Z^0-pole flavour physics at FCC-ee

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FCC-ee Physics Performance meeting

A short introduction

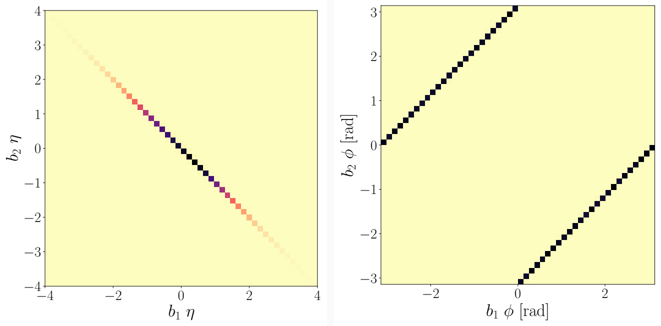
- Thanks a lot for the invitation!
- I work on LHCb - mostly study CP violation in $B^{\pm} \to D^{(*)} K^{\pm}$ decays and semileptonic modes such as $B^0 \to D^{*-} \tau^+ \nu_\tau$
- Approached Clement a short while ago about the upcoming Snowmass FCCSW tutorial
    - Expressed an interest in flavour studies at the Z^0-pole
- Received lots of help to get up and running with some $Z^0 \to b\bar{b}$ Pythia generation in FCCSW with Delphes
- Show initial studies today, describe the software I've been using, and outline what features will be needed going forward

Generation phase

- Setup FCCSW from here
- Used *ee_Z_ddbar.cmd* to create a *ee_Z_bbbar.cmd* Pythia config file, and run Pythia with Delphes using *PythiaDelphes_config.py*
- Generation is inclusive, in that the b-quarks produced hadronise to all sorts
  - *EvtGen* config options have been added to FCCSW, but early tests indicate that it isn't generating purely the decays specified by the user in a *.dec* file
  - Under discussion here
- Have generated 13 million events for the work shown today

b-quark truth-level kinematics

- At the Z^0-pole, expect Z^0 production basically at rest so b-quarks should be produced back-to-back in lab frame
- Plot lab frame η and ϕ distribution of the two b-quarks
  - η equal and opposite, ϕ differs by π - consistent with back-to-back production



B-hadron production fractions

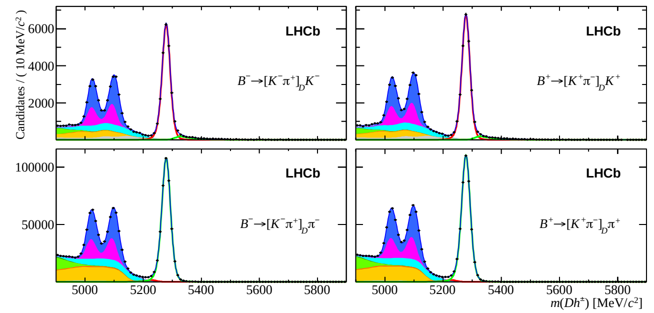
- Look at the *genParticles* container and count fraction of each true particle type produced according to *pdgId*
- Production of B_c^+ mesons is a nice feature at FCC-ee - no B_c^+ produced at Belle II

B-hadron	Production fraction (%)
B^0	43.0
$B^\pm$	43.0
B_s^0	9.6
$B_c^\pm$	0.04
Λ_b^0	3.7

Particle combinations

- Access to stable final-state hadrons via the *pfcharged* container
- Perform particle combinations per-event using awkward array with ROOT file loading using uproot
- These packages provide *numpy*-like access to jagged data from ROOT files
  - Great for dealing with events containing different numbers of particles in each event
  - Solid support within the HSF and PyHEP communities
- Particle combinatorics using *ak.combinations* (same particle type) and *ak.cartesian* (different particle types)

- High-statistics mode at LHCb which forms part of the CKM angle γ measurements
- Related decays $B^- \to (D^0 \to K^-\pi^+)\pi^-$ and $B^- \to (D^0 \to K^-\pi^+)K^-$ (note K charge w.r.t. B) sensitive to γ



$2011 - 2016$ LHCb data [LHCb-PAPER-2017-021]

Expected yield at FCC-ee

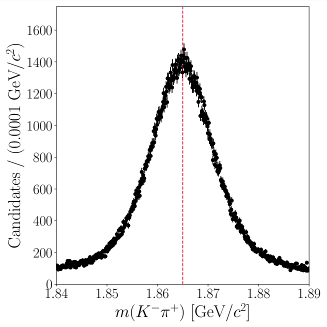
Factor	Value
Z^0 produced at FCC-ee	5×10^{12}
$\mathcal{B}(Z^0 \to b\bar{b})$	0.15
B from either b or $\bar{b}$	2
$B^{\pm}$ production fraction	0.43
$\mathcal{B}(B^- \to D^0\pi^-)$	4.7×10^{-3}
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.04
Total yield	121.3 million

- The yield above is for 7.5×10^{11} $b\bar{b}$ pairs
- My sample contains 13 million $Z^0 \to b\bar{b}$, so expect **2100** $B^- \to D^0\pi^-$ decays in the generated sample[1]

[1] Charge conjugation implied

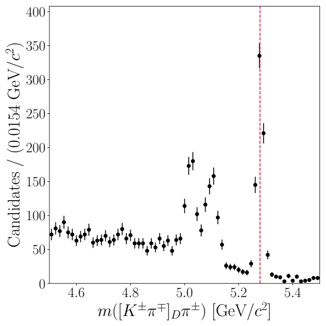
D^0 candidates

- Invariant mass distribution of $D^0 \to K^{\mp}\pi^{\pm}$ candidates built from kaons and pions in the *pfcharged* container
- Select K and π based on their *pdgId* values (assumes perfect PID performance, in reality will have some mis-ID)
- Apply $p > 4$ GeV cut to all candidate tracks - no vertex fits e.t.c.
    - Some background present, but pretty clean given no dedicated selection in place



$B^{\pm}$ candidates

- Take $K\pi$ combinations passing a ± 25 MeV mass window around PDG D^0 mass, and combine them with pion candidates
- Encouraging to see a well-resolved B peak and low background level with minimal selection applied
- Peaks at low mass are due to partially reconstructed $B \to D^{*}\pi$ decays (studied in detail at LHCb, see previous slide)



Rough yield estimate (no mass fit)

- $B^- \to D^0\pi^-$ peak is 330 events high (background-subtracted) and 5 bins wide
- Assume a triangle to give $N = 330 \times 5 \times 0.5 = 825$
- This is **40%** of the total expected $B^- \to D^0\pi^-$ yield in the 13M $Z^0 \to b\bar{b}$ generated sample
- Includes hadron efficiency estimates in the IDEA Delphes card <u>here</u> and the $p > 4$ GeV track cuts
- This would give a total $B^- \to D^0\pi^-$ yield of ~ 50 million in the FCC-ee data
  - Yield in 9 fb^{-1} LHCb Run 1 + 2 sample is ~ 2 million after all selection, so FCC-ee about an order higher [2]

[2] LHCb Upgrade I + II targets 300 fb^{-1}, which would surpass this

Software needs

FCCSW requirements for flavour studies

- Ability to generate samples of exclusive decays using EvtGen
    - Work required in FCCSW to configure EvtGen appropriately
- General candidate building tools at the FCCSW level (rather than at user-level as I have done)
    - Include MC-matching of the full decay chain
    - LHCb software can hopefully help
- Candidate building includes not just kinematic information but track fit and vertex fit information
- Ability to study how often the entire event can be reconstructed
    - If one side of the $b\bar{b}$ event can be fully reconstructed, this gives the 4-vector of the other side (given well-known $\sqrt{s}$)
    - Valuable for modes with missing momentum, same ideas adopted at Belle II

Python analysis software for performance studies

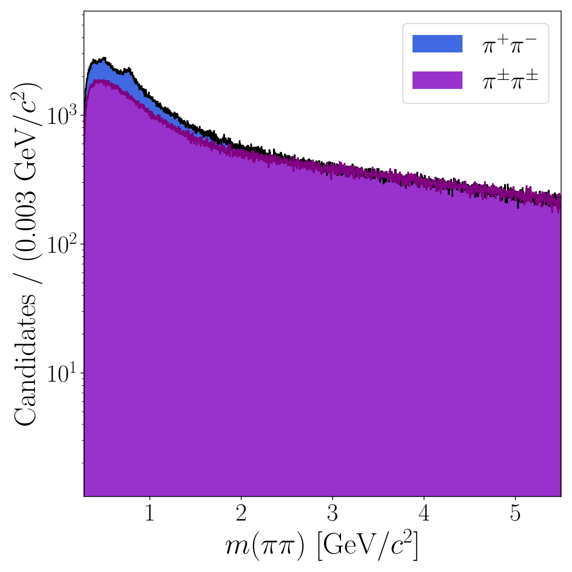
- Initial studies using *uproot* for jagged ROOT file loading and *awkward* for manipulation
- Both packages are well-supported (Jim Pivarski main author) and many tutorials
  - Analysed 13 million events in under 5 mins to produce the D^0 and $B^\pm$ candidates, making combinations across all tracks in every event
  - Interface seamlessly with other industry-standard packages like *numpy* for calculations and *matplotlib* for plotting
  - The *vector* package (Henry Schreiner) is being worked on - will provide support for Lorentz vectors e.t.c. in the *awkward* format
- FCC studies can make use of these packages, with perhaps a common set of helper functions
  - No need to reinvent the wheel with these tools in existence

Summary

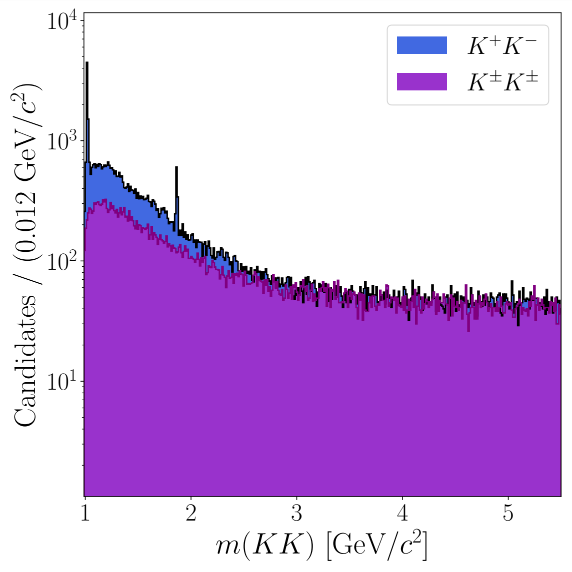
- Many thanks to Clement and co. for the help in getting started with FCCSW and simulating events
- Early performance studies indicate:
  - Sensible rates of B-hadron production
  - High selection efficiencies for hadronic modes
  - Low background levels with minimal selections applied
- Ability to study more decay modes, and in more detail, will help guide detector design requirements
- Low background level and ability to reconstruct other side of the $b\bar{b}$ event are positives for flavour at FCC-ee
- Looking forward: development in FCCSW for candidate building and MC-matching, use of `uproot` and `awkward` for performance studies

Backup

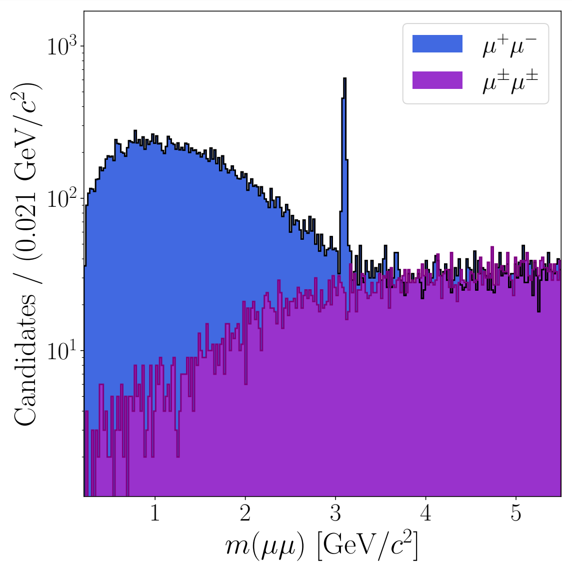
$m(\pi\pi)$ spectrum - ρ visible



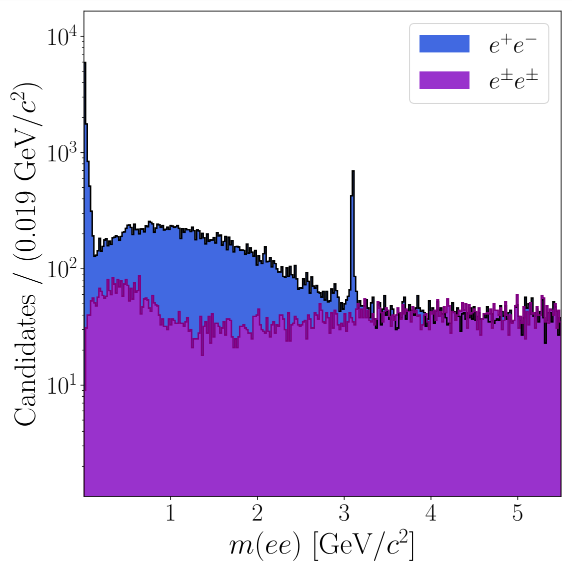
$m(KK)$ spectrum - ϕ and D^0



$m(\mu\mu)$ spectrum - J/ψ



$m(ee)$ spectrum - J/ψ and γ conversion



True particle multiplicities in 1 million events