A Large Ion Collider Experiment

Direct Photon and High-p_T Particle Production with ALICE

Kruger Park Workshop, December 1- 5, 2014

Klaus Reygers, for the ALICE collaboration

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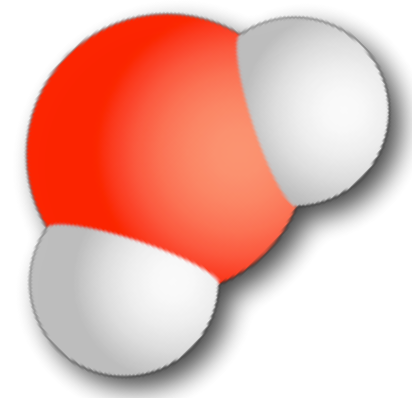
University of Heidelberg, Germany

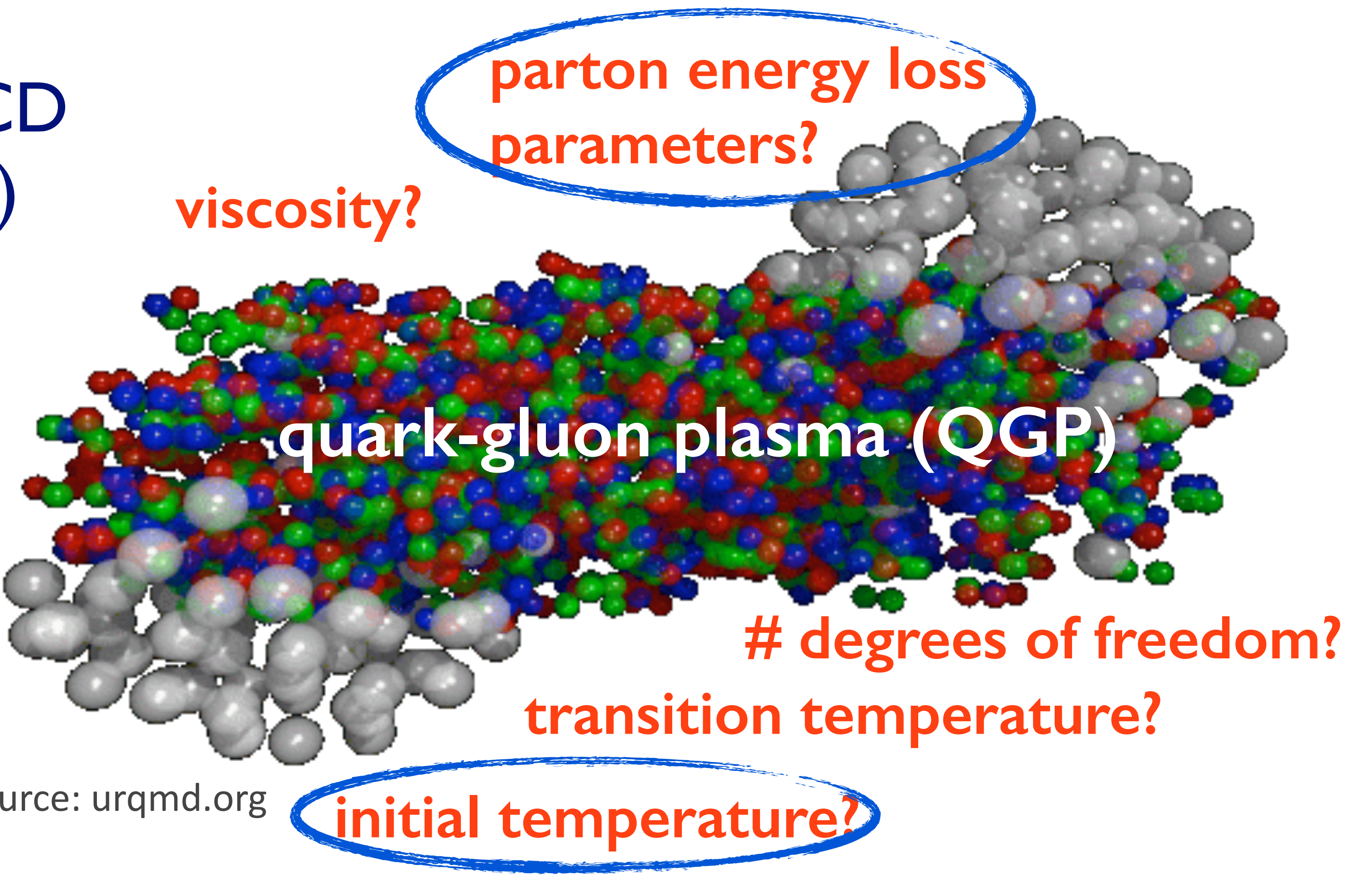
The Objective of Ultra-Relativistic Heavy-Ion Physics: Study of Emergent Properties of QCD

- It is a hard problem to determine the properties of water and its phases (ice, water, steam) from the known properties of a water molecule



source: de.wikipedia.org

- Ultra-relativistic heavy-ion physics: Study of emergent properties of QCD (condensed-matter aspects of QCD)

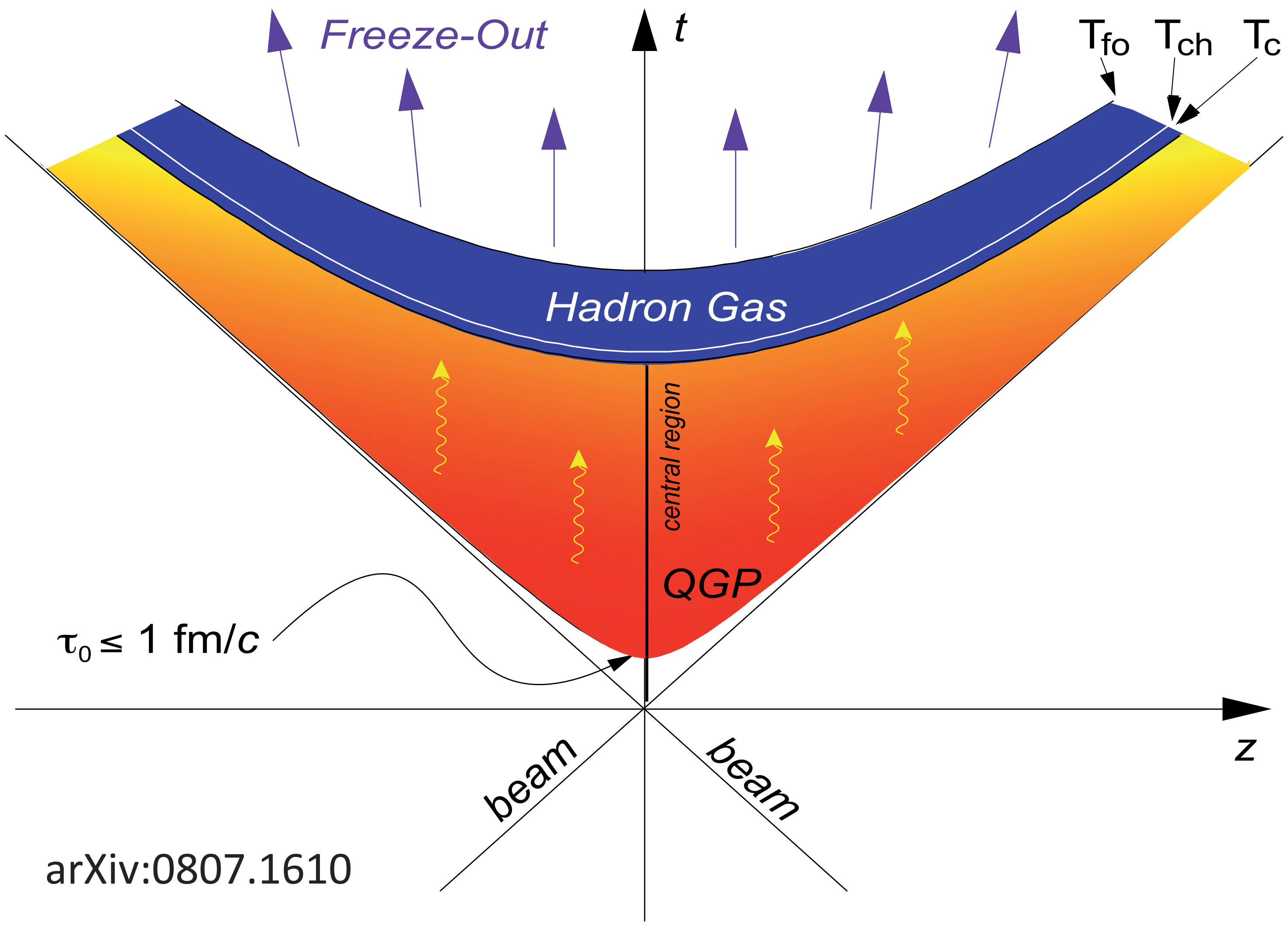


source: urqmd.org

"More is different"

Philip W. Anderson, Science, 177, 1972, S. 393

QGP Space-time Evolution Successfully Modeled with Hydrodynamics

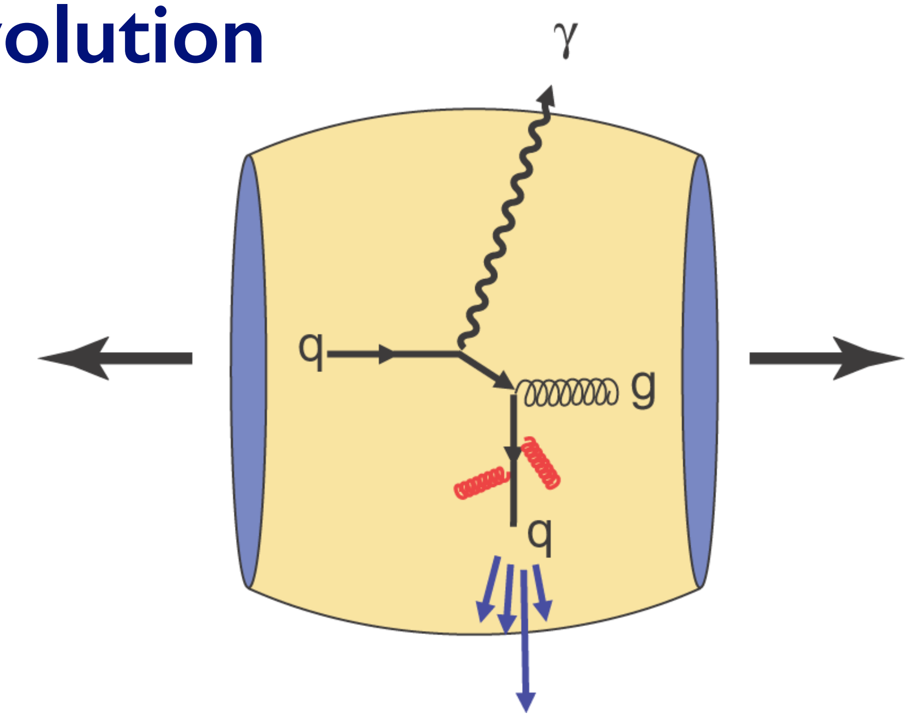


arXiv:0807.1610

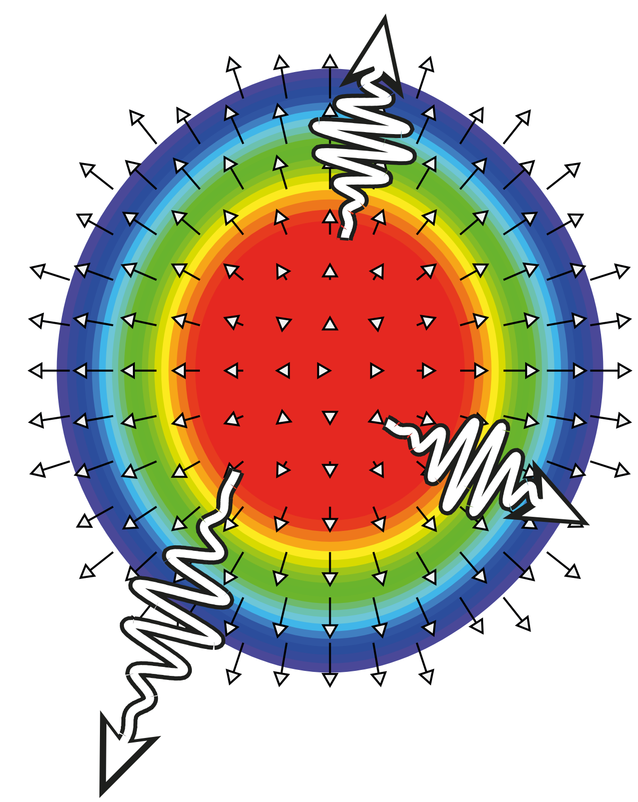
- Gluons liberated from the nuclear wave function during collision
- Rapid thermalization: QGP created at ~ 1 fm/c
- Longitudinal and transverse expansion describable by almost ideal relativistic hydrodynamics ($\eta/s \approx 0$)*
- Transition QGP → hadrons at T_c = 150 - 160 MeV
- Ratio of different particle species fixed at $T_{ch} \approx T_c$ ("chemical freeze-out")
- Shape of momentum spectra fixed at T_{fo} ~ 100 MeV ("kinetic freeze-out")

* conjectured lower bound from string theory: $\eta/s|_{min} = 1/4\pi$
Phys.Rev.Lett. 94 (2005) 111601

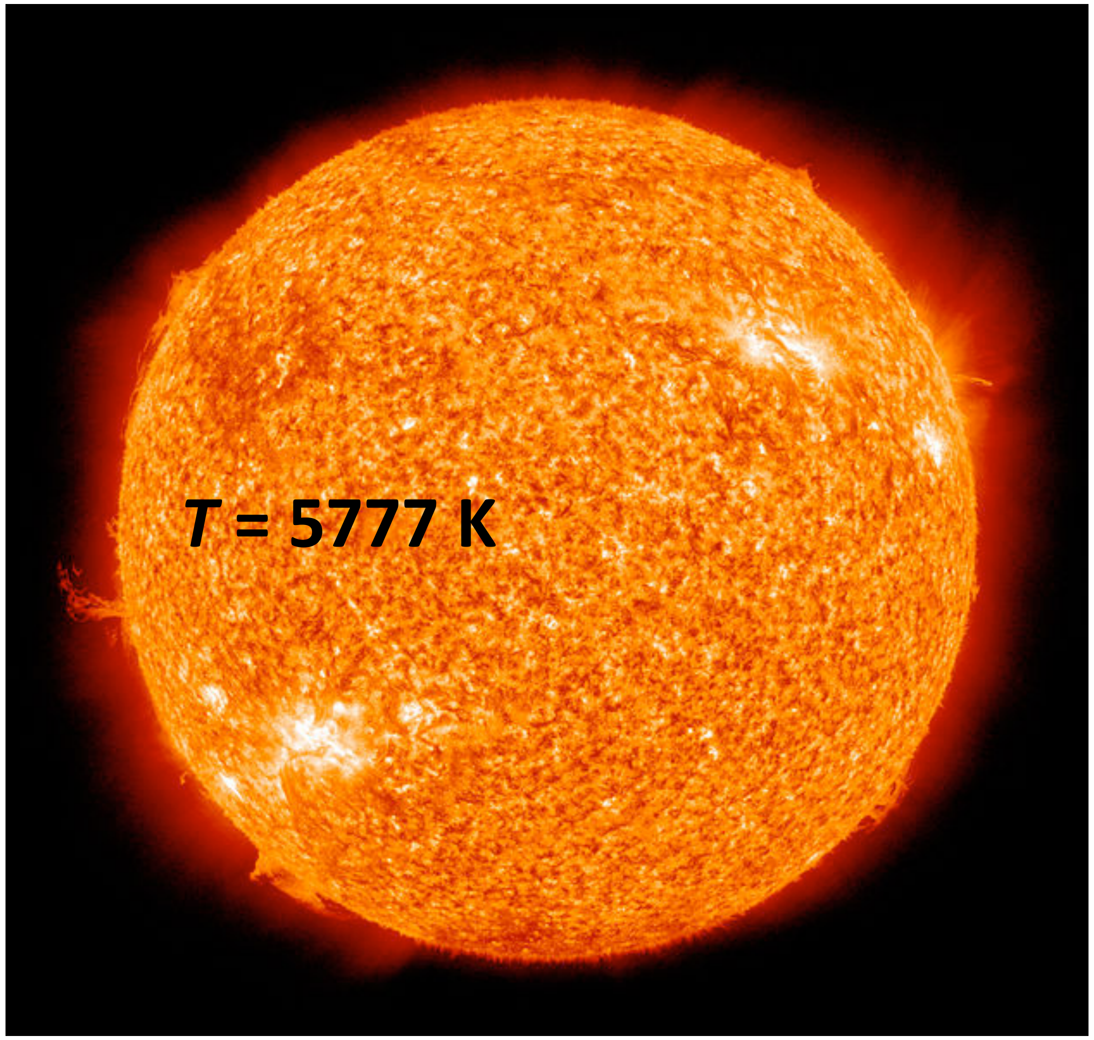
The Role of Direct Photons and High-p_T Particles: Access to the Early Stage of the Medium Evolution



- High p_T particle production and jets
  - Energy loss of quarks and gluons in the medium characterizes the medium
  - Results in suppressed particle production at high p_T
- Direct Photons
  - Escape the medium unscathed (mean free path $\lambda \approx 500$ fm)
  - High p_T (> ~ 6 GeV/c):
    Absence of suppression for prompt (pQCD) photons
    → Confirms parton energy loss picture
  - Low p_T (< ~ 4 GeV/c)
    - Contributions from all stages (unlike hadrons)
    - Test of space-time evolution
    - Access to initial temperature of the QGP (?) [via comparison to hydro models]

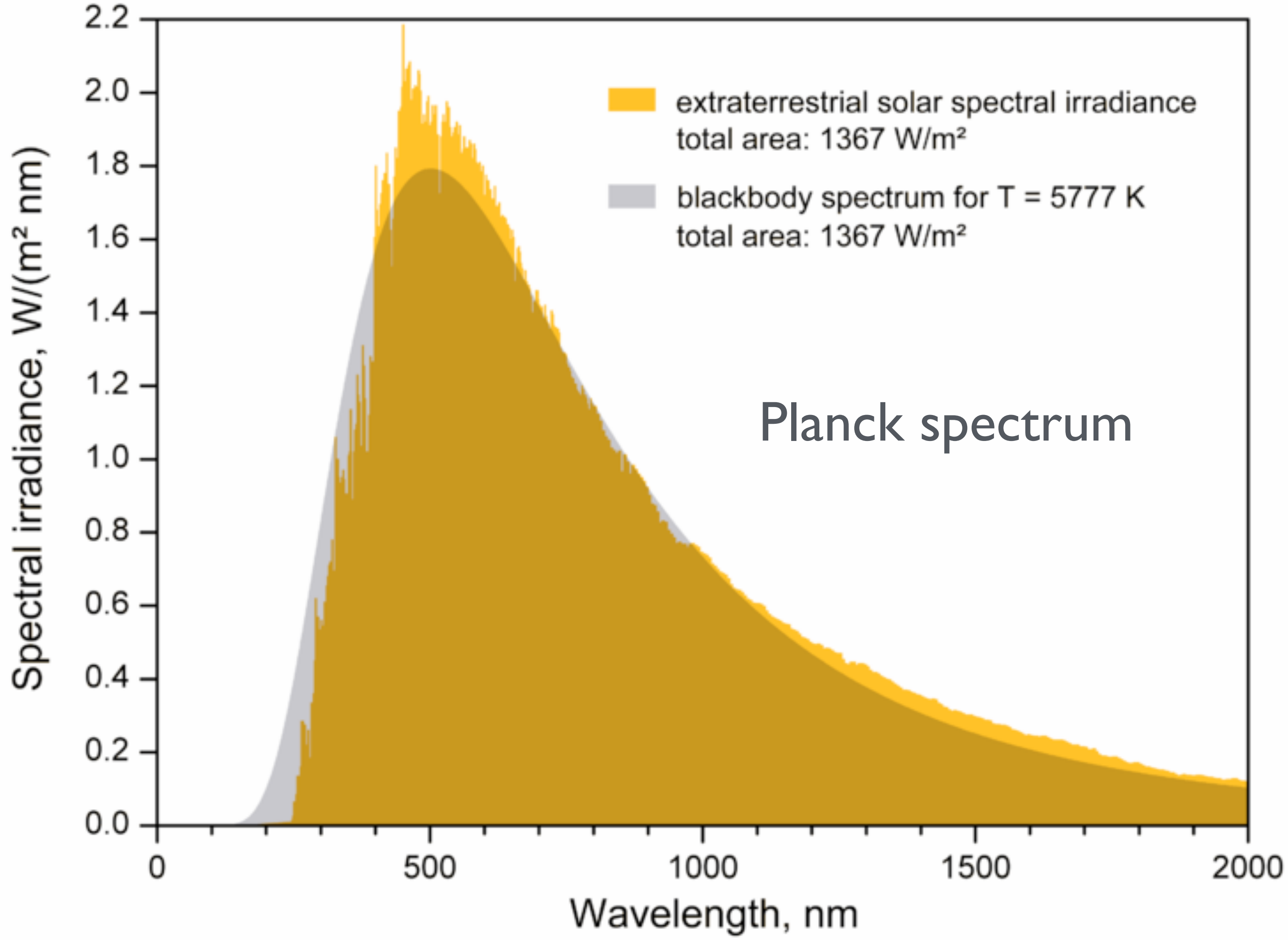


Temperature Measurements via Photons: The Sun …



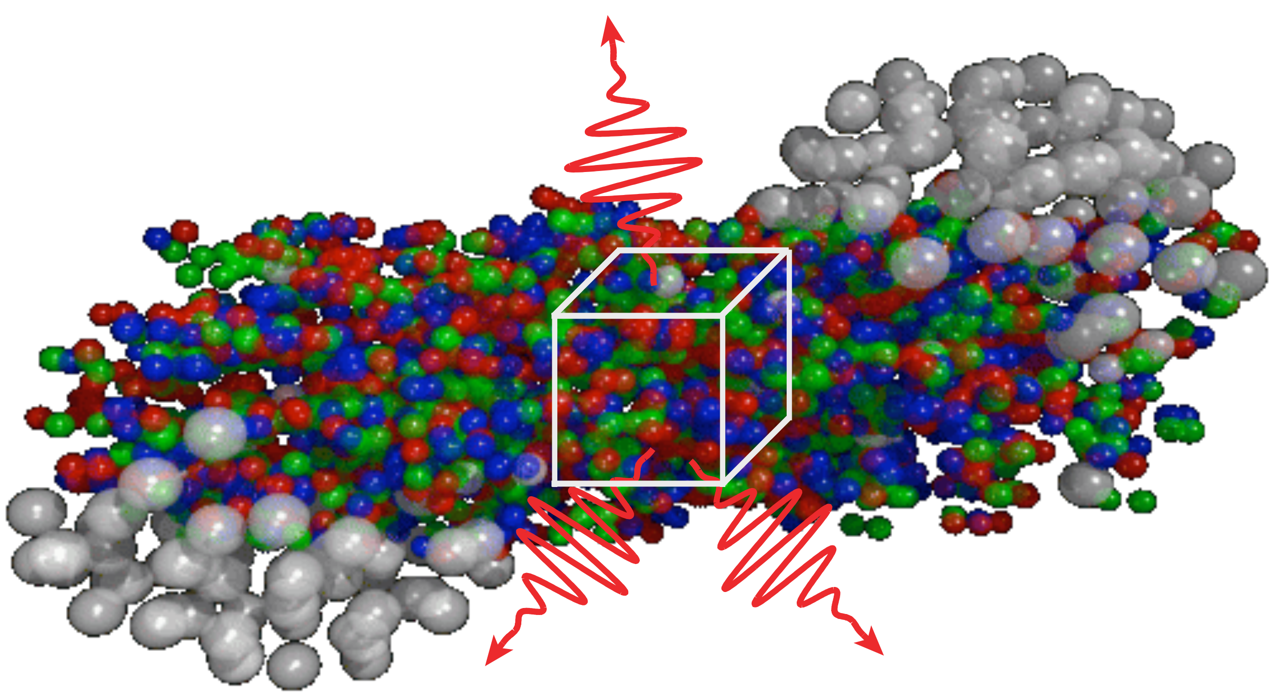
source: http://en.wikipedia.org

source: http://en.wikipedia.org



… and the QGP (analog, but slightly different)

- Photons produced in scatterings of quark and gluons in thermal equilibrium
- Photons not in thermal equilibrium, but energy spectrum reflects QGP temperature

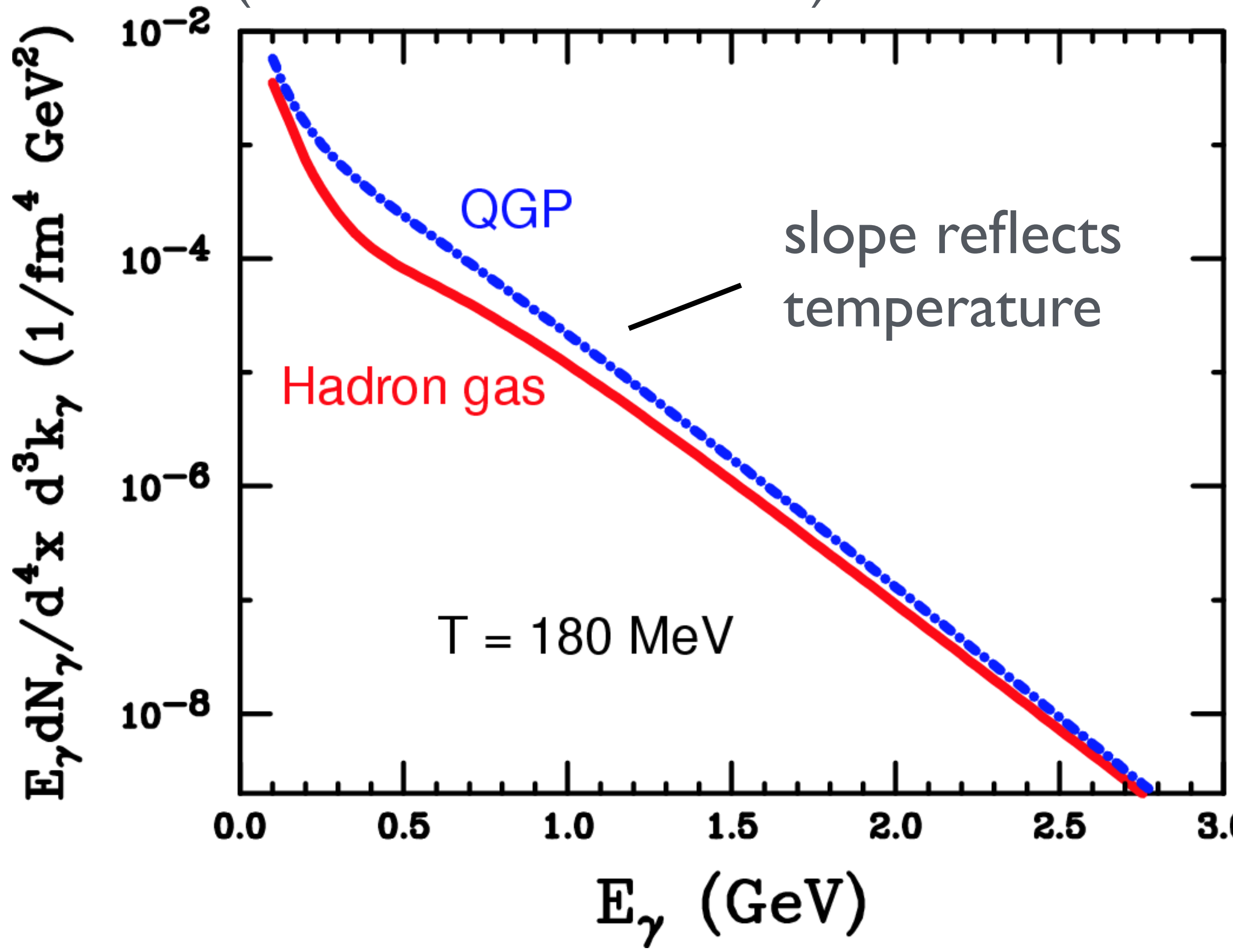


QGP photon rate (lowest order):

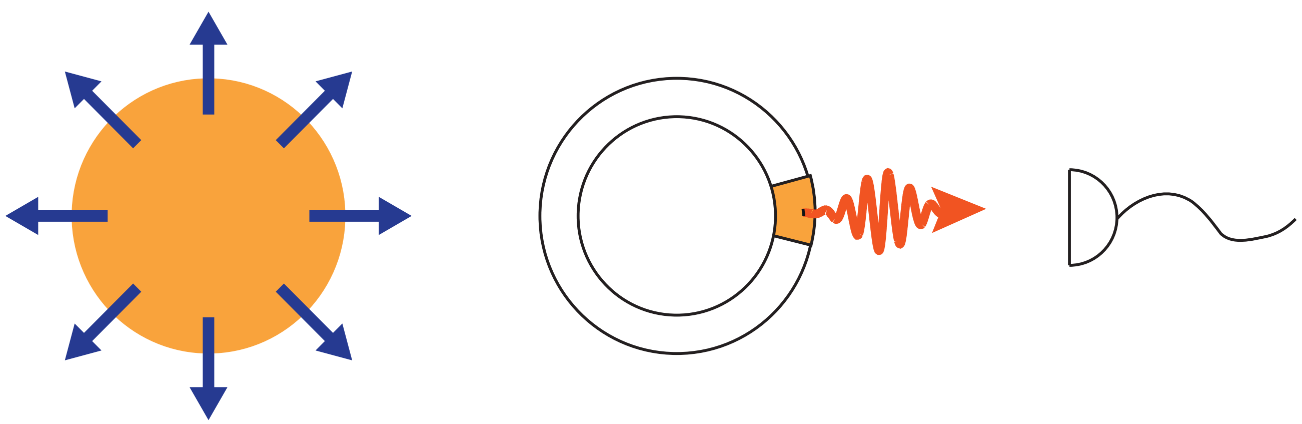
$$E\gamma \frac{dN\gamma}{d^3p} \propto \alpha\alpha_s T^2 e^{-E_\gamma/T} \log \frac{E_\gamma T}{k_c^2}$$

QGP rates: Arnold, Moore, Yaffe, JHEP 0112:009, 2001
HG rates: Turbide, Rapp, Gale, PRC 69 (2004) 014903

Photon rate: yield per unit time and volume as a function of photon energy (theoretical calculation)



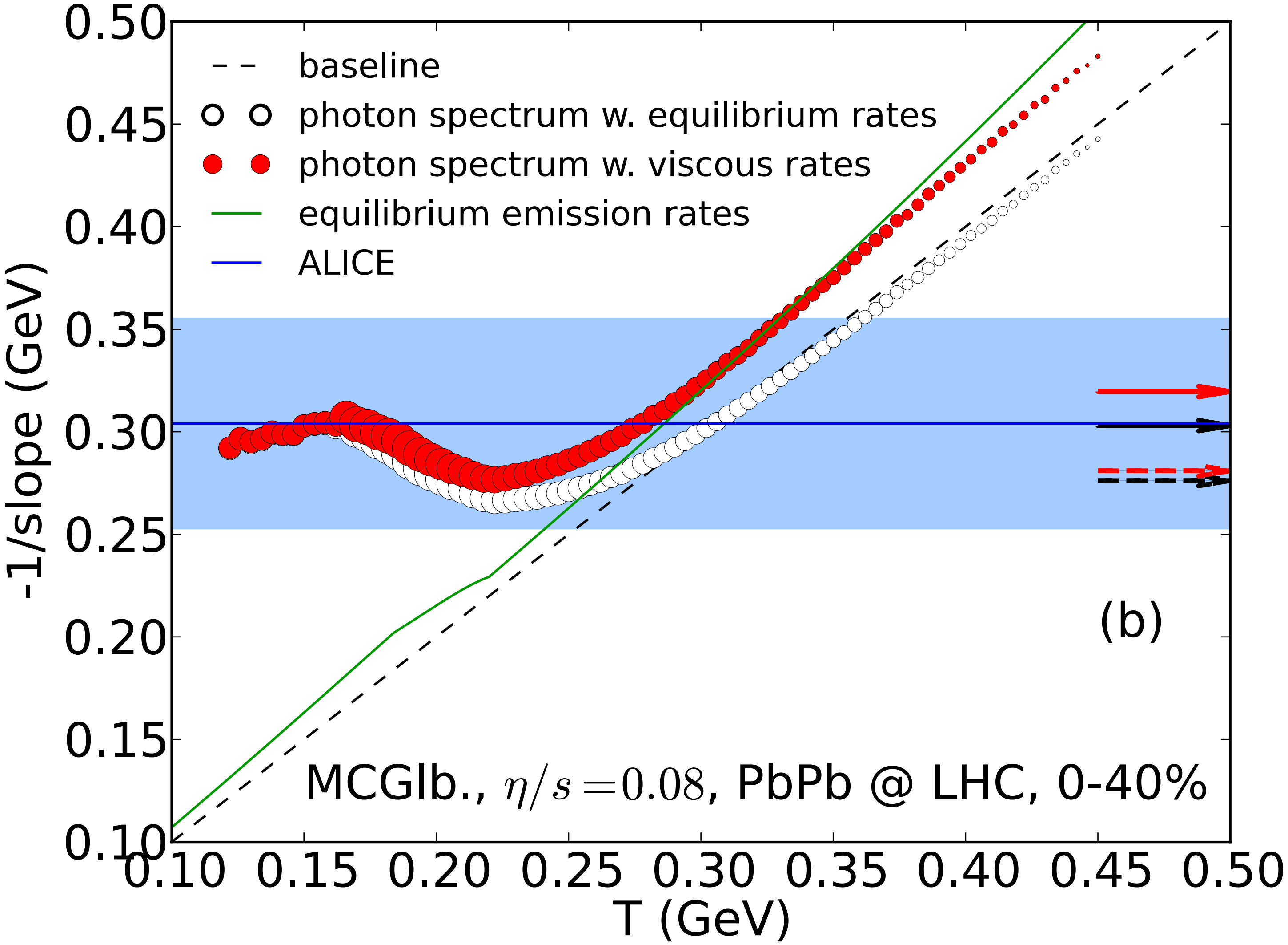
A Complication for the Temperature Measurement: Blueshift due to Radial Flow



$$E_\gamma \frac{d^3 N_\gamma}{d^3 p_\gamma} \propto e^{-E_\gamma / T_{\mathrm{eff}}}$$

$$T_{\mathrm{eff}} = \underbrace{\sqrt{\frac{1+\beta_{\mathrm{flow}}}{1-\beta_{\mathrm{flow}}}}}_{2 \text{ for } \beta_{\mathrm{flow}}=0.6} \times T$$

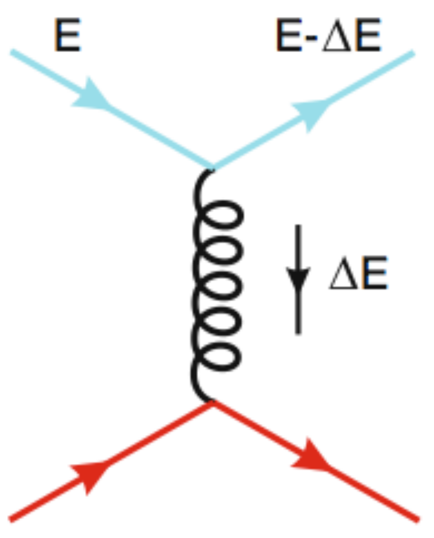
C. Shen, U. Heinz, J.-F. Paquet, C. Gale, PRC 89 (2014) 4, 044910



- Large blueshift at late times when $T \approx$ 150 - 200 MeV
- Extraction of initial temperature from data requires comparison to (hydro) model

Parton Energy Loss

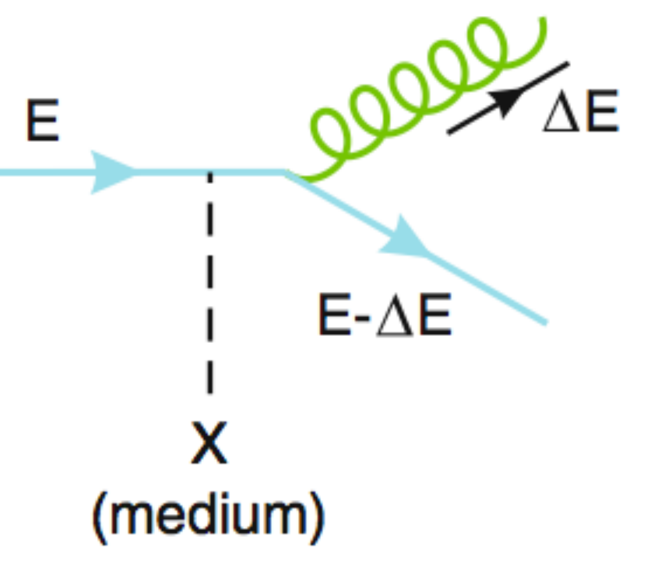
Collisional energy loss:



- Elastic scattering with medium constituents
- Medium often characterized by

$$\hat{e} = dE_{\mathrm{coll}}/dL$$

Radiative energy loss:



- Inelastic scattering with medium (induced bremsstrahlung)
- Expected to be dominant
- Medium often characterized by

$$\hat{q} = \rho \int dq_T^2 q_T^2 \frac{d\sigma}{dq_T^2} = \rho\sigma\langle k_T^2 \rangle = \frac{\mu^2}{\lambda_{\mathrm{mfp}}}$$

More on the Connection between Parton Energy Loss and Thermal Direct Photons

- Radiative energy loss in a static medium (BDMPS model)

$$\Delta E \propto \alpha_s C_F \hat{q} L^2, \qquad C_F = \begin{cases} 3 & \text{for gluons} \\ 4/3 & \text{for quarks} \end{cases}$$

- However, rapid medium expansion in heavy-ion collisions
  - Expected temperature dependence: $\hat{q} \propto T^3$
  - In some models calculated from other hydro quantities, e.g.: $\hat{q} \propto \varepsilon^{3/4}$
- Connection to thermal direct photons:
  - Initial temperature and consistent description of medium evolution essential for extracting medium properties
  - Hydro fitted to spectra and v_2: need photons to check space-time evolution
- Potential to characterize medium as strongly or weakly coupled:

$$\frac{\eta}{s} = K \frac{T^3}{\hat{q}}$$

Measure both sides independently to determine K

Majumder, Müller, Wang, PRL, 99 (2007) 192301

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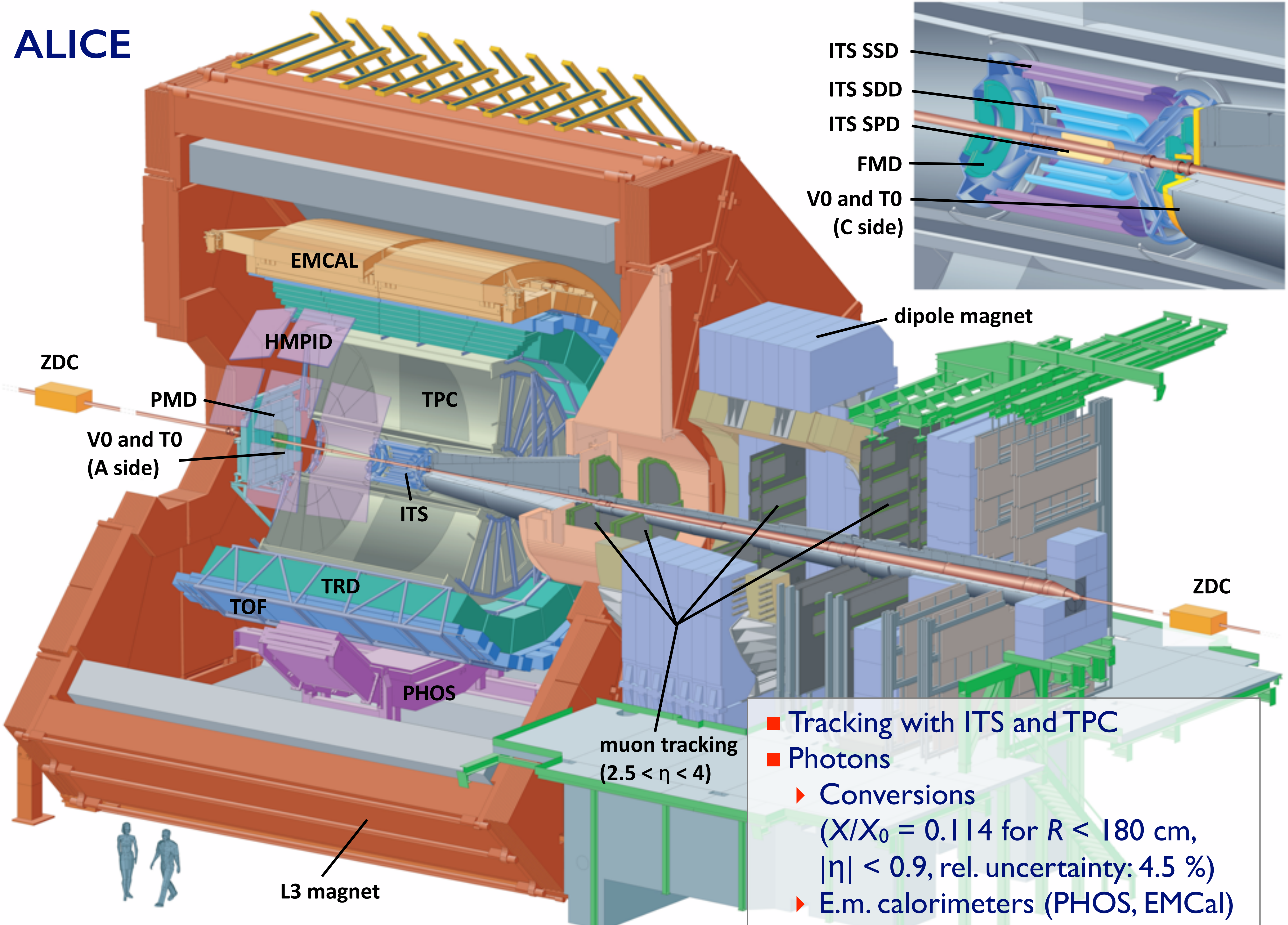


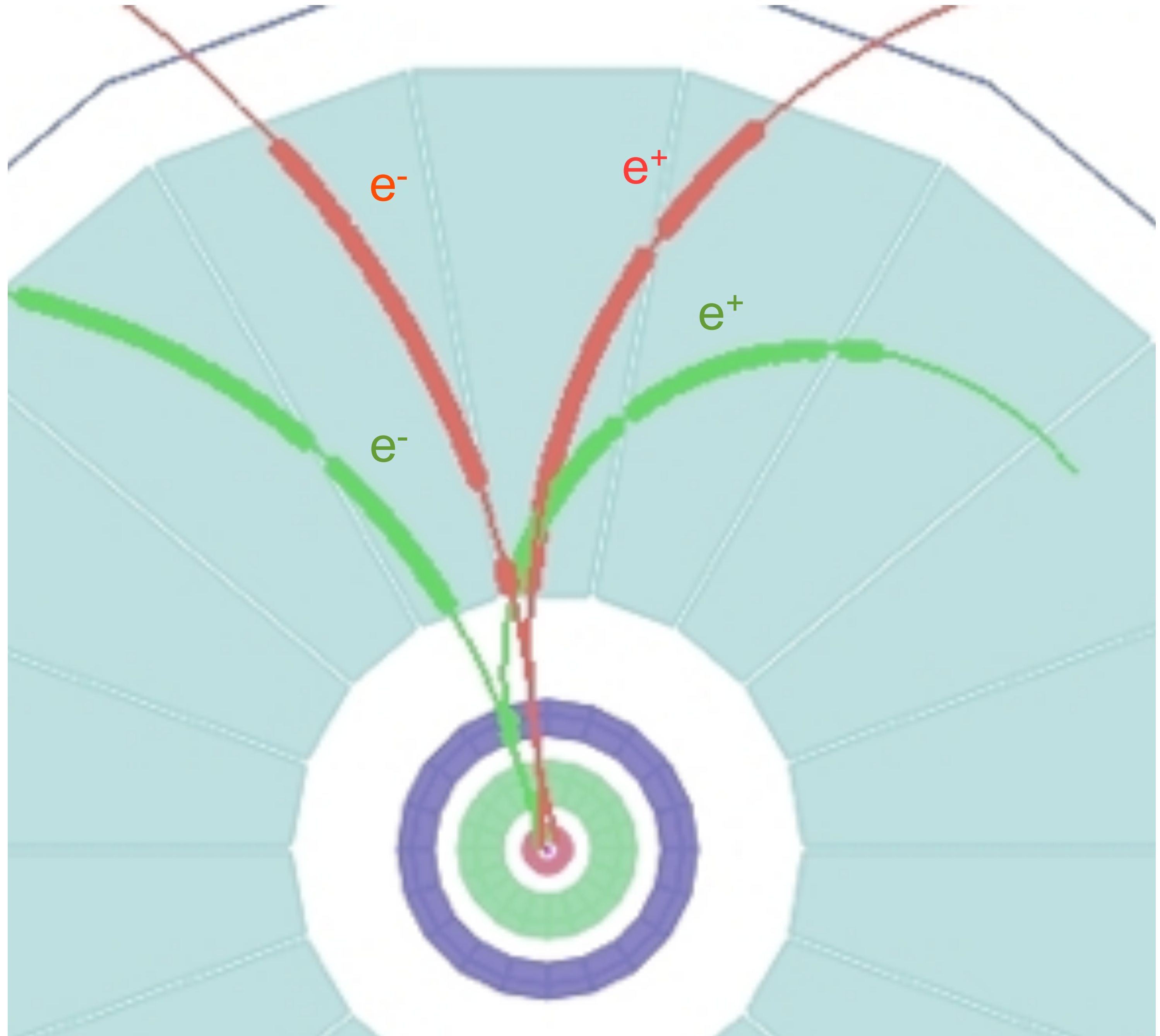
- Tracking with ITS and TPC
- Photons
  - Conversions (X/X_0 = 0.114 for R < 180 cm, $|\eta|$ < 0.9, rel. uncertainty: 4.5 %)
  - E.m. calorimeters (PHOS, EMCal)

I. Direct Photons

Measuring Photons via Conversions

ca. 1950

today



Excellent photon momentum resolution and rather pure photon samples at the expense of loss in statistics

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How to Measure Direct Photons?

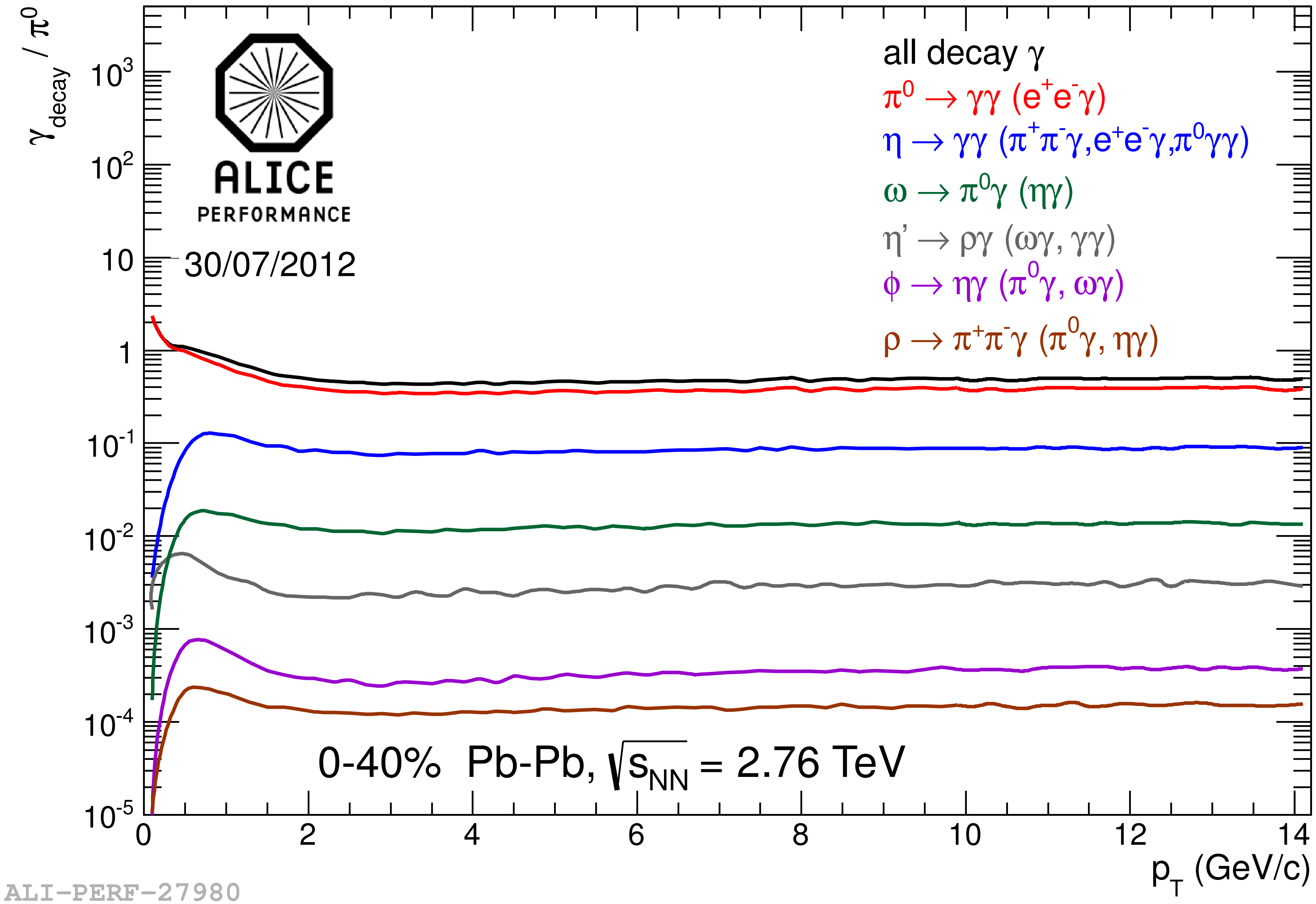
$$\gamma_{\mathrm{direct}} := \gamma_{\mathrm{inclusive}} - \gamma_{\mathrm{decay}} = (1 - \frac{1}{R})\, \gamma_{\mathrm{inclusive}}$$

systematic errors partially cancel in this ratio (efficiency, energy/momentum scale, ...)

$$\text{with } R = \frac{(\gamma_{\mathrm{inclusive}}/\pi^0)_{\mathrm{meas}}}{(\gamma_{\mathrm{decay}}/\pi^0)_{\mathrm{calc}}}$$

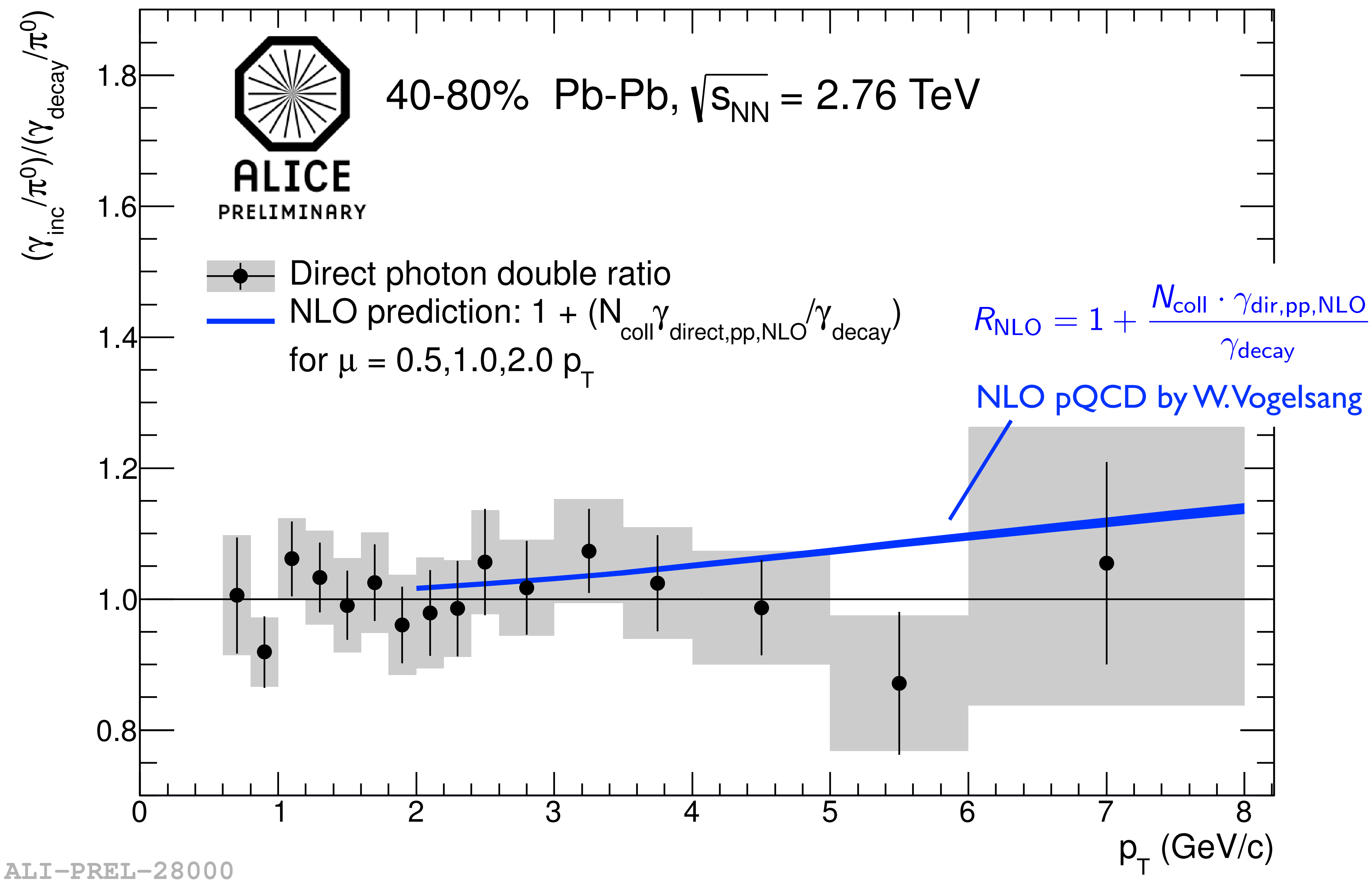
Calculated decay photon cocktail (π^0, η, ω, ...), π^0 measured, other hadrons from m_T scaling so far

Decay Photon Cocktail from Measured π^0 Spectrum



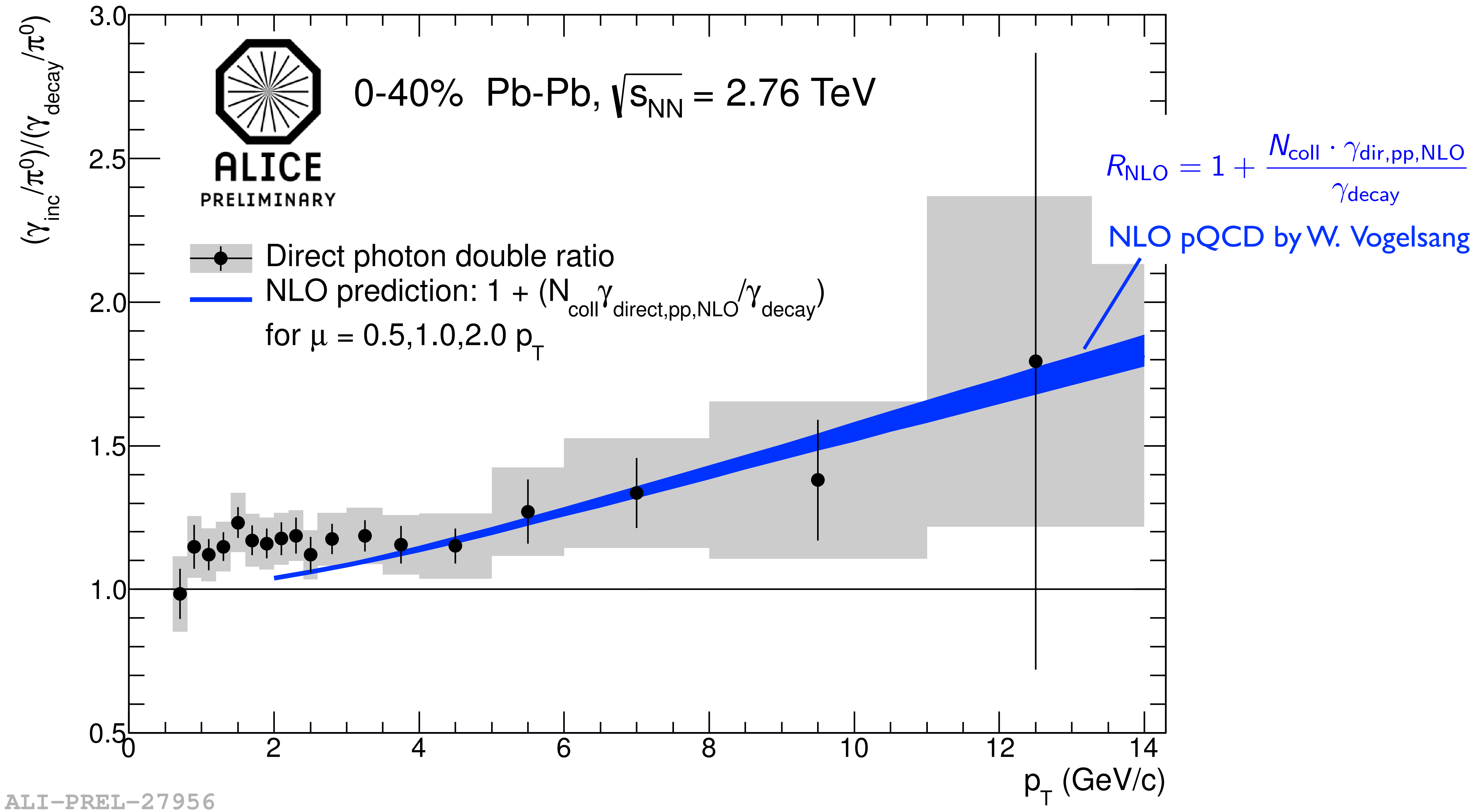
- π^0 spectrum measured, heavier mesons from m_T scaling
- Only π^0, η, ω relevant, the rest is negligible

No Significant Direct-Photon Excess in Peripheral Pb-Pb



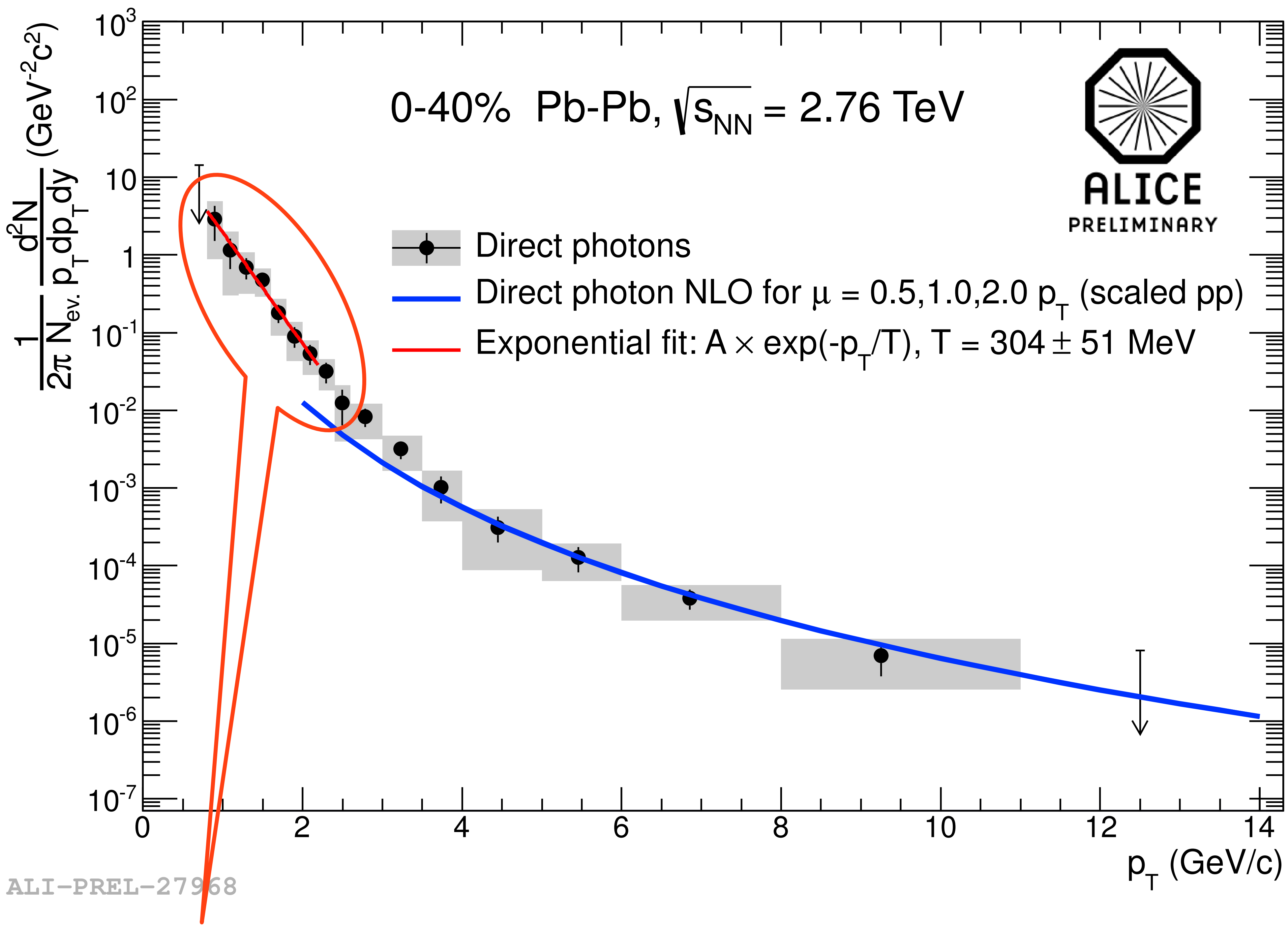
No significant direct-photon excess in peripheral Pb-Pb (same holds for pp at 7 TeV)

Direct-photon Excess in Central Pb-Pb Collisions



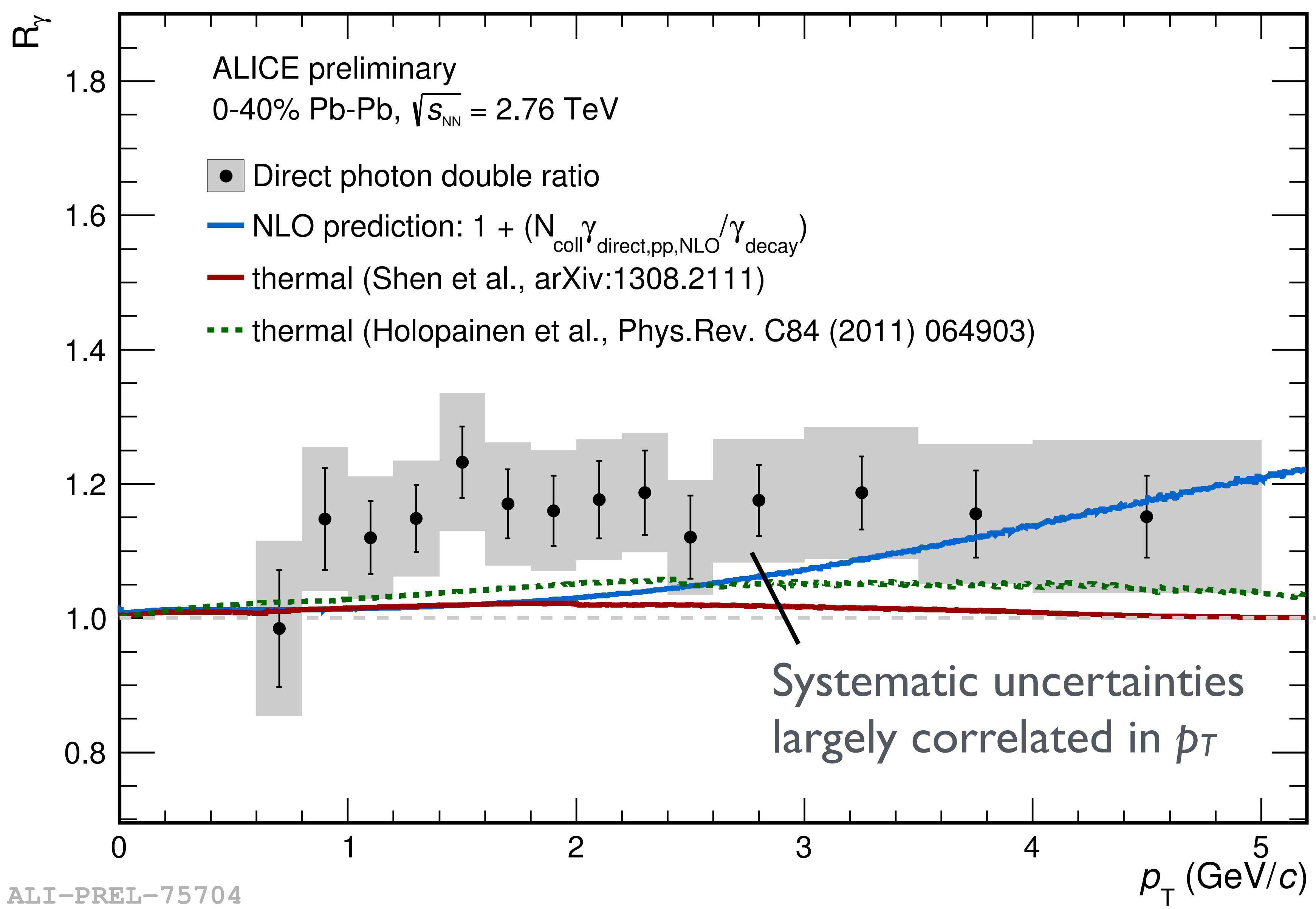
15 - 20% direct-photon excess for 1 < p_T < 2 GeV/*c*
where contribution from pQCD photons is small

Direct Photon Spectrum in Central Pb-Pb Collisions ($\gamma_{direct} := \gamma_{all} - \gamma_{decay}$)



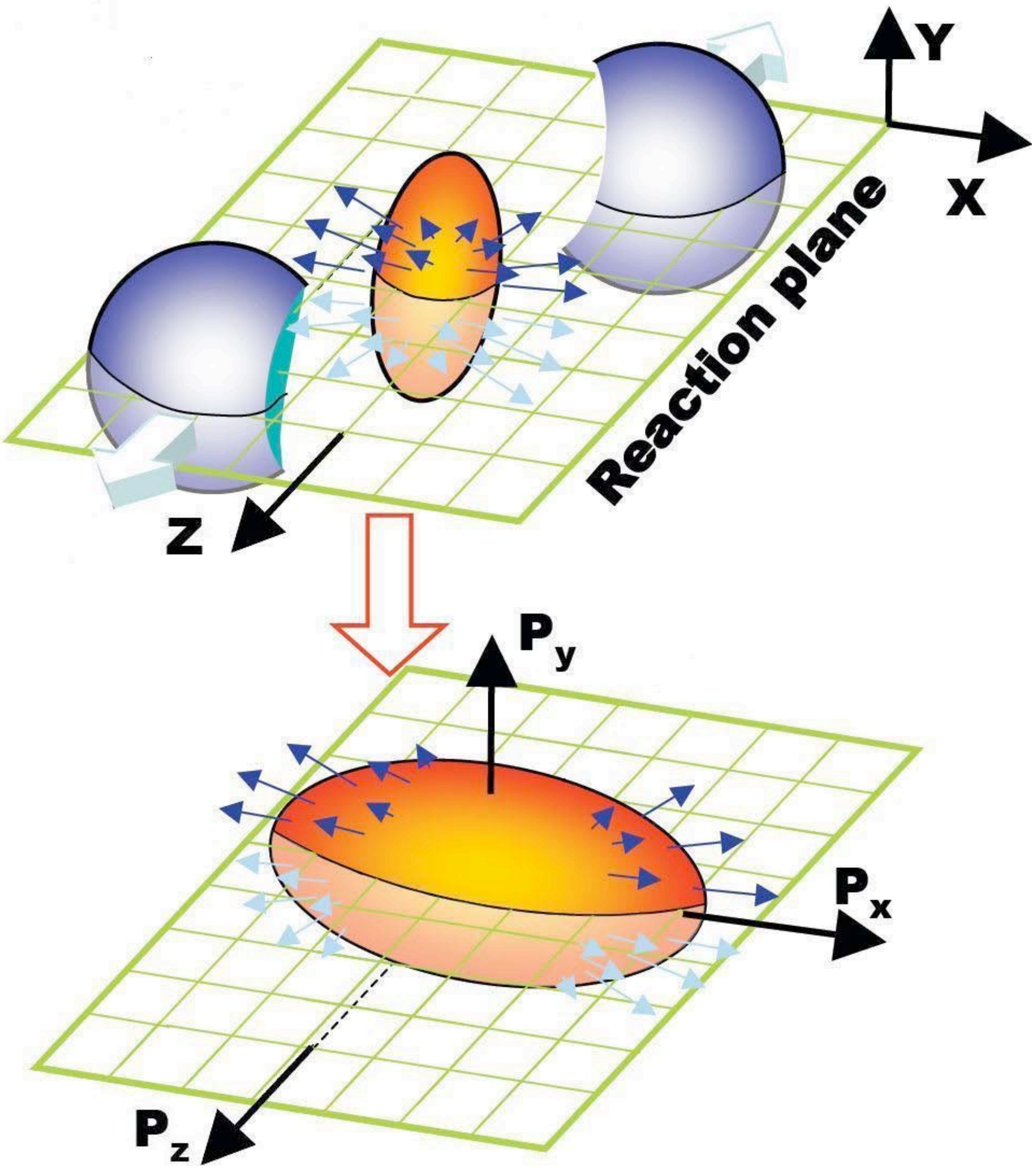
Low p_T part of the spectrum described by exponential with inverse slope T = 304 ± 51 MeV

Comparison of the Direct Photon Excess in 0-40% most central Pb-Pb collisions with Hydro Models



- Direct photon excess appears to be larger than expected in hydrodynamic model
- Are we missing an important photon source in these models?

Further Information from Direct Photon Elliptic Flow

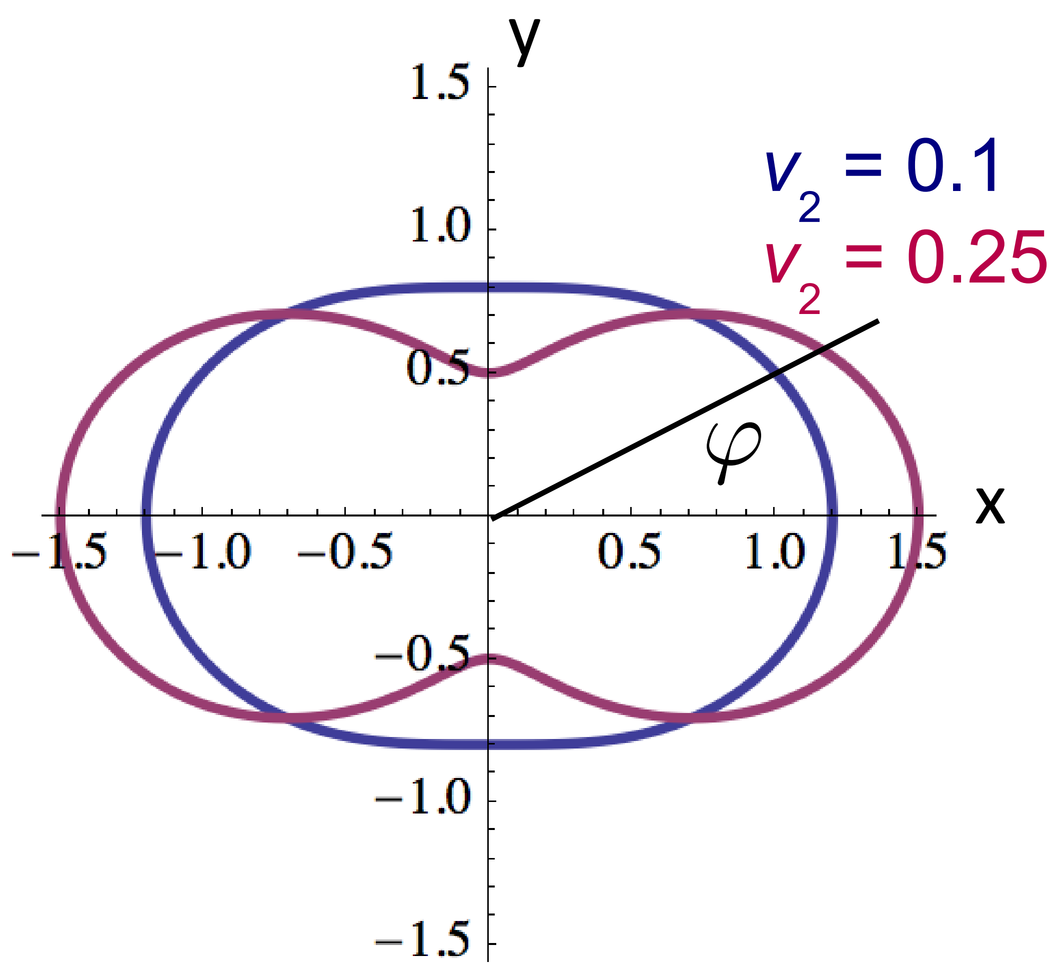


spatial anisotropy

↓

momentum anisotropy

Quantifying elliptic Flow: Fourier Coefficient v_2



$$\frac{dN_{\text{particles}}}{d\varphi} = N_0\,(1 + 2v_2\cos(2\varphi))$$

State of the art for hadrons: higher harmonics up to n = 6:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\varphi - \Psi_n)\right]\right)$$

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How to Measure the Direct-Photon v_2?

- Reaction plane (RP) from charged particles in forward direction
  (2.8 < η < 5.6 [VZEROA], -3.7 < η < -1,7 [VZEROC])

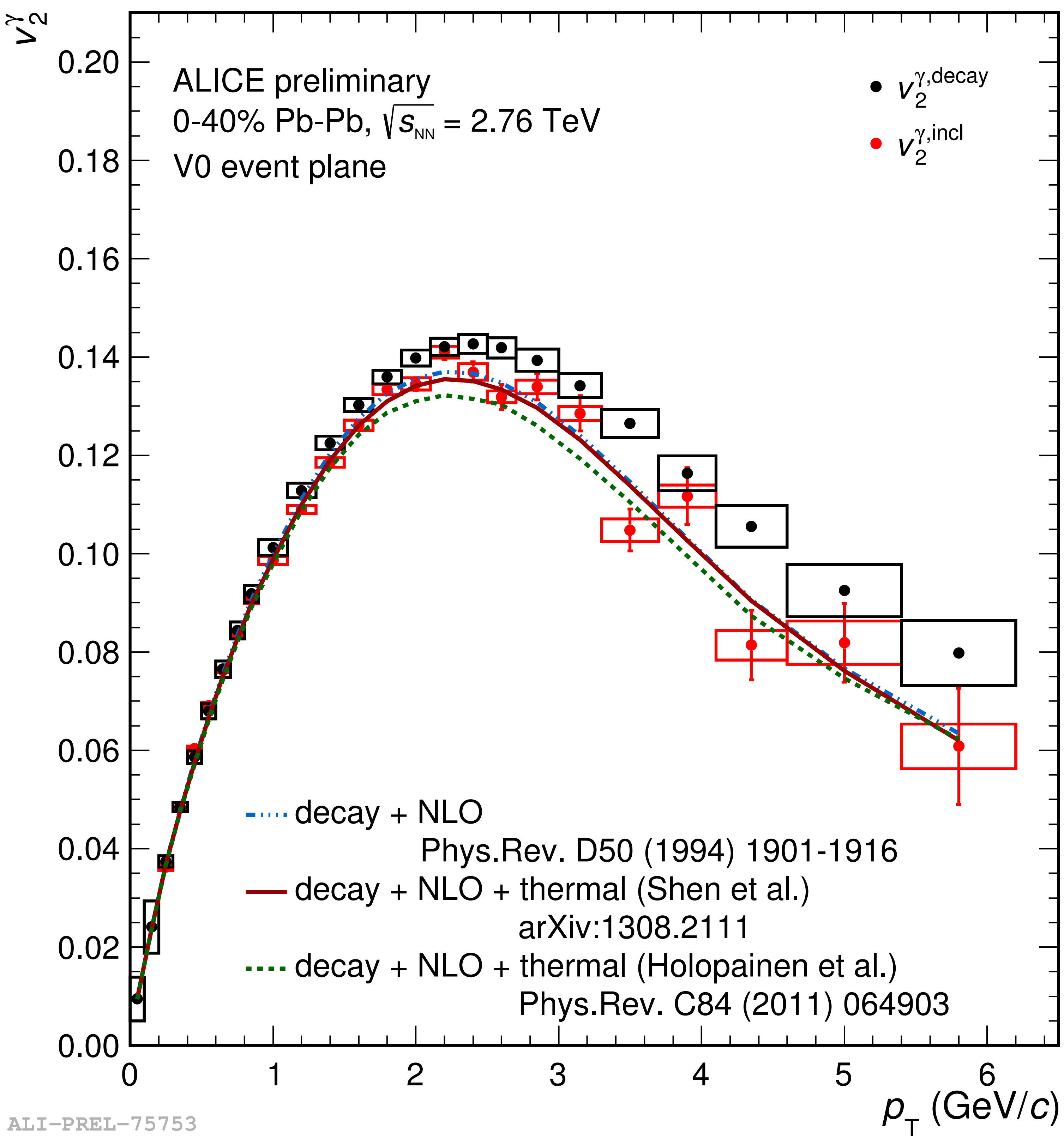
- Inclusive photons: $v_2^{\gamma,\mathrm{incl}} = \frac{\langle \cos(2(\varphi - \Psi_2^{\mathrm{RP}}))\rangle}{C}$, $C = \text{resolution correction}$

- Decay photon v_2 from cocktail calculation based on measured pion v_2
  (+ higher mass hadrons)

- Inclusive photon v_2 is weighted average of decay photon and direct photon v_2. Thus one can calculate the direct-photon v_2 as

$$v_2^{\gamma,\mathrm{direct}} = \frac{R\, v_2^{\gamma,\mathrm{incl}} - v_2^{\gamma,\mathrm{decay}}}{R-1} \qquad \text{with} \quad R = \frac{\gamma_{\mathrm{incl}}}{\gamma_{\mathrm{decay}}} = 1 + \frac{\gamma_{\mathrm{direct}}}{\gamma_{\mathrm{decay}}}$$

Measured Inclusive Photon and Calculated Decay Photon v_2



- v_2(incl) < v_2(decay) for p_T > 3 GeV/c
  - expected from v_2 = 0 for prompt photons
- v_2(incl) ≈ v_2(decay) for p_T < 3 GeV/c:
  - If there is a large direct photon component its v_2 must be very similar to the decay photon v_2
  - v_2(incl) described by models with small R_γ predicted by the same models
  - Uncertainties of v_2(dir) strongly depend on uncertain-ties of photon excess R_γ

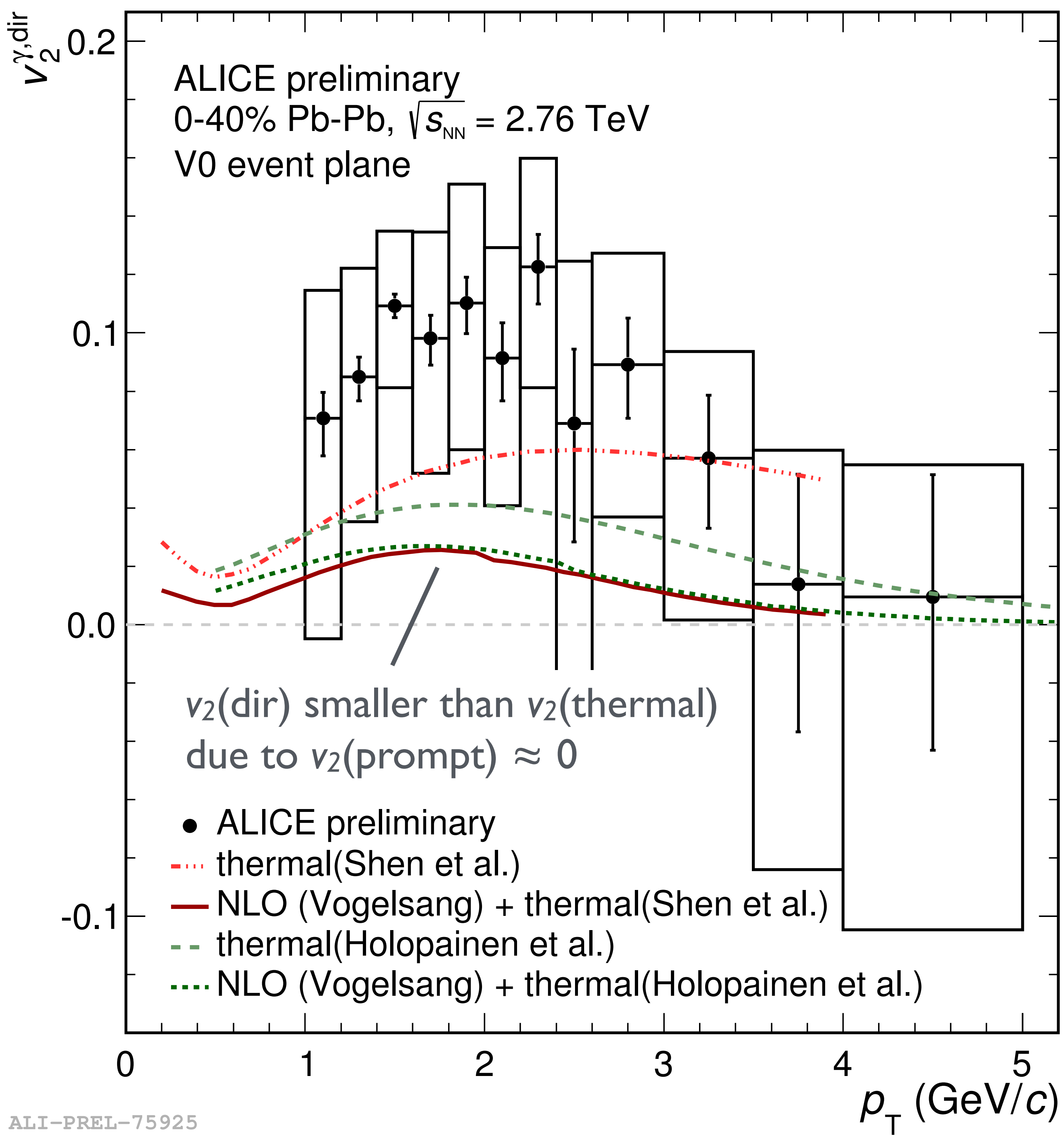
Recap: What to expect for the Direct Photon v_2 ?

- Large inverse slope parameter:
  $T_{slope} \approx 304 \pm 51^{stat+syst}$ MeV (>> T_c = 150 - 160 MeV)

- Could indicate that direct photons mostly come from early hot QGP phase

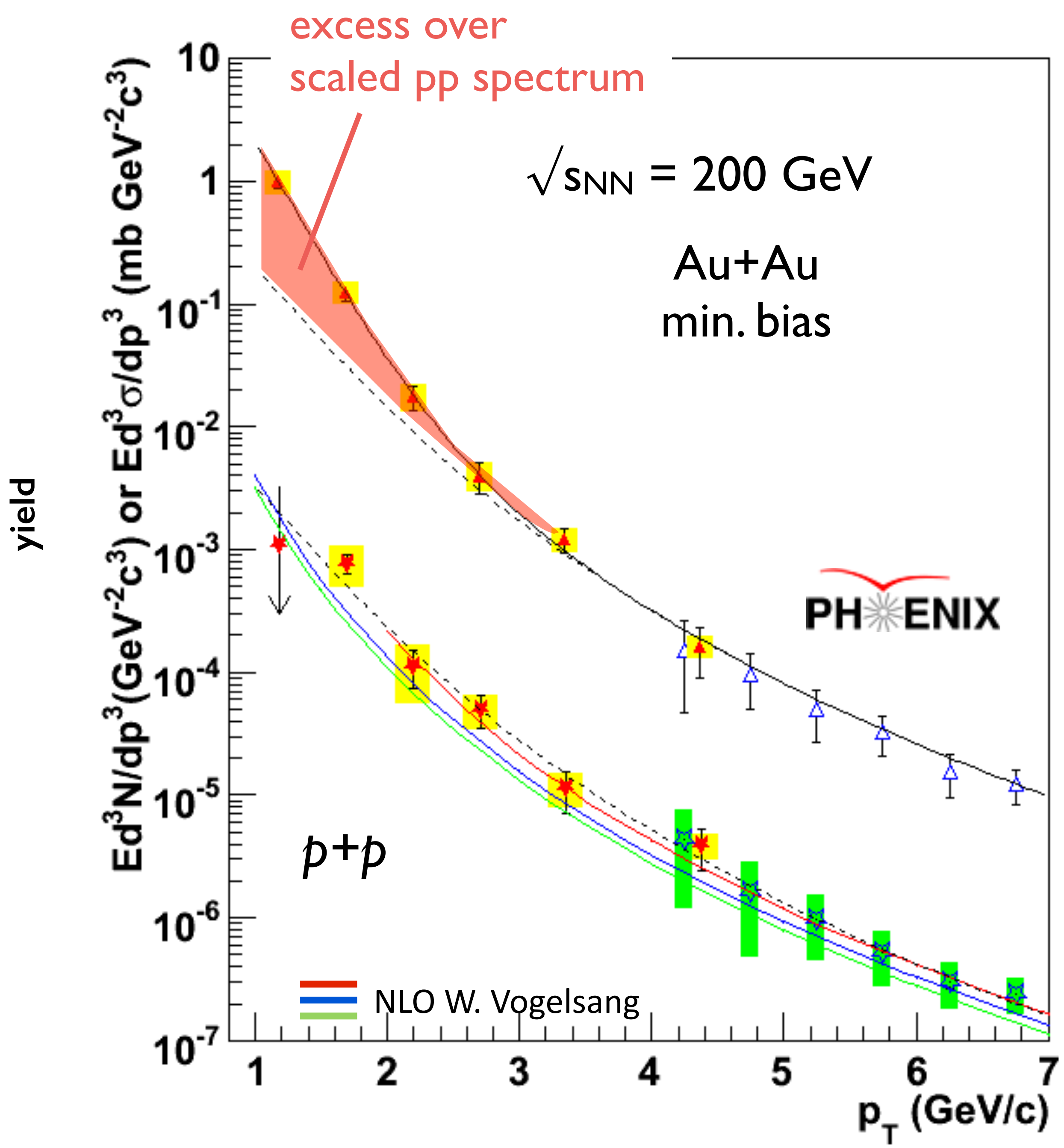
- Expect then small elliptic flow signal ($v_2 \approx 3\%$ or so at maximum) as collective flow needs time to build up

Direct Photon Elliptic Flow Appears to be Larger than Expected in Hydro Models



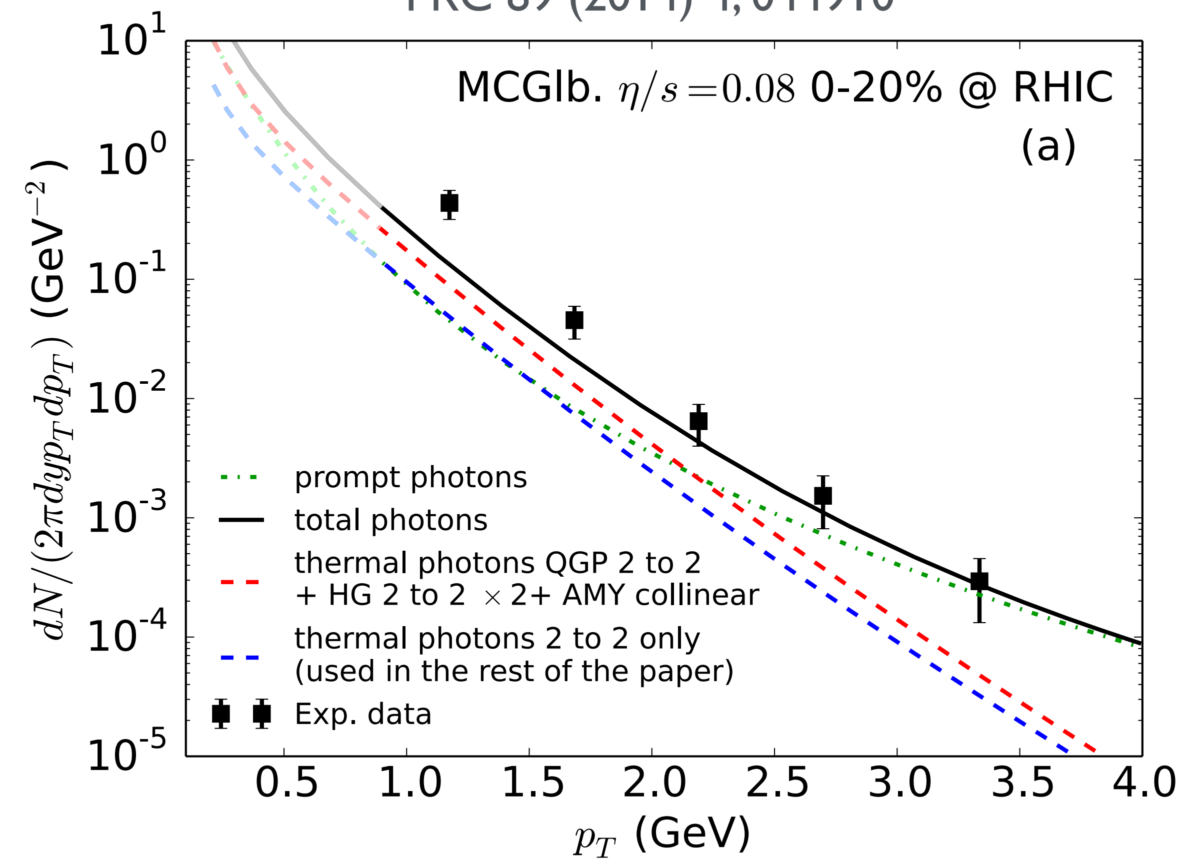
- Maybe many direct photons from late stage with $T \approx 150$ MeV?
- Then large inverse slope parameter due to Doppler blueshift with typical hadronic flow velocity $\beta_{flow} \approx 0.6\,c$?
- However, current systematic uncertainties are sizable so that there is no big puzzle looking at the ALICE data alone

The Puzzle Actually Started at RHIC: Large Inverse Slope Parameter ...



PHENIX:
PRL, 104, 132301 (2010); PRC, 81, 034911 (2010)
and also arXiv:1405.3940

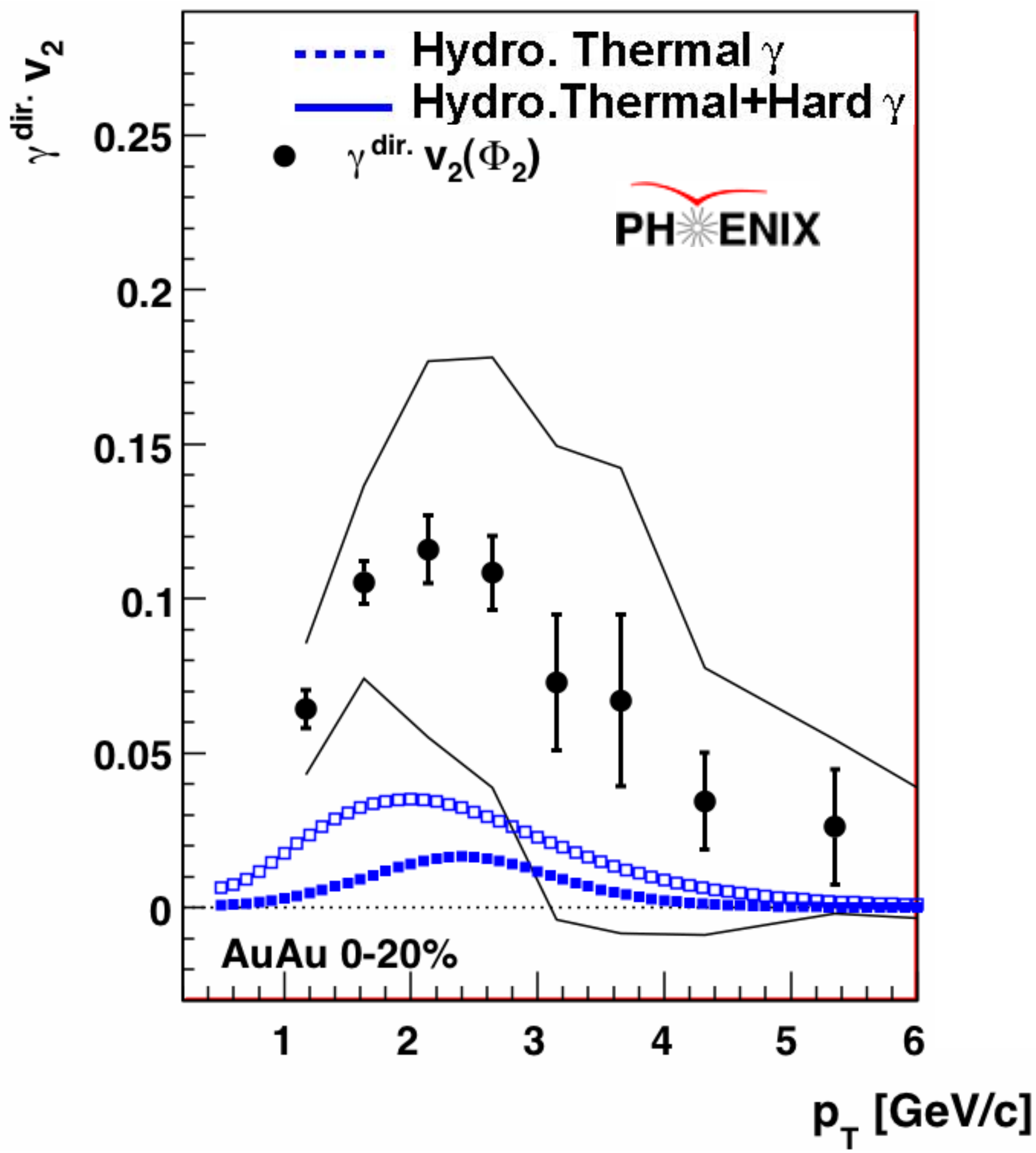
C. Shen, U. Heinz, J.-F. Paquet, C. Gale,
PRC 89 (2014) 4, 044910



- Exponential shape of photon excess (consistent with thermal)
  - Inverse slope (for 0-20%): 221 ± 19^{stat} ± 19^{syst} MeV
  - T_i from hydro: 300 ... 600 MeV
- Hydro models below data

… and Large Direct Photon v_2 for p_T < 3 GeV/c

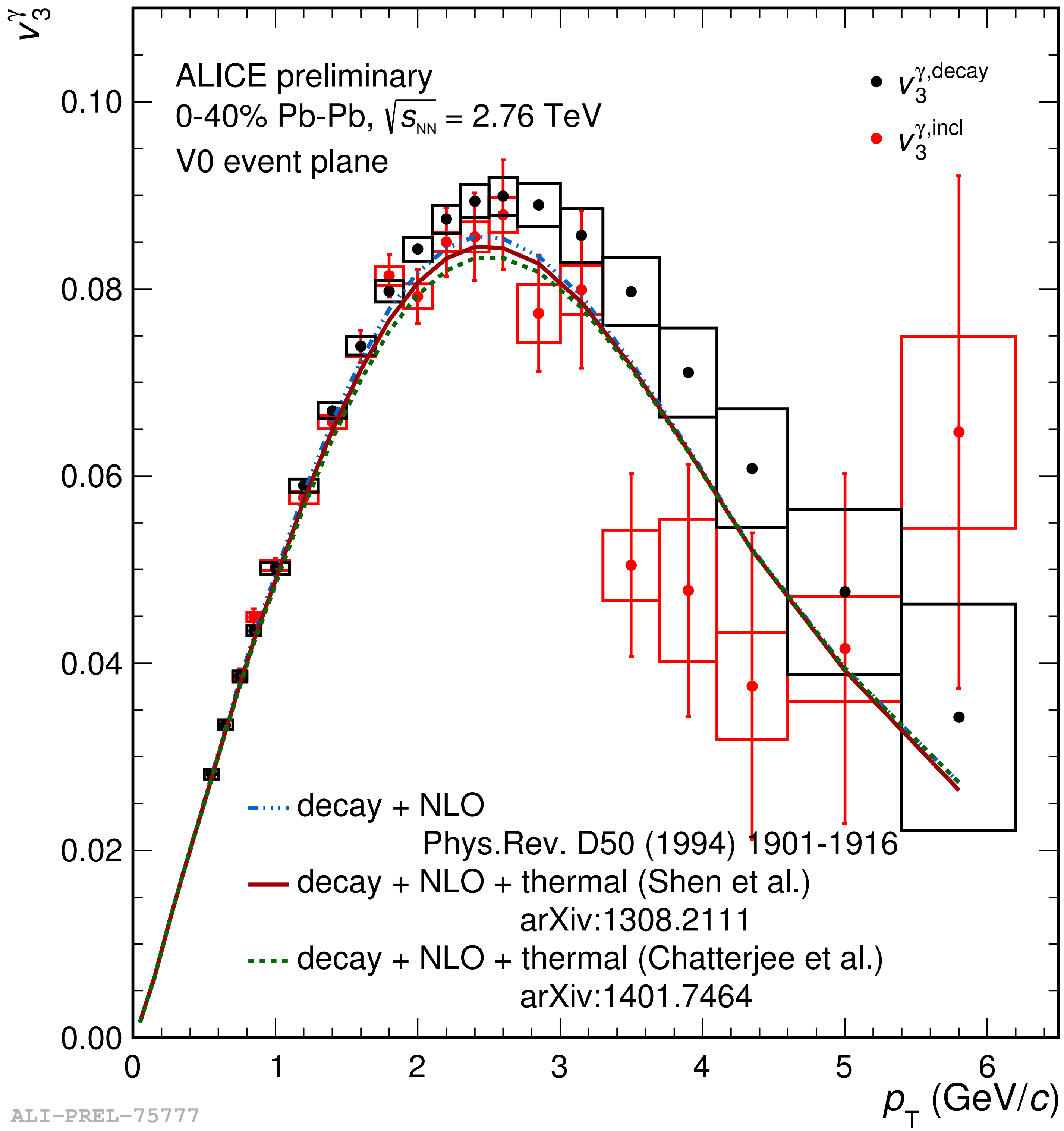
from E. Kistenev, Quark Matter 2011

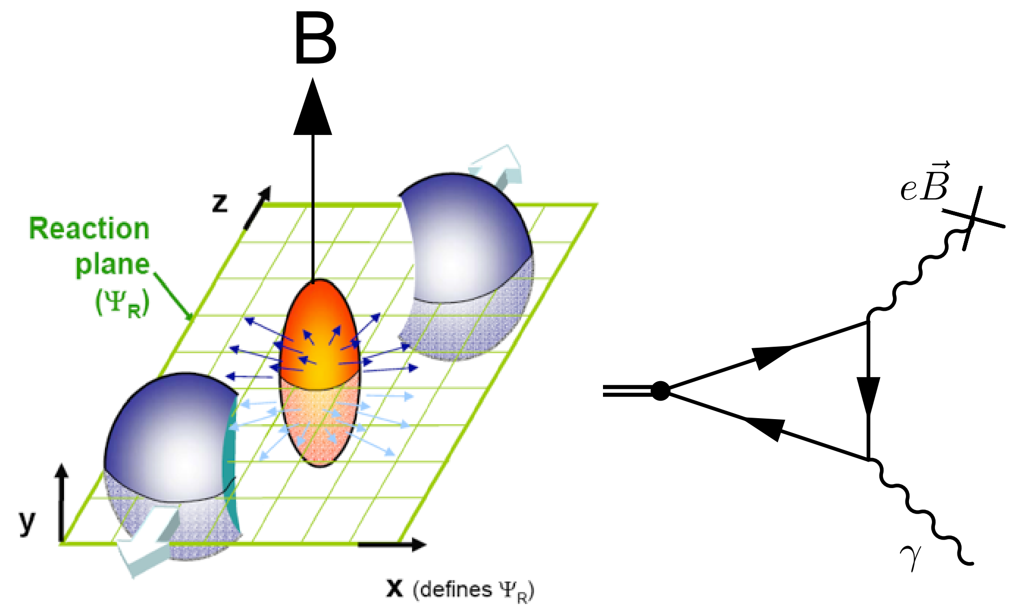


PHENIX, Phys.Rev.Lett., 109, 122302 (2012)

- PHENIX: Data a challenge to theory
- Charles Gale (theorist): „Theory a challenge to the data“
- Direct photon puzzle: Large direct photon v_2 for 1 < p_T < 3 GeV/c challenges
  - the standard model of the space-time evolution of a heavy-ion collision
  - and/or the currently used photon emission rates for the QGP and the hadron gas

Testing "Exotic" Photon Sources By Measuring the Photon v_3





Basar, Kharzeev, Skokov., arXiv:1206.1334

- Photon production resulting from large initial B field?
- Could explain v_2
- Expect small v_3 in these models
- Inclusive photon v_3 measured, not yet conclusive

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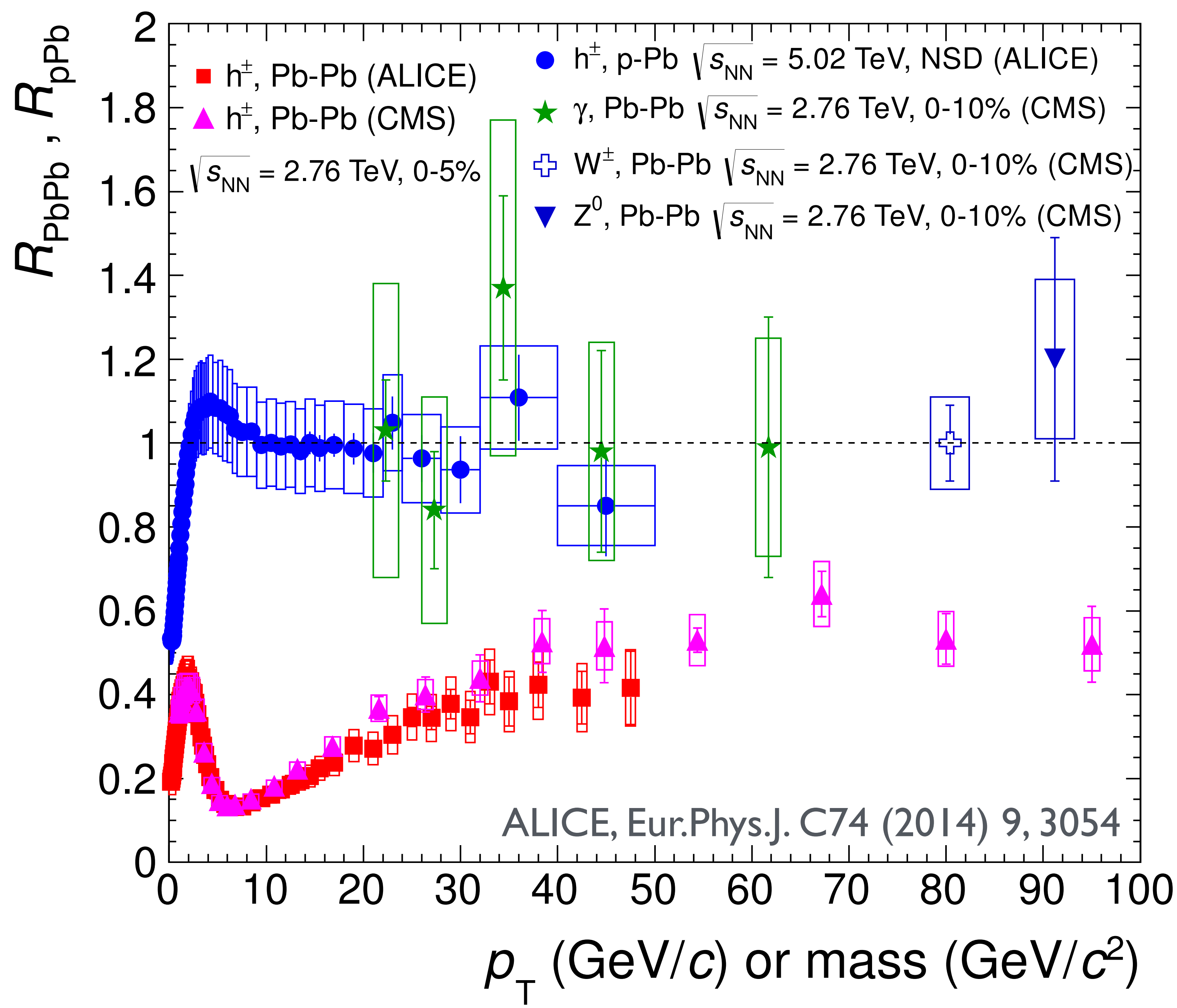
Intermediate Summary: The Direct Photon Puzzle

- The two parts of the puzzle
  - Direct photon yields at low p_T ($1 < p_T < 3$ GeV/c) not described by hydro models
  - Large direct photon v_2, similar in magnitude to pion v_2, not described by hydro models
- A challenge to the "standard model" of the evolution of heavy-ion collisions
- What are we missing?
  - Maybe many more photons from late stage close to T_c and hadron gas phase (need factors 10 - 20 increase in HG rate!)
  - Maybe just bremsstrahlung from the HG?
  - Exotic new photon source, e.g., related to large initial B field?
  - Large initial flow before hydro evolution starts?
  - Glasma photons, i.e., large photon production in very early gluon-rich phase?
  - …

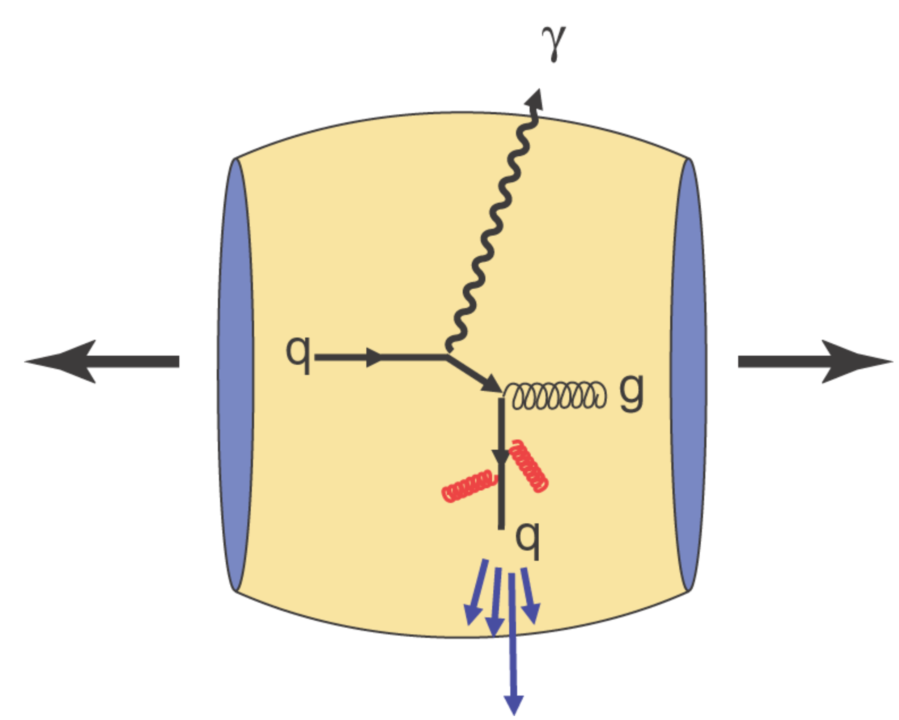
II. High p_T Particle Production and Jets

Hadron Suppression in Pb-Pb: An Effect Related to the Medium

$$R_{AB} = \frac{dN/dp_T|_{A+B}}{\langle T_{AB}\rangle \times d\sigma_{inv}/dp_T|_{p+p}}, \quad \langle T_{AB}\rangle = \frac{N_{coll}}{\sigma_{inel}^{NN}}$$



- Hadron suppression in Pb-Pb w.r.t. to scaling expected for hard processes
- An effect of the medium
  - No suppression in p-Pb
  - No suppression of color neutral probes in Pb-Pb



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Jet Transport Parameter from Data

- Fit of various models to $R_{AA}(p_T)$ at RHIC and the LHC
- Jet transport parameter
  (for E_{parton} = 10 GeV, QGP thermalization at τ_0 = 0.6 fm/c):

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC}, \\ 3.7 \pm 1.4 & \text{at LHC}, \end{cases}$$

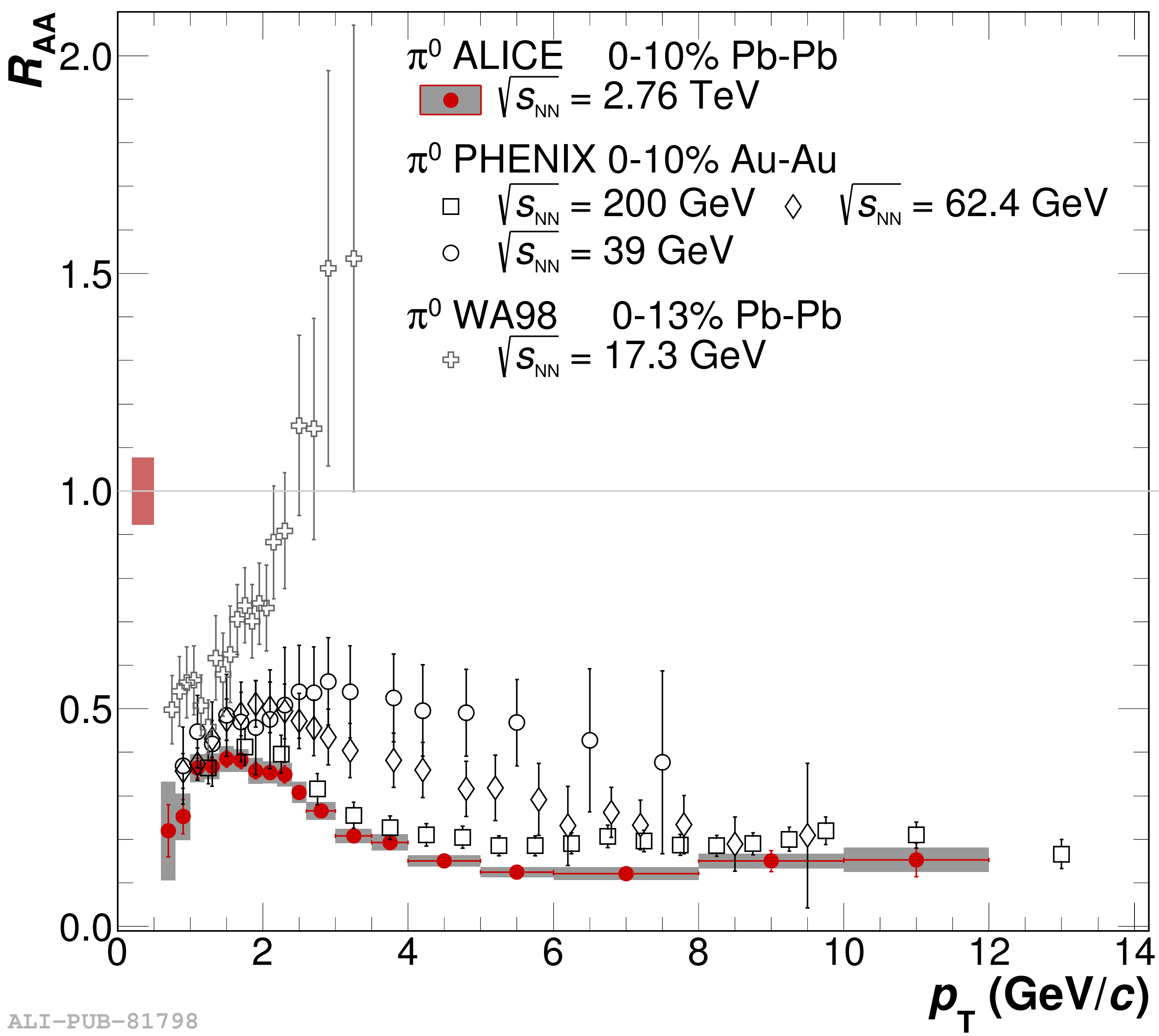
$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \text{GeV}^2/\text{fm} \;\; \text{at} \;\; \begin{array}{l} \text{T=370 MeV}, \\ \text{T=470 MeV}, \end{array}$$

Jet Coll., Phys.Rev. C90 (2014) 014909

- Result relies on standard hydro description of the medium evolution

Energy Dependence of the Hadron Suppression

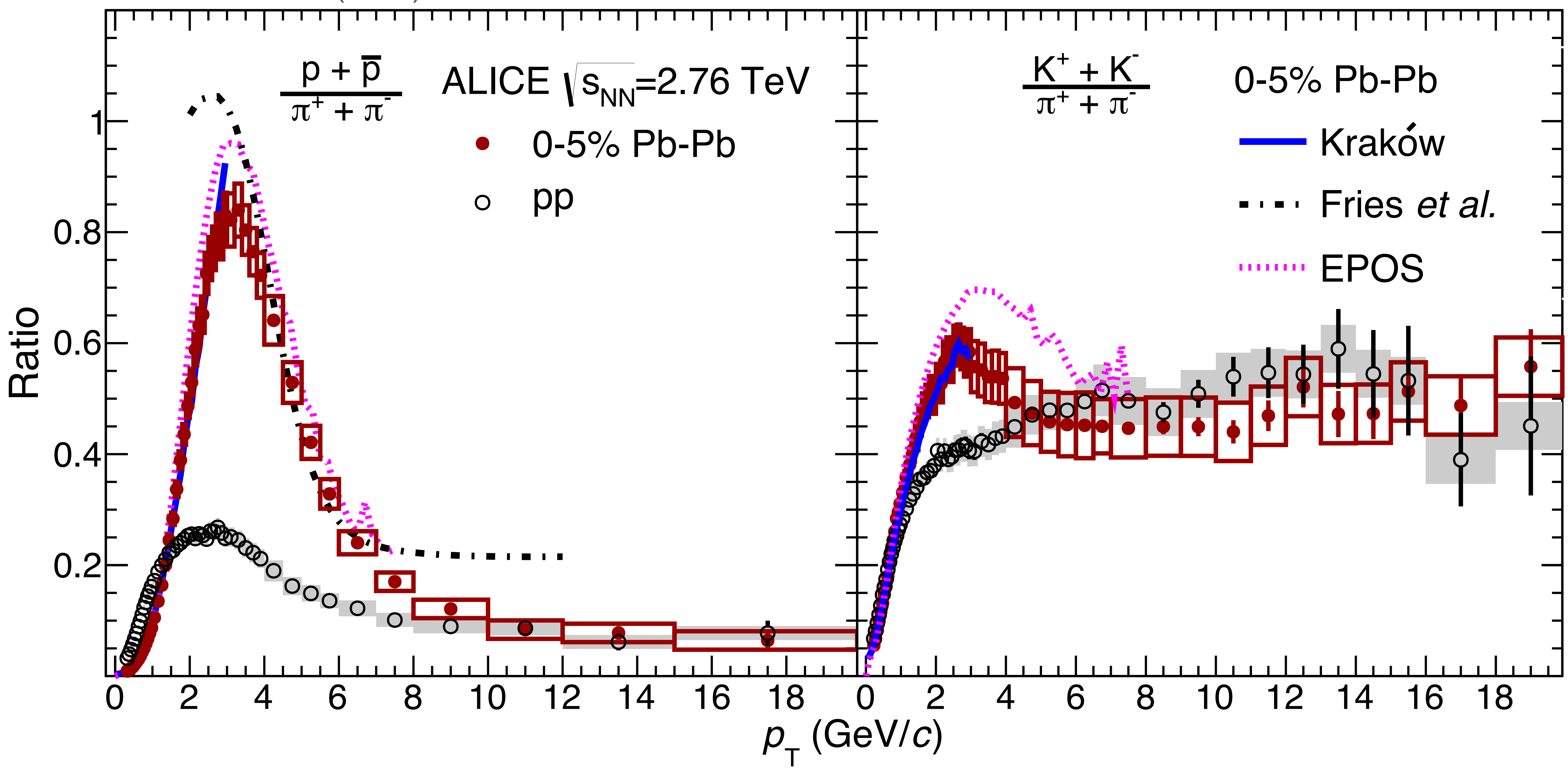
ALICE, Eur. Phys. J. C (2014) 74:3108



- Suppression factor depends on parton energy loss *and* on steepness of the initial parton spectrum
  - More steeply falling spectrum gives larger suppression for same ΔE
- Stronger suppression with increasing $\sqrt{s}$:
  - Increase of medium density dominates over effect of flatter initial parton spectra

p/π and K/π Ratios vs. p_T in pp and Pb-Pb

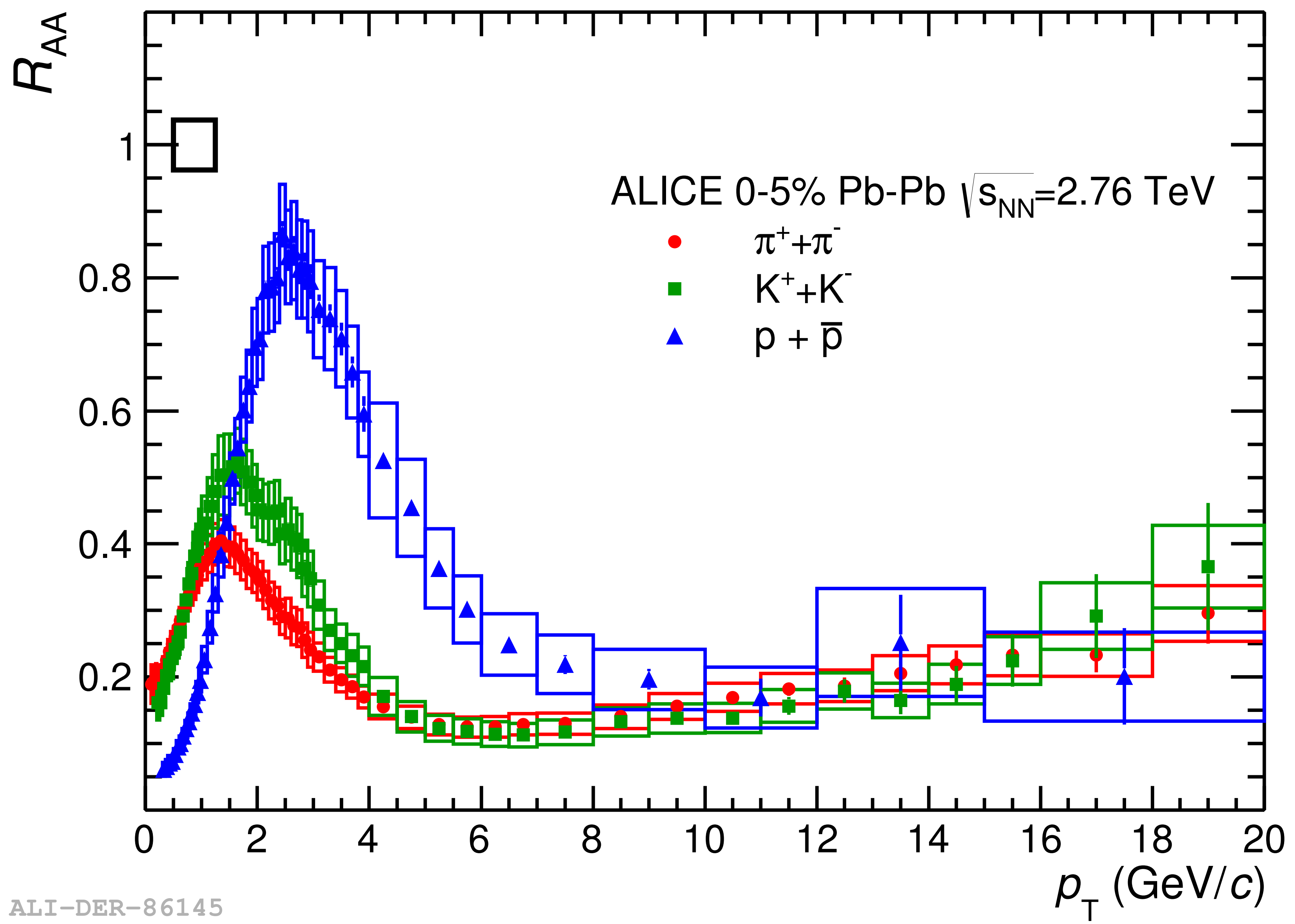
ALICE, PLB 736 (2014) 196



Strong increase of p/π ratio at $p_T \approx 3$ GeV/c in Pb-Pb: due to radial flow alone?

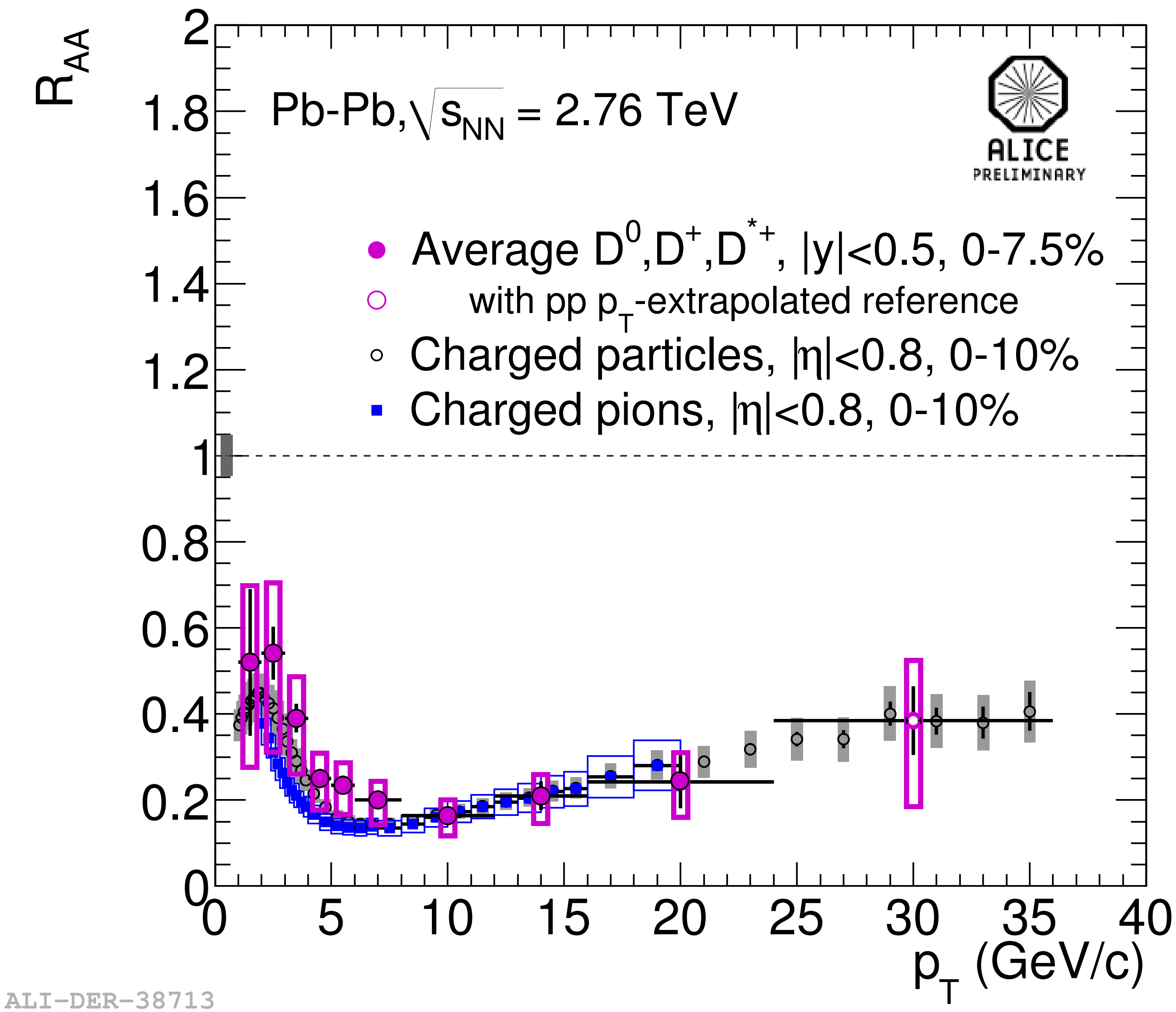
π, K, p R_{AA}

ALICE, PLB 736 (2014) 196



π, K, p R_{AA} similar at high p_T: Leading-parton energy loss followed by fragmentation in QCD vacuum (as in pp) for $p_{T,\mathrm{hadron}}$ > 8 GeV/c?

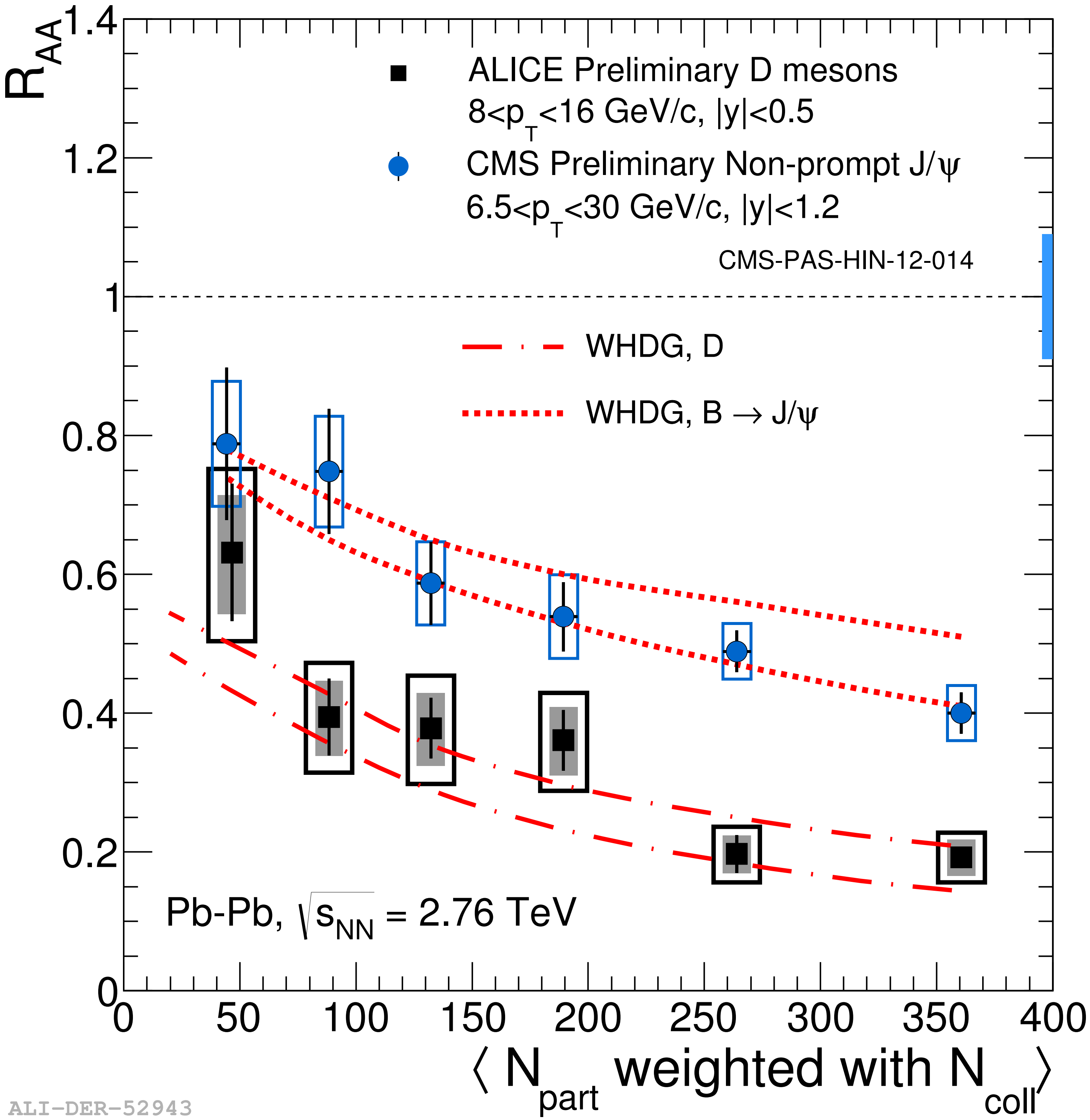
Quark Mass Dependence of the Energy Loss: D Mesons vs. Pions



* e.g., Djordjevic, PLB 734 (2014) 286,
T. Renk, PRC 89 (2014) 054906

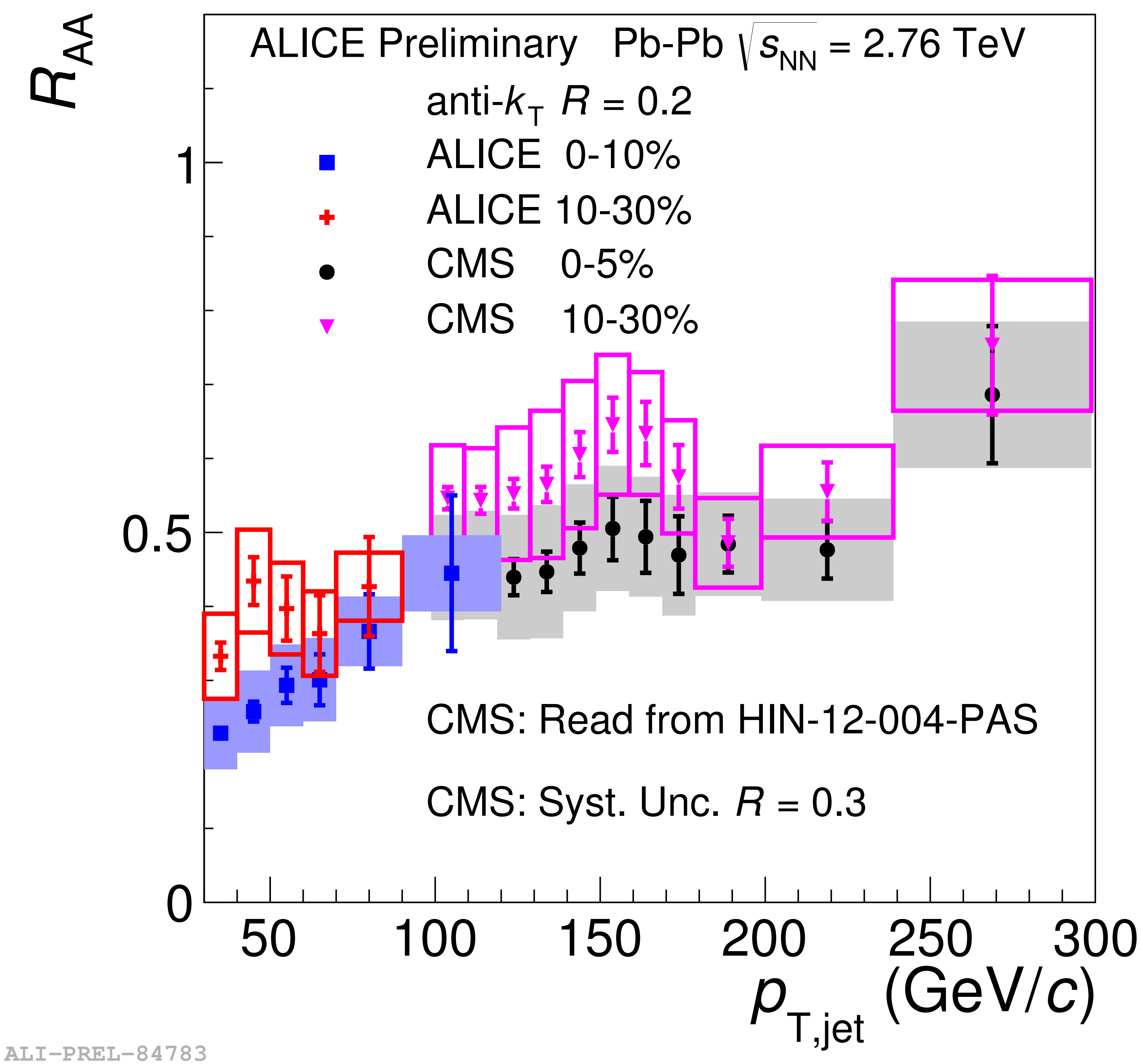
- Heavy quarks:
  Gluon radiation suppressed for angles $\theta \lesssim m_{quark}/E_{quark}$:
  "dead cone effect"
- $\Delta E_{gluon} > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- Pions for p_T < 40 GeV/c mostly from gluon fragmentation
- Different shape of initial parton p_T spectra, different frag. functions for D mesons and pions
- In spite of all that:
  Pion and D meson $R_{AA}(p_T)$ very similar (contrary to naïve expectation)
- However, reproduced by parton energy loss models*

Quark Mass Dependence of the Energy Loss: D Mesons vs. B Mesons



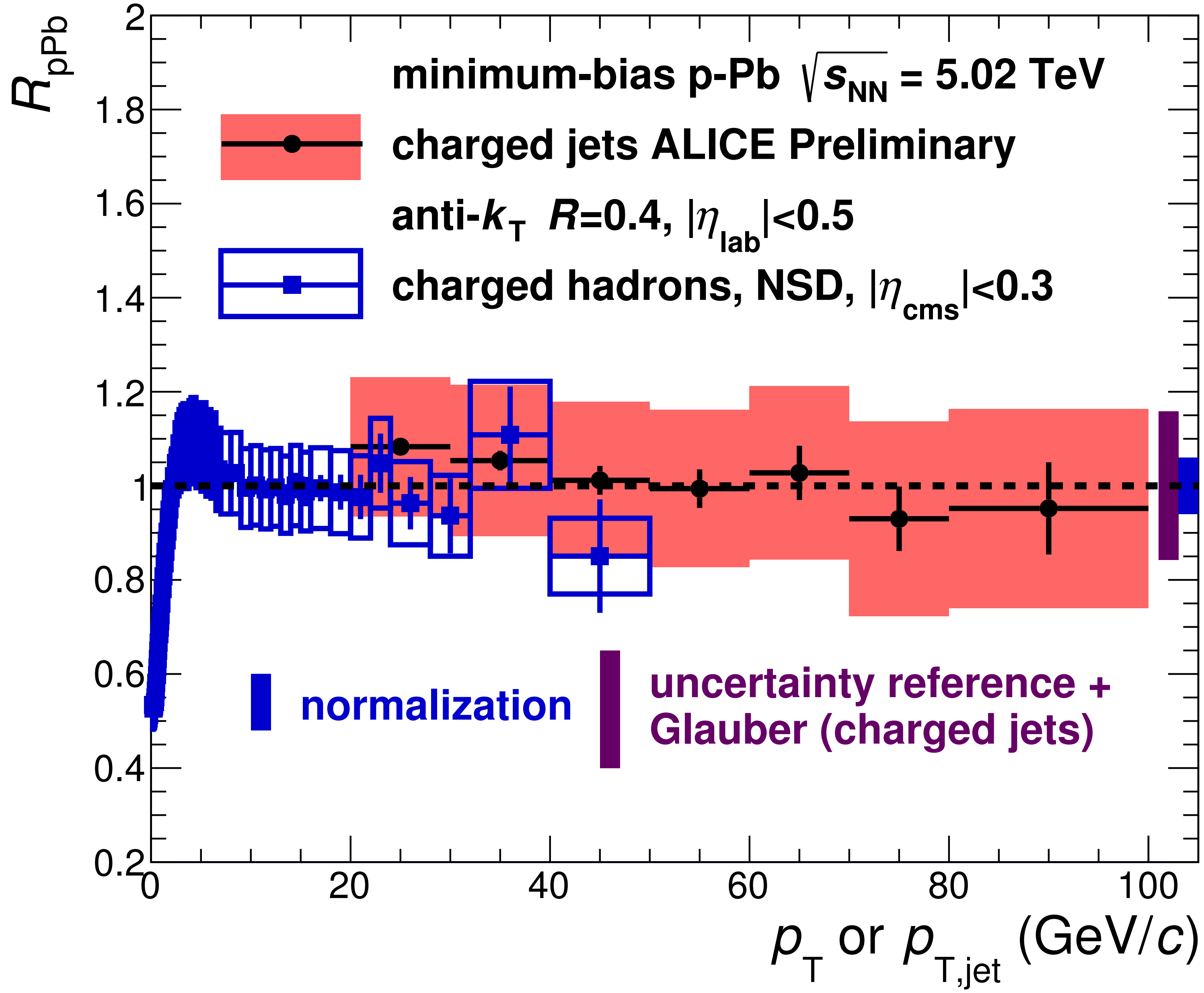
- B mesons energy loss probed indirectly via non-prompt J/Ψ ($B \to J/\Psi$)
- p_T ranges chosen so that $\langle p_T \rangle_D \approx \langle p_T \rangle_B \approx 10$ GeV/c
- Less suppression of non-prompt J/Ψ compared to D mesons
- Reproduced by models which have the dead cone effect built in (WHDG, Djordjevic)
- Evidence for smaller energy loss for b quarks due to the dead cone effect

Studying Parton Energy Loss with Jets



- Why jets?
  - Leading particle energy loss is not the full story (information reduction)
  - A tool to study the modification of the parton shower evolution due to the medium through jet shapes, frag. functions, etc
- Jets reconstructed with jet resolution parameter R = 0.2 and 0.3 are suppressed

Control Experiment: No Jet Suppression in p-Pb collisions (Charged Jets)



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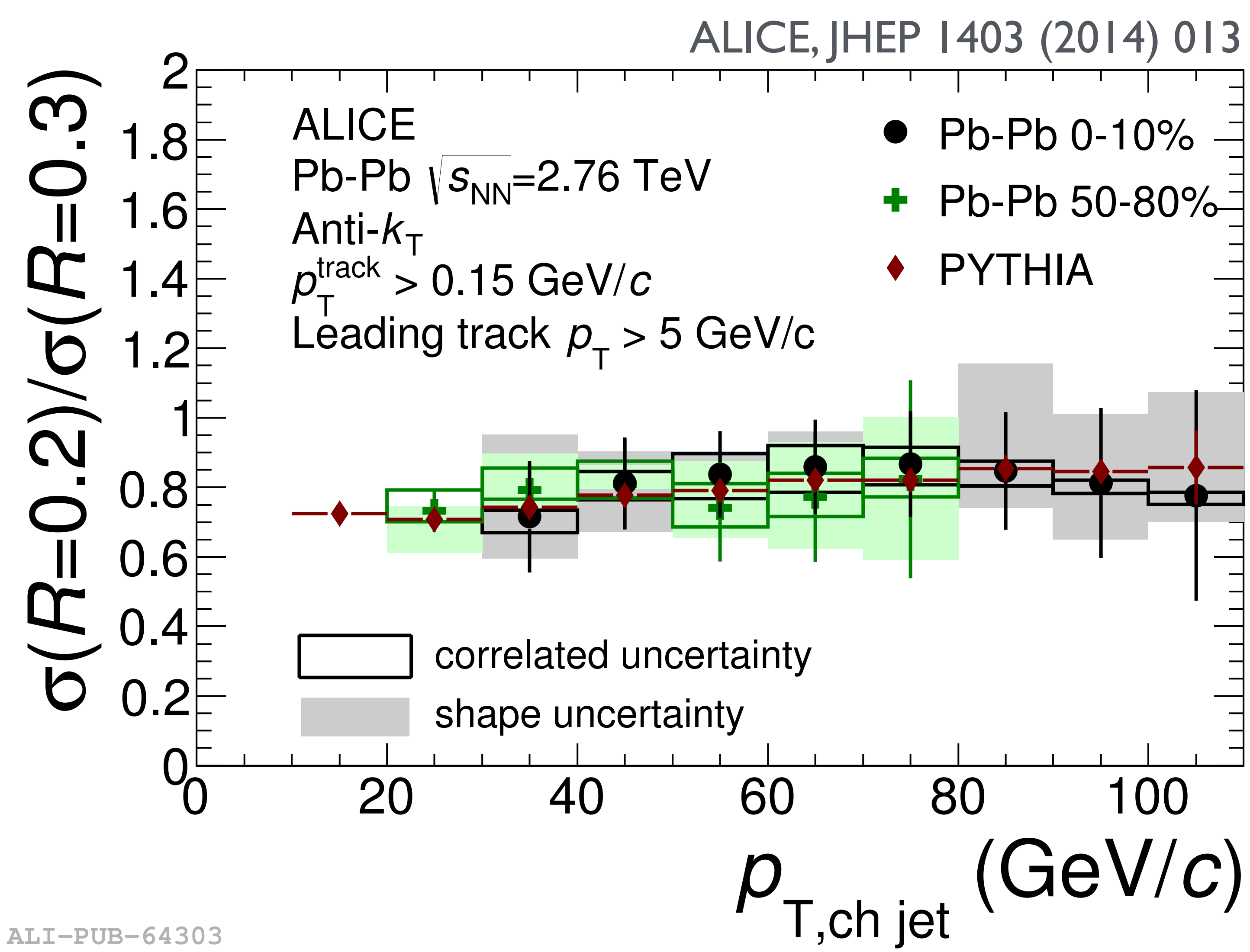
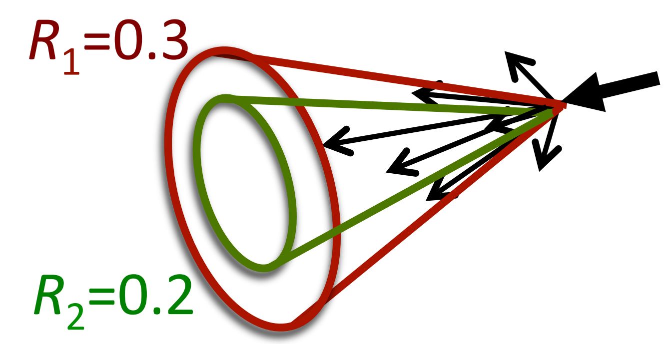
Similar conclusions for jets with R = 0.2 … 0.4 and particle spectra

Studying the Lateral Jet Profile: Ratio of Jet Cross section for R = 0.2 and 0.3 (Charged Jets)





- No centrality dependence of σ(R = 0.2) / σ(R = 0.3)
- Described by PYTHIA (pp)
- No indication of lateral jet shape modification due to the medium

A First Look at Jet Chemistry with Two-Particle ΔΦ-Δη Correlations

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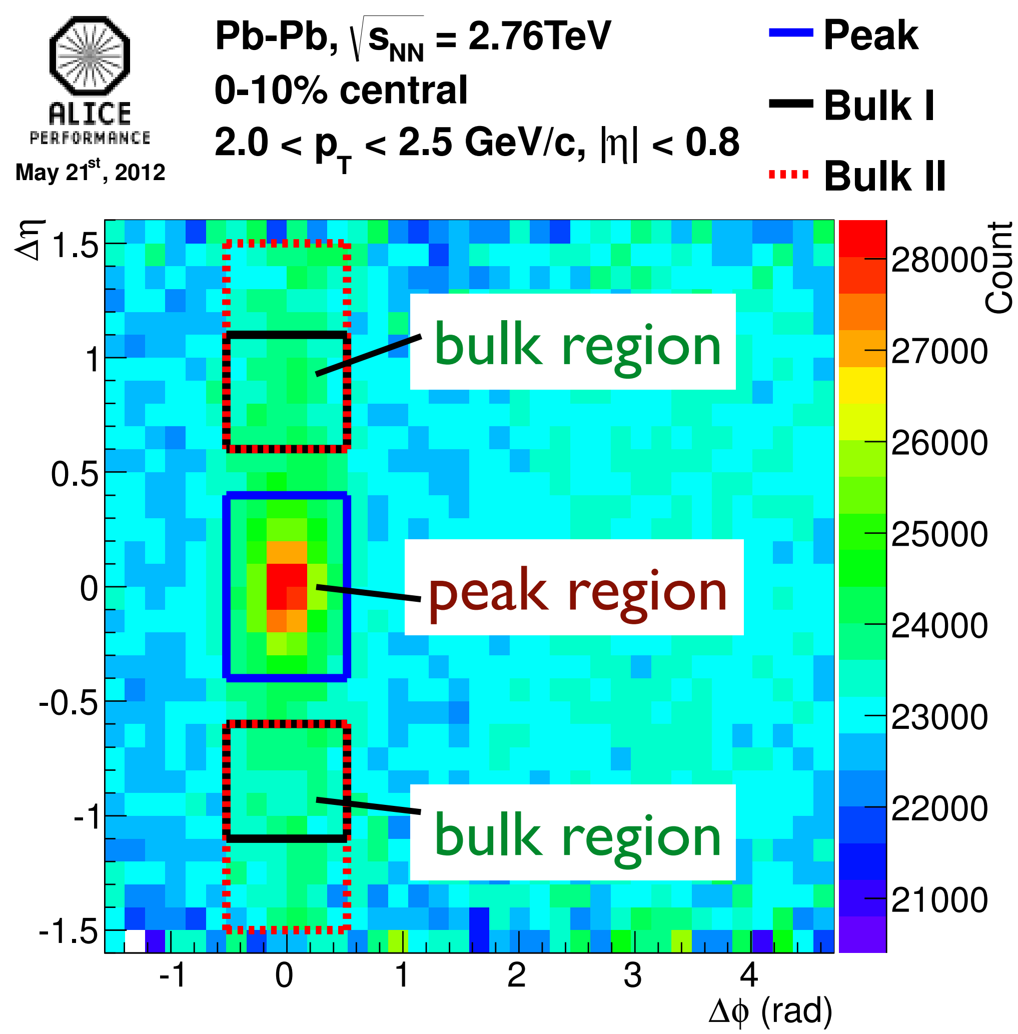
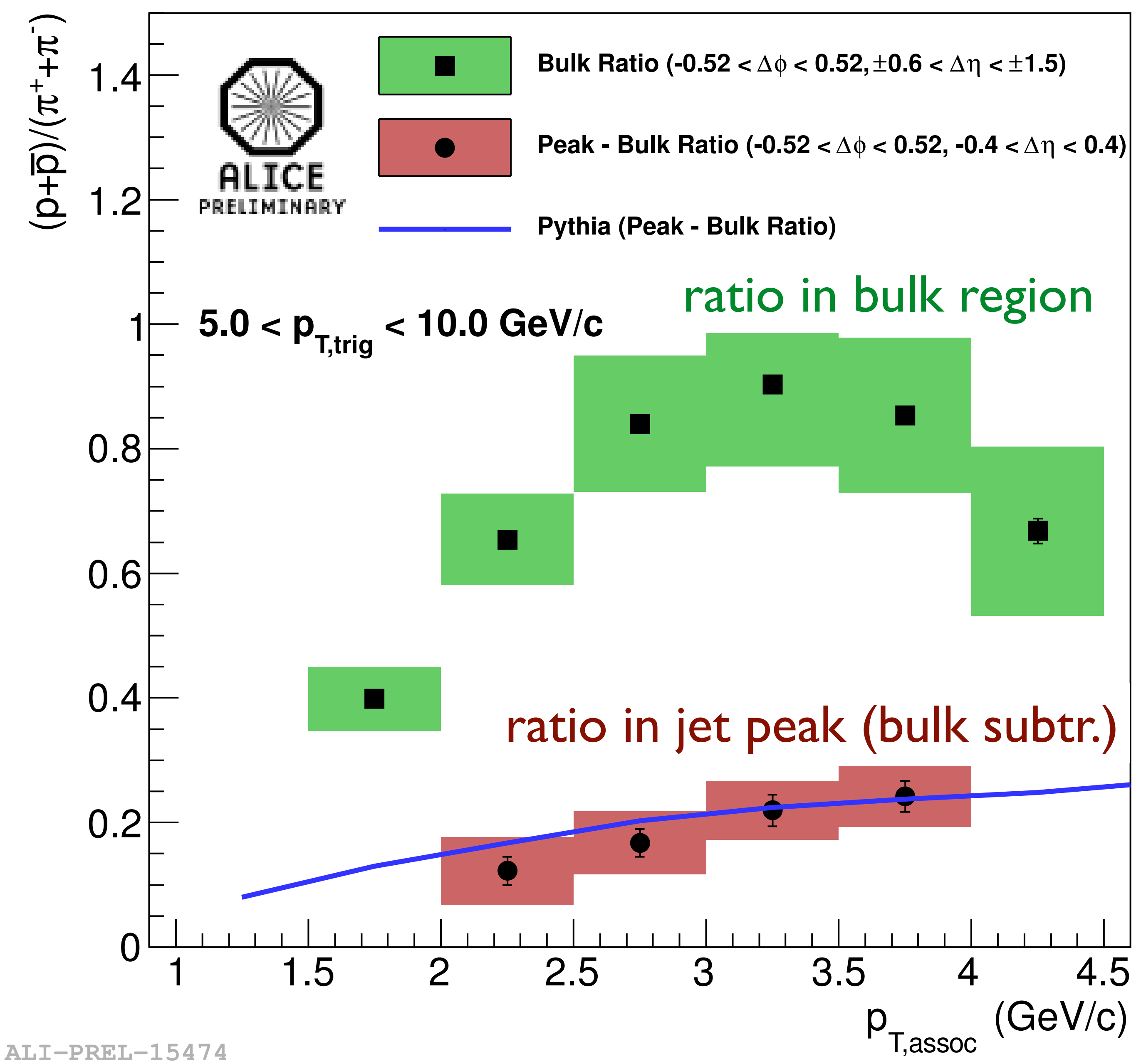


Associated particle identified via d*E*/dx and time of flight



Particle composition in jets appears to be unmodified in Pb-Pb w.r.t. pp

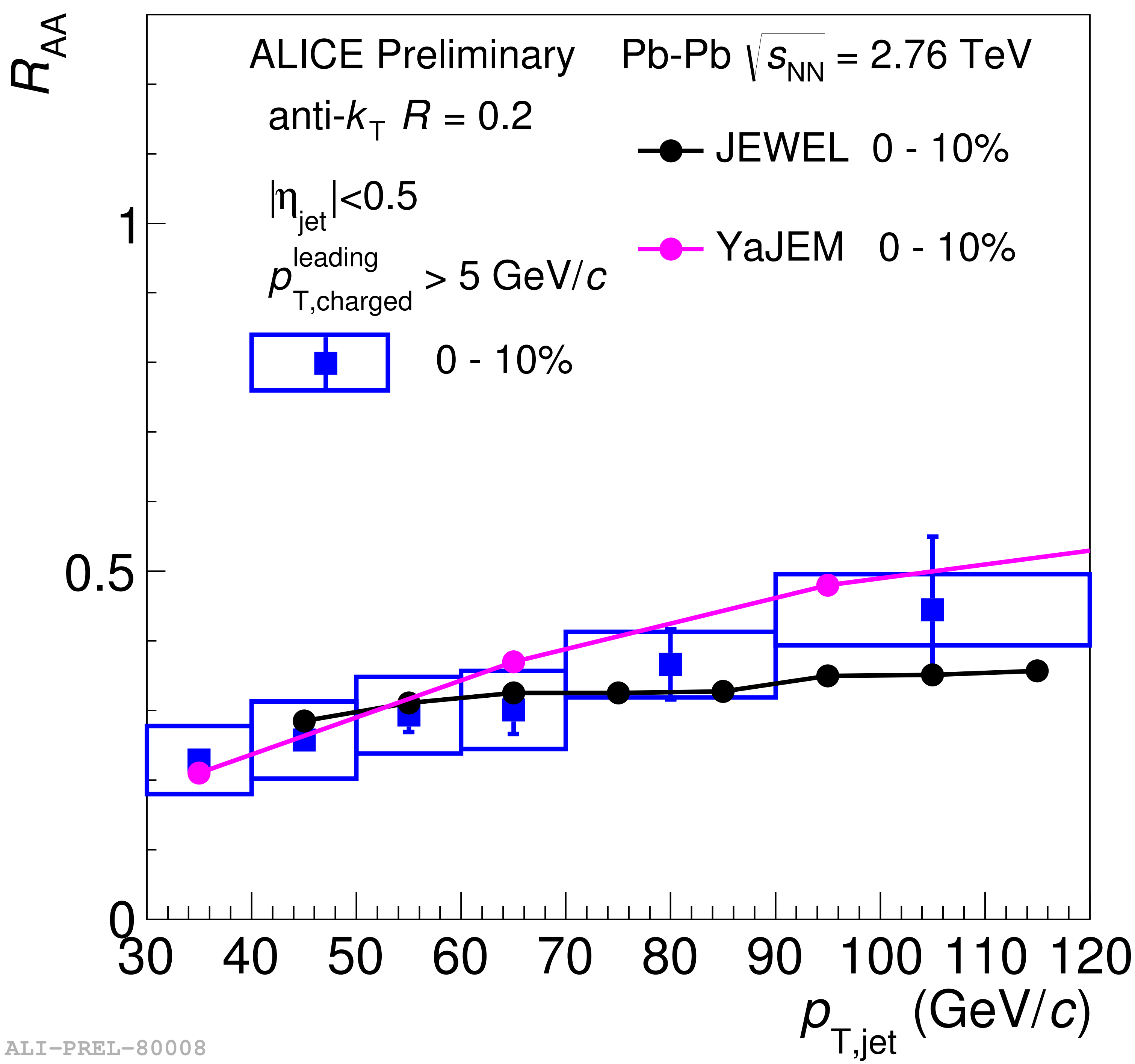
Conclusions

- Direct photons
  - Low p_T (p_T < 3 GeV/c) direct-photon excess not well described by standard hydro models
  - Large direct photon v_2 (similar to pions) at low p_T not well described
  - Qualitatively similar to findings at RHIC (currently larger uncertainties at the LHC)
  - "Direct photon puzzle" (mostly at RHIC with current uncertainties)

- High p_T particle production and jets
  - High p_T particle and jet suppression due to medium formed in Pb-Pb collisions
  - pQCD elastic + radiative energy loss models appear to be consistent with the data (e.g., less suppression for b quarks)

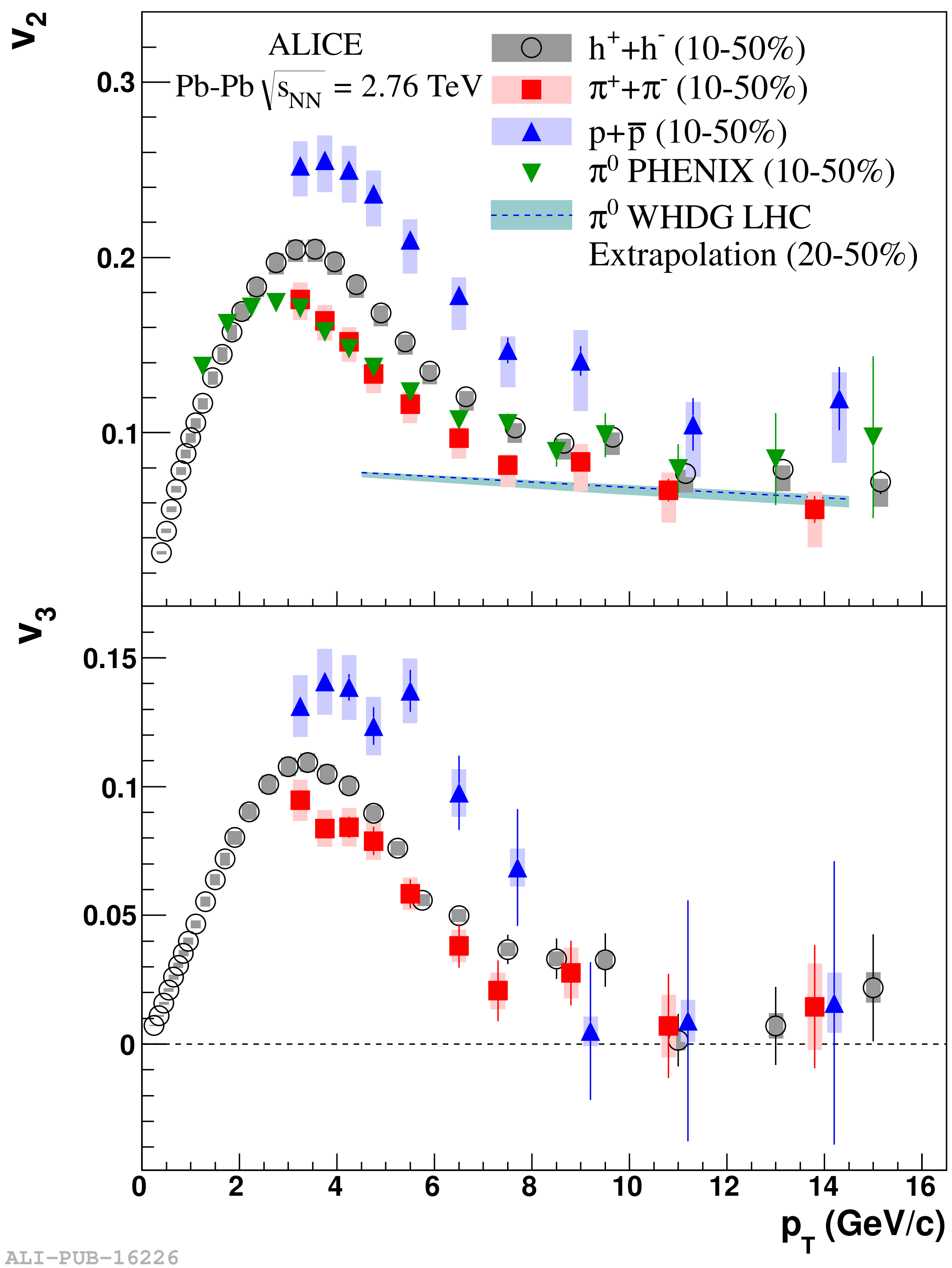
Extra Slides

Jet R_{AA} (R = 0.2) Described by In-Medium Shower Monte Carlo Codes



Current state-of-the-art: Monte Carlo generators with description of in-medium shower evolution with (e.g. JEWEL, YaYEM, Q- PYTHIA, Q-HERWIG, MARTINI)

Azimuthal Anisotropy v_2 at High p_T (above ~ 8 GeV/c) Believed to be due to Parton Energy Loss



(ALICE), Phys. Lett. B719, (2013) 18