Update on the forward tracker studies

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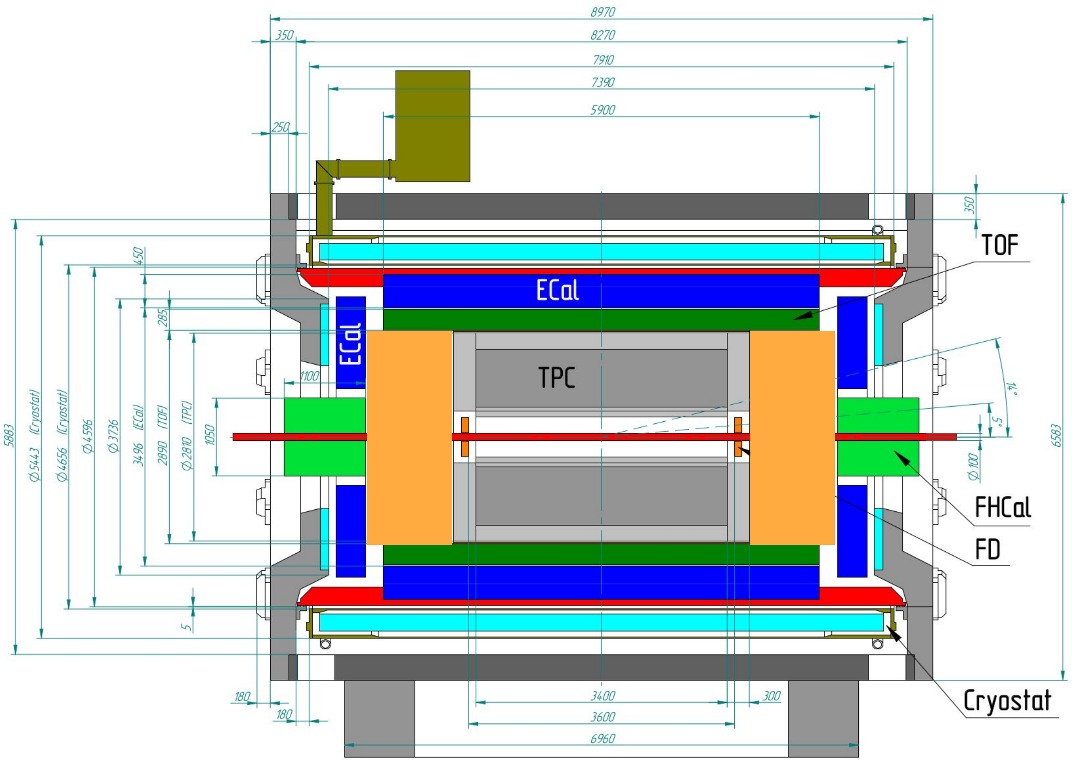
Reminder

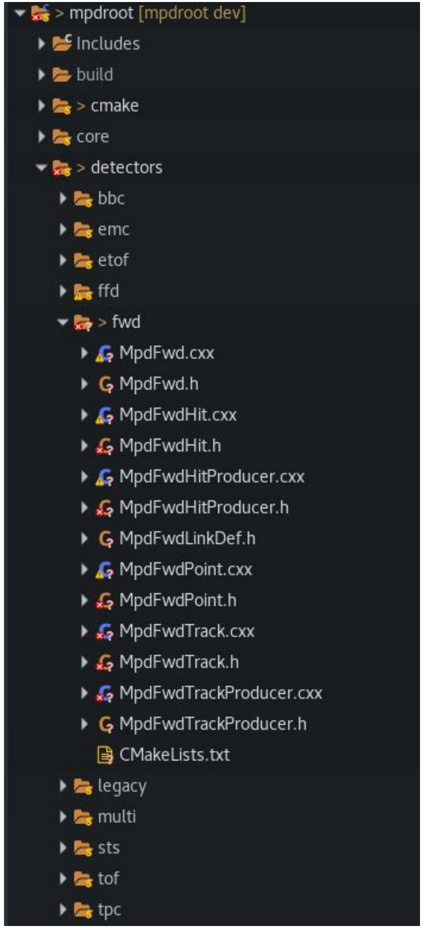
See previous talk on Aug 8: https://indico.jinr.ru/event/3950/

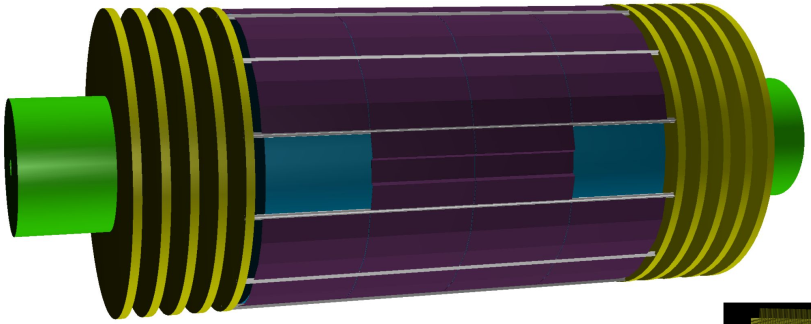


Physics program

- Testing statistical model: the kink, the horn, the step, the dale…
- Baryon anomaly @ 1-4 GeV (full momentum matters → study at forward rapidity)
- Angular correlation studies (stay away from jet peak, high stat. for 4-8 cumulants)
- Directed flow (need wide coverage to measure v1 shape)
- search for critical point with event-by-event net baryon number fluctuations: ideally need full rapidity coverage to reduce statistical fluctuations
- 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 …

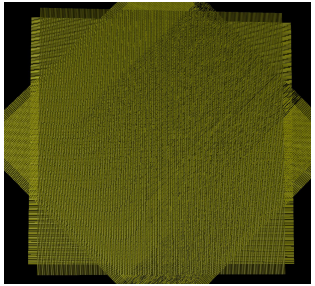
First prototype implemented in MPDROOT

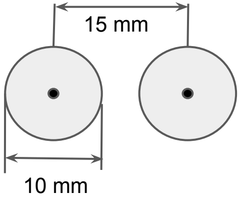




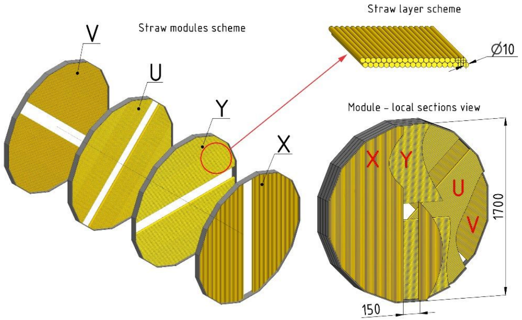
Each straw tube:

- Tube diameter: 10 mm
- Tube thickness: 30 μm kapton
- Wire diameter: 30 μm tungsten
- Gas: $ArCO_2$: 70%/30%
- Hit resolution ~ 100μm
- Effective radiation length: 0.112% X_0 per station





- Flexible detector construction code
  - MpdFwd
- Data structures:
  - MpdFwdPoint
  - MpdFwdHit
  - MpdFwdTrack
- Ideal hit and track producers:
  - MpdFwdHitProducer
  - MpdFwdTrackProducer

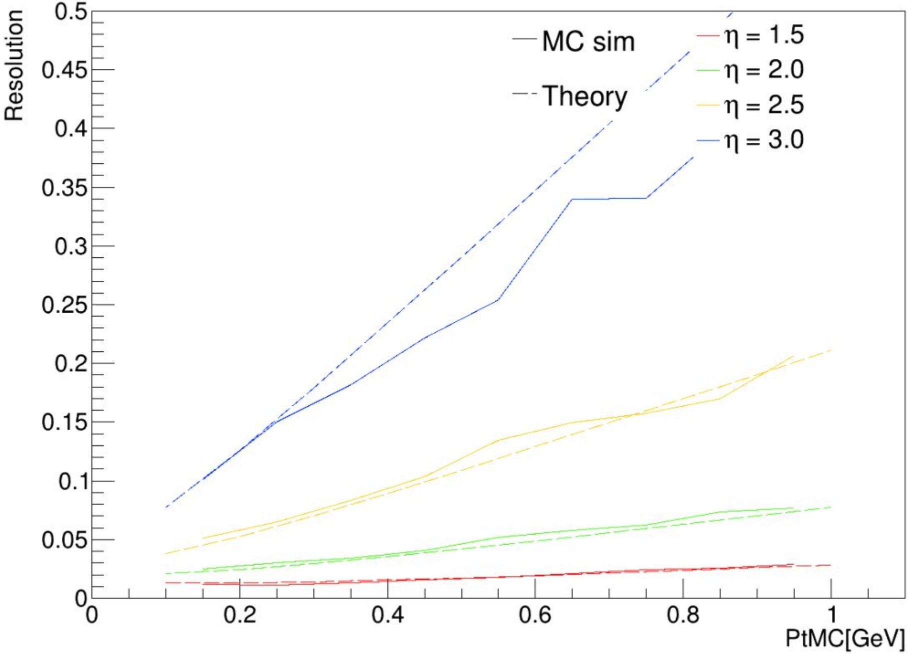


Momentum resolution

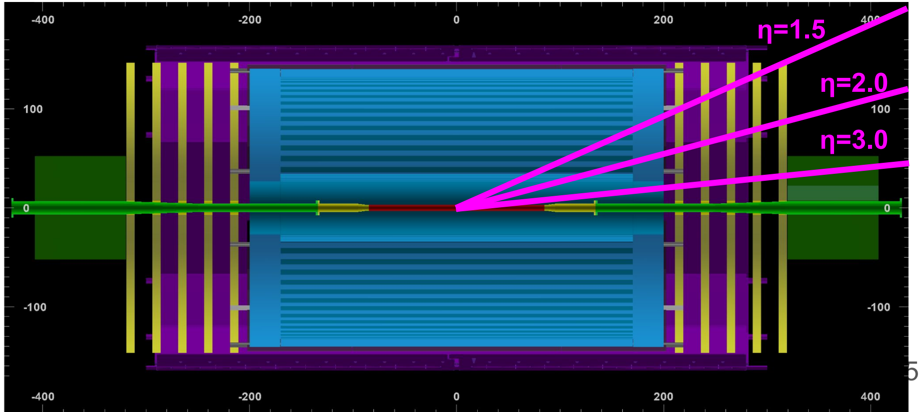
$$Resolution = \sqrt{\left(\frac{\Delta p_T}{p_T}|res.\right)^2 + \left(\frac{\Delta p_T}{p_T}|m.s.\right)^2}$$

$$\frac{\Delta p_T}{p_T}|m.s. = \frac{N}{\sqrt{(N+1)(N-1)}} \frac{0.0136 GeV/c}{0.3\beta B_0 L_0} \sqrt{\frac{d_{tot}}{X_0 \cos\theta}} \left(1 + 0.038 \ln \frac{d}{X_0 \cos\theta}\right)$$

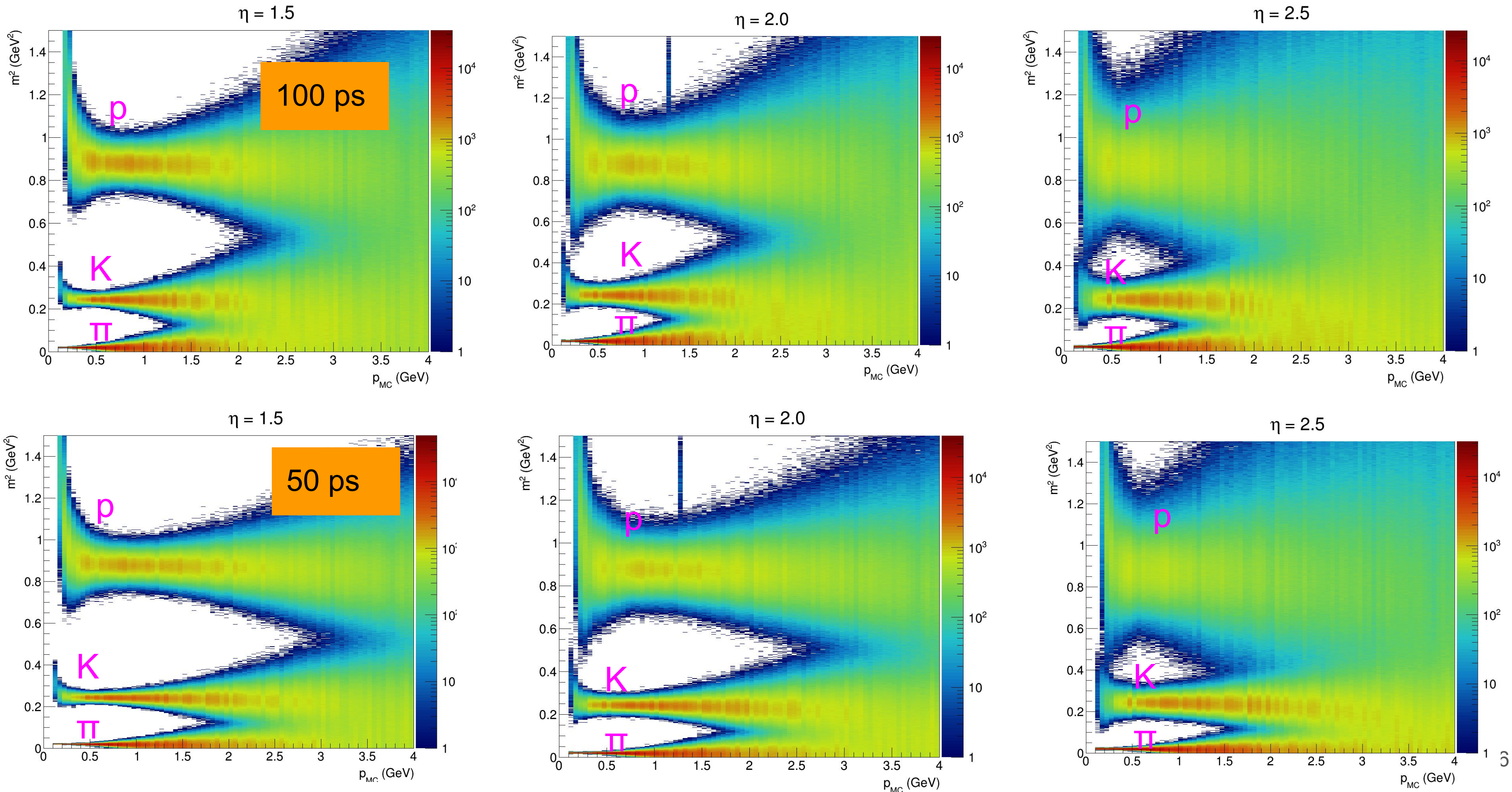
$$\frac{\Delta p_T}{p_T}|res. = \frac{\sigma_{rf} p_T}{0.3 B_0 L_0^2} \sqrt{\frac{720 N^3}{(N-1)(N+1)(N+2)(N+3)}}$$



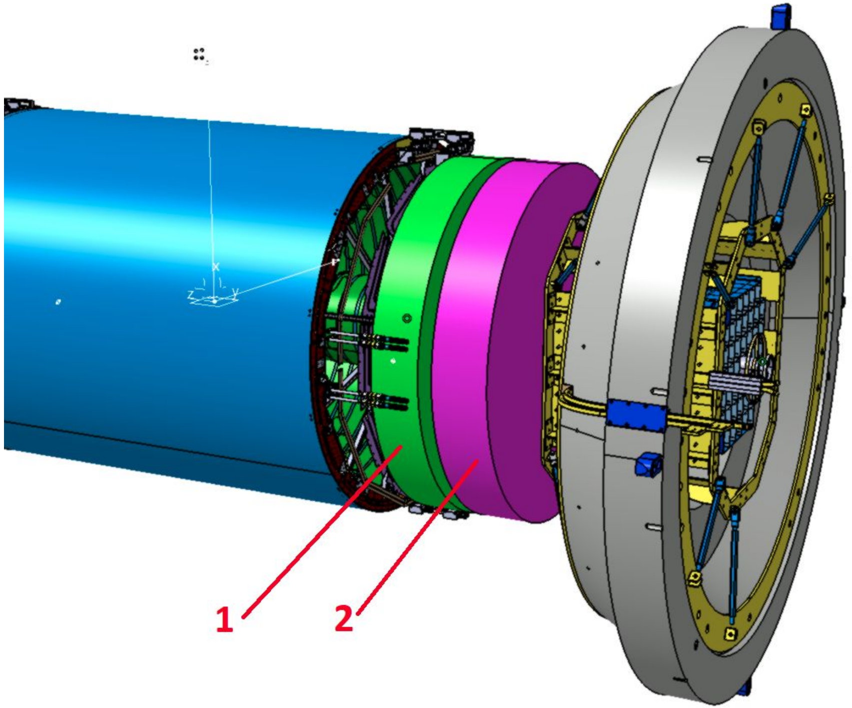
- Momentum resolution in the solenoid field is driven by the radial distance available for track curvature measurement
- Strongly degrades towards large η
- Good agreement between theory and MC
- Hit resolution is the dominant effect
- η ~ 3 is hardly feasible



TOF: squared mass distributions



Realistic 3D model

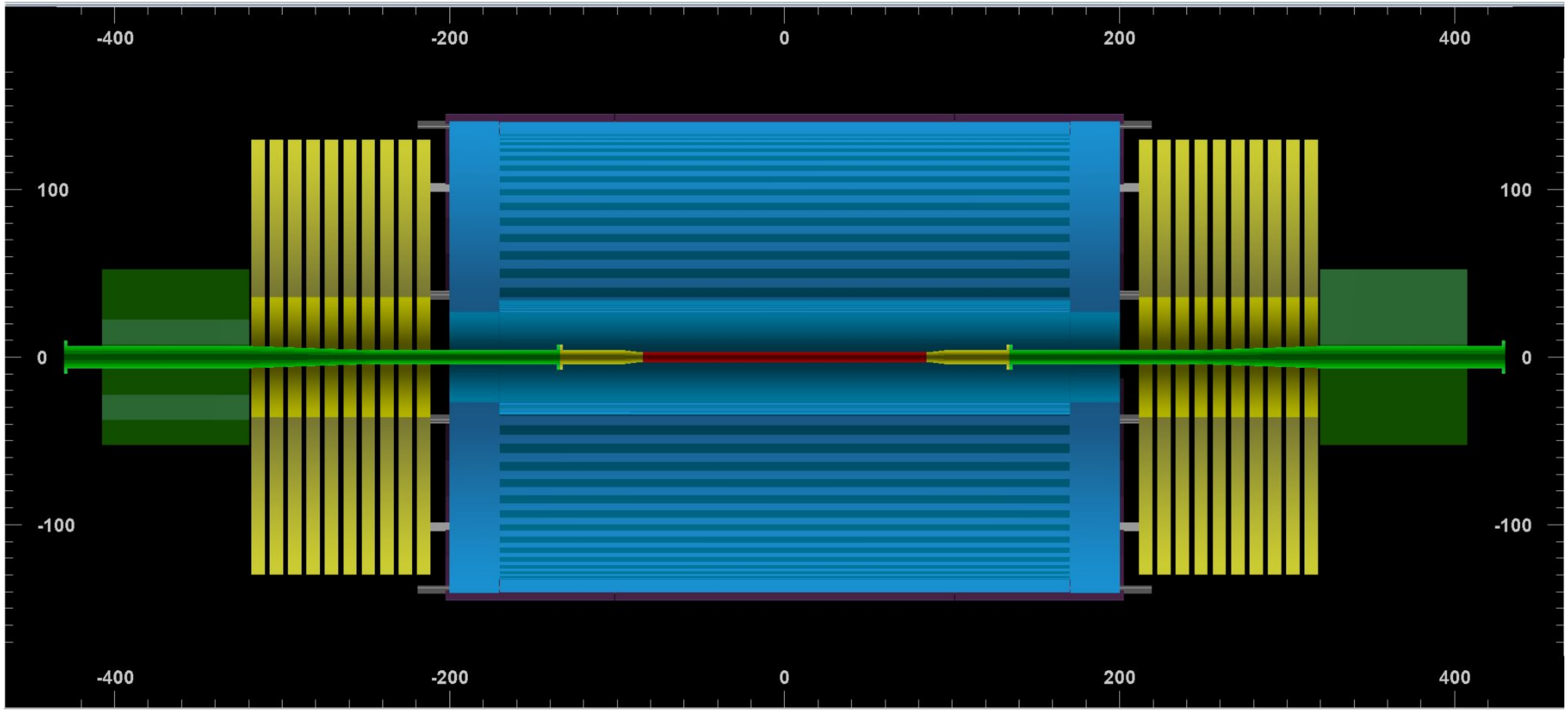


- L_0 = 85 cm instead of 100 cm in the toy model
- η_{min} = 1.55
- η_{max} =2.47

- 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)

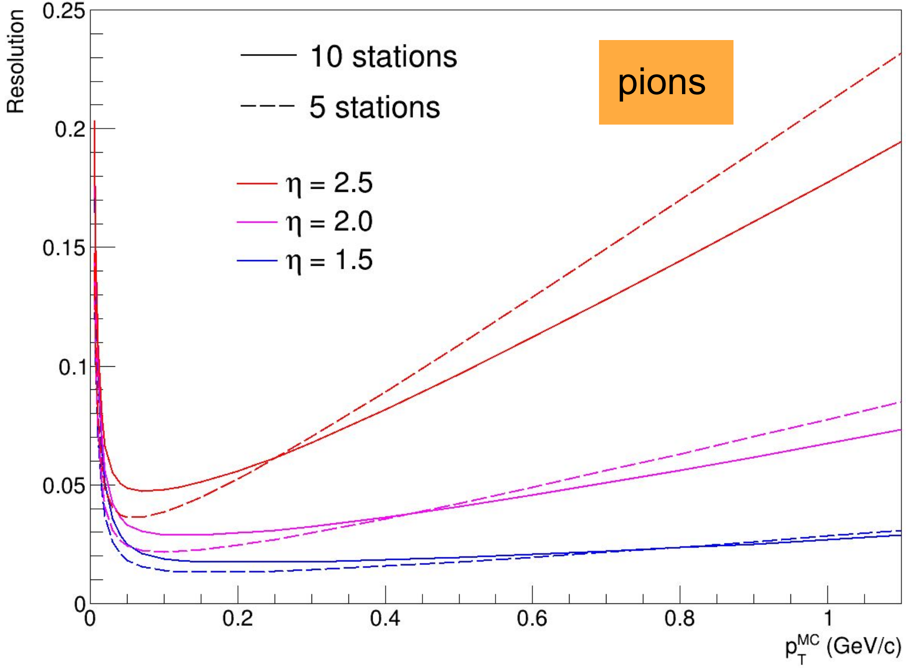
Increase the number of stations?

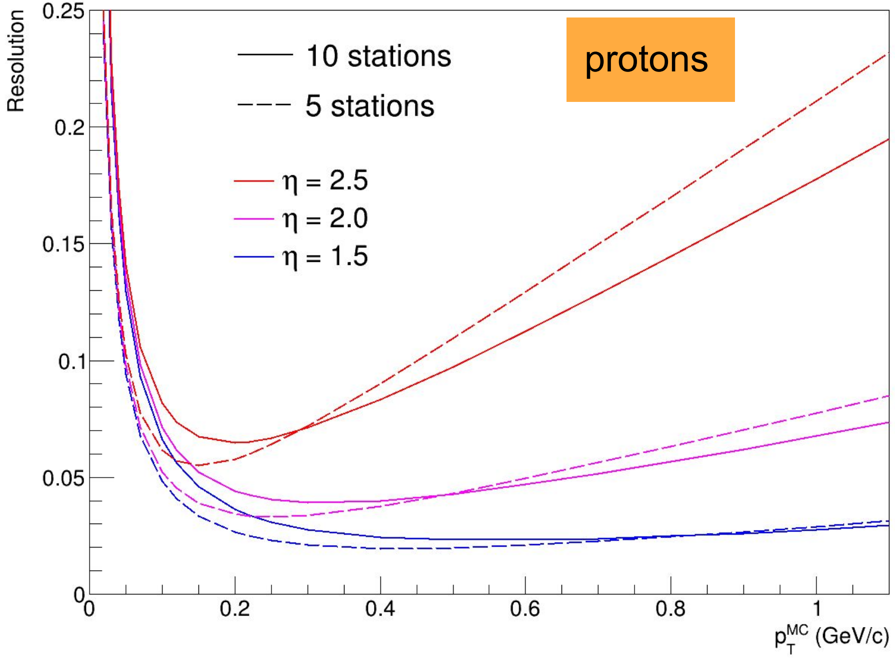
Setup with 10 stations per side



- Main goal: reduce combinatorics for track finding
- 10 equidistant stations
- Rmin = 35.7 cm, Rmax = 130 cm

Momentum resolution: 5 vs 10 stations



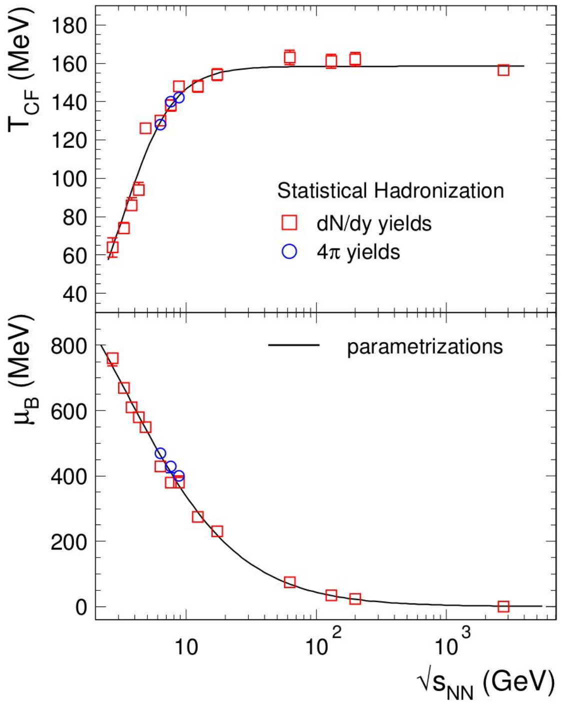


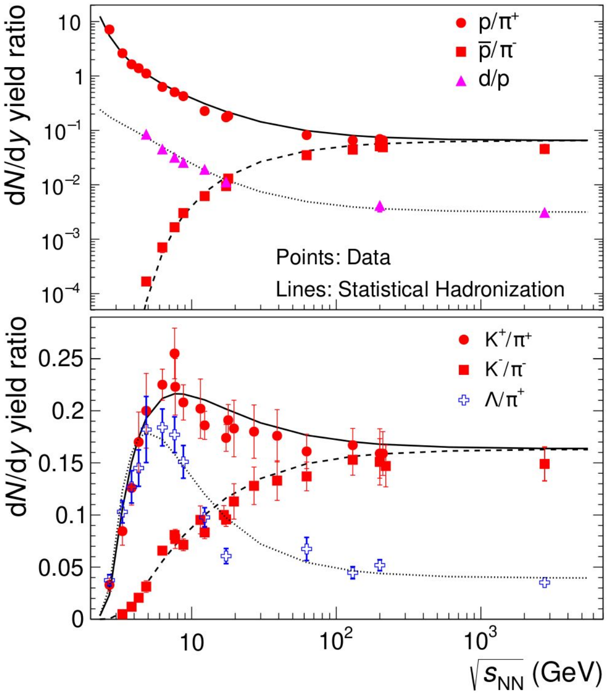
$$\frac{\triangle p_T}{p_T}|m.s. = \frac{N}{\sqrt{(N+1)(N-1)}} \frac{0.0136 GeV/c}{0.3\beta B_0 L_0} \sqrt{\frac{d_{tot}}{X_0 \cos\theta}} (1 + 0.038 \ln \frac{d}{X_0 \cos\theta})$$

$$\frac{\triangle p_T}{p_T}|res. = \frac{\sigma_{rf} p_T}{0.3 B_0 L_0^2} \sqrt{\frac{720 N^3}{(N-1)(N+1)(N+2)(N+3)}}$$

- Using analytical estimates (proved to be consistent with MC)
- 10 stations instead of 5:
  - Degradation at low p_T due to multiple scattering
  - Significant improvement at high p_T
- Increased number of stations looks feasible
- Next: realistic tracking with ACTS

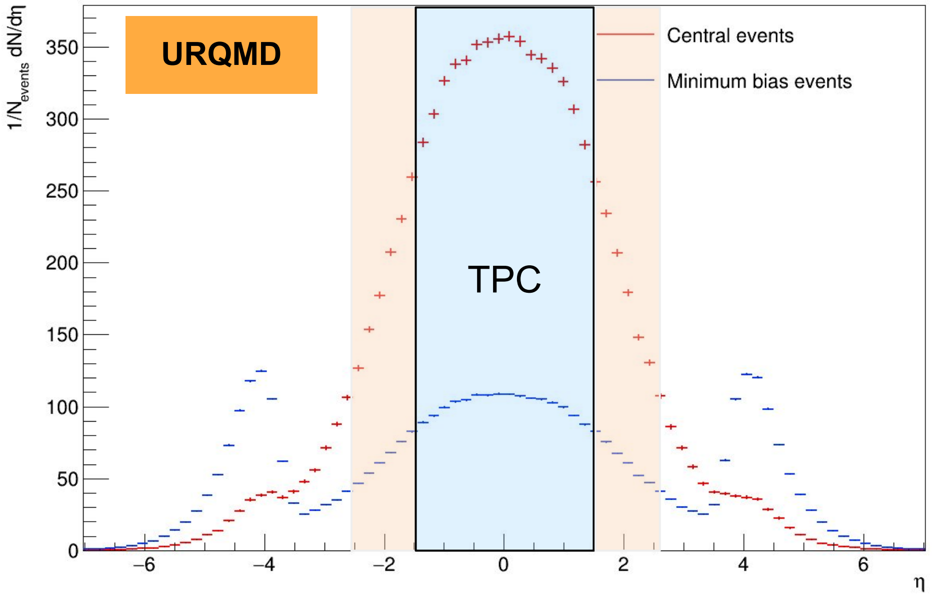
Forward detector for statistical model tests

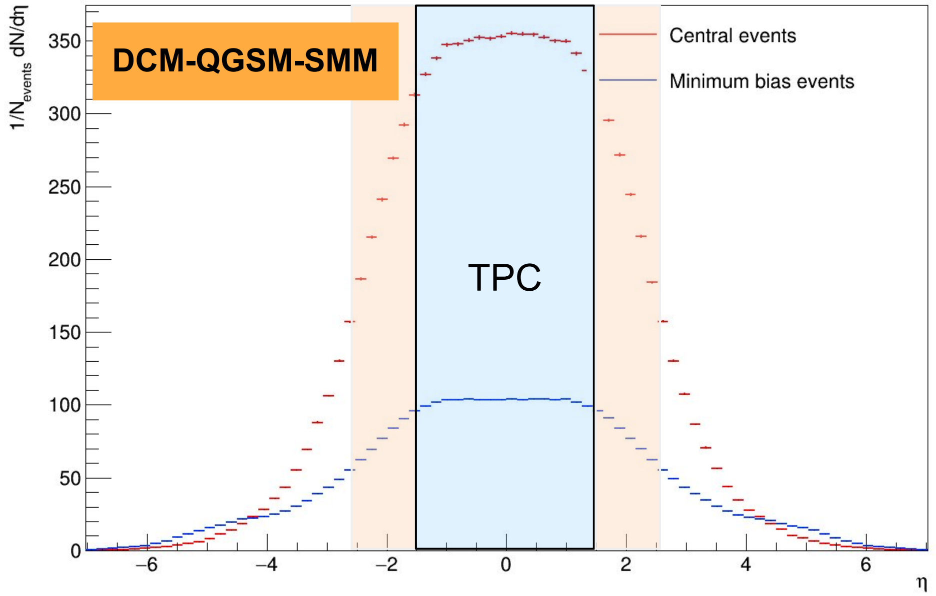




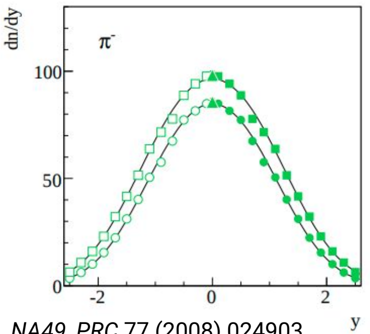
A. Andronic et al, Nature 561 (2018) 7723, 321

Rapidity distributions: URQMD vs DCM-QGSM-SMM

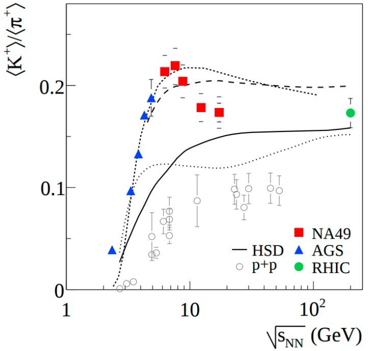




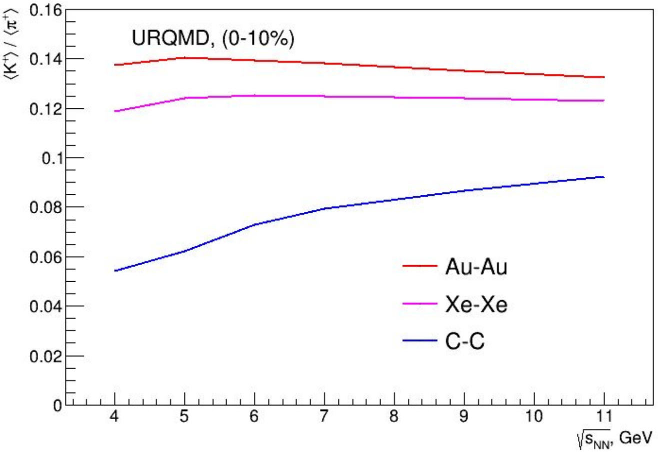
- Ideally need full rapidity coverage for stat. model tests:
  - e.g. see NA49 results
- Significant differences in predicted rapidity distributions
- Results mainly available for heavy ions (Pb, Au) and at mid-rapidity
- Would be interesting to measure A-dependence (vs energy) and search for onset of deconfinement

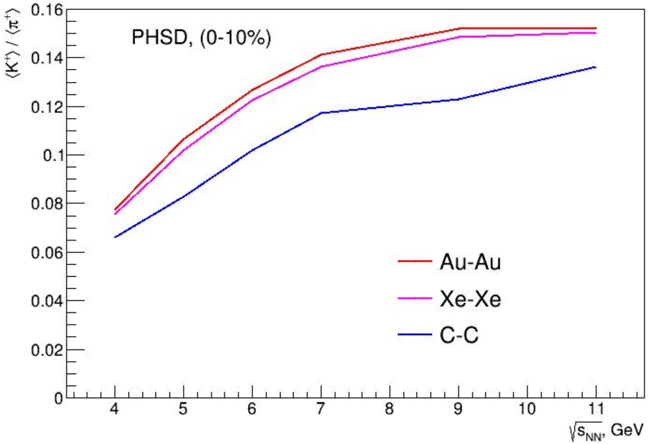


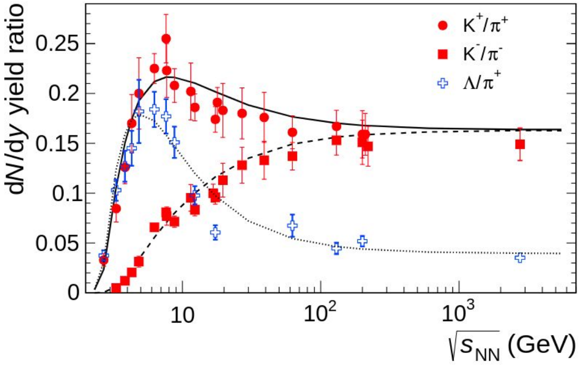
NA49, PRC 77 (2008) 024903

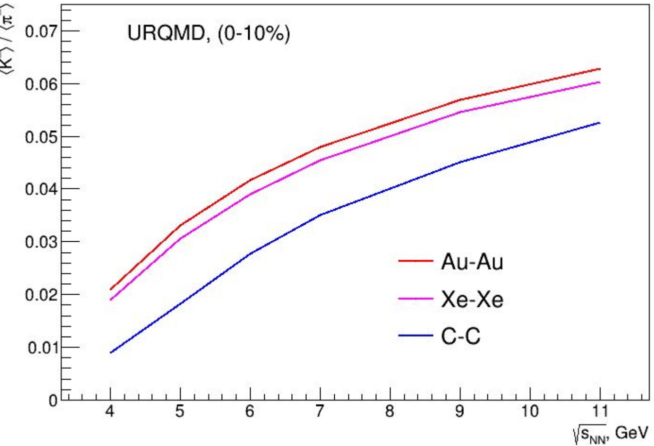


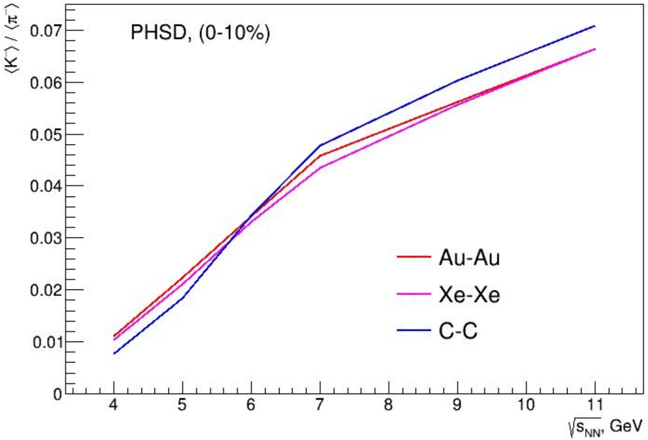
K/π ratios in URQMD and PHSD vs A and energy







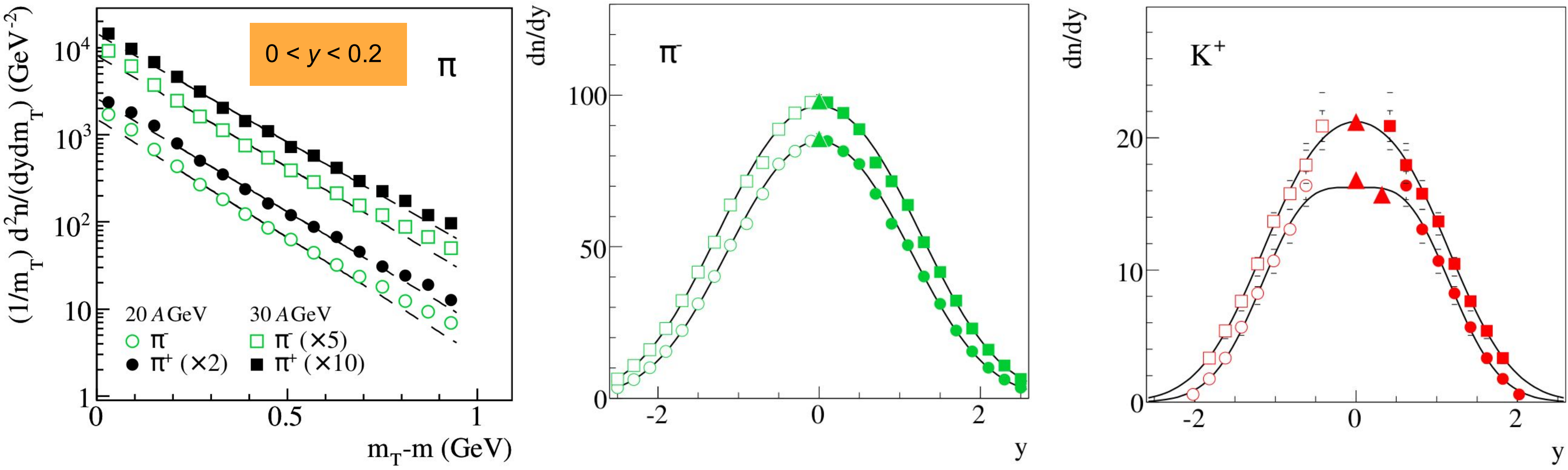




- No distinct horn structure in URQMD or PHSD
- K+/π+ ratio underestimated compared to data
- Need precision measurements to probe the difference between Au-Au and Xe-Xe
- K-/π- ratio: strange inverse dependence on A in PHSD?

How to measure total particle yields/ratios?

NA49, PRC 77 (2008) 024903

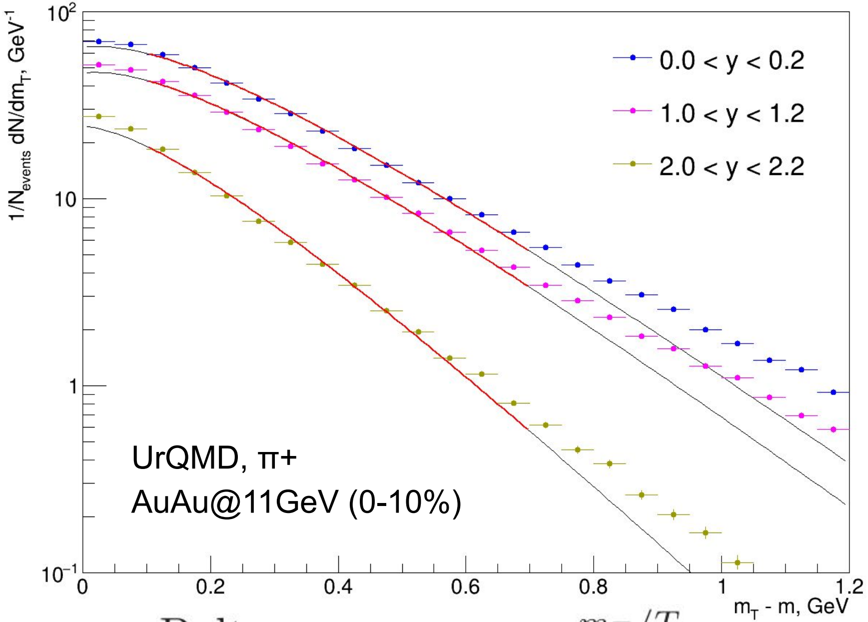


$$\frac{d^2 n}{m_T dm_T dy} = C \exp\left(-\frac{m_T}{T}\right)$$

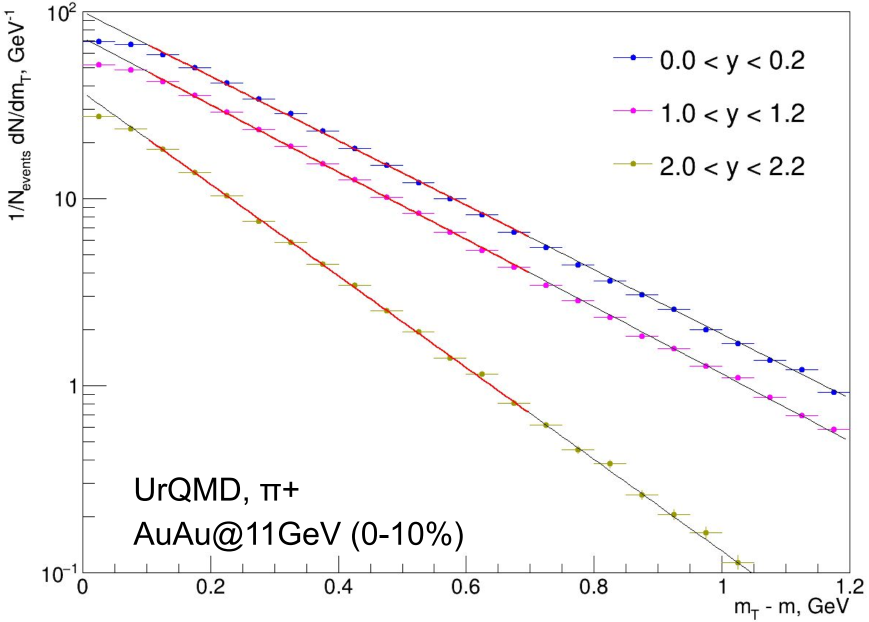
$$\frac{dn}{dy} = \frac{\langle n \rangle}{2\sqrt{2\pi}\sigma}\left\{\exp\left[-\frac{1}{2}\left(\frac{y-y_0}{\sigma}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{y+y_0}{\sigma}\right)^2\right]\right\}$$

- Measure m_T (or p_T) spectra in narrow rapidity bins
- Fit m_T (or p_T) distributions and extrapolate to unmeasured m_T → dn/dy
- Fit dn/dy with double-Gaussian function and extrapolate to unmeasured y

Generator-level studies: m_T spectra



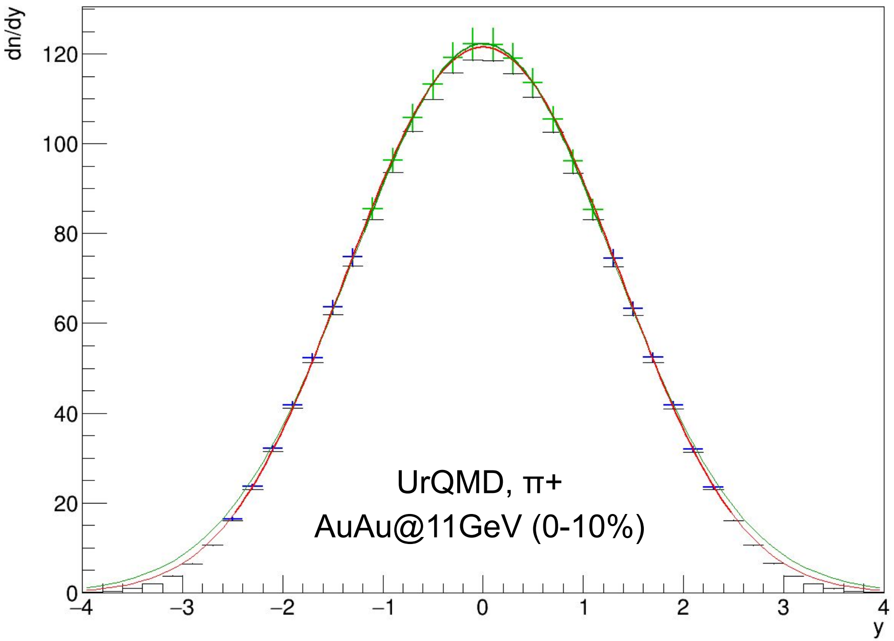
Boltzmann: $\propto m_T e^{-m_T/T}$

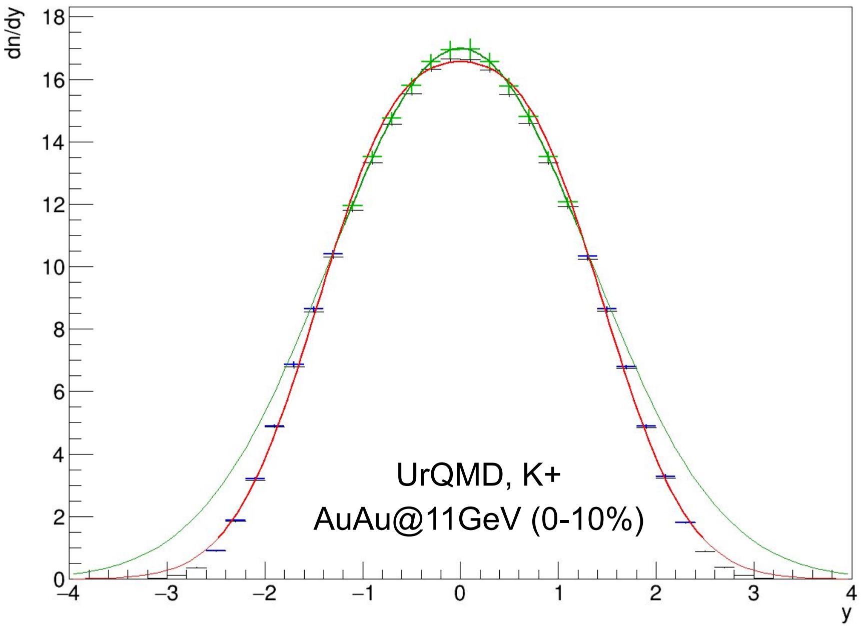


m_T-exponential: $\propto e^{-(m_T-m)/T}$

- Assuming spectra(+PID) can be measured in the range $0.1 < p_T < 1$ GeV
- Clear y-dependence of T-slope, changes visible only at high y →yet another argument to extend y coverage
- Boltzmann shape doesn't really work well in UrQMD
- mT-exponential shape works better but overestimates the yield at low p_T

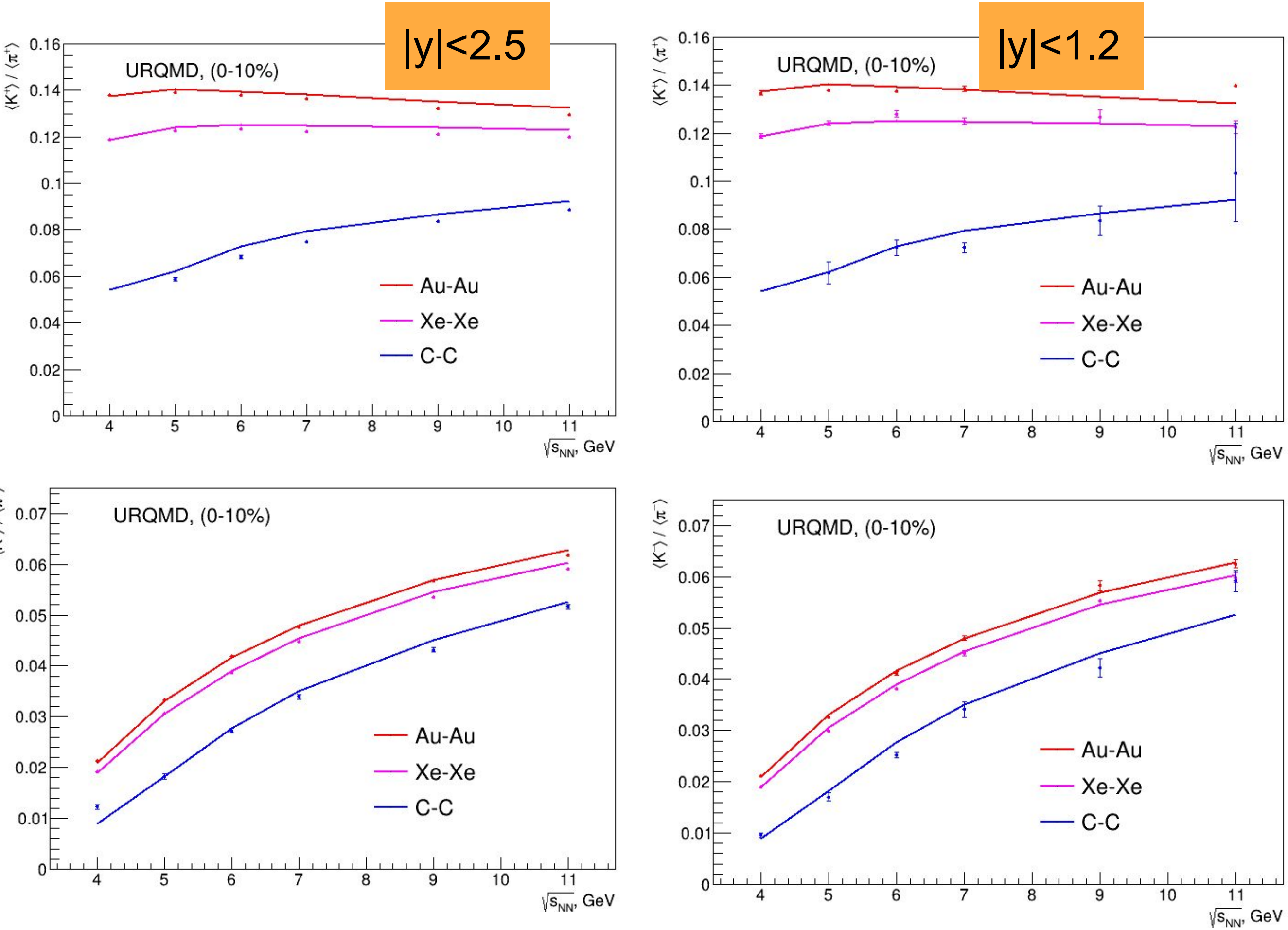
Generator-level studies: rapidity spectra





- dn/dy uncertainties from the difference between true and mt-exp fit
- Considering |y|<1.2 and |y|<2.5 and using double-Gaussian to extract total yields
- Clear advantage of extended rapidity coverage, especially in the kaon case

K/π ratios vs A and energy with/without forward tracker



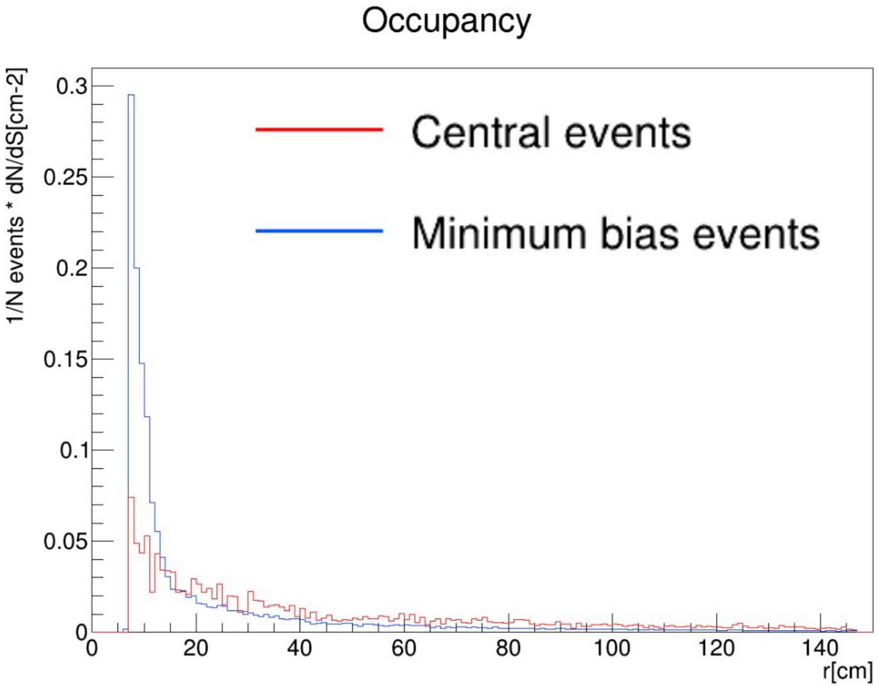
- Clear advantage of extended coverage
- Improved precision
- Better control over biases

Conclusions and next steps

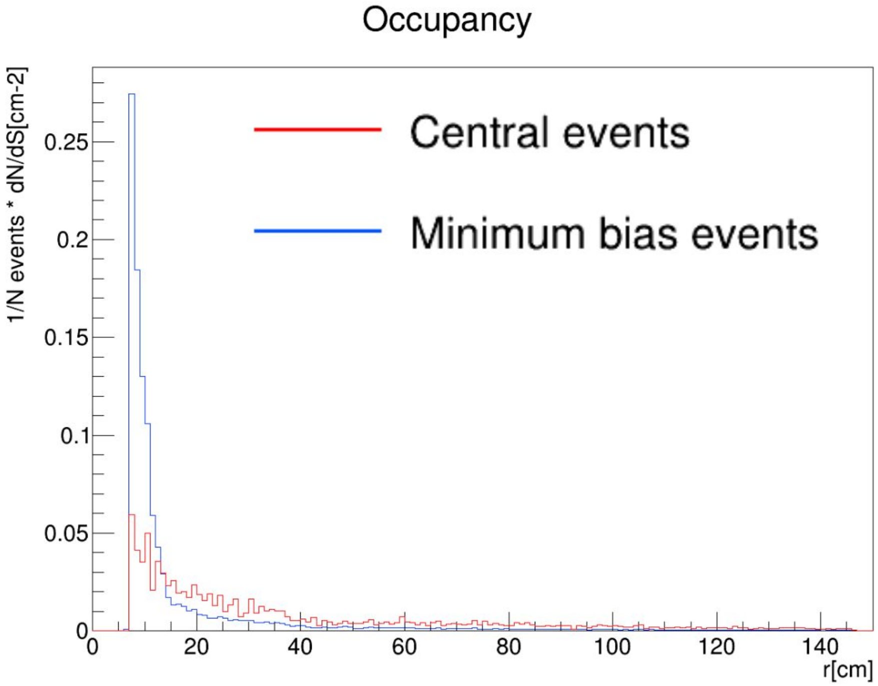
- Strong physics potential of the forward tracker
  - First studies of the impact of the forward tracker on total yield and ratio measurements
  - need further polishing and detailed quantitative studies
- First straw tube tracker prototype implemented in mpdroot
- Track momentum can be measured with reasonable precision up to $\eta \sim 2.5$
- Particle identification can be performed up to $\eta \sim 2.5$
- 10-station setup seems feasible
- NEXT:
  - study the impact of momentum/PID resolution effects on physics observables
  - realistic tracking with ACTS
  - more realistic simulations and further optimization of the forward tracker setup

BACKUP

Occupancy

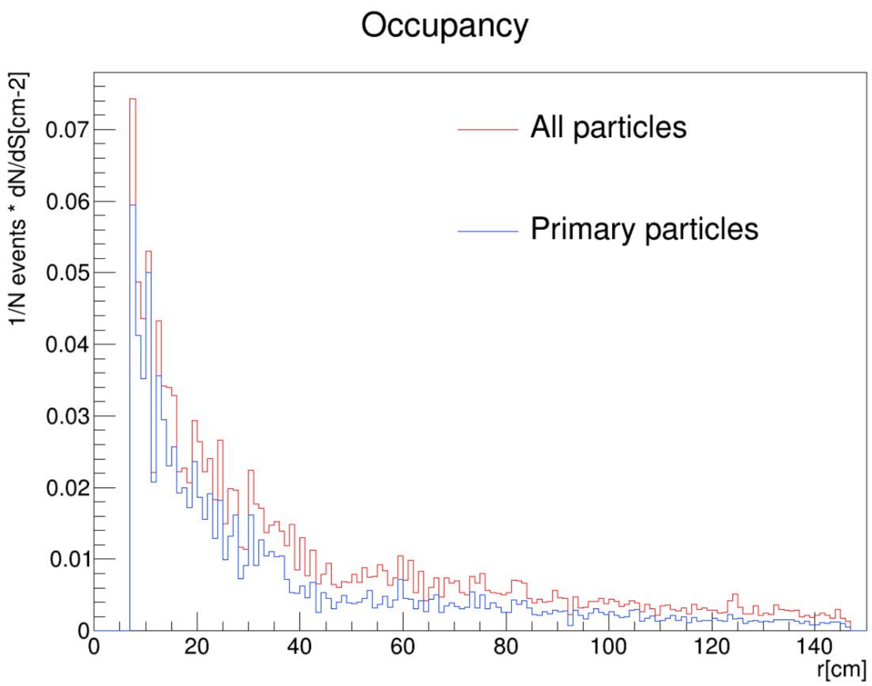


All particles



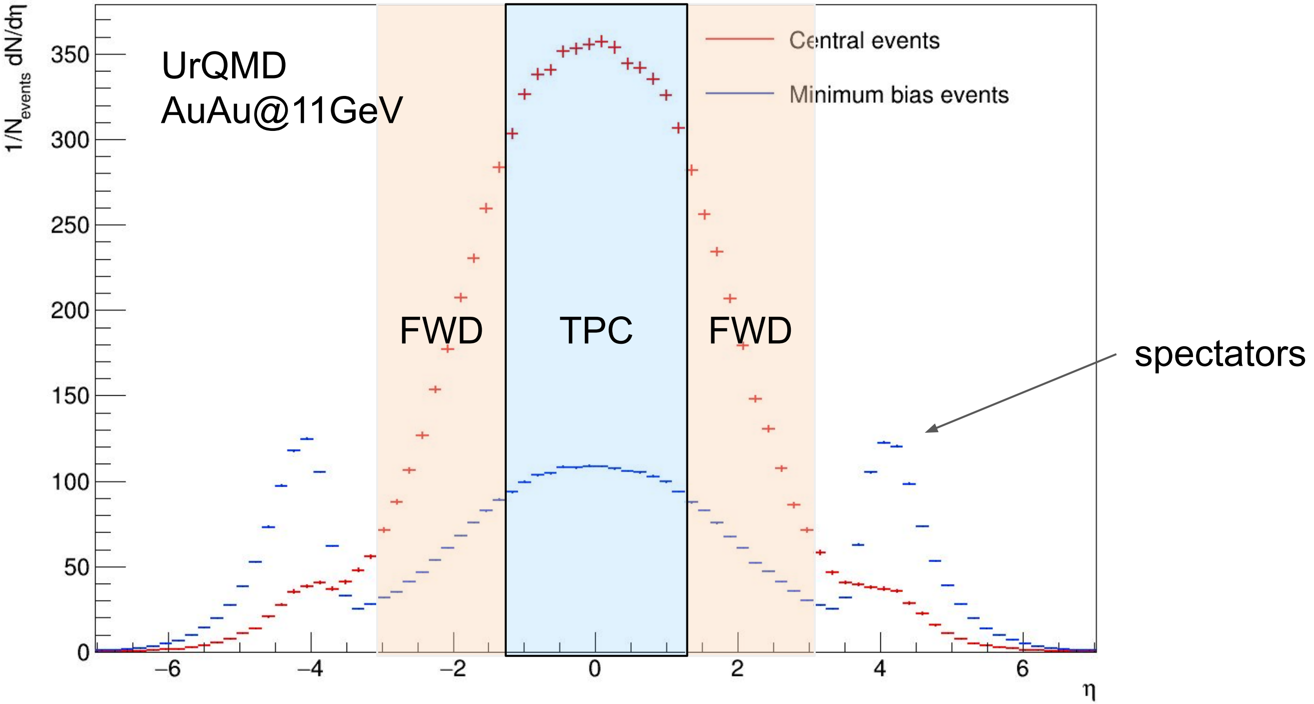
Primary particles

Primary and secondary particles @ station 1



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 90%

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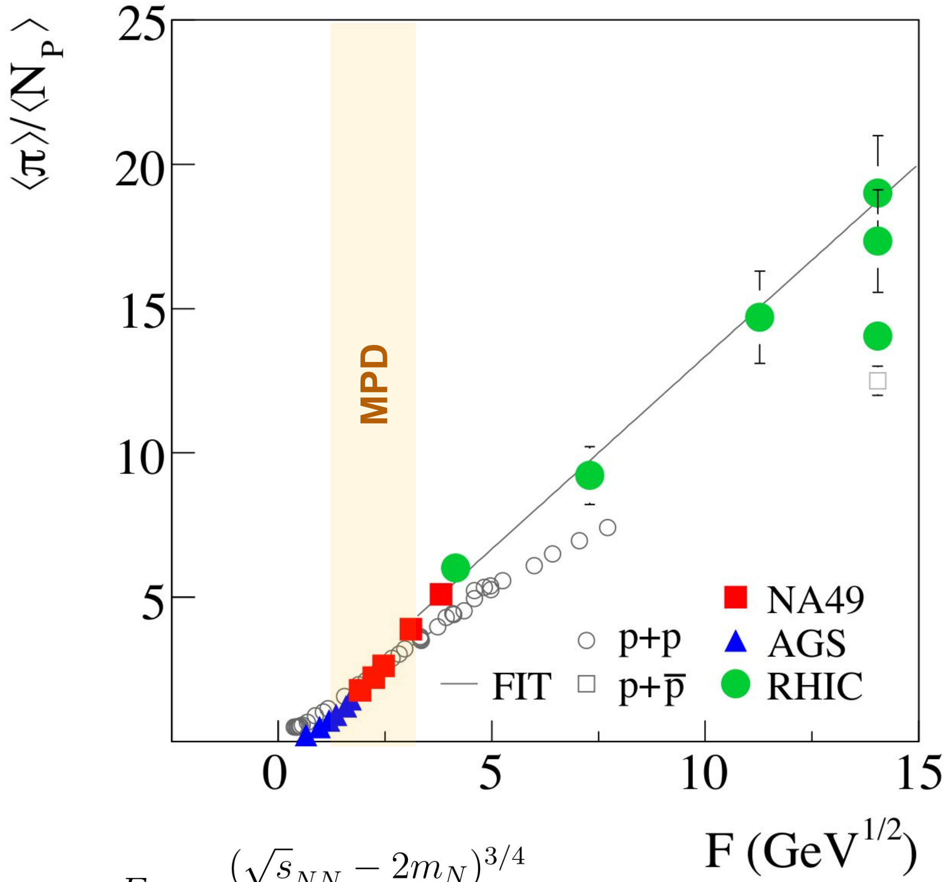
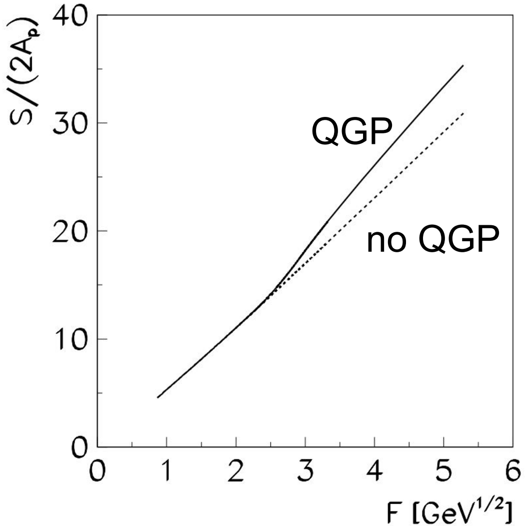
The Kink



$$F = \frac{(\sqrt{s_{NN}} - 2m_N)^{3/4}}{(\sqrt{s_{NN}})^{1/4}}$$

Fermi-Landau variable

- Entropy is expected to increase in the deconfined phase
- Pion multiplicity ~ entropy
- Signal of deconfinement: mean pion multiplicity per participant changes the slope as function of energy
- Need charged pions in the full phase space including 1.2<|η|<3.0



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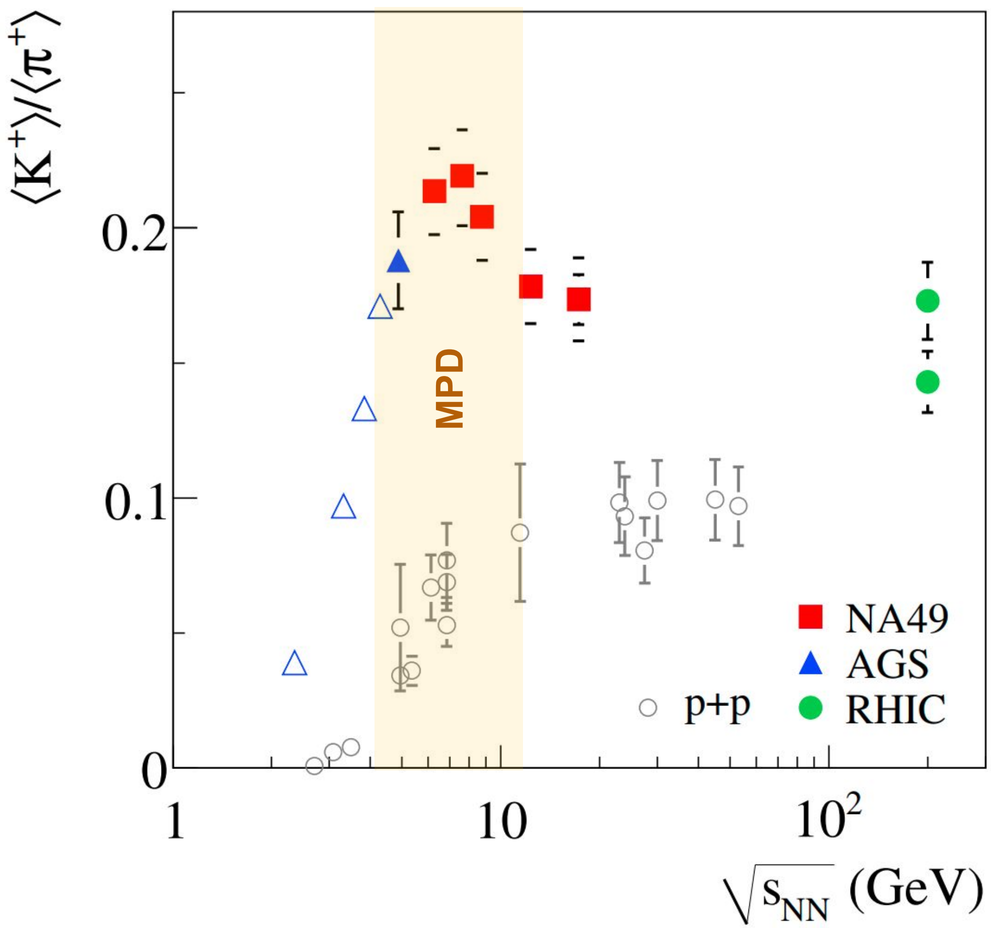
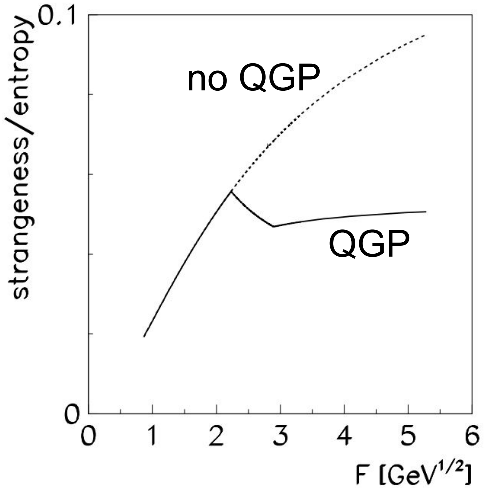
The Horn



- **The horn:** sharp maximum in the ratio of strange particle to pion yields
- **Interpretation in statistical model**: 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 $1.2<|\eta|<3.0$



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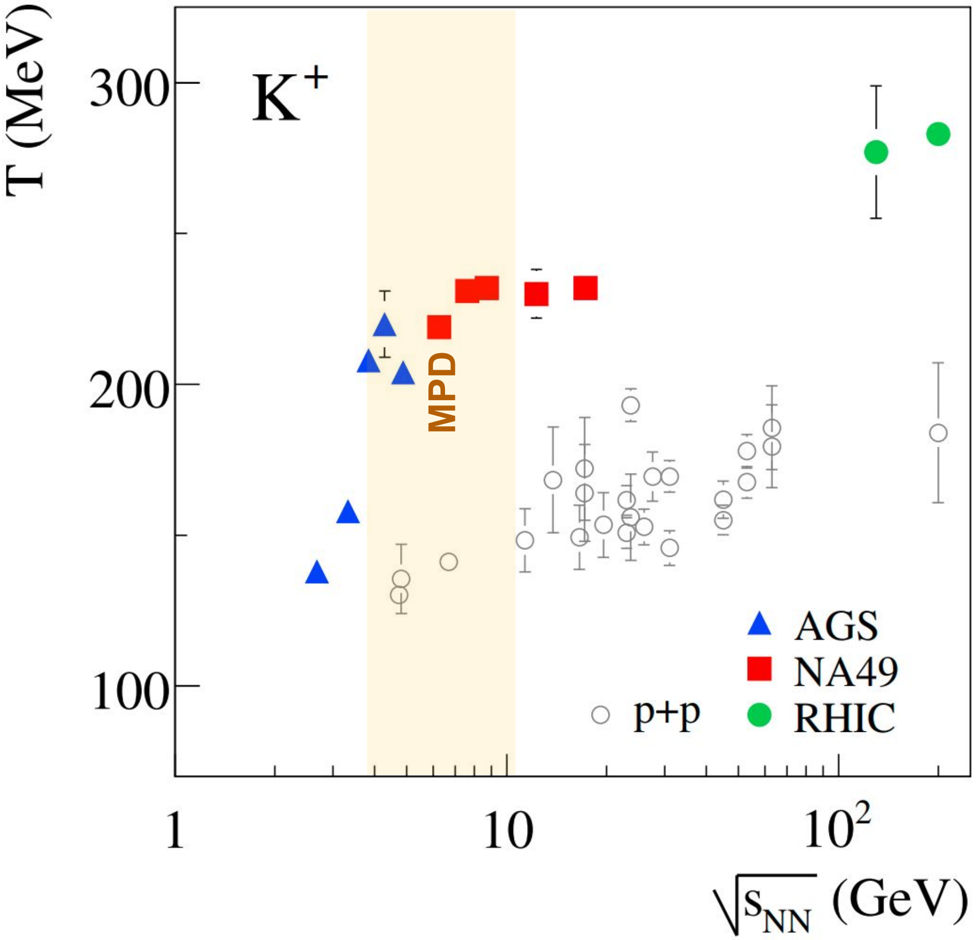
The Step



- **The Step:** flattening of the inverse slope parameter T^* extracted from m_T spectra of various particle species
- Also seen in $<m_T>$ - m vs energy
- Interpretation in statistical model: mixed phase at early stages
- Studied at midrapidity up to now. m_T or p_T spectra for various particle species at forward rapidity would be desirable

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

The Dale

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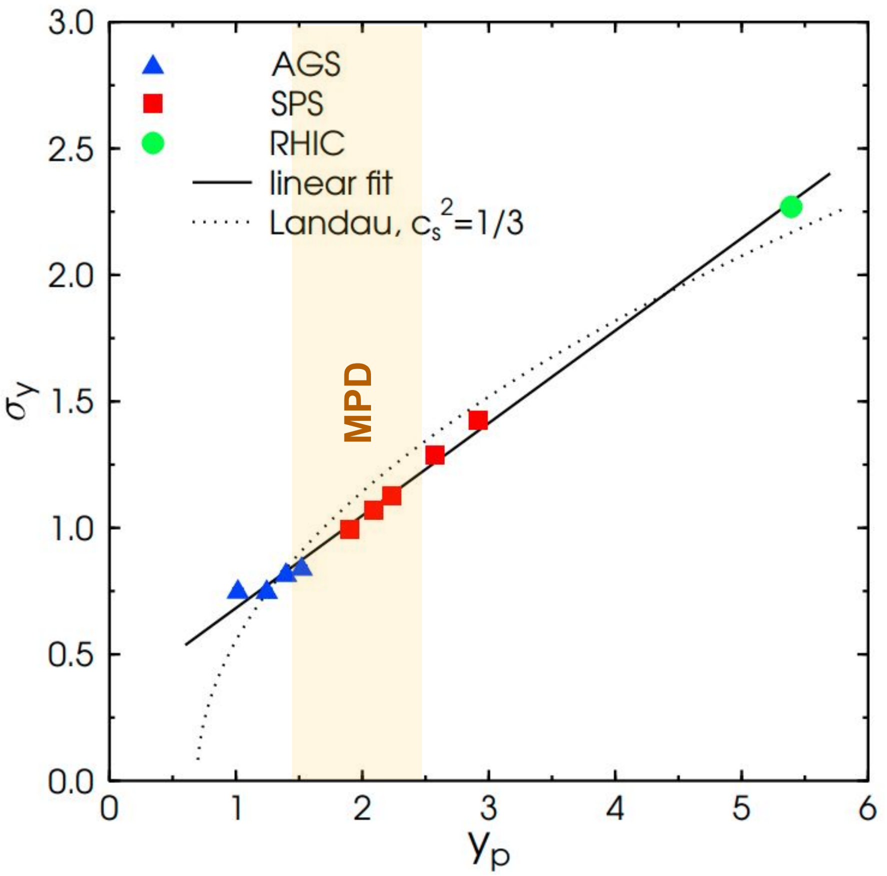


beam rapidity

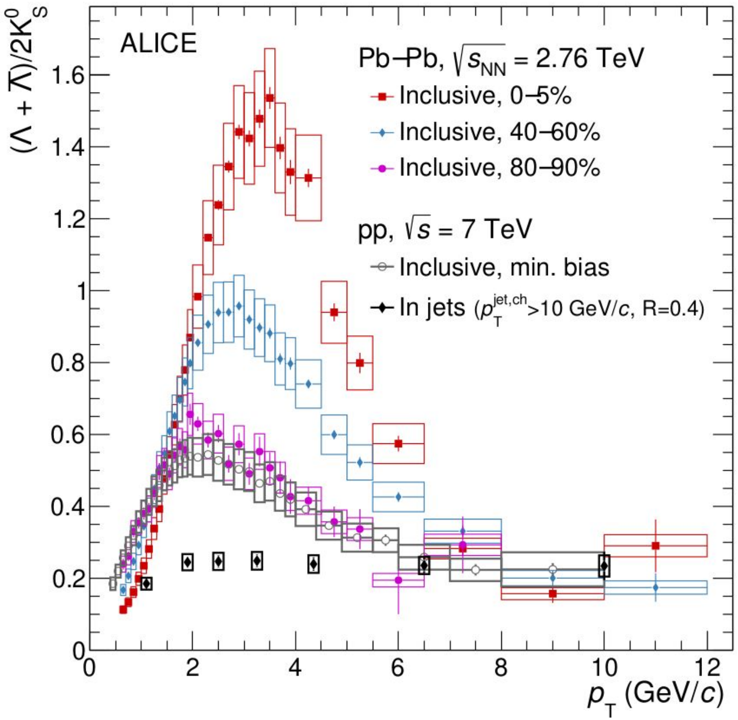
- Rapidity distributions well described by Gaussians in a wide range of energies
- **The Dale:** deviation of rapidity width behaviour from the shape motivated by Landau model (full stopping and thermalization)
- Can be attributed to the softening of EoS due to deconfinement
- Wider rapidity coverage →better determination of the pion rapidity shape

Baryon anomaly

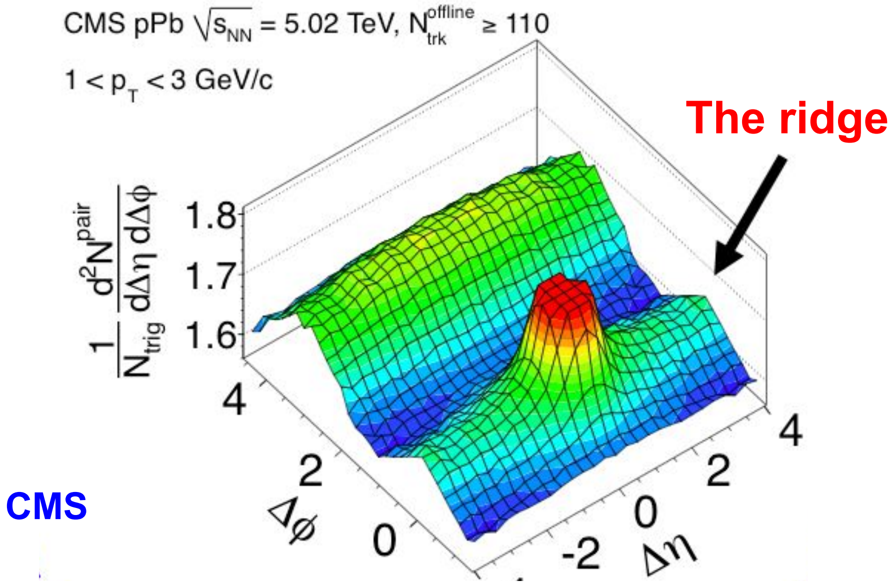
- **Baryon anomaly**: growth of p/π and Λ/K ratios in the p_T range 1-4 GeV
- Tiny yields in this range at low energies → might be difficult to study with MPD at midrapidity
- However: the growth in the p_T range 1-4 GeV is usually explained by coalescence: recombination of constituent quarks into hadrons

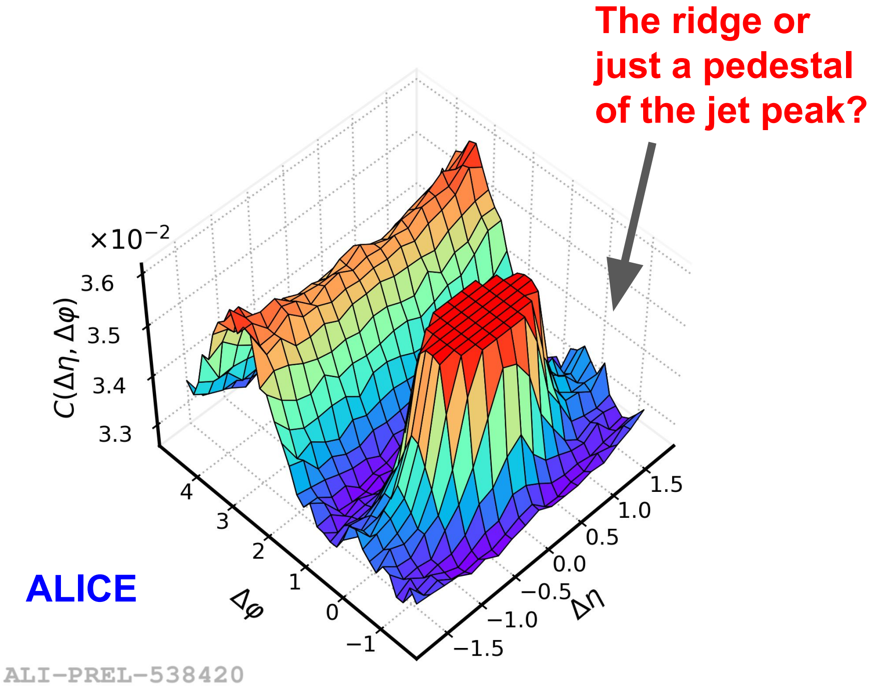
→ full momentum (not p_T) matters

→study at forward rapidity?



Angular correlation studies

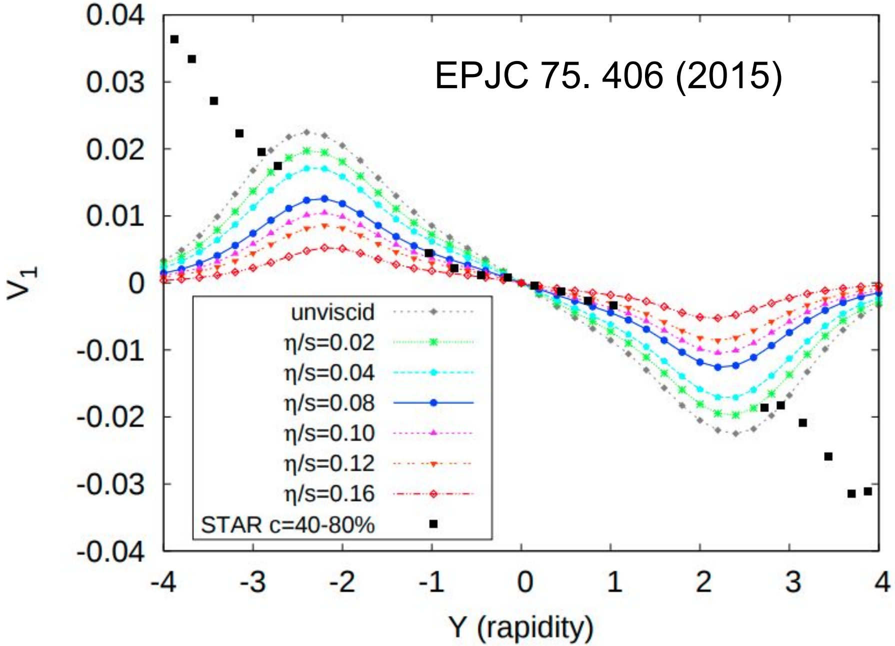




Angular correlation studies strongly profit from extended pseudorapidity coverage:

- 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



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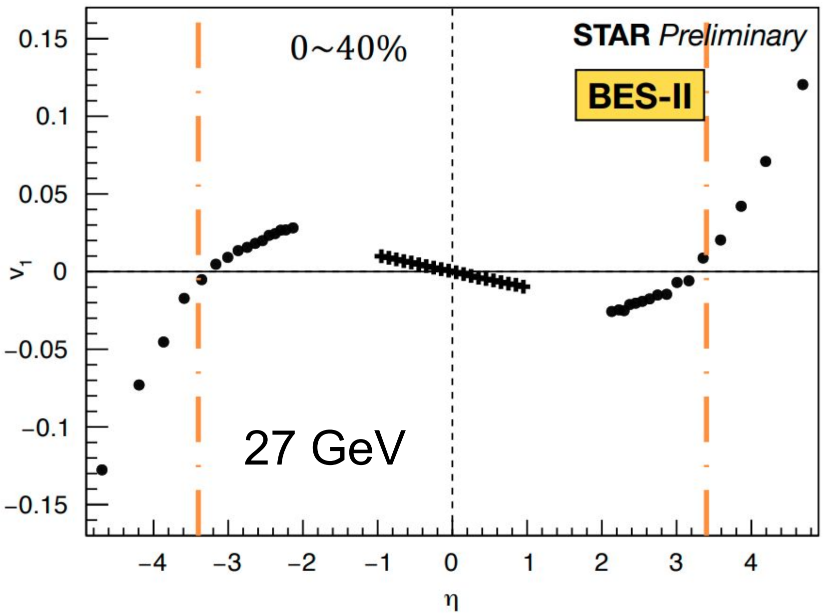
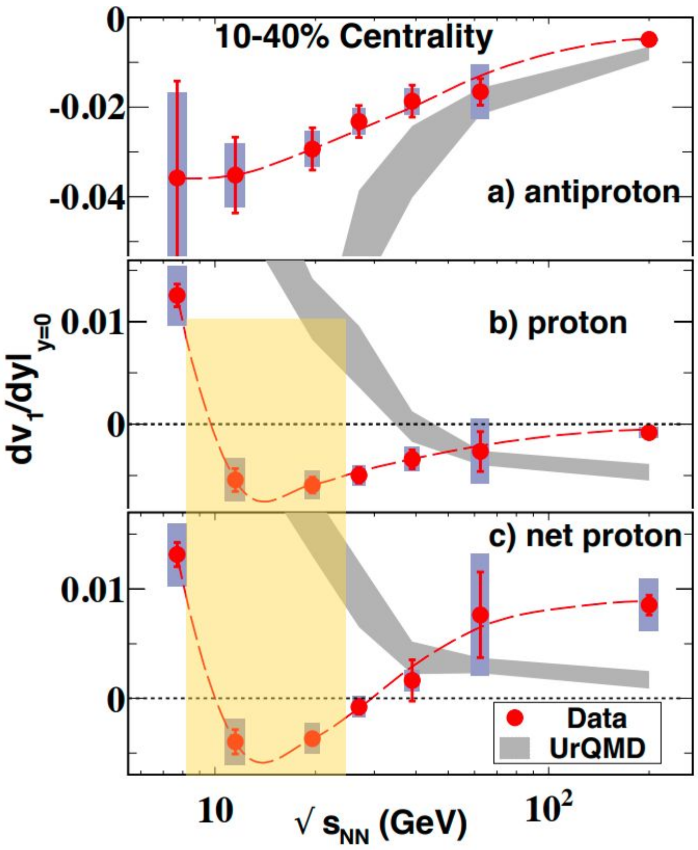


- $v_1(\eta)$ sensitive to the shear viscosity to entropy (η/s) ratio
- $v_1(\eta)$ in both spectator and participant regions may provide insights into the baryon stopping mechanism (see 2211.16408)
- Need wide rapidity coverage!

Directed flow of net protons

STAR BES II



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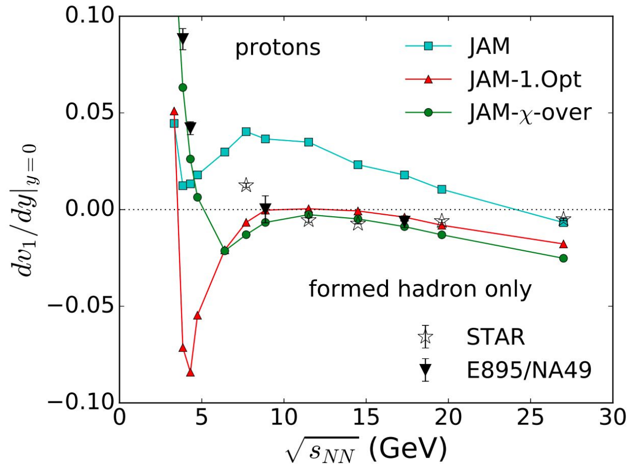
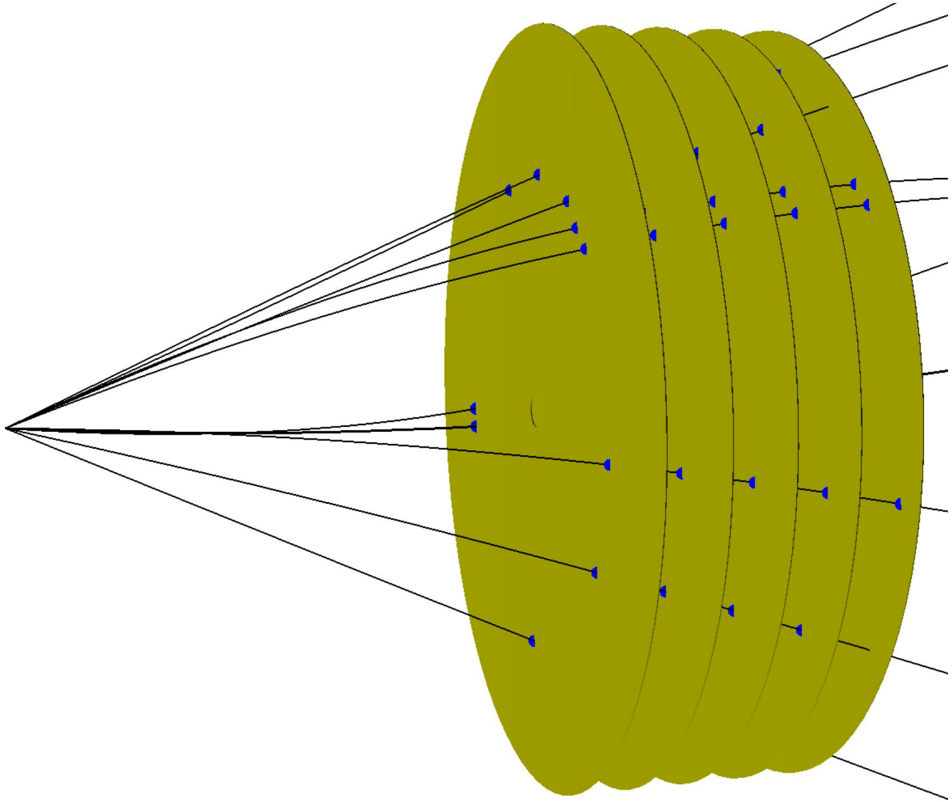


- Model predicts sign change at ~ 5 GeV with 1st order phase transition
- proton and net-proton v_1 change sign around 10-20 GeV
- Need wide rapidity coverage to measure v_1 shape

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

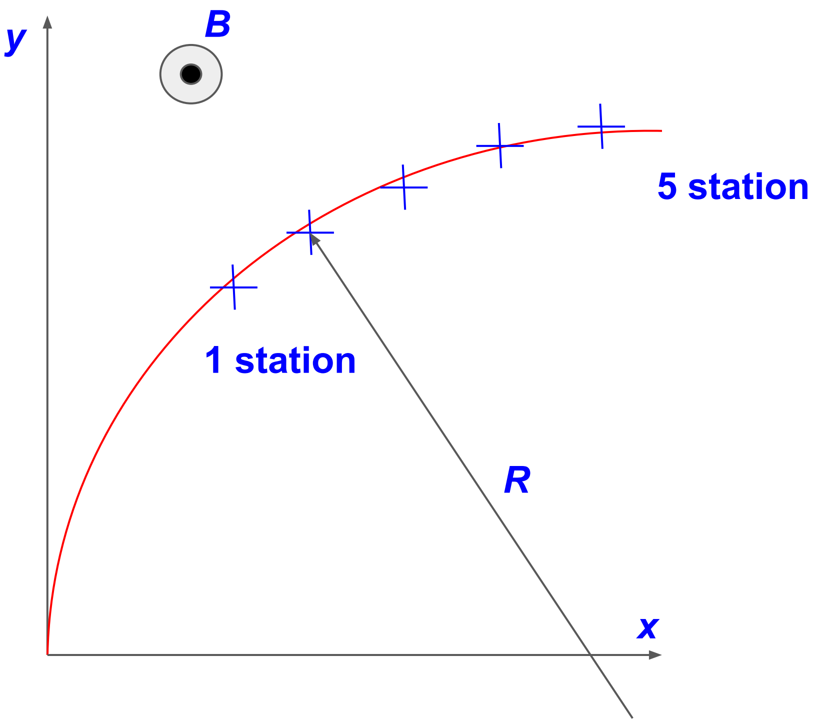
“Ideal” hit producer



Straws not shown to improve visibility

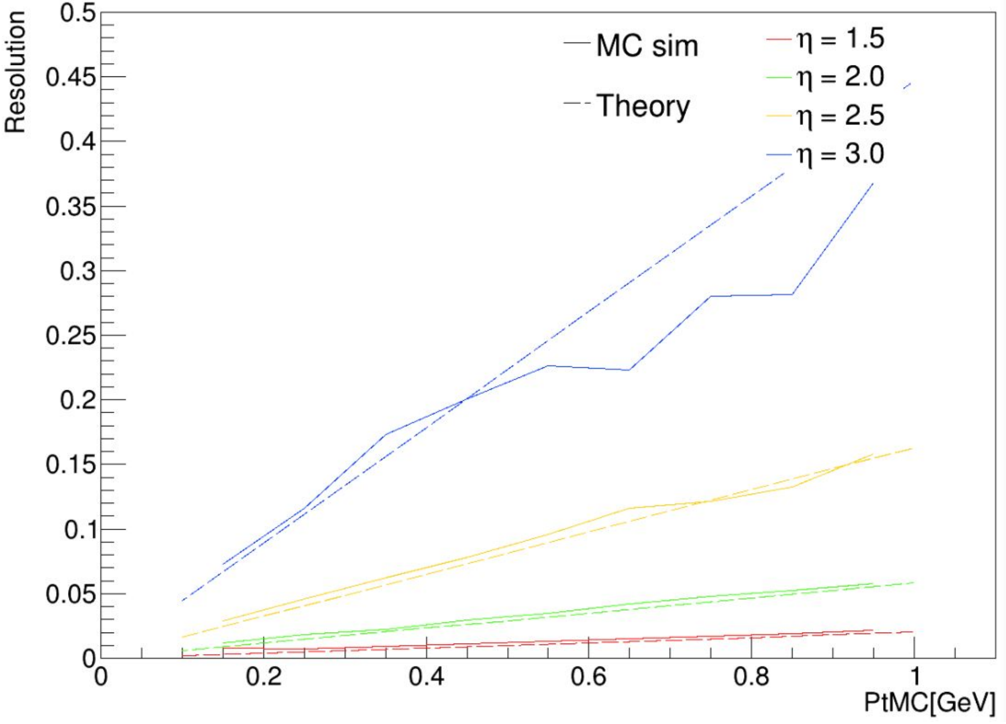
- “Sensitive” layer added in the center of each station to mimic straw tube measurements
- 2D hits produced from each MC point, smeared according to “hit resolution” parameter σ
- Default σ set to 100 μs
- Next: more realistic hit producer with 1D hits per straw and two-fold ambiguity

Trivial tracking algorithm

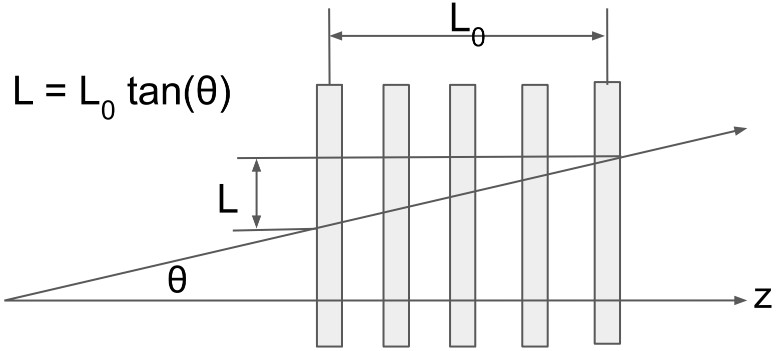


- Collect hits originating from the same MC track
- Fit smeared (x,y) measurements with a circle
- Extract curvature radius R
- Derive reconstructed $p_T = 0.3\ B\ R$
- Compare with generated p_T
- Caveats:
  - constant B only
  - no energy loss correction
  - no accounting for multiple scattering effects
  - TPC track segments not included
- Anyway, good enough for preliminary momentum resolution estimates

Momentum resolution due to hit precision



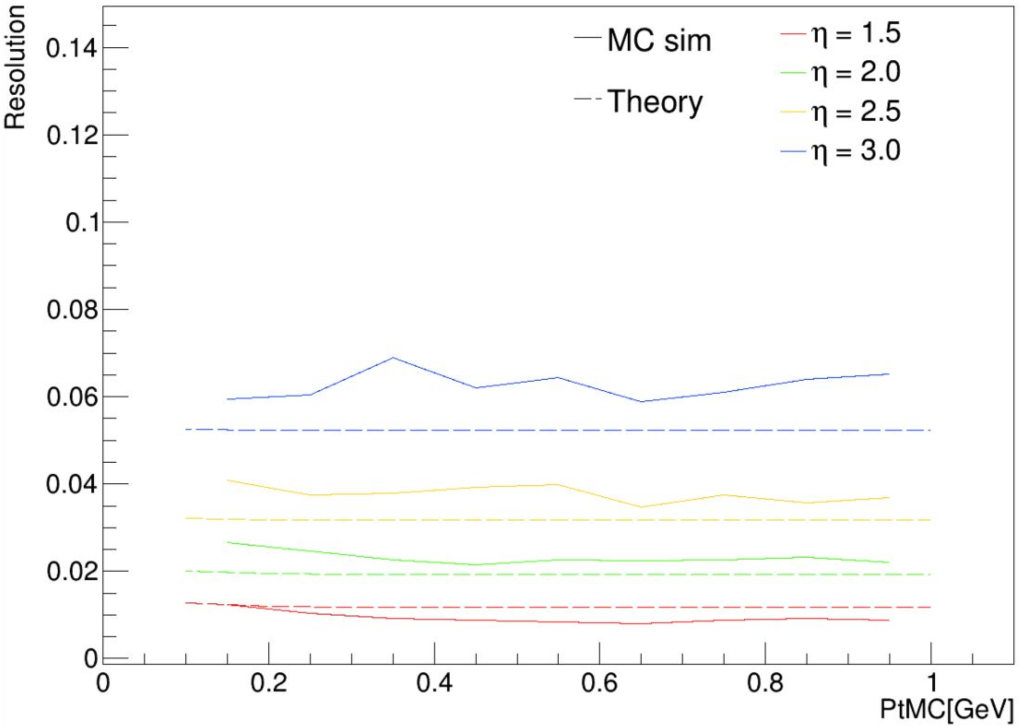
- MC simulations with vacuum-made stations to suppress the effect of multiple scattering
- And applying $\sigma = 100$ um hit smearing
- Linear increase of momentum resolution with p_T
- Momentum resolution proportional to σ
- Inverse square dependence on L_0 (the distance between first and last stations)
  - Extend the tracker as much as possible



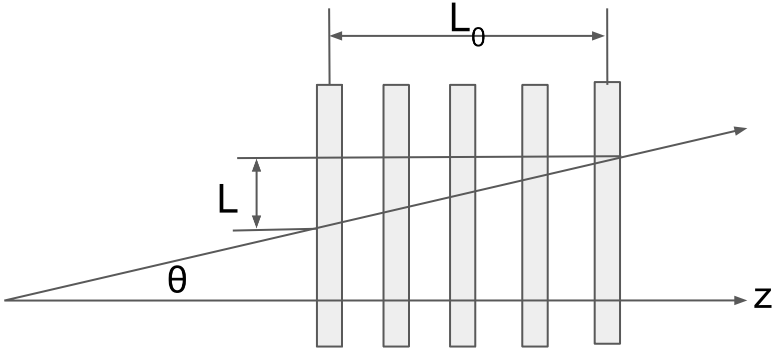
Formulas adopted from Drasal, Riegler, *NIM A* 910 (2018) 127

Momentum resolution due to multiple scattering

$$\frac{\Delta p_T}{p_T}\Big|m.s. = \frac{N}{\sqrt{(N+1)(N-1)}}\frac{0.0136GeV/c}{0.3\beta B_0 L}\sqrt{\frac{d_{tot}}{X_0\cos\theta}}(1+0.038\ln\frac{d}{X_0\cos\theta})$$



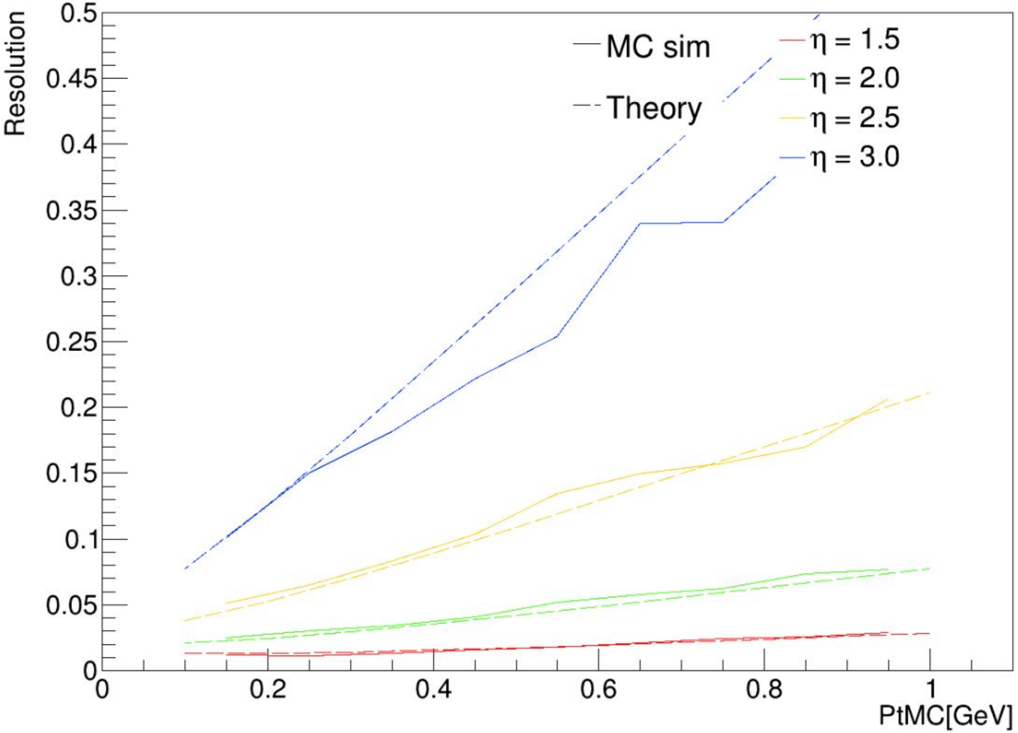
- MC simulations with ideal hits and realistic material budget
- Momentum resolution practically constant at high p_T (at $\beta\sim c$)
- Momentum resolution proportional to sqrt of effective radiation length
- Degradation at large η due to inverse dependence on $L = L_0 \tan(\theta)$



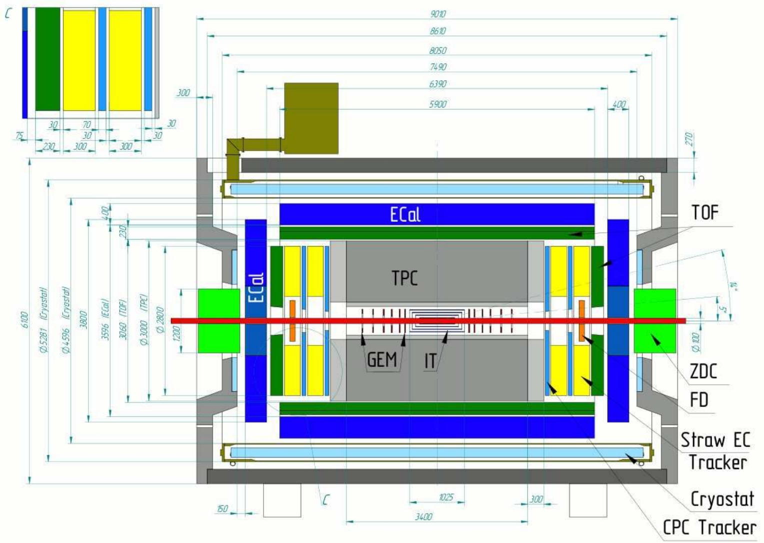
Formulas adopted from Drasal, Riegler, *NIM A* 910 (2018) 127

Momentum resolution

$$Resolution = \sqrt{\left(\frac{\triangle p_T}{p_T}|res.\right)^2 + \left(\frac{\triangle p_T}{p_T}|m.s.\right)^2}$$

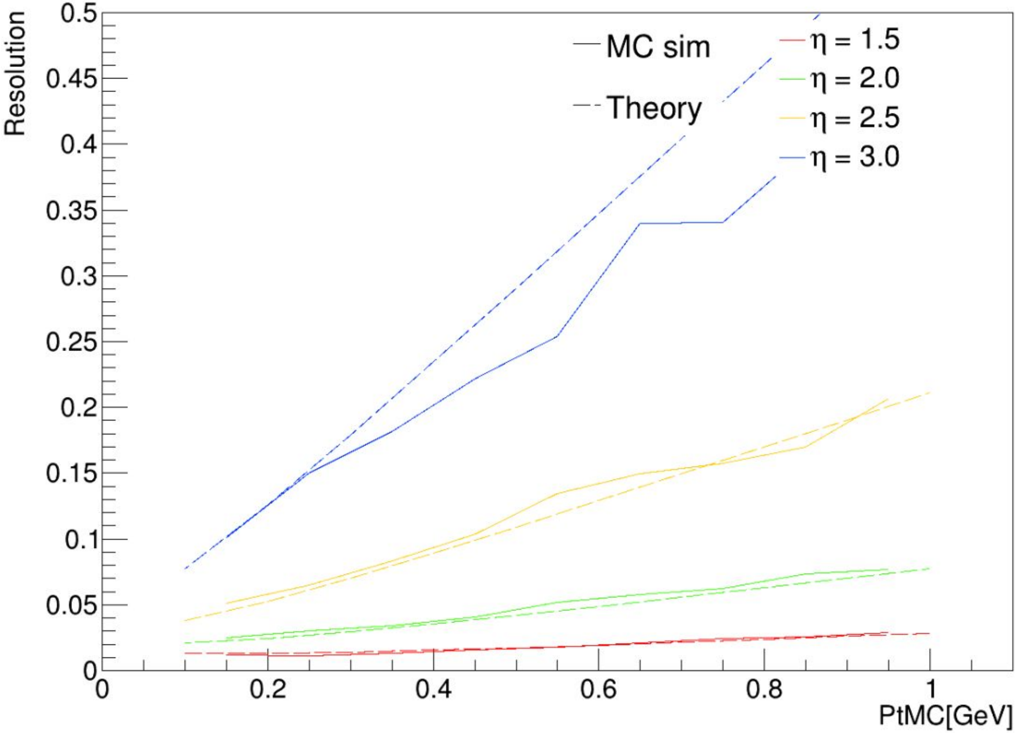


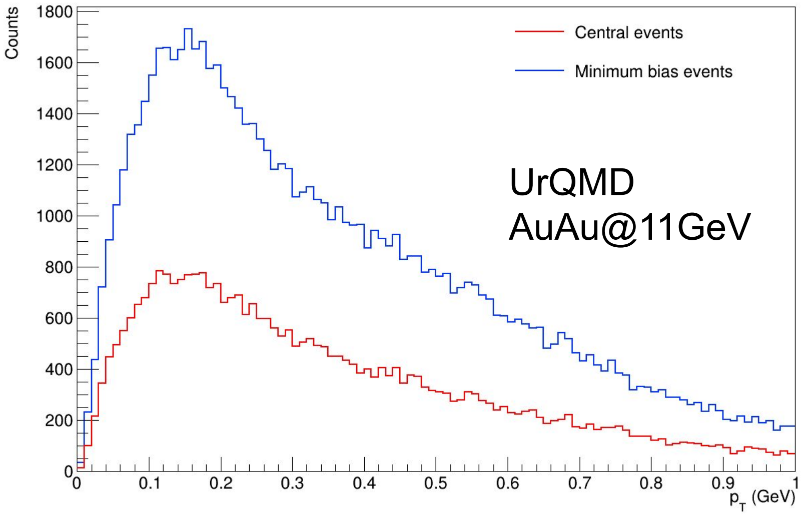
- Good agreement between theory and MC
- Hit resolution is the dominant effect
- η ~ 3 is hardly feasible
- Can we reduce hit resolution below 100 μs?
- Increase effective L?
  Silicon end-cap tracker?



Good news: most of the tracks have p_T ~ 100 MeV

$$Resolution = \sqrt{(\frac{\triangle p_T}{p_T}|res.)^2+(\frac{\triangle p_T}{p_T}|m.s.)^2}$$





Need to study the impact of poor resolution at high p_T on physics observables