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TRACKING IN BELLE II

5th Belle II Starterkit Workshop, KEK

31.01.2020

OUTLINE

- Event properties and backgrounds
- Track parameters and definitions
- Track finding
- Performance
- Summary

If not indicated differently, all plots are taken from Belle II Tracking Paper or from Belle II note PH-2018-041

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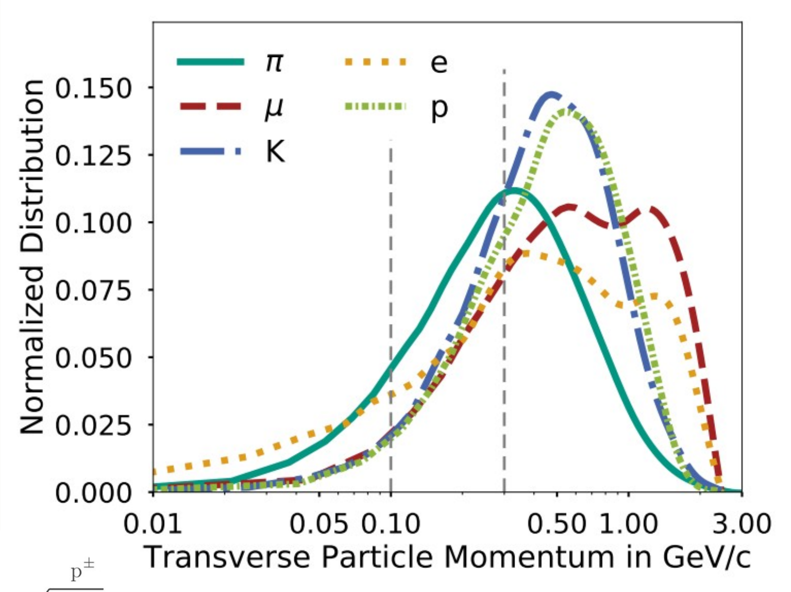
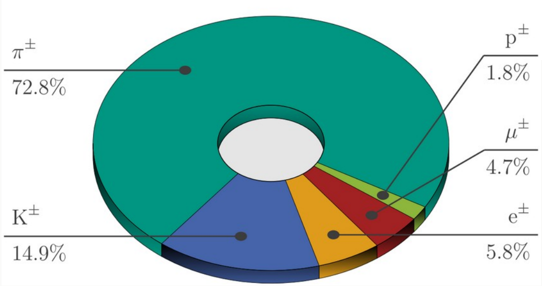
EVENT PROPERTIES AND BACKGROUNDS

How does a typical event in Belle II look like?

- On average we have 11 tracks (charged particles) in $\Upsilon(4S)$ events
- Rather soft momentum spectrum
  - Maximum p_T at ~300 MeV
  - Mean p_T at ~400-500 MeV
- Mostly pions



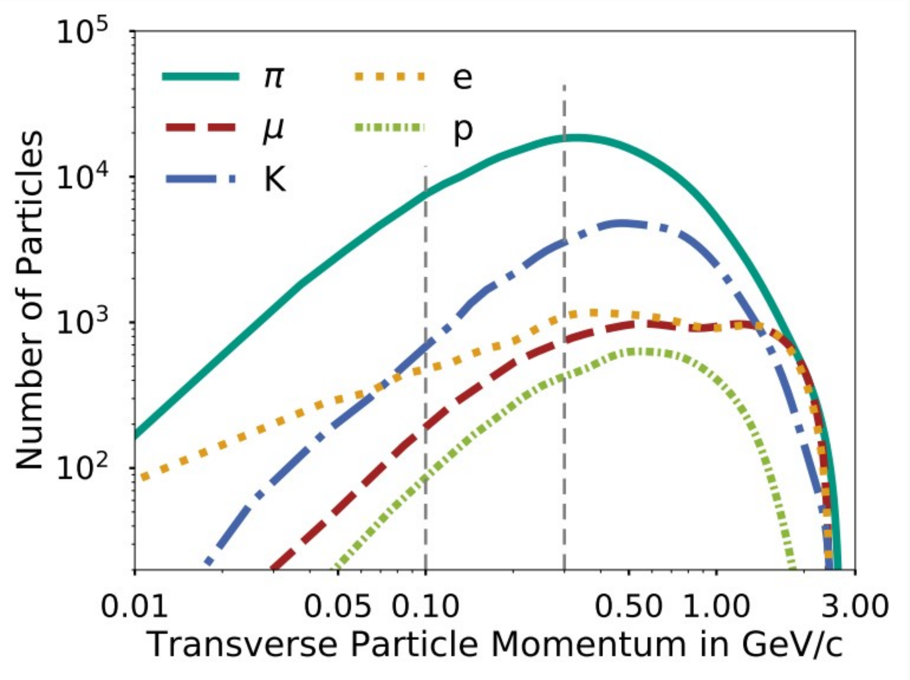
Grey vertical lines indicate where particles can only be found in VXD (left) and don't leave the CDC (right)



EVENT PROPERTIES AND BACKGROUNDS

Difficulties with these event properties

- Low momenta
  - Many tracks only in SVD and partial CDC
  - Multiple scattering and high energy loss
  - Looping tracks in CDC with hundreds of hits
  - No or only partial PID information for these tracks from PID detectors
  - Vertexing difficult since tracks hardly found, es for slow pions from $D^* \rightarrow D\,\pi_s$



EVENT PROPERTIES AND BACKGROUNDS

What are the backgrounds?

(This is **only about beam backgrounds**, not physics backgrounds!)

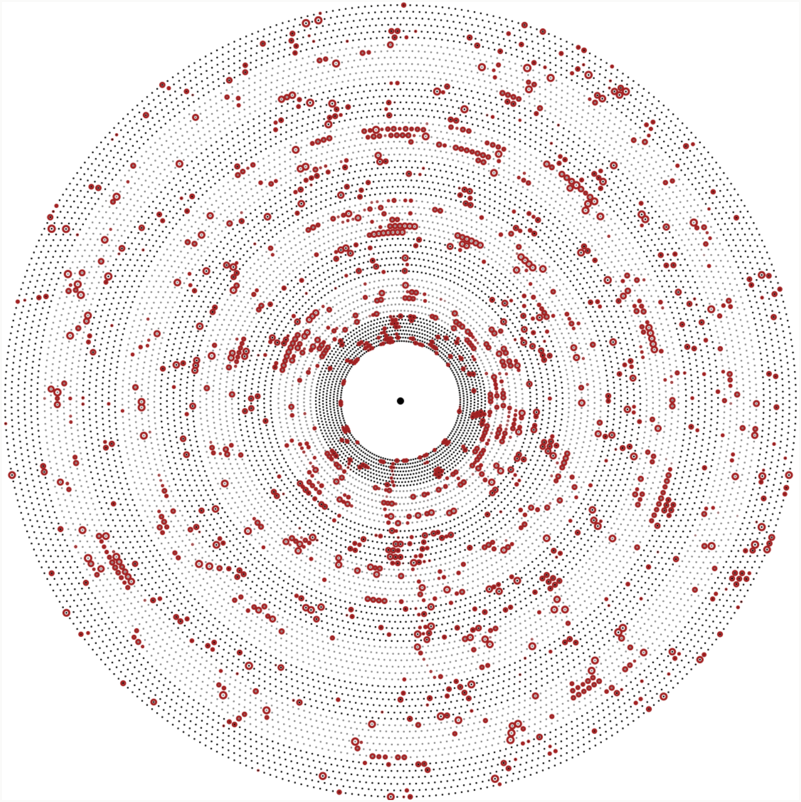
- Touschek scattering: particles of same charge within a bunch scatter at each other, depends on the current in each bunch and the size
- Beam gas: beam particles scattering at residual gas particles in the beam pipe (and on dust and other remainings)
- Two-photon: $e^+e^- \rightarrow e^+e^-e^+e^-$ / $e^+e^-\mu^+\mu^-$ / $\mu^+\mu^-\mu^+\mu^-$, dominant in the VXD volume
- Synchrotron radiation: beam particles emitting a photon when deflected in magnets, especially in QCS (final focussing)
- (Radiative) Bhabha: $e^+e^- \rightarrow e^+e^-$ / $\mu^+\mu^-$ (or τ pair) + one or more photons

EVENT PROPERTIES AND BACKGROUNDS

Influence of the backgrounds

- In PXD most hits due to background
  - On average ~25 hits (space points) per event from tracks, but >20k hits in total
  - With 3% occupancy and 3 pixels per space point: 76.8k space points
  - Dominated by two photon background
- SVD occupancy also dominated by background, mostly two photon background
  - Tracking only possible up to 2-3% occupancy in L3
  - Ghost hits due to combining wrong hits from u and v strips
- In CDC many active wires due to photons or neutrons
  - Single clusters that often can be rejected as background

EXAMPLE FOR CDC BACKGROUND



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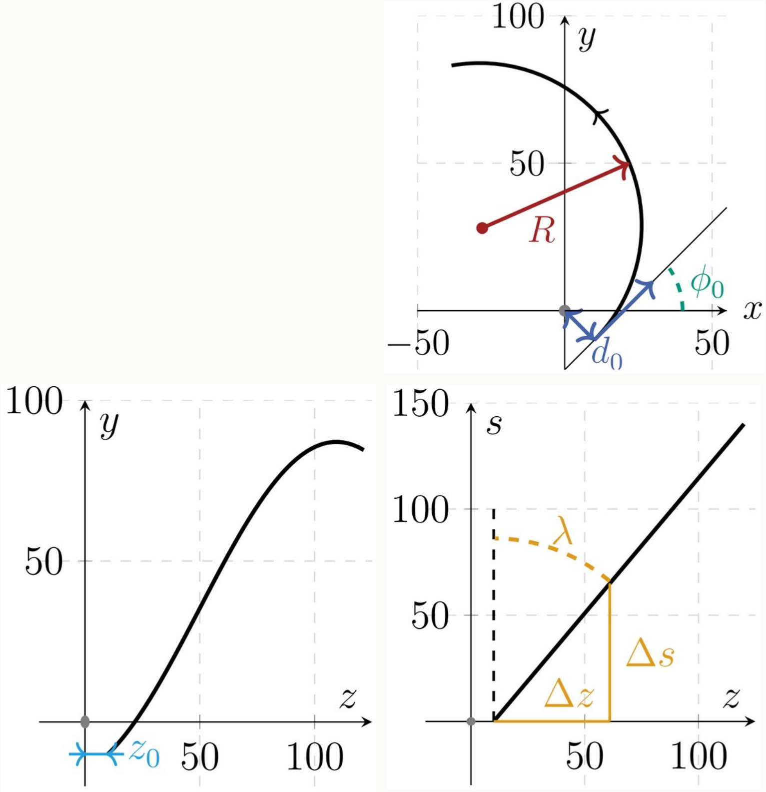
TRACK PARAMETERS

Usually tracks are described in helix parametrisation

- POCA: Point Of Closest Approach
  - d_0: distance of the POCA to the z-axis (in xy-plane)
  - ϕ_0: azimuthal angle of the track at POCA
  - $\omega = 1/R$: inverse radius of the track
    (R is proportional to p_T)
  - z_0: z coordinate of the POCA
  - λ_0: polar angle of the track at POCA
    general definition: $\lambda = \pi/2 - \theta$



DEFINITIONS

- Baseline of tracking validation: MC-tracks
  - Only limited by detector acceptance, efficiency and resolution
  - Defines 100% of all findable tracks
  - Cannot be surpassed by definition
- Track finding also called pattern recognition (PR)
- Ideal track finder performs as closely as possible to MC track finder
- Each track should be assigned all of the hits belonging to exactly that (MC-)track but not incorrect ones (like background hits or hits belonging to a different track)

HIT EFFICIENCY AND HIT PURITY

Two important figures of merit for each MC-track and PR-tracks

- Hit efficiency
  - Quantifies how efficient PR is in identifying **all** hits belonging to a single particle
  - Fraction of hits of a given MC-track contained in a given PR-track
  - Ideally: one and only one PR-track that contains all hits of a given MC-track
- Hit purity
  - Quantifies how precise PR is in identifying the hits belonging to **only one** particle
  - Fraction of hits of a given PR-track contained in a given MC-track
  - Ideally: one and only one MC-track to which all hits of a given PR-track belong
- Both should be 100% for the correct pair and zero for all others

TRACKING EFFICIENCY, FAKES AND CLONES

- Tracking efficiency: fraction of matched MC-tracks
  - Matched: hit purity exceeds 66% **and** hit efficiency exceeds 5%
  - Low hit efficiency requirement for curling tracks that are only partially found
- There are cases where something goes wrong
  - Fake tracks: tracks that are created from e.g. random combinations of hits or hits of two MC-tracks but both with low purity
  - Clone tracks: MC-tracks that are found multiple times in PR
    - E.g. a track is found in SVD and CDC separately, but the two entities are not merged into one single track in the end
  - Both should be close to zero, as each additional track in an event, be it clone or fake, has an impact on analysis since e.g. energy and/or momentum conservation might be violated

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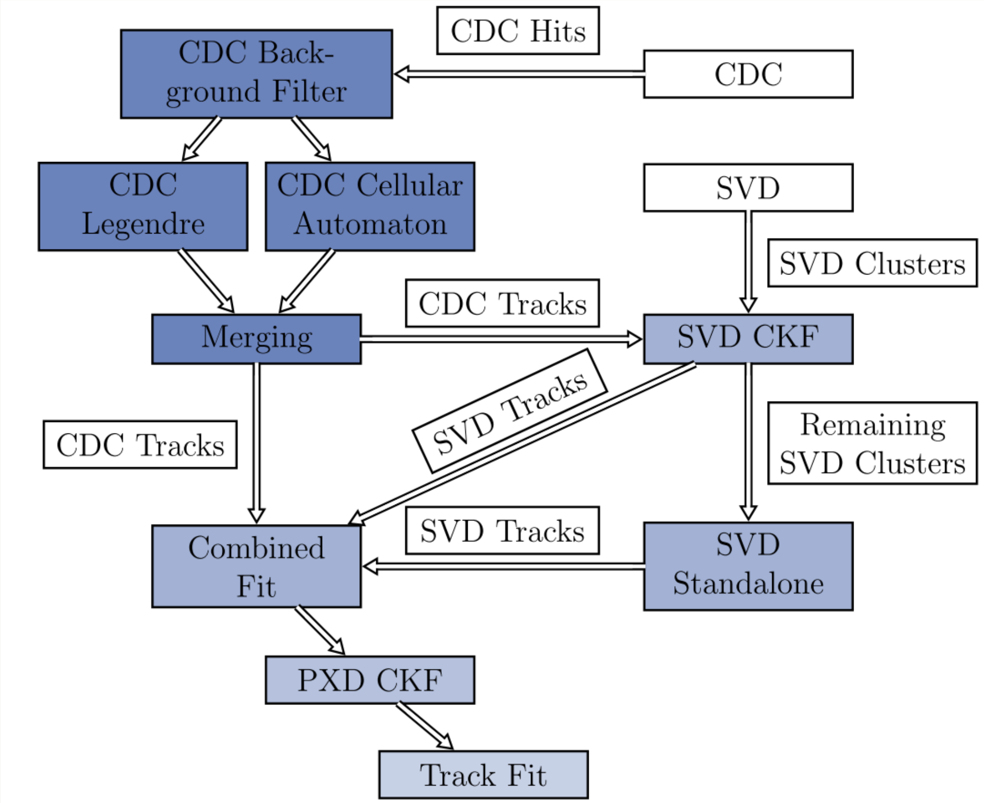
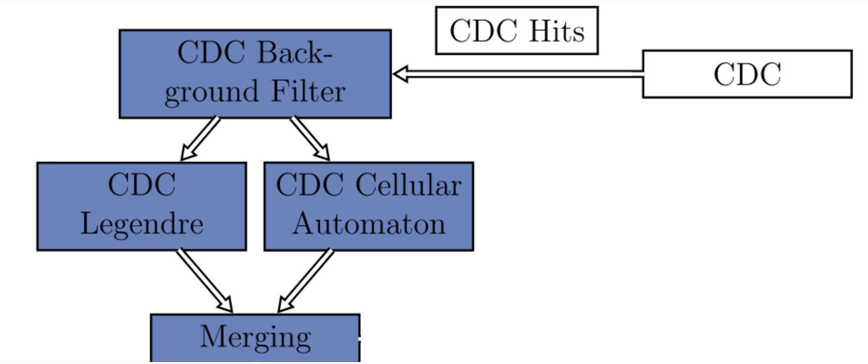
TRACKING FINDING - OVERVIEW



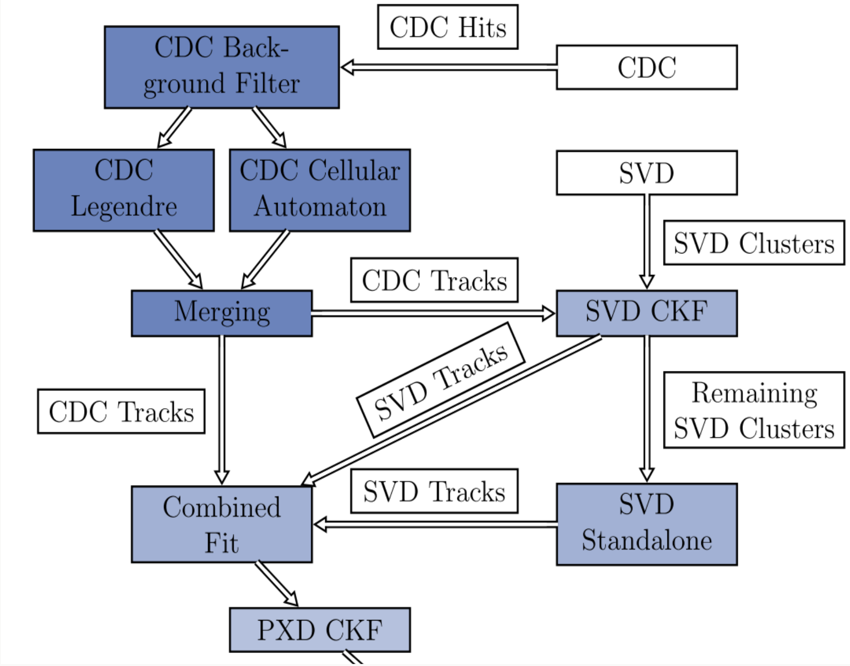
TRACKING FINDING - CDC

- Input to CDC track finding: CDC Hits
- Two different algorithms in CDC
  - Global track finding (CDC Legendre) searches for tracks globally
    - First on axial super layers (SL) only
    - Later attaches hits of stereo SL
  - Local track finding (CDC Cellular Automaton) searches for connected hits in neighbouring wires
- Merge all information into an intermediate set of tracks



TRACKING FINDING - SVD

- Input for SVD tracking: SVD Clusters and CDC tracks
- Extrapolate CDC tracks into SVD using Combinatorial Kalman Filter (CKF) forming first set of SVD tracks
- On remaining SVD clusters: SVD standalone track finding (VXDTF2) forming second set of SVD tracks



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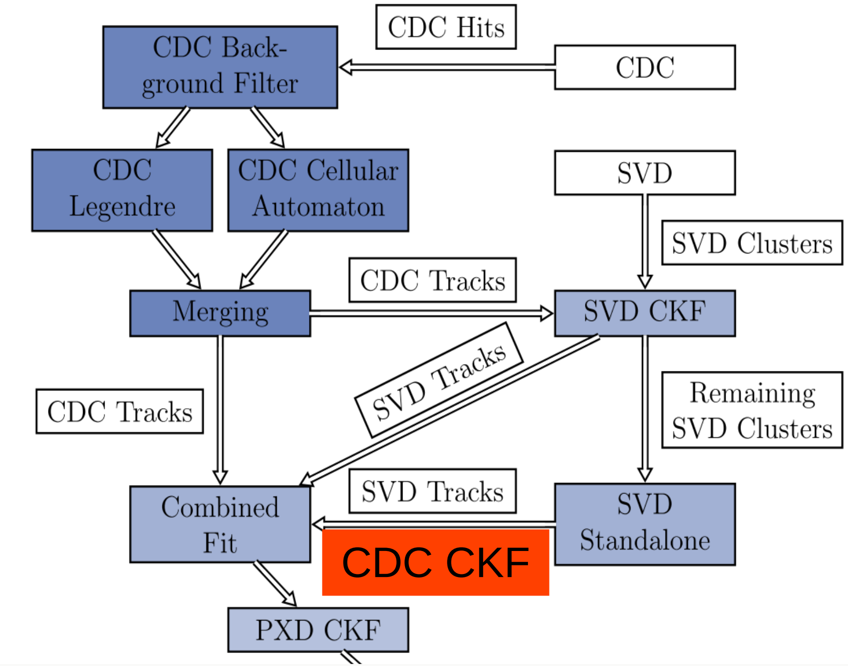
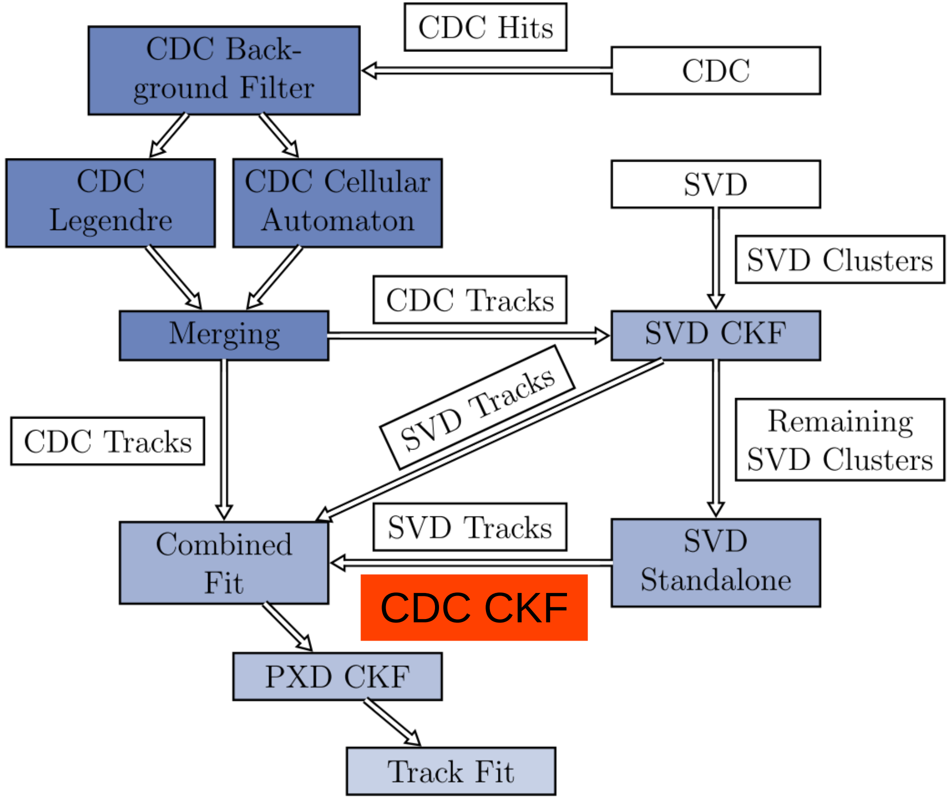
- Extrapolate CDC tracks into SVD using Combinatorial Kalman Filter (CKF) forming first set of SVD tracks
- On remaining SVD clusters: SVD standalone track finding (VXDTF2) forming second set of SVD tracks
- Recent change: tracks from VXDTF2 will be extrapolated into CDC to add more information to these tracks (CDC CKF)
- Combining all possible tracks and performing a combined fit



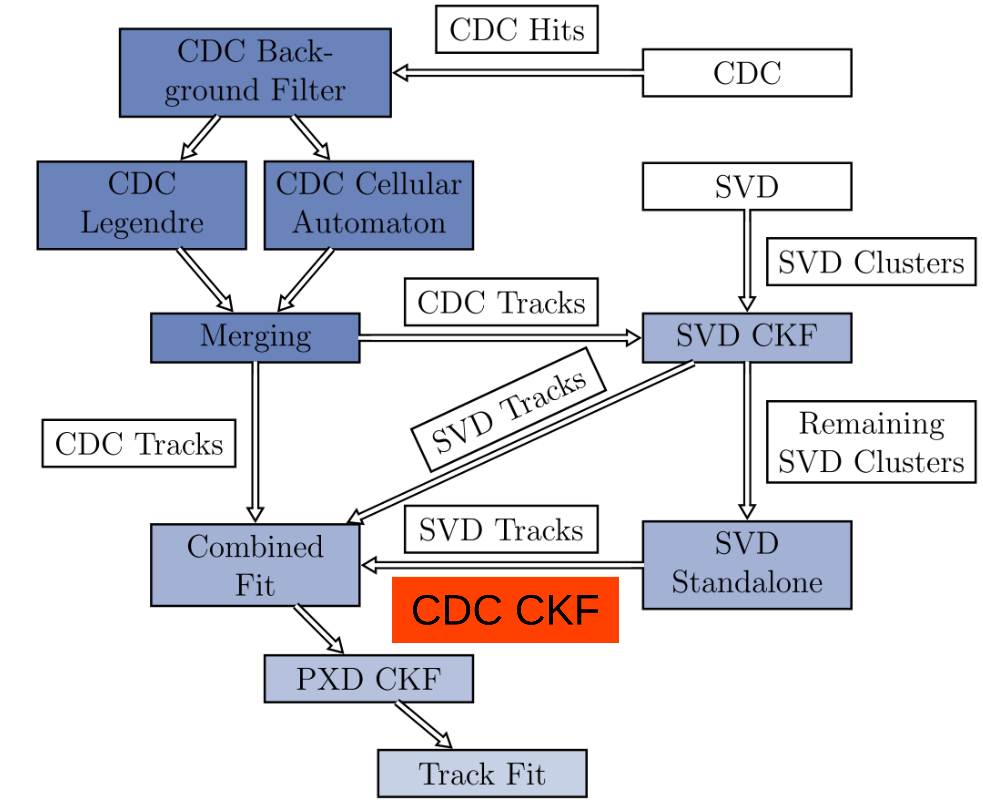
TRACKING FINDING – PXD AND FINAL FIT

- Tracks created in combined fit are extrapolated to PXD (PXD CKF)
- PXD hits are attached and a full and final track fit is performed, using multiple track hypotheses (π, μ, e, K, p, deuteron, He^{2+}) because of different masses
- After final fit with Deterministic Annealing Filter (DAF) provided by Genfit2 extrapolation of tracks to POCA / origin to extract helix parameters and four-momenta as well as all relevant covariance matrices



TRACKING FINDING – ADDITIONAL INFOS

- On HLT tracking without PXD is performed to create Regions of Interest (RoI) on PXD and only safe hits inside these RoI
- Recent development: Create CKF seeds in calorimeter (ECL) with momentum estimate based on ECL clusters.
  This would be an additional step before combined fit and PXD CKF:
  - CDC standalone
  - SVD CKF
  - SVD standalone
  - CDC CKF
  - ECL To CDC CKF



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PERFORMANCE

- Performance plots for simulated instantaneous luminosity of 8 x 10^{35} $cm^{-2}s^{-1}$ and full beam-induced backgrounds
- Full detector in nominal position
- All comparisons against MC, all quantities like purities of efficiencies based on previous definitions
- For the MC simulations only results for the pion hypothesis are shown
- Distinction between
  - Primary particles: particles directly from $\Upsilon(4S)$ decays and decays of the short-lived decay particles
  - Secondary particles: all particles generated by GEANT4 during detector simulation

PERFORMANCE – FINDING EFFICIENCY

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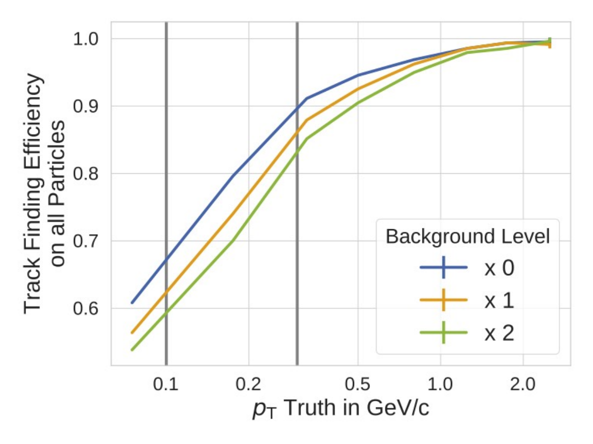
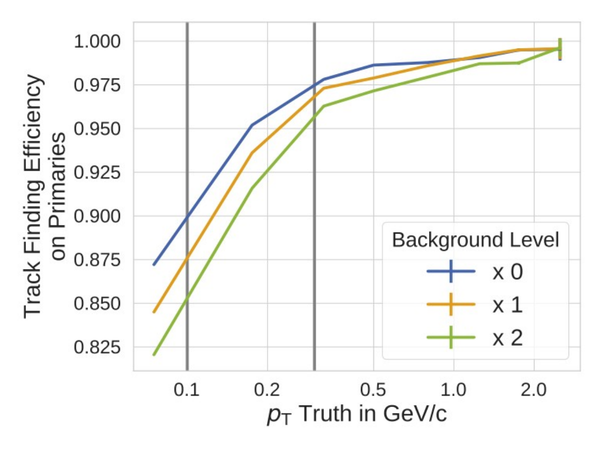
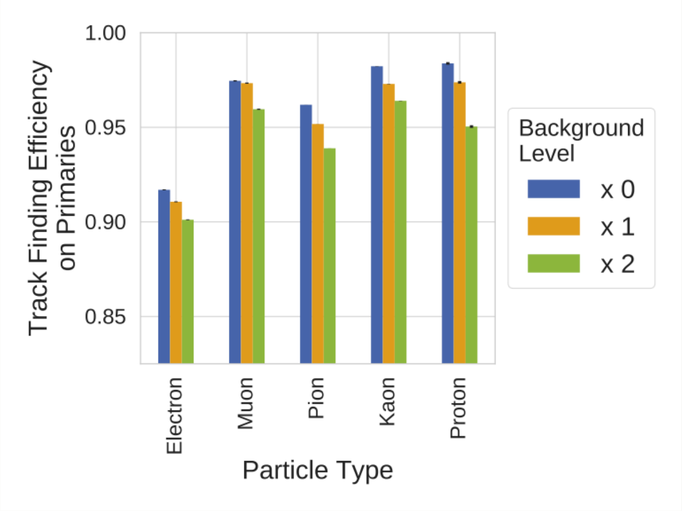
- Finding efficiency for all particles (left) and primaries only (right)
- Efficiency well above 90% for high enough p_T (above 95% for primaries only)
- Higher finding efficiency for higher p_T, and degradation with increasing background
- Higher finding efficiency on primaries only compared to all (and thus secondaries)

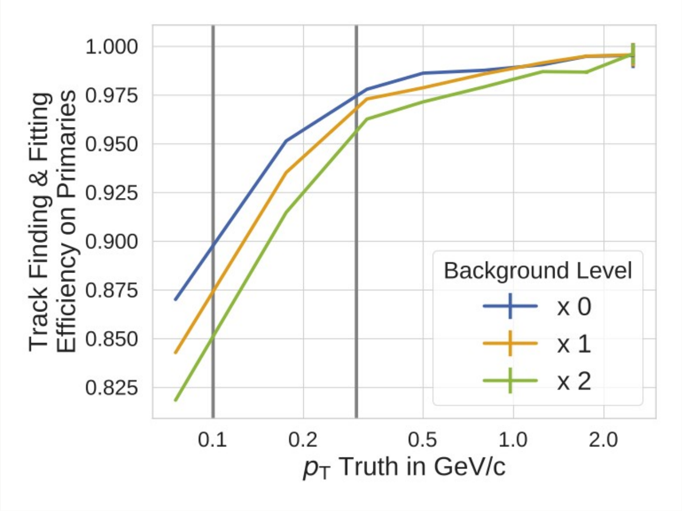




PERFORMANCE – FINDING EFFICIENCY

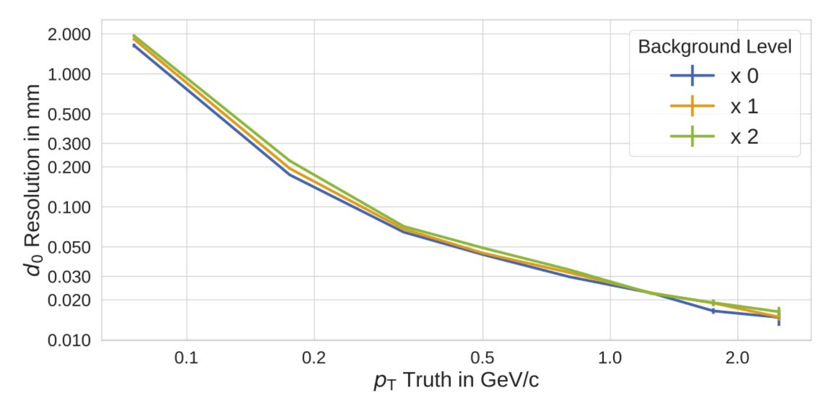
- Finding efficiency for primary particles from $B\bar{B}$-decays for each particle type and different background levels (left), overall efficiency dominated by pions
- Finding and fitting efficiency on primaries for different background levels fitted with DAF (right)

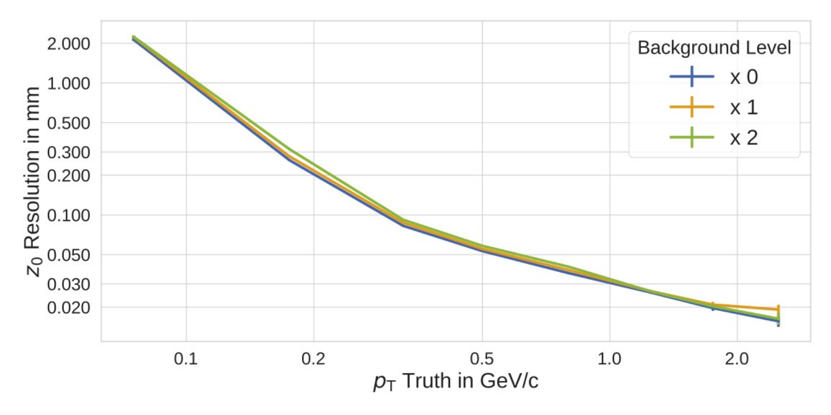




PERFORMANCE – RESOLUTIONS

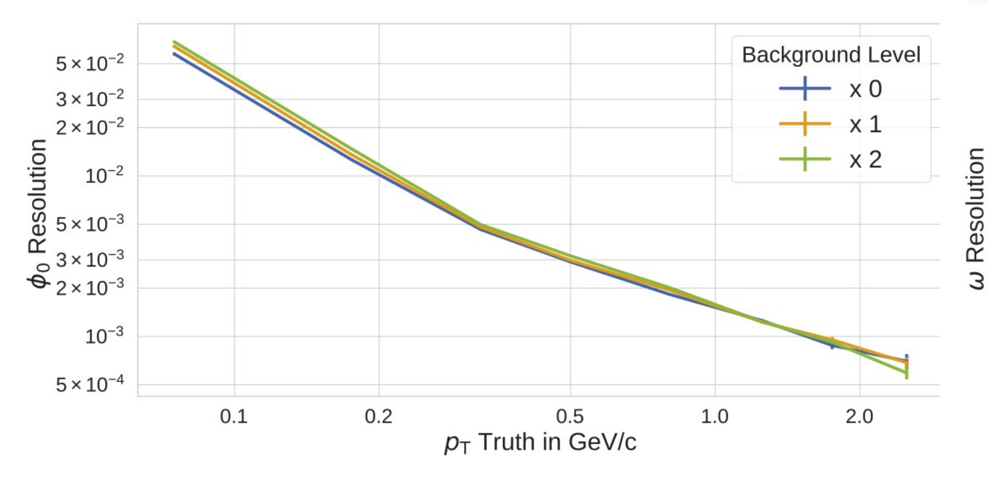
- Resolutions for d_0 (left) and z_0 (right) for simulated Υ(4S) events
- Both well below 100 µm for tracks with $p_T > 200$ MeV (tracks reach CDC)
- Nearly independent of background level
- Useful cuts: $|d_0| < 2$ cm and $|z_0| < 2 \ldots 5$ cm (depending on what you want to do)

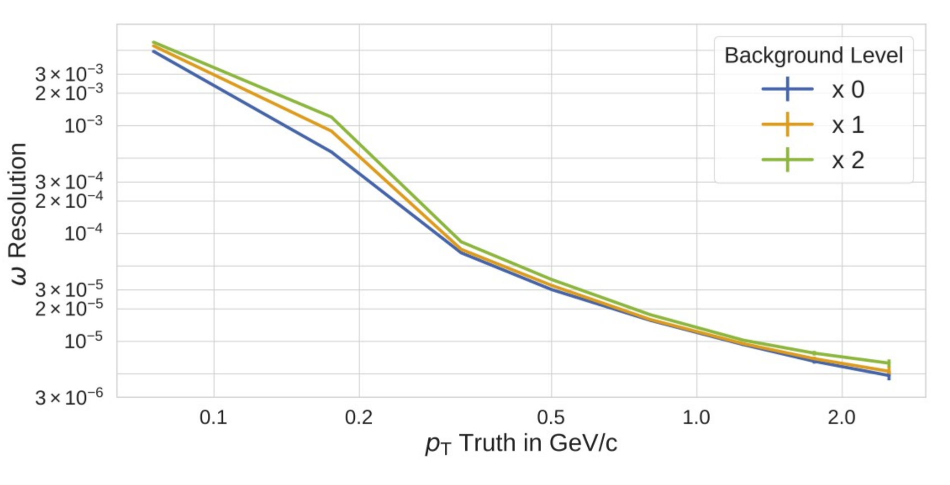




PERFORMANCE – RESOLUTIONS

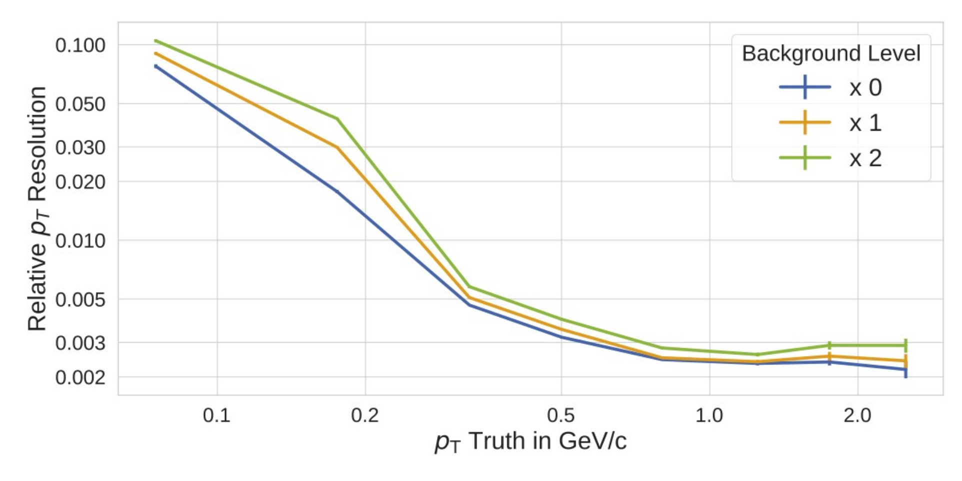
- Resolutions for ϕ_0 (left) and ω (right) for simulated Y(4S) events
- Best performance when tracks pass full CDC (p_T > 300 MeV)
- Nearly independent of background level

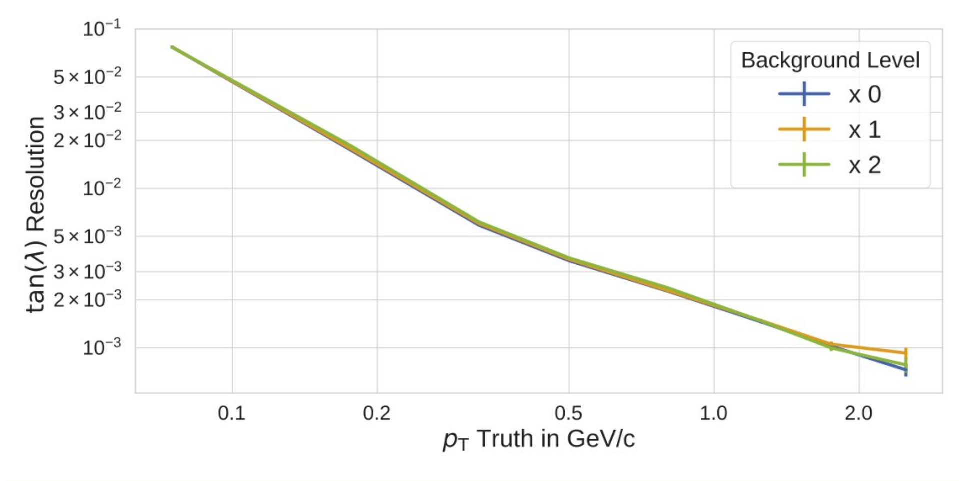




PERFORMANCE – RESOLUTIONS

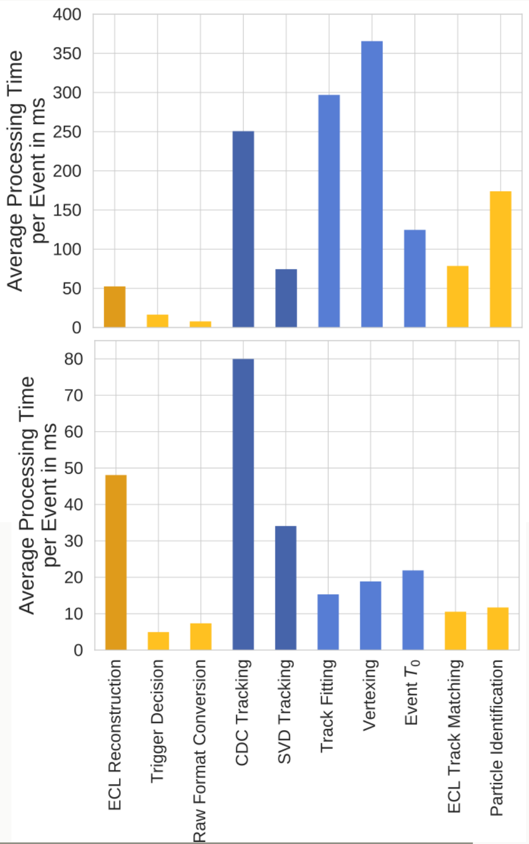
- Resolutions for pT (left) and tan(λ) (right)
- p_T resolution strongly depends on whether particles pass full CDC ($p_T > 300$ MeV)
- Nearly independent of background level





PERFORMANCE – EXECUTION TIME

- Fast execution time crucial for online track reconstruction and triggering
- Average processing time for Y(4S) events (up) and e^+e^- events (down) (notice different scales on y-axes)
- Tracking very time consuming, especially track fitting, vertexing and event T_0 estimation for Y(4S) events because of higher track multiplicity
- If you want to help us improve the processing times, or any other aspect of the tracking software and performance, you‘re welcome to join the tracking group and to contribute to our software (maybe as your service task)

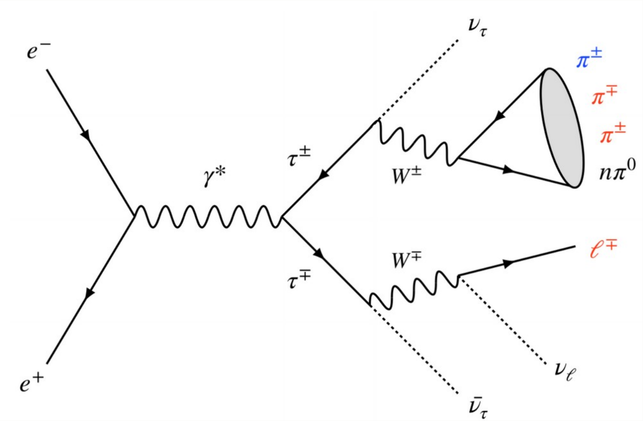


PERFORMANCE – TRACKING WITH TAUS

- $e^+e^- \rightarrow \tau^+\tau^-$ (compare figure)
- One τ decays to lepton (l = e or μ) + neutrinos, the second τ decays to πs (+ neutrino), where one of the charged π is the probe particle (in blue)
- Measure efficiency ε by calculation the ration of detecting all four particles (N_4) vs detecting three (N_3) or four particles (A is the detector acceptance)

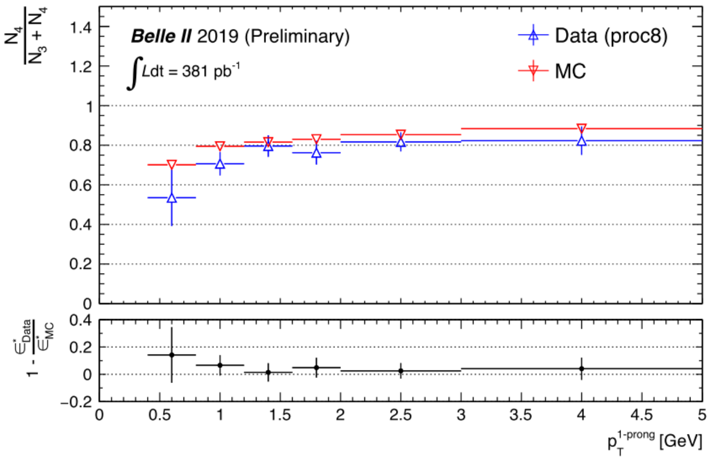
$$\epsilon \cdot A = \frac{N_4}{N_3 + N_4}$$

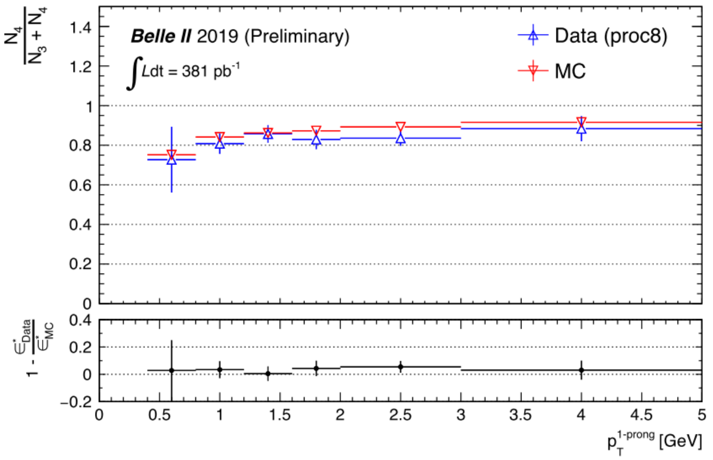
- In following plots, 1-prong describes the properties of the lepton, so the performance is evaluated for different values of the lepton properties



PERFORMANCE – TRACKING WITH TAUS

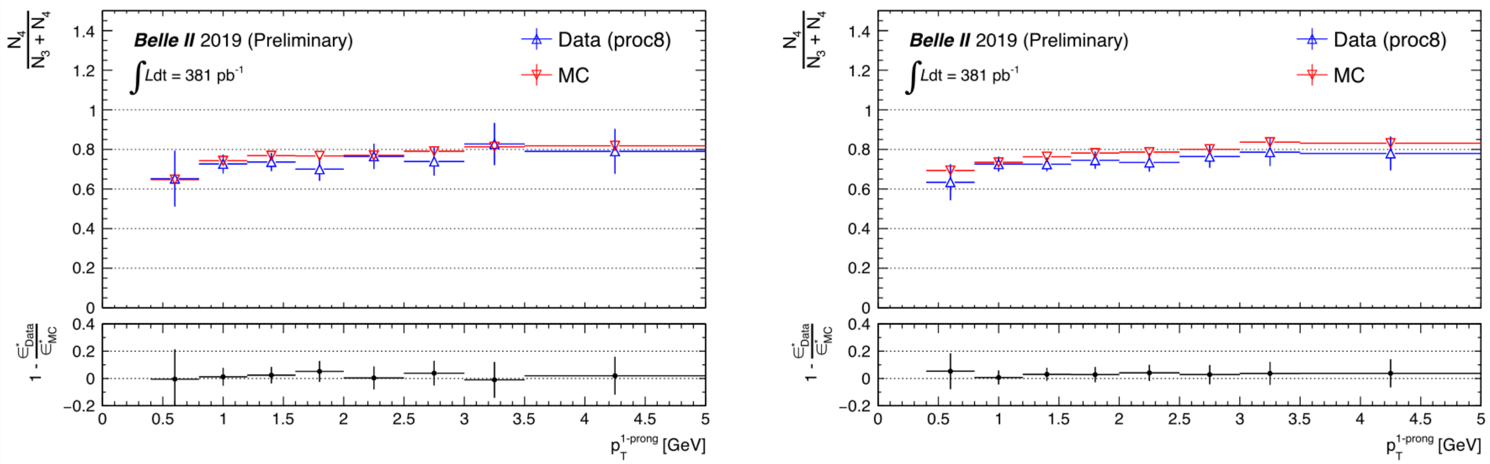
- Tracking efficiency for the electron channel of the tau events, MC-data comparison
- Probe pion and electron with same charge in left, and opposite charge in right plot, as function of p_T
- Similar performance between MC and data (phase 2, reprocessing 8)





PERFORMANCE – TRACKING WITH TAUS

- Tracking efficiency for the muon channel of the tau events, MC-data comparison
- Probe pion and muon with same charge in left, and opposite charge in right plot, as function of p_T
- Similar performance between MC and data (phase 2, reprocessing 8)



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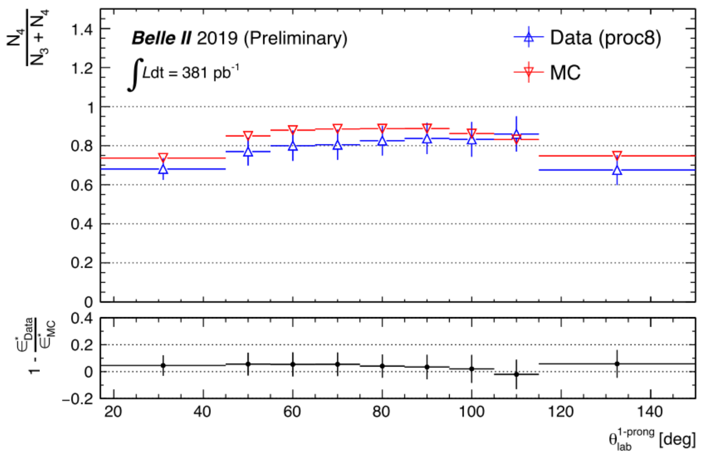
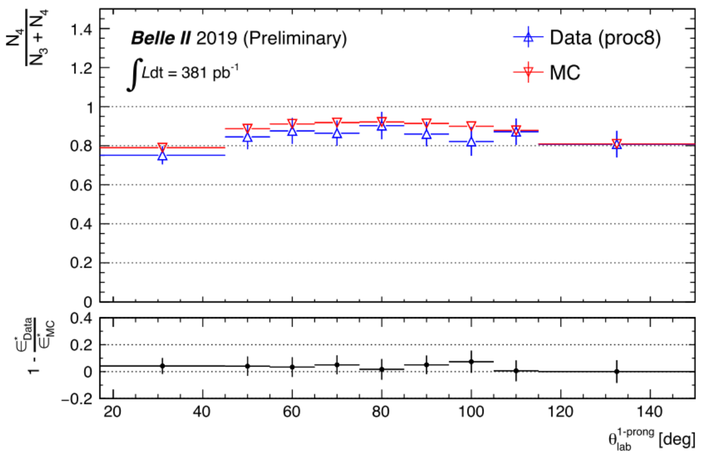
PERFORMANCE – TRACKING WITH TAUS

- Tracking efficiency for the electron channel of the tau events, MC-data comparison
- Probe pion and electron with same charge in left, and opposite charge in right plot, as function of θ
- Similar performance between MC and data (phase 2, reprocessing 8)





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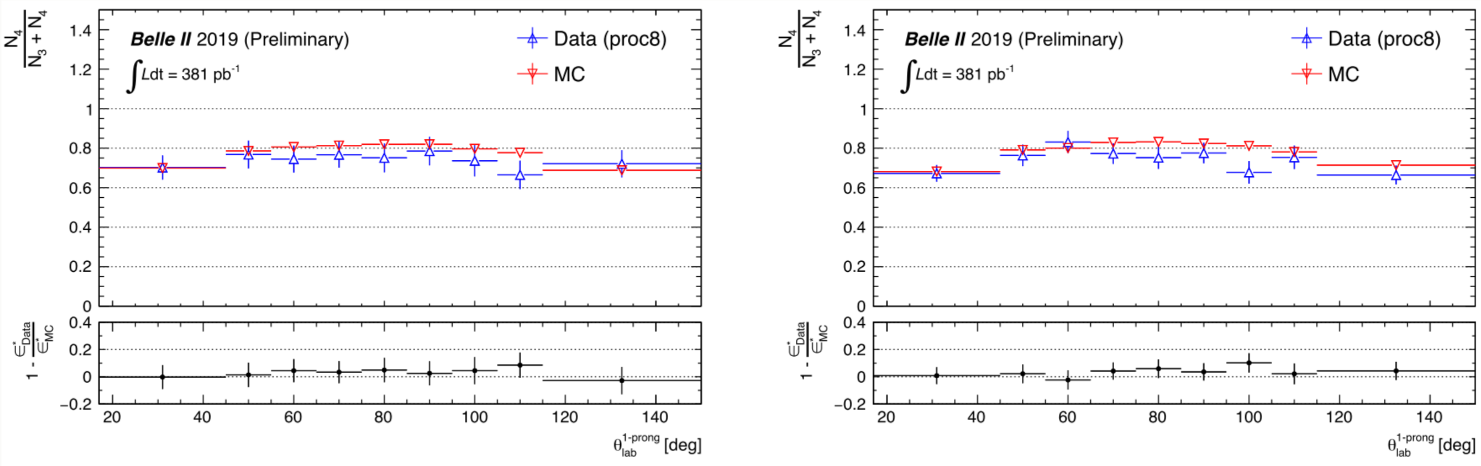
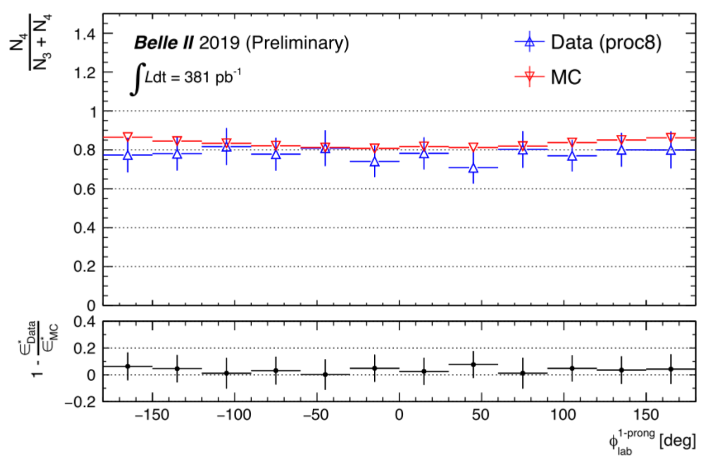
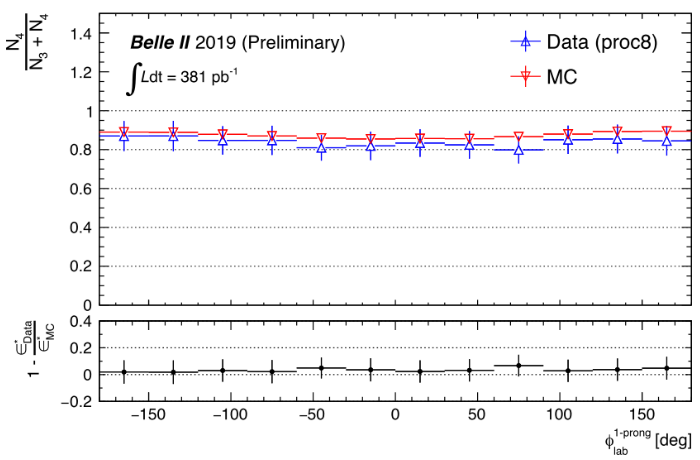


PERFORMANCE – TRACKING WITH TAUS

- Tracking efficiency for the electron channel of the tau events, MC-data comparison
- Probe pion and electron with same charge in left, and opposite charge in right plot, as function of φ
- Similar performance between MC and data (phase 2, reprocessing 8)





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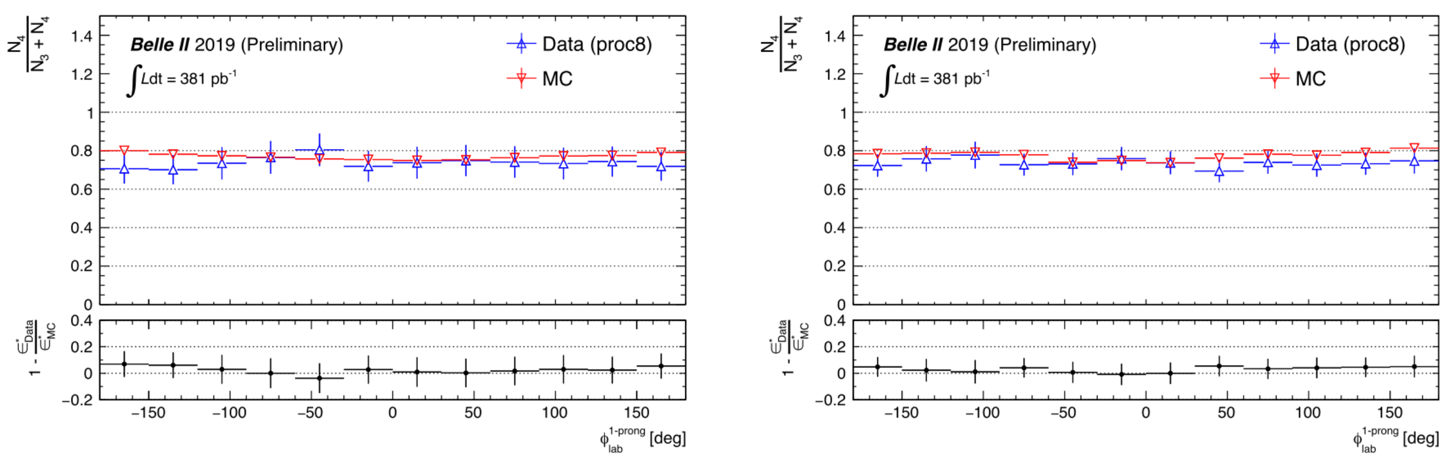

PERFORMANCE – TRACKING WITH TAUS

- Tracking performance for τ pair events is similar between MC and data (phase 2)
- As expected, worse performance for very forward and backward tracks (low or high θ) and for low p_T tracks, but homogeneous in φ
- Thus: tracking algorithms work reliably on MC **and** data :-)
- Differences between both exist, but are within statistical uncertainties (and the phase 2 dataset is small)
- Further studies on τ or other channels need to be conducted – please contact the tracking group or ask your supervisor if you are interested in working on tracking :-)

IMPORTANT QUANTITIES

- Cut on track parameters: $|d_0| < 2$ cm and $|z_0| < 2 \ldots 5$ cm (both depending on analysis)
- Ask for PXD hits: nPXDHits >= 1
- Ask for SVD hits: nSVDHits >= 6 (or >= 8) (note: each sensor contributes two hits of the two strip directions, requiring >= 6 hits (>= 8) means hits from at least three (four) different sensors and thus usually different layers)
- Ask for CDC hits: nCDCHits >= 20 … 40 (depending on analysis)
- And of course cuts on track quality estimators, fit χ^2, momentum and transverse momentum, and what ever you need for your analysis

WHAT YOU WILL GET IN MDST?

- Track (mdst/dataobjects/Track.h)
  - Information on the fitted track results and the particle hypothesis they were fitted with
  - Quality indicator for that track
  - The TrackFitResults for this track
- TrackFitResult (mdst/dataobjects/TrackFitResult.h)
  - Contains hit patterns for VXD and CDC
  - P-value of fit, charge sign
  - Helix parameters, their uncertainties, and covariance matrix
  - position (POCA), momentum, p_T, 4-momentum, energy (depending on particle hypothesis), covariance matrix for all these values (all these at POCA), particle type / PDG code

SUMMARY

- Tracking is an important part in reconstruction and for physics at Belle II
- High tracking efficiencies can be achieved over a wide range of transverse momentum
- Tracking performance nearly independent of background level on MC – except for fake and clone rate
- So far, accelerator backgrounds are worse than expected – this might have influence on all studies at Belle II, starting with tracking (efficiency, fake rate, clone rate)
  - Trigger rate might suffer from higher backgrounds due to increasing processing time
- Cuts on track quantities are needed like d_0, z_0, nPXDHits, nSVDHits, nCDCHits
  - Think twice about which cut might be the best for your analysis
- We are happy if you want to contribute to the tracking group efforts

THANK YOU FOR YOUR ATTENTION!