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Direct Photon Production in Pb-Pb Collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

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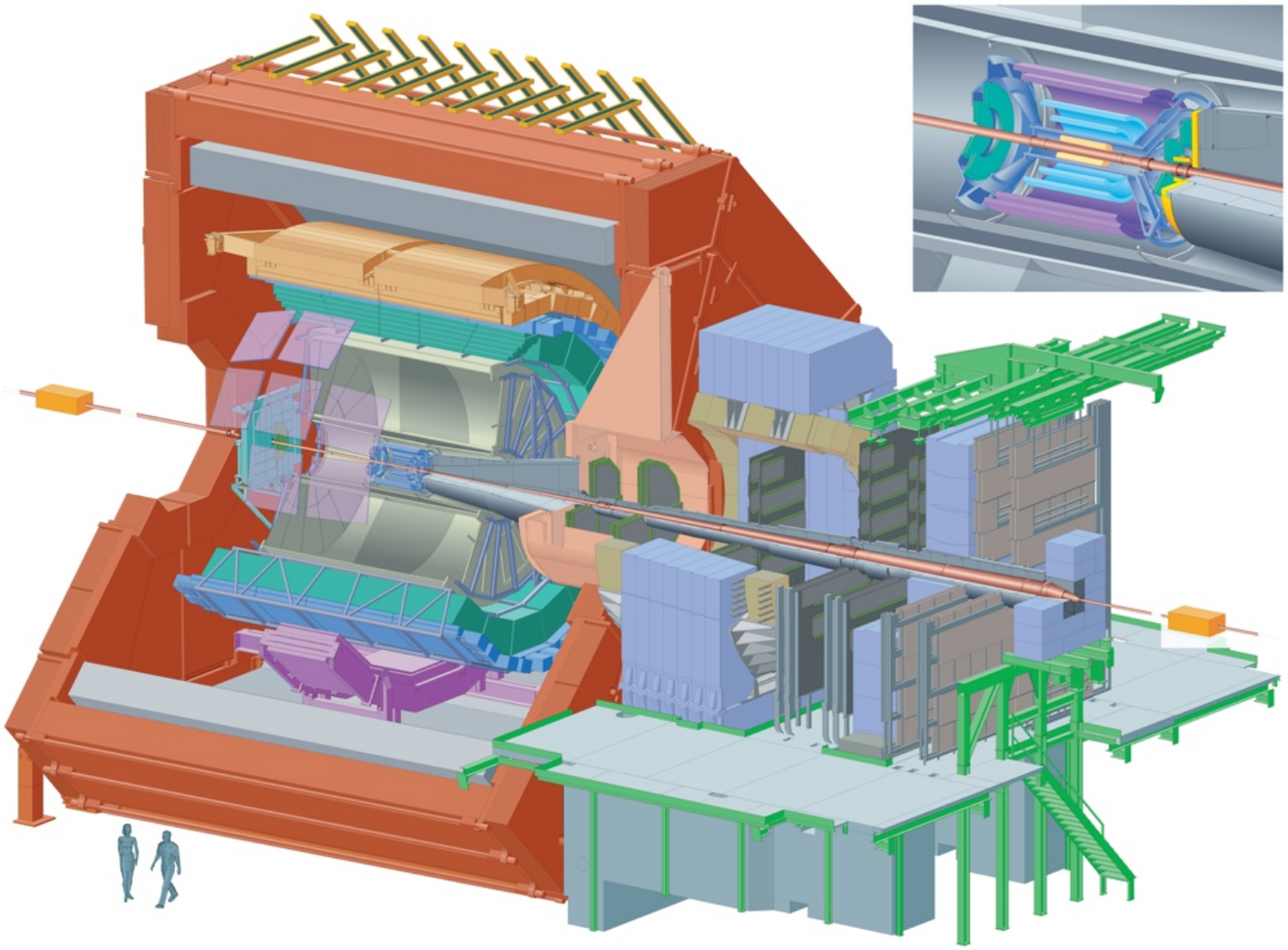
Outline

- Direct photon measurement with ALICE
- Discussion of ALICE preliminary results
- Outlook

Photon Measurements with ALICE

- Photon Conversion Method
  - Inner Tracking System +Time Projection Chamber
  - pseudorapidity coverage: $|\eta|<0.9$
  - azimuthal coverage: 360 deg
- Electro Magnetic Calorimeter (EMCAL)
  - pseudorapidity coverage: $|\eta|<0.7$
  - azimuthal coverage: 110 deg
- Photon Spectrometer (PHOS)
  - pseudorapidity coverage: $|\eta|<0.12$
  - azimuthal coverage: 100 deg



Direct Photon Analysis Strategy

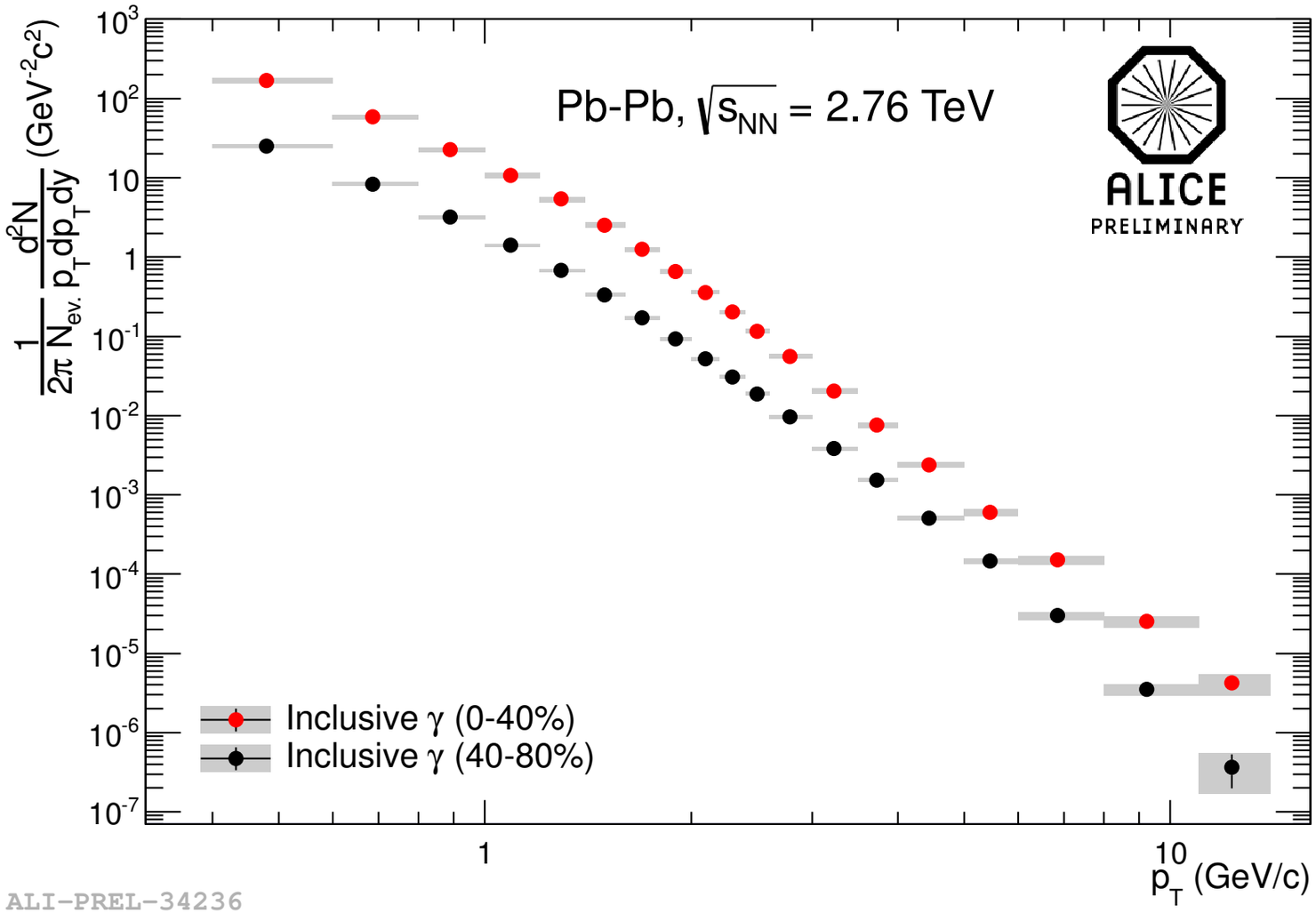
- Direct Photon excess calculated via Double ratio:

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

- inclusive photons = experimentally observed photons
- decay photons from cocktail simulation

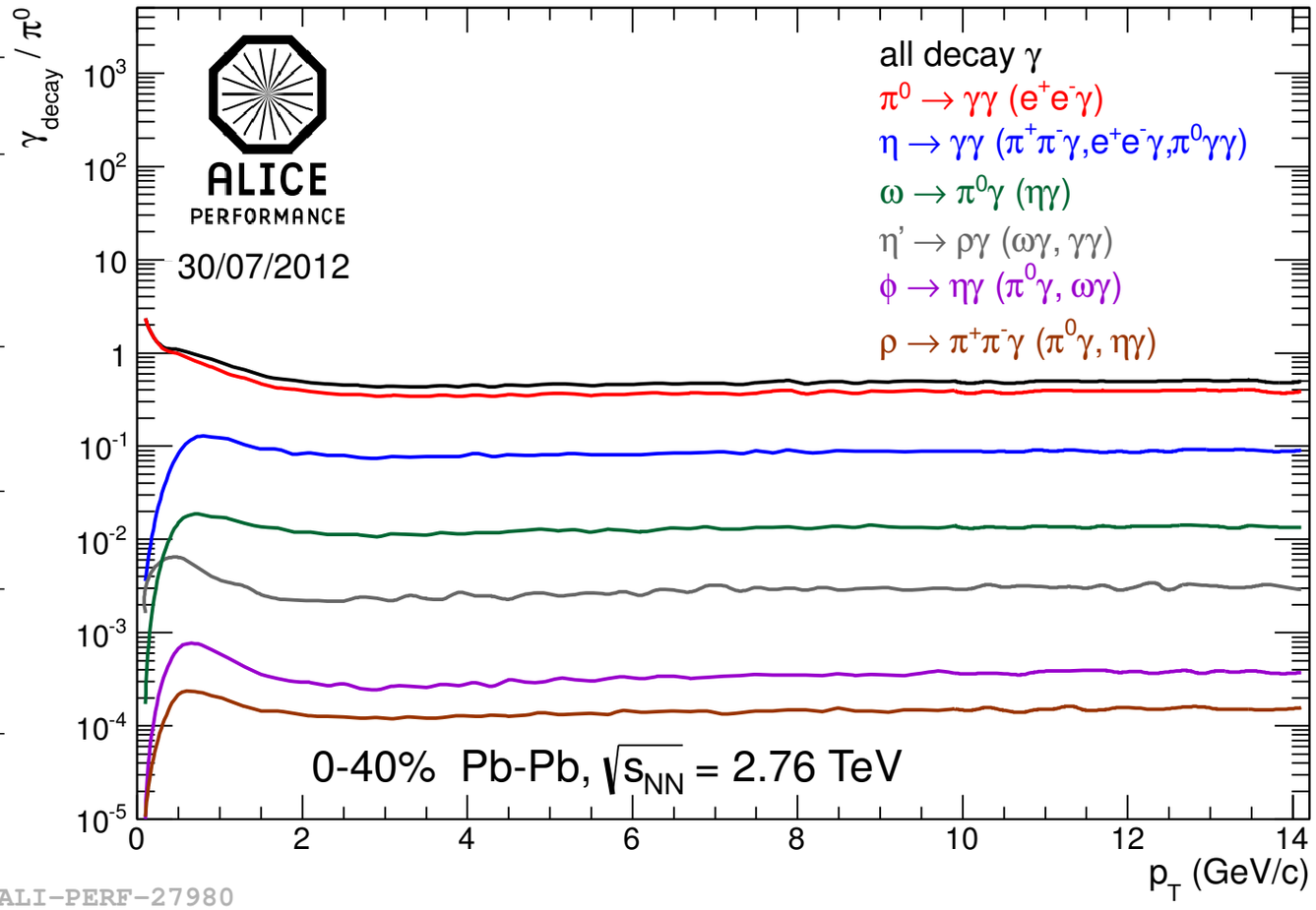
Inclusive Photon Invariant Yield

- Spectra corrected for
  - efficiency + purity
  - conversion probability
- Main systematic uncertainty from
  - Material budget (~4.5 %)
  - Uncertainty estimated by cut variation
    - p_T <5 GeV/c ~ 6%
    - p_T >5 GeV/c ~ 15%



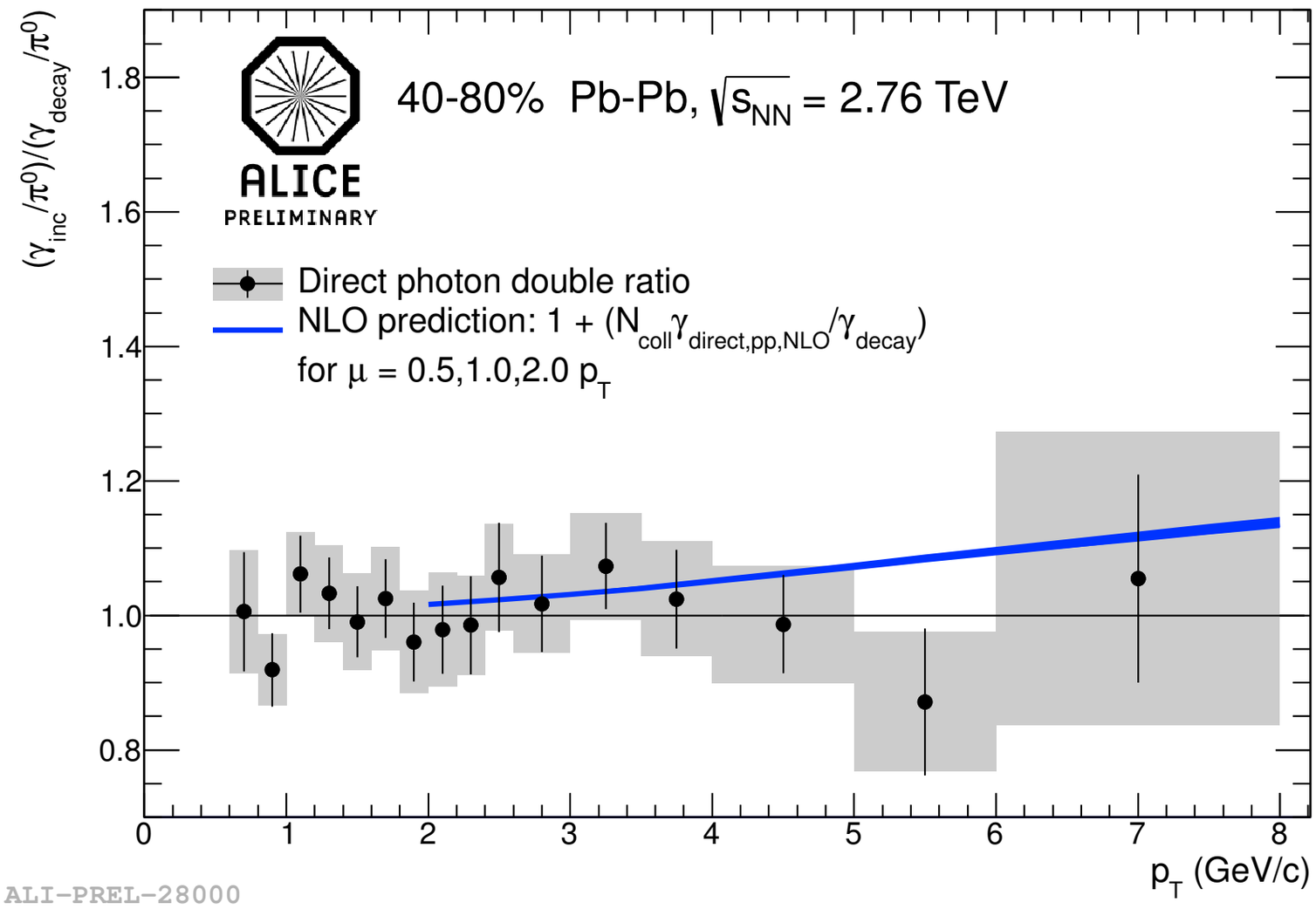
Cocktail Simulation - Spectra

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



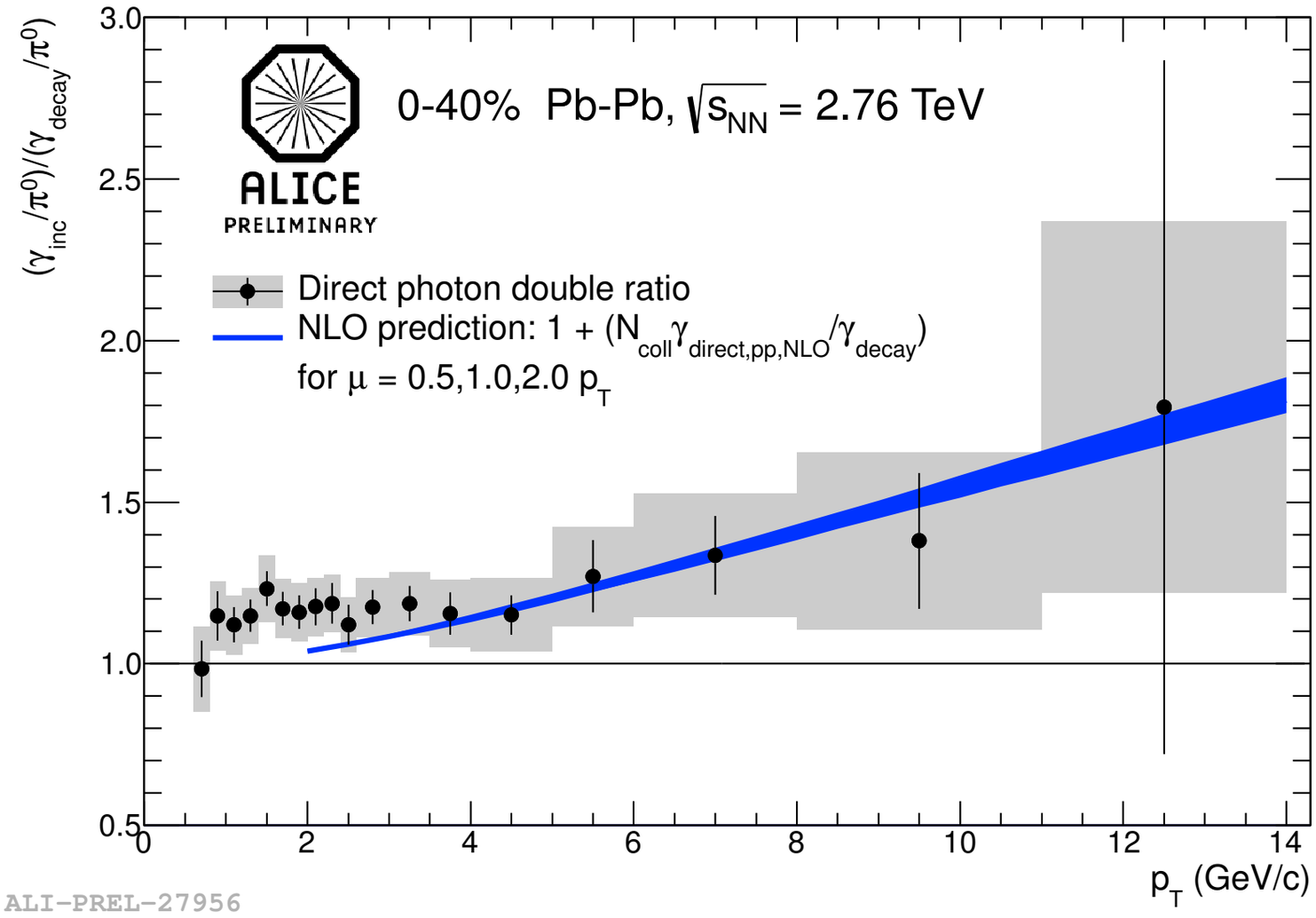
- π^0 parametrized with measured π^0 spectrum
- Higher resonances from transverse mass m_T scaling

Double Ratio Pb-Pb 40-80% peripheral



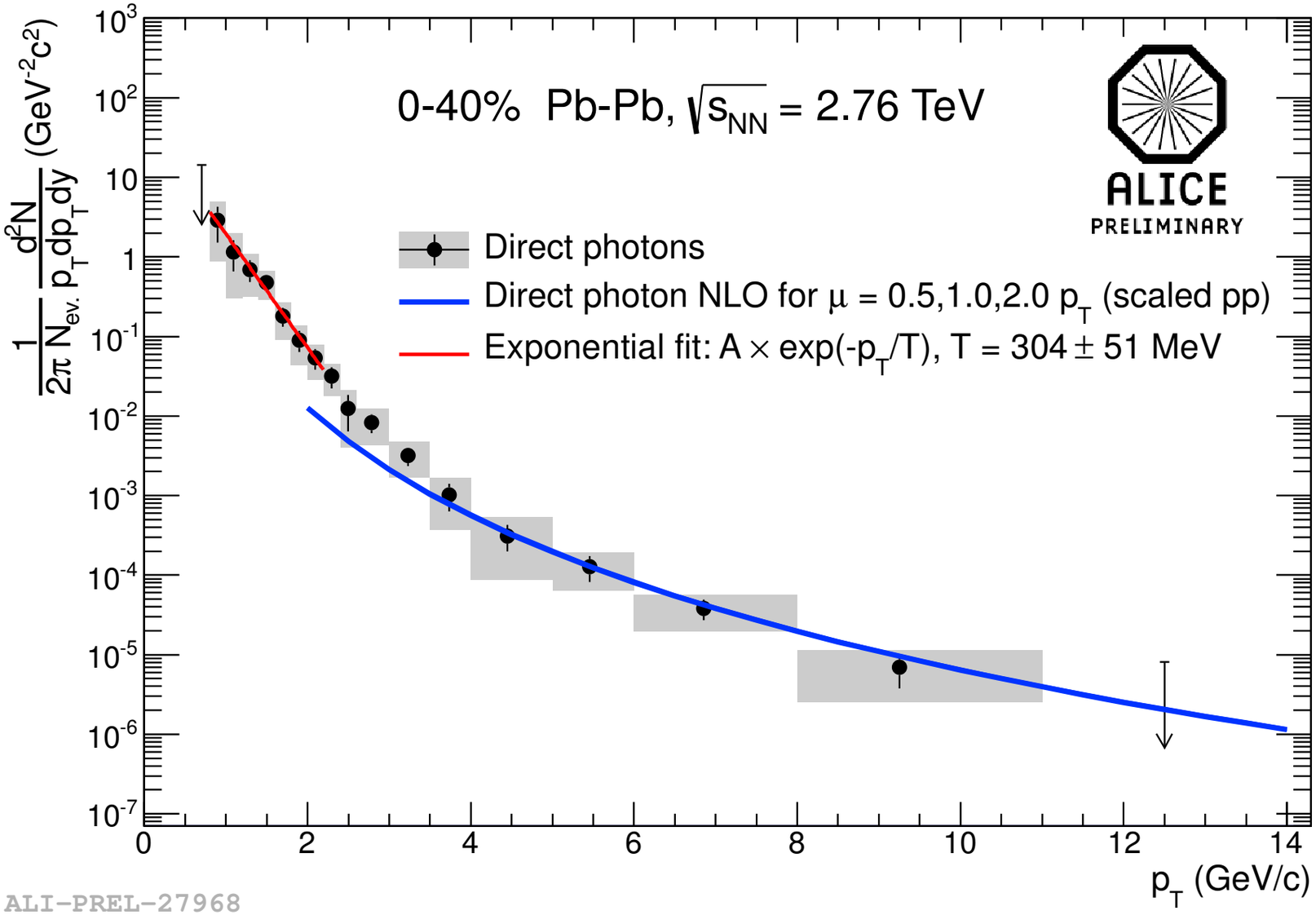
- No significant direct photon excess
- Consistent with binary scaled (N_{coll}) NLO pQCD for pp

Double Ratio in 0-40% central Pb-Pb



- High p_T consistent with binary scaled (N_{coll}) NLO pQCD for pp
- Low p_T excess - thermal photons? Significant?

ALICE Direct Photon Spectrum



- Spectrum consistent with NLO (pQCD) above 4 GeV/*c*
- Low p_T spectrum described by exponential fit with inverse slope $T^{Eff} \approx 300$ MeV
- What is the physical interpretation of T^{Eff} ?

Direct Photon Analysis Strategy

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

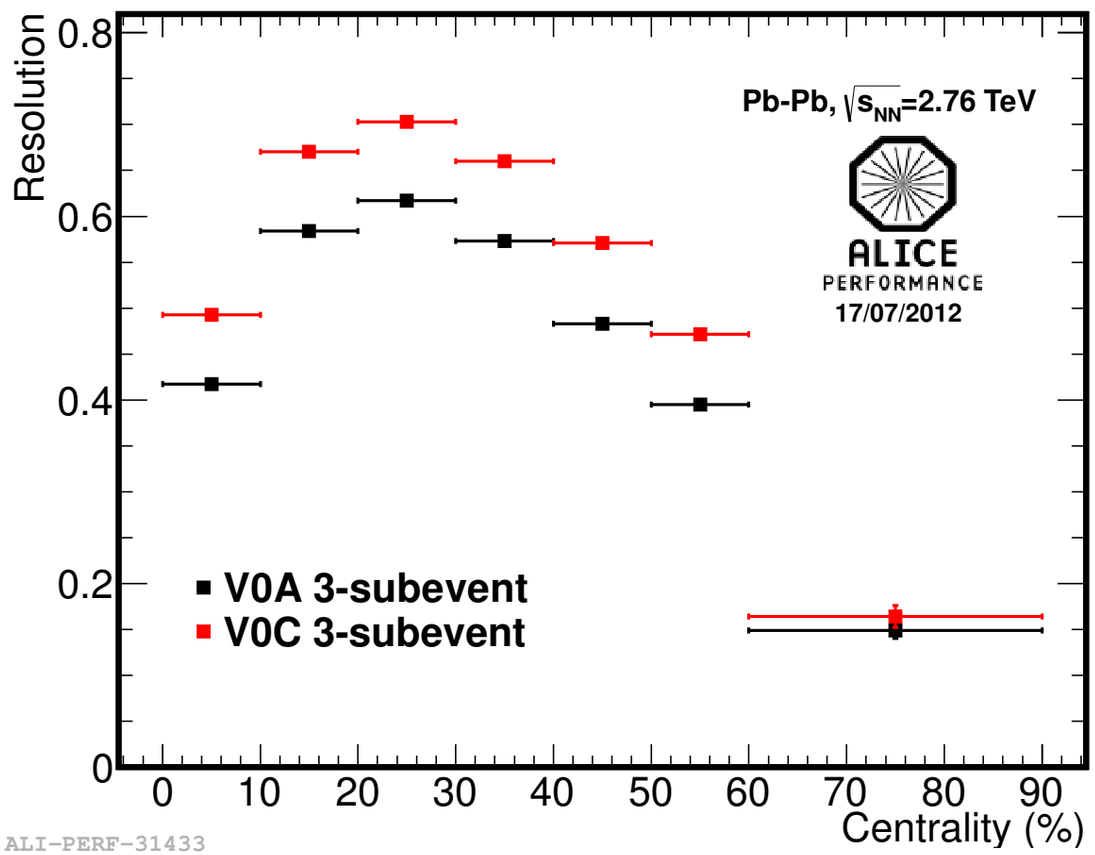
  - inclusive photons = experimentally observed photons
  - decay photons from cocktail simulation

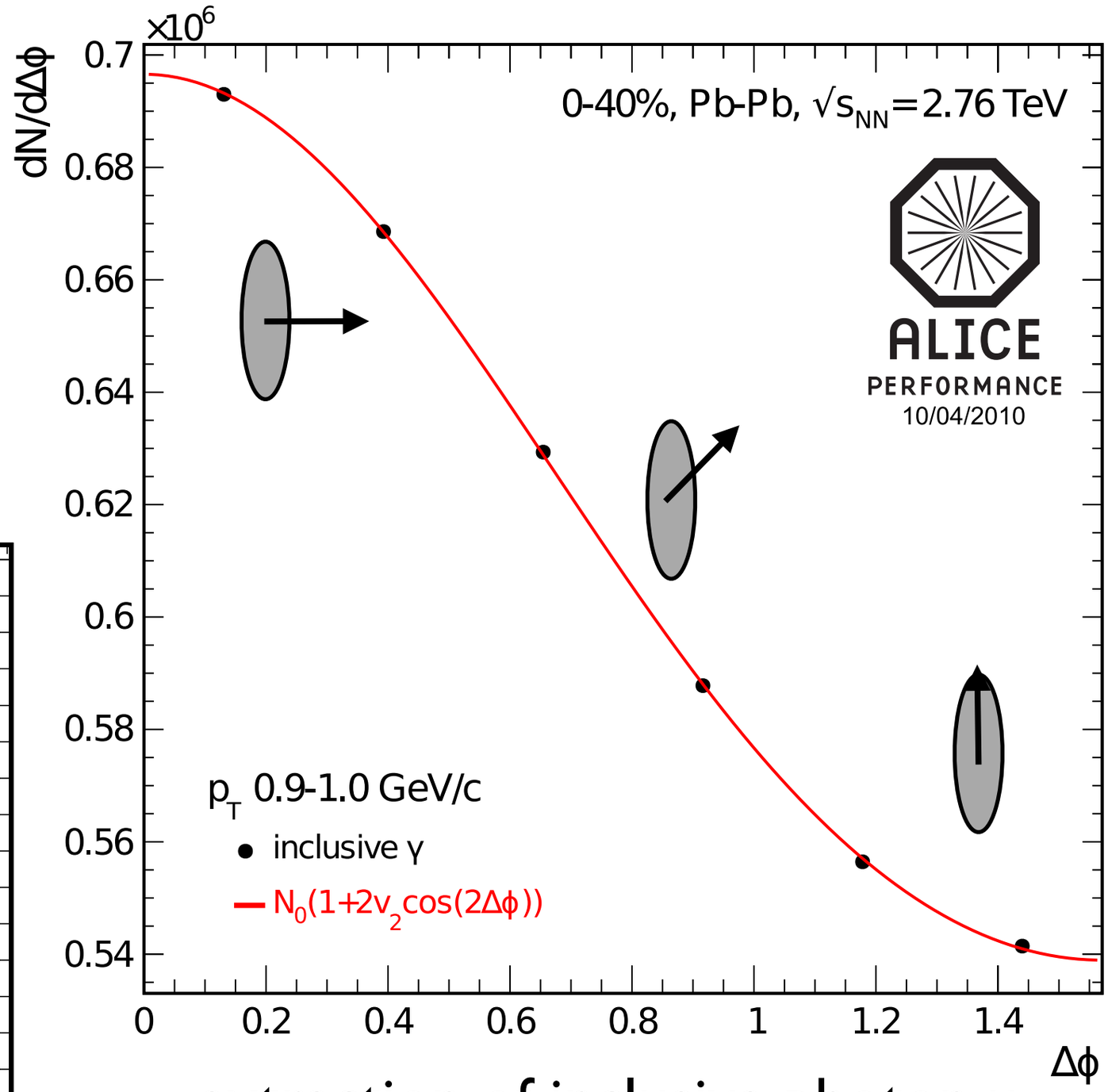
- Direct photon elliptic flow

$$v_2^{\gamma,dir} = \frac{Rv_2^{\gamma,incl} - v_2^{\gamma,decay}}{R-1}$$

Inclusive Photon v_2 Analysis

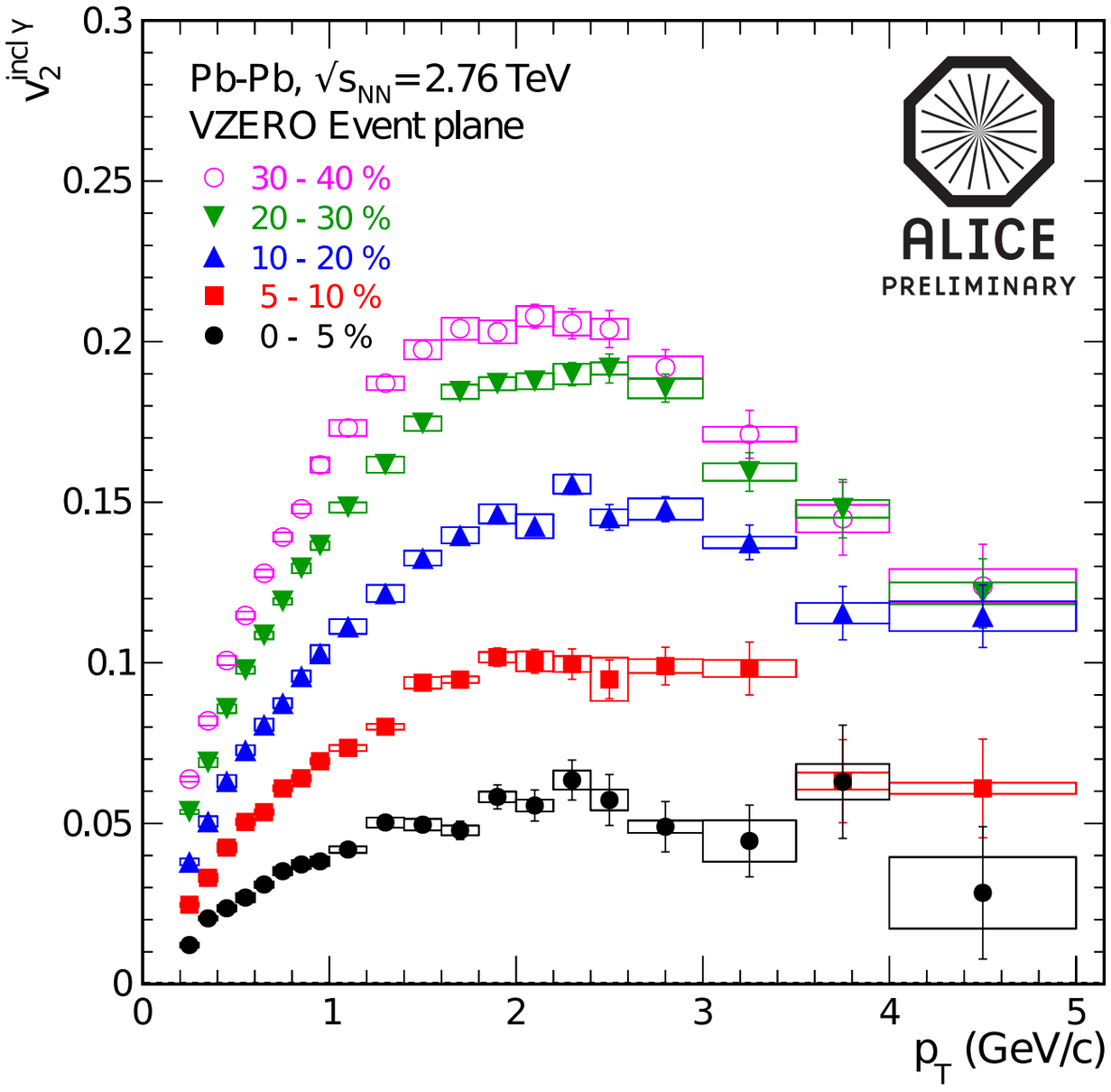
- VZERO event plane (Ψ_2)
  - VZERO A: $\eta \in [2.8, 5.1]$
  - VZERO C: $\eta \in [-3.7, -1.7]$
- $v_2 = v_2^{raw}$ / resolution





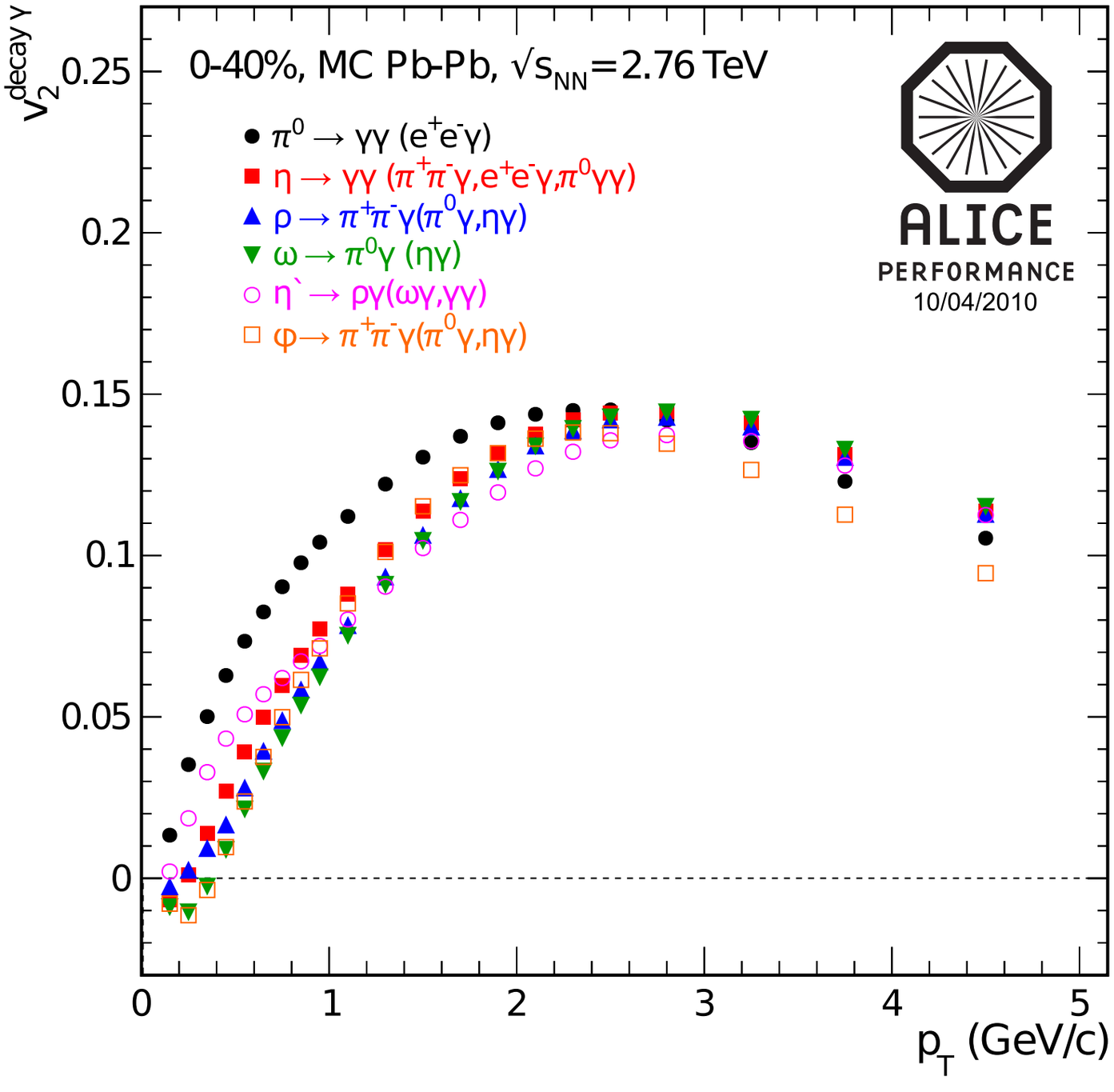
extraction of inclusive photon v_2

Inclusive Photon v_2



- Systematic Uncertainty (~2%) small compared to Spectra:
- v_2 is a relative measure of in/out of plane yields
- Uncertainties on the yield almost cancel out

Cocktail Simulation v_2

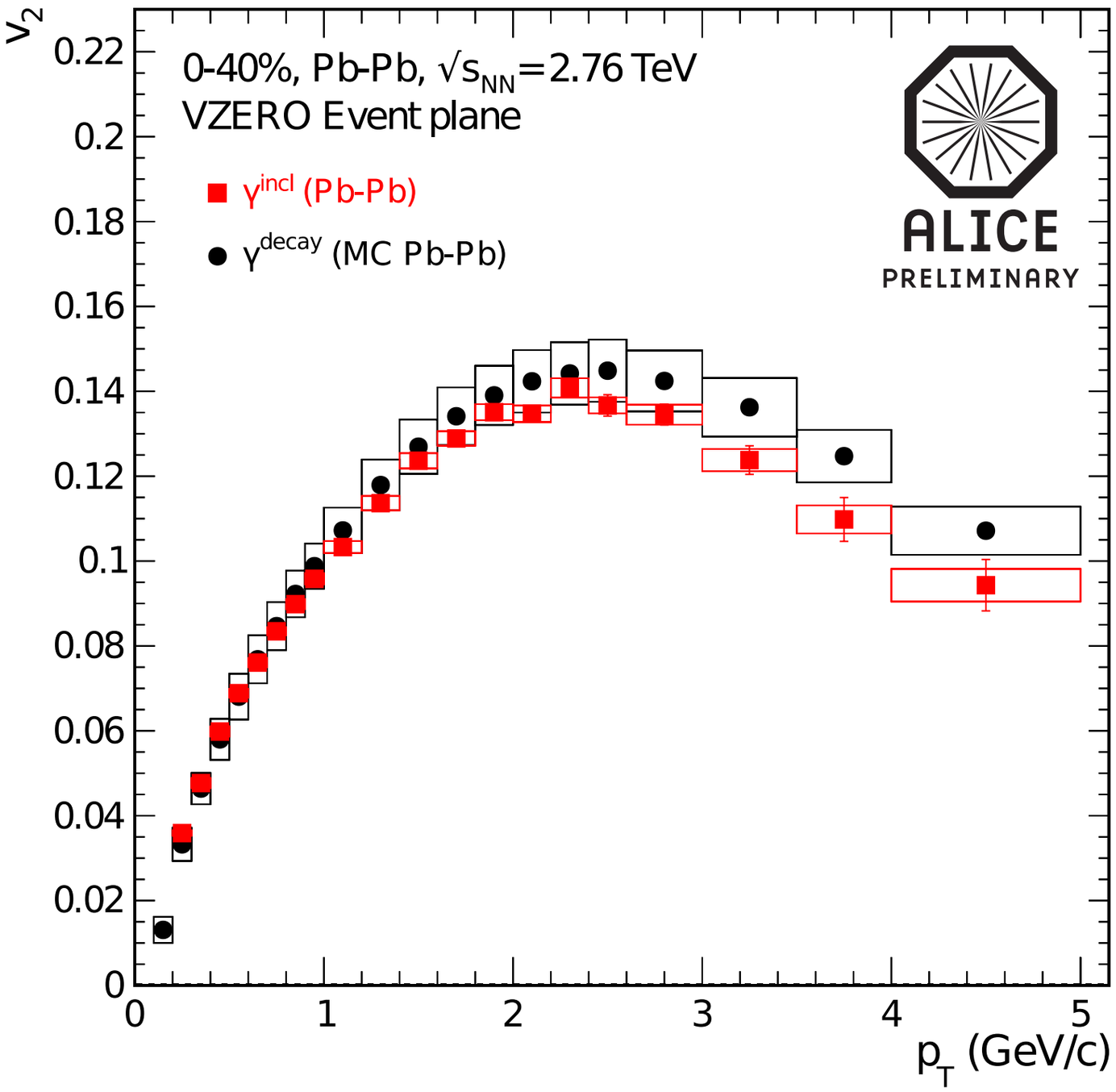


- v_2 of hadron decay photons
- Assumption: $v_2(\pi^{\pm}) = v_2(\pi^0)$
  - 5 % Uncertainty for possible $v_2(\pi^{\pm}) \neq v_2(\pi^0)$ deviation
- Quark number scaling in transverse kinetic energy

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

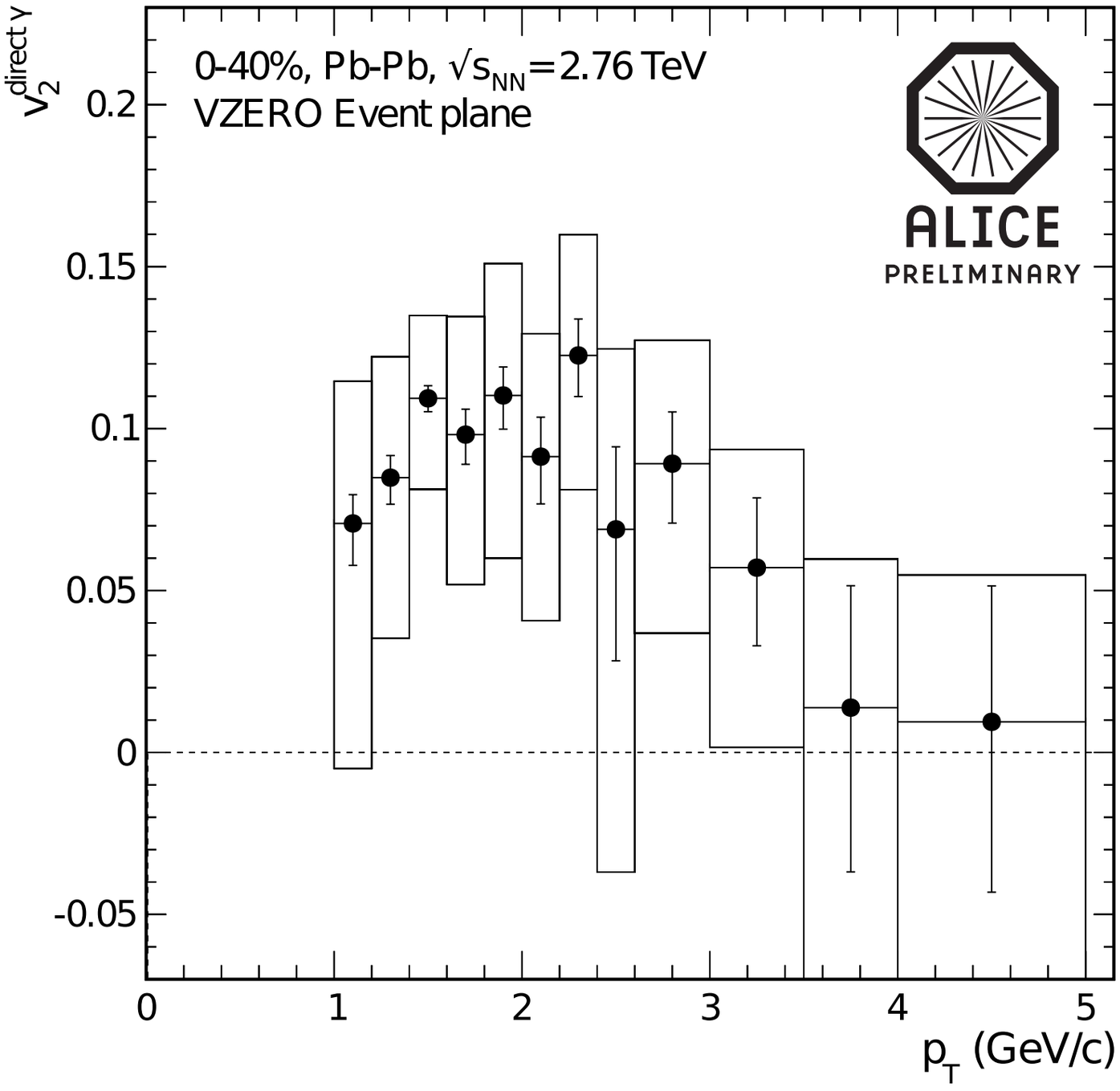
$$KE_T = m_T - m = \sqrt{p_T^2 + m^2} - m$$

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

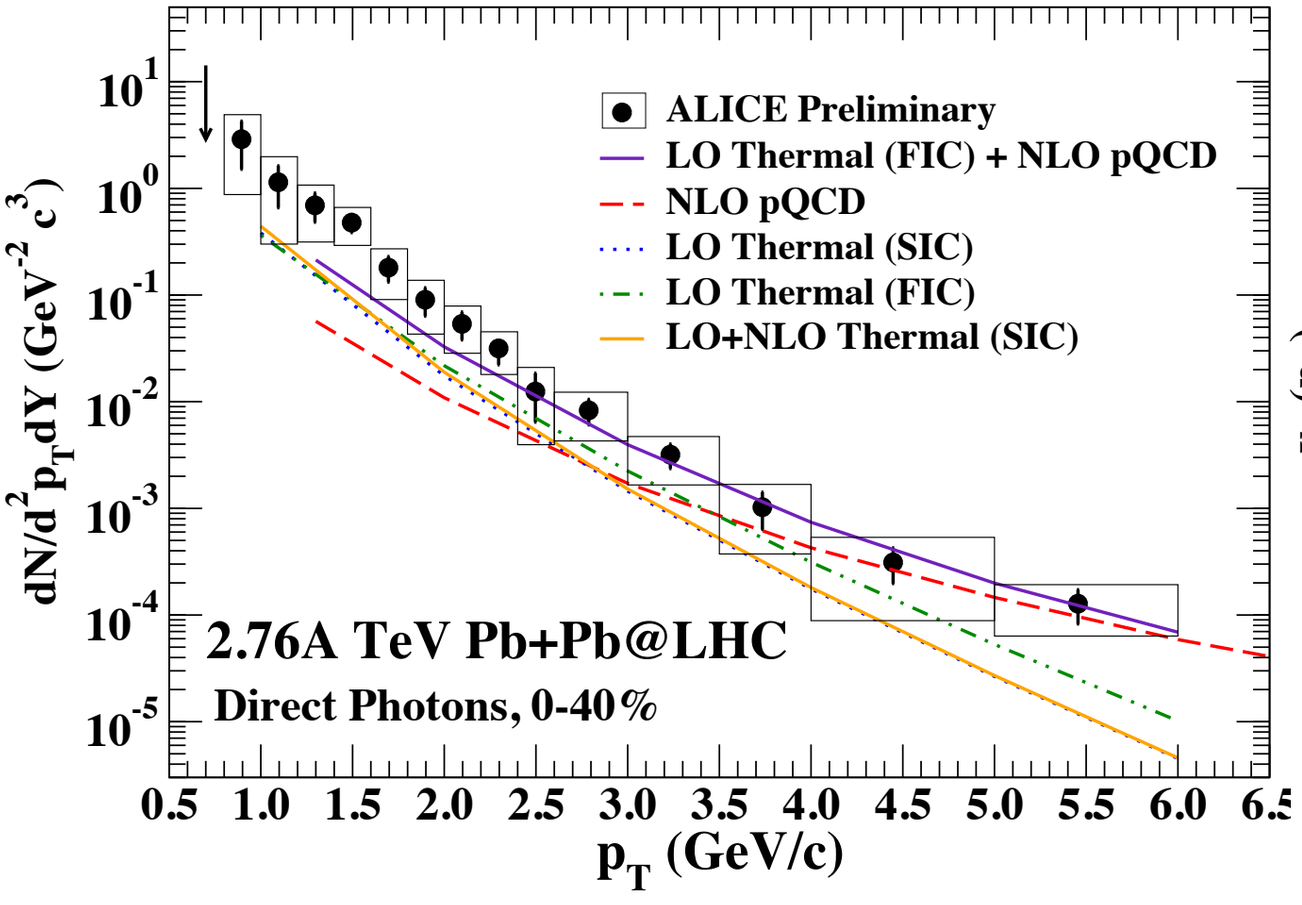
Direct Photon v_2 0-40% and Conclusions

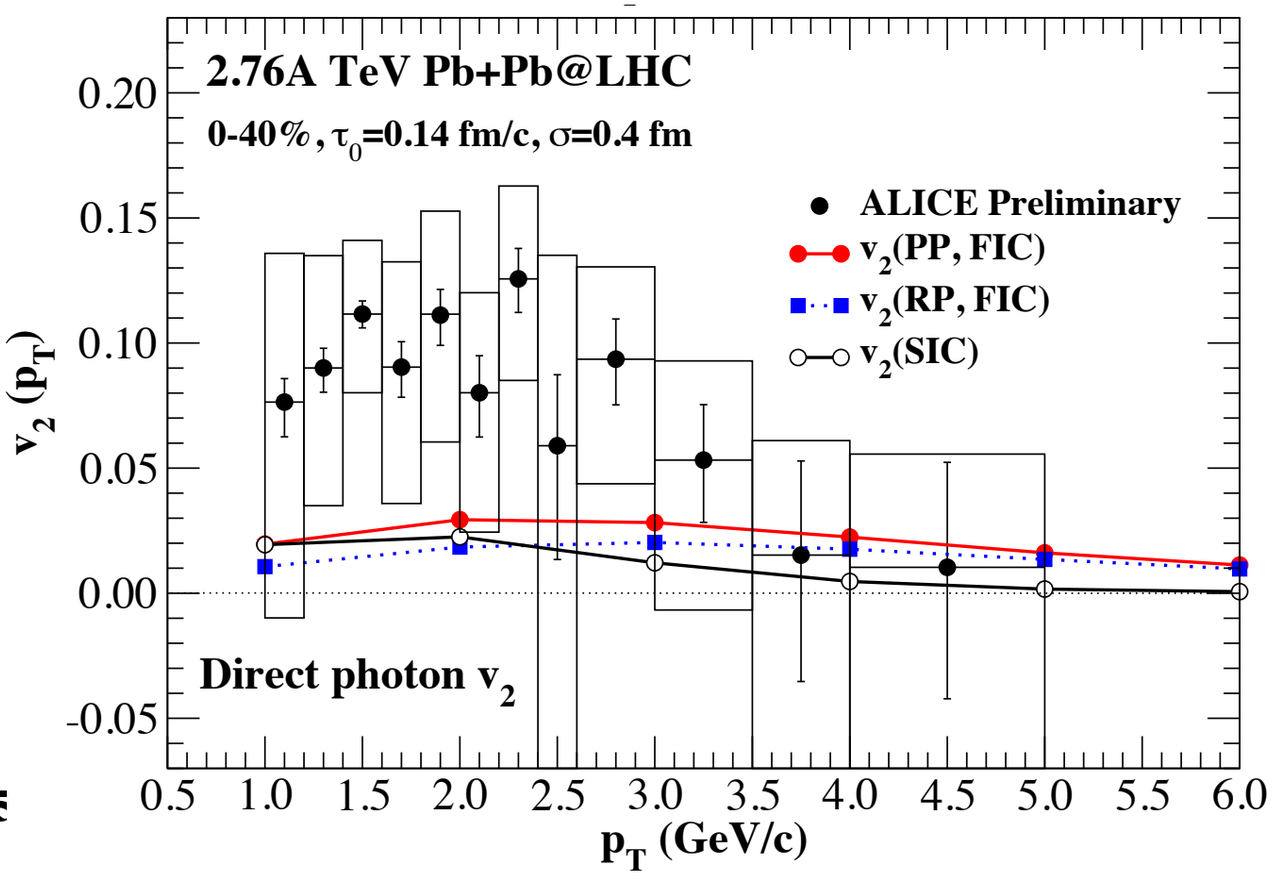


- Direct photons in 0-40% have a significant nonzero elliptic flow below 3 GeV/*c*
- Magnitude of v_2 comparable to hadrons
- Systematic uncertainty mainly from direct photon excess and decay photon v_2

Theory Comparison
'The direct photon puzzle'

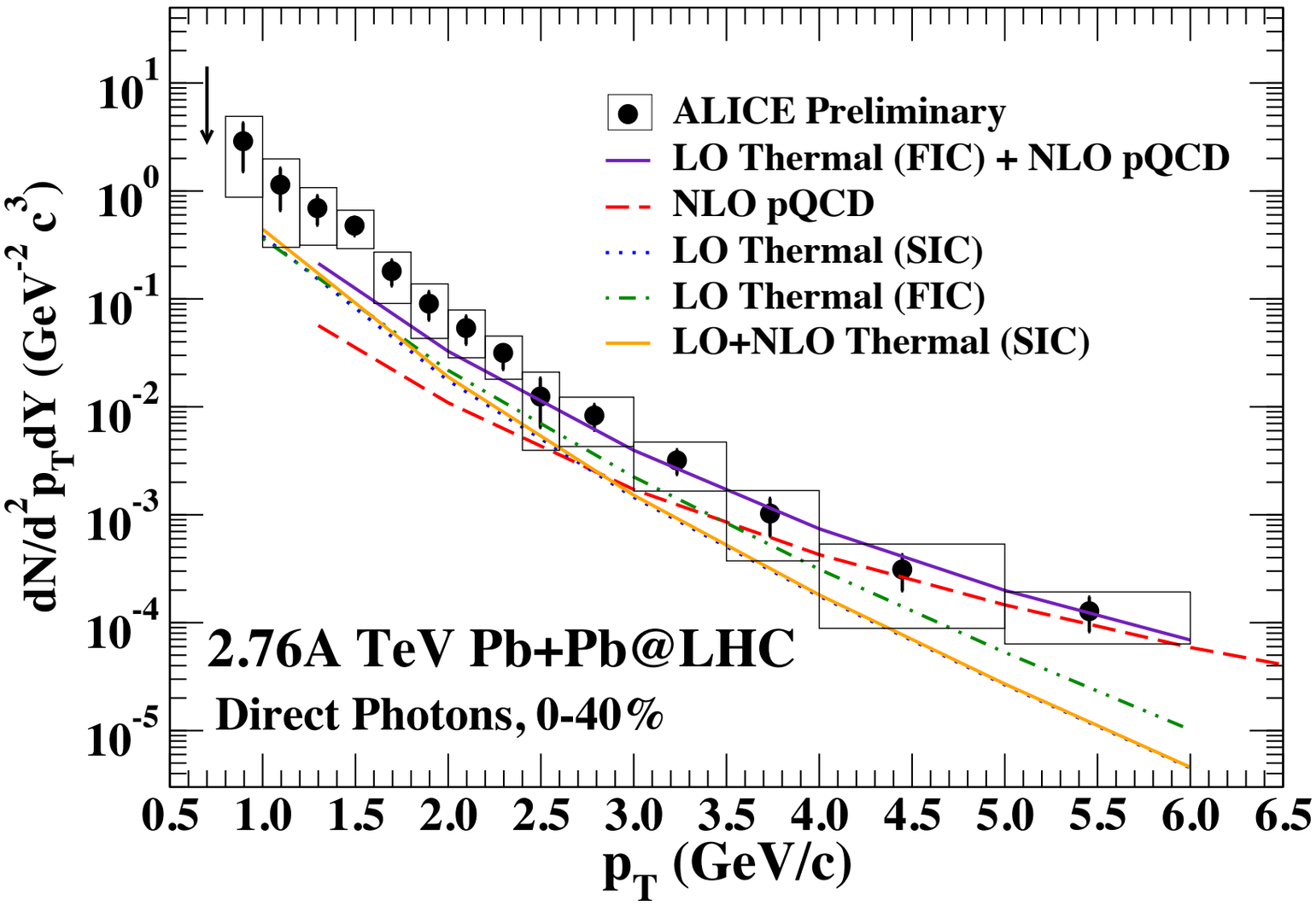
Chatterjee et al.





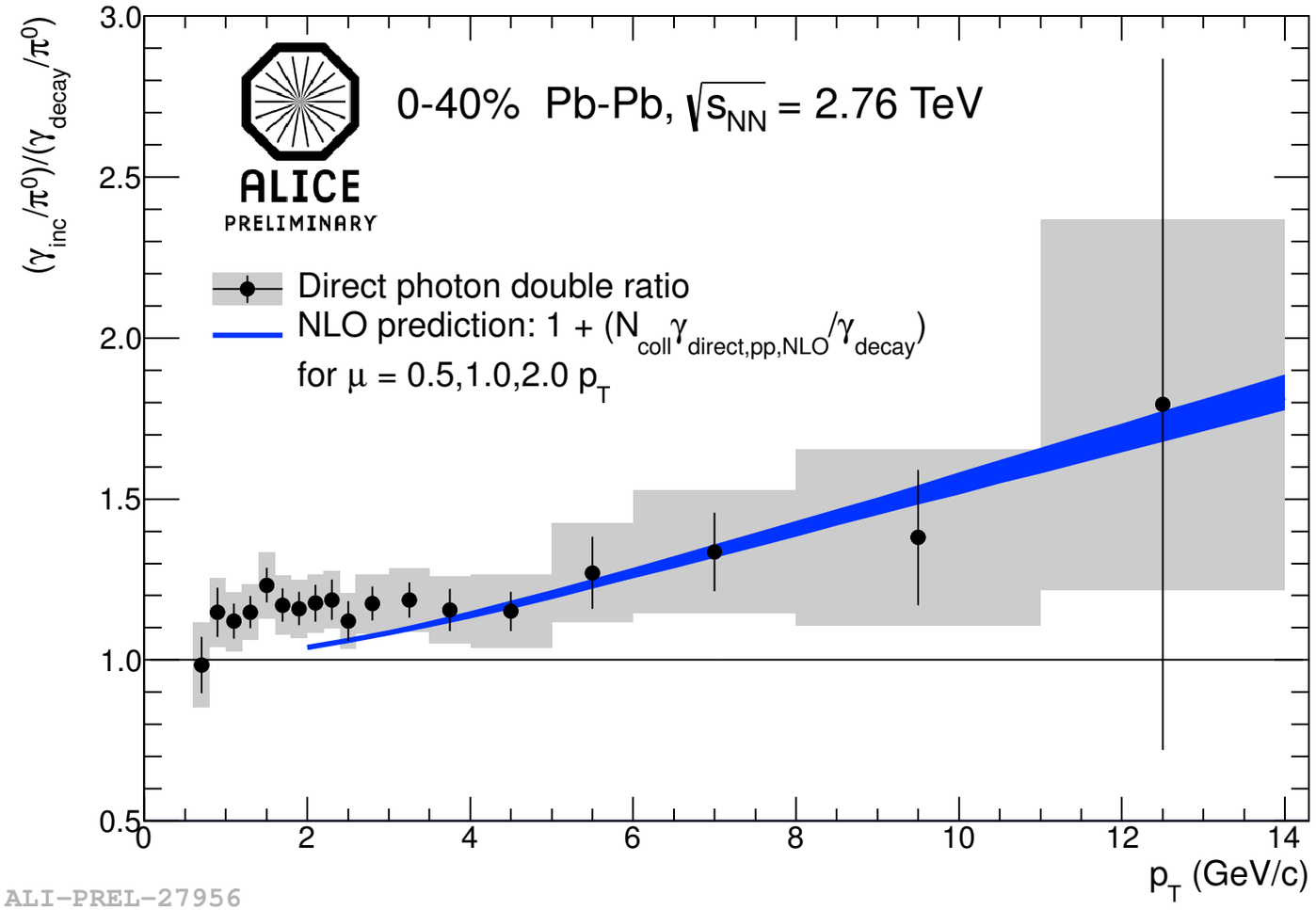
Theory calculations underestimate spectrum and elliptic flow

Closer look at the spectra



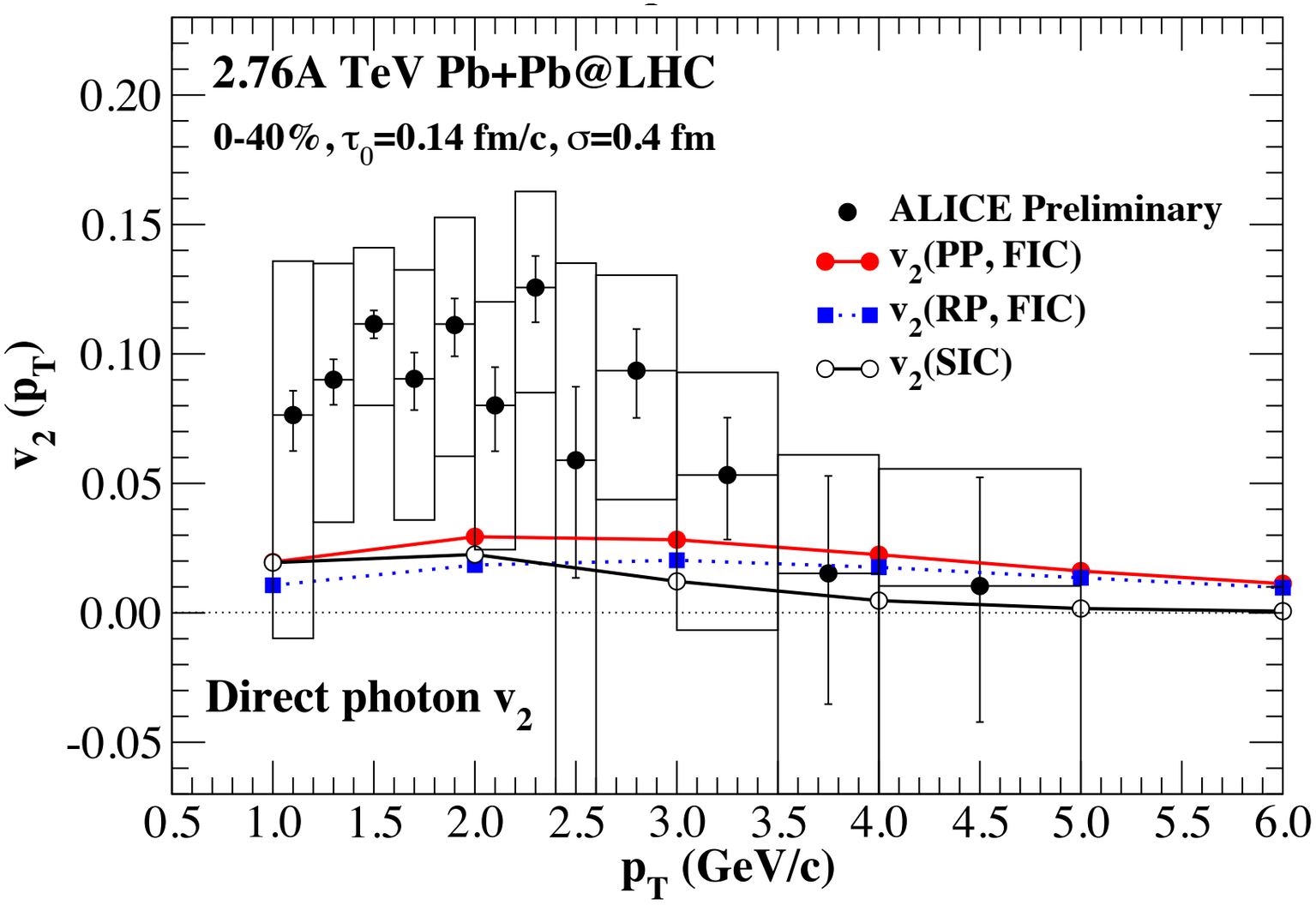
- NLO pQCD "within uncertainties"
- Hydrodynamical predictions numerically about 75% smaller compared to the measurement
  - Is this a significant effect?
  - If not, we should be careful when saying: "Theoretical calculations underestimate data"

Closer look at the double ratio



- ~1.5 sigma difference between data and theory at low p_T
- How large is the correlated part of the systematic uncertainty?
  - 4.5 % uncertainty on material budget
  - There is a ~10 % probability that we can shift all points down by more than 4.5%

Closer look at direct photon v2



- Large systematic uncertainties mainly from direct photon excess
- What is the level of correlation of systematic uncertainties
- Is discrepancy between theory and data significant?

Summary

- It is important to understand the correlation of systematic uncertainties
  - Classification of uncertainties will allow for Chi2 tests and thus more quantitative statements about significance of experimental results
- Final direct photon spectra paper to be published soon
  - Photon Conversion Method and PHOS Calorimeter
  - Measurement in finer centrality bins
- Direct photon v_2 and v_3 paper will follow spectra paper