Study of $B^+ \to K^+\tau^+\tau^-$ decays using hadronic tagging

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Motivation

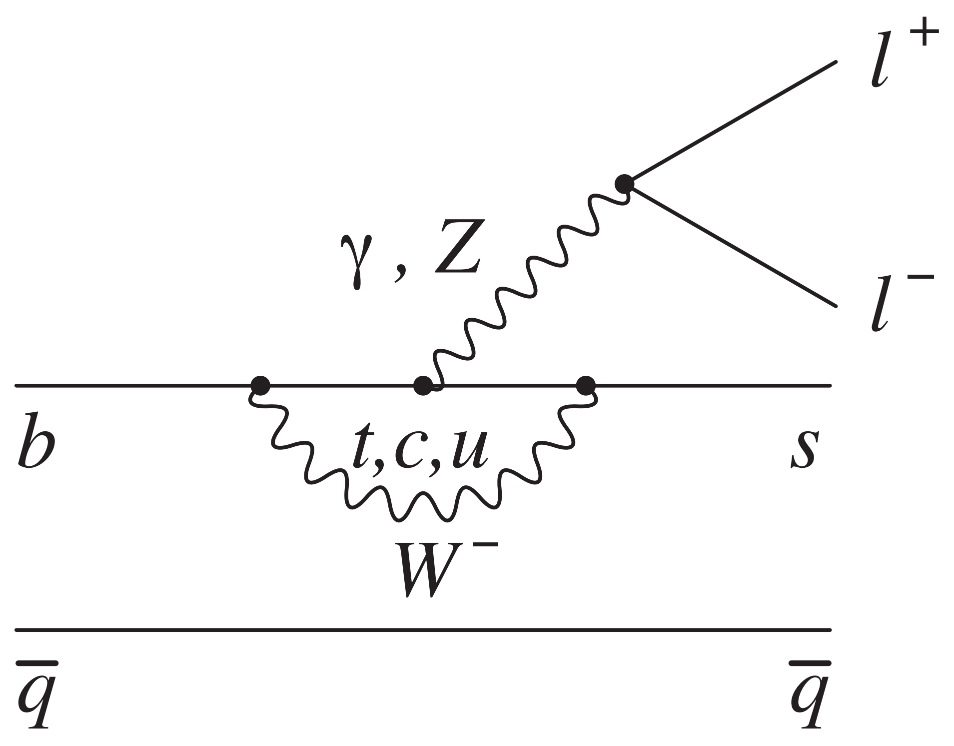
- The flavour changing neutral current processes, $b \to sll$, are forbidden at tree level in SM and only occurs via loop diagrams, $\mathcal{O}(10^{-7})$.

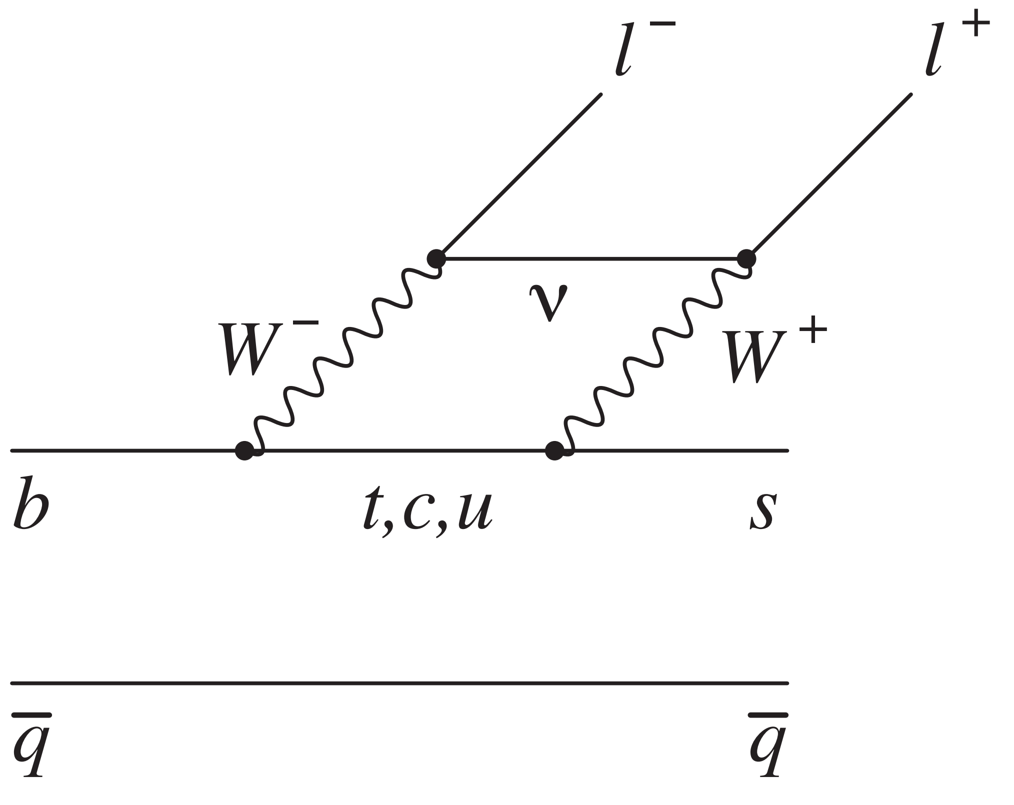
- The recent LHCb measurements of R_K and R_{K^*} are $2.5 \sim 3.1\,\sigma$ away from the SM predictions.

- The new physics models (like PS^3) able to fit these anomalies and explain lepton flavour universality as a low-energy symmetry that breaks at high energy scale.

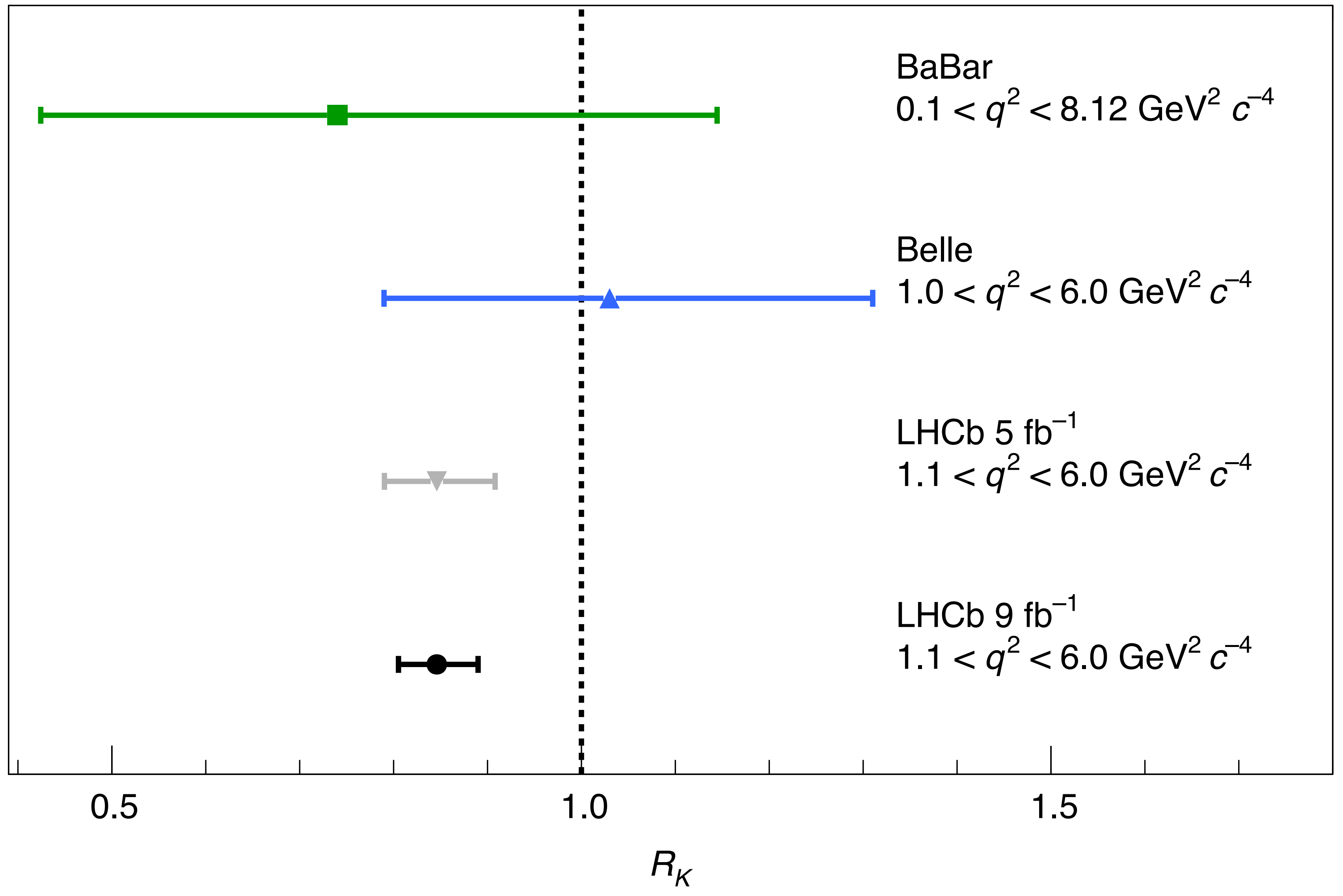
- PS^3 model involves TeV-scale (light) leptoquark which couples only to 3$^{\text{rd}}$ generation.

- PS^3 model predicts $\mathscr{B}(B^+ \to K^+\tau^+\tau^-)$ to be 100 times higher than the SM prediction.





[Nat. Phys. 18, 277–282 (2022)]



[Gino Isidor's talk at FPCP 2020]

	μμ (ee)	ττ	νν	τμ
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)}\tau\tau$ → 100×SM	$B \to K^{(*)}\nu\nu$ O(1)	$B \to K\tau\mu$ → 10^{-6}

Earlier searches of $B^+ \to K^+\tau^+\tau^-$

- BaBar provided the first and only search for this decay with BaBar's full $\Upsilon(4S)$ (on-resonance) data set, 424 fb^{-1}.

- BaBar considered only leptonic τ decays: $\tau^- \to e^-\bar{\nu}_e\nu_\tau$ and $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$.
  Signal efficiency $= 4.5 \times 10^{-5}$

- No significant signal was observed and the upper limit on $\mathscr{B}(B^+ \to K^+\tau^+\tau^-)$ was determined to be 2.25×10^{-3} at 90% C.L. [PhysRevLett.118.031802]

- There was an attempt to search in Belle data (711 fb^{-1}) using hadronic full reconstruction estimating a sensitivity of $\mathscr{B}(B^+ \to K^+\tau^+\tau^-) < 3.17 \times 10^{-3}$ at 90% C.L. [Belle Note- 1394]

- Belle considered also hadronic τ decays: $\tau^- \to e^-\bar{\nu}_e\nu_\tau$, $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$, and $\tau^- \to \pi^-\nu_\tau$.
  Signal efficiency $= 2.7 \times 10^{-5}$

- Goal: To measure $\mathscr{B}(B^+ \to K^+\tau^+\tau^-)$ using hadronic FEI with the full data set of Belle (by Vidya & Karim) and LS1 data set (364 fb^{-1}) of Belle II.

Analysis workflow

Reconstruction: start MC studies with pre-selection of $B^+ \to K^+\tau^+\tau^-$

Background studies: continuum suppression and potential background sources

Optimise selection: identify selection that maximises signal to background ratio

Signal extraction
or
upper limit

Systematics: assess the relevant contribution to systematic uncertainties

Analysis overview

- Main challenge: τ reconstruction as it decays into undetected neutrinos.
- Fully reconstruct one B meson in a hadronic decay (B_{tag}). Putting kinematic constraint from beam energy, we can infer the kinematic properties of τ.
- Obtain typically high signal purity but quite low ($\sim 1\%$) efficiency; limited by sample size.
- We consider only three 1-prong tau decay modes which give 9 signal decay topologies with $2-4$ neutrinos in the final states.
- This analysis is dominated by backgrounds, mainly by $B^+ \to \bar{D}^0 l^+ \nu_l (\bar{D}^0 \to K^+ l^- \bar{\nu}_l)$ modes in B^+B^- samples.

Mode	Branching fraction
$\tau^- \to 1-\text{prong}$	85.58%
$\tau^- \to 3-\text{prong}$	14.20%

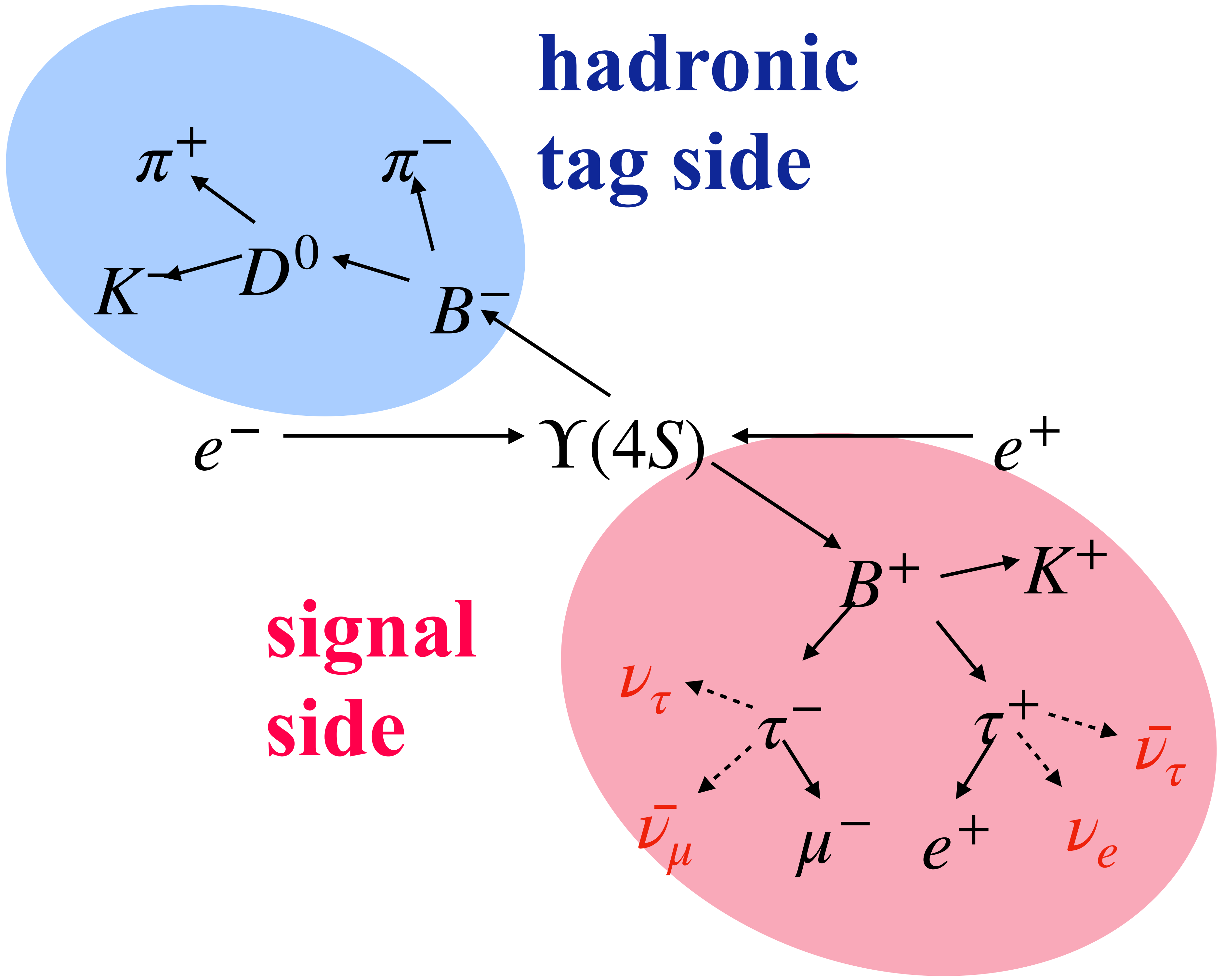
Mode	Branching fraction
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	17.82%
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$	17.39%
$\tau^- \to \pi^- \nu_\tau$	10.82%
Total	46.03%

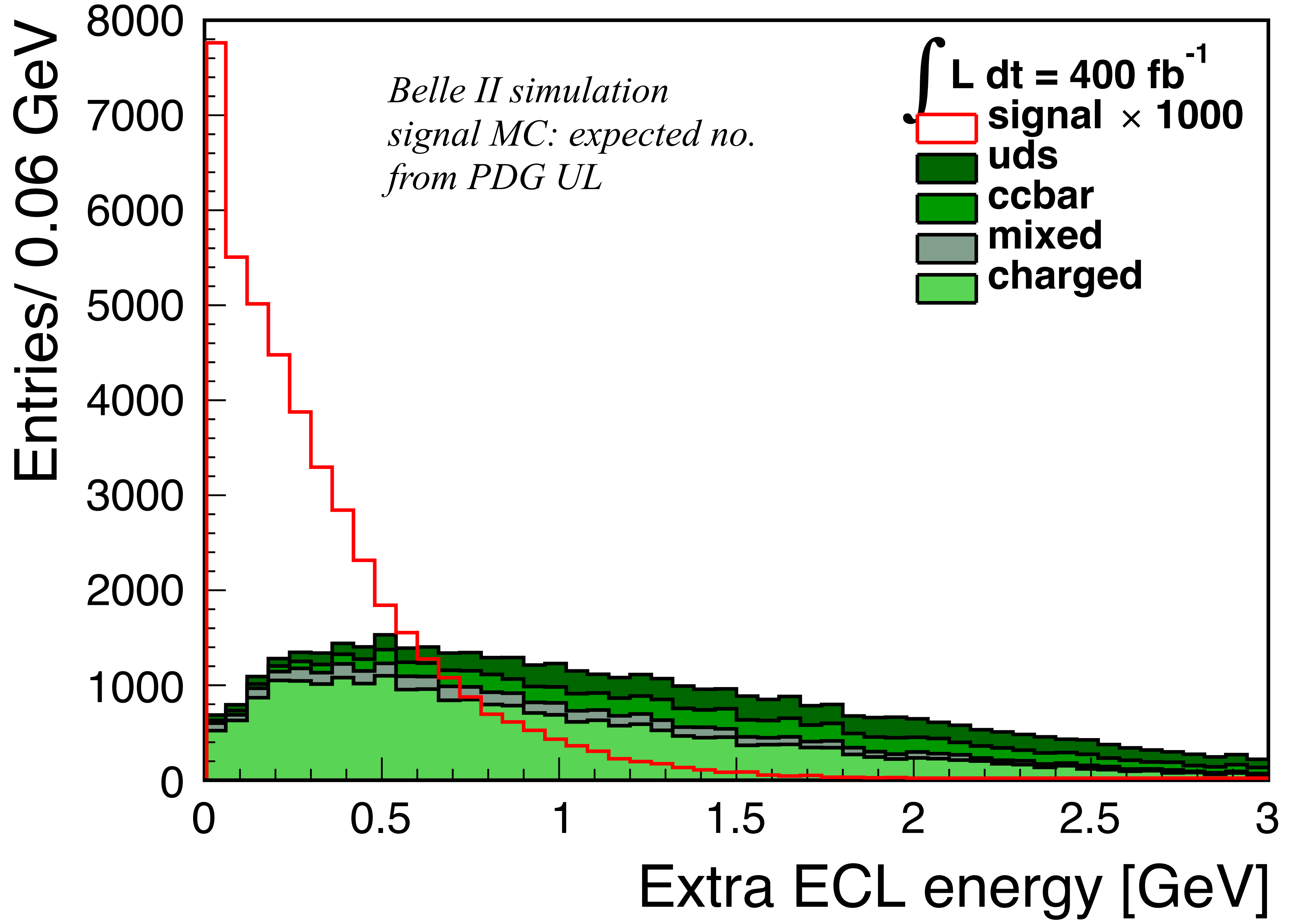
$K^+e^+e^-$	$K^+e^+\mu^-$	$K^+e^+\pi^-$
$K^+\mu^+e^-$	$K^+\mu^+\mu^-$	$K^+\mu^+\pi^-$
$K^+\pi^+e^-$	$K^+\pi^+\mu^-$	$K^+\pi^+\pi^-$

4 neutrinos 3 neutrinos 2 neutrinos

Analysis procedure

- Reconstruct $B_{\rm tag}$ with only hadronic decays using FEI.
- Attribute all other reconstructed particles to the signal B meson ($B_{\rm sig}$).
- Reconstruct $B_{\rm sig}$ by combining K and oppositely charged pair combinations of e, μ, π (eg: $K^+e^+\pi^-$, $K^+\mu^+e^-$,…).
- For signal, there should not be any π^0 in the rest of event of $B_{\rm tag}$: apply π^0 veto
- Signal extraction: narrow peak at zero in the distribution of the energy of all ECL depositions not used in the reconstruction of $B_{\rm sig}$ and $B_{\rm tag}$ candidates.



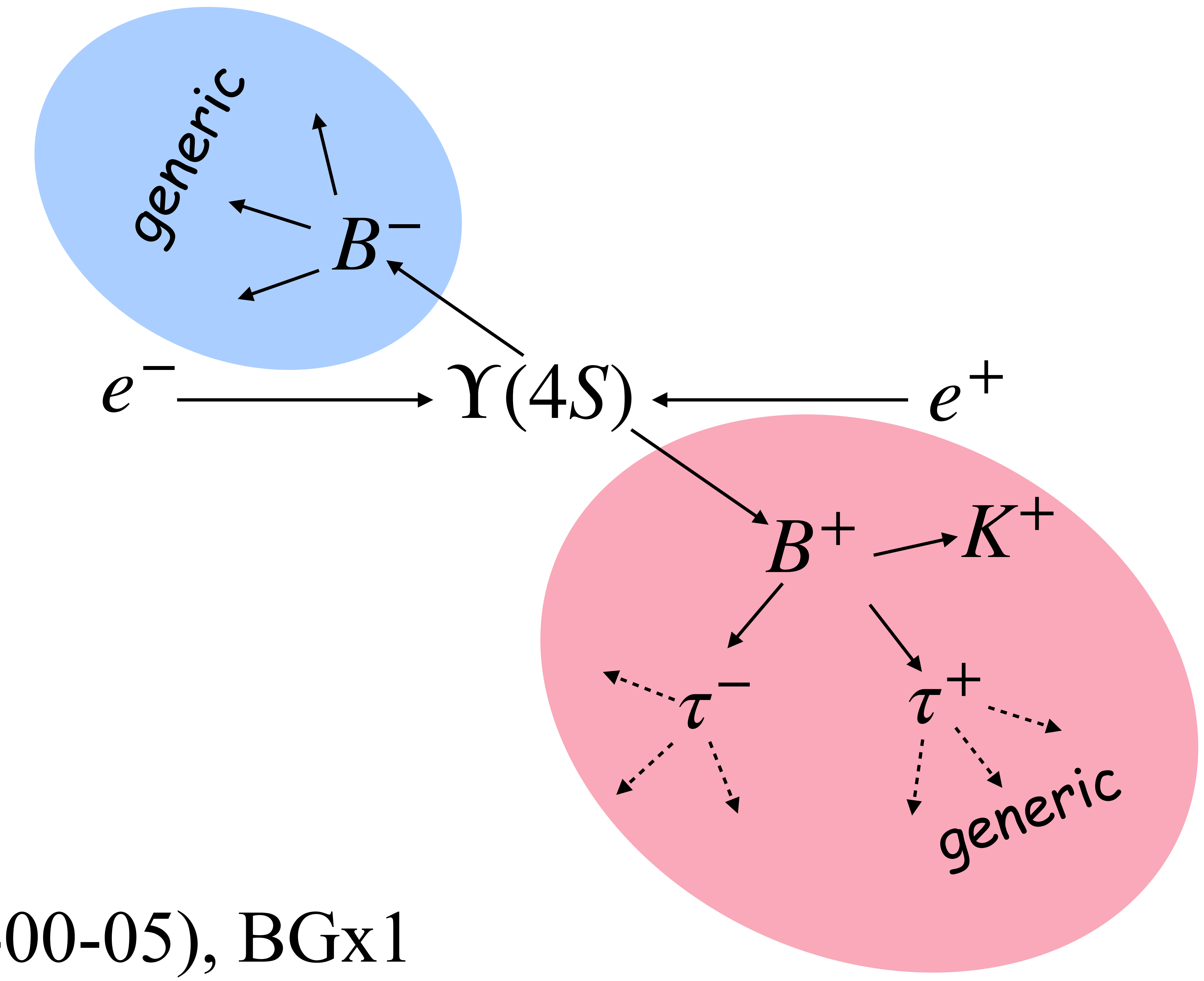


Sample

- release-06-00-03

SignalMC ($B^+ \rightarrow K^+\tau^+\tau^-$):

- Generated 50 million events
- Generator model: <u>BTOSLLBALL</u>
- τ decays generically.*
- Global tag: mc_production_MC15ri_a
- Beam-background: early phase III (release-06-00-05), BGx1



GenericMC (for background):

- Generated events: MC15rib ($\mathscr{L} = 400\,fb^{-1}$)

* In future we will generate only our specific τ decay modes.

Selections

- To start the analysis we use similar selections as of the Belle analysis.
- The final selections will be optimized in future.

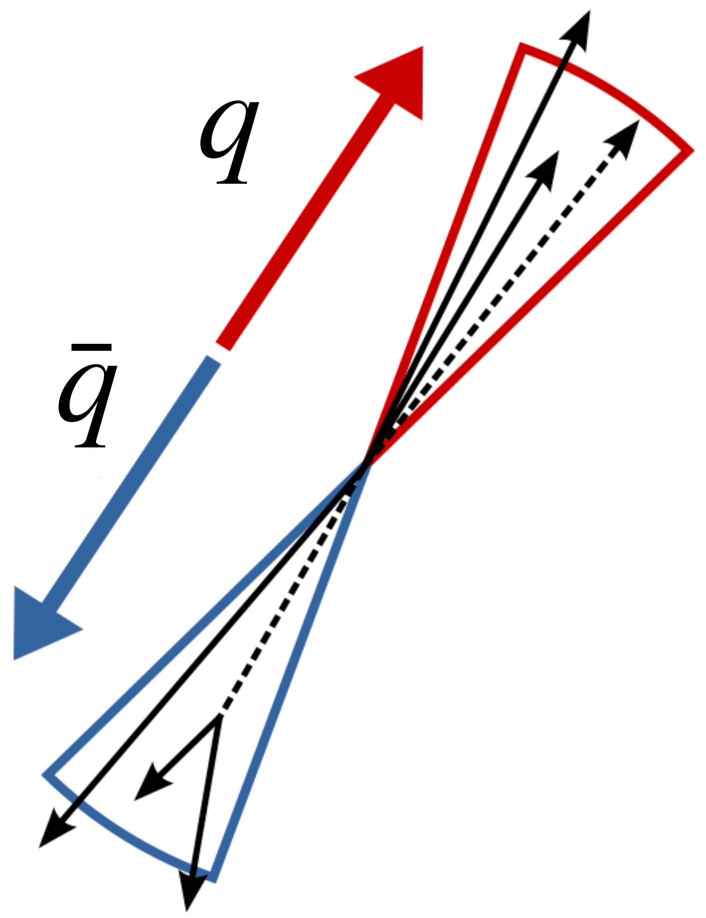
Reconstruct hadronic B_{tag} using FEI:

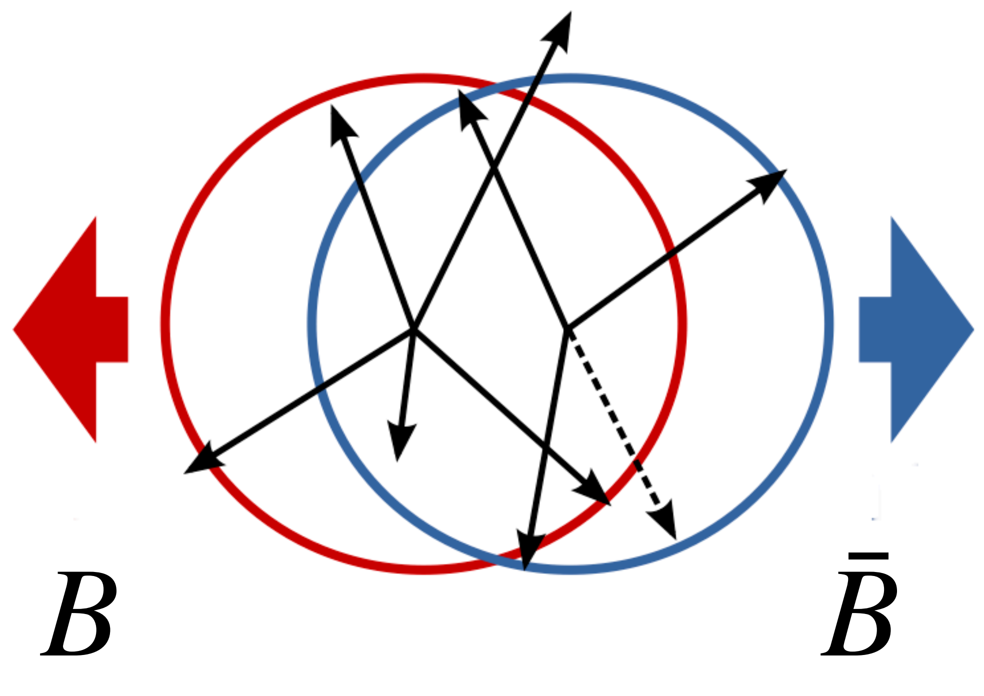
- Database prefix used for all weight files - 'FEIv4_2022_MC15_light-2205-abys'
- $M_{bc} > 5.27\,\mathrm{GeV/c^2}$
- $|\Delta E| < 0.1\,\mathrm{GeV}$
- FEI signal probability > 0.001

B_{tag} should be reconstructed properly

- Two most probable B_{tag} candidates are accepted.
- In the rest of event (ROE) of B_{tag}, only 3 tracks should remain to reconstruct B_{sig}.

Continuum suppression:





- event sphericity > 0.2
- $cos(\theta_{T_B,T_{ROE}}) < 0.9$

  $\theta_{T_B,T_{ROE}}$: angle between thrust axis of B_{tag} and thrust axis of its ROE

Selections

similar selections as
of the Belle analysis

Tracks (e, μ, K, π) selections to reconstruct B_{sig}:

Tracks should be originated near interaction point (IP)

- transverse distance from IP, $dr < 0.5$ cm
- distance in beam direction from IP, $|dz| < 2$ cm
- polar angle is with in CDC acceptance (thetaInCDCAcceptance)

Particle ID selections

- Kaon binary PID, $\mathscr{L}(K/\pi) > 0.6$
- Electron PID, $\mathscr{L}(e) > 0.9$
- Muon PID, $\mathscr{L}(\mu) > 0.9$
- Pion binary PID, $\mathscr{L}(\pi/K) > 0.6$

Global tag:

- analysis_tools_light-2205-abys

Selections

similar selections as
of the Belle analysis

Cluster selections to reconstruct π^0 from 2γ in the ROE of $\Upsilon(4S)$

Remove clusters' energy depositions from
beam-backgrounds, hadronic split-offs, etc.

- clusterNHits > 1.5
- $E > 0.080\,\mathrm{GeV}$ (forward)
  $E > 0.030\,\mathrm{GeV}$ (barrel)
  $E > 0.060\,\mathrm{GeV}$ (backward)

Mass window of π^0 in ROE:

- Cut on ROE π^0: $120 < \mathrm{M} < 150\,\mathrm{MeV/c^2}$
- Select one π^0 per event that has the nearest invariant mass to the PDG mass.

- distance between ECl cluster and nearest track hitting the ECL, minC2TDist > 20 cm
- $|\text{cluster time}| < 200$ ns
- $\left|\dfrac{\text{cluster time}}{\text{cluster error timing}}\right| < 2.0$

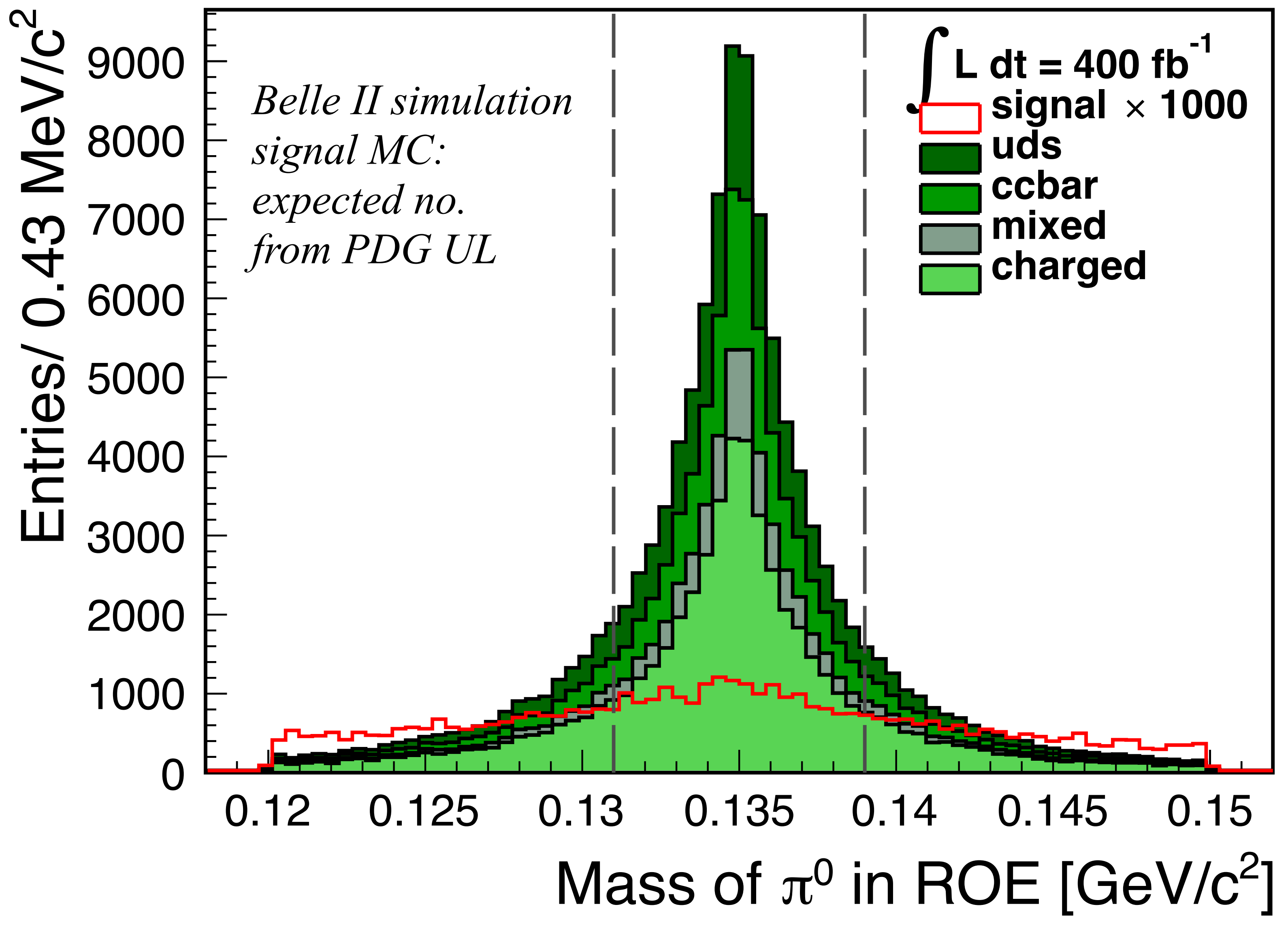
recommended
by neutral group

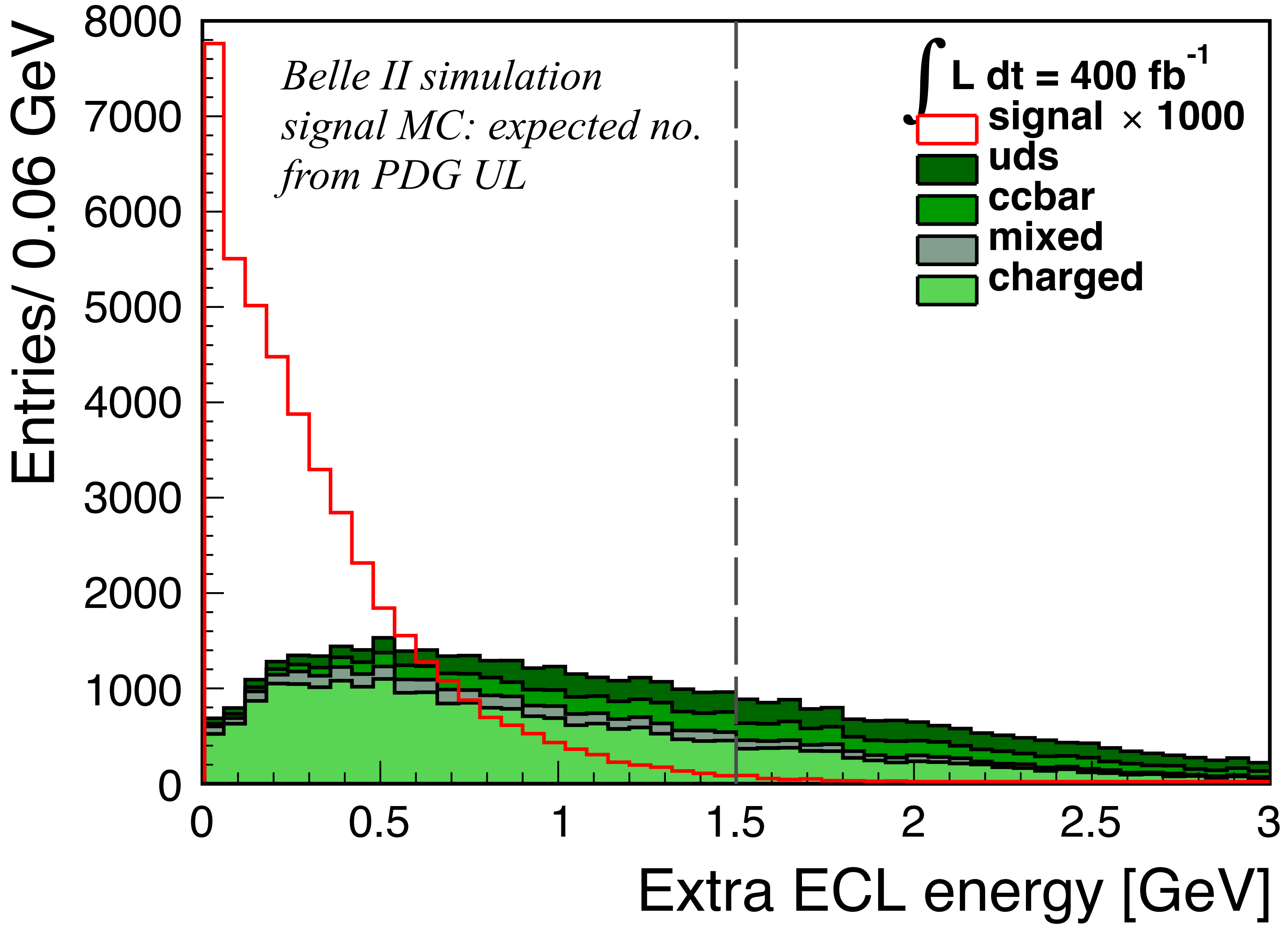
Best candidate selection

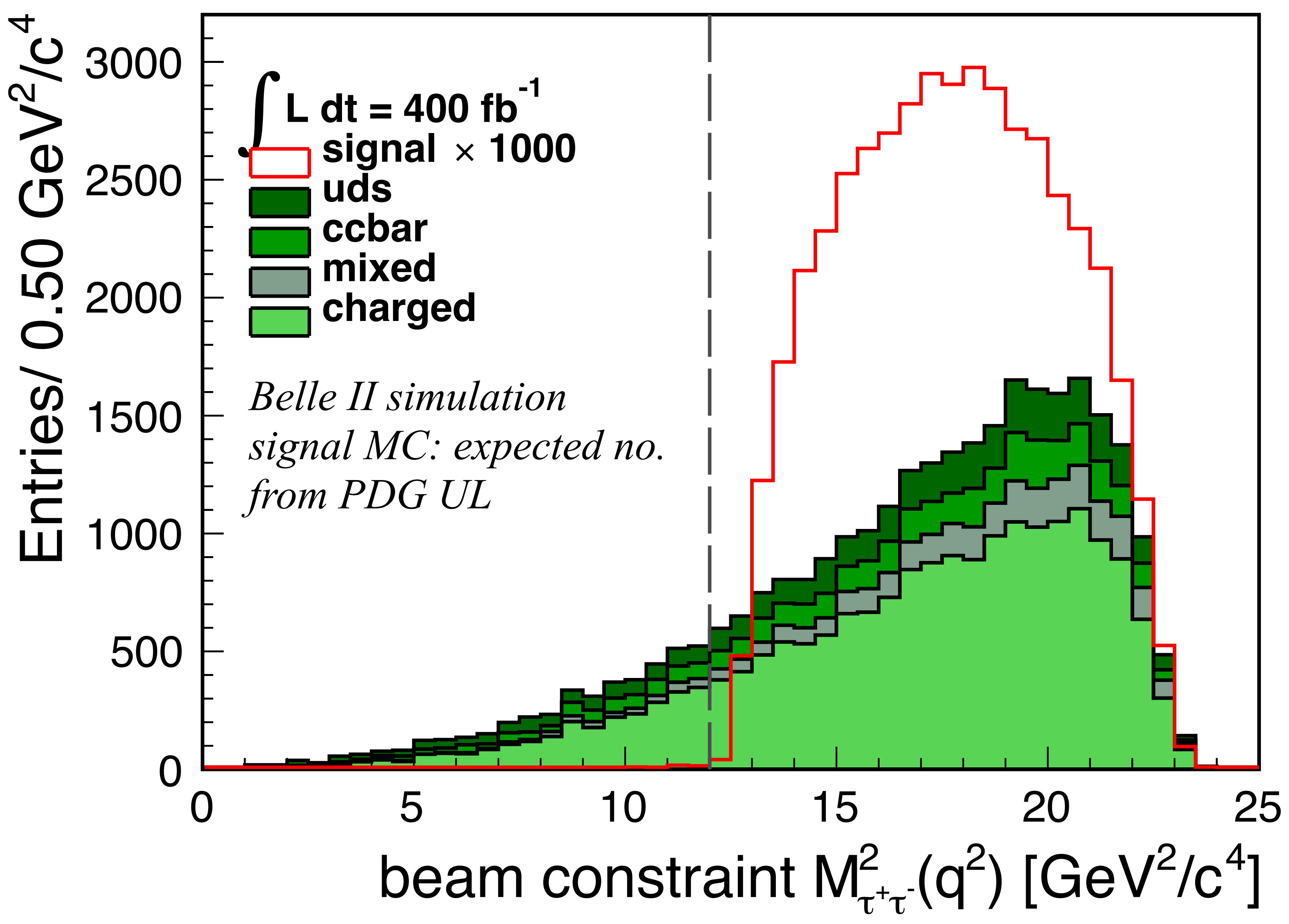
- Select B_{tag} candidate with the highest FEI signal probability.
- Pick one candidate at random
  if there still exists multiple events.

Pre-selections

similar selections as
of the Belle analysis







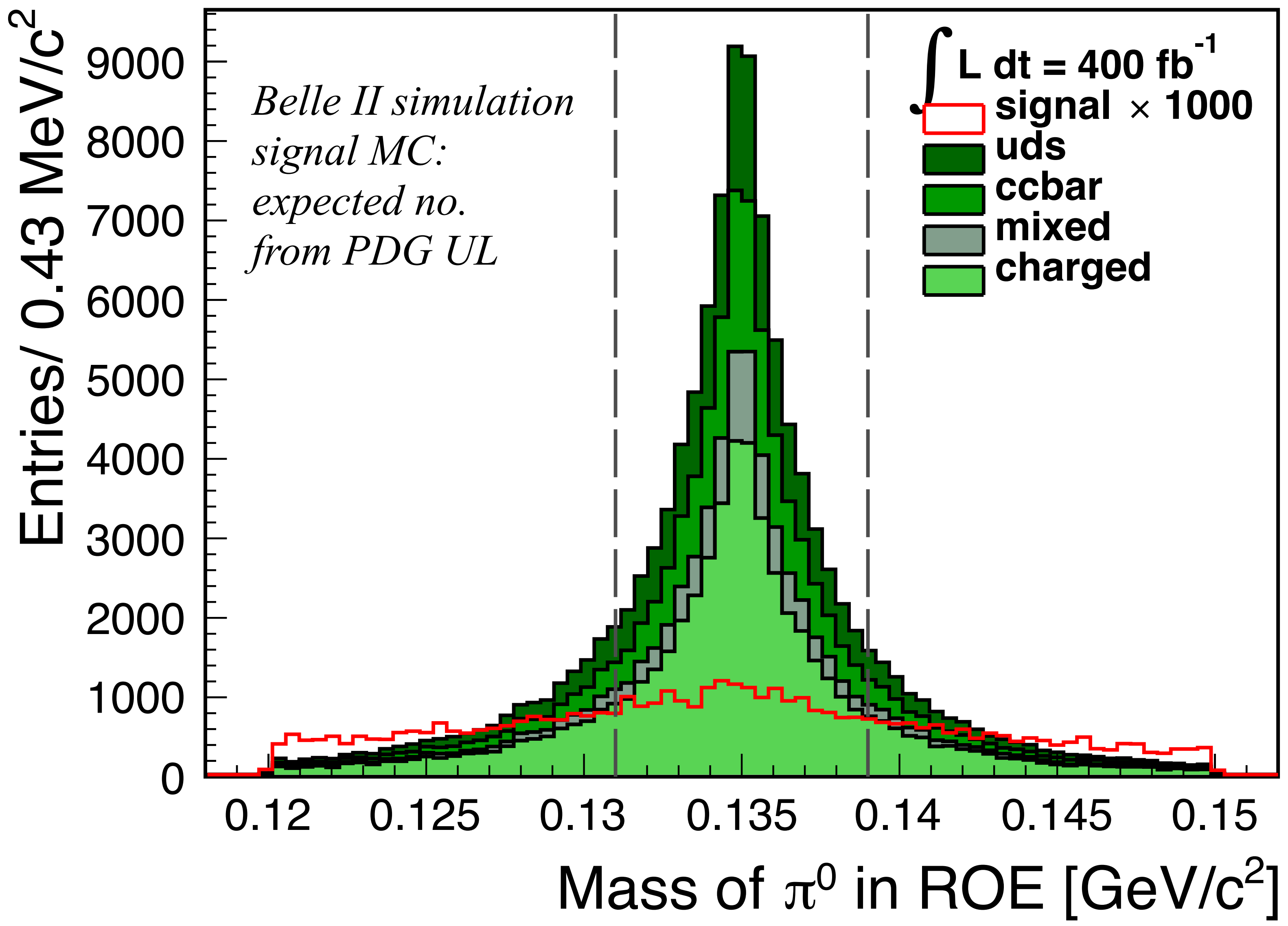
- π^0 is not expected in the rest of event of $\Upsilon(4S)$
- π^0 veto: remove $0.131 < \mathrm{M}_{\pi^0} < 0.139\,\mathrm{GeV/c^2}$

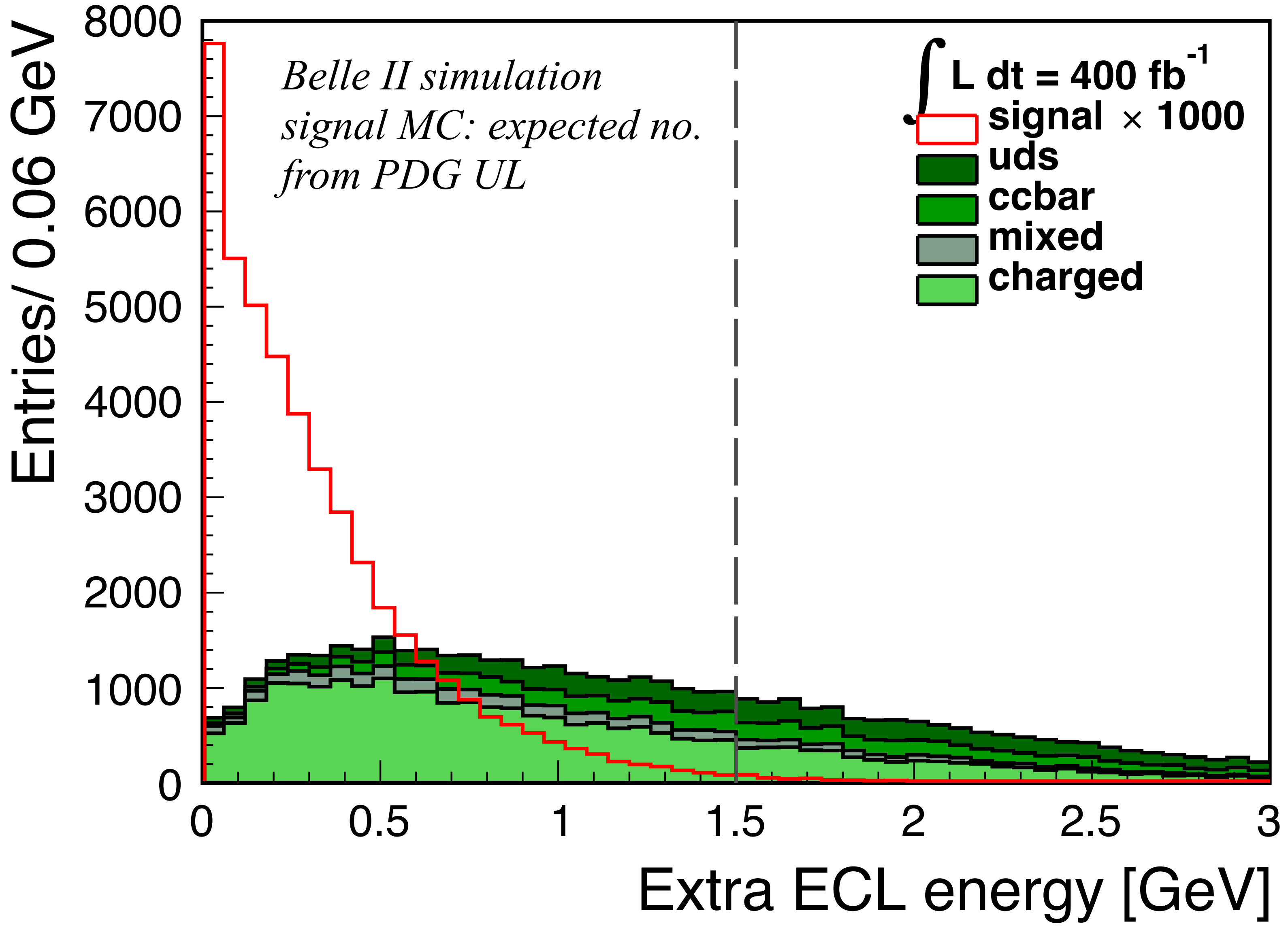
- Residual energy of ECL clusters which are neither used in B_{tag} or B_{sig} reconstructions should ideally be zero for the signal
- Cut: $E_{\mathrm{ECL}} < 1.5\,\mathrm{GeV}$

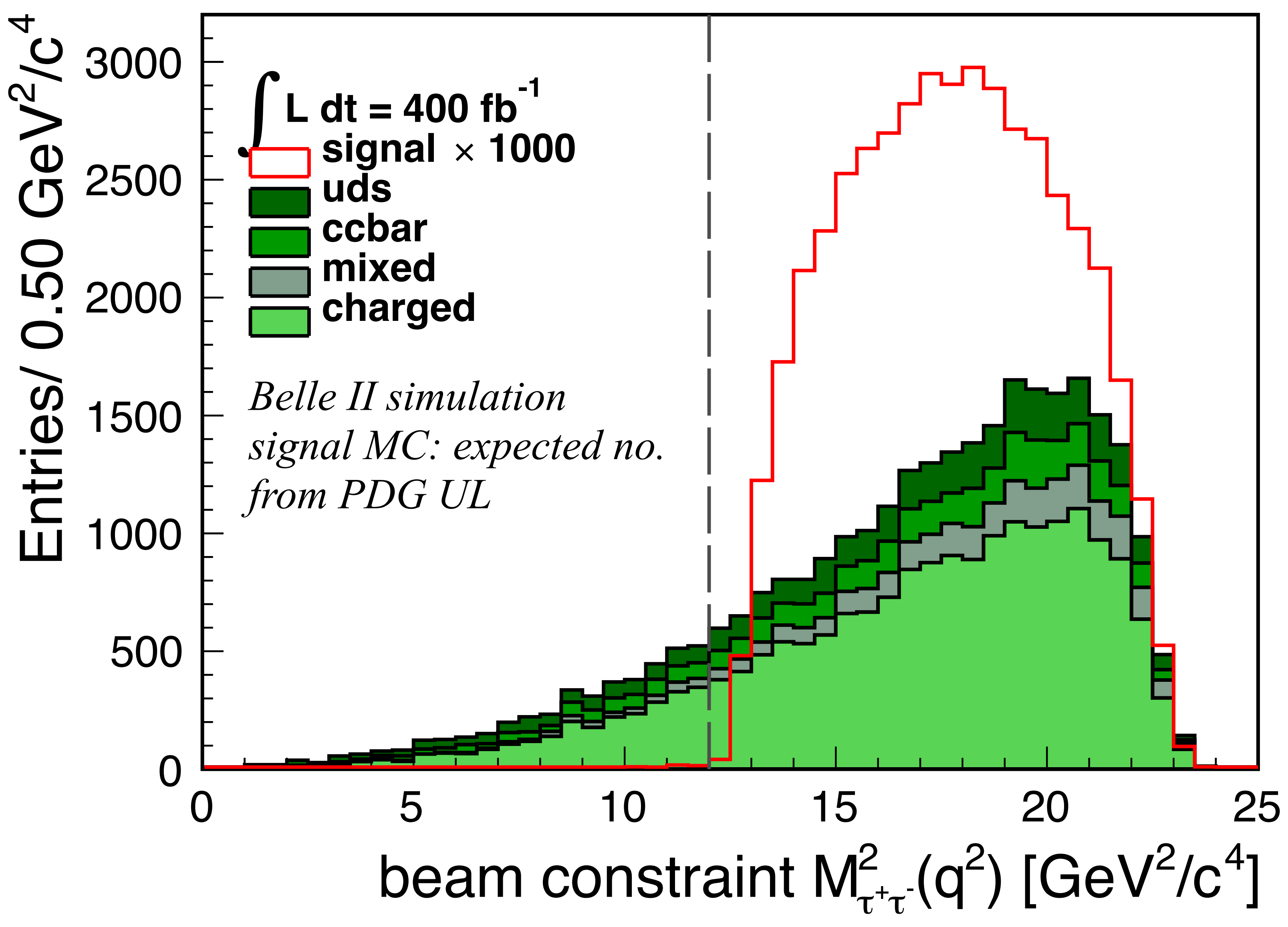
- Beam constrained squared mass of τ pair (q^2) is calculated by $q^2 = (p_{\mathrm{beam}} - p_{B_{tag}} - p_K)^2$ where p_i is the four momenta
- $q^2 > 12\,\mathrm{GeV^2/c^4}$ will remove $J/\psi \to \ell^+\ell^-$ contributions

Pre-selections

similar selections as
of the Belle analysis







Cut-flow table

$q^2 \equiv (p_{\Upsilon(4S)} - p_{B_{tag}} - p_K)^2$

Cuts	Loss in signal (TM)	Loss in signal	Loss in background
Remove $0.131 < M_{\pi^0} < 0.139$ GeV/c^2	12.09%	37.64%*	65.15%
Extra ECL energy < 1.5 GeV	0.91%	7.66%	33.07%
$q^2 > 12$ GeV^2/c^4	0.14%	0.13%	14.99%

#TM: truth matched

* SignalMC is generated with generic τ decays where $\mathscr{B}(\tau^- \to \pi^+\pi^0\nu_\tau) = 25.49\,\%$

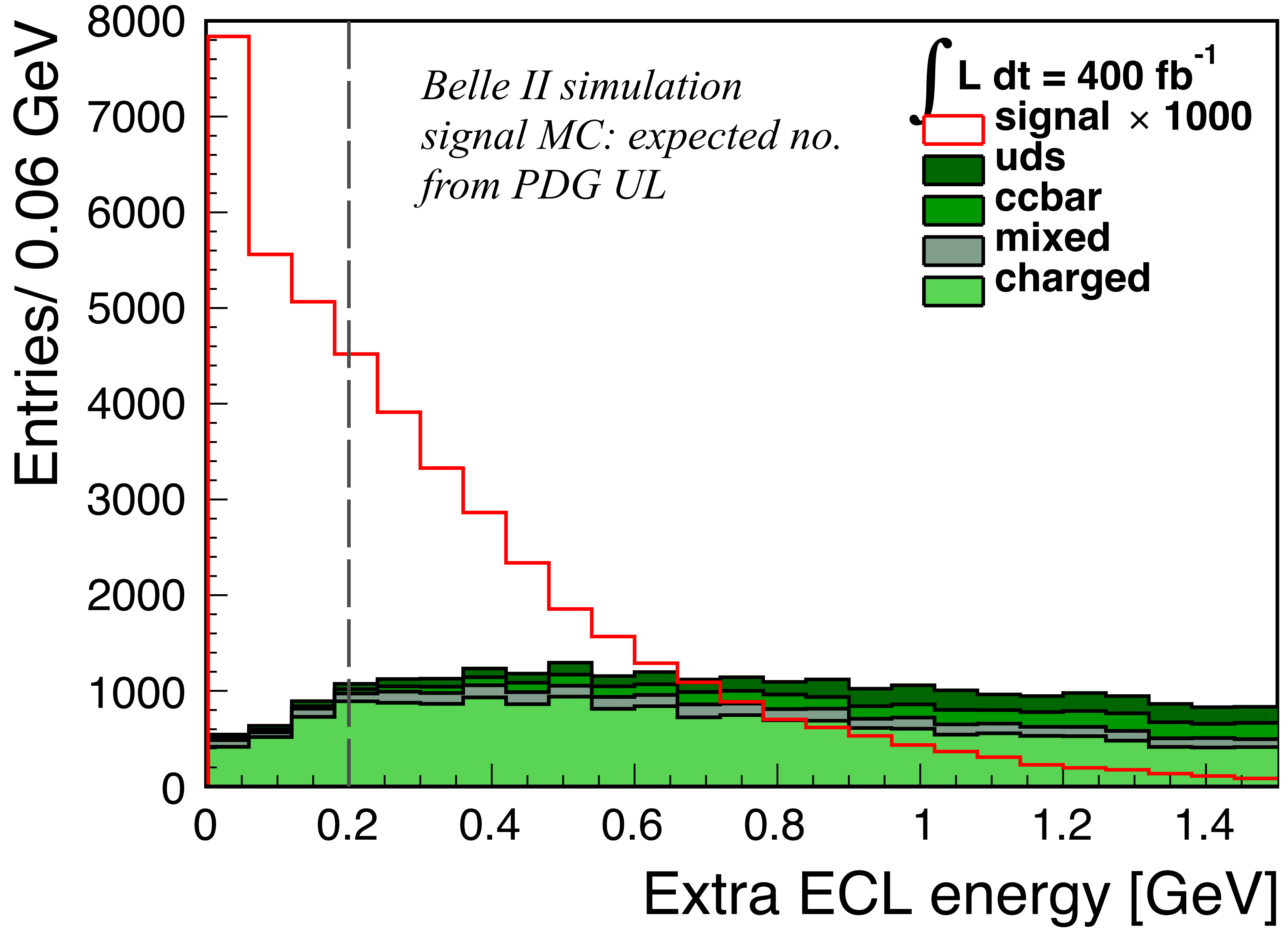
Signal efficiency

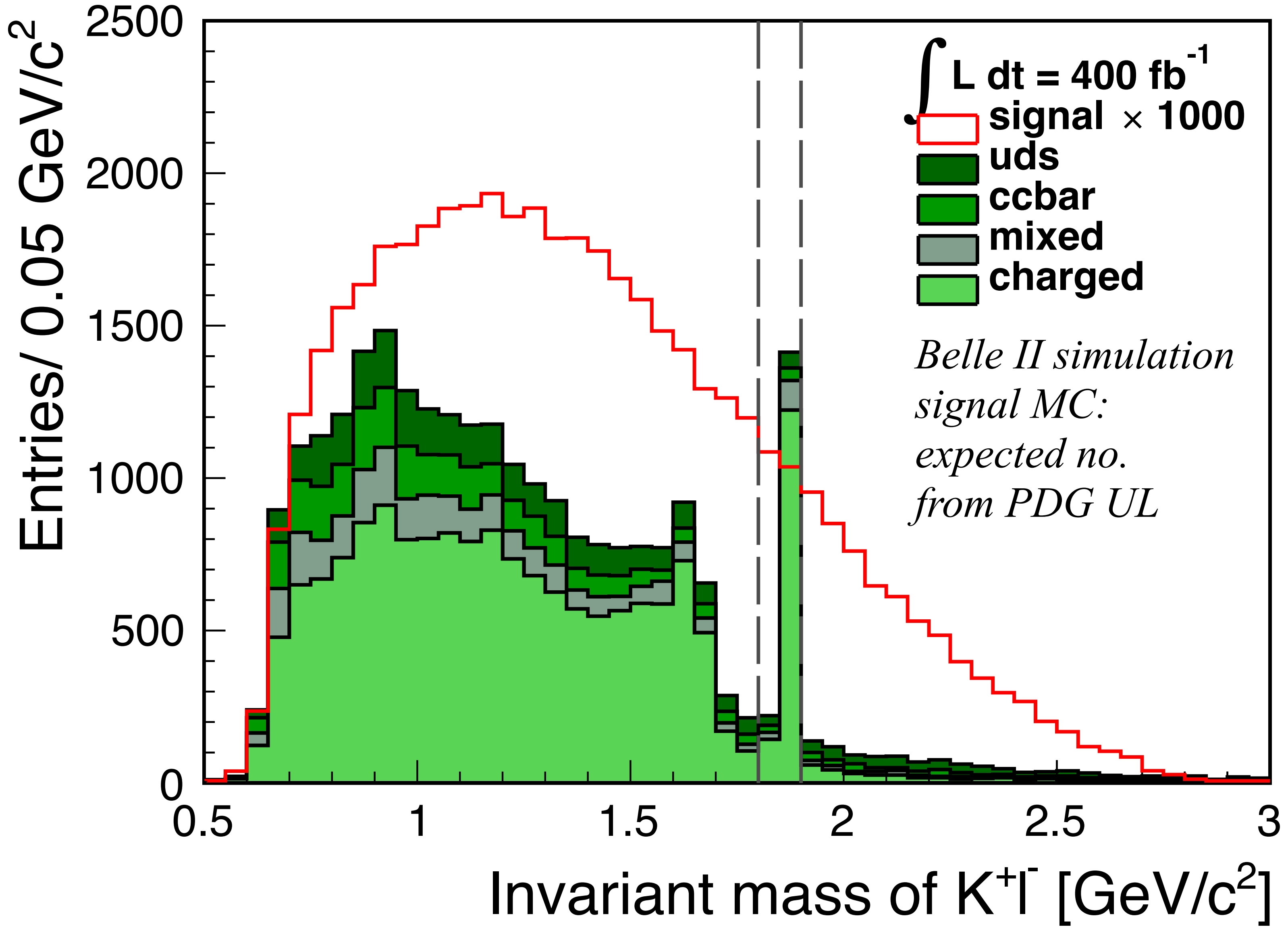
similar selections as of the Belle analysis

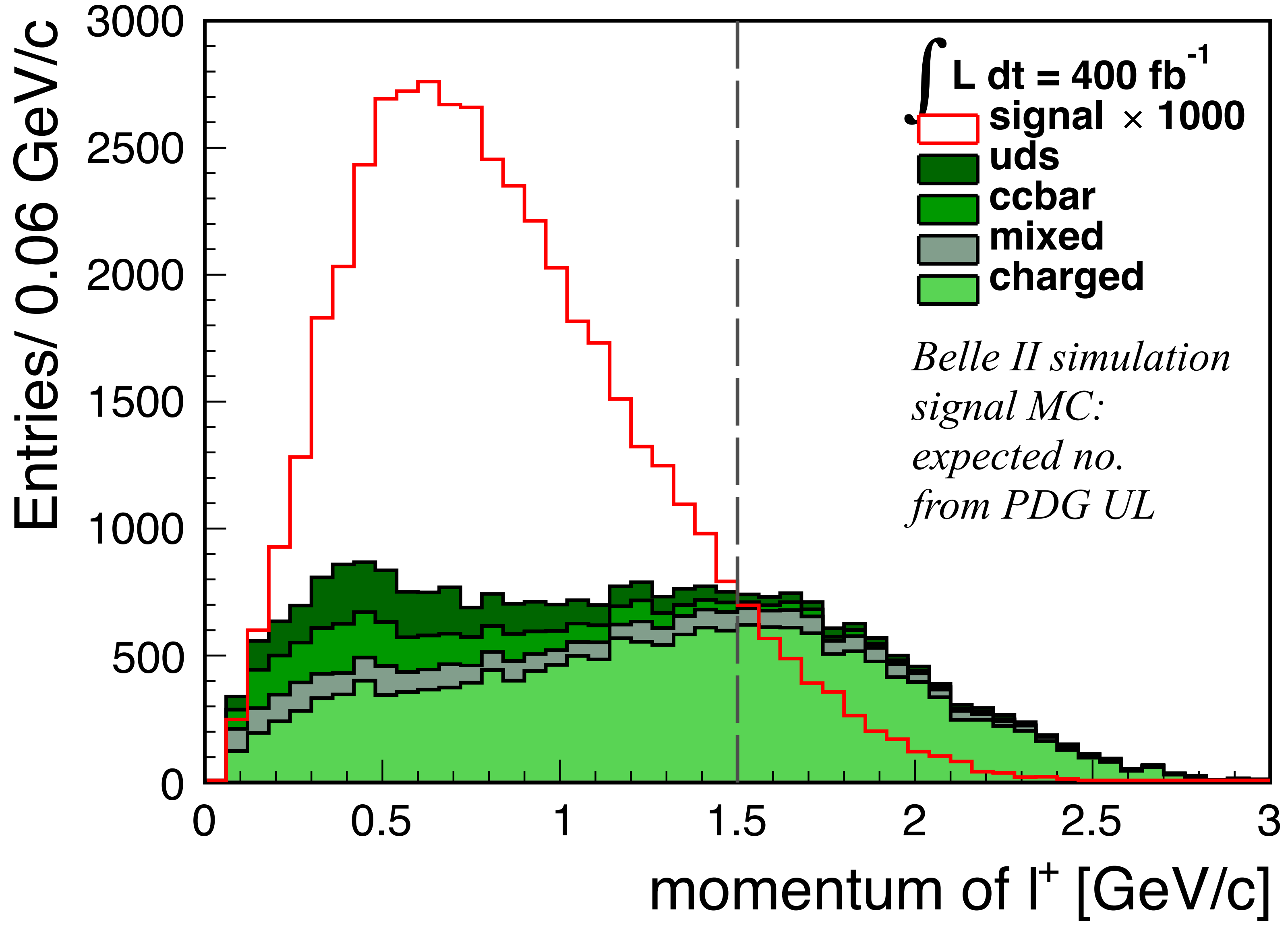
- With some additional selections:
  - Extra ECL energy $< 0.2\,\mathrm{GeV}$
  - $1.8 < M(K^+\ell^-) < 1.9\,\mathrm{GeV/c^2}$ (D meson veto)
  - Momentum, $p_{\ell^+} < 1.5\,\mathrm{GeV/c}$ (remove ℓ that are directly decaying from B mesons, where $\ell \in \{e, \mu, \pi\}$)

- signal efficiency (TM) $= 2.78 \times 10^{-4}$
- signal efficiency $= 5.00 \times 10^{-4}$

* signal efficiency will increase when we will generate SignalMC with our specific τ channels

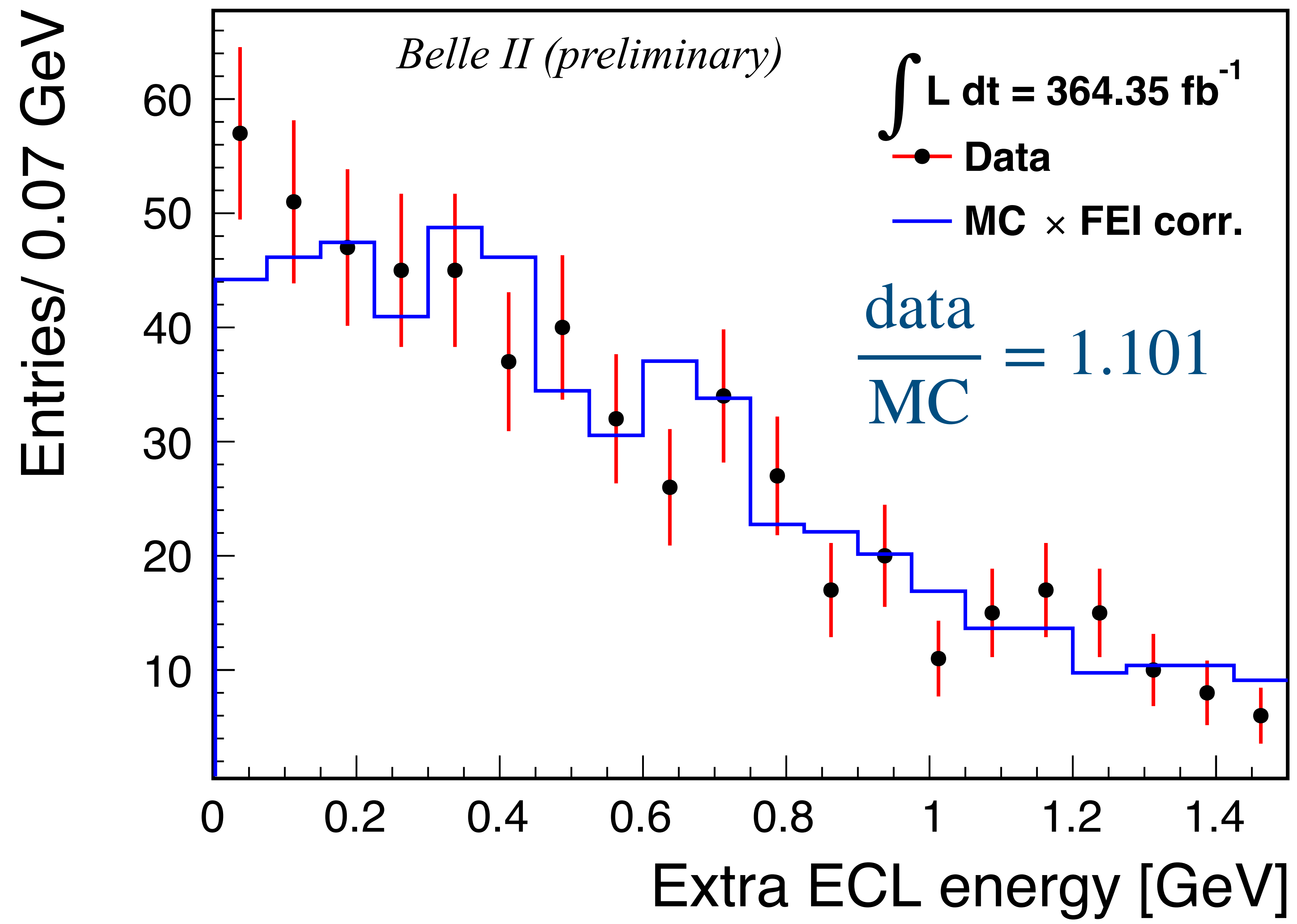


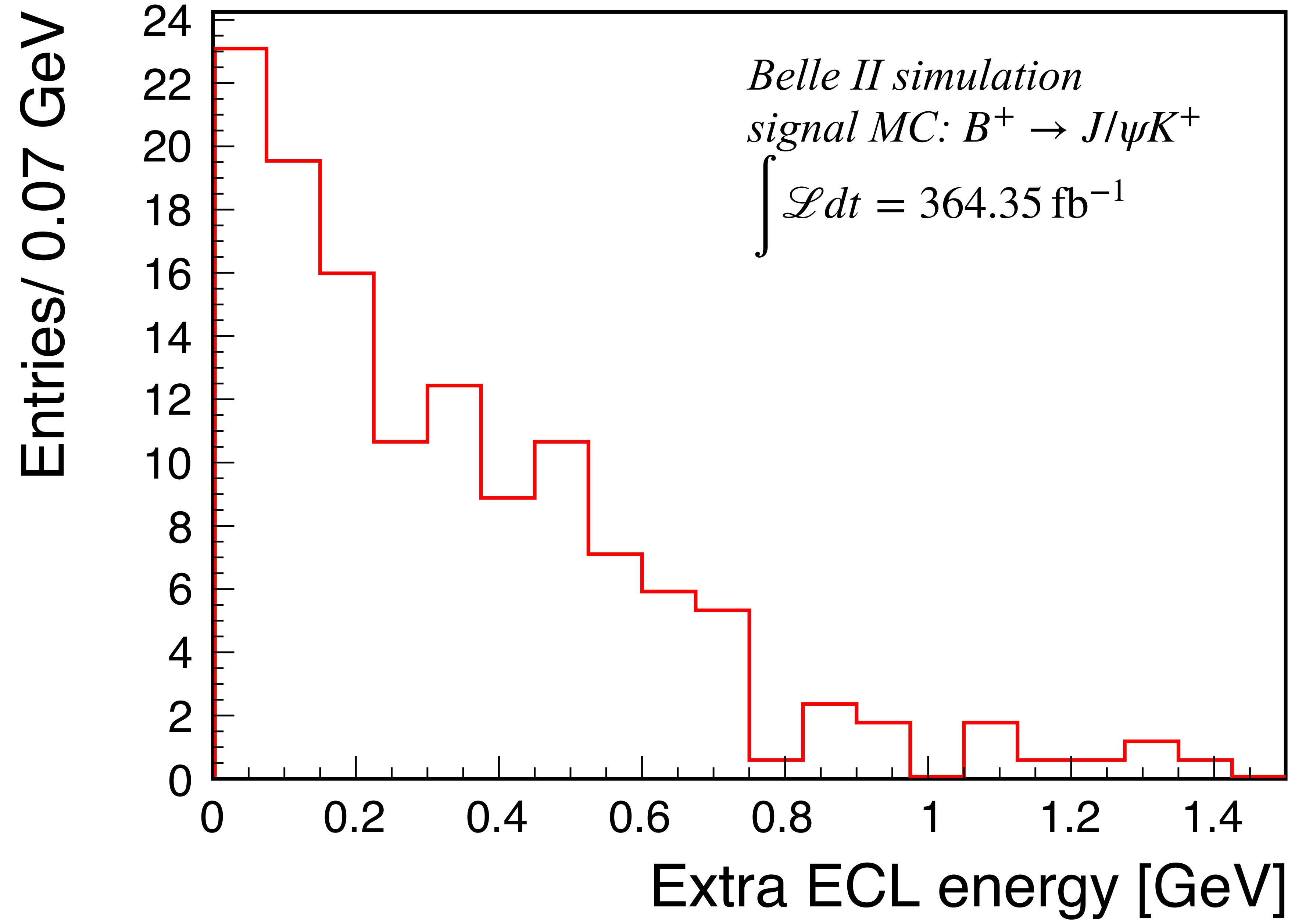




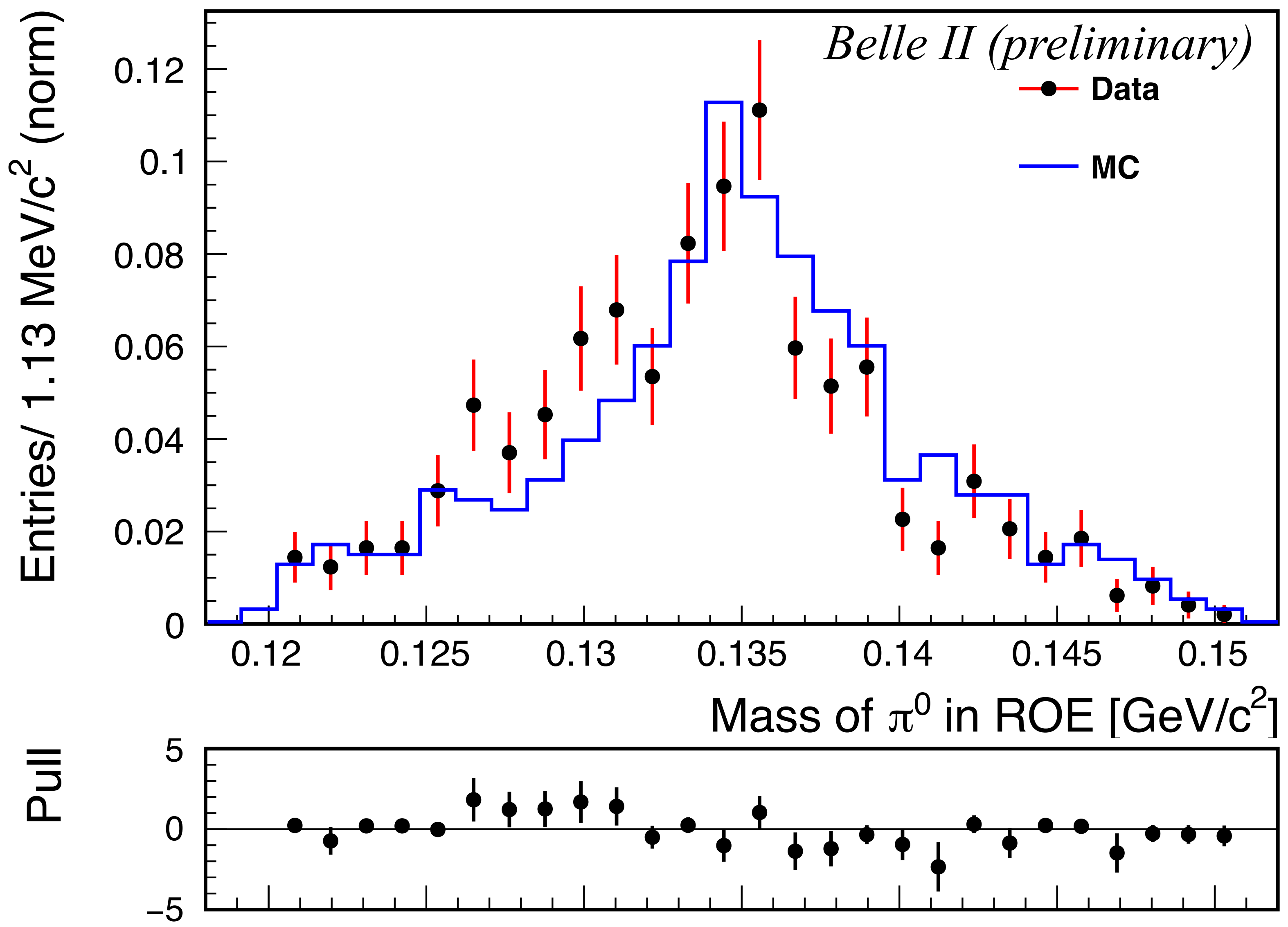
Control channel: $B^+ \to J/\psi K^+$

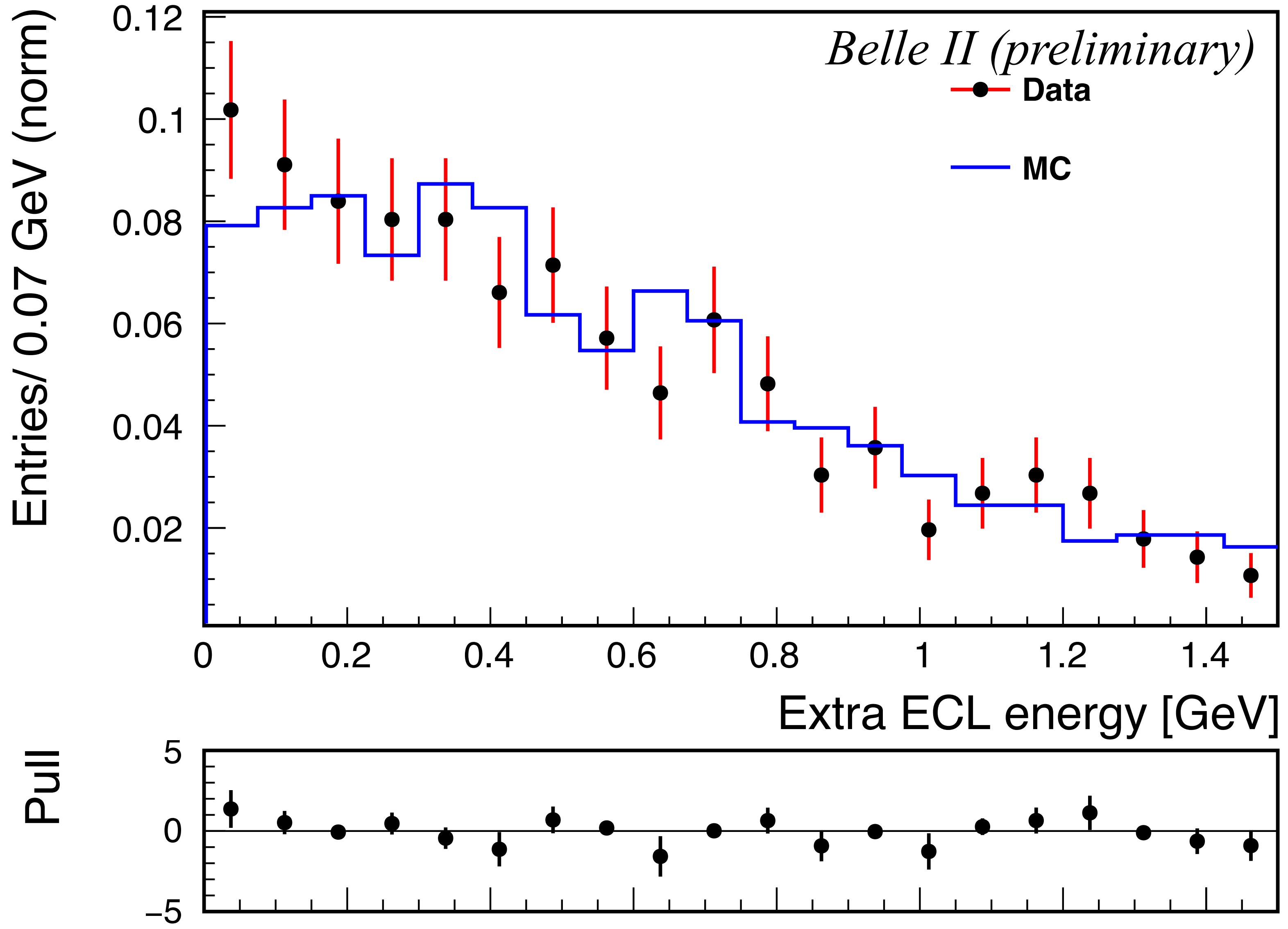
- Control sample with same or equivalent final states: verification of efficiency, data-MC agreement check, validation of the BDT training, etc.
- In the final state, it must have three tracks: K and oppositely charged pair combinations of e, μ, π.
- Look at $B^+ \to J/\psi K^+$ decays using hadronic tagging where $J/\psi \to \ell^+\ell^- (\ell = e, \mu)$
- Reconstruct with same selections as in case of $B^+ \to K^+\tau^+\tau^-$, except the invariant mass of leptons pair cut: $2.90 < M(\ell^+\ell^-) < 3.15$ Gev/c^2
- After π^0 veto, extra ECL energy < 1.5 GeV, and scaling with FEI correction (0.65) on MC, number of TM signal events in MC ($\mathscr{L} = 364.35\,\mathrm{fb}^{-1}$) is 129.

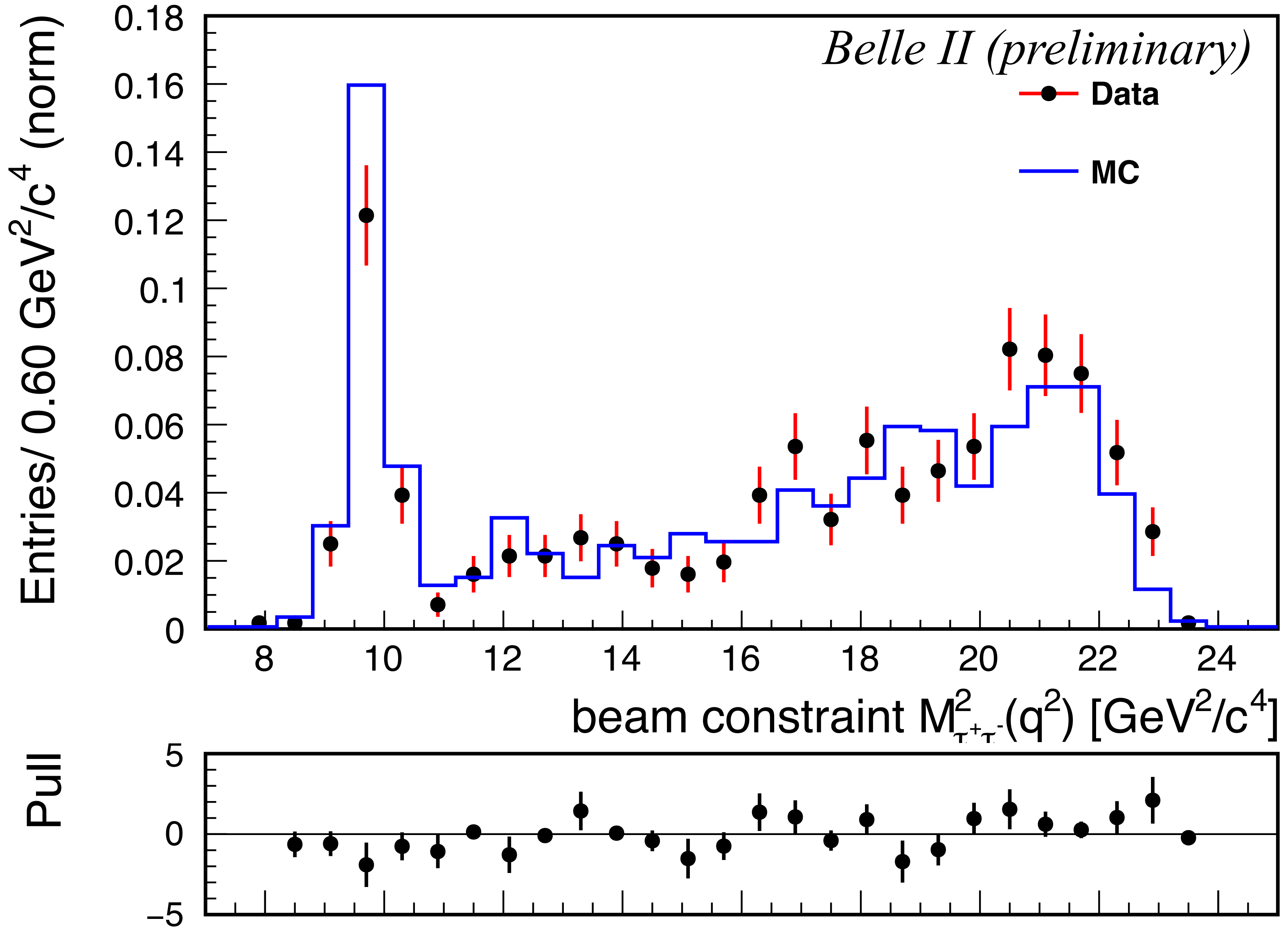


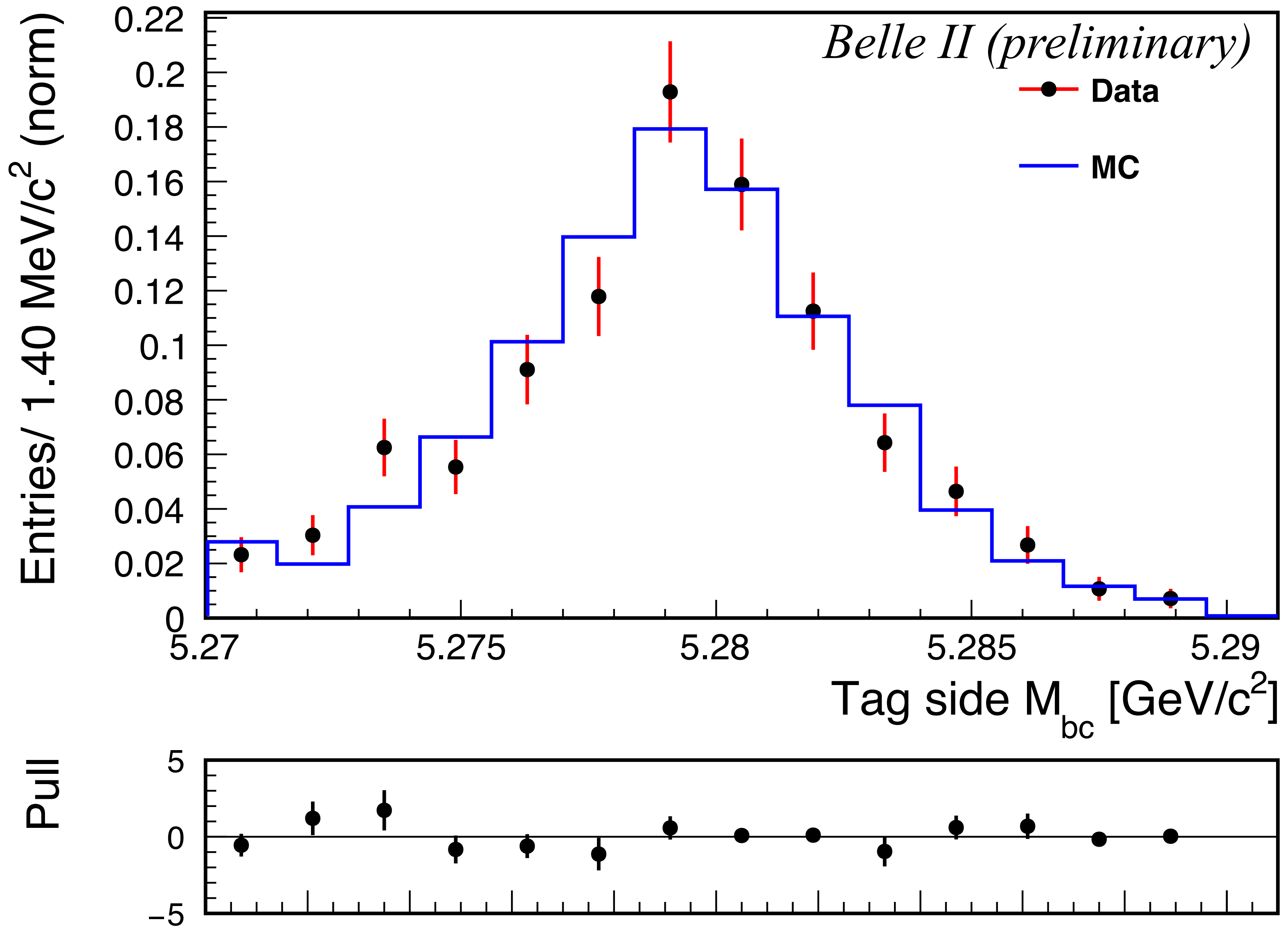


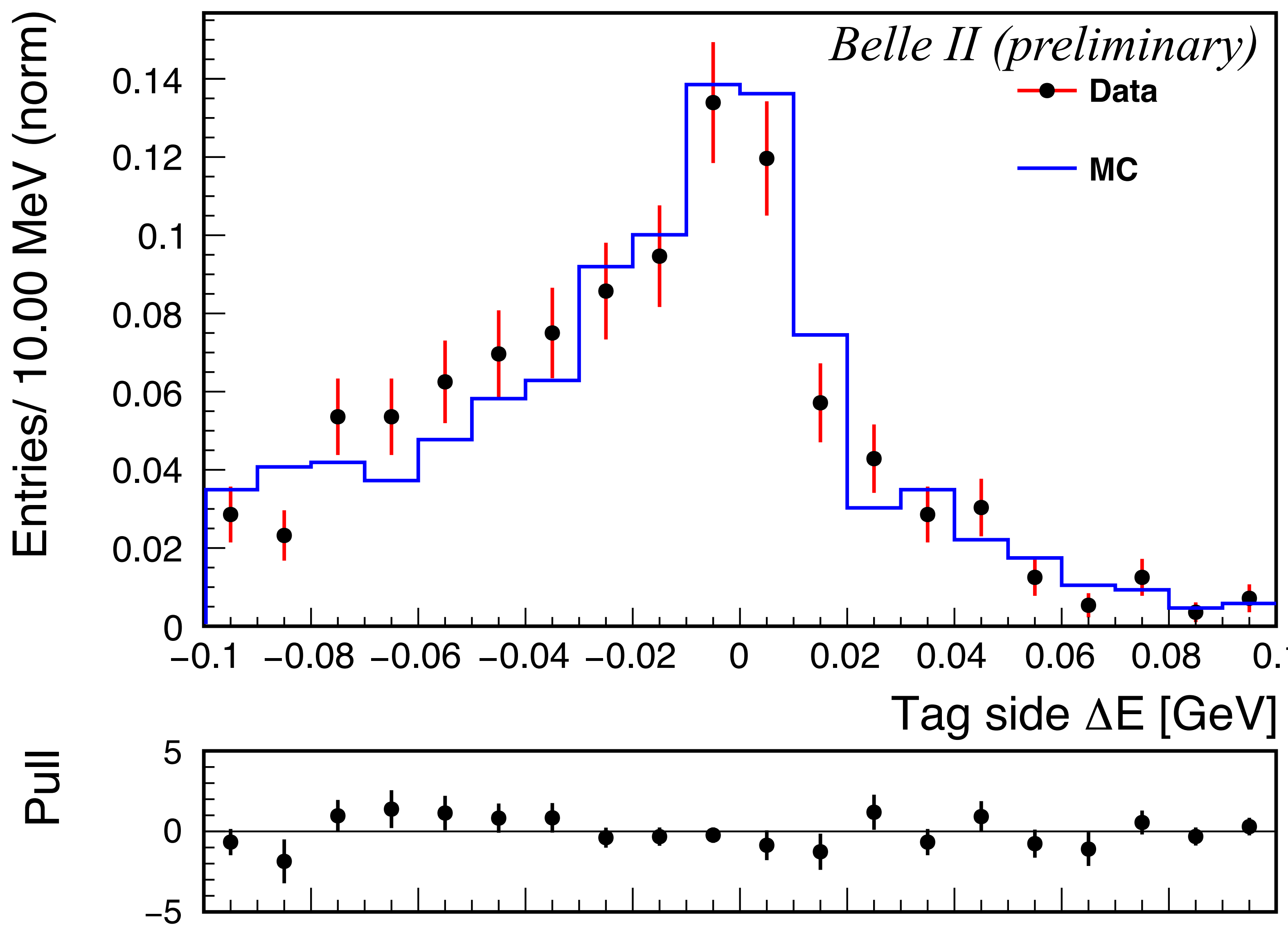
$B^+ \to J/\psi K^+$: data/MC comparison











Good agreement between data and MC among some pre-selections variables

Summary

- Started working on $B^+ \to K^+\tau^+\tau^-$ to do a combined Belle + Belle II analysis.
- Reconstructed $B^+ \to K^+\tau^+\tau^-$ using hadronic tagging and get a rough estimation of the signal efficiency.
- Studied the control sample, $B^+ \to J/\psi K^+$, and found it has small expected number of events in $\mathscr{L} = 364.35\ \mathrm{fb}^{-1}$.

Future work

- For larger statistics, move to other control samples like $B^+ \to \bar{D}^0\rho^+$, $B^+ \to \bar{D}^0\ell^+\nu_\ell$, or aggregation of $B^+ \to J/\psi K^+$ samples with different B_{tag} decay modes.
- BDT inputs: search for variables that have large signal-background separation power.
- Study data/MC agreement of these variables in control sample.

Thank you