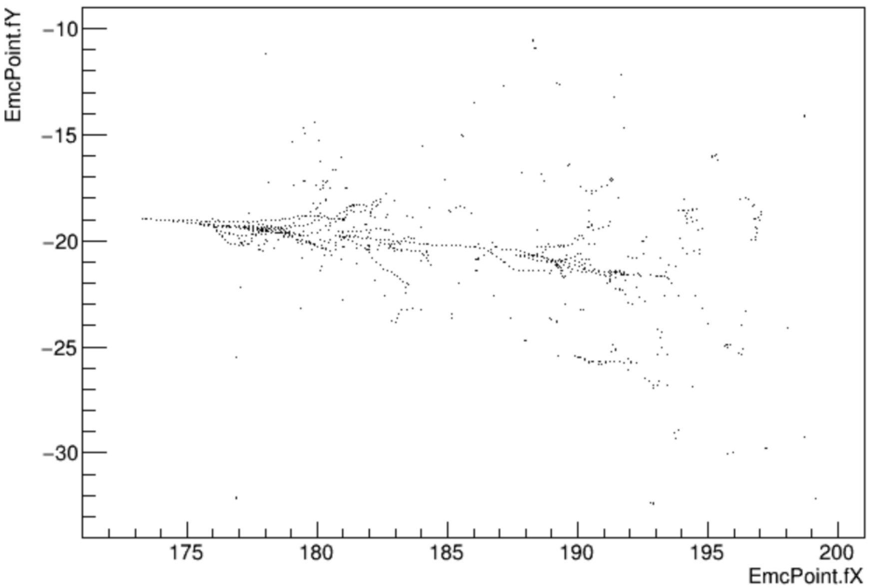
Nuclotron-based
Ion Collider fAcility

Progress in ECAL simulation

V. Riabov for the MPD



Status & structure

- Regular PWG4 meetings since Feb, 2019
  - ✓ https://mpdforum.jinr.ru/c/electromagnetic-probes

- PWG4 scope - electromagnetic probes:
  - ✓ electromagnetic calorimeter (ECAL) reconstruction software
  - ✓ reconstruction of photons and neutral meson in the ECAL and central tracking system ($\gamma \rightarrow e^+e^-$)
  - ✓ dielectron continuum in LMR/IMR, LVM (line shape, in-medium modifications etc.)
  - ✓ estimation of direct photon yields and feasibility studies

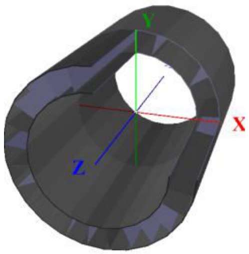
ECAL reconstruction software

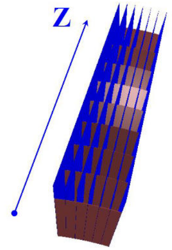
New digitizer-clusterizer

- A new digitizer-clusterizer (emcKI) has been released half an year ago
- Code is committed to Git and is used by default in the MpdRoot for the ECAL simulation/reconstruction
- Basic features:
  - ✓ works with the latest ECAL geometry, v.3
  - ✓ merged shower unfolding in high-multiplicity events → high efficiency of signal reconstruction
  - ✓ fast and efficient
  - ✓ disk space friendly
  - ✓ flexible and easy to tune to beam test results
  - ✓ ready to work with real data

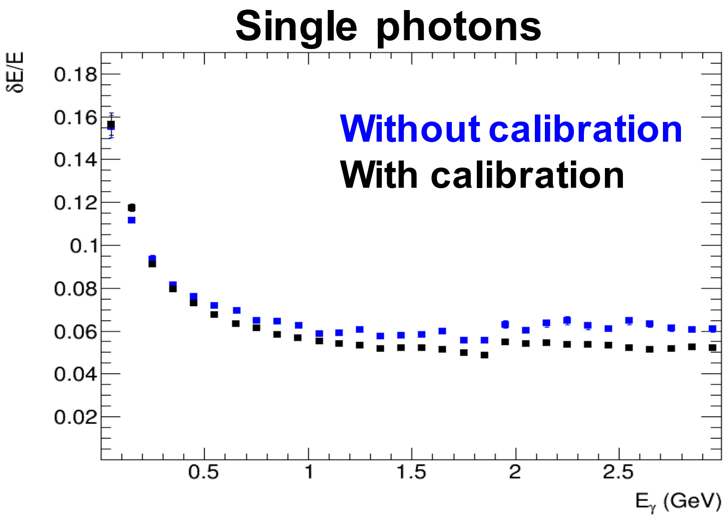
Basic features of the v.3 geometry and emcKI

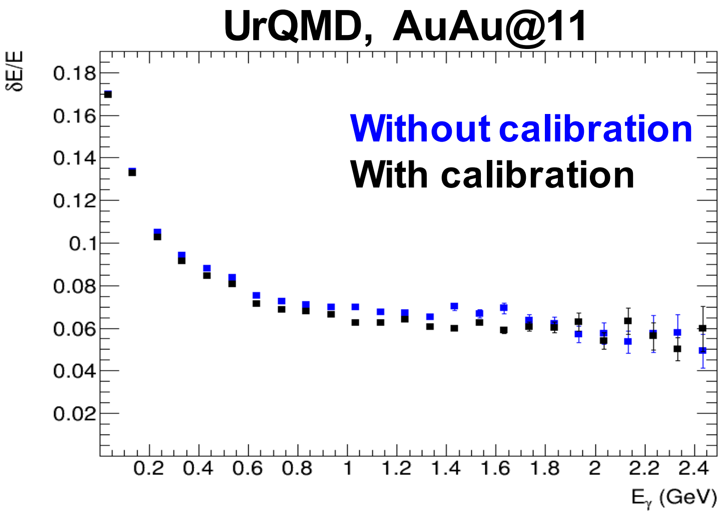
- Non-homogeneous acceptance, towers are intervened with carbon fiber support structures of different width (up to a few centimeters) → irregular structure → variance of the absolute scale
- Support structure of 12.7% X_0 in front of the towers (carbon fiber cylinder)





- Only ~ 60% of primary photons reach the ECAL surface, others convert (TOF+support frame+TPC/pipe)
- ~ 20% variation of a single photon efficiency with centrality at E_γ ~ 100 MeV due to cluster merging
- Large background: purity ~ 0.2 at E_γ ~ 100 MeV
- The real detector energy resolution is multiplicity dependent. The commonly quoted resolution of ~5%/√E can be reached only for <u>single photons</u> with <u>full light collection</u> in <u>ideal/homogeneous geometry</u>





Remaining critical tasks

- Simulated performance of the ECAL should be confirmed/tuned by the beam test results
  - ✓ light collection efficiency
  - ✓ noise level
  - ✓ energy linearity
  - ✓ spatial resolution
  - ✓ energy resolution
  - ✓ shower shape
  - ✓ etc…
- Beam test results are needed for a large prototype (~8x8 towers) in realistic geometry (including passive materials in front and between the towers - carbon fiber frame, glue) with final electronics (including air gaps) for a few electron beam energies
- Absence of such 'beam test results' will eventually result in irreducible systematic uncertainties of measurements in the ECAL: reduced accuracy of calibrations and alignment by physical signals (π^0, $e^{\pm}$ or MIP peaks) due to inability to disentangle the geometry and the energy scale corrections
- Need closer cooperation between the construction and simulation teams

Neutral mesons in ECAL

Neutral mesons in heavy-ion collisions

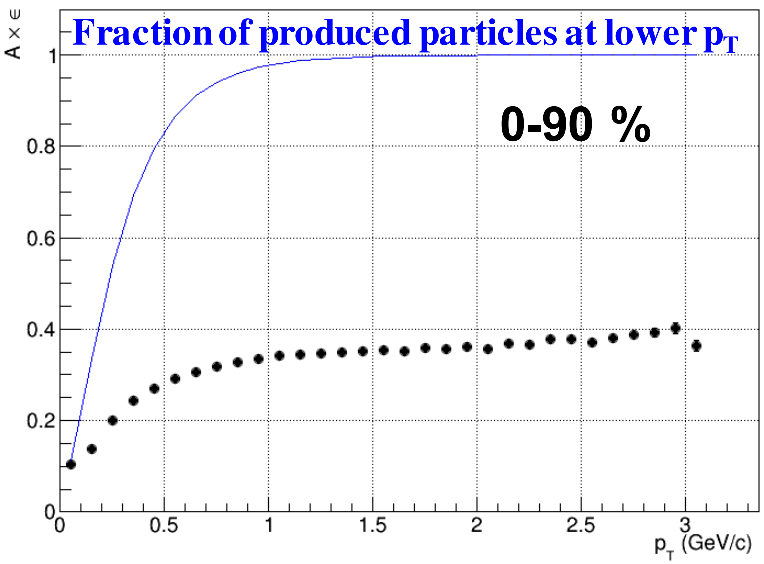
- Wide variety of neutral mesons:
  - ✓ π^0 ($\pi^0 \rightarrow \gamma\gamma$)
  - ✓ η ($\eta \rightarrow \gamma\gamma$, $\eta \rightarrow \pi^0 \pi^+ \pi$)
  - ✓ K_s ($K_s \rightarrow \pi^0 \pi^0$)
  - ✓ ω ($\omega \rightarrow \pi^0 \gamma$, $\omega \rightarrow \pi^0 \pi^+ \pi$)
  - ✓ η' ($\eta' \rightarrow \eta\, \pi^+ \pi$)

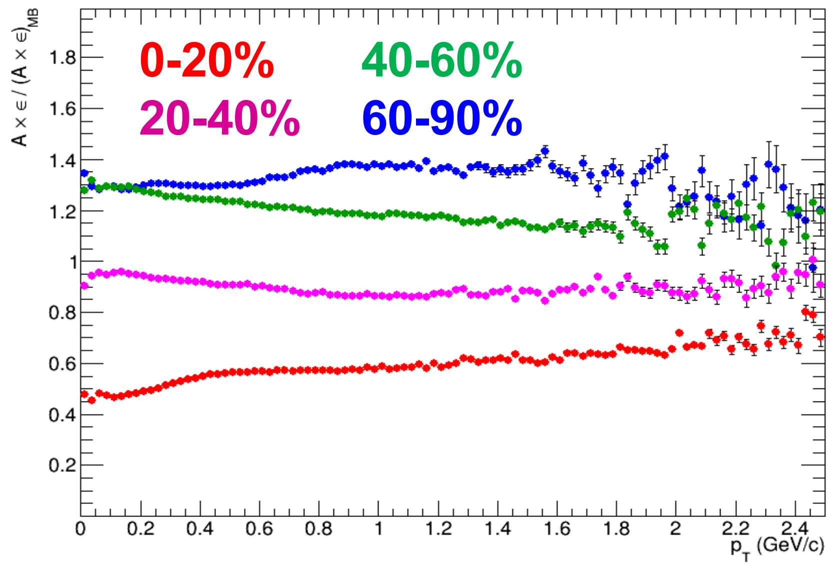
- Neutral mesons are of great interest:
  - ✓ complementary measurements to identified charged hadrons with different systematics
  - ✓ collective flow, parton recombination and energy loss, strangeness production etc. probed with particles of different masses, quark contents/counts
  - ✓ dominant background for other observables such as direct photons, e_{HF} and di-electrons

- π^0, η are the most promising signals for day-one measurements

π^0 reconstruction in AuAu@11

- Measurement uncertainties at low p_T are driven by systematic uncertainties for the raw yield extraction due to non-Gaussian shape of the reconstructed peaks from cluster merging
- Focus is on optimization of the reconstructed peak shapes and less on the reconstruction efficiency
- Optimized selection cuts for higher significance of π^0 and η signals in AuAu@11 (UrQMD, v.3.4):
  - ✓ Photons: $E_{core2\%} > 0$ GeV, $T_{reduced} < 2$ ns, charged track veto, Chi2/NDF < 4.0
  - ✓ Pairs: $|en1-en2|/(en1+en2) < 0.75$, $|y| < 0.5$
- ~ 15M AuAu@11 events - centralized Monte Carlo production

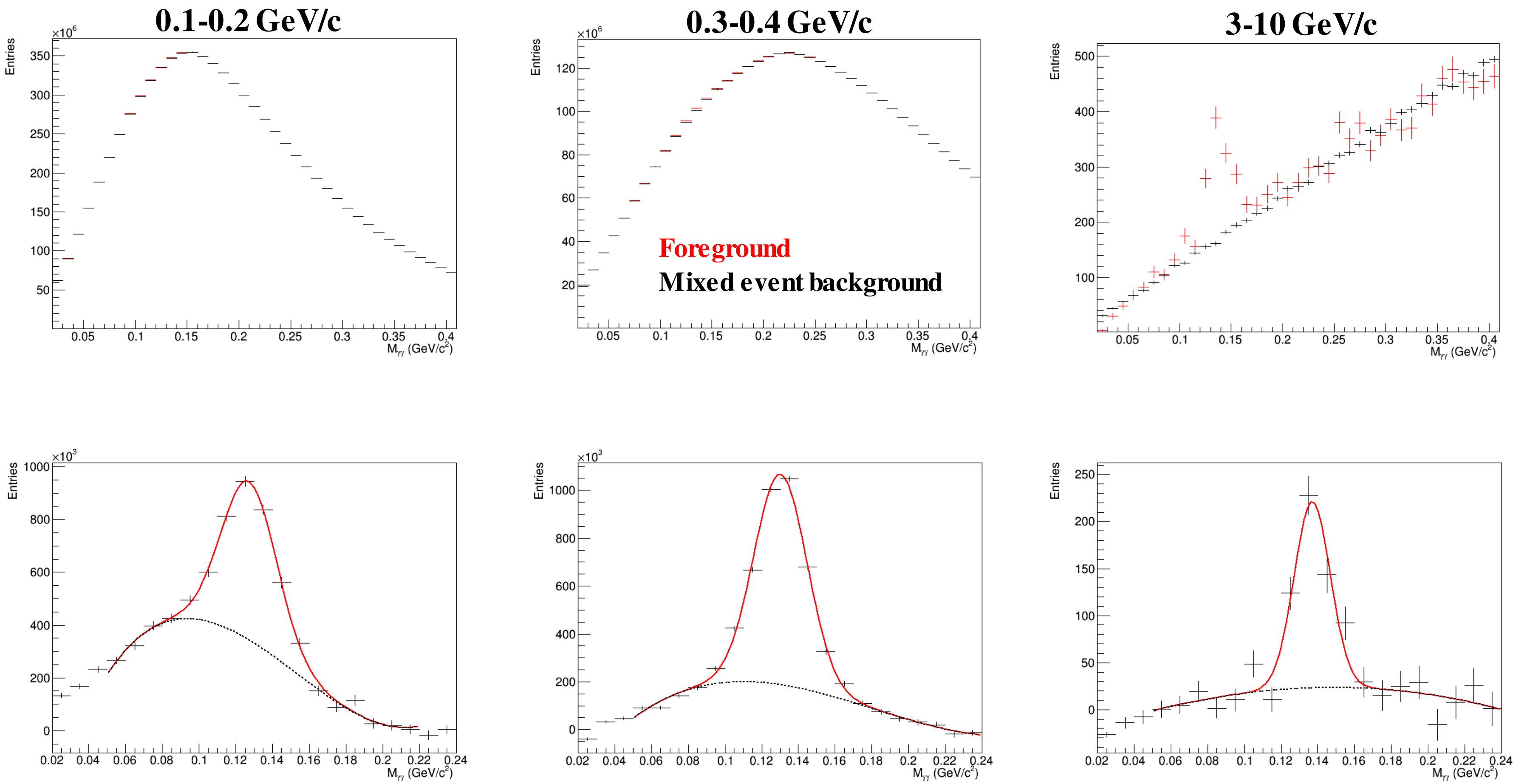




- Efficiency for π^0 is > 10%, increasing with p_T
- Maximum raw yield of π^0 is expected at ~ 300 MeV/c
- Reconstruction efficiency shows strong multiplicity dependence (false veto + shower merging)

π^0 peak examples in AuAu@11

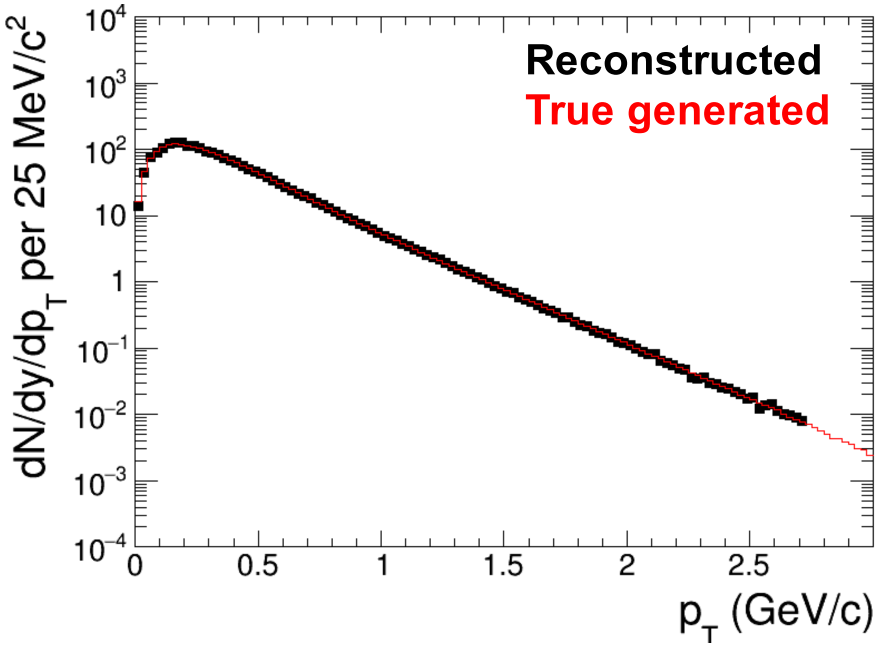
- 15M AuAu@11 (UrQMD v.3.4) events, realistic vertex distribution

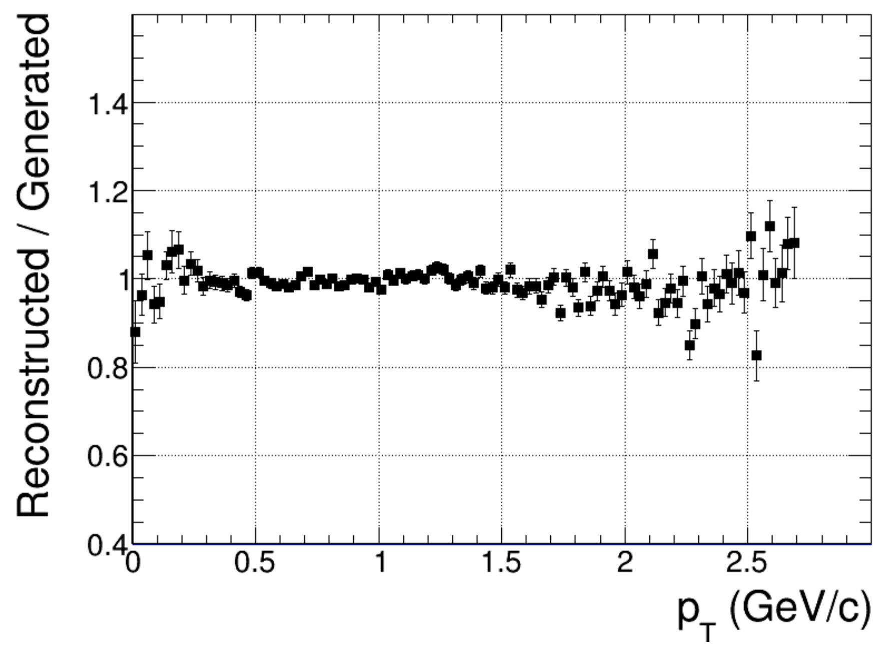


- The peak width decreases with increasing momentum (better energy resolution)
- The S/B improves with increasing momentum

π^0 in AuAu@11: MC closure test

- 15M AuAu@11 (UrQMD v.3.4) events

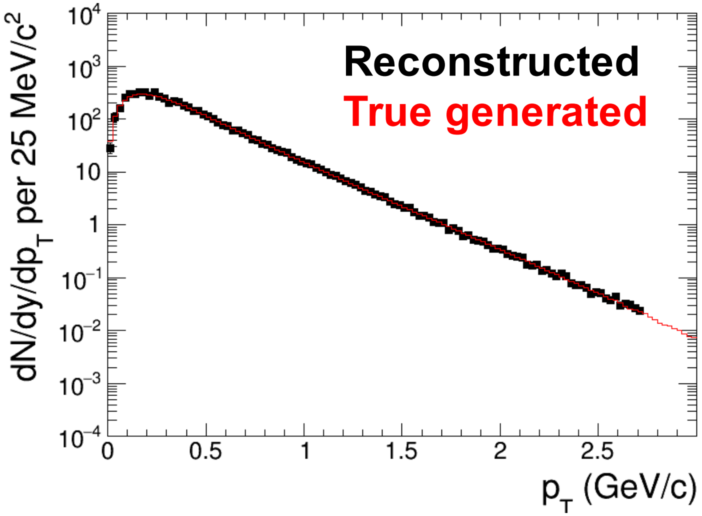


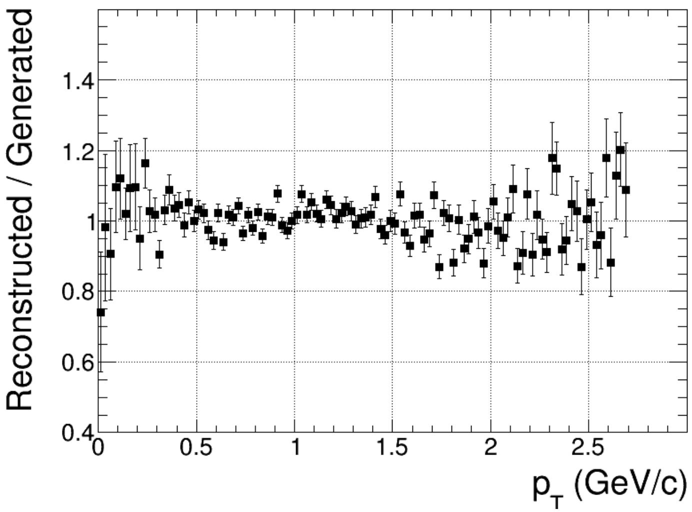


- Reconstructed spectrum matches the generated one within uncertainties
- Reliable raw yield extraction starts at p_T > 50 MeV/c
- Signal is present at lower p_T < 50 MeV/c but the signal shape is not easy to describe/fit
- Significant reduction of systematic effects at low momentum with optimized cuts
- Further improvements are possible

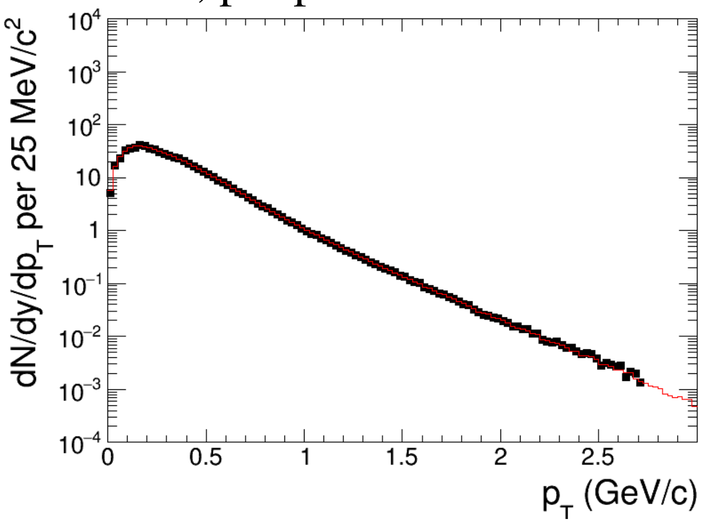
π^0 in 0-20% and 60-90% AuAu@11: MC closure test

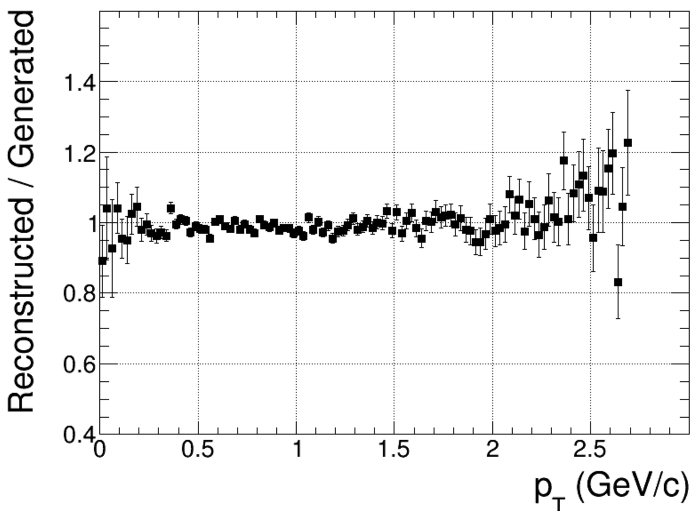
- 0-20%, most central collisions





- 60-90%, peripheral collisions

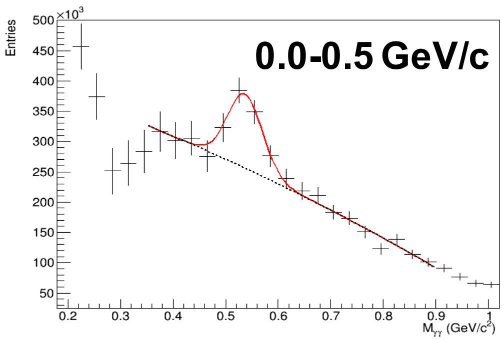


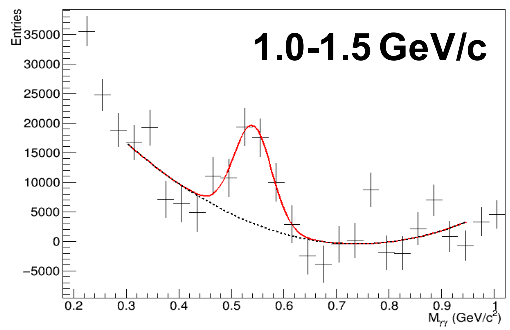


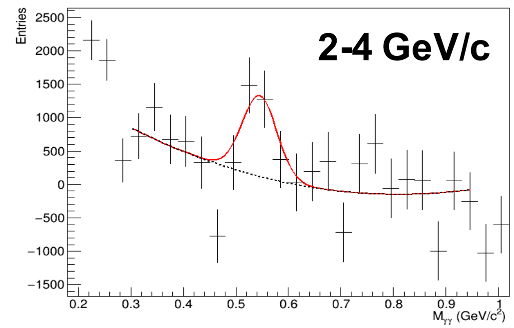
- Reconstructed spectra match the generated ones
- Reliable raw yield extraction starts at p_T > 50 MeV/c

η reconstruction in minbias AuAu@11

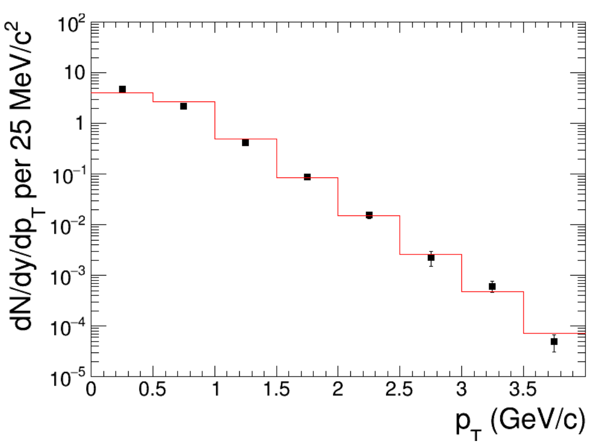
- Need much larger data sample for observation of the signal:
  - ✓ produced at much lower rate compared to π^0 at low $p_T < 2\text{-}3$ GeV/c, $\eta/\pi \sim 0.5$ at $p_T >> 1$
  - ✓ $\eta \to \gamma\gamma$ results in a much wider reconstructed peak (~40 MeV/c vs. ~10 MeV/c for π^0)
- With 15 M minbias AuAu@11 → only observe signals with rough p_T binning and large uncertainties
- Multiplicity dependent studies are not possible

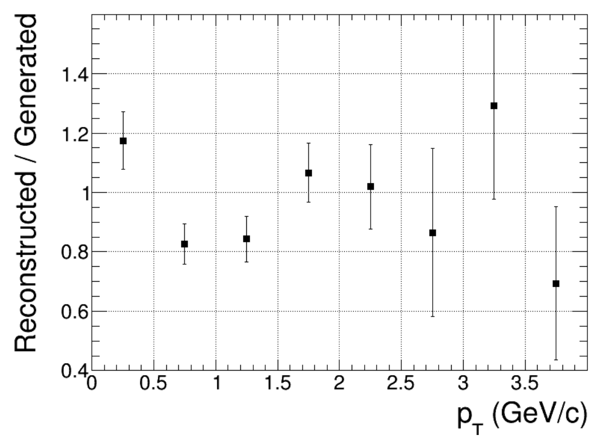






- MC closure test → reconstructed spectrum matches the generated one in minbias AuAu@11





- Possible systematic effects are smeared out by huge statistical fluctuations

Summary for neutral meson studies

- Main conclusions (full acceptance, same performance) :
  - ✓ measurements are possible with ~ 10^7 events → achievable in year-1
  - ✓ range of measurements from p_T ~ 50 MeV/c up to ~ 3 GeV/c
  - ✓ low-p_T uncertainties are driven by signal shape systematic uncertainties, not by statistics
- Remaining tasks for π^0:
  - ✓ better control of the peak shape with different γID selections in the ECAL
  - ✓ BiBi@9.46 for consistency, most probable day-1 beam configuration
- Remaining tasks for η:
  - ✓ extraction of η raw yields in finer p_T bins + multiplicity dependent study
  - ✓ estimation of needed statistics for meaningful centrality-dependent measurements

Dielectron continuum and LVMs

Dielectron continuum studies

- The QCD matter produced in A-A interactions is transparent for leptons, once produced they leave the interaction region largely unaffected

- Dielectron continuum at low and intermediate mass/p_T carries a wealth of information about reaction dynamics and medium properties:
  - ✓ broadening and mass shift of LVMs $\rightarrow e^+e^-$
  - ✓ resonances in e^+e^- vs. hadronic decay channels
  - ✓ direct photon production via internal conversion
  - ✓ charm production and correlations etc.

- Feasibility studies for dielectrons consist of two tasks:
  - ✓ evaluation of background and continuum contributions in AuAu@11
  - ✓ development of eID and pair selection cuts to enhance signal significance

Dielectron sources and background

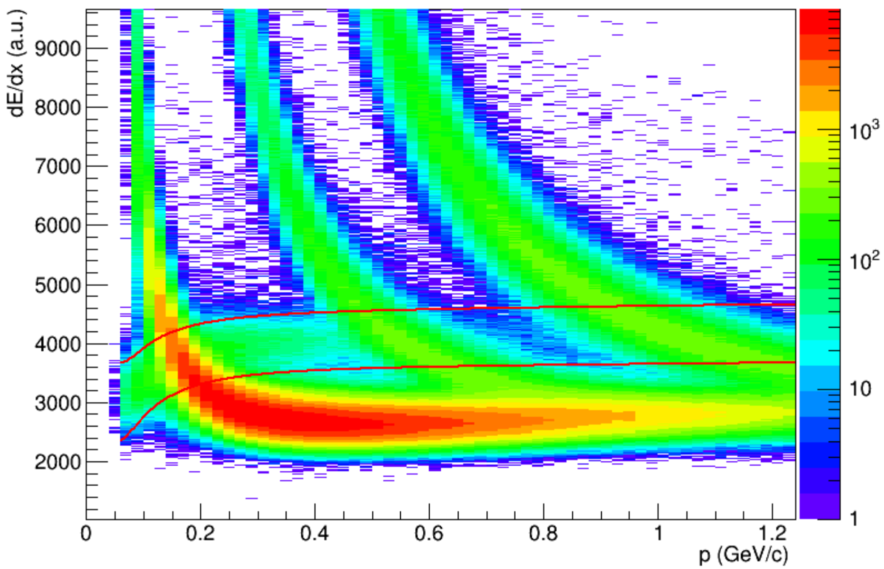
- The main sources of dielectron pairs:

i	Dilepton channels	
1	Dalitz decay of π^0:	$\pi^0 \to \gamma e^+ e^-$
2	Dalitz decay of η:	$\eta \to \gamma l^+ l^-$
3	Dalitz decay of ω:	$\omega \to \pi^0 l^+ l^-$
4	Dalitz decay of Δ:	$\Delta \to N l^+ l^-$
5	Direct decay of ω:	$\omega \to l^+ l^-$
6	Direct decay of ρ:	$\rho \to l^+ l^-$
7	Direct decay of ϕ:	$\phi \to l^+ l^-$
8	Direct decay of J/Ψ:	$J/\Psi \to l^+ l^-$
9	Direct decay of Ψ':	$\Psi' \to l^+ l^-$
10	Dalitz decay of η':	$\eta' \to \gamma l^+ l^-$
11	pn bremsstrahlung:	$pn \to pn l^+ l^-$
12	$\pi^\pm N$ bremsstrahlung:	$\pi^\pm N \to \pi N l^+ l^-$

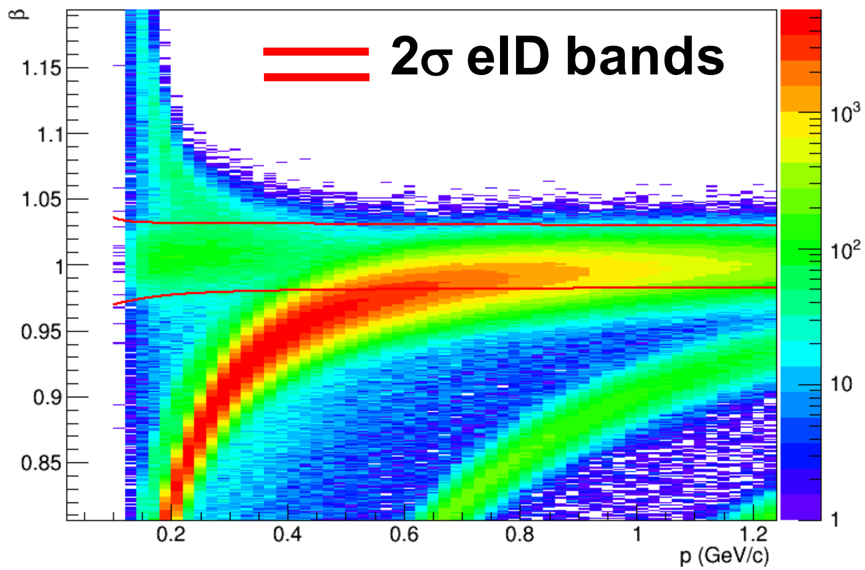
- The main sources of background are Dalitz decays of π^0 and η
  - ✓ most of general-purpose event generators predict consistent yields within ±20% → acceptable for estimations and feasibility studies
- The simulated yields of resonances show a significant model dependence
- UrQMD and PHSD are used for estimations of dielectron signals in heavy-ion collisions at NICA, other inputs are considered …

eID capabilities

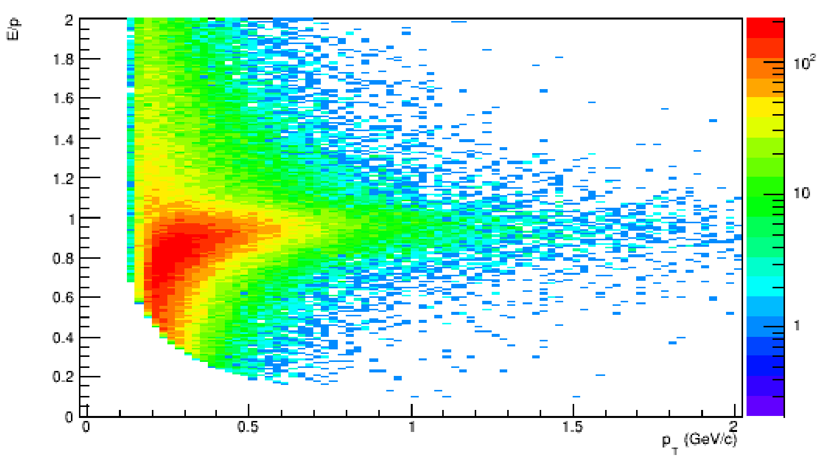
- TPC: dE/dx, for all tracks



- TOF: $\beta = v/c \sim 1$, $p_T > 150$ MeV/c



- ECAL: time-of-flight ($\delta \sim 500$ ps) and E/p ~ 1 for 2σ-matched tracks

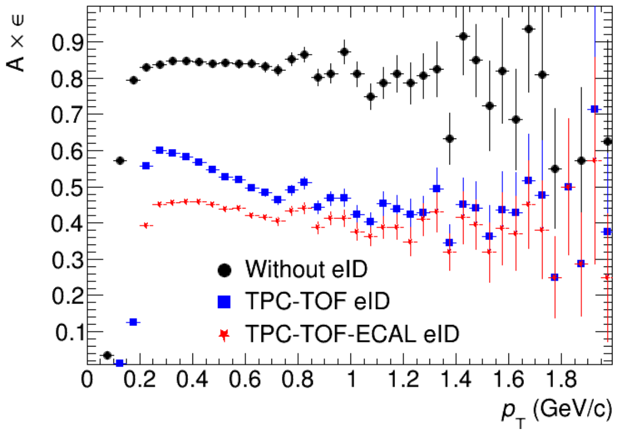


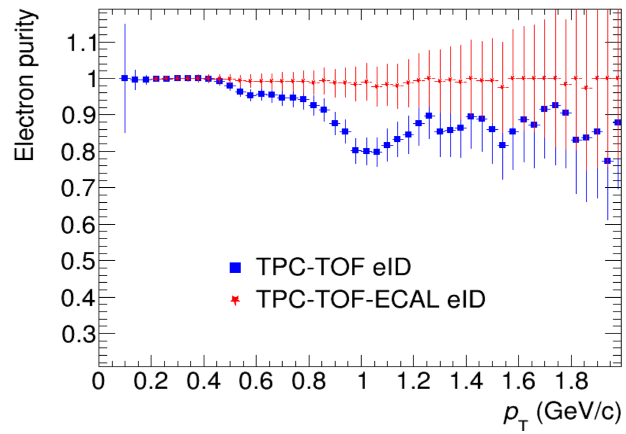
✓ turns on at $p_T > 200$ MeV/c

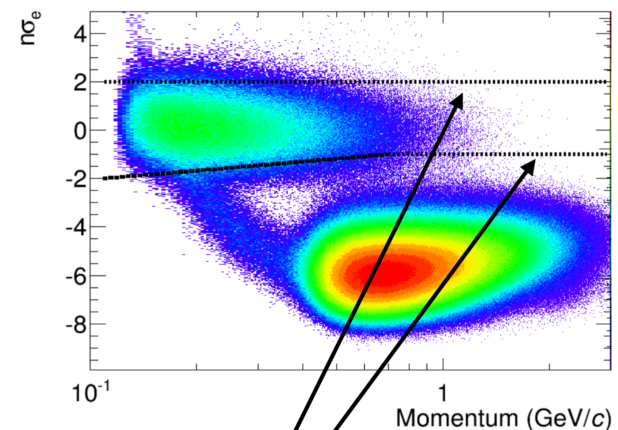
✓ TOF ([-3σ,2σ]) & E/P ([-3σ,2σ]) cuts provide high eID efficiency in a wide p_T range

eID efficiency and purity

- 10 M minbias AuAu@11 (UrMQD v.3.4) events, **noID**, **TPC&TOF** or **TPC&TOF&ECAL**

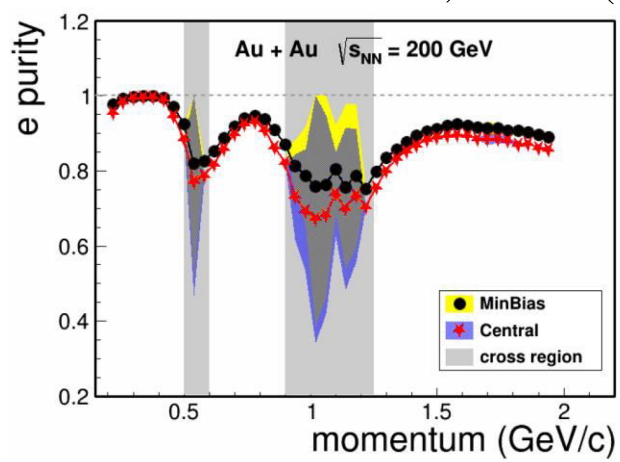






"β cut"

PHYSICAL REVIEW C 92, 024912 (2015)



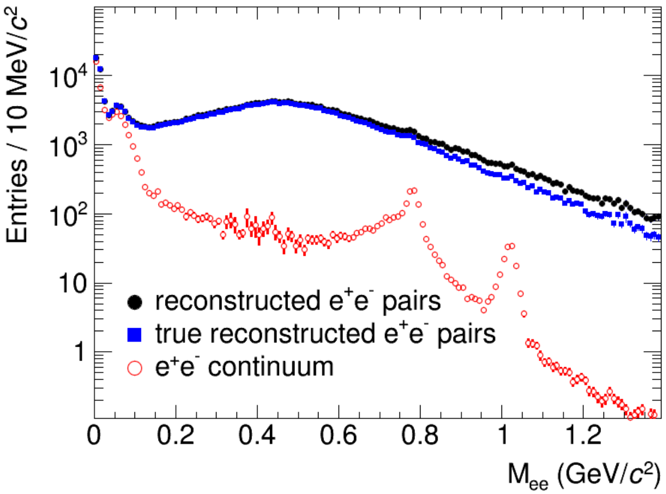
STAR: single electron efficiency at p_T > 200 MeV/c is 30-40%

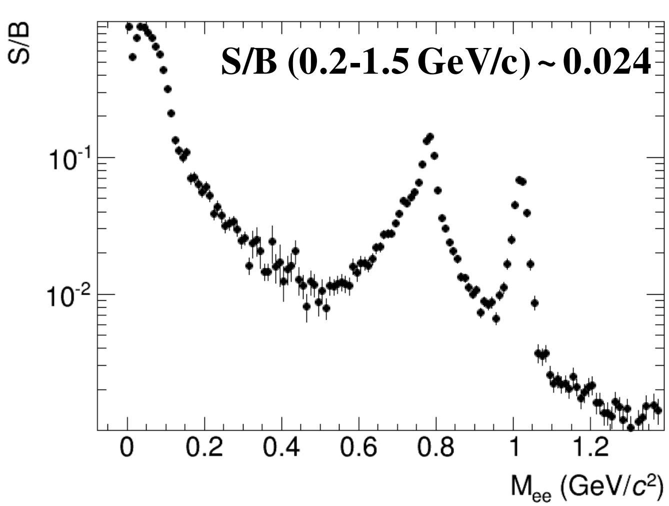
- Achieved purity & efficiency with **TPC&TOF** eID are comparable/better to STAR
- Tight matching cut makes eID by **TPC&TOF** quite sufficient for eID
- Additional **ECAL** eID helps to clean-up the electron sample at high p_T/e^+e^- mass
- Further improvements after tuning of dE/dx calculations in the TPC

Examples of dielectron M_{inv} spectra, p_T integrated

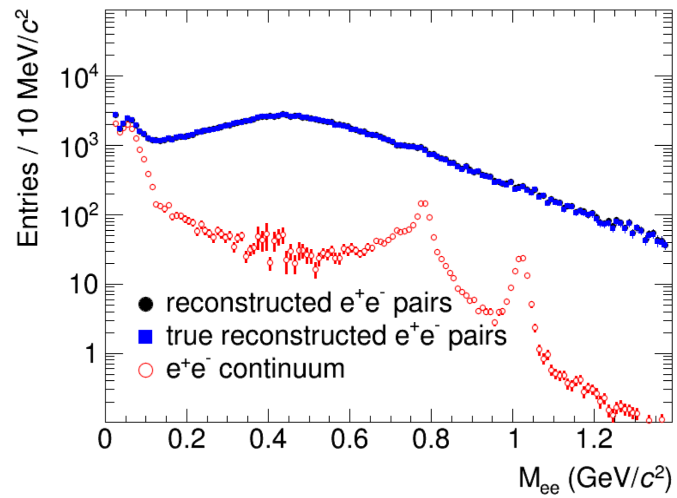
- 10 M minbias BiBi@9.46 (UrMQD v.3.4) events

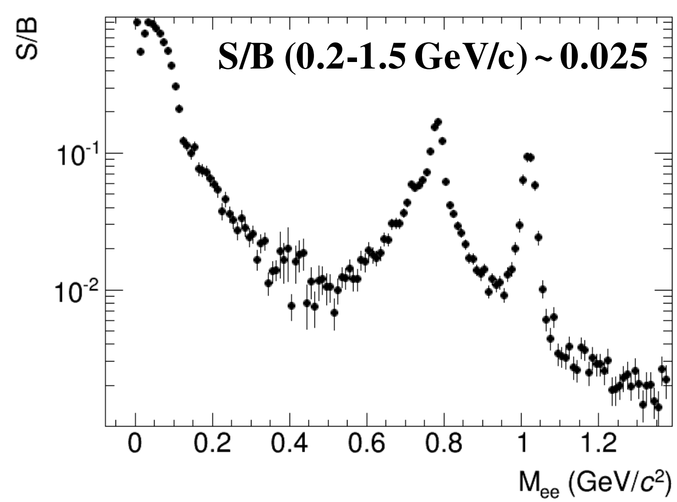
eID with TPC/TOF





eID with TPC/TOF/EMC





- Hadron contamination is reduced at higher masses with an additional ECAL-eID
- The higher the p_T the larger the contribution/importance of the ECAL-eID

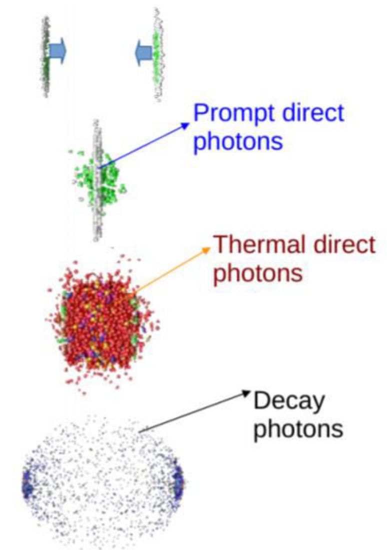
Summary for dielectrons

- eID in the TPC&TOF (with improved TPC matching selections) is sufficient for most of the physics tasks
- Additional eID in the ECAL is important at high e^+e^- masses and high momenta
- Meaningful measurements for e^+e^- continuum and LVMs would require ~ 10^8 AuAu/BiBi events, first observations are possible with 10-30 M events

Direct photons

Sources and estimations

- Direct photons – photons not from hadronic decays.
- Direct photons are produced throughout the system evolution.
- Photons are of great interest in heavy-ion collisions:
  - ✓ QCD matter is transparent for leptons, once produced they leave the interaction region unaffected preserving their properties
  - ✓ estimation of the 'effective' system temperature at low E
  - ✓ hard scattering probe at high E

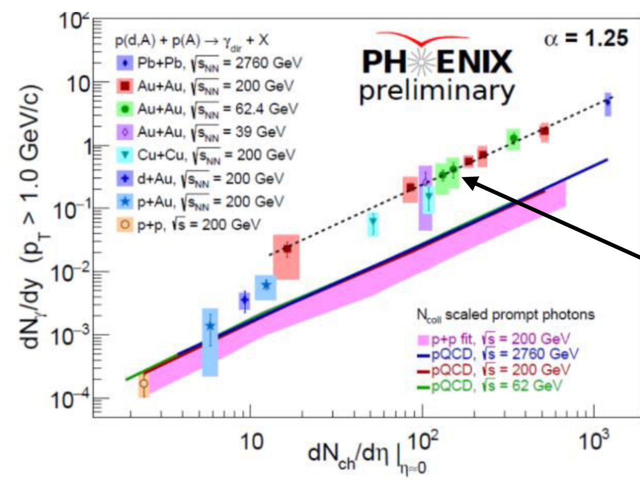


Estimation of the direct photon yields @NICA

model calculations

empirical scaling

- o UrQMD v3.4 with hybrid model (3+1D hydro, bag model EoS, hadronic rescattering and resonances within UrQMD)
- o Each cell have Ti, Ei, μbi:
  - T is high – QGP phase (Peter Arnold, Guy D. Moore, Laurence G. Yaffe, JHEP 0112:009 2001)
  - T is low – HG phase (Simon Turbide, Ralf Rapp, Charles Gale, Phys.Rev.C69:014903,2004)
  - T is intermediate –mixed phase
- o Integrate over all cells and all time steps
- o Calculations reproduce hydro calculations for the SPS



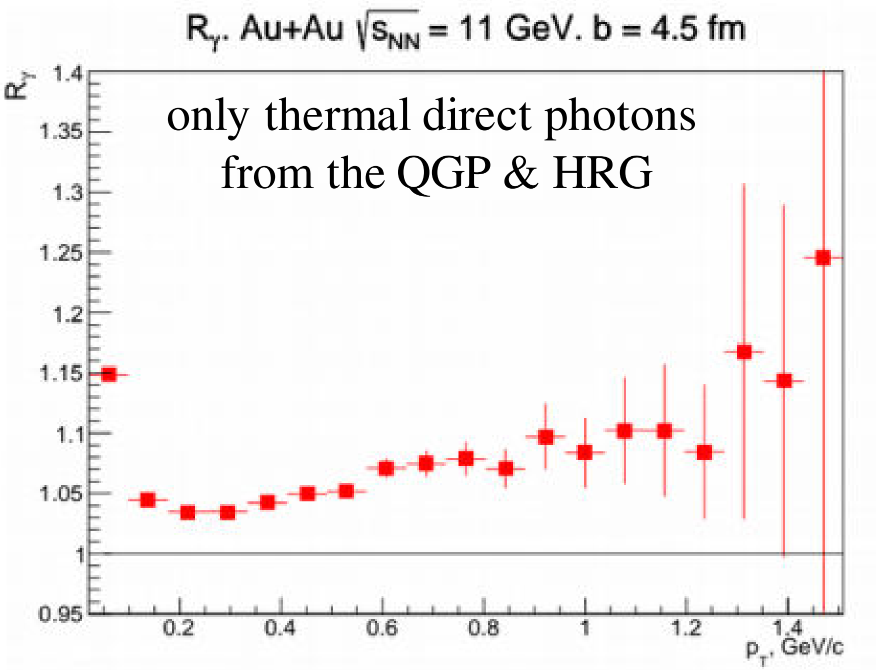
central AuAu@11

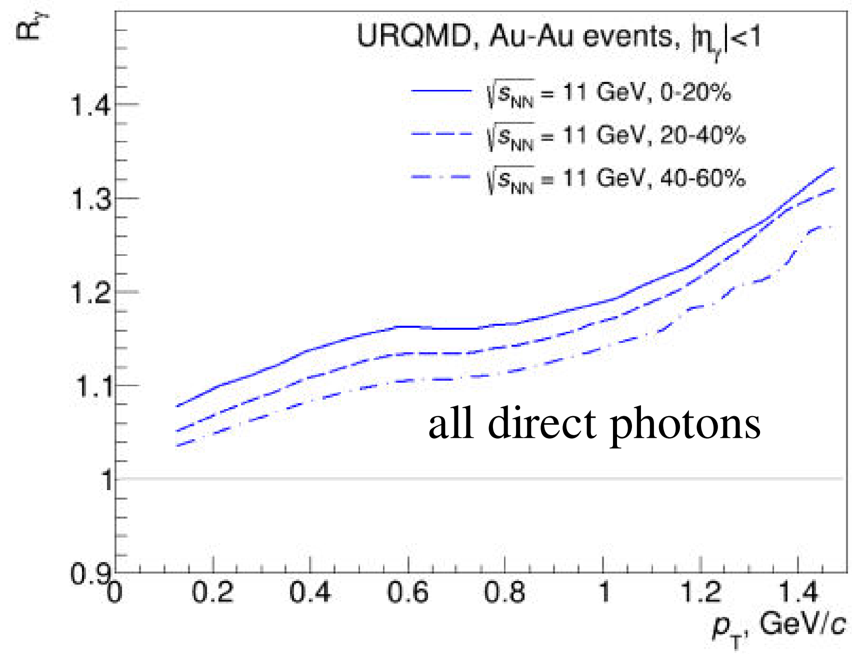
Expected yields of direct photons

Estimation of the direct photon yields @NICA

model calculations

empirical scaling



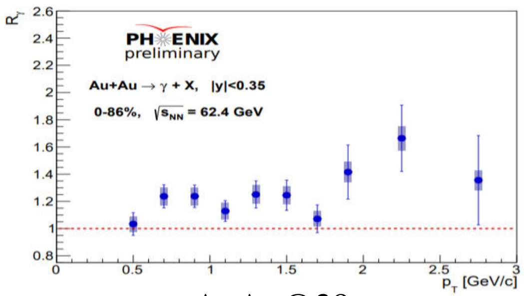


- $R_\gamma = \dfrac{\gamma^{incl}}{\gamma^{hadron}}$
- Rγ estimations vary from 5% to 15% at p_T > 0.5 GeV/c at top NICA energies

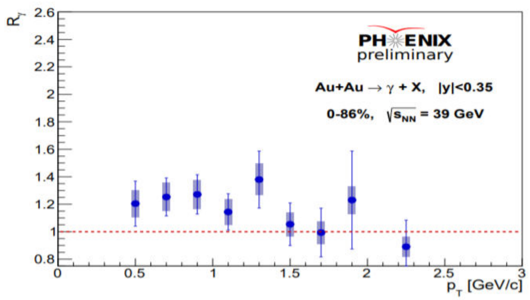
Comparison to RHIC/LHC

- Rγ ~ 1.1-1.2 in heavy-ion collisions at RHIC and the LHC, $\sqrt{s_{NN}}$ = 39-2760 GeV

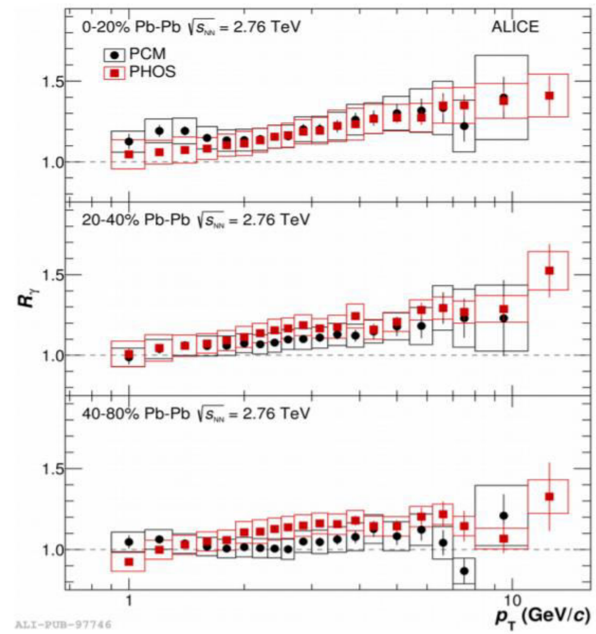
AuAu@62



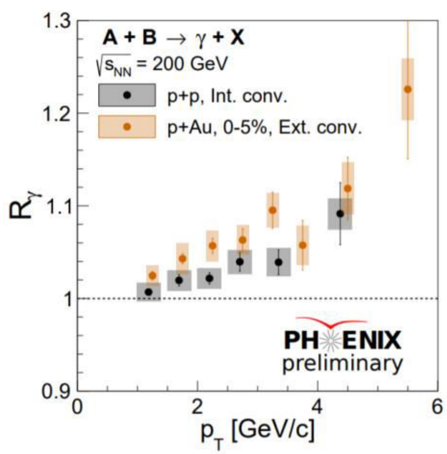
AuAu@39

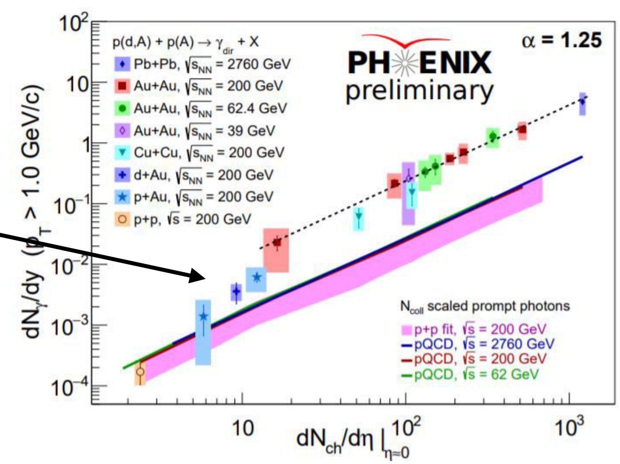


PbPb@2760



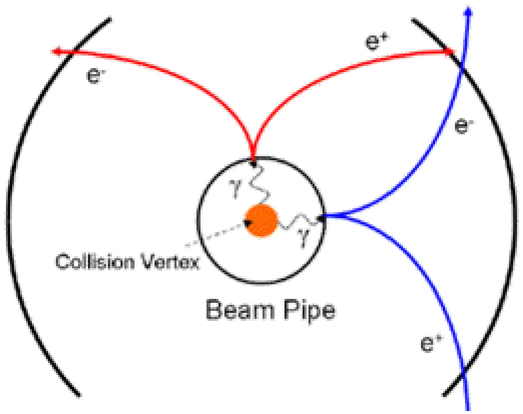
- Rγ ~ 5% is on the verge of experimental measurability (PHENIX in pp/pA@200, ≥ 3σ)

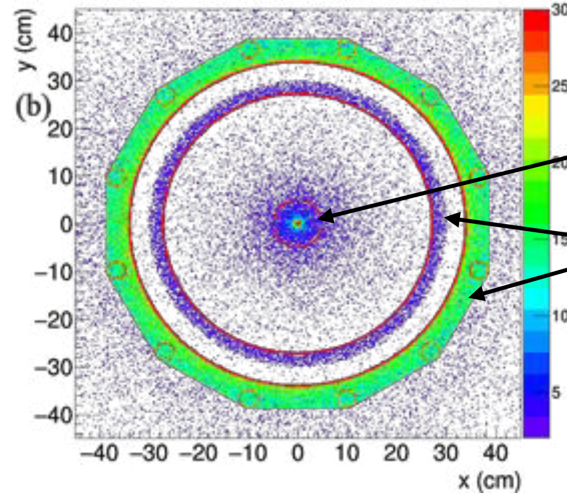




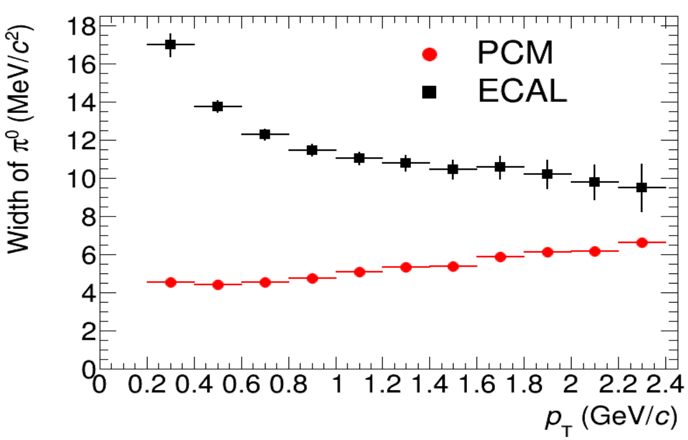
Reconstruction of photons and neutral mesons

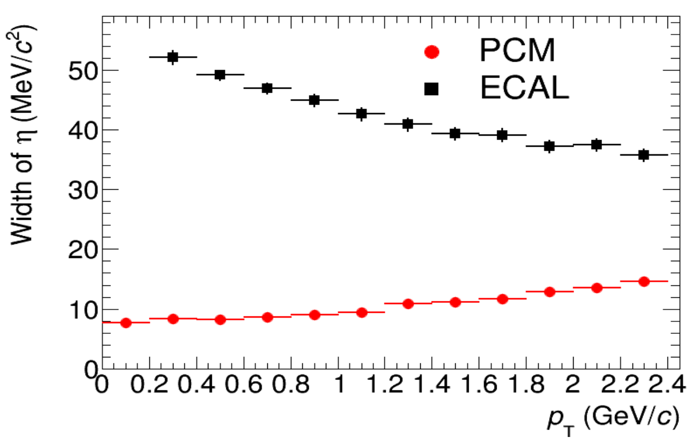
- Photons can be measured in the ECAL or in the tracking system as e^+e^- conversion pairs (PCM):





- Only ~4% of photons convert, ~ 1.5% of photons is reconstructed with the PCM (vs. ~ 60% in the ECAL)
- Efficiencies for neutral mesons are on sub-percent level, ~ $0.15{\cdot}10^{-4}$ (vs. ~ 40% in the ECAL)
- PCM resolution for photons and neutral mesons is much better compared to the ECAL





Summary for (direct) photons

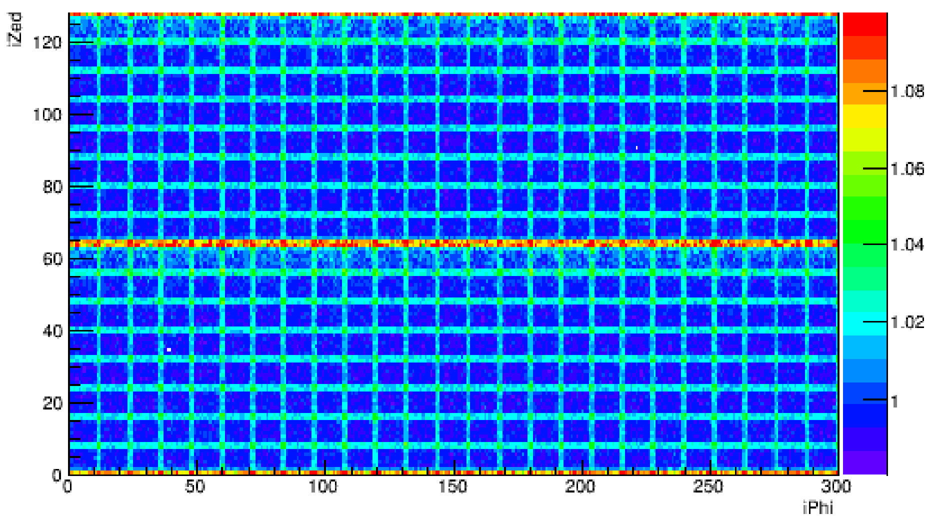
- Measurements of (direct)photons with the ECAL and PCM are complementary:
  - ✓ ECAL provides higher statistics → better at high energies
  - ✓ conversion method benefit from much better energy resolution → better at low energies
- Reconstruction of π^0 with the PCM is possible with $\sim 2\cdot 10^7$ sampled Au+Au@11 events (minbias) → cross check for ECAL measurements
- Reconstruction techniques and estimation of needed statistics for direct photon measurements are in progress, expected yields of direct photons are high enough to allow for experimental measurements with the MPD detector

BACKUP

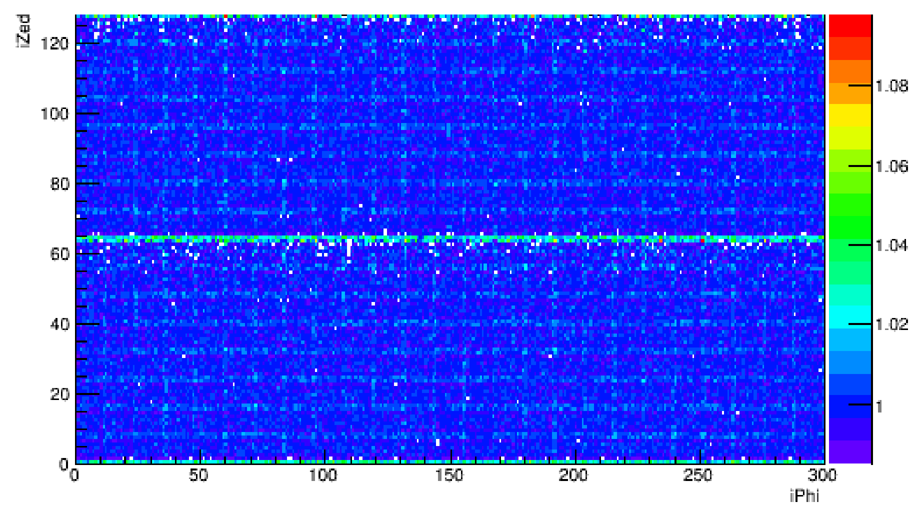
Fine calibration

- Introduced tower-by-tower calibration
- Corrections are evaluated as a ratio of generated to reconstructed cluster energies for central cluster towers
- Process converges in two iterations
- Stored in mpdroot/input/**MpdEmcCalib.root**

Iteration 0

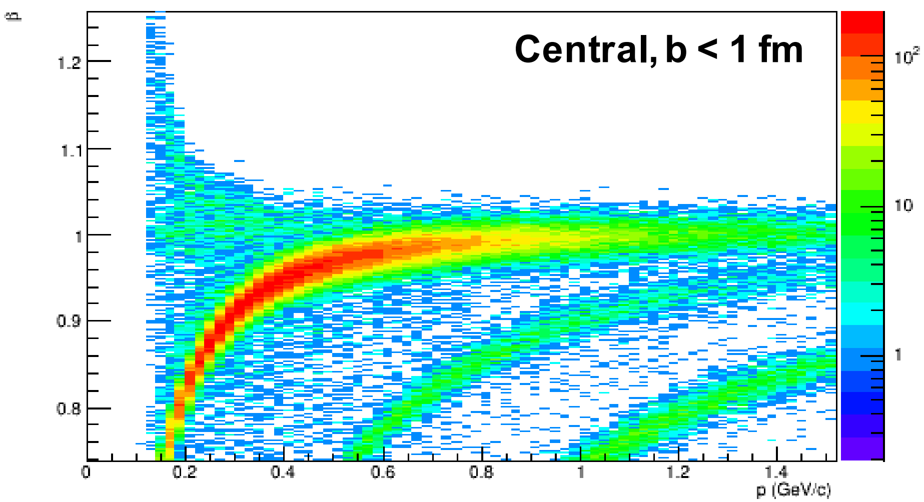


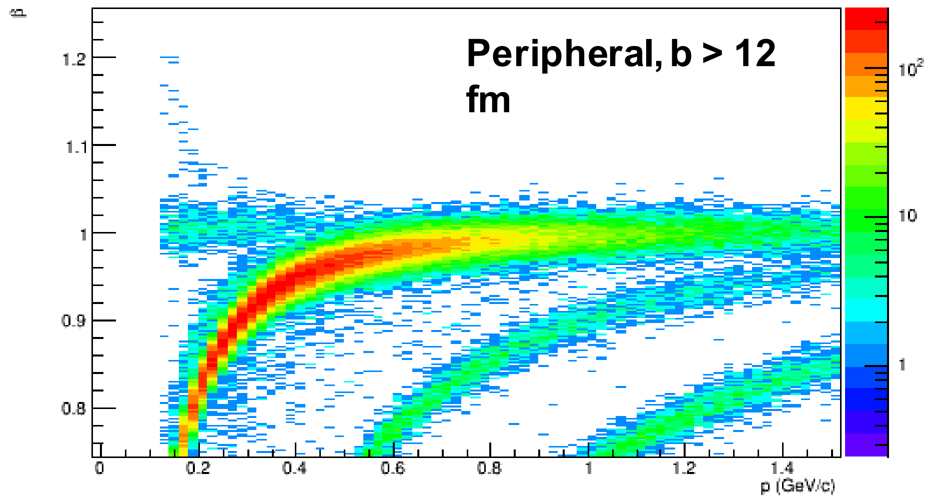
Iteration 2



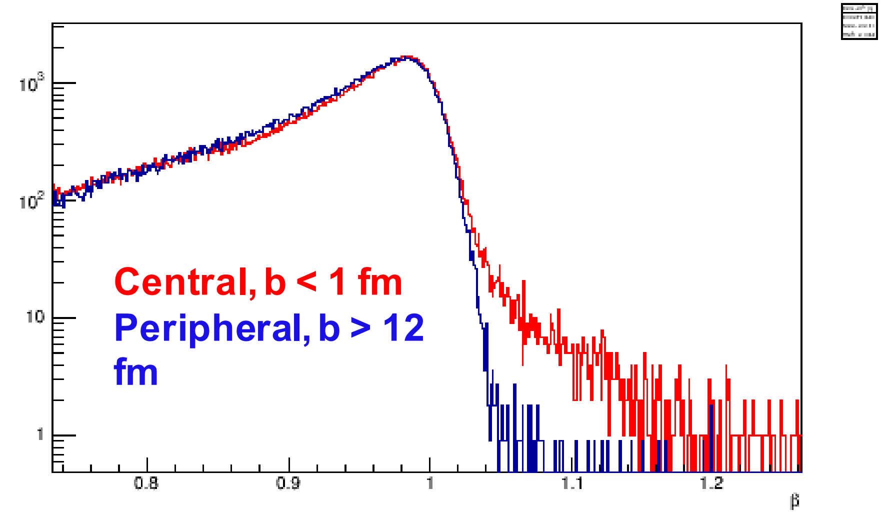
- After tower-by-tower calibration the absolute scale variation is significantly reduced

Particle identification, TOF: MPD



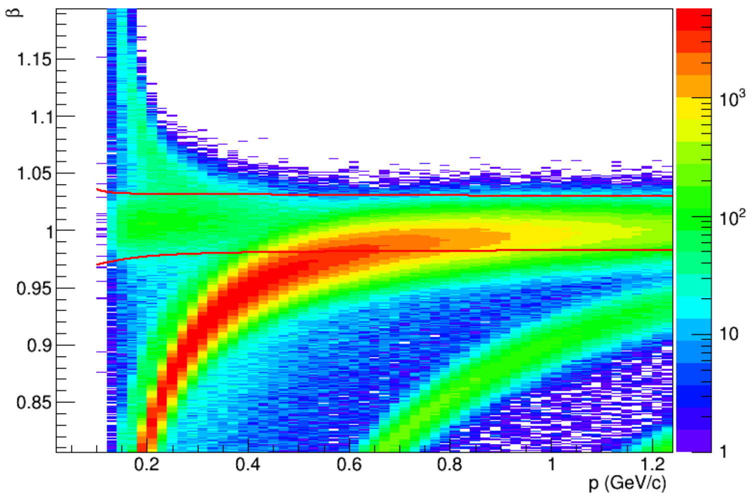


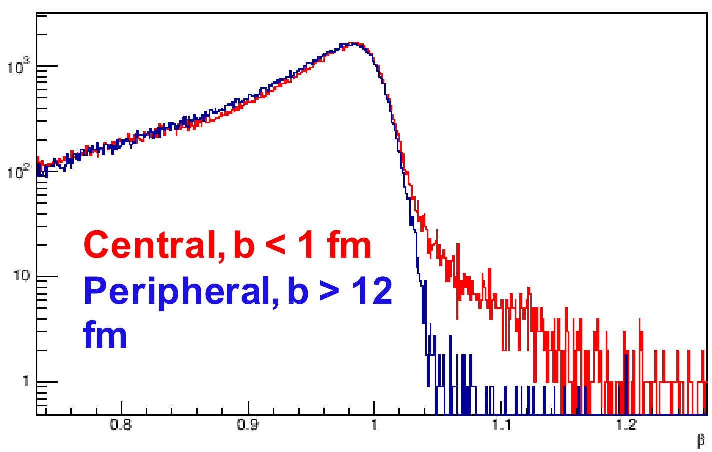
- Observed non-physical tail (β > 1) in the TOF: much more prominent in high multiplicity events (b < 1 fm); the tail is almost absent in peripheral collisions (b > 12 fm)
- Ascribed the effect to track mismatching in the TOF



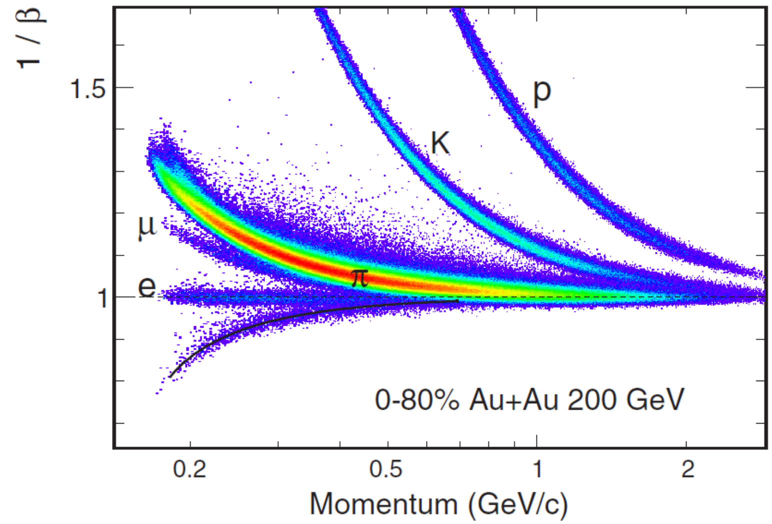
Problem of TOF-TPC track mismatching

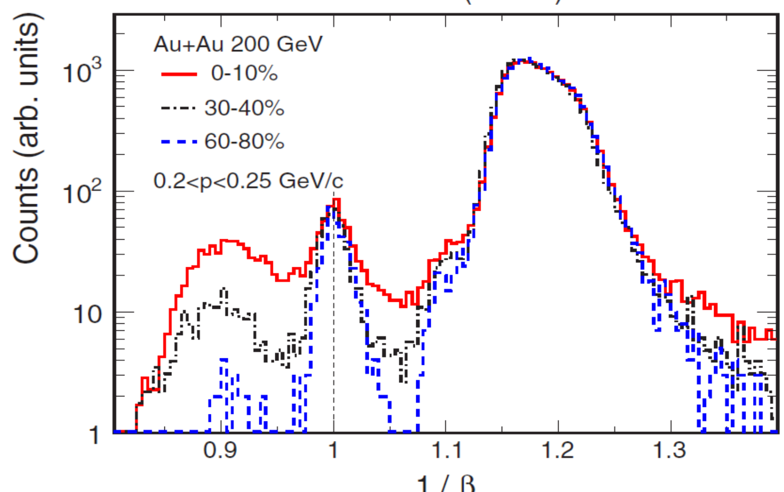
MPD





STAR

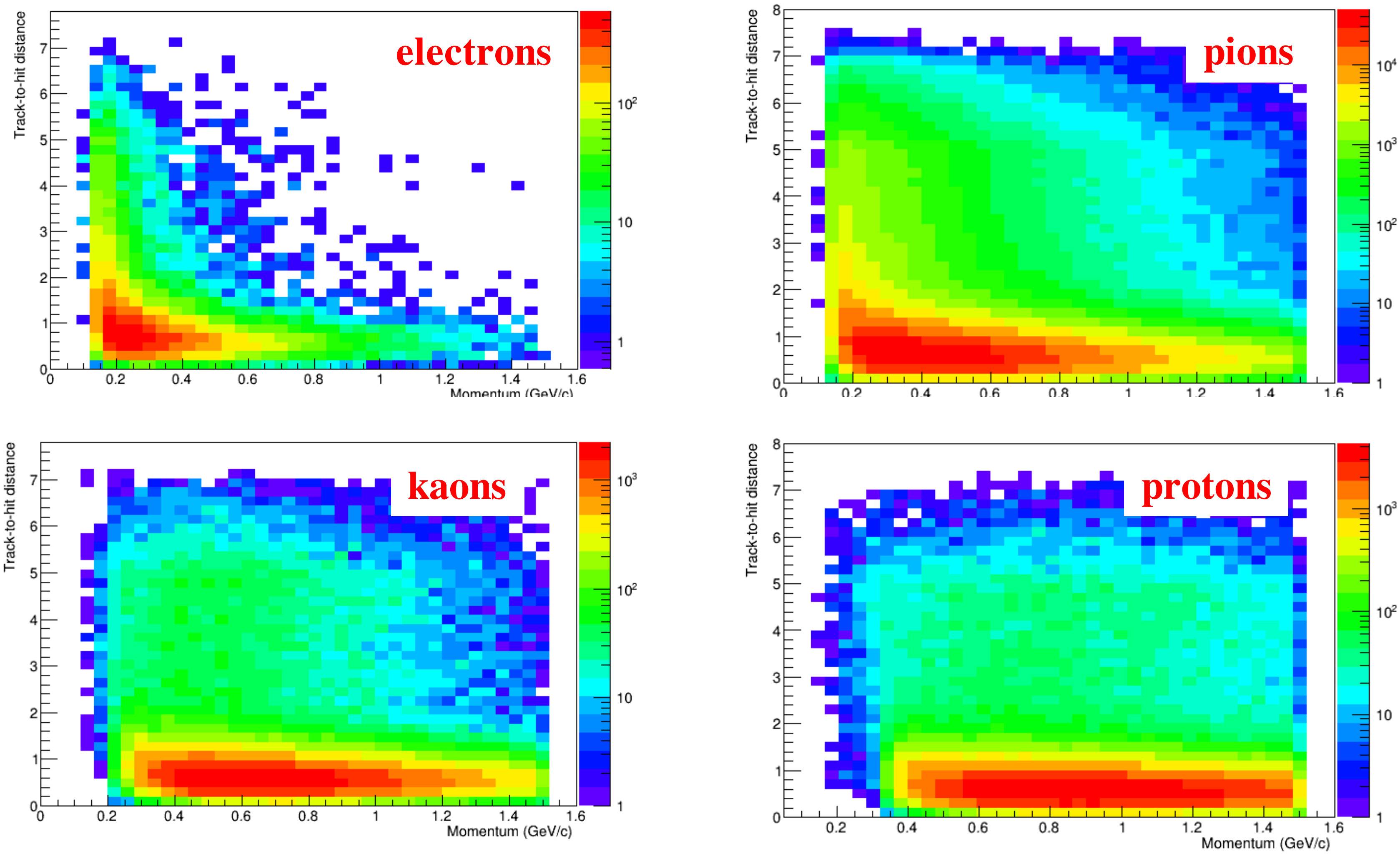




- Both STAR and MPD observe non-physical TOF signals with $\beta > 1$,
- Unphysical signals are most prominent in central collisions, diminished in peripheral
- Effect is explained by track mismatching in the TOF

Matching distributions vs. p_T

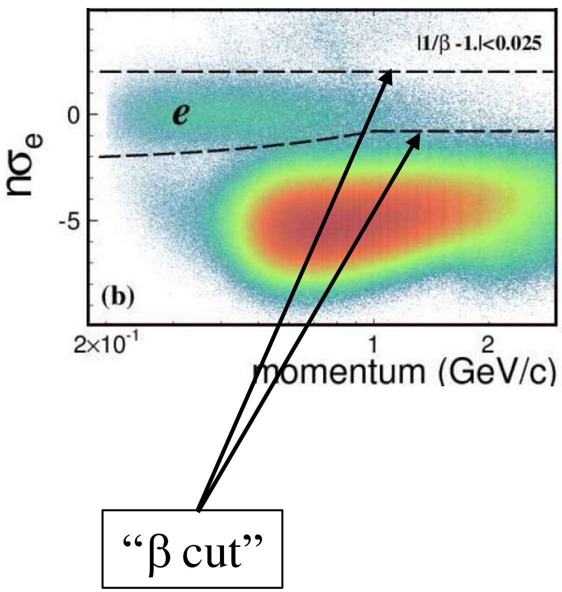
- Track-to-hit distance in the TOF (or 1/weight) vs. p_T, minbias BiBi@9.46



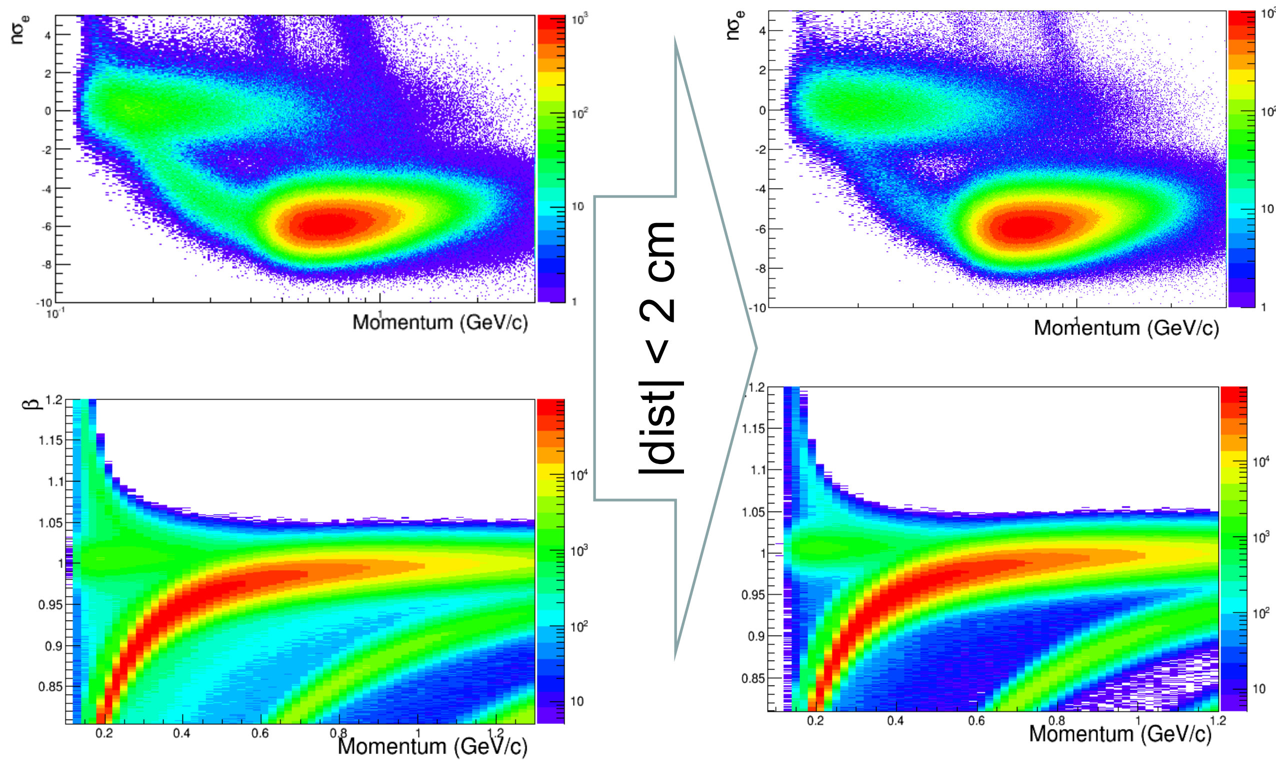
- Matching distributions are quite wide (too wide ???)

dE/dx selections with 2σ eID TOF cut

STAR, AuAu@200



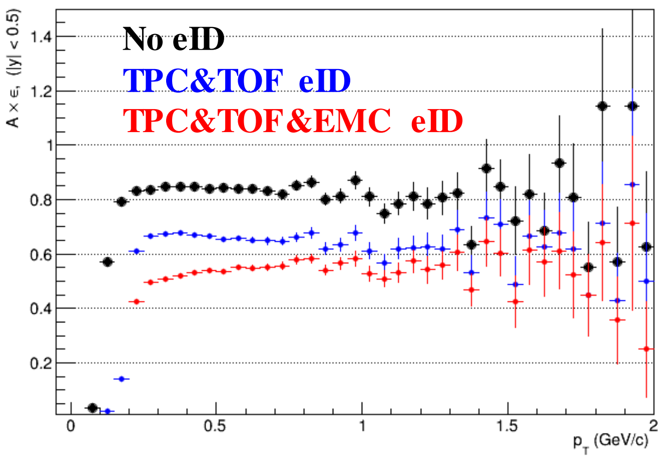
MPD, BiBi@9.46

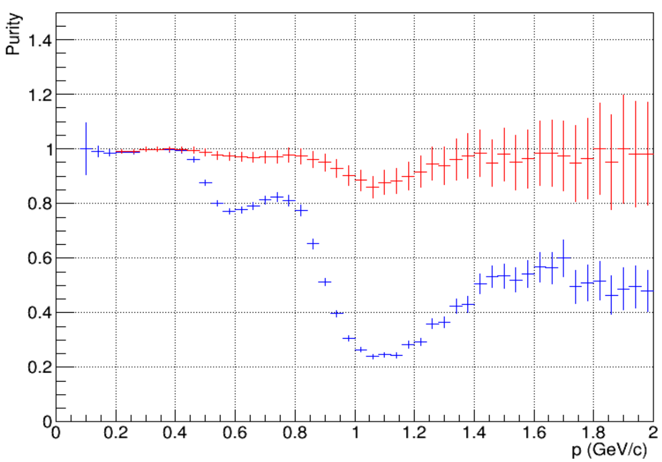


- Tighter matching (|dist| < 2cm) cut:
  - ✓ suppresses the grass and the β > 1 tail
  - ✓ significantly improves e/π and probably π/K separation

Recent improvement of the TOF-eID

- By default, TOF uses rather loose cuts for track matching → high probability of wrong hit association → multiplicity-dependent contamination of the electron sample and distinct unphysical tail at $\beta > 1$
- Hit-to-track matching distributions were parameterized in $d\varphi$ and *dzed* vs p_T, cut on $2\sigma(p_T)$
- Significant improvement of electron purity at reasonably small reduction of electron selection efficiency

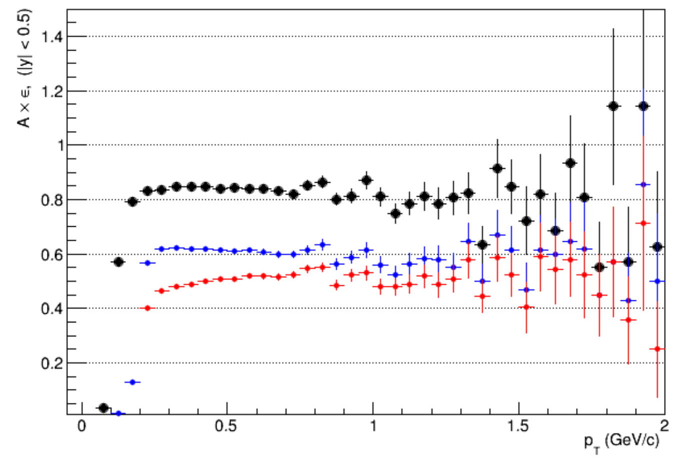


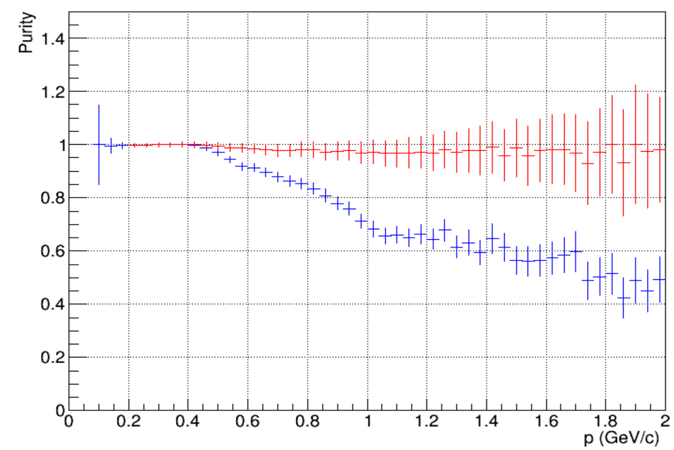


Efficiency

Additional 2-σ TOF-matching cut

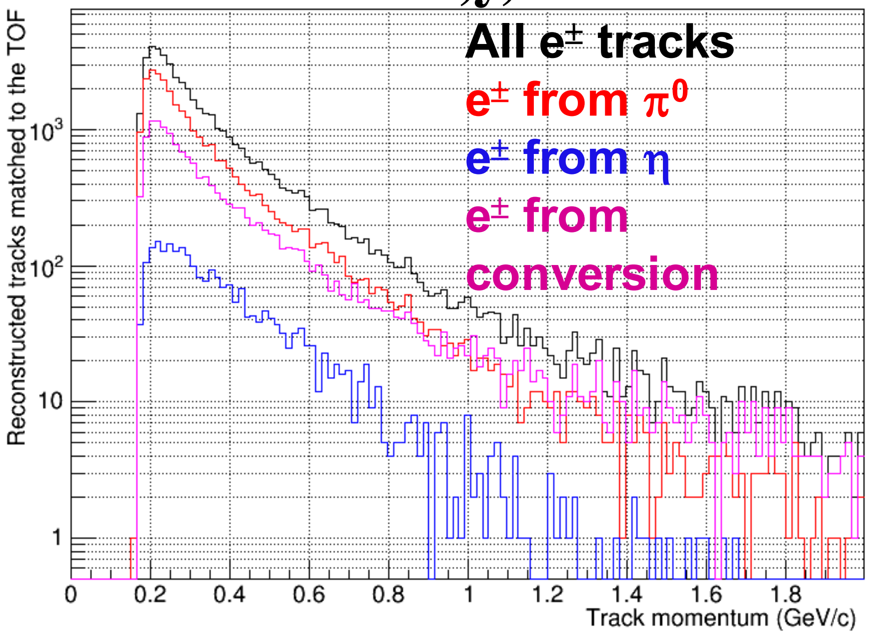
Purity



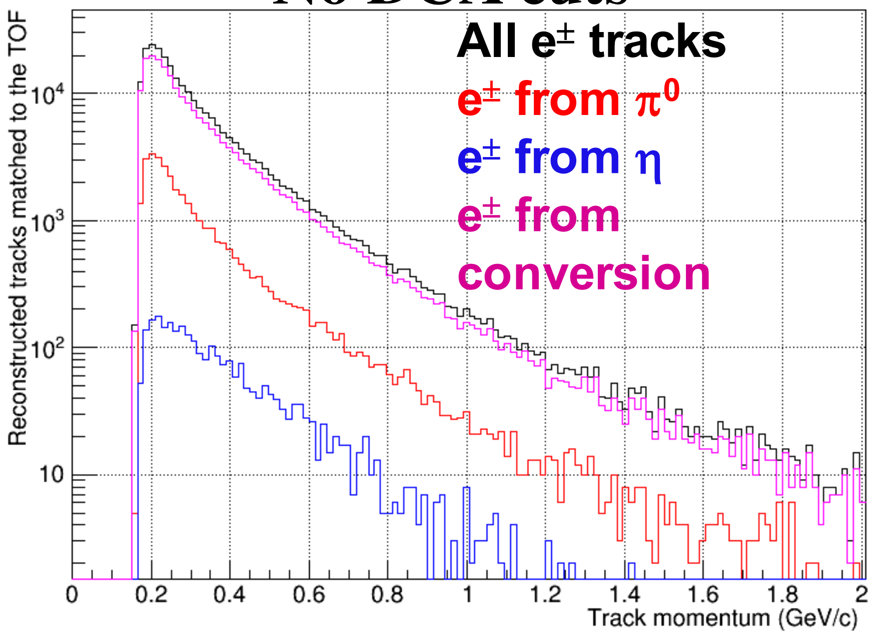


Sources of electrons: MPD

DCAx,y,z < 2 σ



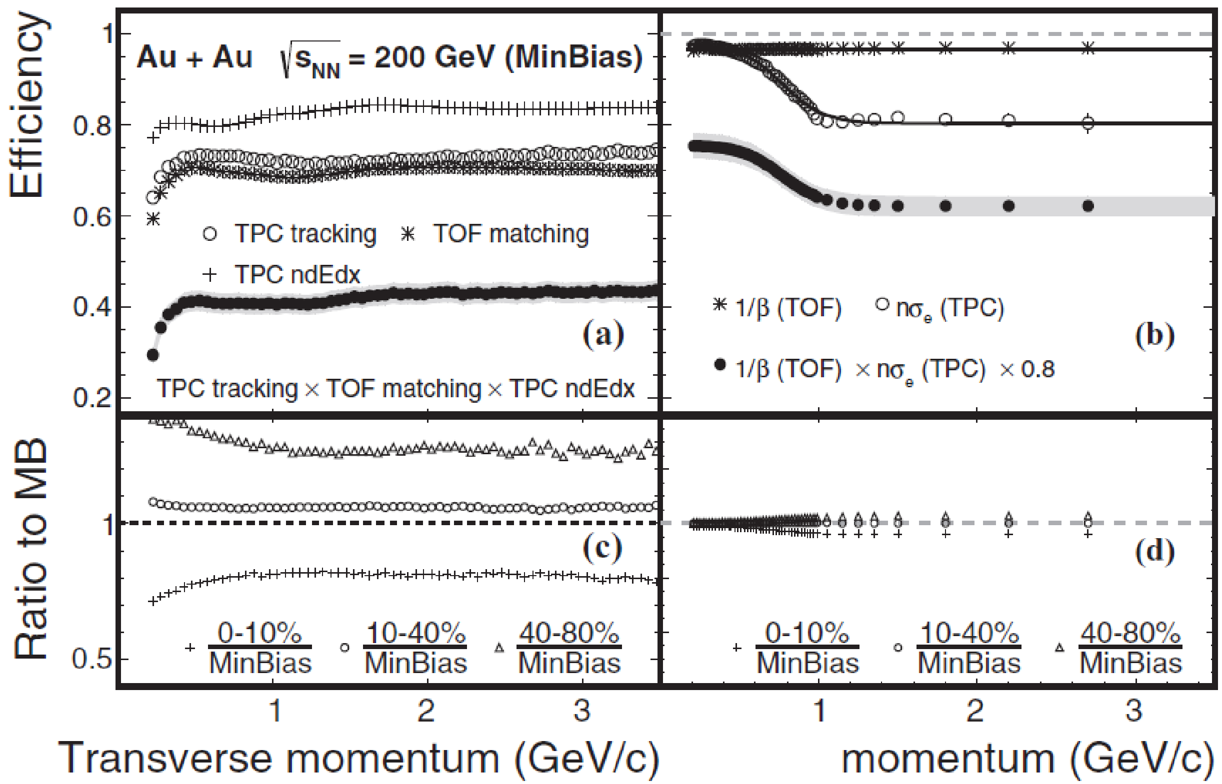
No DCA cuts



- Minbias AuAu@11 collisions (centralized production #3, AuAu@11 with Geant-3)
- Only TPC $e^{\pm}$ tracks matched to the TOF are selected, the only difference is in DCAx,y,z cuts
- With tight DCAx,y,z cuts the main source of electrons is π^0 (Dalitz decays)
- With no DCAx,y,z selections, the electron spectrum is totally dominated (by an order of magnitude) by conversion electrons while contributions from π^0 and η remain ~ the same

→ Comparison of the electron purities make sense only when contributions of conversion are comparable in the experiments (materials and cuts)

eID efficiency: STAR



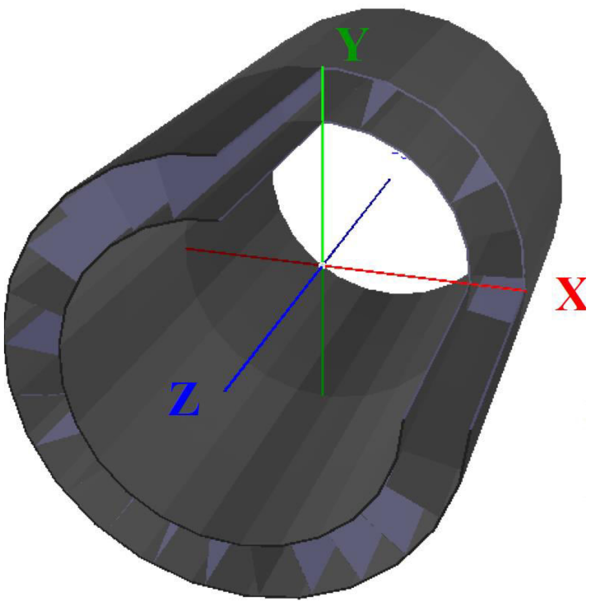
$$\varepsilon_{\mathrm{eID}} = \varepsilon_{\beta} \times \varepsilon_{\mathrm{dEdxPID}}$$

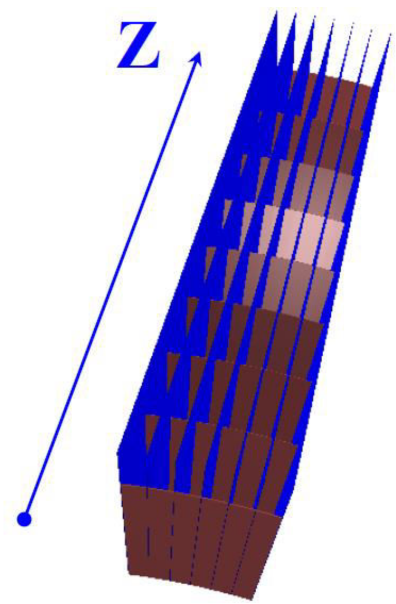
$$\varepsilon_{\mathrm{dEdxPID}} = \varepsilon_{\mathrm{ndEdx}} \times \varepsilon_{n\sigma_e}$$

- Single eID efficiency at p_T > 200 MeV/c (STAR): ~ 0.45 · (0.93-0.75) = 30-40%
- The MPD TPC-TOF-ECAL single eID efficiency with tight cuts is comparable

New ECAL geometry, v.3

- A new ECAL geometry was introduced at the last Collaboration meeting (JINR)
- The new geometry was introduced in Geant (IHEP)
  - ✓ Non-homogeneous acceptance, towers are intervened with carbon fiber support structures of different width (up to a few centimeters) → irregular structure → variance of the absolute scale
  - ✓ Addition of 2.1 cm of paint in each tower, smaller number of tiles
  - ✓ Support structure of 12.7% X_0 in front of the towers (carbon fiber cylinder)

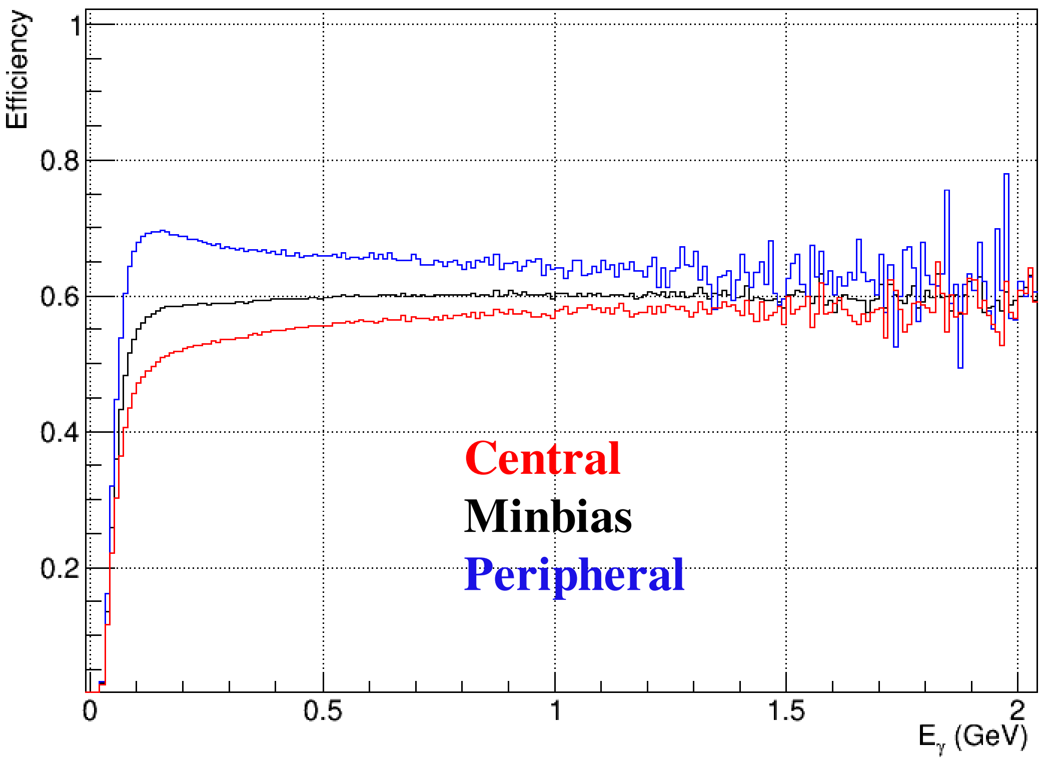


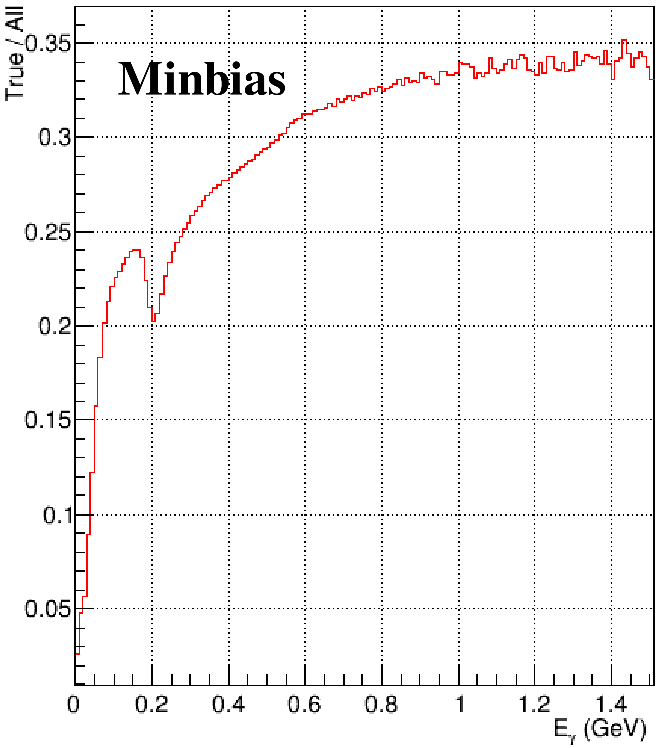


- Worse energy resolution and smaller efficiency due to smaller light collection, smearing of the absolute scale and higher photon conversion probability

ECAL performance: γ efficiency & purity

- UrQMD. Minbias AuAu@11; realistic vertex distribution

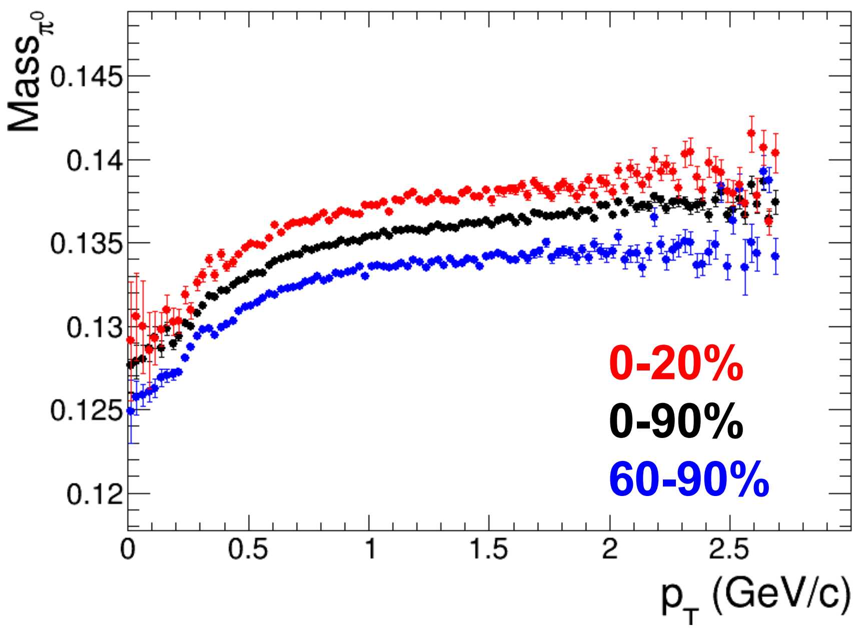


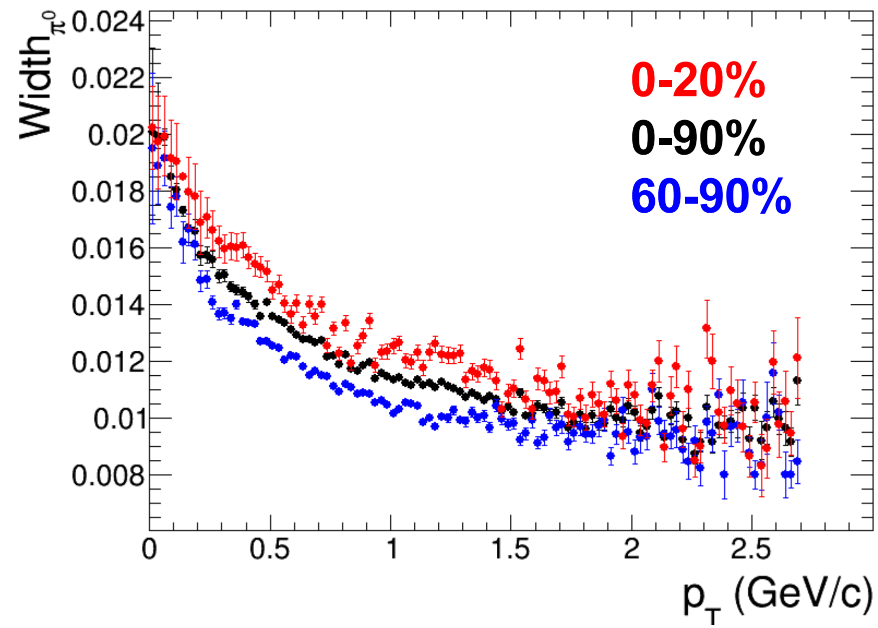


- Only ~ 60% of primary photons reach the ECAL surface, others convert (TOF + carbon fiber)
- Efficiency drop in central collisions is caused by overlap of the showers
- The real efficiency is higher because some of e^+e^- conversion pairs are reconstructed as a single cluster; such clusters differ by shape though
- Measurements at low energy suffer from large backgrounds

π^0 in AuAu@11: mass and width

- Same cuts and selections for all centralities

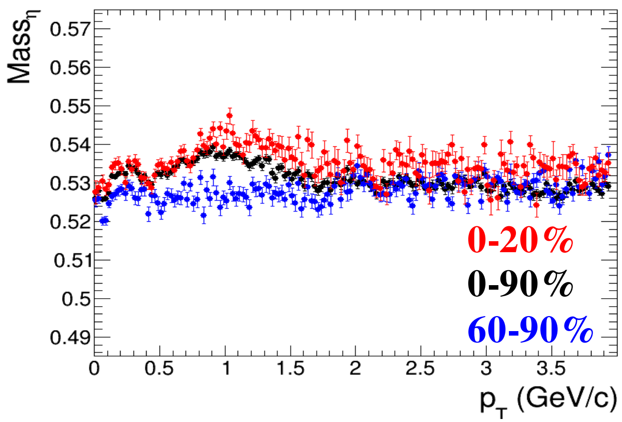


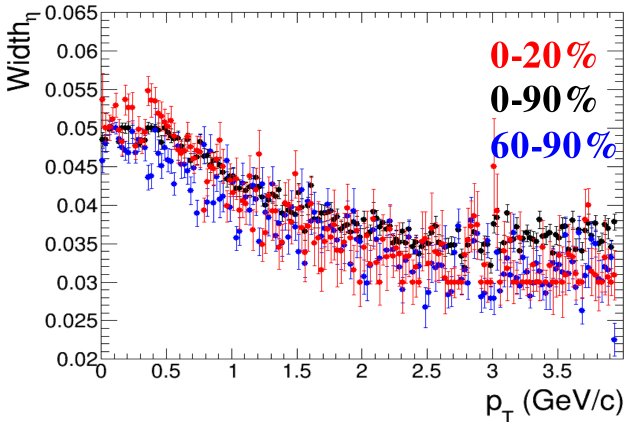


- Reconstructed mass increases with multiplicity and p_T:
  - ✓ shower merging at high multiplicity
  - ✓ energy leakage and non-linearity
- Reconstructed width increases with multiplicity and decreases with p_T:
  - ✓ energy resolution is multiplicity dependent
  - ✓ energy resolution improves with increasing energy

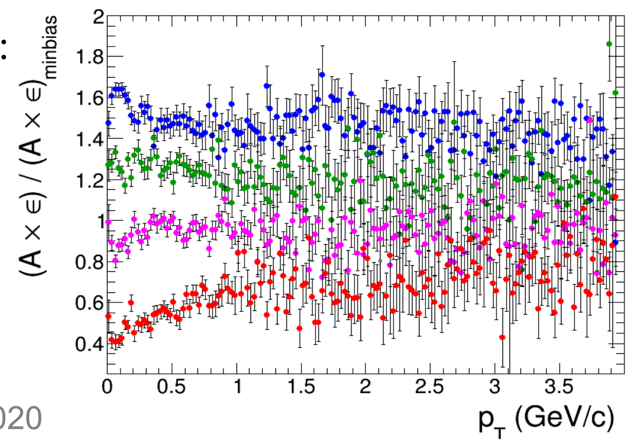
Embedded simulation for η

- For minimization of statistical uncertainties and multiplicity dependent studies need much higher statistics
- It is not possible to increase number of simulated events → embedded simulation
  - ✓ 7 embedded η mesons per event with flat p_T and rapidity distributions
  - ✓ average multiplicity is barely affected even in peripheral collisions (60-90%)
  - ✓ distortion of the shapes of p_T spectra for η are multiplicity dependent → corrected via weights
- Studies are ongoing, first results for the reconstructed mass&width and efficiencies
- Weak dependence of the reconstructed mass and width on multiplicity (relatively high energy of photons)

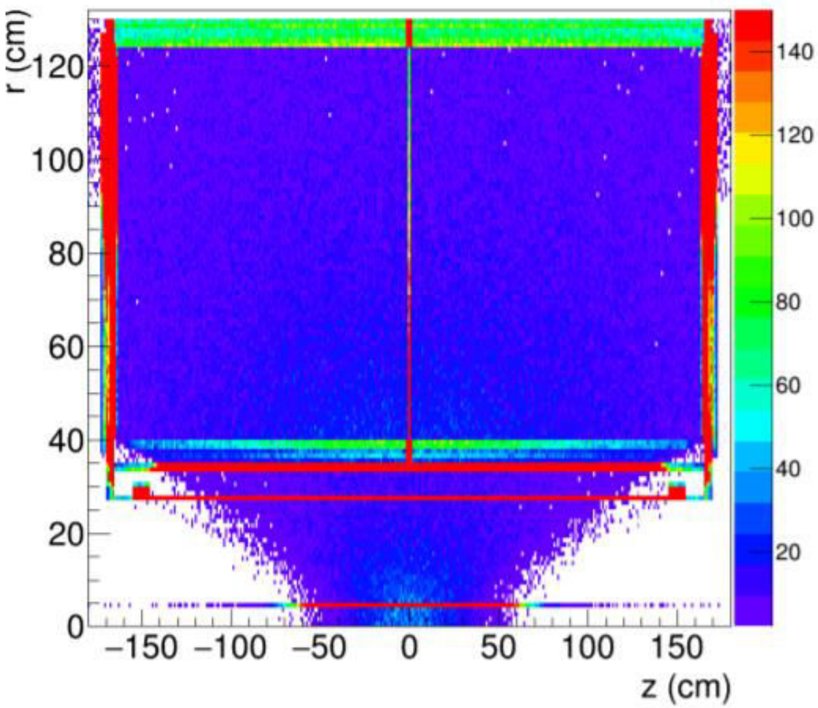


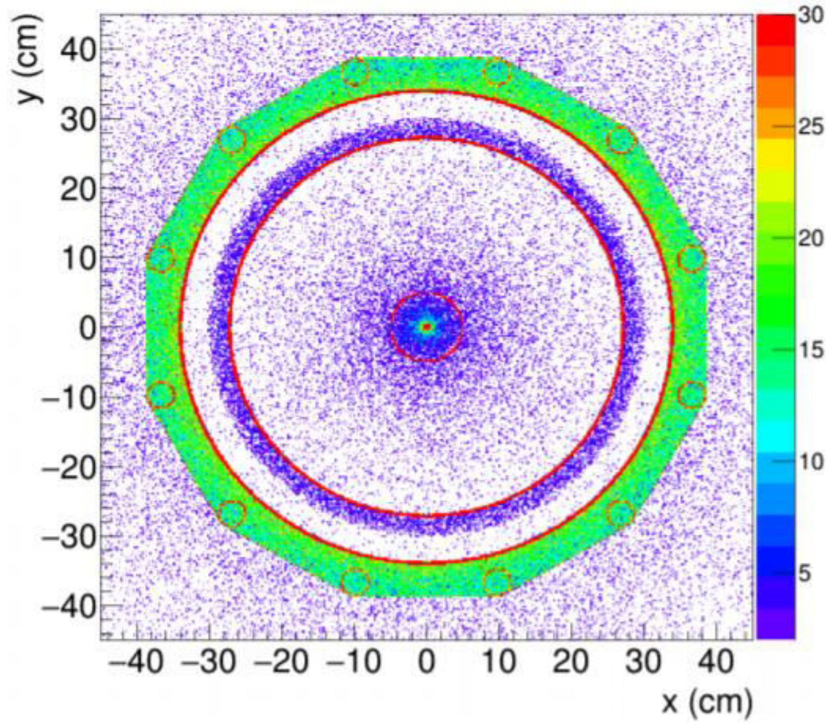


- Reconstruction efficiency → strong multiplicity dependence:
  - ✓ multiplicity dependence of false track matching (false veto)
  - ✓ larger fraction of merged clusters with non-EM shower shapes at high multiplicity



Photon conversion centers





Main conversion structures in Stage 1:

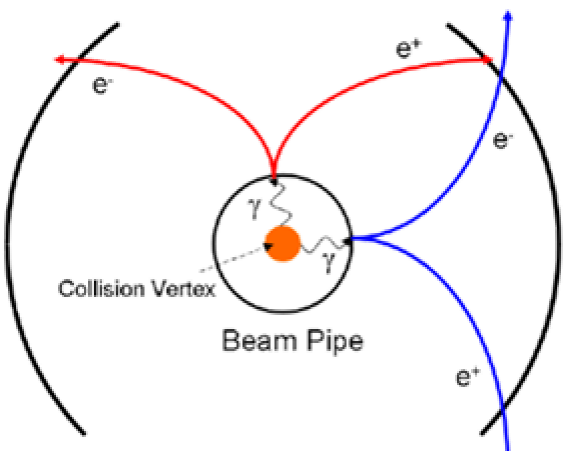
- Beam pipe: 0.3% X_0
- Inner TPC barrel structures: 2.4% X_0

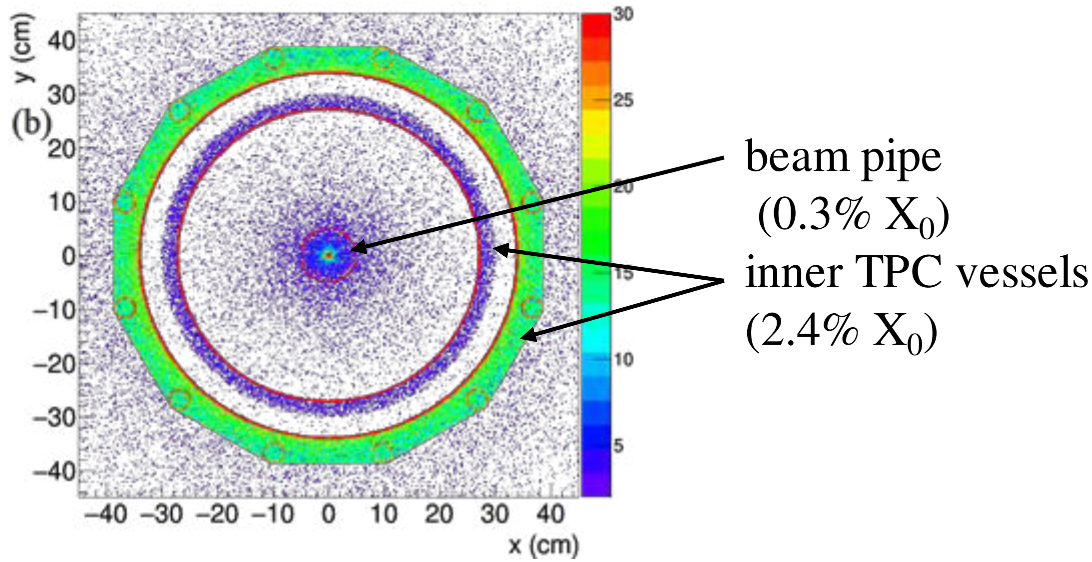
Future:

- Inner tracking system
- Dedicated photon convertor (cylindrical metal pipe) under investigation

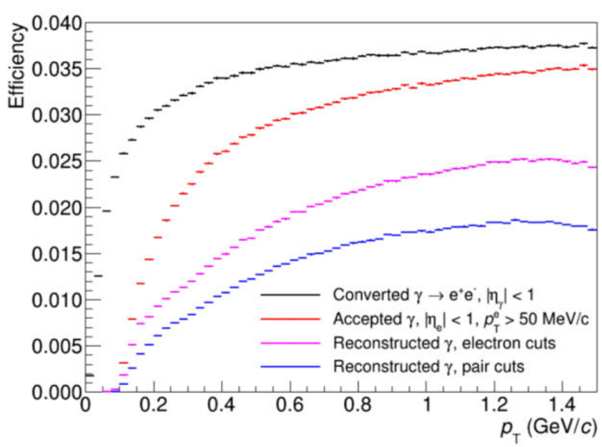
Reconstruction of photons and neutral mesons

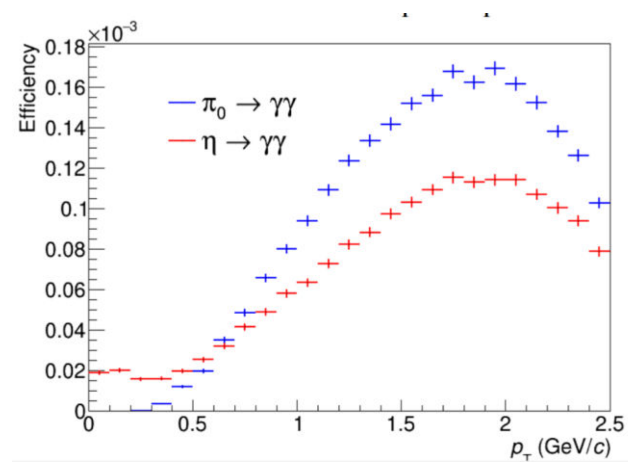
- Photons can be measured in the ECAL or in the tracking system as e^+e^- conversion pairs (PCM):





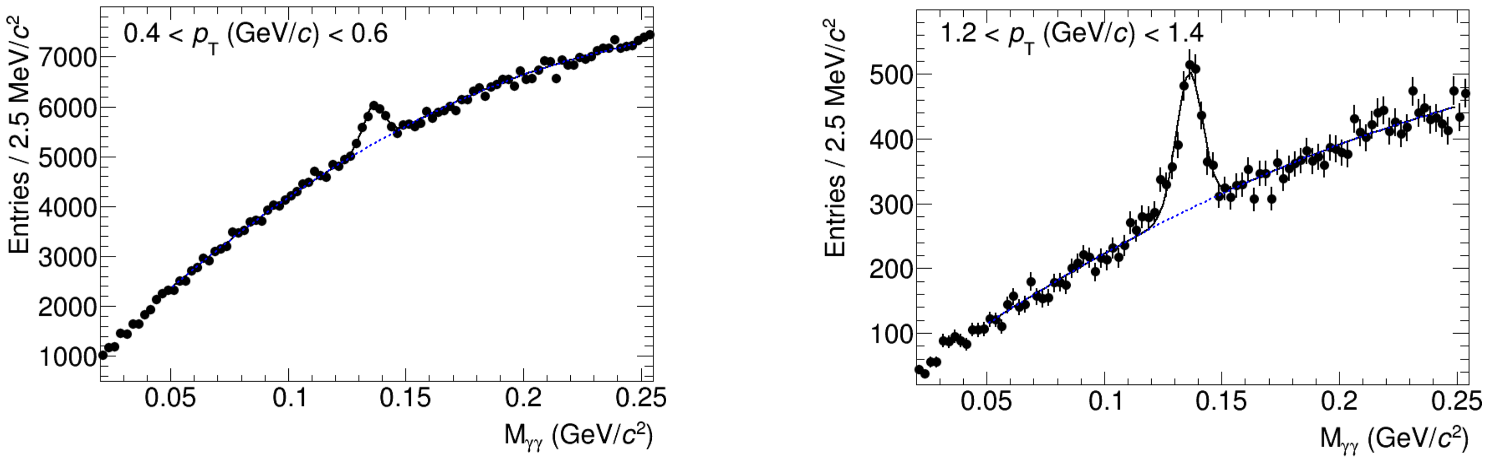
- Only ~4% of photons convert, ~ 1.5% of photons is reconstructed with the PCM (vs. ~ 60% in the ECAL)
- Efficiencies for neutral mesons are on sub-percent level (vs. ~ 40% in the ECAL)



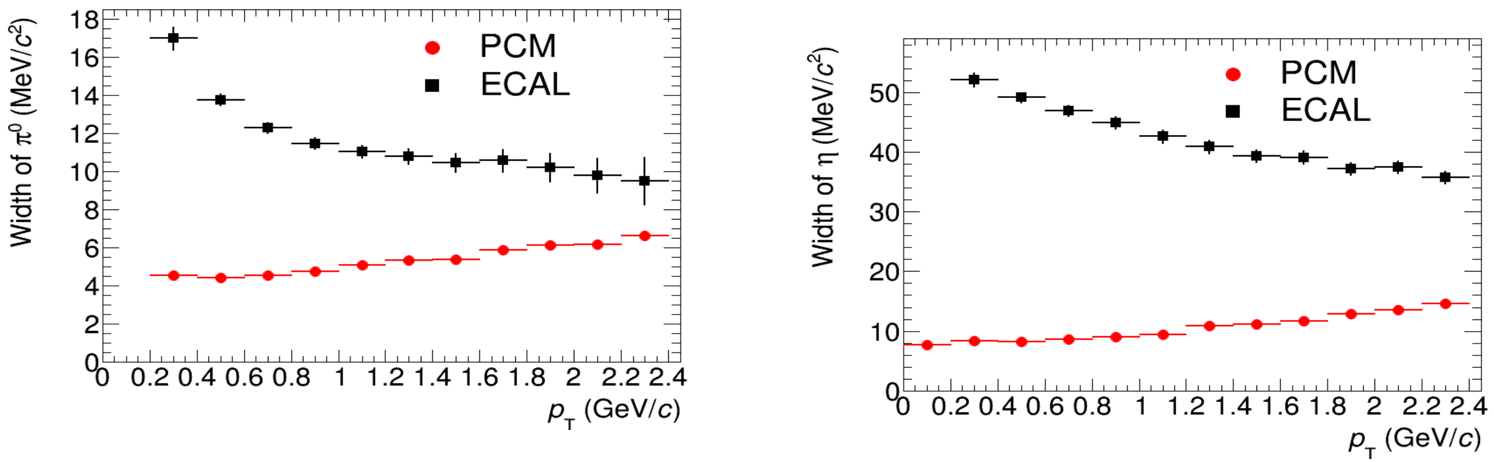


PCM resolution

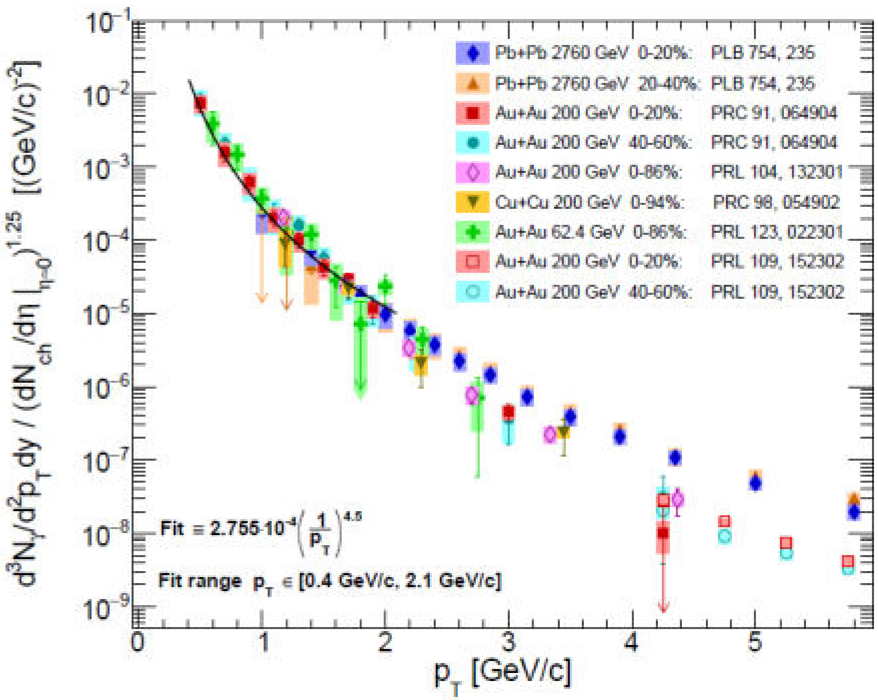
- π^0 reconstructed with the PCM (no background subtraction)



- PCM resolution for photons and neutral mesons is much better compared to the ECAL



p_T-differential direct photon yields



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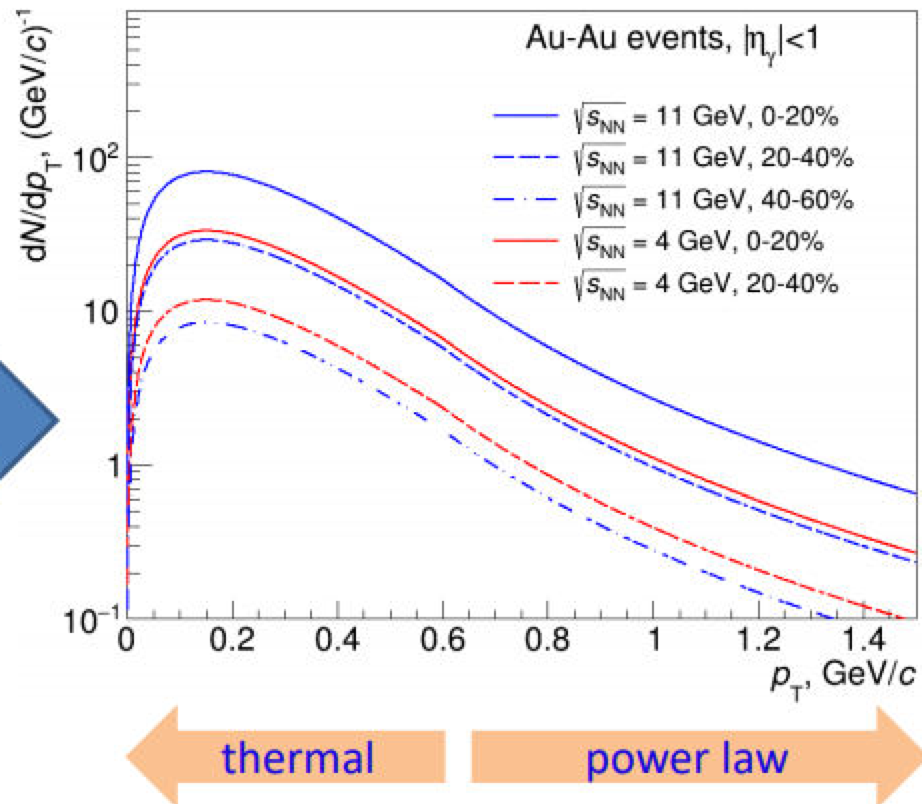

- Universal scaling of p_T-differential direct photon yields at moderate p_T is observed at RHIC/LHC
- It can be used to predict p_T spectra of direct photons at NICA energies for p_T > 0.6 GeV/c
- Switch to thermal spectrum at p_T < 0.6 GeV/c: $dN/dp_T \sim p_T \exp(-p_T/T)$
- Using conservative effective temperature T = 150 MeV (see e.g. *PRC* 93 (2016) 054901)