HARD PROBES 2018

International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

30 September 2018 to 5 October 2018 ● Aix-Les-Bains ● France

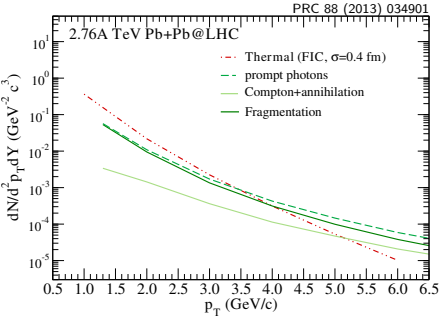
Direct Photon Production and Flow at Low Transverse Momenta in pp, p-Pb and Pb-Pb Collisions

OAK RIDGE National Laboratory

Nicolas Schmidt (ORNL/IKF)
for the ALICE Collaboration

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Direct Photons in pp, p–Pb and Pb–Pb Collisions



γ created during entire space time evolution after collision, leave medium unaffected

$\Rightarrow$ ideal probe

pp, p–Pb & Pb–Pb collisions

Prompt Photons

- Calculable within NLO pQCD
- Test of binary scaling in p–Pb & Pb–Pb at high p_T
- Not affected by collective expansion

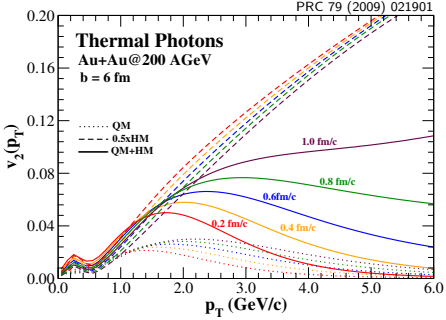
Additional sources Pb–Pb (p–Pb, pp?) collisions

Thermal Photons

- Scattering of thermalized particles
- Exponentially decreasing, dominant at low p_T
- Susceptible to flow evolution

Jet-Medium Interactions

- Scattering of hard partons with thermalized partons
- In-medium (photon) bremsstrahlung emitted by quarks
- Possibly affected by flow evolution



Direct Photon Extraction

Subtraction Method:

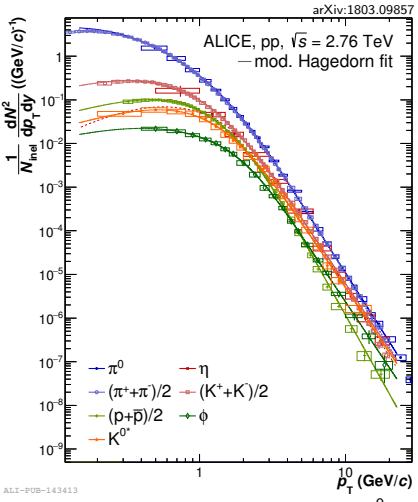
$$\gamma_{\text{direct}} = \gamma_{\text{inc}} - \gamma_{\text{decay}} = (1 - \frac{\gamma_{\text{decay}}}{\gamma_{\text{inc}}}) \cdot \gamma_{\text{inc}}$$

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

- **Inclusive photons:** measure all photons that are produced
- **Decay photons:** calculated by decay simulation from measured or m_T scaled particle spectra (PRC 96 064907)

Double Ratio:

$$R_\gamma = \frac{\gamma_{\text{inc}}}{\pi^0} / \frac{\gamma_{\text{decay}}}{\pi^0_{\text{param}}} \quad \text{if } R_\gamma > 1 \rightarrow \text{ direct photon signal}$$



Numerator: Measured inclusive γ spectrum per π^0 Denominator: Estimated sum of all decay photons per π^0

$\rightarrow$ advantage of ratio method: cancellation of some large uncertainties

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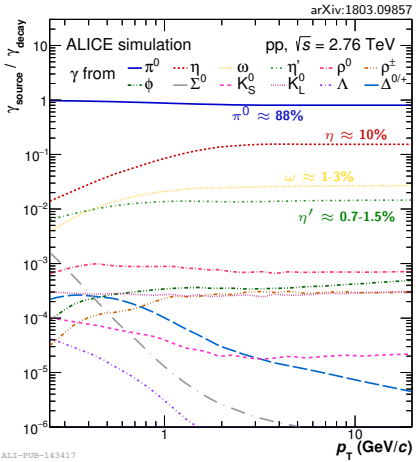

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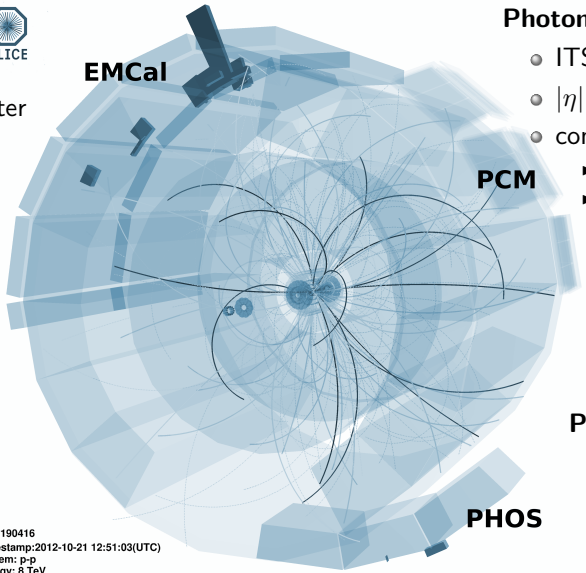
Measuring Photons, π^0 and η Mesons with ALICE

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 $\sim 8\%$

PHOS calorimeter

- $PbWO_4$ crystals
- $|\eta| < 0.12$, $260^\circ < \varphi < 320^\circ$

ALI-PERF-153661

Calorimeter configuration 2011-2013

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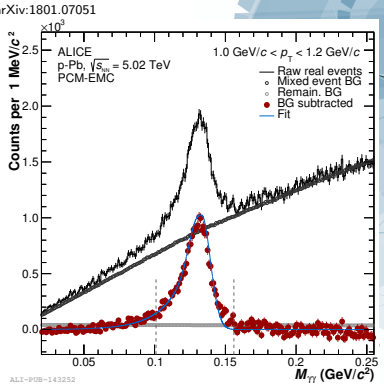

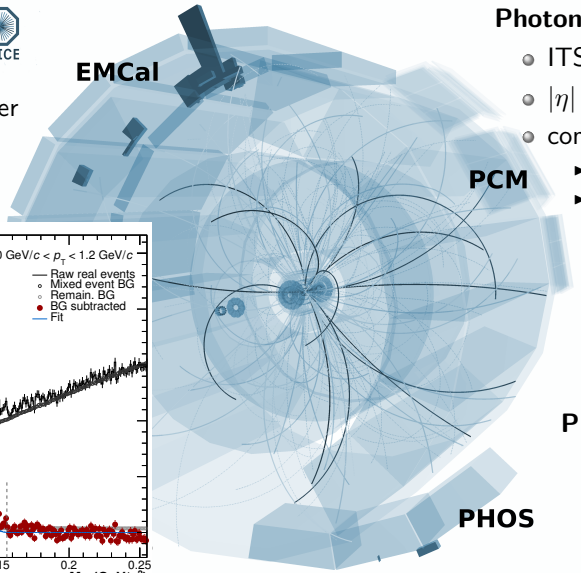

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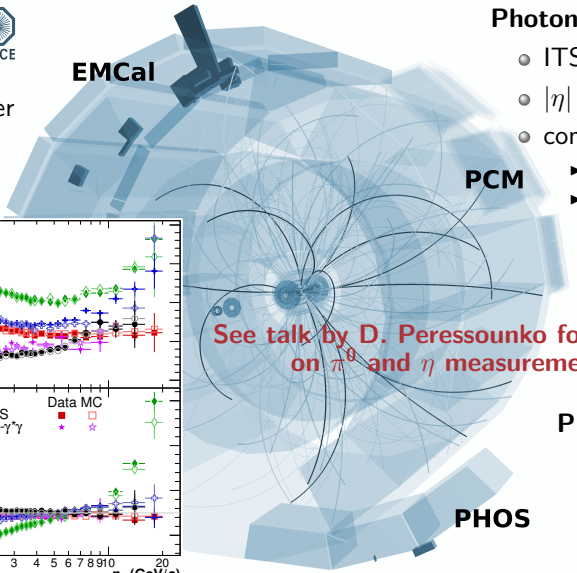

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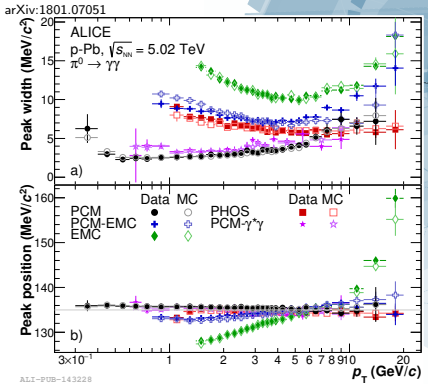

See talk by D. Peressounko for more information on π^0 and η measurements in ALICE

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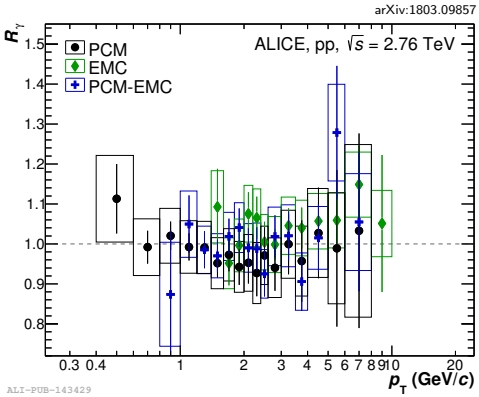

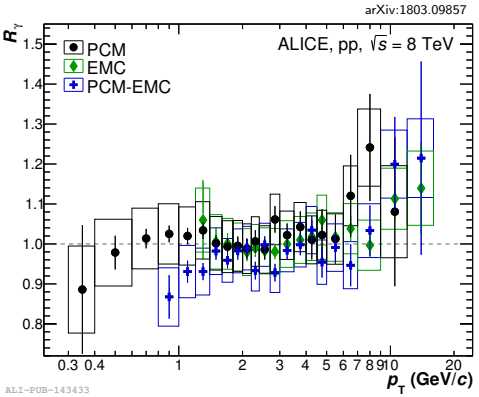

- Dominating systematic uncertainties:

→ p_T-independent material unc. of 4.5% PCM, 2.8% EMC

- p_T reach:

→ $0.4 < p_T < 10$ GeV/c in pp, $\sqrt{s} = 2.76$ TeV

→ $0.3 < p_T < 14$ GeV/c in pp, $\sqrt{s} = 8$ TeV

- Combination of 3 reconstruction techniques via BLUE method
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→ supports interpretation in Pb–Pb as medium effects

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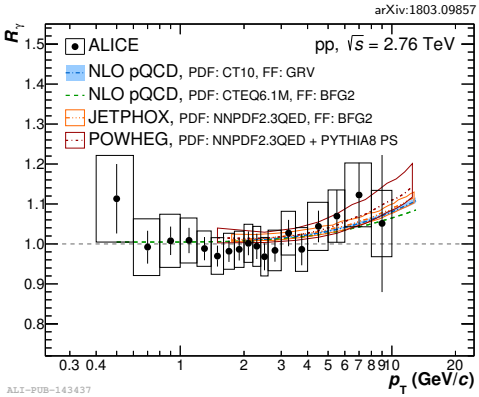

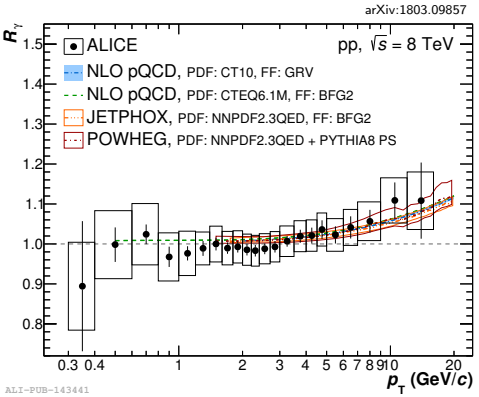

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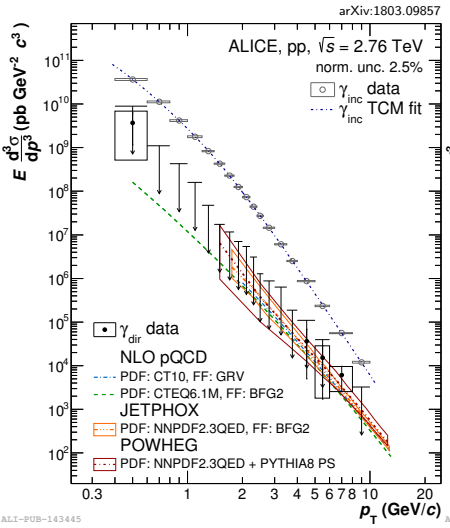
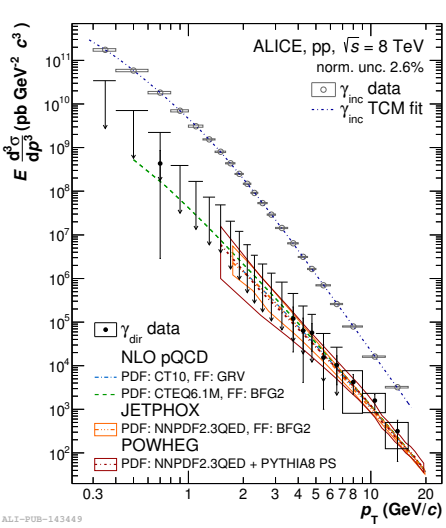
Direct Photons in pp Collisions (2)

- **Upper limits at 90% C.L.** (arrows) determined where R_γ with total uncertainties consistent with unity
- **NLO calculations consistent with measurements** at both pp energies

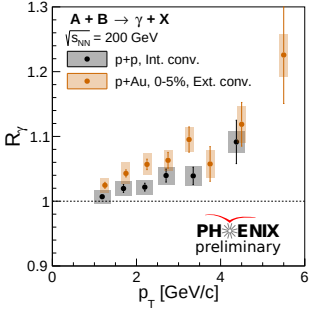


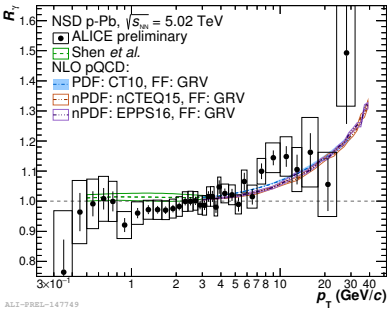


Theory calculations from:
W. Vogelsang (CT10/GRV), J.F. Paquet (CTEQ6.1M/BFG), JETPHOX, POWHEG

Direct Photons in p-Pb Collisions

From Quark Matter 2018





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- Additional PHOS reco. method
- p_T reach:

→ $0.3(0.4) < p_T < 32(24)$ GeV/c in NSD (mult. dep) p-Pb $\sqrt{s_{NN}} = 5.02$ TeV

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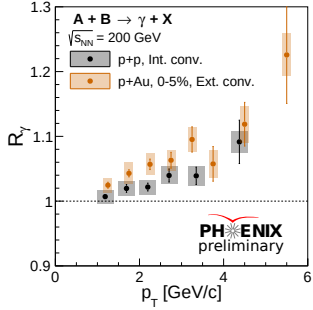
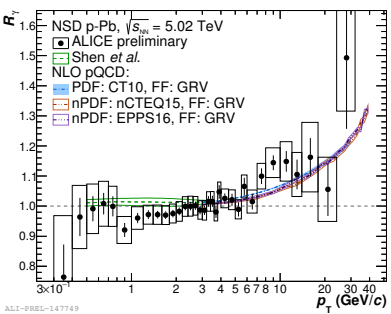
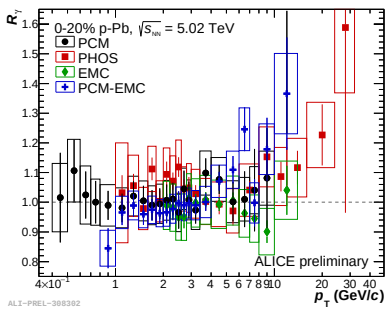
Direct Photons in p-Pb Collisions

First multiplicity dependent γ_{dir} measurement in p-Pb in ALICE







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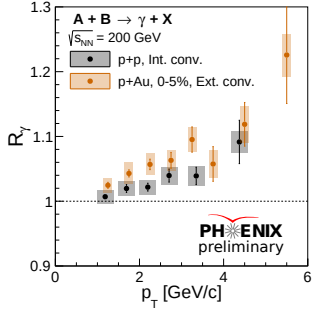

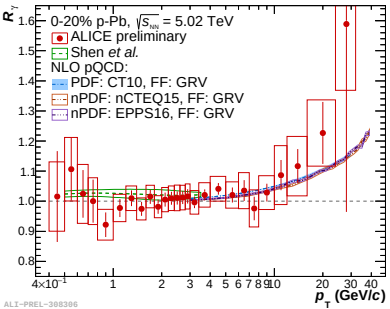

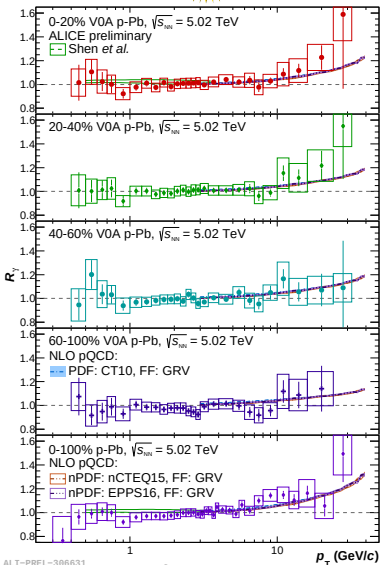

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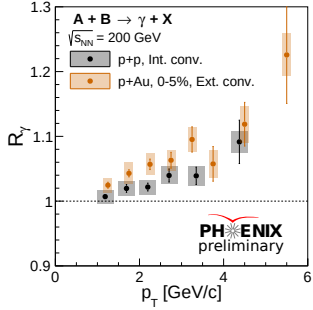

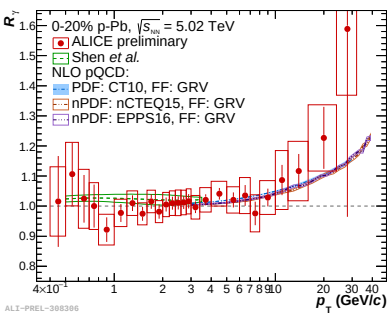

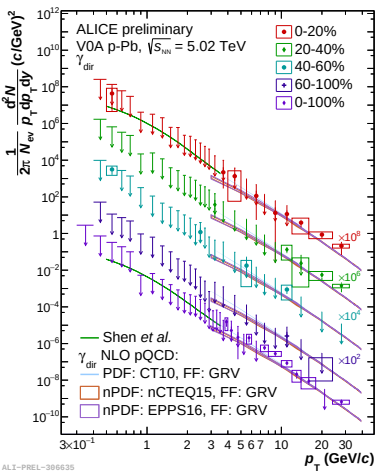

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Direct Photons in Pb-Pb

- Direct photon excess measured with combined PCM + PHOS in 3 centrality classes with 2010 Pb–Pb data
- R_γ **excess at high** p_T **for all centralities**
- γ^{dec} suppressed by $\approx R_{AA}^{\pi^0}$
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- **Low** $p_T \sim 15\%$ **excess in** $0-20\%$ **and** $\sim 9\%$ **in** $20-40\%$
- In agreement with NLO pQCD, JETPHOX above 5 GeV/c
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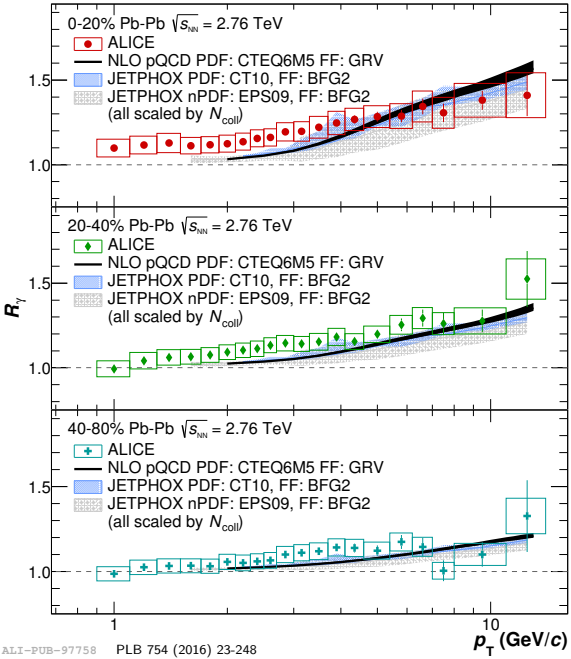
- **Scaled pp spectrum & upper limits fully consistent with Pb–Pb results**



ALI-PUB-97758 PLB 754 (2016) 23-248

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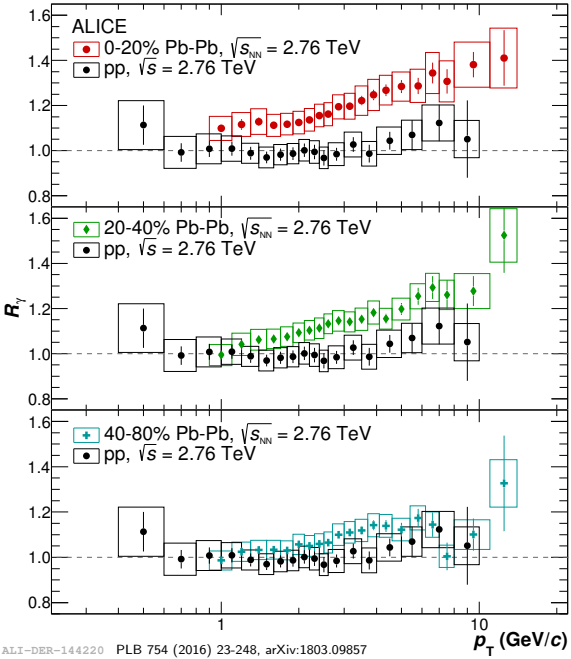

ALI-DER-144220 PLB 754 (2016) 23-248, arXiv:1803.09857

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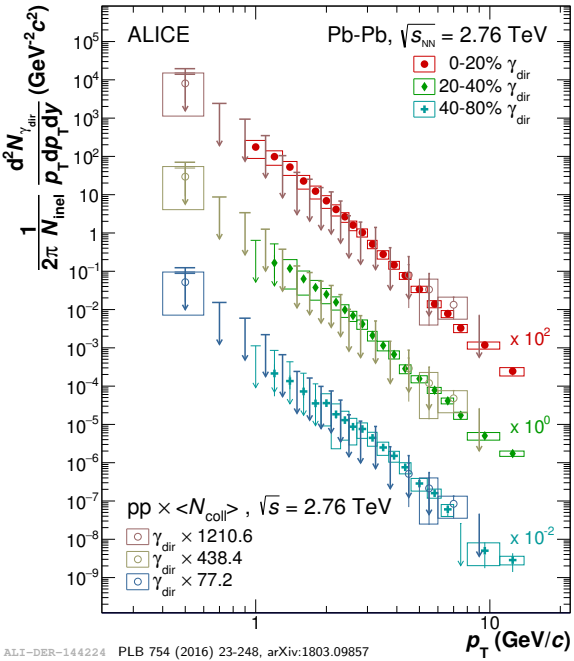


ALI-DER-144224 PLB 754 (2016) 23-248, arXiv:1803.09857

Cocktail Simulation of Decay Photon v_2

Decay photon v_2:

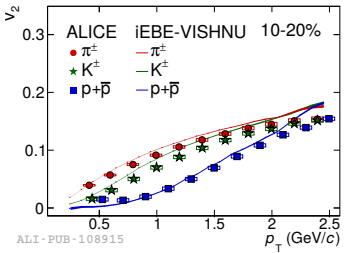
- KE_T scaling: v_2 of mesons scales with KE_T
  $KE_T = m_T - m = \sqrt{p_T^2 + m^2} - m$

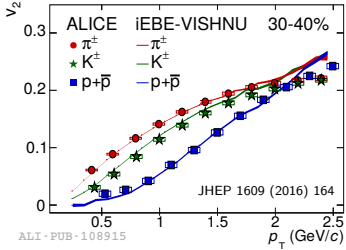
$\Rightarrow v_2^{\pi^0} \approx v_2^{\pi^\pm}$ $(m^{\pi^0} \approx m^{\pi^\pm})$

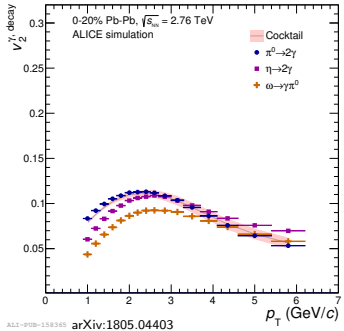
$\rightarrow$ v_2 of various mesons (X) calculated via KE_T (quark number) scaling from $v_2^{K^\pm}$

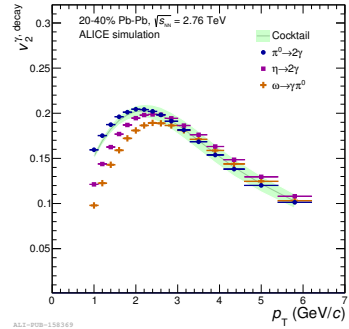
$$v_2^X(p_T^X) = v_2^{K^\pm}\left(\sqrt{(KE_T^X + m^{K^\pm})^2 - (m^{K^\pm})^2}\right)$$

- **Decay photon v_2 from different mesons obtained from cocktail calculation**









arXiv:1805.04403

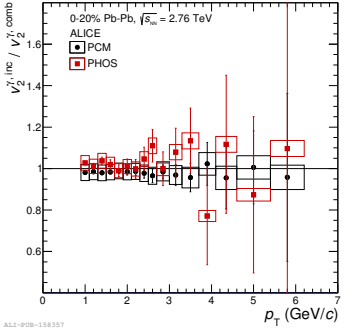
v_2^{γ} Inclusive and Decay

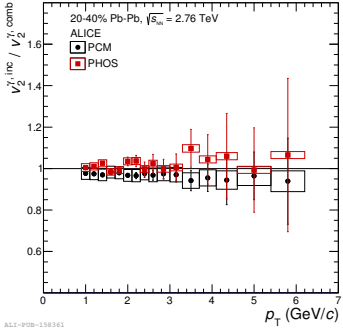
- $v_2^{\gamma,\mathrm{inc}}$ measured with PCM & PHOS

→ Corrected for BG flow from impurities
[JPG 44 (2917) no. 2, 025106]

→ Assumed to be independent

→ Consistent, p-values of
0.93 (0-20%) & 0.43 (20-40%)





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→ Consistent, p-values of 0.93 (0-20%) & 0.43 (20-40%)

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

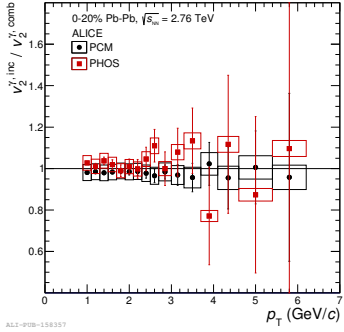
⇒ Either no contribution of γ_{dir} or $v_2^{\gamma,\mathrm{inc}} \approx v_2^{\gamma,\mathrm{dec}}$

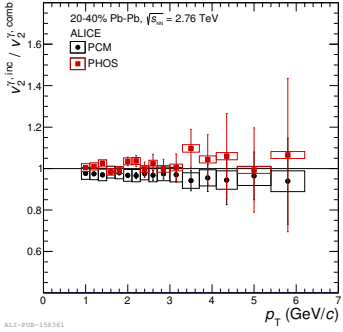
→ Theory $\sim 30 - 40\%$ too high

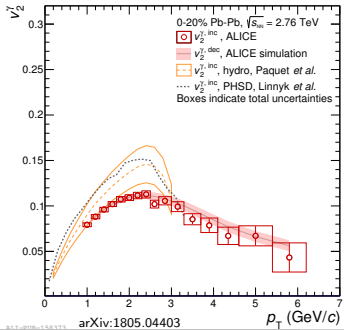
- $\mathbf{p_T > 3\ GeV/}c$: $\mathbf{v_2^{\gamma,inc} < v_2^{\gamma,dec}}$

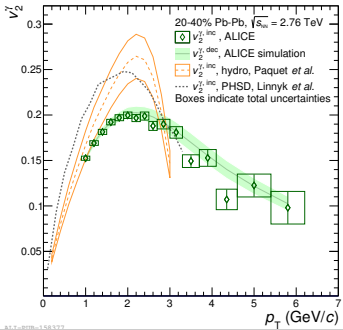
→ Direct photon v_2 contribution with $v_2^{\mathrm{direct}} < v_2^{\mathrm{decay}}$

→ Mainly prompt photons









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Direct Photon v_2 in 0-20% & 20-40% Pb-Pb Collisions

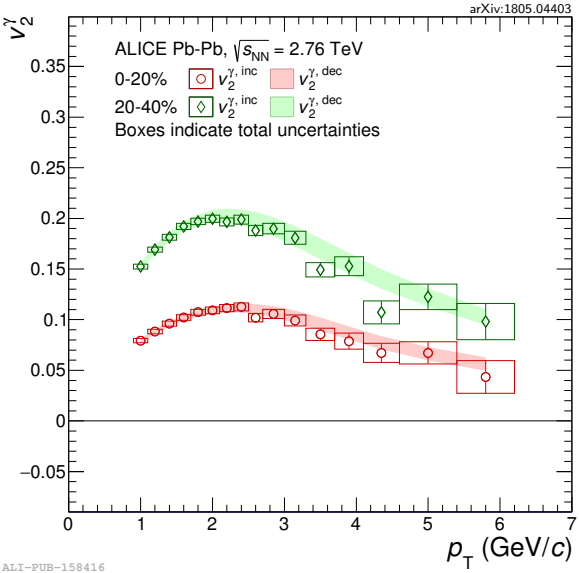
Direct photon v_2:

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

- Measured R_γ often less than $2\sigma_{\mathrm{sys}}$ deviation from 1

$\Rightarrow$ Central value & unc. calculated using MC simulation following Bayesian approach with probability distributions of true (t) values of $R_\gamma^{\mathrm{t}}(p_{\mathrm{T}})$, $v_2^{\gamma,\mathrm{dec,t}}(p_{\mathrm{T}})$, $v_2^{\gamma,\mathrm{inc,t}}(p_{\mathrm{T}})$ assuming R_γ^{t} can't be smaller than unity & partially p_{T}-correlated unc.

- **Large direct photon v_2 for $p_{\mathrm{T}} < 3$ 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



ALI-PUB-158416

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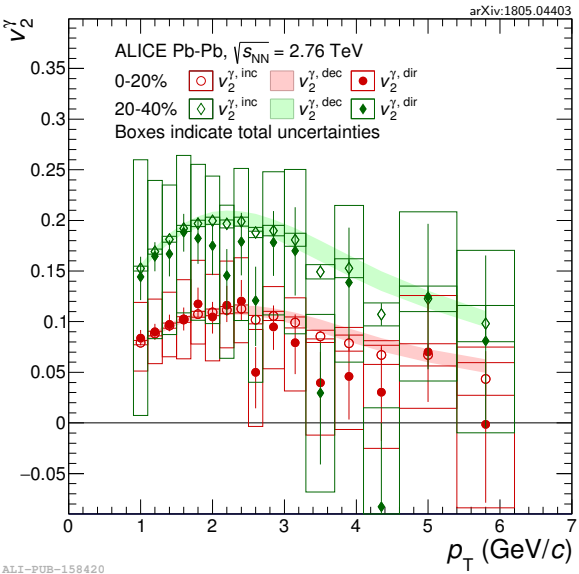
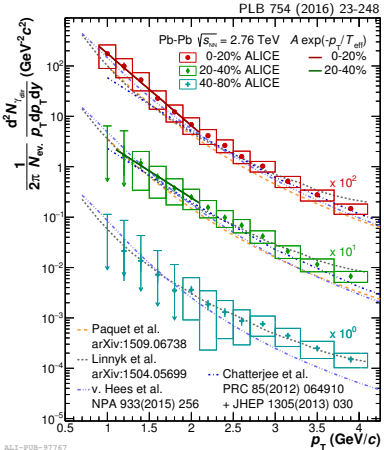


ALI-PUB-158420

Direct Photon Yield and Flow

- Central points for direct photon yield and $v_2^{\gamma,\mathrm{dir}}$ **underestimated by most theoretical calculations**
  by factors of 2-5



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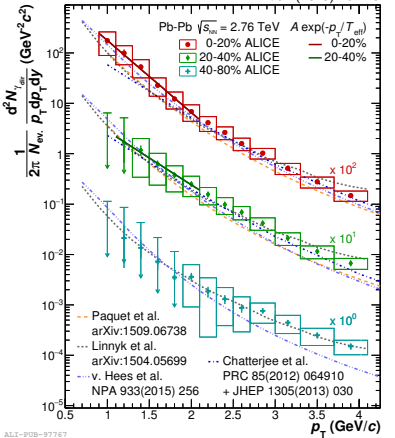
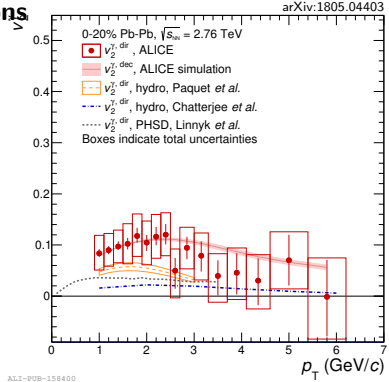
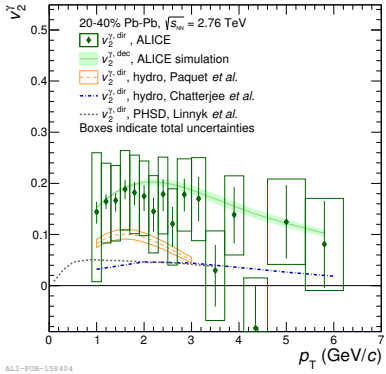


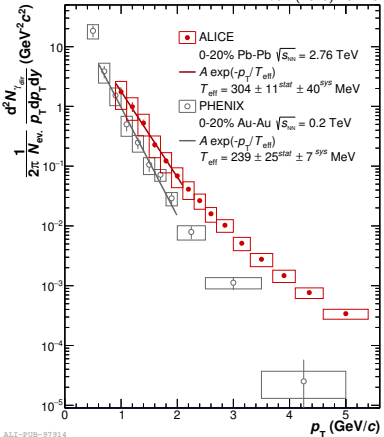


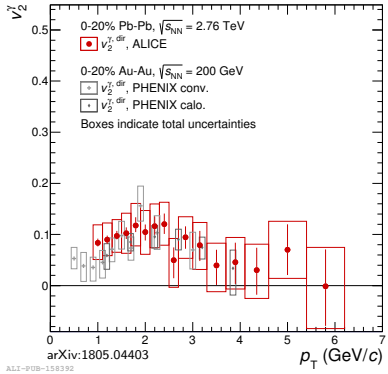


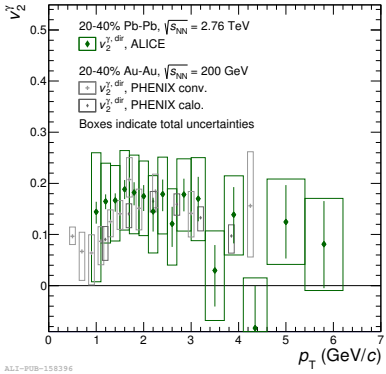
- $v_2^{\gamma,\mathrm{dir}}$ compatible with $v_2^{\gamma,\mathrm{dir}} = 0$ within $1.4(1.0)\sigma$ in p_T range $(0.9 < p_T < 2.1$ GeV$/c)$ in 0-20%(20-40%) centrality
- No deviation beyond 2σ from theory observed for spectra or v_2
- Similar observations for all theoretical calculations despite very different setups

Direct Photon Yield and Flow - Comparison to PHENIX

- Photon yield increased by factor ≈ 2 for $p_T < 3$ GeV/c
- Larger T_{eff} for direct photons at LHC energies







- v_2 compatible with v_2 measured at $\sqrt{s_{NN}} = 0.2$ TeV
- **Similar scaling behavior of direct photon v_2 as for charged hadrons**
- Higher significance for PHENIX result due to larger signal in R_{γ} at Au-Au $\sqrt{s_{NN}} = 0.2$ TeV

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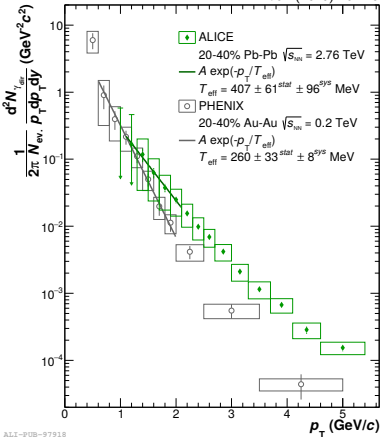

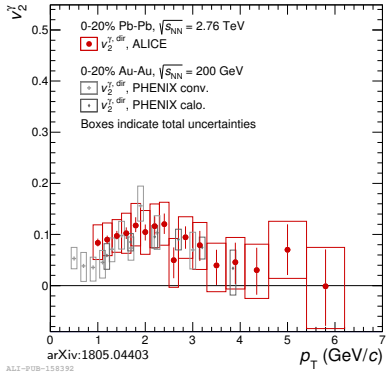

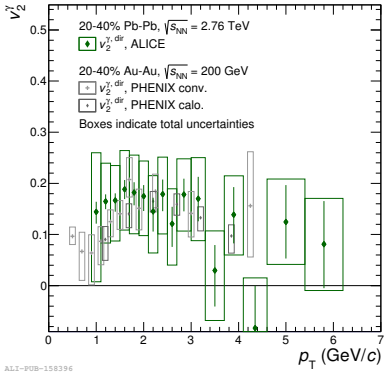

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Summary

γ_{dir} production in pp & p-Pb collisions:

- First direct photon measurements at the LHC for pp and p-Pb collisions at low transverse momenta
  $\rightarrow$ New measurement of multiplicity dependence of γ_{dir} in p-Pb NEW!
- No significant direct photon excess observed in thermal photon region ($p_{\text{T}} < 3$ GeV/c)
- Consistent with NLO pQCD calculations at higher p_{T}

γ_{dir} production and flow in Pb-Pb Collisions:

- Direct photon excess for $p_{\text{T}} < 3$ GeV/c observed with 2.6σ for 0-20% and 1.5σ in 20-40% consistent with theory expectations
- Spectrum consistent with NLO pQCD calculations at high p_{T}
- First direct photon flow measurement at the LHC with 2 independent reconstruction techniques in 0-20% and 20-40% Pb–Pb collisions
- Direct photon v_2 in 0-20% & 20-40% of similar size as the charged hadron flow and inclusive photon flow, but compatible with 0 within 1.4σ or 1.0σ in p_{T} range ($0.9 < p_{\text{T}} < 2.1$ GeV/c)