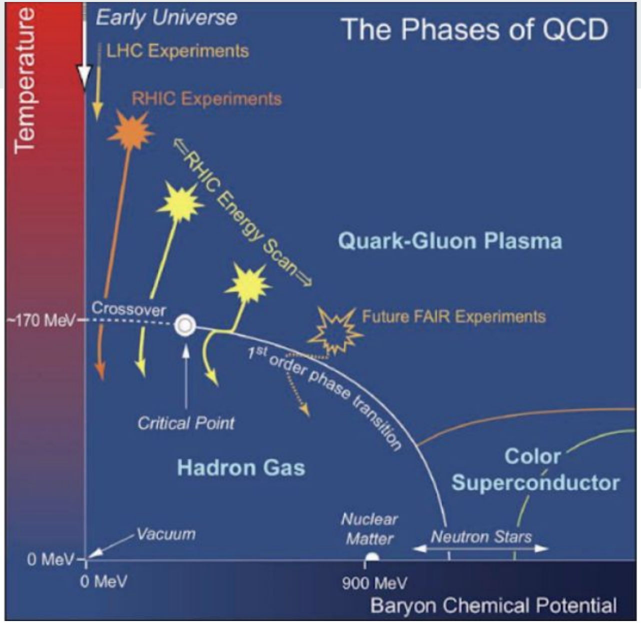
Overview of heavy-ion results at LHC

Catalin Ristea
Institute of Space Science, RO

Heavy ion collisions and QGP

- QCD predicts at high temperature/density the quark-gluon plasma (QGP): a deconfined system of quarks and gluons
- QGP might have existed in the expanding Universe in the first μs after the Big Bang
  - **Achieved in the laboratory by colliding heavy ions**



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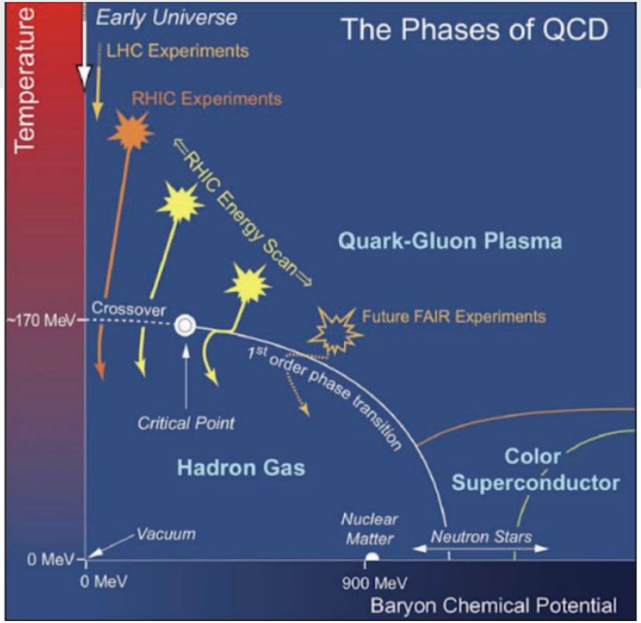
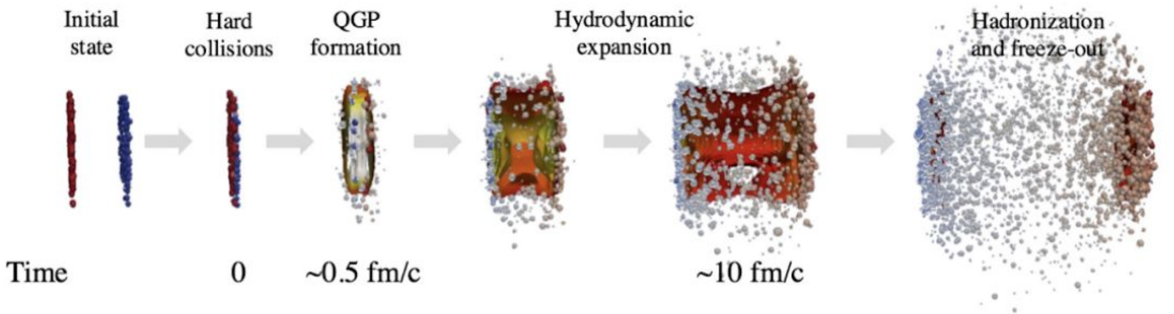
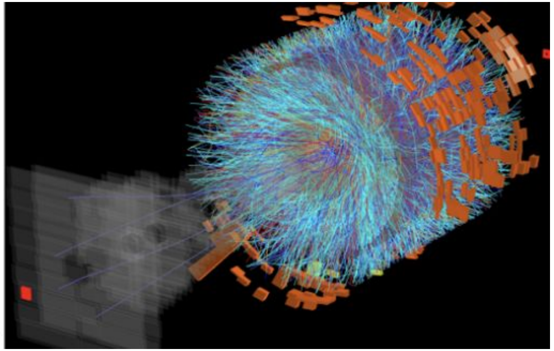
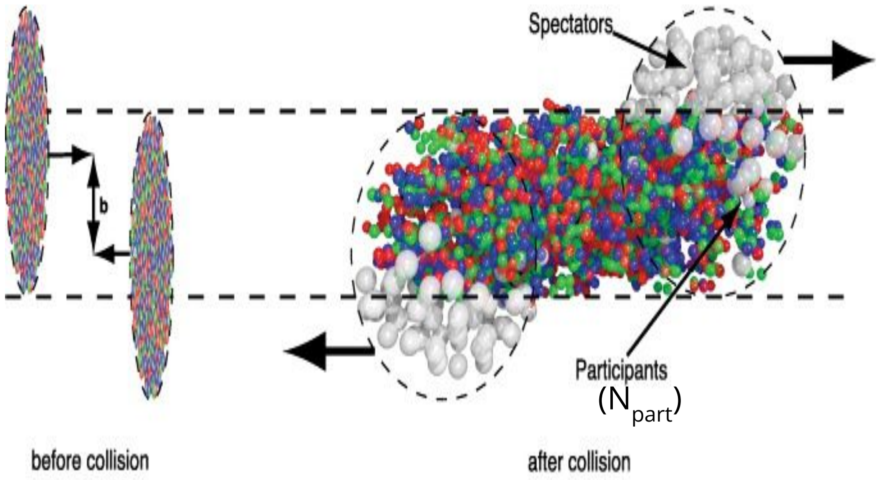




Visualization by J.E. Bernhard, arXiv:1804.06469



Collision system → centrality



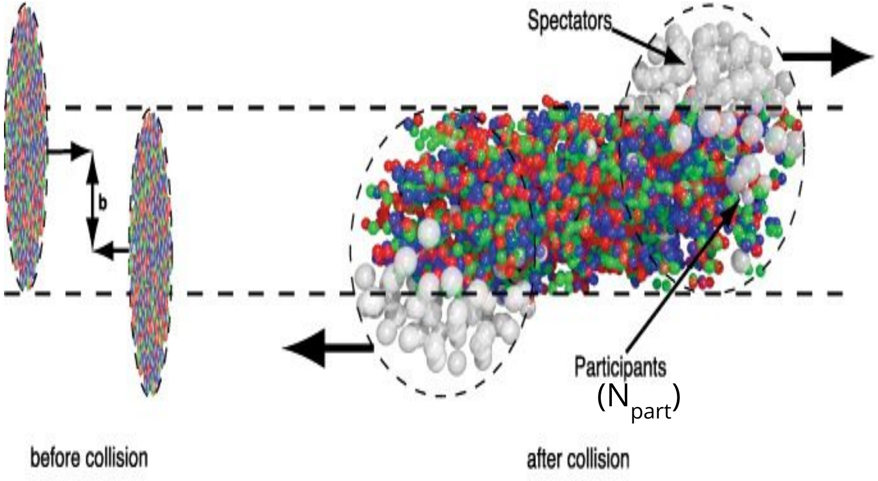
Impact parameter b

Perpendicular to beam direction

Connects centers of colliding nuclei

Not measured directly → estimated by centrality

Collision system → centrality



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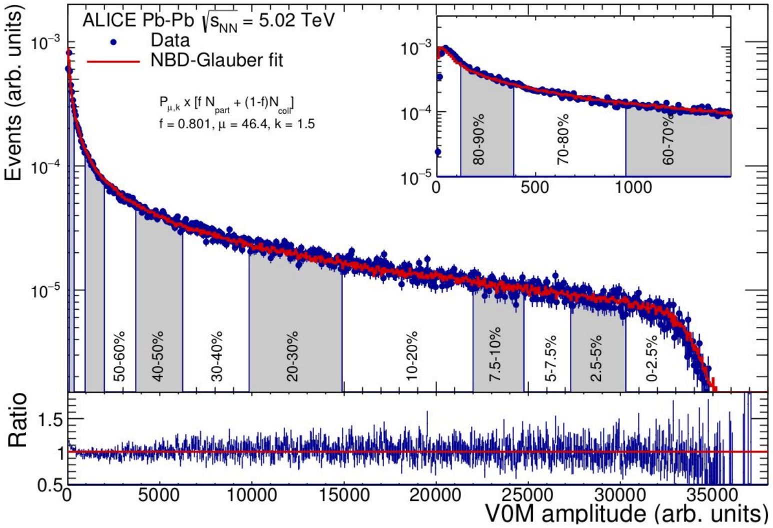
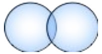
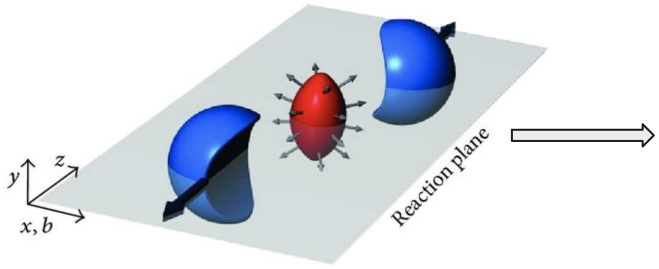


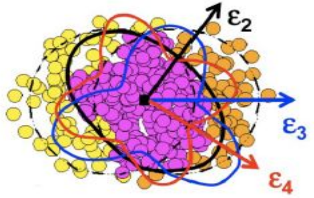
Centrality

Determined from *particle multiplicities*

- Most central: 0-5% centrality 
- Peripheral: 70-80% centrality 

Anisotropic flow

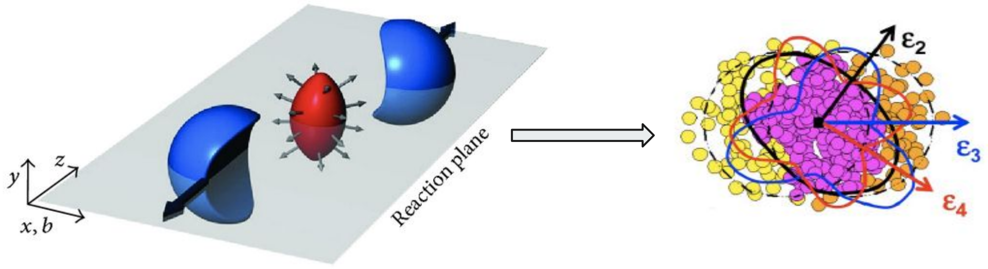


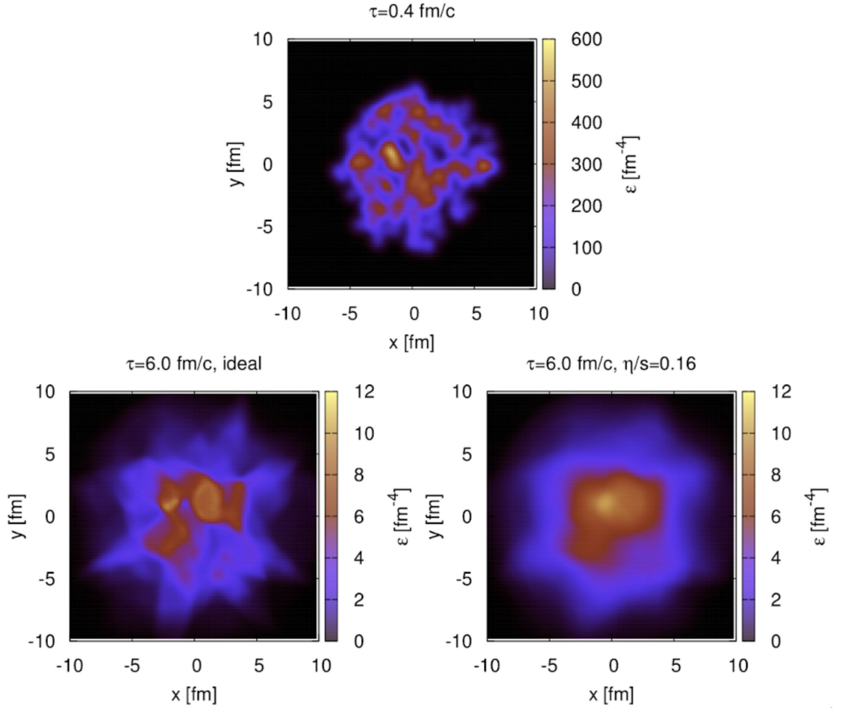


Anisotropic flow: the transfer of initial spatial anisotropy into the final anisotropy in momentum space via collective interactions

$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\phi-\Psi_n)]\right)$$

Anisotropic flow





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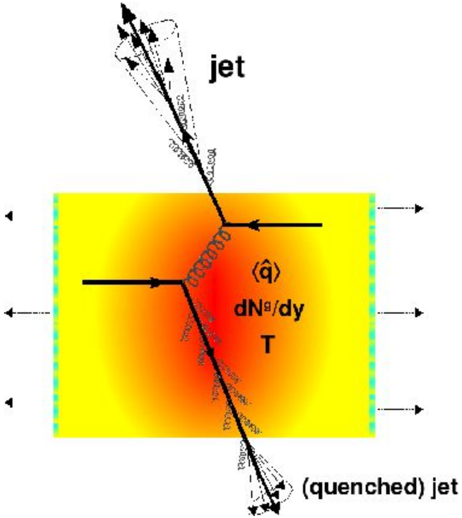
Sensitive to the system evolution

- Constrain initial conditions, equation-of-state (EOS), transport properties
- Stronger constraints are obtained from measurements of identified particles

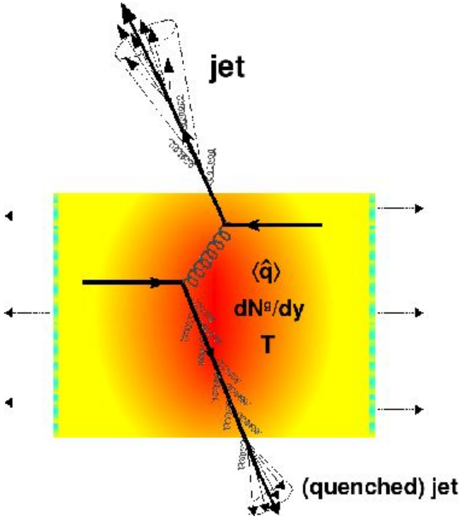
Jet quenching and nuclear modification factor - R_{AA}

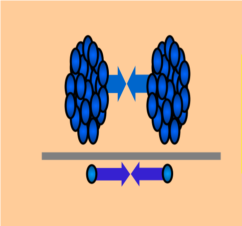


- Jet: high-p_T parton (quark, gluon) produced at early stage of the collision
- Jet: a collimated spray of particles produced by a high-p_T parton
- Informs about the medium properties due to parton energy loss (jet quenching)

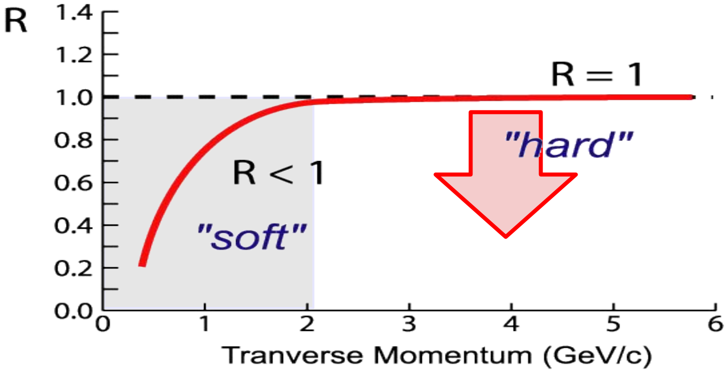
$$\Delta E_{\text{gluon}} > \Delta E_{\text{light quarks}} > \Delta E_{\text{heavy quarks}}$$

Jet quenching and nuclear modification factor - R_{AA}





$$R_{AA} = \frac{d^2N^{AA}/dp_T dy}{\langle N_{bin}\rangle d^2N^{NN}/dp_T dy}$$



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$$\Delta E_{gluon} > \Delta E_{light\ quarks} > \Delta E_{heavy\ quarks}$$

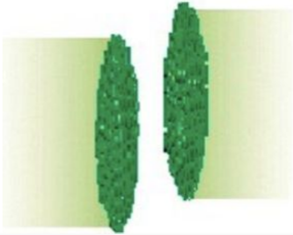
R_{AA} < 1 at high p_T – nuclear effects suppress the particle production

R_{AA} ~ 1 at high p_T (binary scaling) – no nuclear effects

Collision systems

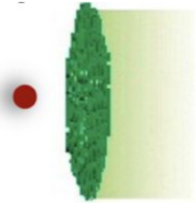
RUN I 2009-2013	LS1	RUN 2 2015-2018	LS2	RUN 3 2022-2025	LS3	RUN 4 2029-2032
pp, p-Pb, Pb-Pb		pp, p-Pb Xe-Xe, Pb-Pb		pp, p-O, O-O p-Pb, Pb-Pb		pp, p-Pb, Pb-Pb

A-A



"*hot/dense QCD matter*"
final state effects
thermal and collective particle production (flow)

p-A



"*cold nuclear matter*"
initial state effects
shadowing and gluon saturation

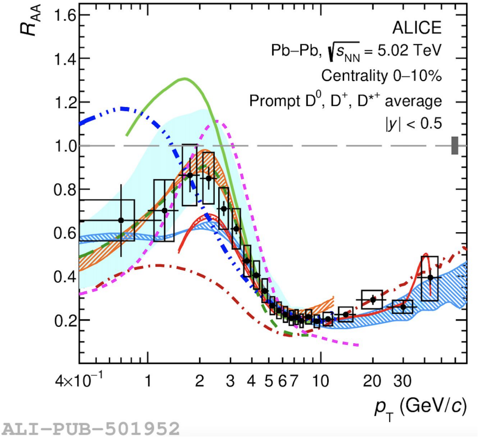
pp

"*vacuum*"
reference

Exciting physics also in
high multiplicity pp and p-A collisions

Open charm - prompt D⁰ meson

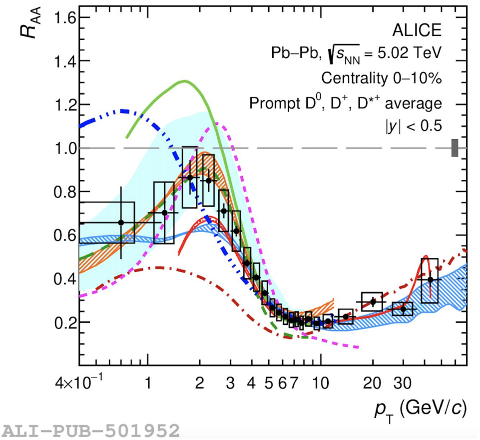
ALICE, JHEP 01 (2022) 174



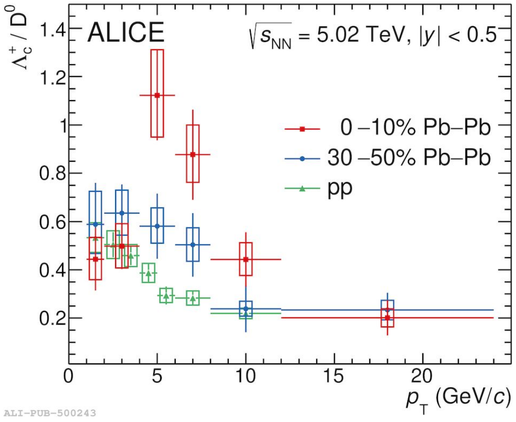
- Precise D meson measurements down to low p_T

Open charm - prompt D^0 meson

ALICE, JHEP 01 (2022) 174



ALICE, arXiv:2112.08156



- Precise D meson measurements down to low p_T
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Open charm - prompt D^0 meson

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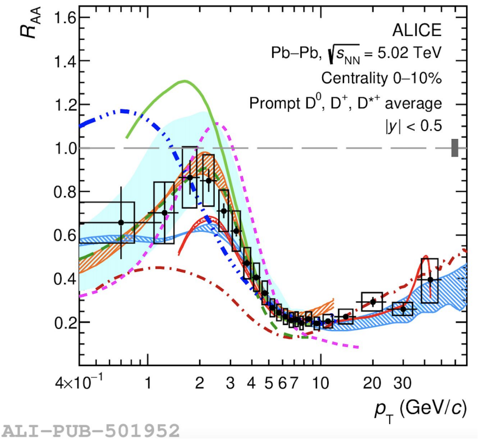

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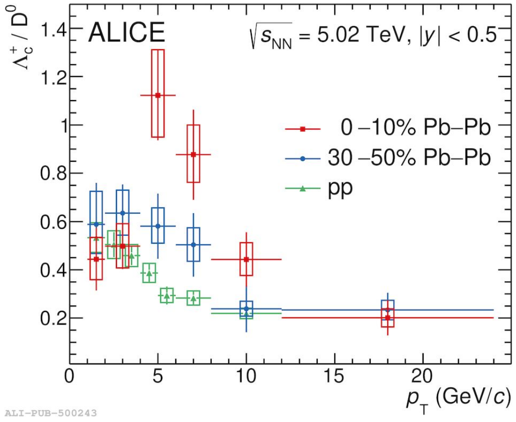
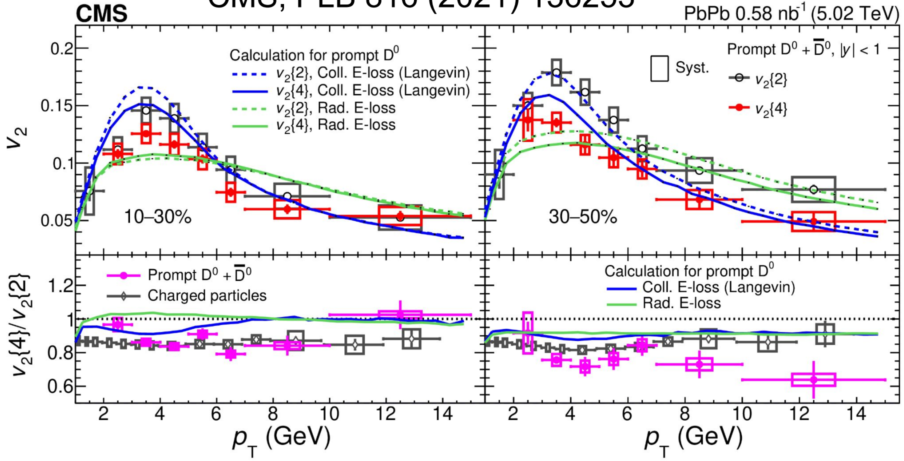


CMS, PRL 129 (2022) 022001
CMS, PLB 816 (2021) 136253

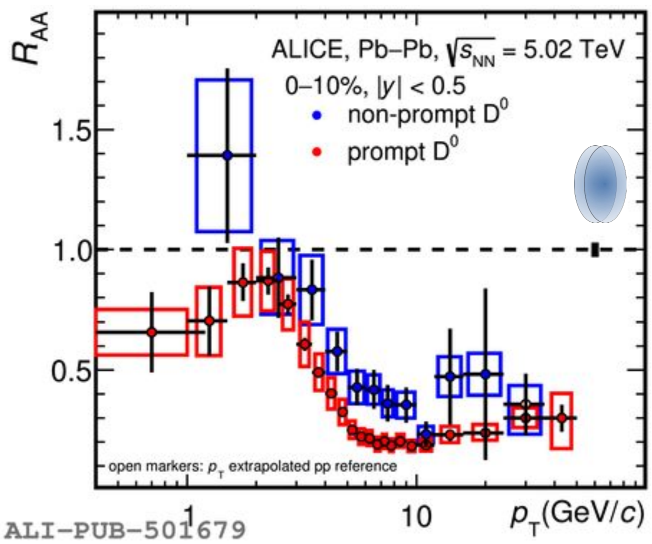


M. Nguyen, Tue 11:00

- Precise D meson measurements down to low p_T
- Additional constraints from Λ_c measurements
  - Suggests hadronization by recombination + mass-dependent p_T shift from collective expansion
- The elliptic flow of prompt D^0 has similar pattern to that of charged hadrons
  → D mesons acquire additional flow via c and light quark recombination
- **Charm production suppressed in heavy-ion collisions and charm quark flows**

Prompt D⁰ vs b →D⁰

ALICE, arXiv:2202.00815



- Energy loss predicted to depend on QGP density, but also on quark mass
  - "Dead cone" effect reduces small-angle gluon radiation for high-mass quarks
- Less suppression for (non-prompt) D^0 mesons from B decays than prompt D^0 mesons

$R_{AA}(b) > R_{AA}(c) \Rightarrow dE(b) < dE(c)$

Prompt D⁰ vs b →D⁰

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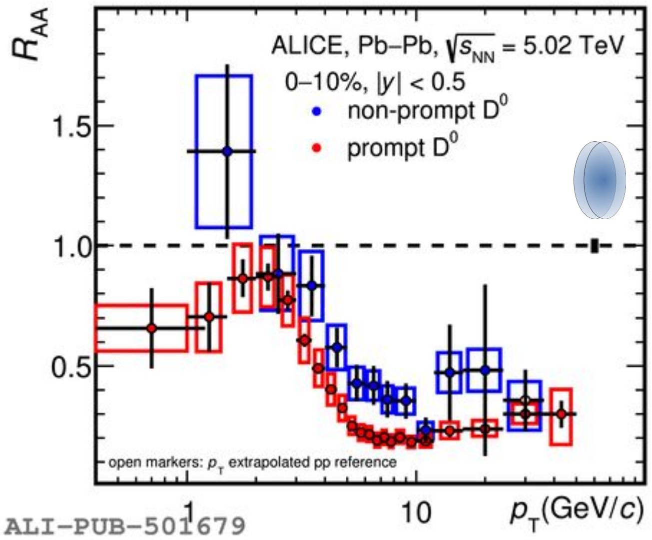
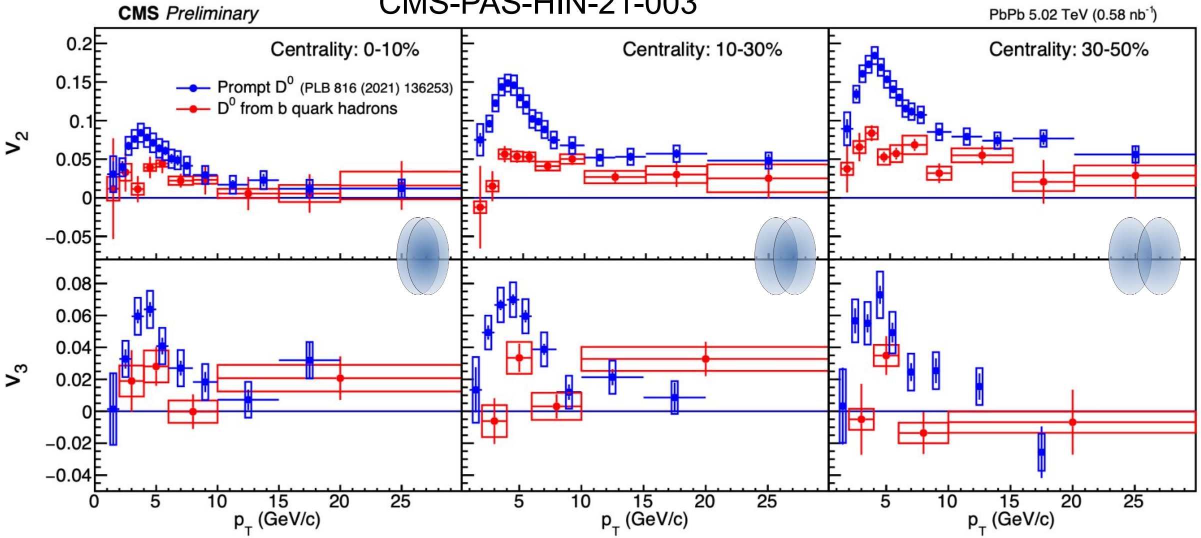


CMS-PAS-HIN-21-003



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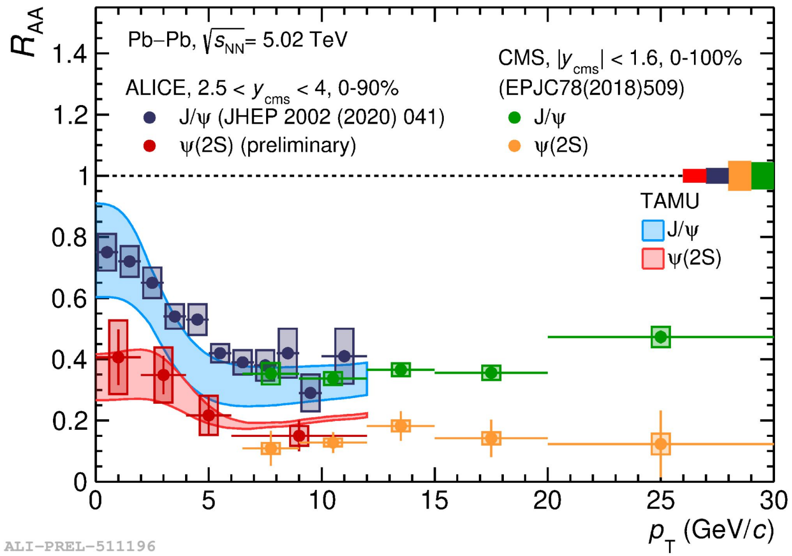
$R_{AA}(b) > R_{AA}(c) \Rightarrow dE(b) < dE(c)$

- Non-zero v_2 observed → b-quarks partially thermalise in the medium or recombine with light quarks
- Significant non-zero v_3 for b D^0 for all centrality bins → b hadron collectivity is sensitive to fluctuation of initial geometry

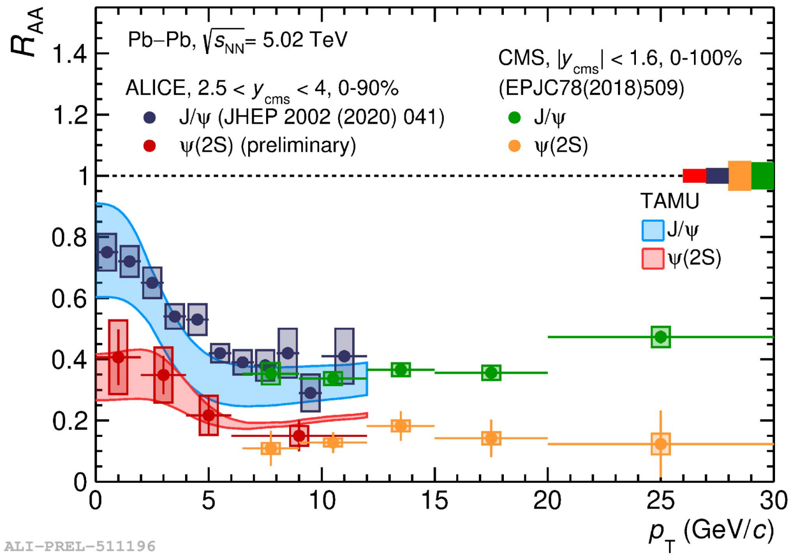
J/ψ and ψ(2S)



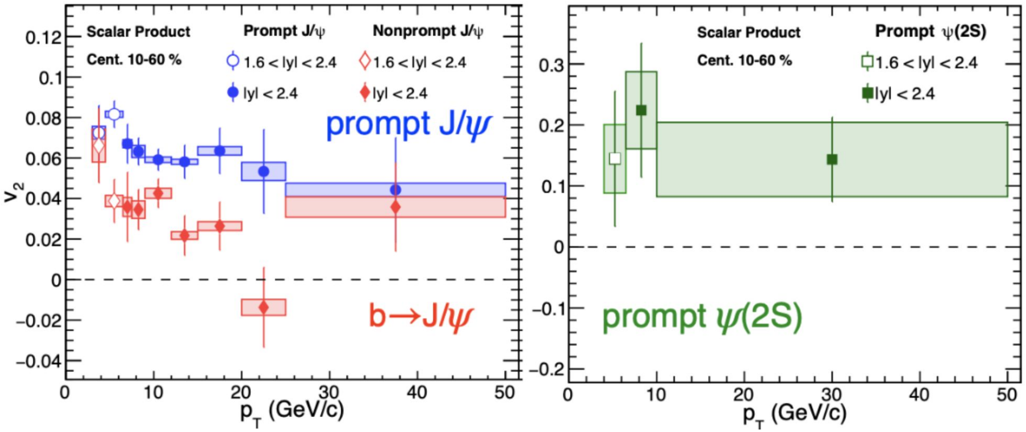
Inclusive J/Ψ, Ψ(2S)

- Stronger suppression at high-p_T and increasing trend of R_{AA} towards low-p_T for both charmonium states → hint of regeneration
- Good agreement between CMS and ALICE in the common p_T range

J/ψ and ψ(2S)



CMS-PAS-HIN-21-008



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Prompt J/Ψ

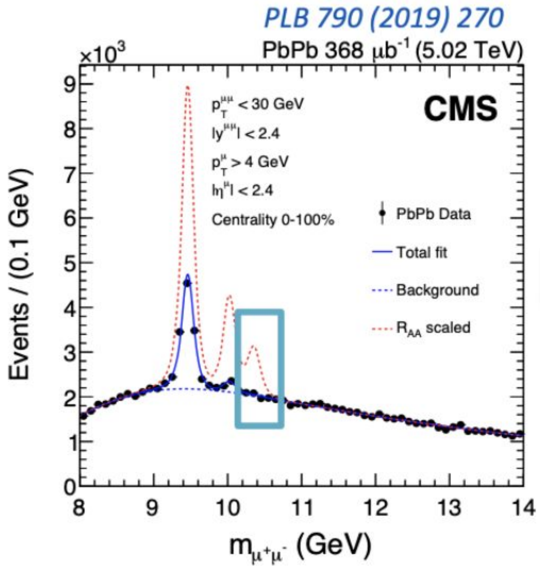
- Significant v_2 up to high-p_T
- b→J/Ψ has lower v_2 and decreases faster

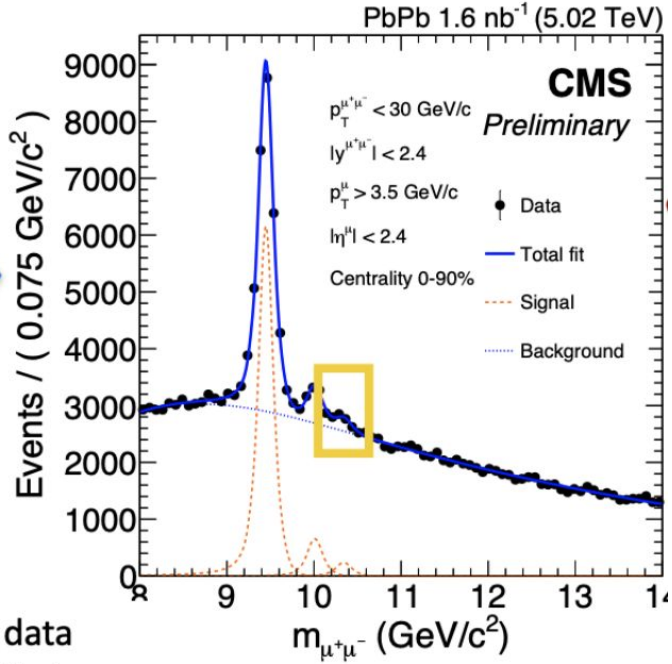
Ψ(2S) $v_2 \gtrsim 0.1$ > J/Ψ v_2

- Hint of different regeneration contribution for ground and excited states

Phys. Rev. C 95 (2017) 034908

Υ(3S), first time observation





2015 data: **370 μb-1**,
No clear Υ(3S) peak

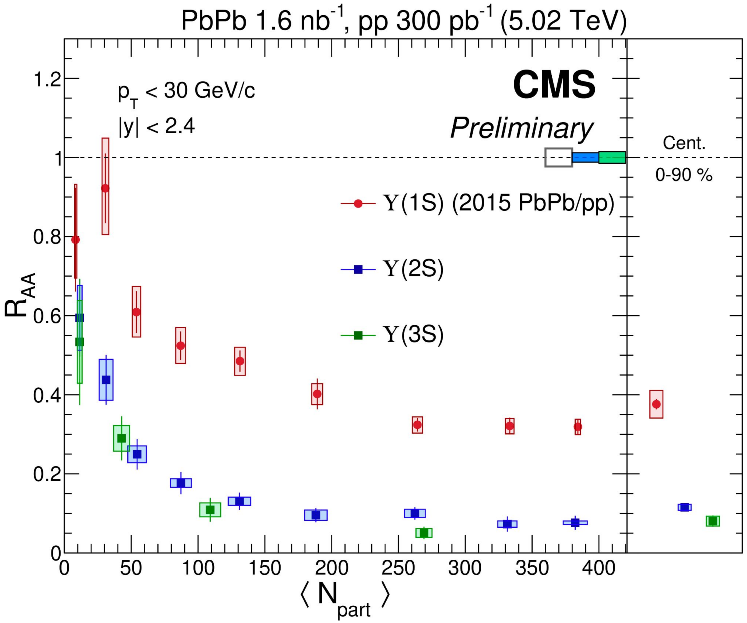
x4.3 more data
& BDT applied

2018 data: 1600 μb-1,
Significance above 5σ

High statistic data is really important

Y(nS) measurements

CMS-PAS-HIN-21-007



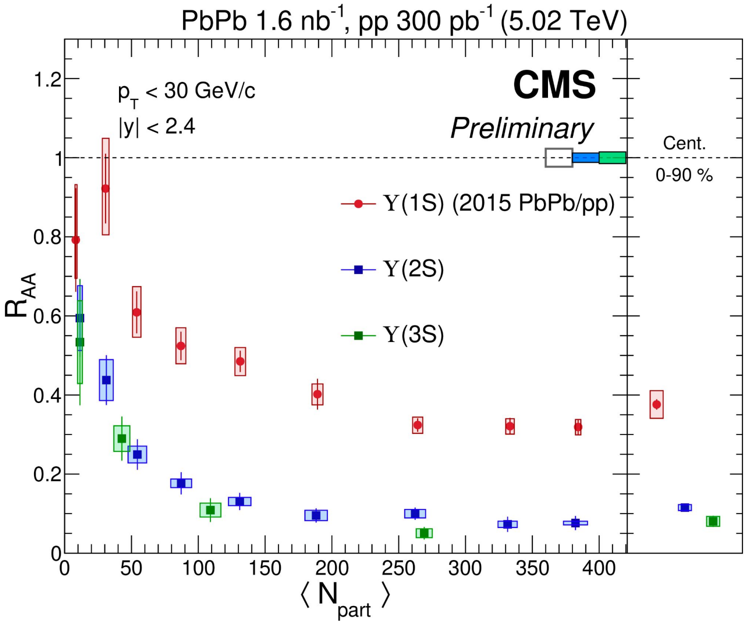
Υ(1S) R_{AA} >> Υ(2S) R_{AA} ≳ Υ(3S) R_{AA}

Sequential melting of Υ(ns) states

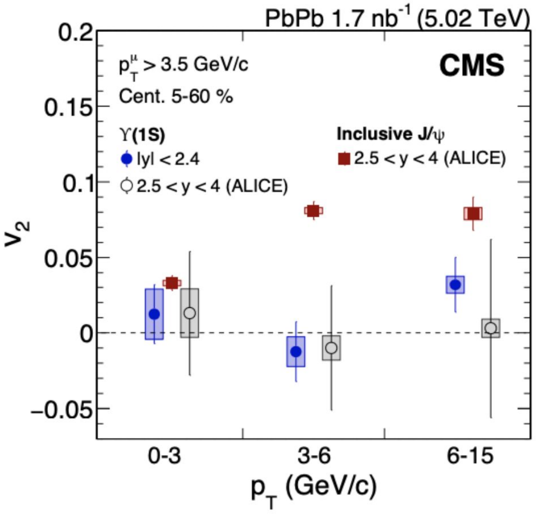
See also ATLAS: arXiv:2205.03042

Y(nS) measurements

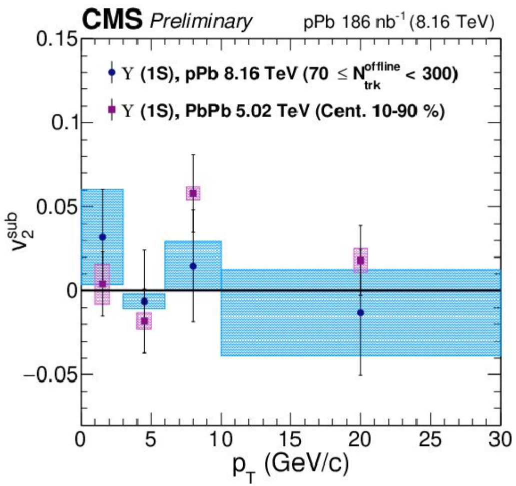
CMS-PAS-HIN-21-007



CMS, PLB 819 (2021) 136385



CMS-PAS-HIN-21-001



Υ(1S) R_{AA} >> Υ(2S) R_{AA} ≳ Υ(3S) R_{AA}

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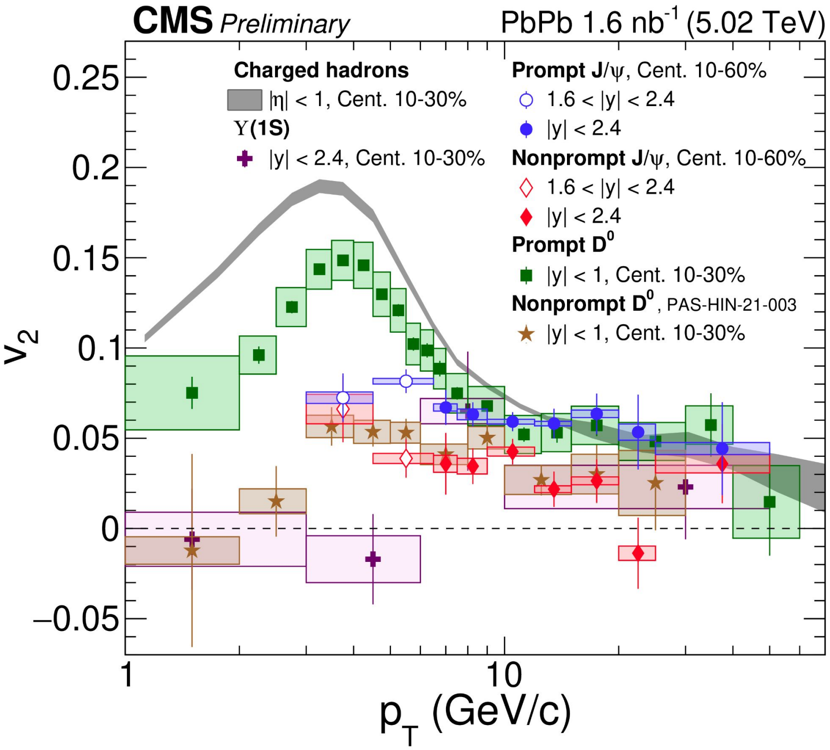
0 ~ Υ(1S) $v_2^{\text{HM p-Pb}}$ ~ Υ(1S) $v_2^{\text{Pb-Pb}}$ < J/Ψ v_2

Υ's strong binding make itself less sensitive to initial geometry

I. Yeletskikh, Thu 9:50

Summary: heavy-flavor elliptic flow

CMS-PAS-HIN-21-008



- Comprehensive picture of elliptic flow in Pb-Pb collisions
- Low p_T: step increase following mass hierarchy hydrodynamic regime

light quarks > charm > beauty

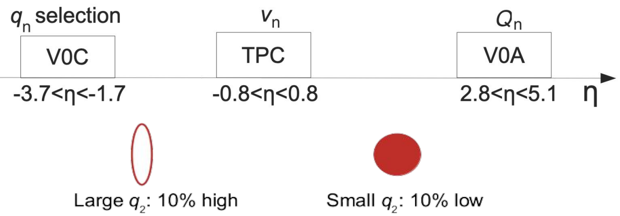
- Maximum v_2 reached at $3 < p_T < 6$ GeV/c:

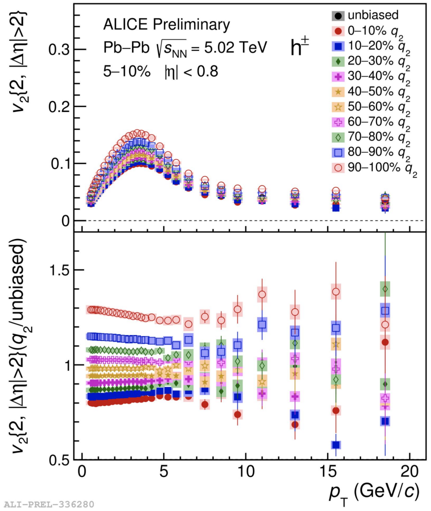
light quarks ≳ prompt D^0 > prompt J/Ψ > b→hadrons
→ coalescence of heavy quarks with light quarks at play

- High p_T: convergence toward non-zero v_2

Event shape engineering

Select events with similar centralities and different shapes based on the event-by-event flow/eccentricity fluctuations





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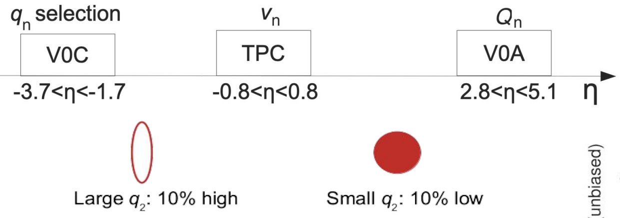
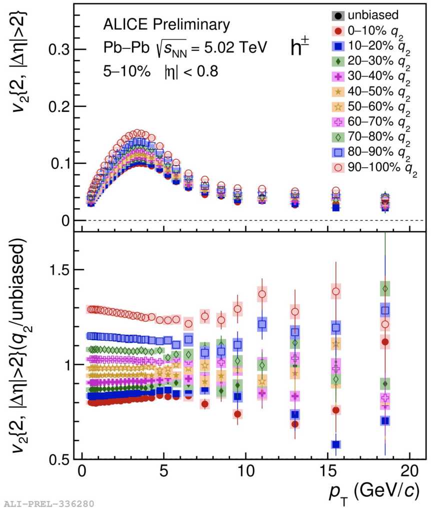
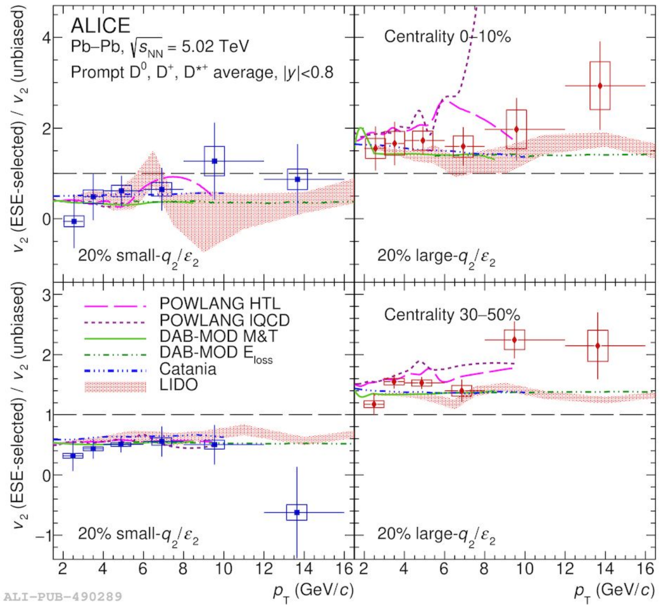


ALICE, PLB 813 (2021) 136054





D mesons are sensitive to the light-hadron bulk collectivity and event-by-event fluctuations in the initial stage

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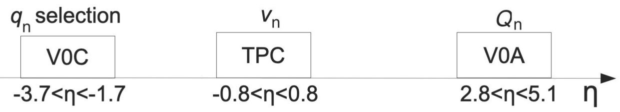
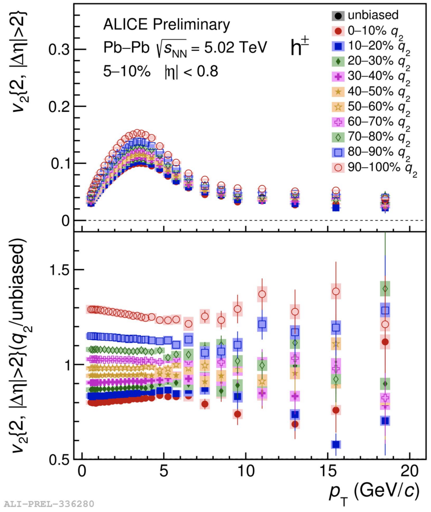
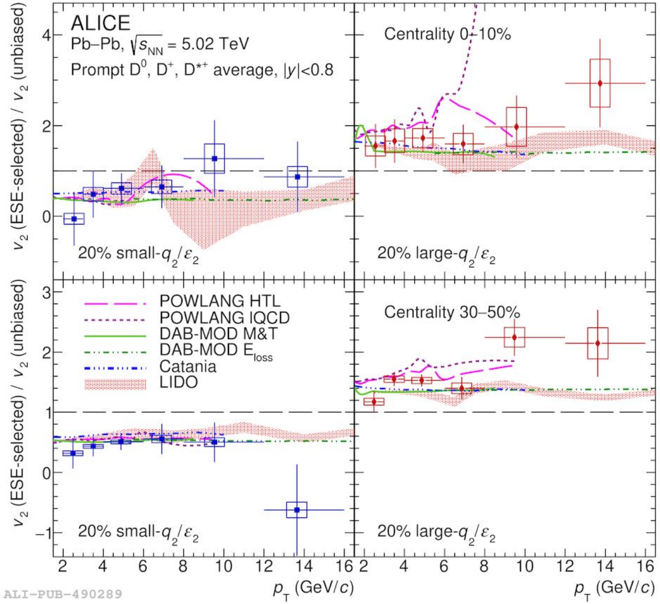


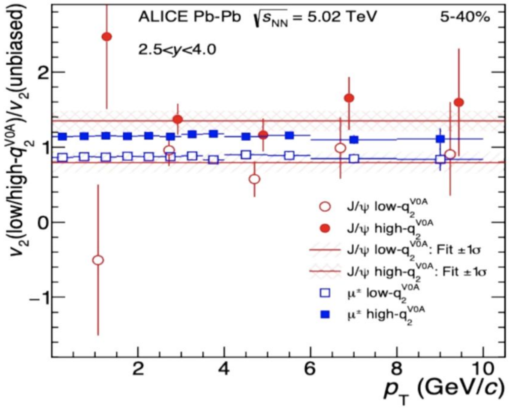
Large q_2: 10% high   Small q_2: 10% low

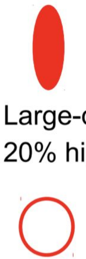


ALICE, PLB 813 (2021) 136054



ALICE, JHEP 02 (2019) 012





Large-q_2: 20% high

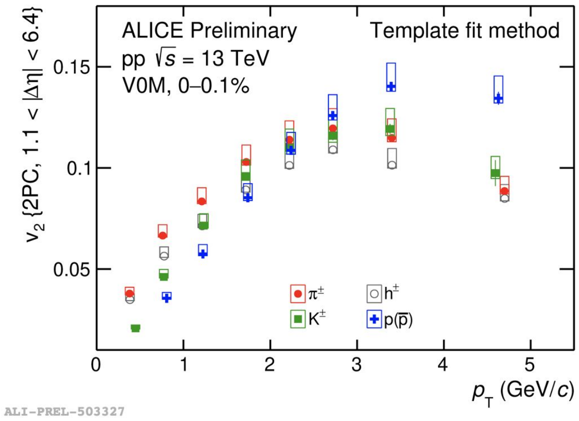
Small-q_2: 20% low

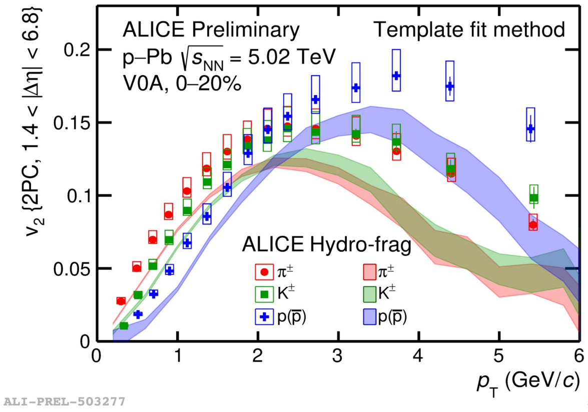
D mesons are sensitive to the light-hadron bulk collectivity and event-by-event fluctuations in the initial stage

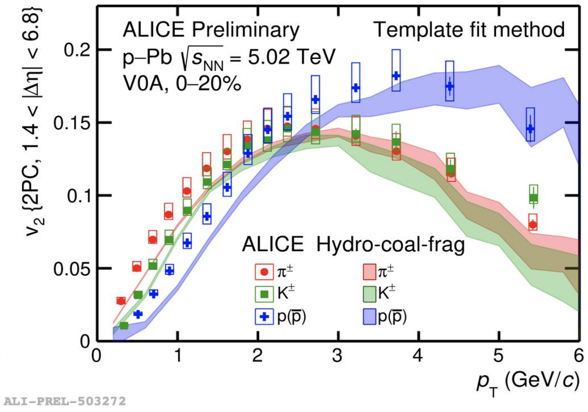
Ratio (ESE/unbiased) of J/Ψ v_2 consistent with those of single muons within uncertainties

→ J/Ψ v_2 compatible with the expected variations of the initial geometry

Elliptic flow in small systems







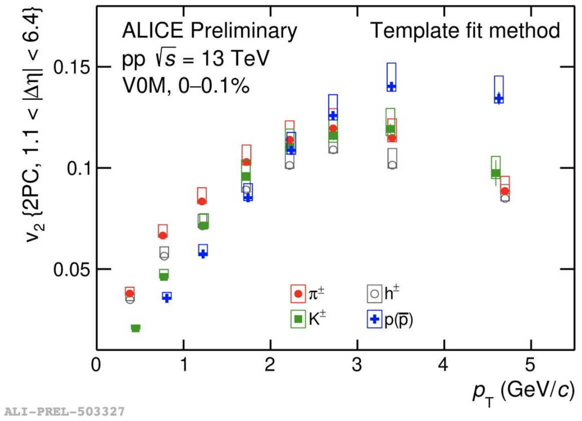
Light flavors: p-Pb model comparison indicates partonic flow + coalescence

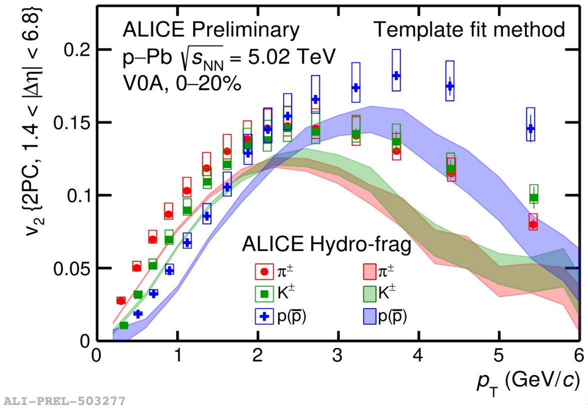
→ baryon - meson splitting in both pp and p-Pb

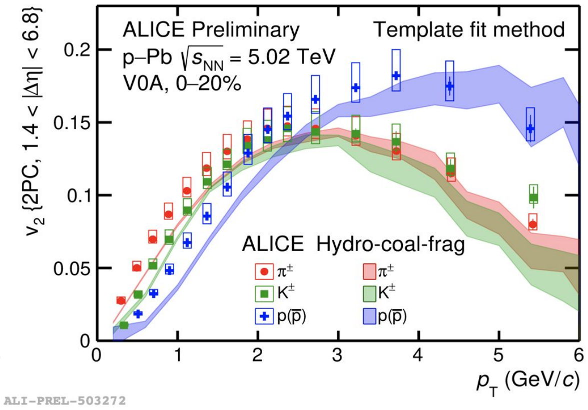
→ quark-level flow + recombination in high-multiplicity p-Pb (and pp)

S. Bufalino, Tue 10:15

Elliptic flow in small systems





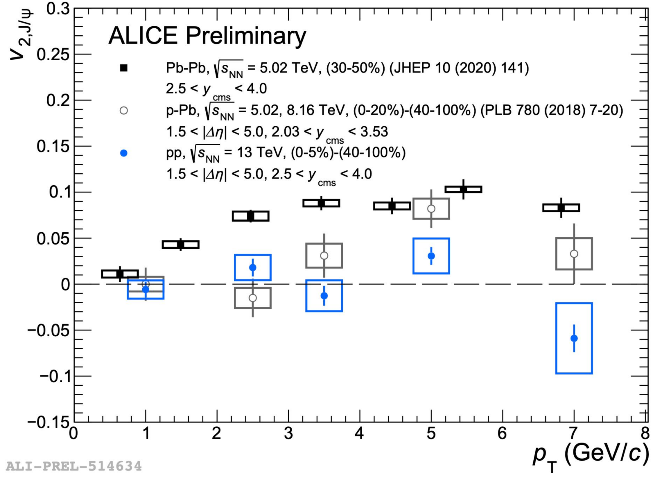


Light flavors: p-Pb model comparison indicates partonic flow + coalescence

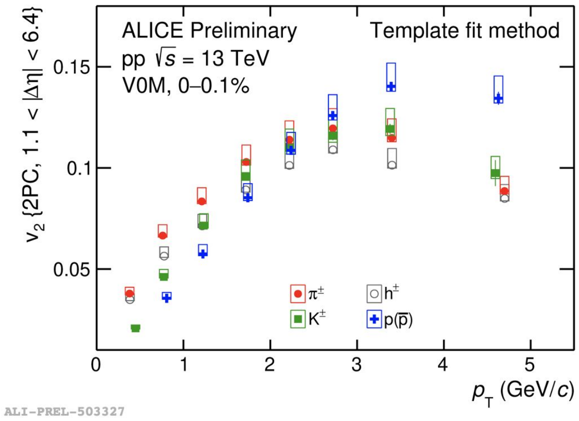
→ baryon - meson splitting in both pp and p-Pb

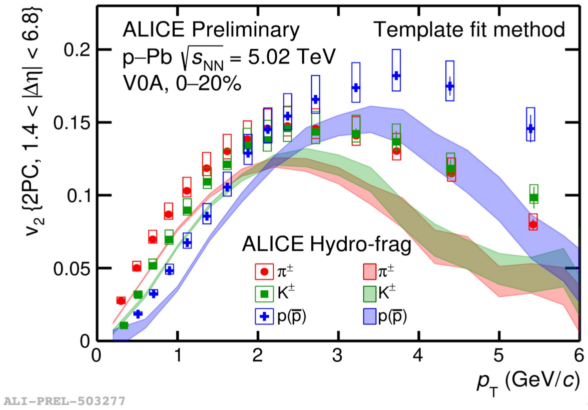
→ quark-level flow + recombination in high-multiplicity p-Pb (and pp)

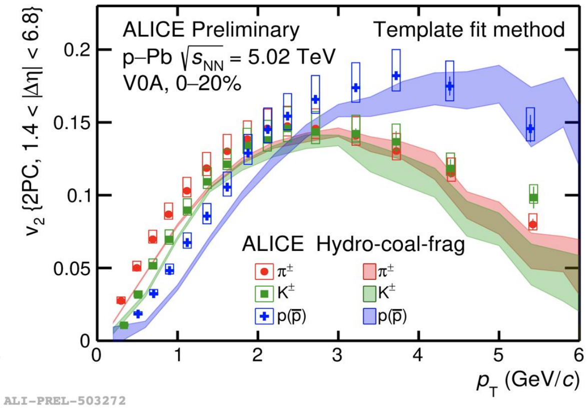
Heavy flavors: No significant p_T dependence and $v_2^{J/\psi}$ in pp compatible with 0 ($v_2^{pp} < v_2^{p\text{-}Pb} < v_2^{Pb\text{-}Pb}$)



Elliptic flow in small systems







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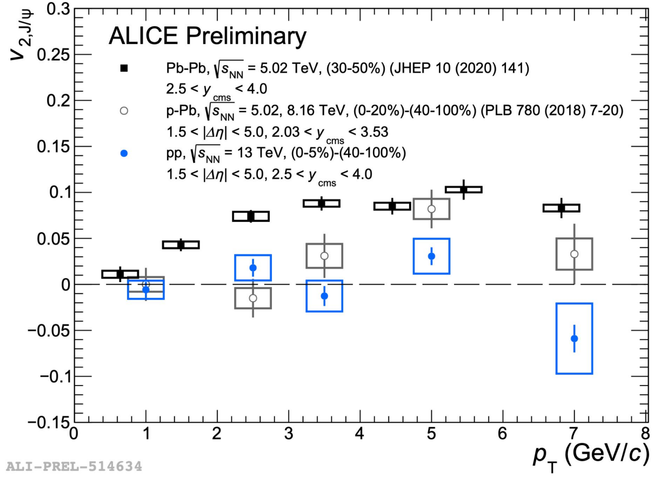
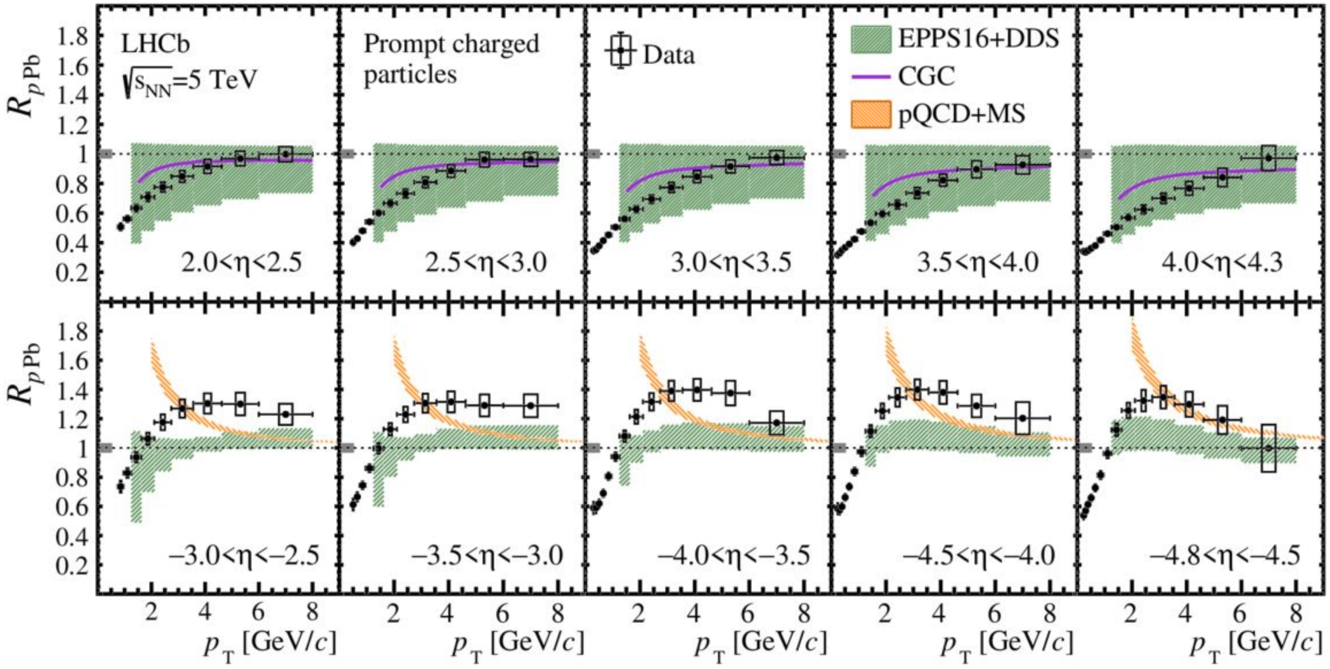


More small systems measurements:

ATLAS, PRC 104 (2021) 014903; CMS, arXiv:2204.13486

Nuclear modification factor in p-Pb collisions

Phys.Rev.Lett. 128 (2022), 142004



Complementary measurements in backward and forward η regions

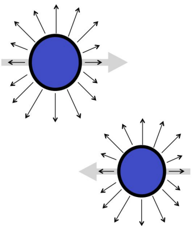
Forward region
a suppression is observed, especially for low p_T

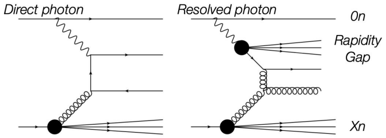
Backward region
significant enhancement for high p_T

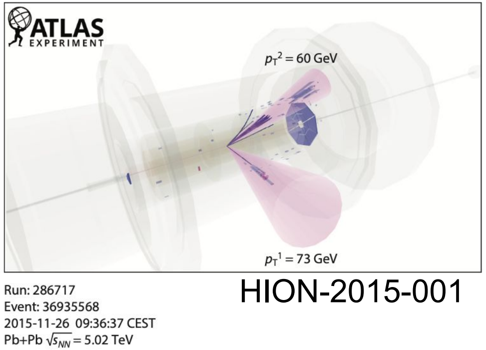
Clear pseudorapidity dependence, that nPDFs alone cannot described
Differences with CGC calculations at the lowest p_T
→ Multiple scattering calculations fail to describe the backward region

A. Lupato, Thu 9:25

UPC: probing nPDF through photo-nuclear dijet production







HION-2015-001

$$H_T \equiv \sum_i p_T^i$$

$$x_A \equiv \frac{M_{jets} e^{-y_{jets}}}{\sqrt{s_{NN}}}$$

$$z_\gamma \equiv \frac{M_{jets} e^{+y_{jets}}}{\sqrt{s_{NN}}}$$

At intermediate photon energies, we can access higher-x partons
Going higher in photon energy opens up the low-x shadowing region

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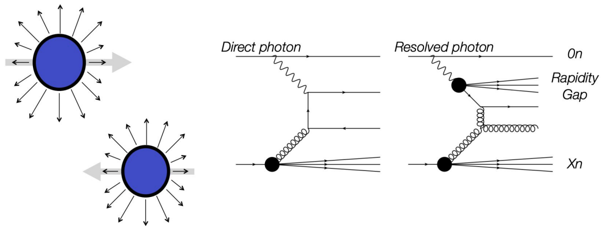

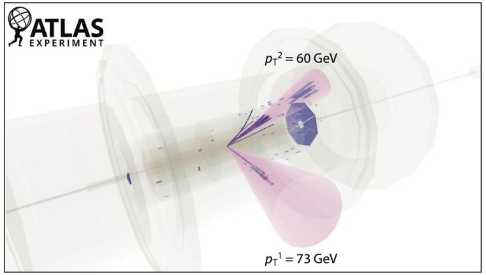

Run: 286717
Event: 36935568
2015-11-26 09:36:37 CEST
Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV

HION-2015-001

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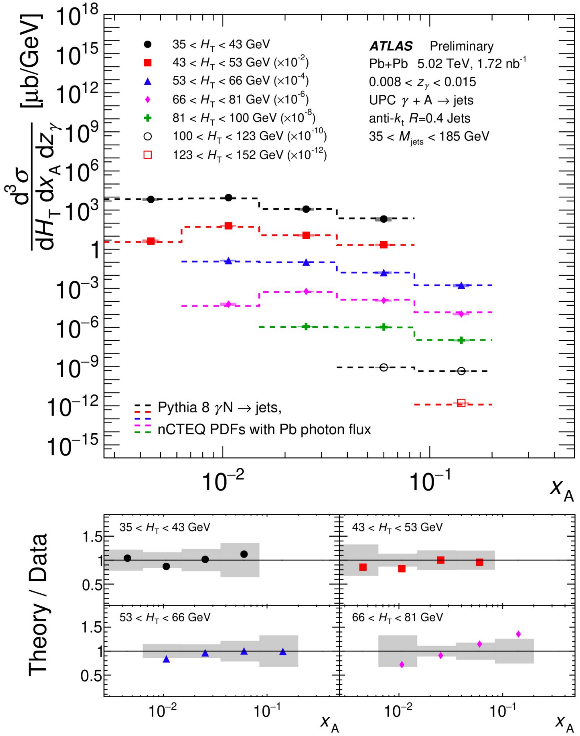
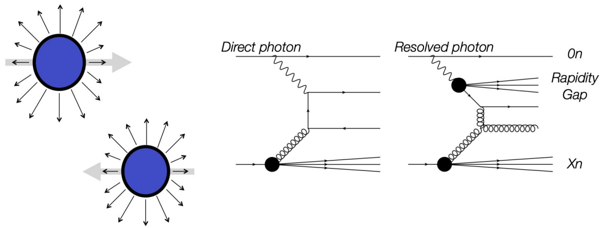
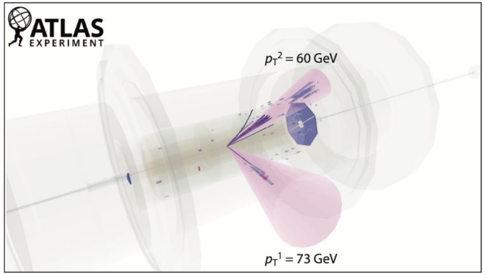
ATLAS-CONF-2022-021



At intermediate photon energies, we can access higher-x partons
Going higher in photon energy opens up the low-x shadowing region
Results are consistent with theoretical calculations

UPC: probing nPDF through photo-nuclear dijet production





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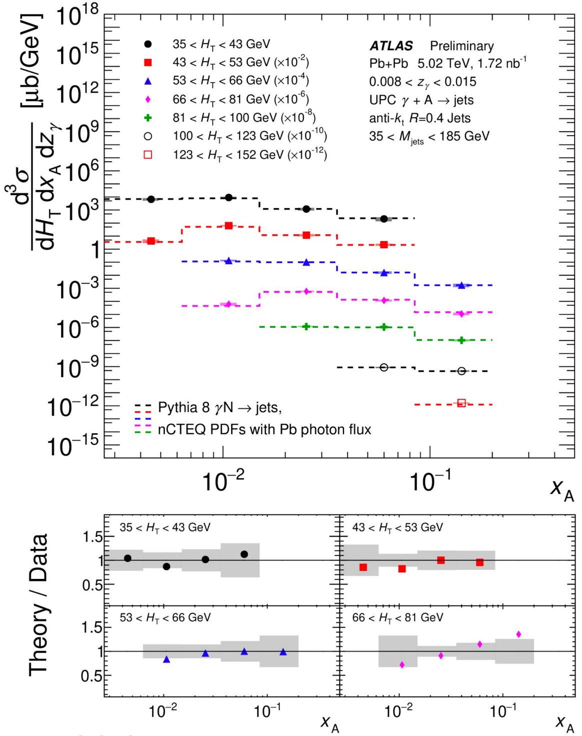
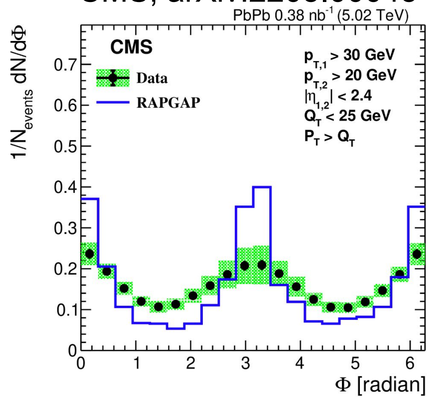
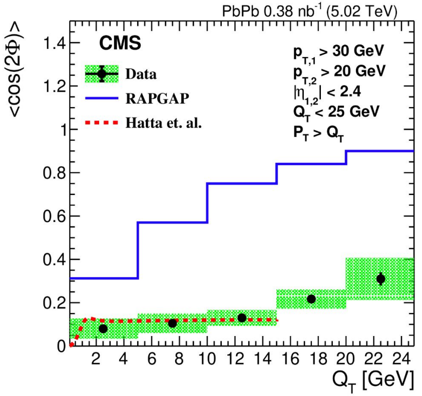
ATLAS-CONF-2022-021



CMS, arXiv:2205.00045

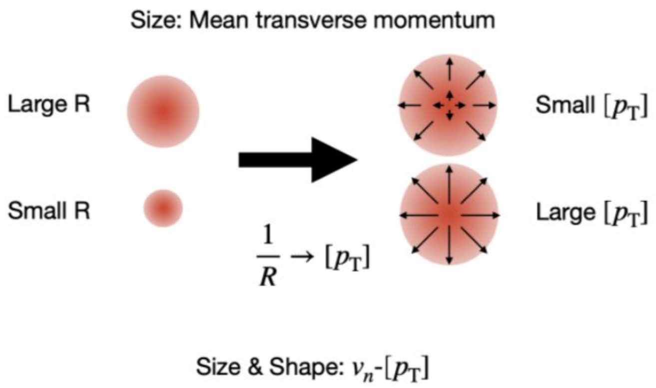




At intermediate photon energies, we can access higher-x partons
Going higher in photon energy opens up the low-x shadowing region
Results are consistent with theoretical calculations

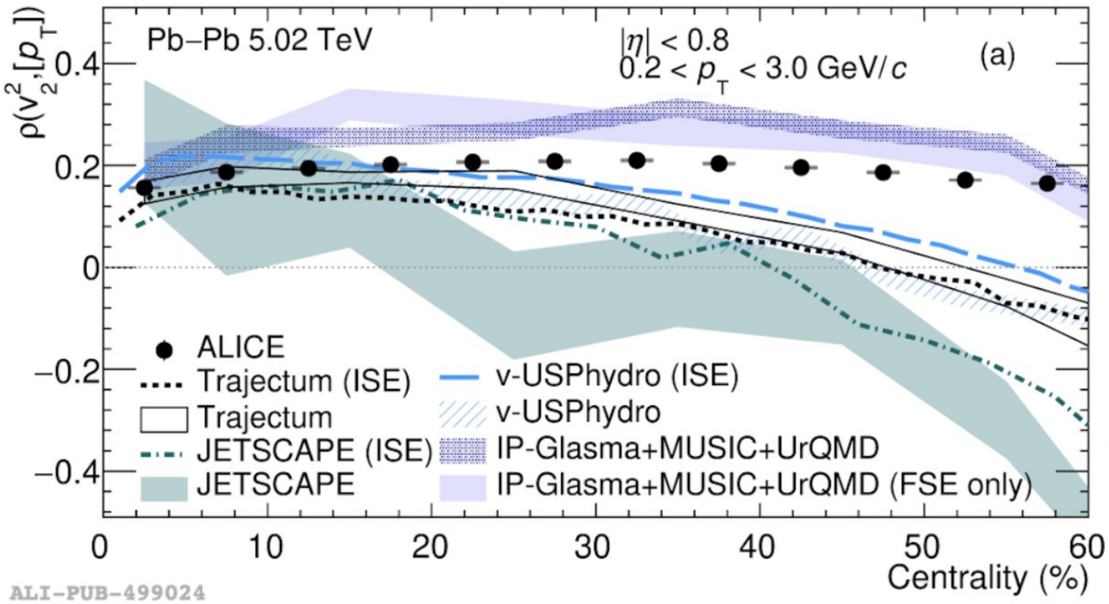
Dijet azimuthal angular correlations
→ gluon polarisation in nuclear targets

Investigating the initial stages with correlations



$$\rho(v_n^2, [p_T]) = \frac{cov(v_n^2, [p_T])}{\sqrt{var(v_n^2)}\sqrt{var([p_T])}}$$

ALICE, Phys. Lett. B 834 (2022) 137393



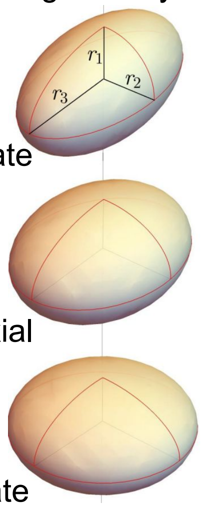
Study of the correlation between the shape of the fireball (v_2) and its size ($[p_T]$)
Access to the initial conditions through bulk observables
No quantitative description of the data
 Slightly better agreement with models using IP-Glasma initial conditions

Accessing nuclear deformation through v_n-p_T correlation

v_n-p_T correlation (ρ_n) in initial state between size and eccentricities

PRL 128 (2022) 8, 082301

Sensitive to nuclear geometry

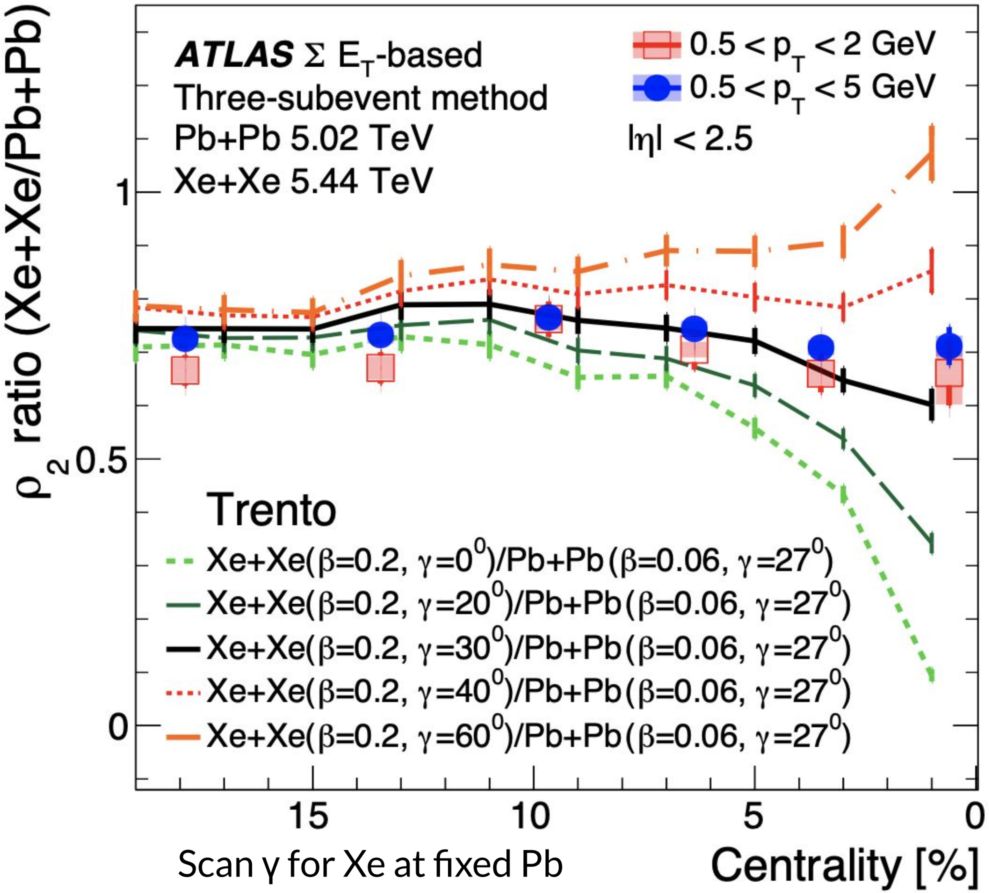


Prolate

Triaxial

Oblate

ATLAS-CONF-2021-001



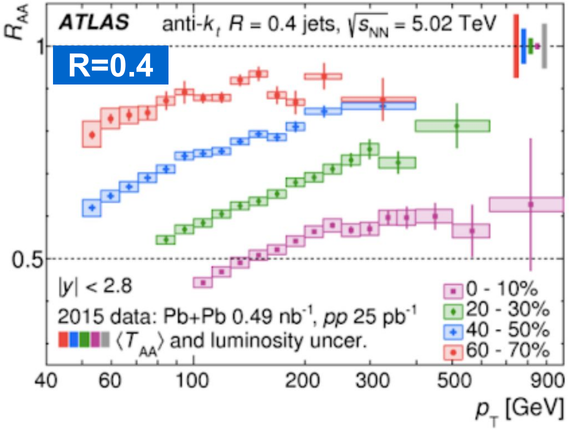
Scan γ for Xe at fixed Pb

Ratio of ρ_2 in Xe-Xe and Pb-Pb to take out the final state dependencies

Trento (initial state only) shows large sensitivity to γ of deformed nucleus in central collisions events (where it matters)

Inclusive jet suppression in medium

ATLAS, PLB 790 (2019) 108



R_{AA} increases with jet p_T reaching a value of about 0.6 at p_T = 1 TeV in central Pb-Pb collisions for R=0.4

R↑ Energy loss recovered within jet "cone"**?**

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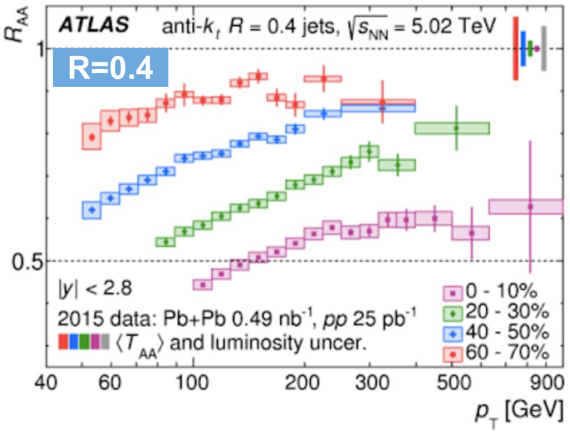
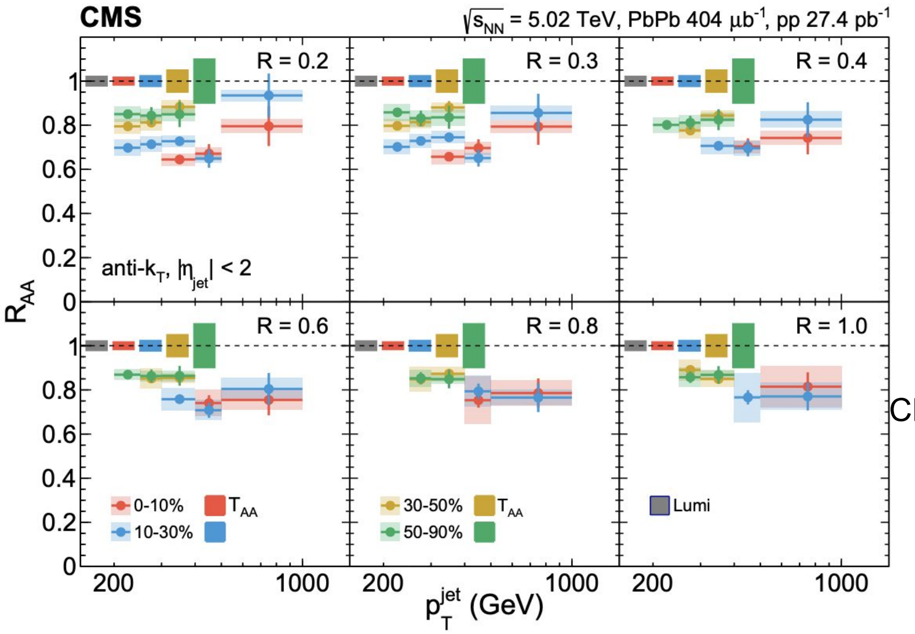
ATLAS, PLB 790 (2019) 108





Jet R_{AA} in Pb-Pb collisions shows only a modest increase, R_{AA} never reaches unity

CMS, JHEP 05 (2021) 284

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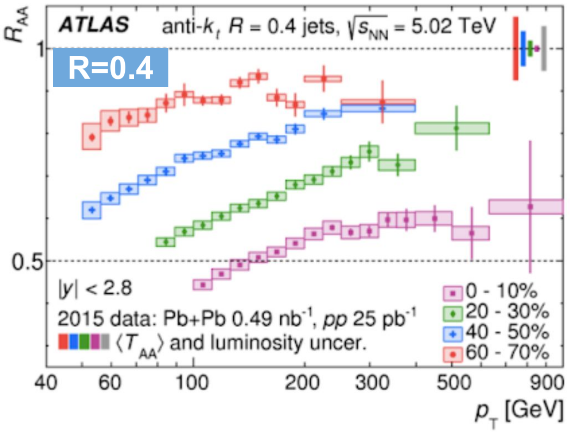

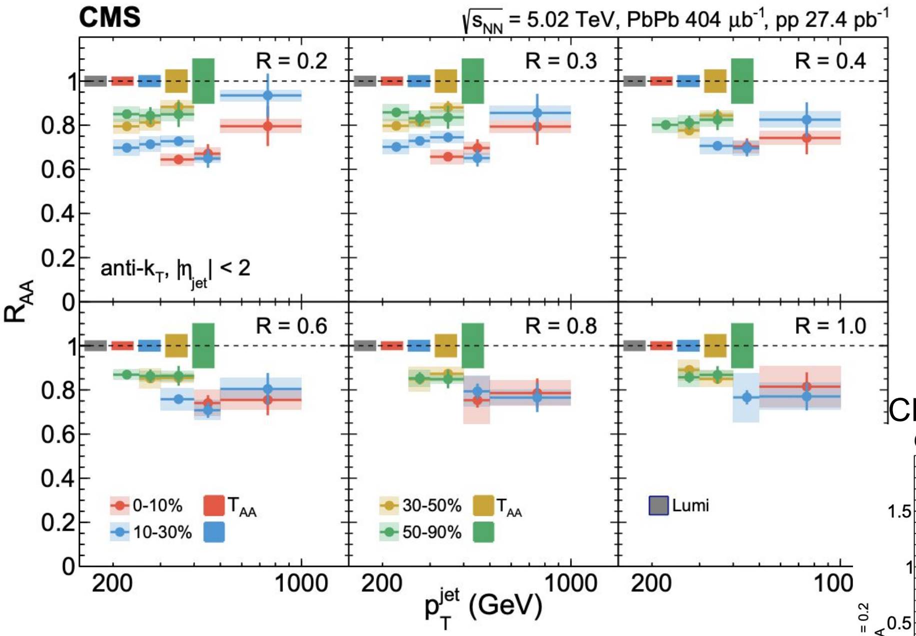

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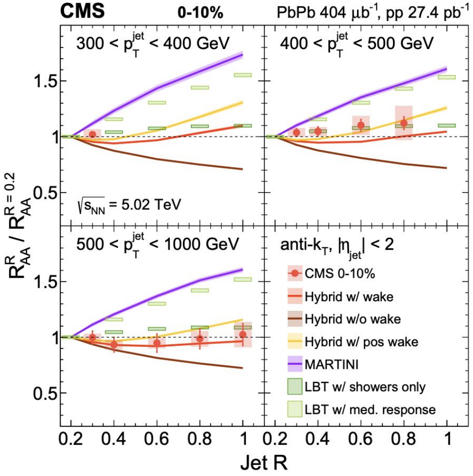
CMS, JHEP 05 (2021) 284



R_{AA} increases with jet p_T reaching a value of about 0.6 at p_T = 1 TeV in central Pb-Pb collisions for R=0.4

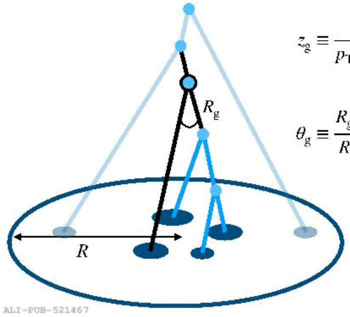
Significant constraints on models of jet quenching, medium response, wide angle radiation

R↑ Energy loss **not** recovered within jet "cone"

Exploring angular dependence via groomed jet substructure

Vacuum:
Parton shower is a multi-scale process with a given momentum and angular/virtuality scale

Medium:
Angular/virtuality scale can be related to a "resolution scale" at which the jet probes the medium



$$z_g \equiv \frac{p_{T,\mathrm{subleading}}}{p_{T,\mathrm{leading}} + p_{T,\mathrm{subleading}}}$$

$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}$$

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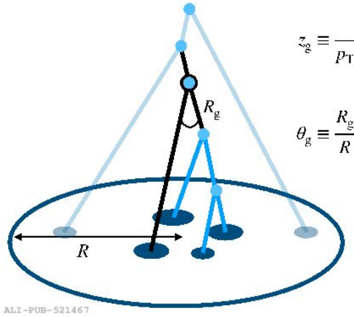

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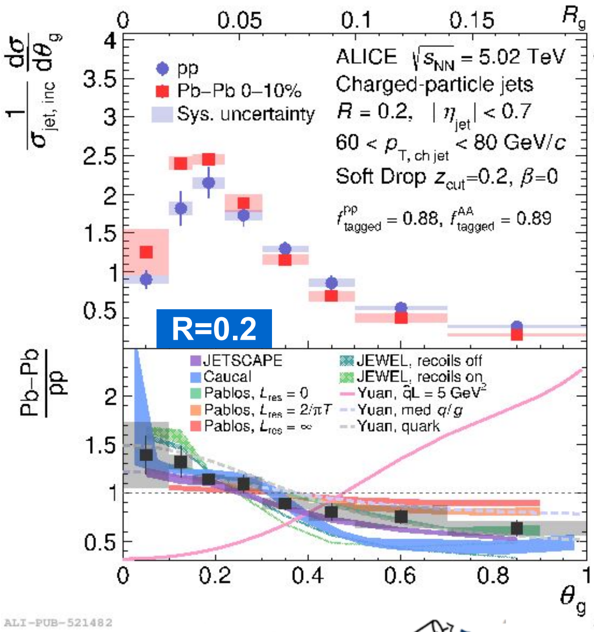
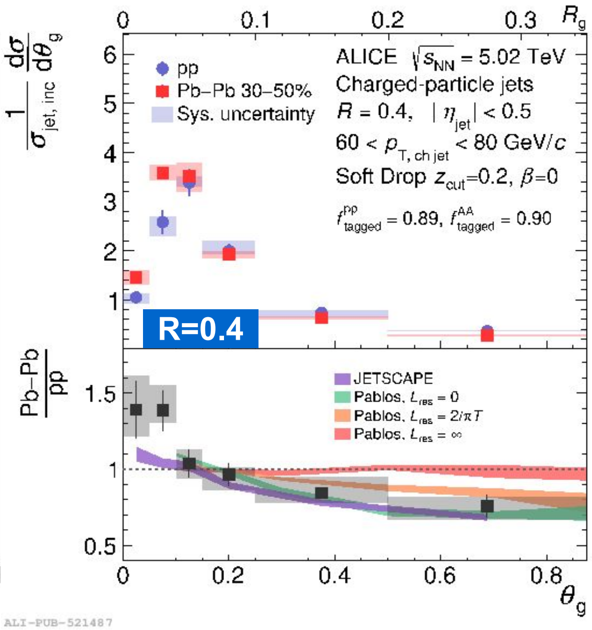
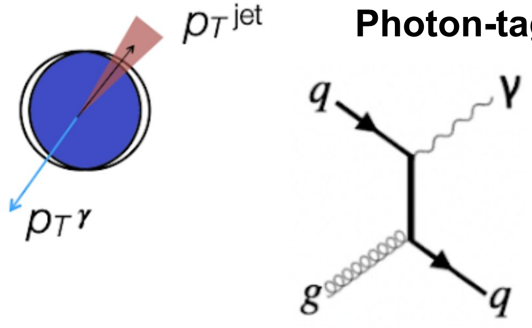




See also ATLAS-CONF-2022-026

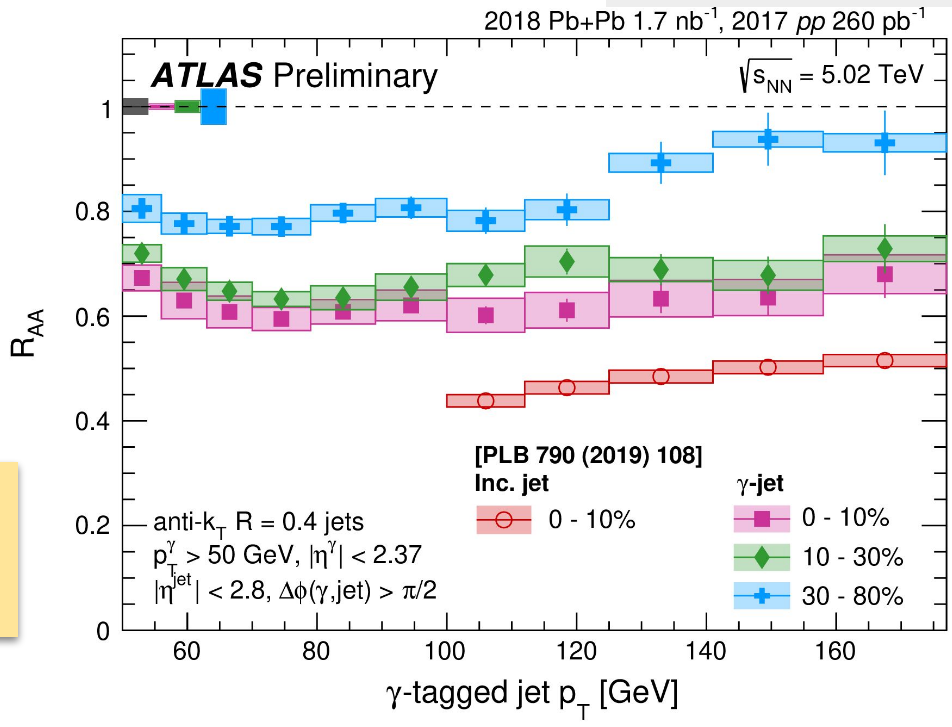
Suppression of large angles and enhancement of small angles. Medium has resolving power for splittings (promotes narrow splittings, filters out wider subjets)

Color charge dependence of jet energy loss



Photon-tagged jets → sample dominated by **quark-initiated jets** (quark gluon Compton scattering)

ATLAS-CONF-2022-019

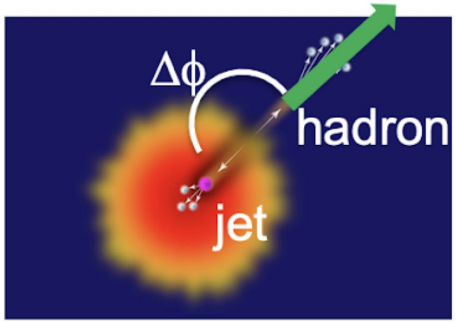


The **photon-tagged jet R_{AA}** higher than the **inclusive jet R_{AA}**

Clear observation of color factor dependence of Parton-QGP interaction

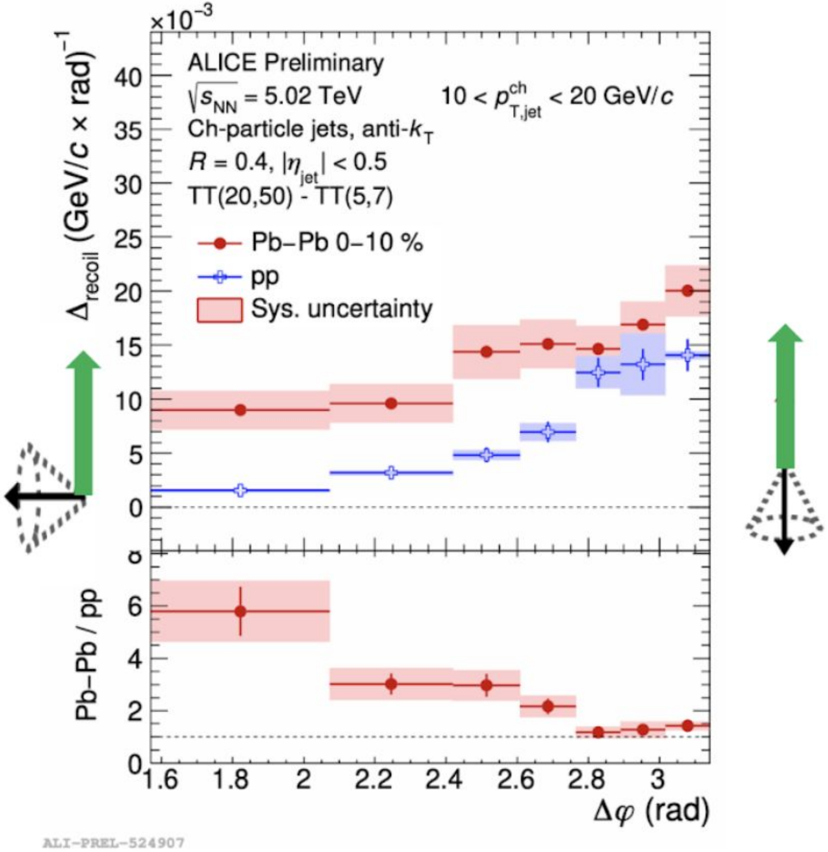
Semi-inclusive "soft" jets deflected, acoplanarity

- Jets recoiling against a high-p_T hadron
  → down to jet p_T ~ 10 GeV/c

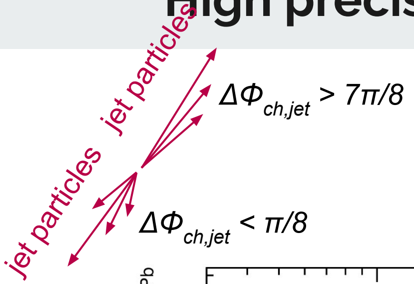


Δ_{recoil} vs ΔΦ broader in Pb-Pb than in pp

Angular deflection of soft large-R jets:
- Scattering on QGP constituents?
- Medium response to energy loss?



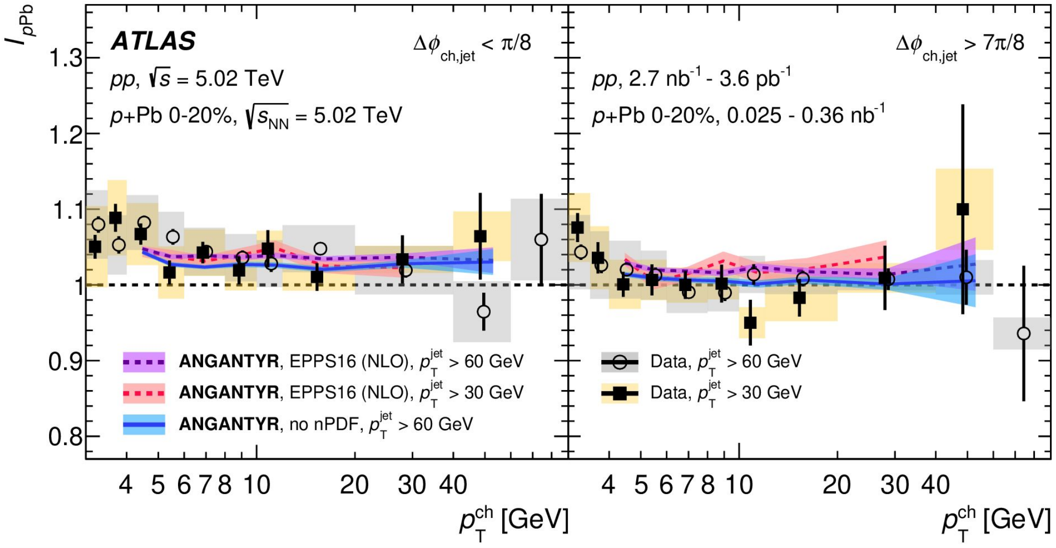
High precision measurement of jet quenching in p-Pb collisions



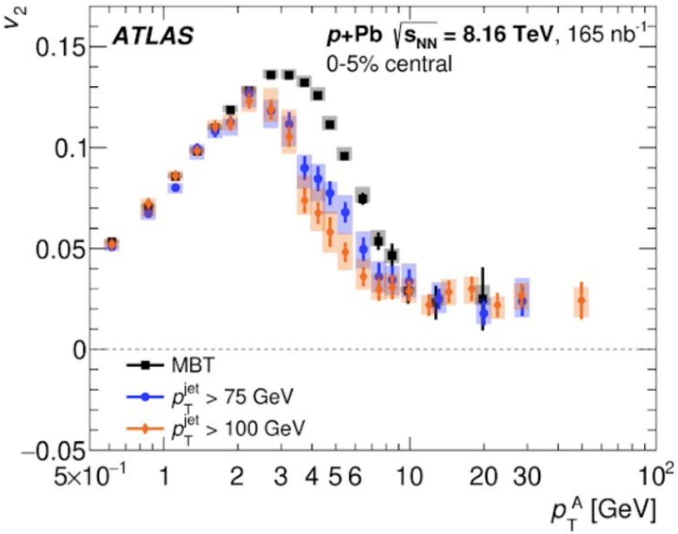
No jet quenching observed in p-Pb despite of collectivity of high-p_T particles

$I_{p\text{-}Pb}$=p-Pb/pp of per-jet yields

arXiv:2206.01138 [nucl-ex]



Eur. Phys. J. C80 (2020) 73



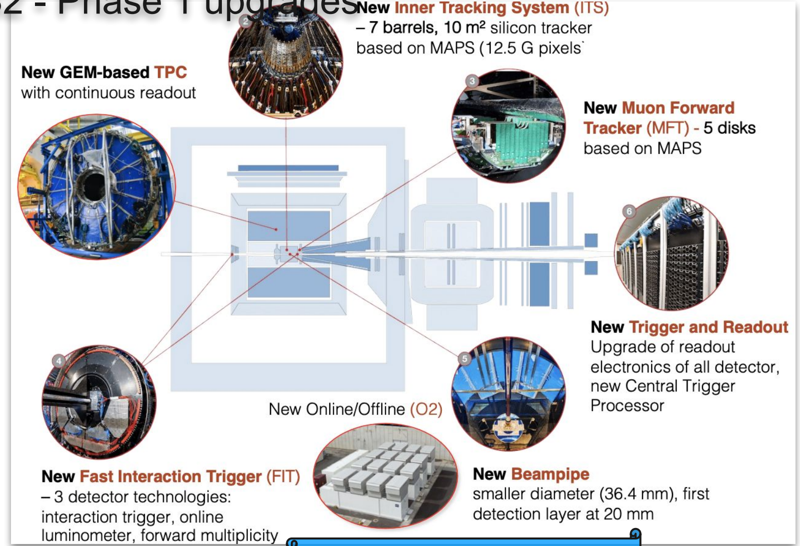
Small to no modifications of hadron yields observed in central p-Pb collisions

- Modification of the jet fragmentation
- Strong constraints on E-loss scenarios

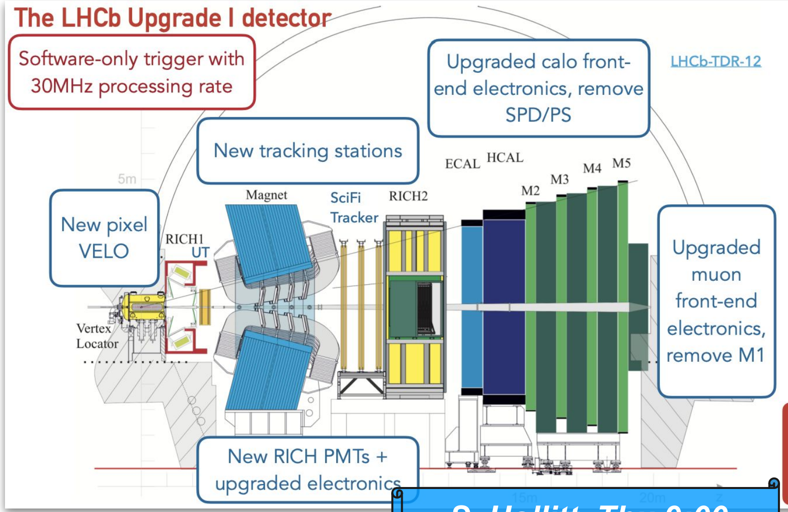
Upgrade of experiments

RUN I 2009-2013 | LS1 | RUN 2 2015-2018 | **LS2** | RUN 3 2022-2025 | LS3 | RUN 4 2029-2032 | LS4 | RUN 5 2035-2038 | LS5 | RUN 6 2040-2041

LS2 - Phase 1 upgrades



N. Poljak, Tue 9:00



- Less than 10% of the detector channels have been kept
- 100% of the readout electronics has been replaced
- NEW data acquisition system and data center

Very challenging installation and commissioning!

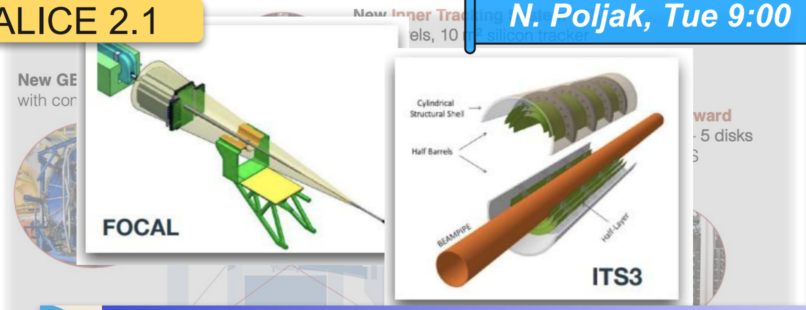
S. Hollitt, Thu 9:00

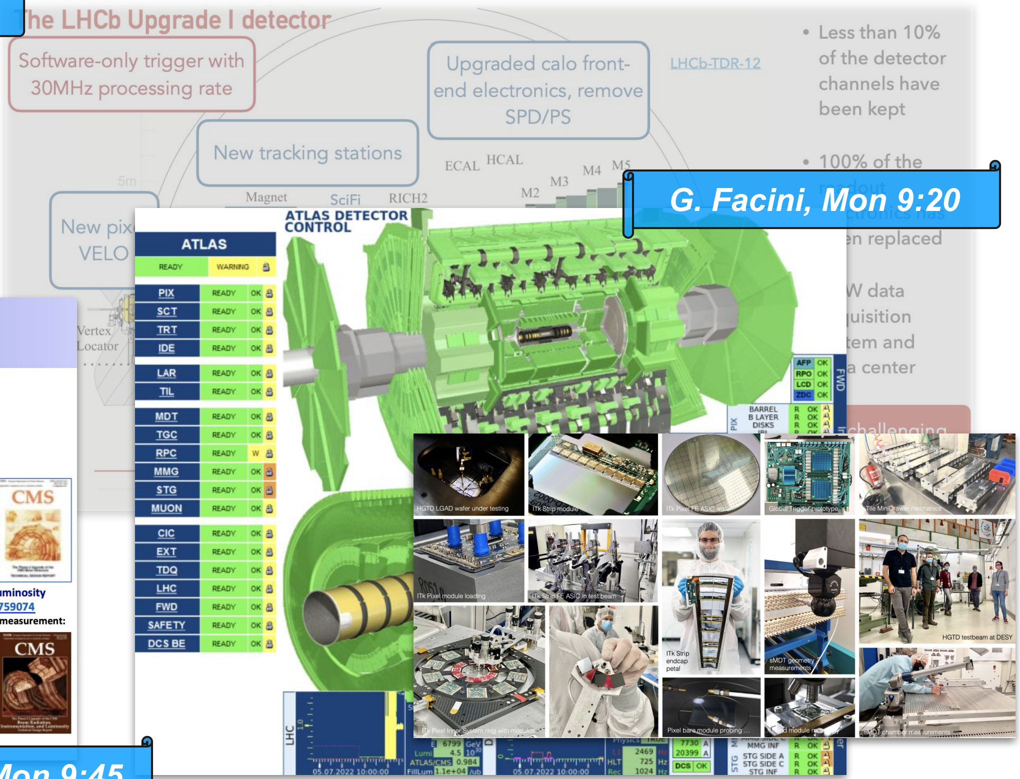
Upgrade of experiments

RUN I 2009-2013 | LS1 | RUN 2 2015-2018 | LS2 | RUN 3 2022-2025 | **LS3** | RUN 4 2029-2032 | LS4 | RUN 5 2035-2038 | LS5 | RUN 6 2040-2041

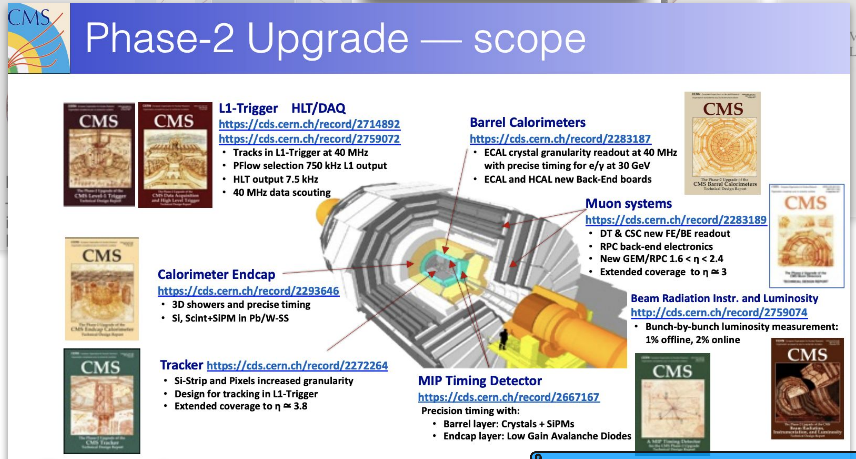
ALICE 2.1

N. Poljak, Tue 9:00





G. Facini, Mon 9:20



LS3 - Phase 2 upgrades

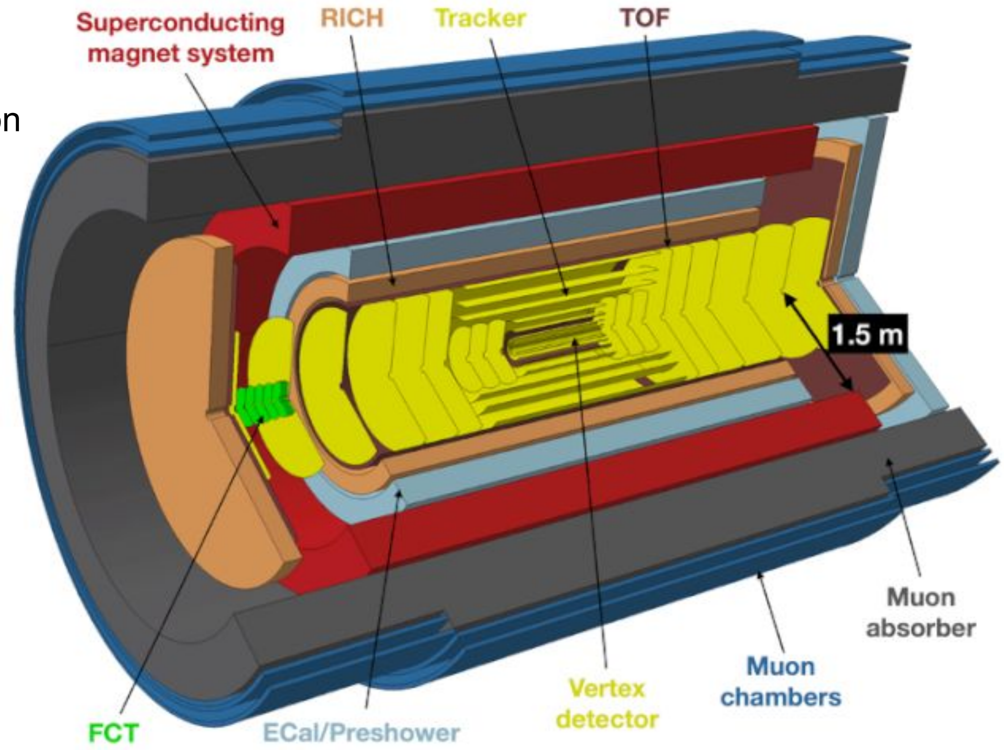
G. Pugliese, Mon 9:45

Next generation heavy-ion detector: ALICE3

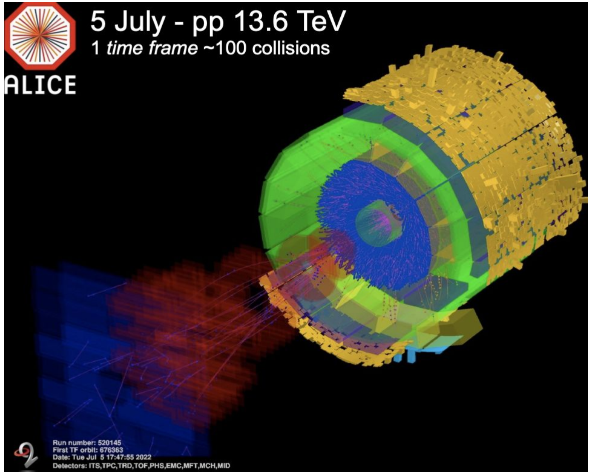
RUN I 2009-2013 | LS1 | RUN 2 2015-2018 | LS2 | RUN 3 2022-2025 | LS3 | RUN 4 2029-2032 | LS4 | RUN 5 2035-2038 | LS5 | RUN 6 2040-2041

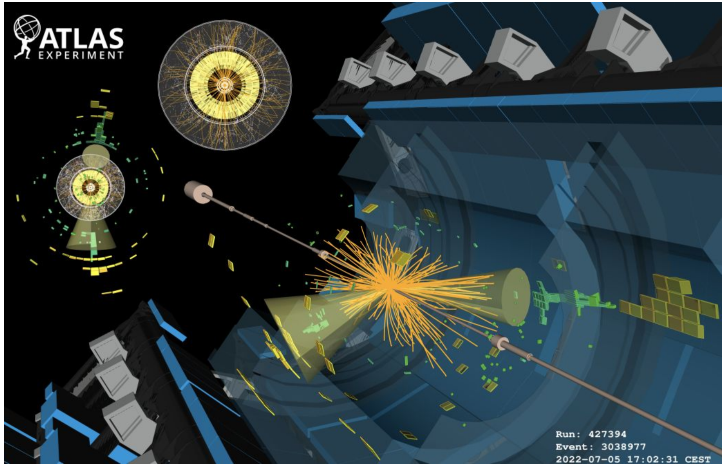
Compact all-silicon tracker
→ clean separation of signal and background
Vertex detector with excellent pointing resolution
→ clean reconstruction of decay chains
Particle identification
→ background suppression
Large acceptance
→ statistics and correlations
Superconducting magnet system
→ effective provision of required magnetic field
Continuous read-out and online processing
→ large data sample to access rare signals

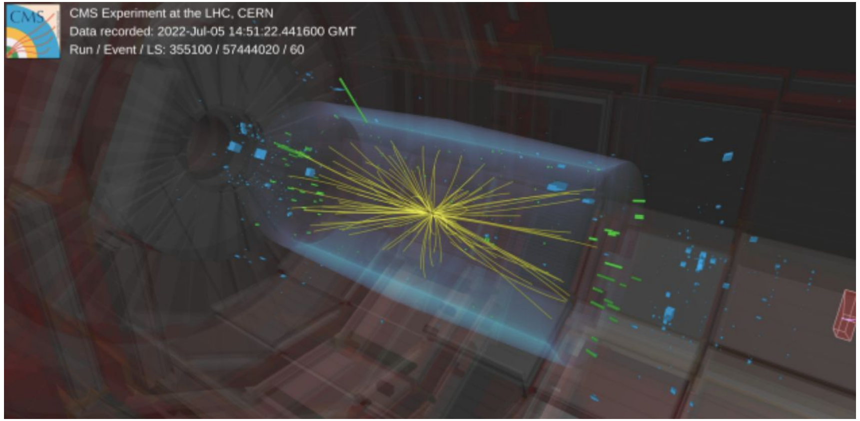
N. Poljak, Tue 9:00

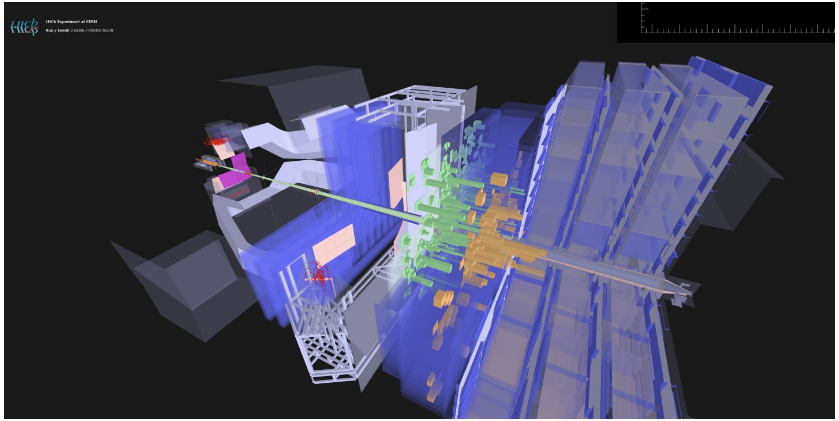


pp collisions @ 13.6 TeV!









Summary

Initial stages

Investigating the initial stages with correlations
Probes of nPDF through photo-nuclear dijet production

Medium properties

Comprehensive picture of elliptic flow in Pb-Pb collisions
R_{AA} of J/ψ and D meson from beauty
ψ(2S) production in Pb-Pb collisions
Υ(1S) has weak flow in Pb-Pb
Collectivity in small systems

Medium induced jet modifications

Inclusive jet suppression
Exploring angular dependence via groomed jet substructure
Color charge dependence of jet energy loss
Semi-inclusive "soft" jets deflected
High precision measurement of jet quenching in p-Pb collisions


Thank you!