CHARGED PION EMISSION IN AG+AG COLLISIONS AT $\sqrt{s_{NN}} = 2.55\ GEV$ MEASURED WITH HADES

HADES

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Marvin Nabroth FAIRNESS 2022

Outline

- Motivation and experimental setup
- Charged pion spectra
- Impact of the Coulomb field
- Anisotropic flow

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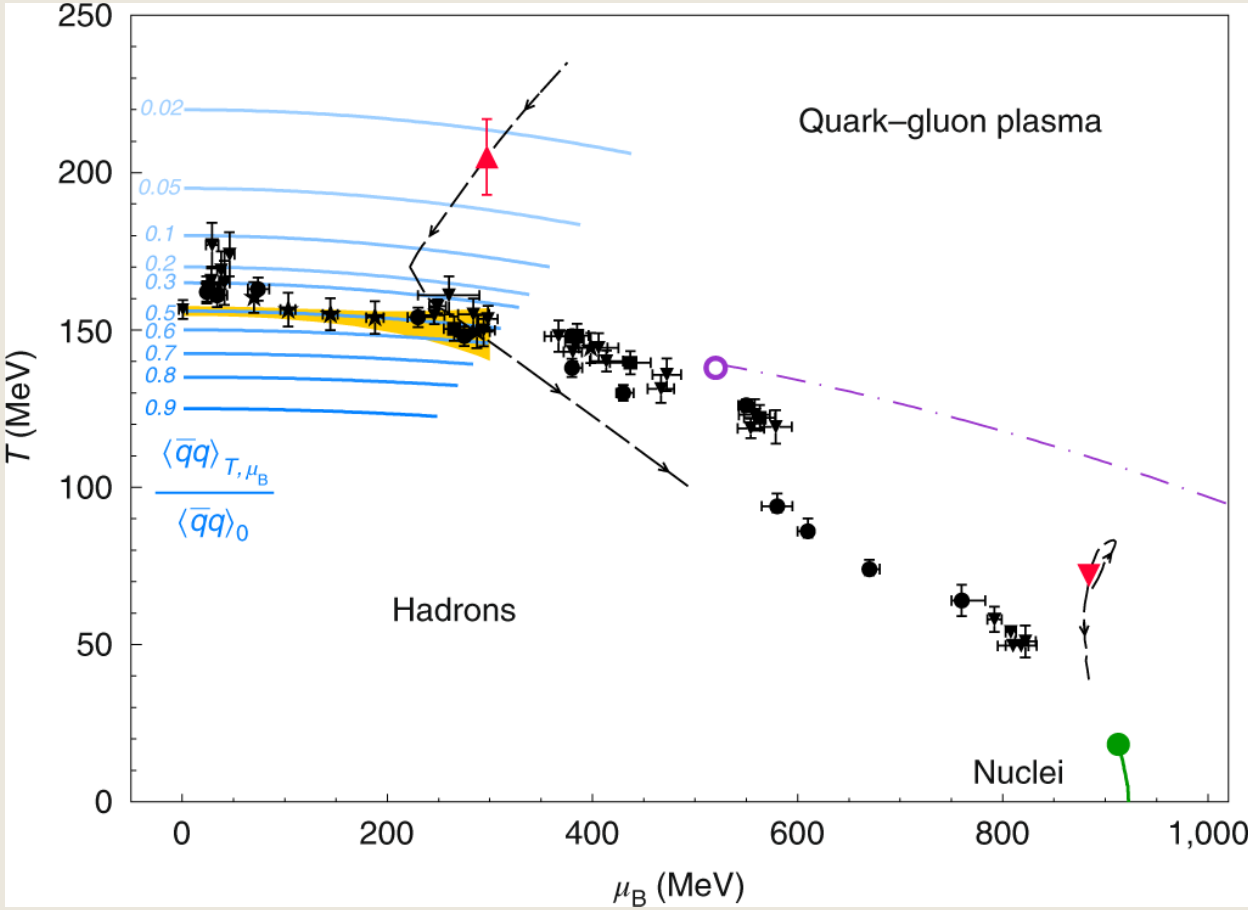
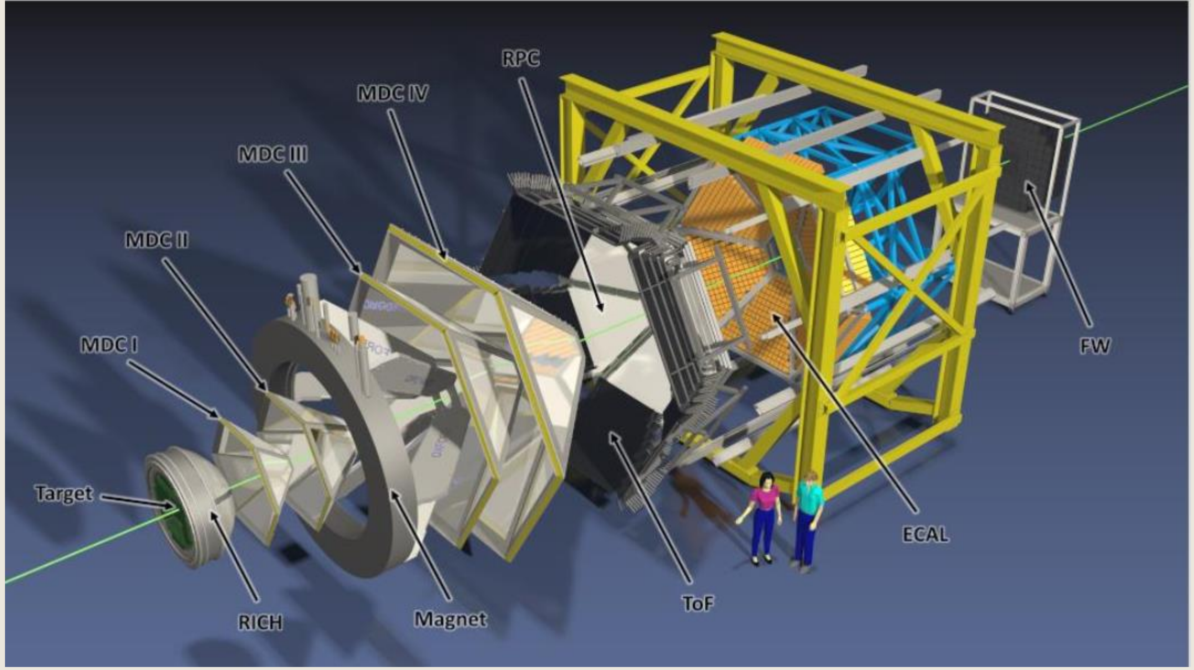
- Probing the QCD phase space diagram in the region of high baryon-chemical potentials at low temperatures
- Similar conditions as assumed to be found in merging neutron stars [1]

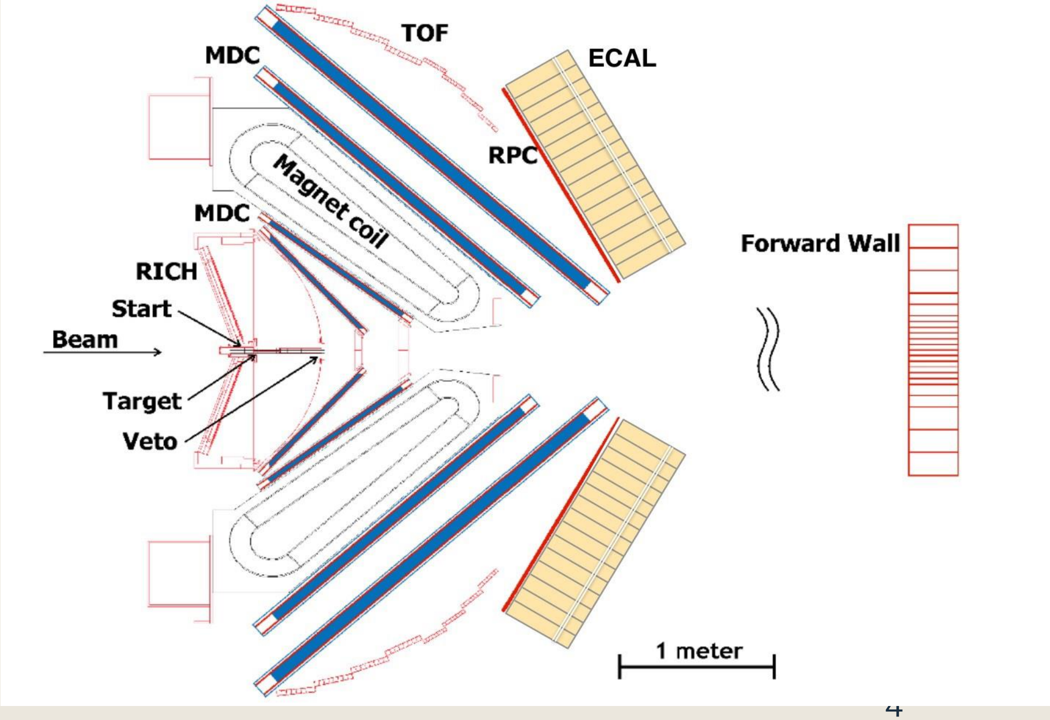


[1] Nature Phys. 15.10 (2019), pp. 10401045. doi: 10.1038/s41567-019-0583-8. url: https://hal.archives-ouvertes.fr/hal-02383397.

HADES

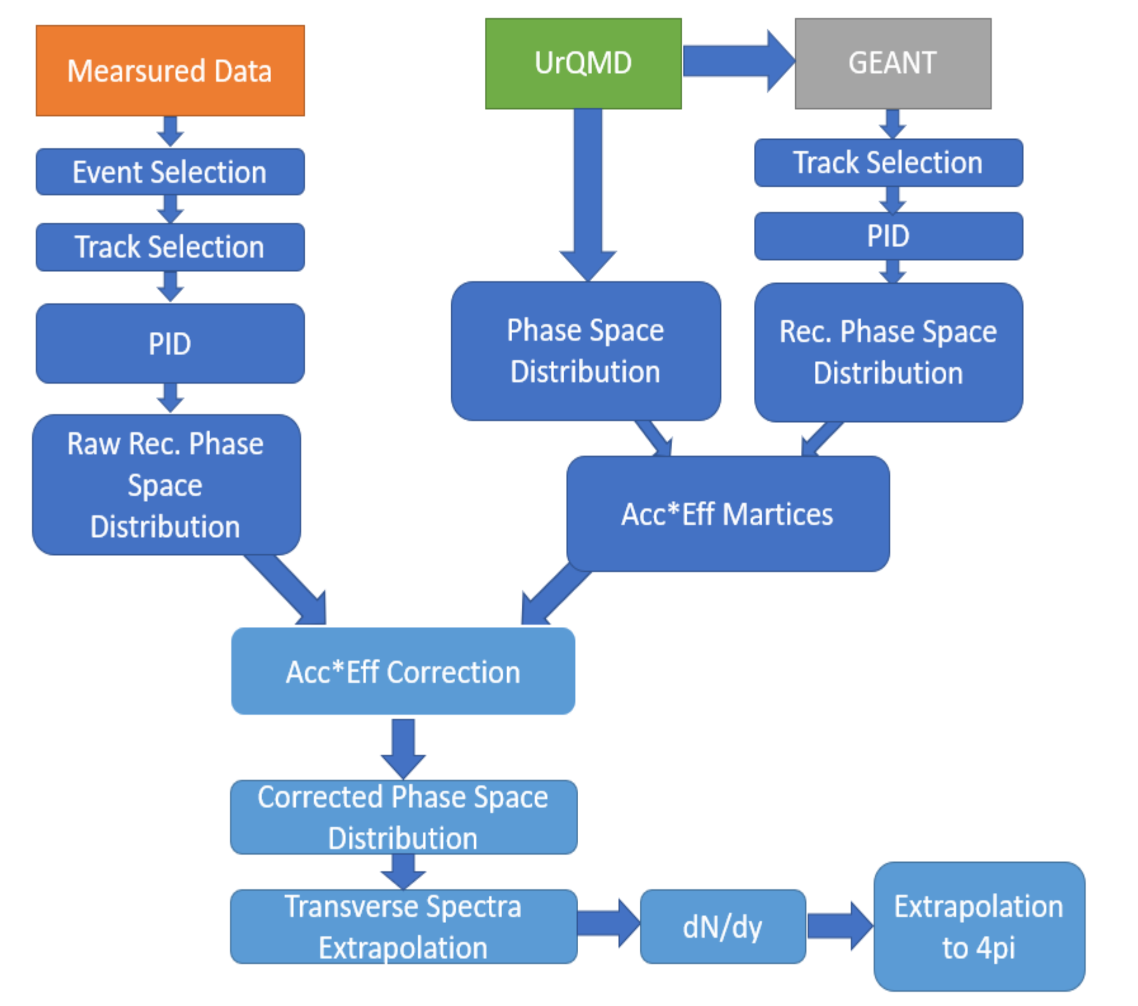
- Fixed-target experiment
- Almost complete azimuthal coverage
- High trigger rate: 50 kHz
- Polar angle coverage: $15\,° \; to \; 85\,°$
- Charged particle detection based on magnet spectroscopy (**MDCs** and **Magnet**), time-of-flight (**STRAT**, **RPC** and **TOF**) and energy loss measurement (**MDC** and **TOF**)
- ECAL and RICH
- Forward Wall for projectile spectator measurement





Charged pion spectra analysis

1. Event selection
2. Select high quality tracks
3. Pion identification
4. Raw phase space distribution
5. Acceptance and Efficiency correction
6. Extrapolation to uncovered p_t (m_t) regions
7. Integration → dN/dy
8. 4π Yield



For details see Jan Orliński talk

Charged pion spectra analysis

$$m_t = \sqrt{m_0^2 + p_t^2}$$

$$p_t = \sqrt{p_x^2 + p_z^2}$$

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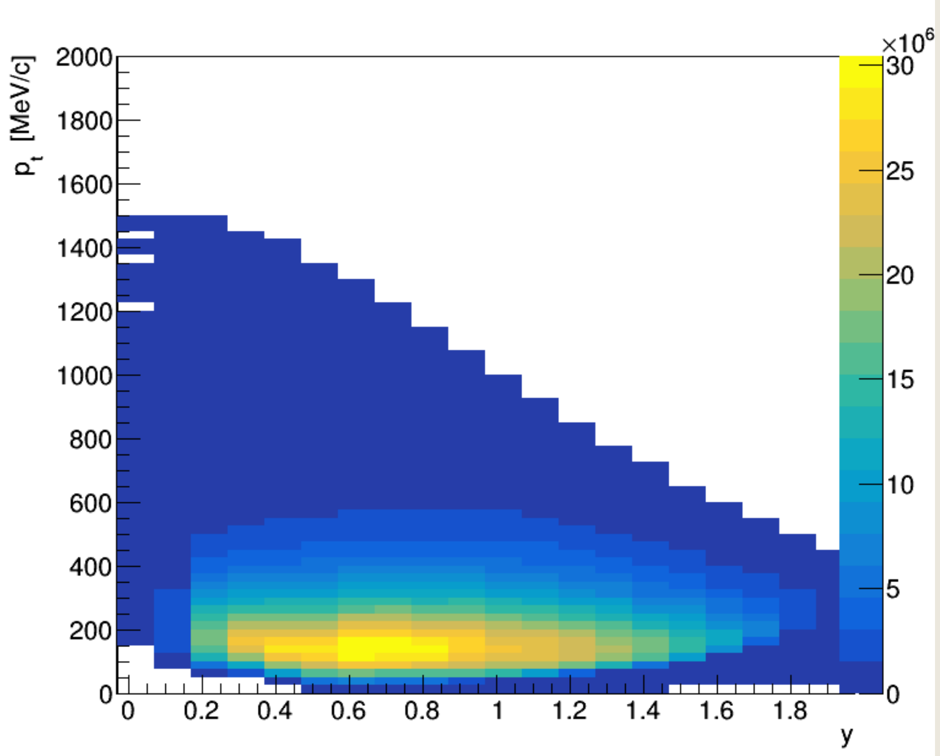


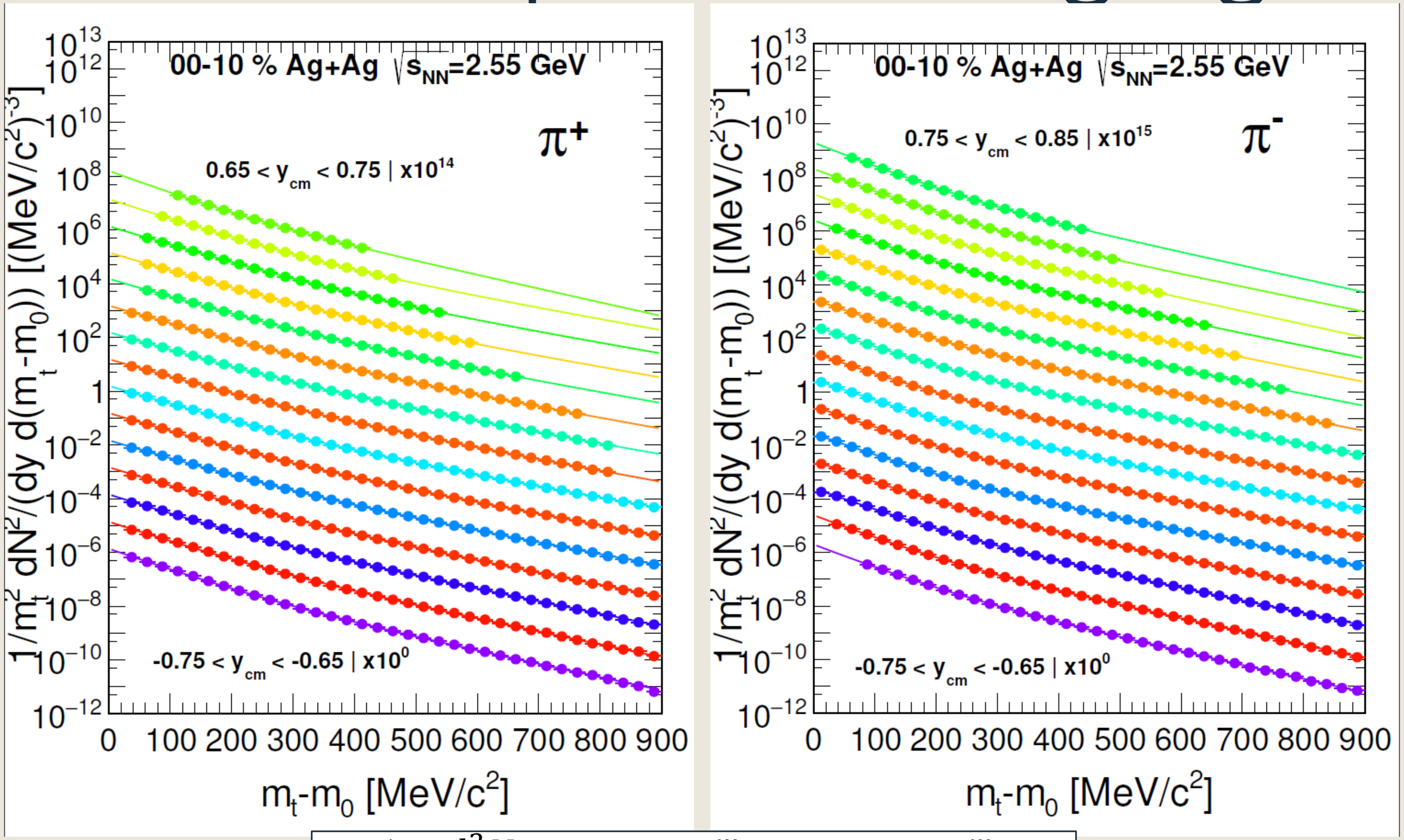
➢ Phase space distribution spanned by

$$y = \frac{1}{2}\ln(\frac{E + p_z}{E - p_z})$$

Rapidity y: Kinemetiacs in beam direction

Transverse mass m_t (momentum p_t) : Transverse Kinematics

Transverse spectra from Ag+Ag

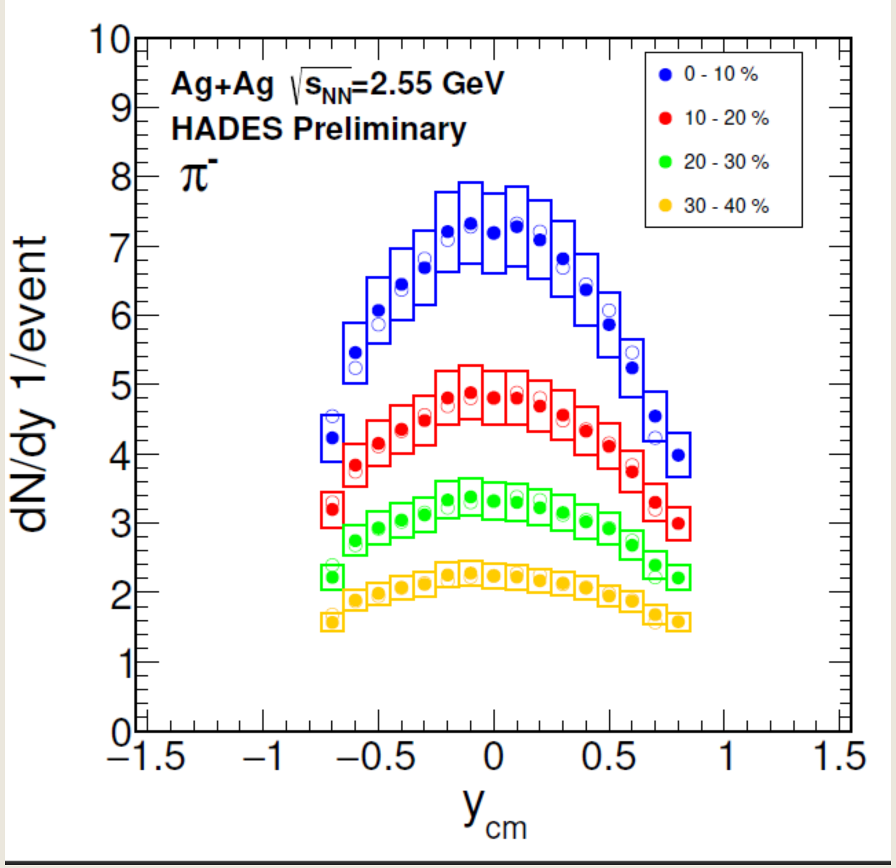


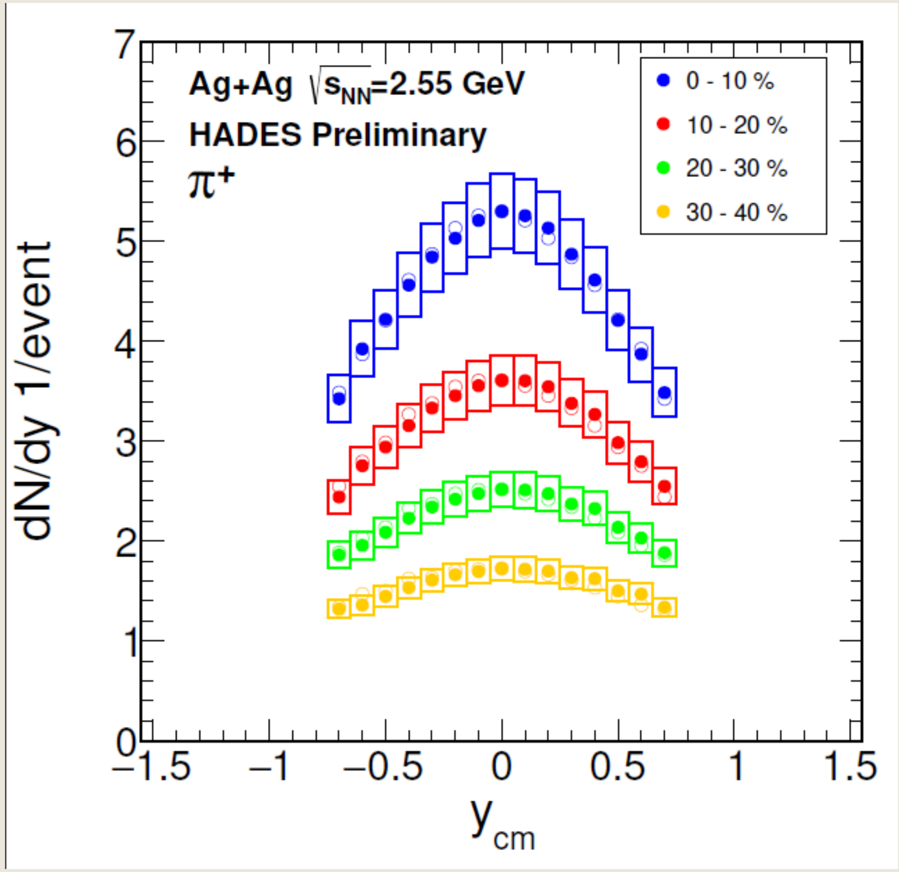
$$\frac{1}{m_t^2}\frac{d^2N}{dm_t dy} = A\left(f\, e^{-\frac{m_t}{T_1}} + (1-f)e^{-\frac{m_t}{T_2}}\right)$$

- High statistics, good coverage
- Double-Boltzmann function are used for extrapolation

$$m_t = \sqrt{m_0^2 + p_t^2}$$

Transverse spectra from Ag+Ag (1.58 AGeV)

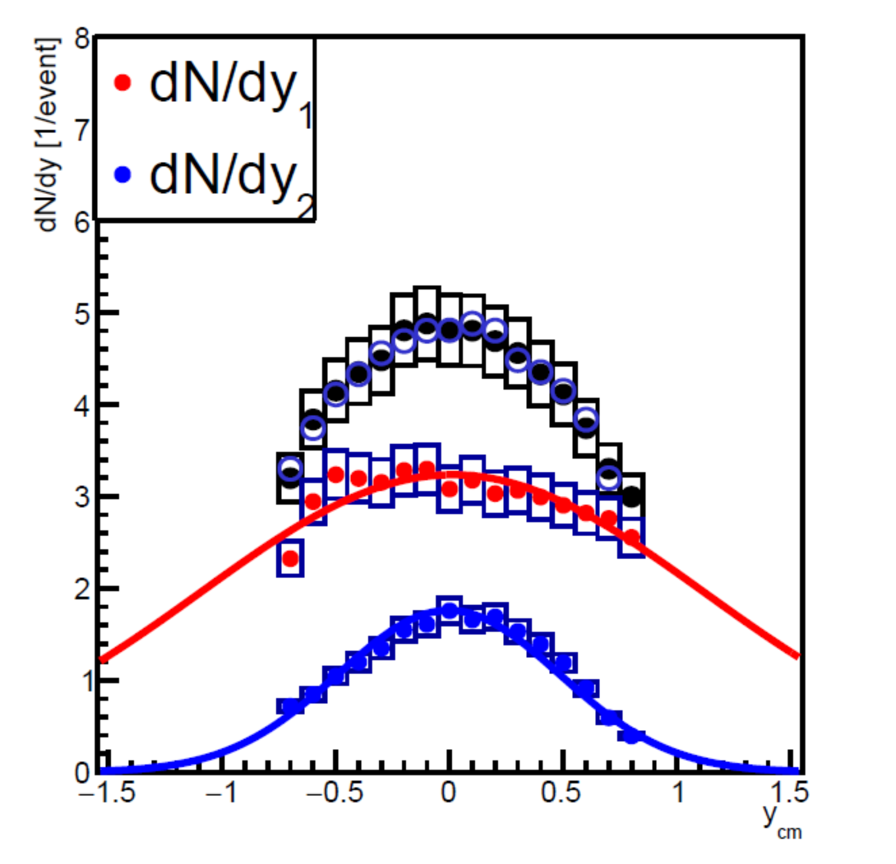




- Centrality dependent analysis in the range of 0-40 %
- 16 (15) Rapidity bins for π^- (π^+)
- Plotted are systematic errors

$$\frac{1}{m_t^2}\frac{d^2N}{dm_t dy} = A\left(f\, e^{-\frac{m_t}{T_1}} + (1-f)e^{-\frac{m_t}{T_2}}\right)$$

dN/dy in low ("Δ-like") and high p_t ("Fireball like")



$$\frac{dN}{dy} = \int A\, m_t^2\, e^{-\frac{m_t - m_0}{T_1}}\, dm_t + \int B\, m_t^2\, e^{-\frac{m_t - m_0}{T_2}}\, dm_t$$

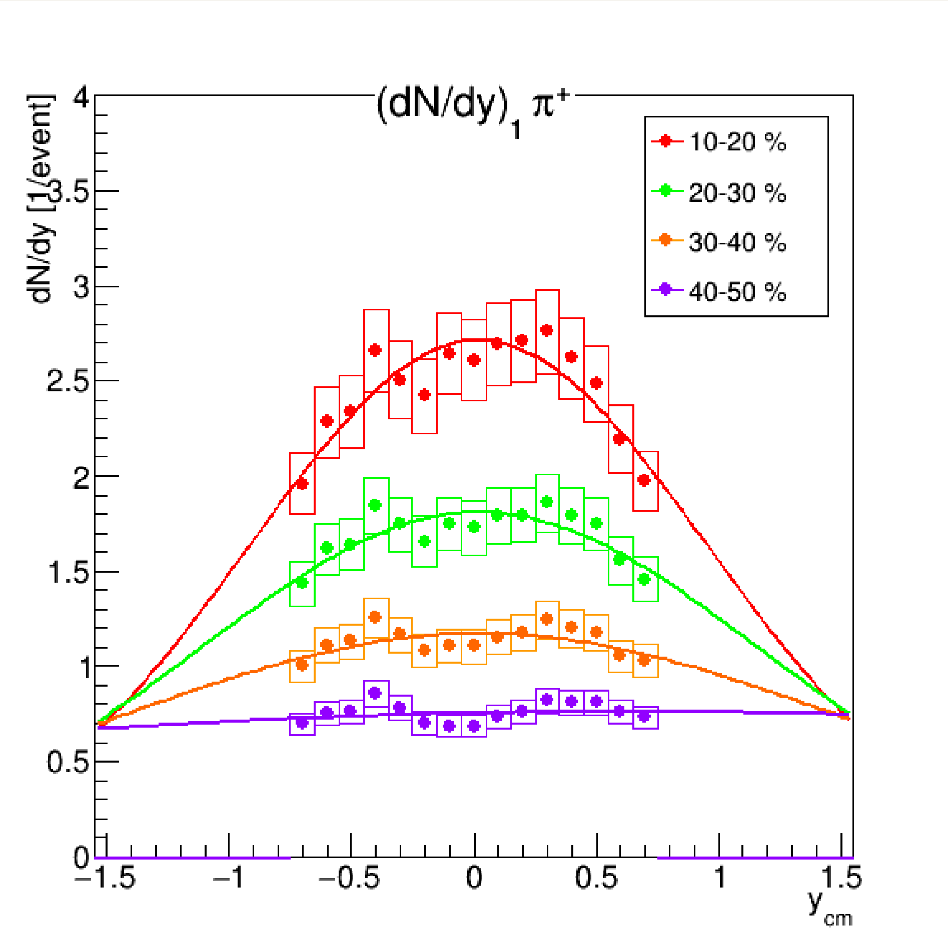
$$\left(\frac{dN}{dy}\right)_1$$

- Production mainly via Delta-Resonances
  → "Δ- like"

$$\left(\frac{dN}{dy}\right)_2$$

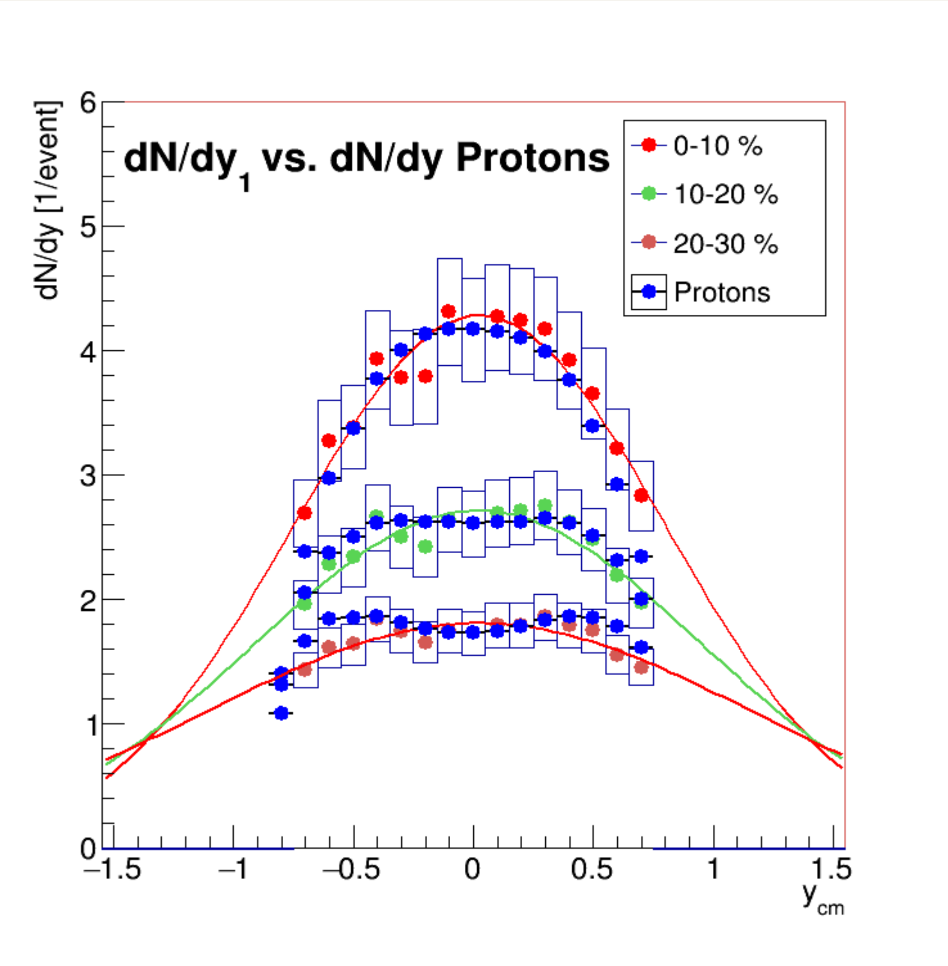
- Production via multiple nucleon Resonances in the higher energy region
  → "Fireball like"

dN/dy in low (“Δ-like”) and high p_t (“Fireball like”)



- Plateau pattern towards semi-central collisions for Δ-like pions
- Similarities of dN/dy_1 to dN/dy of the protons

dN/dy in low ("Δ-like") and high p_t ("Fireball like")

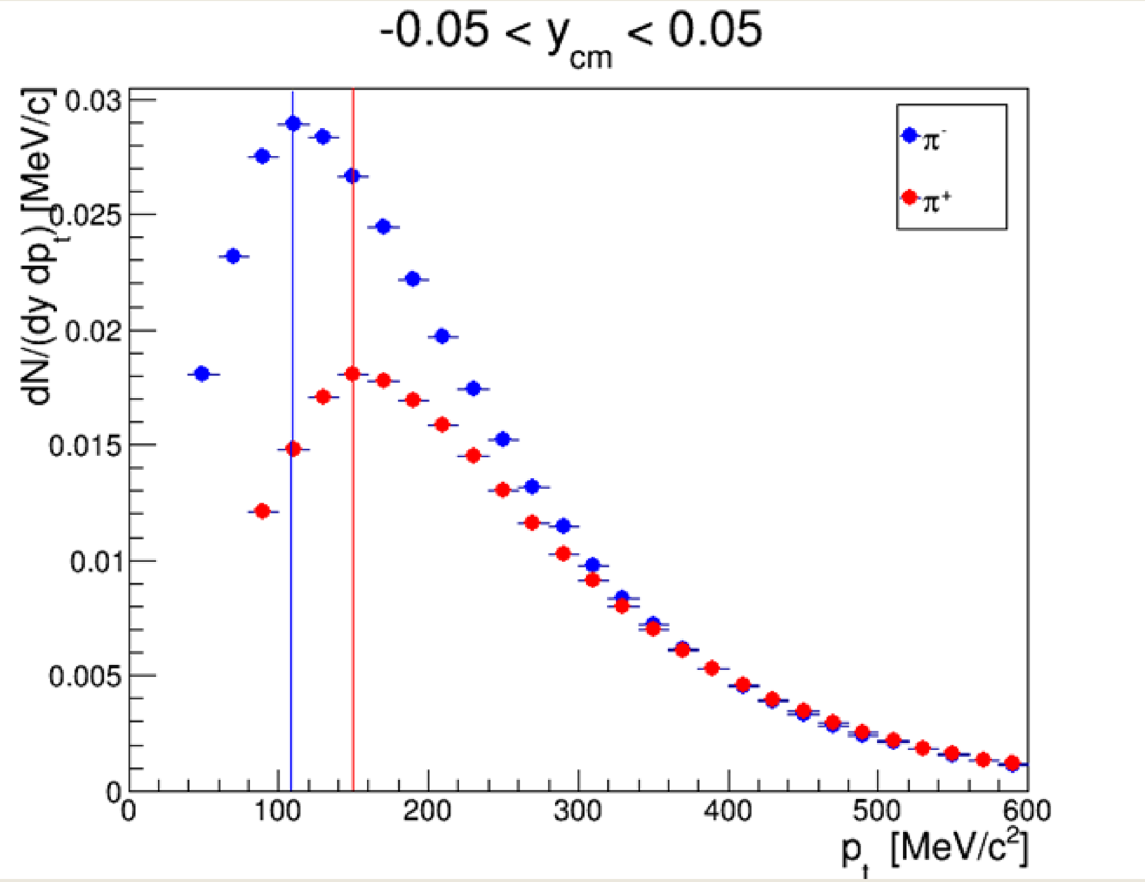


- Plateau pattern towards semi-central collisions for Δ-like pions
- Similarities of dN/dy_1 to dN/dy of the protons
- Kinematic similarities to protons

Impact of the Coulomb force

- Participant protons introduce positive charge in the fireball
- Coulomb force modifies the initial emission spectra
- Maxima on the $\frac{dN}{dydp_t}$ –spectra are at difference position for the polarities
- Best observed for particles with high statistic at low transverse momenta and that occur in opposite polarities → charged pions

$$E_f(p_f) = E_i(p_i) \pm V_c$$



How to extrcat the Coulomb potential?

- Starting from a Double-Boltzmann-Function

$$\frac{1}{m_t^2}\frac{d^2N}{dm_t dy} = A\,(f\,e^{-\frac{E}{T_1}} + (1-f)e^{-\frac{E}{T_2}})$$

How to extrcat the Coulomb potential?

- Starting from a Double-Boltzmann-Function

$$\frac{1}{m_t^2}\frac{d^2N}{dm_t dy} = A\left(f\, e^{-\frac{E}{T_1}} + (1-f)e^{-\frac{E}{T_2}}\right)$$

Express E by E_f and the Coulomb potential V_c

→ Energy coordinate transformation

$$\frac{1}{m_t^2}\frac{d^2N}{dm_t dy} = A\left(f\, e^{-\frac{E_f \mp V_c}{T_1}} + (1-f)e^{-\frac{E_f \mp V_c}{T_2}}\right) \underbrace{J}_{\text{Jacobian}}$$

- Assmung: E = $m_t \cosh(y)$

How to extrcat the Coulomb potential?

- The coulomb potential dependents on the pion‘s velocity
- Pions with a velocity smaller than the expansion velocity of protons feel a smaller potential → Energy dependence → Effective potential V_{eff}
- Assuming that the proton‘s velocities follow a nonrelativistic Boltzmann distribution:

$$V_{eff} = \begin{cases} V_c\left(1 - e^{-x^2}\right) & \textit{2D cylindrical geoemetry} \\ V_c\left(\mathrm{erf}(x) - \left(\frac{2}{\sqrt{\pi}}\right) x\, e^{-x^2}\right) & \textit{3D spherical geometry} \end{cases}$$

H. W. Barz et al. In: Phys. Rev. C 57 (5 May 1998)

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For low energy regime

- Spectator charges are ignored

$$x = \sqrt{\left(\frac{E_f}{m_\pi} - 1\right) \quad m_p / T_p}$$

$$J = \frac{E_f \pm V_{eff} \sqrt{(E_f \pm V_{eff})^2 - m_\pi{}^2}}{E_f \sqrt{E_f{}^2 - m_\pi{}^2}} \left(1 \pm \frac{2}{\sqrt{\pi}} \frac{V_C m_p}{m_\pi T_p}\, x\, e^{-x^2}\right)$$

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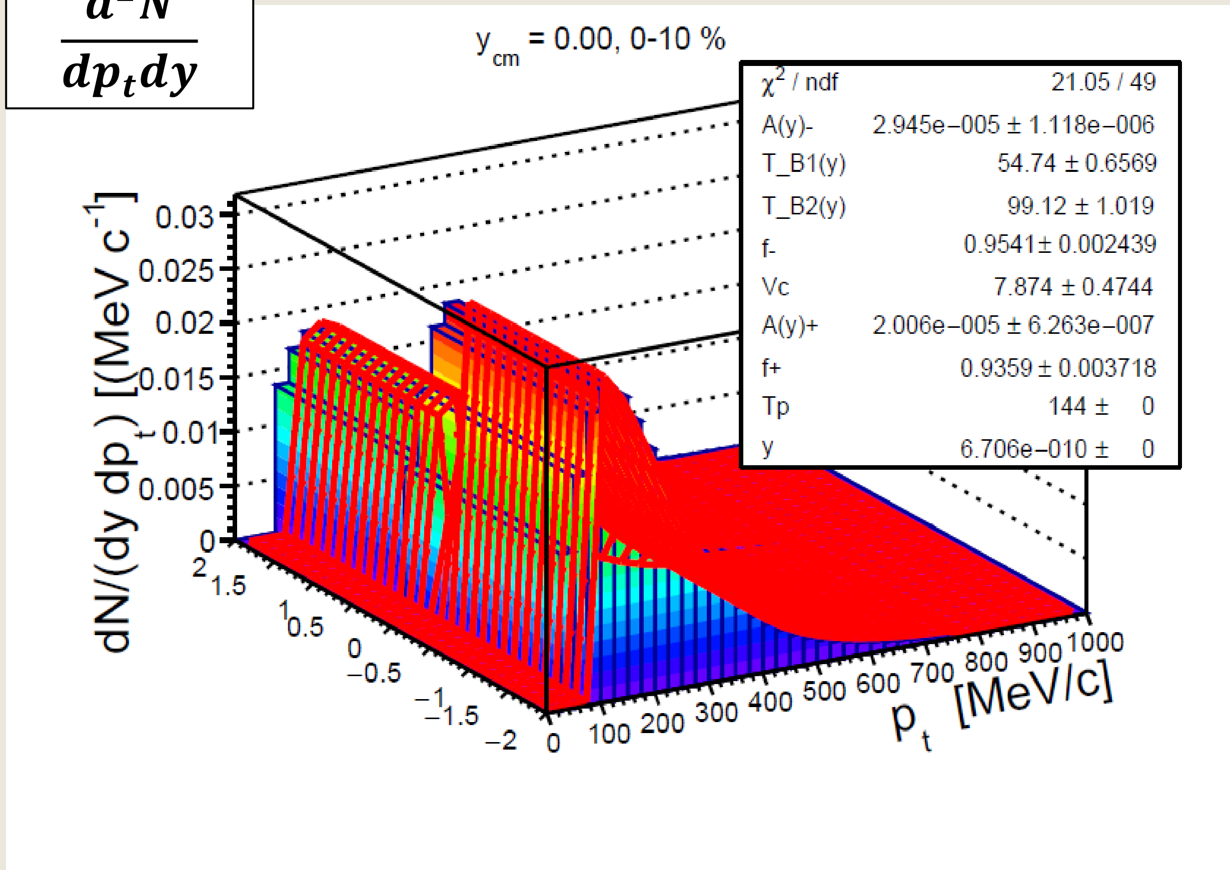
$$\Rightarrow \quad \frac{1}{m_t^2} \frac{d^2N}{dm_t dy} = A \left(f\, e^{-\frac{E_f \mp V_{eff}}{T_1}} + (1 - f) e^{-\frac{E_f \mp V_{eff}}{T_2}}\right) J$$

How to extrcat the Coulomb potential?

Ag+Ag 1.58 AGeV

$\frac{d^2N}{dp_t dy}$



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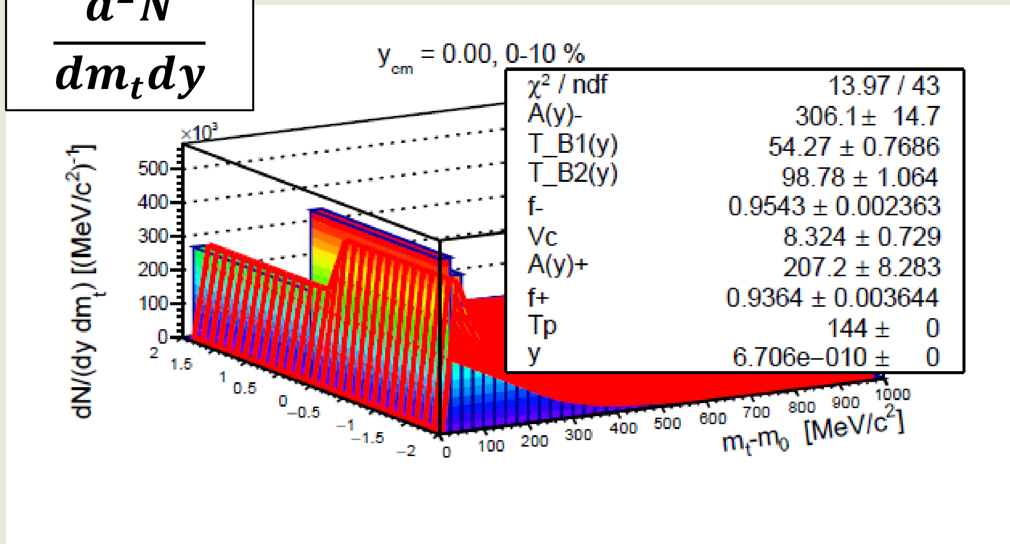
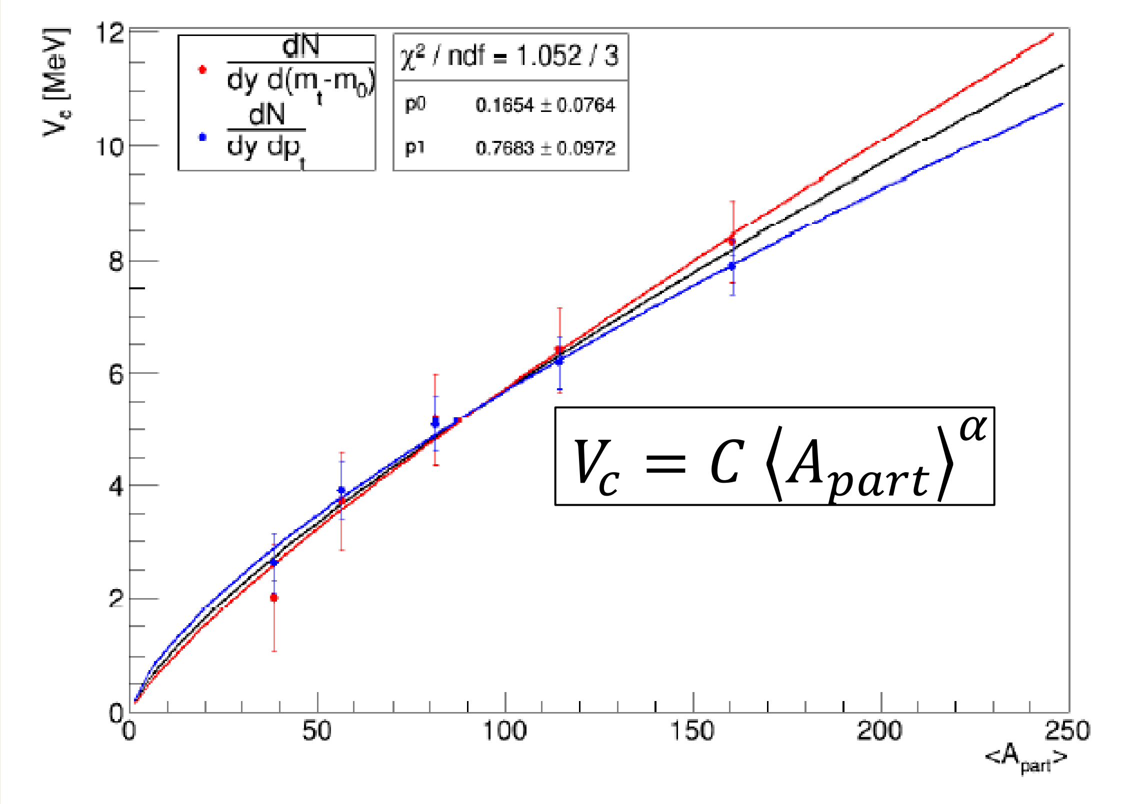


- 2D fitting procedure, assuming common V_c for the two polarities

$Vc = 8.1 \pm 0.6\ MeV$ for 0-10 %

How to extrcat the Coulomb potential?

Ag+Ag 1.58 AGeV



- Weaker than linear scaling

$\alpha = 0.77 \pm 0.1$

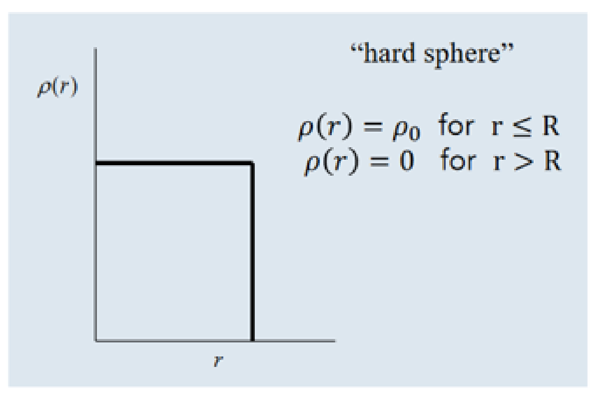
Expected: $V_c \propto \frac{Z_{part}}{R} \propto A_{part}^{2/3}$

- Higher α due to spectator charges

Connecting the Coulomb potential to a Freeze-out Baryon-Density

- Assume a uniformly charged sphere of protons

$$V_c = \begin{cases} \frac{3}{2}\frac{Ze^2}{R}\left[1 - \frac{1}{3}\left(\frac{r}{R}\right)^2\right] & for\ r < R \\ \frac{Ze^2}{R} & for\ r \geq R \end{cases}$$



- The extracted Vc corresponds to an average over all pions
  - *Assuming a homogenous distribution for the pion as well:*

$$< V_c > = \frac{\int d^3r\, \theta(R-r) V_c(r)}{\int d^3r (R-r)} = \frac{6\, e^2 Z}{5\, R}$$

$$\mathrm{R} = \frac{6\, e^2 Z}{5 < V_c >}$$

$$\rho_B = \frac{< A_{part} >}{\frac{4}{3}\pi R^3}$$

Connecting the Coulomb potential to a Freeze-out Baryon-Density

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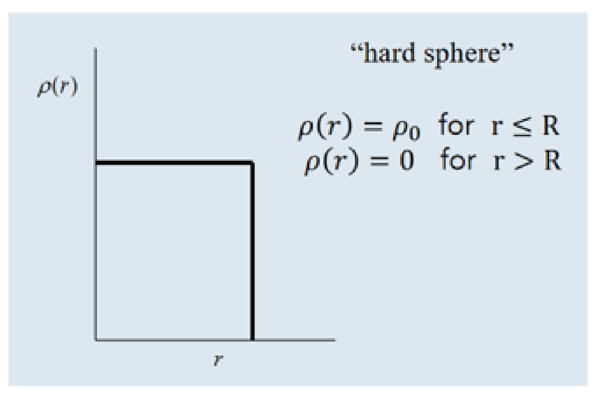


- The extracted Vc corresponds to an average over all pions

$$< V_c >= \frac{\int d^3r\, \theta(R-r) V_c(r)}{\int d^3r (R-r)} = \frac{6\, e^2 Z}{5\, R}$$

$For\ 0-10\ \%\ most\ Ag+Ag\ (1.58\ AGeV)-central\ collision:$

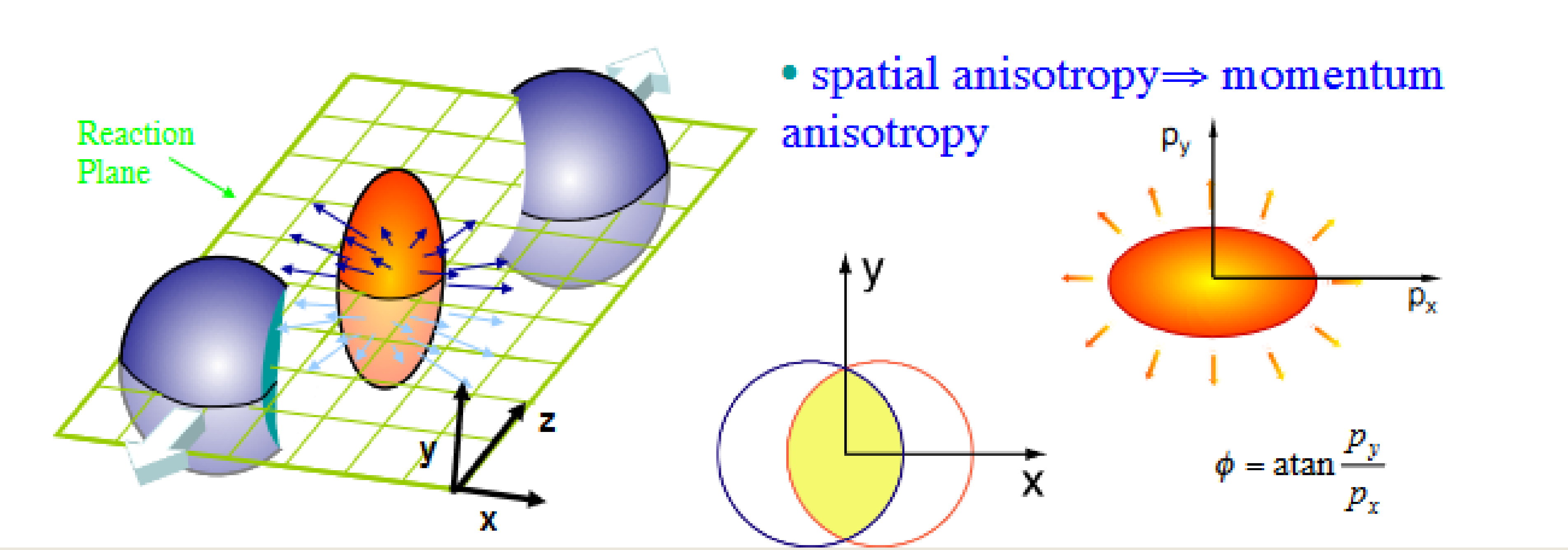
$$R = \frac{6\, e^2 Z}{5 < V_c >}$$

$$\rho_B = 0.07\, \rho_0$$

Azimuthal flow

- Azimuthal angular dependance in momentum space for non-central collisions due to spatial anisotropy
- They way how spatial anisotropies are translated to momentum space is potentially guided by an **Equation of State (EOS)**

→ Flow is a curial observable for exploring properties of nuclear matter under extreme densities



Picture taken from „Latest Results from RHIC + Progress on Determining q^L in RHI Collisions Using Di-Hadron Correlations", Michael J. Tannenbaum, Physics Department, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

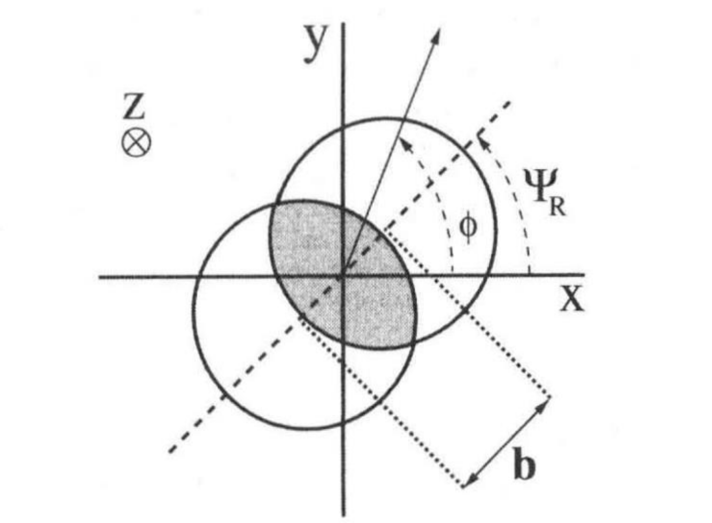
Azimuthal flow analyis

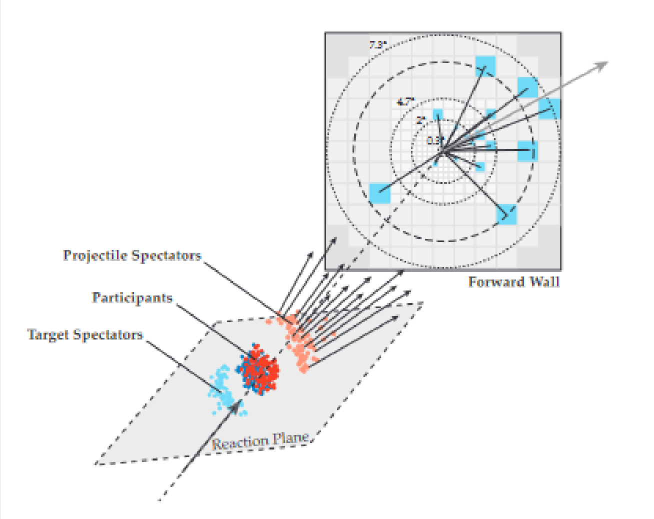
v_1	*Directed Flow*
v_2	*Elliptic Flow*
v_3	*Triangular Flow*

- Examine azimuthal anisotropies relative to the **event plane** by a Fourier series:

$$\frac{dN}{dp_t d_y} \propto \left(1 + 2\sum_{n=1}^{\infty} v_n(p_t, y)\cos(n(\phi - \Psi_{RP}))\right)$$

- *Fitting of Fourier series*
- $v_n = \langle \cos(n(\phi - \Psi_{RP})) \rangle$





Event plane reconstruction

- Reconstruction of the event plane is based on the **projectile spectator hits** on the forward wall

- $\tan(\Psi_{EP}) = \frac{Q_x}{Q_y}$

Azimuthal flow analyis – Experimental corrections

Event plane correction

- Extracted harmonics are always smaller than the real one

$$v_n = \frac{v_{n,obs}}{R_n}$$

- Due too limited event plane resolution
- Correction method according to:

J.Y. Ollitrault, On the measurement of azimuthal anisotropies in nucleus-nucleus collisions(1997).arXiv:nucl-ex/9711003

$$R_n = \langle \cos(n(\Psi_{EP} - \Psi_{RP})) \rangle$$
$$= \frac{\sqrt{2}}{2}\chi \ \exp(-\frac{\chi^2}{2})(I_{\frac{n-1}{2}}(\chi^2) - I_{\frac{n+1}{2}}(\chi^2))$$

Occupancy correction

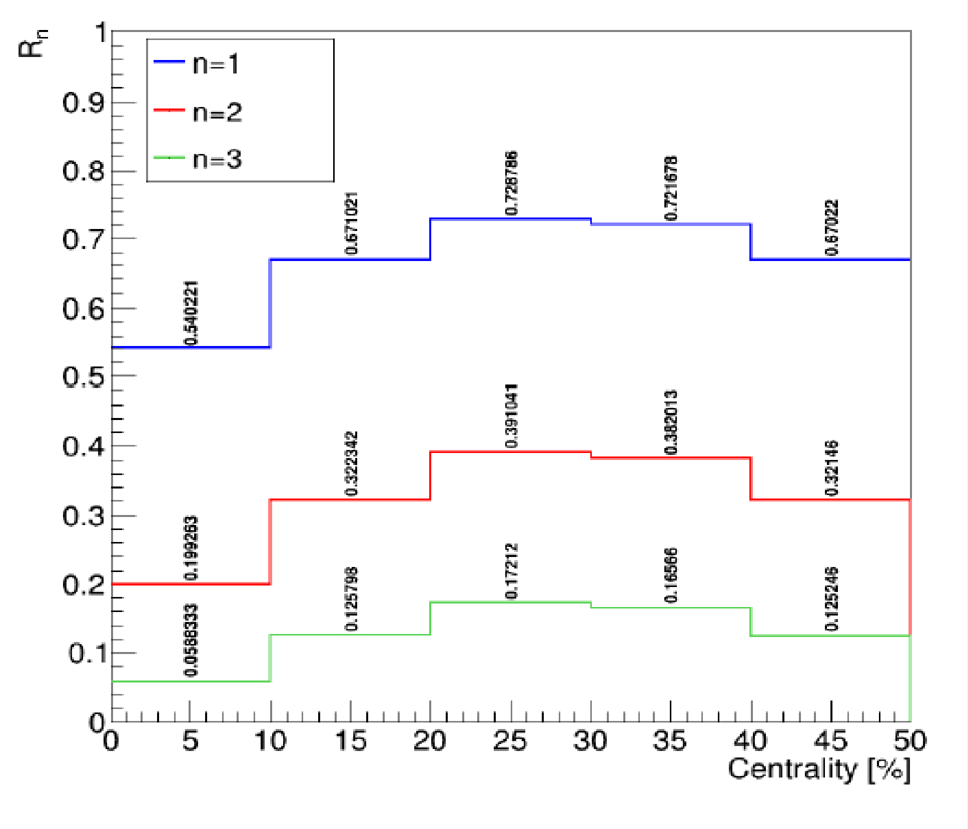
- Deviation of v_1 flow from being zero at mid-rapidity due to multicity-dependent track efficiency
- Correction as a function of polar angle, emission angle relative to event plane and collision centrality

$$\epsilon(\rho_{track}) = \epsilon(\theta, \phi_{EP}, centr) = \epsilon_{single} - c_\epsilon \, \rho_{track}(\theta, \phi_{EP}, centr)$$

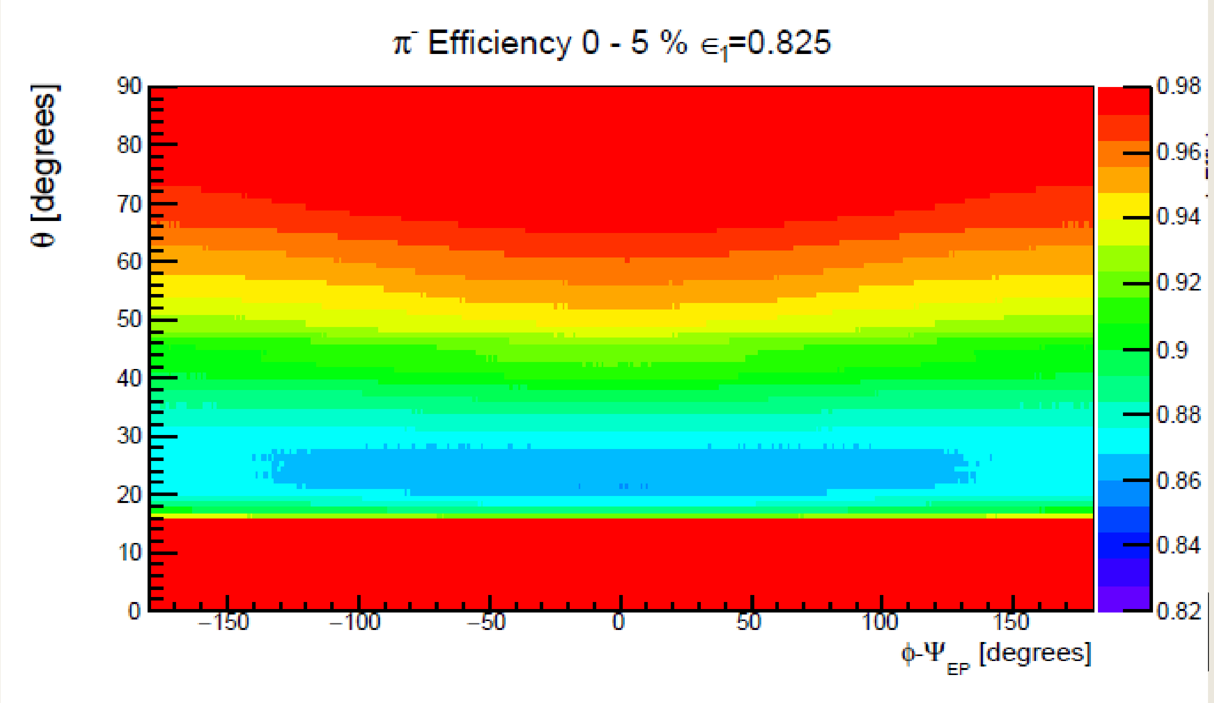
For details see: Phys.Rev.Lett. 125 (2021) 26, 262301

Azimuthal flow analyis – Experimental corrections

- **Ollitrault correction**

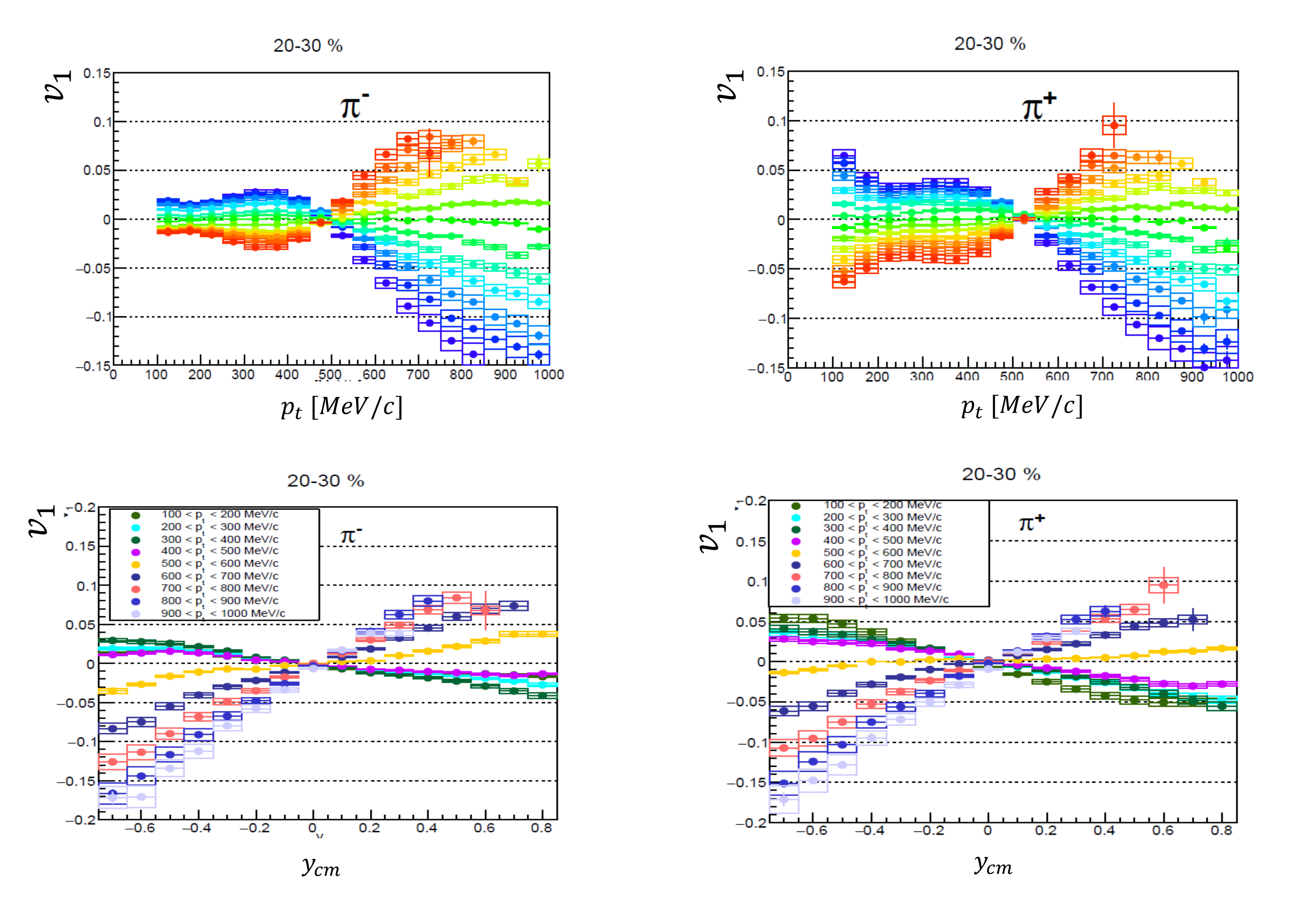


- **Occupancy correction**



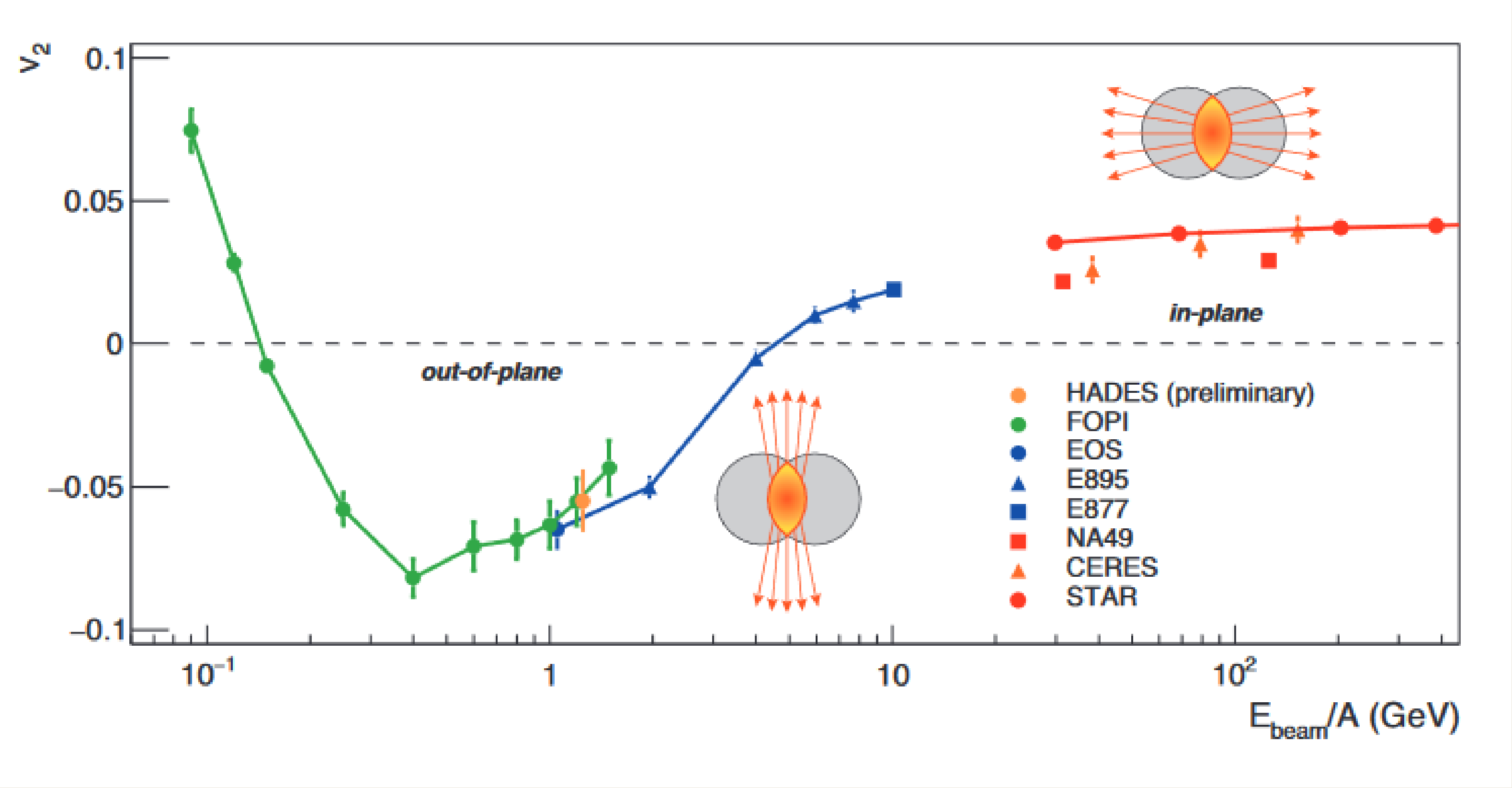
For details see: [Phys.Rev.Lett. 125 (2021) 26, 262301]

Directed flow for Ag+Ag 1.58 AGeV



- Differences between polarities in low and high p_t
- Approximate Point-symmetry as expected from collision symmetry

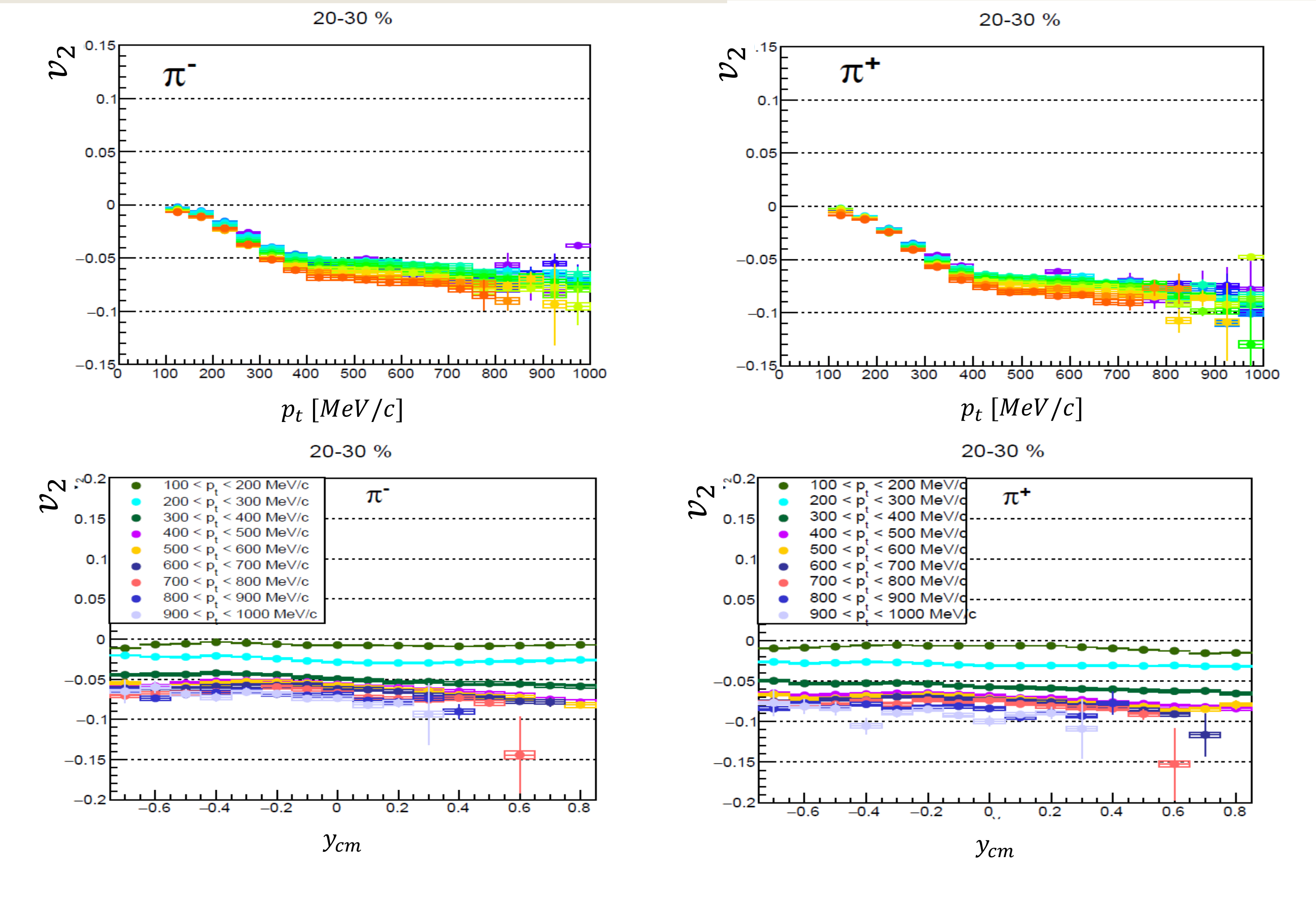
Elliptic flow



B. Kardan, "Flow harmonics of Au+Au collisions at 1.23 AGeV with HADES", J. Phys. Conf. Ser., Jg. 742, Nr. 1, S. 012 008, 2016. doi: 10.1088/1742-6596/742/1/012008.

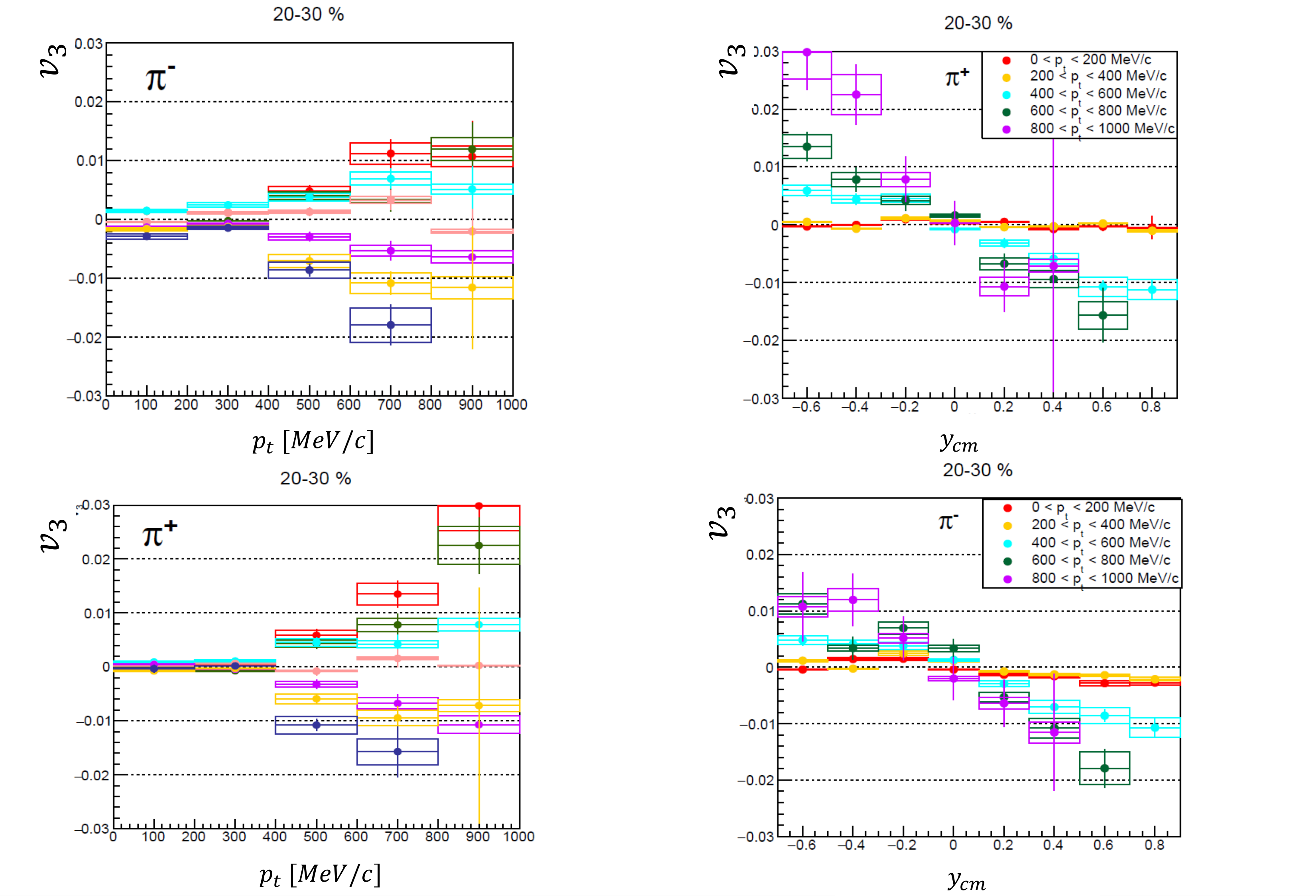
- Negative elliptic flow → out off plane emission in this energy regime is expected
- Due to absorptions effects with spectators

Elliptic flow for Ag+Ag 1.58 AGeV



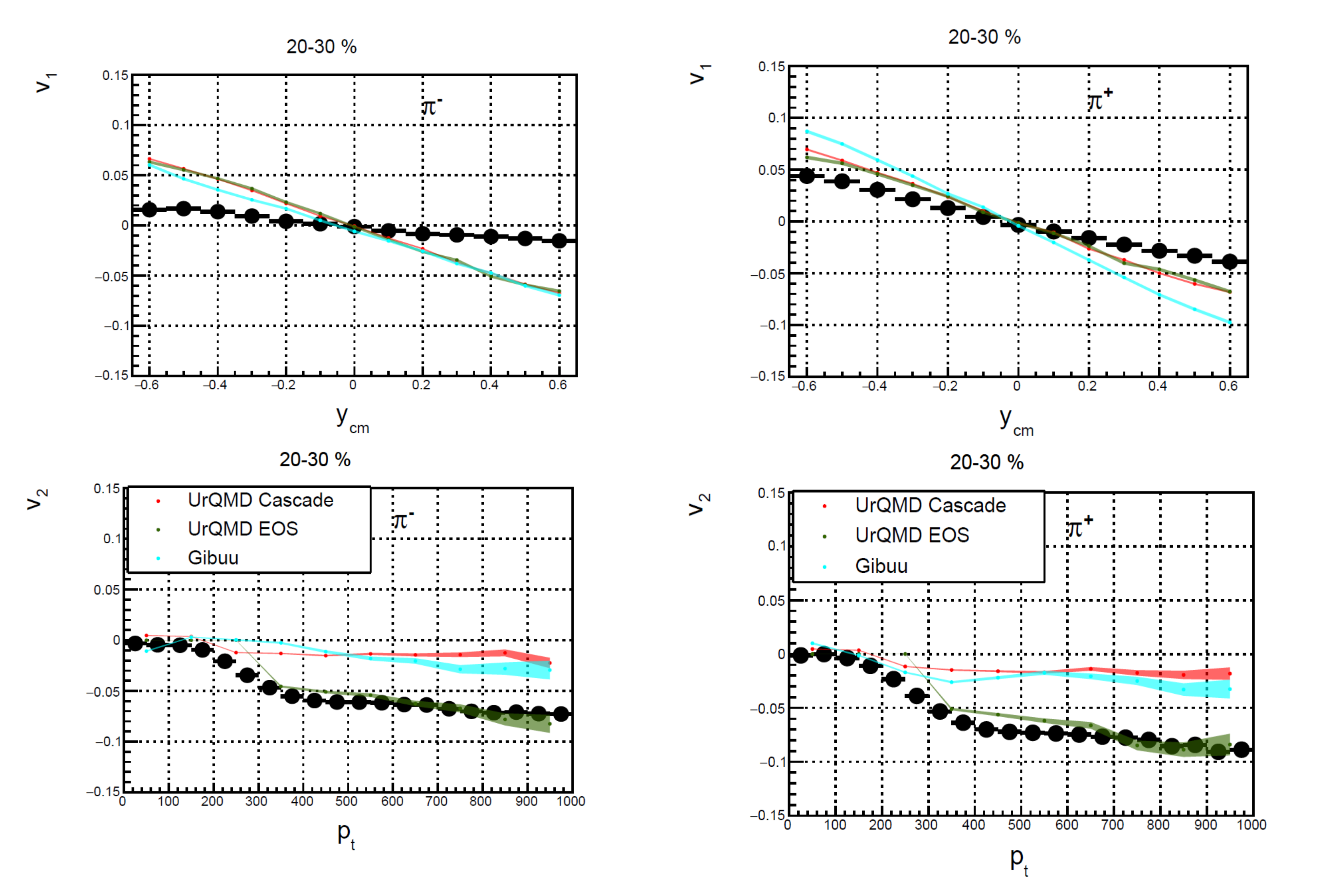
- Negative elliptic flow → out off plane emission for charged pions
- Small rapidity dependence

Trinangular flow for Ag+Ag 1.58 AGeV



- Larger phase bin division to allow for significant values
- One of the first v_3 flow observation for low energy regime
- Small triangular flow
- Approximate point-symmetry as observed for v_1 flow

Flow – some model comparisons for Ag+Ag



- UrQMD Cascade Version 3.4
- UrQMD EOS Hard Skyrme pot
- GiBUU Release 2021

- v_1: Quantitative difference to models, different slopes
- v_2: UrQMD Cascade and GiBUU exhibit smaller v_2 flow
- Good quantitative agreement with UrQMD EOS

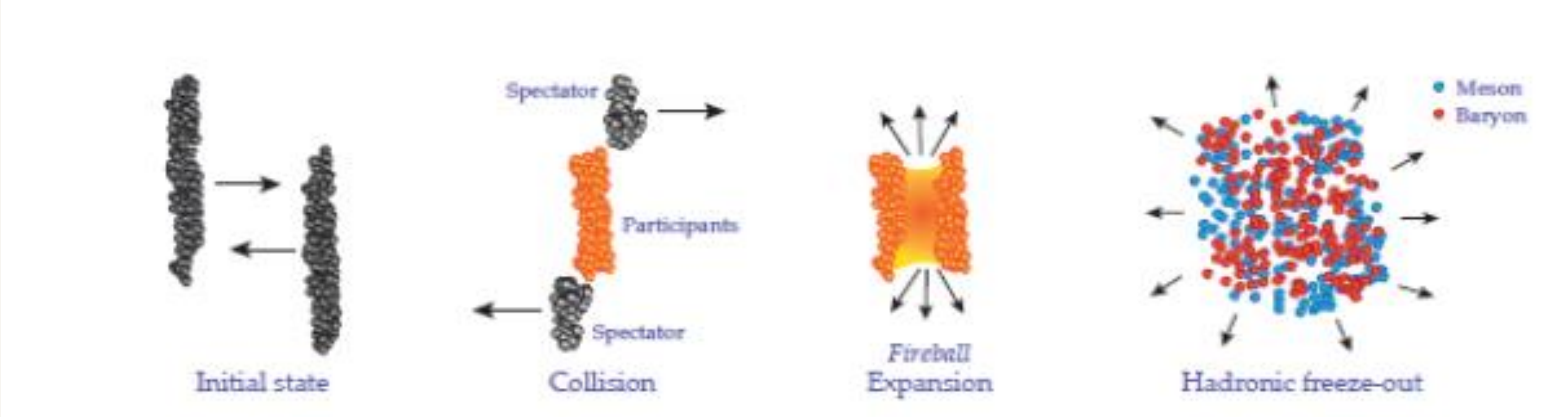
Summary

- Charged pion transverse spectra and rapidity density distribution for Ag+Ag (1.58 AGeV)
  - *Separation of* Δ *and fireball like pions in* dN/dy
- Large geometrical coverage allows extraction of the Coulomb potential and connection to the baryon freeze-out density
- Differential analysis of Directed and Elliptic flow → Differences to transport models
- One of the first observation of pion v_3 flow in this energy regime

Thank you for your attention!

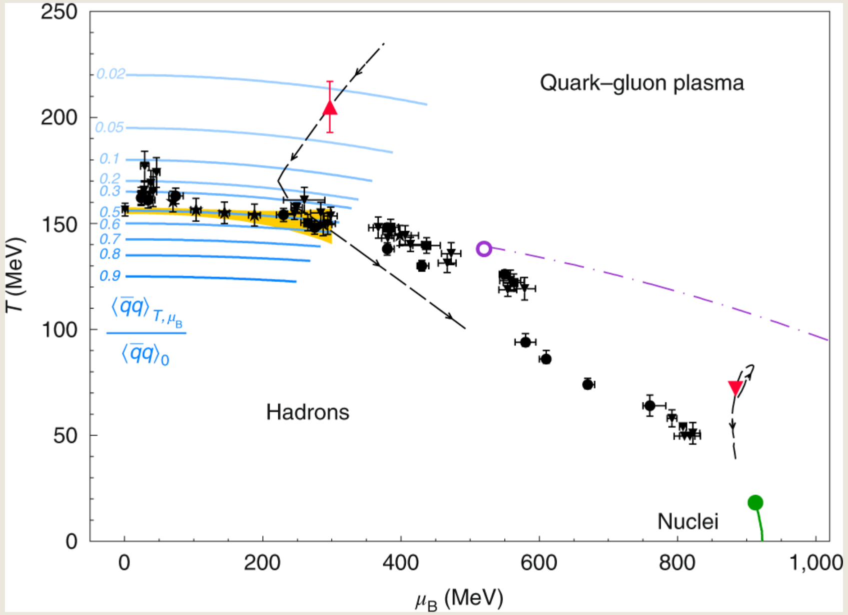
Back Up

Heavy-ion collisions

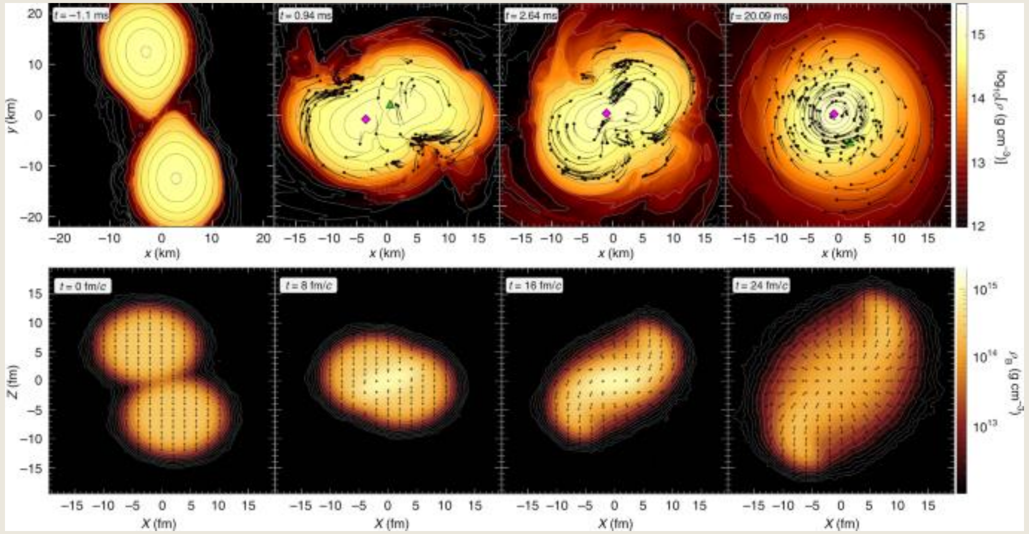


- Relativistic heavy-ion collisions generate nuclear matter under extreme densities and hot temperatures (**Fireball**) → Exploring various QCD phases
- Condition of interest only persist for less than $10^{-22}\ s$
  - → *not measurable directly*
- Analyzing their properties (Kinematic distributions, yields, angular dependency…) allow to draw conclusions to the fireball state

HADES



- ➢ Examine the reaction products of heavy-ion collision at SIS 18 energies.
- ➢ Probing the QCD phase space diagram in the region of high baryon-chemical potentials at low temperatures
- ➢ Investigate strongly interacting QCD matter at extreme densities as assumed to be found in merging neutron stars [1]



[1] Nature Phys. 15.10 (2019), pp. 10401045. doi: 10.1038/s41567-019-0583-8. url: https://hal.archives-ouvertes.fr/hal-02383397.

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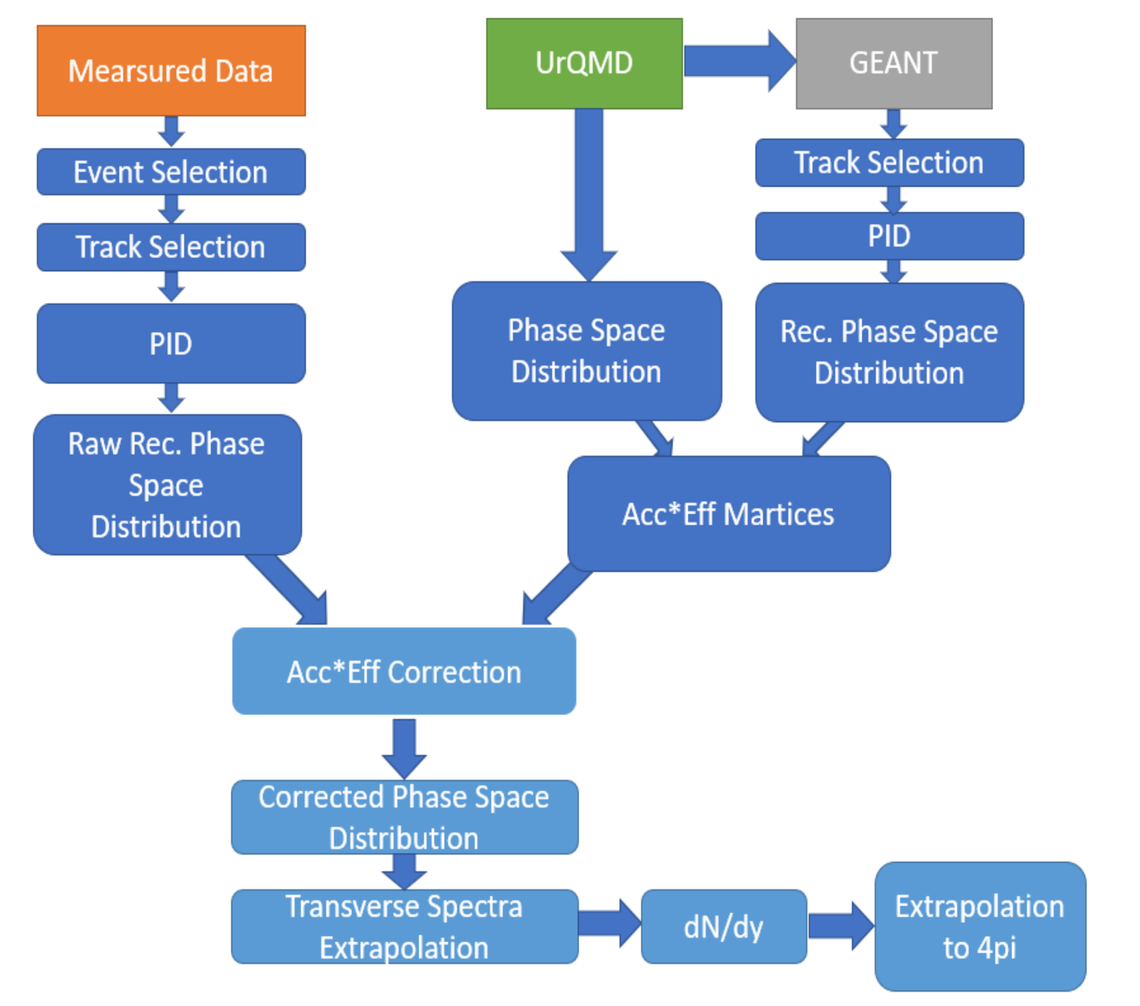

For details → See Jan Orlinskis talk

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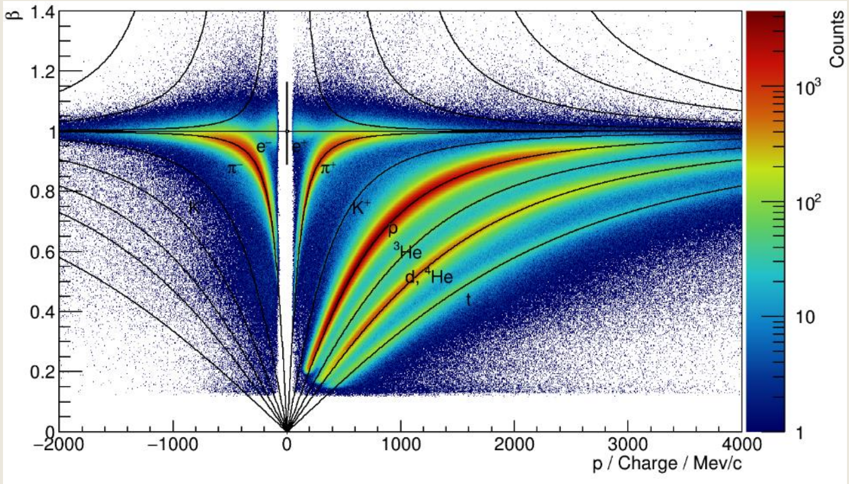
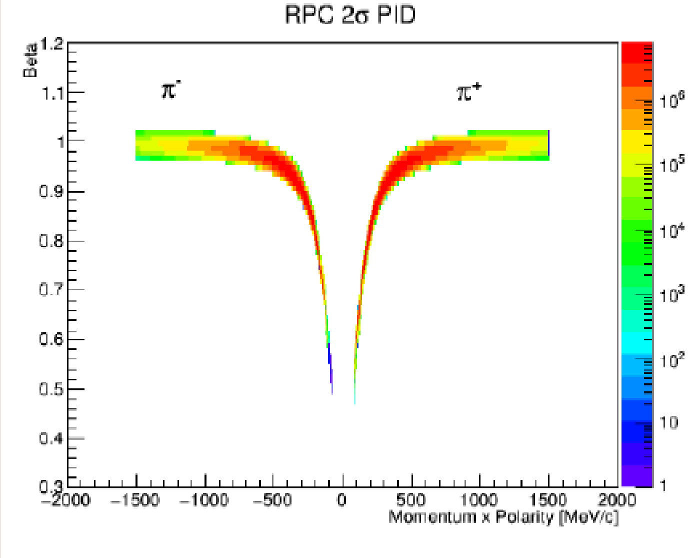
$$\beta = \sqrt{\frac{p^2}{(mc^2) + p^2}}$$

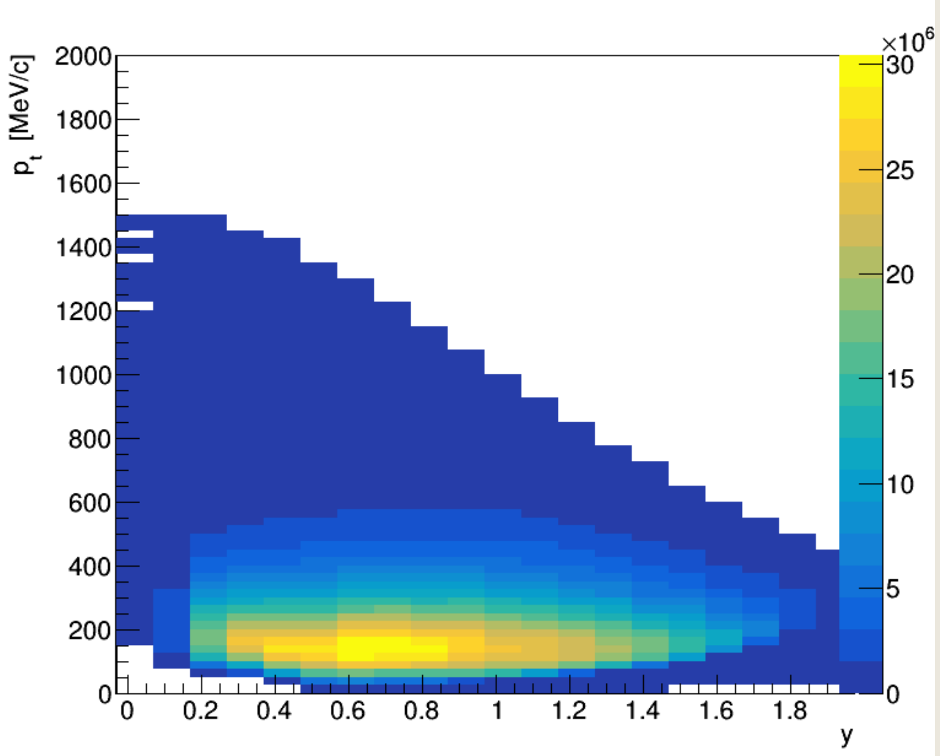




Charged pion spectra analysis

$$p_t = \sqrt{p_x^2 + p_z^2}$$

1. Event selection
2. Select high quality tracks
3. Pion identification
4. Raw phase space distribution
5. Acceptance and Efficiency correction
6. Extrapolation to uncovered p_t (m_t) regions
7. Integration → dN/dy
8. 4π Yield



- Phase space distribution spanned by

$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

Rapidity y: Kinemetiacs in beam direction

Transverse mass m_t (momentum p_t) : Transverse Kinematics

Charged pion spectra analysis

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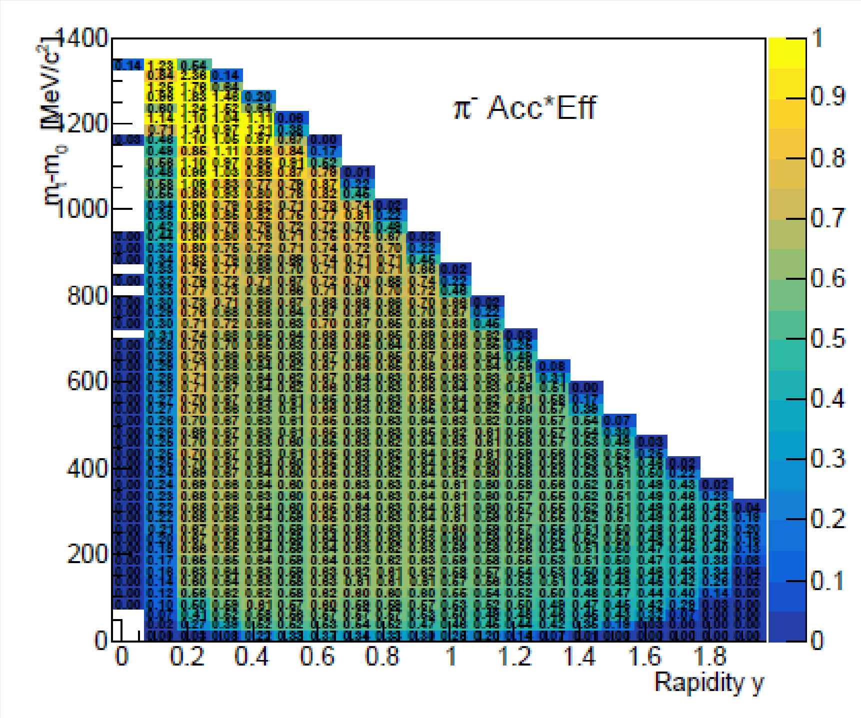
- Detector's acceptance is limited, selection criteria remove real particles → Correction necessary

$$Acc \cdot Eff = \frac{N_{rec,GEANT}(m_t, y)}{N_{UrQMD}(m_t, y)}$$



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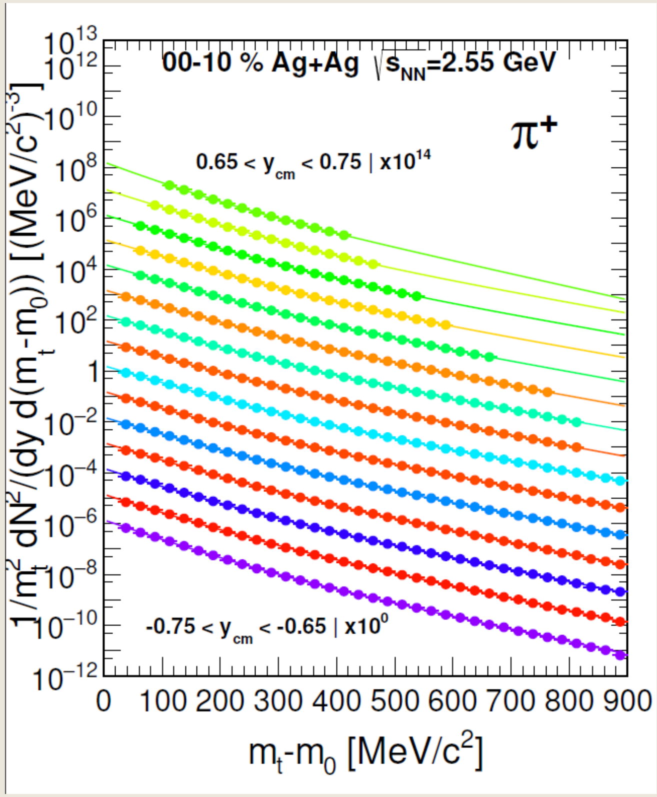
- No coverage toward zero and high transverse momenta → extrapolation



- Assuming Max-Well–Boltzmann statistic
- Two Inverse-Slope-Parameter to account for different energy transfers

$$\frac{1}{m_t^2}\frac{d^2N}{dm_t dy} = A\left(f\, e^{-\frac{m_t}{T_1}} + (1-f)e^{-\frac{m_t}{T_2}}\right)$$

Charged pion spectra analysis

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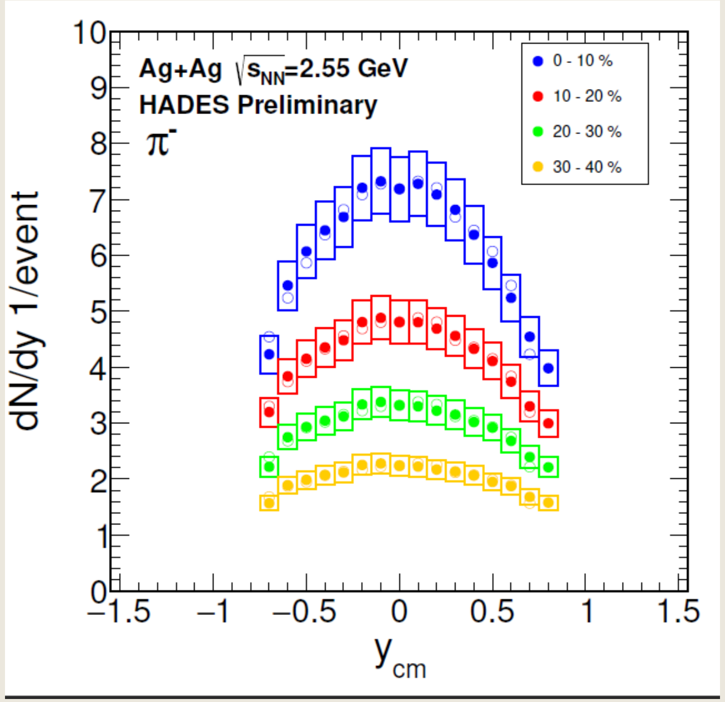


- Integration over dm_t lead to the rapidity density distribution dN/dy
- Using transport models (e.g. UrQMD) to extrapolate into uncovered region

How to extrcat the Coulomb potential?

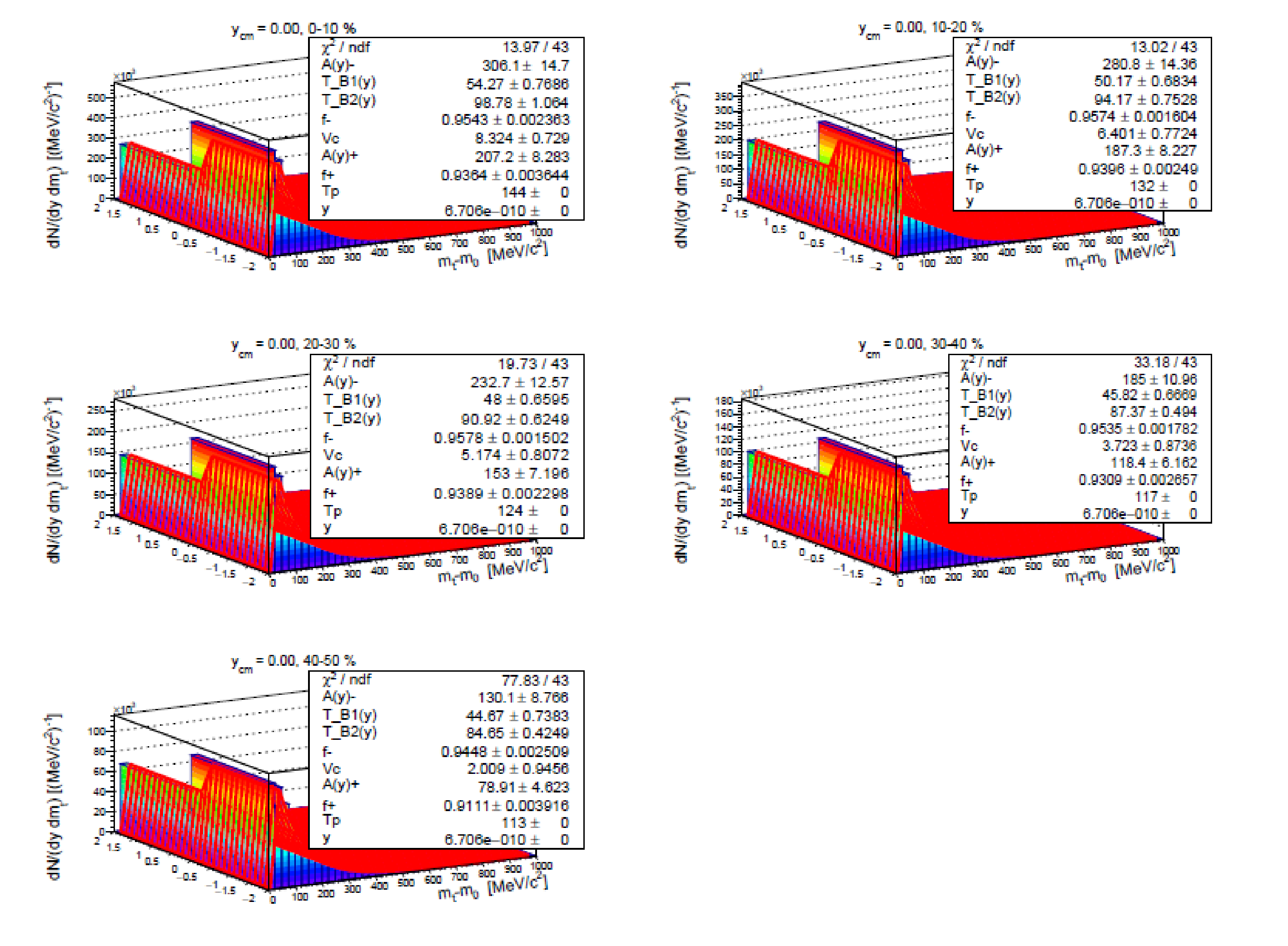
- The coulomb potential dependents on the pion‘s velocity
- Pions with a velocity smaller than the expansion velocity of protons feel a smaller potential → Energy dependence → Effective potential V_{eff}
- Assuming that the proton‘s velocities follow a nonrelativistic Boltzmann distribution:

$$V_{eff} = \begin{cases} V_c\left(1 - e^{-x^2}\right) & \mathit{2D\ cylindrical\ geoemetry} \\ V_c\left(\mathrm{erf}(x) - \left(\frac{2}{\sqrt{\pi}}\right) x\, e^{-x^2}\right) & \mathit{3D\ spherical\ geometry} \end{cases}$$

H. W. Barz et al. Coulombeffects on particle spectra in relativistic nuclear collisions
. In: Phys. Rev. C 57 (5 May 1998), pp. 25362546. doi: 10.1103/PhysRevC.57.2536. url: https://link.aps.org/doi/10.1103/PhysRevC.57.2536.

How to extrcat the Coulomb potential?

Ag+Ag 1.58 AGeV

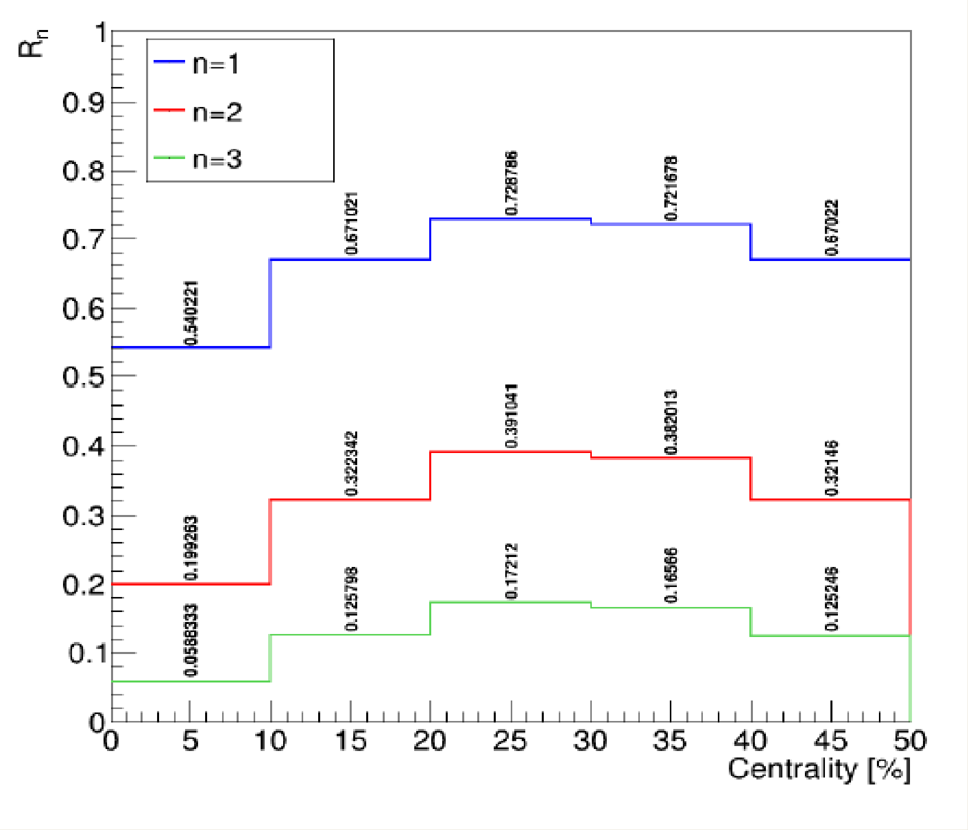


- 2D fitting procedure, assuming common V_c and common inverse slope parameters for the two polarities

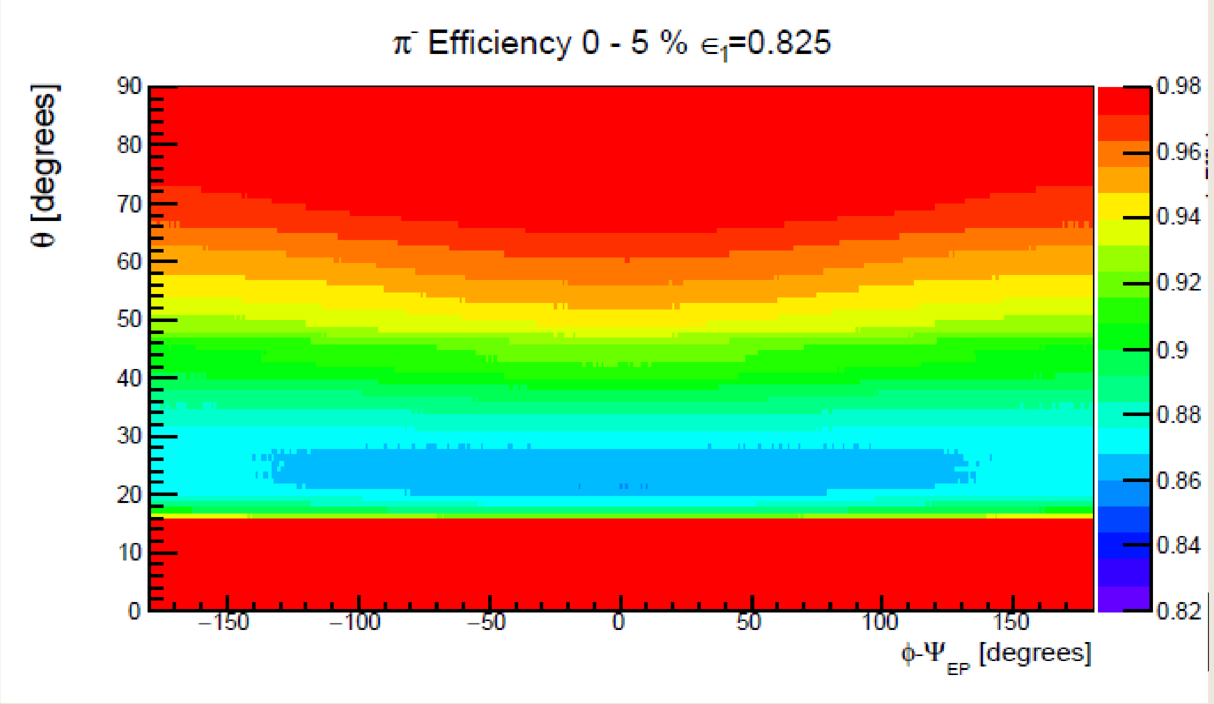
$Vc = 8.1 \pm 0.6\ MeV$ for 0-10 %

Azimuthal flow analyis – Experimental corrections

- **Ollitrault correction**



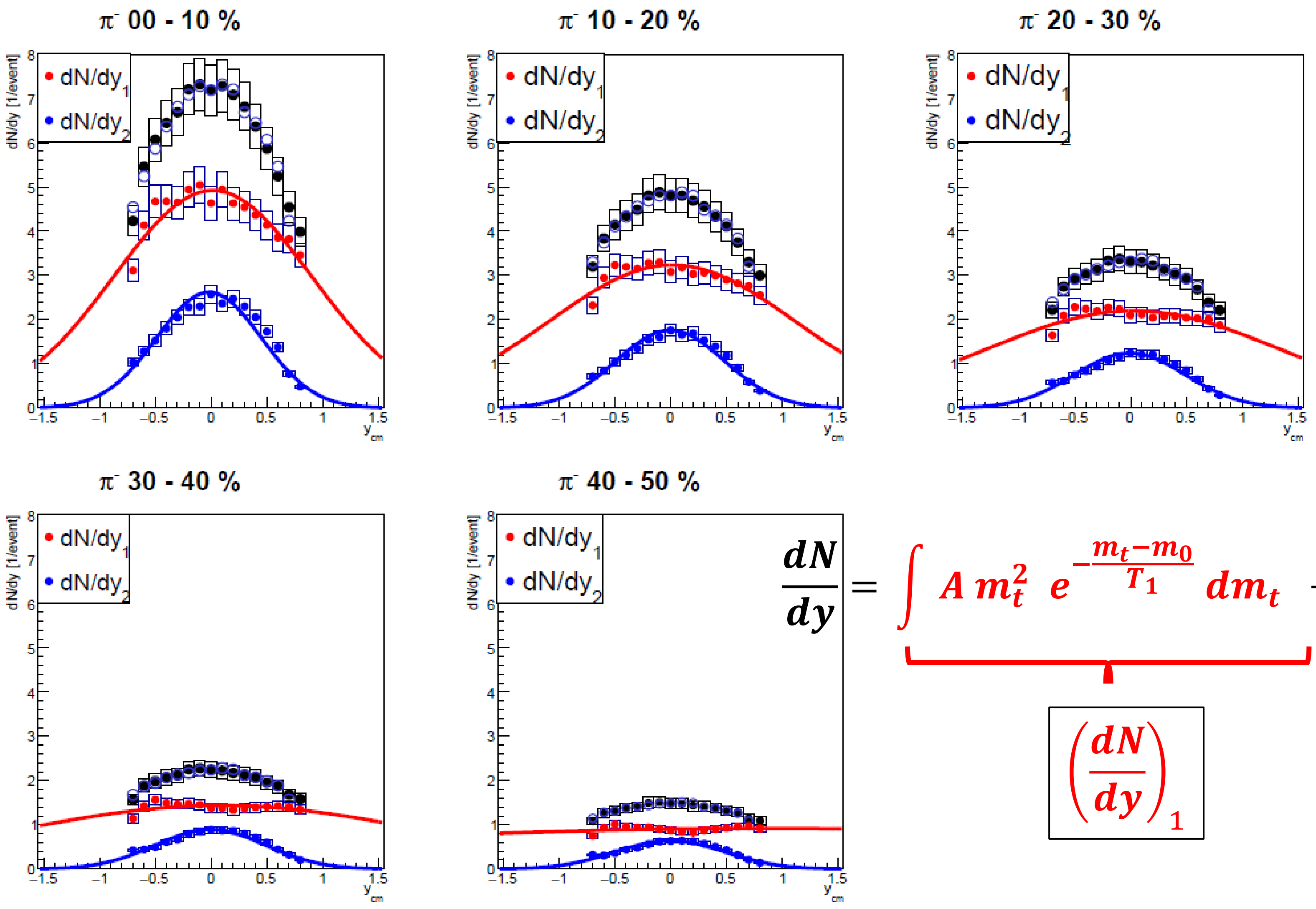
- **Occupancy correction**



For details see: [Phys.Rev.Lett. 125 (2021) 26, 262301]

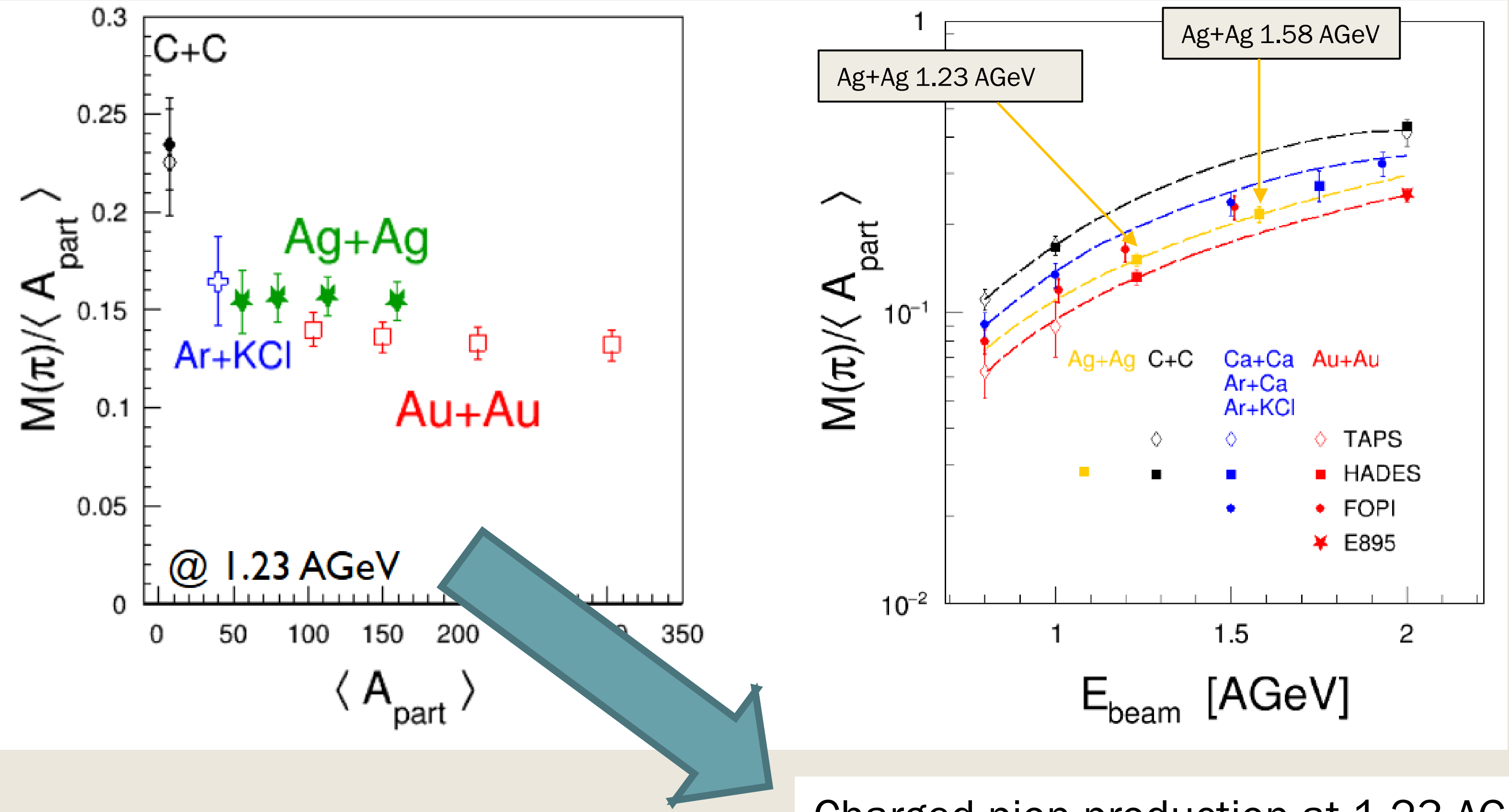
dN/dy in low ("Delta like") and high pt ("Fireball like")

Ag+Ag 1.58 AGeV



$$\frac{dN}{dy} = \underbrace{\int A\, m_t^2\, e^{-\frac{m_t - m_0}{T_1}}\, dm_t}_{\left(\frac{dN}{dy}\right)_1} + \underbrace{\int B\, m_t^2\, e^{-\frac{m_t - m_0}{T_2}}\, dm_t}_{\left(\frac{dN}{dy}\right)_2}$$

Yield comparison with world data and scaling with number of particpiants



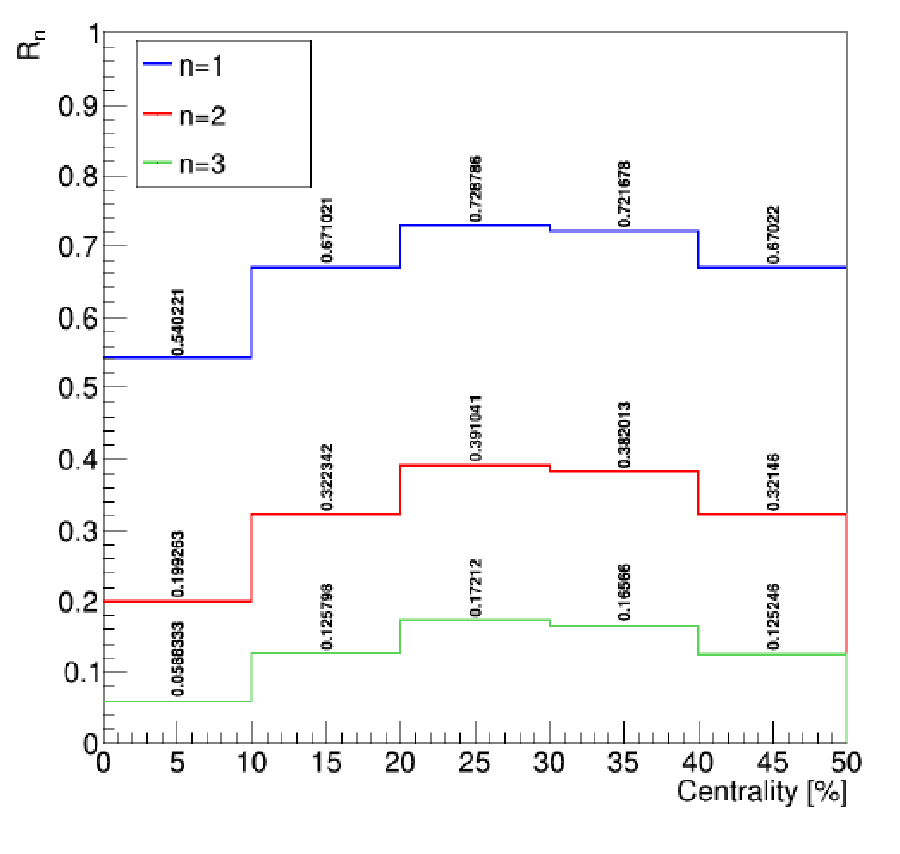
- Assuming iso-spin symmetry: $M(\pi^0)$ = ½ $M(\pi^-) + M(\pi^+)$
- Ag+Ag yield in between Ca+Ca,Ar+Ca,ArKCl and AuAu
- Approx. linear Apart scaling
- Excitation function for Ag+Ag:

$$\frac{M(\pi)}{A_{part}} = a_0 + a_1\,E_{beam} + a_2\,E_{beam}^2$$

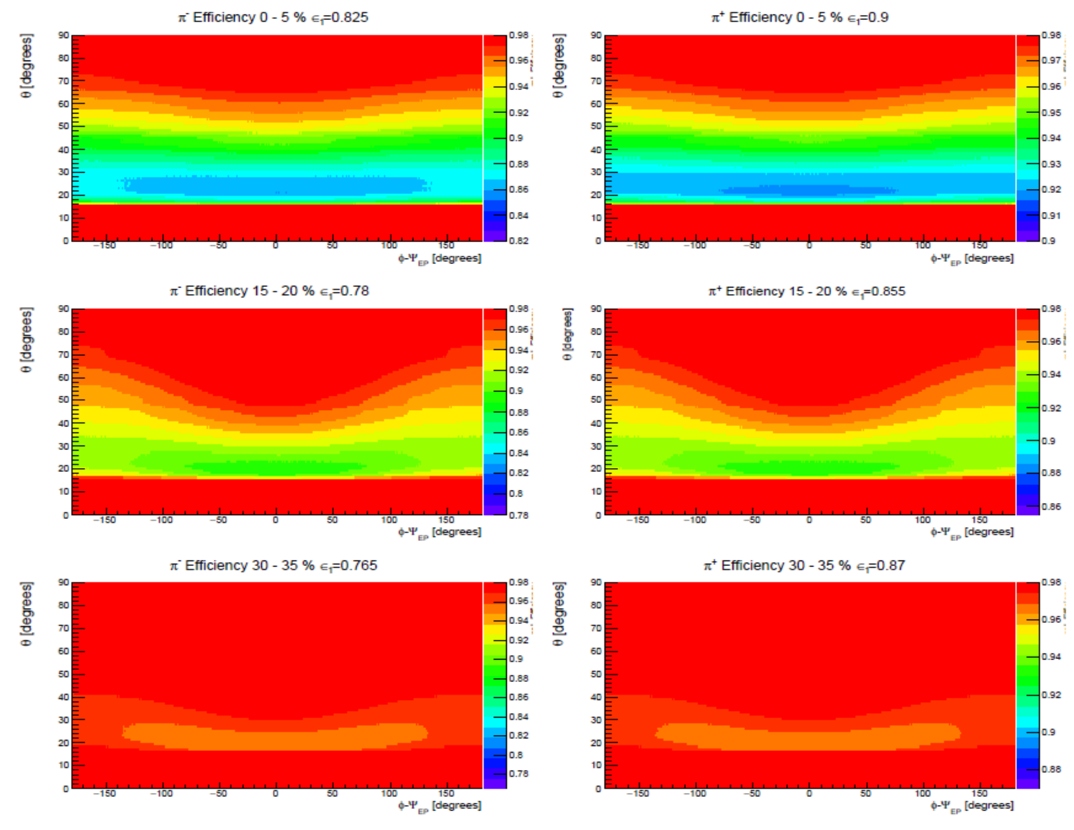
Charged pion production at 1.23 AGeV: see talk from Jan Orlinski

Charged pion azimuthal flow analyis– Experimental corrections

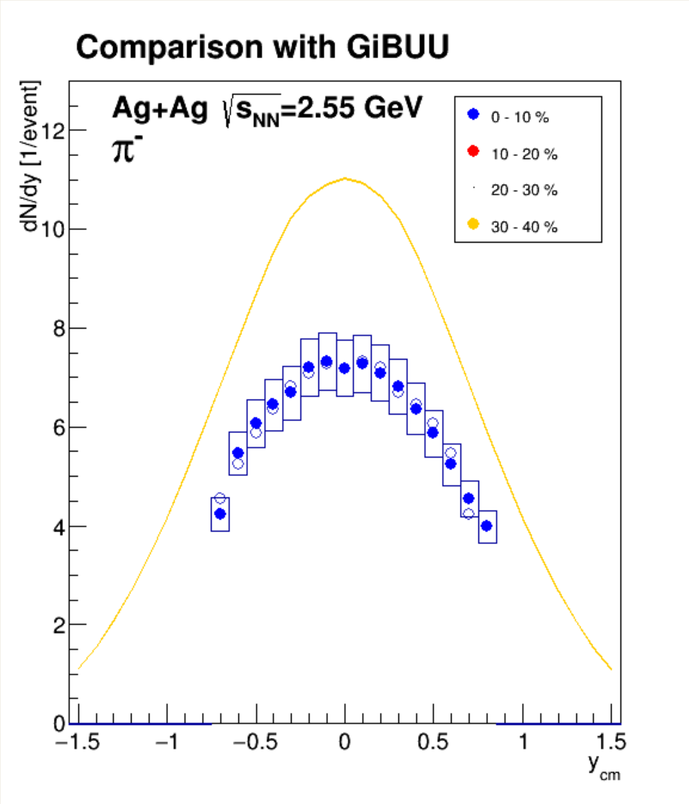
➢ **Ollitrault correction**

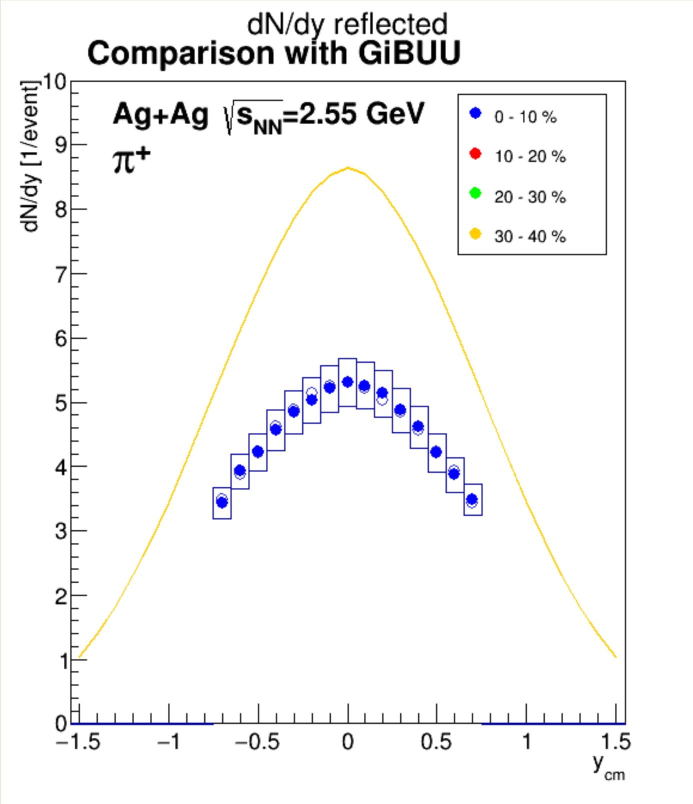


➢ **Occupancy correction**



Comparison with transport models





- Ag+Ag: Model comparison started for GiBUU → same trend as for Au+Au → too high yield