Neutral meson flow and yield in $AgAg@1.58AGeV$ at HADES

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Outline

1. HADES apparatus and Ag+Ag experiment
2. Calibration of the new Electromagnetic calorimeter (ECAL)
   - Lepton precalibration
   - π^0 peak calibration
3. π^0 yield
   - Efficiency-acceptance corrections (embedding)
   - Systematics
   - Comparison to average of charged pions and world data
4. π^0 flow
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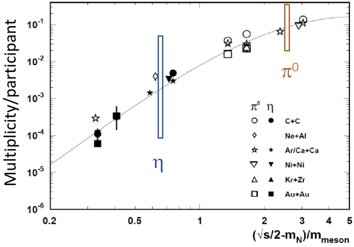
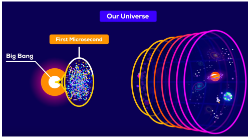
Motivation

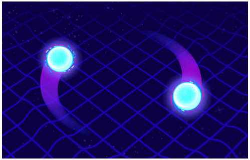
- Study of particle production from fireball and constrains of EOS
- Neutral meson production is an important observable to study reaction mechanism and normalize dilepton yield
- With ECAL $\rightarrow$ studying of various reaction channels with photons (e.g. hyperons)



Phys.Rec. C67 (2003) 024903

Equation of state





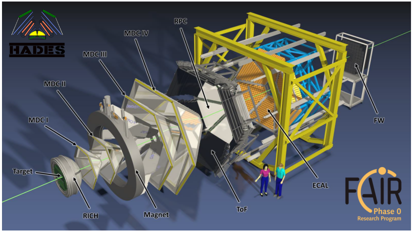
Neutron star merger

Kurzgesagt.org*

HADES apparatus

The HADES apparatus

- Fixed target experiment at SIS18 (GSI, Germany)
  - Large acceptance
  - Symmetric azimuthal coverage
  - 18° - 85° in polar angle
  - Magnet up to 3.6T
- Particle identification :
  - **RICH** – leptons
  - **RPC/TOF** – hadrons + trigger
  - **ECAL** – photons and leptons
  - **MDC** – tracking system
  - **Forward Wall** – reaction plane reconstruction



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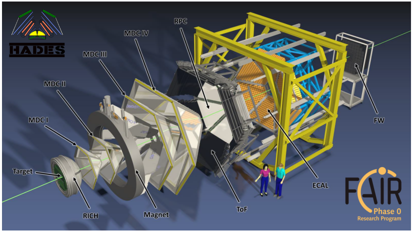

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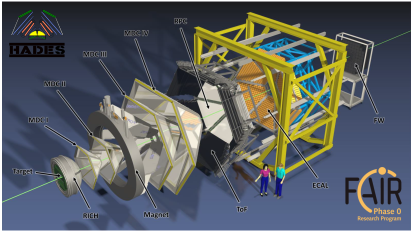

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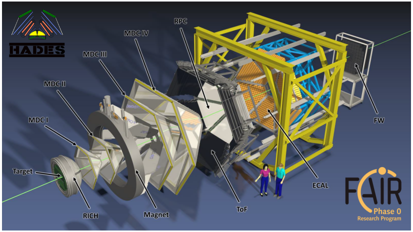

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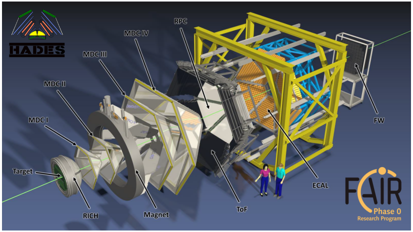

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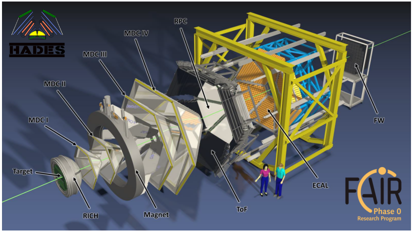

The Ag+Ag experiment

- Collected about 14 billion events in Ag+Ag@1.58A GeV experiment in March 2019
- New electromagnetic calorimeter ECAL is based on lead-glass modules → detection of direct photons
- ECAL was used for the first time
  - 4 sectors were installed in March 2019
  - by end of 2022 – full setup

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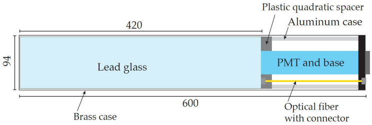

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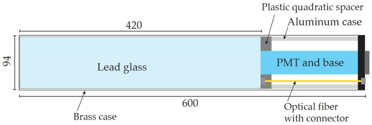

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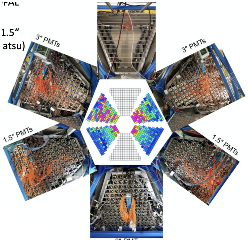

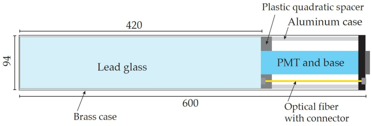

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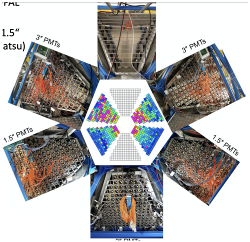
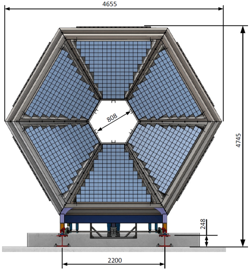
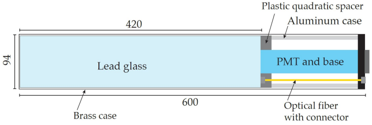
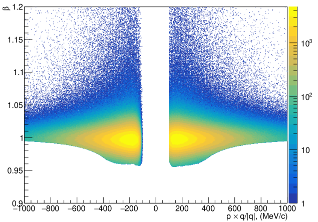






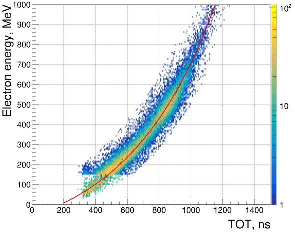
ECAL calibration

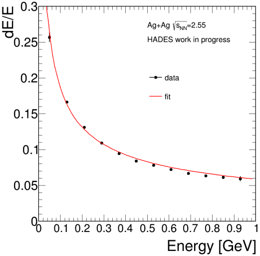
Lepton precalibration



A pure sample of leptons identified in the rest of HADES detector. The ECAL signal is measured in Time-over-Threshold (TOT)

$$E = a_0 + \exp\left(a_1 + a_2\, TOT\right)$$

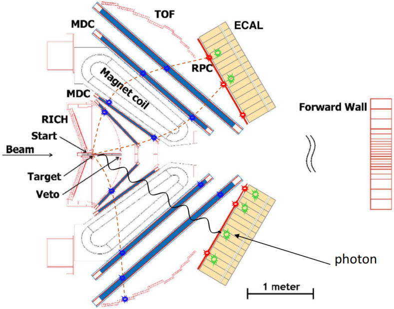




$$\frac{dE}{E} = \frac{5.9\%}{\sqrt{E}}$$

π^0 identification via 2-photon decay

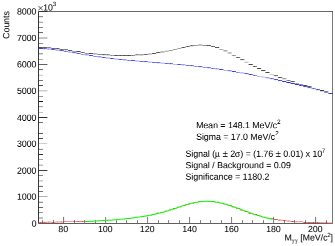
- Standard good event selection
- Photon selection
  - No match with RPC
  - No match with Runge-Kutta track
  - Minimum energy 100 MeV
  - ECAL beta cut : $\beta_{ECAL} < 1\sigma$
- Fit invariant mass of photon pairs
- Subtract mixed-event background



ECAL Calibration based on π^0 mean mass

$$m_{\pi^0} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\Theta_{12})},$$

Before calibration



$m_{\pi^0} = 148.1$ MeV

$\sigma_{\pi^0} = 17.0$ MeV

Same-event pairs Mixed-event CB Subtracted Signal Fit

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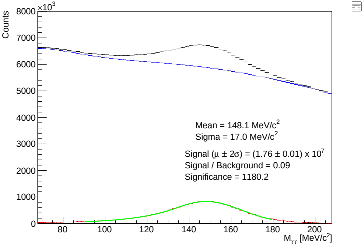

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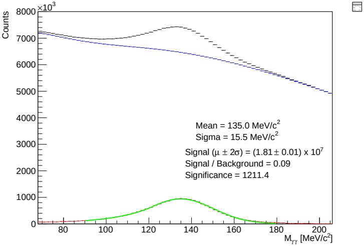
After $k = 14$ iteration steps



$m_{\pi^0} = 135.0$ MeV
$\sigma_{\pi^0} = 15.5$ MeV

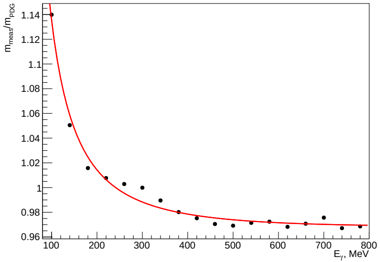
Same-event pairs Mixed-event CB Subtracted Signal Fit

Energy non-linearity correction

Sources of nonlinear response:

- For lower energies:
  - threshold settings
  - digitization
- For higher energies:
  - shower leakage

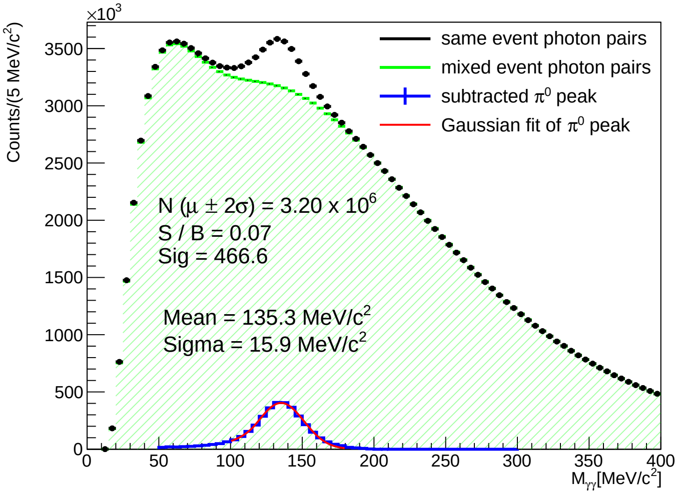
$$E_{corr} = aE + b\sqrt{E} + c + d/\sqrt{E} + e/E.$$



Estimation of nonlinearity using symmetric π^0 decays defined by $|E_{\gamma,1} - E_{\gamma,2}| < 0.05(E_{\gamma,1} + E_{\gamma,2})$.

Calibration results

20-30 % centrality



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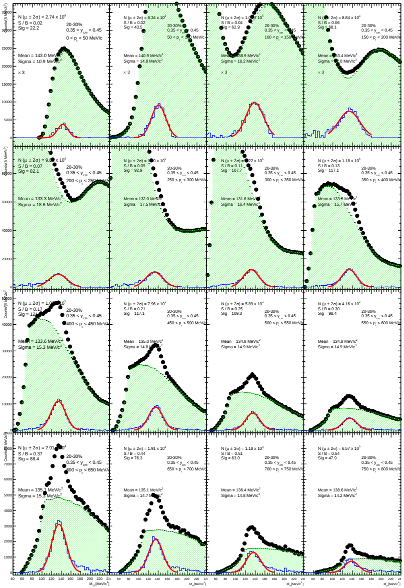
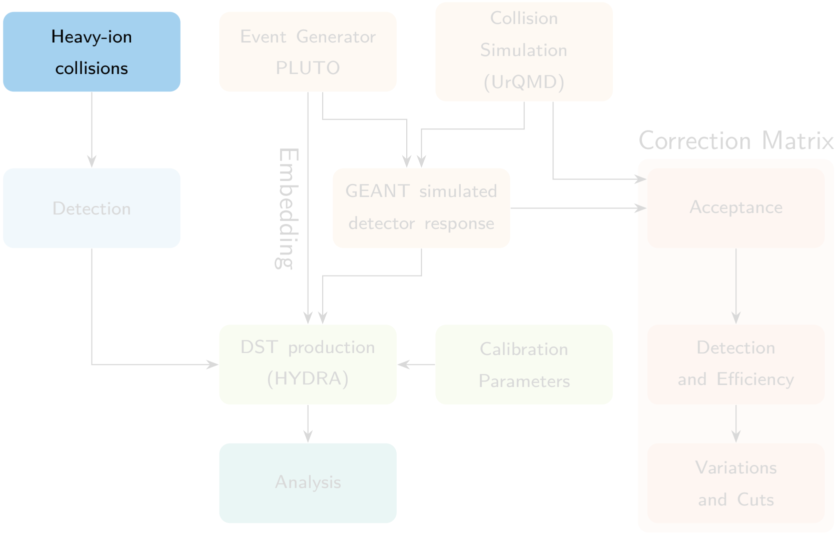


π^0 yield

Analysis scheme



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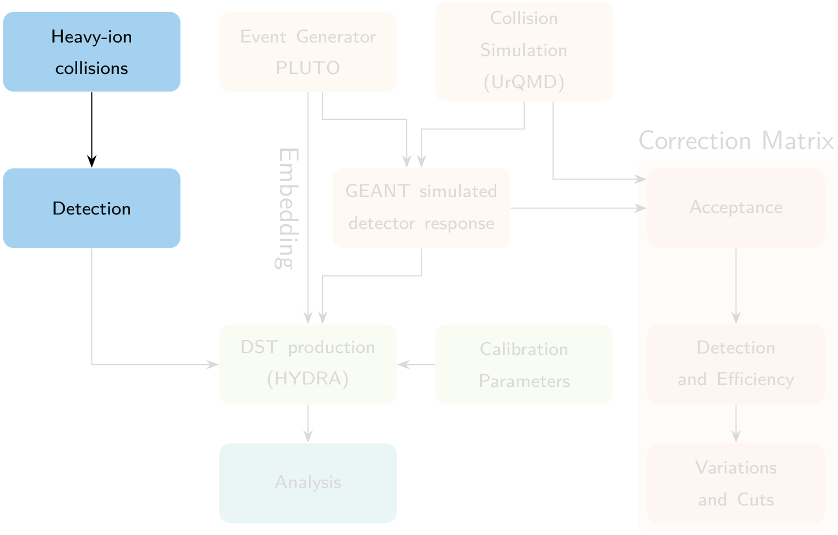

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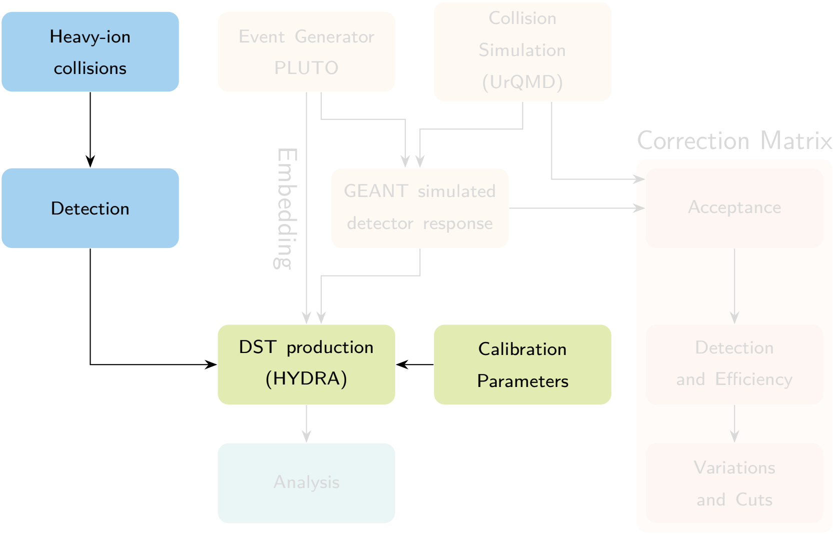

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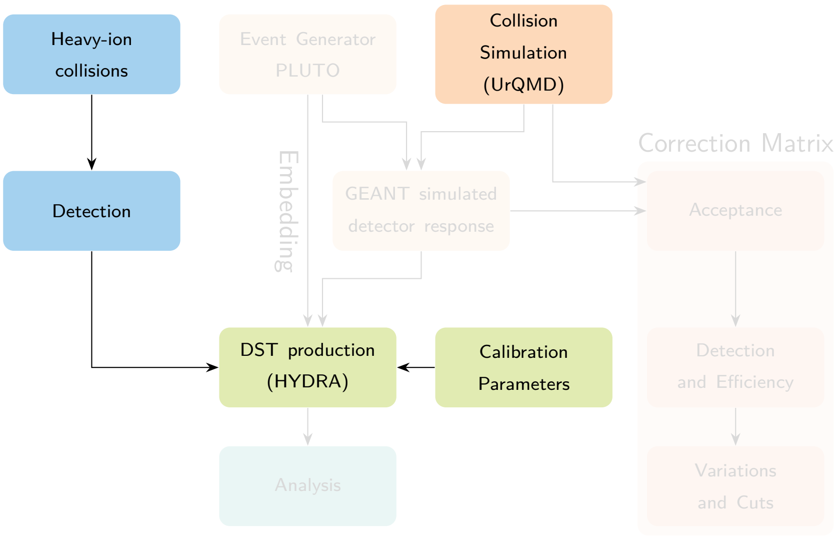

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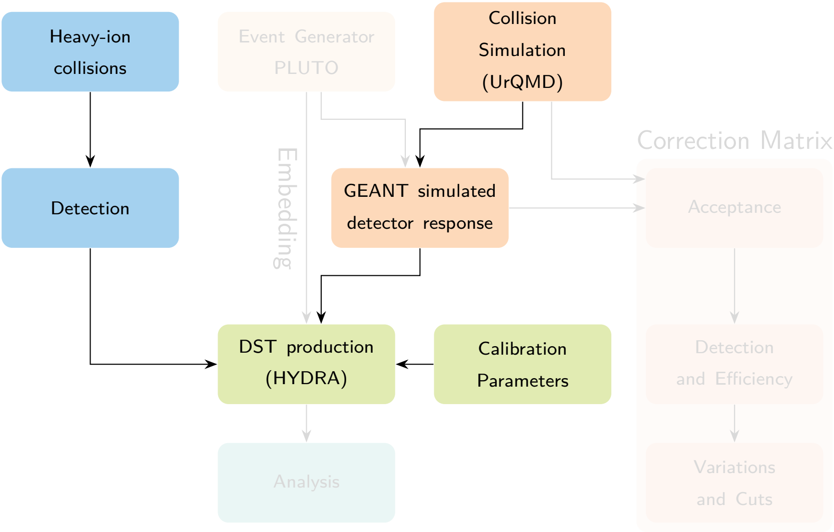

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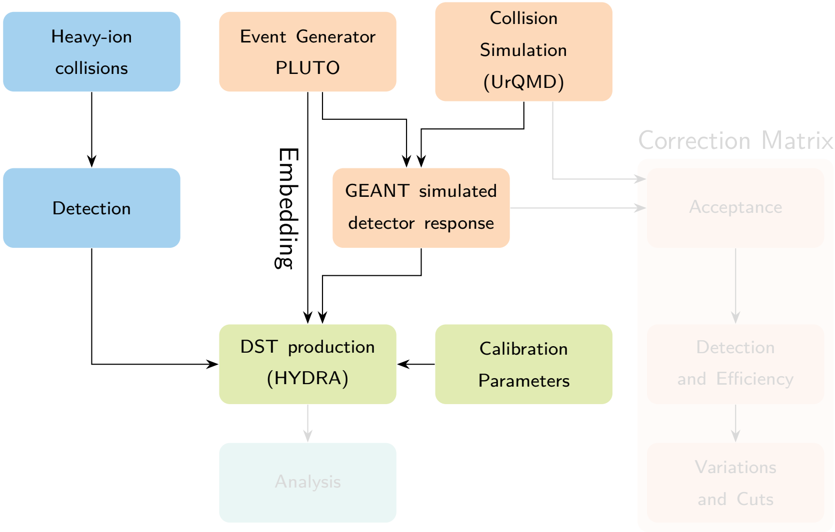

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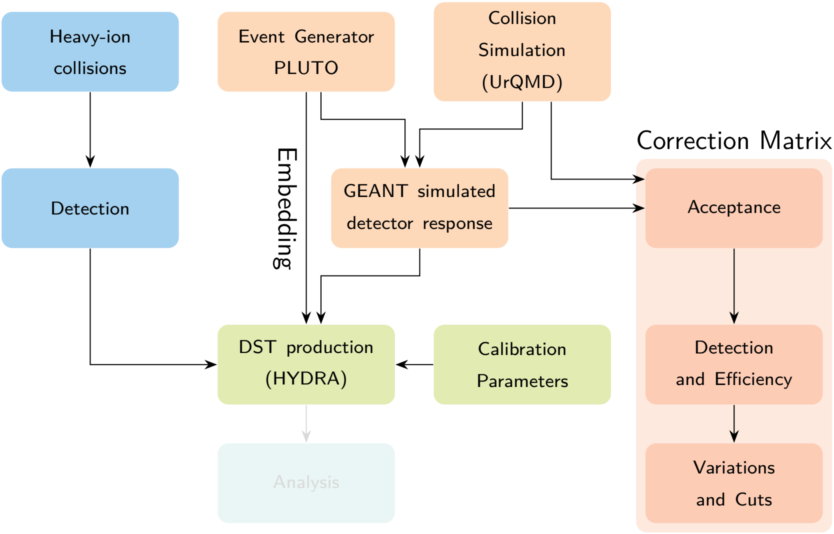

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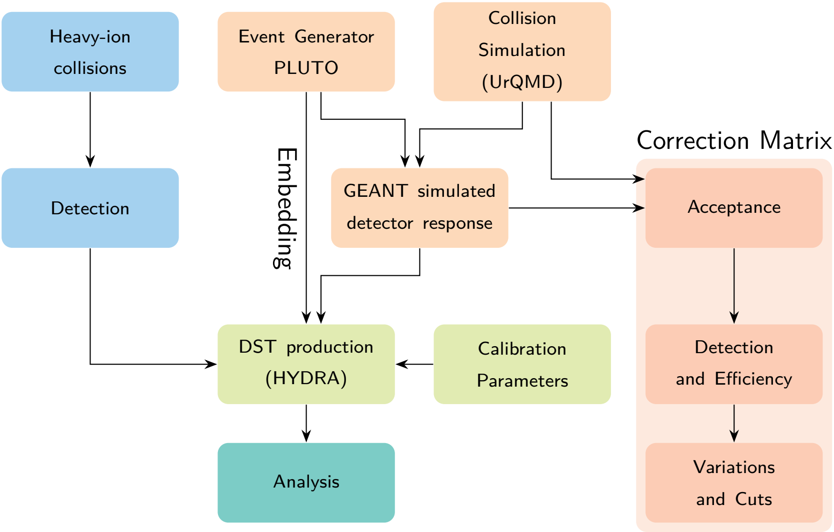
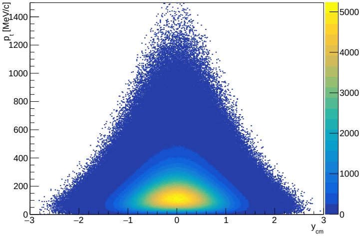
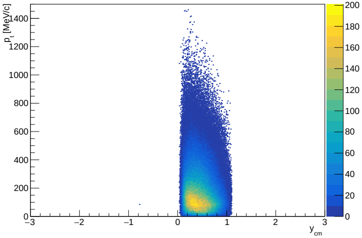


Efficiency-acceptance corrections

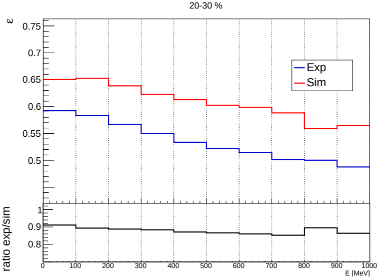
PLUTO original distribution



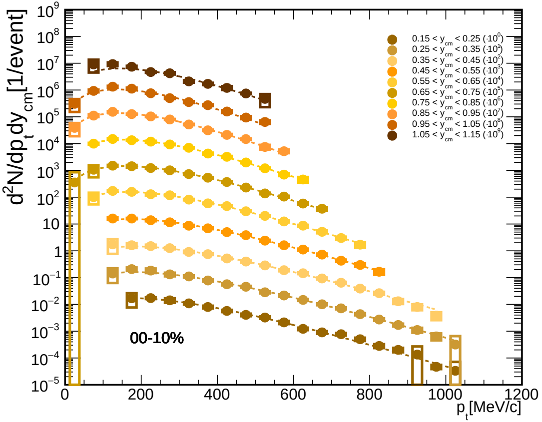
In ECAL acceptance



Efficiency of photons from embedding:



π^0 Phase Space distribution 0-10 %



$$\frac{dN}{dp_t} = C p_t m_t \exp\left(-\frac{m_t}{T}\right).$$

Systematics

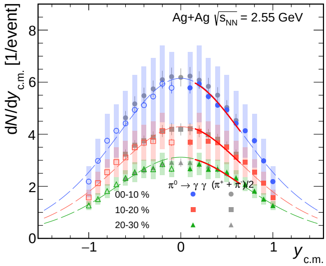
There were several sets of variations performed for each phase space bin, including:

- photon velocity β cut
- photon minimum energy E_{min}
- cluster size cut
- number of mass bins
- normalization
- extraction region
- matching with RPC in time Δ_t
- matching with track in position Δ_{xy}
- ECAL sector combinations

The systematical error is calculated as follows:

$$\sigma_{var\ sys} = |N_{\pi^0} - N_{\pi^0}^{var}|, \quad \sigma_{total\ sys} = \sqrt{\sum_{variations} {\sigma^2}_{var\ sys}}$$

Pion production yields

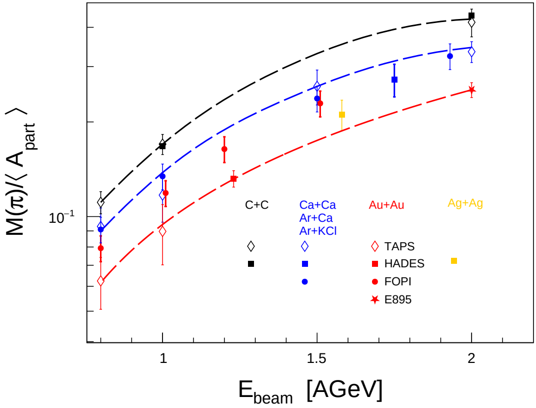


Centrality	$1/2(M(\pi^+) + M(\pi^-))$	$M(\pi^0)$
00-10 %	11.8 ± 1.3	11.8 ± 1.8
10-20 %	8.25 ± 0.9	8.1 ± 1.5
20-30 %	5.9 ± 0.7	6.1 ± 1.1

The extrapolation for the transverse kinematics is based on the Boltzmann thermal distribution.

$$\frac{dN}{dy} \propto T \exp\left(-\frac{m_0 \cosh y}{T}\right)\left(m^2{}_0 + 2m_0\frac{T}{\cosh y} + 2\frac{T^2}{\cosh^2 y}\right)$$

Comparison to existing data



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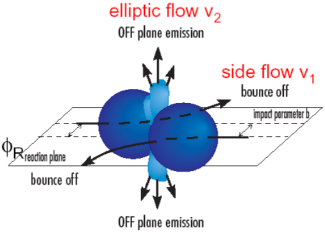
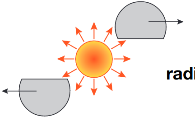
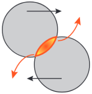
π^0 flow

Anisotropic (collective) flow



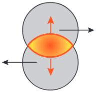


radial flow



directed flow

$$v_1 = \langle \cos(\phi) \rangle = \left\langle \frac{p_x}{p_t} \right\rangle$$



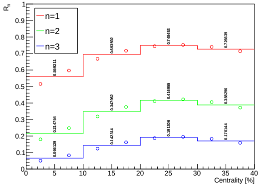
elliptic flow

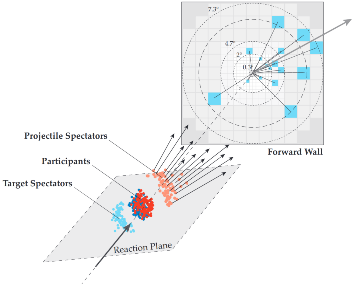
$$v_2 = \langle \cos(2\phi) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle$$

Flow determination

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_{RP})]\right)$$

- Resolution of EP reconstruction based on Ollitrault method described in *arxiv:nucl-ex/9711003*(2 subevent method)
- All further presented flow coefficients are corrected by resolution factors

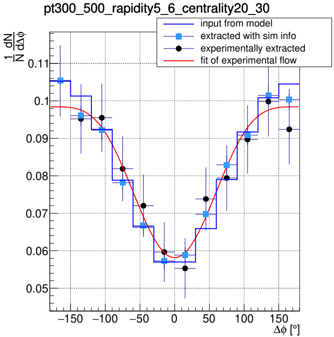




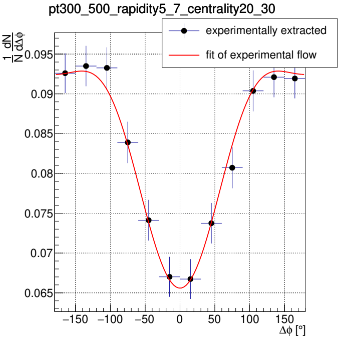
Centrality	0 — 10%	10 — 20%	20 — 30%
$\Re_1$	0.54	0.67	0.73
$\Re_2$	0.20	0.32	0.39

Check on simulations (closure test)

Simulation



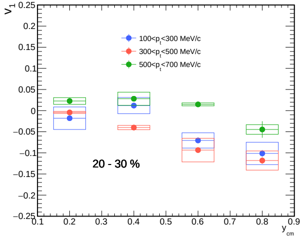
Experiment

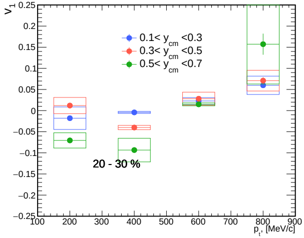


$$\frac{dN}{d\Delta\phi} = c \cdot \left(1 + 2\nu_1 \cos(\Delta\phi) + 2\nu_2 \cos(2\Delta\phi)\right)$$

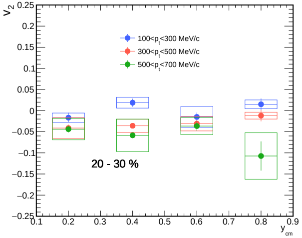
Results for 20-30 %

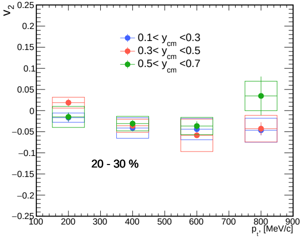
v_1





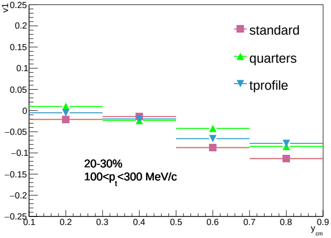
v_2



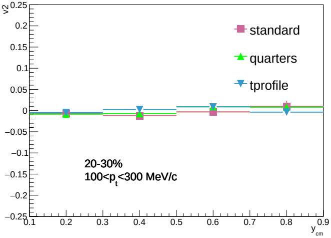


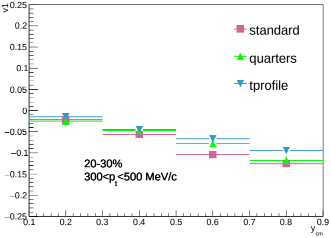
Systematics

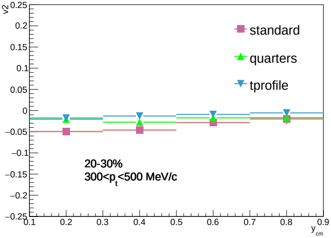
ν_1



ν_2

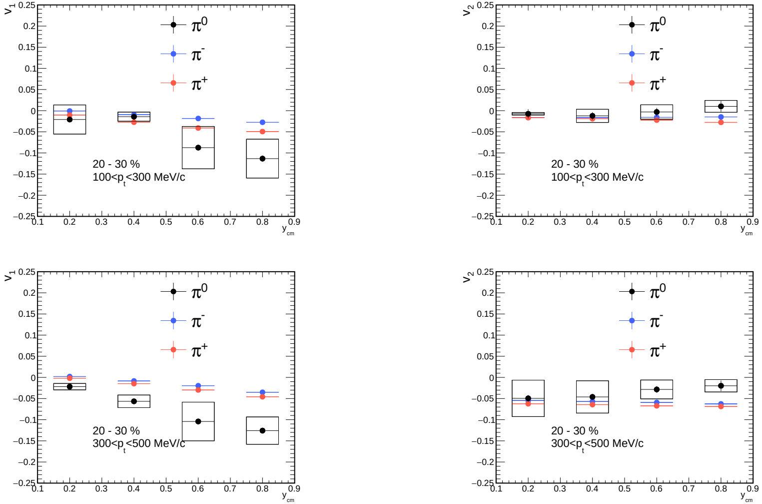






Comparison with charged Pions 20-30 %

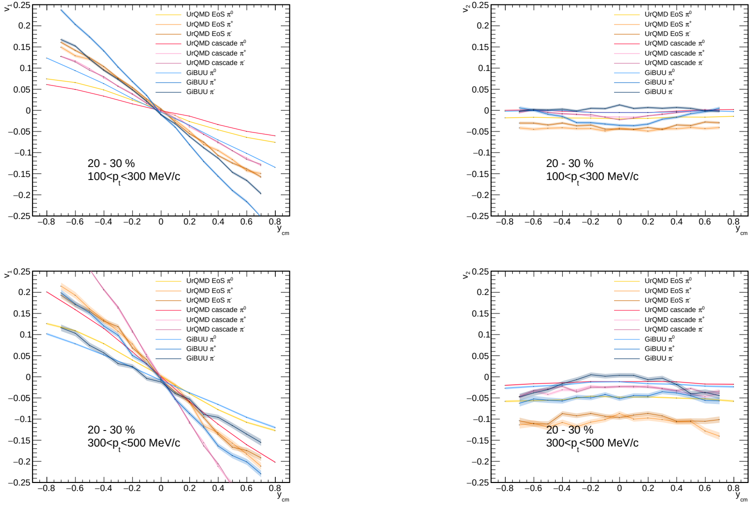
ν_1 ν_2



Emission patterns of charged pions from Ag+Ag collisions at 1.58A GeV. M.Nabroth

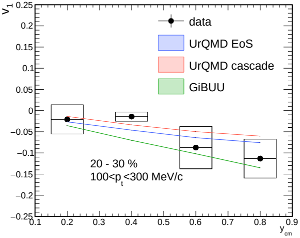
Models 20-30 %

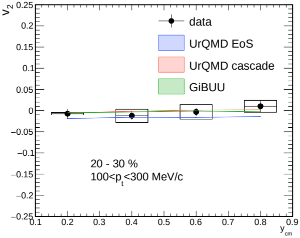
ν_1 ν_2

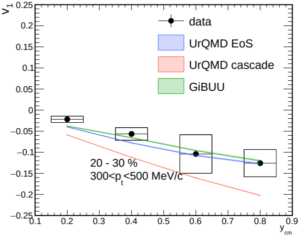


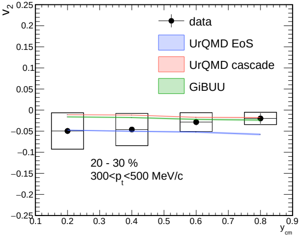
Comparison of models with data 20-30 %

ν_1 ν_2









Summary and Outlook

- First successful use of new ECAL detector
- Calibration methods were developed and applied, future experiments will use the calibration procedure as well
- π^0 yield was extracted and compared to existing data
- π^0 flow was calculated and can be used to tune simulation cascade models

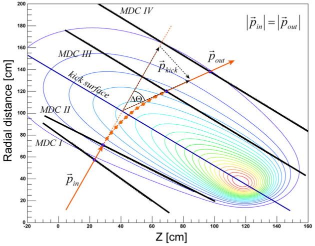
Work supported by:
MEYS CZ - LM2018112 grant
FAIR-CZ-OP grant CZ.02.1.01/0.0/0.0/16-013/0001677
FAIR-CZ-OP grant CZ.02.1.01/0.0/0.0/18-046/0016066
LTT17003

Thank you for your attention!

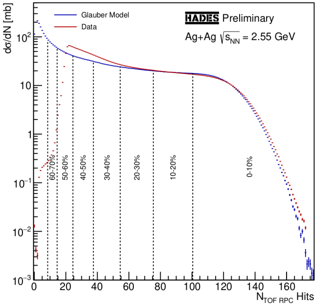
Backup

Tracking and centrality determination

- Momentum determination is done via Runge-Kutta method (approximate numerical solution of the equation of motion)
- Time-of-flight measurement is calculated by time difference between START and TOF/RPC detectors

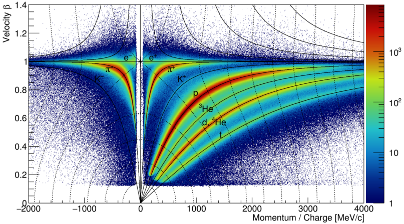


- The centrality is determined by TOF+RPC hit multiplicity and compared to Glauber MC model



Identification of charged particles

- By measuring time-of-flight and momentum : $m^2 \frac{1}{q} = \frac{p^2}{\beta^2\gamma^2 c^2} \frac{1}{q}$



- Energy loss in MDC and TOF via Bethe-Bloch

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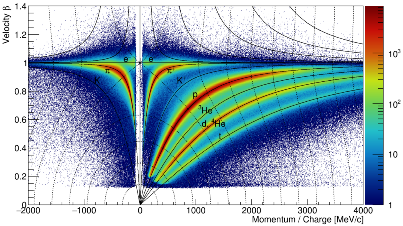

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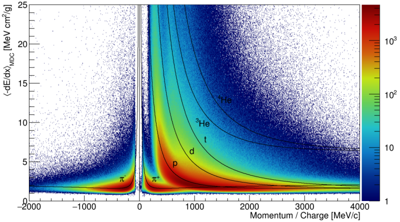
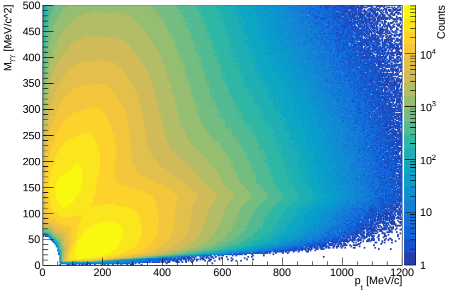
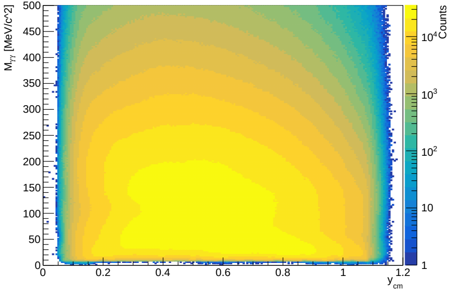
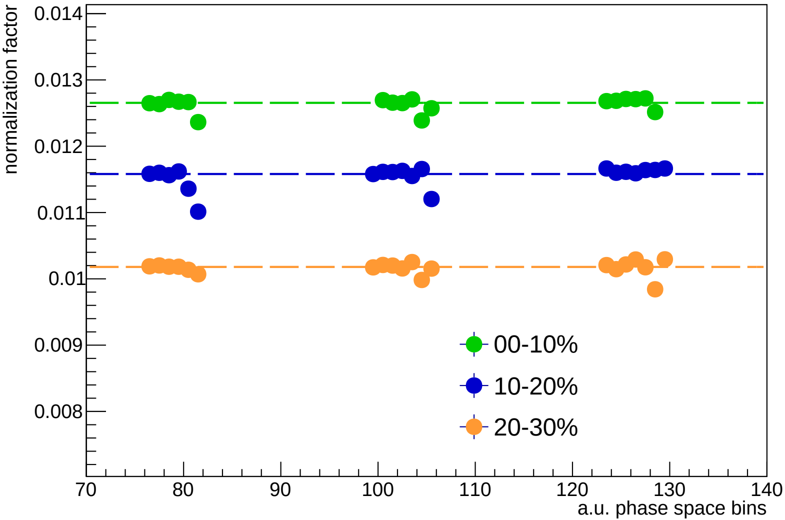


$P_t - y$ vs $M_{\gamma\gamma}$





Normalization factors

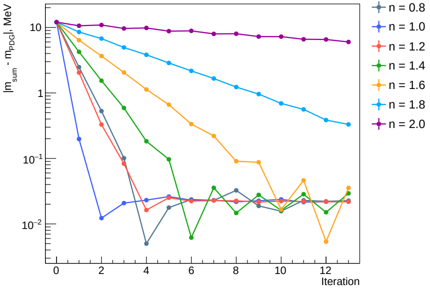


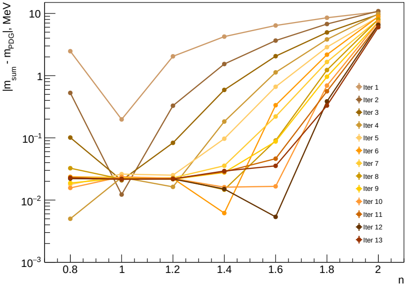
Calibration based on π^0 mean mass

Mass of π^0 : $m_{\pi^0} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\Theta_{12})}$

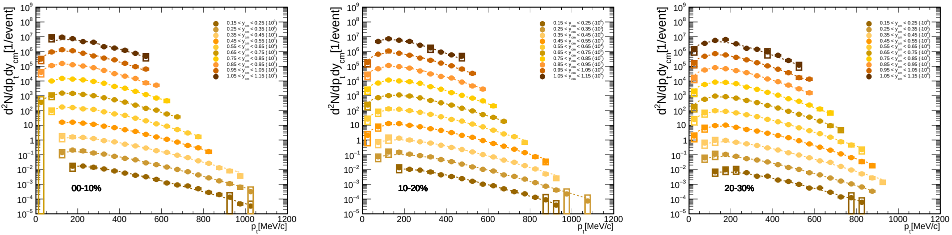
- For each cell i, fill invariant mass distribution, where one photon is in the cell i, second – anywhere in ECAL
- Find π^0 peak position by mixed-event CB subtraction, i.e. m_i
- At iteration step k calculate correction factor $c_i^k = c_i^{k-1} \cdot \left(\frac{m_{\pi^0 PDG}}{m_i}\right)^n, c_i^0 = 1.$
- Recalculate mass with new energies and repeat iterations $E_{corr,i} = c_i(E_{old,i}) \cdot E_{prev,i}$

Parameter n estimation for π^0 peak calibration

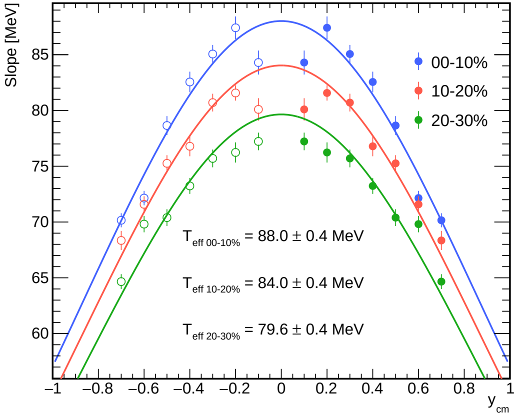




π^0 phase space distributions



Temperature extraction



$$T_B(y) = \frac{T_{eff}}{\cosh(y)} \tag{1}$$

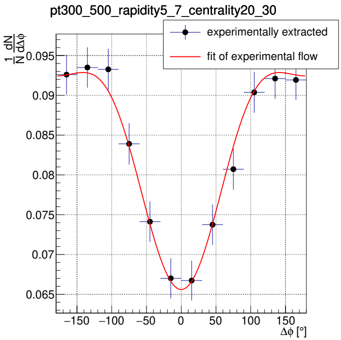
Flow methods

- Fourier decomposition

$$\frac{dN}{d\Delta\phi} \propto \left(1+2\sum \nu_n \cos(n\Delta\phi)\right)$$

- fitting TProfile histograms of $\cos(n\Delta\phi)$ vs m_{inv} with $\frac{S}{S+B}\nu_n + \frac{B}{S+B}Pol_3$

- "Quarters" method: Divide number of particles N in 4 parts around major axes $\Delta\phi = 0, 90, 180, 270°$



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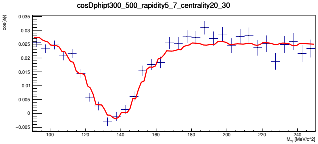

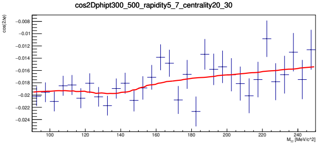

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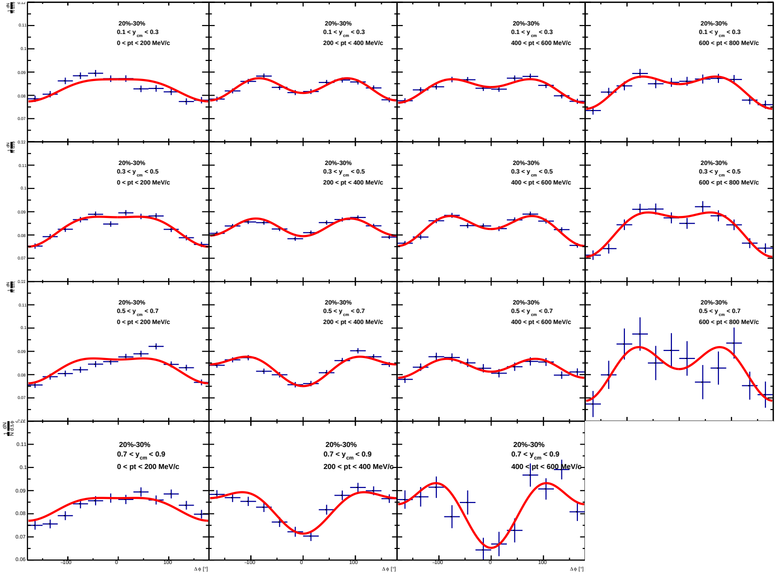
$$R_{in} = \frac{N_0}{N_{180}} \quad R_{out} = \frac{N_{90} + N_{270}}{N_0 + N_{180}}$$

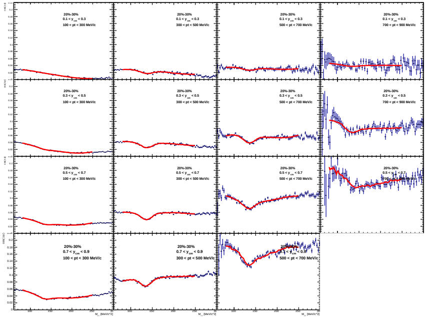
$$\nu_2 = \frac{1 - R_{out}}{2(1 + R_{out})}$$

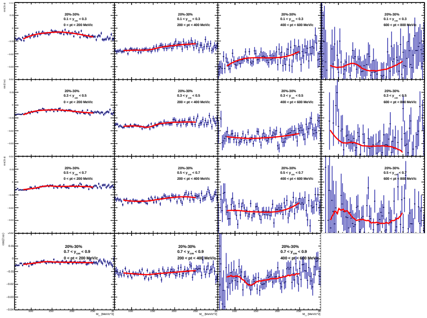
$$\nu_1 = \frac{(1 + \nu_2)(R_{in} - 1)}{2\sqrt{2}(1 + R_{in})}$$

Standard method check

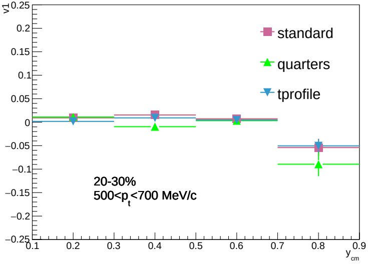


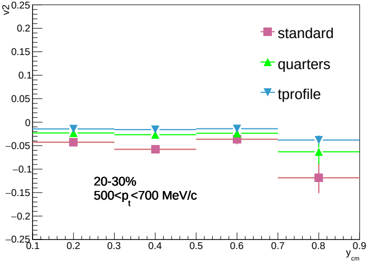
TProfile method check

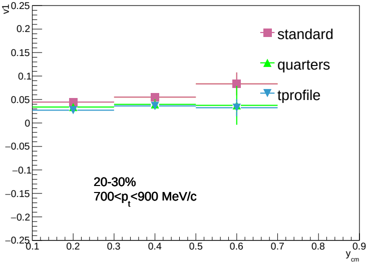


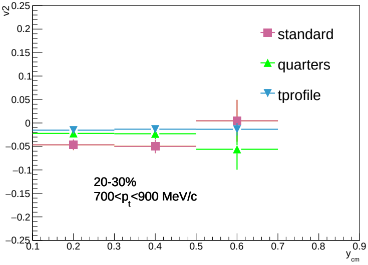


Systemtaics

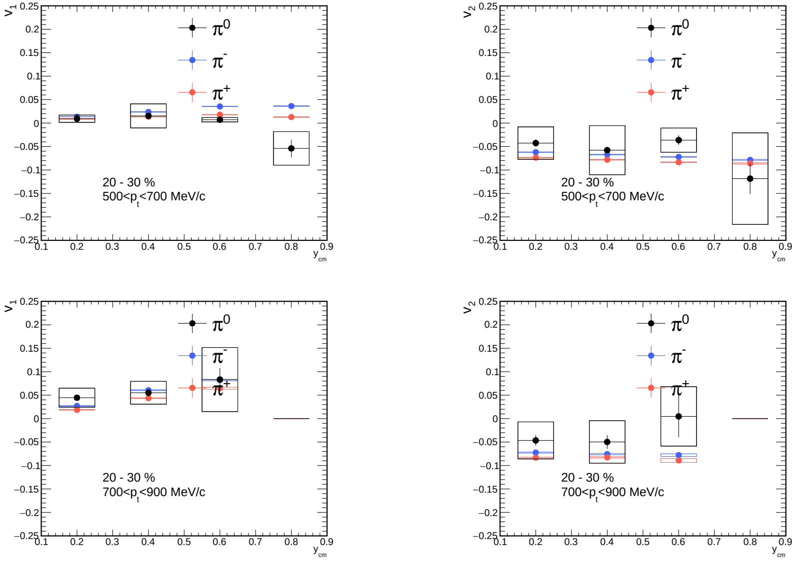




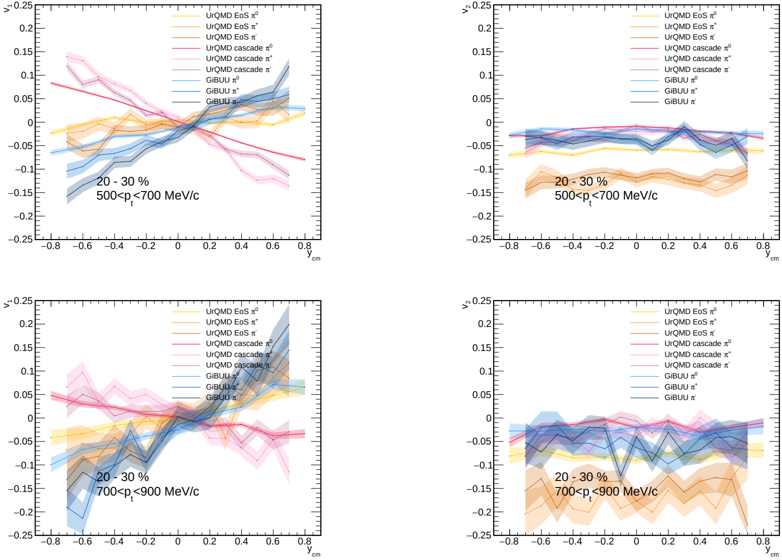




Charged Pions comparison 20-30 %



Models 20-30 %



v_1
v_2
y_{cm}
UrQMD EoS π^0
UrQMD EoS π^+
UrQMD EoS π^-
UrQMD cascade π^0
UrQMD cascade π^+
UrQMD cascade π^-
GiBUU π^0
GiBUU π^+
GiBUU π^-
20 - 30 %
500<p_t<700 MeV/c
20 - 30 %
500<p_t<700 MeV/c
20 - 30 %
700<p_t<900 MeV/c
20 - 30 %
700<p_t<900 MeV/c

Models comparison with data 20-30 %