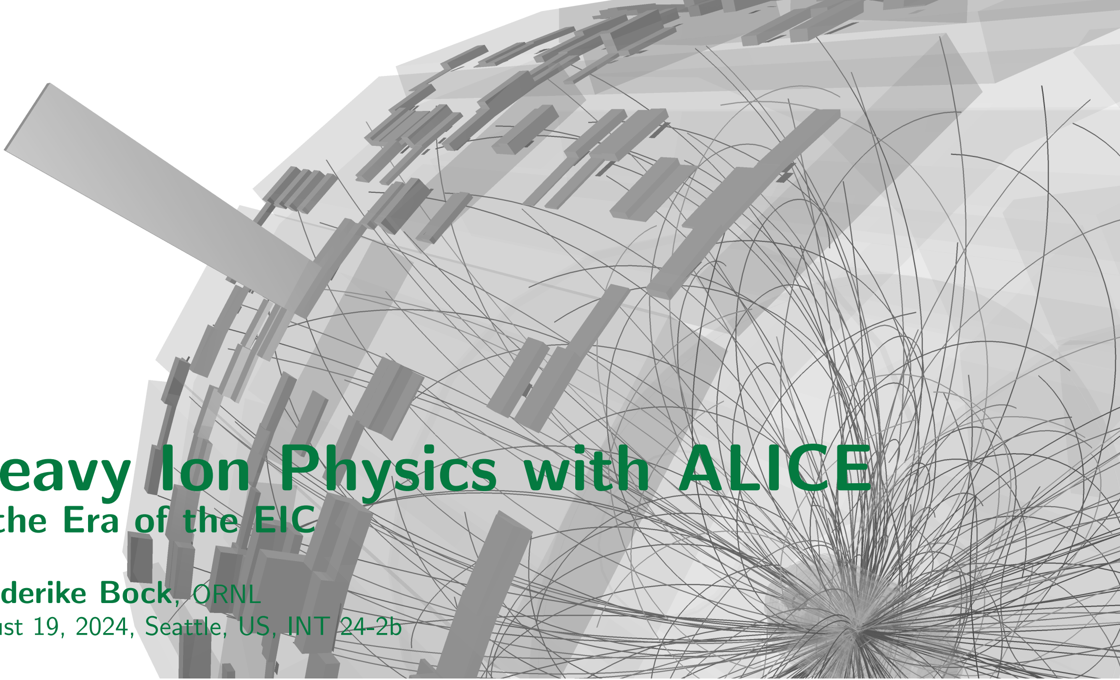


Heavy Ion Physics with ALICE

in the Era of the EIC

Friederike Bock, ORNL

August 19, 2024, Seattle, US, INT 24-2b

The Evolution of ALICE & its Strengths

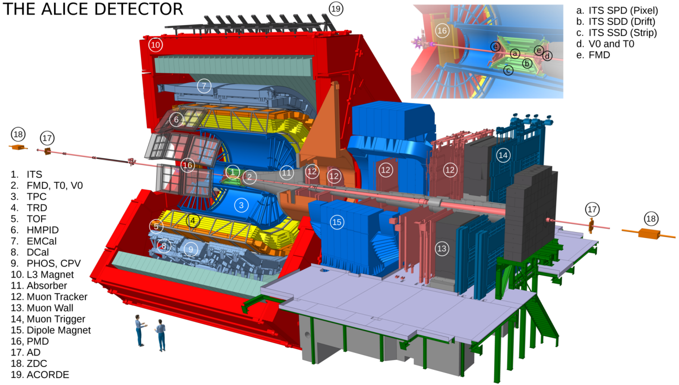
Run 1	LS 1	Run 2	LS 2	Run 3	LS 3	Run 4	LS 4	Run 5&6
2009-2013	2013-2014	2015-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2041

The Evolution of ALICE & its Strengths

Run 1 2009-2013	LS 1 2013-2014	Run 2 2015-2018	LS 2 2019-2021	Run 3 2022-2025	LS 3 2026-2028	Run 4 2029-2032	LS 4 2033-2034	Run 5&6 2035-2041
Pb-Pb p-Pb		Pb-Pb Xe-Xe p-Pb		Pb-Pb O-O p-O		Pb-Pb p-Pb		Pb-Pb

ALICE 1: The Original

THE ALICE DETECTOR



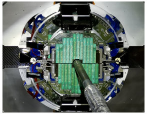
- Dedicated HI experiment designed for up to $dN/dy \approx 8000$ at mid-rapidity.
- Excellent low p_T resolution
- Excellent particle identification for π, K, p, e (mid-rapidity) & μ (forward-rapidity)
- Maximum Pb-Pb read-out rate: 500 Hz (Run 2)

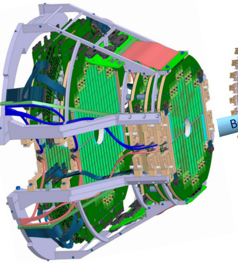
The Evolution of ALICE & its Strengths

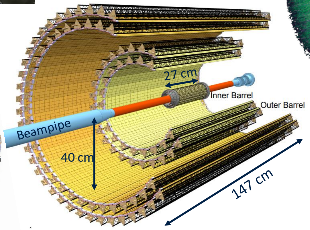
Oak Ridge National Laboratory

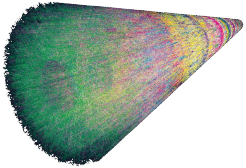
Run 1 2009-2013	LS 1 2013-2014	Run 2 2015-2018	LS 2 2019-2021	Run 3 2022-2025	LS 3 2026-2028	Run 4 2029-2032	LS 4 2033-2034	Run 5&6 2035-2041
Pb-Pb p-Pb		Pb-Pb Xe-Xe p-Pb		Pb-Pb O-O p-O		Pb-Pb p-Pb		Pb-Pb

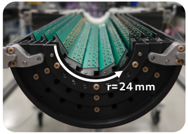
ALICE 2.0: TPC GEMs, ITS2 & MFT MAPS









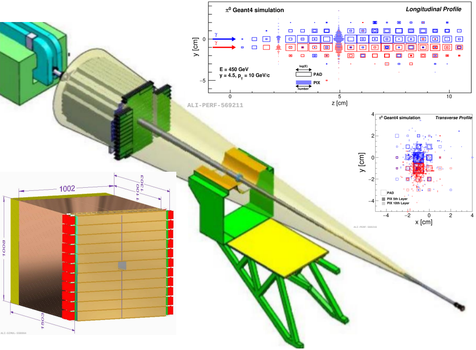


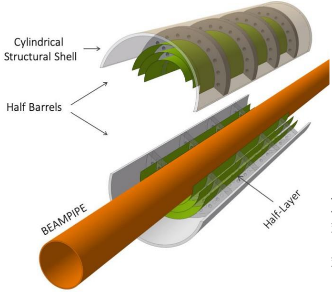
- Continuous read-out of TPC with Gas Electron Multiplier (GEM) detectors
- New silicon pixel detector based on Monolithic Active Pixel Sensors (MAPS) pixel size of $27 \times 29 \mu m$ & $5 \mu m$ spatial resolution
- Improved impact parameter resolution
- Maximum Pb-Pb read-out rate: 50 kHz

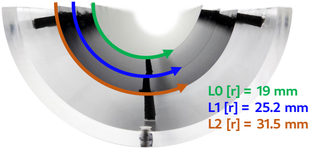
The Evolution of ALICE & its Strengths

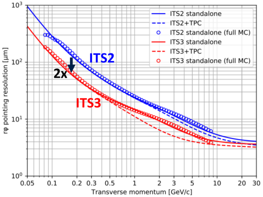
Run 1	LS 1	Run 2	LS 2	Run 3	LS 3	Run 4	LS 4	Run 5&6
2009-2013	2013-2014	2015-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2041
Pb-Pb p-Pb		Pb-Pb Xe-Xe p-Pb		Pb-Pb O-O p-O		Pb-Pb p-Pb		Pb-Pb

ALICE 2.1: FOCal & ITS3 MAPS









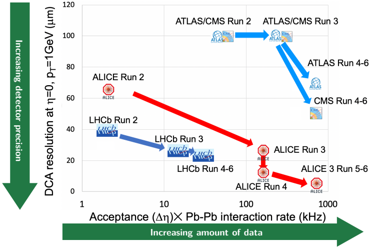
- Excellent forward calorimeter at $3.2 < \eta < 5.8$
- Further improved impact parameter resolution

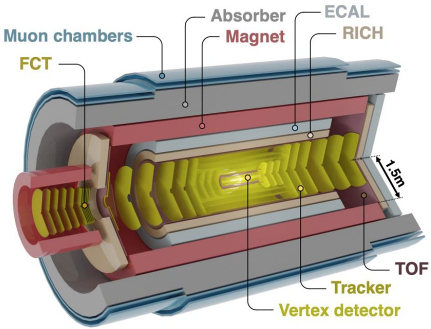
The Evolution of ALICE & its Strengths

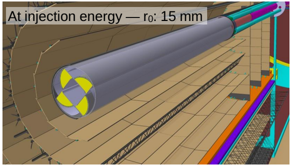
Run 1 2009-2013	LS 1 2013-2014	Run 2 2015-2018	LS 2 2019-2021	Run 3 2022-2025	LS 3 2026-2028	Run 4 2029-2032	LS 4 2033-2034	Run 5&6 2035-2041
Pb-Pb p-Pb		Pb-Pb Xe-Xe p-Pb		Pb-Pb O-O p-O		Pb-Pb p-Pb		Pb-Pb

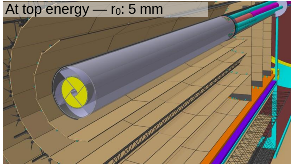
ALICE 3: A New Experiment

- Compact all silicon MAPS based detector
- Retractable vertex detector
- Enhanced PID performance
- Large acceptance: $|\eta| < 4$









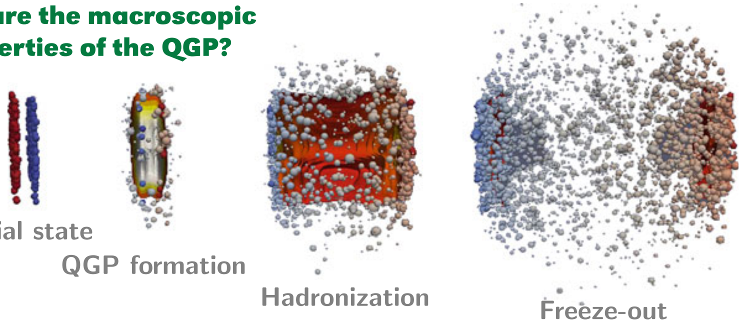
HI-Physics: Where can we contribute?

How does particle production work?

[I. Karpenko]

What are the macroscopic properties of the QGP?

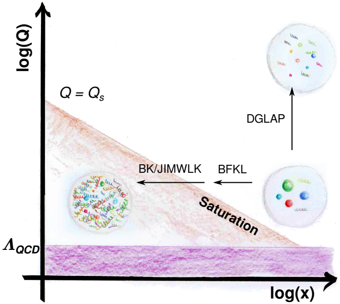
What is the sub-structure of the proton and ion?

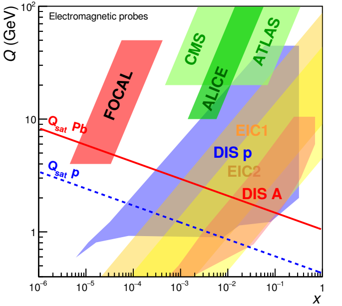


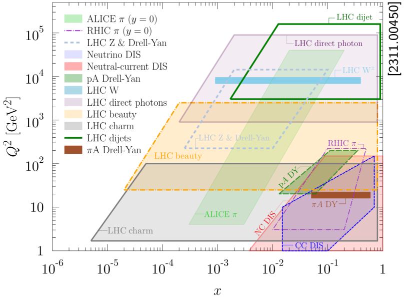
How are particles traversing the QGP influenced by it?

What can we learn about particle interactions in general?

Imaging the Proton and Ion







What can we learn from pp, p-A & A-A collisions about the substructure of the nuclei?

Our toolkit:

- forward particle production
- isolated photons
- UPC
- Drell-Yan
- jets in p-A

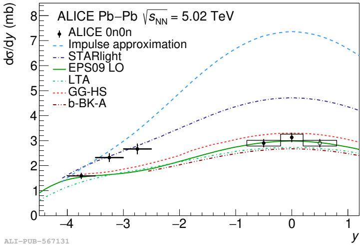
Differential J/Ψ photo-production

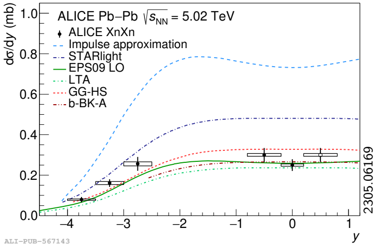
Pb-Pb - probing the Pb-pdf

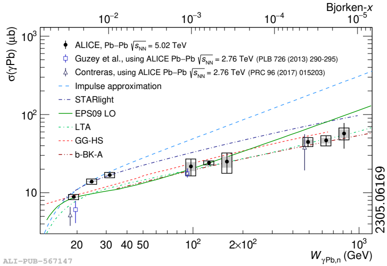
- Measured J/Ψ as function of additional neutron production in ZDCs

→ Constrain kinematic of exchange-photon & access to small x in nucleus

- Are we reaching the black disk limit?
- Lowest x so far, data favor saturation and shadowing models







Differential J/Ψ photo-production

Pb-Pb - probing the Pb-pdf

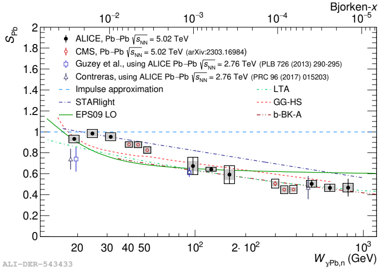
- Lowest x so far, data favor saturation and shadowing models
- Coherent & incoherent J/Ψ vs $|t|$

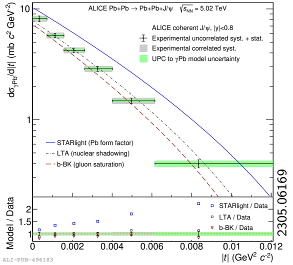
→ Coherent: favor nuclear shadowing/ gluon saturation similar to HERA

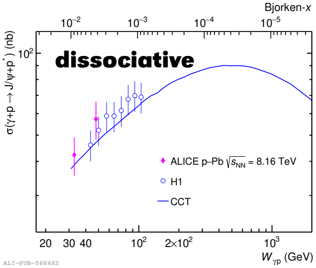
→ Incoherent: probing gluonic "hot spots" in Pb, slope of data favors subnucleon fluctuations

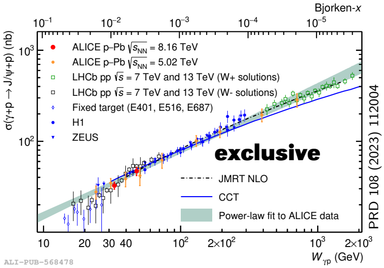
p-Pb - probing the proton-pdf

- No change in behaviour compared to HERA
- First measurement of J/Ψ dissociative production, consistent with HERA

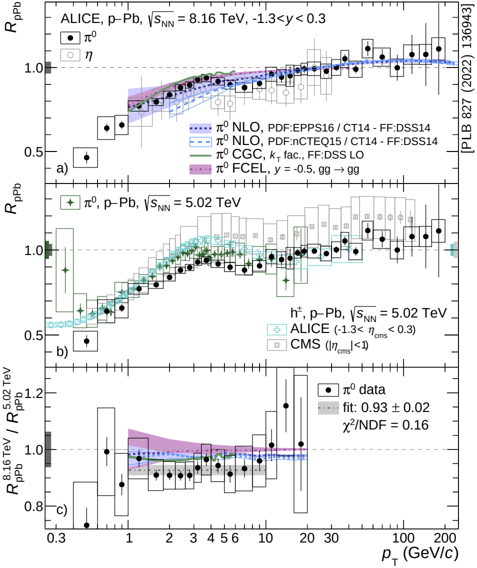






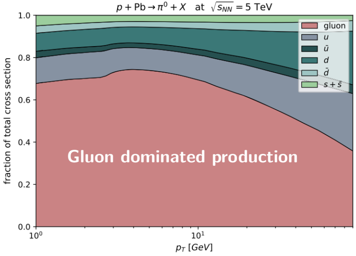


Imaging the Nuclei/Nucleus: Light flavor particles

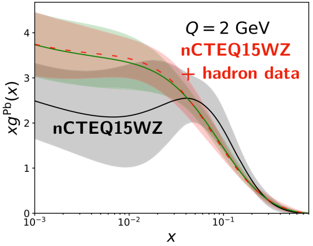


- π^0 & η measured over unprecedented pT range
- π^0 & η R_{pA} imposes strong constraints on nPDF
- For $p_T > 10$ GeV/c: R_{pA} consistent with unity
- For $p_T < 10$ GeV/c: significant suppression in agreement with gluon shadowing and saturation effects of parton energy loss in CNM

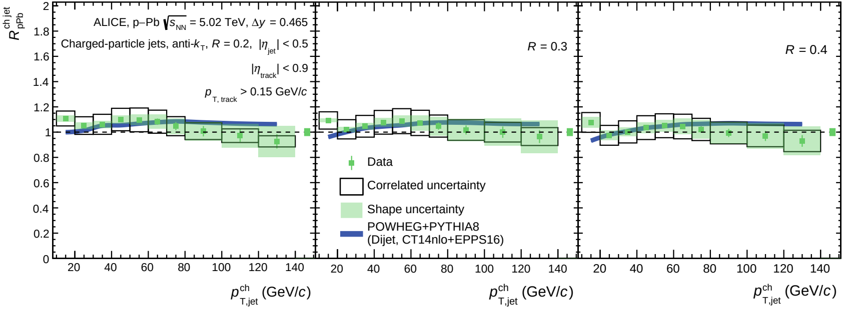
Large gluon contribution to π^0 cross section

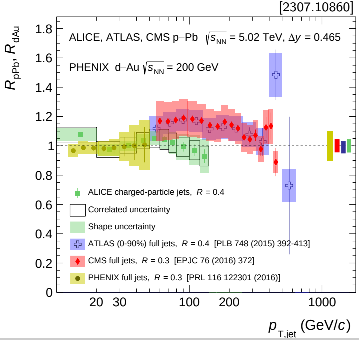


Constrains on gluon n(PDF)



Imaging the Nuclei/Nucleus: Jets





- First charged jet R_{pA} measurement at LHC for $p_T < 50$ GeV/c including pp reference
- Charged-jet R_{pA} at 5 TeV consistent with unity & POWHEG expectation
- Consistent with CMS & ATLAS in overlap region
- Mid-rapidity jets with discrimination power between different models

→ Jets in forward/backward region highly sensitive

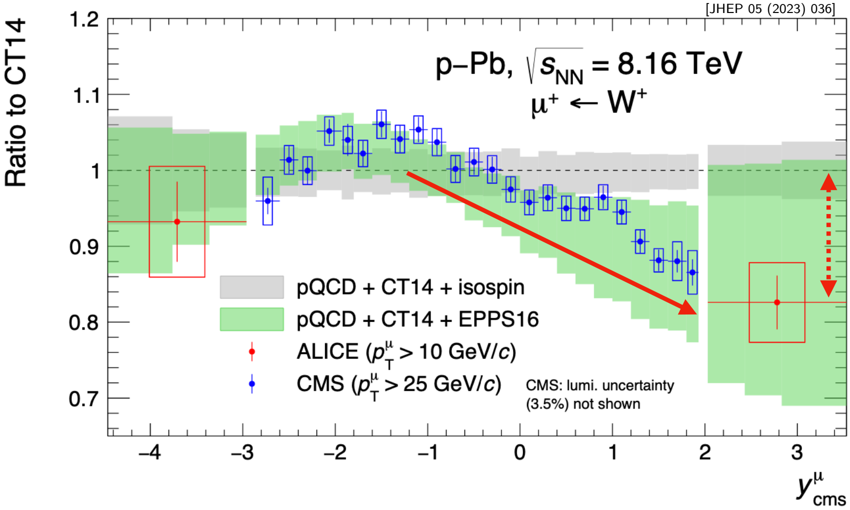
→ FOCal jets at highest LHC rapidities

Imaging the Nuclei/Nucleus: W-production

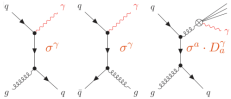
W boson production:

- Only participates in electroweak interaction
- Sensitive to light quark content of nucleus
- Indication of nuclear effects at forward rapidities $(2.03 < y^{\mu}_{\text{cms}} < 3.53)$

Constrains on nPDFs at $x \sim 10^{-4}$

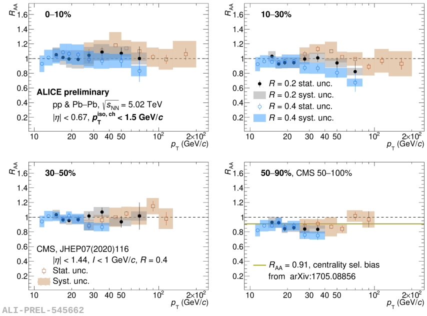


Imaging the Nuclei/Nucleus: Isolated Photons

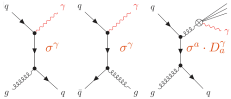


Low momentum iso. γ Pb-Pb

- γ iso. spectra reproducted by theory within uncertainties for both radii
- $R_{AA} = 1$ for $> 50\%$ centrality
- R_{AA} for $50 - 90\%$ in agreement with cent. selection bias (~ 0.91)
- Consistent with CMS
- NLO predicts stronger suppression at low p_T



Imaging the Nuclei/Nucleus: Isolated Photons



Low momentum iso. γ Pb-Pb

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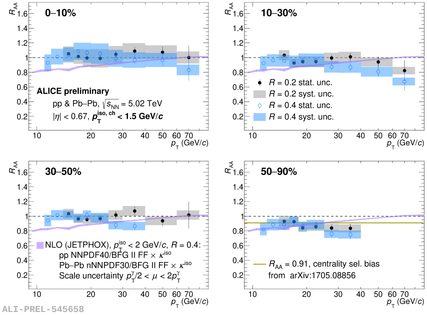


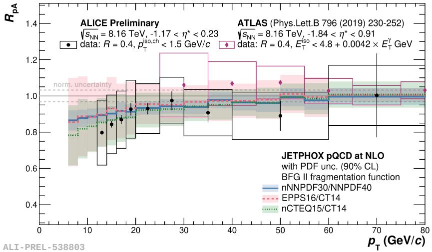
Low momentum iso. γ p-Pb

- Consistent with nPDFs and FF (JETPHOX)
- **Hint of suppression in R_{pA} at low p_{T}**

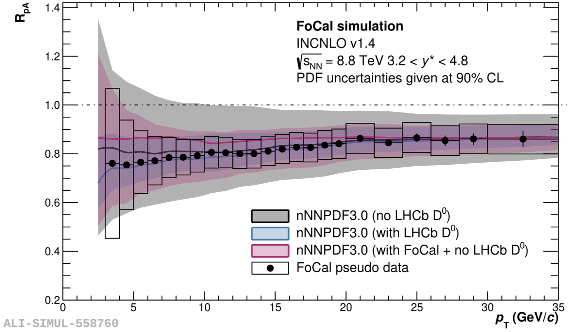
$\rightarrow$ CNM effect?

$\rightarrow$ Favors gluon shadowing

- Consistent with ATLAS

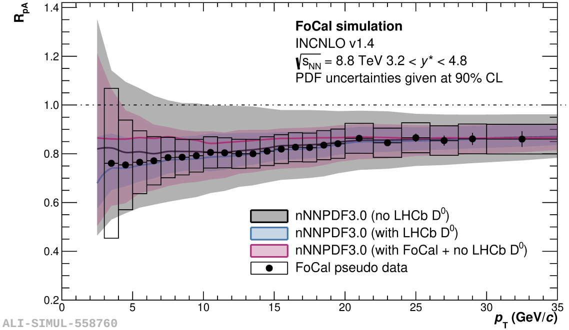


Prompt photon production at forward rapidities

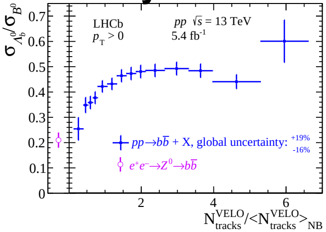


- **FoCal pseudo-data** of R_{pA} constructed using input from NLO+nPDF and assumptions on stat. and sys. uncertainties from perf. studies
- **Bayesian re-weighting of nNNPDF30** prediction showcases **significant reduction of nPDF uncertainties** when including FoCal data; comparable to D meson measurement by LHCb

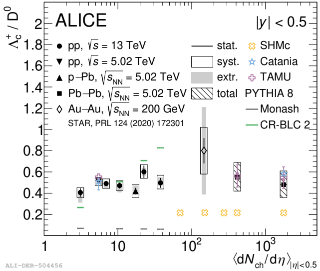
Prompt photon production at forward rapidities



Are fragmentation functions really universal?



b-production



c-production

- **FoCal pseudo-data** of R_{pA} constructed using input from NLO+nPDF and assumptions on stat. and sys. uncertainties from perf. studies
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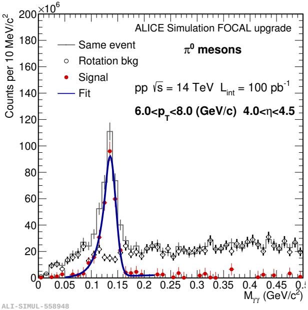
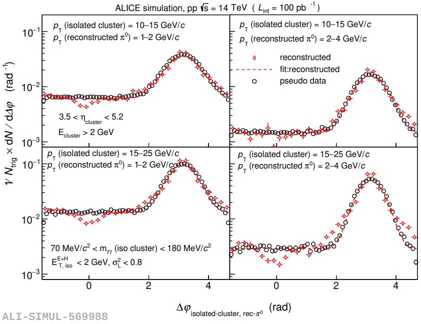
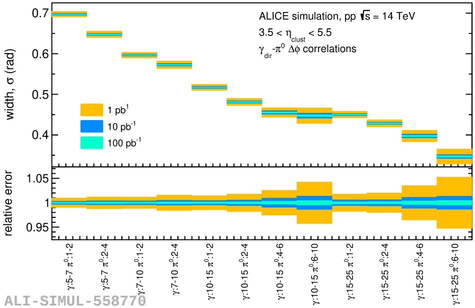
Universality test of low-x formalism

γ-hadron and γ-jet correlations at forward rapidities







Theory:

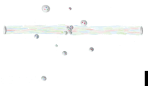
- γ-hadron correlations with additional sensitivity to low-x dynamics
- Expectation: Yield suppressed and decorrelated due to saturation effects

Focal studies:

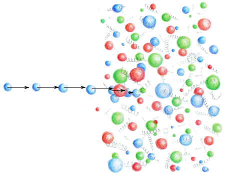
- Analysis of $\gamma - \pi^0$ corr. in simulated pp collision events + detector smearing
- Correlation peak can be measured: stat. unc. of peak width ~ 0.001 rad for expected Run 4 luminosities

How can we study the properties of the QGP?

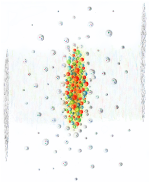
pp

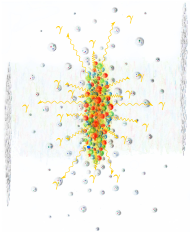


p-Pb

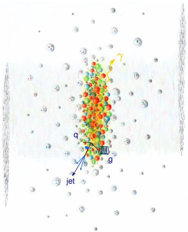


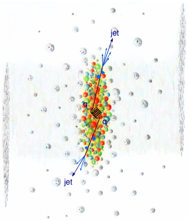
Pb-Pb





electro-magnetic radiation

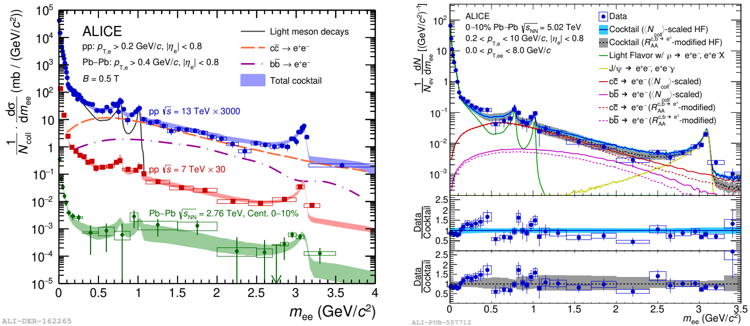




heavy quarks, di-jets & photon-jets

What can we learn from pp, p-A & A-A collisions about the QGP and its interactions with natures building blocks?

Exploring the QGP: Di-lepton production



Run 1 & 2: pp & Pb-Pb

- **Run 1 & 2:** First measurement of di-electron spectra at LHC at low masses. Determination of HF background
- **Run 3 & 4:** Suppression of heavy-flavor BG, measurement of ρ medium modification
- **Run 5 & 6:** Measurement of spectral shape ρ and chiral partner a_1 is unambiguous way to measure chiral symmetry restoration.

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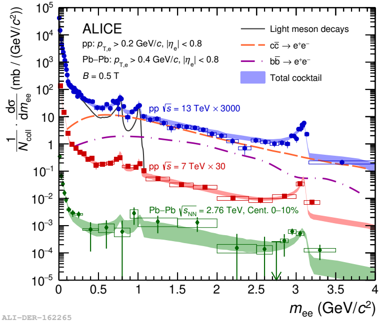

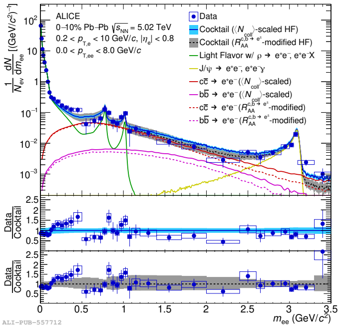

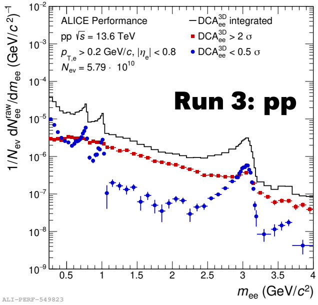

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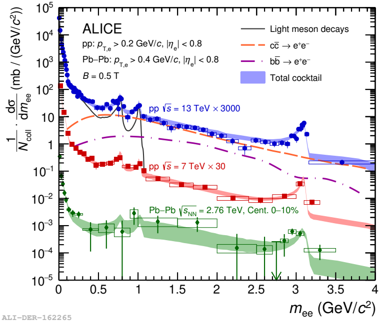
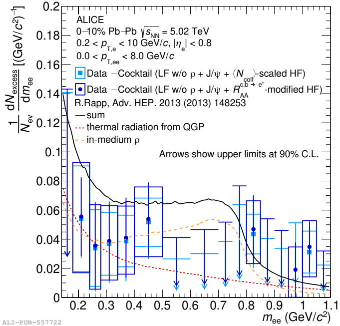
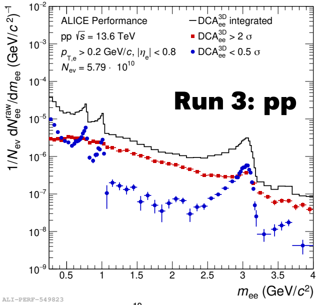
Exploring the QGP: Di-lepton production

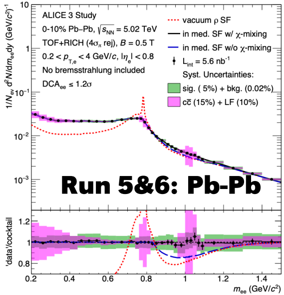




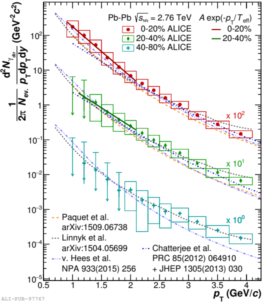


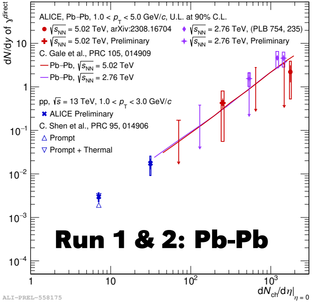
Run 1 & 2: pp & Pb-Pb

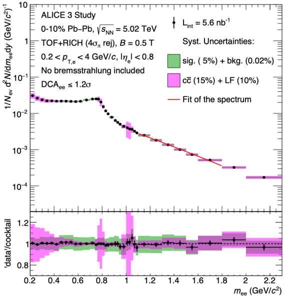
- **Run 1 & 2:** First measurement of di-electron spectra at LHC at low masses. Determination of HF background
- **Run 3 & 4:** Suppression of heavy-flavor BG, measurement of ρ medium modification
- **Run 5 & 6:** Measurement of spectral shape ρ and chiral partner a_1 is unambiguous way to measure chiral symmetry restoration.

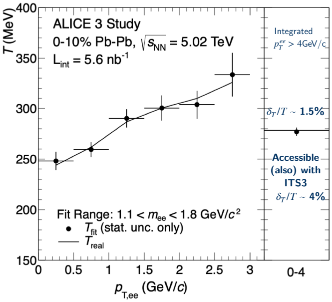


Exploring the QGP: Extracting its Temperature

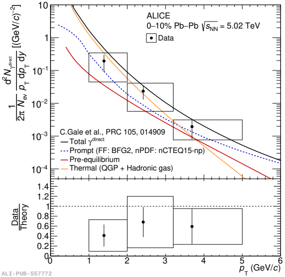






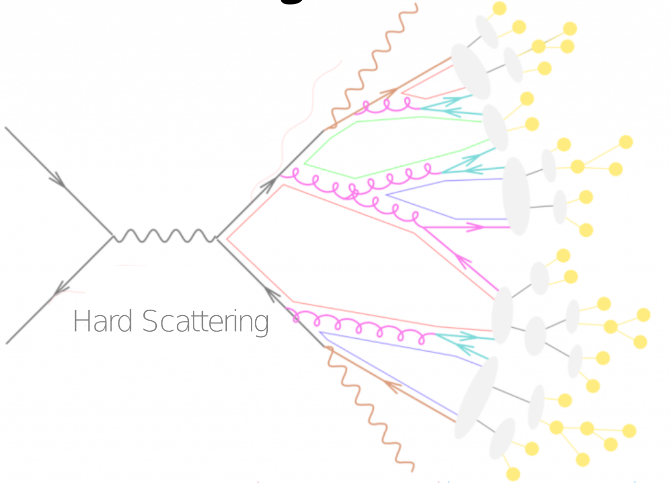


Run 5 & 6: Pb-Pb



- **Run 1 & 2:** First measurement QGP temperature measurements at the LHC
- **Run 3 & 4:** First QGP temperature determination from low mass di-leptons. On-set of QGP production in pp & p-Pb?
- **Run 5 & 6:** Effective QGP temperature determination with stat. unc. < 1.5% (integrated case) & differential in p_T

Understanding Hadronization Processes



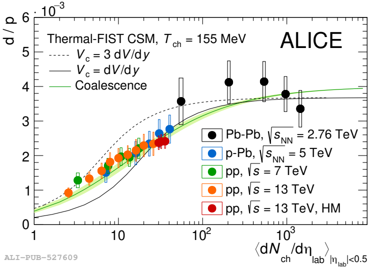
How are hadrons formed?

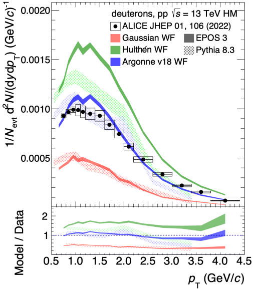
Are there other states?

Does factorization hold in dense environments?

Hadronization - Light nuclei production

- Success of coalescence model for light-nuclei production
  - d/p & ^{3}He/p ratios vs. multiplicity and system size well described
  - $^{3}_{\Lambda}$H/p support coalescence model
  - Successful description of d spectrum with coalescence model w/o free parameters





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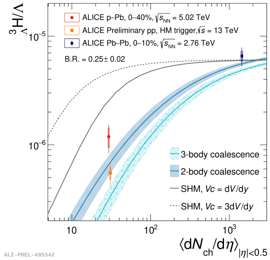
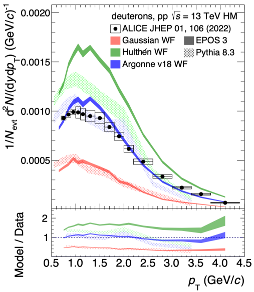


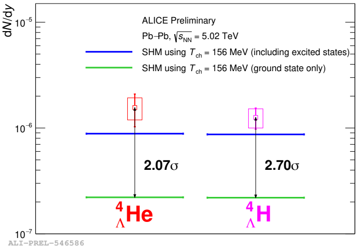


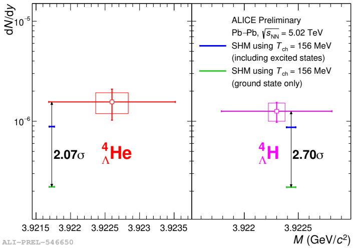
- First $^{4}_{\Lambda}$H & $^{4}_{\Lambda}$He in Pb-Pb at LHC

→ Results agree with hypothesis of excited states

- Testing the dependence of the yields of the SHM with the spin-degeneracy

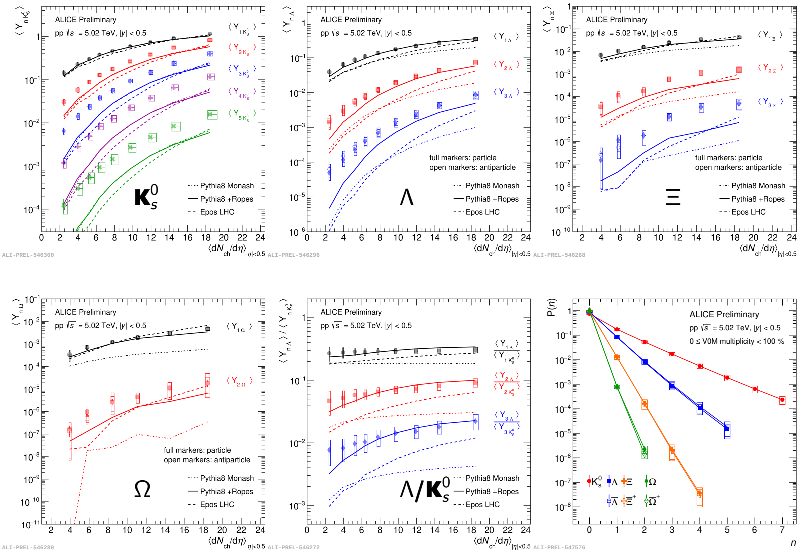
Run 3& Run 4 will give access to more complex nuclei & hypernuclei productions! Bound states?





Hadronization - Multi-strange particle production

- Average yield increases stronger than linear increase vs. multiplicity for multiple strange hadrons, trend described by Pythia with ropes
- 1 strange meson/event described better than higher orders
- 2 & 3 Λ/K^0_s increase with multiplicity $\rightarrow$ baryon related effect



Hadronization: Charm fragmentation in pp & p-Pb

- pp: Prompt Λ_C^+/D^0in not described with pure e$^+$e$^-$ FF
- p-Pb: Prompt shift of peak to higher p_T

→ **Recombination with lighter quarks in p-Pb?**

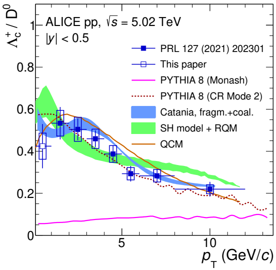
- Ξ_c^0 & Ξ_c^+ production in pp
- Ξ_c^0 in p-Pb: slight enhancement, not consistent with recombinaton alone
- p_T integrated Λ_C^+/D^0 consistent for pp to A-A vs. mult.

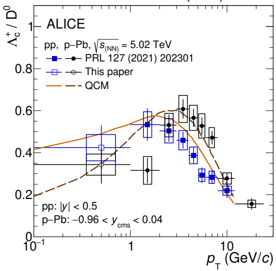
→ Redistribution of momentum

- 3x more baryons produced than measured in ee/ep-collisions

→ **Are there additional processes at play?**

PRC 107 (2023) 064901





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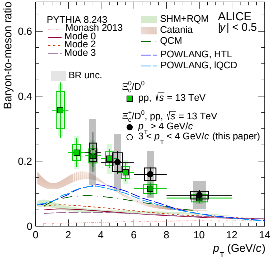

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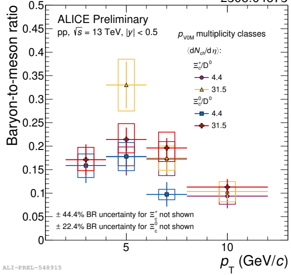

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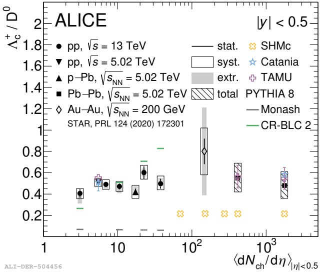
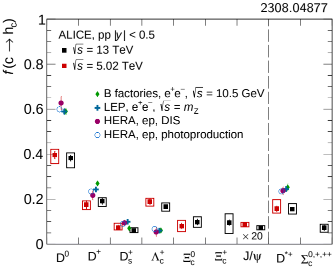
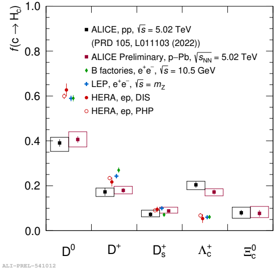
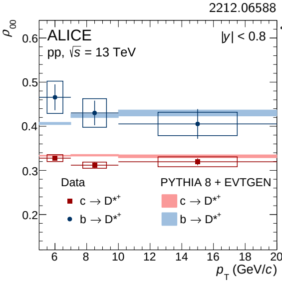


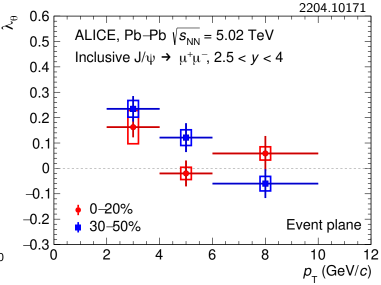


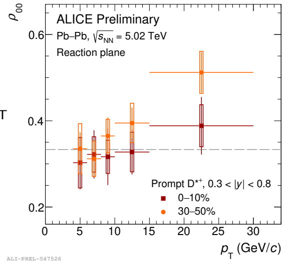


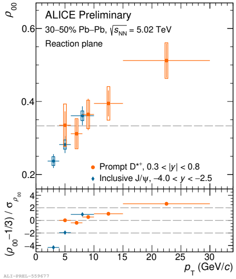
Hadronization: Polarization transfer

- **pp prompt $D^{\star+}$:**
  - ▸ No polarization
  - ▸ Non prompt $\rho_{00} > 1/4$ helicity conservation from B (S= 0)
  - → $D^{*+}(S = 1) + X$ described by PYTHIA
- **Pb-Pb J/Ψ:**
  - → Small polarization observed at low p_T
  - → In agreement with quark-recombination scenario
- **Pb-Pb $D^{\star+}$:**
  - → 0-10% $\sim 1/3$ & 30-50% $> 1/3$ at high p_T
  - → High p_T ρ_{00} consistent with quark fragmentation through polarization by magnetic field?

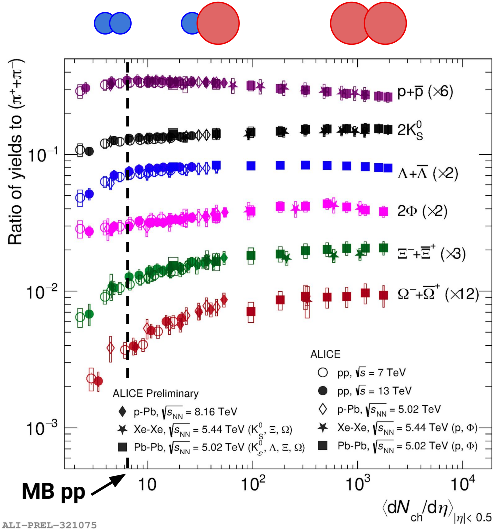








Hadronization: ALICE 3 a whole new Era!



- **Run 1&2:** Multi-differential study of strangeness production in pp, p-Pb & A-A collisions
- **Run 3&4:** Explore single charmed baryon production differentially
- **Run 4&5:** Track strange baryon (Ξ^-) before it decays
  → **Access to multi-charm baryons in HI collisions**

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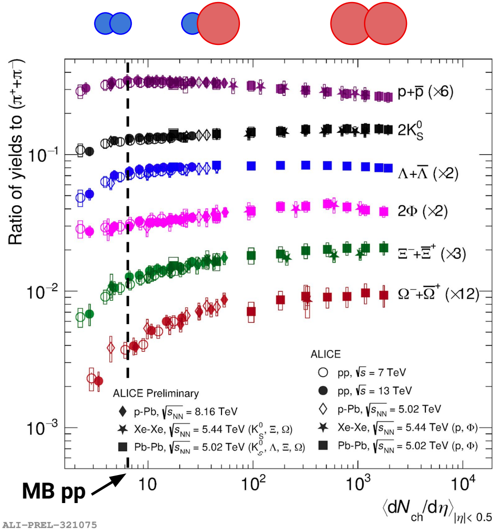

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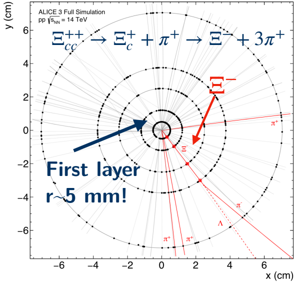
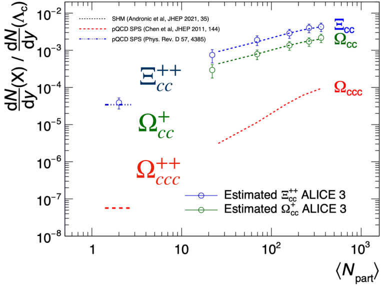
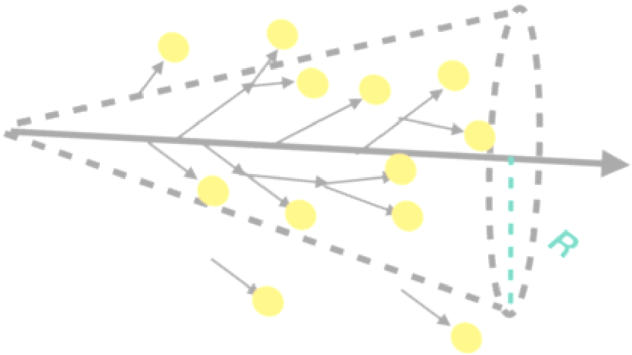
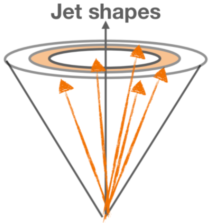


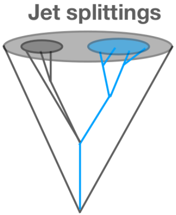


Understanding Quark & Gluon Fragmentation!





Focus on distribution of radiation within the jet (hadron level)



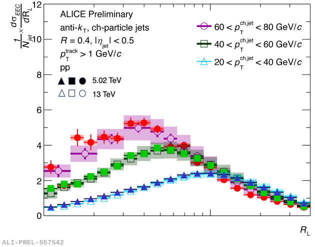
Focus on hard substructure (parton level)

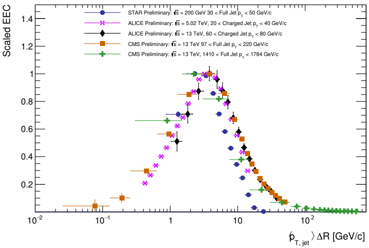
How does the fragmentation process work?

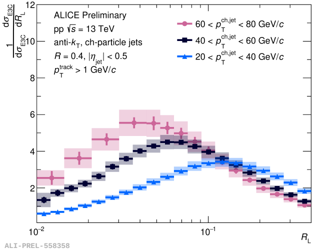
Is the fragmentation process modified in presence of a medium?

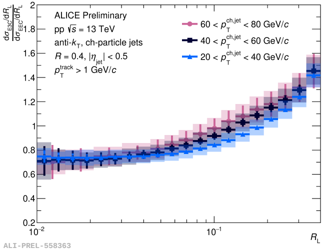
Understanding fragmentation: EECs

- Energy-Energy-Correlators(EECs) well defined probe w/o need for grooming
- **Probing fixed scale with fixed R_L:**
  - **Large $R_L \rightarrow$ perturbative, partonic degrees of freedom**
  - **Small $R_L \rightarrow$ non perturbative scales, free hadron scaling $\propto R_L$**
- **Transition to confinement region at** $R_L \sim O(\Lambda_{QCD})/p_{T,jet}$
- E3C access $1 \rightarrow 3$ splittings, NP effects cancelled in E3C/EEC ratio
- Similar shape for E3C, but different pQCD scaling behavior
- E3C/EEC ratio $\propto \alpha_S(Q)\ln(R_L) + O(\alpha_S^2)$
  - $\rightarrow$ High precision contraint on α_S, jet-p_T proxy for Q
  - $\rightarrow$ Larger p_T, smaller slope, running coupling

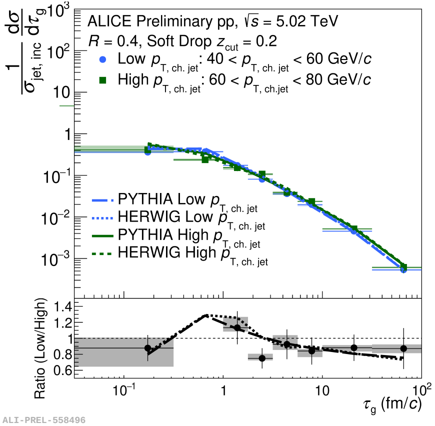


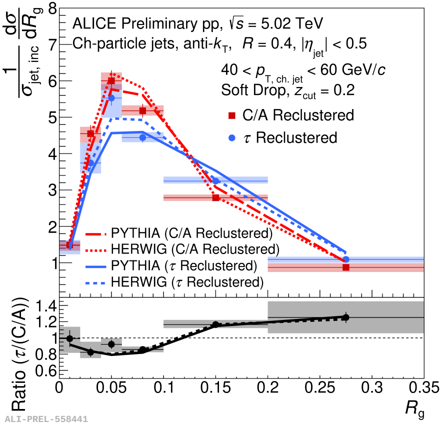






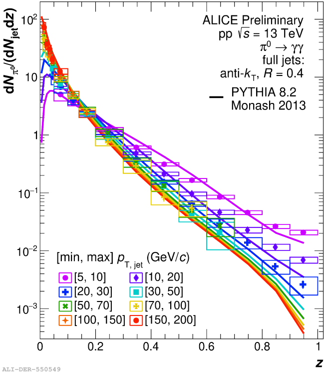
Understanding fragmentation: τ declustering

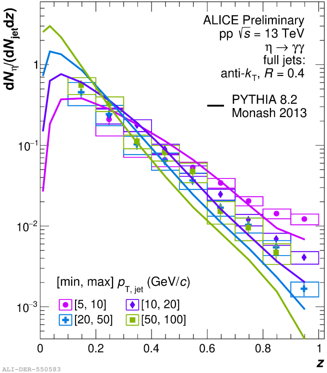


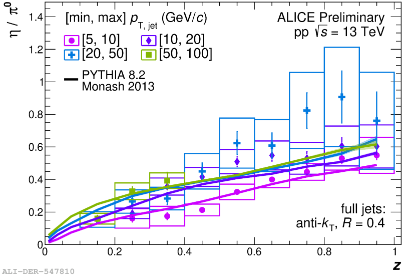


- Probe temporal structure of jet at boundary between parton shower & hadronization
- In Pb—Pb could be used to probe time structure of jet quenching
- No strong p_T dependence
- τ - declustering selects wider splittings in R_g

Neutral Mesons inside Jets: FF







- **First measurement of neutral meson fragmentation at LHC energies**
- For $p_{T,\,jet} > 20$ GeV$/c$:
  Only small dependence on $p_{T,\,jet}$
- η/π^0 ratio similar for $p_{T,\,jet} > 10$ GeV$/c$ as function of z

Comparison to PYTHIA

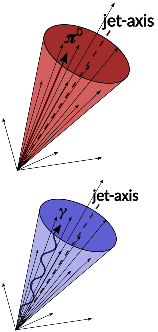
- General ordering and magnitude described, shape slightly different

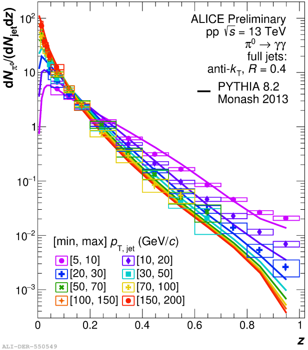
→ Softer fragmentation predicted by PYTHIA

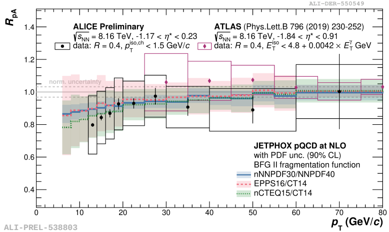
- $p_{T,\,jet}$ dependence of η/π^0 described

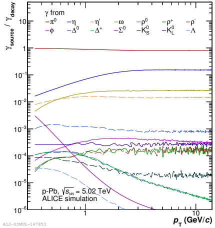
Where could we go from here?

- **Largest uncertainties for many theoretical calculations arise from fragmention functions & (n)PDFs**
  - We have proven we can measure these for light neutral mesons!
  - **Run 2:** K^0_s & Λ FF would be feasible!
  - **Run 3:** Statistics should allow to measure ω & η' FF directly and many other hadrons!
- **Could we measure the fragmentation photons directly?**
  - Would reduce uncertainties of nPDF extraction from photons
  - Could follow a fragmentation photon cocktail approach in multiple dimensions similar to thermal photon extraction
- **Are the fragmentation functions modified in p-A & A-A collsions?**









Into the Future!

Run 1 2009-2013	LS 1 2013-2014	Run 2 2015-2018	LS 2 2019-2021	Run 3 2022-2025	LS 3 2026-2028	Run 4 2029-2032	LS 4 2033-2034	Run 5&6 2035-2041
Pb-Pb p-Pb		Pb-Pb Xe-Xe p-Pb		Pb-Pb O-O p-O		Pb-Pb p-Pb		Pb-Pb

The HL-LHC & detector upgrades allow for up to 100 times more statistics in Pb-Pb collisions than before Run 3

We have the tools to explore all stages of a heavy-ion collisions, including the QGP:

- with unprecedented precision
- in a wider phasespace
- more differentially
- with entirely new observables