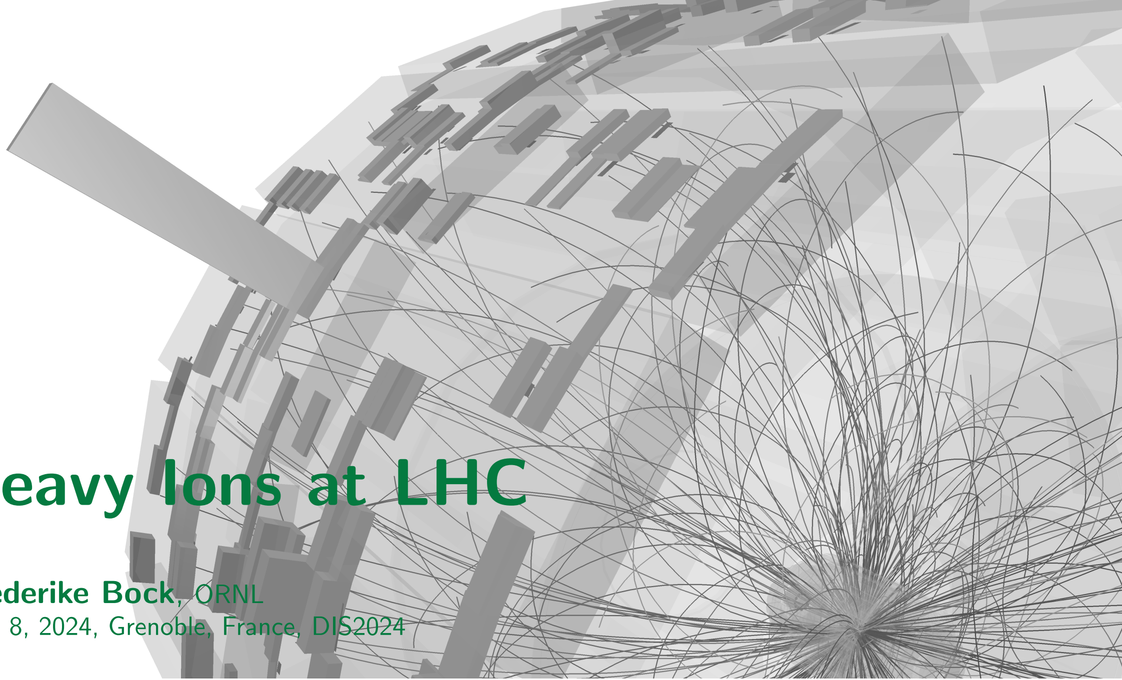
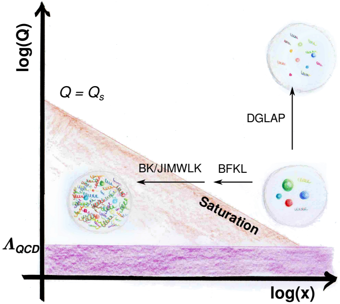


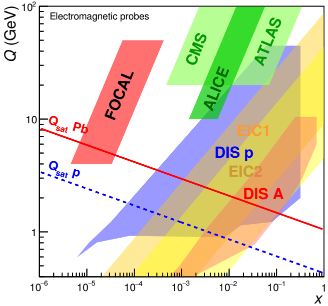
Heavy Ions at LHC

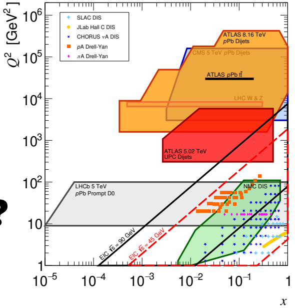
Friederike Bock, ORNL

April 8, 2024, Grenoble, France, DIS2024

Imaging the Proton and Ion







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

Coherent J/Ψ production in Pb-Pb collisions

- **New measurments by CMS & LHCb at forward rapidity**
- Completing the picture of coherent J/Ψ production in UPC vs y & p_{T} complementing ALICE measurement
- Coherent J/Ψ production vs centrality w/o significant centrality dependence
- Strong y-dependence predicted at high y

→ Better differentiation of models

- 70-90% Raw yield excess in all rapidity intervals → hadronic yield
- **70-90% rapidity dependence not reproduced by models, but overall x-section**
- Inclusion of nuclear overlap doesn't solve the problem

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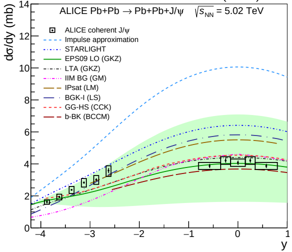

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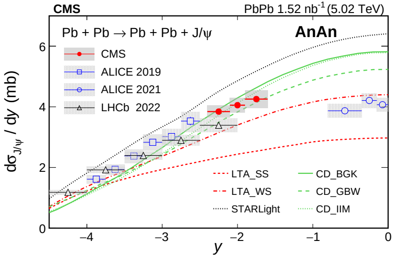

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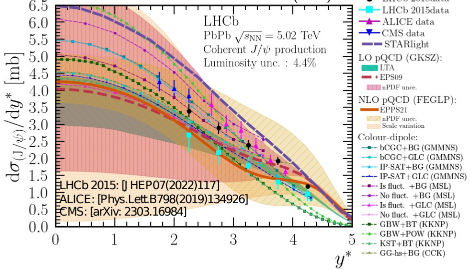

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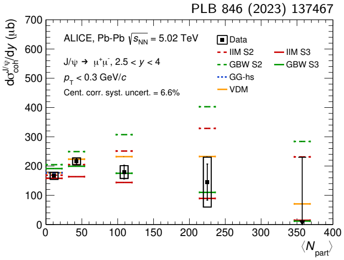

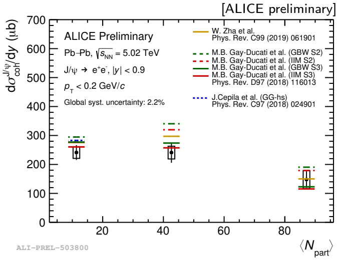

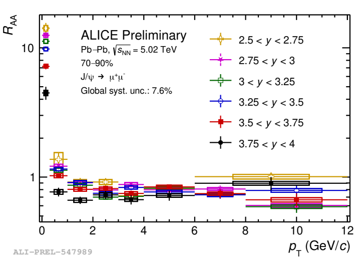

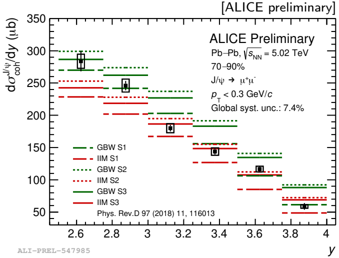

Coherent $\Psi(2S)$ production in UPC events

- **First precise coherent $\Psi(2S)$ prod in UPC y & p_T**
- Complementing ALICE measurement at mid-rapidity
- First cross-section ratio vs rapidity in UPC events at LHC

→ **Strong contrains to nPDF from coherent quarkonia production**

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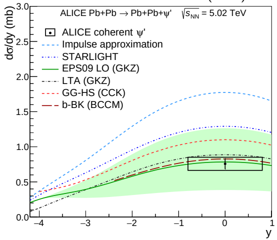

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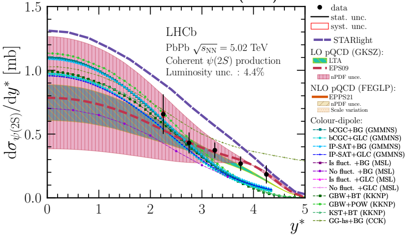

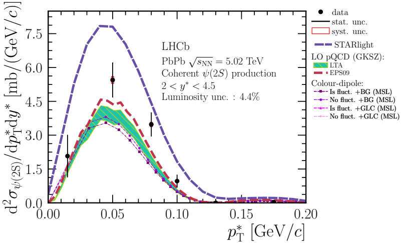

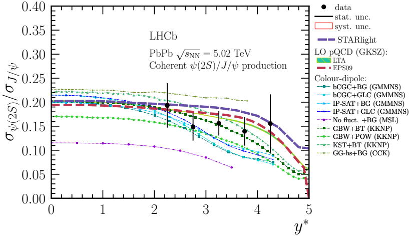

J/Ψ polarization in UPC events

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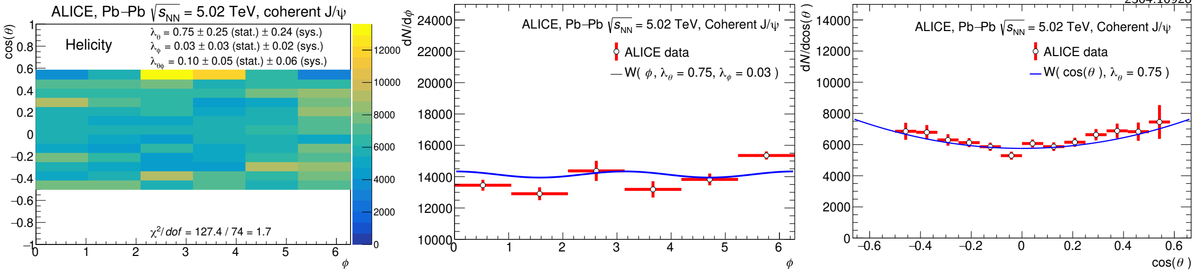

- S-channel helicity conservation

→ Photon heilicity transfered to vector meson

- **First polarization measurement of coherently photo-produced J/Ψ**

→ Tranverse polarization of J/Ψ observed in UPC

- **Hint for J/Ψ tranverse polarized in 70-90%**

→ **Coherent photo-production dominant**

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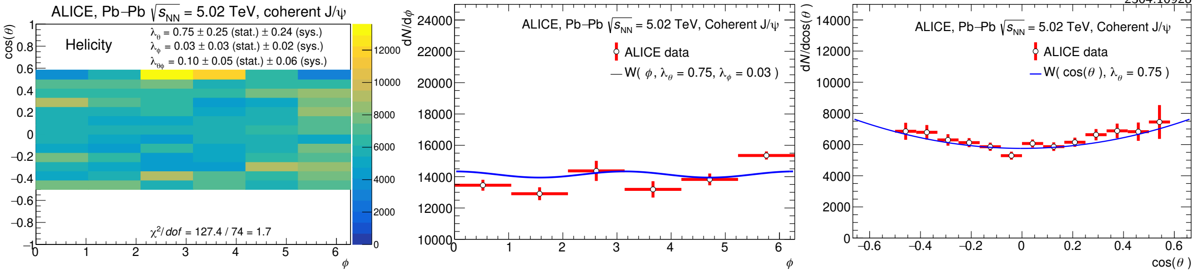

[ALICE preliminary]

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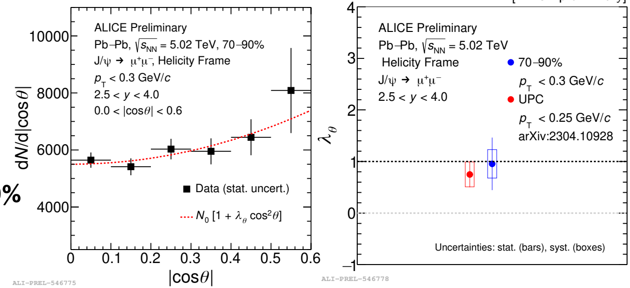


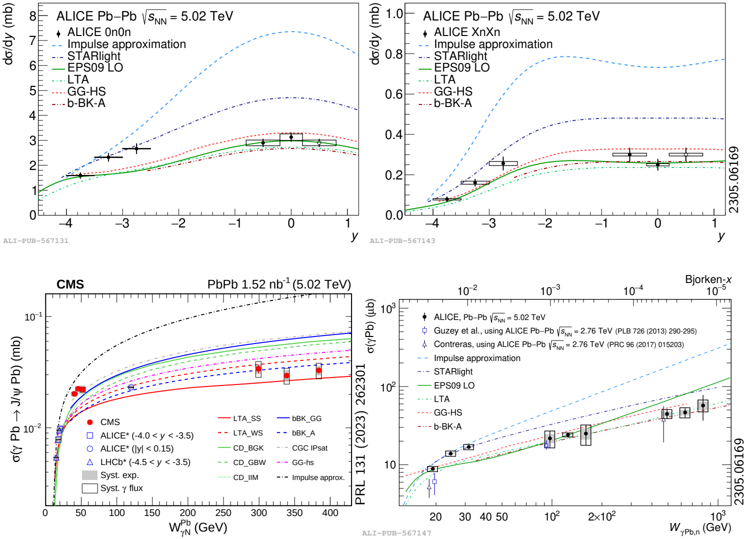
Differential J/Ψ photo-production

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



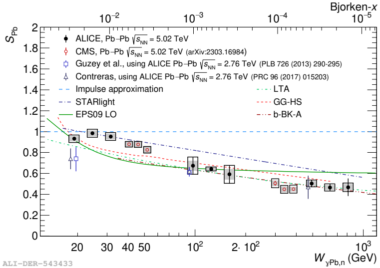
Differential J/Ψ photo-production

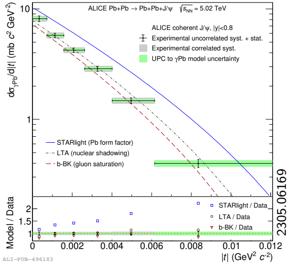
Pb-Pb - probing the Pb-pdf

- 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

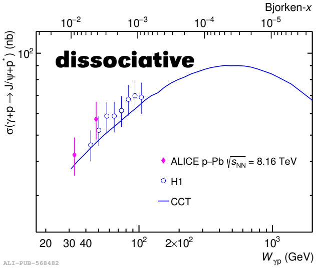
→ Incoherent: probing gluonic "hot spots" in Pb, slope of data favors subnucleon fluctuations

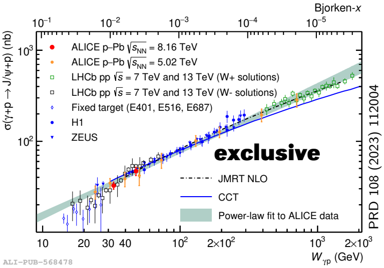




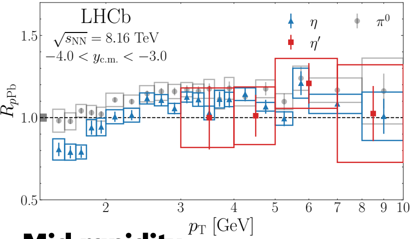
p-Pb - probing the proton-pdf

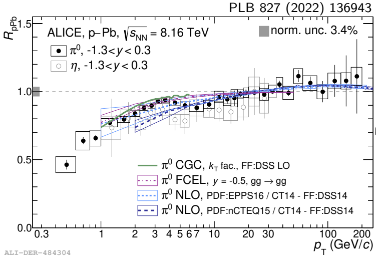
- No change in behaviour compared to HERA
- First measurement of J/Ψ dissociative production, consistent with HERA

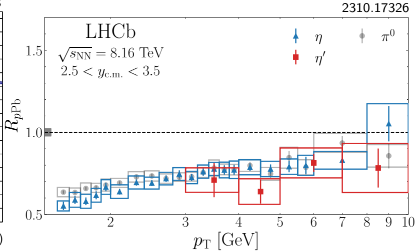




Imaging the Nuclei/Nucleus: Light flavor particles







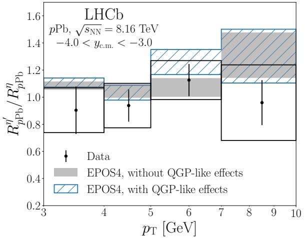
Mid-rapidity

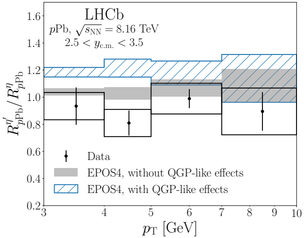
- π^0 & η R_{pA} imposes strong constraints on nPDF

Forward/Backward-rapidity

- π^0 low x suppression ($\eta > 0$) & excess at high x ($\eta < 0$)
- η & η' similar suppresion as π^0, nearly no mass effect
- Complementary to D mesons & charged particles

→ Constraints on QGP effects in small collision systems

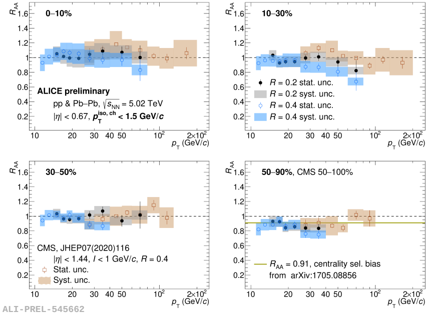




Imaging the Nuclei/Nucleus: Isolated Photons

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}



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- Consistent with CMS
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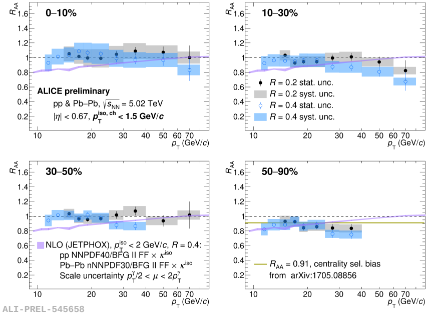
Low momentum iso. γ p-Pb

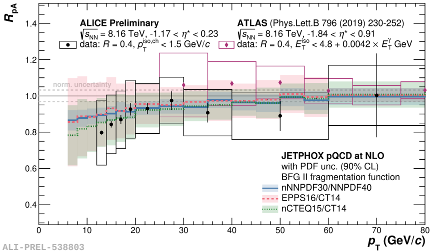
- Consistent with nPDFs and FF (JETPHOX)
- Hint of suppression in R_{pA} at low p_T

→ CNM effect?

→ Favors gluon shadowing

- Consistent with ATLAS





Imaging the Nuclei/Nucleus: Jets

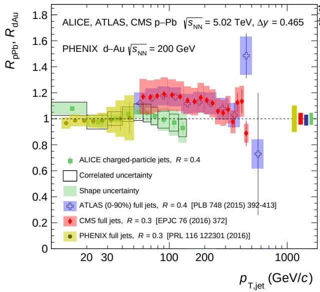
- Charged-jet R_{pA} at 5 TeV consistent with unity & POWHEG expectation
- Centrality dependence for inclusive jets in p-Pb, due to color fluctuations in proton

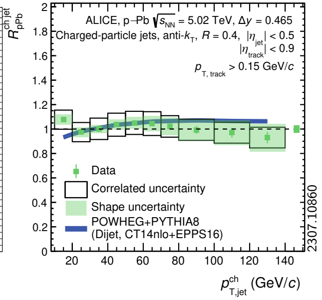
→ **Can we scan x_p?**

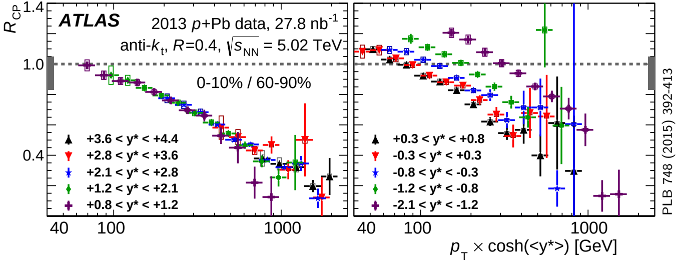
- Di-jets as probes for pdfs
  - Di-jets in p-Pb - R_{CP} jets scales with $p_{\mathrm{T}}\cosh(\langle y^{*}\rangle)$ (GeV)

  → Probe primarily x_p
  - UPC di-jets can adjust probed photon energy by cutting in H_{T}

  → Probe primarily x_{Pb}







Imaging the Nuclei/Nucleus: Jets

$$x_F = \frac{2m_T \times \sinh y^{CM}}{\sqrt{s_{NN}}}$$

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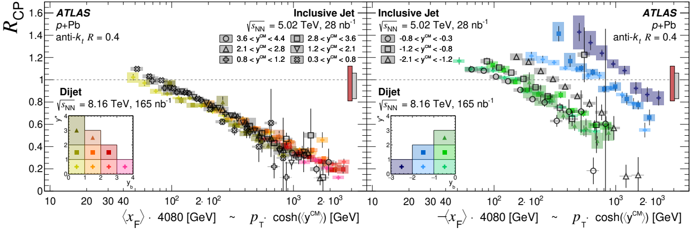

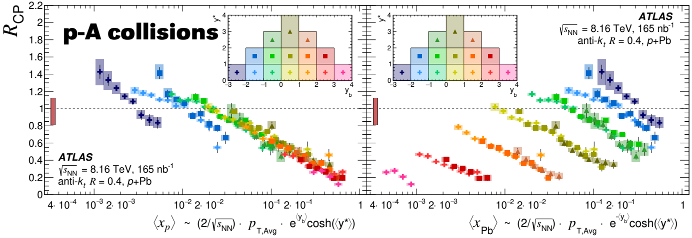

PRL 132 (2024) 102301

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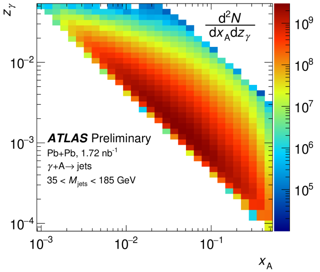
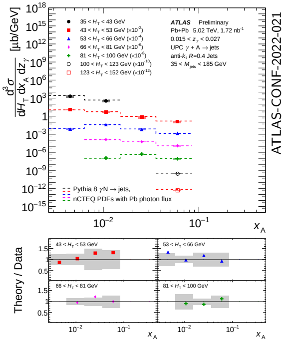
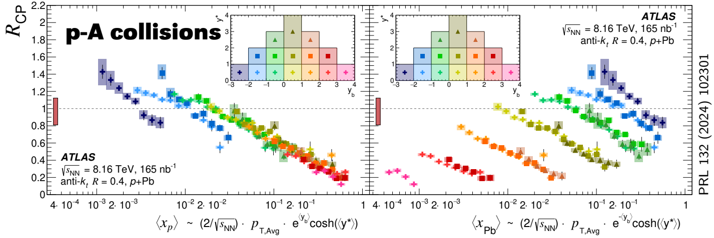
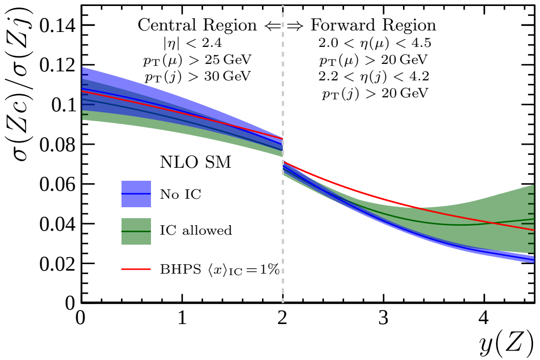
UPC collisions



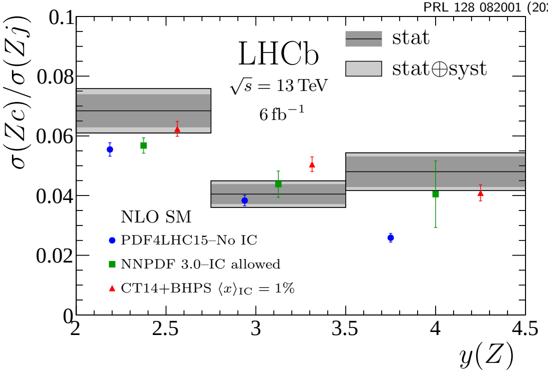




Imaging the Nucleus: Z+c jets in pp



PRL 128 082001 (2022)



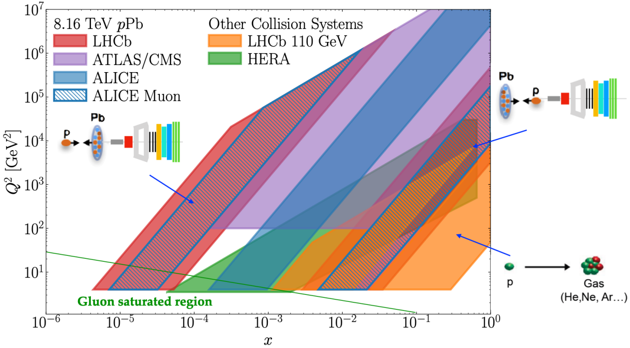
- Z + c-jet production at forward rapidity probes high x region – sensitive to intrinsic charm (IC)
- LHCb data favors calculations allowing IC at most forward rapidity
- **Recent global PDF analysis finds 3σ evidence for IC in proton** *[NNPDF collab, Nature 608 (2022)]*

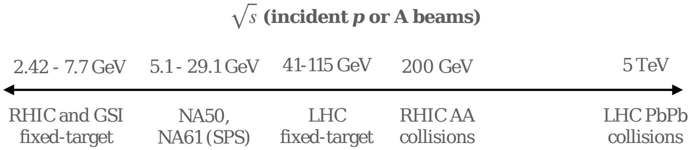
→ Similar behavior as for valence quark

- Current analysis primarily limited by statistics - New Run 3+ data allows future exploration

Imaging the Nuclei/Nucleus: LHCb fixed target

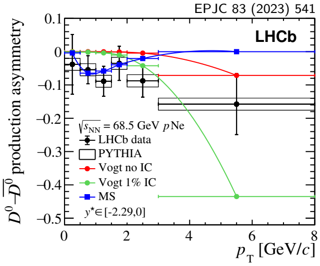
- **Complementary to other LHC experiments and energies** $\sqrt{s_{\mathrm{NN}}} = 41 \rightarrow 115$ **GeV**
- Unique access to high Bjorken x and low Q^2 phase space
- **Variety of nuclear targets**
  - Constrain nPDF
  - Study nuclear absorption

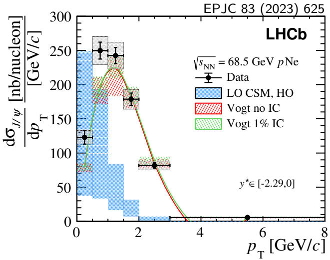


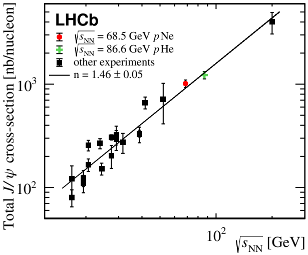


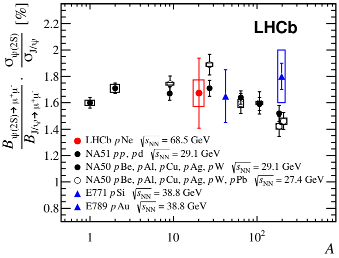
Imaging the Nuclei/Nucleus: HF production in p-Ne

- D^0 $p_\mathrm{T}$spectra not reproduced by standard calculations
  - → Needs intrinsic charm or recombination
- $D - \bar{D}$ production asymmetric vs y not reproduced in any calculation
- Measured J/Ψ x-section consistent with $\sqrt{s_\mathrm{NN}}$ dependence
- Differential J/Ψ x-sections
  - → No differentiation between w/ or w/o IC, LO fails
- Ψ(2S)/J/Ψ ratio consistent with light nucl. collision









Imaging the Nuclei/Nucleus: HF production in Pb-Ne

- No significant recombination expected as $N_{c\bar{c}} \approx 1$
- $\sigma_{J/\psi}/\sigma_{D^0}$ little dependence on $y*$, strong p_{T} dependence
- Ratio decreases similarly as N_{Coll}

$\rightarrow$ J/Ψ experiences additional nuclear effects

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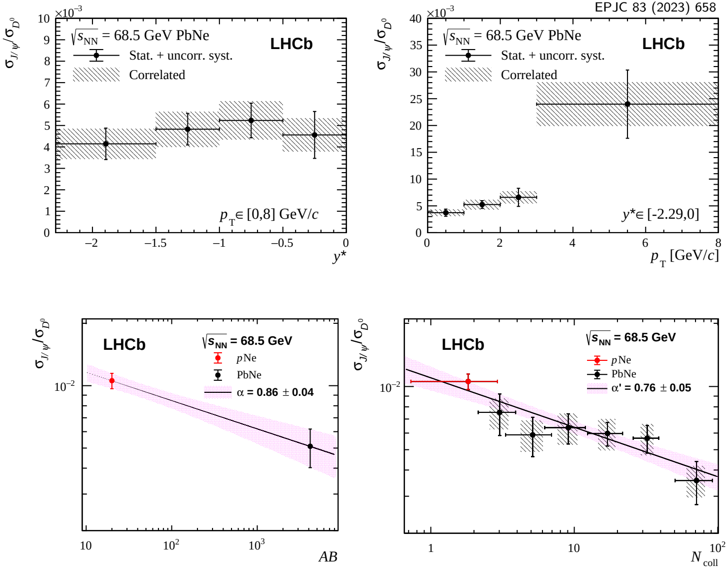
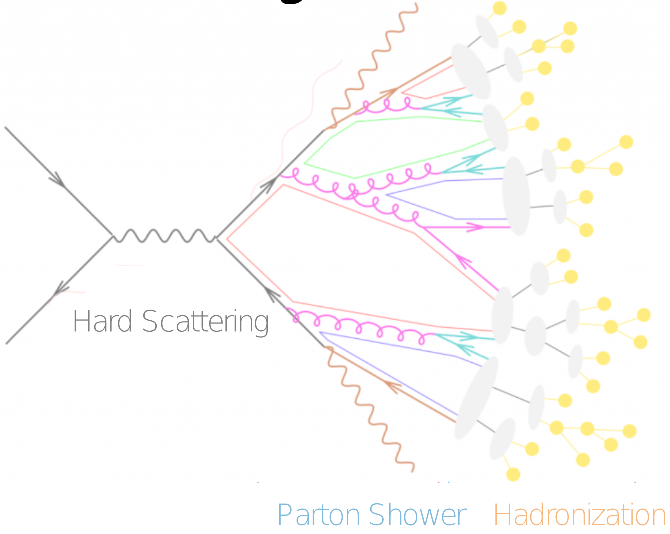


Understanding Hadronization Processes



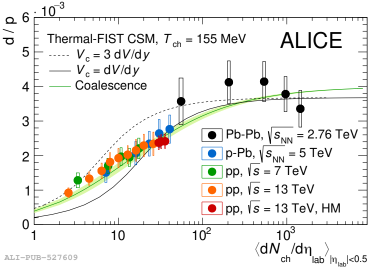
How are hadrons formed?

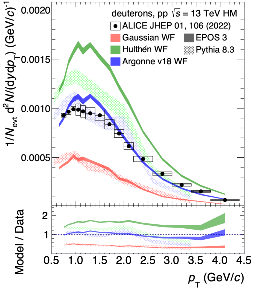
Are there other states?

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





Hadronization - Light nuclei production

OAK RIDGE National Laboratory

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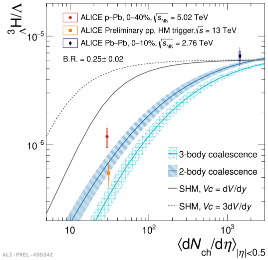
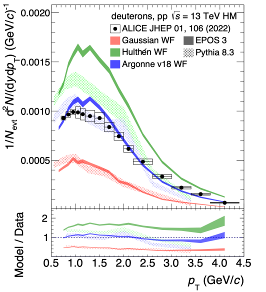
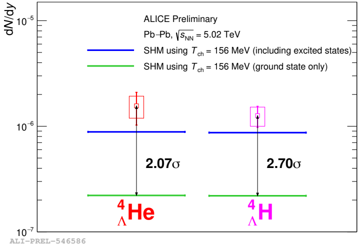


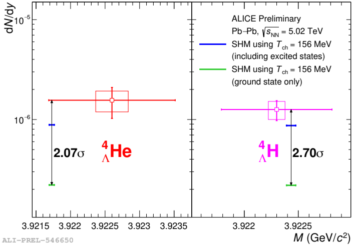


- First $^{4}_{\Lambda}$H & $^{4}_{\Lambda}$He in Pb-Pb at LHC

→ Results agree with hypothesis of excited states

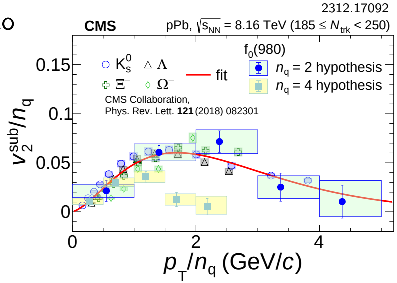
- Testing the dependence of the yields of the SHM with the spin-degeneracy

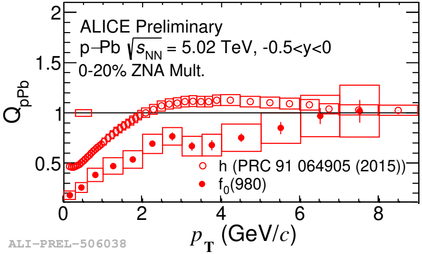




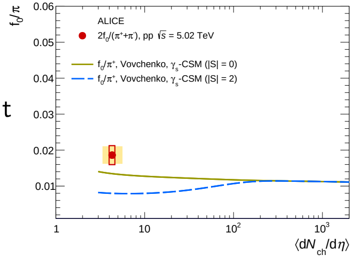
Exploring the resonance states: $f^0(980)$

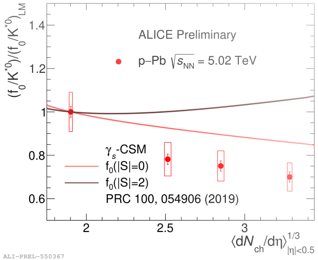
- Using HI-observables in p-Pb to determine quark substructure
  - v_2 scales with n-quarks
  - → Scale E_T with n_q
  - → consistent with 2 quark assumption
  - → 4-quark or KK molecule excluded with 7.7σ
  - → baryon excluded with 3.5σ
  - R_{pA} shows no cronin peak at low p_T
  - → Ordinary meson structure?





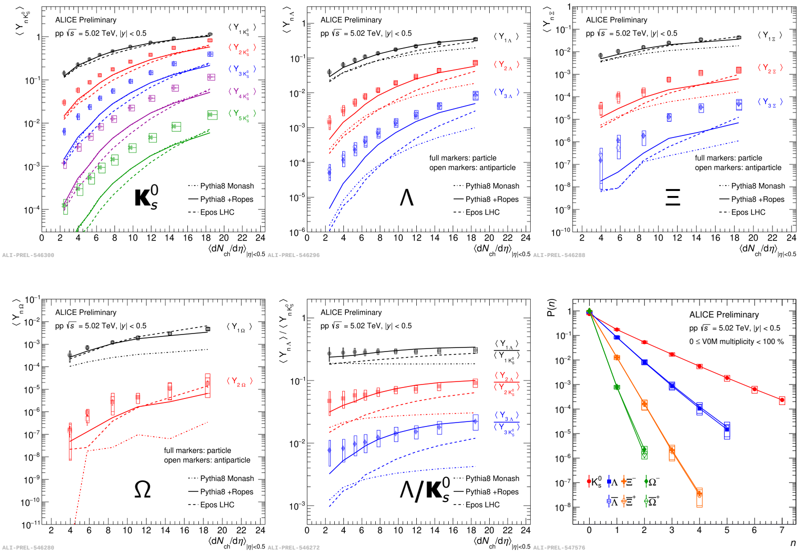
- CSM underestimate f^0/π in pp, consistent with $|S| = 0$
- f^0/K^{*0} indicates $|S| = 0$ based on CSM





Hadronization - Multi-strange particle production

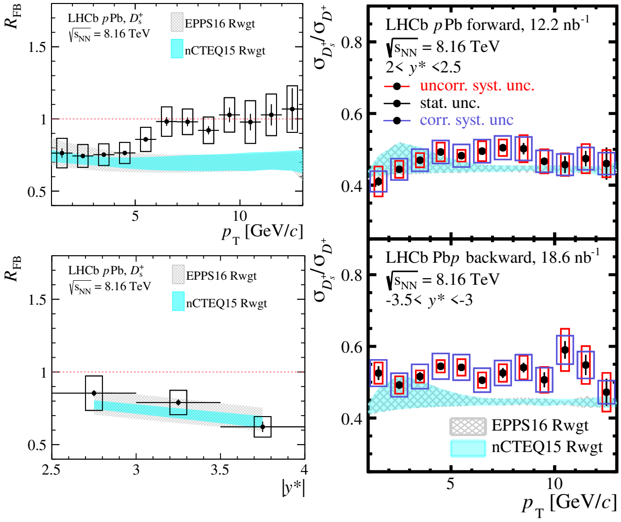
- Average yield increases stronger than linear increase vs. multiplicity for multiple strange hadrons, trend described by Pythia with ropes
- 1 strange meson/event described better than higher orders
- 2 & 3 Λ/K^0_s increase with multiplicity $\rightarrow$ baryon related effect



nPDFs vs. Hadronization: D_s^+ production in p-Pb

- D_s^+ x-section well reproduced in forward y
- Unexpected suppression in backward rap.
- R_{FB}:
  - → Suppressed at low p_T - consistent with nPDFs
  - → Increases at high p_T
- **nPDF calculations cannot describe forward/backward ratio for D_s^+**
  - → Final state effects?
  - → Hadronization modified?
- D_s^+/D^+ strong y-dependence, increased in backward region
  - → Increased coalescence contribution?
- **Strangeness enhancement in charm sector observed in p-Pb collisions**

2311.0849



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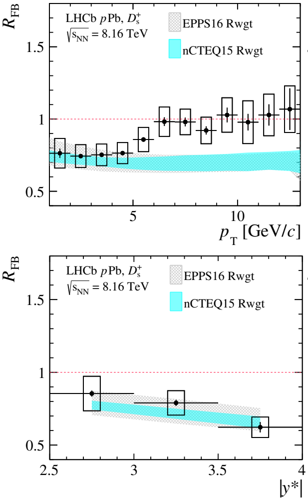
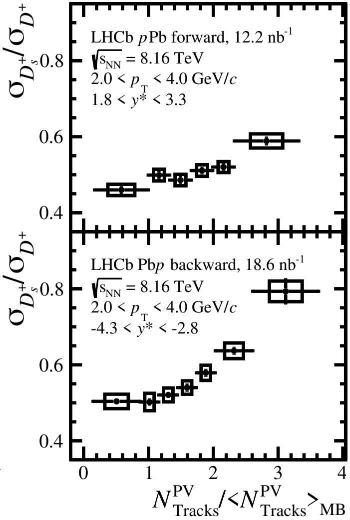
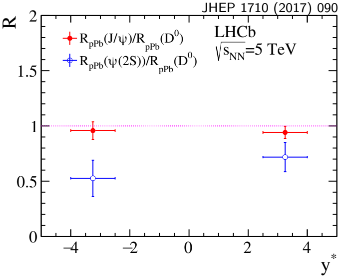




Testing FSE: Higher Charmonia production in p-Pb

- **Test melting vs comover breaking scenarios**
  - → Use R_{pA} ratios between mesons to cancel ISE
  - → J/Ψ suppression largely dominated by ISE
- Double ratio Ψ(2S)/J/Ψ: Ψ(2S) affected by FSE
  - → Only for prompt ratio affected not feeddown contribution
  - → Comover expectation most promissing explanation
- χ_c/J/Ψ no ISE
  - → consistent with pp at forward
  - → backward larger at low p_{T}, no final state effects
- $\Upsilon(3S)$ suppressed vs $\Upsilon(1S)$, slower & heavier than χ_c
  - → Comover breaking scenario?



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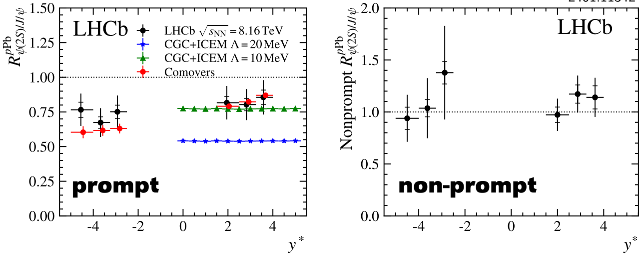
2401.11342



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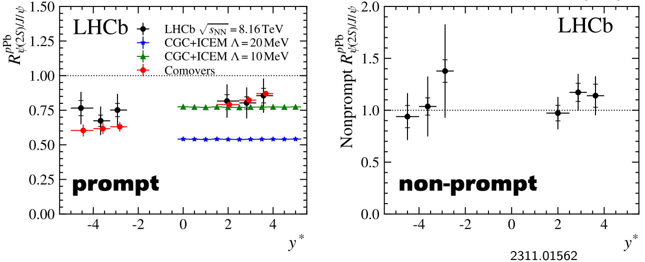

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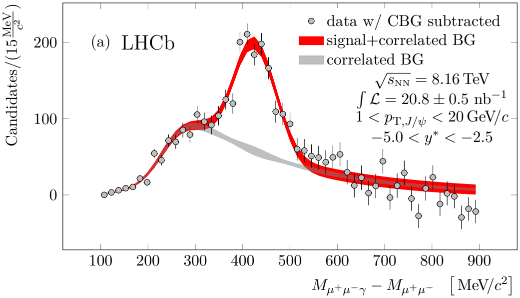

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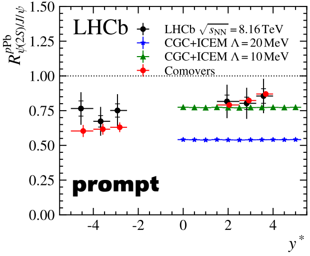

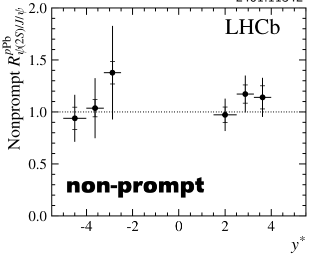

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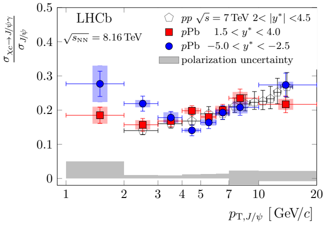
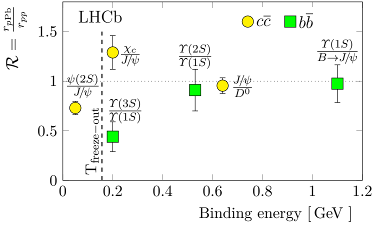
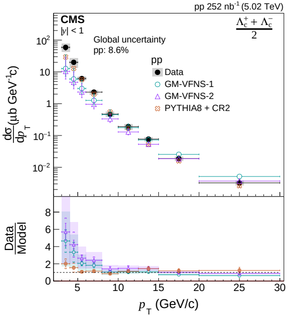




Hadronization: Λ_c production in p-Pb & Pb-Pb

Λ_C^+/D^0 pp

- Prompt Λ_c production not described using Belle FF, needs PYTHIA8 with ropes
- pp Λ_C^+/D^0 underpredicted by PYTHIA8, coalescence model or stat. had. model describes reasonably well



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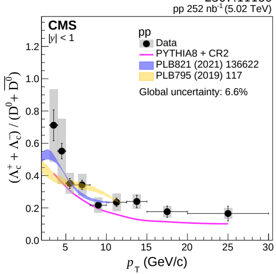

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Λ_C^+/D^0 Pb-Pb

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- c quark e-loss, follows other HF meas.
- pp and Pb-Pb consistent, recombination not really relevant?

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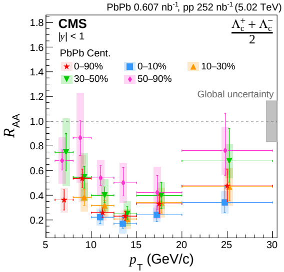

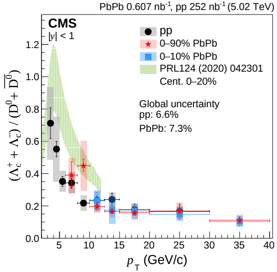

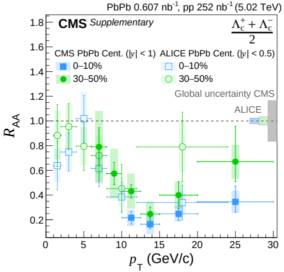

Hadronization: Λ_c production in p-Pb & Pb-Pb

OAK RIDGE
National Laboratory

Λ_C^+/D^0 pp

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- Prompt Λ_c Pb-Pb systematically suppressed in all centralities
- c quark e-loss, follows other HF meas.
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Λ_C^+/D^0 p-Pb

- Nearly no multiplicity dependence
- Coalescence process saturates early from quark-quark scattering with mult.?

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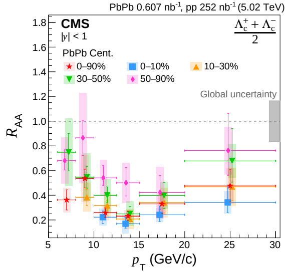

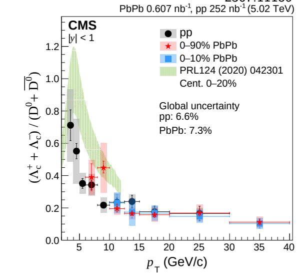

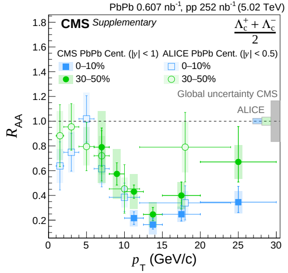

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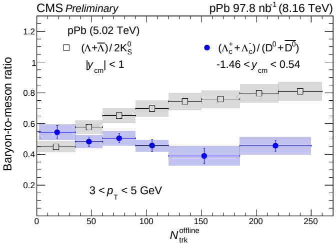

Hadronization: Charm fragmentation in pp & p-Pb

- 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?**

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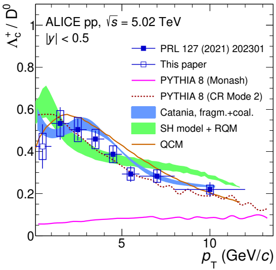

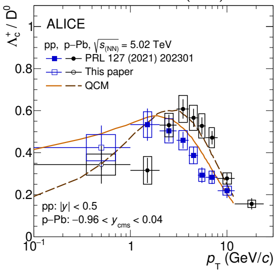

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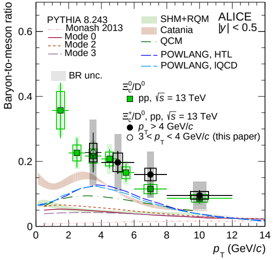

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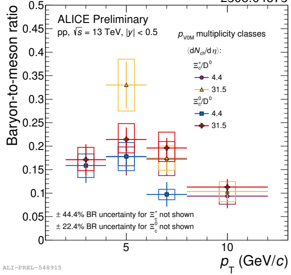

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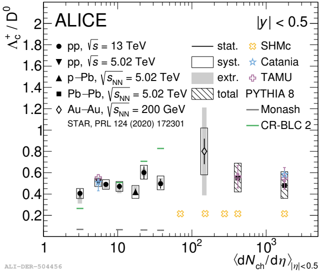

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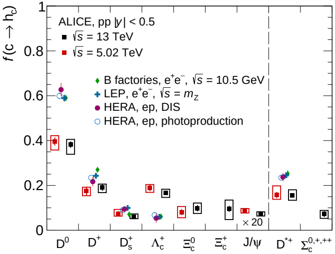
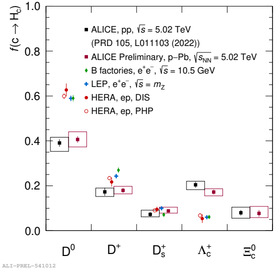
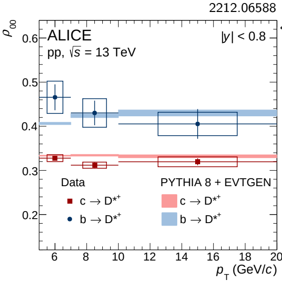
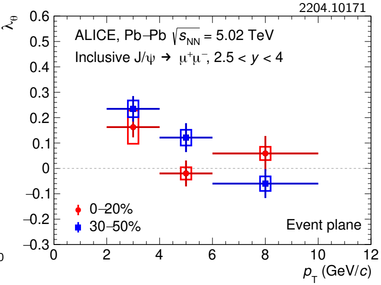


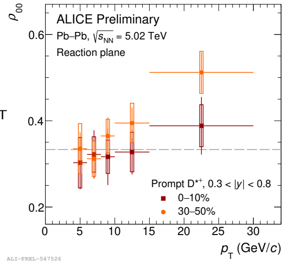


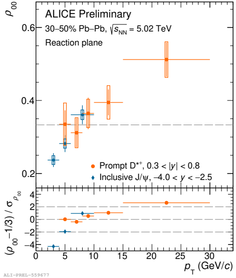
Hadronization: Polarization transfer

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









Hadronization - b-Hadron production in pp & p-Pb

B^+ p-Pb

- Constraining FONLL, unc. smaller
- Multiplicity dependence similar to other HF particle

Λ_b^0/B^0 pp

- Consistent with previous p-Pb measurements
- Data favor enhancement from so far unobserved excited b-baryon decays
- Lowest multiplicity bin similar to e^+e^-

→ Coalescence additional hadronization meachnism for higher mult. events

- High p_T value approaches e^+e^-

→ Dominance of fragmentation?

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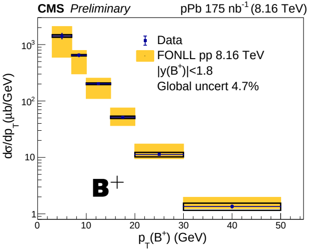

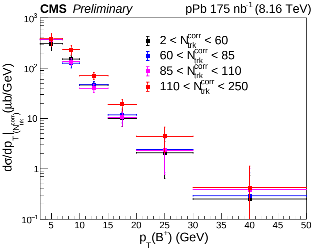

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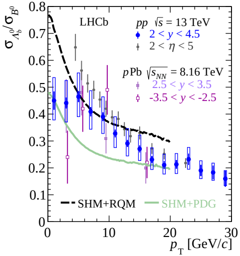
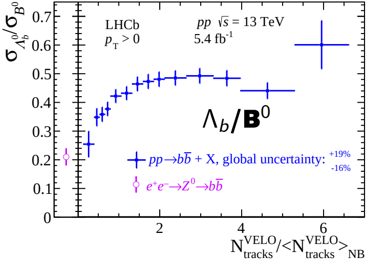
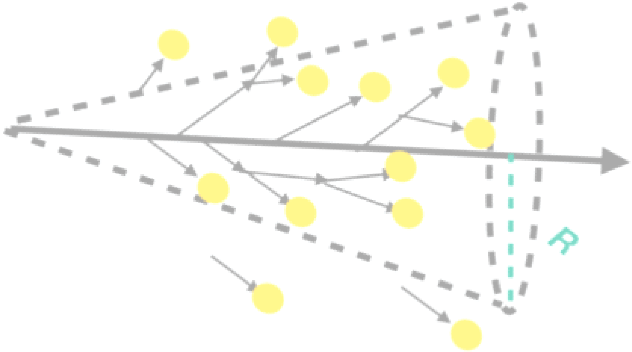
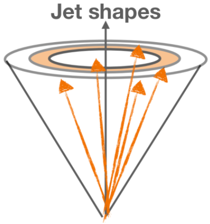


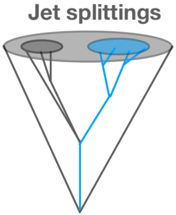


Understanding Quark Fragmentation!





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



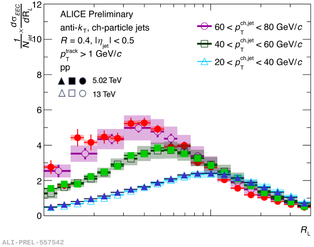
Focus on hard substructure (parton level)

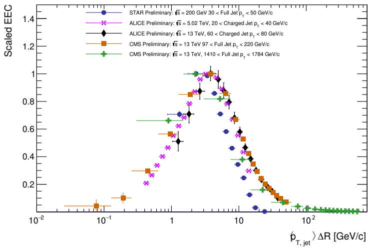
How does the fragmentation process work?

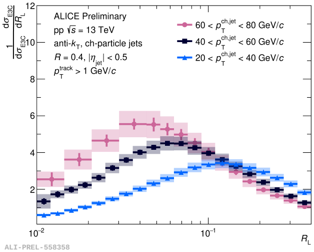
Is the fragmentation process modified in presence of a medium?

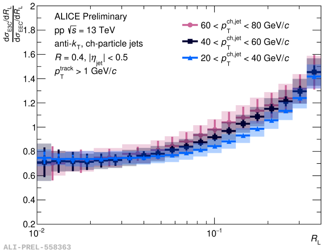
Understanding fragmentation: EECs

- 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

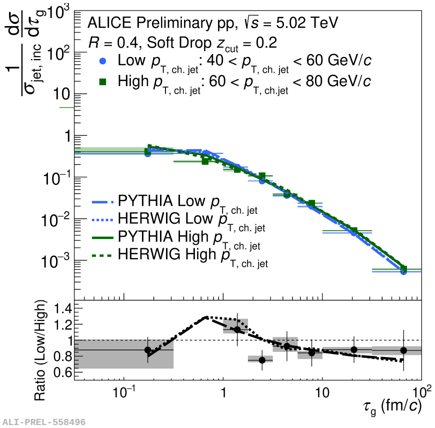


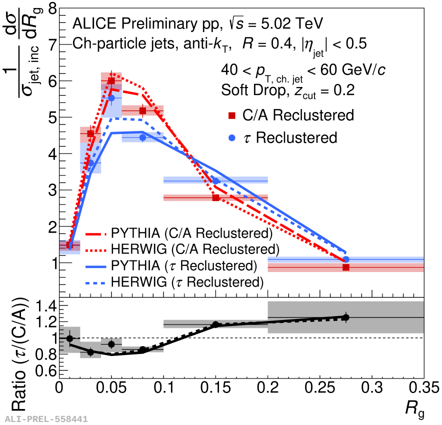






Understanding fragmentation: τ declustering



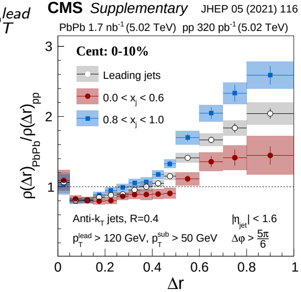


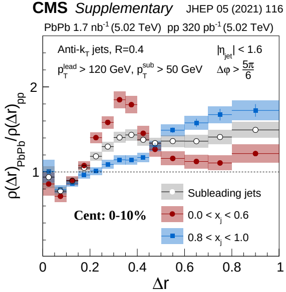
- Probe temporal structure of jet at boundary between parton shower & hadronization
- In Pb—Pb could be used to probe time structure of jet quenching
- No strong p_T dependence
- τ - declustering selects wider splittings in R_g

Understanding fragmentation: Jet substructure Pb-Pb

Jet shape $\rho(\Delta r)$ $x_j = p_T^{sub}/p_T^{lead}$

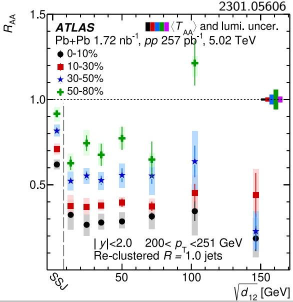
- Leading jets:
  - Modifications largest in balanced events ($0.8 < x_j < 1.0$)
- Sub-leading jets:
  - Enhancement of high-p_T particle outside jet cone
  - → 3^{rd} jet needed to produce imbalance
  - → Medium energy loss?
  - Unbalanced events most quenched, pp reference widened by 3^{rd} jet

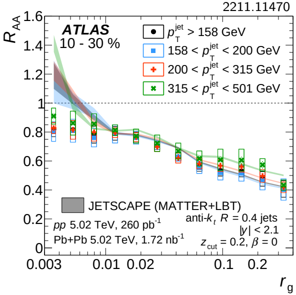




Subject distance & r_g

- $\sqrt{d_{12}}$, jets with multiple subjets (R=0.2) significantly suppressed (SSJ)
- Inclusive narrow jets less suppressed than wide jets (R_{AA} vs r_g/in r_g bins)
- Similar suppression independent of p_T at same r_g





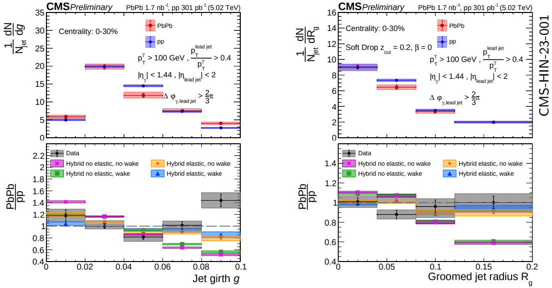
Separating quark & gluon jets in Pb-Pb

γ-jet grooomed radius

$x_{j,\gamma} = p_T^{jet} / p_T^{\gamma}$

- Predominantly quark jets, reduction of selection bias
- $x_{j\gamma} > 0.4$ no narrowing seen in Pb-Pb events with more jet quenching
- Large R_g suppression seen for inclusive jets not seen for photon tagged jets
- $x_{j\gamma} > 0.8$ narrowing seen when increasing selection bias

$x_{j,\gamma} > 0.4$ **[quenched & unquenched jets]**



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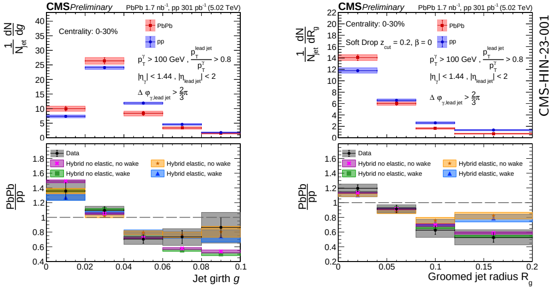

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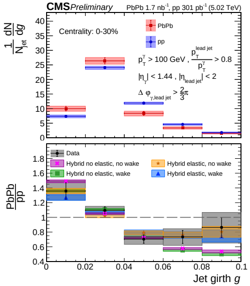
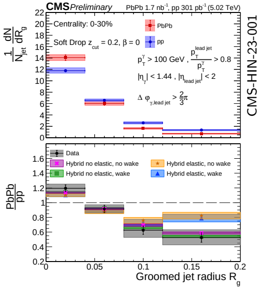
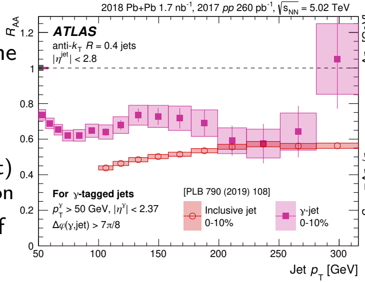
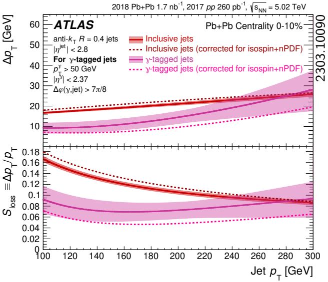




R_{AA} γ-tagged jets

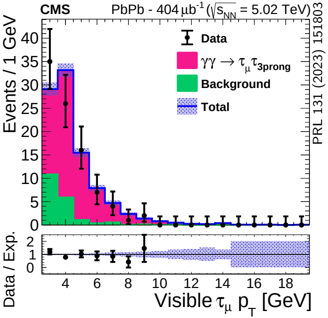
- γ-jets less suppressed than incl. jets in same centrality class
- Possible origins:
  - q vs g medium interactions
  - Different slope in pp (possible 10% effect)
  - Isospin + nPDF (10 %) opposite direction
- γ + multijet suggests greater suppresion of asymmetric pairs

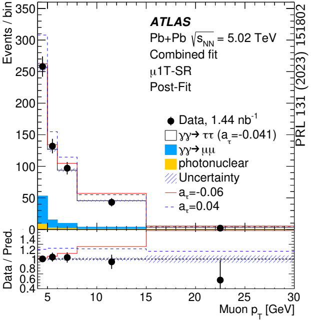


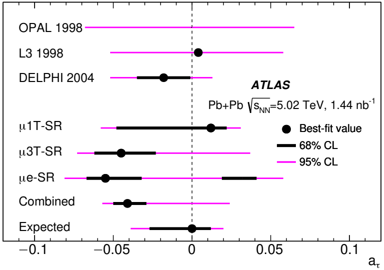


$\gamma\gamma \to \tau\tau$ in Pb-Pb & pp

- **Search for anomalous magnetic moment & physics beyond the standard model**
- CMS use of single channel $\mathbf{a}_\tau = \mathbf{0.001}^{+0.055}_{-0.089}$ 68% CL
- ATLAS use all channels to reconstruct τ combined $\mathbf{a}_\tau \in (-\mathbf{0.057}, \mathbf{0.024})$ 95% CL
- **New:** CMS pp $\sqrt{s} = 13$ TeV measurement with even better precision







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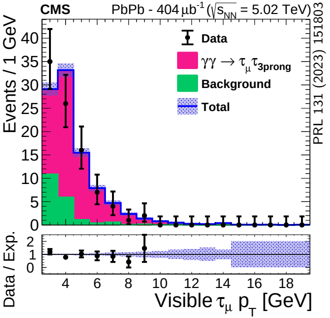

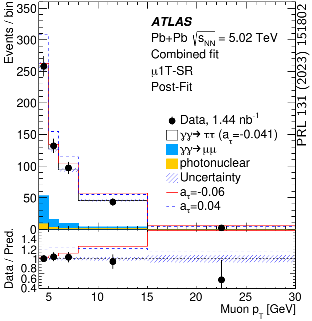

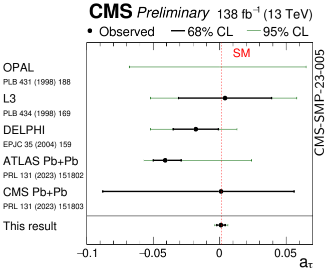

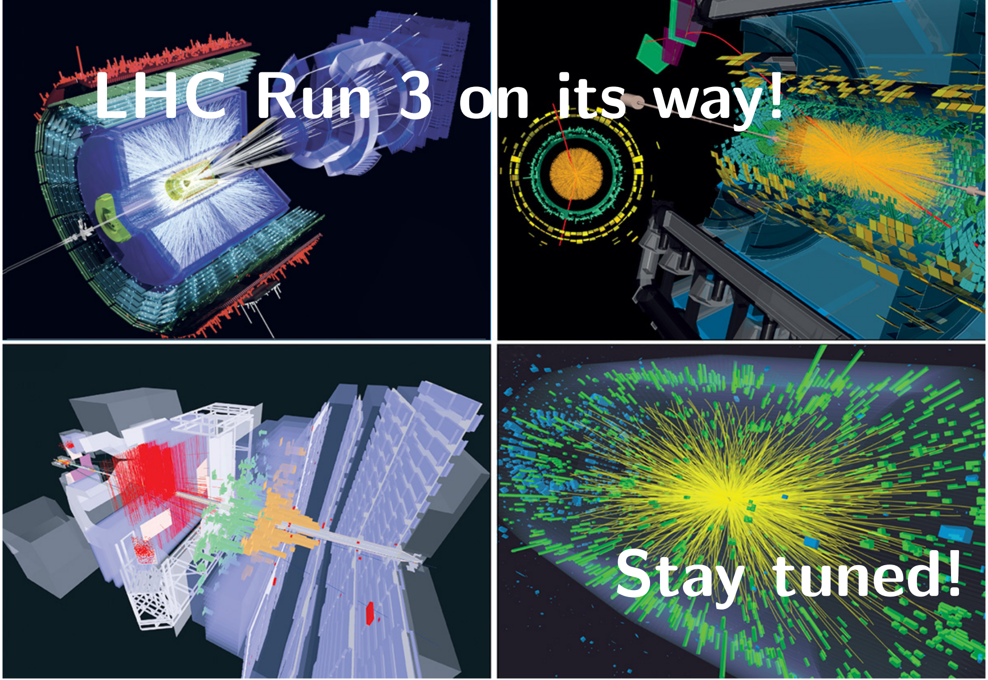
LHC Run 3 on its way!
Stay tuned!