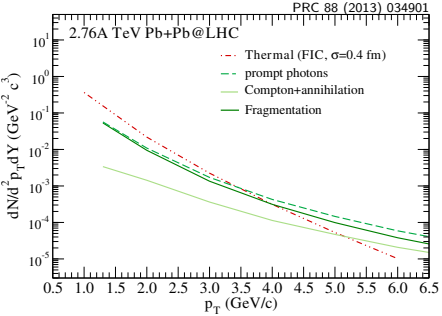
Direct Photon Production and Flow at Low Transverse Momenta in pp, p-Pb and Pb-Pb Collisions

Friederike Bock for the ALICE Collaboration
CERN

Main Publications

PLB 754 (2016) 235-248 - arXiv:1509.07324
arXiv:1803.09857
Poster ELW-23, Mike Sas - arXiv:1805.04403

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

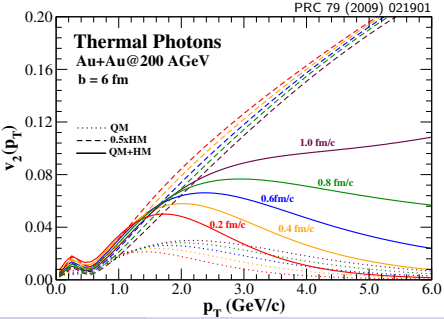
Additional sources Pb–Pb (p–Pb, pp?) collisions

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:

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

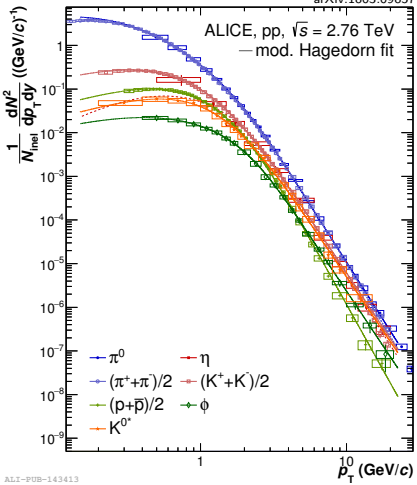
$$= (1 - \frac{1}{R_\gamma}) \cdot \gamma_{\text{inc}}$$

- Inclusive photons: measure all photons that are produced
- Decay photons: calculated by decay simulation from measured or m_T scaled particle spectra

Double Ratio:

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

arXiv:1803.09857



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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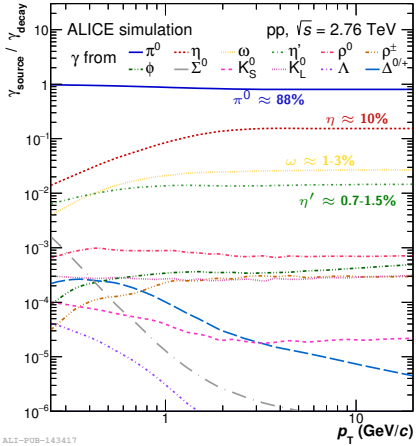

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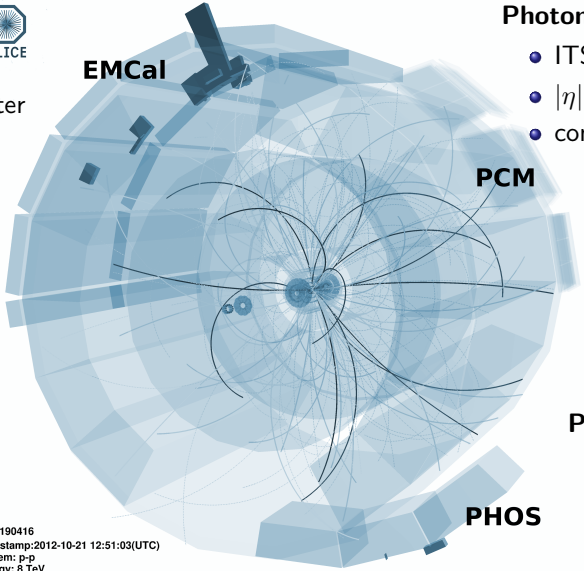
Measuring Photons, π^0 and η Mesons with ALICE

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
- $|\eta| < 0.12$, $260^\circ < \varphi < 320^\circ$ (2009-2013)

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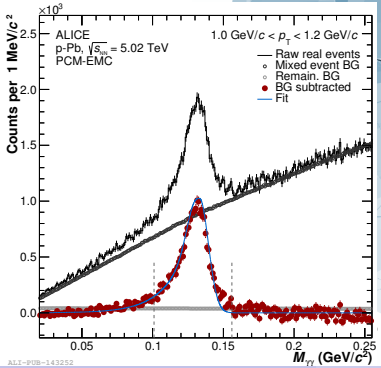
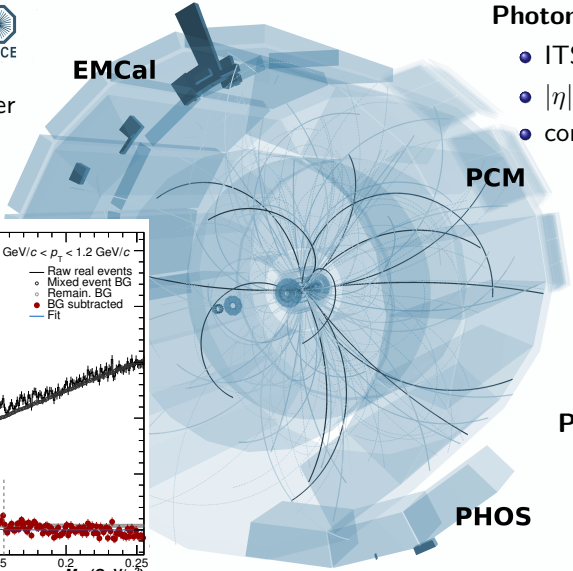
arXiv:1801.07051





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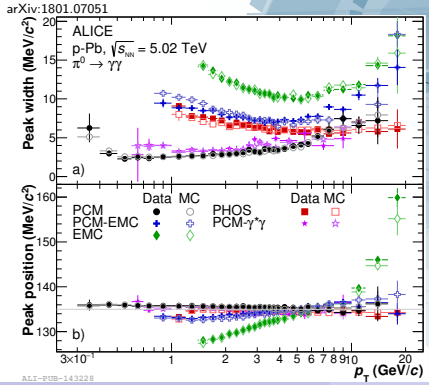

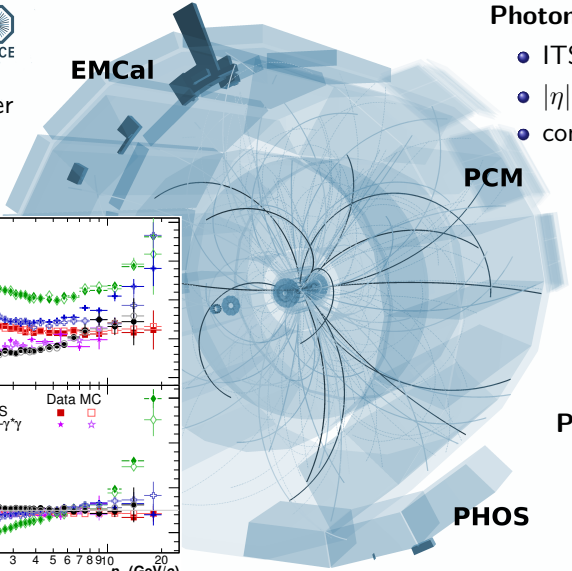

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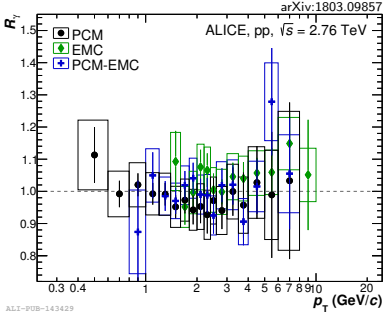

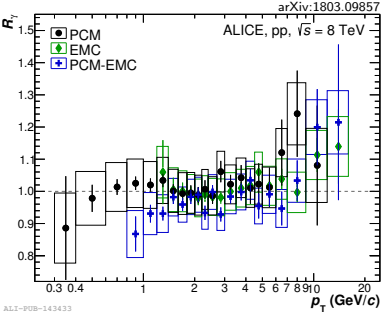

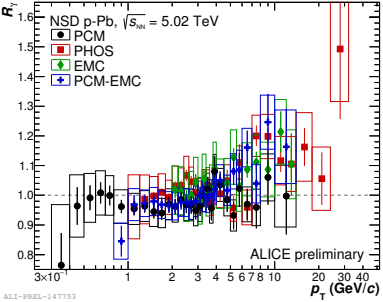

- Systematic uncertainties of individual meas.
  $\rightarrow$ dominated by p_T-independent
  material unc. of 4.5% PCM, 2.8% EMC &
  global E-scale unc. 3% PHOS
- p_T reach
  - $0.4 < p_T < 10$ GeV/c in pp, $\sqrt{s} = 2.76$ TeV
  - $0.3 < p_T < 14$ GeV/c in pp, $\sqrt{s} = 8$ TeV
  - $0.3 < p_T < 32$ GeV/c in p-Pb $\sqrt{s_{NN}} = 5.02$ TeV

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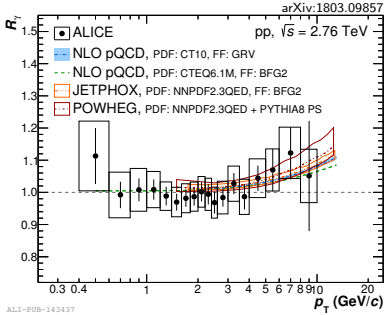

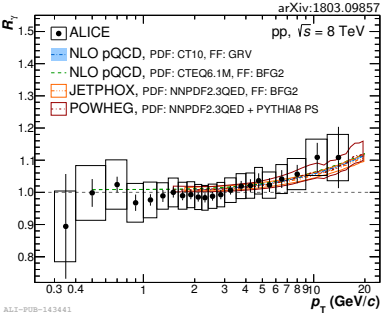

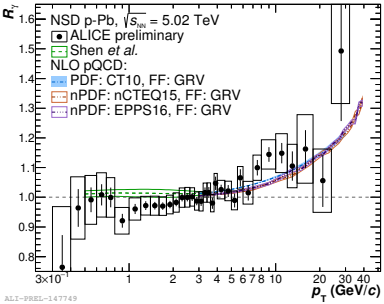

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- Combination of 3 (4) reconstruction techniques via BLUE method
- NLO prediction plotted as
  $$R_{\mathrm{NLO}} = 1 + (\gamma_{\mathrm{dir}}^{\mathrm{NLO}} \cdot N_{\mathrm{Coll}})/\gamma_{\mathrm{dec}}$$
- Within uncertainties no significant excess at low p_T observed

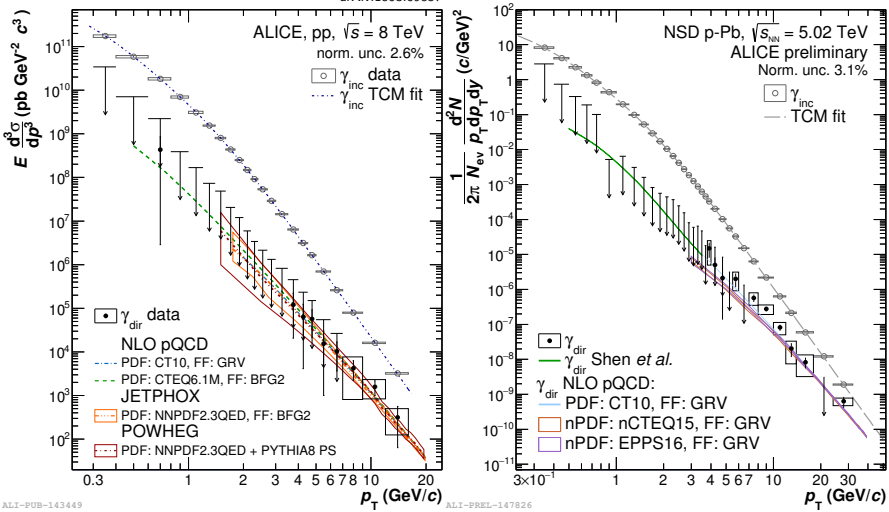
$\rightarrow$ supports interpretation in Pb–Pb as medium effects

- About $1-2\sigma$ deviation from unity for $p_T > 7$ GeV/c

Direct Photons in pp & p–Pb (2)

- Upper limits at 90% C.L. (arrows) determined where R_γ with total uncertainties consistent with unity
- NLO & thermal *(Shen et al.)* calculations consistent with measurements at all pp energies and for NSD p–Pb collisions

arXiv:1803.09857

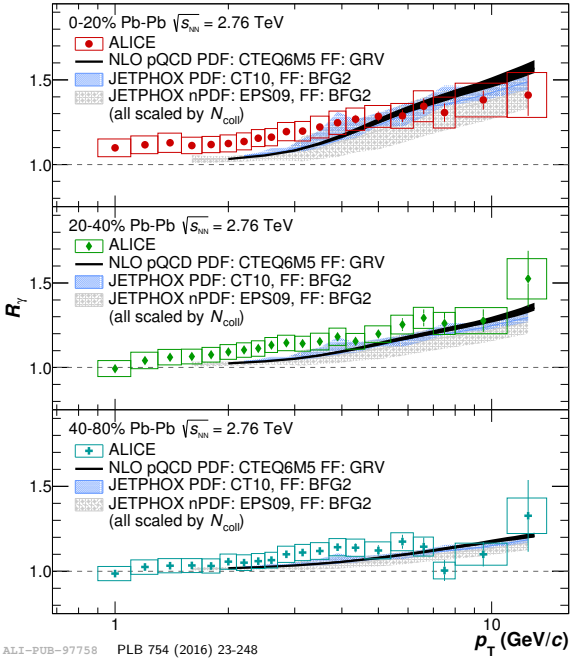


Theory calculations from:
W. Vogelsang (CT10,nCTEQ15,EPPS16/GRV), J.F. Paquet (CTEQ6.1M/BFG), C. Shen , JETPHOX, POWHEG

Shen *et al.* arXiv:1609.02590

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 $\approx R_{AA}^{\pi^0}$
  $\rightarrow$ larger excess in central collisions
- 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
- No low p_T excess seen in pp collisions at same center-of-mass energy
- Scaled pp spectrum & upper limits fully consistent with Pb–Pb results



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

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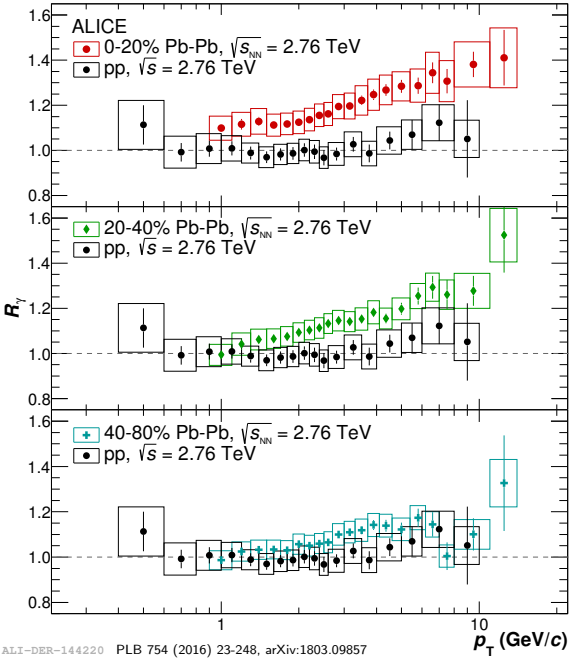

ALI-DER-144220 PLB 754 (2016) 23-248, arXiv:1803.09857

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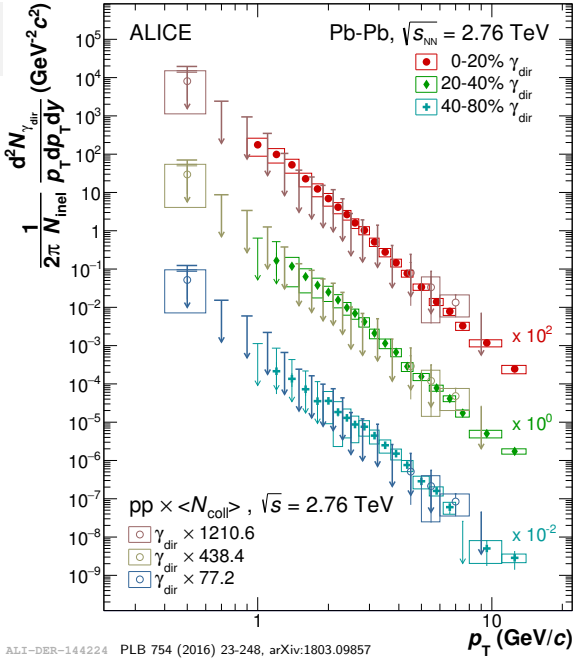


ALI-DER-144224 PLB 754 (2016) 23-248, arXiv:1803.09857

Cocktail Simulation of Decay Photon v_2

Decay photon v_2:

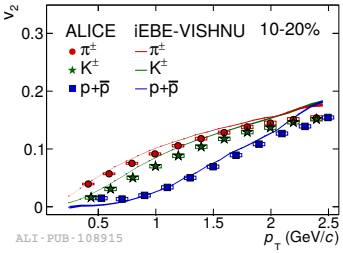
- KE_T scaling: v_2 of mesons scales with KE_T
  $KE_T = m_T - m = \sqrt{p_T^2 + m^2} - m$

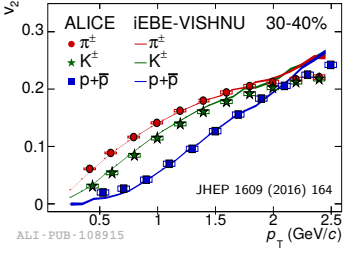
$\Rightarrow$ $v_2^{\pi^0} \approx v_2^{\pi^\pm}$ $(m^{\pi^0} \approx m^{\pi^\pm})$

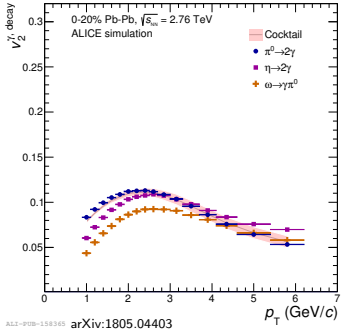
$\rightarrow$ v_2 of various mesons (X) calculated via KE_T (quark number) scaling from $v_2^{K^\pm}$

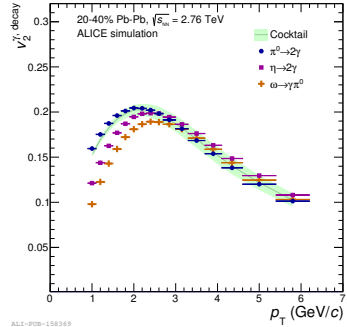
$$v_2^X(p_T^X) = v_2^{K^\pm}\left(\sqrt{(KE_T^X + m^{K^\pm})^2 - (m^{K^\pm})^2}\right)$$

- Decay photon v_2 from different mesons obtained from cocktail calculation









arXiv:1805.04403

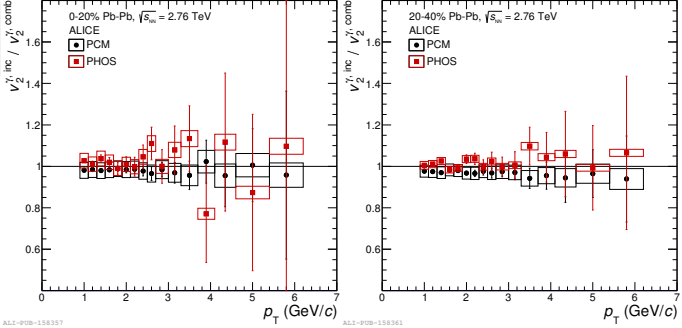
v_2^{γ} Inclusive and Decay

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

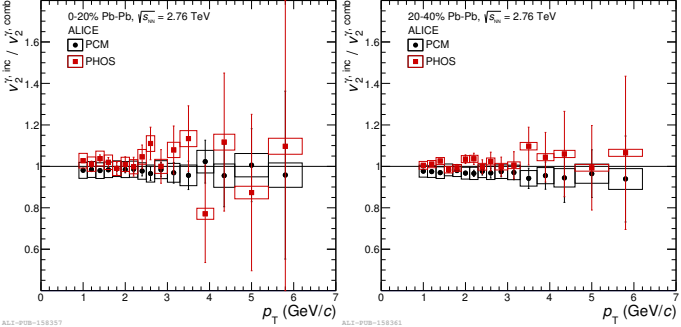
⇒ Either no contribution of γ_{dir}
or $v_2^{\gamma,\mathrm{inc}} \approx v_2^{\gamma,\mathrm{dec}}$

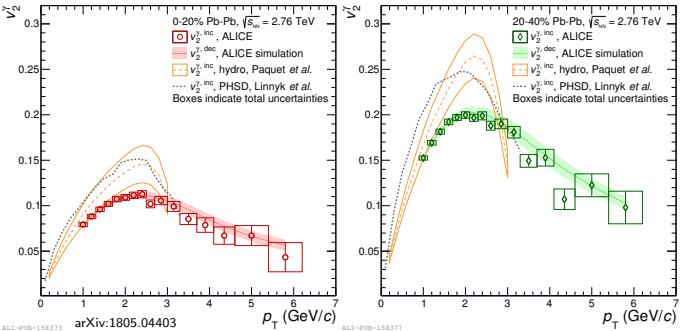
→ Theory $\sim 30 - 40\%$ too high

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

→ 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 0-20 & 20-40

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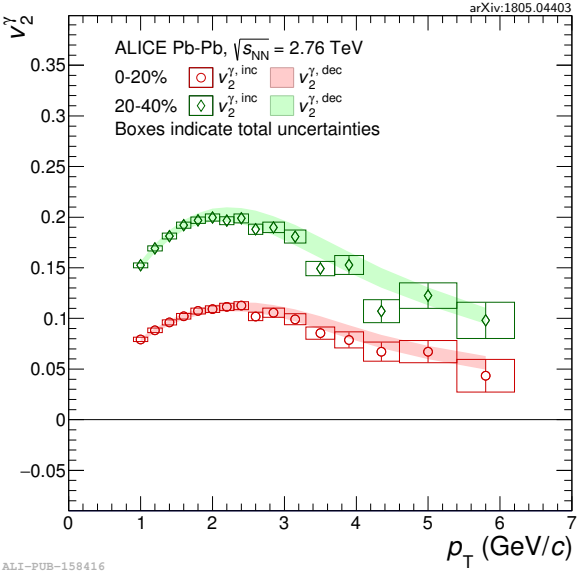
$$v_2^{\gamma,\mathrm{dir}} = \frac{R_\gamma \cdot v_2^{\gamma,\mathrm{inc}} - v_2^{\gamma,\mathrm{dec}}}{R_\gamma - 1}$$

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

⇒ Central value & unc. calculated using MC simulation following Bayesian approach with probability distributions of true 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 can't be smaller 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



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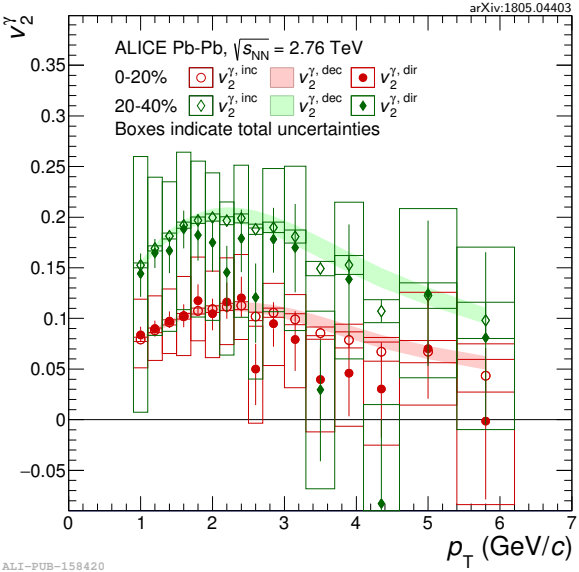

Direct Photon Yield and Flow

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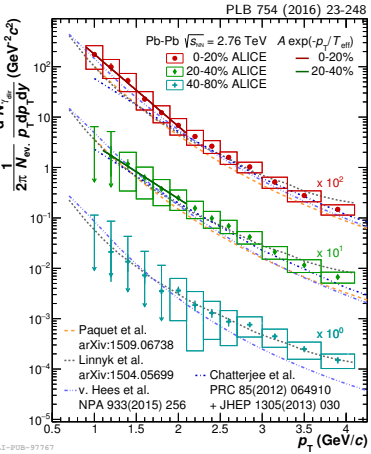

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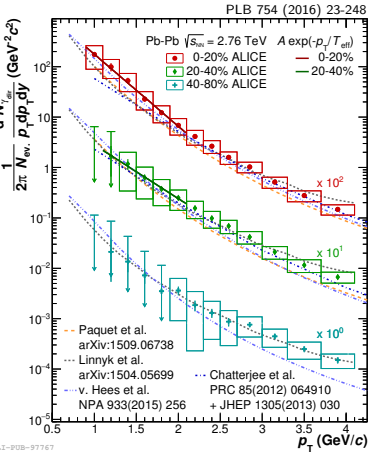

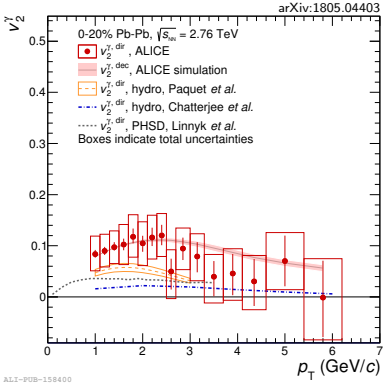

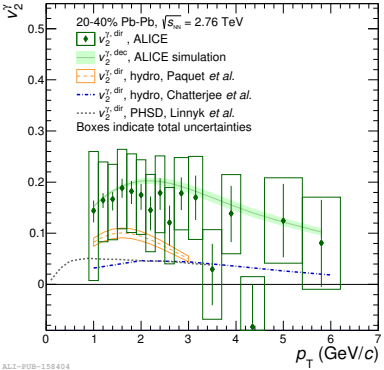

- $v_2^{\gamma,\mathrm{dir}}$ compatible with $v_2^{\gamma,\mathrm{dir}} = 0$ within $1.4(1.0)\sigma$ in p_T range ($0.9 < p_T < 2.1$ GeV/c)
- No deviation beyond 2σ from theory observed for spectra or v_2
- Similar observations for all theoretical calculations despite very different setups

Direct Photon Yield and Flow - Comparison to PHENIX

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

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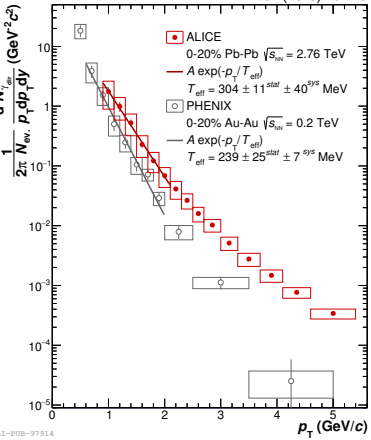

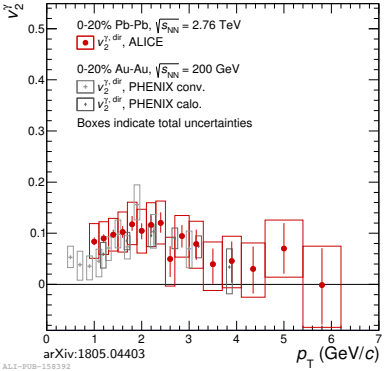

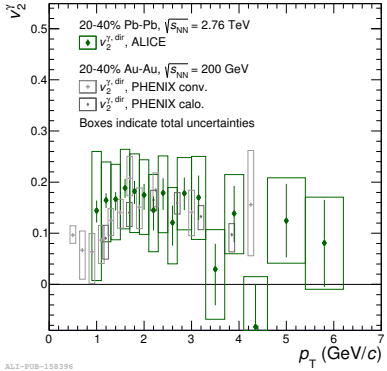

- v_2 compatible with v_2 measured at $\sqrt{s_{NN}} = 0.2$ TeV
- Similar scaling behavior of direct photon v_2 as for charged hadrons
- Larger significance for PHENIX result due to larger R_γ and larger significance of R_γ at $\sqrt{s_{NN}} = 0.2$ TeV

Direct Photon Yield and Flow - Comparison to PHENIX

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

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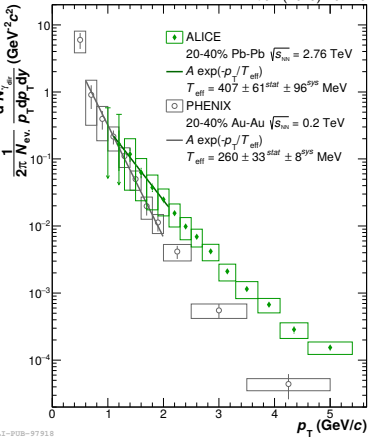

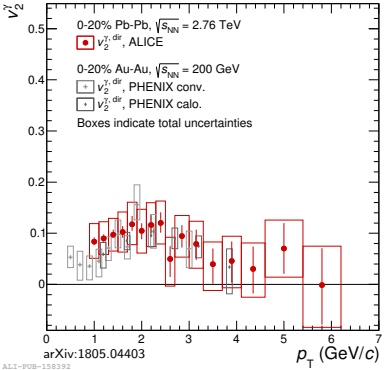

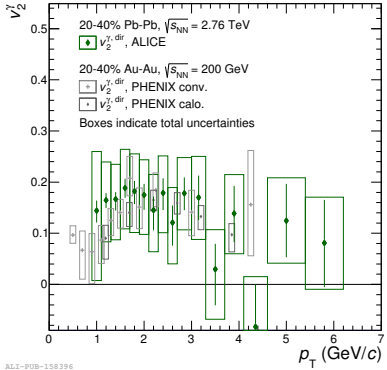

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Summary

γ_{dir} production in pp & pPb collisions:

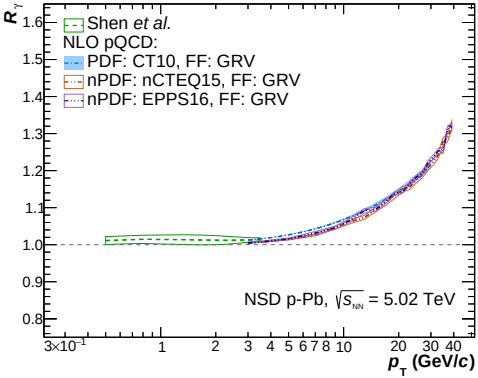
- First direct photon measurements at the LHC for pp and p–Pb collisions at low transverse momenta
- No significant direct photon excess observed in thermal photon region ($p_{\mathrm{T}} < 3$ GeV/c)
- Consistent with NLO pQCD calculations at higher p_{T}

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

- Direct photon excess for $p_{\mathrm{T}} < 3$ 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 $1.4(1.0)\sigma$ in p_{T} range ($0.9 < p_{\mathrm{T}} < 2.1$ GeV/c)

Backup Slides

Direct Photons in pp, p–Pb, 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
- Dominant at high p_T
- Test of binary scaling in Pb–Pb

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

Thermal Photons

- Scattering of thermalized particles
- Exponentially decreasing but dominant at low p_T

Jet-Medium Interactions

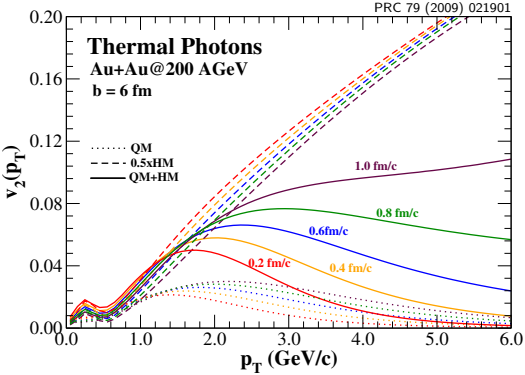
- Scattering of hard partons with thermalized partons
- In-medium (photon) bremsstrahlung emitted by quarks

Direct Photon Flow

Initial azimuthal asymmetry in coordinate space in non-central A+A
$\Rightarrow$ asymmetry in momentum space

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

- v_2: elliptic flow, collective expansion at low p_T
- v_3: triangular flow

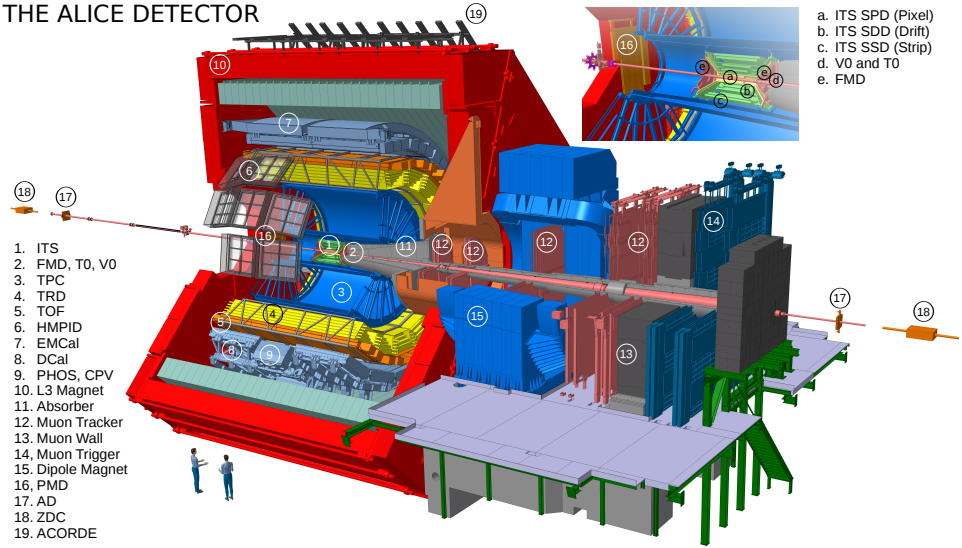


Thermal Photon v_2

- Constrains onset of direct photon production
  - Early production $\rightarrow$ small v_2
  - Late production $\rightarrow$ hadron-like v_2

Measuring photons, π^0 and η Mesons in ALICE

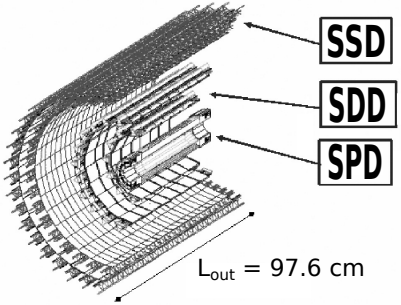
THE ALICE DETECTOR

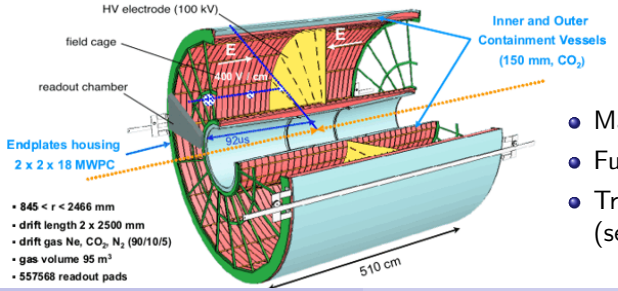


Closer Look at the Central Barrel - ITS and TPC

Inner Tracking System - ITS

- Full azimuth coverage, six cylindrical layers
- Three different detector types: silicon pixel / drift / stripes
- Designed for primary / secondary vertex finding (inner radius $R_{BP} = 2.94\,\mathrm{cm}$)
- Tracks charged particles down to $p_T = 100\,\mathrm{MeV/c}$

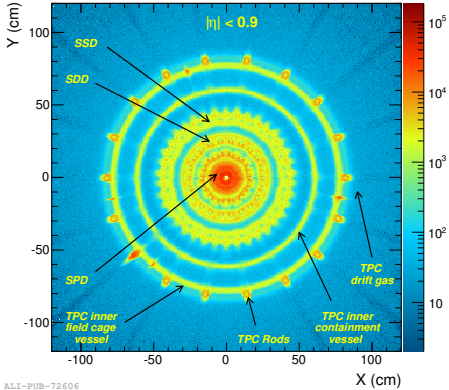


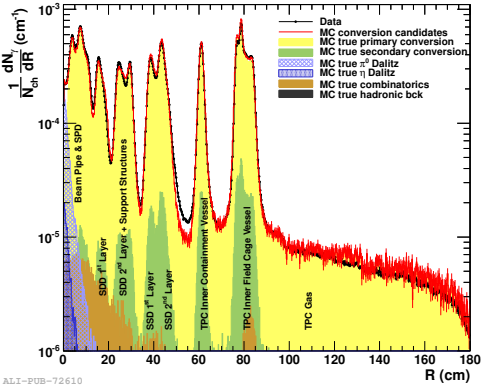


Time Projection Chamber - TPC

- Main tracking and PID detector
- Full azimuth coverage, $R = 84.8\,\mathrm{cm}$ up to $246.6\,\mathrm{cm}$
- Tracking: $100\,\mathrm{MeV/c}$ (primary) or $50\,\mathrm{MeV/c}$ (secondary) up to $100\,\mathrm{GeV/c}$

γ - Ray Tomography of ALICE





Performance of the ALICE Experiment at the CERN LHC
arXiv:1402.4476 [nucl-ex]

- Cuts on the decay topology of photons and electron track properties
- Background is mainly combinatorial - Strange particle contribution negligible

- Very useful tool to check the material budget:
  - Effective radiation length: $X/X_0 = 0.114 \pm 0.005$ $(|\eta| < 0.9, R < 180\,\mathrm{cm})$
  - Final systematic error is $\sim 4.5\%$

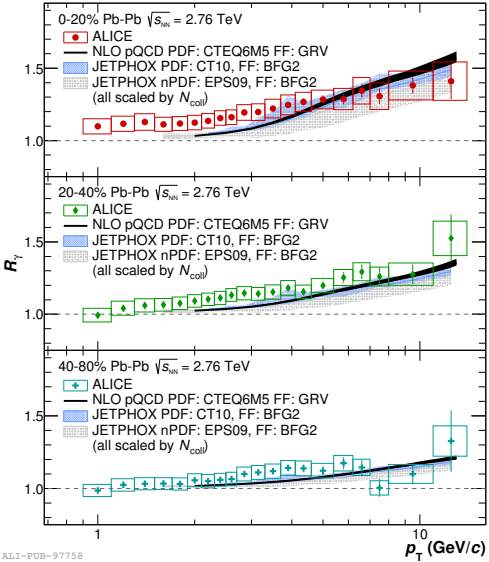
Definition of Excess in Central Pb–Pb collisions

Experimental definition of Direct Photons:

- Every photon which is not directly produced by: π^0, η, ω, η', φ, ρ^0 and Σ^0
- Decay photons simulated via a cocktail calculation based on measured yield of π^0 (Pb–Pb, p-Pb, pp) and η (p-Pb, pp), remaining spectra are obtained from m_T scaling of measured π^0, K, p etc. (if not measured)

Experimental measurement of π^0:

- Published π^0 measurements contain feed-down from higher mass particles going to π^0, except π^0 from K_s^0
- Measured spectra are taken as input for cocktail calculation



Cocktail Generation

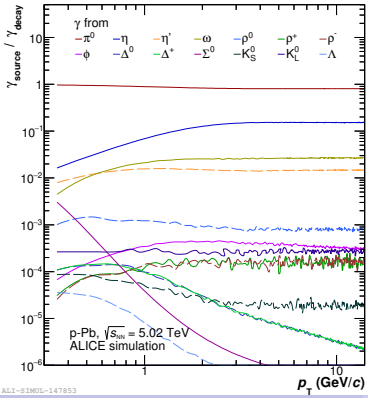
Decay photon spectra are obtained via calculation

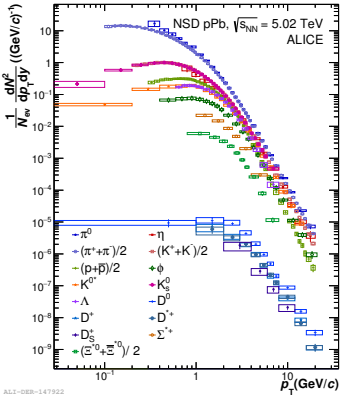
- Based on a fit to measured π^0 (Pb–Pb, pp) and η (pp)
- Other particle spectra obtained via m_T-scaling of measured π^0, K, p
- Incorporated mesons: π^0, η, η', ω, φ, ρ_0, $\rho_\pm$, K^0_S, K^0_L and baryons: Σ^0, $\Delta^{0,+}$

m_T-Scaling: arXiv:1710.01933

Same shape of cross sections, $f(m_T)$, of various mesons

$$E\frac{d^3\sigma_m}{dp^3} = C_m \cdot f(m_T)$$



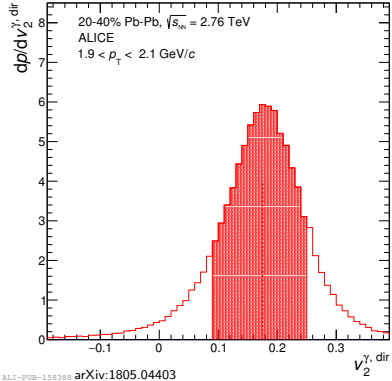


Meson (C_m)	meas.	Mass	Decay Branch	B. Ratio
π^0	pp, p–Pb	134.98	$\gamma\gamma$	98.82%
	Pb–Pb		$e^+e^-\gamma$	1.174%
η	pp, p–Pb	547.3	$\gamma\gamma$	39.21%
	Pb–Pb		$\pi^+\pi^-\gamma$	4.22%
(0.48)			$e^+e^-\gamma$	0.69%
ρ^0	pp	770.0	$\pi^+\pi^-\gamma$	0.99%
			$\pi^0\gamma$	0.06%
(1.0)			$\eta\gamma$	0.03%
$\rho^\pm$ (1.0)		775.49	$\pi^\pm\gamma$	0.045%
ω	pp	781.9	$\pi^0\gamma$	8.5%
(0.9)			$\eta\gamma$	0.46%
η'		957.8	$\rho^0\gamma$	29.08%
			$\omega\gamma$	2.75%
(0.25)			$\gamma\gamma$	2.20%
φ	pp, p–Pb	1019.5	$\eta\gamma$	1.31%
	Pb–Pb		$\pi^0\gamma$	0.125%
(0.35)			$\pi^0\pi^0\gamma$	0.013%
Λ (1.0)		1115.68	$n\gamma$	0.084%
Σ^0 (1.0)		1192.6	$\Lambda\gamma$	100%
Δ^0 (1.0)		1232.0	$n\gamma$	0.6%
Δ^+ (1.0)		1232.0	$n\gamma$	0.6%

Propagation and Correlation of Errors on the R_γ

- Measured R_γ often less than $2\sigma_{\text{sys}}$ deviation from 1
- Gaussian error propagation only applicable if:
  a) Relation between observable and input observables is linear or
  b) Uncertainties sufficiently small

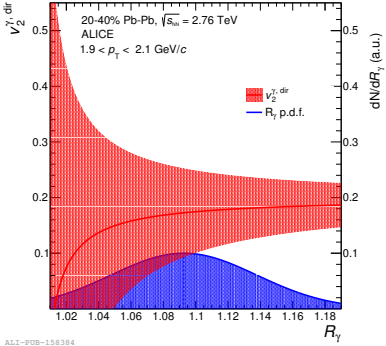
both conditions not fulfilled



arXiv:1805.04403

Gaussian error propagation:

$$\frac{\partial v_n^{\gamma,\,\text{dir}}}{\partial R_\gamma} = \frac{v_n^{\gamma,\,\text{decay}} - v_n^{\gamma,\,\text{inc}}}{(R_\gamma - 1)^2}$$



- Central values and errors for $v_n^{\gamma,\,\text{dir}}(p_T)$ calculated using MC simulation following Bayesian approach with probability distributions of true values of $R_\gamma^t(p_T)$, $v_n^{\gamma,\text{dec,t}}(p_T)$, $v_n^{\gamma,\text{inc,t}}(p_T)$ assuming R_γ can't be smaller unity
- p_T correlated uncertainty, like material budget (4.5%), complicates error propagation

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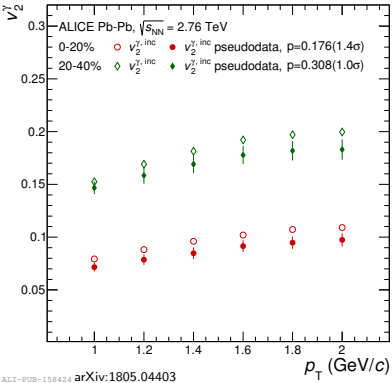

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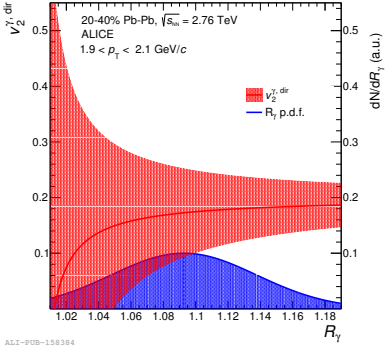

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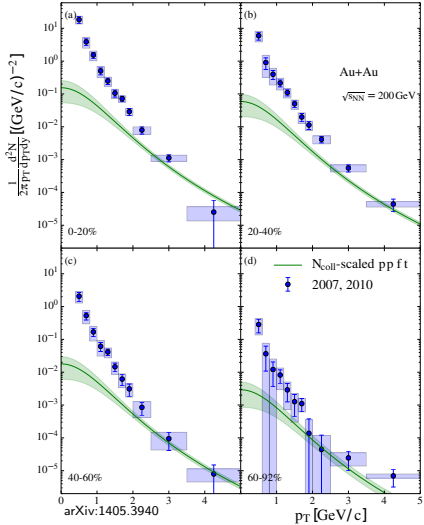
Interlude: Situation at RHIC
Direct Photon Spectra

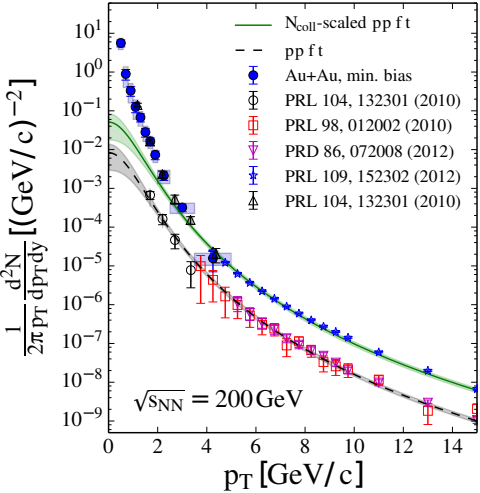


arXiv:1405.3940

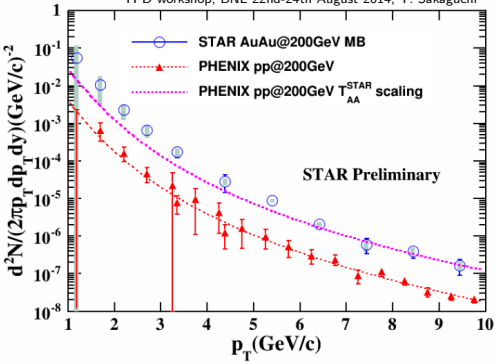
- Strong excess above extrapolated pp measurement (green curve) seen in all centrality classes
- Slope of excess depends very little on centrality ($T_{eff} \approx 235 \pm 40$ MeV/c)

Interlude: Situation at RHIC
Direct Photon Spectra

arXiv:1405.3940

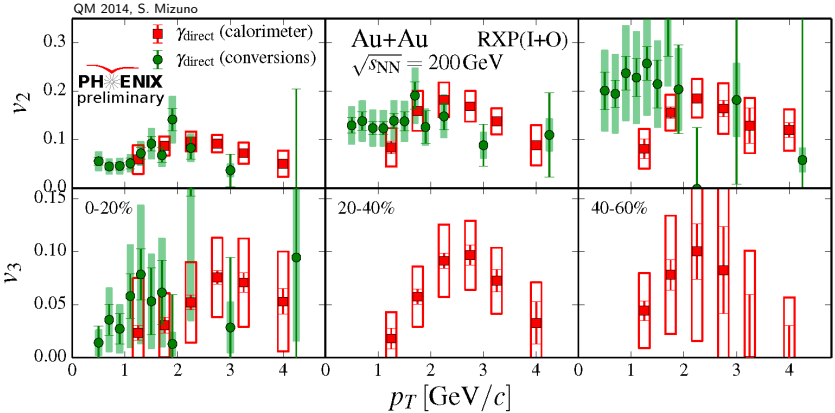


TPD workshop, BNL 22nd-24th August 2014, T. Sakaguchi



- Direct photon spectrum measured by STAR in MB (via virtual photons) disagrees between 1-3 GeV/c by a factor 2
- BUT: Large syst. errors due to unmeasured eta contribution at low p_T

Interlude: Situation at RHIC
PHENIX Direct Photon ν_2/ν_3 Results



- Direct photon ν_2 & ν_3 comparable to that of other hadrons
- Two independent methods give comparable result
- Theory not able to reproduce large ν_2 and even less ν_3