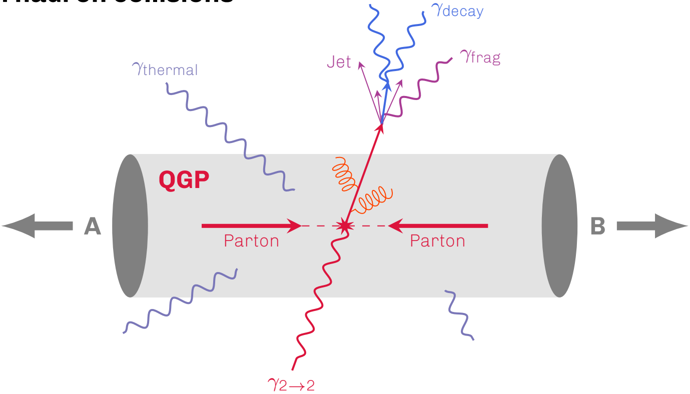
Isolated Photon Production in pp and p–Pb Collisions at the LHC measured with the ALICE experiment

Erwann Masson
Laboratoire Subatech, Nantes

On behalf of the ALICE Collaboration

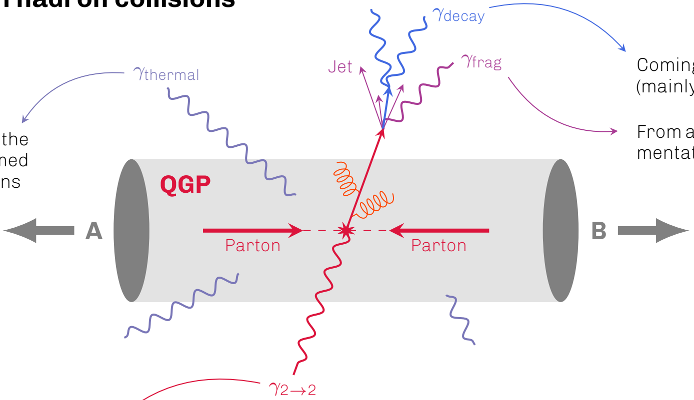
PHOTON 2019, Frascati

Photons in hadron collisions



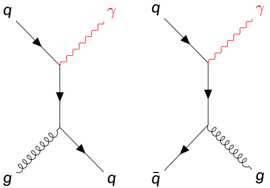
Photons in hadron collisions

Produced by the medium formed in AA collisions

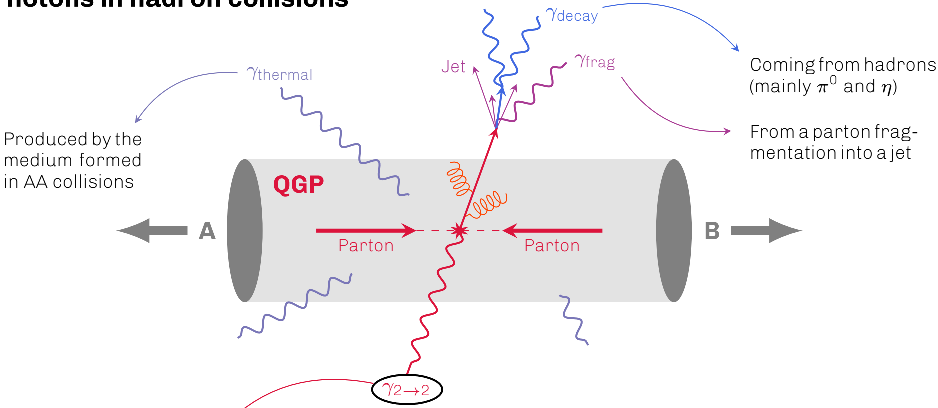


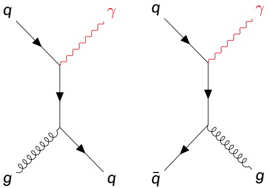
Coming from hadrons (mainly π^0 and η)

From a parton fragmentation into a jet



Photons in hadron collisions





Main interests in pp and p–Pb collisions

- Calibrated energy **reference for parton energy loss studies** through γ-hadron and γ-jet correlations
- Key observable to **test pQCD** and put new **constraints on theory**
- Measurement in p–Pb collisions $\rightarrow$ address **cold nuclear matter effects** by comparing with pp results, and have a **reference for Pb–Pb** measurement and studying the QGP

Photons in hadron collisions

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

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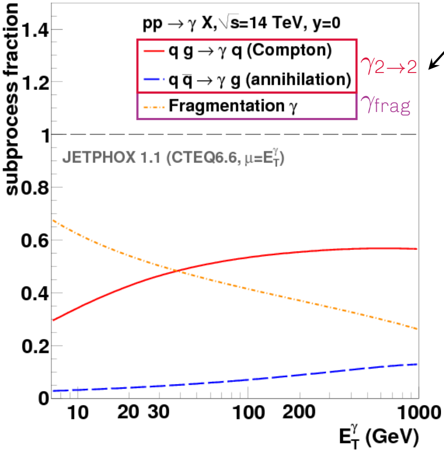
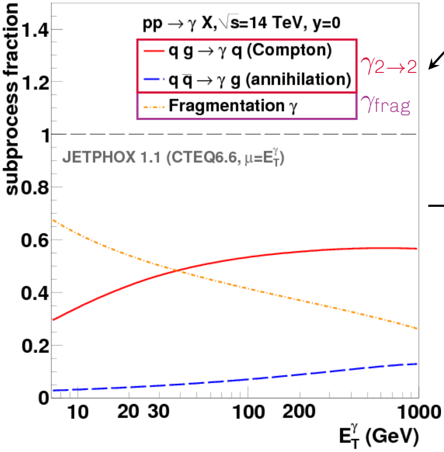


[PRD 82, 014015 (2010)]

Photons in hadron collisions

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



How can we access $\gamma_{2\to2}$ photons?

[PRD 82, 014015 (2010)]

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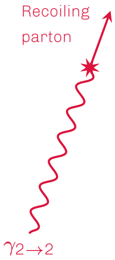
- $\gamma_{2\to2}$ emitted back to the other hard products → selection using an **isolation method**



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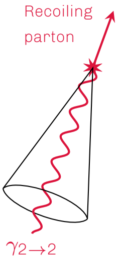
Isolated photons

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

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

- Photon declared **isolated** if $p_{\mathrm{T}}^{\mathrm{iso}} < p_{\mathrm{T}}^{\mathrm{max}}$ (typical values → $R_{\mathrm{cone}} = 0.4$, $p_{\mathrm{T}}^{\mathrm{max}} = 2\,\mathrm{GeV}/c$)



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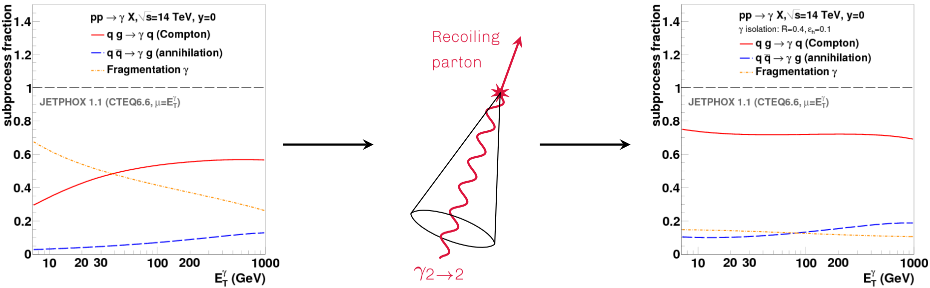
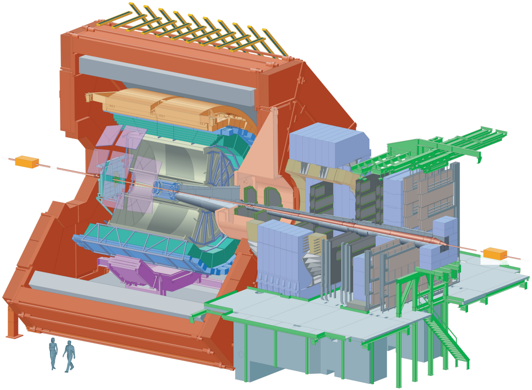


[PRD 82, 014015 (2010)]

Photon reconstruction with ALICE (Run I configuration)



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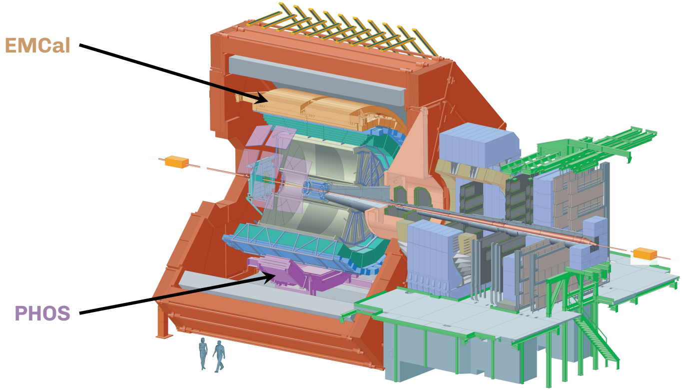

Calorimetry

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

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

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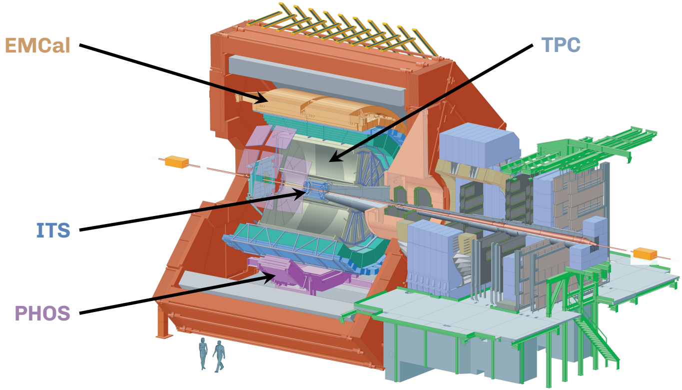

Tracking ($|\eta| < 0.9$, $0° < \varphi < 360°$)

ITS Primary/secondary vertex determination

TPC Tracking and particle identification (PID)

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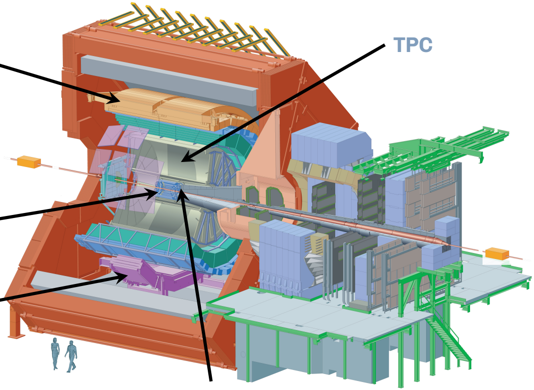

Tracking ($|\eta| < 0.9$, $0° < \varphi < 360°$)

ITS Primary/secondary vertex determination

TPC Tracking and particle identification (PID)

Triggering

V0 Minimum bias, luminosity and centrality measurement

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

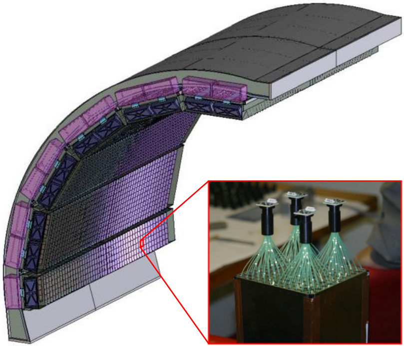
PHOS Lead tungstate crystals
$|\eta| < 0.12$, $260° < \varphi < 320°$

+ extended p_{T} reach thanks to EMCal and PHOS triggering capabilities

Photon reconstruction with EMCal

Specifications

- 12 supermodules (10 in this work) $\rightarrow$ **12288 cells** with a $6 \times 6\,\mathrm{cm}^2$ area (4.28 m from IP)
- Covers $|\eta| < $ **0.7** and **100°** in azimuth (φ)
- Each cell $\rightarrow$ **153 lead/scintillator** alternating layers (24.6 cm thick in total)
- Energy/position resolutions $\rightarrow$ $4.8\,\%/E \oplus 11.3\,\%/\sqrt{E} \oplus 1.7\,\%$ and $5.3\,\mathrm{mm}/\sqrt{E} \oplus 1.5\,\mathrm{mm}$
- Used as **trigger detector** (photons/jets)



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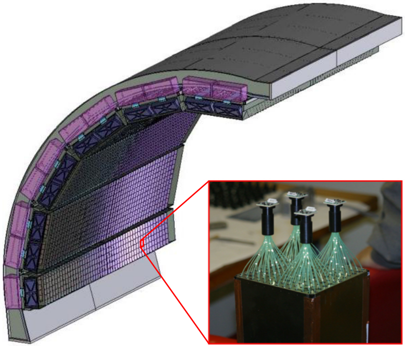
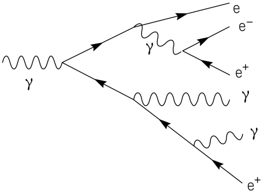
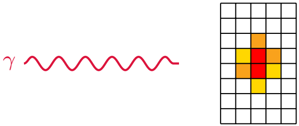




Clusterisation →



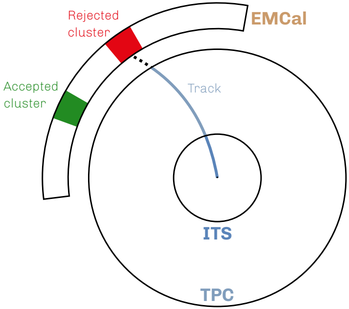
Photon selection

Neutral clusters (charged particle veto)

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

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

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



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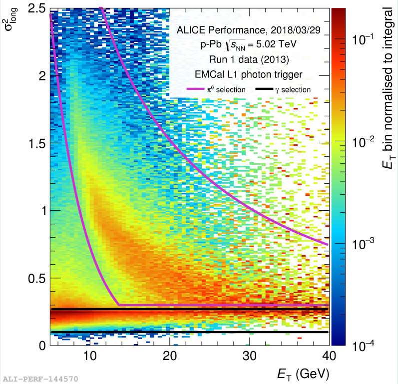
Candidate photons (shower shape cuts)

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

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



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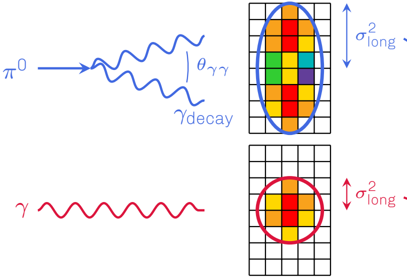

⚠ Not discriminant above ∼ 20 GeV

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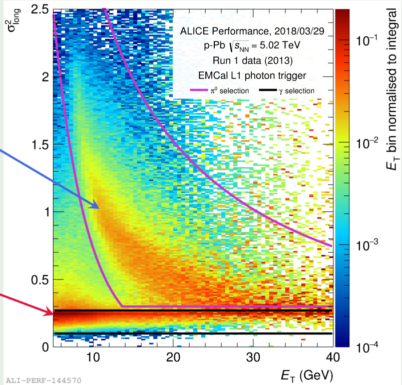
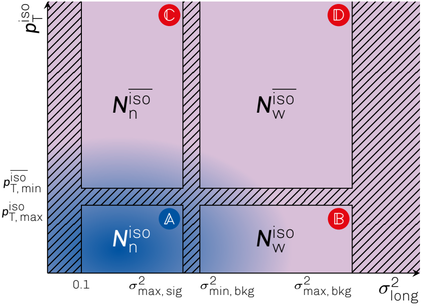


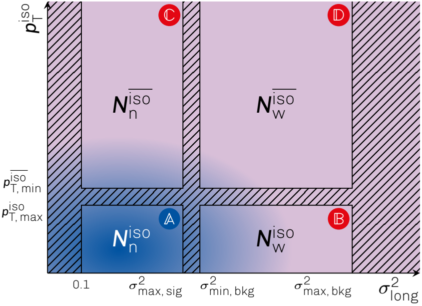
Signal extraction



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)

Signal extraction



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

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

- Isolation with **neutral** + **charged** particles
- Isolation criterion (Ⓐ, Ⓑ) $\rightarrow p_T^{iso} < 2\,\text{GeV}/c$
- Anti-isolation criterion (Ⓒ, Ⓓ) $\rightarrow p_T^{\overline{iso}} > 3\,\text{GeV}/c$
- Fraction of region Ⓐ clusters truly induced by $\gamma_{2\rightarrow2}$ → **data-driven purity P_{dd}** of the N_n^{iso} sample

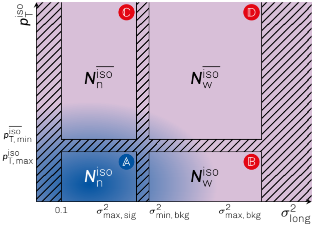
Particle quantities

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

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

Purity estimation

- Data-driven background (and purity) estimation in the signal region Ⓐ



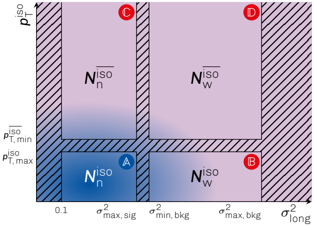
Two strong assumptions

- Only **background clusters** in background regions (Ⓑ, Ⓒ and Ⓓ)
- Similar **background isolation fraction** in narrow (Ⓐ, Ⓒ) and wide (Ⓑ, Ⓓ) cluster regions

$$B_n^{iso} = \frac{N_w^{iso} \times N_n^{\overline{iso}}}{N_w^{\overline{iso}}} \Rightarrow P_{dd} = 1 - \frac{B_n^{iso}}{N_n^{iso}} = 1 - \left(\frac{N_w^{iso} \times N_n^{\overline{iso}}}{N_w^{\overline{iso}} \times N_n^{iso}} \right)_{data}$$

Purity estimation

- Data-driven background (and purity) estimation in the signal region (A)



Two strong assumptions

- Only **background clusters** in background regions (B, C and D)
- Similar **background isolation fraction** in narrow (A, C) and wide (B, D) cluster regions

Two corrections with PYTHIA MC [JHEP 05, 026 (2006)]

- Possibly **signal leakage** in background regions (B, C and D)
- Background isolation fraction **depending on the shower shape σ^2_{long}**
- MC jet-jet (JJ, **background**) and γ-jet (GJ, **signal**) → used to compute a **correction factor α**

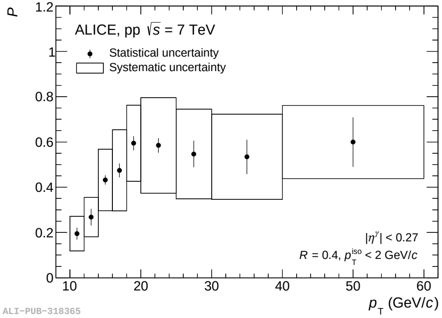
$$\alpha = \frac{\overbrace{\left(B_{\mathrm{n}}^{\mathrm{iso}}\right)_{\mathrm{JJ}}}^{\text{real bkg.}}}{\underbrace{\left(B_{\mathrm{n}}^{\mathrm{iso}}\right)_{\text{MC mix}}}_{\text{estimated bkg.}}} \Rightarrow P = 1 - \underbrace{\left(\frac{B_{\mathrm{n}}^{\mathrm{iso}} \times N_{\mathrm{w}}^{\overline{\mathrm{iso}}}}{N_{\mathrm{w}}^{\mathrm{iso}}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

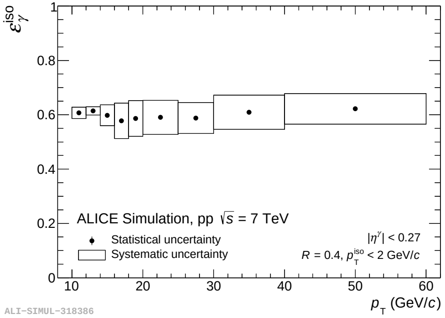
Results in pp collisions at $\sqrt{s} = 7$ TeV – Purity and efficiency

[arXiv:1906.01371] – Submitted to EPJC

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



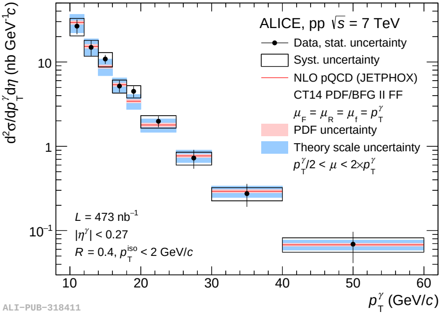


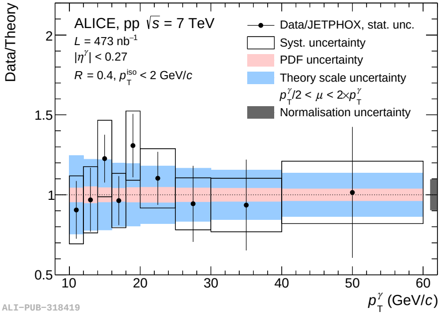
- Purity ranging **from 20% to 60%** $\rightarrow$ interplay between physics and detector effects
- Total efficiency $\sim$ **60%** $\rightarrow$ correcting data from reconstruction, ID and isolation inefficiencies

Results in pp collisions at $\sqrt{s} = 7$ TeV – Cross section

[arXiv:1906.01371] – Submitted to EPJC

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

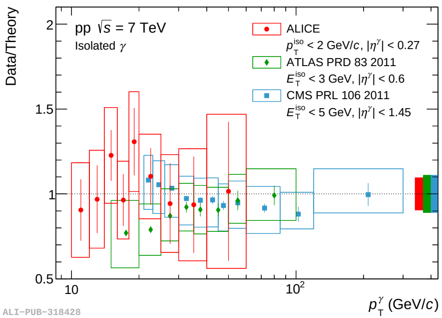


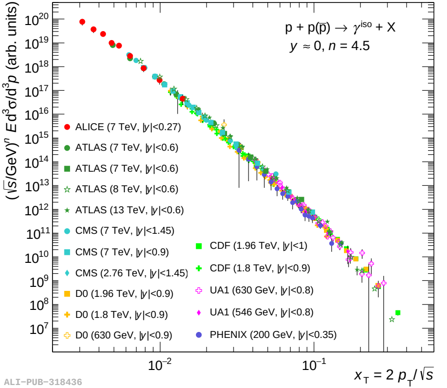


- Syst. unc. ranging **from 19% to 24%** → dominated by the isolation technique
- ALICE data compared to **pQCD at Next-to-Leading Order** (JETPHOX [PRD 73, 094007 (2006)] with CT14 PDF [PRD 93, 033006 (2016)] and BFG II FF [EPJC 2, 529-537 (1998)])
- Good agreement between our measurement and theory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

Results in pp collisions at $\sqrt{s} = 7$ TeV – Comparison to other experiments

[arXiv:1906.01371] – Submitted to EPJC





- **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$\bar{\text{p}}$ collisions [NPB 860, 311-338 (2012)]

Results in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$

Specifications

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

Results in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$

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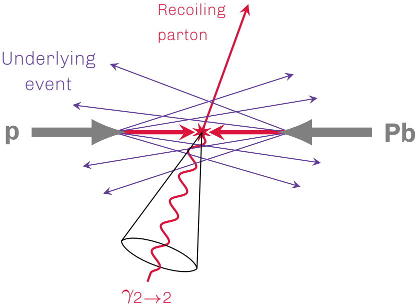
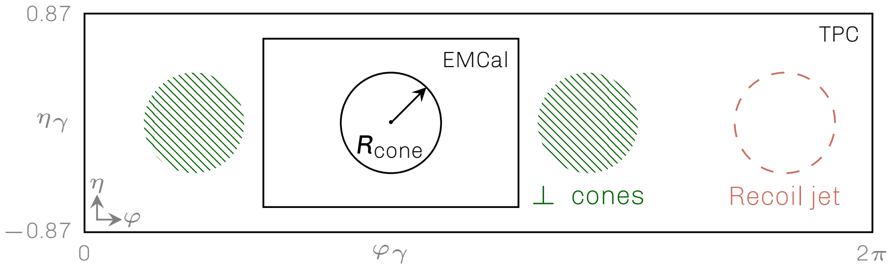
⚠ Larger contribution from the **underlying event (UE)** in p–Pb than in pp collisions



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

Underlying event estimation

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



- Charged UE measurement in **perpendicular cones** then "neutral + charged" extrapolation $\rightarrow \langle \rho_{\mathrm{UE}} \rangle \approx 1.7$ GeV/c inside the isolation cone

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

Specifications

- 2013 data sets, EMCal Level-1 γ triggers (7/11 GeV) $\rightarrow$ **photons measured in 10–60 GeV/c**
- Integrated luminosity $\rightarrow \mathcal{L}_{int} = 4.54 \pm 0.37\,\text{nb}^{-1}$
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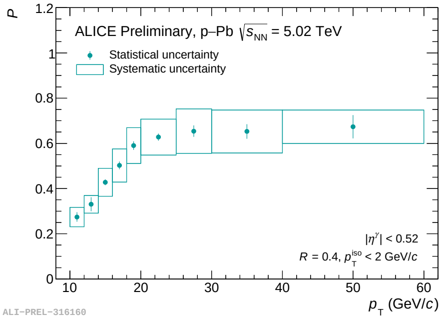
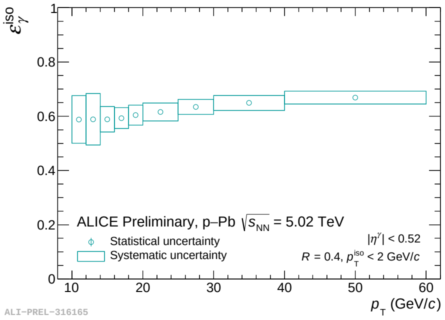
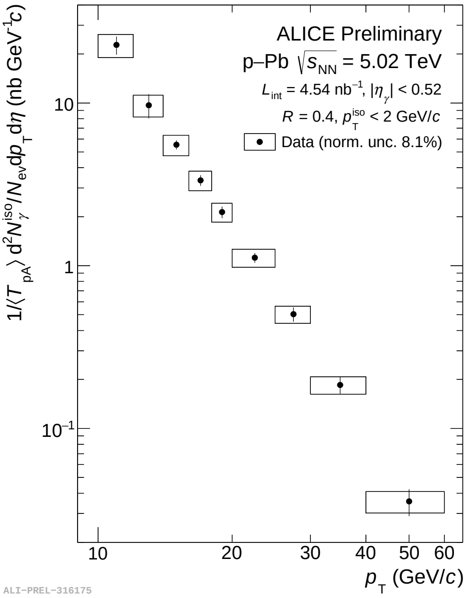




- Purity ranging **from 27% to 67%** $\rightarrow$ interplay between physics and detector effects
- Total efficiency $\gtrsim$ **60%** $\rightarrow$ correcting data from reconstruction, ID and isolation inefficiencies

Results in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV – Cross section



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

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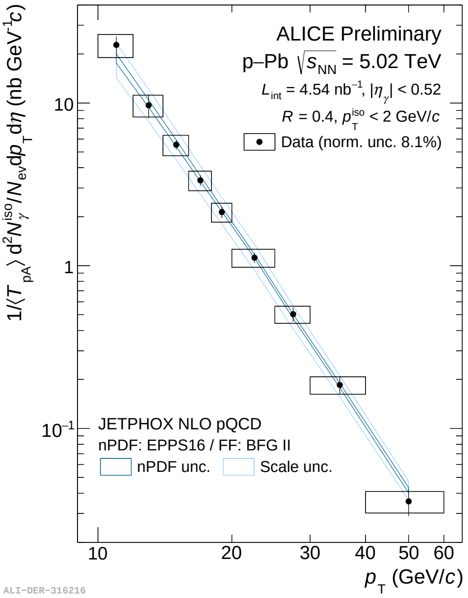

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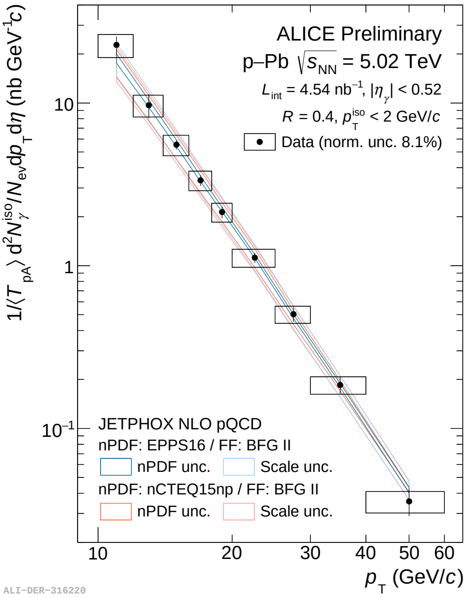

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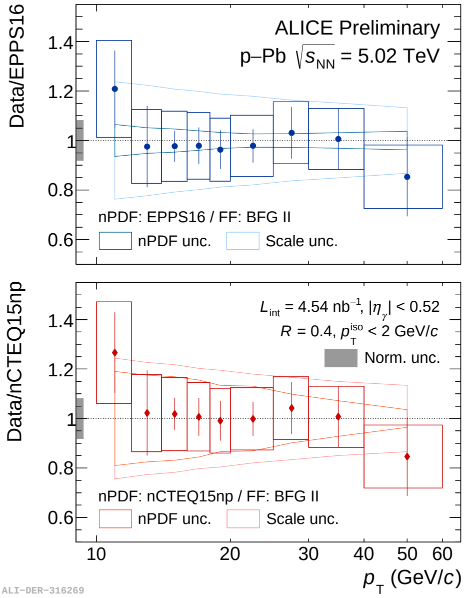

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Conclusions and outlook

Measuring photons in hadron collisions

- Photons **not affected** by the QCD medium → initial information on collision dynamics
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- Measurement in the **p_{T} range 10–60 GeV/c** 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 **p_{T} reach to lower values** compared to ATLAS and CMS $\rightarrow$ valuable result for understanding the low-p_{T} direct photon region (thermal photons?)
- Further outlook $\rightarrow$ γ-jet and γ-hadron correlations

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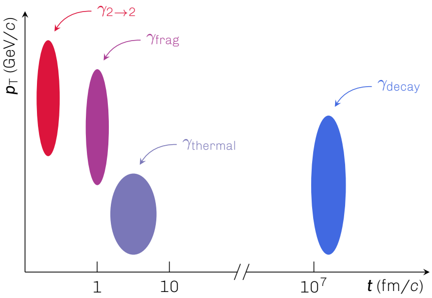
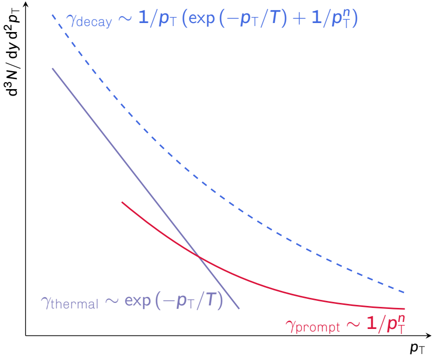
Thank you for your attention!

Backup

Why study the $\gamma_{2\to2}$ component?

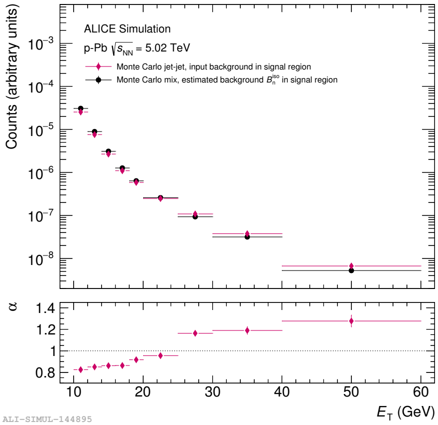
- $\gamma_{2\to2}$ **produced early** in hard processes and **not affected** by the traversed medium
  $\to$ Calibrated energy **reference for parton (q, g) energy loss** studies (correlations)
- Crucial to study their contribution to the total γ population to extract the **thermal component**

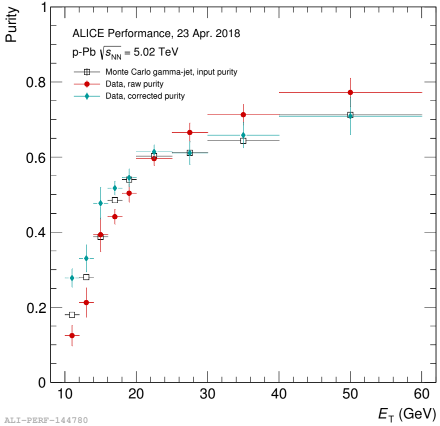




- $\gamma_{2\to2}$ well described by perturbative QCD calculations $\to$ measuring them helps to **test and constrain theory**

Purity correction (p–Pb)



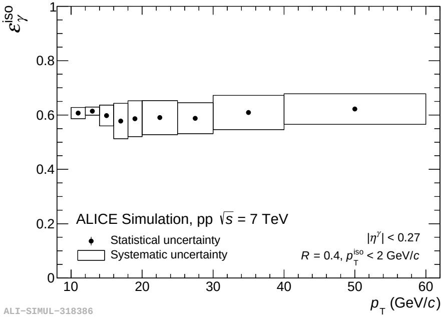


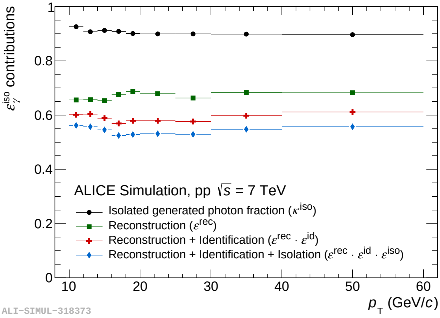
- α rises from lower to greater than unity → raw purity P_{dd} is clearly **underestimated (over-estimated) at low (high) photon p_T**
- Corrected estimated purity **closer to "ideal purity"** → mandatory step

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

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



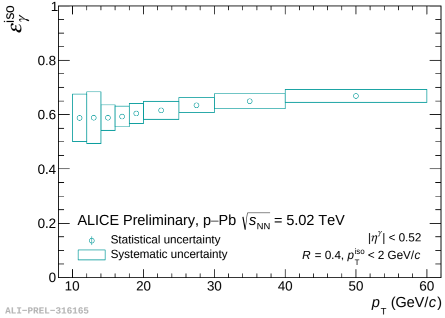


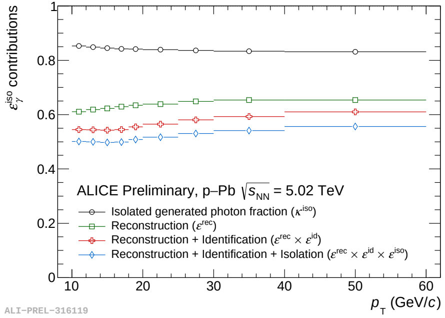
- Total efficiency $\sim$ **60%** $\rightarrow$ correcting data from reconstruction, ID and isolation inefficiencies

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

Specifications

- 2013 data sets, EMCal Level-1 γ triggers (7/11 GeV) $\rightarrow$ **photons measured in 10–60 GeV/c**
- Integrated luminosity $\rightarrow \mathcal{L}_{int} = 4.54 \pm 0.37\,\mathrm{nb}^{-1}$
- 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