# (Jet) physics in LHC run 3 and beyond

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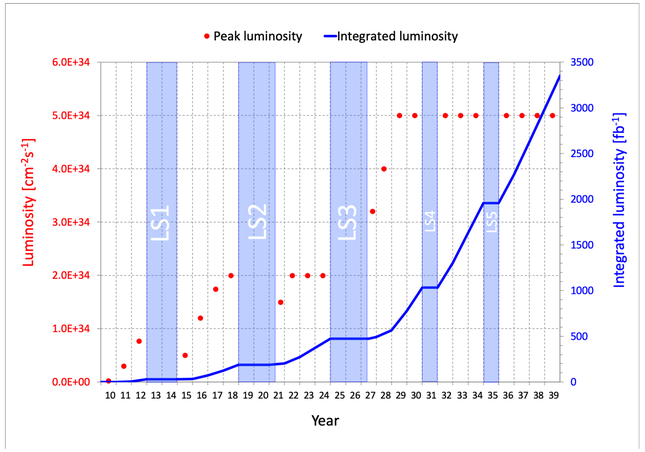
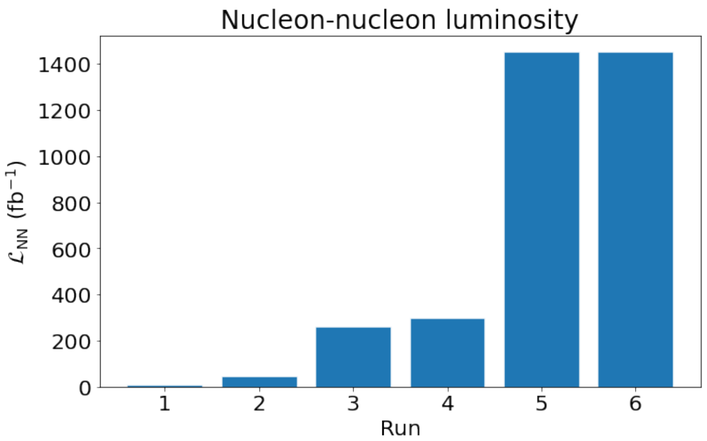
Physics Utrecht
EMMEΦ

Nikhef

# LHC upgrades time line



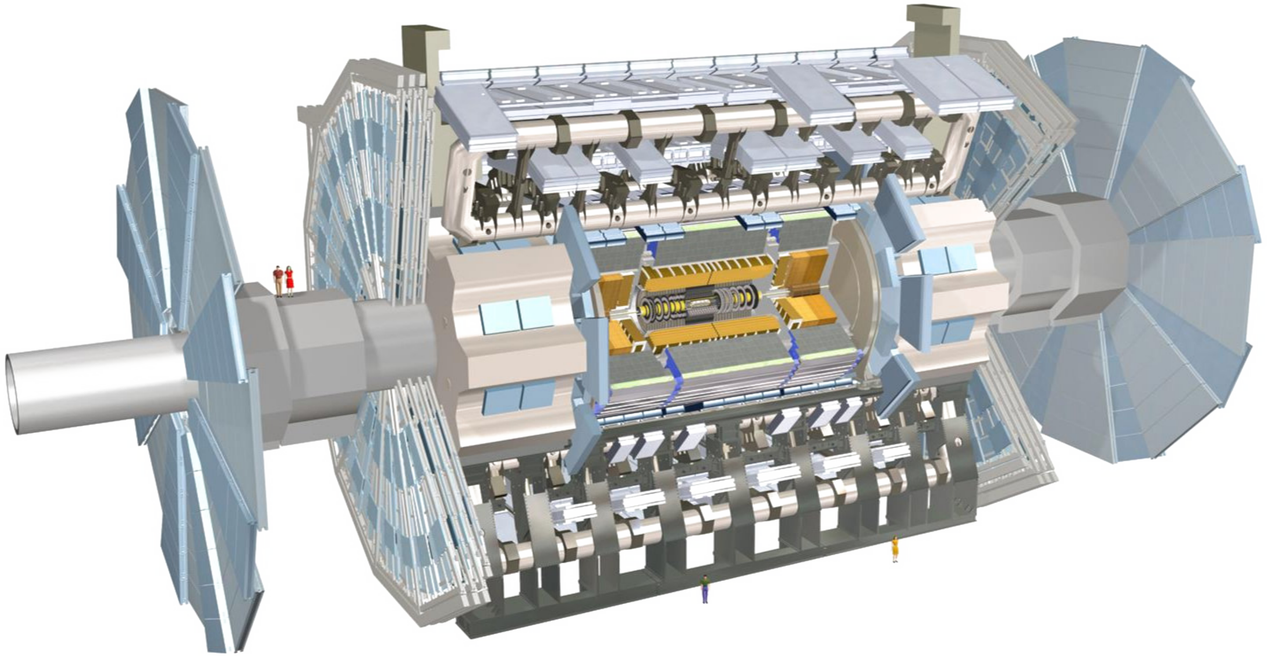

High luminosity for ions

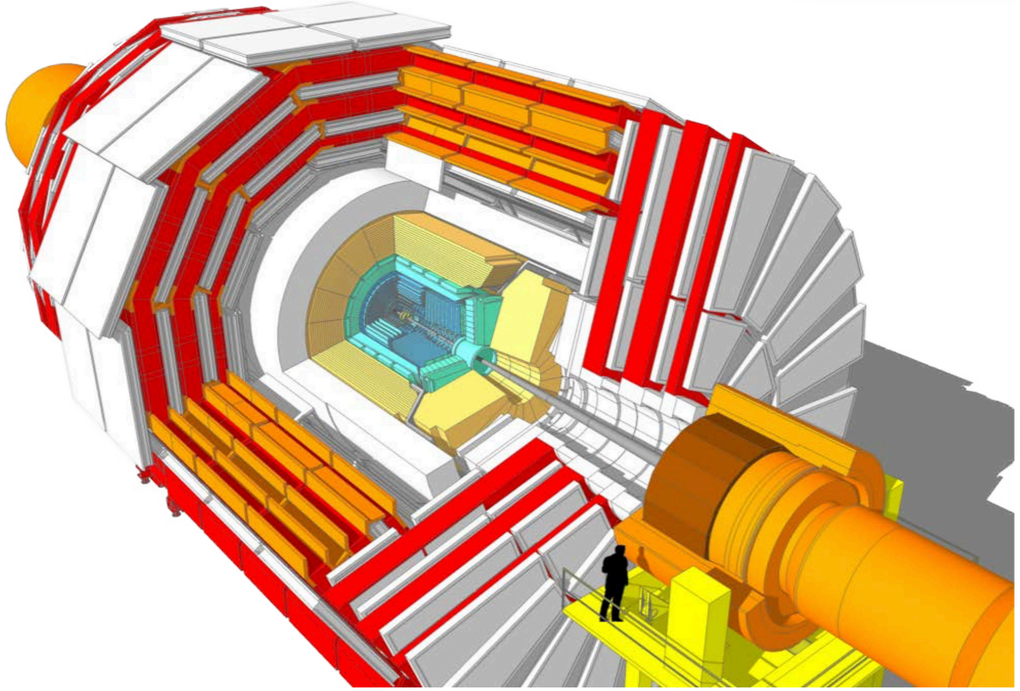
HL-LHC

| Run 1 2009 - 2013 | Run 2 2015 - 2018 | Run 3 2022 - 2025 | Run 4 2029 - 2032 | Run 5 | Run 6 |
|---|---|---|---|---|---|
| ALICE 1 | ALICE 2 upgrade | ALICE 2.1 upgrade | ALICE 3 upgrade | | |
| LHCb | LHCb upgrade I(a) | LHCb upgrade Ib | LHCb upgrade II | | |
| ATLAS | ATLAS phase I upgrades | ATLAS phase II upgrades | | | |
| CMS | CMS phase I upgrades | CMS phase II upgrades | | | |

From: J Klein QM2022 talk

# ATLAS and CMS upgrades (run 4)



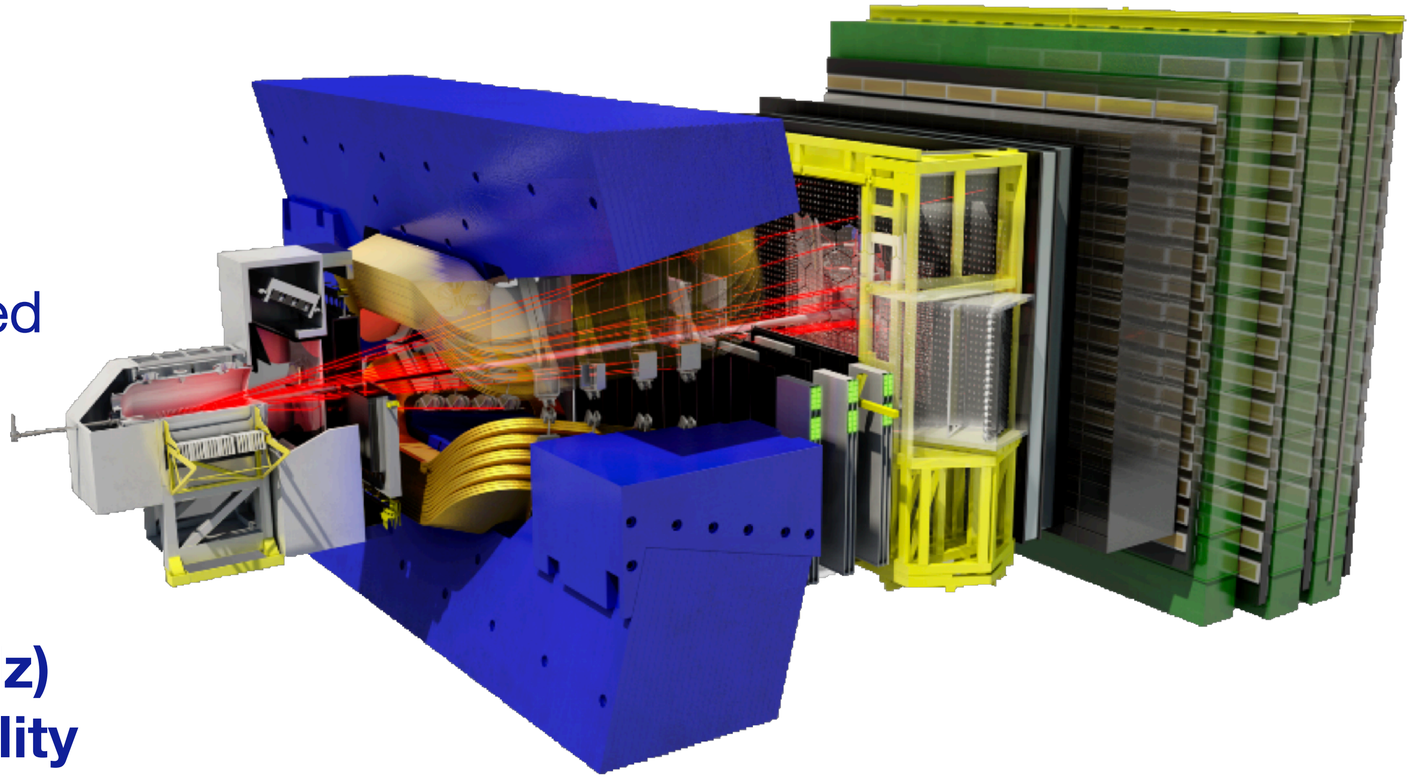


**Main upgrades: Phase II, 2028-**

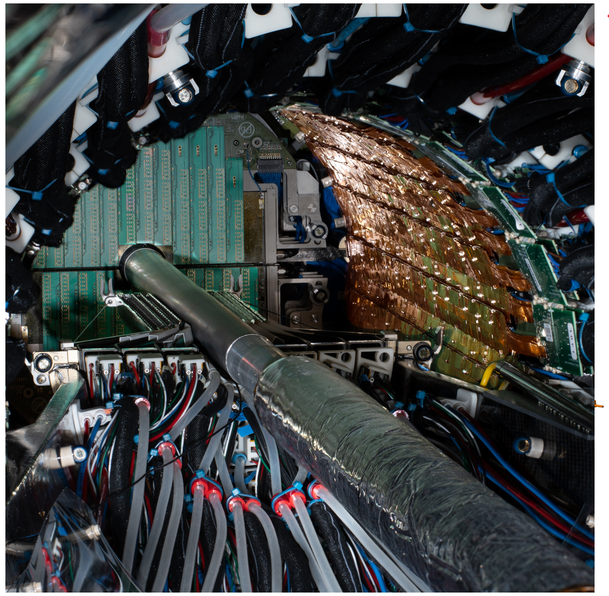
- Trackers: improved tracking up to $\eta \approx 4$
- Timing detectors at fwd rapidity: time of flight PID
- CMS: improved muon system at fwd rapidity
- ZDC upgrades
- Trigger and readout

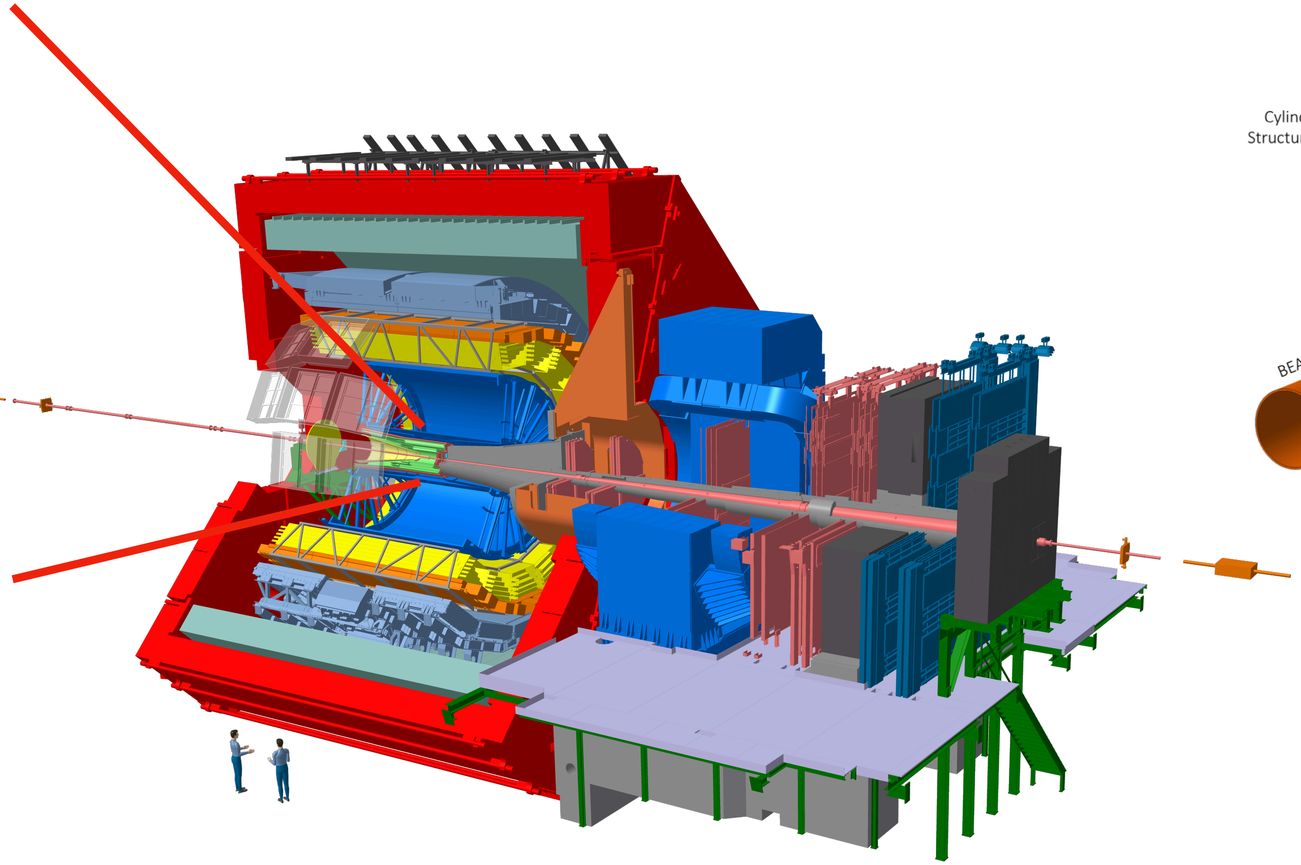
# LHCb Run 3 upgrades

- Many detector system upgraded
  - VELO tracker
  - Outer tracker stations: SciFi
    - Further upgrades for run 4 planned
  - RICH
  - Fixed target: SMOG 2
  - Readout & trigger
  - **High-rate capability for pp (40 MHz) and Pb-Pb (50 kHz) > 30 % centrality**

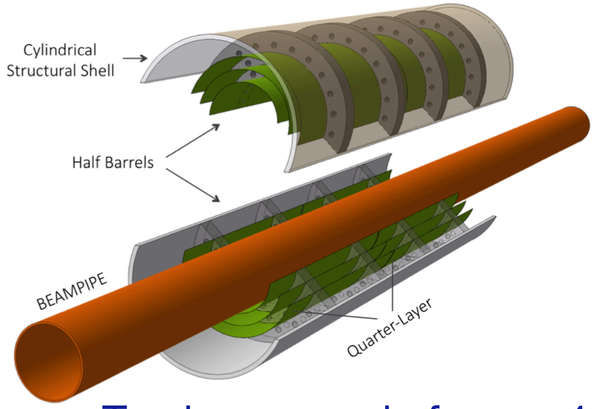


# ALICE run 3 upgrades





**ITS 3**




Tracker upgrade for run 4: improve pointing resolution, reduce material budget

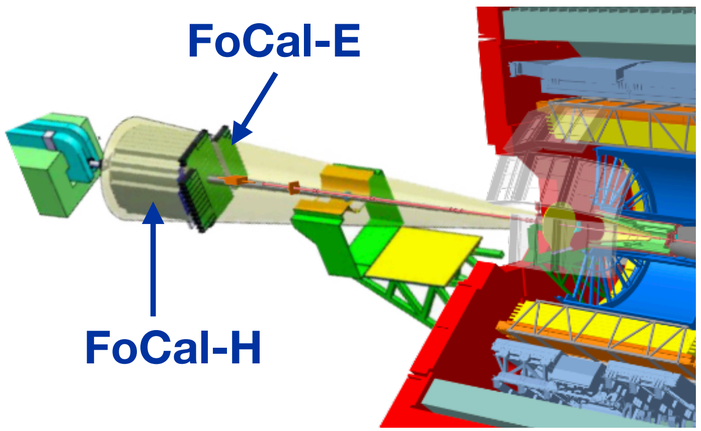
LoI: CERN-LHCC-2019-018

+ FoCal for run 4 (next slide)

- Major upgrade of Inner Tracking System, Time Projection Chamber, interaction trigger
- Continuous readout and online data processing facility
- **Readout rate: 50 kHz Pb-Pb, > 500 kHz pp**

# Initial state and nuclear PDFs

ALICE Forward Calorimeter

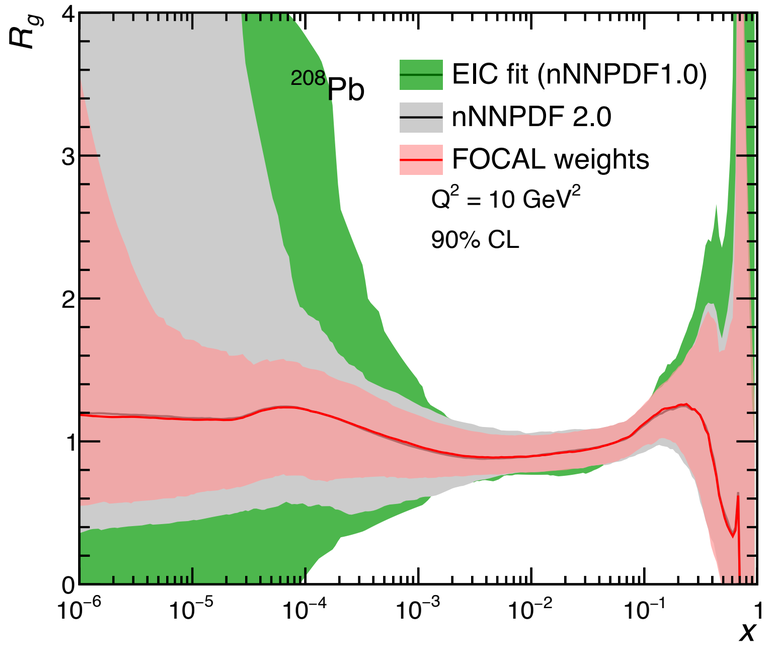



CERN-LHCC-2020-009

High-granularity EM calo + HCAL:

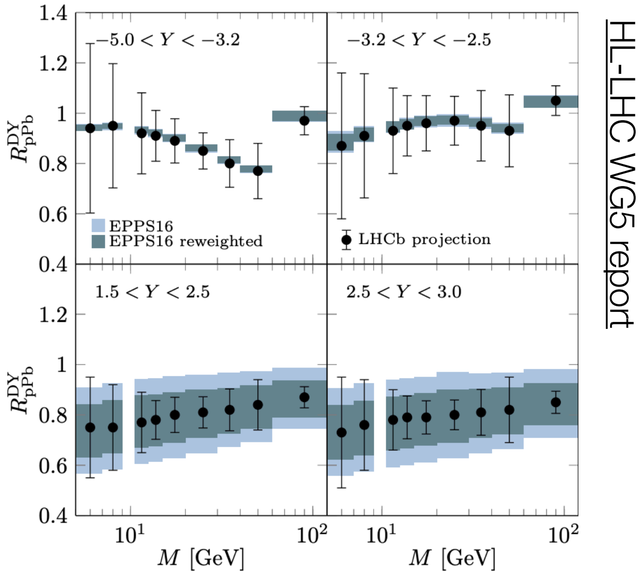
- Direct photons in pp, pPb
- $\pi^0$ in pp, pPb, PbPb
- jets at fwd rapidity

Projected PDF uncertainties



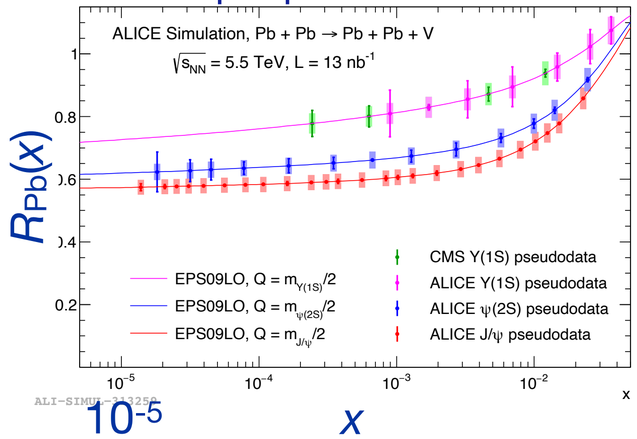

Constrain gluon density in nuclei over a broad range:
$x$ ~$10^{-5}$ - $10^{-2}$ at small $Q^2$

Drell-Yan in p-Pb collisions




HL-LHC WG5 report

Photoproduction of J/ψ, ψ, Υ in ultraperipheral Pb-Pb coll.

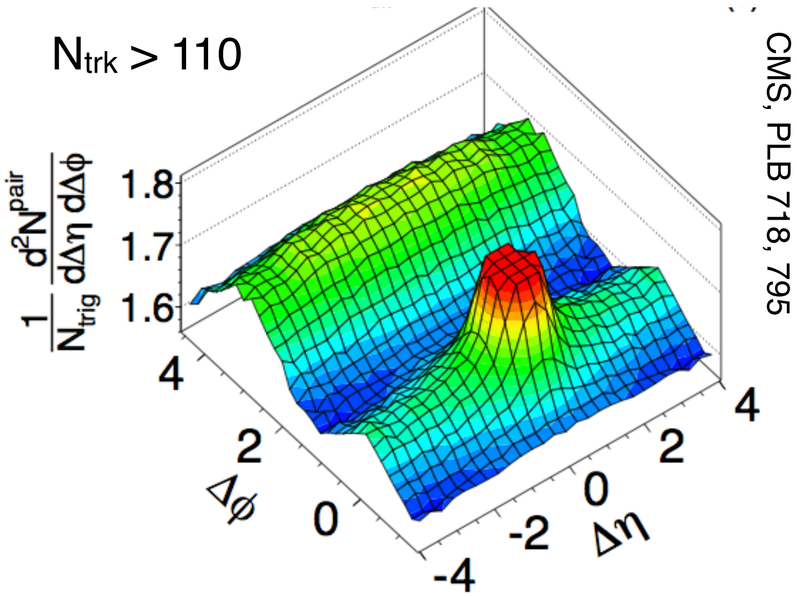



HL-LHC WG5 report

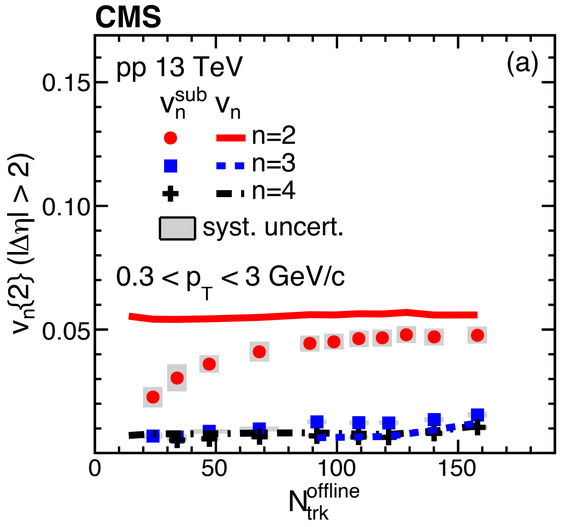
$10^{-5}$ $x$

# Collective effects in pp collisions: final state scattering?

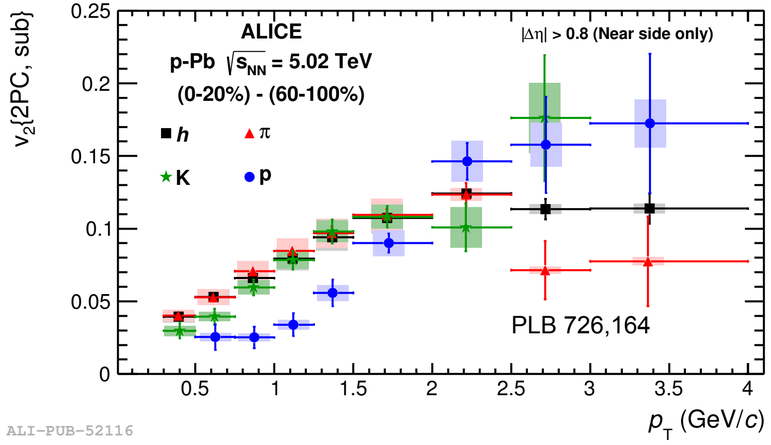
Long-range azimuthal correlations



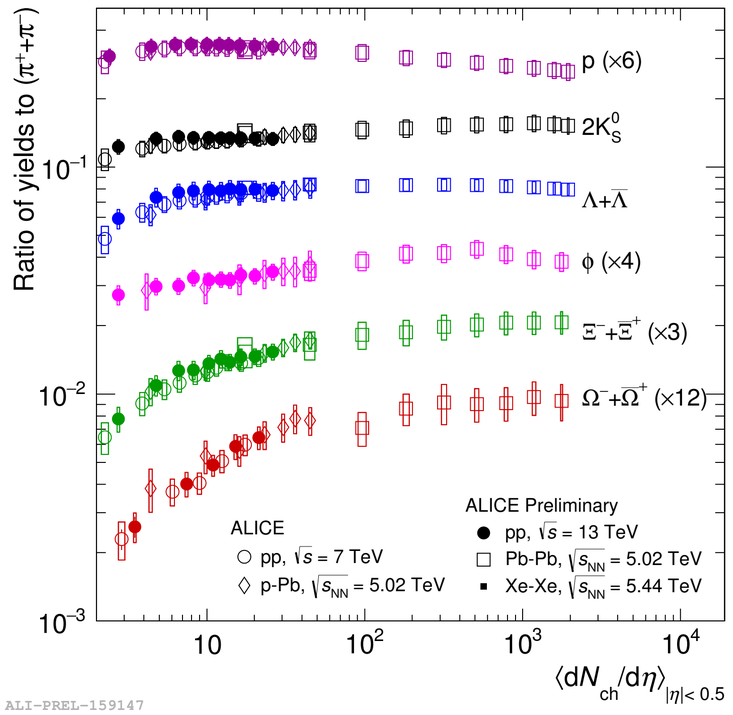

CMS, PLB 718, 795




CMS, PRL 120, 092301




Strangeness/baryon enhancement

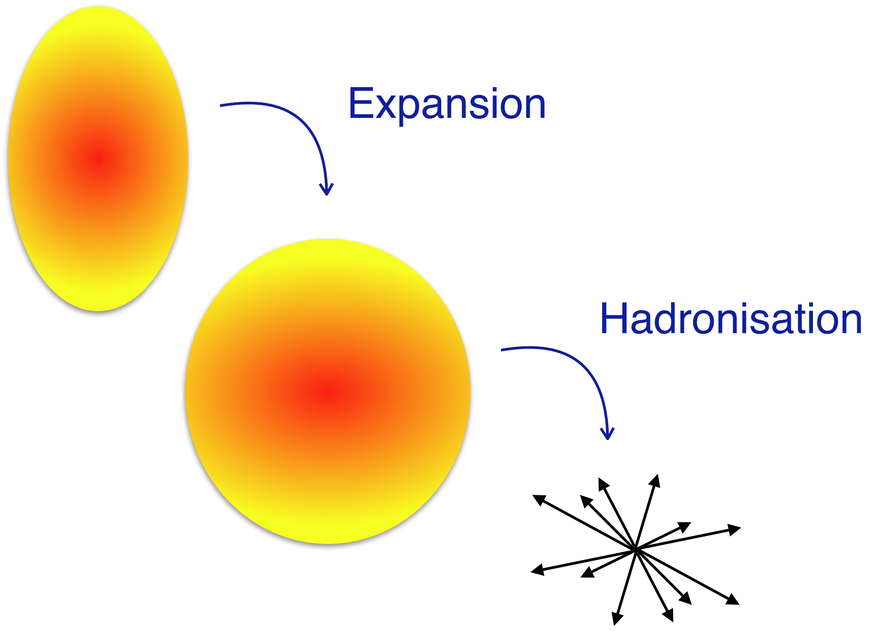



- **Understand evolution from small to large systems**
  → measurements of flow and particle production
  → large high-multiplicity pp samples and new collision systems

# Reminder: two physical pictures for origin of azimuthal anisotropy

## Hydrodynamical expansion

Conversion of pressure gradients into momentum space anisotropy



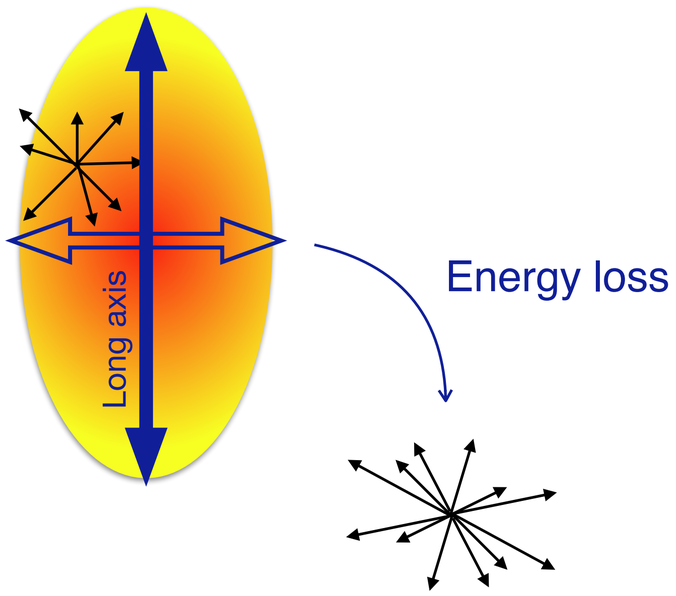

$$\nabla p = \rho \frac{d\vec{v}}{dt}$$

Underlying picture: fluid motion  short mean free path

Mostly appropriate for light flavor, low-intermediate $p_T$, large systems

## Parton energy loss

Path length differences




$$\Delta E_{med} \sim \alpha_S \hat{q} L^2$$

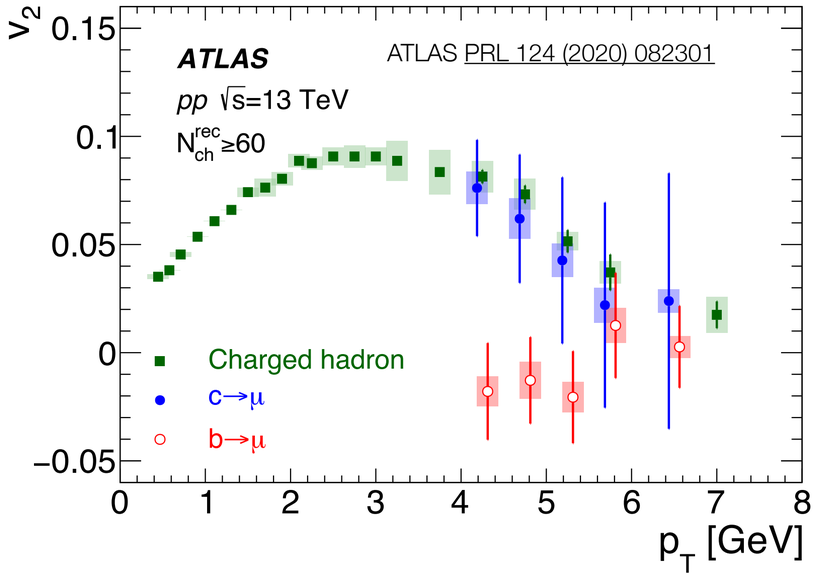
Underlying picture: interactions of partons with medium

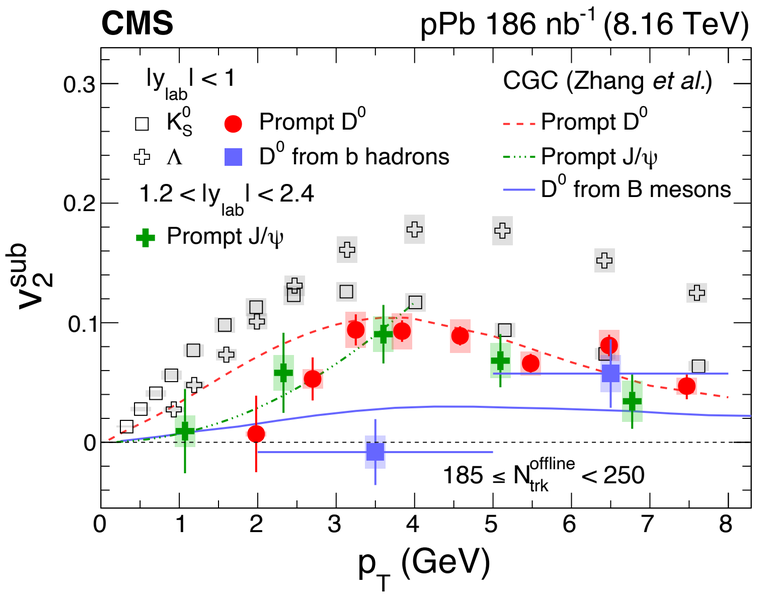
Appropriate for jets, heavy flavour

**Small systems at high multiplicity: explore the connection between these regimes**

# Azimuthal asymmetry in pp, p-Pb: heavy flavor

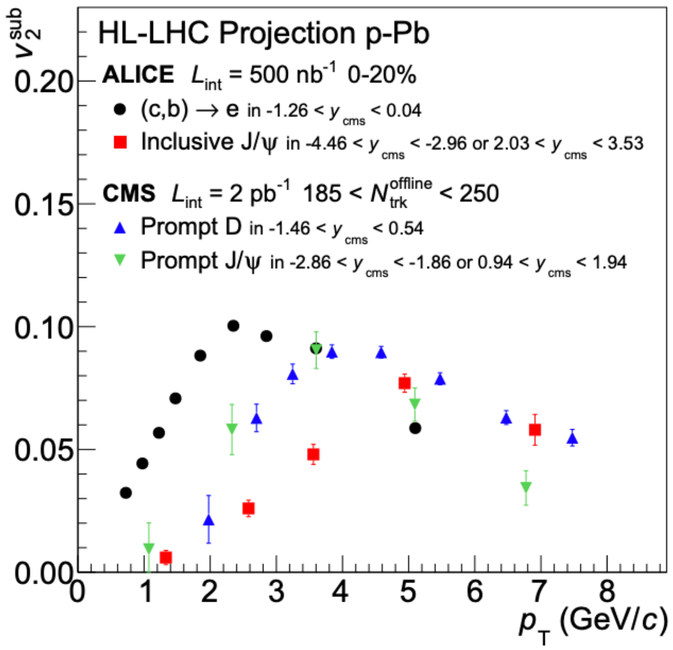
Current status: charm and beauty $v_2$ in pp, p-Pb




CMS, PLB 813, 136036

Projection: open and hidden heavy flavor $v_2$ in p-Pb




HL-LHC WG5 report

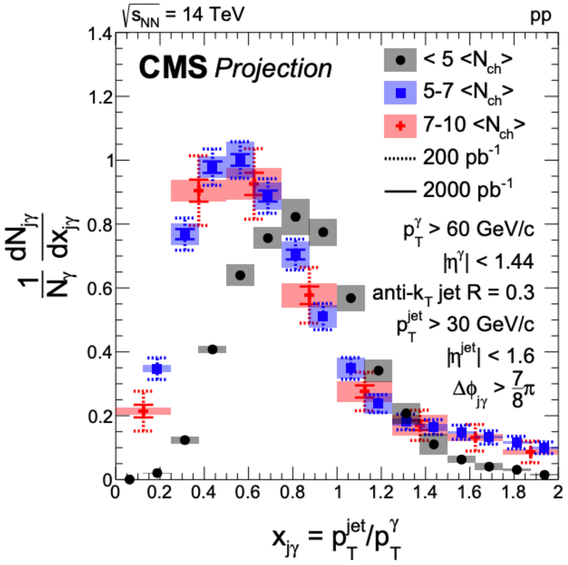
Data suggest no or very small azimuthal asymmetry for beauty

'Limit of thermalisation'?

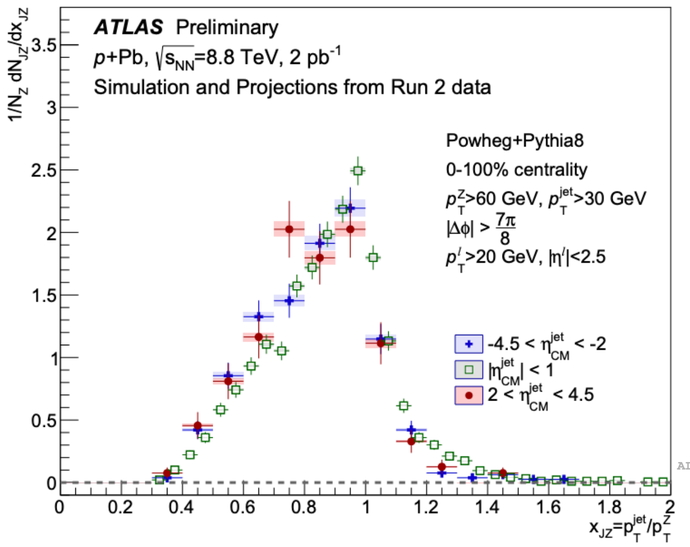
Run 3+4: quantify hierarchy light flavour — heavy flavour

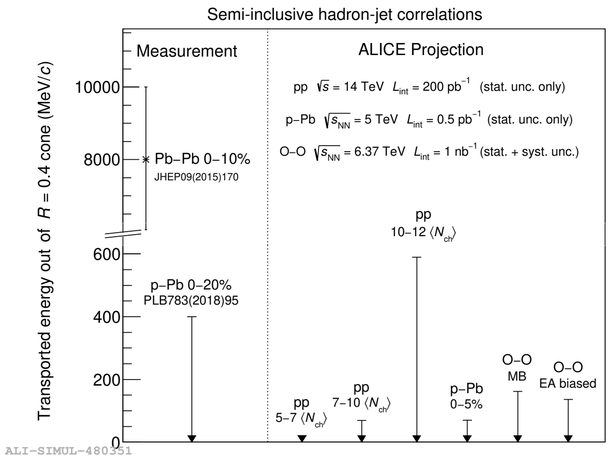
*Is flow built up at the quark level or hadron level?*

# Looking for energy loss in pp, p+Pb, O+O in run 3 and 4

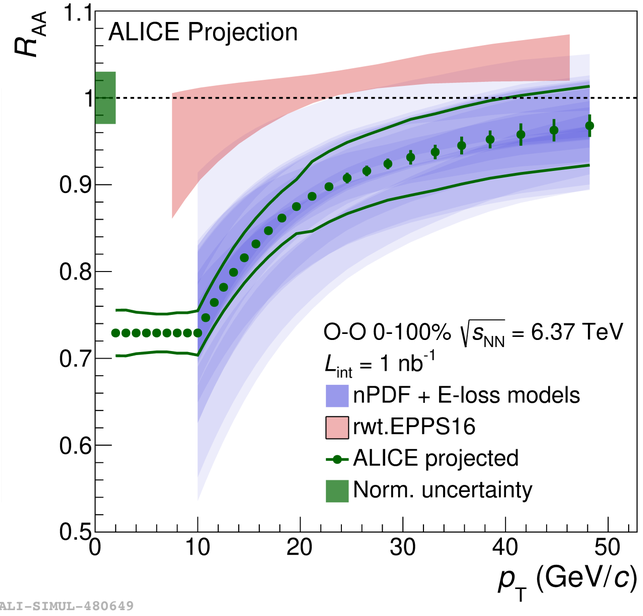



## $\gamma$-jet, Z-jet imbalance




## $R_{AA}$ in OO energy loss



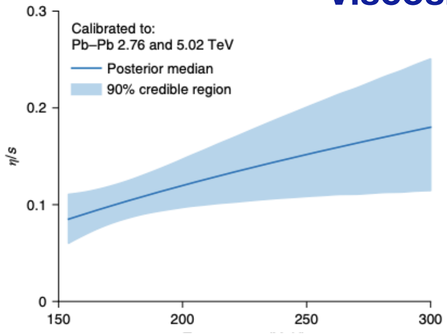

Recoil measurements: $\gamma$/Z-jet and hadron-jet

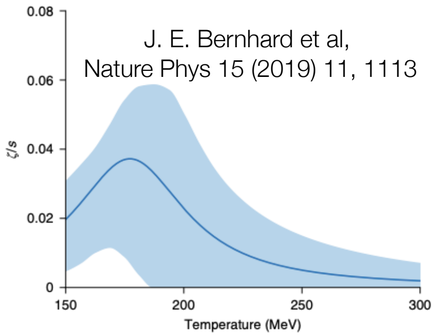
**clean probe of energy loss**

Expect small energy loss ⇒ push to low $p_T$ in pp, p-Pb?

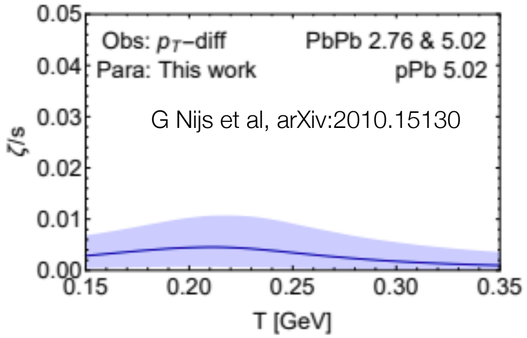
# Determining QGP (transport) properties

## Viscosity

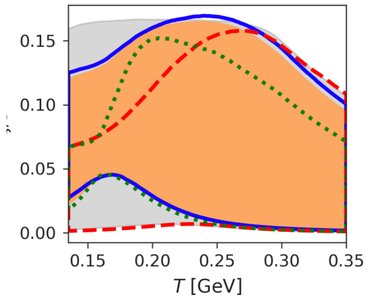


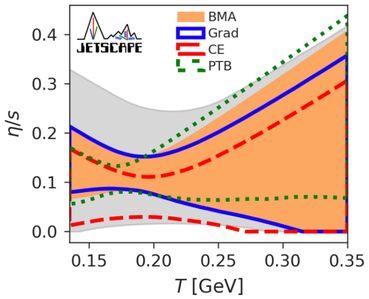




J. E. Bernhard et al,
Nature Phys 15 (2019) 11, 1113



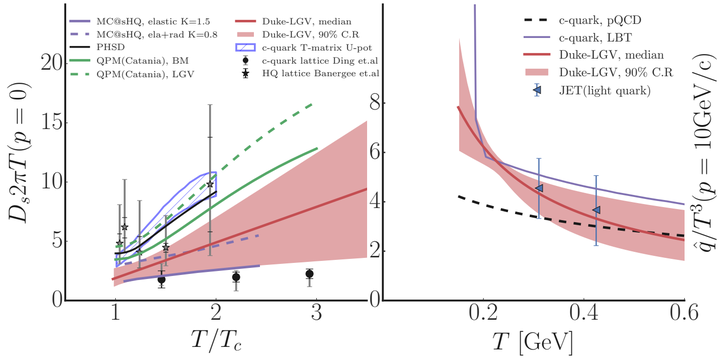

G Nijs et al, arXiv:2010.15130



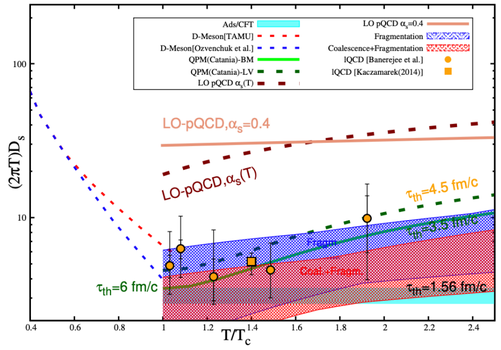




JETSCAPE, PRL 126, 242301

## Heavy quark diffusion coefficient

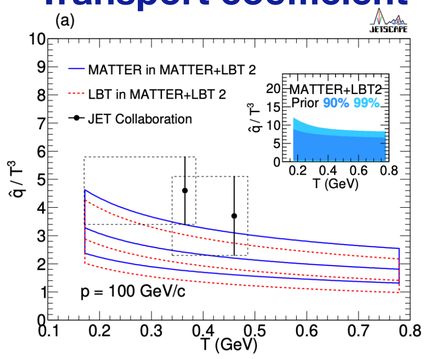



Y. Xu et al, PRC 97, 014907

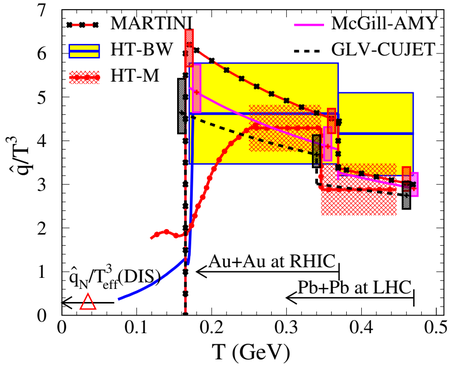



S. K. Das et al PLB747, 260

## Transport coefficient

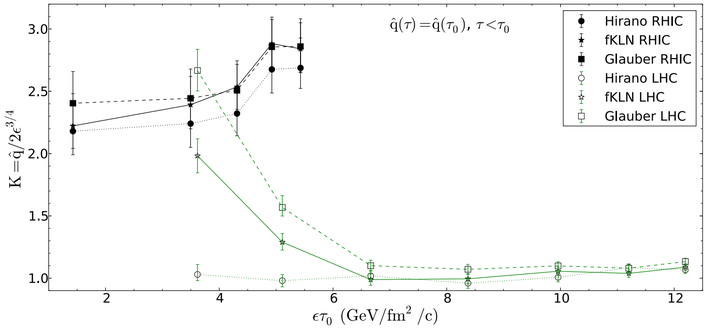



JETSCAPE, PRC 104, 024905

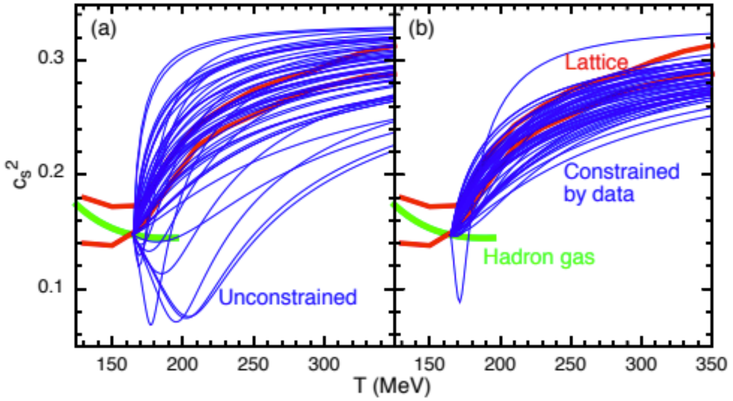



Burke et al, arXiv:1312.5003

Armesto et al, arXiv:1606.04837



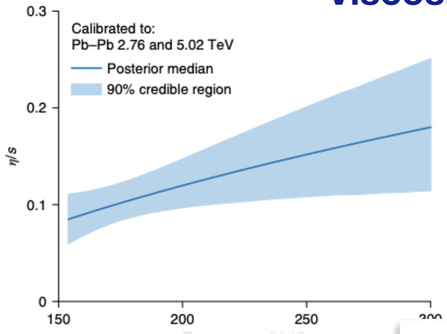

## Equation of state

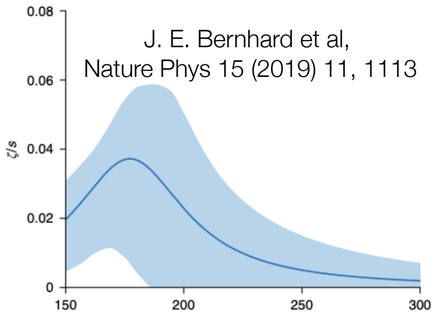



Pratt, Sangeline, et al, *PRL* 114, 202301

# Determining QGP (transport) properties

## Viscosity

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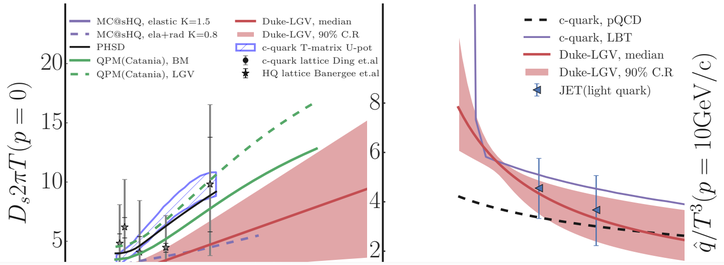


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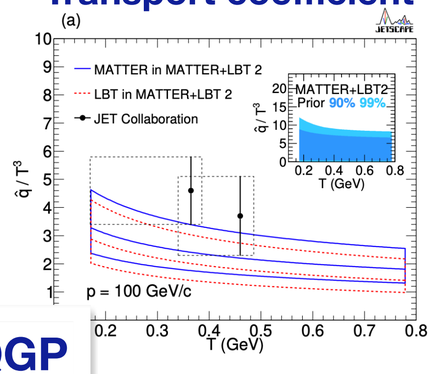
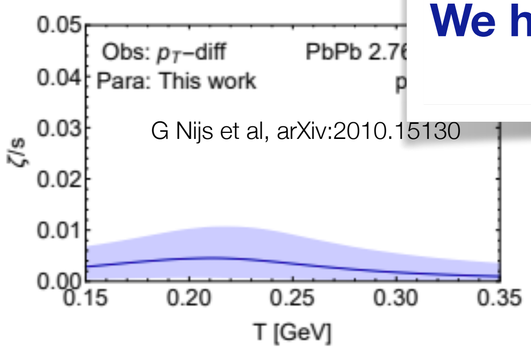
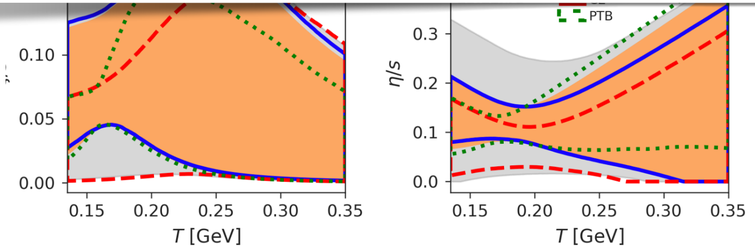



JETSCAPE, PRC 104, 024905

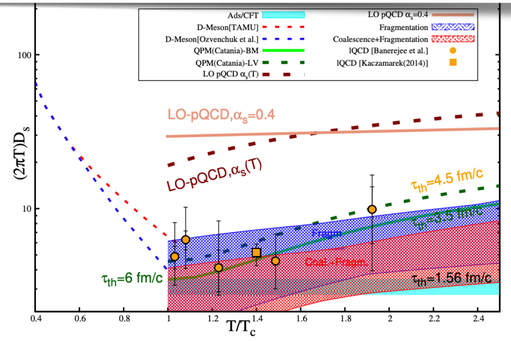
**We have a clear understanding of multiple transport properties of the QGP and the main 'systematic' uncertainties!**



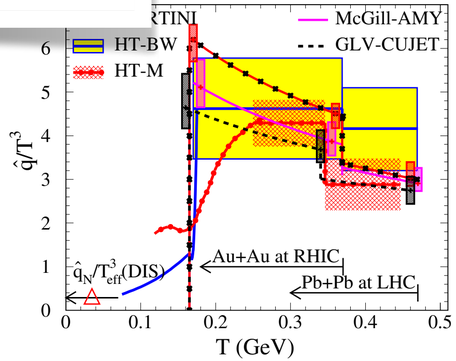

G Nijs et al, arXiv:2010.15130




JETSCAPE, PRL 126, 242301




S. K. Das et al PLB747, 260

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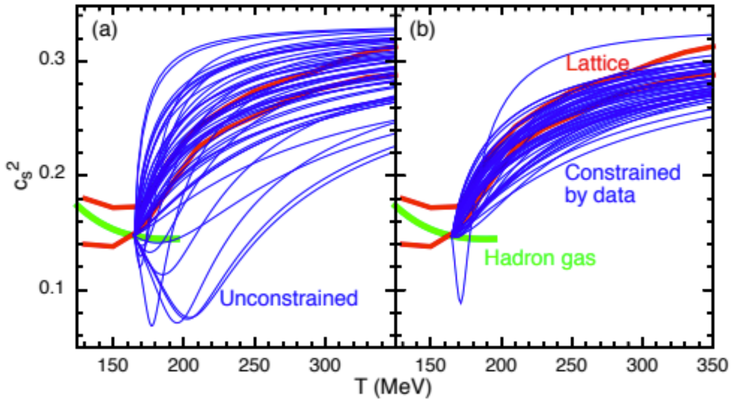
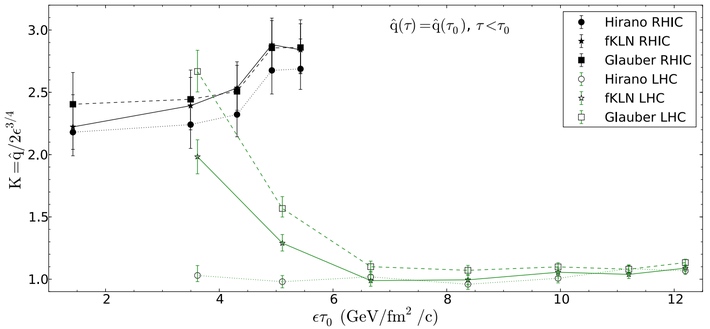
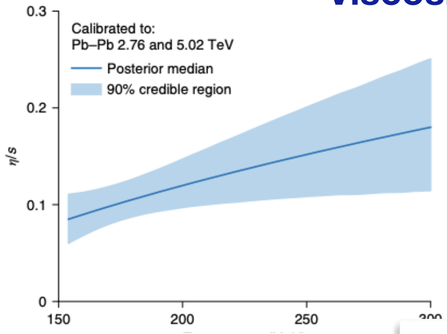


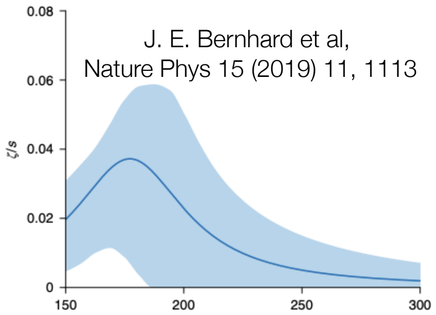

Pratt, Sangeline, et al, *PRL* 114, 202301



# Determining QGP (transport) properties

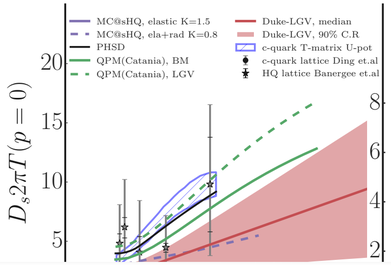
**Viscosity**

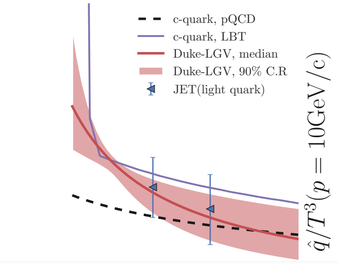


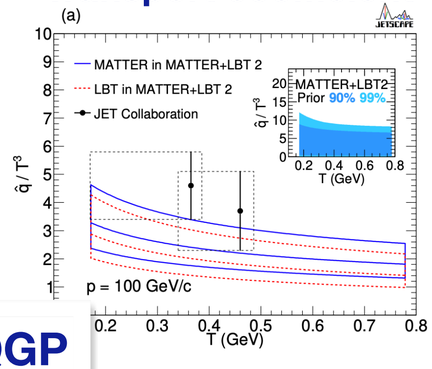

J. E. Bernhard et al,
Nature Phys 15 (2019) 11, 1113

**Heavy quark diffusion coefficient**



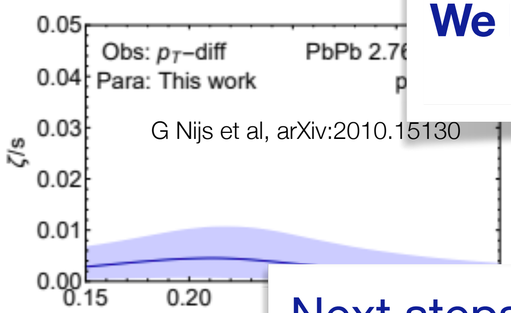




**Transport coefficient**

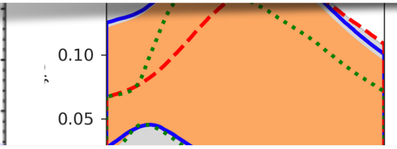


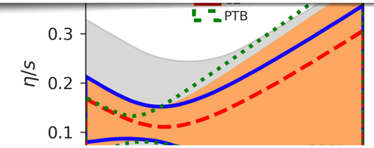

JETSCAPE, PRC 104, 024905

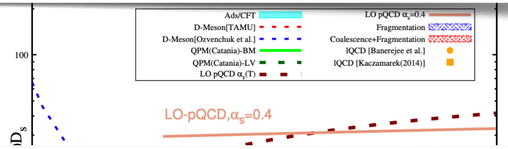
**We have a clear understanding of multiple transport properties of the QGP and the main 'systematic' uncertainties!**



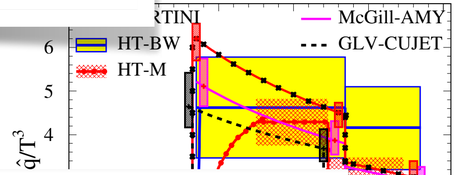

G Nijs et al, arXiv:2010.15130






S. K. Das et a

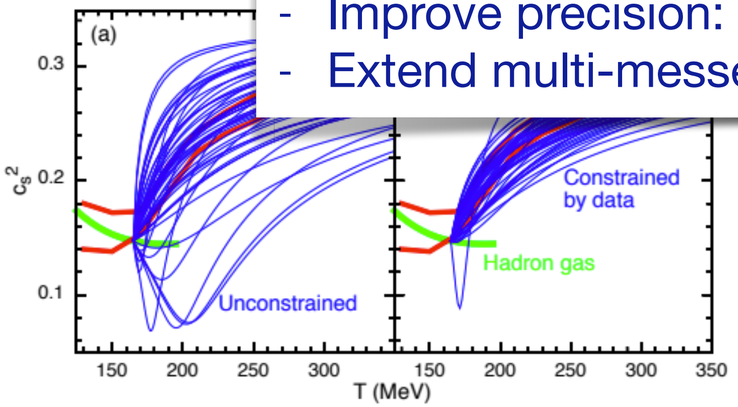



Burke et al, arXiv:1312.5003

Next steps:

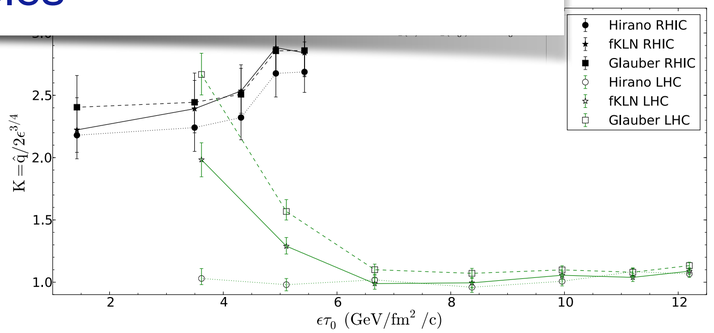
- New inputs for several 'systematic uncertainties' (e.g. hadronisation, medium response)
- Improve precision: narrow down uncertainties
- Extend multi-messenger approach: more (differential) observables

**stress-test modeling**



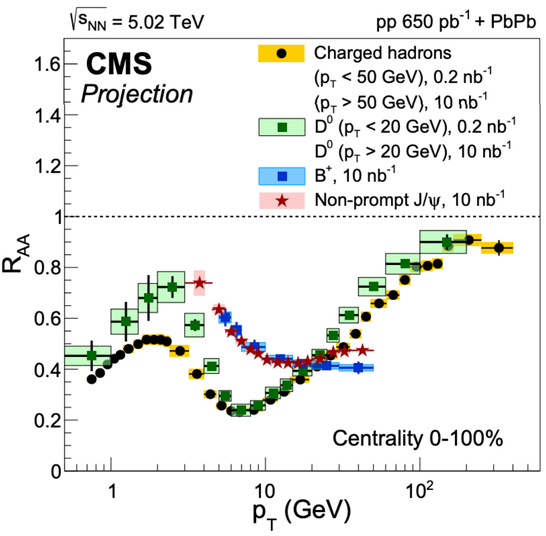

Pratt, Sangeline, et al, *PRL* 114, 202301

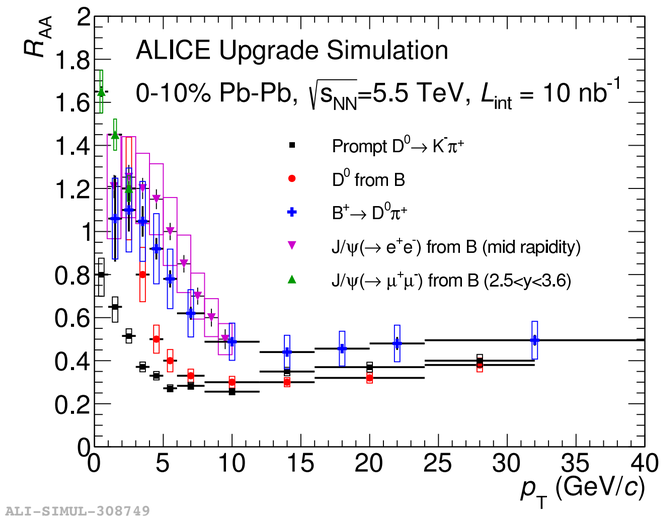
:1606.04837



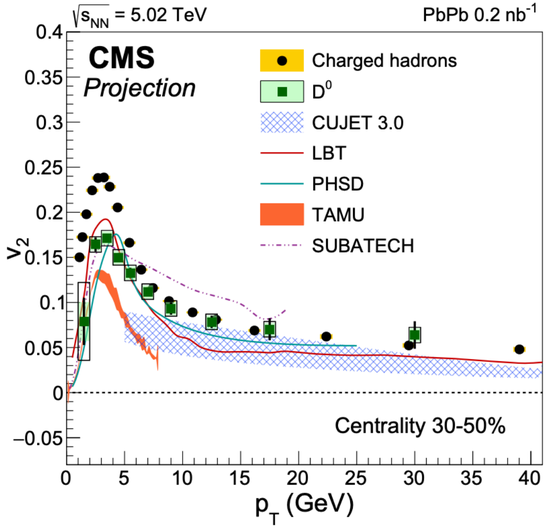
# Determining transport coefficients: heavy flavour

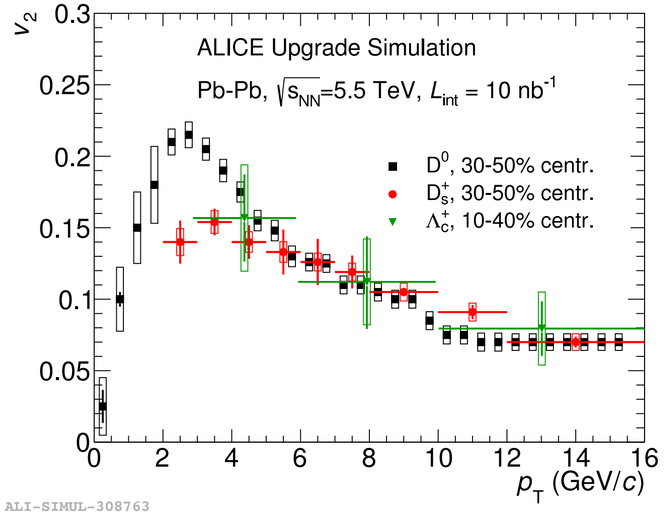
Nuclear modification factor $R_{AA}$




Elliptic flow $v_2$



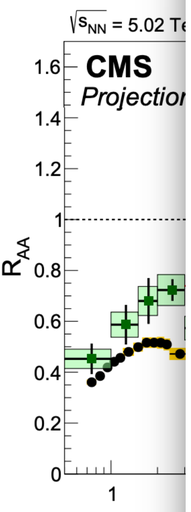




Measure $R_{AA}$ and $v_2$ of charm to determine transport coefficients, and test/validate models at the same time

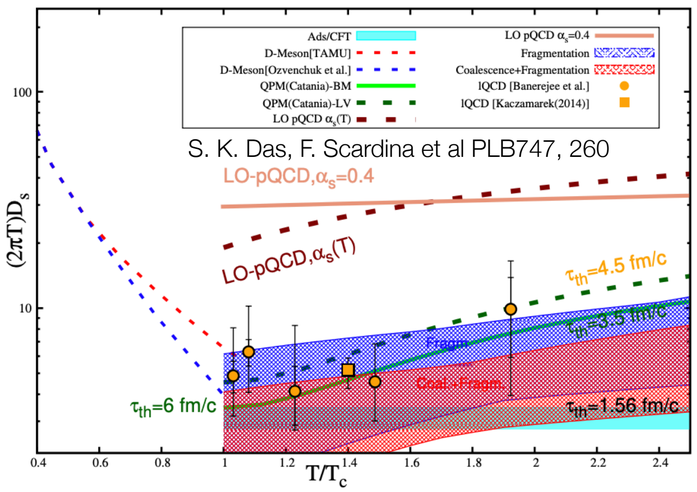
Run 3+4: high-precision beauty measurements; heavy flavor baryons

New techniques being added to repertoire, e.g. event shape engineering

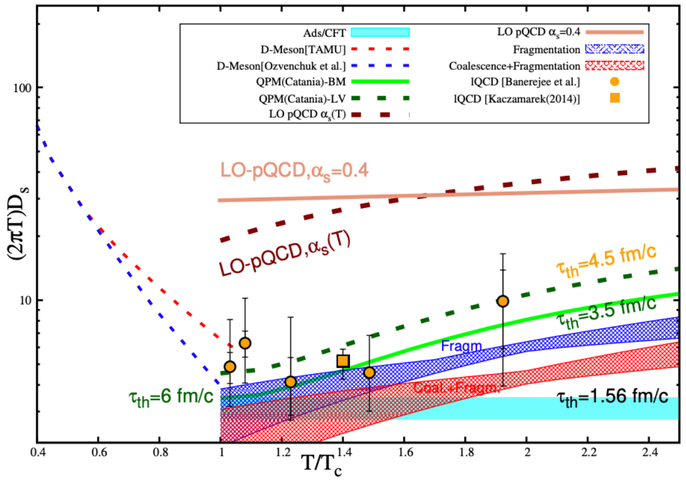
# Determining transport coefficients: heavy flavour



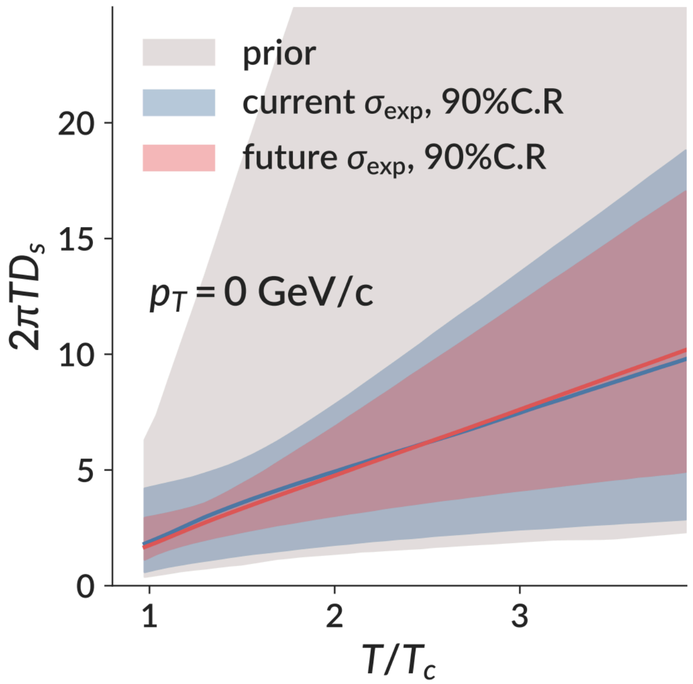

Current state




With run 3+4 data




Improvement on $D_s$ uncertainties




Y. Xu, J. E. Bernhard, et al, PRC97, 1, 014907

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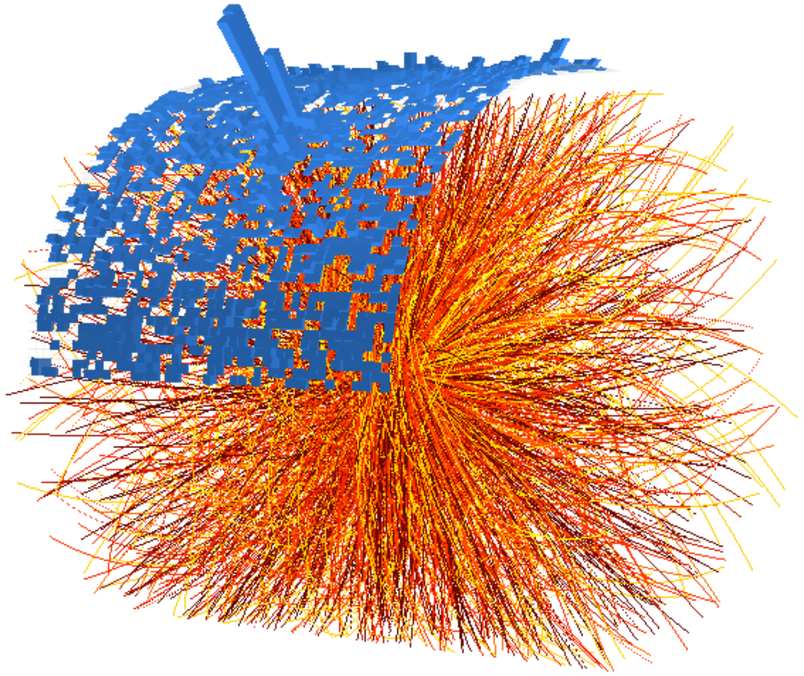
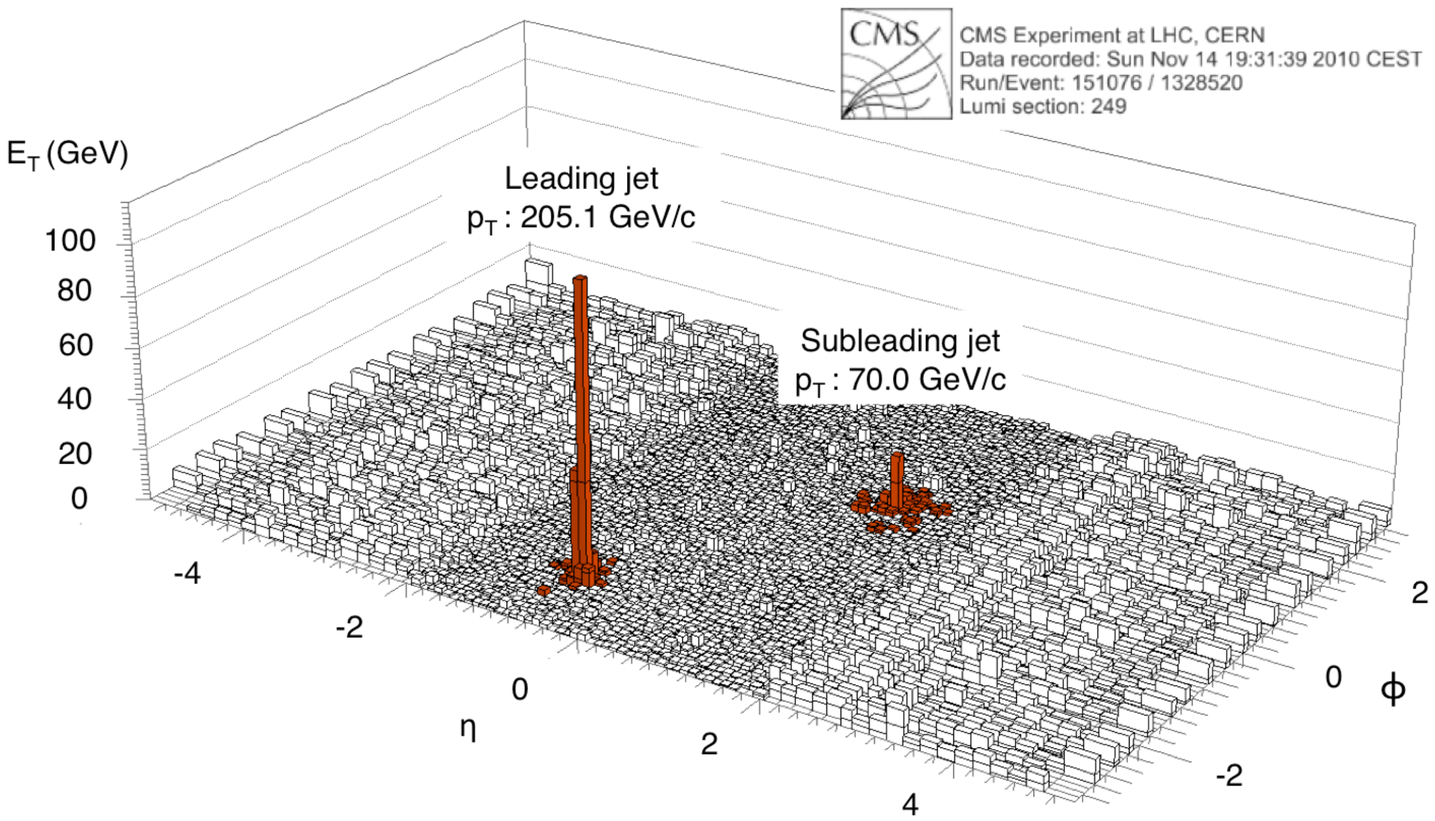
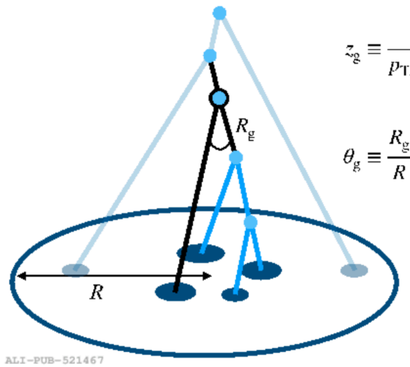
# Probing the QGP with jets at LHC



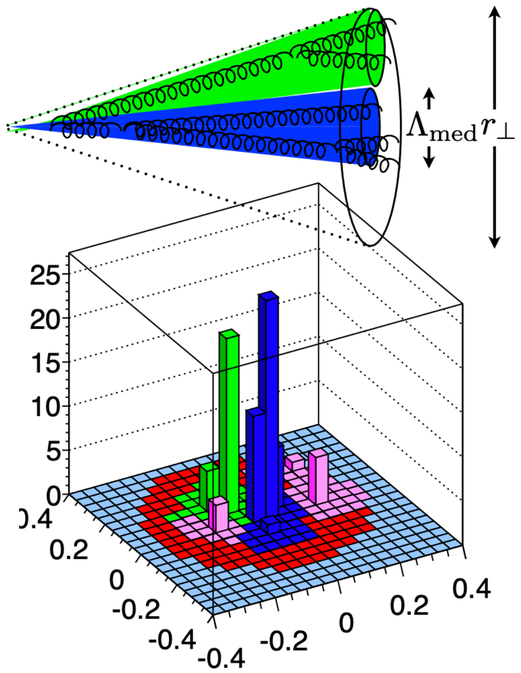


# Jet shapes and jet structure




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

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

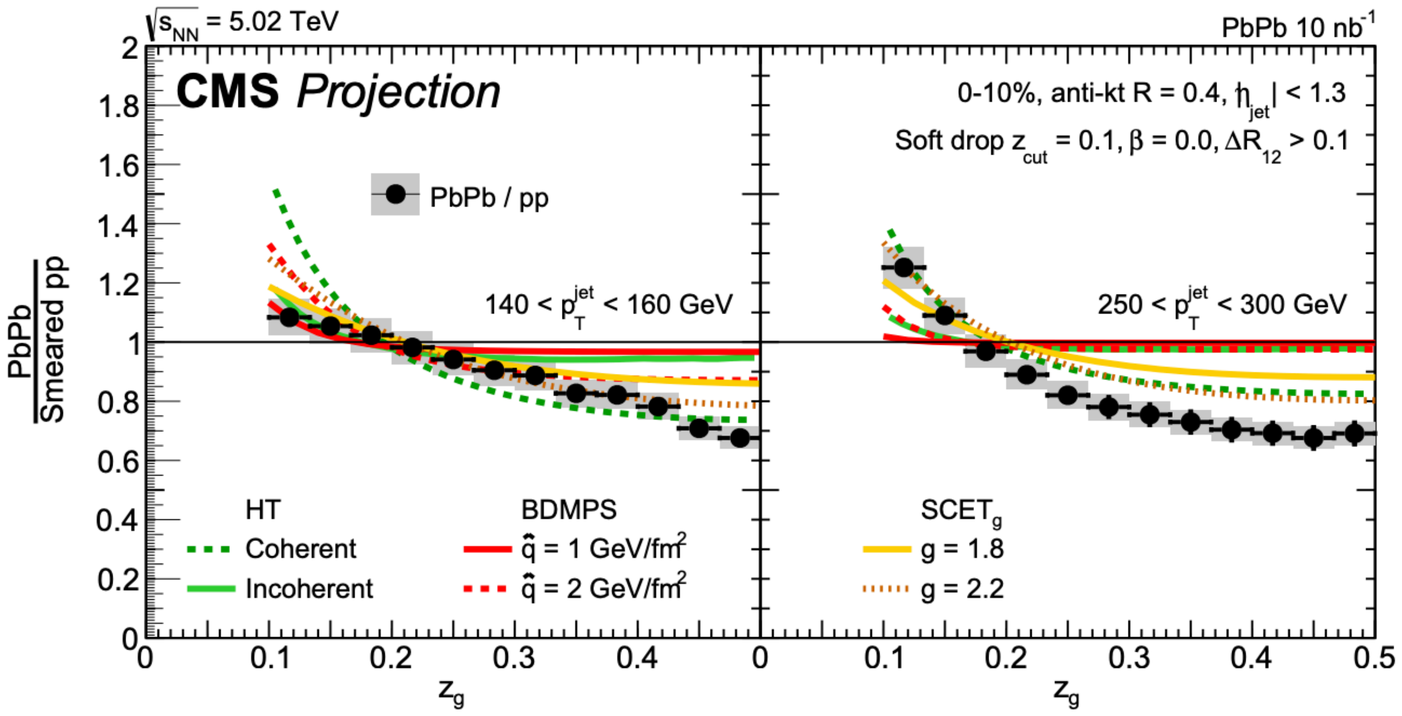



- Motivation: study radiation patterns:
  - hard medium-induced branchings
  - coherence
  - hard recoil/acoplanarity
  - soft radiation + medium response

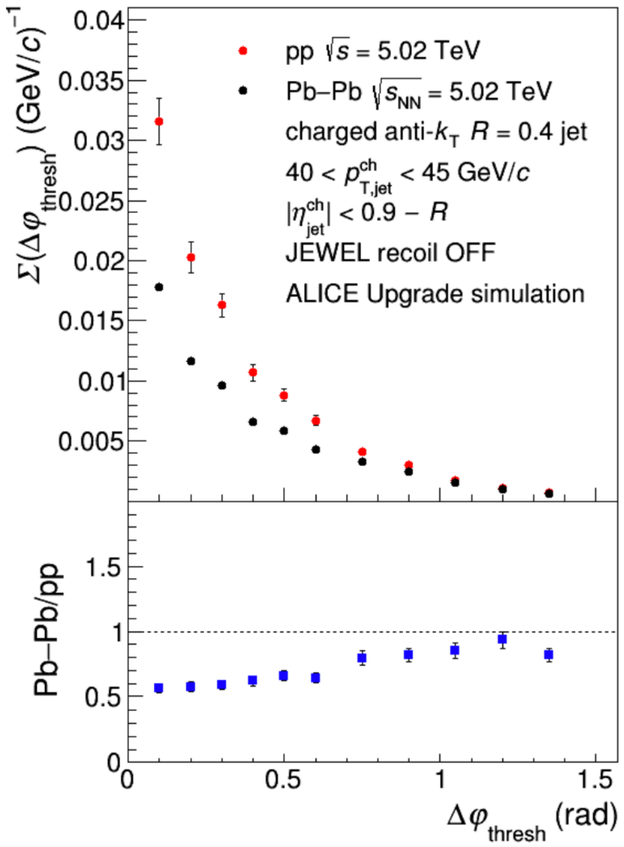
Different observables being explored
⇒ understanding of sensitivity to physics effects evolving

# Run 3 and 4: improved precision

Jet structure: softdrop $z_g$



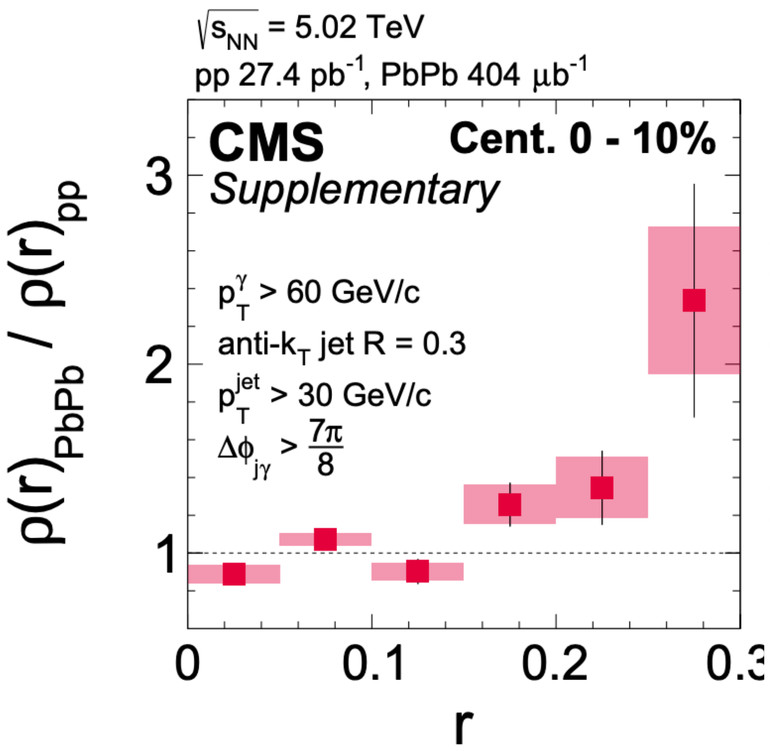

h-jet acoplanarity



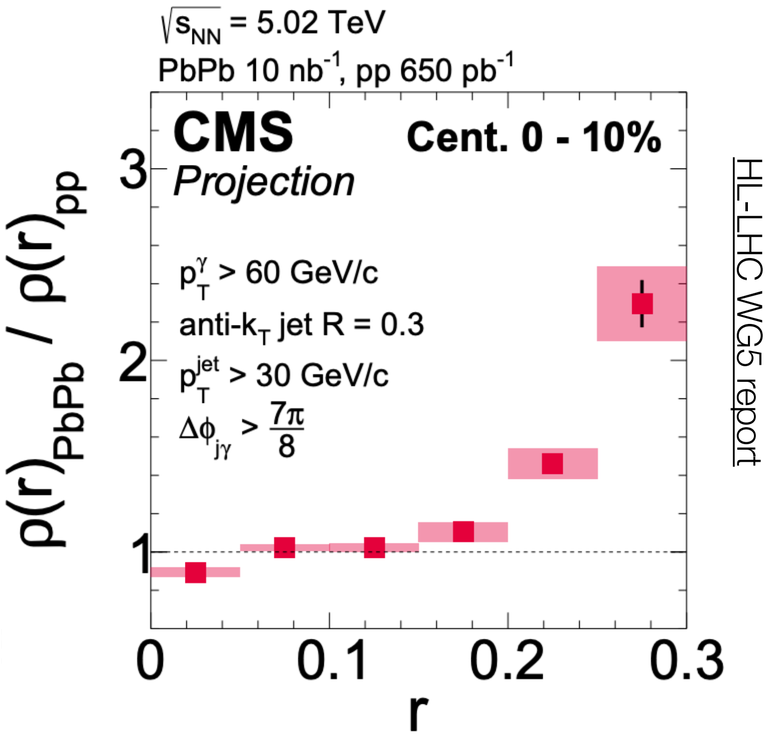

**Improving precision in multiple observables key to disentangle physics mechanisms**

# Jet structure: radial profiles

Current result (2015)

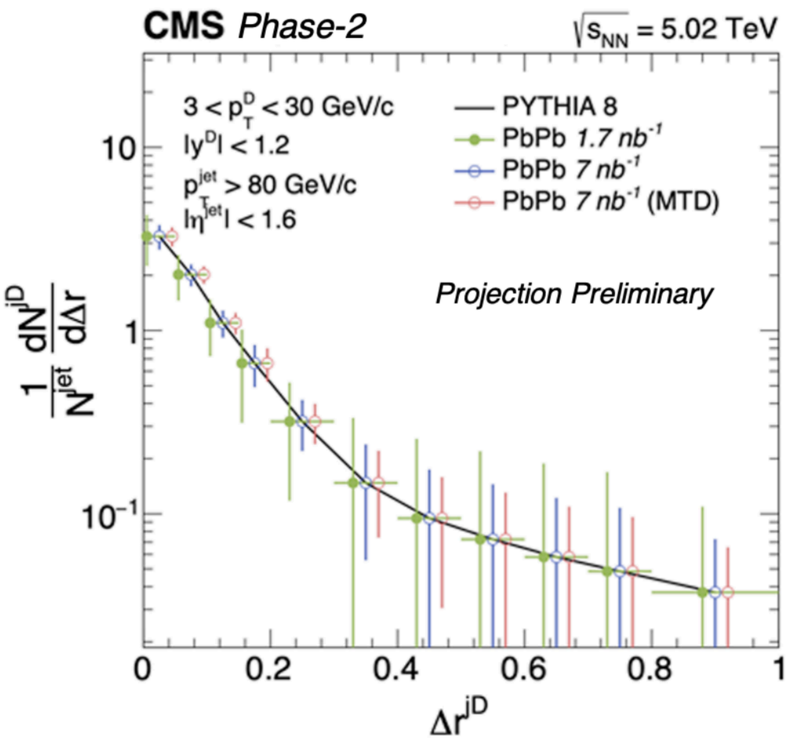



Run 3 + 4 projection




HL-LHC WG5 report

Radial distribution of D-mesons




CMS-DP-2021-037

Large angle radiation: small signal on large background:
Need large samples from 3 and 4 for precision

… and extend to heavy flavour

# Challenge/opportunity: fluctuations

- Degree of quenching differs from jet to jet:
  - path length variations
  - coherence/dependence on early emissions
  - intrinsic ‘quantum’ fluctuations

**Challenge**: e.g. inclusive jet measurements tend to reflect jets with small modifications

**Opportunity**: study/leverage physics origins of fluctuations

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- Recoils/correlations: hadron-jet, jet-jet, boson-jet

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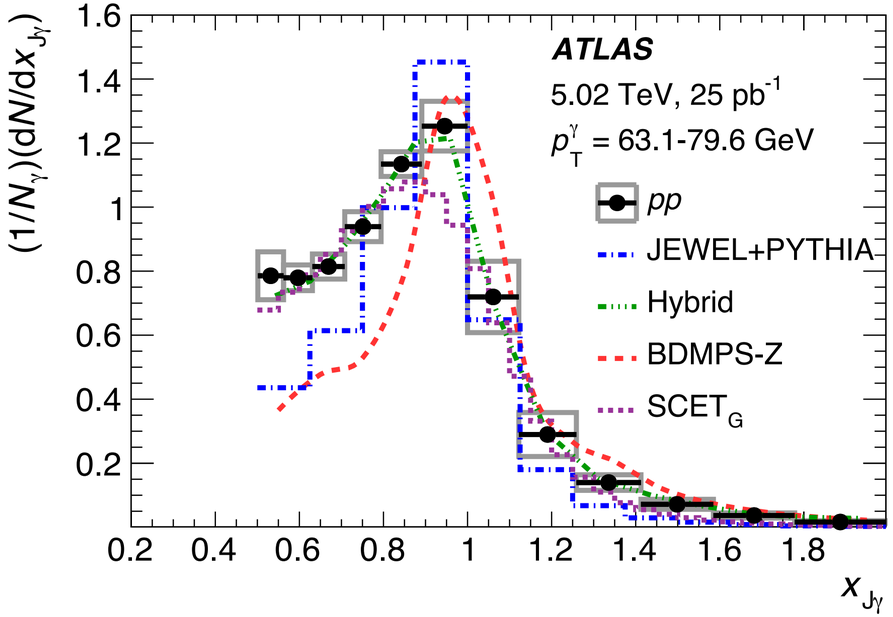
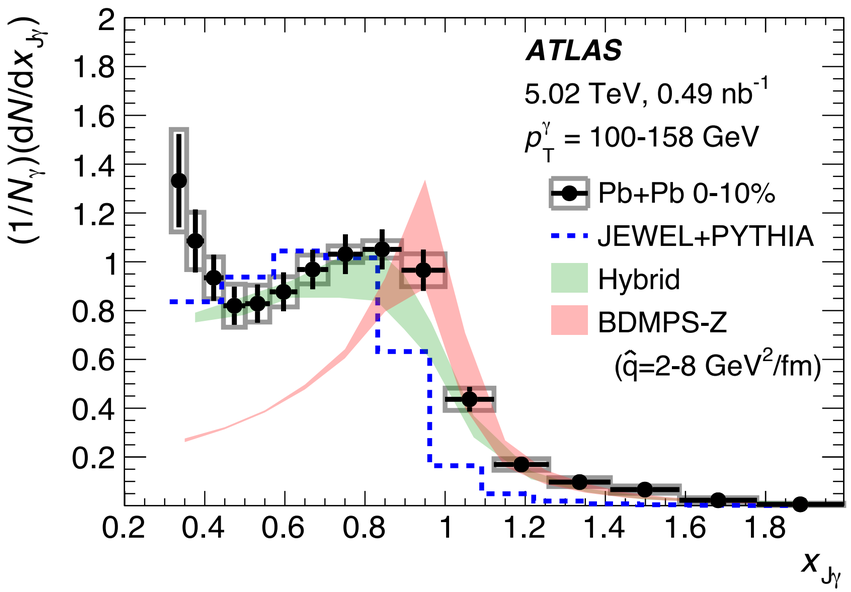
⇒ Differential studies require large data samples

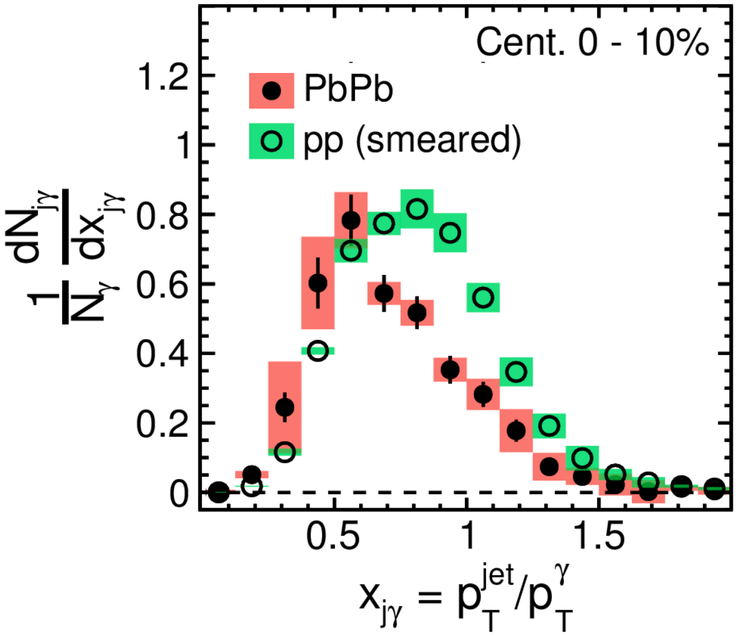
# $\gamma$-jet energy balance: sensitive to fluctuations

proton-proton

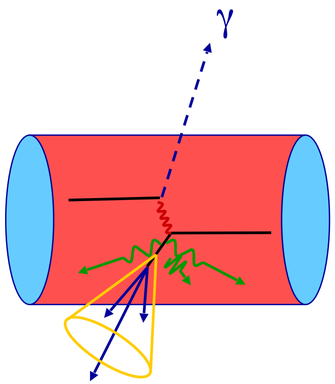



Central Pb-Pb




CMS, PLB 785, 14



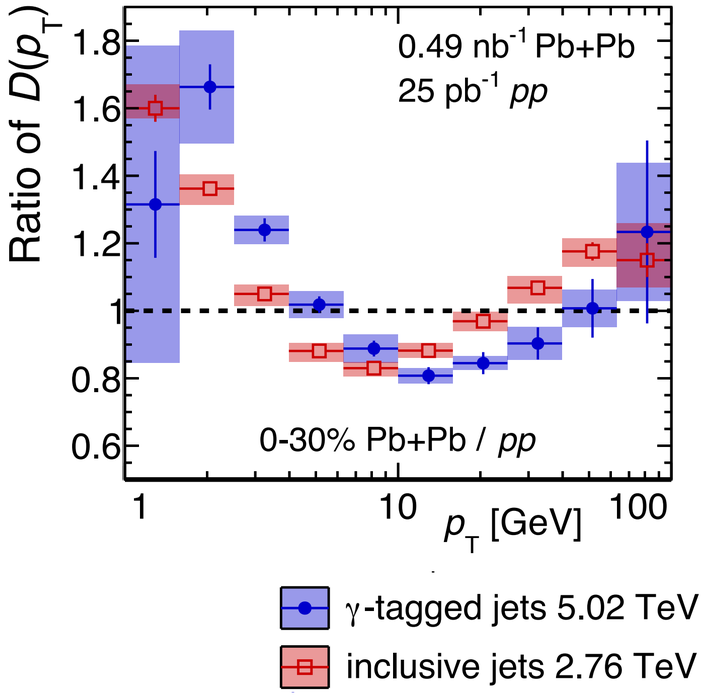

Broadening of distribution is a measure of energy loss fluctuations:
Events with small $x_{j\gamma}$ correspond to large loss

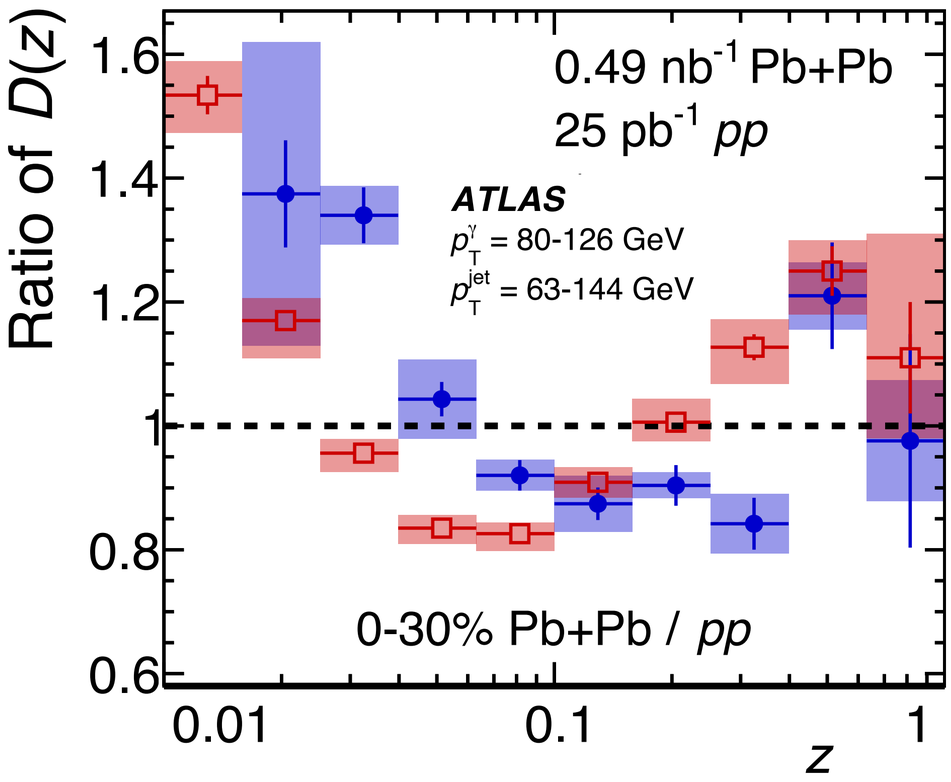
**Opportunity: select on asymmetry to study heavily modified jets**

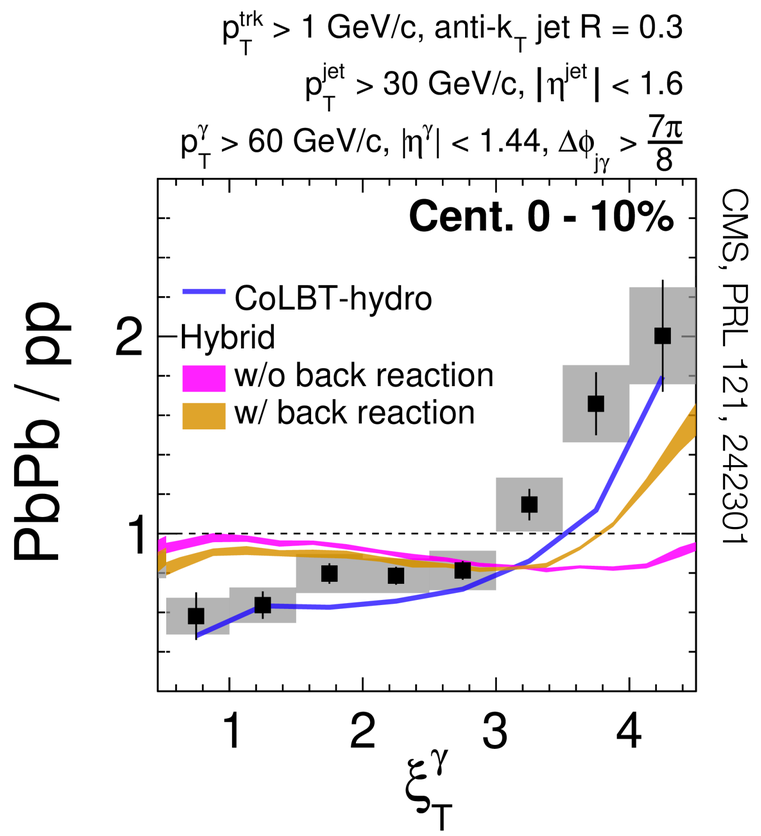
Challenge: comparison to pp — use inclusive sample as reference?

Large statistics measurements in run 3 and 4 will explore this

# Recoil jet fragmentation




- $\gamma$-jet and jet-jet
  - different selection bias: reconstructed energy vs gamma energy
  - quark vs gluon (inclusive) jet

$$z = \frac{p_{T,\mathrm{part}} \cos(R_i)}{p_{T,\mathrm{jet}}}$$

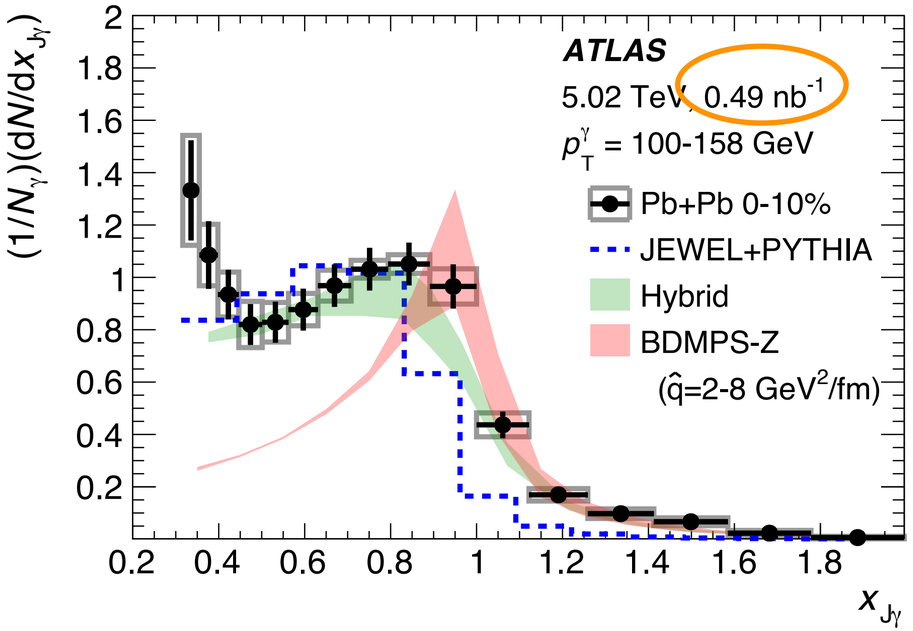
$$\xi_T^\gamma = \ln \frac{E_\gamma}{p_{T,\mathrm{part}}}$$

**$\gamma$-jet: important tool to reduce/use biases**

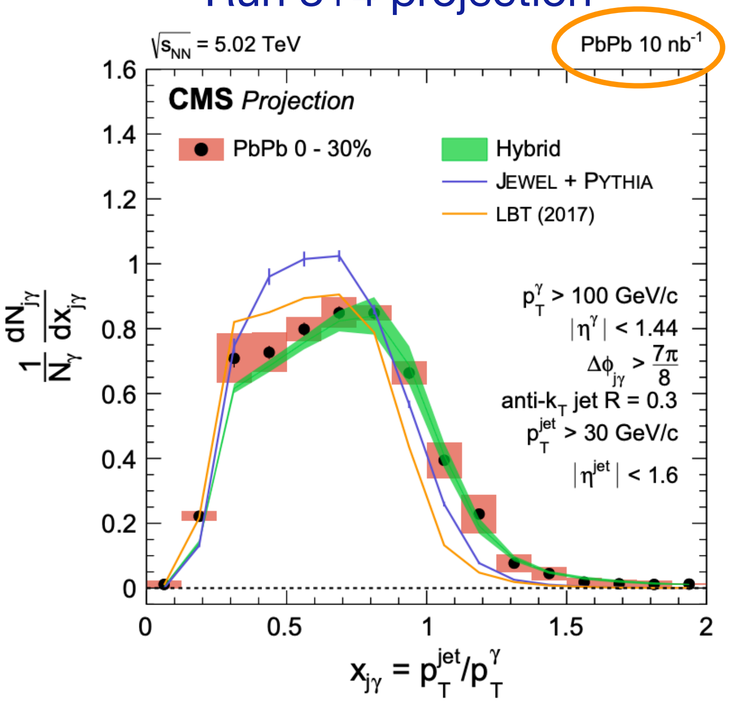
# $\gamma$-jet: outlook for 3 and 4

Momentum balance

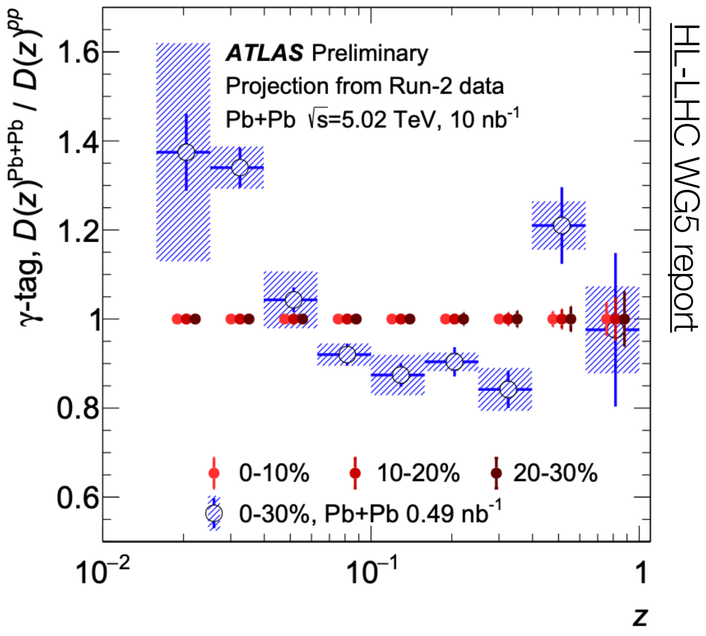
Current result




Run 3+4 projection




Fragment distributions $\gamma$-jet

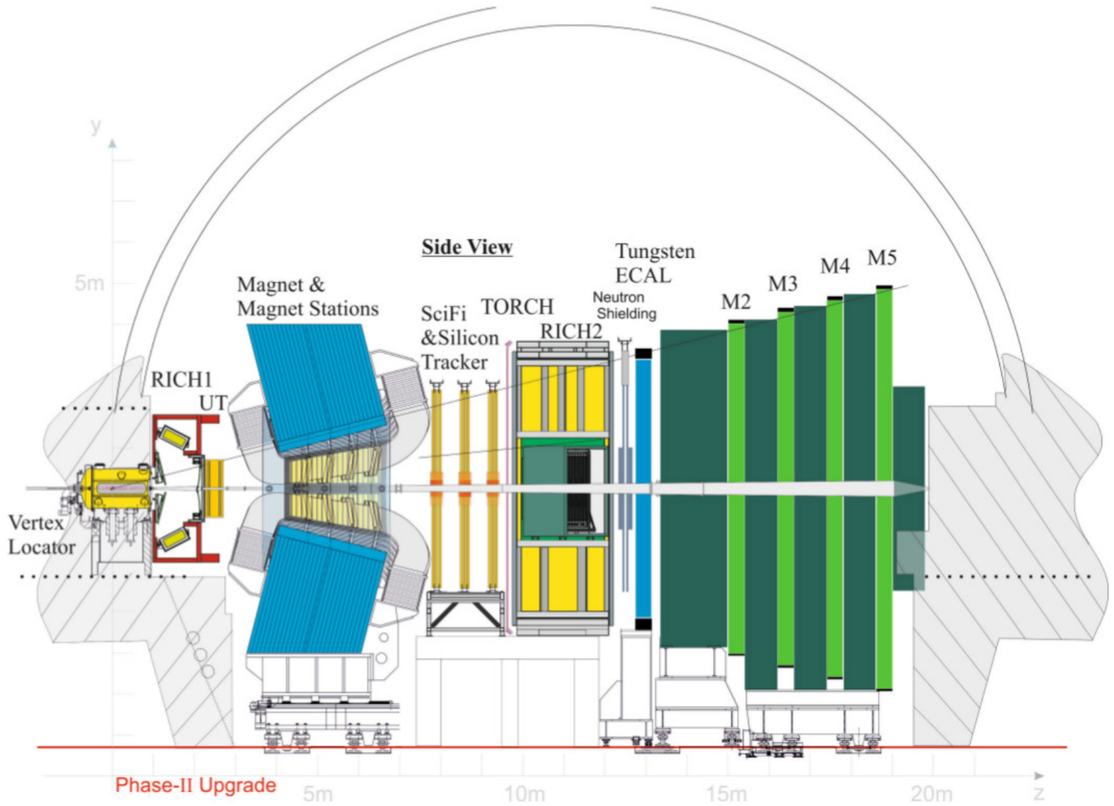



Run 3 and 4 samples needed to fully exploit $\gamma$ - jet as a tool to differentiate mechanisms/models

**Opportunities to go more differential in most cases**

# Beyond run 3 and 4

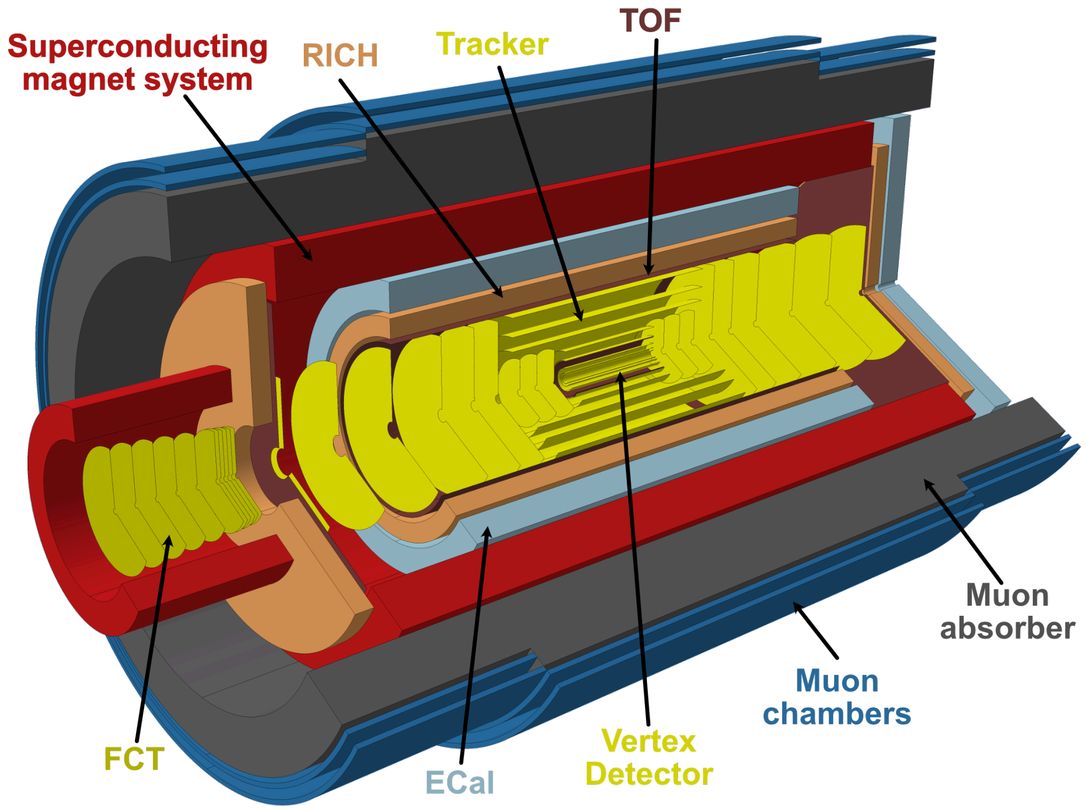
## LHCb II




CERN-LHCC-2021-012

LHCb II: extensive upgrades for higher rates (pile-up rejection)
Tracker expected to be able to **handle central Pb-Pb**

## ALICE 3




LoI: CERN-LHCC-2022-009

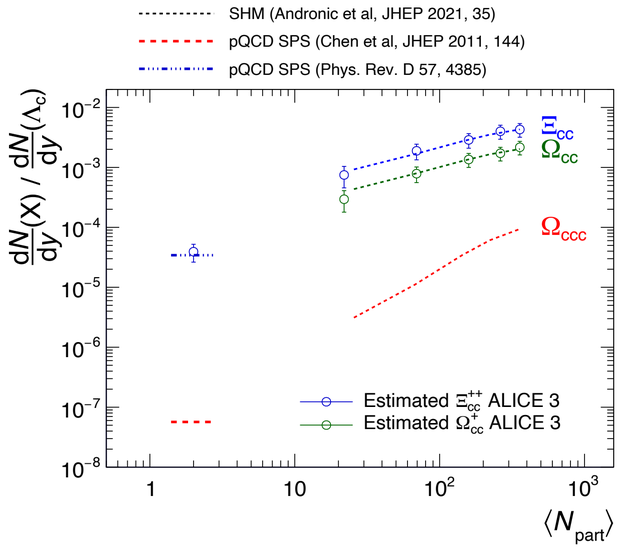
ALICE 3: Large acceptance with **excellent pointing**, electron, hadron **ID**, EMCal and muon ID

ATLAS and CMS phase II upgrades for Run 4

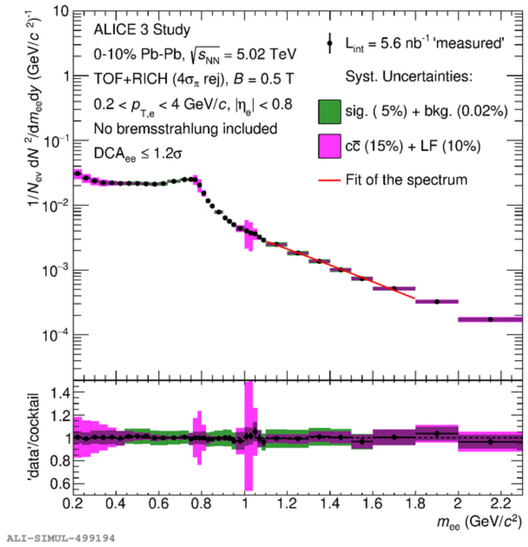
# ALICE 3 physics program

- **Thermal radiation, chiral symmetry restauration**
  - Di-electron mass, $p_T$ spectra, $v_2$
- **Heavy flavour transport, thermalisation**
  - Beauty meson, baryon $v_2$
  - $D\overline{D}$ azimuthal correlations
  - Multi-charmed baryons
- Hadron interactions, structure
- Net-quantum-number fluctuations
- (Forward) Ultra-soft photon production
- BSM searches, e.g. ALPs

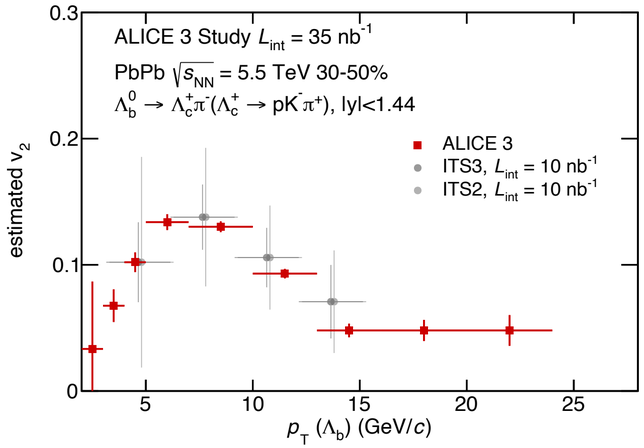
multi-charm baryons



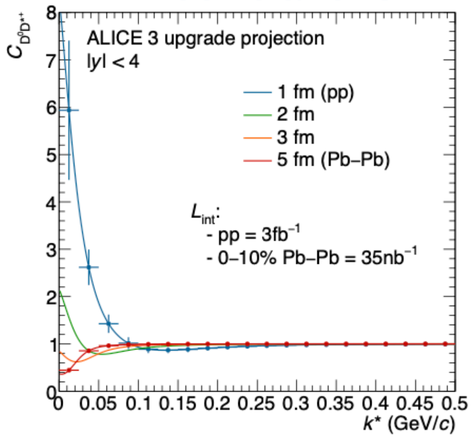

di-electron mass




$\Lambda_b$ $v_2$ performance

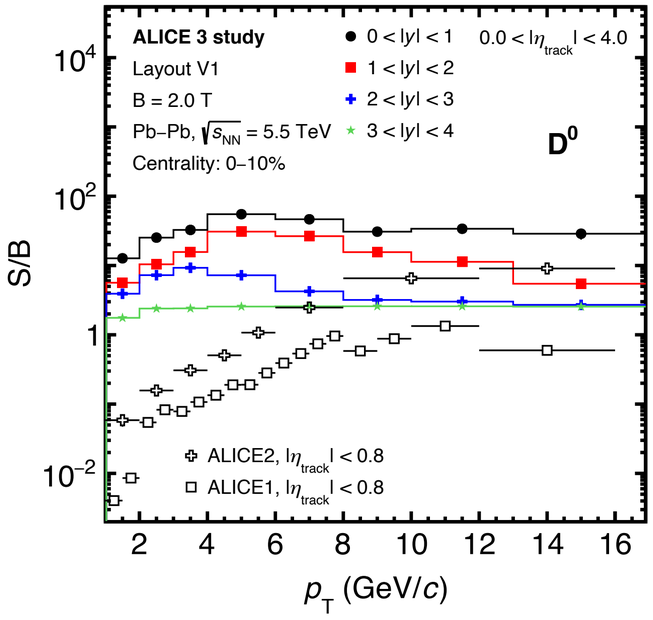



DD* correlations

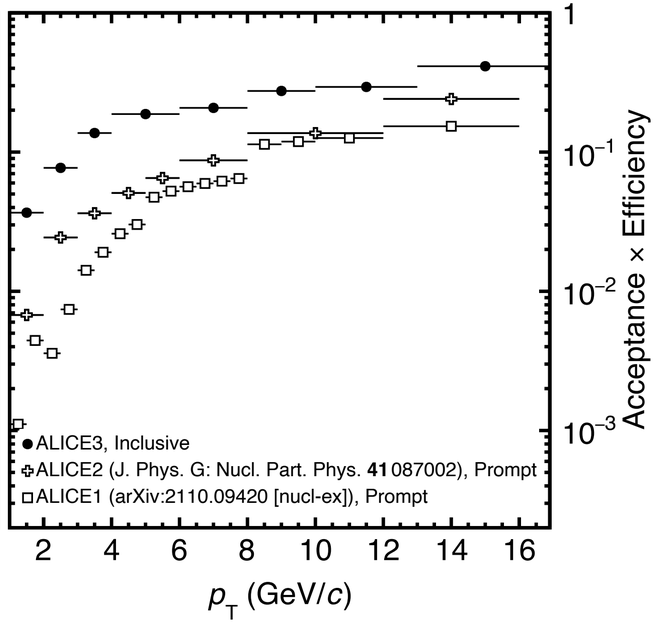


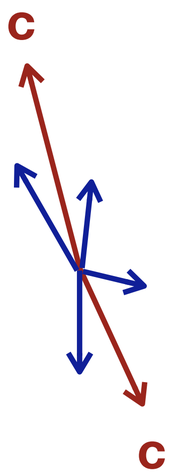
# ALICE 3 example: open heavy flavour correlations

$D^0$ signal/background

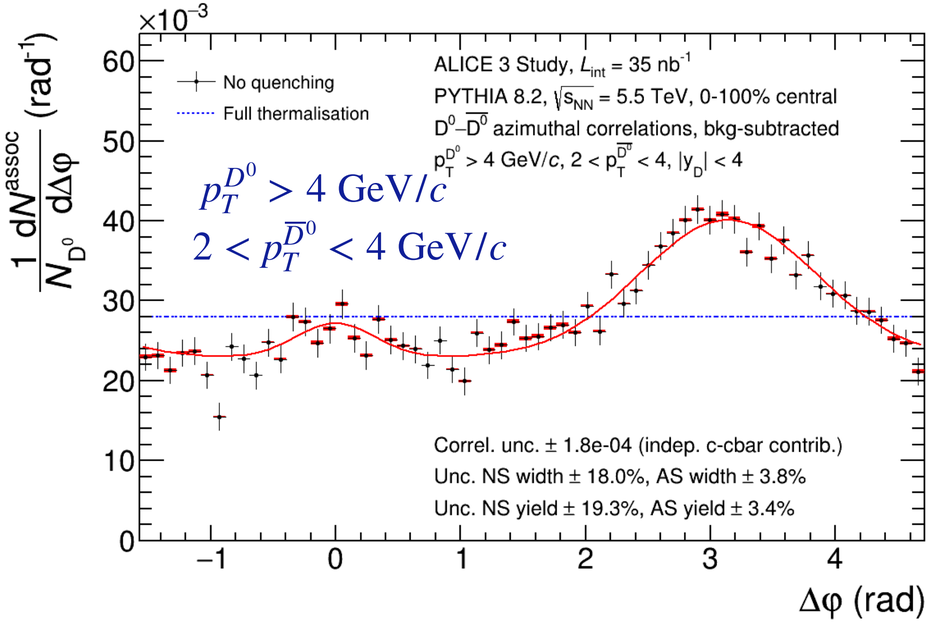



Efficiency




ALICE 3 projection: $D\overline{D}$ correlations




Excellent pointing resolution and PID:
**Large S/B and efficiency**
10-20x ALICE 1 and ITS 2 at $p_T$ < 4 GeV

High purity key ingredient for $D\overline{D}$ pair measurement

**Access to gluon splitting, HF acoplanarity, HF fragmentation…**

E.g.: FlavorCone algo, Ilten et al, *PRD* 96, 054019

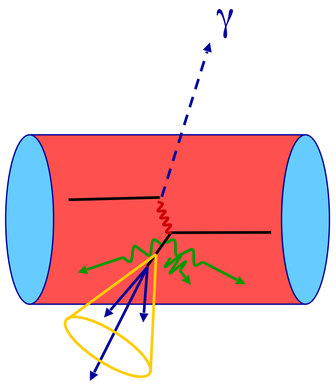
# Summary/conclusions

- LHC experiments are gearing up for run 3 and 4
- Major upgrades of ALICE and LHCb
- Large data samples, improved detectors:
  - Increased precision
  - More differential measurements — e.g. selecting quenched jets
- Run 4: ATLAS and CMS phase II upgrades extend rapidity reach, hadron ID capabilities
- Run 5 and 6: LHCb II and ALICE 3

**Exciting times ahead for jet physics at the LHC**

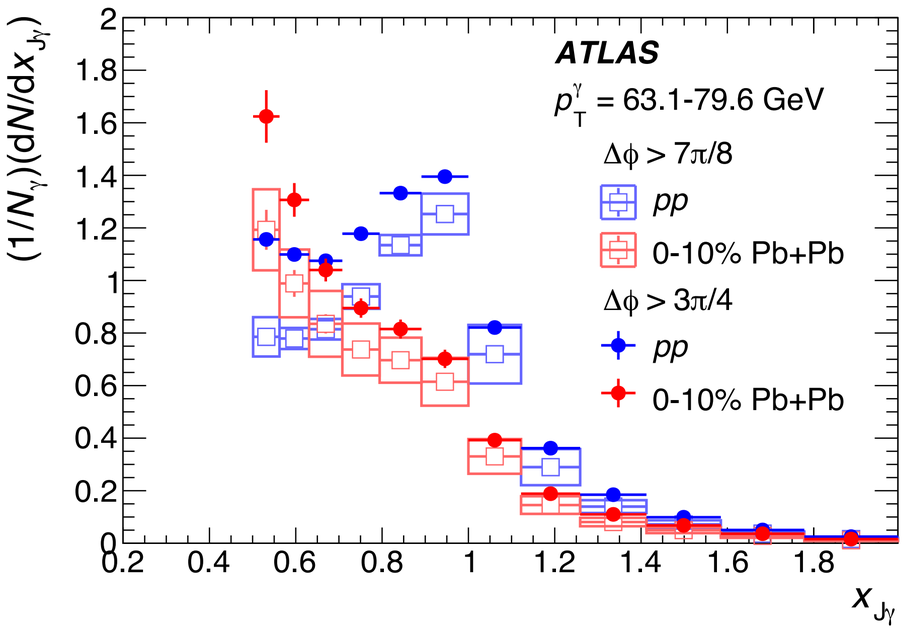
Thank you for your attention!

# Boson-jet example: $\gamma$-jet

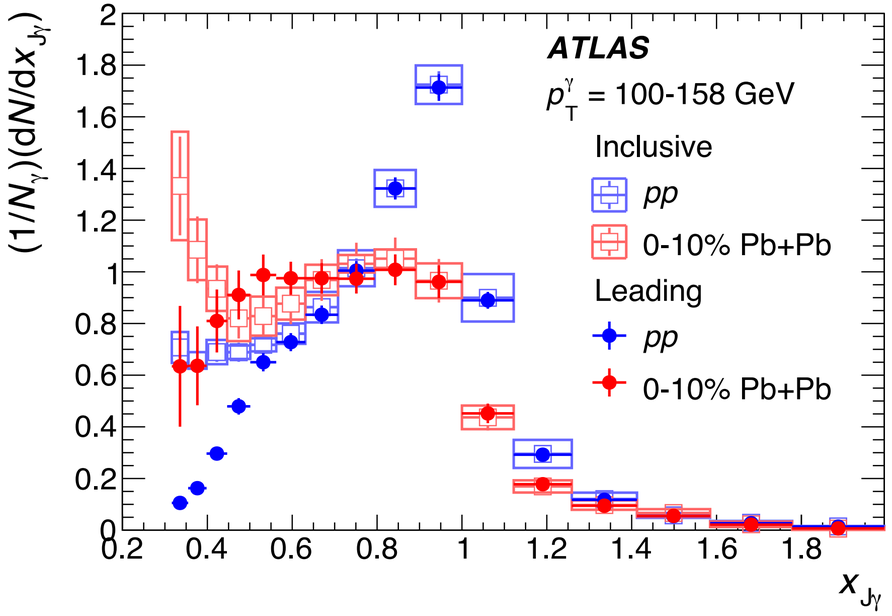



Photon does not lose energy
Clean selection of initial $p_T$

60 GeV trigger photon




100 GeV trigger photon



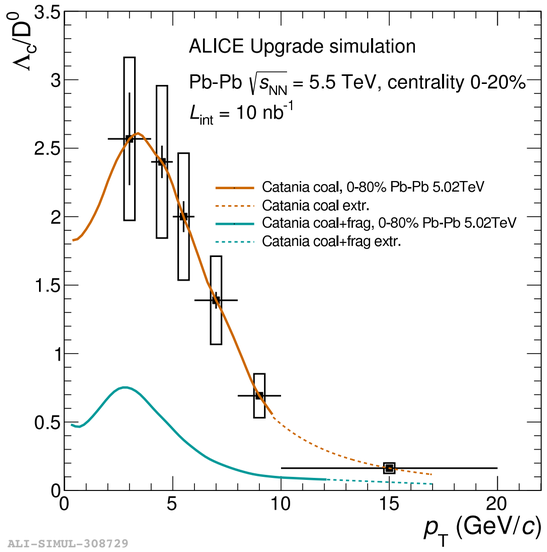

ATLAS, PLB 789,167-190

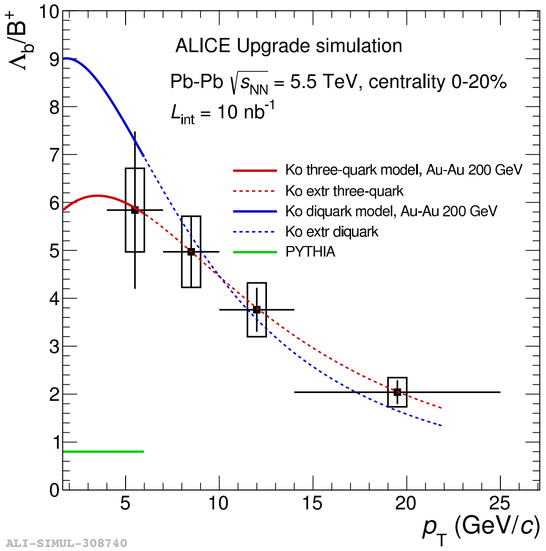
Peak at low $x_{J\gamma}$ from additional jets

Also allows to explore energy dependence of lost energy

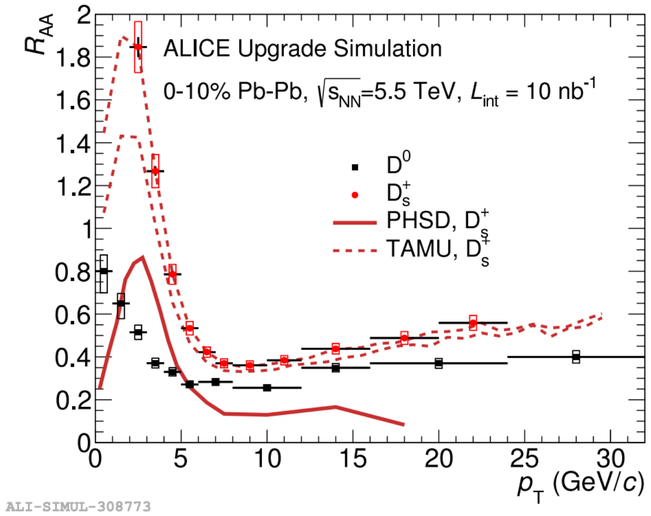
# Heavy flavour hadronisation

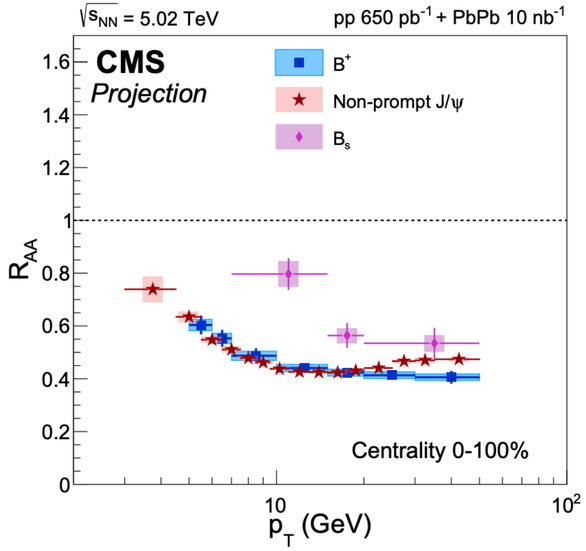
Baryon/meson ratios: charm and beauty




Heavy-strange hadrons: $D_s$ and $B_s$

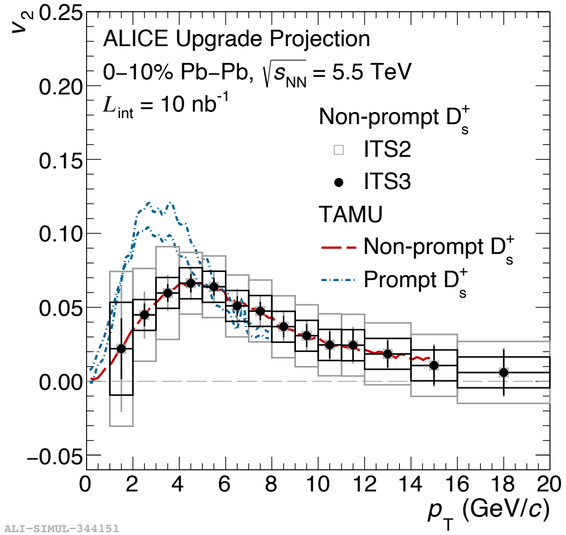



Extend heavy flavour measurements to beauty sector, $D_s$, $B_s$, and baryons

Input for:

- Total HF cross sections: charm balance, shadowing
- Interplay strangeness enhancement and heavy flavors
- Baryon formation — coalescence



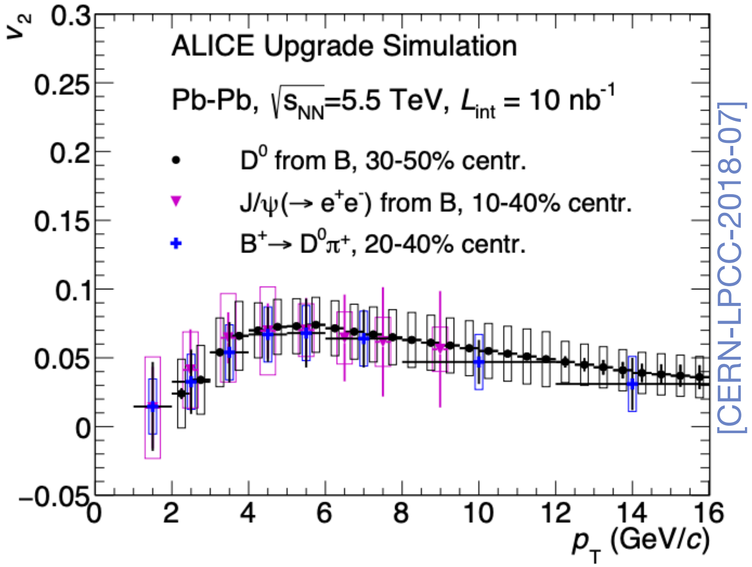

HL-LHC WG5 report

# Heavy-flavour transport (cont'd)

- **Understand transport and thermalisation in the QGP**
  → measurements of $D\bar{D}$ correlations and in the beauty sector
  → statistics and vertexing

$$\tau_Q = (m_Q/T)\, D_s$$

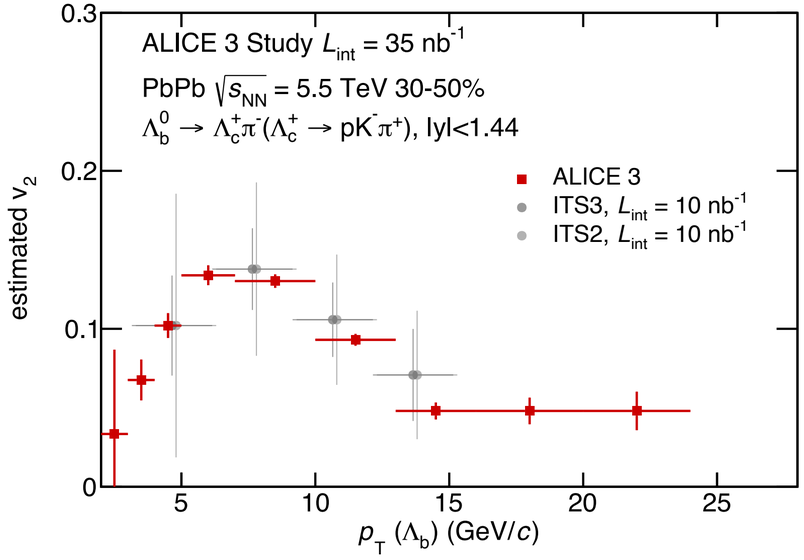
**B meson $v_2$**




[CERN-LPCC-2018-07]

Run 3 & 4

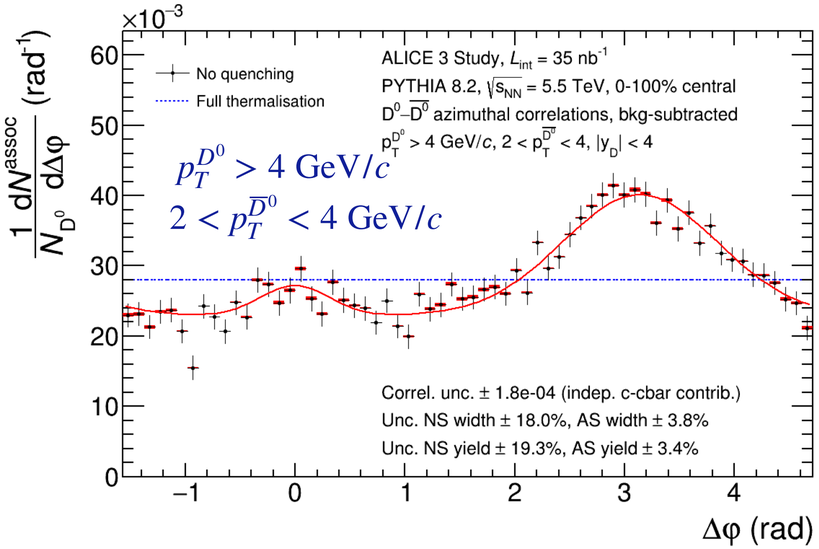
**$\Lambda_b$ $v_2$**




[CERN-LHCC-2022-009]

Run 3 & 4: constraints
Run 5 & 6: precision

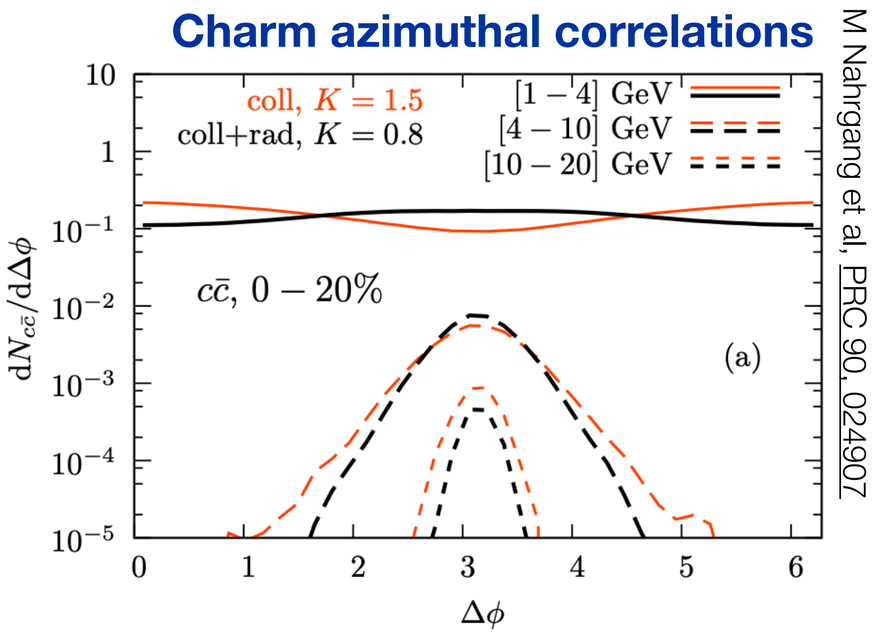
**$c\bar{c} \rightarrow D^0\bar{D}^0$ correlations**

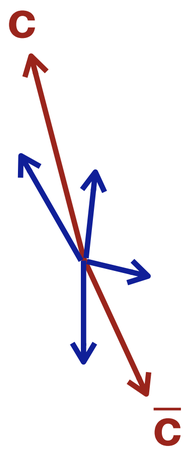



[CERN-LHCC-2022-009]

Run 5 & 6

# In-medium broadening: $D\bar{D}$ azimuthal correlations

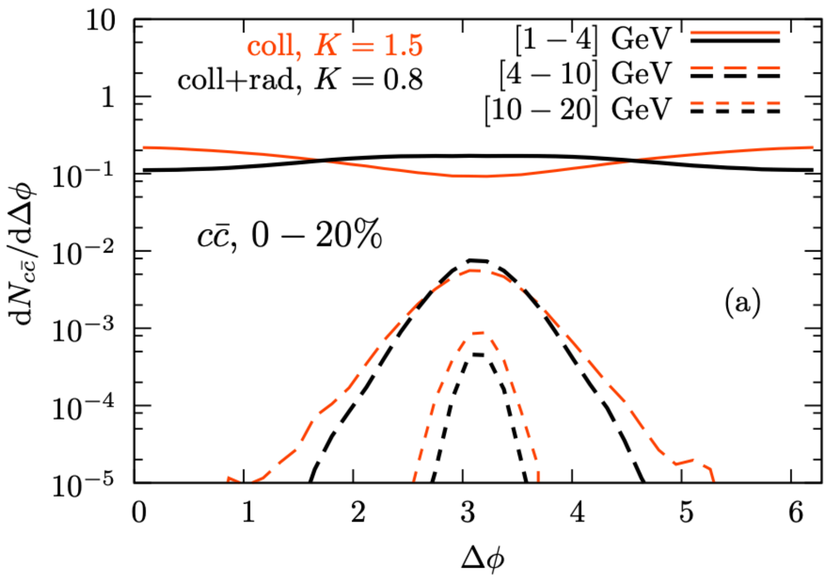


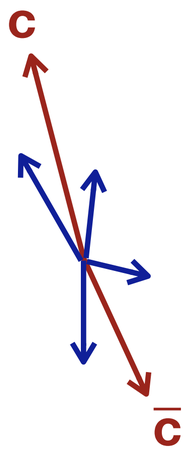

- **Angular decorrelation directly probes QGP scattering**
  - Signal strongest at low $p_T$

# In-medium broadening: $D\bar{D}$ azimuthal correlations

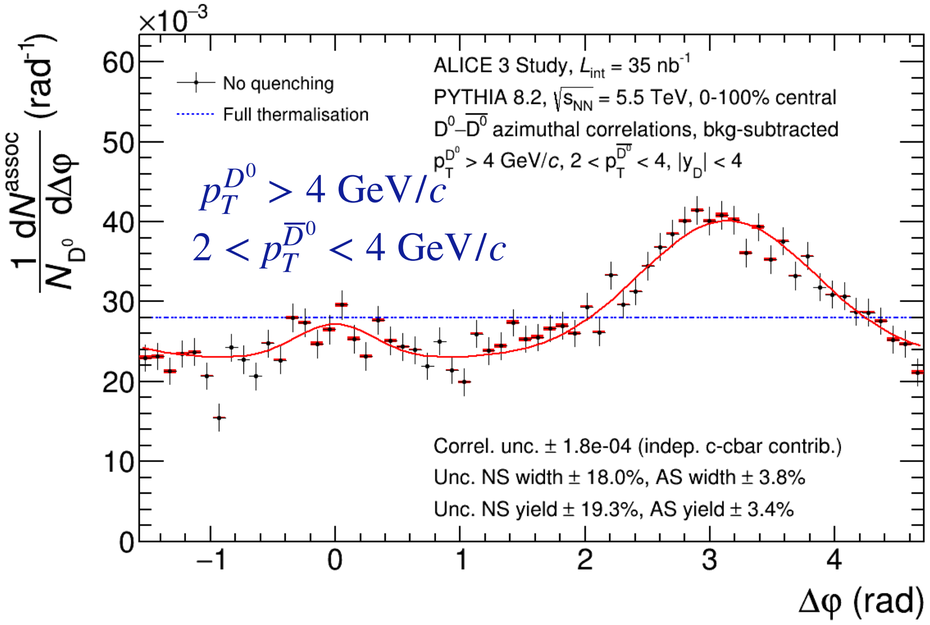
## Charm azimuthal correlations




M Nahrgang et al, PRC 90, 024907



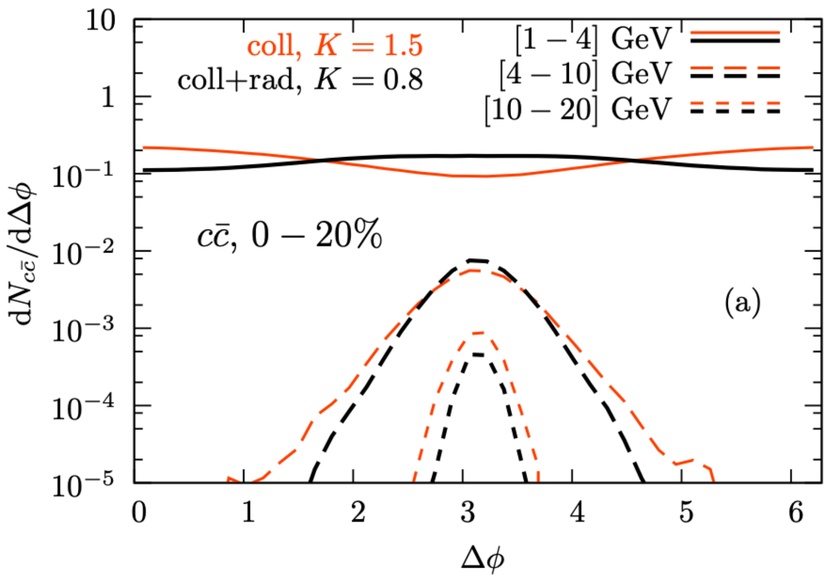

## ALICE 3 projection: $D\bar{D}$ correlations




- **Angular decorrelation directly probes QGP scattering**
  - Signal strongest at low $p_T$
- Very challenging measurement:
  need good purity, efficiency and η coverage
  → ALICE 3

# In-medium broadening: $D\bar{D}$ azimuthal correlations

## Charm azimuthal correlations

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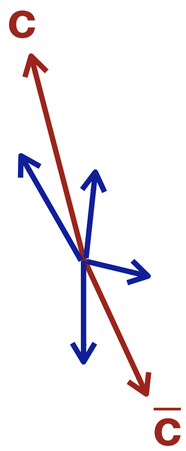
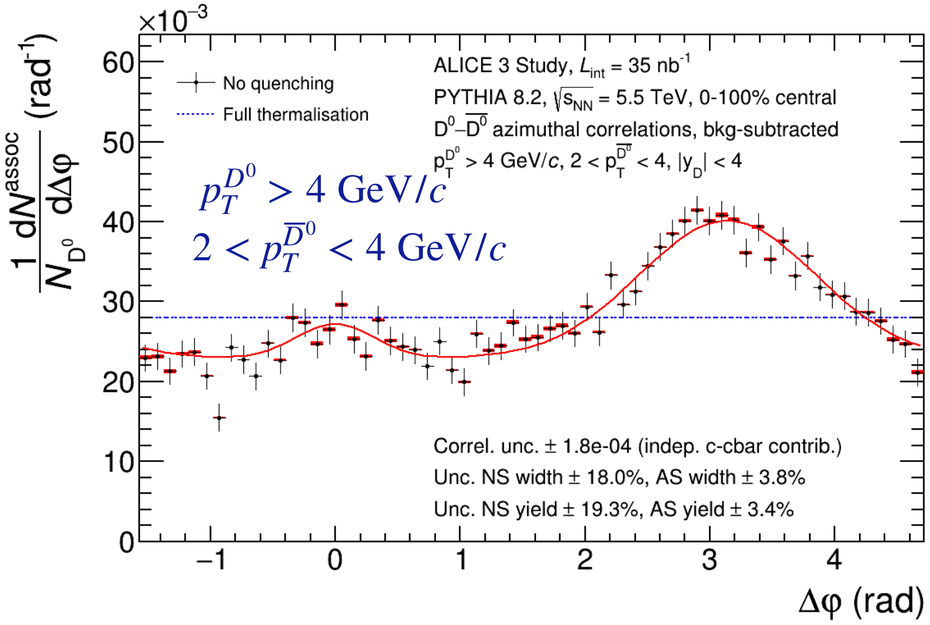
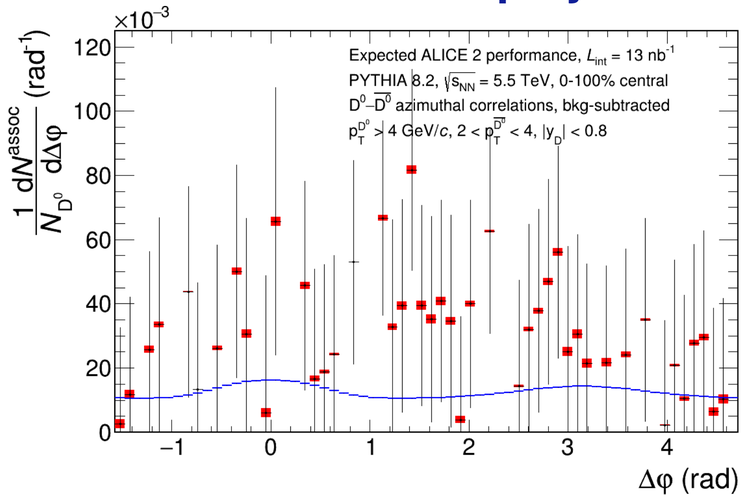



## ALICE 3 projection: $D\bar{D}$ correlations



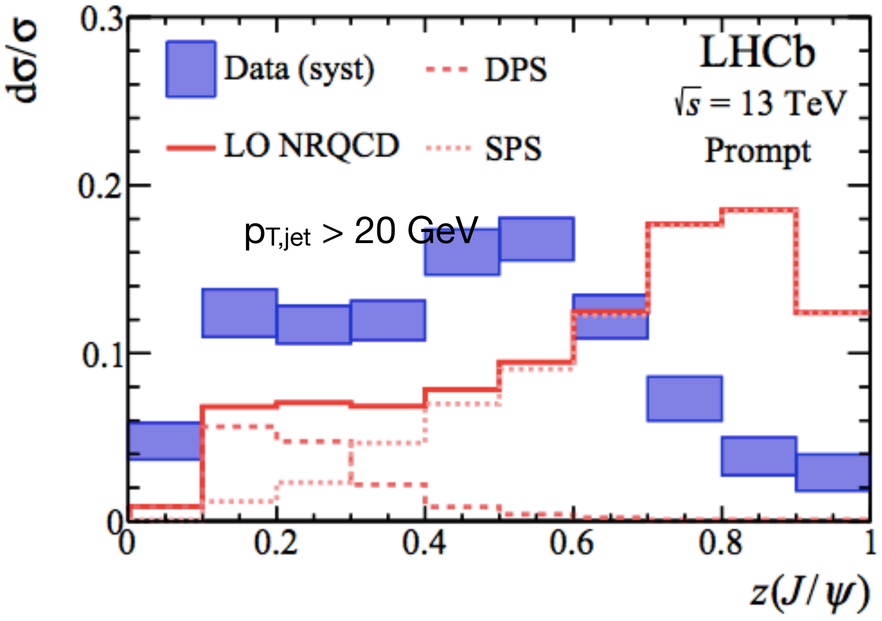

## ALICE Run 3 + 4 projection

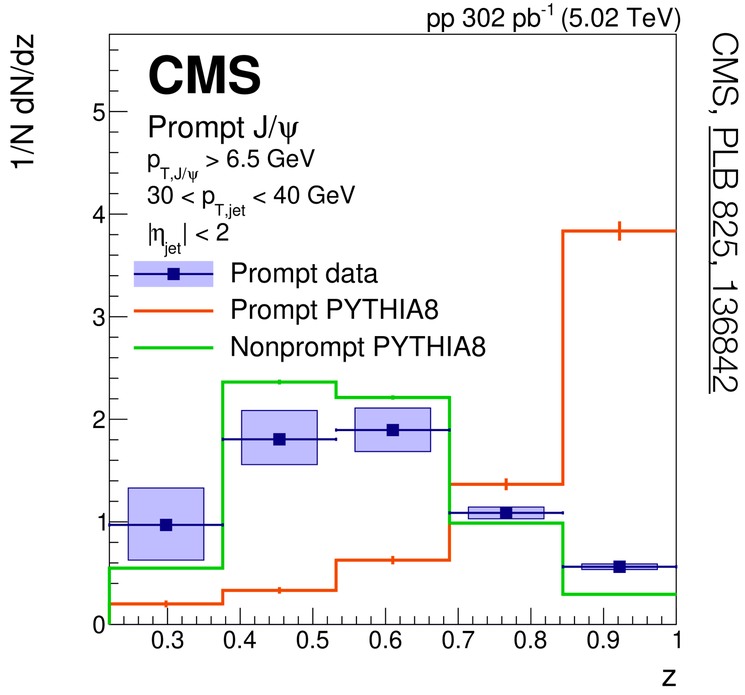



- **Angular decorrelation directly probes QGP scattering**
  - Signal strongest at low $p_T$
- Very challenging measurement:
  need good purity, efficiency and η coverage
  → ALICE 3

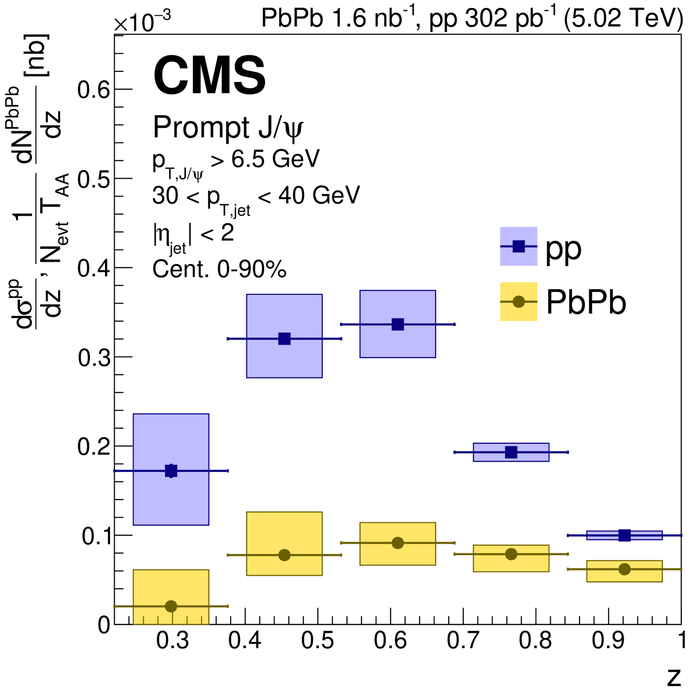
# Production mechanism: J/$\psi$ in jets

LHCb, PRL 118, 192001 (2017)



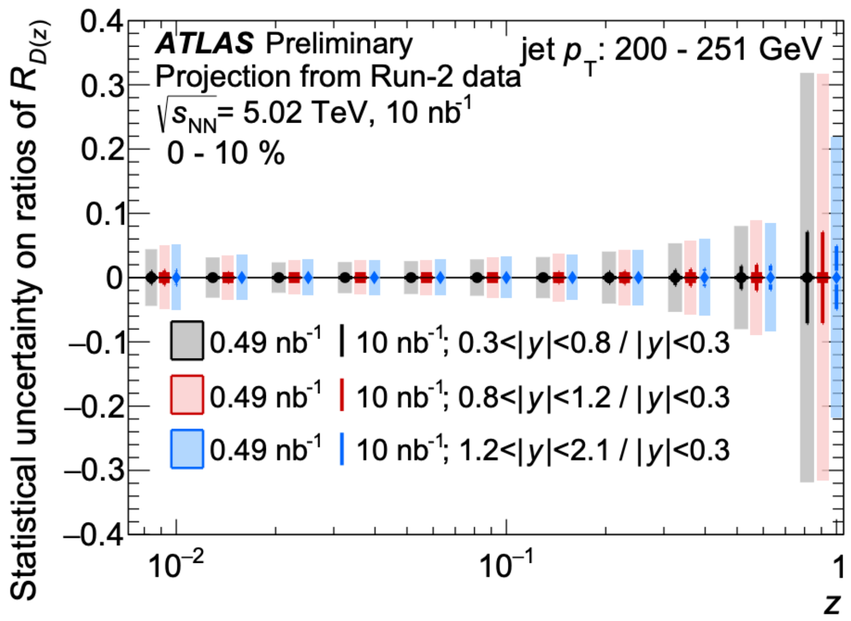

CMS, PLB 825, 136842

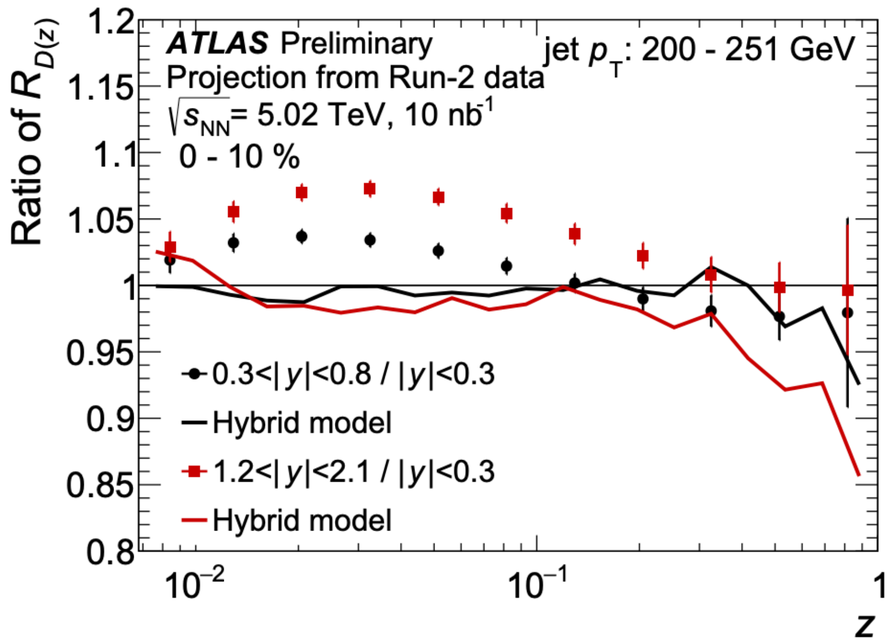



Initial expectation: color-singlet J/$\psi$ could be produced without accompanying fragments

New insight: high-$p_T$ J/$\psi$ produced in jets

# Fragmentation function projections

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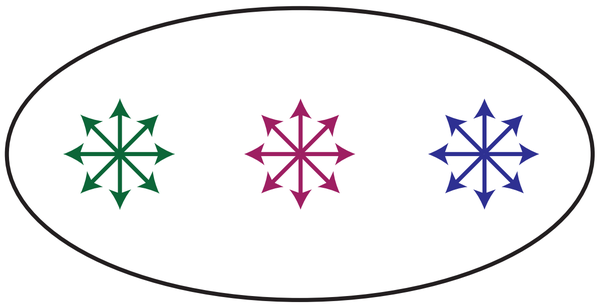
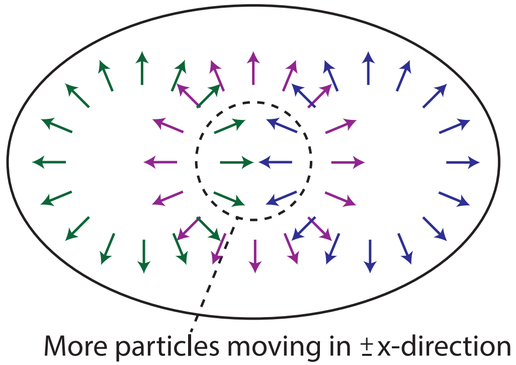
# Building up azimuthal anisotropy with few scatterings

Can you have flow with a few scatterings?
'anisotropic escape' mechanism

Kurkela, Wiedemann, Wu, arXiv:1805.04031



Initially isotropic
momentum distribution




Kurkela, Wiedemann, Wu, arXiv:1803.02072

Scattering randomises directions; more scatterings to 'out-of-plane'

Anisotropic density converted
into anisotropic momentum distribution by few scatterings

# Building up azimuthal anisotropy with few scatterings

Can you have flow with a few scatterings?
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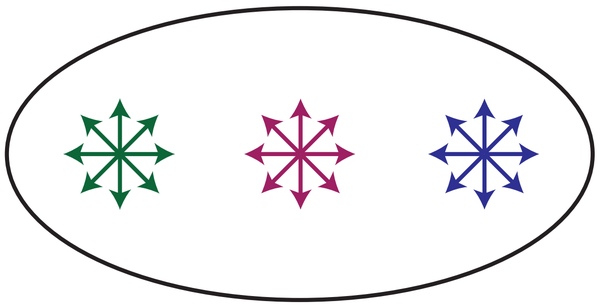

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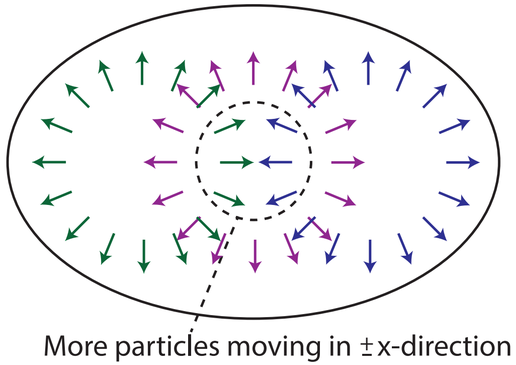


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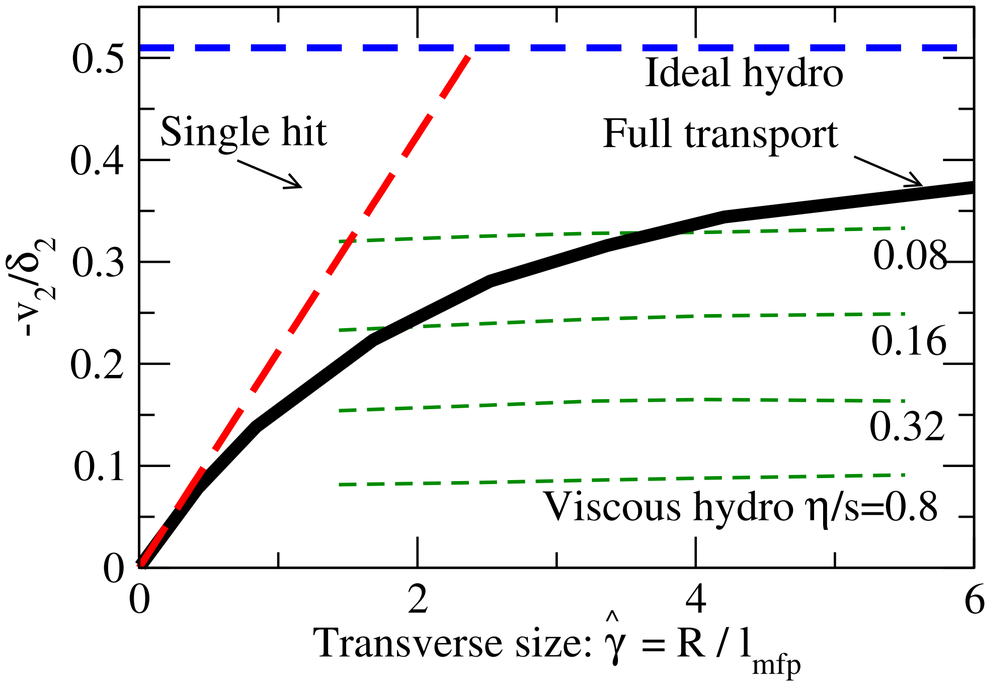
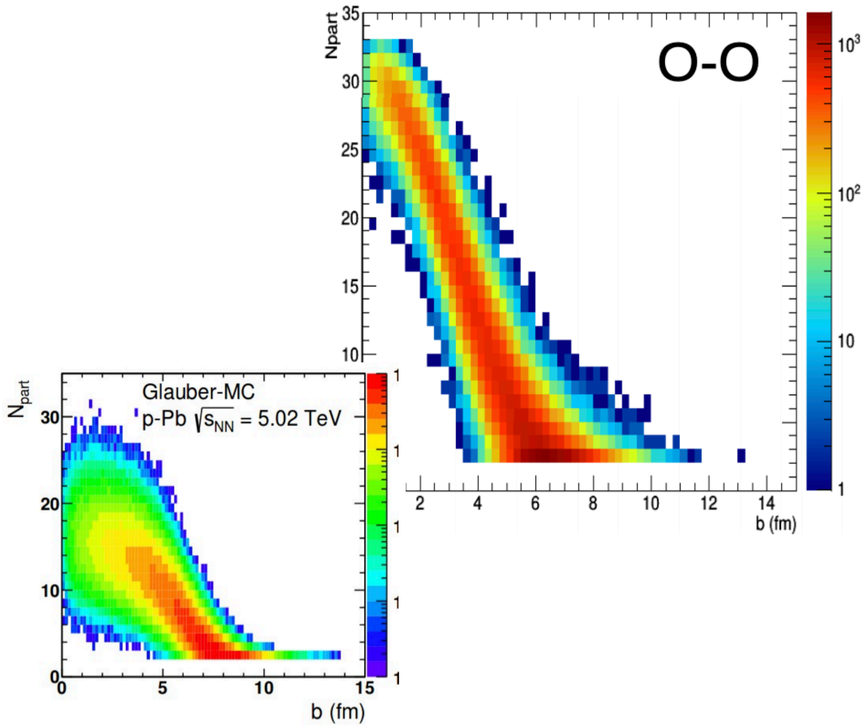



Small systems: 'single hit' kinetic transport
equal to full hydro

# O-O: bridging the gap between p-Pb and Pb-Pb

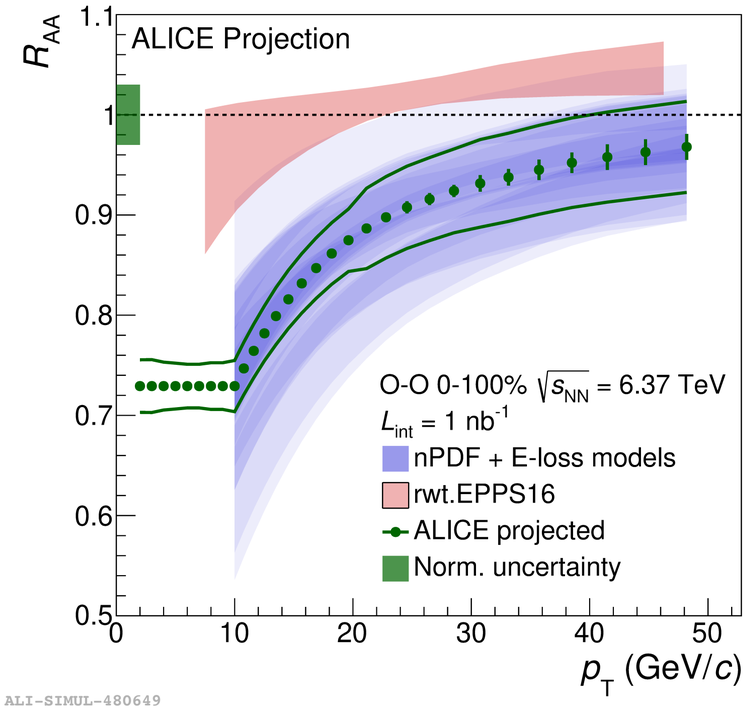
More at Workshop on Opportunities in OO and pO collisions…

Glauber: $N_{part}$ vs $b$

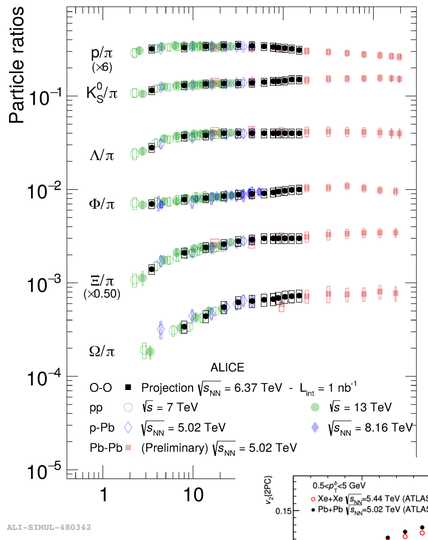



O-O: better control over geometry than p-Pb

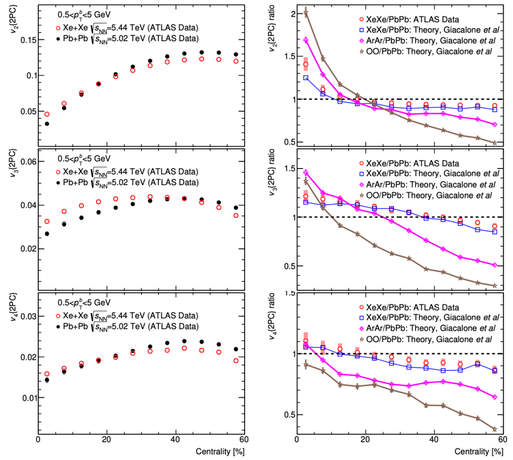
$R_{AA}$: energy loss




Strangeness




Flow

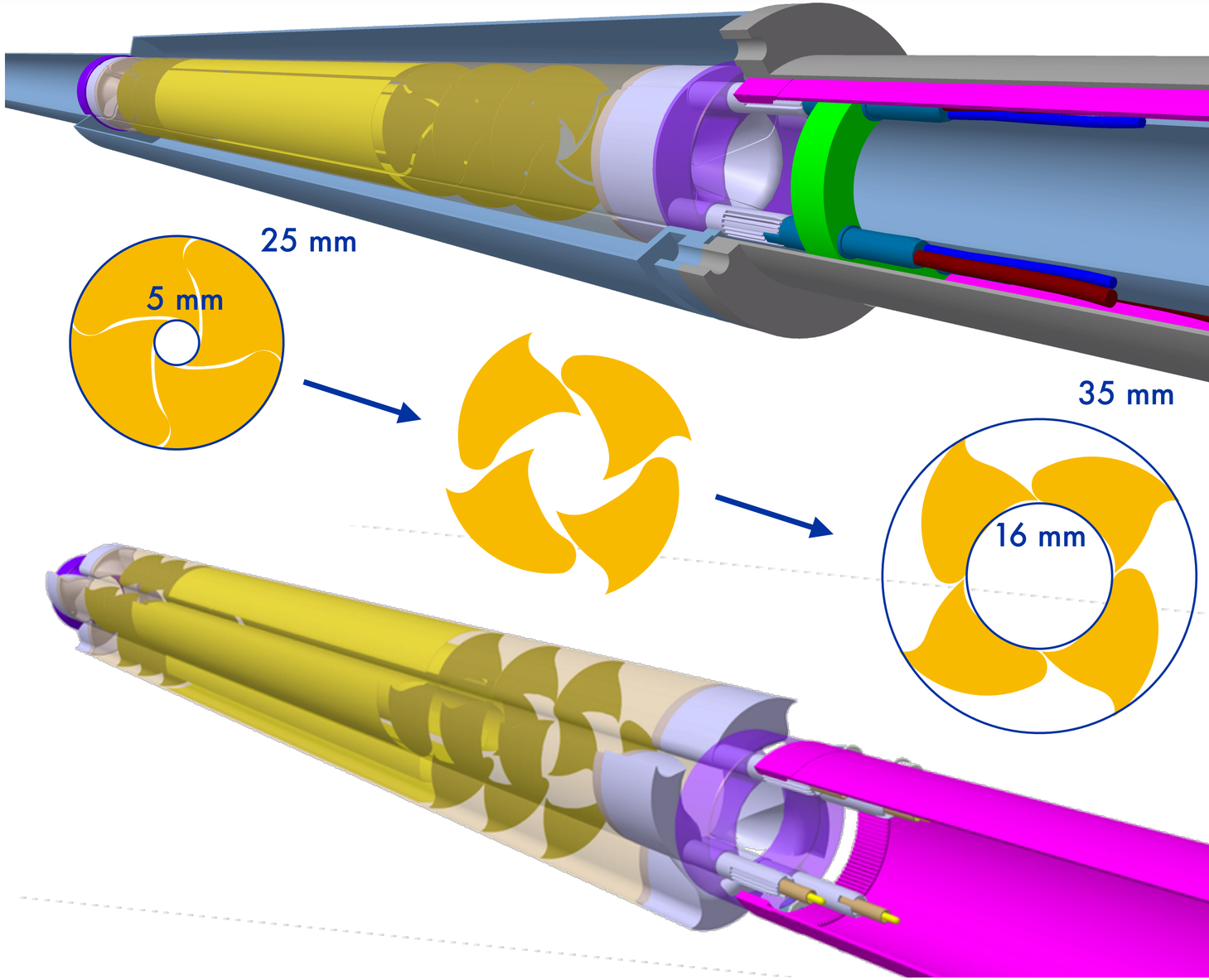



Short OO run allows to explore
'small system' limit with symmetric collisions

+ p-O for cosmic ray studies

# ALICE 3 vertex detector

- **Conceptual study of iris tracker**
  - wafer-sized, bent MAPS (leveraging on ITS3 activities)
  - rotary petals (thin Be walls) for secondary vacuum
  - match beampipe parameters (impedance, aperture, …)
  - feed-throughs for power, cooling, data
- **R&D programme** on mechanics, cooling, radiation tolerance



# Heavy ions for Run 5 & 6

- **Baseline approach for heavy-ion programme**
  - maximise statistics for rare probes
    ➟ identify species best suited for physics programme
  - 6 running years with 1 month / year with that species
- Complemented with high-rate **pp running** (3 $fb^{-1}$ / year) at 14 TeV
- Consider **special runs** (pp reference, small systems), also based on insights from Run 3 & 4

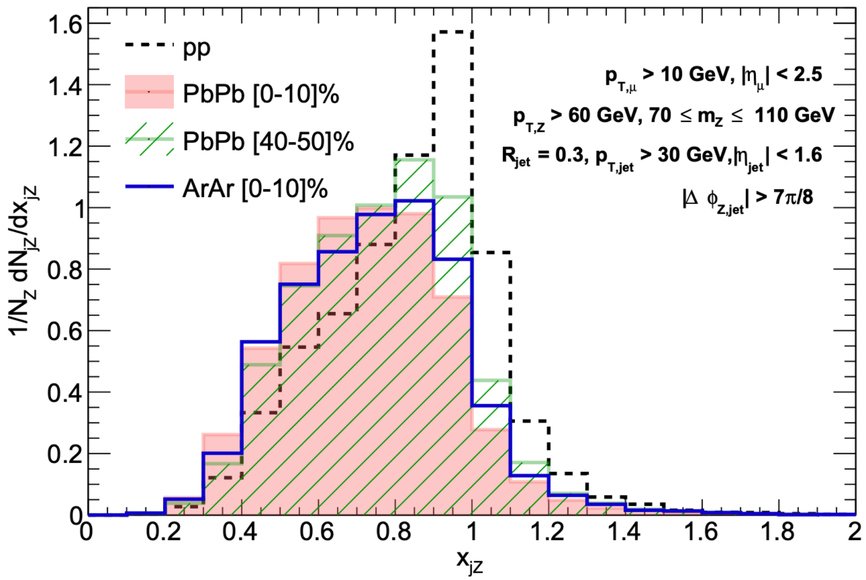
[https://indico.cern.ch/event/1078695/]

Nucleon-nucleon luminosity:
$\mathscr{L}_{\mathrm{NN}} = A^2 \cdot \mathscr{L}_{\mathrm{AA}}$

| optimistic scenario | O-O | Ar-Ar | Ca-Ca | Kr-Kr | In-In | Xe-Xe | Pb-Pb |
|---|---|---|---|---|---|---|---|
| $\langle L_{AA} \rangle$ ($cm^{-2}\ s^{-1}$) | $9.5 \cdot 10^{29}$ | $2.0 \cdot 10^{29}$ | $1.9 \cdot 10^{29}$ | $5.0 \cdot 10^{28}$ | $2.3 \cdot 10^{28}$ | $1.6 \cdot 10^{28}$ | $3.3 \cdot 10^{27}$ |
| $\langle L_{NN} \rangle$ ($cm^{-2}\ s^{-1}$) | $2.4 \cdot 10^{32}$ | $3.3 \cdot 10^{32}$ | $3.0 \cdot 10^{32}$ | $3.0 \cdot 10^{32}$ | $3.0 \cdot 10^{32}$ | $2.6 \cdot 10^{32}$ | $1.4 \cdot 10^{32}$ |
| $\mathscr{L}_{AA}$ ($nb^{-1}$ / month) | $1.6 \cdot 10^{3}$ | $3.4 \cdot 10^{2}$ | $3.1 \cdot 10^{2}$ | $8.4 \cdot 10^{1}$ | $3.9 \cdot 10^{1}$ | $2.6 \cdot 10^{1}$ | $5.6 \cdot 10^{0}$ |
| $\mathscr{L}_{NN}$ ($pb^{-1}$ / month) | **409** | **550** | **500** | **510** | **512** | **434** | **242** |

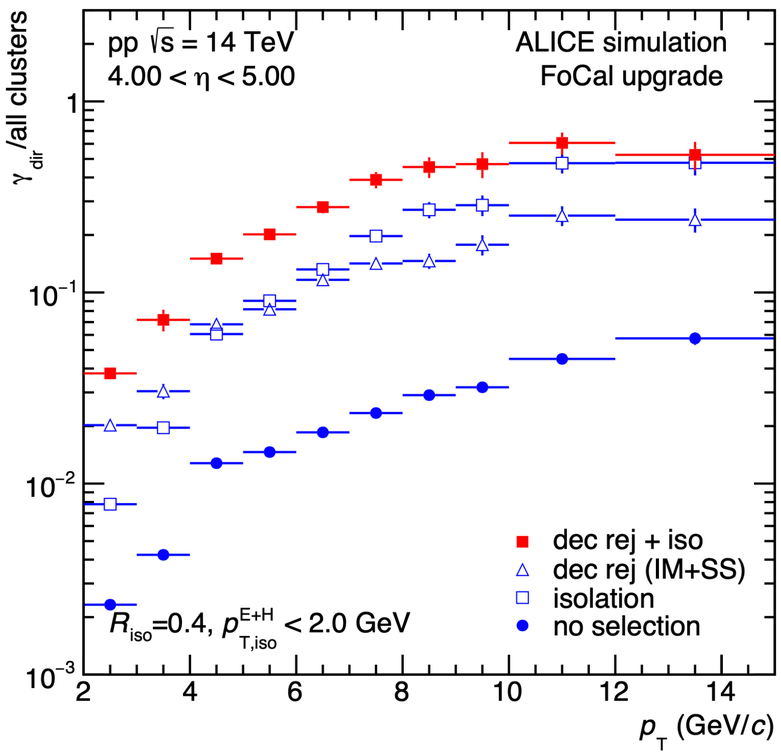
Strength of QGP effects
(e.g. charm abundance, quenching, also background)

# Z-boson jet asymmetry vs system size



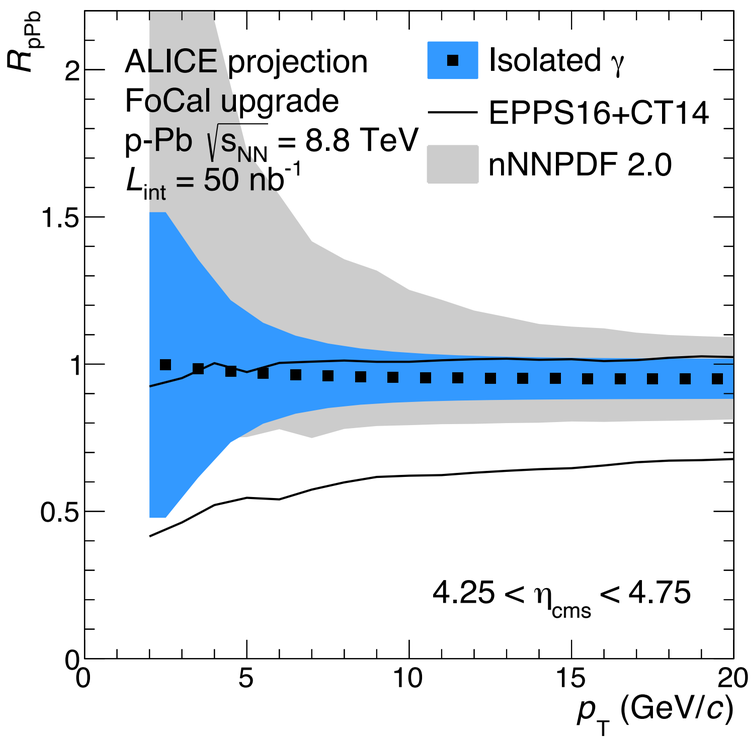
# Forward photons with FoCal

## Signal photon fraction



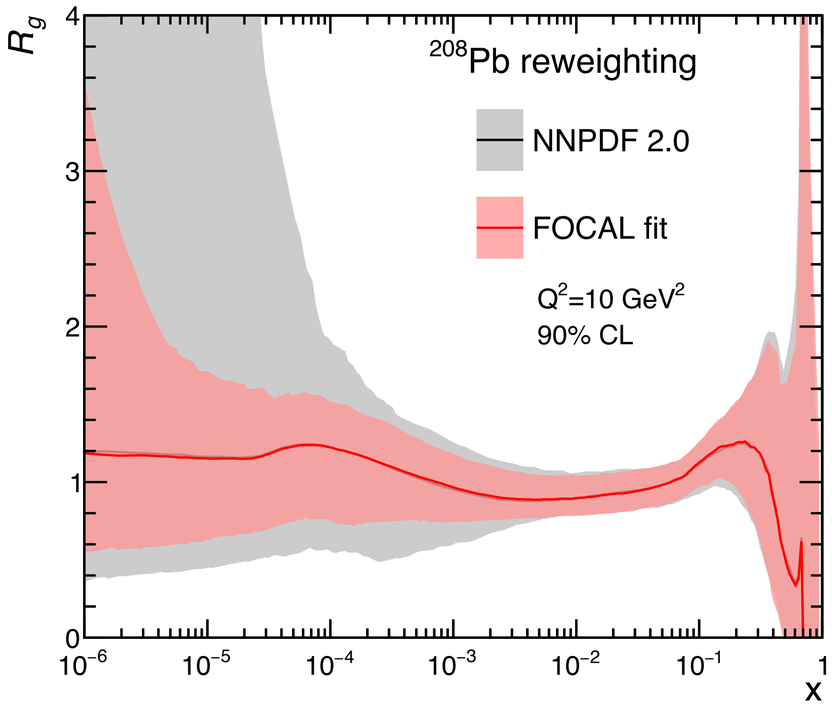

High granularity to reject decay background

## Projected photon uncertainties




High precision direct photon measurement down to low $p_T$

## Projected PDF uncertainties




Constrain gluon density in nuclei over a broad range:
$x \sim 10^{-5} - 10^{-2}$ at small $Q^2$

# Inclusive/average vs jet-by-jet

- Intra-jet distributions ('fragmentation functions', radial profile) measure **averages over a sample of jets**
- Jet shape variables (mass, angularities, $z_g$ etc): jet-by-jet quantity, in principle sensitive to fluctuations

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  - Could be stronger effect in jets 'fat jets loose more energy'

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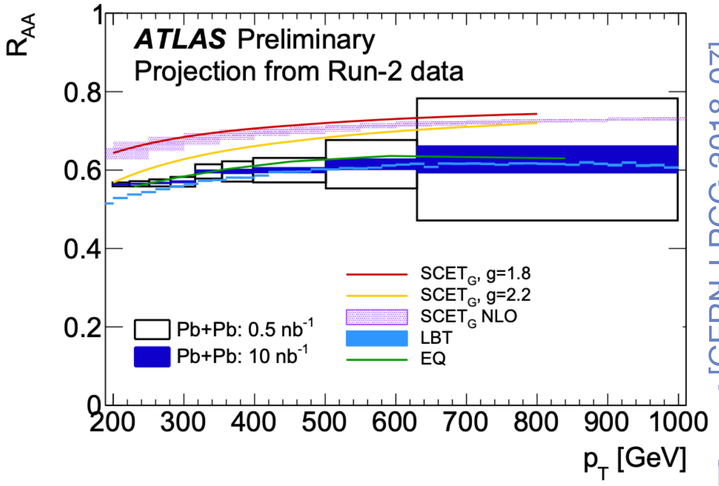
Measuring fluctuations constrains these aspects of models !

# Quenching

- **Understand mass and time dependence as well as onset in small systems**
  → precision measurements, also with new probes and in intermediate systems
  → statistics and new collision systems (OO, pO, also high-multiplicity pp)

**Precise jet $R_{AA}$ up to high $p_T$**

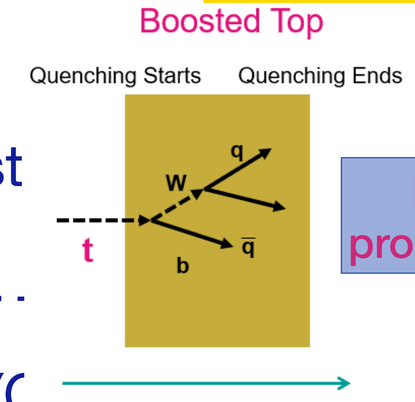



[CERN-LPCC-2018-07]

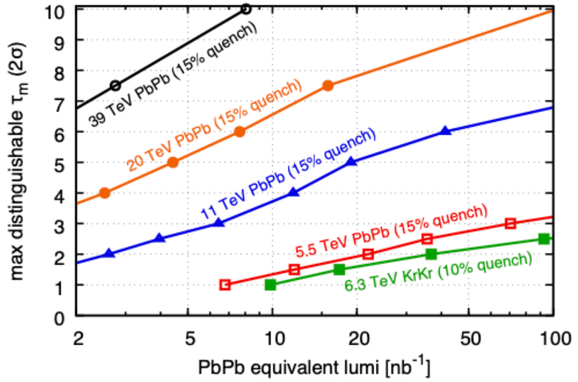
**large samples allow us to look at tagged jets, substructure, …**

Run 3 & 4

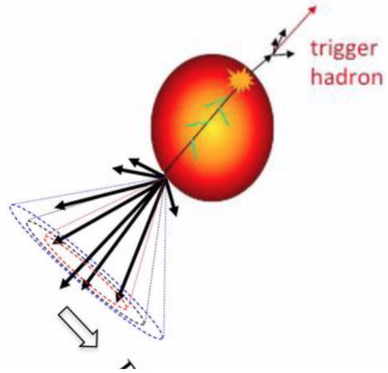
**t → b + W → qq̄**
**→ probe medium after τm**




Run 3 & 4:
proof of concept

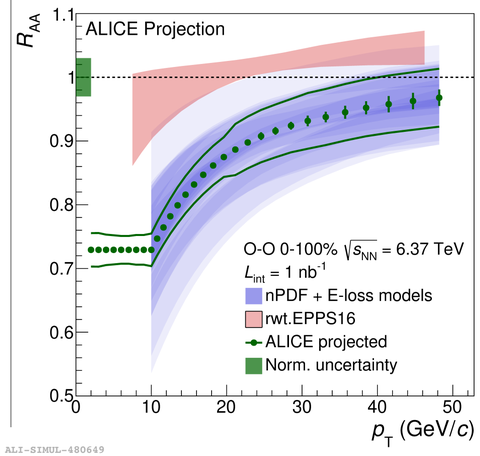



**Limits on quenching in small systems**




**Limits for energy shift out of R = 0.4 cone:**

- **pp (7-10 ⟨$N_{ch}$⟩): 70 MeV/**
- **pp (10-12 ⟨$N_{ch}$⟩): 600 Me**
- **OO: 150 MeV/*c***

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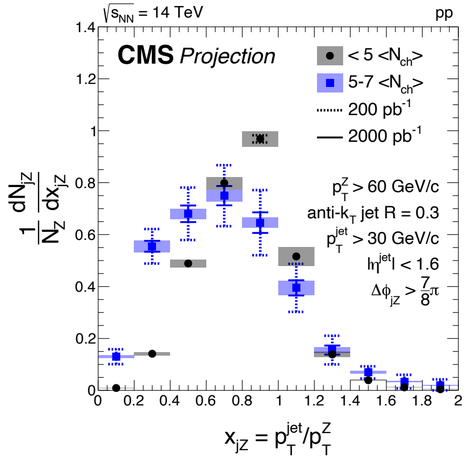
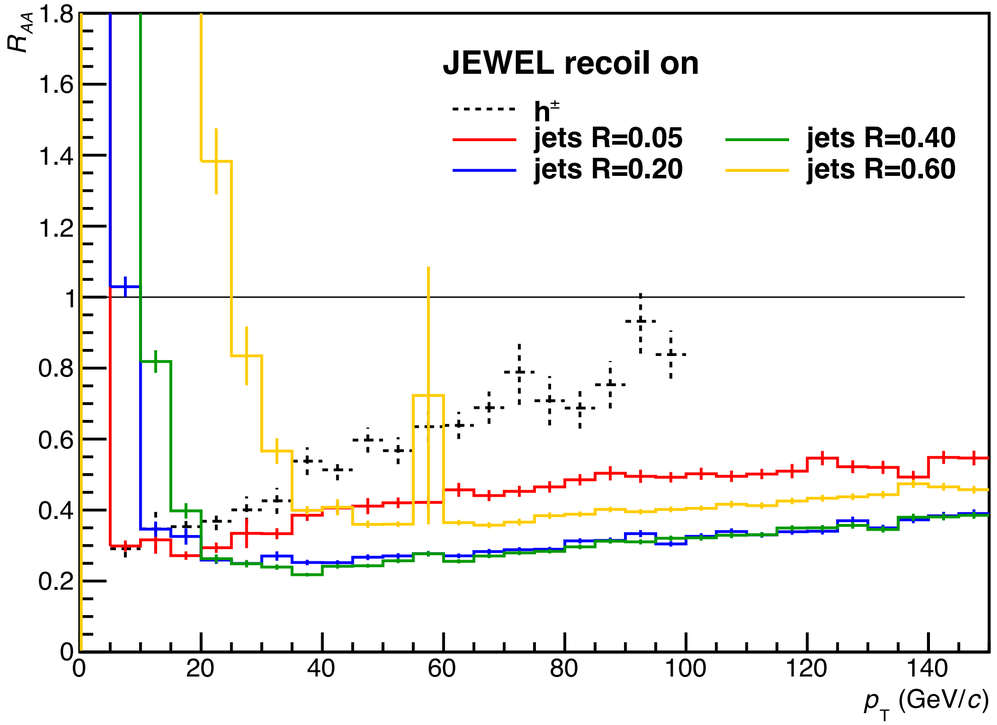
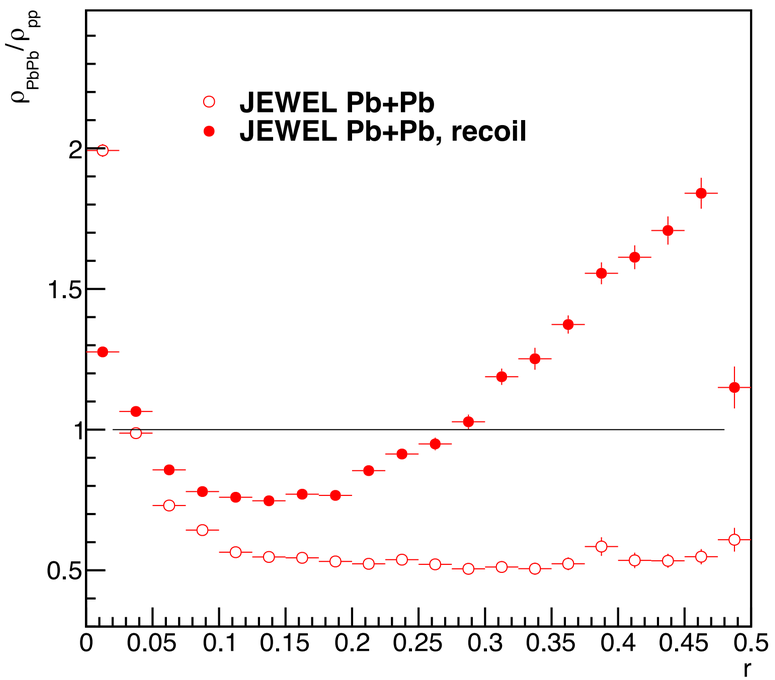



Run 3 (pp HM, OO, p-Pb)

# Relation radial profile and $R_{AA}$ vs R



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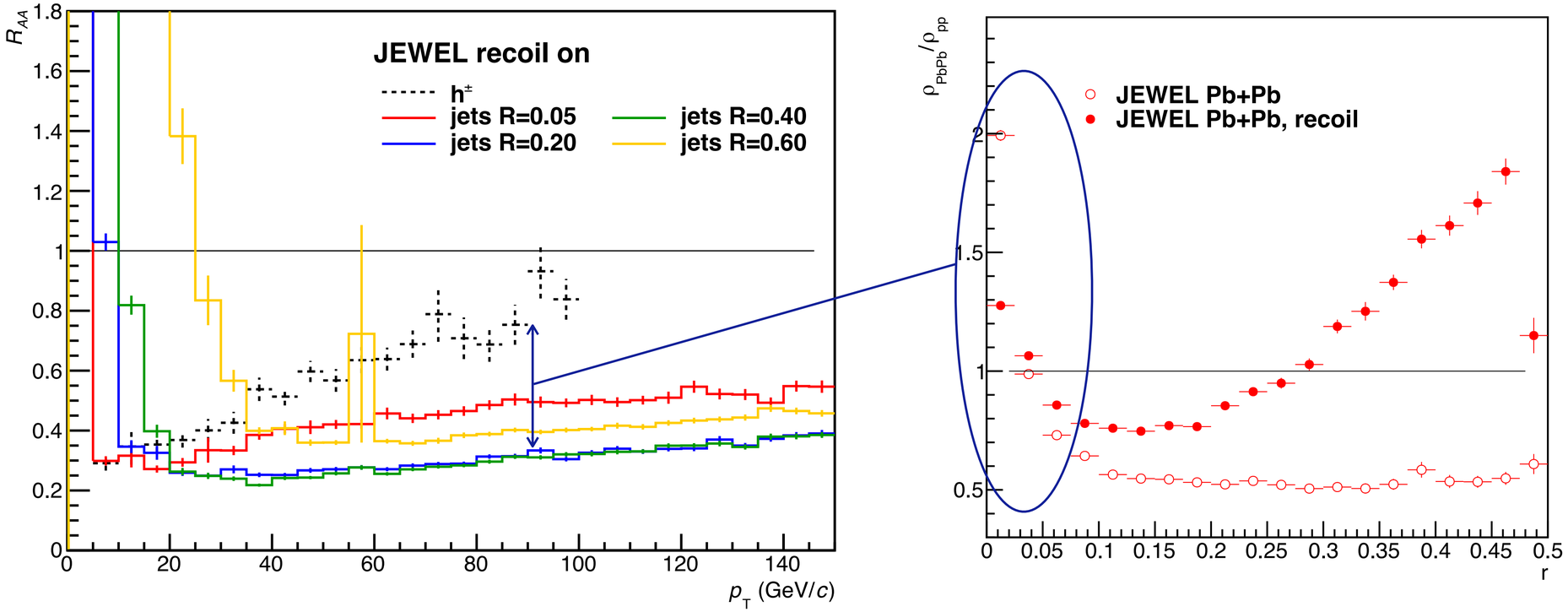


Stronger peak at small r ⇒ decrease of $R_{AA}$ with R for R < 0.2

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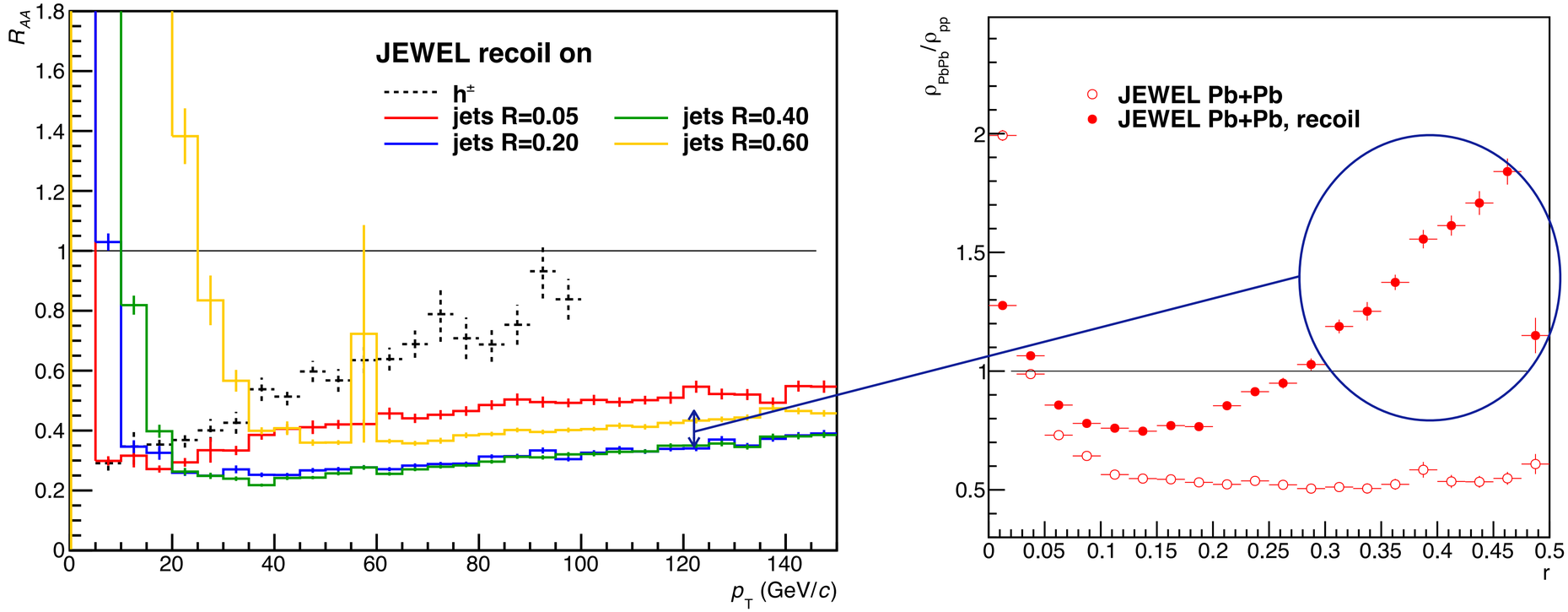
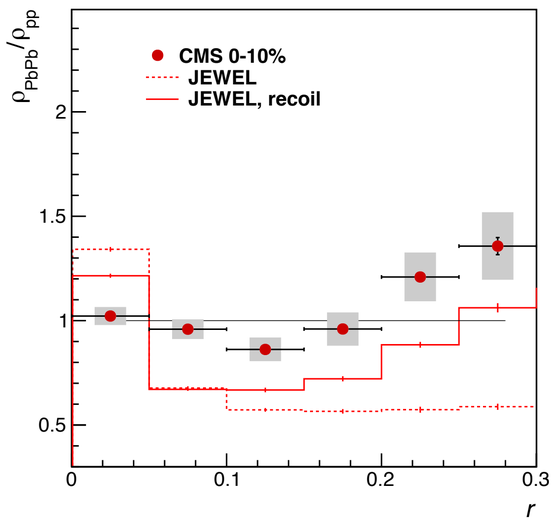



Stronger peak at small r ⇒ decrease of $R_{AA}$ with R for R < 0.2

Increase of ratio at large r (only with recoil): increase of $R_{AA}$ for R > 0.4
(small effect because total momentum flow is small at large R)

# Example: girth, radial profiles

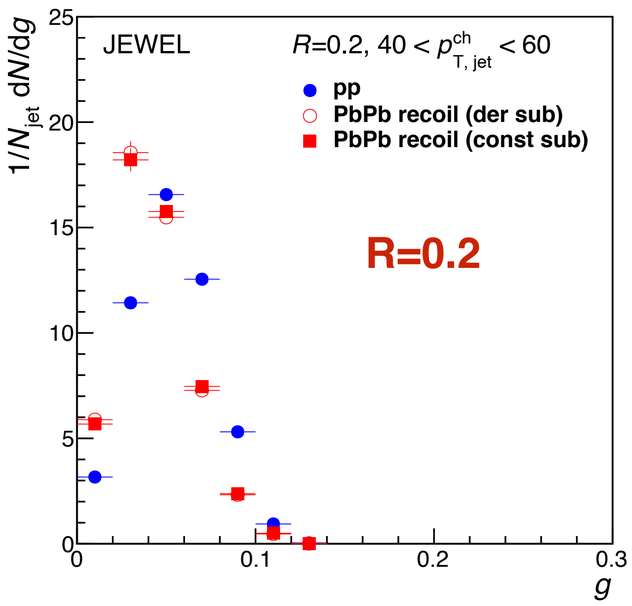



Radial profiles
('CMS jet shape')

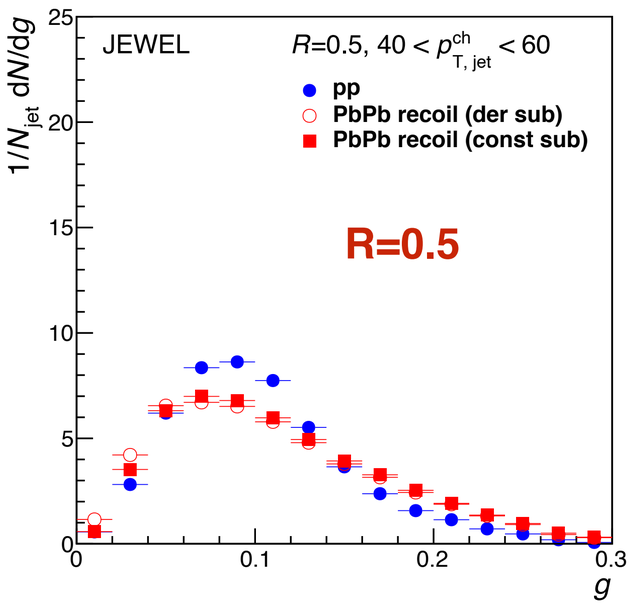
**Average over events**

girth: First moment of radial profile

$$g = \frac{1}{p_\perp^{\text{jet}}} \sum_{k \in J} p_\perp^{(k)} \Delta R_{kJ}$$




Small jet R: narrowing
mean *g* decreases

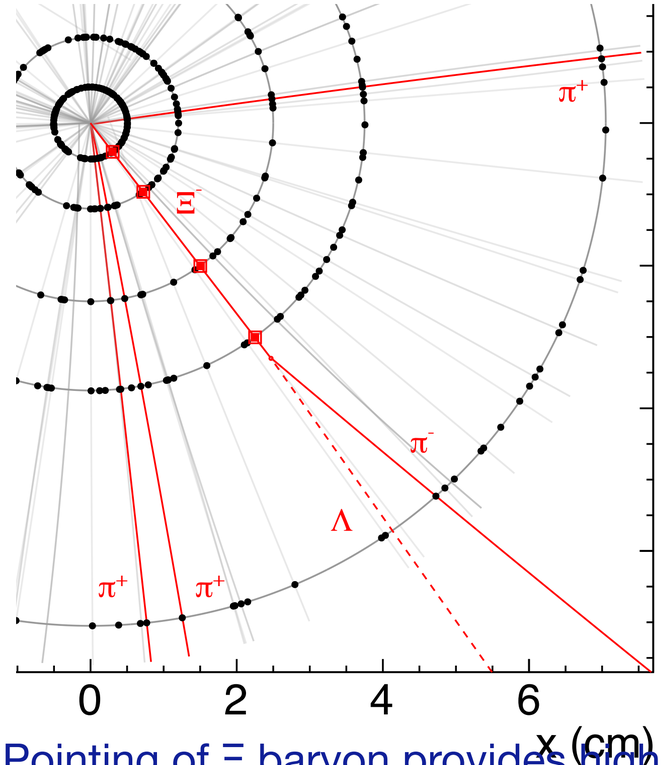



Large jet *R*: broadening
mean *g* increases

***g* is measured jet by jet**
Mean g corresponds to the profile measurement,
width of distribution contains new information

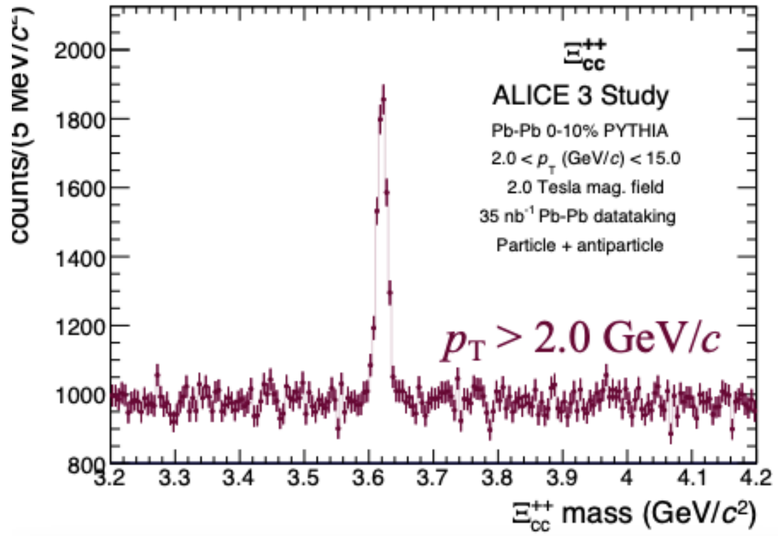
# Multi-charm baryons

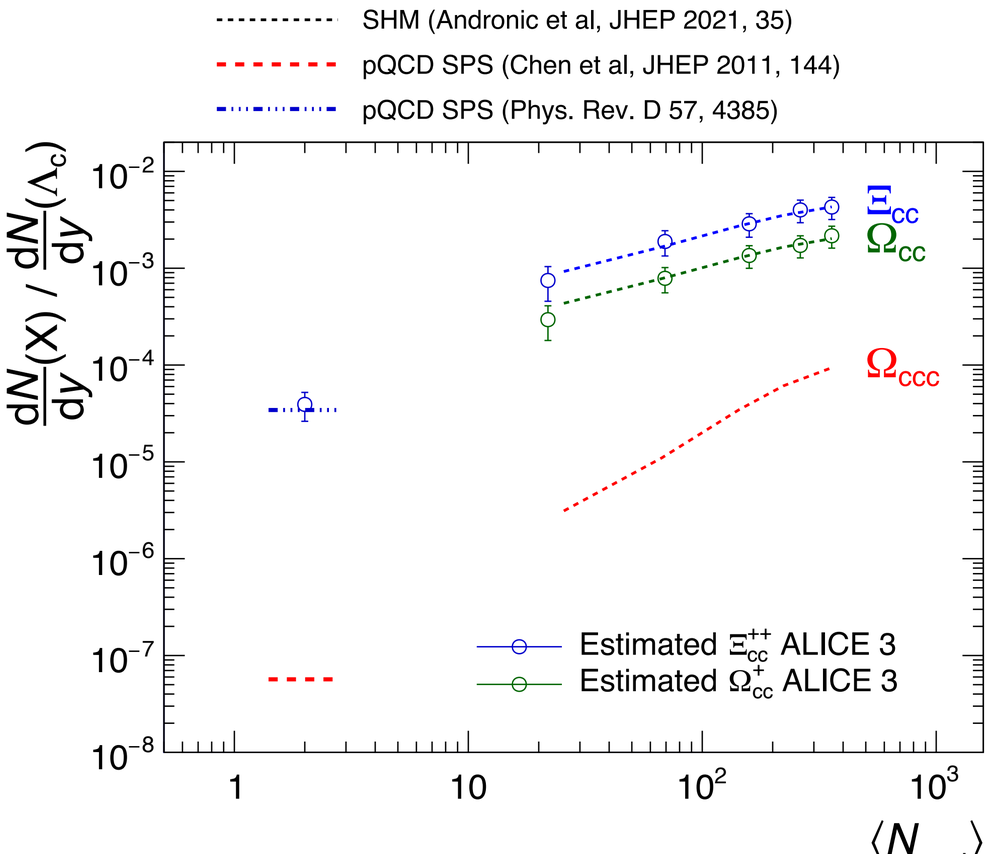
**New technique: strangeness tracking**




Pointing of Ξ baryon provides high selectivity

Expected mass peak in Pb-Pb collisions




$$\Xi_{cc}^{++} \to \Xi_c^{+} + \pi^{+}$$

$$\Xi_c^{+} \to \Xi^{-} + 2\pi^{+}$$

Multi-charm baryons vs system size: unique insight in thermalisation and hadronisation dynamics

ALICE 3: unique experimental access in Pb-Pb collisions