The Belle II B-tagging and the unknown side of B decays

Dortmund seminar

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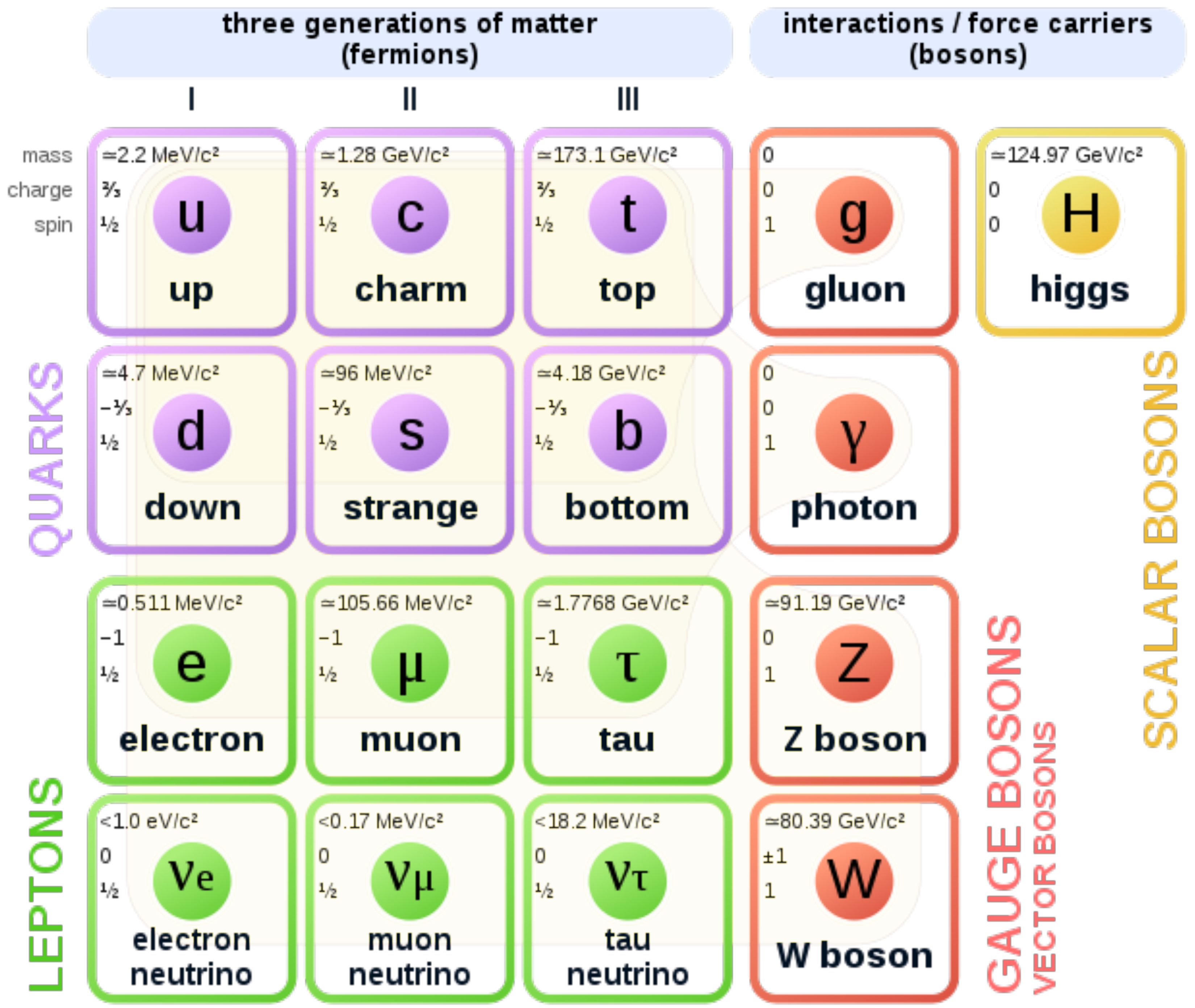
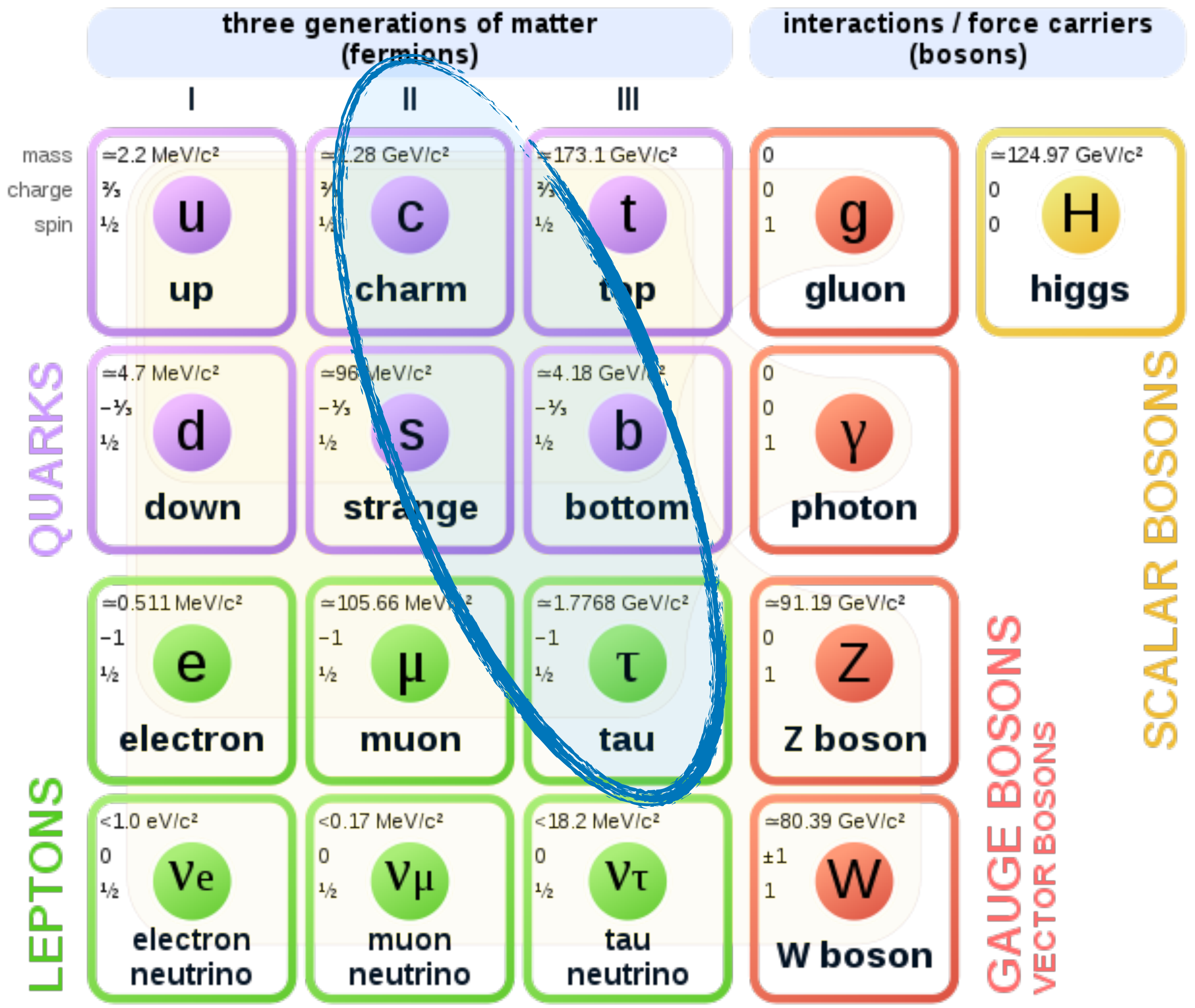
The Standard Model (SM) of elementary particles



- No *evidence* of Beyond the Standard Model (BSM) phenomena at microscopic level
- but:
  - **larger-scale phenomena** (dark matter, baryonic asymmetry…) not predicted by the SM
  - several **tensions** in SM measurements
  - **fine tuning** of different sectors of SM (Higgs, strong CP violation)

Why the (heavy) Flavours?



1. Several New Physics (NP) models which are **not flavour universal** → the third generation (can) couple differently with NP

Interesting **BSM predictions**

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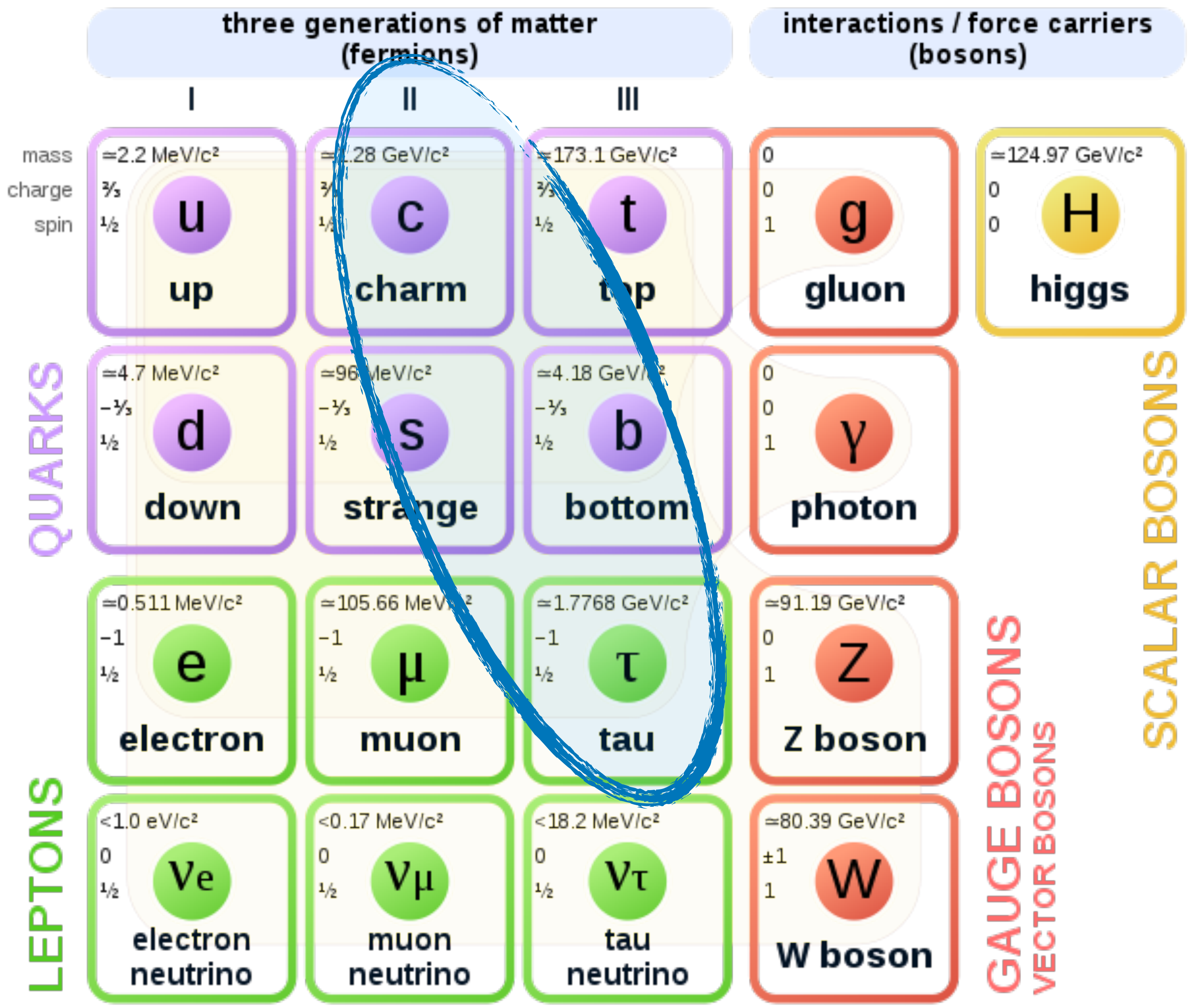

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2. In heavy-flavour hadrons processes **non-perturbative QCD** is less important

   Precise **SM predictions**

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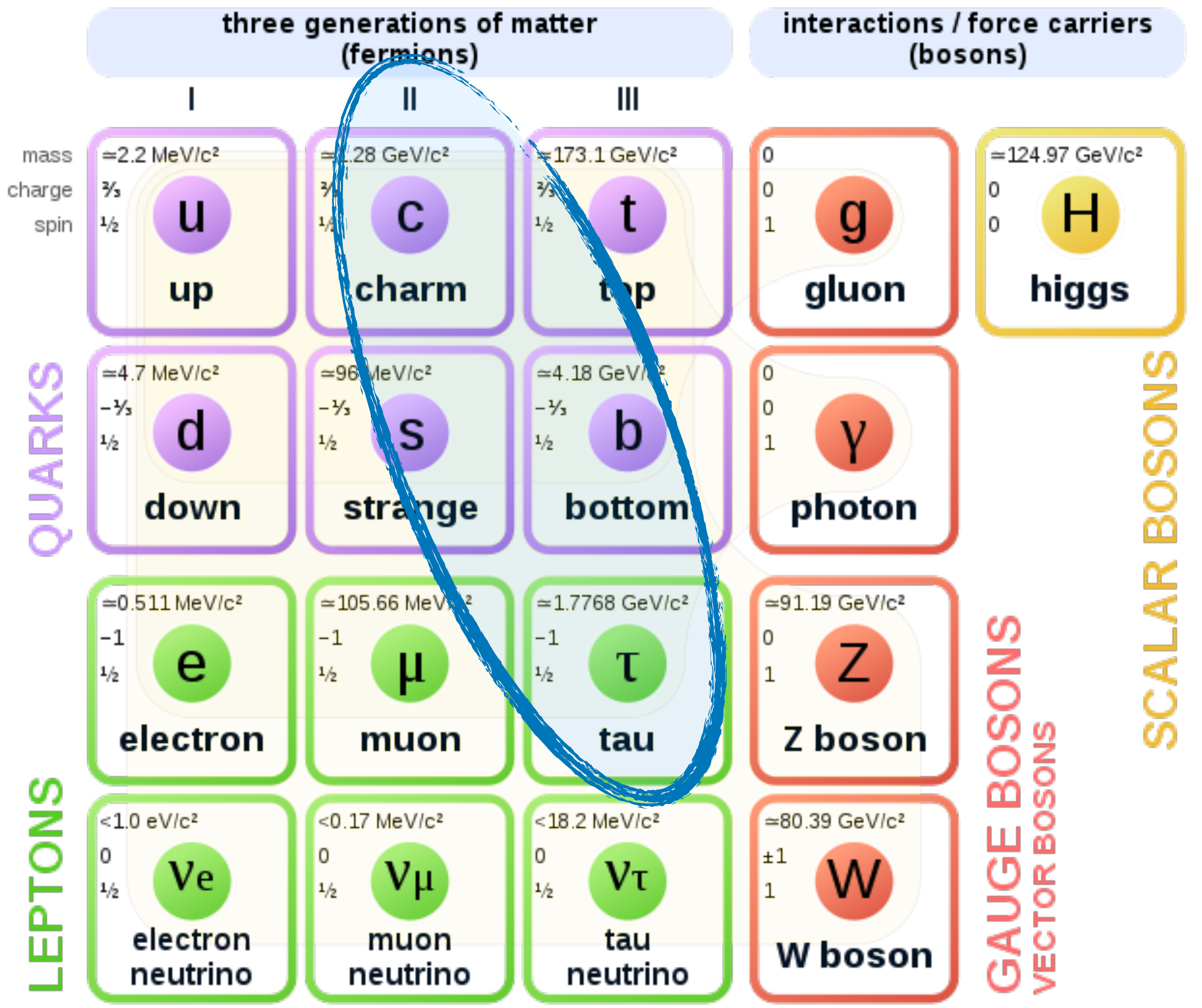

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Precise **SM predictions**

The SM can be **tested via precise measurements** in the heavy flavours sector!

take home message (for students)

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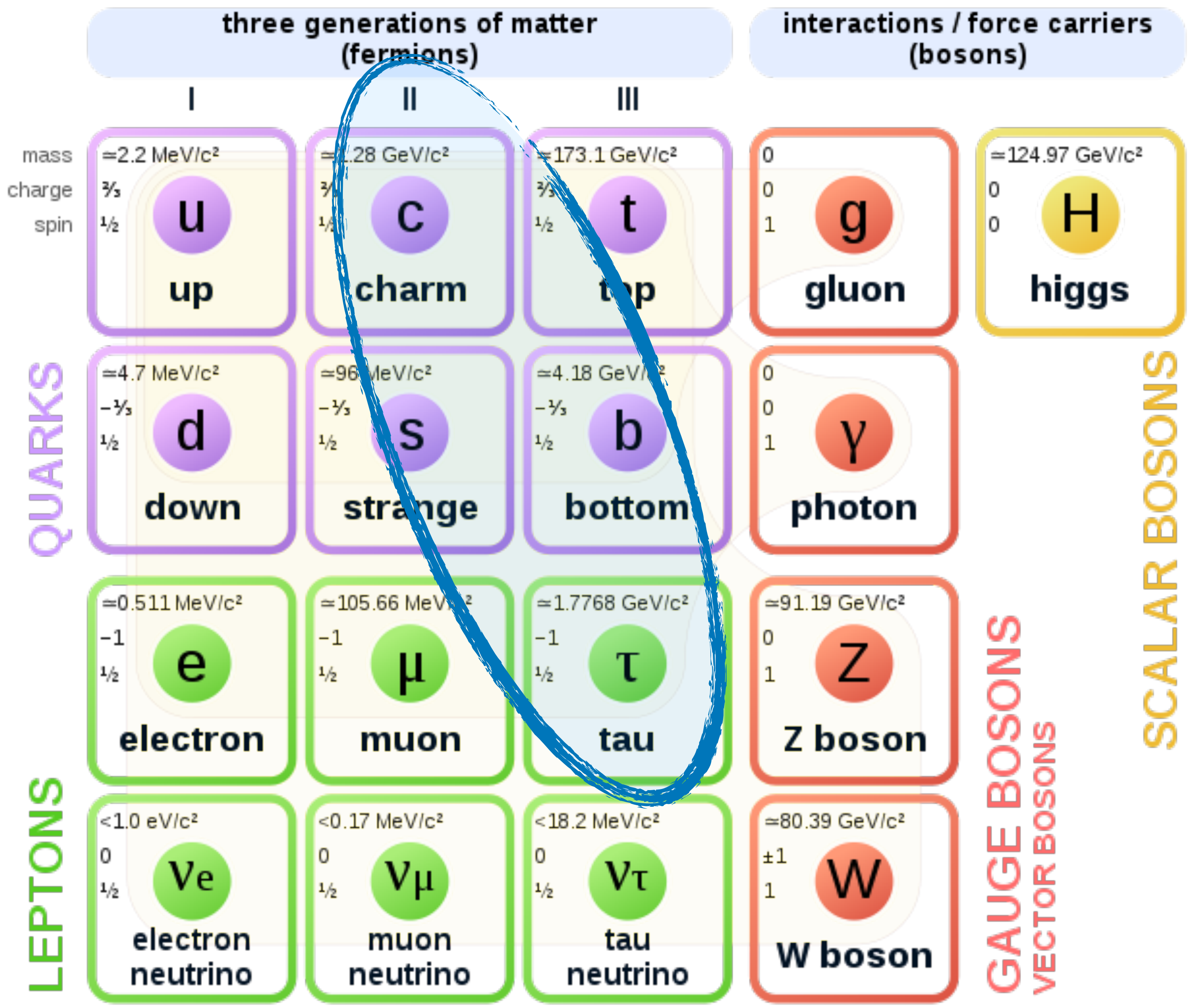

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B mesons ($B^0 = \overline{b}d,\ B^+ = \overline{b}u, B_s^0 = \overline{b}s$) are the only bounds states which involves the 3rd quark generation → particularly interesting sector

B meson branching fractions (BF) status

So, after decades of flavour physics, do we know B meson very well both experimentally and theoretically?

Branching fraction=
decay rate in a certain channel
or
partial width over the total width

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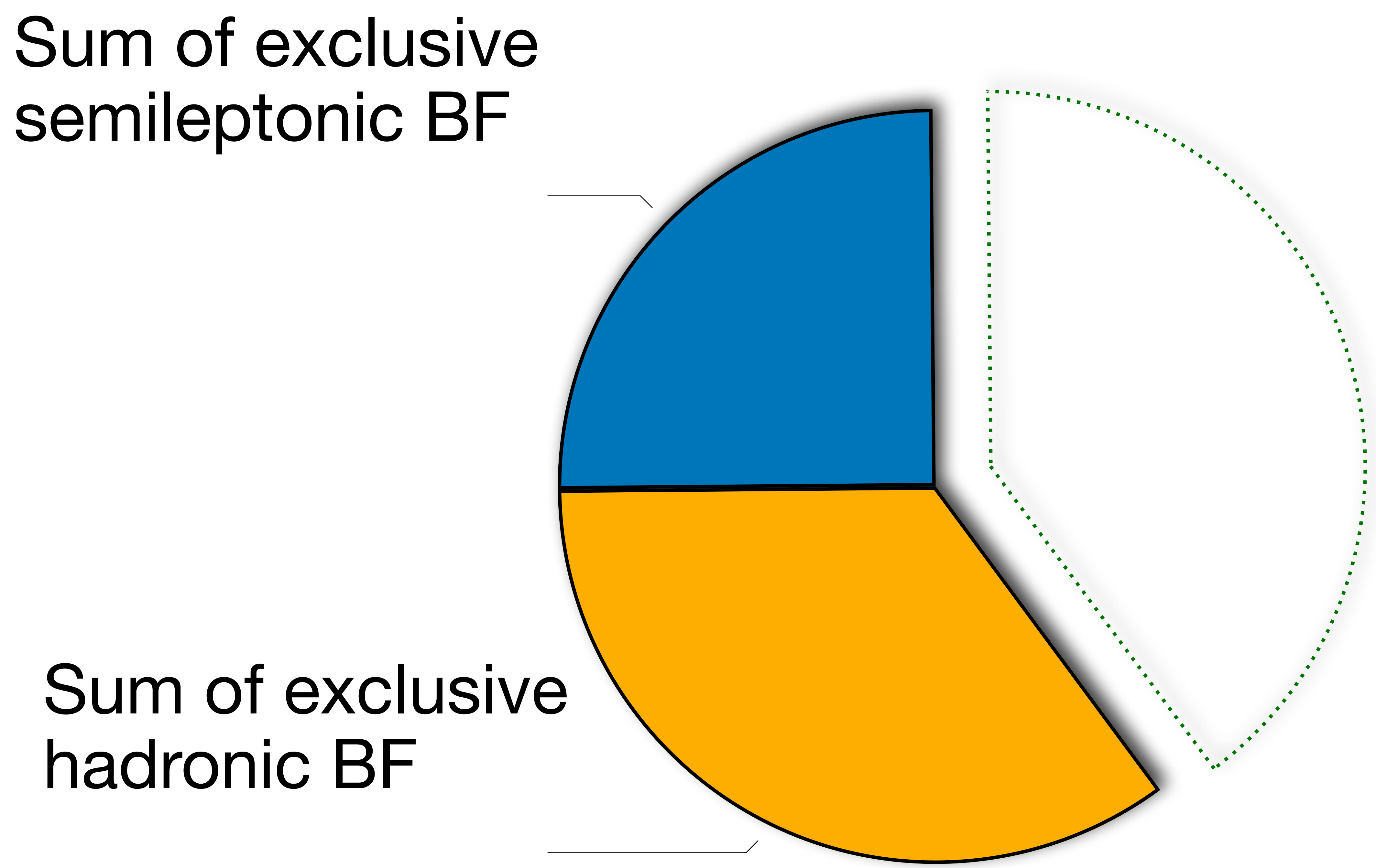

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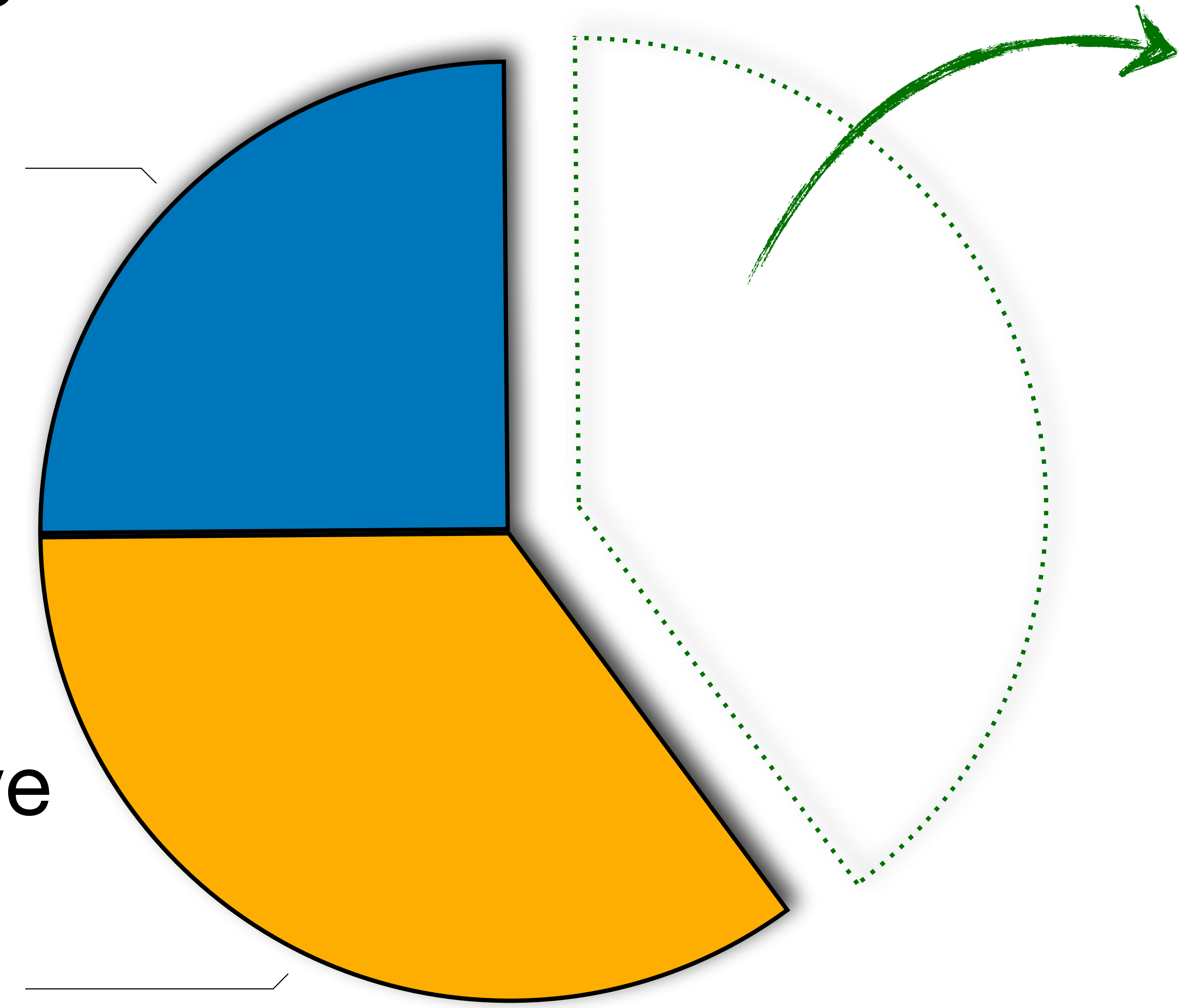

- 40% of BFs **unknown in term of exclusive** final states
- We have access to this fraction by ***inclusive*** measurements
- In term of exclusive composition is made of:
  - **high multiplicity** hadronic final states $B \to D^{(*)}(D)(K)(n\pi)(\pi^0)$ $(D^+ = c\bar{d},\ D^0 = c\bar{u})$
  - **Gap modes**: few % missing semileptonic BF

[from PDG]

mode	BF
$D^0 X$	$(8.6 \pm 0.7)\%$
$\overline{D}^0 X$	$(79 \pm 4)\%$
$D^+ X$	$(2.5 \pm 0.5)\%$
$D^- X$	$(9.9 \pm 1.2)\%$
$D_s^+ X$	$(7.9^{+1.4}_{-1.3})\%$
$D_s^- X$	$(1.10^{+0.40}_{-0.32})\%$
$\Lambda_c^+ X$	$(2.1^{+0.9}_{-0.6})\%$
$\overline{\Lambda}_c^- X$	$(2.8^{+1.1}_{-0.9})\%$
$\overline{c} X$	$(97 \pm 4)\%$
$c X$	$(23.4^{+2.2}_{-1.8})\%$

B meson branching fractions in simulation

- Reliable simulation (MC) is a crucial tool to perform our analysis
- The **background studies** often relies on MC (when sideband/control sample not available)
- The **machine learning tools** (BDT, Neural Networks…) often use MC to be trained

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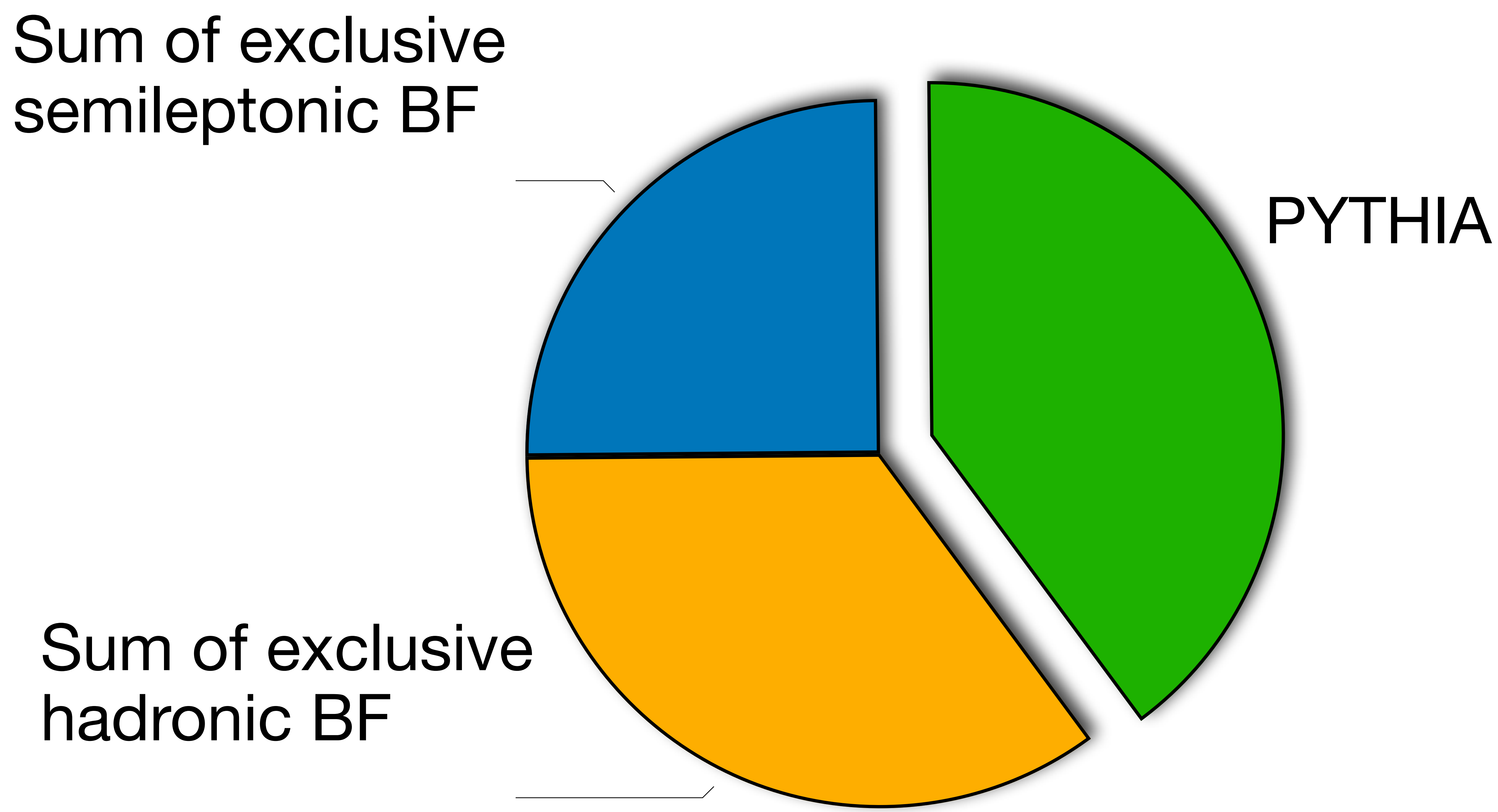
Simulated B^+ branching fractions



- Exclusive BFs are simulated with specific generator (EvtGen, Tauola, Photos, Herwig…)
- **PYTHIA** is used to cover the missing BF:
  - combination of partons and fragmentation model are specified

e.g. `0.26209371 u anti-d anti-c d   PYTHIA 23;`

  - PYTHIA is handling the **hadronization** producing *all the possible final states* missing in the exclusive list

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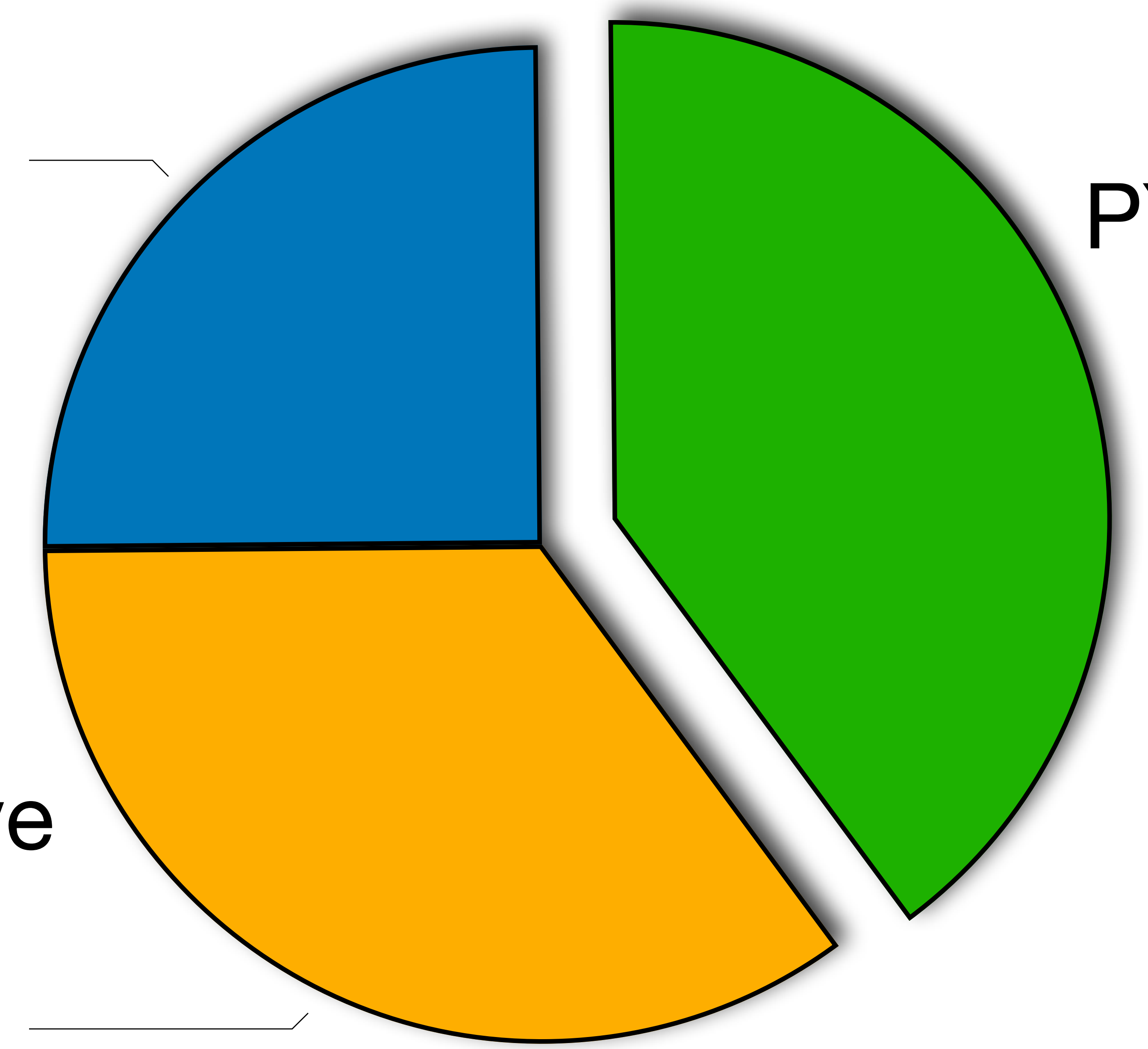
How do we use the MC in Belle II?

Simulated B^+ [partially hidden]



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Belle II collaboration

over **1100 physicists and engineers** from **122 institutions** in **27 countries**

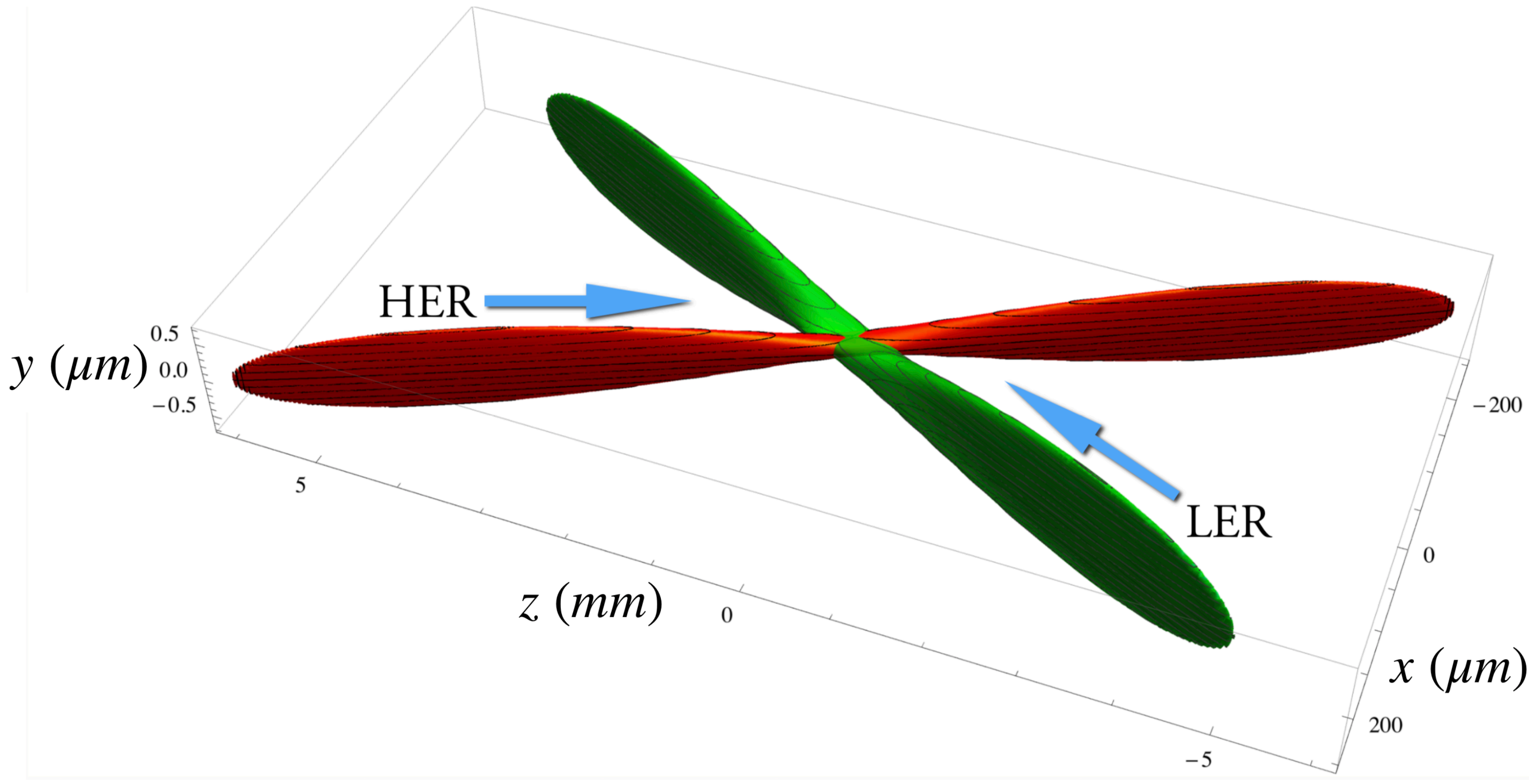
Belle II experiment at SuperKEKB collider

SuperKEKB

- Successor of KEKB (1999-2010, KEK, Japan)
- Asymmetric e^+e^- collider

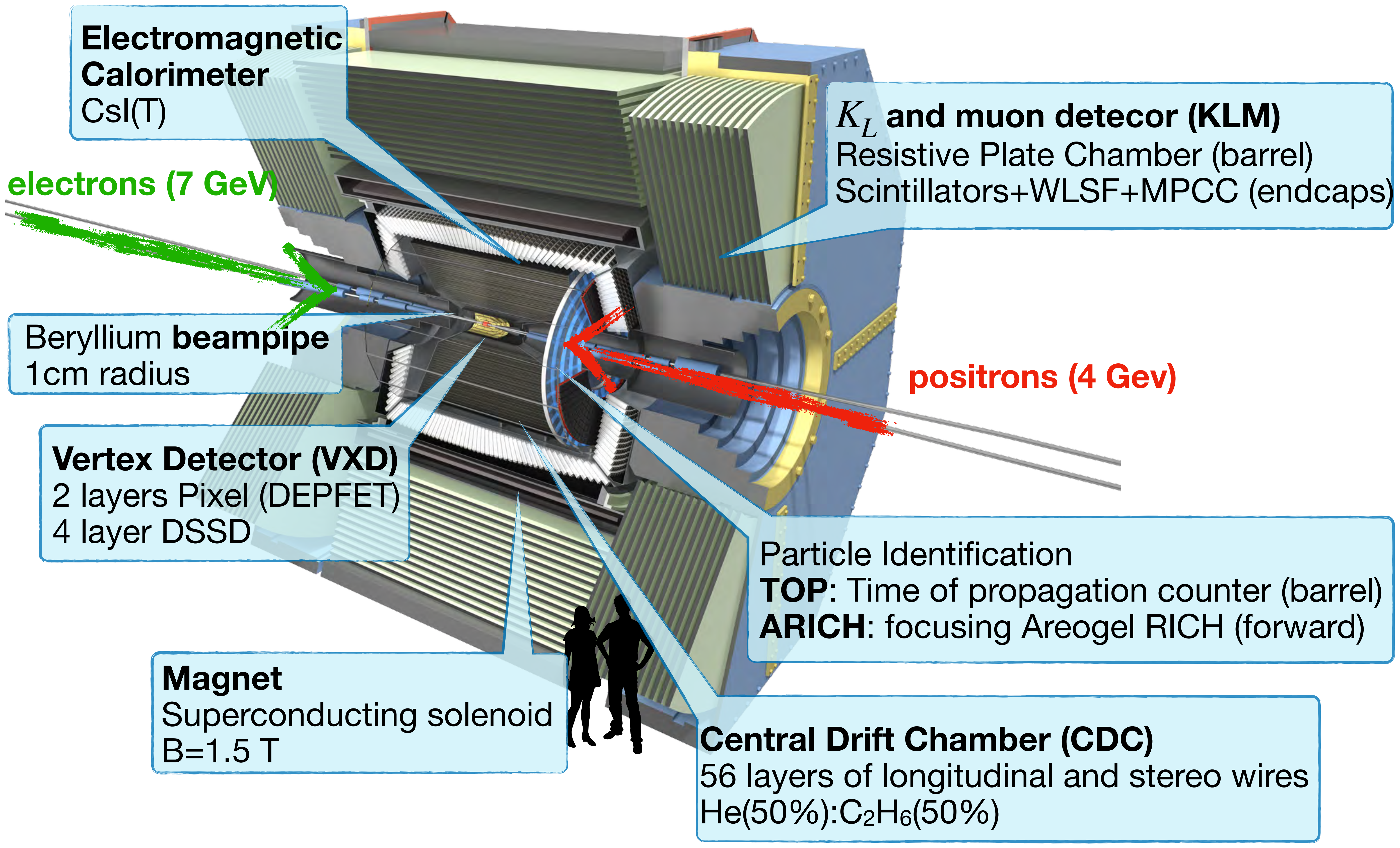
$$\sqrt{s} = m(\Upsilon(4S)) = 10.58\ \text{GeV}$$
$$(\Upsilon(4S) = b\bar{b})$$

- Target peak luminosity: $\mathbf{6 \cdot 10^{35}\ cm^{-2}s^{-1}}$ (x 30 of KEKB)



Nano-beam scheme:
250 μm (Z) × 10 μm (X) × 50 nm (Y)

Belle II

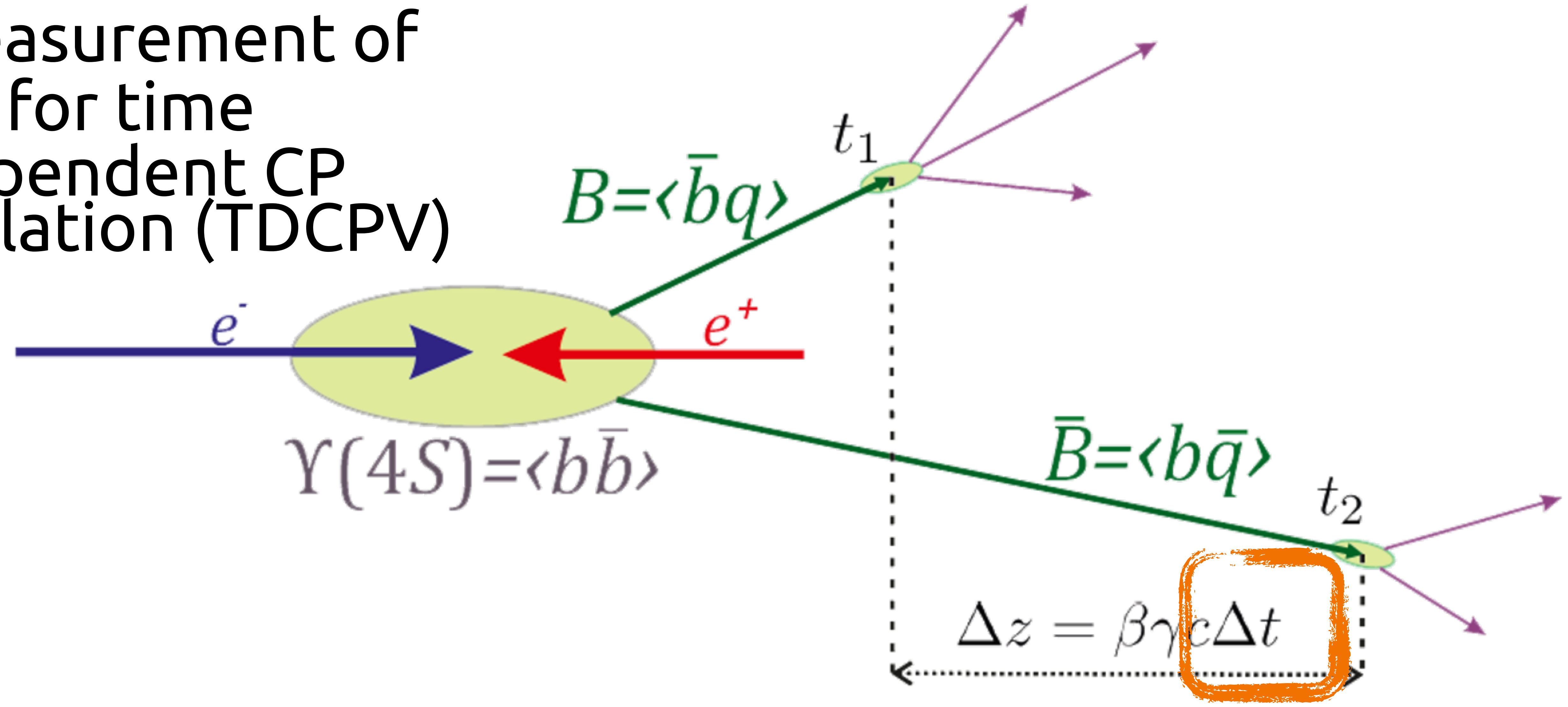


[Belle II Technical Design Report, arXiv:1011.0352]

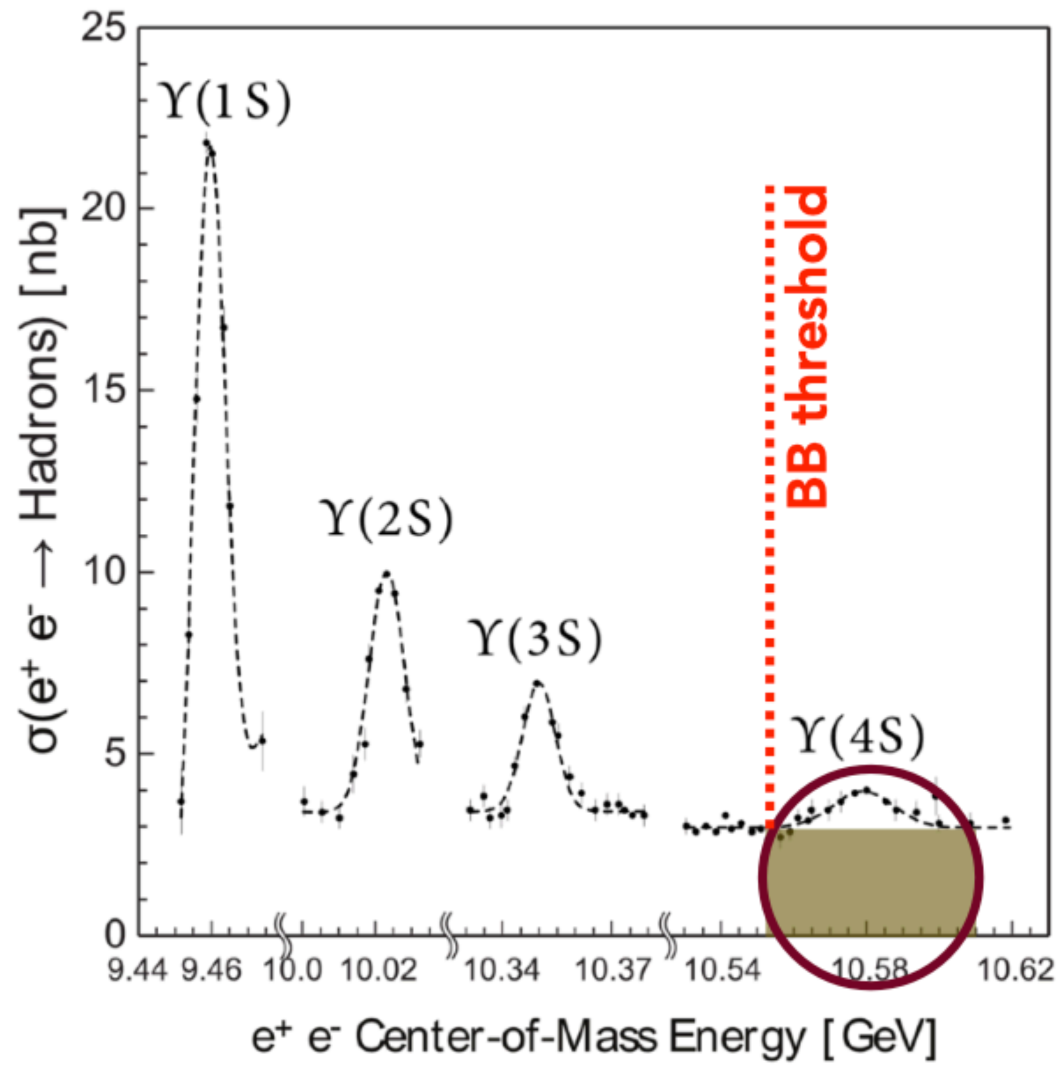
B-Factory basics

- **Asymmetric** collider ⇒Boost of center-of-mass
- Excellent **vertexing** performance ($\sigma \sim 15\ \mu$m)
- coherent $B\overline{B}$ pairs production
- Excellent **flavour tagging** performance

measurement of Δt for time dependent CP violation (TDCPV)



- $\sqrt{s} = m(\Upsilon(4S)) = 10.58\ \text{GeV} \simeq 2m_B \Rightarrow$ **constrained kinematics**
- **Hermetic** detector ⇒ complete event reconstruction:
  - **Absolute** BF measurements
  - measurements with several **neutral** particles or **neutrinos**

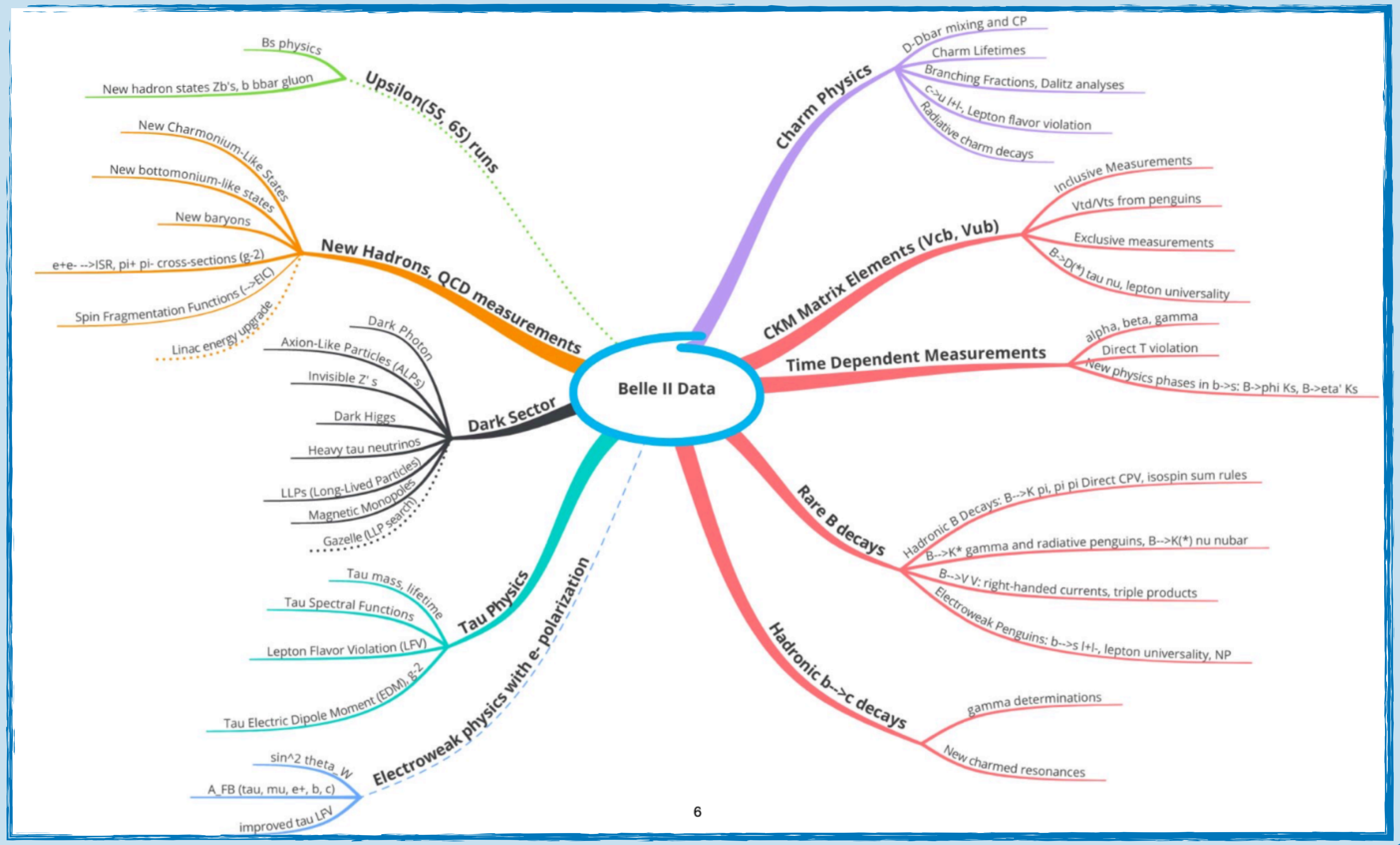


$e^+e^- \to$	Cross section [nb]
$\Upsilon(4S)$	1.05 ± 0.10
$c\bar{c}$	1.30
$s\bar{s}$	0.38
$u\bar{u}$	1.61
$d\bar{d}$	0.40
$\tau^+\tau^-(\gamma)$	0.919
$\mu^+\mu^-(\gamma)$	1.148
$e^+e^-(\gamma)$	300 ± 3

B-Factory basics

Belle II physics program

- Not only precision measurements using $\Upsilon(4S) \to B\bar{B}$
- Charm ($c\bar{c}$) and tau ($\tau^+\tau^-$) factory as well
- Dark matter searches
- Higher mass $b\bar{b}$ resonances ($\Upsilon(5S)$, $\Upsilon(6S)$) which can decay in excited B mesons pairs



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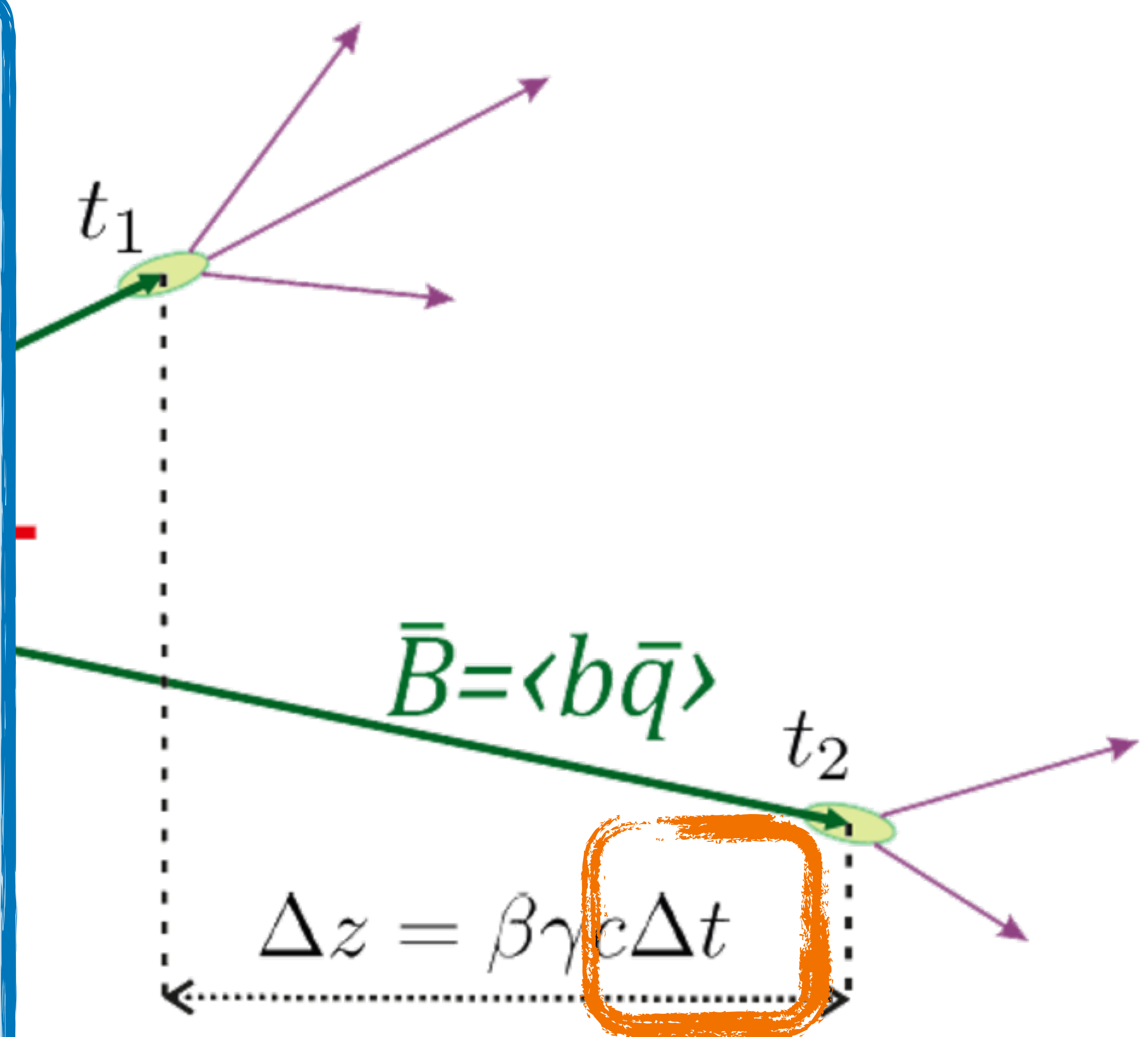

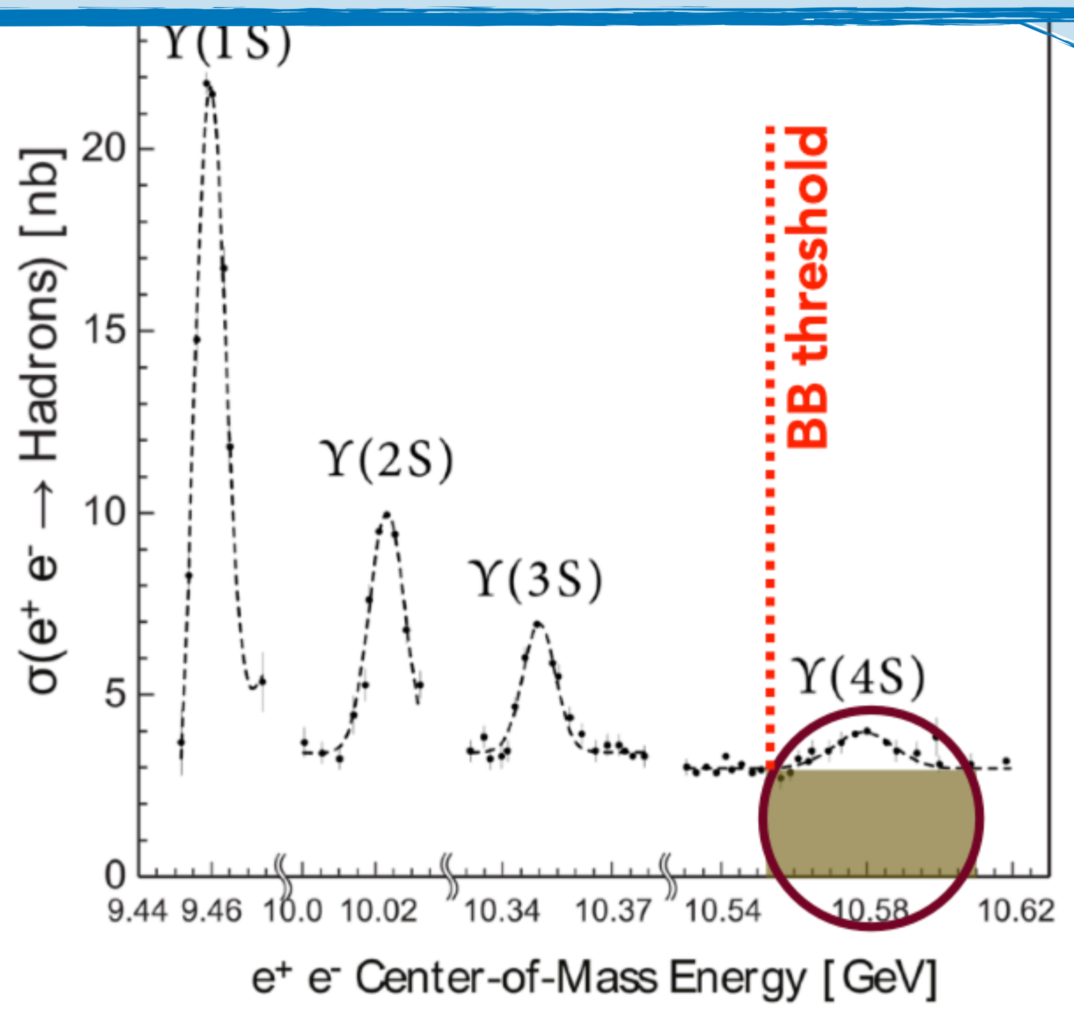

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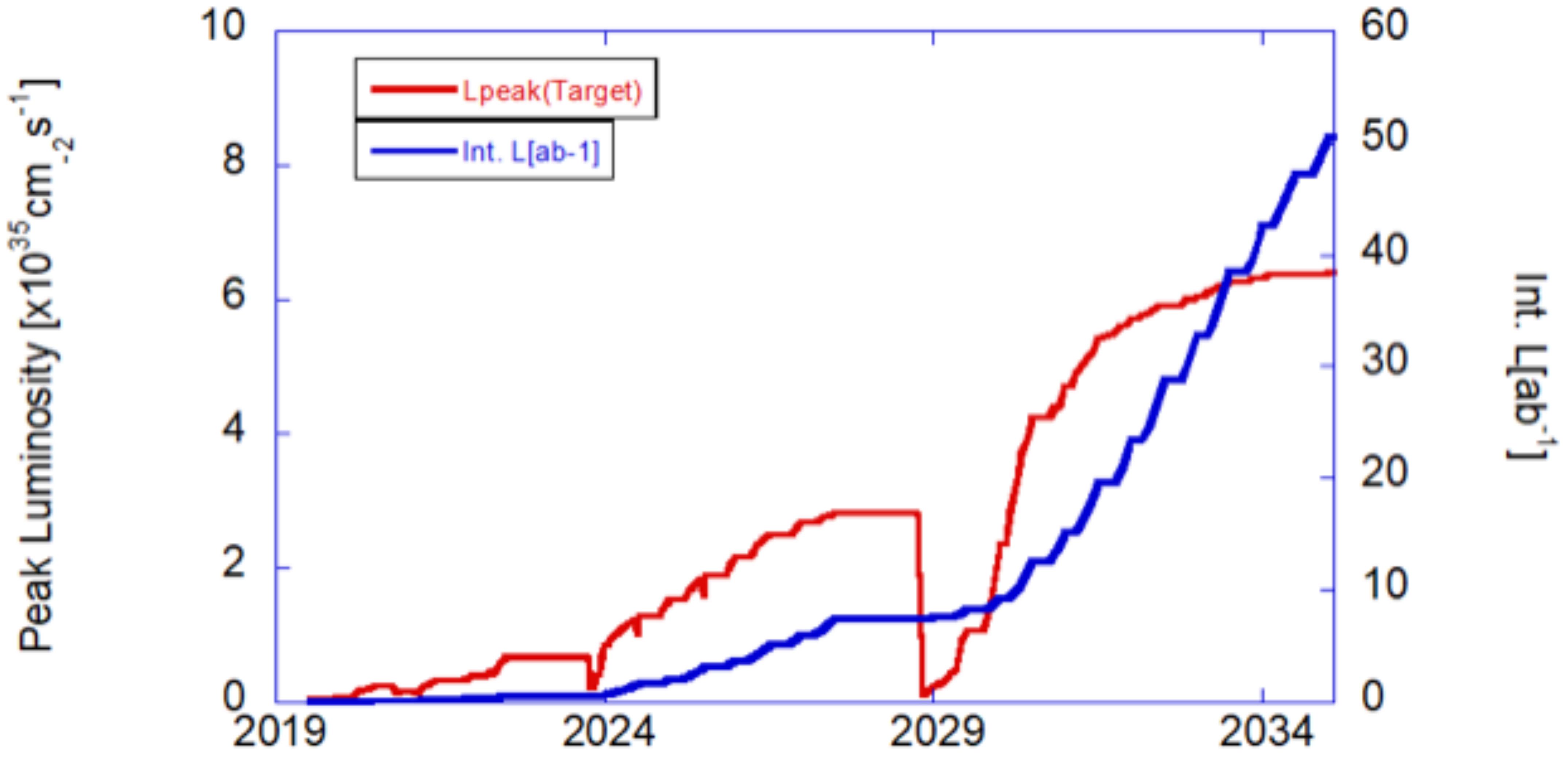
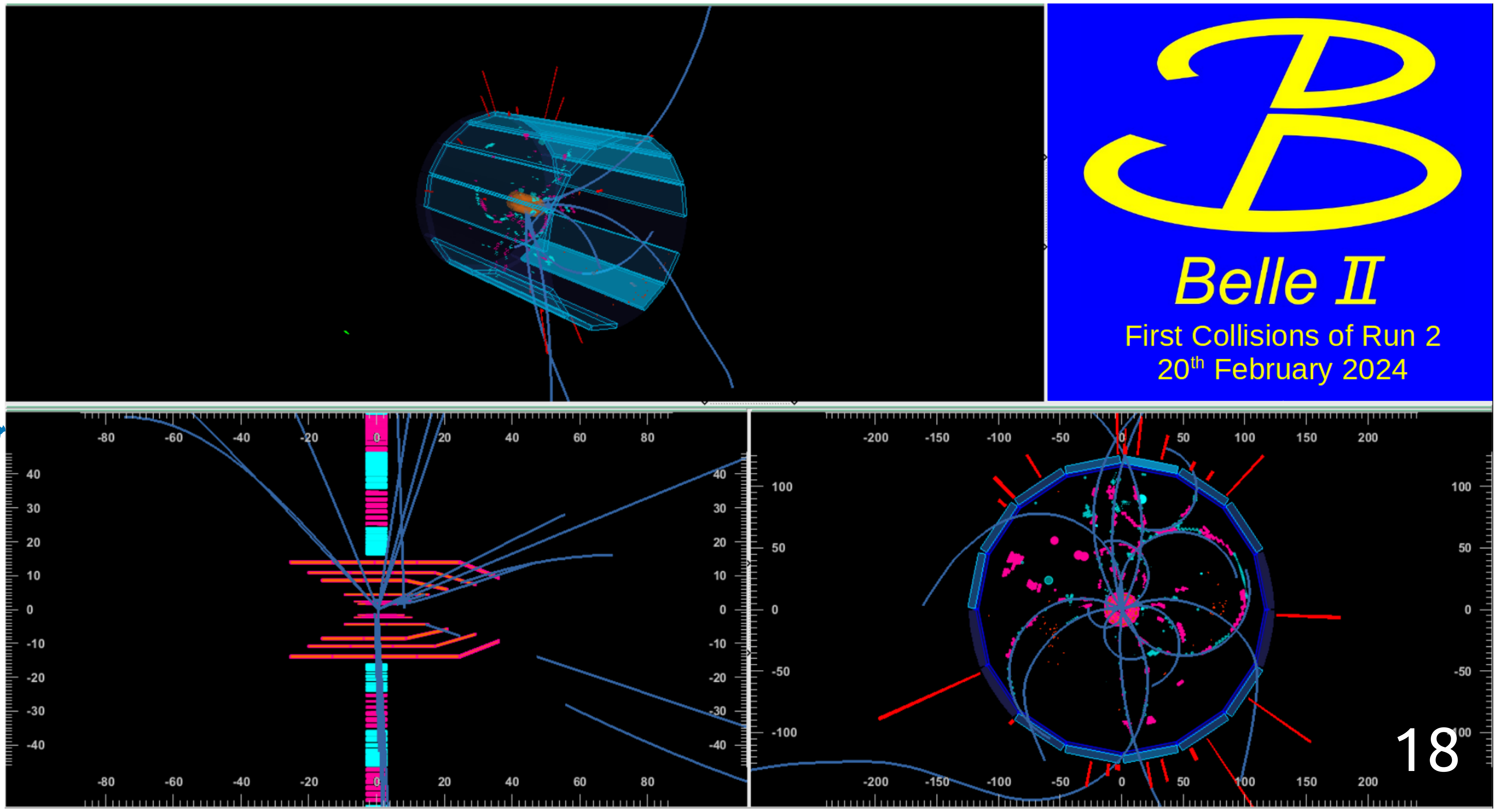
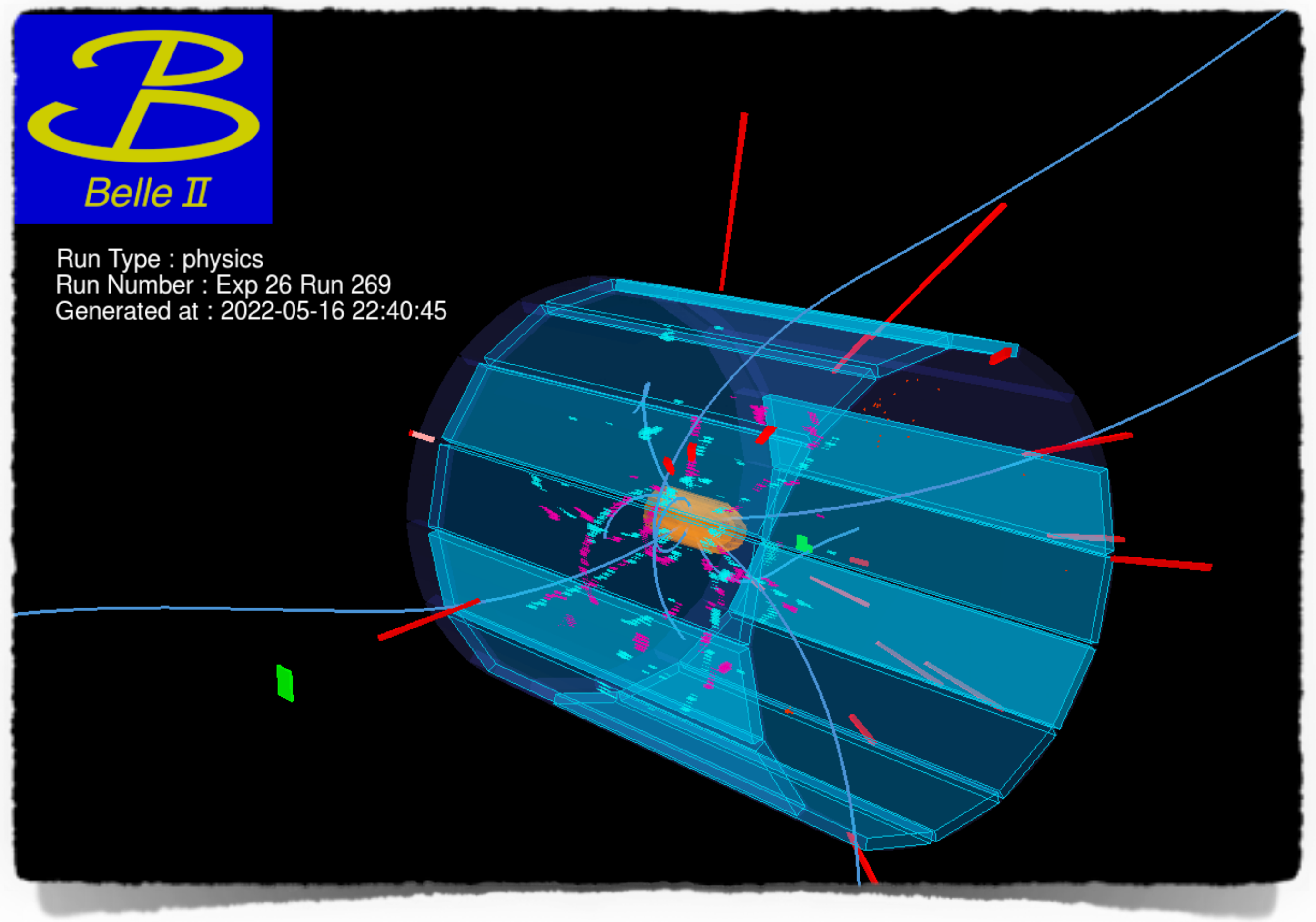
Belle II & SuperKEKB status

- Run 1 (2019-2022)
  - Peak luminosity $\mathbf{4.7 \cdot 10^{34}\ cm^{-2}s^{-1}}$ (reached the 22/06/2022)
  - Integrated luminosity: $\mathbf{424\ fb^{-1}}$ (~Babar, 0.5 Belle)
- Long Shutdown 1 (07/2022-01/2024) for major upgrades
  - new **two-layers pixel detector**
- Run 2: **data taking resumed** in February 2024
  - recovered Run 1 luminosity (peak luminosity: $\mathbf{5.1 \cdot 10^{34}\ cm^{-2}s^{-1}}$
  - ~150 fb^{-1} collected so far





Comparison with LHCb

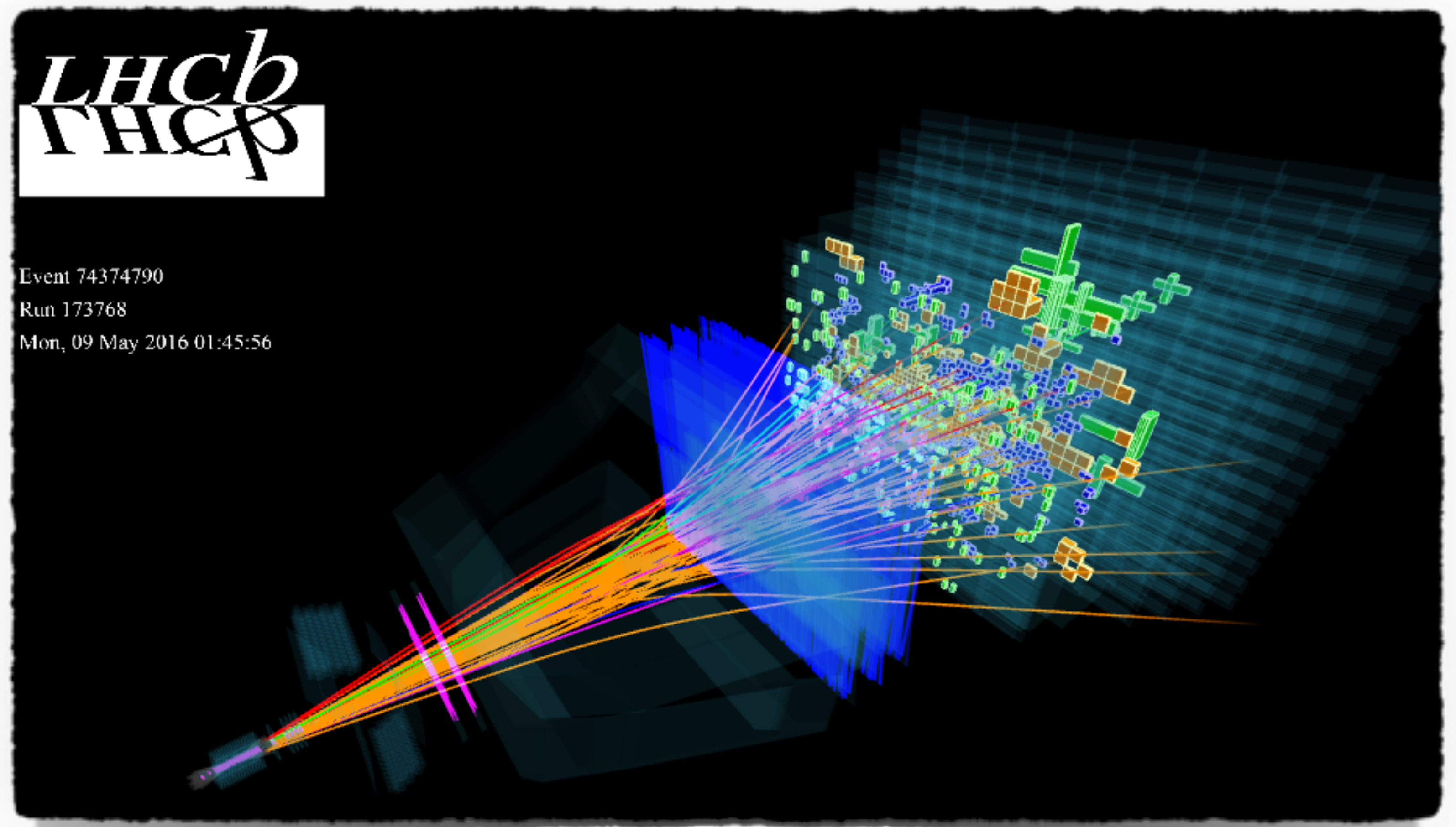


Initial state

- $e^+e^- \to \Upsilon(4S) \Rightarrow$ full knowledge
  - cross section: 1 nb $\Rightarrow 10^6$ B-mesons /fb
  - SNR~0.2
- $\sqrt{s} = 10.58$ GeV
  - $B^0, B^{+/-}$ only (+$c\bar{c}, \tau^+\tau^-$)
  - ~at rest in cm-frame, boosted in lab. (B flies 128 μm, $\sigma_{\text{vert}} \sim 10\mu$m)

Detector configuration:

- Hermetic around IP



Initial state

- pp collisions $\Rightarrow$ actual qq'/gg' initial state unknown
  - cross-section much larger: 1-100 μb $\Rightarrow 10^6$-10^8 B-meson/pb
  - much higher bkg: SNR~$10^{-3} \Rightarrow$ *Rule of thumb:* ***Belle2 (1/ab)= LHCb (1/fb)***
- $\sqrt{s} = 14$ TeV $\Rightarrow$ completely different kinematic region
  - also $B_s, B_c, \Lambda_b, \Sigma_b\ldots$ can be produced
  - Large boost ($p_B \sim 50$ GeV) $\Rightarrow$decay vertex of b hadrons within the detector volume (B flies for O(10mm), with a $\sigma_{\text{vert}} \sim 100\mu$m)

Detector configuration:

- forward spectrometer $\Rightarrow$ complete event reco. not possible

LHCb - missing energy channels

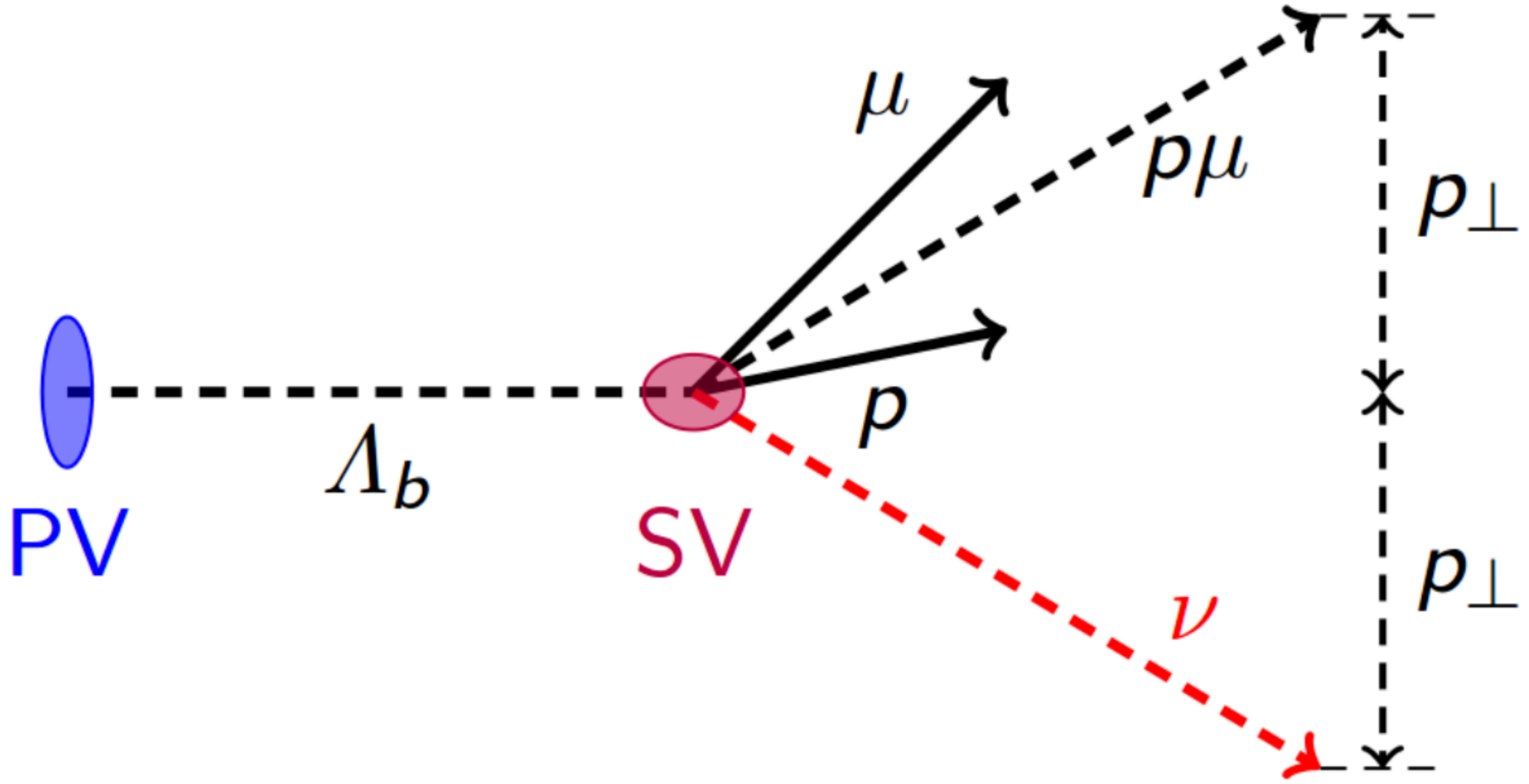
- If ν in the final state $\Rightarrow$ can't reconstruct invariant mass and pointing of the decay products

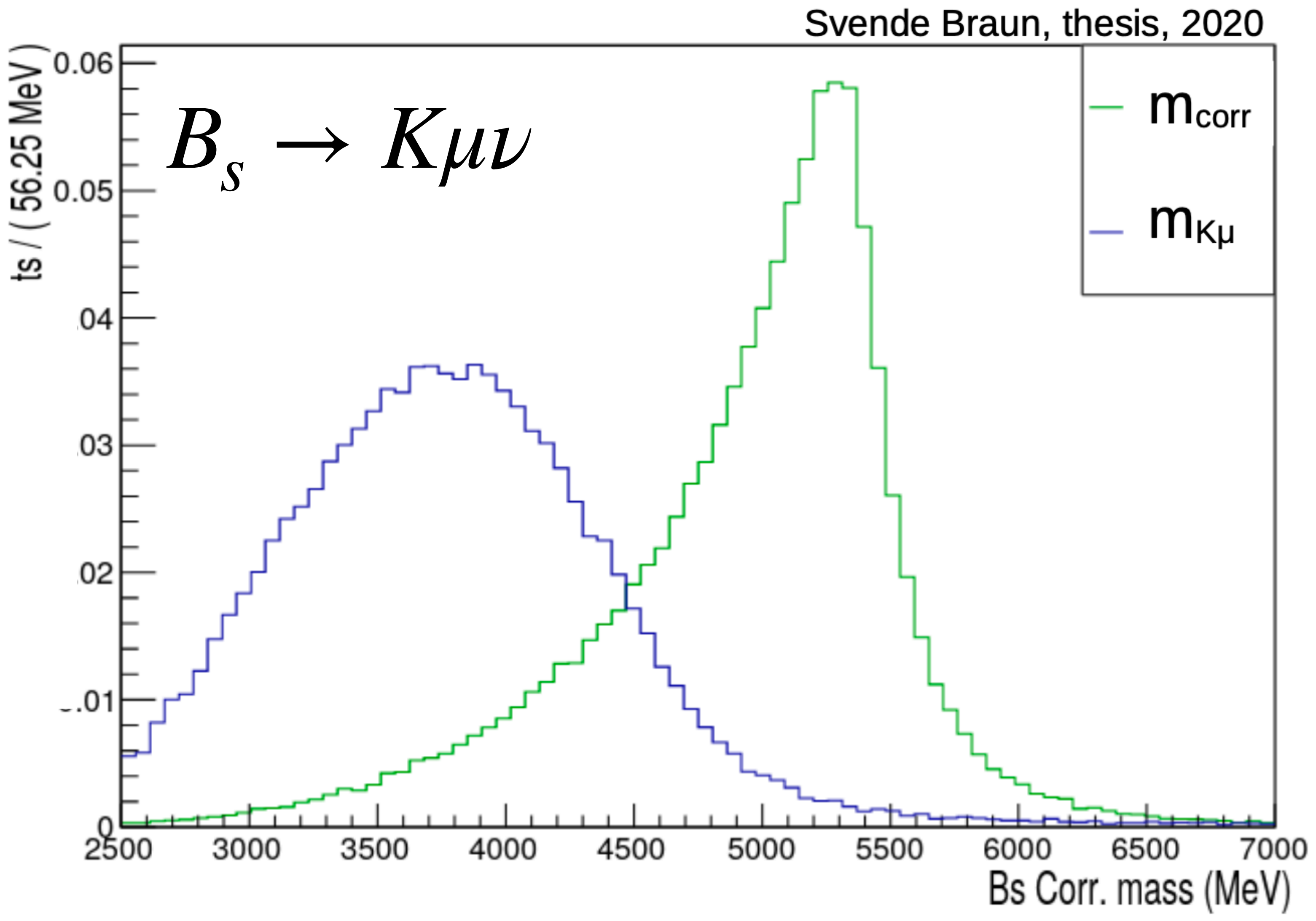
- **Corrected mass:**

$$m_{\text{corr}} = \sqrt{m_{\text{visbile}}^2 + p_\perp^2} + p_\perp$$

with $p_\perp$ = transverse momentum of the visible system wrt b-particle momentum (direction reconstructed using vertex info) = p_T^{missing}

- other variables according to the final state q^2, τ vertex displacement...





B-tagging

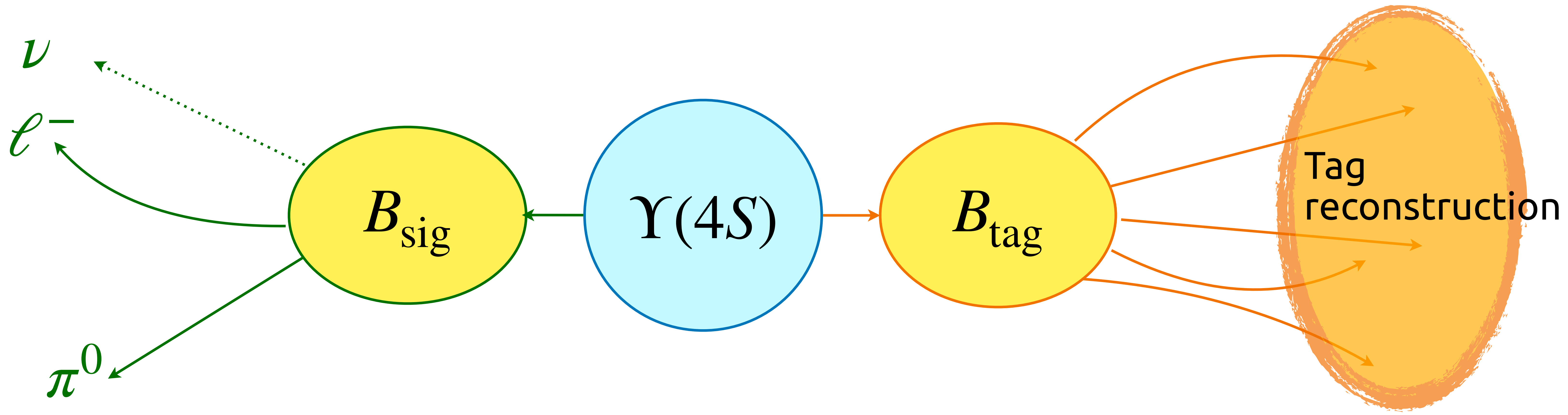
In B decay channels with **missing energy** in the final state (SM channels with neutrinos, NP searches...) ⇒ use of the the **Rest of the Event (ROE)** information:

- **Exclusive tagging:**

  Step 1: Reconstruction of the partner B (B_{tag}) using **well-known channels**

  Step 2: Using the $\Upsilon(4S)$ constraint, infer the information on the second B (B_{sig}): **flavour**, **charge** and **kinematic** constraints

- **Inclusive tagging:**
  signal reconstruction first, and then use of the ROE+$\Upsilon(4S)$ constraint to infer the signal signature



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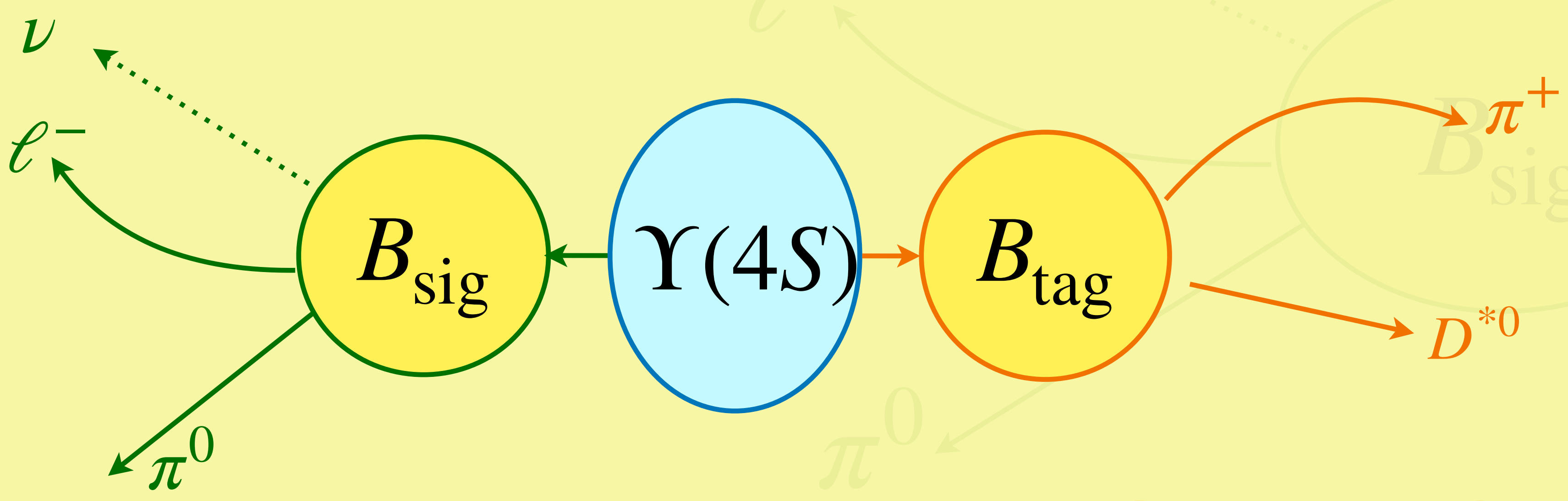
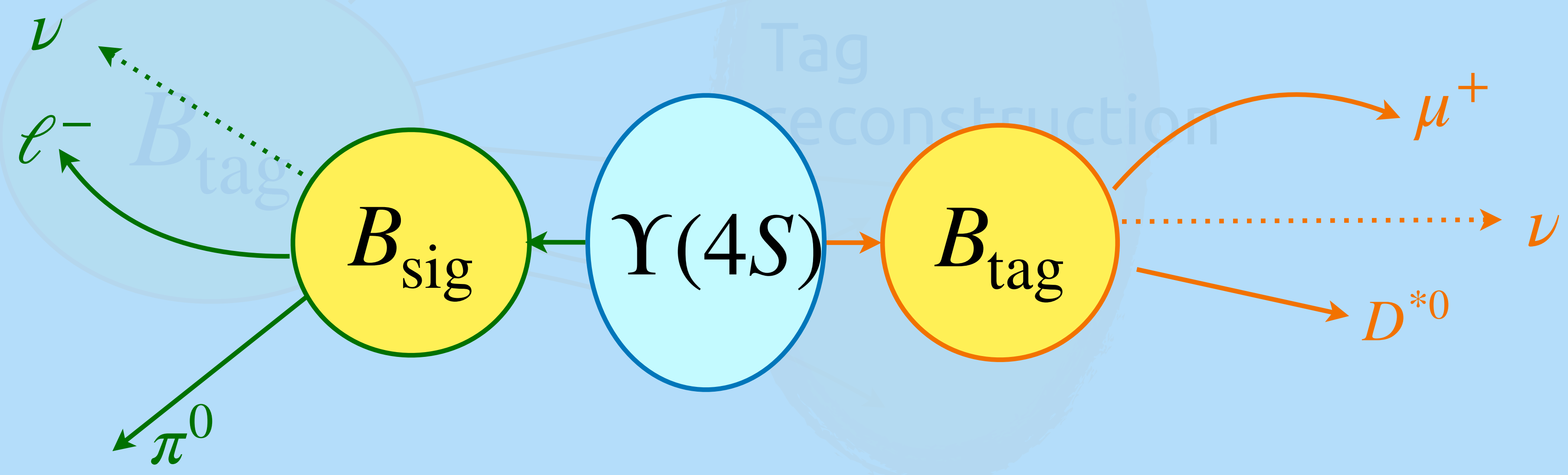
Hadronic B-tagging: B_{tag} reconstructed in known hadronic decays

- **Pro**: **full reconstruction** of the B_{tag}
- **Cons**: lower efficiency (because of lower BF)



Semileptonic B-tagging: B_{tag} reconstructed in known semileptonic decays

- **Pro**: **higher efficiency** (because of higher BF)
- **Cons**: neutrino(s) in the tagging side→ larger uncertainties on B_{sig} variables

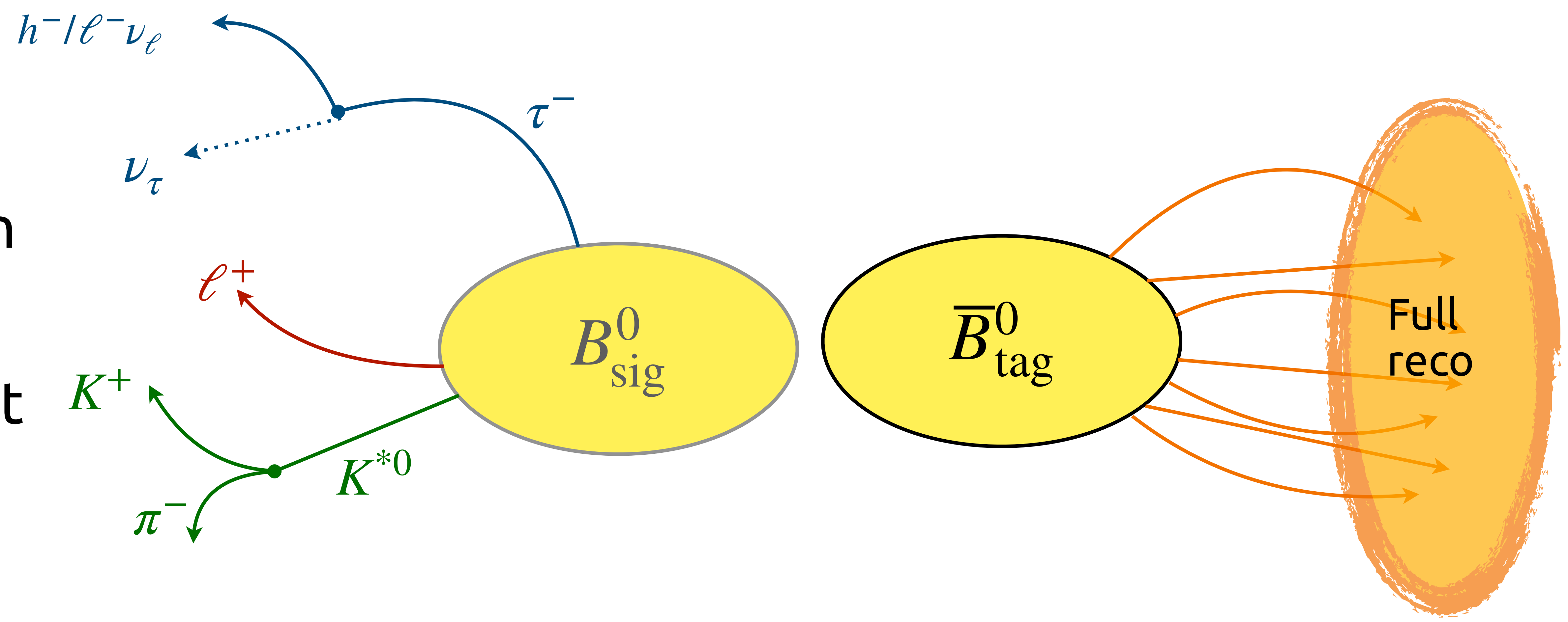


B-tagging example: $B^0 \to K^{*0}\tau e$

[Analysis ongoing in Belle II @CPPM by C. Lemettais]

Why?

- This channel is **forbidden in the SM** because violate lepton flavour
- This search has been never done before and we want to set an upper limit on its BF



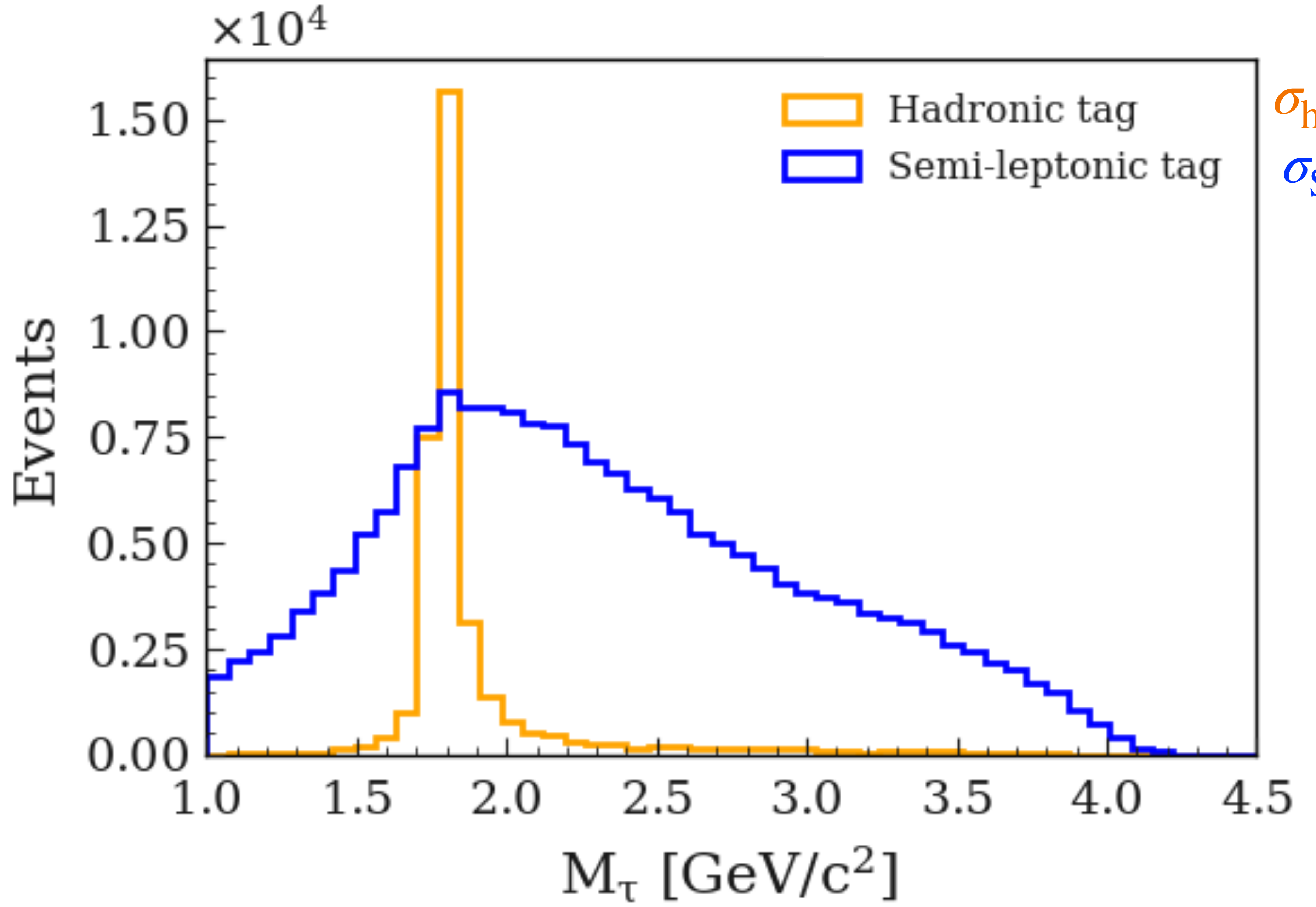
How?

- Reconstruct B_{tag} and K, ℓ tracks
- Missing energy only from τ decay $\to$ **recoil τ mass**:

$$p_\tau = p_{e^+e^-} - (p_K + p_\ell + p_{B_{tag}})$$

$$m_\tau^2 = m_B^2 + m_{K\ell}^2 - 2(E_B^* E_{K\ell} + |\vec{p}_B^*||\vec{p}_{K\ell}^*|\cos\theta_{B_{tag},K\ell})$$

- Hadronic tagging: lower efficiency, but better resolution
- Semileptonic tag: higher efficiency but worst resolution
- Here the worst determination of the B_{tag} momentum is the mayor offender

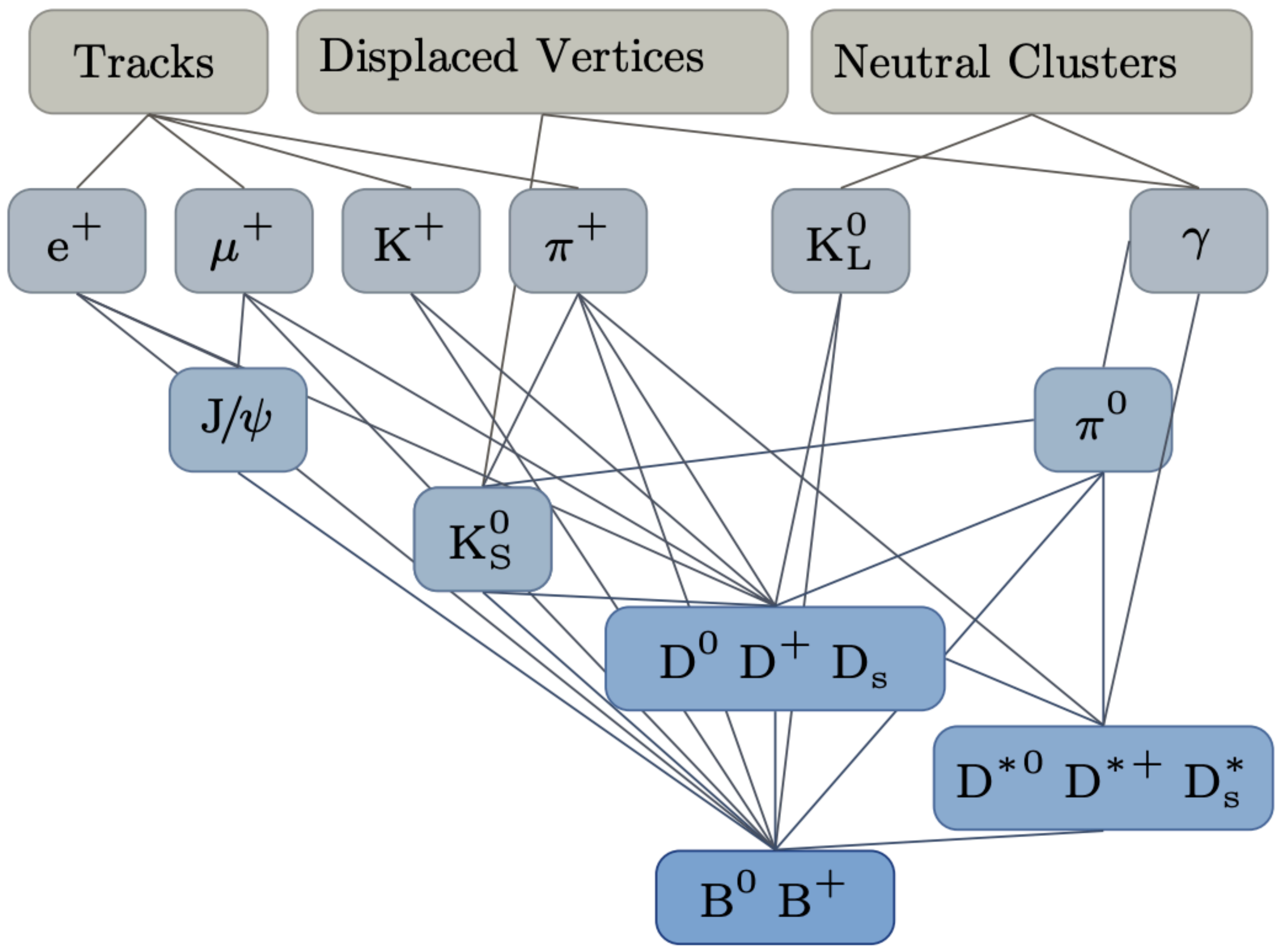


$\sigma_{had} \sim 50\,\text{MeV}$
$\sigma_{SL} \sim 720\,\text{MeV}$

B-tagging at Belle II: Full Event Interpretation (FEI)

[T. Keck et al, Comput Softw Big Sci 3, 6 (2019)]

- **MVA based** B-tagging algorithm
- **hierarchical approach** to reconstruct $\mathcal{O}(10^4)$ decay chains
  - NB: only the B decays which are **explicitly listed** will be identified
- $\varepsilon_{\mathrm{had}} \simeq 0.5\,\%\,, \quad \varepsilon_{\mathrm{SL}} \simeq 2\,\%$
- **Training**: on millions simulated $\Upsilon(4S) \to B\overline{B}$ events



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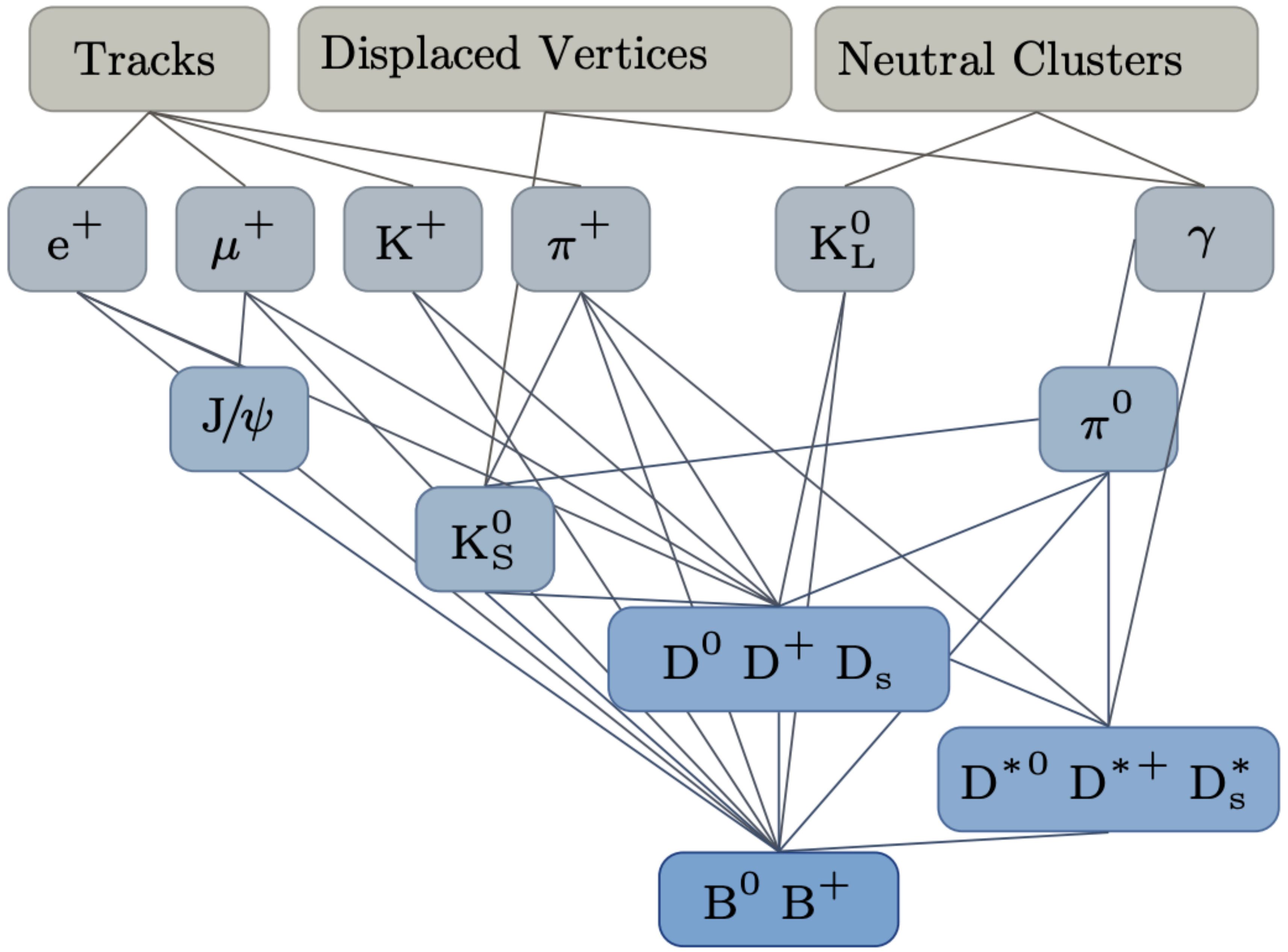
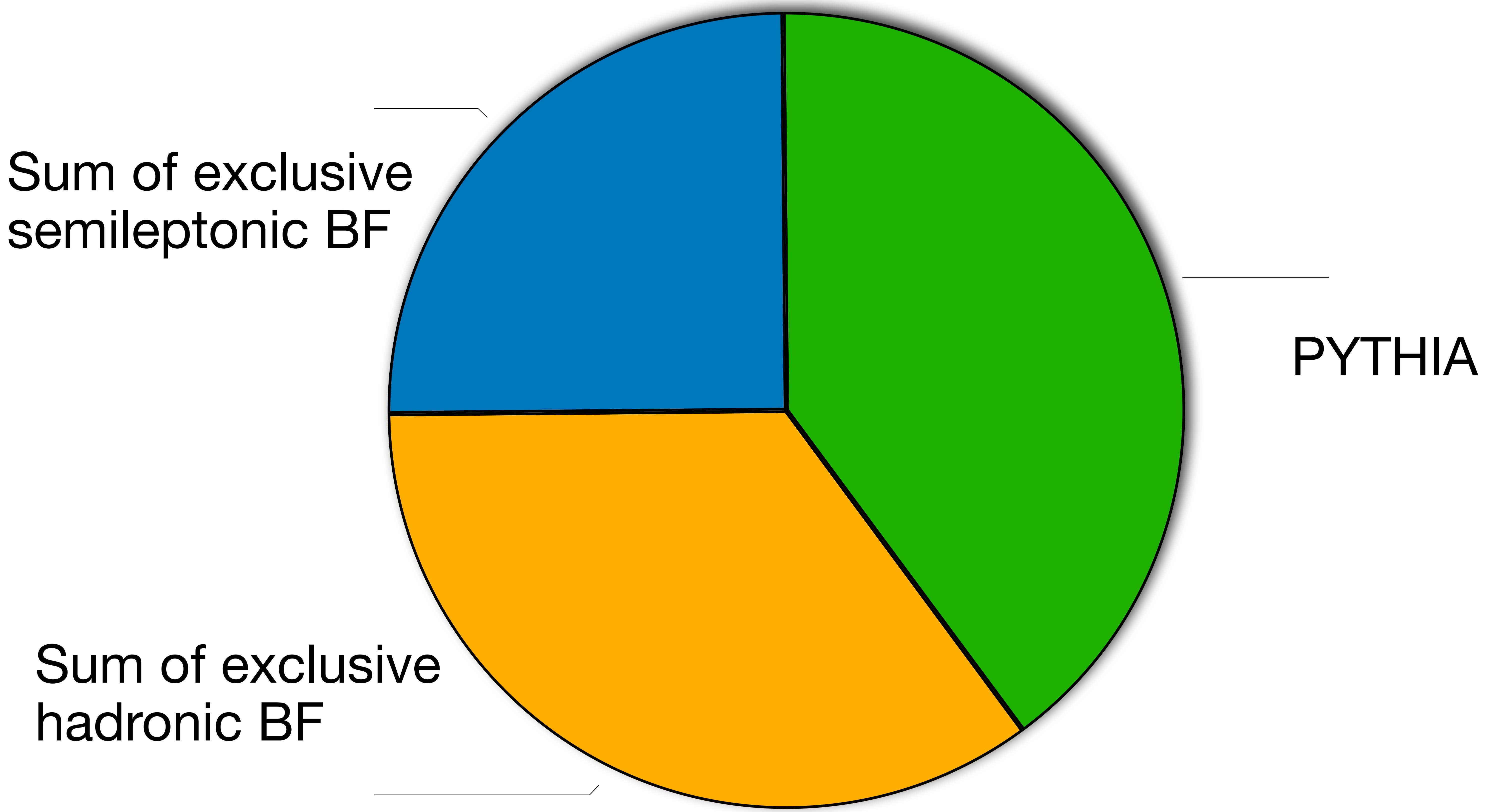


Simulation for B-tagging

We have to come back to the B^+ branching fraction simulation chart



Simulation for B-tagging: FEI usage

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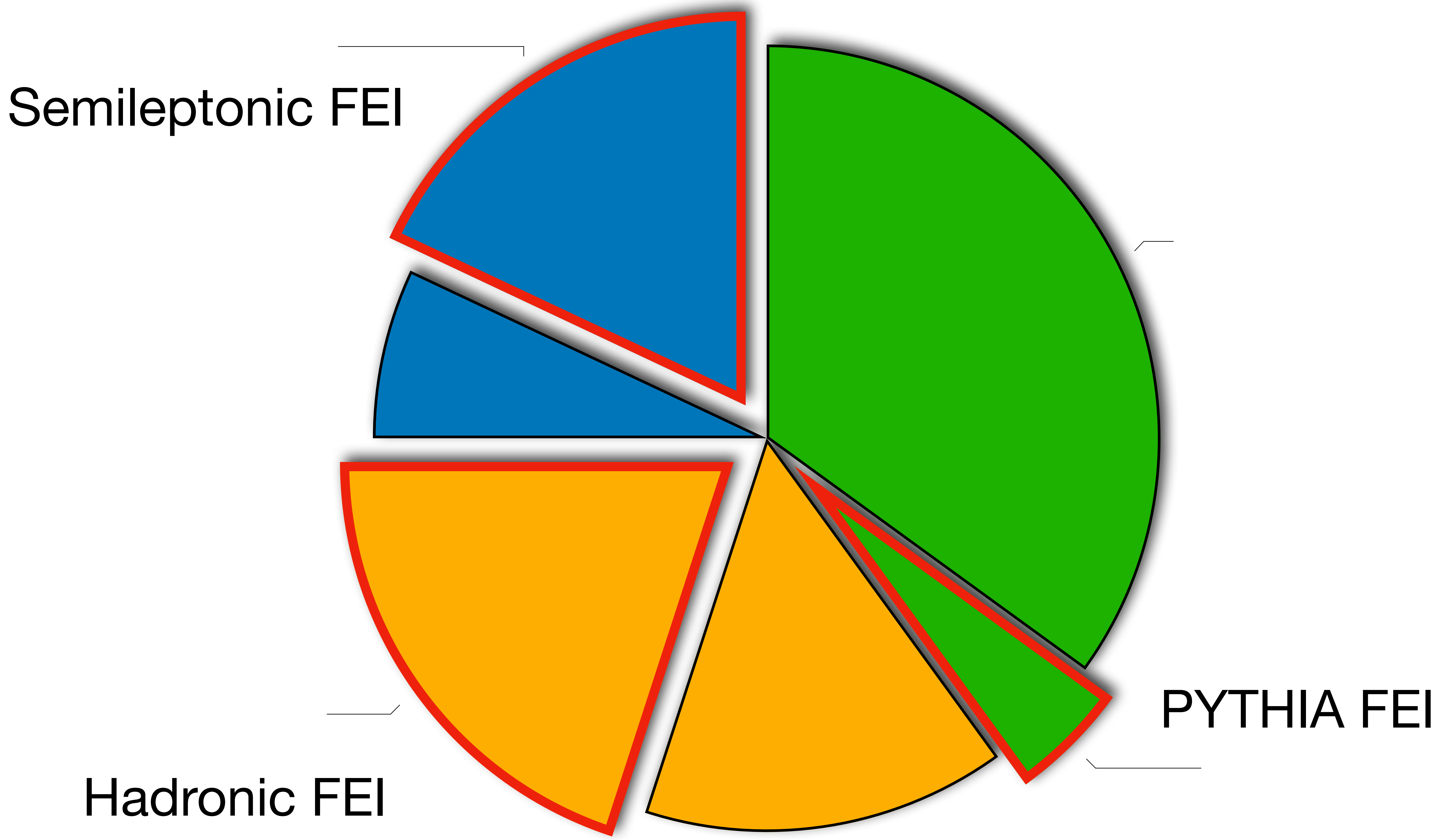

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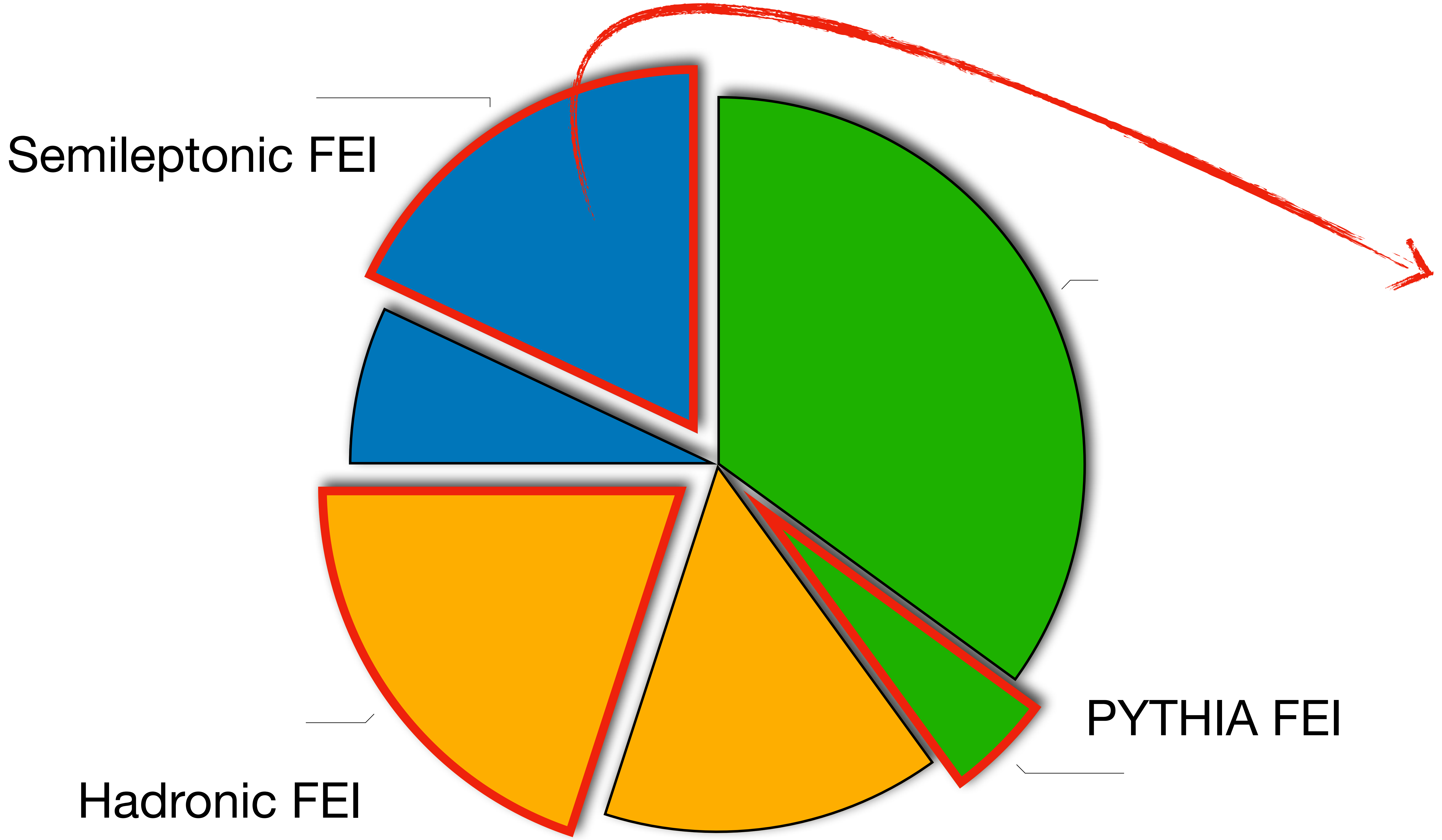

- SL BR almost mostly covered by FEI
- Included modes: $(\ell = e, \mu)$
  - $B^+ \to \overline{D}^{(*)0} \ell \nu$
  - $B^+ \to D^{(*)-} \ell^+ \nu \pi^+$
- Missing modes:
  - $B^+ \to \overline{D}^{(*(*))0} \tau \nu (\gamma)$
  - $B^+ \to \overline{D}^{(*(*))0} \ell \nu (\pi^0)$

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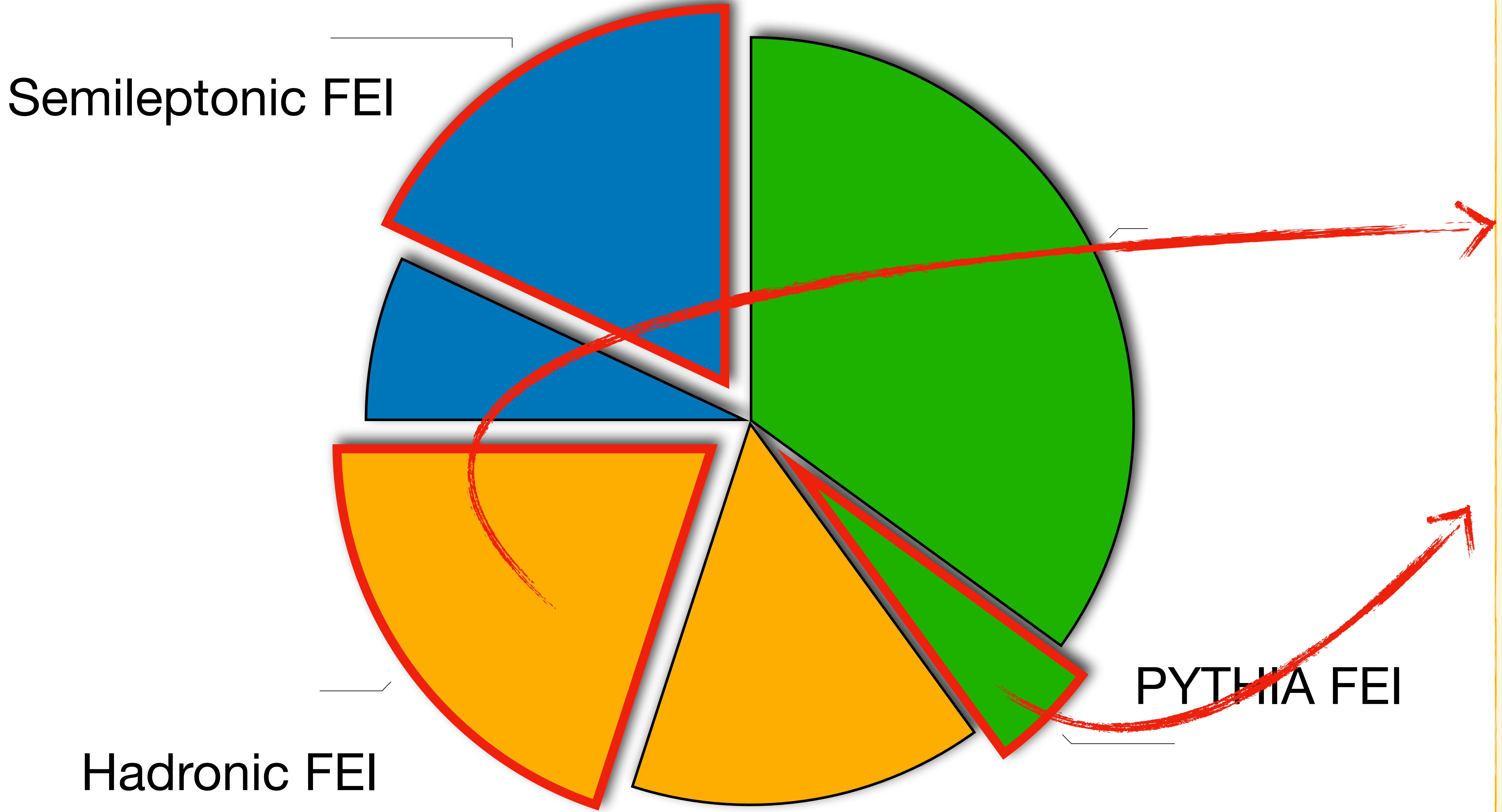

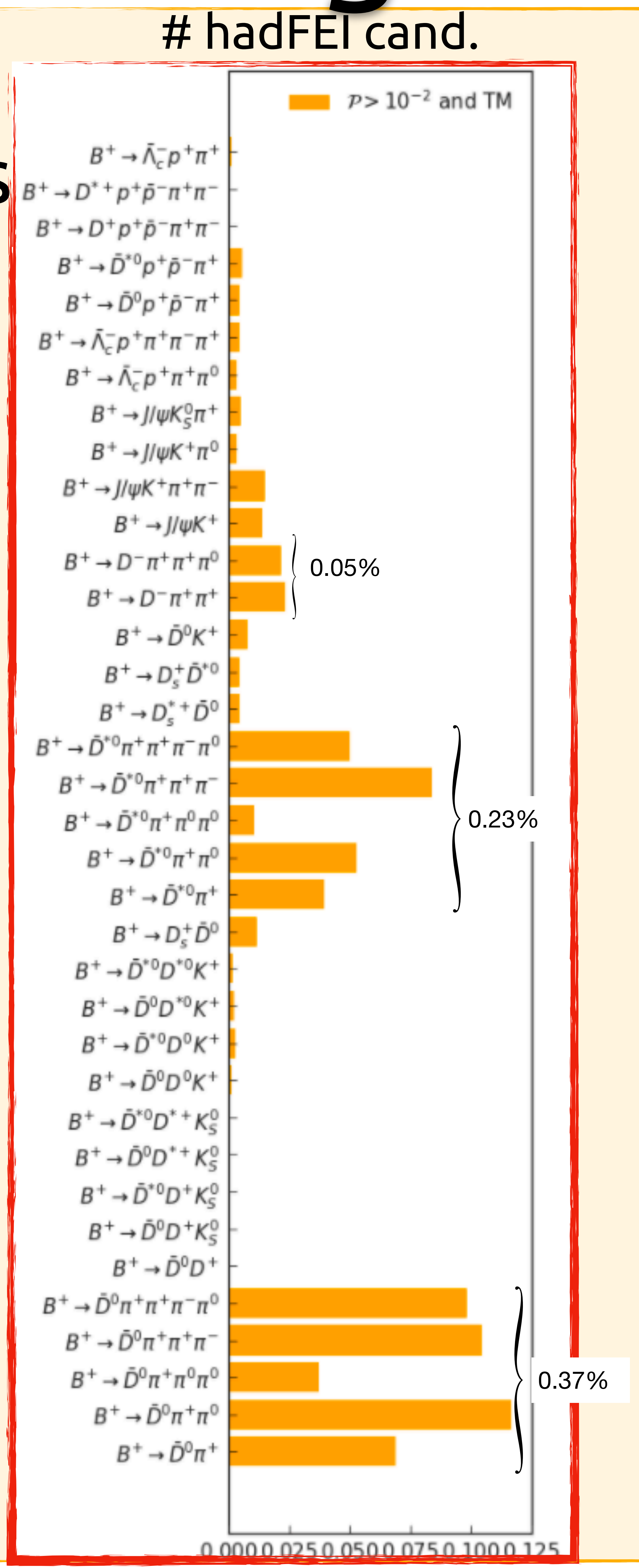

- Hadronic BR largely unexploited:
- considering ε, FEI relies on ~10% of the hadronic B decays

Belle II B-tagging improvements

- $\varepsilon_{\mathrm{Data}} \neq \varepsilon_{\mathrm{MC}} \rightarrow$ (large) **calibration factor** needed because of "wrong" simulation description
  - constant effort in improving the calibration
- Large room for improvement in hadronic FEI
  - **Improving old measurements**, both in BF and in in decay modelling to reduce the calibration factor
  - **Measuring new decay channels**, with a focus with the the high-purity ones (which may compensate the lower BFs...)
- New Tagging approaches are in development (GNN-based, semi-inclusive...)

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An example for each approach in the next slides

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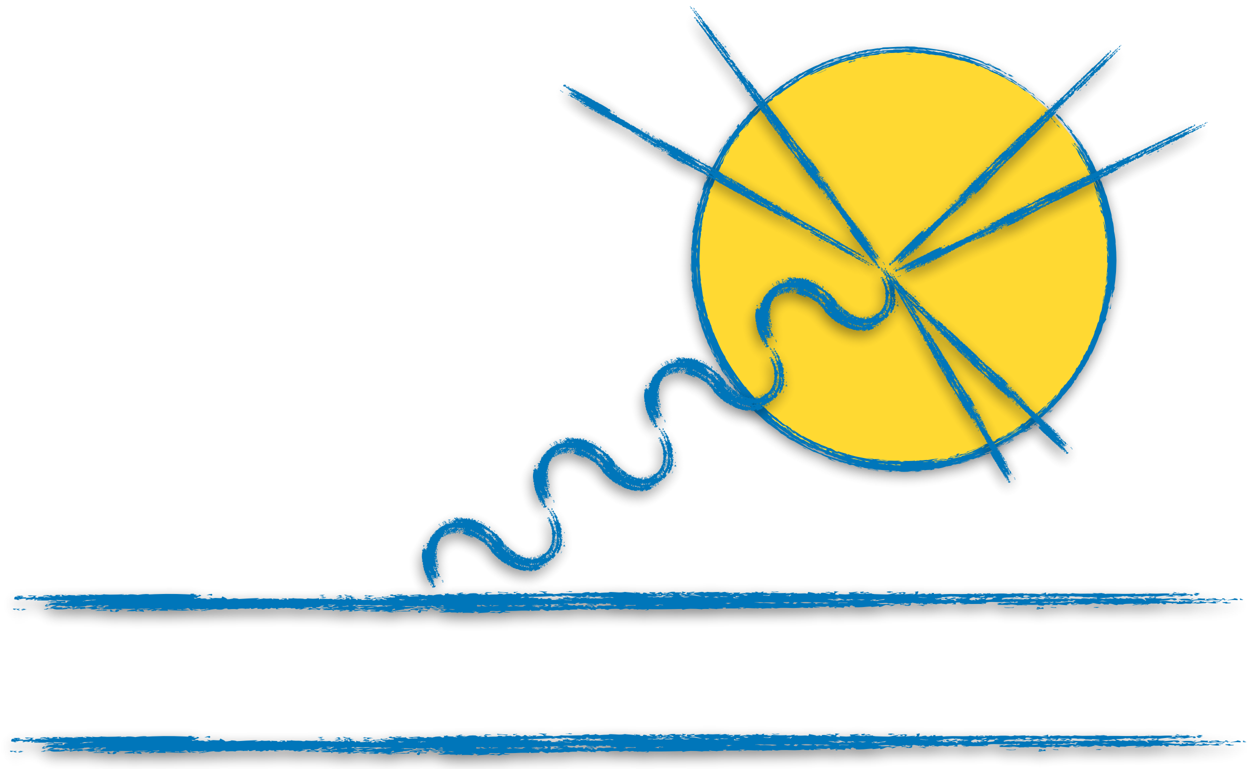
Example 1 :

Measurement of the branching fraction of the decay $B^- \to D^0 \rho(770)^-$ at Belle II

[PRD 109, L111103 (2024)]

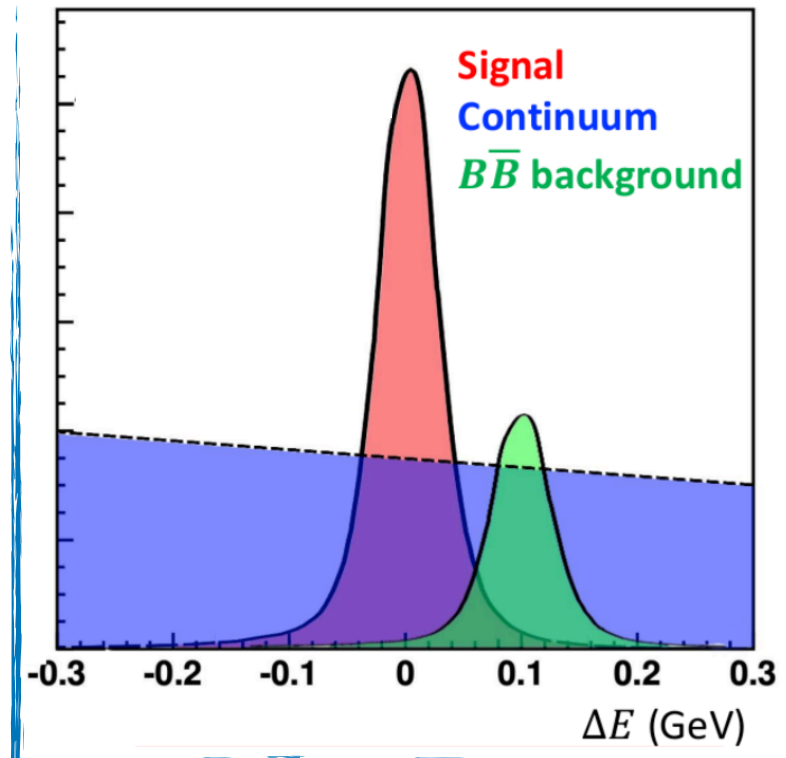


Branching fraction of $B^- \to D^0\rho(770)^-$

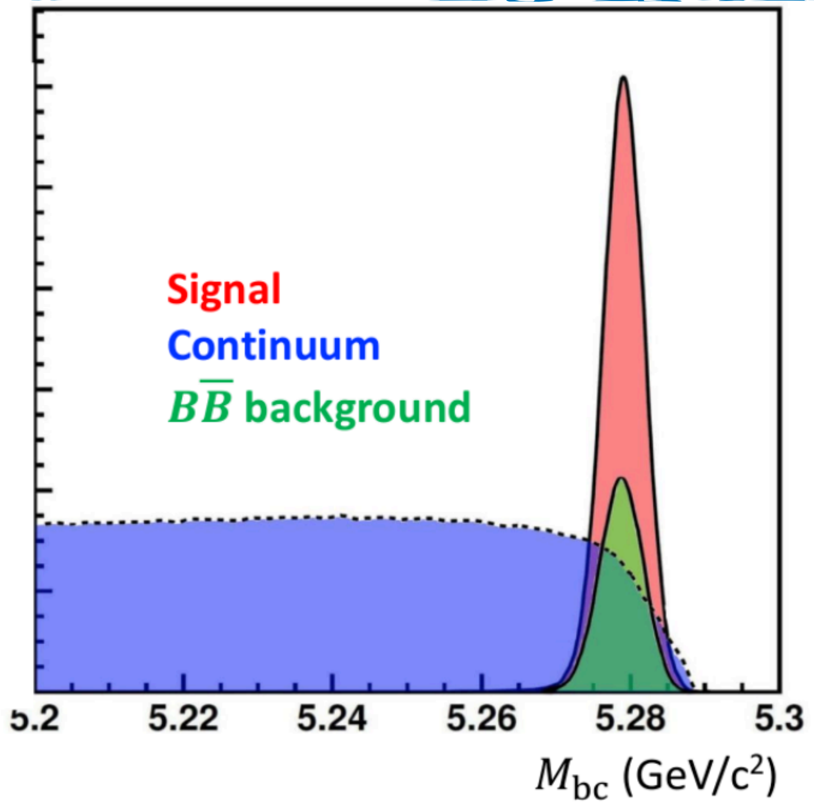
- Motivations:
  - $B^- \to D^0\rho(770)^-$ is one of the main modes of **hadronic B-tagging**, but tagging efficiency between data and simulation differs significantly in this channel.
  - One of the ingredients to test heavy-quark limit and factorization models (see for instance: *[Nucl. Phys. B 591, 313 (2000)]* , more details in the backup)
  - World average $\mathrm{BF}(B^+ \to D^0\rho) = (1.34 \pm 0.18)\,\%$ is driven by an **old measurement** *[CLEO, PRD 50, 43 (1994)]*)
- Decay channel: $B^- \to D^0\rho(770)^-, D^0 \to K^-\pi^+, \rho^- \to \pi^-\pi^0$
- Sample used: full Belle II Run 1 sample at $\Upsilon(4S)$ ($362\ \mathrm{fb}^{-1}$ i.e. about 387 million $B\overline{B}$ pairs)

$B^- \to D^0 \rho(770)^-$: introducing some variables

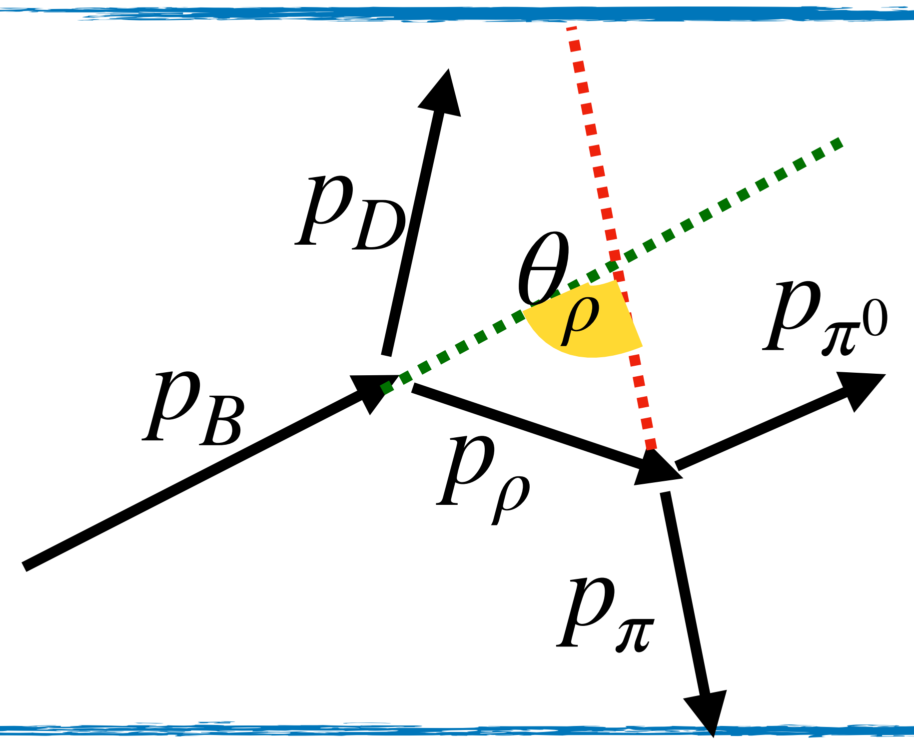
- Selection:
  - D^0 mass: $1.85 < m(K\pi) < 1.88$ GeV
  - $-0.18 < \Delta E < 0.2$ GeV
  - $M_{\rm bc} > 5.27$ GeV
  - Helicity angle $\cos\theta_\rho < 0.7$ to suppress $m(D^0\pi^0) < 2.6$ GeV, enriched of $D^{**} \to D^0\pi^0$
  - Boosted Decision Tree to separate signal and $q\bar{q}$ background



- $\Delta E = E_B^* - E_{\rm beam}^* = E_B^* - \sqrt{s}/2$
- Expected $\Delta E \simeq 0$ for properly reconstructed signal



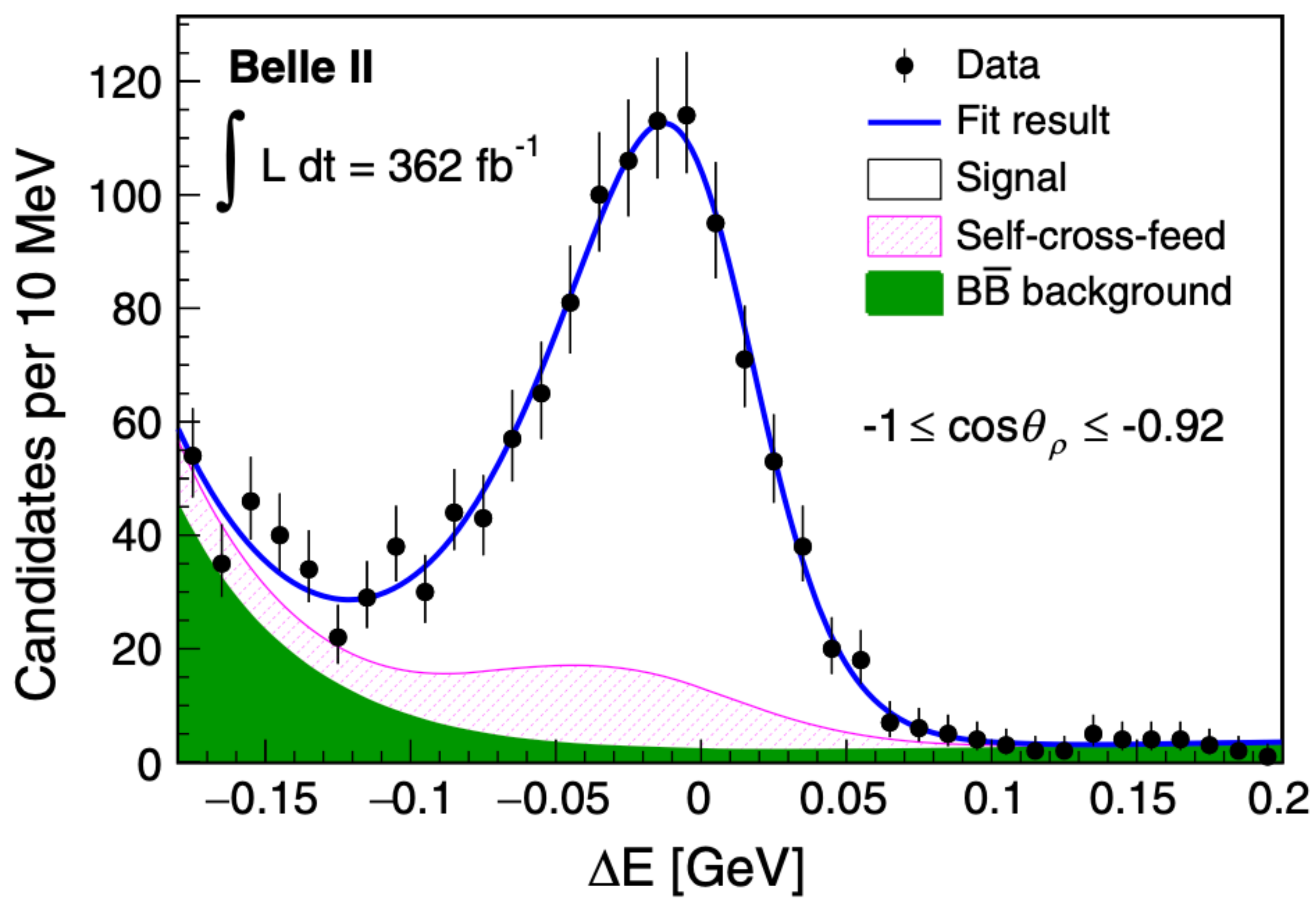
- $M_{bc} = \sqrt{(\sqrt{s}/2)^2 - \vec{p}_B^{*2}}$
- Expected $M_{bc} \simeq m_B$ for properly reconstructed signal

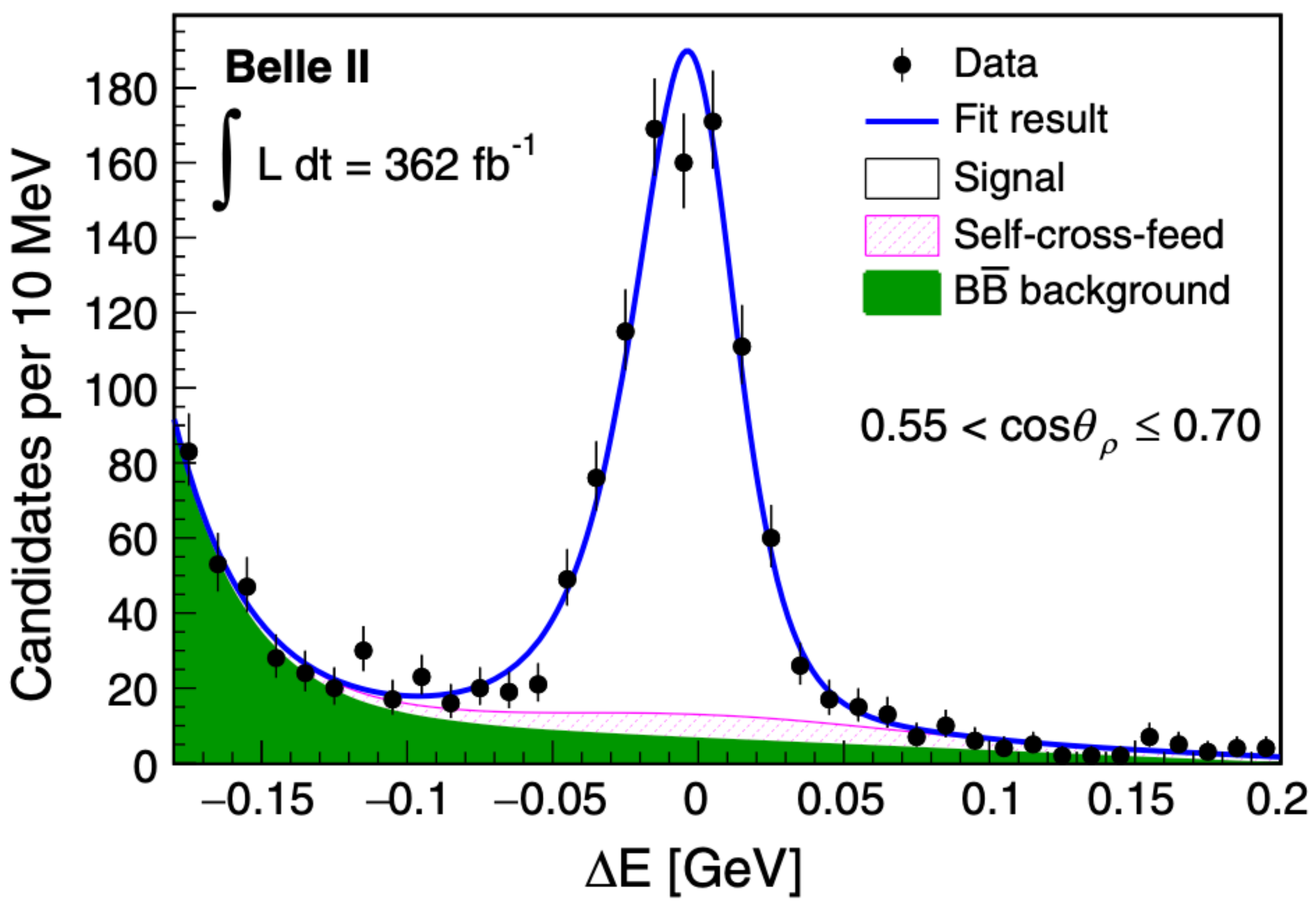


angle between the momentum of the π^- and the opposite of the direction of the B, in ρ frame (not shown)

$B^- \to D^0\rho(770)^-$: signal extraction

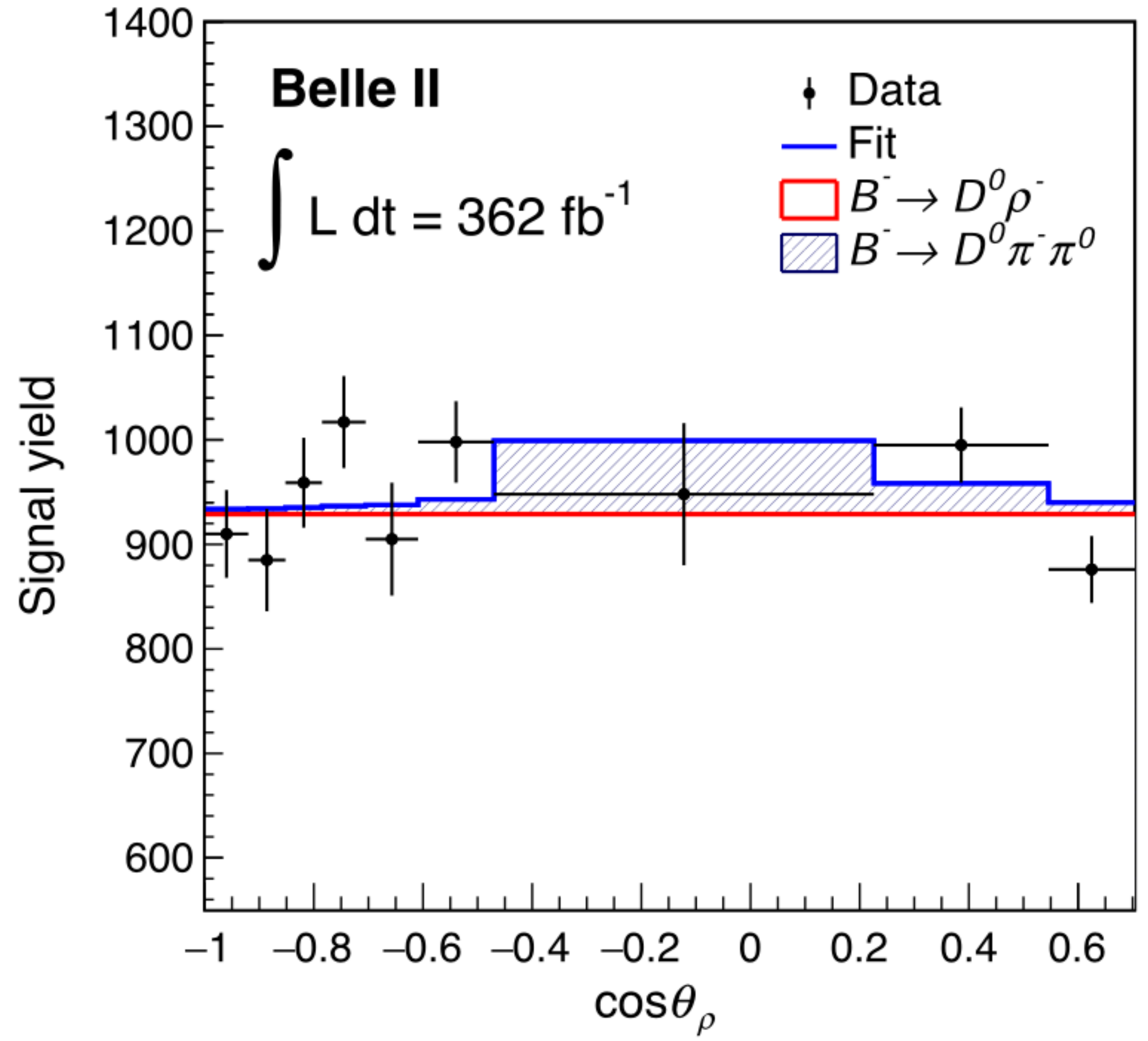
- Fit to ΔE **distribution** to separate signal and background
- Residual bkg:
  - $B\overline{B}$: mostly semileptonic decays
  - self-cross feed i.e. misreconstructed signal events: mostly wrongly associated π^0
- in bin of **helicity angle**, to separate $B \to D^0\rho(\to \pi^+\pi^0)$ and $B \to D^0\pi^+\pi^0$ components

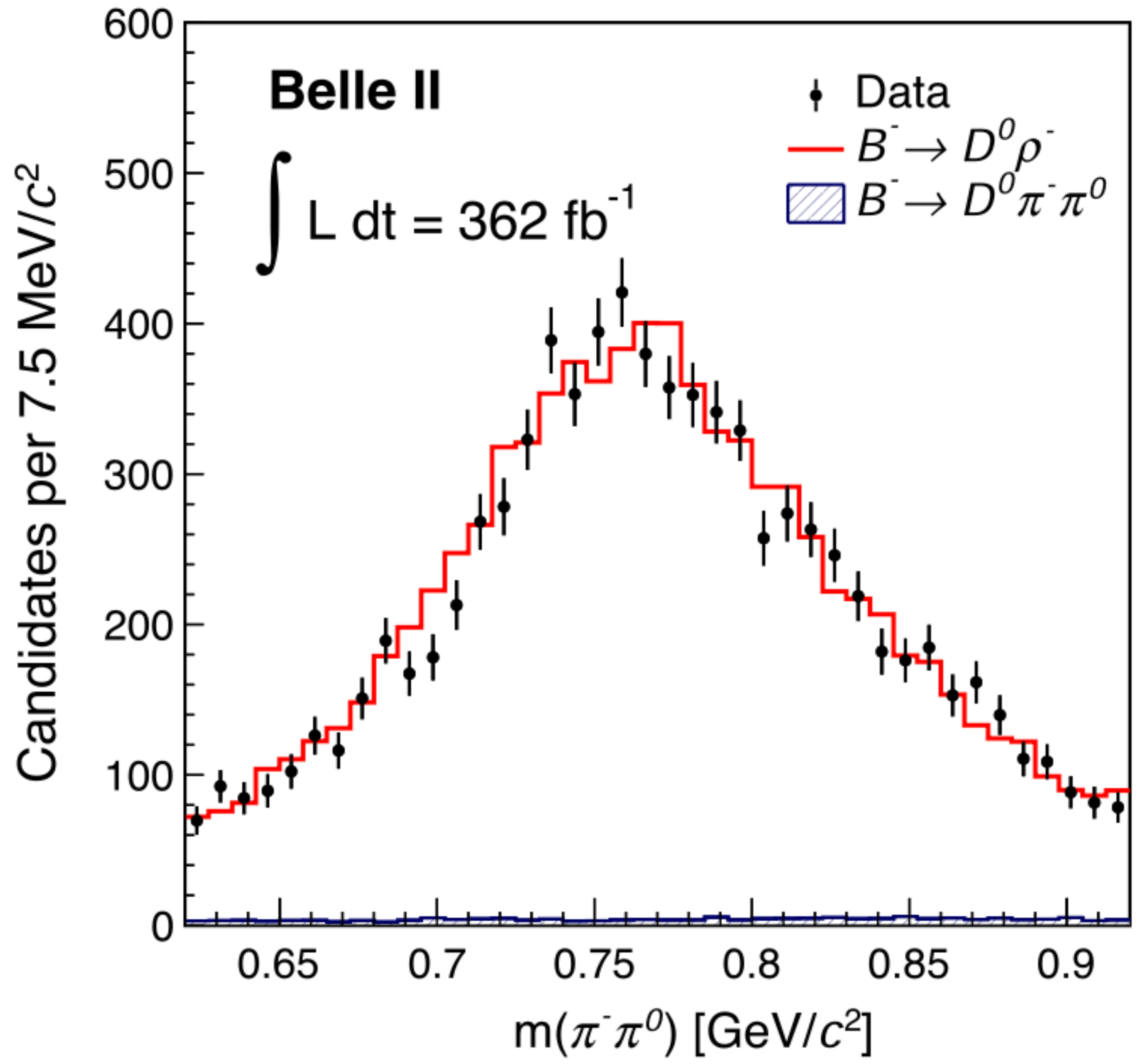




$B^- \to D^0\rho(770)^-$: non-resonant bkg

- **Template fit** to $\cos\theta_\rho$ distribution using $B \to D^0\rho$ and $B \to D^0\pi^+\pi^0$ templates
- $\cos\theta_\rho(D\rho) \sim \cos^2\theta$ vs $\cos\theta_\rho(D\pi^0\pi^-) \sim$ uniform
- Fit with non-uniform binning to have $\cos\theta_\rho$ uniform distribution for the $B \to D^0\rho$
- found $(1.9 \pm 1.8)\,\%$ of $B \to D^0\pi^+\pi^0$





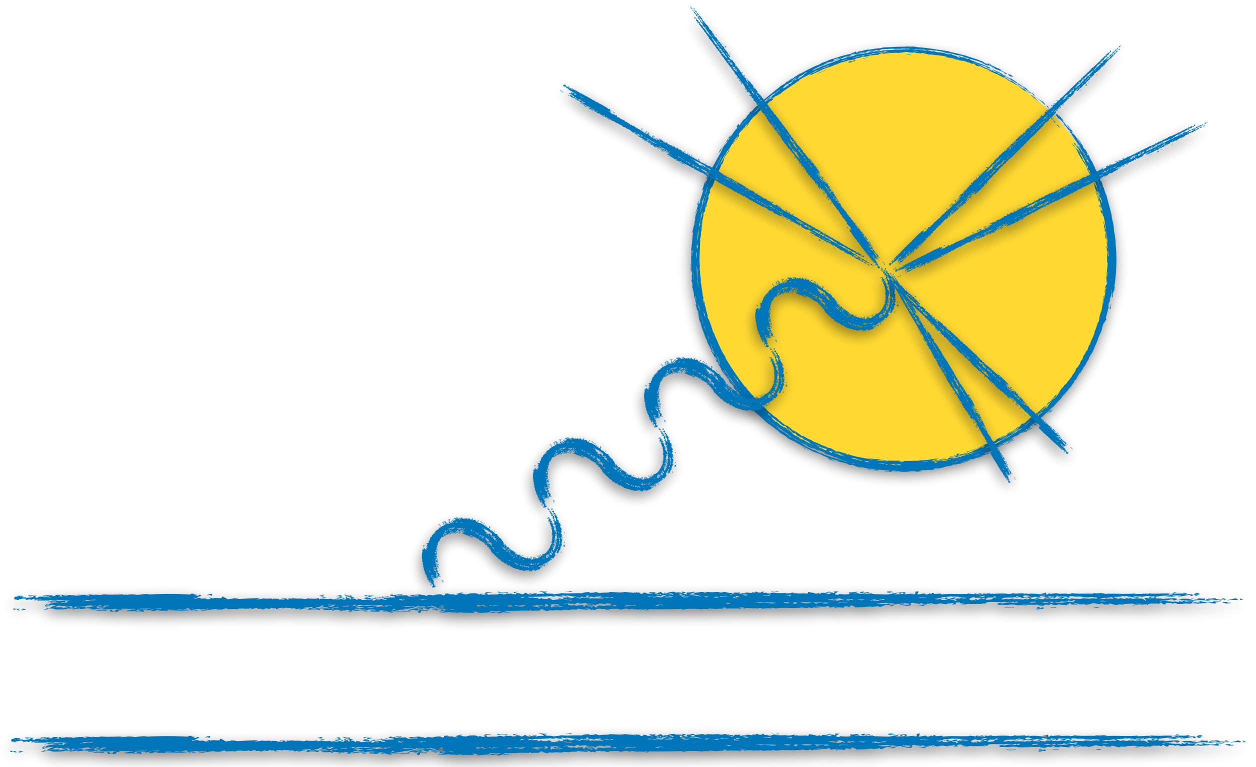
$B^- \to D^0 \rho(770)^-$: results

- Signal Yield: 8360 ± 180 events
- $$\mathrm{BF}(B^- \to D^0 \rho^-) = \frac{N_{B \to D\rho}}{2 N_{B\overline{B}} f^{+/-} \varepsilon \mathrm{BF(inter)}} = (0.939 \pm 0.021 \pm 0.050)\,\%$$
- **World best result**, more than a **factor 2 improvement in precision** (and about 2σ tension with the world average)
- **Systematically limited**, by π^0 efficiency calibration and fit modelling
- Will be used to improve the **calibration of this mode in Belle II hadronic B-tagging**.

Example 2 :

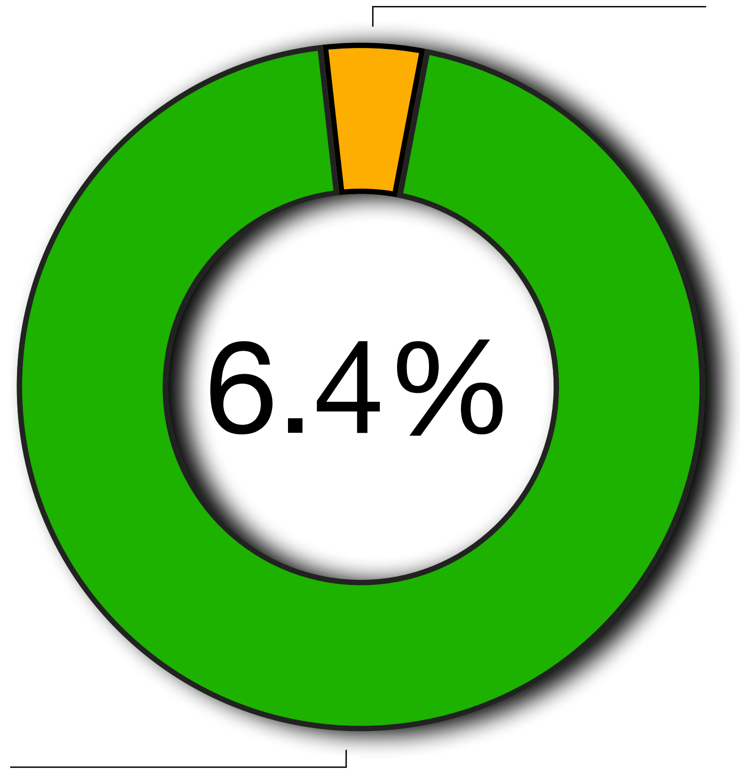
Measurement of the branching fraction of $B \to \overline{D}^{(*)} K^- K^{(*)0}_{(S)}$ and $B \to D^{(*)} D_s^-$ decays at Belle II

[JHEP 08 (2024) 206]



[Analysis performed @CPPM & IJCLab by V. Bertacchi and K. Trabelsi]

Motivations: the DKK opportunity



- The $B \to DKK$ sector is **mostly unexplored**
  - In Belle II MC: $(B^+ \to DKK(n\pi)) \simeq 6\,\%$ (where $D = D^{\pm,0,*}$, $K = K^{\pm,0,*}$)
  - Measurements from a single paper [Belle, Phys.Lett.B,542(2002)]
    29.4 fb^{-1}, 5 modes (BR=0.28%)
  - The remaining is generated by Pythia

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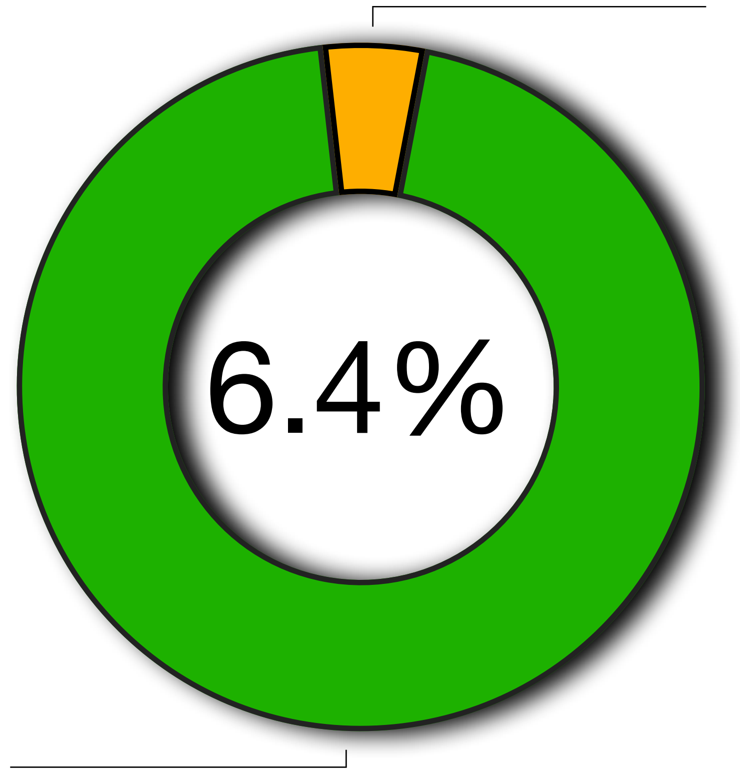

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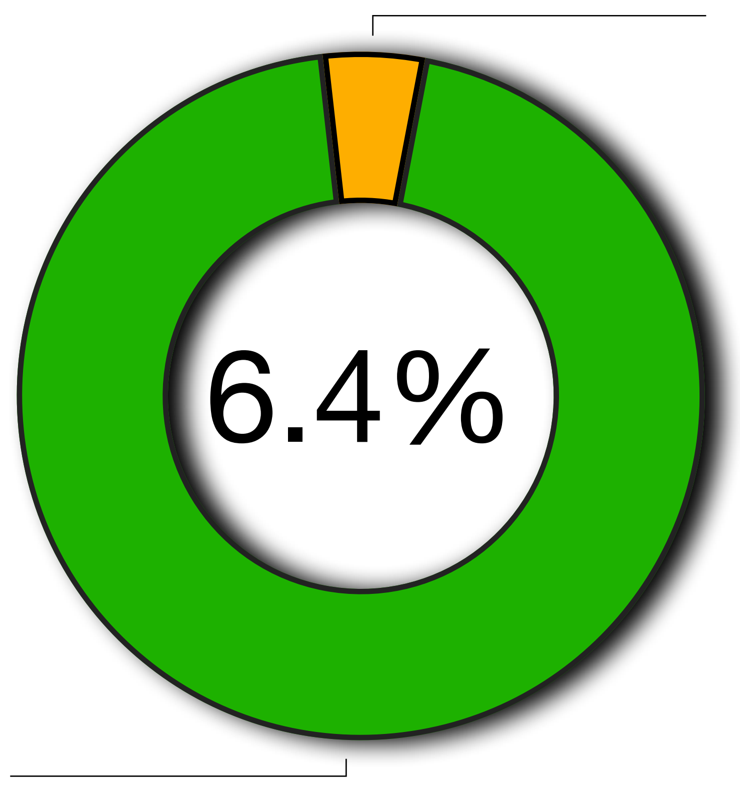

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- A better knowledge of this sector can be very useful to **extend the b-tagging modes,** thanks to their **high purity**

- The Belle II integrated luminosity (362 fb^{-1}) already recorded allows:
  - to improve over the Belle measurement with **higher precision**
  - to **observe additional 3 new** $B \to DKK_S^0$ modes (2-3 sigmas in Belle paper)
  - to **understand the resonant contribution** $(a_1, \rho'...)$ of this class of decays
  - to perform the world best measurement of the four $B \to D_s^- D^{(*)}$ channels

$B \to D^{(*)} K^- K^{(*)0}_{(S)}$: Analysis strategy

- **Signal yield:** ΔE fit: signal + background ($q\bar{q}, B\bar{B}$...), where $\Delta E = E^*_B - \sqrt{s}/2$
- **Branching Fractions:**
  - Event by event efficiency correction, as a function of $(m_{K^-K^{(*)}}, m_{D^{(*)}K^{(*)}})$
  - $$\mathrm{BF} = \frac{N^{\varepsilon\ \mathrm{corr}}_{\mathrm{reco}}}{2f_{+-,00} N_{B\bar{B}} \cdot \mathrm{BF(inter)}},$$

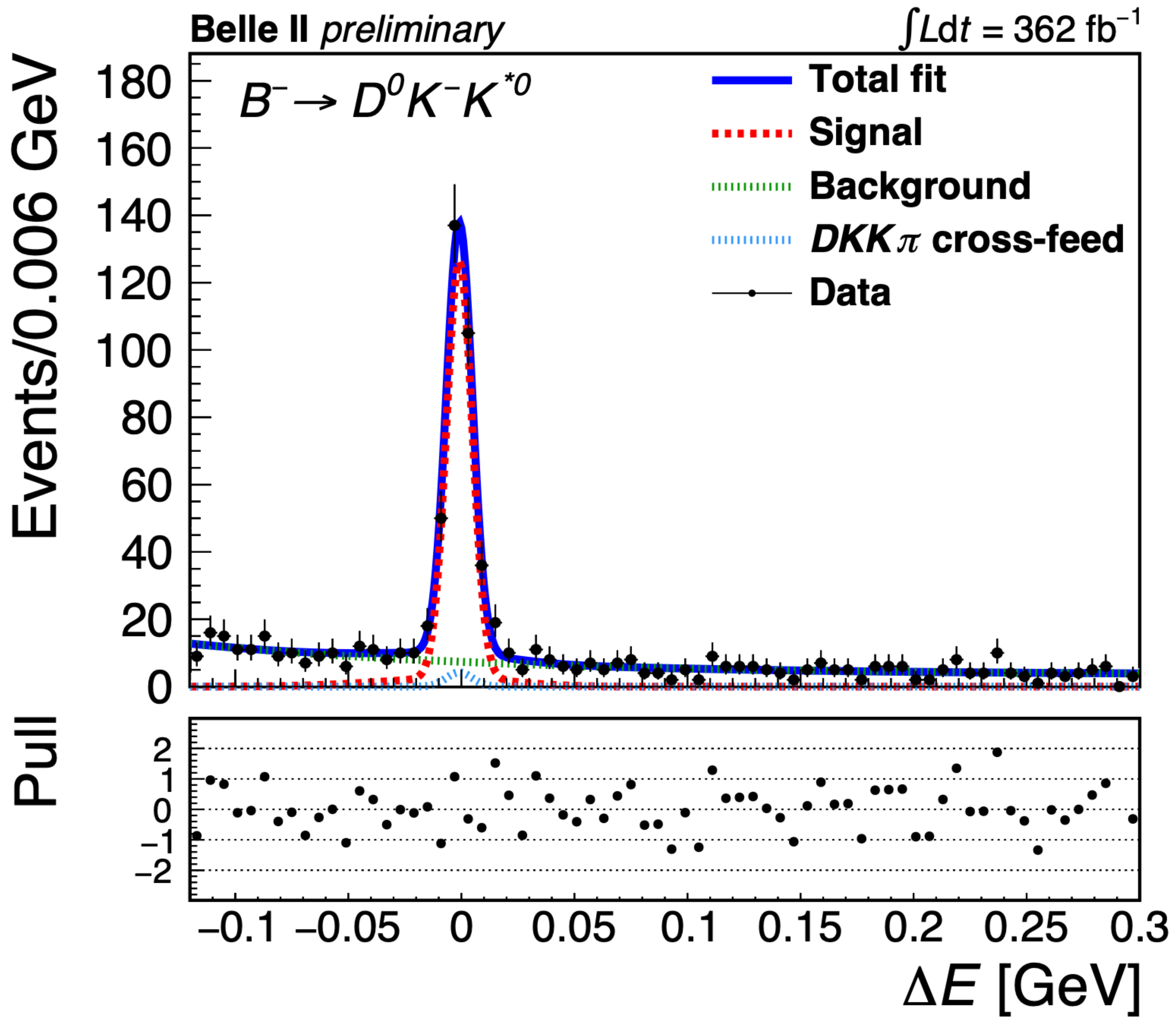
    $N^{\varepsilon\ \mathrm{corr}}_{\mathrm{reco}}$ → bkg-subtracted and efficiency corrected yield
- **Invariant Masses/angular variables:**
  - sPlot is performed on the required variable: $\Delta E \times \mathrm{Var} \to \mathrm{Var}$ bkg free
  - Event by event efficiency Correction, as a function of $(m_{K^-K^{(*)}}, m_{D^{(*)}K^{(*)}})$

Studied decay channels

$B^- \to D^0 K^- K^{*0}$
$\overline{B}^0 \to D^+ K^- K^{*0}$
$B^- \to D^{*0} K^- K^{*0}$
$\overline{B}^0 \to D^{*+} K^- K^{*0}$
$B^- \to D^0 K^- K^0_S$
$\overline{B}^0 \to D^+ K^- K^0_S$
$B^- \to D^{*0} K^- K^0_S$
$\overline{B}^0 \to D^{*+} K^- K^0_S$

Sample used: full Belle II Run 1 sample ($362\ \mathrm{fb}^{-1}$)

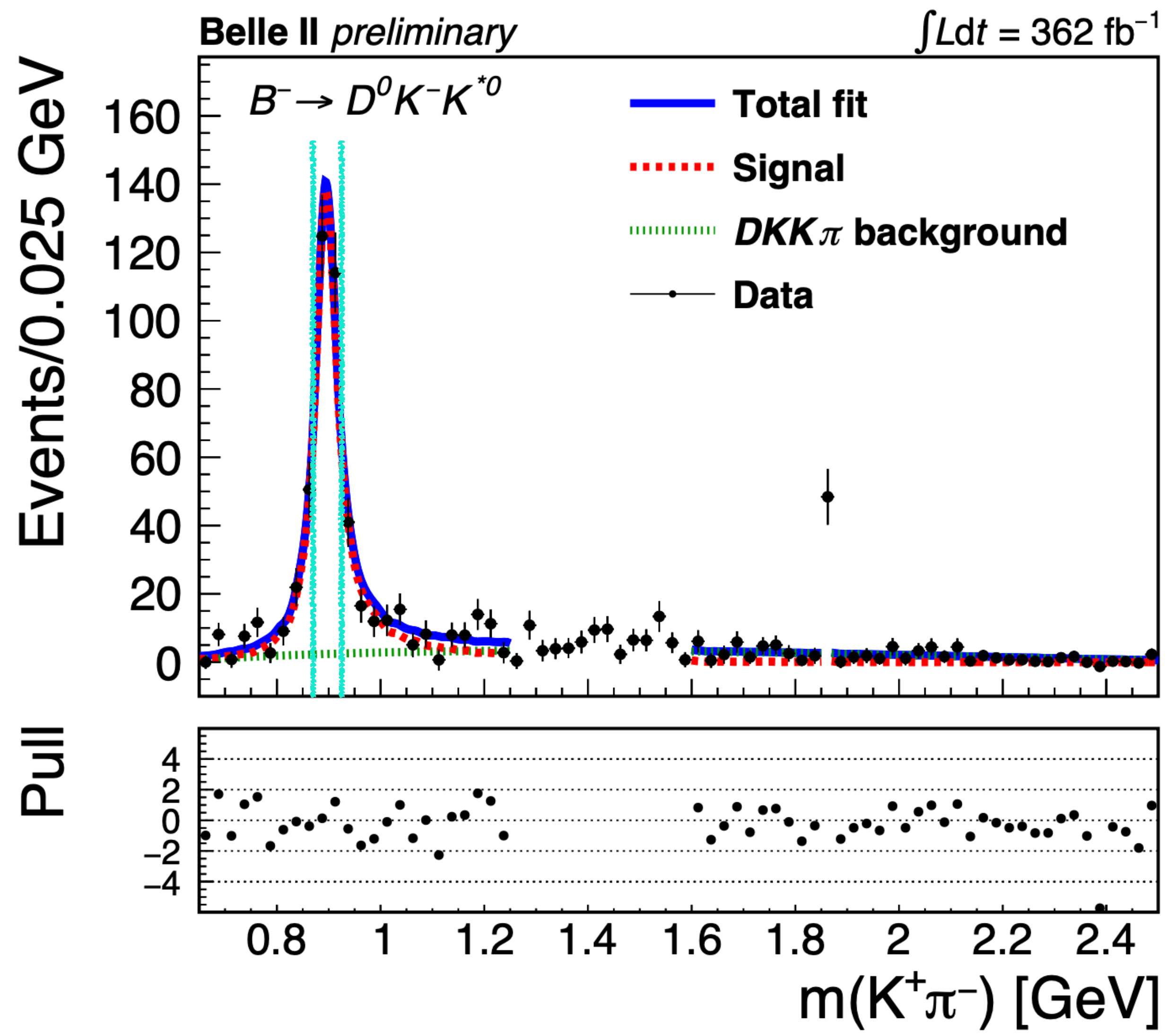
$B \to D^{(*)}K^-K^{(*)0}_{(S)}$: Yield extraction - example channel



fit to ΔE distribution

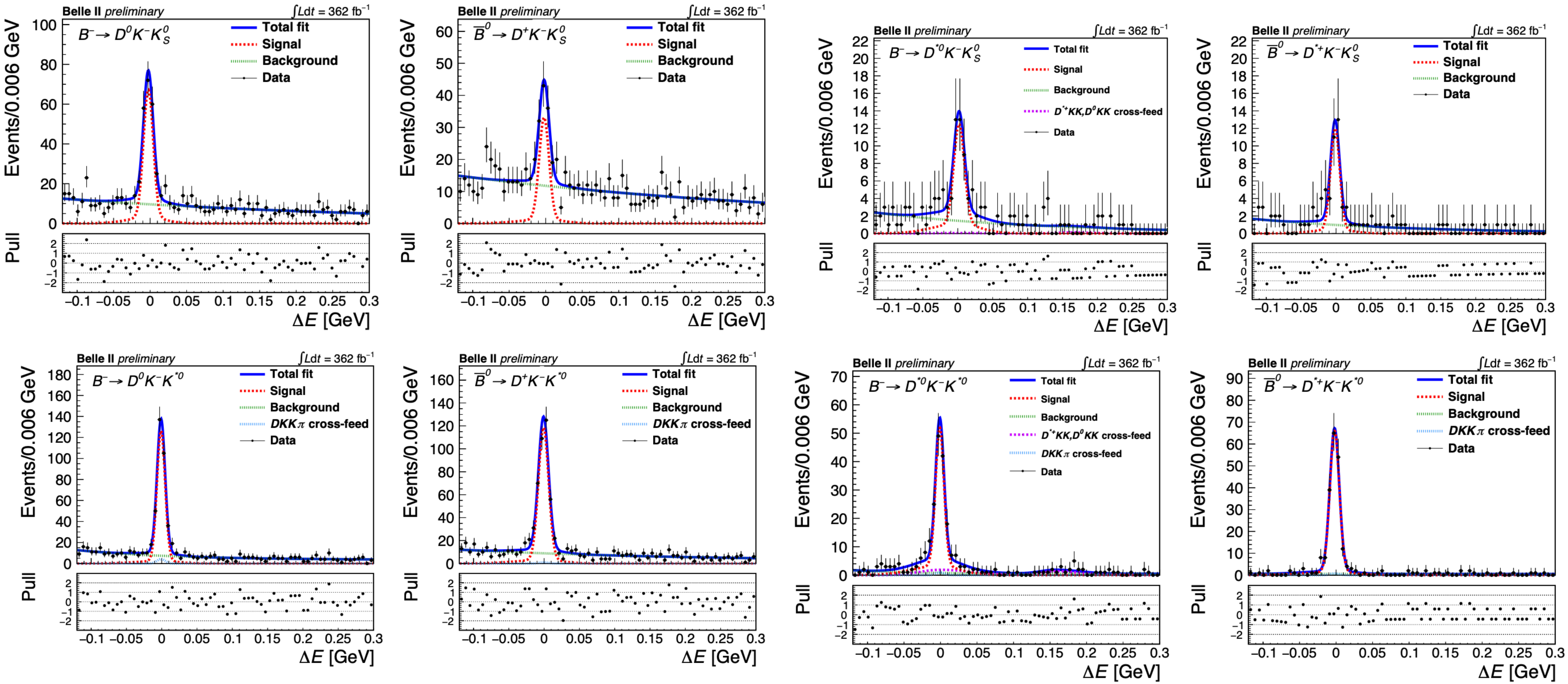
- **Signal** [gaussian+asymmetric gaussian]
- **Background**: mostly from other B decays [exponential+constant]
- $B \to DK^-K^+\pi^-$, indistinguishable from signal in $\Delta E \to$ fraction of $K^+\pi^-/K^{*0}$ measured from an ancillary fit to $m(K^+\pi^-)$ distribution, fitting the two population in the signal region

[more details in the backup]



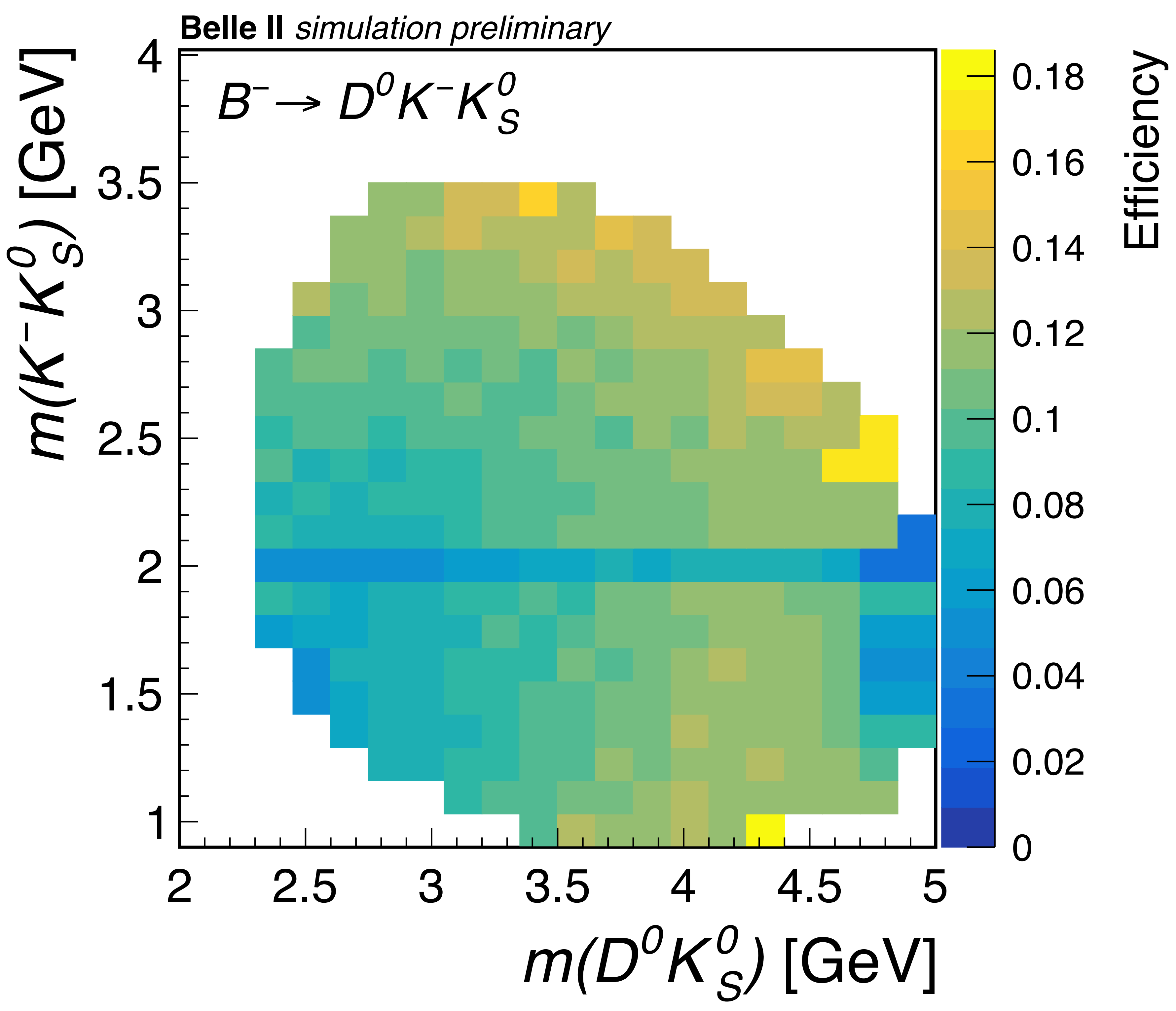
$B \to D^{(*)}K^{-}K^{(*)0}_{(S)}$: Yield extraction

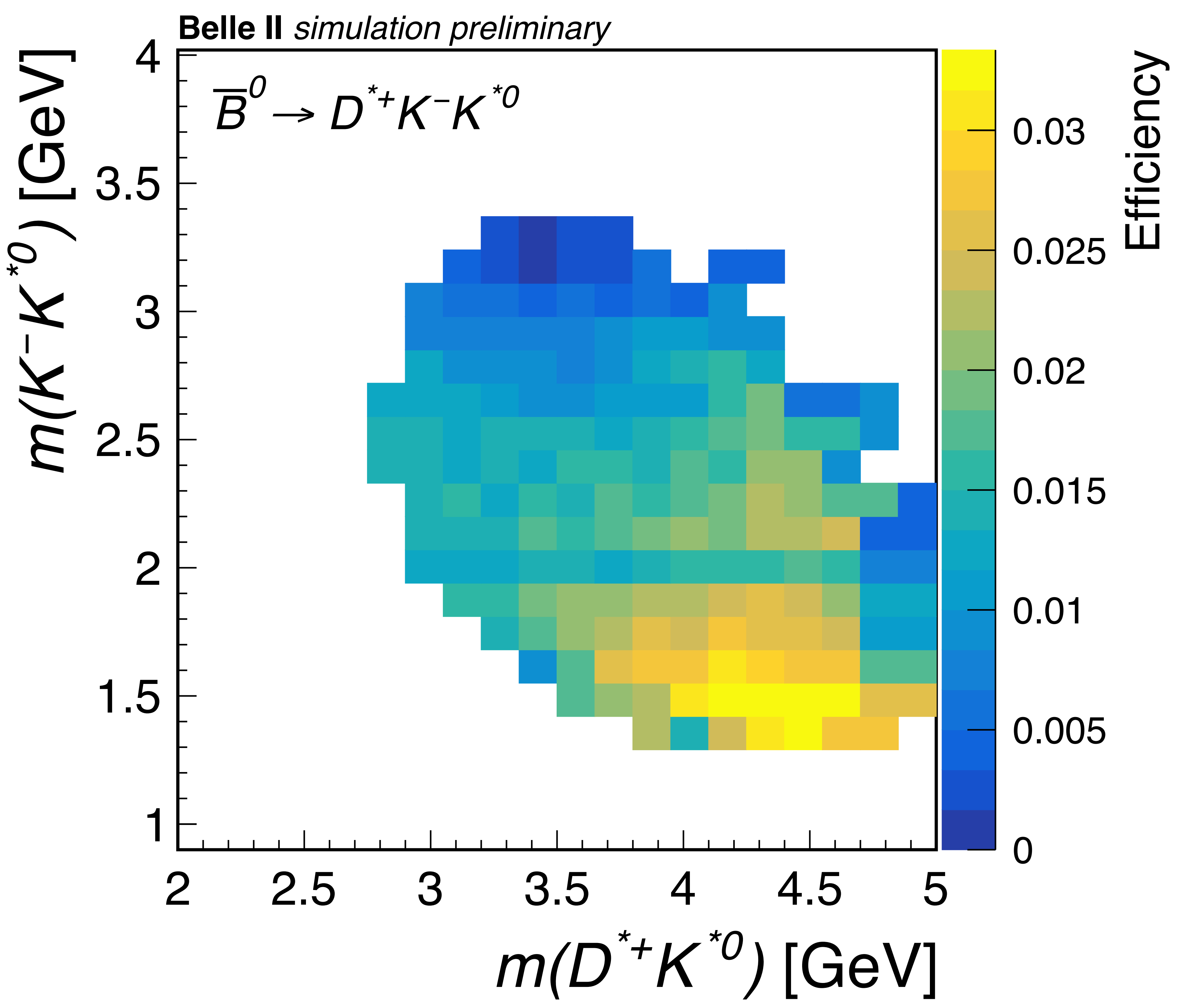
- Extremely clear signal in al the channels
- some of the fit has some specific background *[more details in the backup]*



$B \to D^{(*)}K^-K^{(*)0}_{(S)}$: Efficiency estimation

- Estimated using signal MC
- differential in $\varepsilon(m_{K-K^{(*)}}, m_{D^{(*)}K^{(*)}})$ → to be independent from the 3-body decay model of the MC
- Two examples of the efficiency maps:





$B \to D^{(*)} K^- K^{(*)0}_{(S)}$: Branching Fractions

- **Observation** of **3 new decay modes** $(D^+, D^{*0}, D^{*+}) K^- K^0_S$
- **x3 precision** on $D^0 K K^0_S$ and $D K K^{*0}$ modes

first observation

Channel	Yield	Average ε	$\mathcal{B}$ $[10^{-4}]$
$B^- \to D^0 K^- K^0_S$	209 ± 17	0.098	$1.82 \pm 0.16 \pm 0.08$
$\overline{B}^0 \to D^+ K^- K^0_S$	105 ± 14	0.048	$0.82 \pm 0.12 \pm 0.05$
$B^- \to D^{*0} K^- K^0_S$	51 ± 9	0.044	$1.47 \pm 0.27 \pm 0.10$
$\overline{B}^0 \to D^{*+} K^- K^0_S$	36 ± 7	0.046	$0.91 \pm 0.19 \pm 0.05$
$B^- \to D^0 K^- K^{*0}$	325 ± 19	0.043	$7.19 \pm 0.45 \pm 0.33$
$\overline{B}^0 \to D^+ K^- K^{*0}$	385 ± 22	0.021	$7.56 \pm 0.45 \pm 0.38$
$B^- \to D^{*0} K^- K^{*0}$	160 ± 15	0.019	$11.93 \pm 1.14 \pm 0.93$
$\overline{B}^0 \to D^{*+} K^- K^{*0}$	193 ± 14	0.020	$13.12 \pm 1.21 \pm 0.71$

- Extra: in the same final states, just reverting the $|m_{D_s} - m_{KK}| > 20$ MeV veto, we can obtain the **world best measurement** $B \to D^{(*)} D_s^-$ BFs, reconstructed in $D_s^- \to K^- K^0_S$ and $D_s^- \to K^- K^{*0}$

Channel	Yield (K^0_S / K^{*0})	Average ε (K^0_S / K^{*0})	$\mathcal{B}$ $[10^{-4}]$
$B^- \to D^0 D_s^-$	144 ± 12 / 153 ± 13	0.09 / 0.04	$95 \pm 6 \pm 5$
$\overline{B}^0 \to D^+ D_s^-$	145 ± 12 / 159 ± 13	0.05 / 0.02	$89 \pm 5 \pm 5$
$B^- \to D^{*0} D_s^-$	30 ± 6 / 29 ± 7	0.04 / 0.02	$65 \pm 10 \pm 6$
$\overline{B}^0 \to D^{*+} D_s^-$	43 ± 7 / 37 ± 7	0.04 / 0.02	$83 \pm 10 \pm 6$

- These information can be now exploited in the Belle II **B-tagging algorithm** → few % efficiency gain expected

$B \to D^{(*)} K^- K^{(*)0}_{(S)}$: Structures investigation - example channel

- extracted bkg-subracted and efficiency-corrected **invariant mass** and **helicity angles** with an sPlot

$B \to D^{(*)}K^{-}K^{(*)0}_{(S)}$: Structures investigation - example channel

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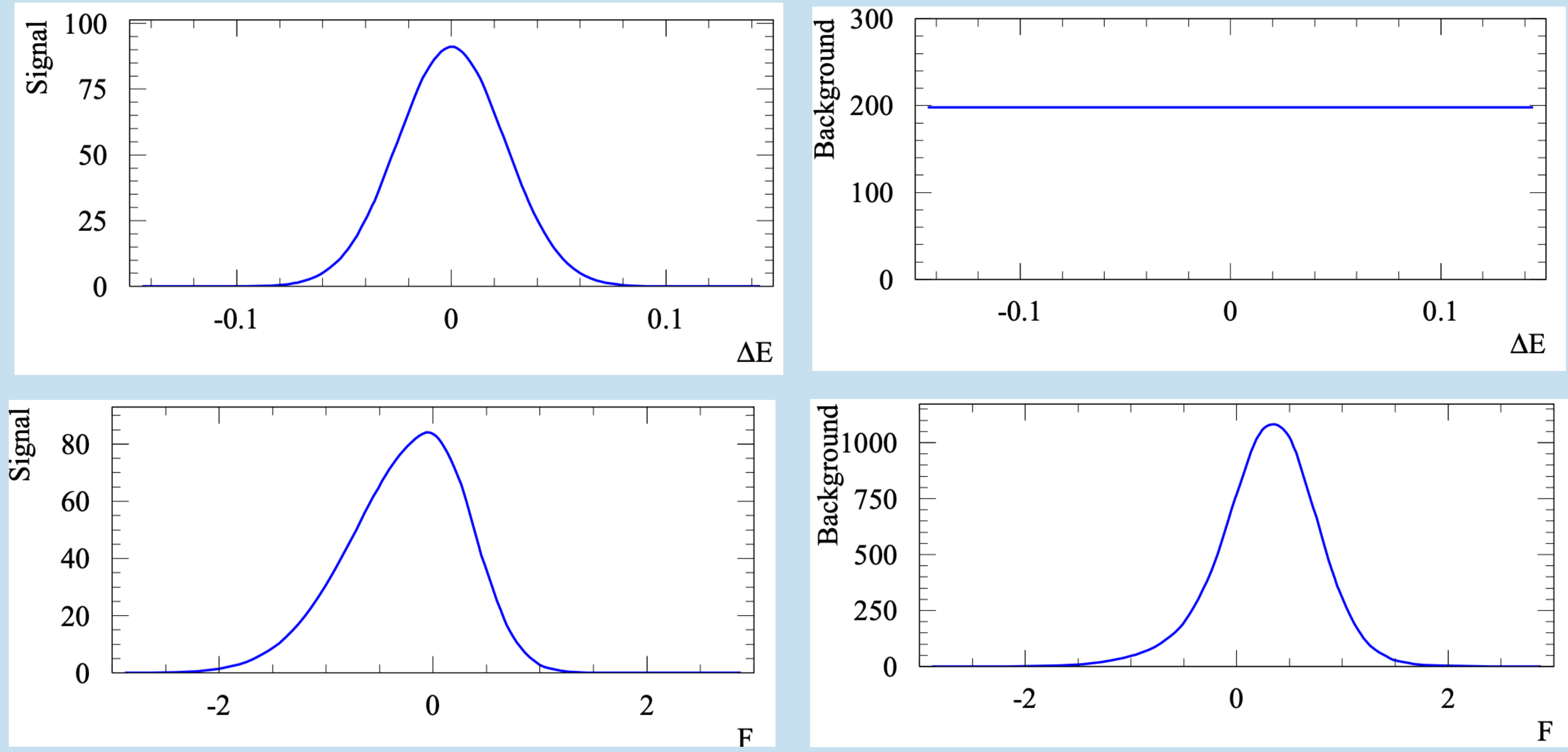
Imagine to have this nice discriminating variable (ΔE):

And you want to know the signal and bkg distribution of this other variable (Var), where is not easy to distinguish signal and bkg

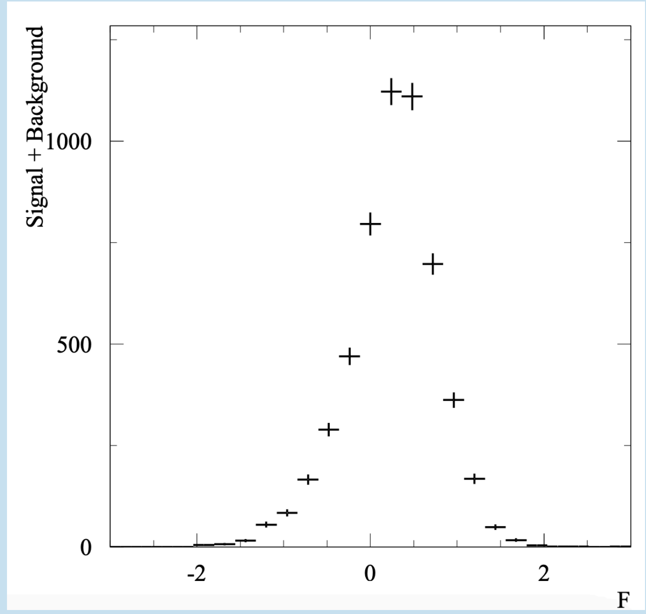
What you can do is fit ΔE, assign a **per-event-weight** according to the fitted distribution, and plotting the the Var distribution of the events the applying this weighs (*sWeights*)

[arXiv:physics/0402083]

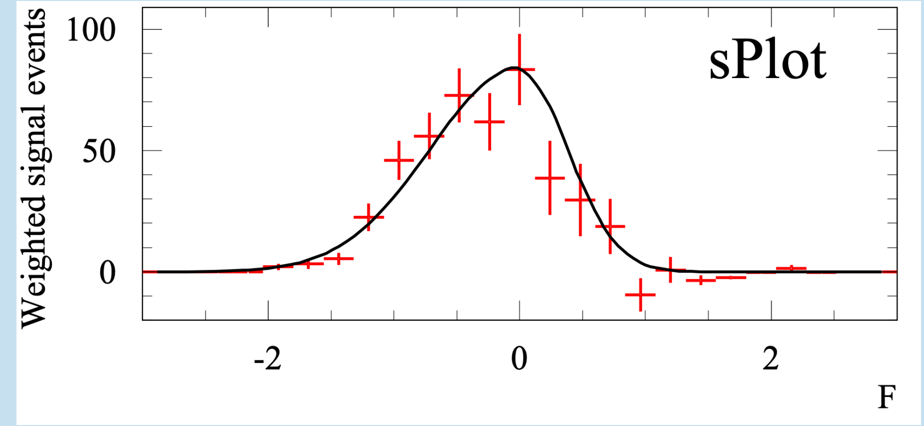


(from MC)

(This again, from MC, but you want it for data!)



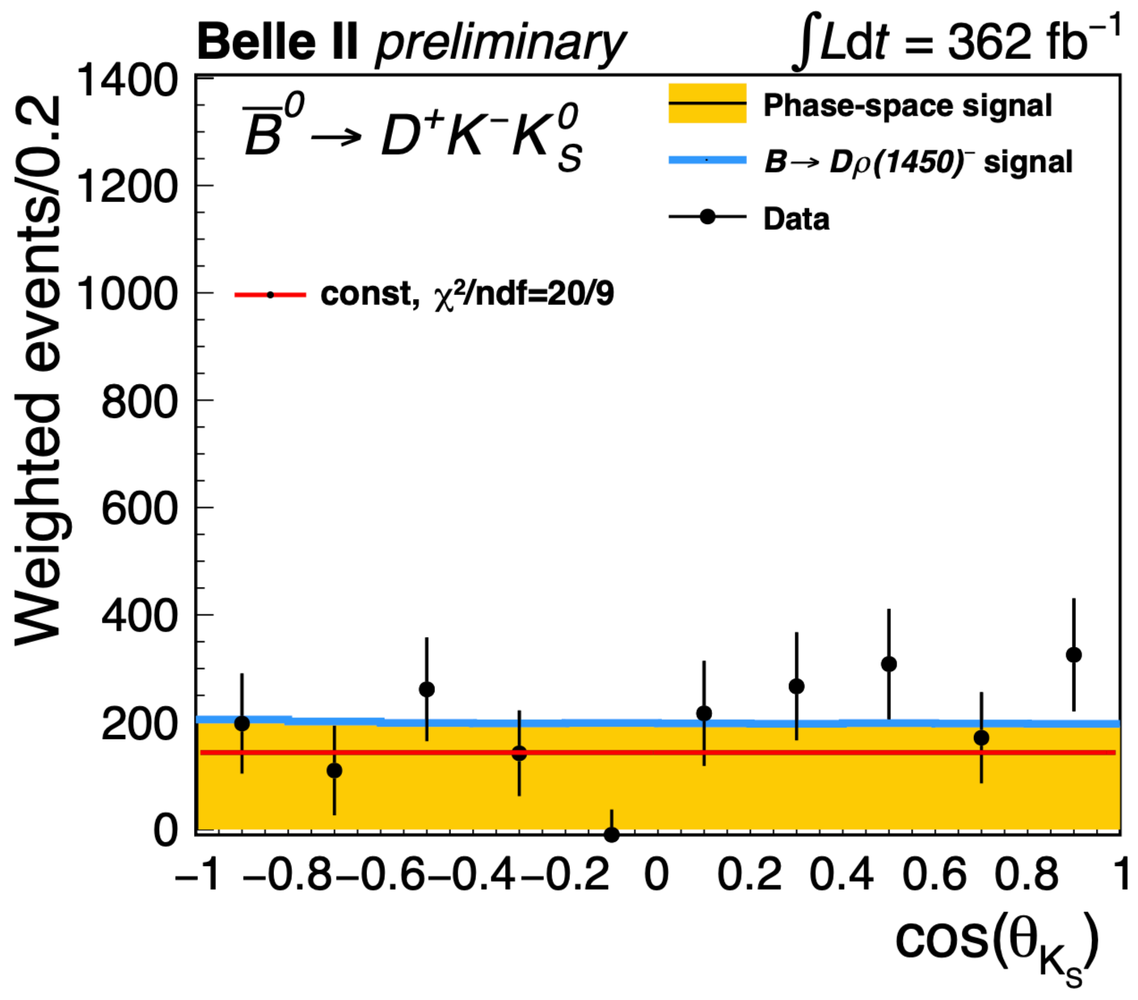
sWeights

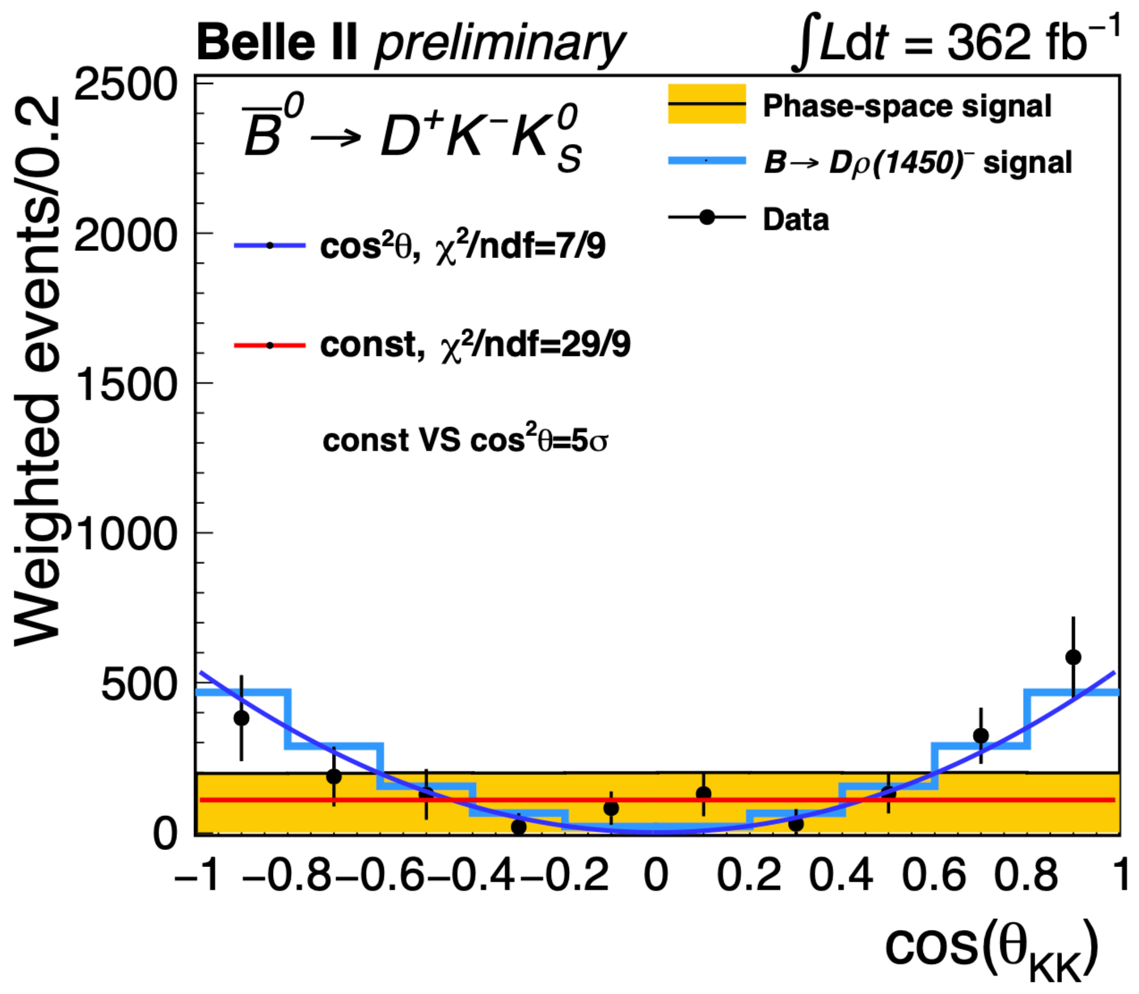


(from data)

$B \to D^{(*)} K^- K^{(*)0}_{(S)}$: Structures investigation - example channel

- extracted bkg-subracted and efficiency-corrected **invariant mass** and **helicity angles** with an sPlot
- helicity angles (defined as for ρ)
  - θ_{K_S} is uniform→ 3-body or $J^P = 1^-$
  - $\theta_{KK} \sim \cos^2\theta$→ $J^P = 1^-$





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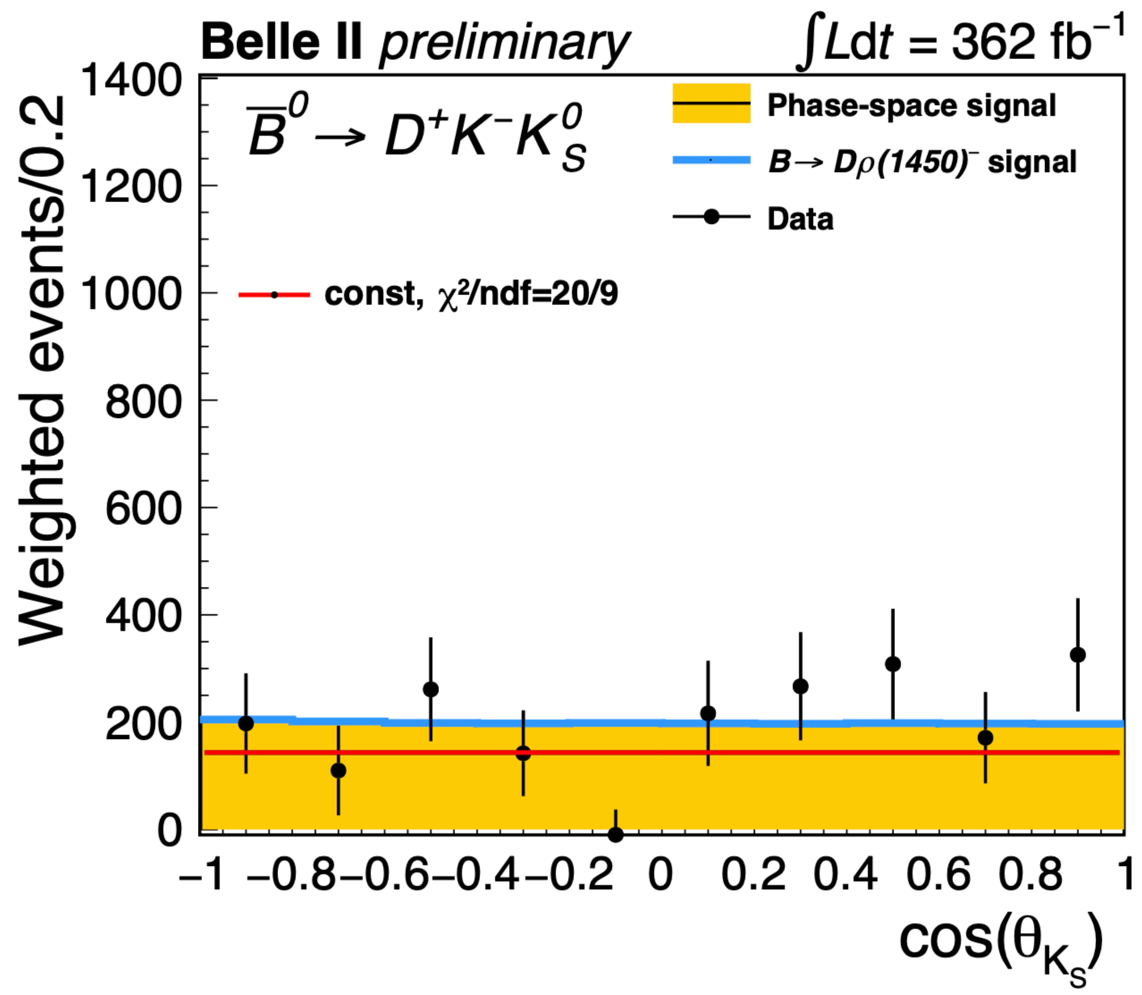
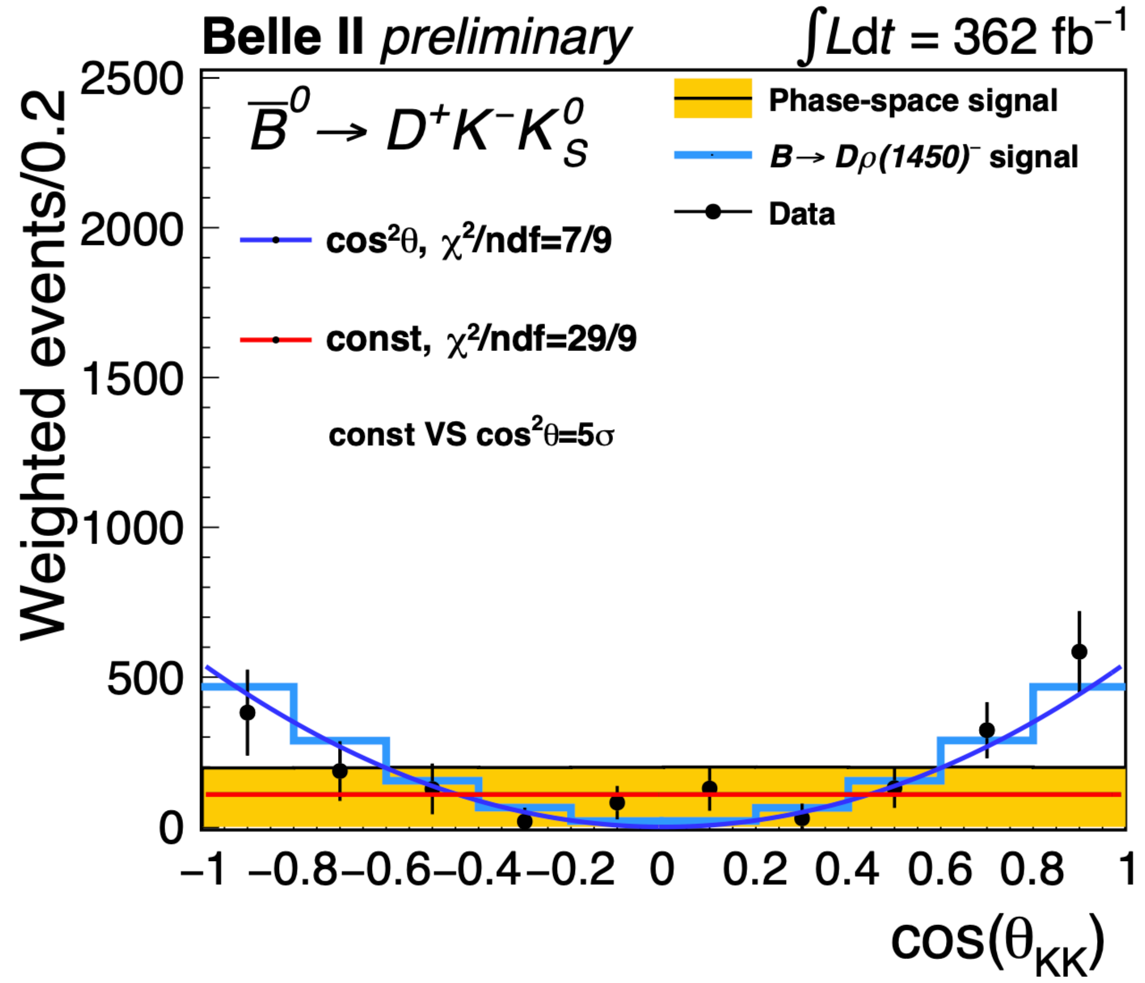
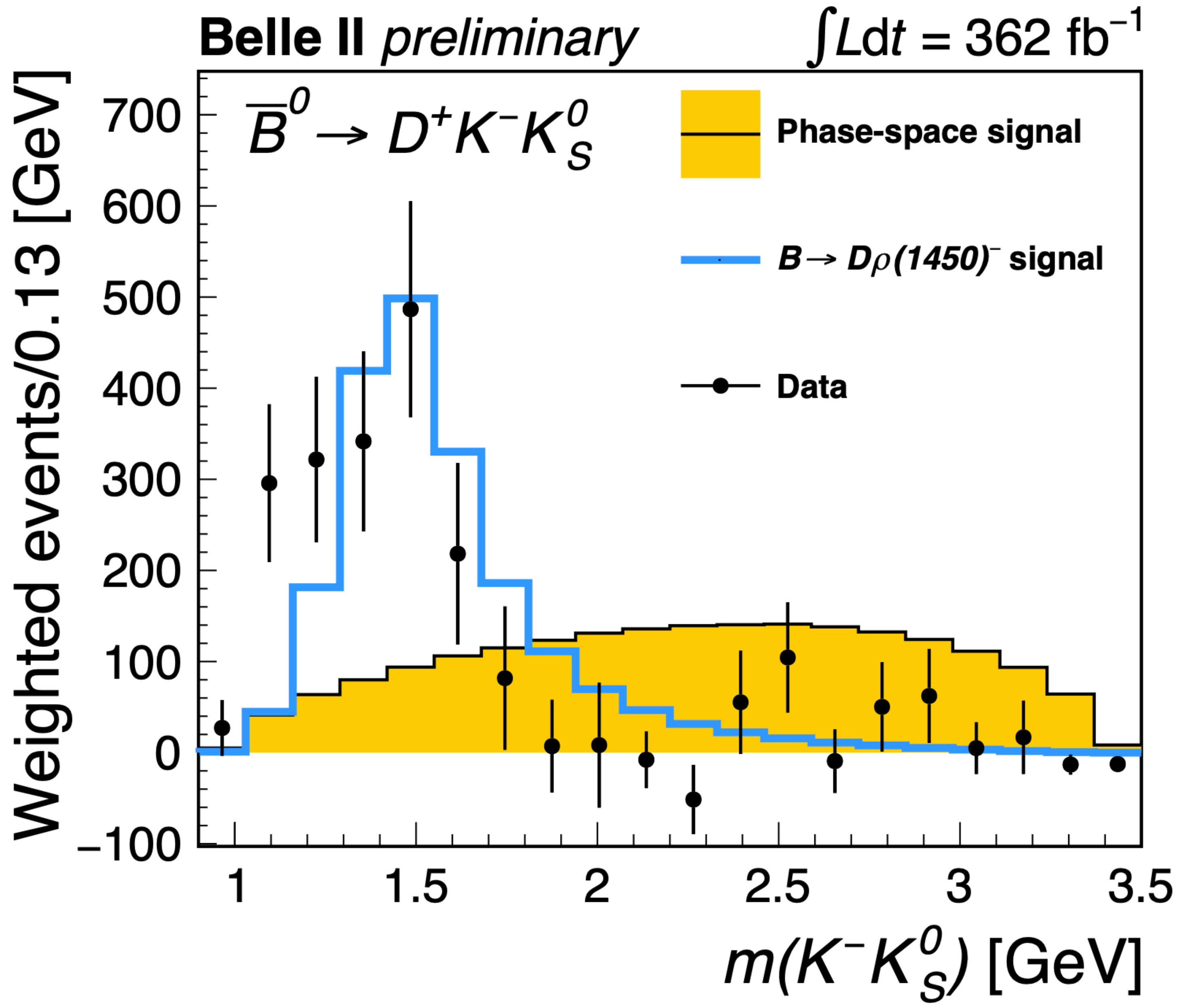


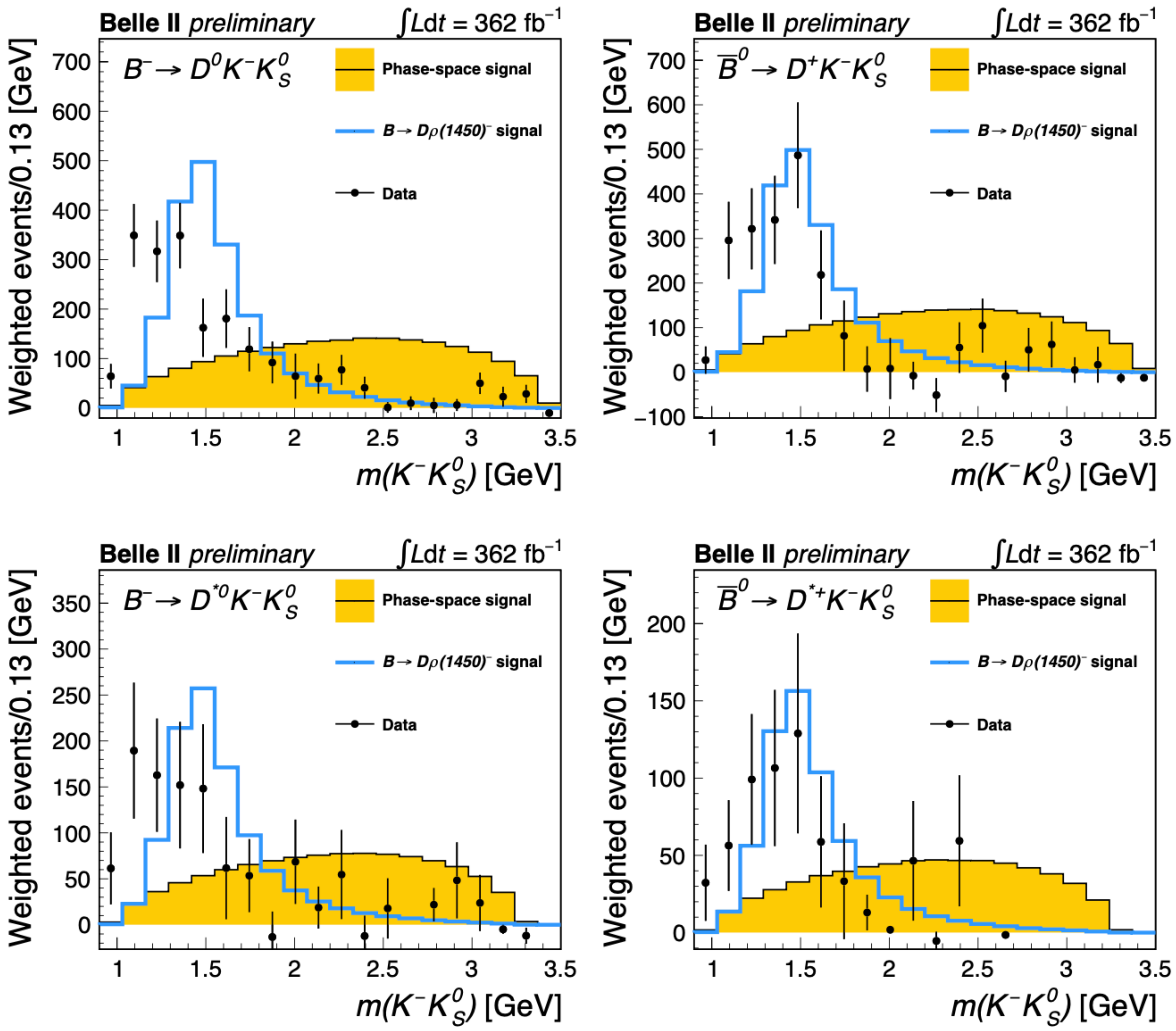


- invariant masses:
  - $m(K^-K^0_S)$ shows a clear low mass-structure
  - The lineshape is more complicate that a single resonance overlay



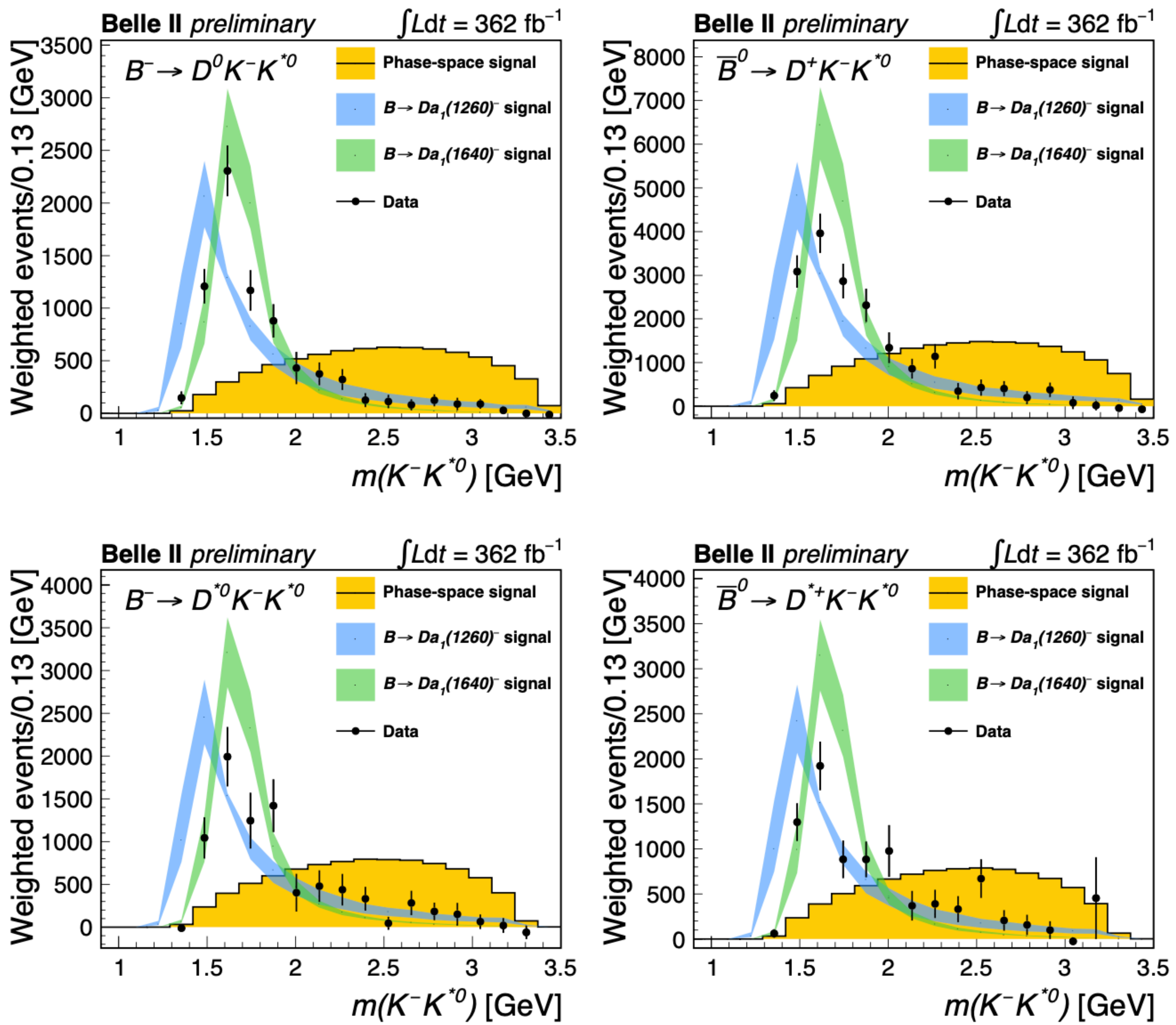
$B \to D^{(*)} K^- K^{(*)0}_{(S)}$: Invariant mass analysis (K^0_S channels)

- Low-mass **structures** observed in $m(K^- K^0_S)$ system
- dominant $J^P = 1^-$ transition
- one or more ρ' resonances
- spin-even states may be interfering in $D^{(*)0}$ channel (color-suppressed)
- This model must be plugged in Belle II MC, for **B-tagging training**



$B \to D^{(*)}K^-K^{(*)0}_{(S)}$: Invariant mass analysis (K^{*0} channels)

- Low-mass **structures** observed in $m(K^-K^{*0})$ system
- compatible with $J^P = 1^+$ transition
- one or more a_1 resonances is the most likely interpretation
- This model must be plugged in Belle II MC, for **B-tagging training**



Take home messages

- A large part of the hadronic B width is **not known in term of exclusive decays**
- This makes our simulations **inaccurate** and limits our possibility of exploiting them, for **background estimation** in particular
  - In Belle II the this lack of knowlege limits the **B-tagging performances**
- SM measurements of **hadronic B decays** are very useful to reduce this lack of knowledge. Two successful examples are:
  - $B \to D^{(*)} K^- K^{(*)0}_{(S)}$ [JEHP 08 (2024) 206]
  - $B^- \to D^0 \rho(770)^-$ [PRD 109, L111103 (2024)]

Thank you for your attention!

BACKUP SLIDES

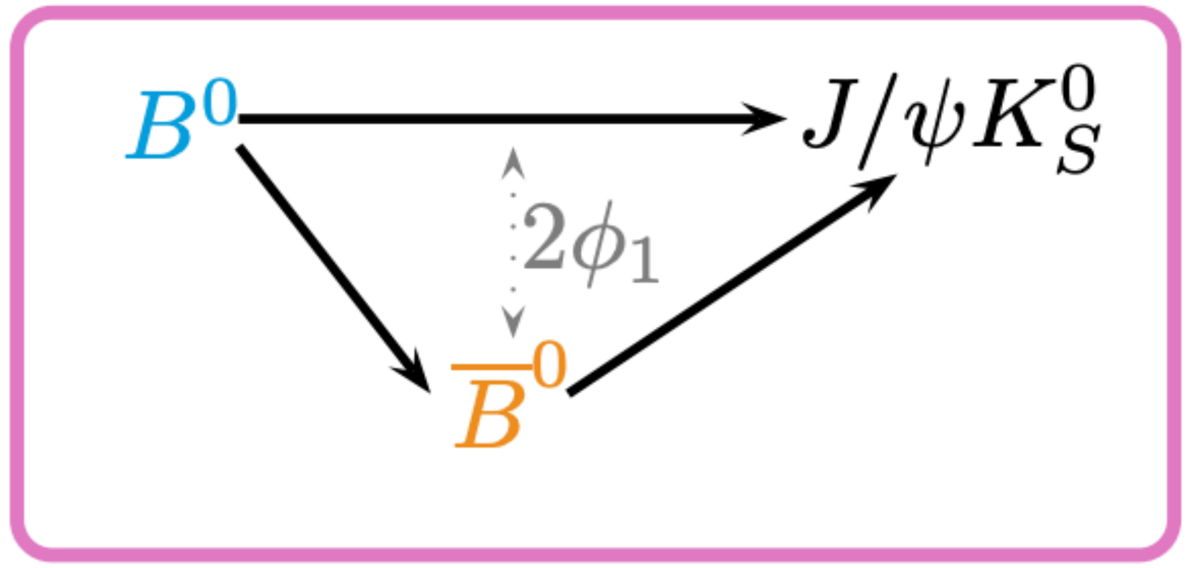
FEI modes with PYHTIA contribution ($D n\pi$, n=3,4)

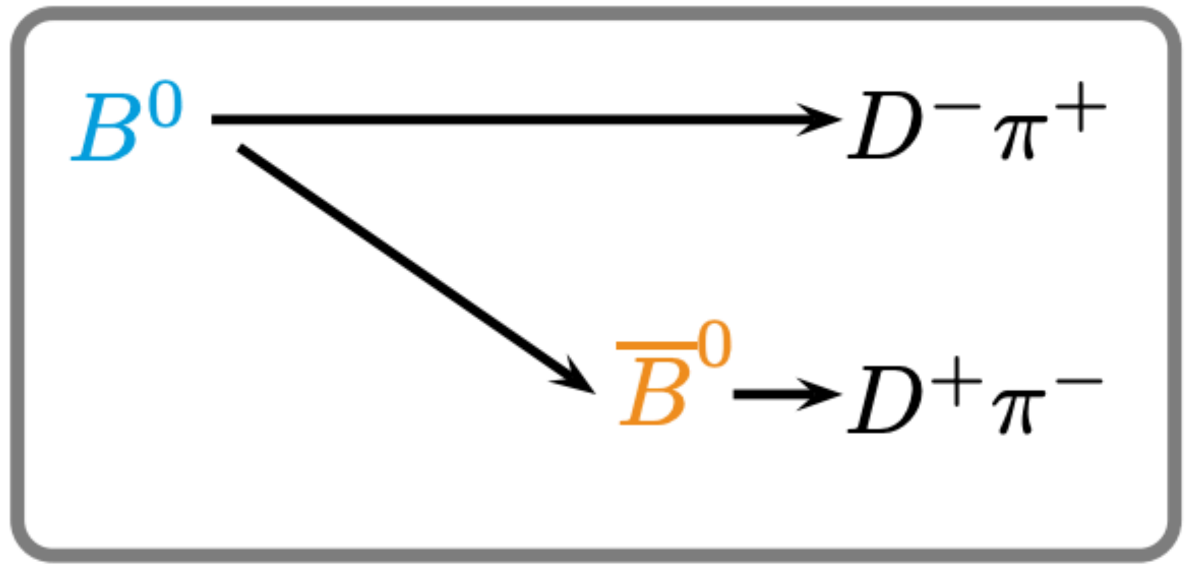
B^+ FEI mode	Contribution	$\mathcal{B}^{\text{off}}$ (%)
$D^-\pi^+\pi^+\pi^0$	$D^-\pi^+\pi^+\pi^0$ (NR)	0.20
	$D^-\rho^+\pi^+$	0.20
	$\overline{D}^{**0}\rho^+$	0.09
	$\overline{D}^{**0}\pi^+$	0.04
	$\overline{D}^{**0}\pi^+\pi^0$	0.11
		0.64
$\overline{D}^0\pi^+\pi^-\pi^+$	$\overline{D}^0\pi^+\pi^-\pi^+$ (NR)	0.46
	$\overline{D}^0\rho^0\pi^+$	0.39
	$\overline{D}^0 a_1^+$	0.18
	$\overline{D}_1^0\pi^+$	0.04
	$\overline{D}_1^{\prime 0}\pi^+$	0.03
	$\overline{D}_2^{*0}\pi^+$	0.02
	$\overline{D}^0\omega\pi^+$	0.01
		1.11
$\overline{D}^{*0}\pi^+\pi^-\pi^+$	$\overline{D}^{*0}\pi^+\pi^-\pi^+$ (NR)	1.03
	$\overline{D}^{*0}a_1^+$	0.91
	$\overline{D}^{*0}\omega\pi^+$	0.01
	$\overline{D}^{*0}f_0\pi^+$	0.07
		2.01
$\overline{D}^0\pi^+\pi^0\pi^0$	$\overline{D}^{*0}\rho^+$	0.96
	$\overline{D}^0 a_1^+$	0.15
	$\overline{D}^{*0}\pi^+\pi^0$	0.03
	$\overline{D}^0\rho^+\pi^0$	0.30
	$\overline{D}^0\pi^+\pi^0\pi^0$ (NR)	0.10
	$\overline{D}^{**0}\rho^+$	0.04
	$\overline{D}^{**0}\pi^+$	0.02
	$\overline{D}^{**0}\pi^+\pi^0$	0.05
		1.68
$\overline{D}^{*0}\pi^+\pi^0\pi^0$	$\overline{D}^{*0}a_1^+$	0.79
	$\overline{D}^{*0}\rho^+\pi^0$	0.05
	$\overline{D}^{*0}\pi^+\pi^0\pi^0$ (NR)	0.05
	$\overline{D}^{**0}\rho^+$	0.05
	$\overline{D}^{**0}\pi^+\pi^0$	0.04
	$\overline{D}^{*0}f_0\pi^+$	0.03
		1.02

B^+ FEI mode	Contribution	$\mathcal{B}^{\text{off}}$ (%)
$\overline{D}^0\pi^+\pi^-\pi^+\pi^0$	$D^{*-}\pi^+\pi^+\pi^0$	1.02
	$\overline{D}^{*0}\pi^+\pi^-\pi^+$	0.64
	$\overline{D}^{*0}a_1^+$	0.56
	$\overline{D}^0\omega\pi$	0.37
	$D^{*-}\rho^+\pi^+$	0.14
	$\overline{D}^{*0}\omega\pi$	0.00
	$\overline{D}^0\rho^0\rho^+$	0.20
	$\overline{D}^0\eta\pi^+$	0.05
	$\overline{D}^0\omega\rho^+$	0.00
	$\overline{D}^0\rho^+\pi^+\pi^-$	0.20
	$\overline{D}^0\omega\pi^+\pi^0$	0.00
	$\overline{D}^0\rho^-\pi^+\pi^+$	0.10
	$\overline{D}^0\rho^0\pi^+\pi^0$	0.10
	$\overline{D}_2^{*0}\rho^0\pi^+$	0.02
	$\overline{D}_0^{*0}\omega\pi^+$	0.00
	$\overline{D}_0^{*0}\rho^0\pi^+$	0.03
	$\overline{D}_0^{\prime 0}\pi^+\pi^0$	0.05
	$\overline{D}_2^{*0}\omega\pi^+$	0.00
	$\overline{D}_2^{*0}\pi^+\pi^0$	0.02
	$\overline{D}_2^{*0}f_0\pi^+$	0.04
		3.53
$\overline{D}^{*0}\pi^+\pi^-\pi^+\pi^0$	$\overline{D}^{*0}\pi^+\pi^-\pi^+\pi^0$ (NR)	1.80
	$\overline{D}^{*0}\omega\pi$	0.41
	$\overline{D}^{*0}\eta\pi^+$	0.14
	$\overline{D}^{*0}\rho^0\rho^+$	0.49
	$\overline{D}^{*0}\omega\rho^+$	0.01
	$\overline{D}^{*0}\rho^0\pi^+\pi^0$	0.40
	$\overline{D}^{*0}\rho^+\pi^-\pi^-$	0.40
	$\overline{D}^{*0}\omega\pi^-\pi^0$	0.00
	$\overline{D}^{*0}\rho^-\pi^+\pi^+$	0.20
	$\overline{D}_2^{*0}\rho^0\pi^+$	0.01
	$\overline{D}_2^{*0}\omega\pi^+$	0.00
	$\overline{D}_1^{\prime 0}\omega\pi^+$	0.00
	$\overline{D}_1^{\prime 0}\rho^0\pi^+$	0.03
		3.89

- grey=generated by PYHTIA
- table from *G. De Marino Thesis*

Time-Dependent CPV analysis scheme





CP-asymmetry in interference between mixing and decay:

$$\mathcal{A}_{\mathrm{CP}}(t) = \frac{N(B^0 \to f_{CP}) - N(\overline{B}^0 \to f_{CP})}{N(B^0 \to f_{CP}) + N(\overline{B}^0 \to f_{CP})}(t) = (S_{CP}\sin(\Delta m_d t) + A_{CP}\cos(\Delta m_d t))$$

with S_{CP}: time-dependent asymmetry and A_{CP}: direct CP-asymmetry.

B^0-$\overline{B}^0$ mixing:

$$\mathrm{mix}(t) = \frac{N(B^0 \to B^0) - N(B^0 \to \overline{B}^0)}{N(B^0 \to B^0) + N(B^0 \to \overline{B}^0)}(t) = \cos(\Delta m_d t)$$

with Δm_d the oscillation frequency.

[From Thibaud Humair, Moriond EW 22]

Long shutdown 1 plans

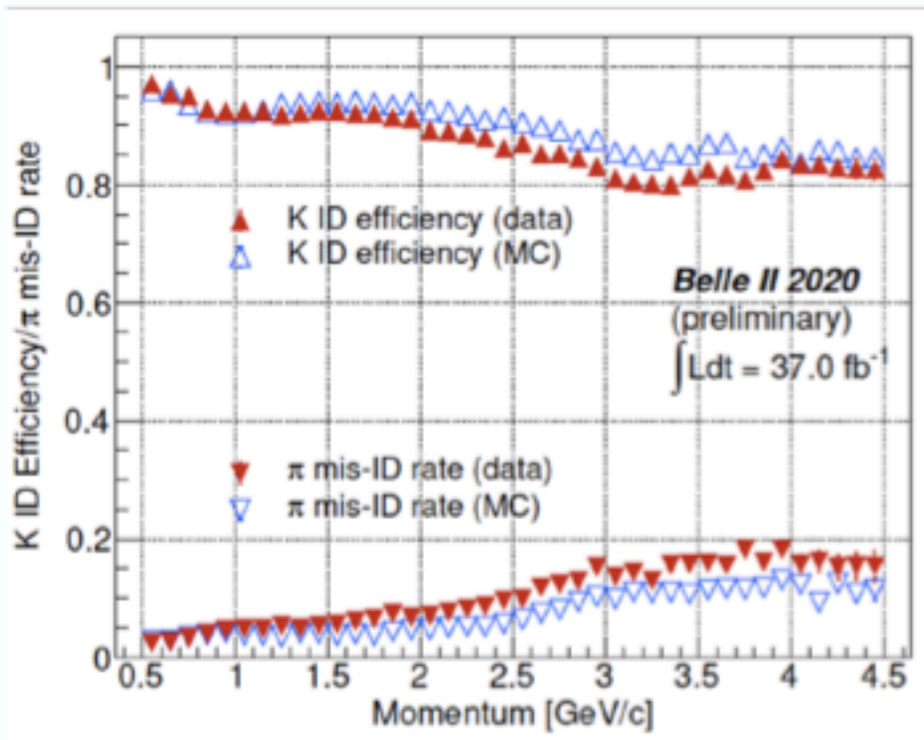
Long shutdown 1 (LS1): data-taking sopped in July 2022

Data taking restated in February 2024!

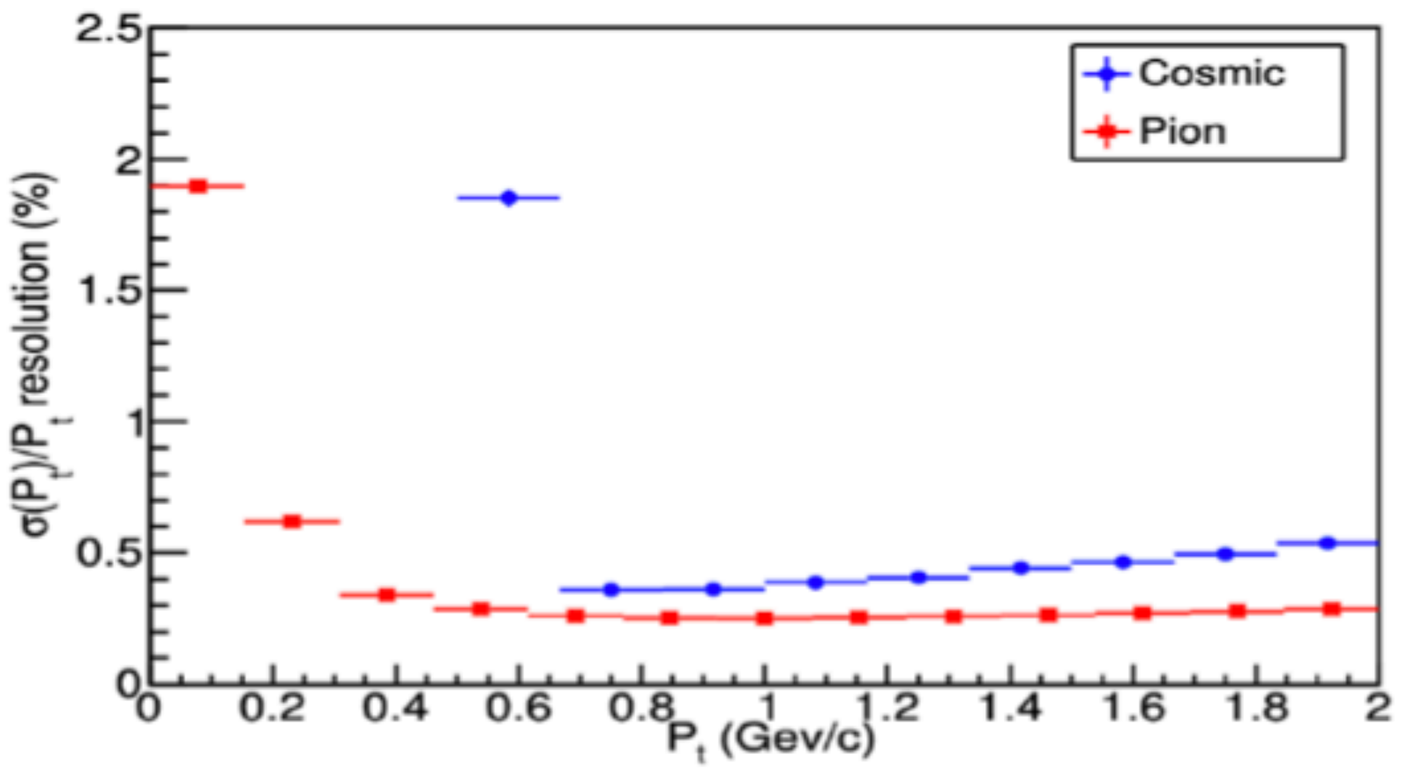
LS1 activities:

- replacement of the **beam-pipe**
- replacement of PMT of central PID detector (**TOP**)
- installation of 2-layer of **pixel detector**
  - shipped to KEK mid-March
  - final test scheduled in April
- improvement of data-quality monitoring and alarm system
- complete transition to new DAQ boards (PCle40)
- replacement of aging components
- additional shielding against beam backgrounds
- accelerator improvements: injection, non linear-collimators, monitoring

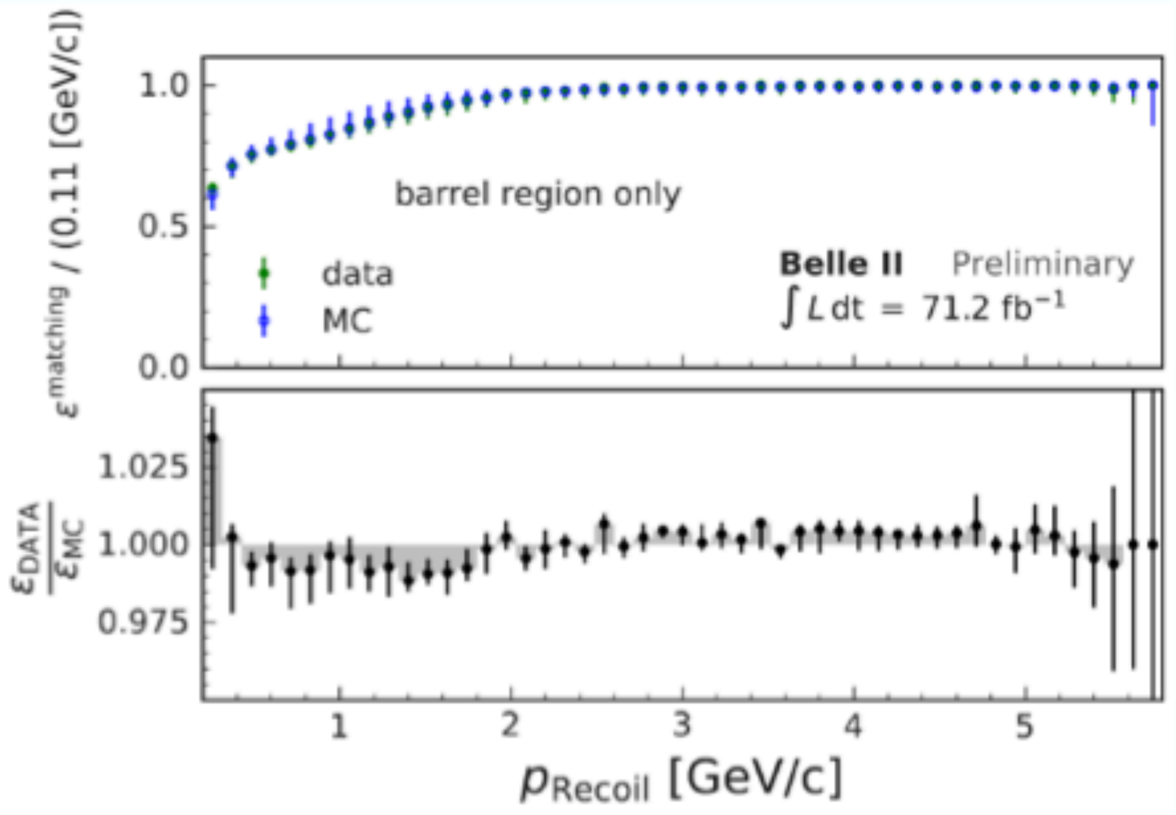
Belle II performance



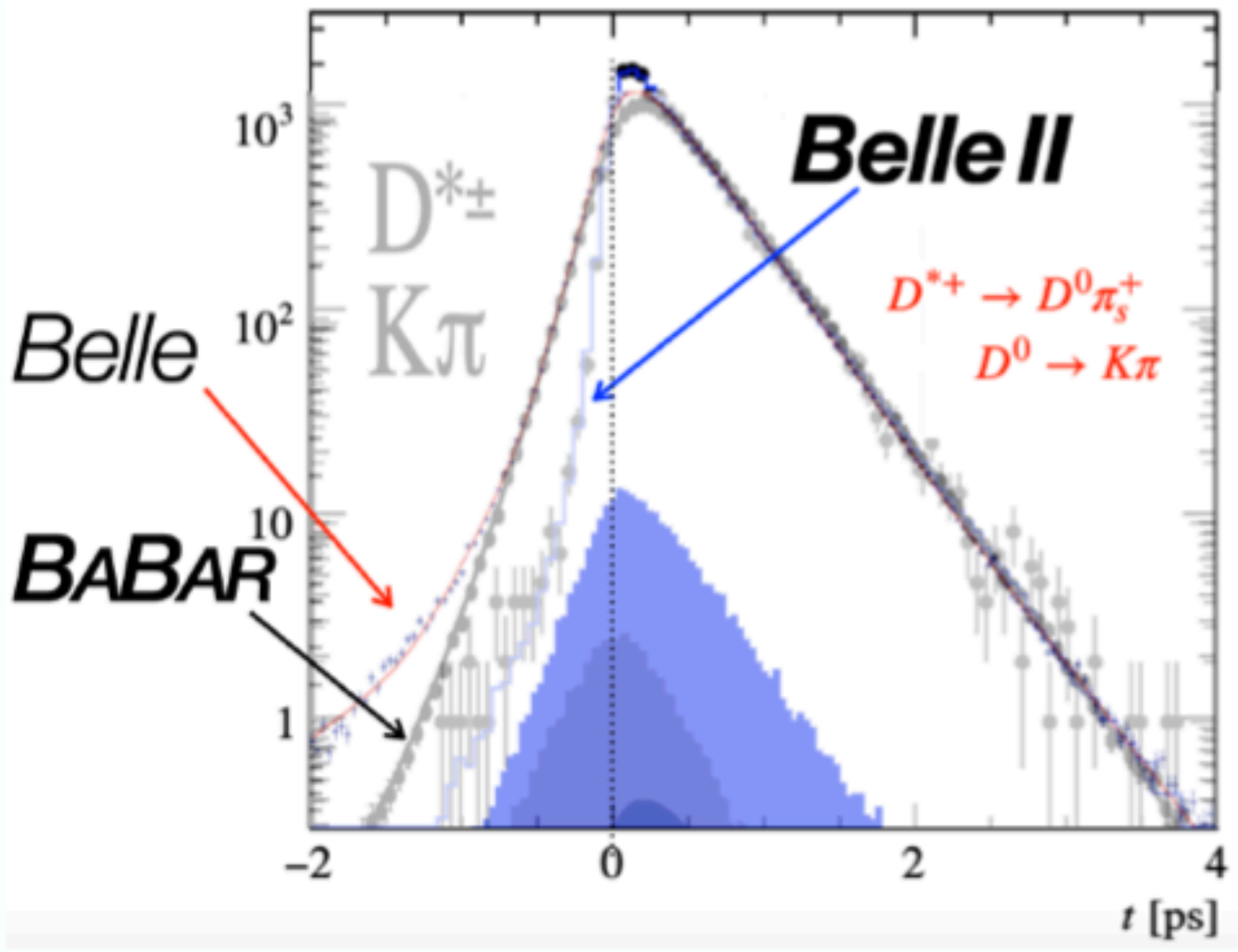
PID still 20% worse than Belle but improving



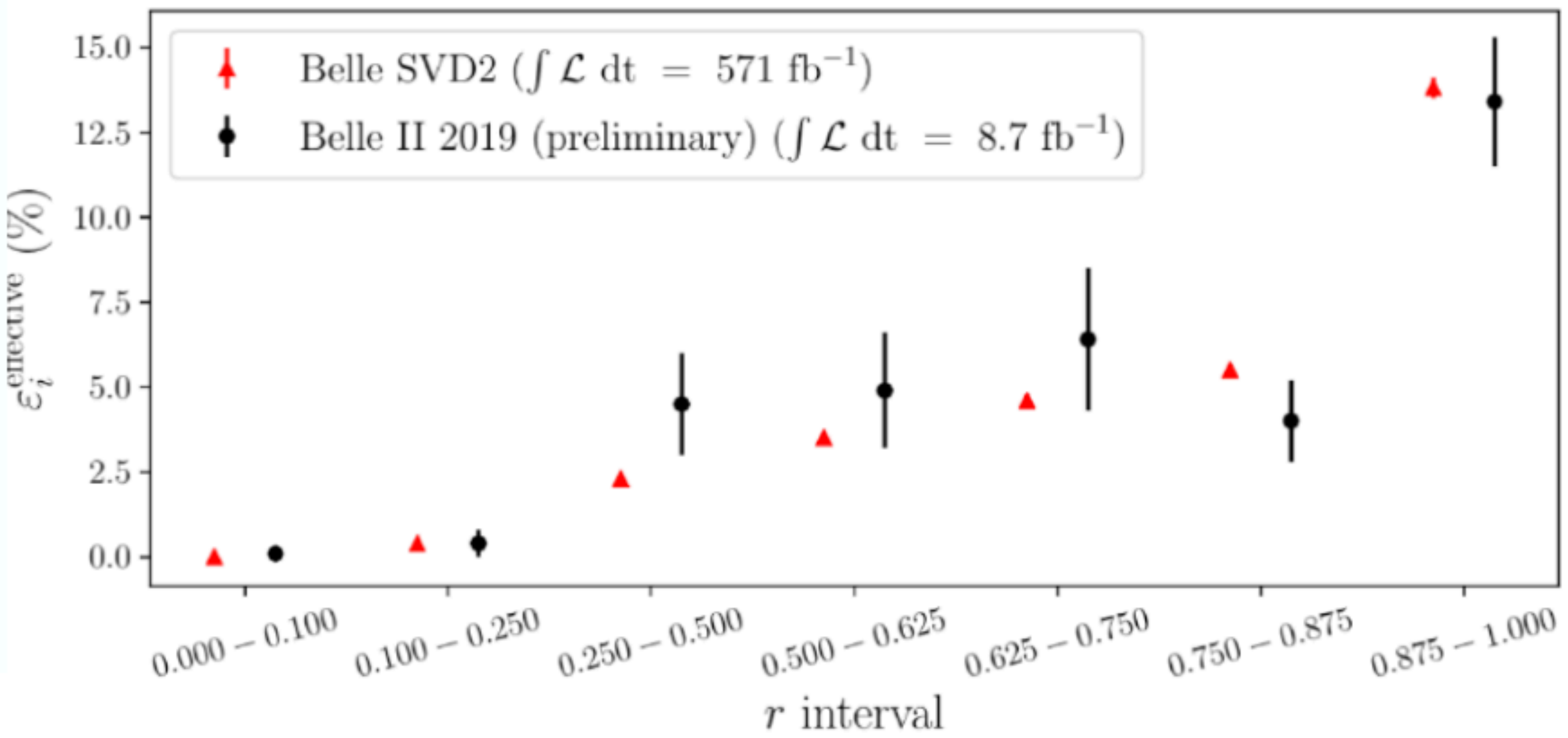
Momentum resolution 20% better than Belle



High photon efficiency,



Nearly 2x better decay-time resolution than Belle

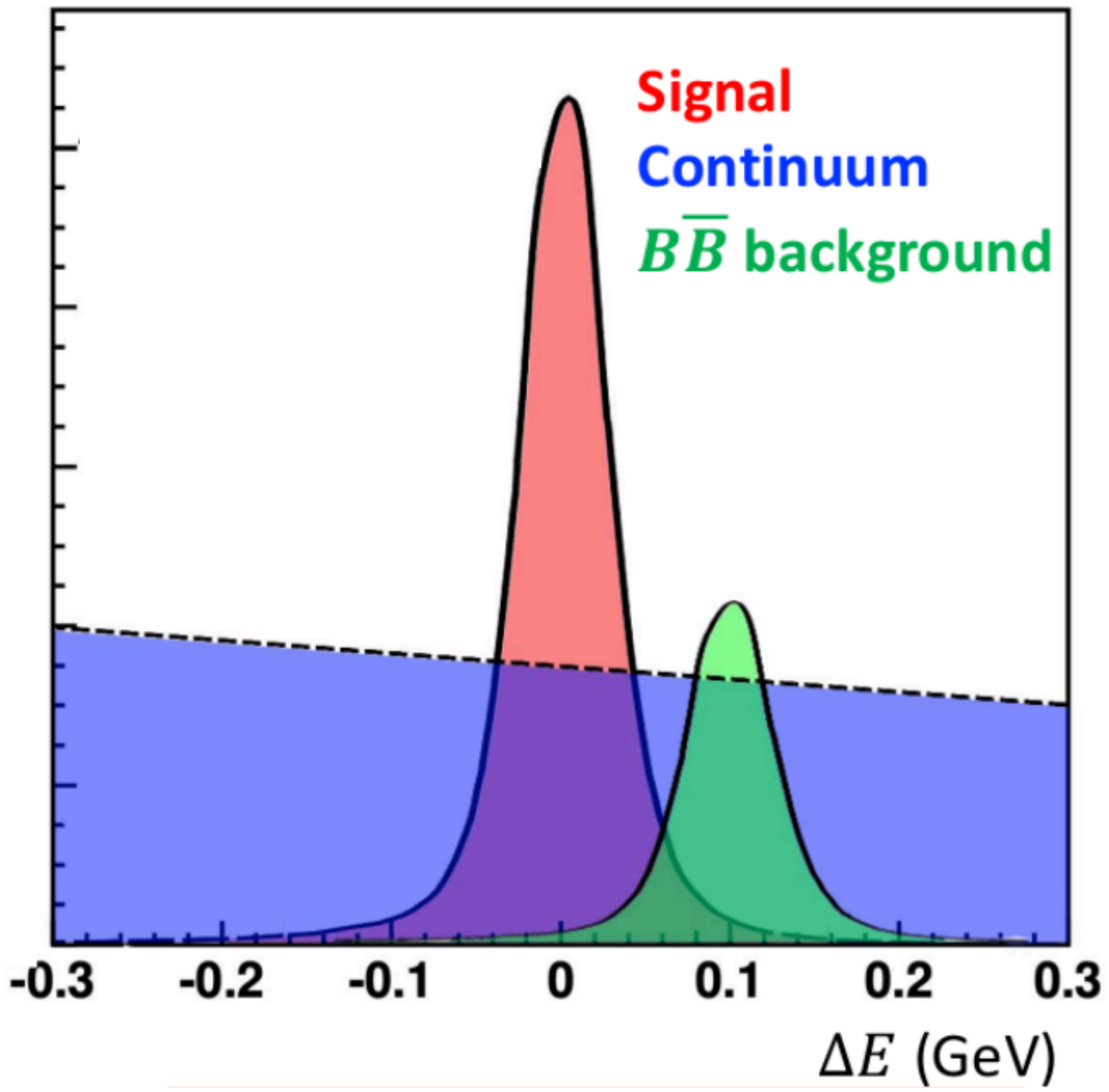


Tagging performance similar to Belle and improving

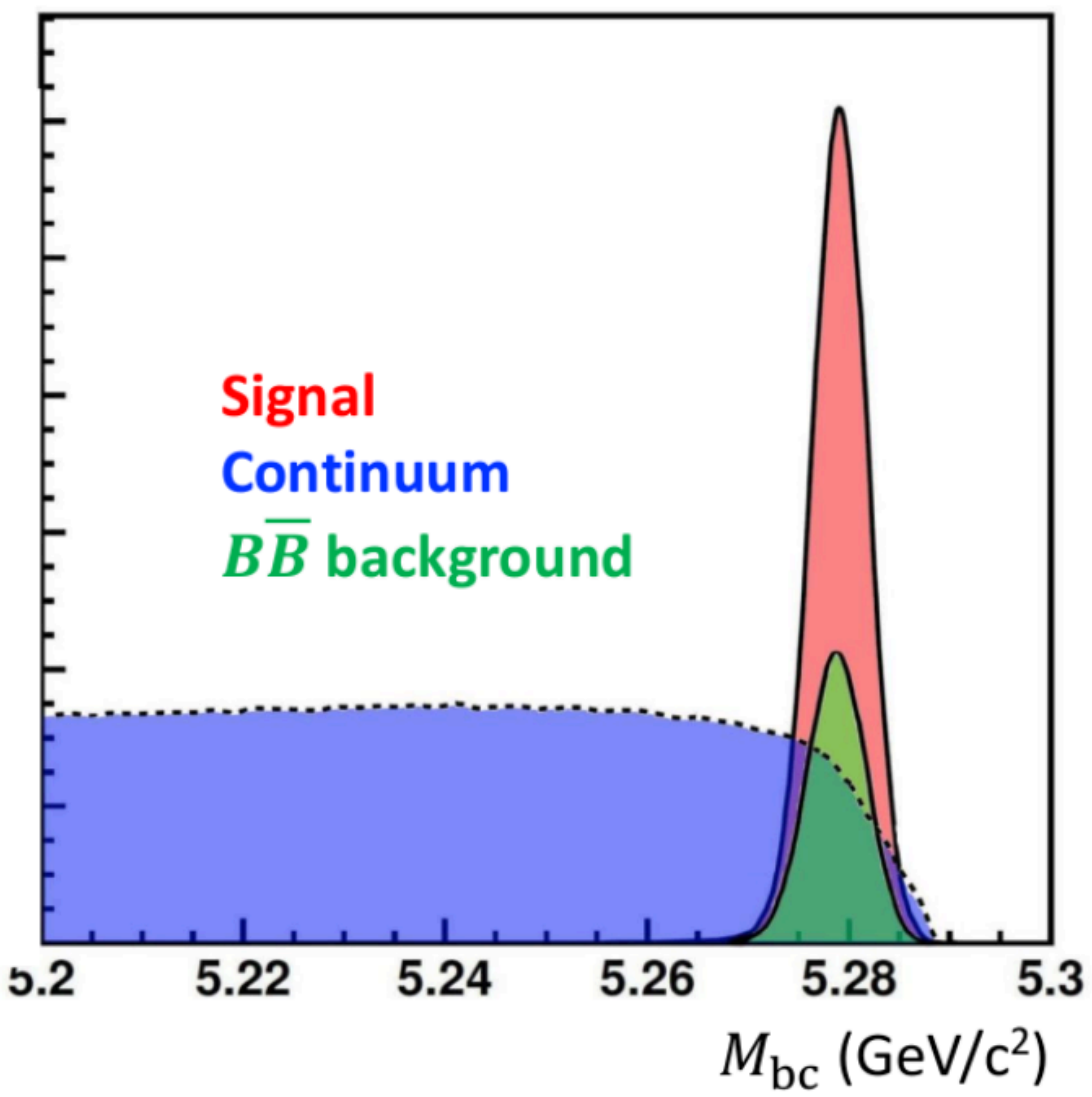
[From D. Tonelli]

B factory variables

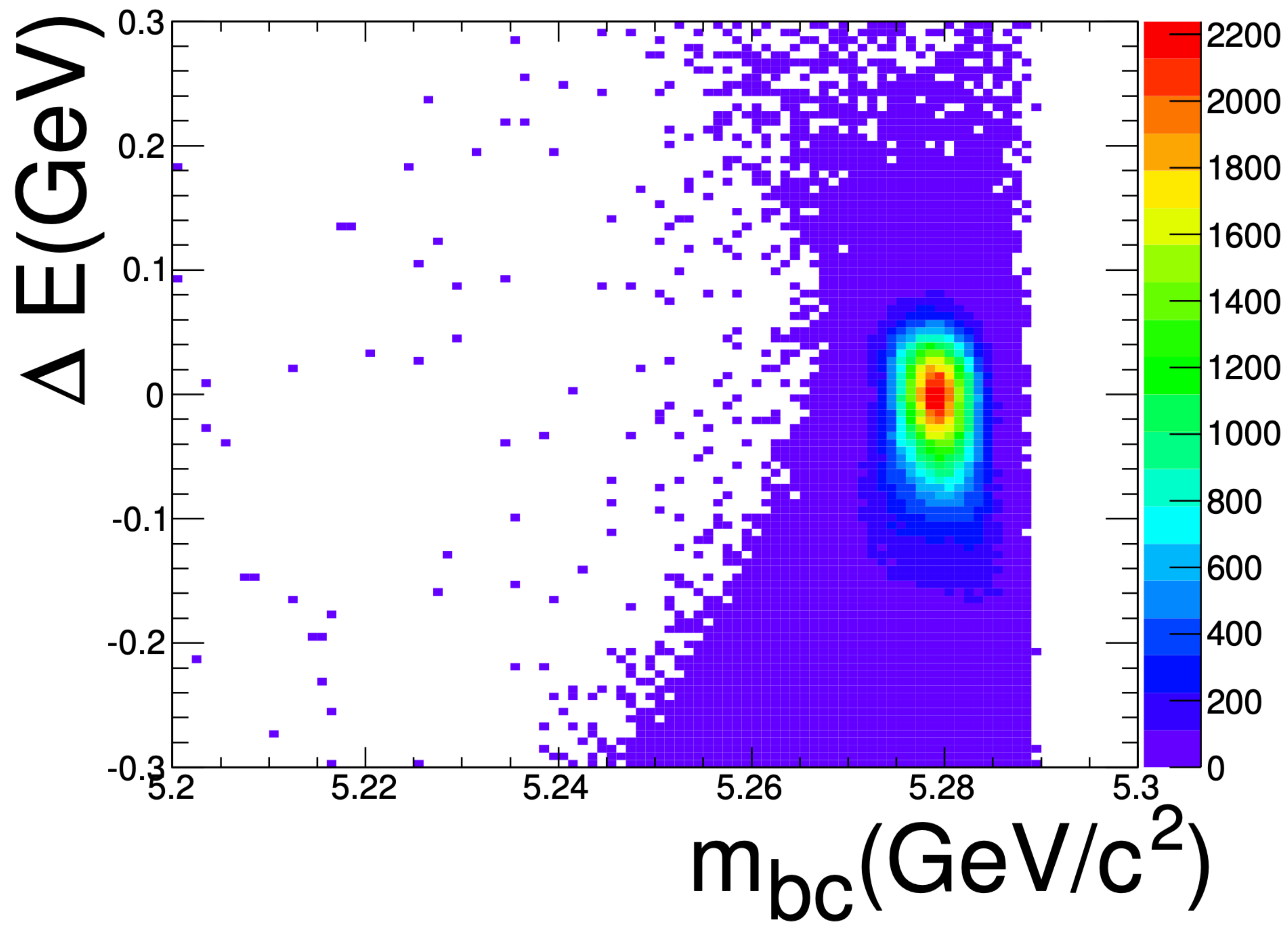
- $\Delta E = E^*_B - E^*_{\text{beam}}$
- Expected $\Delta E \simeq 0$ for properly reconstructed signal
- Sensitive to wrong mass assignment (mis-ID)



- $M_{bc} = \sqrt{(\sqrt{s}/2)^2 - \vec{p}_B^{*2}}$
- Expected $M_{bc} \simeq m_B$ for properly reconstructed signal
- Insensitive to mis-ID



- 2 variable mostly uncorrelated
- tag-signal relation:
  - $E^*_{B_{\text{tag}}} = E^*_{B_{\text{sig}}} = \sqrt{s}/2,$
  - $\vec{p}^*_{B_{\text{tag}}} = -\vec{p}^*_{B_{\text{sig}}}$



$B^+ \to D^0\rho(770)^+$: theory impact

- in heavy-quark limit, factorization predicts:
  $R = 1 + O(\Lambda_{QCD}/m_b)$,
  $\delta = O(\Lambda_{QCD}/m_b)$

$$R = \left(\frac{3}{2}\frac{\tau_+}{\tau_0}\frac{\mathcal{B}(D^+\rho^-) + \mathcal{B}(D^0\rho^0)}{\mathcal{B}(D^0\rho^-)} - \frac{1}{2}\right)^{\frac{1}{2}},$$

$$\cos\delta = \frac{1}{2R}\left(\frac{3}{2}\frac{\tau_+}{\tau_0}\frac{\mathcal{B}(D^+\rho^-) - 2\mathcal{B}(D^0\rho^0)}{\mathcal{B}(D^0\rho^-)} + \frac{1}{2}\right)$$

($\tau^{+/0} =$ lifetime of $B^{+/0}$)

- BFs are the experimental limiting factor

  - Before this result:
    - $R = 0.69 \pm 0.15$
    - $\cos\delta = 0.984^{+0.113}_{-0.048}$
  - After this result:
    - $R = 0.93^{0.11}_{-0.12}$
    - $\cos\delta = 0.919^{+0.012}_{-0.009}$

$B^+ \to D^0\rho(770)^+$: systematics

Systematic uncertainties

Source	Relative uncertainty (%)
$N_{B\bar{B}}$	1.5
f^{+-}	2.4
$\mathcal{B}_{\text{sub}}$	0.8
Fit modelling	1.7
π^0 efficiency	3.7
Particle-identification efficiency	0.6
Continuum-suppression efficiency	1.5
Tracking efficiency	0.7
Total	5.3

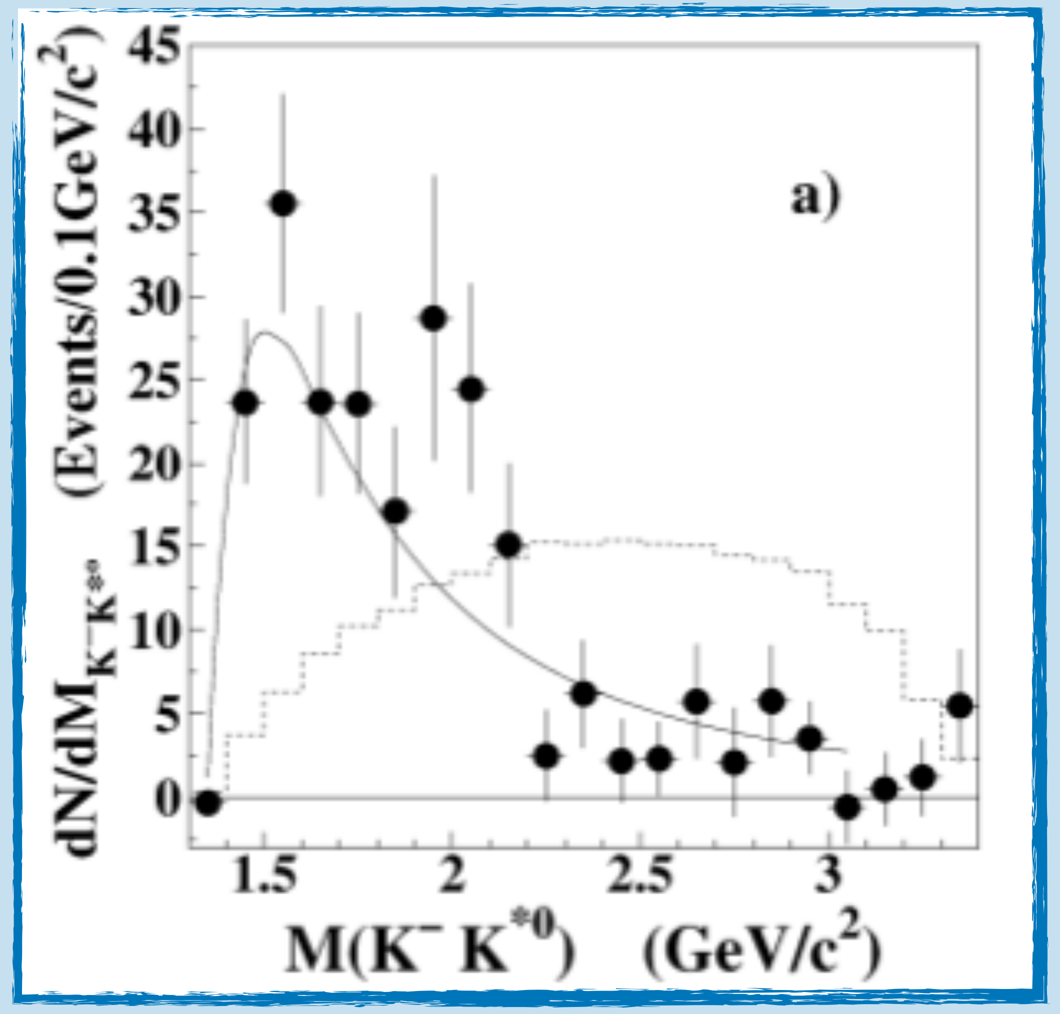
- Toys with alternative model

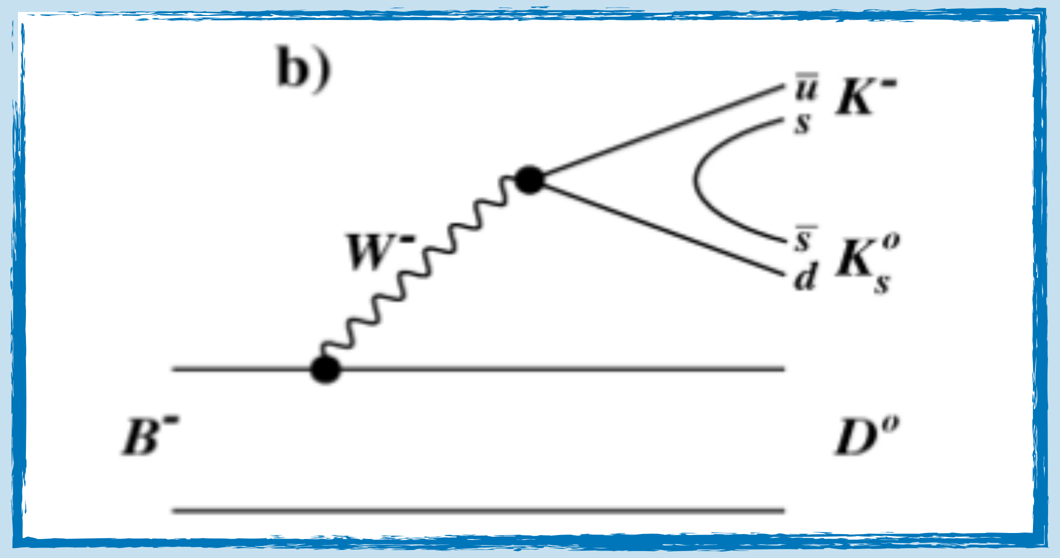
- data/MC ratio correction
- $D^{*+} \to D^0(\to K^-\pi^+\pi^0)\pi^+$ and $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$
- as a function of momentum and polar angle of π^0

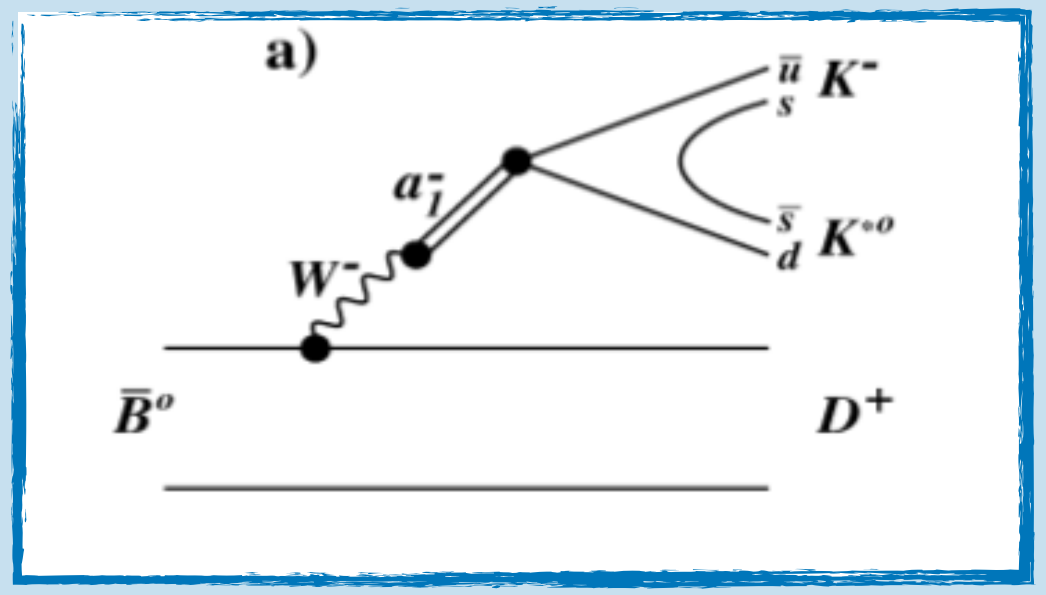
Motivations: the DKK opportunity

Belle studied the K^-K^{*0} **mass distribution**

- far from 3 body phase-space
- compatible with resonant $a_1^- \to K^-K^{*0}$ resonance
- angular analysis K^-K^{*0}: $J^P = 1^+$ (agrees with a_1)
- Also $m(K^-K_S^0)$ far from phase-space







- The Belle II integrated luminosity (362 fb^{-1}) already recorded allows:
  - to improve over the Belle measurement with **higher precision**
  - to **observe additional 3 new** $B \to DKK_S^0$ modes (2-3 sigmas in Belle paper)
  - to **understand the resonant contribution** (a_1, ρ'...) of this class of decays
  - to perform the world best measurement of the four $B \to D_s^- D^{(*)}$ channels

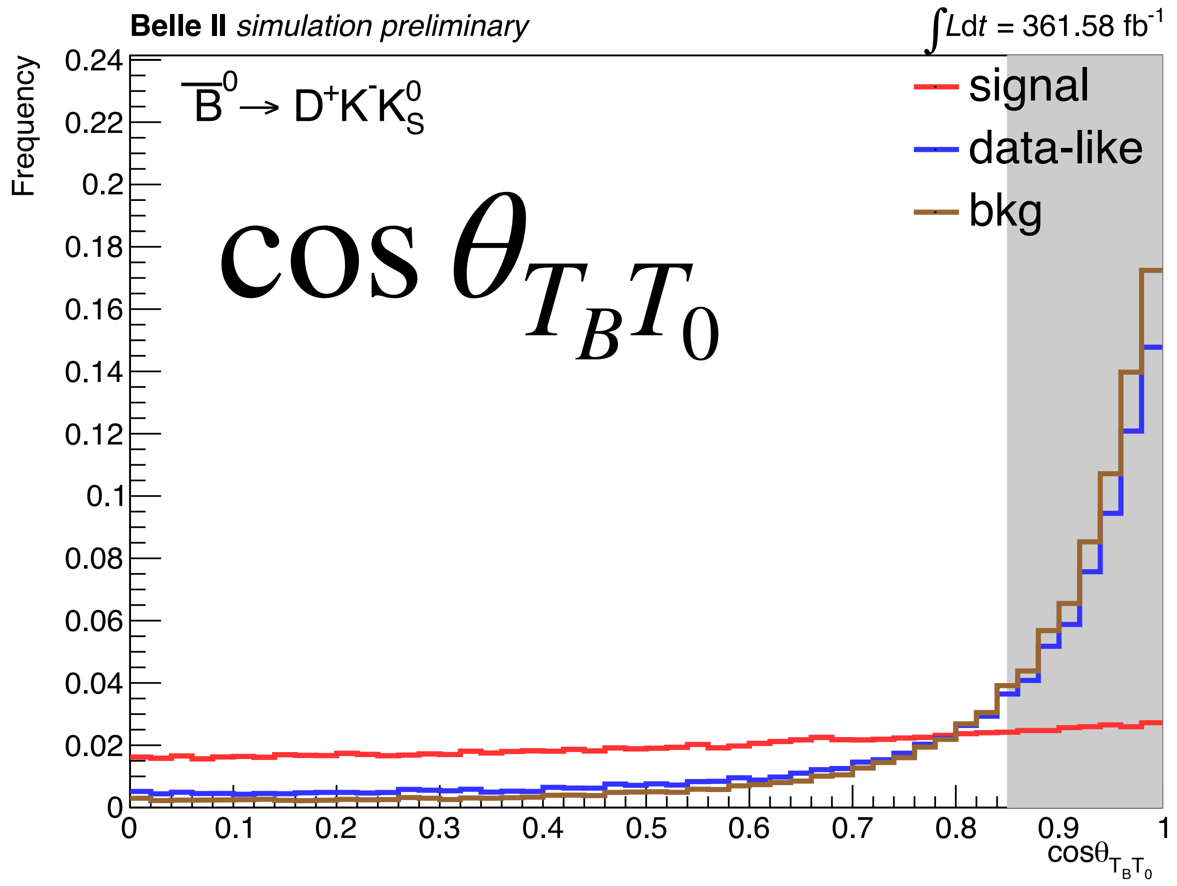
$B \to D^{(*)}K^- K^{(*)0}_{(S)}$: Reconstruction and selection

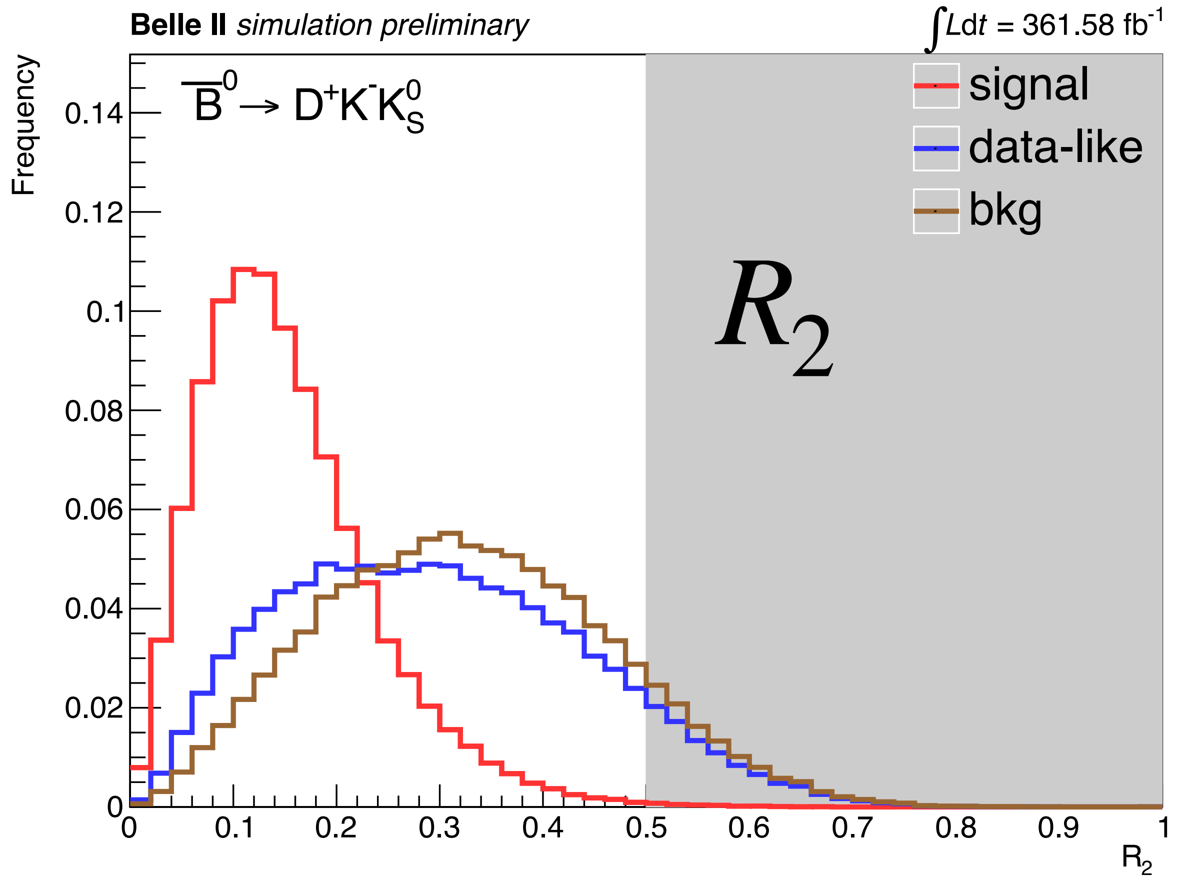
Decay chain

$B \to D^{(*)}K^- K^{(*)0}_{(S)}$

- $K^0_S \to \pi^+\pi^-$
- $K^{*0} \to K^+\pi^-$
- $D^0 \to K^-\pi^+$
- $D^+ \to K^-\pi^+\pi^+$
- $D^{*0} \to D^0\pi^0$
  - $\pi^0 \to \gamma\gamma$
- $D^{*+} \to D^0\pi^+$

$B\overline{B}$ and $q\overline{q}$ suppression



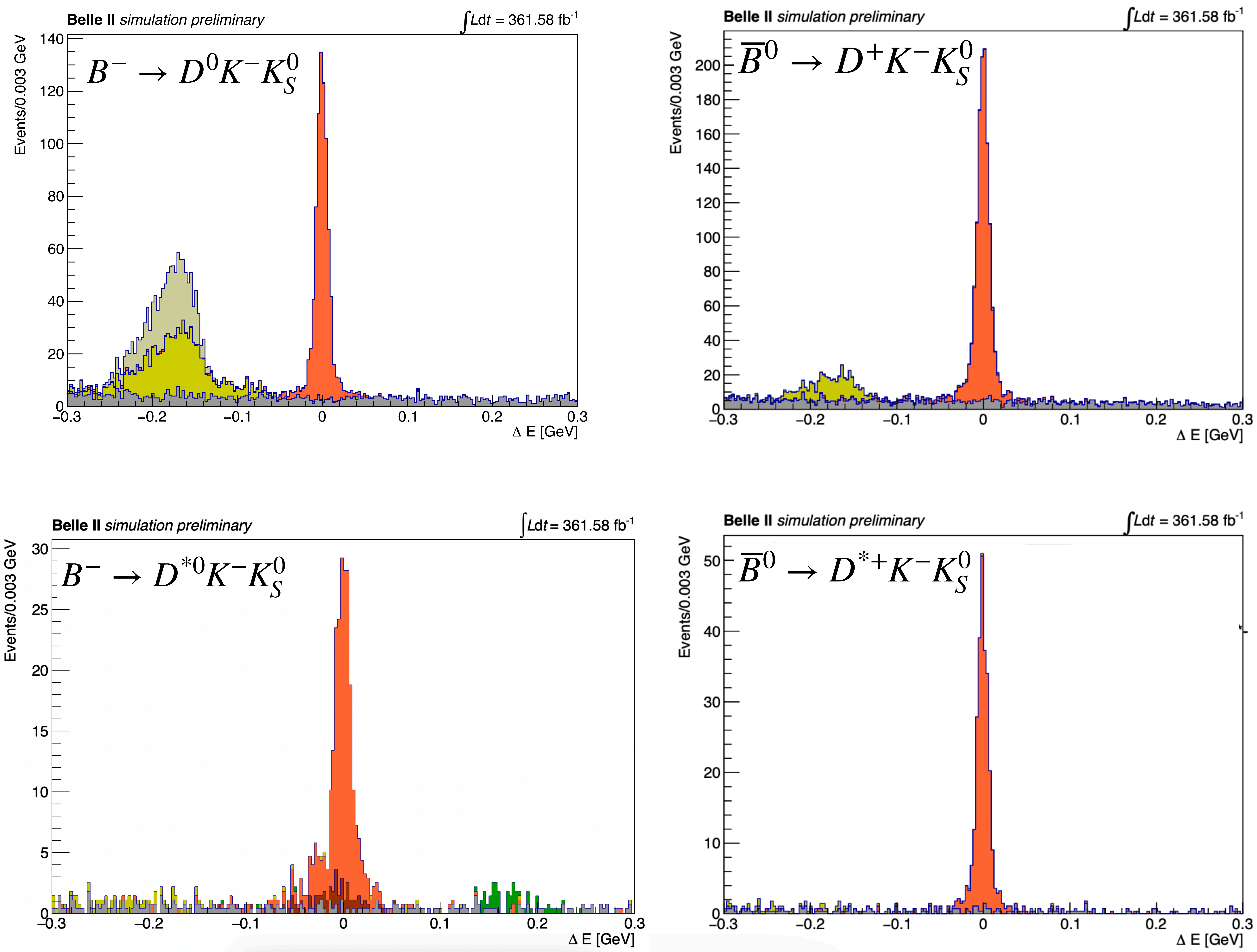


- ...
- ... [see backup for full details and definitions]

- $M_{bc} = \sqrt{(\sqrt{s}/2)^2 - \vec{p}_B^{*2}} > 5.272$ GeV
- $B \to DD_s^-(\to KK)$ **veto**: $\Rightarrow |m_{D_s} - m_{KK}| > 20$ MeV
- **Best candidate selection:** $\min|M_{bc} - M_B|$
- $|M^{\text{reco}}_{K^*} - M^{\text{PDG}}_{K^*}| < 50$ MeV

Reconstructed sample composition - K_S^0 channels

[MC Simulation]



= signal

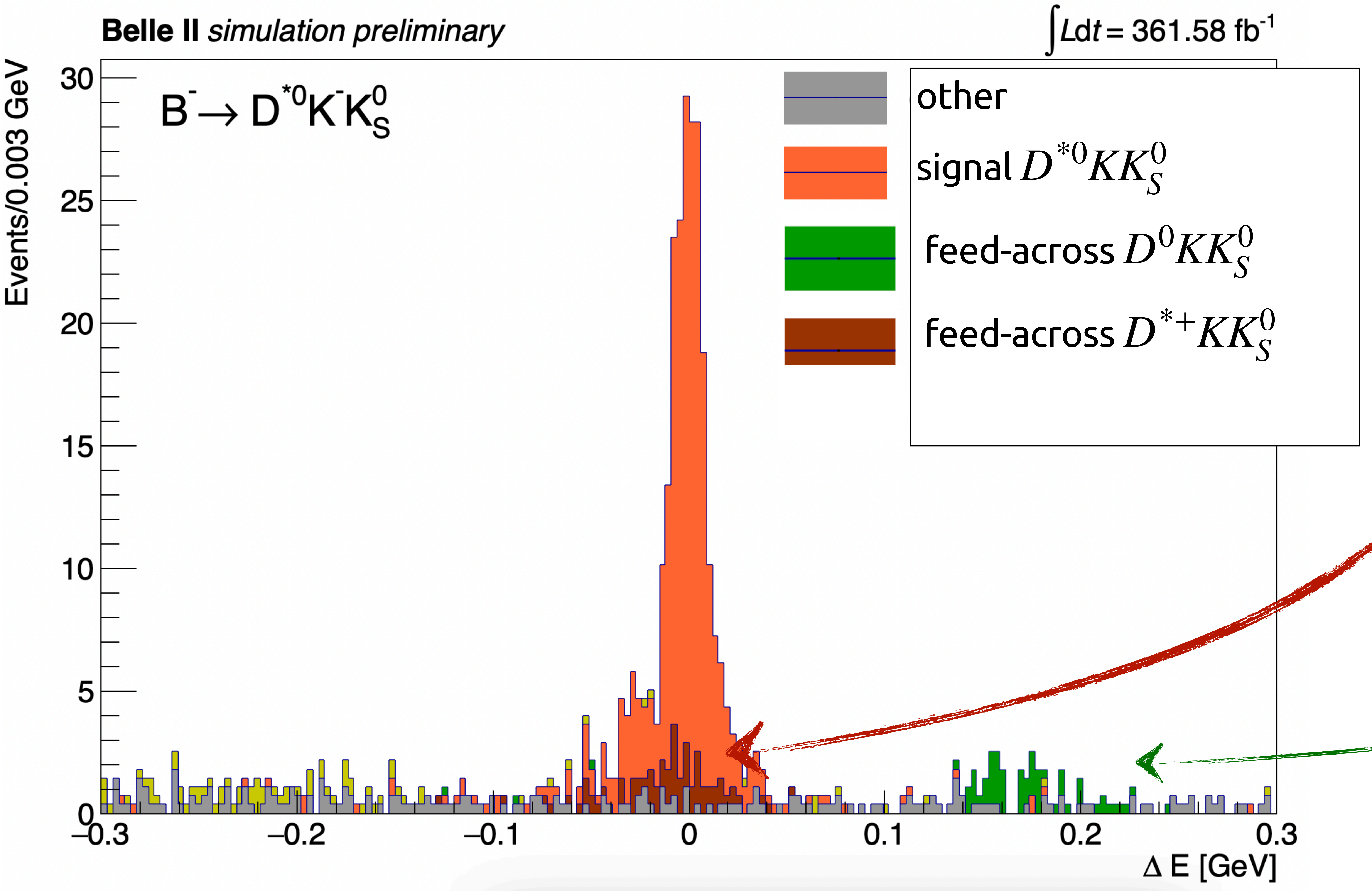
= feed-across between channels

= other bkg

- all the channels are very clean
- some off-peak feed across
- only in $D^{*0} K K_S^0$ has a peaking bkg *[next slides]*

Peaking background in $B^- \to D^{*0} K^- K^0_S$

[MC Simulation]



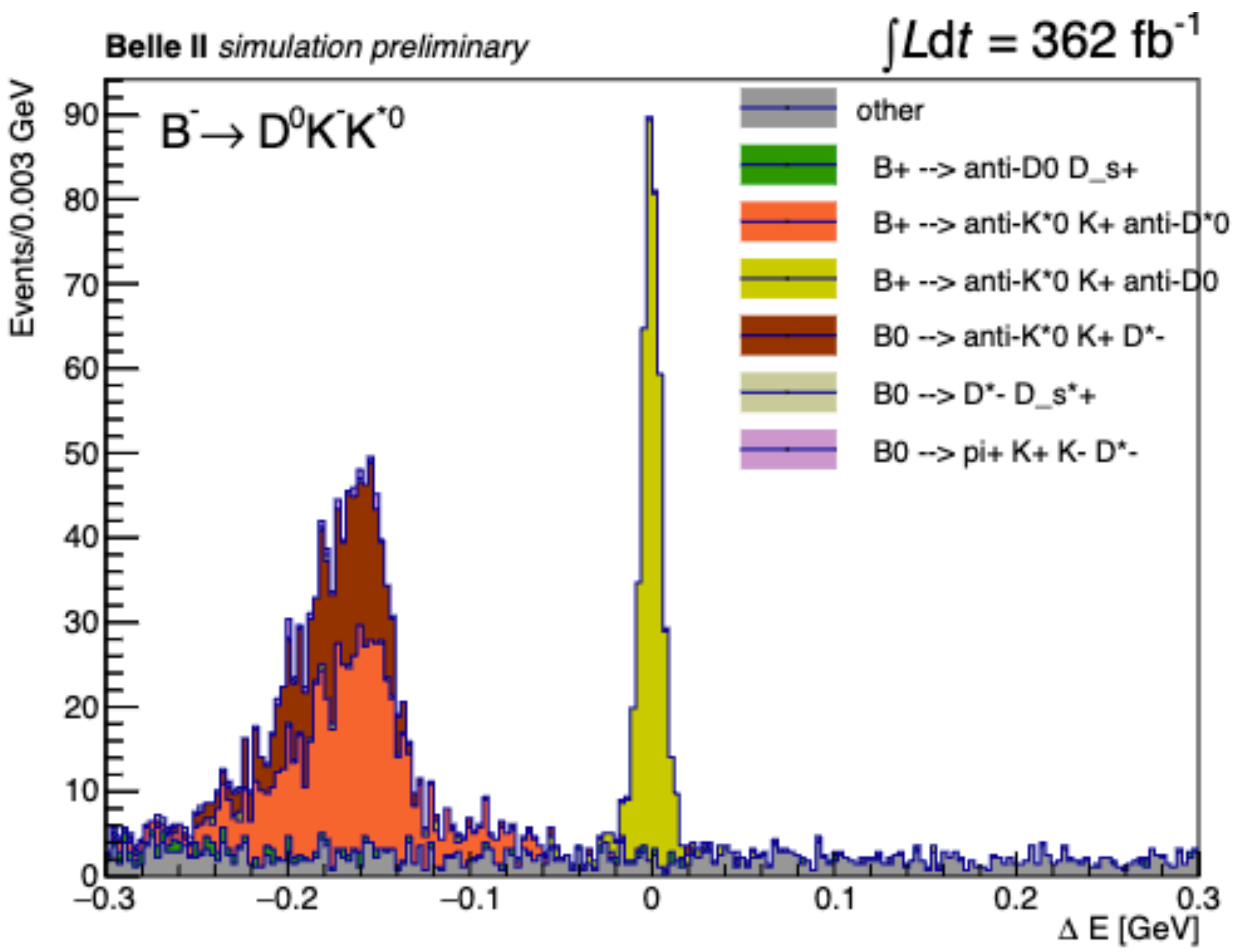
- peaking feed across from $D^{*+} K K^0_S$ (lost π^+ and added a wrong π^0)
- yield estimated using:

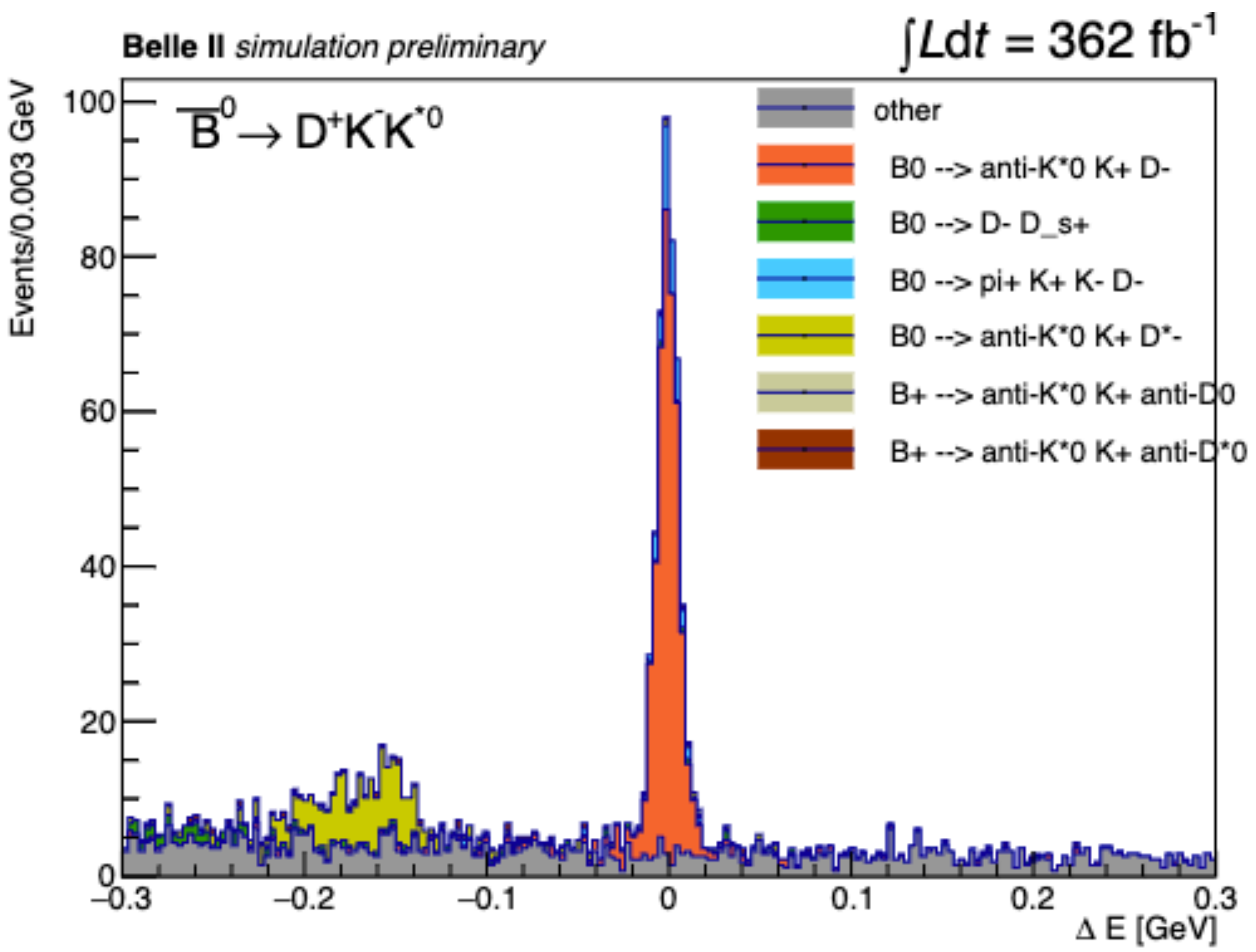
$$N^{bkg}_{D^{*+}} = \frac{BR(\overline{B}^0 \to D^{*+} K^- K^0_S)}{BR(B^- \to D^0 K^- K^0_S)} \cdot N^{bkg}_{D^0}$$

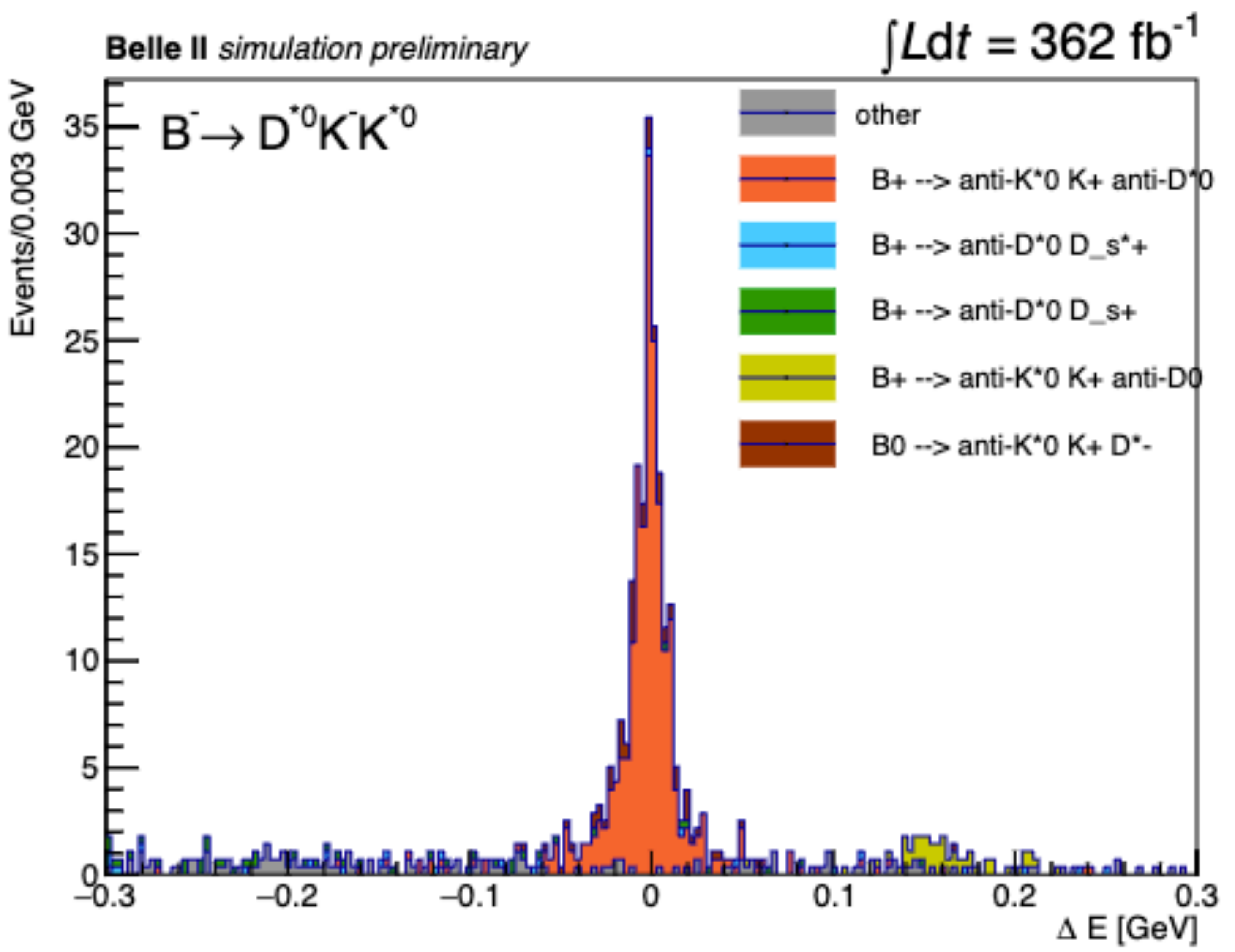
- *[More details in backup]*

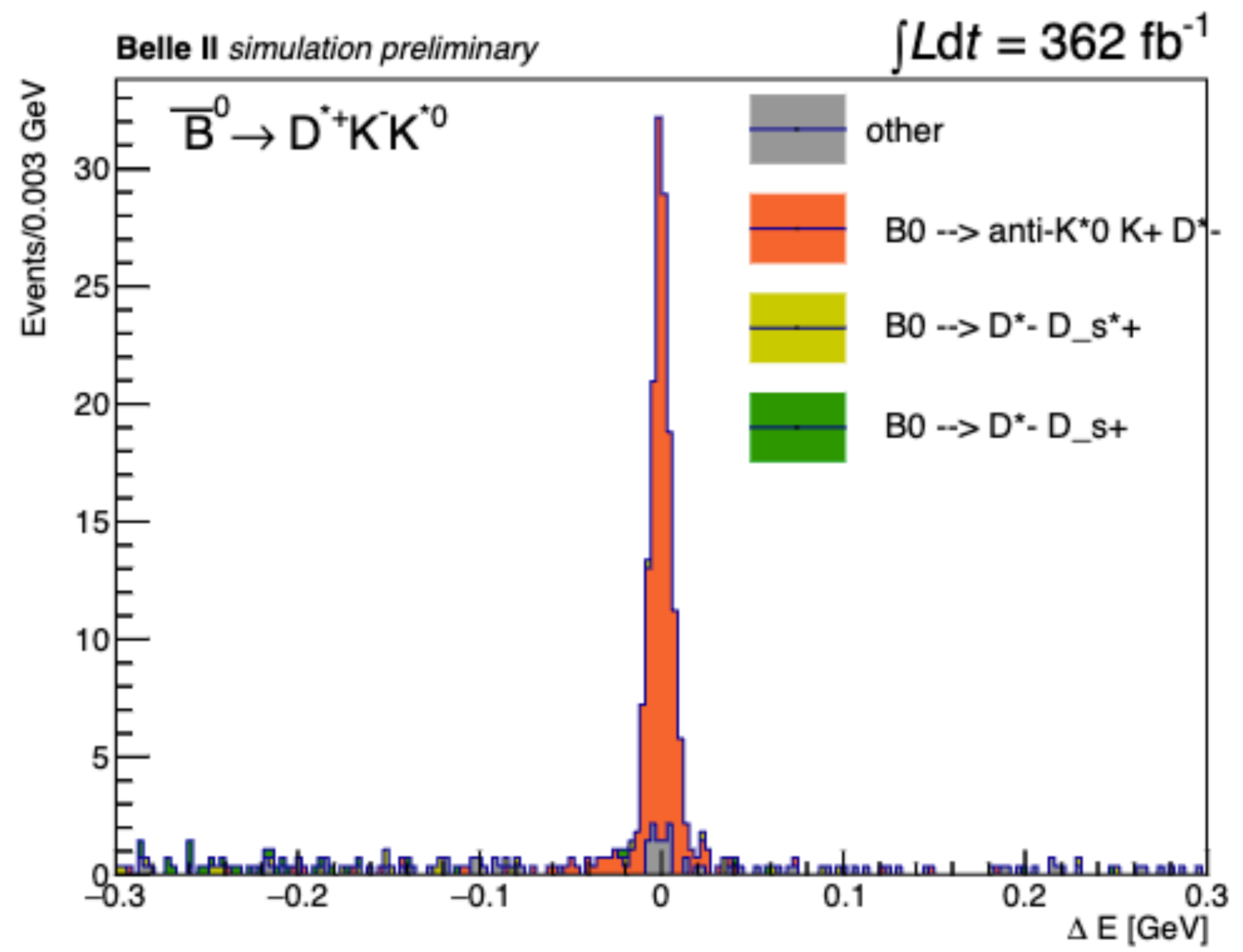
Reconstructed sample composition - K^{*0} channels

[MC Simulation]







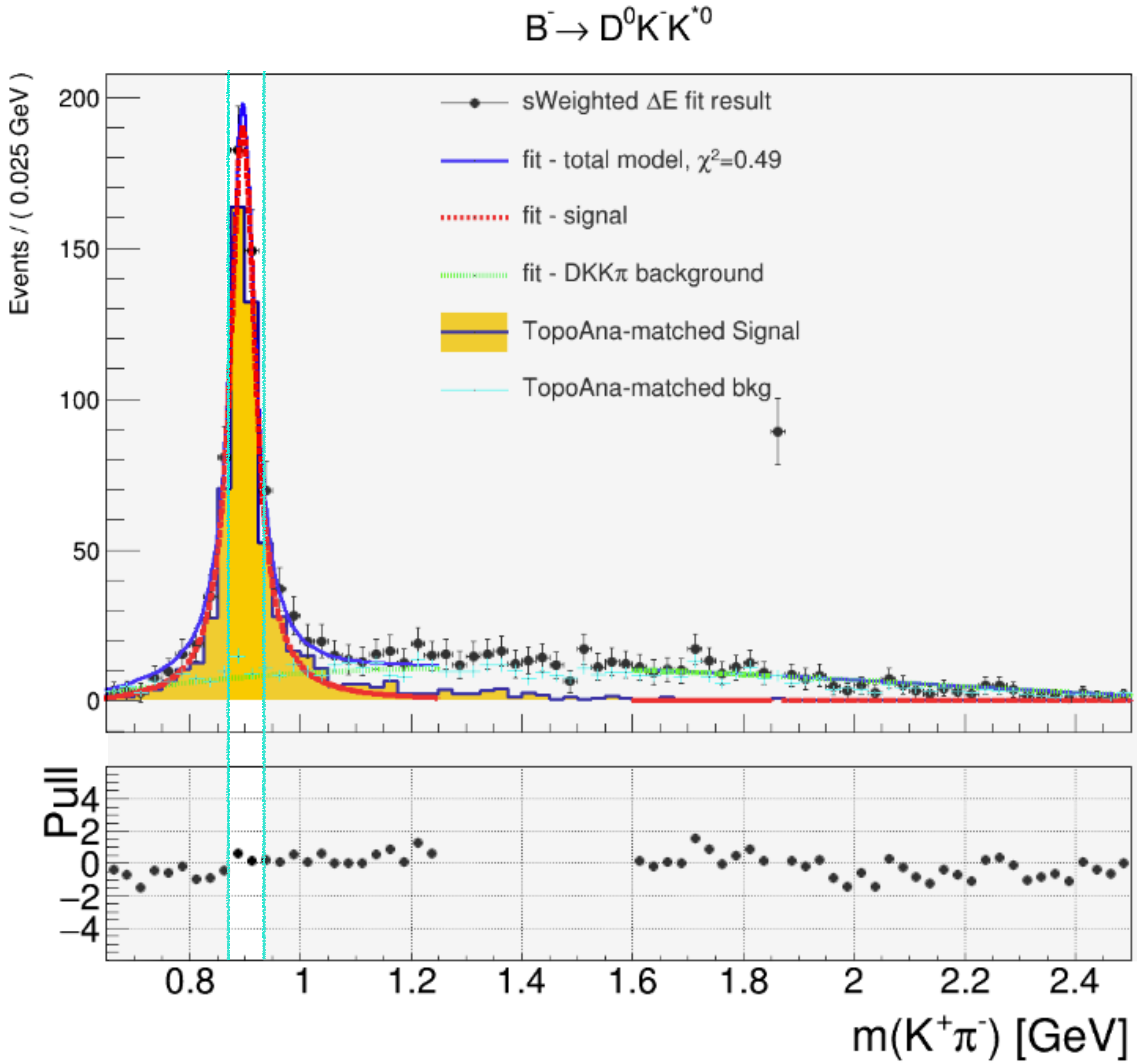


- all the channels are very clean
- some off-peak feed across
- All the channels have a $B \to DKK\pi$ peaking bkg *[next slides]*
- The $D^{*0}KK^{*0}$ has an additional peaking bkg, likewise the K_S^0 case

$B \to DKK\pi$ background

[MC Simulation]

- Do not apply the cut in $m(K^+\pi^-)$
- **perform a fit in ΔE** to separate $q\bar{q}/B\bar{B}$ bkg
- **use the sPlot to obtain the $m(K^+\pi^-)$** distribution, free from $q\bar{q}/B\bar{B}$ bkg
- **fit the resulting $m(K^+\pi^-)$** distribution
  - Signal: BW phase-space corrected, with mean=$m_{K^{*0}}$ and free width
  - Bkg: 3rd degree Chebyshev polynomial (parameters fixed)
  - veto on $m(K^+\pi^-) \approx m_D$ for $B \to D^{(*)}DK$ + veto [1.25 GeV,1.60 GeV] for additional K* resonances
- **Extract the fraction** $R_{NR} = N_{DKK\pi}/N_{DKK^*}$ in signal region (under the K* peak)
- applying the cut $|m(K^+\pi^-) - m_{K^*}| < 50$ MeV
- **Perform the ΔE fit**, including the NR $DKK\pi$ component



$B \to D^{(*)}K^- K^{(*)0}_{(S)}$ and $B \to D^{(*)}D_s^-$: extra info (2)

Example of all the derived results for a single channel ($\bar{B}^0 \to D^+ K^- K^0_S$)

$B \to D^{(*)}K^-K^{(*)0}_{(S)}$: systematic uncertainties

Source	$D^0K^-K^0_S$	$D^+K^-K^0_S$	$D^{*0}K^-K^0_S$	$D^{*+}K^-K^0_S$	$D^0K^-K^{*0}$	$D^+K^-K^{*0}$	$D^{*0}K^-K^{*0}$	$D^{*+}K^-K^{*0}$
Eff. - MC sample size	0.5	0.8	1.1	0.9	0.5	0.7	0.9	1.2
Eff. - tracking	0.7	1.0	0.7	1.0	1.0	1.2	1.0	1.2
Eff. - π^+ from D^{*+}	-	-	-	2.7	-	-	-	2.7
Eff. - K^0_S	2.4	2.7	2.3	2.3	-	-	-	-
Eff. - PID	1.3	1.7	0.5	0.6	2.5	2.6	1.6	1.7
Eff. - π^0	-	-	5.1	-	-	-	5.1	-
Eff. - modeling	0.2	0.3	0.6	0.7	1.3	2.0	3.1	2.4
Signal model	1.5	3.6	2.3	2.7	0.8	1.0	2.5	0.6
Bkg model	0.8	1.1	0.8	0.8	1.1	0.4	0.2	0.1
$DKK\pi$ bkg	-	-	-	-	1.4	0.7	0.7	0.8
D^{*0} peaking bkg	-	-	< 0.1	-	-	-	2.0	-
$N_{B\overline{B}}$	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
$f_{+-,00}$	2.4	2.5	2.4	2.5	2.4	2.5	2.4	2.5
Intermediate $\mathcal{B}$s	0.8	1.7	1.6	1.1	0.8	1.7	0.6	1.1
Total systematic	4.4	6.1	7.1	5.7	4.6	5.1	7.8	5.4
Statistical	8.8	14.4	18.1	20.5	6.2	6.0	9.6	9.2

Source	$B^- \to D^0D_s^-$	$\overline{B}^0 \to D^+D_s^-$	$B^- \to D^{*0}D_s^-$	$\overline{B}^0 \to D^{*+}D_s^-$
Eff. - MC sample size	< 0.1	< 0.1	< 0.1	< 0.1
Eff. - tracking	0.8	1.0	0.8	1.0
Eff. - π^+ from D^{*+}	-	-	-	2.7
Eff. - K^0_S	1.2	1.2	1.2	1.2
Eff. - PID	1.9	2.1	1.1	1.3
Eff. - π^0	-	-	5.1	-
Signal model	< 0.1	< 0.1	1.1	0.3
Bkg model	0.7	0.7	1.6	0.1
DKK bkg	1.7	2.1	6.1	4.5
D^{*0} peaking bkg	-	-	0.6	-
$N_{B\overline{B}}$	1.4	1.4	1.4	1.4
$f_{+-,00}$	2.4	2.5	2.4	2.5
Intermediate $\mathcal{B}$s	2.5	2.9	2.8	2.9
Total systematic	5.0	5.6	9.5	7.0
Statistical	6.0	5.9	15.2	11.9

$B \to D^{(*)} K^- K^{(*)0}_{(S)}$: expected angular distributions

Table 5. Possible angular distributions given a specific spin-parity state of the $K^- K^{(*)0}_{(S)}$ system, subdividing between pseudoscalar channels (D^0, D^+) and vector channels (D^{*0}, D^{*+}). The hyphen (-) stands for a forbidden spin-parity assuming factorization and exact isospin symmetry; mix stands for a polarization dependent distribution; const stands for a uniform distribution; the † symbol indicates that the uniform distribution requires S-wave dominance.

	$K^- K^{*0}$ channels				$K^- K^0_S$ channels			
	D^0, D^+ channels		D^{*0}, D^{*+} channels		D^0, D^+ channels		D^{*0}, D^{*+} channels	
J^P	$dN/d\theta_{KK}$	$dN/d\theta_{K^*}$	$dN/d\theta_{KK}$	$dN/d\theta_{K^*}$	$dN/d\theta_{KK}$	$dN/d\theta_{K_S}$	$dN/d\theta_{KK}$	$dN/d\theta_{K_S}$
Three-body	const	const	const	const	const	const	const	const
0^-	const	$\cos^2\theta$	const	$\cos^2\theta$	-	-	-	-
1^-	$\sin^2\theta$	$\sin^2\theta$	mix	$\sin^2\theta$	$\cos^2\theta$	const	mix	const
1^+	const†	const†	const†	const†	-	-	-	-

FEI calibration

- SL FEI calibrated using $B \to D^* \ell \nu$ sample
  - BF measured in data and MC
  - Discrepancy due to FEI→scale factor
- Hadronic FEI calibrated using $B \to D\pi$
  - Partial reconstruction of $B \to D\pi$, reconstructing only the π^+
  - Recoil mass calculation: fit the D and D^* signal, with easy-to-model bkg
- Hadronic FEI calibrated using $B \to X \ell \nu$
  - minimal requirement on signal side (lepton)
  - Data and MC comparison in M_{bc}