Direct photon production in pp, p-Pb and Pb-Pb collisions measured with the ALICE experiment

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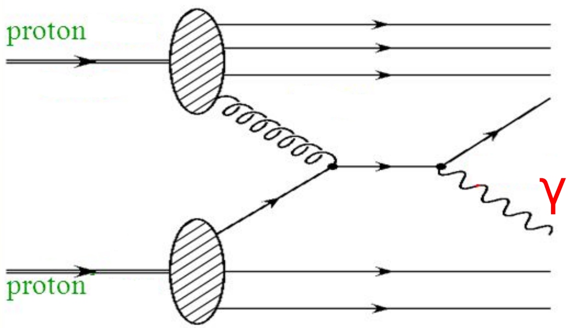
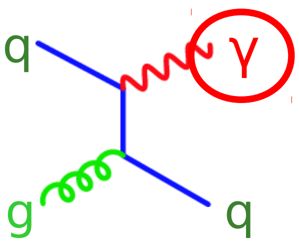
NRC “Kurchatov institute”

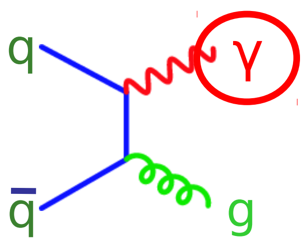
Direct photons in pp collisions



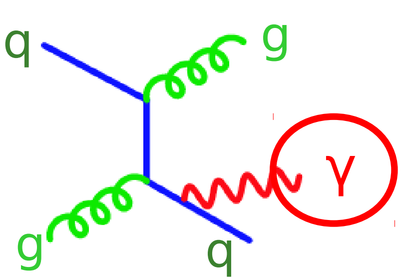
Direct photons – photons not originating from hadronic decays but produced in electromagnetic interactions in course of collision.

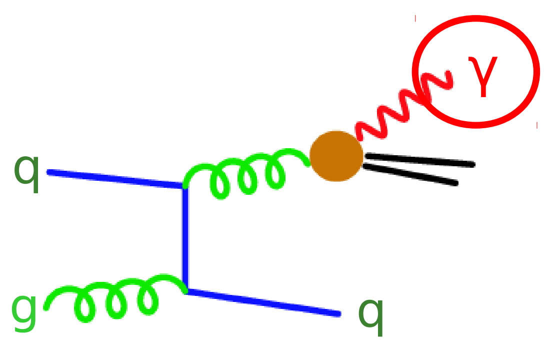
$$\frac{d\sigma^{\gamma,dir}}{dp_T\,d\eta} = F_{i/h} \otimes \sigma_{ij} \otimes D_{\gamma/k}$$



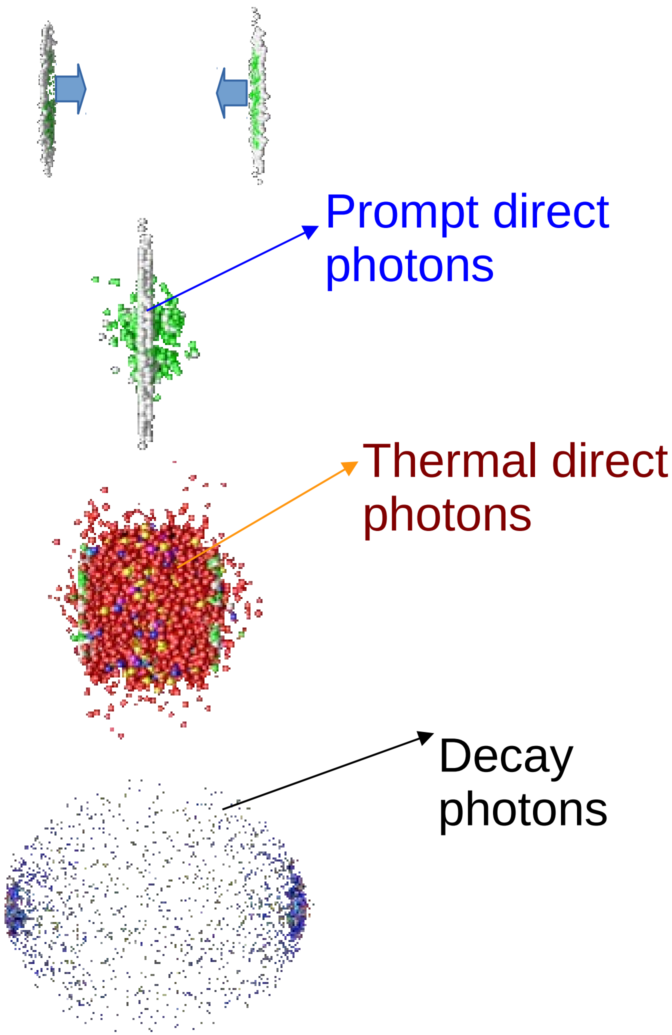


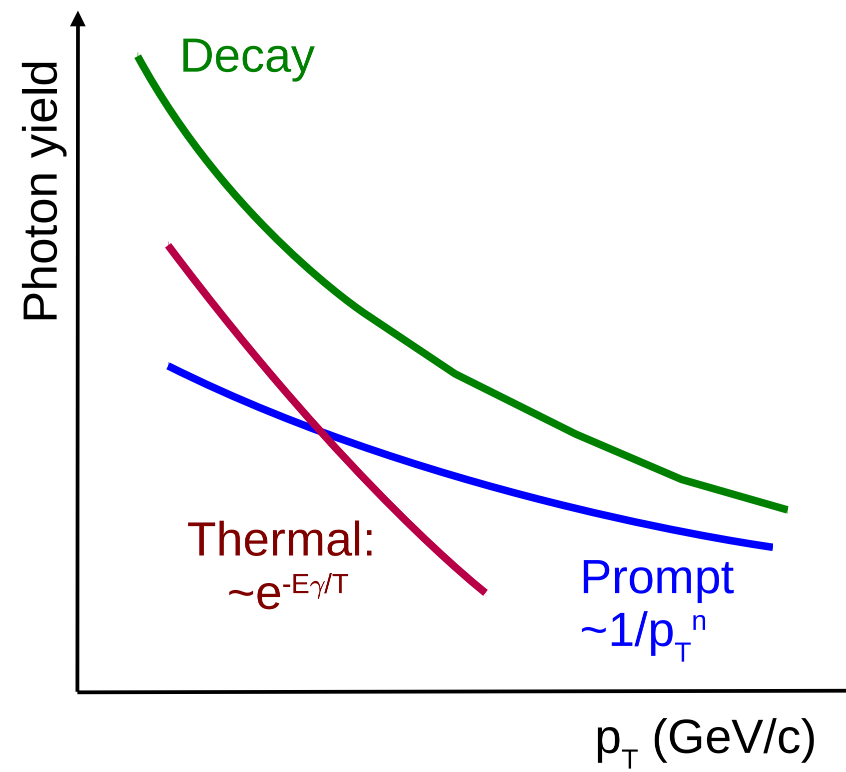
$F_{i/h}$ – nucleon structure function
σ_{ij} – cross-section of the elementary process
$D_{\gamma/k}$ – fragmentation function



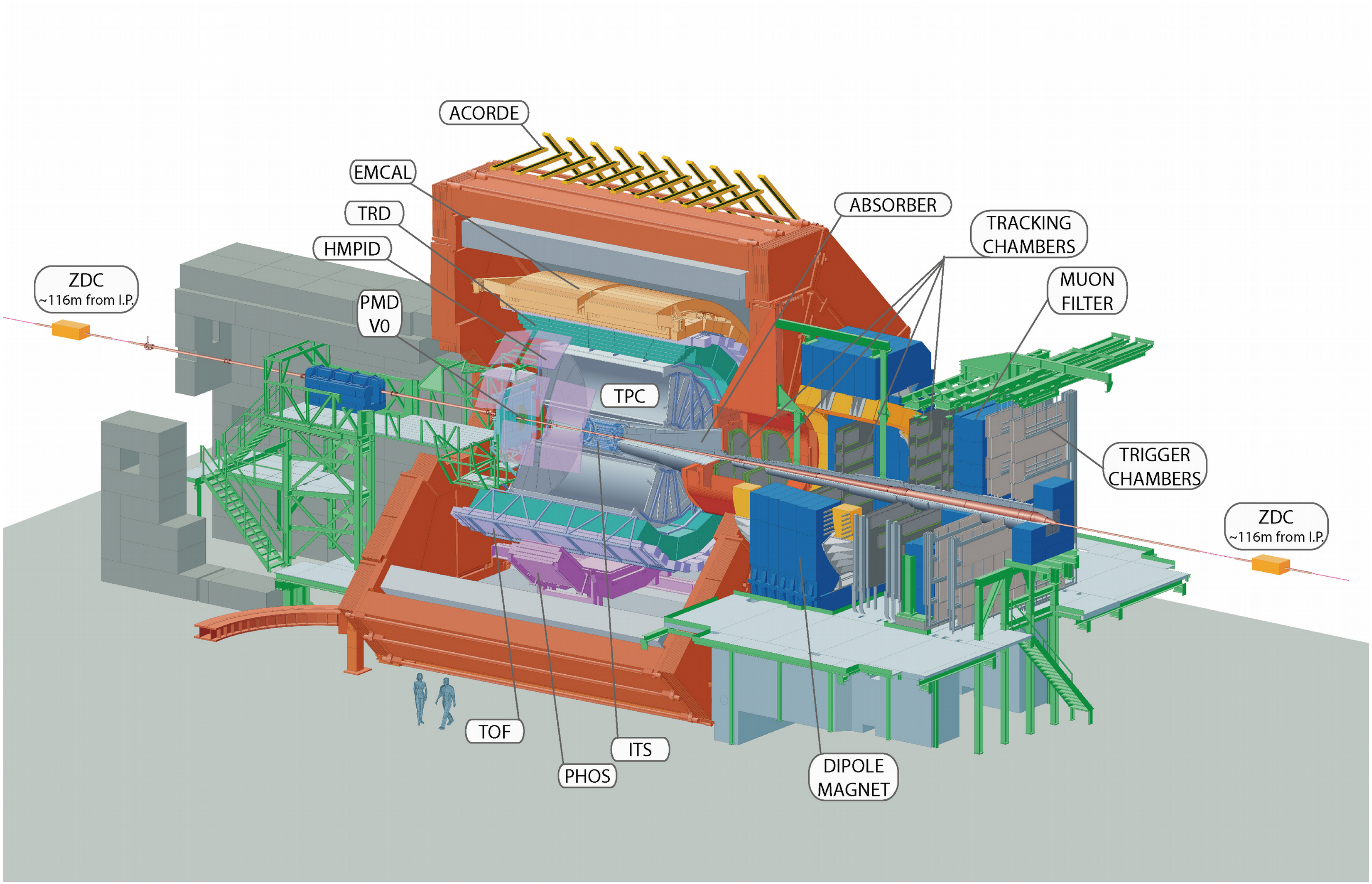


Direct photons in AA (and p-A?) collisions





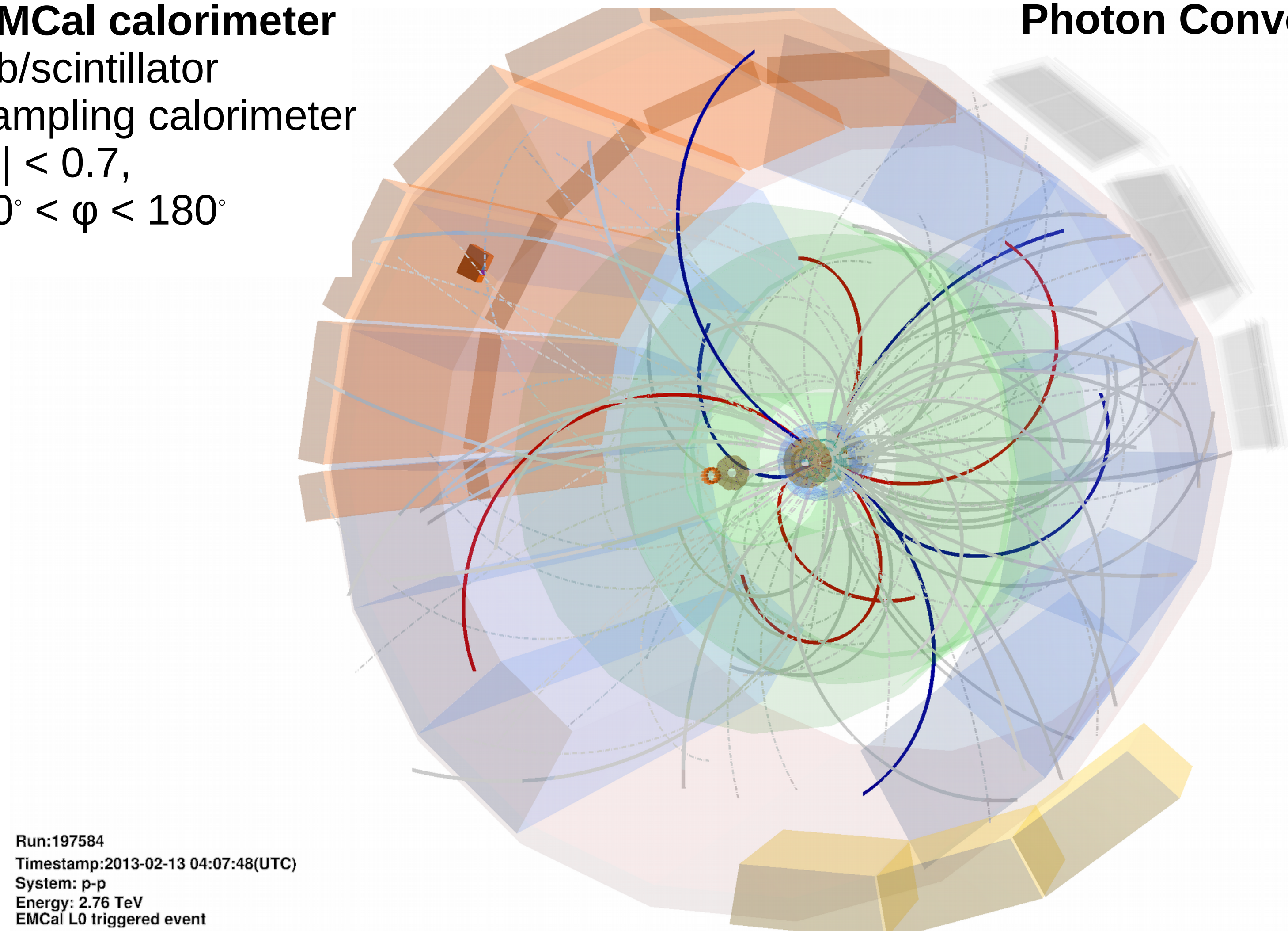
ALICE apparatus



Photon measurement in ALICE

EMCal calorimeter
Pb/scintillator
sampling calorimeter
$|\eta| < 0.7$,
$80^{\circ} < \varphi < 180^{\circ}$

Photon Conversion Method (PCM)
ITS and TPC
$|\eta| < 0.9$, $0^{\circ} < \varphi < 360^{\circ}$
conversion in
detector material
$X/X_0 = (11.4 \pm 0.5)\%$
conv. probability ~ 8%



PHOS calorimeter
$PbWO_4$ crystals
$|\eta| < 0.12$,
$260^{\circ} < \varphi < 320^{\circ}$

Direct photon extraction

Subtraction method:

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

Inclusive photons: all photons that are produced

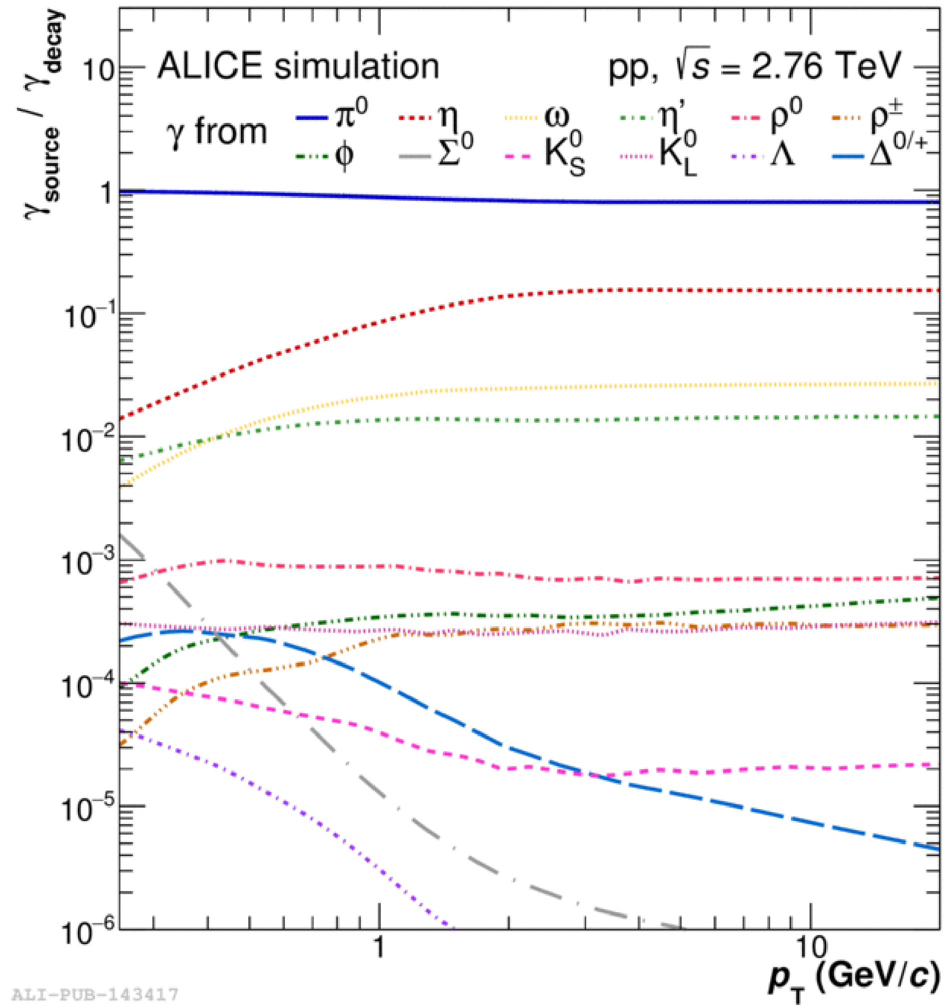
Decay photons: calculated by decay simulation from measured or m_T scaled hadron spectra

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

Numerator:
Measured inclusive γ spectrum per measured π^0

Denominator:
Estimated sum of all decay photons per π^0

ArXiv:1803.09857

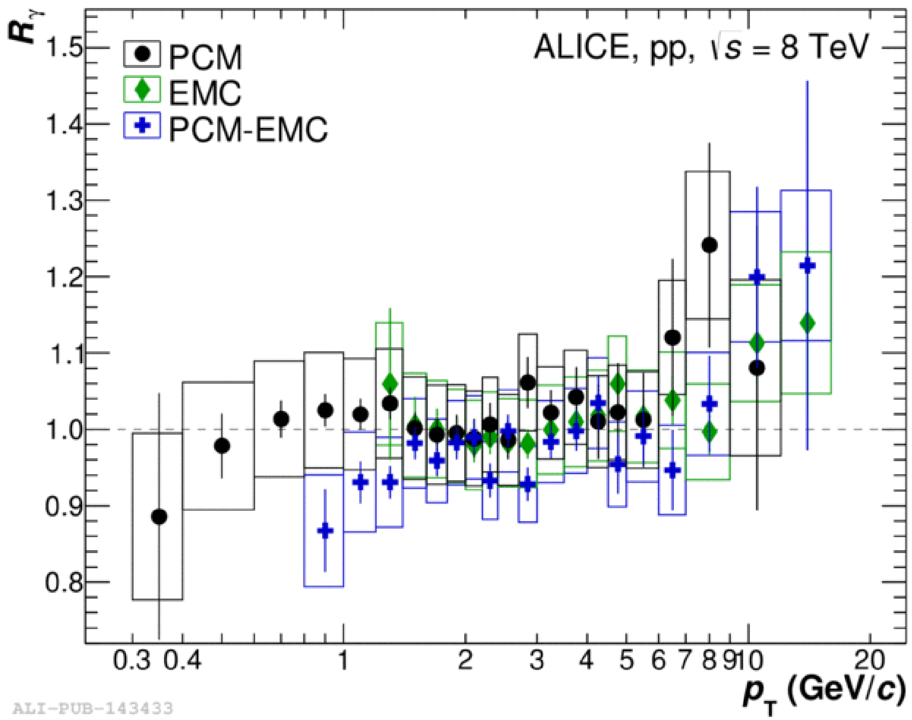


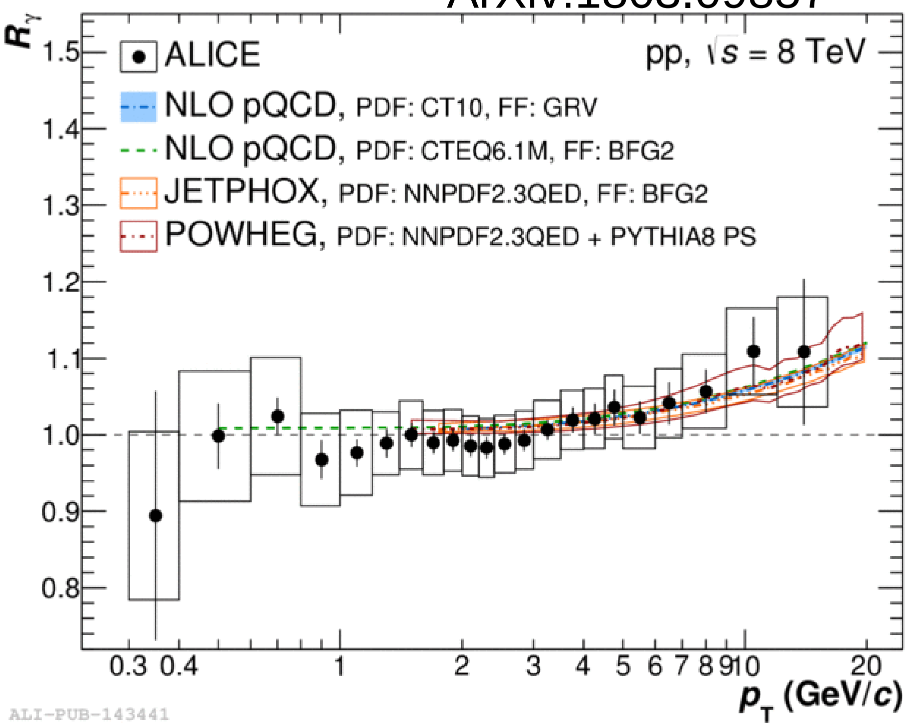
Advantage of ratio: cancellation of some large systematic uncertainties

Double ratio in pp collisions

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

ArXiv:1803.09857





Systematic uncertainties of individual meas. are dominated by p_T-independent ones: material budget unc. of 4.5% PCM, 2.8% EMC

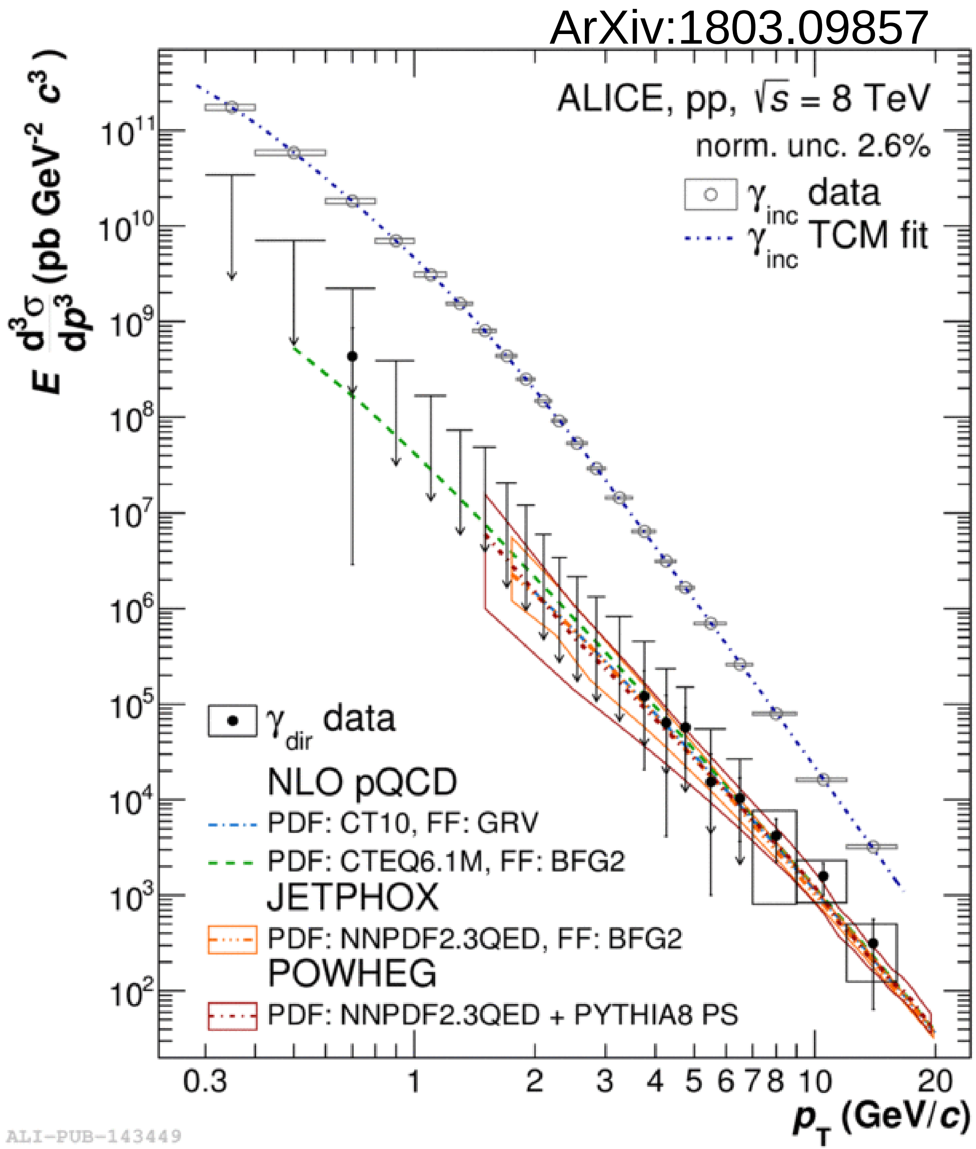
Combination of several reconstruction techniques via BLUE method.
Theoretical NLO prediction plotted as

$$R_{\gamma,NLO} = 1 + \frac{\gamma_{dir}^{NLO}}{\gamma_{dec}}$$

Within uncertainties no significant excess at low p_T observed
About 1 − 2σ deviation from unity for p_T > 7 GeV/c

Direct photon spectrum in pp collisions

ArXiv:1803.09857

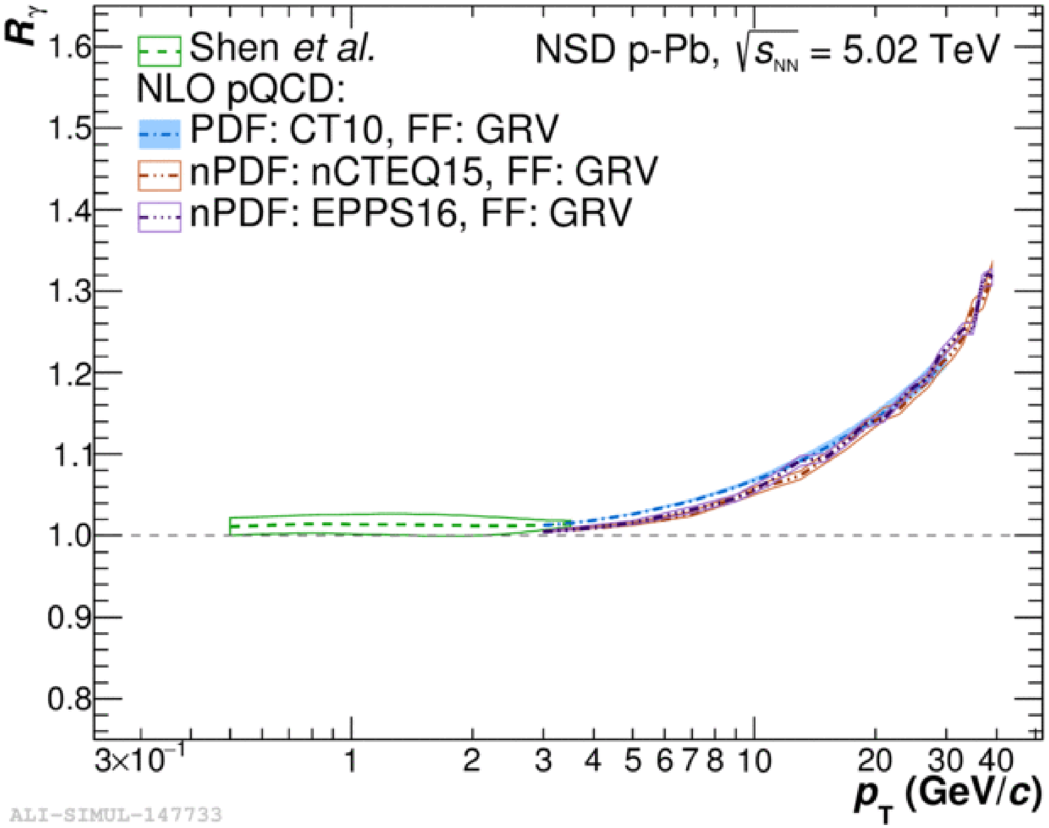


- Upper limits at 90% C.L.(arrows) determined where R_γ with total uncertainties consistent with unity

- Theory NLO calculations:
  - W. Vogelsang (CT10, GRV)
  - J.F. Paquet (CTEQ6.1M, BFG)
  - Thermal (Shen et al.)

are consistent with measurements

Direct photons in p-Pb



Theoretical NLO prediction plotted as

$$R_{\gamma,NLO} = 1 + \frac{N_{coll}\,\gamma_{dir}^{NLO}}{\gamma_{dec}}$$

Is hot matter created in collisions of small systems?

Pro

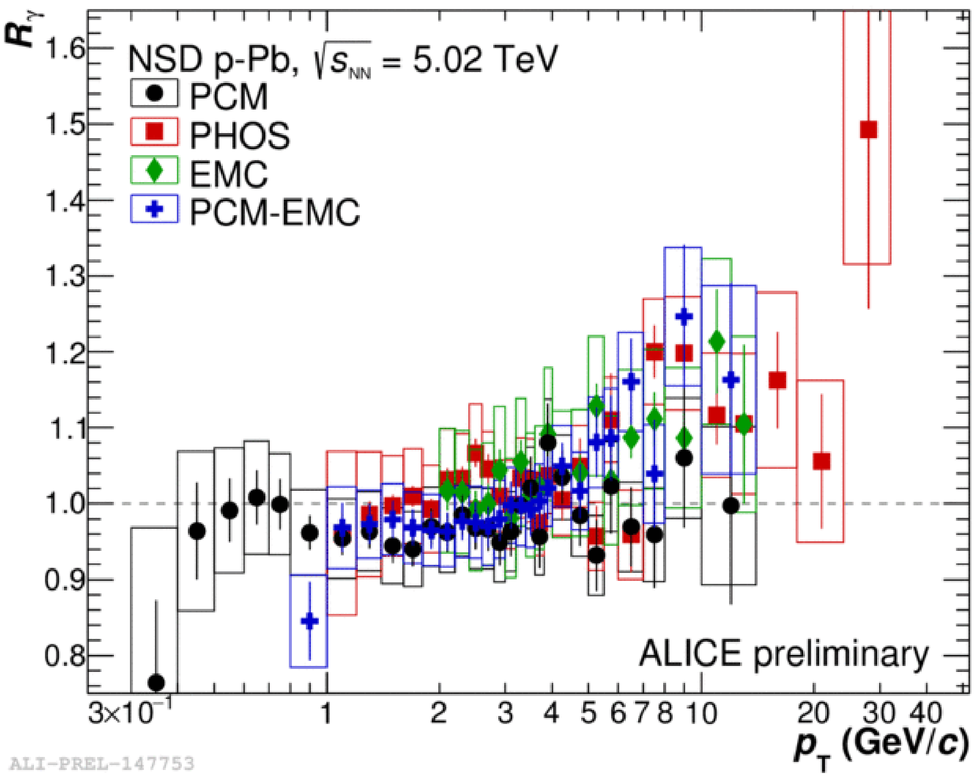
- Observation of collective flow
- Increase of strangeness yield

Contra

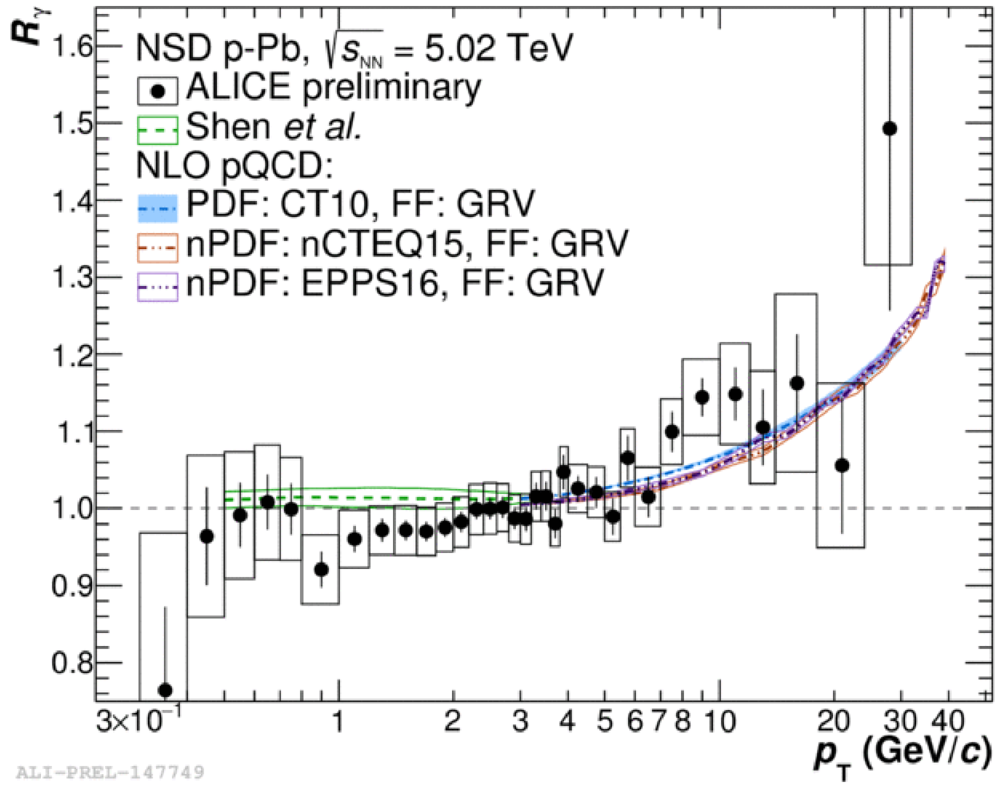
- No hard hadron suppression

Can we see thermal radiation in p-Pb collisions?

Direct photons in p-Pb

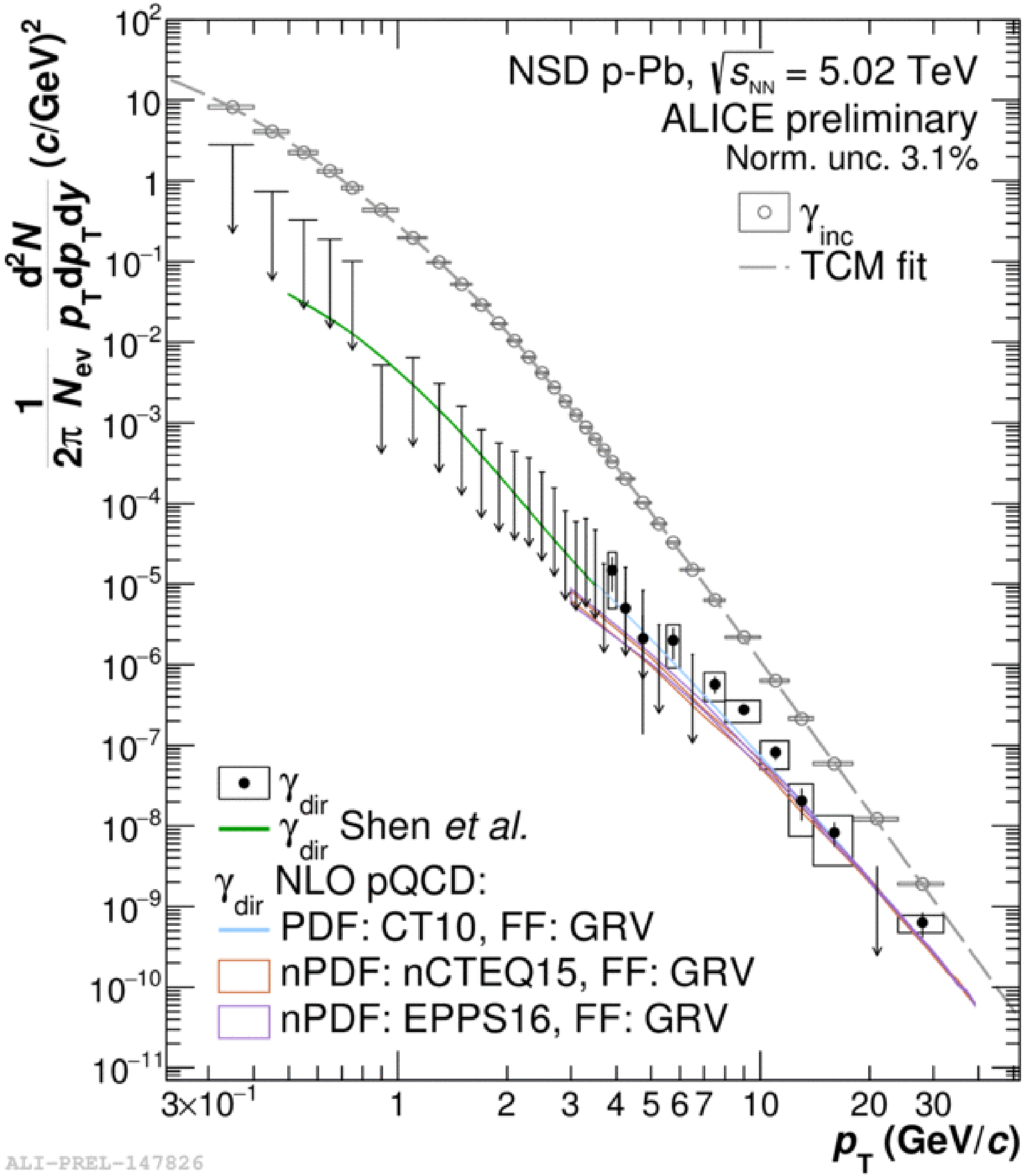


Systematic uncertainties of individual measurements are mostly p_T-independent



Within uncertainties no significant excess at low p_T observed. Accuracy is not yet sufficient to confirm/close thermal radiation at p-Pb collisions.

Direct photons in p-Pb

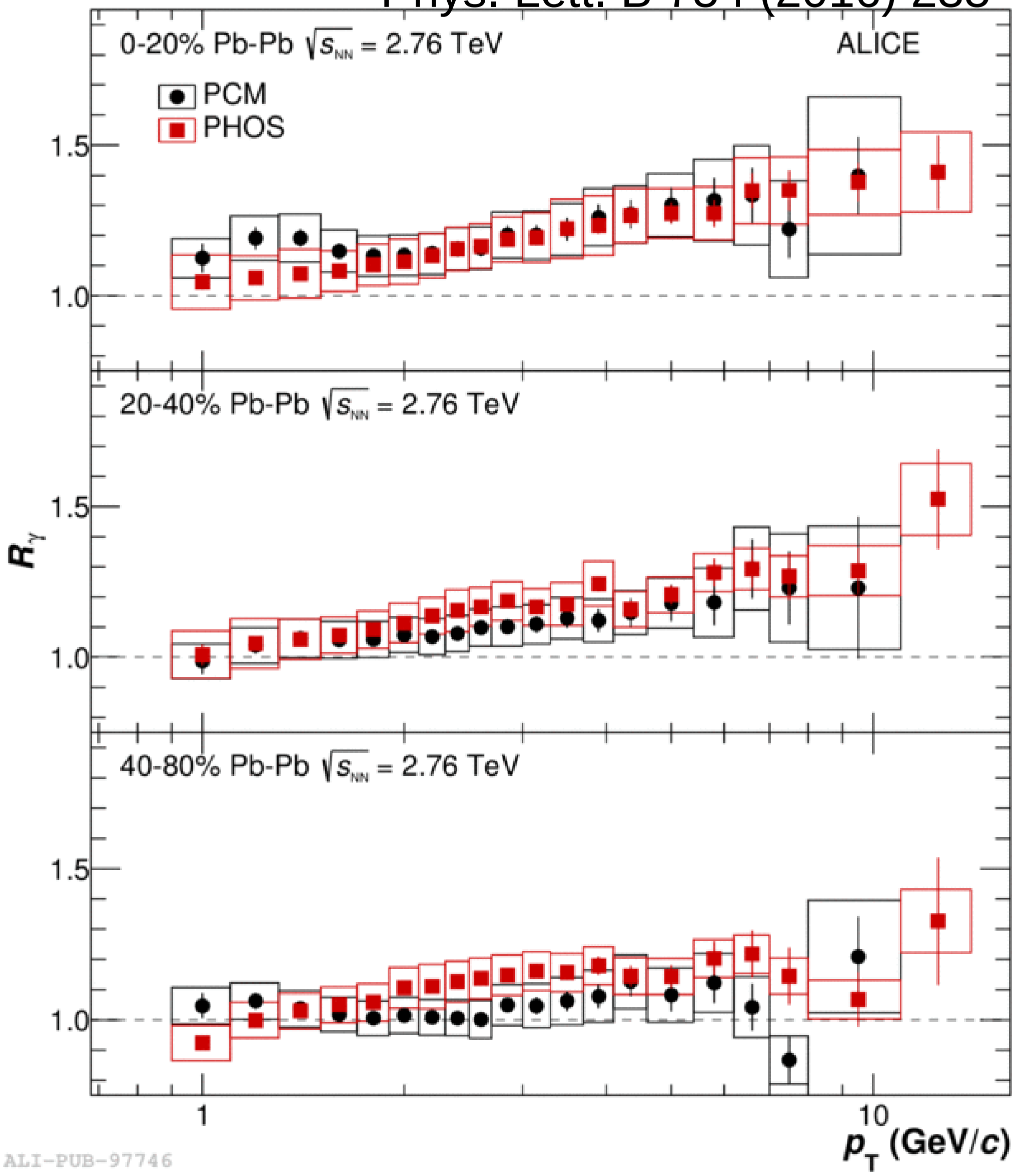


Upper limits at 90% C.L.(arrows) determined where R_γ with total uncertainties consistent with unity

Both NLO calculations scaled with number of binary collisions N_{coll} (W . Vogelsang) and hydrodynamic model predictions (Shen et al.) are consistent with measurements

Direct photon spectrum in Pb-Pb

Phys. Lett. B 754 (2016) 235

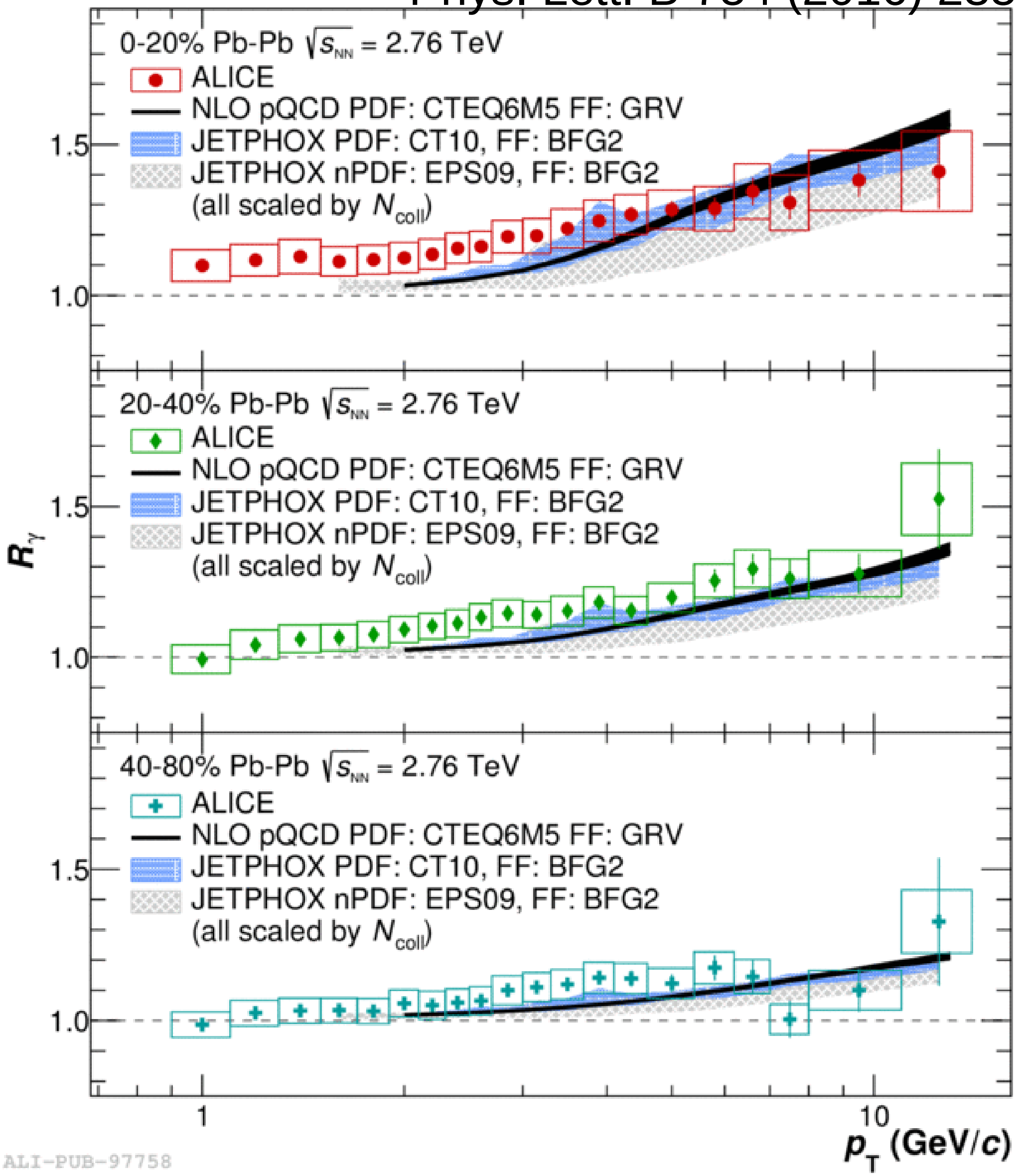


Double ratio was measured in 3 centrality classes with 2010 Pb–Pb data by two methods, PCM and PHOS.

Measurements are consistent (remember that systematic unc. are mostly p_T-independent)

Direct photon excess in Pb-Pb

Phys. Lett. B 754 (2016) 235



At low p_T

~ 15% excess in 0 − 20% ;

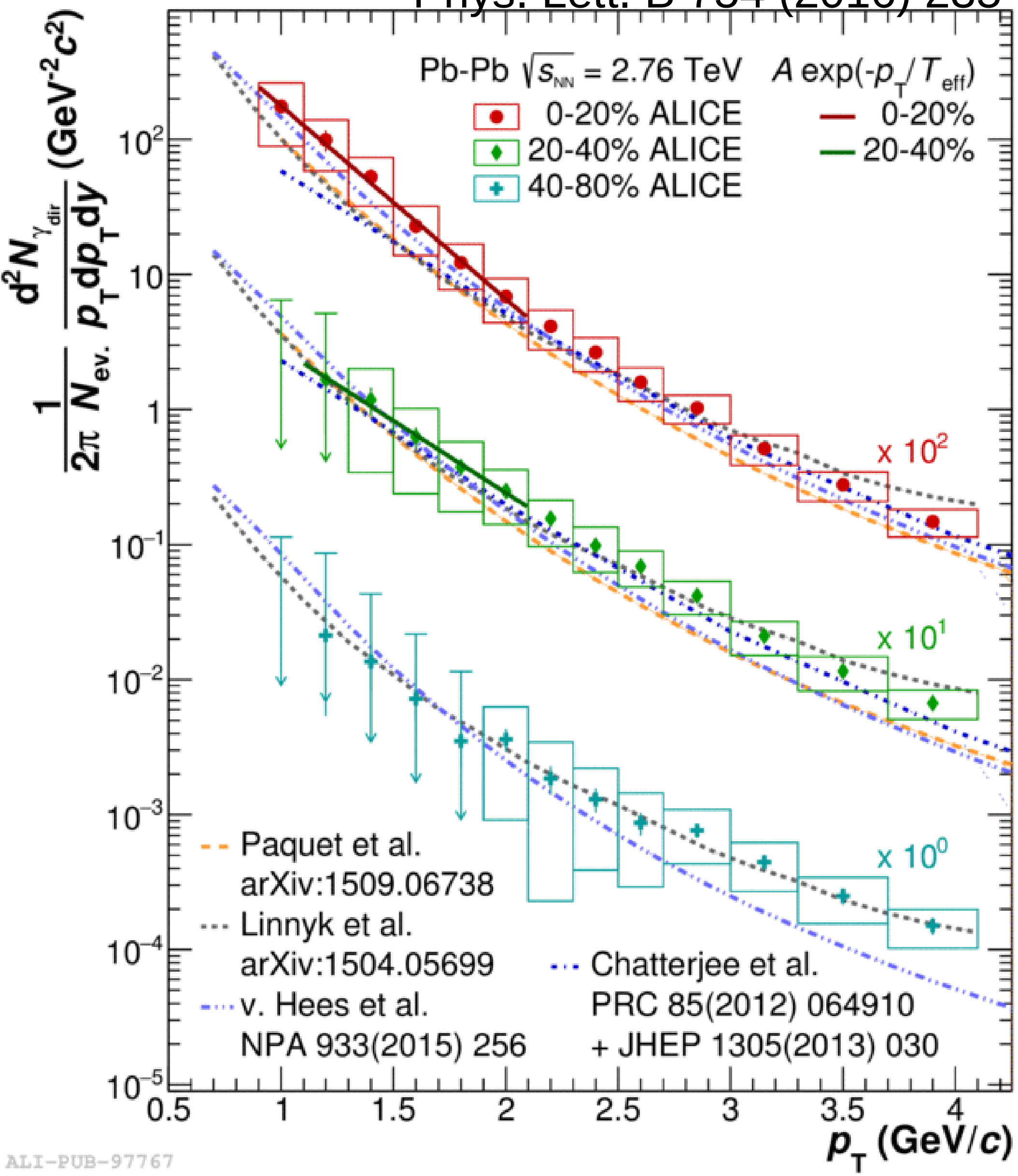
~ 9% in 20 − 40%

At high p_T above ~5 GeV/c

in agreement with NLO pQCD and JETPHOX

Remember, in pp collisions: no low p_T excess seen at same center-of-mass energy

Direct photon spectrum in Pb-Pb

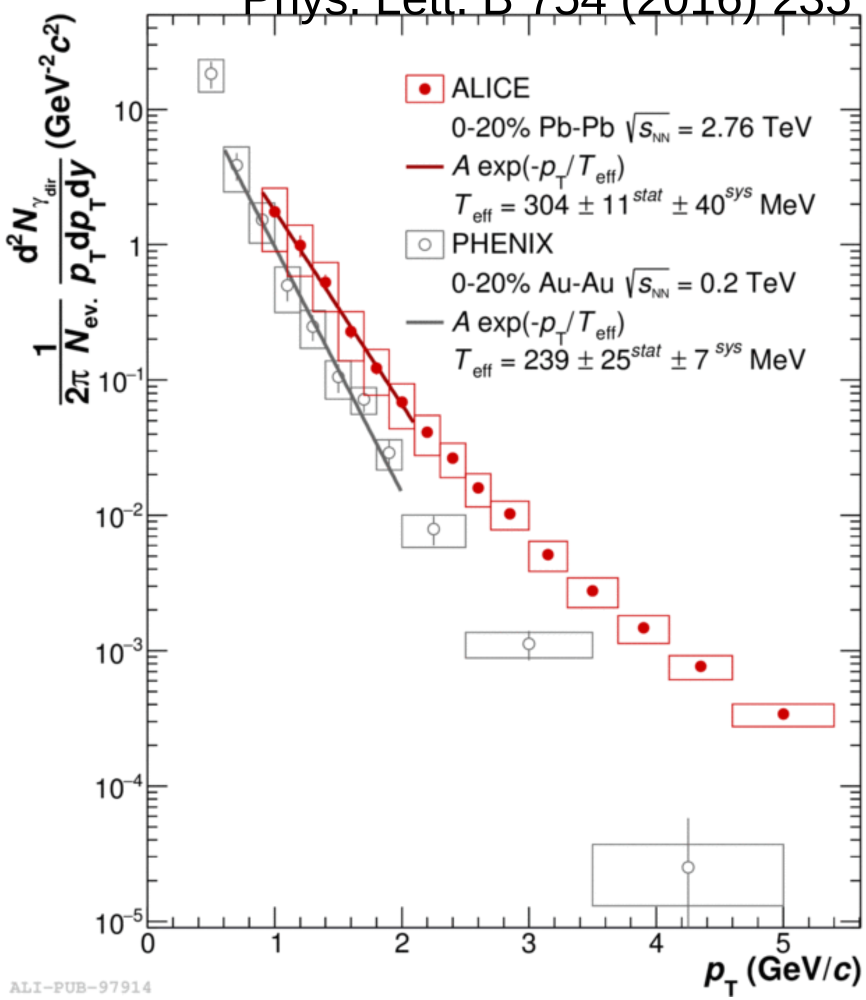


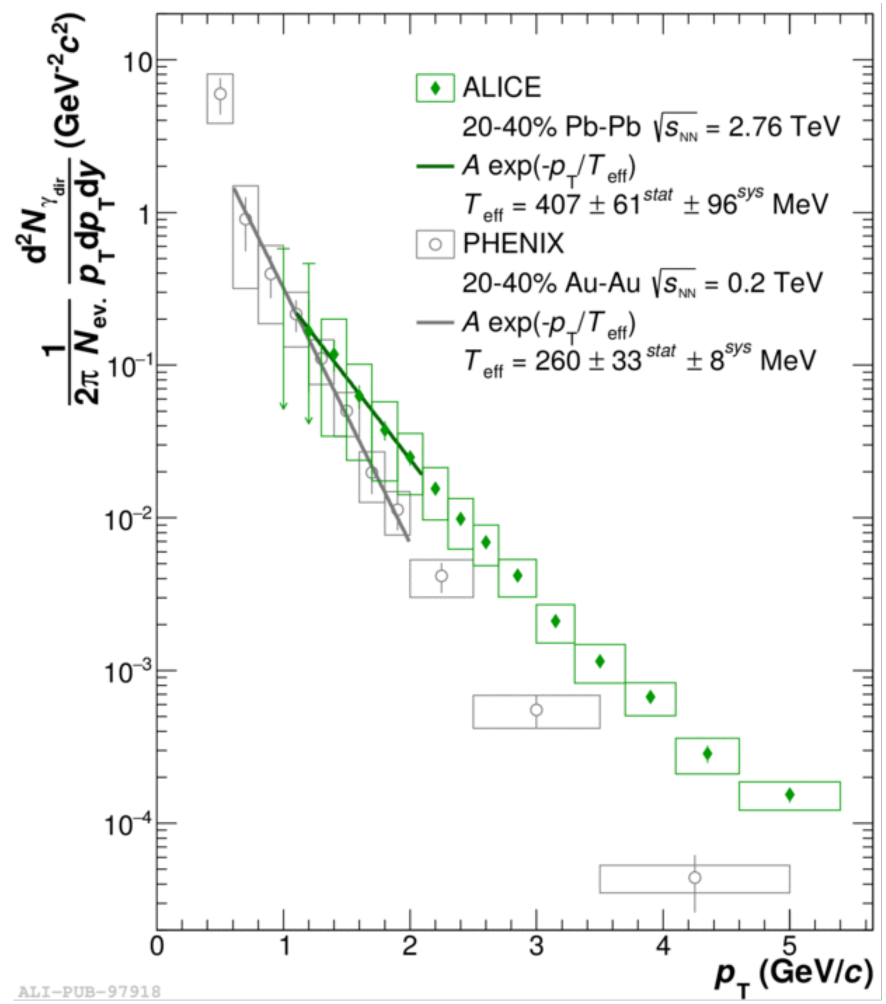
Direct photon spectra are measured in 3 centrality classes

Hydrodynamic models, assuming thermal emission and prompt contribution predict 2-7 times smaller yield, though within uncertainties

Direct photon spectrum in Pb-Pb

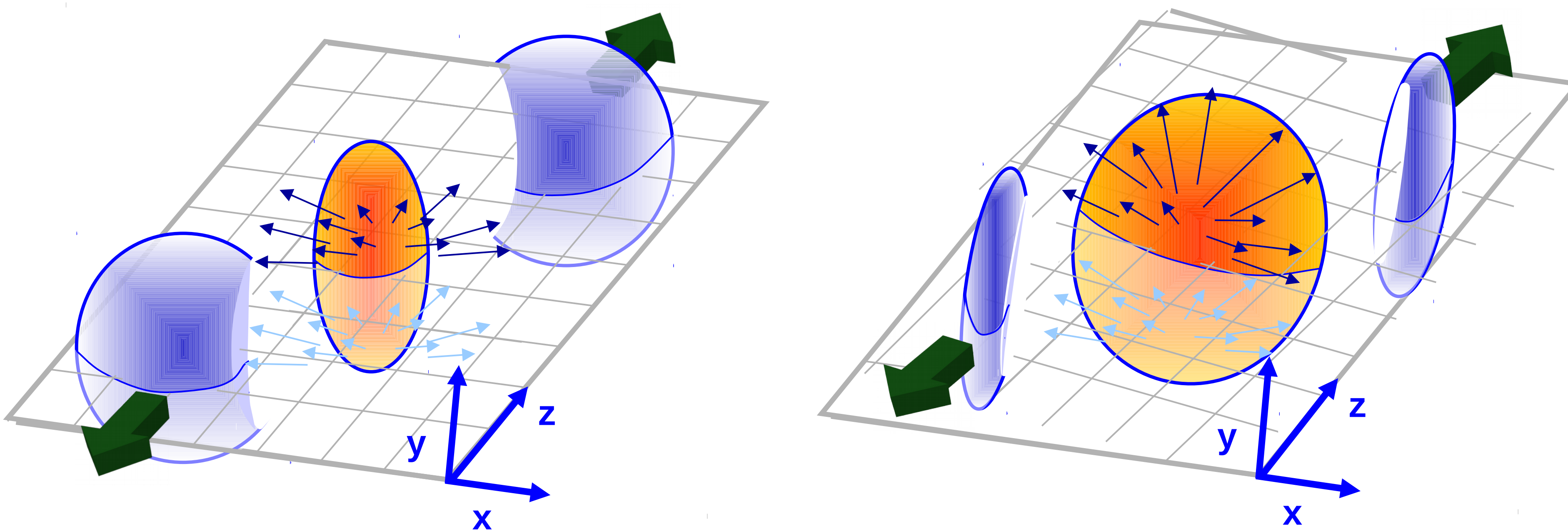
Phys. Lett. B 754 (2016) 235





Both absolute yield of direct photons and effective slope increases in increase of the collision energy.

Collective flow

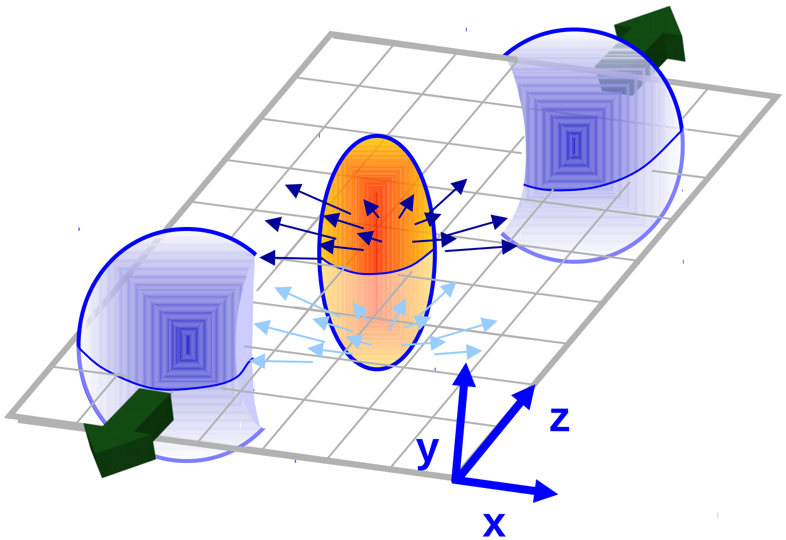


Collective flow – asymmetry in particle production, common for all soft particles in event.

$$\frac{dN}{d\phi}=1+2v_1\cos\left(\phi-\Psi_{RP}\right)+2v_2\cos\left[2\left(\phi-\Psi_{RP}\right)\right]+2v_3\cos\left[3\left(\phi-\Psi_{RP}\right)\right]+\ldots$$

v_1 - directed, v_2 – elliptic, v_3 – triangular flow, ...

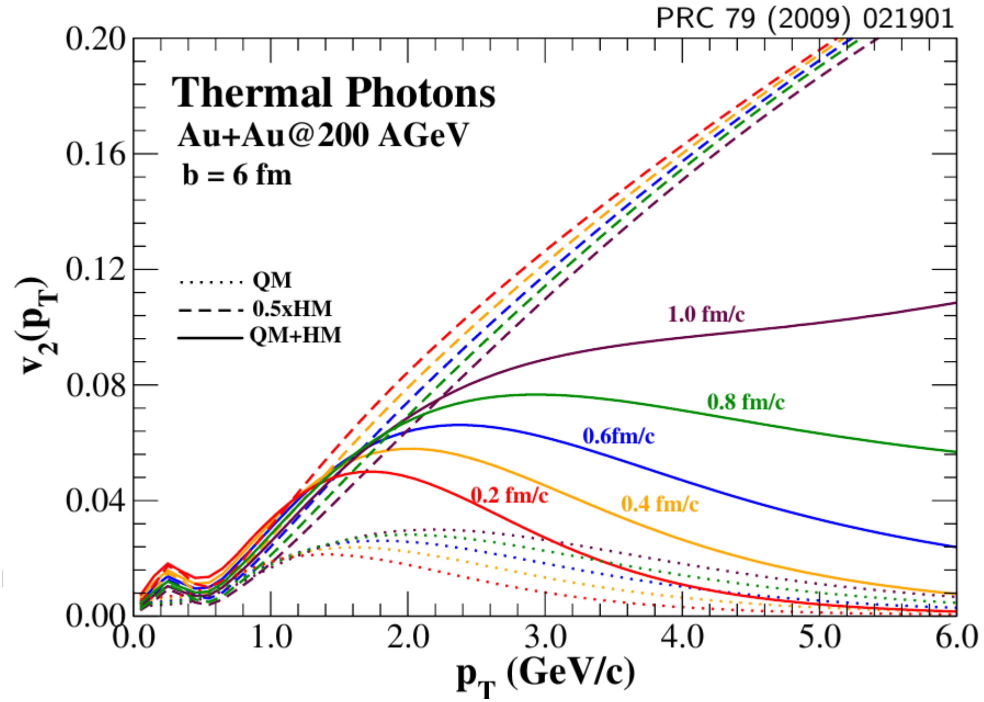
Direct photon collective flow



Collective expansion transforms initial spacial asymmetry of fireball to asymmetry in momentum space.

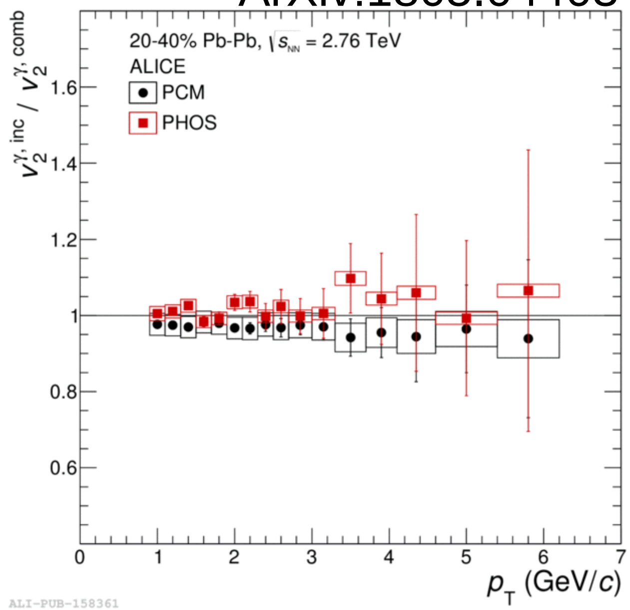
Thermal photons, emitted early from hotter fireball carry smaller collective flow than those, emitted at later stages.

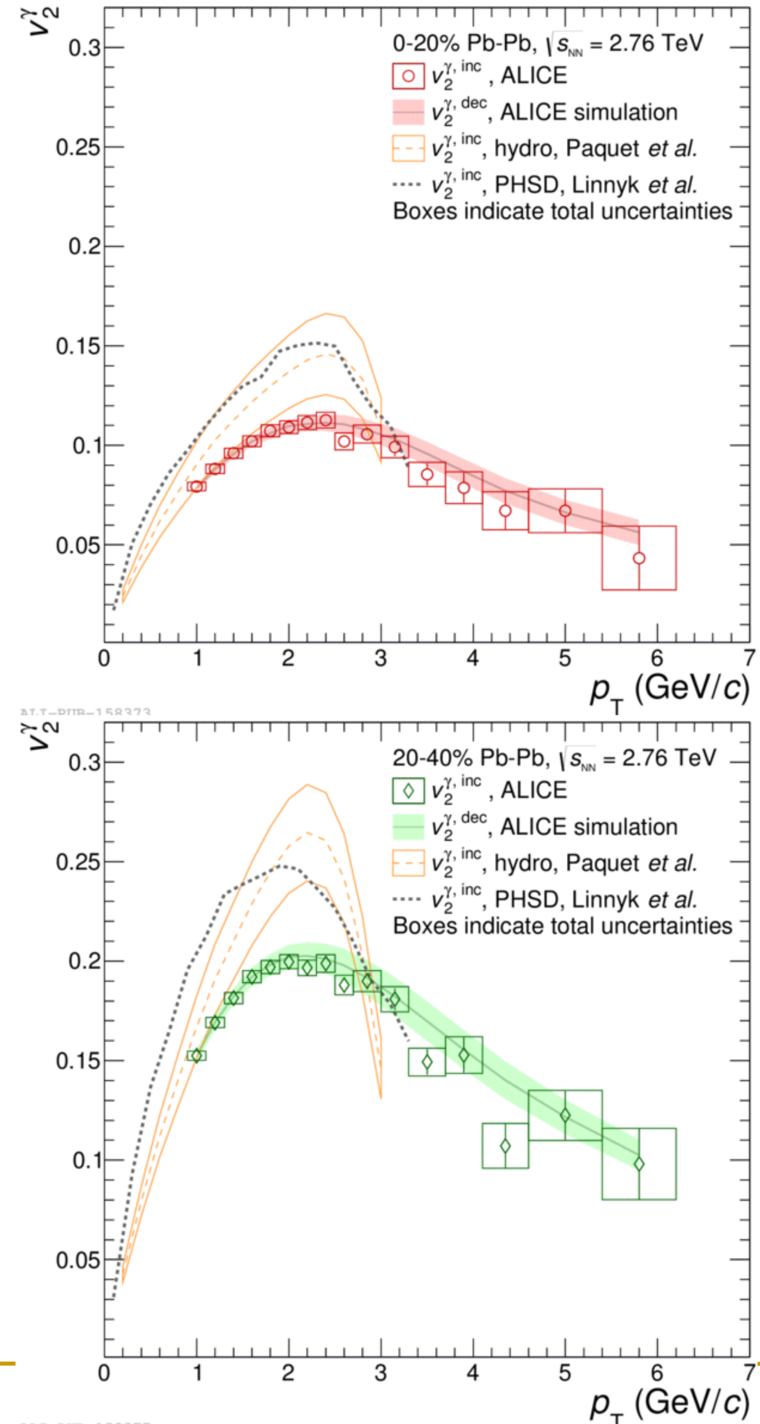
=> one can test development of collective flow with direct photons.



Inclusive photon flow

ArXiv:1805.04403





Elliptic flow of inclusive photons was measured with PCM and PHOS and found to be consistent.

p_T < 3 GeV/c: $v_2^{\gamma,inc} = v_2^{\gamma,dec}$

⇒ Either no contribution of γ,dir
or $v_2^{\gamma,dir} = v_2^{\gamma,dec}$

→ Theory ~ 30 − 40% too high

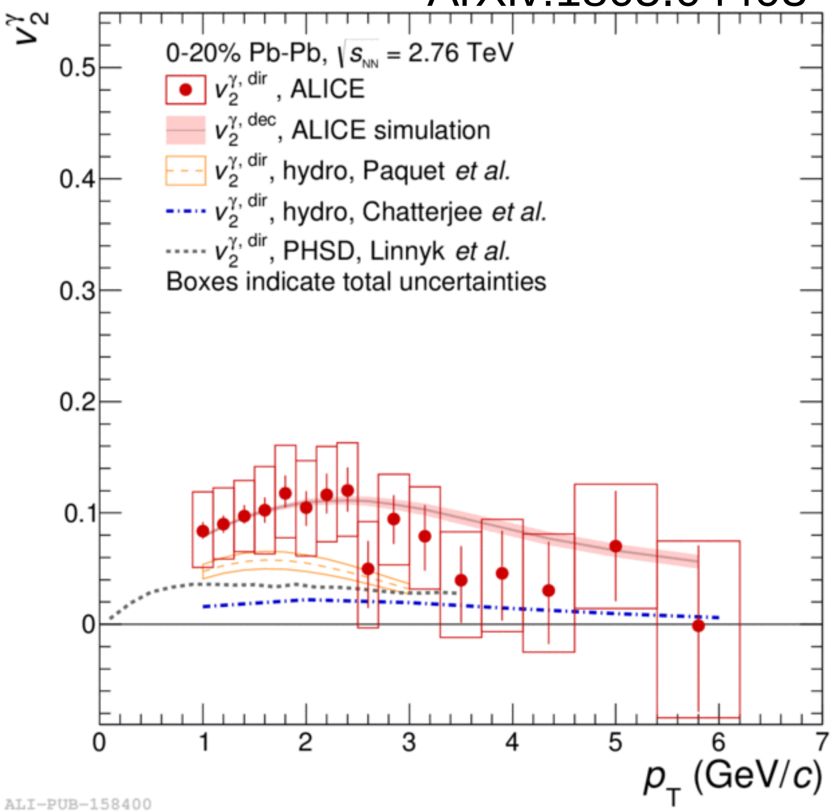
p_T > 3 GeV/c: $v_2^{\gamma,inc} < v_2^{\gamma,dec}$

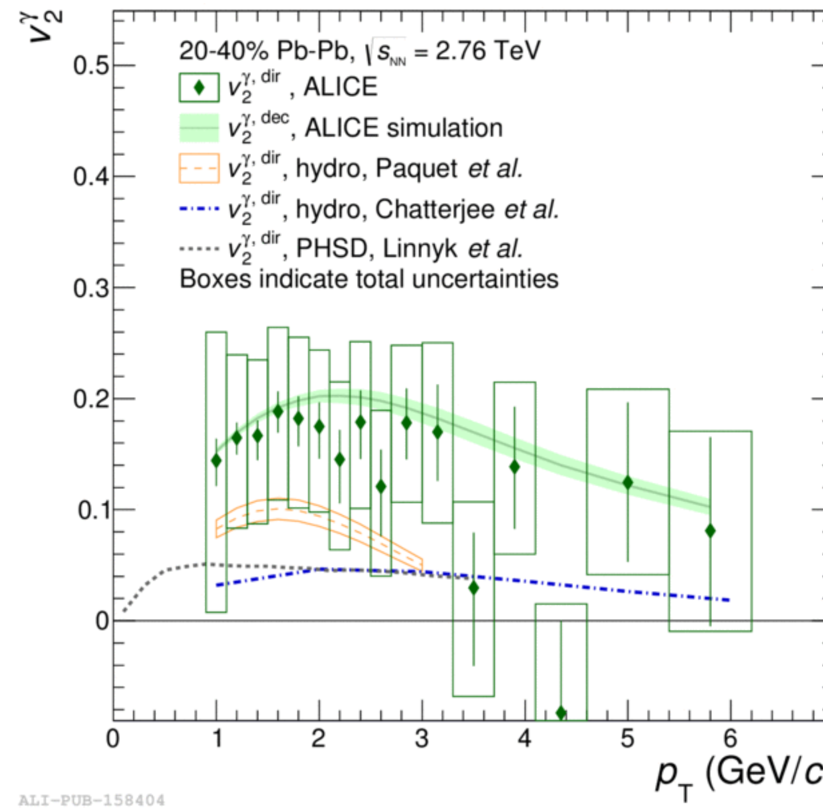
→ prompt photon contribution

Direct photon flow

$$v_2^{\gamma,\mathrm{dir}} = \frac{R_\gamma \cdot v_2^{\gamma,\mathrm{inc}} - v_2^{\gamma,\mathrm{dec}}}{R_\gamma - 1}$$

ArXiv:1805.04403





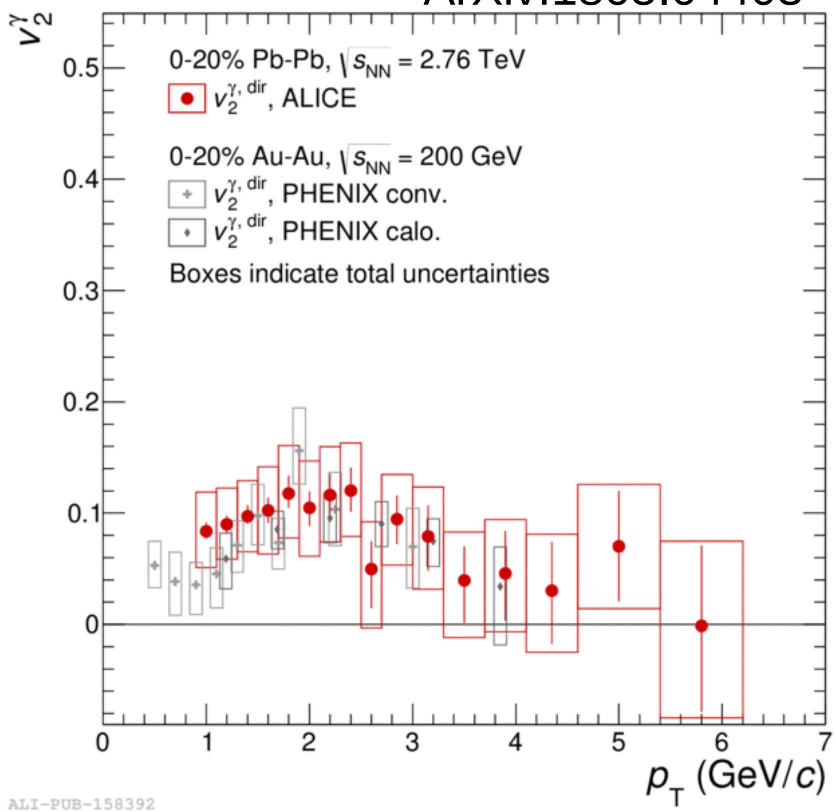
- Large direct photon v_2 for $p_T < 3$ GeV/c
- Measured magnitude of $v_2^{\gamma,\mathrm{dir}}$ comparable to hadrons
- Result points to late production times of direct photons after flow is established

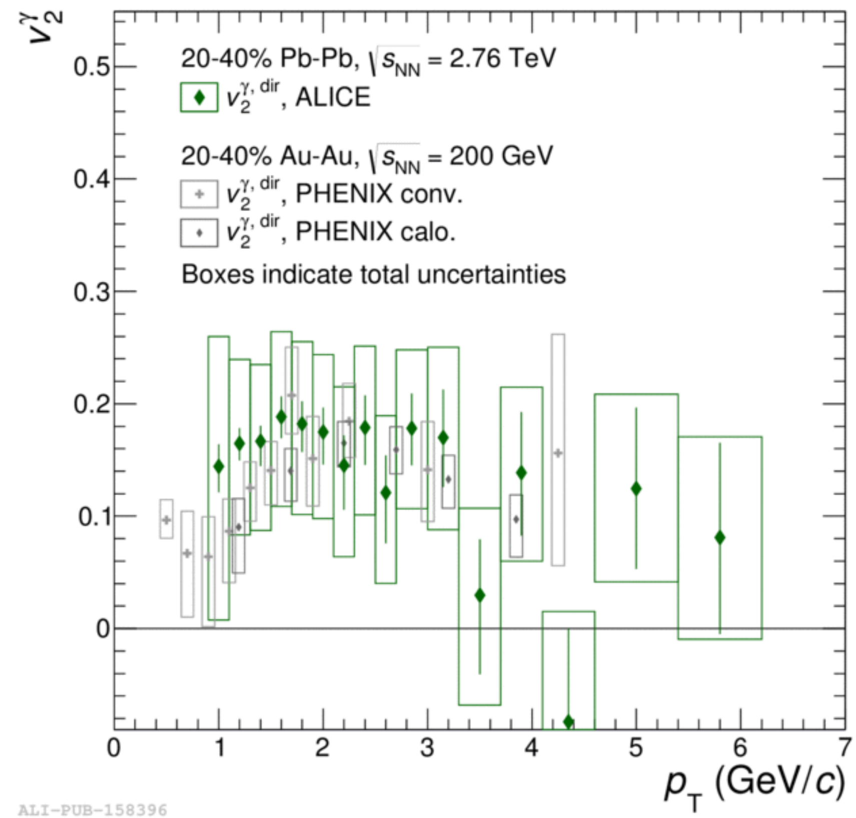
$v_2^{\gamma,\mathrm{dir}}$ compatible with $v_2^{\gamma,\mathrm{dir}} = 0$ within 1.4(1.0)σ in p_T range ($0.9 < p_T < 2.1$ GeV/c)

No deviation beyond 2σ from theory observed for $v_2^{\gamma,\mathrm{dir}}$

Comparison with direct photon flow at RHIC

ArXiv:1805.04403





$$\left(v_2^{\gamma,dir}\right)_{LHC} \approx \left(v_2^{\gamma,dir}\right)_{RHIC}$$

Conclusions

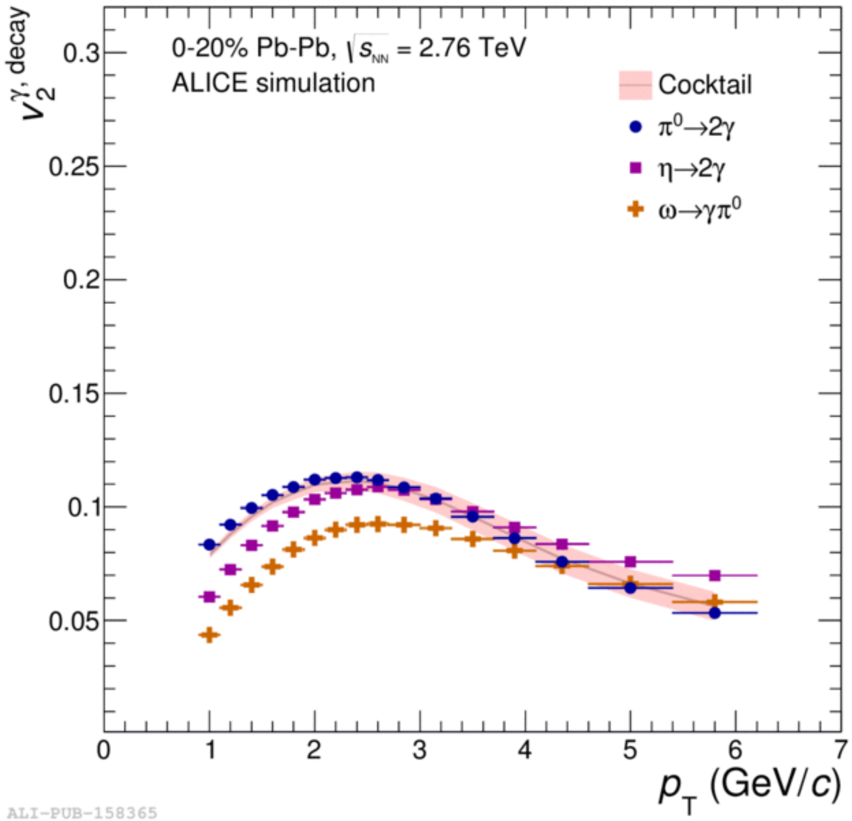
- γ^{dir} production in pp & p-Pb collisions:
  - No significant direct photon excess observed in thermal photon region
  - Consistent with N_{col} scaled NLO pQCD calculations at higher p_T
- γ^{dir} production and flow in Pb-Pb Collisions:
  - Direct photon excess for $p_T < 3$ GeV/c observed with 2.6σ for 0-20% and 1.5σ in 20-40% centrality classes
  - Spectrum consistent with N_{col} scaled NLO pQCD calculations at high p_T
  - Al low p_T spectrum consistent with hydrodynamic model predictions
  - Direct photon flow measurement with 2 independent reconstruction techniques in Pb–Pb collisions
  - Direct photon flow v_2 in centrality classes 0-20% & 20-40% of similar size as the charged hadron flow and inclusive photon flow, but compatible with 0 within 1.4(1.0)σ in p_T range ($0.9 < p_T < 2.1$ GeV/c)
- Direct photons confirm creation in Pb-Pb collisions of hot matter with significant collective expansion

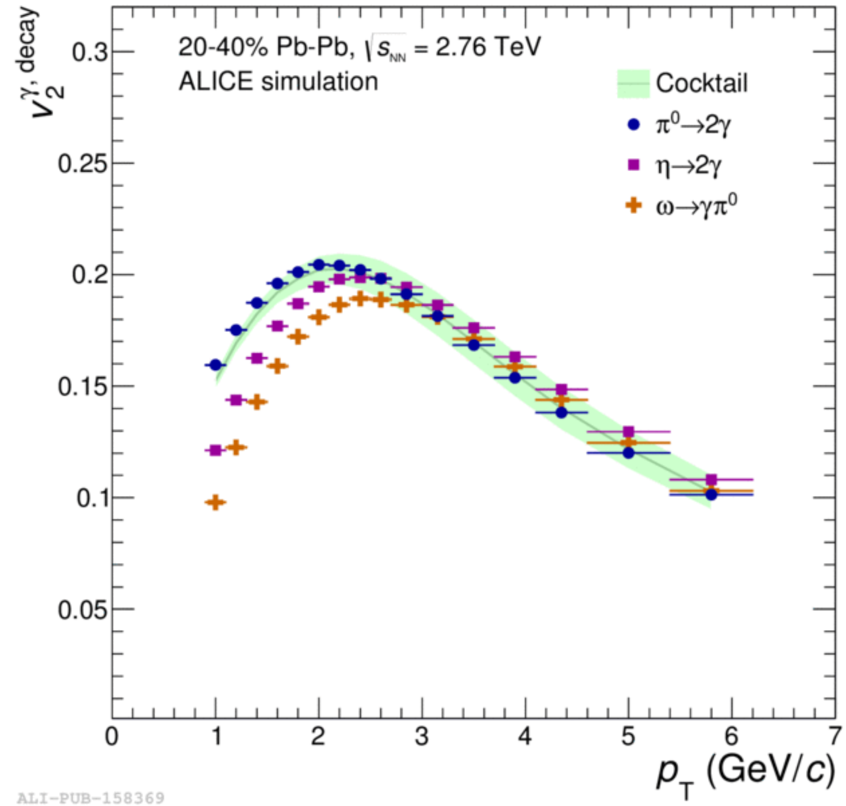
Acknowledgements

This work was supported by Russian Science Foundation grant 17-72-20234

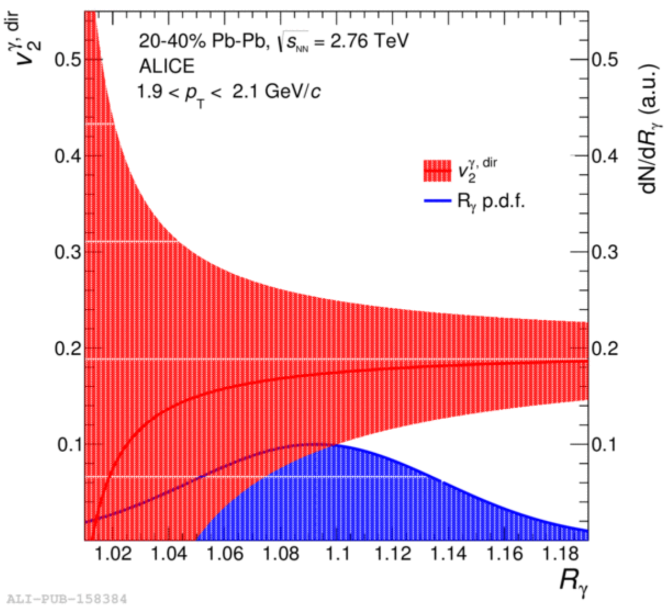
Backup

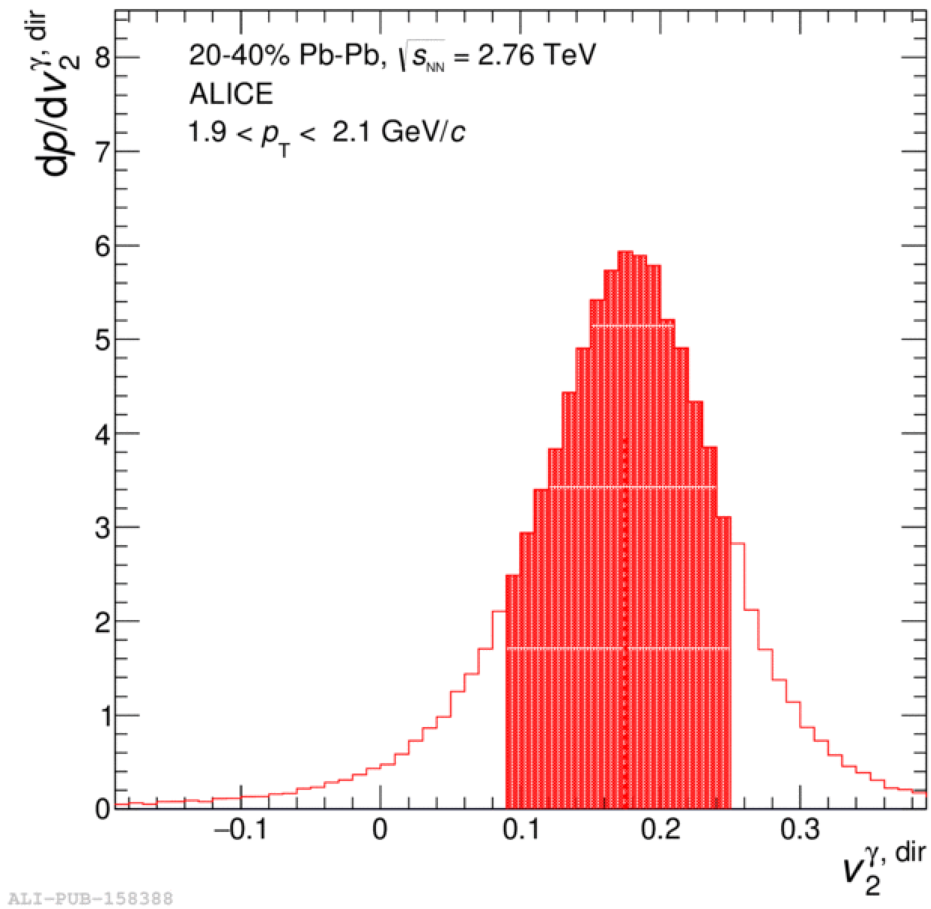
Decay photon flow





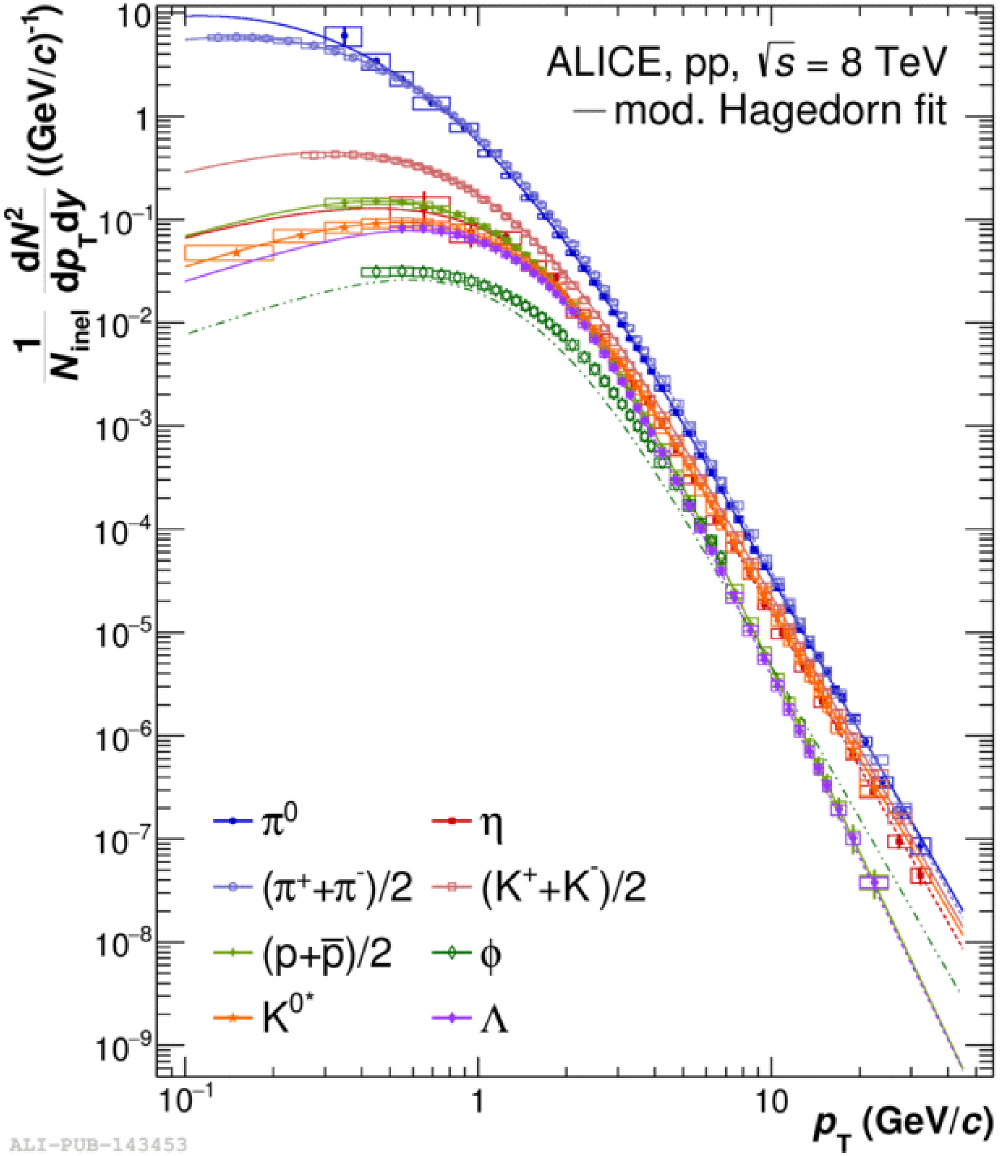
Direct photon flow uncertainties



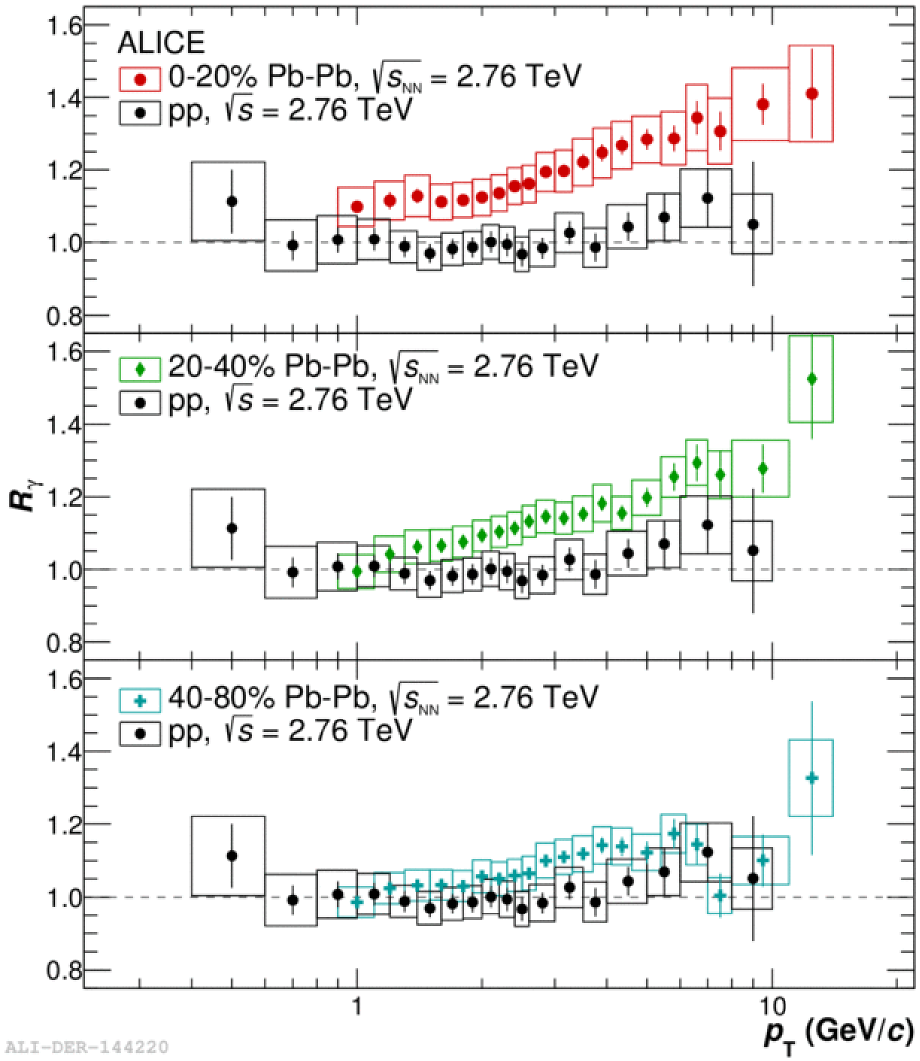


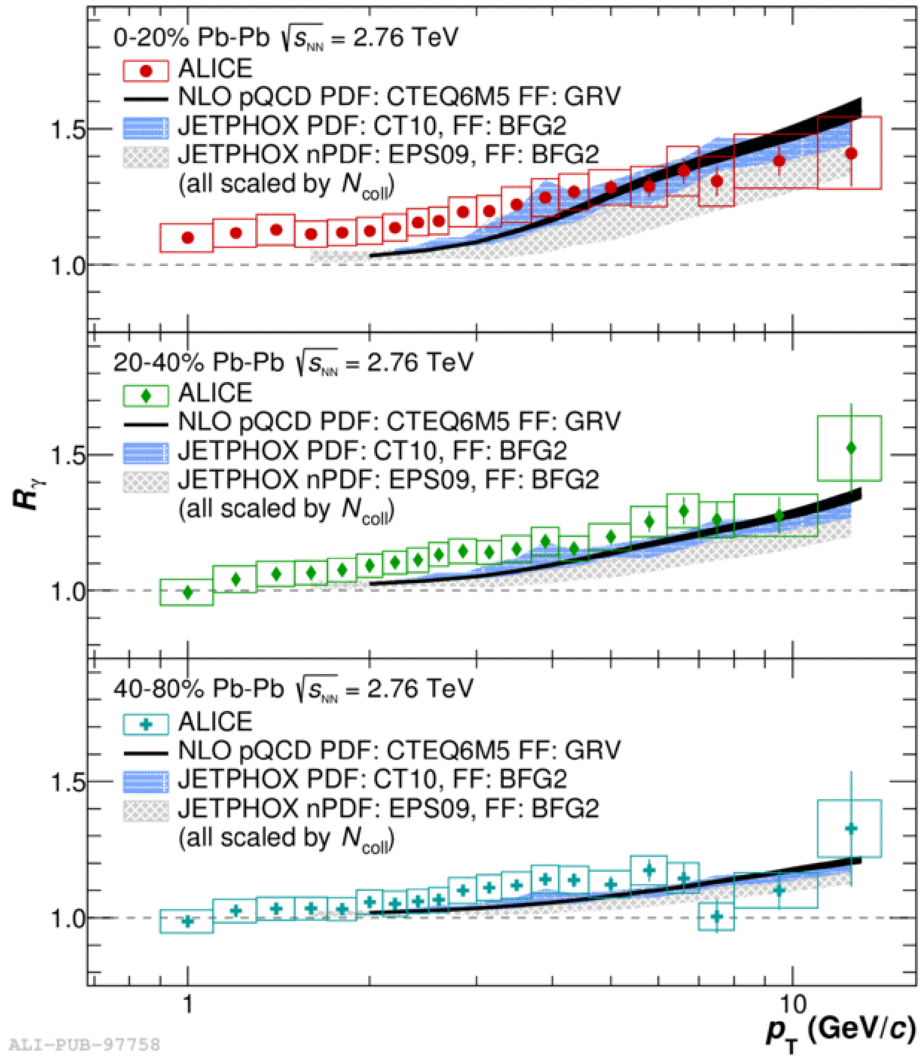
$$v_2^{\gamma,\mathrm{dir}} = \frac{R_\gamma \cdot v_2^{\gamma,\mathrm{inc}} - v_2^{\gamma,\mathrm{dec}}}{R_\gamma - 1}$$

Hadron spectra used for decay photon calculation

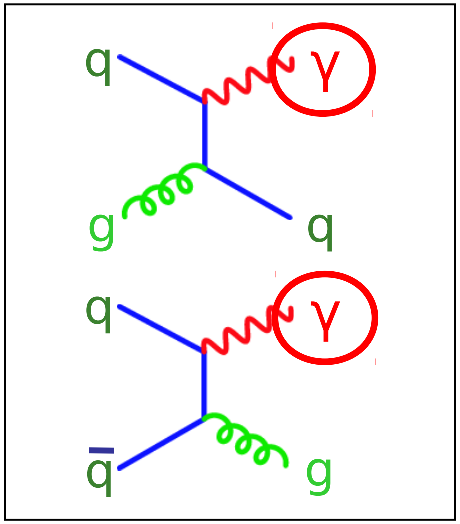


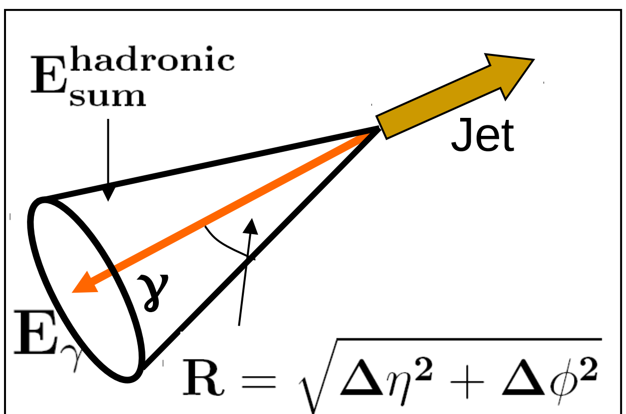
Direct photon excess in Pb-Pb



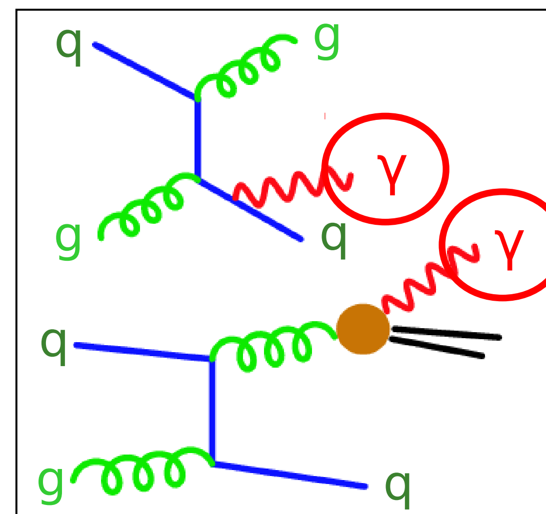


Direct and isolated photons





$$\mathbf{E_{sum}^{hadronic}(R < 0.5\ rad) < 0.1 \times E_\gamma}$$



Isolated photons