Systematics in Flavour Physics Analyses (rare decays)

Systematic Effects and Nuisance Parameters in Particle Physics Data Analyses

BIRS, Banff, Canada, April 27, 2023

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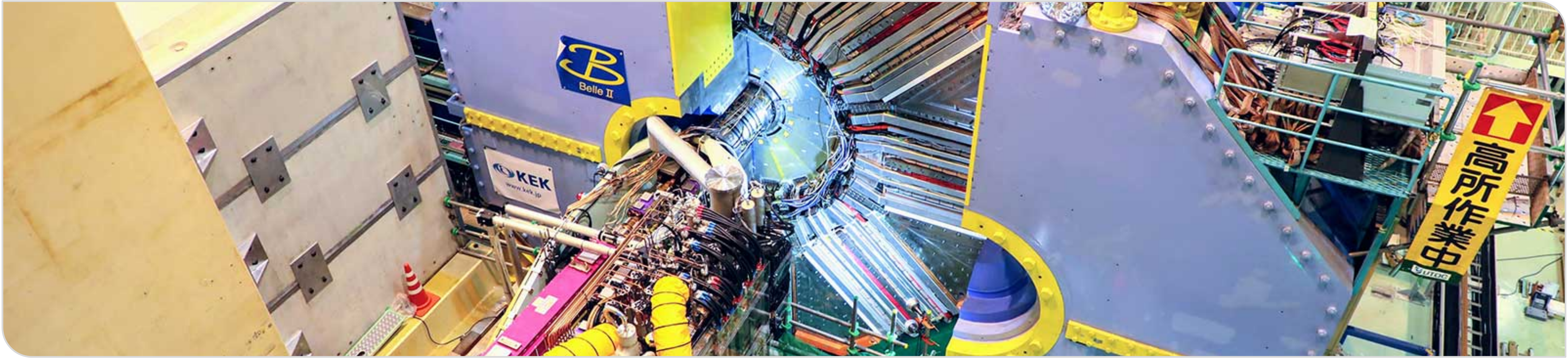
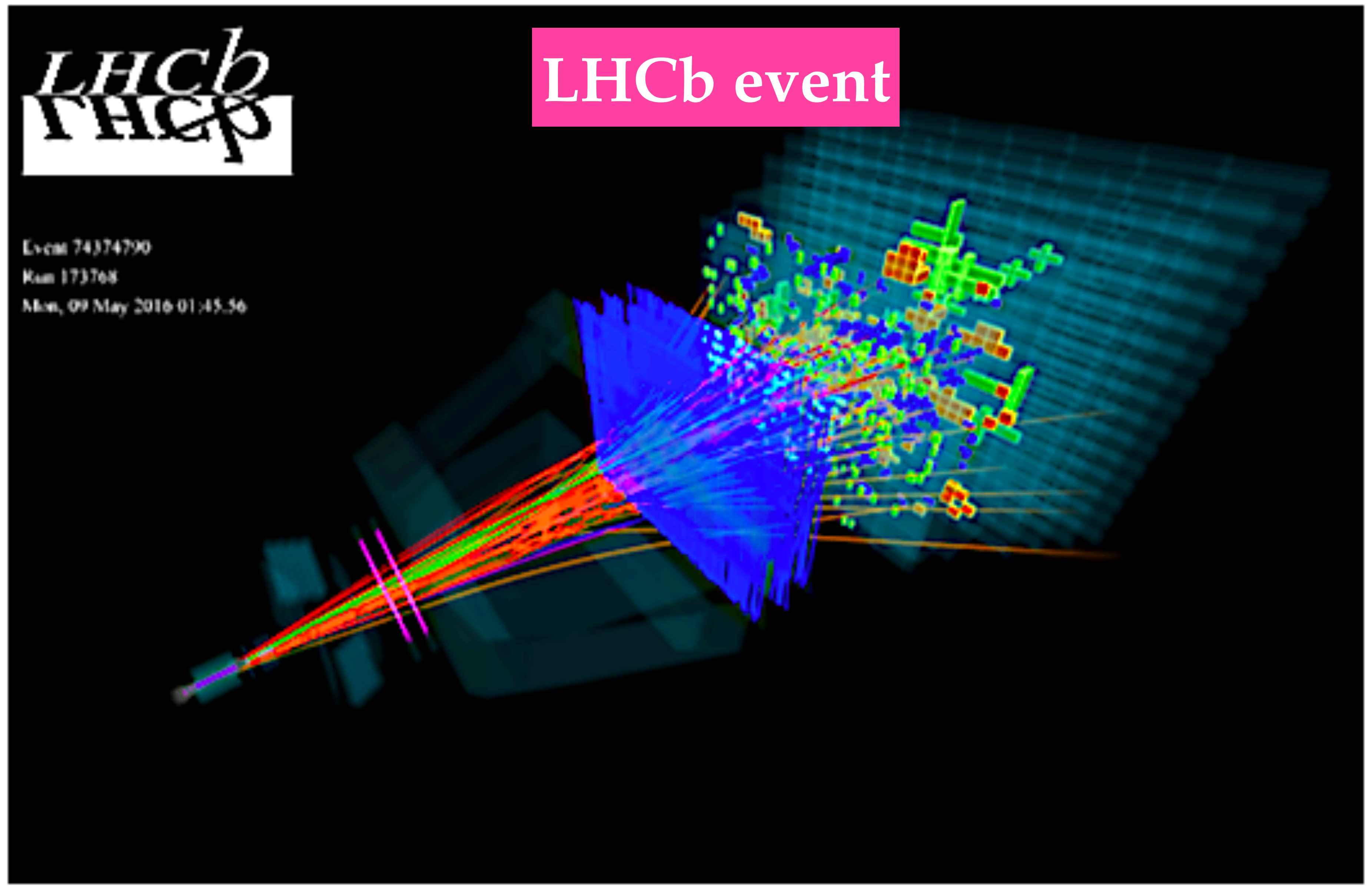
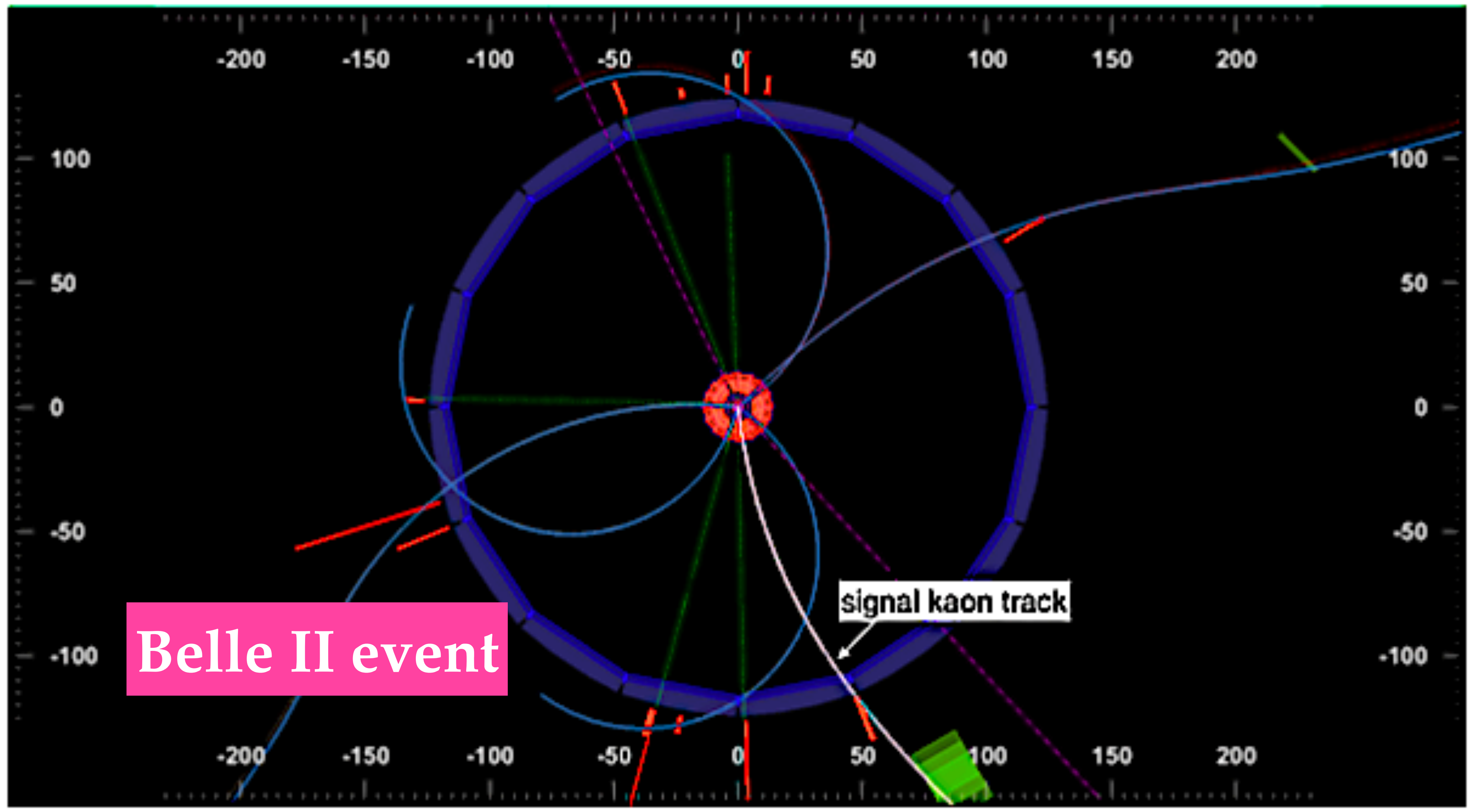


Flavour experiments in nutshell

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 ~ 5.2 GeV (*B*-hadron at LHCb)
    - The innermost detector has excellent vertex resolution close to IP

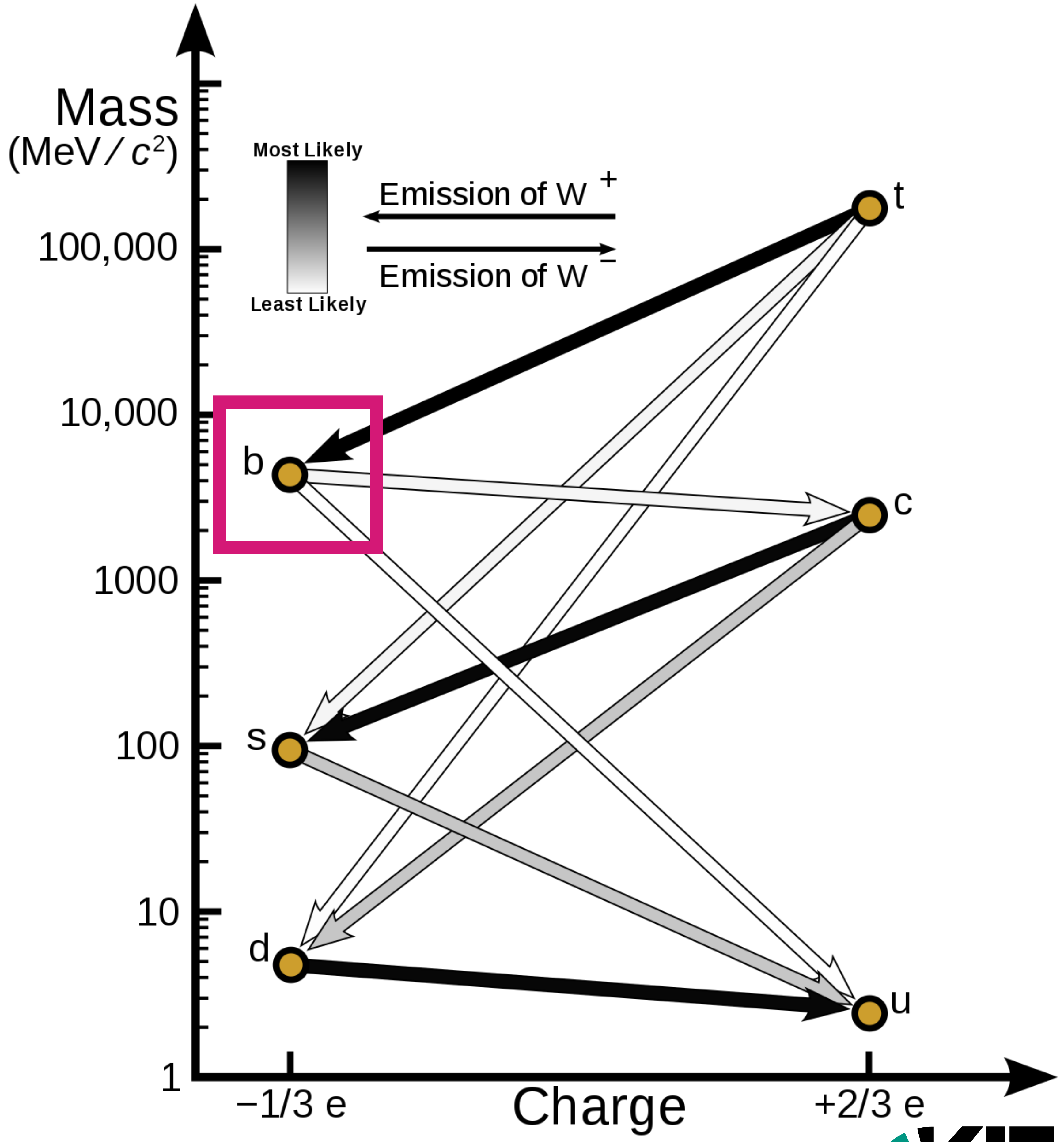




B-decays measurements (and others)

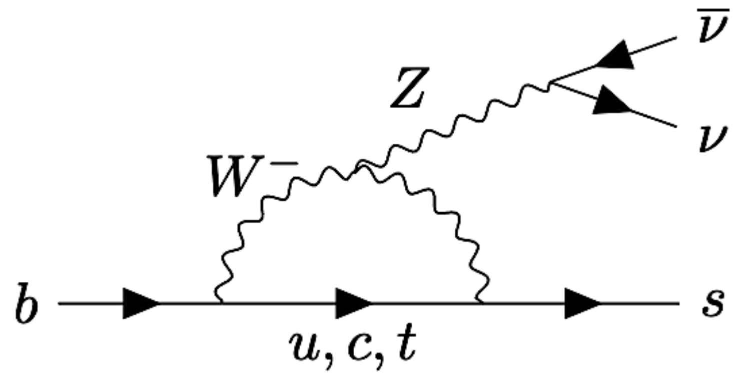
- *B*-decay can be **abundant** or **rare**:
    - Precision measurements of CP violation (**rare and abundant**)
    - Indirect searches for NP in rare *B*-decays (**rare**)
    - Indirect searches for NP in semileptonic *B*-decays (**abundant**)
    - Spectroscopy of *B*-decays (**abundant**)

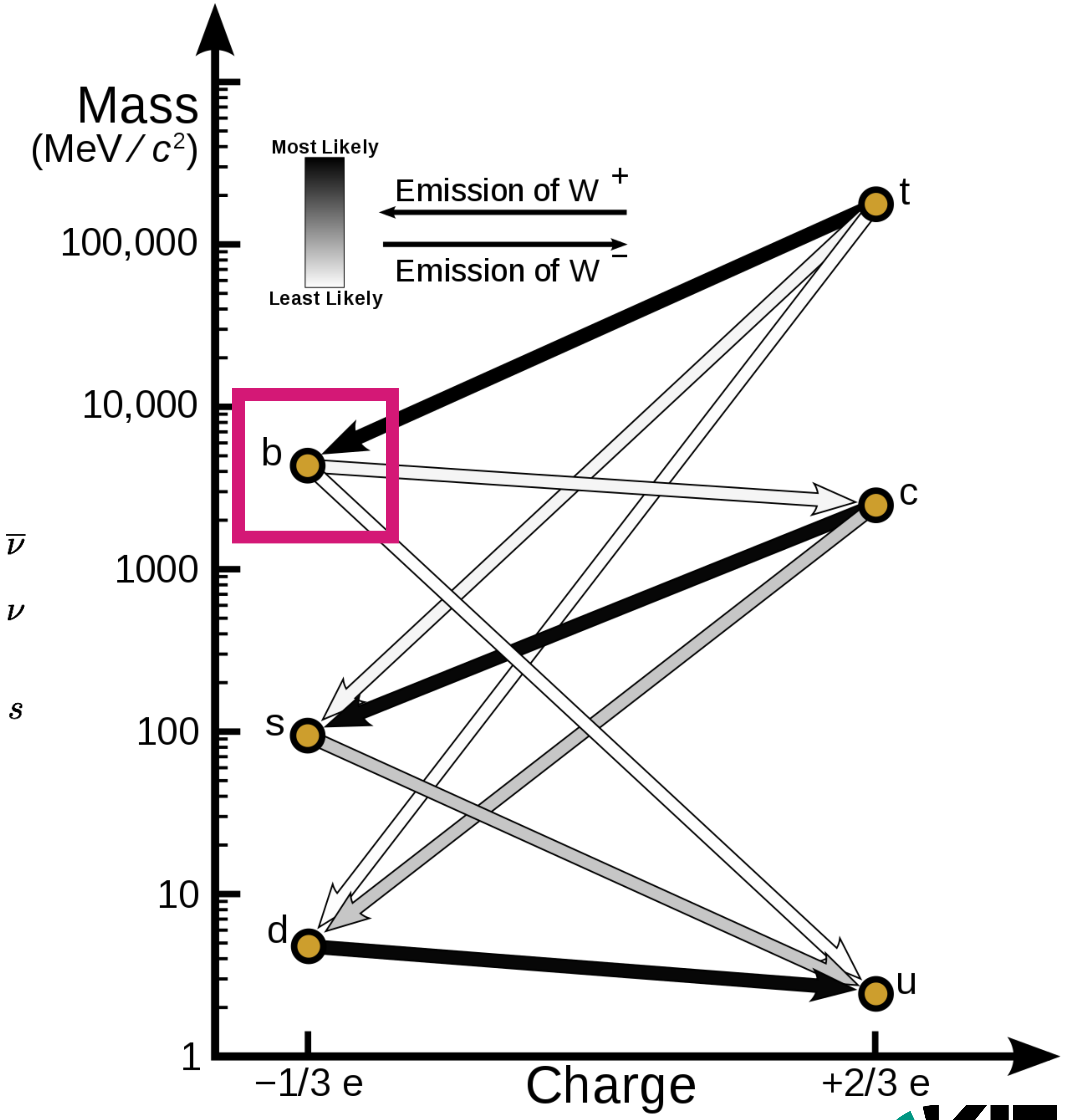
- Belle II and LHCb also well suited
    - for measurements of decays involving c and τ
    - for direct searches for NP, e.g DM, mediators connected to DM, leptoquarks, Z', …..



B-decays measurements (and others)

- *B*-decay can be **abundant** or **rare**:
  - Precision measurements of CP violation (**rare and abundant**)
  - **Indirect searches for NP in rare *B*-decays (rare)**
  - Indirect searches for NP in semileptonic *B*-decays (**abundant**)
  - Spectroscopy of *B*-decays (**abundant**)





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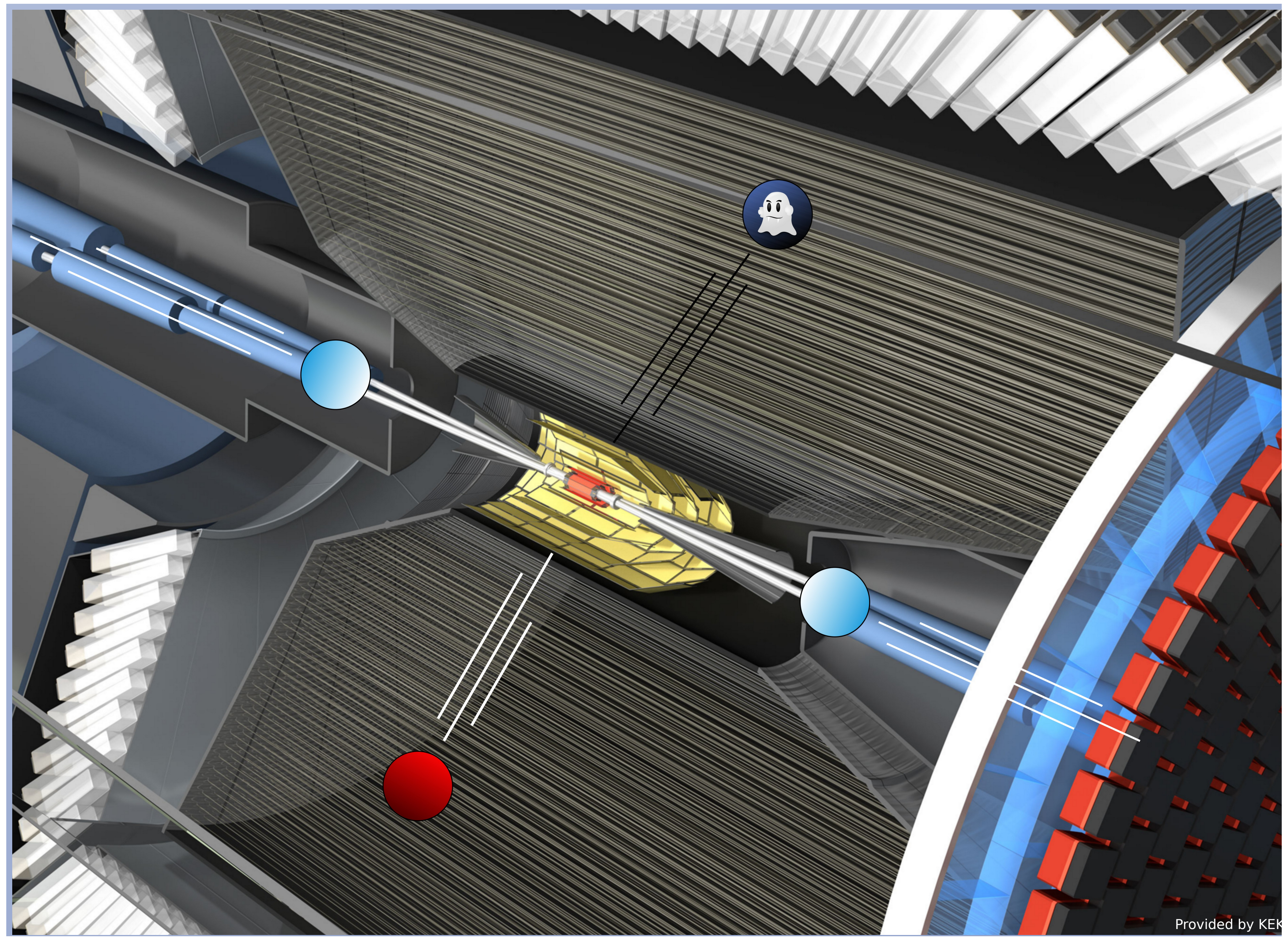
Direct and indirect searches for NP

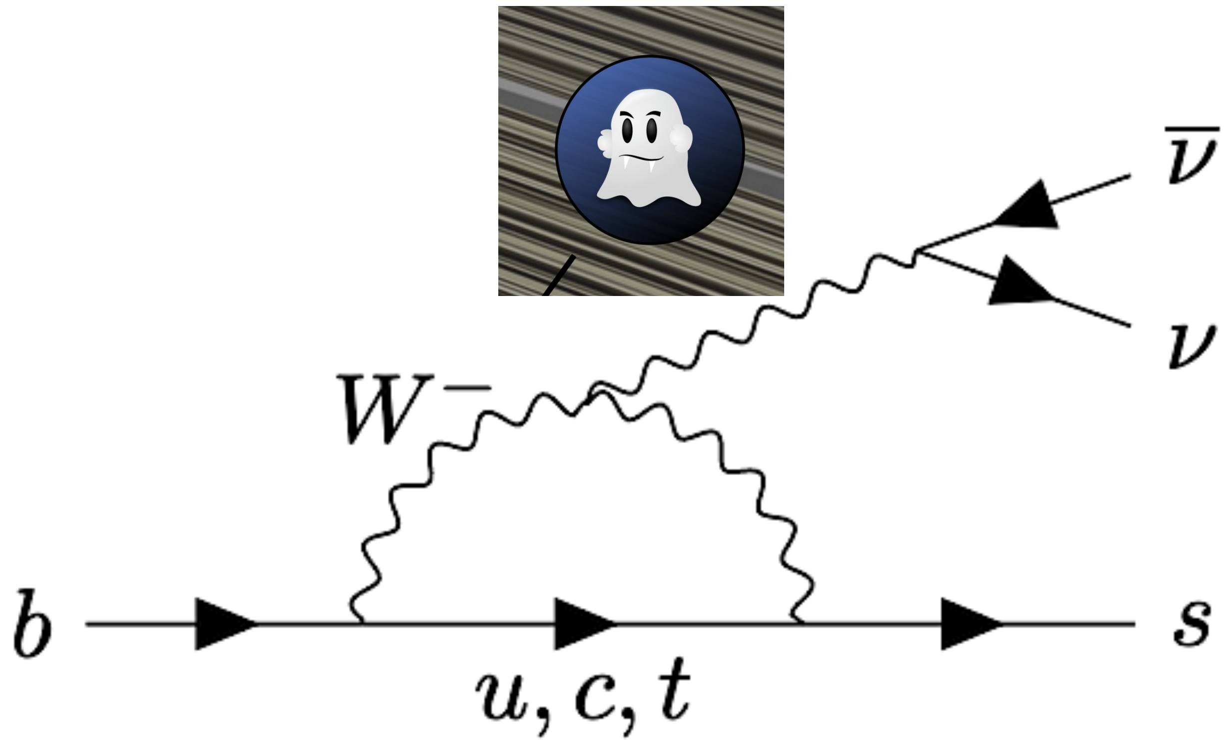
Direct



$$E = mc^2$$

Mass of the new particle limited by collision energy

Indirect

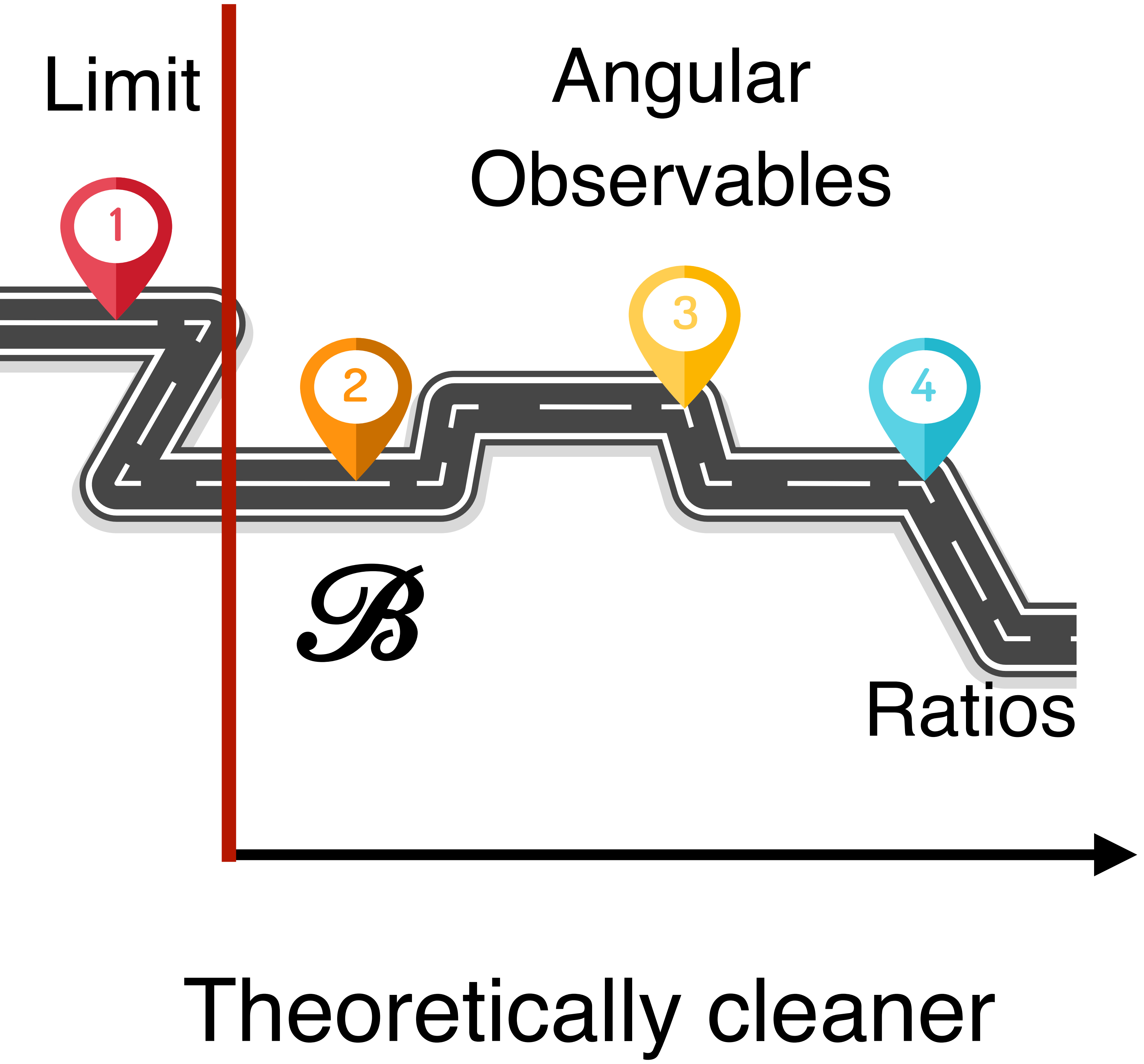


Heisenberg's uncertainty principle:

$$\Delta E \Delta t > \frac{h}{2}$$

Mass of the particle can be very high

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



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

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

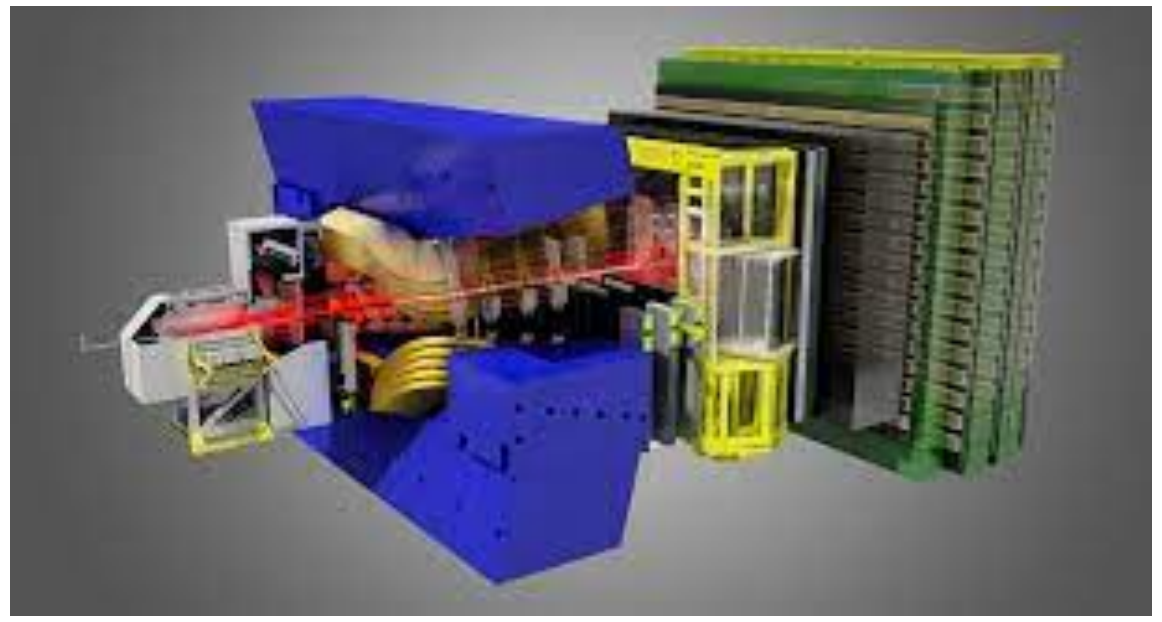
$\boxed{\mathscr{B}}$ How often does *B*-decay into the decay products?
rare → $\mathscr{B}$(process) < 1x10^{-5}

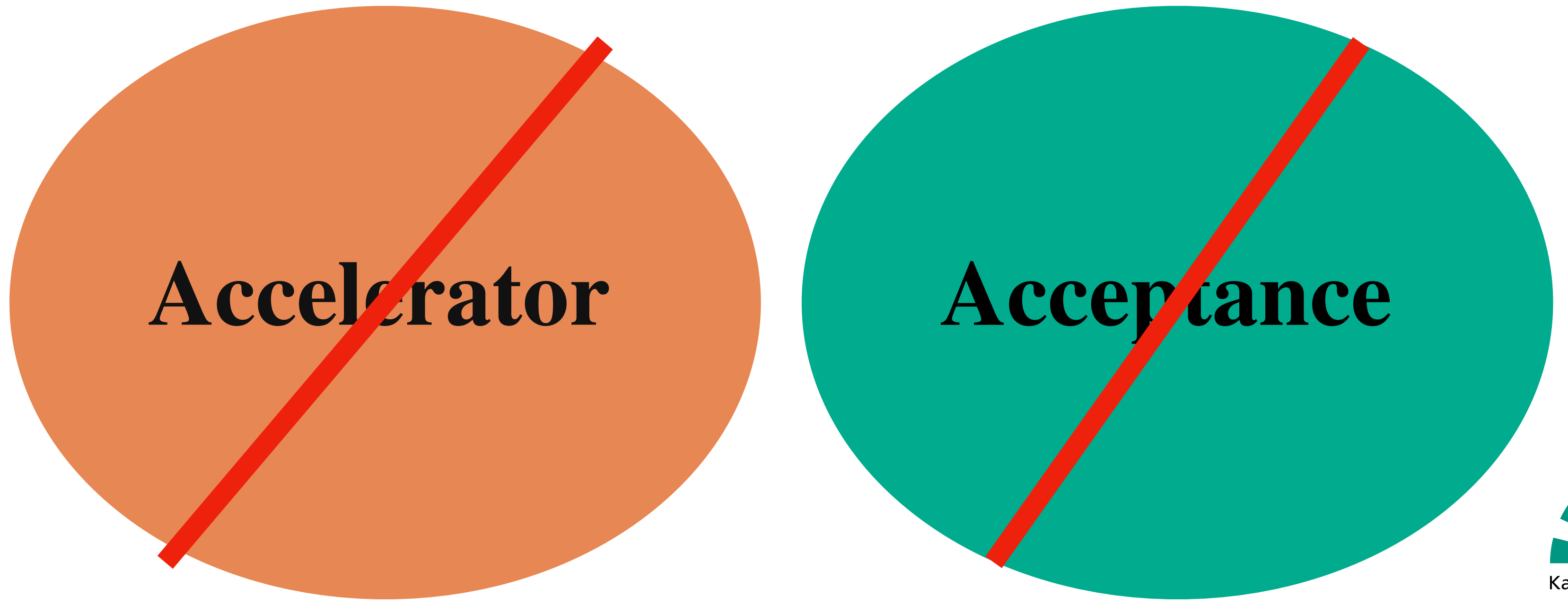
LHCb and Belle II: measurement style

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

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

- Systematic uncertainties need to be derived on the efficiencies in Belle II or on relative efficiencies in LHCb:
  - Relative measurements have advantage in cancelling uncertainties due to accelerator



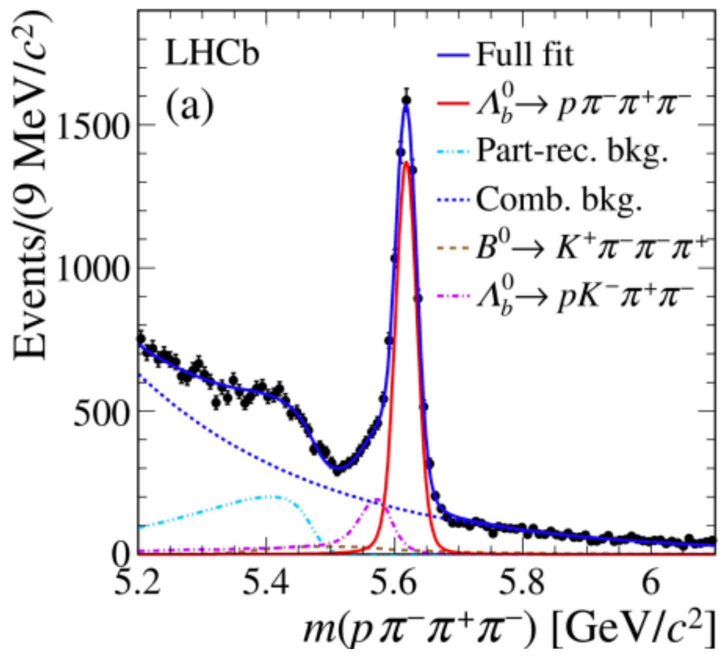


~~Accelerator~~

~~Acceptance~~

Model-building

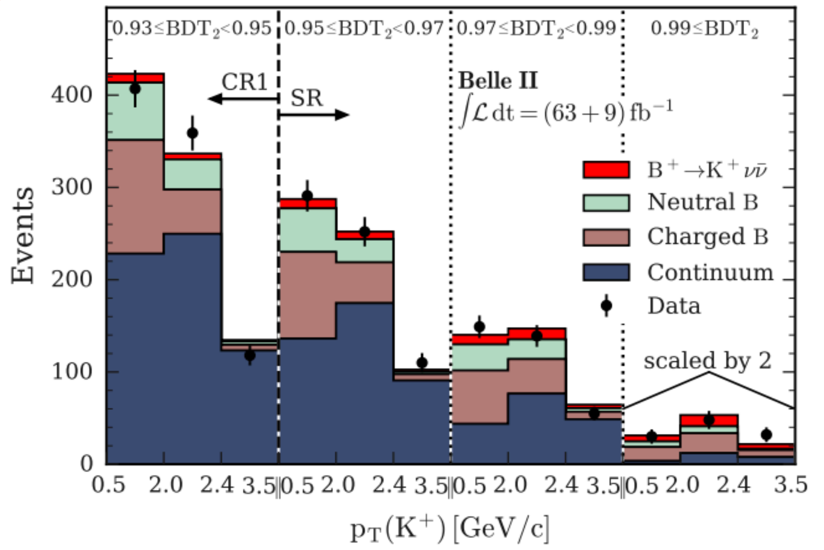
Unbinned



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)

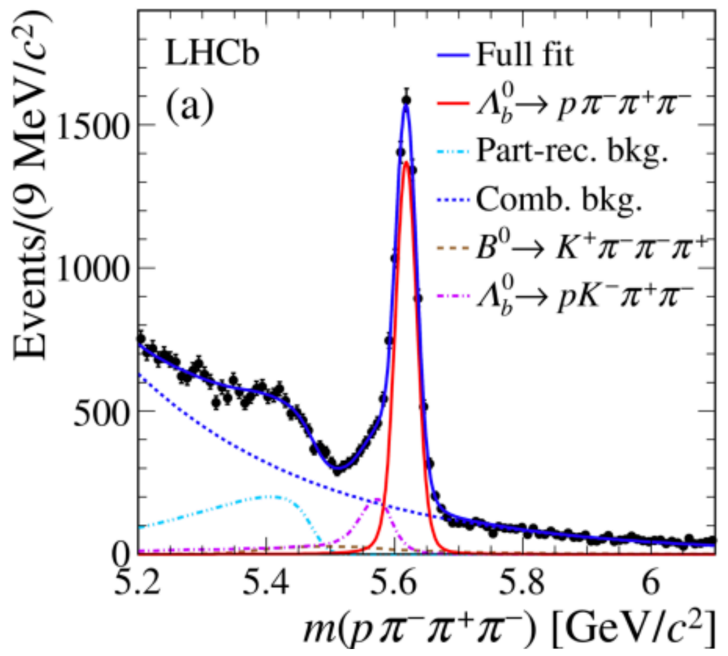
Parametrised histograms

Encode systematic uncertainties →

$$f(\boldsymbol{n},\boldsymbol{a}\,|\,\boldsymbol{\eta},\boldsymbol{\chi}) = \underbrace{\prod_{c\in\,\text{channels}}\ \prod_{b\in\,\text{bins}_c} \mathrm{Pois}\left(n_{cb}\,|\,\nu_{cb}(\boldsymbol{\eta},\boldsymbol{\chi})\right)}_{\text{Simultaneous measurement of multiple channels}}\ \underbrace{\prod_{\chi\in\boldsymbol{\chi}} c_\chi(a_\chi\,|\,\chi)}_{\text{constraint terms for “auxiliary measurements}}$$

Model-building and fitting

Unbinned



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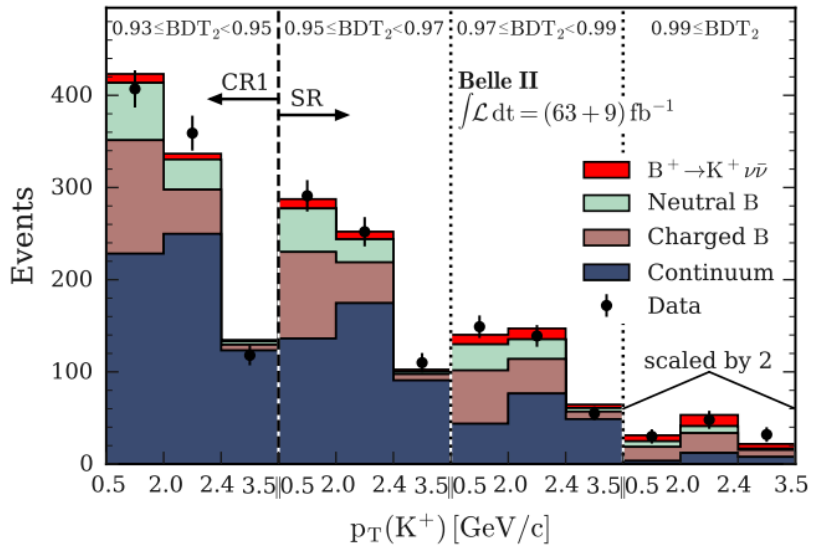
Binned



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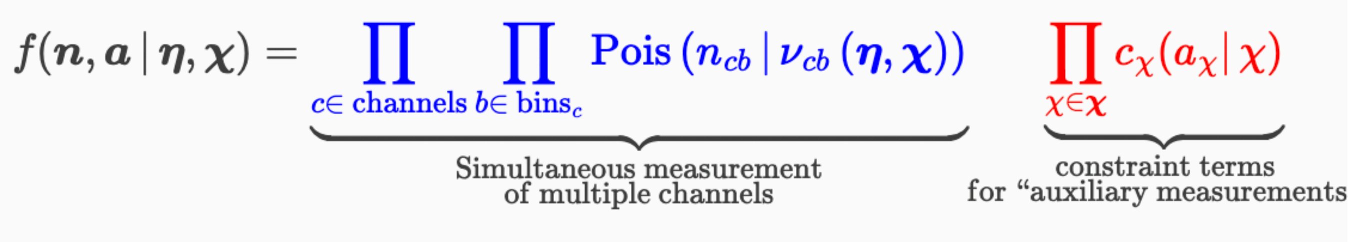


$$f(\boldsymbol{n},\boldsymbol{a}\,|\,\boldsymbol{\eta},\boldsymbol{\chi}) = \underbrace{\prod_{c\in\,\text{channels}}\;\prod_{b\in\,\text{bins}_c} \mathrm{Pois}\left(n_{cb}\,|\,\nu_{cb}\left(\boldsymbol{\eta},\boldsymbol{\chi}\right)\right)}_{\text{Simultaneous measurement of multiple channels}} \;\; \underbrace{\prod_{\chi\in\boldsymbol{\chi}} c_\chi(a_\chi\,|\,\chi)}_{\text{constraint terms for “auxiliary measurements}}$$

Parametrised histograms

Fitting

Maximum Likelihood Fit

$$L(\mu, \vec{\theta})$$

Limit Setting

- Frequentist
  - Asymptotic
  - Toy-based
- Bayesian

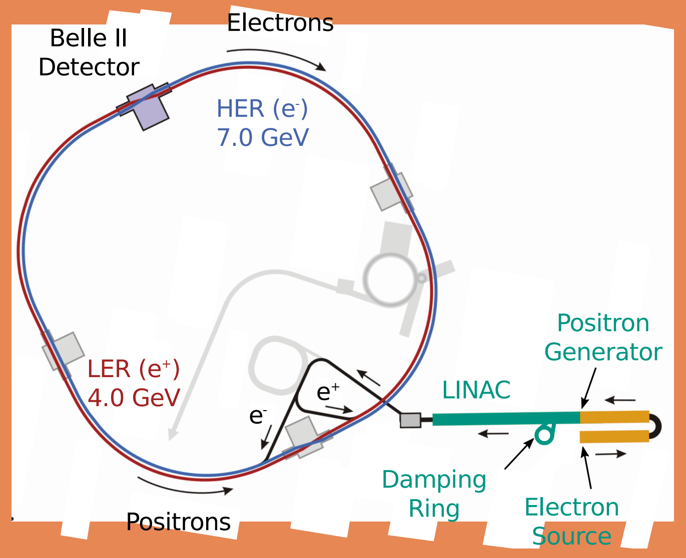
Observation

- Significance

$$\lambda(\mu) = \frac{\mathcal{L}(\mu,\hat{\hat{\theta}})}{\mathcal{L}(\hat{\mu},\hat{\theta})}$$

Types of systematic uncertainties

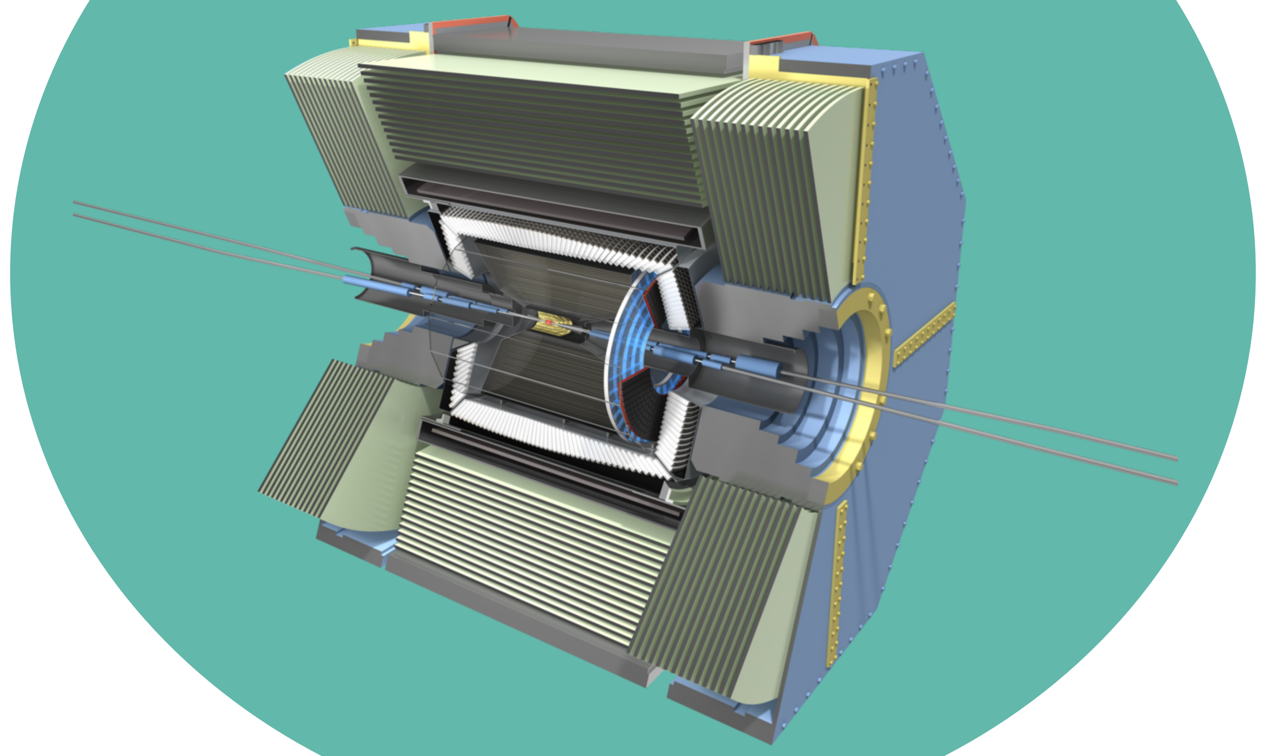
Accelerator



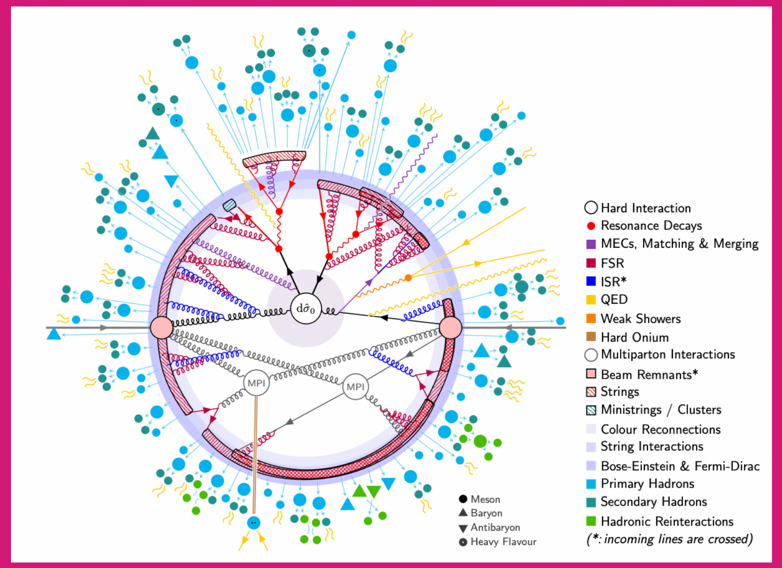
External Measurement

BESIII

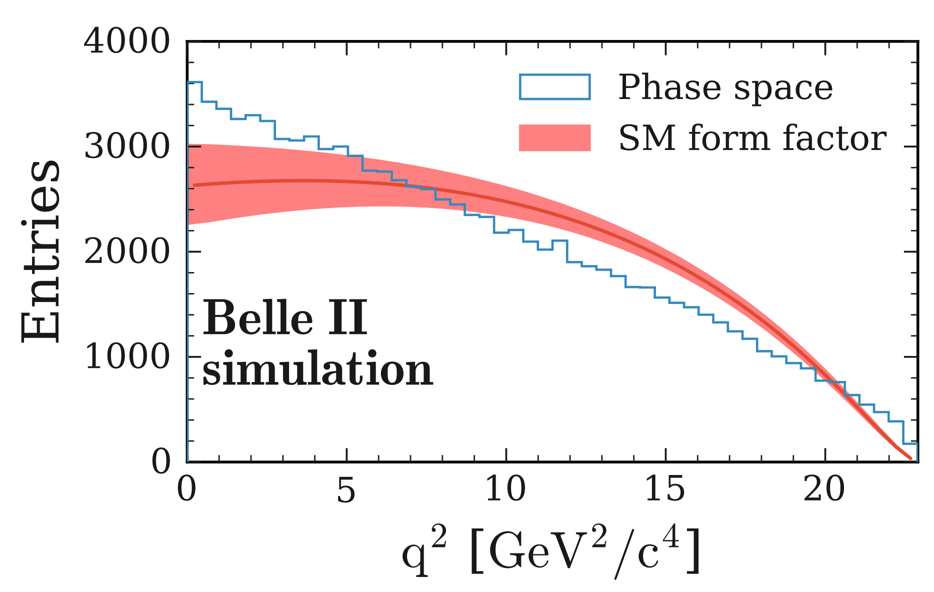
Detector



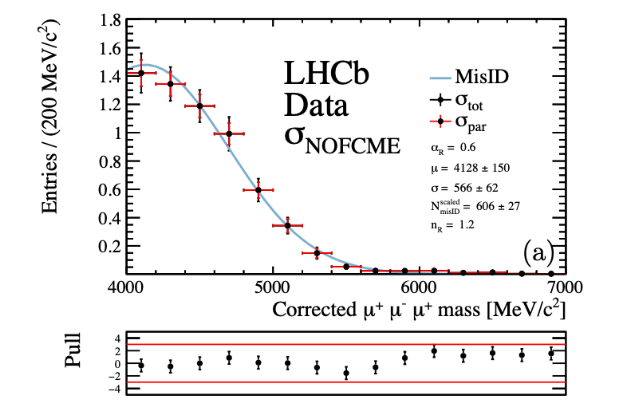
Simulation



Theory



Analysis Technique



How do we get systematic variations?

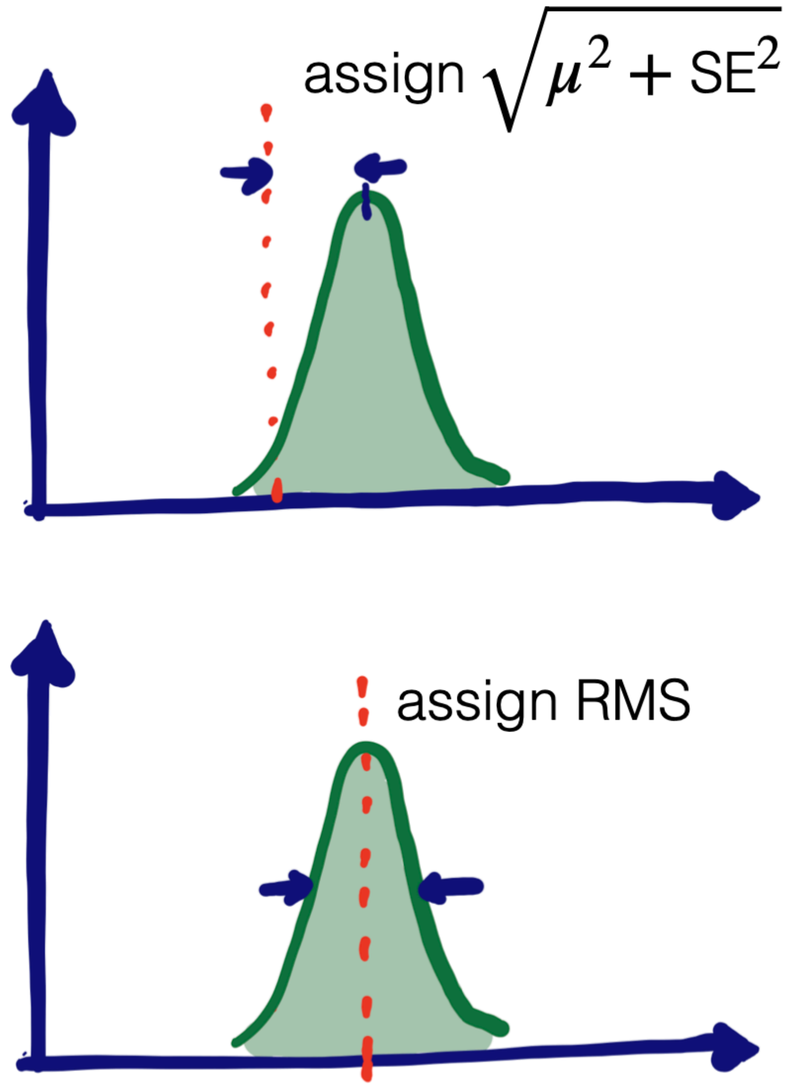
→ Systematic uncertainties can affect shape, normalisation or both

What samples do we use?

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

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

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

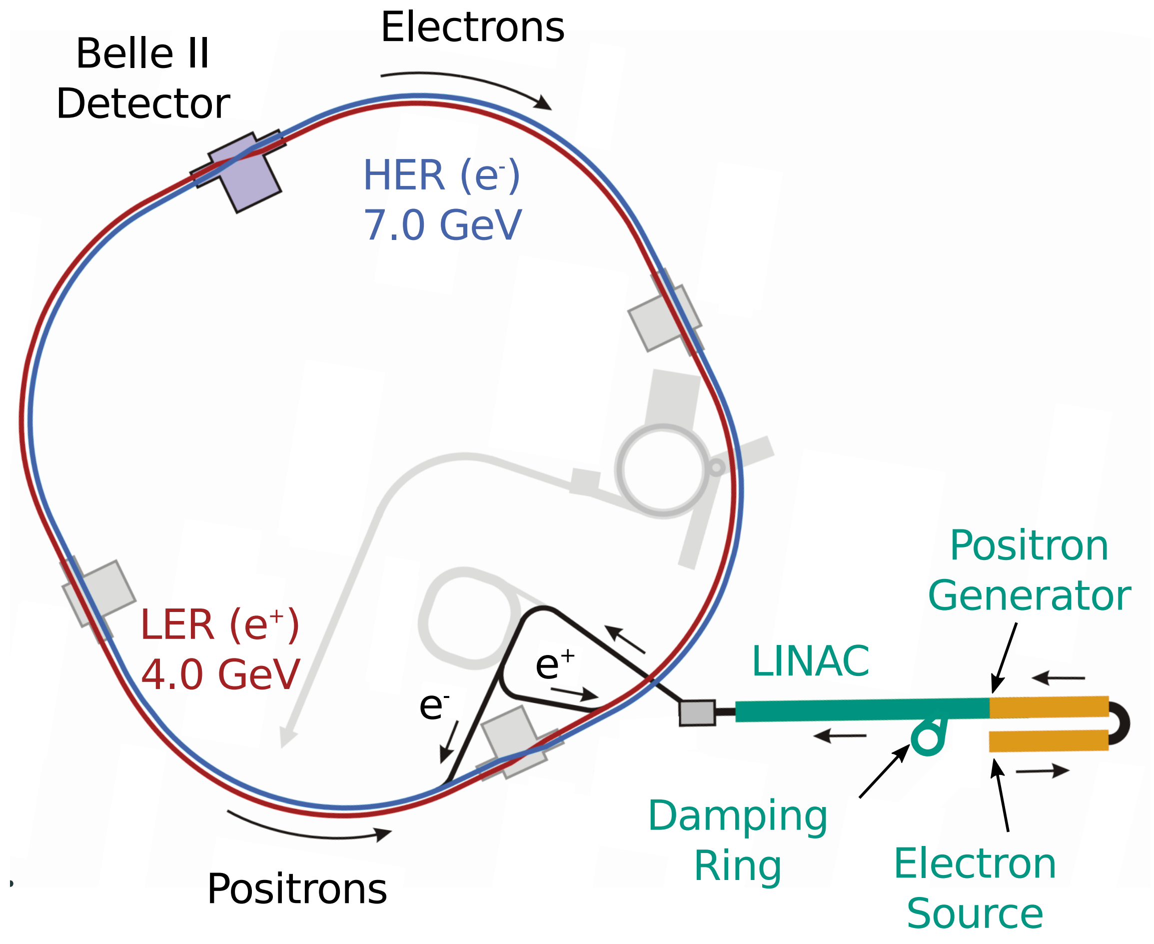


Practical examples of systematics*

*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)	



$\mathscr{B}(B^+ \to K^+ \nu\bar{\nu}) = 5 \times 10^{-6}$

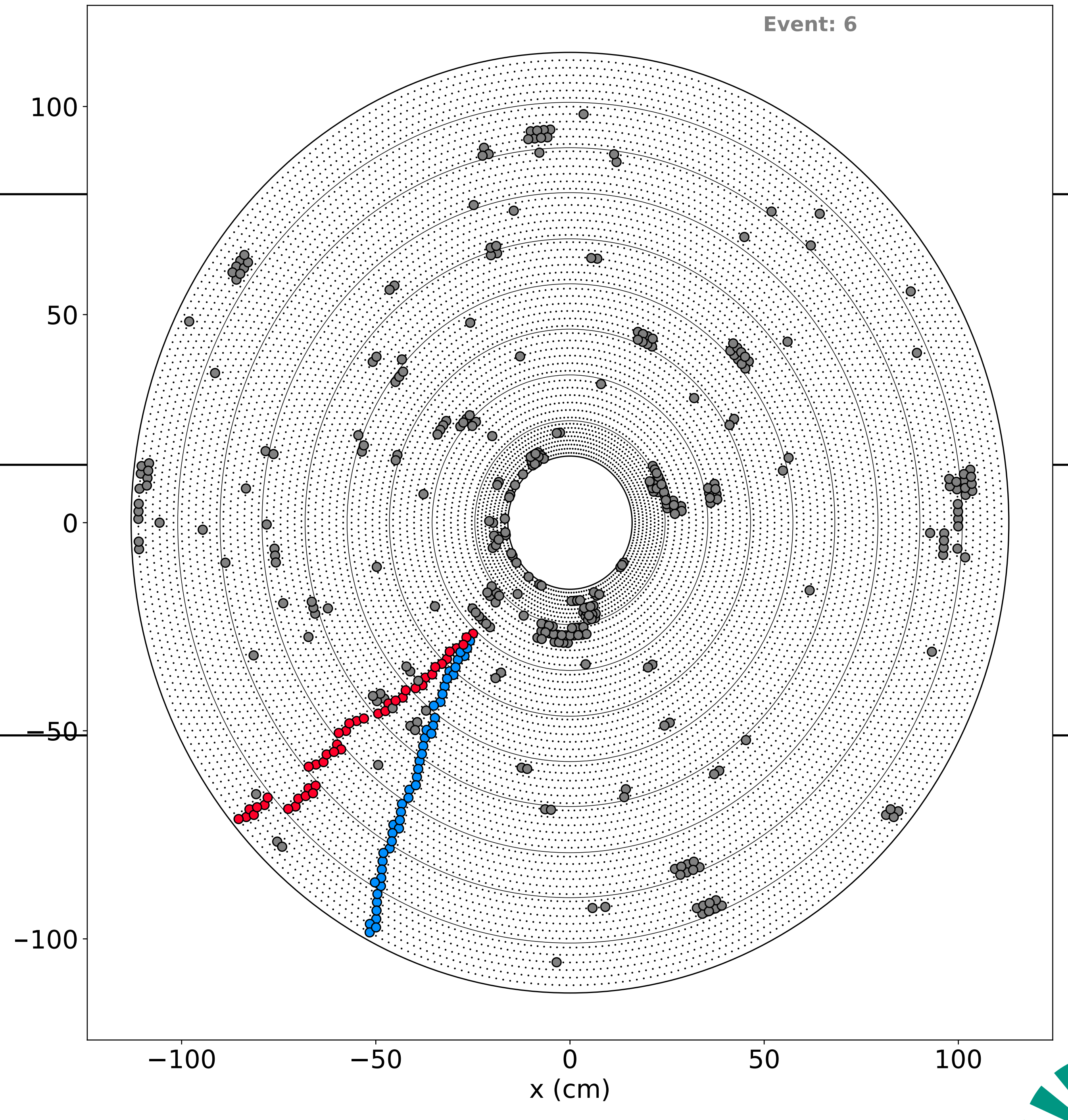
[Phys. Rev. Lett. 127, 181802 (2021)]

$\mathscr{B}(B^+ \to \mu^+\mu^-\mu^+\nu) = 1 \times 10^{-9}$

[Eur. Phys. J. C 79 (2019) 675]

Systematic uncertainties: Detector

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



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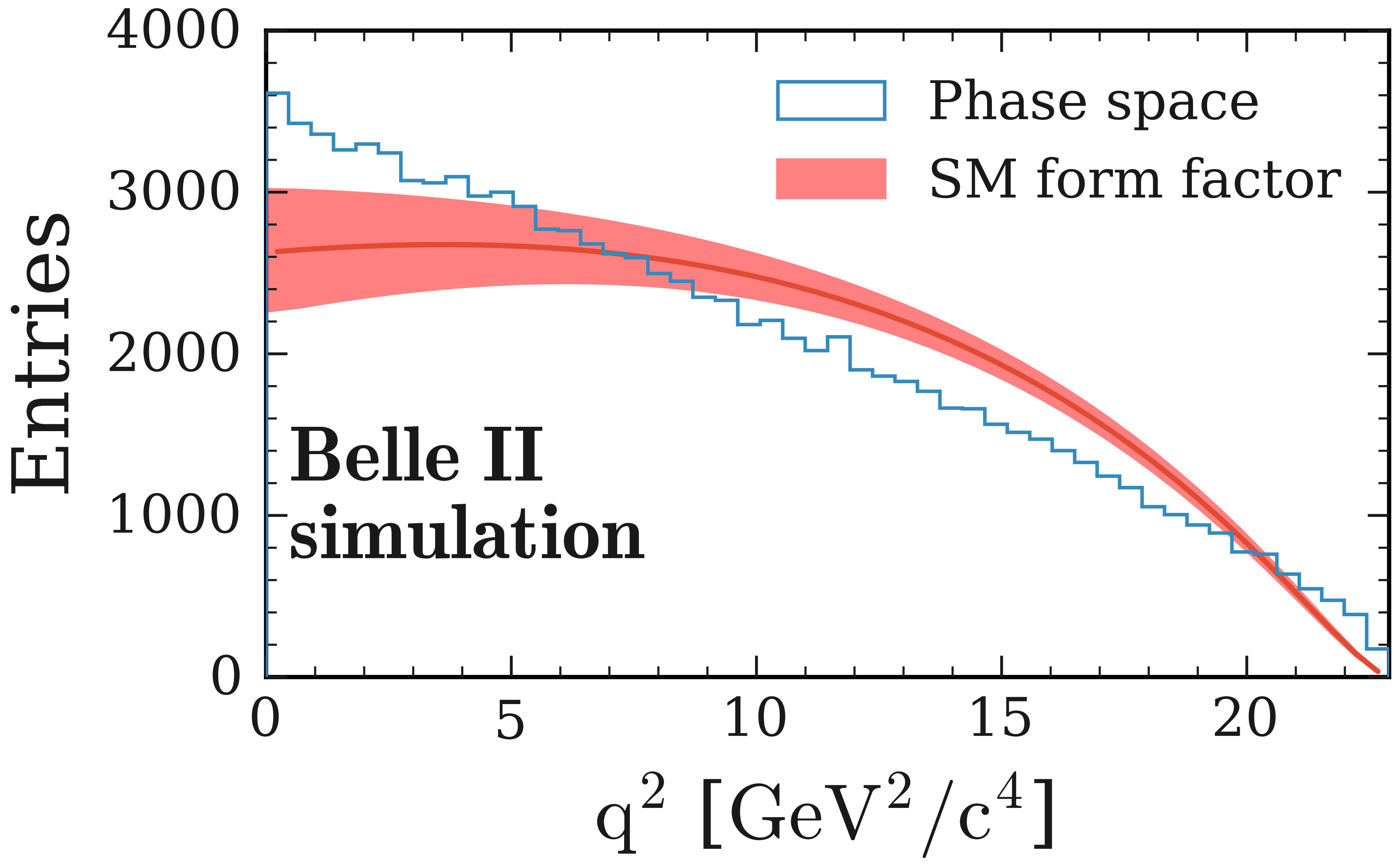
Systematic uncertainties: Theory

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)

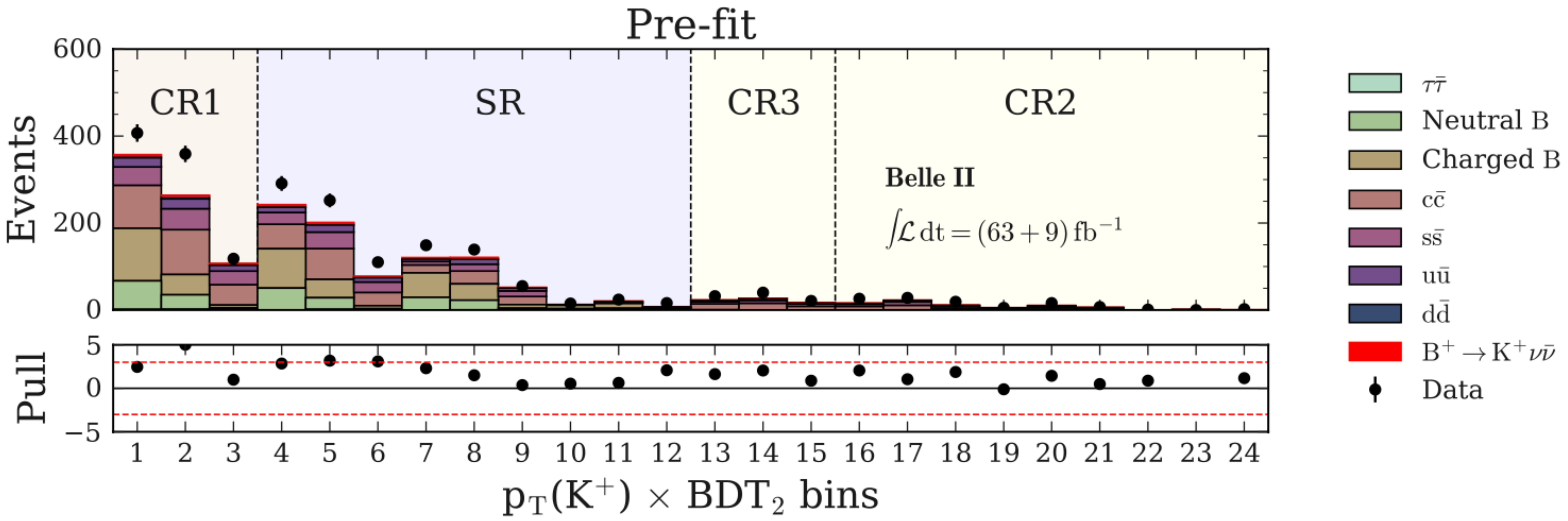
Systematic uncertainties: Further Analysis

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)

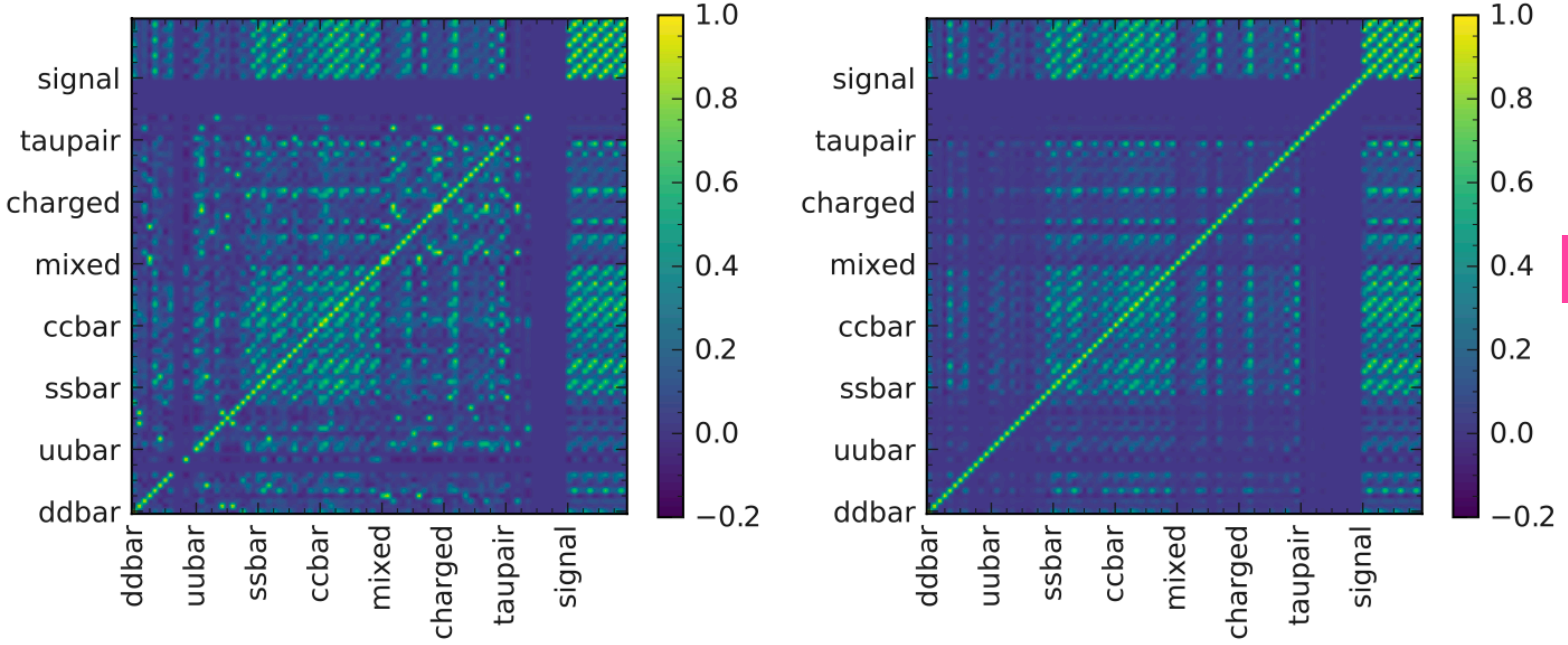
Method explained in [S.Glazov (Phystat 2021)]

Bootstrap

- PID (statistical error=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)
  - Construct covariance matrix
  - Translation to nuisance parameters: SVD decomposition + leading eigenvectors as the nuisances

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

Full covariance



3 leading eigenvectors

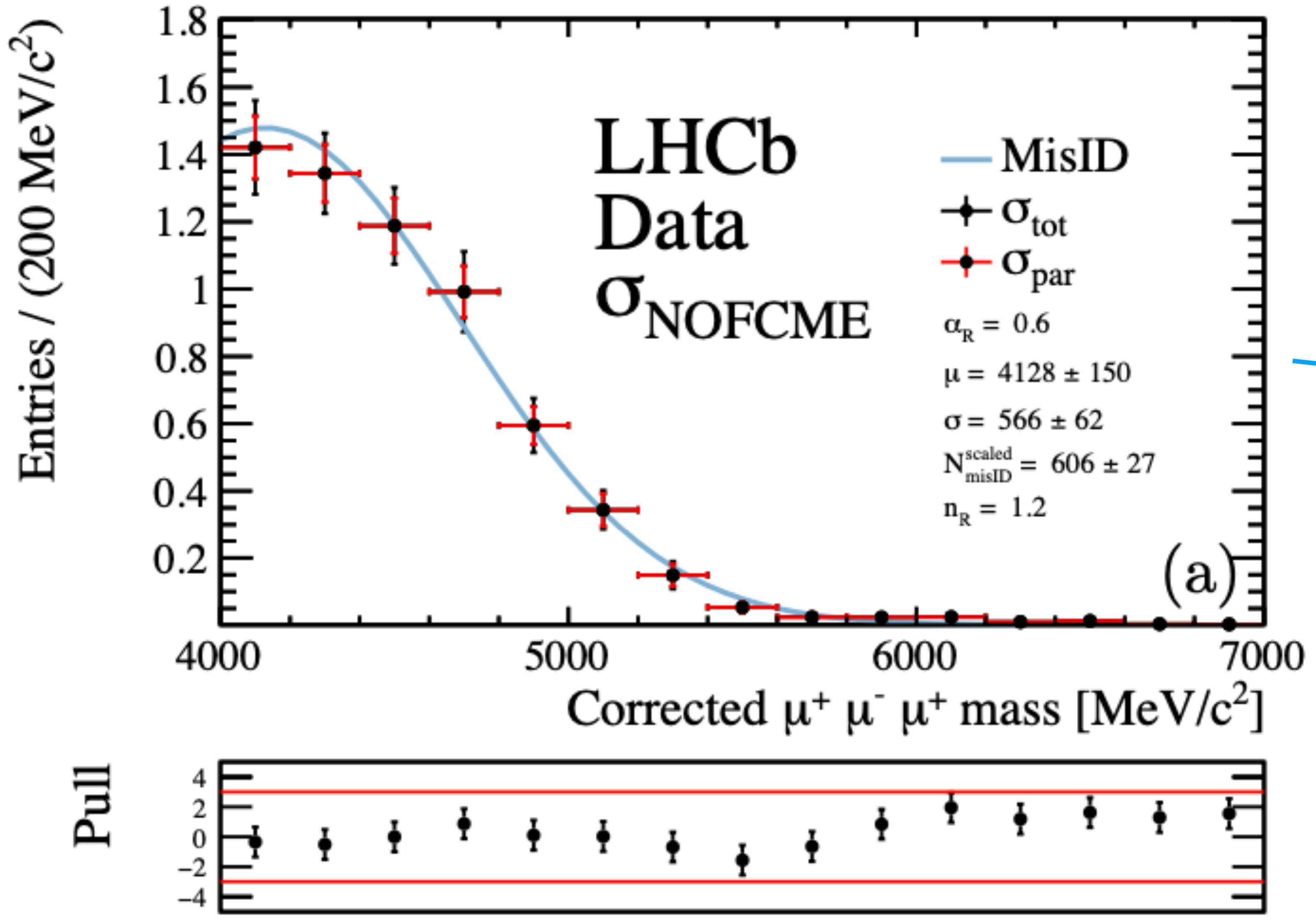
Correlated systematics (II)

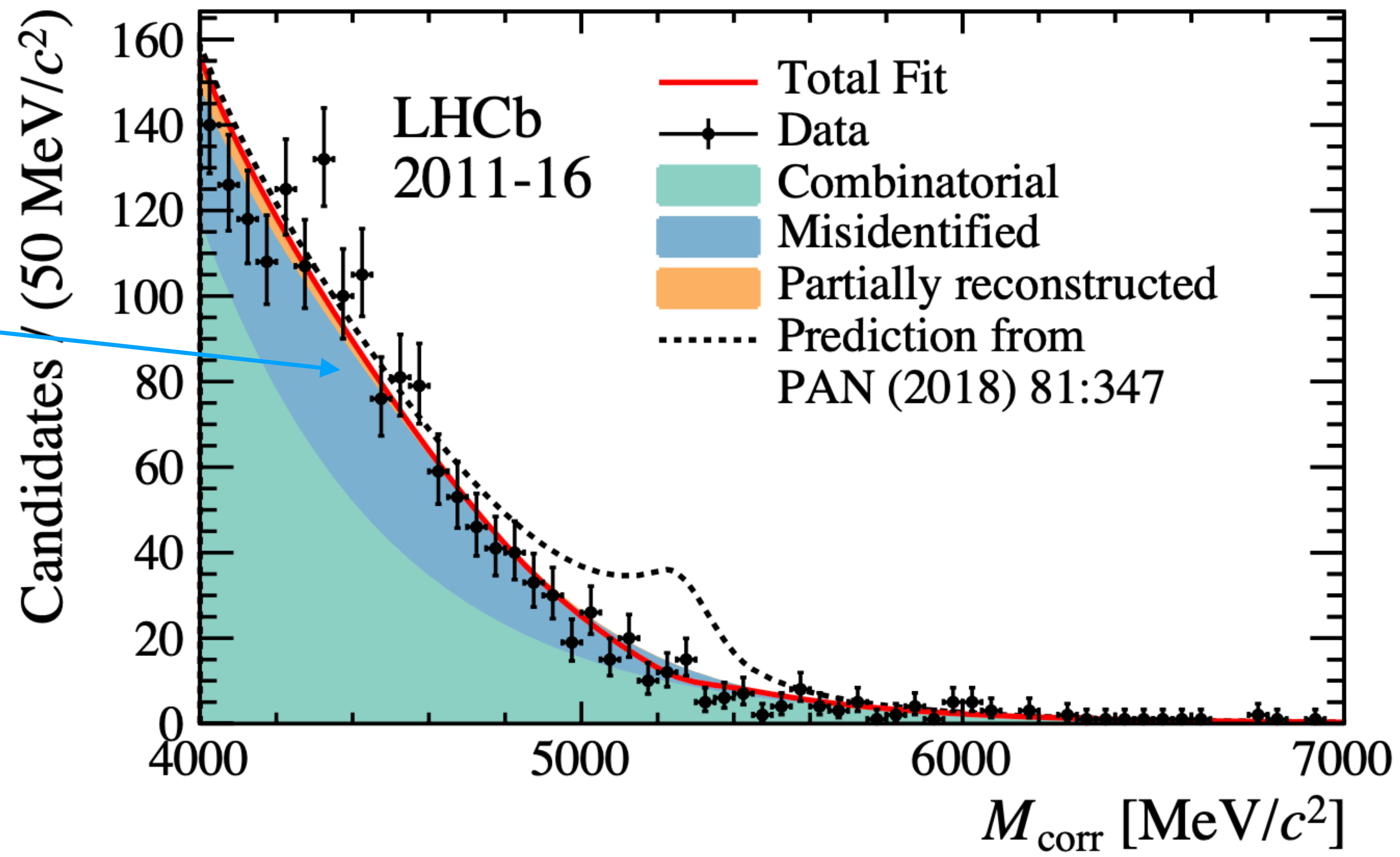
MVA-Gaussian

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

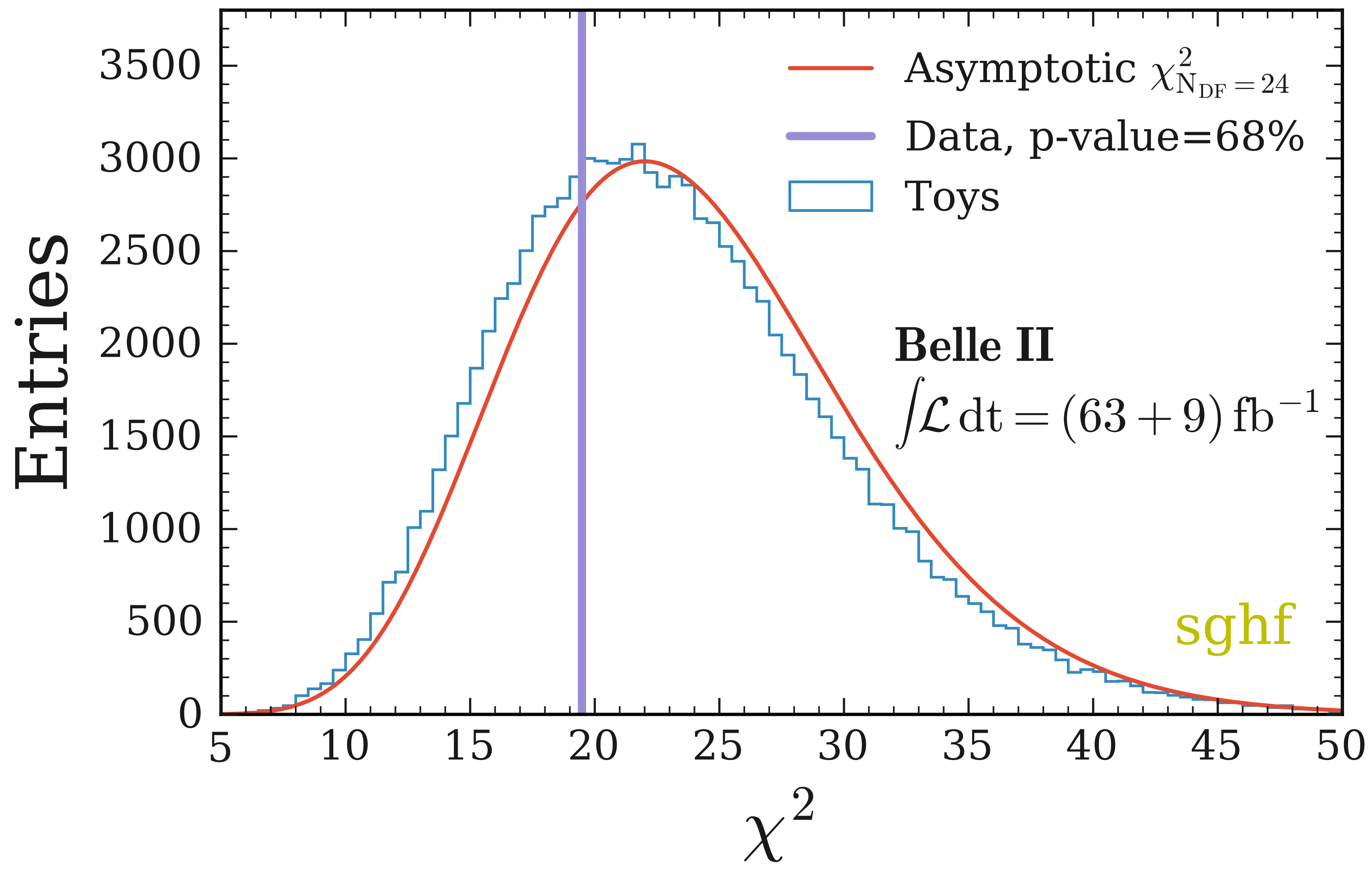


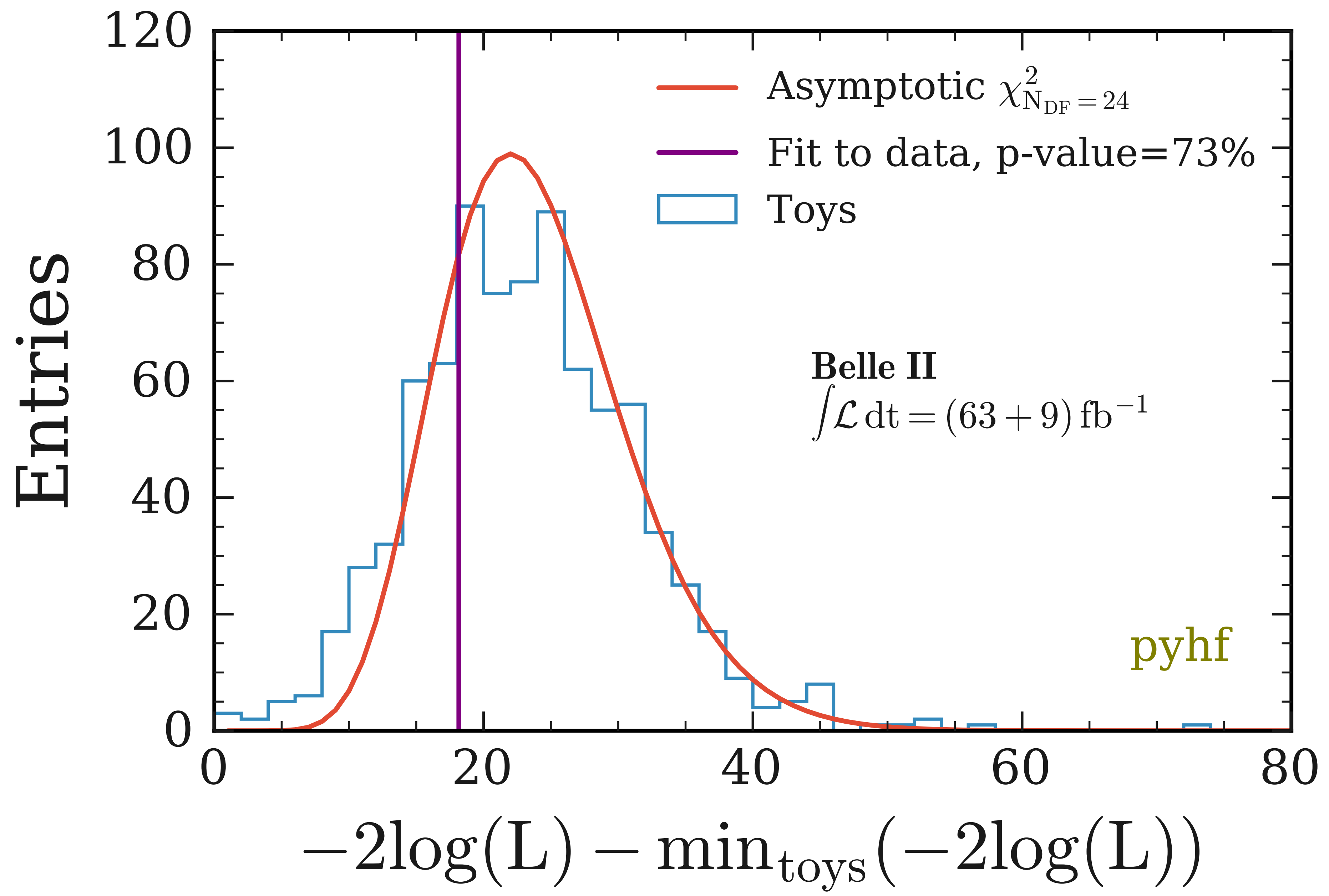


Data-model compatibility

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

Control samples are not always so easy to get by!

- Sometimes it is quite challenging to find a control sample (this is especially true for LHCb)
- Inflates the nuisances (if it does not make the nuisance parameters 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
- Incorporating such decays in your model is always very challenging? Is signal "background" strength to be unconstrained if you know it exists?

Calibration samples may not be necessarily very large

- Some of the analyses of rare decays are MC statistical error becomes prominent

Conclusion

In this presentation I have summarised the

- Statistical modelling of rare B-decay searches/measurements
- 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

Thank you!

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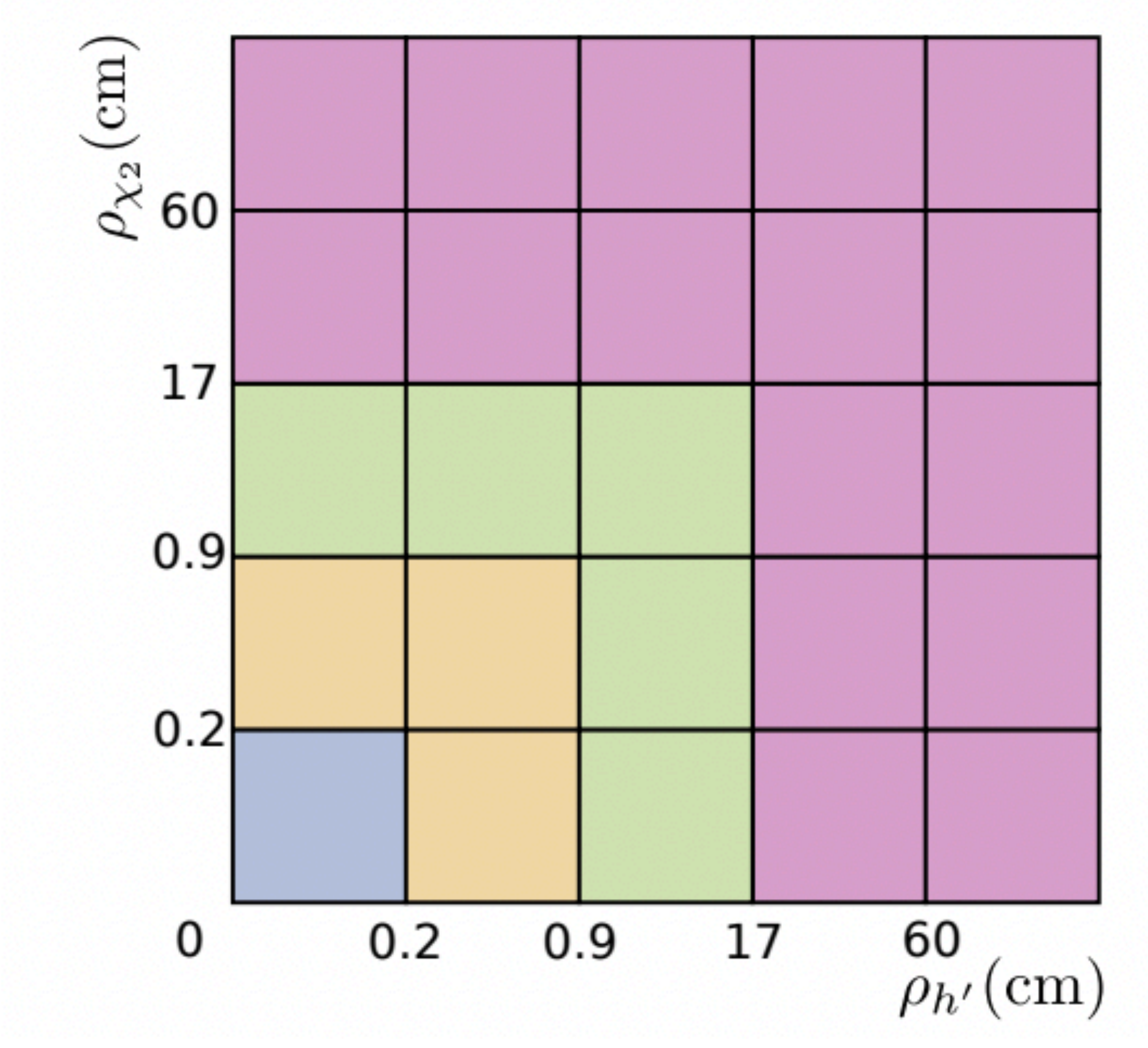
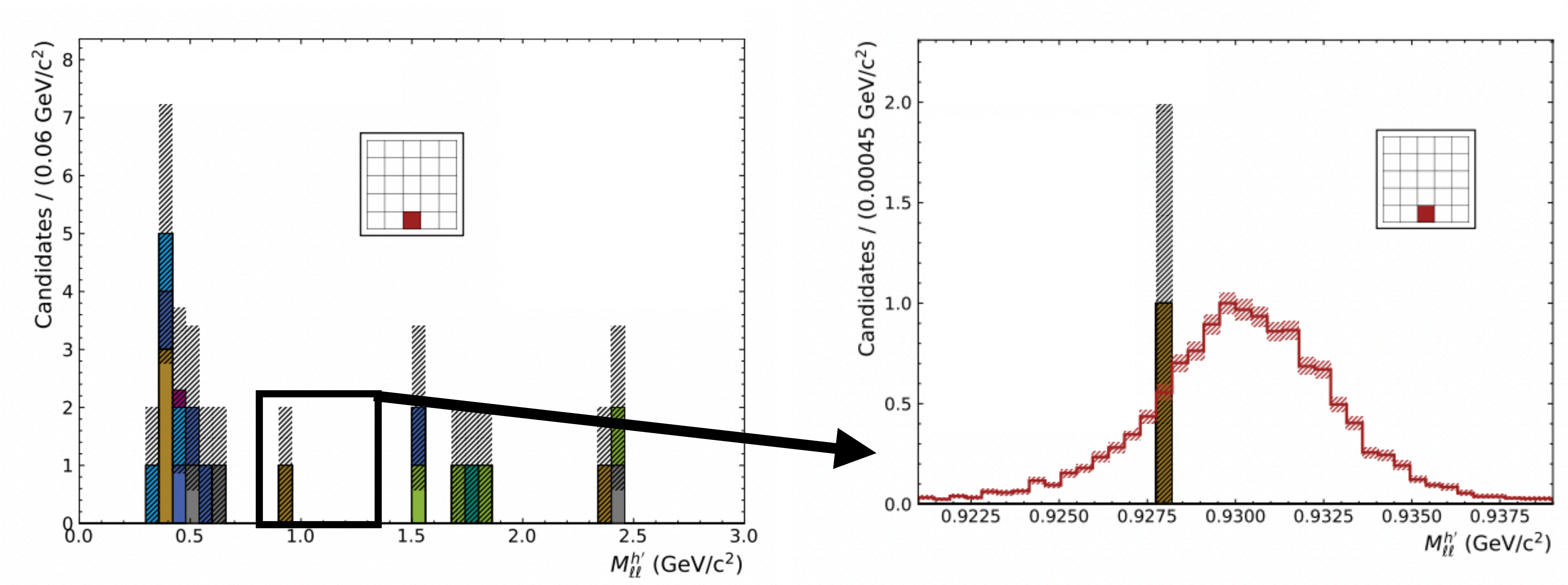
Back-up

Aside: DM searches

Another pitfall of very low statistics samples:

- If signal resolution very narrow (near delta like), dance of fitting to single events
- Asymptotic approximation may not hold





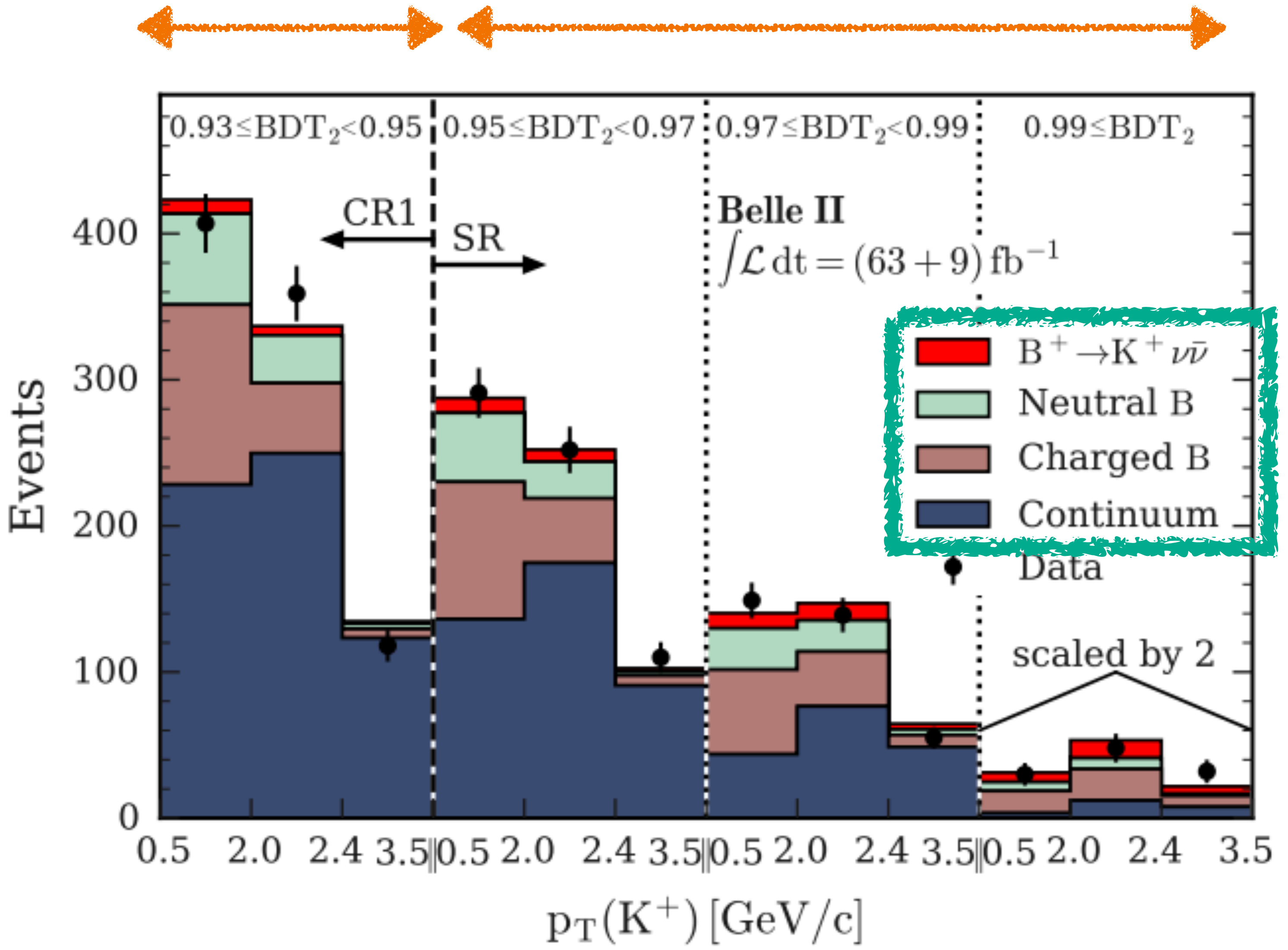
HistFactory Template

HistFactory Template

$$f(\vec{n},\vec{a}|\vec{\eta},\vec{\chi}) = \prod_{c\in\text{channels}} \prod_{b\in\text{bins}_c} \text{Pois}\left(n_{cb}|\nu_{cb}(\vec{\eta},\vec{\chi})\right) \prod_{\chi\in\vec{\chi}} c_\chi(a_\chi|\chi)$$

$$\nu_{cb}(\vec{\eta},\vec{\chi}) = \sum_{s\in\text{samples}} \underbrace{\left(\sum_{\kappa\in\vec{\kappa}}\kappa_{scb}(\vec{\eta},\vec{\chi})\right)}_{\text{multiplicative}} \left(\nu^0_{scb}(\vec{\eta},\vec{\chi}) + \underbrace{\sum_{\Delta\in\vec{\Delta}}\Delta_{scb}(\vec{\eta},\vec{\chi})}_{\text{additive}}\right)$$

Channels = disjoint measurement regions eg. signal, control



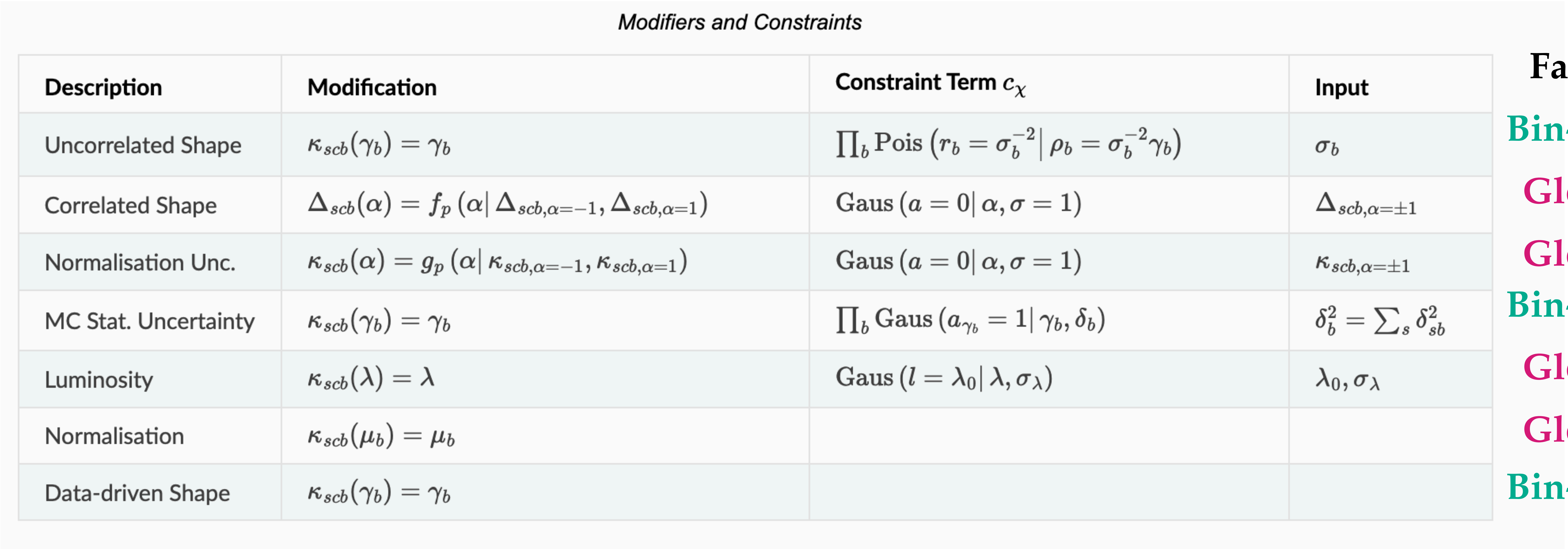
Use: Multiple disjoint channels (or regions) of binned distributions with multiple samples contributing to each with additional (possibly shared) systematics between sample estimates

Main pieces:

- Main Poisson p.d.f. for simultaneous measurement of multiple channels
- Event rates ν_{cb} from nominal rate ν^0_{scb} and rate modifiers κ and Δ
- Constraint p.d.f. (+ data) for "auxiliary measurements"
  - encoding systematic uncertainties (normalization, shape, etc)
- $\vec{n}$: events, $\vec{a}$: auxiliary data, $\vec{\eta}$: unconstrained pars, $\vec{\chi}$: constrained pars

Samples = physics processes

HistFactory Template



Modifiers and Constraints

Description	Modification	Constraint Term c_χ	Input
Uncorrelated Shape	$\kappa_{scb}(\gamma_b) = \gamma_b$	$\prod_b \mathrm{Pois}\left(r_b = \sigma_b^{-2} \middle| \rho_b = \sigma_b^{-2}\gamma_b\right)$	σ_b
Correlated Shape	$\Delta_{scb}(\alpha) = f_p\left(\alpha \middle| \Delta_{scb,\alpha=-1}, \Delta_{scb,\alpha=1}\right)$	$\mathrm{Gaus}\left(a = 0 \middle| \alpha, \sigma = 1\right)$	$\Delta_{scb,\alpha=\pm1}$
Normalisation Unc.	$\kappa_{scb}(\alpha) = g_p\left(\alpha \middle| \kappa_{scb,\alpha=-1}, \kappa_{scb,\alpha=1}\right)$	$\mathrm{Gaus}\left(a = 0 \middle| \alpha, \sigma = 1\right)$	$\kappa_{scb,\alpha=\pm1}$
MC Stat. Uncertainty	$\kappa_{scb}(\gamma_b) = \gamma_b$	$\prod_b \mathrm{Gaus}\left(a_{\gamma_b} = 1 \middle| \gamma_b, \delta_b\right)$	$\delta_b^2 = \sum_s \delta_{sb}^2$
Luminosity	$\kappa_{scb}(\lambda) = \lambda$	$\mathrm{Gaus}\left(l = \lambda_0 \middle| \lambda, \sigma_\lambda\right)$	$\lambda_0, \sigma_\lambda$
Normalisation	$\kappa_{scb}(\mu_b) = \mu_b$		
Data-driven Shape	$\kappa_{scb}(\gamma_b) = \gamma_b$		

Factor	"Data"
Bin-wise	Per-bin
Global	Per-bin
Global	Per-sample
Bin-wise	Per-bin
Global	Nothing
Global	Nothing
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

Systematic Uncertainties

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

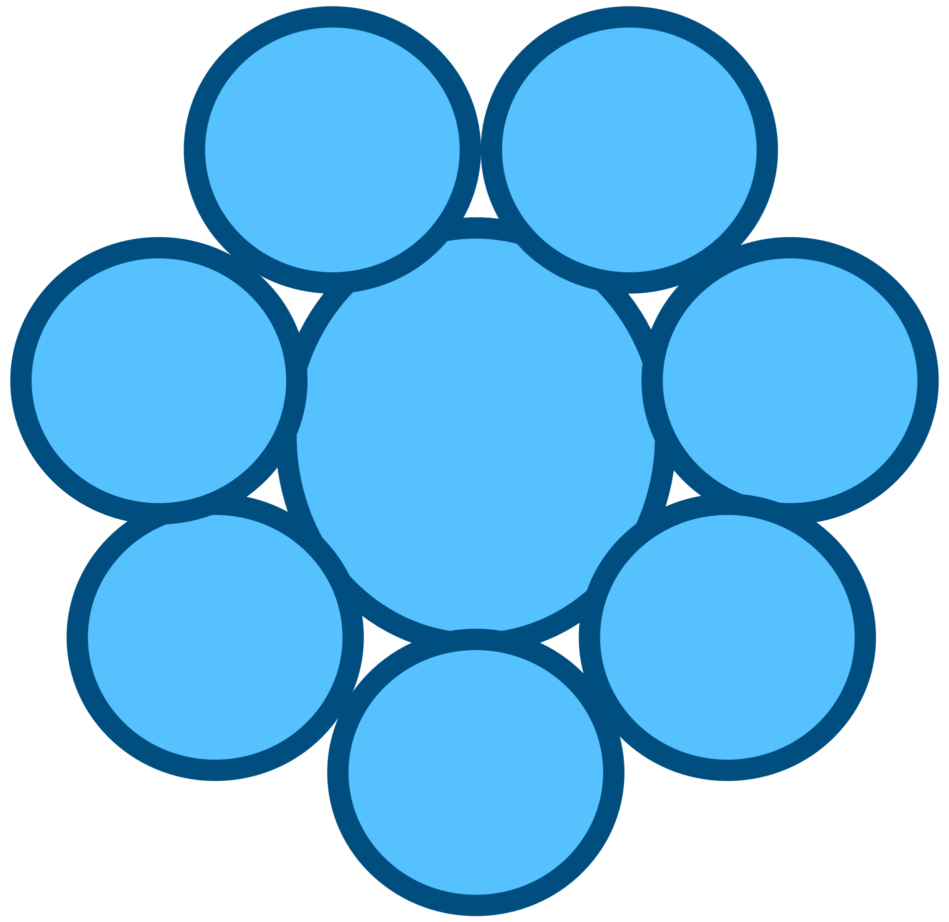
Systematic Uncertainties

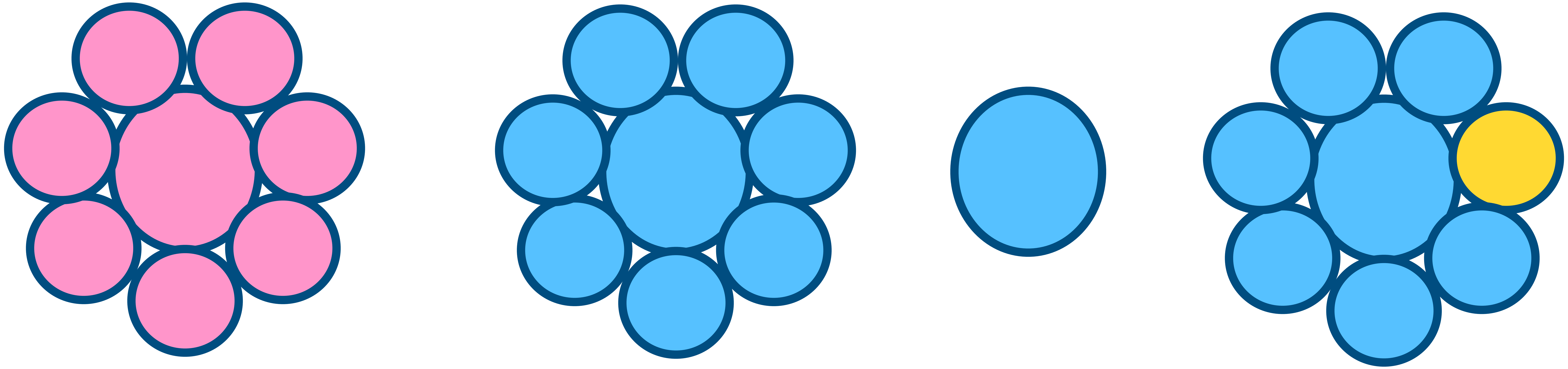
Further Analysis	**B+ -> K+ nu \bar{nu} (Belle II)**	**B+ ->mu+ mu- mu+ nu (LHCb)**	
		Trigger efficiency	
	Tracking efficiency	Tracking effciency	

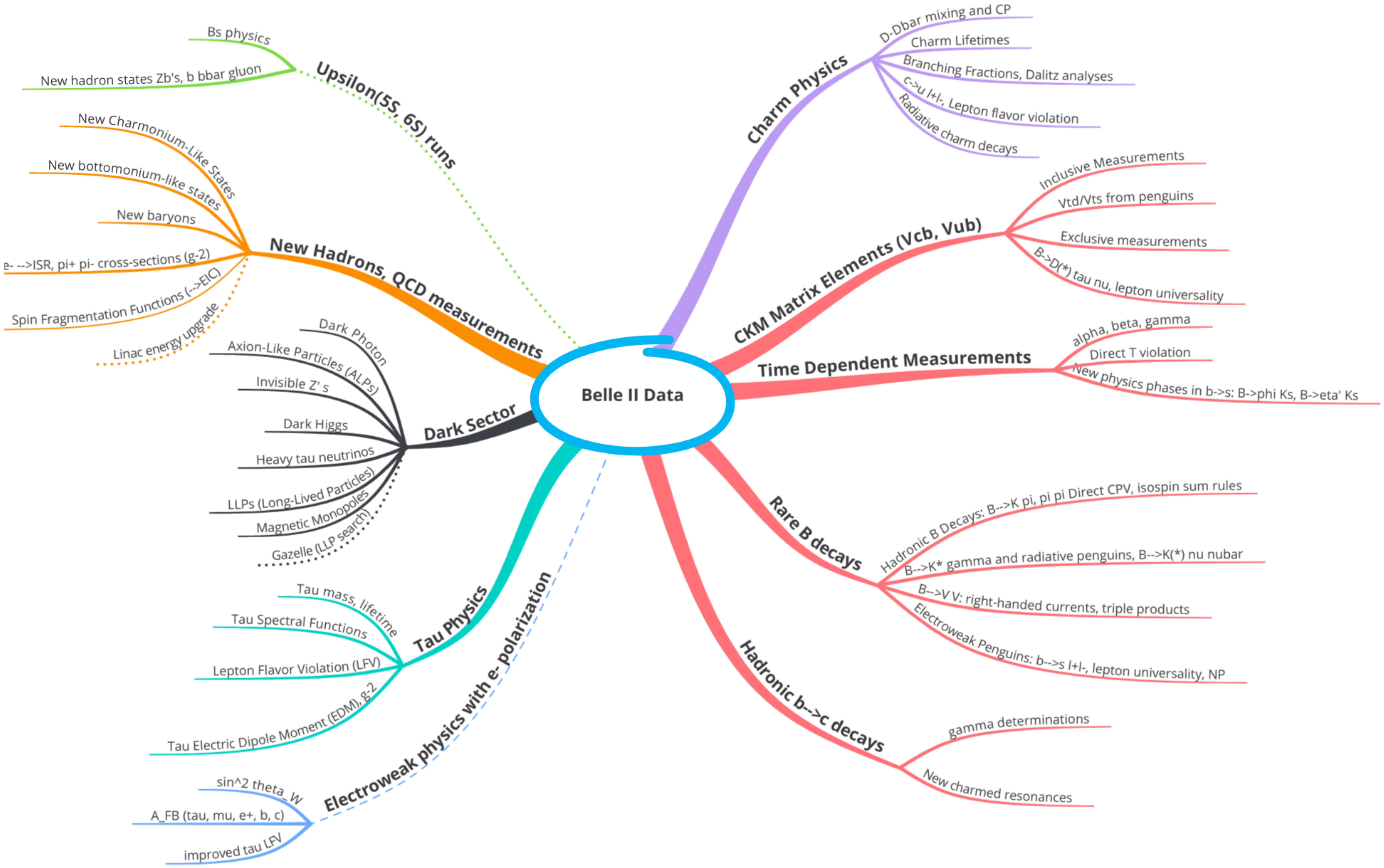
Slavomira Stefkova, slavomira.stefkova@kit.edu

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**





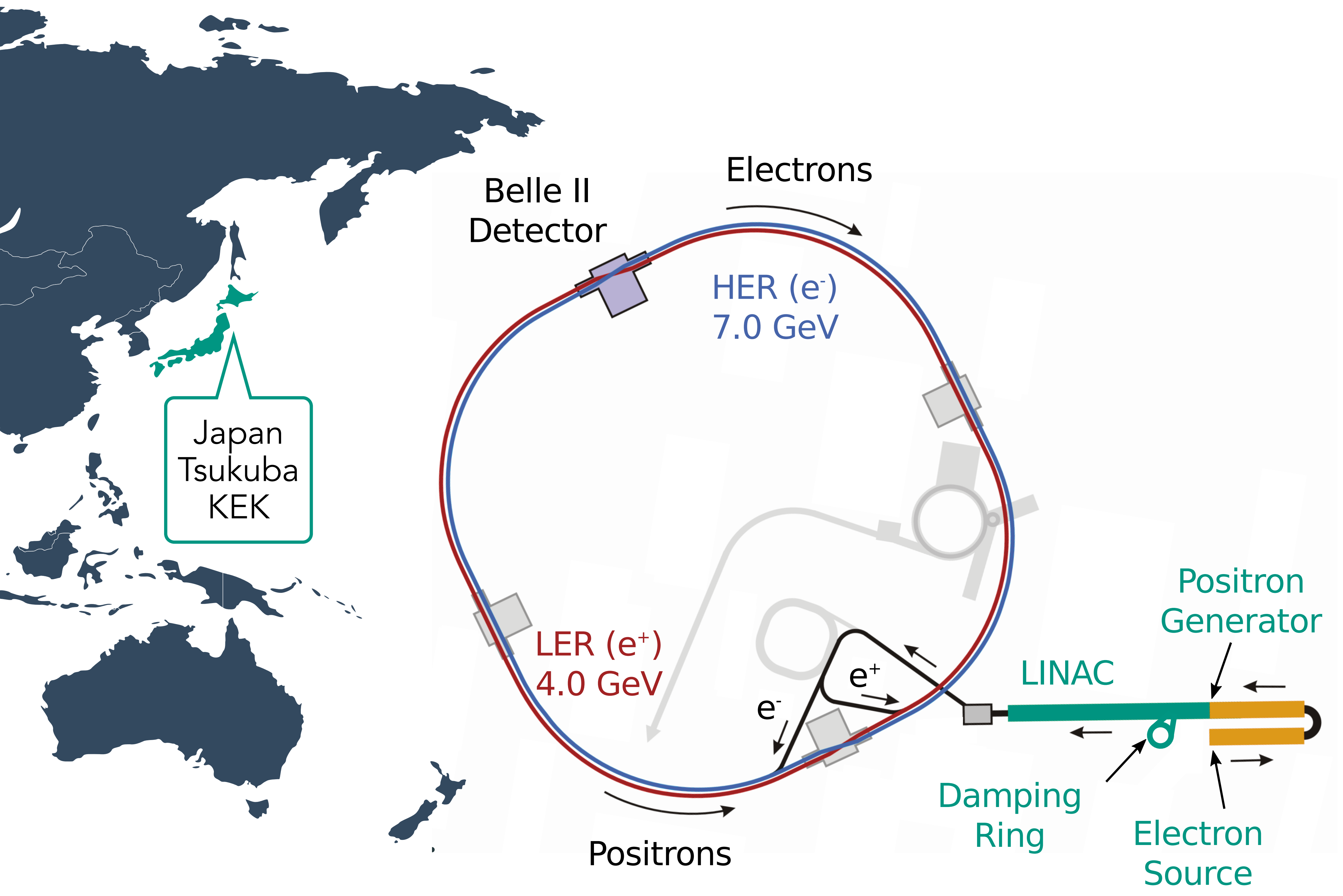


- **Belle II Data**
  - Upsilon(5S, 6S) runs
    - Bs physics
    - New hadron states Zb's, b bbar gluon
  - New Hadrons, QCD measurements
    - New Charmonium-Like States
    - New bottomonium-like states
    - New baryons
    - e- -->ISR, pi+ pi- cross-sections (g-2)
    - Spin Fragmentation Functions (-->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

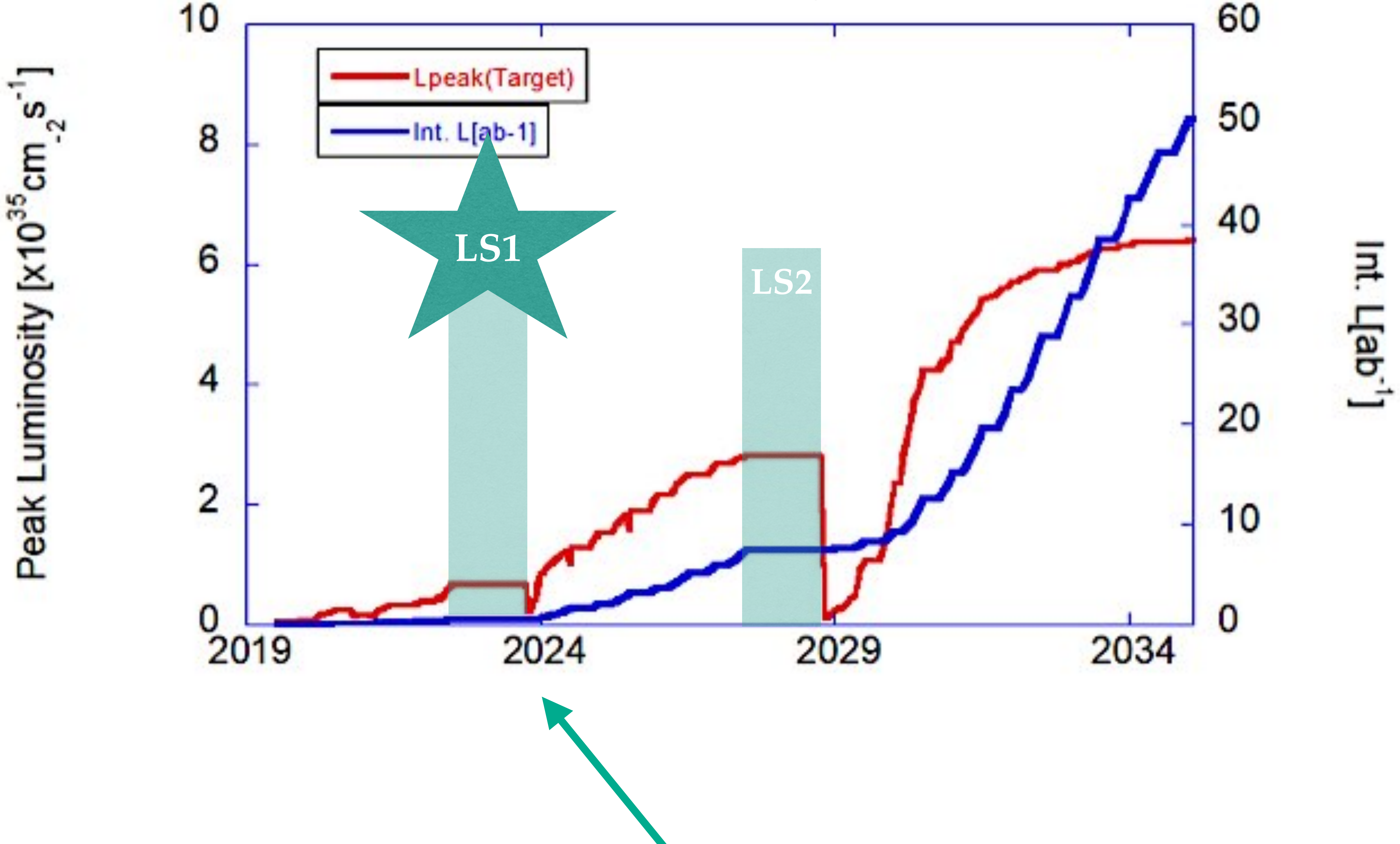
SuperKEKB

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

- $\Upsilon(4S) \rightarrow B\bar{B}$ 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



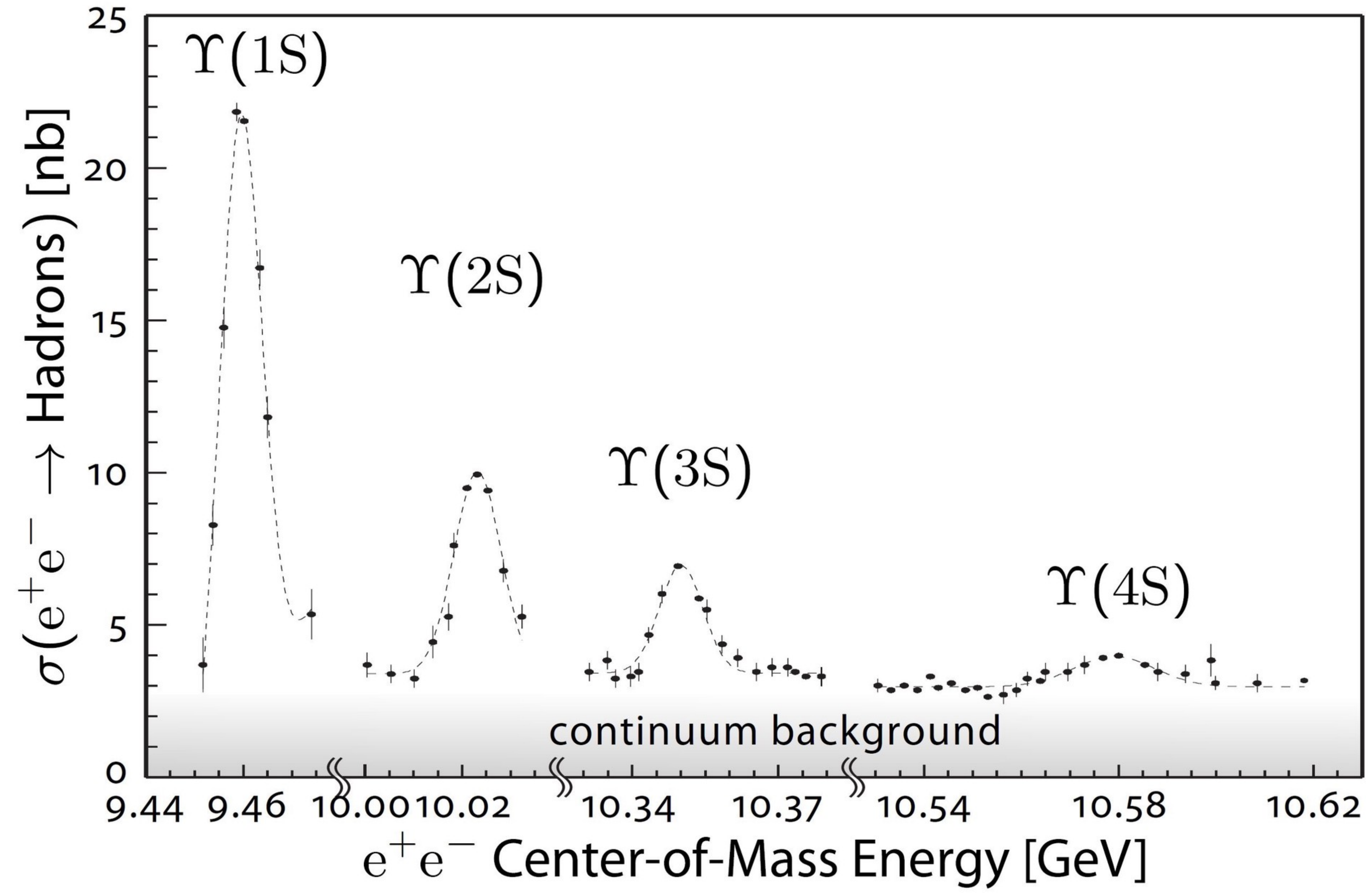
- Now in long shutdown **(LS1)** until this autumn
- **Final aim:** operate at **30 × higher $\mathscr{L}_{\text{inst}}$** than KEKB at a cost of **$\mathcal{O}(10)$ × higher** backgrounds
- **Final luminosity goal: $\mathscr{L}_{int} = 50$ ab^{-1}**

Backgrounds at e^+e^- Collider

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

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

Continuum backgrounds



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

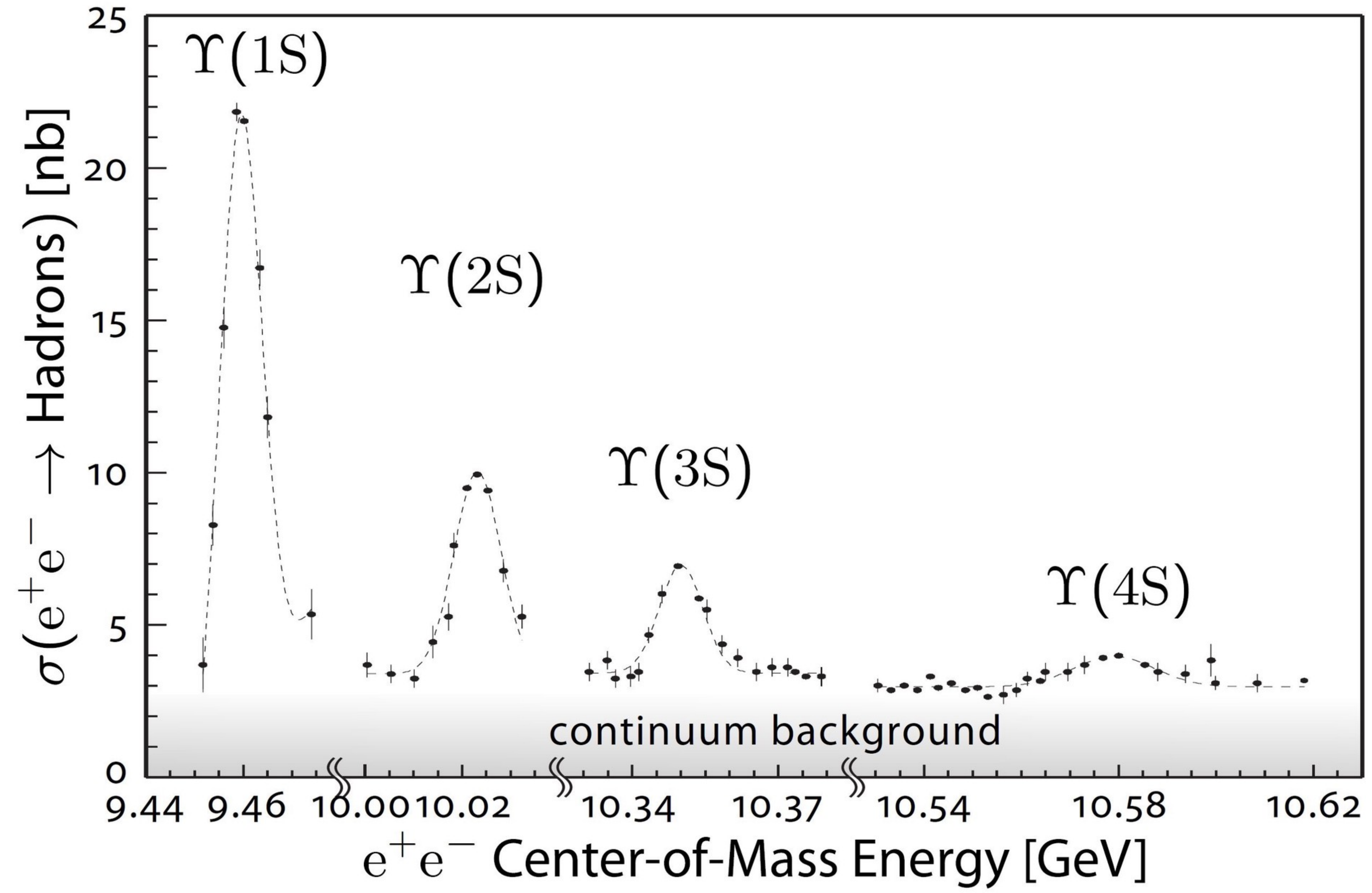
Backgrounds at e^+e^- Collider

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



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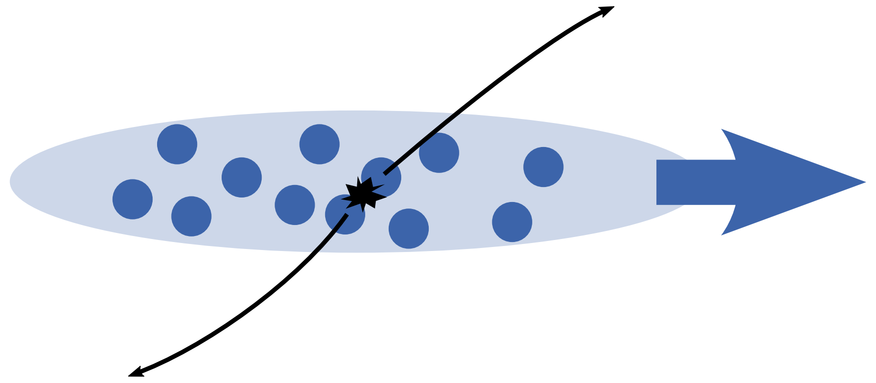
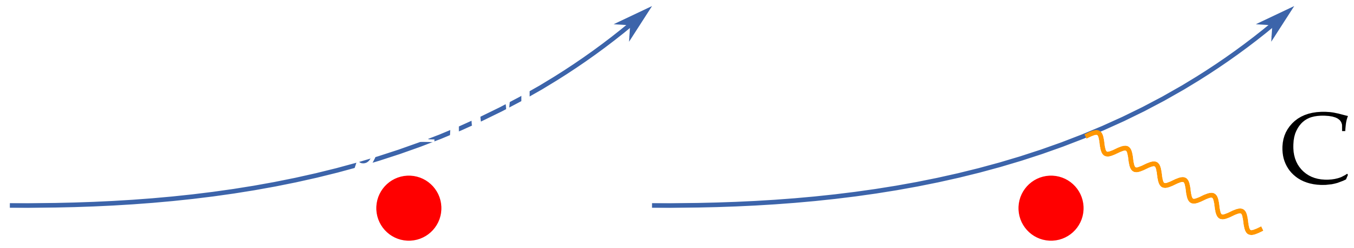
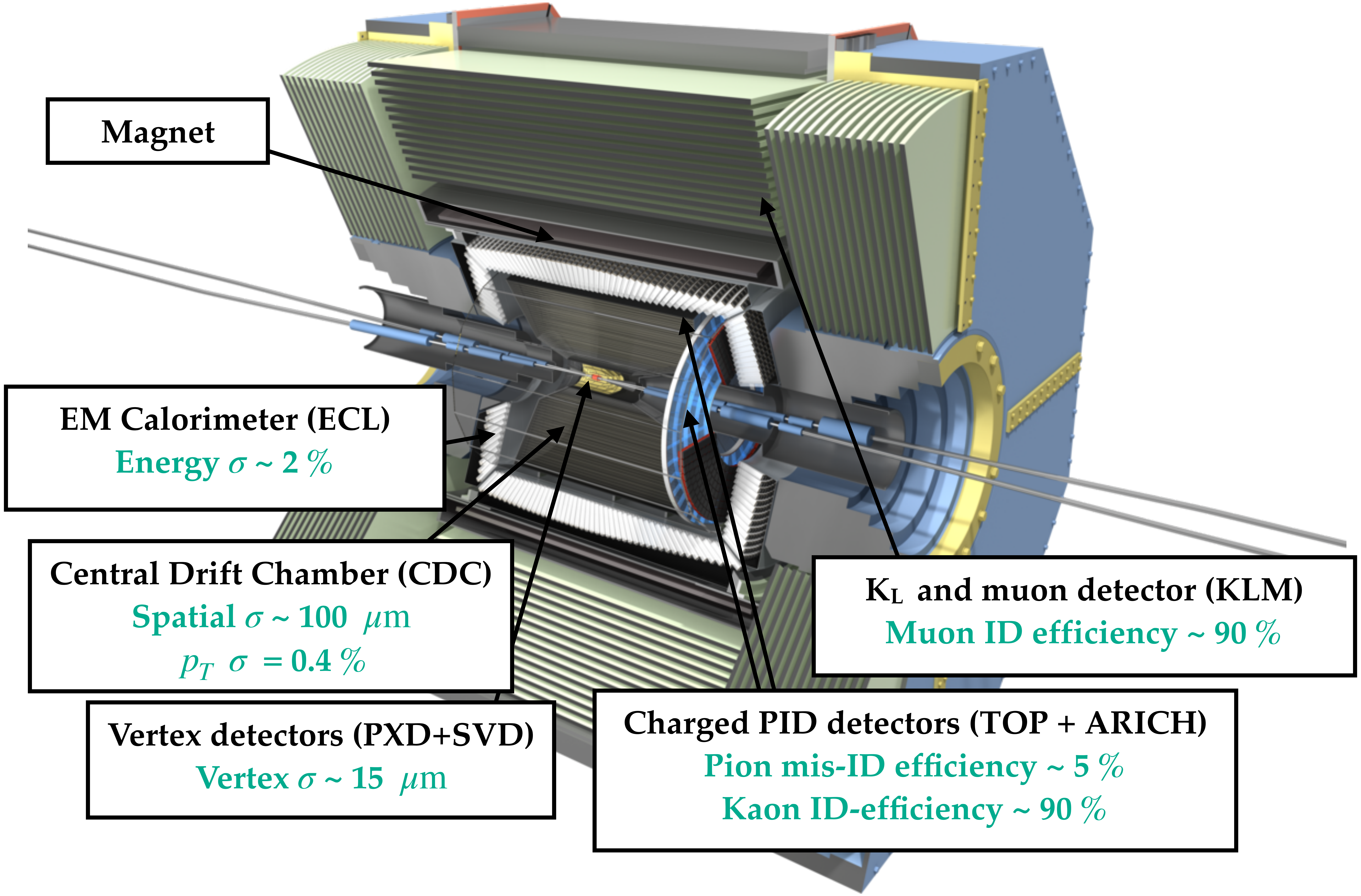


Touschek scattering



Coulomb scattering

Belle II Detector



Magnet

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

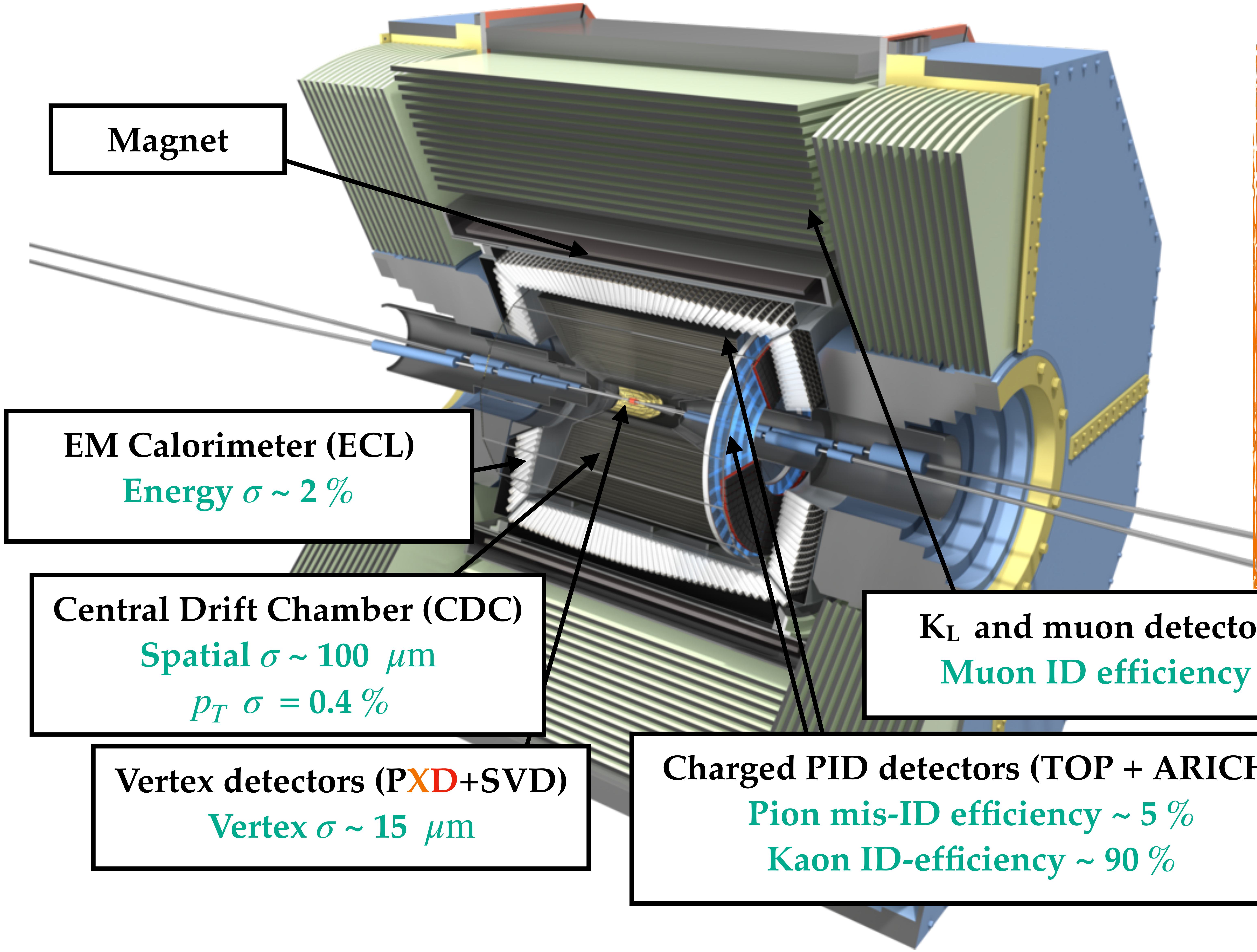
Central Drift Chamber (CDC)
Spatial $\sigma \sim 100\ \mu\mathrm{m}$
$p_T\ \sigma = 0.4\,\%$

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

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

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

Belle II Detector



Magnet

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

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

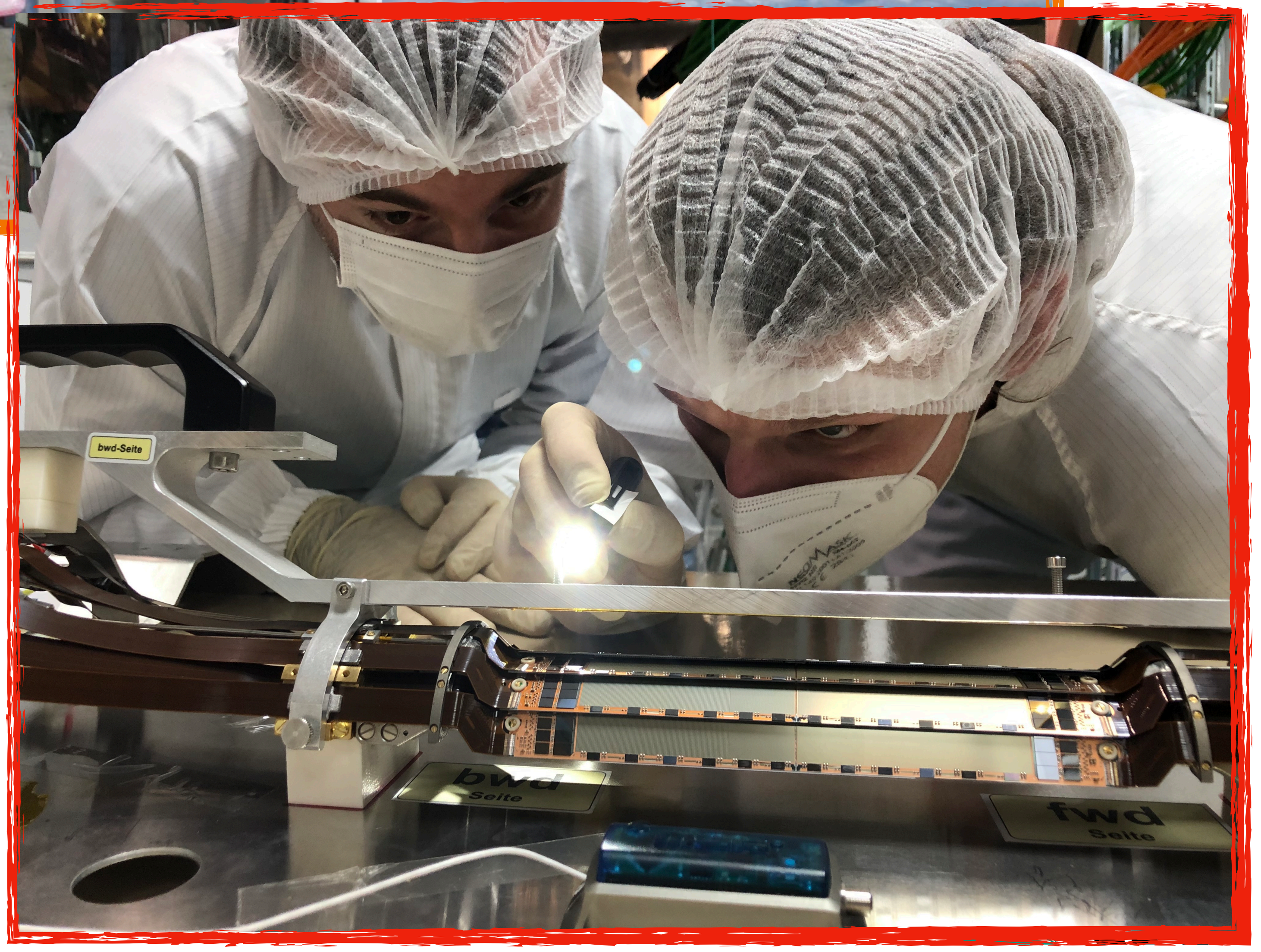
Vertex detectors (PXD+SVD)
Vertex $\sigma \sim 15\ \mu m$

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

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

New PXD arrived safely to KEK!

Belle II Deutschland @belle2germany · Mar 18
Auch Detektoren haben weite Wege hinter sich! Unser neuer Pixeldetektor PXD2 hat sich am Mittwoch morgen auf den Weg vom @desy in Hamburg nach Japan gemacht. Damit nichts kaputt geht, bekam der empfindliche Detektor einen eigenen Sitzplatz.
Mehr dazu: belle2.de/detail/belle-i...

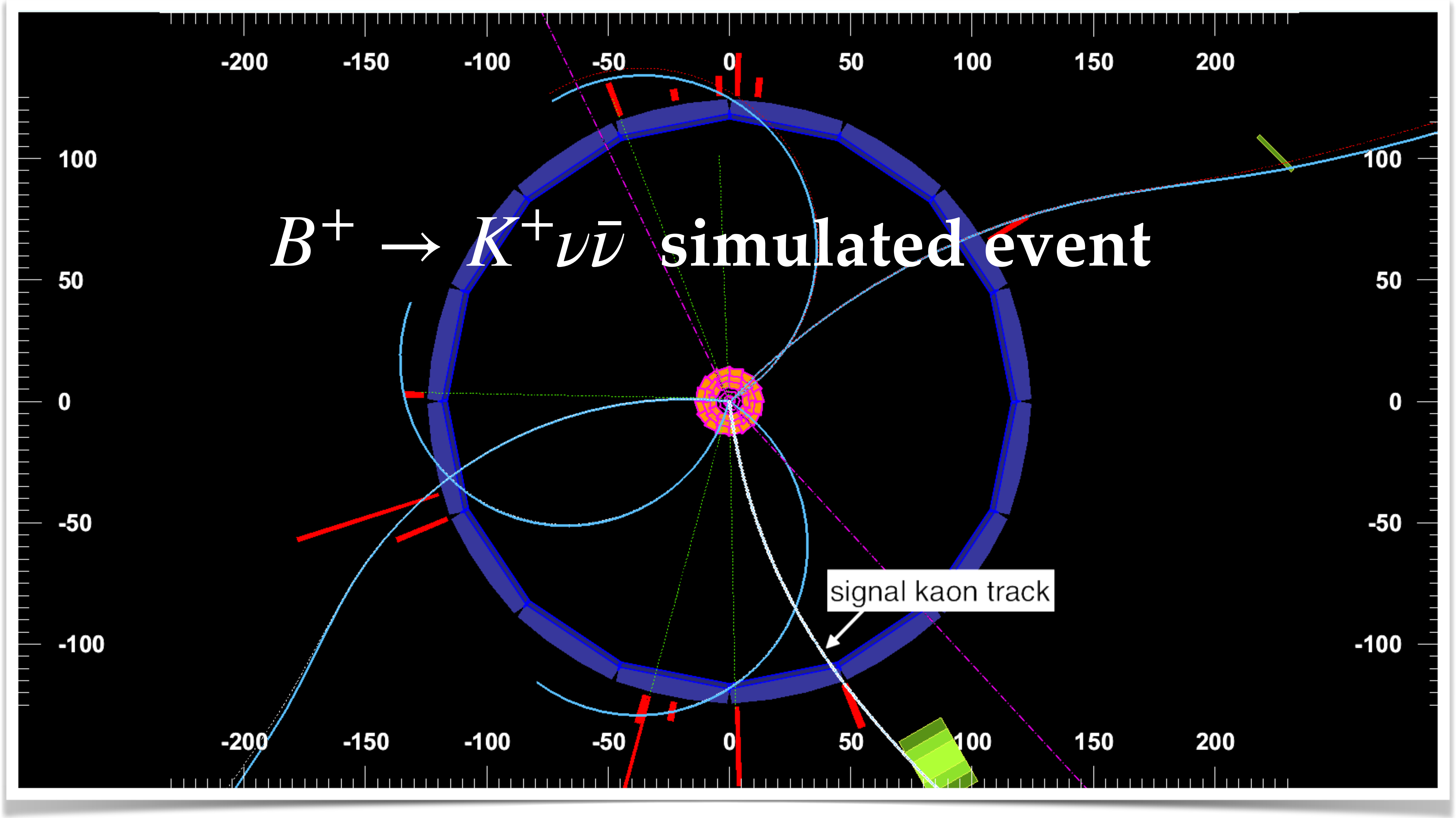


Karlsruhe Institute of Technology

Slavomira Stefkova, slavomira.stefkova@kit.edu

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

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

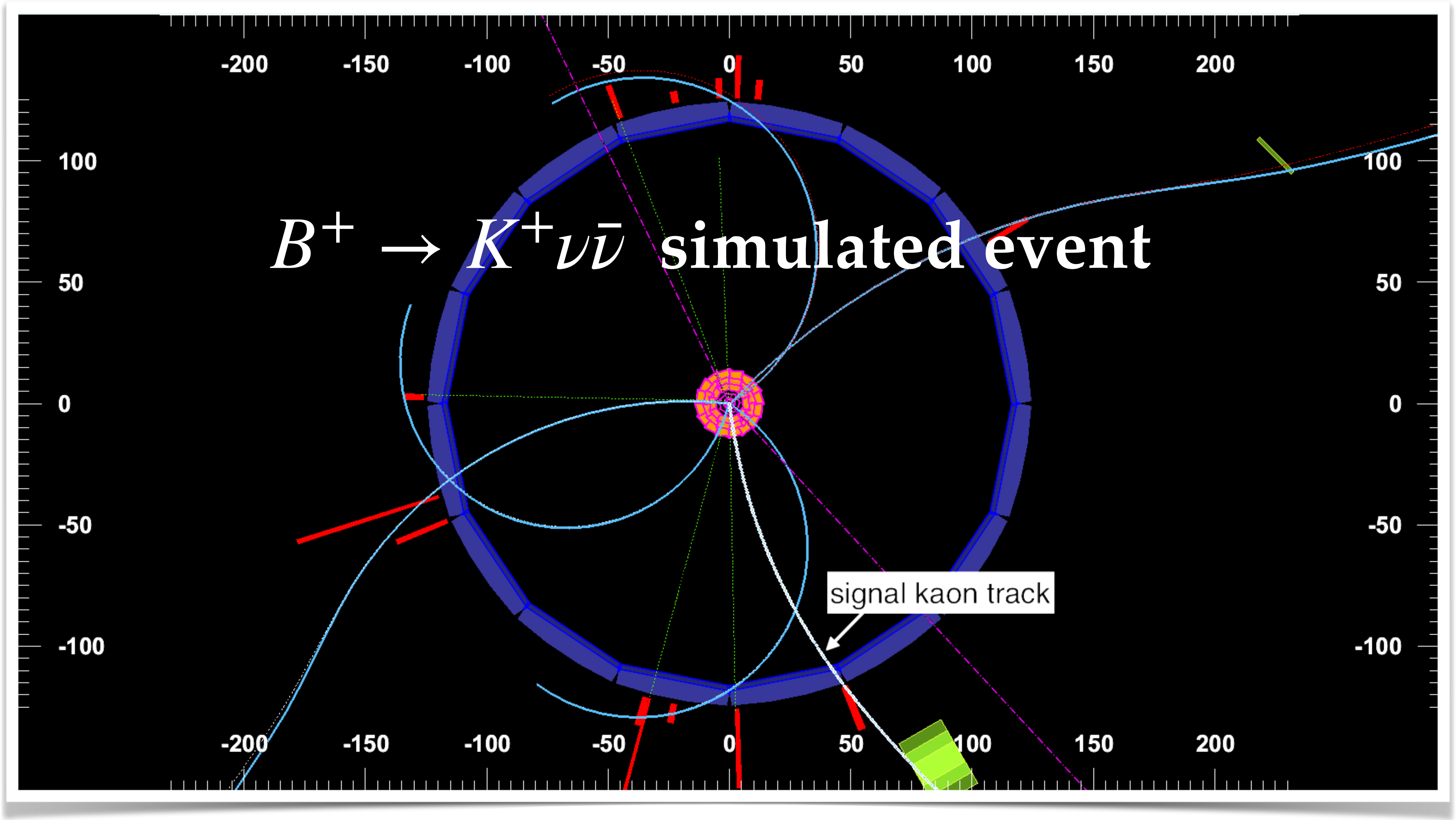


Typical $B \rightarrow K^{(*)}\nu\bar{\nu}$ event benefits from

- 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, $\gamma, \dots$)

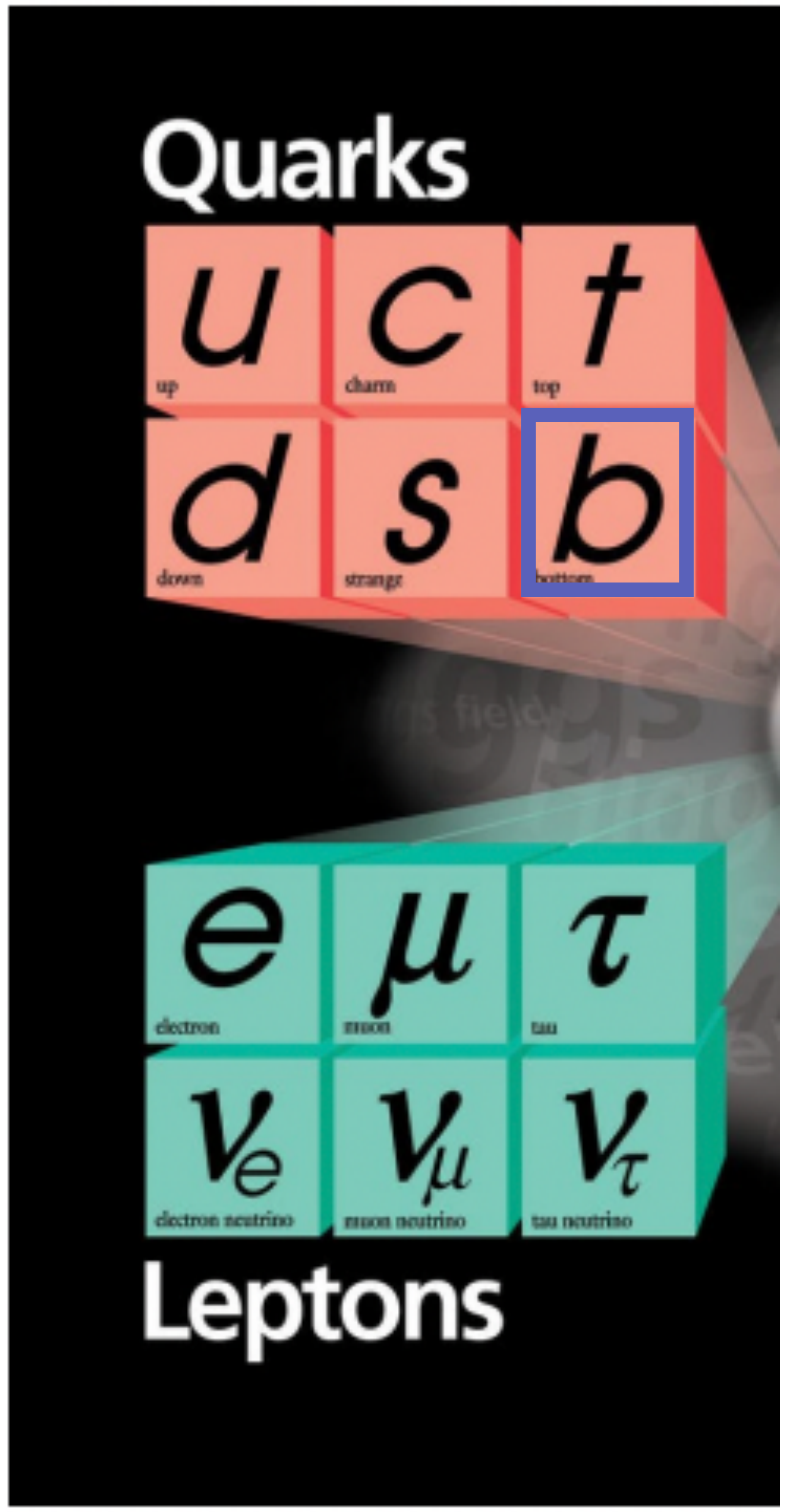
Why Flavour Physics?

- 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

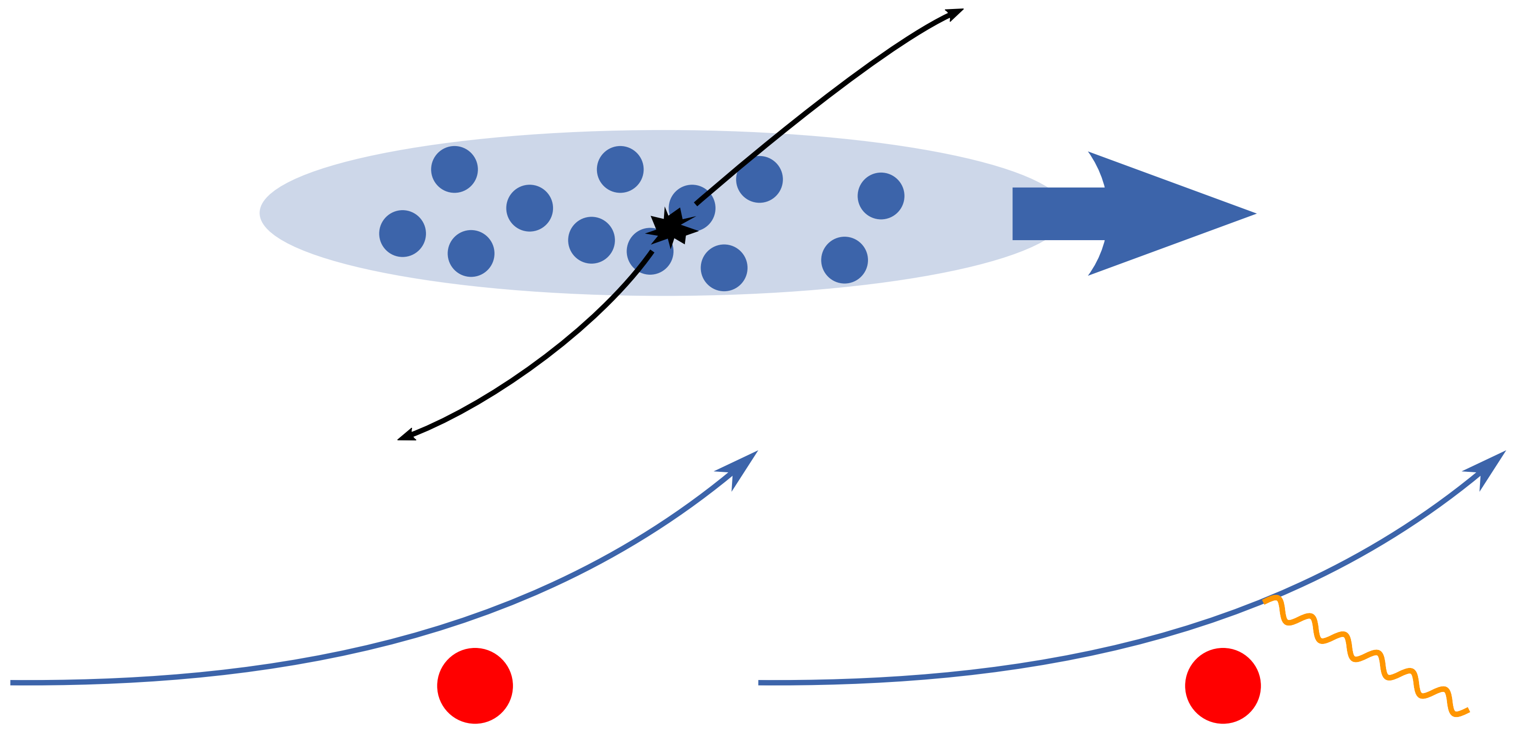
- With *B*-decays we perform
  - Precision measurements of CP violation
  - (In-)direct searches for NP in rare decays

Focus of this talk



Beam-backgrounds

Single-beam backgrounds:



- ▷ **Touschek scattering** → scattering of particles within a bunch → **Touschek rate** $\propto N_{particles} \times \rho \rightarrow \mathbf{I} \times \frac{\mathbf{I}}{\sigma_\mathbf{y} \mathbf{n_b}}$
- ▷ **beam-gas scattering** → Coulomb scattering and Bremsstrahlung (scattering off gas molecules) → **Beam-gas rate** $\propto N_{gas\ molecules} \times N_{particles} \rightarrow \mathbf{P} \times \mathbf{I} \times \mathbf{Z^2_{eff}}$
- ▷ **synchrotron radiation background** → consequence of a radial acceleration of the beam's particles achieved in bending magnets and quadrupoles
- ▷ **injection background** → continuous injection of charge into beam bunch modifying the beam bunch

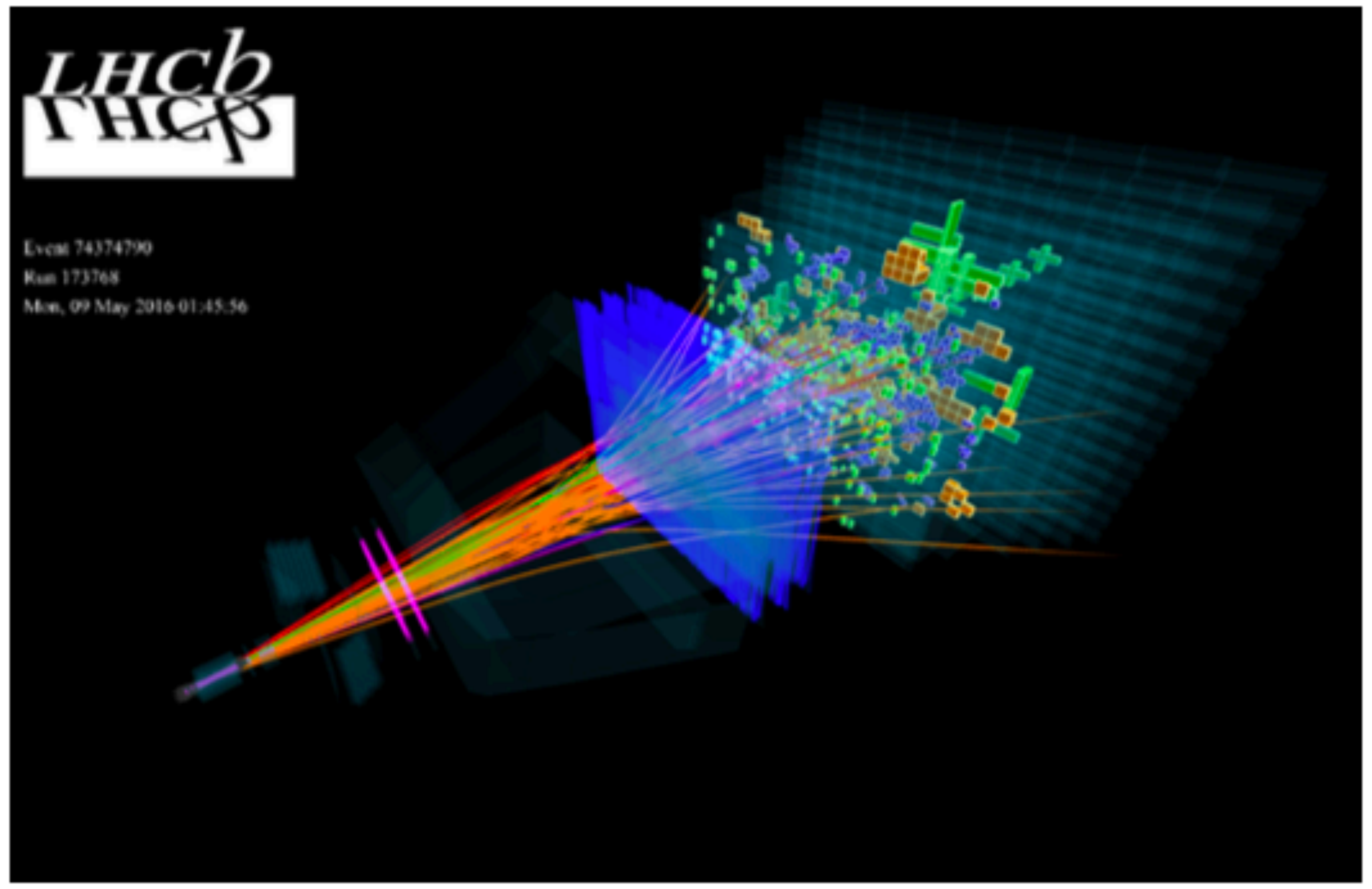
Single-beam backgrounds can be mitigated with beam-steering, collimators, and vacuum-scrubbing

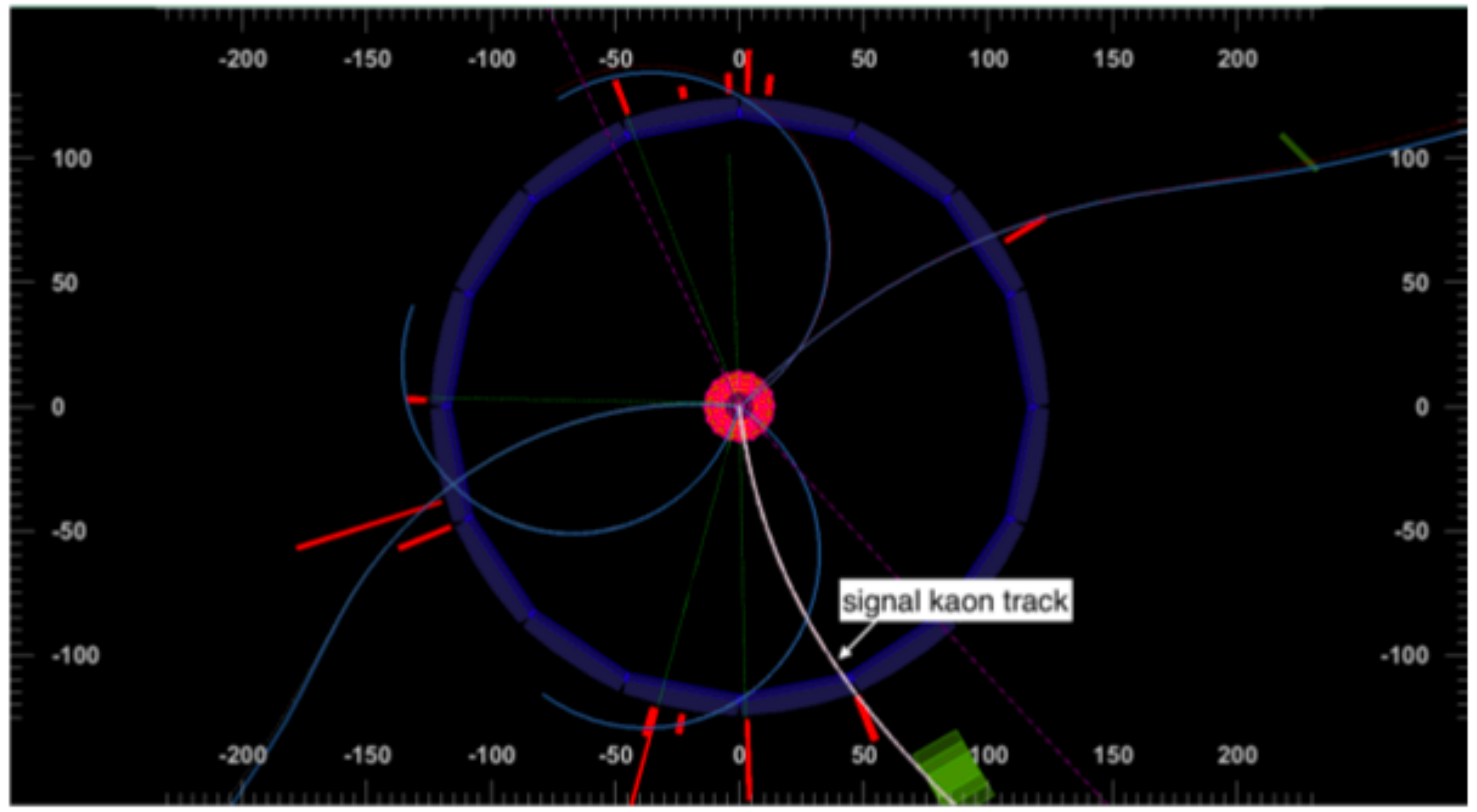
Luminosity backgrounds:

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

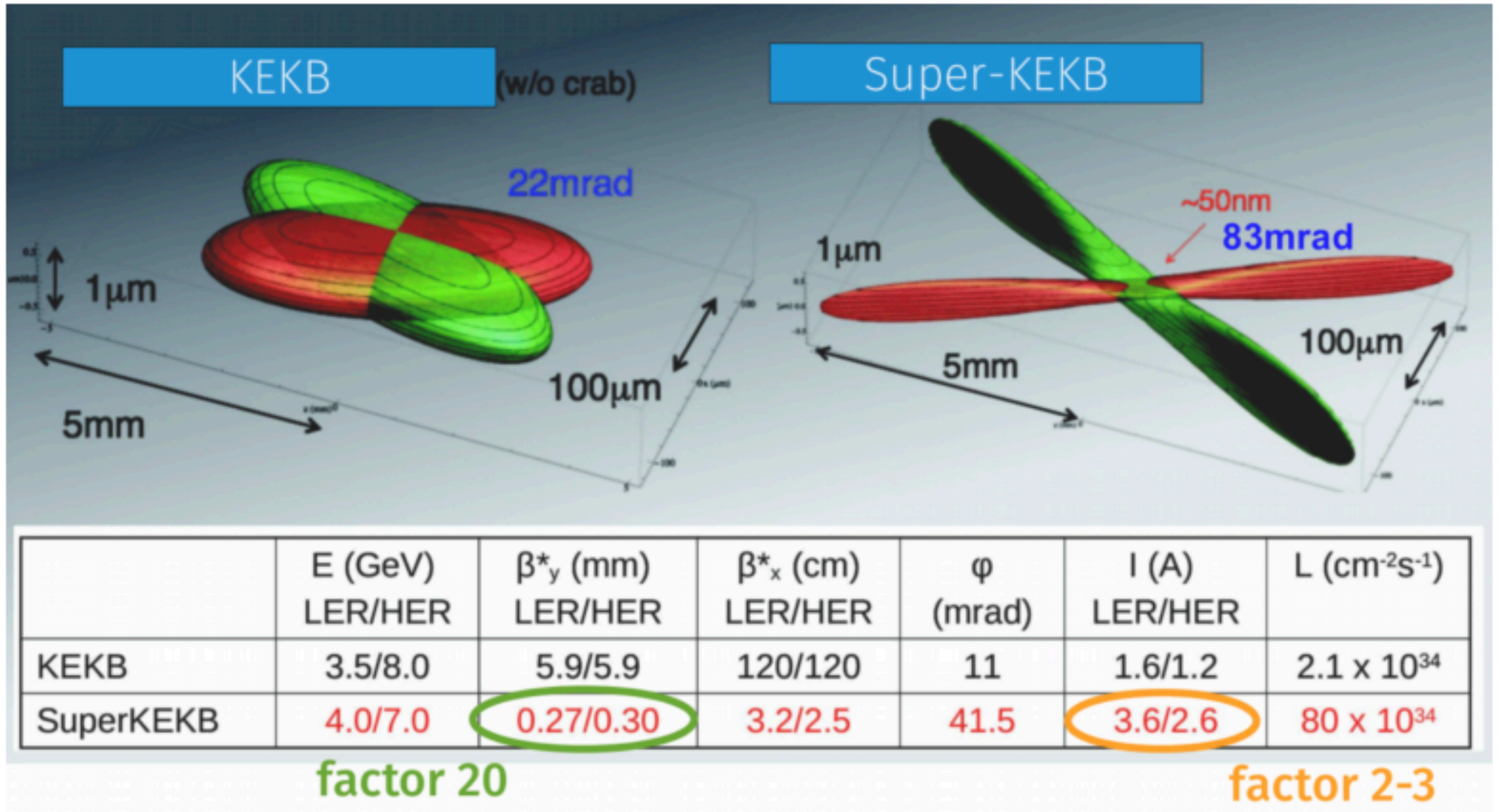
Belle II vs LHCb

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

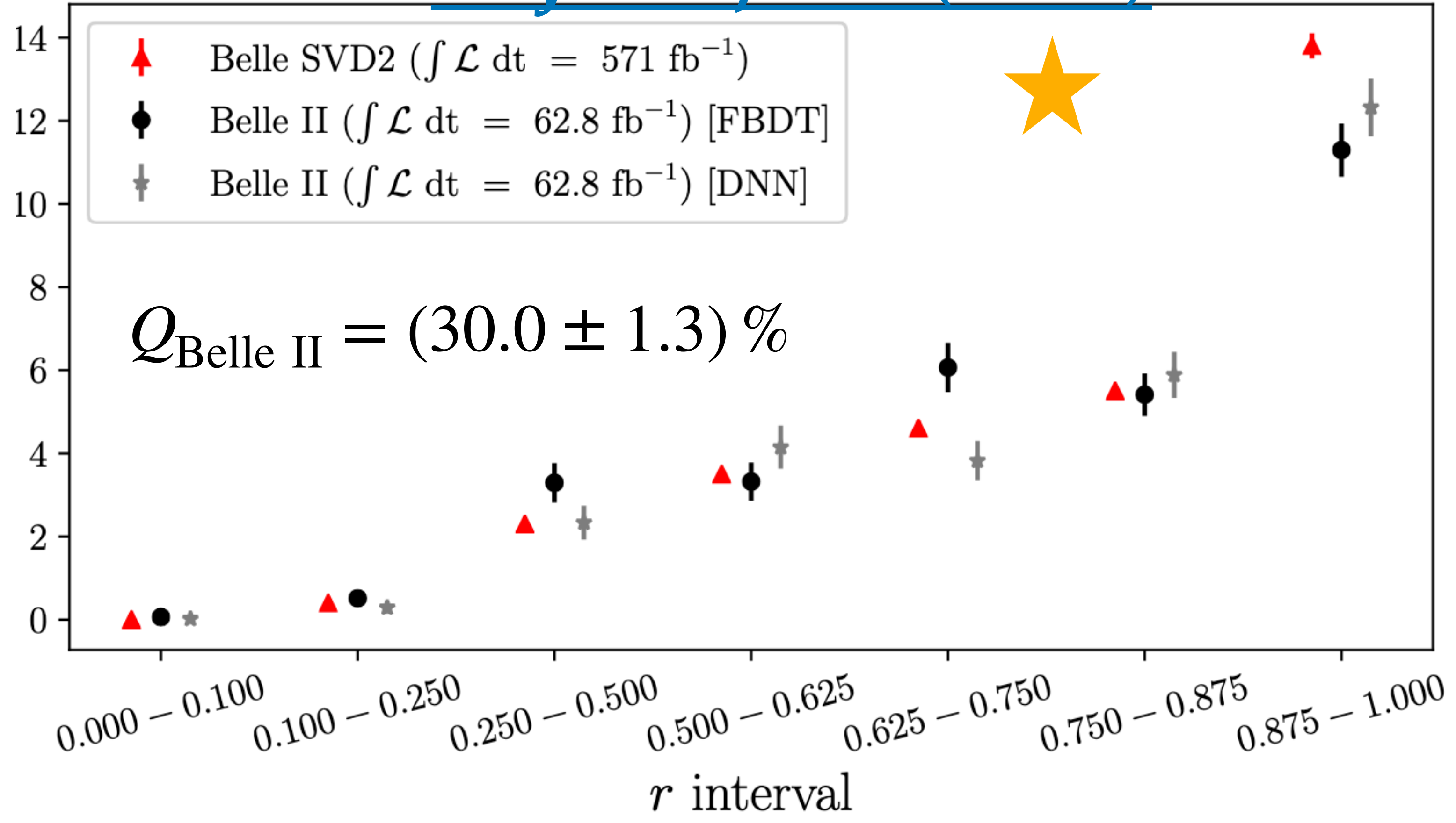
factor 2-3

	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	

Performance

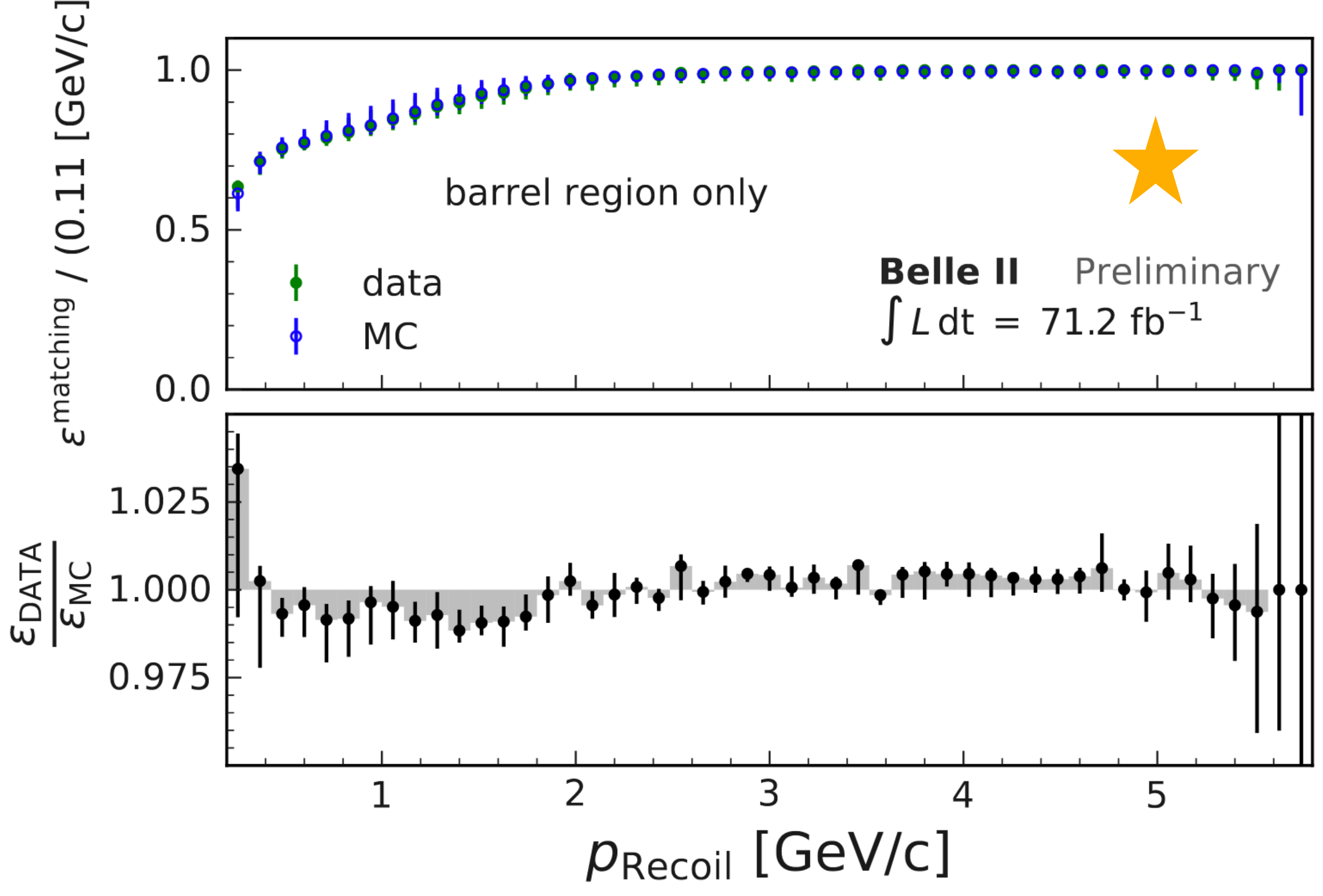
Good flavour tagger performance

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



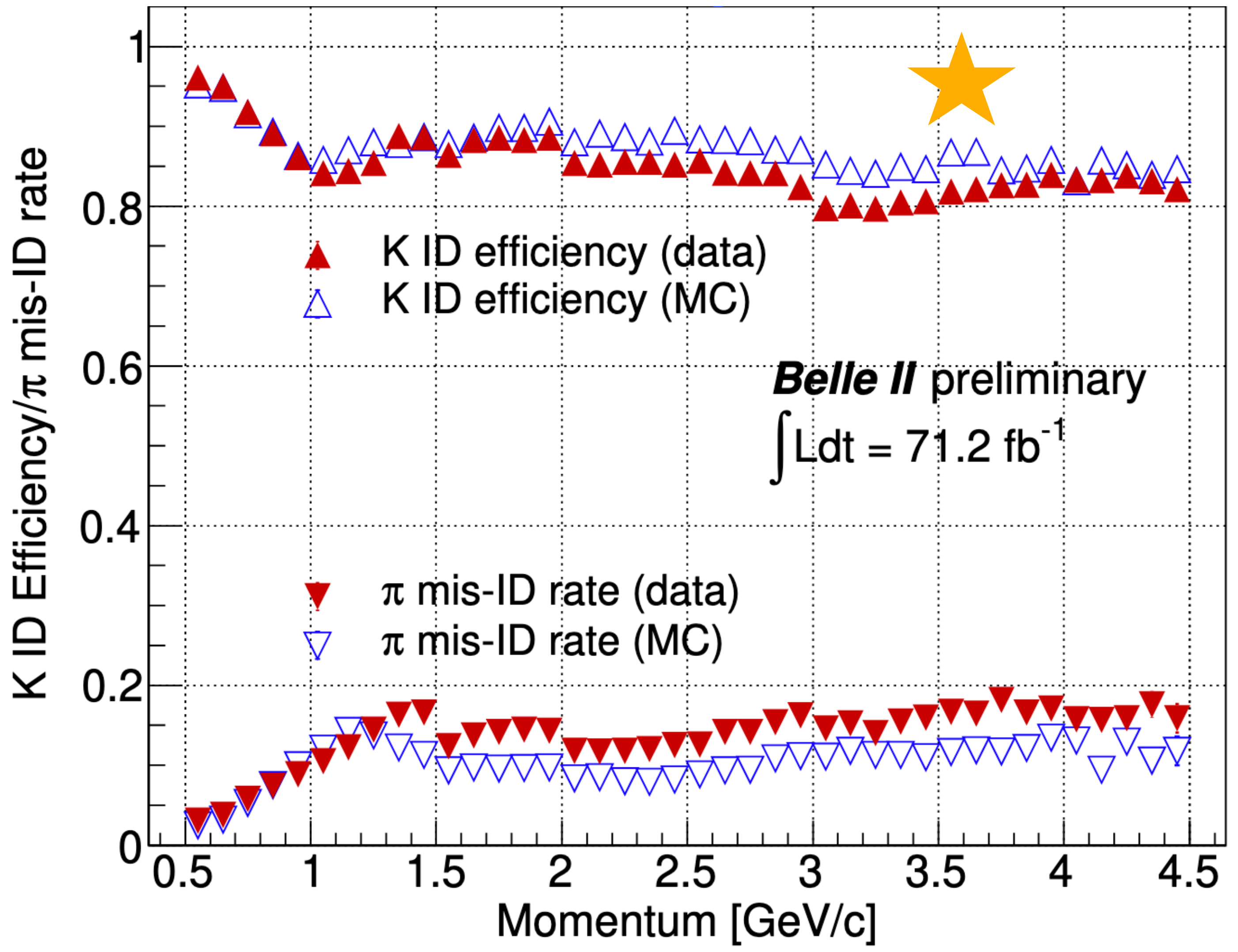
High photon matching efficiency

[BELLE2-NOTE-PL-2021-008]

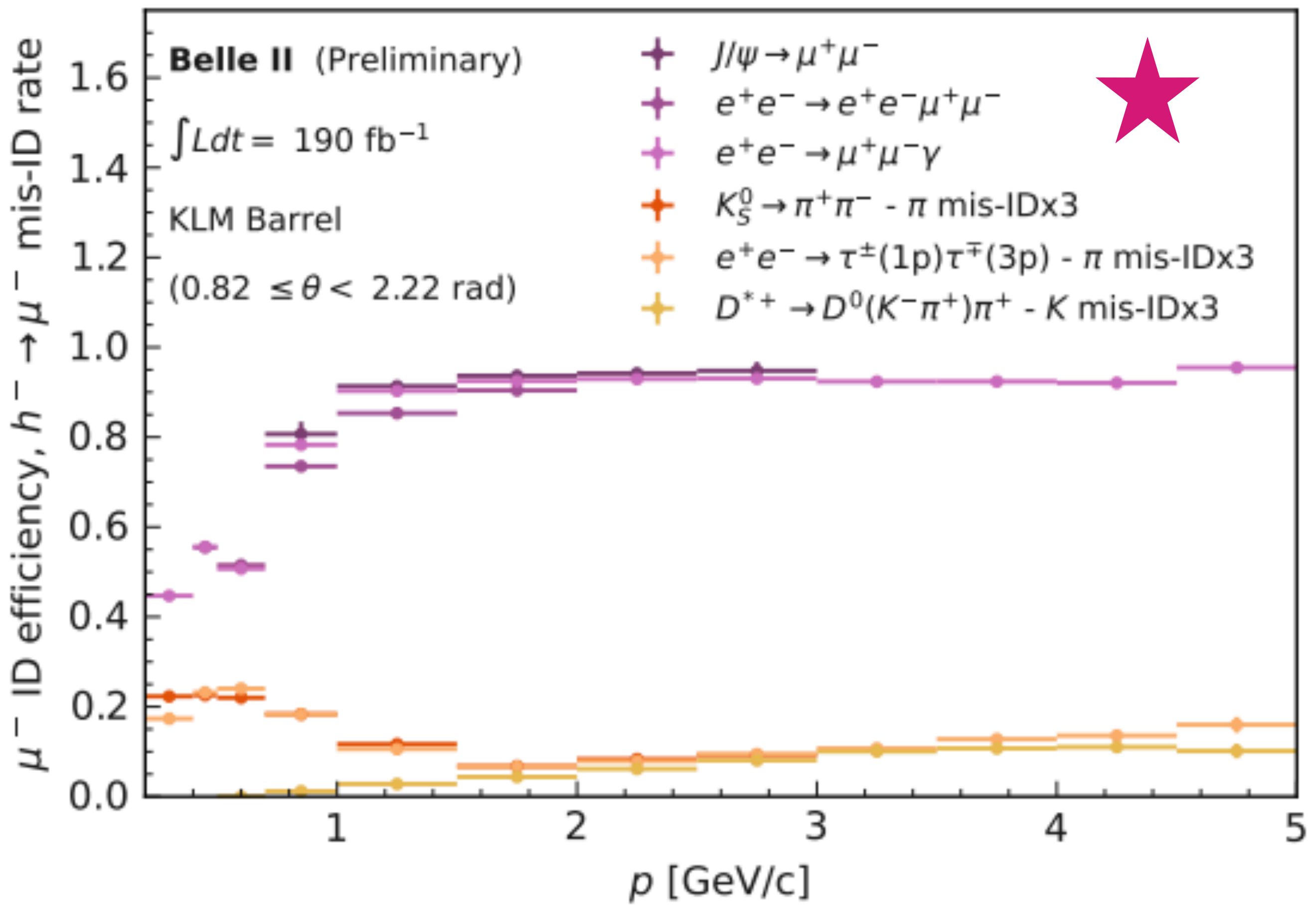


Good particle identification

[BELLE2-NOTE-PL-2020-024]

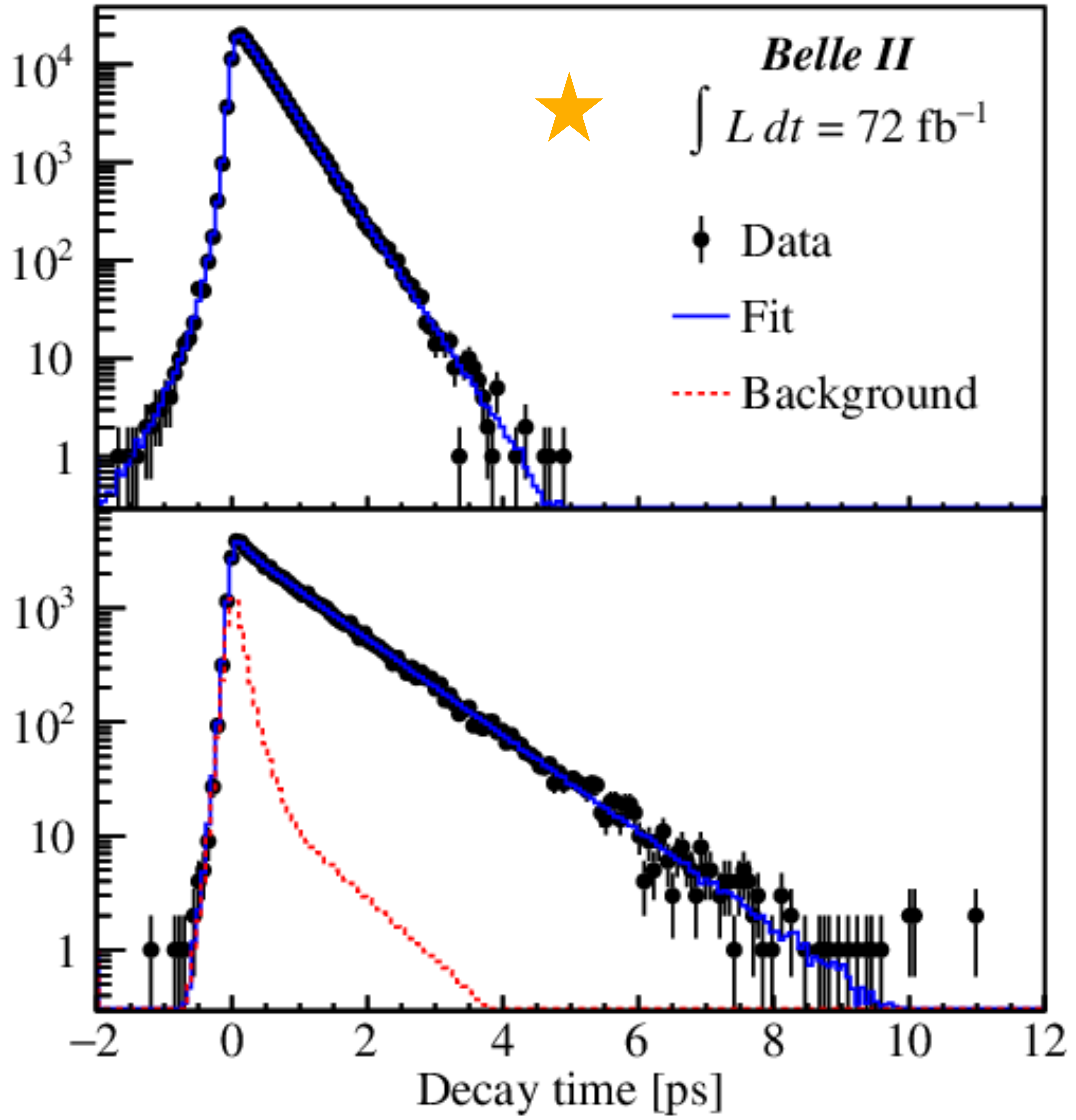


[BELLE2-NOTE-PL-2022-003]



Most precise measurement of *D* lifetimes

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

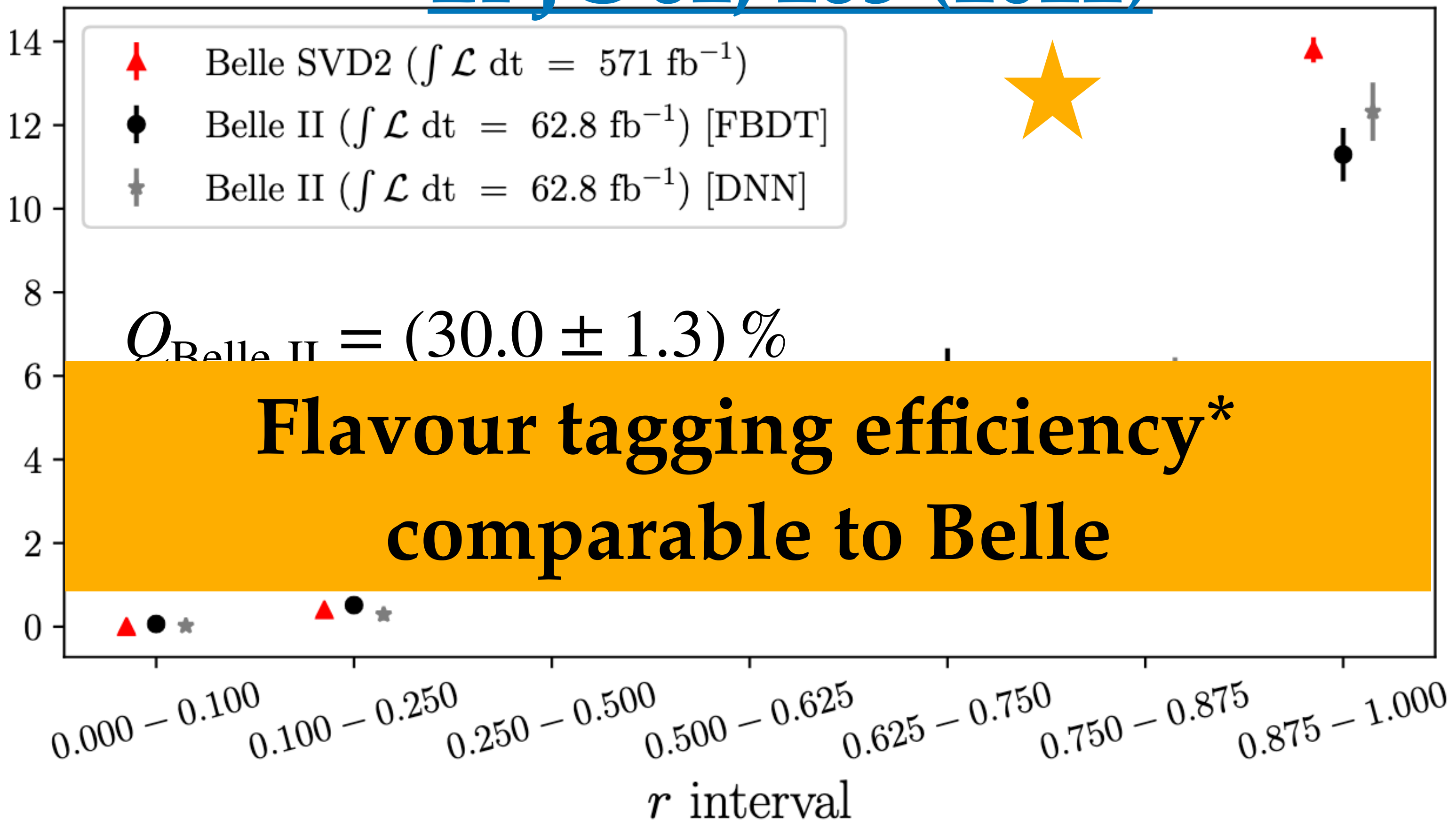


*tagging power indicating the statistical precision of the sample = $\epsilon_{tag}(1-2\omega)^2$

Performance

Good flavour tagger performance

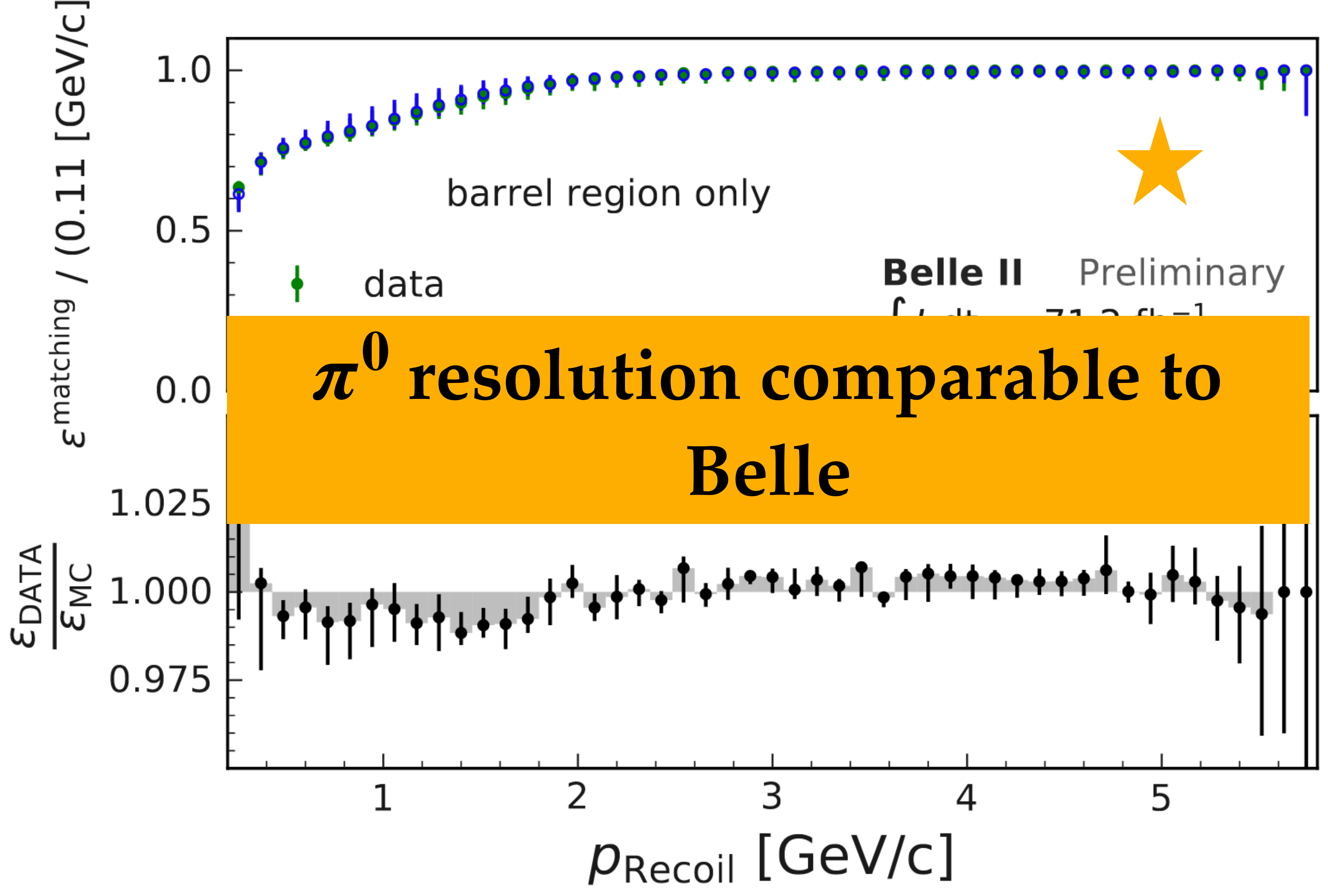
EPJC 82, 283 (2022)



Flavour tagging efficiency* comparable to Belle

High photon matching efficiency

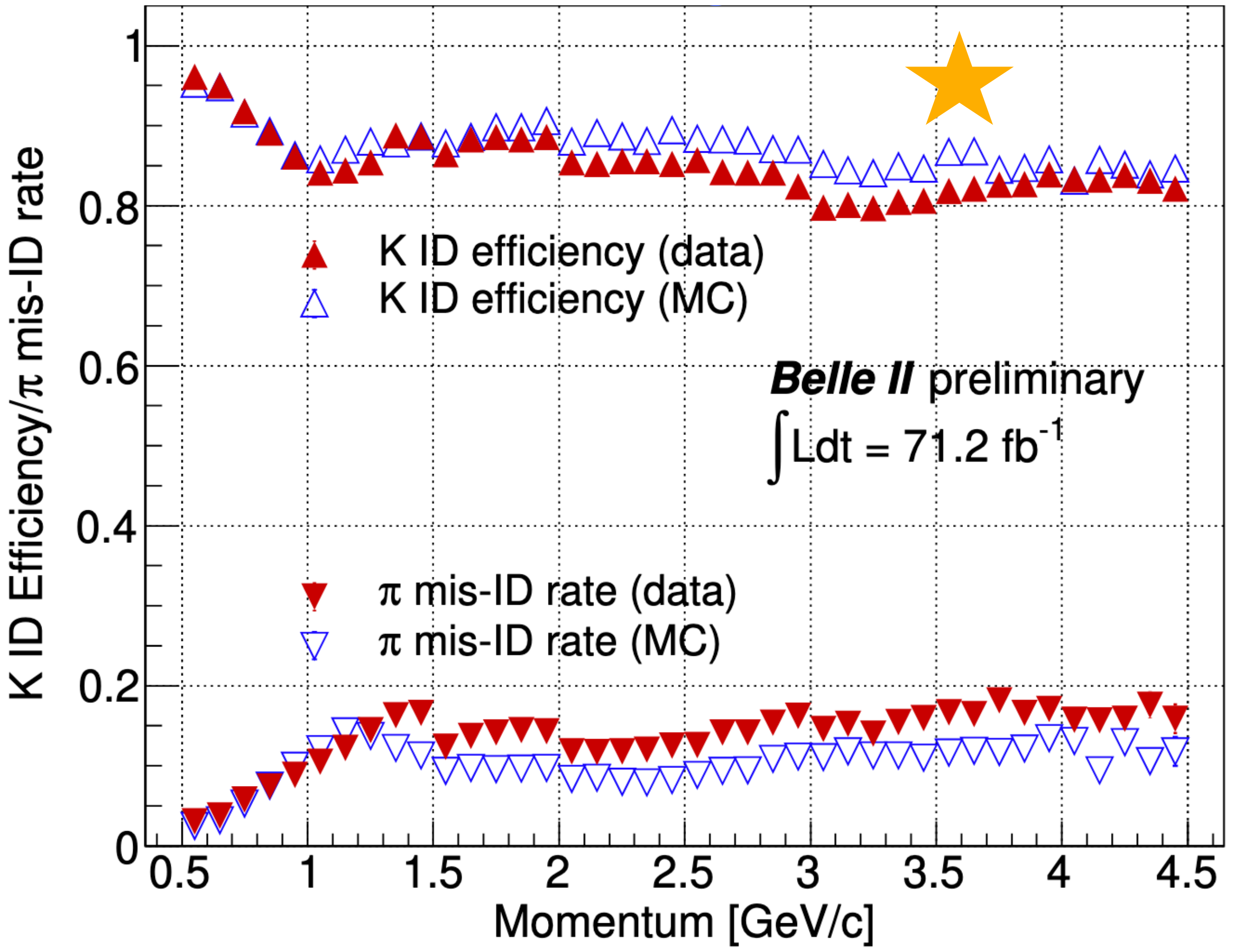
[BELLE2-NOTE-PL-2021-008]



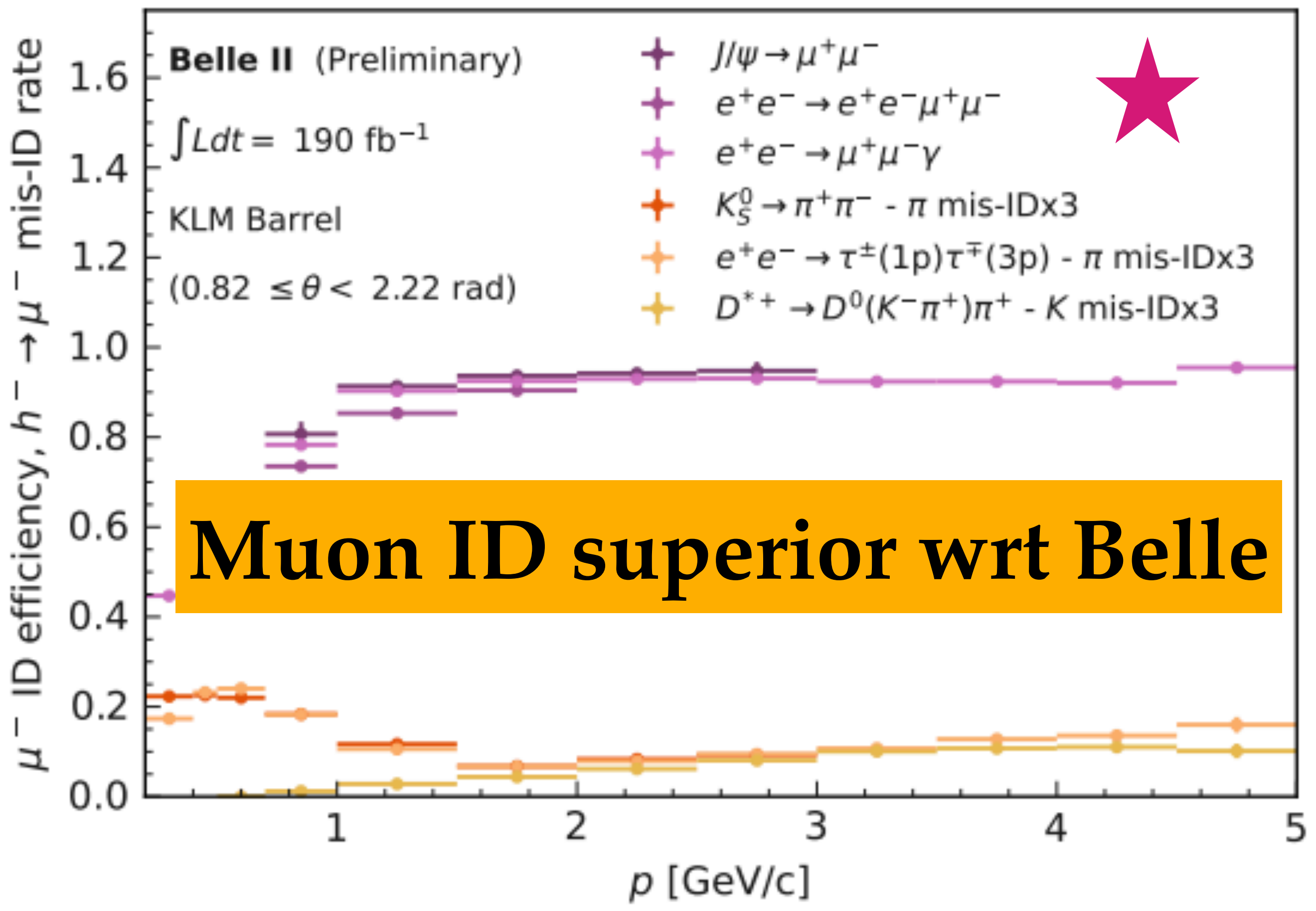
π^0 resolution comparable to Belle

Good particle identification

[BELLE2-NOTE-PL-2020-024]



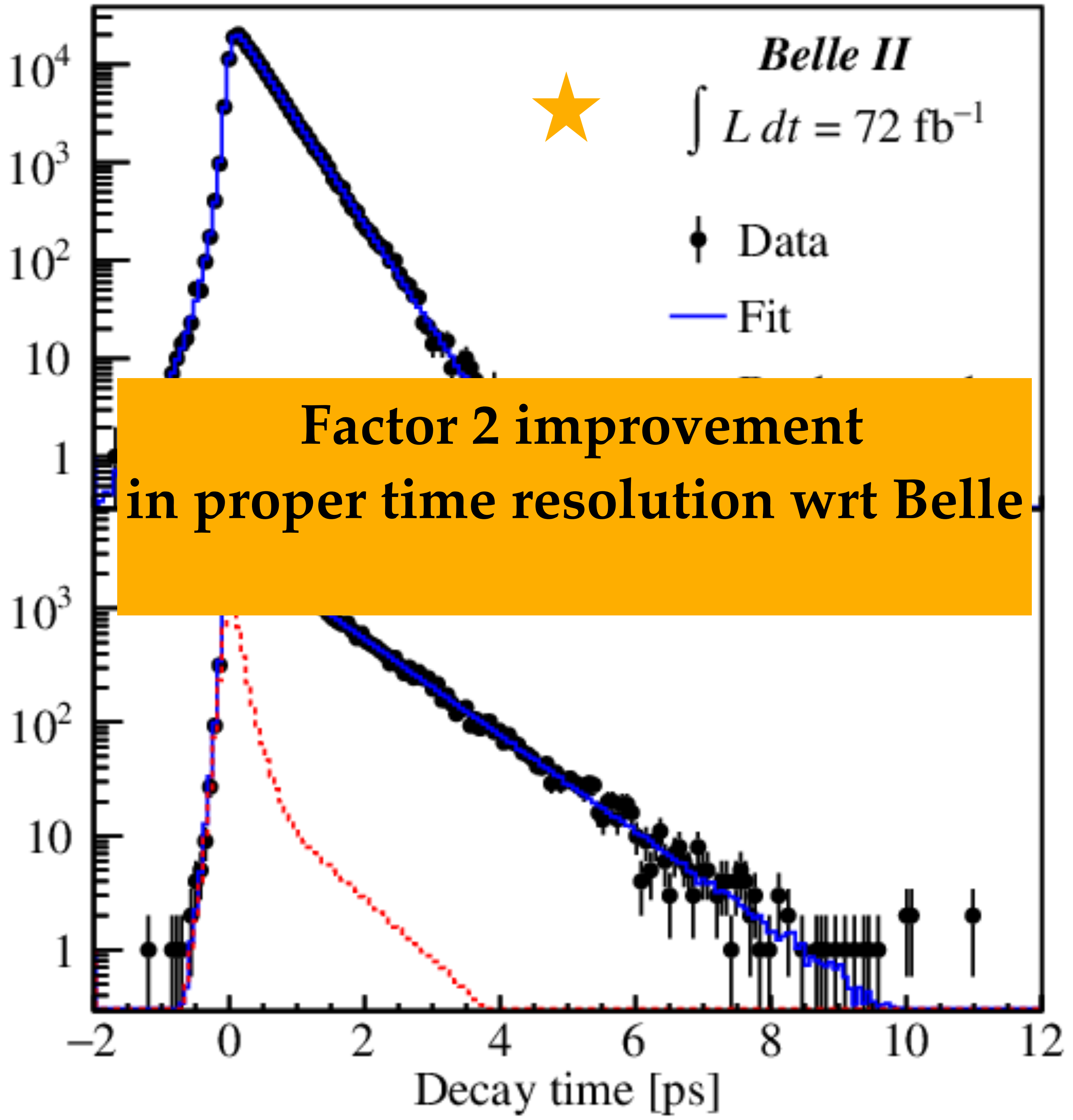
[BELLE2-NOTE-PL-2022-003]



Muon ID superior wrt Belle

Most precise measurement of *D* lifetimes

PRL 127, 211801 (2021)



Factor 2 improvement in proper time resolution wrt Belle

---

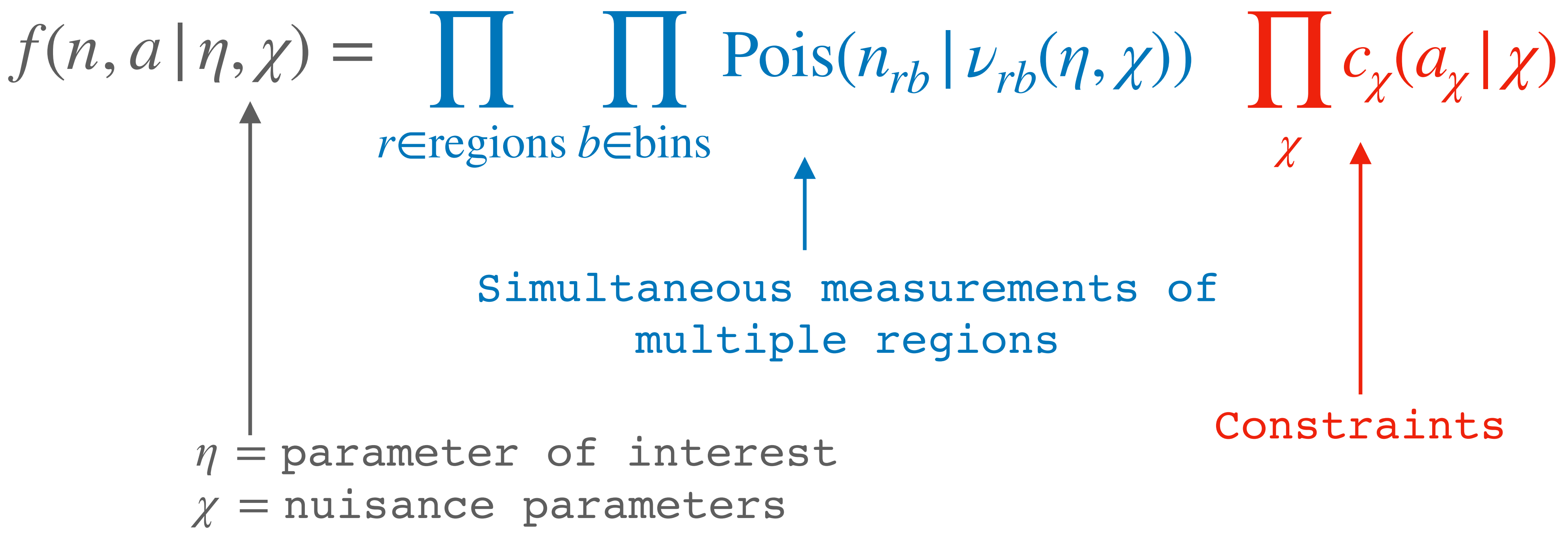
*tagging power indicating the statistical precision of the sample = $\epsilon_{tag}(1-2\omega)^2$

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



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

Simultaneous measurements of multiple regions

Constraints

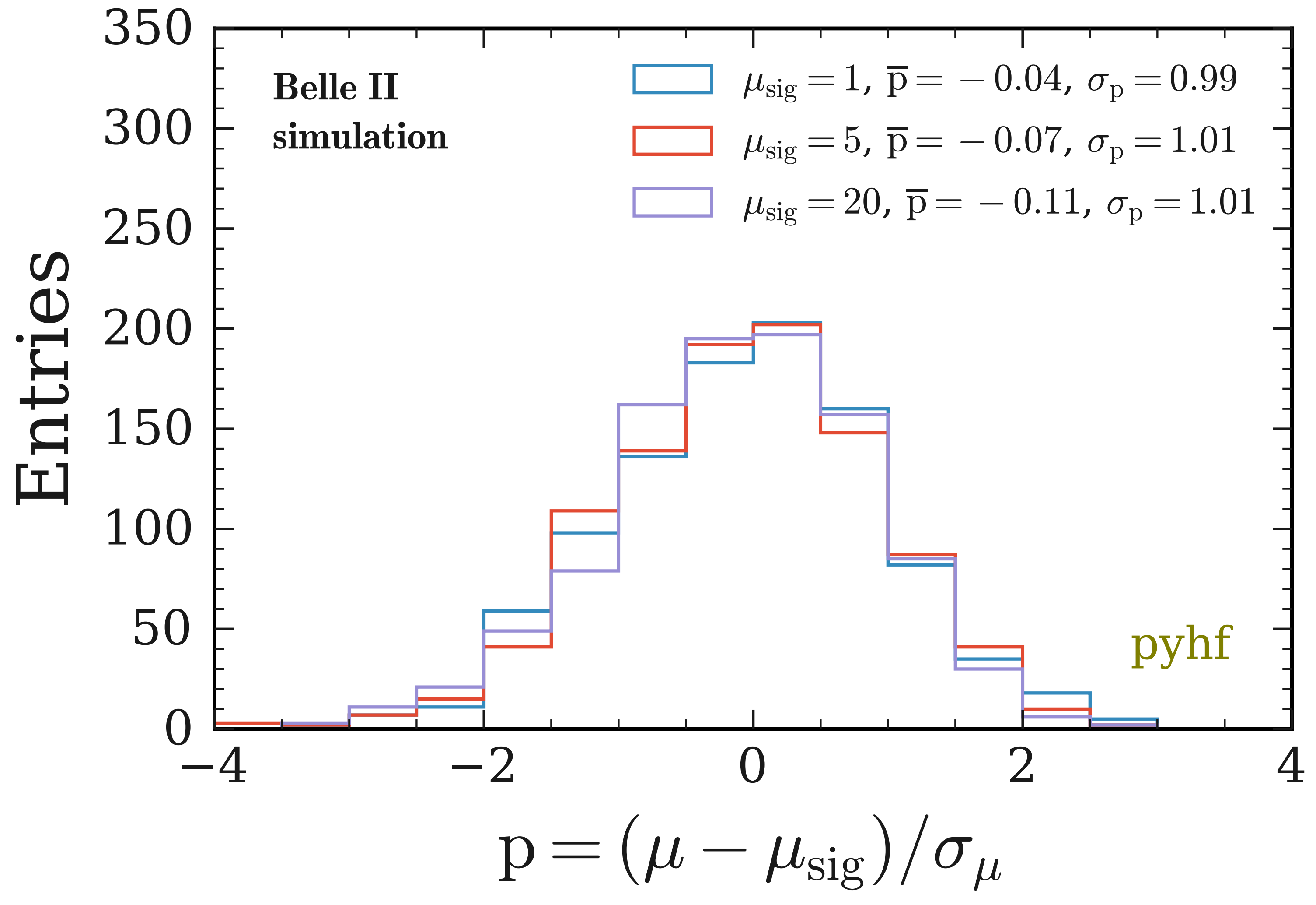
η = parameter of interest
χ = nuisance parameters

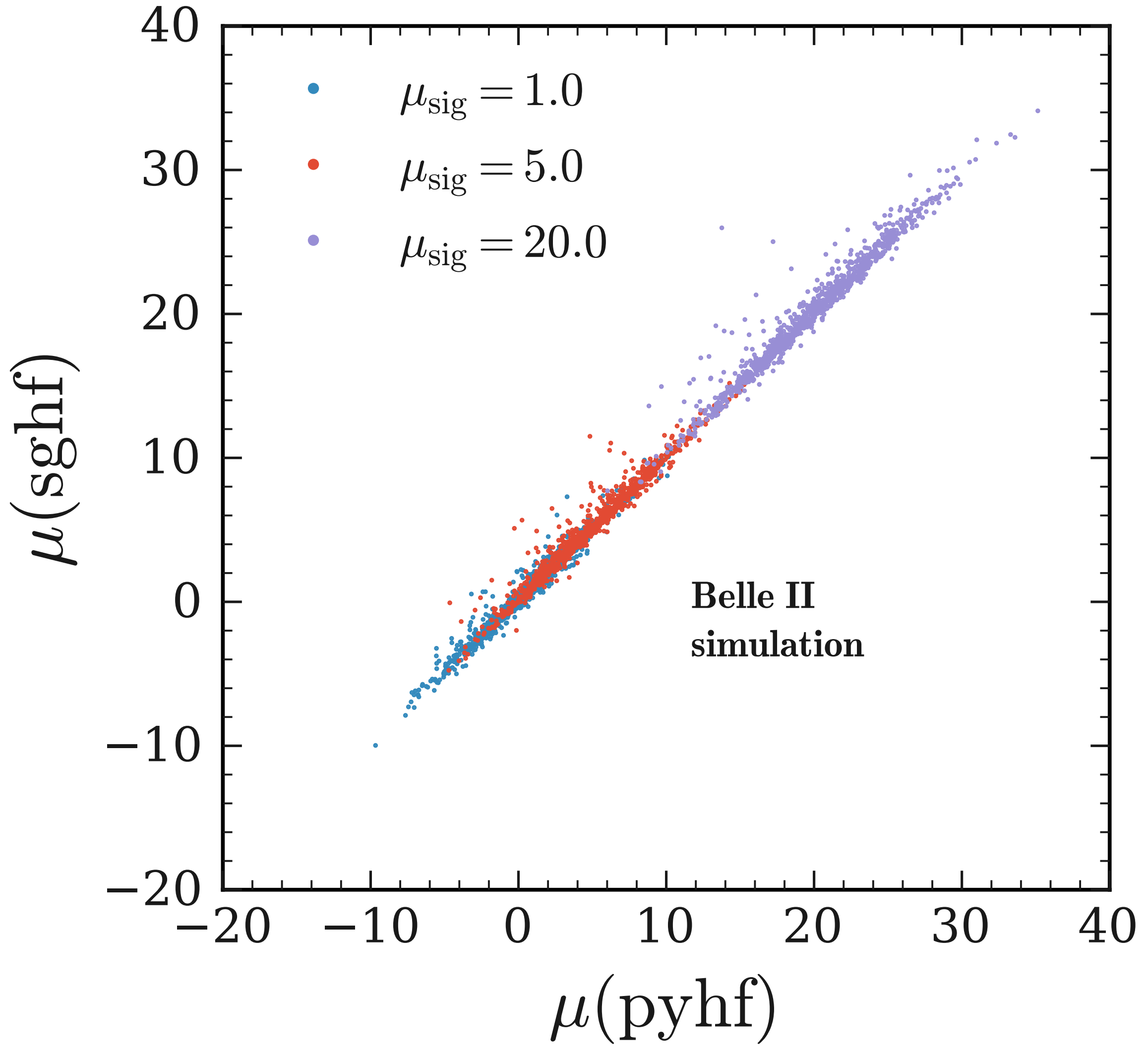
Fit validation

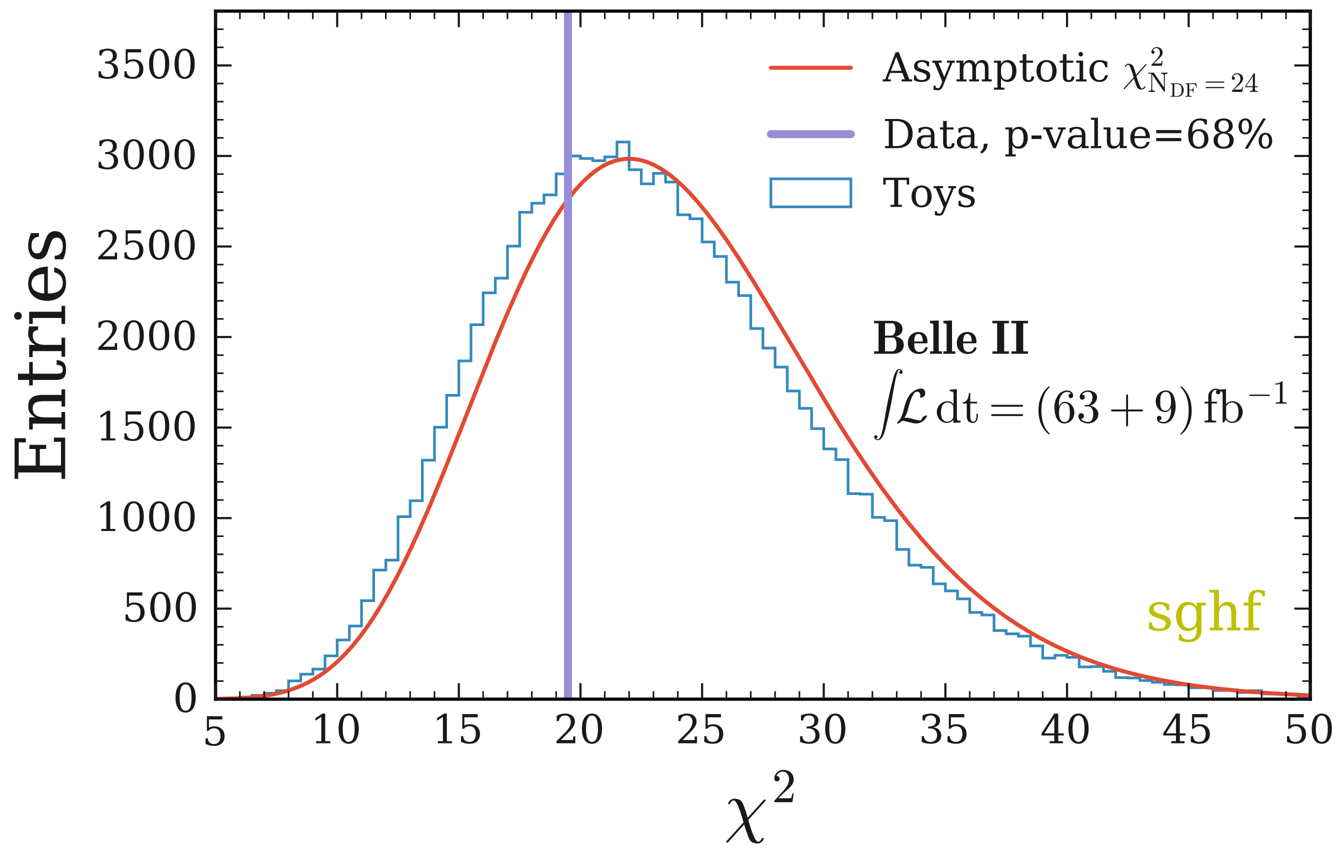
[PRL 127, 181802 (2021)]

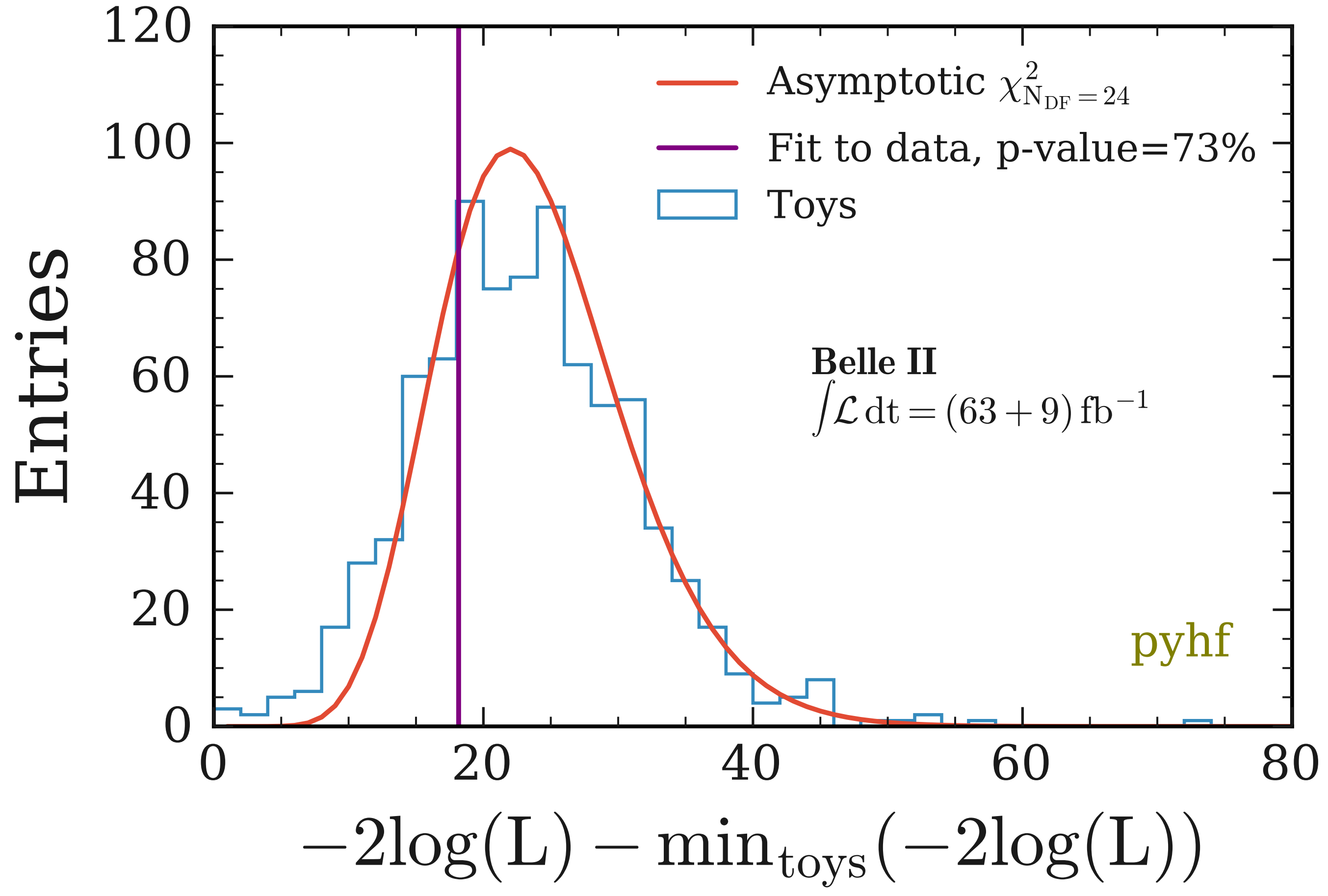
Perform Fit Bias Check

- 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







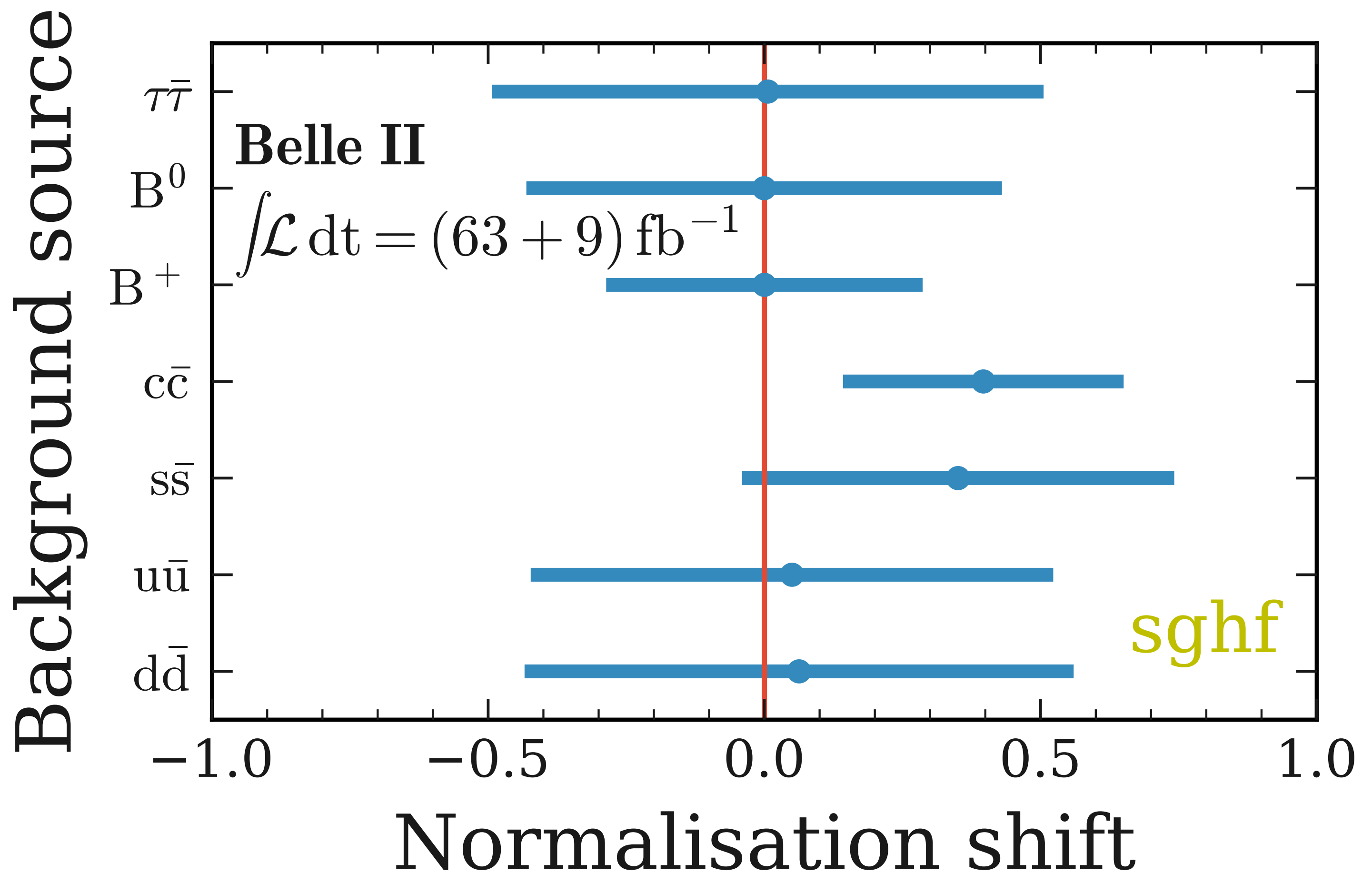


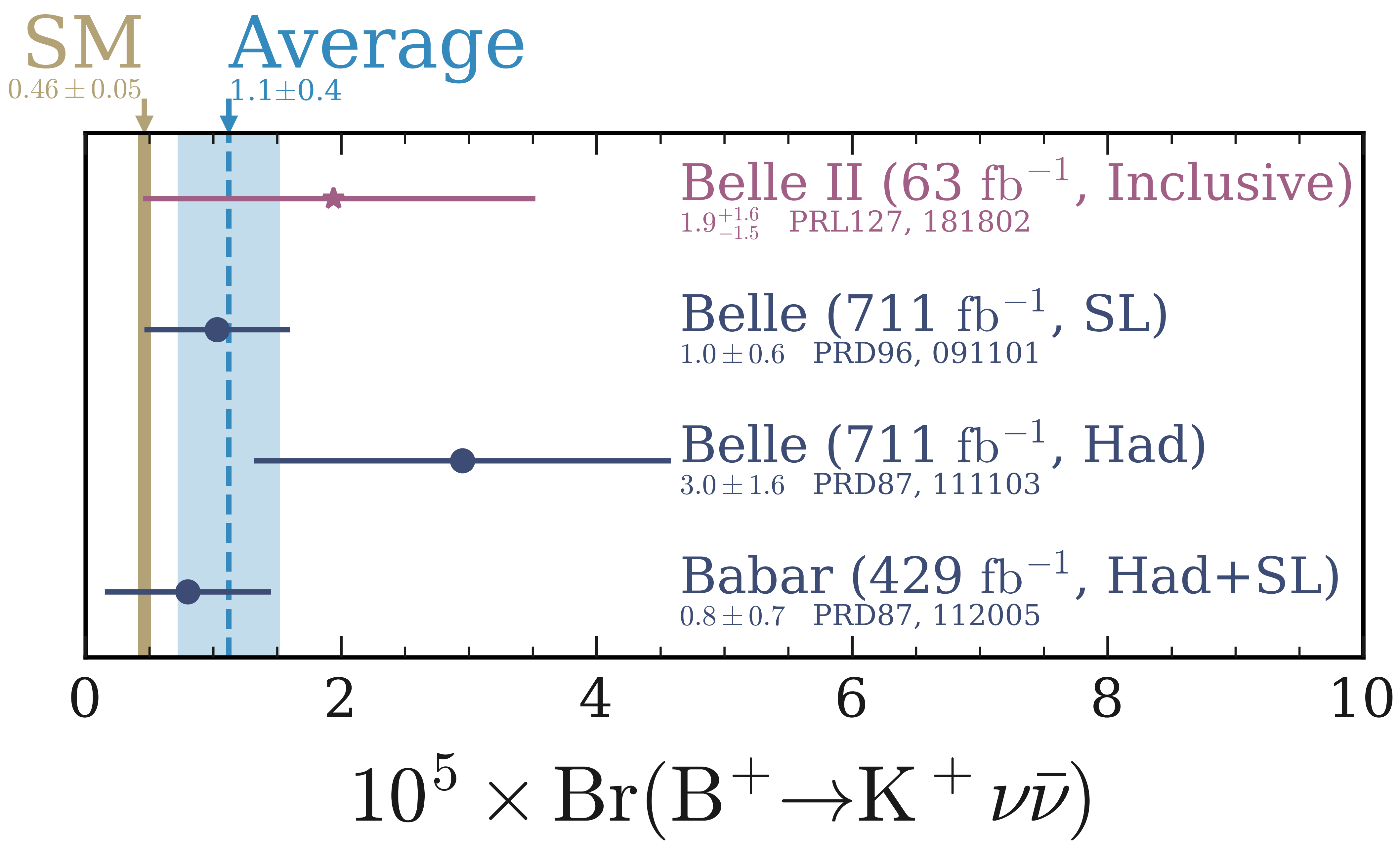
Check Data-Model Compatibility

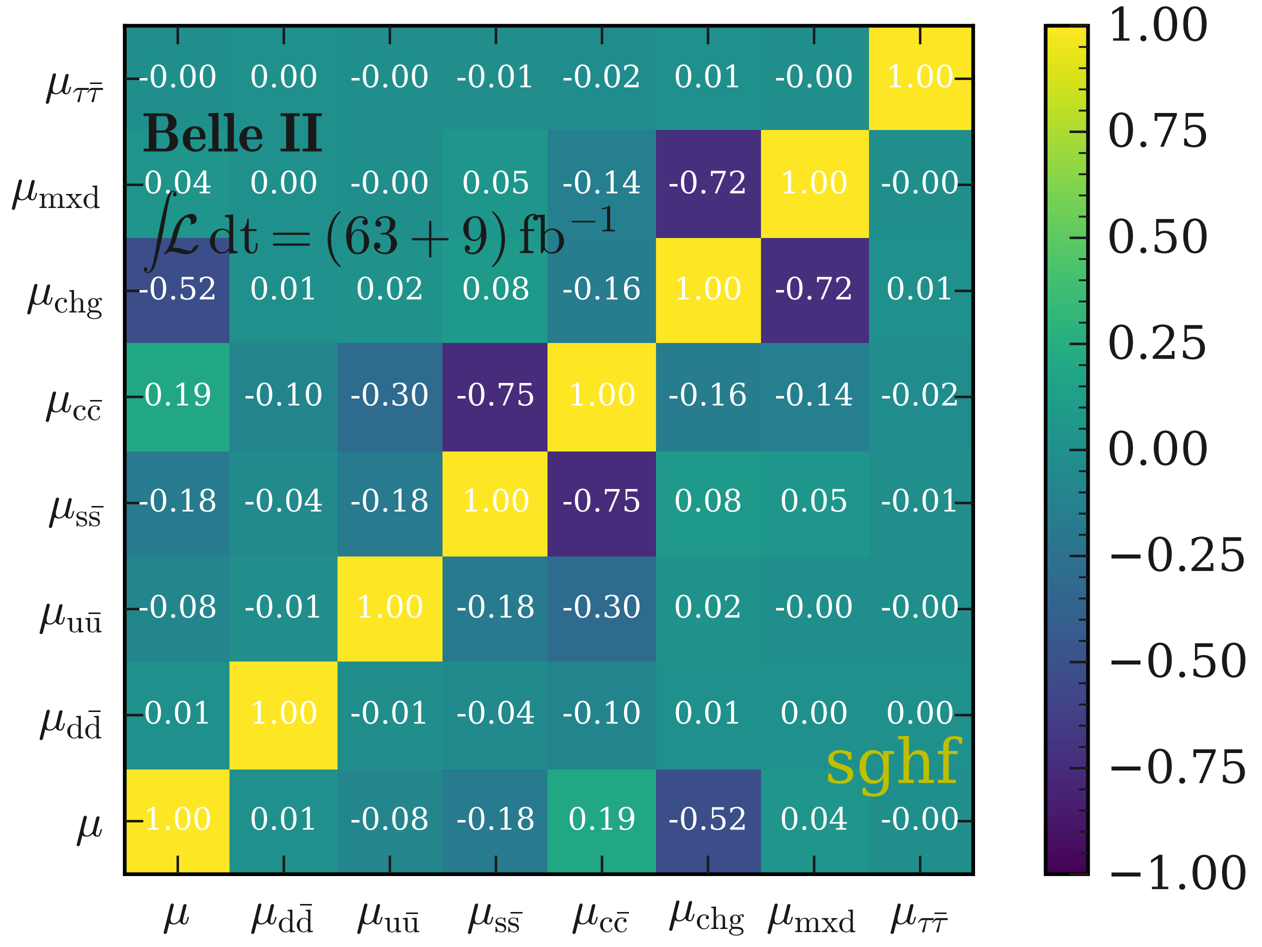
- Generate toys and check fit quality
- Results: *p*-value shows good data model compatibility for both pyhf and sghf

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}







	μ	$\mu_{d\bar{d}}$	$\mu_{u\bar{u}}$	$\mu_{s\bar{s}}$	$\mu_{c\bar{c}}$	μ_{chg}	μ_{mxd}	$\mu_{\tau\bar{\tau}}$
$\mu_{\tau\bar{\tau}}$	-0.00	0.00	-0.00	-0.01	-0.02	0.01	-0.00	1.00
μ_{mxd}	0.04	0.00	-0.00	0.05	-0.14	-0.72	1.00	-0.00
μ_{chg}	-0.52	0.01	0.02	0.08	-0.16	1.00	-0.72	0.01
$\mu_{c\bar{c}}$	0.19	-0.10	-0.30	-0.75	1.00	-0.16	-0.14	-0.02
$\mu_{s\bar{s}}$	-0.18	-0.04	-0.18	1.00	-0.75	0.08	0.05	-0.01
$\mu_{u\bar{u}}$	-0.08	-0.01	1.00	-0.18	-0.30	0.02	-0.00	-0.00
$\mu_{d\bar{d}}$	0.01	1.00	-0.01	-0.04	-0.10	0.01	0.00	0.00
μ	1.00	0.01	-0.08	-0.18	0.19	-0.52	0.04	-0.00

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