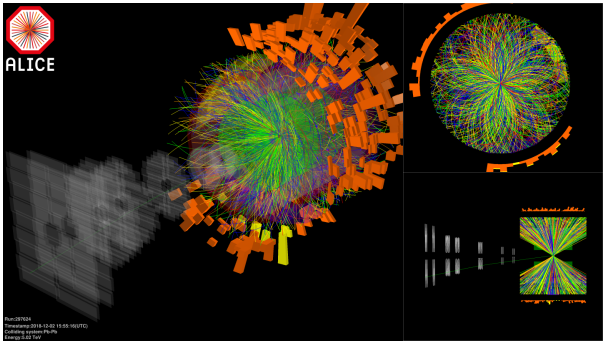
New Vistas in Photon Physics in Heavy-Ion Collisions



Electromagnetic probes in ALICE

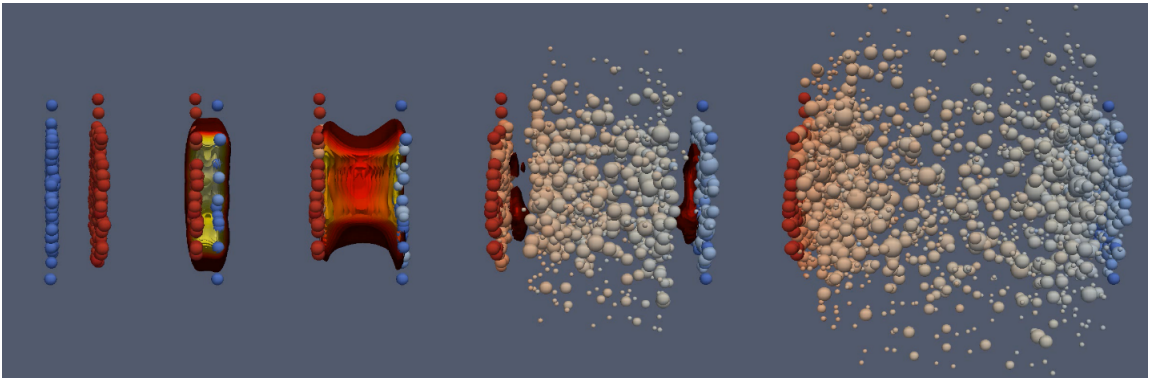
Mike Sas

CERN

Sep 22, 2022

Heavy-ion collisions

Initial state → QGP → hadronization → hadron cascades



Over the whole evolution we have production of photons!
From **direct**(prompt, pre-equilibrium, thermal, fragmentation) to **decay** photons ($\pi^0, \eta, \omega, ...$)
This talk: focus on photon reconstruction and neutral meson production in ALICE

Signatures of the QGP

- **Modified particle production**
  Particles are produced via

$$\sigma_{h_1 h_2 \to x} = f_i^{h_1}(x_1, Q^2) f_j^{h_2}(x_2, Q^2) \otimes \sigma^{ij \to k}(x_1 p_1, x_2 p_2, Q^2) \otimes D_{k \to x}(z, Q^2)$$

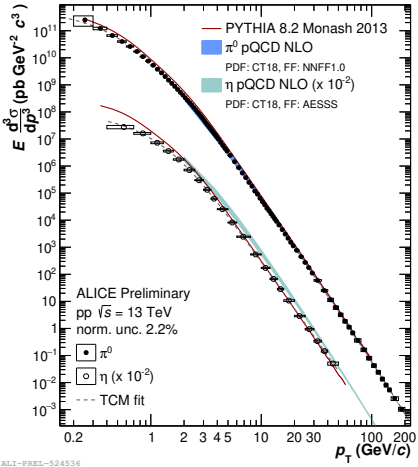
- **Energy loss**
  Particles lose energy by traversing the medium

$$R_{\mathrm{AA}} = \frac{dN^{\mathrm{AA}}/dp_{\mathrm{T}}}{< T_{\mathrm{AA}} > d\sigma^{\mathrm{pp}}/dp_{\mathrm{T}}}$$

- **Anisotropic flow**
  Spatial anisotropy of the produced system leads to a momentum anisotropy

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n cos(n(\varphi - \Psi_R))\right)$$

π^0 and η production



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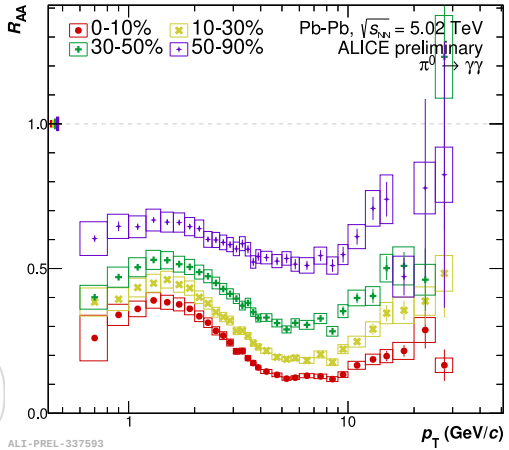
π^0 energy loss in Pb–Pb collisions



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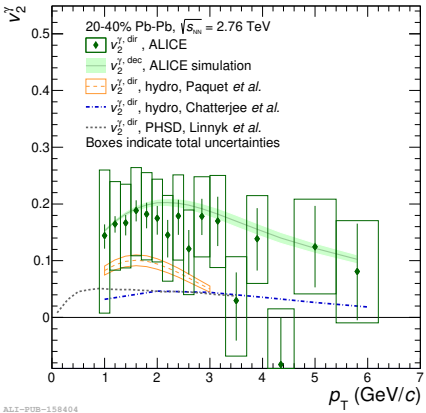
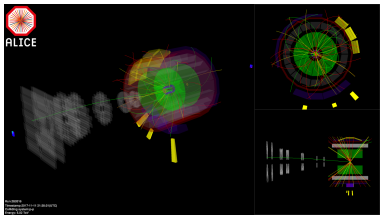
Direct photon flow in Pb–Pb collisions



My big questions in heavy-ion physics

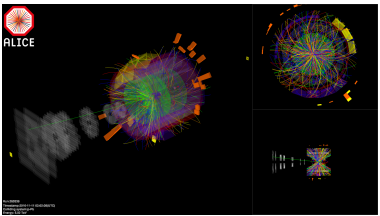
- What are the different particle production mechanisms across different system sizes?
- How does the Quark Gluon Plasma form, evolve, and transition again into hadronic matter?
- Can we find the onset of the QGP? $\rightarrow$ Is there a QGP droplet formed in small systems?

pp



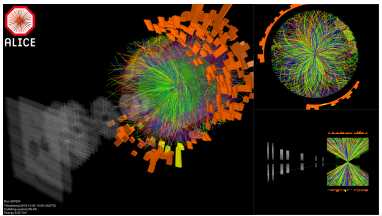
$N_{\text{particles}} \sim 10^1$

p–Pb



$N_{\text{particles}} \sim 10^2$

Pb–Pb



$N_{\text{particles}} \sim 10^4$

Measuring photons with the ALICE detector

Photon Conversion Method (PCM)

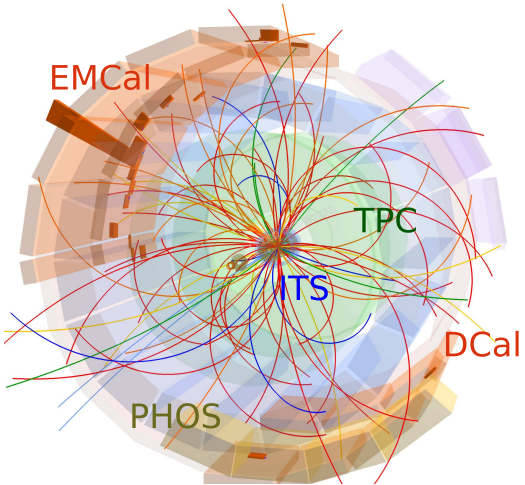
- ITS and TPC, conversion probability $\sim 8\%$
- $|\eta| < 0.9$ and $0^\circ < \varphi < 360^\circ$
- $E_\gamma > 100$ MeV, $E_{\pi^0} > 300$ MeV

PHOS calorimeter

- $PbWO_4$ crystals (cell size 2.2 cm x 2.2 cm)
- $|\eta| < 0.12$ and $250^\circ < \varphi < 320^\circ$
- $E_\gamma > 200$ MeV, $E_{\pi^0} > 400$ MeV

EMCal calorimeter

- Pb-scintillator towers (cell size 6 cm x 6 cm)
- EMCal: $|\eta| < 0.7$, $80^\circ < \varphi < 187^\circ$
- DCal: $0.22 < |\eta| < 0.7$, $260^\circ < \varphi < 320^\circ$
- DCal: $|\eta| < 0.7$, $320^\circ < \varphi < 327^\circ$
- $E_\gamma > 700$ MeV, $E_{\pi^0} > 1.4$ GeV

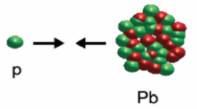
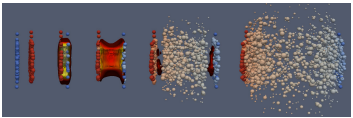


Neutral meson production

Why measure neutral mesons?

$\pi^0 \to \gamma\gamma, \quad \eta \to \gamma\gamma, \quad \omega \to \pi^0\gamma, \quad \ldots$

- Straightforward identification (M_{inv}) $\to$ study the particle production mechanisms
- Main background for $\gamma_{\mathrm{direct}} \to$ precise neutral meson measurements lead to precise γ_{direct} measurements

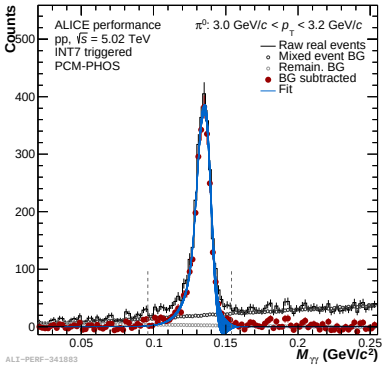
pp	p–Pb	Pb–Pb
		
• Jet production • Underlying event studies	• Cold nuclear matter effects • Multiplicity dependence	• QGP effects • Centrality dependence

Neutral meson reconstruction in ALICE

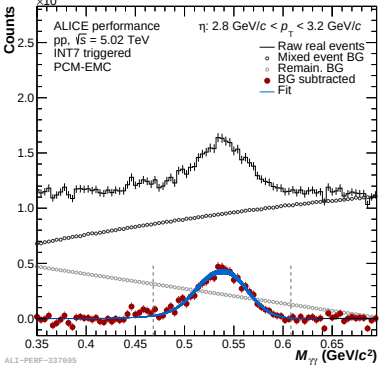
Analysis strategy:

1. Reconstruct the photons
2. Obtain the meson raw yield: integrate M_{inv} distributions
3. Correct raw yield for efficiency, acceptance, feed-down from secondaries
4. Combine the different reconstruction methods
5. More differential studies

π^0



η



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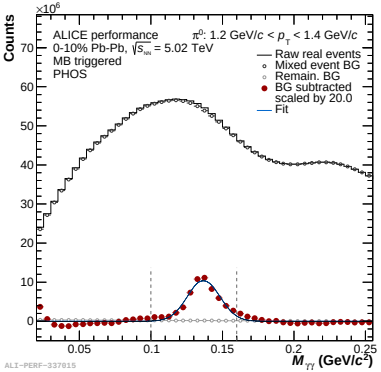
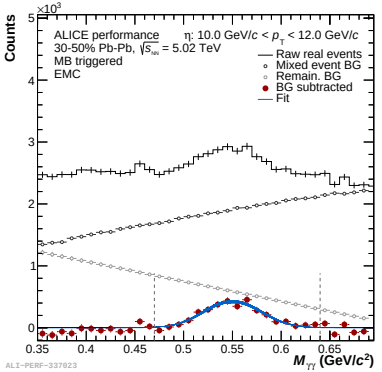


η



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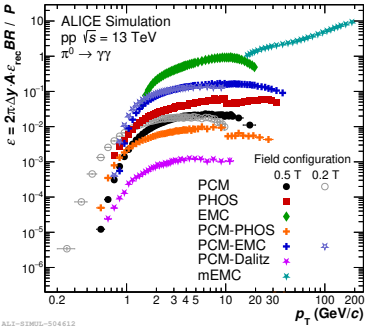

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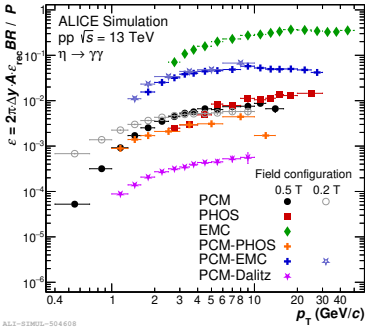

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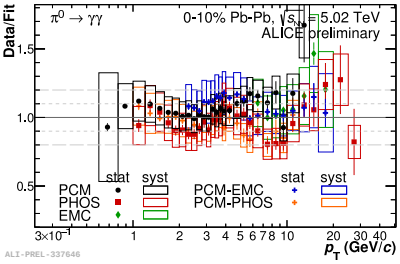

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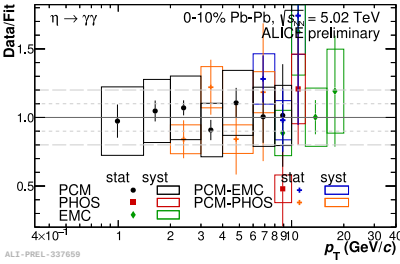

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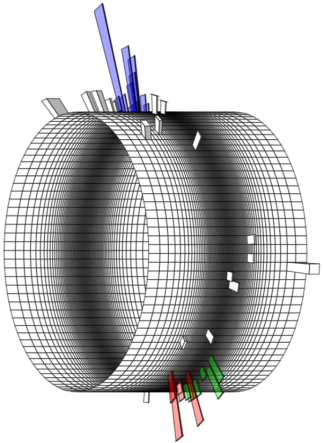
- vs. event multiplicity
- vs. Sphericity: $0 < S_{\mathrm{T}} < 1$
  - Pencil-like: $S_{\mathrm{T}} \approx 0$
  - Spherical: $S_{\mathrm{T}} \approx 1$
- In-jet production
  - Reconstruct neutral mesons inside charged jets
  - Algorithm: anti-k_{t}, $R = 0.4$, $E > 10$ GeV

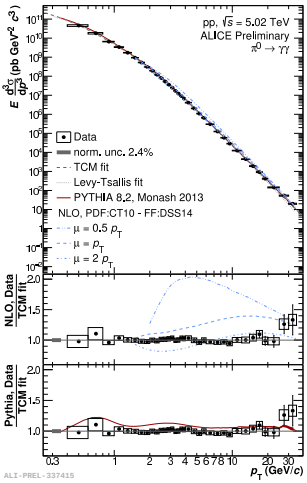


Neutral mesons in pp collisions

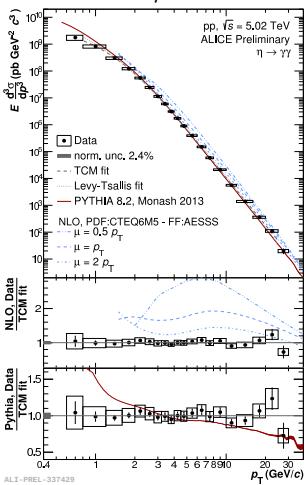
Main reasons for study:

- Fragmentation
- Contribution underlying event
- Main background for γ_{direct}

π^0



η



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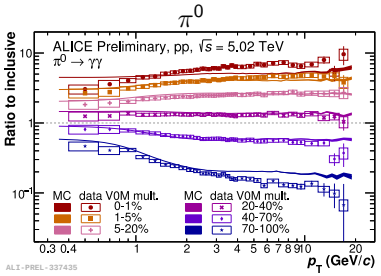
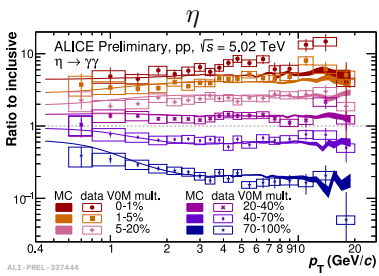
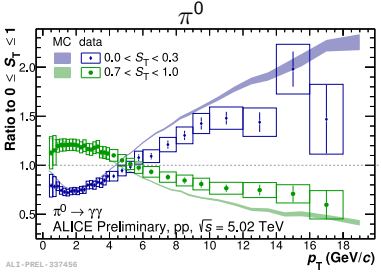
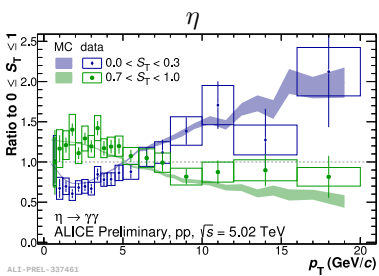
Comparisons to predictions:

- PYTHIA overpredicts π^0, except for high multiplicity
- PYTHIA overpredicts π^0 pencil-like events, underpredicts spherical events
- η/π^0 significantly modified for the in-jet production









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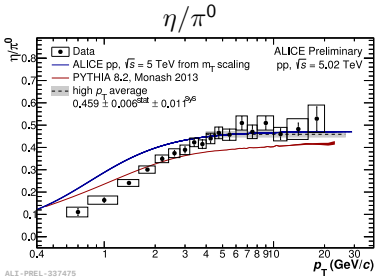
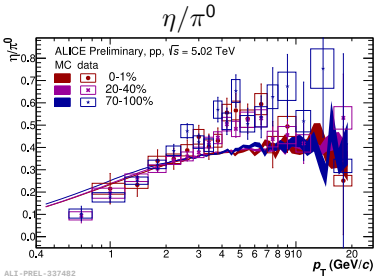
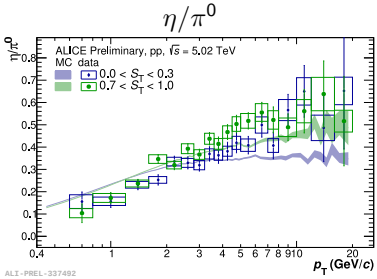
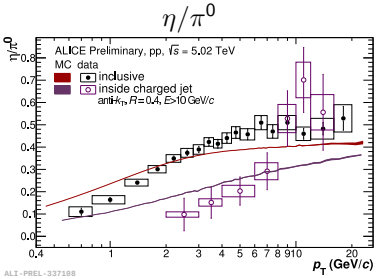
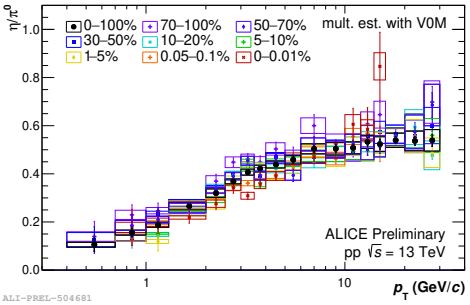




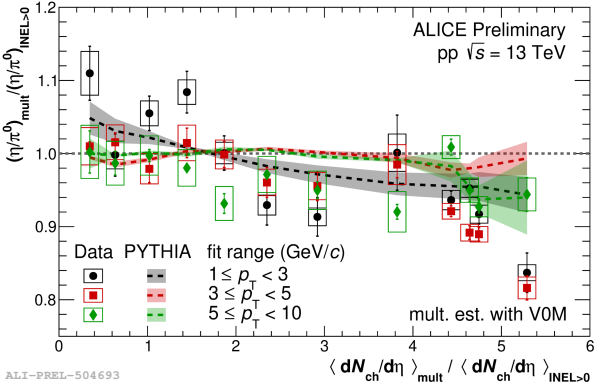




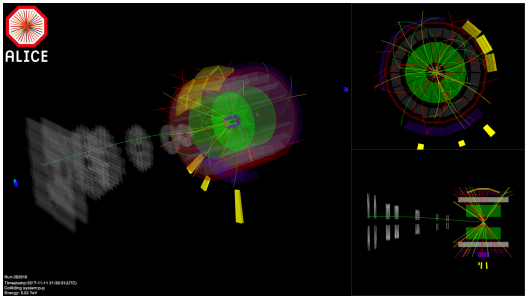
New surprising result in pp collisions at 13 TeV

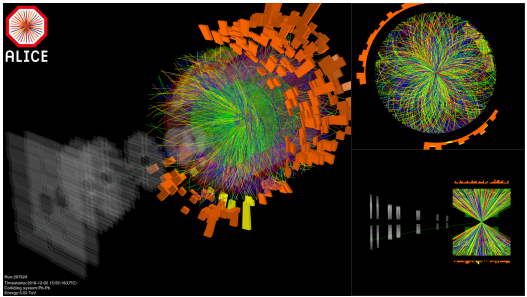


- Indication of an ordering of η/π^0 ratio from low to high multiplicity
- Fits of the double ratio, for a given range in p_T, show a decreasing trend with increasing $dN_{\rm ch}/d\eta$
- Stronger effect in data compared to predictions in PYTHIA



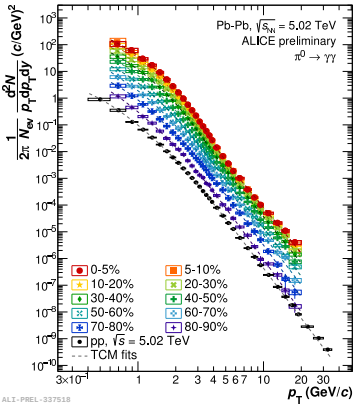
From pp to Pb–Pb collisions...



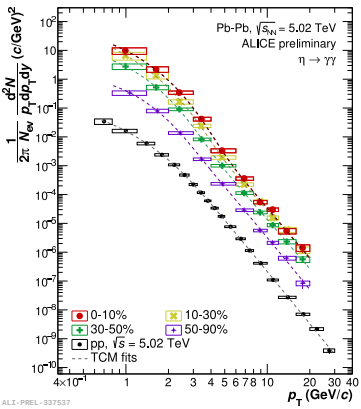


Neutral mesons in Pb–Pb collisions

π^0



η

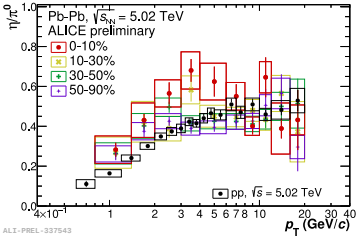


Multiplicity dependent production

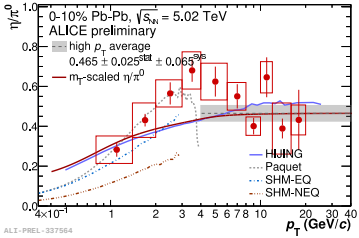
- Precise spectra over large momentum range
- Main background for direct photon analysis
- η/π^0 shows significant modification for non-peripheral collisions
- R_{AA} shows strong suppression for central collisions

Neutral mesons in Pb–Pb collisions

η/π^0



η/π^0 0-10%



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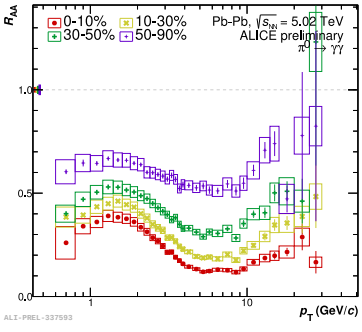
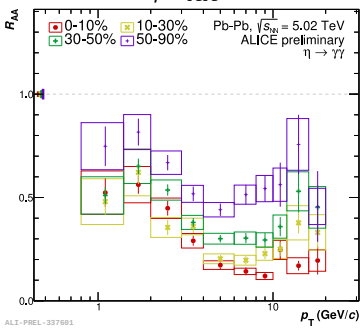
π^0 R_{AA}



η R_{AA}



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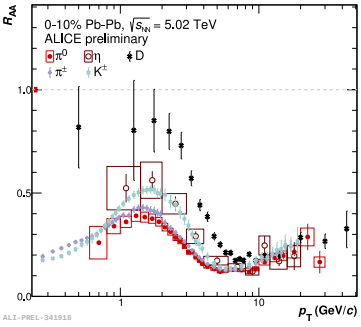
Nuclear modification factor:

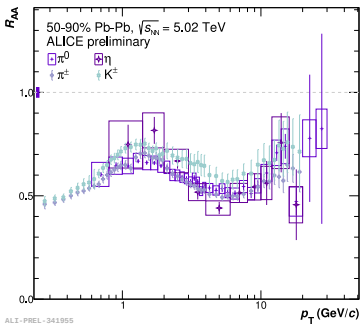
$$R_{\mathrm{AA}} = \frac{dN^{\mathrm{AA}}/dp_{\mathrm{T}}}{< T_{\mathrm{AA}} > d\sigma^{\mathrm{pp}}/dp_{\mathrm{T}}}$$

Neutral mesons in Pb–Pb collisions

R_{AA} 0-10%



R_{AA} 50-90%



Multiplicity dependent production

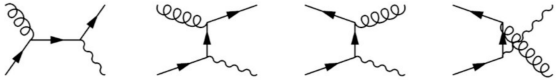
- Precise spectra over large momentum range
- Main background for direct photon analysis
- η/π^0 shows significant modification for non-peripheral collisions
- R_{AA} shows strong suppression for central collisions

Nuclear modification factor:

$$R_{\mathrm{AA}} = \frac{dN^{\mathrm{AA}}/dp_{\mathrm{T}}}{< T_{\mathrm{AA}} > d\sigma^{\mathrm{pp}}/dp_{\mathrm{T}}}$$

Prompt photon (and jet) production

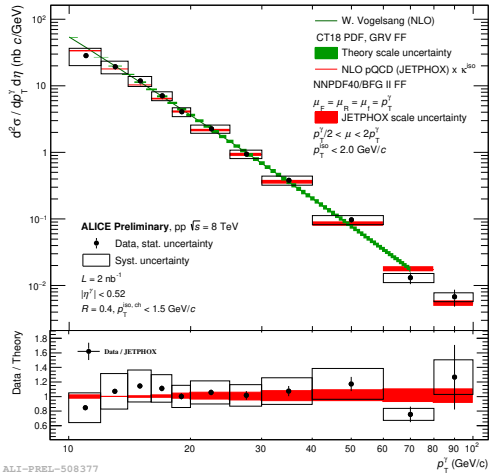
Prompt photon production in pp collisions



- Challenging measurement, done via charged isolation of the (calorimeter) photons
- Important input for proton PDFs, test of pQCD (LO to NLO to NNLO)
- The basis for many and more complicated analyses:
  - in pp: reconstruct the other outgoing leg, quark/gluon jets, investigate NLO production
  - in pPb: provide strong constraints for nuclear PDF and cold nuclear matter effects
  - in PbPb: extremely insightful probe, next slide

What is next?

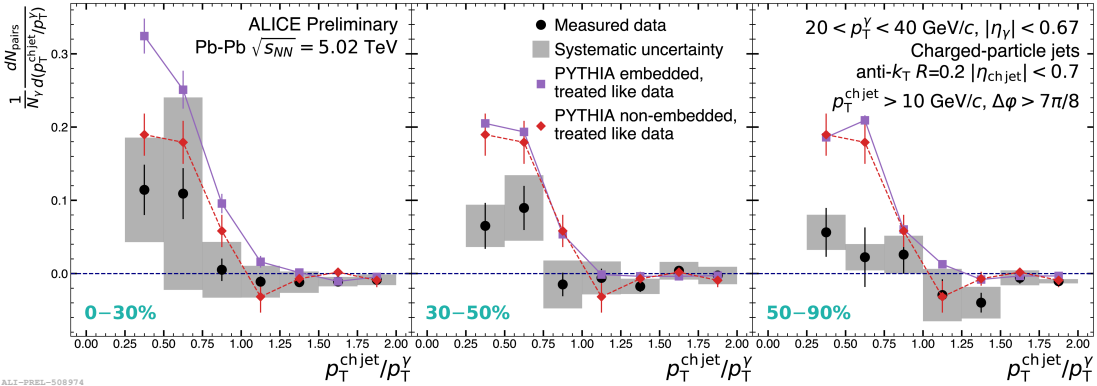
- FoCal: more forward → lower x, huge reduction of uncertainties on the gluon PDF.



Isolated photon - jet measurements in Pb-Pb collisions

Powerful probe: photon escapes the medium unaffected → measure absolute energy loss of the jet!

Current most advanced analysis in heavy-ion collisions in ALICE:



Summary

Neutral mesons:

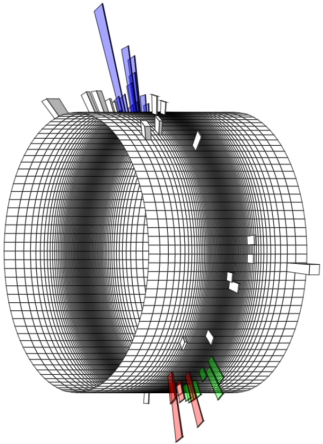
- Benchmark for all photon analyses in ALICE
- Information on particle production mechanisms using detailed comparisons to model calculations
- Decay photon background for direct photon measurements

Prompt photons:

- Probing the proton and nuclear PDFs, as well as testing pQCD
- First isolated photon - jet analysis performed

What is next?

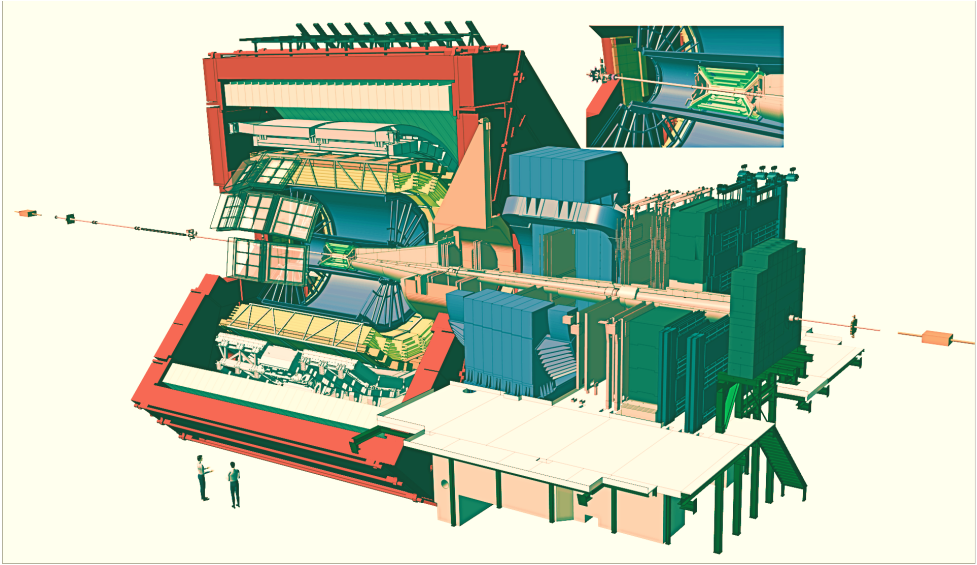
1. Build a consistent picture for light neutral meson production
2. Direct photons $\rightarrow$ **under which conditions do we measure an excess of low p_{T} direct photons?**
3. Investigate jet quenching phenomena via gamma-jet measurements



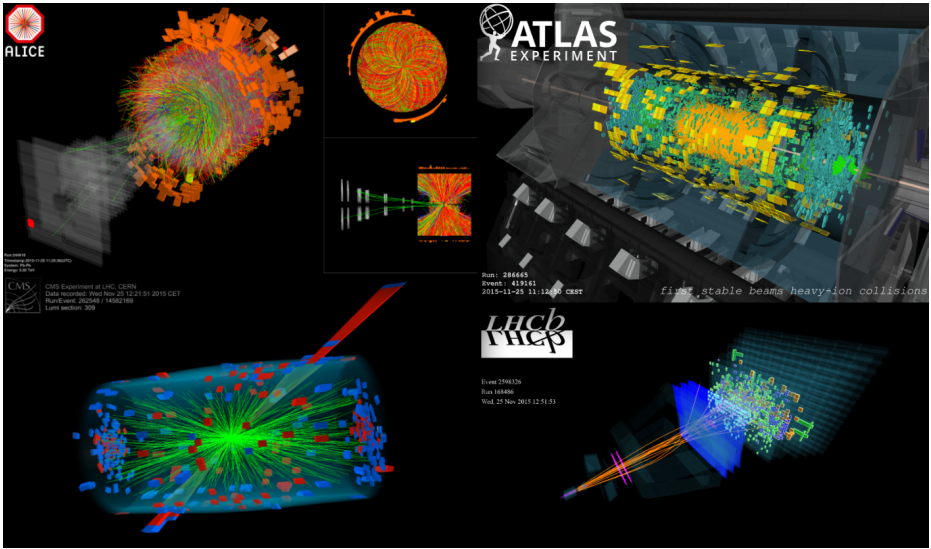
Backup

The ALICE detector

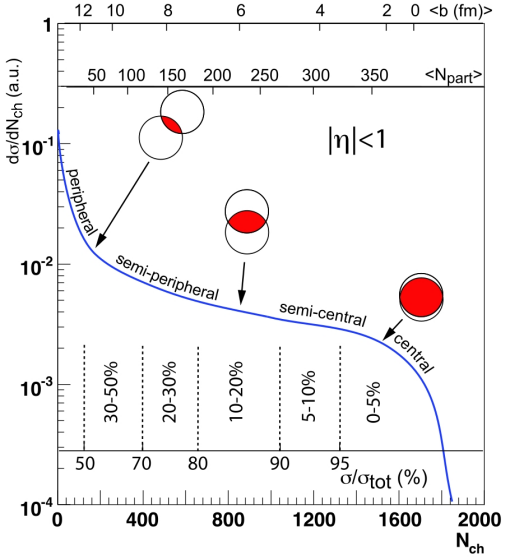
- ITS
- TPC
- EMCal
- PHOS



Backup – all event displays



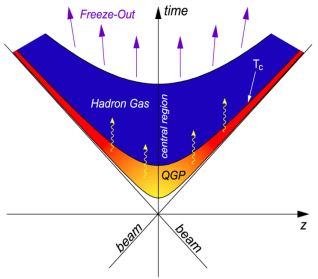
Backup – centrality



Direct photon production sources

Definitions:

- **Inclusive photons:** photons from any source
- **Direct photons:** photons *not* from hadronic decays
- **Decay photons:** photons from hadronic decays
- $\gamma_{incl} = \gamma_{direct} + \gamma_{decay}$



Sources of direct photons

In all collision systems:

- **prompt photons**
  - dominant at high p_{T}
  - calculable within NLO pQCD

Additional sources in AA collisions:

- **Thermal photons**
  - Scattering of thermalized particles
- **Pre-equilibrium photons**
  - Production from the glasma phase
- **Jet-Medium interactions**
  - Hard partons scattering on QGP constituents