Thermal photon and neutral meson measurements using photon conversion method in the MPD experiment at the NICA collider

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for the MPD collaboration

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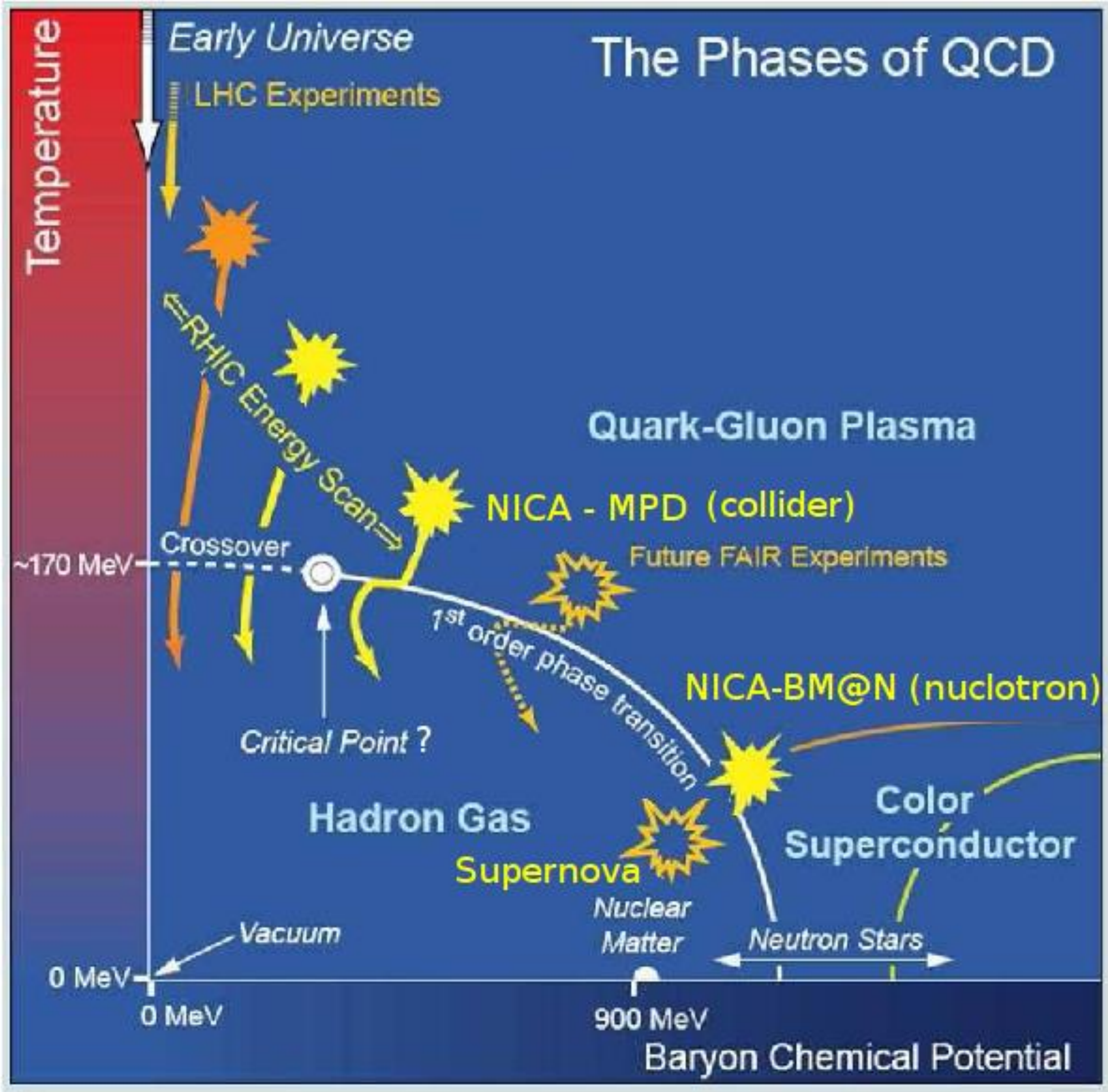
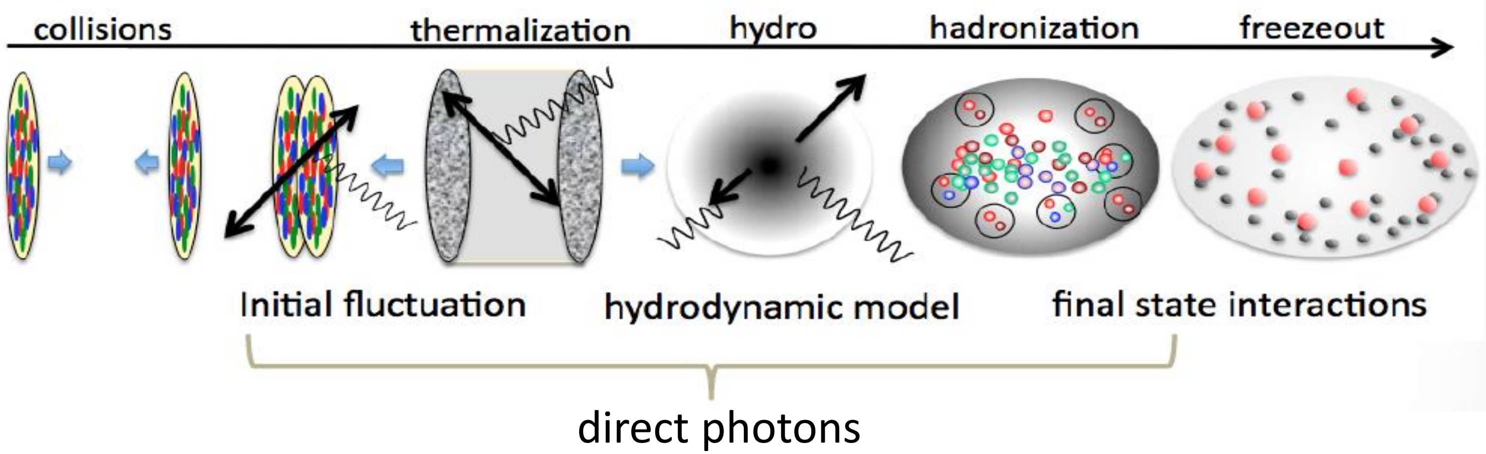
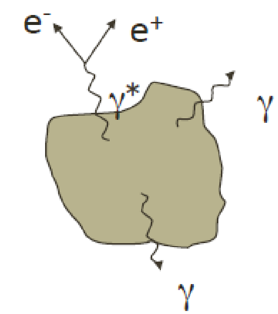
Phase diagram of nuclear matter



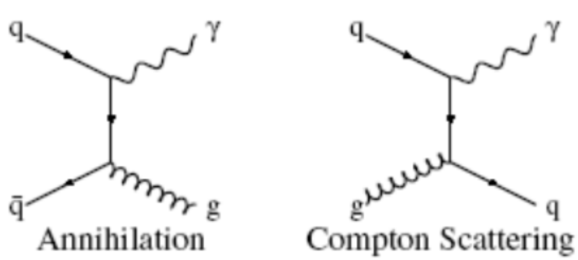
Thermal radiation in heavy ion collisions



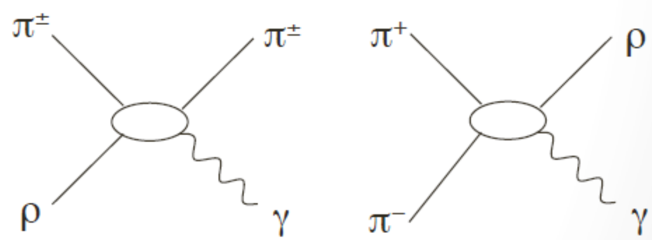


- Photons leave the medium without interaction
- Black body radiation: inverse slope proportional to T_{eff}

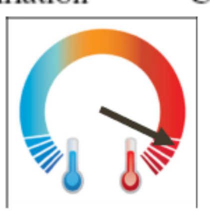
Thermal photons from QGP



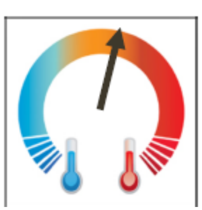
Thermal photons from hadron gas



Naïve:



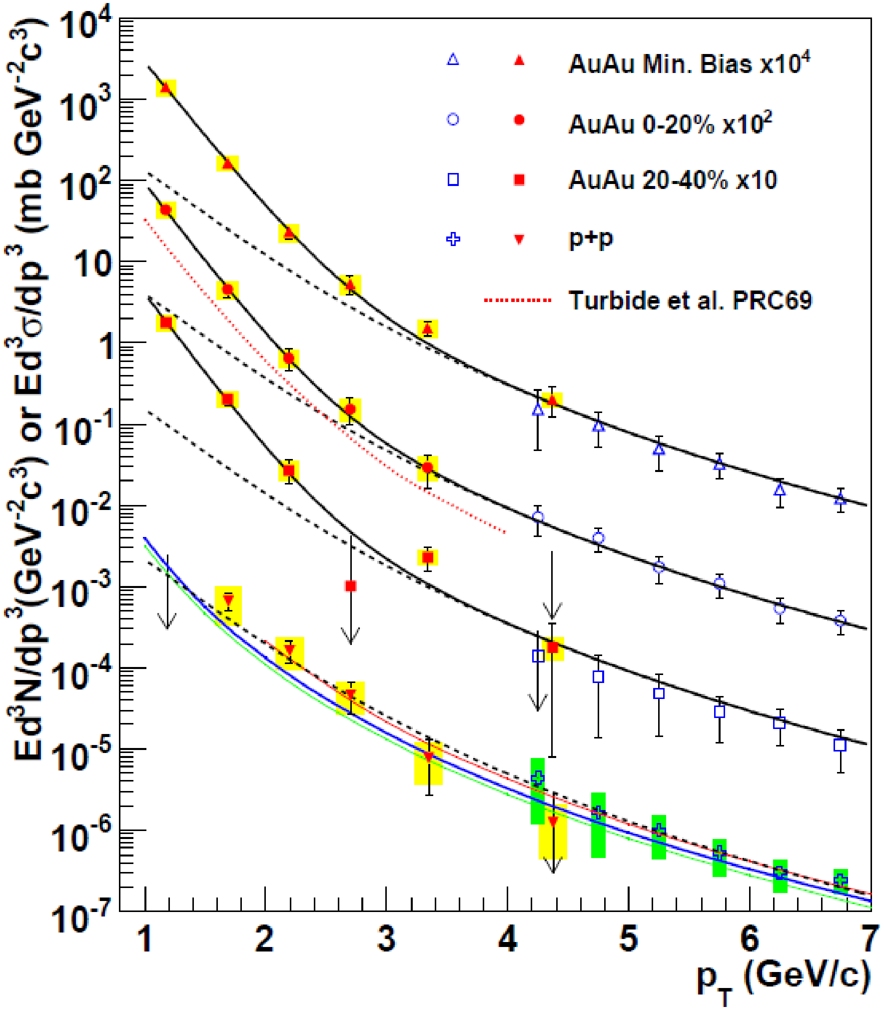
Hot medium
Large yield



Warm medium
Moderate yield

Photon spectra at RHIC and LHC

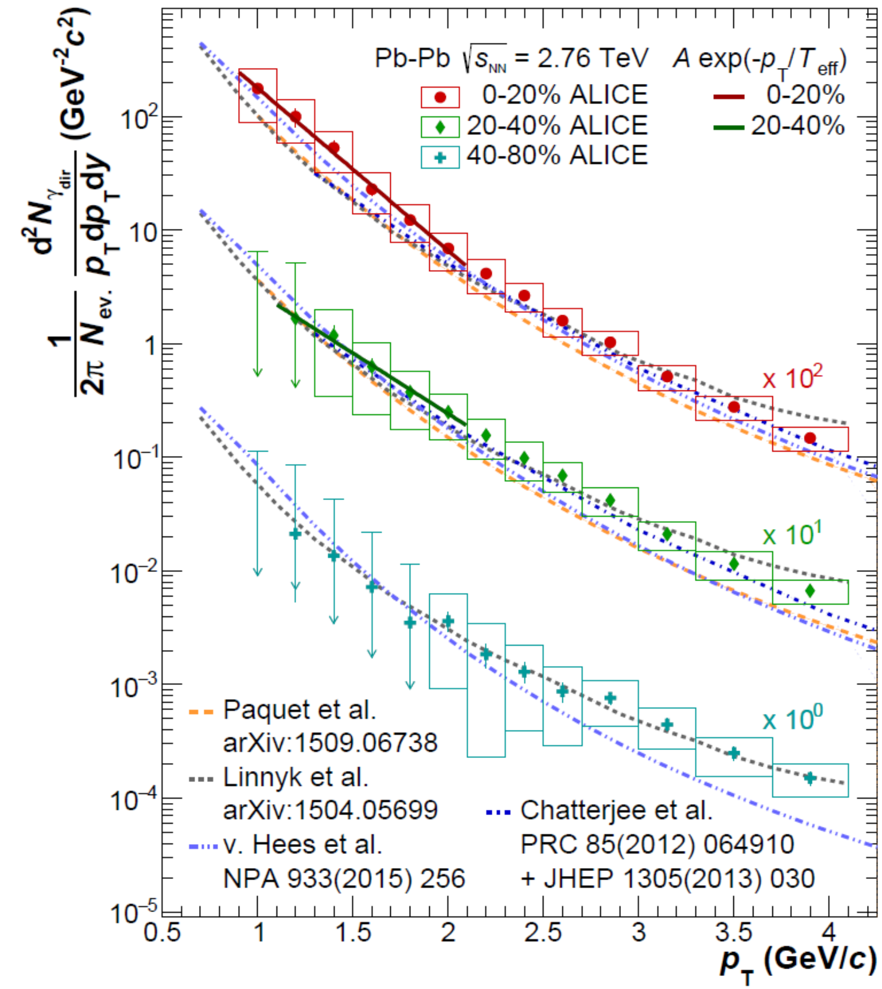
PHENIX (AuAu @ 200 GeV)



T_{eff} = 239 ± 25 (stat) ± 7 (syst) MeV

PHENIX: Phys. Rev. Lett. 104 (2010) 132301

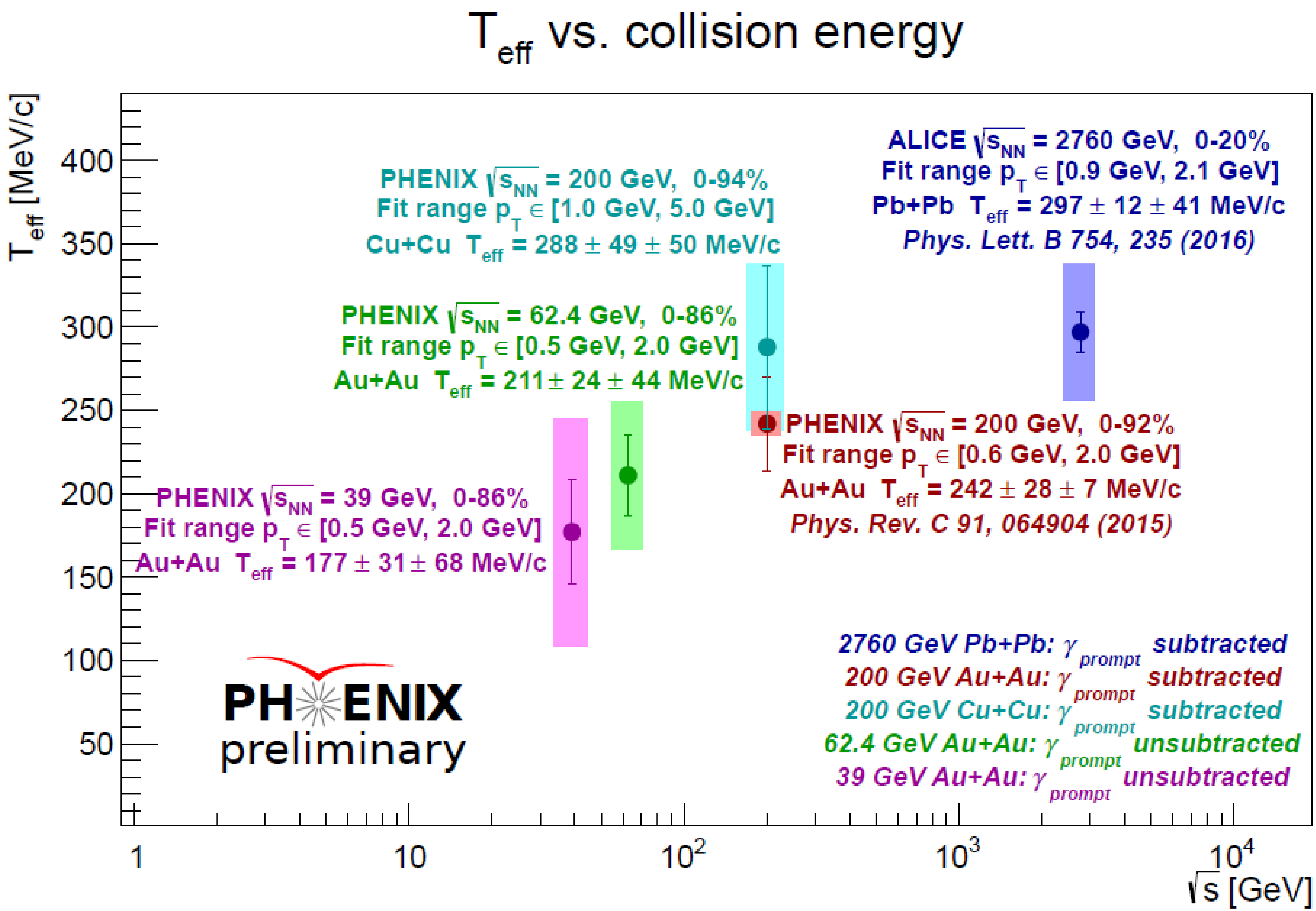
ALICE (PbPb @ 2760 GeV)



T_{eff} = 297 ± 12 (stat) ± 41 (syst) MeV

ALICE: Phys. Lett. B754 (2016) 235

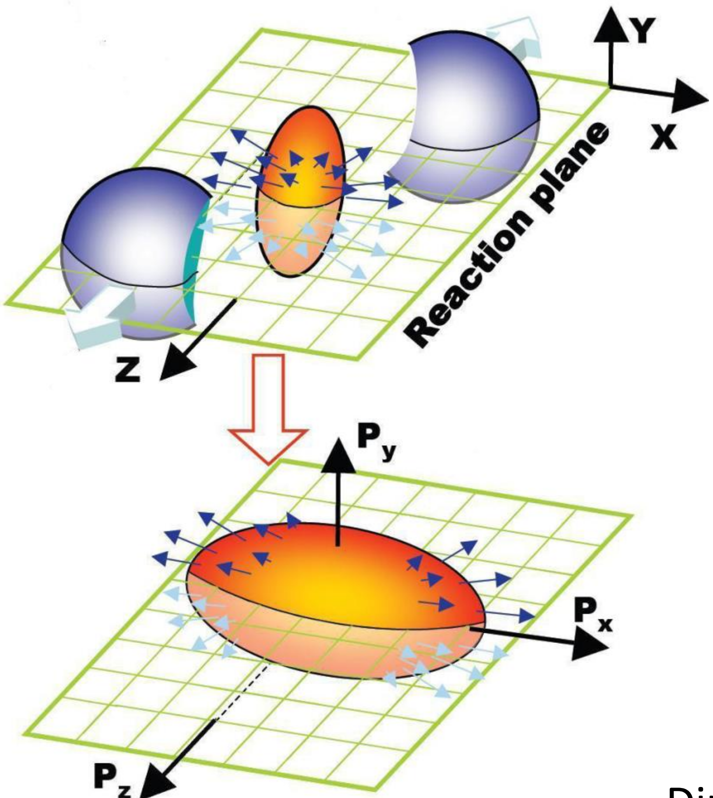
Effective temperature vs energy



J. Phys.: Conf. Ser. 1070 (2018) 012012

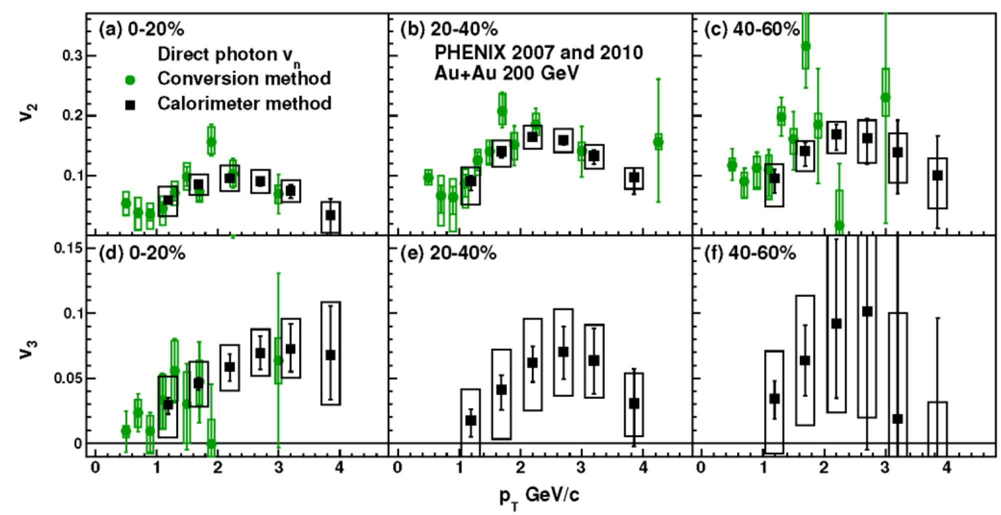
Flow of direct photons

Spatial asymmetry of the initial state translates into the momentum asymmetry



$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$

Elliptic flow of direct photons



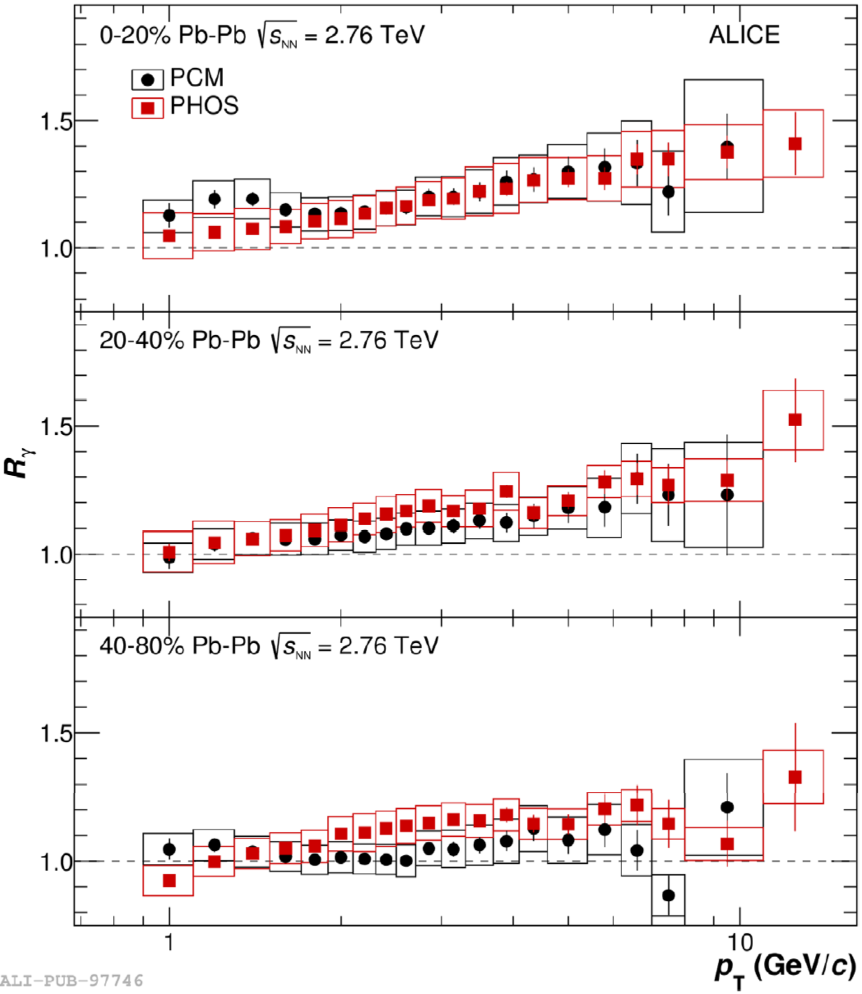
Direct photon puzzle:

- flow of thermal photons is similar to charged pion flow
- thermal photons are predominantly emitted at early stages – no time to develop significant flow

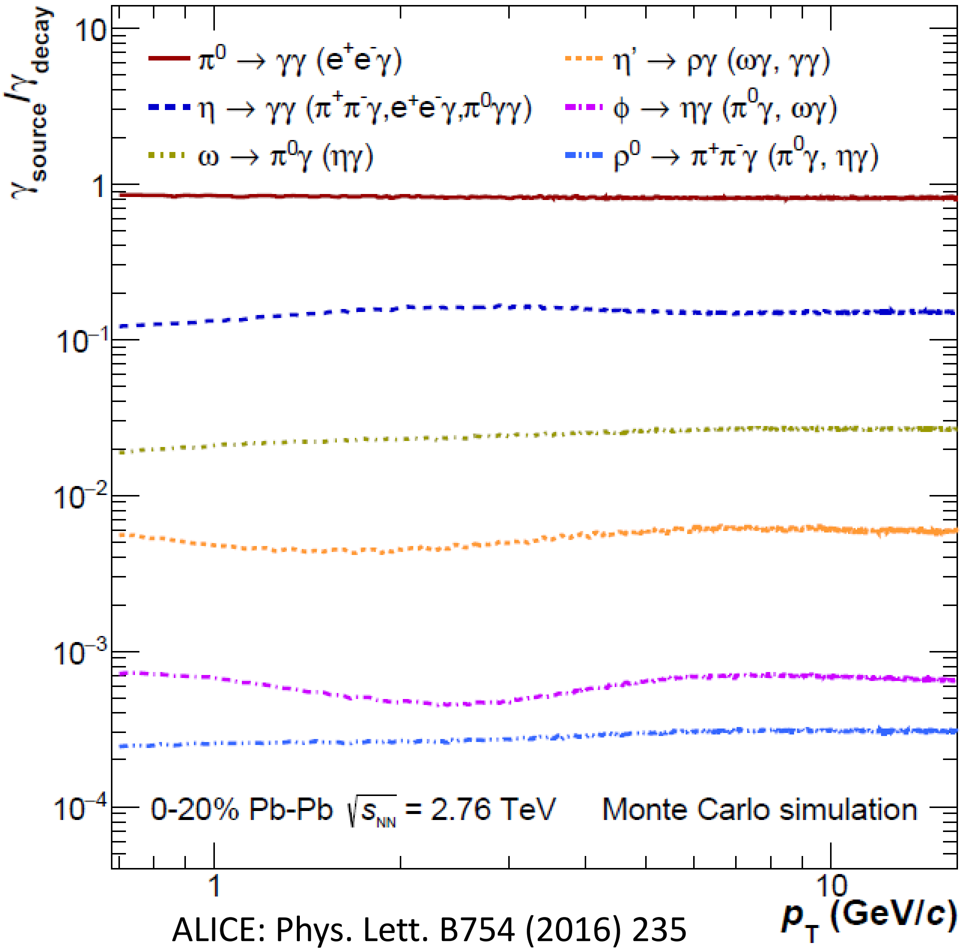
Challenge: decay photons

Inclusive photon spectra are dominated by decay photons

$$R_\gamma = \gamma_{\text{inc}} / \gamma_{\text{decay}}$$

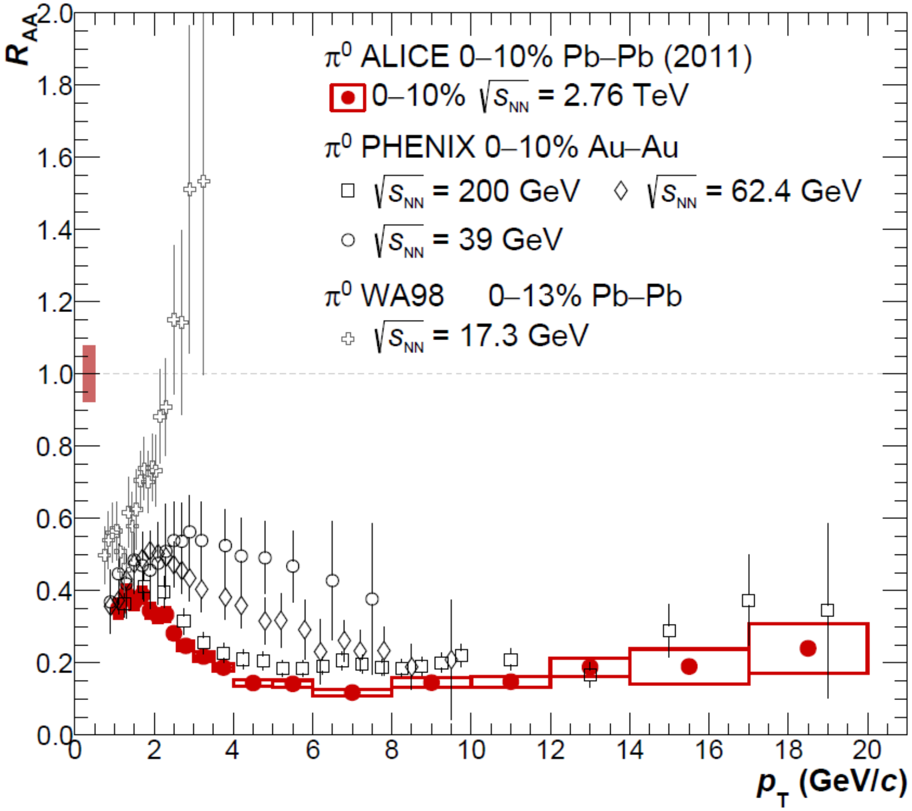


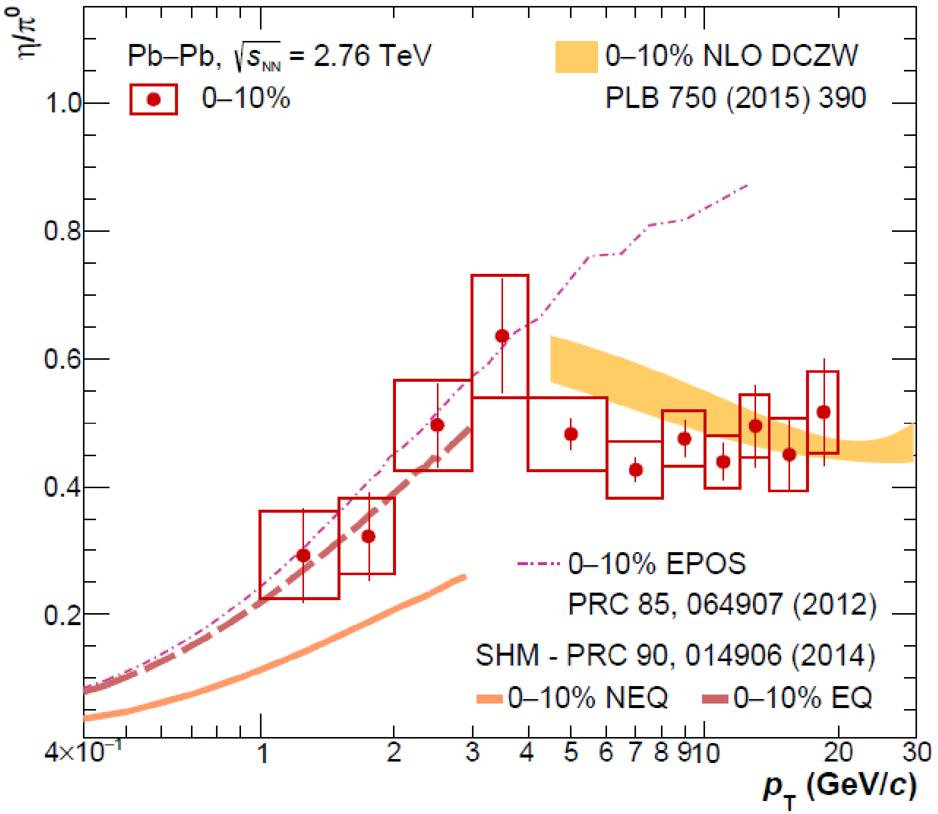
Relative contributions of different hadrons to the total decay photon spectrum as a function of the decay photon transverse momentum



ALICE: Phys. Lett. B754 (2016) 235

Neutral meson spectra





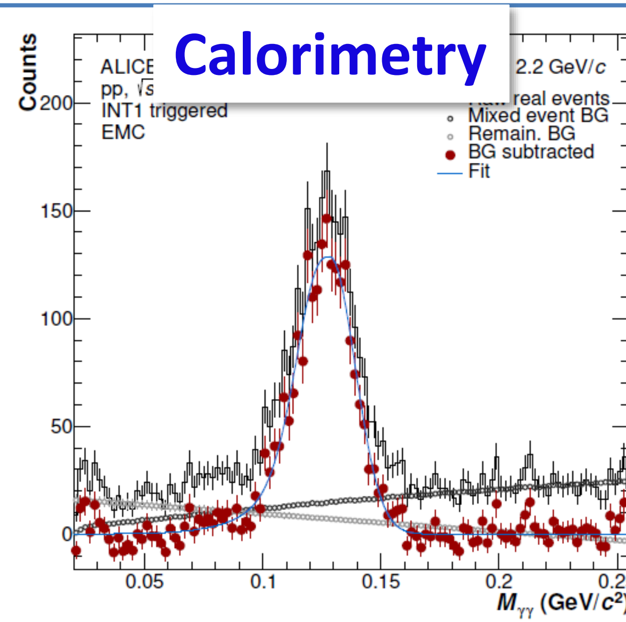
ALICE: Phys.Rev. C98 (2018) 044901

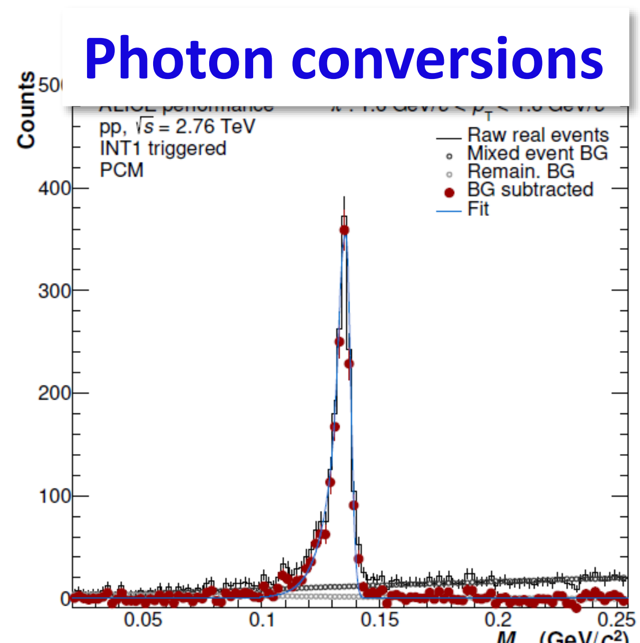
$$R_{AA} = \frac{N_{AA}^{J/\psi}}{\langle N_{coll} \rangle \, N_{pp}^{J/\psi}} \quad \begin{array}{l} = 1 \rightarrow \text{No medium effect} \\ < 1 \rightarrow \text{Suppression} \\ > 1 \rightarrow \text{Enhancement} \end{array}$$

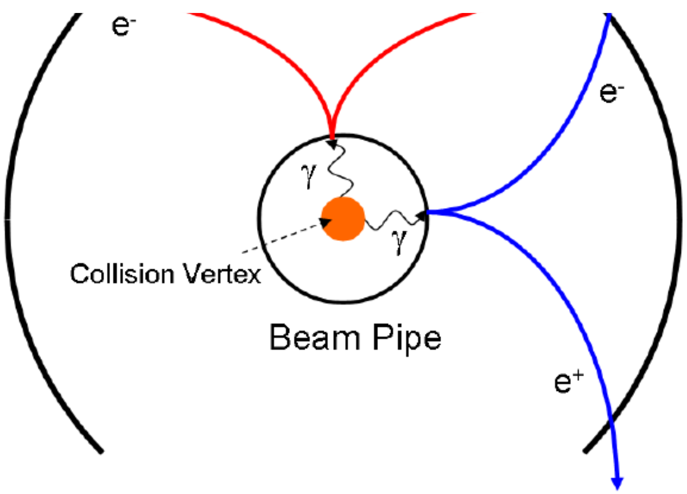
Photon reconstruction: two methods

- Electromagnetic calorimeters
  - Efficient at $p_T > 2$ GeV/c
  - Hardware trigger capabilities

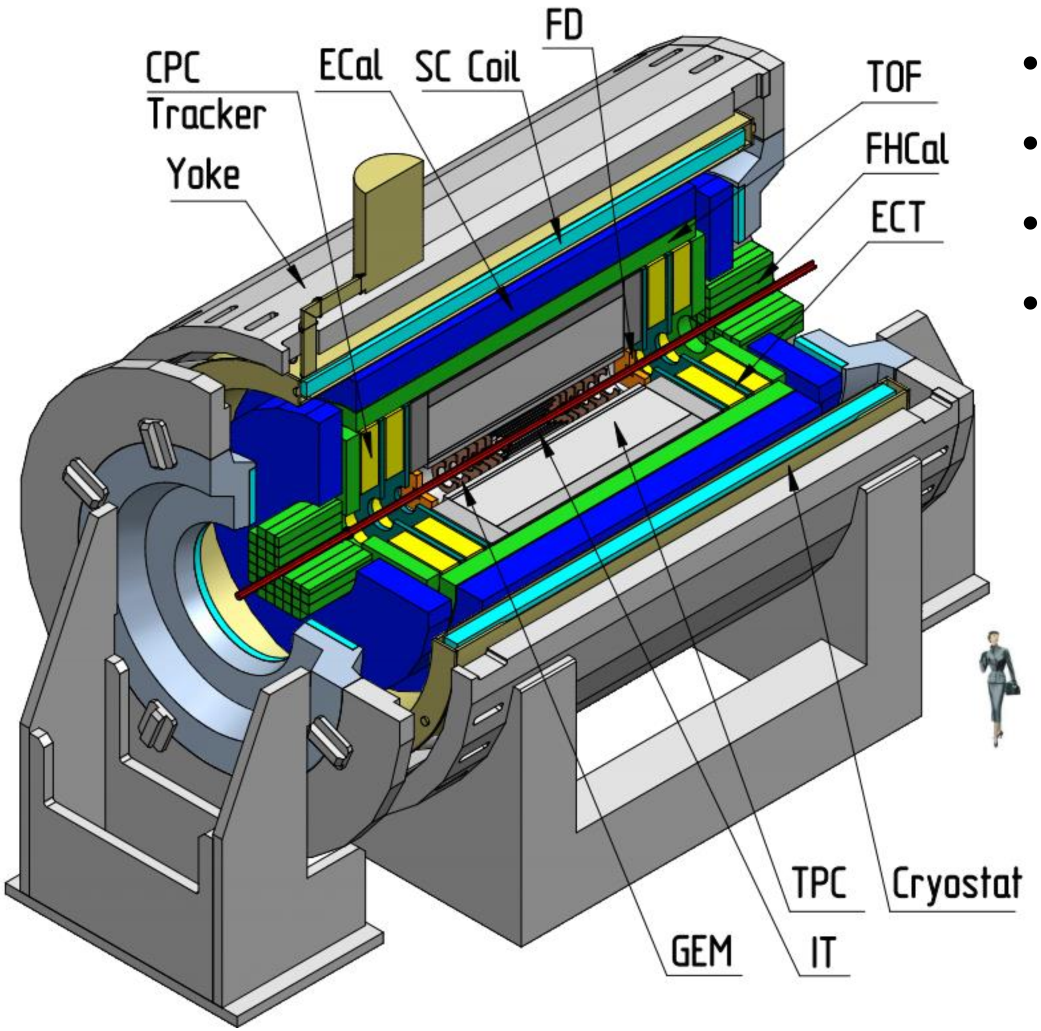
- Photon conversion $\gamma \rightarrow e^+e^-$ in the material
  - $P = 1 - \exp(-7/9\ x/X_0)$
  - Efficient at $0.5 < p_T < 4$ GeV/c
  - Much better resolution at low p_T



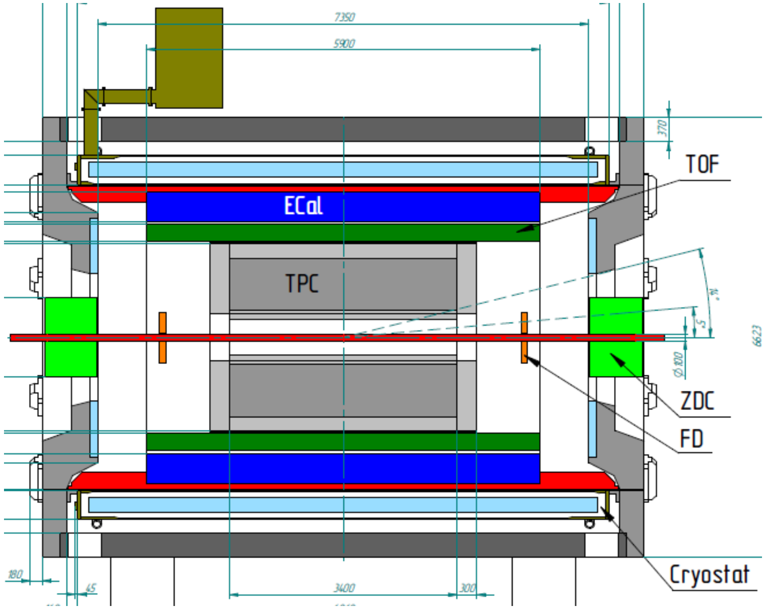




MPD experiment at NICA

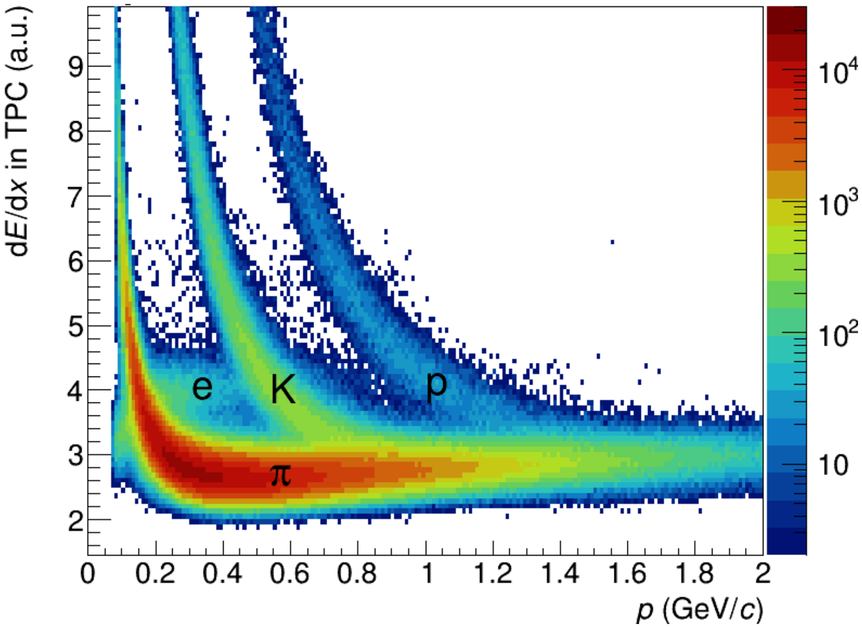


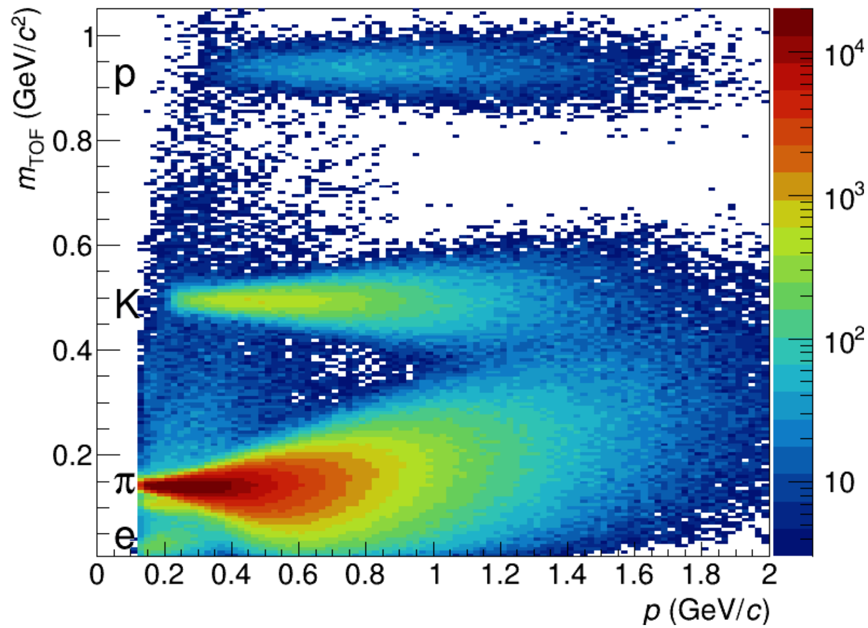
- CMS Energy: 4-11 GeV
- Design luminosity: 10^{27} cm^{-1} s^{-1}
- Stage 1: TPC, TOF, ECAL, FHCal, FFD
- Stage 2: + ITS + EndCap



MPD: NIM A 628 (2011) 99-102

Electron PID

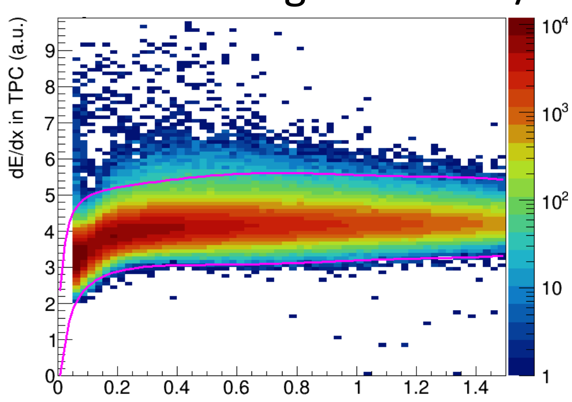


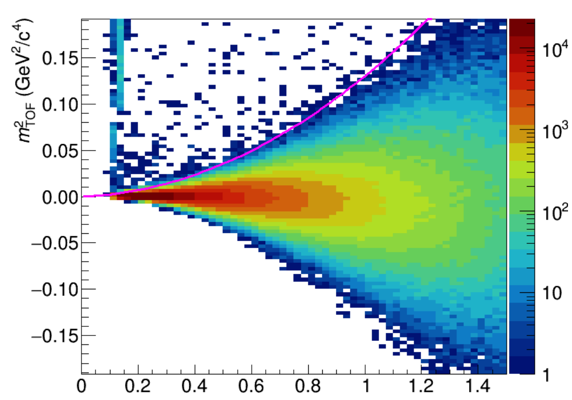


TPC dE/dx: 0.2 - 0.5 GeV/*c*

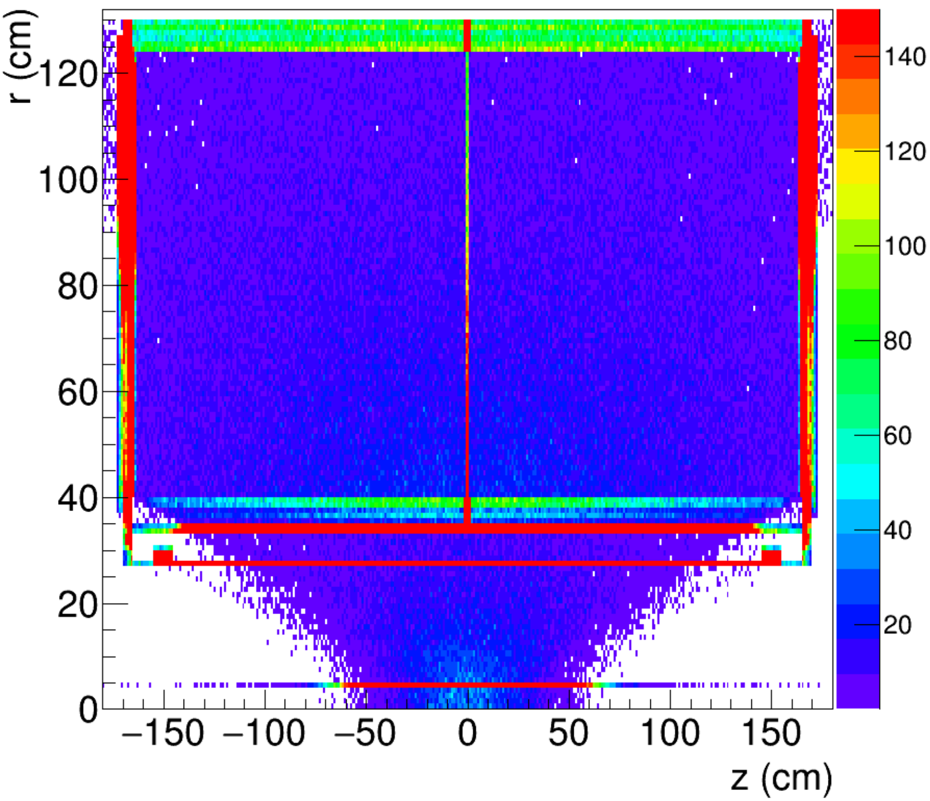
TOF: p_T < 0.3 GeV/*c*

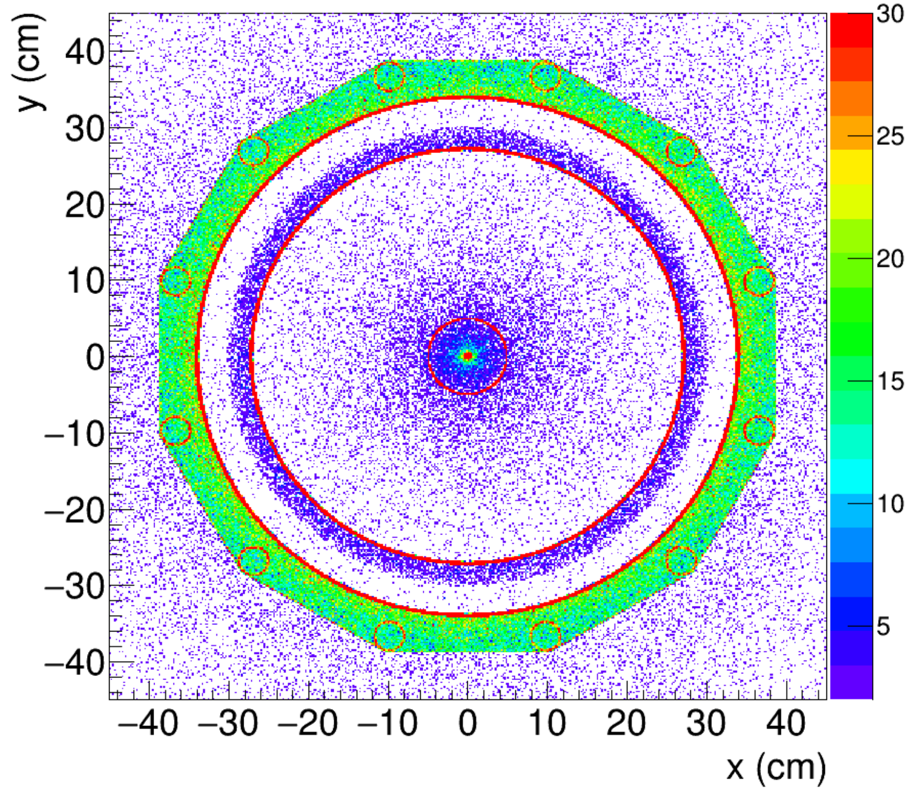
Selecting tracks in +/-4σ around the mean value:





Photon conversion centers





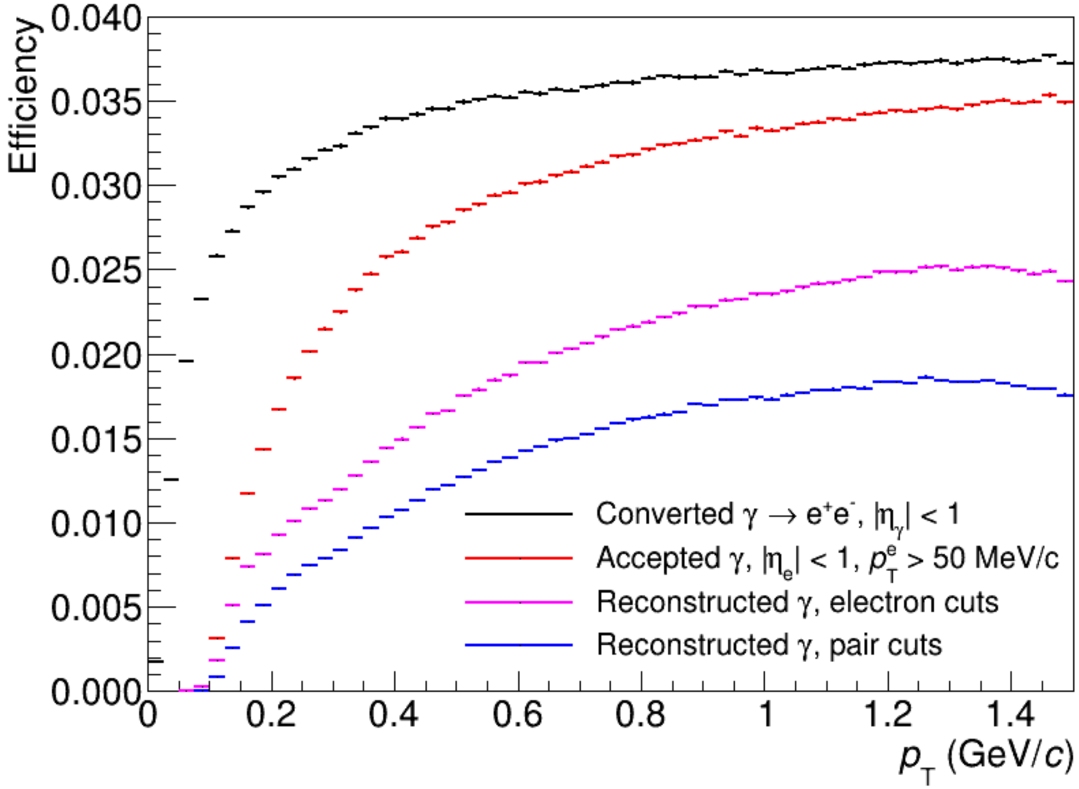
Main conversion structures in Stage 1:

- 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

Conversion reconstruction efficiency



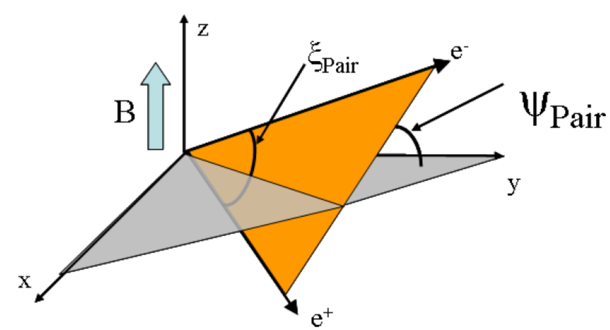
Typical cuts on electrons:

- $|\eta|<1$
- $p_T > 50$ MeV/c
- at least 20 hits in TPC
- +/-4σ electron PID in TPC/TOF

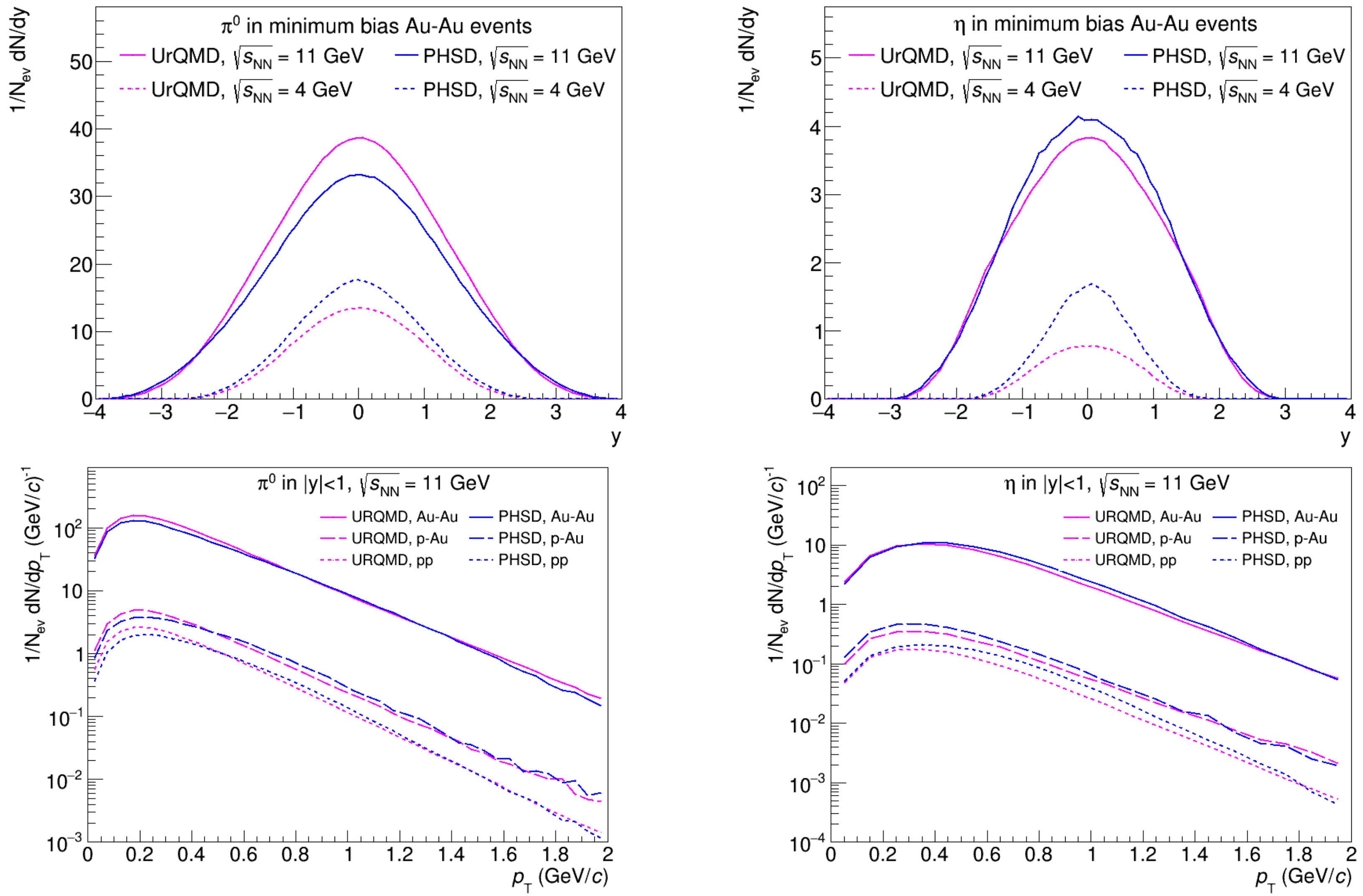
Typical cuts on ee pair:

- Small DCA ($\chi^2 < 10$)
- Vertex R > 10 cm
- Direction to vertex: $\theta < \exp(-2.777-2.798 * p_T) + 0.0175$
- $m_{ee} < 22.6 + 17.4 * p_T$
- ee plane orientation wrt B: $\Psi_{Pair} < 0.1$ rad

- Studied with UrQMD generator + MPDROOT Stage 1 setup
- Using MpdParticle to build secondary vertices
- Cuts optimized to maximize signal significance
- Contribution of (non-gamma) background < 10-20%
  - can be further improved with tighter cuts

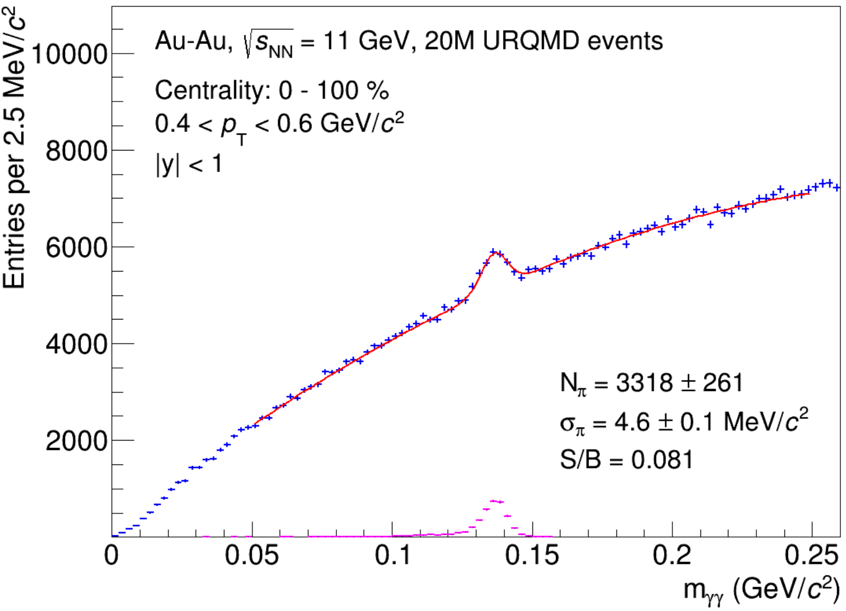


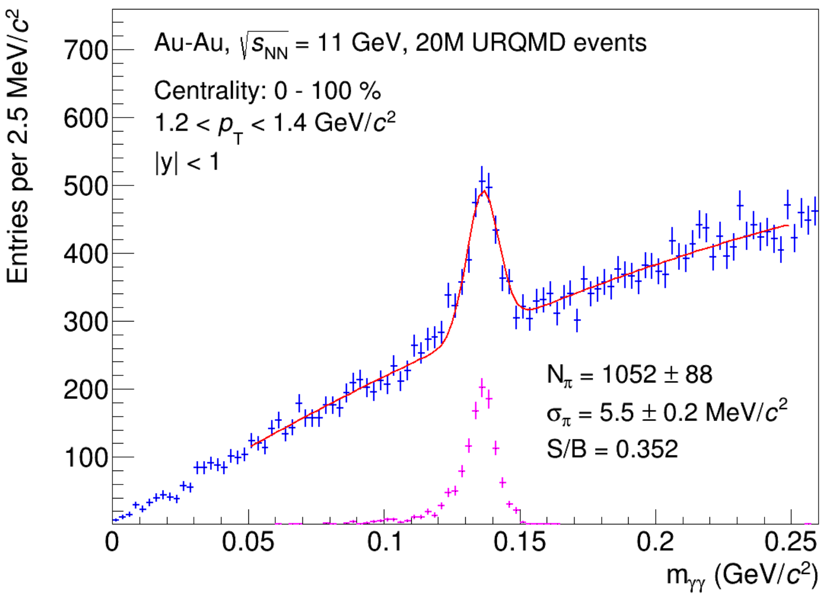
UrQMD and PHSD predictions at NICA energies



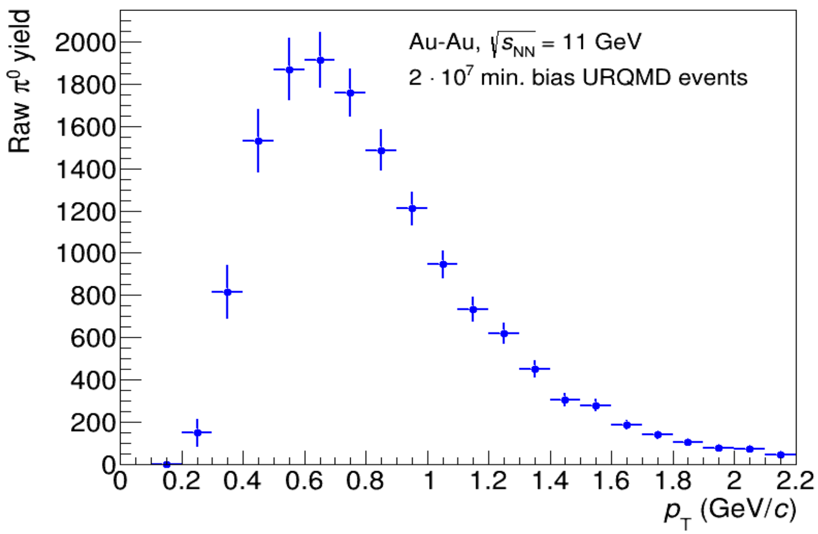
- UrQMD and PHSD generators: good agreement in neutral meson cross sections

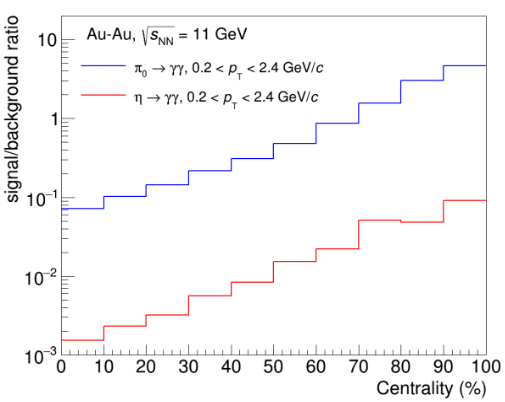
Neutral meson reconstruction

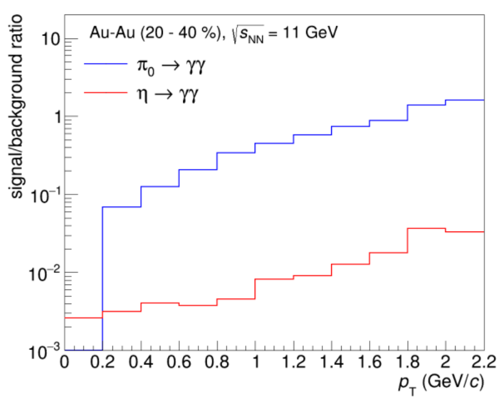




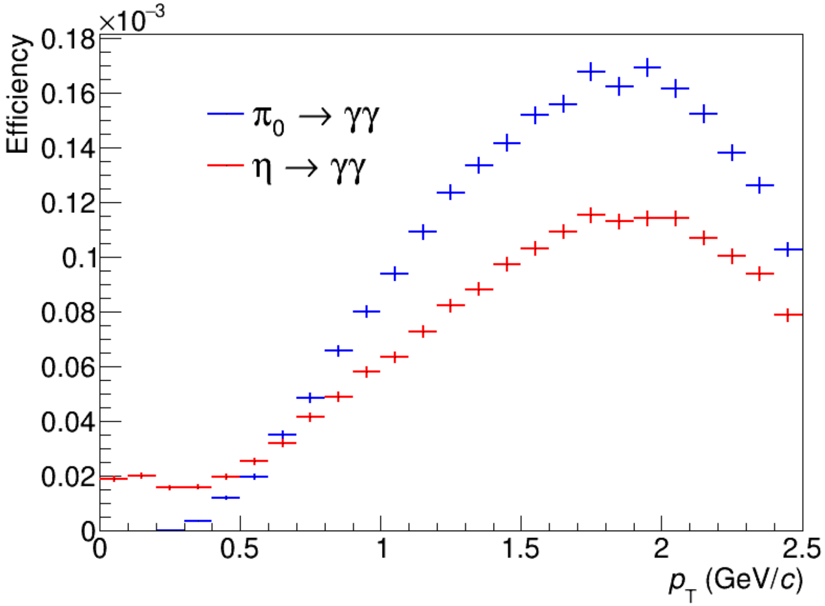
- Using 20M minimum bias URQMD events
- Pion signal is clearly visible in a wide p_T range
- Statistics not enough to study eta reconstruction



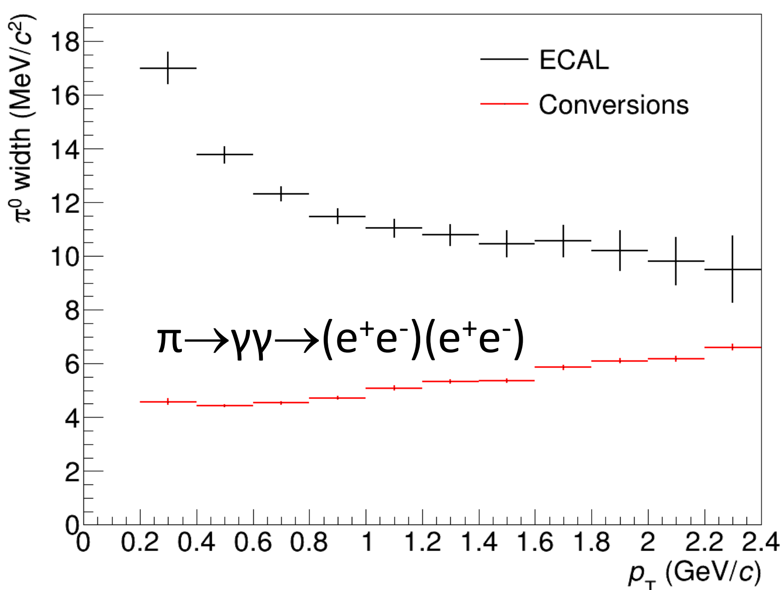


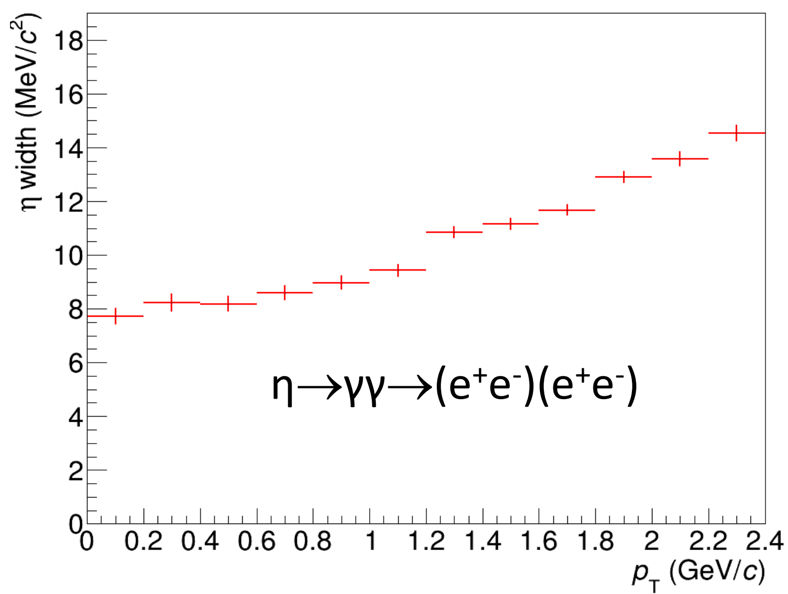


Neutral meson reconstruction efficiency



- Embedding technique used to study reconstruction efficiency vs p_T
- 700 000 min. bias UrQMD events @ 11 GeV
- 500 π^0 + 500 η embedded with flat p_T distribution
- Neutral meson reconstruction efficiency ~ 10^{-4}
- π^0 peak is significantly narrower with conversion method compared to ECAL

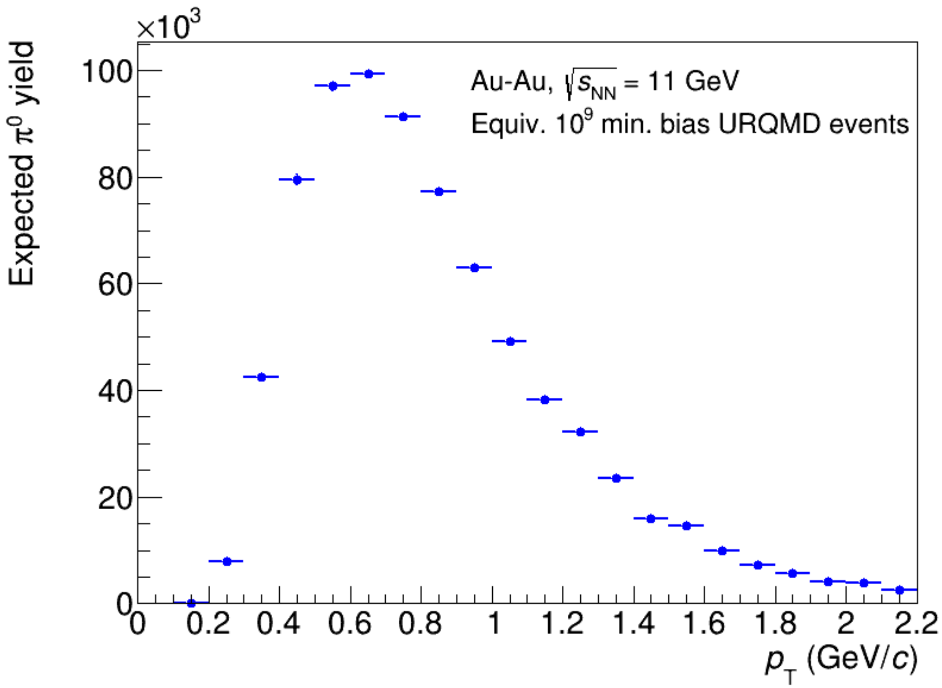




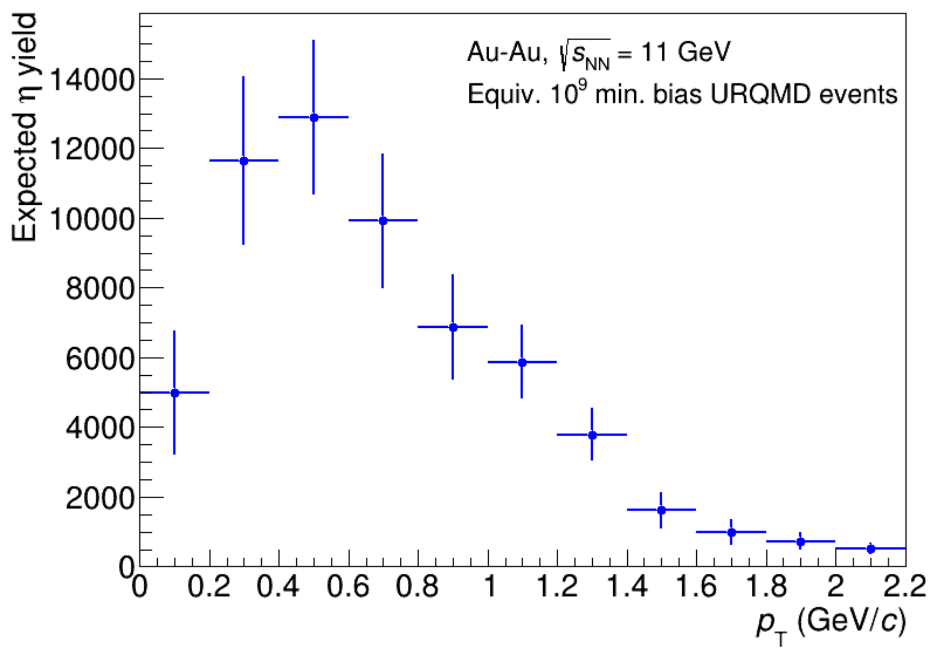
First-year projections

- L ~5 x 10^{25} cm^{-1} s^{-1}
- 10 weeks
- 50% duty factor
- => 10^9 minimum bias events
- Background and signal distributions scaled to 10^9 min. bias events
- Statistical uncertainties estimated as sqrt(S+B)

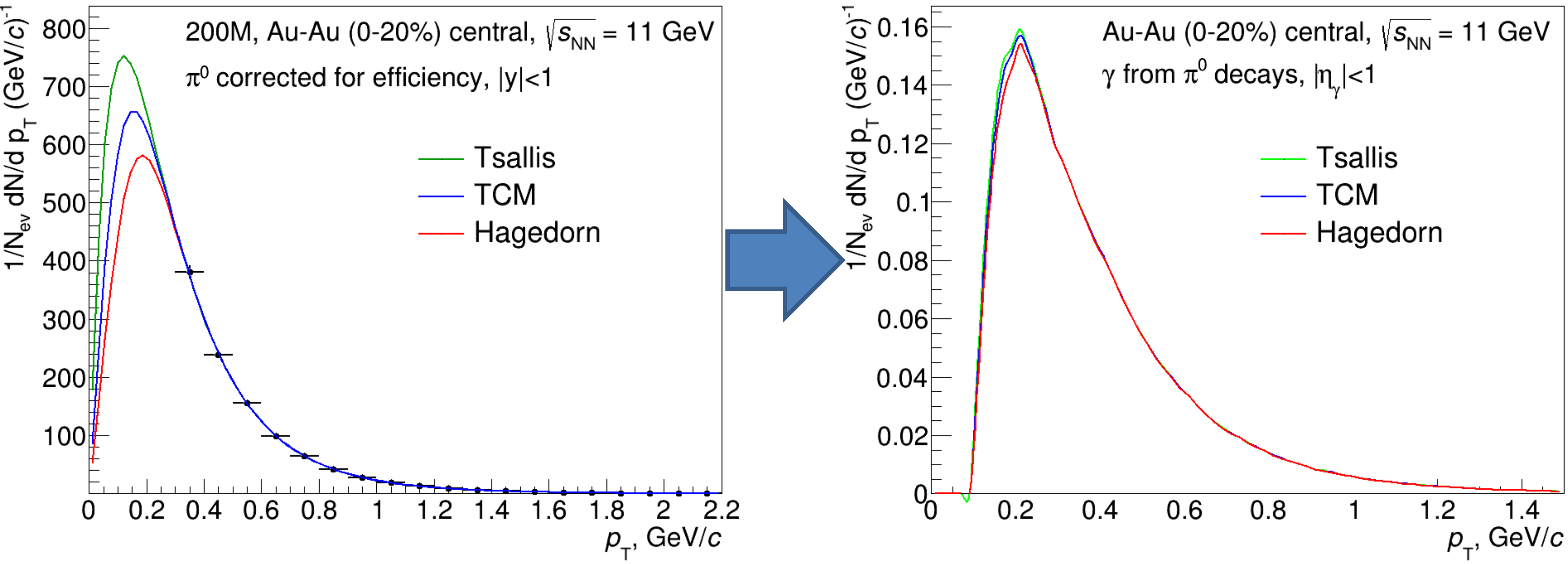
$\pi \rightarrow \gamma\gamma \rightarrow (e^+e^-)(e^+e^-)$



$\eta \rightarrow \gamma\gamma \rightarrow (e^+e^-)(e^+e^-)$



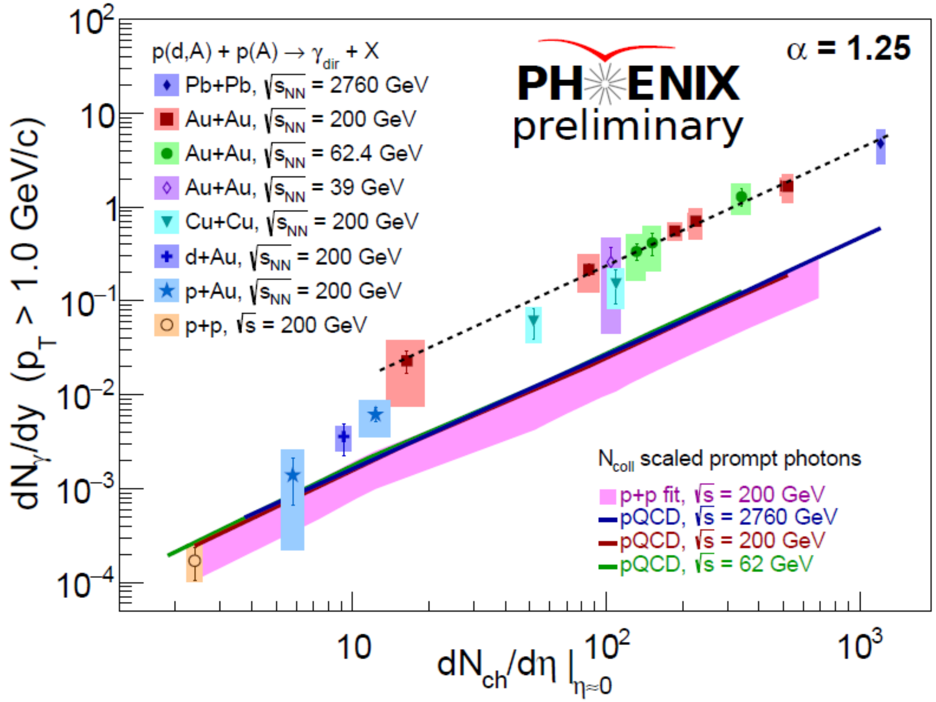
Corrected π^0 spectra

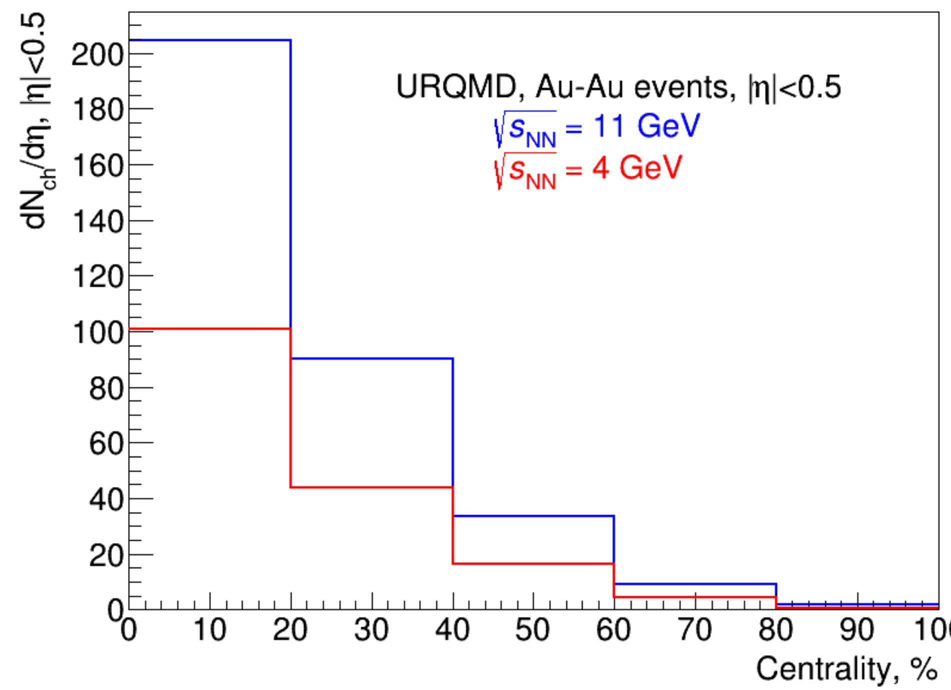


- Efficiency-corrected spectra are extrapolated down to 0 p_T:
  - Tsallis function
  - Two-component model (Bylinkin, Rostovtsev)
  - Hagedorn function
- The obtained fits cab be used to calculate photon spectra from π^0 decays
- Extrapolation uncertainties are significant only at low photon p_T < 0.3 GeV/c

Integrated direct photon yield

No reliable predictions for photons in UrQMD/PHSD -> using data driven method





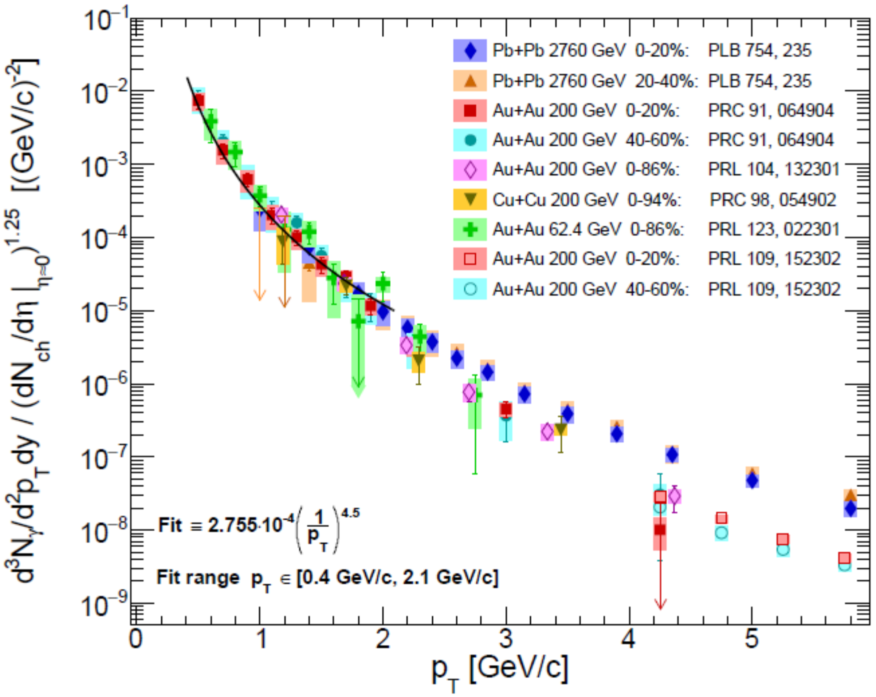
The integrated direct photon yield:

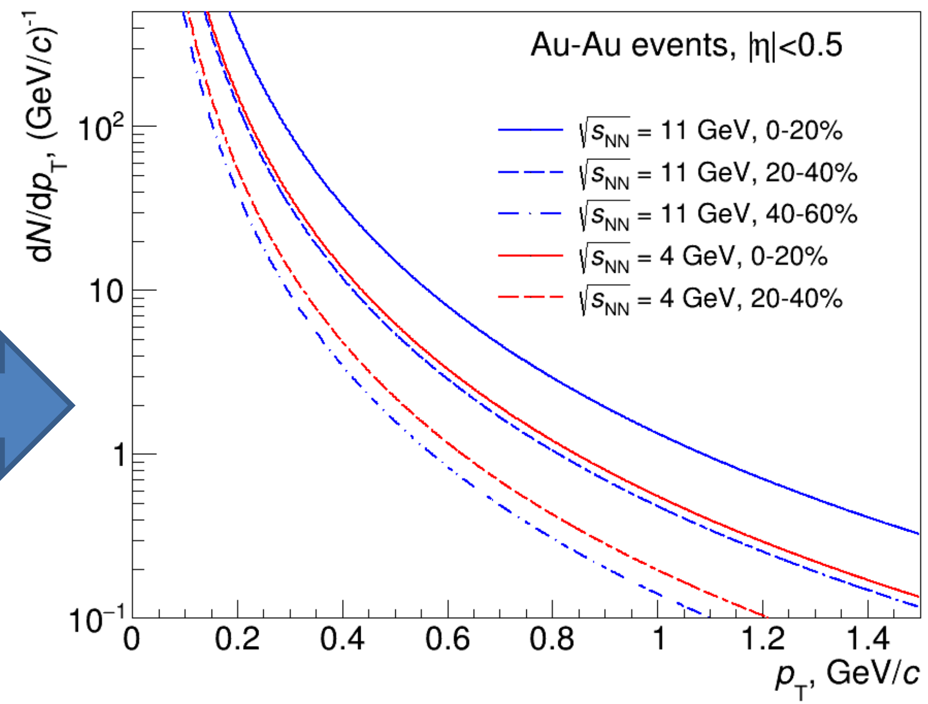
- scales as $(dN_{ch}/d\eta)^{1.25}$ in a wide range of multiplicities/collision energies
- the scaling is violated in small collision systems / small multiplicities ($dN_{ch}/d\eta$ < 20)
- AA yield is a factor of ~10 larger than the N_{coll}-scaled yield in pp

Assuming this scaling still holds at lower energies, we can expect universal multiplicity scaling for

- (0-60)% centralities at 11 GeV
- (0-40)% centralities at 4 GeV

p_T-differential direct photon yields





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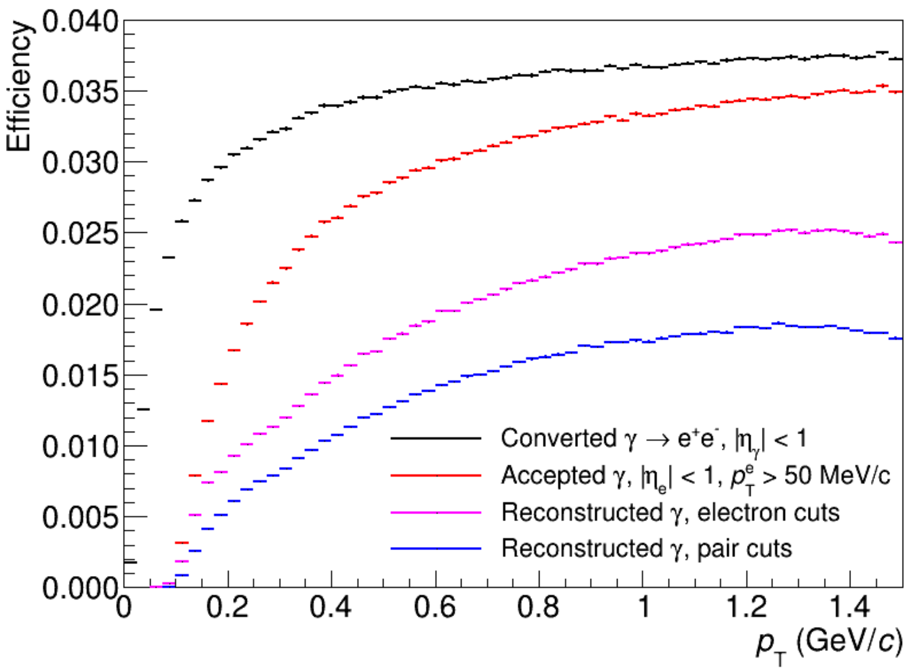
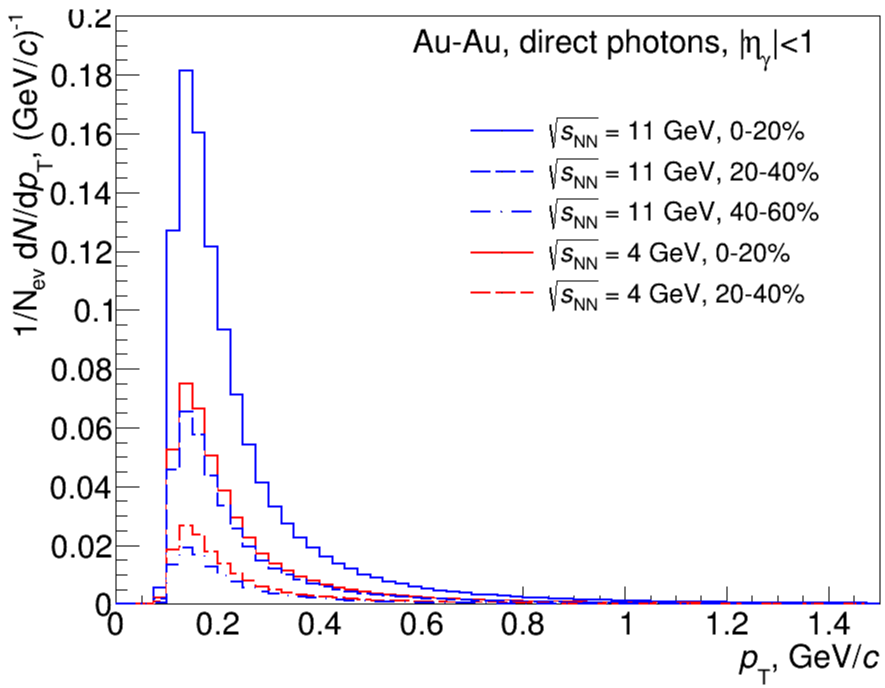
- Universal scaling of p_T-differential direct photon yields is observed at RHIC/LHC
- It can be used to predict p_T spectra of direct photons at NICA energies down to pt ~0.4 GeV/c
- Use thermal-like behavior at lower pt?

Reconstructed direct photons





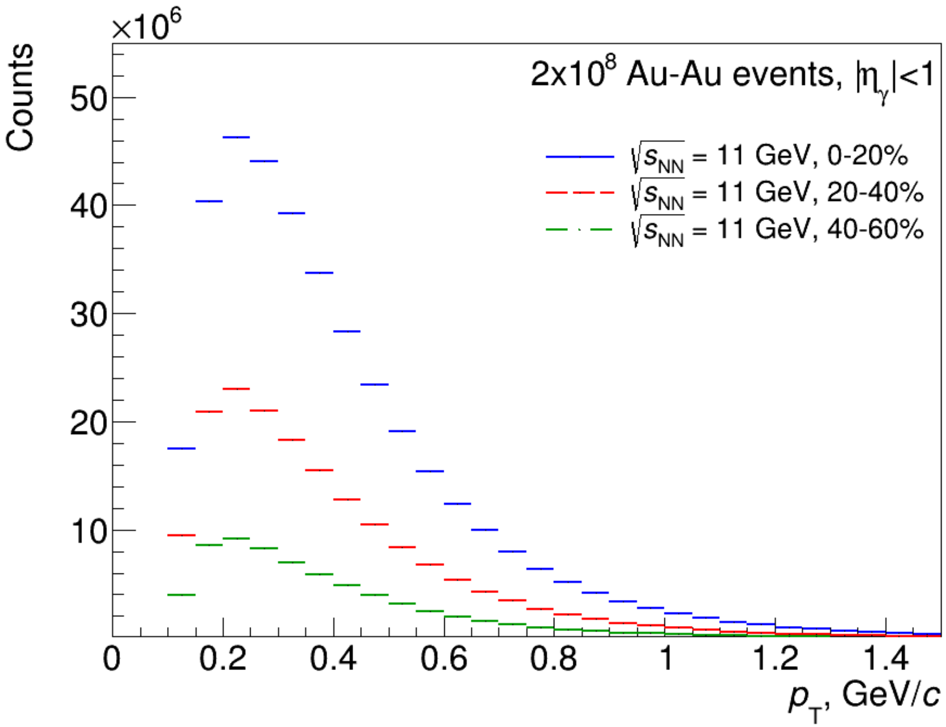
- Reconstructed direct photon spectra can be obtained from predicted direct photon yields multiplied by the photon reconstruction efficiency

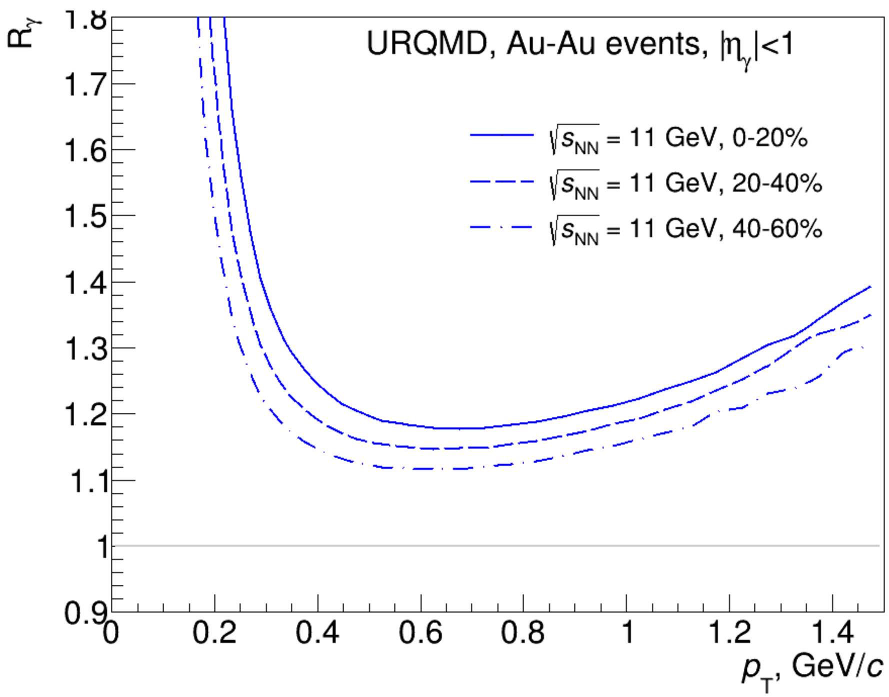
Inclusive photon spectra and R_γ ratio

$$R_\gamma = \frac{\gamma_{\rm inc}}{\gamma_{\rm decay}} = \frac{\gamma_{\rm inc}/\pi^0}{\gamma_{\rm decay}/\pi^0_{\rm param}}$$

Inclusive photon spectrum was simulated as a sum of direct and decay photon spectra

Excess over 1 shows the fraction of direct photons





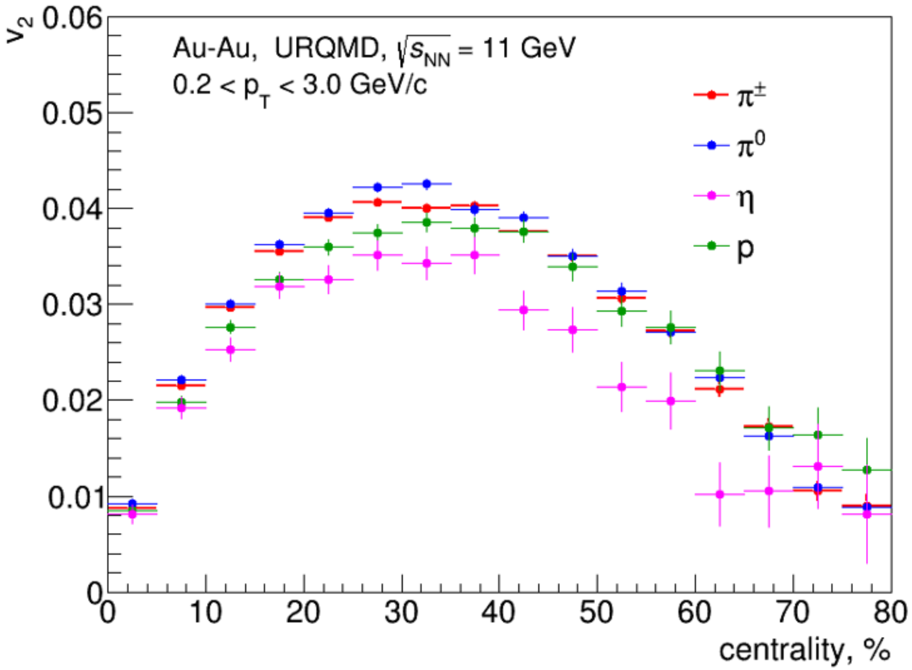
- Systematic uncertainties on R_γ can be reduced to ~5%
- Conclusion: direct photon yields can be extracted with good accuracy

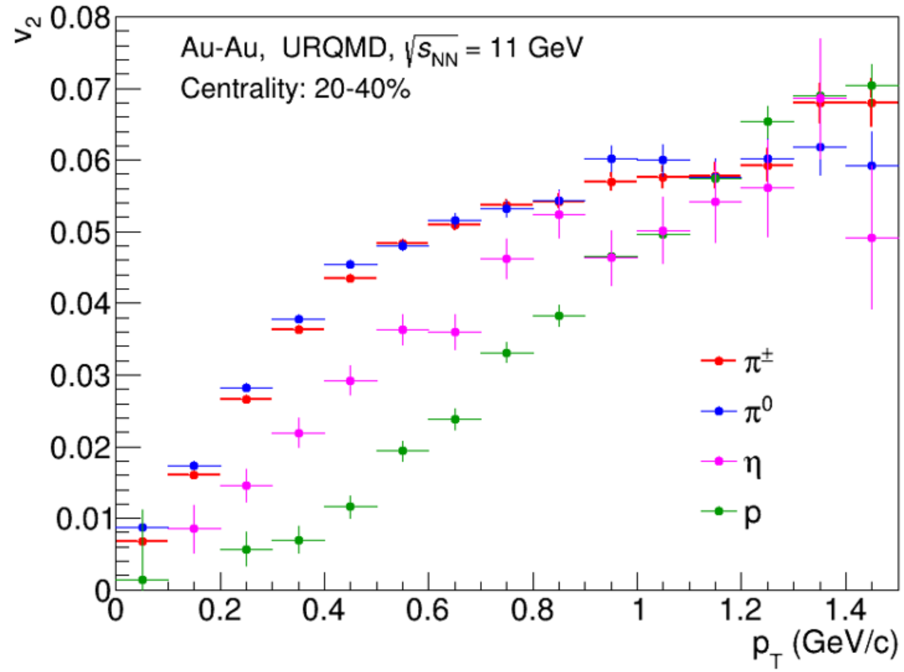
$$\gamma_{\rm direct} = \left(1 - \frac{1}{R_\gamma}\right) \cdot \gamma_{\rm inc}$$

Elliptic flow of neutral mesons

Generator-level studies using true reaction plane

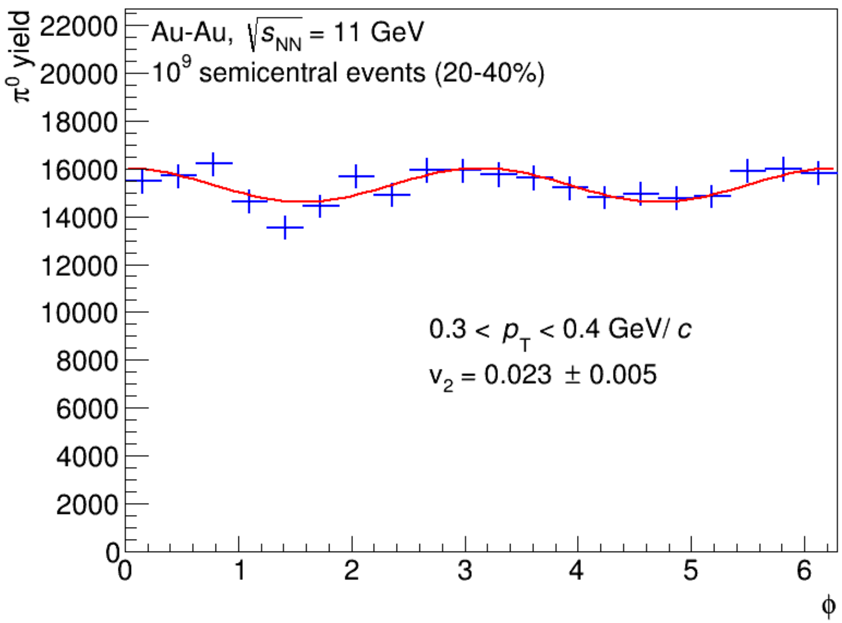
$$\frac{dN}{d\varphi} \sim 1 + 2\sum_n v_n \cos n(\varphi - \Psi_{RP})$$

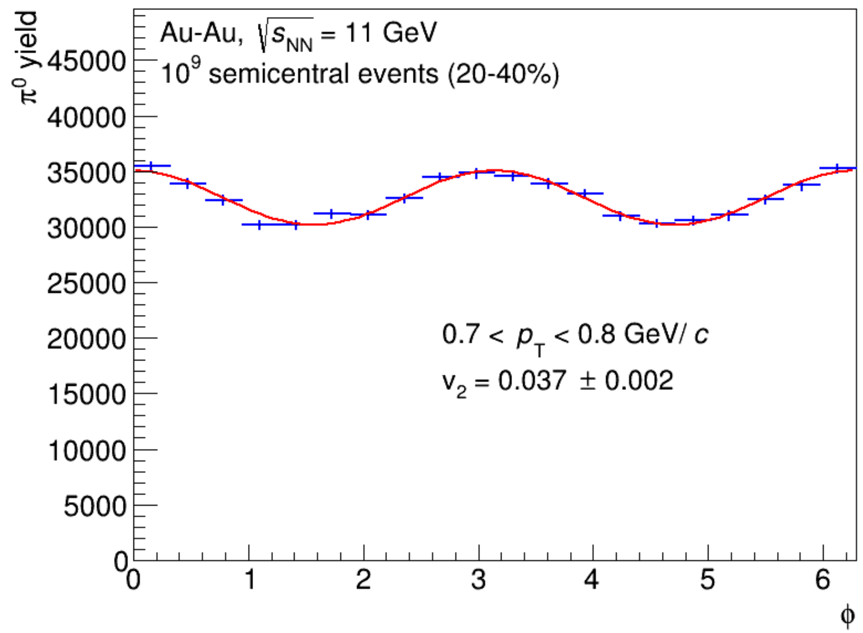




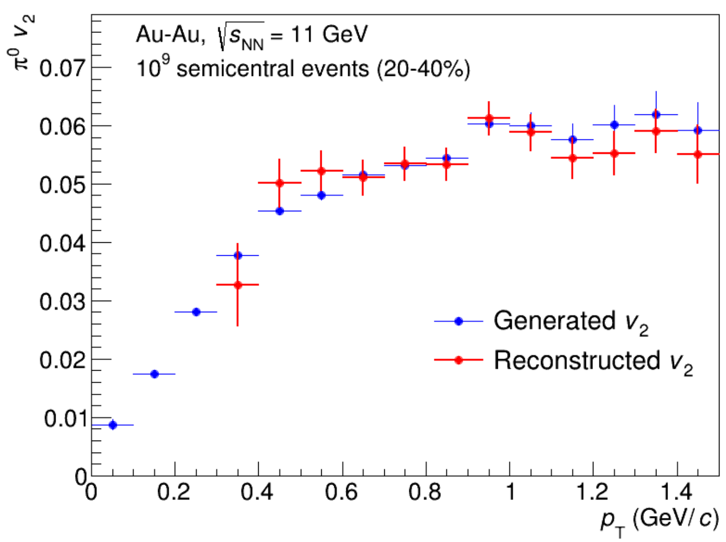
- Significant v_2 values predicted for all particle species
- As expected, elliptic flow of $\pi^\pm$ and π^0 mesons is very similar
- There is a clear mass ordering of v_2 as function of p_T:
  eta meson v_2 (intermediate mass range) is between proton and pion v_2

Toy model for π^0 elliptic flow





- Azimuthal distributions of reconstructed π^0s are generated assuming 10^9 semi-central (20-40%) events and taking into account predicted v_2 and event plane resolution effects.
- v_2 coefficients are then extracted and corrected for resolution in several p_T bins
- 10^9 semi-central (20-40%) events are required to measure neutral pion v_2 with ~10% precision
  => not a "first-year goal"



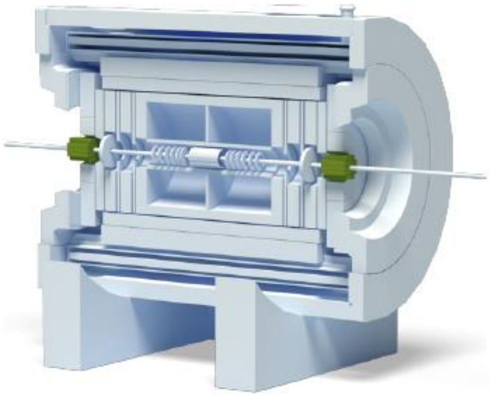
Conclusions and outlook

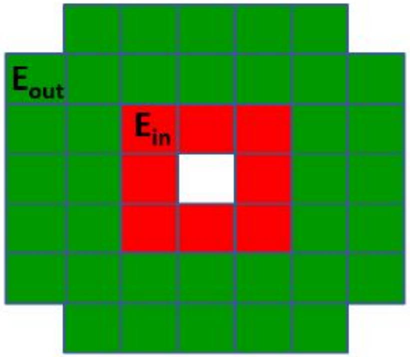
- Photons and neutral mesons - valuable probes of dense hadronic matter produced in heavy ion collisions
- Photon conversion method is a powerful tool to measure photon and neutral meson spectra
- Standard MPD configuration allows one to reconstruct π^0 mesons via conversions already with the first year data taking
- Reconstruction of thermal photon yields looks promising
- Next:
  - Evaluate perspectives of thermal photon flow measurements
  - Feasibility studies on the dedicated convertor and Stage 2 setup

BACKUP

Event plane determination with FHCal

$2 < |\eta| < 5$





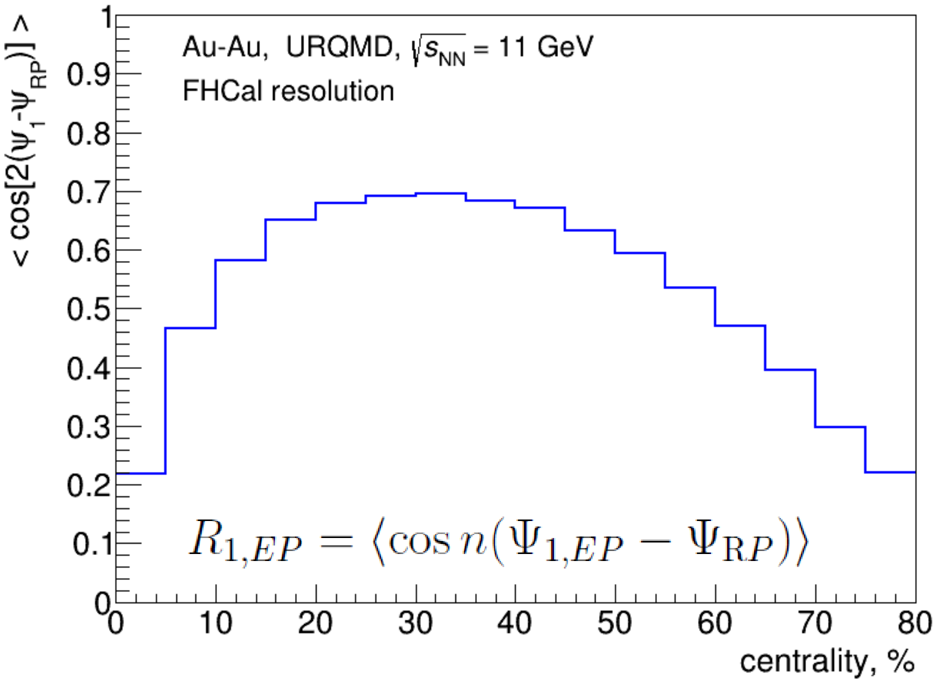
- Event plane:

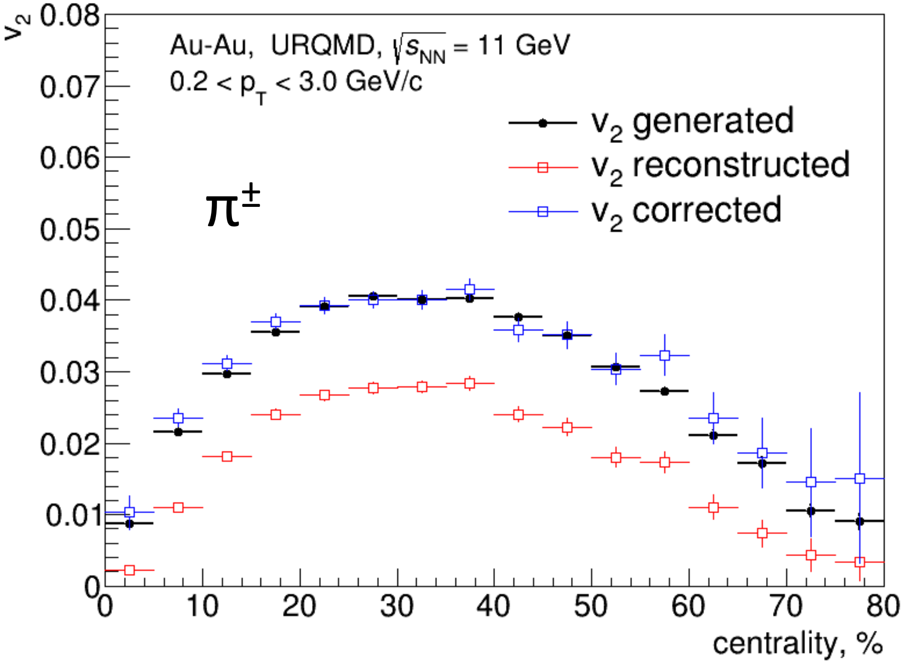
$$\Psi_{1,EP}^{L(R)} = \arctan\left(\frac{\sum E_i \sin\varphi_i}{\sum E_i \cos\varphi_i}\right)$$

- v_n corrected for event plane resolution effects:

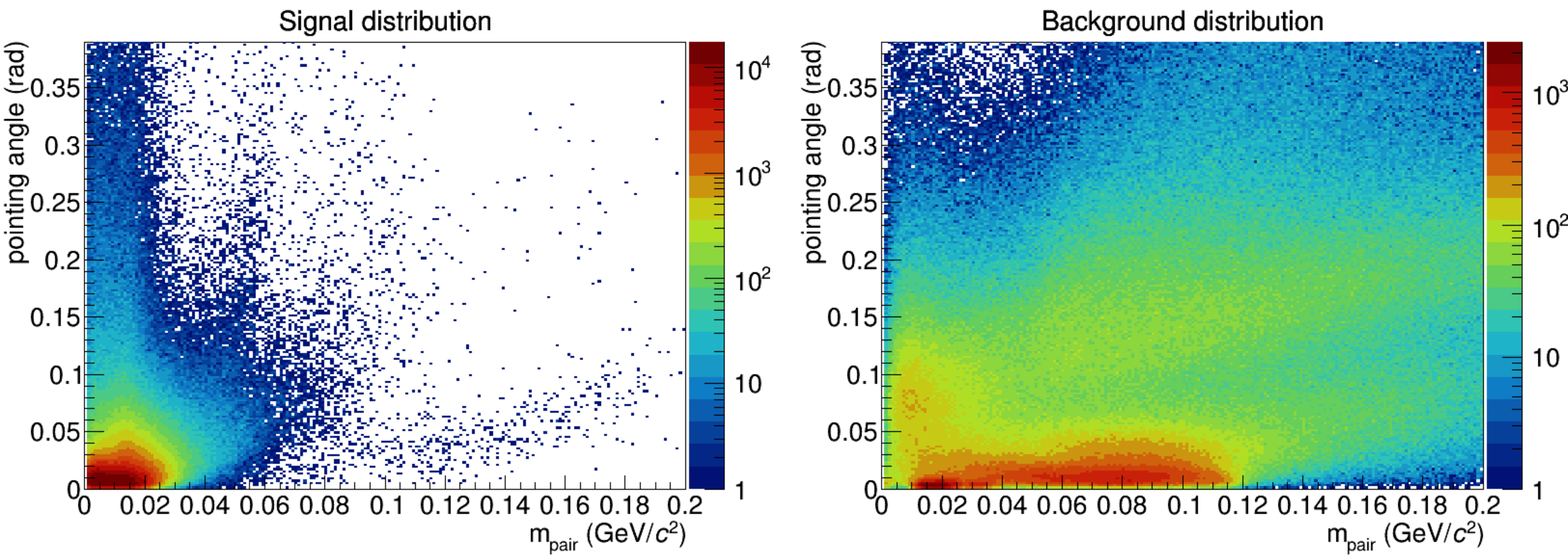
$$v_n\{\Psi_{1,EP}\} = \frac{\langle \cos n(\varphi - \Psi_{1,EP})\rangle}{R_{1,EP}}$$

Resolution correction factor

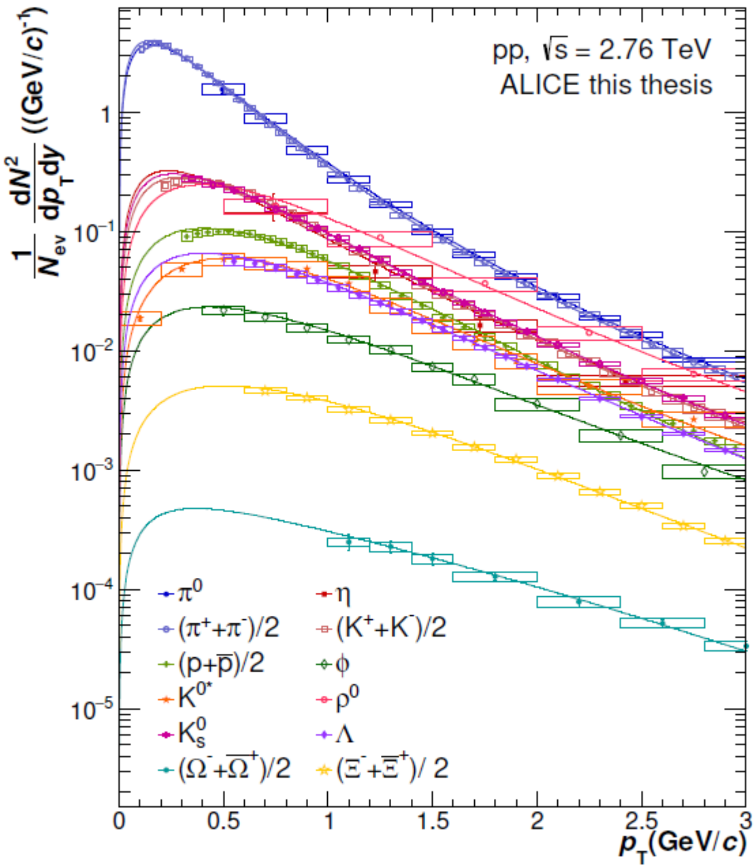




Optimization of electron pair selection cuts



Fit functions for pt distributions



- Two-component model (Bylinkin, Rostovtsev):

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}p^3} = A_\mathrm{e} \exp\frac{(M - \sqrt{p_\mathrm{T}^2 + M^2})}{T_\mathrm{e}} + A\left(1 + \frac{p_\mathrm{T}^2}{n_\mathrm{br} T^2}\right)^{-n_{br}}$$

- Hagedorn fit:

$$\frac{dN}{dydp_\mathrm{T}} = p_\mathrm{T}\ A\ \left(\exp\left(-a * p_\mathrm{T} - |b|p_\mathrm{T}^2\right) + \frac{p_\mathrm{T}}{p_0}\right)^{-n}$$