Study of extra ECL energy in $B^+ \rightarrow \bar{D}^0 l^+ \bar{\nu}_l$ decays

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(S)L/ EWP mini-workshop
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**E\textsubscript{ECL}** importance in $B^+ \rightarrow K^+\tau^+\tau^-$

- Extra ECL energy ($E\textsubscript{ECL}$) is the residual energy left in calorimeter after reconstructing hadronic tagged $B$ meson ($B\textsubscript{tag}$) and signal $B$ meson ($B\textsubscript{sig}$).

- $E\textsubscript{ECL}$ is the signal extraction variable: spot the signal as a peak at zero in $E\textsubscript{ECL}$.

- Control sample, $B^+ \rightarrow \bar{D}^0 l^+\bar{\nu}_l (\bar{D}^0 \rightarrow K^+\pi^-)$, is used to check data/MC comparison as it has three tracks in the final states (similar to signal).

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**Diagram Description**

- **Hadronic Tag Side**
  - $B^-$
  - $K^-$
  - $D^0$
  - $\pi^+$
  - $\pi^-$

- **Signal Side**
  - $e^-$
  - $\gamma(4S)$
  - $e^+$
  - $B^+$
  - $K^+$
  - $\nu_\tau$
  - $\tau^-$
  - $\nu_\mu$
  - $\mu^-$
  - $e^+$
  - $\nu_e$

**Graph**

- **Legend**
  - Belle II simulation
  - Signal MC: expected no. from PDG UL
  - $L dt = 400 \text{ fb}^{-1}$
  - Charged
  - Mixed
  - Ccbar
  - Uds

- **Plot**
  - X-axis: Extra ECL energy [GeV]
  - Y-axis: Candidates per 0.06 GeV
  - $B^+ \rightarrow K^+\tau^+\tau^-$
Samples and selections

- Data: Proc 13 + Moriond 23 prompt ($\mathcal{L} = 362 \, fb^{-1}$)
- Simulation: MC15 run dependent ($4 \times \mathcal{L}$)
- Release: light-2212-foldex

Reconstruct hadronic $B_{\text{tag}}$ using FEI:

- Weight files-
  ‘FEIv4_2022_MC15_light-2205-abys’
- $M_{bc} > 5.27 \, \text{GeV}/c^2$; $|\Delta E| < 0.1 \, \text{GeV}$
- FEI signal probability > 0.001
- Best probable $B_{\text{tag}}$ candidates is accepted

Continuum suppression

- event sphericity > 0.2
- $\cos(\text{Trust}(B_{\text{tag}}), \text{Trust(ROE})) < 0.9$

 photon energy bias correction is applied on data

Rest of $B_{\text{tag}}$ selection:

- only 3 tracks should remain to reconstruct $B_{\text{sig}}$.
- $dr < 0.5 \, \text{cm}; |dz| < 2 \, \text{cm}; \theta_{\text{InCDA}}$
- Cluster energy > 55 MeV (to avoid the interplay of the variable $|\frac{\text{cluster timing}}{\text{cluster error}}|$)

Reconstruct $B_{\text{sig}} \rightarrow \bar{D}^0 l^+\bar{v}_l; \bar{D}^0 \rightarrow K^+\pi^-$:

- Kaon binary PID, $\mathcal{L}(K/\pi) > 0.6$
- Electron PID, $\mathcal{L}(e) > 0.9$
- Muon PID, $\mathcal{L}(\mu) > 0.9$
- Pion binary PID, $\mathcal{L}(\pi/K) > 0.6$
- $1.84 < m(K^+\pi^-) < 1.89 \, \text{GeV}/c^2$
- Shows large data/MC discrepancy
- Needs to investigate gamma level properties which contribute to this distribution.
- $E_{ECL}$ is the sum of all photons energy per event: depends on photon energy, $E(\gamma)$, and photon multiplicity, $N(\gamma)$
**Photon energy $E(\gamma)$ and multiplicity $N(\gamma)$**

- $E_{ECL}$ discrepancy comes from both $E(\gamma)$ and $N(\gamma)$ data/MC discrepancies
- These may originate from certain types of photon: real photons, fake photons or beam-backgrounds photons
- Study each photon type separately to get better understanding of these discrepancies
Isolating pure samples

Fake photon dominated

Beam-background dominated

Selections:
- $E > 55$ MeV
- minimum cluster to track distance <20 cm

Unable to find a real photon enriched sample. Need to study in other channel containing $\pi^0$: $B^+ \to \bar{D}^*(0\bar{D}^0\pi^0)\pi^-$, $B^+ \to J/\psi K^*(0K^+\pi^0)$

MC and data are normalised to same luminosity in these plots
**Fake photon**

- Both fake and beam-background photons have $E_{ECL}$ data/MC disagreement

**Beam-background**

- Check how $E(\gamma)$ and $N(\gamma)$ contribute to $E_{ECL}$ mismodeling

Normalized candidates per 30 MeV

Neutral extra ECL energy [GeV]

Normalized to unit area

Neutral extra ECL energy [GeV]
Photon energy $E(\gamma)$

Fake photon

Beam-background

Only fake photons has $E(\gamma)$ data/MC disagreement
Photon multiplicity $N(\gamma)$

Fake photon

Beam-background

Only beam-background photons has $N(\gamma)$ data/MC disagreement
Fix $E(\gamma)$ mismodeling: strategy

- $E(\gamma)$ discrepancy comes from fake photon: fixing fake photon energy should fix overall $E(\gamma)$ data/MC disagreement

- Method to find $E(\gamma)$ correction factor: perform $\chi^2$ minimization by optimizing the correction factors which modify fake photon energy in MC to get the best $E(\gamma)$ data/MC agreement

- Correction factor may vary with different photon energies: divide $E(\gamma)$ in bins and find corrections for each bin simultaneously

- Easy to calculate $E_{ECL}$ from the corrected photon energy
Fake photon $E(\gamma)$ correction

- Tried to find 10 correction factors for 10 different bins of $E(\gamma)$
- Fit doesn’t converge yet. However, parameters optimize towards the right direction: shows better data/MC agreement of $E(\gamma)$ in fake photon

\[ \chi^2_{\text{norm}} = 4.09 \]

\[ \chi^2_{\text{norm}} = 3.26 \]
Corrected $E(\gamma)$

- Data/MC agreement of $E(\gamma)$ of all photons improve after applying fake photon energy correction

\[
\chi^2_{\text{norm}} = 3.26
\]

\[
\chi^2_{\text{norm}} = 2.03
\]
\( E_{\text{ECL}} \) with corrected \( E(\gamma) \)

- Data/MC agreement of \( E_{\text{ECL}} \) slightly improves after applying \( E(\gamma) \) correction in the integrated MC sample

\[
\chi^2_{\text{norm}} = 3.03
\]

\[
\chi^2_{\text{norm}} = 1.95
\]

- Need to correct beam-background photon multiplicity to fix \( E_{\text{ECL}} \) mismodeling completely
Next steps

• Fix the $\chi^2$ minimization fitter and validate the correction factors in other control channels: $B^+ \rightarrow \bar{D}^0 \pi^+, B^+ \rightarrow J/\psi K^+$.

• Perform a similar study to get correction factor of N($\gamma$) from beam-background sample.

• Find a real photon sample in $B^+ \rightarrow \bar{D}^* (\bar{D}^0 \pi^0) \pi^-$ or $B^+ \rightarrow J/\psi K^{*+} (K^+ \pi^0)$ channel and study E($\gamma$) and N($\gamma$) data/MC comparison

• Check other $\gamma$ properties such as cluster timing, clusterNhits etc
Summary

• $E_{ECL}$ is important for most of the missing energy analyses.

• Studied data/MC comparison of photon energy and multiplicity to understand better $E_{ECL}$ discrepancy using $B^+ \rightarrow \bar{D}^0 l^+ \bar{\nu}_l$ channel.

• The fake-photon shows data/MC discrepancy in photon energy and beam-background photons shows discrepancy in photon multiplicity.

• Correction of fake photon energy slightly improves $E_{ECL}$ data/MC agreement.

• Correction of beam-background photon multiplicity is required to fix $E_{ECL}$ mismodeling completely.
Backup
Reason of $E(\gamma) > 55$ MeV selection

without any selection

Low energy photon ($E(\gamma) < 50$ MeV) has cluster time ratio selections:

- $\frac{\text{cluster timing}}{\text{cluster error timing}} < 1$

- $\frac{\text{cluster timing}}{\text{cluster error timing}} \geq 1$

Data $\quad$ MC

Normalized candidates per 30 MeV

Normalized to unit area

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Data $\quad$ MC

Normalized candidates per 30 MeV

Normalized to unit area
Definition of photon types

- Following definitions are taken from this post: https://questions.belle2.org/question/11685/how-can-i-identify-merged-pi0s-and-beam-background-clusters-in-mc/

- Real photon: $\text{mcPDG}=22$ and $\frac{\text{clusterTotalMCMatchWeight}}{\text{clusterE}} > 0$

- Fake photon: $\text{mcPDG} \neq 22$ and $\frac{\text{clusterTotalMCMatchWeight}}{\text{clusterE}} > 0$

- Beam background: $\frac{\text{clusterTotalMCMatchWeight}}{\text{clusterE}} = 0$
Polar angle and minC2TDist

MC is scaled by FEI correction factor
- charged: 0.65
- mixed: 0.65
- $q\bar{q}$: 0.86
$E(\gamma)$ vs $N(\gamma)$

 normalized to unit area

- $1 \leq N(\gamma) < 4$
- $4 \leq N(\gamma) < 7$
- $7 \leq N(\gamma) < 10$
- $10 \leq N(\gamma)$
$E_{\text{ECL}}$: $\gamma$ selections

selection: $E(\text{fwd, brl, bkwd}) > (80,55,60)$MeV

![Graph 1: Normalized Data and MC for no minC2TDist selection](image1)

![Graph 2: Normalized Data and MC for minC2TDist>30](image2)
$E_{\text{ECL}}$: $\gamma$ selections

selection: $E(\text{fwd, brl, bkwd}) > (80,55,60) \text{MeV}$
**$E_{\text{ECL}}$: $\gamma$ selections**

Common selection: $E(\text{fwd}, \text{brl}, \text{bkwd}) > (80,55,60)$ MeV

- $\text{minC2TDist}>30$
- $\text{clusterNHits}>1.5$
- $|\text{clusterTime}|<200$

### Data vs. MC

- **Data**
- **MC**

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### Normalized Data vs. MC

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$N(\gamma)$ vs $D^0$ FEI mode

\[ \bar{D}^0\pi^+ \]

\[ \bar{D}^0\pi^+\pi^0 \]

\[ \bar{D}^0\pi^+\pi^0\pi^0 \]

\[ \bar{D}^0\pi^+\pi^+\pi^- \]

\[ \bar{D}^0\pi^+\pi^+\pi^-\pi^0 \]
$N(\gamma)$ vs $D^*$ FEI mode

\[ \bar{D}^*0\pi^+ \]
\[ \bar{D}^*0\pi^+\pi^0 \]
\[ \bar{D}^*0\pi^+\pi^+\pi^- \]
\[ \bar{D}^*0\pi^+\pi^+\pi^-\pi^0 \]
$N(\gamma)$ vs $D^-$ FEI mode

$D^-\pi^+\pi^+$

$D^-\pi^+\pi^+\pi^0$

![Graph showing $N(\gamma)$ vs $D^-$ FEI mode for $D^-\pi^+\pi^+$ and $D^-\pi^+\pi^+\pi^0$.](image-url)
Data/MC comparison of other $\gamma$ variables

- $\gamma$ variables like minC2TDist and cluster time are important to suppress beam background and fake photons
- Only minC2TDist has good data/MC agreement
\[ \begin{align*} \vec{B}^+ & \rightarrow \bar{D}^0 \pi^+ \\ 
\text{E(\gamma)} & \text{ has good agreement;} \\
\text{N(\gamma)} & \text{ has disagreement in lower bins} 
\end{align*} \]
$B^+ \rightarrow D^0 \pi^+$

**Fake photon dominated**

$N(\gamma)$

**Beam-bkg photon dominated**

$E(\gamma)$