Measurement of the photon energy spectrum in inclusive hadronic-tagged $B \to X_s\gamma$ decays at the Belle II experiment

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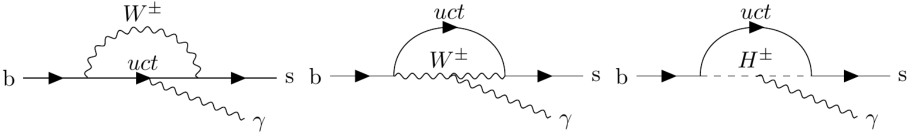
ErUM-FSP T09 Belle II

Inclusive rare radiative decays

Leading Standard Model diagrams | Two-Higgs Doublet Model scenario



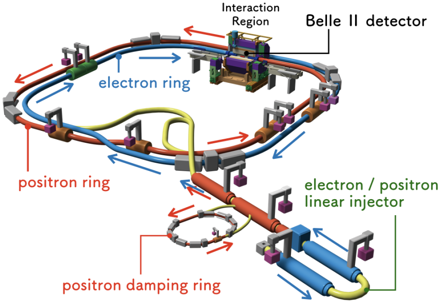
$\mathcal{B}(B \to X_s\gamma) \sim 3.5 \times 10^{-4}$ [PDG, 2020]

- Inclusive measurement: no constraints on X_s hadronic system
- Complementary to studies of exclusive decays, e.g. $B \to K^*\gamma$
- Several SM extensions could contribute in $\mathcal{B}(B \to X_s\gamma)$
  $\to$ important ingredient in many global fits
- E_γ spectrum allows to determine m_b and non-perturbative parameters, important for $|V_{ub}|$ extraction from $B \to X_u l\bar{\nu}$
- Hadronic-tagged measurement performed by BaBar [PhysRevD.77.051103, 2008]

SuperKEKB

Located at KEK in Tsukuba, Japan.

e^- (7 GeV) e^+ (4 GeV)



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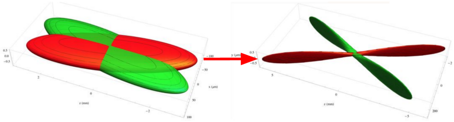
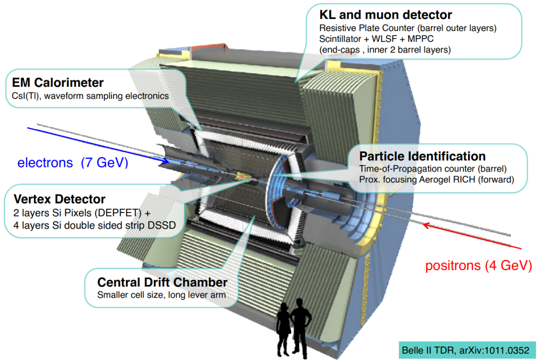
KEKB

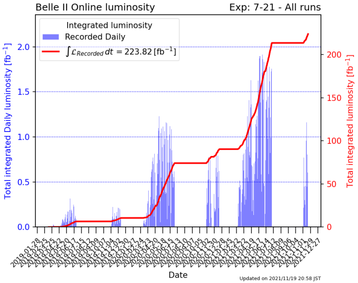
SuperKEKB



- Asymmetric electron-positron collider
- B factory: $\sqrt{s} = 10.58$ GeV $\rightarrow$ operates at the $\Upsilon(4S)$ mass
- Nano-beam scheme
- Increased beam currents $\rightarrow$ Factor of 30 increased $\mathcal{L}_{\text{peak}}$
- Luminosity record June 2021: $\sim 3.1 \times 10^{34} cm^{-2} s^{-1}$

Belle II detector

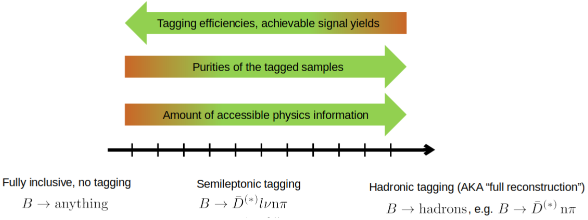


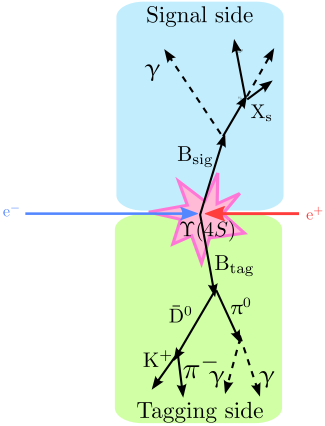


- Most of the sub-detectors upgraded, triggering improvements
- Data taking still ongoing despite Covid-19 pandemic:
  $\rightarrow$ up to now collected more than 200 fb^{-1}
- Target: $\mathcal{L}_{\text{int}} = 50\ \text{ab}^{-1}$ which is $40 \times$ Belle dataset

Inclusive measurements at Belle II

Known initial state at Belle II allows several different approaches:





The overall idea of hadronic tagged inclusive analysis:

- Fully reconstruct the tagging side ($B \to$ hadrons)
- Reconstruct the signal γ
- Infer the X_s kinematics
- Can access observables in the signal B rest frame

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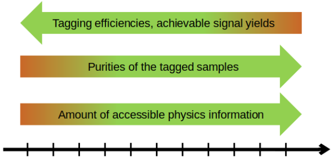
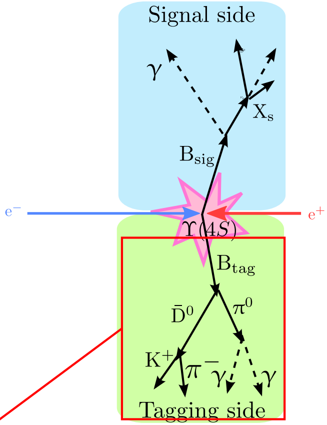


Fully inclusive, no tagging
$B \to \text{anything}$

Semileptonic tagging
$B \to \bar{D}^{(*)} l \nu \text{n}\pi$

Hadronic tagging (AKA "full reconstruction")
$B \to \text{hadrons}$, e.g. $B \to \bar{D}^{(*)}\,\text{n}\pi$



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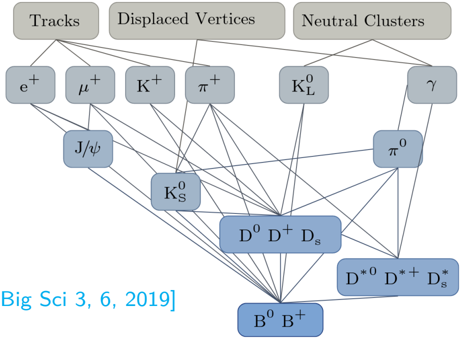
Beam constrained mass and ΔE :

$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - {p^*_{Btag}}^2} \quad \Delta E = E^*_{Btag} - \sqrt{s}/2$$

Tag side reconstruction

- Use the **F**ull **E**vent **I**nterpretation: tagging algorithm of Belle II
- Hierarchical reconstruction starting at detector level objects
- Combines candidate B in $\mathcal{O}(10000)$ decay chains
- Gradient-boosted decision trees (BDTs) assign a candidate probability score $\mathcal{P}_{\rm FEI}$ at every reconstruction step
- Relative increase in tagging efficiency by 30–50% compared to conventional algorithms



[Comput Softw Big Sci 3, 6, 2019]

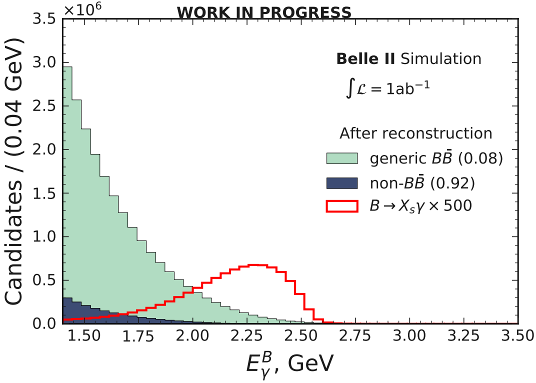
Reconstruction of $B \to X_s\gamma$

Reconstruction of signal side (blinded):

- Highest energy γ in event (E_γ^B>1.4 GeV), with cluster quality selection
- Inclusive measurement: X_s system not explicitly reconstructed

Selected dataset contains two types of events:

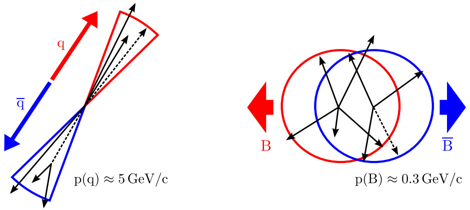
- $e^+e^- \to q\bar{q}$ $(q = u, d, c, s)$ $\to$ solely background ("Non-$B\bar{B}$")
- $e^+e^- \to B\bar{B}$ $\to$ primarily background, but also signal component ("Generic $B\bar{B}$")



Main sources of background photons:

- $\pi^0 \to \gamma\gamma$ $(\sim 80\%)$
- $\eta \to \gamma\gamma$ $(\sim 10\%)$

Non $B\bar{B}$ suppression



$e^+e^- \to q\bar{q} \quad (q \in \{u, d, s, c\})$

More'jet-like'

$e^+e^- \to \Upsilon(4S) \to B\bar{B}$

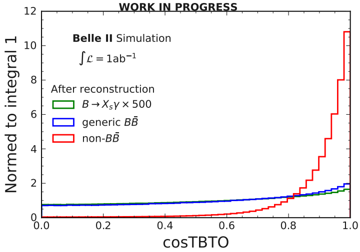
More 'spherical'

- Use event shape/tag-side information for selection
→ e.g.: Angle between thrust axis of the tag B and rest of event
- Train a BDT to pick out signal events

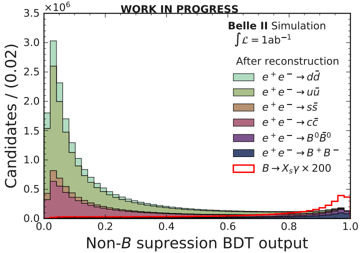
Challenge:

- Biases on the E_γ and X_s system
  → event-shape variable include γ, X_s system.

Example separating variable:

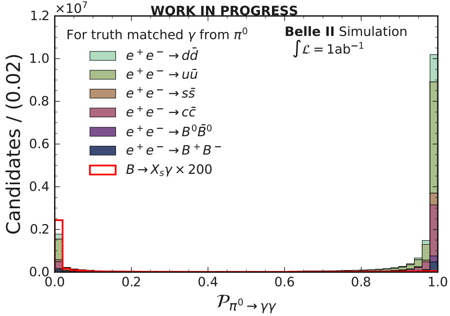


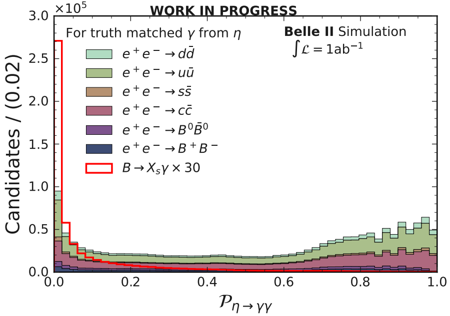
Combination via BDT:



Suppression of photons from $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$

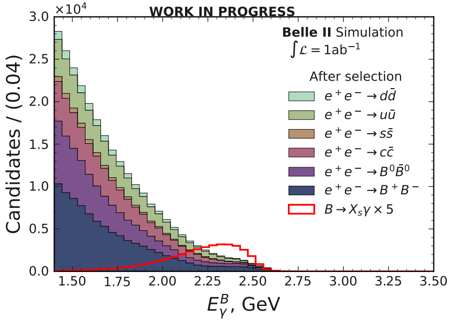
- Dominant background: γ from π^0 and η decays
  $\to$ signature of a high-energy γ and a low-energy γ
- Vital to build a veto against such photons
- Combine signal candidate γ with other γ in event
- Classifier distinguishes fake combinations effectively
  $\to$ based on low-E γ shower shape parameters, energy, M of combination



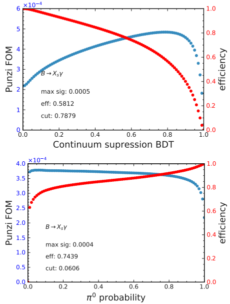


Application of background suppression

- Continuum suppression and π^0/η veto values have to be optimised
- To optimise all selections two possibilities are explored:
  - Train a 2nd BDT taking as input variables for background suppression or
  - Apply a simple variable-by-variable optimisation using a figure of merit
- The final decision will be based on the expected impact on the final result
- From preliminary studies, post-reconstruction γ candidate retention is around 35%



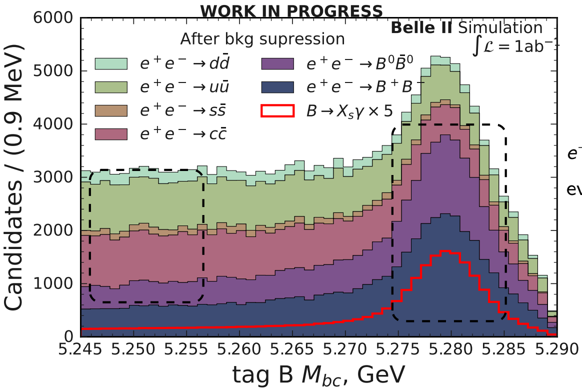
Optimisation examples:



Good tag selection

- After applying all the selections, there can still be multiple tag-side candidates in an event
- We select only the candidate B^0/B^+ with the highest $\mathcal{P}_{\mathrm{FEI}}$ score
- At this point it ensures 1 tag + 1 photon combination in each event
- However, not all tag candidates constrain the signal side correctly
- One can fit M_{bc} to extract number of 'good' tag candidates:
  $\rightarrow$ good tags peak in M_{bc}

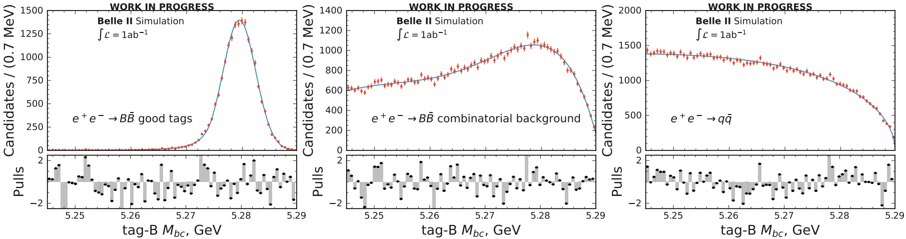
More $e^+e^- \rightarrow q\bar{q}$ events in the tail



$e^+e^- \rightarrow B\bar{B}$ events peak

Fitting strategy

- Using Monte Carlo matching information, identify components in the dataset:
  - Peaking 'good' tags (**described by Crystal Ball function**)
  - Less peaking combinatorial $B\bar{B}$ background (**described by Chebyshev polynomial**)
  - Continuum background (**described by Argus function**)



- Goal: performing the fit in bins of E_γ^B
- These PDFs are to be used as building blocks for the fit of the total dataset

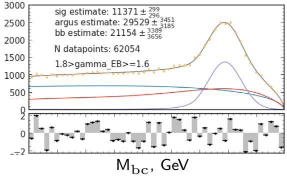
M_{bc} fit in bins of E_γ^B

Fit is performed in bins of E_γ^B on $1\ \mathrm{ab}^{-1}$ of simulated data

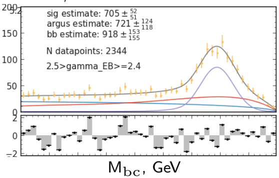
- E_γ^B range: $[1.4 - 3.5]$ GeV
- However different bins have different expected number of candidates
- Setup needs to be stable and consistent even on smaller datasets:
  $\rightarrow$ PDF shapes defined in a prefit step (previous slide)
  $\rightarrow$ Shared PDF shape for low population bins
  $\rightarrow$ Only PDF yields and one background shape parameter floating

Example fits on E_γ^B bins:

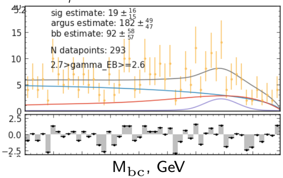
$1.8 > E_\gamma^B > 1.6$ GeV



$2.5 > E_\gamma^B > 2.4$ GeV

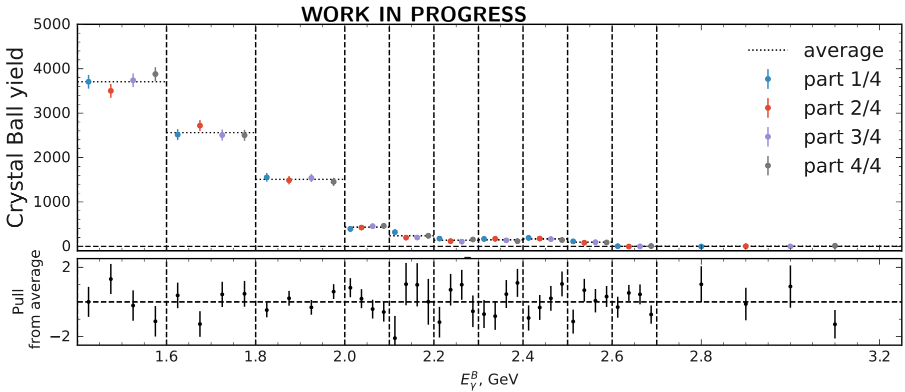


$2.7 > E_\gamma^B > 2.6$ GeV



Extracted yields

- Fitting procedure stability is evaluated using generated toys from the final fit PDF
  $\rightarrow$ helps to decide on the optimal setup
- To ensure that fit is also stable on smaller datasets, split the simulated 1 ab^{-1} dataset into four 250 fb^{-1} chunks
  $\rightarrow$ consistent output from fitting setup in all cases



- Next step: subtract leftover background (simulation reliant)
  $\rightarrow$ work ongoing

Summary and further steps

- Hadronic tagged $B \to X_s\gamma$ measurement is very suitable for Belle II:
  $\to E_\gamma$ spectrum in the B frame can be directly measured
- One of the main challenges for the analysis is to efficiently suppress dominating $q\bar{q}$ background events and photons originating from $\pi^0 \to \gamma\gamma$
- M_{bc} fitting allows to further suppress backgrounds and extract a sample of high purity
- Analysis moving towards the goal: unfolded E_γ^B spectrum

Thanks!