Optimization and Evaluation of K_L Identification Performance

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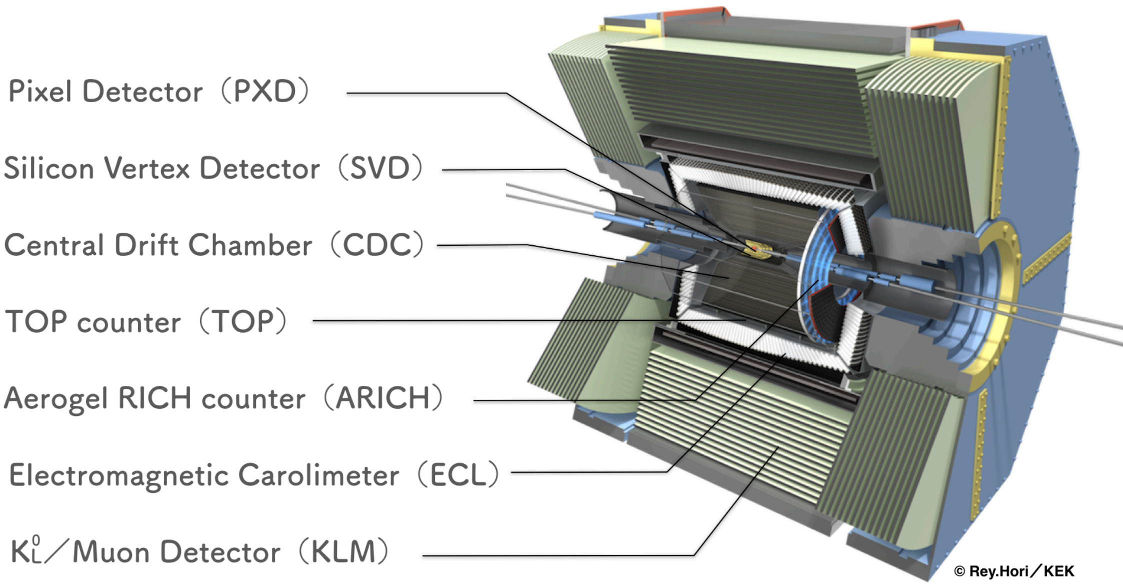
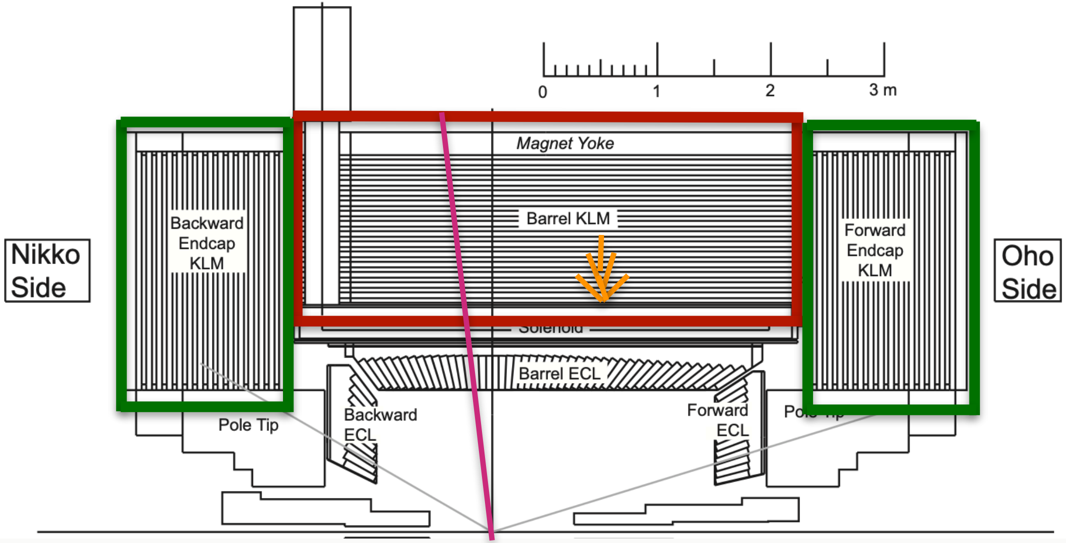
Outline of my activities

- Develop improved K_L identification (ID) using a Boosted Decision Tree (BDT)
- Identify KLM clusters from true K_L's in experimental data using $\phi \rightarrow K_L K_S$ events
- Identify KLM clusters from true K_L's in experimental data using $B \rightarrow D^*\pi$ events
- Goal: identify K_L with a higher identification efficiency and ***lower fake-rate***



The K-Long Muon Detector (KLM)

- Consists of barrel and forward and backward endcap
- KLM polar angle acceptance: 20° < θ < 155°
- Barrel setup: Alternating resistive plate chambers (RPCs) and iron plates
- Endcap setup: plastic scintillators with silicon photomultipliers
- Detect muons by hit along their path and K_L by hadronic shower



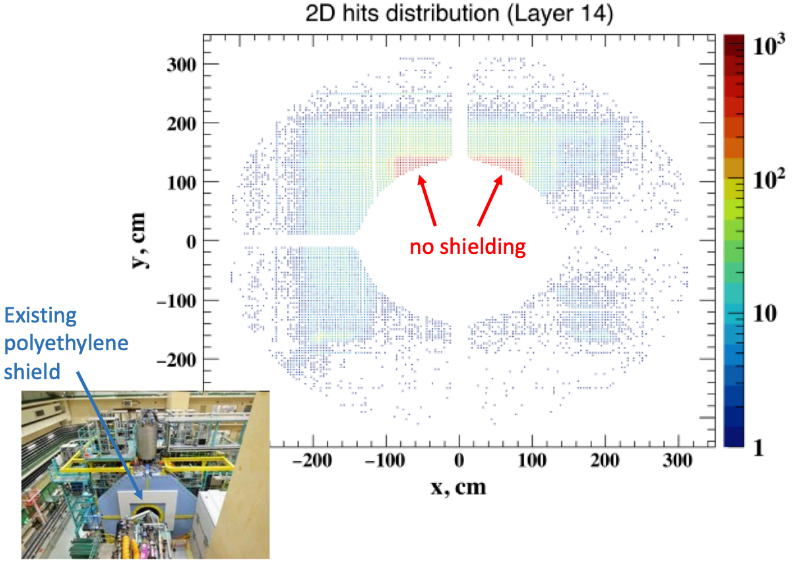
[T. Abe et al., Belle II Technical Design Report, 2010, ArXiv:https://arxiv.org/pdf/1011.0352.pdf]

Beam induced neutrons as background

[Leo Piilonen, KLM Work Plan for Summer 2022, 2010, indicohttps://indico.belle2.org/event/3781/contributions/18728/attachments/9438/14494/KLM_Summer2022Plans.pdf]

- Important beam background sources are:
  - Beam-Gas interaction
  - Touschek effect
  - Radiative Bhabha scattering
- Fast neutrons are created outside the detector region
- Neutrons interact hadronically with detector material —> Causes clusters in KLM that can produce fake K_L candidates

Neutron illumination is not uniform across FWD endcap face



What do we need, do and want?

We need:

Good K_L candidate sample

Bad K_L candidate sample

We do:

BDT training on KLM variables

We want:

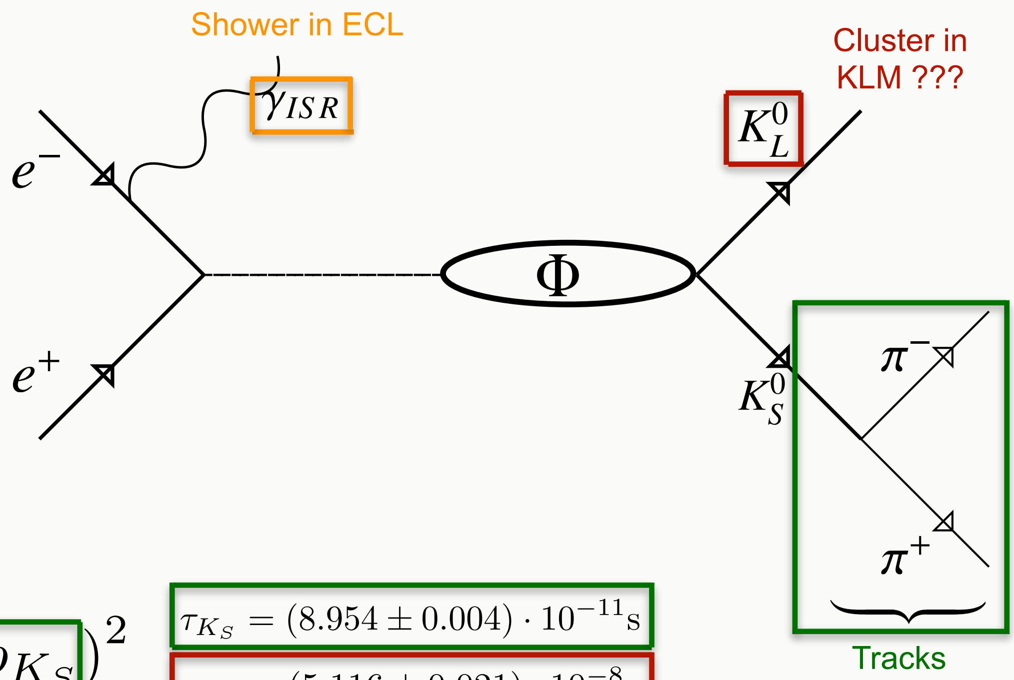
Classification for each KLM cluster whether to be a K_L or not

What to do First?

- Find good K_L clusters and bad K_L clusters in the KLM
- Use a very clean decay:

  $e^+e^- \longrightarrow \gamma_{ISR}\phi \longrightarrow K_L K_S$

  with $K_S \longrightarrow \pi^+\pi^-$
- γ_{ISR} and K_S is easy to reconstruct
- Do not reconstruct K_L, but predict where the K_L should be in an event



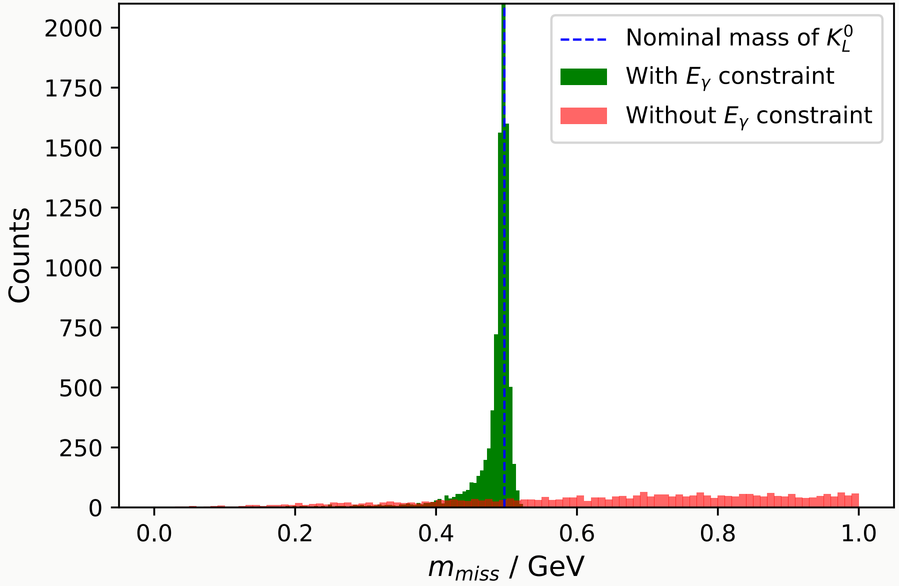
$$m_{miss}^2 = p_{miss}^2 = (p_{beam} - p_\gamma - p_{K_S})^2$$

$$\tau_{K_S} = (8.954 \pm 0.004) \cdot 10^{-11}\text{s}$$

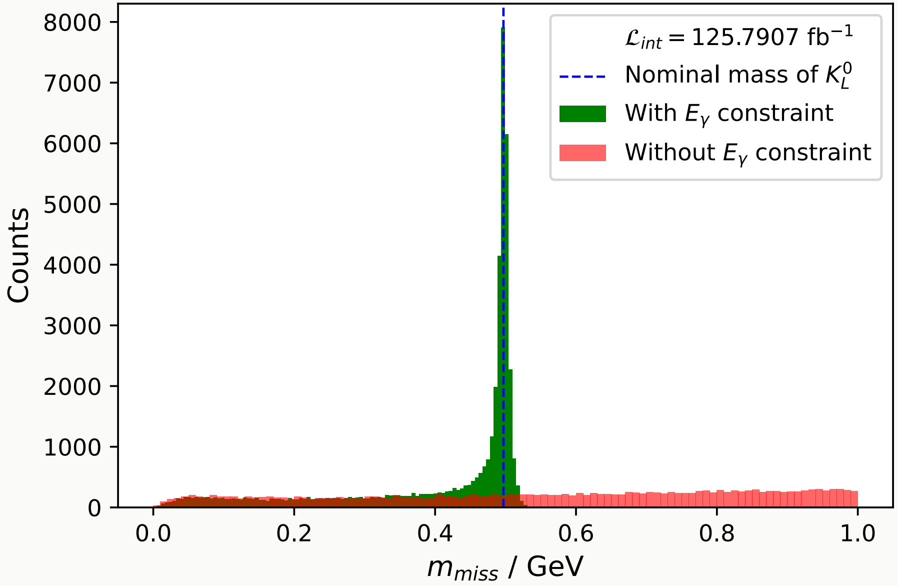
$$\tau_{K_L} = (5.116 \pm 0.021) \cdot 10^{-8}\text{s}$$

[Particle Data Group, Particle Physics Booklet, 2021, https://pdg.lbl.gov]

Missing Mass with/without Photon Energy Constraint

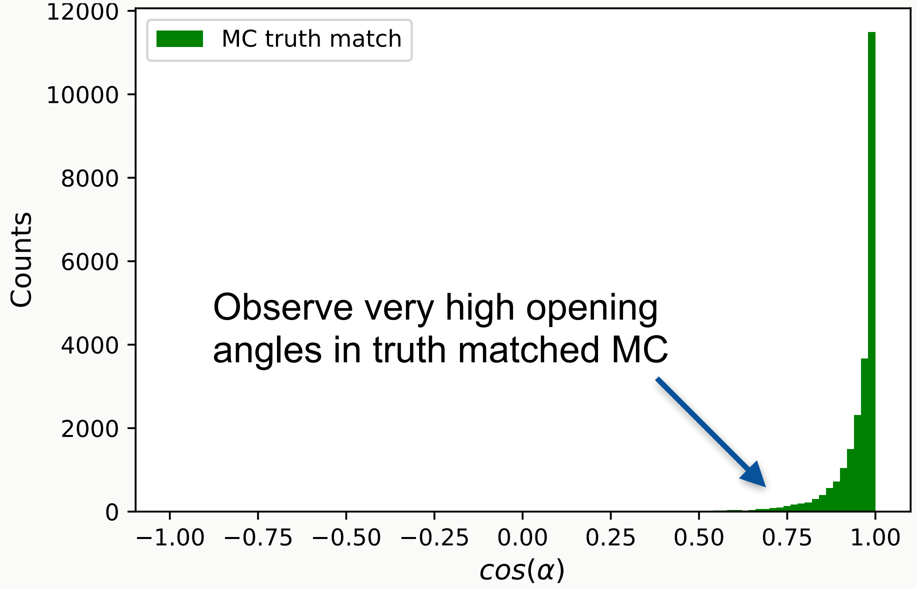


Signal MC

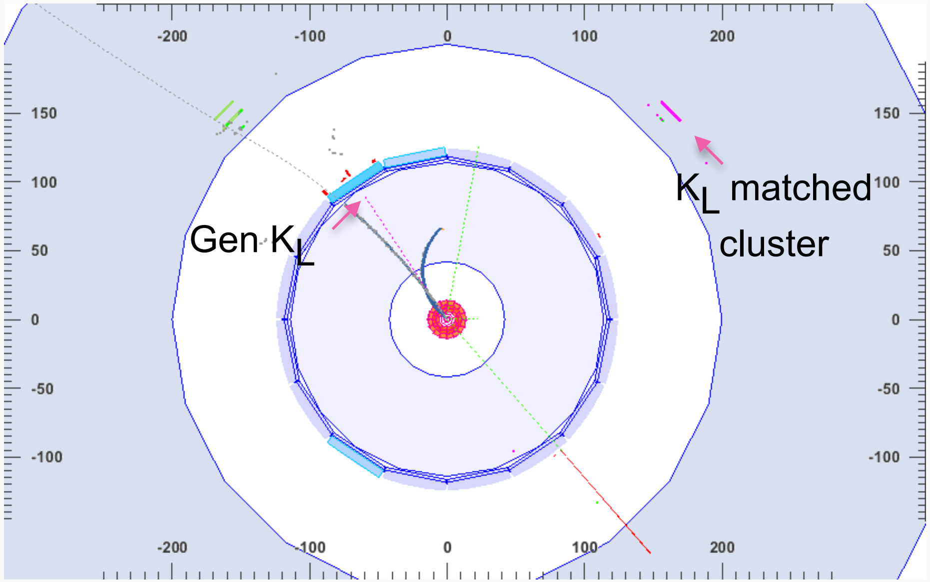


Data

Cluster truth matching is failing?



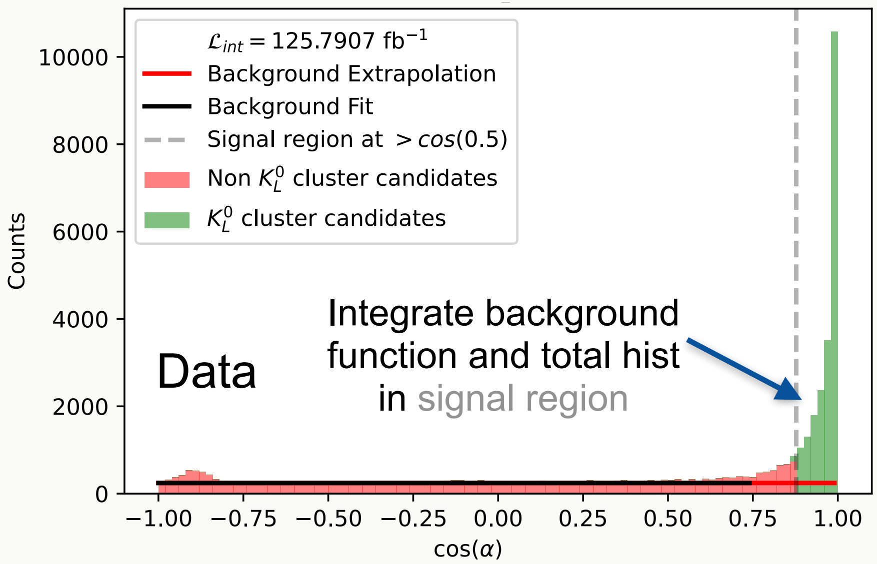
Signal MC



- ***KLM Cluster-Truth matching is broken***

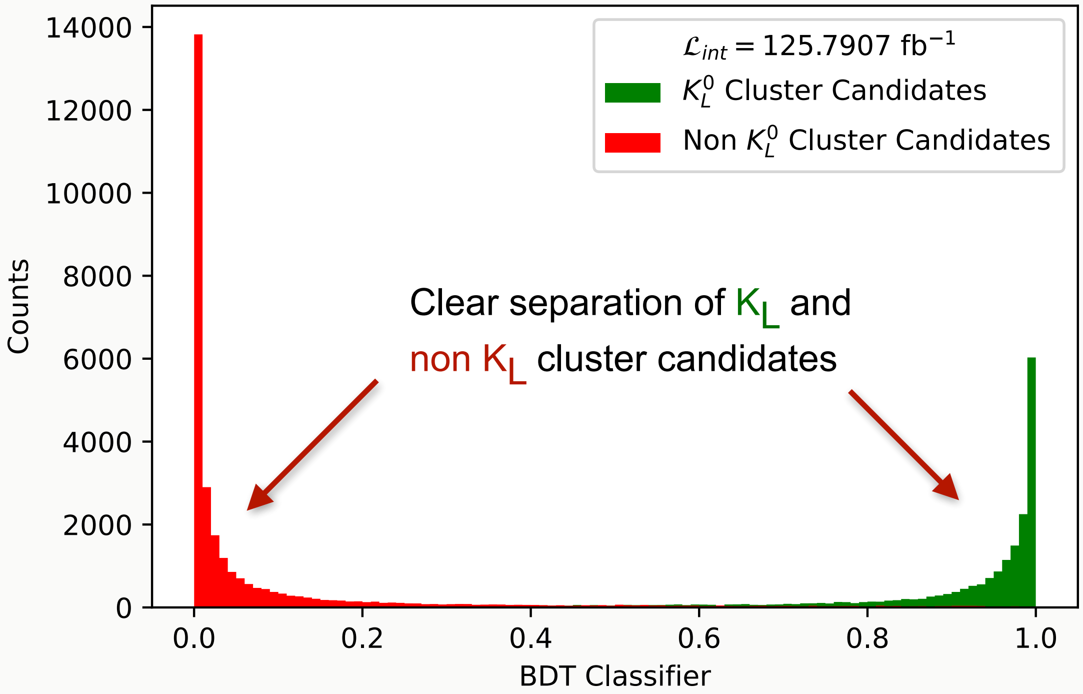
Preliminary definition of K-Long Cluster Candidates

- Preliminary definition of K_L cluster candidates by the opening angle between missing momentum and KLM cluster vector
- Good K_L cluster candidates defined by α < 0.5 rad
- Identification efficiency ≈ 0.733±0.007, fake-rate ≈ 1.225±0.008 average fake cluster per event
- This efficiency **does not include the detection efficiency** but only the identification of a cluster as a K_L

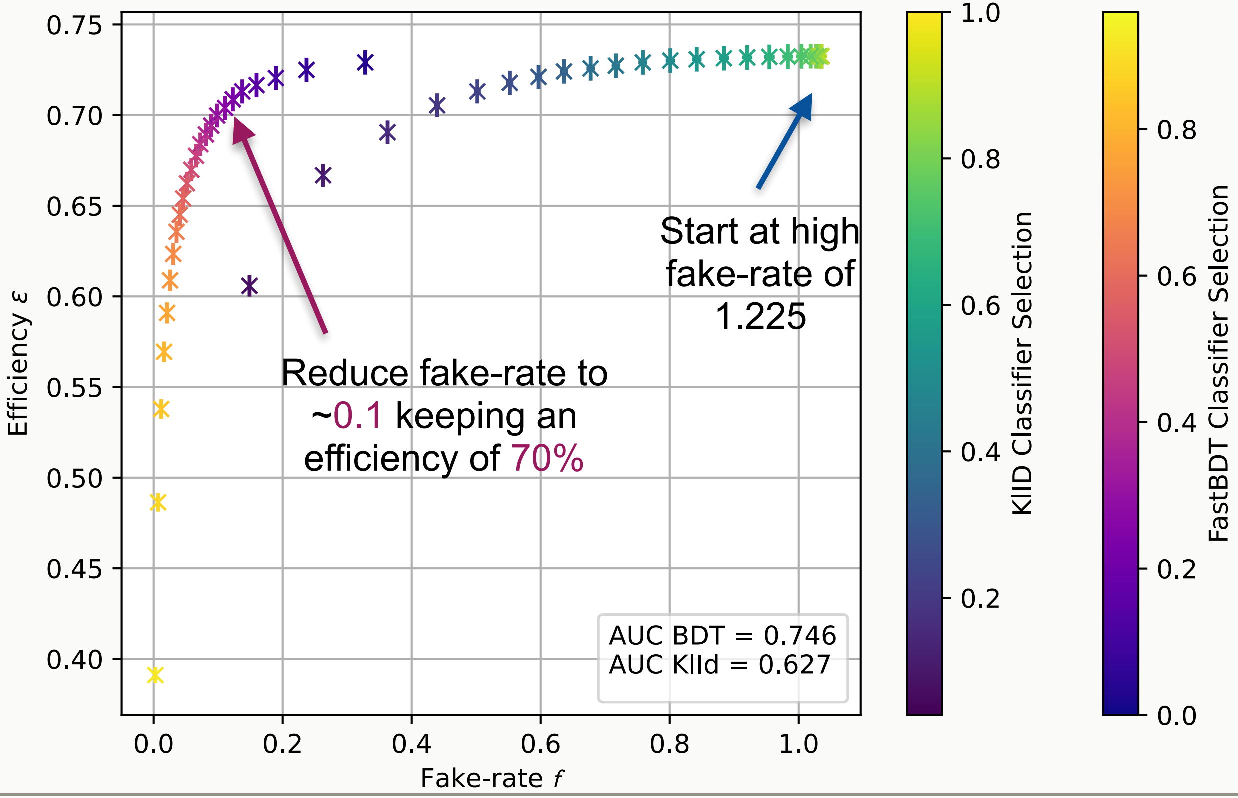


Start the BDT Training

- Start training BDT on a large number of KLM variables of experimental data
- In the end use 12 out of the 23 KLM variables
- BDT clearly distinguishes between K_L cluster candidates and expected fast neutron cluster candidates plus other background clusters



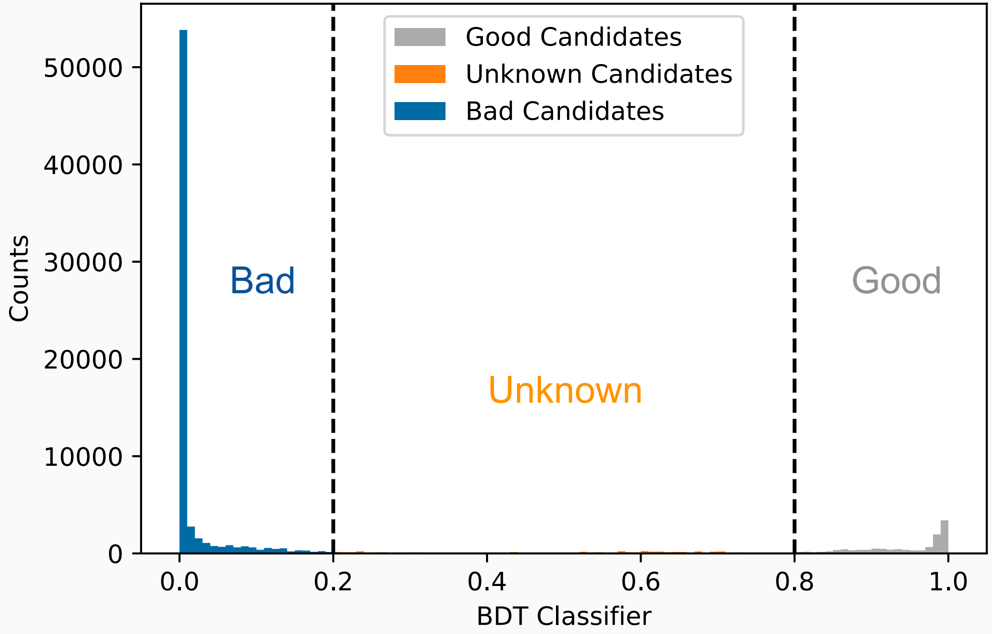
BDT Identification Efficiency and Fake-Rate



Apply BDT to a Data sample with low momentum K_L

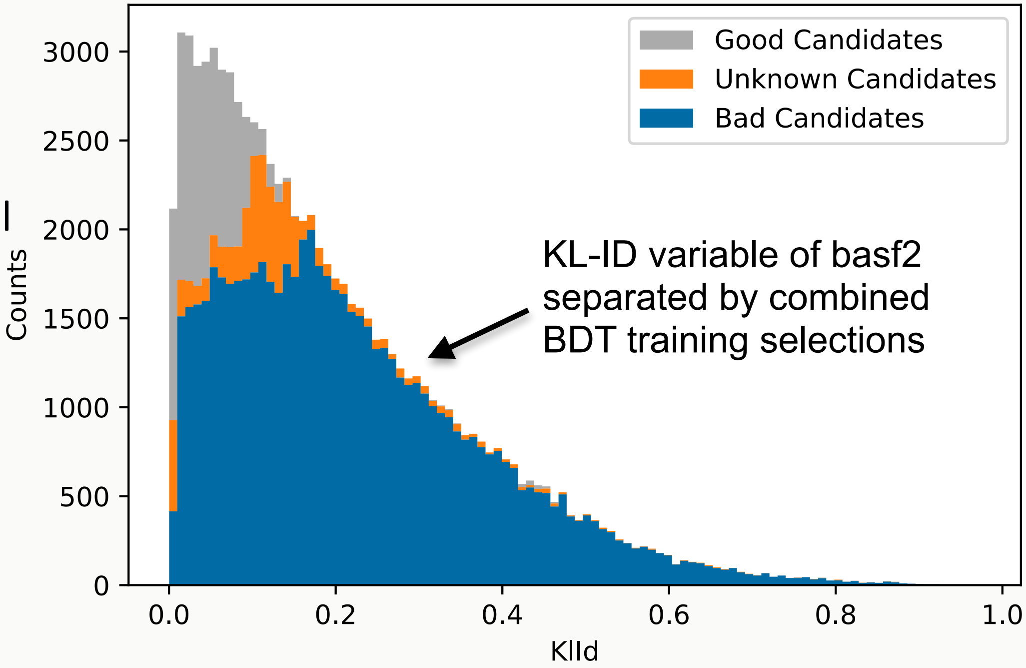
- Use custom GEANT4 simulated signal events of generated K_L's
- Train on:
  - klmClusterInnermostLayer
  - klmClusterEnergy
  - klmClusterPhi
  - klmClusterPositionZ
  - klmClusterKlId
- Apply FastBDT training to hadronic skimmed Data
- Only reconstruct KLM clusters with no matched tracks
- Cut at <0.2 —> **fake-rate ~ 0.25** average fake clusters per event

$$f_{\text{comb}} = \frac{f_\phi \cdot N_{\text{obs}} - N_{\text{removed}}}{N_{\text{obs}}}$$



Compare FastBDT to current tools

- Overlap of bad, unknown and good clusters is observed
- In current classifier (KlId) not distinguishable
- FastBDT performs better than current tool for K_L identification —> above 0.15 we observe only potential bad candidate clusters
- Need validation that the potential good clusters are indeed good K_L clusters



Validation of new K_L identification

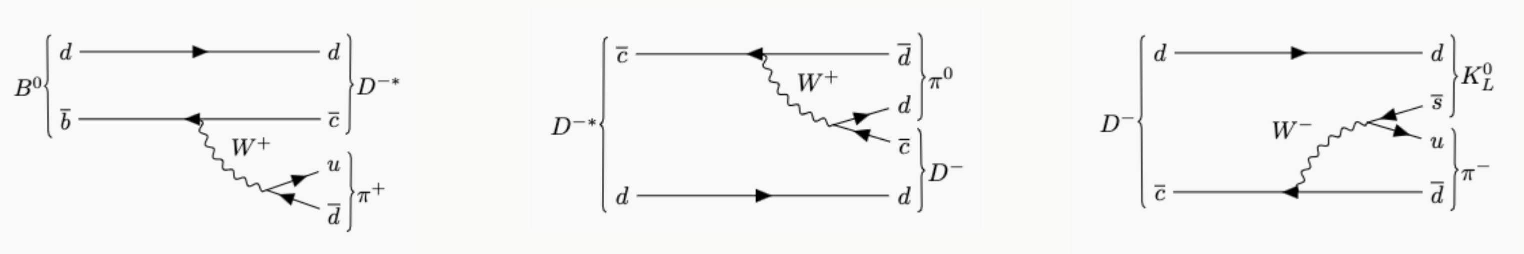
- Generate 25k signal MC events of $B \to \pi^+ \left[D^{-*} \to \pi^0 \left[D^- \to K_L^0 \pi^-\right]\right]$
- Use constraints on the B, D^- and D^{-*} to solve for missing KL energy and momentum components

$$E_{K_L} = E_B - E_{\pi^-} - E_{\pi^0} - E_{\pi^+}$$

$$|\vec{p}_B|^2 = (\vec{p}_{K_L} + \vec{p}_{\pi^-} + \vec{p}_{\pi^0} + \vec{p}_{\pi^+})^2$$

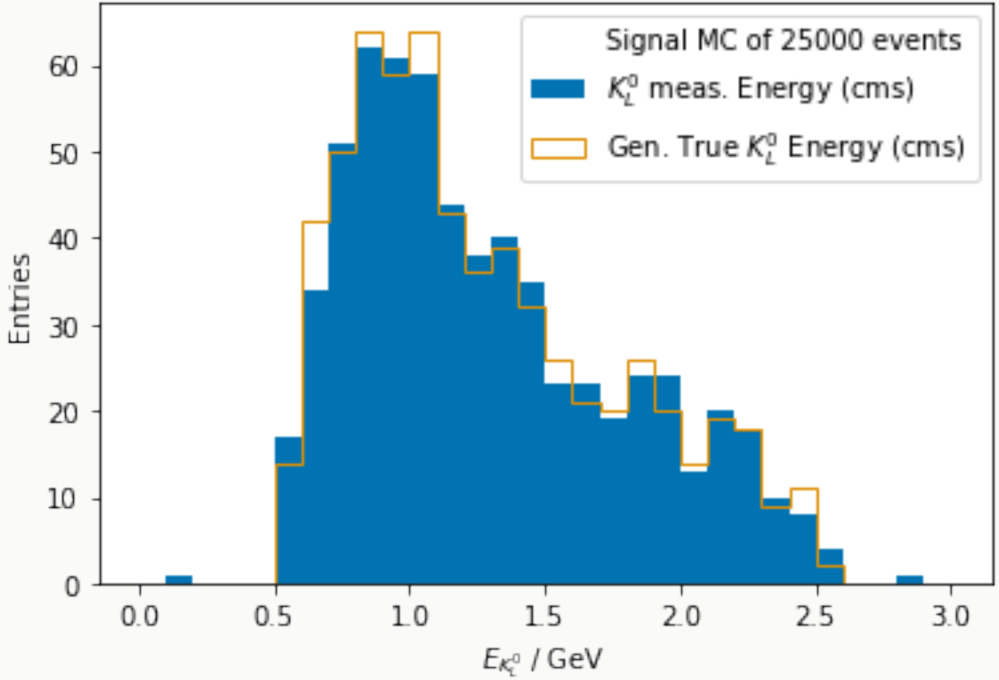
$$|\vec{p}_{D^{-*}}|^2 = (\vec{p}_{K_L} + \vec{p}_{\pi^-} + \vec{p}_{\pi^0})^2 \longrightarrow |\vec{p}_{D^{*-}}|^2 = E_{D^{*-}}^2 - m_{D^{*-}}^2$$

$$|\vec{p}_{D^-}|^2 = (\vec{p}_{K_L} + \vec{p}_{\pi^-})^2 \longrightarrow |\vec{p}_{D^-}|^2 = E_{D^-}^2 - m_{D^-}^2$$

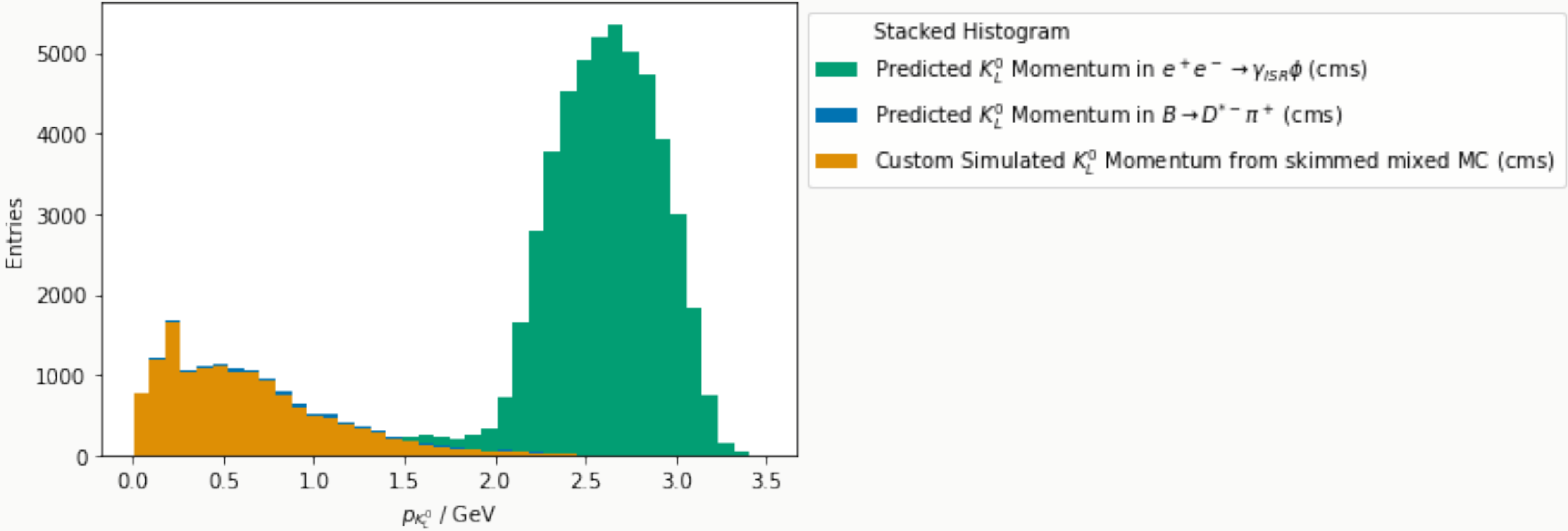


Predicted KL energy

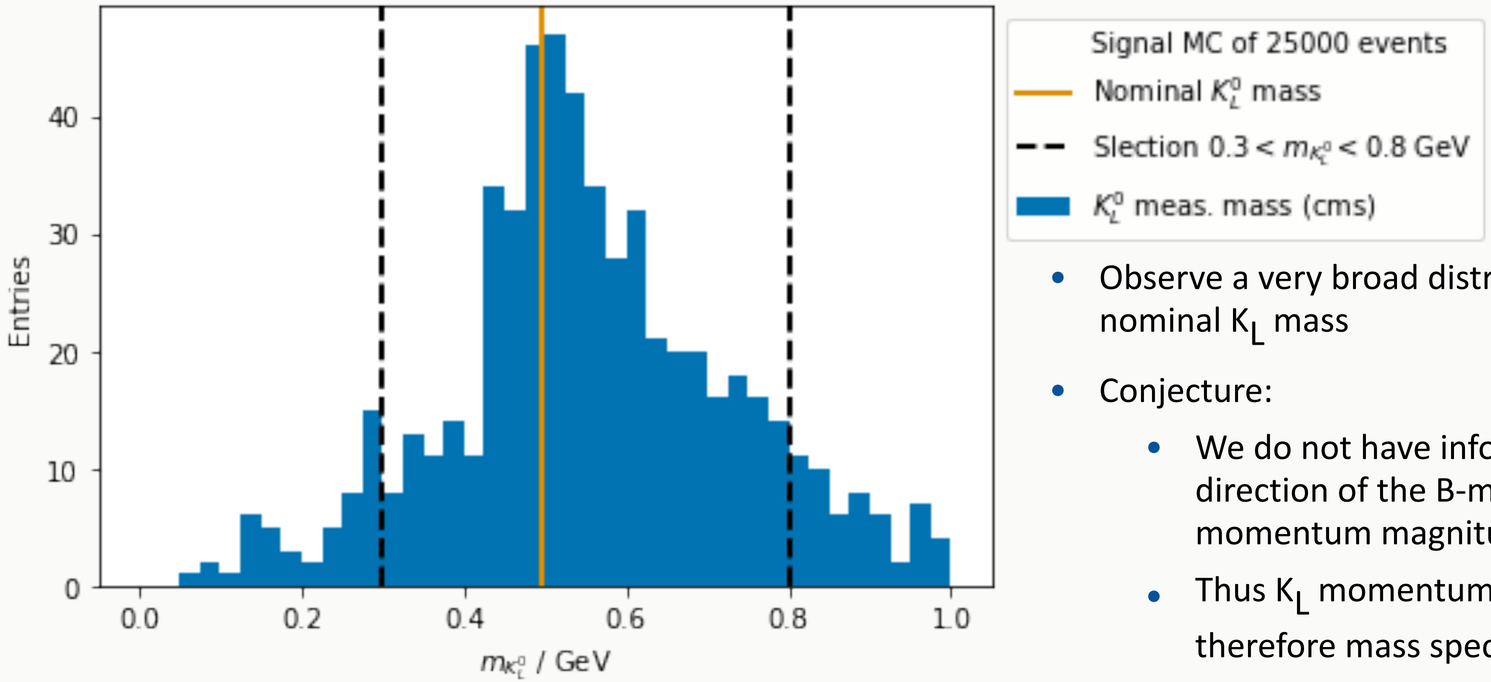
- Observe good agreement between generated true and predicted K_L energy
- Difference comes through resolution effects of pion reconstruction



Momentum comparison of all studies

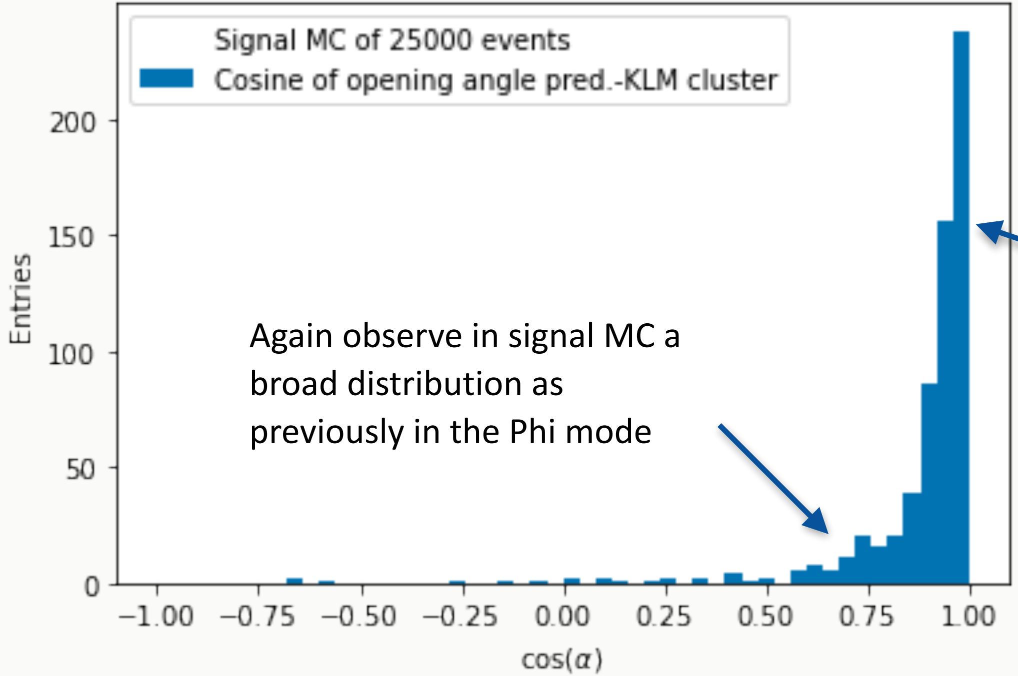


Predicted missing mass



- Observe a very broad distribution around the nominal K_L mass
- Conjecture:
  - We do not have information about the direction of the B-meson but only its momentum magnitude
  - Thus K_L momentum shows smearing and therefore mass spectrum as well

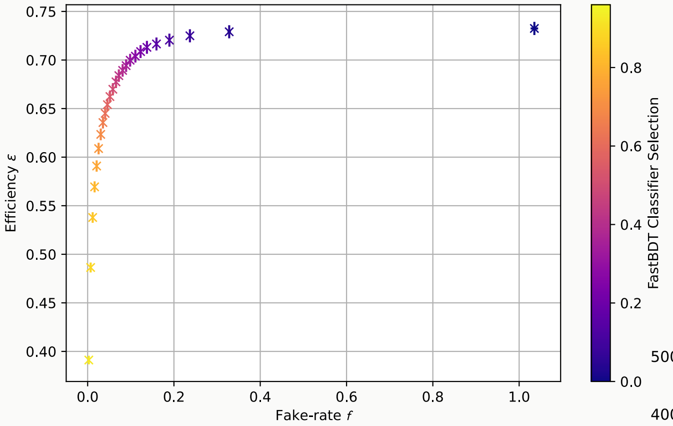
Opening angle between predicted vector and cluster in KLM



Observe a peak close to one as expected

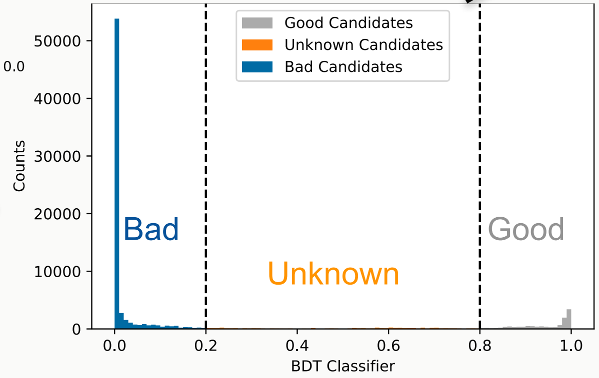
Again observe in signal MC a broad distribution as previously in the Phi mode

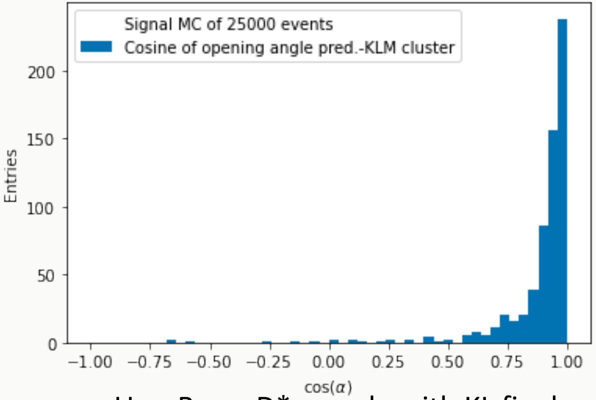
Summary & Outlook



- In the Φ mode we are able to reduce the fake-rate while keeping a high identification efficiency
- But only high momentum KL
- Thus …

- Training on MC signal against data background shows potentially good separation power
- Needs to be validated
- Thus …



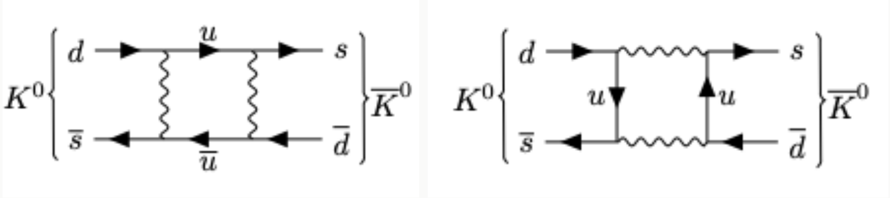


- Use B —> D*π mode with KL final state as validation mode
- Could predict the KL energy/ momentum
- Observe same behavior of opening angle as in Φ signal MC
- Next step repeat for mixed MC and experimental data

Thank you for your attention!

Backup: Neutral long living Kaons?

- Neutral Kaons mix via box diagrams —> no CP eigenstates by itself but linear combination K_1 and K_2
- Found physical state of a short living and long living neutral Kaon
- If CP conserved
  $|K_S >\approx |K_1 >, \ |K_L >\approx |K_2 >$
- Cronin and Fitch found $K_L \to \pi\pi$ decays which was the first evidence of direct CP violation
- K_S and K_L are linear combinations of K_1 and K_2 with a correction factor ε



$$\tau_{K_S} = (8.954 \pm 0.004) \cdot 10^{-11}\mathrm{s}$$

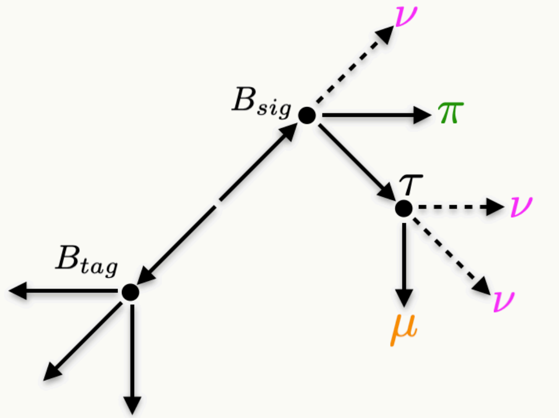
$$\tau_{K_L} = (5.116 \pm 0.021) \cdot 10^{-8}\mathrm{s}$$

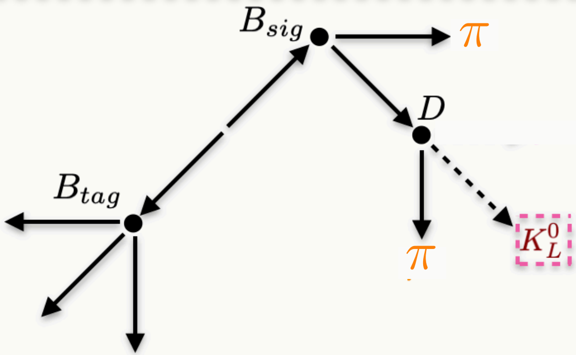
$$|K_S > = \frac{1}{\sqrt{1+|\epsilon|^2}} \left(|K_1 > + \epsilon |K_2 >\right) e^{-i\lambda_S t}$$

$$|K_L > = \frac{1}{\sqrt{1+|\epsilon|^2}} \left(|K_2 > + \epsilon |K_1 >\right) e^{-i\lambda_L t}$$

Backup: Who ordered this background?

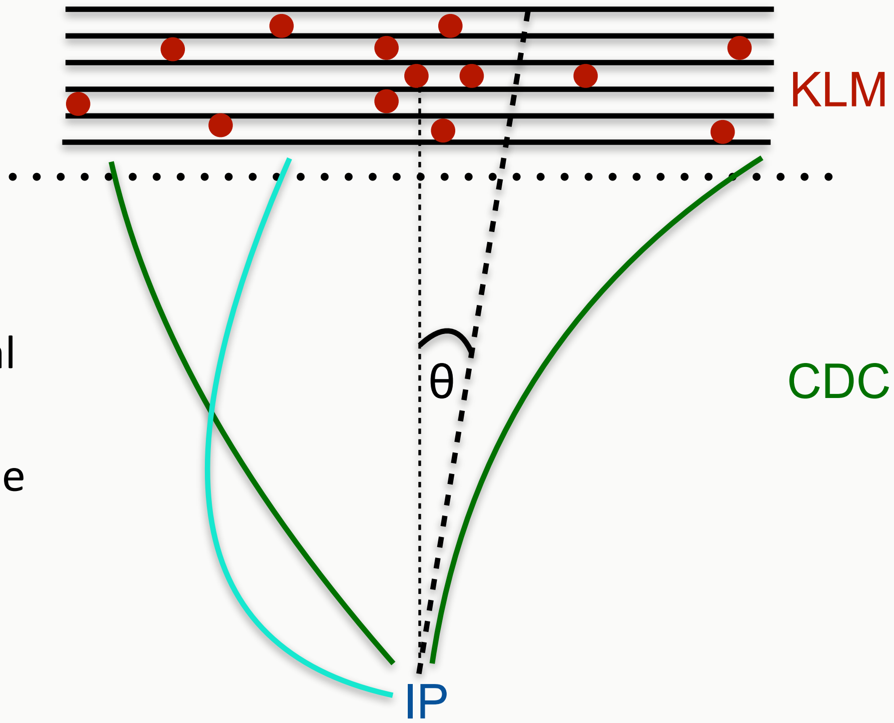
- In B —> πτν followed by τ —> μνν, events with K_L's mirror the signature of this decay process
- Decays like B —> Dπ and D —> K_Lπ are possible background sources
- Vetoing these events decreases the efficiency





Backup: K-Long cluster building

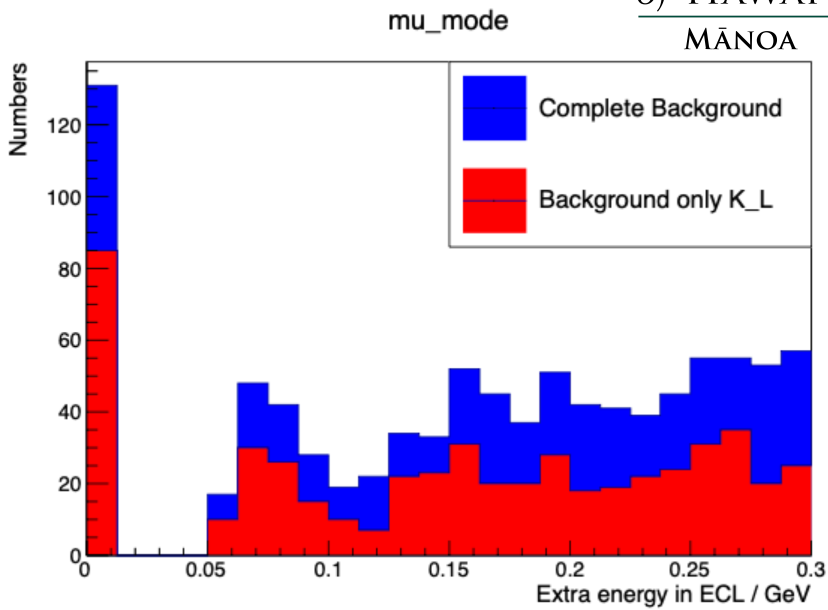
- In KLM, hits within a θ=5° cone drawn from the interaction point (IP) are formed to a cluster
- K_L identification:
  - Only considered to be K_L cluster candidate if no charged track from central drift chamber (CDC) can be extrapolated into the KLM and lies within 150 cm to the cluster



[T. Abe et al., Belle II Technical Design Report, 2010, ArXiv:https://arxiv.org/pdf/1011.0352.pdf]

Backup: Why are we doing this?

- In semitauoninc B decays we observe deviations from the standard model
- Studies of B —> πτν can help to understand this deviation, however those decays come with a lot of background
- One of the major background sources are events with missing K_L's, especially low momentum K_L's
- We see, in mixed MC of Belle B —> πτν followed by τ —> μνν, approximately in 55.1% of the events a K_L is found
- In Belle a K_L veto led to a 5% increase of B—> τν sensitivity [1]

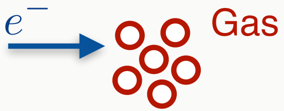


Belle Mixed MC of B —> πτν followed by τ —> μνν

[1] [Yasuyuki Horii, B –> lν (l=τ,μ,e) Belle results and outlook for Belle II, 2012, Talk at the CKM Unitary Triangle Workshop in Cincinnati, Ohio USA]

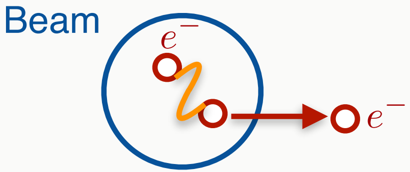
Backup: Fast Neutrons in e^+e^- collision?

Beam-Gas Interaction:



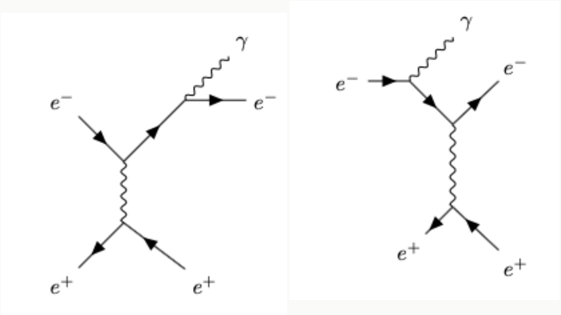
- Electron scatters on nuclei or atomic electron of the gas
- Creates secondary particles
- Detected as background in the Detector

Touscheck Effect:



- Large momentum transfer
- Transfer from transverse to longitudinal
- Longitudinal momentum higher then energy acceptance of the ring electron is lost

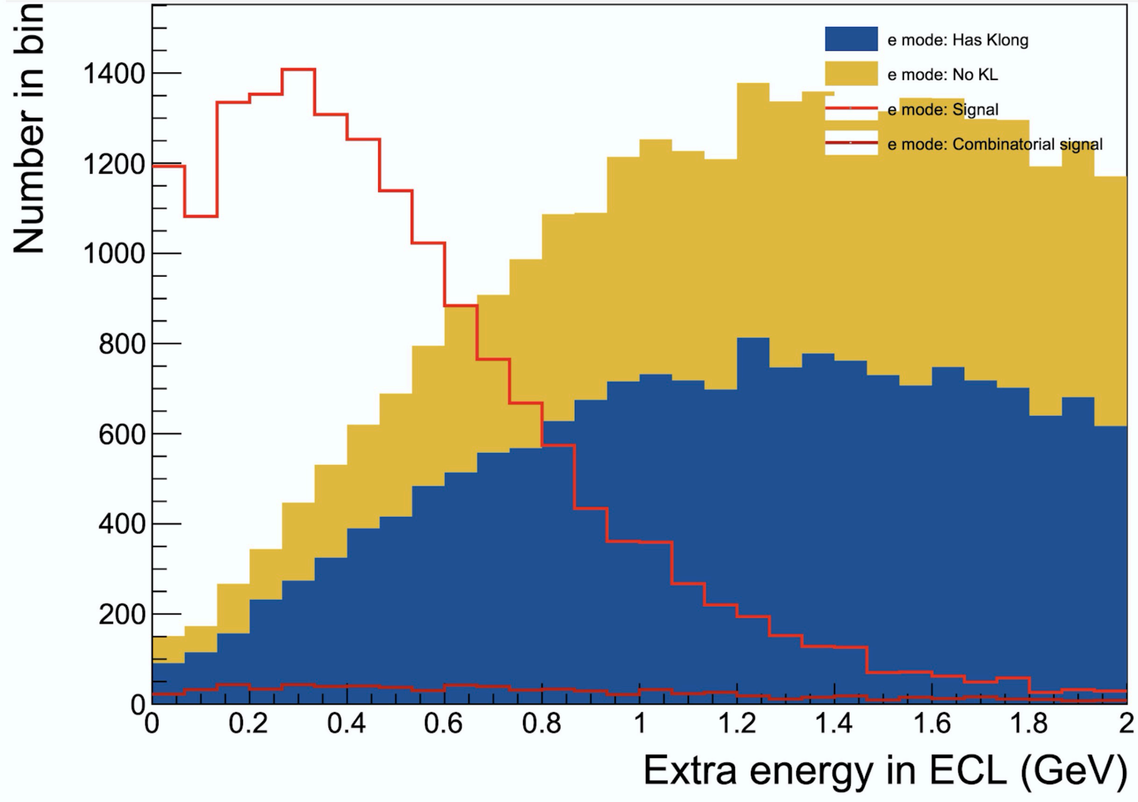
Radiative BhaBha scattering:



- ISR or FSR of a photon in e^+e^- scattering

- Shower from off-orbit beam particles or photons interact with beam pipe material
- The created secondaries excite nuclei via giant dipole resonance —> producing neutrons

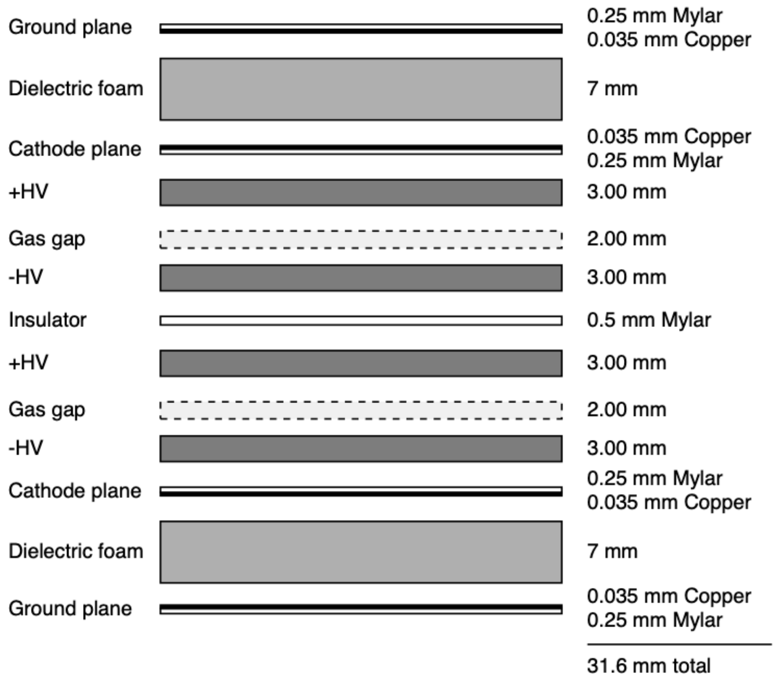
Backup: Who ordered this background?



[Peter M. Lewis, 2022, Talk on "Importance of KL's in B–>πτν events"]

Backup: Resistive Plate Chambers (RPC’s)

- A gas volume is enclosed by two glass electrodes supplied with a high voltage
- In Belle II use two chambers to form a superlayer —> Resulting in 99% detection efficiency
  - Advantage: If one chamber fails, detection efficiency still up to 90 - 95%
- Orthogonal readout stripes are placed behind an insulator on both ends
- Use 48 readout stripes for θ and 36 (48) stripes in layers 0 to 6 (7 to 14) for ϕ measurement in one module



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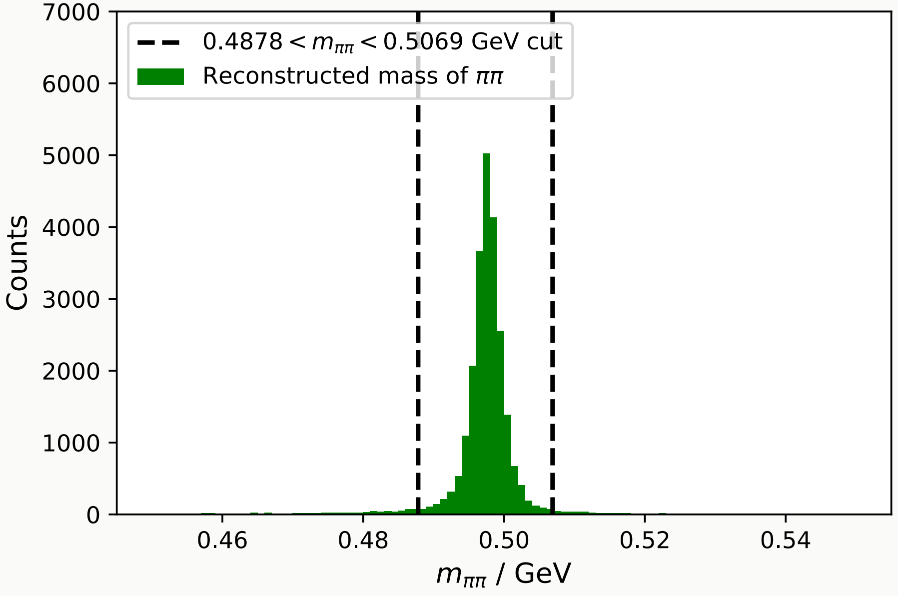
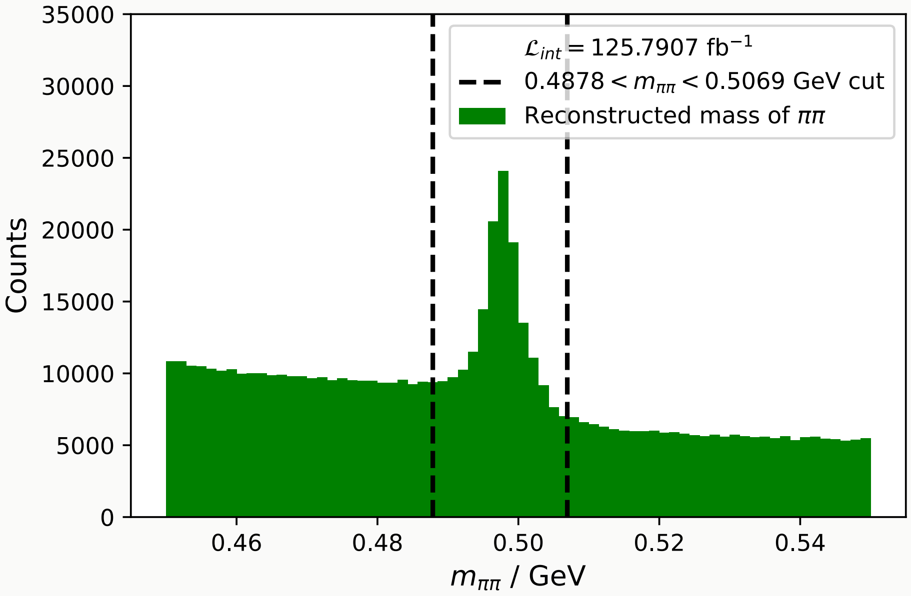
Backup: Reconstructed K-Short Mass

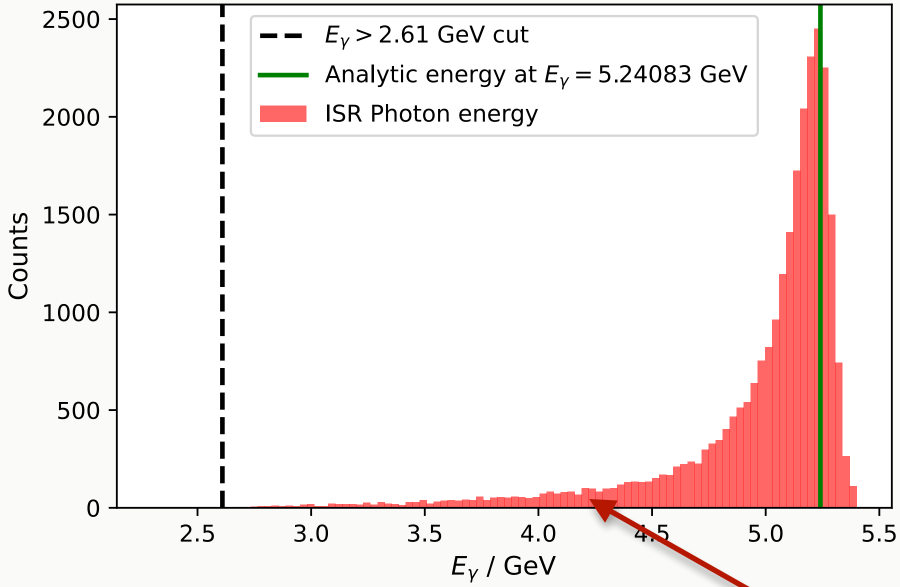


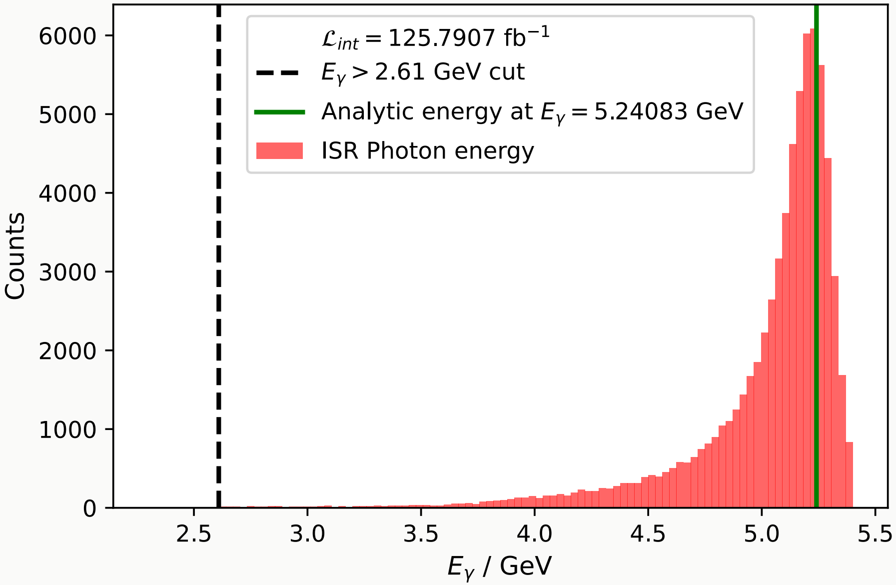
Signal MC



Data

Backup: Photon Energy Signal MC and Data





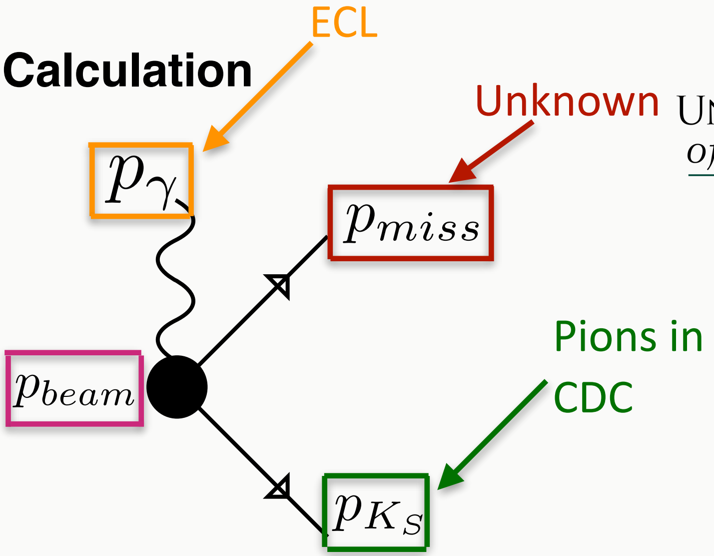
Long tail, due to ECL energy leakage for high energy photons

Signal MC

Data

Backup: Missing Mass Calculation

- Do not use any KLM information
- Use four-momentum vector of K_S, γ_{ISR} and beam
- Thus get missing four-momentum vector and missing mass
- Use constraint on γ_{ISR} energy and correct momentum components



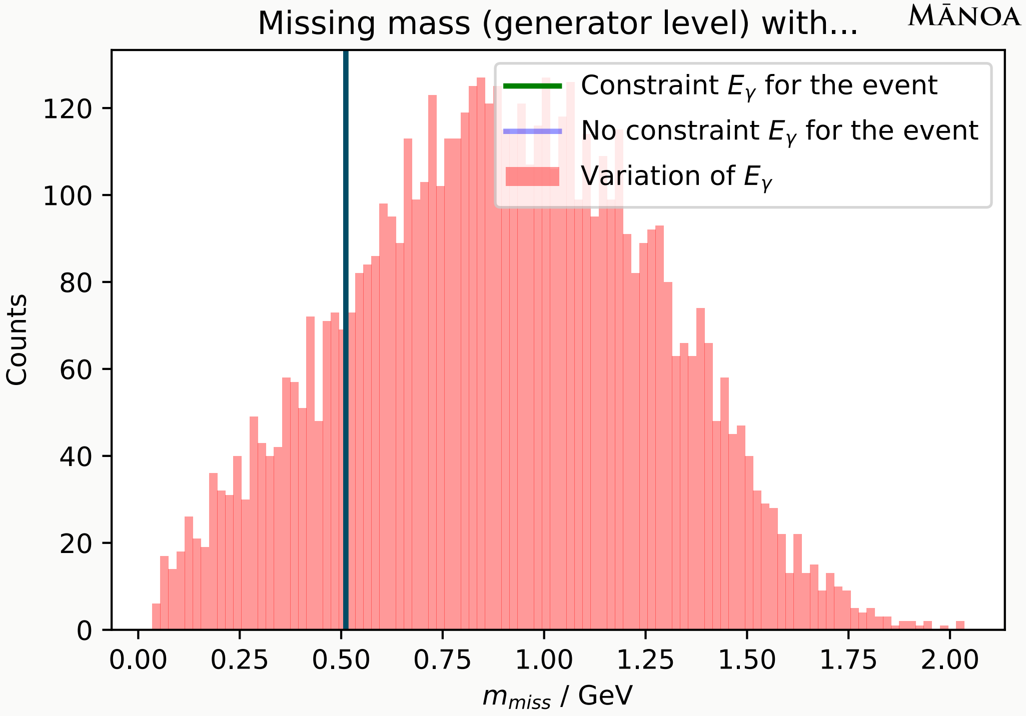
$$m^2_{miss} = p^2_{miss} = (p_{beam} - p_\gamma - p_{K_S})^2$$

$$E^{con}_\gamma \equiv E_\gamma = |\vec{p}_\gamma| = \frac{s - m^2_\phi}{2\sqrt{s}}$$

$$p^{con}_{\gamma,i} = p^{meas}_{\gamma,i} \cdot \frac{E^{con}_\gamma}{E^{meas}_\gamma}$$

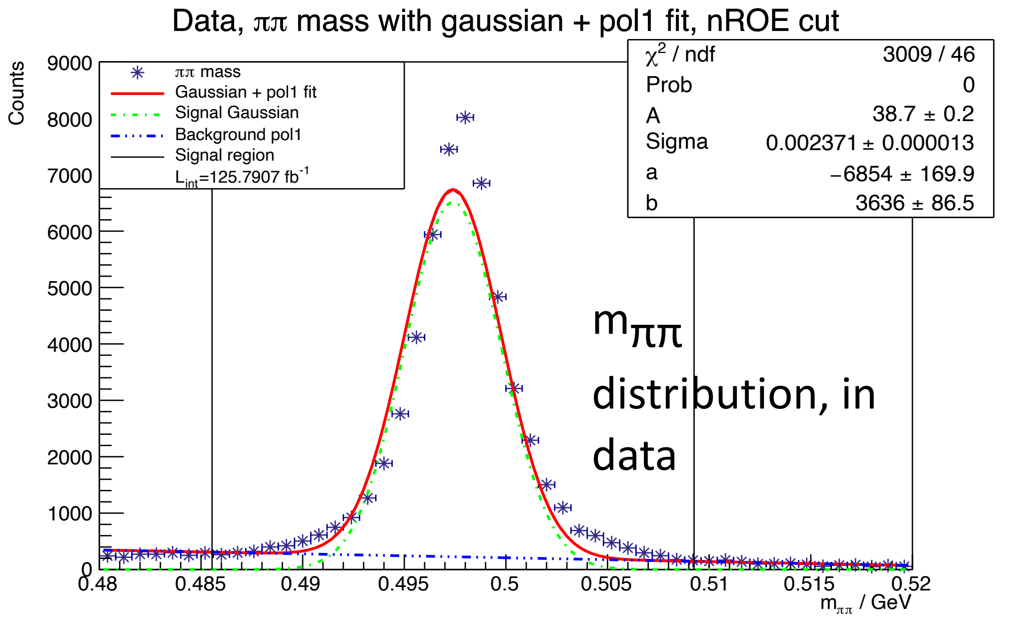
Backup: Variation of Photon Energy and Influence on the Missing Mass

- Study the influence of a small variation on the photon energy
- Use MC generator information and add a variation in form of a gaussian random variable with μ=0 and σ=0.1 GeV
- We can observe a broadening, of the same level as in signal MC and data



Backup: Purity and Efficiency of our Selection

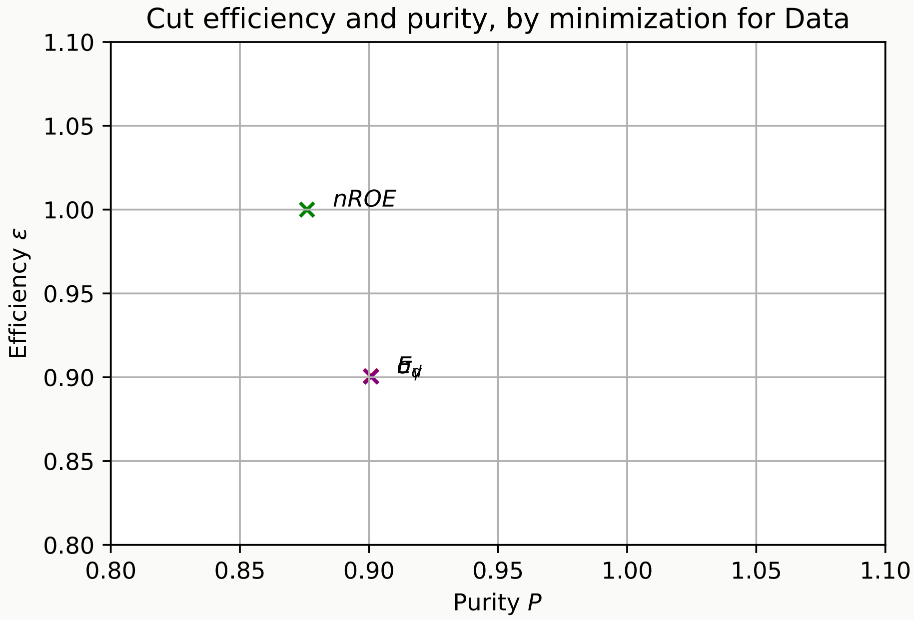
- Determine the purity looking at the $m_{\pi\pi}$ distribution using background subtraction
- Fit Gaussian (sig) + pol 1st order (back)
- Define signal region by mean of fit +- 5σ
- Integrate signal and background function over signal region
- End up with a purity and efficiency of 90%



$m_{\pi\pi}$ distribution, in data

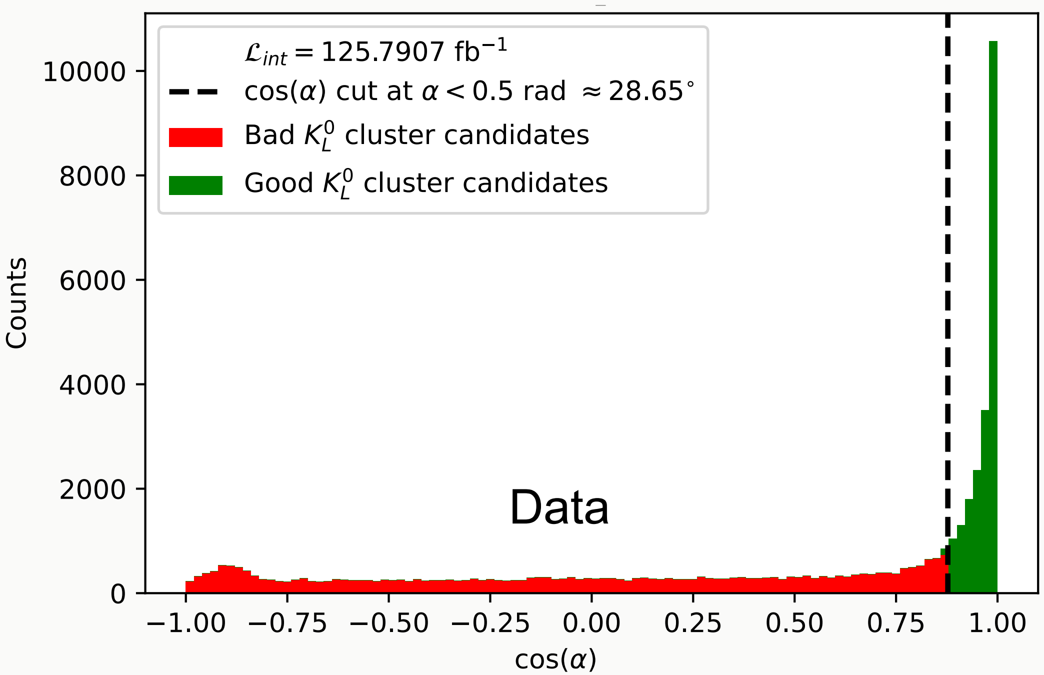
Backup: Purity and Efficiency for Data BDT Training

- For BDT Training create more Data
- Reiterate minimisation of cut purity and efficiency
- New cuts give p=90% and ε=90%



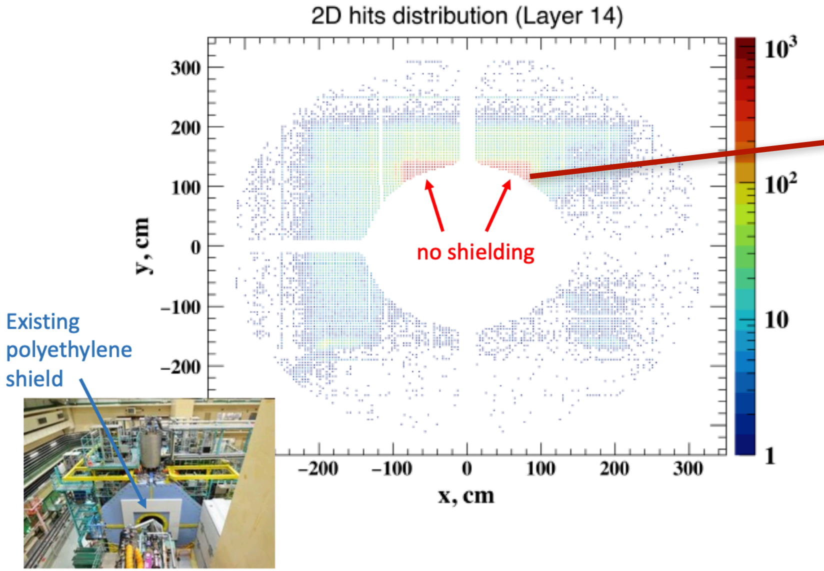
Backup: Preliminary definition of K-Long Cluster Candidates

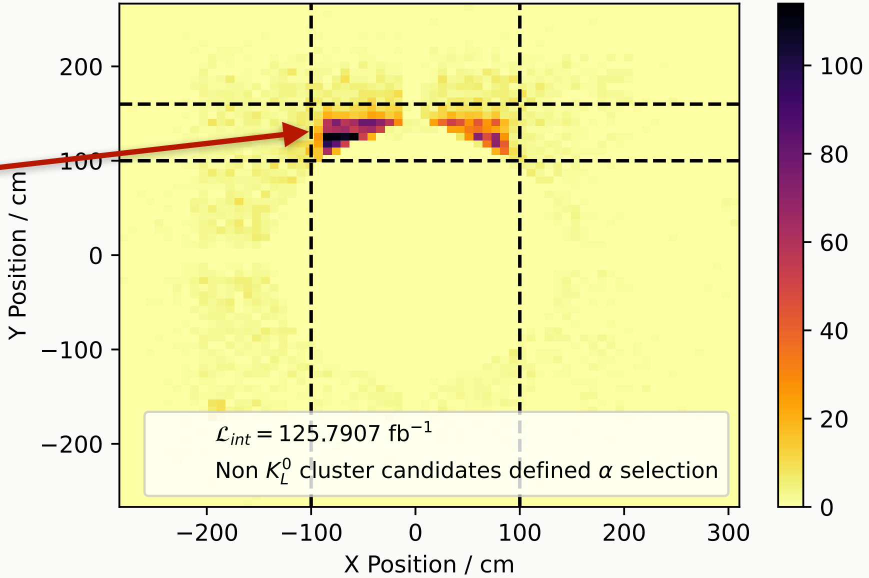
- Preliminary definition of K_L cluster candidates by the opening angle between missing momentum and KLM cluster vector
- Good K_L cluster candidates defined by $\alpha < 0.5$ rad
- What are these bad K_L cluster candidates?



Backup: Even More Background

Neutron illumination is not uniform across FWD endcap face

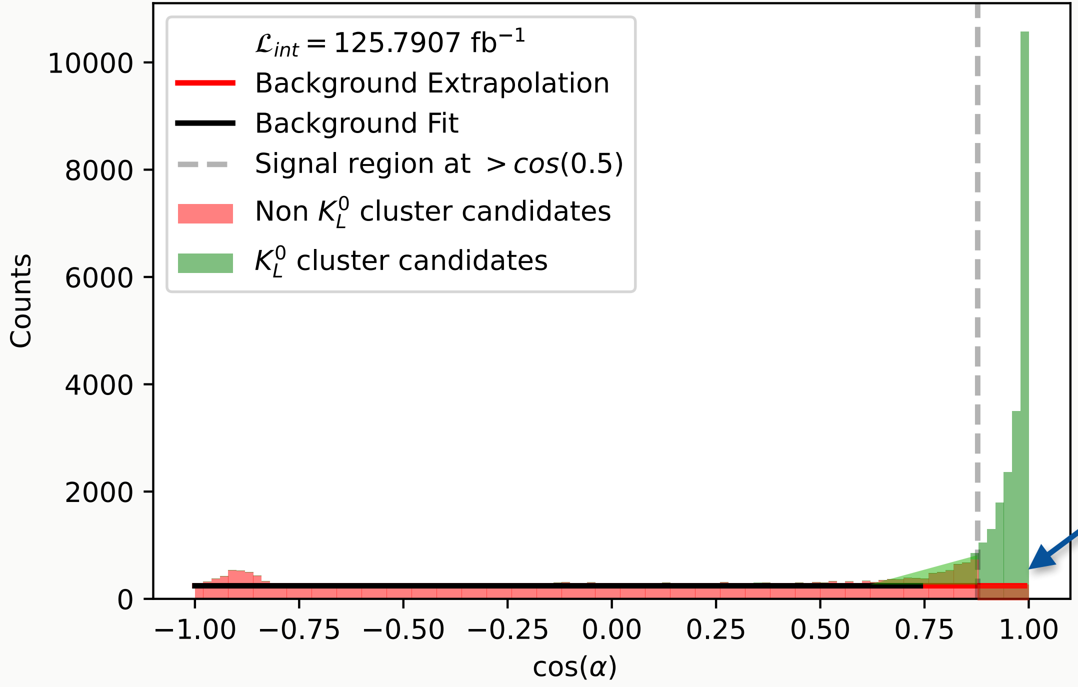




- Apply selection and thereby neglect 4557 background clusters from beam induced fast neutrons

[Leo Piilonen, KLM Work Plan for Summer 2022, 2010, indicohttps://indico.belle2.org/event/3781/contributions/18728/attachments/9438/14494/KLM_Summer2022Plans.pdf]

Backup: Background subtraction for Efficiency and Fake-Rate

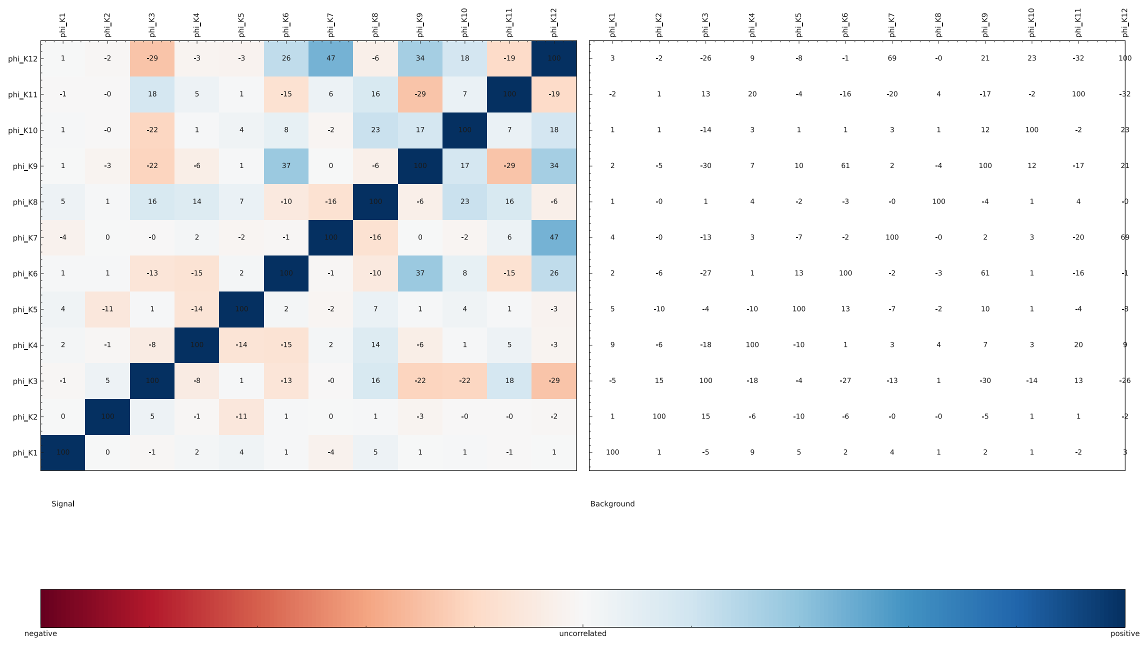


Integrate background function and total hist in signal region

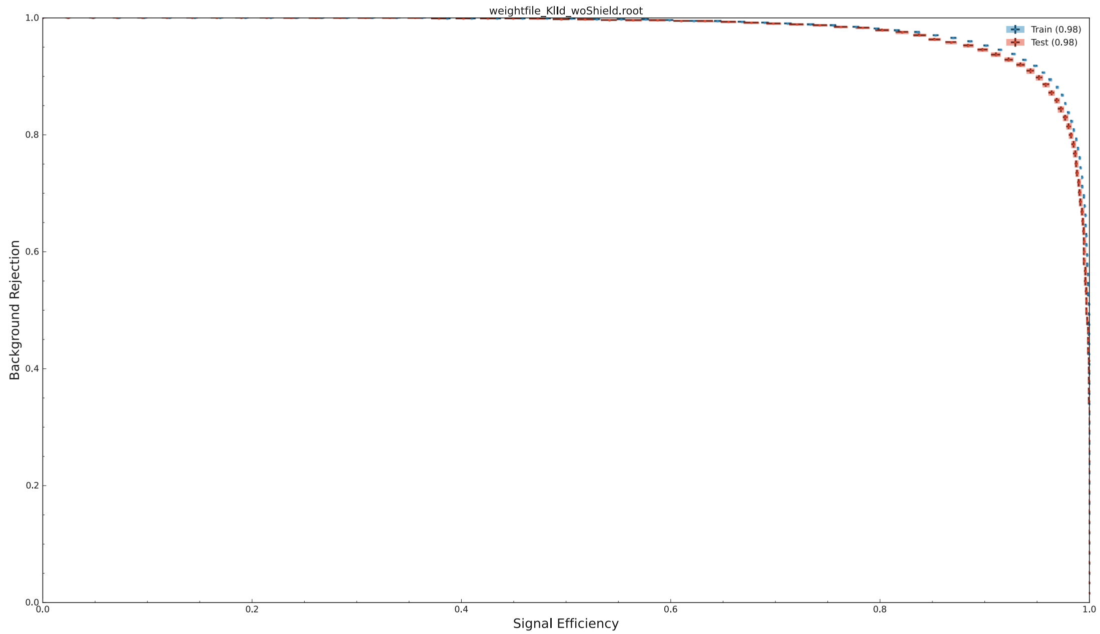
- Identification efficiency ≈ 0.733±0.007, fake-rate ≈ 1.225±0.008 average fake cluster per event

Backup: Variables and Correlations for BDT Training

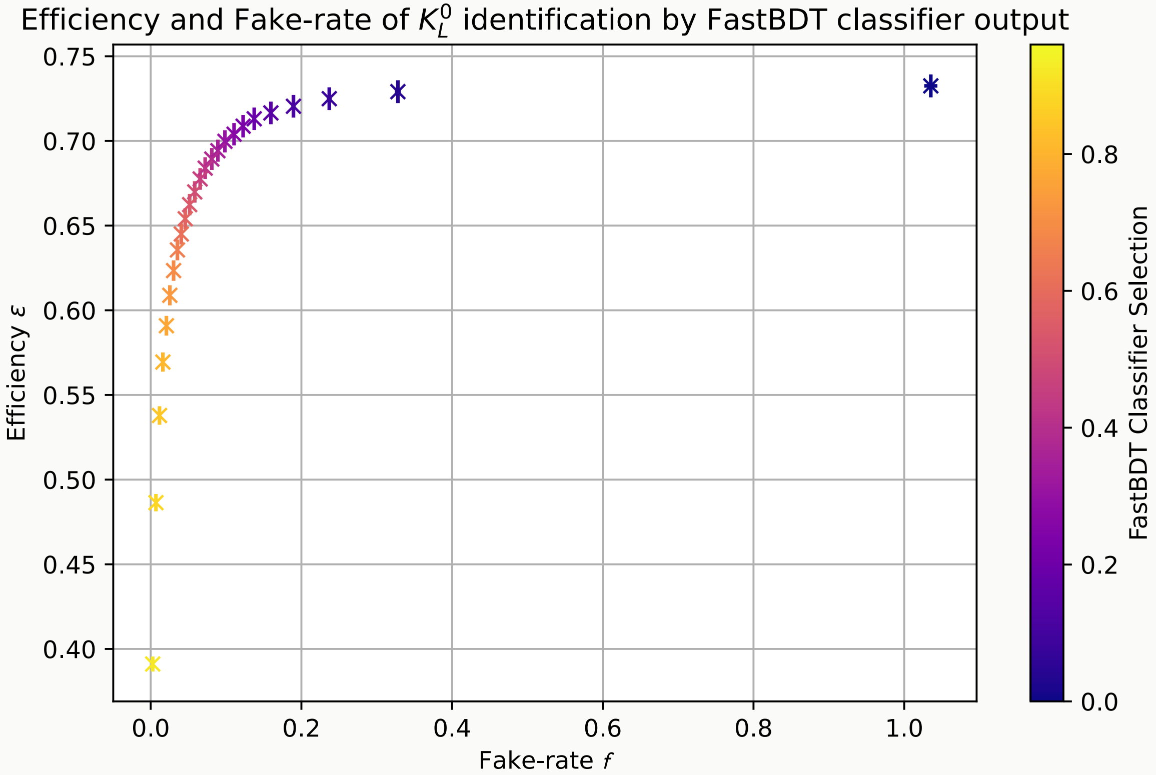
- phi_K1: KLM Cluster x Position
- phi_K2: KLM Cluster z Position
- phi_K3: KLM Cluster Inner Most Layer
- phi_K4: KLM Cluster Theta
- phi_K5: KLM Cluster Max Angle in CMS
- phi_K6: KLM Cluster Matches nECL Cluster
- phi_K7: KLM Cluster Track Distance
- phi_K8: KLM Cluster Timing
- phi_K9: KLM Cluster Belle ECL Flag
- phi_K10: KLM Cluster Layers
- phi_K11: KLM Cluster KlId
- phi_K12: KLM Cluster Matches nTracks



Backup: BDT ROC Curve

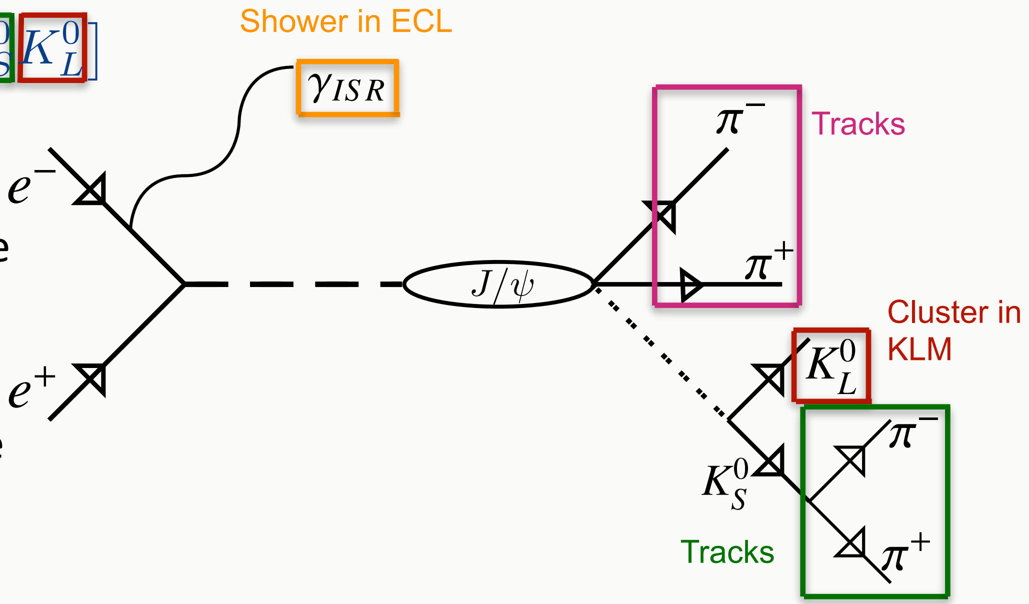


Backup: Compare ID's of BDT and current KL-ID variable

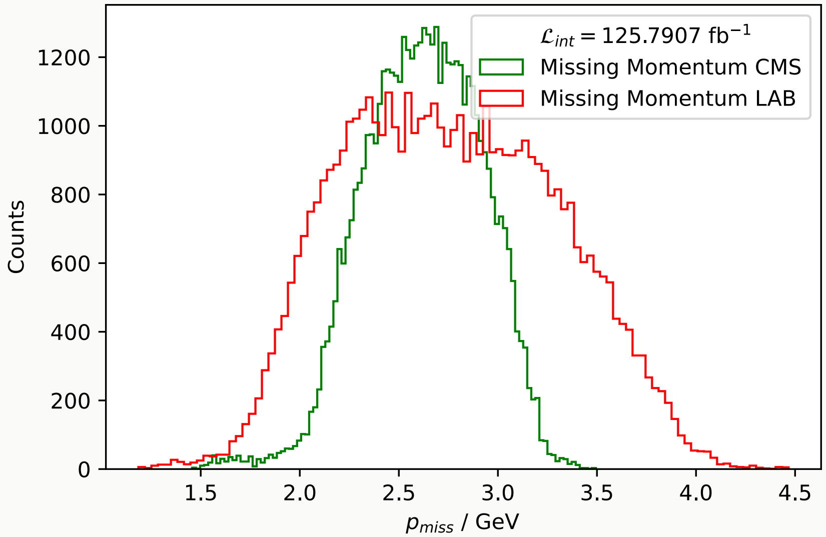


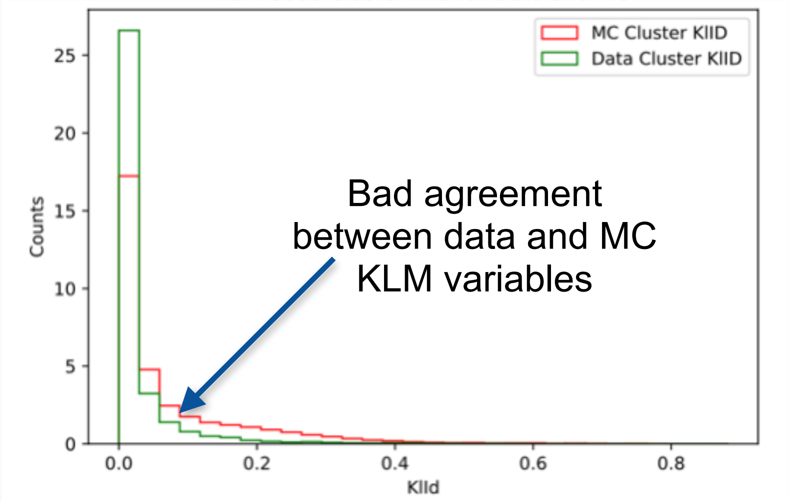
Backup: If one channel closes another opens

- In order to predict low momentum K_L use a different decay channel
- Use: $e^+e^- \rightarrow \gamma_{\text{ISR}} [J/\psi \rightarrow \pi^+\pi^- K_S^0 K_L^0]$
- Find high energy photon and K_S from two pions, plus two additional pions
- Problem are the pions in the final state and the pions from the K_S
- Through different combinations multiple candidates per event possible
- Need a Best K_S Selection
- Use same procedure as in ϕ study



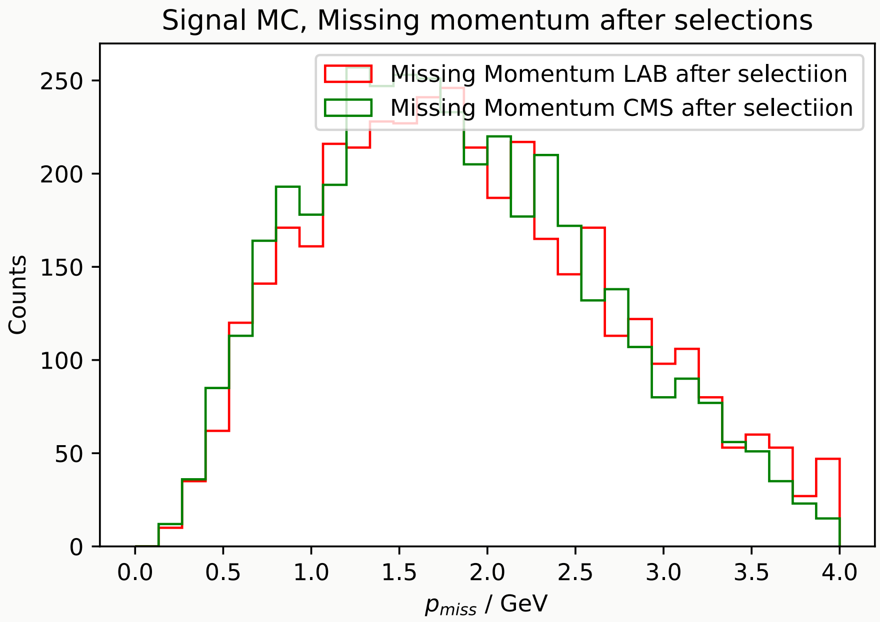
Backup: The momentum problem



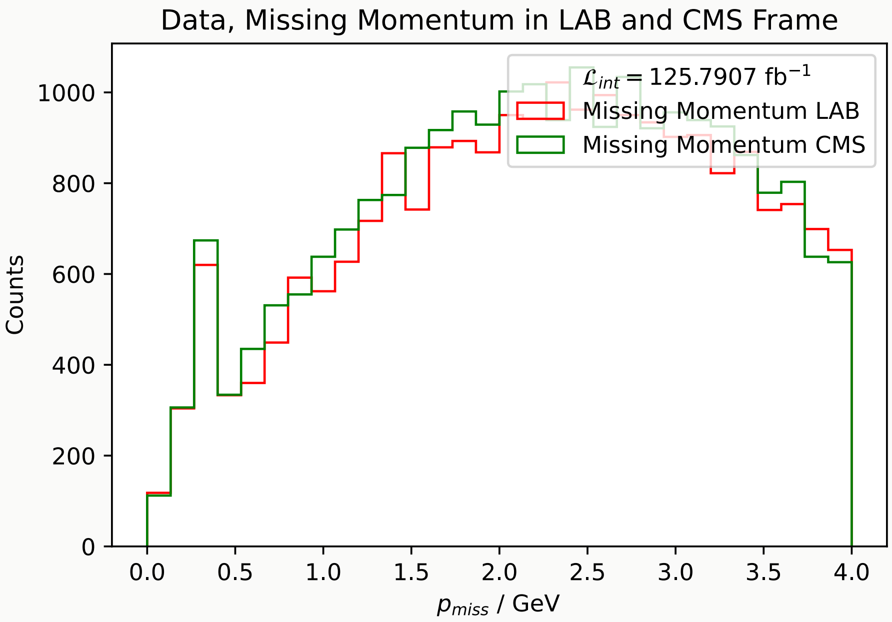


- Studies of: $e^+e^- \to \gamma_{\mathrm{ISR}}\left[J/\psi \to \pi^+\pi^- K^0_S K^0_L\right]$ showed no evidence for low momentum candidates
- Idea: use MC to train on low momentum K_L candidates

Backup: Missing Momentum in ISR J/ψ Decay

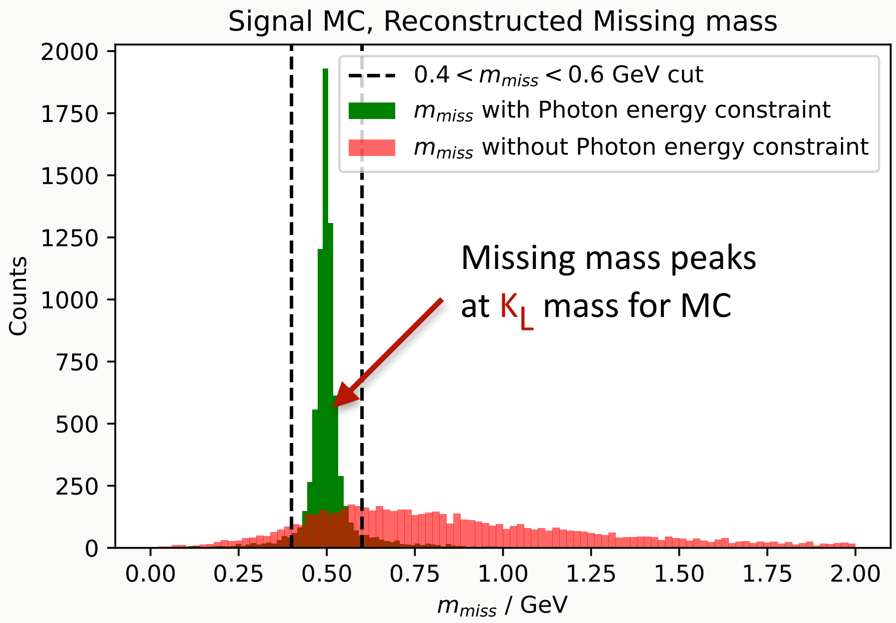


Signal MC

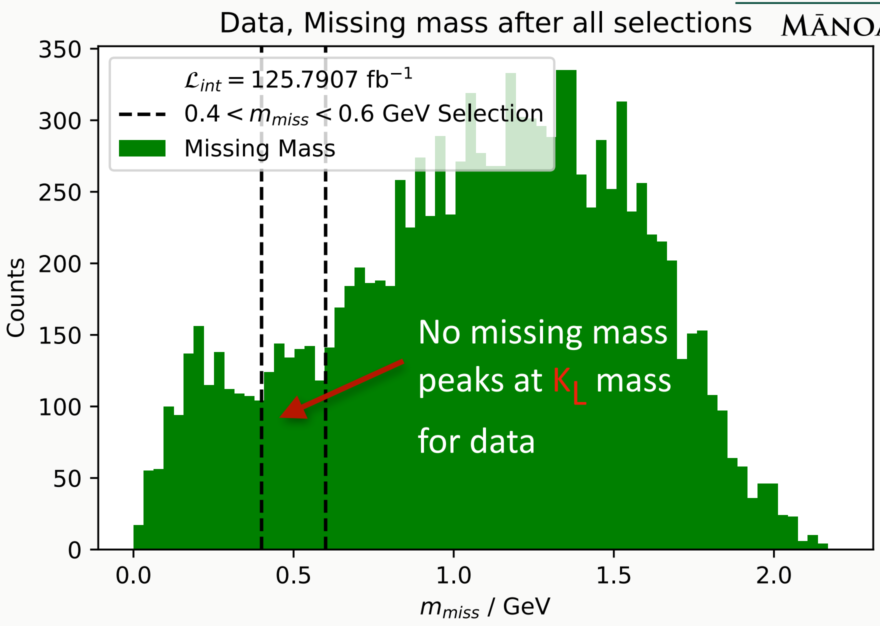


Data

Backup: Missing Mass with/without Photon Energy Constraint



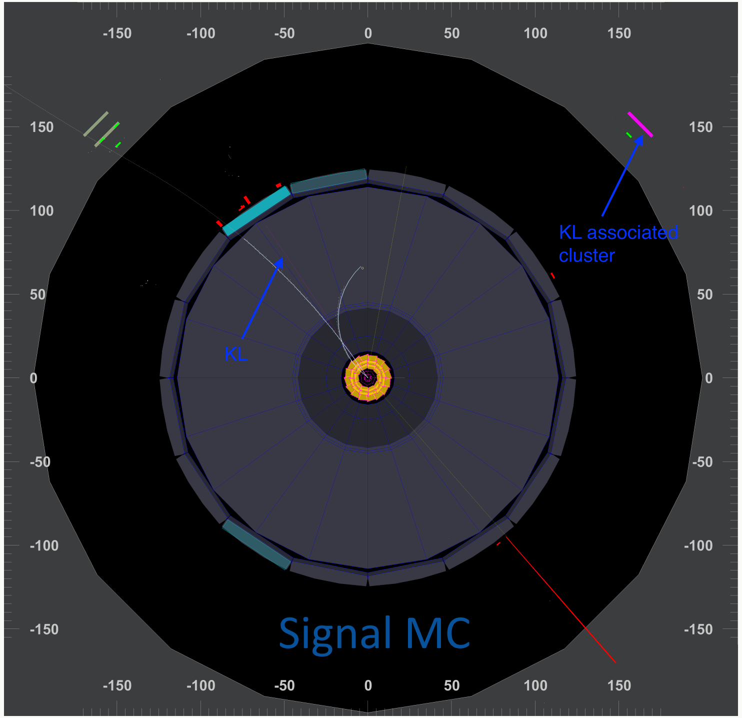
Signal MC

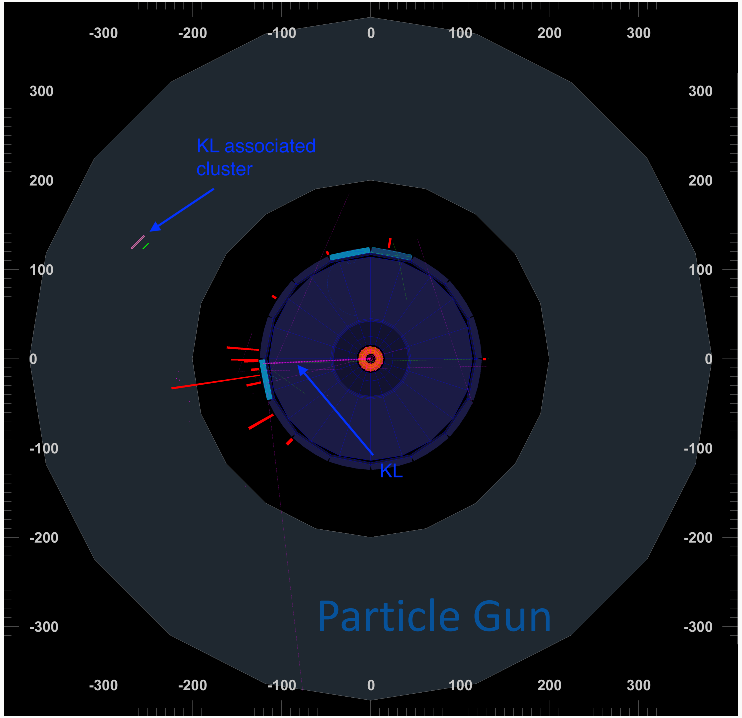


Data

- No evidence for good KL candidates due to massive background overlap in signal region

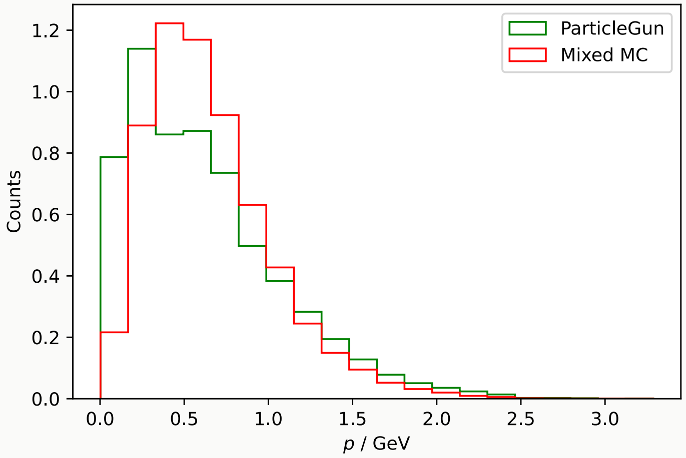
Backup: Width of cos(α) for signal MC and a particle gun

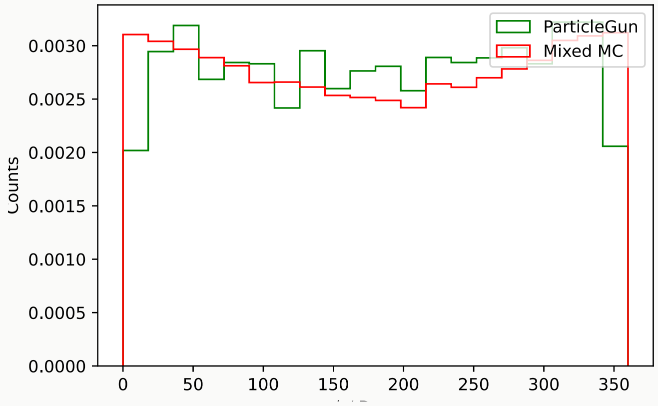


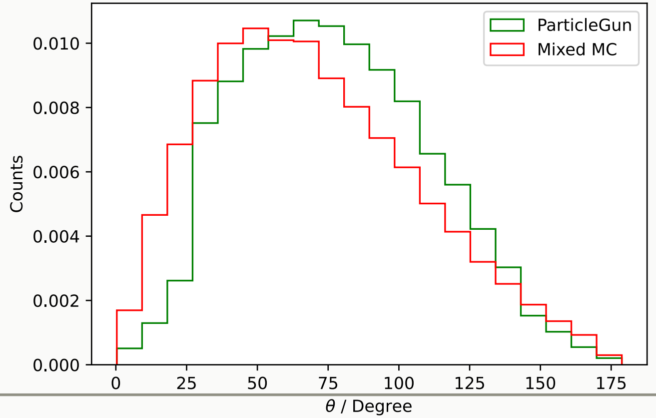


Backup: Training custom GEANT4 simulated signal against Data background events

- Model K_L momentum, phi and theta distribution based on MC generated K_L particles
- Differences due to assuming the variables are 1dim and not correlated

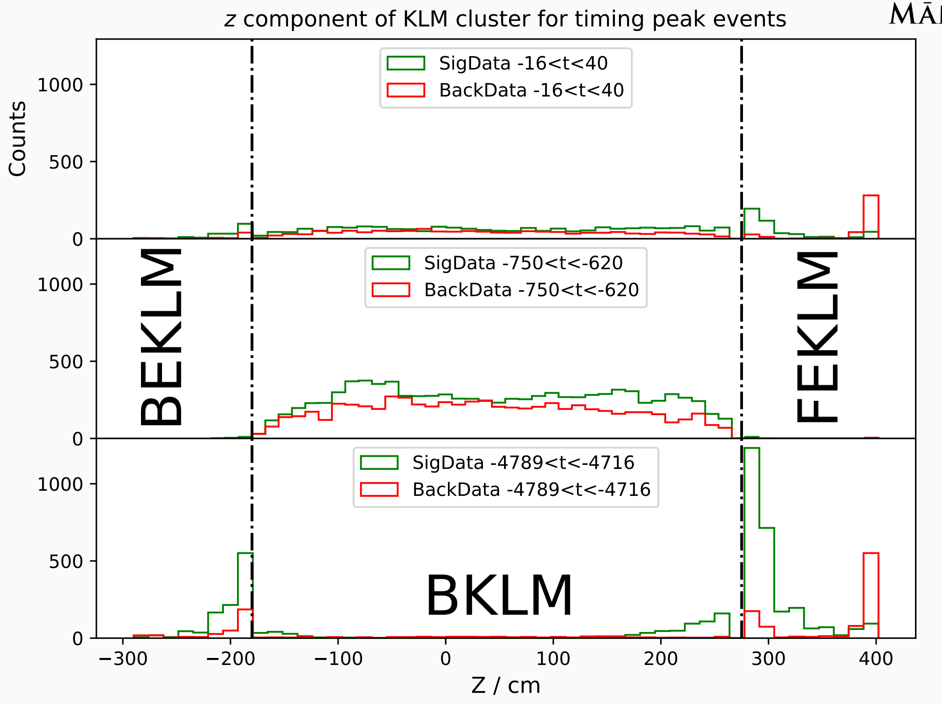






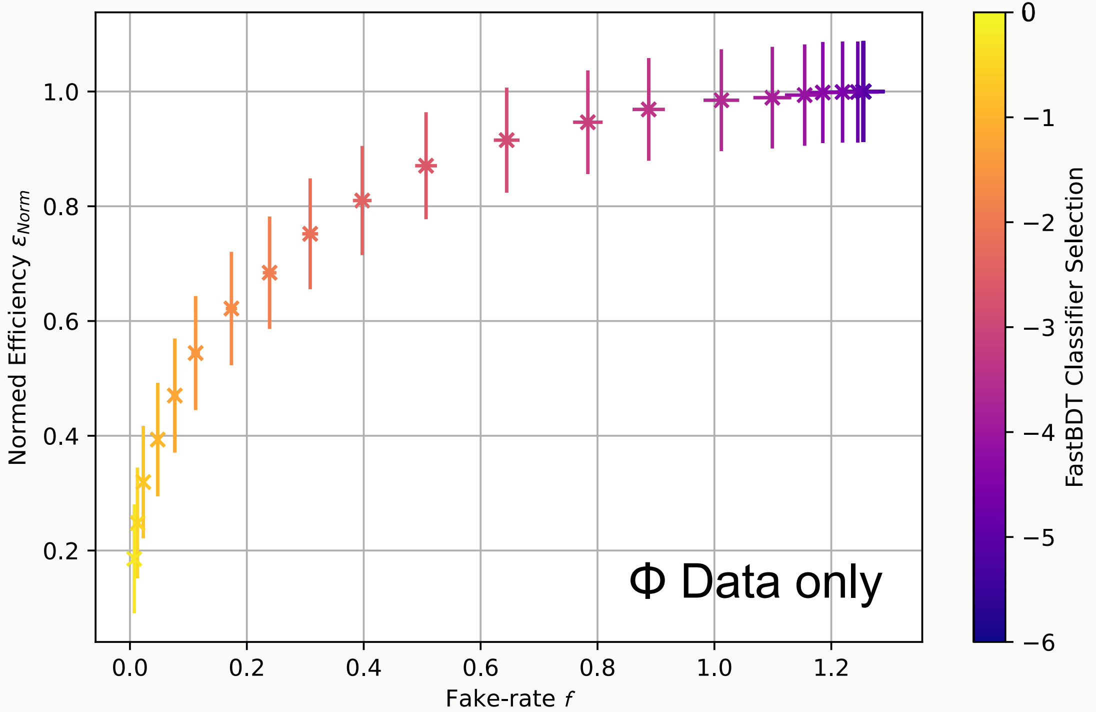
Backup: Selections for Combined Training

- Use Timing of KLM although no time calibration
- Neglect clusters in the back of the forward endcap
- Neglect events with matched tracks

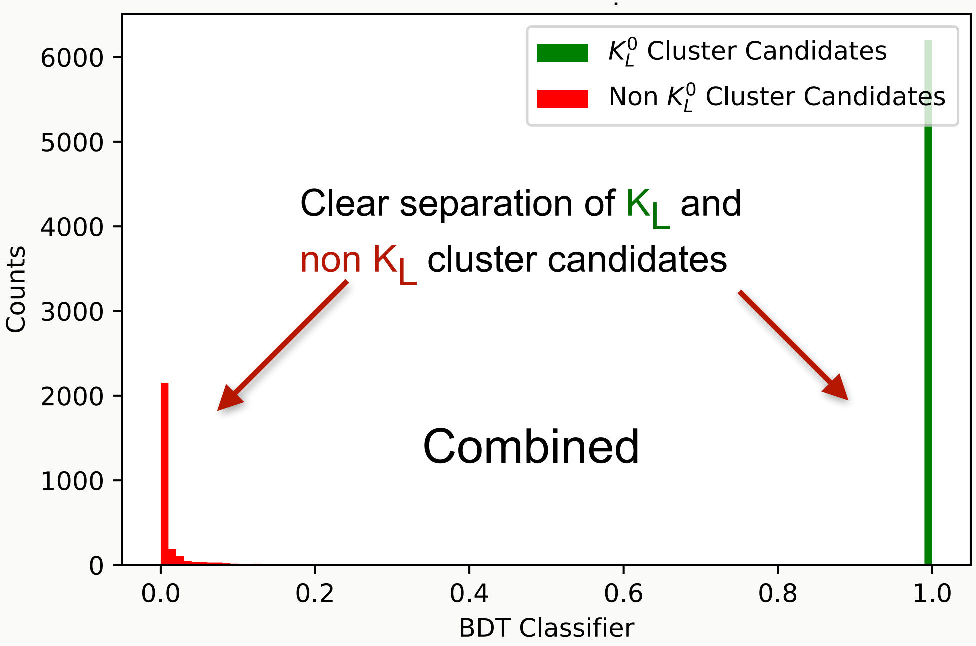


Backup: BDT Identification Efficiency and Fake-Rate

- We norm the efficiency in the data only sample by it initial value (without applying a cut)
- Achieve ~ (68.4 ± 9.8)% identification efficiency of K_L and a fake-rate of 0.23 average fake K_L clusters per event
- Thus provided a tool to reduce the fake-rate of K_L clusters with a good efficiency (regarding the overall KLM efficiency)

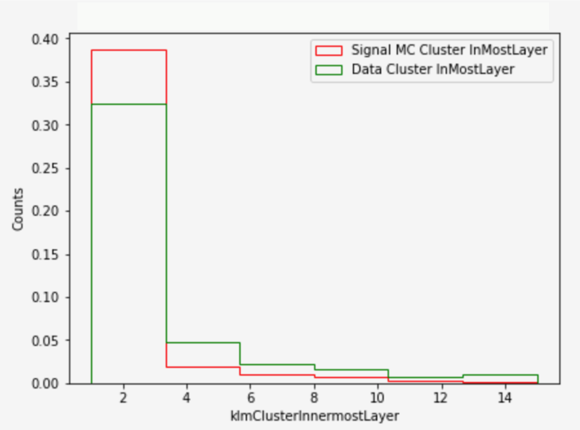


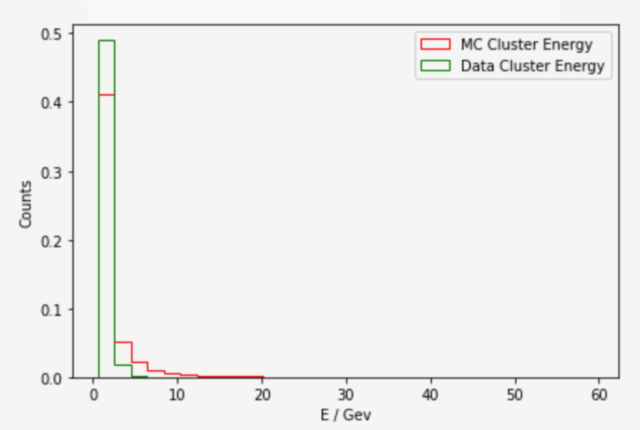
Backup: Start the BDT Training

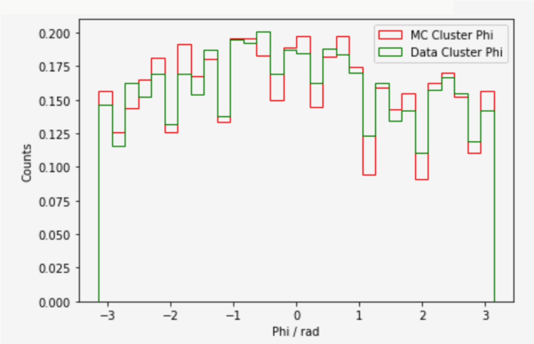


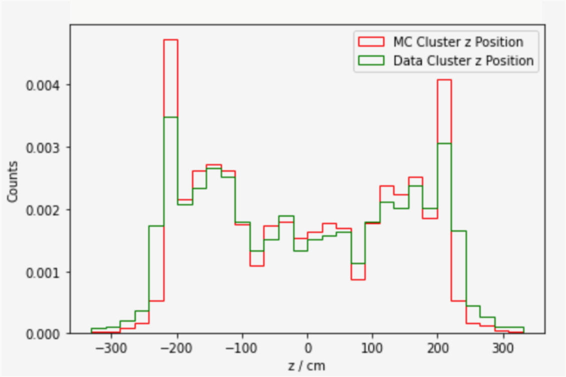
- Apply FastBDT to combined sample of MC signal and data background
- BDT show good separation power in both cases

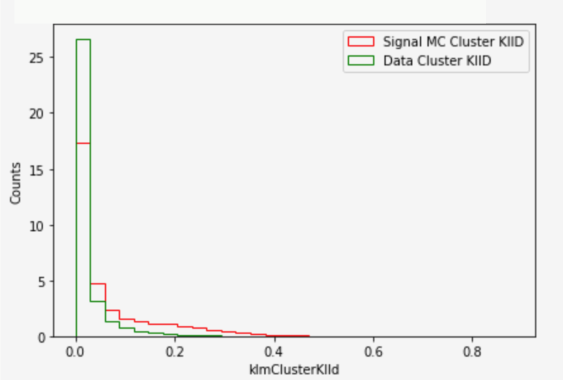
Backup: Data - MC agreement Phi study

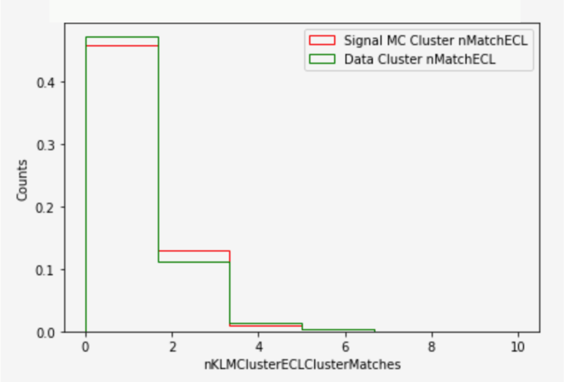












Backup: Mass broadening