Direct photon measurements with the ALICE Experiment at LHC

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On behalf of the ALICE Collaboration

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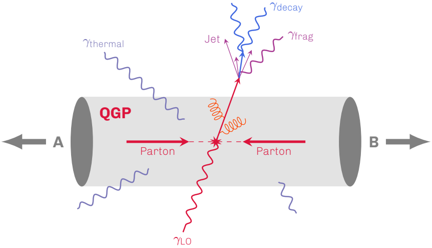
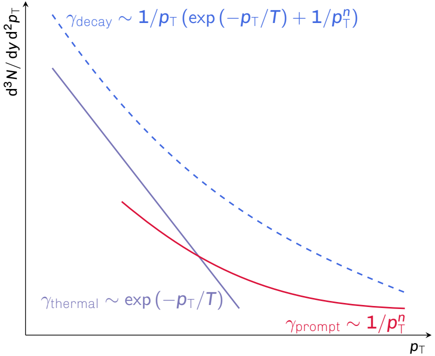
Direct photons in hadron collisions

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



$$\overbrace{\gamma_{LO} + \gamma_{frag}}^{\gamma_{prompt}} \underbrace{+ \gamma_{thermal}}_{} = \gamma_{inc} - \gamma_{decay}$$

$$\gamma_{direct} = \gamma_{LO} + \gamma_{frag} + \gamma_{thermal}$$



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**

How to extract direct photons?

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

- Direct photons → all photons except from particle decays

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

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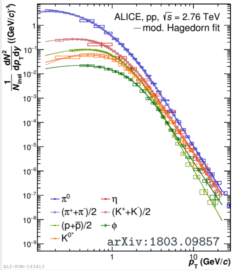
- Direct photon **excess ratio** $R_\gamma = \frac{\gamma_{\text{inc}}}{\gamma_{\text{decay}}} \equiv \frac{\gamma_{\text{inc}}}{\pi^0_{\text{param}}} \Big/ \frac{\gamma_{\text{decay}}}{\pi^0_{\text{param}}}$

  (γ_{inc} = measured, γ_{decay} = simulated, π^0_{param} = parametrised)

- Ratio advantage → **cancellation of some uncertainties**



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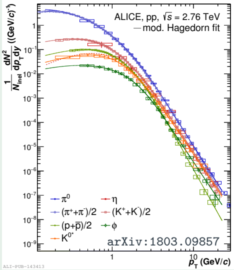
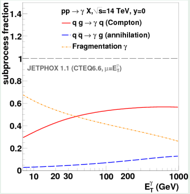
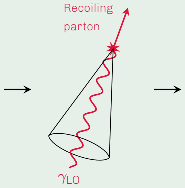


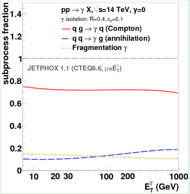
High p_T component ($\gtrsim 10$ GeV/c) → **isolation method**

- Strong **reduction of γ_{frag} and γ_{decay}** contributions
- Access to γ_{LO} (hard produced γ_{direct})

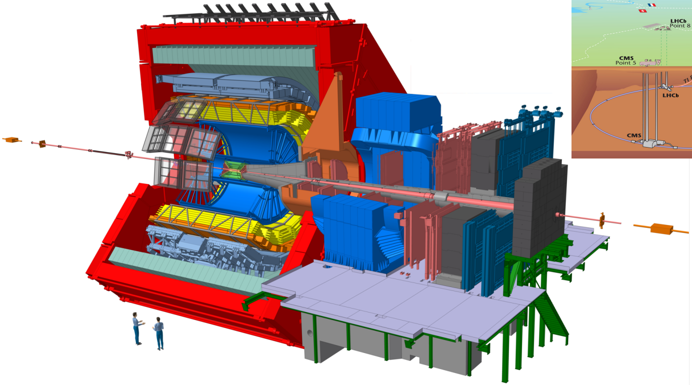
Phys. Rev. D 82, 014015 (2010)

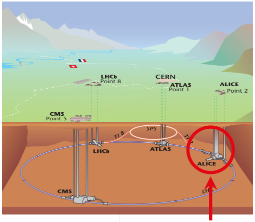






The ALICE Experiment





ALICE

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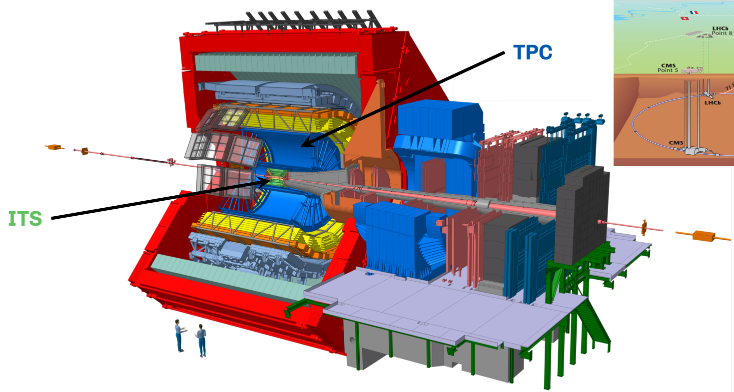
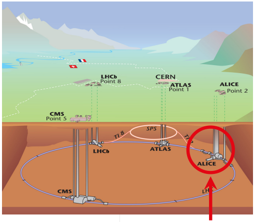




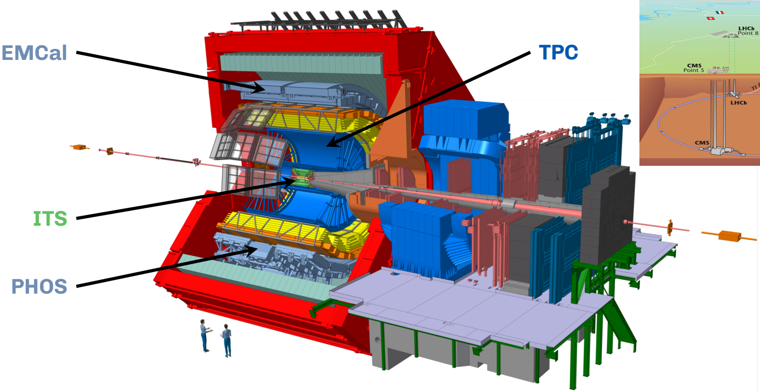
ALICE

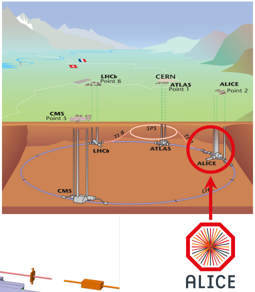
Tracking ($|\eta| < 0.9$, $0° < \varphi < 360°$)

ITS Primary/secondary vertex determination

TPC Tracking and particle identification (PID)

The ALICE Experiment





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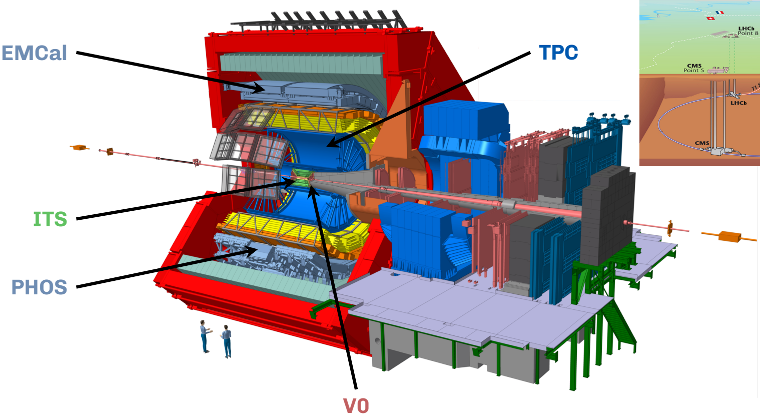
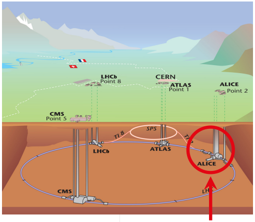
Calorimetry

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

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

The ALICE Experiment





ALICE

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

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Triggering

V0 Minimum bias, luminosity and centrality measurement

+ extended p_T reach thanks to EMCal and PHOS triggering capabilities

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

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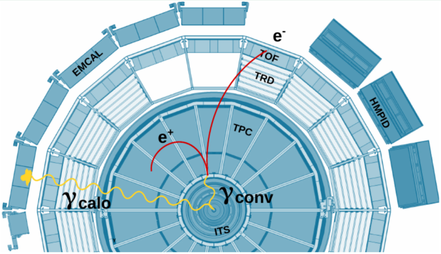
Photon reconstruction techniques

Photon Conversion Method (PCM)



- Based on photon conversion **in detector material** (ITS, TPC)
- Reconstruction of **neutral particle secondary vertices** V^0 from close tracks
- Selection criteria on V^0 → **candidate photons**
- Small **conversion probability** $\lesssim$ **9 %** but very good **energy resolution** $\sim$ **1.6 %** at low p_T

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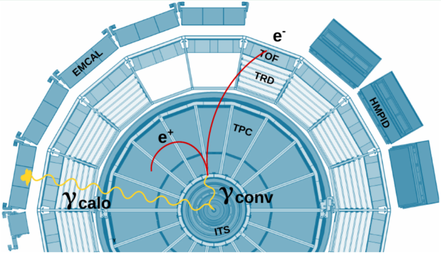

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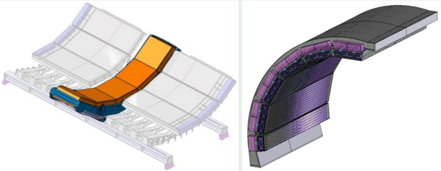
PHOS and EMCal (EMC)

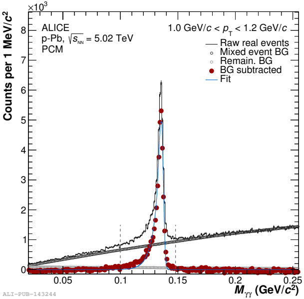


- Direct measurement of photon **deposited energy** in adjacent calorimeter cells → grouped in **clusters** for reconstructing photon energy
- Selection criteria on clusters → **candidate photons**
- Poorer energy resolution at low p_T but **higher statistic at high p_T** (γ triggers)

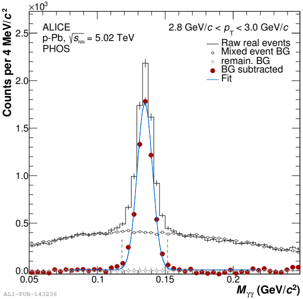
- Three **independent** techniques to measure direct photons in overlapping p_T ranges → **possible combination** to reduce uncertainties and cover a broad p_T range

Photon reconstruction techniques, π^0 reconstruction performance

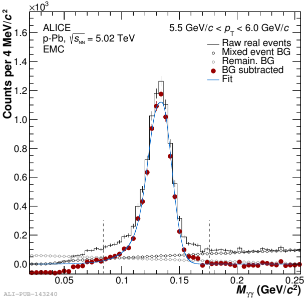
PCM



PHOS



EMC



Eur. Phys. J. C 78 (2018) no. 8, 624

- 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

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

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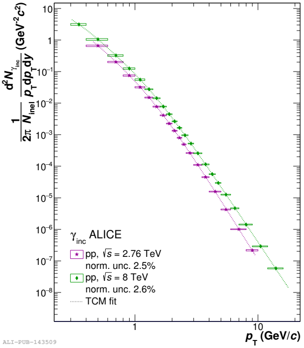
γ_{inc}



arXiv:1803.09857

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

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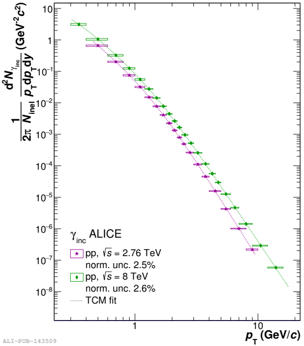

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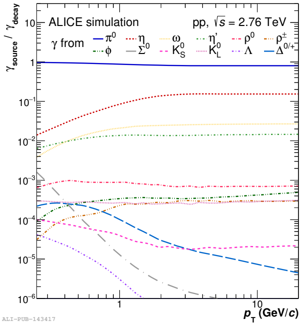
γ_{decay}



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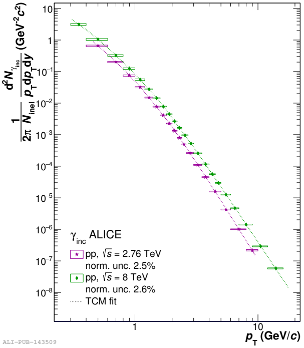
- Decay photon spectrum $\rightarrow$ **cocktail simulation**
- Mother particle abundances based on **parametrised measured spectra** (or m_T scaling)

Subtraction ingredients

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

$\gamma_{\rm inc}$



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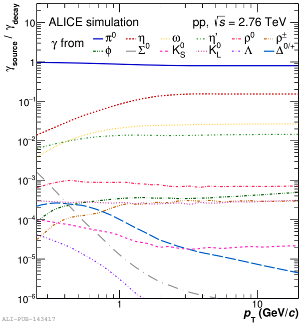
$\gamma_{\rm decay}$



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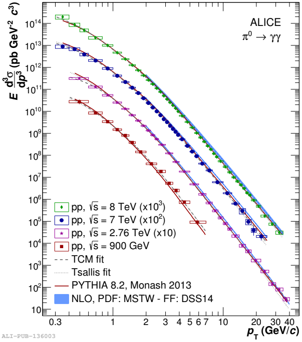
$\pi^0_{\rm param}$



Eur. Phys. J. C 78 (2018) no. 3, 263

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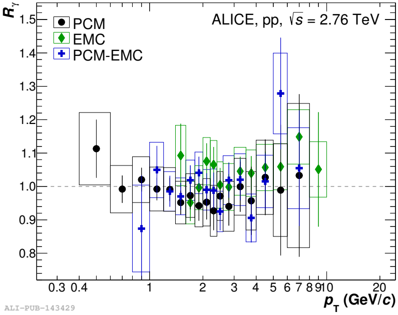
- Decay photon spectrum $\to$ **cocktail simulation**
- Mother particle abundances based on **parametrised measured spectra** (or m_T scaling)

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

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

arXiv:1803.09857



- Three independent reconstruction techniques $\rightarrow$ **good agreement** between them

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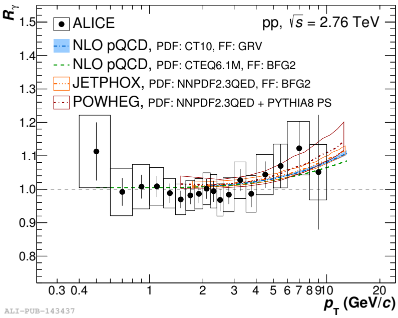

- Three independent reconstruction techniques $\rightarrow$ **good agreement** between them
- Combination using the **BLUE method** $\rightarrow$ uncertainty correlation treatment
- At low p_T, **no excess observed within uncertainties** $\rightarrow$ supports Pb–Pb medium-induced enhancement scenario
- For $p_T > 7$ GeV/c, $\sim 1\sigma$ deviation **consistent with pQCD** at NLO (prompt photons)

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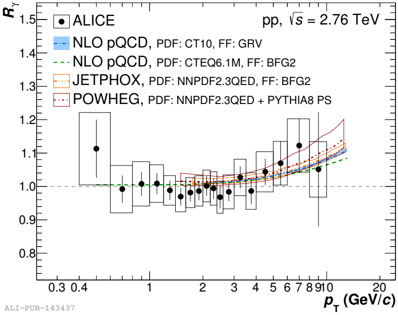

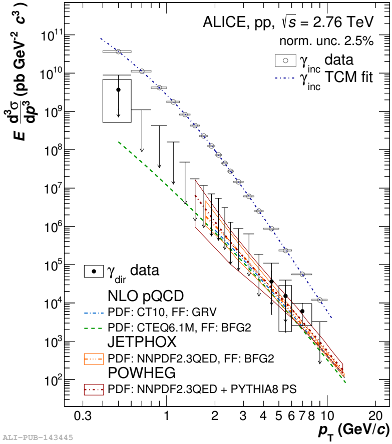

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- Covering **very low p_T**, $0.4 < p_T < 10$ GeV/c
- 90 % C.L. (arrows) $\rightarrow$ points where R_γ **agrees with unity** within uncertainties
- Consistent with pQCD (Paquet PRC 93, 2016, Vogelsang PRD 67, 2003, JETPHOX, POWHEG)

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

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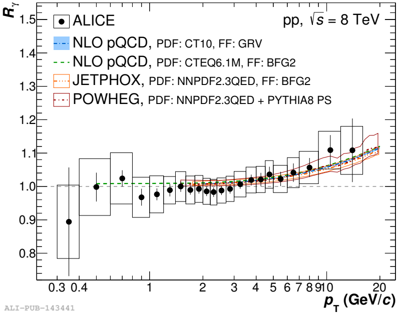

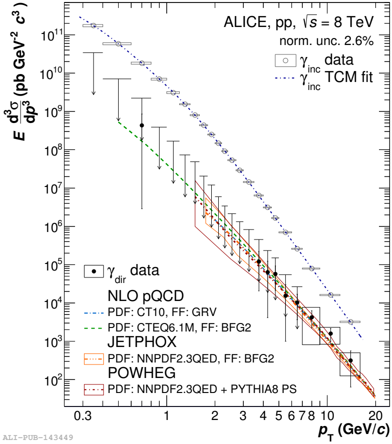

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- For $p_T > 7$ GeV/c, $\sim 1\sigma$ deviation **consistent with pQCD** at NLO (prompt photons)

- Covering **very low p_T**, $0.3 < p_T < 16$ GeV/c
- 90 % C.L. (arrows) → points where R_γ **agrees with unity** within uncertainties
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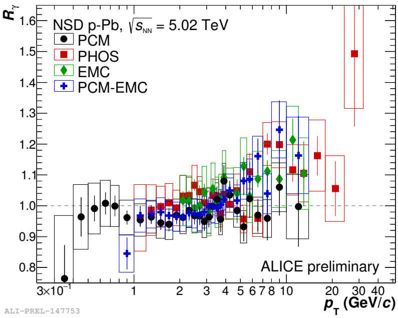
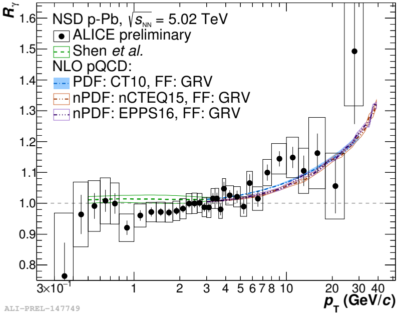
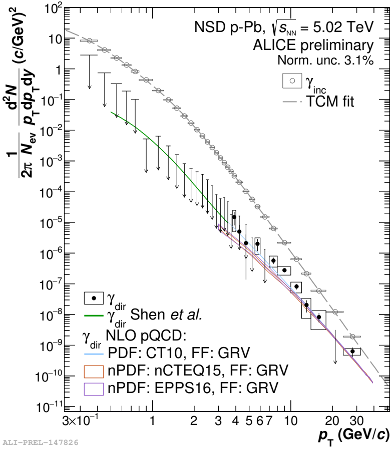
Direct photons at low p_T, p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV



- Four independent reconstruction techniques → **good agreement** between them

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





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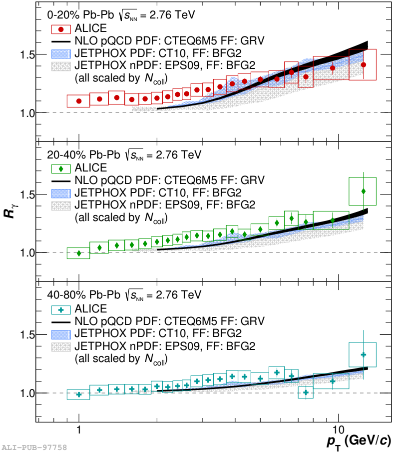
- At low p_T, **no excess observed within uncertainties** → supports Pb–Pb medium-induced enhancement scenario
- For $p_T > 7$ GeV/c, $\sim 1\sigma$ deviation **consistent with binary scaled pQCD** at NLO

- Covering $0.3 < p_T < 32$ GeV/c
- 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

Phys. Lett. B 754 (2016) 235-248



- 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

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

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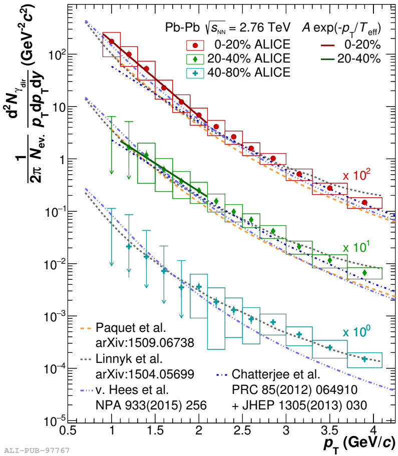

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- For $p_T > 5$ GeV/c, R_γ excess **consistent with binary scaled pQCD prompt photons** in each centrality class
- At low p_T, **10–15 % excess observed in central collisions** → another source of photons
- Comparison to several hydrodynamic models → yield **consistent with a thermal radiation**

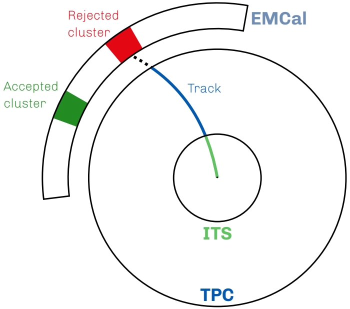
Photon reconstruction at high p_T

Neutral clusters (charged particle veto)

- Clusters spatially matching a track **(charged clusters)** must be rejected

$$\Delta\eta = |\eta_{\text{clus}} - \eta_{\text{track}}| > 0.02$$

$$\Delta\varphi = |\varphi_{\text{clus}} - \varphi_{\text{track}}| > 0.03$$



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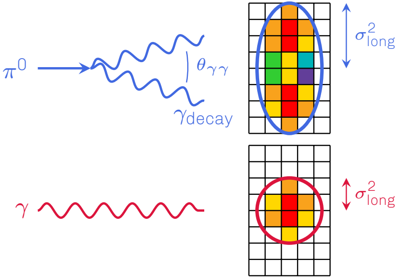
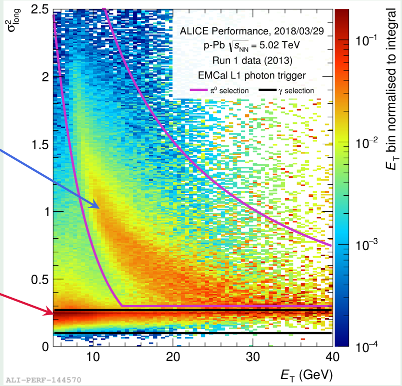


⚠ Not discriminant for $E_T \gtrsim 20$ GeV

Candidate photons (shower shape cuts)

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

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



Photon isolation and purity estimation

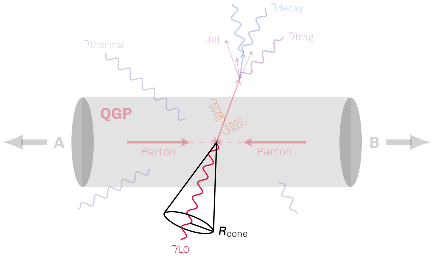
Isolated photons

- **Isolation cone** of radius R_{cone} defined **around a candidate photon** at $(\eta_\gamma, \varphi_\gamma)$

$$R_{cone} = \sqrt{(\eta - \eta_\gamma)^2 + (\varphi - \varphi_\gamma)^2} \; (= 0.4)$$

- Photon declared **isolated** if

$$\sum_{cone} p_T^{neutral + charged} < p_T^{max} \; (= 2\,\mathrm{GeV}/c)$$



Photon isolation and purity estimation

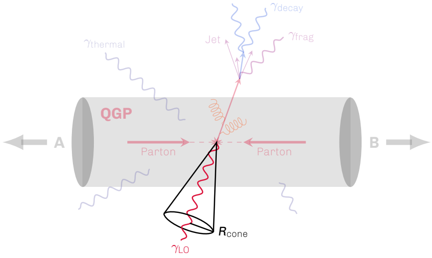
Isolated photons

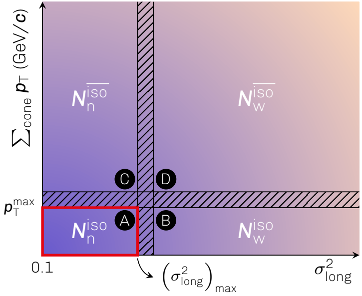
- **Isolation cone** of radius R_{cone} defined **around a candidate photon** at $(\eta_\gamma, \varphi_\gamma)$

$$R_{\mathrm{cone}} = \sqrt{(\eta - \eta_\gamma)^2 + (\varphi - \varphi_\gamma)^2} \; (= 0.4)$$

- Photon declared **isolated** if

$$\sum_{\mathrm{cone}} p_{\mathrm{T}}^{\mathrm{neutral+charged}} < p_{\mathrm{T}}^{\mathrm{max}} \; (= 2\,\mathrm{GeV}/c)$$





$N = S + B = \gamma_{\mathrm{direct}}$ signal + background

Purity estimation: the ABCD method

Phys. Rev. D 83, 052005 (2011)

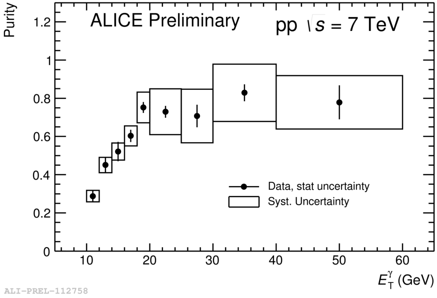
- Part of region Ⓐ clusters truly induced by γ_{direct} → **purity** of the $N_{\mathrm{n}}^{\mathrm{iso}}$ sample

$$\mathbb{P} = S_{\mathrm{n}}^{\mathrm{iso}} / N_{\mathrm{n}}^{\mathrm{iso}} = 1 - \frac{B_{\mathrm{n}}^{\mathrm{iso}}}{N_{\mathrm{n}}^{\mathrm{iso}}}$$

- Background $B_{\mathrm{n}}^{\mathrm{iso}}$ **estimated with data** and **corrected with simulation**

$$\mathbb{P}_{\mathrm{corr}} = 1 - \left(\frac{B_{\mathrm{n}}^{\mathrm{iso}} \times N_{\mathrm{w}}^{\overline{\mathrm{iso}}}}{N_{\mathrm{w}}^{\mathrm{iso}} \times N_{\mathrm{n}}^{\overline{\mathrm{iso}}}} \right)_{\mathrm{simu}} \times \left(\frac{N_{\mathrm{w}}^{\mathrm{iso}} \times N_{\mathrm{n}}^{\overline{\mathrm{iso}}}}{N_{\mathrm{w}}^{\overline{\mathrm{iso}}} \times N_{\mathrm{n}}^{\mathrm{iso}}} \right)_{\mathrm{data}}$$

Isolated photons, pp at $\sqrt{s} = 7$ TeV



- At high E_T, **high purity $\sim$ 80 %** reached
- Systematic uncertainties dominated by **cluster shower shape modelling** (imperfect reproduction in simulation)

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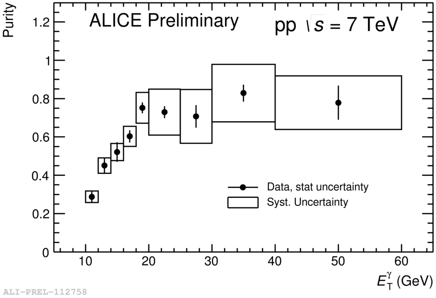
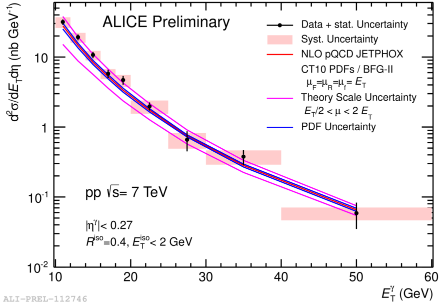
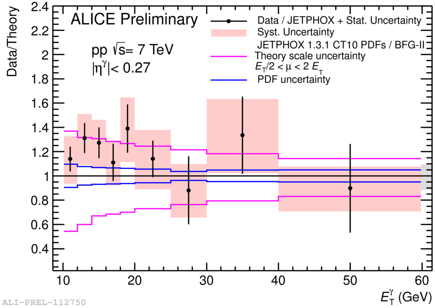


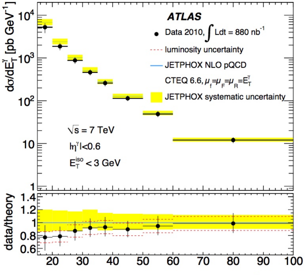


- At high E_T, **high purity $\sim$ 80 %** reached
- Systematic uncertainties dominated by **cluster shower shape modelling** (imperfect reproduction in simulation)
- EMCal **photon triggered** data → covering $10 < E_T < 60$ GeV
- Good agreement with **pQCD calculations at NLO** (JETPHOX)

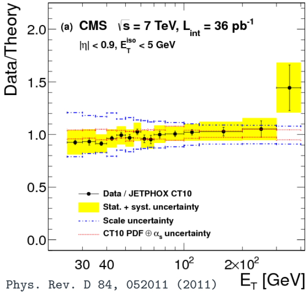
Isolated photons, pp at $\sqrt{s} = 7$ TeV



- Reasonable agreement with the **ATLAS and CMS** measurements in the overlapping E_T region
- **Lower E_T reach** → potential constraints on prompt photons and therefore on **thermal photons** in Pb–Pb collisions
- Preliminary result → final checks ongoing



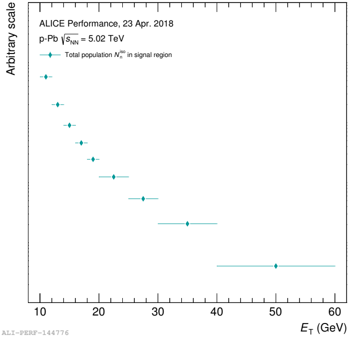
Phys. Rev. D 83, 052005 (2011)



Phys. Rev. D 84, 052011 (2011)

Isolated photon raw yield and purity, p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

- Greater **underlying event** contribution in p–Pb collisions → estimated in perpendicular cones and **subtracted from the isolation cone** before isolation



- Raw yield → direct photon signal + contamination
- E_T reach **similar to pp measurement**

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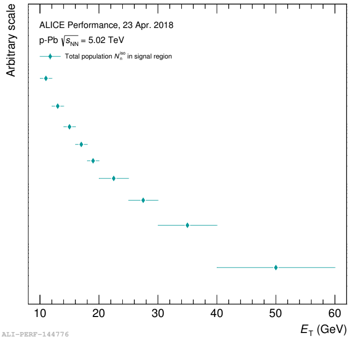

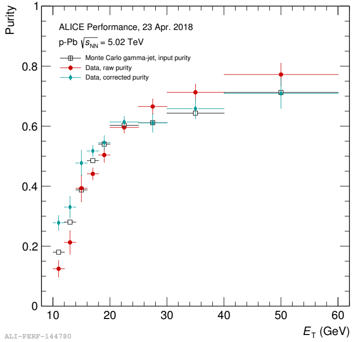

- Raw yield → direct photon signal + contamination
- E_T reach **similar to pp measurement**

- Purity **from ∼ 30 % to ∼ 70 %** over the probed photon energy range

- Final corrections and systematic uncertainties being applied → **isolated photon cross section** coming soon

Direct photon measurements with the ALICE Experiment at LHC

Conclusions and outlook

Direct photons at low p_T, subtraction method

- Measurement **from $p_T = 0.3\,\mathrm{GeV}/c$ to $p_T = 32\,\mathrm{GeV}/c$** 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 $p_T > 7\,\mathrm{GeV}/c$** $\rightarrow$ prompt photons
- Low p_T excess observed in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV $\rightarrow$ **compatible with a thermal radiation**

Direct photons at high p_T, isolation method

- Measurement **from $E_T = 10\,\mathrm{GeV}$ to $E_T = 60\,\mathrm{GeV}$** in pp at $\sqrt{s} = 7$ TeV and p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV
- Results **compatible with pQCD calculations at NLO** and in agreement with ATLAS and CMS
- ALICE extends the **E_T reach to lower values** compared to ATLAS and CMS

Direct photon measurements with the ALICE Experiment at LHC

Conclusions and outlook

Outlook

- Isolated photon **cross section** in p–Pb collisions at $\sqrt{s} = 5.02$ TeV → comparison with pQCD
- Isolated photon R_{pA} → binary scaling test
- γ-hadron and γ-jet **correlations** → parton energy loss studies

Direct photon measurements with the ALICE Experiment at LHC

Conclusions and outlook

Outlook

- Isolated photon **cross section** in p–Pb collisions at $\sqrt{s} = 5.02$ TeV → comparison with pQCD
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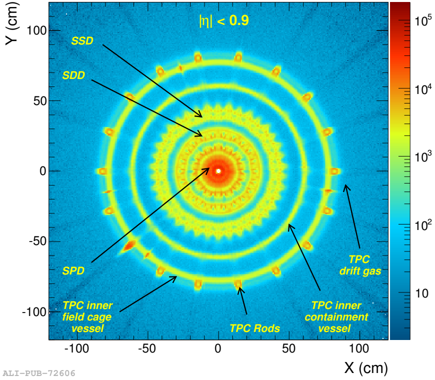
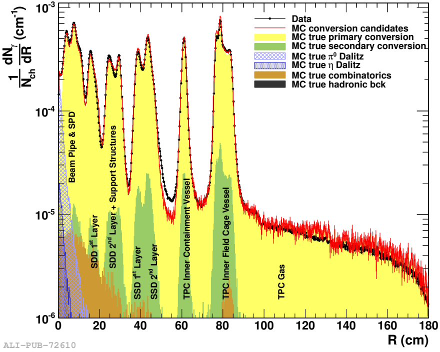
Thanks for your attention!

Backup

PCM reconstruction technique and ALICE central barrel



Int. J. Mod. Phys. A 29 (2014) 1430044



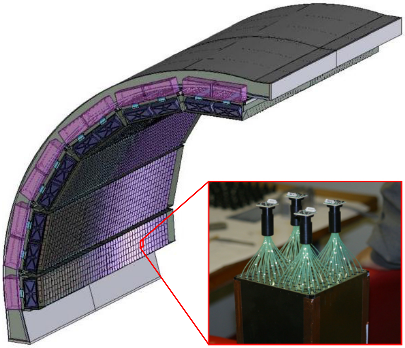
Int. J. Mod. Phys. A 29 (2014) 1430044

- “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 $6 \times 6\,\mathrm{cm}^2$ 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 $5.3\,\mathrm{mm}/\sqrt{E} \oplus 1.5\,\mathrm{mm}$
- Covers $|\eta_\gamma| < $ **0.7** and **100°** in azimuth (φ)
- Used as **trigger detector** (γ/jets)

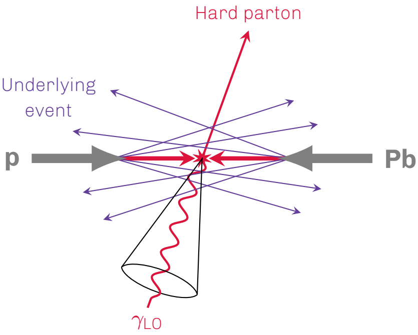


Isolated photons, p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

Specifications

- Run I data, EMCal γ triggers at 11 GeV and 7 GeV
- Integrated luminosity $\rightarrow \mathcal{L}_{int} = 4.64 \pm 0.41\,\mathrm{nb}^{-1}$

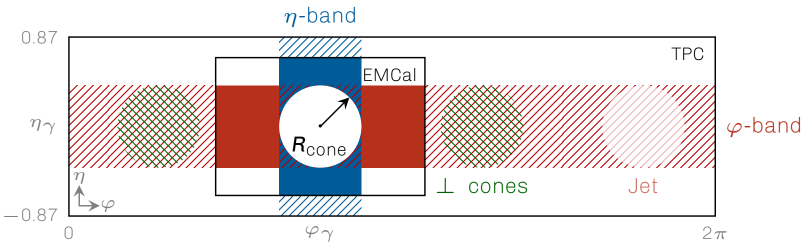
⚠ Larger contribution from the **underlying event (UE)** in p–Pb than in pp collisions



- Underlying event $\rightarrow$ **all processes but the hardest** LO parton interaction

Isolated photons, underlying event estimation

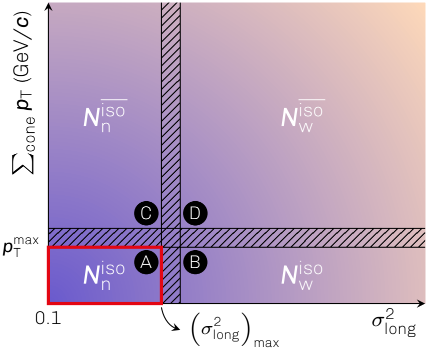
- UE estimated and **subtracted before** isolation, event-by-event $\rightarrow p_{\mathrm{T}}^{\mathrm{iso}} - \rho_{\mathrm{UE}} \times A_{\mathrm{cone}} < 2\ \mathrm{GeV}/c$



Method	Pros	Cons
⊥ 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) → $p_{\text{T}}^{\text{iso}} < 2$ GeV/c
- Anti-isolation crit. (C, D) → $p_{\text{T}}^{\text{iso}} > 3$ GeV/c

The ABCD method (Phys. Rev. D 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 $N_{\text{n}}^{\text{iso}}$ sample

$$\mathbb{P} = S_{\text{n}}^{\text{iso}} / N_{\text{n}}^{\text{iso}} = 1 - B_{\text{n}}^{\text{iso}} / N_{\text{n}}^{\text{iso}}$$

- Background $B_{\text{n}}^{\text{iso}}$ **estimated with data** and **corrected with MC**

Isolated photons, purity estimation

- Data-driven background estimation in signal region Ⓐ

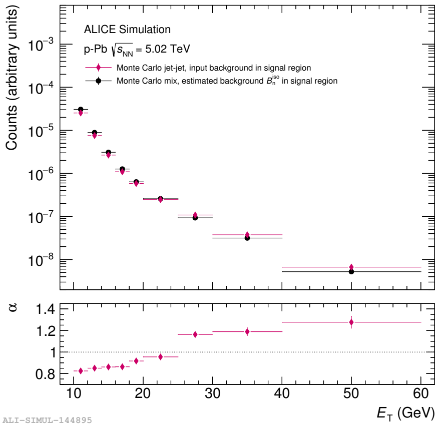
$$B_{\mathrm{n}}^{\mathrm{iso}} = \frac{N_{\mathrm{w}}^{\mathrm{iso}} \times N_{\mathrm{n}}^{\overline{\mathrm{iso}}}}{N_{\mathrm{w}}^{\overline{\mathrm{iso}}}} \Rightarrow \mathbb{P} = 1 - \frac{B_{\mathrm{n}}^{\mathrm{iso}}}{N_{\mathrm{n}}^{\mathrm{iso}}} = 1 - \left(\frac{N_{\mathrm{w}}^{\mathrm{iso}}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

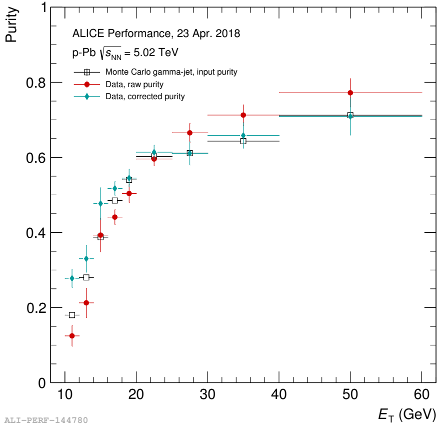
- Possibly **signal contamination** in background regions Ⓑ, Ⓒ and Ⓓ and **non-constant** background isolation probability → purity must be **corrected using MC simulations**

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

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

Isolated photons, purity correction, p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

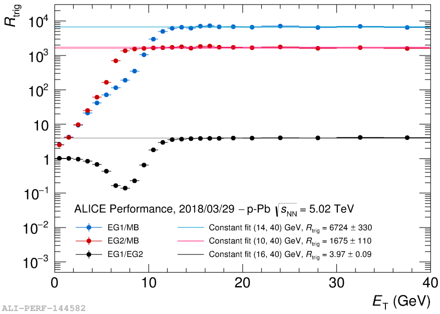




- α rises from lower to greater than unity $\rightarrow$ raw purity $\mathbb{P}$ is clearly **underestimated (overestimated) at low (high) photon E_T**

Isolated photon luminosity, p–Pb at $\sqrt{s_{NN}} = 5.02$ TeV

$$\mathcal{L}_{int} = \frac{N_{ev}^{EG1} \times R_{trig}^{EG1} + N_{ev}^{EG2} \times R_{trig}^{EG2}}{\sigma_{min\ bias}}$$



- $\sigma_{min\ bias}$ measured with vdM scans ~ 2.1 b (JINST 9, P11003 (2014))
- Here $\rightarrow$ $\mathcal{L}_{int} = \mathbf{4.64 \pm 0.41\ nb^{-1}}$ (systematic uncertainty obtained by multi-varying R_{trig} fit ranges)