ALICE
A JOURNEY OF DISCOVERY

BERKELEY LAB
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Azimuthal Anisotropy of Direct Photons in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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BMBF Forschungsschwerpunkt
ALICE Experiment 201
ALICE

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

DFG
GRK 1039: Development and Application of Intelligent Detectors

Photon Production in Pb-Pb Collisions

Direct Photons = Photons not produced by particle decays (e.g. π^0)

pp and Pb-Pb

- Prompt photons from hard initial scattering (NLO pQCD)
  - Predominant source in pp
  - Signal scales with binary collisions in Pb-Pb (cold nuclear matter effects?)
- Fragmentation photons
  - May be modified by parton energy loss in the medium

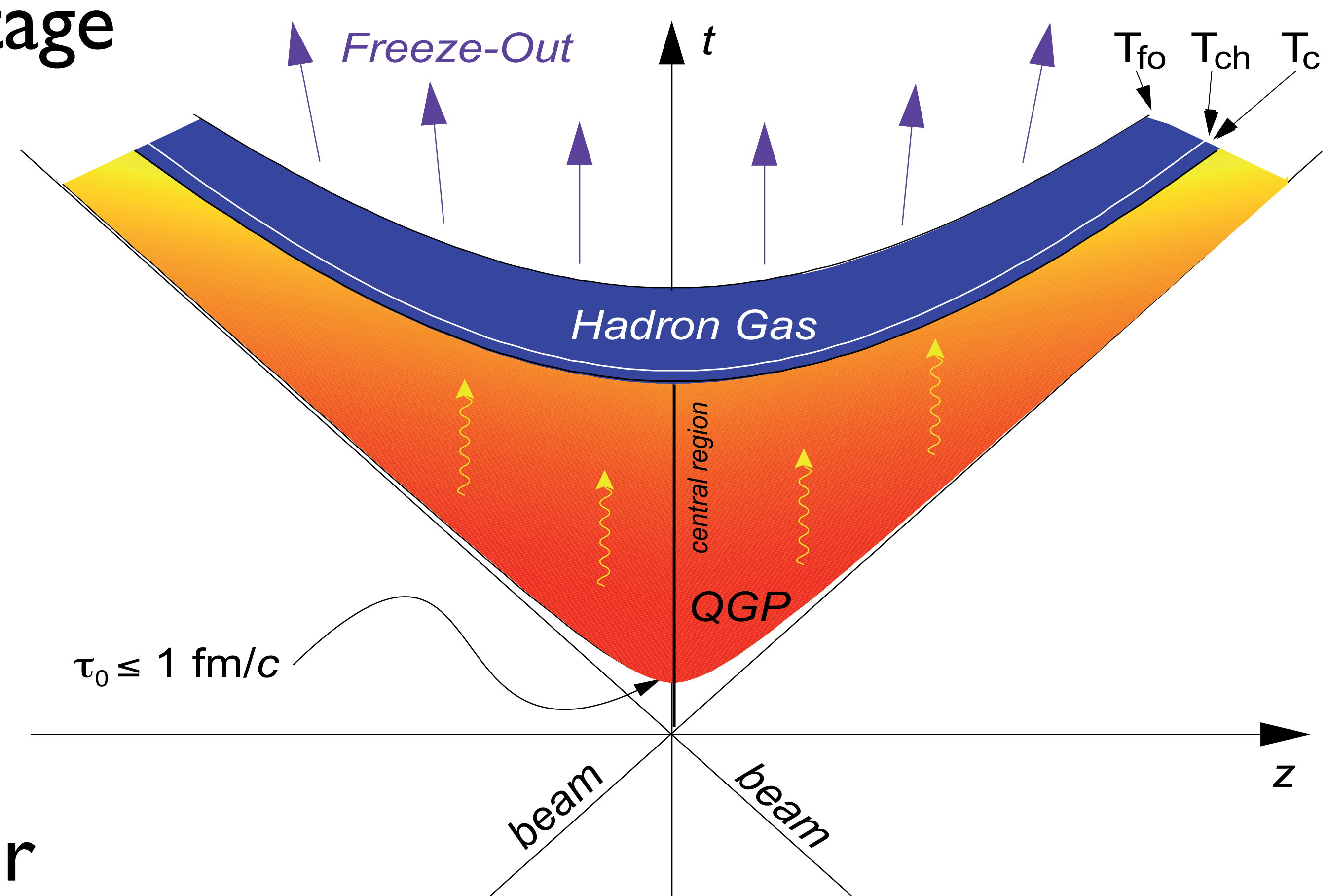
only Pb-Pb

- Thermal photons
  - Scattering of thermalized particles (QGP)
  - Hadronic interactions (HG)
- Jet-plasma photons
  - Scattering of hard partons with thermalized partons
  - In-medium bremsstrahlung

What can we learn from Direct Photons?

Direct Photons = Photons not produced by particle decays (e.g. π^0)

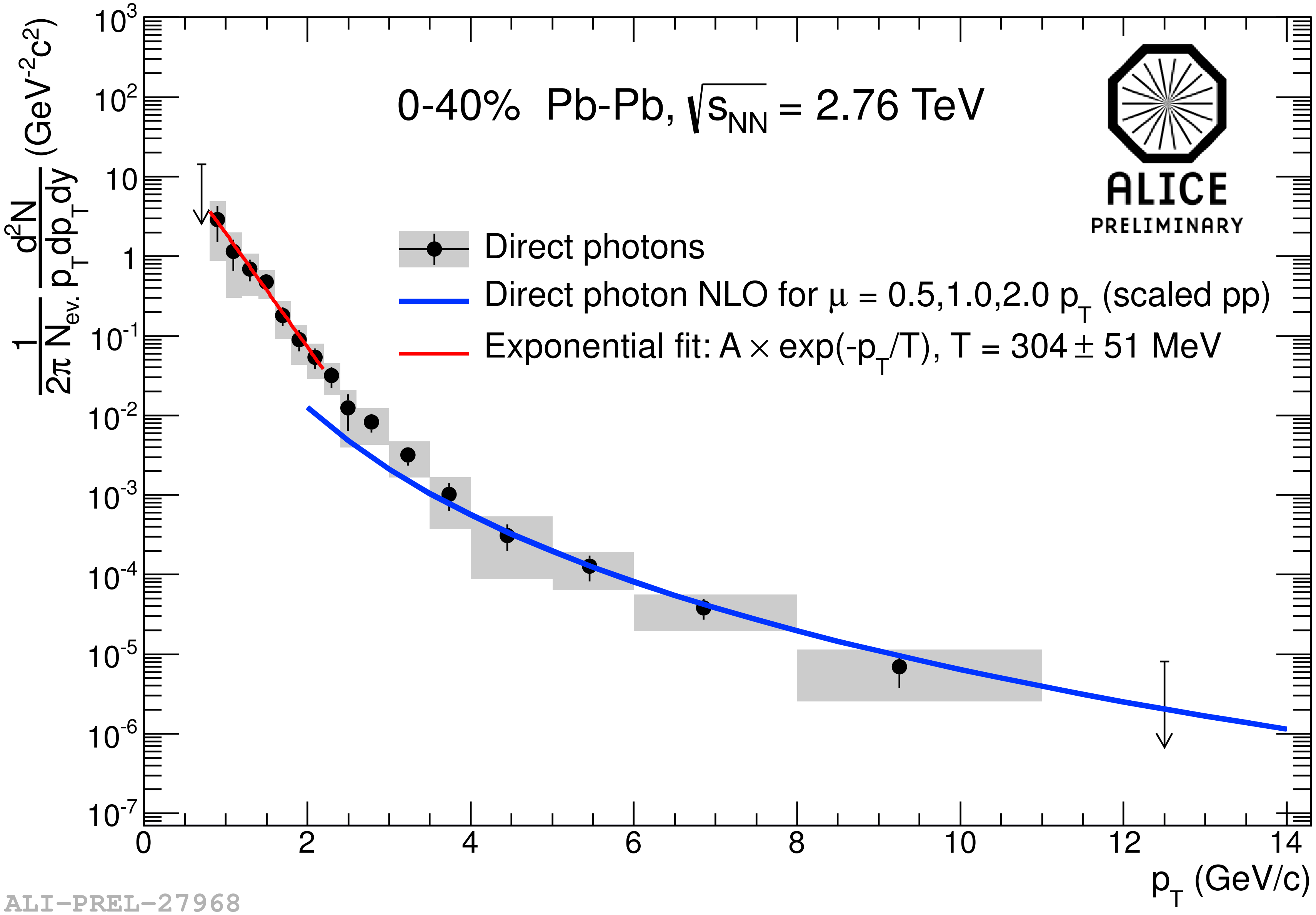
- Photons come out from every stage of the system evolution
- Mean free path of photons much larger than system size
  - No interaction with medium (direct photon $R_{AA} = 1^*$)
- Photons carry undistorted information about system at their production time
  - Hadrons carry system information at kinetic freeze-out



Reinhard Stock arXiv:0807.1610

* PHENIX arXiv:1205.5759 [nucl-ex]

Direct Photon Spectrum QM 2012

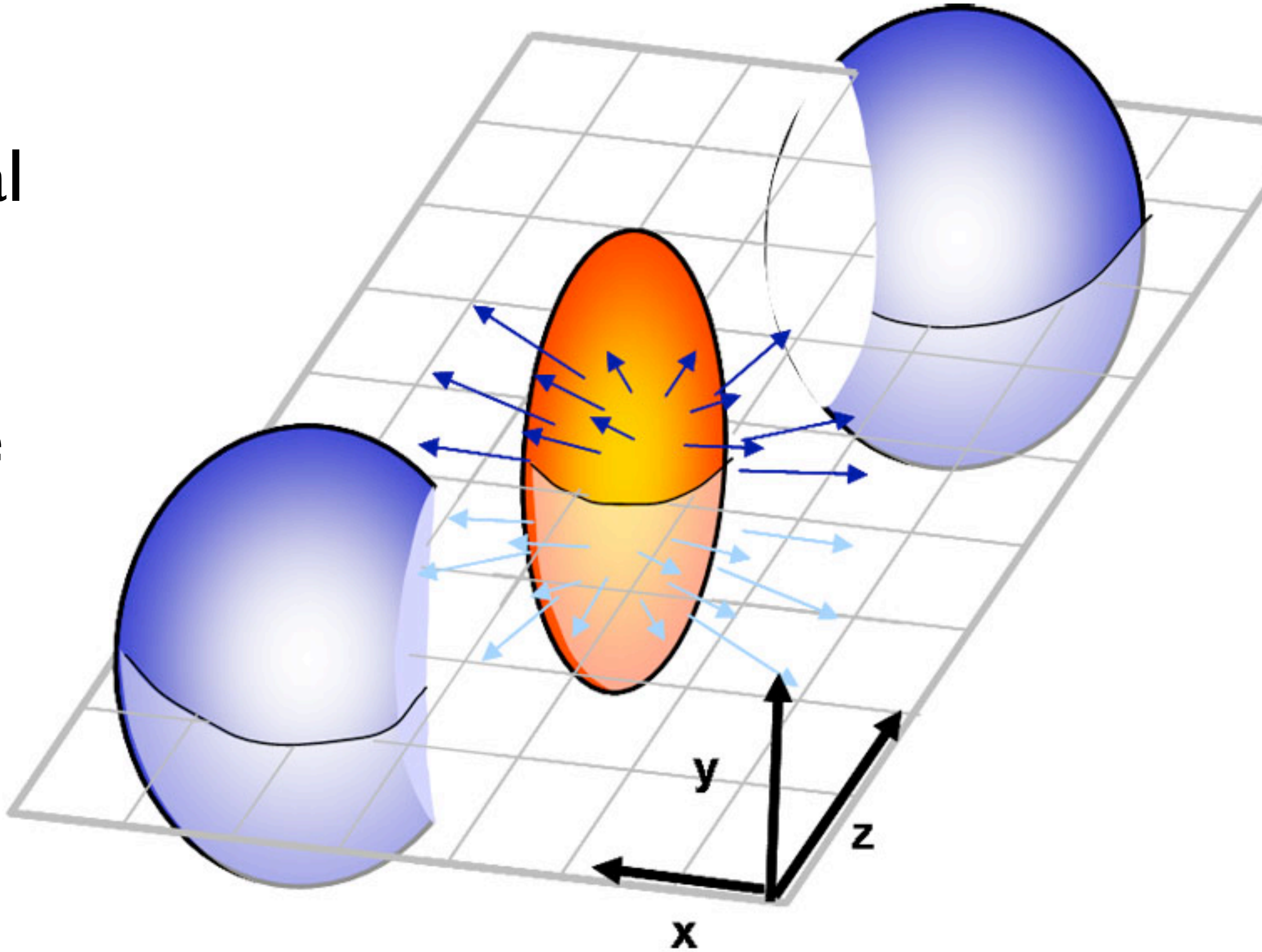


- Spectrum consistent with NLO (pQCD) above 4 GeV/*c*
- Excess at low p_T interpreted as thermal photon signal
- Effective temperature T^{Eff}=(304 ± 51) MeV
- $T^{Eff} > T_c^*$ ⇒ dominant contribution from QCD phase

*T_c ≈ 170 MeV M. Cheng et al. arXiv:hep-lat/0608013

Azimuthal Anisotropy of Particle Production

- Initial azimuthal asymmetry coordinate space in non-central A+A ⇒ momentum space
- Low p_T : elliptic flow (collective expansion)
- High p_T : path length dependence of in-medium parton energy loss
- Fourier decomposition:



$$\frac{dN}{d\phi} = \frac{1}{2\pi}\left(1 + 2\sum_{n\geq 1} v_n \cos(n(\phi - \Psi_n^{RP}))\right)$$

v_2: elliptic flow

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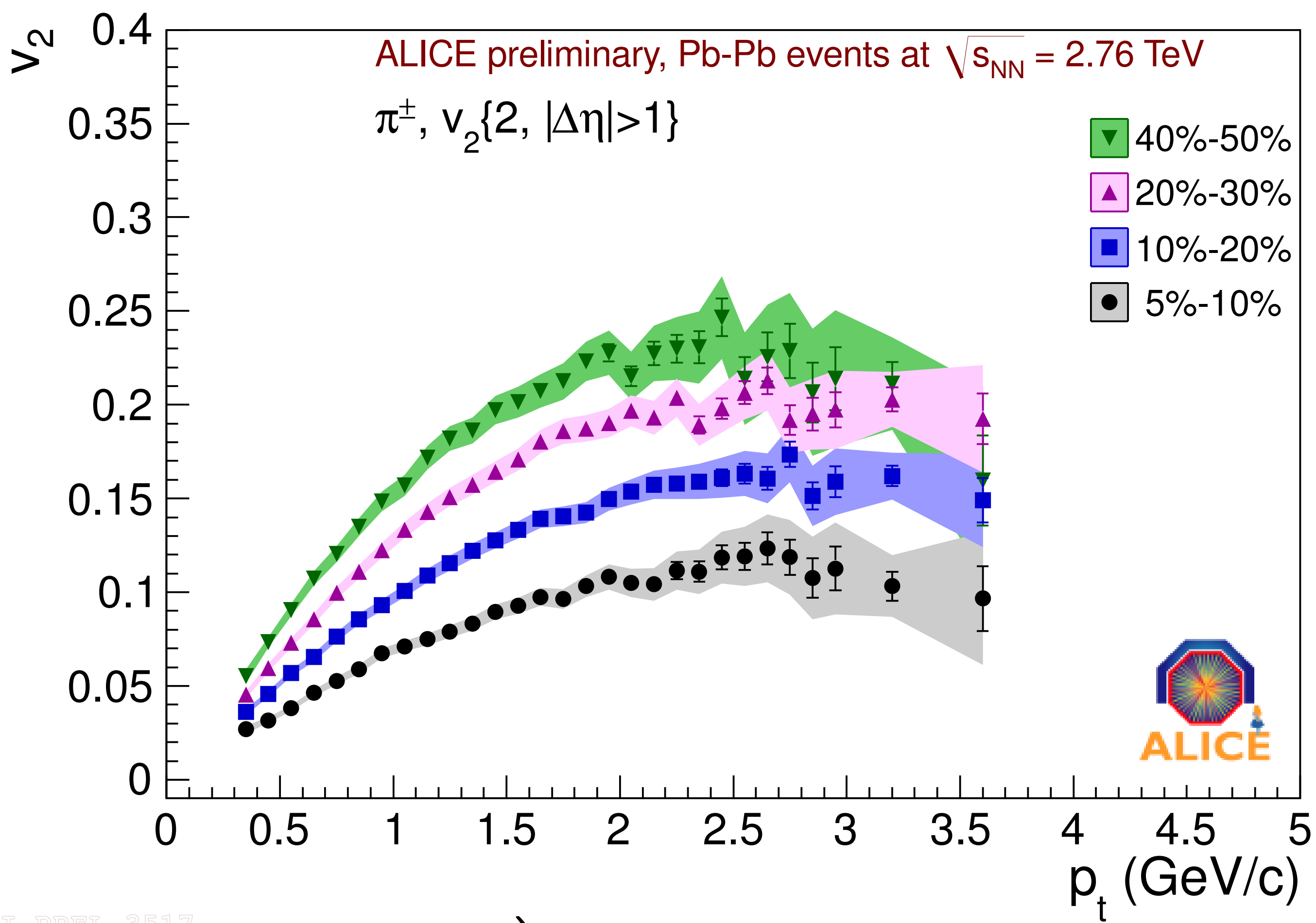


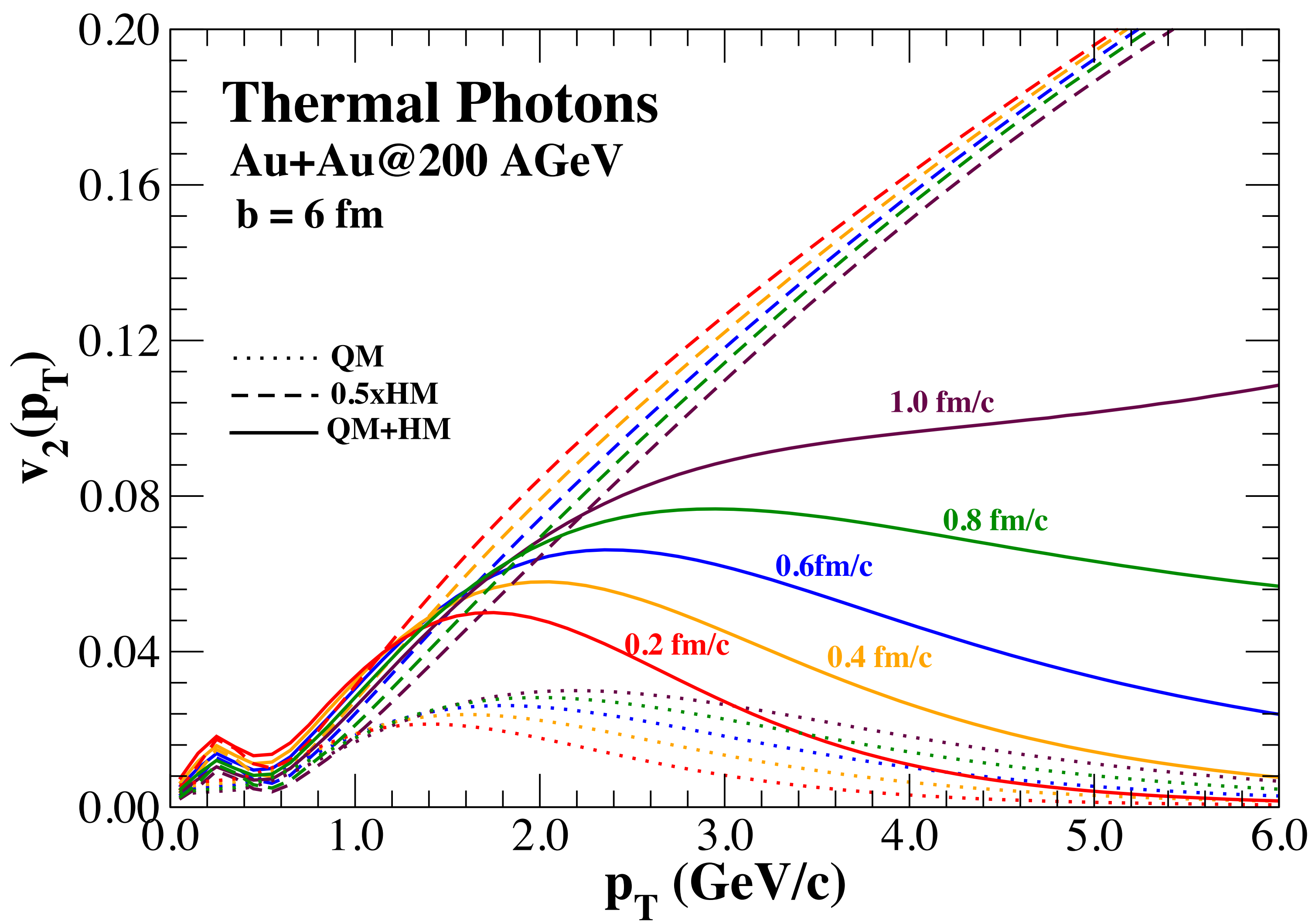
$$\frac{dN}{d\phi} = \frac{1}{2\pi}\left(1 + 2\sum_{n\geq 1} v_n \cos(n(\phi - \Psi_n^{RP}))\right)$$

v_2: elliptic flow

What can we learn from direct photon v_2?

- v_2 sets constraints on onset of direct photon production
  - Early (QGP) ⇒ small flow
  - Late (HHG)⇒ large flow like hadrons
- From high T^{Eff} expect dominance of thermal photons and small direct photon v_2

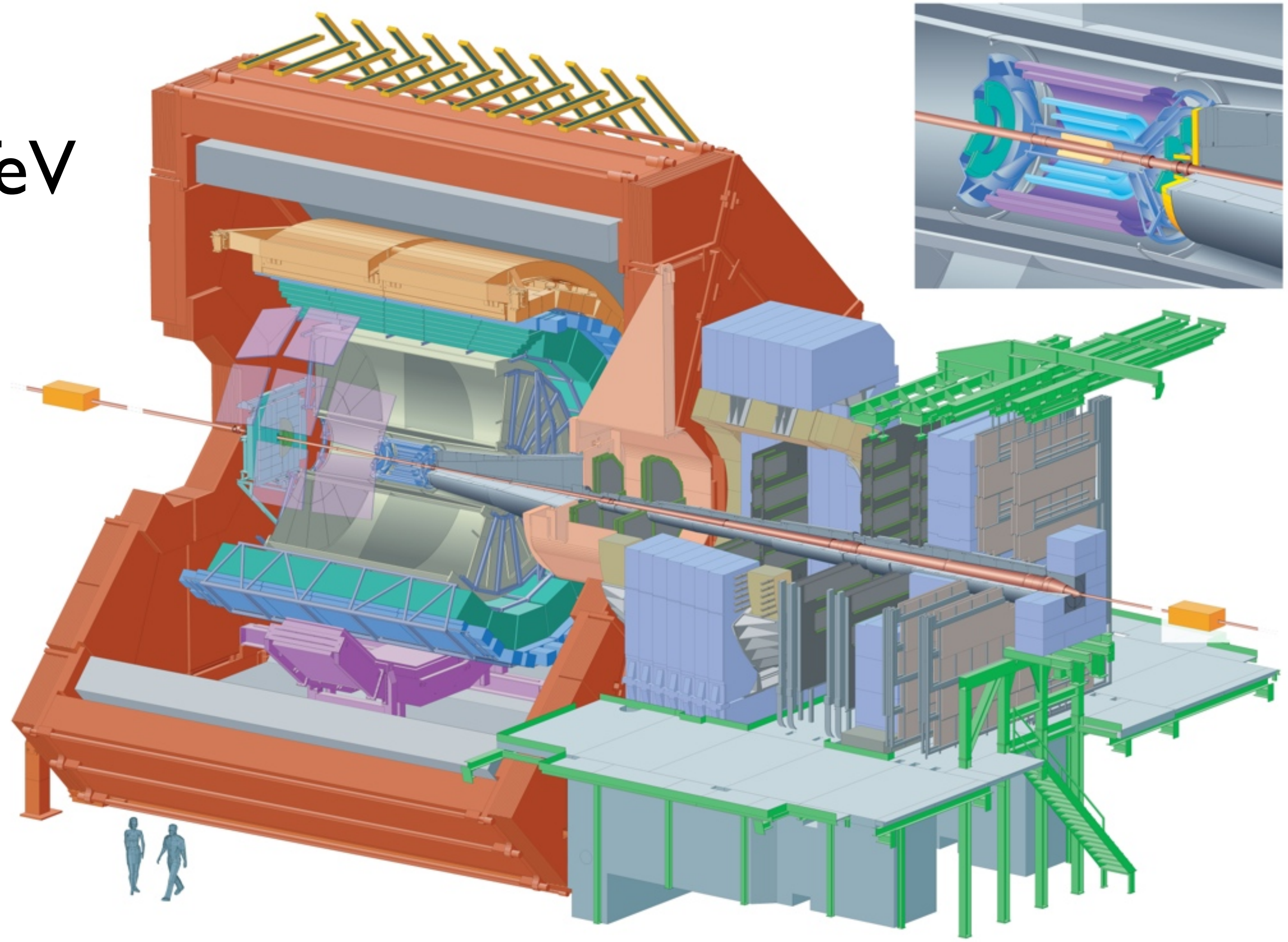
ideal hydro thermal photon v_2 for different QGP formation times τ_0

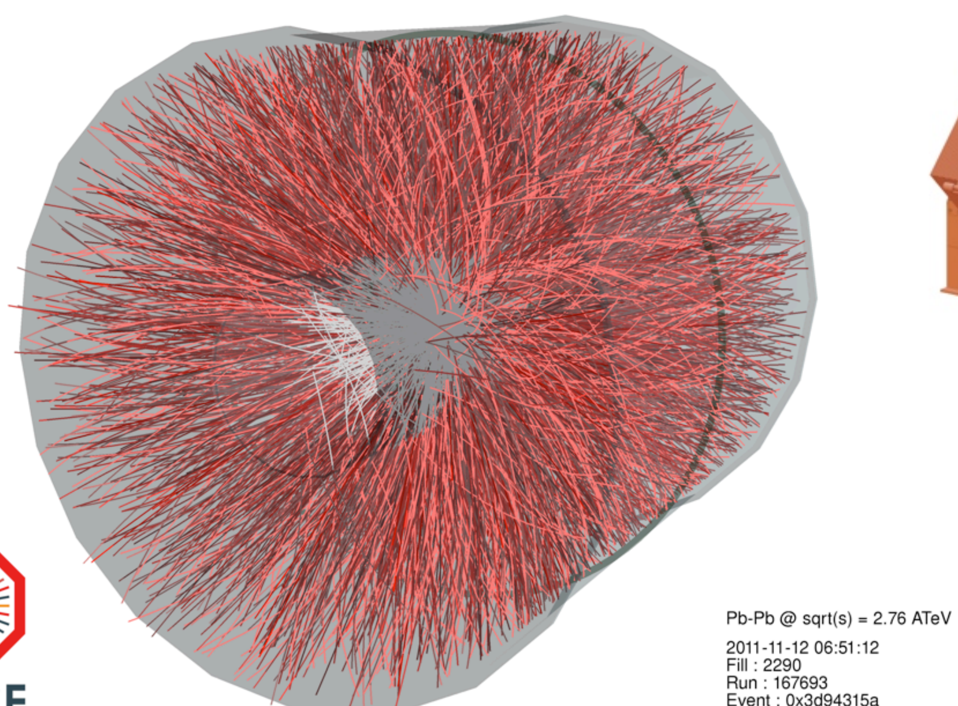


R. Chatterjee, D.K.Srivastava
arXiv:0809.0548 [nucl-th]

ALICE Detector and Data Sample

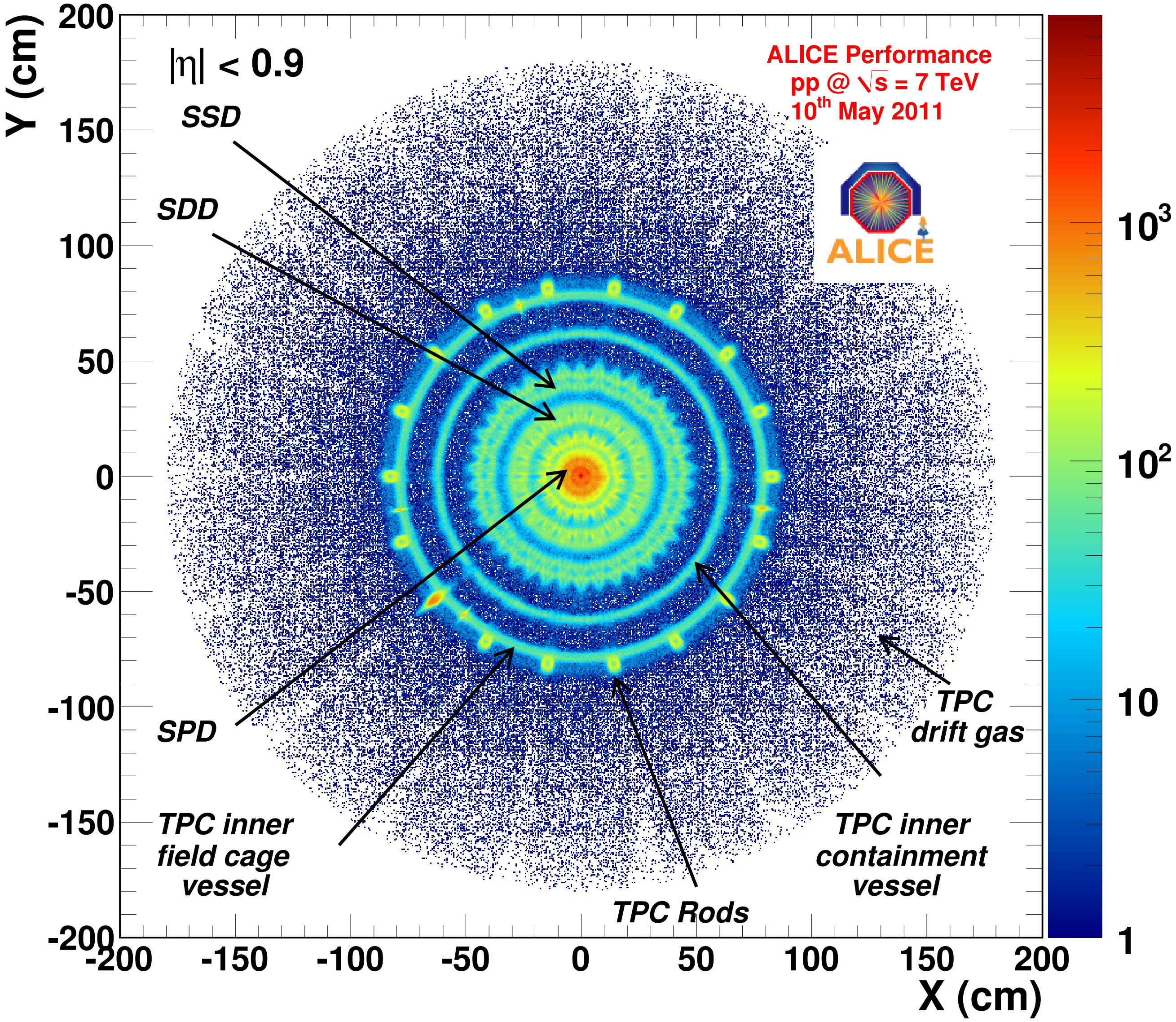
- Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV
- 17 M min. bias events (2010)

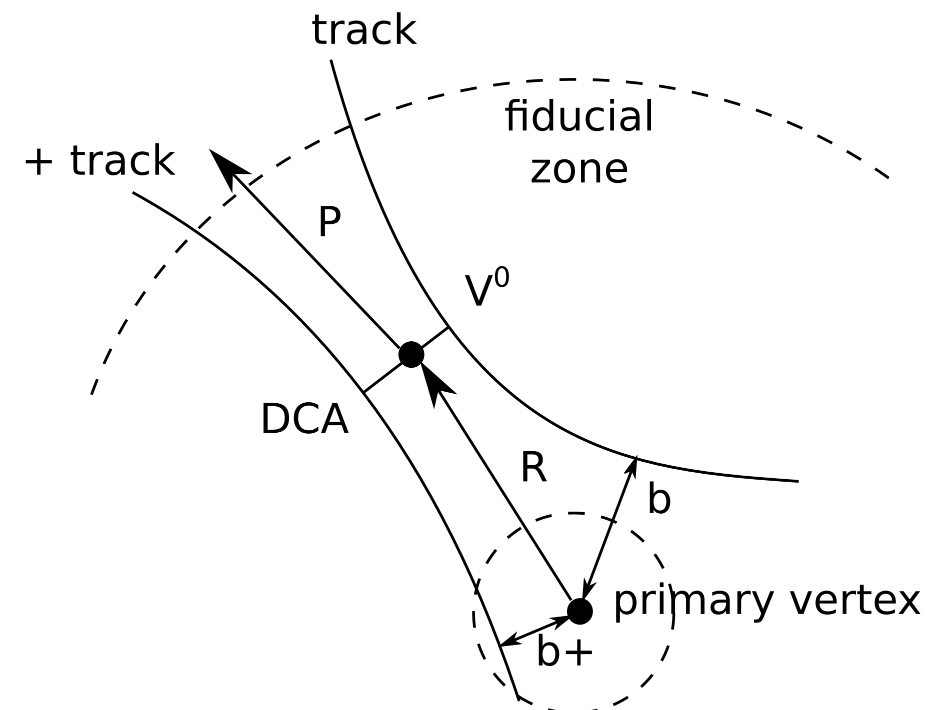




Photon Conversion Reconstruction using the ALICE Detector

- Photon conversion probability in $|\eta|<0.9$ up to R=180 cm at 8.5 %





- Track reconstruction in TPC and ITS
- Electron identification using TPC dE/dx and TOF
- Reconstruction of V0 decay vertex using Kalman filter

Measurement of Direct Photon v_2

$$v_2^{\text{direct}\,\gamma} = (R v_2^{\text{incl}\,\gamma} - v_2^{\text{decay}\,\gamma})/(R-1)$$

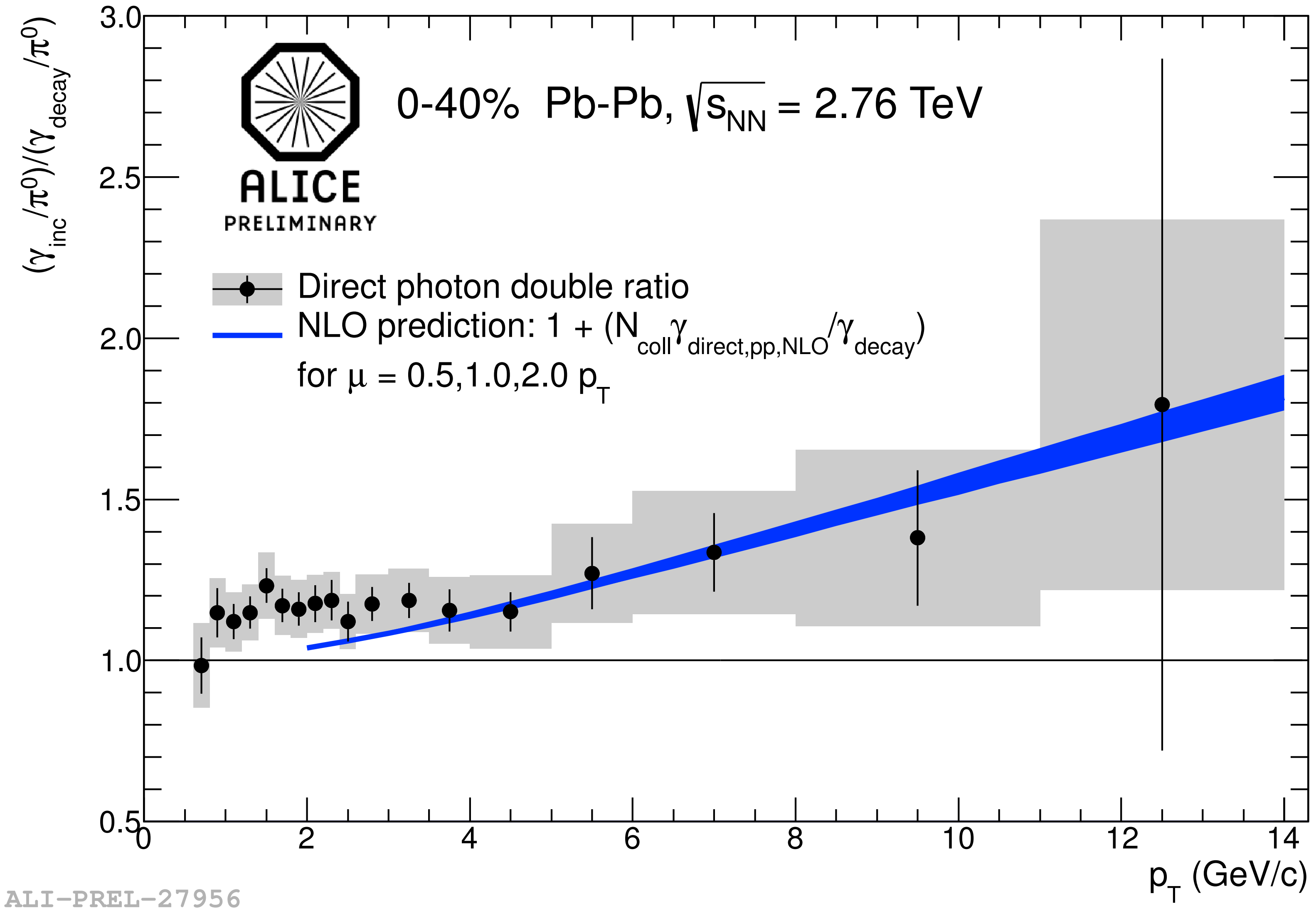
- Ratio $R = N^{\text{incl}\,\gamma}/N^{\text{decay}\,\gamma}$
- Inclusive photon $v_2^{\text{incl}\,\gamma}$
- Decay photon $v_2^{\text{decay}\,\gamma}$ from cocktail simulation

Measurement of Double Ratio 0-40%

- Double ratio:

$$R = \frac{\left(\frac{dN^{incl\gamma}/dy}{dN^{\pi^0}/dy}\right)}{\left(\frac{dN^{decay\gamma}/dy}{dN^{\pi^0}/dy}\right)_{MC}} = \frac{N^{incl\gamma}}{N^{decay\gamma}}$$

- $N^{\text{incl}\ \gamma}$ from Pb-Pb data
- $N^{\text{decay}\ \gamma}$ from cocktail simulation



- R=1: $N^{\text{incl}\ \gamma}=N^{\text{decay}\ \gamma} \Rightarrow$ no direct photons
- Double Ratio R>1: $\Rightarrow$ contribution of direct photons

  $N^{\text{direct}\ \gamma}= (1-1/R)N^{\text{incl}\ \gamma}$

Measurement of Direct Photon v_2

$$v_2^{\text{direct } \gamma} = (R v_2^{\text{incl } \gamma} - v_2^{\text{decay } \gamma})/(R-1)$$

- ✔ Ratio $R = N^{\text{incl } \gamma}/N^{\text{decay } \gamma}$
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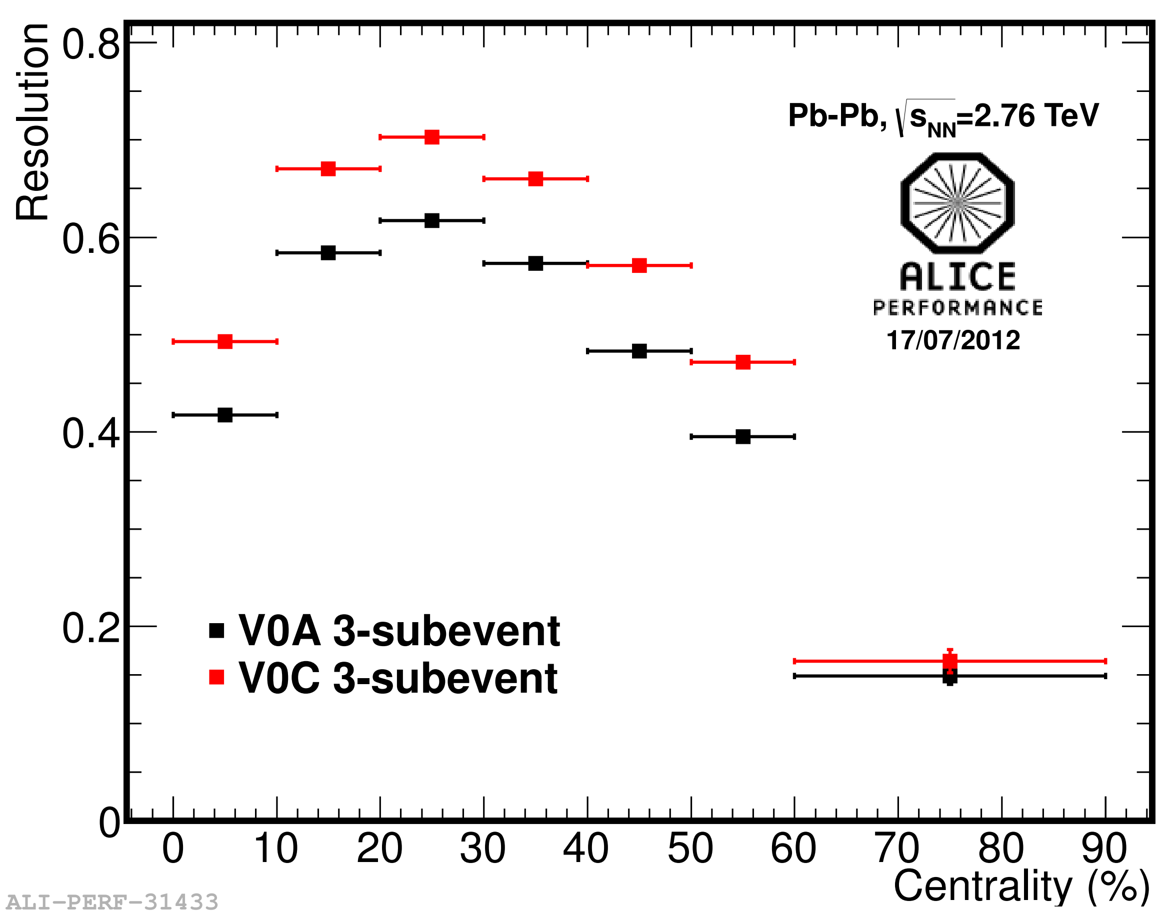
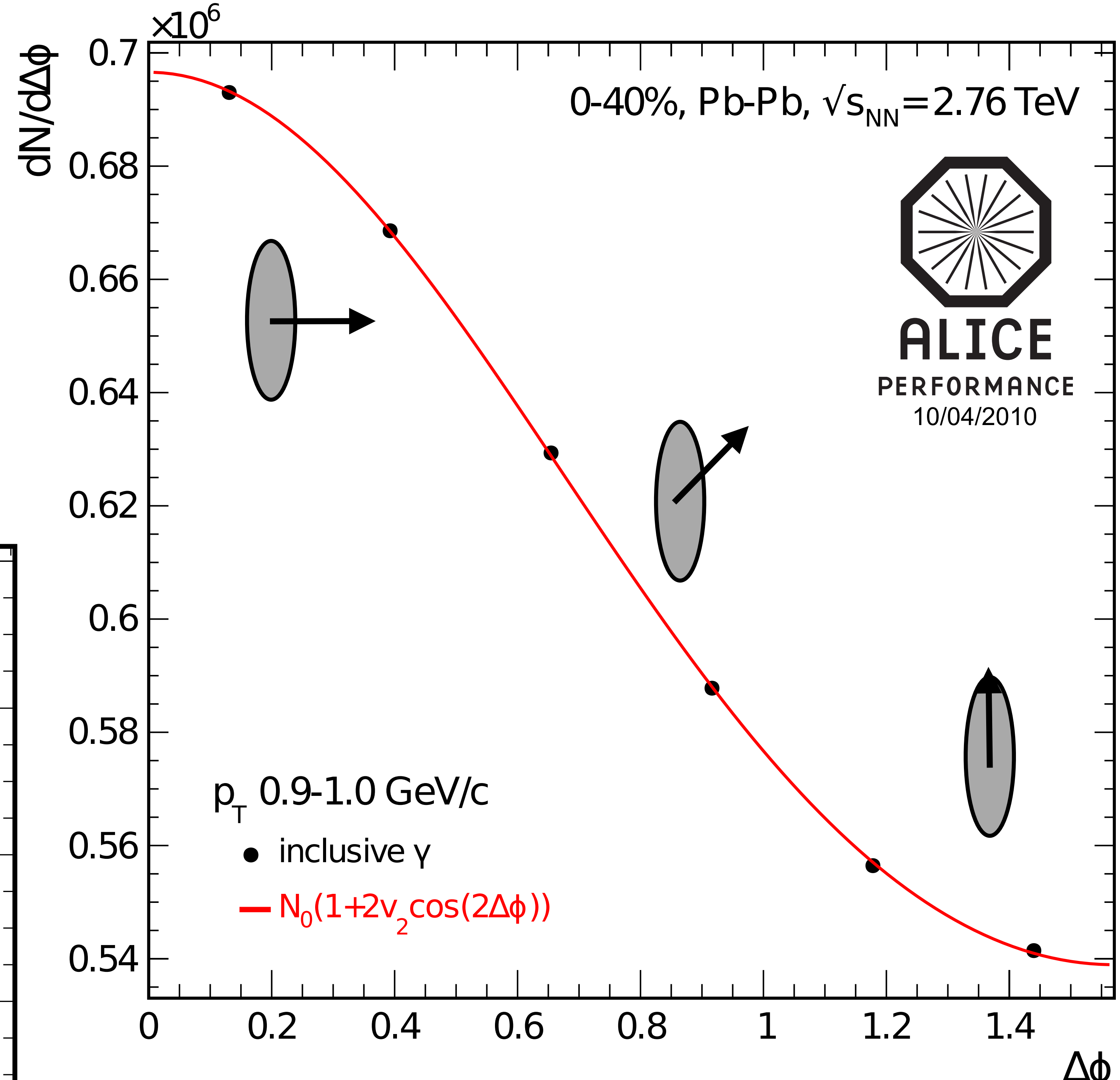
Inclusive Photon v_2 Analysis

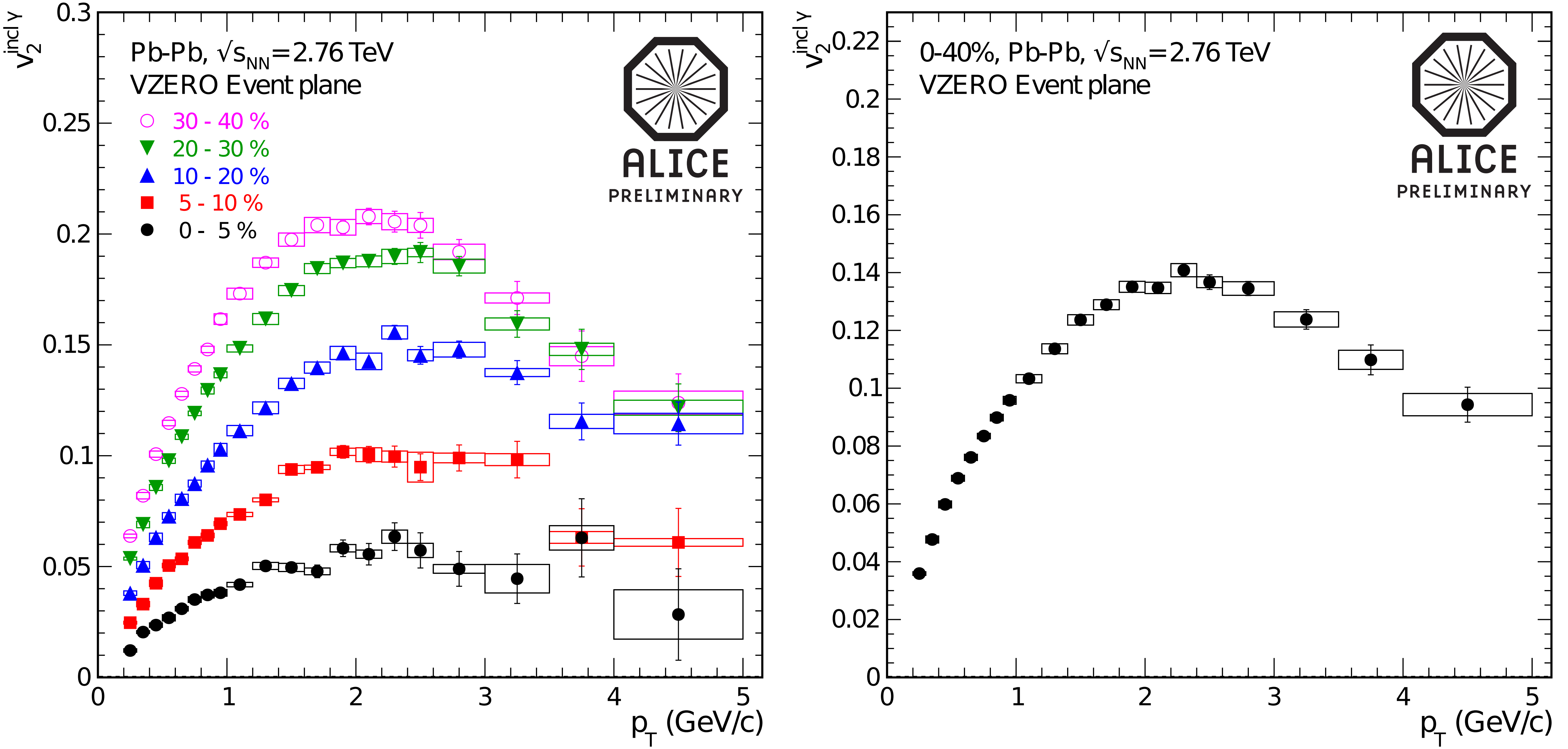
- VZERO event plane
  - VZEROA: $\eta \in [2.8, 5.1]$
  - VZEROC: $\eta \in [-3.7, -1.7]$
- $v_2 = v_2^{raw}$ / resolution





extraction of inclusive photon v_2

Inclusive Photon v_2 0-40%



- Magnitude increases with decreasing centrality
- Similar to hadrons

Measurement of Direct Photon v_2

$$v_2^{\text{direct}\,\gamma} = (R v_2^{\text{incl}\,\gamma} - v_2^{\text{decay}\,\gamma})/(R-1)$$

- ✔ Ratio $R = N^{\text{incl}\,\gamma}/N^{\text{decay}\,\gamma}$
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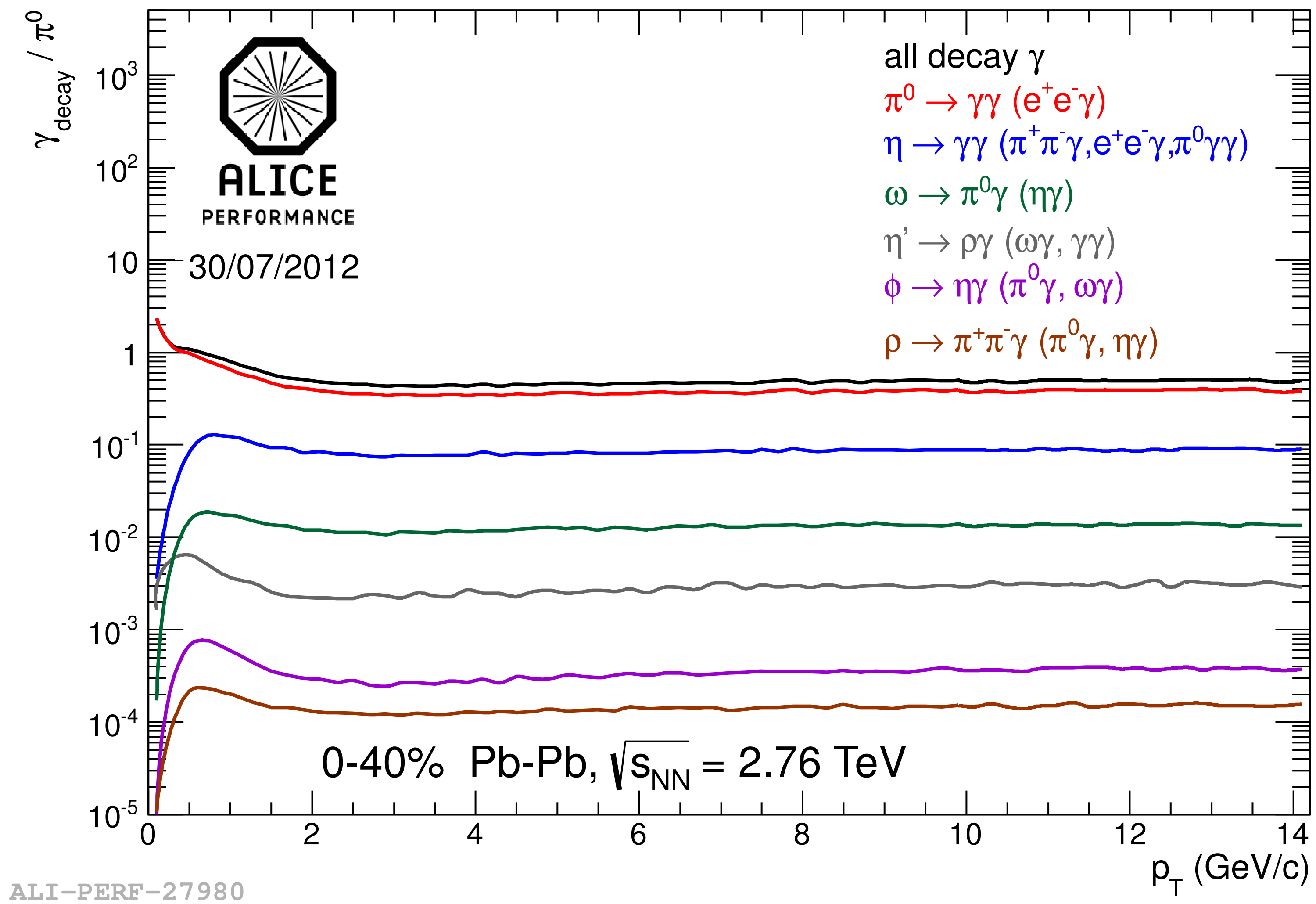
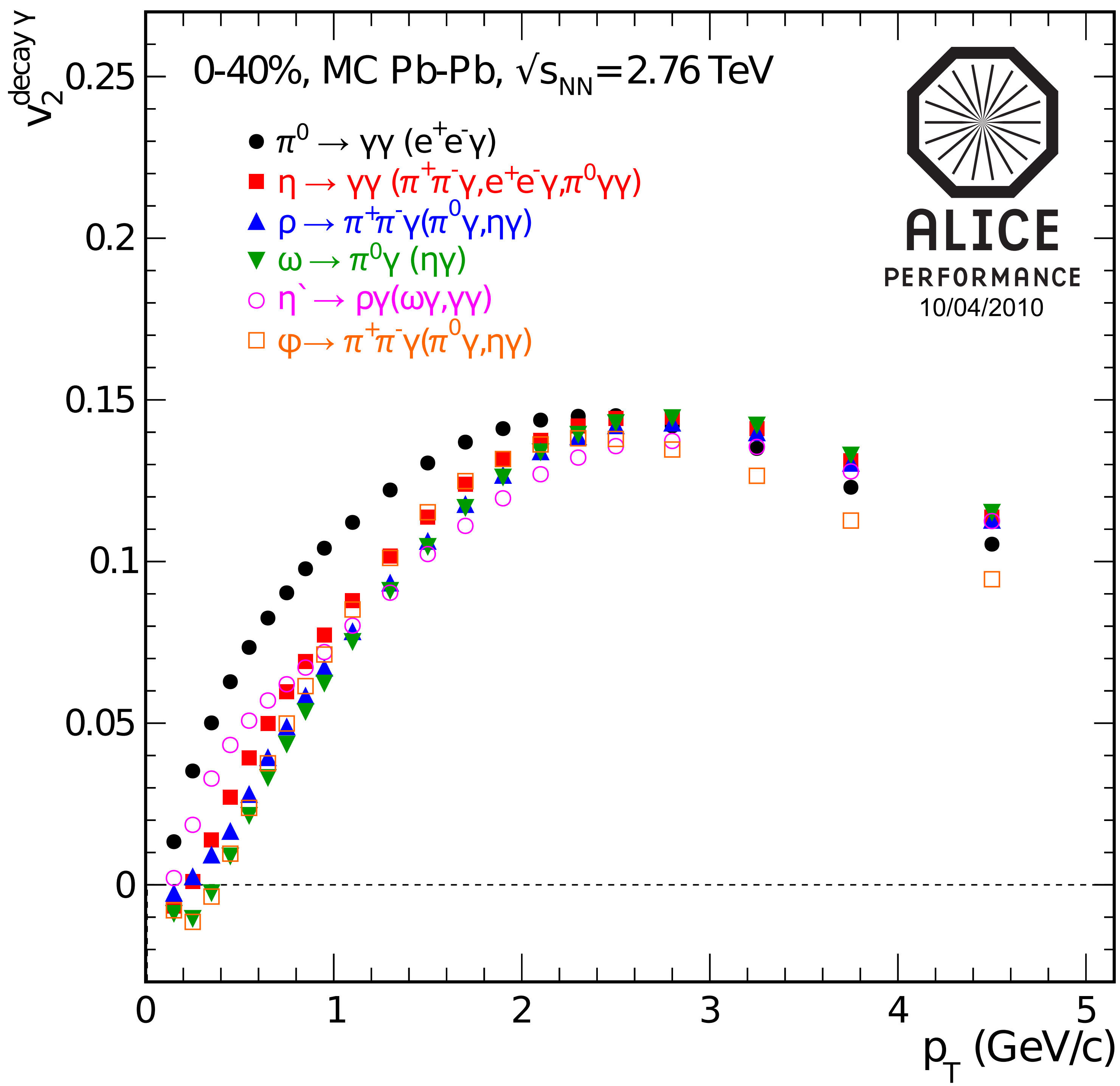
Cocktail Simulation - Spectra



- π^0 parametrized with measured 0-40% spectrum
- Higher resonances from m_T scaling

Cocktail Simulation v_2

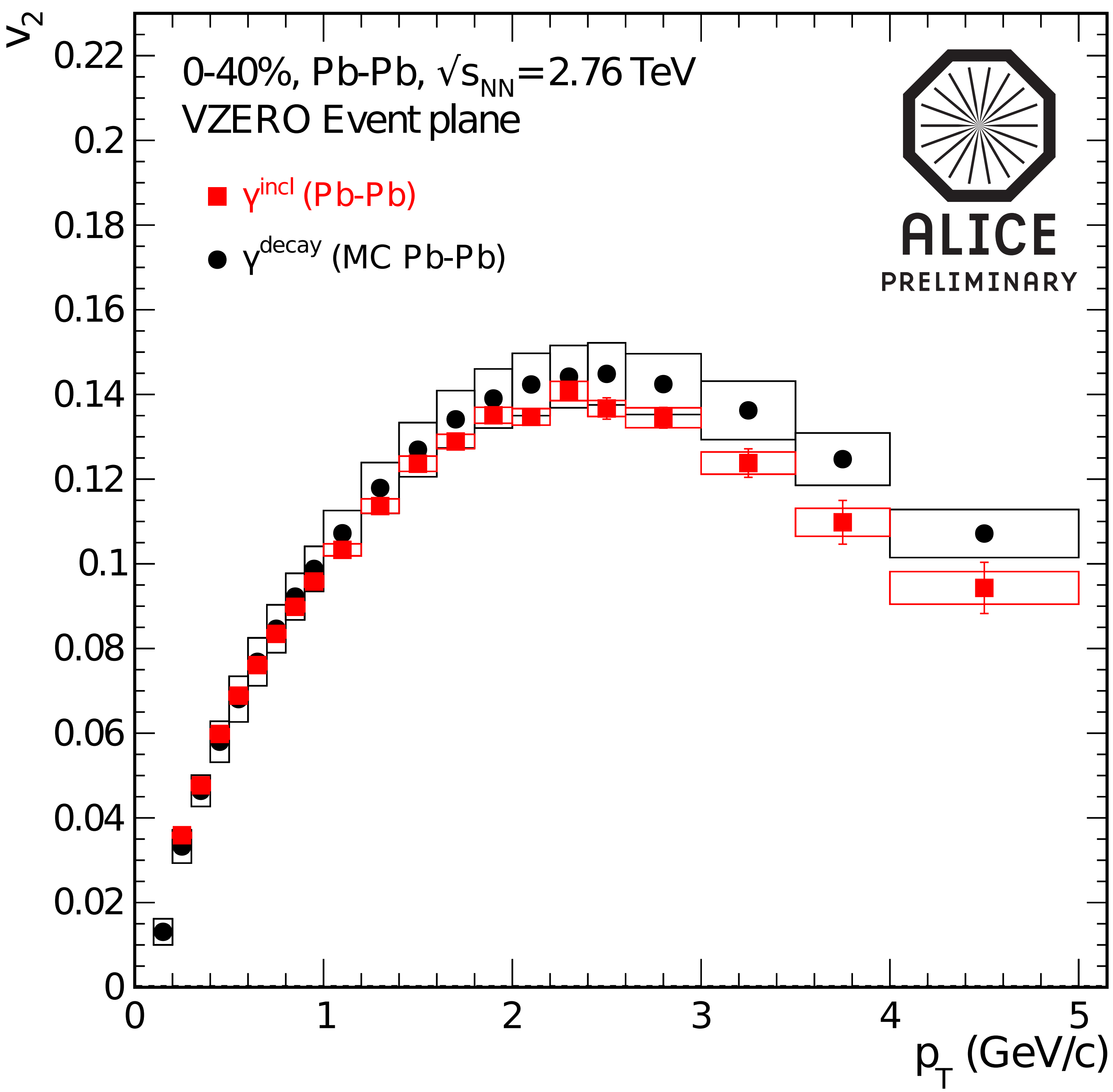


- v_2 of hadronic resonance decay photons
- Assumption: $v_2(\pi^\pm) = v_2(\pi^0)$
- Quark number scaling in transverse kinetic energy scaling with $v_2(\pi^\pm)$:

$$v_2^X(p_t^X) = v_2^{\pi^\pm}\left(\sqrt{(KE_T^x + m^{\pi^\pm})^2 - (m^{\pi^\pm})^2}\right)$$

$$KE_T = m_T - m = \sqrt{p_T^2 + m^2} - m$$

Comparison of Inclusive and Decay Photon v_2 and Interpretation



- Above 3 GeV/c inclusive photons significantly smaller than decay photons
  - There must be a direct photon contribution with smaller v_2
- Below 3 GeV/c consistent within uncertainties
  - Either contribution of direct photons with similar v_2 or no direct photons

Measurement of Direct Photon v_2

$$v_2^{\text{direct}\,\gamma} = (R v_2^{\text{incl}\,\gamma} - v_2^{\text{decay}\,\gamma})/(R-1)$$

- ✔ Ratio $R = N^{\text{incl}\,\gamma}/N^{\text{decay}\,\gamma}$
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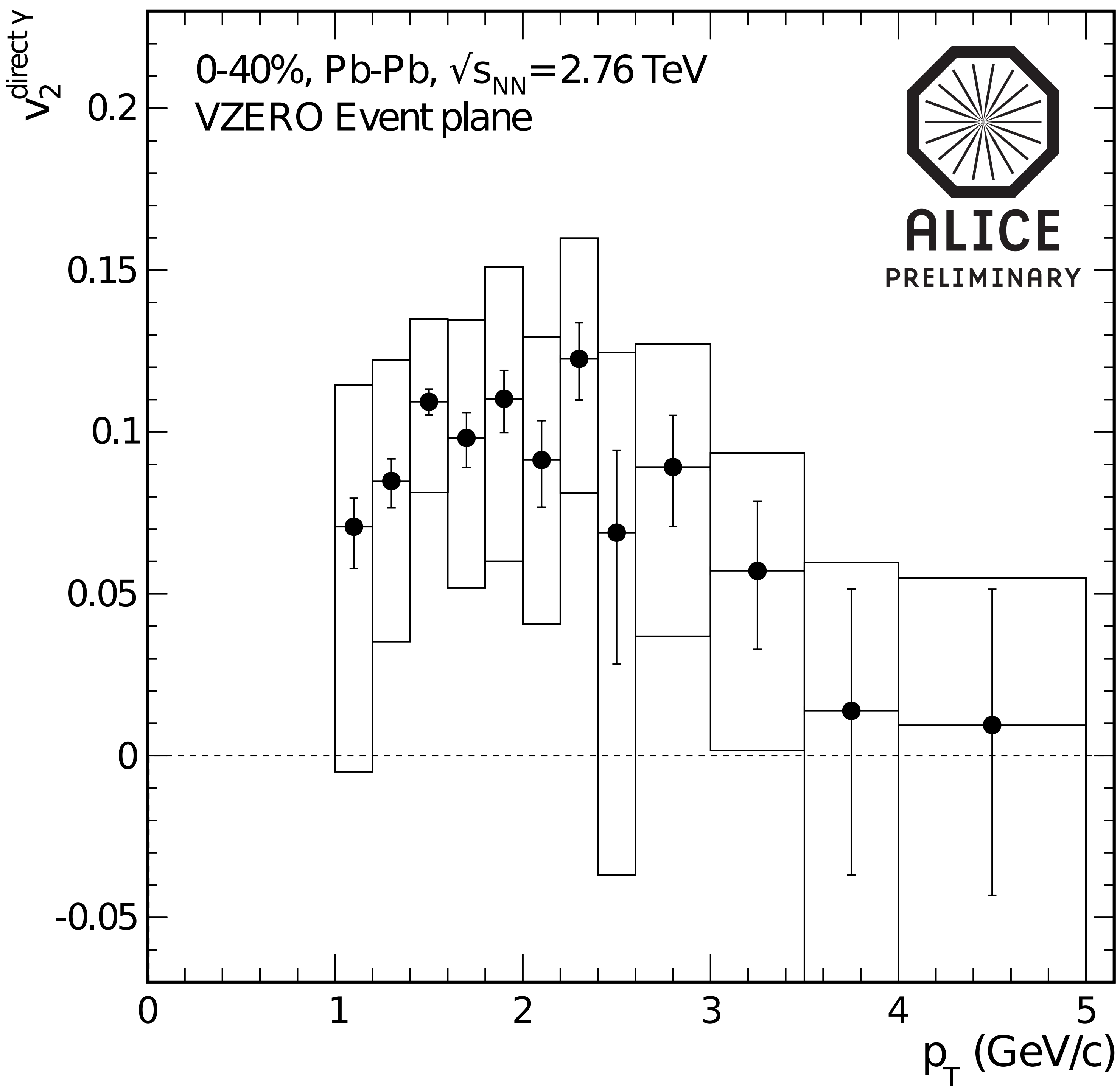
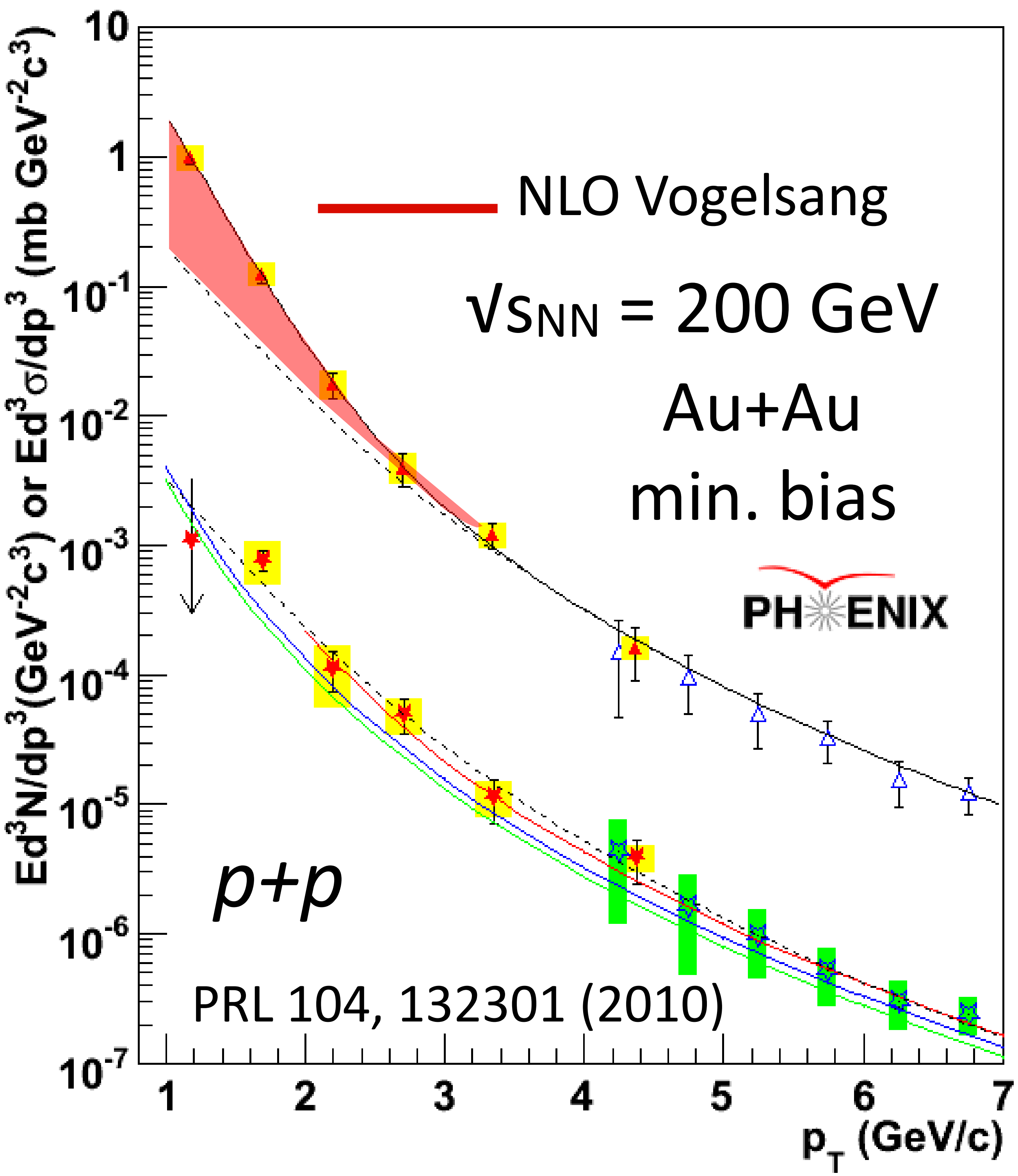
Direct Photon v_2 0-40% and Conclusions



- Direct photons in 0-40% have a significant nonzero elliptic flow below 3 GeV/*c*
- Magnitude of v_2 comparable to hadrons
  - Unexpected from T^{Eff}
  - Similar results reported by PHENIX (RHIC)

Backup

Effective Temperature from PHENIX

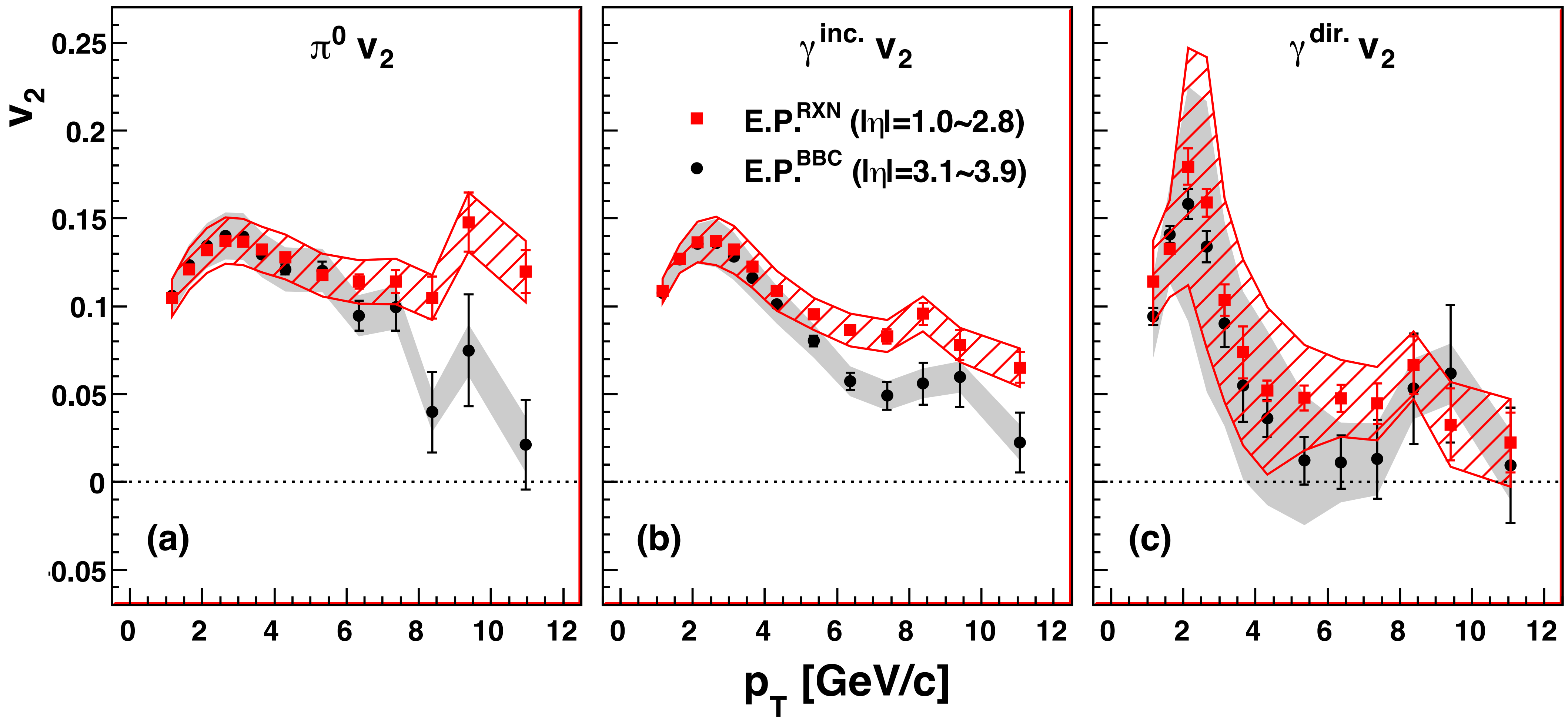


- Exponential thermal photon spectrum
- Inverse slope $T^{Eff} \simeq 220 \pm 20$ MeV
- T_i from hydro 300-600 MeV (PHENIX arXiv:0912.0244)

⇒ Photons produced at early time

Direct Photon $v2$ from PHENIX

PHENIX nucl-ex, arXiv:1105.4126



- Large v_2^{direct} compared to hadron v_2 supports theory of production in hadronic phase
- Temperature ($T^{Eff} \simeq 220 \pm 20$ MeV) favors early production time

Hadron EM decay modes

Meson	Mass (MeV/c^2)	Decay Mode	Γ_i/Γ (%)
π^0	(134.9766 ± 0.0006)	$2\,\gamma$	(98.798 ± 0.032)
		$e^+e^-\gamma$	(1.198 ± 0.032)
η	(547.51 ± 0.18)	$2\,\gamma$	(39.38 ± 0.26)
		$\pi^+\pi^-\gamma$	(4.69 ± 0.11)
		$e^+e^-\gamma$	$(6.0 \pm 0.8) \times 10^{-3}$
		$\pi^0\,\gamma$	$(4.4 \pm 1.6) \times 10^{-4}$
ρ	(775.5 ± 0.4)	$\pi^+\pi^-\gamma$	$(9.9 \pm 1.6) \times 10^{-3}$
		$\pi^0\,\gamma$	$(6.0 \pm 0.8) \times 10^{-4}$
		$\eta\gamma$	$(2.95 \pm 0.30) \times 10^{-4}$
ω	(782.65 ± 0.12)	$\pi^0\,\gamma$	$(8.9^{+0.27}_{-0.23})$
		$\eta\gamma$	$(4.9 \pm 0.5) \times 10^{-4}$
η'	(957.78 ± 0.14)	$\rho\gamma$	(29.4 ± 0.9)
		$\omega\gamma$	(3.03 ± 0.31)
		2γ	(2.12 ± 0.14)
ϕ	(1019.460 ± 0.019)	$\eta\gamma$	(1.301 ± 0024)
		$\pi^0\,\gamma$	$(1.25 \pm 0.07) \times 10^{-3}$
		$\omega\gamma$	< 5