Direct photon measurements in different collision systems with the ALICE experiment at the LHC

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On behalf of the ALICE Collaboration

25e Congrès Général de la Société Française de Physique, Nantes

Hard probes in different collision systems

pp	p–Pb	Pb–Pb
pQCD		
PDF		

Hard probes in different collision systems

pp	p–Pb	Pb–Pb
pQCD	pQCD	
PDF	nPDF	
	Cold nuclear matter effects	

Hard probes in different collision systems

pp	p–Pb	Pb–Pb
pQCD	pQCD	pQCD
PDF	nPDF	nPDF
	Cold nuclear matter effects	Cold nuclear matter effects
		Hot nuclear matter effects
		QGP

Hard probes in different collision systems

	pp	p–Pb	Pb–Pb
Test theory	pQCD	pQCD	pQCD
	PDF	nPDF	nPDF
Study collectivity		Cold nuclear matter effects	Cold nuclear matter effects
			Hot nuclear matter effects
			QGP

- Small systems (pp, p–Pb) vs. Pb–Pb → **not so trivial** (see S. Porteboeuf-Houssais' plenary talk on Wednesday at 11pm)

Hard probes in different collision systems

	pp	p–Pb	Pb–Pb	
Test theory	pQCD	pQCD	pQCD	
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		Cold nuclear matter effects	Cold nuclear matter effects	
			Hot nuclear matter effects	**Study collectivity**
			QGP	

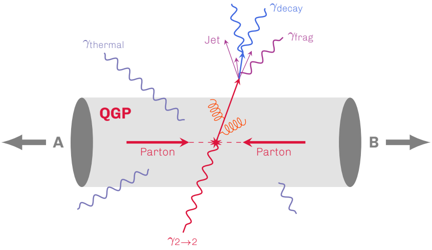
- Small systems (pp, p–Pb) vs. Pb–Pb → **not so trivial** (see S. Porteboeuf-Houssais' plenary talk on Wednesday at 11pm)

Experimental approach

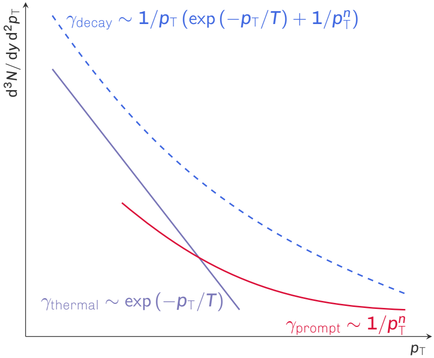
- Measure many observables **in the three systems** and compare (e.g. R_{pA}, R_{AA})
- Many hard probes (Z. Conesa del Valle's talk) → among them, **direct photons** (including also **a valuable soft component**)

Direct photons in hadron collisions

- Produced at every stage of the collision, **not affected** by QCD medium → valuable probe



$$\underbrace{\overbrace{\gamma_{2\to2} + \gamma_{\text{frag}}}^{\gamma_{\text{prompt}}} + \gamma_{\text{thermal}}}_{\gamma_{\text{direct}}} = \gamma_{\text{inc}} - \gamma_{\text{decay}}$$



Prompt photons (pp, p–Pb, Pb–Pb)

- Dominant at **high p_T**
- Very good description within **pQCD at NLO**
- Access to **parton energy loss** (correlations)
- Test p–Pb and Pb–Pb **binary scaling**

Thermal photons (Pb–Pb)

- Dominant at **low p_T**
- From QGP/hadron gas **thermalisation**
- Access to **medium properties**
- Sensitive to **QGP space-time evolution** (flow)

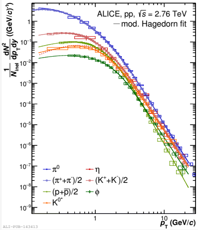
How to extract direct photons?

Low/intermediate-p_T component ($\lesssim 10$ GeV/c) → **subtraction method**

- Direct photons → all photons except from particle decays

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

- Direct photon **excess ratio** $R_\gamma = \frac{\gamma_{\mathrm{inc}}}{\gamma_{\mathrm{decay}}} \equiv \frac{\gamma_{\mathrm{inc}}}{\pi^0_{\mathrm{param}}} \Big/ \frac{\gamma_{\mathrm{decay}}}{\pi^0_{\mathrm{param}}}$
- Ratio advantage → **cancellation of some uncertainties**



[PRC 99, 024912 (2019)]

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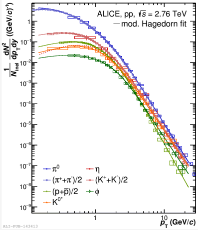
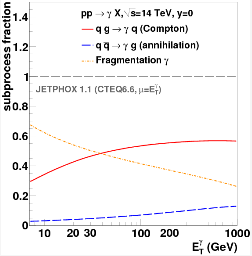


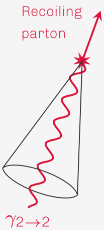
[PRC 99, 024912 (2019)]

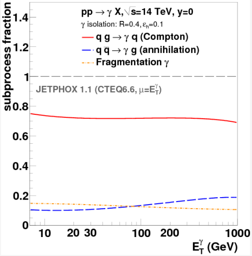
High-p_T component ($\gtrsim$ 10 GeV/c) → **isolation method**

- Focus on $\gamma_{2\to2}$ (hard-produced γ_{direct})
- Strong **reduction of γ_{frag} and γ_{decay}** contributions

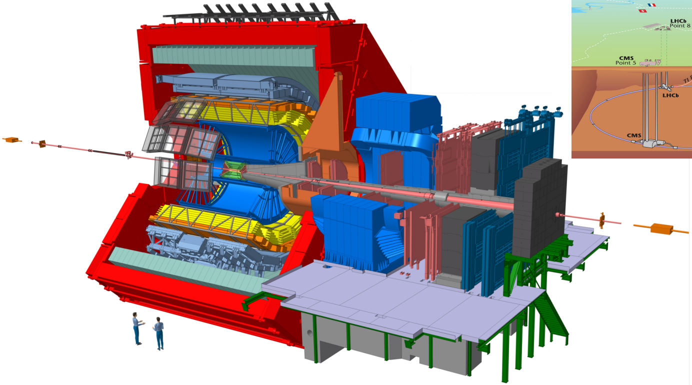
[PRD 82, 014015 (2010)]

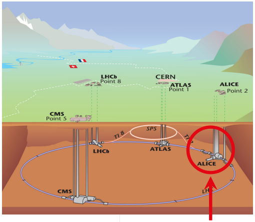






The ALICE Experiment





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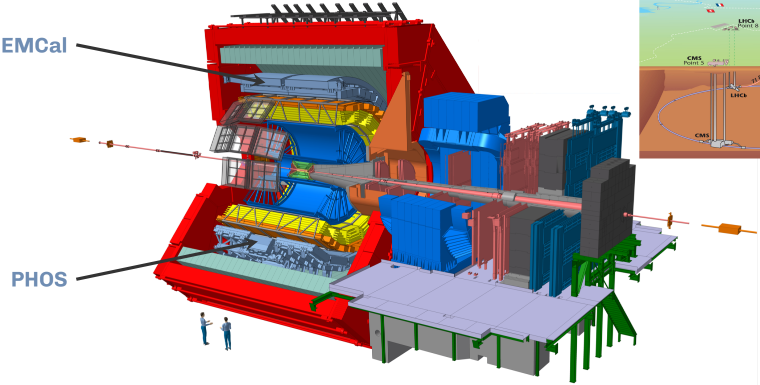

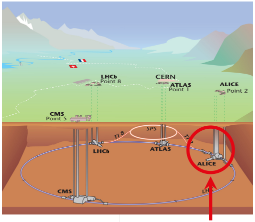

ALICE

Calorimetry

EMCal Lead/scintillator sampling layers
$|\eta| < 0.7$, $80° < \varphi < 180°$

PHOS Lead tungstate crystals
$|\eta| < 0.12$, $260° < \varphi < 320°$

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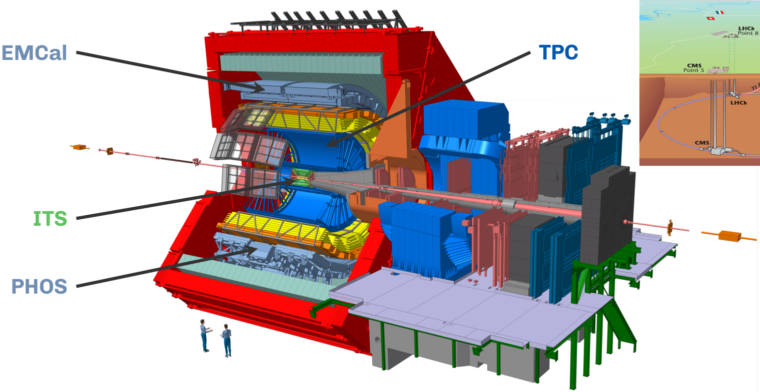

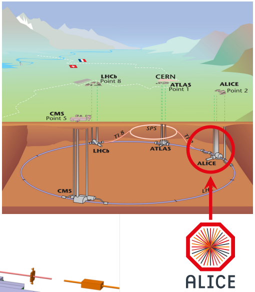

Tracking ($|\eta| < 0.9$, $0° < \varphi < 360°$)

ITS Primary/secondary vertex determination

TPC Tracking and particle identification (PID)

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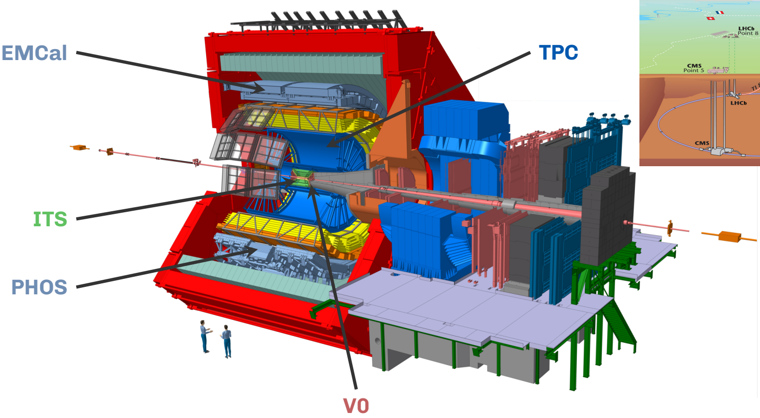

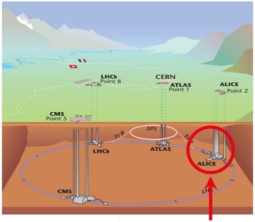

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Triggering

V0 Minimum bias, luminosity and centrality measurement

+ extended p_T reach thanks to EMCal and PHOS triggering capabilities

Calorimetry

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$|\eta| < 0.7$, $80° < \varphi < 180°$

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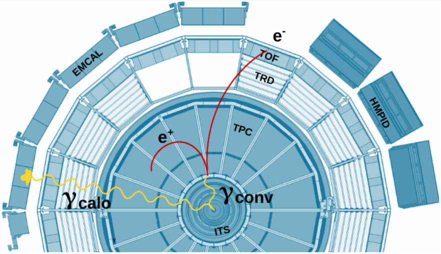
Photon reconstruction techniques

Photon Conversion Method (PCM)



- Based on photon conversion **in detector material** (ITS, TPC)
- Small **conversion probability** $\lesssim$ **9 %** but very good **energy resolution** $\sim$ **1.6 %** at low p_T

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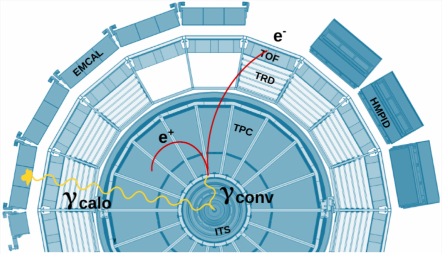

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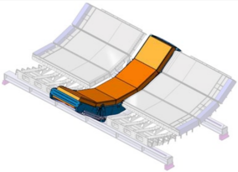
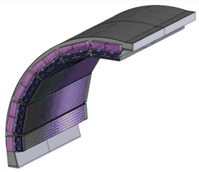
PHOS and EMCal (EMC)



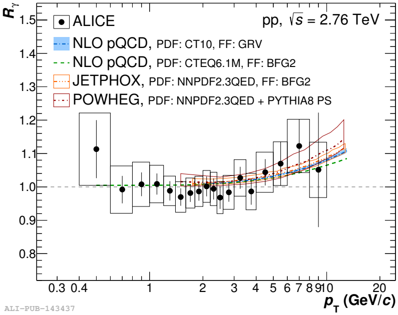


- Direct measurement of photon **deposited energy** in adjacent calorimeter cells $\rightarrow$ grouped in **clusters** for reconstructing photon energy
- Poorer energy resolution at low p_T ($3.3/\sqrt{E} \oplus 1.1\%$ for PHOS, $11/\sqrt{E} \oplus 1.7\%$ for EMCal) but **higher statistic at high p_T** (γ triggers)

- Possible **combination** to reduce uncertainties and cover **a broad p_T range**

Direct photons at low p_T, pp at $\sqrt{s} = 2.76$ TeV

[PRC 99, 024912 (2019)]



- At low p_T, **no excess observed within uncertainties** → supports Pb–Pb medium-induced enhancement scenario
- For $p_T > 7$ GeV/c, $\sim 1\sigma$ deviation **consistent with pQCD** at NLO (prompt photons)

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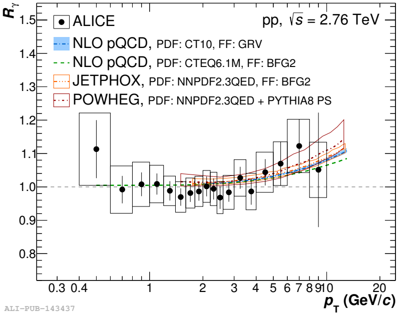

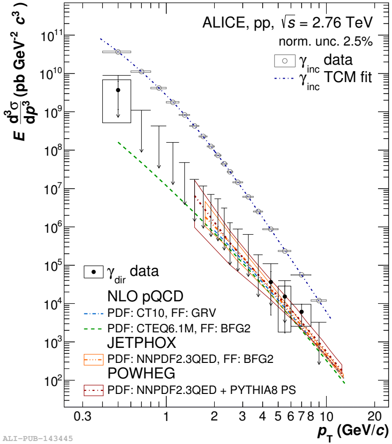

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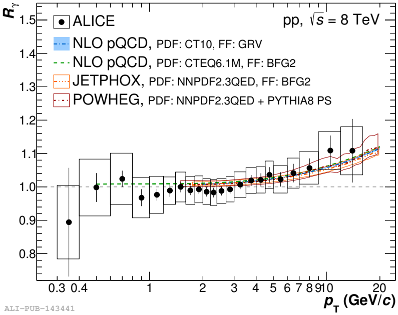
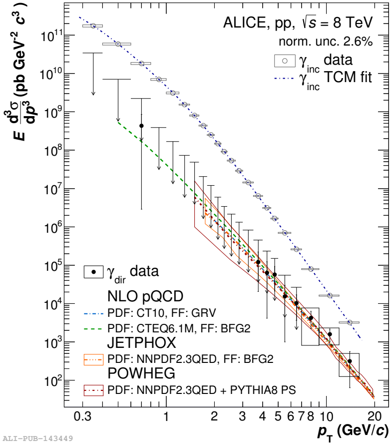
- 90 % C.L. (arrows) → points where R_γ **agrees with unity** within uncertainties
- Consistent with pQCD (Paquet [PRC 93 (2016)], Vogelsang [PRD 67 (2003)], JETPHOX, POWHEG)

Direct photons at low p_{T}, pp at $\sqrt{s} = 8$ TeV

[PRC 99, 024912 (2019)]





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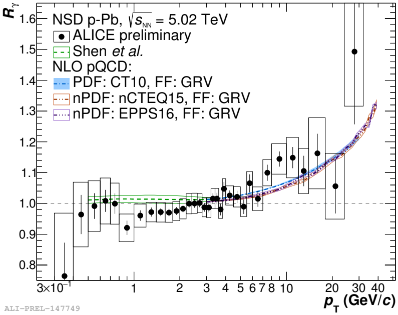
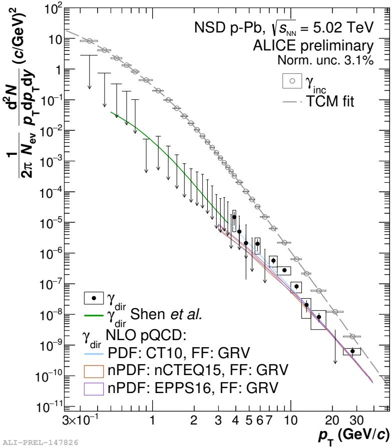
Direct photons at low p_T, p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV



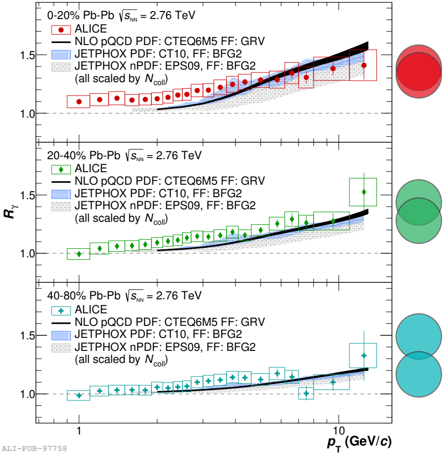


- At low p_T, **no excess observed within uncertainties** → supports Pb–Pb medium-induced enhancement scenario
- For $p_T > 7$ GeV/c, $\sim 1\sigma$ deviation **consistent with binary scaled pQCD** at NLO

- 90 % C.L. (arrows) → points where R_γ **agrees with unity** within uncertainties
- Consistent with pQCD (Vogelsang [PRD 67 (2003)]) and a hydrodynamic model (Shen [PRC 95 (2017)])

Direct photons at low p_T, Pb–Pb at $\sqrt{s_{NN}} = 2.76$ TeV

[PLB 754, 235-248 (2016)]



- Two reconstruction techniques combined (PCM, PHOS) → covering **very low p_T**, $0.9 < p_T < 14$ GeV/c
- For $p_T > 5$ GeV/c, R_γ excess **consistent with binary scaled pQCD prompt photons** in each centrality class
- At low p_T, **10–15 % excess observed in central collisions** → another source of photons

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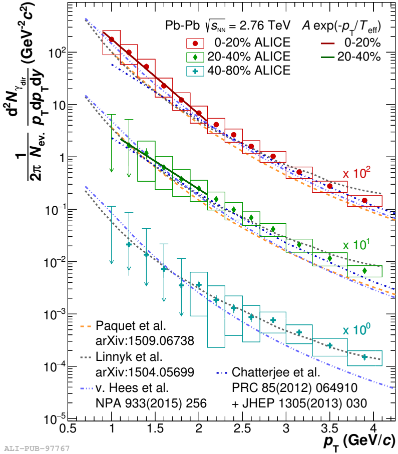

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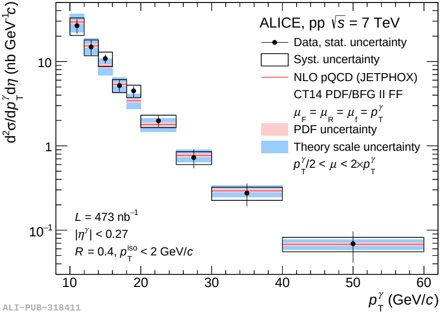
- At low p_T, **10–15 % excess observed in central collisions** → another source of photons
- Comparison to several hydrodynamic models → yield **consistent with a thermal radiation**

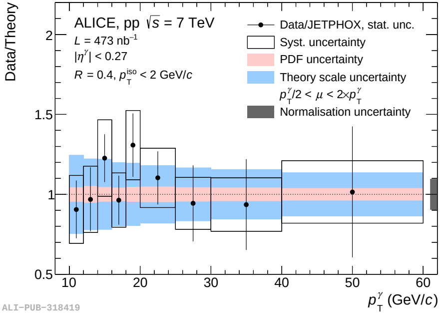
- Effective QGP temperature (0–20%) → $T_{eff}^{LHC} \sim$ **304 MeV** $\gg$ $T_{eff}^{RHIC} \sim$ **239 MeV** measured by PHENIX in Au–Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV [PRC 91, 064904 (2015)]

Direct photons at high p_T, pp at $\sqrt{s} = 7$ TeV

[arXiv:1906.01371]

$$\frac{d^2\sigma}{dp_T^\gamma\, d\eta} = \frac{N_{ev}}{\mathcal{L}_{int}\,\varepsilon_{trig}\,\mathcal{C}} \times \frac{d^2N_n^{iso}}{N_{ev}\, dp_T^\gamma\, d\eta} \times \frac{P}{\varepsilon}$$

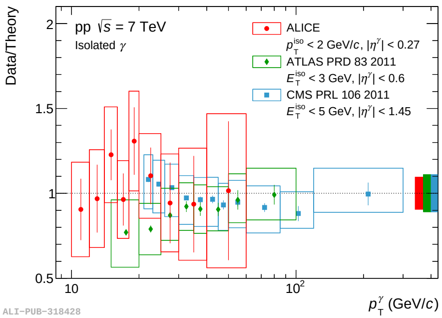


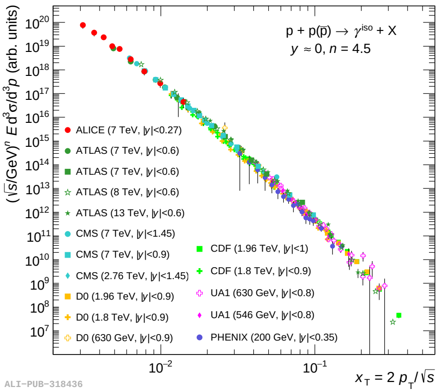


- Syst. unc. ranging **from 19% to 24%** → dominated by the isolation method
- ALICE data compared to **pQCD at Next-to-Leading Order** (JETPHOX [PRD 73, 094007 (2006)] with CT14 PDF [PRD 93, 033006 (2016)] and BFG II FF [EPJC 2, 529-537 (1998)])
- Good agreement between this measurement and theory within stat. and syst. uncertainties

Direct photons at high p_T, pp at $\sqrt{s} = 7$ TeV

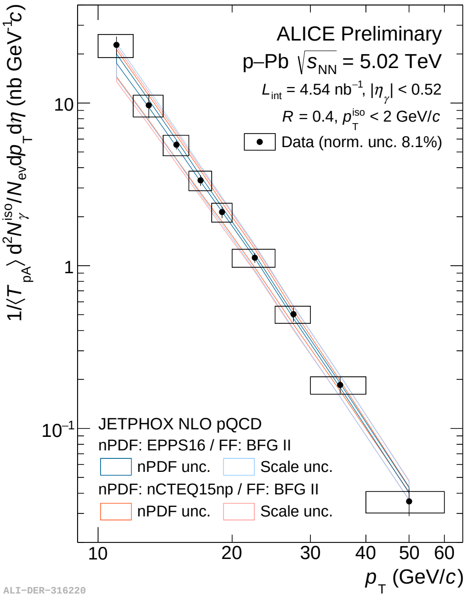
[arXiv:1906.01371]





- **Consistent data-to-theory ratios** among ALICE, ATLAS [PRD 83, 052005 (2011)] and CMS [PRL 106, 082001 (2011)]
- Extending the p_T^γ **reach down** compared to other LHC experiments → access to lower x_T
- Compatible with isolated photon data at different centre-of-mass energies in pp and p$\bar{p}$ collisions [NPB 860, 311-338 (2012)]

Direct photons at high p_T, p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV



$$\left(\frac{d^2\sigma}{dp_T\, d\eta}\right)_{pp\text{-}eq} = \frac{1}{\langle T_{pA}\rangle} \times \left(\frac{d^2N_\gamma^{iso}}{N_{ev}\, dp_T\, d\eta}\right)_{p\text{-}Pb}$$

- Binary nucleon collision scaling → **nuclear overlap factor** $\langle T_{pA}\rangle = 0.09923\,\text{mb}^{-1}$ [ALICE-PUBLIC-2018-011]
- JETPHOX pQCD calculations at Next-to-Leading Order [PRD 73, 094007 (2006)] using **EPPS16** [EPJC 77, 163 (2017)] and **nCTEQ15np** [PRD 93, 085037 (2016)] nPDFs
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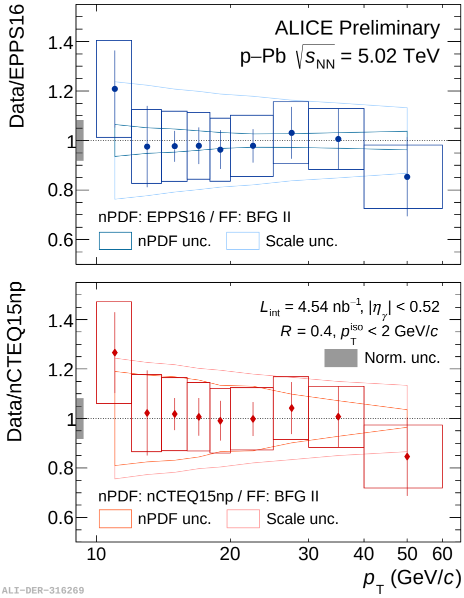
Direct photons at high p_T, p–Pb at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$



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Conclusions and outlook

Direct photons at low p_{T}, subtraction method

- Measured **from $p_{\mathrm{T}} = 0.3\,\mathrm{GeV}/c$ to $p_{\mathrm{T}} = 32\,\mathrm{GeV}/c$** in pp, p–Pb and Pb–Pb collisions at different centre-of-mass energies thanks to the **ALICE independent reconstruction techniques**
- Results **compatible with pQCD calculations at NLO for $p_{\mathrm{T}} > 7\,\mathrm{GeV}/c$** $\rightarrow$ prompt photons
- Low-p_{T} excess observed in Pb–Pb collisions $\rightarrow$ **compatible with a thermal radiation**
- Outlook $\rightarrow$ LHC Run III (100 times more Pb–Pb data and improved detector knowledge) to better constrain thermal models and unravel the **direct photon puzzle**

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- ALICE extends the **p_T reach to lower values** compared to ATLAS and CMS $\rightarrow$ valuable result to get a good understanding of pQCD **towards the thermal photon region**
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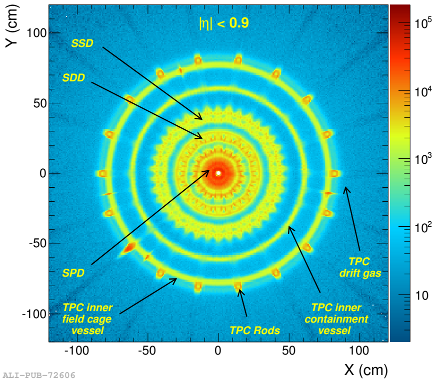
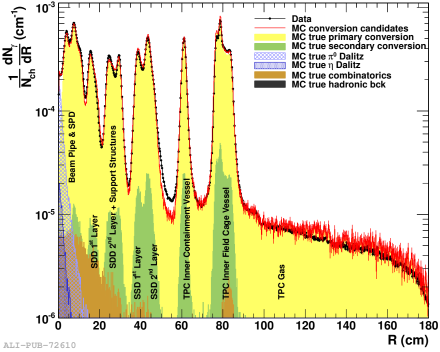
Merci pour votre attention !

Backup

PCM reconstruction technique and ALICE central barrel



[IJMPA 29, 1430044 (2014)]



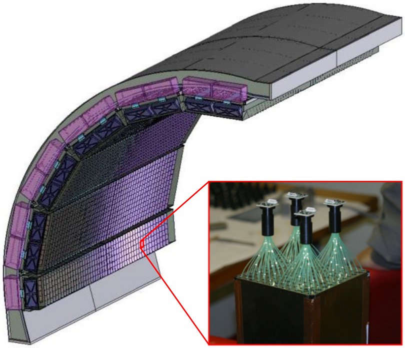
[IJMPA 29, 1430044 (2014)]

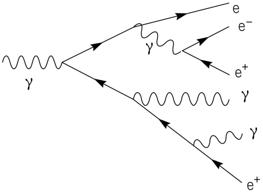
- "γ-ray tomography" used to determine the **material budget** $\rightarrow \sim 4.5\,\%$ in PCM measurement systematic uncertainties

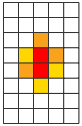
EMCal, the ALICE ElectroMagnetic Calorimeter

Specifications

- 12 supermodules → 3072 modules → **12288 cells** with a 6 × 6 cm^2 area
- Each cell → **153 lead/scintillator** alternating layers (24.6 cm thick in total)
- Energy/position resolutions → $4.8\,\%/E \oplus 11.3\,\%/\sqrt{E} \oplus 1.7\,\%$ and $5.3\,\text{mm}/\sqrt{E} \oplus 1.5\,\text{mm}$
- Covers $|\eta_\gamma| < \mathbf{0.7}$ and **100°** in azimuth (φ)
- Used as **trigger detector** (γ/jets)

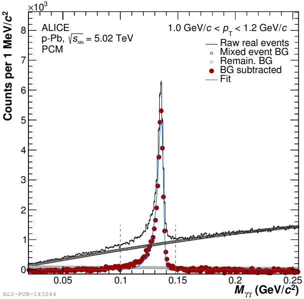




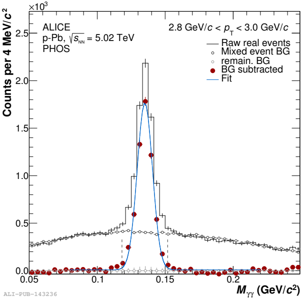


Photon reconstruction techniques, π^0 reconstruction performance

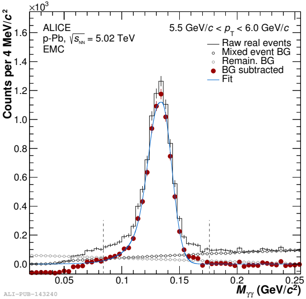
PCM



PHOS



EMC



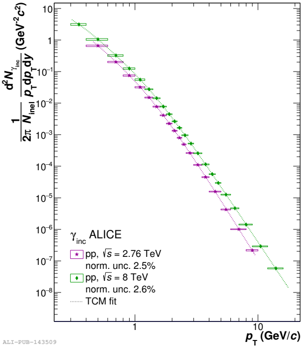
[EPJC 78, 624 (2018)]

- π^0 mesons enter R_γ computation through π^0_{param} → reconstructed with the **same techniques** as inclusive photons
- Best resolution on the π^0 mass peak with PCM

Subtraction ingredients

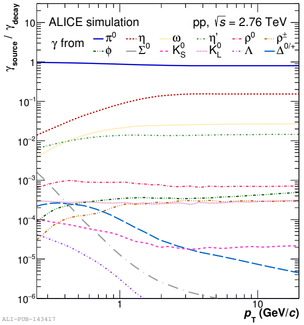
$$R_\gamma = \frac{\gamma_{\mathrm{inc}}}{\pi^0_{\mathrm{param}}} \Big/ \frac{\gamma_{\mathrm{decay}}}{\pi^0_{\mathrm{param}}}$$

γ_{inc}



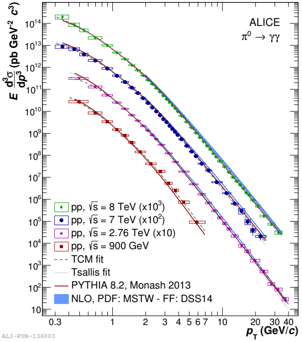
[PRC 99, 024912 (2019)]

γ_{decay}



[PRC 99, 024912 (2019)]

π^0_{param}



[EPJC 78, 263 (2018)]

- Inclusive photon yield measured with **different techniques**
- Systematic uncertainties dominated by p_{T}-independent **material budget** (PCM), global **E scale** (PHOS) or **clustering** (EMC)

- Decay photon spectrum $\rightarrow$ **cocktail simulation**
- Mother particle abundances based on **parametrised measured spectra** (or m_{T} scaling)

- Measured through **$\pi^0 \rightarrow \gamma\gamma$ decay channel** with the same techniques as γ_{inc} for **cancelling uncertainties**
- π^0 spectrum parametrised with **different models**

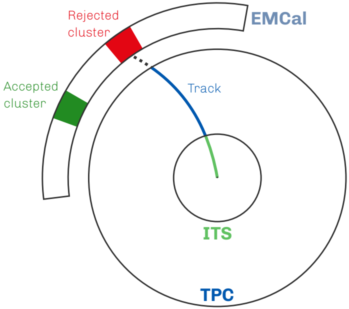
Photon reconstruction at high p_{T}

Neutral clusters (charged particle veto)

- Candidate clusters **must not** match a track spatially (ALICE γ_{direct} parametrisation)

$$|\Delta\eta| \leq 0.010 + (p_{\mathrm{T}}^{\mathrm{track}} + 4.07)^{-2.5}$$

$$|\Delta\varphi| \leq 0.015 + (p_{\mathrm{T}}^{\mathrm{track}} + 3.65)^{-2}$$



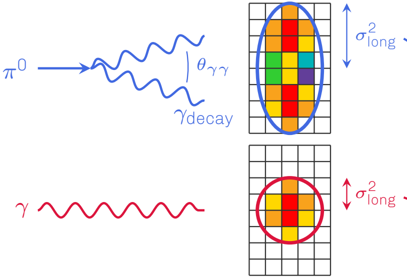
Photon reconstruction at high p_T

Neutral clusters (charged particle veto)

- Candidate clusters **must not** match a track spatially (ALICE γ_{direct} parametrisation)

$$|\Delta\eta| \leq 0.010 + (p_T^{\text{track}} + 4.07)^{-2.5}$$

$$|\Delta\varphi| \leq 0.015 + (p_T^{\text{track}} + 3.65)^{-2}$$

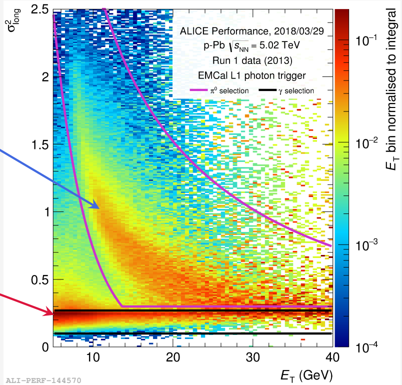


⚠ Not discriminant for $E_T \gtrsim 20$ GeV

Candidate photons (shower shape cuts)

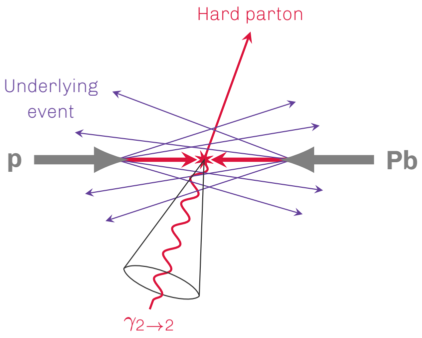
- Clusters **shower shape σ^2_{long}** is used to reject the γ_{decay} component

$$0.1 < \sigma^2_{\text{long}} < \left(\sigma^2_{\text{long}}\right)_{\text{max}}$$



Underlying event estimation in p–Pb collisions (high-p_{T} photons)

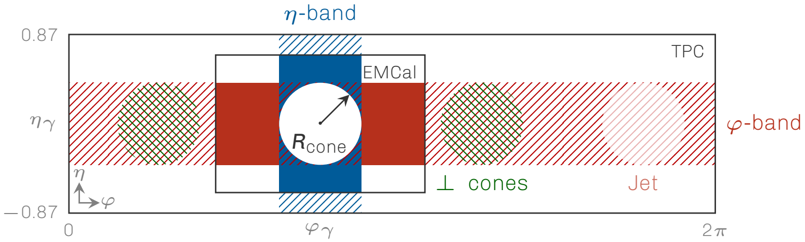
Larger contribution from the **underlying event (UE)** in p–Pb than in pp collisions



- Underlying event → **all processes but the hardest** LO parton interaction

Underlying event estimation in p–Pb collisions (high-p_{T} photons)

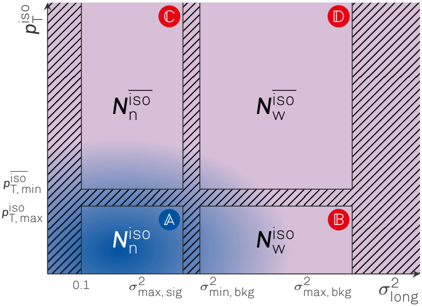
- UE estimated and **subtracted before** isolation, event-by-event $\rightarrow p_{\mathrm{T}}^{\mathrm{iso}} - \rho_{\mathrm{UE}} \times A_{\mathrm{cone}} < 2\ \mathrm{GeV}/c$



Method	Pros	Cons
$\perp$ cones	– Far from the isolation cone – Can be crosschecked with ALICE PHOS	– Neutral part not measurable
η-band	– Neutral and charged parts both measurable	– Affected by a hard contribution from cone
φ-band	– Neutral and charged parts both measurable	– Affected by a hard contribution from cone – Possibly sensitive to the opposite jet

- Charged UE measurement in **perpendicular cones** then “neutral + charged” extrapolation $\rightarrow$ isolation using neutral + charged particles

Isolated photons, signal extraction



σ^2_{long} limit	10 – 12	12 – 16	16 – 18	18 – 60
narrow min	0.10	0.10	0.10	0.10
narrow max	0.40	0.35	0.32	0.30
wide min	0.60	0.45	0.35	0.33
wide max	2.10	1.95	1.85	1.83

- Isolation crit. (A, B) → $p_T^{iso} < 2$ GeV/c
- Anti-isolation crit. (C, D) → $p_T^{iso} > 3$ GeV/c

The ABCD method [PRD 83, 052005 (2011)]

- Mainly **signal** region
  A = isolated narrow clusters (iso, n)
- Mainly **background** regions
  B = isolated wide clusters (iso, w)
  C = non-isolated narrow clusters ($\overline{\text{iso}}$, n)
  D = non-isolated wide clusters ($\overline{\text{iso}}$, w)

Particle quantities

- $S = \gamma_{\text{direct}}$ signal
- B = background (π^0, η, their γ_{decay}, etc.)
- $N = S + B \rightarrow$ **what is measured**

- Part of region A clusters truly induced by $\gamma_{\text{direct}} \rightarrow$ **purity** of the N_n^{iso} sample

$$P_{dd} = S_n^{iso}/N_n^{iso} = 1 - B_n^{iso}/N_n^{iso}$$

- Background B_n^{iso} **estimated with data** and **corrected with MC**

Isolated photons, purity estimation

- Data-driven background estimation in signal region A

$$B_{\mathrm{n}}^{\mathrm{iso}} = \frac{N_{\mathrm{w}}^{\mathrm{iso}} \times N_{\mathrm{n}}^{\overline{\mathrm{iso}}}}{N_{\mathrm{w}}^{\overline{\mathrm{iso}}}} \Rightarrow P_{\mathrm{dd}} = 1 - \frac{B_{\mathrm{n}}^{\mathrm{iso}}}{N_{\mathrm{n}}^{\mathrm{iso}}} = 1 - \left(\frac{N_{\mathrm{w}}^{\mathrm{iso}} \times N_{\mathrm{n}}^{\overline{\mathrm{iso}}}}{N_{\mathrm{w}}^{\overline{\mathrm{iso}}} \times N_{\mathrm{n}}^{\mathrm{iso}}} \right)_{\mathrm{data}}$$

- Possibly **signal contamination** in background regions B, C and D and **non-constant** background isolation probability → purity must be **corrected using MC simulations**

- Jet-jet (JJ, **background**) + γ-jet (GJ, **signal**) → mixed and used to compute a **correction factor** α

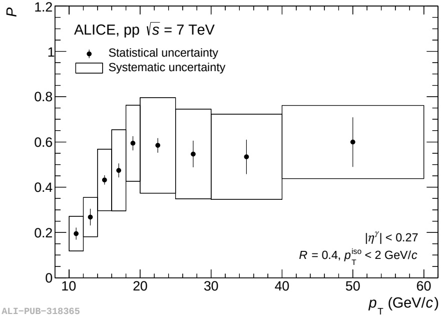
$$\alpha = \frac{\overbrace{\left(B_{\mathrm{n}}^{\mathrm{iso}}\right)_{\mathrm{JJ}}}^{\text{real bkg.}}}{\underbrace{\left(B_{\mathrm{n}}^{\mathrm{iso}}\right)_{\text{MC mix}}}_{\text{estimated bkg.}}} \Rightarrow P = 1 - \underbrace{\left(\frac{B_{\mathrm{n}}^{\mathrm{iso}} \times N_{\mathrm{w}}^{\overline{\mathrm{iso}}}}{N_{\mathrm{w}}^{\mathrm{iso}} \times N_{\mathrm{n}}^{\overline{\mathrm{iso}}}} \right)_{\mathrm{MC}}}_{\alpha} \times \left(\frac{N_{\mathrm{w}}^{\mathrm{iso}} \times N_{\mathrm{n}}^{\overline{\mathrm{iso}}}}{N_{\mathrm{w}}^{\overline{\mathrm{iso}}} \times N_{\mathrm{n}}^{\mathrm{iso}}} \right)_{\mathrm{data}}$$

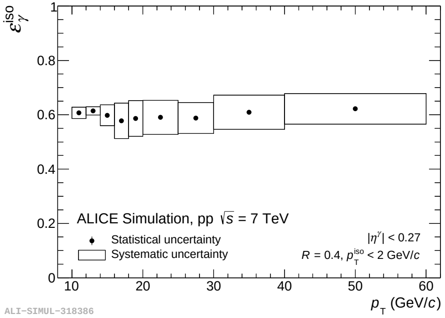
Isolated photons in pp collisions at $\sqrt{s} = 7$ TeV – Purity and efficiency

[arXiv:1906.01371]

Specifications

- 2011 data sets, EMCal Level-0 trigger (5.5 GeV) $\rightarrow$ **photons measured in 10–60 GeV/c**
- Integrated luminosity $\rightarrow \mathcal{L}_{\text{int}} = 473 \pm 28\,(\text{stat.}) \pm 17\,(\text{syst.})\,\text{nb}^{-1}$
- Photons selected in $|\eta^{\gamma}| < 0.27$ and $\Delta\varphi^{\gamma} = 0.9$ rad





- Purity ranging **from 20% to 60%** $\rightarrow$ interplay between physics and detector effects
- Total efficiency $\sim$ **60%** $\rightarrow$ correcting data from reconstruction, ID and isolation inefficiencies

Isolated photons in pp collisions at $\sqrt{s} = 7$ TeV – Efficiency

[arXiv:1906.01371]

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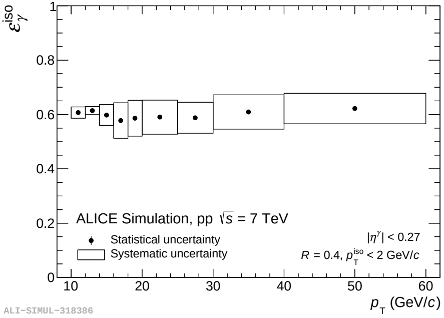
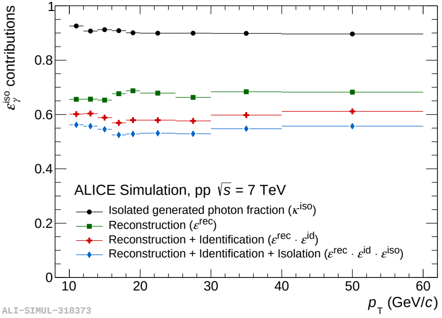


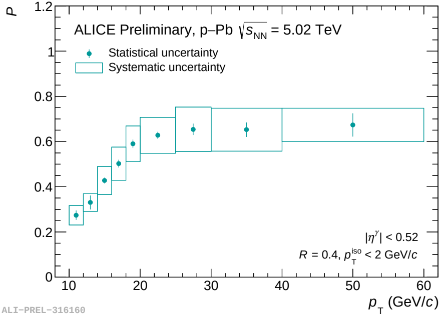


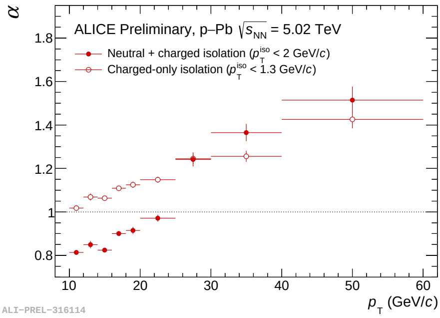
- Total efficiency $\sim$ **60%** $\rightarrow$ correcting data from reconstruction, ID and isolation inefficiencies

Results in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV – Purity and correction

Specifications

- 2013 data sets, EMCal Level-1 γ triggers (7/11 GeV) → **photons measured in 10–60 GeV/c**
- Integrated luminosity → $\mathcal{L}_{\text{int}} = 4.54 \pm 0.37\,\text{nb}^{-1}$
- Photons selected in $|\eta^{\gamma}| < 0.52$ and $\Delta\varphi^{\gamma} = 1.39$ rad (enlarged acceptance)



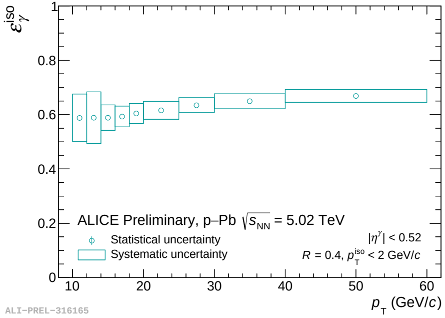


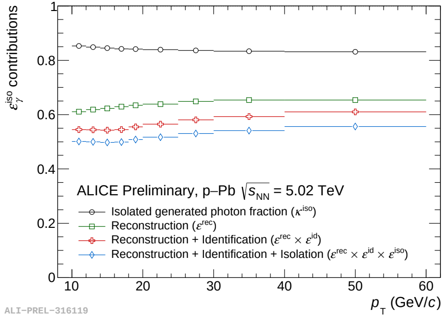
- Purity ranging **from 27% to 67%** → interplay between physics and detector effects
- α correction factor **different from unity** → raw purity P_{dd} does need this MC correction

Isolated photons in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV – Efficiency

Specifications

- 2013 data sets, EMCal Level-1 γ triggers (7/11 GeV) $\rightarrow$ **photons measured in 10–60 GeV/c**
- Integrated luminosity $\rightarrow \mathcal{L}_{\text{int}} = 4.54 \pm 0.37\,\text{nb}^{-1}$
- Photons selected in $|\eta^\gamma| < 0.52$ and $\Delta\varphi^\gamma = 1.39$ rad (enlarged acceptance)





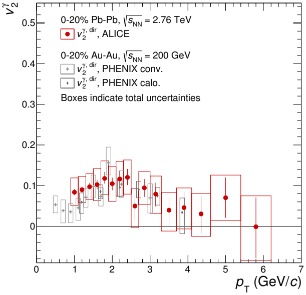
- Total efficiency $\gtrsim$ **60%** $\rightarrow$ correcting data from reconstruction, ID and isolation inefficiencies

The direct photon puzzle

[PRC 94, 064901 (2016)] [PLB 754, 235-248 (2016)]

- γ_{direct} **yields are well reproduced by hydrodynamic models** in a variety of systems (Au–Au at RHIC, Pb–Pb at LHC)

- However, the **non-zero direct photon flow** coefficient $v_2^{\gamma,\,\text{dir}}$ observed by PHENIX [PRC 94, 064901 (2016)] and ALICE [PLB 754, 235-248 (2016)] is **underestimated** by these models



→ Direct photon puzzle