ALICE results on ultra-peripheral collisions

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Joint ECFA-NuPECC-APPEC Workshop
Synergies between the EIC and the LHC

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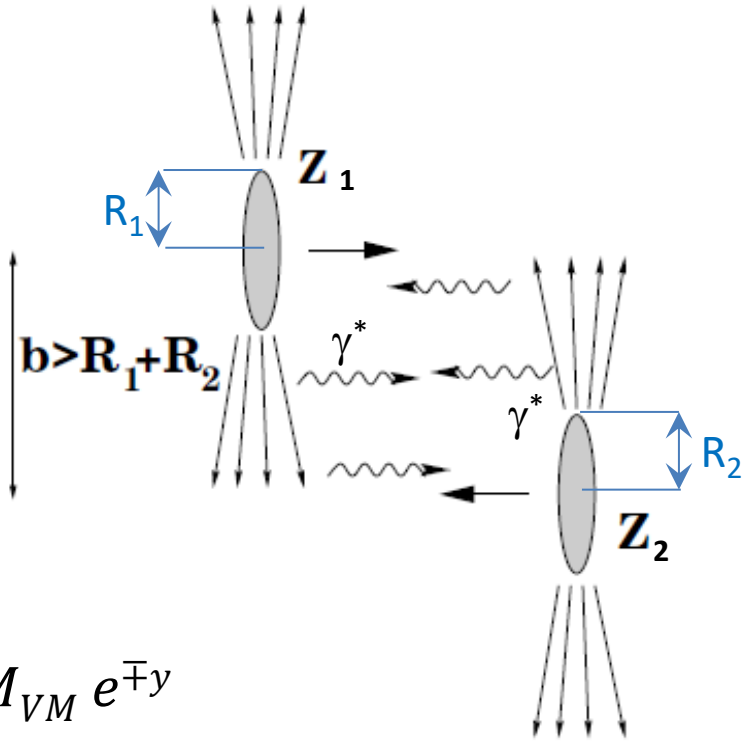
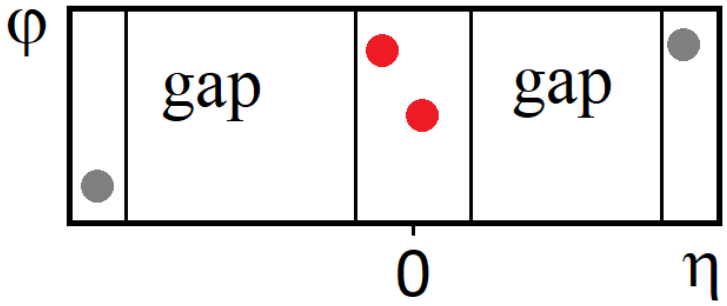
Outline

- Introduction
- Experimental apparatus
- Measurements in Run 3
  - π, K, p spectra in UPC at $\sqrt{s_{\mathrm{NN}}}$ = 5.36 TeV
  - Strangeness production in UPC at $\sqrt{s_{\mathrm{NN}}}$ = 5.36 TeV
  - Charm production in UPC at $\sqrt{s_{\mathrm{NN}}}$ = 5.36 TeV
  - Exclusive τ pair production in UPC at $\sqrt{s_{\mathrm{NN}}}$ = 5.36 TeV
- Summary

Ultra-peripheral collisions (UPC)

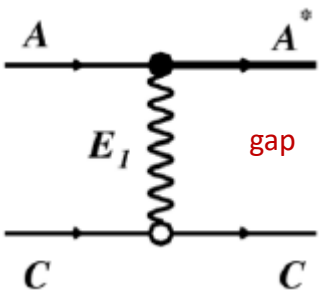
- Impact parameter $b > R_1 + R_2$
  - Hadronic interactions suppressed
- Photon induced reactions:
  - Well described in Weizsäcker-Williams approximation
  - Photon flux ~ Z^2 ($Z_{Pb} = 82$)
  - Maximum photon energy at Run 3:
    - $E_\gamma^{max} \approx \gamma\hbar c/R \approx 80$ GeV
  - Photon virtuality at LHC
    - $Q^2 \approx (\hbar c/R_{nucleus})^2 \approx (30\ \text{MeV})^2$
  - Photo-nuclear c.m. energy, $W_{\gamma N}{}^2 = 2E_N\, M_{VM}\, e^{\mp y}$
    - $40 \lesssim W_{\gamma N} \lesssim 900$ GeV
  - Large γ-induced interaction cross section
- Clear signature:
  - Low detector activity
  - Rapidity gap(s)



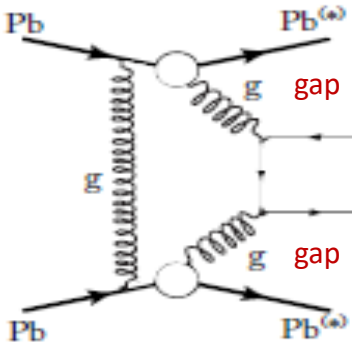


Classes of processes

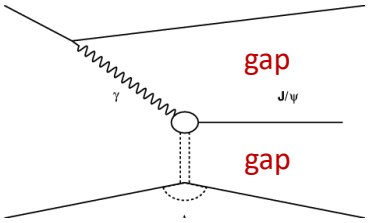
- Exclusive processes (no colour exchange)



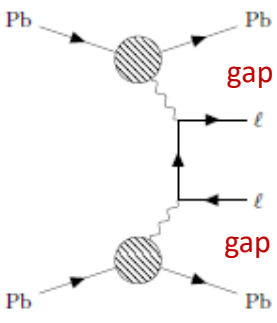
Electromagnetic dissociation (EMD) single or mutual

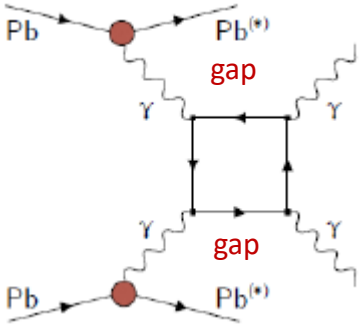


Pomeron – Pomeron CEP



Photoproduction Coherent or Incoherent

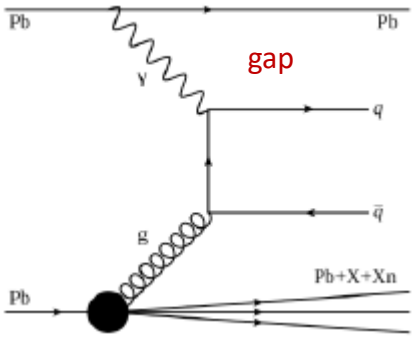




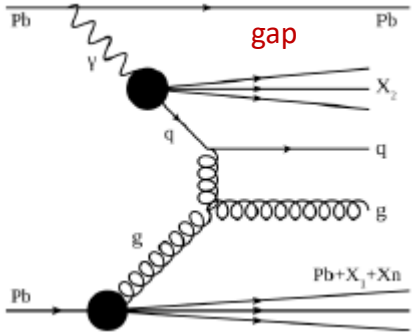
Double photon exchange

- Inclusive processes (with colour exchange)

- Photon itself takes part in the hard scattering



Direct production



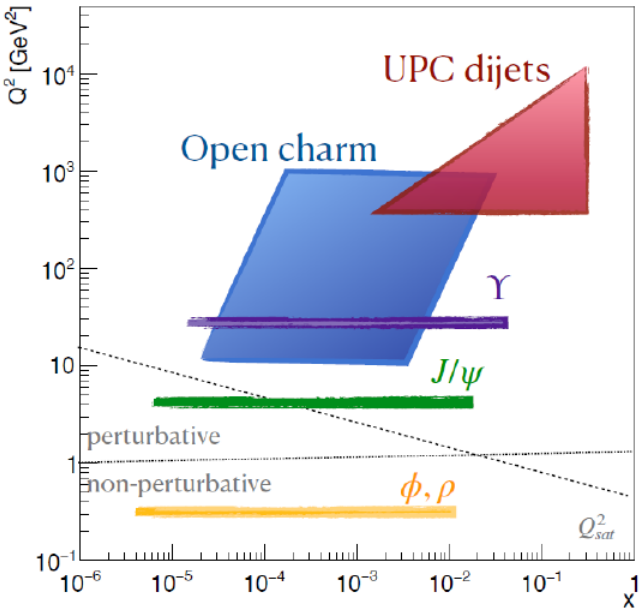
Resolved production

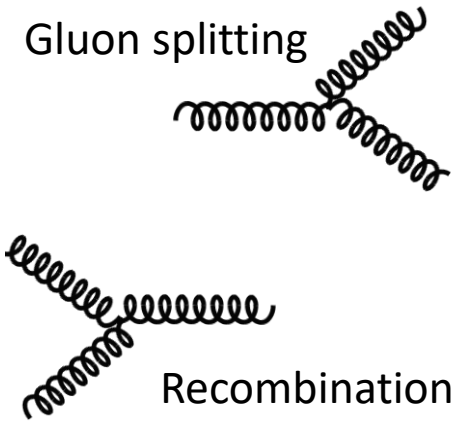
- Virtual excitation of the photon
- Participants of the hard scattering:
  - qq-bar pair
  - multiple gluons

Motivation

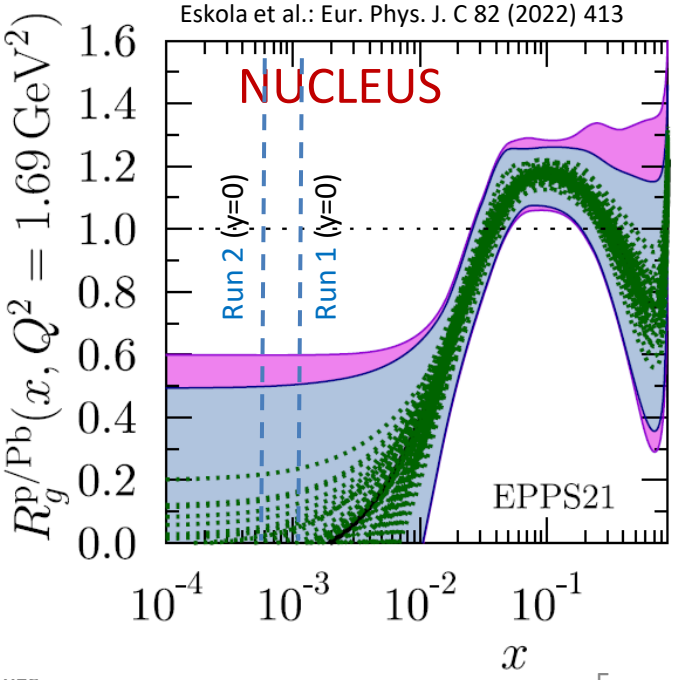
- Studies of **gluon structure**
- Different **proton ↔ nucleon PDF**
  - Gluon **shadowing** (destructive interference at low x_B caused by coherent multiple scattering)
  - Gluon **saturation** (equilibrium between gluon splitting and recombination)
    - Saturation scale enhanced for nuclei by factor $A^{1/3}$: $(Q_s^A)^2 \approx cQ_0^2\,[A/x]^{1/3}$
- **Heavy flavour** → probe **nuclear PDF** in large phase space down to $x_B \sim 10^{-4}$
- **Collectivity** in small systems in UPC
- Disentangle initial state effects from QGP-driven behavior

Fig. from A. Ogrodnik



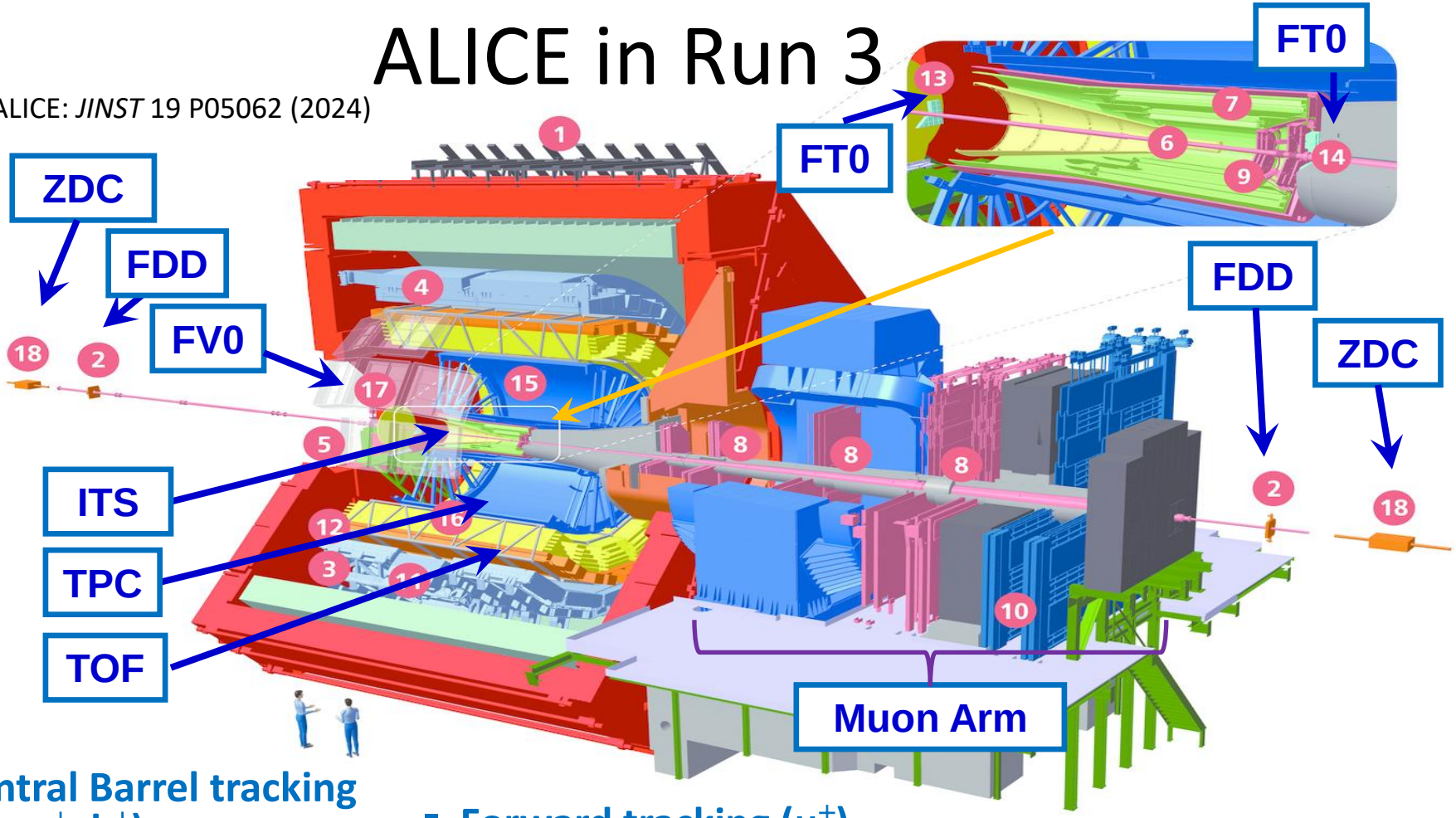


Eskola et al.: Eur. Phys. J. C 82 (2022) 413



ALICE in Run 3

ALICE: *JINST* 19 P05062 (2024)

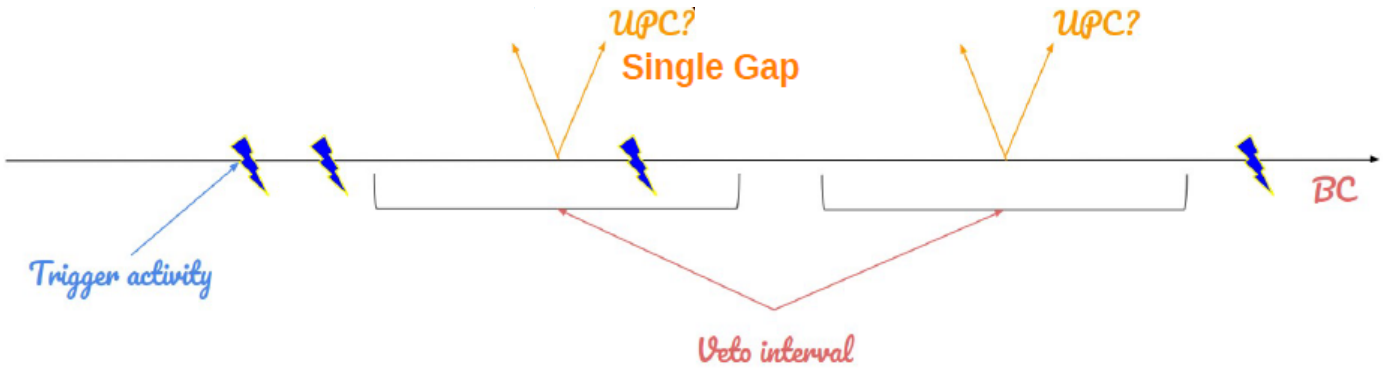


- **Central Barrel tracking ($e^{\pm}$, $\mu^{\pm}$, $h^{\pm}$)**
  - $|\eta| < 0.9$, $0 < \varphi < 2\pi$
  - ITS - silicon detector
  - TPC - gas drift detector
  - TOF - resistive plate chambers
- **PID:** TPC, TOF

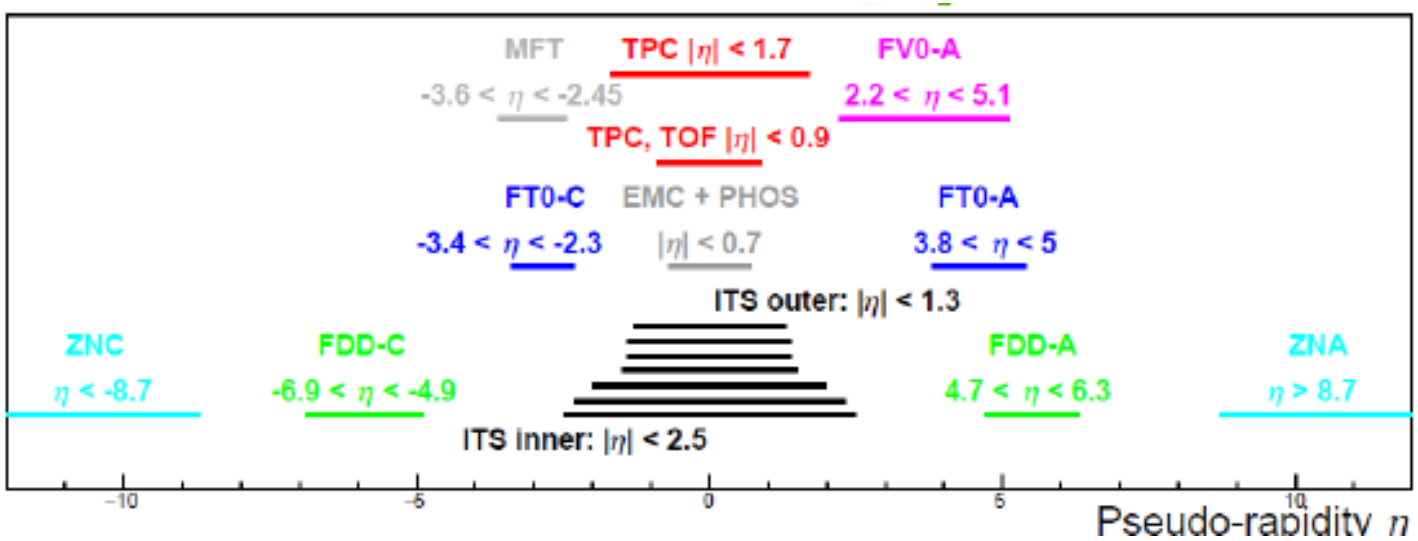
- **Forward tracking ($\mu^{\pm}$)**
  - $-4 < \eta < -2.5$
  - Absorber
  - Muon tracker (8)
  - Muon trigger (10)
  - Muon Forward Tracker (9)
  - Dipole magnet

- **Diffractive detectors**
  - FT0 - scintillator counter
  - FV0 - scintillator counter
  - ZDC - sampling calorimeter
- **Vertex**
  - ITS

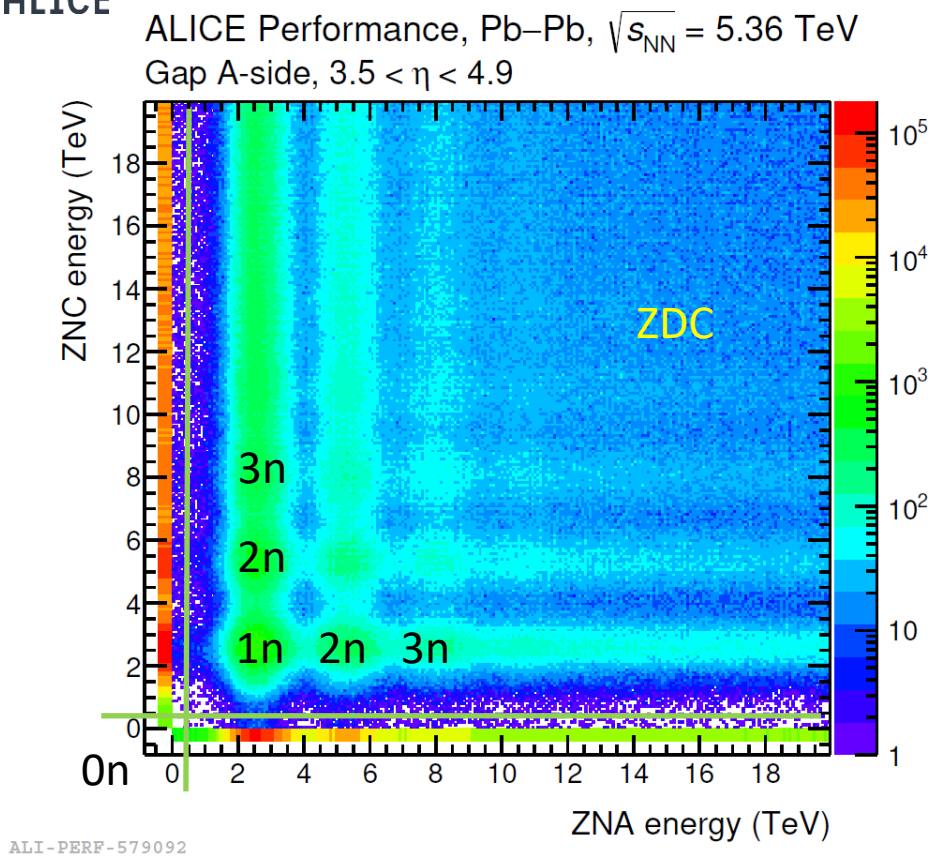
Event selection

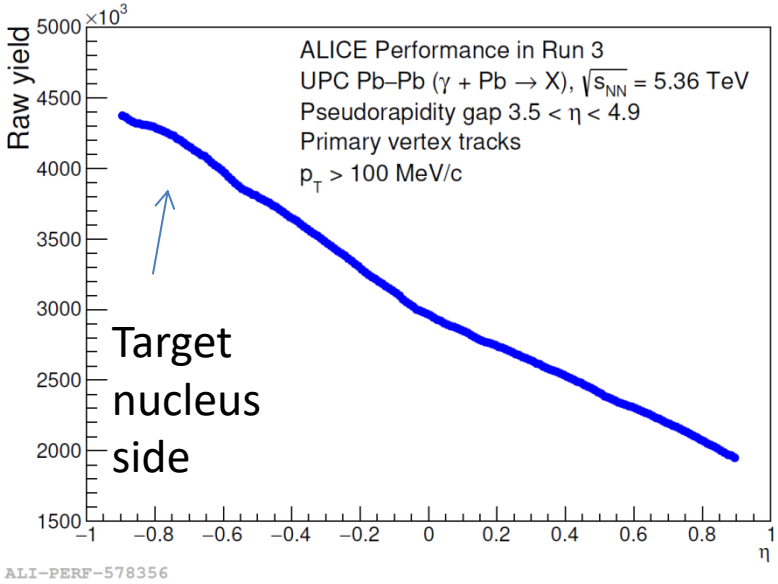


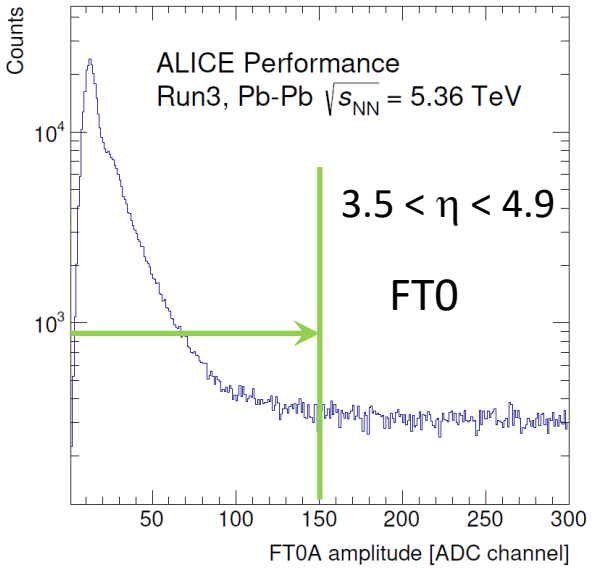
- Continous (trigger-less) readout
- Rapidity gap on one side only
  - Single Gap C side: (FT0A OR FV0A OR ZNA) AND (!FT0C AND !ZNC)
  - Single Gap A side: (FT0C OR ZNC) AND (!FT0A AND !FV0A AND !ZNA)



ALICE detectors' performance in Run 3

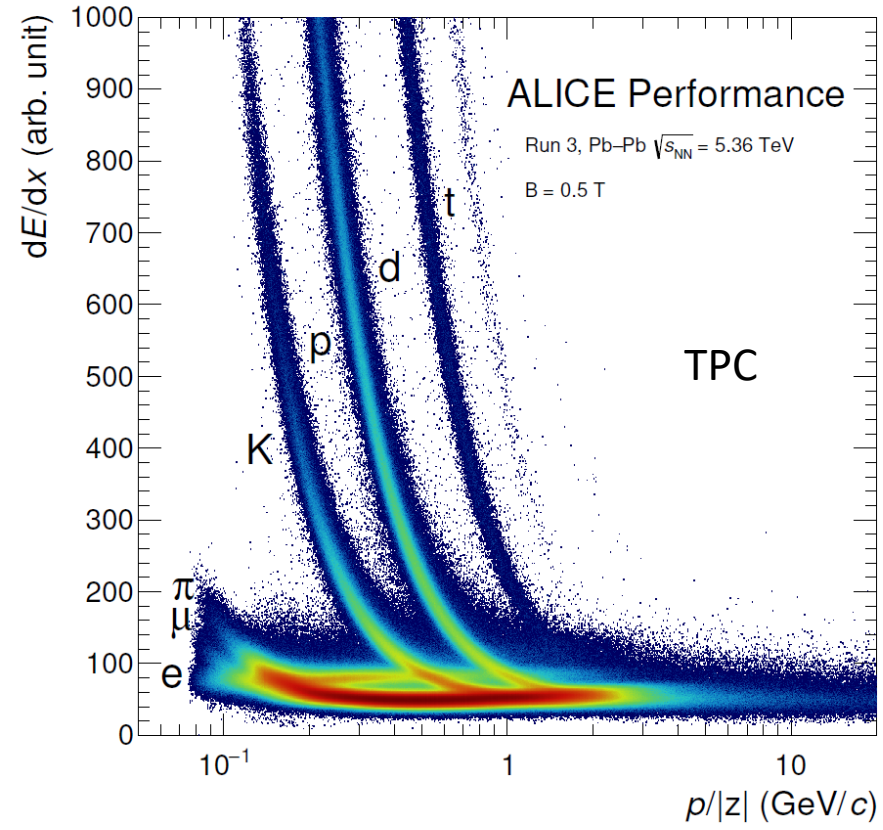




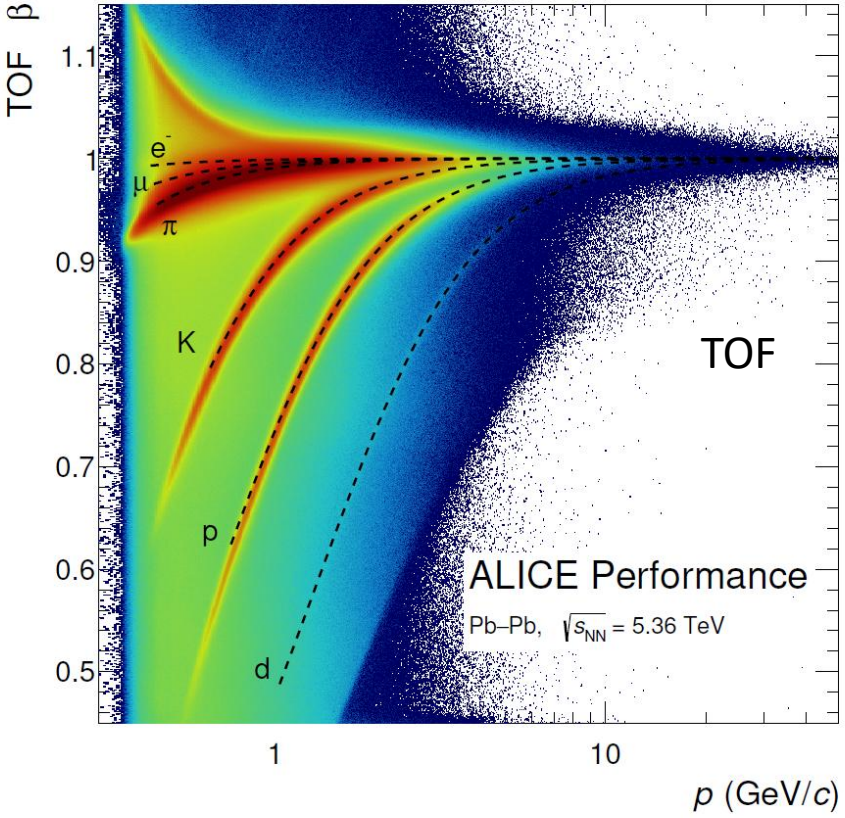


- Clear separation between neutron classes in ZDC:
  - 0n0n, Xn0n, 0nXn, XnXn
- Asymmetric rapidity distribution due to gap requirement on one side
  → better detector and continuous readout
- FT0 threshold tuned to 1 or 2 $e^{\pm}$ production

ALICE detectors' performance in Run 3



ALI-PERF-529714



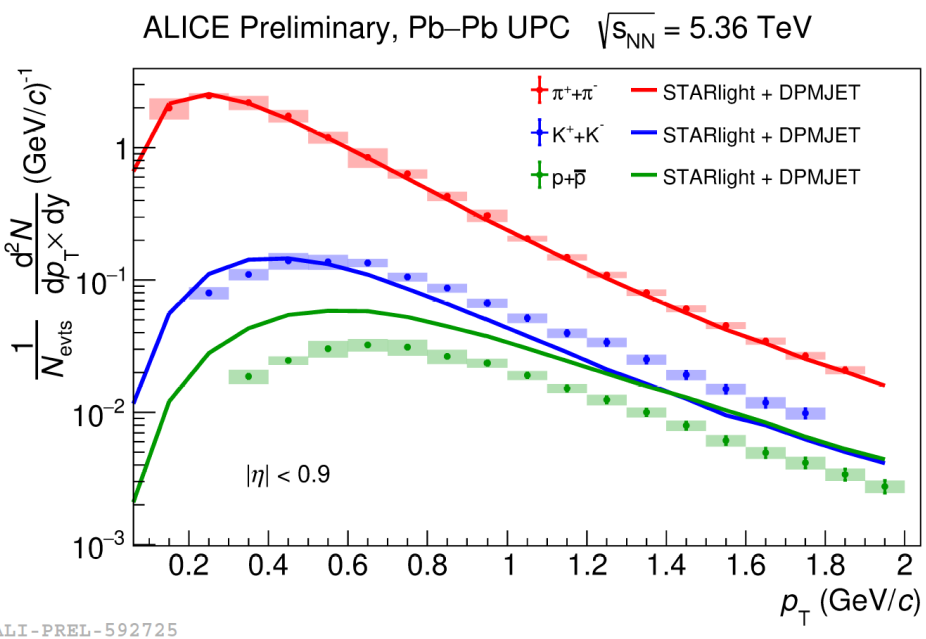
ALI-PERF-577978

- Excellent tracking capabilities
- Information in TPC and TOF in complementary particles momenta
- Down to p = 100 MeV/c
- Various particle species from electrons to tritium

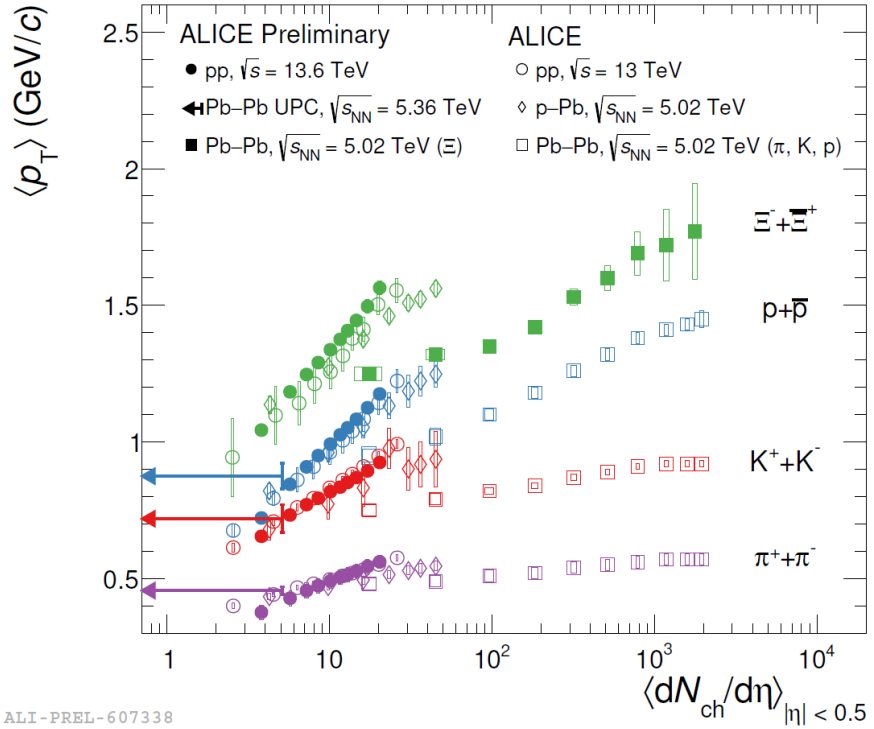
Inclusive particle production

- Fully corrected yields of π, K, p in inclusive photonuclear reactions
- Rapidity gap on the photon side
- Spectra compared to STARLight (photon flux) + DPMJET (nuclear breakup)
  - Good descriptions of π
  - Strangeness underpredicted
  - Baryons overpredicted
- Spectra well parametrised by Two Component Model (TCM)
  - Integrated yields and $\langle p_T \rangle$ extracted
  - $\langle p_T \rangle$ agrees with trend of pp and Pb-Pb

TCM: A.Bylinkin and A. Rostovtsev, *Phys.Atom.Nucl.* 75 (2012) 999-1005, *Yad.Fiz.* 75 (2012) 1060
A.Bylinkin and A. Rostovtsev, Eur.Phys.J.C 74 (2014) 5, 2898



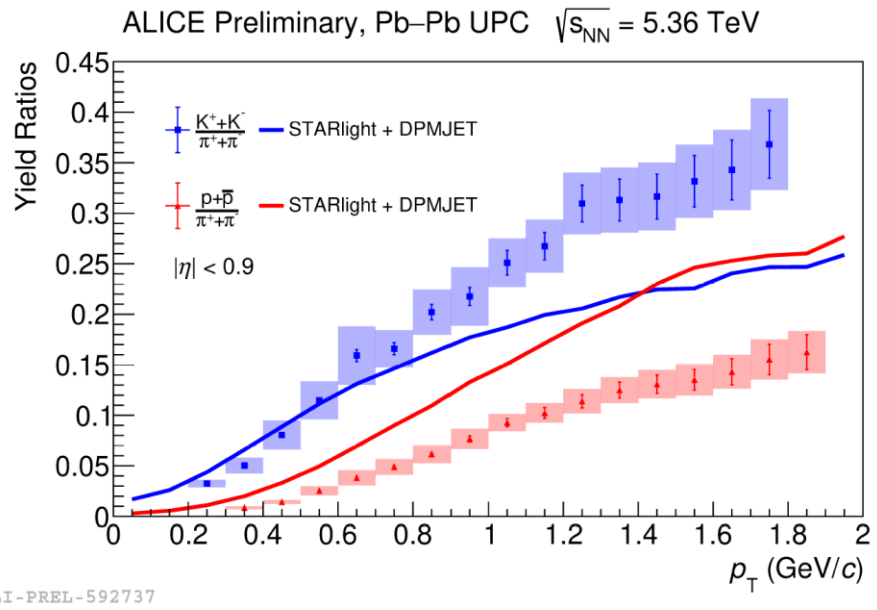
ALI-PREL-592725

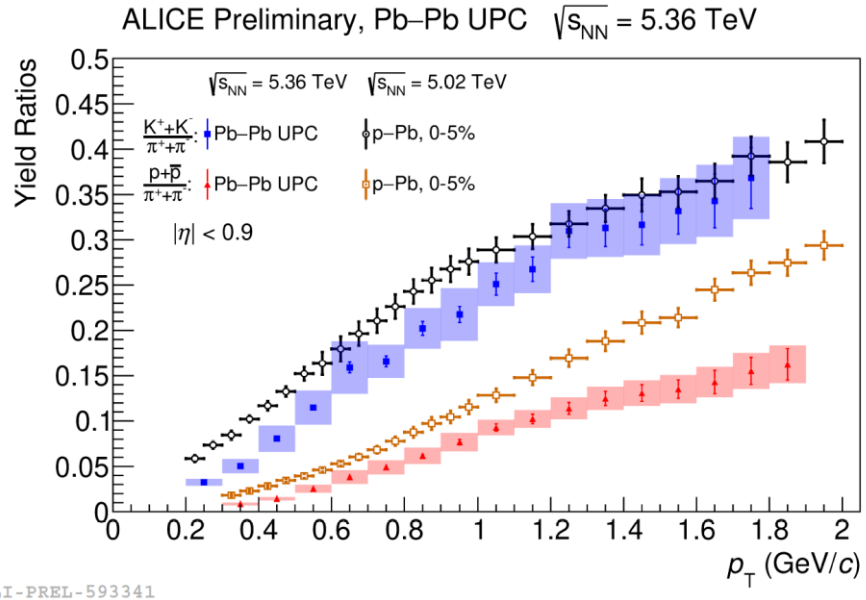


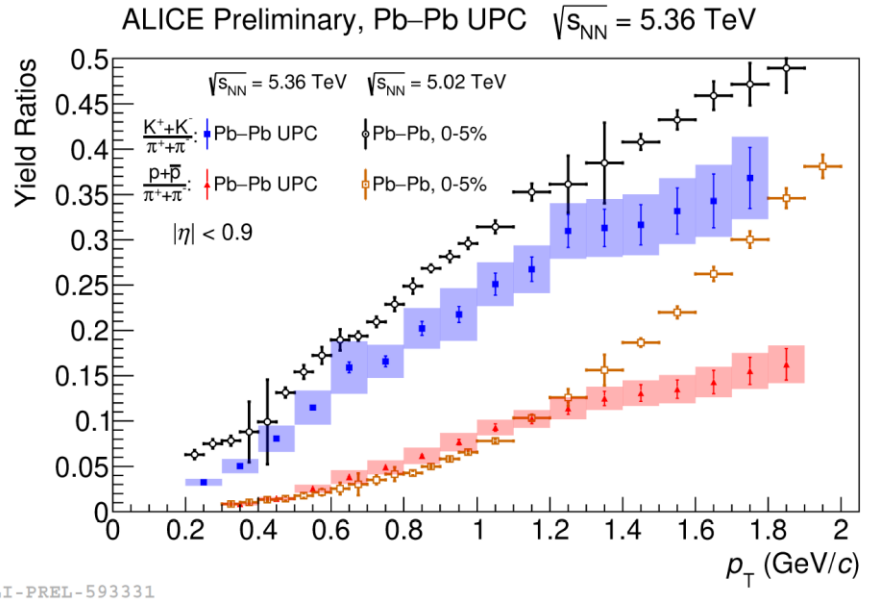
ALI-PREL-607338

Particle production ratios

- Ratios up to p_T = 2 GeV/c
- MC failed to describe ratios
  - Like (expected) in pp collisions
- Compared to other systems
  - K/π: γ-Pb shape similar to p-Pb and Pb-Pb
  - K/π: γ-Pb lower than other systems
  - p/π: γ-Pb shape similar to smaller systems (p-Pb or pp)



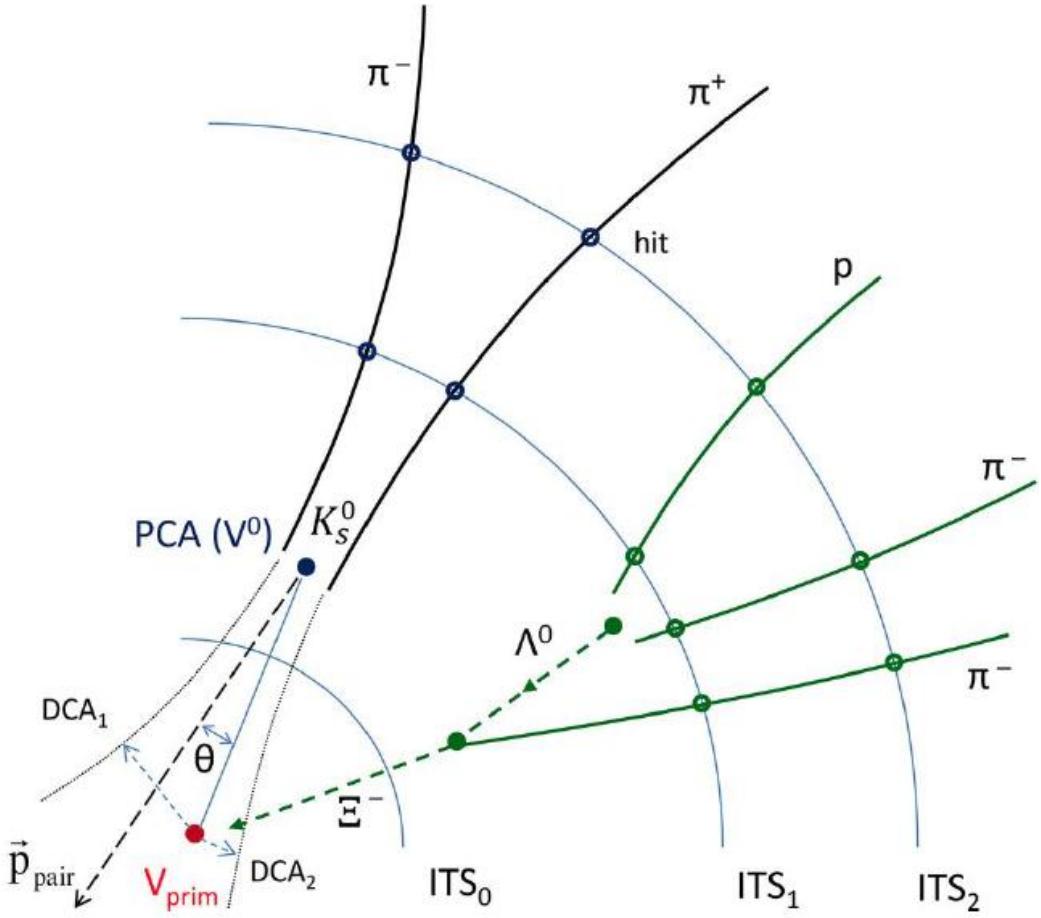




Strange particle reconstruction

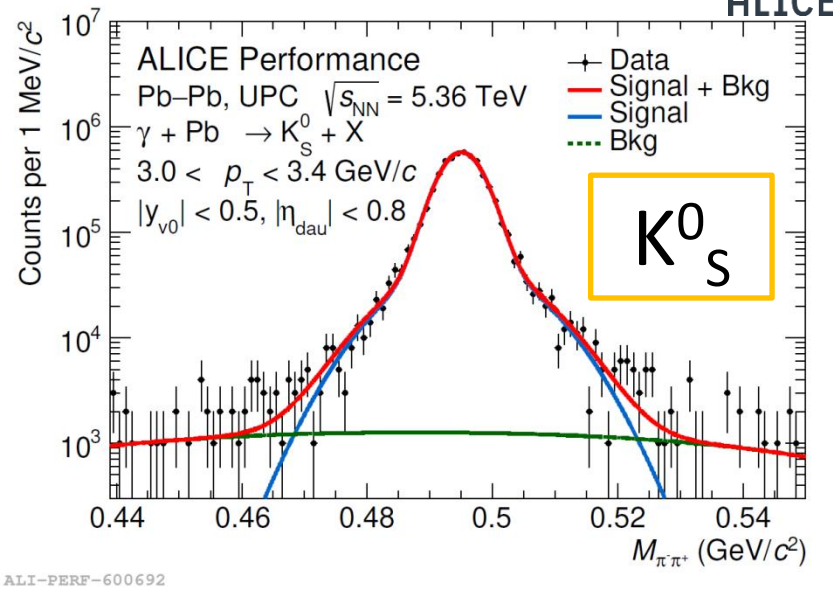
Multi starange hadron reconstruction topologies

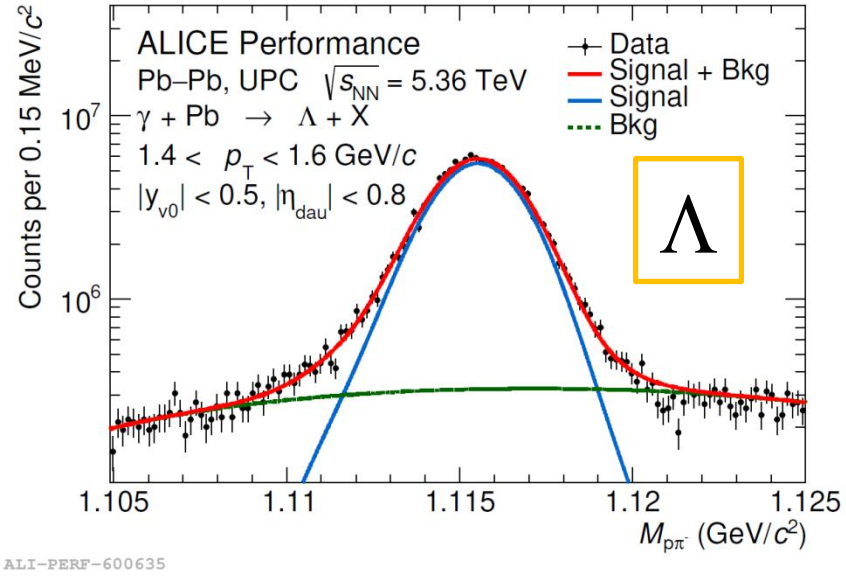
- V^0 – weak decay of neutral particle into pair of charged descendants (V-shape decay)
  - $K^0_S \rightarrow \pi^+ \pi^-$ [d $\bar{s}$]
  - Λ ($\bar{\Lambda}$) $\rightarrow$ p π^- ($\bar{p}$ π^+) [uds]
- Cascade – weak decay of charged particle in to V^0 and charge particle
  - Ξ^- (Ξ^+) $\rightarrow \Lambda \pi^-$ ($\bar{\Lambda}\pi^+$) [dss]
  - Ω^- (Ω^+) $\rightarrow \Lambda K^-$ ($\bar{\Lambda}K^+$) [sss]

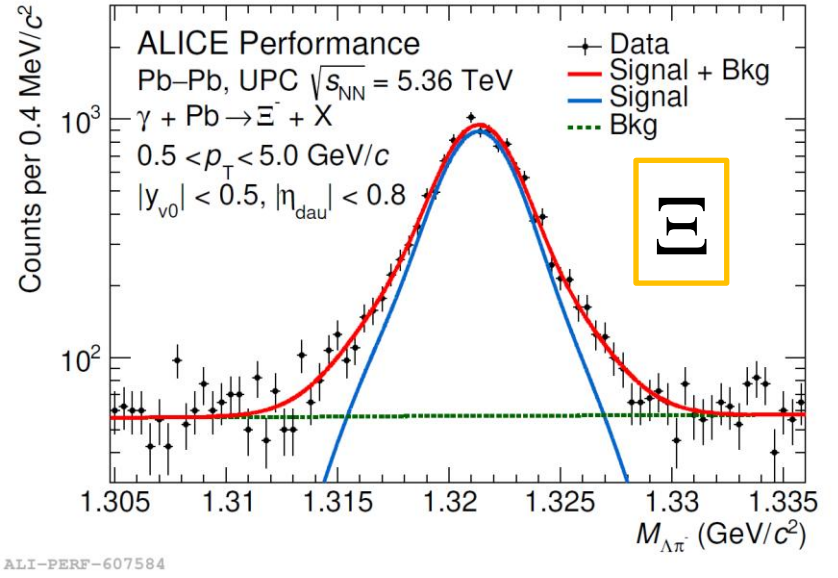


Signal extraction

- Invariant mass of K^0_S, Λ and Ξ in p_T intervals
- Two Gaussians (signal) + polynomial (background)
- Signal integrated within 5 σ
- Acceptance and reconstruction efficiency corrected
- Feeddown for Λ not taken into account



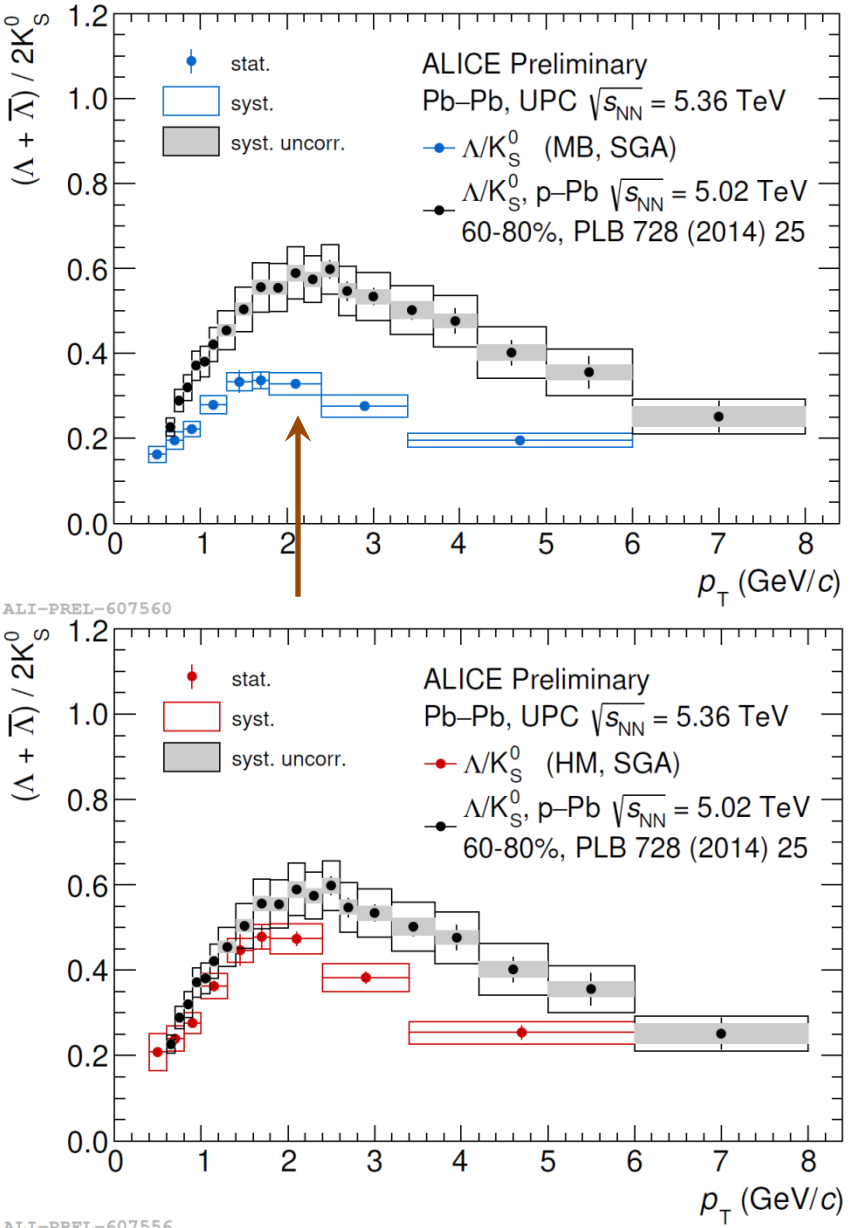




Strangeness and collectivity

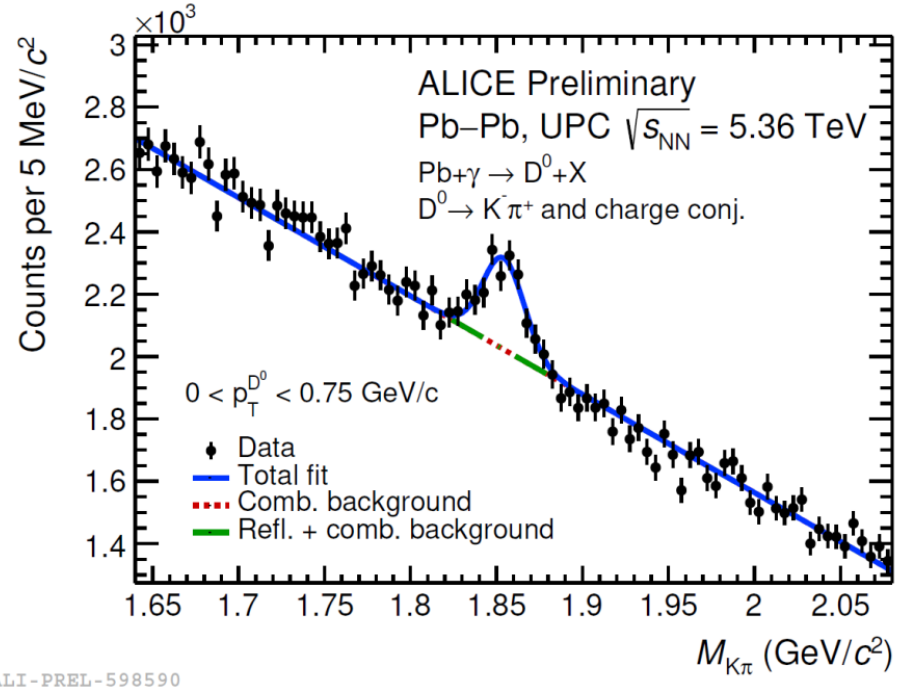
- K^0_S mesons and Λ baryons spectra measured in inclusive photonuclear reactions
- Baryon/meson enhancement at the intermediate p_T
- Similar shape to ratio in low multiplicity p-Pb collisions
- γ-Pb and p-Pb spectra are closer when moving from minimum bias (MB) to higher multiplicity class (HM)
- Studies of collective expansion in UPC
  - γ-Pb collisions are ruled mainly by Vector Meson Dominance model
    $\rightarrow$ effectively hadron-Pb collisions

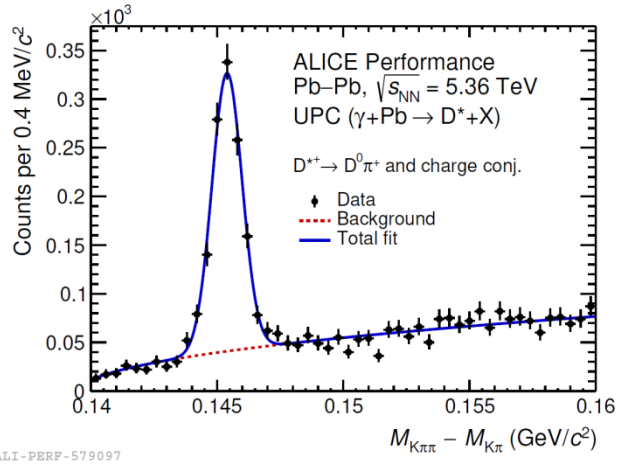
Event class	Multiplicity
HM	$8 \leq N_{\mathrm{ch}}^{\mathrm{rec}} < 41$
MB	$0 \leq N_{\mathrm{ch}}^{\mathrm{rec}} < 41$

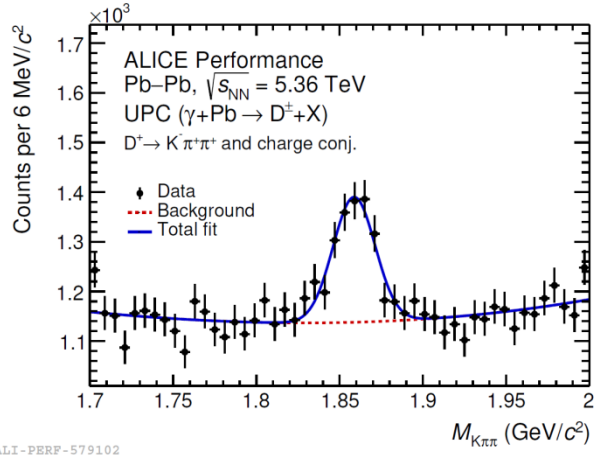


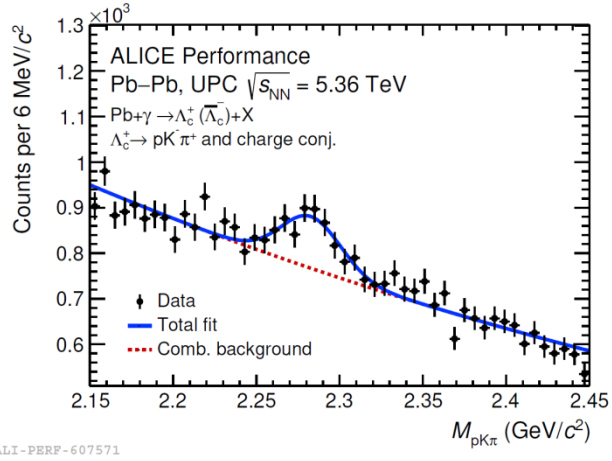
Inclusive open charm photoproduction

- First measurement of open heavy flavour in UPC in ALICE
  - $D^0 \rightarrow K^- \pi^+$
  - $D^+ \rightarrow K^- \pi^+ \pi^+$
  - $D^{*+} \rightarrow D^0 \pi^+$
  - $\Lambda_c^+ \rightarrow p K^- \pi^+$



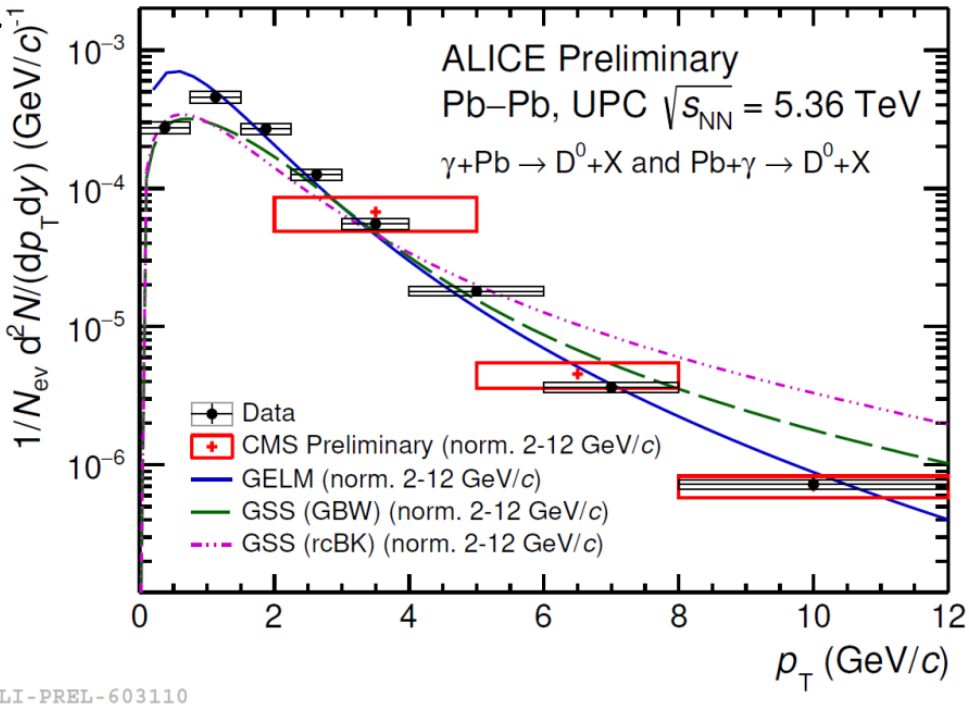






Inclusive open charm photoproduction

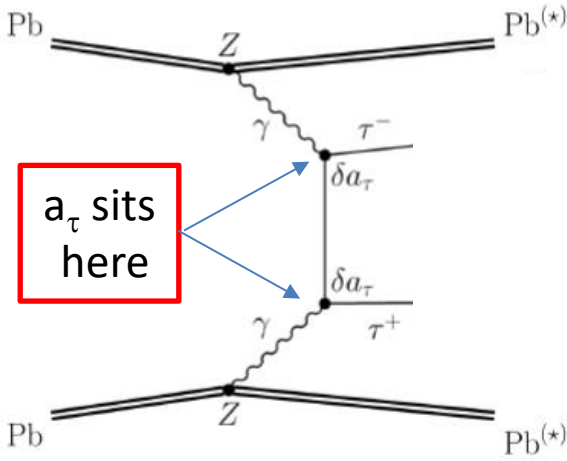
- p_T spectrum of D^0 meson down to $p_T = 0$
  $\rightarrow$allow for mean p_T extraction
  - CGC model (GELM) reproduces the shape above ~1 GeV/c
  - Agreement between CMS and ALICE
  - Data $\langle p_T \rangle = 1.476 \pm 0.026$ (stat) ± 0.048 (syst) GeV/c
- Mean p_T not described by models
- Comparison for mean p_T in a range 0.2 to 12 GeV/c
  - Data $\langle p_T \rangle = 1.593 \pm 0.056$ GeV/c
  - GELM $\langle p_T \rangle = 1.403$ GeV/c
  - GBW $\langle p_T \rangle = 1.821$ GeV/c
  - rcBK $\langle p_T \rangle = 1.931$ GeV/c



GELM: arXiv: 2503.16108 (2025).
GSS: Nucl. Phys. A976 (2018) 33.
CMS: CMS-PAS-HIN-24-003 (2024).

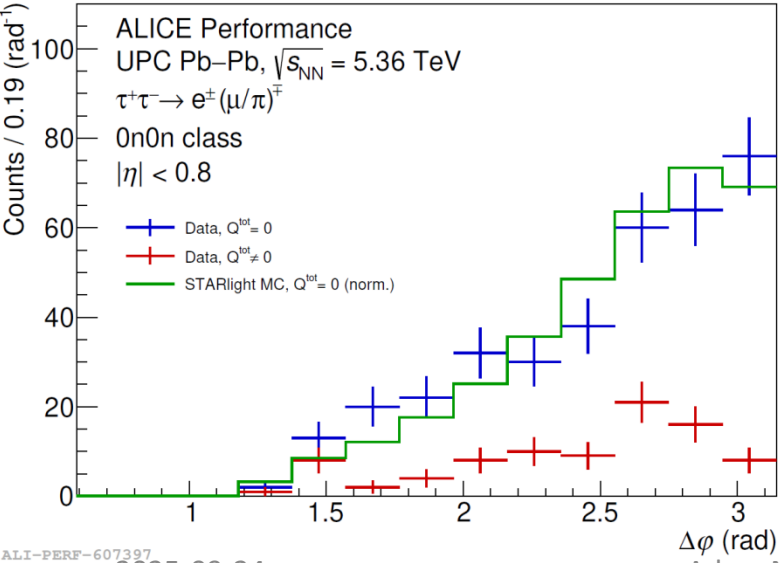
Exclusive τ pair production

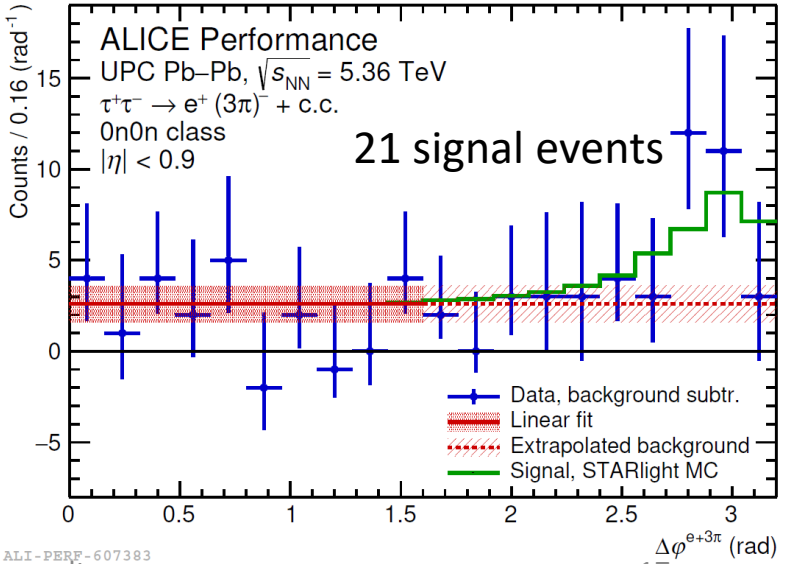
- τ pair photoproduction in Pb-Pb UPC → Cross section scales with Z^4
- τ leptons decays quickly and can not be observed directly
  - Difficult due to at least 1 ν in each τ decay
- Sensitive to anomalous magnetic moment: $a_\ell = (g-2)_\ell/2$
  - $a_\tau^{exp} = 0.0009^{+0.0032}_{-0.0031}$ (CMS-PAS-SMP-23-005 (2024))
  - $a_\tau^{SM} = 0.00117721(5)$ (Mod. Phys. Lett. A 22, 159 (2007))
- Cross section and τ kinematics sensitive to a_τ
  - L. Beresford and J. Liu, PRD 102 (2020) 113008
  - M. Dyndał et al., PLB 809 (2020) 135682
  - Burmasov et al., arXiv:2203.00990 (2022)



τ decay topologies:

- 1 prong + 1 prong (e+e, e+μ/π)
- 1 prong + 3 prong (e+3π, μ/π +3π)





Summary

- New **inclusive results** in UPC at $\sqrt{s_{NN}}$ = 5.36 TeV
  - First π, K, p spectra
  - Strangeness production spectra
  - Charm production spectra

  $\Rightarrow$ Fully corrected cross sections are on the way
- First exclusive τ **pair** production in ALICE
- **Hints of collectivity** in γ-Pb collisions
- The **baryon anomaly** is now observed in γ-Pb collisions
- Novel probes for studies of **cold nuclear matter**

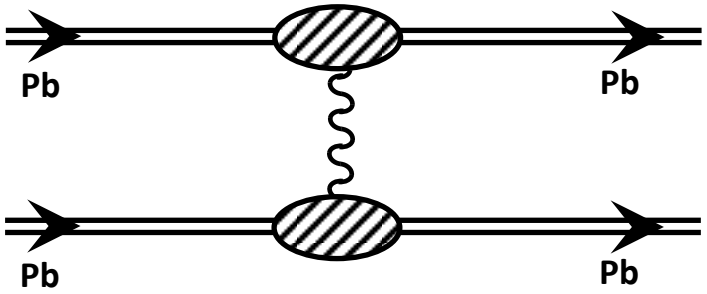
Backup

ALICE measurements in UPC

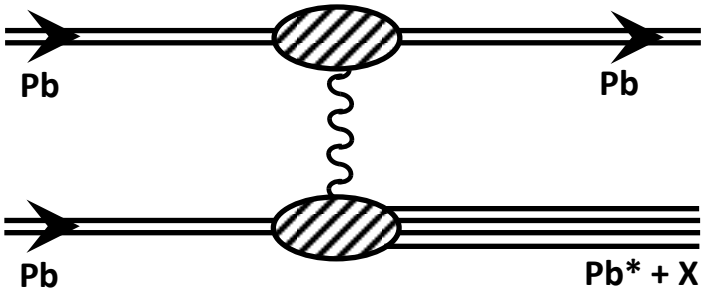
- Run 1
  - Cross section for electromagnetic dissociation with neutron emission in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV - **PRL 109 (2012) 252302**.
  - Inelastic, single- and double-diffraction cross sections in pp - **EPJC 73 (2013) 2456**.
  - Coherent J/ψ photoproduction in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV - **PLB 718 (2013) 1273-1283**.
  - J/ψ and e^+e^- pair photoproduction at mid-rapidity in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV - **EPJC 73 (2013) 2617**.
  - Coherent ρ^0 photoproduction in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV - **JHEP 09 (2015) 095**.
  - Coherent ψ(2S) photoproduction in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV - **PLB 751 (2015) 358-370**.
- Run 2
  - J/ψ photoproduction in p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV - **PRL 113 (2014) 232504**.
  - Energy dependence of exclusive J/ψ photoproduction in p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV - **EPJC (2019) 79: 402**.
  - Coherent ρ^0 photoproduction in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV- **JHEP 06 (2020) 035**.
  - Coherent J/ψ photoproduction at forward rapidity in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV - **PLB 798 (2019) 134926**.
  - Coherent ρ^0 photoproduction in Xe-Xe at $\sqrt{s_{NN}}$ = 5.44 TeV - **PLB 820 (2021) 136481**.
  - Coherent J/ψ and ψ' photoproduction at midrapidity in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV - **EPJC 81 (2021) 712**.
  - $|t|$-dependent coherent J/ψ in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV - **PLB 817 (2021) 136280**.
  - Neutron emission in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV - **PRC 107 (2023) 064902**.
  - Polarisation of coherently photoproduced J/ψ in Pb−Pb at $\sqrt{s_{NN}}$ = 5.02 TeV - **PLB 865 (2025) 139466**.
  - Exclusive and dissociative J/ψ photoproduction, and exclusive dimuon production, in p−Pb at $\sqrt{s_{NN}}$ = 8.16 TeV - **PRD 108, 112004 (2023).**
  - $|t|$-dependence of incoherent J/ψ in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV - **PRL 132, 162302 (2024).**
  - Energy dependence of coherent photoproduction of J/ψ in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV - **JHEP 10 (2023) 119**.
  - Photoproduction of K^+K^- pairs in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV - **PRL 132 (2024) 222303**.
  - 4π photoproduction in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV - **arXiv:2404.07542**.
  - Azimuthal anisotropy in coherent ρ^0 photoproduction in Pb−Pb at $\sqrt{s_{NN}}$ = 5.02 TeV - **PLB 858 (2024) 139017**.
  - Proton emission in ultraperipheral Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV - **PRC 111 (2025) 054906**.
  - Evidence for J/ψ suppression in incoherent photonuclear production in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV - **arXiv:2503.18708**.

Impact parameter dependence

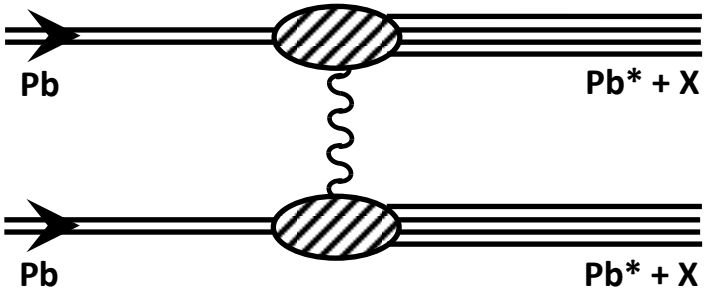
No breakup (0n0n)



Single breakup (Xn0n + 0nXn)



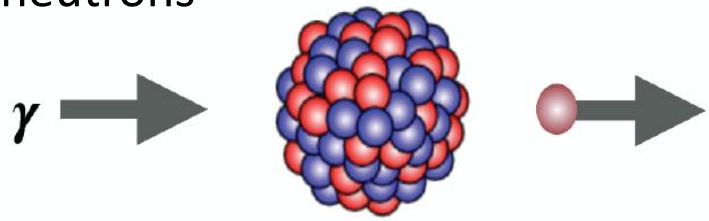
Double breakup (XnXn)

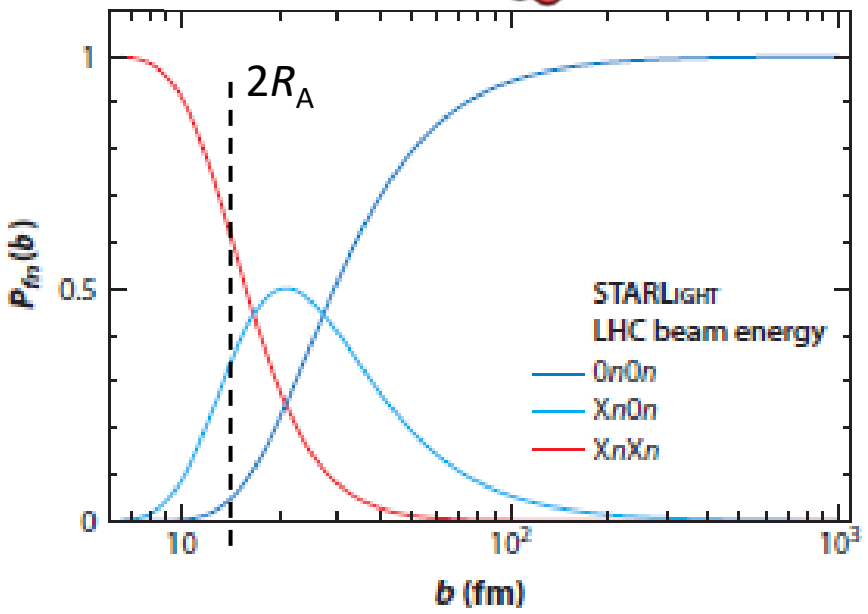


- Excitation of the nuclei possible through the secondary photon exchange

$\Rightarrow$ Giant dipole resonance

All protons vibrating against all neutrons $\rightarrow$ Knocks out neutrons





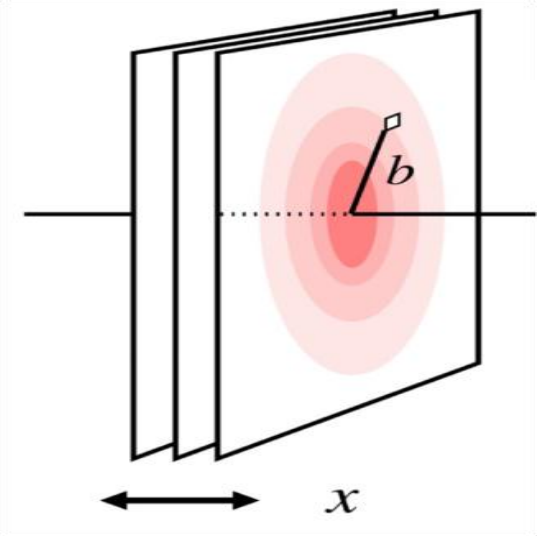
UPC event clasifier: 0n0n, 0nXn, XnXn

$\rightarrow$ via electromagnetic dissociation (EMD)

S. Klein, P. Steinberg, Annu. Rev. Nucl. Part. Sci. 70(1), 323 (2020)

Motivation for *t*-dependent measurements

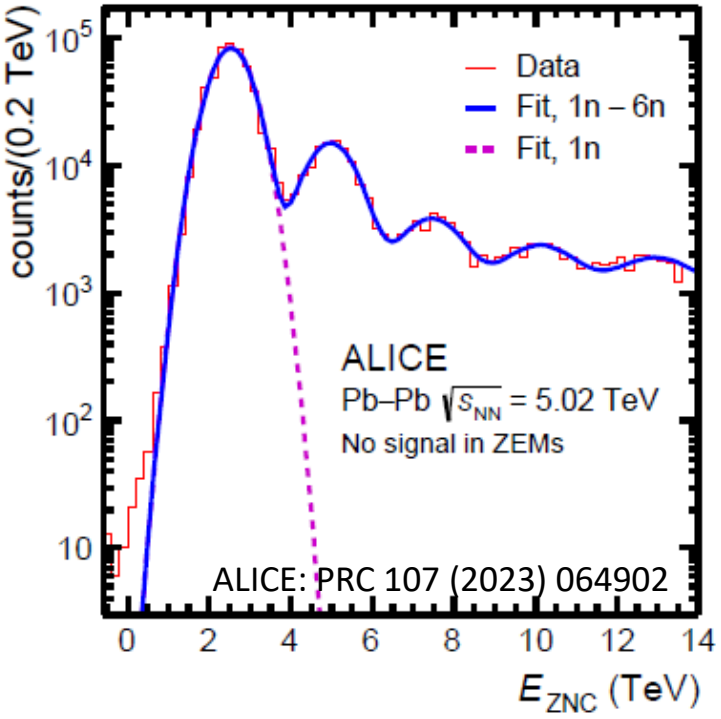
- Gluon density is impact parameter b dependent at given Bjorken-x and Q^2
- b and p_T are Fourier conjugates
- $p_T^2 \approx |t|$ - dependence of the cross section helps to constrain **transverse gluonic structure** at low x_B
- In Good – Walker approach
  - Coherent photoproduction tells about transverse dependence of the gluon shadowing
    - Saturation may contribute to nuclear shadowing
  - Incoherent photoproduction is sensitive to the variance of the spatial gluon distribution (subnucleonic fluctuations)

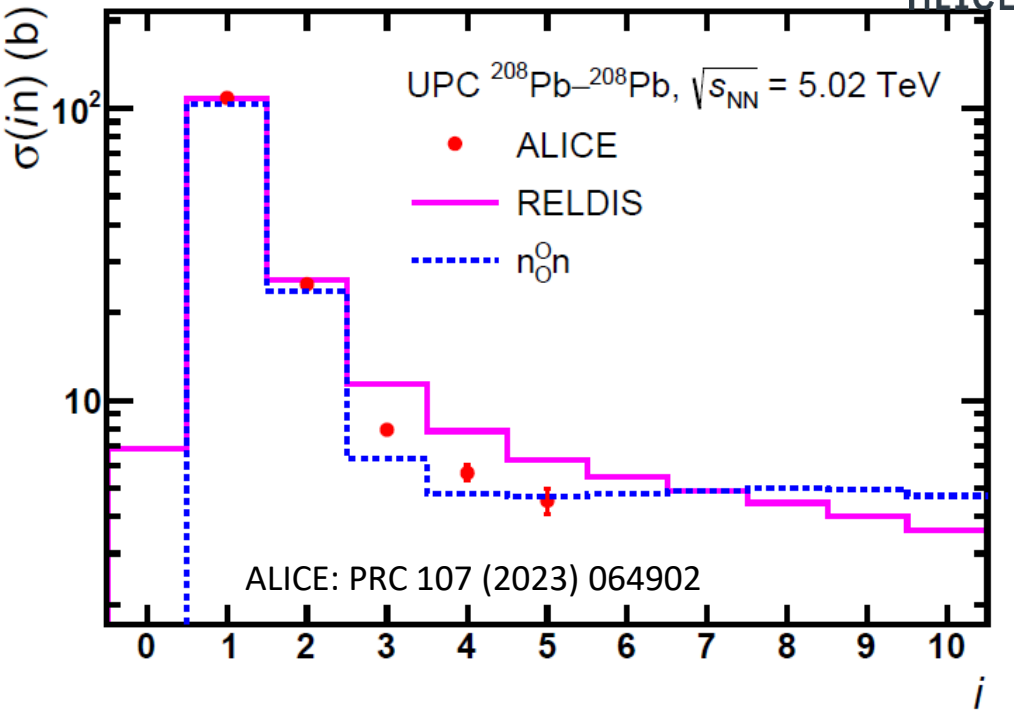


$$\frac{d\sigma^{inc}}{dt} = \frac{R_g{}^2}{16\pi}(\langle|A(x,Q^2,\vec{\Delta})|^2\rangle - |\langle A(x,Q^2,\vec{\Delta})\rangle|^2)$$

Total Coherent

Neutron emission in UPC





ZN	$\sigma(in)$ (b)	$\sigma^{\mathrm{RELDIS}}(in)$ (b)	$\sigma^{n^{O}_{O}n}(in)$ (b)
1n	$108.4 \pm 0.1 \pm 3.7$	108.0 ± 5.4	103.7 ± 2.1
2n	$25.0 \pm 0.1 \pm 1.3$	25.9 ± 1.3	23.6 ± 0.5
3n	$7.95 \pm 0.04 \pm 0.23$	11.4 ± 0.6	6.3 ± 0.1
4n	$5.65 \pm 0.03 \pm 0.33$	7.8 ± 0.4	4.8 ± 0.1
5n	$4.54 \pm 0.03 \pm 0.44$	6.3 ± 0.3	4.7 ± 0.1
1n–5n	$151.5 \pm 0.2 \pm 4.6$	159.8 ± 5.6	143.1 ± 2.2

ALICE: PRC 107 (2023) 064902

- It is huge!
- Up to 5 neutrons
- Hadronic cross section $\sigma_{had} = 7.67 \pm 0.24$ b
- Good description of 1n and 2n emission , but other classes are not so well described

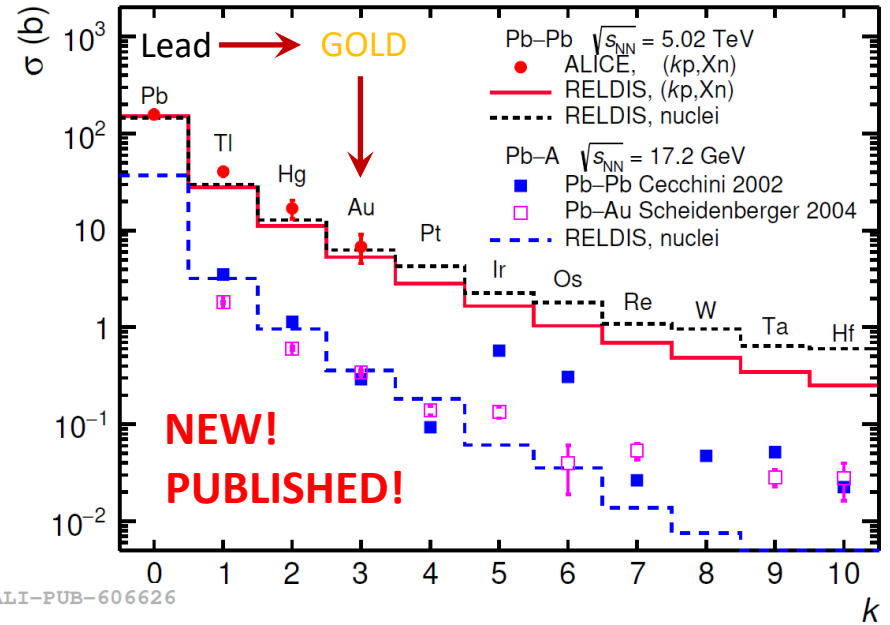
RELDIS: Phys. Part. Nucl. 42 (2011) 215.
N00N: Comput. Phys. Commun. 253 (2020) 107181.

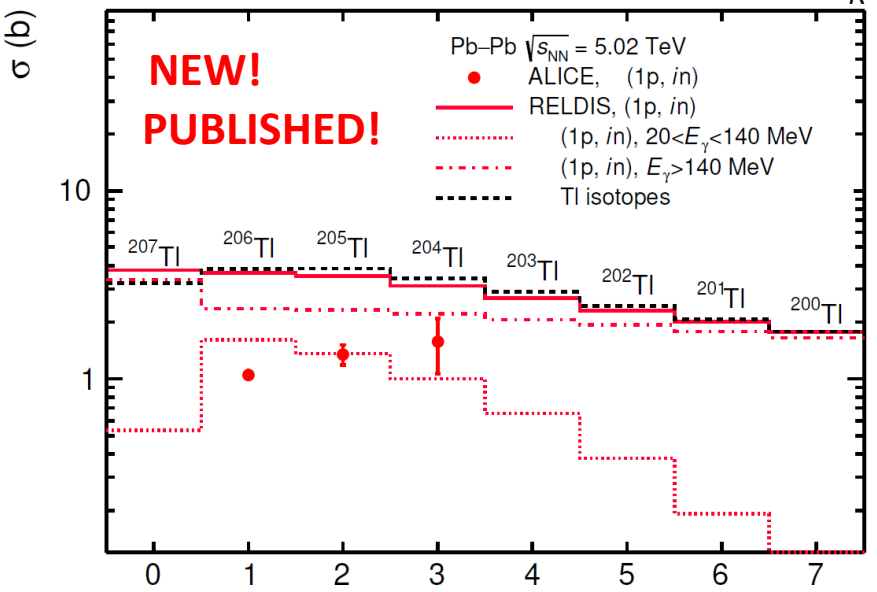
Proton emission in EMD of ^{208}Pb

- Absorption of photons (E_γ > 140 MeV)
  → emission of several neutrons and protons
- Proton emission accompanied by at least 1 neutron emission
  → production of Thallium, Mercure, GOLD (media release)
  → 0p and 3p agree with RELDIS predictions, but 1p and 2p underestimated by 17-25%
- Single proton emission accompanied by 1, 2, 3 neutrons
  → production of the isotopes ^{206,205,204}Tl
  → RELDIS overestimates the data 2-3x
  → Better description for E_γ > 20 MeV, but opposite trend

- Confirms very good ZDC performance
- Possibility to measure 1n or 2n classes:
  → access to different impact parameters
- ZDC is used to measure centrality
- Relevant constraints on models for Tl

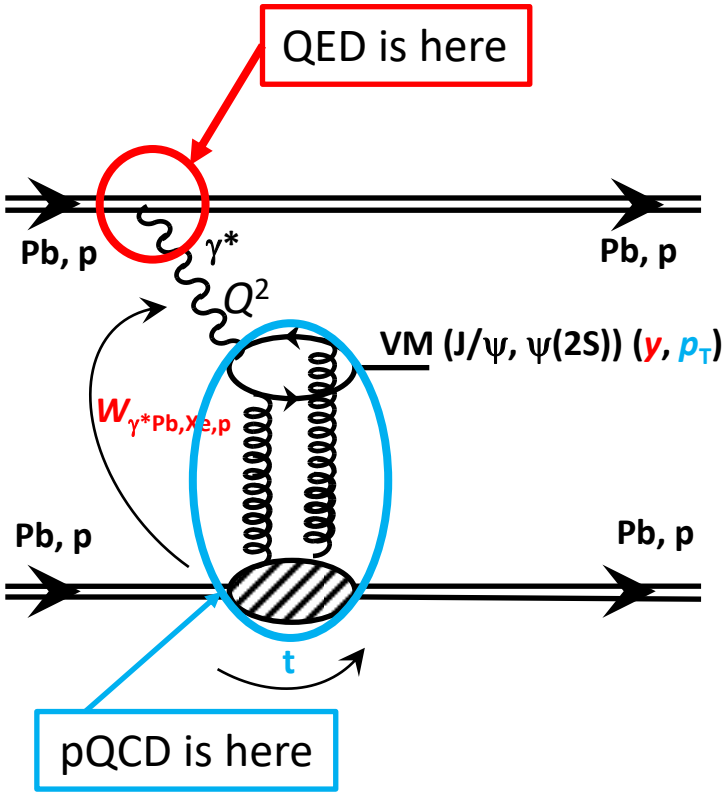
Phys. Rev. C 111 (2025) 054906





Phys. Rev. C 111 (2025) 054906

Photoproduction and main variables



- Momentum scale $Q^2 \sim M_{VM}^2 / 4$
  - Hard scale assured by high mass of J/ψ, ψ' meson
  - Semi-hard scale for ρ^0 meson
- Vector Meson (VM) quantum numbers:
  - $J^{PC} = 1^{--}$
- Bjorken-*x:* fraction of longitudinal momentum of proton

$$x_B = \frac{M_{VM}}{\sqrt{s_{NN}}} e^{\pm y}$$

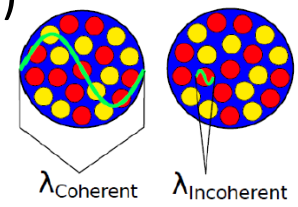
- Photon-target centre-of-mass energy

$$W^2_{\gamma^* Pb,p} = 2E_{Pb,p} M_{VM} e^{\mp y}$$

- 4-momentum transfer $|t| \sim p_T^2$

Coherent VM photoproduction:

- Photon couples coherently to all nucleons (whole nucleus)
- $\langle p_T^{VM} \rangle \sim 1/R_{Pb} \sim 50$ MeV/c
- Target ion stays intact



Incoherent VM photoproduction:

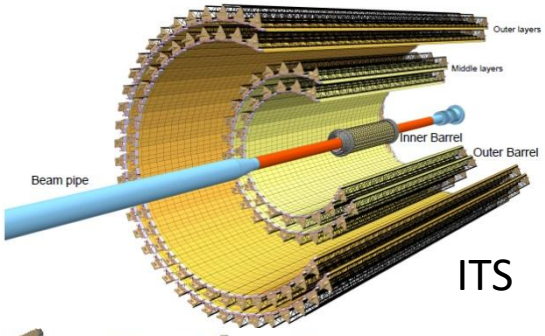
- Photon couples to a single nucleon
- $\langle p_T^{VM} \rangle \sim 1/R_P \sim 400$ MeV/c
- Target ion breaks, nucleon stays intact
- Usually accompanied by neutron emission

ALICE: *JINST* 19 P05062 (2024)

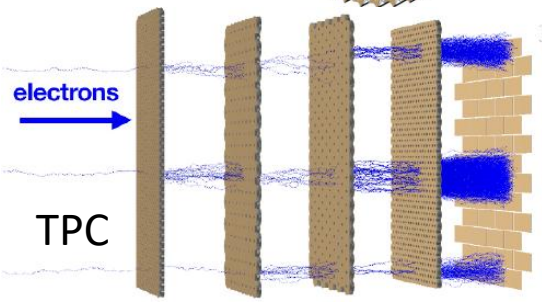
ALICE in Run 3

- Large **upgrade** during LS2
  - **I**nner **T**racking **S**ystem – full pixel layers
  - **T**ime **P**rojection **C**hamber – GEM readout
  - New **M**uon **F**orward **T**racker
  - New **F**ast **I**nteraction **T**rigger (FV0 + FT0 + FDD)
  - New Event Processing Nodes Farm
  - Upgraded readout for most of detectors

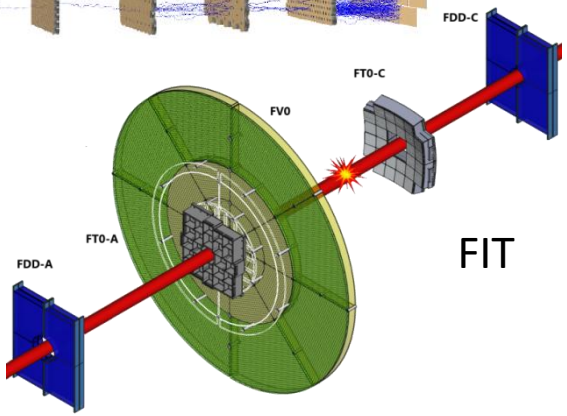
  $\Rightarrow$ **continuous readout** at high rate
- **Pb-Pb data** taking at 50 kHz
  - **All data stored** on tape



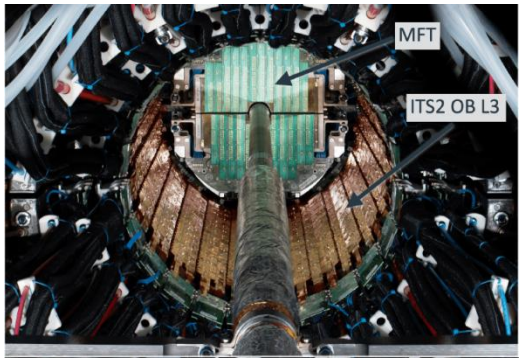
ITS



TPC

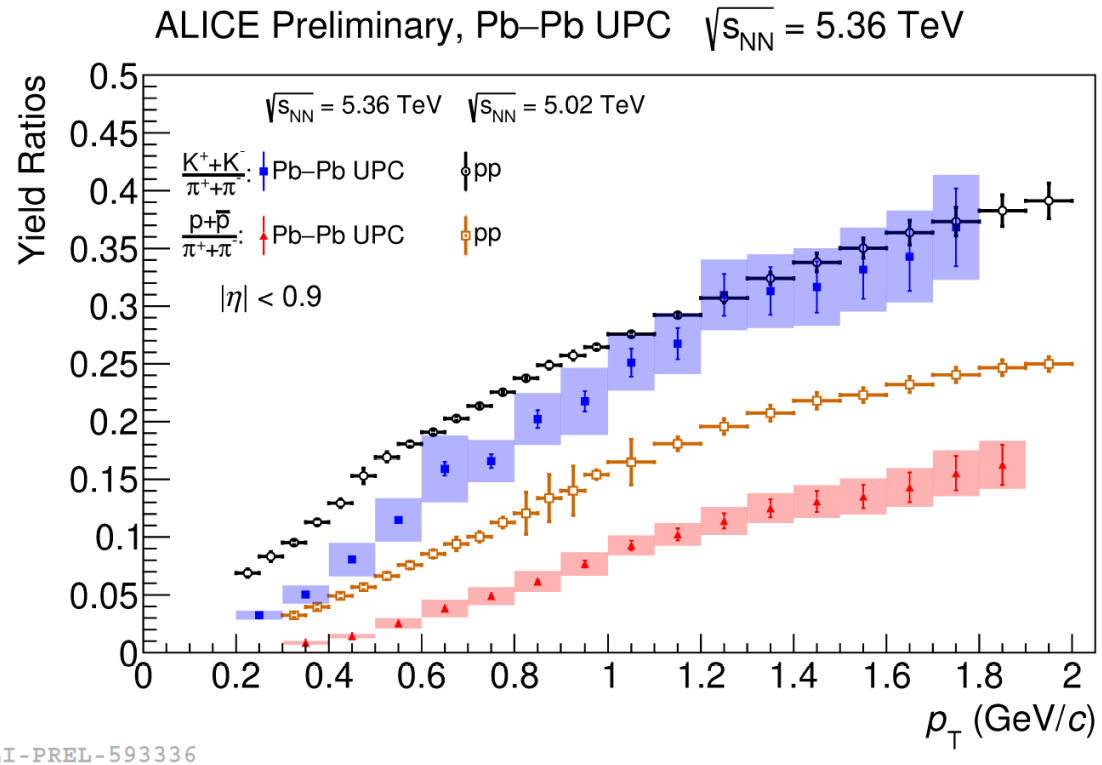


FIT



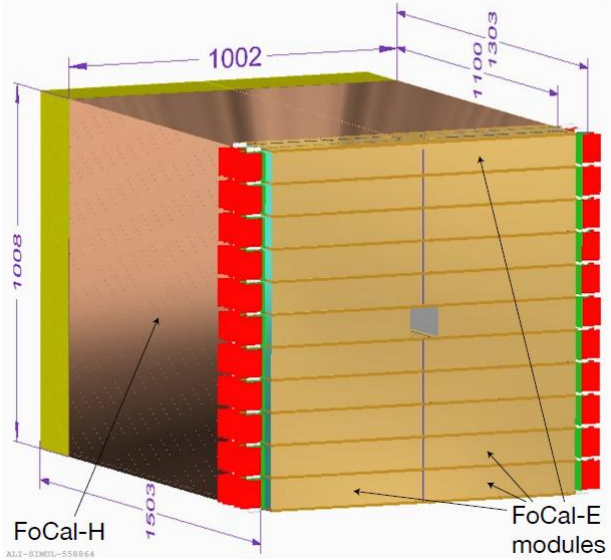
ALICE upgrade detectors:

- ITS: NIM 1032, 166632 (2022)
- TPC: JINST 16, P03022 (2021)
- FIT: NIM 1039, 167021 (2022)
- O^2: CERN-LHCC-2015-006, ALICE-TDR-019


ALICE Preliminary, Pb–Pb UPC $\sqrt{s_{NN}}$ = 5.36 TeV
Yield Ratios
$\sqrt{s_{NN}}$ = 5.36 TeV
$\sqrt{s_{NN}}$ = 5.02 TeV
$\frac{K^+ + K^-}{\pi^+ + \pi^-}$: Pb–Pb UPC
pp
$\frac{p + \bar{p}}{\pi^+ + \pi^-}$: Pb–Pb UPC
pp
$|\eta| < 0.9$
p_T (GeV/c)
ALI-PREL-593336

Forward Calorimeter (FoCal)

- Upgrade to ALICE detector
- LOI: CERN-LHCC-2020-009
- During LS3 (2026-2029) FoCal should be installed
- $3.2 < \eta < 5.8 \rightarrow x_B \sim 10^{-6}$
- 700 cm away from IP
- FoCal-E (22 modules)
- FoCal-H (~10000 channels)



- Forward physics (large η) at low Bjorken-*x*
  - Explore gluon dynamics and non-linear QCD evolution in pp, p-Pb and Pb-Pb
    - Isolated photons, neutral mesons, and jet production and correlations in hadronic collisions
    - Vector meson photoproduction in UPC
  - QGP probes in Pb–Pb collisions at large η
    - based on jet quenching phenomena and long-range correlations of neutral pions, jets, and photons