Recent Results from the ALICE Experiment

O. Villalobos Baillie
University of Birmingham

Recent Results 

from the ALICE Experiment

…and almost all LHC

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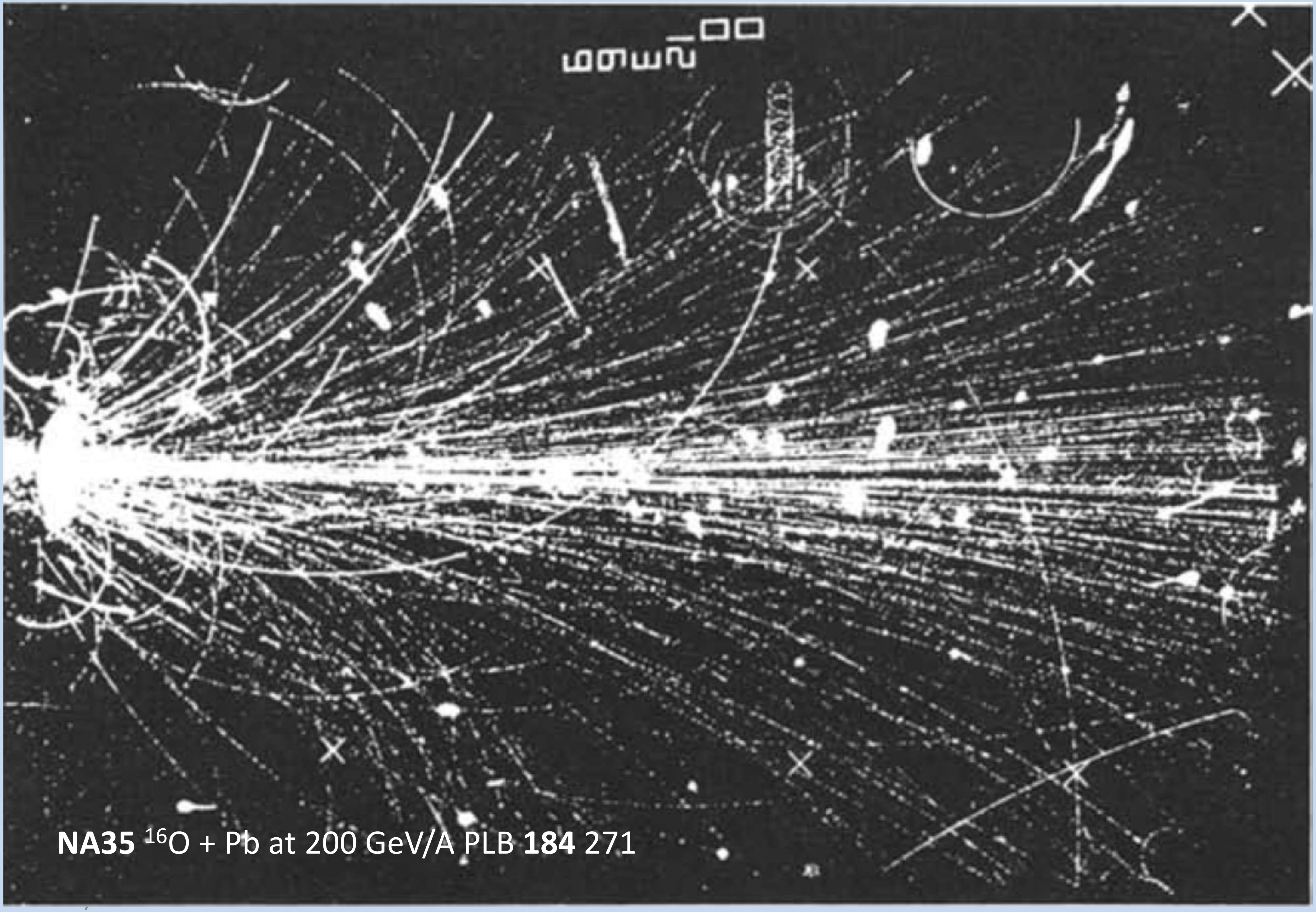
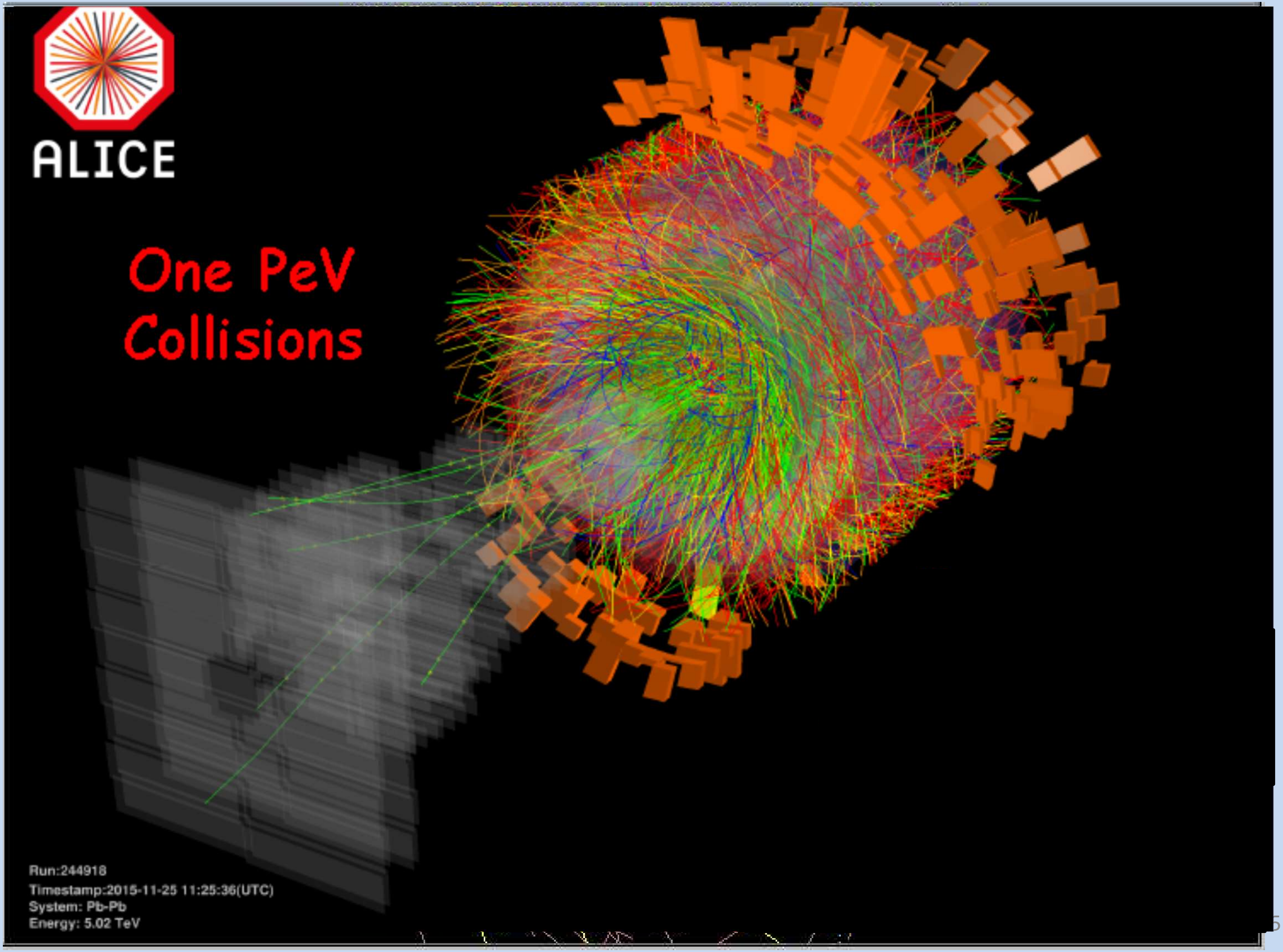
Prologue

- *The field of ultrarelativistic heavy ion physics began about 30 years ago, when developments with the beams at BNL (AGS) and CERN (SPS) allowed the acceleration of heavy ion beams*
  - c. *1986* — *Si/O/S beams*
  - *1994* — *Au beams (BNL) and Pb beams (CERN)*
  - *2000* — *RHIC Au-Au collider ($\sqrt{s}$ = 200 GeV) starts at BNL*
  - *2010* — *LHC collides Pb ions at $\sqrt{s}$ = 2.76 TeV*
  - *2015* — *LHC collides Pb ions at $\sqrt{s}$ = 5.02 TeV*
- *Initially, the aim was to find out whether a phase transition to a deconfined phase of matter, the QGP, occurred; subsequently, it has become a systematic study of the properties of this phase.*
- *What has been achieved, and what are the next steps?*



NA35 ^{16}O + Pb at 200 GeV/A PLB **184** 271


ALICE
One PeV
Collisions
Run:244918
Timestamp:2015-11-25 11:25:36(UTC)
System: Pb-Pb
Energy: 5.02 TeV

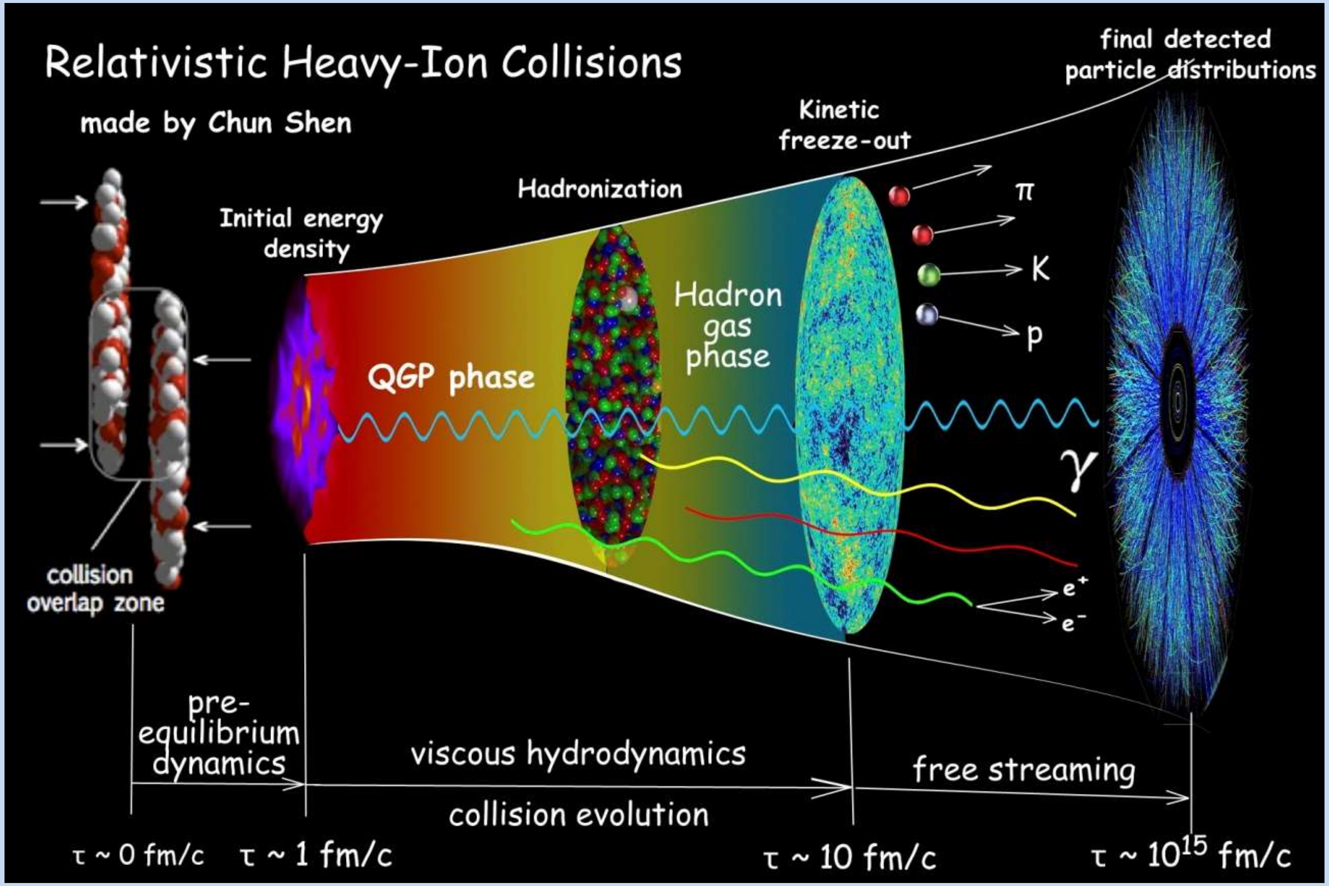
ALICE Data taking

System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010-2011	2.76	~75 μb^{-1}
	2015	5.02	~250 μb^{-1}
	by end of 2018	*5.02*	*~1 nb^{-1}*
Xe-Xe	2017	5.44	~3 mb^{-1}
p-Pb	2013	5.02	~15 nb^{-1}
	2016	5.02, 8.16	~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013	0.9, 2.76, 7, 8	~200 μb^{-1}, ~100 nb^{-1}, ~1.5 pb^{-1}, ~2.5 pb^{-1}
	2015,2017	5.02	~1.3 pb^{-1}
	2015-2017	13	~25 pb^{-1}

Plan of Talk

- Development of a Heavy ion collision
- Initial Stages
- Formation of a Quark-Gluon Plasma
- Interaction of partons with the medium
- Freeze-out
- What can be done with more statistics at LHC?

Stages in a Heavy Ion Collision



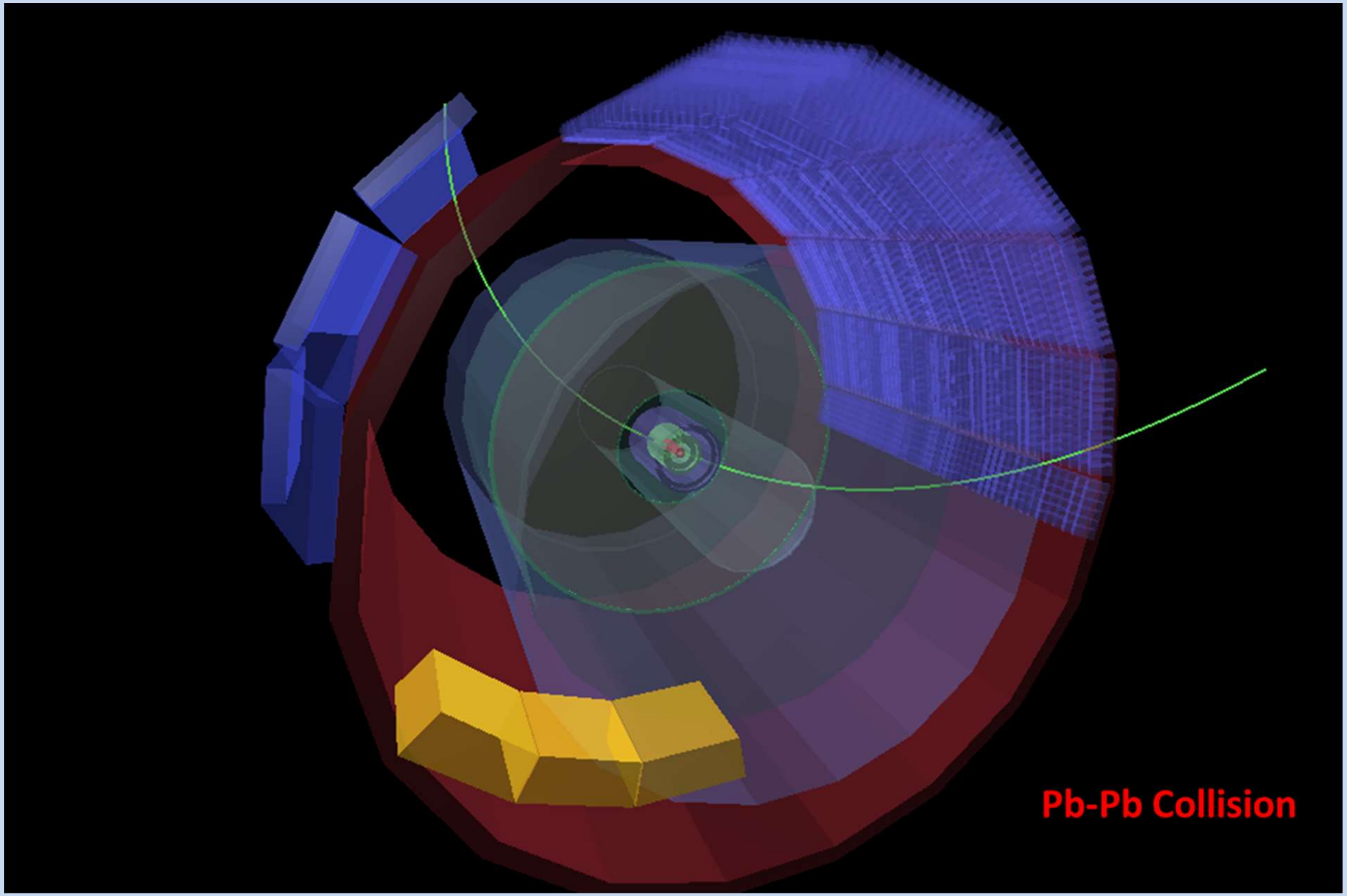
- Initial state of nuclei, dependent on nuclear pdfs
- First hard collisions, quickly leading to formation of QGP
- Expanding QGP, with shape and momentum distribution conditioned by fluid hydrodynamics
- Cooling and freeze-out, technically in two stages: chemical and thermal freeze-out

INITIAL STAGES

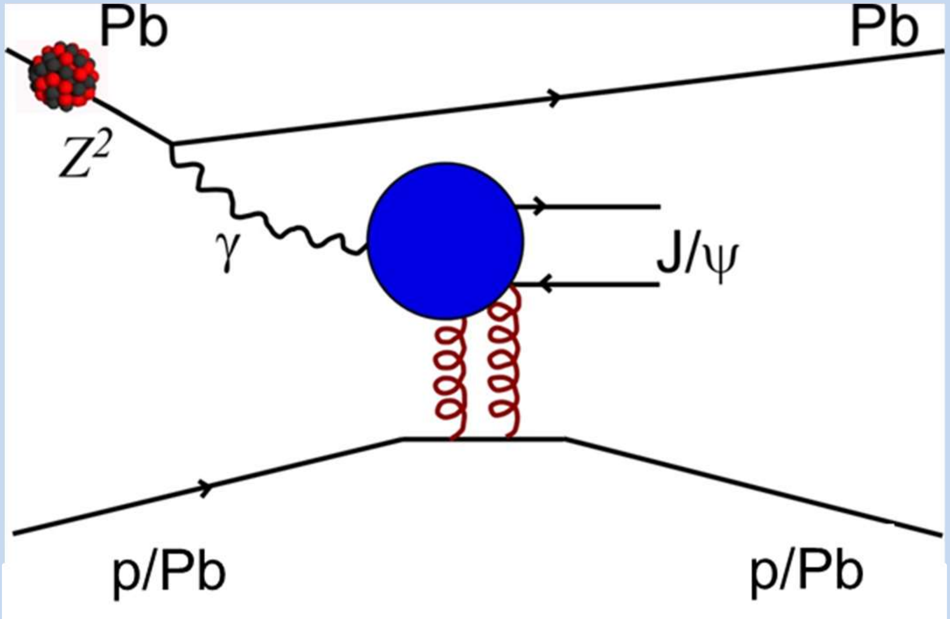
Initial Stages

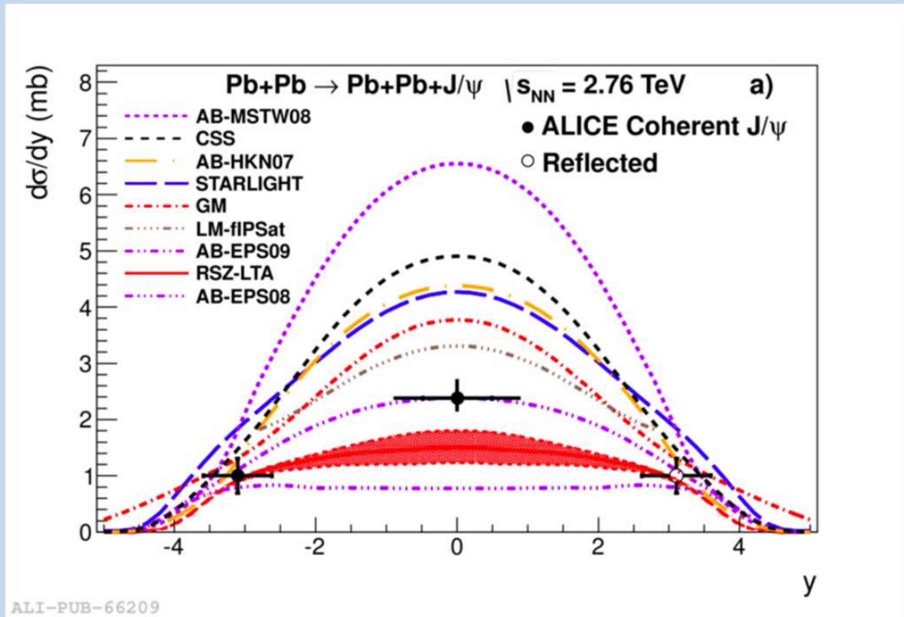
- *Ultra-Peripheral Collisions*, where the two nuclei do not overlap, but only interact electromagnetically, producing a vector meson, can probe the gluon structure function of the nucleus.
- Comparison with models, using a variety of different structure function sets, indicates that "moderate" shadowing is taking place.

Mid-rapidity J/ψ



Exclusive Vector Meson Production





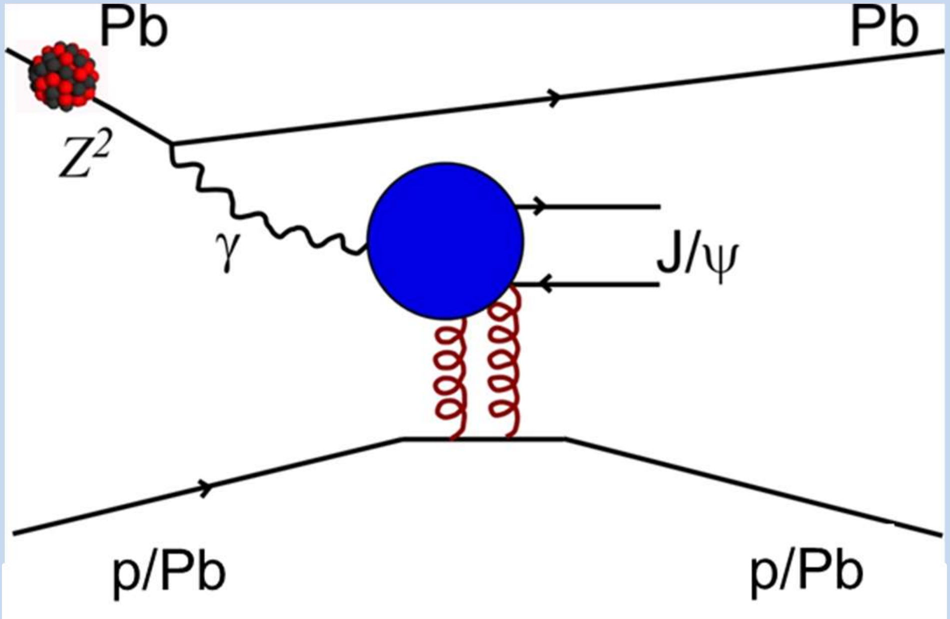
E. Abbas et al., Eur. Phys Journal C73 (2013) 2617

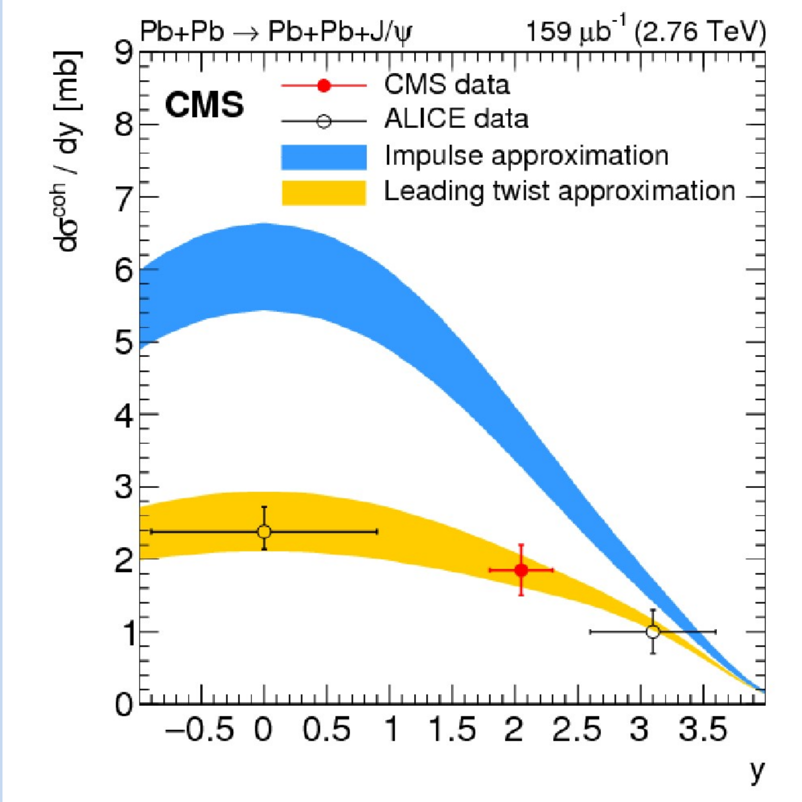
$$\frac{d\sigma_{\gamma^* \mathrm{p/Pb}}(t=0)}{dt} = \frac{16\Gamma_{ee}\pi^3}{3\alpha_{\mathrm{em}} M_{J/\psi}^5}\left\{\alpha_s\left(Q^2\right) x G_{\mathrm{p/Pb}}\left(x, Q^2\right)\right\}^2$$

LEADING ORDER

First analyses from ALICE and CMS, using Run 1 data, point to moderate shadowing in the nucleus. Run 2 analyses, currently underway, will already yield a very large increase in statistics (e.g. factor 50 for ALICE in the forward region) allow more detailed differential studies to be made.

Exclusive Vector Meson Production





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LEADING ORDER

ArXiv:1605.06966

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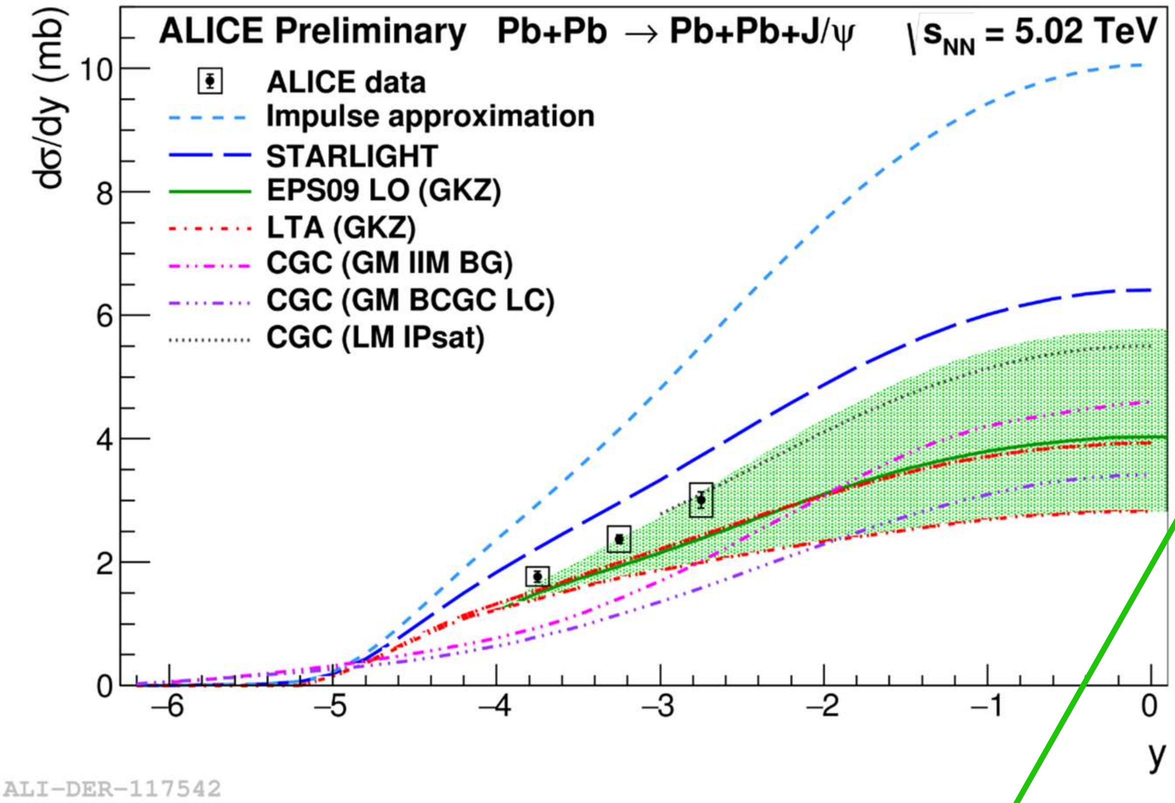
Coherent J/ψ forward cross section



- Impulse approximation: no nuclear effects
- STARLIGHT: VDM + Glauber (Klein, Nystrand *et al* Comput. Phys. Commun. 212 (2017) 258)
- EPS09 LO: EPS09 shadowing (Guzey, Kryshen, Zhalov, PRC93 (2016) 055206)
- LTA: Leading Twist Approximation (Guzey, Kryshen, Zhalov, PRC93 (2016) 055206)
- CGC GM: color dipole model + IIM/BCGC (Goncalves, Machado *et al*, PRC 90 (2014) 015203, JPG 42 (2015) 105001)
- CGC LM: Color dipole model + IPSat (Lappi, H. Mäntysaari, PRC 83 (2011) 065202; 87 (2013) 032201)

Cross section consistent with moderate nuclear gluon shadowing

DIS2017

B'ham interest

Ultra-Peripheral Production in pPb

- Exclusive vector meson production in pPb Ultra-Peripheral collisions has the advantage that the Pb is almost always the emitter of the photon, so the reaction

$$p + Pb \rightarrow J/\psi + p + Pb$$

can be used to study photoproduction of a J/ψ off a proton (like in HERA)

$$\gamma + p \rightarrow J/\psi + p$$

J/ψ Photoproduction in pPb

- In principle, there is an ambiguity in the energy $W_{\gamma p/Pb}$ of the measurement, according to whether the photon is emitted from one projectile or the other.
  - For a J/ψ produced with rapidity y, the two solutions are of the form

$$\omega = \frac{M_{J/\psi}}{2}\exp(\pm y), \qquad x = \left(M_{J/\psi} / \sqrt{s_{NN}}\right)\exp(\pm y)$$

- The two solutions coincide for $y=0$, but forward rapidity and identical beams an *ansatz* is needed to weight the two solutions:

$$\frac{dN}{dy} = n(\omega_1)\sigma_{\gamma p}(\omega_1) + n(\omega_2)\sigma_{\gamma p}(\omega_2)$$

- In p-Pb (Pb-p) the ambiguity is essentially lifted, as the photon is preferentially emitted from the Pb nucleus (~95% STARLIGHT estimate).

J/ψ pPb measurements

Exclusive J/ψ photoproduction in p-Pb

ALICE

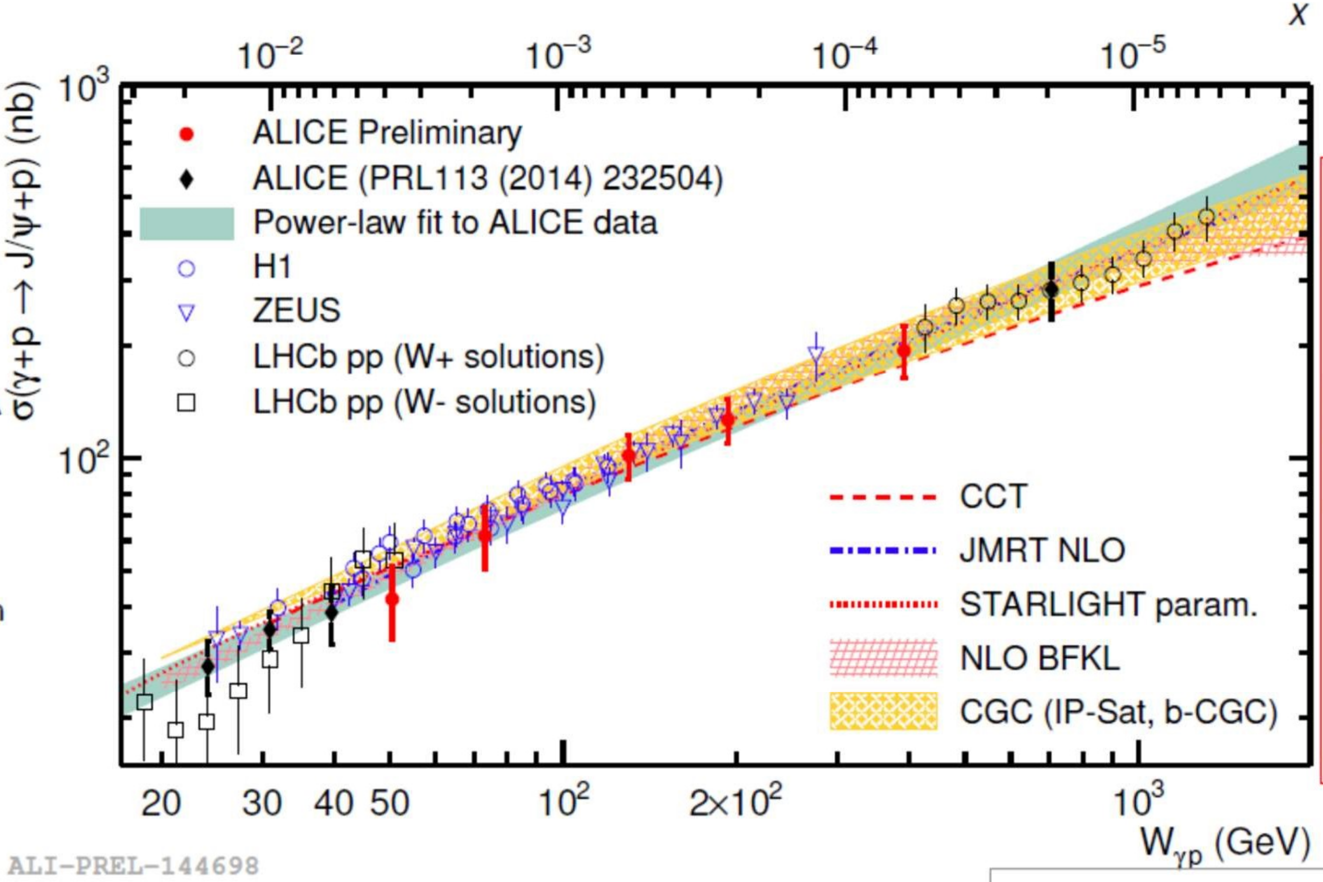
CCT
energy-dependent hot spot model
PLB766 (2017) 186

JMRT NLO
DGLAP formalism + main NLO contributions
EPJC76 (2016) 633

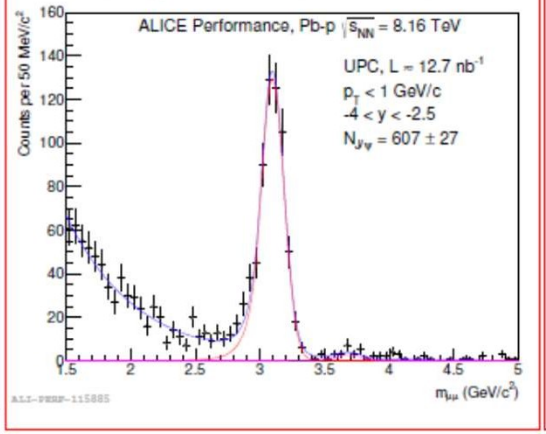
STARLIGHT
Parameterization of HERA and fixed-target data
CPhC 212 (2017) 258

NLO-BFKL
proton impact factor from F2 HERA data
PRD94 (2016) 054002

CGC
color-gluon-condensate models with saturation
PRD90 (2014) 054003



New RUN2 data will allow ALICE to explore the region above 1 TeV:



Good description by all models

for LHCb measurements in **pp at 13 TeV** see LHCb-CONF-2016-007

5/14/18 12

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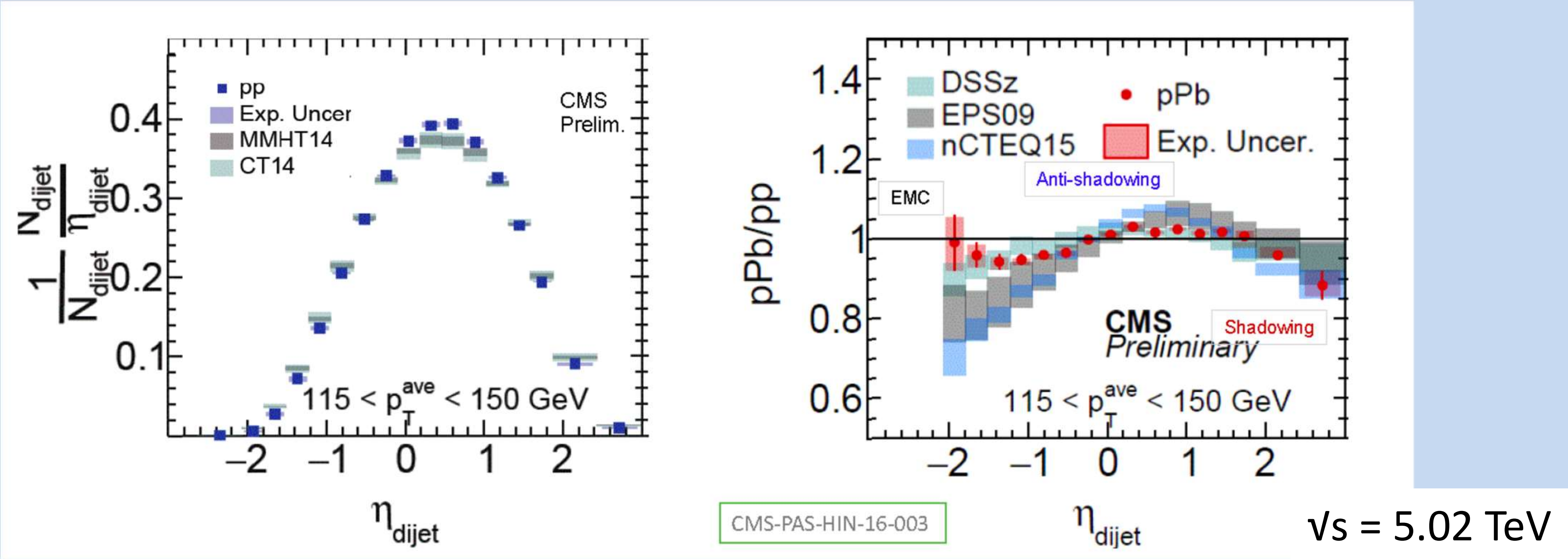
Dijet Production



- Precision measurements of η_{dijet} = (η1+η2)/2∝0.5 log(x_p/x_{Pb}) + ηCM
- Sensitive to (n)PDFs. Allows access to Q^2 dependence
- No PDF set satisfactory over whole range. Authors claim EPS09 does better than most.

First evidence that the gluon PDF at large Bjorken x in lead ions is strongly suppressed

Data are incompatible with predictions using nucleon PDFs or using nPDFs **without large-x gluon suppression**.

Based on a statistical analysis, *the EPS09 nPDF provides the best overall agreement* with the data

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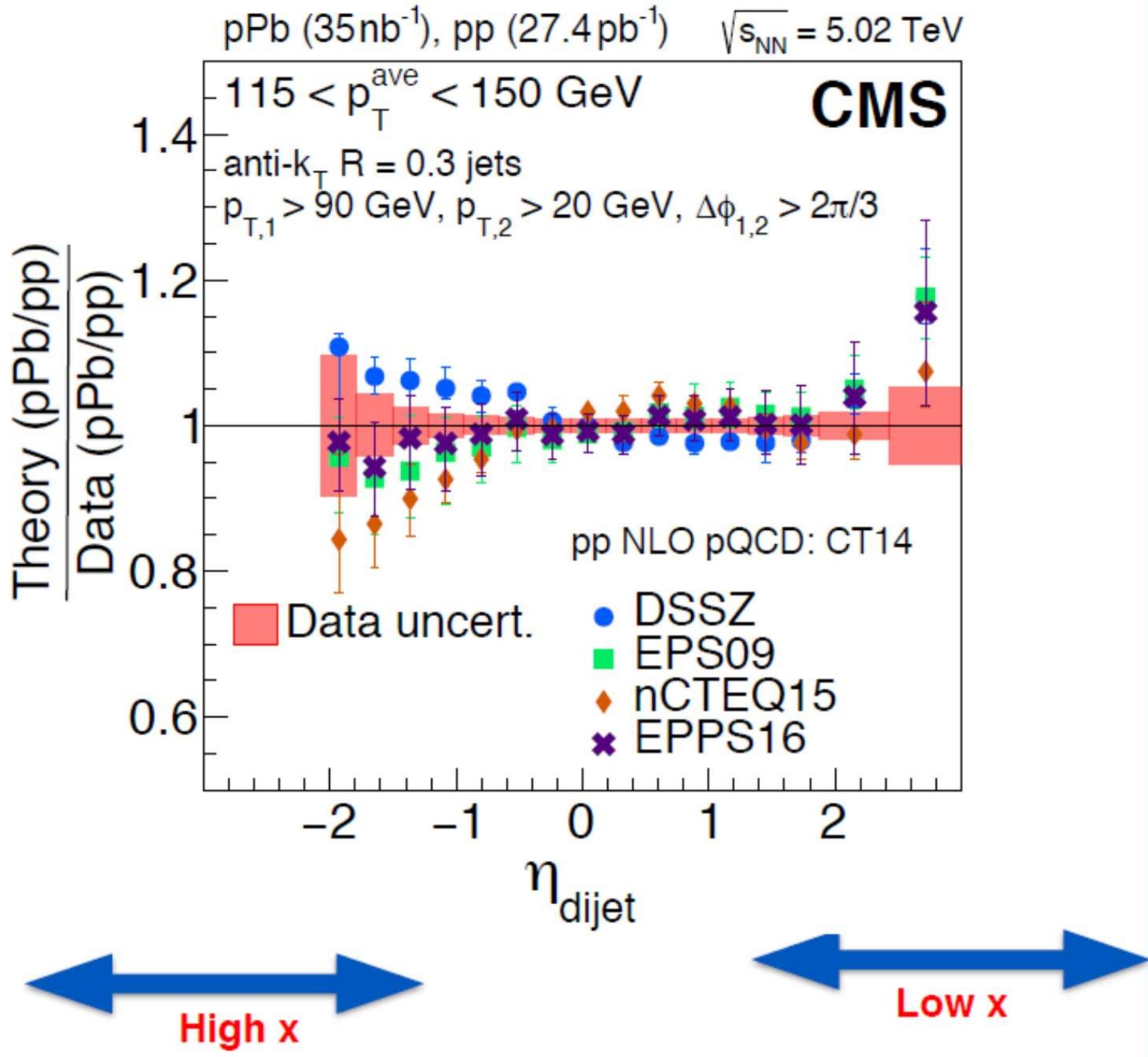
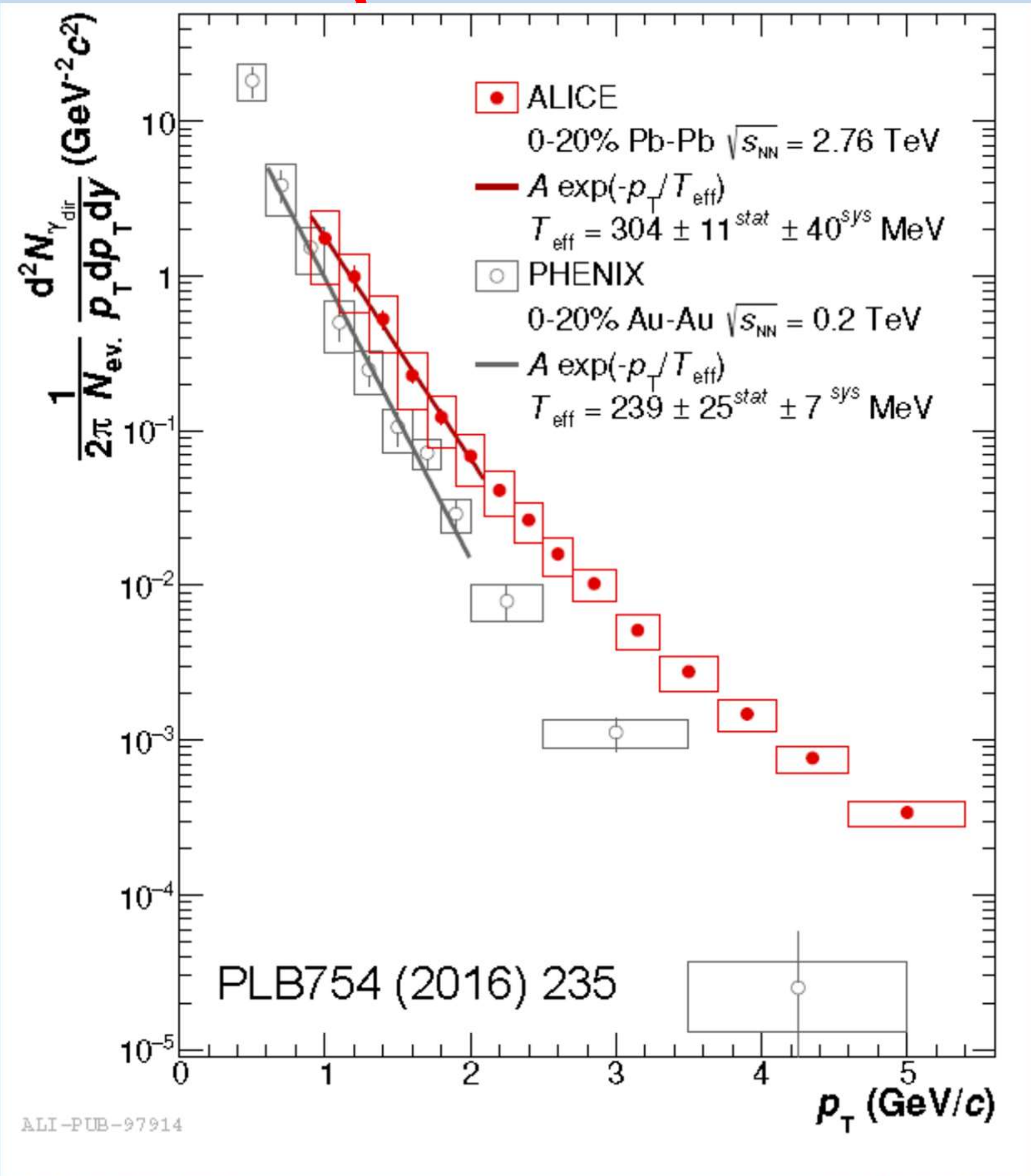


SYSTEM TEMPERATURE

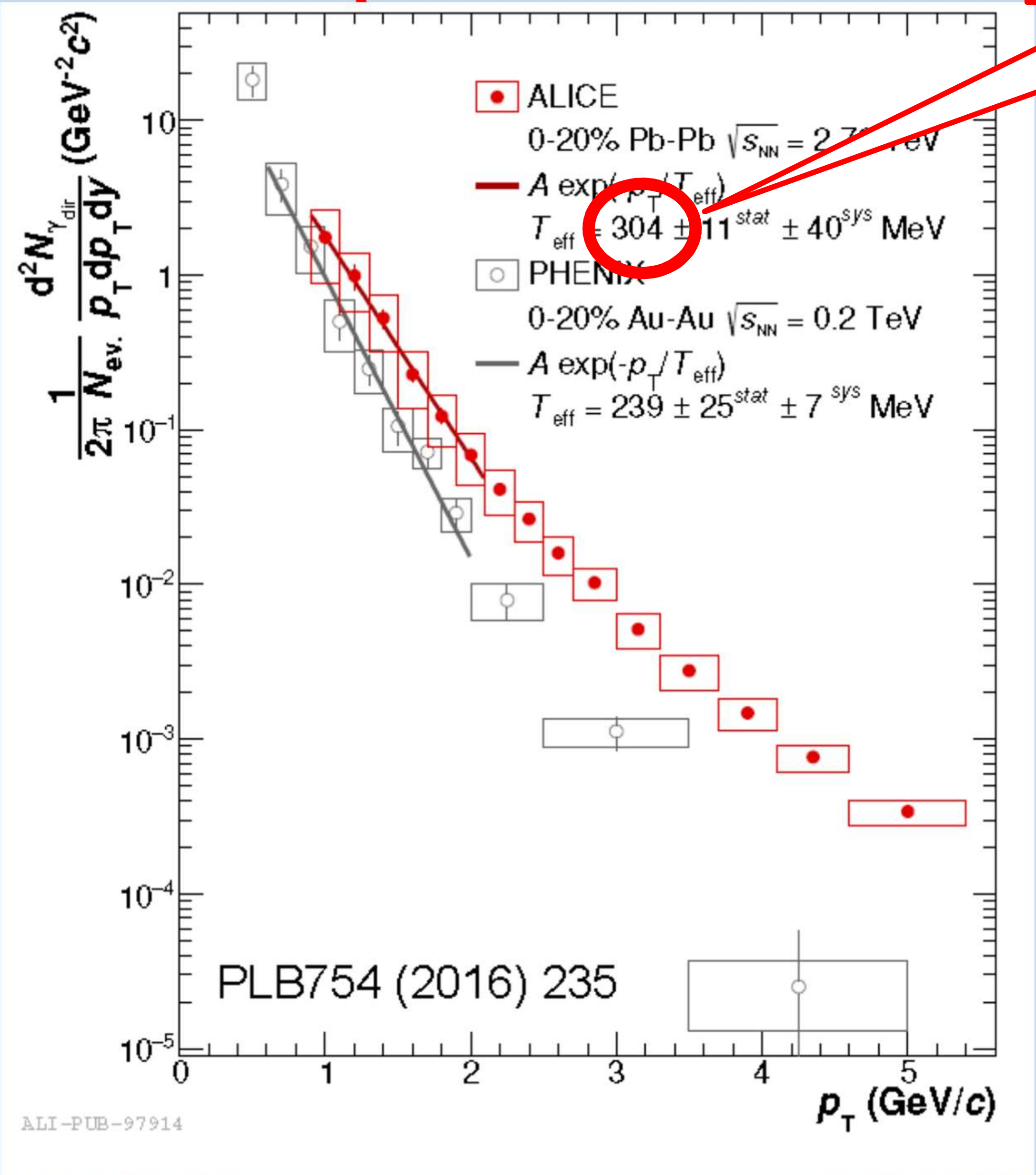
Temperature via Direct Photons



- Measurement of photons radiating from the plasma
- Backgrounds from meson decays and hard processes
- Important to characterise collisions. Need more differential measurements.

Temperature via ons

Highest temperature recorded in a laboratory 304 MeV = 3.53 x 10^{12} K



- Measurement of photons radiating from the plasma
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FLOW

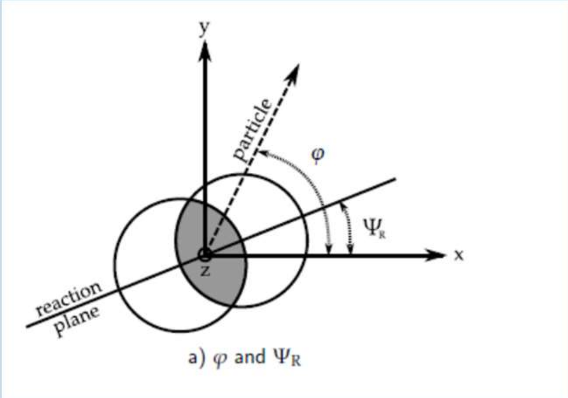
Flow

- In all but the most central (head-on) collisions, there is a transverse geometrical asymmetry in the shape of the colliding system when seen in the transverse plane.
- This spatial asymmetry manifests itself in the azimuthal distribution of the momenta of the particles emitted from the created fireball.
- Study has two parts:
  - Exploitation of the properties of the Fourier series expansion of the azimuthal distribution, to understand the angular asymmetry, with short-range correlations (e.g. resonances) removed.
  - Modelling of the shape of the distribution using a hydrodynamic model with energy and momentum conservation. (*Now accessible via generators.)*

Fourier Series

- Fundamental equation is the Fourier expansion of the azimuthal angle distribution

$$\frac{dN}{d\varphi} = A\sum_n v_n \cos n(\varphi - \Psi_R)$$



N. Van der Kolk
Ph.D thesis

- Problems arise in determining Ψ_R, which are avoided by using multi-particle correlations to construct cumulants, in which Ψ_R cancels.
  - Simplest example “scalar product” estimator:

$$Mv_2^2 = \frac{1}{M}\sum_{k=1}^{M} e^{i2(\varphi_k - \Psi_R)} \sum_{j=1, j\neq k}^{M} e^{-i2(\varphi_j - \Psi_R)}$$

$$= \frac{1}{M}\sum_{k,j=1, j\neq k}^{M} e^{i2(\varphi_k - \varphi_j)}$$

Ψ_R drops out

Cumulants

Standard method

m-particle cumulant

$$c_n\{2\} = \langle\langle 2 \rangle\rangle_n$$

$$c_n\{4\} = \langle\langle 4 \rangle\rangle_n - 2 \cdot \langle\langle 2 \rangle\rangle_n^2$$

$$c_n\{6\} = \langle\langle 6 \rangle\rangle - 9 \cdot \langle\langle 2 \rangle\rangle \cdot \langle\langle 4 \rangle\rangle + 12 \cdot \langle\langle 2 \rangle\rangle^3$$

$$c_n\{8\} = \langle\langle 8 \rangle\rangle - 16 \cdot \langle\langle 6 \rangle\rangle\langle\langle 2 \rangle\rangle - 18 \cdot \langle\langle 4 \rangle\rangle^2 + 144 \cdot \langle\langle 4 \rangle\rangle\langle\langle 2 \rangle\rangle^2 - 144 \cdot \langle\langle 2 \rangle\rangle^4$$

Symmetric Cumulants

$$SC(m,n) = \langle\langle 4 \rangle\rangle_{m,n} - \langle\langle 2 \rangle\rangle_m \langle\langle 2 \rangle\rangle_n$$

flow coefficients

$$v_n\{2\} = \sqrt{c_n\{2\}} \qquad v_n\{6\} = \sqrt[6]{(1/4)\, c_n\{6\}}$$

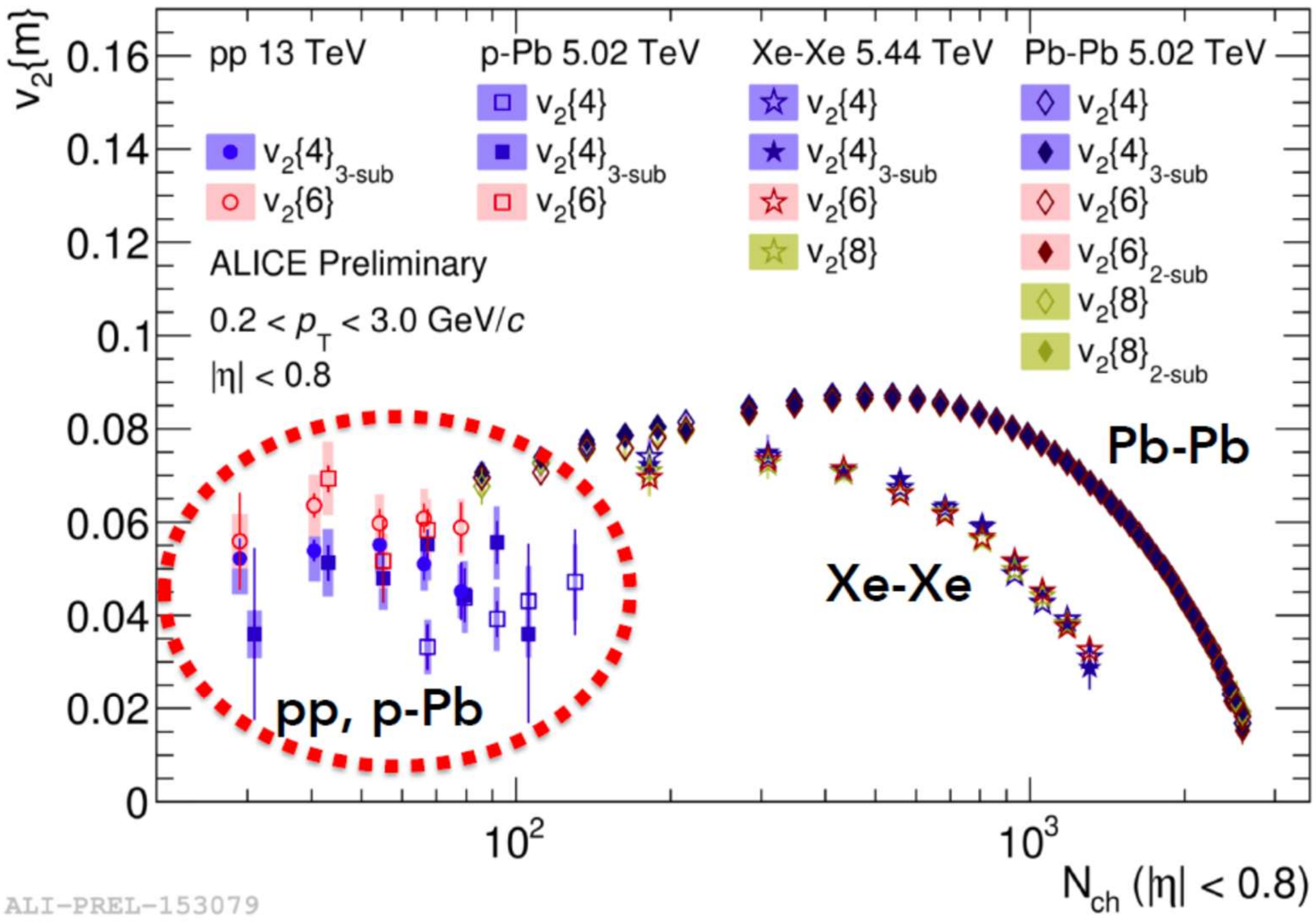
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}} \qquad v_n\{8\} = \sqrt[8]{(-1/33)\, c_n\{8\}}$$

- Double angle brackets mean average over
  - (i) tracks in an event, and
  - (ii) events in sample
- Subtractions, such as those in the symmetric cumulant series, get rid of unwanted short-range correlations

Flow

Elliptic flow in different collision systems (3)

K. Gajdosova, Tue 12:50



→ Detailed measurement of $v_2\{m\}$ as a function of charged particle density for **different geometries**.

→ Collective behavior is observed in multi-particle cumulants (where non-flow contributions are suppressed) even in the smallest systems.

Flow occurs, even in the smallest systems

10

Flow

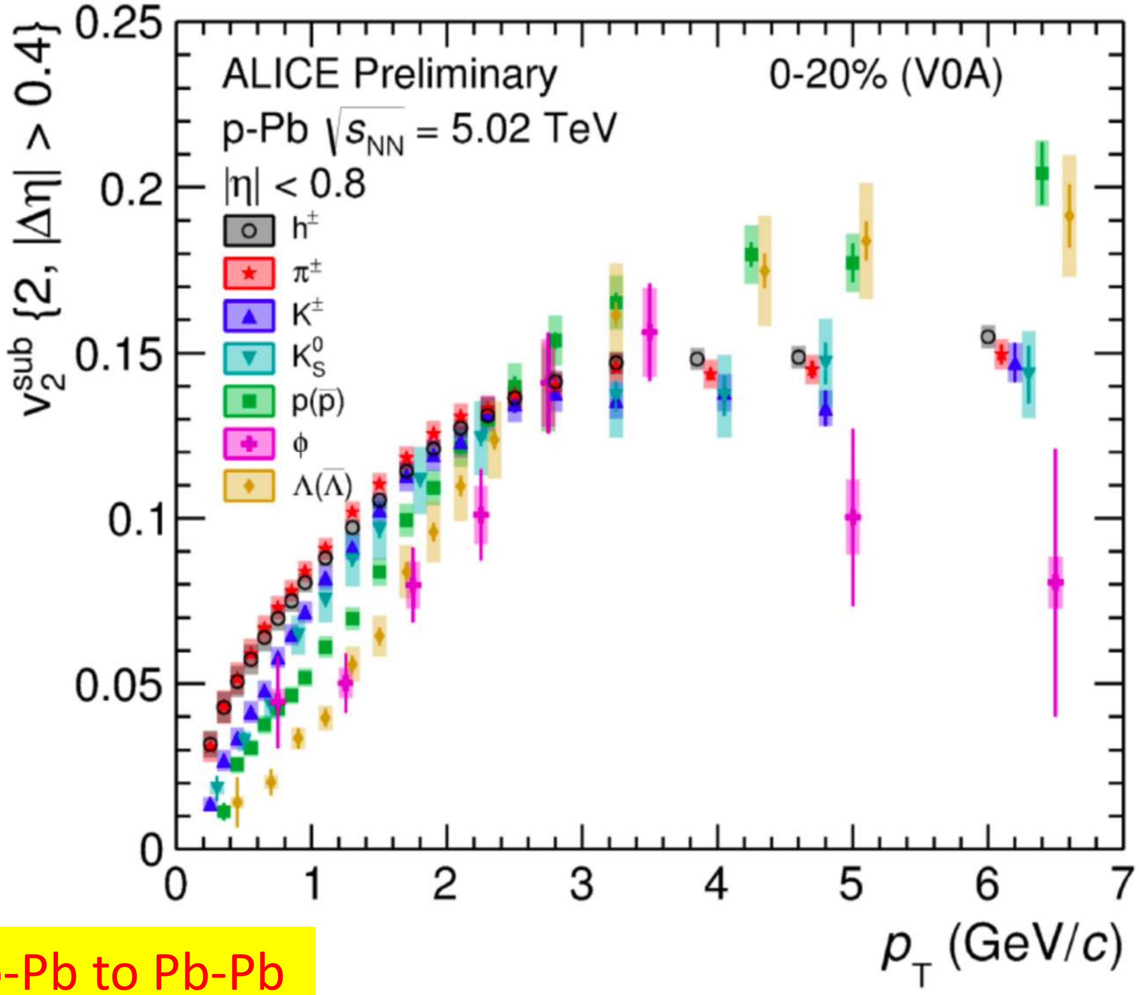
v_2 in p-Pb collisions for identified particles

V. Pacik, Mon 16:30

→ **New results on identified particle v_2^{sub} show a clear mass ordering in small collision systems.**

→ Consistent with hydrodynamic expansion, but can also be mimicked by other effects such as initial stage effects (PYTHIA+Lund string), parton escape (AMPT), or hadronic re-scattering (UrQMD).

→ Baryon/meson grouping observed at intermediate p_T as in AA collisions.



Similar mass-ordering in p-Pb to Pb-Pb

11

JET PRODUCTION

Jet Production

Fermi National Accelerator Laboratory

FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

- In 1982 Bjorken wrote a preprint (never published) proposing two ideas
- QGP might be formed in high multiplicity pp collisions.
- In a QGP, jets might undergo substantial quenching.

Jet Production

roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

- In 1982 Bjorken wrote a preprint (never published) proposing two ideas
- QGP might be formed in high multiplicity pp collisions.
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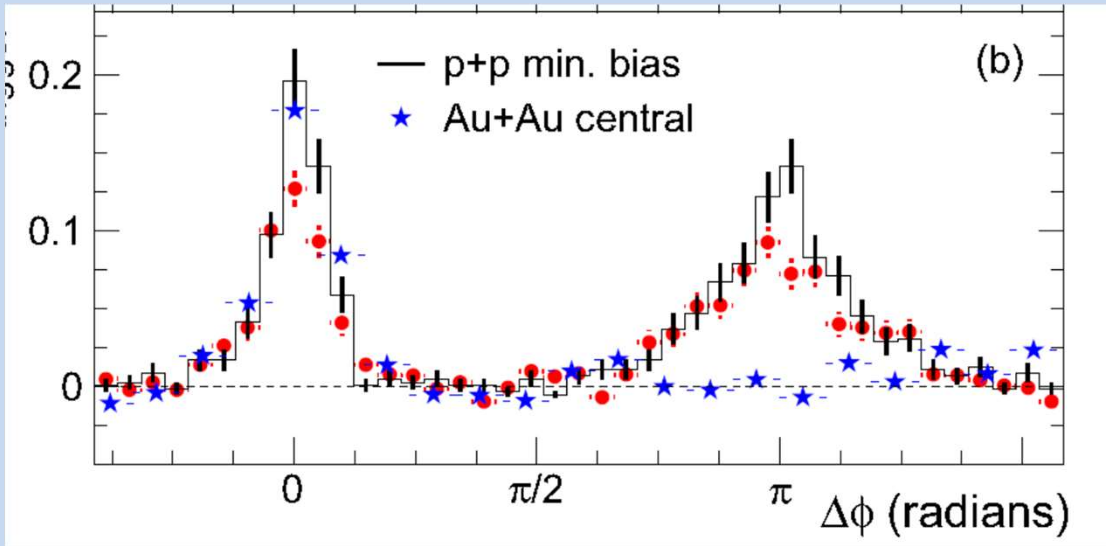
Jet Production in AA collisions



STAR √s = 200 AGeV AuAu

Phys.Rev.Lett.91:072304,2003

- First evidence seen at RHIC. Looking at particles above pt cutoff, the away side jet signal disappears in Au-Au, but not in pp

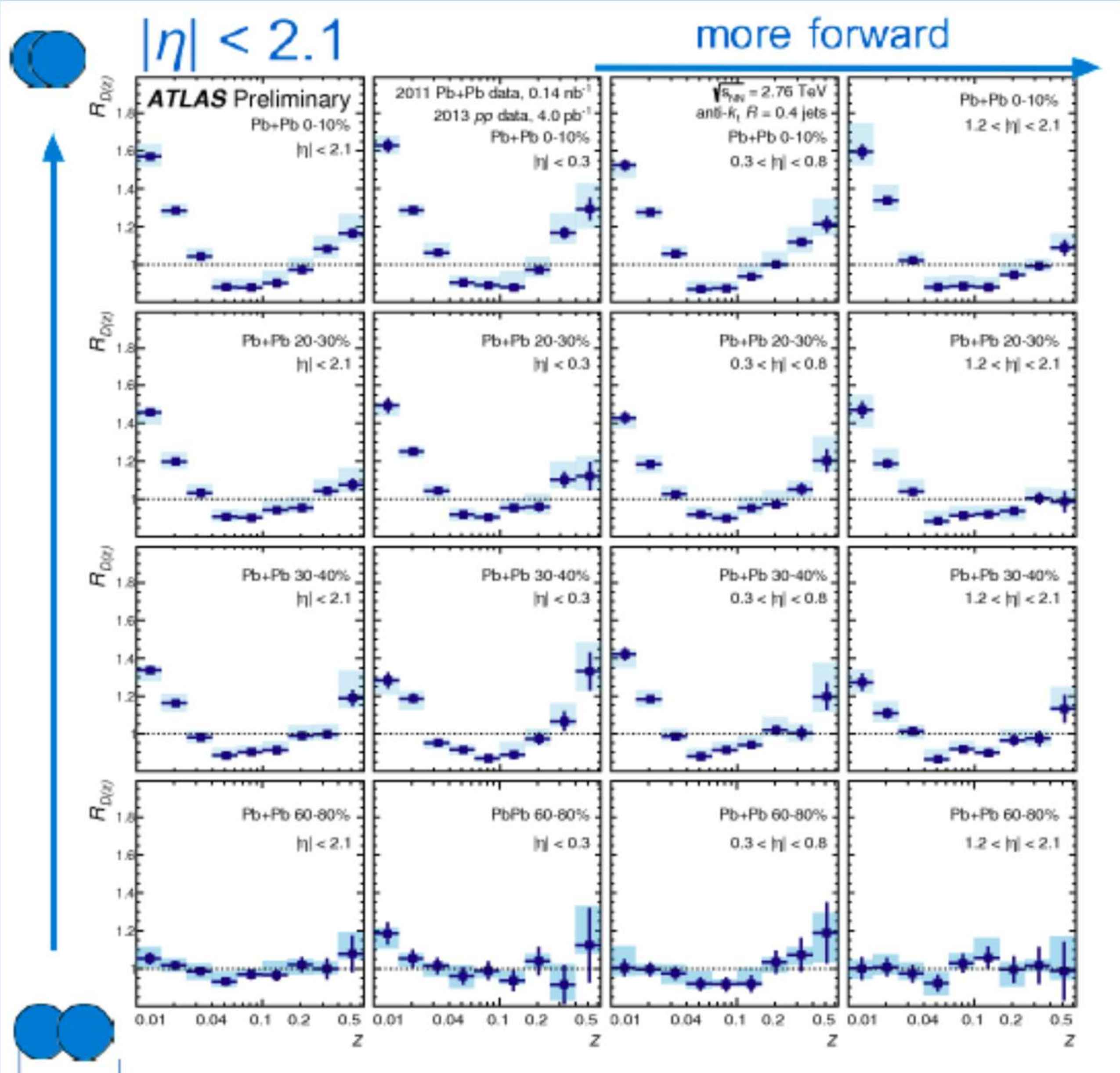
Comparison of AA to pp

- Fundamental measurement is R_{AA}, the ratio of particle production in AA to pp, normalised by the number of hard collisions

$$R_{AA} = \frac{\mathrm{d}N / \mathrm{d}p_T \,|_{AA}}{N_{coll} \mathrm{dN/d}_T \,|_{pp}}$$

- Hard production is normalised by N_{coll}, since each hard collision can give rise to a high pt particle.
  - In contrast, overall particle production scales with N_{part}

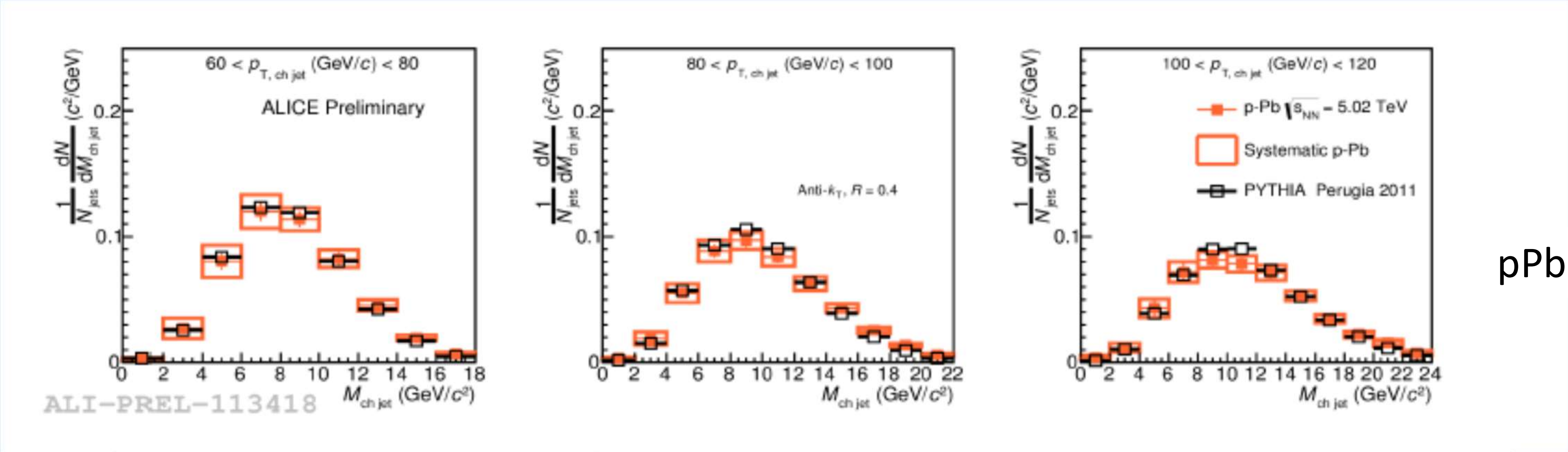
Fully reconstructed Jets



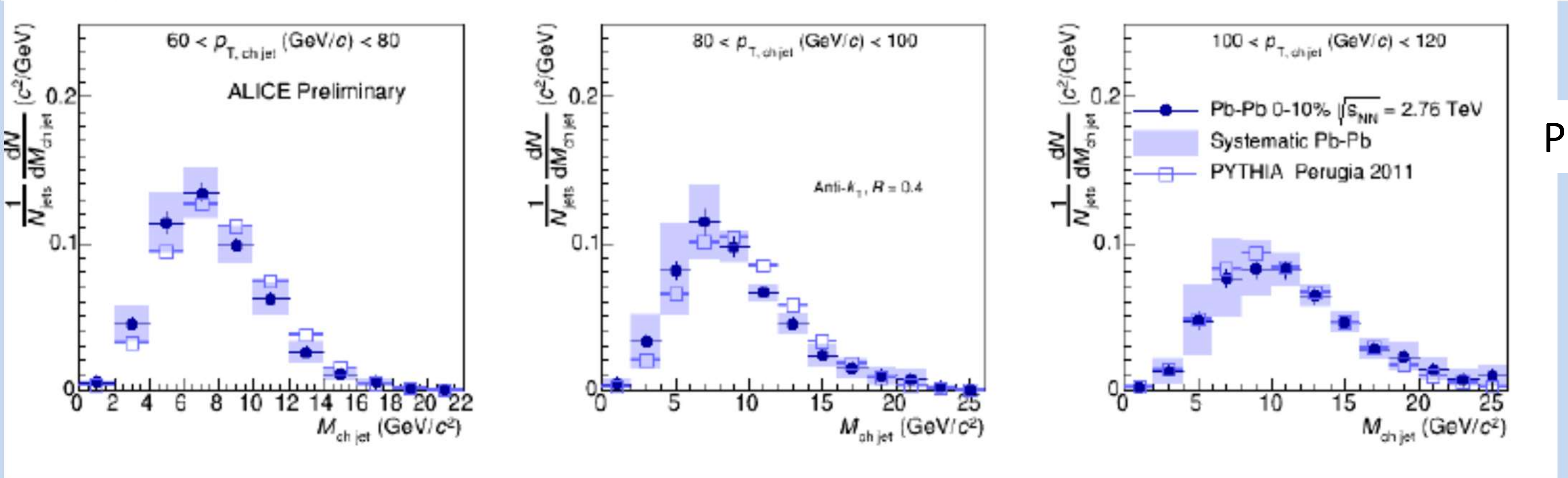
ATLAS

- Ratio of fragmentation functions shows a substantial increase in low-*z* production in central events with respect to peripheral events.
- Similar effect in all rapidity intervals.

Jet Masses in pPb and PbPb

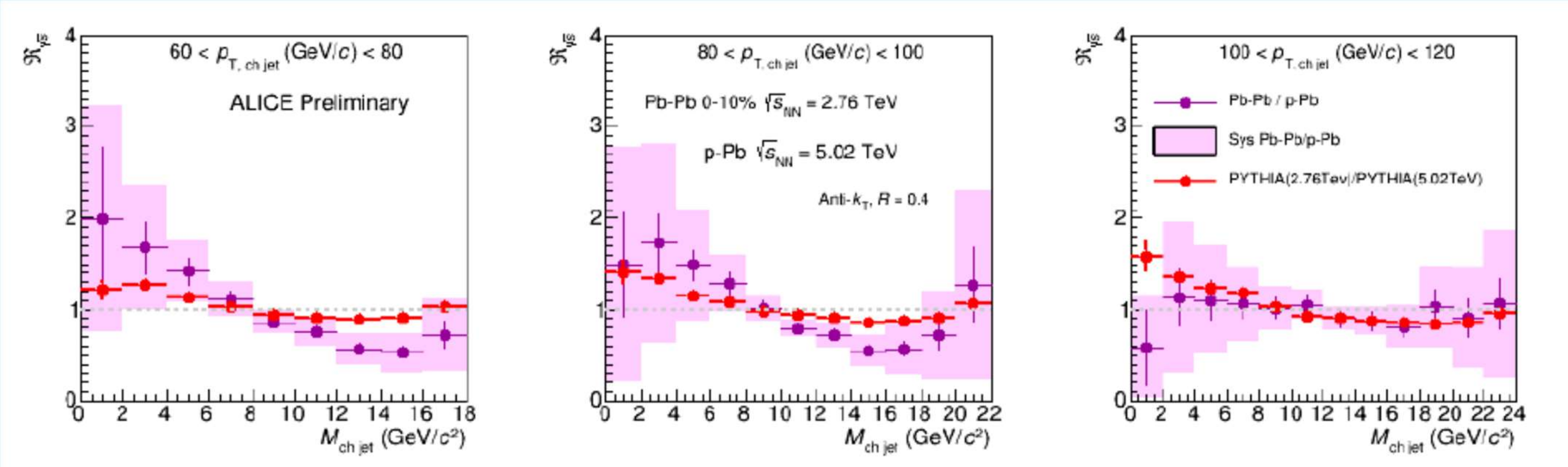


pPb



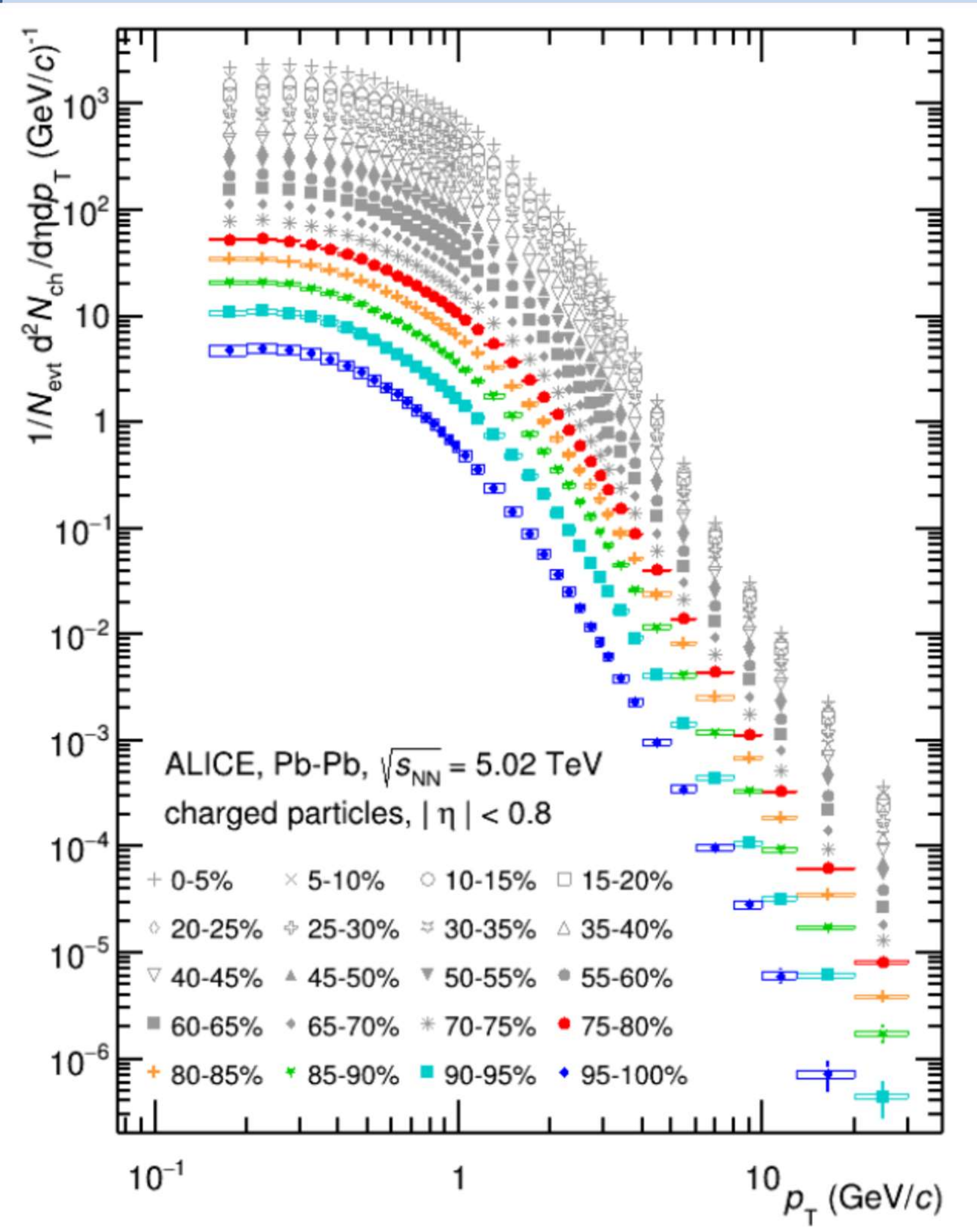
PbPb

Jet Masses pPb and PbPb



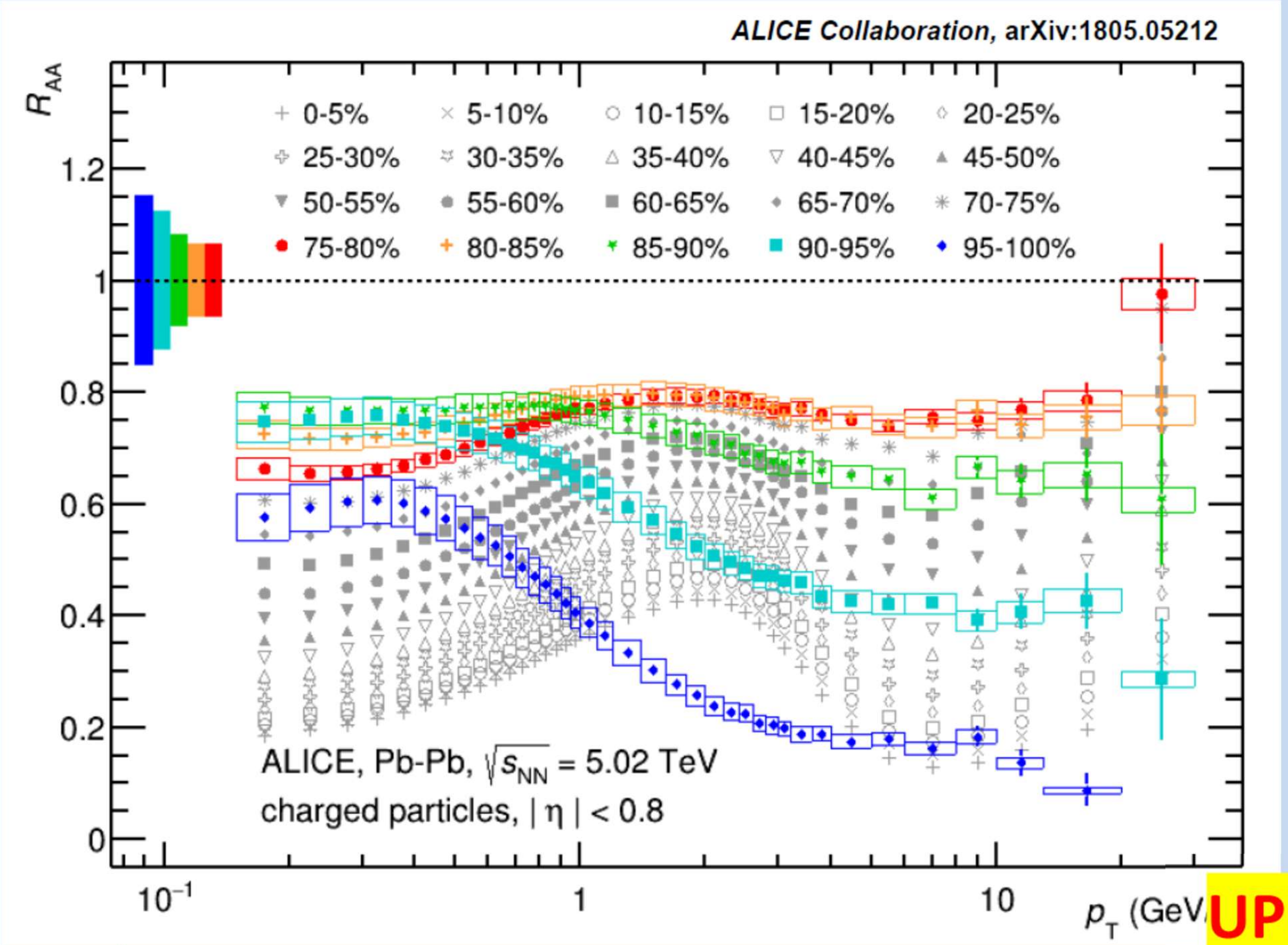
- Ratio of jet masses Pb-Pb/pPb shows PbPb has a shift towards lower jet masses, not reproduced in current quenching models.
- Related to virtuality of jets.

ALICE Pb-Pb p_T Measurements



- 5% centrality bins
- 0.15-30 GeV/*c*
- Allows systematic study of R_{AA}

Behaviour of R_{AA} for very peripheral Pb-Pb events



- RAA suppression lifts systematically to peripheral region, then appears to drop again for very peripheral events (centrality >80%)

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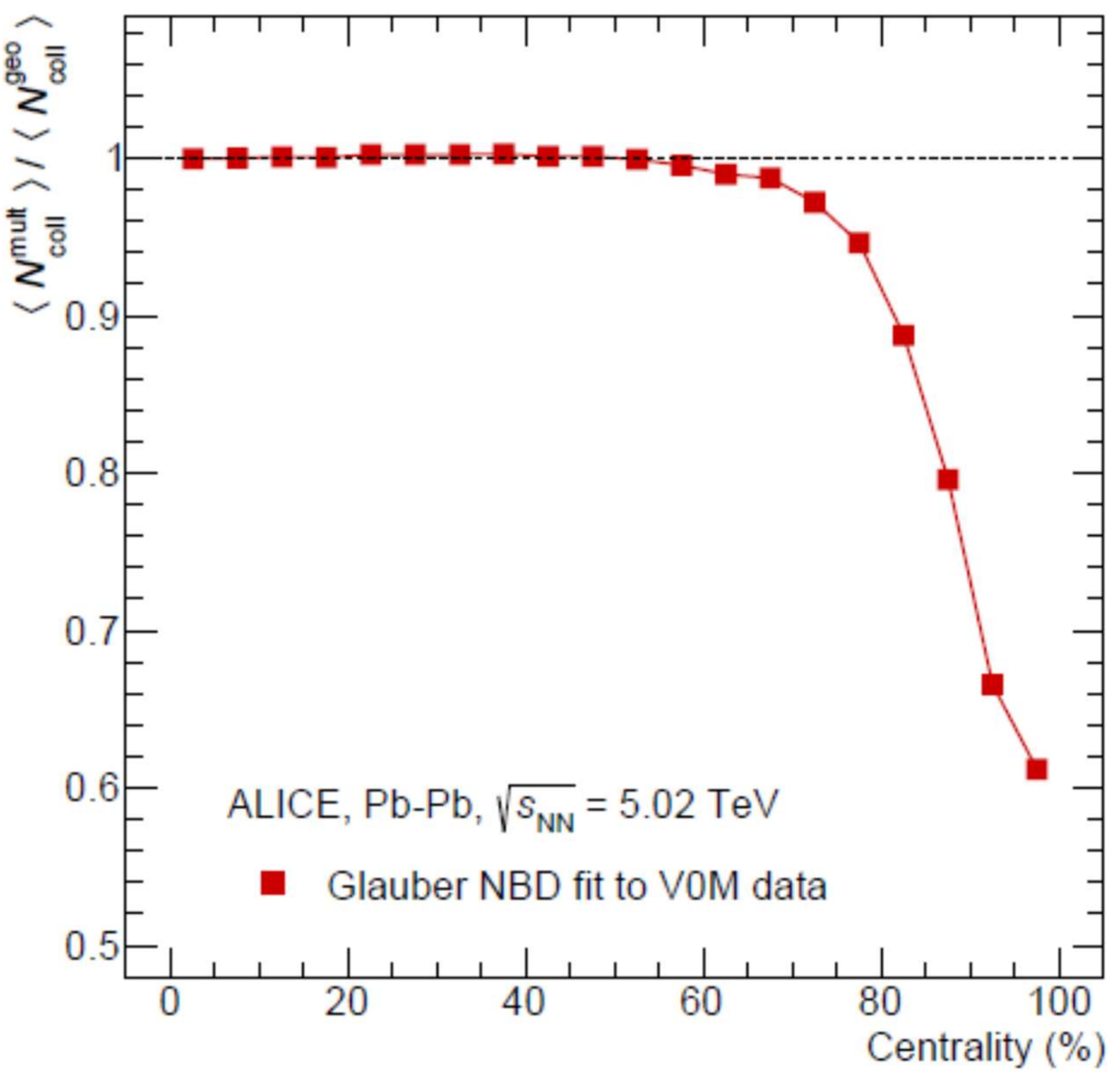
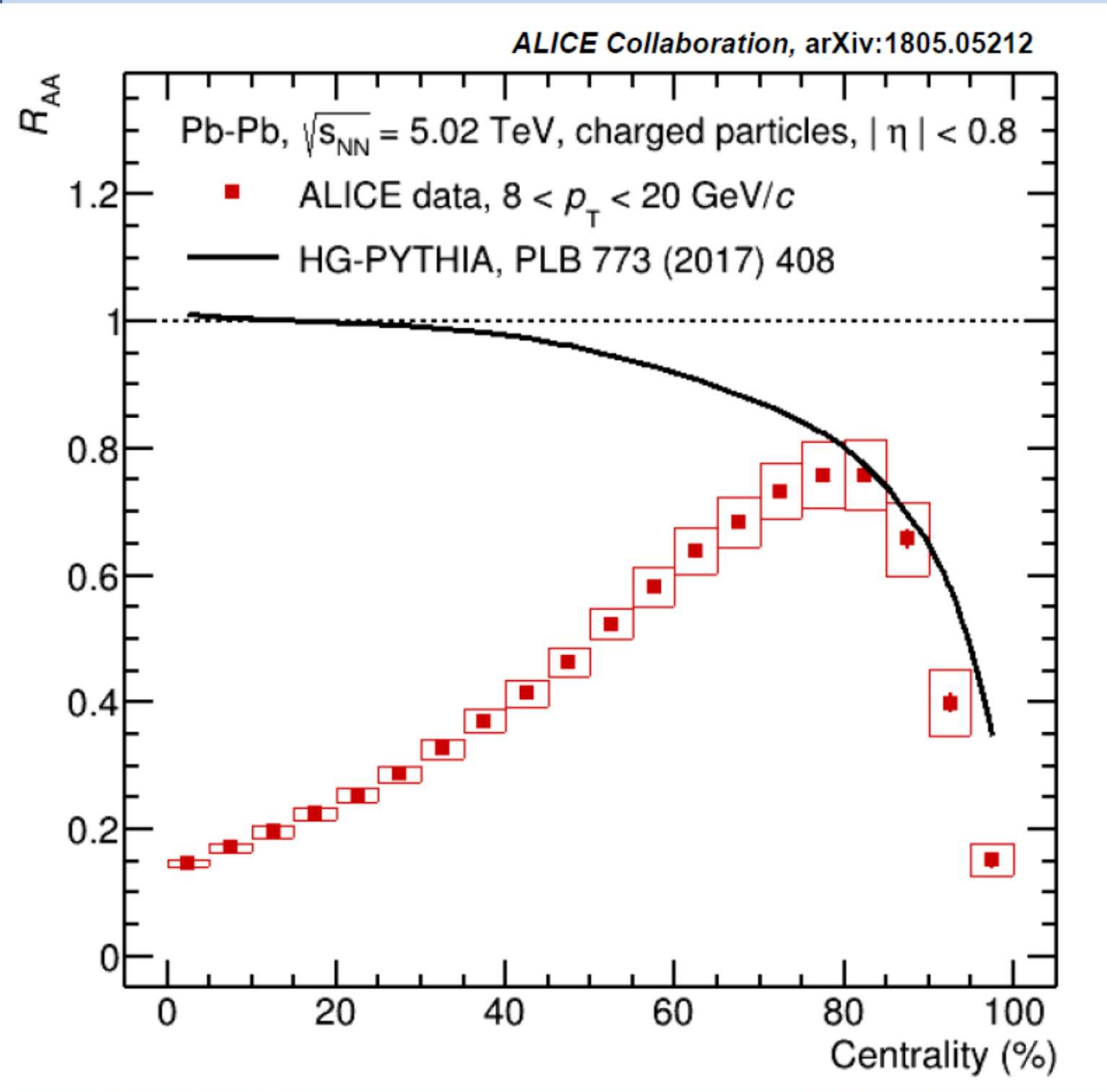
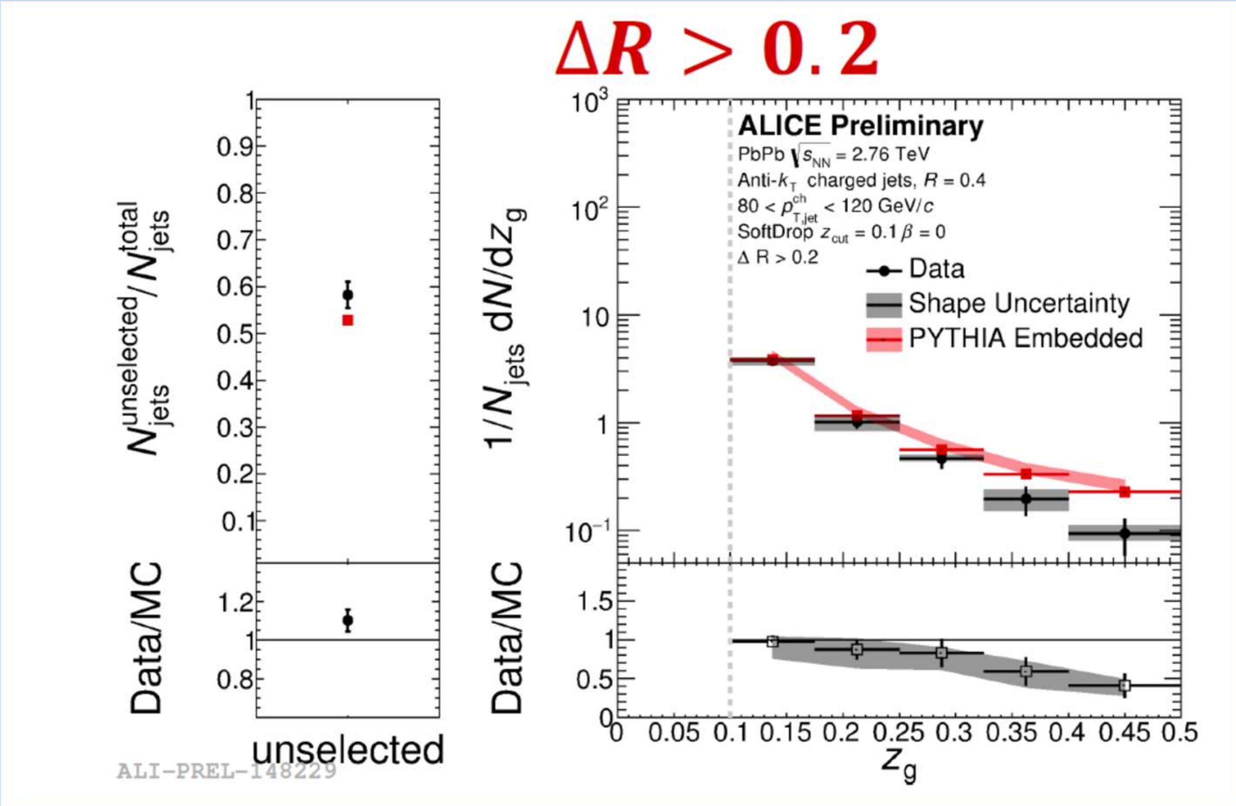


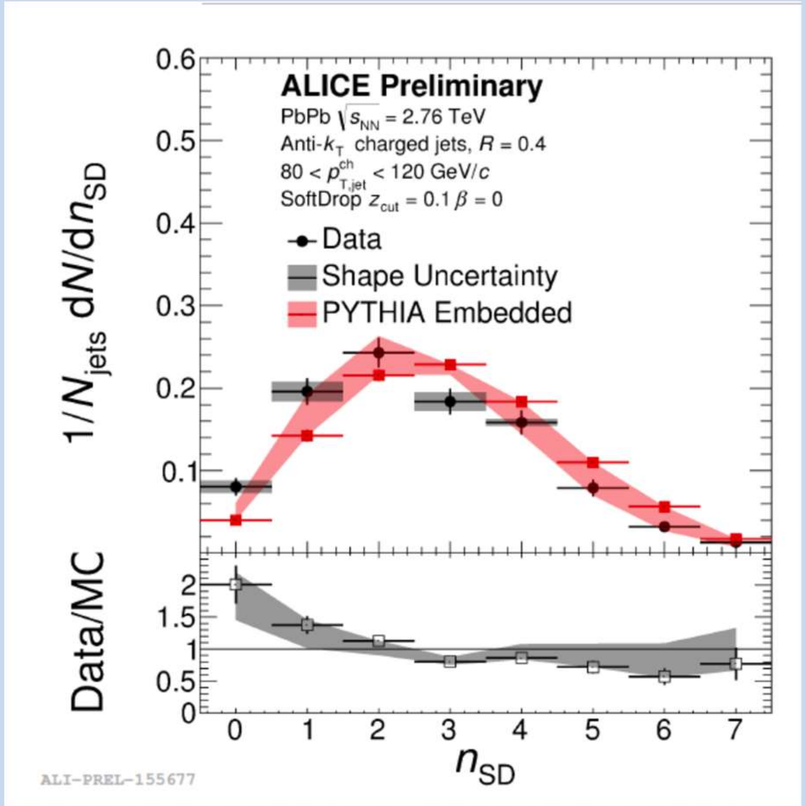
- Drop at high centrality comes about from a bias coming from identifying multiplicity slices with Ncoll slices
- Multiplicity estimator works well at low centrality, but fails for peripheral events.
- Reproduces observed drop.



- Drop at high centrality comes about from a bias coming from identifying multiplicity slices with Ncoll slices
- Monte Carlo does not describe quenching for more central events.
- Reproduces observed drop. Therefore origin is geometric, NOT because of parton energy loss (not included in model)

Jet splitting in ALICE





- Analysing subjet structure using **soft drop** algorithm gives descriptive parameters z_g, n_{SD}, r_g for Pb-Pb jets, to compare to pp
  - Momentum fraction of subjects modified (suppressed) at large z_g
  - No major modification in overall number of splittings

H. Andrews QM2018

B'ham interest

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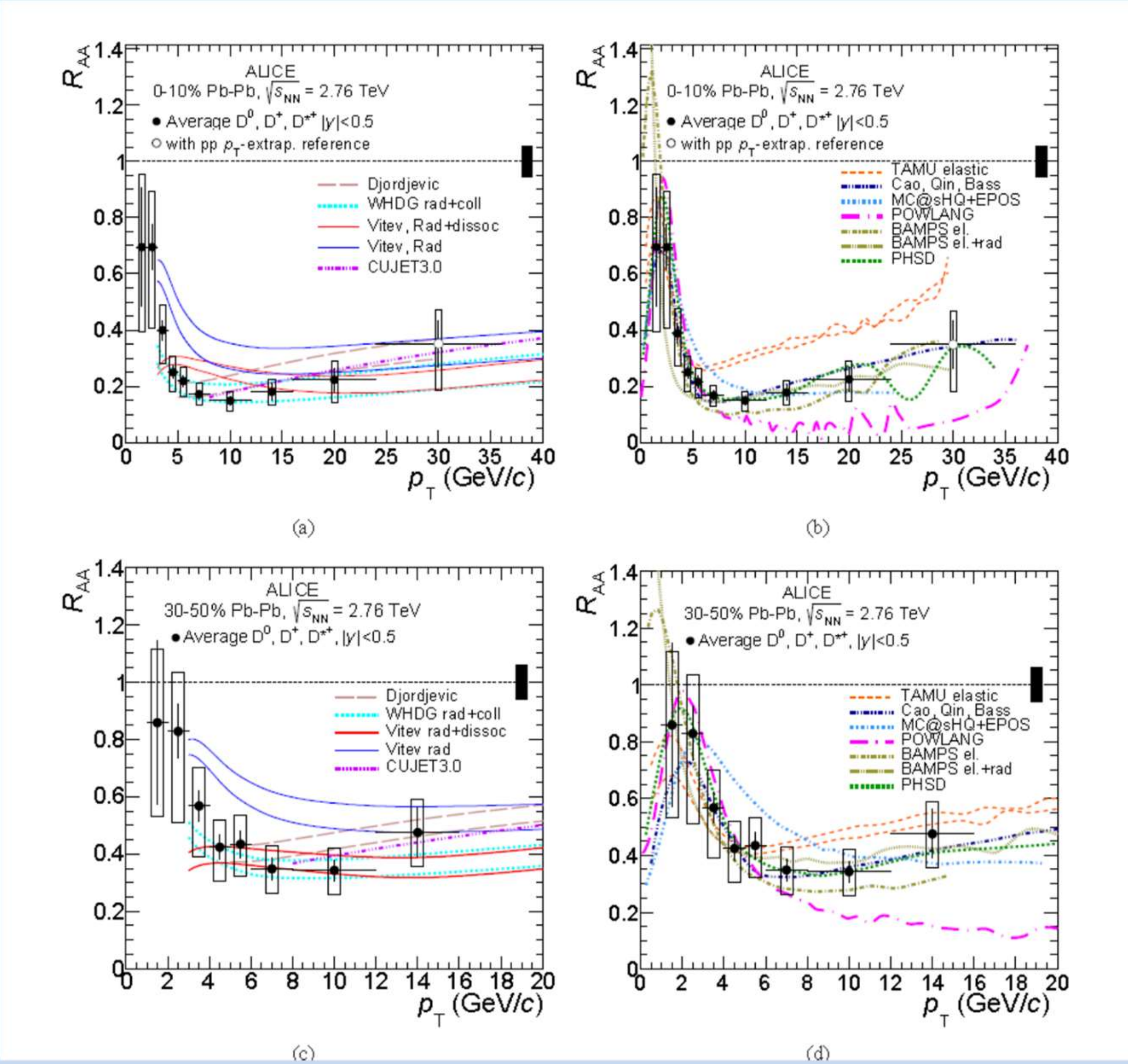
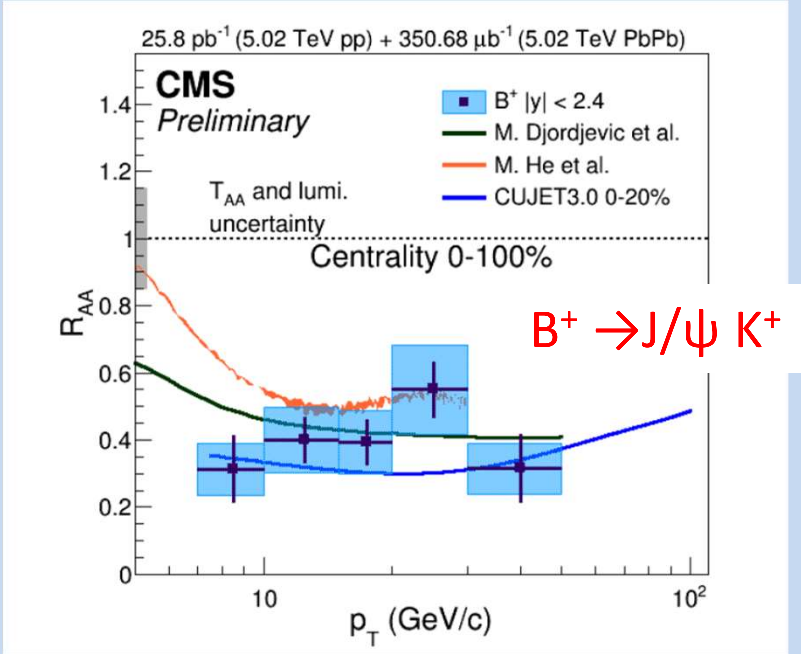
HEAVY FLAVOUR

Production of Heavy Flavour



ArXiv:1509.06888 D^0, D^+, D^*



CMS PAS HIN-16-011

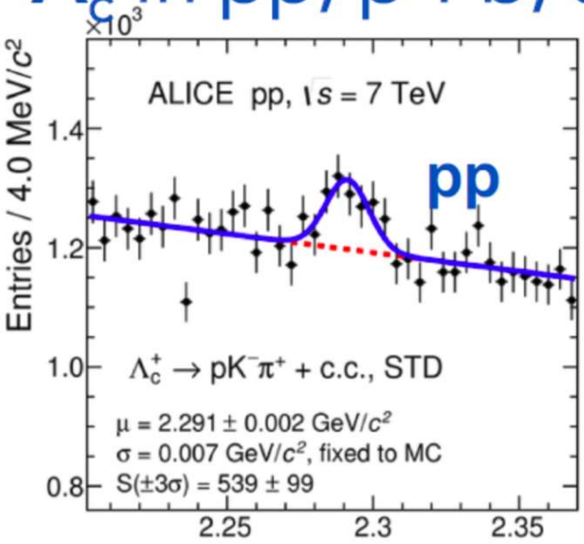
- Interaction of heavy particles with medium measured using R_{AA}.
- Also sensitive to nPDF

$$R_{AA} = \frac{dN/dp_T|_{AA}}{N_{coll} dN/d_T|_{pp}}$$

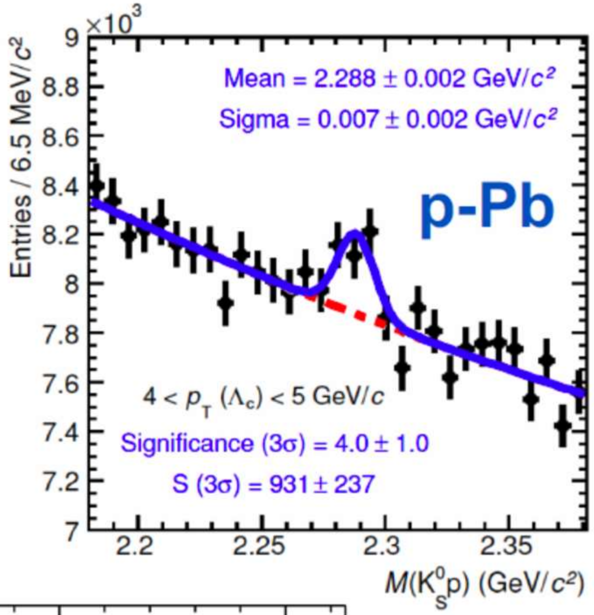
Λ_C measurements in pp,pPb and Pb-Pb

Λ_c in pp, p-Pb, and Pb-Pb collisions (1)

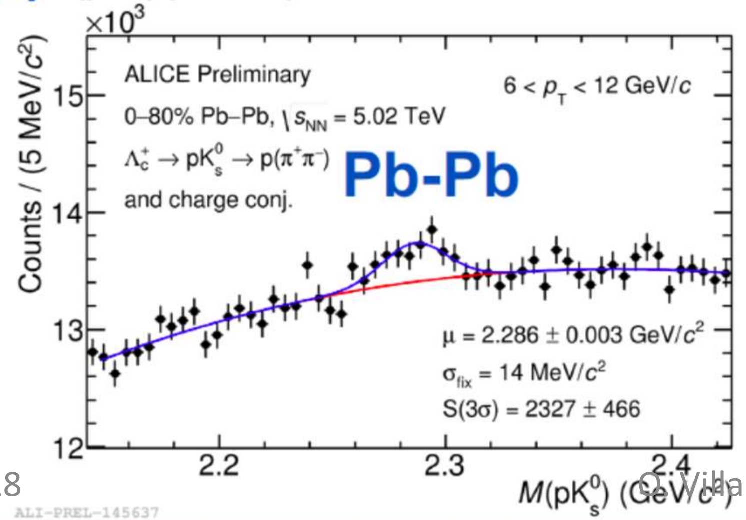
X. Peng, Wed 09:20



[arXiv:1712.09581]



→ Very challenging measurement: extensive use of precise tracking and particle identification as well as multi-variate techniques.



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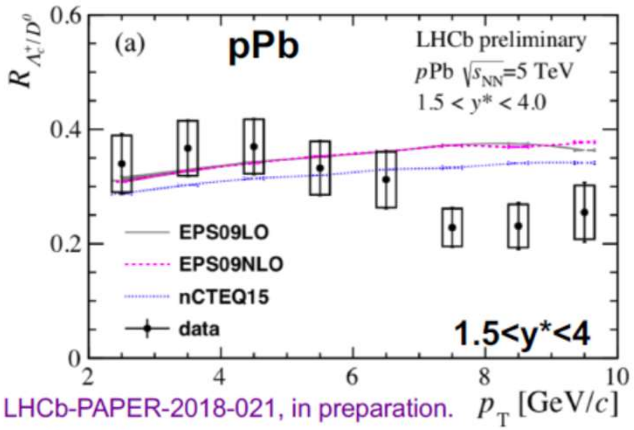
Comparison to Models

Charm baryons: understand hadronization

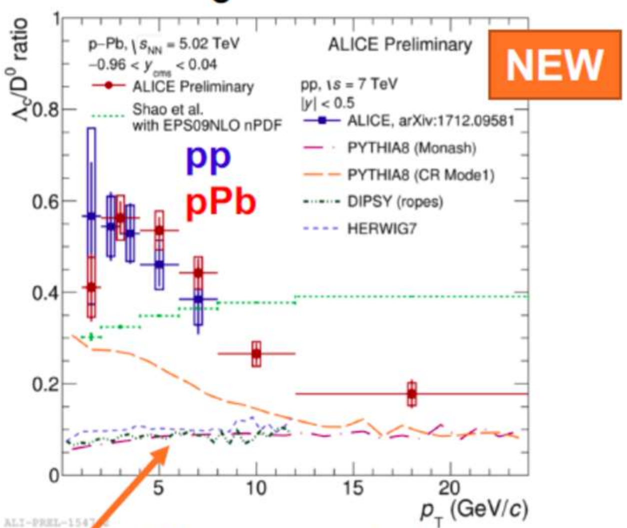
INFN

Λ_c/D^0



LHCb-PAPER-2018-021, in preparation.

Λ_c/D^0 arXiv: 1712.09581



Λ_c^0/D^0:

- compatible in **pp** and **p-Pb** collisions within uncertainties
- slight different in p-Pb at mid- and forward rapidity

- Mid rapidity → ratio higher than MC generators (tuned on e^+e^-)
- Ratio better described by data-driven approach with nPDF

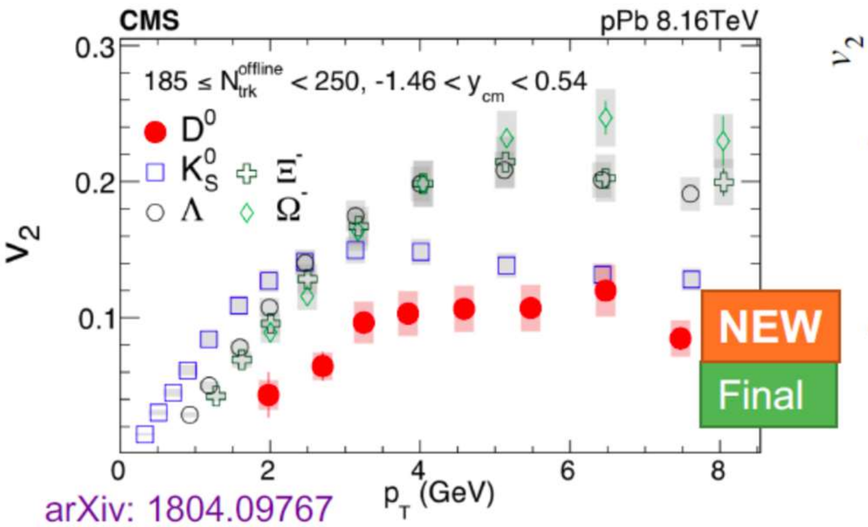
J.P Lansberg, H.-S Shao, EPJC 77 (2017) 1

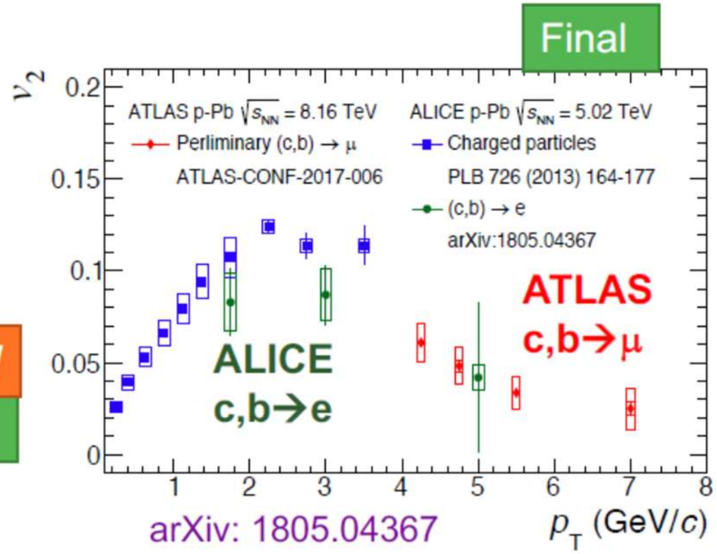
X. Peng (Wed 09:20)
J. Sun (Wed 14:40)

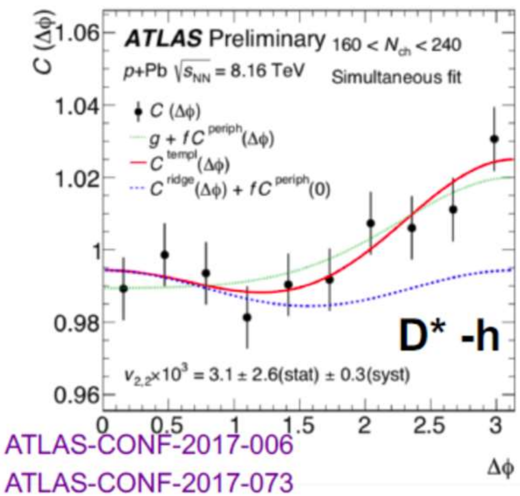
Interaction with medium

Collectivity in p(d)-A?

INFN







ATLAS-CONF-2017-006
ATLAS-CONF-2017-073

Z. Shi (Tue 14:40)
H. Zanoli (Wed 15:20)

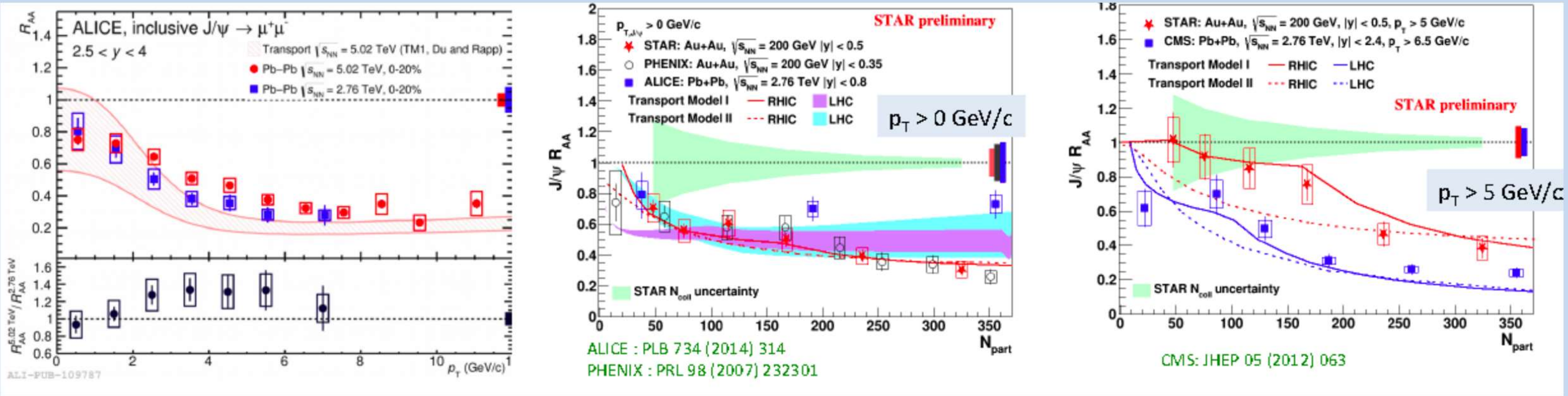
Positive v_2 for HF particles (D^0 , D* mesons, $e^\pm$ and $\mu^\pm$ from HF) from 2-particle correlations in **high-multiplicity p-Pb**

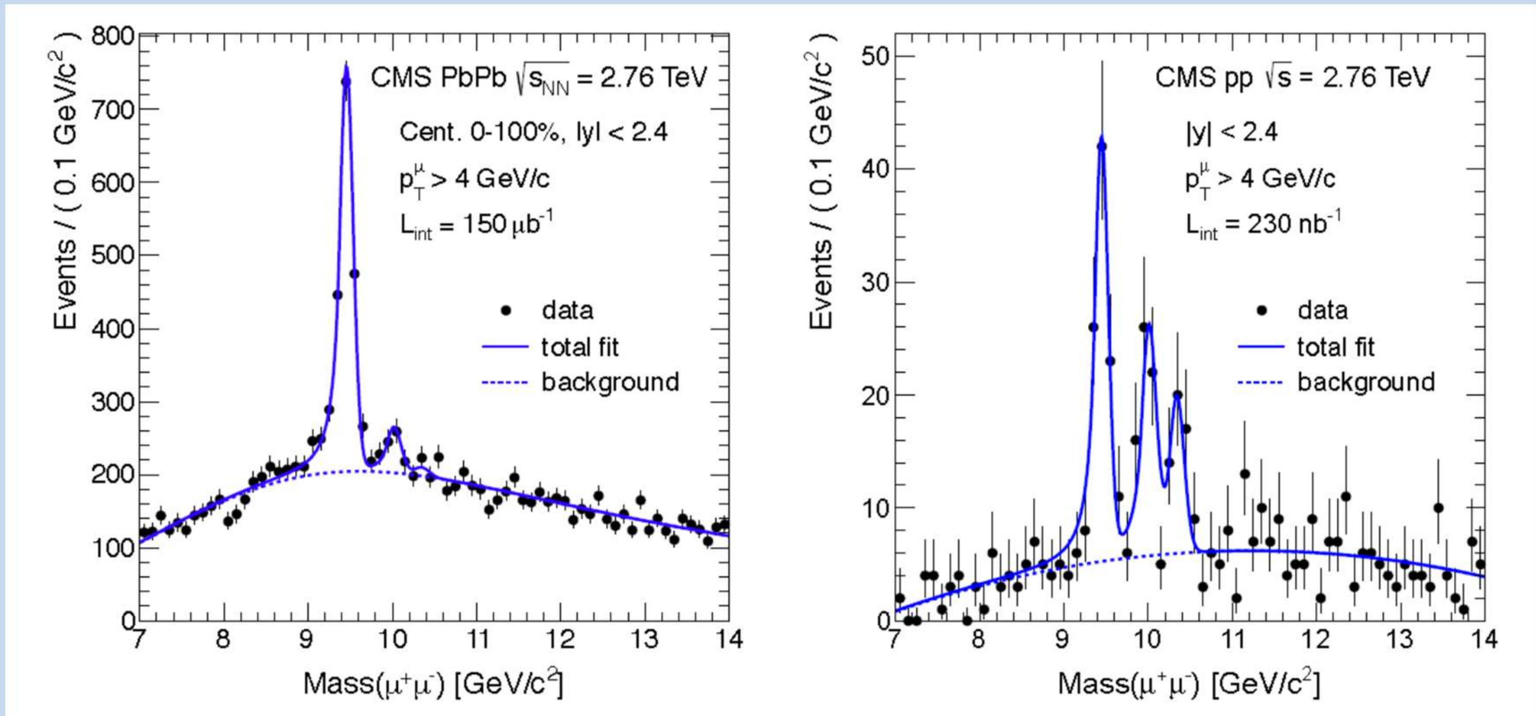
D^0 v_2 persists up to high p_T, weaker than that of light flavors

Quarkonium -Two effects

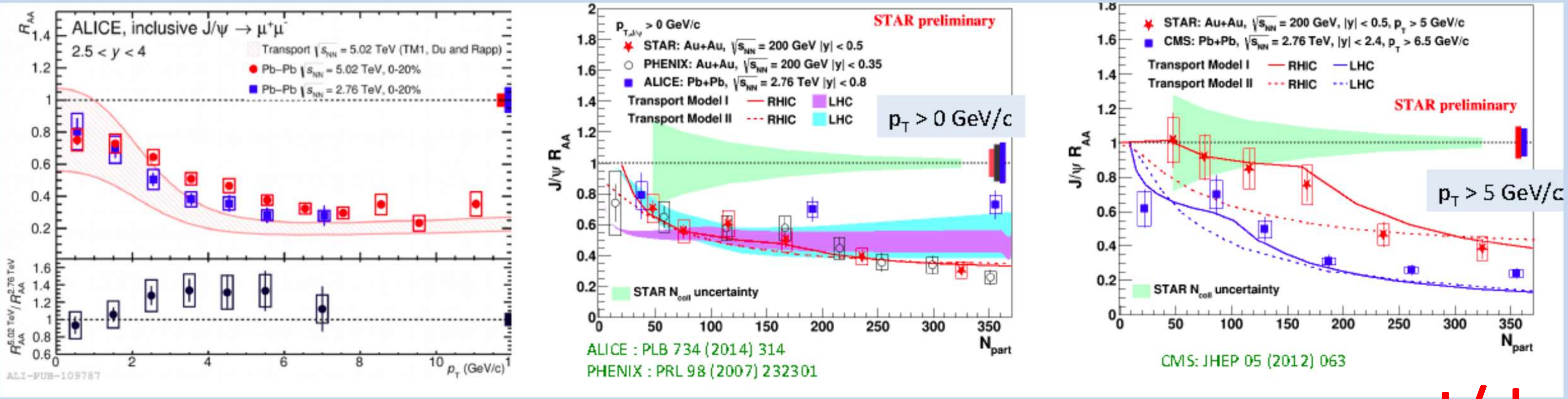
- Two separate effects are expected for quarkonium
  - Suppression because of Debye colour screening. The amount of suppression depends on the "size" of the meson. The larger the effective radius, the more the suppression
  - *Warning:* other descriptions exist.
  - Regeneration (if temperature high enough) because of thermal production)
    - At LHC, for the first time, temperature is high enough that regeneration of charmonium could be significant
    - Should be small or negligible for Upsilon states.

Quarkonium Production

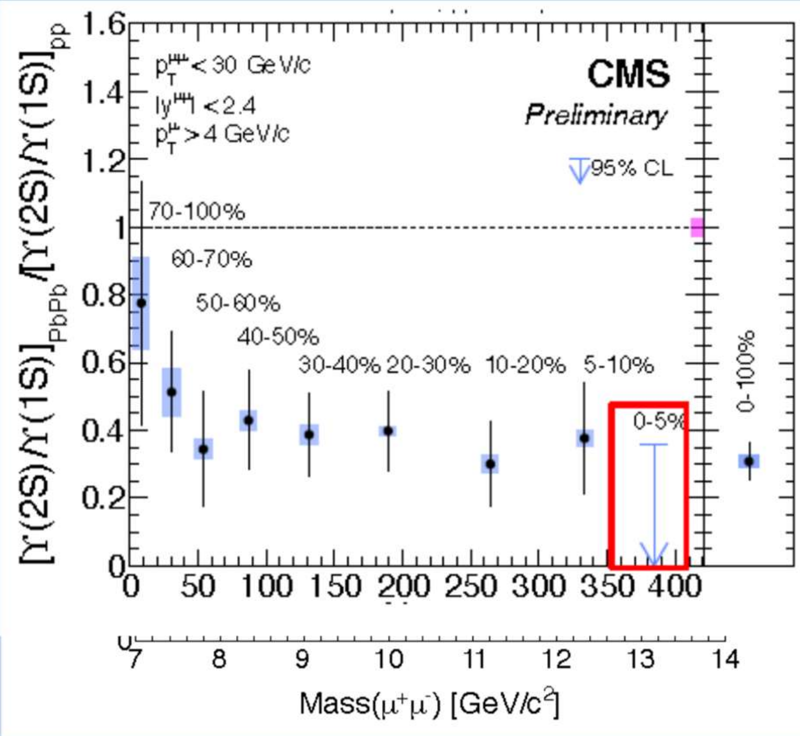


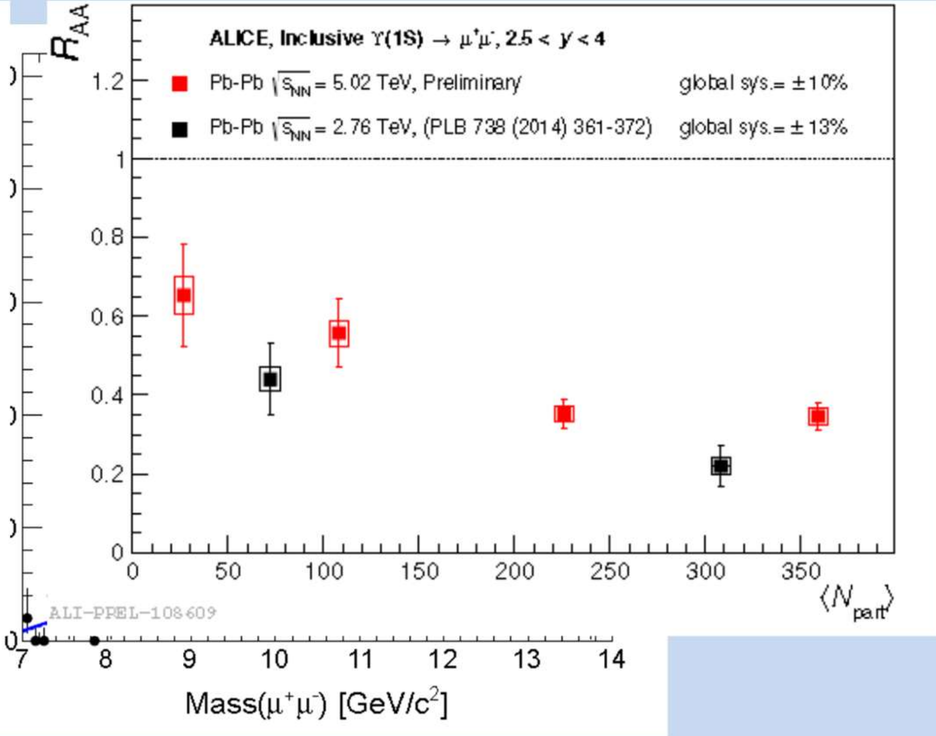


Quarkonium Production R_{AA}



J/ψ

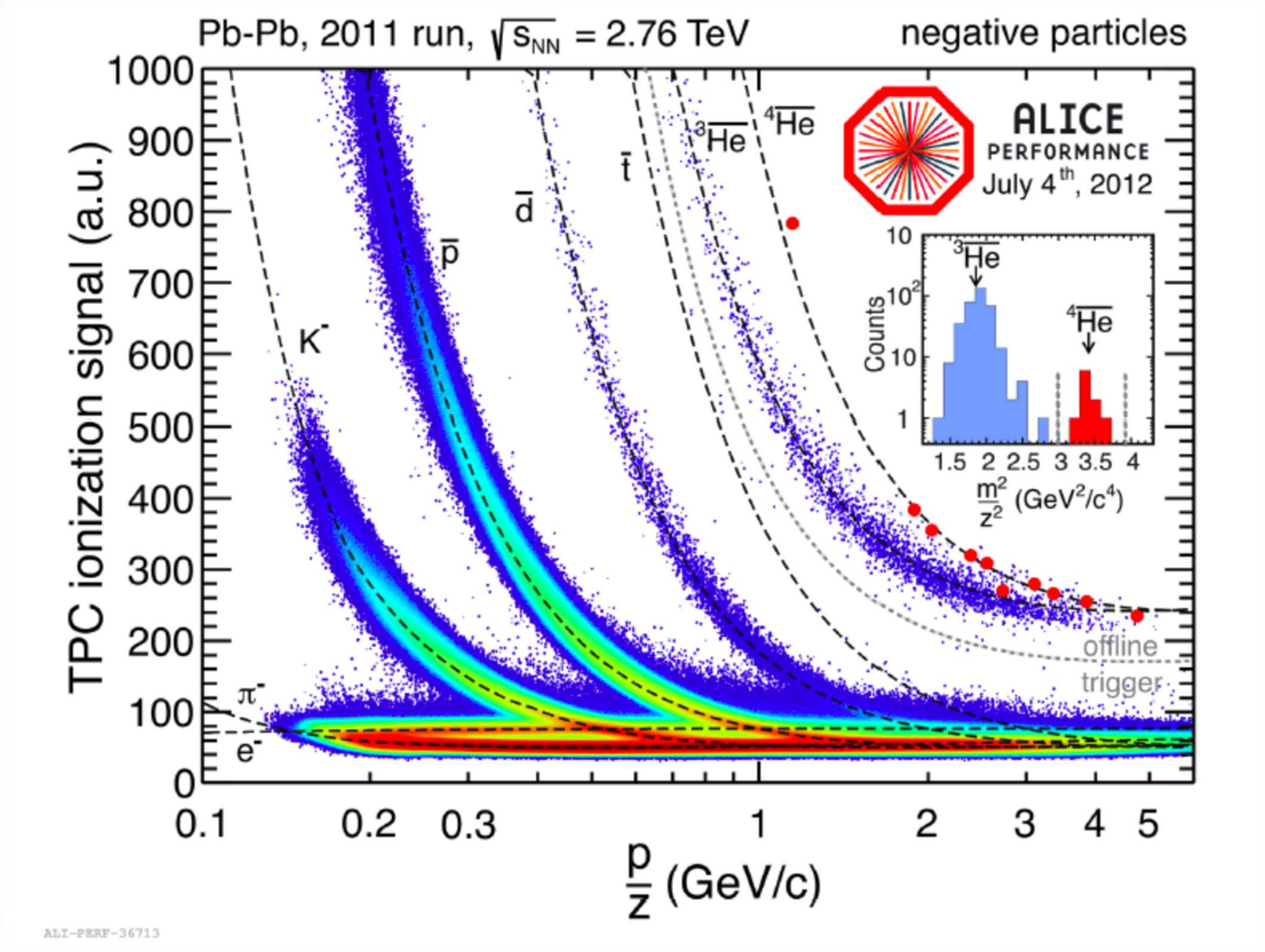




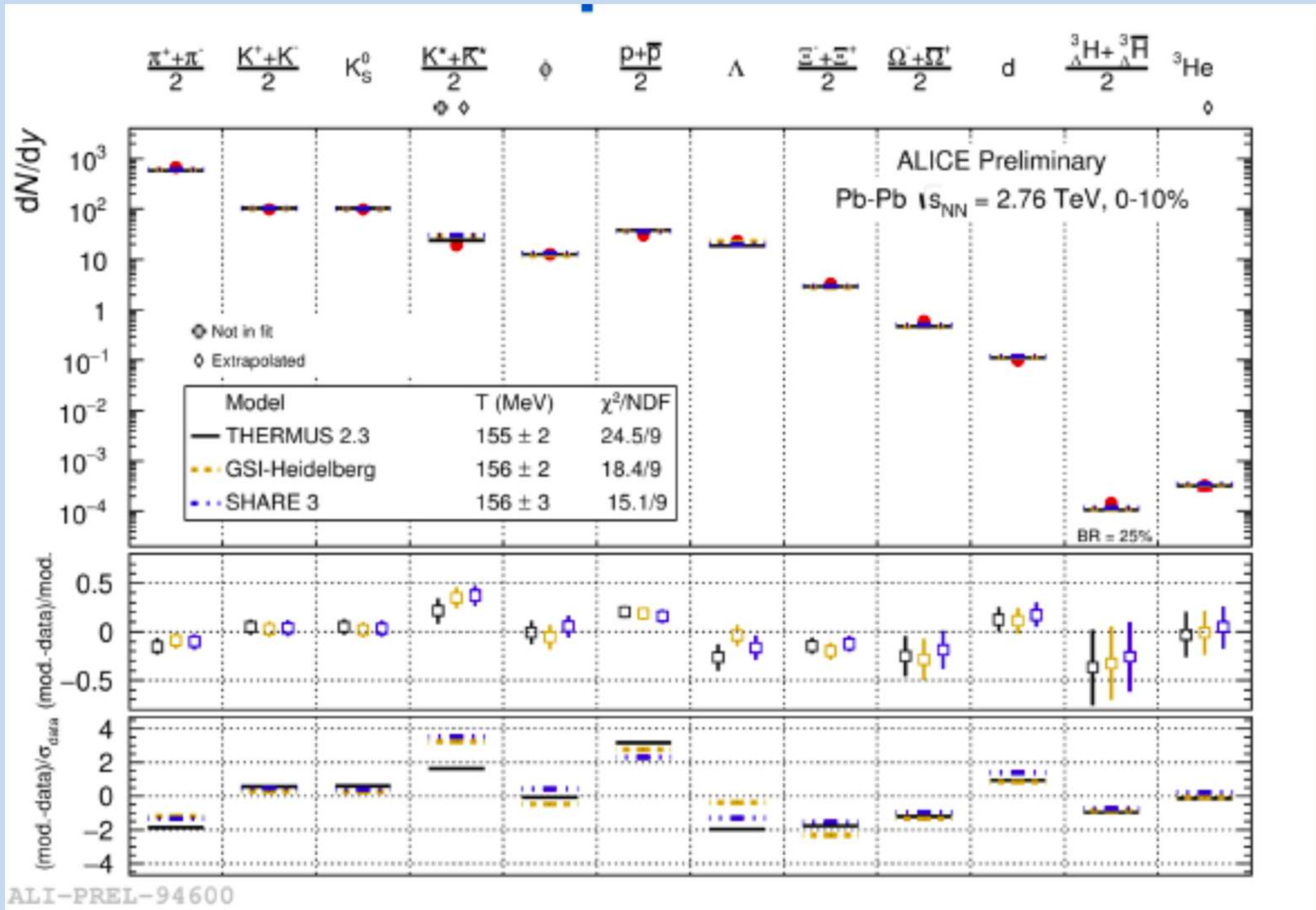
ϒ

LIGHT FLAVOUR PRODUCTION

ALICE PID by dE/dx

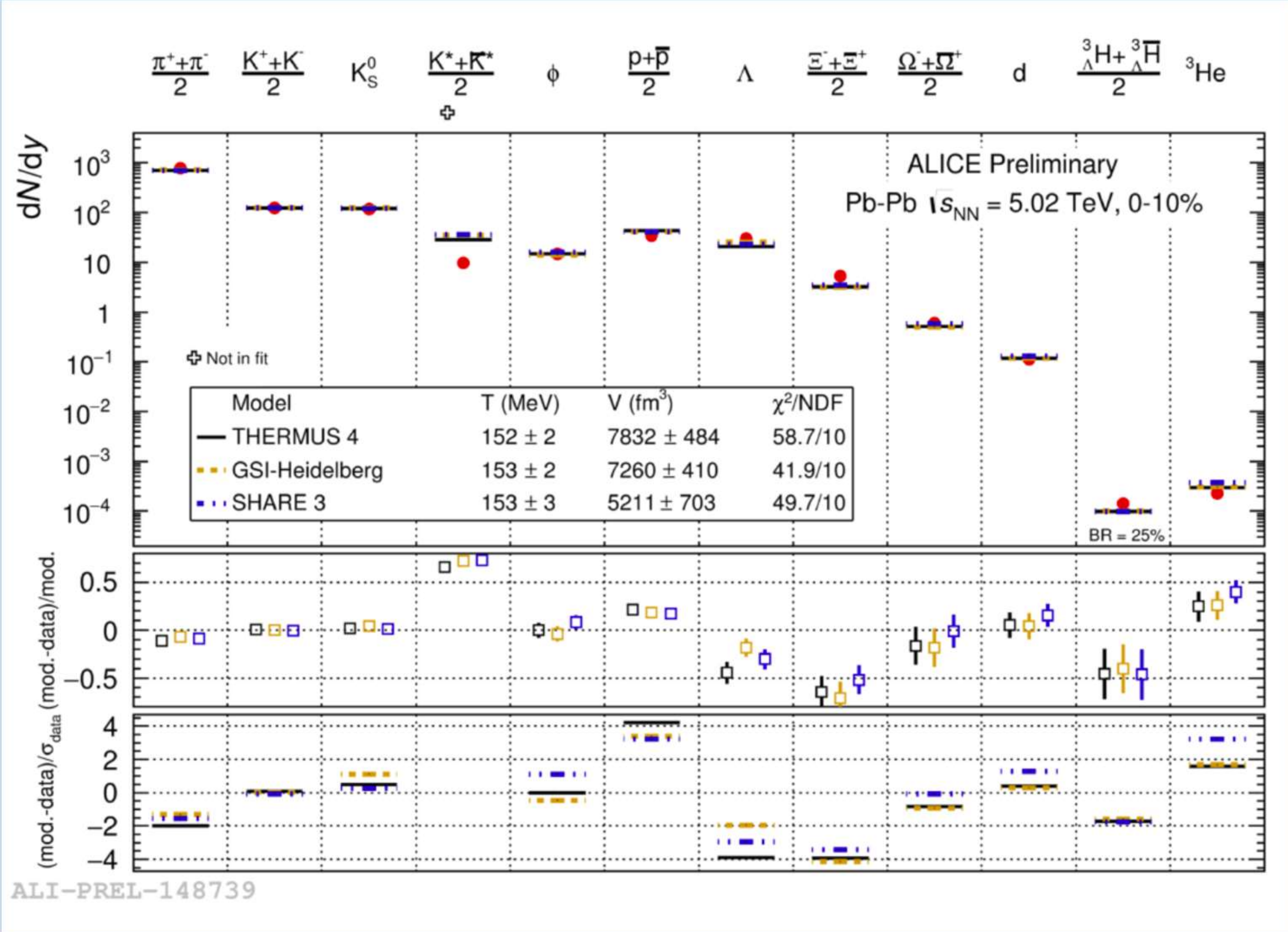


Particle Production



- Abundances of particles can be described in terms of just two parameters in Pb-Pb.
- Current status is that there is more than one model. Internal assumptions of the models are different, predictions have become very similar.
- Models assume chemical equilibrium. In one case equilibrium achieved in hadronic phase (THERMUS), in the other in QGP phase followed by hadronization (SHARE).

Particle Production



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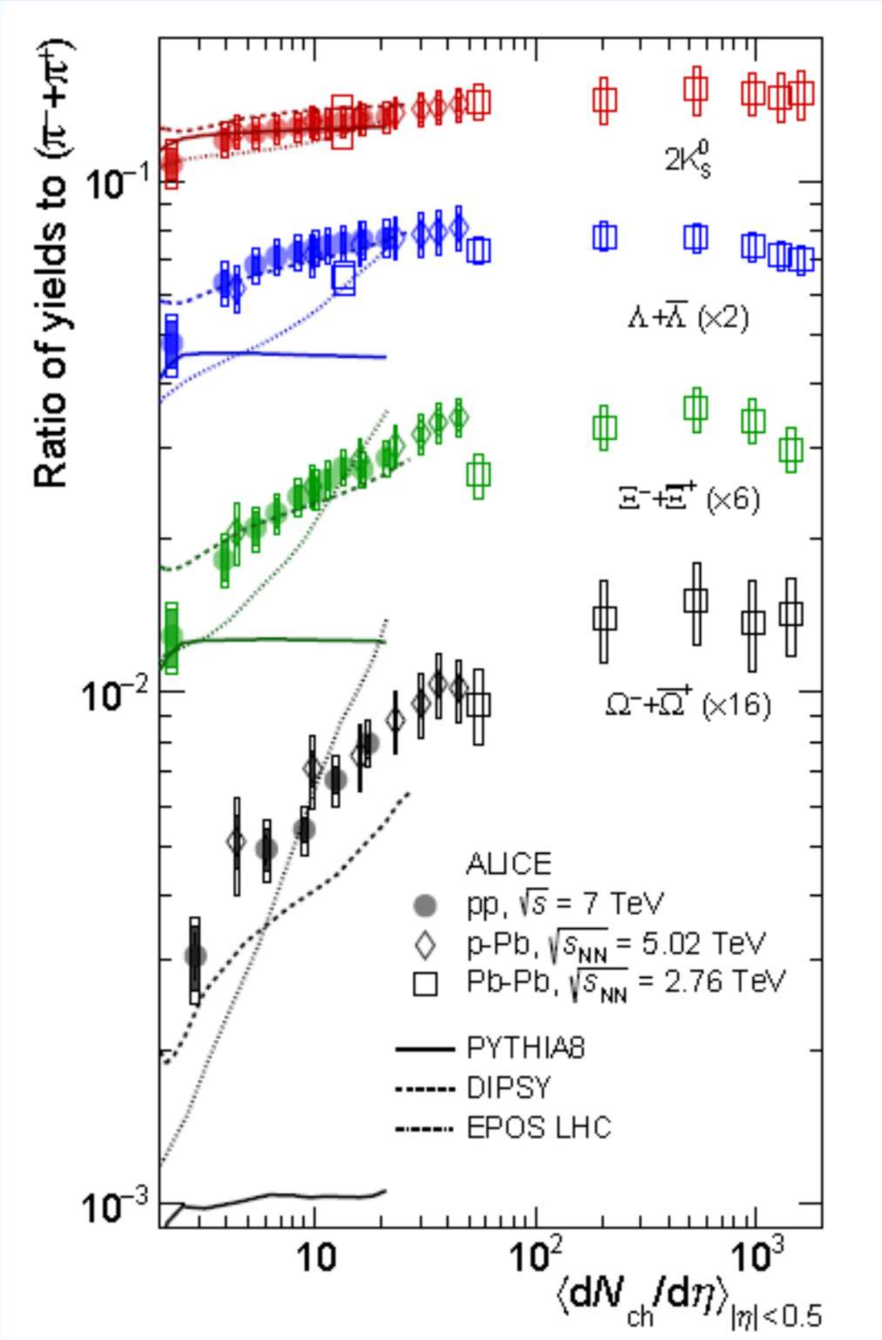
- Current status is that there is more than one model. Internal assumptions of the models are different, predictions have become very similar.
- Models assume chemical equilibrium. In one case equilibrium achieved in hadronic phase (THERMUS), in the other in QGP phase followed by hadronization (SHARE).
- Both good fits. Temperature for 5.02 TeV slightly lower than for 2.76 TeV (152 vs 156 MeV)

UPDATE QM2018

SMALL SYSTEMS

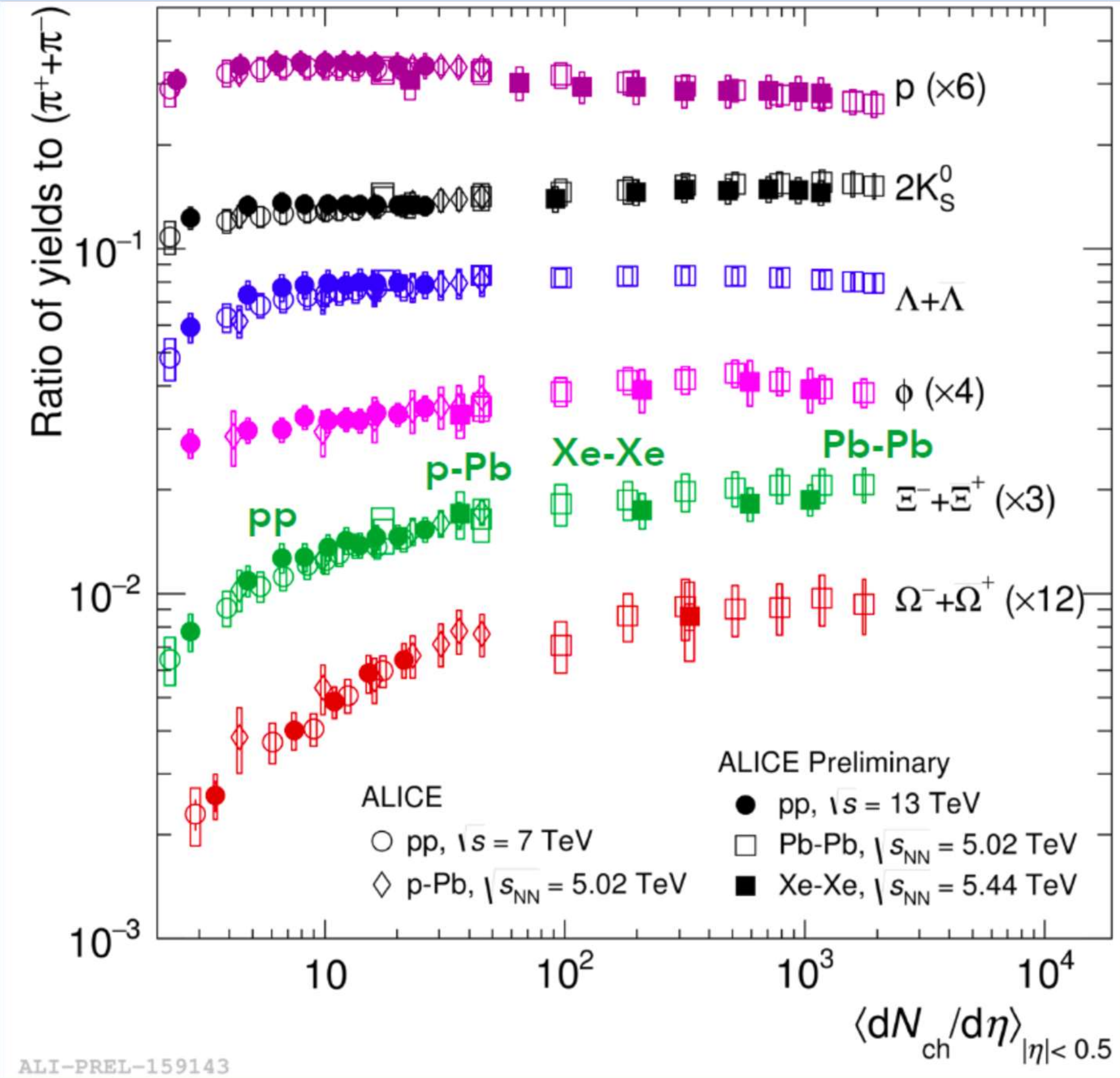
Strangeness Production in Small Systems



- Strangeness production in pPb and even in pp increases with multiplicity, and becomes comparable to Pb-Pb at the same multiplicity
- Not reproduced by models.

ArXiv:1606.07424

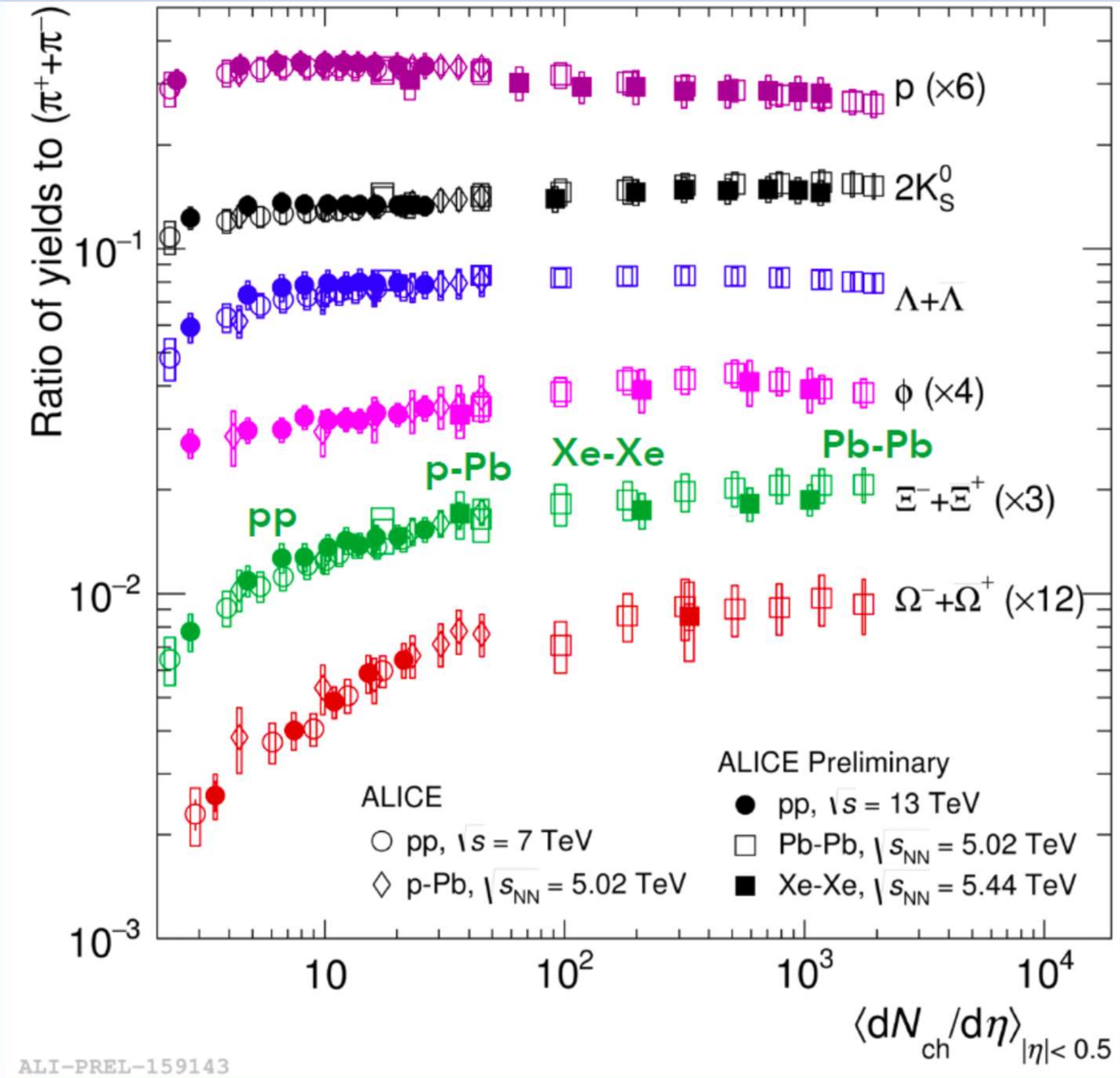
Particle yields from pp to Pb-Pb



- New update for QM2018 shows particle ratios for different sized systems from pp to Pb-Pb.
  - Includes new data from Xe-Xe (5.44 TeV) and pp (13 TeV)
- All data sets show a smooth evolution, dependant only on <d*N*/dη>
- Large increase in multistrange yield in small systems.

UPDATE QM2018

Particle yields from pp to Pb-Pb



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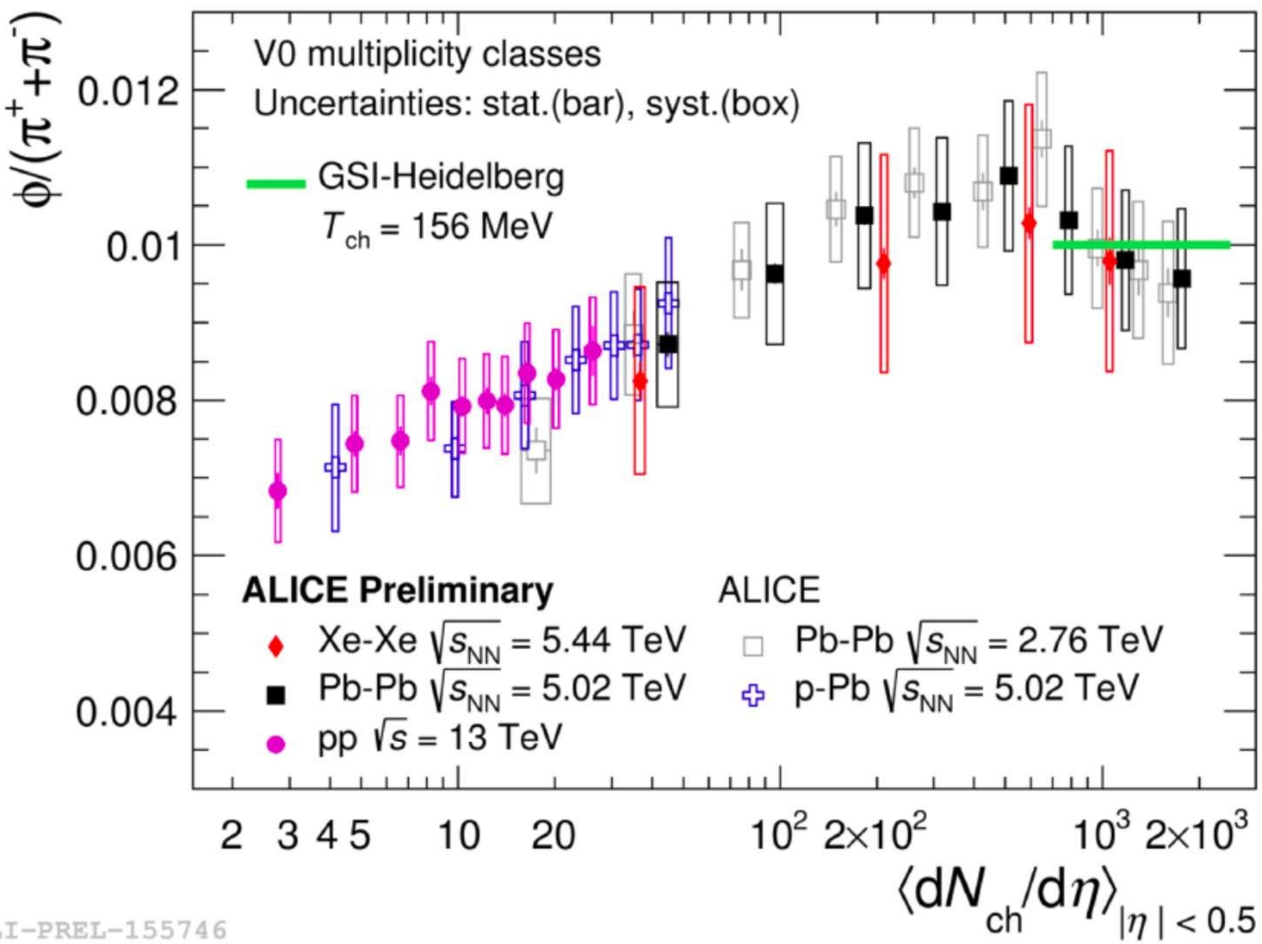
B'ham interest

UPDATE QM2018

Look at ϕ production

Particle chemistry across system size (3)

G. Bencedi, Tue 16:40



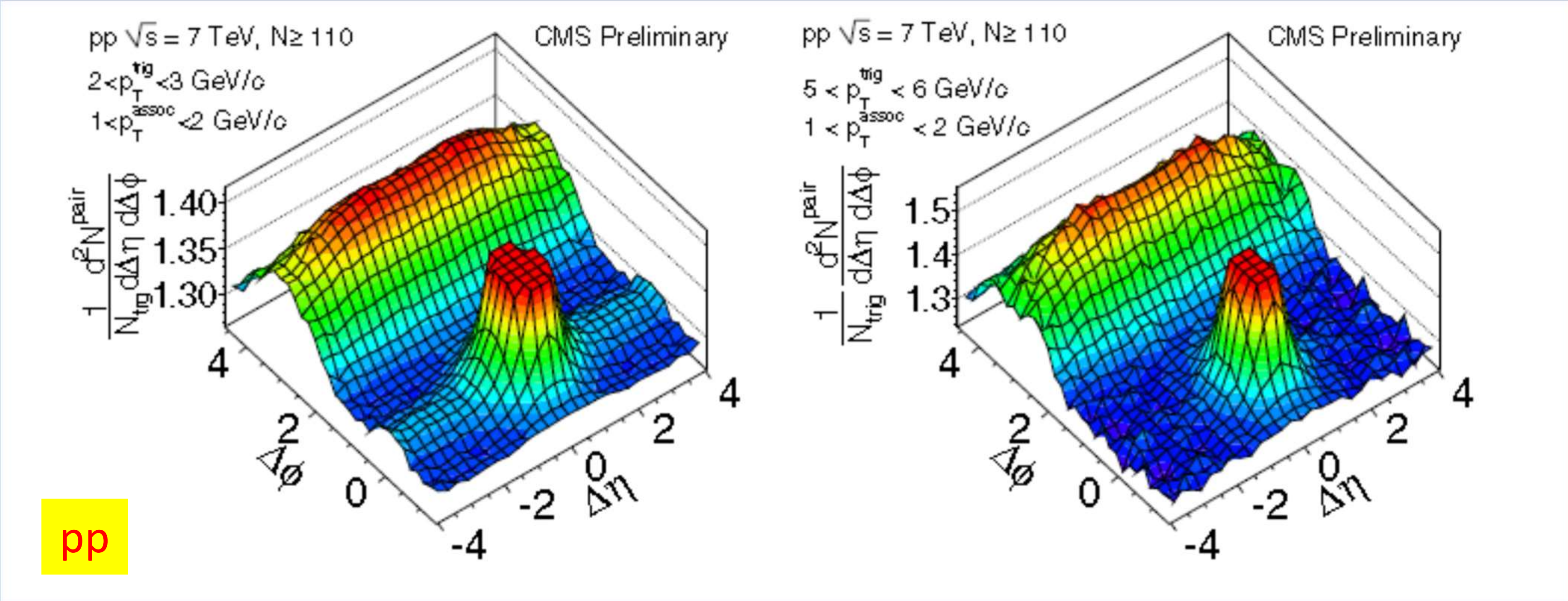
Significantly increasing trend of ϕ-meson ($s\bar{s}$) to pion ratio with increasing multiplicity

→ In contrast to expectation from simple strangeness canonical suppression: favors non-equilibrium production of either only the **ϕ** or of all strange particles (γ_s)

→ Pivotal role of the **ϕ**-meson in the understanding of strangeness production with thermal-statistical, core-corona, and MC models.

14

Collectivity in Small Systems

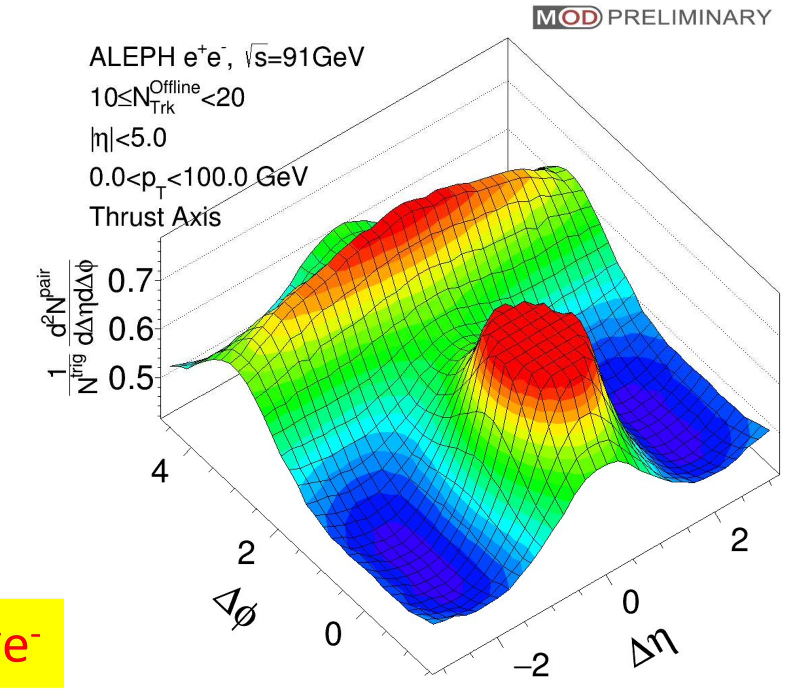


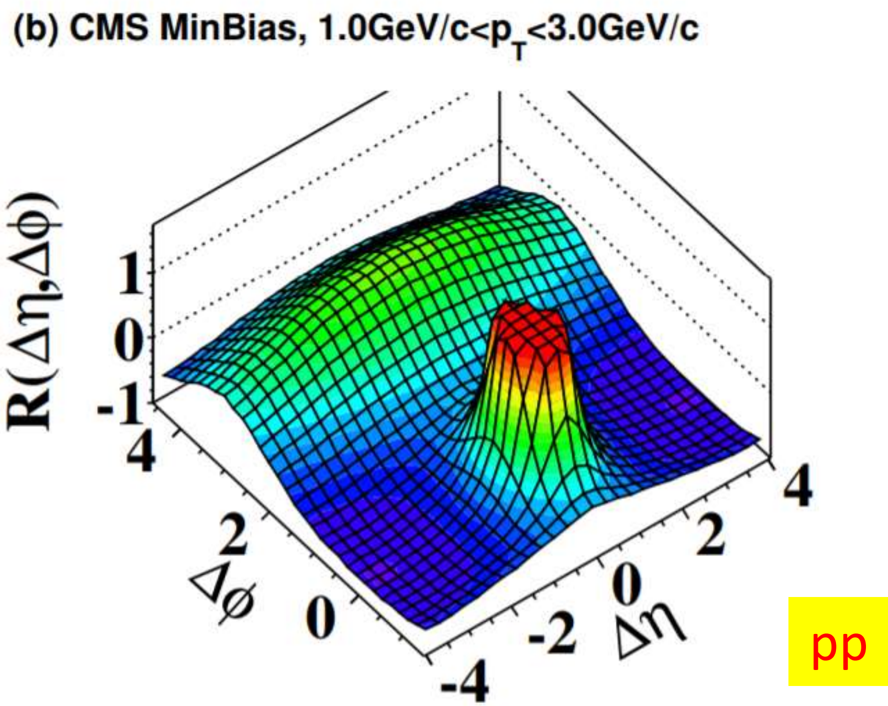
First indications of “anomalous behaviour=“ in high multiplicity pp came from CMS
who reported a ridge structure in η similar to what is observed in AA collisions in high multiplicity pp at 7 TeV

Correlation Function with Thrust Axis

ALEPH e^+e^-
10≤N<20 Thrust axis

CMS pp
Inclusive Beam axis



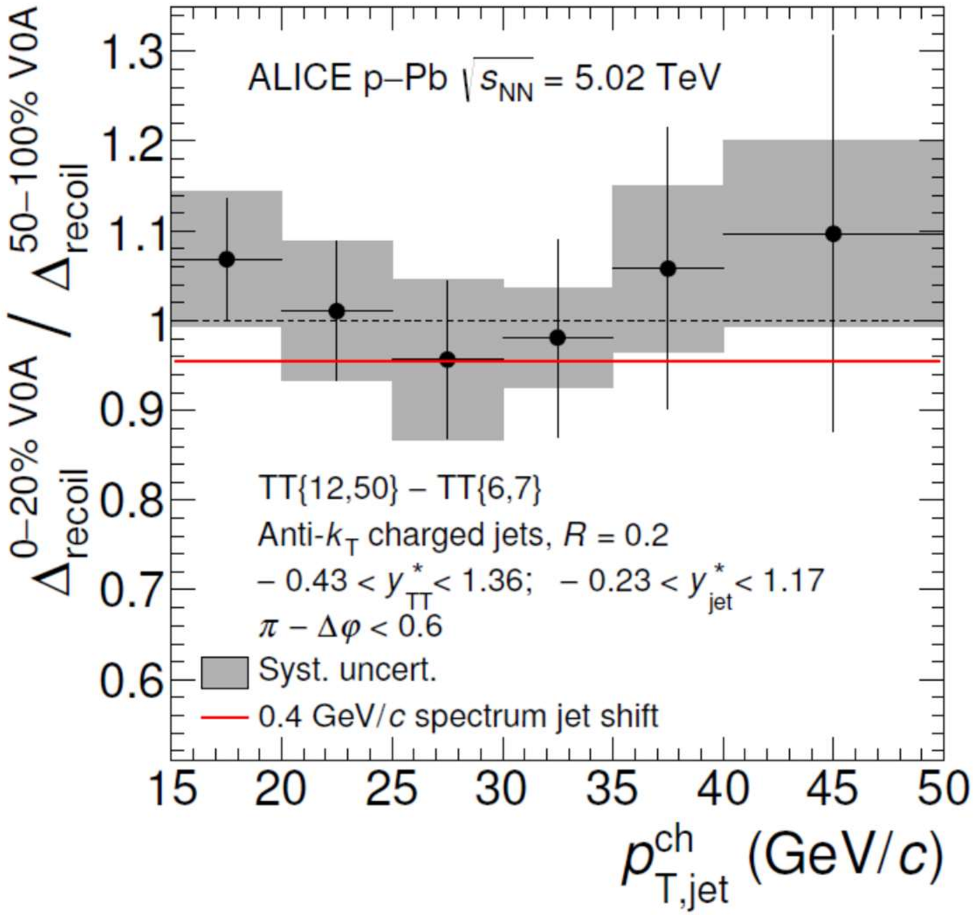


Correlation function with **Thrust Axis** as reference become much more similar to the beam axis result in pp collisions (with many caveats / differences)

UPDATE QM2018

No jet quenching in pPb

Constraints on jet-quenching in p-Pb collisions (2)



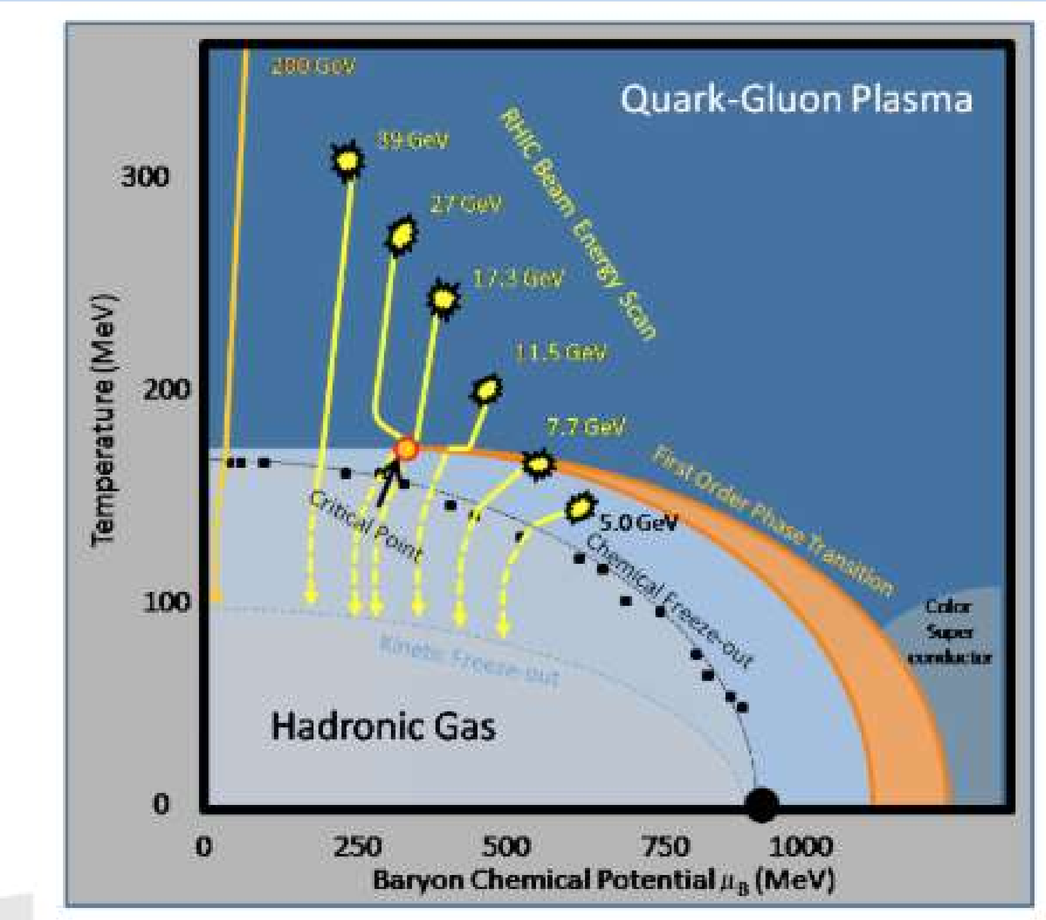
→ Jet-hadron correlations show no significant evolution from low to high multiplicity p-Pb collisions.

→ Jet quenching in p-Pb collision (if existing at all) is very small: out-of-cone energy transport due to jet quenching is less than 0.4 GeV/c.

[arXiv:1712.05603] R. Hosokawa, Wed 18:10

25

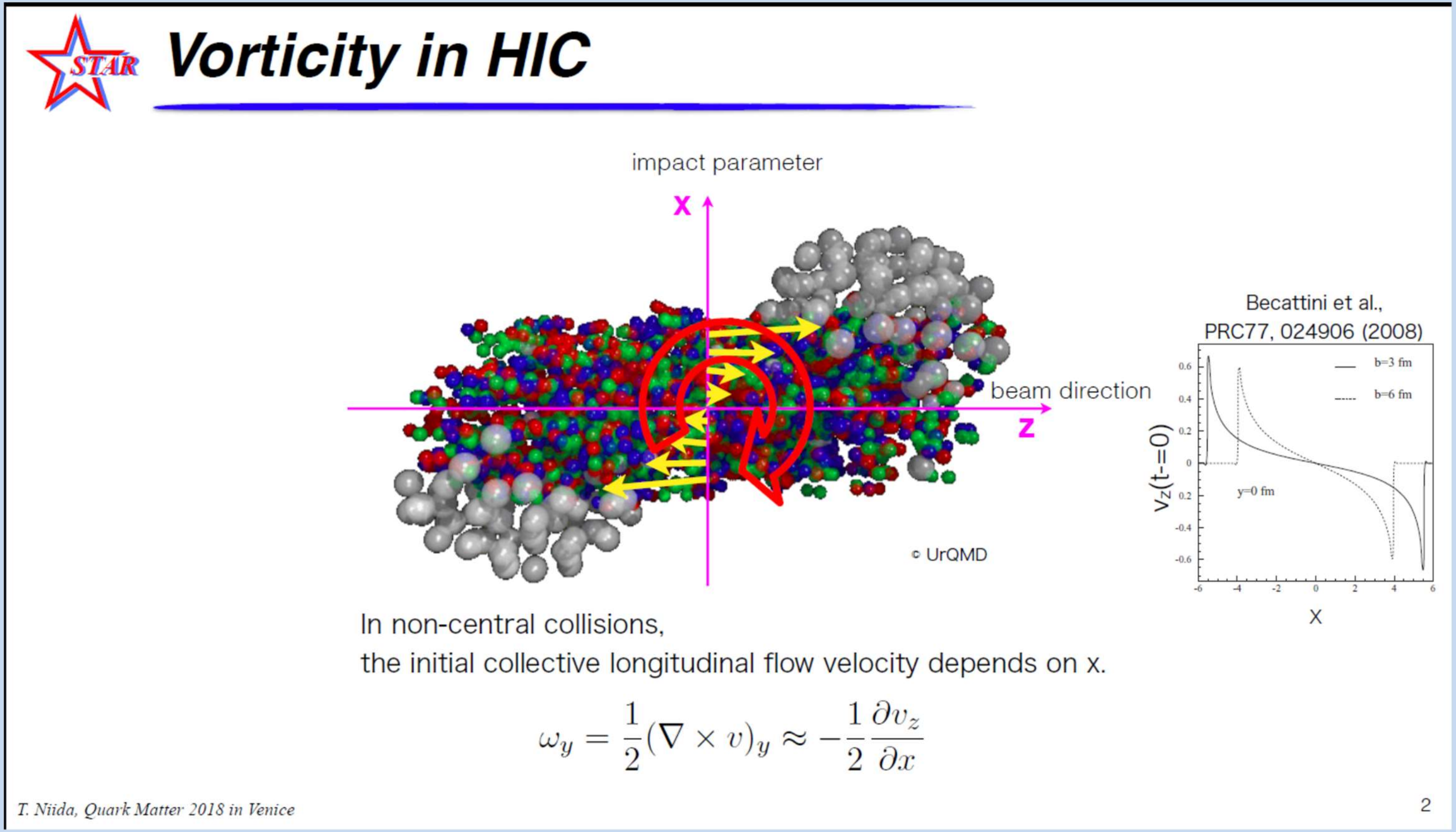
What else is going on?



- RHIC is focussing on large increase in statistics in a scan of lower energies, to try to find the onset of the QGP
- If energy low enough, this may be studied even better in very high luminosity collisions at FAIR (GSI) and at NICA (Dubna).
- Aim is to re-equip PHENIX with upgraded detectors to make new detector aimed at jets and electromagnetic probes at higher luminosity.
- Complementarity between two programmes.

Still many new results from RHIC at top energy

Global Λ polarization

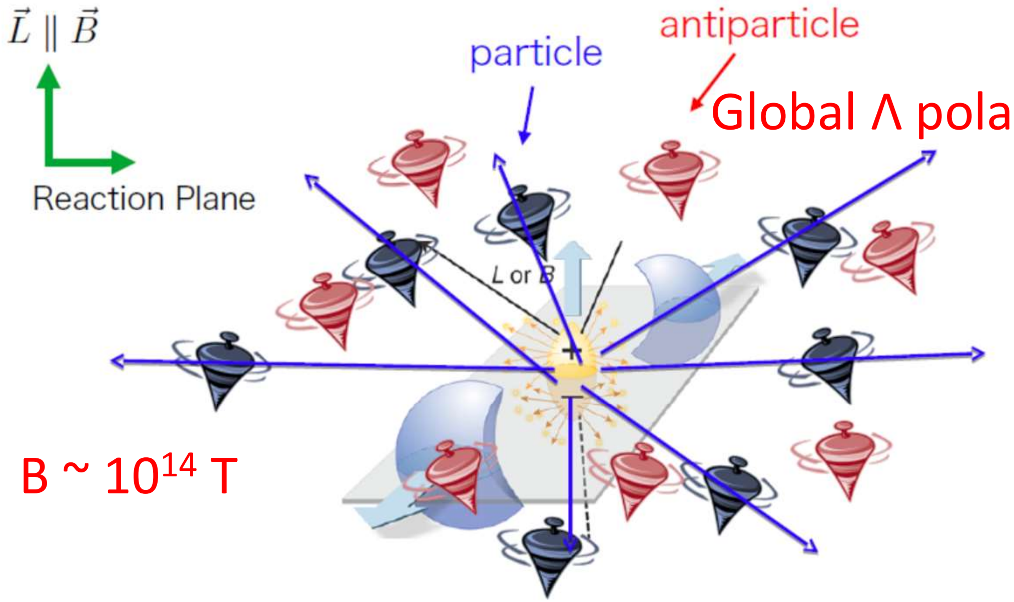


Global Λ polarization

Global polarization

★ Non-zero angular momentum transfers to the spin degrees of freedom

- Z.-T. Liang and X.-N. Wang, PRL94, 102301 (2005)
- S. Voloshin, nucl-th/0410089 (2004)



B ~ 10^{14} T

∗direction of ***B*** is the same as ***L***

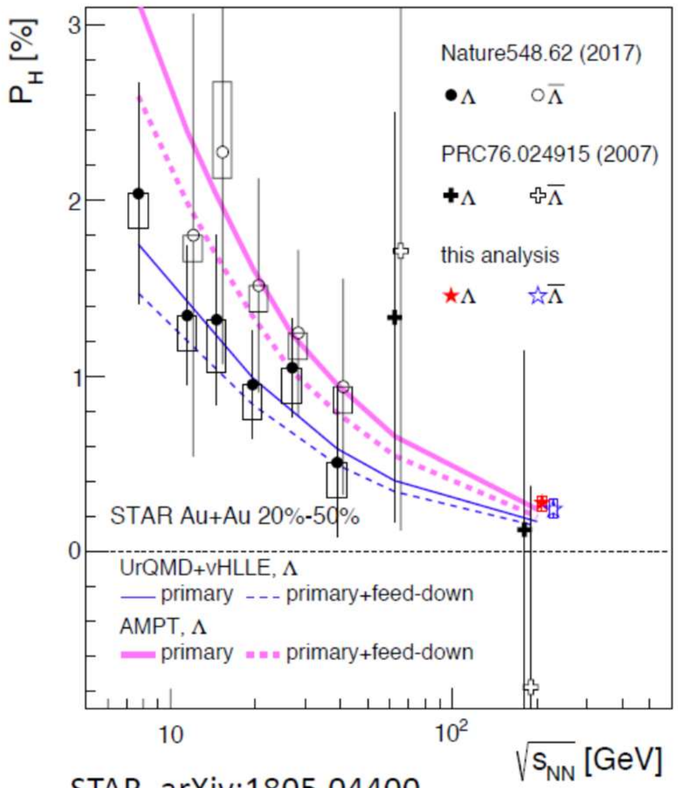
Global Λ polarizatio n

- Polarization due to spin-orbit coupling
  - Particle' and anti-particle's spins are aligned with angular momentum ***L***
- Spin alignment by B-field
  - Particle and antiparticle's spins are aligned oppositely along ***B*** due to the opposite sign of magnetic moment

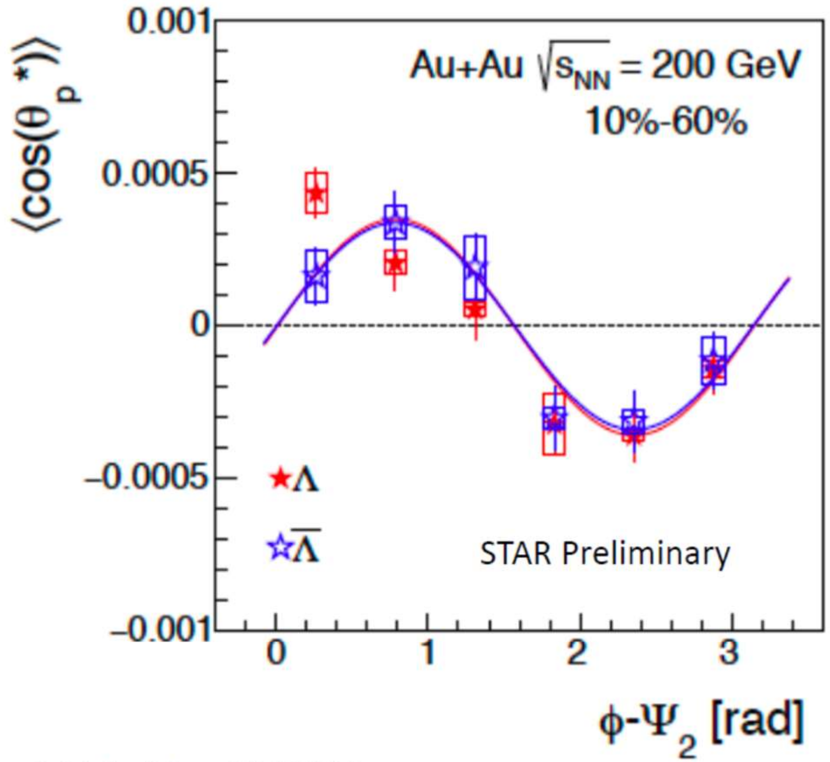
T. Niida, Quark Matter 2018 in Venice 3

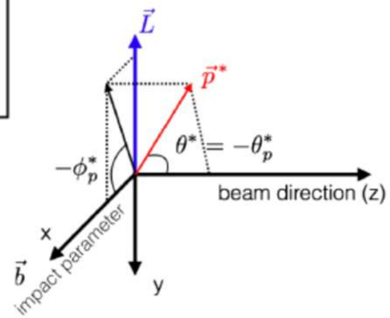
Global Λ polarization

Λ Global and Local Polarization in 200 GeV Au+Au Collisions



STAR, arXiv:1805.04400





S. Voloshin, sQM2017
F. Becattini and I. Karpenko, PRL120, 012302 (2018)

- First observation of Λ **global** polarization at 200 GeV
- First observation of quadrupole structure of Λ **local** polarization along beam direction

Takafumi Niida
#584, May 15, 9:00

FUTURE

Future running

	2010–2011 2.76 TeV 160 μb^{-1}	HL-LHC 5.5 TeV 10 nb^{-1}
Jet p_T reach (GeV/c)	~ 300	~ 1000
Dijet ($p_{T,1} > 120$ GeV/c)	$50k$	$\sim$ 10M
b-jet ($p_T > 120$ GeV/c)	~ 500	$\sim$ 140k
Isolated γ ($p_T^{\gamma} > 60$ GeV/c)	$\sim$ 1.5k	$\sim$ 300k
Isolated γ ($p_T^{\gamma} > 120$ GeV/c)	–	$\sim$ 10k
W ($p_T^{W} > 50$ GeV/c)	~ 350	$\sim$ 70k
Z ($p_T^{Z} > 50$ GeV/c)	~ 35	$\sim$ 7k

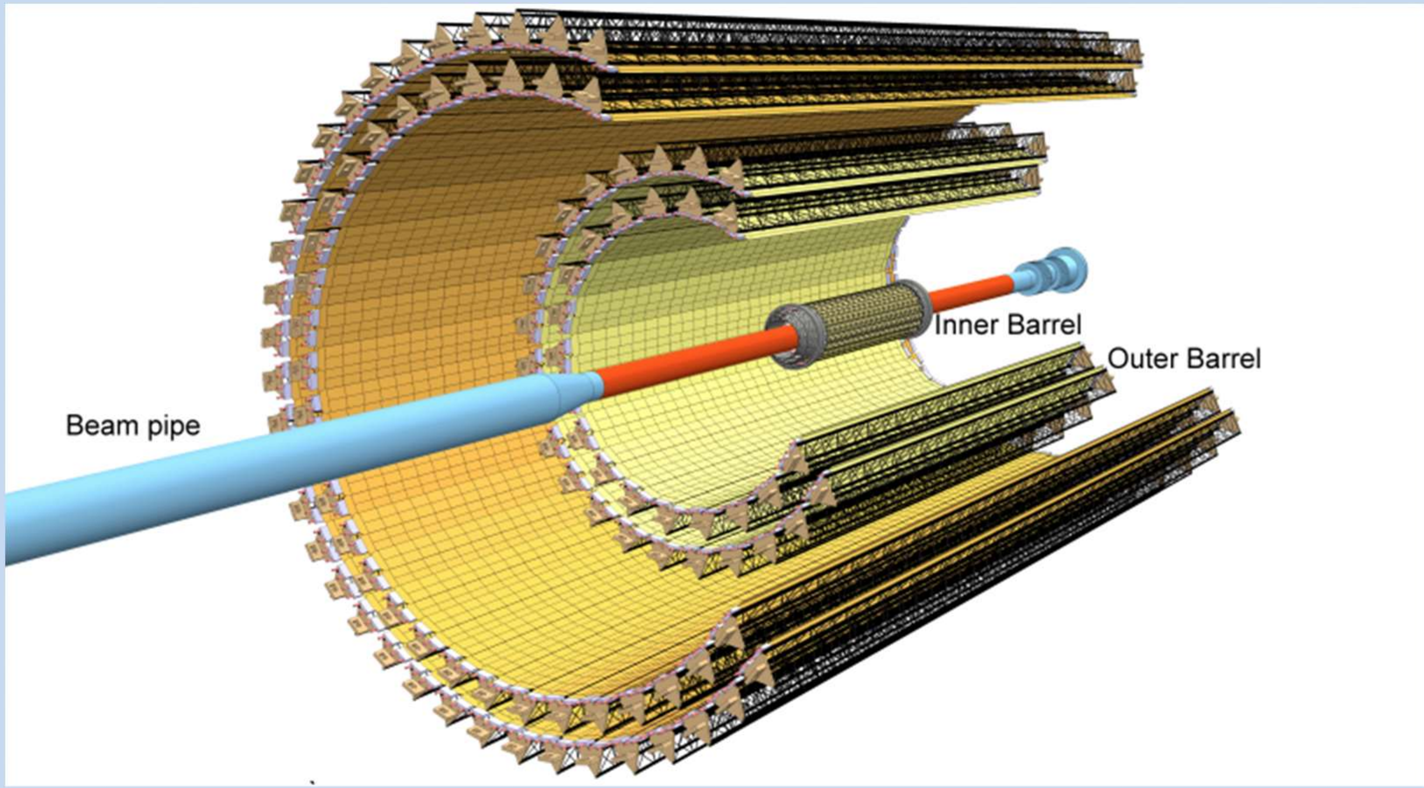
CMS

- Data taking in Runs 2 and 3 will make a huge improvement in statistics, allowing detailed studies of processes currently barely detectable.
- ATLAS and CMS will focus on high p_T studies, covering both jets and heavy flavour production
- ALICE will focus on lower p_T jets and heavy flavour, while continuing detailed studies of soft variables.

ALICE upgrade

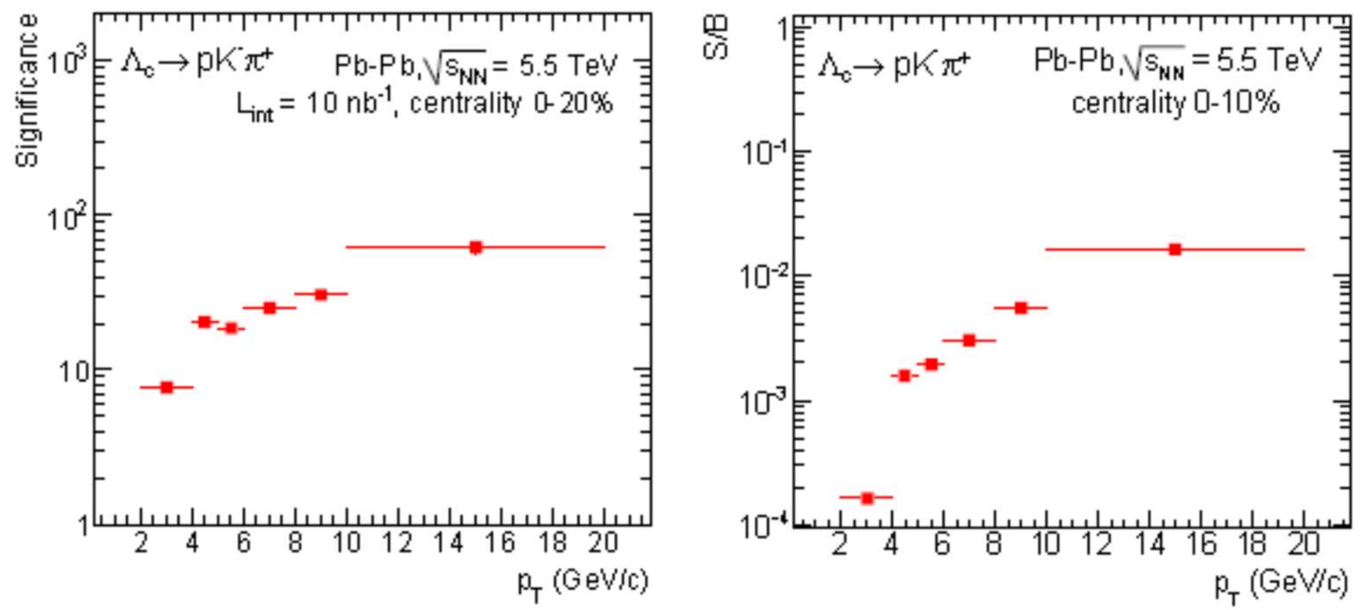
- ALICE will undergo a substantial upgrade during LS2, so as to be ready for new higher luminosity ion-ion running in run 3
  - New TPC readout, using GEM technology
  - New 7 layer ITS (instead of current 6 layer) using monolithic ALPIDE pixels.
    - Higher allowed occupancy and increased precision
  - New muon chamber readout, new muon detector before muon absorber to improve tracking
  - New forward detectors
  - Redesign of DAQ and trigger to allow *continuous readout* of principal detectors. Events will be picked out of the datastream by the reconstruction program.

New ALICE ITS



- The ALICE inner tracker (ITS) will be completely rebuilt with a new all-pixel tracker, using monolithic pixels (ALPIDE).
- The inner layer is significantly closer to the beam line, giving improved vertexing precision for heavy flavour decays.

New ALICE ITS



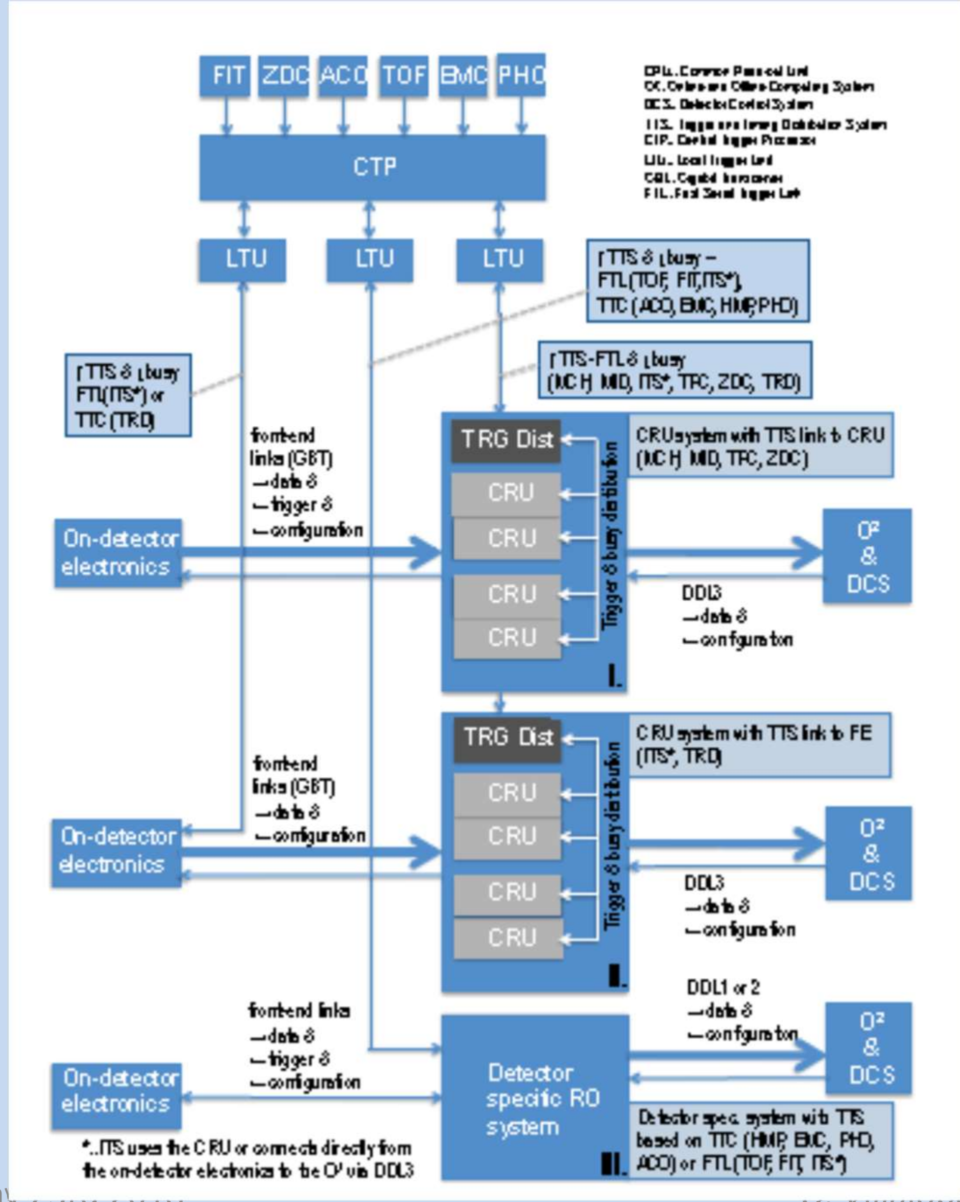
Benchmark $\Lambda_C \to pK\pi$. Barely accessible with current ITS.

- The ALICE inner tracker (ITS) will be completely rebuilt with a new all-pixel tracker, using monolithic pixels (ALPIDE).
- The inner layer is significantly closer to the beam line, giving improved vertexing precision for heavy flavour decays.

New TPC

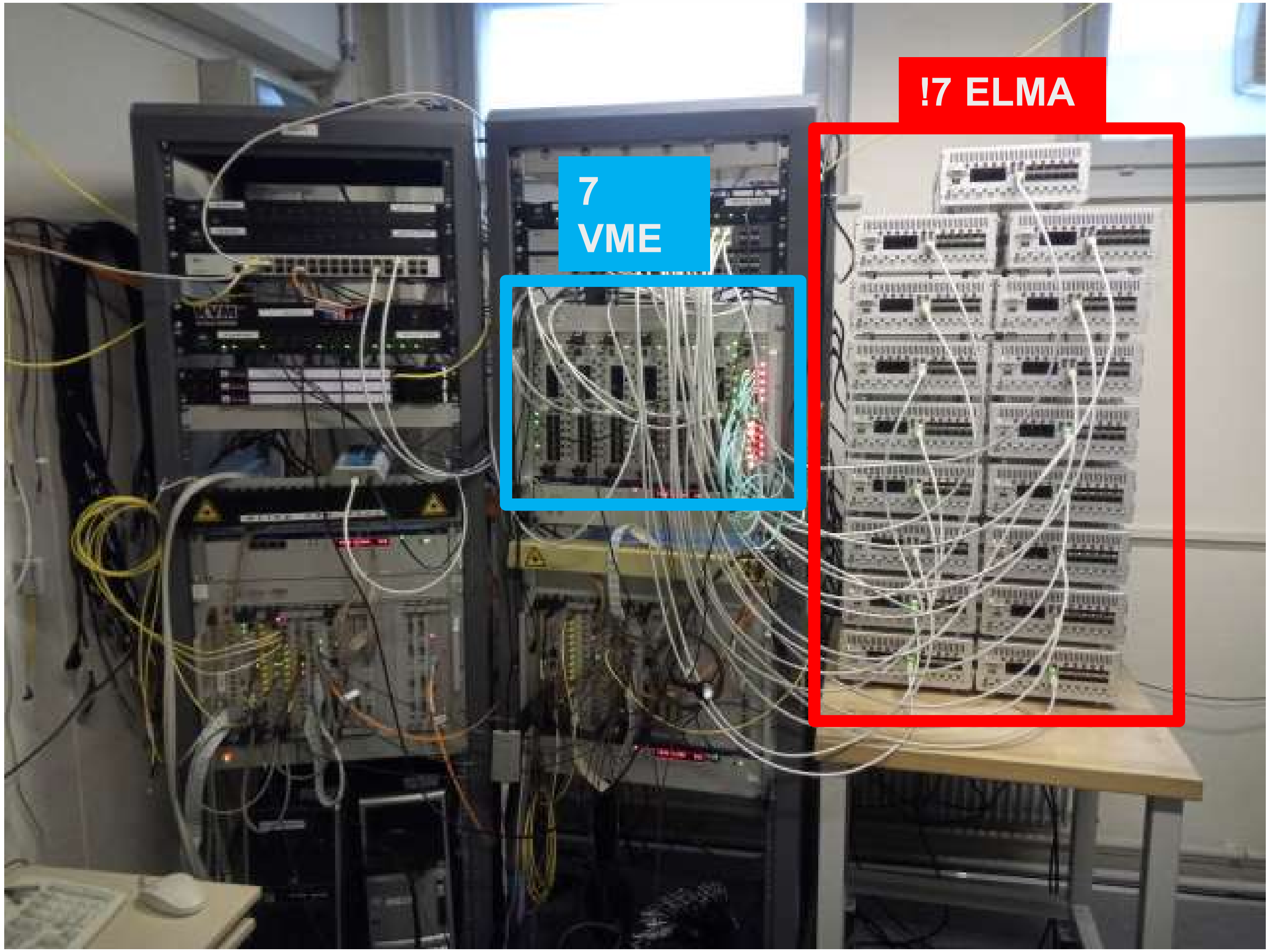
- The ALICE TPC will have new readout modules, using GEM technology, so as to allow continuous readout without substantial space-charge buildup
- Production underway. Tests scheduled later in year.

Trigger and DAQ



- Not all detectors will upgrade, so new system will be hybrid.
- Continuous readout detectors will have readout split into "frames", separated by a *heartbeat* trigger
- Triggering detectors identify bunch crossings in which collisions occur
- Potential for substantial use of HLT in event filtering

CTP/LTU board tests in B'ham CTP lab at CERN



Upgrade Summary

- Upgrades will allow far more detailed studies than currently possible of the properties of a QGP
- Focus on improving hard probes, currently still very much limited by statistics.
- Also great interest in “small systems”. High multiplicity collisions in pp very interesting.

Summary

- Ultrarelativistic Heavy ion collisions have come a very long way over the last 30 years.
- Focus has changed from establishing whether a QGP might exist to a detailed study of its properties.
- Choice of signatures available to address different stages in the collision
  - Tie down nuclear pdfs (e.g. UPC)
  - Understand hydrodynamic properties of QGP (flow)
  - Interaction of energetic partons with medium (jets)
    - *(Heavy flavour also addresses these points)*
  - Hadronization (light flavour production)
- Ambitious program going on complementary to LHC in other parts of the world (RHIC, FAIR, NICA, ….)

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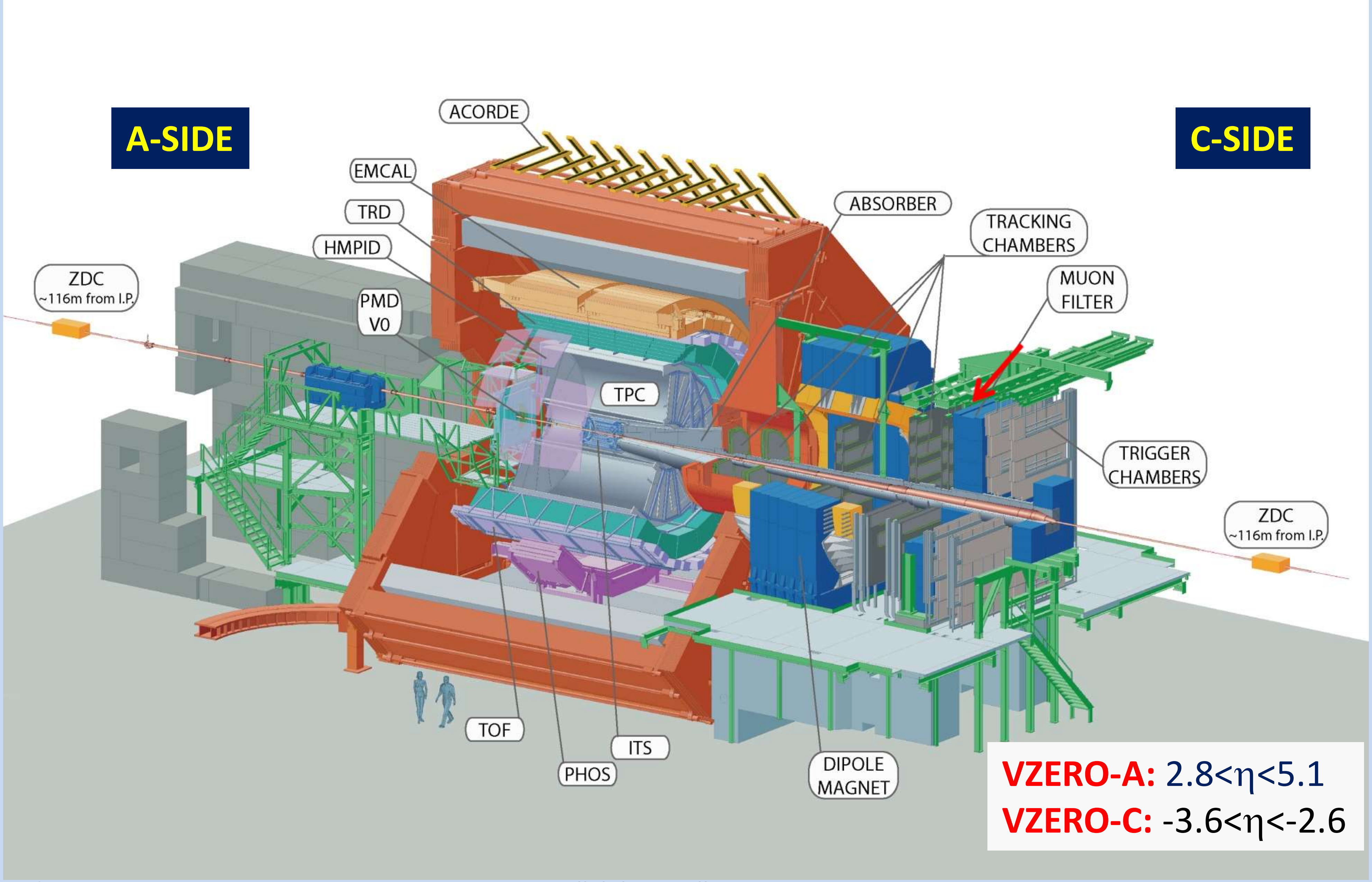
Summary

- "Small systems", e.g. pp and p-Pb, were originally supposed to provide control samples, where collective effects would not be present.
- Surprise that since early on in the LHC, it has been seen that small systems display collective behaviour.
  - Azimuthal Flow ✓
  - Longitudinal Flow ✓
  - Strangeness Enhancement ✓
  - Jet Quenching ✗
- Very important to understand these systems

BACKUP

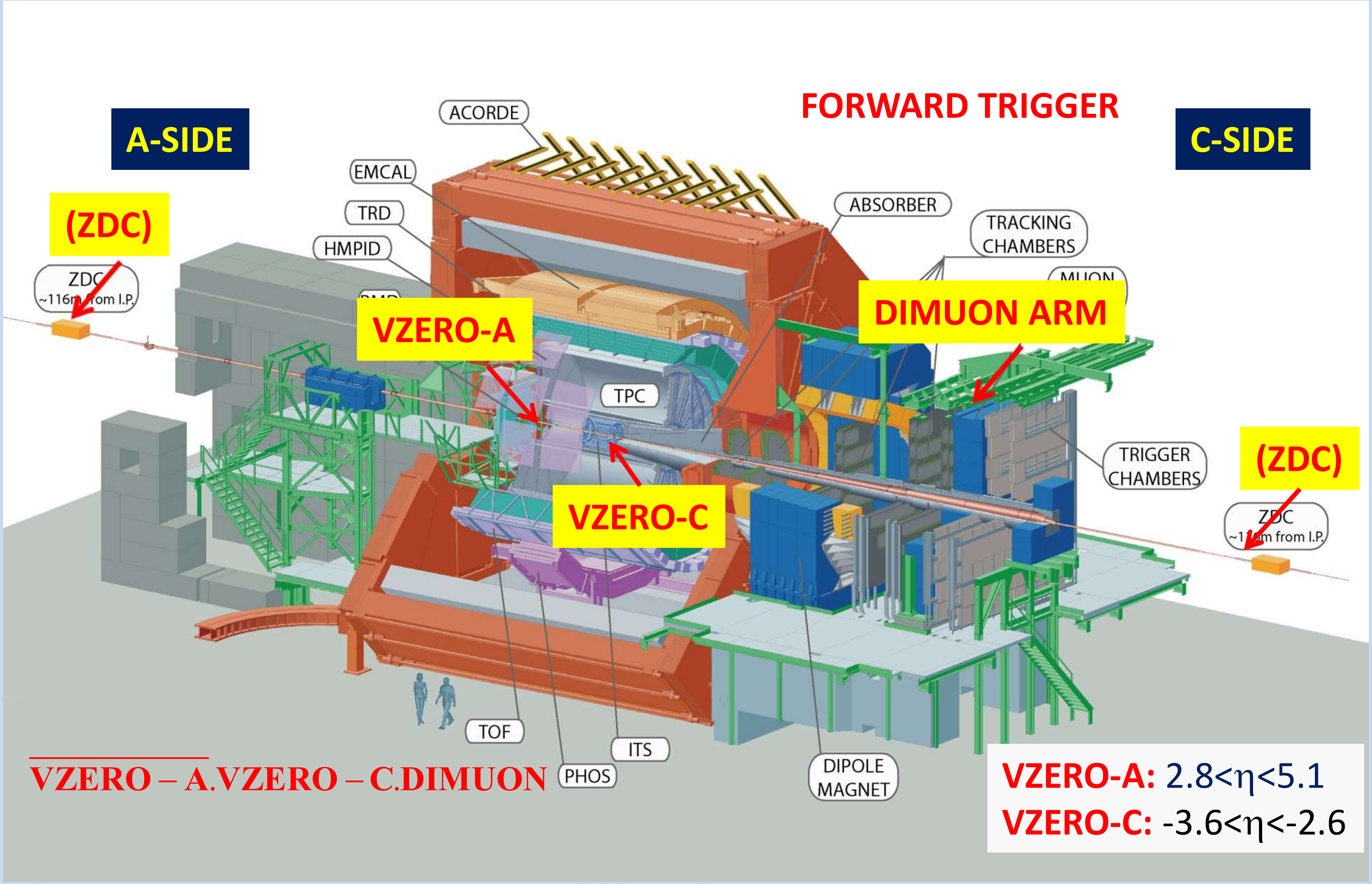
ALICE Apparatus



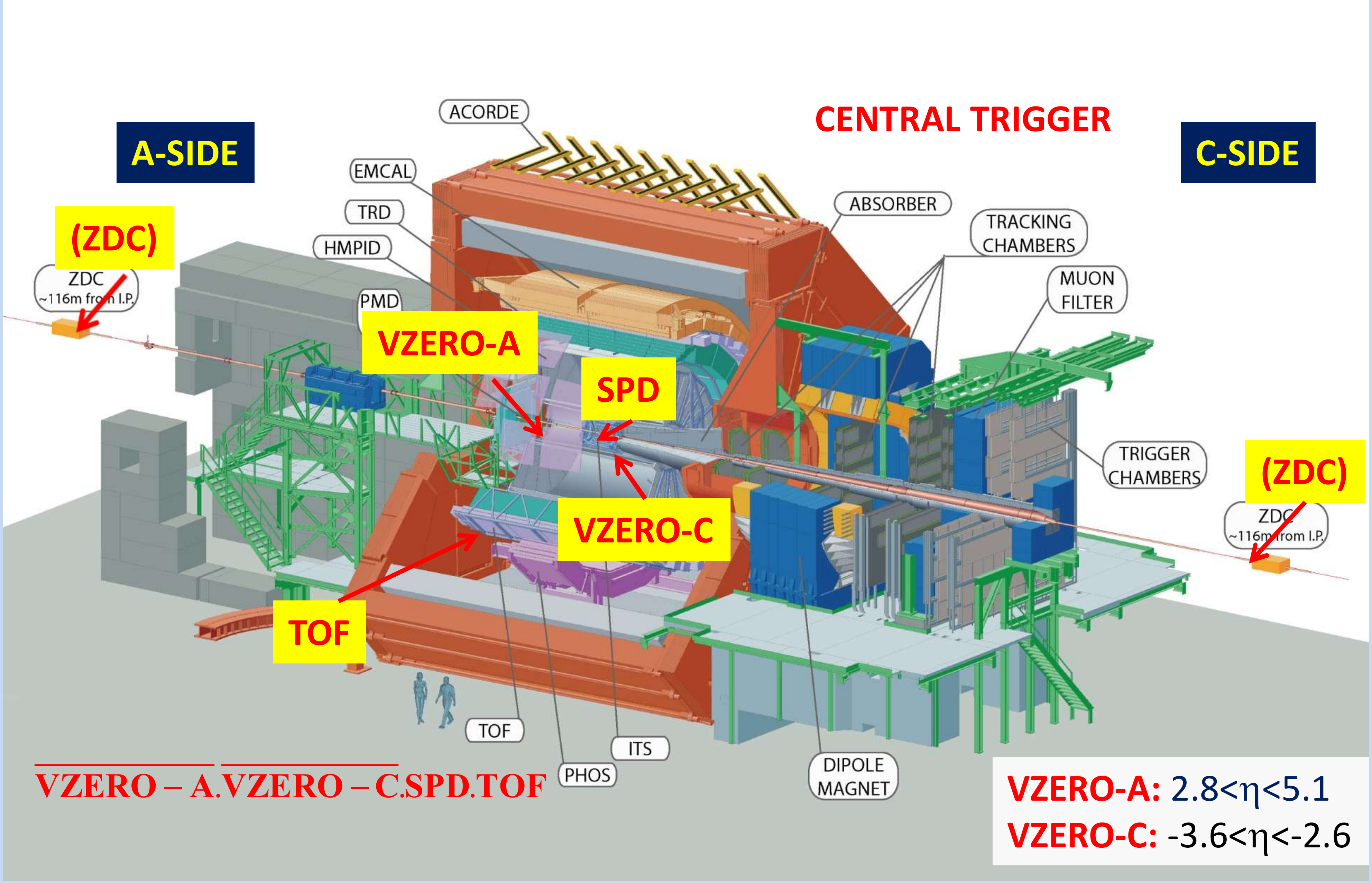
VZERO-A: $2.8<\eta<5.1$

VZERO-C: $-3.6<\eta<-2.6$

ALICE Apparatus



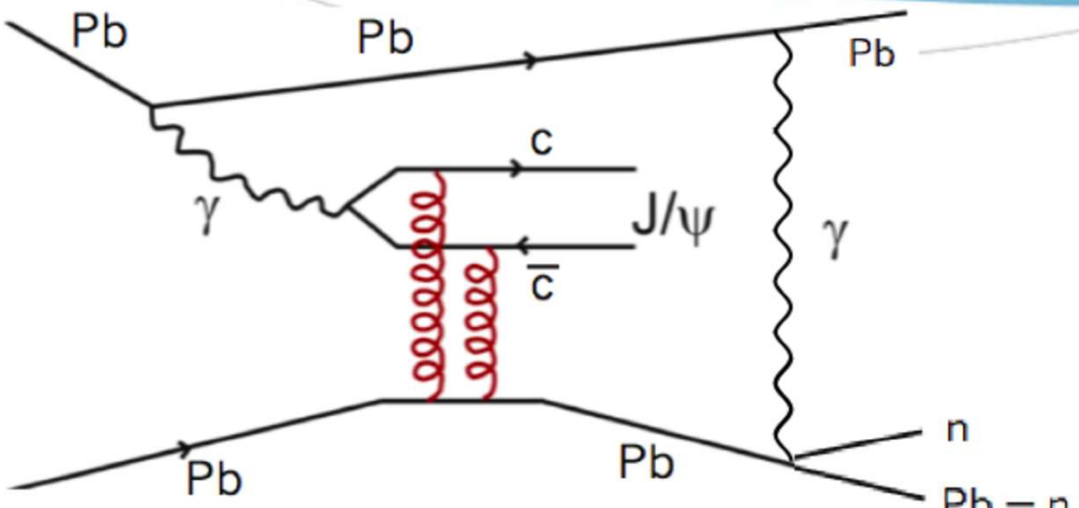
ALICE Apparatus

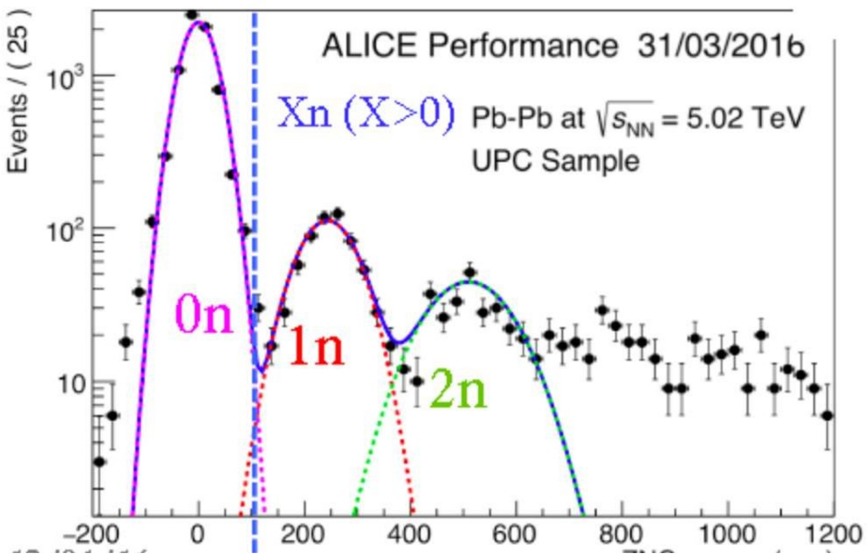


BACK UP

Forward neutron production

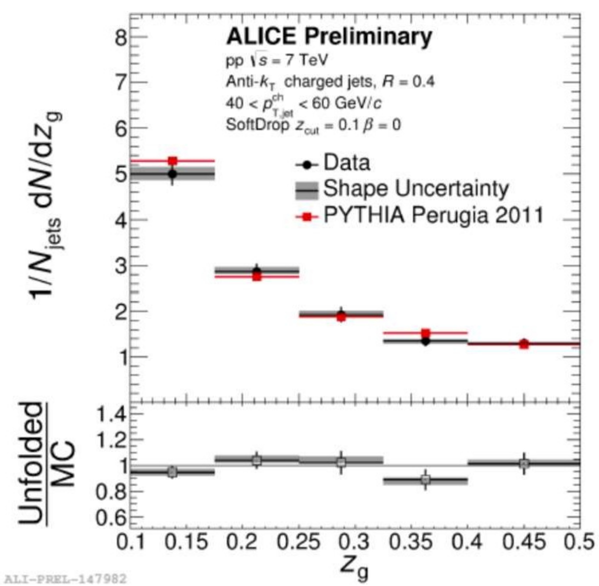
Separation of low-x and high-x components

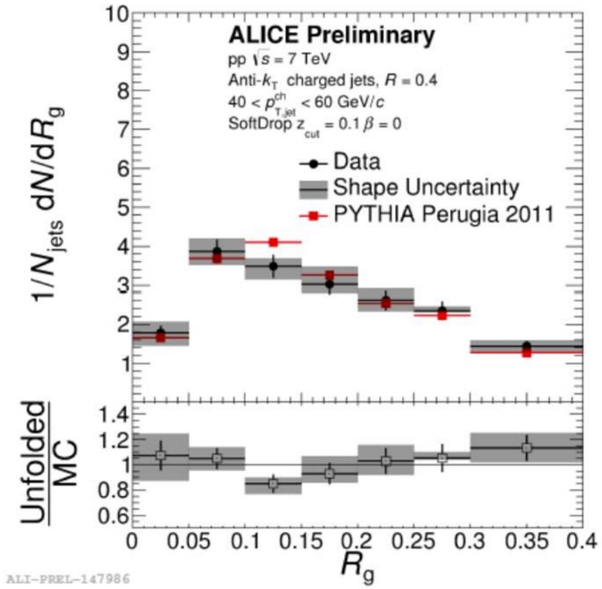


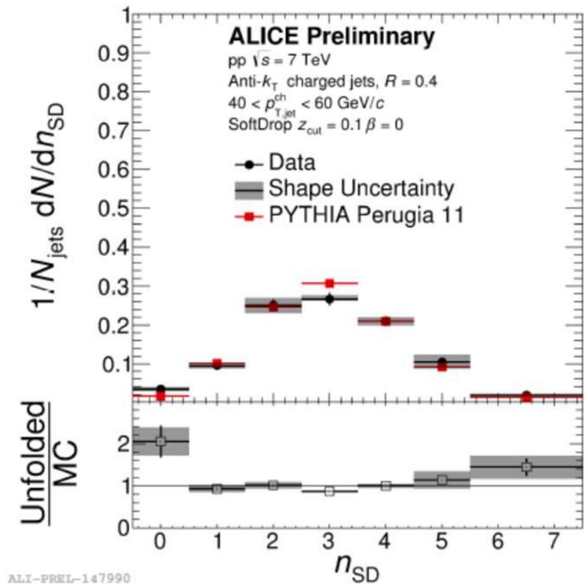


- Separately from the coherent J/ ψ production, the nuclei can photodissociate resulting in neutron emission
- Using the ZDCs we can separate events with 0n0n, 0nXn and XnXn
- These three categories have different proportions of low-x and high-x production, from which the two components can be separated
- See Baltz, Klein & Nystrand, PRL **89** (2002) 012301; Guzey, Kryshen & Zhalov, arXiv:1602.01456 (2016) for more detailed explanations

pp Substructure Results





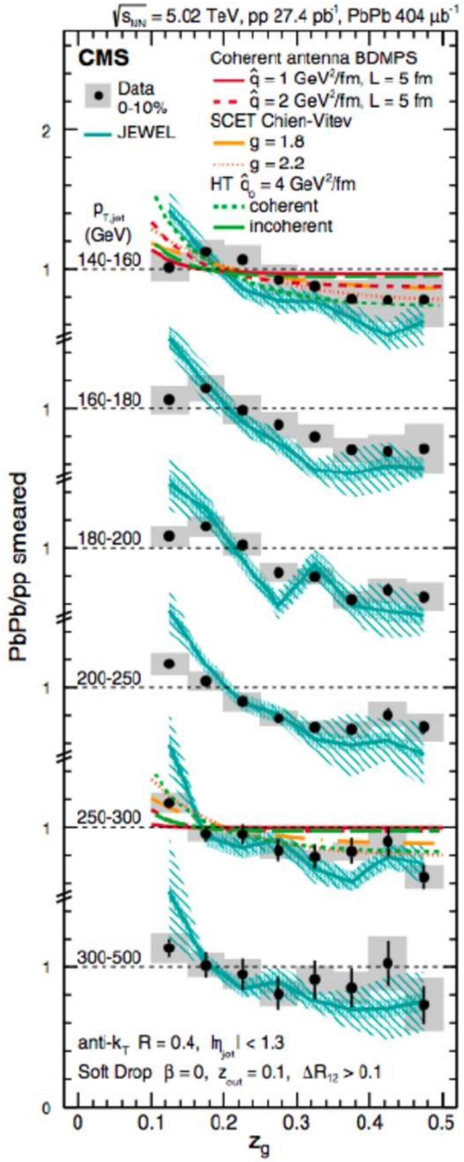


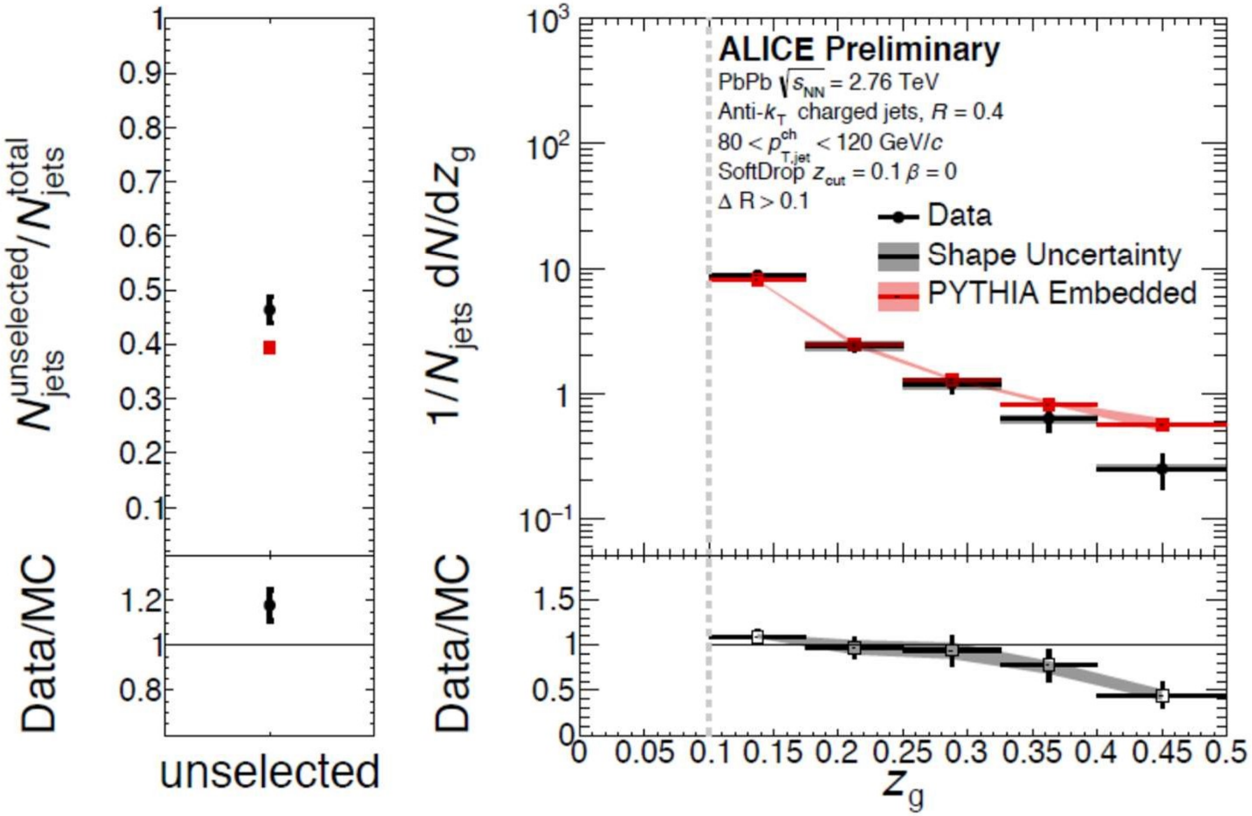
- Jets satisfying $z > z_{cut} = 0.1$:
  1. Data 97.3(0.5)%
  2. PYTHIA 98.9(0.1)%
- Good agreement observed between data and PYTHIA Perugia 2011

7 TeV pp

pp and PYTHIA agree at 7 TeV. Therefore it is reasonable to use PYTHIA to describe pp expectation at 5.02 TeV, where results from data are not yet available.

Comparison to CMS with same normalisation





❖ Normalsing by the population selected by Soft Drop and cut on ΔR

A. M. Sirunyan *et al.*
Phys. Rev. Lett. **120**, 142302

Harry Andrews