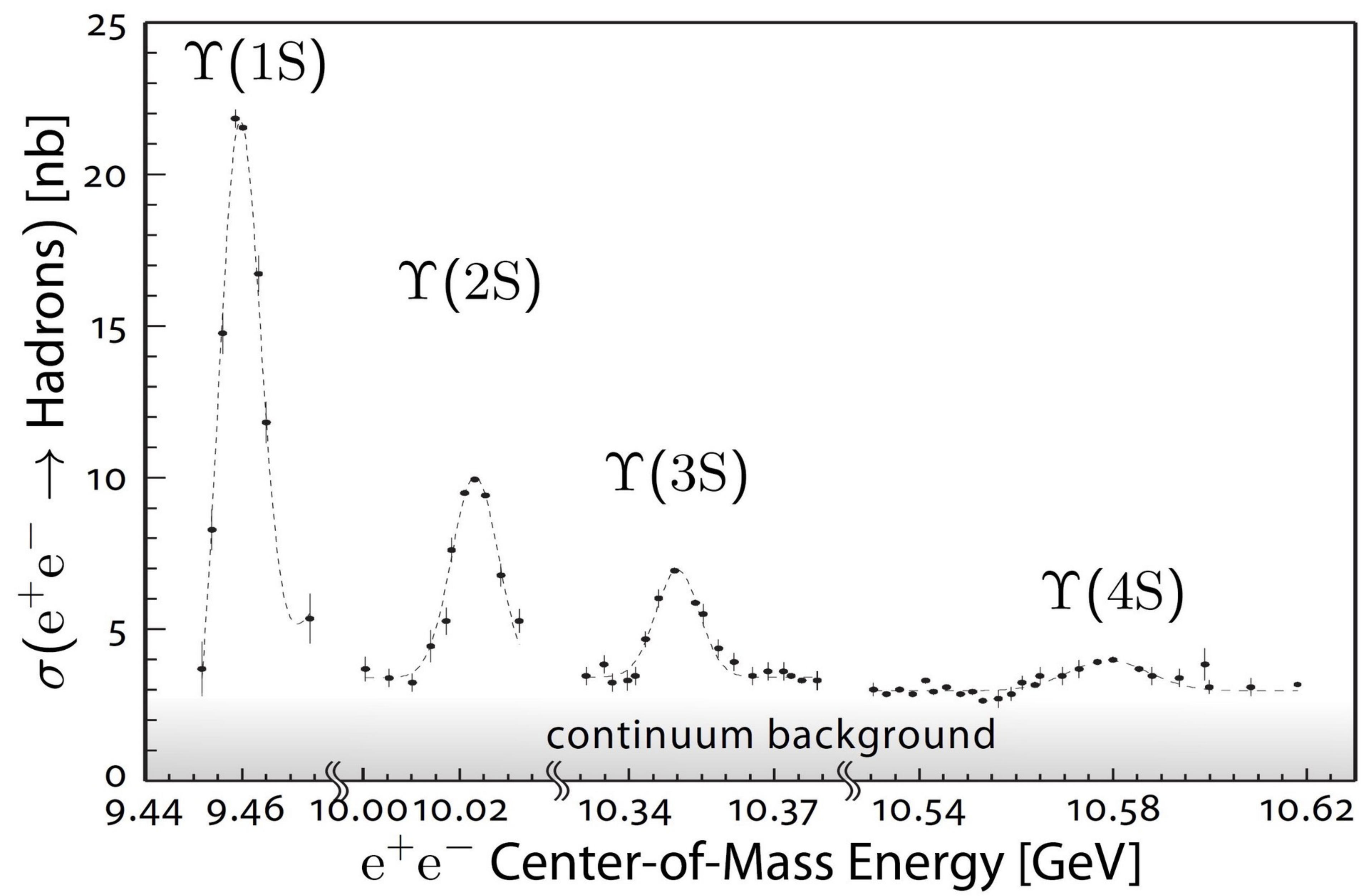
Backgrounds at e^+e^- Collider

Four types of backgrounds at e^+e^- colliders:

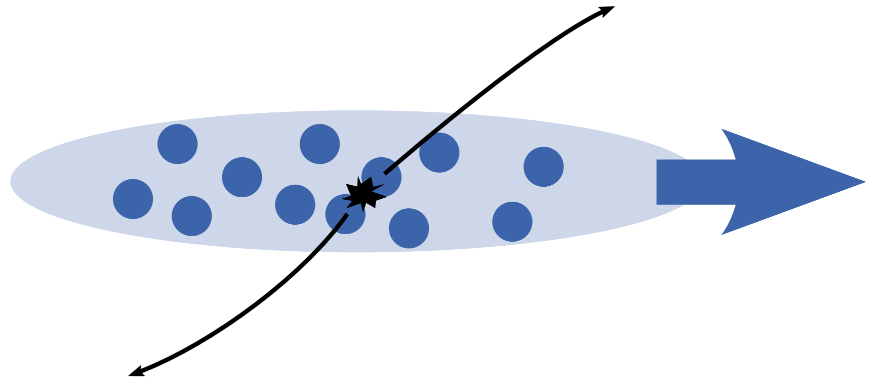
- **Continuum Backgrounds $e^+e^- \to q\bar{q}$, where $q \in (s, c, d, u)$ and $e^+e^- \to \tau\bar{\tau}$**
- ***B*-backgrounds**
  - **misidentified**
  - **mis-reconstructed**
  - **combinatorial**
- Beam-backgrounds:
  - Touschek scattering, Coulomb scattering, synchrotron radiation, injection background, …
- Luminosity Backgrounds:
  - $e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-e^+e^-$

Increase with $\mathscr{L}_{inst}$ (↑)

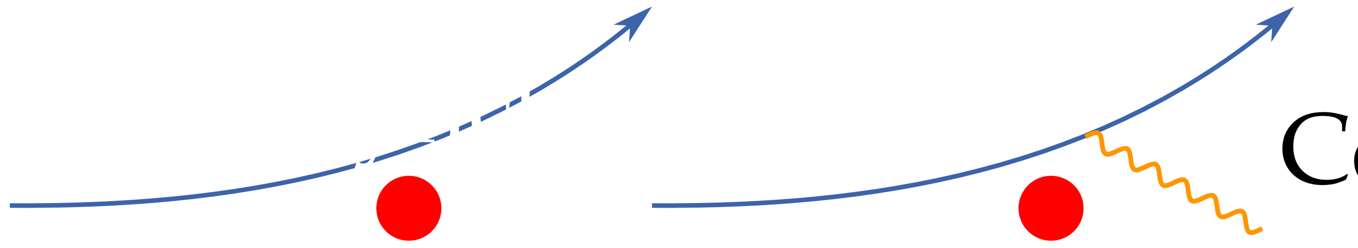
Continuum backgrounds



$\sqrt{s} = 10.52$ GeV → control sample to constrain continuum backgrounds

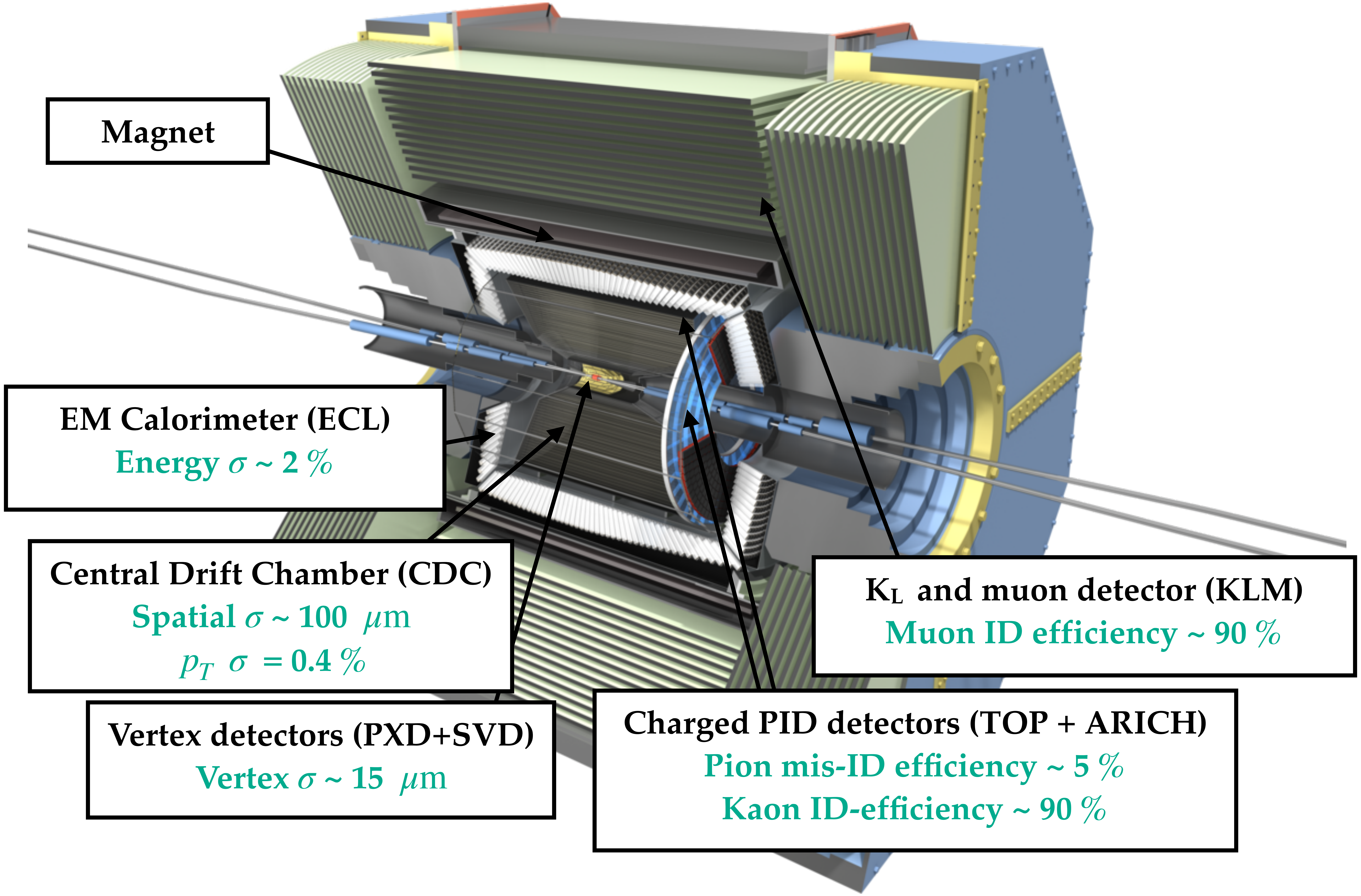


Touschek scattering



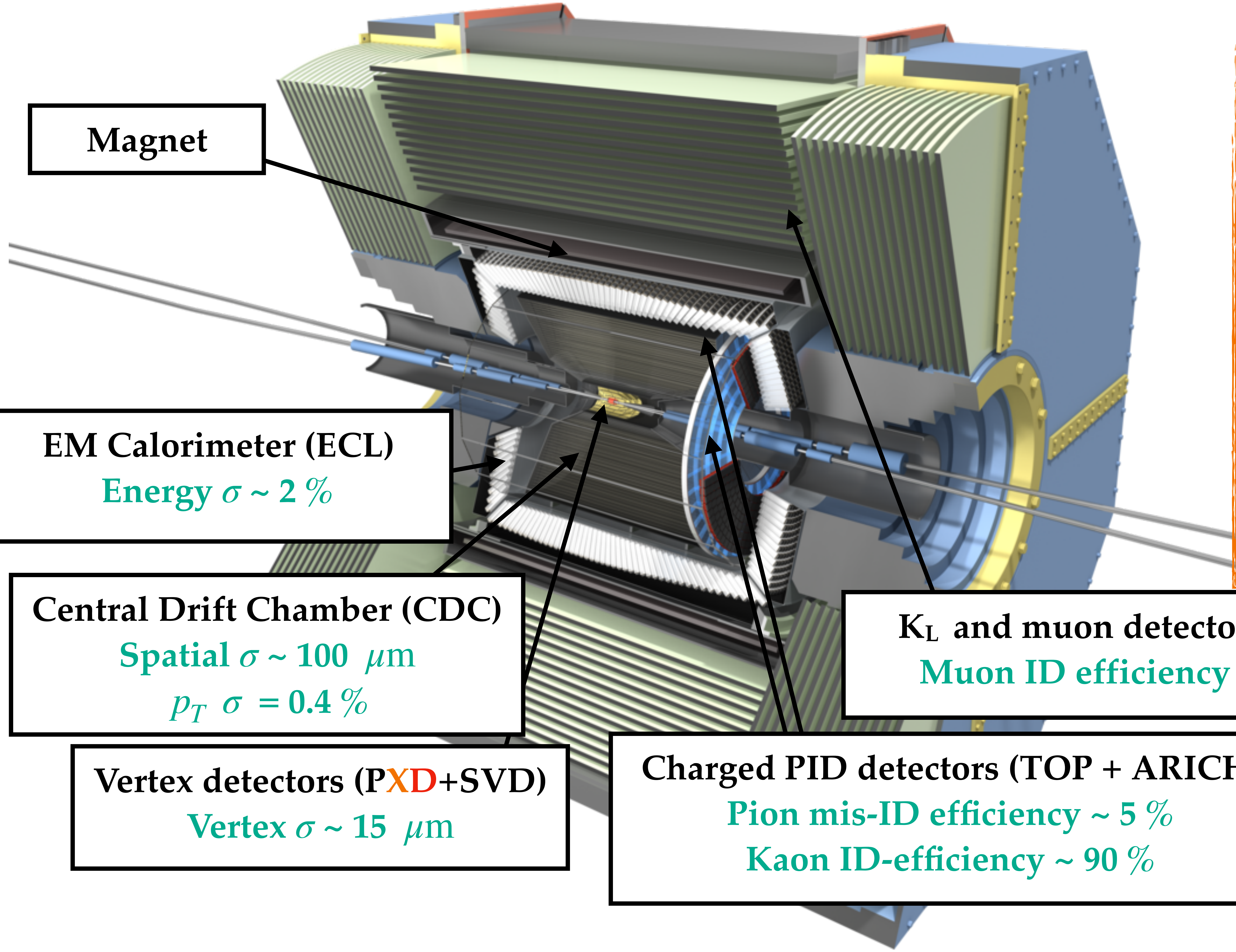
Coulomb scattering

Belle II Detector



Belle II Detector

New PXD arrived safely to KEK!



Magnet

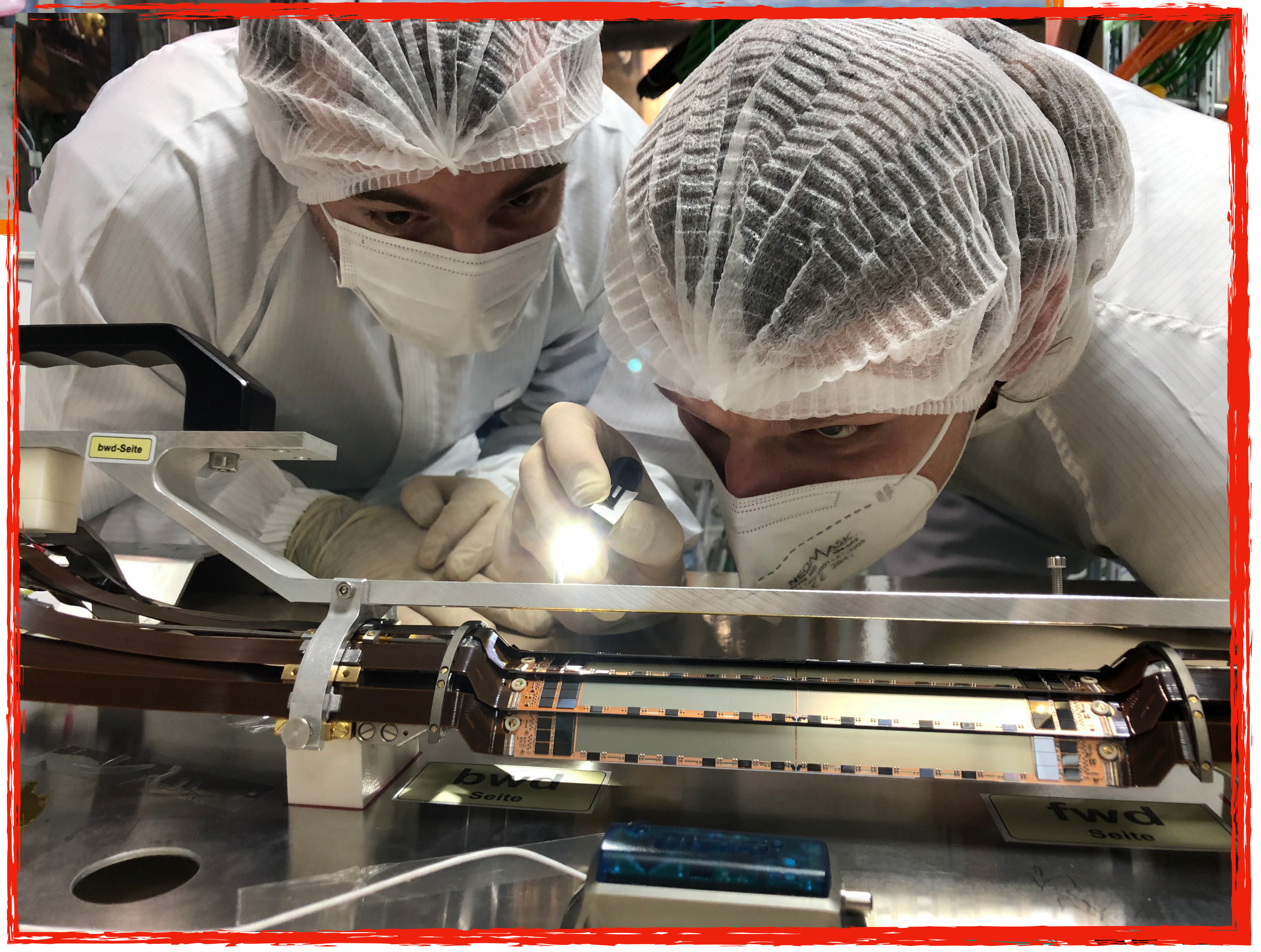
EM Calorimeter (ECL)
Energy $\sigma \sim 2\,\%$

Central Drift Chamber (CDC)
Spatial $\sigma \sim 100\ \mu m$
$p_T\ \sigma = 0.4\,\%$

Vertex detectors (PXD+SVD)
Vertex $\sigma \sim 15\ \mu m$

Charged PID detectors (TOP + ARICH)
Pion mis-ID efficiency ~ 5 %
Kaon ID-efficiency ~ 90 %

K_L and muon detector (KLM)
Muon ID efficiency ~ 90 %



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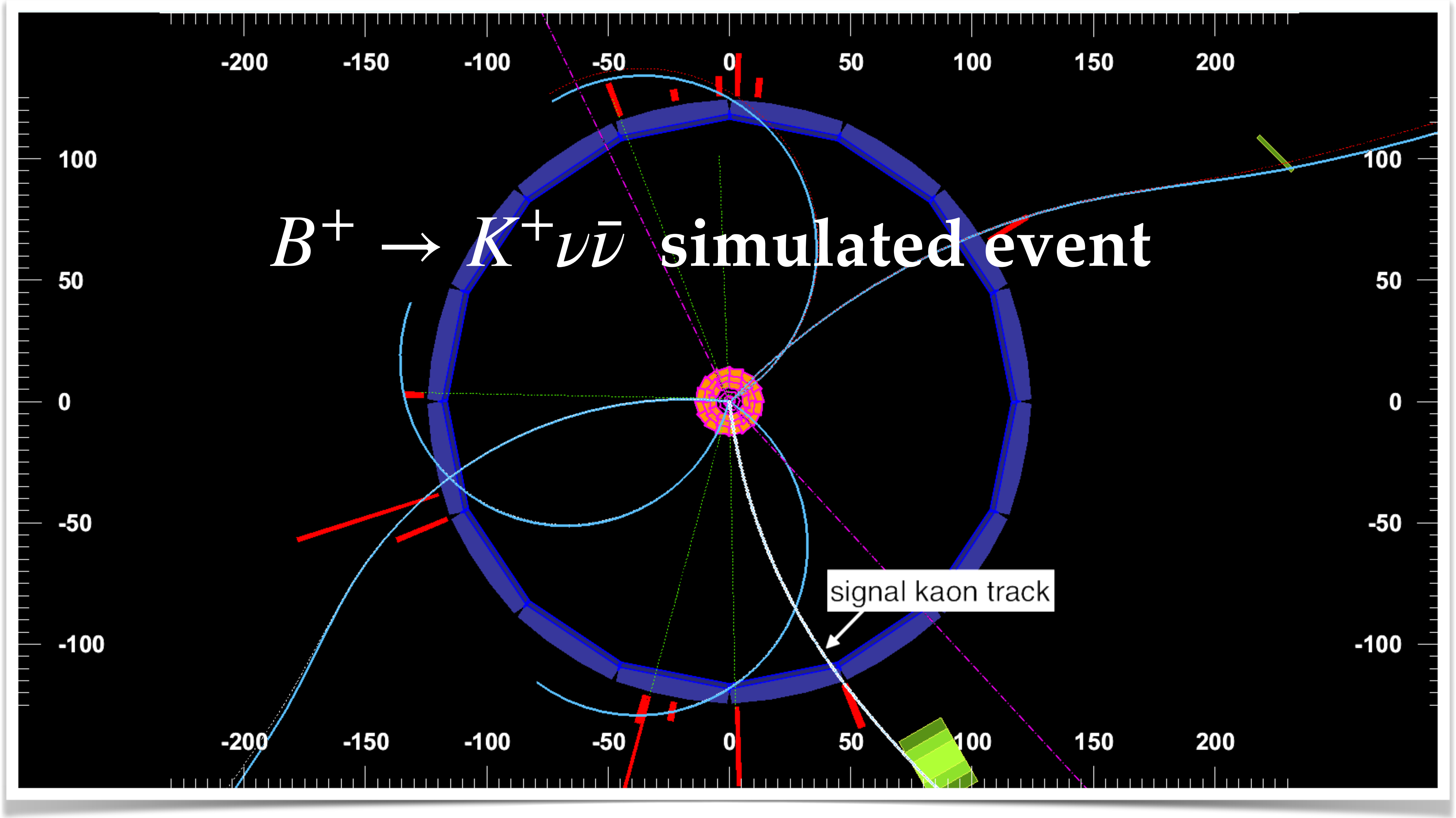
$B \to K^{(*)}\nu\bar{\nu}$ Event in Belle II

Belle II is best-suited to measure B-decays with significant missing energy

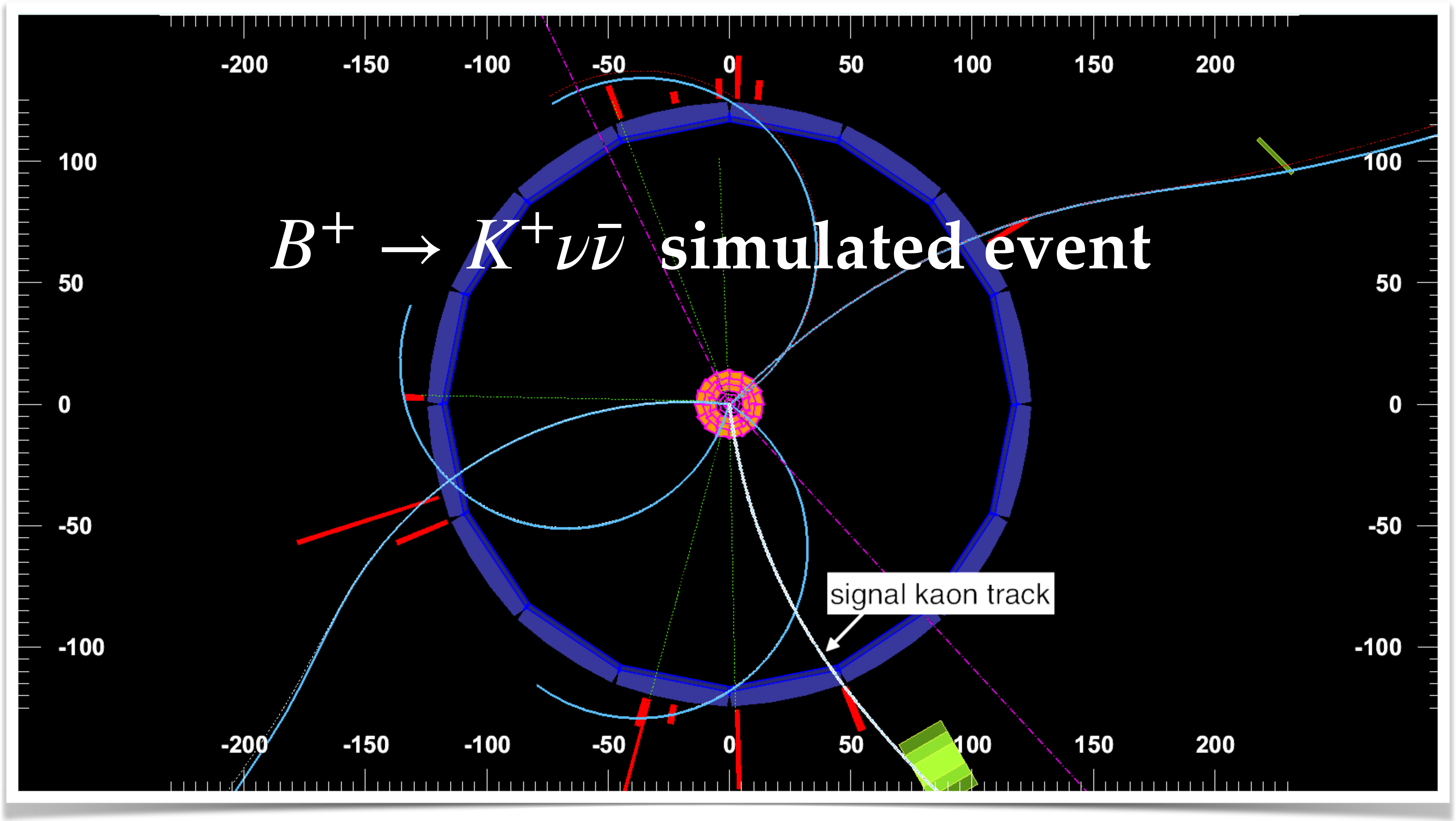


Typical $B \to K^{(*)}\nu\bar{\nu}$ event benefits from

- Detector with nearly full 4π coverage with excellent sensitivity to low deposits
- Cleaner environment compared to LHCb
- Constraints from well-known initial state kinematics

$B \to K^{(*)}\nu\bar{\nu}$ Event in Belle II

Belle II is best-suited to measure B-decays with significant missing energy



Typical $B \to K^{(*)}\nu\bar{\nu}$ event benefits from

- Detector with nearly full 4π coverage with excellent sensitivity to low deposits
- Cleaner environment compared to LHCb
- Constraints from well-known initial state kinematics

Challenges of rare B-decays

- High reconstruction efficiency for visible particles
- Excellent MC modelling

+

Challenges of channels with neutrinos

- Excellent understanding of the neutral objects (π^0, K_L^0, K_s^0, n, $\gamma, \ldots$)

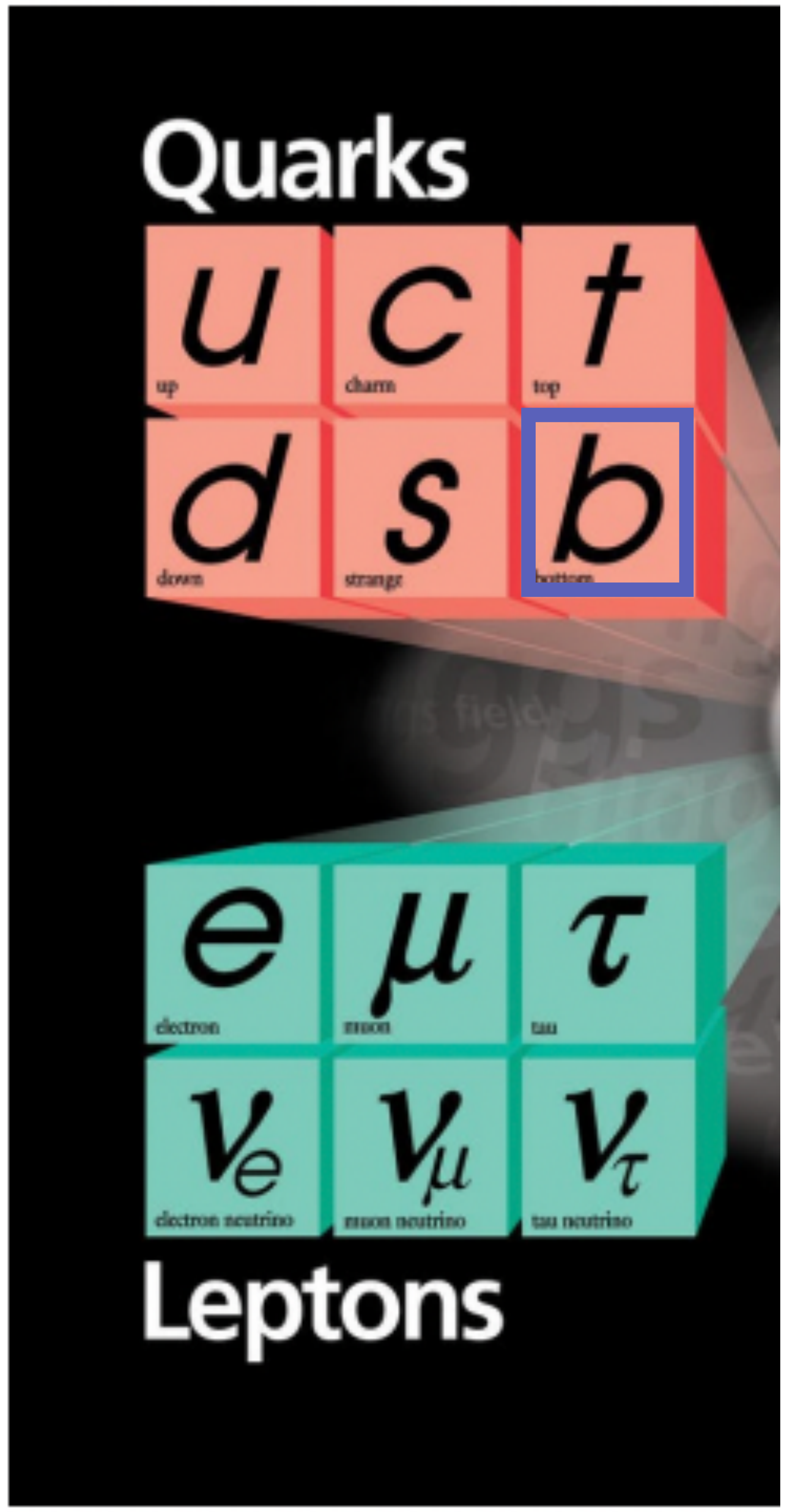
Why Flavour Physics?

- Quarks, leptons and interactions within the SM are the main protagonists of flavour physics

- *B*-decays are especially good probes since
  - *B*-hadrons are light enough to be produced abundantly and heavy enough to have many decays
  - Predictions for SM observables are well-known

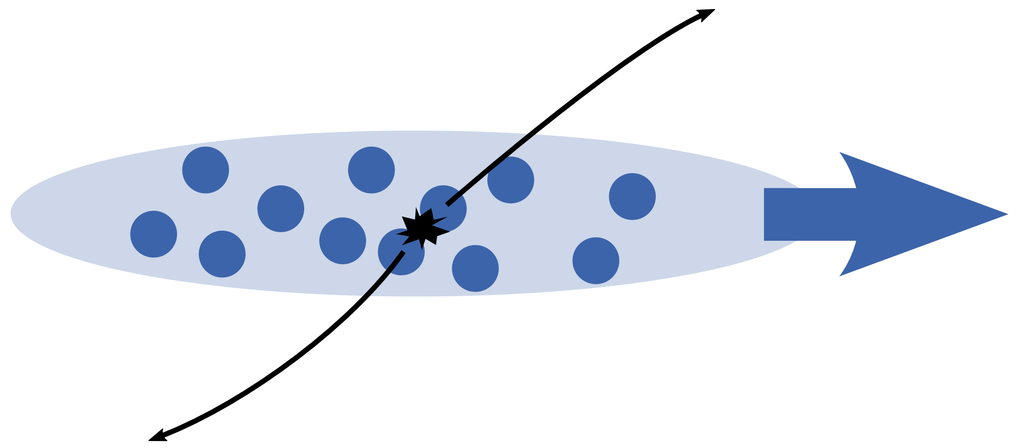
- With *B*-decays we perform
  - Precision measurements of CP violation
  - (In-)direct searches for NP in rare decays

Focus of this talk

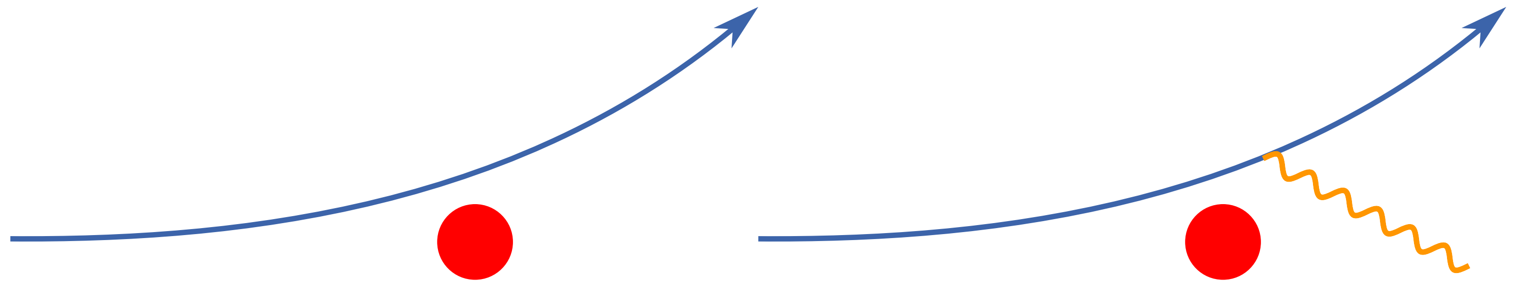


Beam-backgrounds

Single-beam backgrounds:



- **Touschek scattering** $\rightarrow$ scattering of particles within a bunch $\rightarrow$ **Touschek rate** $\propto N_{particles} \times \rho \rightarrow \mathbf{I} \times \frac{\mathbf{I}}{\sigma_{\mathbf{y}} \mathbf{n_b}}$
- **beam-gas scattering** $\rightarrow$ Coulomb scattering and Bremsstrahlung (scattering off gas molecules) $\rightarrow$ **Beam-gas rate** $\propto N_{gas\ molecules} \times N_{particles} \rightarrow \mathbf{P} \times \mathbf{I} \times \mathbf{Z_{eff}^2}$



- **synchrotron radiation background** $\rightarrow$ consequence of a radial acceleration of the beam's particles achieved in bending magnets and quadrupoles
- **injection background** $\rightarrow$ continuous injection of charge into beam bunch modifying the beam bunch

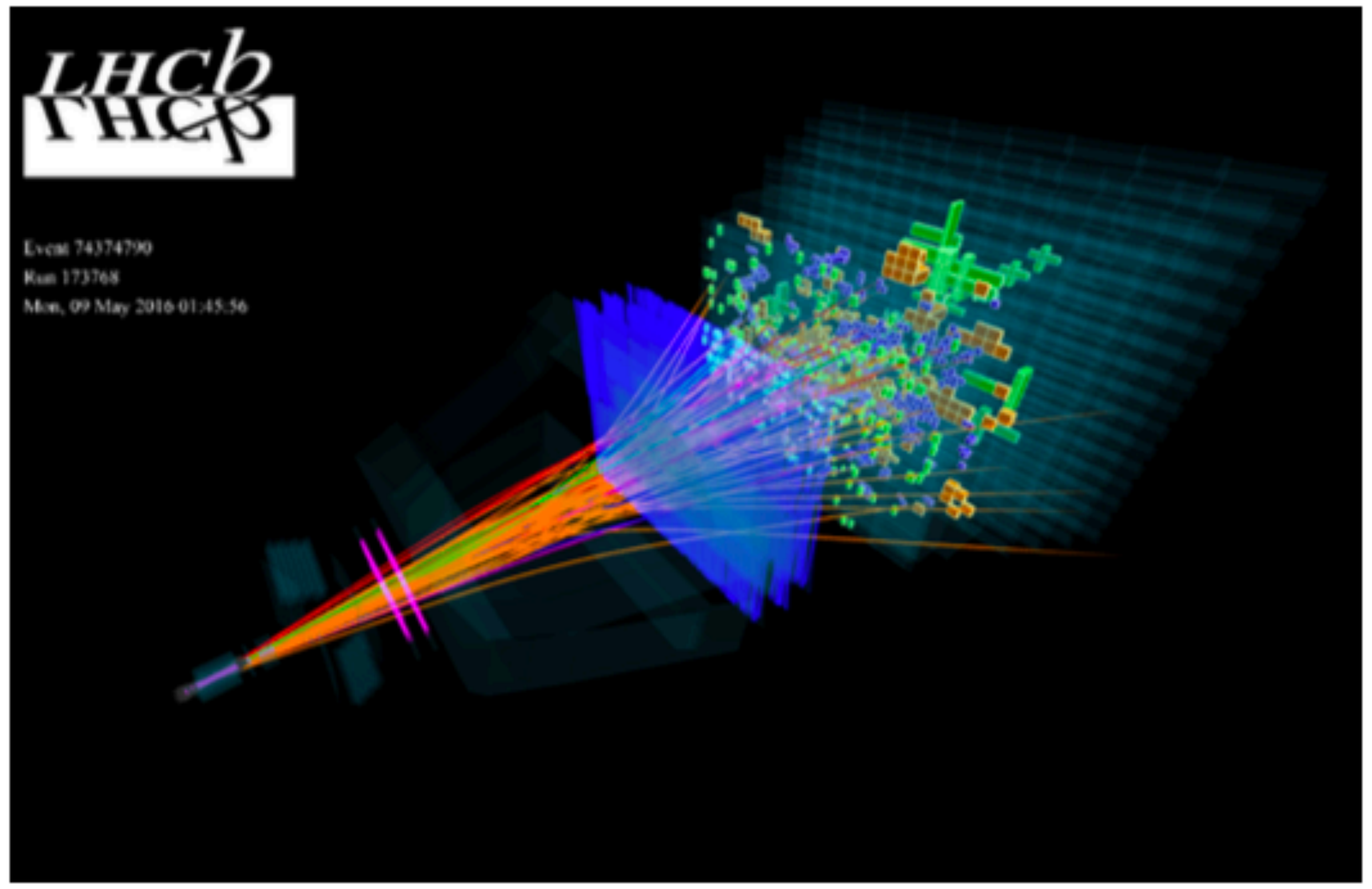
Single-beam backgrounds can be mitigated with beam-steering, collimators, and vacuum-scrubbing

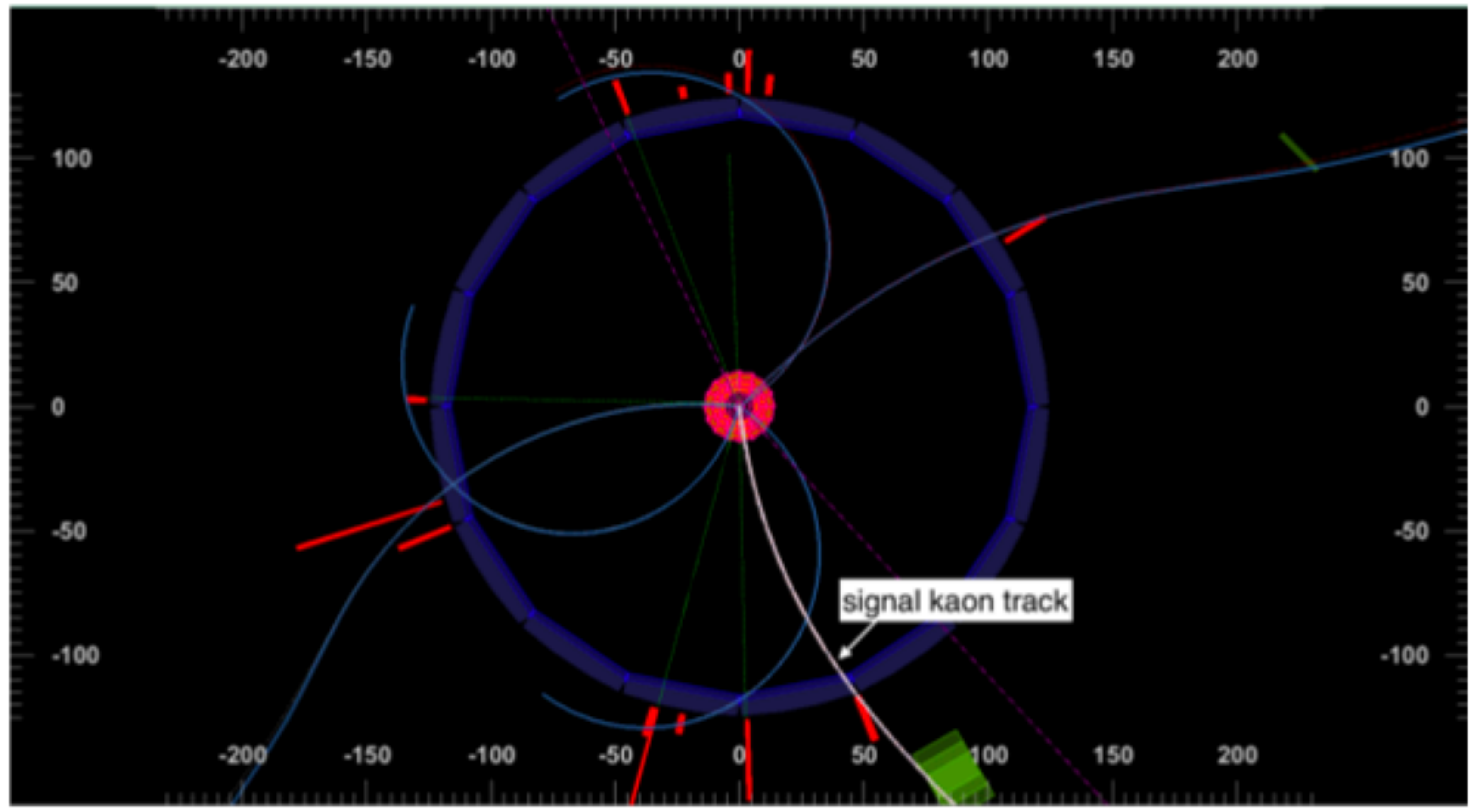
Luminosity backgrounds:

- **two-photon background** $\rightarrow$ leading luminosity background ($e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^-e^+e^-$), unlike any of the backgrounds above cannot be reduced!

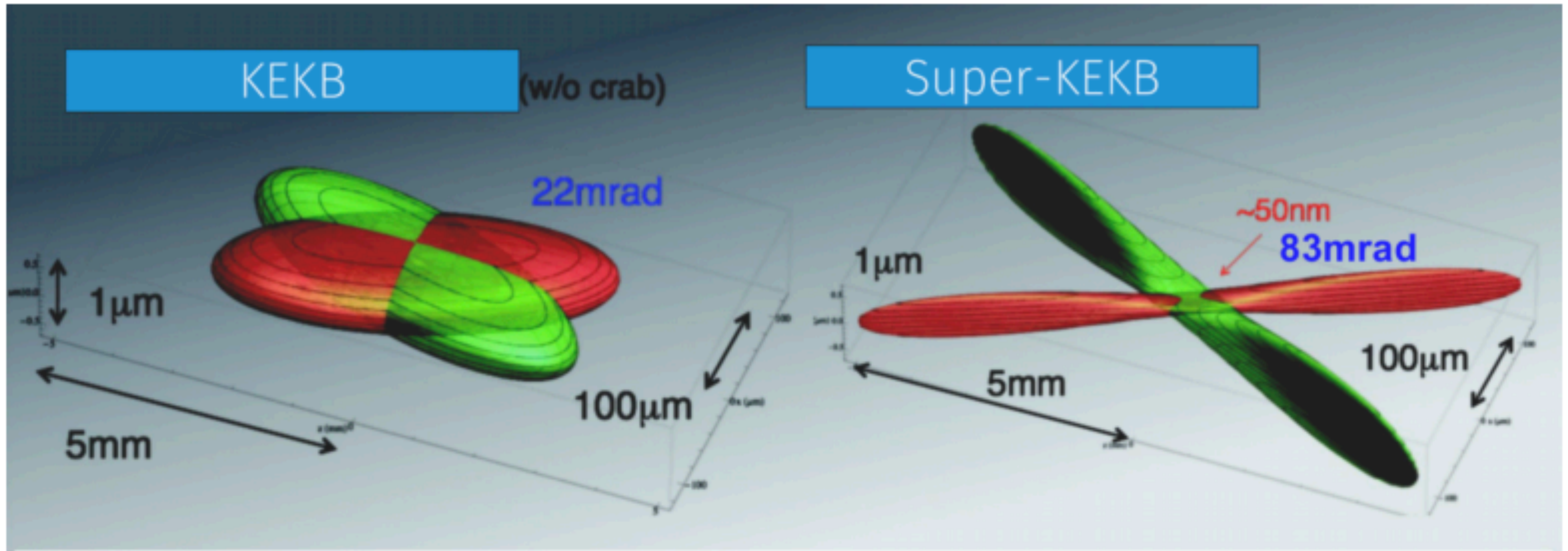
Belle II vs LHCb

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)





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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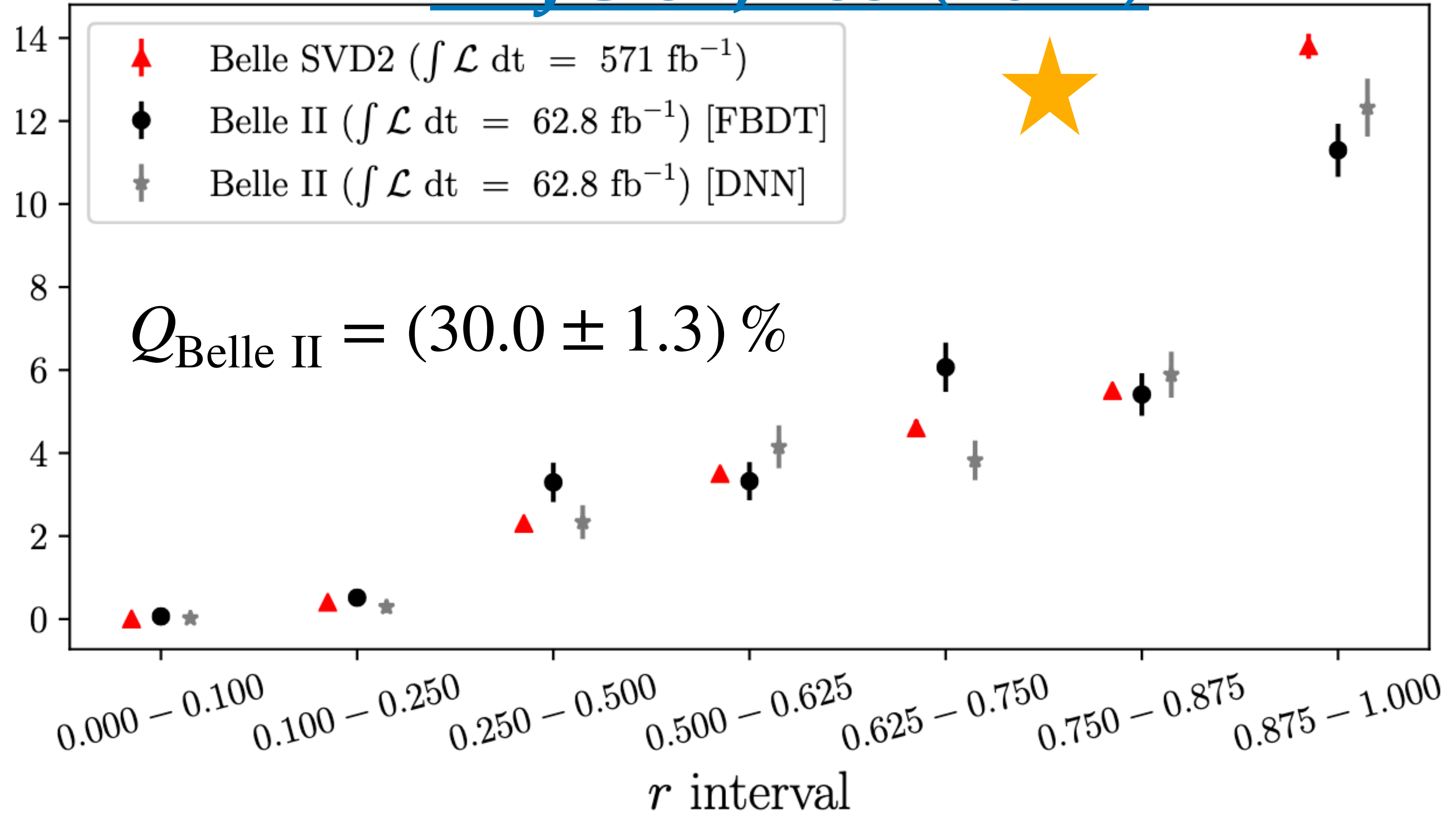
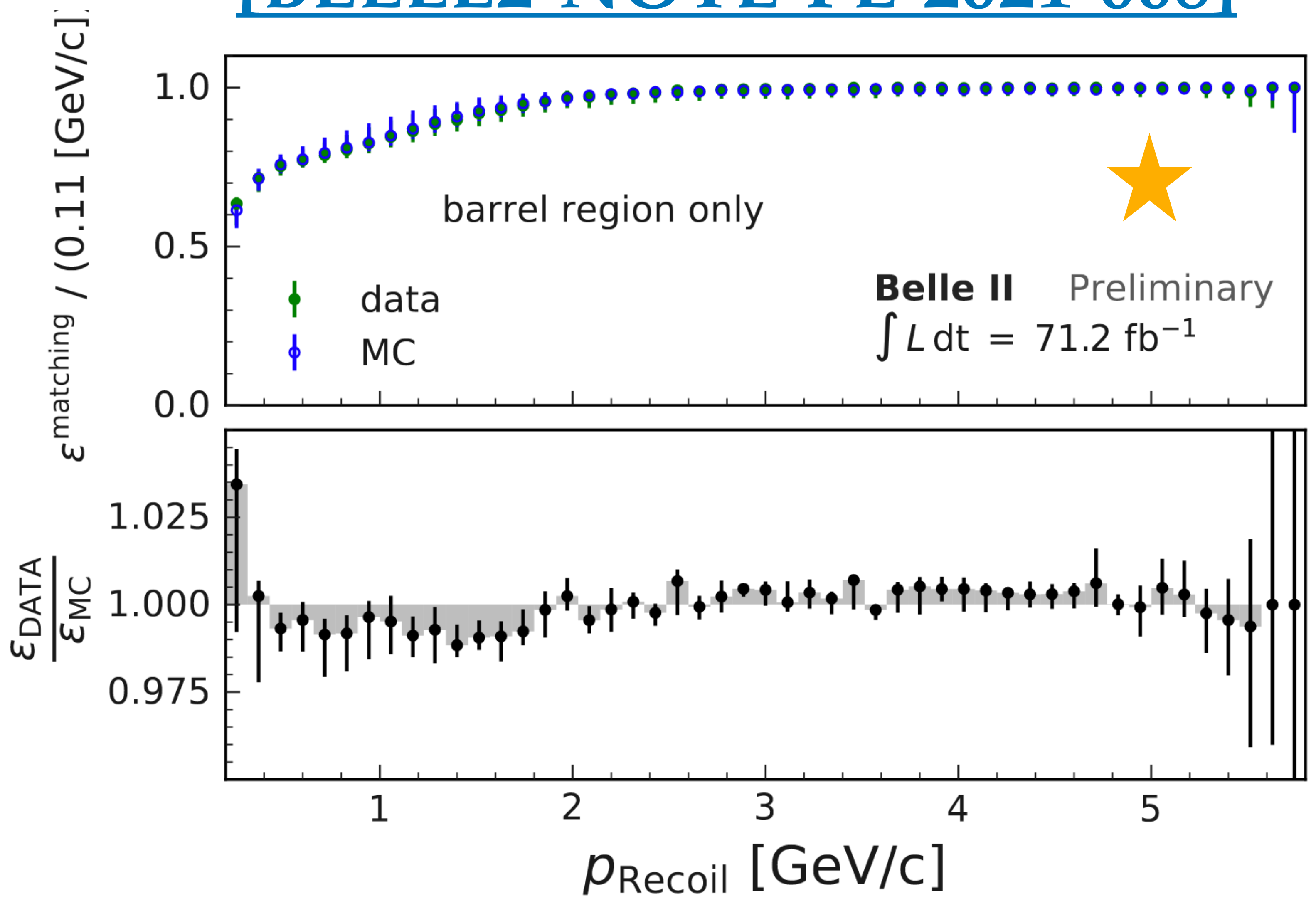
Performance

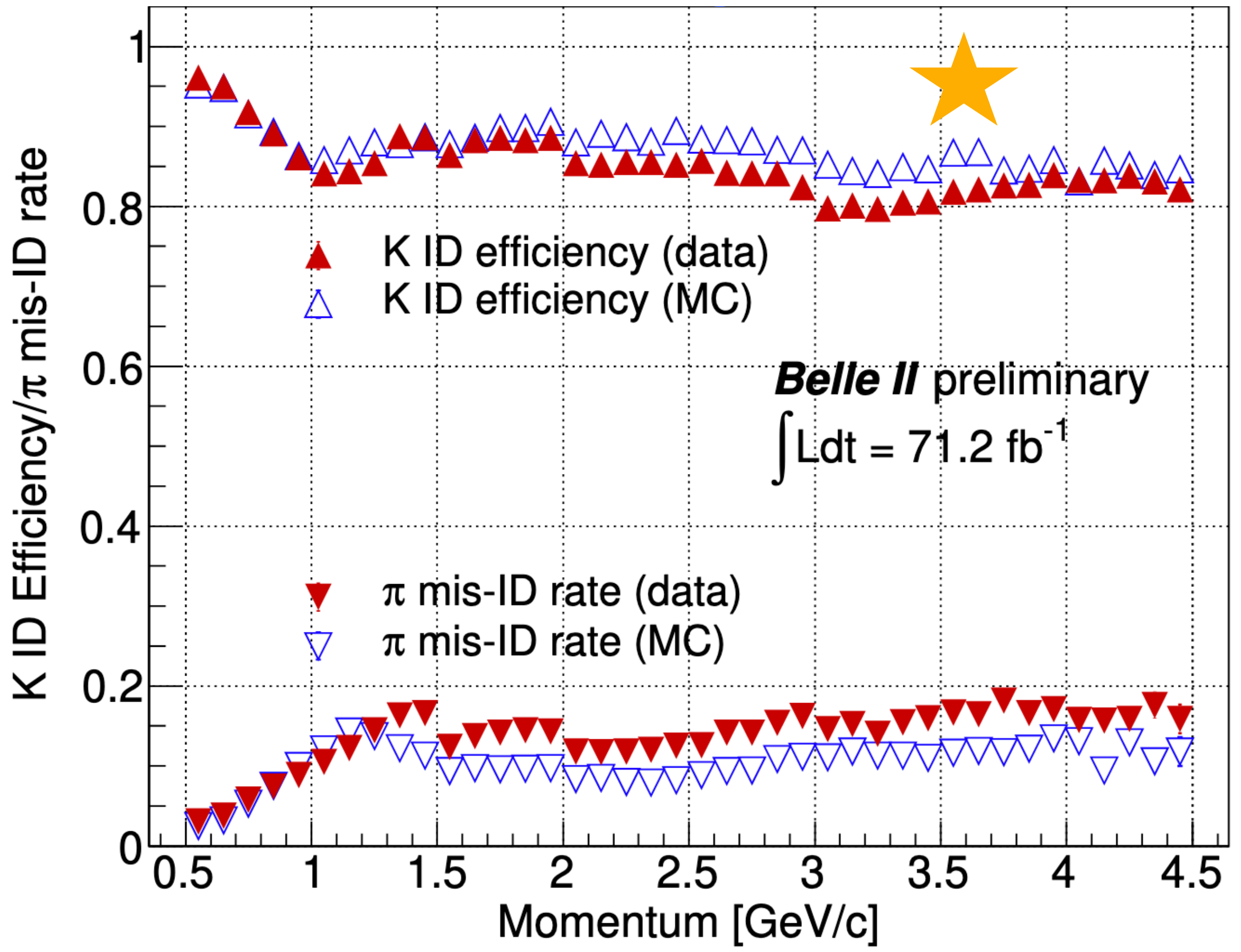
Good flavour tagger performance
[EPJC 82, 283 (2022)](#)



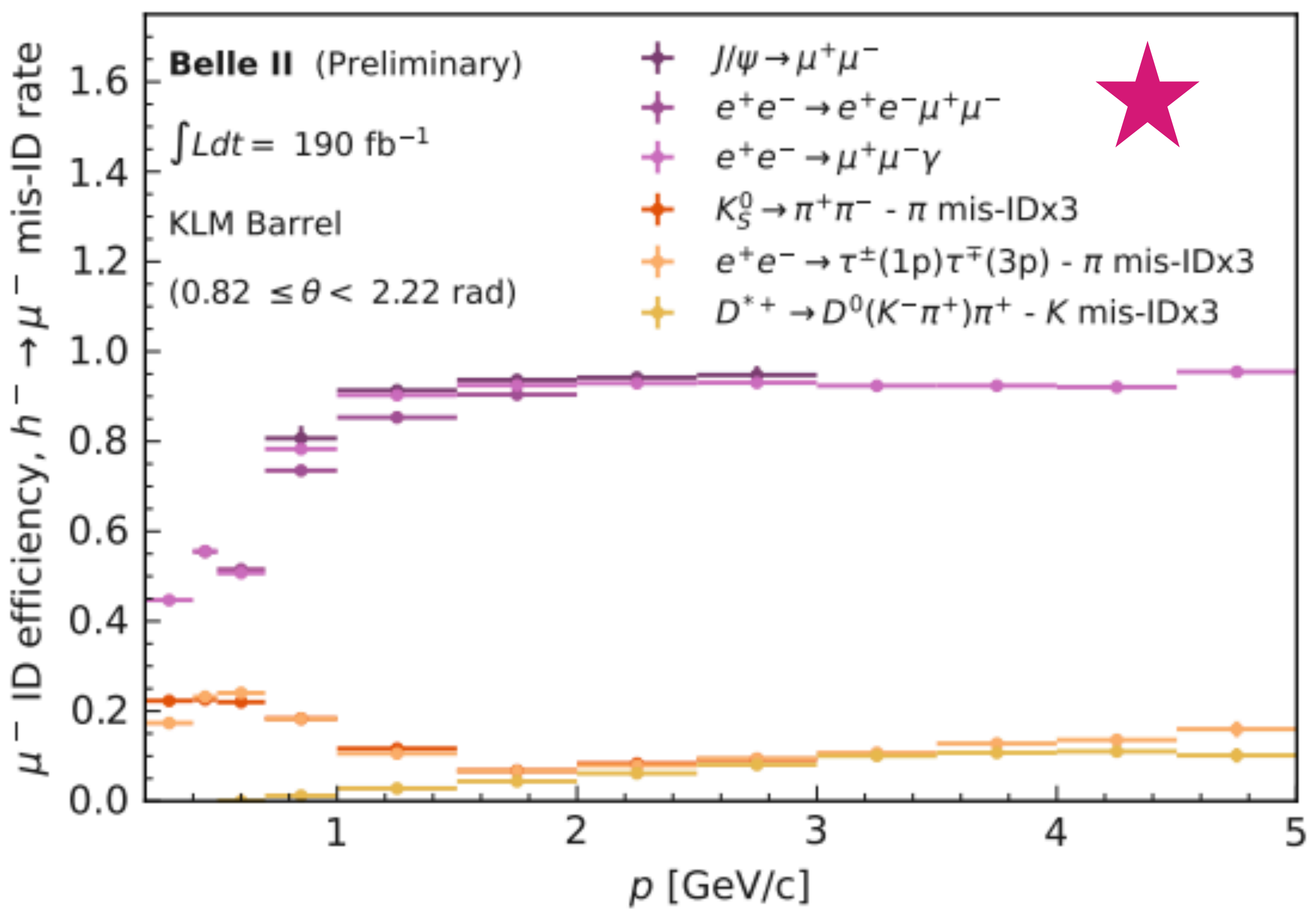
High photon matching efficiency
[BELLE2-NOTE-PL-2021-008]



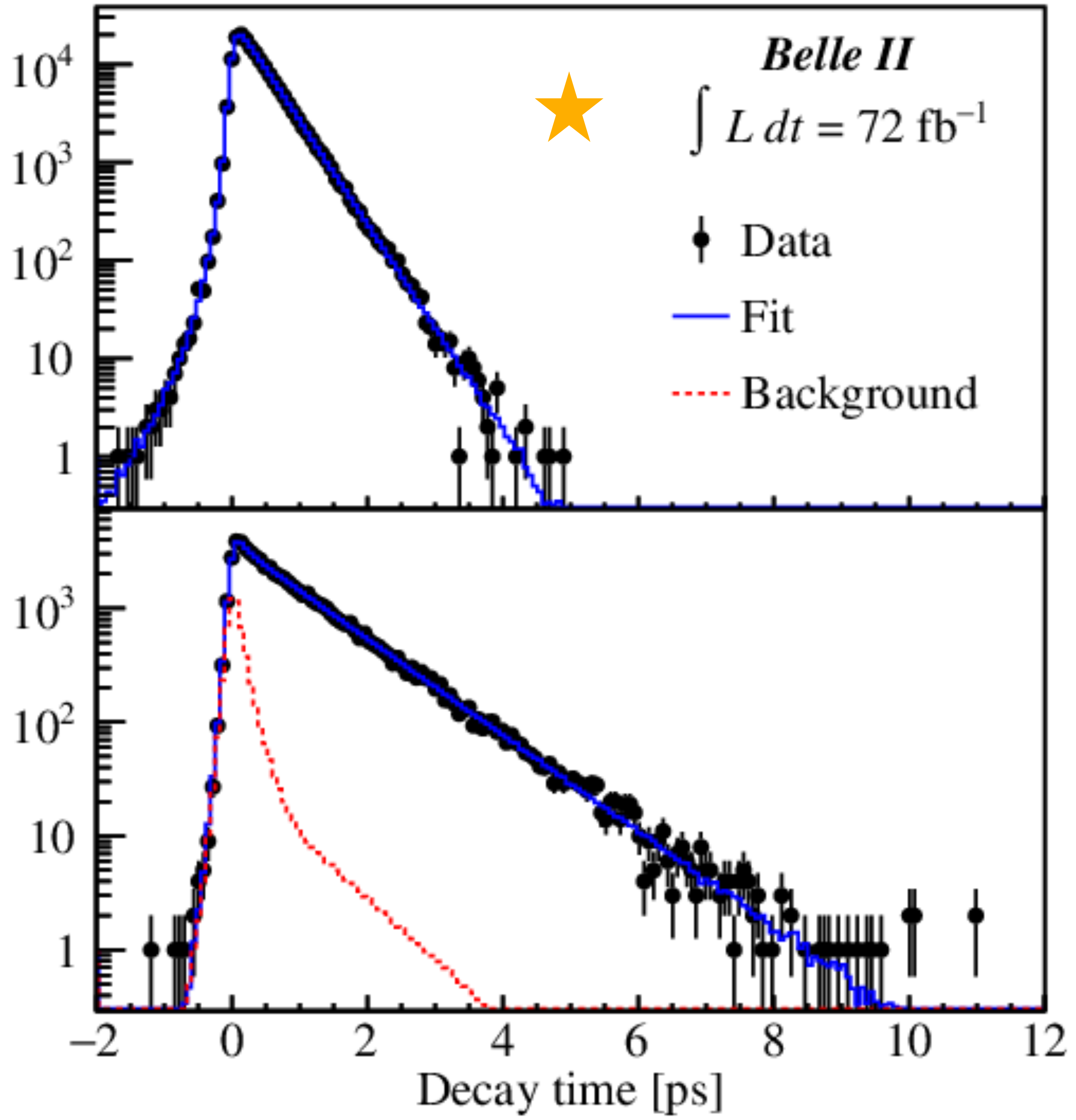
Good particle identification
[BELLE2-NOTE-PL-2020-024]



[BELLE2-NOTE-PL-2022-003]



Most precise measurement of *D* lifetimes
[PRL 127, 211801 (2021)](#)

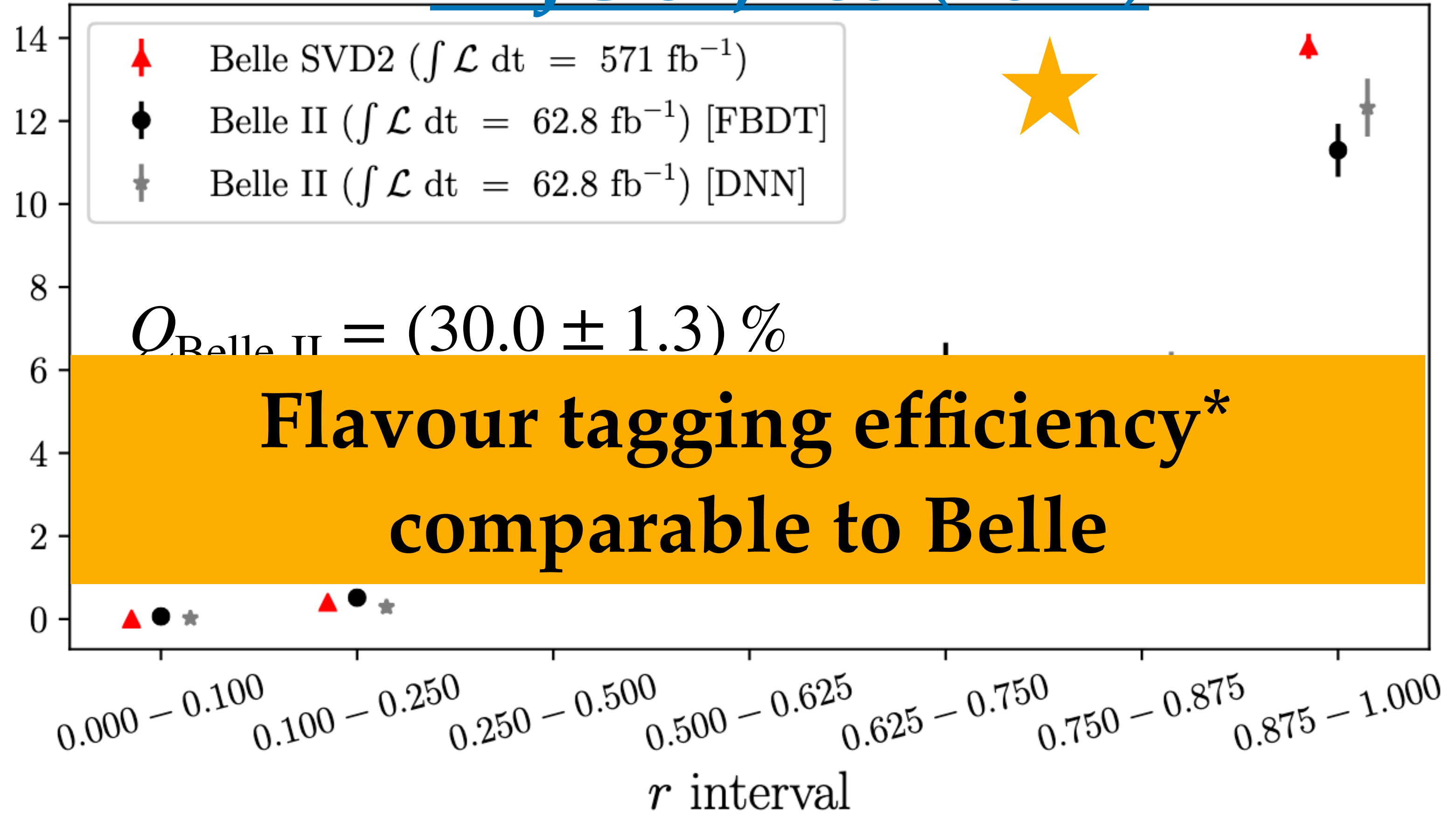


*tagging power indicating the statistical precision of the sample = $\epsilon_{tag}(1-2\omega)^2$

Performance

Good flavour tagger performance

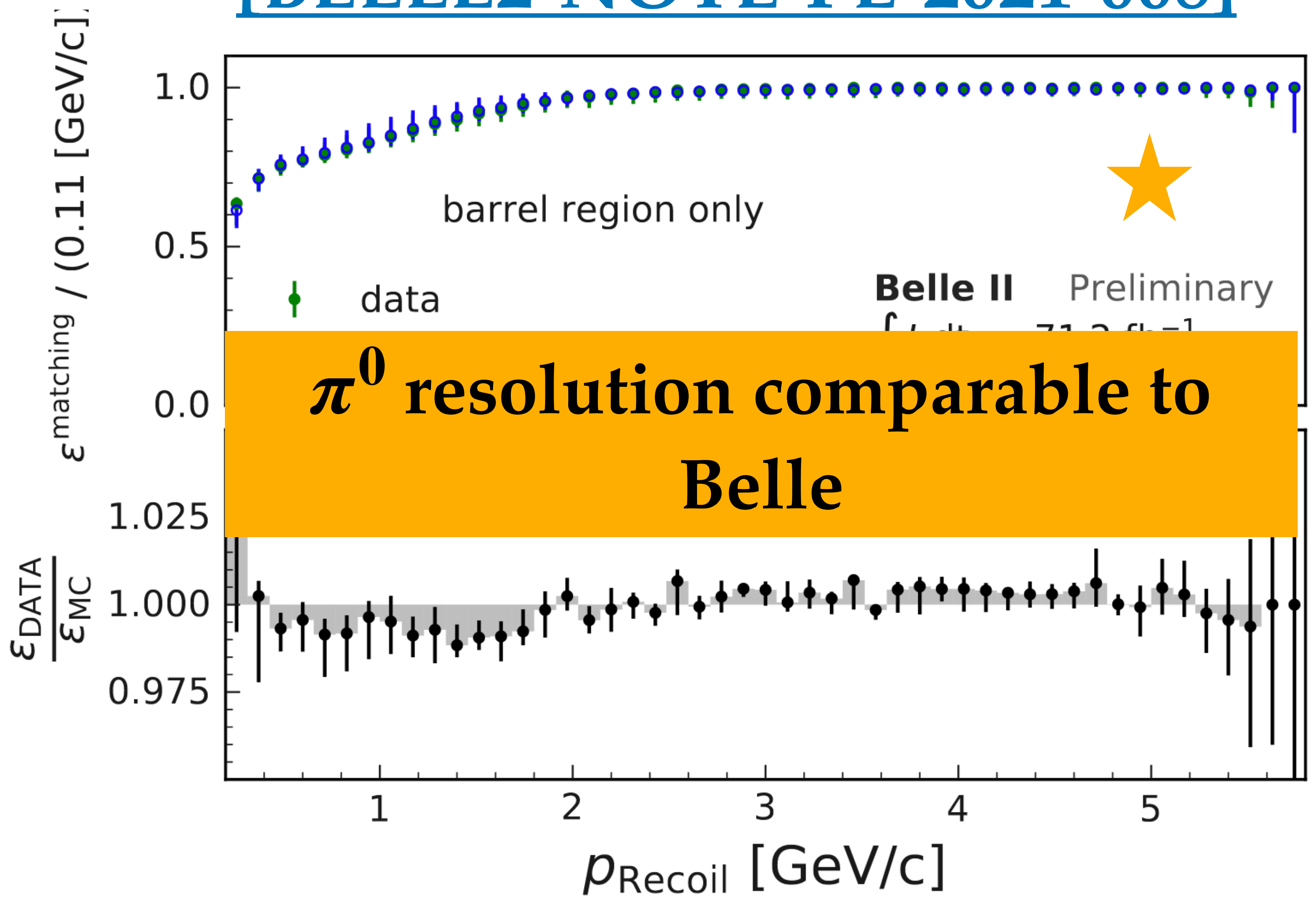
[EPJC 82, 283 (2022)]



Flavour tagging efficiency* comparable to Belle

High photon matching efficiency

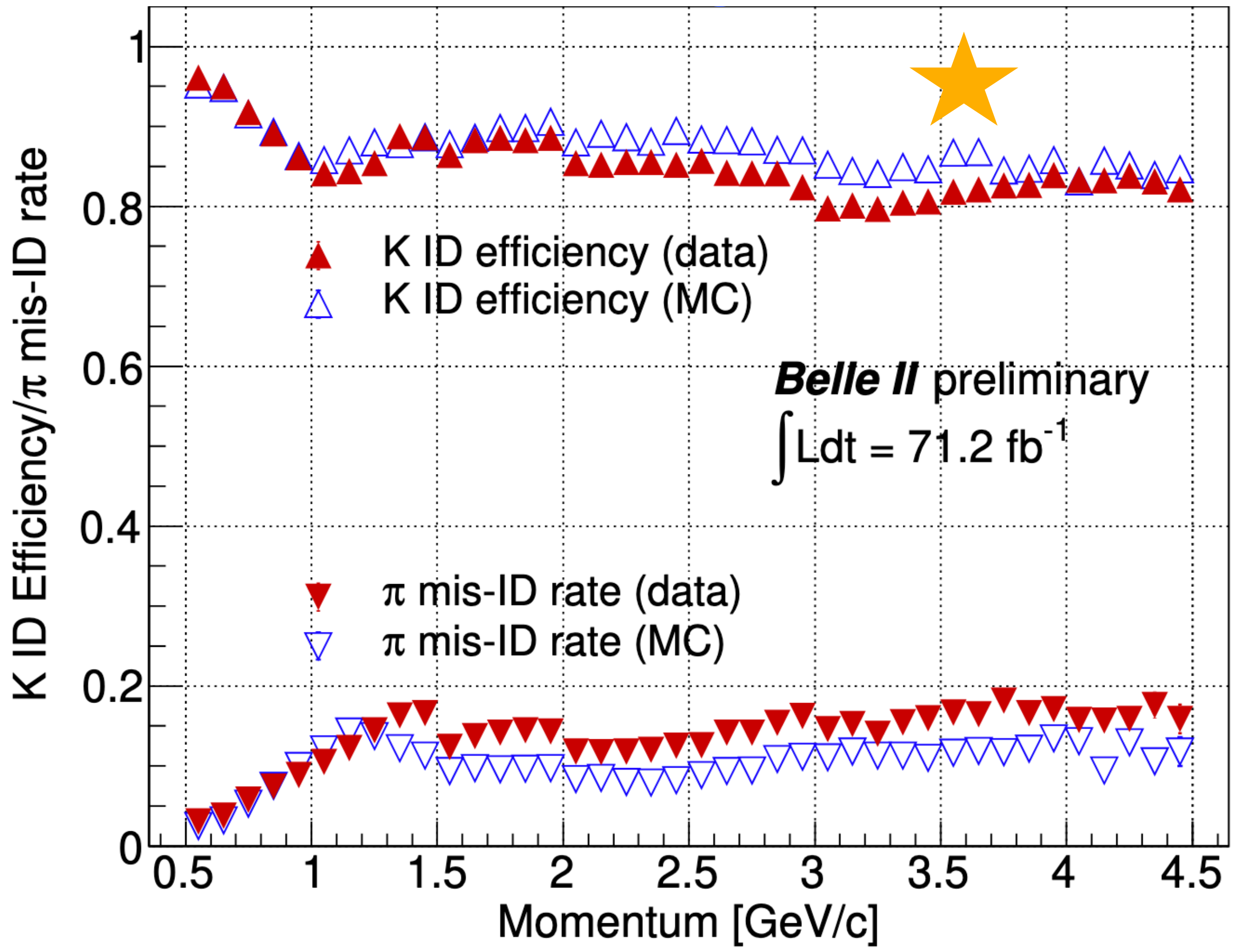
[BELLE2-NOTE-PL-2021-008]



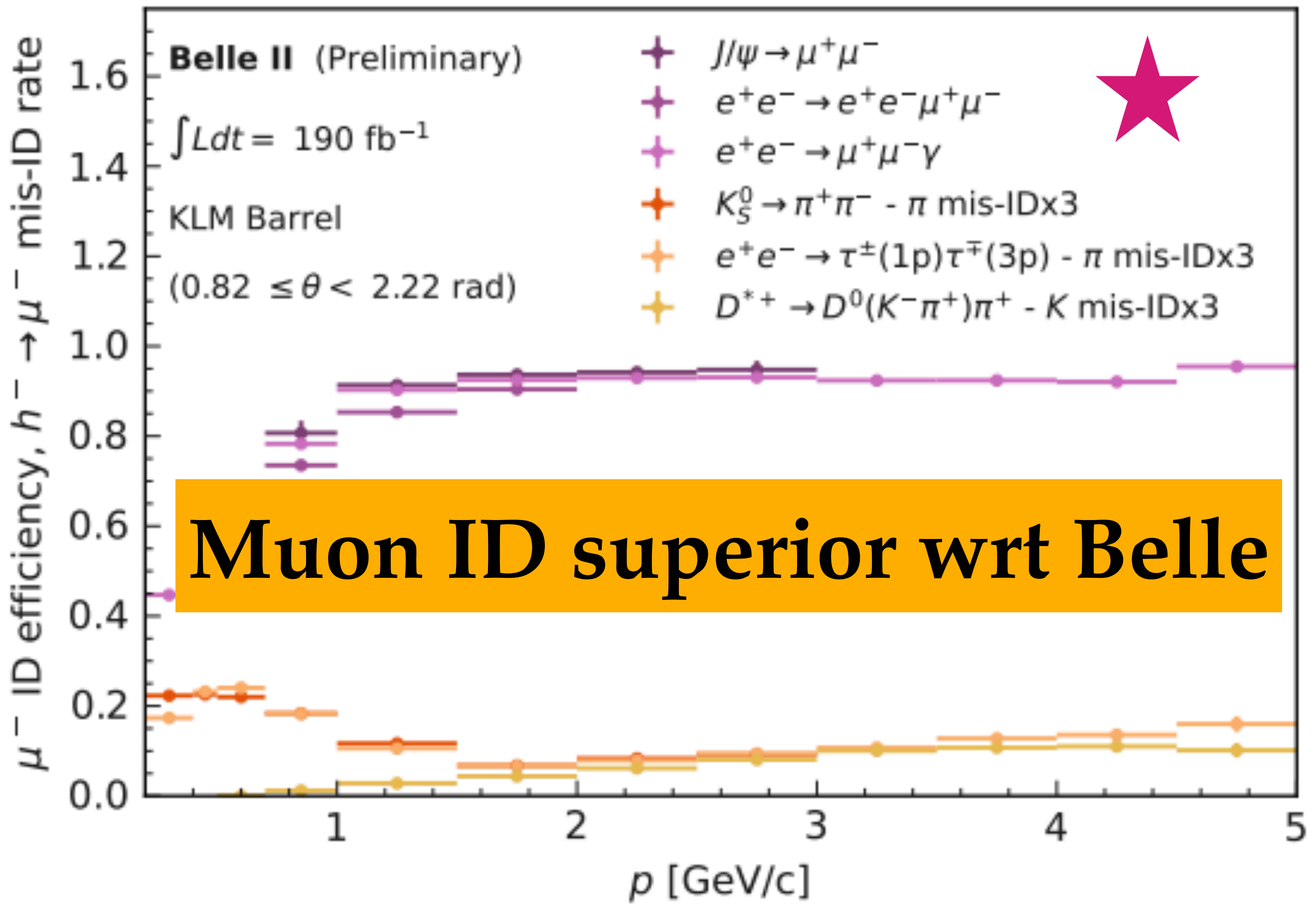
π^0 resolution comparable to Belle

Good particle identification

[BELLE2-NOTE-PL-2020-024]



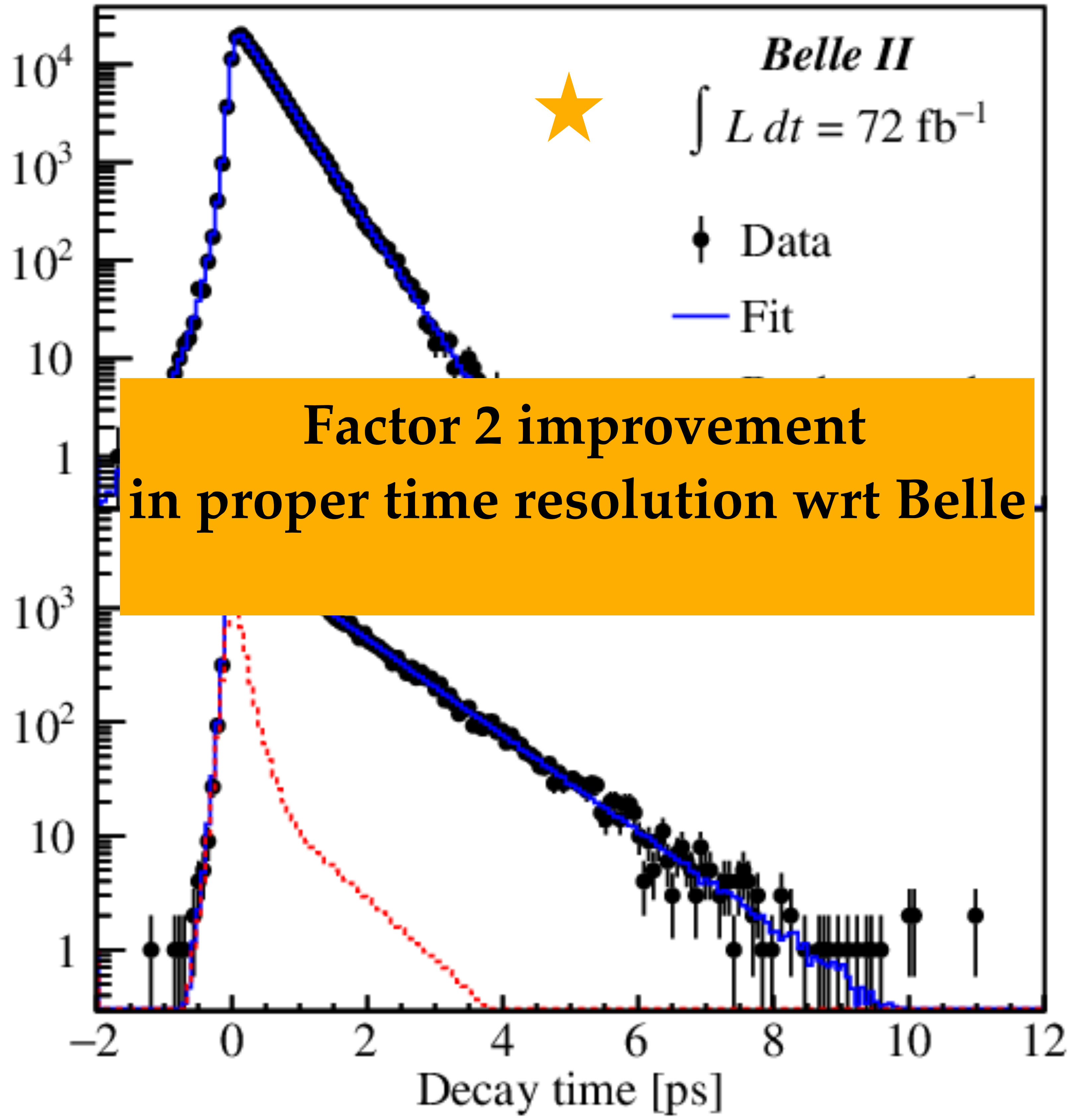
[BELLE2-NOTE-PL-2022-003]



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 = $\epsilon_{tag}(1-2\omega)^2$

Statistical model

[PRL 127, 181802 (2021)] ★

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 $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$**

pyhf ∂ifferentiable ℒikelihoods

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

Simultaneous measurements of multiple regions

Constraints

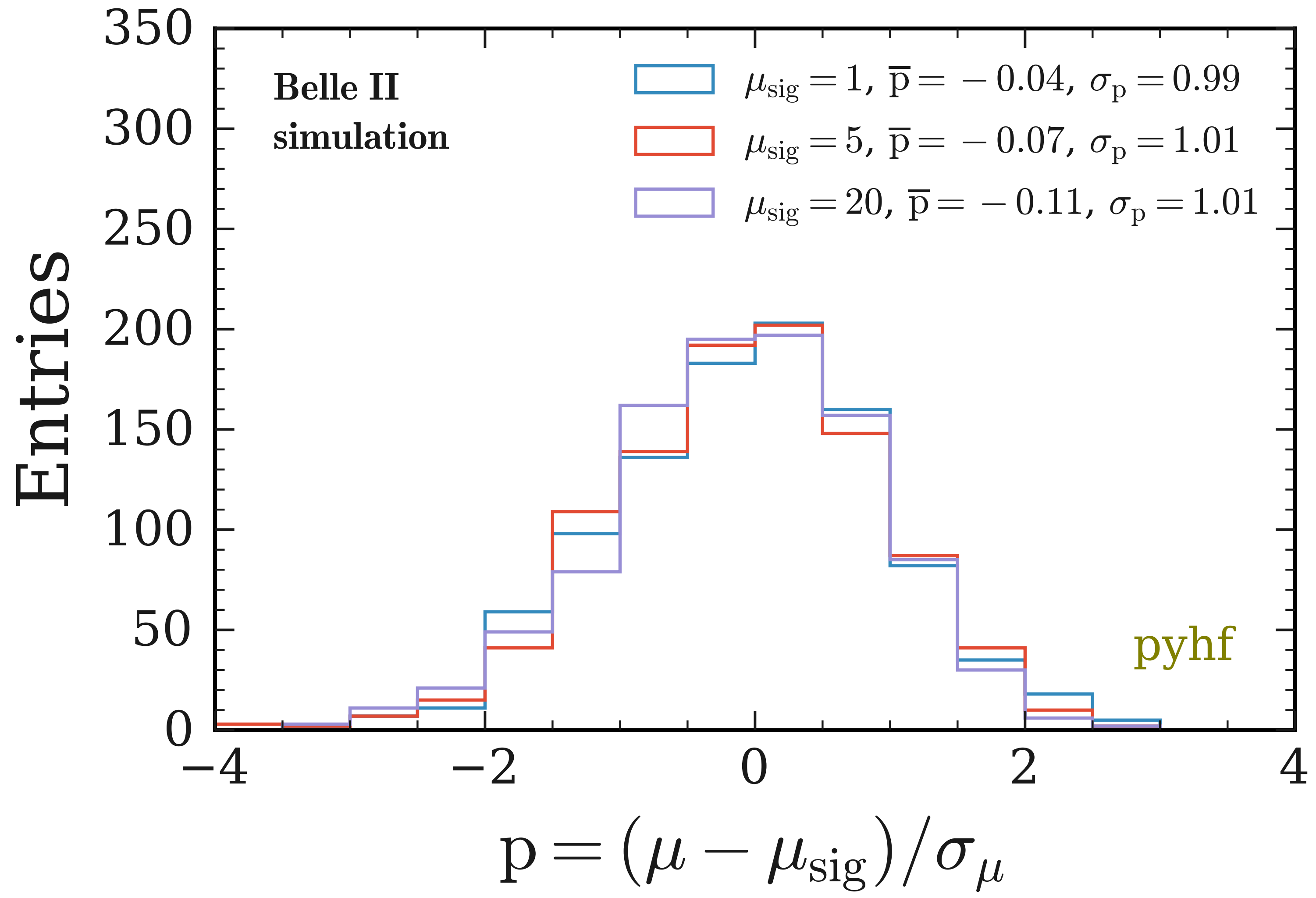
η = parameter of interest
χ = nuisance parameters

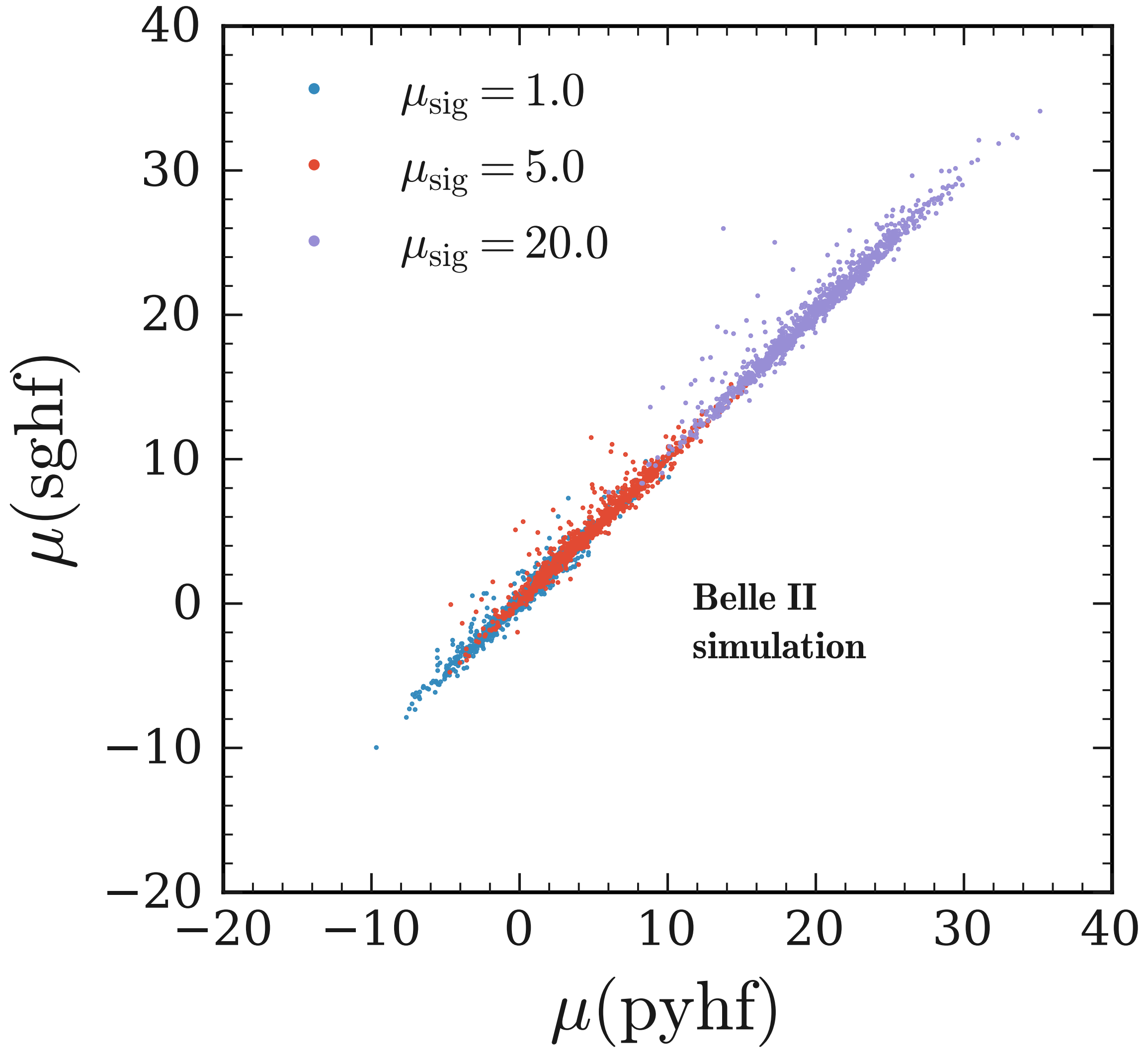
Fit validation

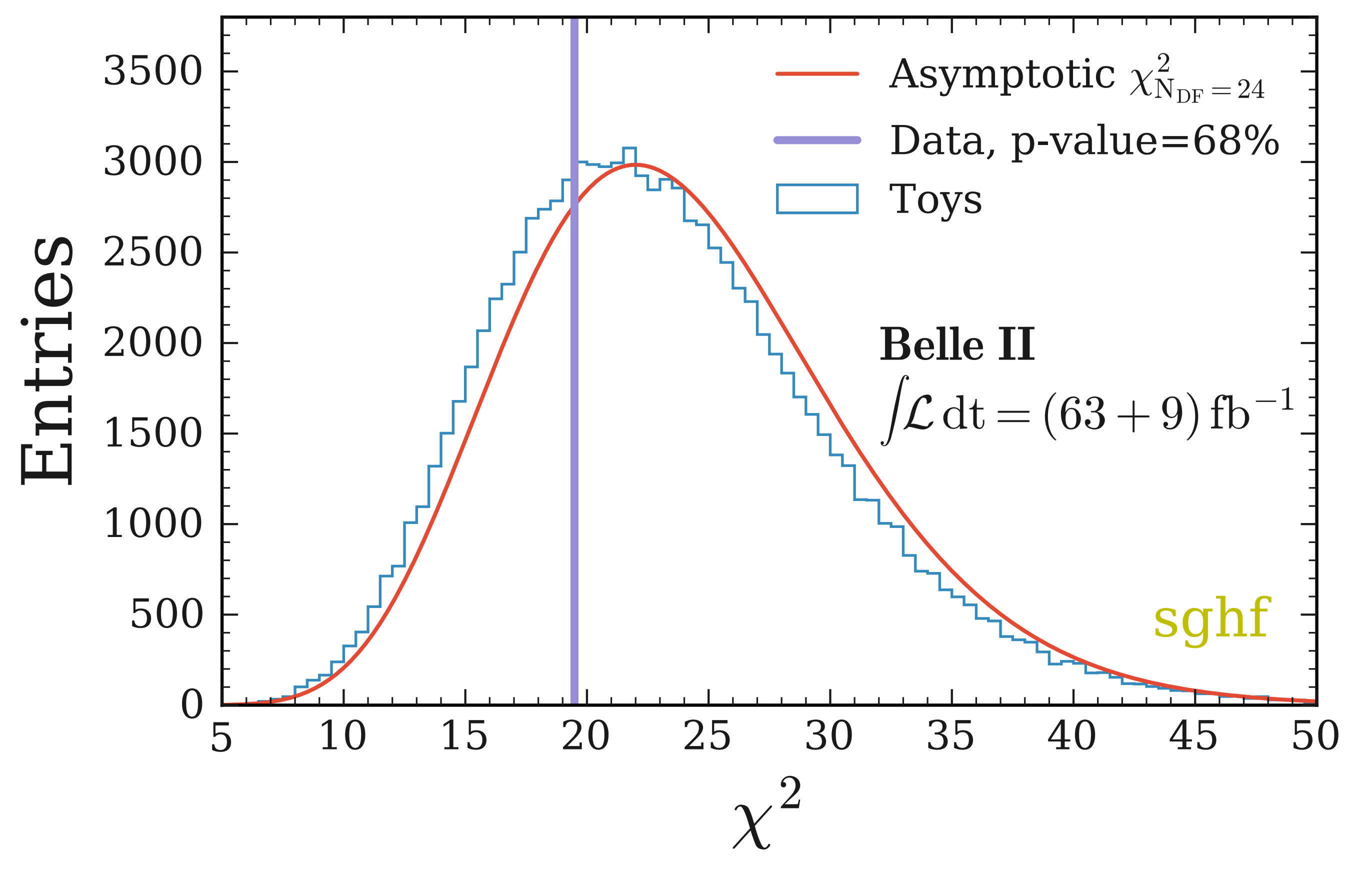
[PRL 127, 181802 (2021)] ★

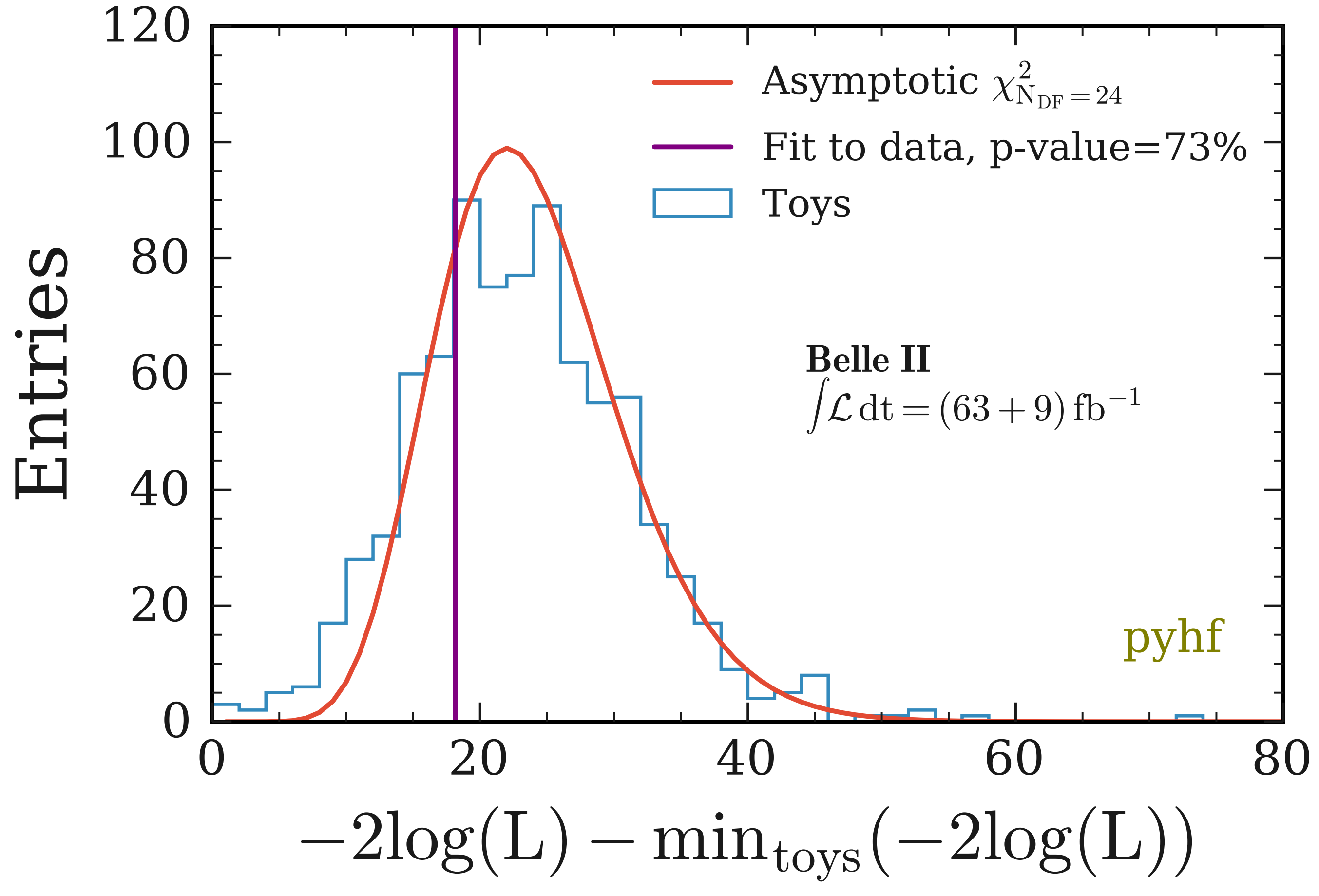
Perform Fit Bias Check

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







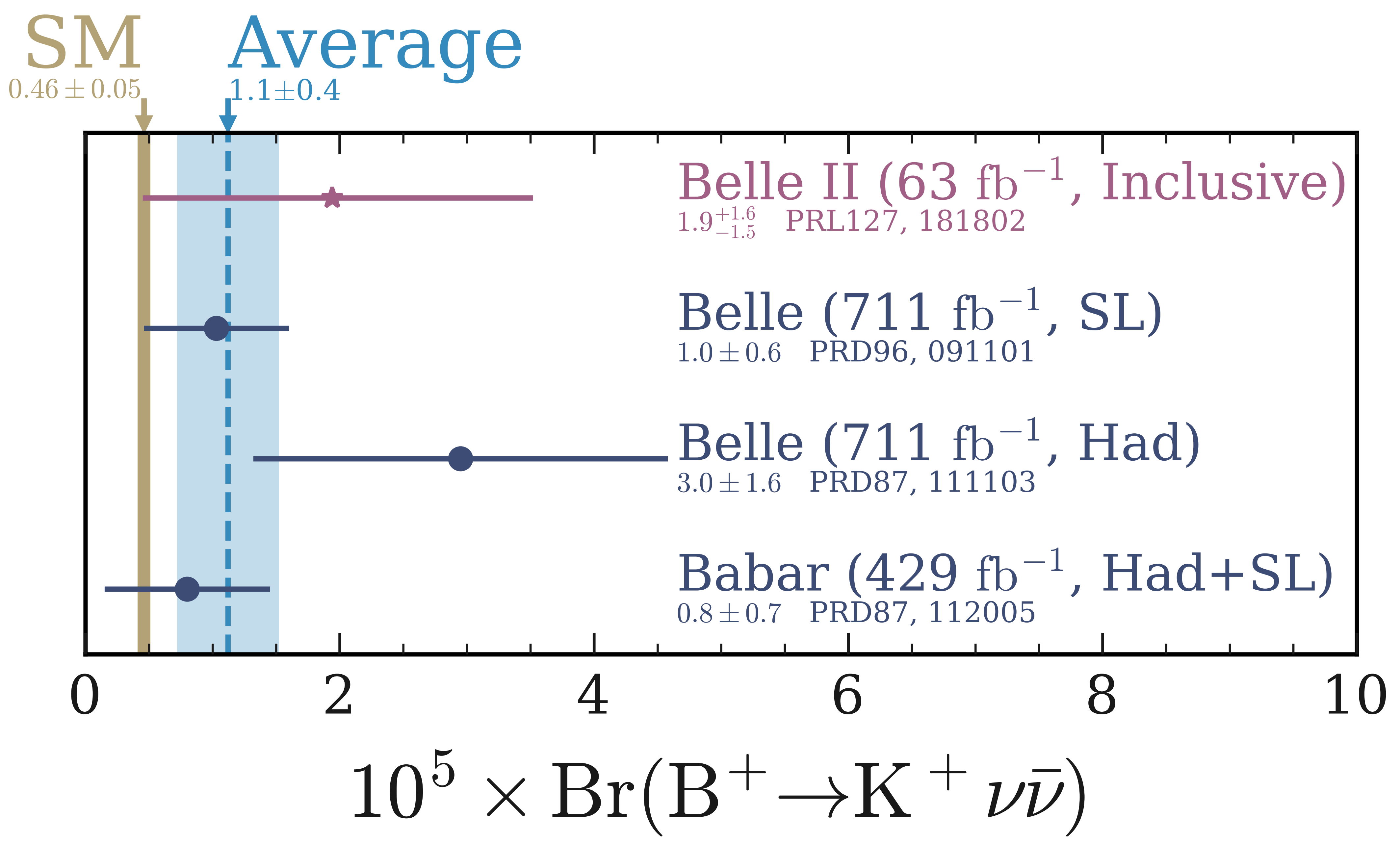


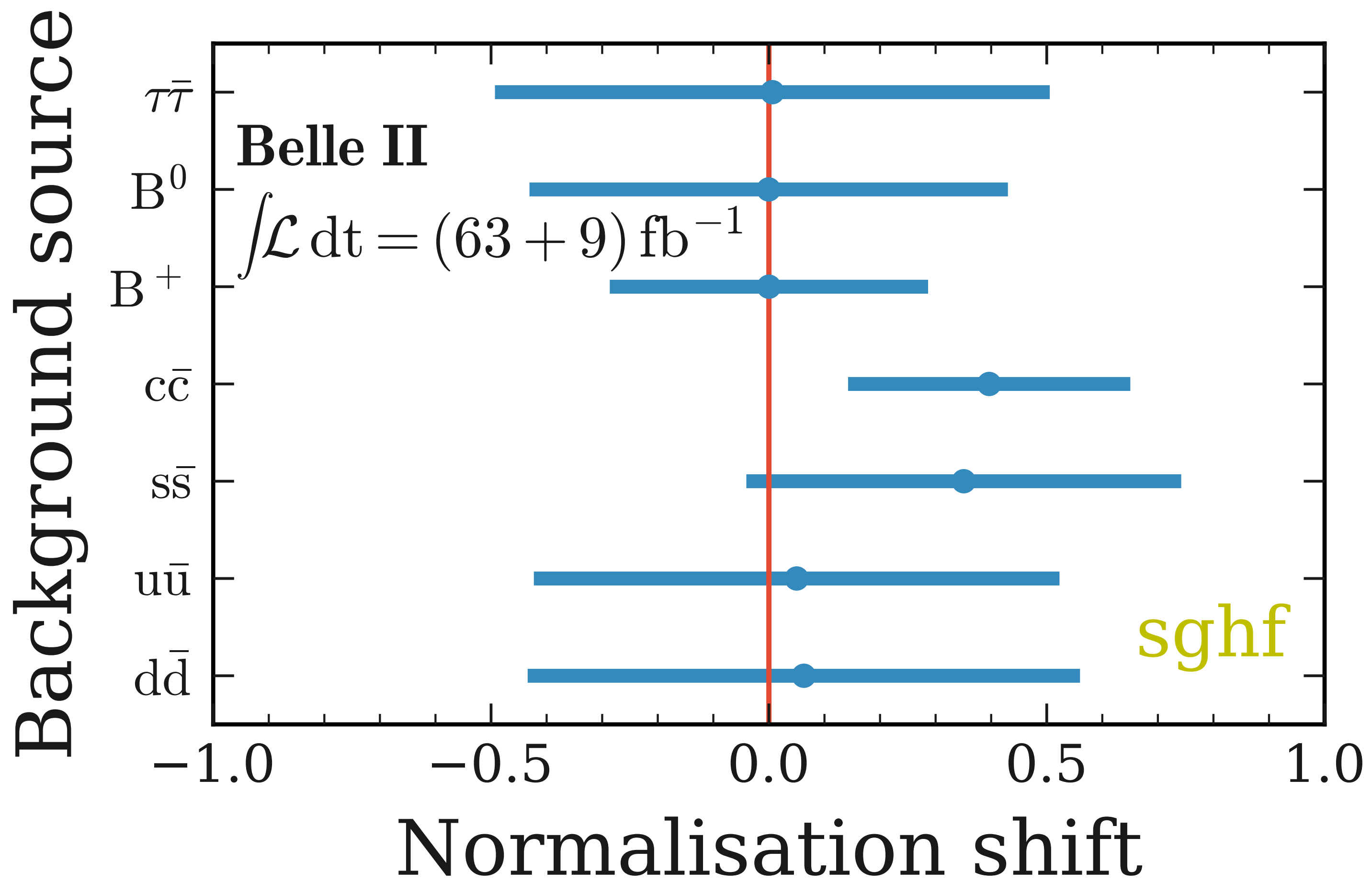
Check Data-Model Compatibility

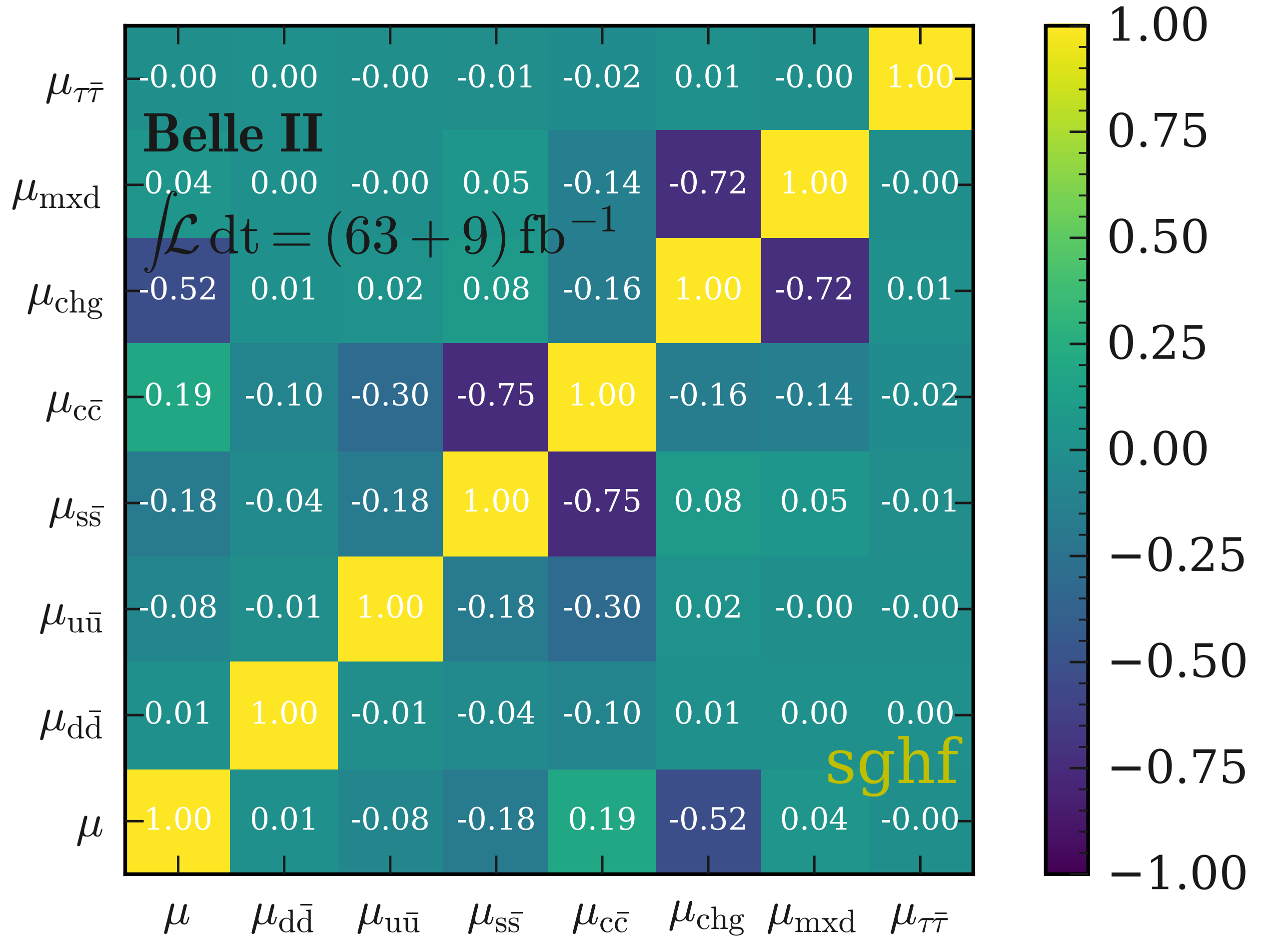
- Generate toys and check fit quality
- Results: p-value shows good data model compatibility for both pyhf and sghf

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}







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