Forward upgrade: physics and possible solutions

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The 2nd China-Russia Joint Workshop on NICA Facility
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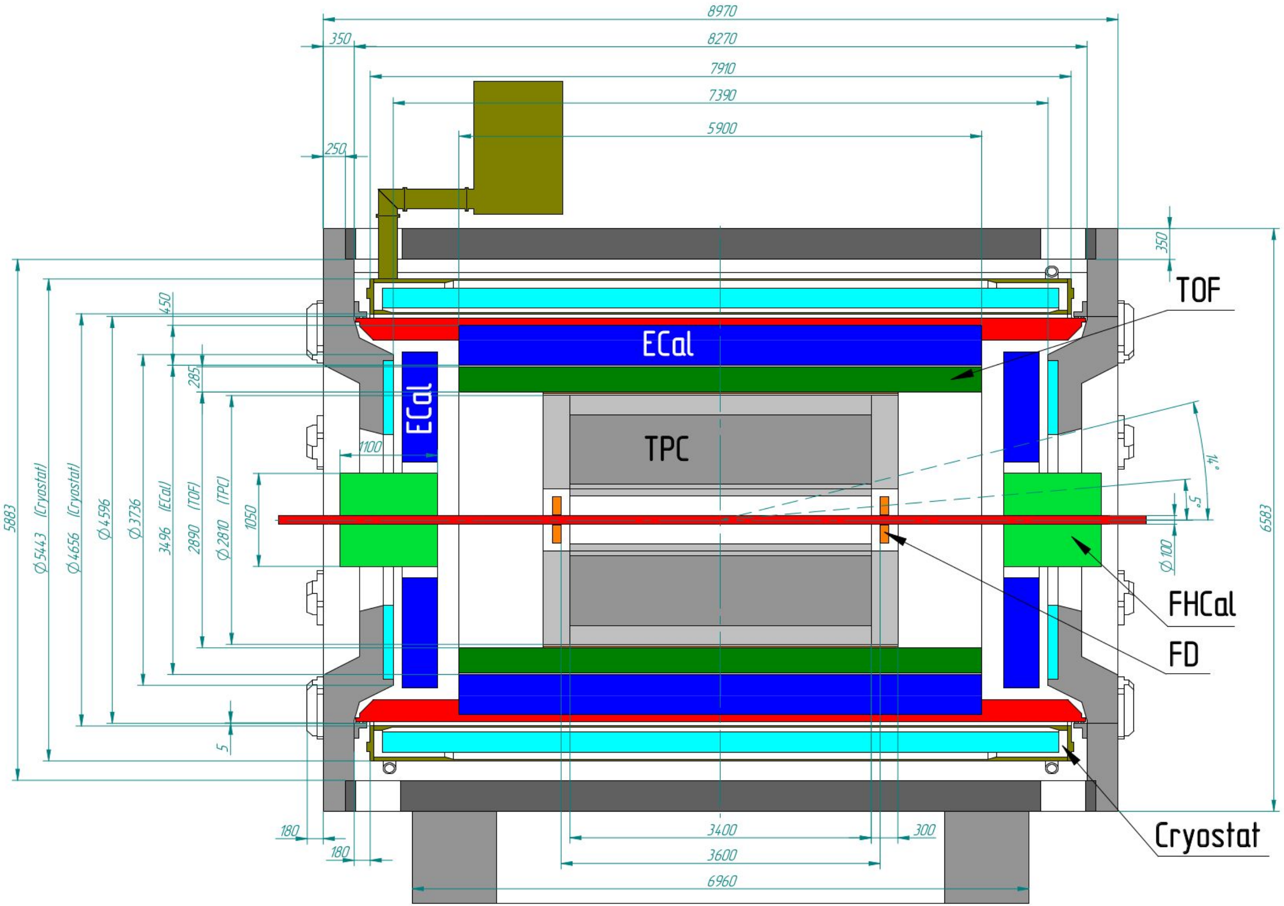
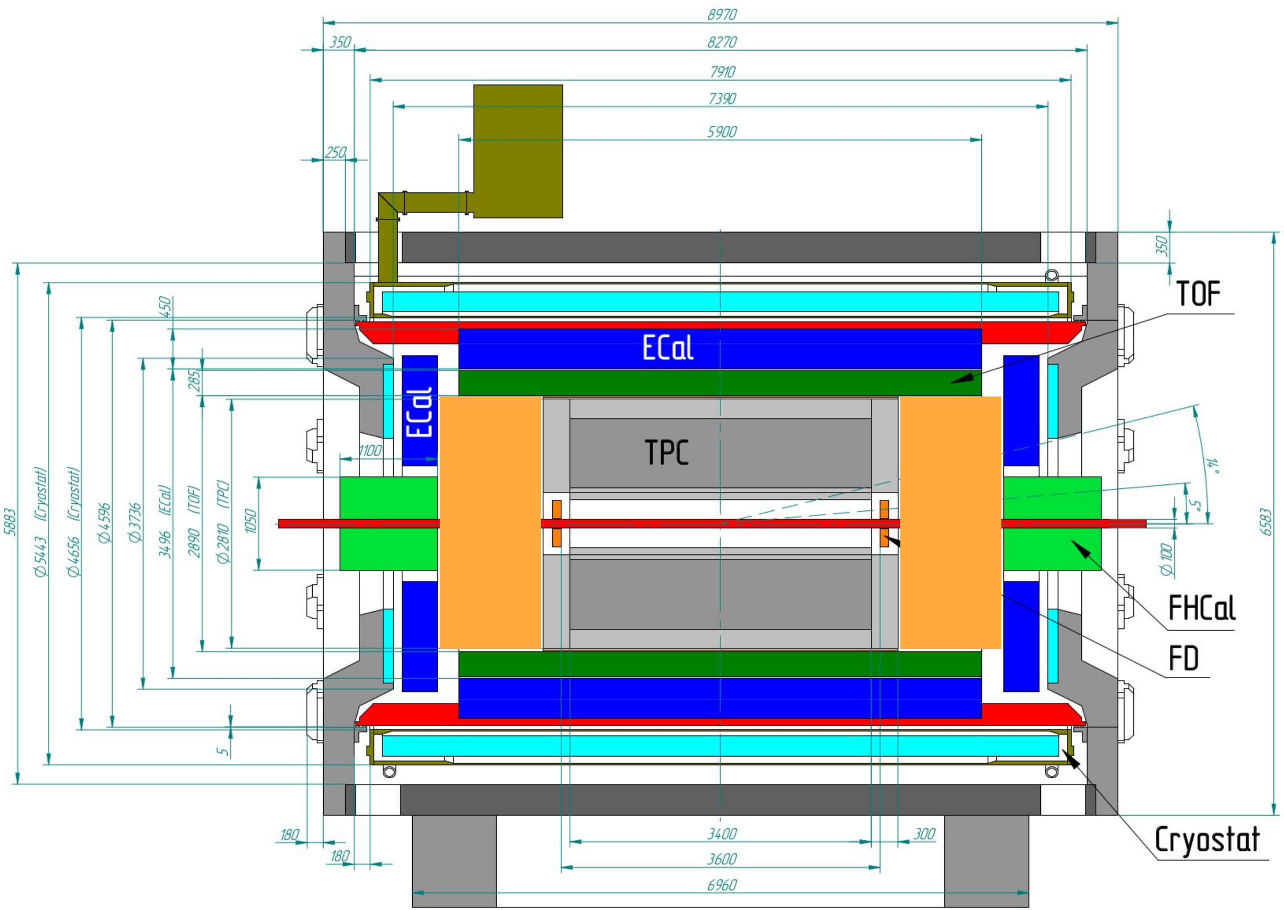
Stage I setup



Extend rapidity coverage with forward tracker?

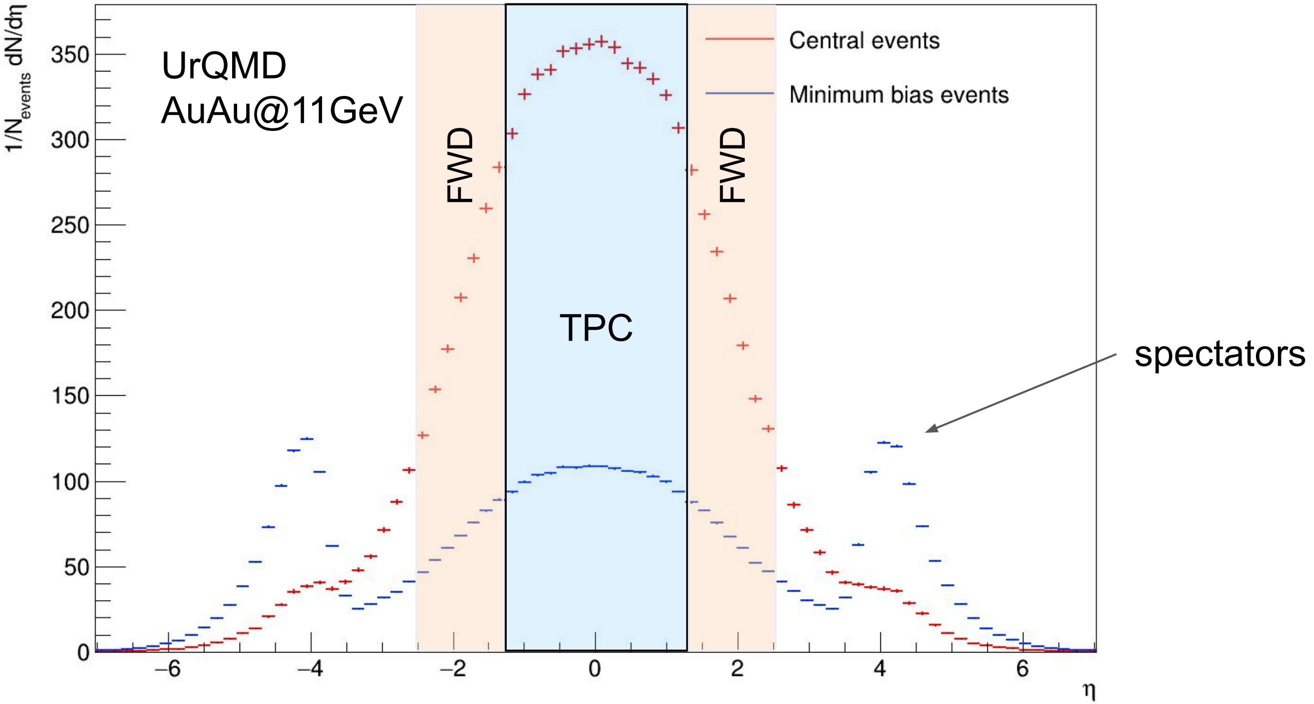


Outline

- Do we need forward tracker?
- Can we integrate the tracker in the current MPD setup?
- Can we measure track momentum at forward rapidities with existing solenoid field?
- What is the impact of TPC endcaps on the track resolution?
- Track finding at forward rapidity in high multiplicity collisions?
- Can we measure PID at forward rapidities?

Do we actually need forward tracker?

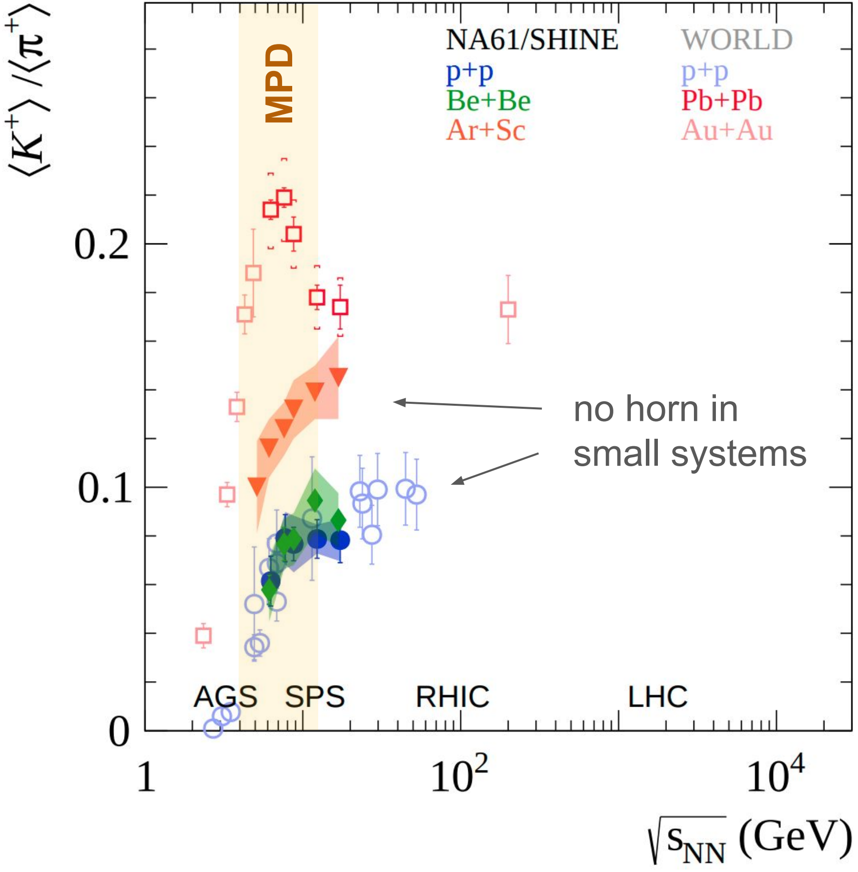
Pseudorapidity coverage



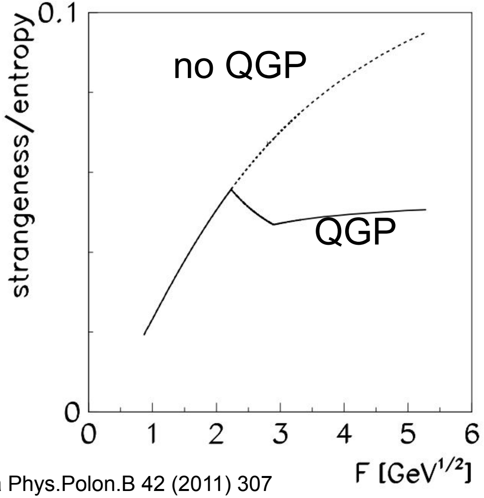
- TPC covers only ~55% of particle production yield in central events
- Forward tracker would allow us to cover more than 80%

The Horn

NA61: EPJC 84 (2024) 416



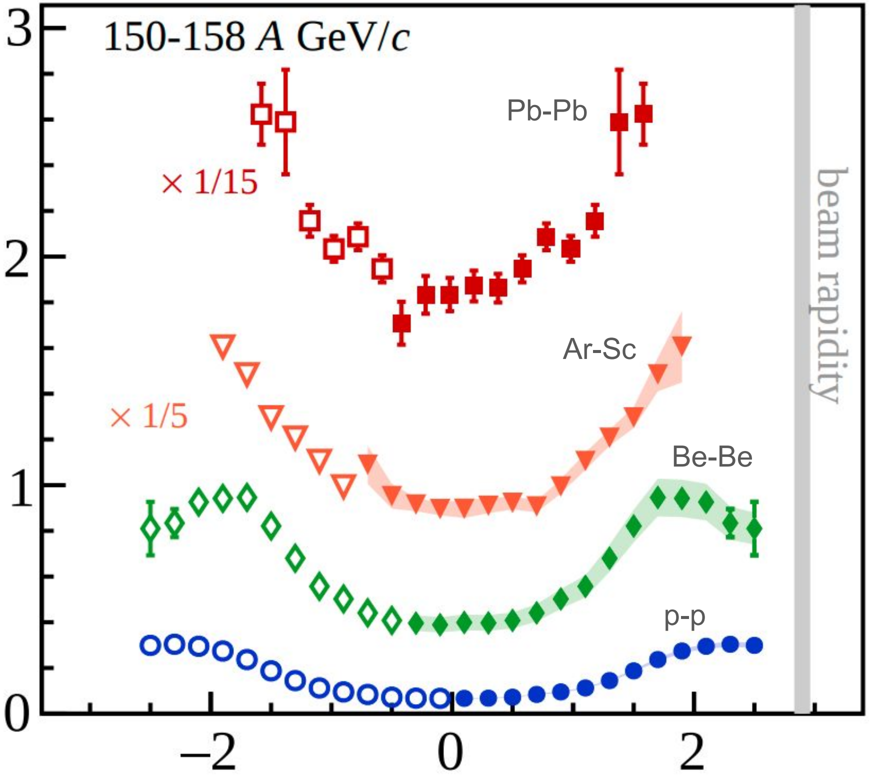
- **The horn:** sharp maximum in the ratio of strange particle to pion yields
- **Interpretation in statistical model (SMES)**: change of strangeness / entropy ratio due to deconfinement transition
- For precision measurements, we need strange particle yields (K, Λ) in the full phase space including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



Acta Phys.Polon.B 42 (2011) 307

See also talk by V. Kolesnikov

Rapidity distributions for protons and light nuclei



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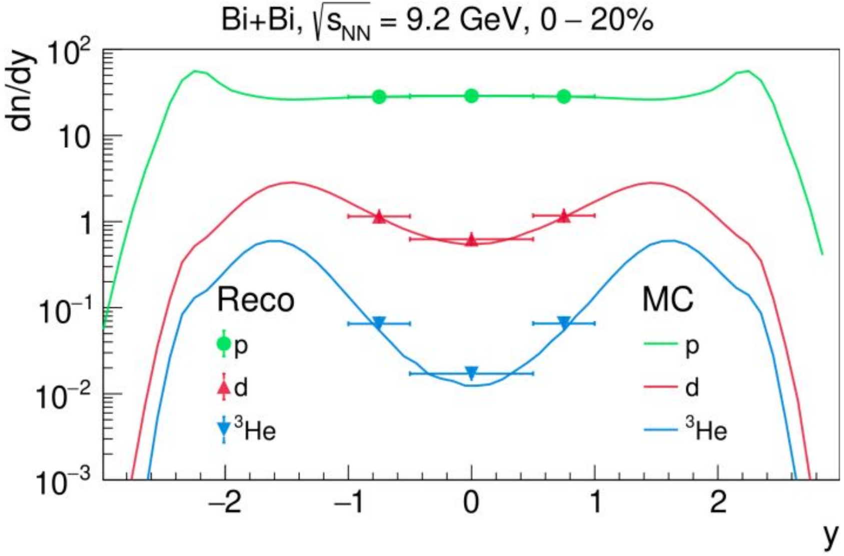
A forward tracker with PID may provide a substantial increase of MPD capability for baryon measurements (stopping, total yields)



See talk by V. Kolesnikov

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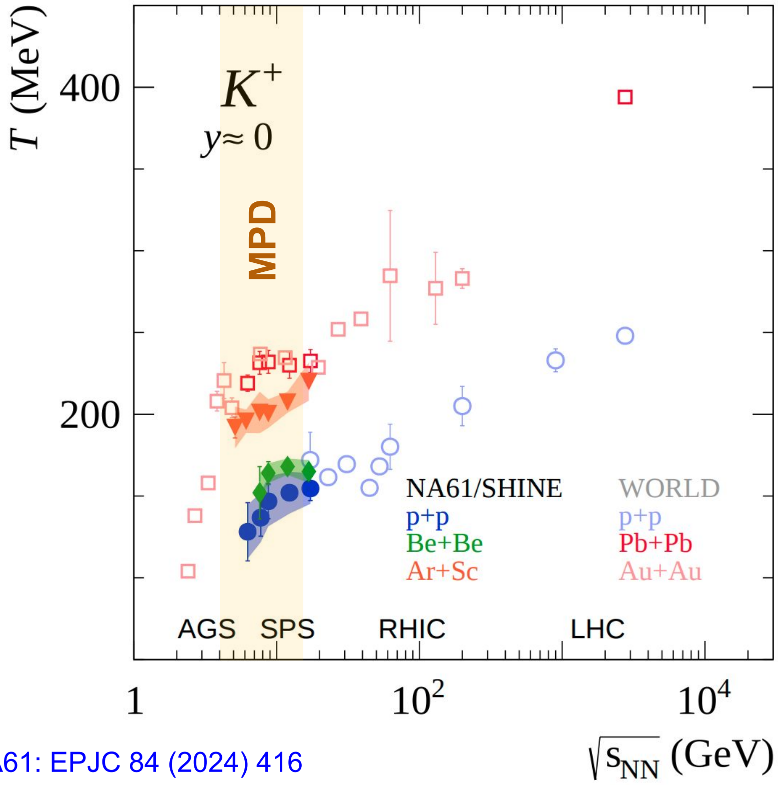
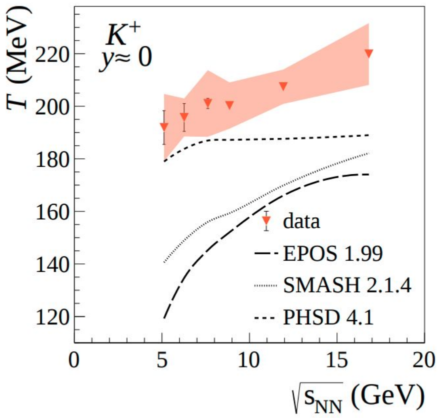
The Step

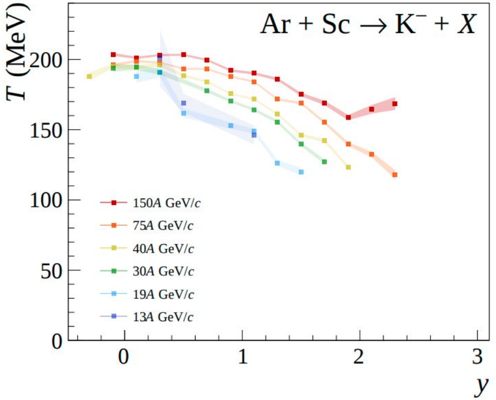


NA61: EPJC 84 (2024) 416

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

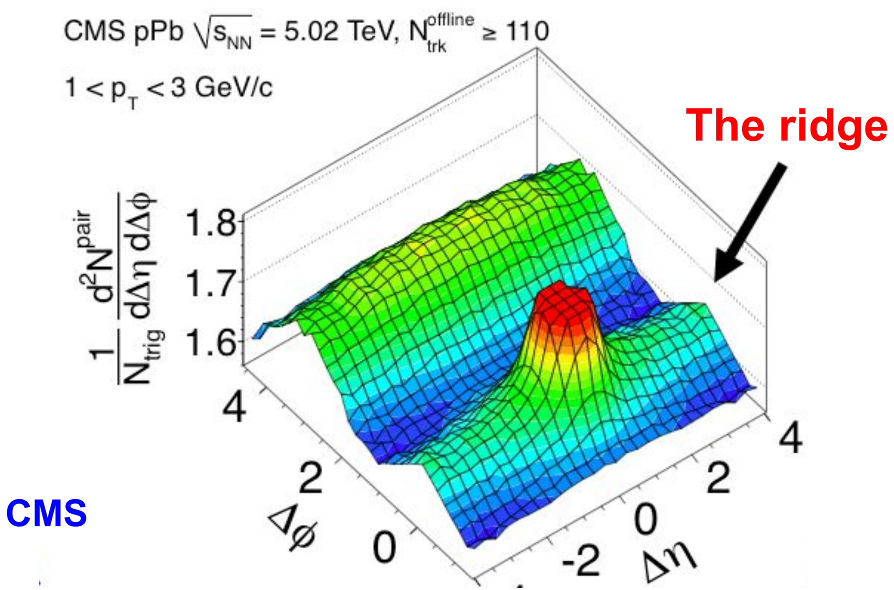
- **The Step:** flattening of the inverse slope parameter T^* extracted from m_T spectra of various particle species
- Interpretation in statistical model (SMES): mixed phase at early stages
- m_T or p_T spectra for various particle species at forward rapidity would be desirable

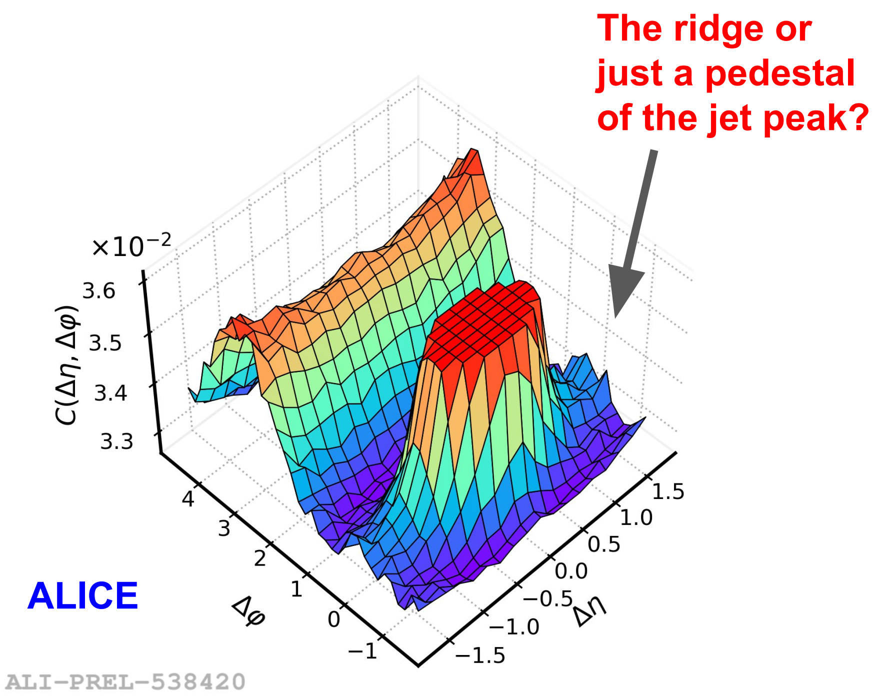




Angular correlation studies

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

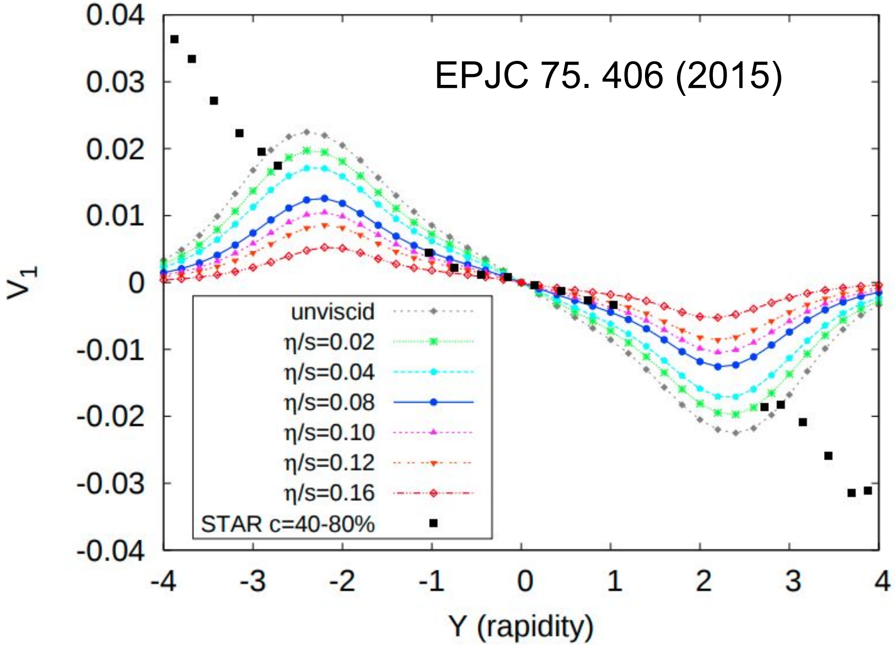




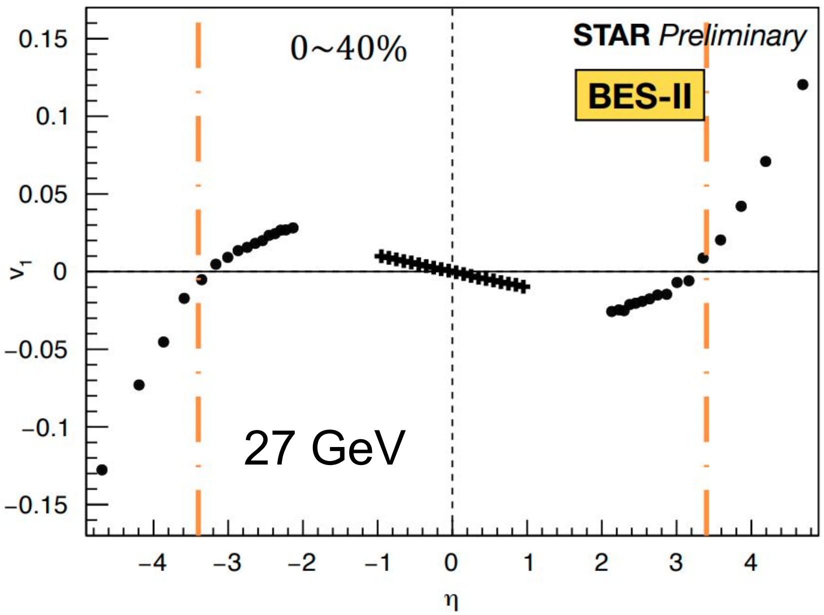
Angular correlation studies strongly profit from extended pseudorapidity coverage:

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

Directed flow of charged pions



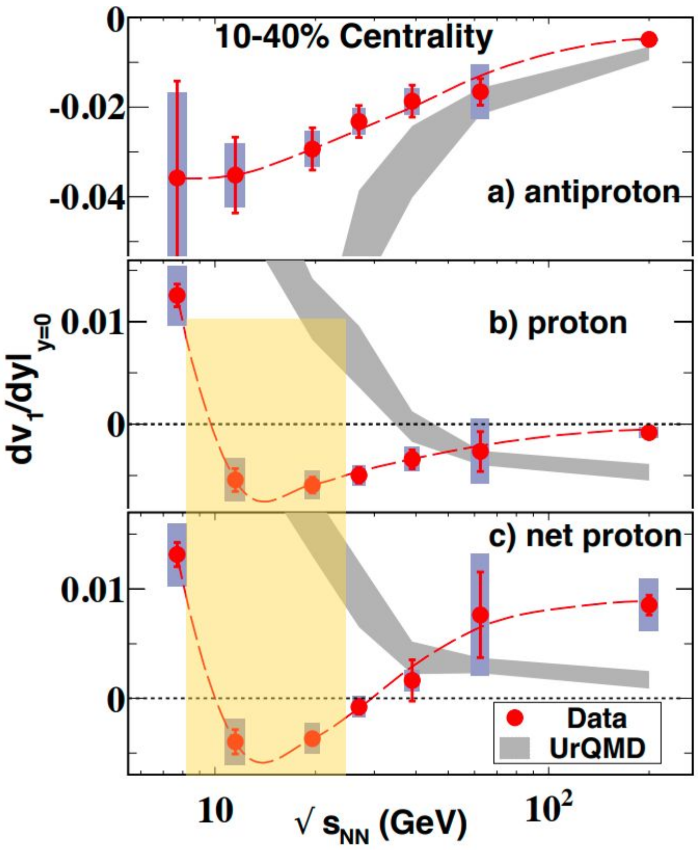
https://indico.cern.ch/event/1176274/contributions/5323690/



- $v_1(\eta)$ 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!

Directed flow of net protons

STAR BES II



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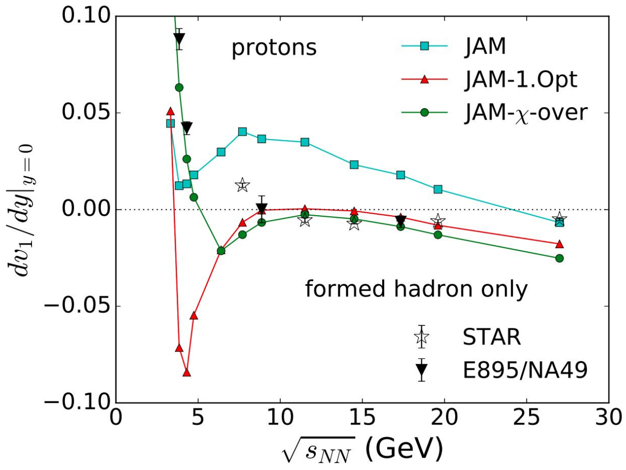


- Model predicts sign change at ~ 5 GeV with 1st order phase transition
- proton and net-proton v_1 change sign around 10-20 GeV
- Need wide rapidity coverage to measure v_1 shape

https://indico.cern.ch/event/1176274/contributions/5323690/

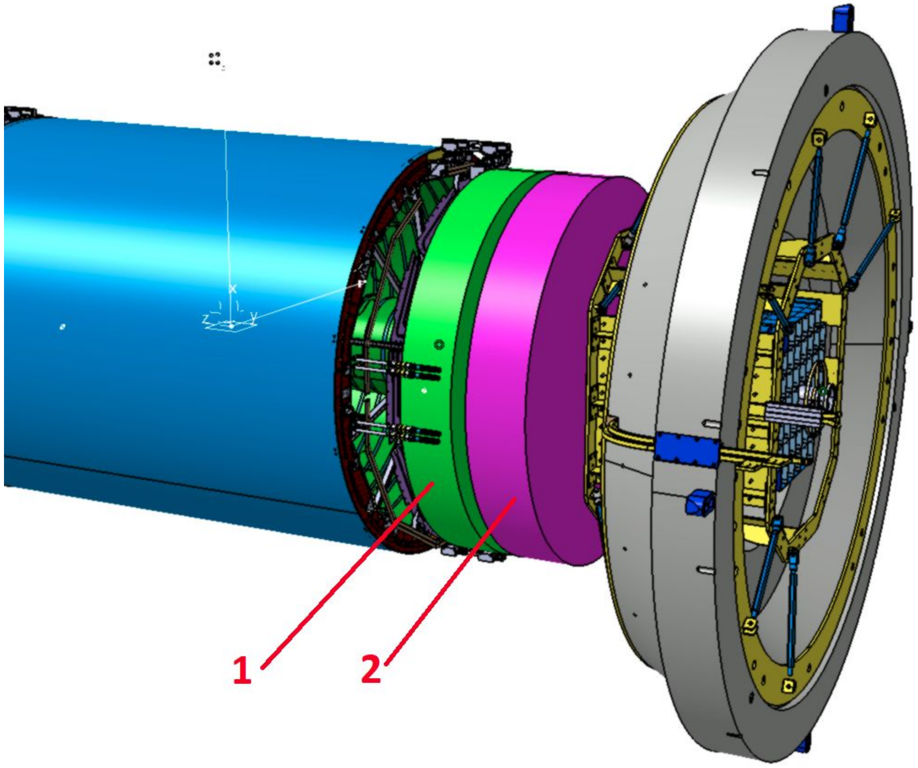
And more…

- 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 (need continuous readout)
- aspects of non-perturbative QCD, e.g. diffractive studies, QCD instanton
- and more …

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

Can we actually integrate the tracker in the current MPD setup?

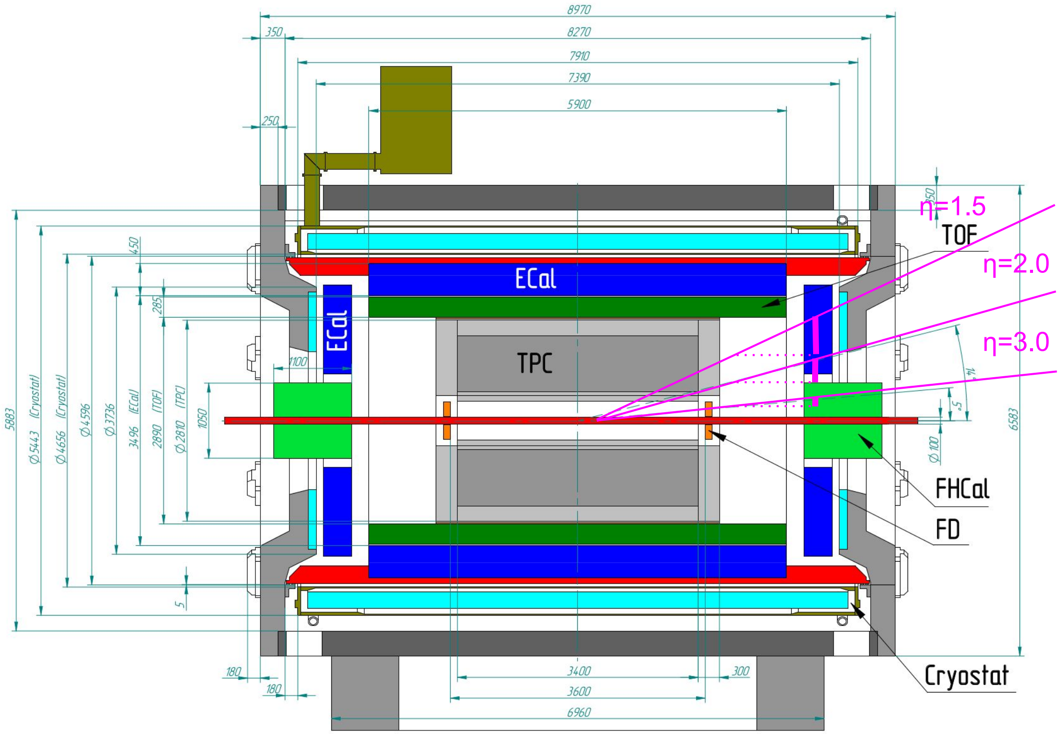
Limitations from realistic 3D model



- 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)
- Resulting pseudorapidity coverage:
  - η_{min} = 1.55
  - η_{max} =2.47

Can we measure track momentum at forward rapidities with existing solenoid field?

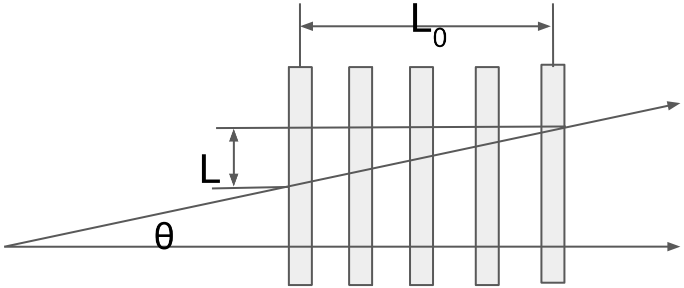
The problem



- Momentum resolution in the solenoid field is driven by the radial distance available for track curvature measurement
- Strongly degrades towards large η
- Two options to improve momentum resolution:
  - minimize multiple scattering effects (reduce effective radiation length)
  - improve hit resolution

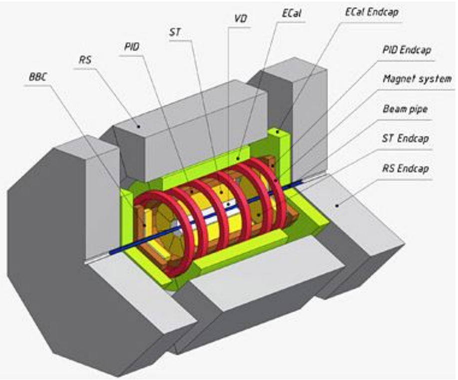
$$\left.\frac{\Delta p_\mathrm{T}}{p_\mathrm{T}}\right|_{\mathrm{m.s.}} = \frac{N}{(N+1)(N-1)} \frac{0.0136\,\mathrm{GeV}}{0.3\beta BL} \sqrt{\frac{d_{\mathrm{tot}}}{X_0 \cos\theta}} \left(1 + 0.038 \ln \frac{d}{X_0 \cos\theta}\right)$$

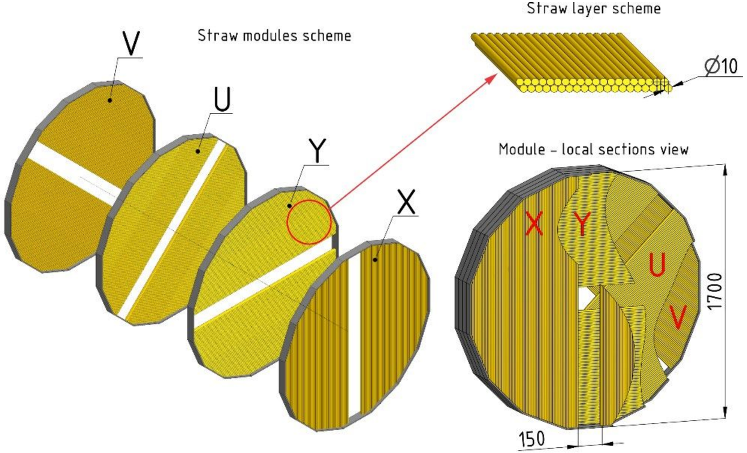
$$\left.\frac{\Delta p_\mathrm{T}}{p_\mathrm{T}}\right|_{\mathrm{res.}} = \frac{\sigma_{\mathrm{hit}}\, p_\mathrm{T}}{0.3BL^2} \sqrt{\frac{720N^3}{(N-1)(N+1)(N+2)(N+3)}}$$



Possible technology: straws similar to SPD endcap tracker?

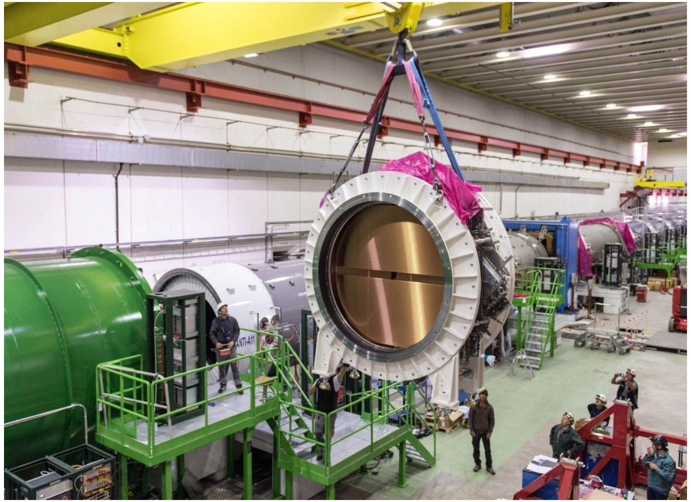
SPD endcap tracker proposal





SPD TDR: 2404.08317

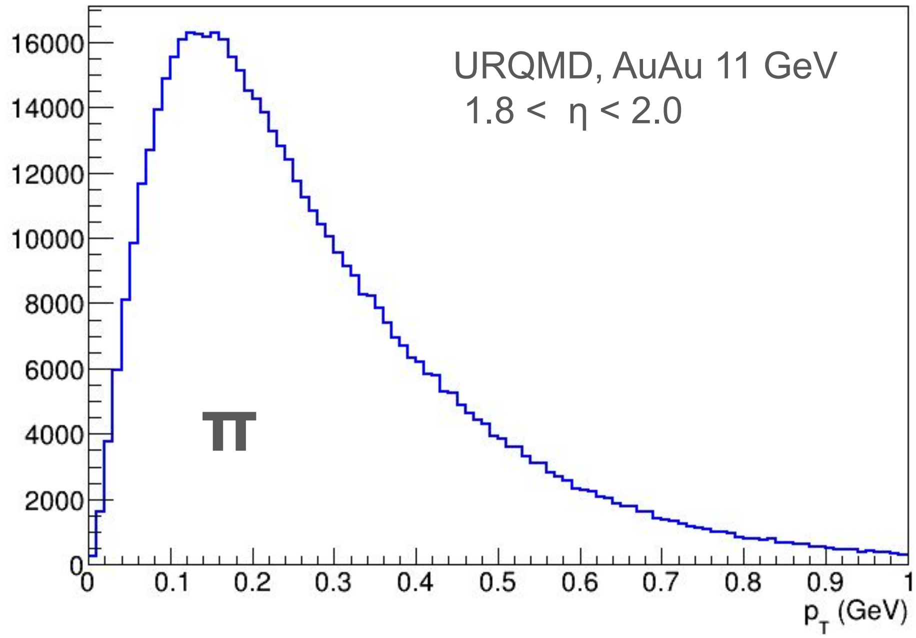
NA62

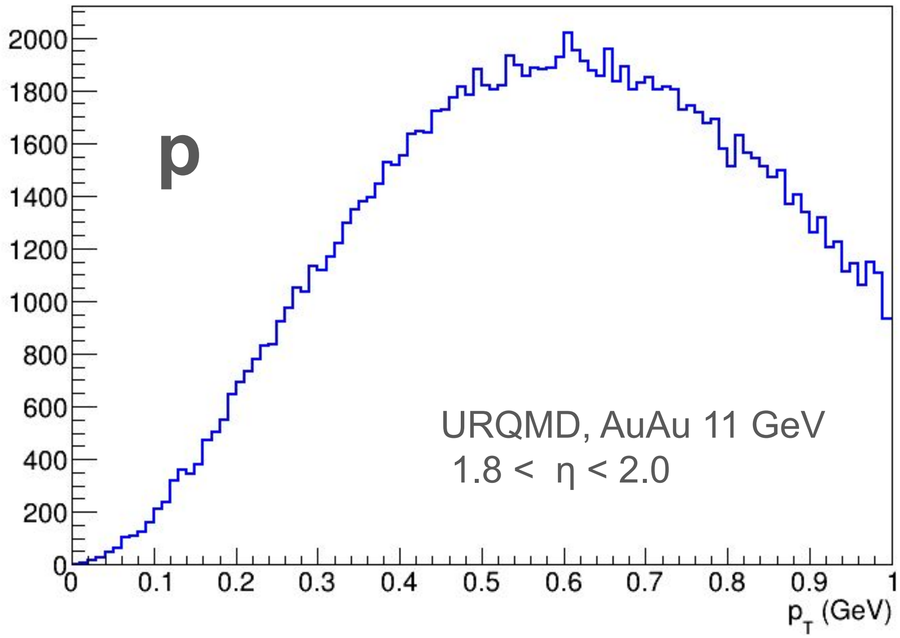


NA62 TDR

- Hit resolution ~ 80 - 100μm
- Small material budget (~1% X_0)
- Large areas (not feasible with silicon detectors)

Transverse momentum spectra at forward rapidity





- Pion p_T: mainly below 1 GeV, ideally need to go down to 0.1 GeV to catch the maximum
- Proton p_T goes far beyond 1 GeV…
- Let's try 0.1 - 1 GeV region for the moment

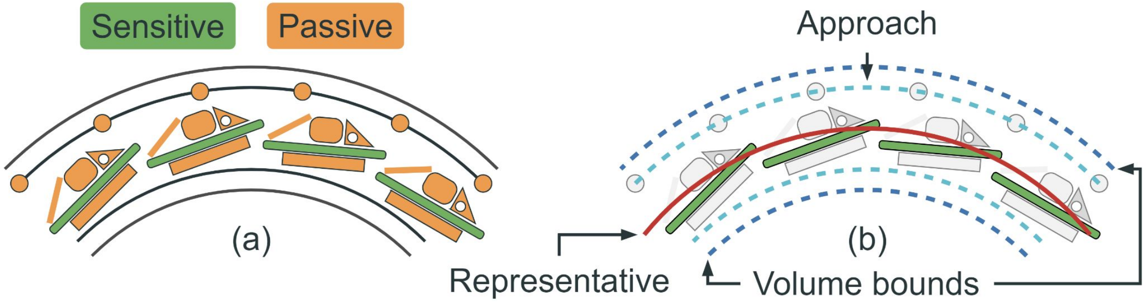
Use ACTS for tracking

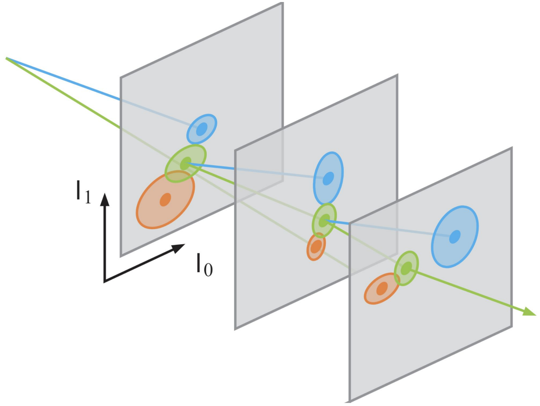
https://acts.readthedocs.io/

- 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.

```cpp
// 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));
```





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

Getting used to ACTS tracking algorithms…

Considering “ideal” tracker:

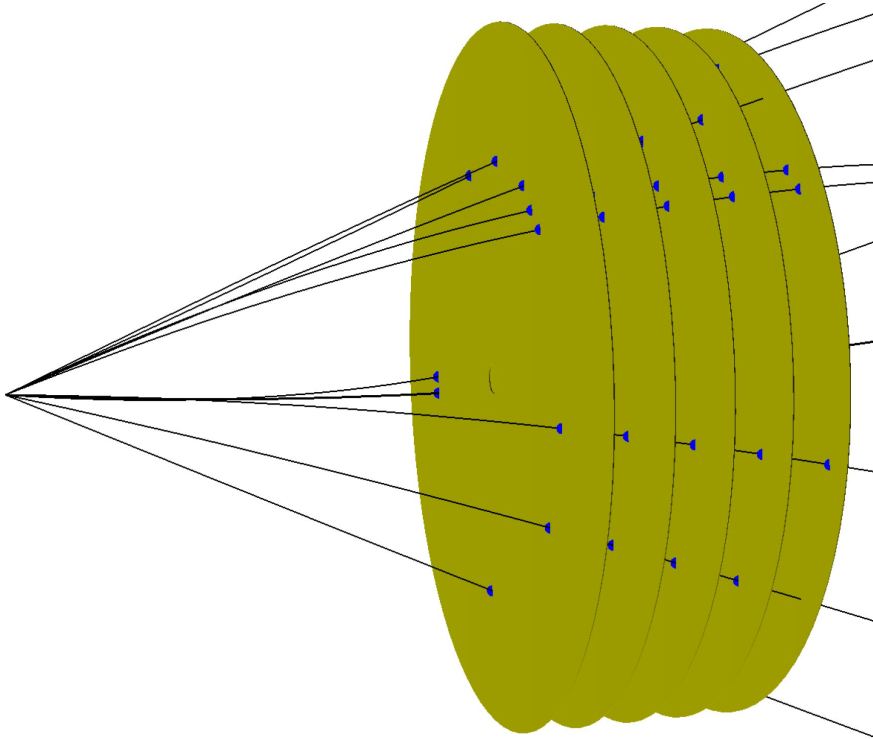
- 5 tracking layers placed between 210 and 300 cm
- R_{inner} = 35.7 cm → η_{max} =2.47
- R_{outer} = 130 cm → η_{min} = 1.55
- Thickness per layer: 200 um silicon ~ 0.2% X_0
- Gaussian smearing in x and y with σ = 80 um

Simulation config:

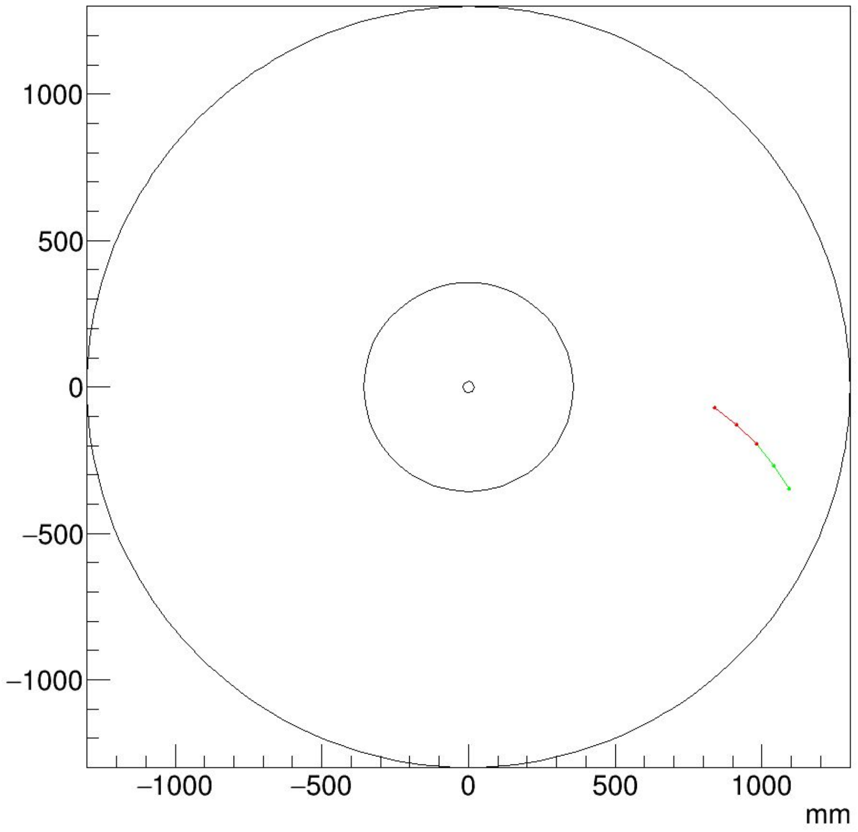
- Particle gun (π or p) with p_T from 0.1 to 1 GeV
- Build-in fatras transport (only EM processes)
- Seed finding using hits on first three layers (adopte seed finding algorithm for cylindrical layers)
- Track finding with combinatorial Kalman filter

Study:

- seeding and tracking efficiency vs p_T and η
- p_T resolution vs p_T and η
- pulls (residuals normalized to estimated uncertainty)



Example event: pion 110 MeV at η = 1.6

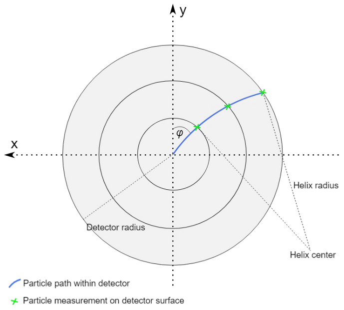


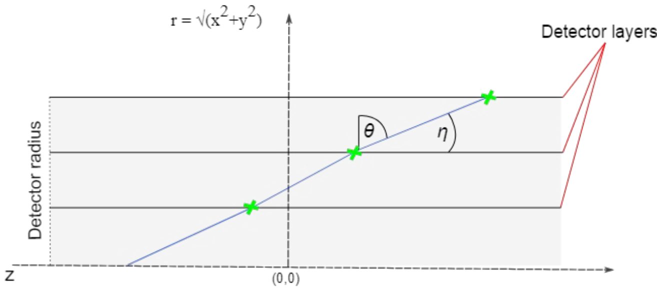
Visualization: hits in xy plane

- green - findable primary (5 hits, p_T > 100 MeV)
- red - found seed

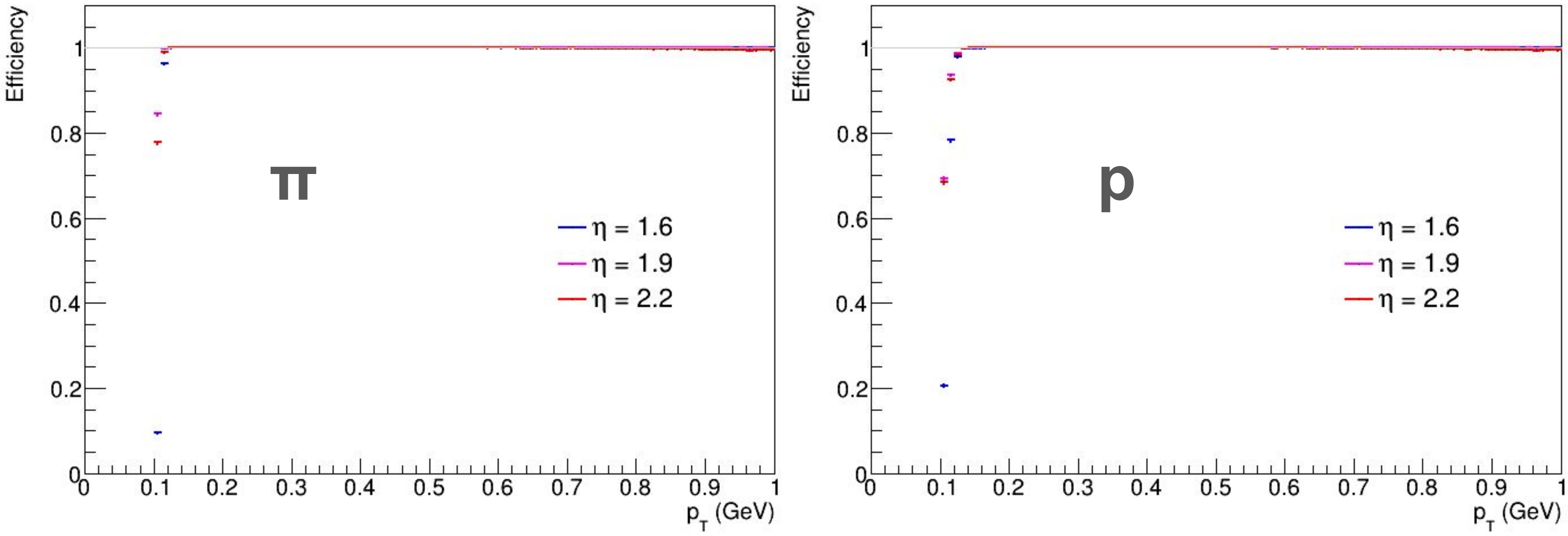
Seeding algorithm:

- xy plane: helix pointing to (x,y) ~ (0,0). impact parameter in r < impactMax ~ rMin
- rz plane: angular difference between two doublets consistent with expected mult. scattering
- selection on impact parameter in z direction



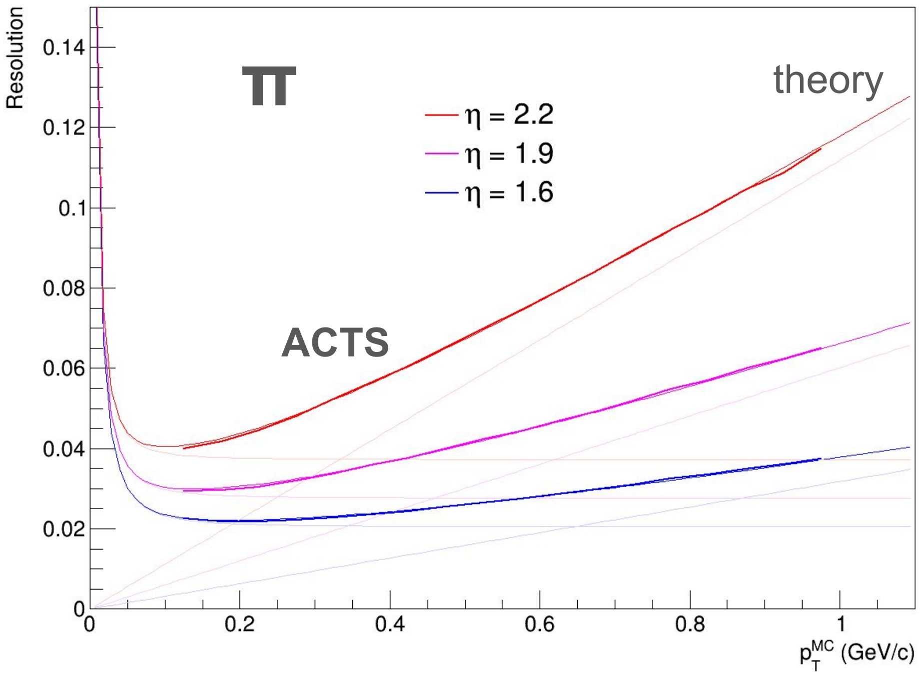


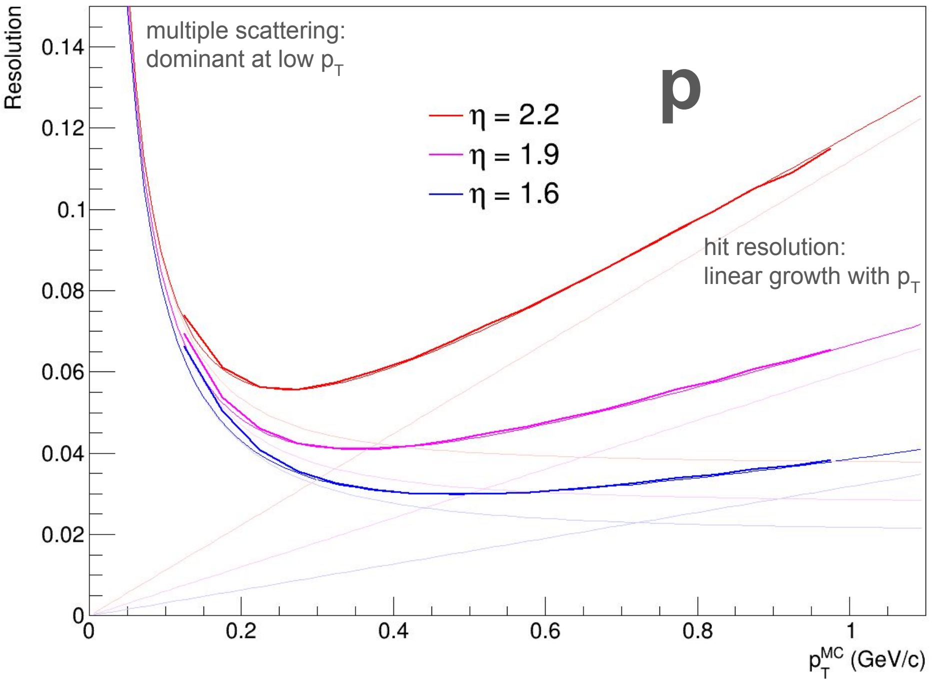
Tracking efficiency without TPC endcap



- Perfect efficiency for pions and protons in all eta regions
- Drop at 0.1 GeV due to limitation of the default seeding algorithm (curvature radius should be larger than $R_{max}/2$)

Momentum resolution





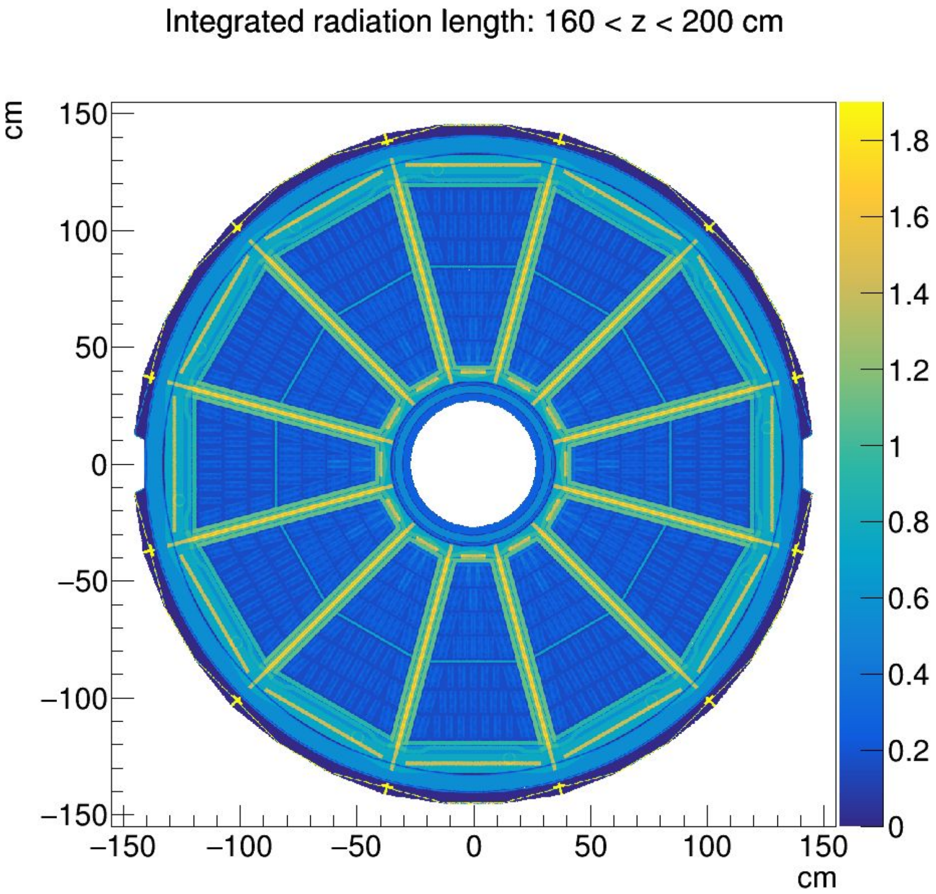
$$\left.\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}}\right|_{\mathrm{m.s.}} = \frac{N}{(N+1)(N-1)} \frac{0.0136\,\mathrm{GeV}}{0.3\beta B L} \sqrt{\frac{d_{\mathrm{tot}}}{X_0 \cos\theta}} \left(1 + 0.038 \ln \frac{d}{X_0 \cos\theta}\right)$$

$$\left.\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}}\right|_{\mathrm{res.}} = \frac{\sigma_{\mathrm{hit}}\, p_{\mathrm{T}}}{0.3 B L^2} \sqrt{\frac{720 N^3}{(N-1)(N+1)(N+2)(N+3)}}$$

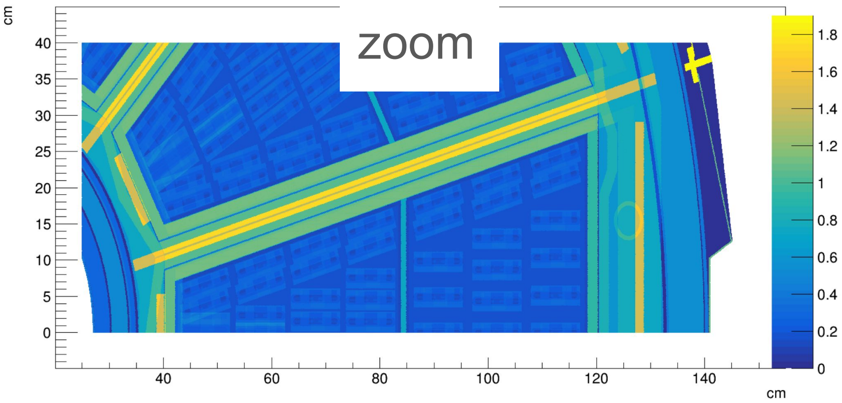
- momentum resolution is within 3-11% depending on p_T and pseudorapidity
- strong effect of multiple scattering for protons at low p_T
- perfect agreement of ACTS fits with theory

What is the impact of TPC endcaps on the track resolution?

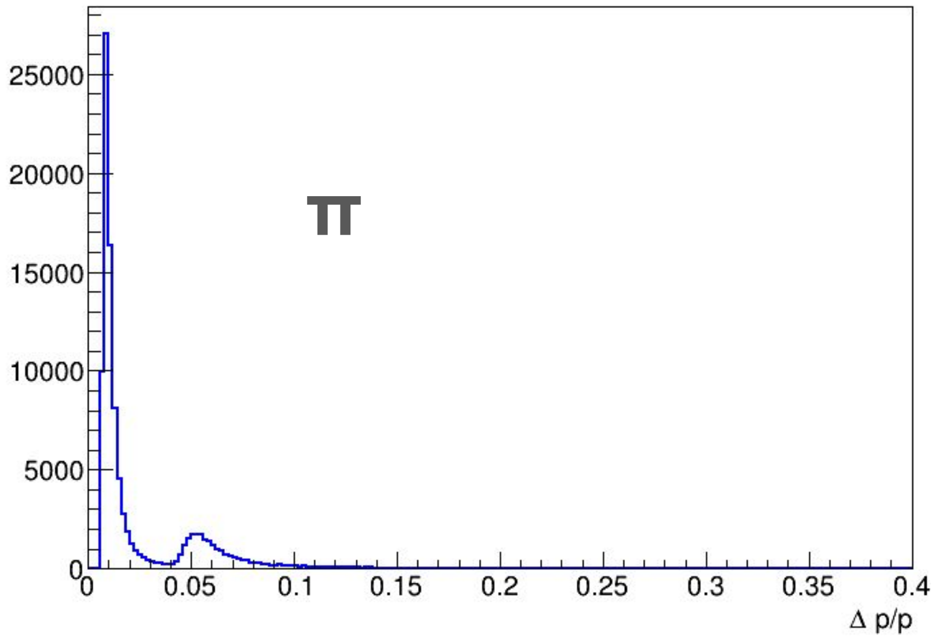
Radiation length of TPC endcaps in mpdroot

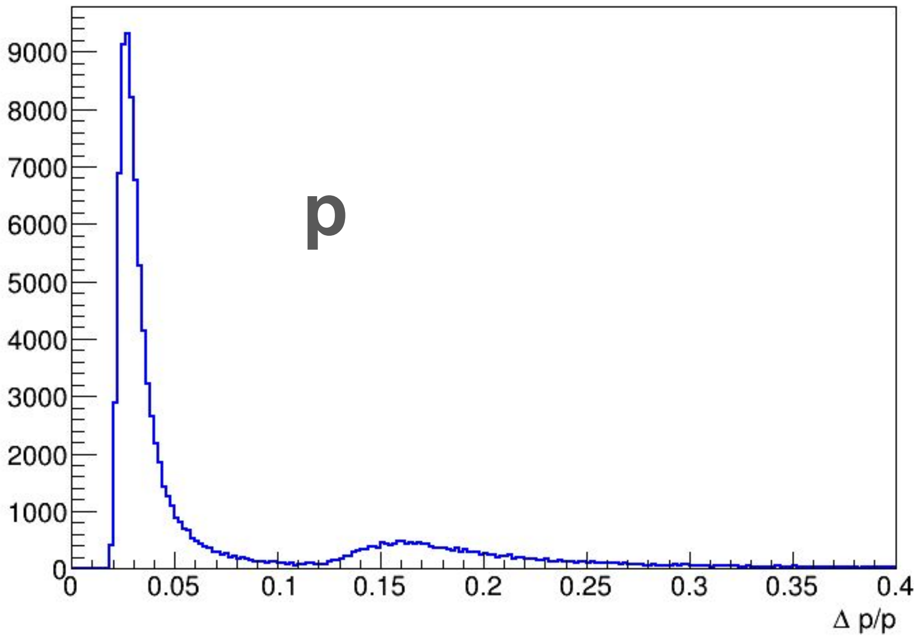


- Using standard fairroot tools:
  - particle gun with geantinos
  - fRun->SetRadLenRegister(kTRUE)
  - Analysing “RadLen” branch with TClonesArray of "FairRadLenPoint"
- All structures (e.g. FEC) are clearly visible
- ~ 0.2-0.3 X_0 in ROC region
- ~ 1.1 X_0 in the frame region



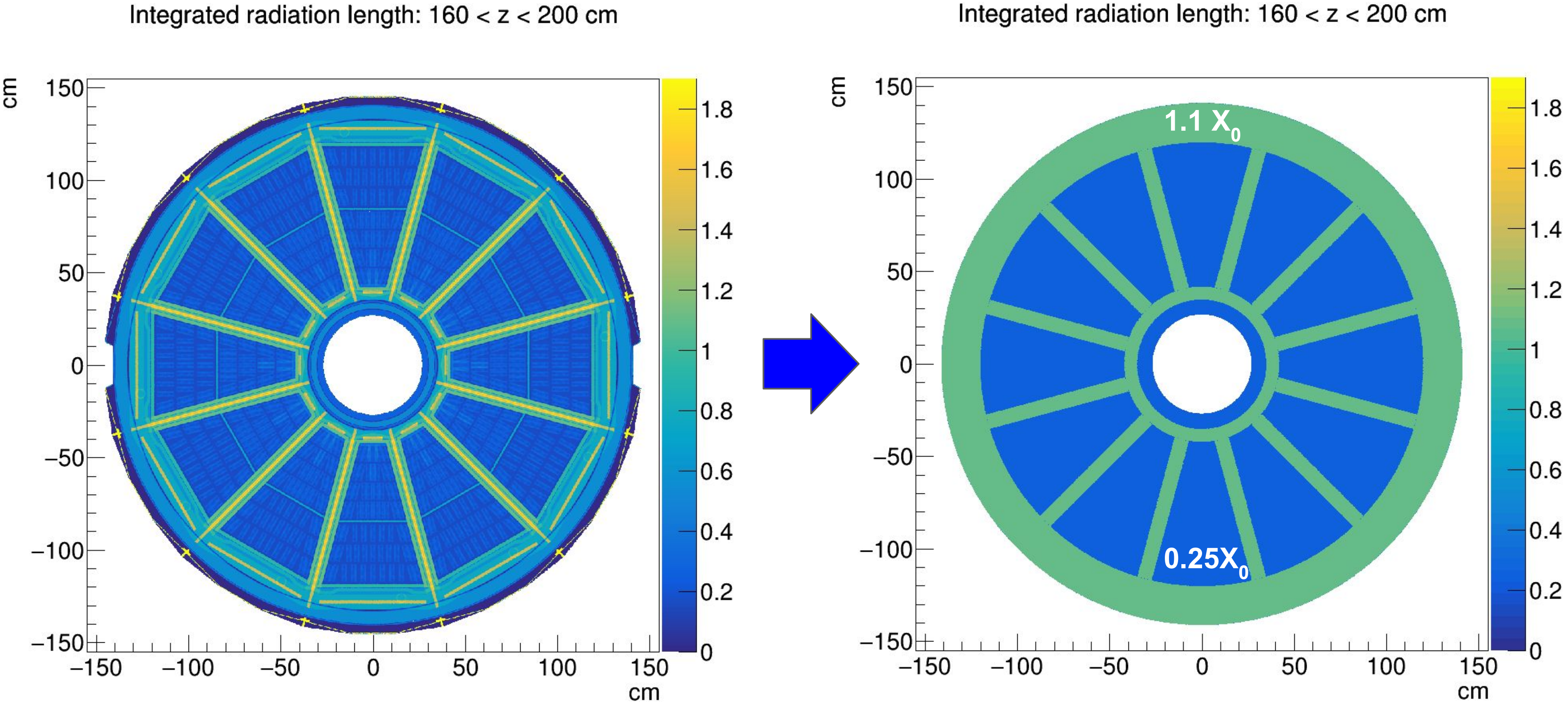
Typical energy loss of pions and protons ($\eta \sim 1.6$, $p_T = 0.35$ GeV)





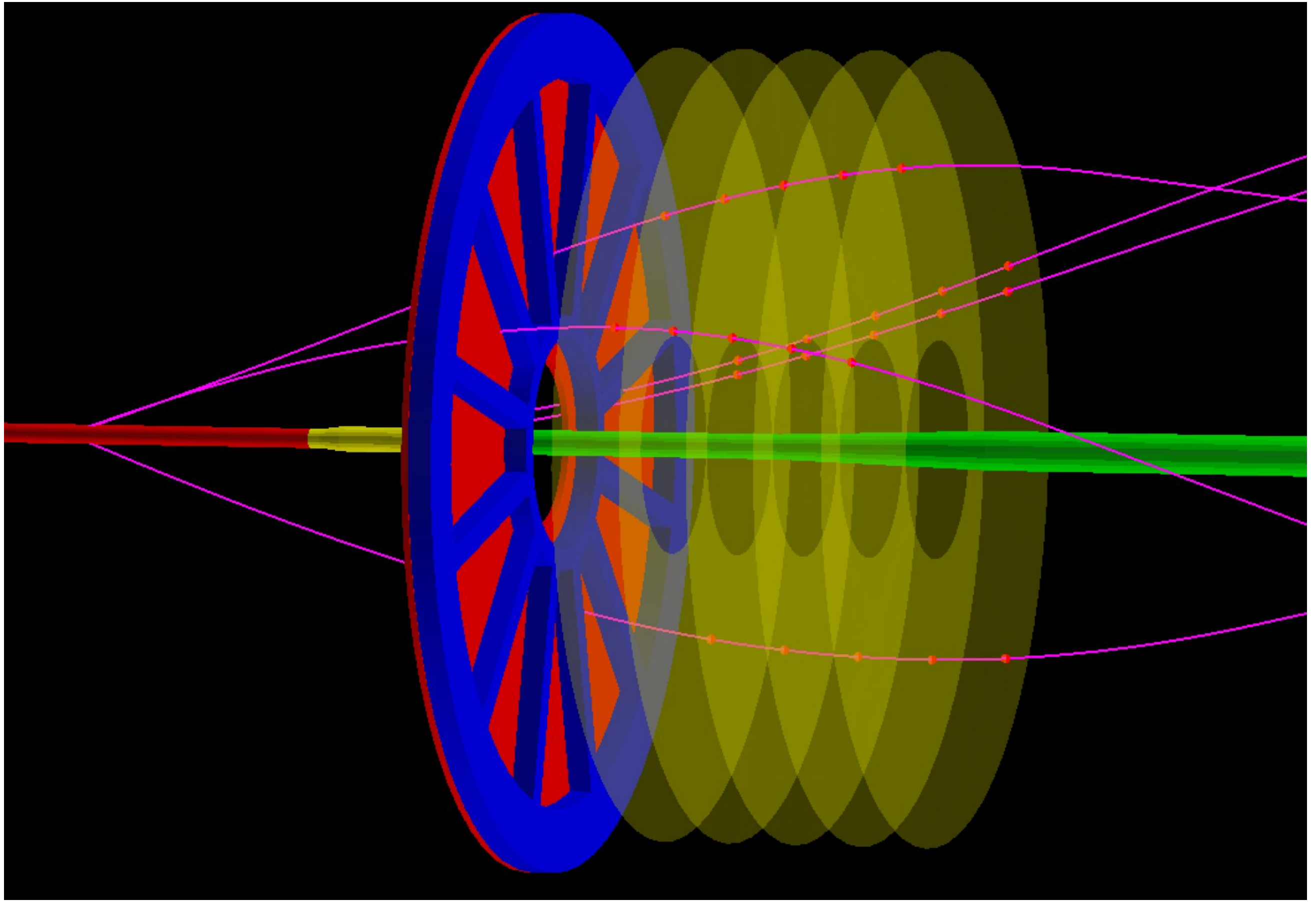
- Two-peak structure corresponding to particles crossing 25% and 110% X_0 regions
- Mean energy loss can be corrected by KF

Toy TPC model with realistic endcap radiation length

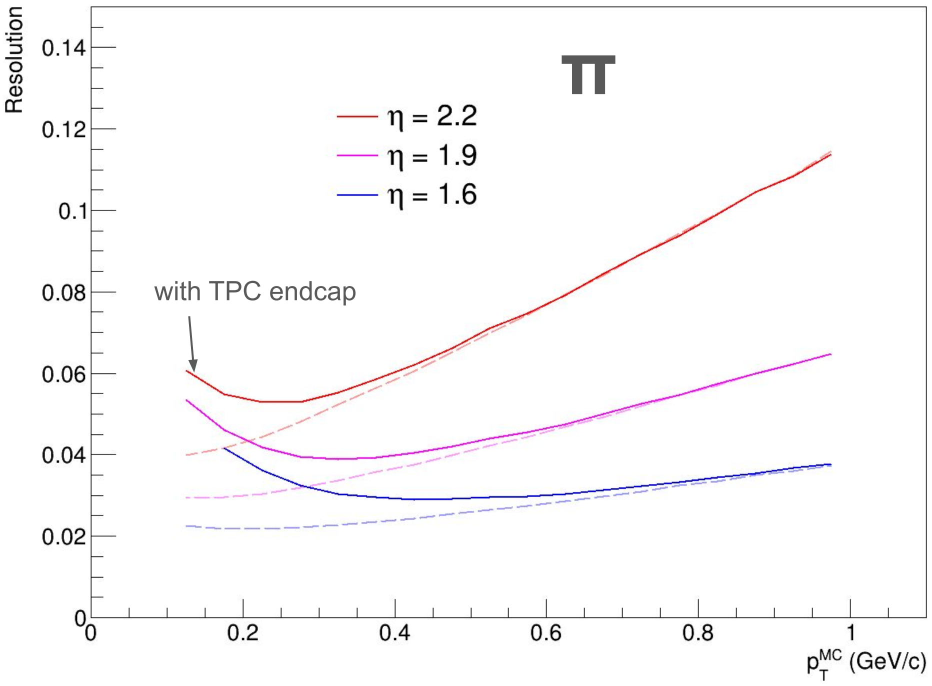


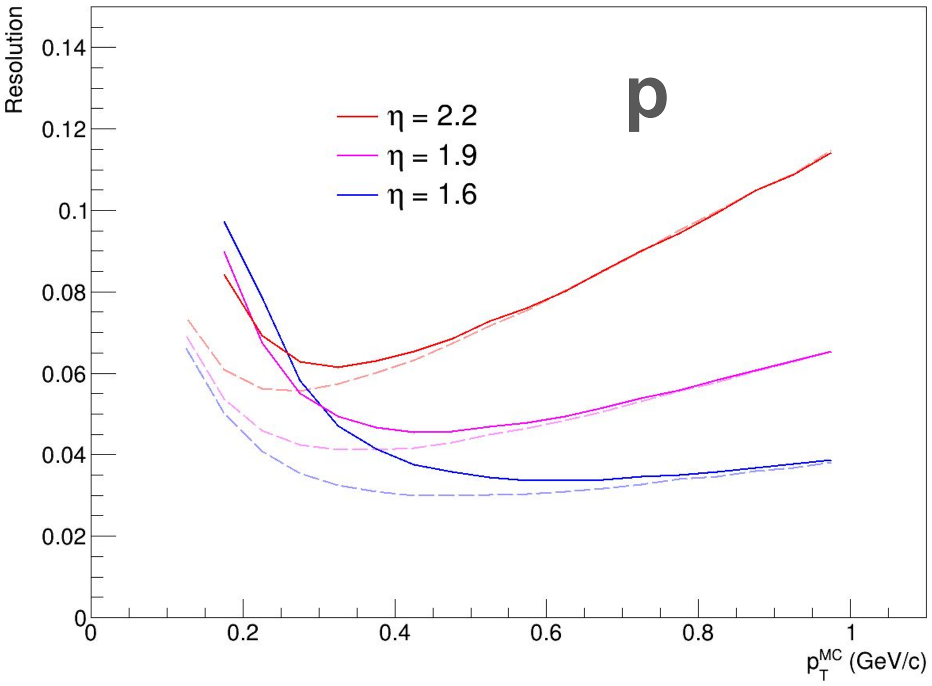
- Toy model with ROC-like and Frame-like layers

Toy TPC+FWD model in mpdroot



Momentum resolution in the ROC region (25% X_0)

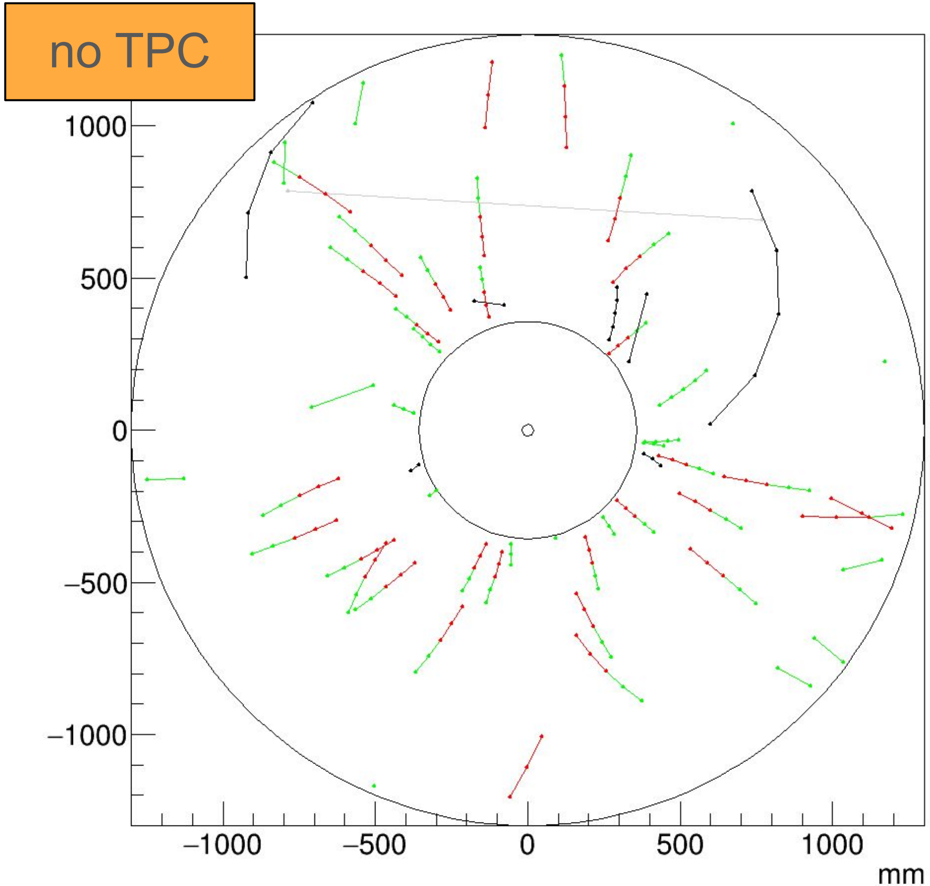


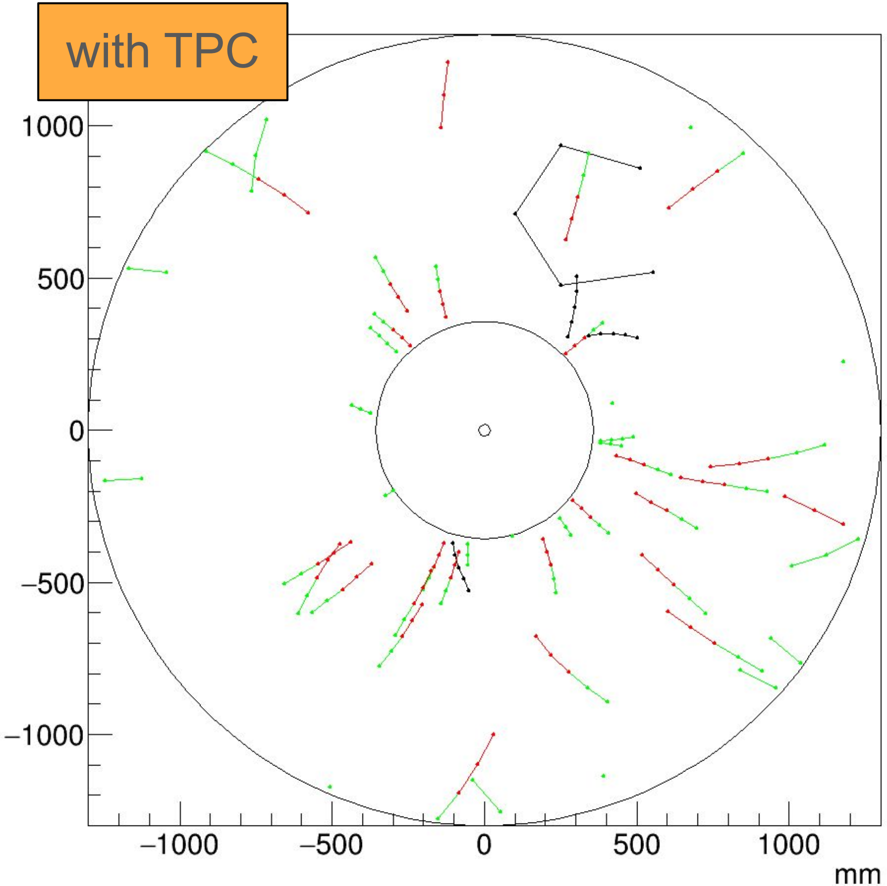


- Significant degradation of momentum resolution at low p_T
  ⇒ but still better than 10%
- Combine TPC and forward tracks to improve resolution?

Track finding at forward rapidity in high multiplicity collisions?

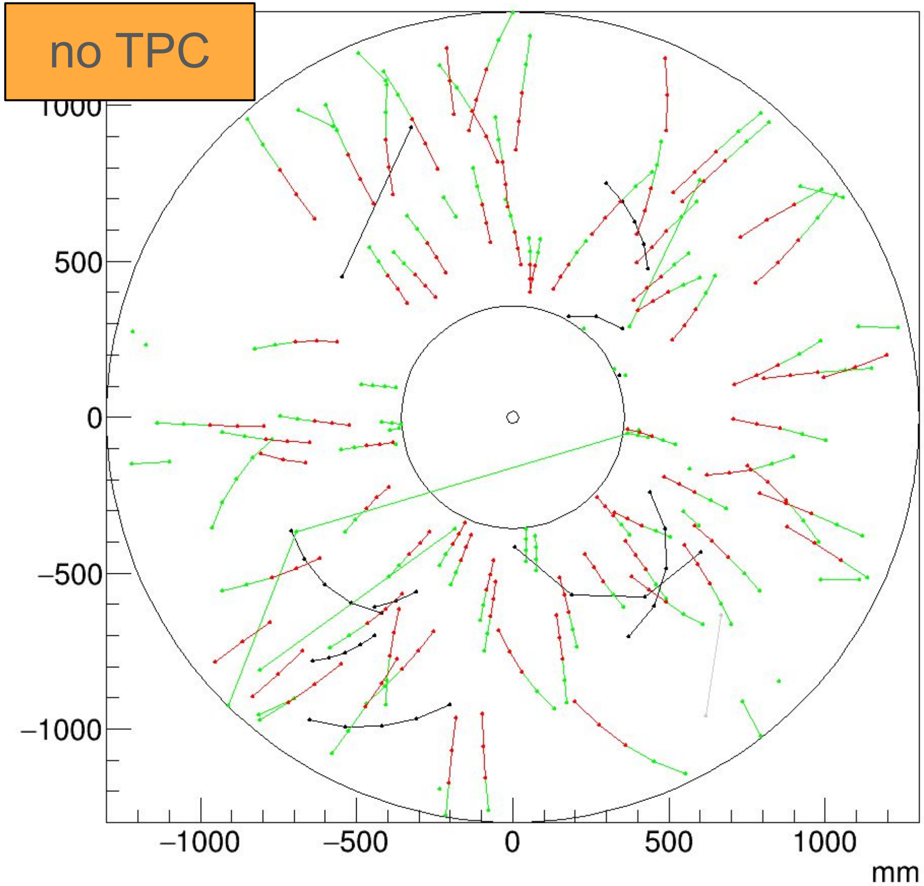
Event displays with/without TPC endcap

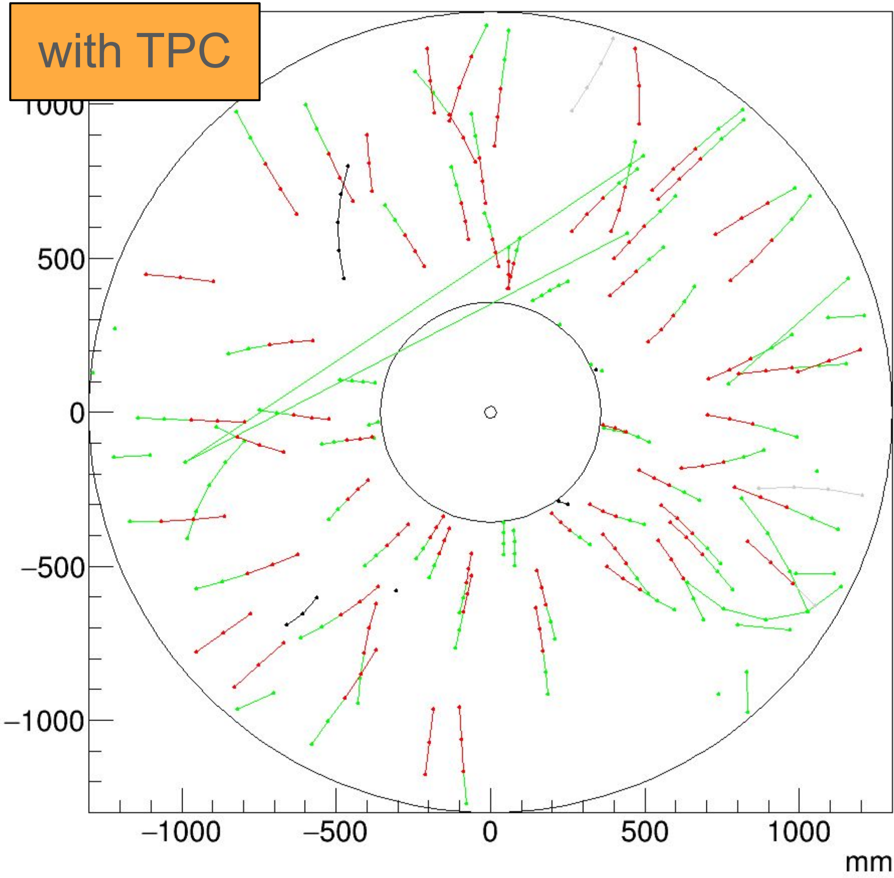




- black: tracks below 0.1 GeV threshold

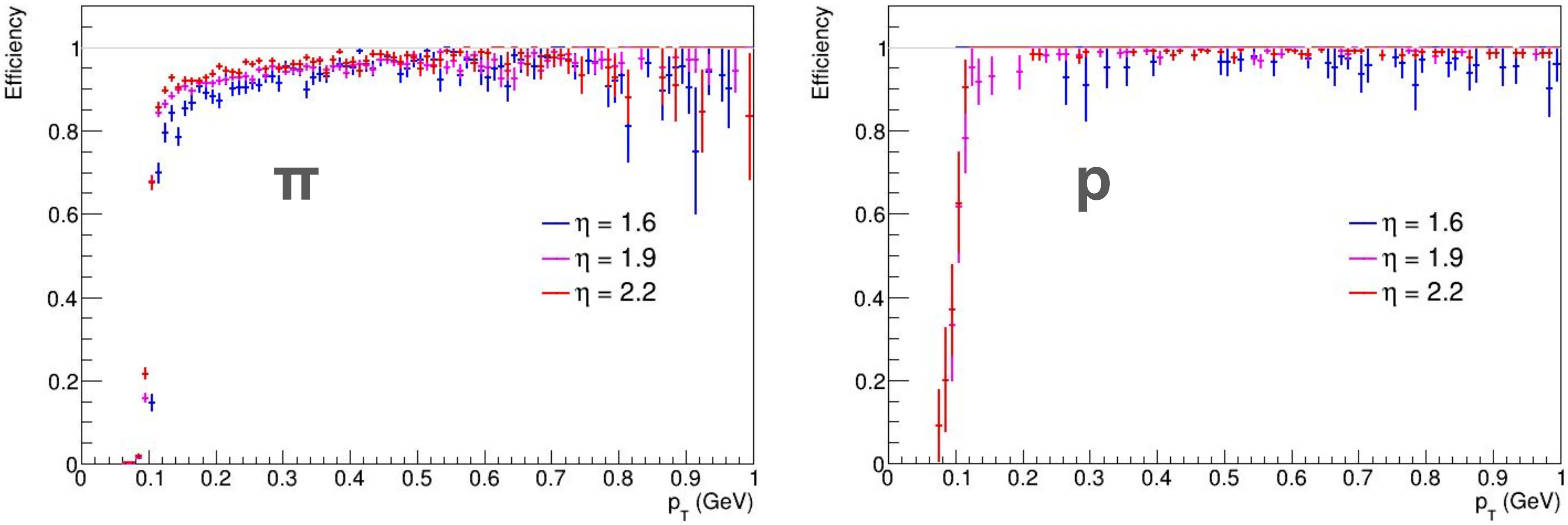
Event displays with/without TPC: high multiplicity





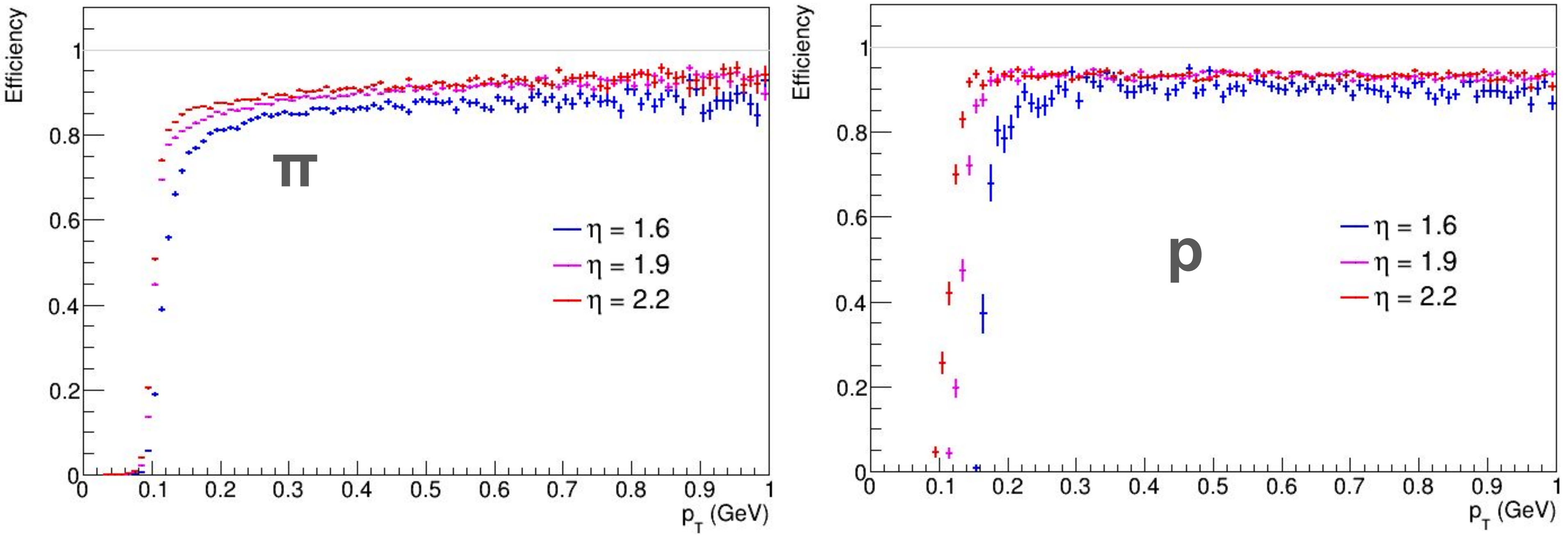
- black: tracks below 0.1 GeV threshold, gray: secondaries

Tracking efficiency without TPC endcap



- Reasonably high efficiency, especially for protons
- Reduced efficiency for pions explained by pion decays

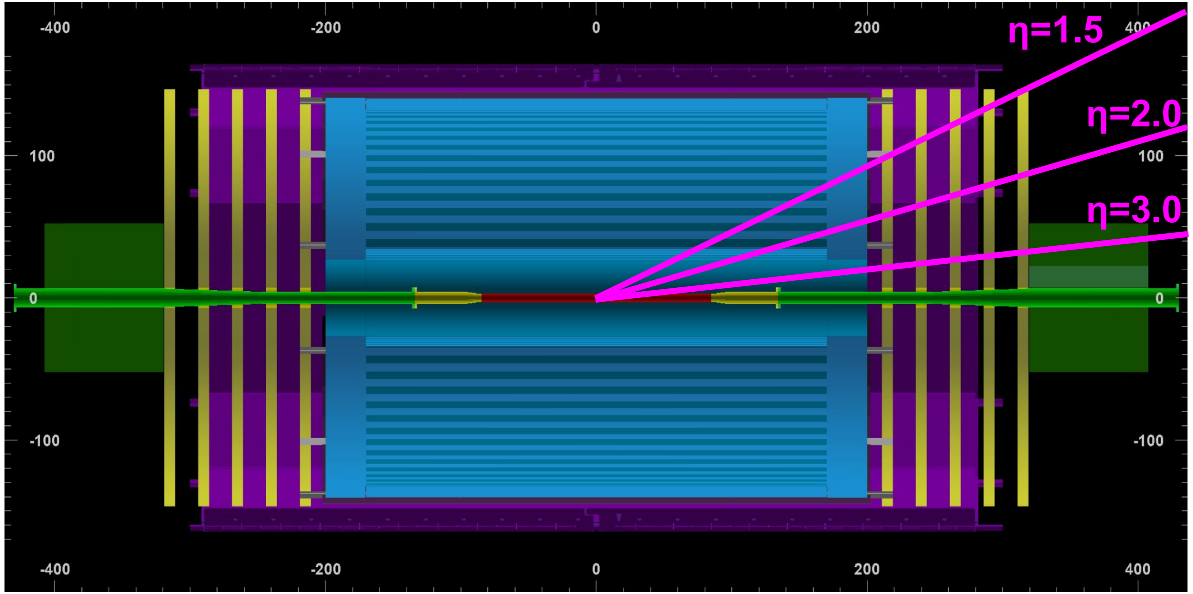
Tracking efficiency with ROC (25% X_0), but without frame



- 5%-tish efficiency losses due to nuclear interactions with TPC endcap (Al ~ 2.2 cm):
  - pion interaction length for Al ~ 40 cm
  - nuclear interaction length for Al ~ 50 cm

PID at forward rapidities?

Time-of-flight measurements?

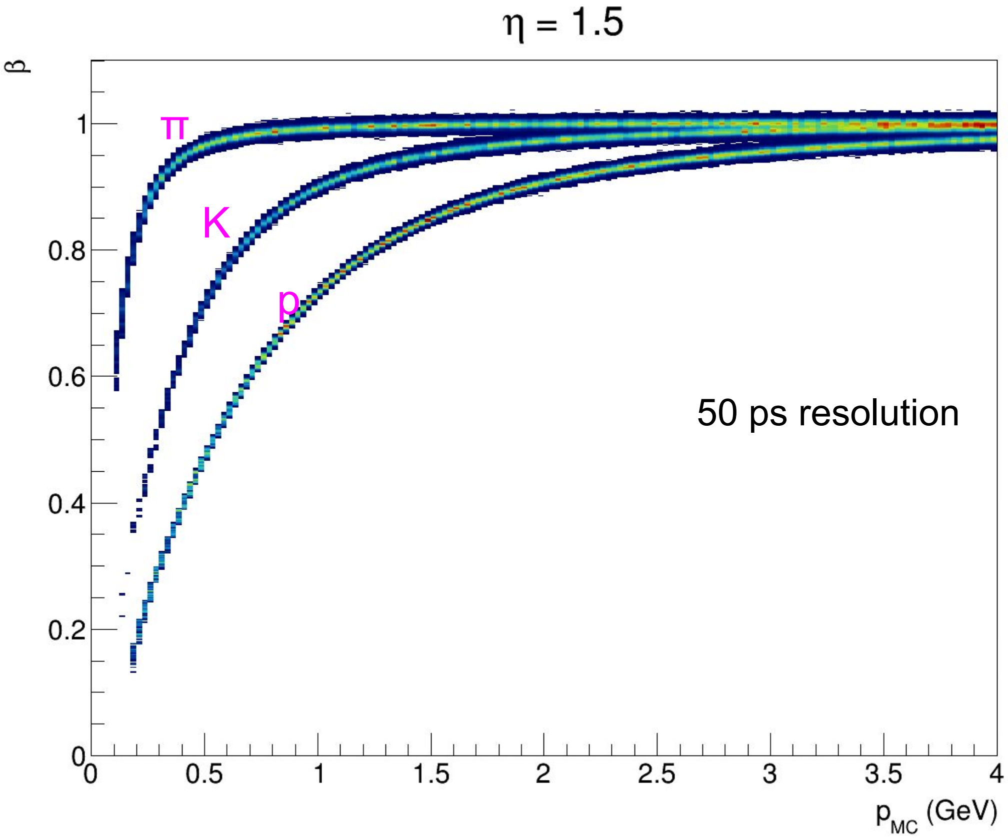


- TOF: replace the last station with RPCs?
  - ~ 50 ps resolution
  - At relatively large distance (~ 3m)
  - BUT: poor momentum resolution…

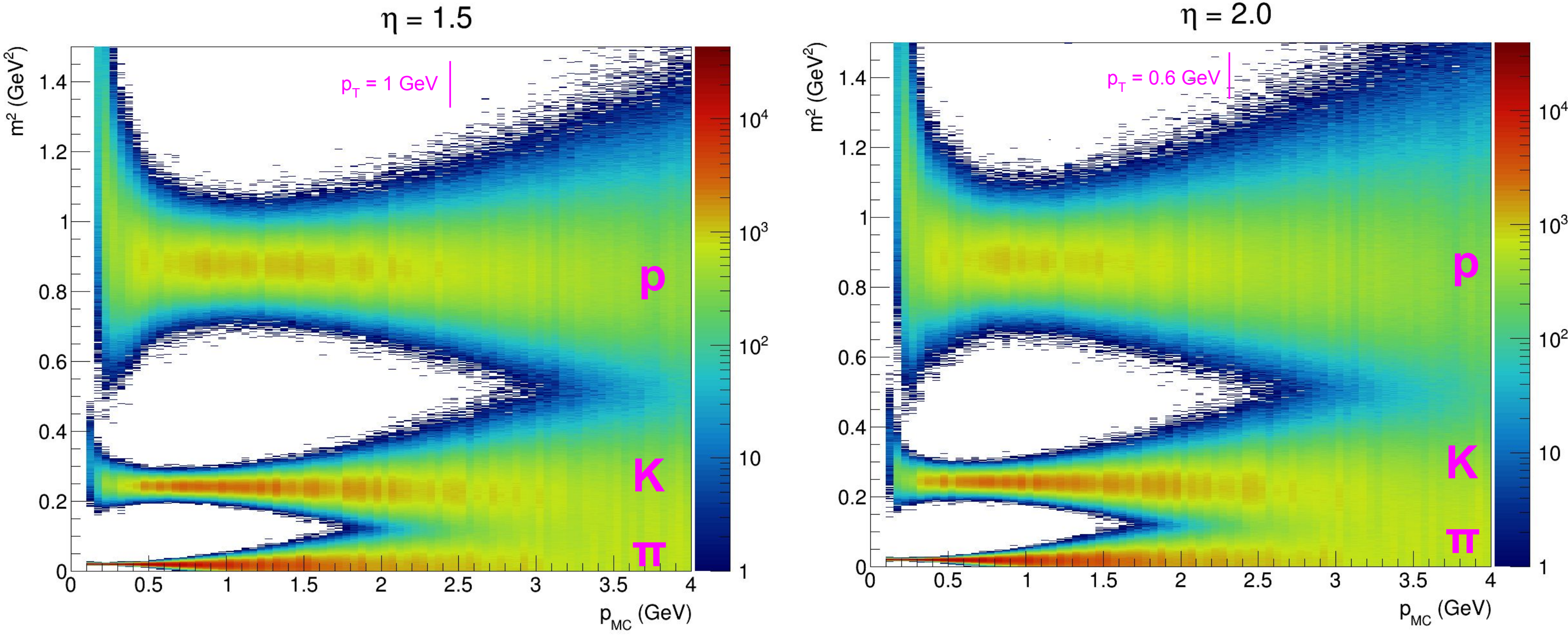
See talks by Yongjie Sun and Vadim Babkin

Toy model for TOF resolution estimates

- Generate π, K, p with box generator in different η ranges
- Extract time (t_{MC}) and track length (L) from the measurement in the last station
- Apply Gaussian smearing to the MC time to mimic reconstructed time t
- Derive $\beta = L/t/c$
- Smear MC momentum according to theoretical momentum resolution estimates
- Derive m^2



Squared mass distributions for 50 ps TOF resolution



- Momentum resolution also plays an important role for PID
- Good π/K and K/p separation

Conclusions and next steps

- Strong physics potential of the forward tracker
    - need further polishing and detailed quantitative studies
    - new ideas are highly welcome!
- First tracker prototype implemented in mpdroot
- Realistic track finding and track fitting using ACTS
    - tools are ready to study various detector options
- Track momentum can be measured with reasonable precision up to $\eta \sim 2.2$
- Particle identification with TOF looks feasible
- NEXT:
    - study the impact of momentum/PID resolution effects on physics observables
    - choose detector technology: your input is highly welcome!
    - more realistic simulations and further optimization of the forward tracker setup