# CHARGED PARTICLE PSEUDORAPIDITY DISTRIBUTIONS MEASURED WITH THE STAR EPD

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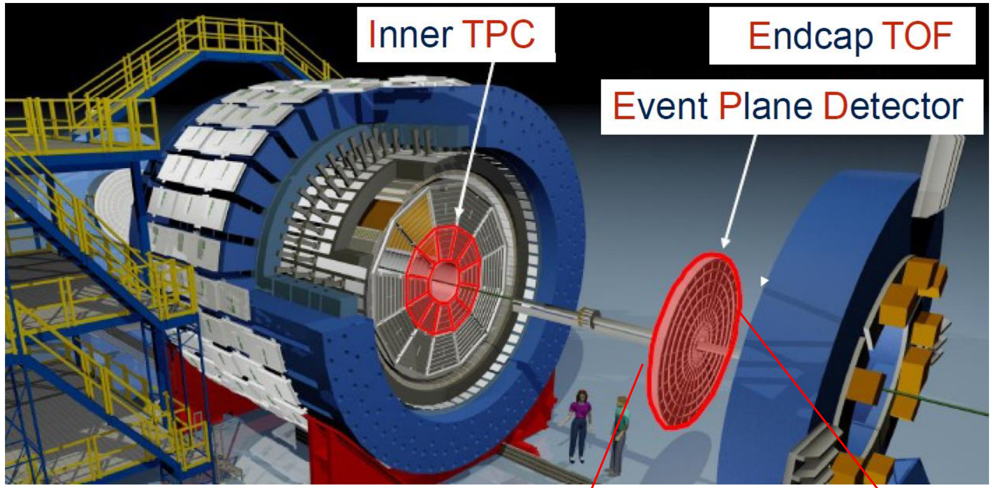
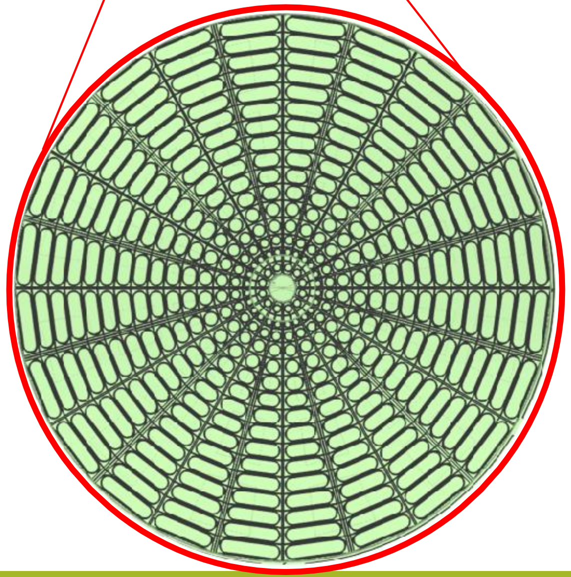
STAR

# STAR upgrades for BES-II

- STAR upgrades:
  - Fixed target program:
    down to $\sqrt{s_{NN}} \approx 3$ GeV, up to $\mu_B \approx 700$ MeV
  - innerTPC: better dE/dx (PID) and momentum resolution
  - Endcap TOF: extended forward PID
  - Event Plane Detector: better triggering, Event Plane resolution and centrality
  - LEReC: electron cooling for low energy RHIC running

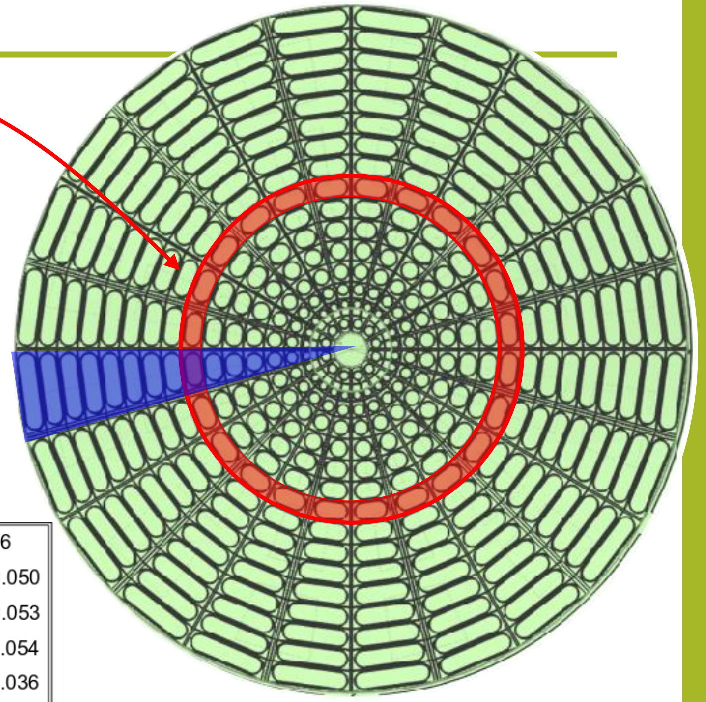


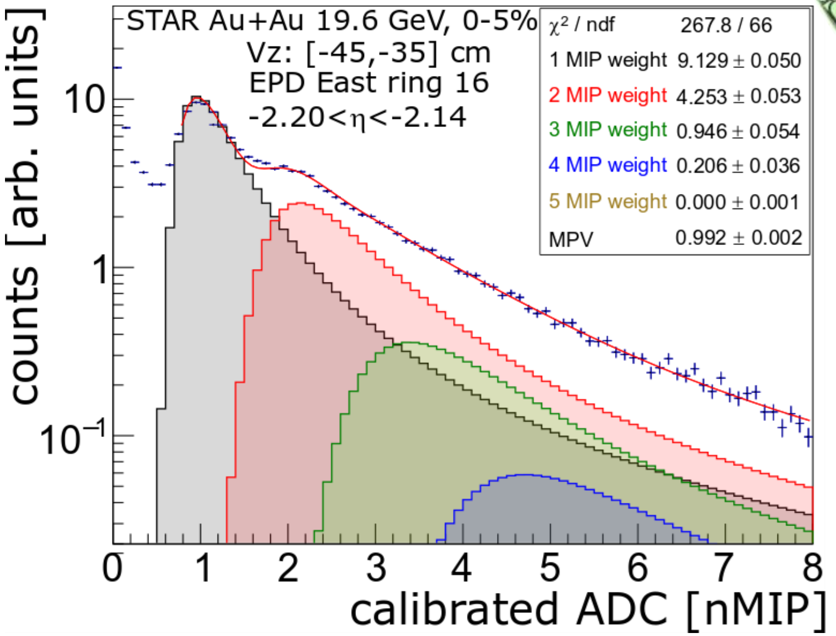
- EPD motivations:
  - Independent centrality determination for fluctuation measurements
  - Improved Event Plane resolution for flow measurements
  - Trigger in high luminosity environment (BES-II)

# The STAR Event Plane Detector

- Much finer granularity compared to BBC
  - BBC: 36 tiles (only 18 inner ones used) ⇒ EPD: 372 tiles
  - Also larger acceptance: [3.3,5.0] ⇒ [2.1,5.1]
  - 16 radial segments (rings)
  - 24 azimuthal segments (sectors)

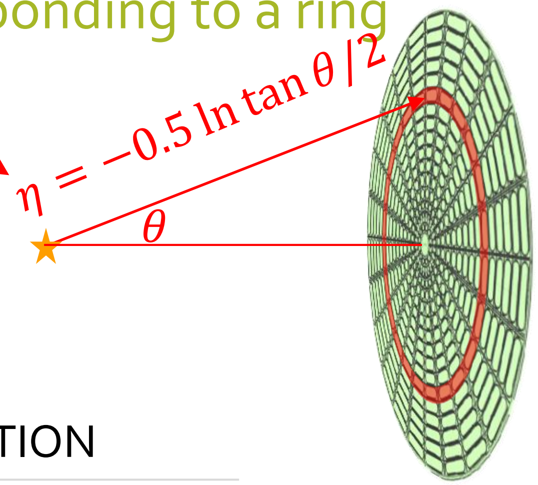


- Radial segmentation need driven by flow, vertex, trigger
- Azimuthal segmentation driven by higher-order flow harmonics
- Each tile registering hits, mostly MIPs
  - Landau distribution of a single hit
  - Convolution for multiple hits
  - Poisson distribution of MIP weights

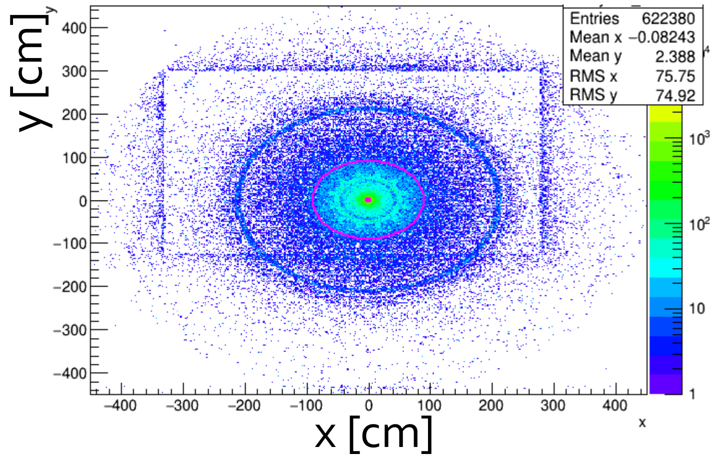


# How (not) to measure $dN_{ch}/d\eta$ with the EPD

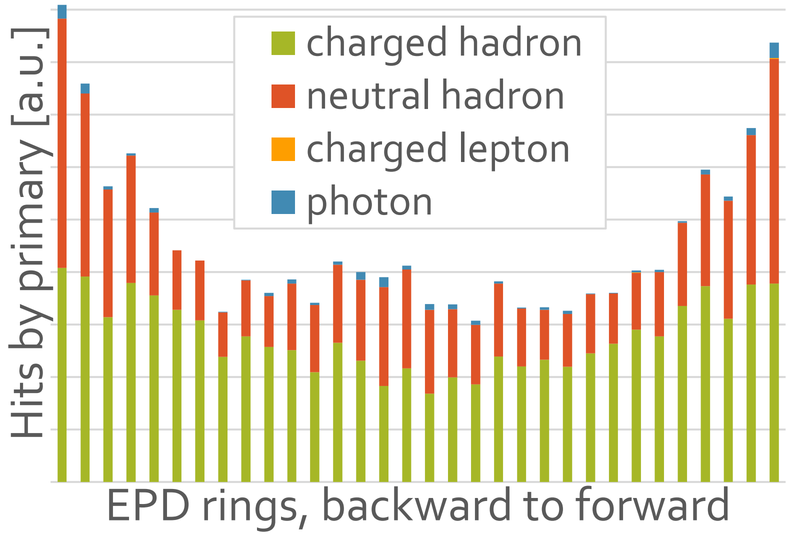
- We can calculate $dN_{ch}/d\eta$ with raw EPD hit numbers, based on $\eta$ corresponding to a ring
- This does not take into account scattering and decays
  - Charged particles scatter in detector material, creating secondaries
    - Secondaries have large contribution to $dN_{ch}/d\eta$
  - Neutral particles contribute through decays (e.g. $\Lambda \to p + \pi$) and secondaries




HIJING+GEANT SIMULATION

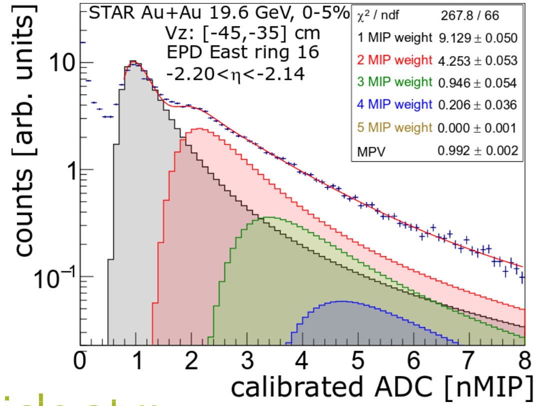



HIJING SIMULATION



# Measuring $dN/d\eta$ with the EPD

- EPD measures signal (ADC) → Convolution of several Landau distributions




- With "multiple Landau" fits, one can extract $dN/dn_{\mathrm{MIP}}$ for each ring
- Number of hits in a given ring: $N(i_{\mathrm{Ring}})$
- Given the underlying $dN/d\eta$, $N(i_{\mathrm{Ring}})$ can be calculated as

$$N(i_{\mathrm{Ring}}) = \int R(\eta, i_{\mathrm{Ring}}) \frac{dN}{d\eta} d\eta$$

- Here $R$ is the response matrix: no. of hits in given ring originating from primary particle at $\eta$
- Calculate $R$ via simulations, then determine $dN/d\eta$ via **unfolding**
  - Bayesian iterative unfolding, G. D'Agostini, Nucl. Instr. Meth. A362 (1995) 487

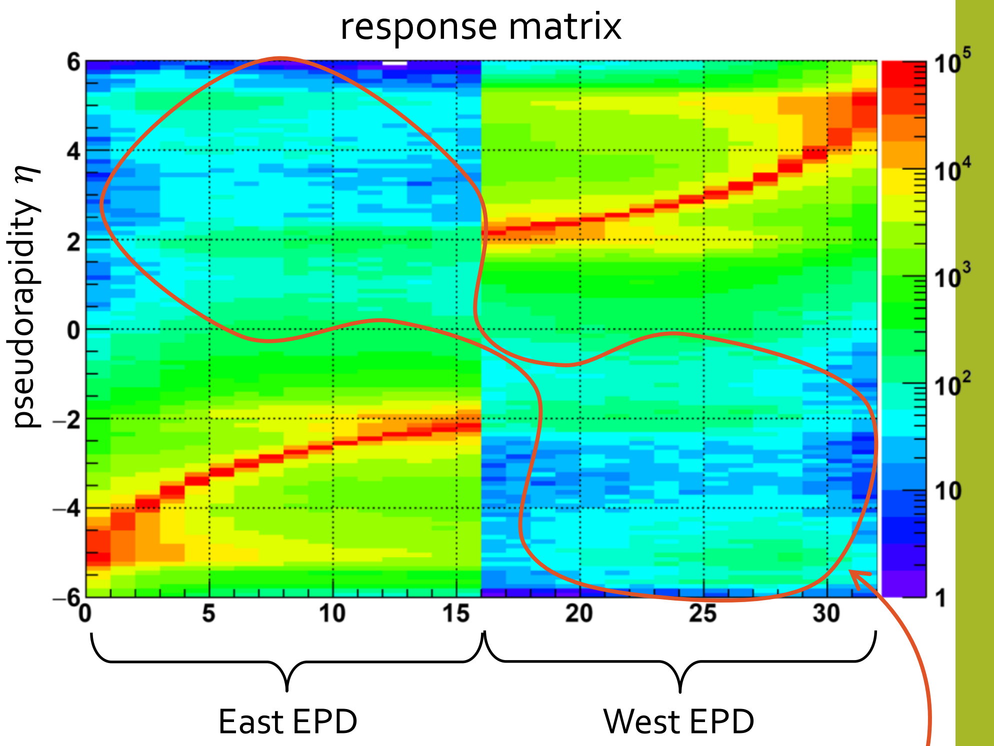
- Three methods for extracting $dN_{ch}/d\eta$

1. Correcting the unfolded $dN/d\eta$ using the charged particle fraction $N_{ch}(\eta)/N_{tot}(\eta)$ from HIJING
2. Correcting raw EPD data via $N_{ch}(i_{ring})/N_{tot}(i_{ring})$; unfolding "corrected" EPD distribution
3. Utilizing RooUnfold's Fakes() method " (neutrals ⇔ "fake" hits)

# The EPD response matrix

- Use iterative unfolding, based on G. D'Agostini, Nucl. Instr. Meth. A362 (1995) 487
- Implemented in RooUnfold, response matrix to be calculated as:

```
for(PrimaryTracks)
{
  if(no EPD hits from that Primary Track)
  {
    R->Miss(TrackEta); //This track "missed" the EPD
  }
  else
  {
    for(EPD hits of that Primary Track)
    {
      R->Fill(EPDRingNumber,TrackEta);
    }
  }
}
```

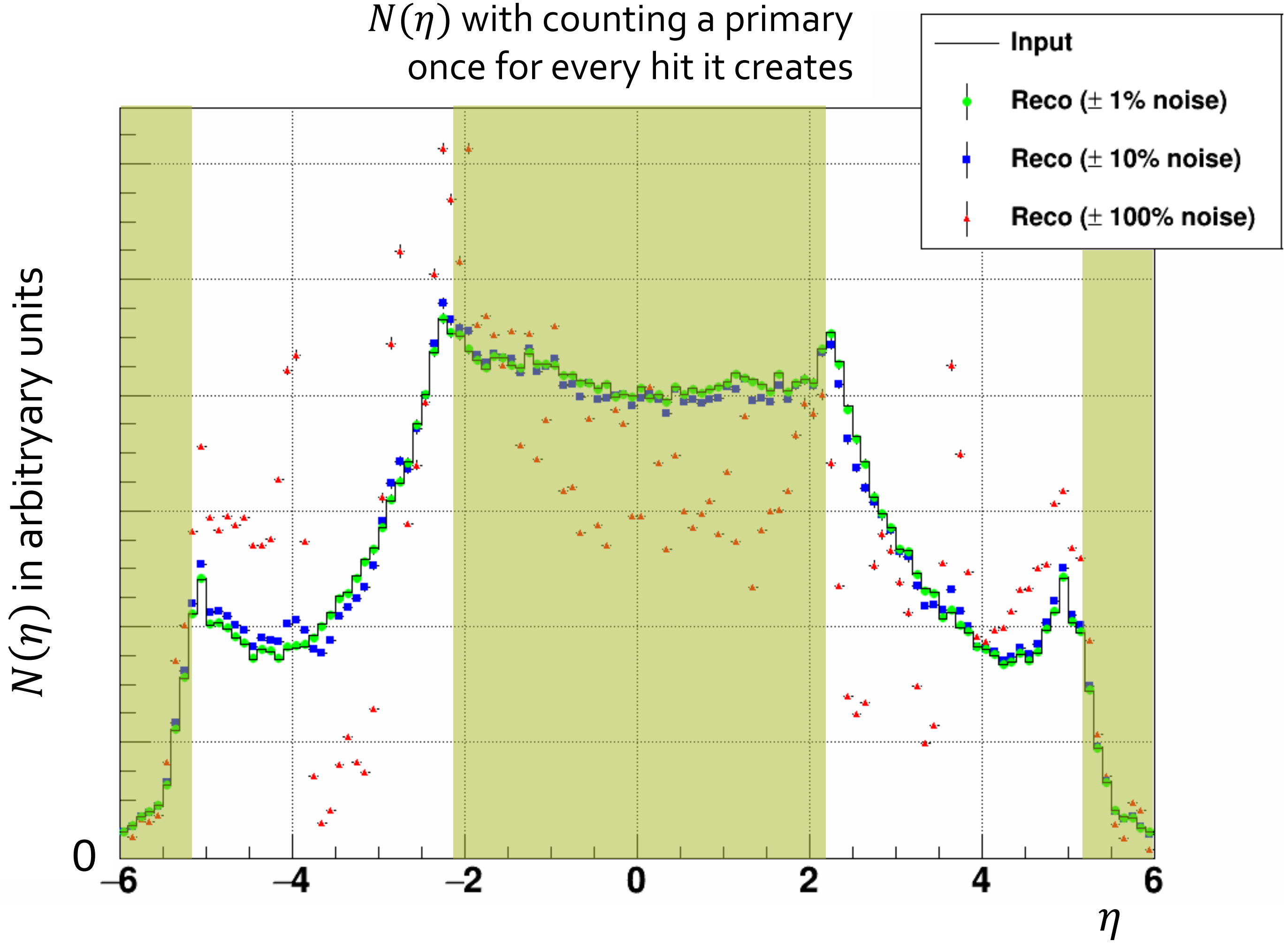



- In the simulation, we need:
  - list of **primary tracks**
  - list of **EPD hits**, linked to the primary track causing them
- All possible in HIJING+GEANT simulation
- Note: no (light) ion fragments in HIJING; note PHOBOS paper Phys.Rev.C 94 (2016) 024903
- Note 2: many primaries create hit in the opposite side EPD via secondaries!

# Does the unfolding work?

- If unfolding on training sample: returns input perfectly
- Adding some noise: imperfect but still good
- Why the peaks near $\eta = 2$ and 5?
  - One unfolded track for each individual EPD hit
  - One track can cause multiple hits
  - Need to correct for this
  - Correction calculated via simulation
- How can it work near $\eta = 0$?
  - It reconstructs $dN/d\eta$ of input!

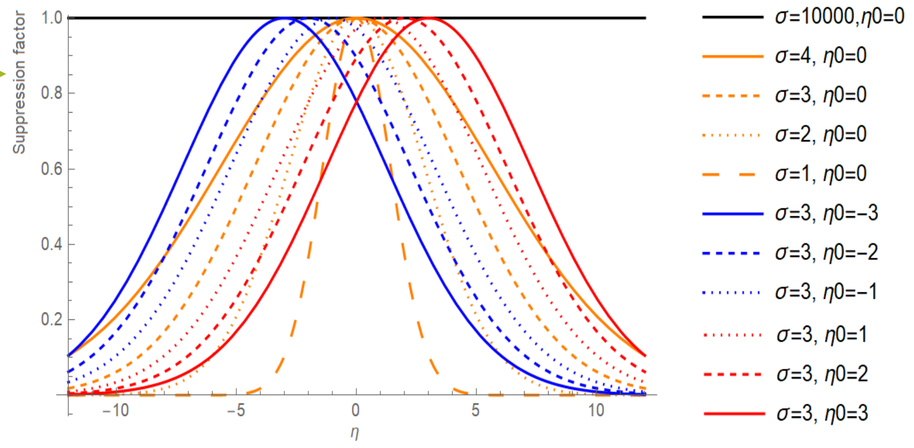
$N(\eta)$ with counting a primary once for every hit it creates



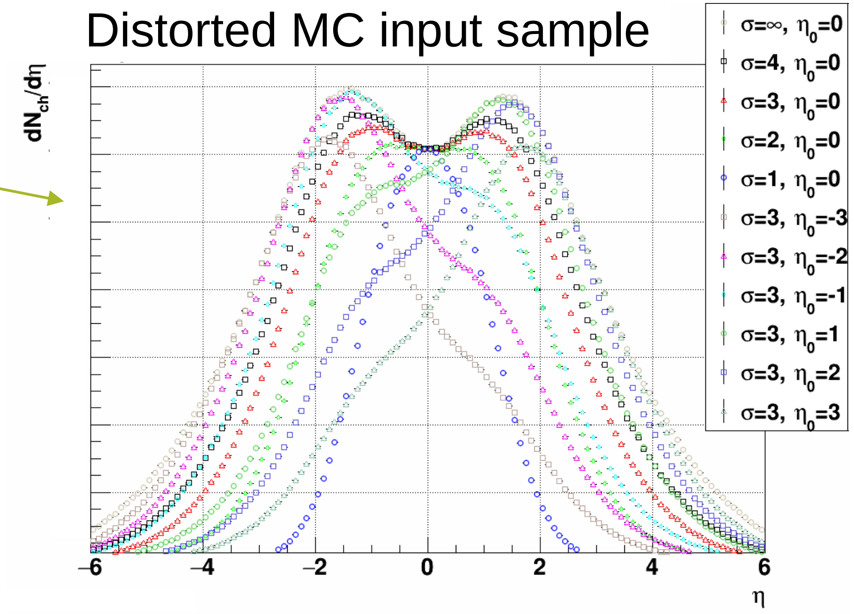
# Dependence on input distribution

- Distort simulated sample with suppression factor:

```
for(primary MC tracks with nonzero EPD hits)
{
  if(random_selection_based_on_Gaussian_distortion) continue;
  float eta = mctrack->Eta();
  MCtruth->Fill(eta);
  if(no_EPD_hits_for_this_primary) response->Miss(eta);
  for(EPD hits of this primary track)
  {
    int ring_bin = number between 0...31 (15&16 are the outermost rings of the two sides)
    response->Fill(ring_bin,eta);
  }
}
```



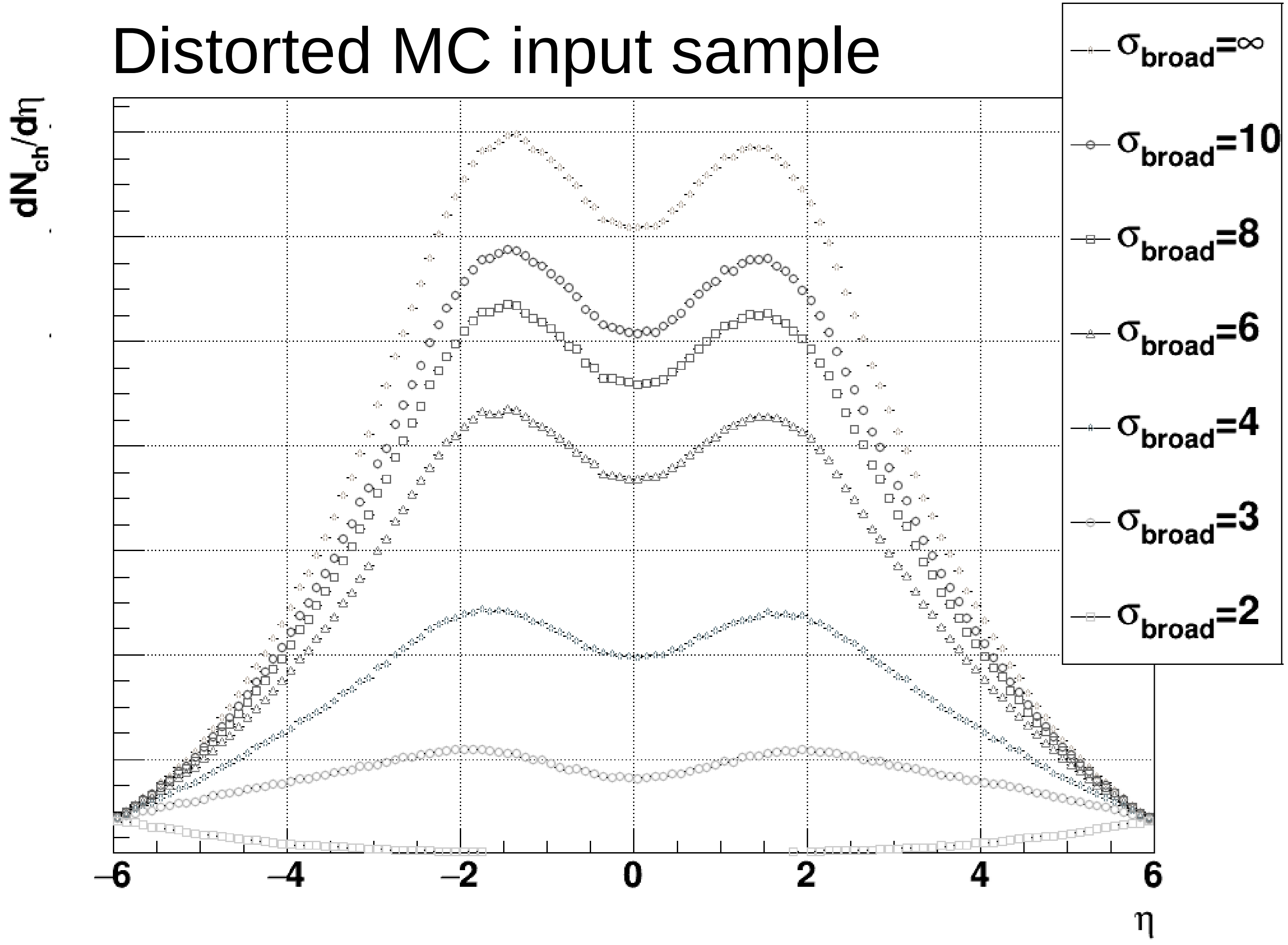

- Measure response with distorted sample




- Analyzed all combinations:
  - Unfold i-th sample with j-th distortion
  - If i=j: perfect unfolding
  - If $\sigma \approx 1$ or smaller: bad unfolding
  - Otherwise: ~10% variation in the EPD $\eta$ region

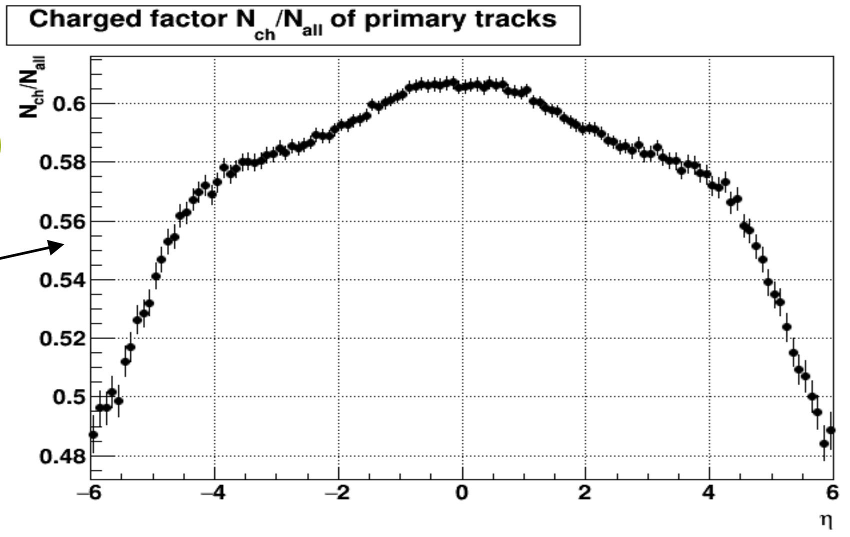
# How about broader $dN/d\eta$ than in MC?

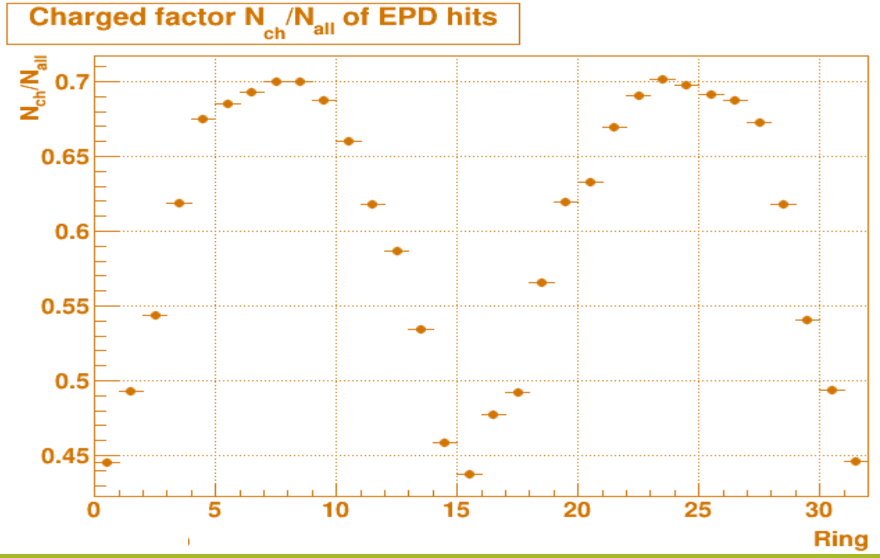
- Previous modifications only make $dN/d\eta$ narrower
- How to broaden it?
- Reject tracks via factor of $\exp\left[\frac{\eta^2-\eta_{\max}}{2\sigma_{\text{broad}}}\right]$
  - Zero suppression for $|\eta| > \eta_{\max}$
  - Set $\eta_{\max} = 6$
  - Works up to $\sigma_{\text{broad}} \approx 3$
- Unfold data with these
- Will decrease midrapidity value



# Measuring $dN_{ch}/d\eta$

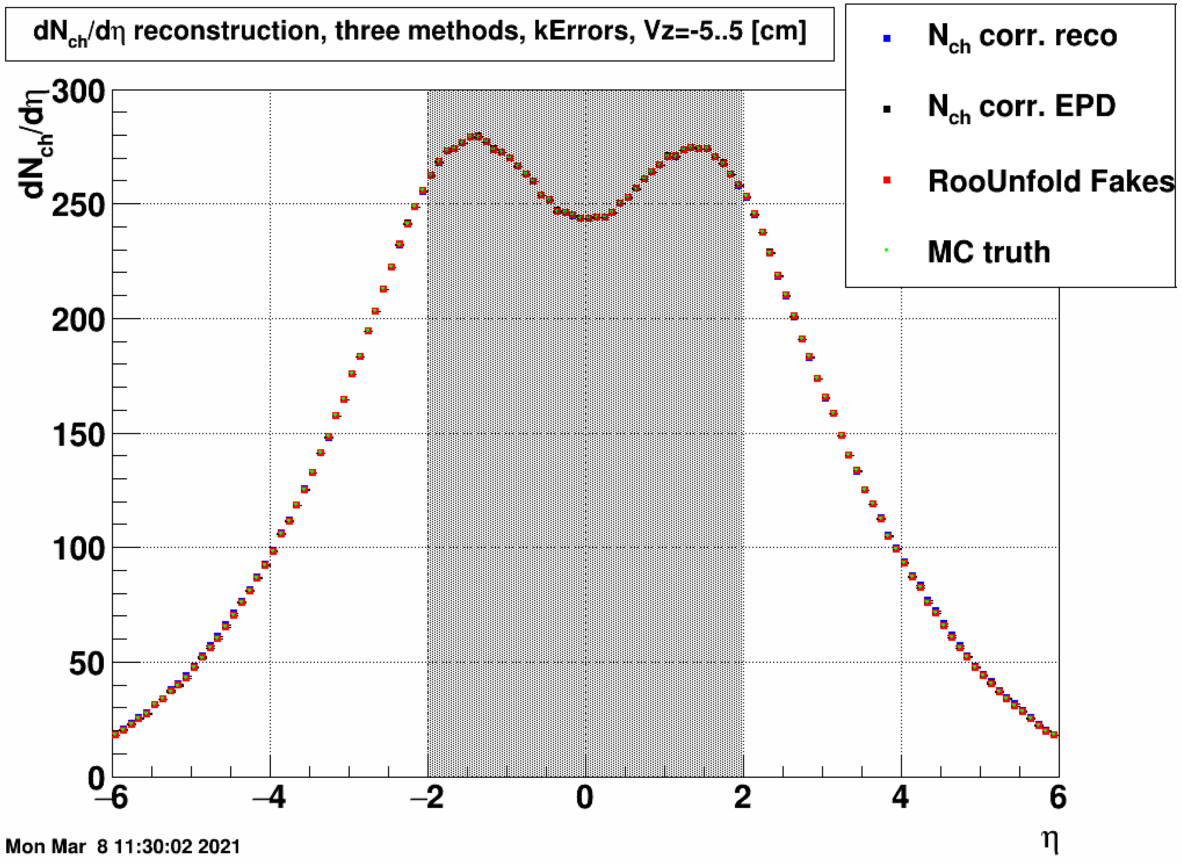
- From simulations: charged particle fraction
  - For primary tracks and for EPD hits (based on primary cause)
- Applied 3 different methods
  1. Unfolding $dN/d\eta$; correcting via $N_{\rm ch}(\eta)/N_{\rm tot}(\eta)$
  2. Correcting via $N_{\rm ch}(i_{\rm ring})/N_{\rm tot}(i_{\rm ring})$, unfolding "corrected" EPD distribution
  3. Use RooUnfold's "Fakes" (neutrals ⇔ "fake" hits)
- "Fakes" slightly different from the others
  - Also least reliable in terms of dependence on input $dN/d\eta$
  - Reason of this unclear yet
- Closure test works for all: MC input recovered when unfolding simulated EPD data
- Difference of methods: incorporated in systematics

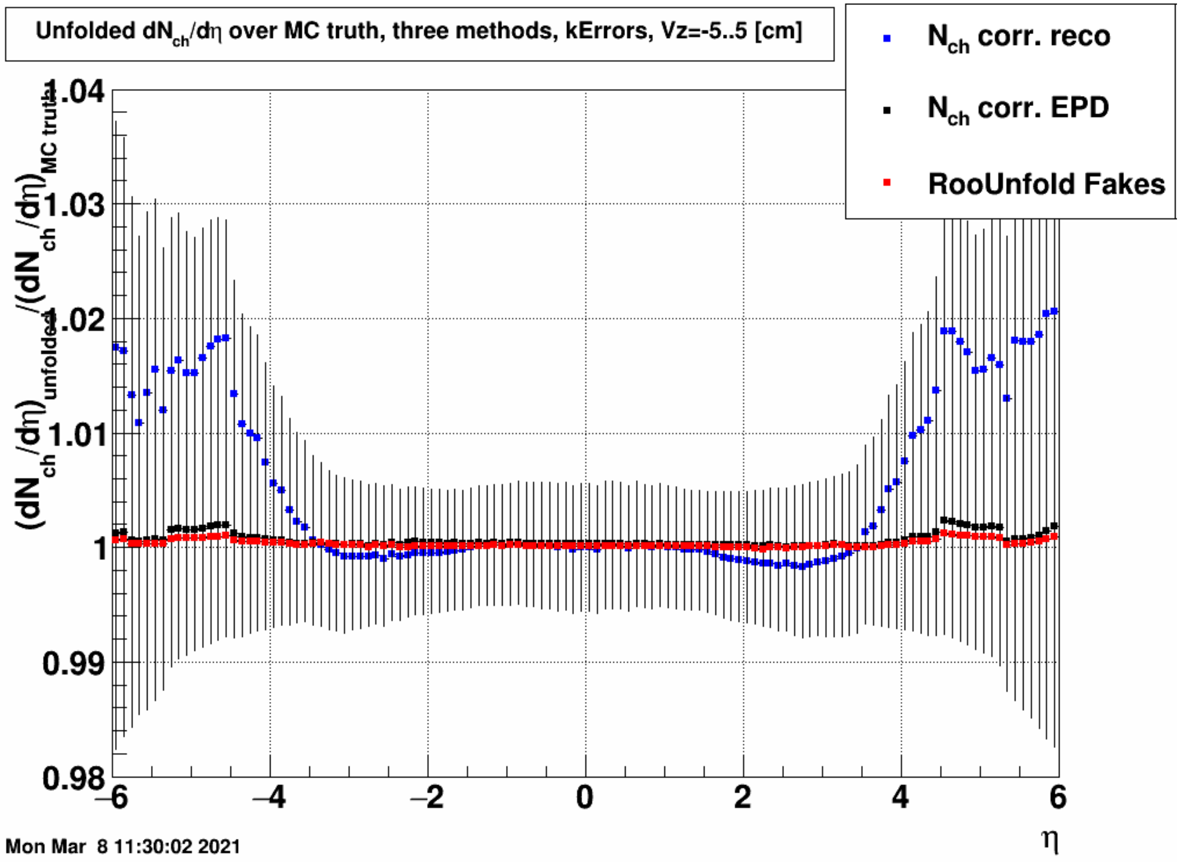


# Closure test for the three methods

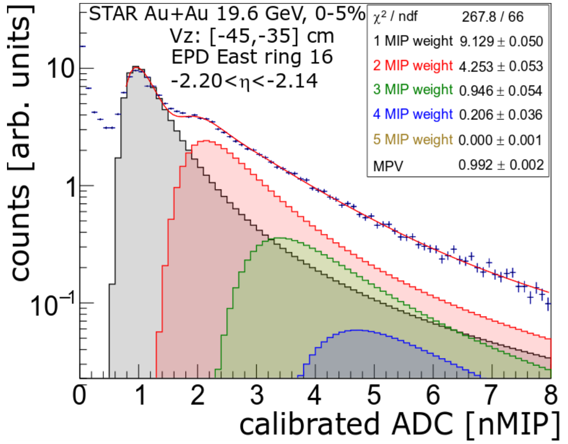
- Tested the three methods on an MC sample: which reproduces the „true" $dN_{ch}/d\eta$? All!
- 1% deviation at the edges for the 1st method, <0.1% deviation for the others

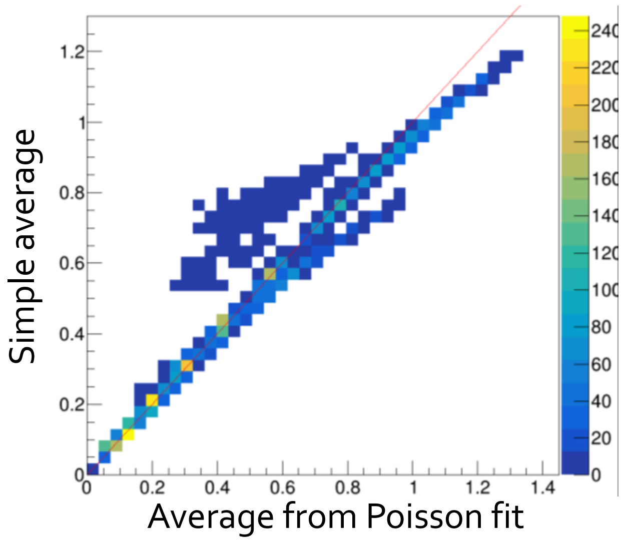


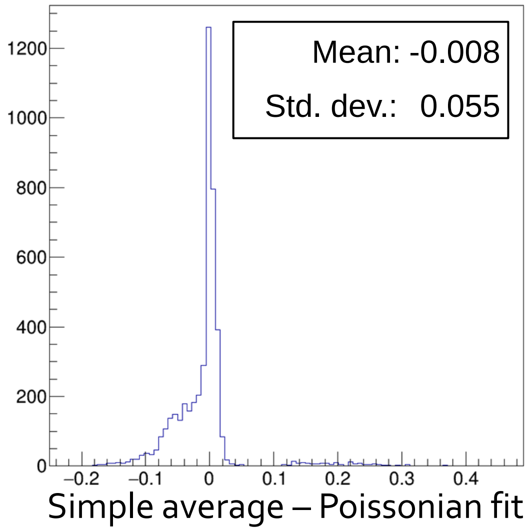



# EPD related uncertainties

- EPD nMIP determined based on a convoluted Landau-fit
  - Amplitude of $n$-th component: $A_n$
  - The fit needs a cutoff, both in ADC and in $n$
- Total nMIP: $\sum n \cdot A_n$, sum on fitted Landau curves ($n = 1 \dots 5$)
- How about fitting $A_n$ versus $n$ with a Poissonian?
  - Difference compared to simple sum is small
  - Unfolding is a linear operation
  - Can only have small effect on $dN/d\eta$
- Note furthermore: EPD+SiPM+QT chain fully efficient
  - Except "dead areas" from glue and gaps, which are correctly handled in the simulation



# Systematic investigations

- Systematic checks in the unfolding
  - Determination of the longitudinal vertex position (±5 cm shift) & centrality (±5% change)
  - Comparison of several vertex intervals (+40 cm and -40 cm from geometric center)
  - Unfolding method (difference of the three methods of obtaining $dN_{ch}/d\eta$)
  - Charged/neutral ratio change in the training sample (±15%)
  - Change of transverse momentum slope in training sample
  - Change in $dN/d\eta$ of training sample
    - Broadening to $\Delta\eta$=10, tightening to $\Delta\eta$=2
    - Shifting by ±3 units of rapidity

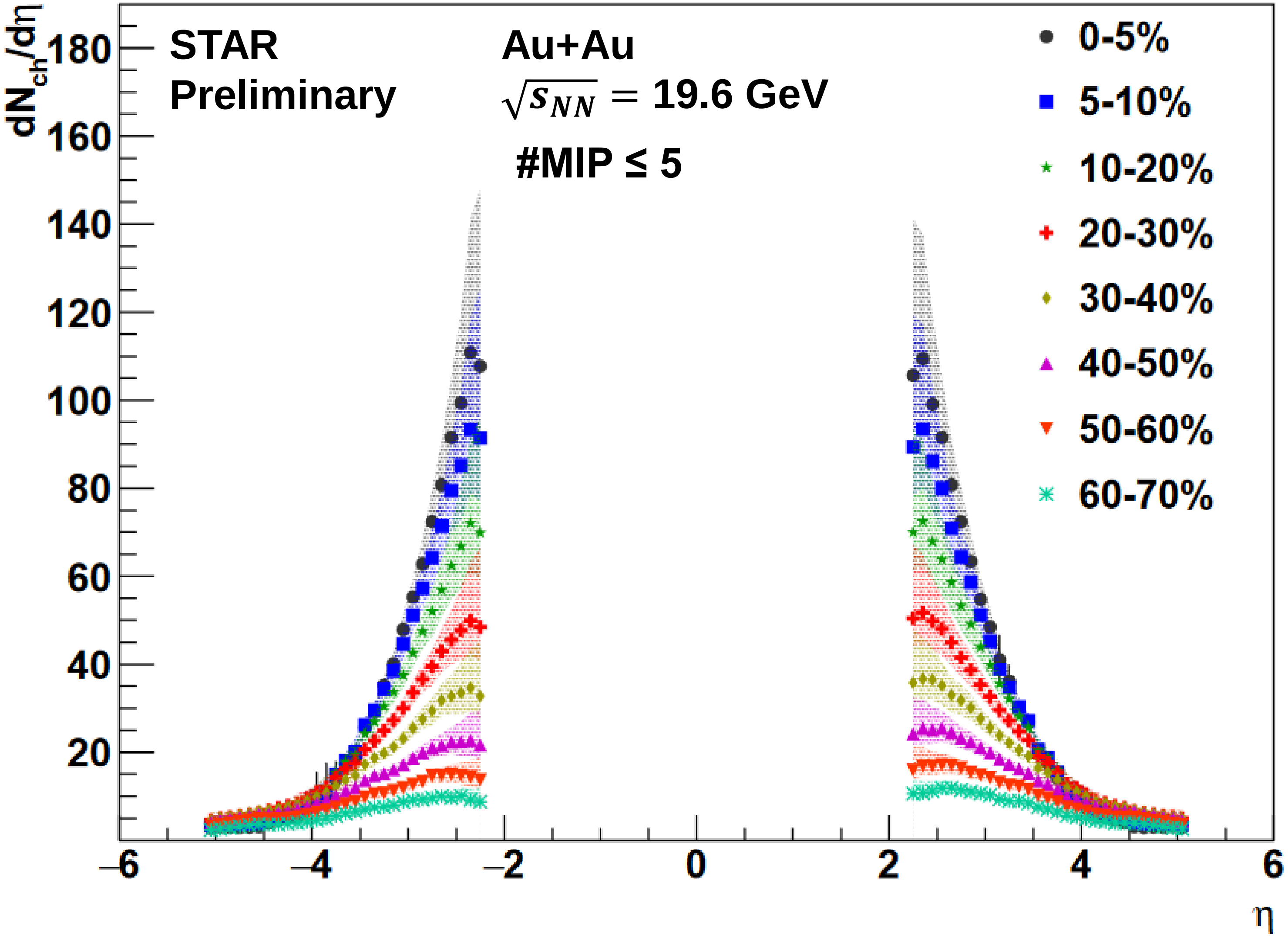
**Systematics summary**

| | |
|---|---|
| charged fraction | 6% |
| $dN/d\eta$ broadened | 4% |
| $dN/d\eta$ tightened, shifted | 6% |
| $p_T$ slope | 1% |
| centrality selection | 2% |
| unfolding method choice | 8% |
| z-vertex choice | 1% |
| z-vertex selection | negligible |
| EPD electronics, efficiency | negligible |

- EPD: number of MIPs ≤ 5, more systematic checks to be done
- Discrepancy with PHOBOS: several differences, multiple reasons possible
  - Unfolding vs correction, segmentation, simulation imperfection, neglections in raw signal

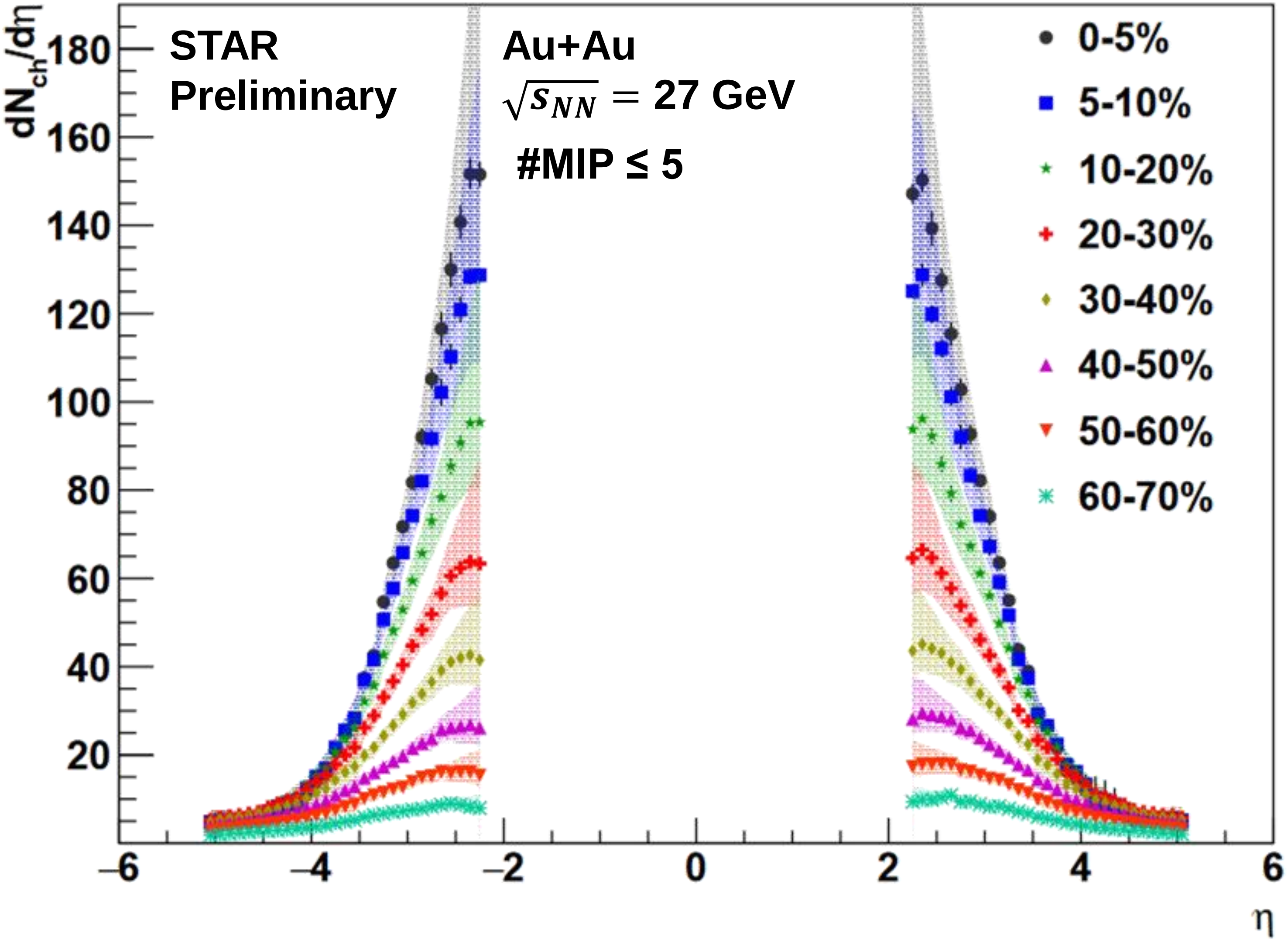
# Results at 19.6 GeV

- Measurement done in eight centrality bins, in EPD $\eta$ range
- Vertex within ±5 cm
- Based on EPD ring-by-ring hit distributions
  - Fit up to #MIP≤5
- Detailed systematic investigations
  - Vertex, centrality calibration
  - Vertex range choice
  - Unfolding method
  - Simulation input



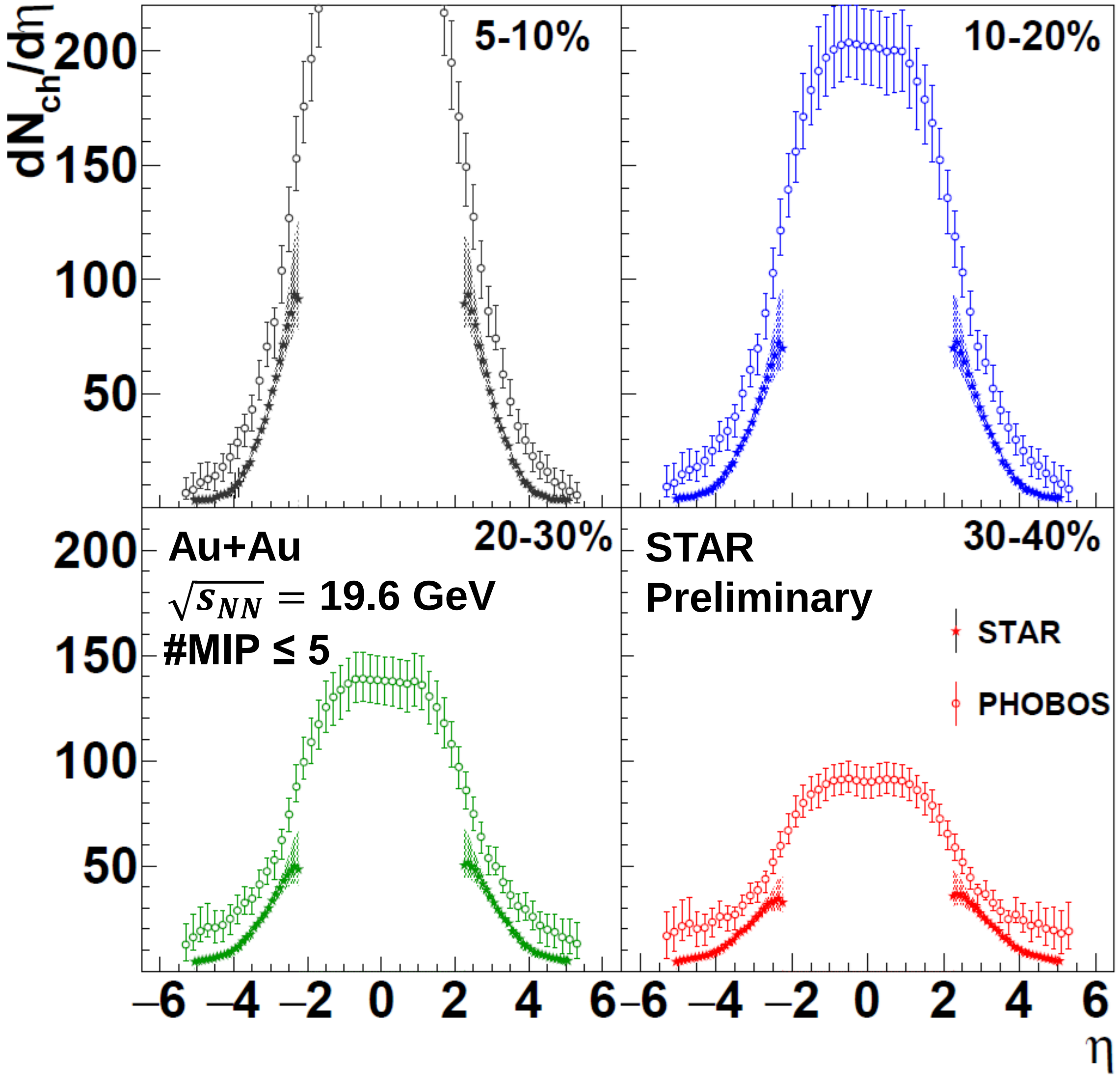
# Results at 27 GeV

- Measurement done in eight centrality bins, in EPD $\eta$ range
- Vertex within ±5 cm
- Based on EPD ring-by-ring hit distributions
  - Fit up to #MIP≤5
- Detailed systematic investigations
  - Vertex, centrality calibration
  - Vertex range choice
  - Unfolding method
  - Simulation input



# Comparision to PHOBOS 19.6 GeV data

- PHOBOS $dN/d\eta$ paper
  - PRC83(2011)024913
  - Results at 19.6, 62.4, 130, 200 GeV
  - Slightly different centrality binning: 5-10% vs 6-10%
- Sizeable differences between measurements
  - Depending on $\eta$, around factor 2
- Ratio increases towards fwd/bwd rapidities
- What about light fragments?
  - They appear in form of separate neutrons and protons in the simulation
  - PHOBOS, PRC94 (2016) 024903: Not a significant source of charged particles
- What about central rapidities?

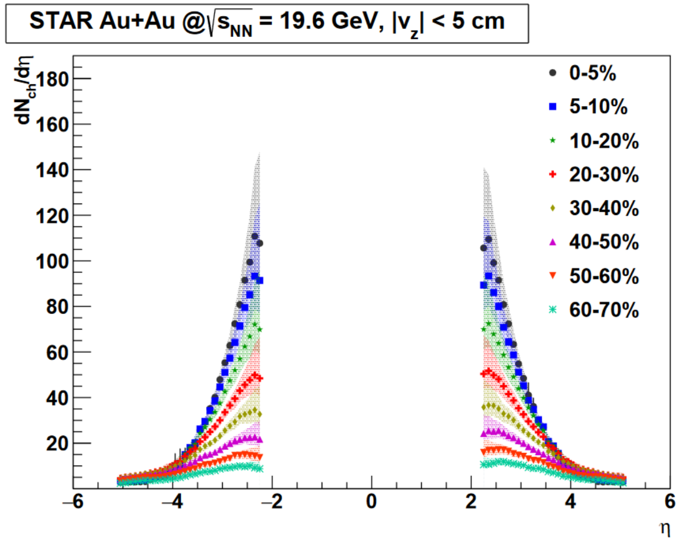


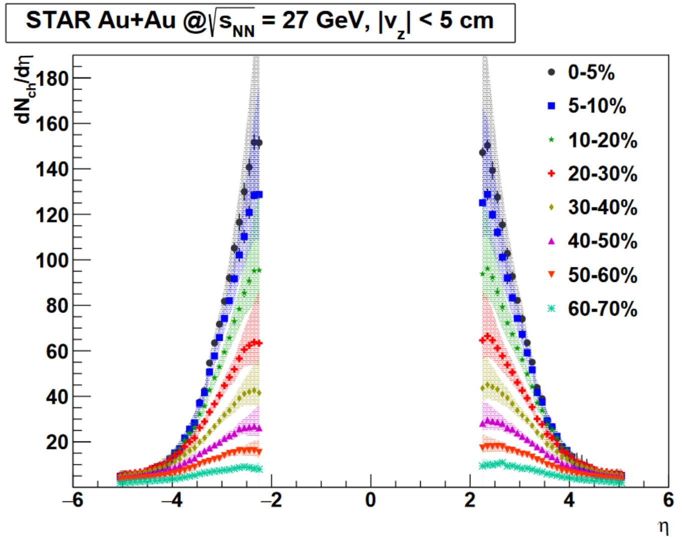
# What about comparing at midrapidity?

- STAR measured identified hadron spectra $\left(\frac{d^2N}{2\pi p_T dp_T dy}\right)$ at 19.6 GeV
  - Phys.Rev.C 96 (2017) 044904, 2017 [arXiv:1701.07065]
- We can roughly estimate $\frac{dN}{d\eta}(\eta = 0)$ based on these published data
  - Take the 5-10% 19.6 GeV Au+Au data tables
  - Take Jacobian $\frac{dy}{d\eta} = \frac{p}{E}$, integrate resulting $\frac{d^2N}{2\pi p_T dp_T d\eta}$ spectra over $p_T$ (multiplying by $2\pi p_T$ and $\Delta p_T$)
  - Results: $\pi^-$: 108, $\pi^+$: 105, $K^-$: 13.0, $K^+$: 20.6, $\bar{p}$: 2.05, $p$: 20.5
- Final estimate: $\frac{dN}{d\eta}(0) \approx 201$ (<u>without</u> other species, <u>without</u> $p_T$ extrapolation)
- PHOBOS result (averaged over $|\eta| < 1$ ) is $\frac{dN}{d\eta}(0) \approx 262$
- Better agreement at midrapidity, more complete calculation would be interesting

# Summary and conclusions

- $\frac{dN_{ch}}{d\eta}$ measured with the STAR EPD
  - Detailed systematic uncertainty investigations
  - Expected rapidity, centrality, $\sqrt{s_{NN}}$ dependence
  - Method to be extended to other $\sqrt{s_{NN}}$ values (BES-II & FXT)
  - Important for the Beam Energy Scan (e.g., tuning of models)
- $\sqrt{s_{NN}} = 19.6$ GeV: PHOBOS also measured $\frac{dN_{ch}}{d\eta}$
  - Significant difference compared to PHOBOS PRC82(2011)024913
  - Four components in this comparison:
    - STAR GEANT simulation
    - STAR EPD spectrum measurement
    - STAR unfolding procedure
    - PHOBOS data



# BACKUP

# Multiple counting correction

- Need to correct for multiple counting (multiple hits from one primary track)
  - Check "inverse efficiency": how many hits on average from primary particles at given $\eta$
- For charged and all primaries separately
- Largest maximum at around $|\eta| \approx 5$
- Edge of EPD, support structures
- One primary can cause on average up to ~5 hits