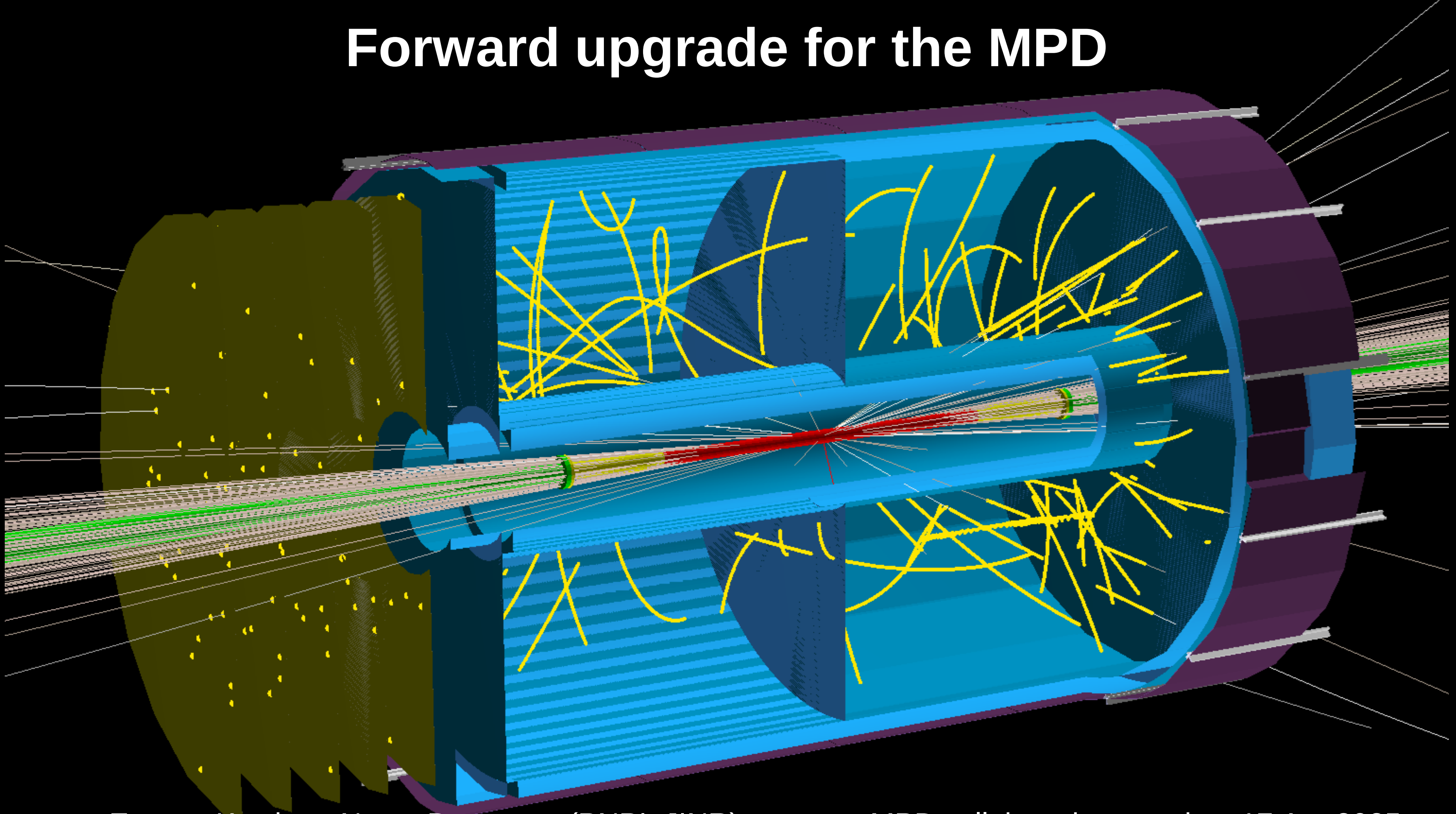
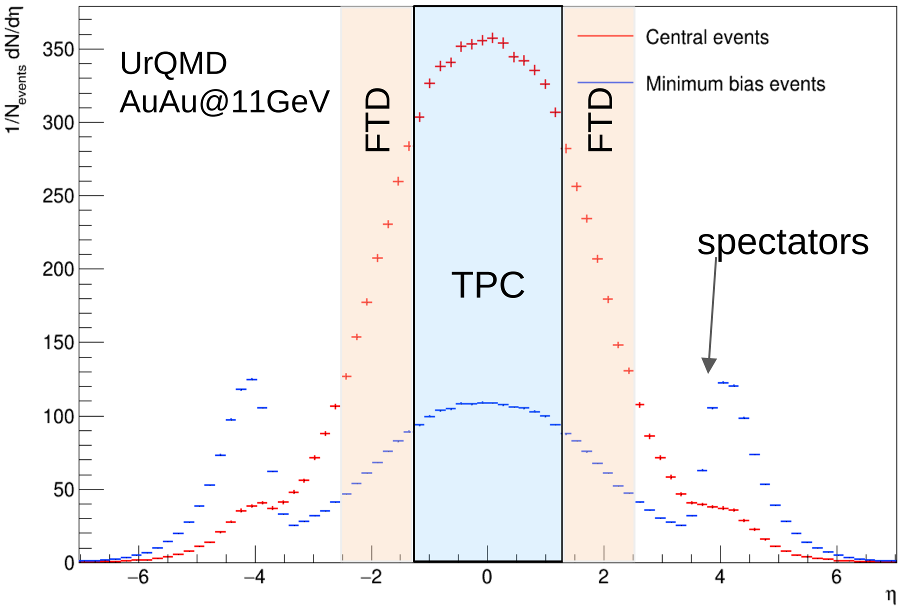
Forward upgrade for the MPD

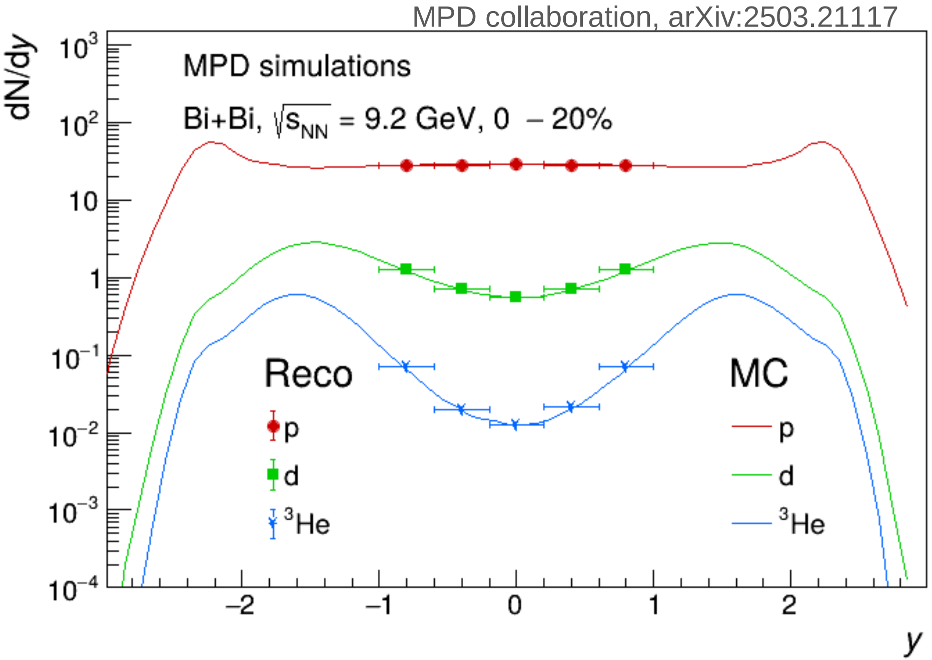


Evgeny Kryshen, Nazar Burmasov (PNPI, JINR)

MPD collaboration meeting, 17 Apr 2025

Physics motivation: reminder



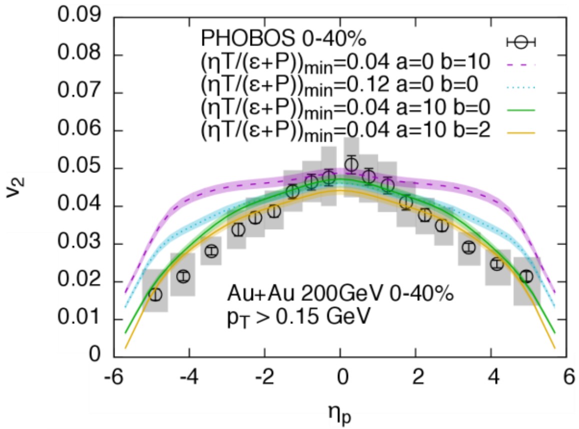


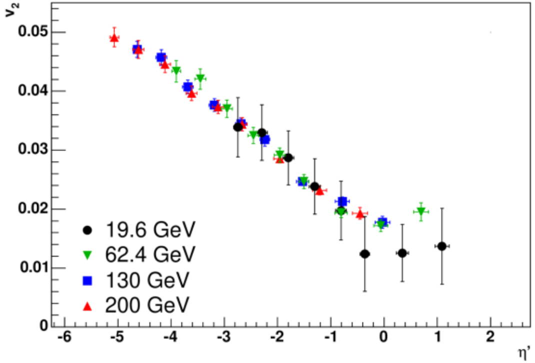
- TPC covers only ~55% of particle production yield in central events
  ➜ Forward tracker would allow us to cover more than 80%

- Production of light nuclei mainly at forward rapidities
  ➜ forward tracker would allow one to study the interplay of coalescence and baryon stopping mechanisms

And more…

- the horn and the step effects at forward rapidities
- anisotropic flow: limiting fragmentation mechanism, temperature dependence of QGP etc., see talk by A. Taranenko on Tuesday
- thermal photons via conversions on TPC endcaps
- global polarization of Λ hyperons: rapidity dependence?
- improve precision of centrality and reaction plane determination
- improved trigger efficiency for small systems
- possibility to access various observables of the SPD physics program
- aspects of non-perturbative QCD, e.g. diffractive studies, QCD instanton



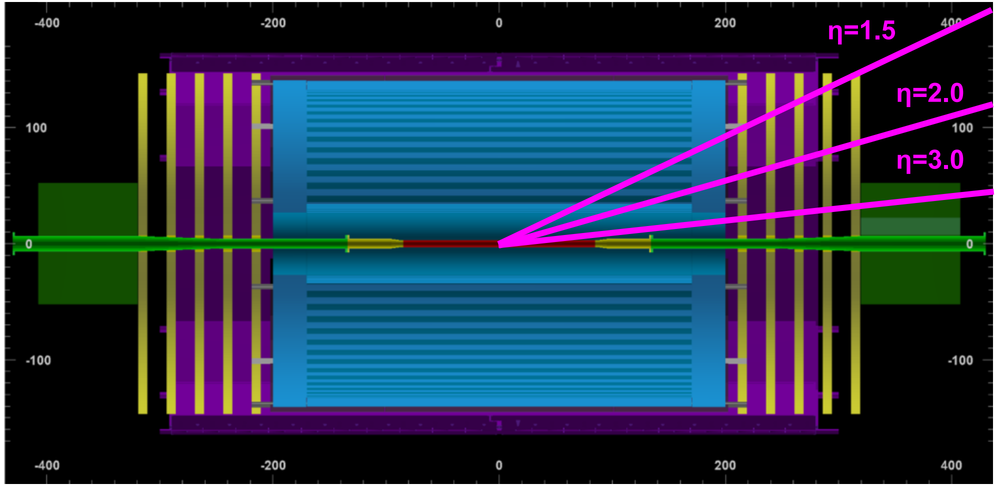


More ideas/suggestions for the physics program are highly welcome!

Reminder

Main challenges:

- Momentum resolution is driven by the radial distance available for the track curvature measurement
  ➜ resolution strongly degrades towards large η
- Large and poorly known material budget of TPC endcaps
- High occupancy in central AA collisions
  ➜ Seeding and ghost hit issues for 1D hits



Considering "ideal" tracker (FTD):

- 5 tracking layers placed between 210 and 300 cm
- Thickness per layer: 0.2% X_0
- Gaussian smearing in x and y with σ = 100 um
- Geometry implemented in mpdroot

Using ACTS for tracking:

- FTD standalone tracking
- New: TPC+FTD tracking (use TPC seeds)
- New: considering 1D and 2D hits in FTD

Links:

- Forward upgrade for the MPD
- ACTS tracking in TPC with sector geometry
- ACTS tracking in the forward detector using TPC seeds
- Update on ACTS tracking in the forward detector

Towards TPC+FTD tracking

Geometry hierarchy in ACTS: volumes

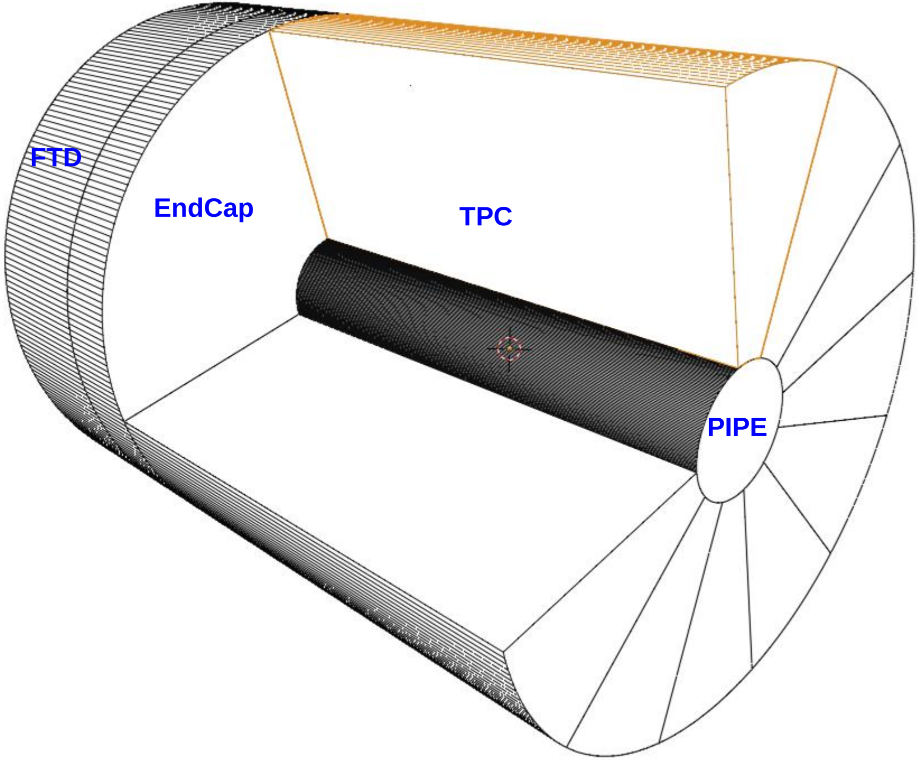
Volumes:

z binning

- BARREL
  - PIPE
  - TPC:
    - TPC0
    - TPC1
    - …
    - TPC11
- EndCap
- FTD

r binning

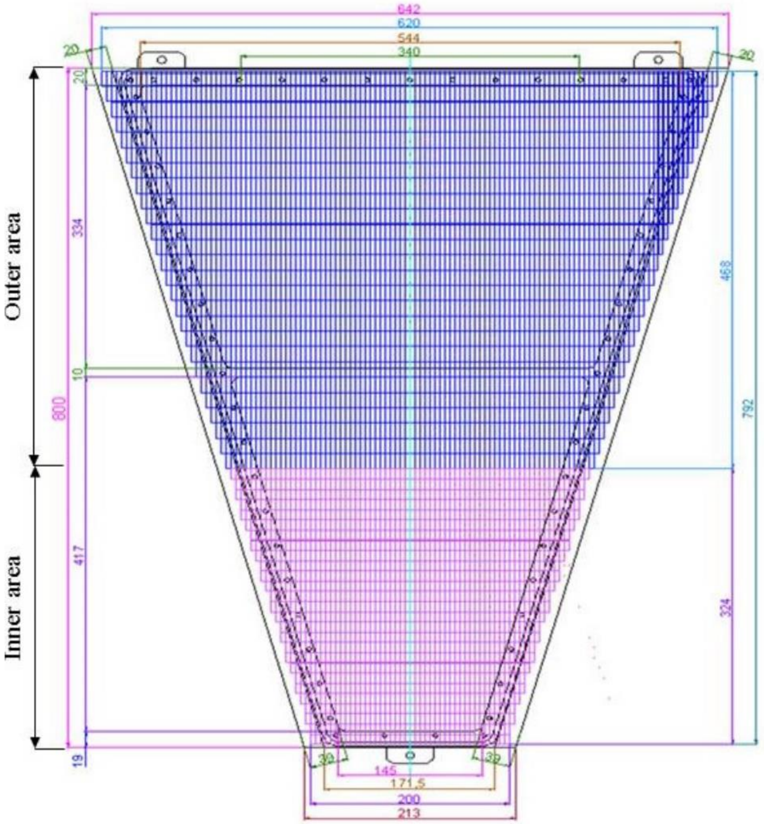
phi binning

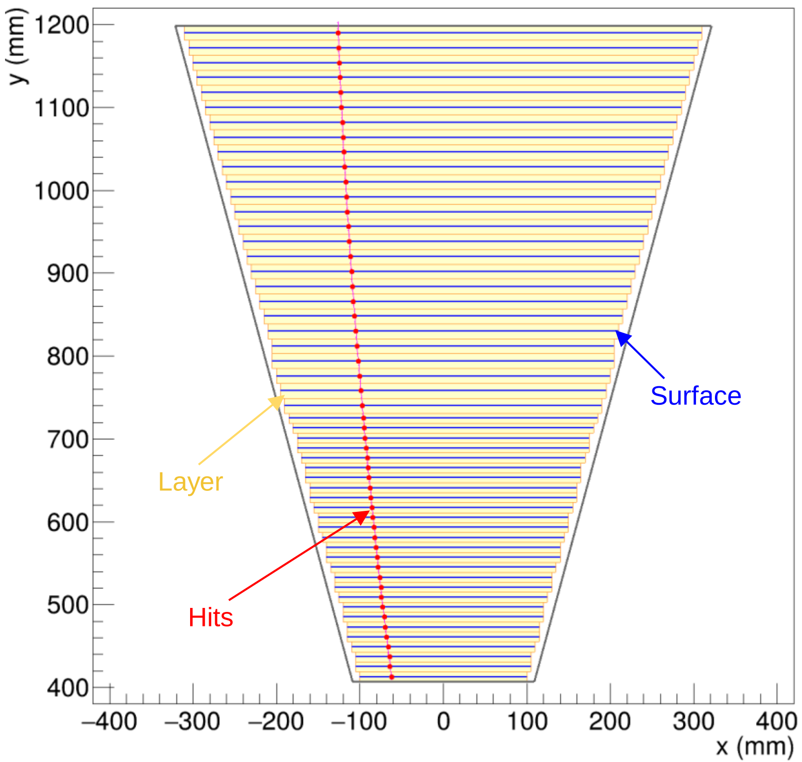


Fully connected geometry:

- Common boundary surfaces are glued (e.g. FTD and EndCap)
- If boundary is shared by several volumes, volumes must be attached to boundary (e.g. TPC0… TPC11 to pipe boundary)

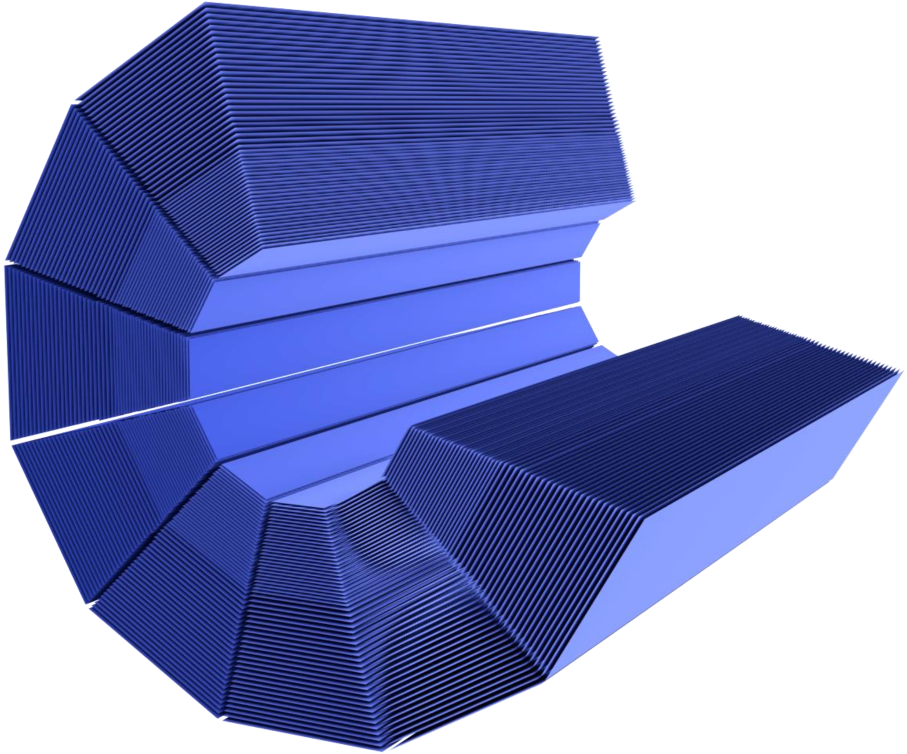
Virtual sector geometry in ACTS



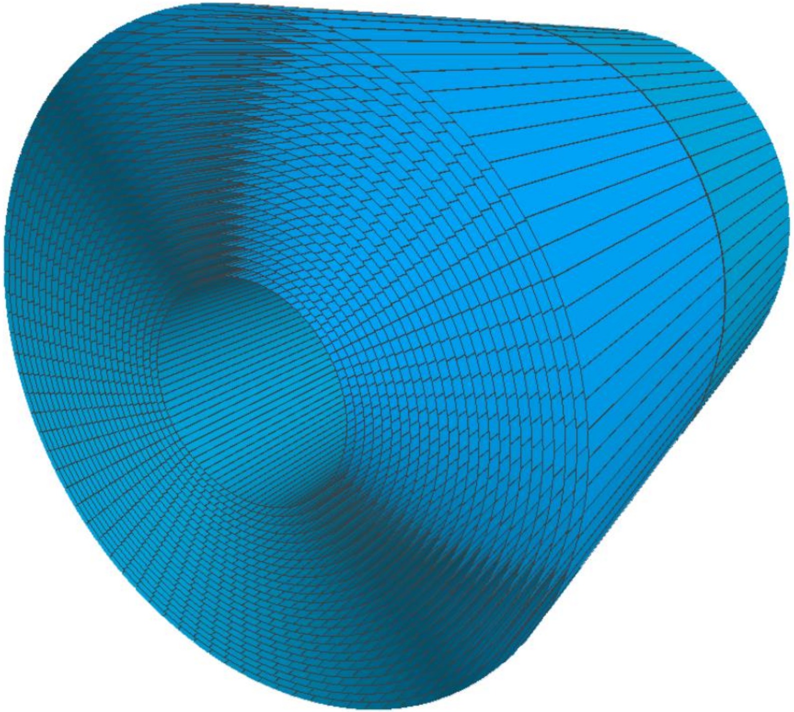


- Surfaces are used to account for multiple scattering effects
- Measurements (TPC hits) must be attached to surfaces
- Ordered layer array needed for navigation

Sector vs cylinder TPC geometry in ACTS

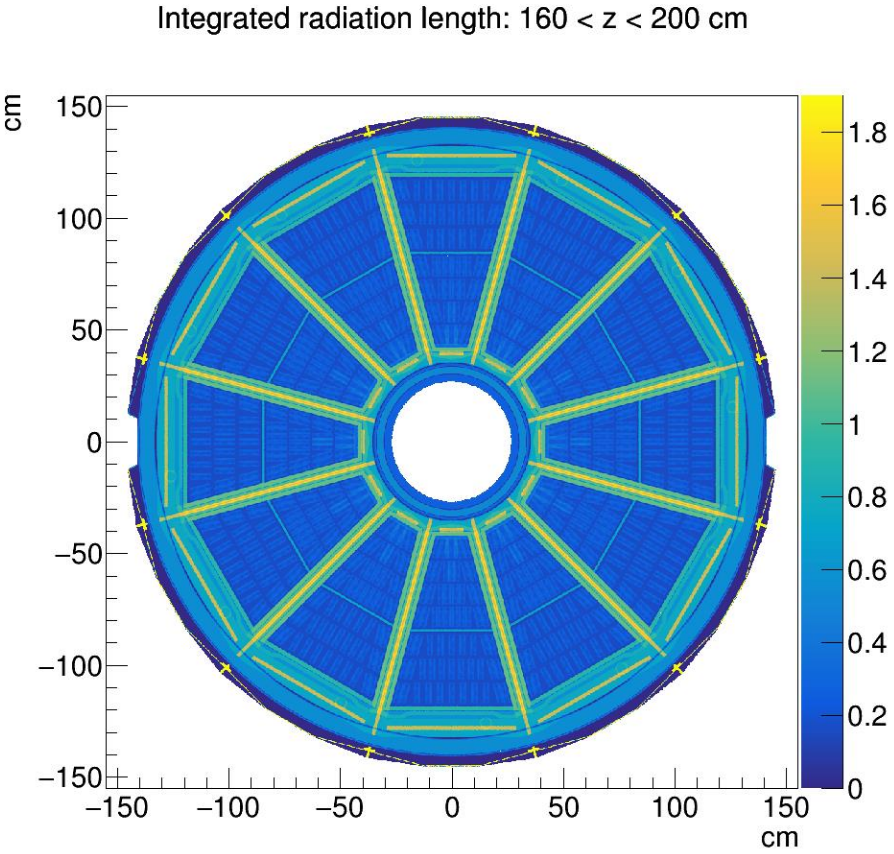


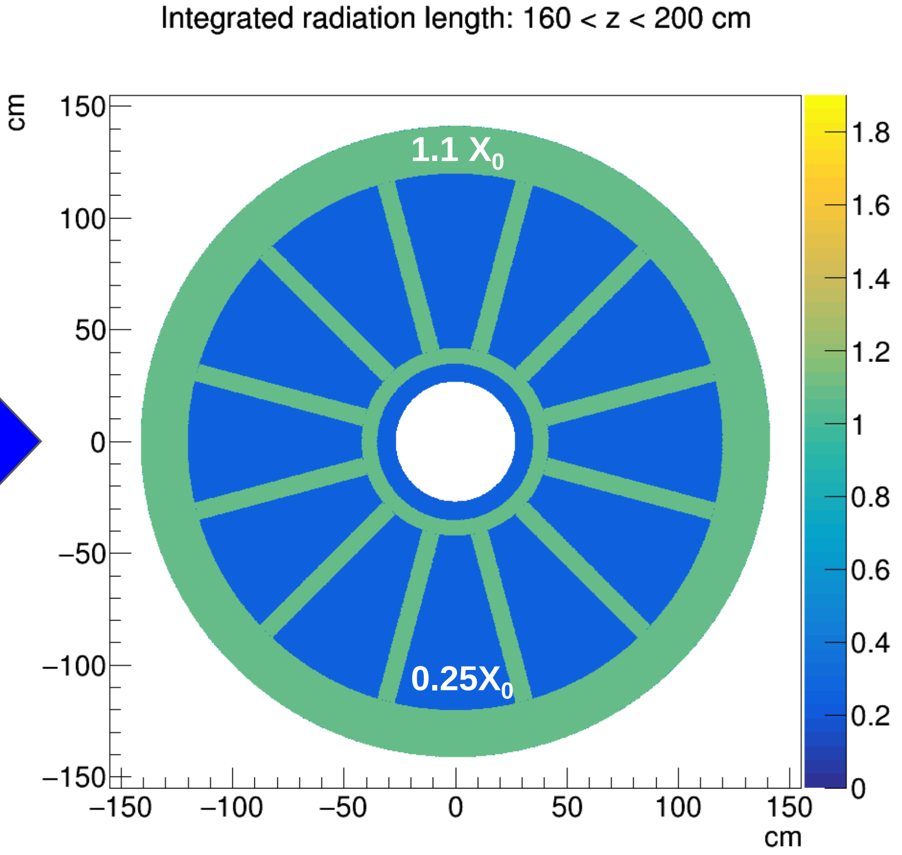
Sector-like geometry:
53 x 12 rectangular surfaces



Cylinder-like geometry
(P. Belecky, S. Hnatic et al.)
see talk by Slavomir on Tuesday

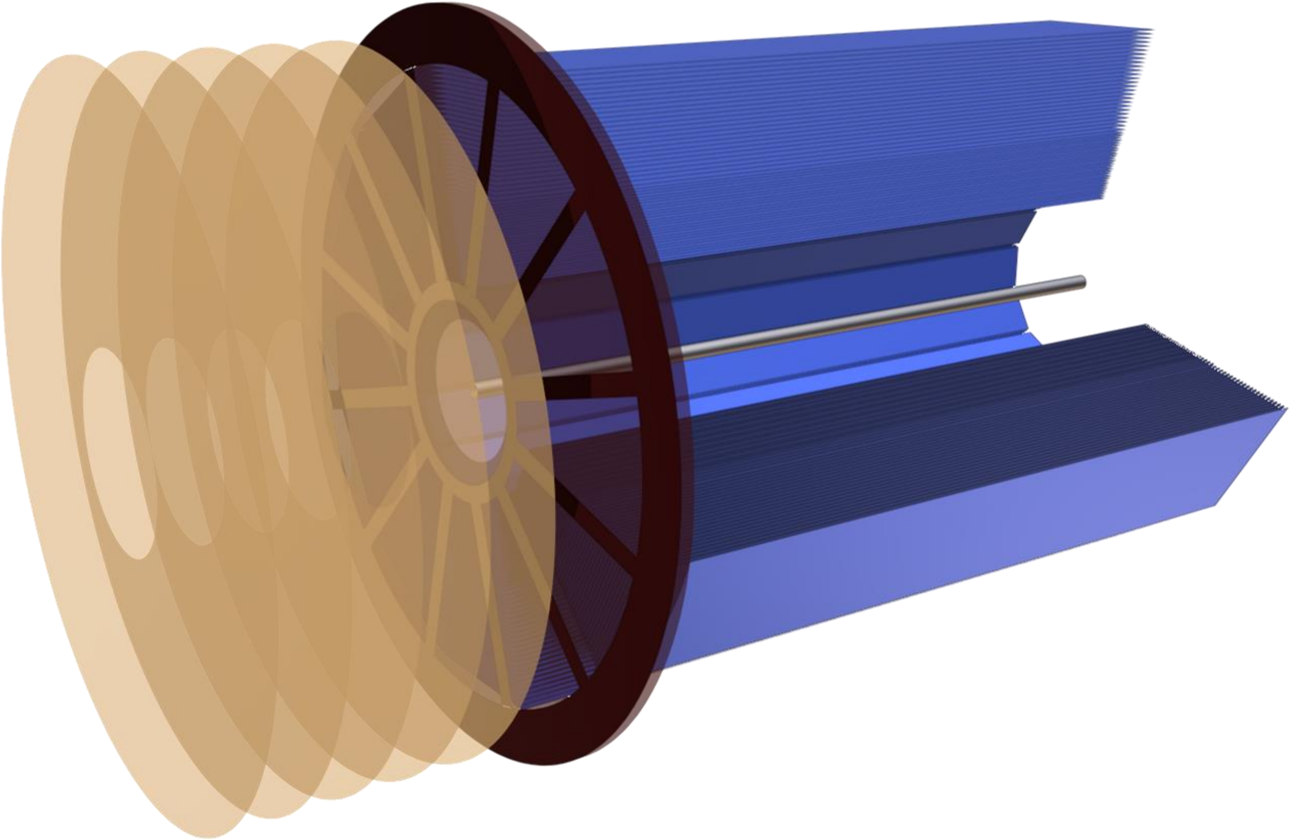
Simplified description of TPC endcap material in ACTS





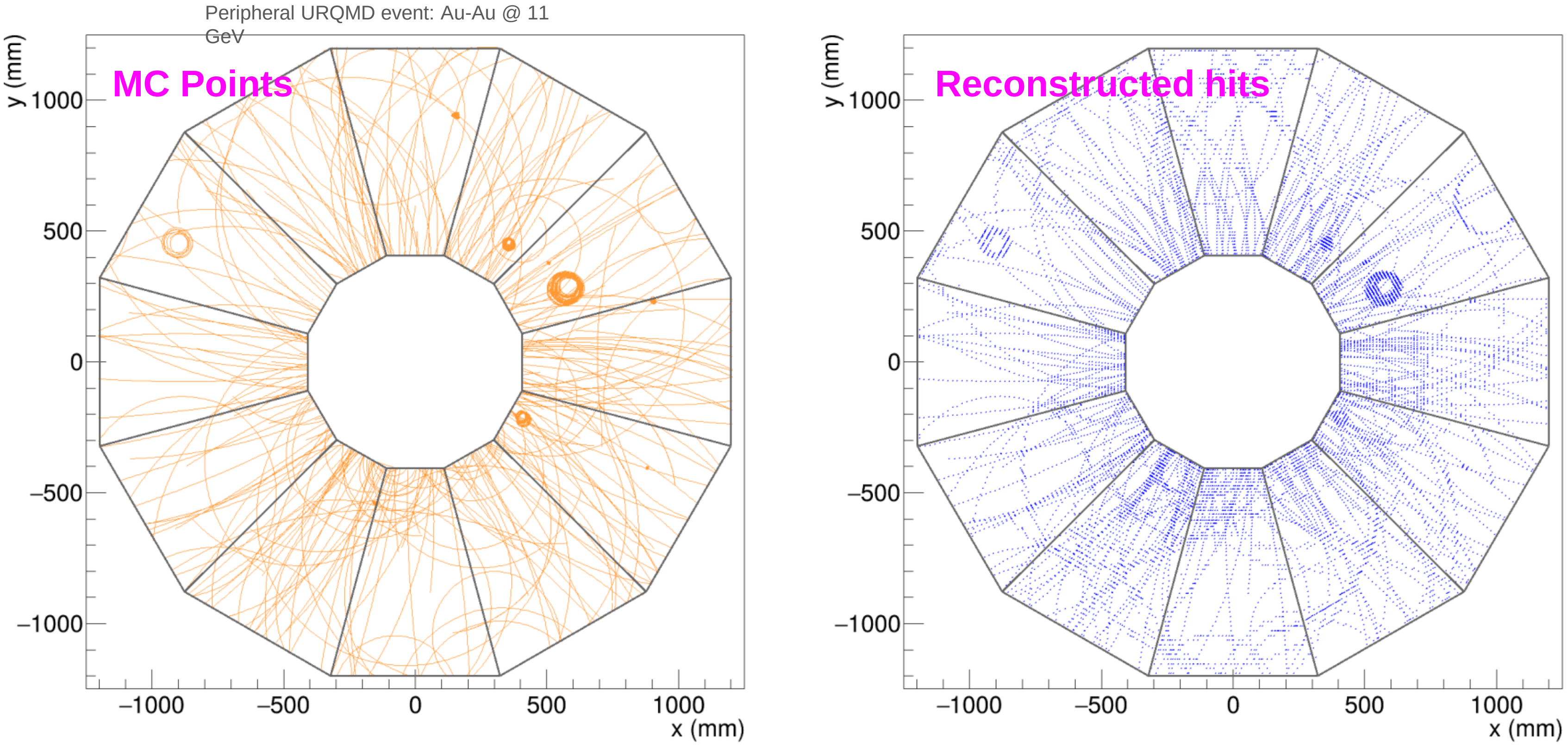
- Toy model with ROC-like and Frame-like layers

Surfaces in TPC, FTD, Pipe and EndCap (ACTS view)



Tracking in TPC

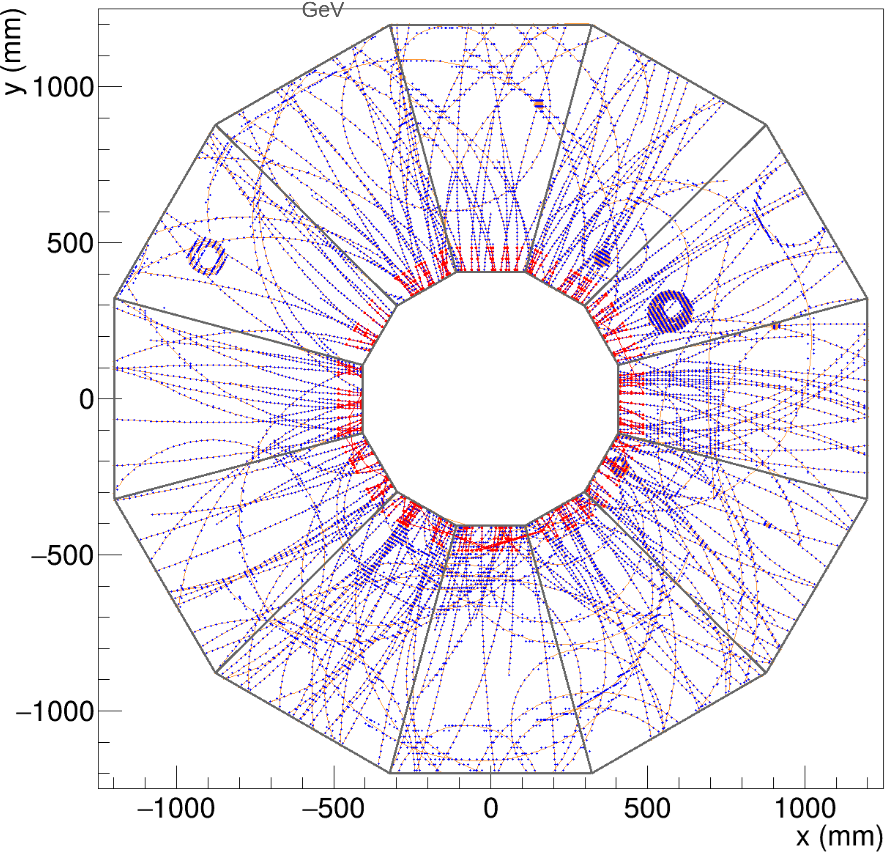
Typical MC and reconstructed hit distributions in TPC



- McTracks, McPoints, and TPC hits converted to ACTS format
- Using realistic hits from MLEM clustering algorithm

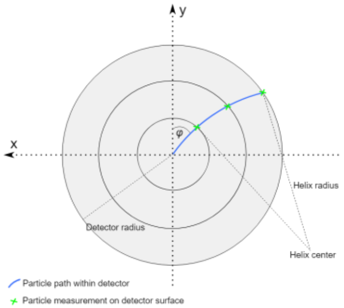
Seeding algorithm

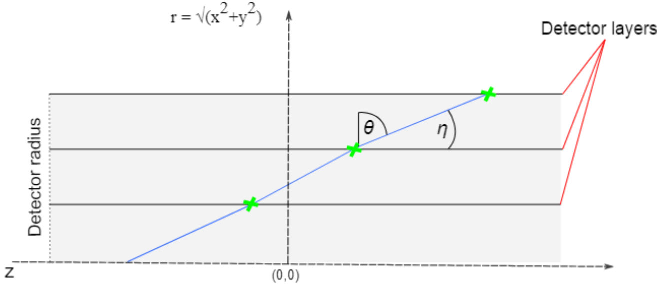
Peripheral URQMD event: Au-Au @ 11 GeV



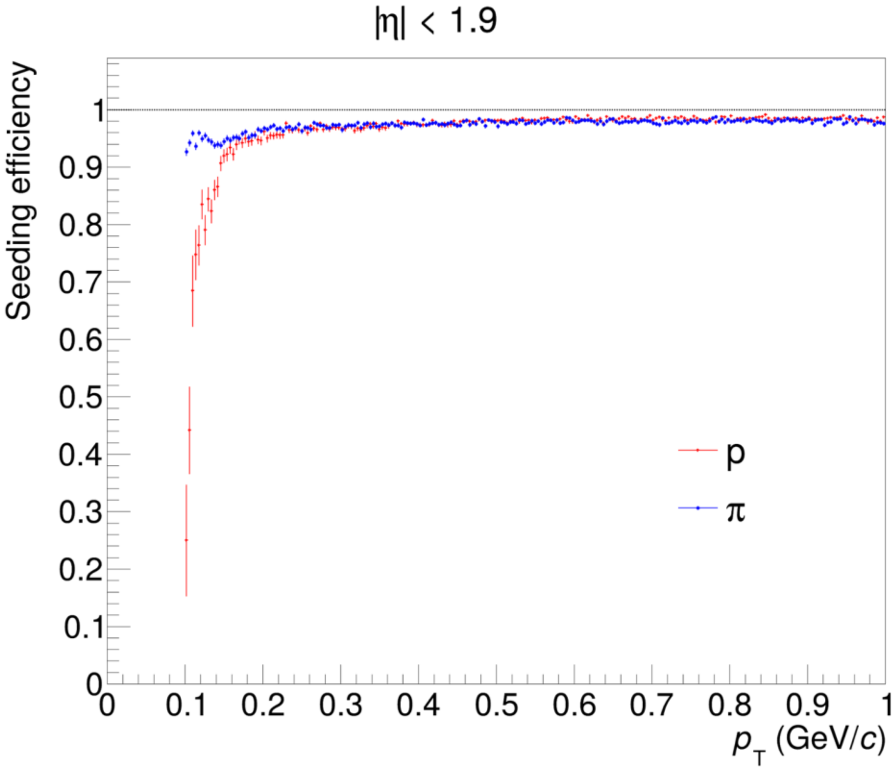
red: seeds

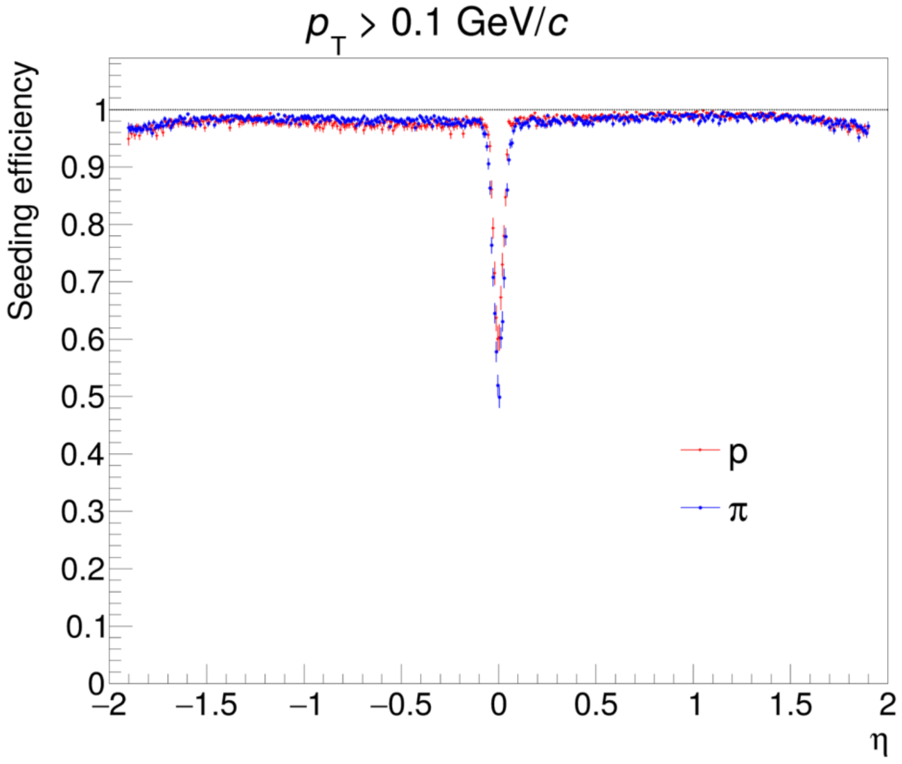
- Selecting triplets of hits from padrows 1, 4 and 7
- Seeding algorithm checks:
  - xy plane: helix pointing to (x,y) ~ (0,0).
  - rz plane: angular difference between two doublets consistent with expected mult. scattering
  - selection on impact parameter in r and z directions
- Had to relax most of the selection parameters





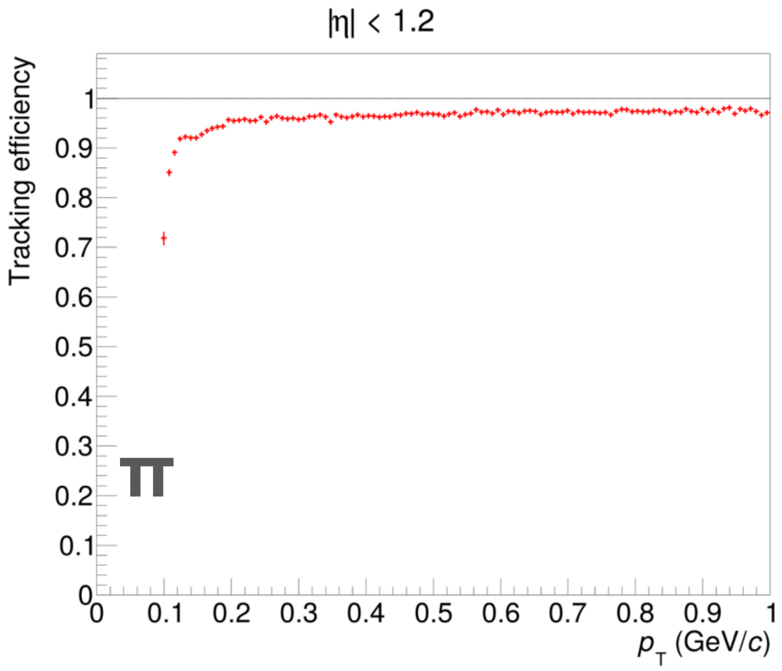
Seeding efficiency for single tracks (boxgen)

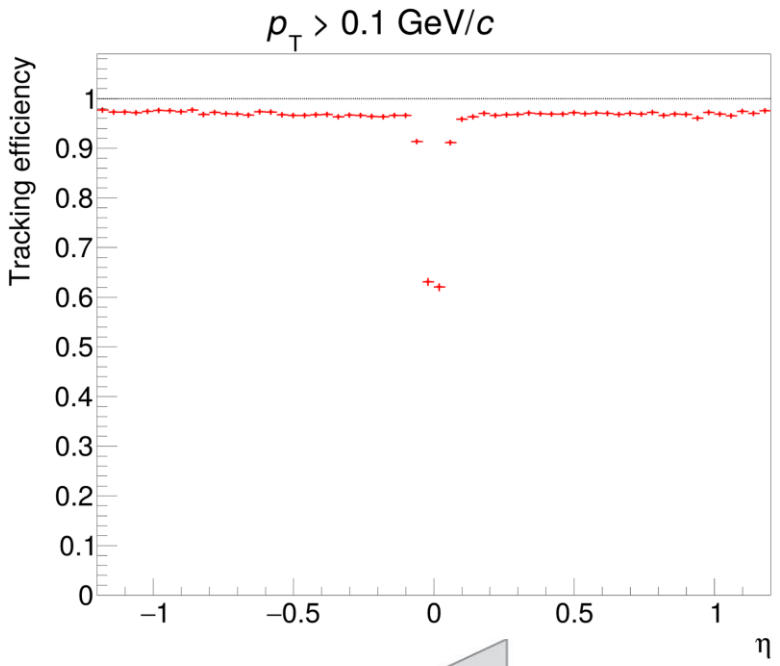




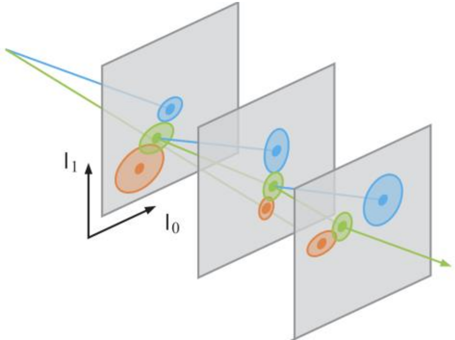
- Seeding efficiency for “seedable” tracks (with hits at padrows 1, 4, 7)
- Still some missing seeds, need further tuning

Combinatorial KF tracking performance in TPC (boxgen)

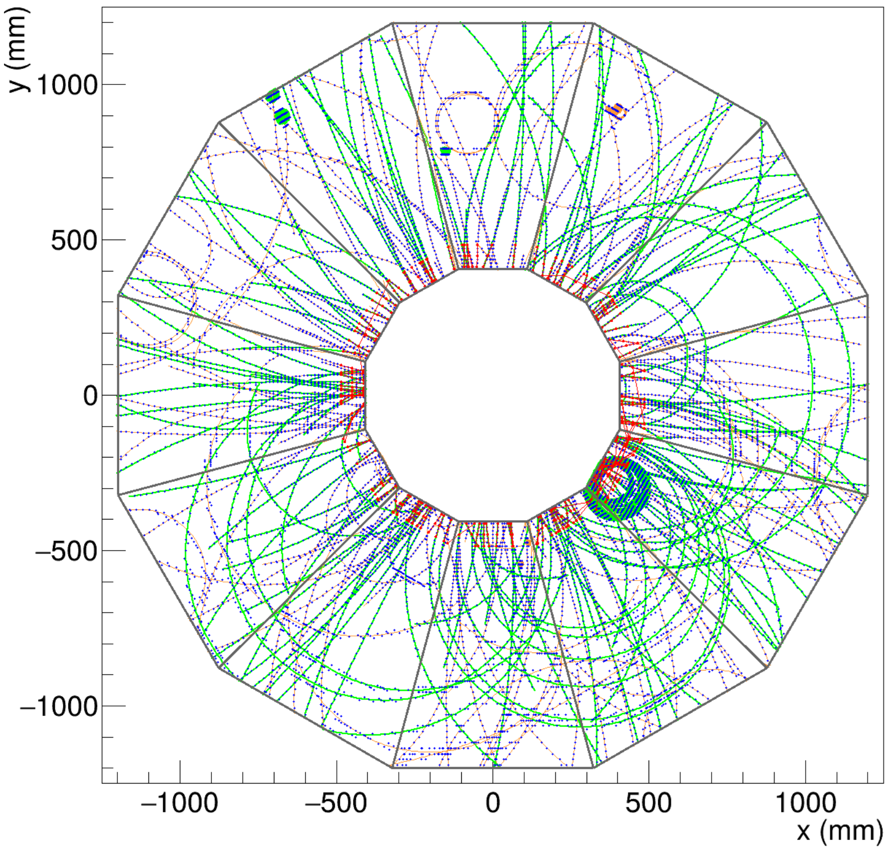


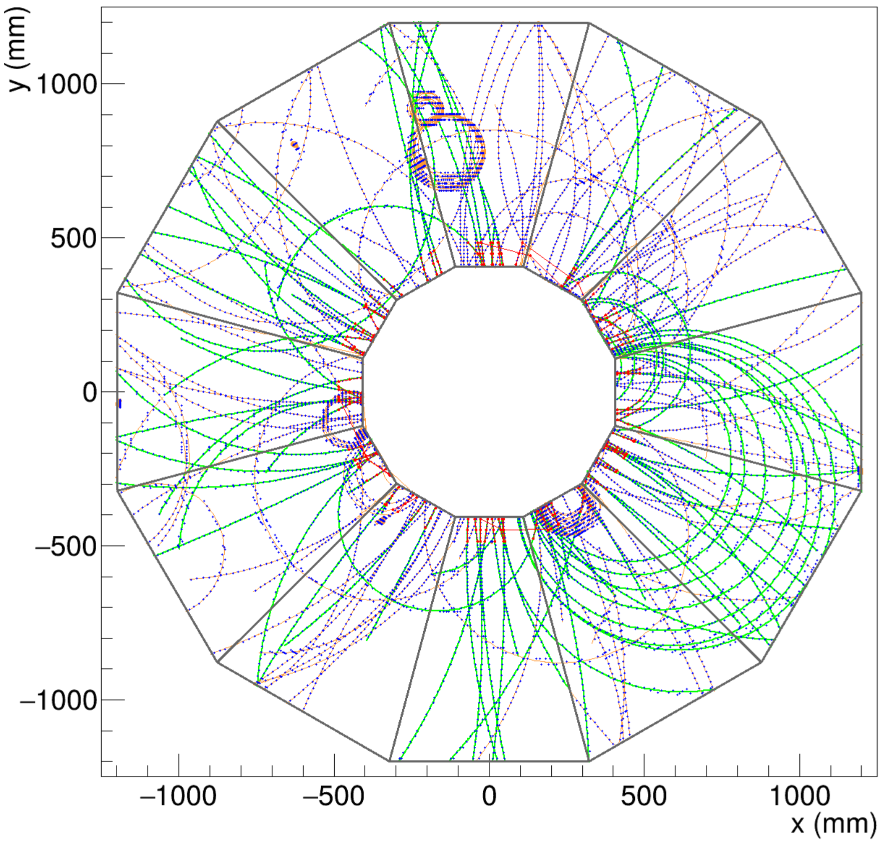


- Shown: “trackable” efficiency for single-pion box generator
  Trackable = hits at 1, 4, 7 padrows (seeding) + at least 20 hits in total
- Small inefficiencies mainly due to sector edges



Examples from UrQMD generator (AuAu @ 11 GeV)

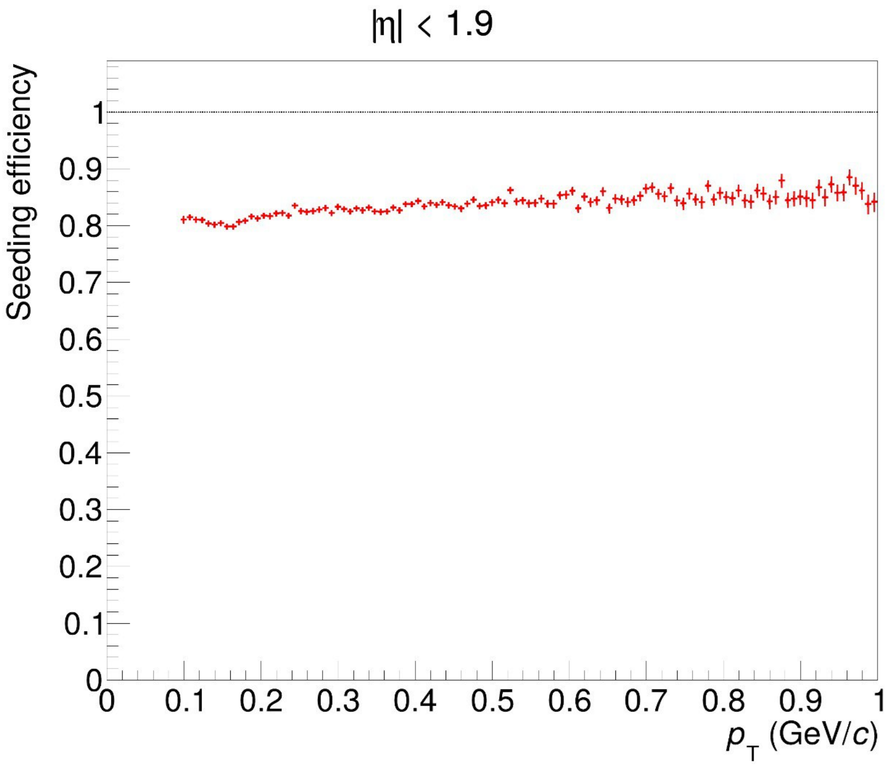


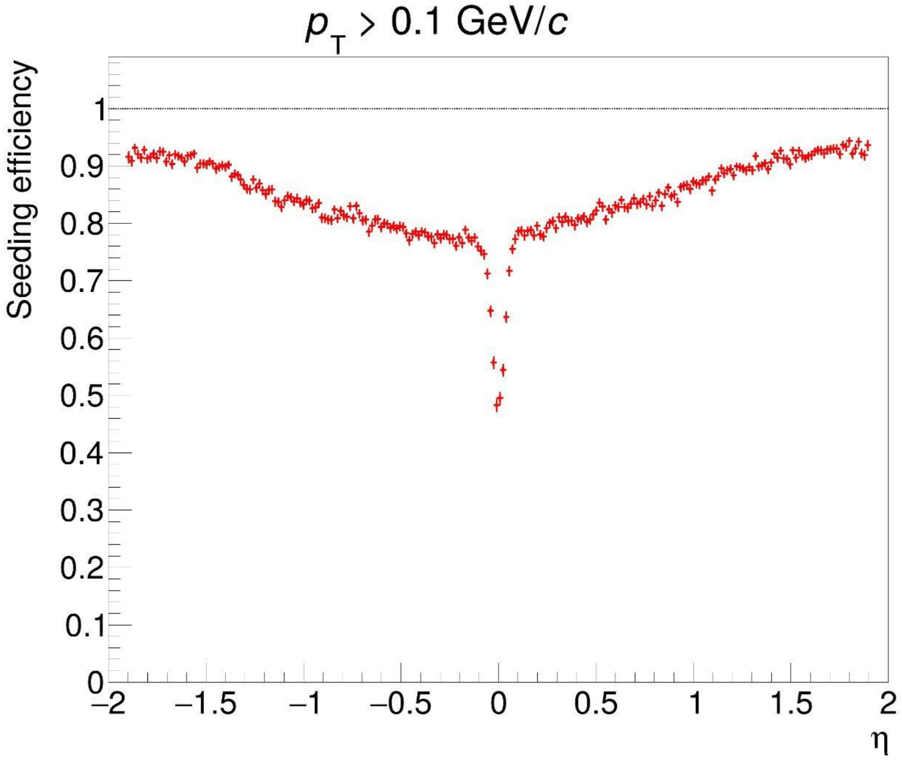


red: seeds

green: reconstructed tracks

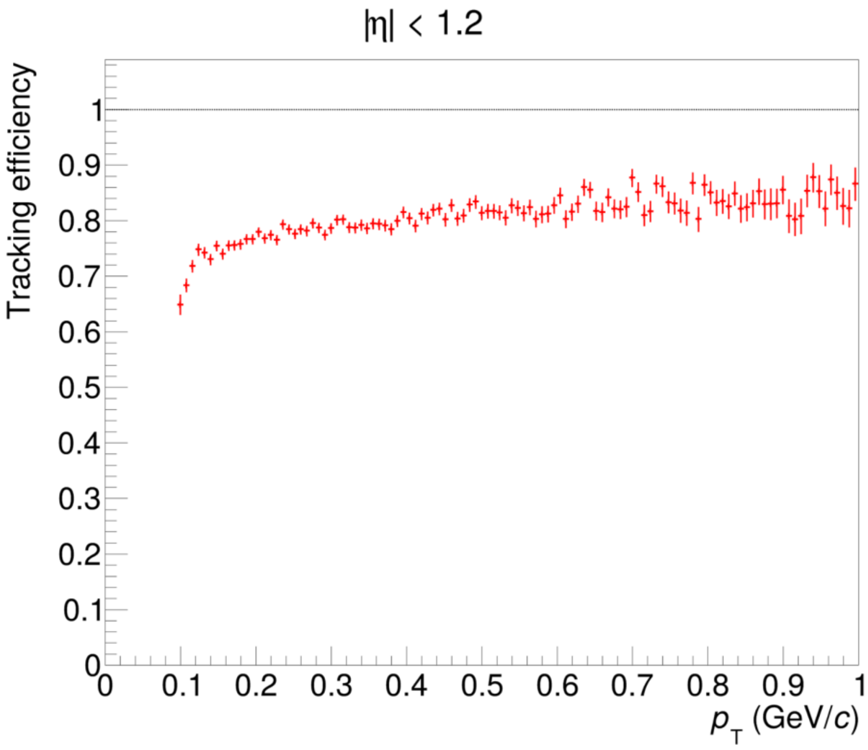
Seeding efficiency for URQMD events

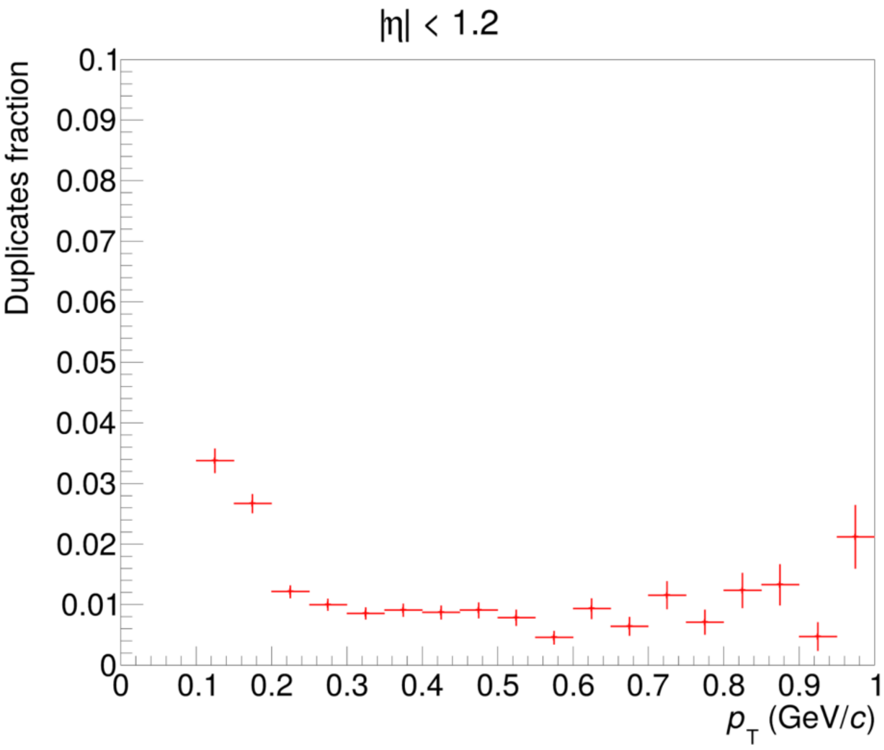




- Seeding efficiency for “seedable” tracks (with hits at padrows 1, 4, 7)
- Significant degradation wrt single-track events ➜ seeder needs further tuning

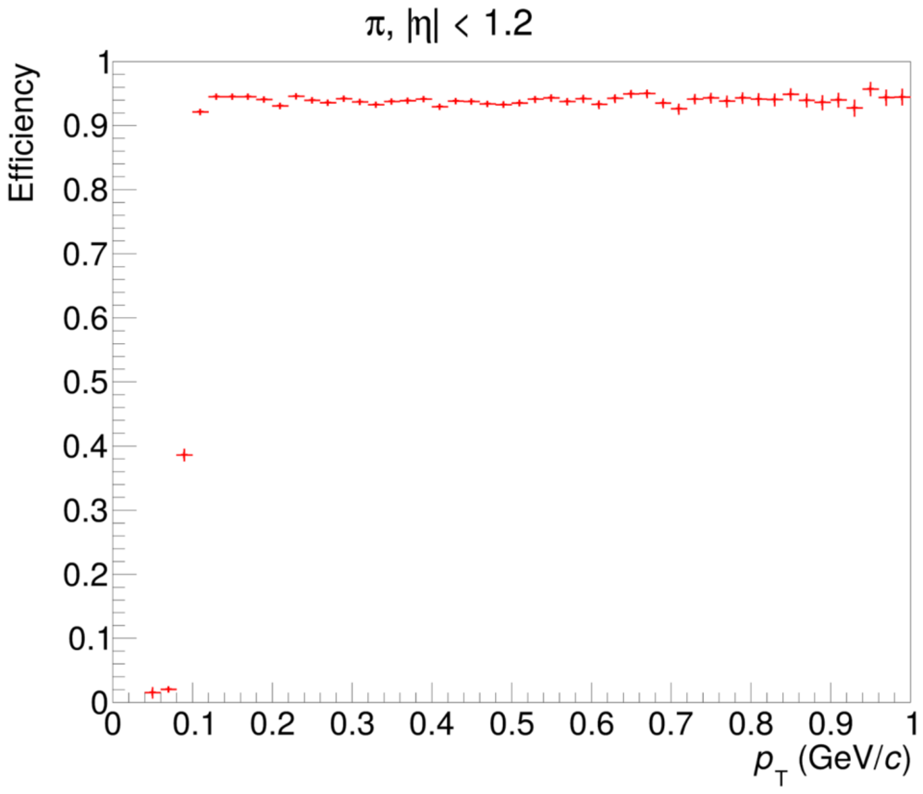
Combinatorial KF tracking performance in TPC (UrQMD)

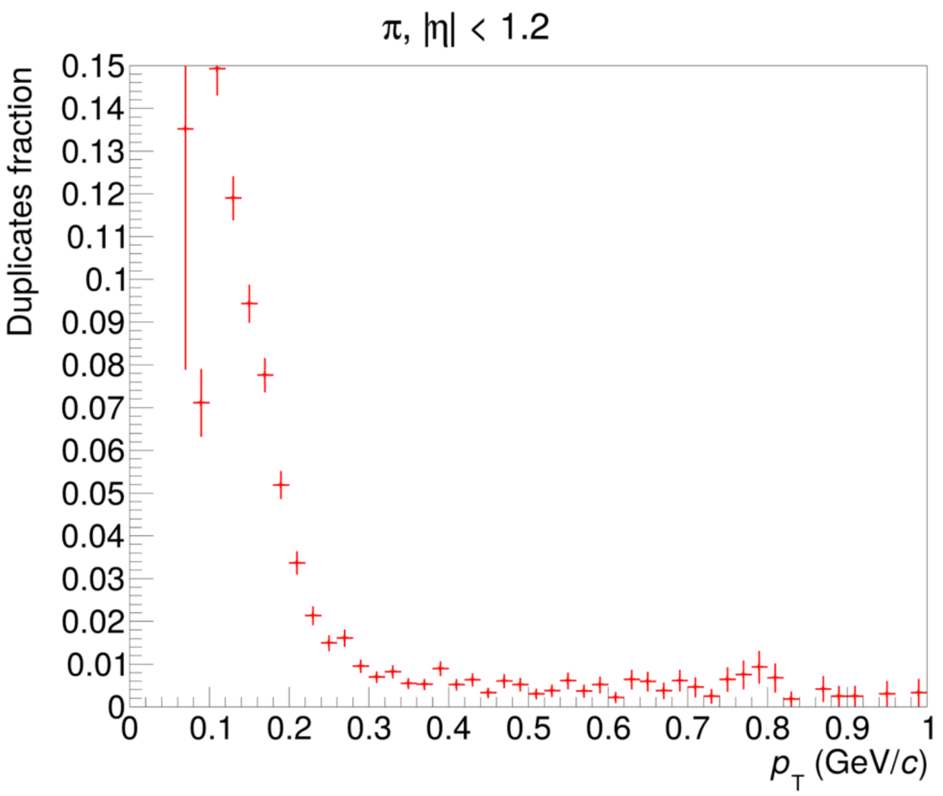




- Tracking efficiency and duplicates with standard 1-4-7 seeding
- No fakes, small fraction of duplicates

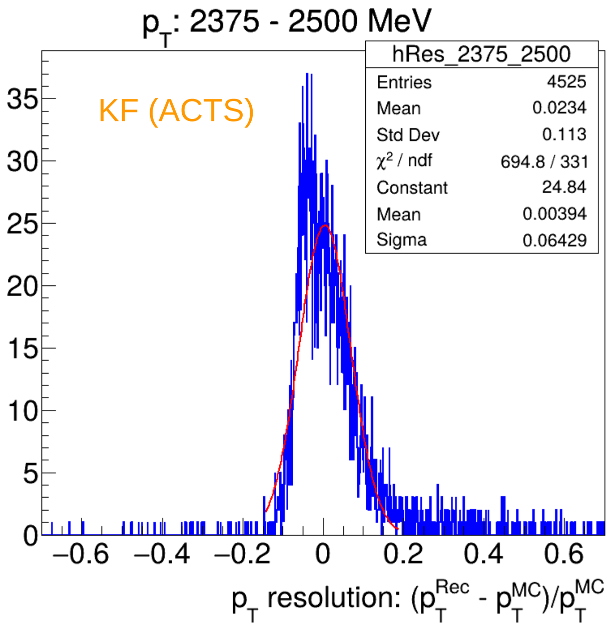
Quick test with improved seeding



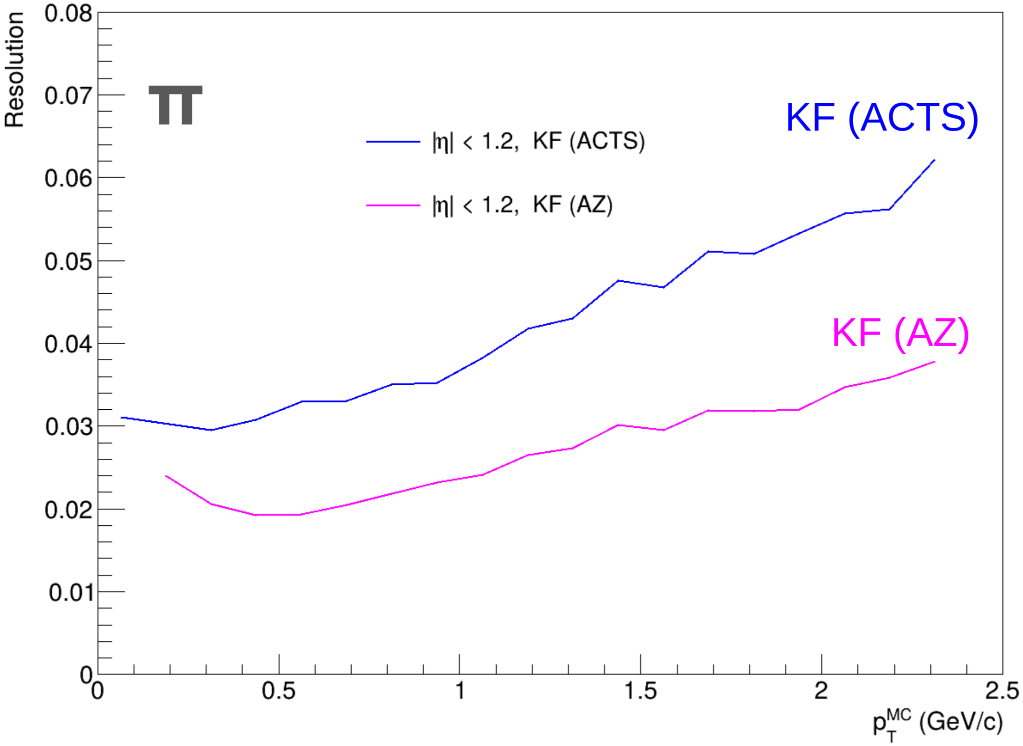


- Quick test with relaxed seeding using all available hits
- Clear potential for improvements

Momentum resolution



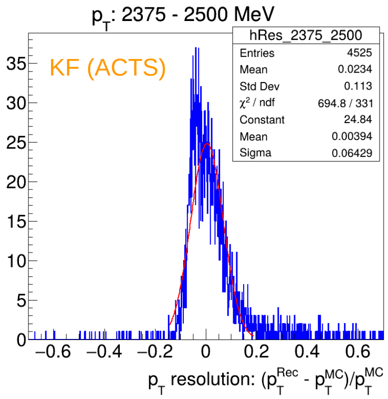
Significant tails and biases in p_T residual plots with the KF from ACTS

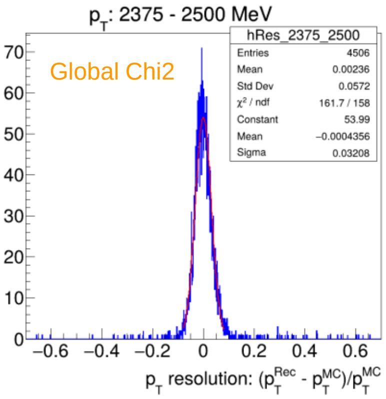


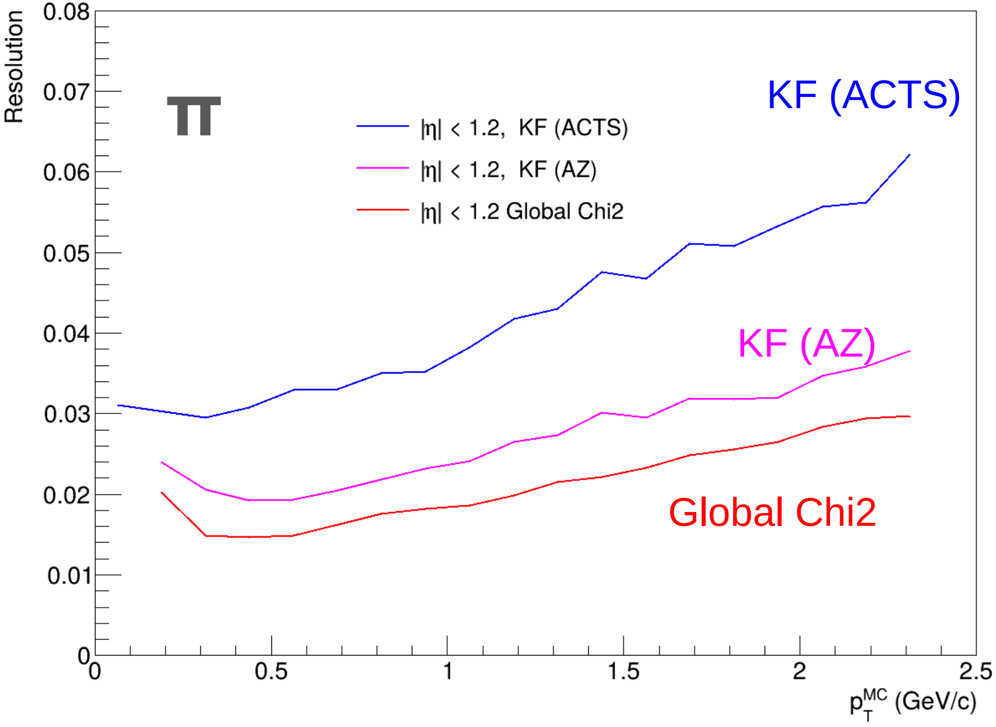
Momentum resolution with KF from ACTS significantly worse compared to KF implementation by A. Zinchenko

Refitting with Global Chi2 fitter

- Custom refitting algorithm developed to explore different fitting options (KF, Global Chi2 etc)
- Much better residuals with Global Chi2
- p_T resolution from Global Chi2 fitter appears to be much better compared to KF from ACTS and also slightly better compared tom KF from AZ





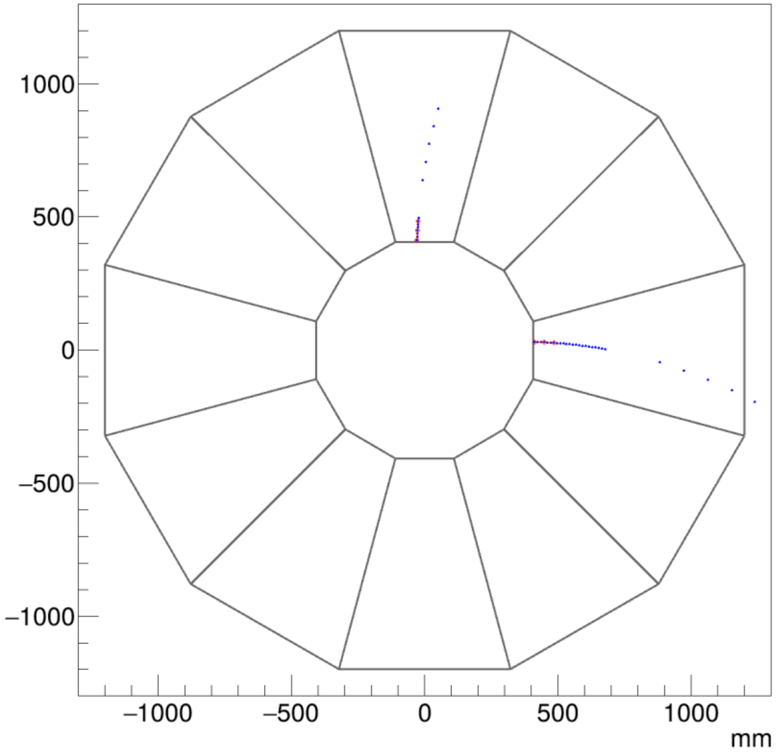


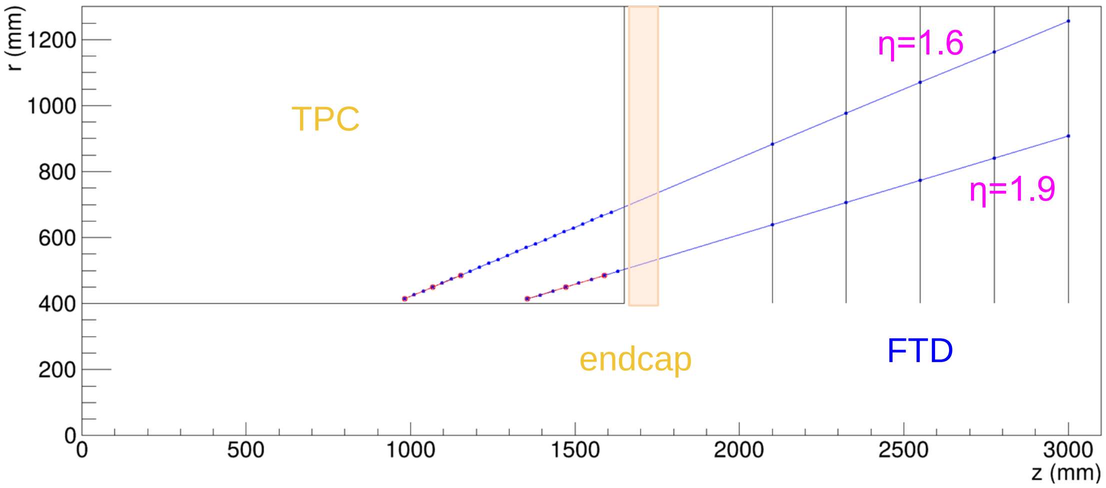
- The refitting algorithm can also be used to refit reconstructed tracks with different mass hypotheses

Towards TPC+FTD tracking

Occupancy in FTD

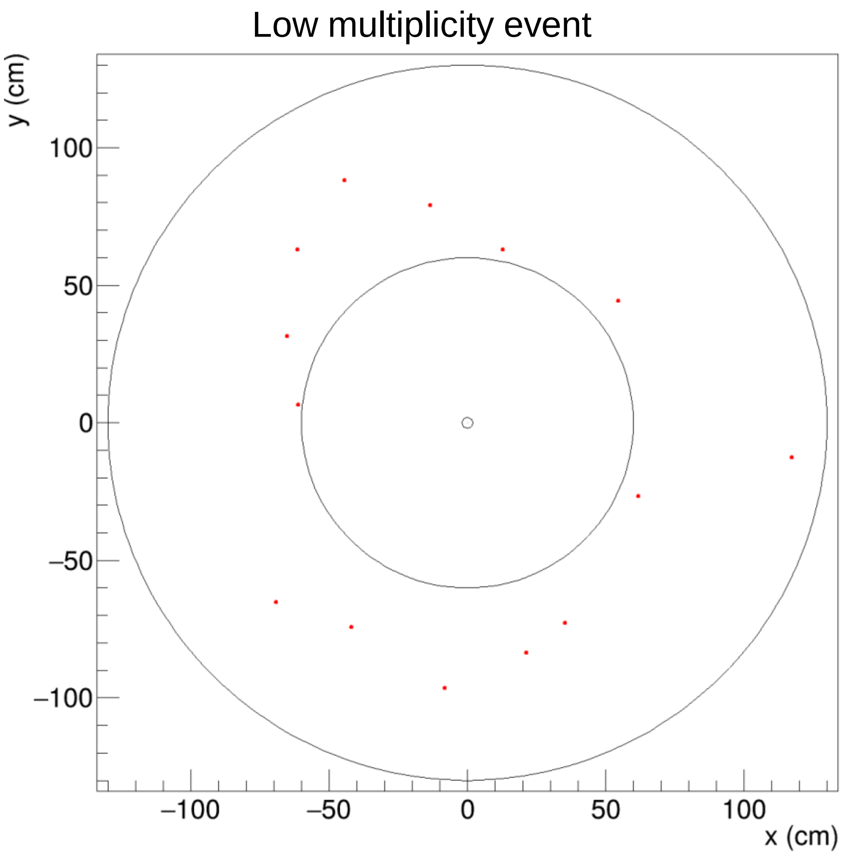
FTD tracking with TPC seeds

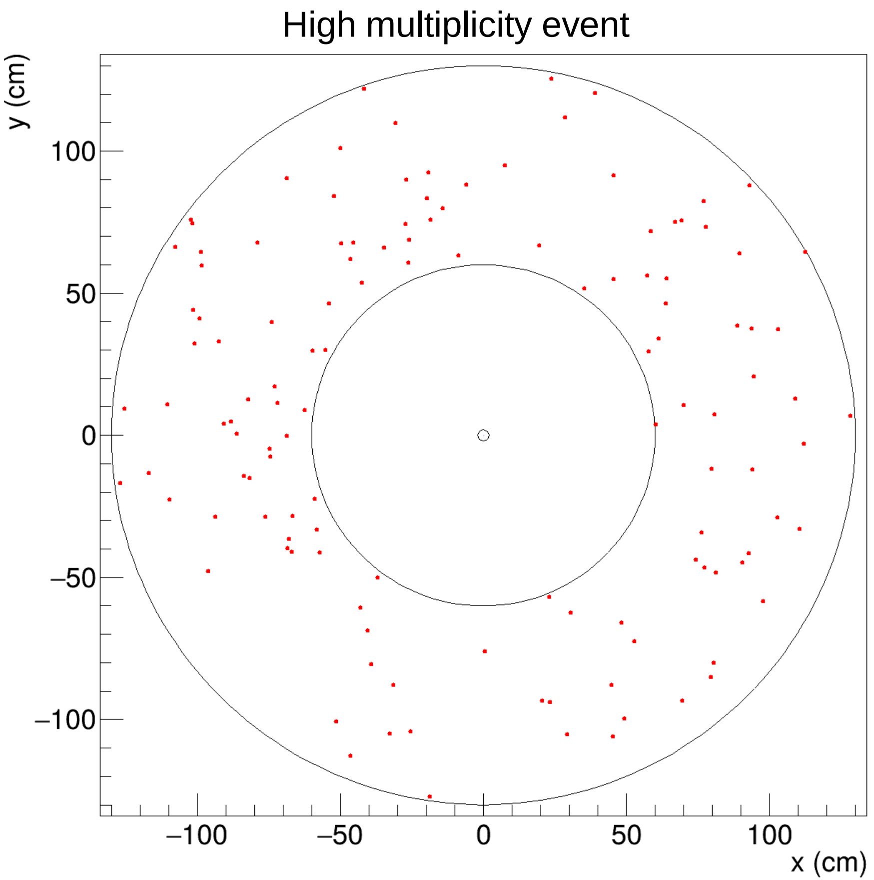




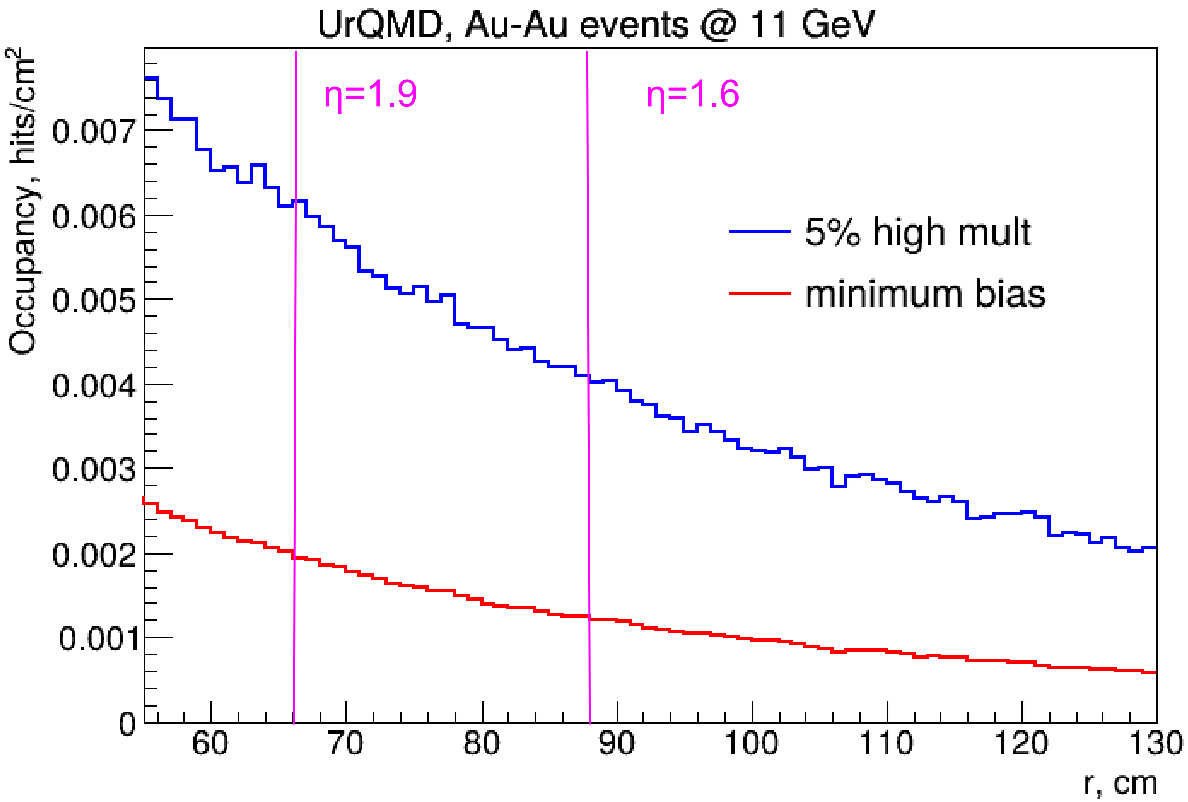
- FTD hits converted to ACTS format
- Use TPC seeds (1,4,7 padrows)
- Apply combinatorial KF to attach TPC and FTD measurements to tracks

Hit distributions in the 1st FTD station



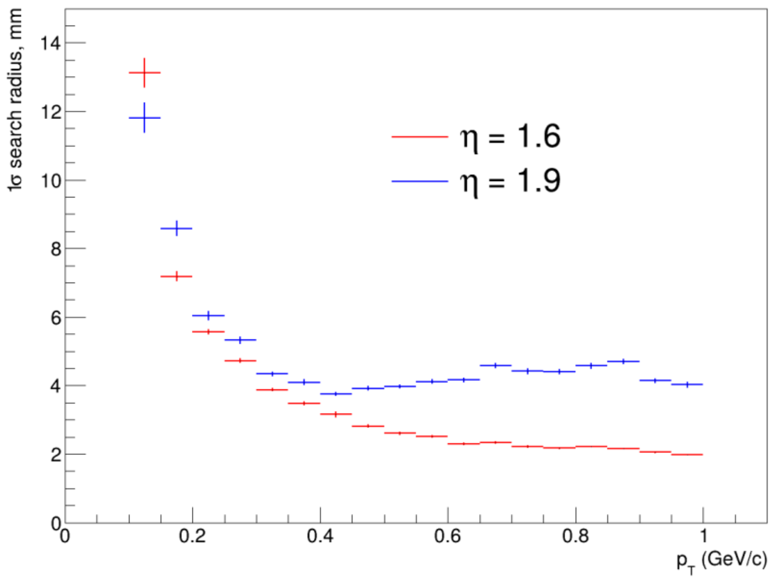


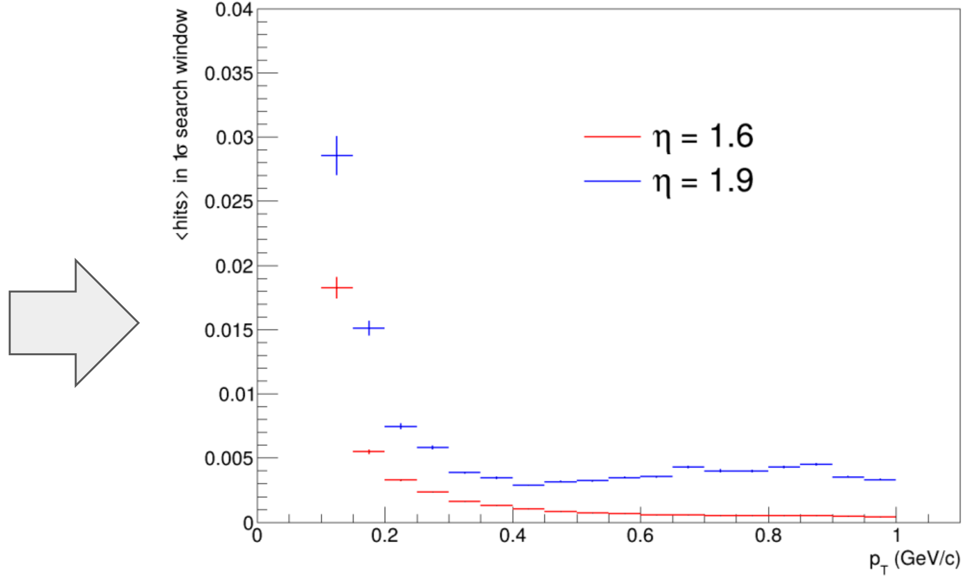
Occupancy at the first FTD station (z = 210 cm)

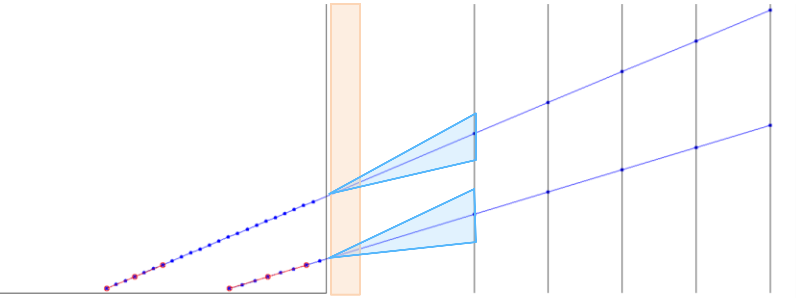


- Average occupancy < 1 hit per 100 cm^2

Extrapolating TPC tracks to FTD: uncertainties







- 1σ-search radius at the first FTD station about 2-4 mm for p_T>300 MeV
- Hit density in 1σ-search window < 0.01
- TPC+FTD tracking seems feasible

Towards TPC+FTD tracking:
Efficiency and resolution

FTD tracking performance: efficiency (Boxgen)

Seeding:

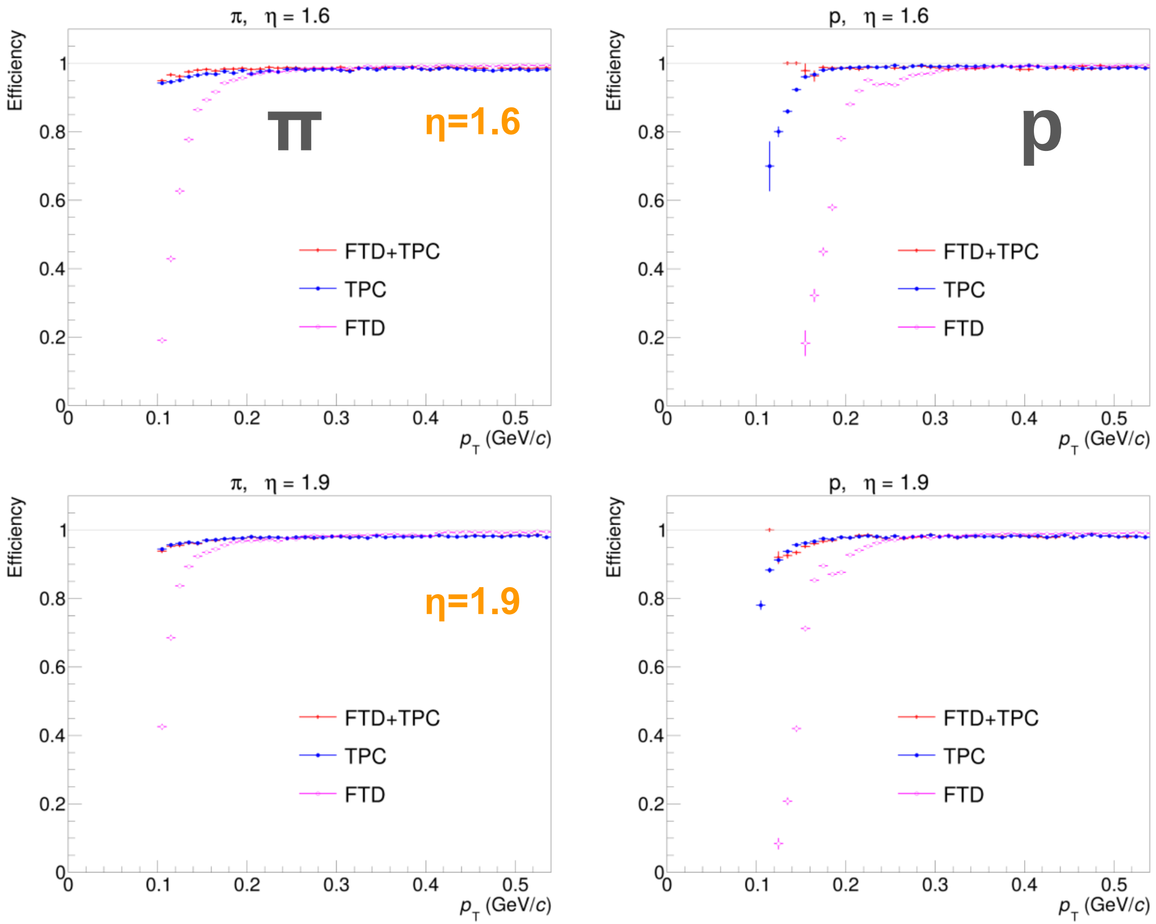
- TPC: for TPC and FTD+TPC
- FTD: for FTD

Shown trackable efficiencies. Minimum requirements:

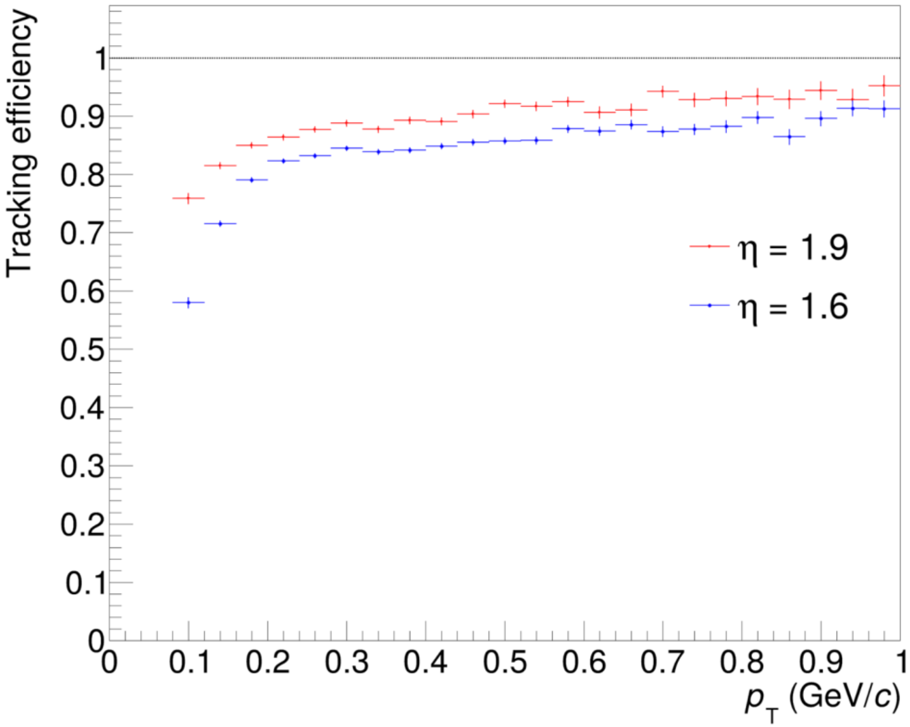
- TPC: hits in 1,4,7 padrows
- TPC+FTD: hits in 1,4,7 padrows, at least 3 hits in FTD
- FTD: 5 hits in FTD
- ALL: stay away from end-cap frame (~110% X_0)

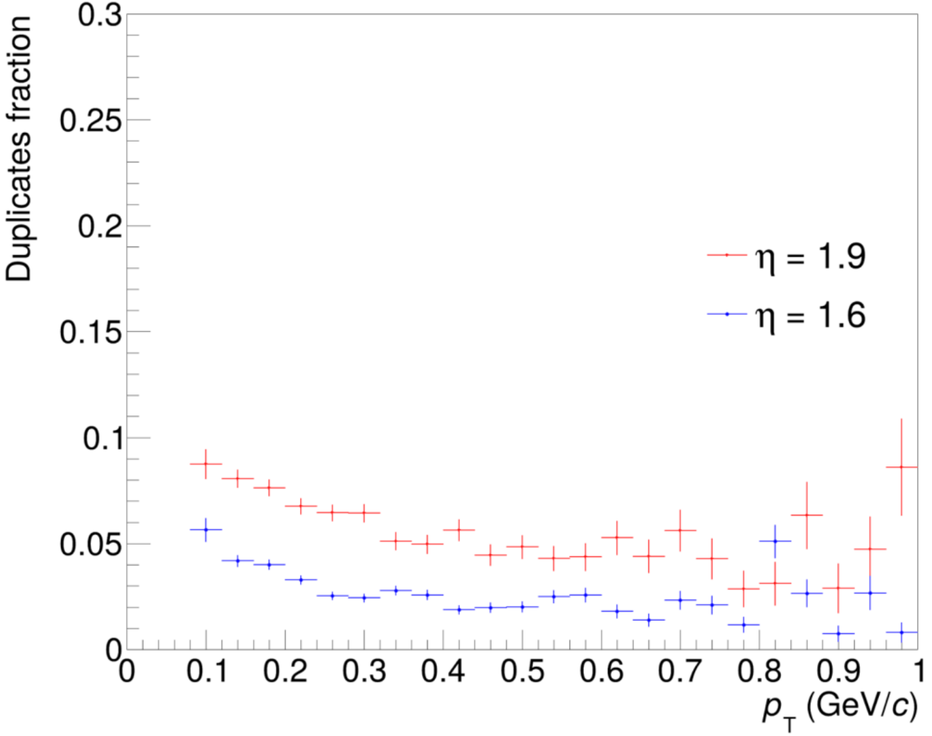
Results:

- Close to perfect efficiencies for single-track boxgen



TPC+FTD tracking performance (UrQMD)



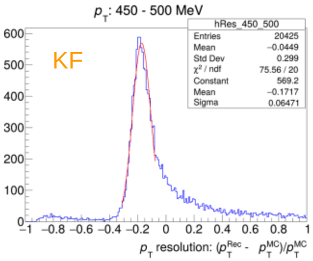


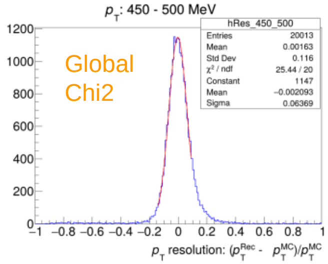
- Efficiency with standard 1-4-7 seeding

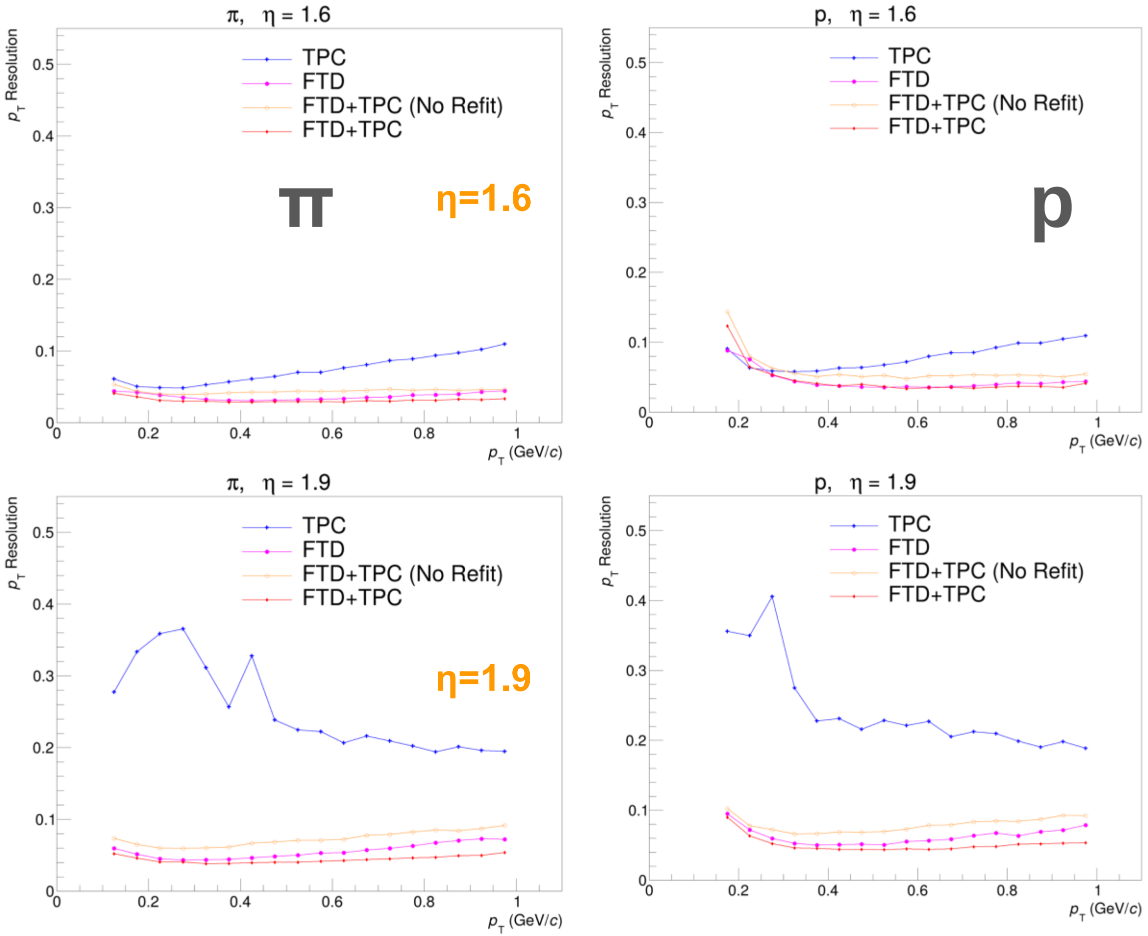
FTD tracking performance: momentum resolution

- KF: Biased momentum estimate with long tails
- Global Chi2: Much better Gaussian-like distributions
- FTD significantly improves momentum resolution, especially at large eta
- Combined FTD+TPC fit further improves momentum resolution

Resolution from TPC-only fit for pions at eta = 1.6

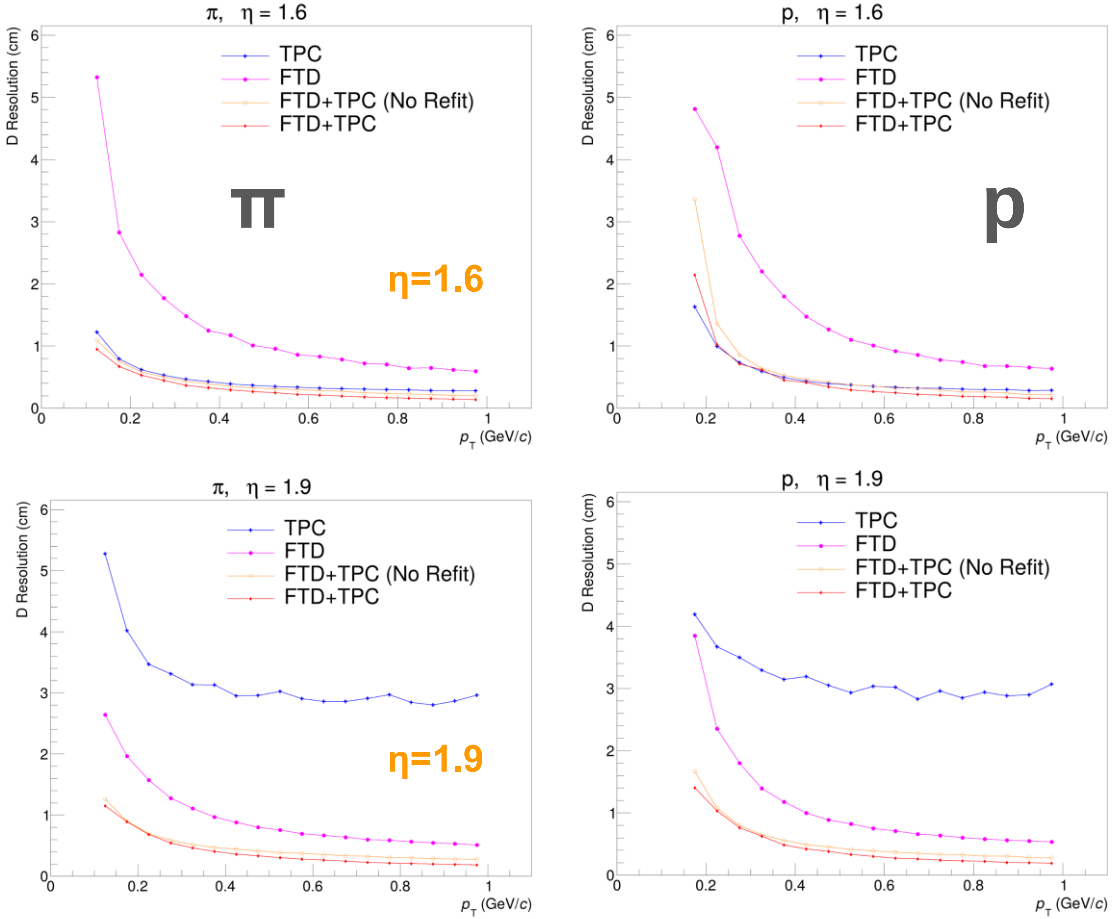






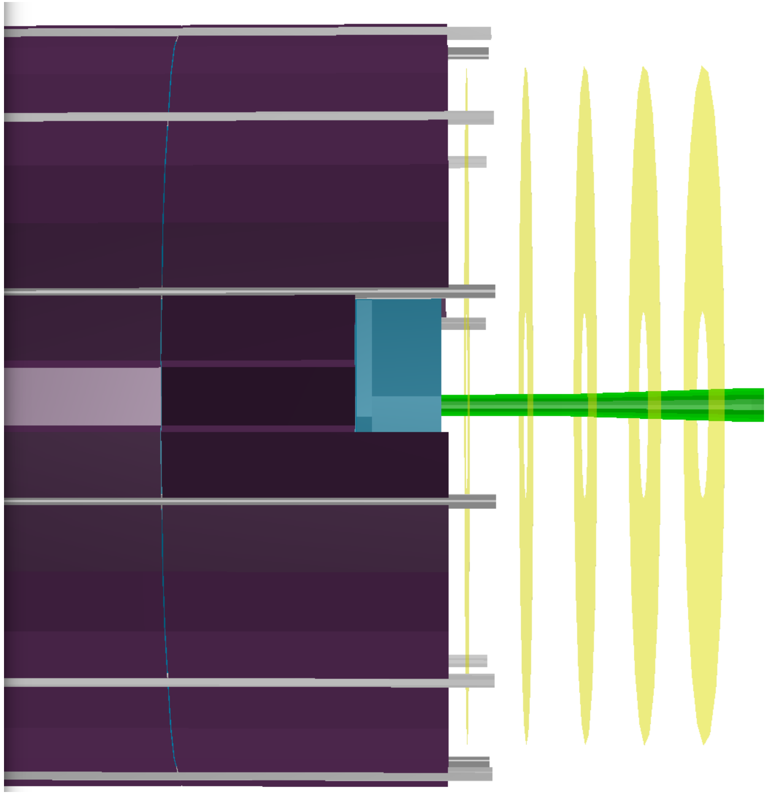
FTD tracking performance: DCA resolution

- TPC-matching helps to improve DCA resolution at moderate eta
- Poor DCA resolution for TPC-only at large eta
- TPC-FTD-matching helps to improve DCA resolution

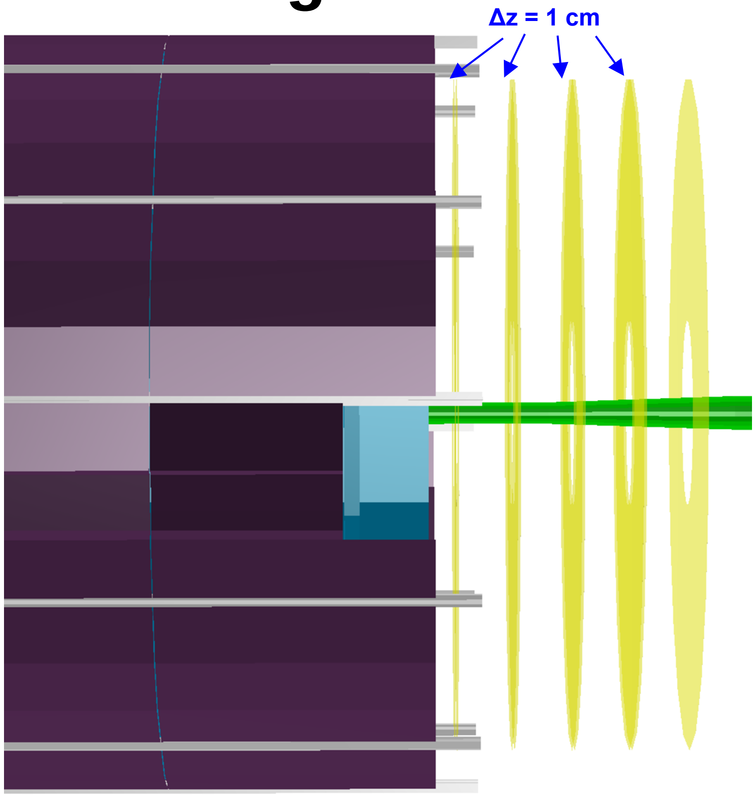


ACTS tracking
in strip-like forward detector
using 1D-hit info

2D tracking vs 1D tracking

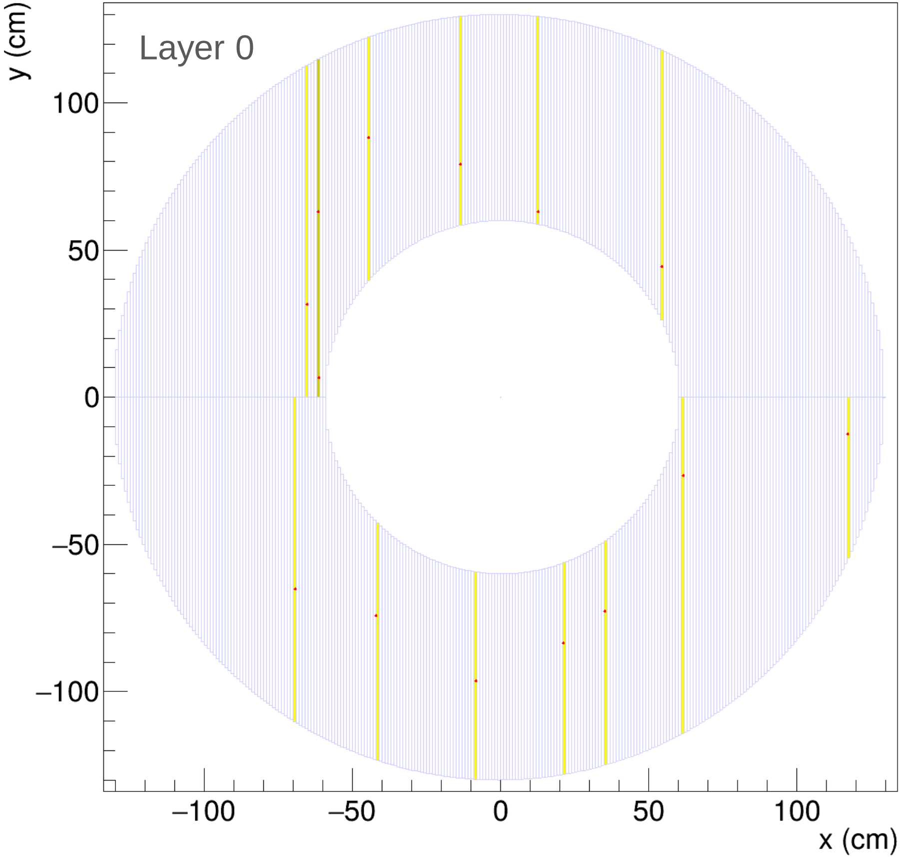


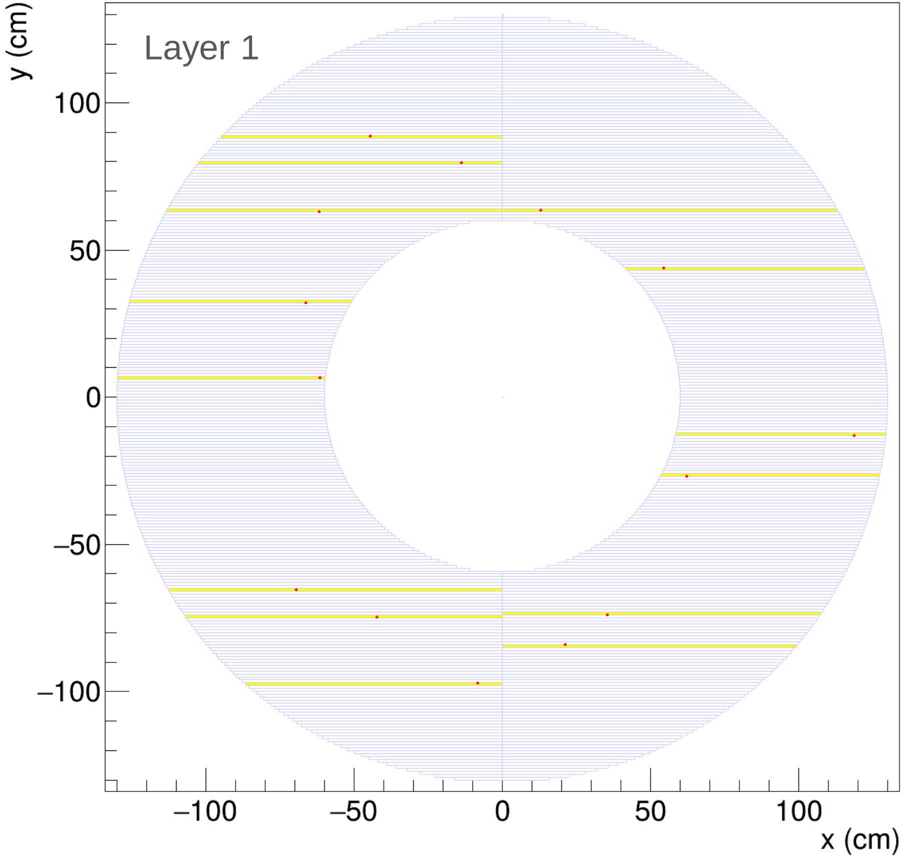
- 5 stations with pixel-like 2D layers



- 4 stations with 2 strip-like 1D layers + 1 pixel-like 2D layer
- In strip-like stations:
  first layer measures x coordinate
  second layer measures y coordinate

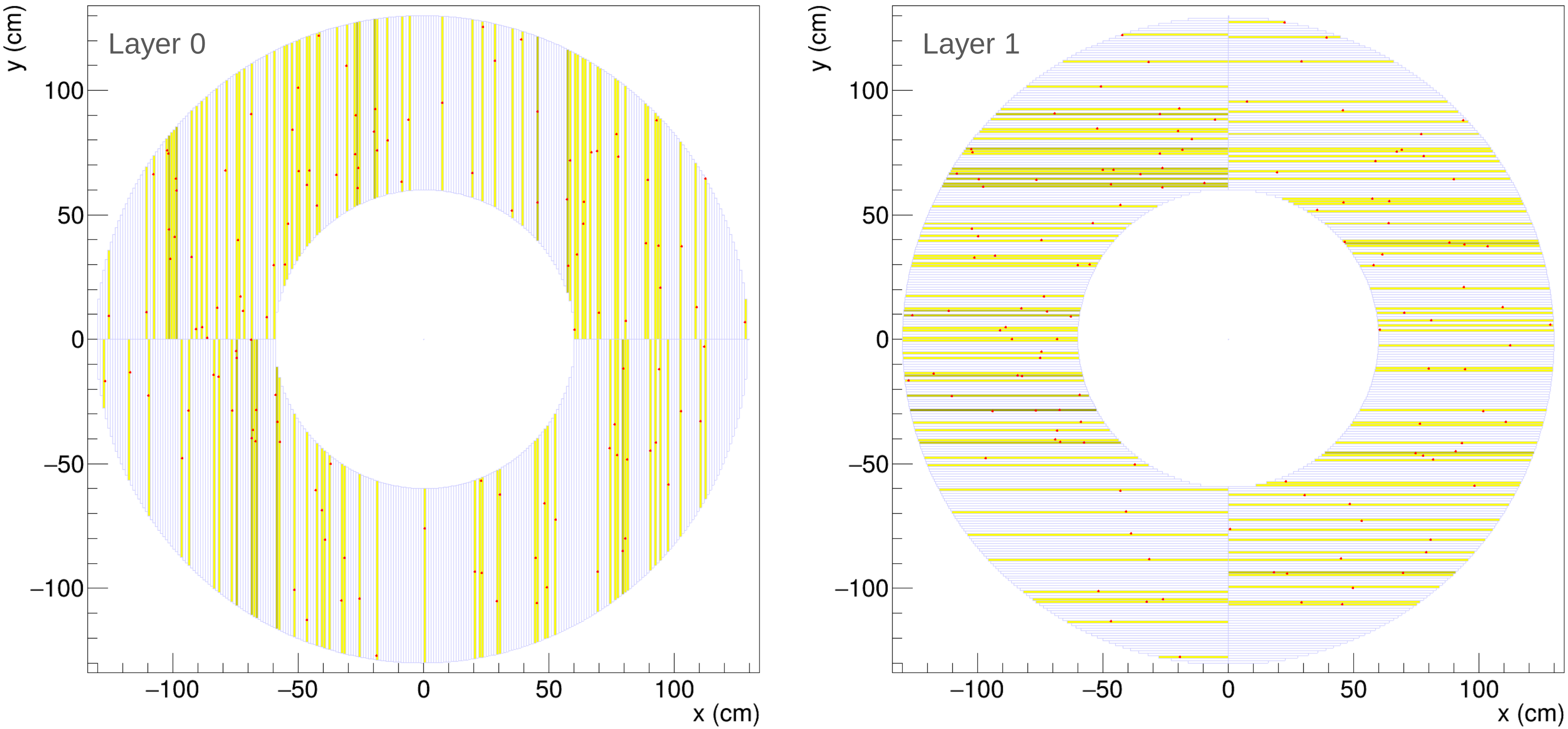
Typical UrQMD event in strip-like forward detector station





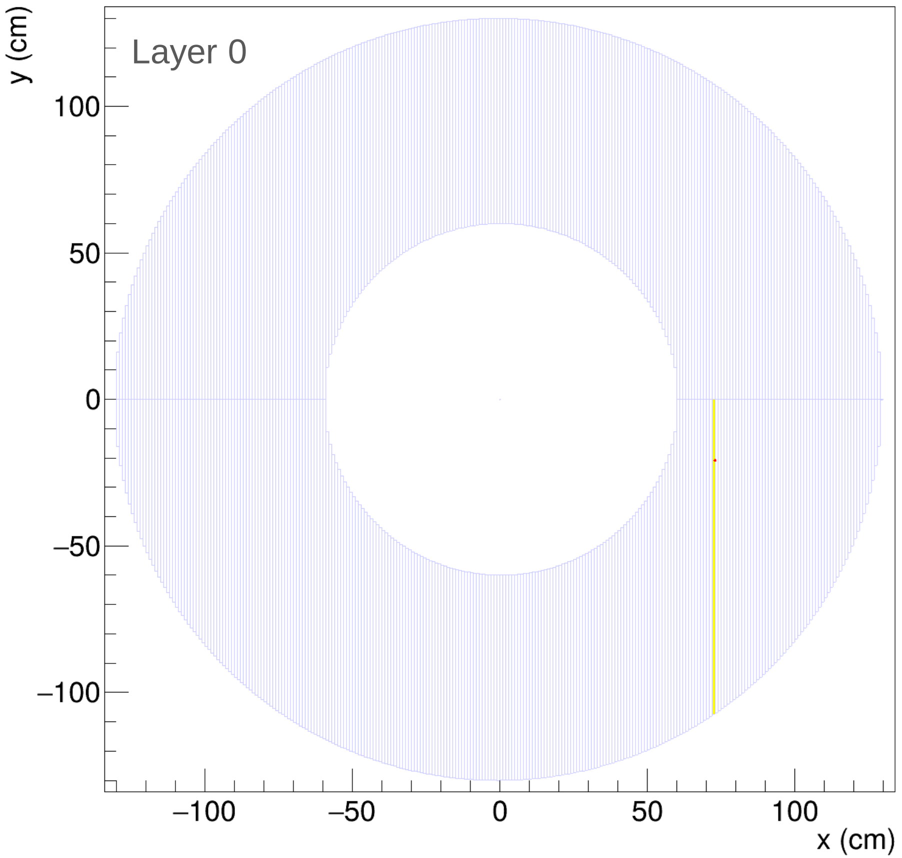
Considering simple strip-like geometry with 1 cm strips, second layer rotated by 90 degrees

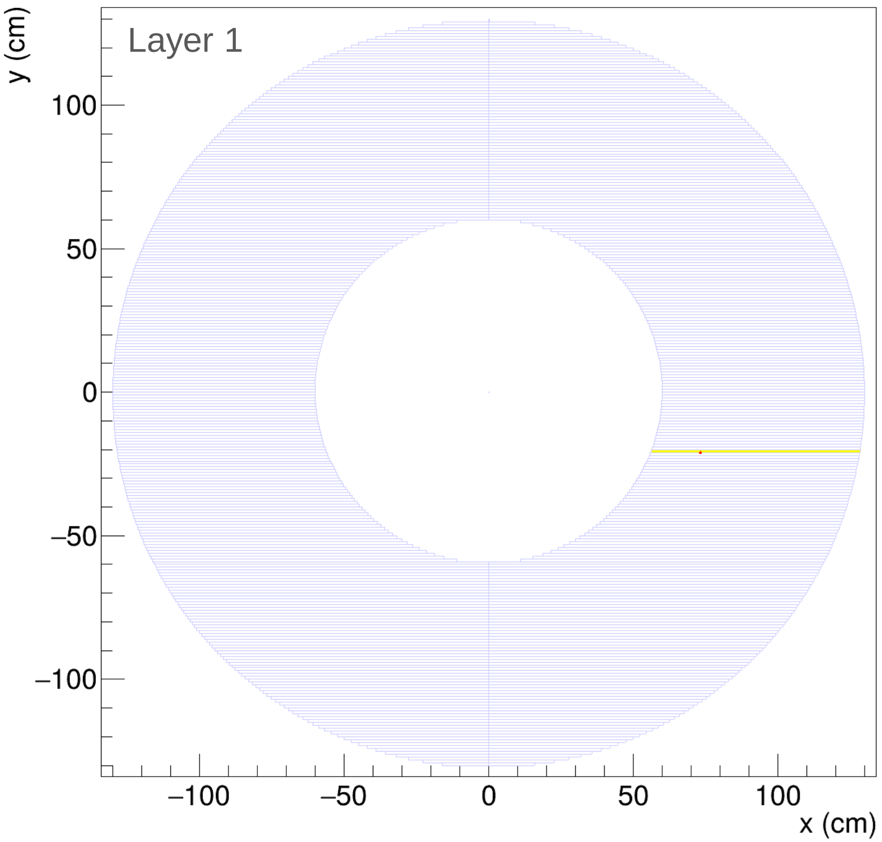
High-multiplicity UrQMD event example



Too high occupancy… Consider shorter segmented strips?

Single-pion box generator



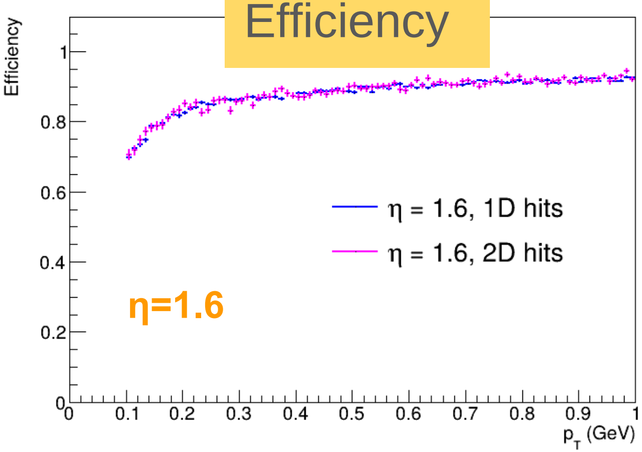


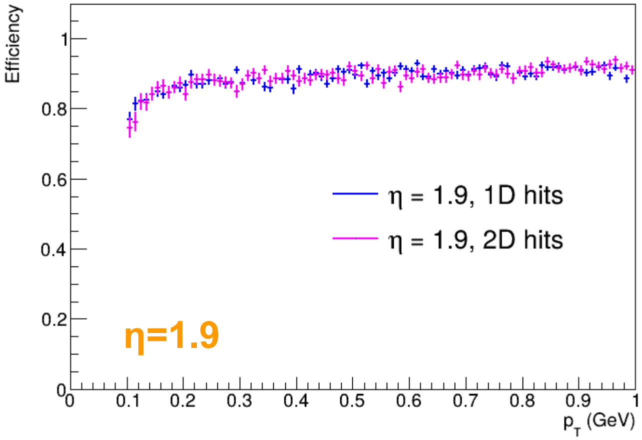
Let’s first check 1D tracking with single pion box generator

2D-vs-1D tracking performance (single pion boxgen)

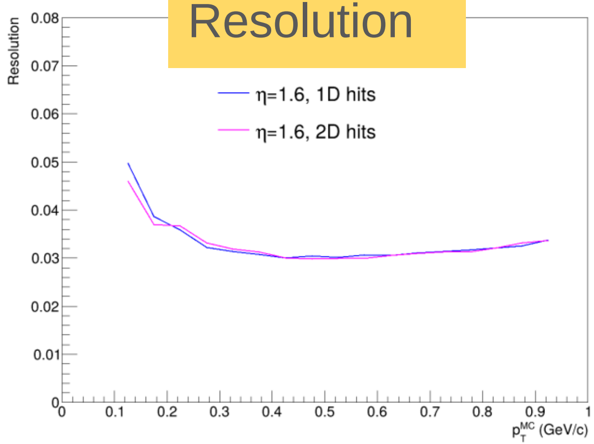
- Single pion boxgen
- TPC+FTD tracking, resolution after refit
- Perfect agreement between 1D and 2D tracking both for track resolution and reconstruction efficiency
- Tools are ready for the forward detector optimization with realistic 1D-tracking algorithms

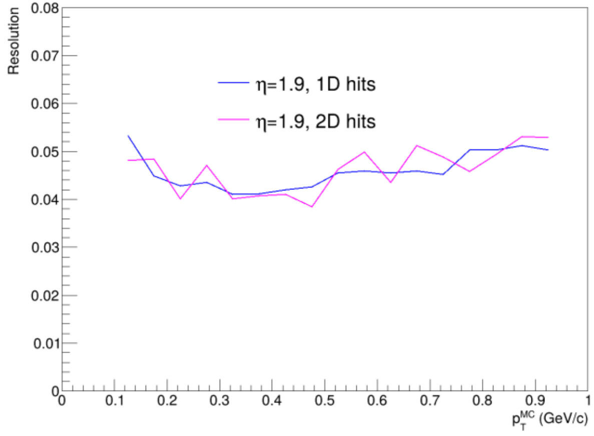
Efficiency



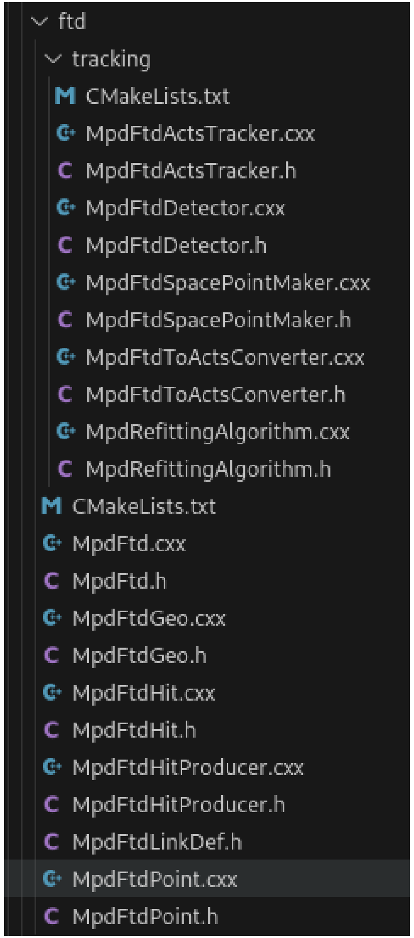


Resolution





Code structure



New detector library (ftd) added under detectors subfolder

Fork in git: https://git.jinr.ru/ekryshen/mpdroot

Code structure:

- MpdFtd.h/cxx - FTD geometry and MC point processing
- MpdFtdGeo.h/cxx - FTD geometry settings
- MpdFtdPoint.h/cxx - MC point container for FTD
- MpdFtdHit.h/cxx - reco hit container for FTD
- MpdFtdHitProducer.h/cxx - ideal hit producer for FTD
- Tracking subfolder (compiled if ACTS package is found):
  - MpdFtdDetector.h/cxx - ACTS geometry (TPC + FTD)
  - MpdFtdToActsConverter.h/cxx - converts mpdroot info to ACTS format
  - MpdFtdActsTracker.h/cxx - FairTask: ACTS tracking in TPC and/or FTD
  - MpdRefittingAlgorithm.h/cxx - Refitting with GlobalChi2 fitter (+mass hypothesis)
  - MpdFtdSpacePointMaker.h/cxx - Making space points from 1D hits in FTD

Running procedure:

```
FairTask* ftdHitProducer = new MpdFtdHitProducer();
fRun->AddTask(ftdHitProducer);

FairTask* ftdActsTracker = new MpdFtdActsTracker();
fRun->AddTask(ftdActsTracker);
```

Algorithms used in MpdFtdActsTracker

Trying to use native ACTS algorithms when possible

```
// create algorithms
fConverter = new MpdFtdToActsConverter(converterCfg, logLevel);
fSpacePointMaker = new ActsExamples::MpdFtdSpacePointMaker(spCfg, logLevel);
fSeedingAlgorithm = new ActsExamples::SeedingAlgorithm(seedingCfg, logLevel);
fTrackParamsEstimationAlgorithm = new ActsExamples::TrackParamsEstimationAlgorithm(paramsEstimationCfg, logLevel);
fTrackFindingAlgorithm = new ActsExamples::TrackFindingAlgorithm(trackFindingCfg, logLevel);
if (fDoRefit) fTrackRefittingAlgorithm = new ActsExamples::MpdRefittingAlgorithm(trackRefitCfg, logLevel);
fTrackTruthMatcher = new ActsExamples::TrackTruthMatcher(trackTruthMatcherCfg, logLevel);
fRootParticleWriter = new ActsExamples::RootParticleWriter(particleWriterCfg, logLevel);
fRootSimHitWriter = new ActsExamples::RootSimHitWriter(simhitWriterCfg, logLevel);
fRootMeasurementWriter = new ActsExamples::RootMeasurementWriter(measWriterCfg, logLevel);
fRootSpacepointWriter = new ActsExamples::RootSpacepointWriter(spWriterCfg, logLevel);
fRootSeedWriter = new ActsExamples::RootSeedWriter(seedWriterCfg, logLevel);
fRootTrackStatesWriter = new ActsExamples::RootTrackStatesWriter(trackStatesWriterCfg, logLevel);
fRootTrackSummaryWriter = new ActsExamples::RootTrackSummaryWriter(trackSummaryWriterCfg, logLevel);
if (fDoRefit) fRootTrackRefitSummaryWriter = new ActsExamples::RootTrackSummaryWriter(trackRefitSummaryWriterCfg, logLevel);
```

Conclusions and outlook

- Implemented TPC and TPC+FTD tracking with sector-based TPC geometry
- Reasonable performance of TPC+FTD tracking
- Seeding still needs further tuning
- Developed custom refitting algorithm supporting KF and Global χ^2:
    - Improved resolution comparable with the standard KF results
    - Possibility to set a particle hypothesis → correct accounting for material effects
- Working towards realistic strip-like FTD geometry with 1D tracking
    - Tools are ready for detector optimization

Backup

ACTS project

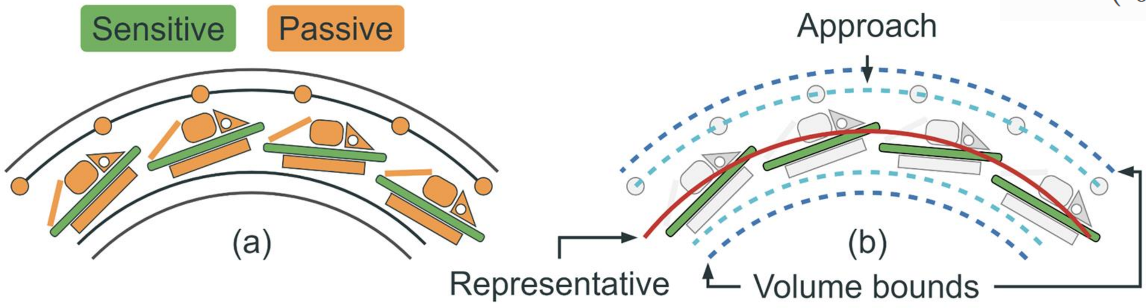
https://acts.readthedocs.io/

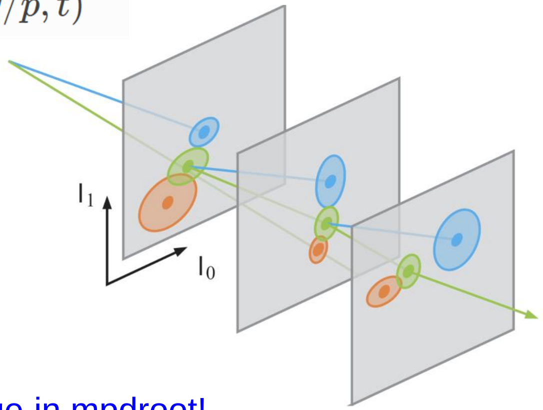
- A Common Tracking Software project
- Contains:
  - Box generator or interface to read external particles
  - Fatras (fast simulation tool) or interface to read hits
  - Digitization algorithm (smearing etc)
  - Seeding (several algorithms, including truth seeding)
  - Track finding/fitting with Combinatorial KF
- Accounting for energy losses, multiple scattering etc.
- Supporting multi-core execution, GPU etc.

```
// Start sequencer
ActsExamples::Sequencer sequencer(sequencerCfg);

if (inputDir.Contains("none")){ // particle gun + fartras simulation
  sequencer.addReader(std::make_shared<ActsExamples::EventGenerator>(evgenCfg, logLevel));
  sequencer.addElement(std::make_shared<ActsExamples::FatrasSimulation>(fatrasCfg, logLevelFatras));
} else { // read particles and hits from input file
  sequencer.addReader(std::make_shared<ActsExamples::RootParticleReader>(particleReaderCfg, logLevel));
  sequencer.addReader(std::make_shared<ActsExamples::RootSimHitReader>(simhitReaderCfg, logLevel));
}
sequencer.addAlgorithm(std::make_shared<ActsExamples::DigitizationAlgorithm>(digiCfg, logLevelDigi));
sequencer.addAlgorithm(std::make_shared<ActsExamples::SpacePointMaker>(spCfg, logLevel));
sequencer.addAlgorithm(std::make_shared<ActsExamples::SeedingAlgorithm>(seedingCfg, logLevelSeed));
sequencer.addAlgorithm(std::make_shared<ActsExamples::TrackParamsEstimationAlgorithm>(paramsEstimationCfg, logLevel));
sequencer.addAlgorithm(std::make_shared<ActsExamples::TrackFindingAlgorithm>(trackFindingCfg, logLevelFinder));
sequencer.addAlgorithm(std::make_shared<ActsExamples::TrackTruthMatcher>(trackTruthMatcherCfg, logLevelMatcher));
sequencer.addWriter(std::make_shared<ActsExamples::RootParticleWriter>(particleWriterCfg, logLevel));
sequencer.addWriter(std::make_shared<ActsExamples::RootSimHitWriter>(simhitWriterCfg, logLevel));
sequencer.addWriter(std::make_shared<ActsExamples::RootMeasurementWriter>(measWriterCfg, logLevelMeasWriter));
sequencer.addWriter(std::make_shared<ActsExamples::RootSpacepointWriter>(spWriterCfg, logLevel));
sequencer.addWriter(std::make_shared<ActsExamples::RootSeedWriter>(seedWriterCfg, logLevel));
sequencer.addWriter(std::make_shared<ActsExamples::RootTrackStatesWriter>(trackStatesWriterCfg, logLevel));
sequencer.addWriter(std::make_shared<ActsExamples::RootTrackSummaryWriter>(trackSummaryWriterCfg, logLevel));
```

$$\vec{x} = (l_0, l_1, \phi, \theta, q/p, t)^T$$

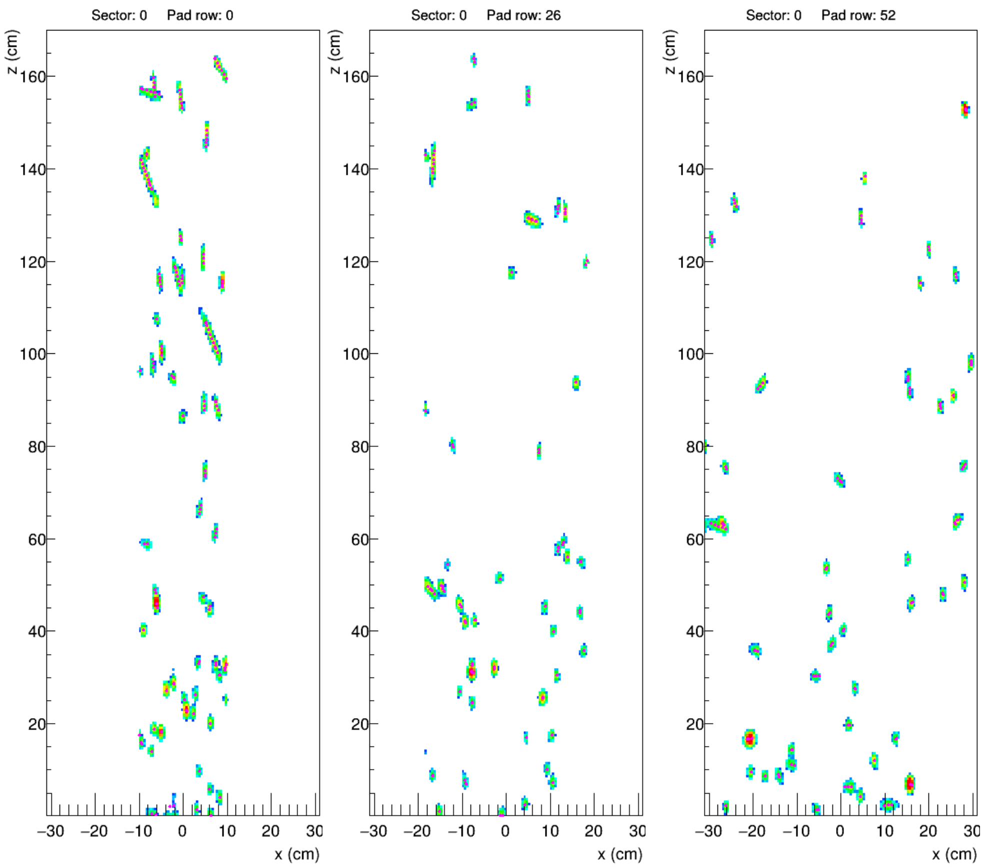




Using latest v38.1 from nicadist

Many thanks to Slavomir Hnatic and Jan Busa for integration of latest ACTS package in mpdroot!

Reminder: digits in TPC

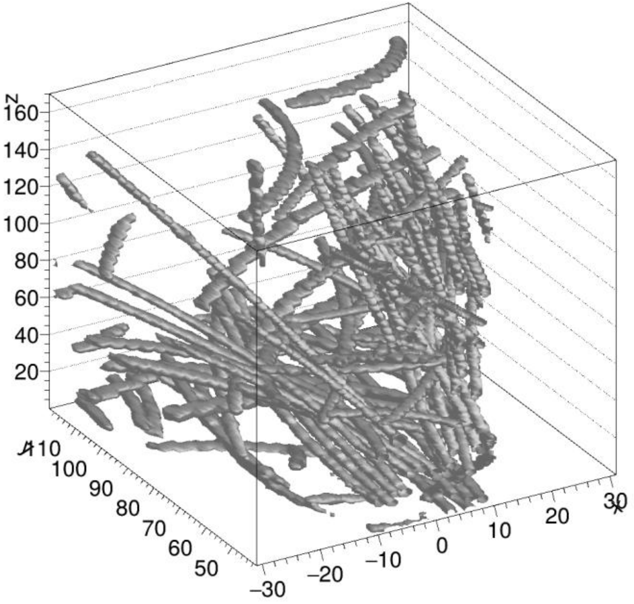


Central URQMD event: Au-Au @ 11 GeV

MC points in magenta

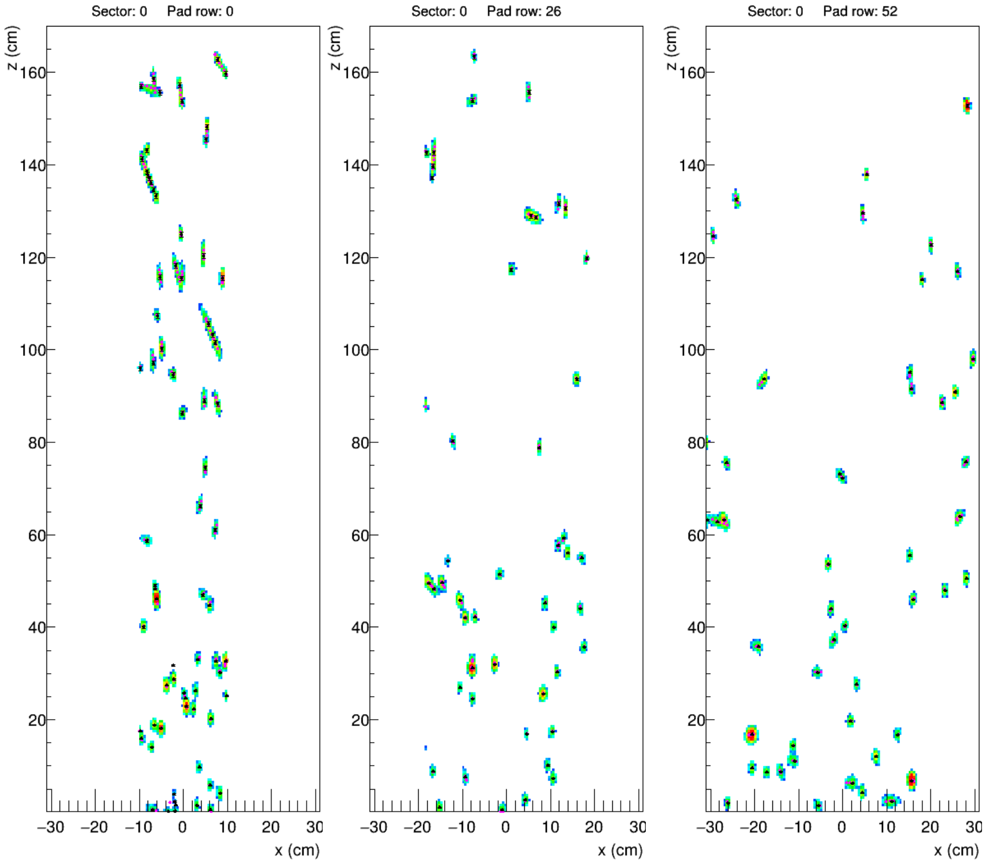
Digits produced by MpdTpcDigitizerAZlt*:

- Pad rows in local y: 12 mm (inner) 18 mm (outer)
- Pad size in local x: 5 mm
- Time bin 100 ns -> z-bin size: 5.5 mm



* Core developer: A. Zinchenko

Reminder: hits in TPC



Digits produced by MpdTpcDigitizerAZlt*:

- Pad rows in local y: 12 mm (inner) 18 mm (outer)
- Pad size in local x: 5 mm
- Time bin 100 ns -> z-bin size: 5.5 mm

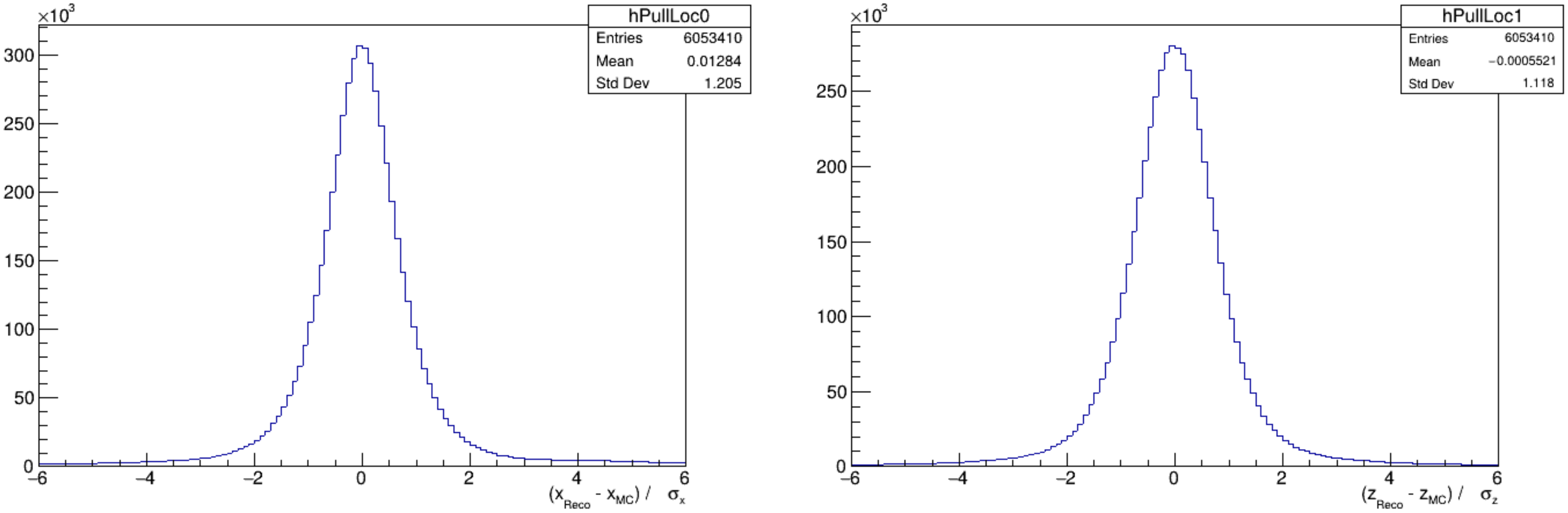
Clusters and hits produced by TpcClusterHitFinderMlem*:

- Several hits produced for complex clusters
- Nice matching between hits and MC points
- Typical assigned uncertainty in local x: 0.25 mm
- Typical assigned uncertainty in local z: 1 mm

Central URQMD event: Au-Au @ 11 GeV MC points in magenta, hits in black

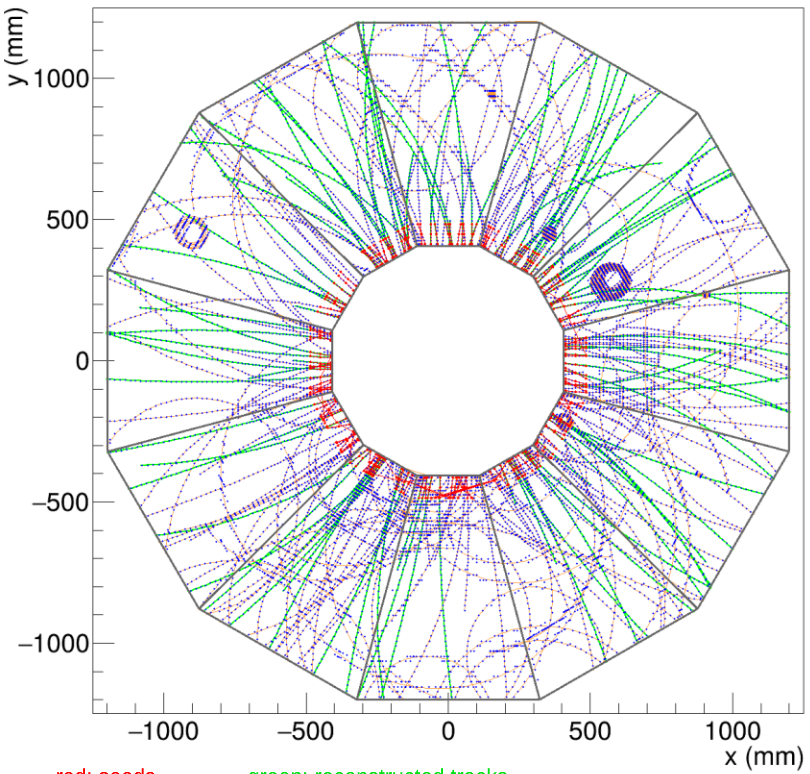
* Core developer: A. Zinchenko

Measurement pulls



- Pull = difference between reco and MC point / estimated uncertainty
- Allow to control biases and validate uncertainty estimation
- On average: no significant bias neither in x nor in z
- On average: pull widths close to 1
- -> Reasonably good for tracking

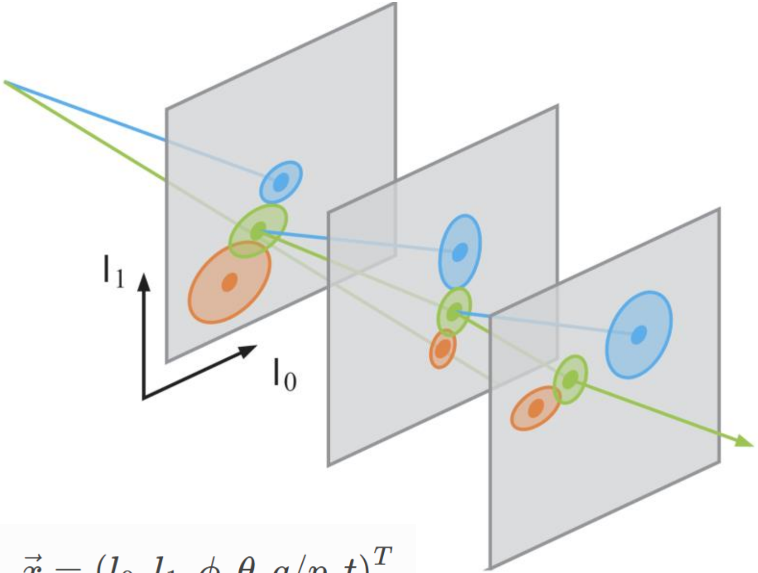
Track finding algorithm



red: seeds green: reconstructed tracks

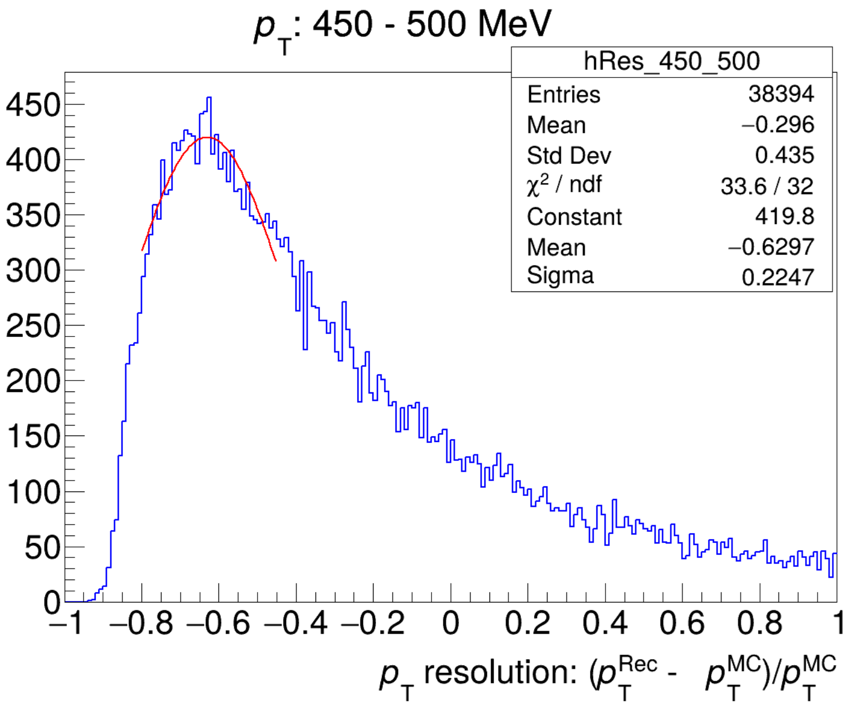
- Failed track finding for many seeds (propagation errors)
- Need further tuning

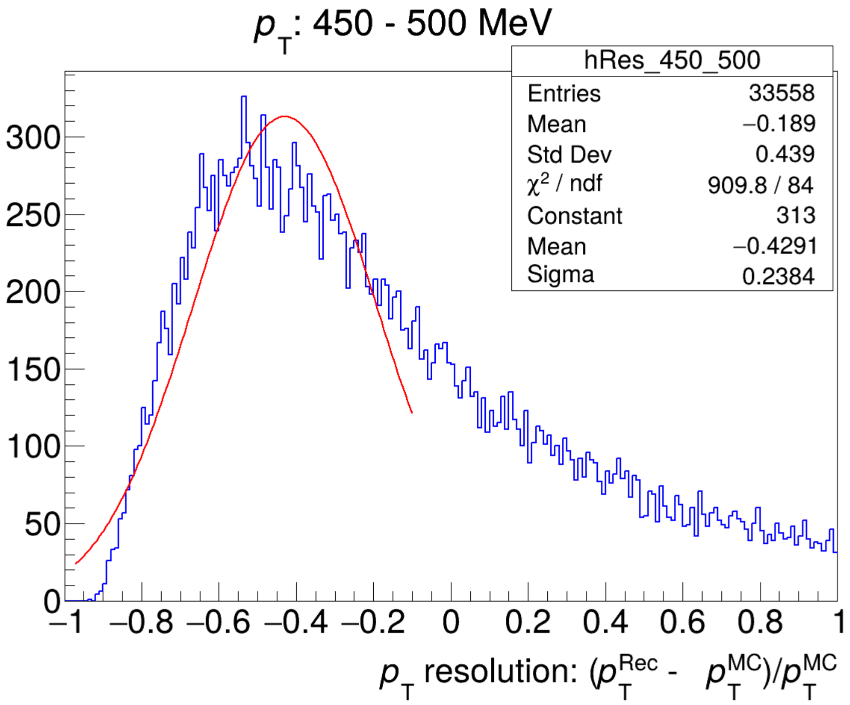
- Combinatorial Kalman Filter using initial track parameters from seeds
- Backward refit + smoothing



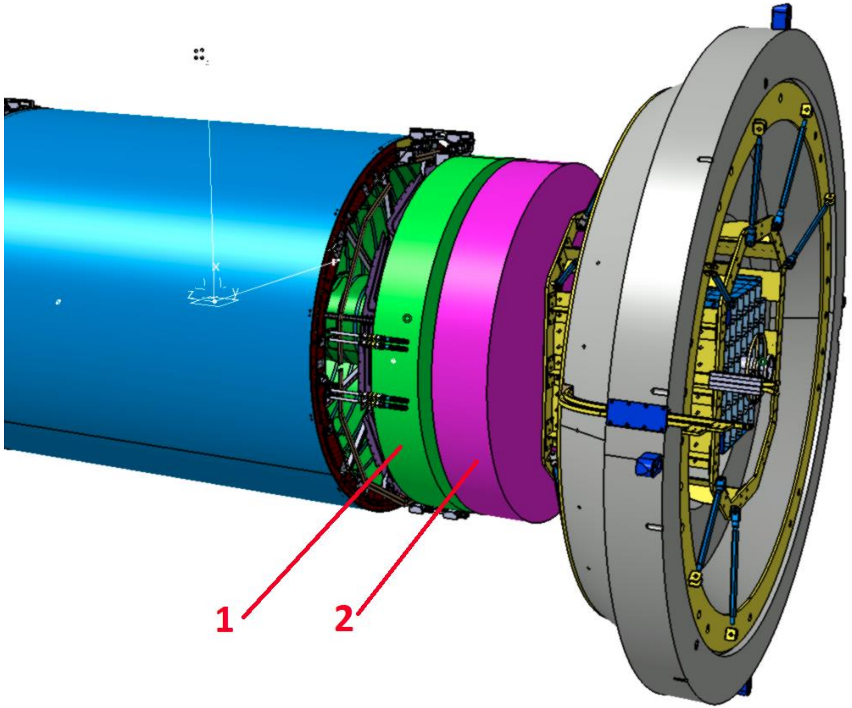
$$\vec{x} = (l_0, l_1, \phi, \theta, q/p, t)^T$$

Illustration of TPC-only fit for pions at eta = 1.9





Integration restrictions

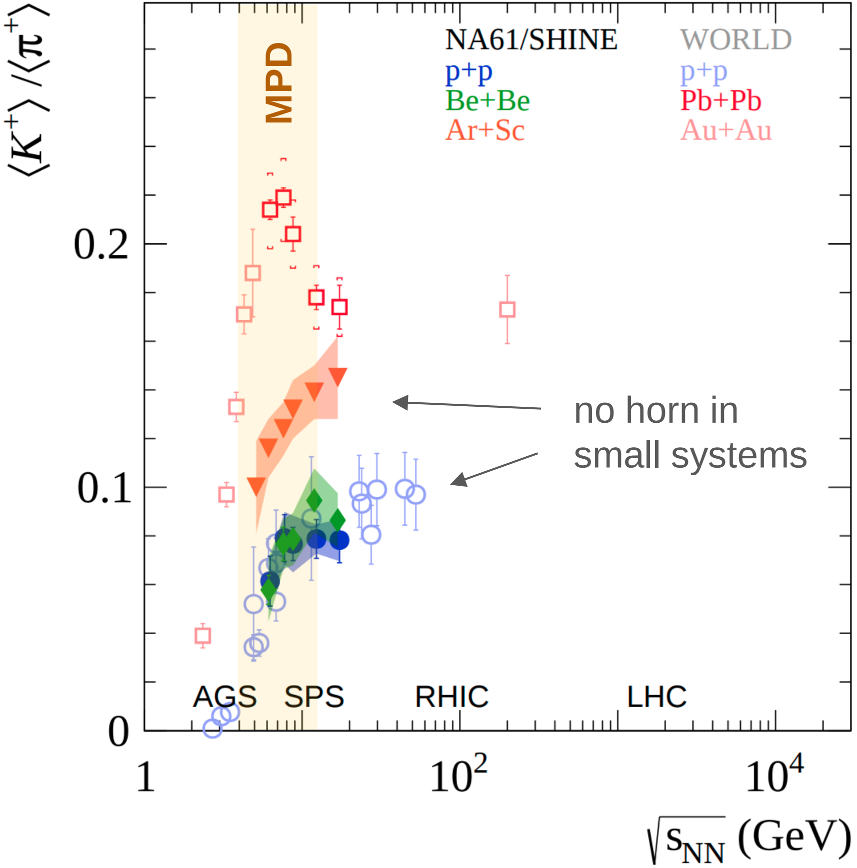


- L_0 = 85 cm instead of 100 cm in the toy model
- η_{min} = 1.55
- η_{max} =2.47

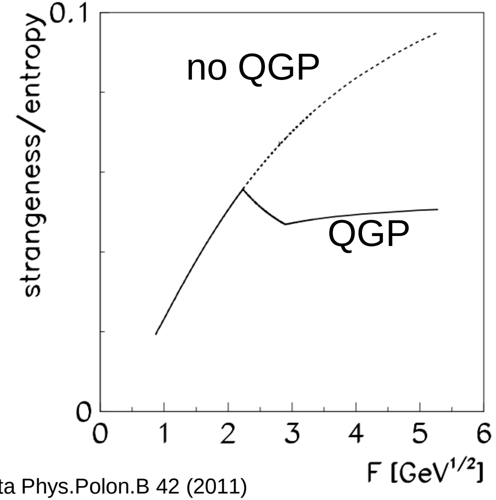
- Just received a realistic 3D model with all mechanical substructures
- Defines a more realistic envelope for the forward tracker
- Radial limitations:
  - R_{inner} = 357 mm
  - R_{outer} = 1300 mm
- Two volumes possible:
  - Green: z from 2100 to 2450 mm
  - Pink: z from 2550 to 2950 mm
  - The gap due to beam pipe support (can be eliminated if beam pipe is fixed to the tracker volume)

The Horn

NA61: EPJC 84 (2024) 416



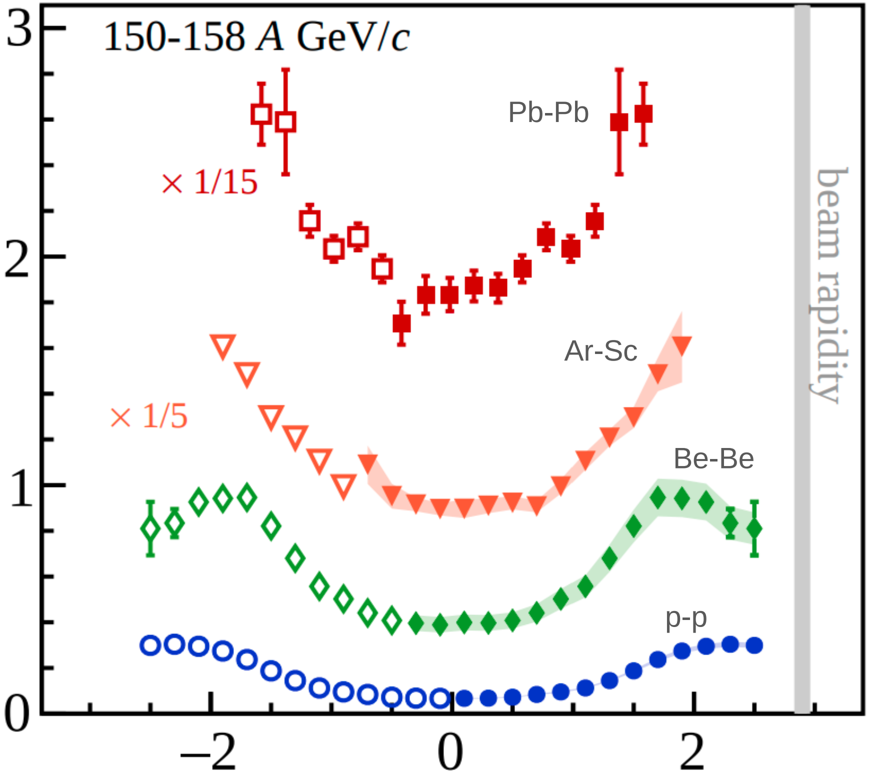
- **The horn:** sharp maximum in the ratio of strange particle to pion yields
- **Interpretation in statistical model (SMES)**: change of strangeness / entropy ratio due to deconfinement transition
- For precision measurements, we need strange particle yields (K, Λ) in the full phase space including 1.2<|η|<2.0



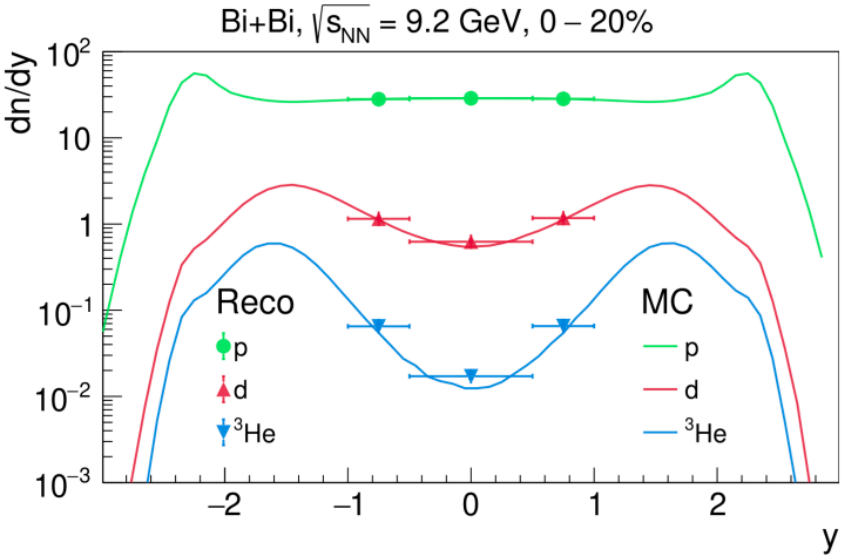
Acta Phys.Polon.B 42 (2011)

See also talk by V. Kolesnikov

Rapidity distributions for protons and light nuclei



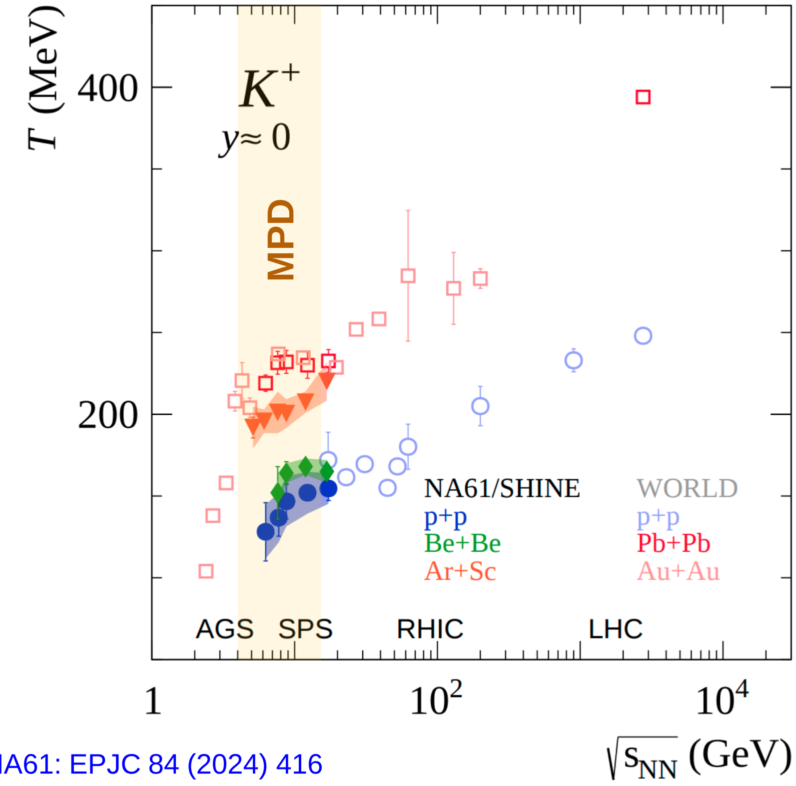
A forward tracker with PID may provide a substantial increase of MPD capability for baryon measurements (stopping, total yields)



NA61: EPJC 84 (2024) 416

The Step

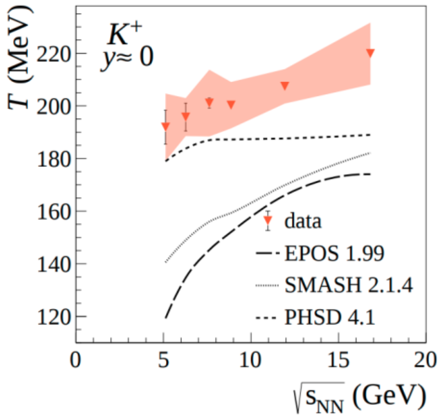
Acta Phys.Polon.B 42 (2011) 307

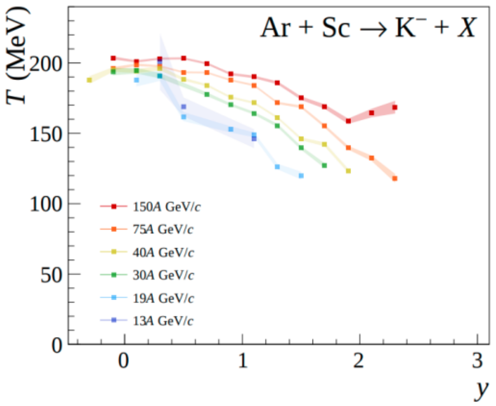


NA61: EPJC 84 (2024) 416

$$\frac{dN}{m_T dm_T} \cong C \exp\left(-\frac{m_T}{T^*}\right)$$

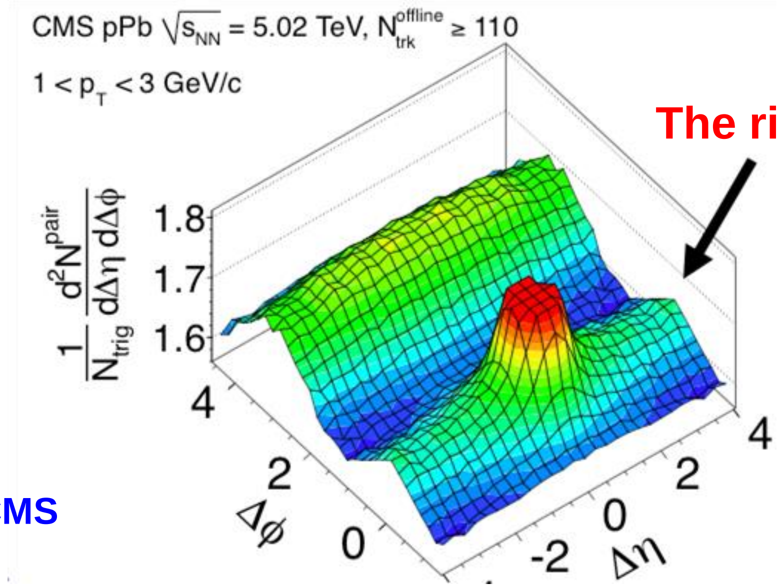
- **The Step:** flattening of the inverse slope parameter T^* extracted from m_T spectra of various particle species
- Interpretation in statistical model (SMES): mixed phase at early stages
- m_T or p_T spectra for various particle species at forward rapidity would be desirable





Angular correlation studies

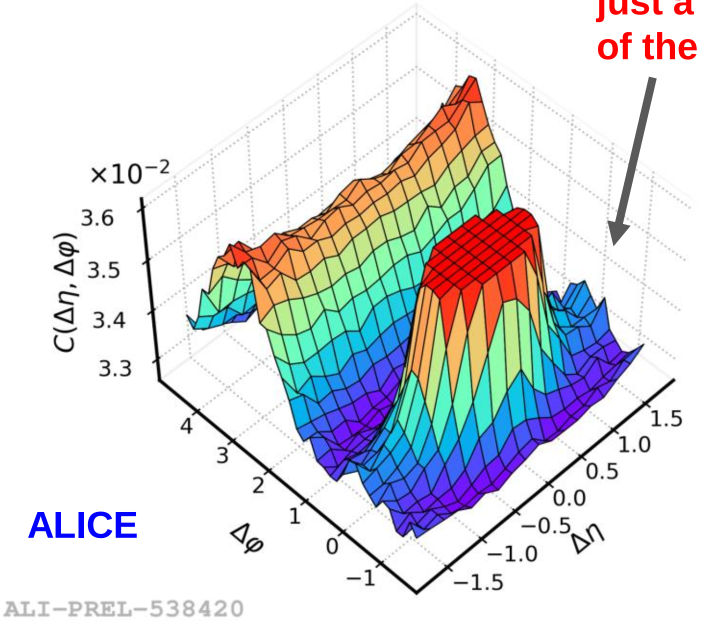
CMS: Phys. Lett. B 718 (2013) 795



The ridge

CMS

The ridge or just a pedestal of the jet peak?



ALICE

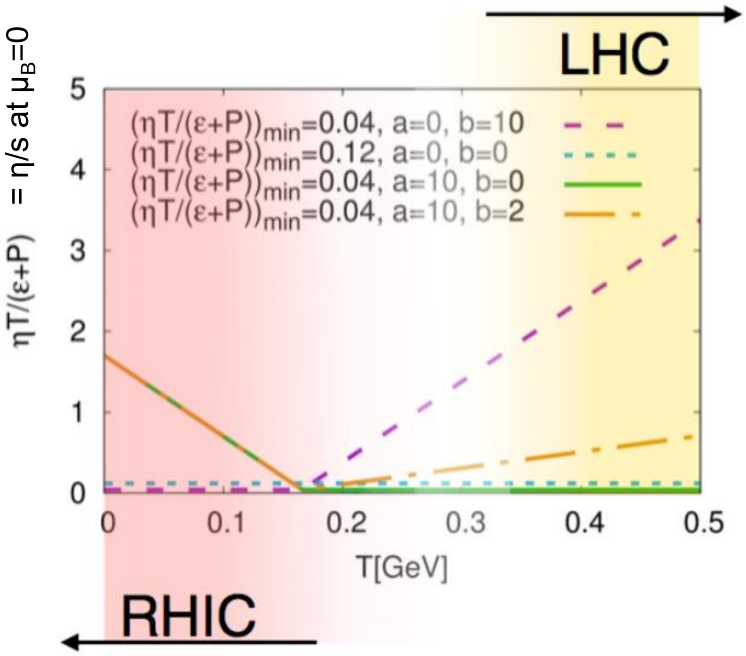
Angular correlation studies strongly profit from extended pseudorapidity coverage:

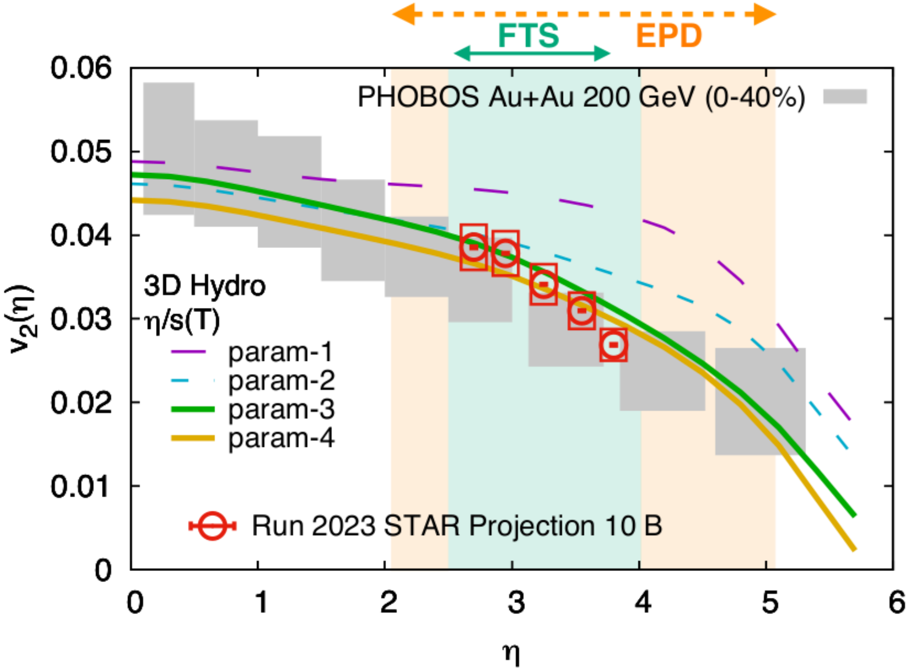
- stay away from jet peak
- much higher statistics for 4-particle and 8-particle cumulants
- study decorrelation effects vs η

“Moving forward to constrain the shear viscosity”*

*Denicol, Monnai, Schenke PRL 116 (2016) 212301
Figures from The STAR Beam Use Request for Run-23-25

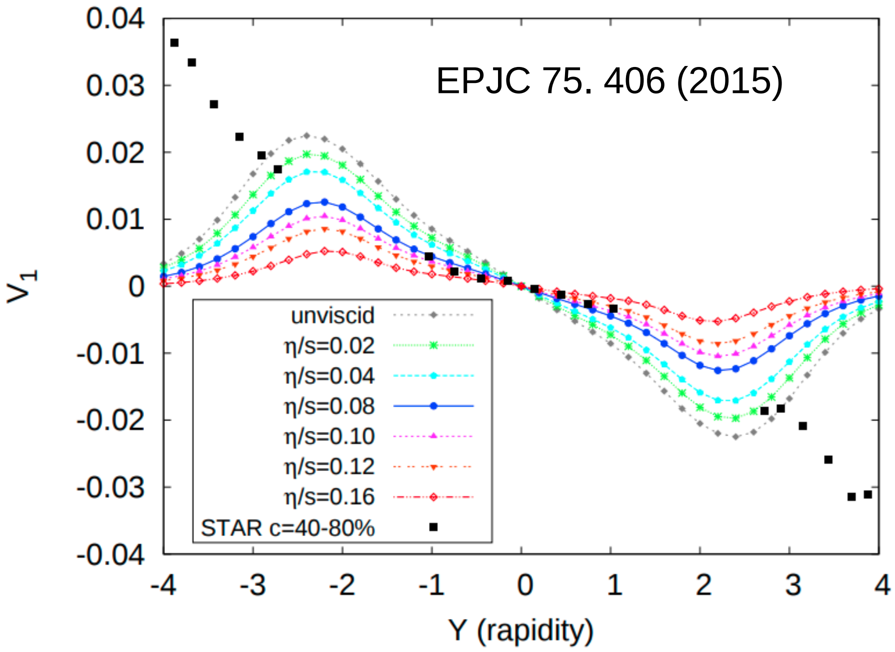
19.6-200 GeV scan by PHOBOS, PRL 94 (2005) 122303



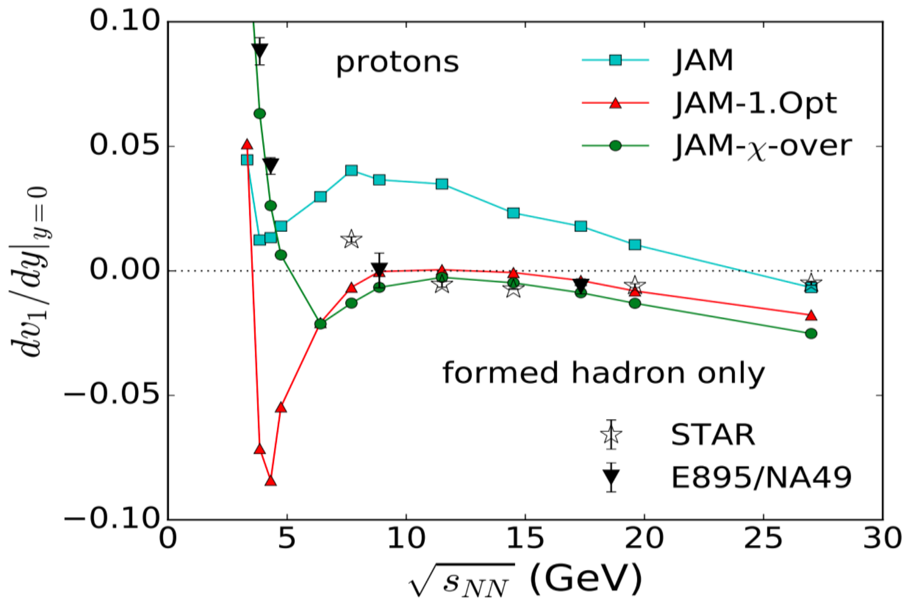


- Elliptic flow at forward rapidity provides sensitivity to the temperature dependence of shear viscosity
- RHIC: strong evidence that ηT /(ε + P) must grow with decreasing temperature

Directed flow

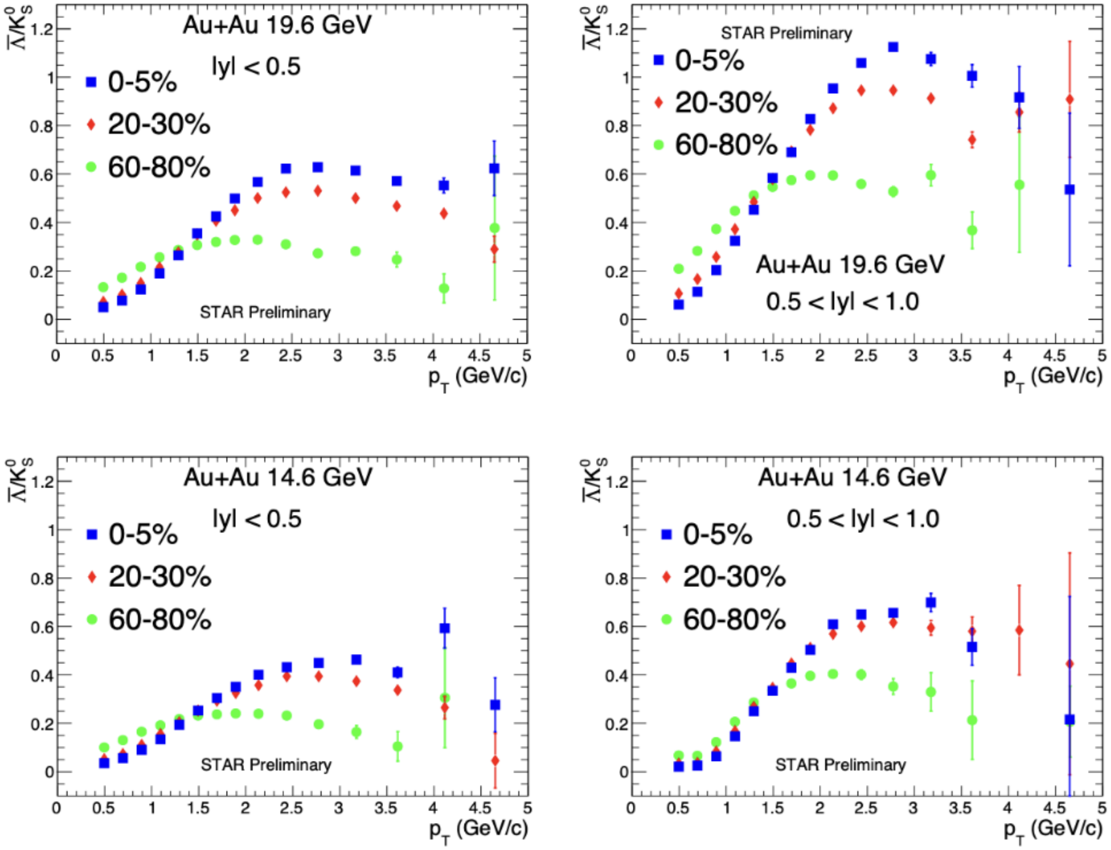


PLB 769 (2017) 543



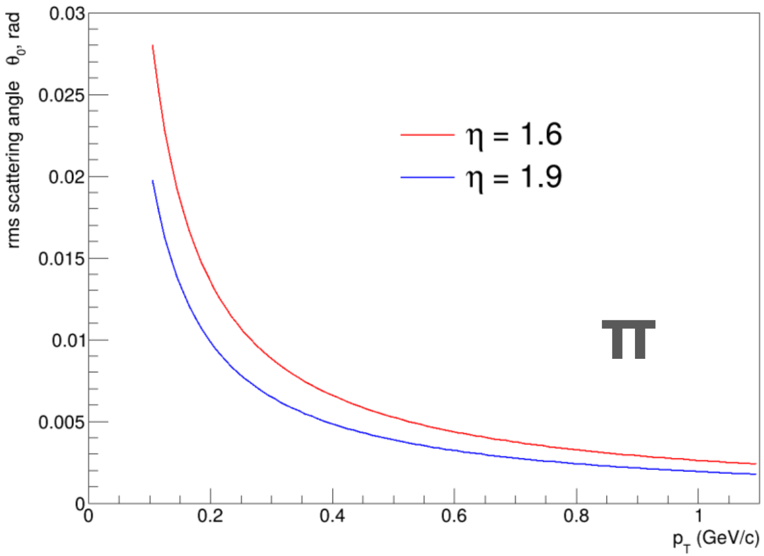
- $v_1(\eta)$ sensitive to the shear viscosity to entropy (η/s) ratio
- $v_1(\eta)$ in both spectator and participant regions may provide insights into the baryon stopping mechanism (see 2211.16408)
- Need wide rapidity coverage!

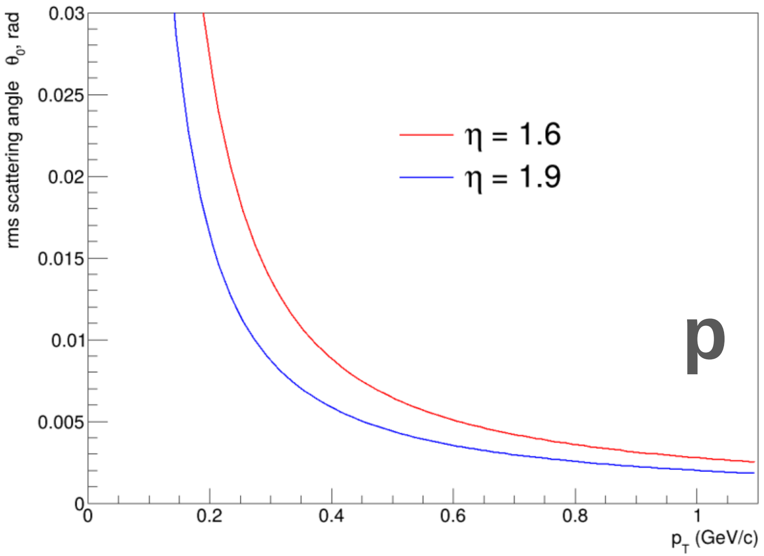
Eta dependence of baryon/meson ratio



- Baryon anomaly: growth of p/π and Λ/K ratios in the pT range 1-3 GeV
- usually explained by coalescence: recombination of constituent quarks into hadrons → full momentum (not pT) matters
- STAR 14.6 - 19.6 GeV: the growth more pronounced towards more forward rapidity

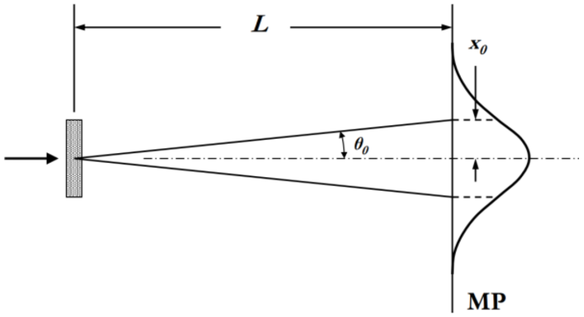
RMS scattering angle in endcap (d = 25% X_0)



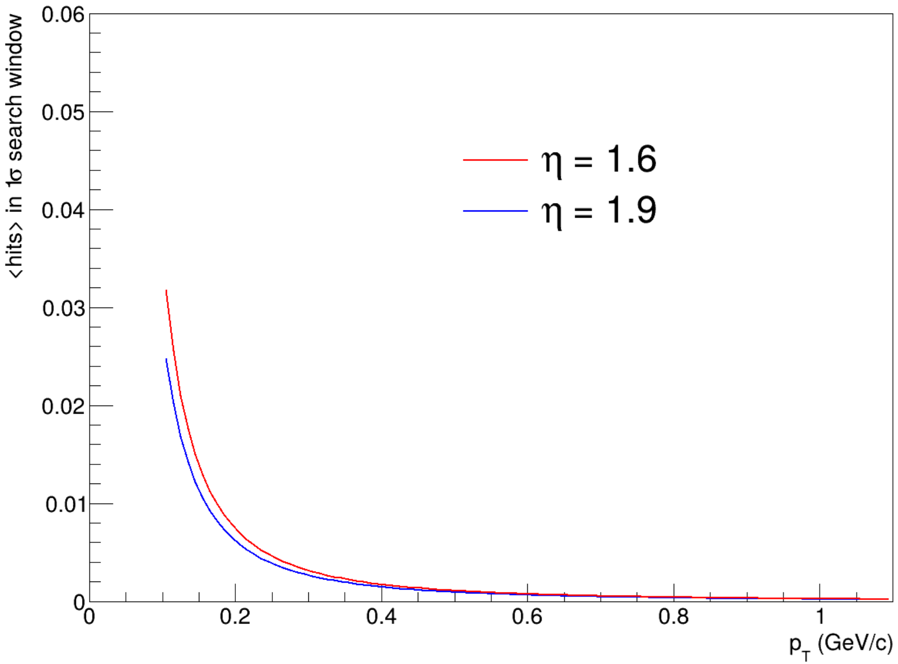


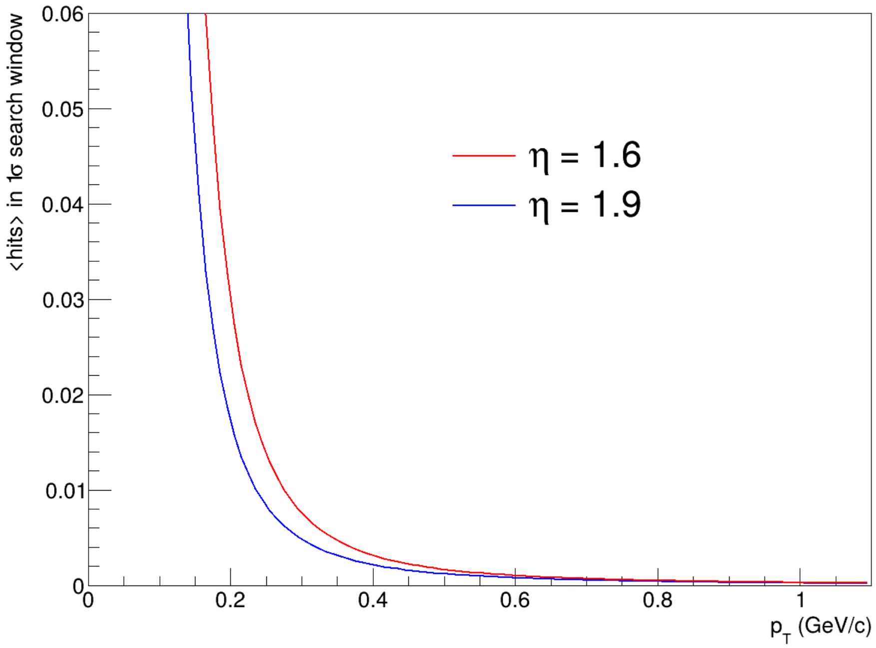
Highland formula:

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038\ln(x/X_0)\Big]$$



Expected number of hits in 1σ-search window in HM events





- η=1.9 - Hits per cm^2: n = 0.0063
- η=1.6 - Hits per cm^2: n = 0.0040
- Combinatorics after TPC-track propagation is expected to be small