Experimental status of heavy-ion collisions at LHC

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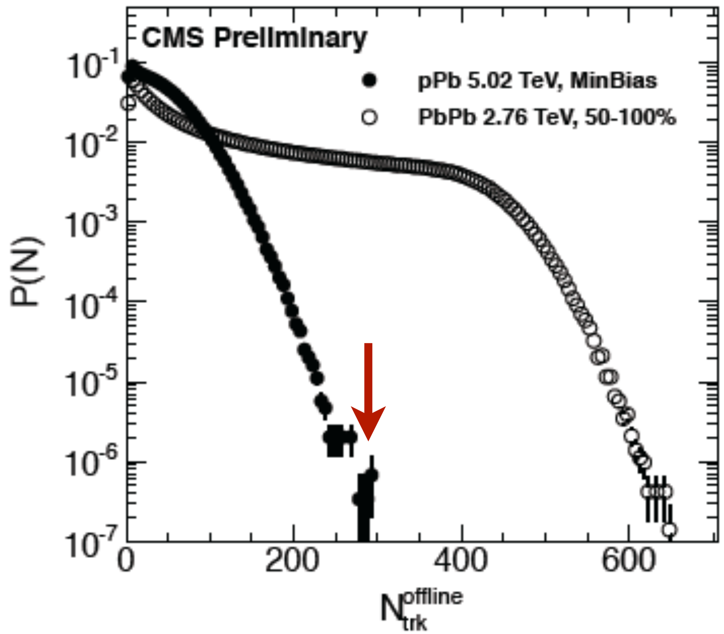
Outline

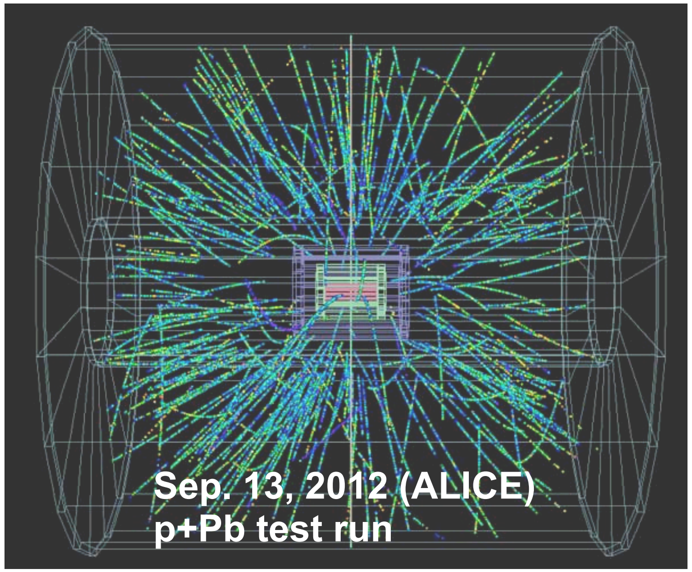
1. Collectivity in p-Pb vs. PbPb
2. Energy loss (jet, γ-jet, heavy quarks)
3. Melting temperature, quark recombination via quarkonia production
4. Summary

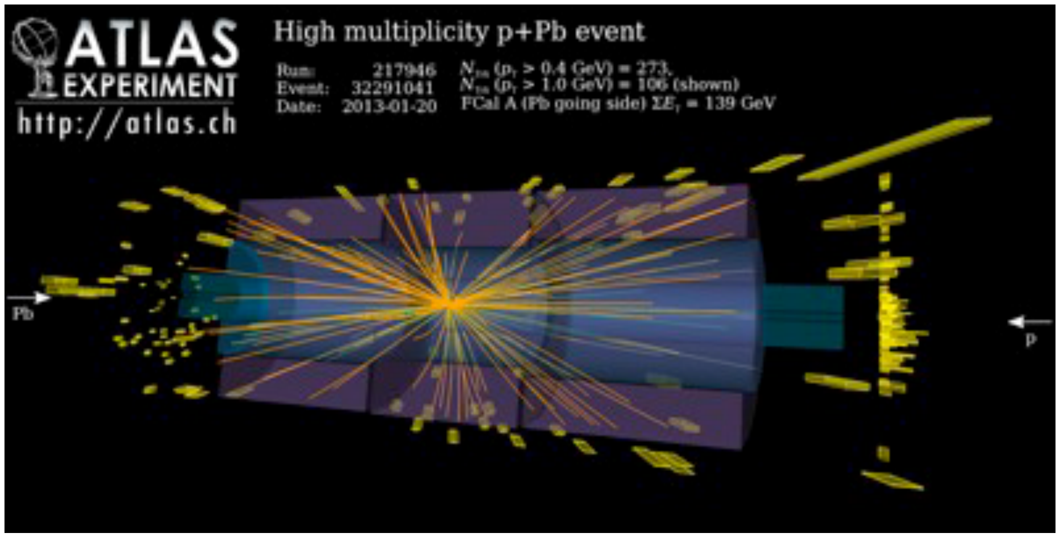
***Note:** *This talk is not intend to a complete review of LHC HI results, but rather to show selected recent results (from QM14 w/ personal bias), try to summarize the current understanding of LHC HIC.*

1. Collectivity (pPb and PbPb)



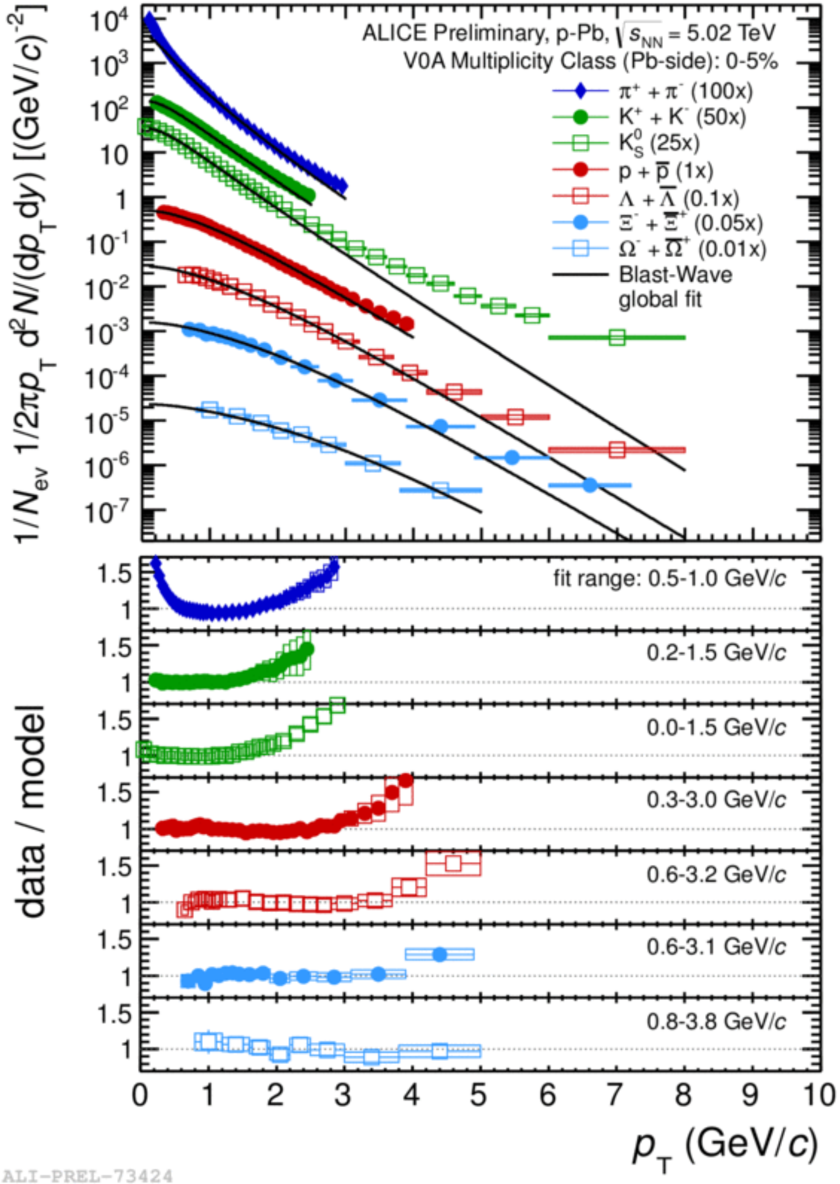
Highest pPb multiplicity ~ 55-60% Pb-Pb.



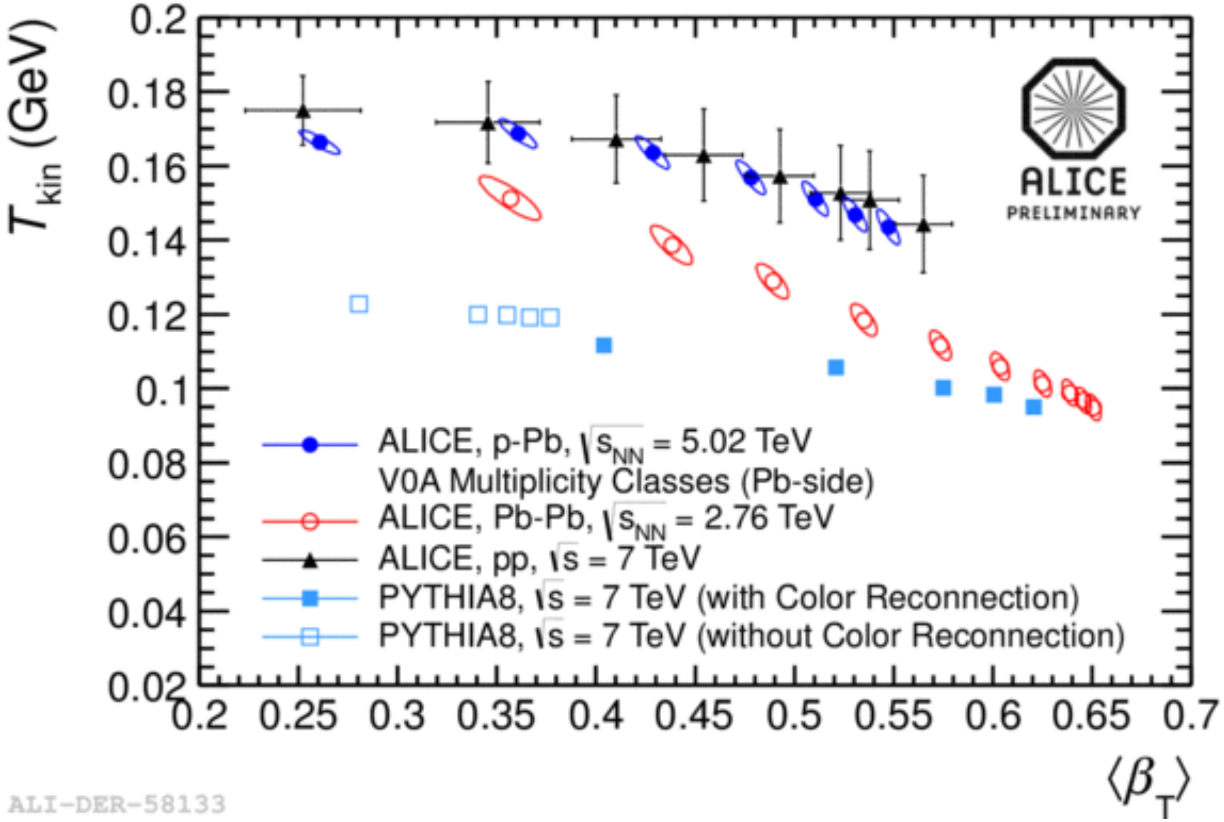


PID p_T spectra in p-Pb

- ALICE preliminary results of p_T spectra in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.
- Shown here are for π, K, p, K^0, Λ, Ξ, Ω
- Fitted by the blast wave model (global fit).



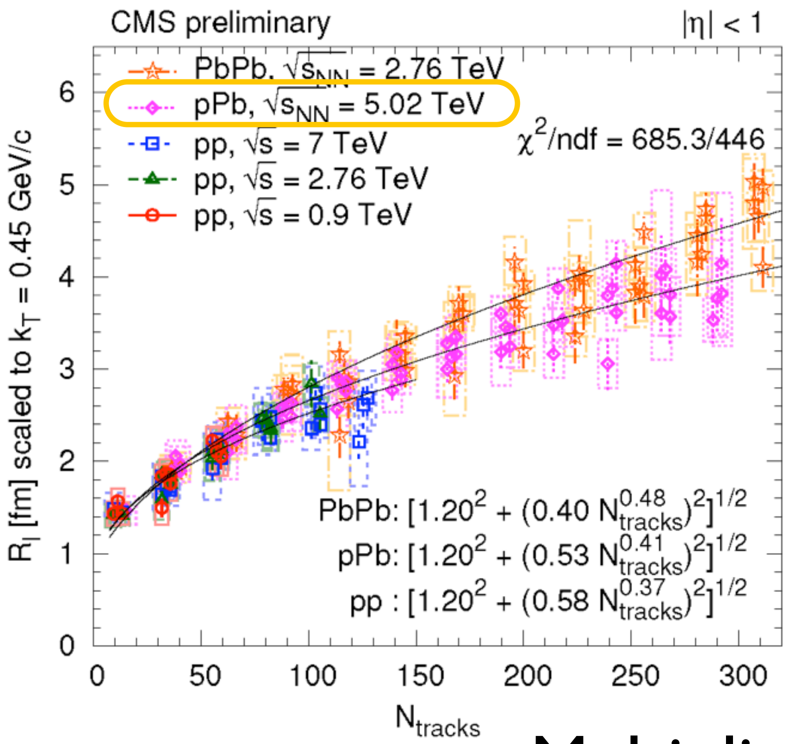
T_{kin} vs. $<\beta_T>$ in blast wave



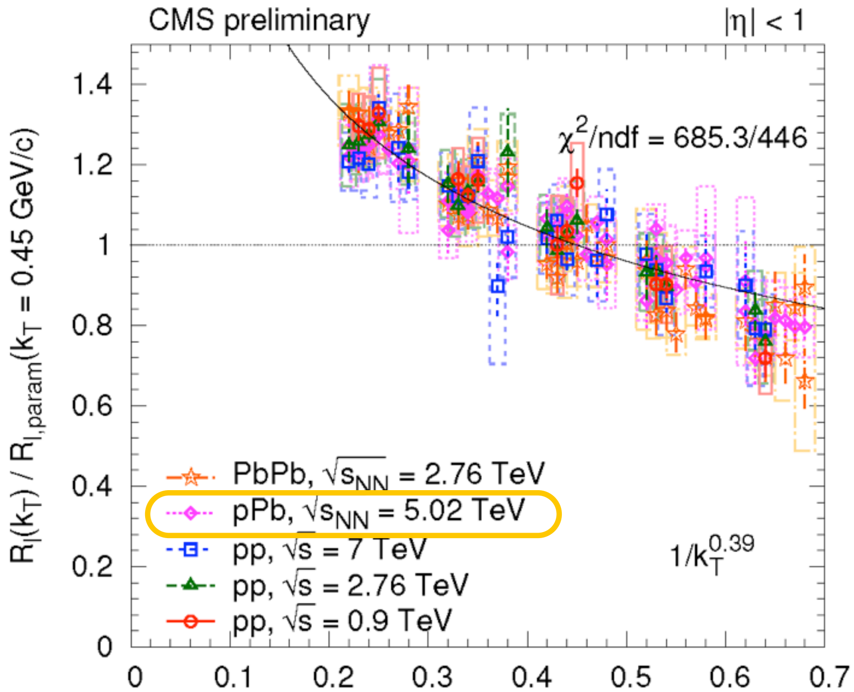
p-p
p-Pb
Pb-Pb
p-p (PYTHIA)

- Coherent fit for π, K, p, K^0, Λ, Ξ, Ω for different centrality (pp, pPb, PbPb)
- At same N_{ch}, $<\beta_T>$ larger in p-Pb than in that in Pb-Pb, but also, $<\beta_T>$ similarly large in pp and p-Pb (at same N_{ch}) with large T.
- Strong correlation between T and $<\beta_T>$.

HBT correlation in p-Pb



Multiplicity

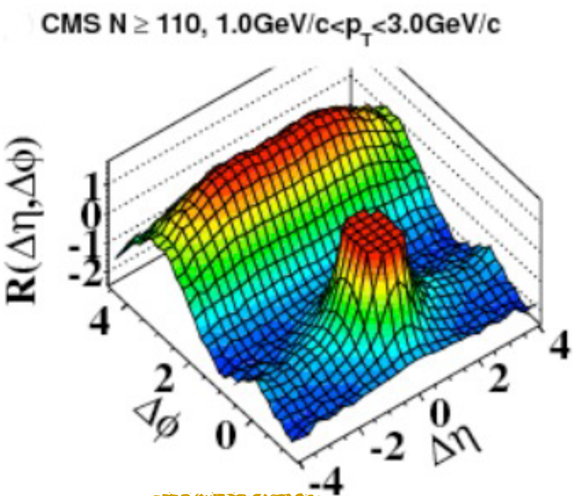


$k_T = (p_{T1} + p_{T2})/2$ [GeV/c]

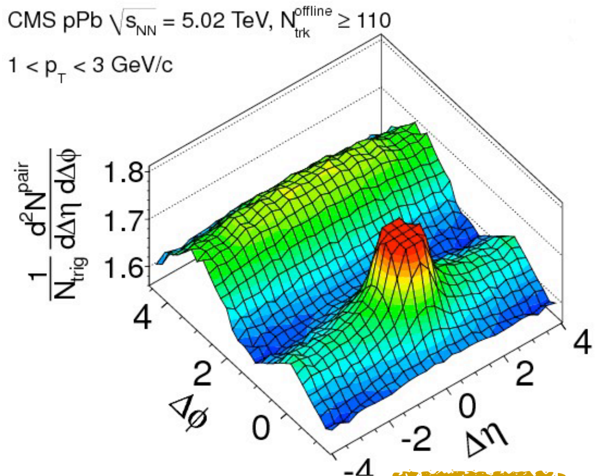
Similar large radii (R_{long} up to 5 fm) in pPb & PbPb at the same N_{ch}.
Scaling with multiplicity and k_T (dynamical behavior).

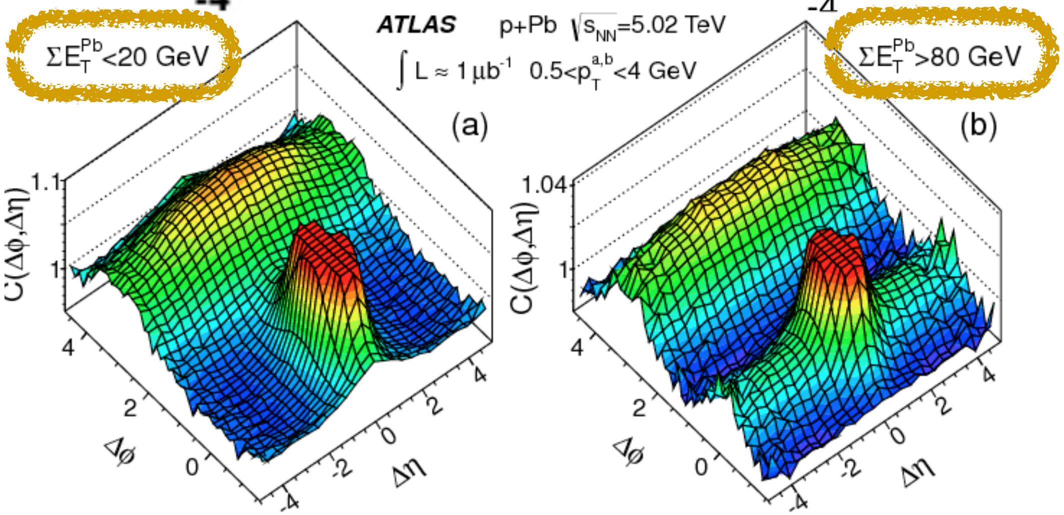
Di-Hadron Correlations in p-p & p-Pb

p-p (N ≧110)



p-Pb (N ≧110)





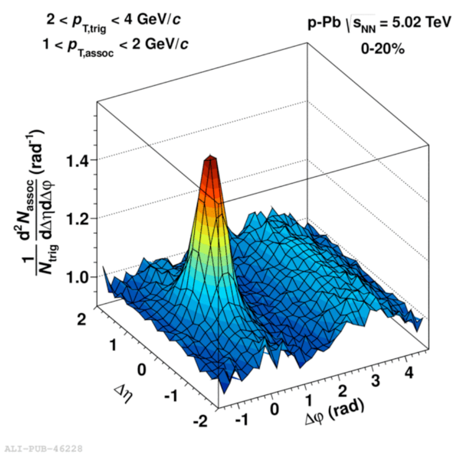
p-Pb (ΣE_T ^{Pb}) < 20 GeV   p-Pb (ΣE_T ^{Pb}) > 80 GeV

- First observation of **ridge structure in high multiplicity p-p** (CMS).
- Also confirmed in **p-Pb high multiplicity events**.
- Alway side ridge structure is observed in high multiplicity p-Pb.

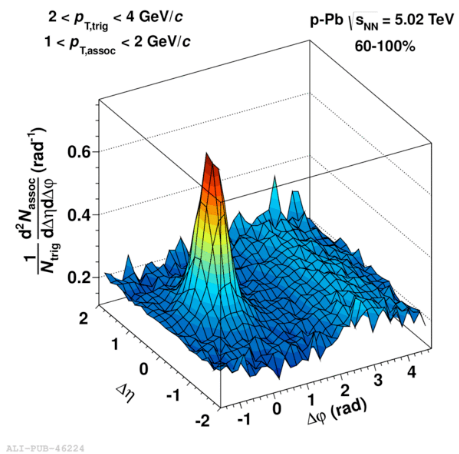
CMS, JHEP 1009 (2010) 91
CMS, PLB 718 (2012) 795
ATLAS, PRL 110, 182302 (2013)

Double ridge structure in p-Pb

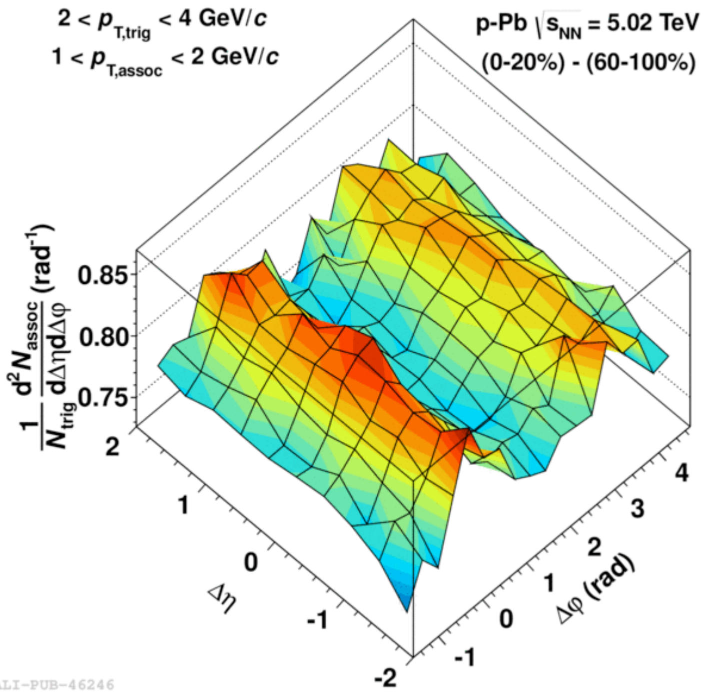
ALICE, PLB 719 (2013) 29



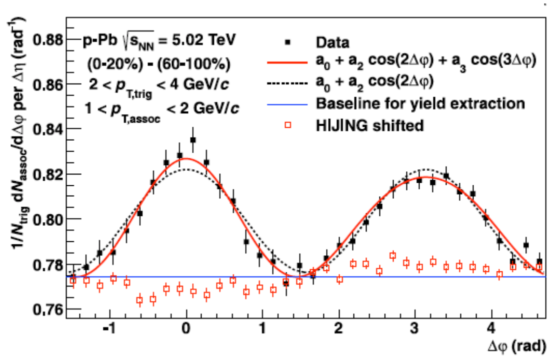
0-20%



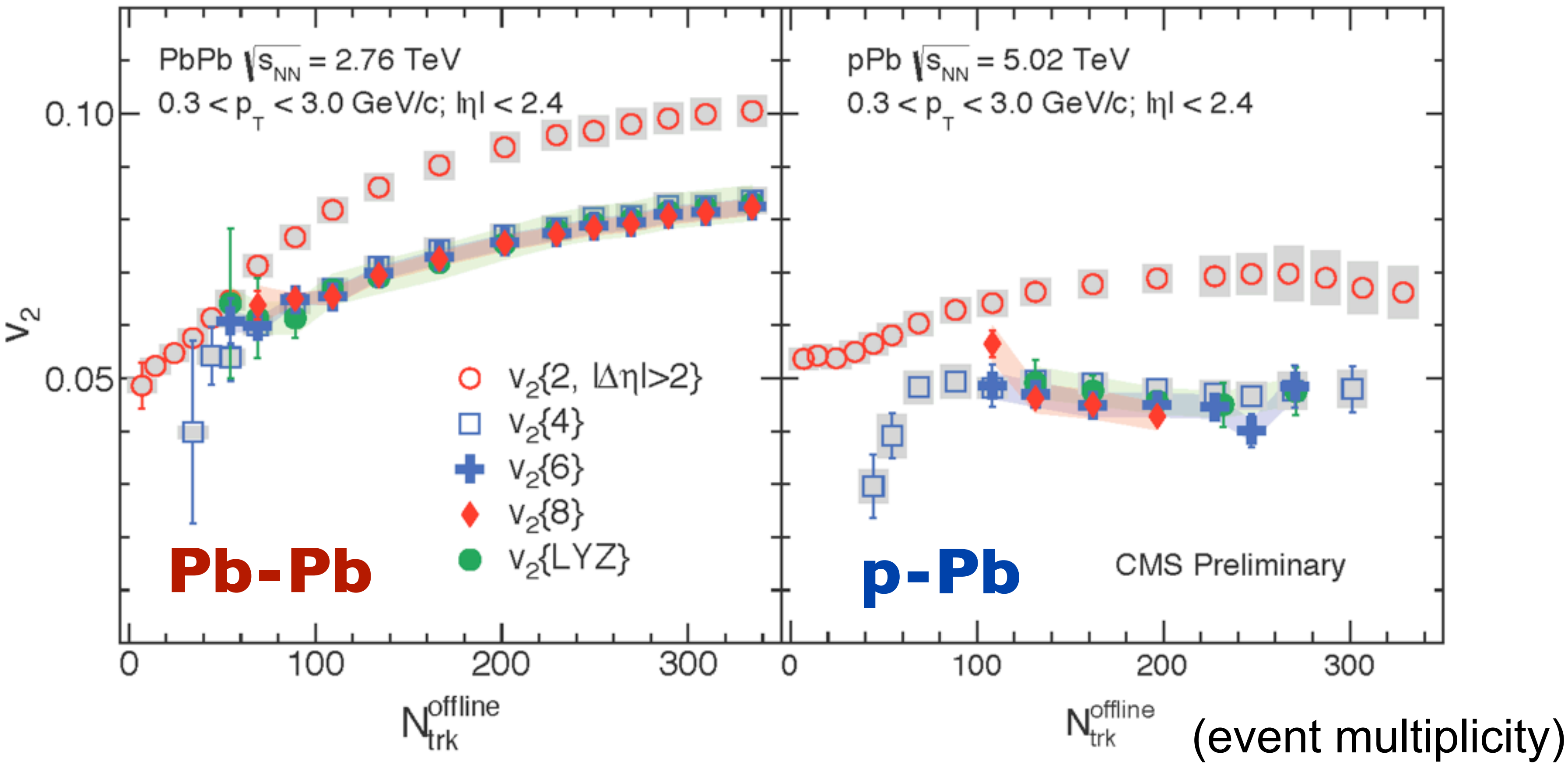
60-100%



- Extract double ridge structure by subtracting p-p jet like distribution in p-Pb (60-100%) from central p-Pb (0-20%).
- Confirmed that near and away side ridges are almost same structure, a la **"Double ridge"**.
- **Strong correlation between near and away side yields, suggesting the same origin.**



Multi-particle correlations (PbPb vs.pPb)



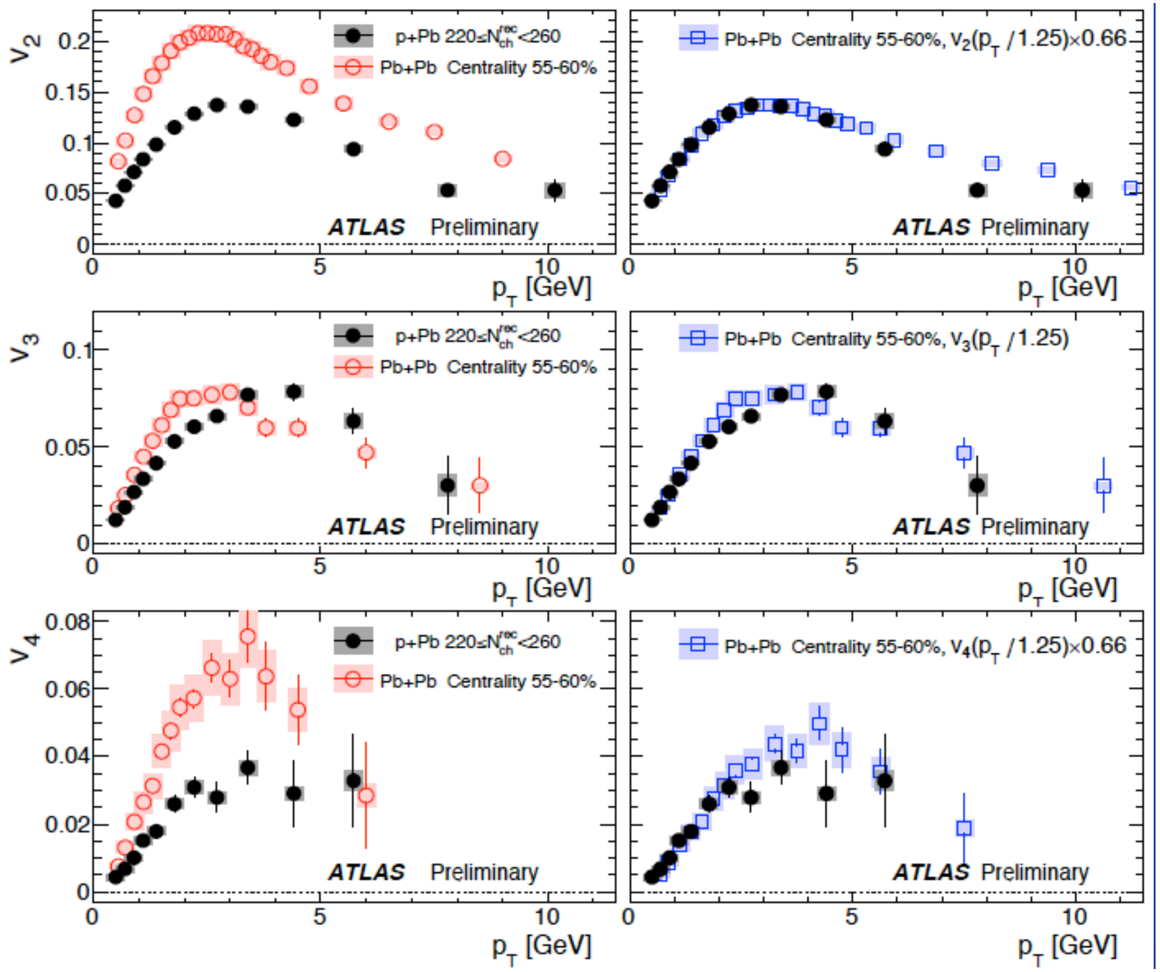
- Observed non-flow effect in $v_2\{2\}$.
- **v_2 stays large when calculated with multi-particles.**
- $v_2\{4\}=v_2\{6\}=v_2\{8\}=v_2\{LYZ\}$ within 10%
- Suggest collectivity in p-Pb.

v_2, v_3, v_4 comparisons; p-Pb vs. Pb-Pb

before scaling after scaling

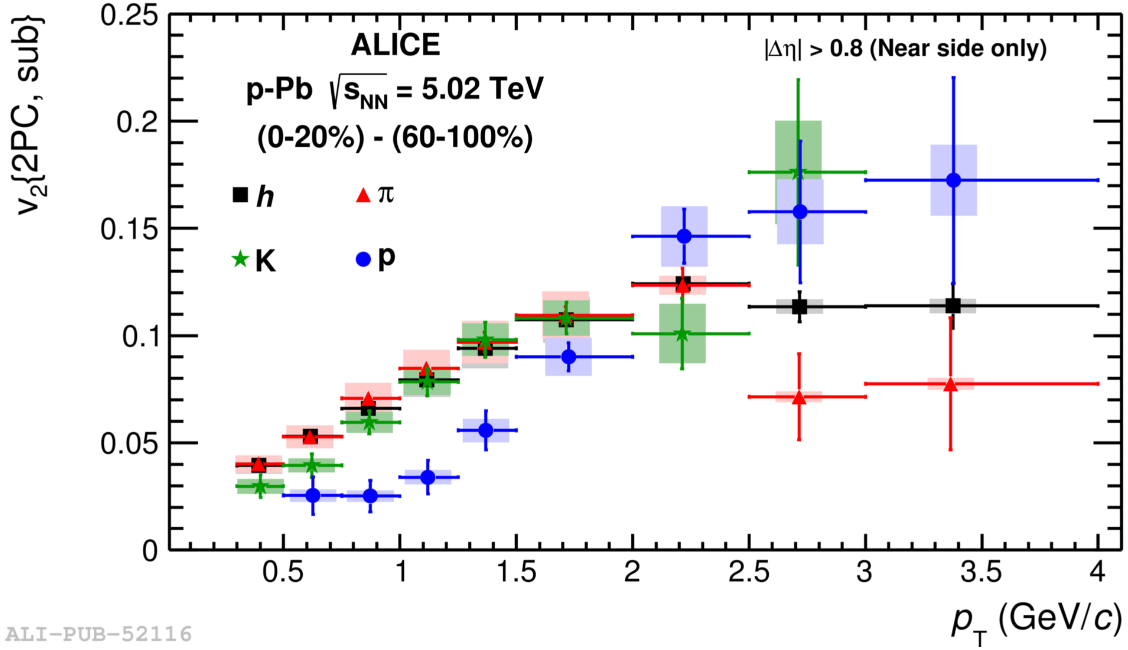
1. Adjust p+Pb p_T scale by 4/5 to account for difference in <p_T> (Teany et al.) for ATLAS data.
2. Pb+Pb v_2 and v_4 multiplied by 0.66 to match p+Pb

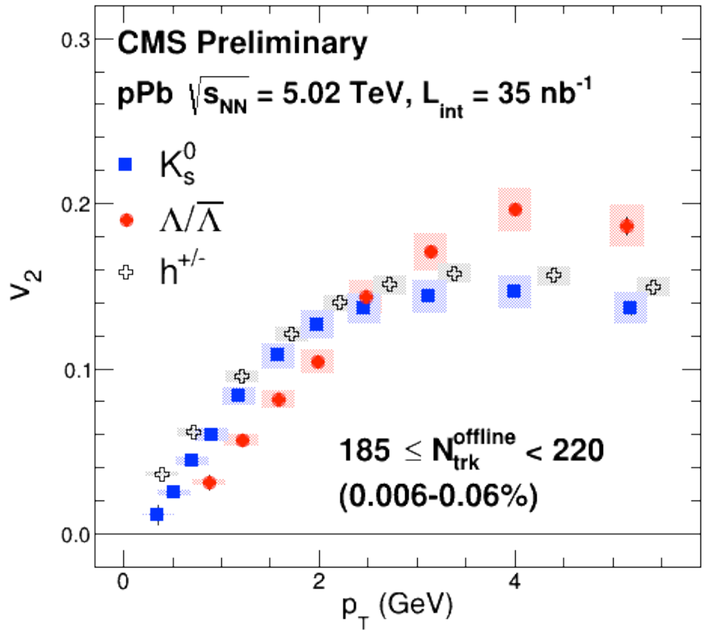
- Compare p+Pb and Pb+Pb
  - Good agreement between p-Pb and Pb-Pb **when including p_T and v_2, v_4 rescaling**



PID v_2 in p-Pb

PLB719 (2013) 29
PLB726 (2013) 164



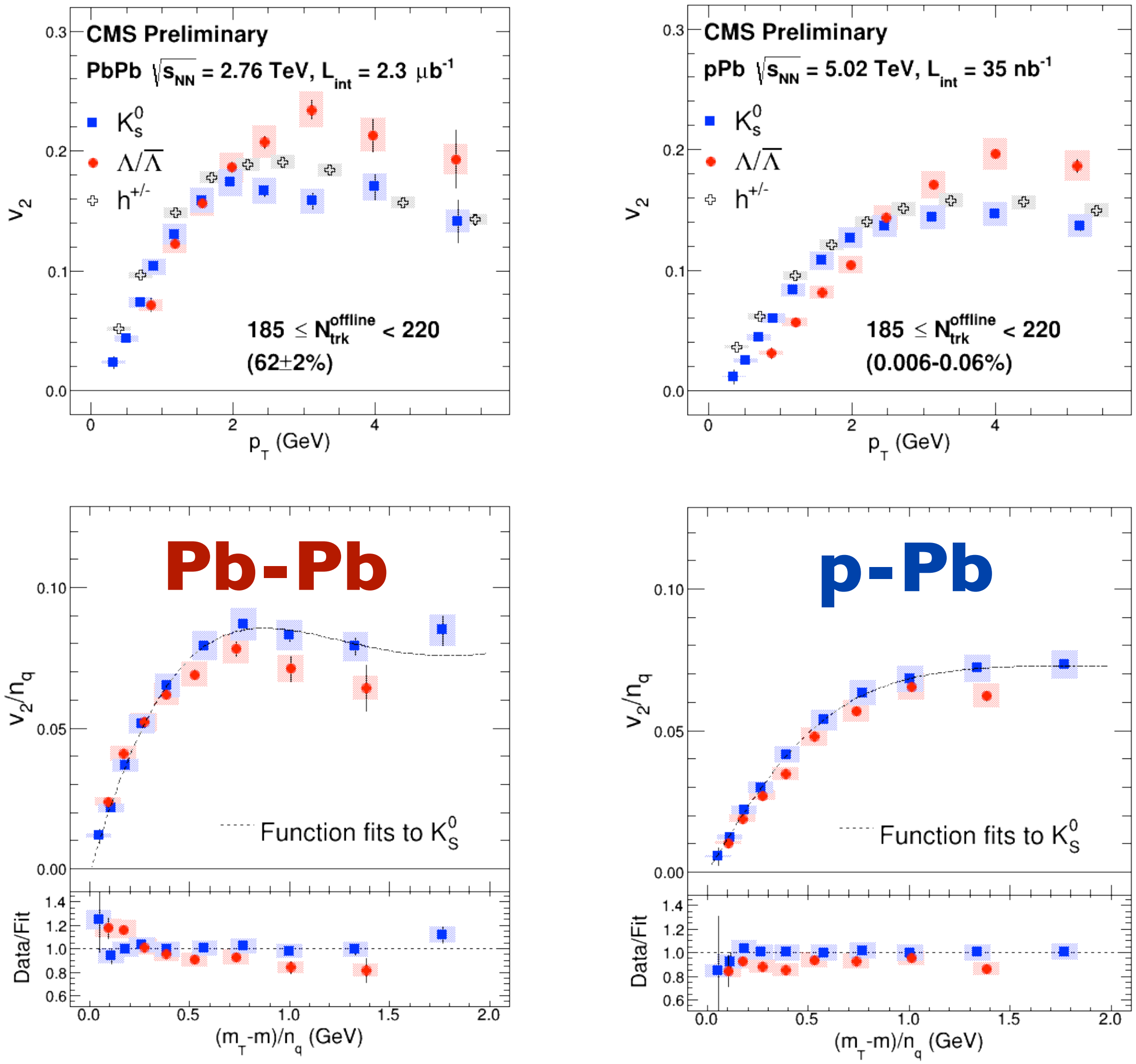


- v_2 for π, K, p (ALICE) and K_s^0, Λ (CMS)
- Very similar behaviour for v2 in Pb-Pb, i.e, **Mass ordering & crossing**

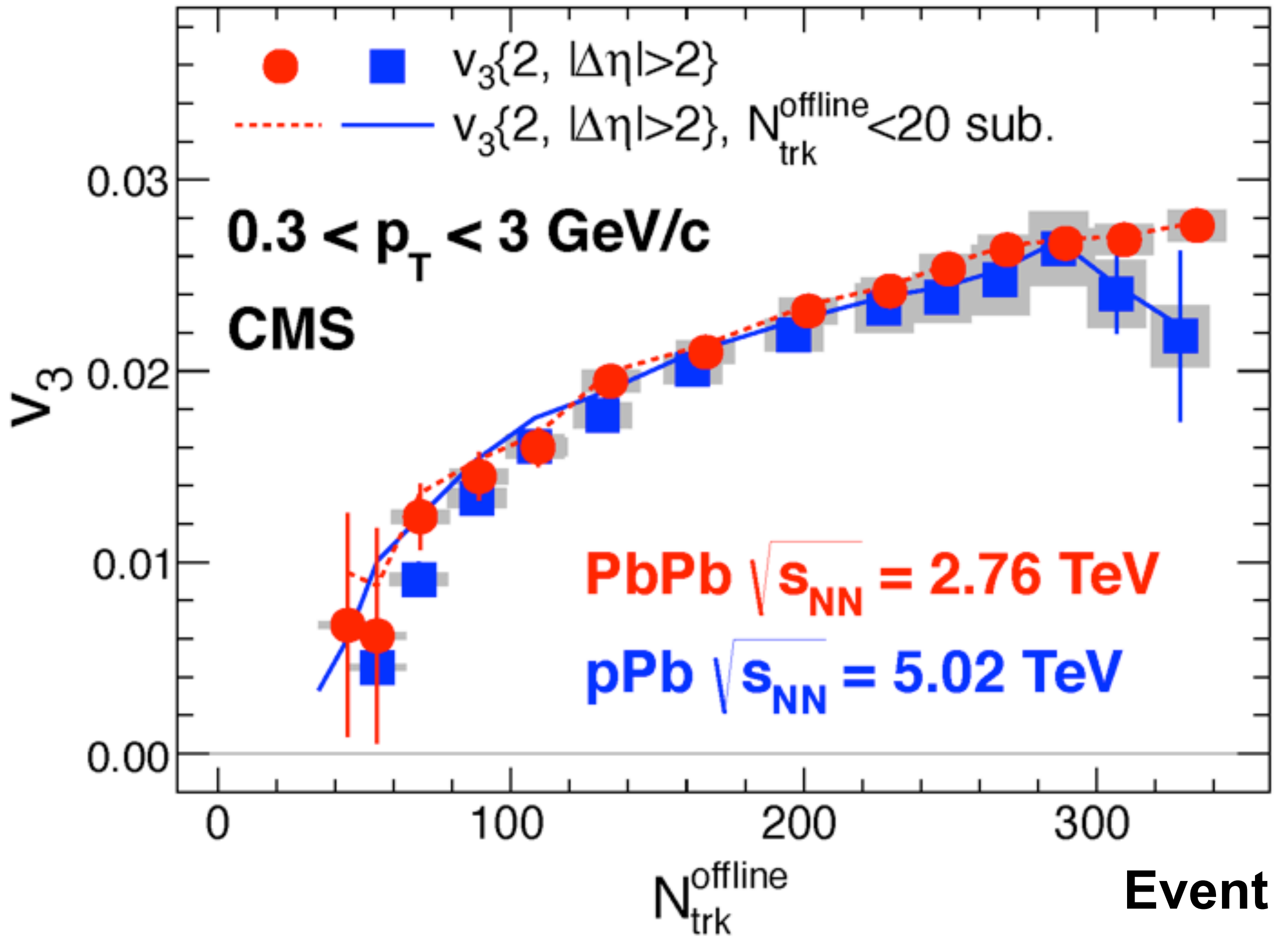
Quark number scaling test in pPb

Quark number scaling of v_2.

- Comparison in p-Pb and Pb-Pb in same N_{ch}.
- Seems better in pPb.



v_3 in Pb-Pb vs. p-Pb



Event multiplicity

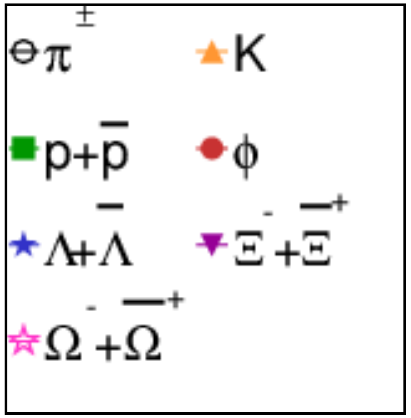
Remarkable similarity in v_3 as a function of multiplicity in **p-Pb** and **Pb-Pb**

Now on PbPb;

towards precession measurements of identified particle v_2

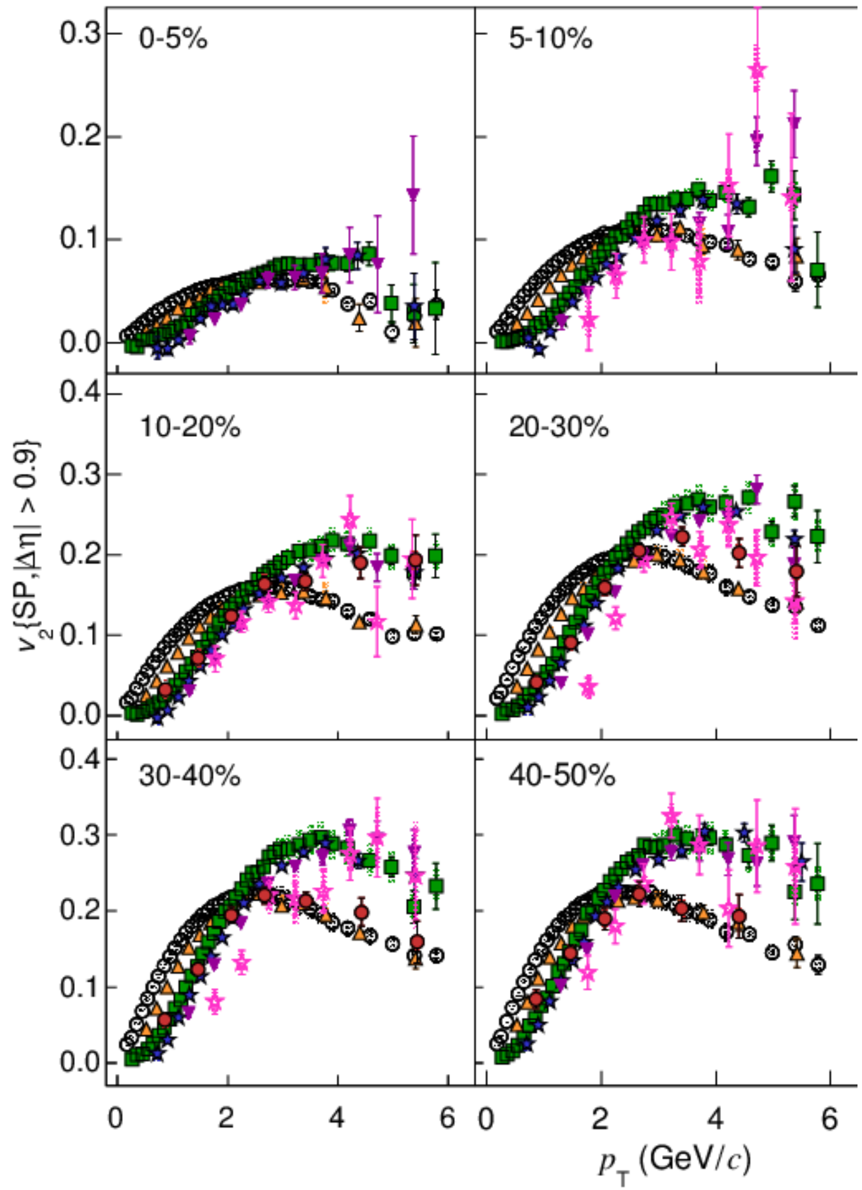
PID v_2 in Pb-Pb

arXiv:1405.4632



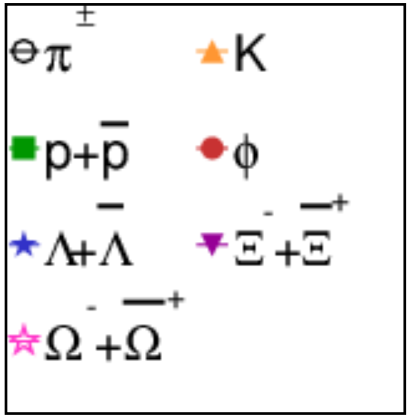
- ALICE data of v_2 measured for π, K, K^0, p, ϕ, Λ, Ξ, Ω

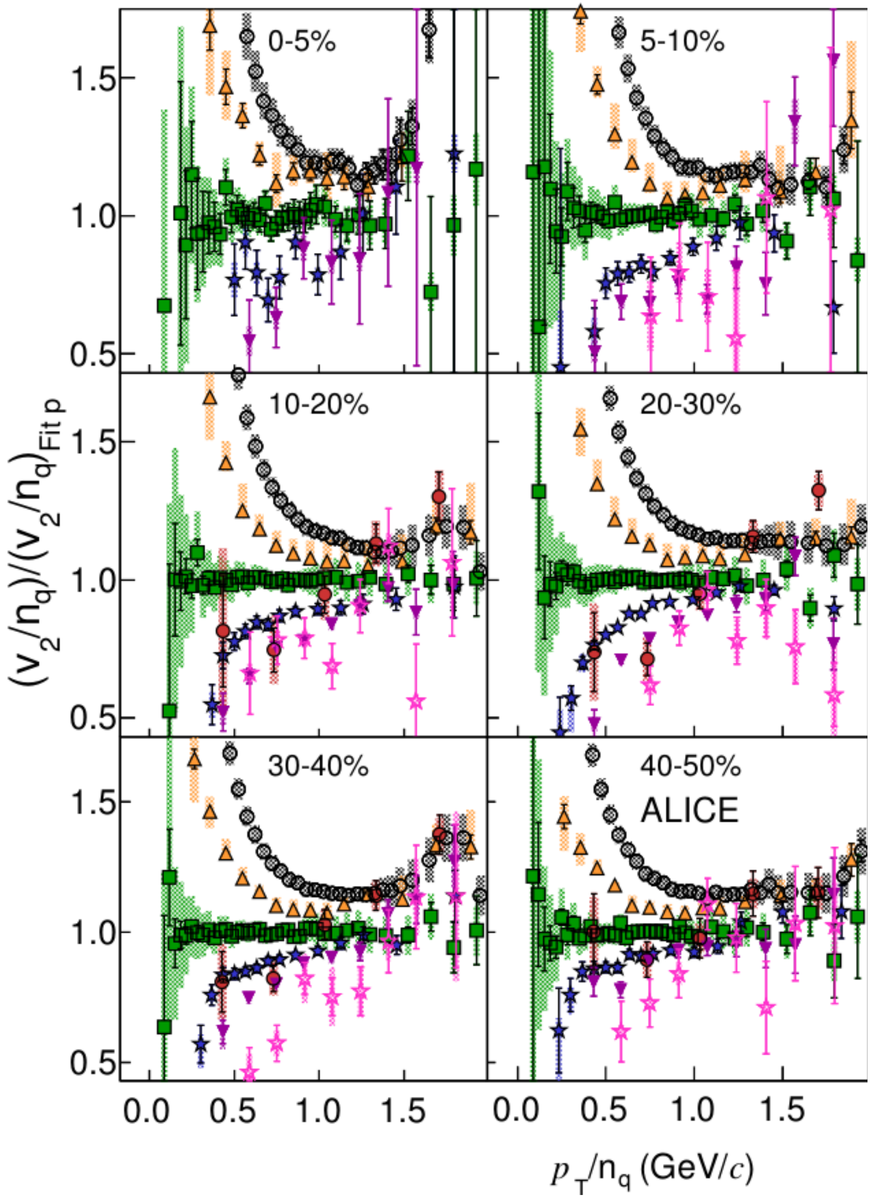
- Mass ordering (p_T < 2.5 GeV/c).



PID v_2 in Pb-Pb

arXiv:1405.4632





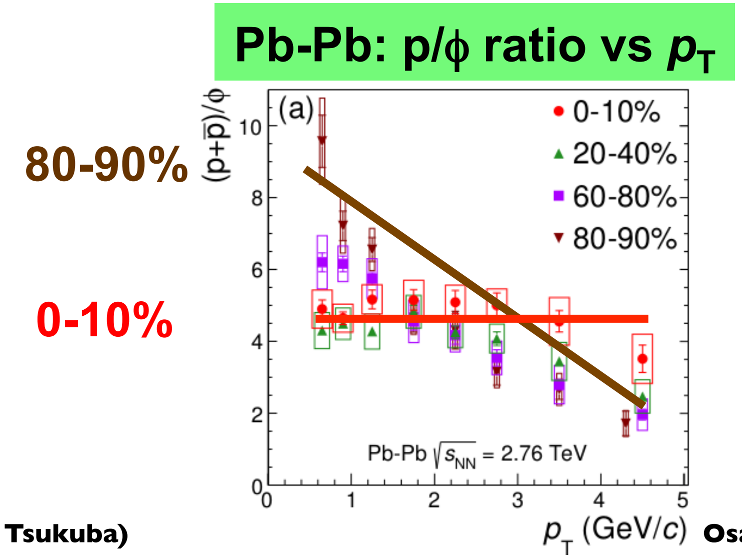
- Number of quark constituent **scaling violated by ~20%** in particular **in central collisions** **(p_T/n_q > 1 GeV/c)**

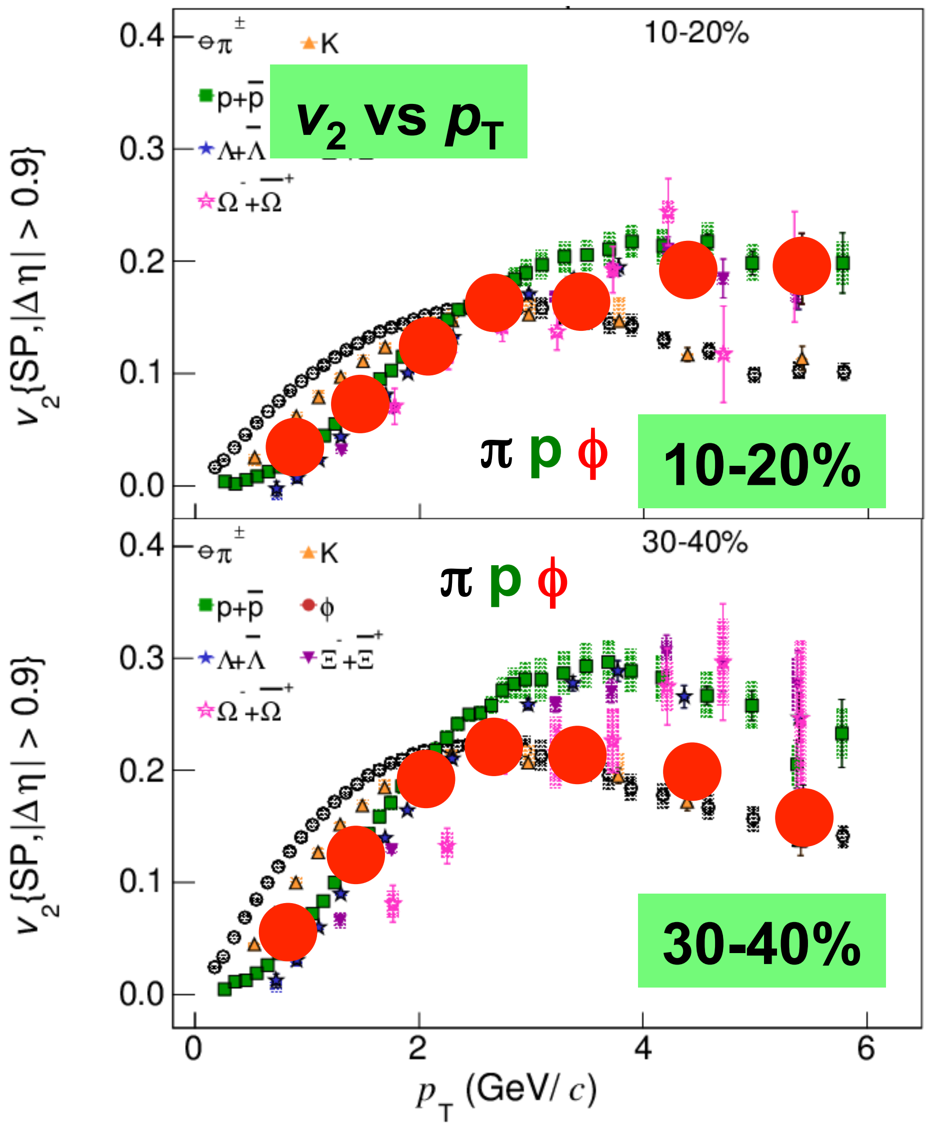
Closer look at ϕ meson v_2 (Pb-Pb)

- v_2 at low p_T follows mass ordering
- v_2 at high p_T close to p in central, and close to π in mid-central

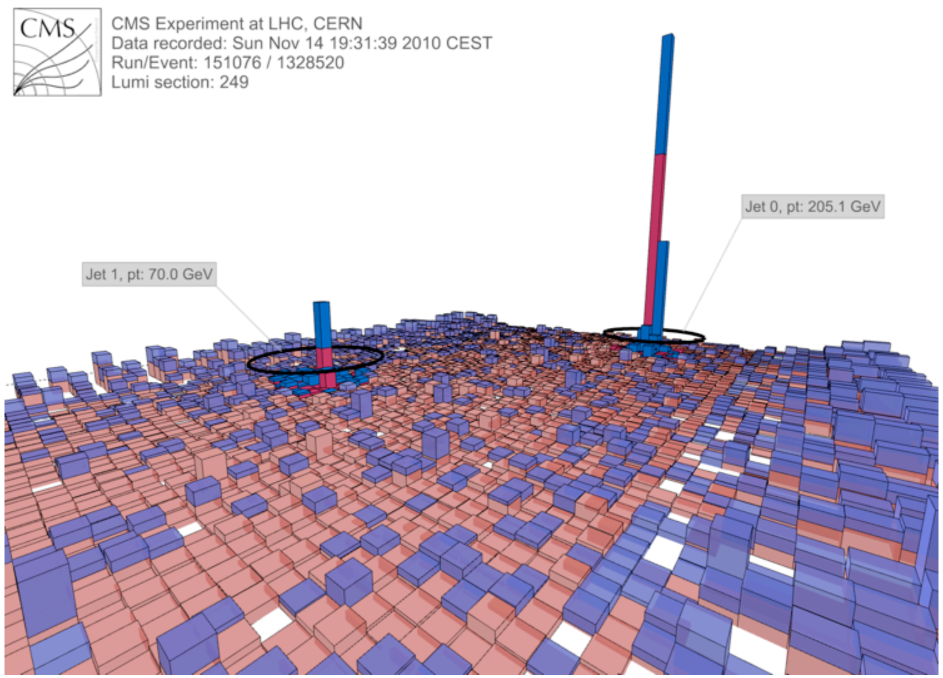
- In central collisions p and ϕ p_T spectra have similar shape up to ~4 GeV/*c*, as expected from radial flow.

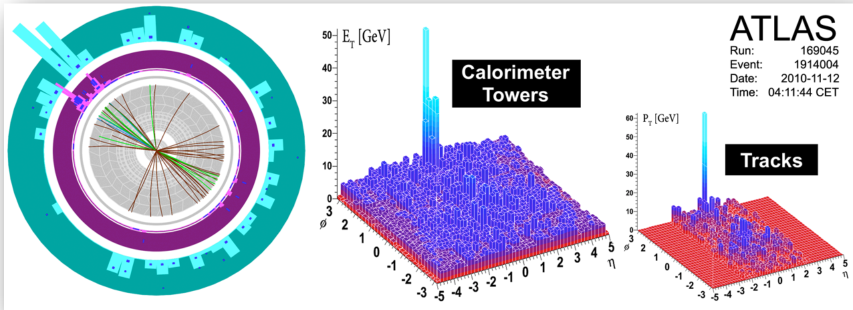
- Indicated that mass (and not number of constituent quarks) is main driver of v_2 and spectra in central only?

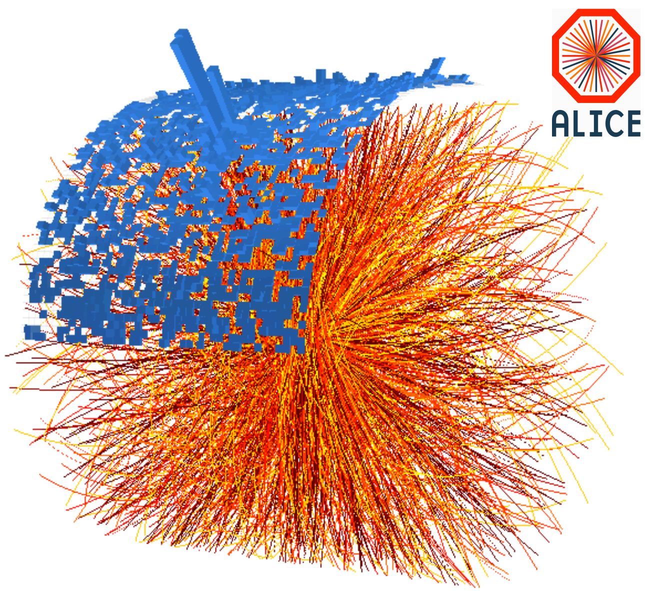




2. Energy loss

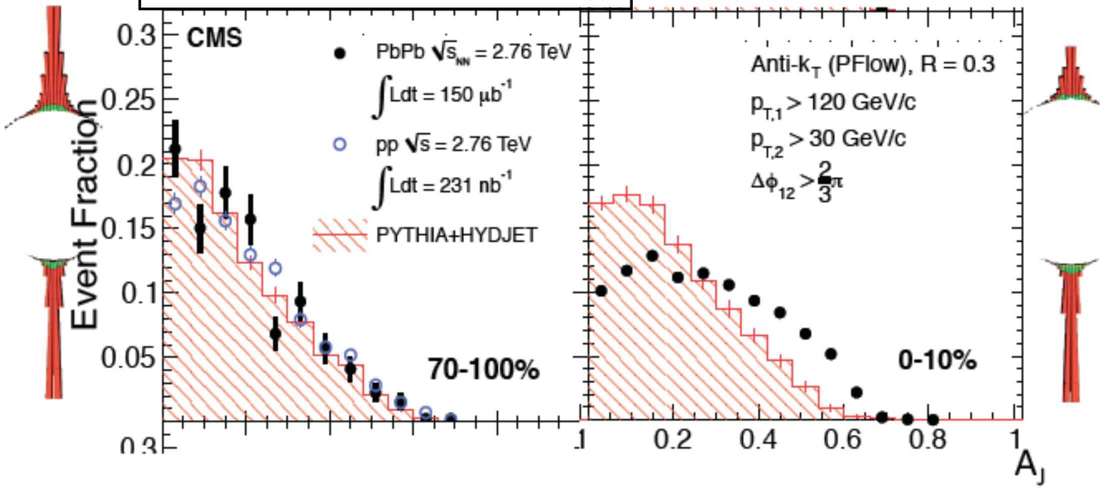




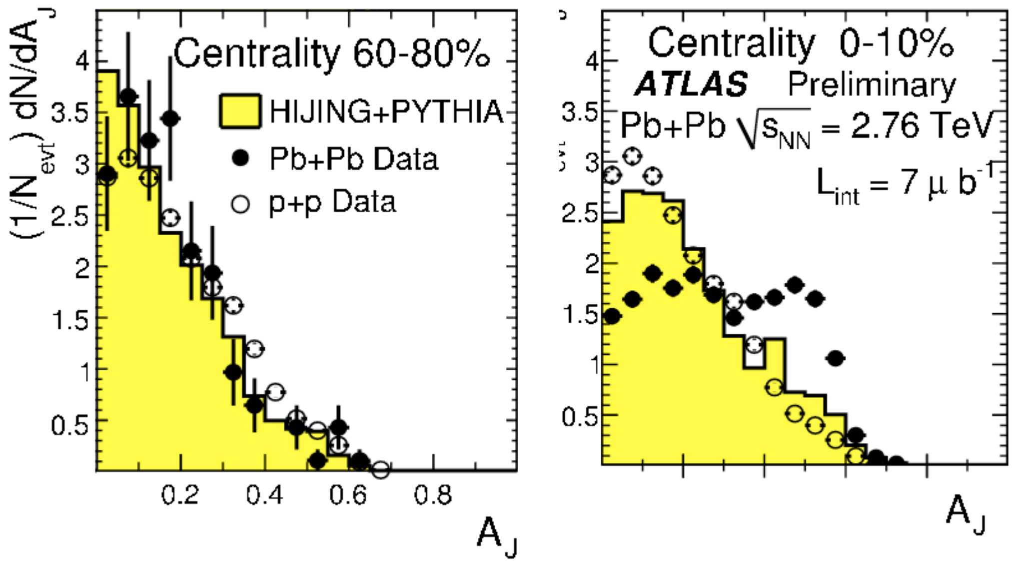


Di-jet energy imbalance

CMS, PRC 84, 024906 (2011)



ATLAS, PRL, 105 (2010) 252303



1) Large energy imbalance is observed in central Pb-Pb.

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

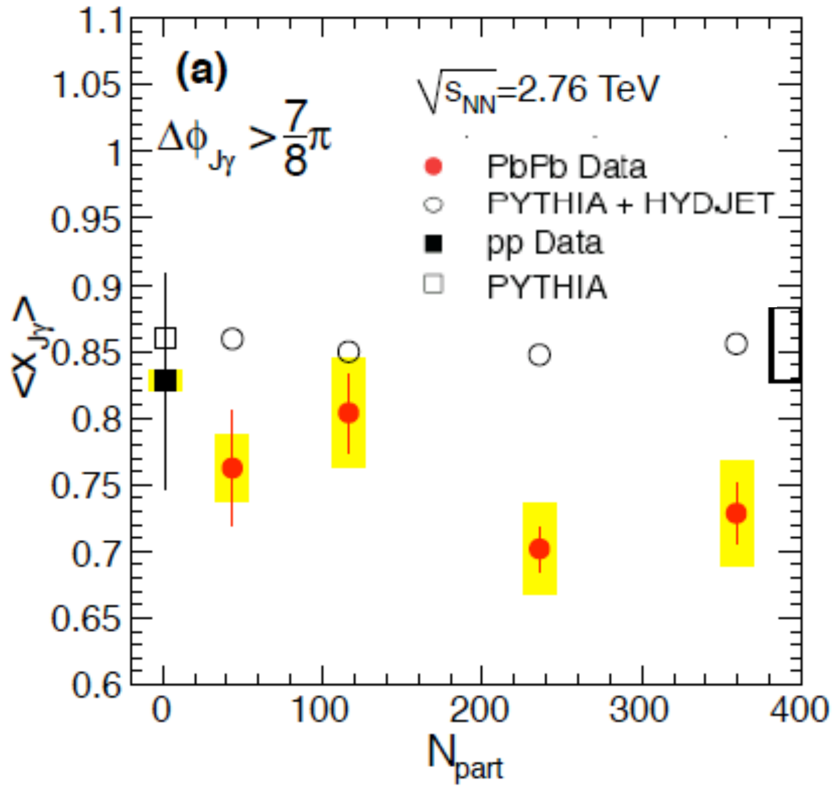
$p_{T,1}$: leading jet
$p_{T,2}$: sub-leading jet

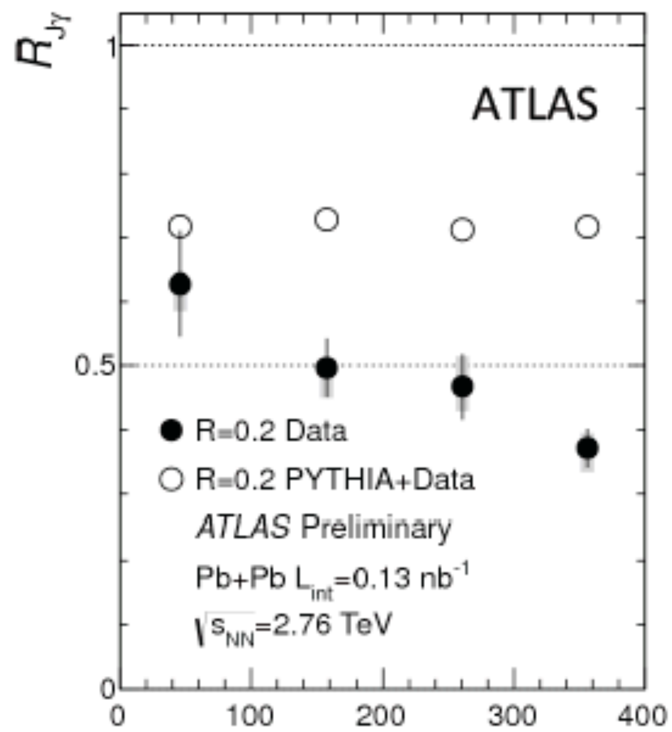
2) Large A_J : low momentum particle (< 4 GeV/c) emitted at large angle on away side.

γ-jet: jet tomography

CMS, Phys. Lett. B 718 (2013) 773 $< x_{J\gamma} >= p_T^{jet}/p_T^{\gamma}$

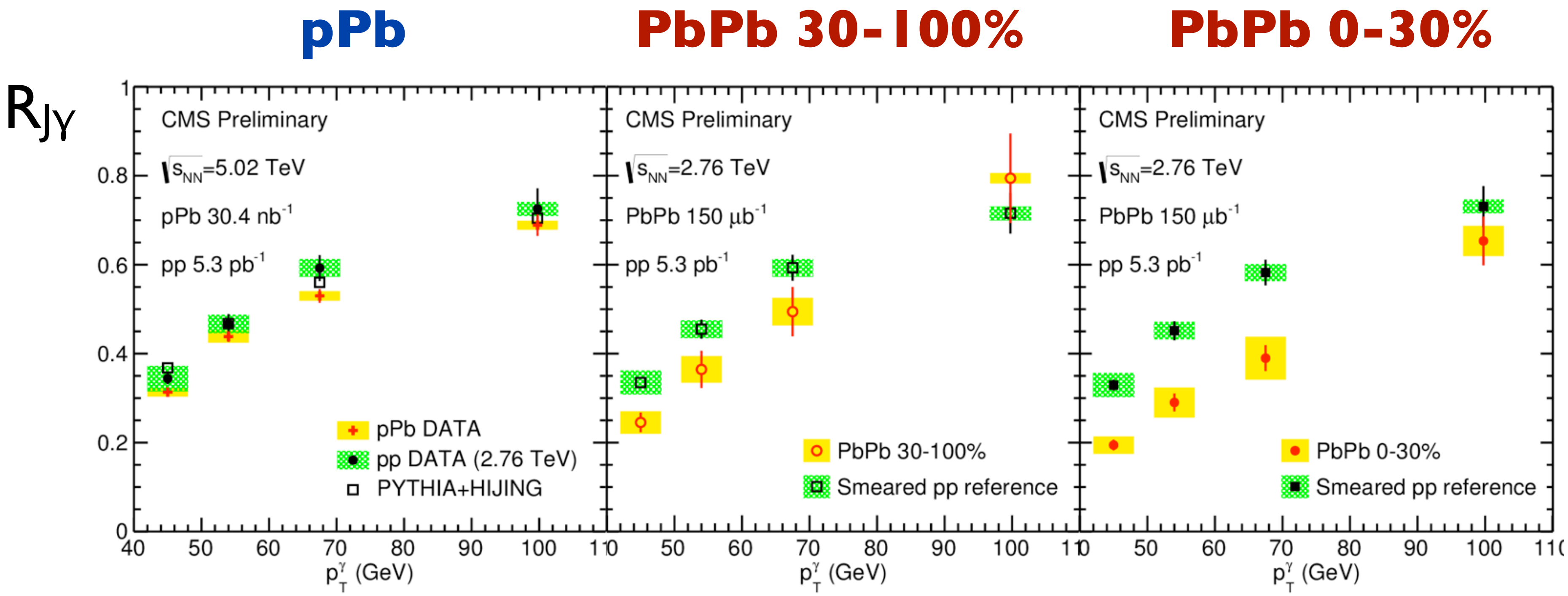
$R_{J\gamma}$: fraction of photons with jet partner





- γ as a calibrated probe of jet energy.
- significant change in $R_{J\gamma}$, $<x_{J\gamma}>$ compared to PYTHIA and pp.

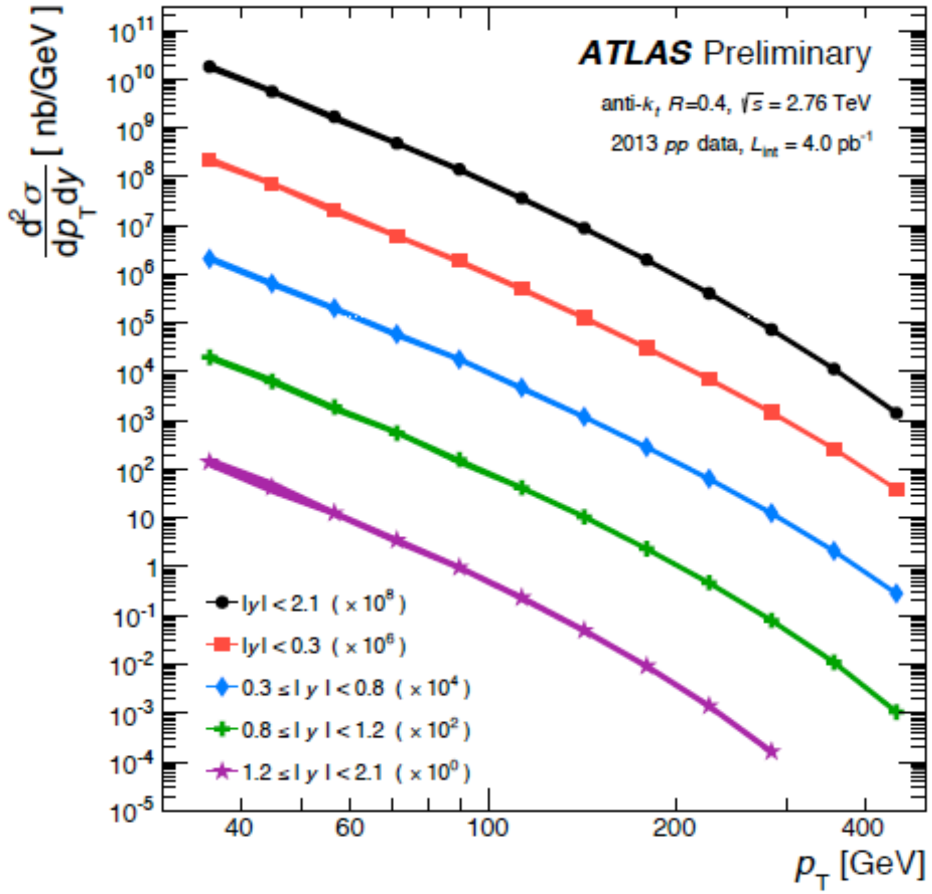
γ-jet in pPb, PbPb

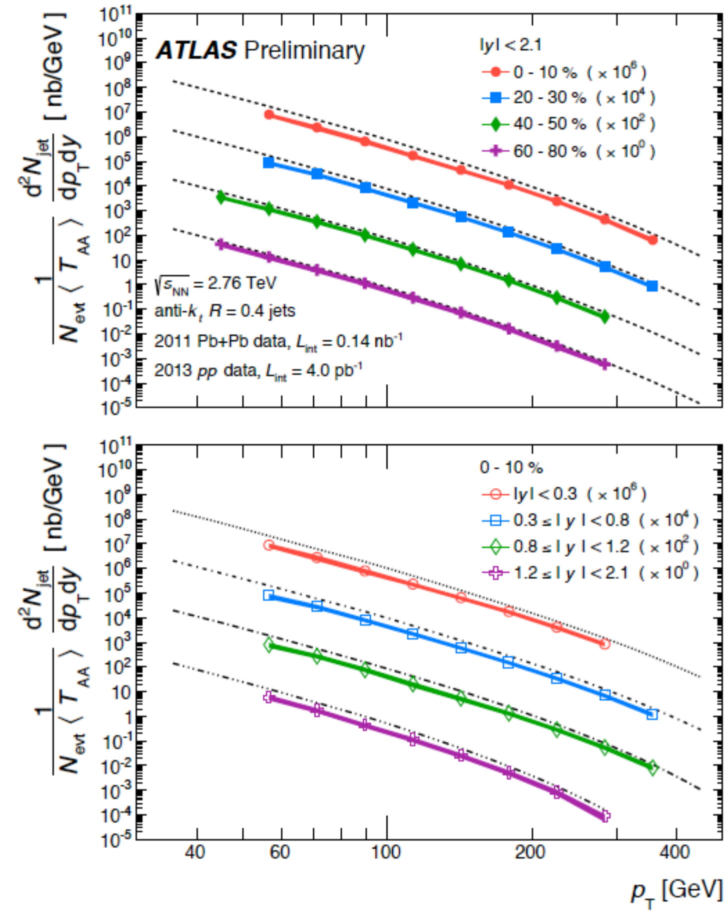


- $R_{J\gamma}$ = fraction of photons with a jet of $p_{T,\,jet}$ > 30 GeV
- Jet energy is essentially unmodified in pPb.

Jet spectra in Pb-Pb, p-p

pp 2.76 TeV **Pb-Pb 2.76 TeV**

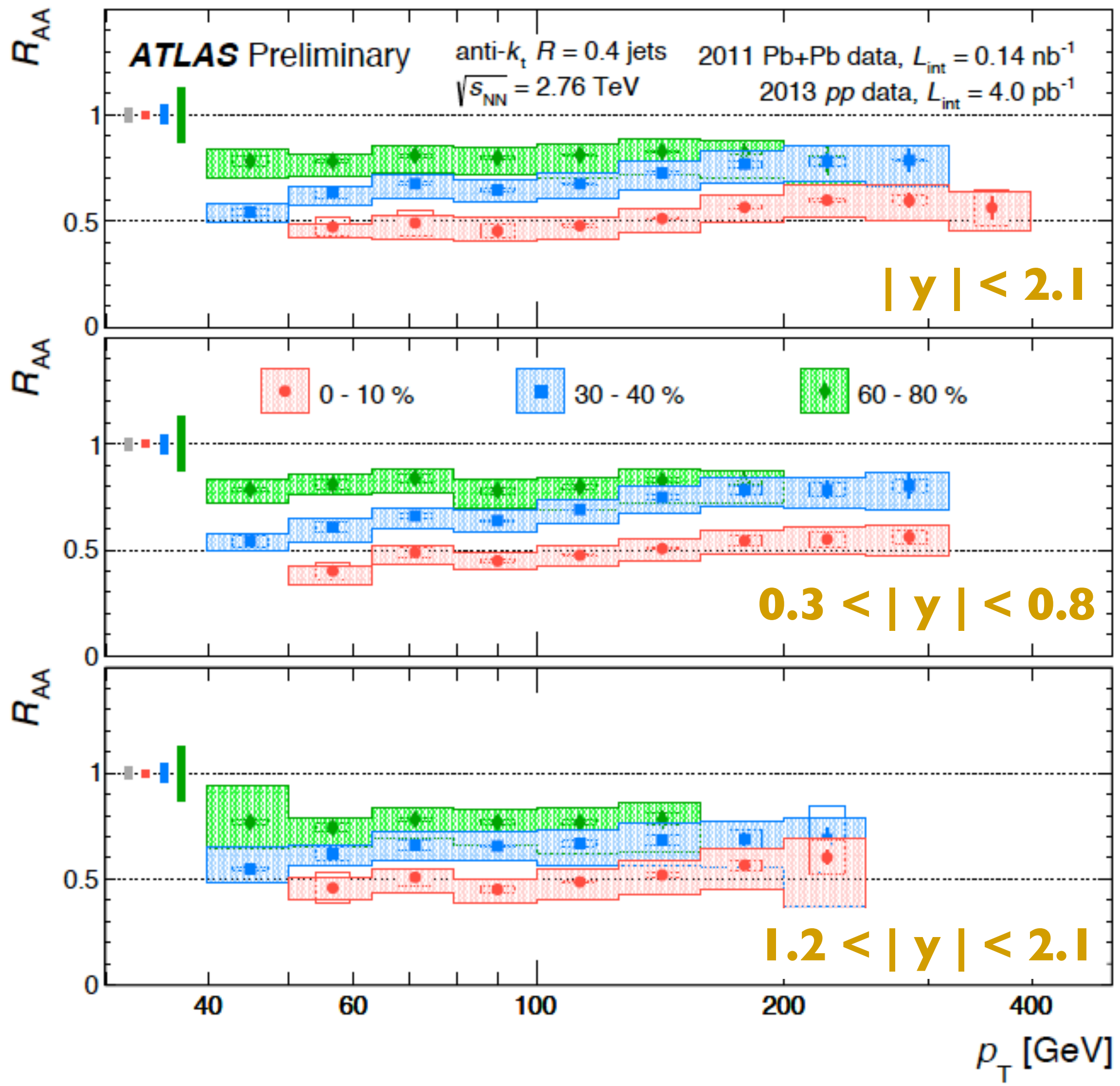




- ATLAS: in different y and centrality, up to p_T < 400 GeV

Jet R_{AA}: centrality and y dep.

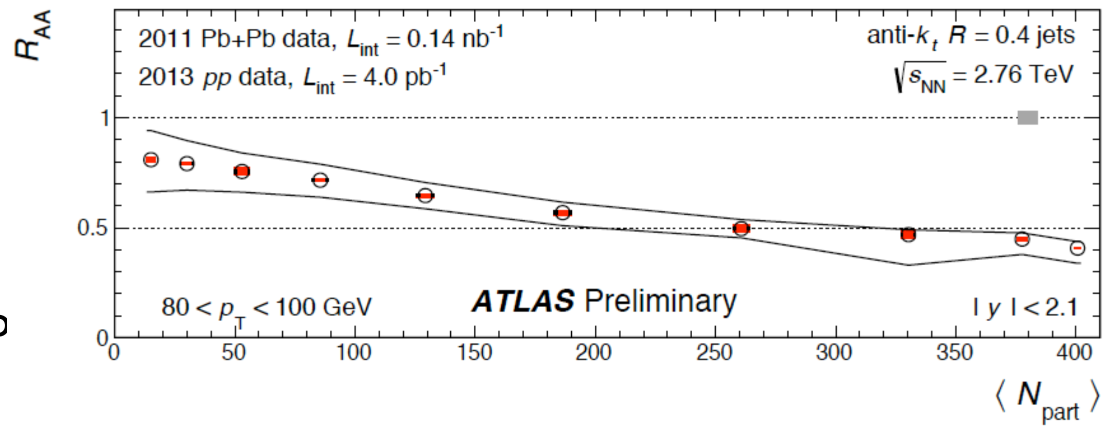
- Jet R_{AA} vs p_T and y.
- Factor of ~2 suppression **up to jet p_T of 400 GeV**
- Slow increase with increasing jet p_T, may vary with centrality



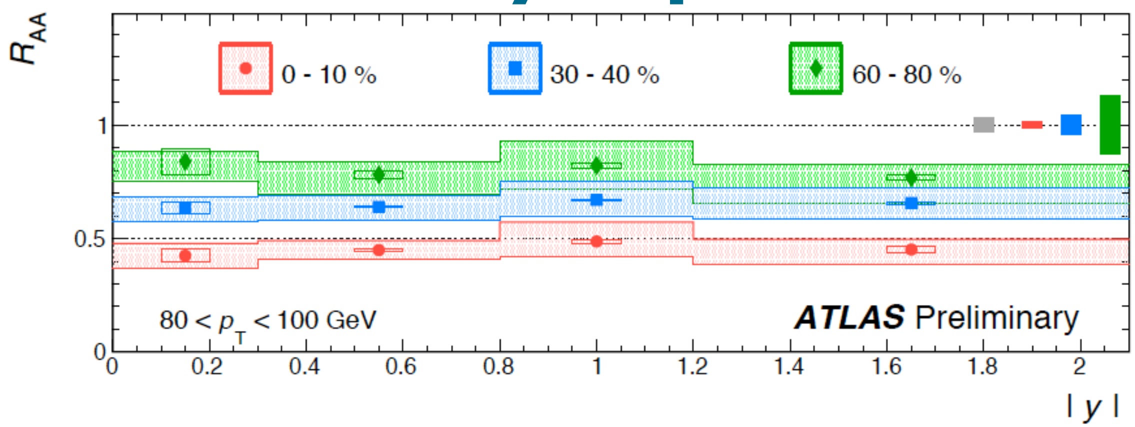
Jet R_{AA}: centrality and y dep.

- R_{AA} **monotonically decreases** vs N_{part}
  - R_{AA} ~0.8 in 60-80%,
  - R_{AA} ~0.4 in 0-1% at lower jet p
- No significant dependence on rapidity observed
  - Even though both spectrum shape and q/g fractions vary with y

Centrality dep.



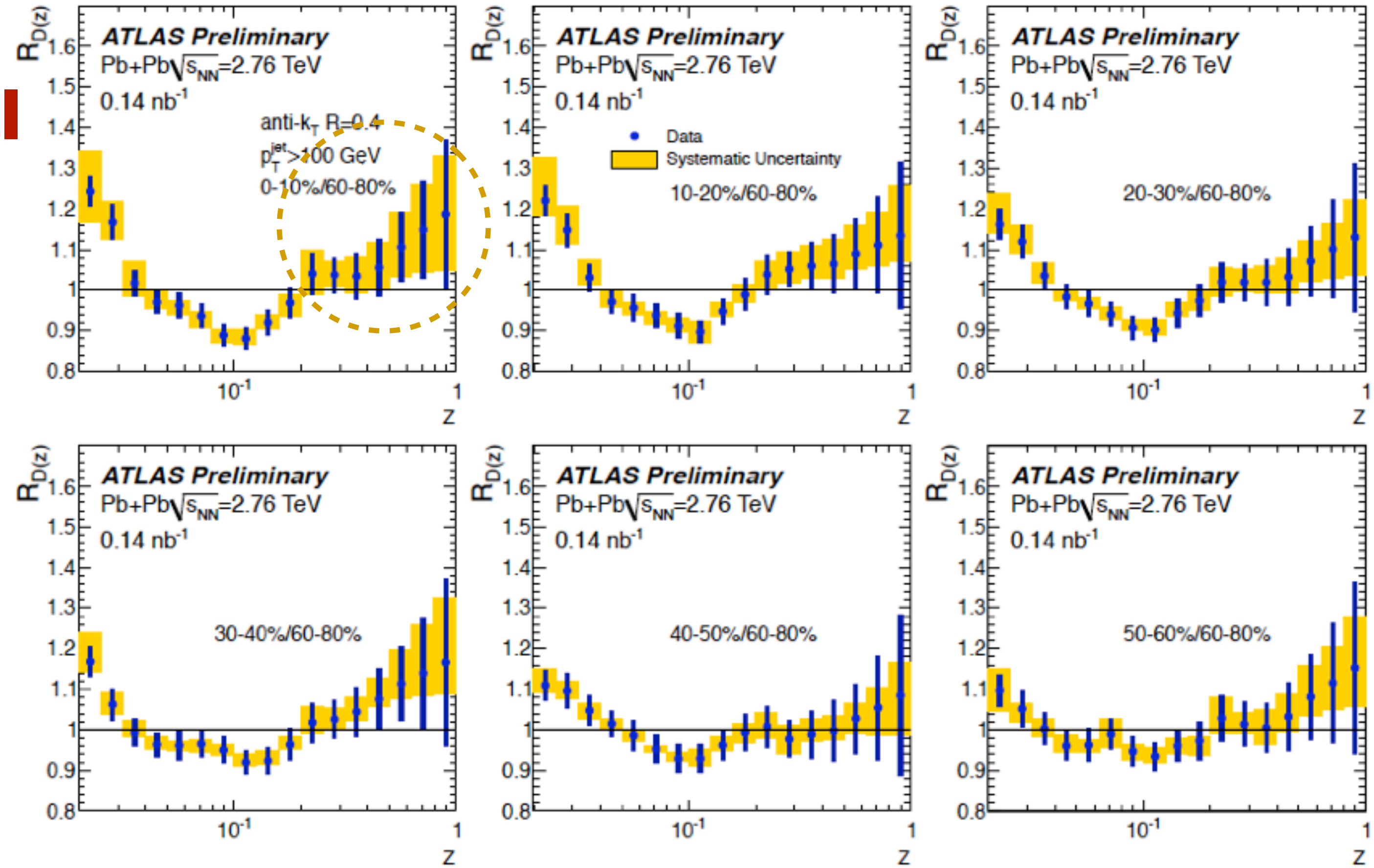
y dep.



Jet Fragmentation in PbPb

central

R= 0.4



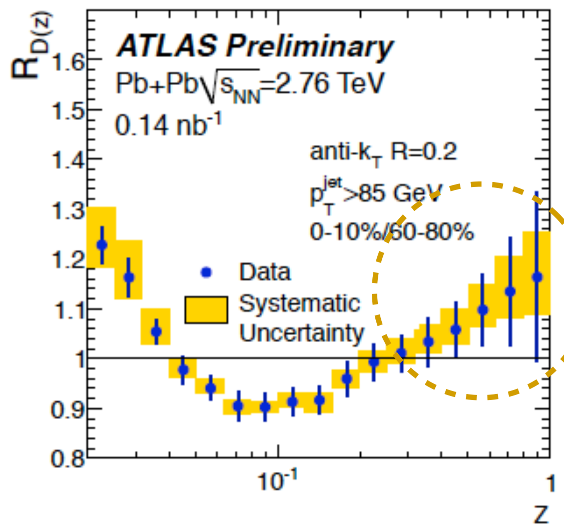
peripheral

- **Ratios of D(z)** vs centrality, using baseline peripheral (60-80%)
- In addition to features previously seen (modification of small z (low pT)), **indication of an enhancement at large z**

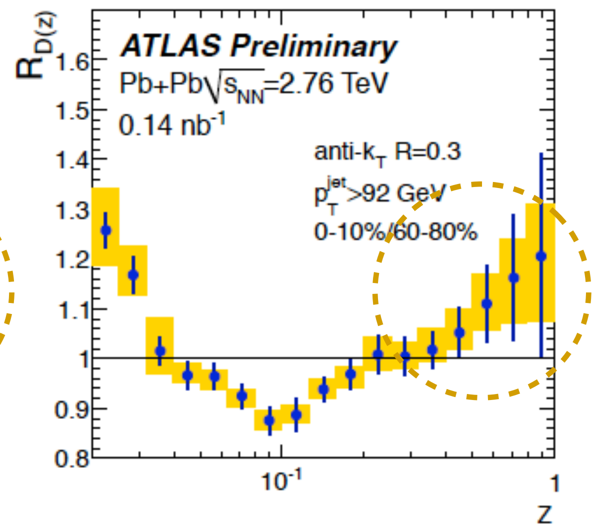
Jet Fragmentation in PbPb

- Enhancement at large z (or pT)clearer for smaller jet radii (R = 0.2, 0.3).

R= 0.2

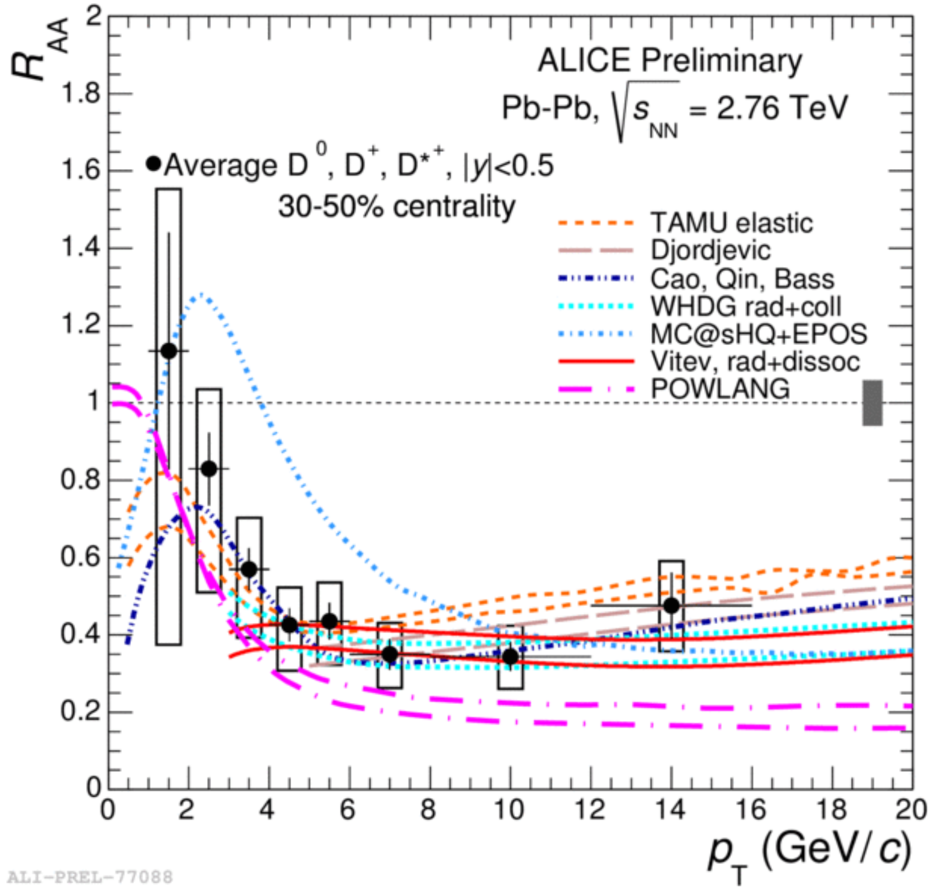


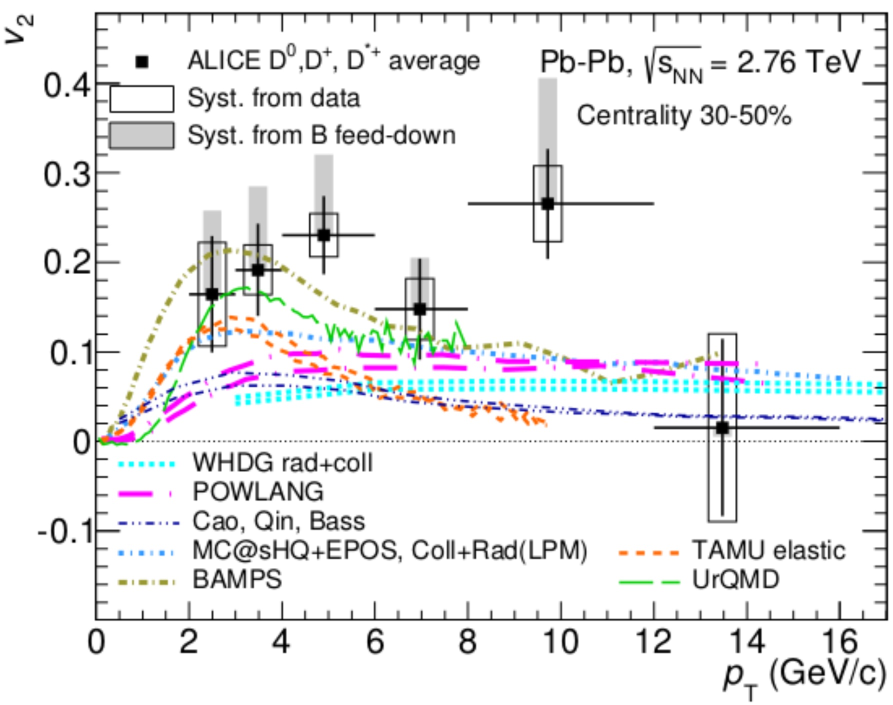
R= 0.3



D meson R_{AA} and v_2

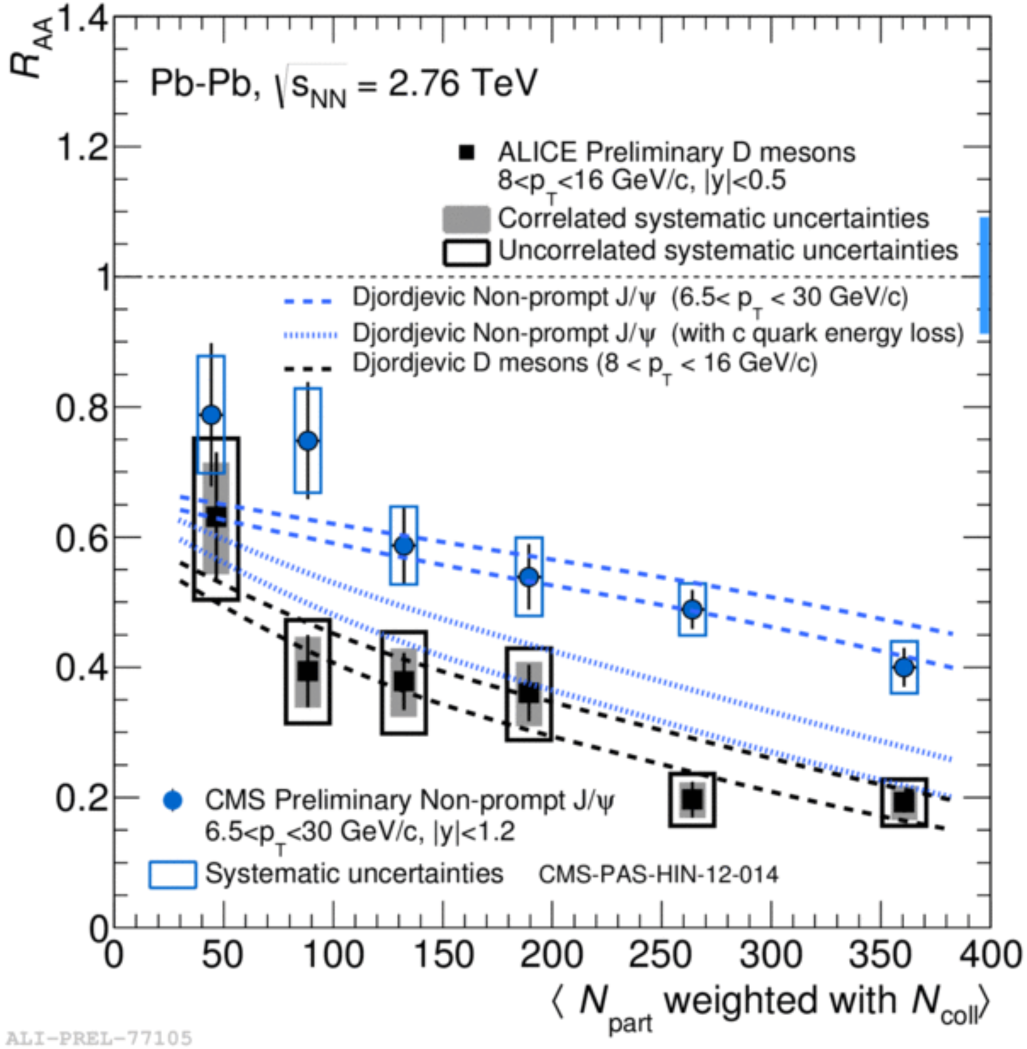
arXiv:1405.2001





- D mesons are also strongly suppressed.
- **significant non-zero v2 for D.**

Charm vs. Bottom



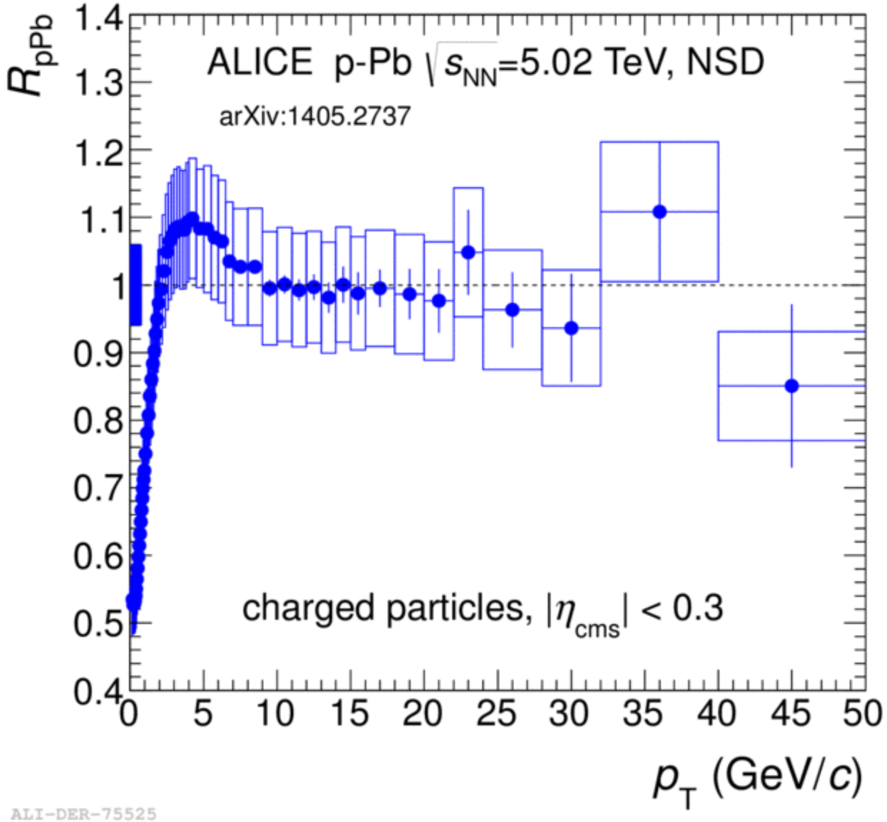
- R_{AA} for charmed meson (D) vs. bottom meson (J/ψ from B decay).
- First indication of a flavor dependence of R_{AA}.
- $R_{AA}^B > R_{AA}^D$

Now on pPb;

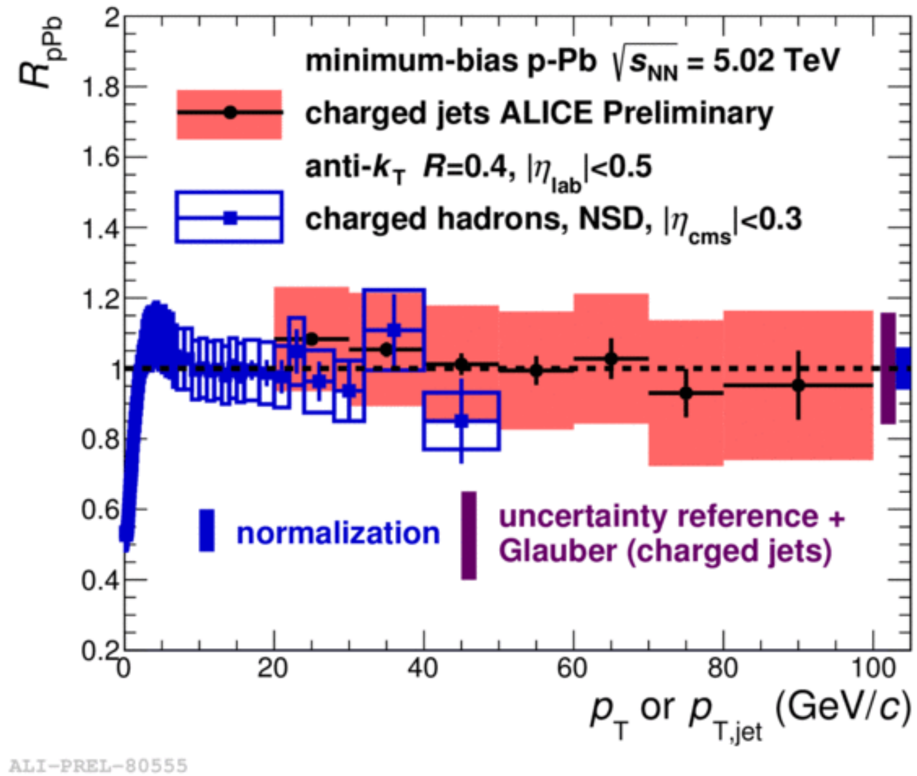
Jet/heavy q in pPb

R_{AA} for $h^{\pm}$ and jet in p-Pb

Charged hadron

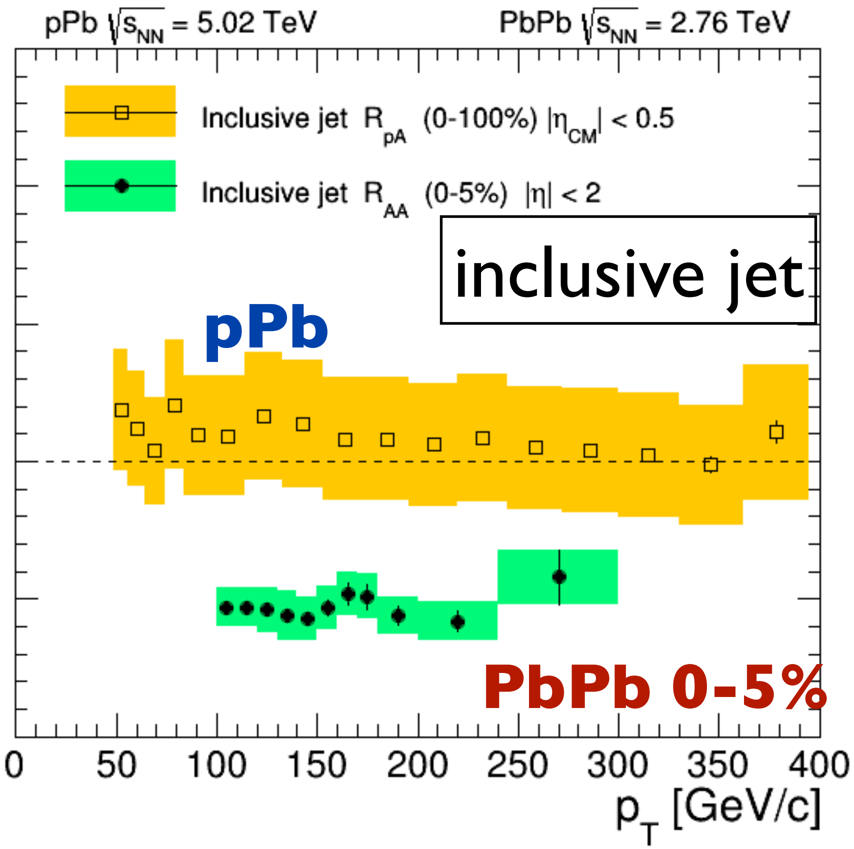


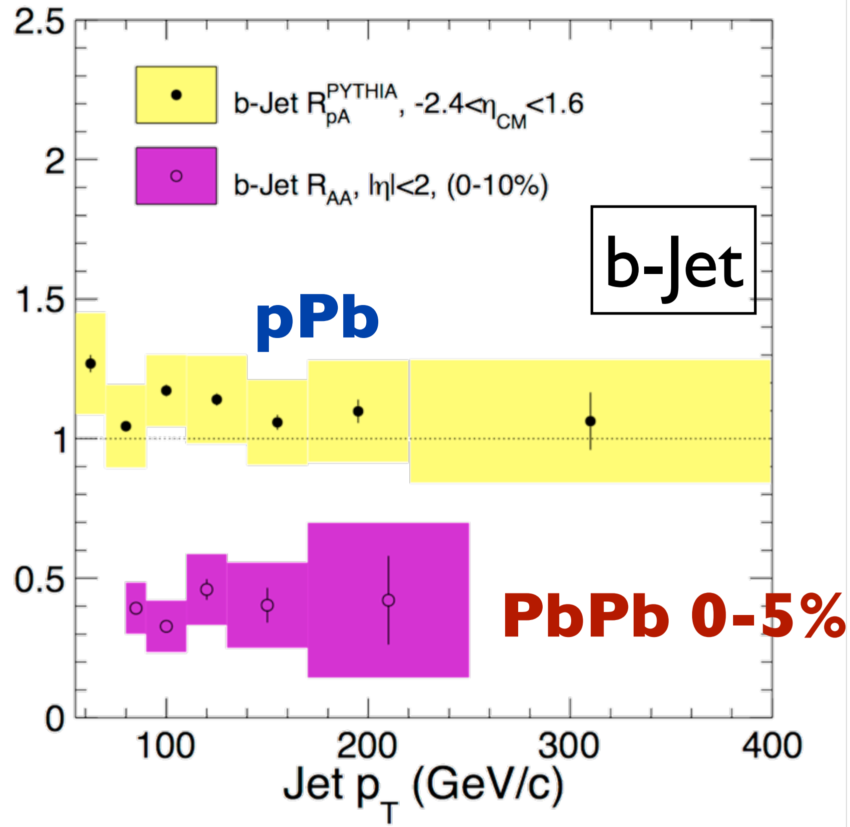
Jet (charged)



- Unmodified for charged hadron and jet in pPb.

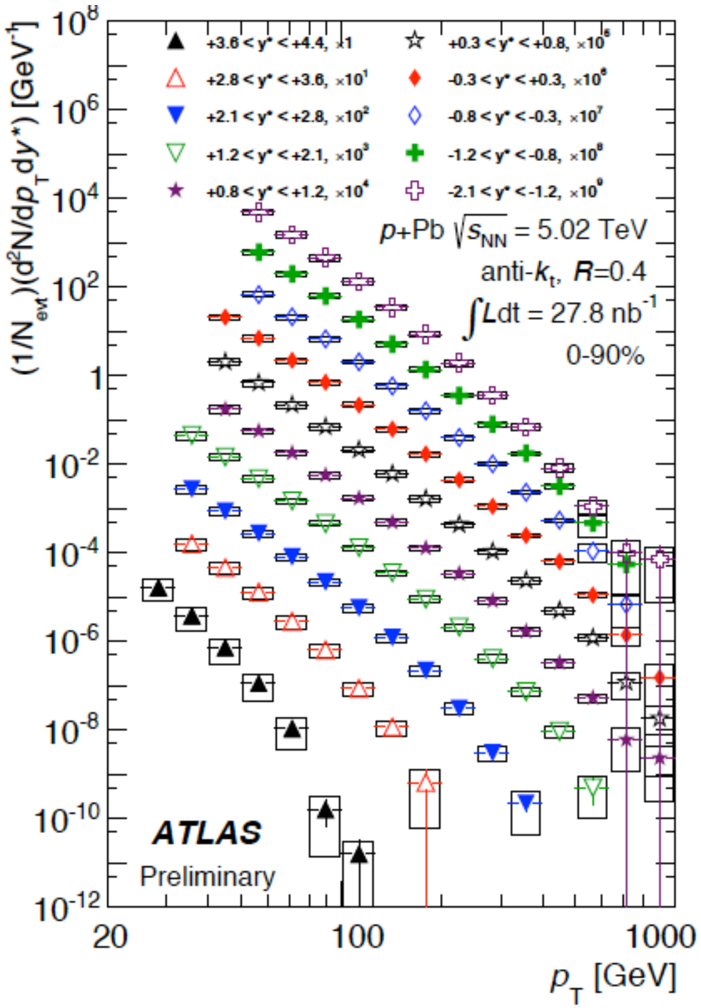
R_{pA} & R_{AA} for jets and b jets

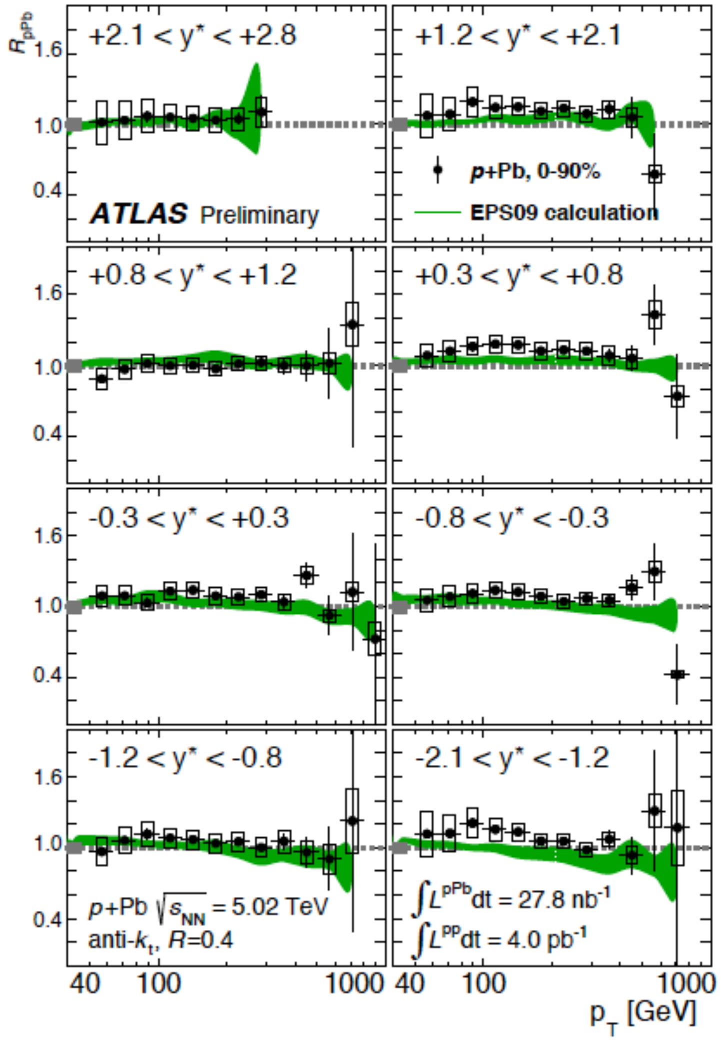




- Jets coming from b (second vertex)
- As suppressed as incl. jets ($R_{AA} \approx 0.5$)
- Not suppressed in pPb ($R_{pA} \approx 1$)

Jet in pPb, R_{AA}, y dep.

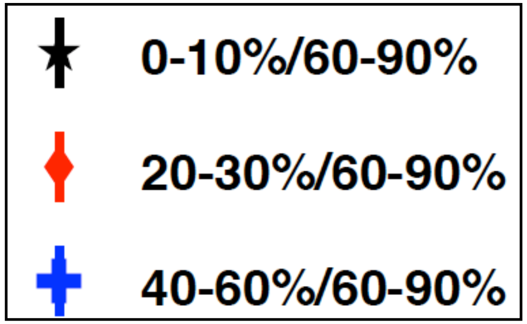




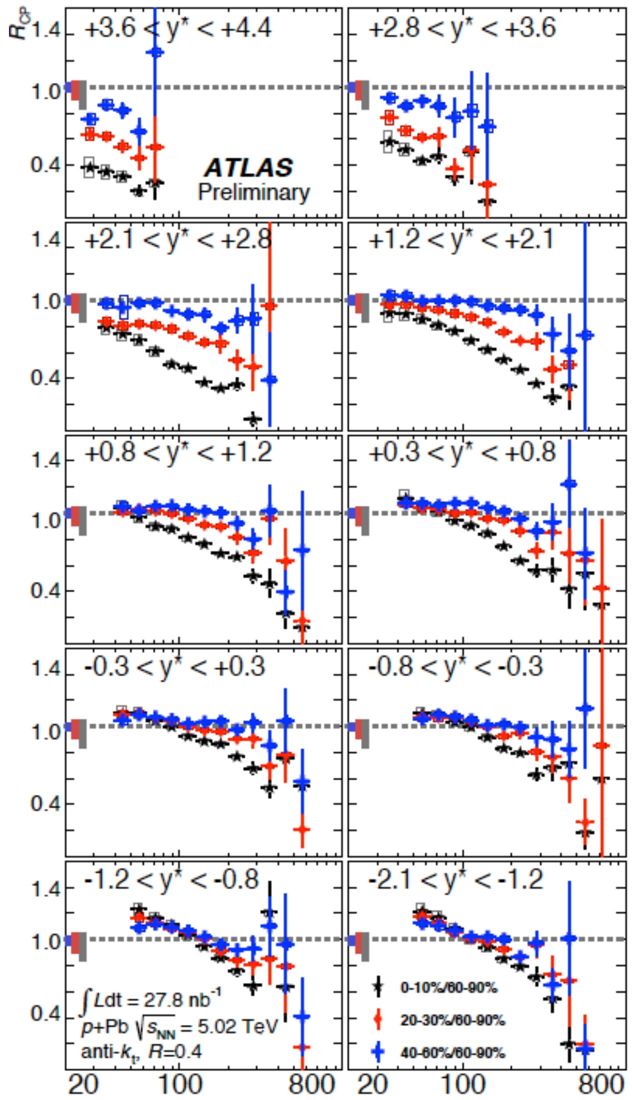
- Inclusive jet in pPb, no y dependence seen

Jet R_{CP} for pPb (centrality and y dep.)

- ATLAS observes a **strong variation in jet yield with centrality at high p_T or forward rapidities.**



R_{cp}



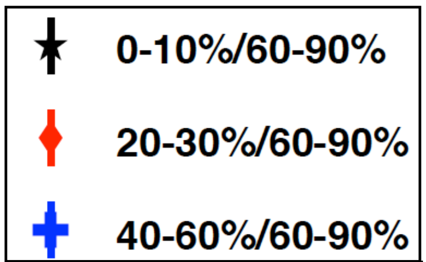
p_T (GeV)

Jet R_{pPb} (centrality dep.)

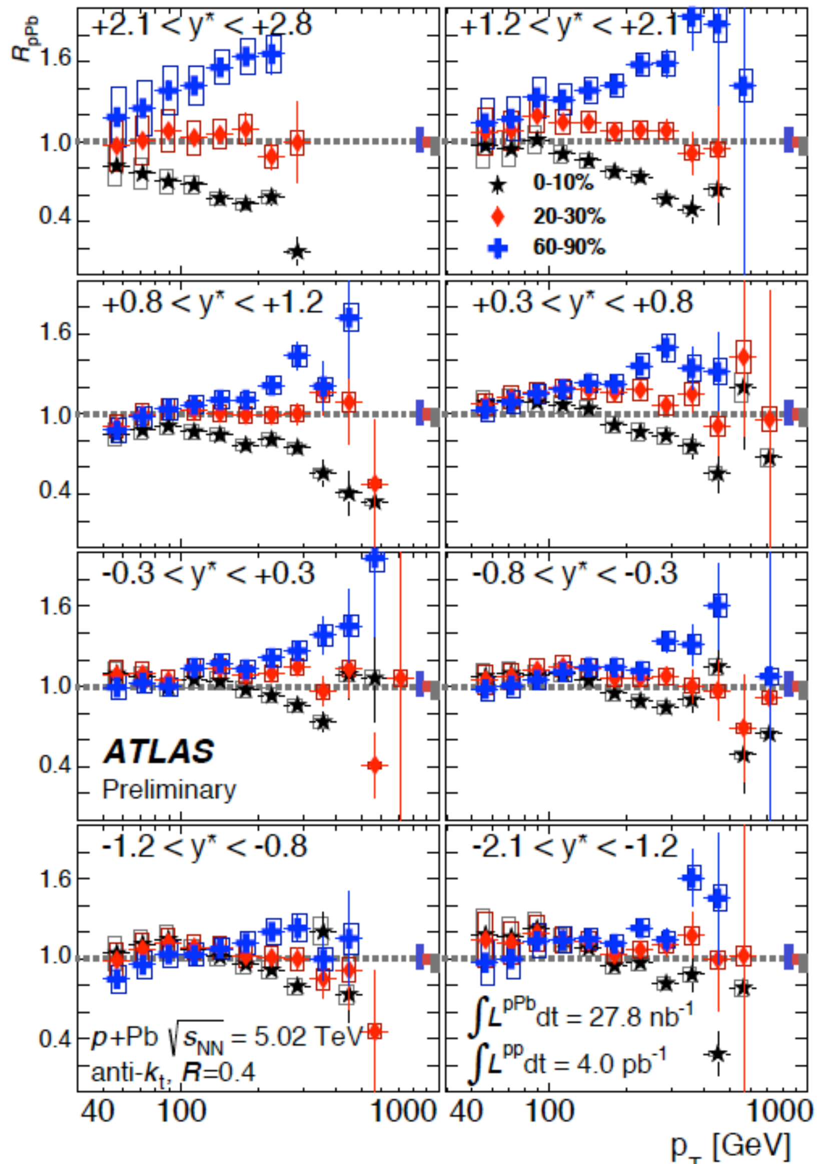
- If inclusive $R_{pPb} \sim 1$ and R_{CP} shows such effects, necessarily;
  - Peripheral enhancement
  - Central suppression

Some explanations:

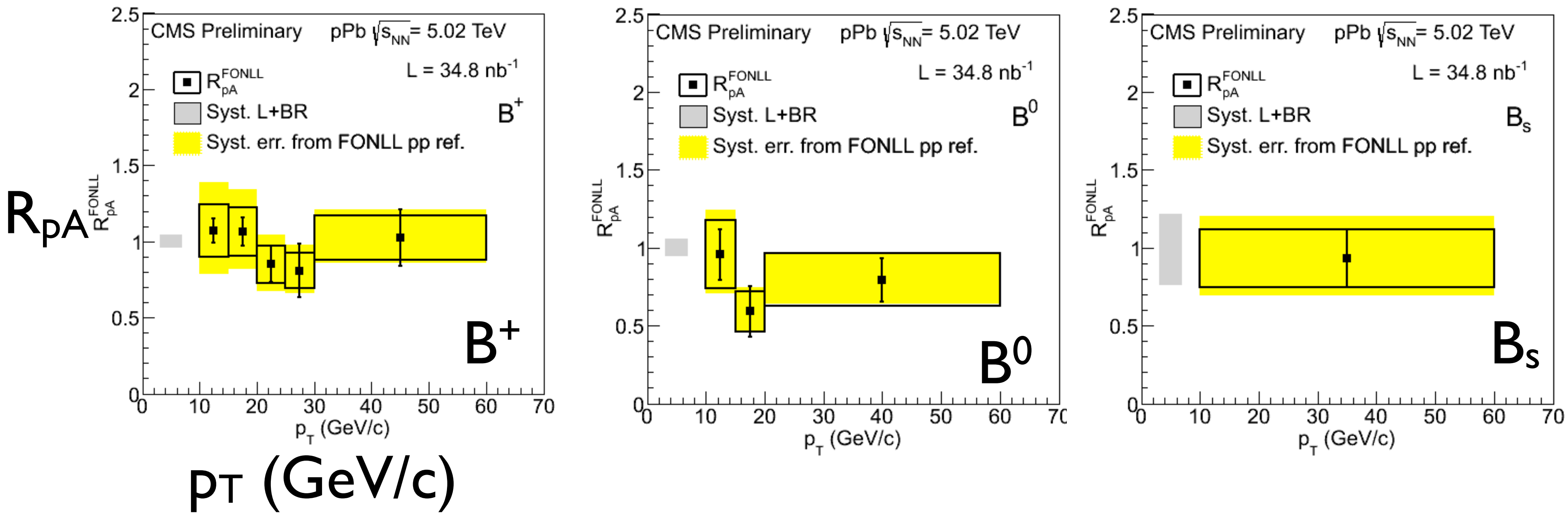
- Geometrical effect (proton special configuration, protons with larger x partons have a reduced soft cross section)
- It is still unclear for this effect...



R_{pPb}



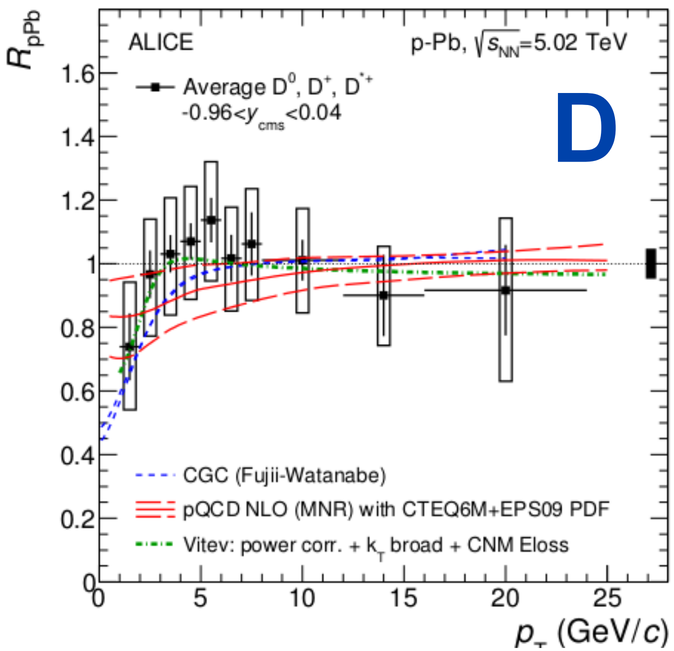
B meson in p-Pb

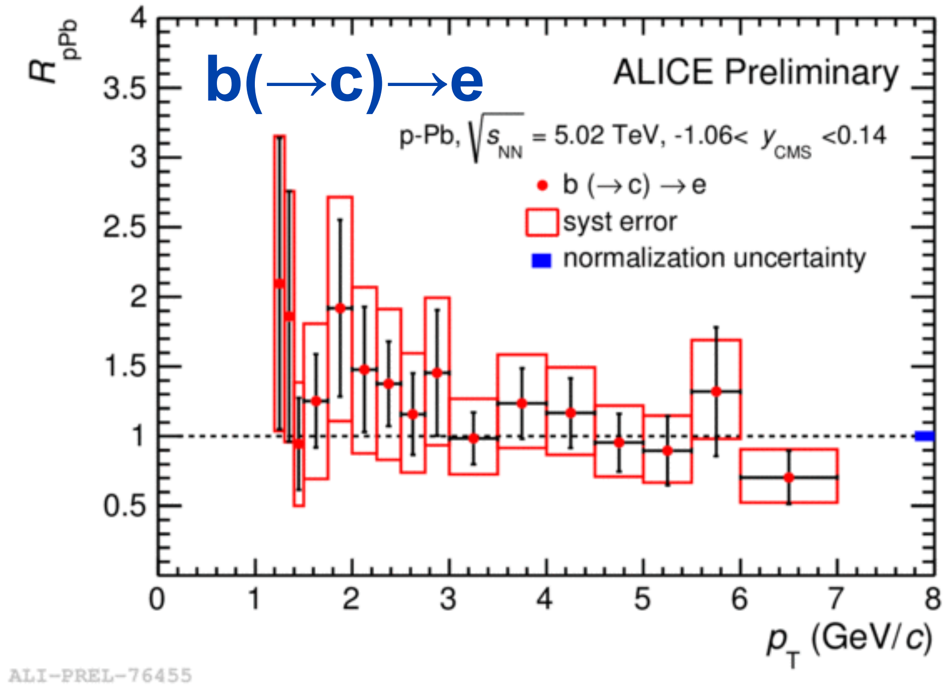


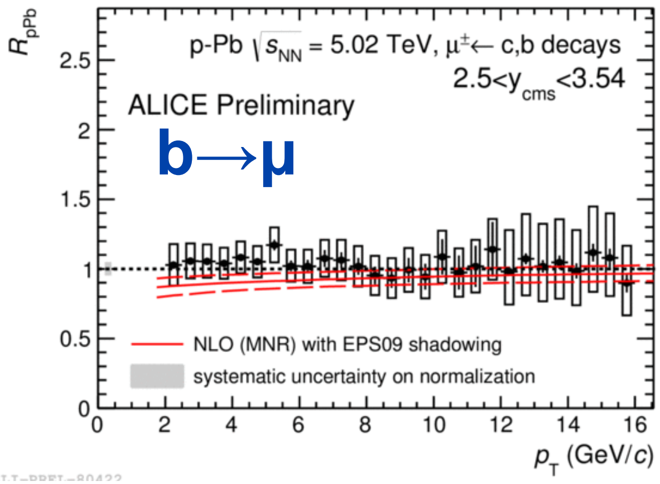
$B^+ \rightarrow J/\psi K^+$, $B^0 \rightarrow J/\psi K^*$, $B_s \rightarrow J/\psi \phi$

- **Showing no modification** (large uncertainty, incl. the FONLL ref)

RpPb for heavy quark



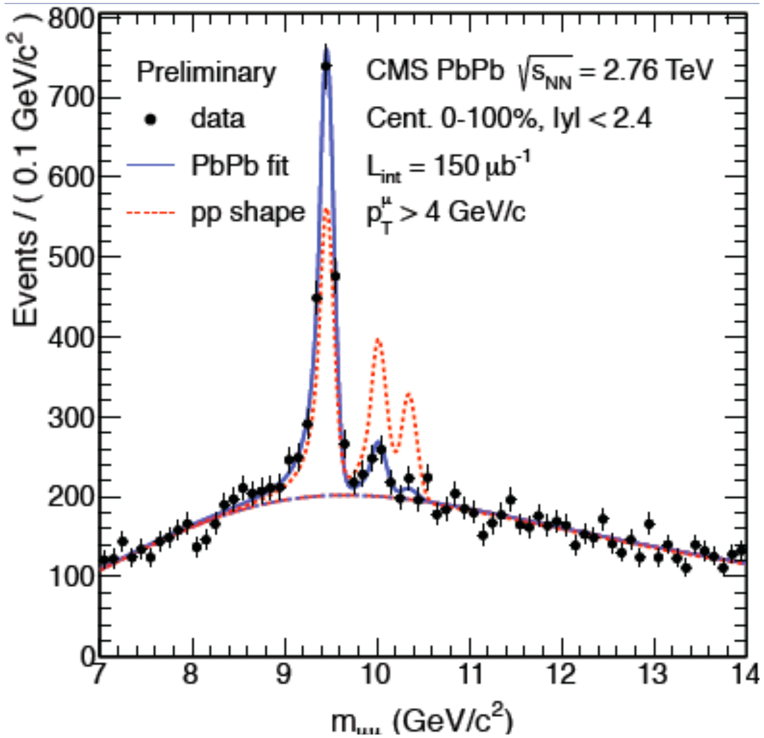


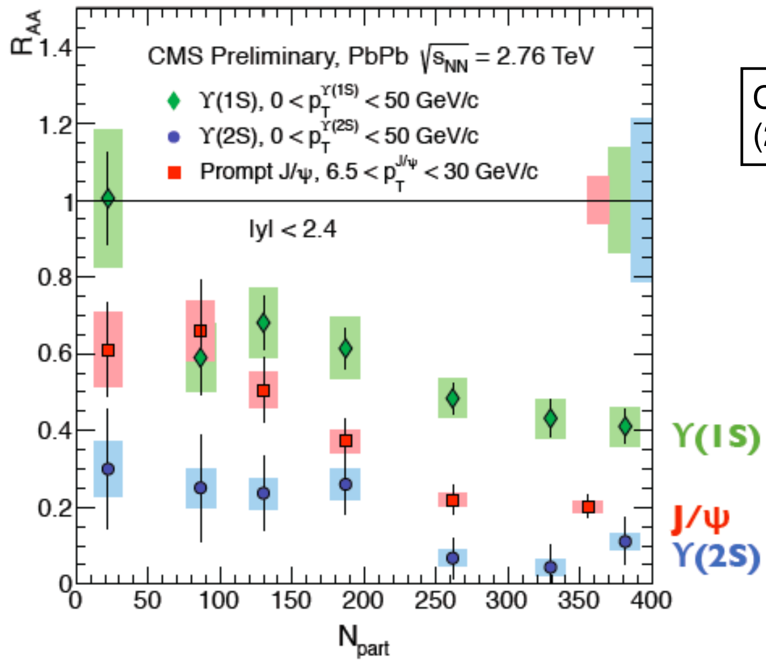


•Showing no modification for D, b(→c)→e, c,b →μ

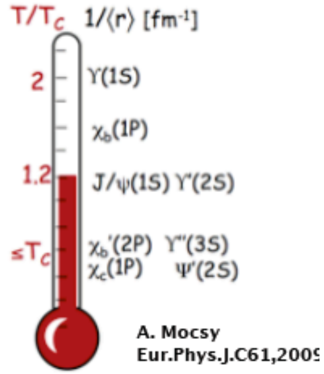
3. Melting temperature for quarkonia, and recombination

Dissociation temperature





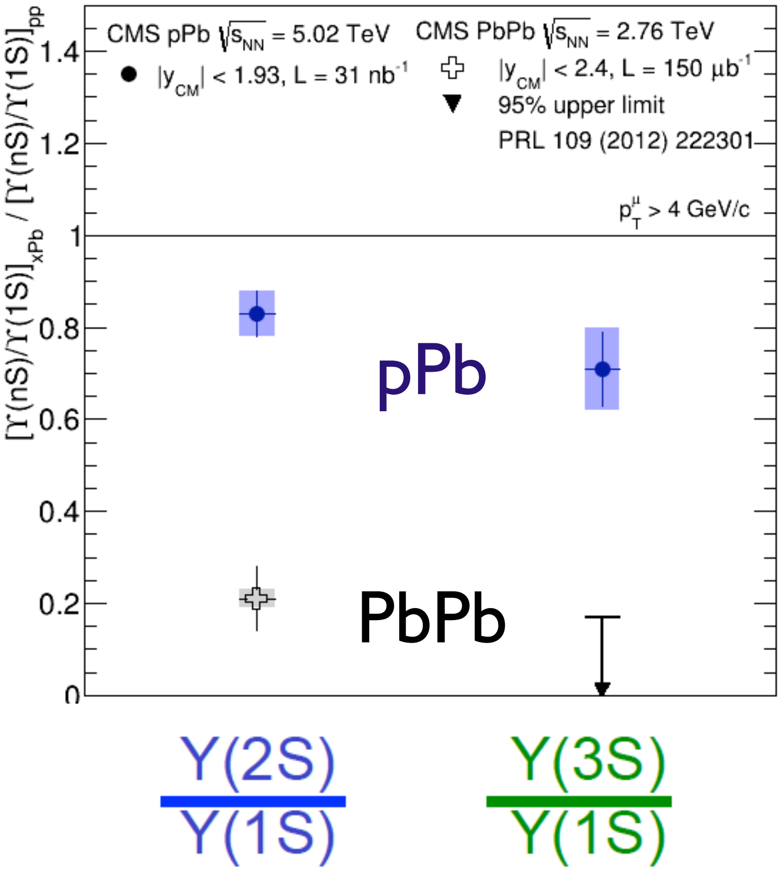
CMS, PRL 109 (2012) 222301

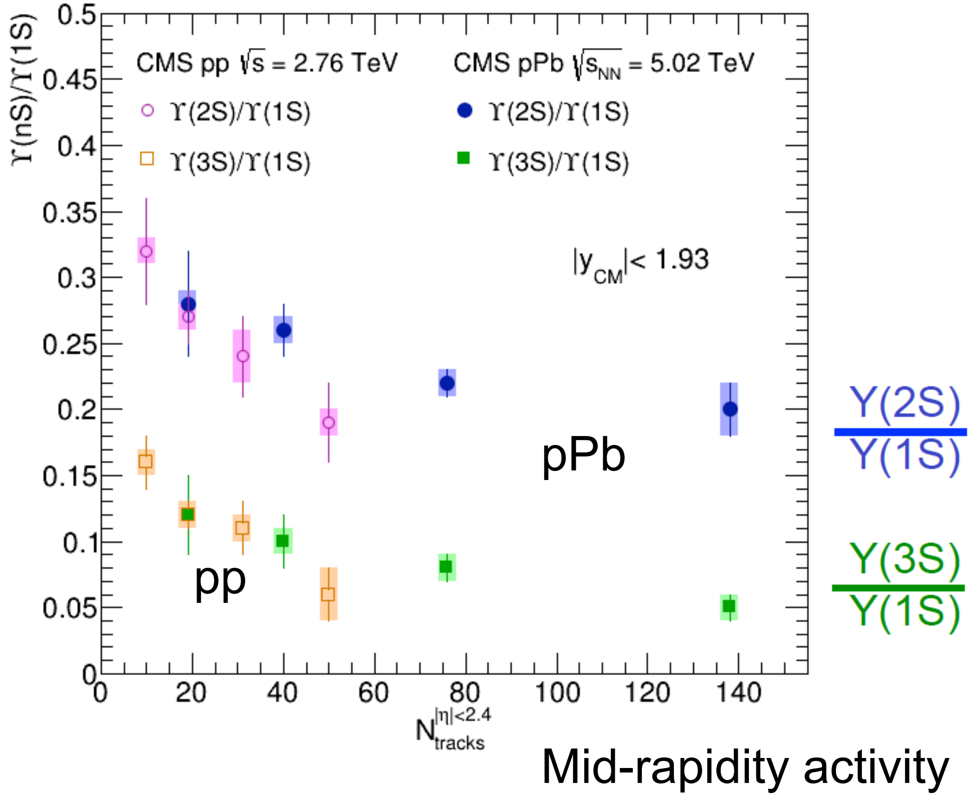


Melting excited ϒ states

- Suppression of ground state Y(1s), and excited states Y(2S) and Y(3S).
- Consistent with **the sequential melting scenario**, Y(3S) > Y (2S) > Y (1S).

Y in pPb

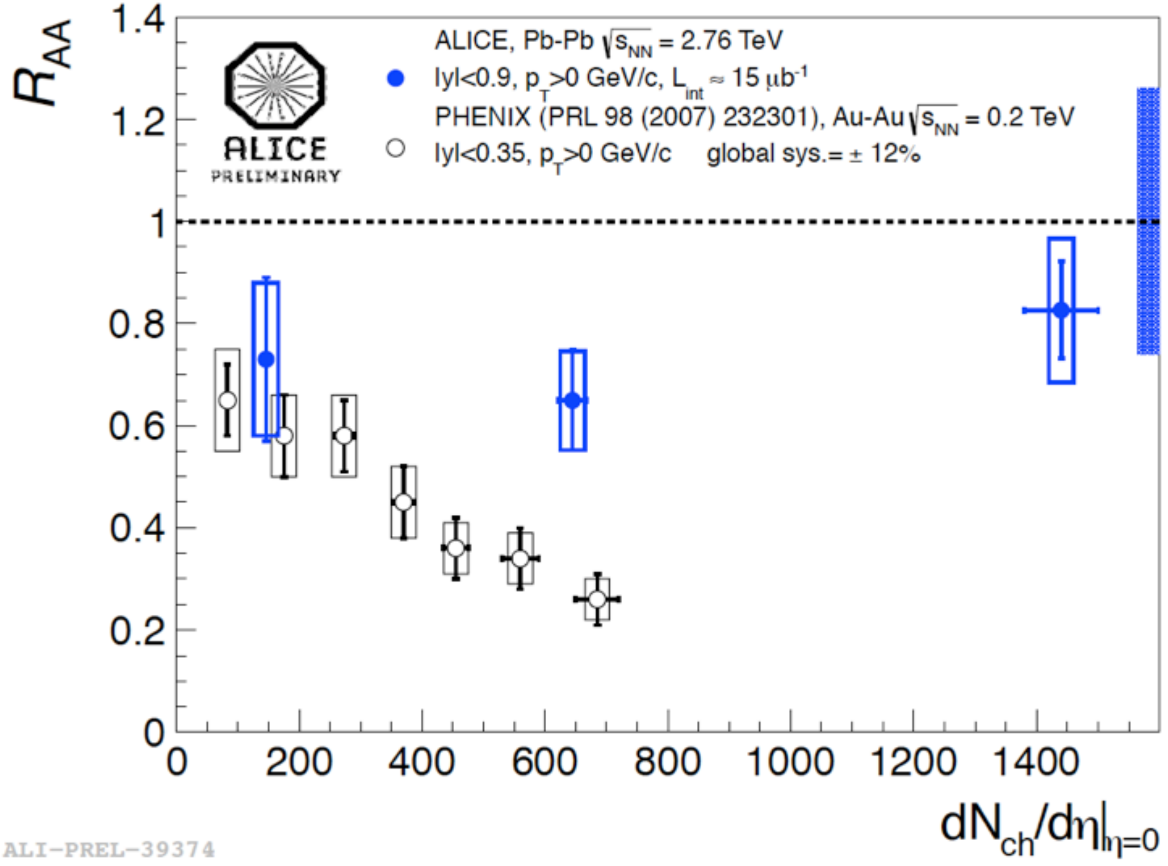




- **Excited states in pPb: less suppressed than in PbPb**
- Excited/ground state ratio appears to **vary w.r.t. the pPb and pp event multiplicity (at mid-rapidity)**

J/ψ (color screening vs. regeneration)

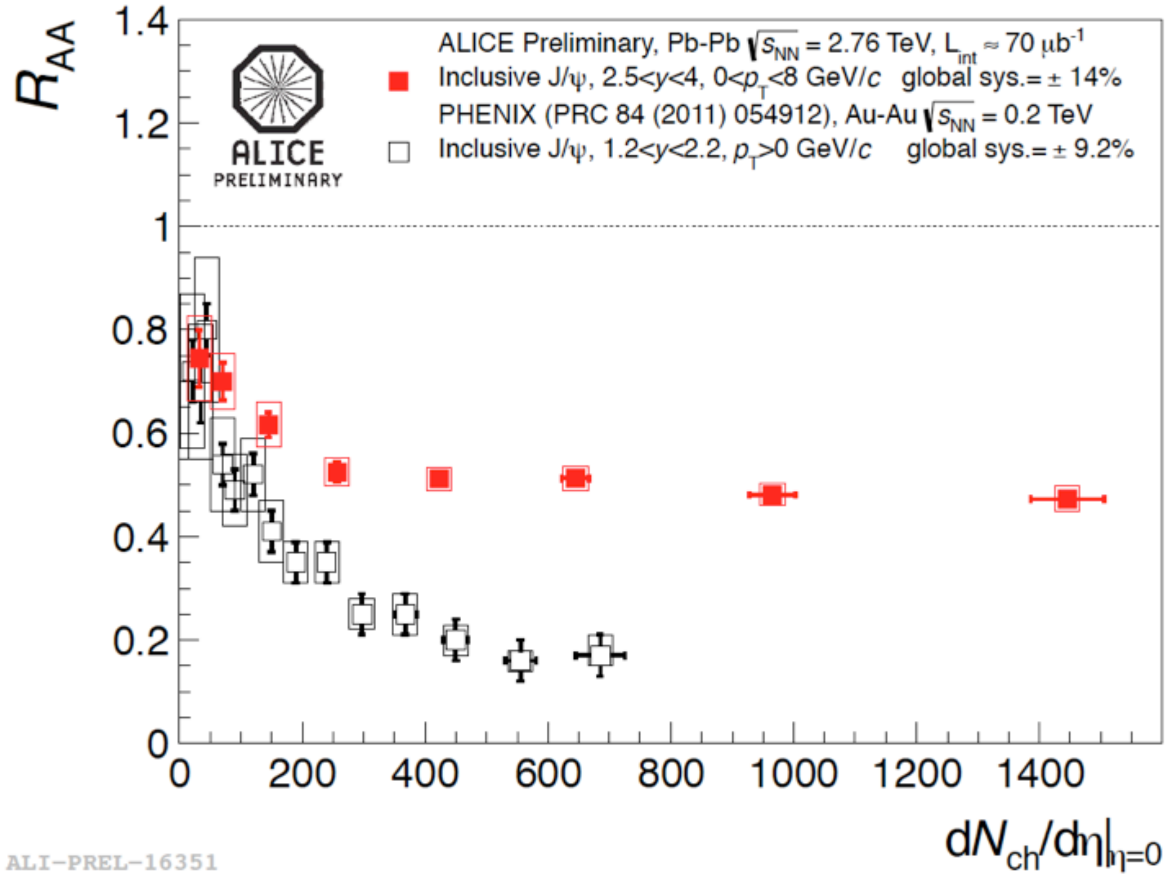
mid-rapidity R_{AA} for J/ψ



- J/ψ measured at mid-rapidity |y|< 0.9, by e^+e^- at LHC.
- Compared to RHIC mid-rapidity data.
- Significant larger R_{AA} than those at RHIC.

J/ψ (color screening vs. regeneration)

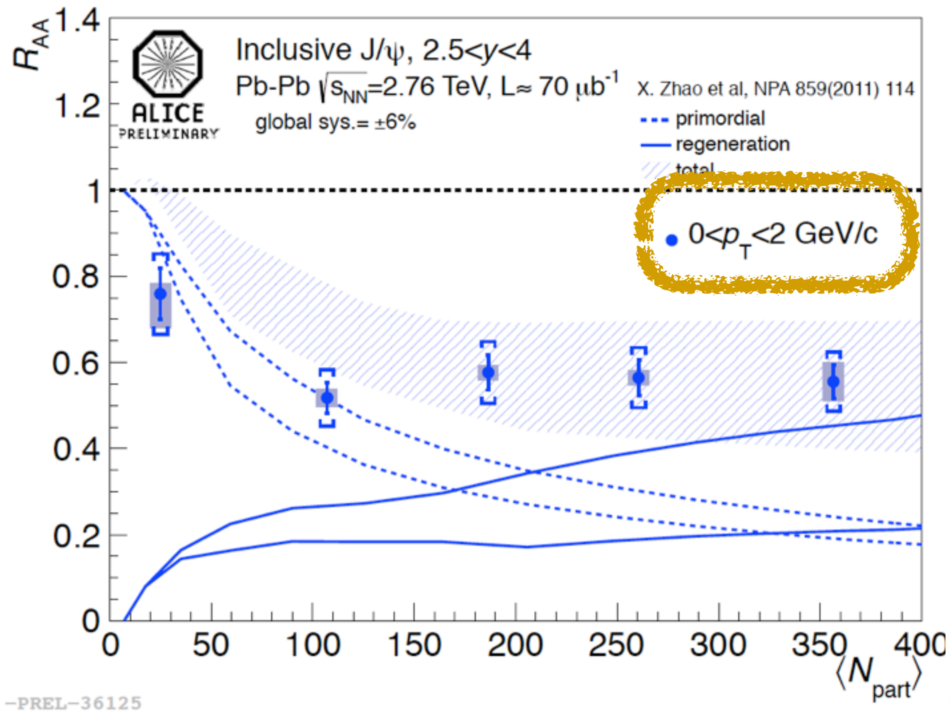
forward-rapidity R_{AA} for J/ψ



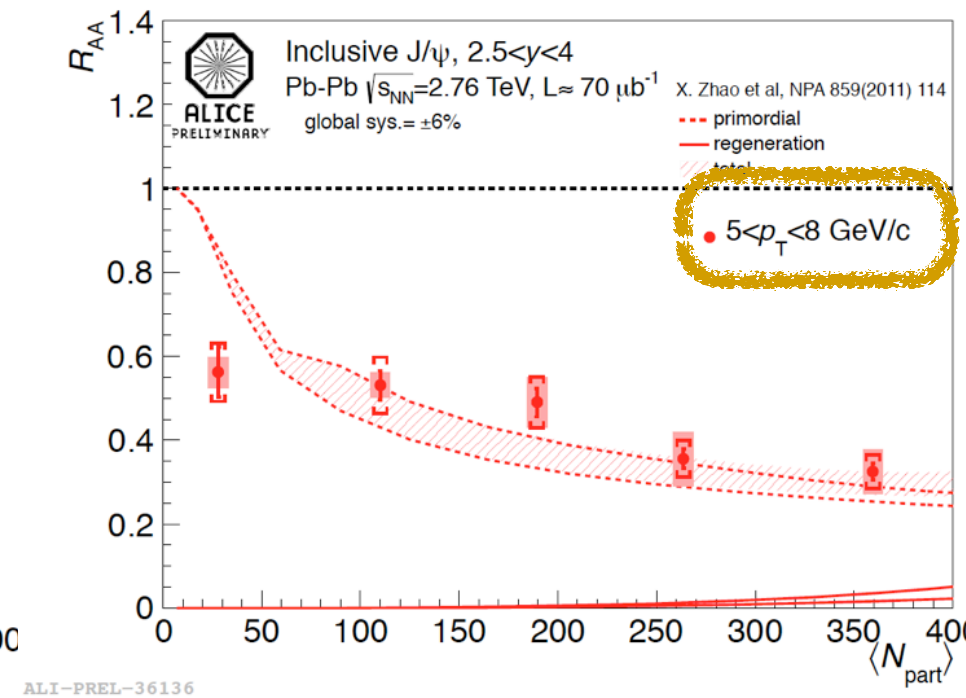
- J/ψ measured at forward-rapidity 2.5 < y < 4, by $\mu^+\mu^-$ at LHC.
- Compared to RHIC forward data.
- Significant larger R_{AA} than those at RHIC.
- Suppression is stronger than that at mid-rap.

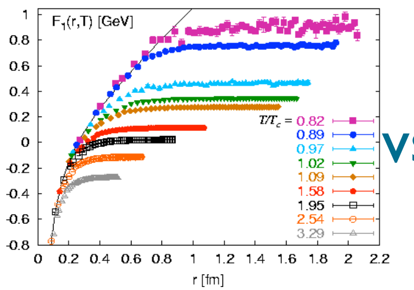
J/ψ (color screening vs. regeneration)

Low p_T: R_{AA} at forward y, $J/\psi \rightarrow \mu^+\mu^-$

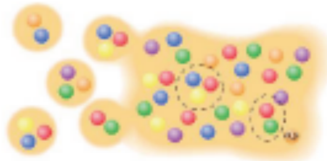


High p_T: R_{AA} at forward y, $J/\psi \rightarrow \mu^+\mu^-$





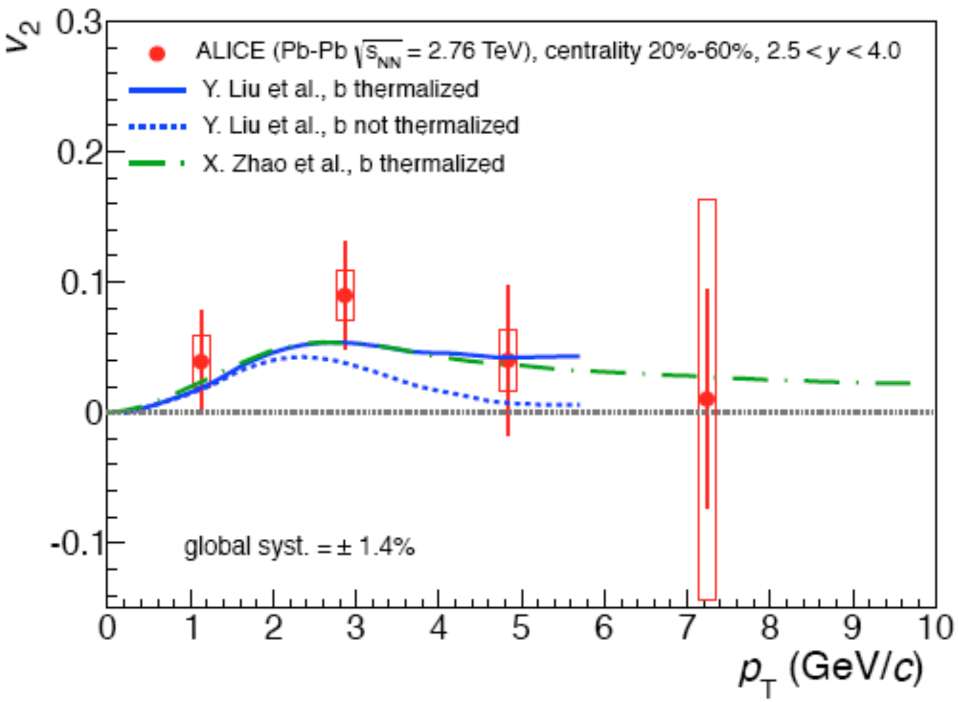
vs.

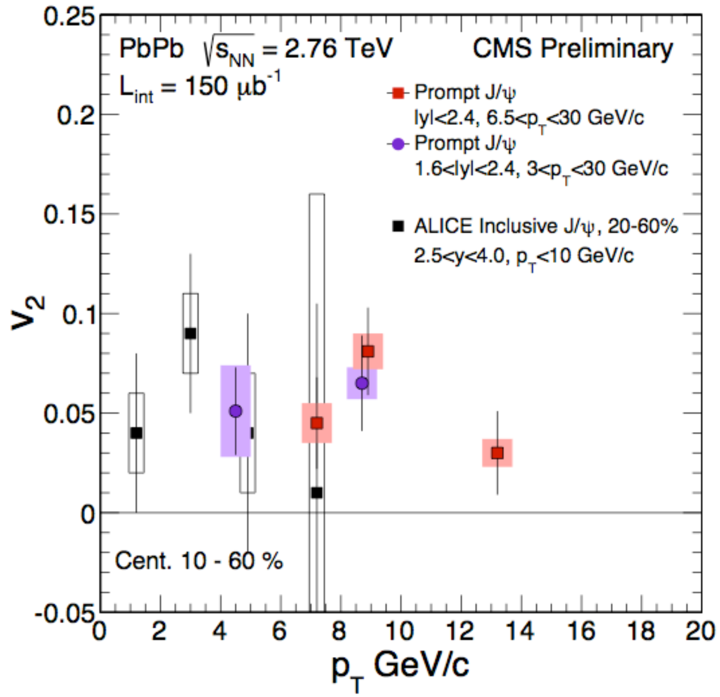


- J/ψ R_{AA} is enhanced at low p_T.
- Compatible with models including regeneration.

J/ψ v_2

ALICE: arXiv:1303.5880





- J/ψ produced via regeneration of thermal de-confined c-quarks should show **a non zero v_2.**
- **Data: Hint of non-zero v_2.**
- Consistent with the transport model with regeneration.

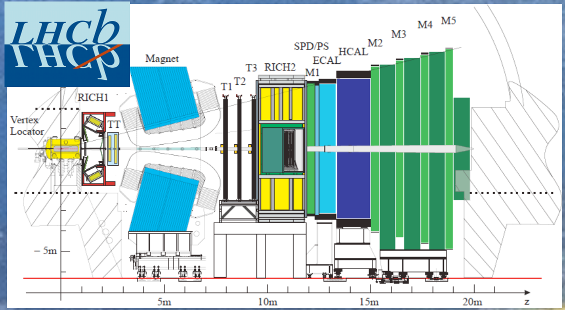
Summary

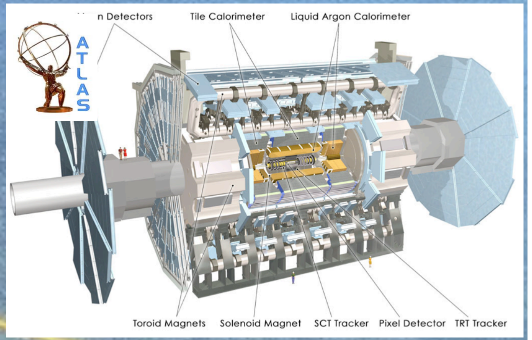
- **p-Pb**
  - High multi. events: collectivity, similar to those in Pb-Pb, but not same.
  - Inclusive hard probes (jet, γ-jet, heavy q) do not show modification.
  - Indication of centrality dep. of jet yields in high p_T (ATLAS).
- **Pb-Pb**
  - ϕ: mass effect dominant in central only?
  - Stronger suppression for D than that for B.
  - J/psi: importance of regeneration of cc-bar, non-zero v_2.

Questions to be answered in Run-1/2

My personal view!

1. **What is the driving force of collectivity in p-Pb and p-p high multiplicity events?**
   - Multi-parton int. is the only cause?
   - Role of CGC?
2. **Medium response to jet.**
   - Measurements of hard + soft interaction, i.e. soft observables w/ jet axis.
3. **Jet tomography.**
   - di-jet, γ-jet, $h(\pi^0)$-jet, correlations etc. w.r.t. reaction plane.





Thank you for your attentions!