Recent Results from ALICE

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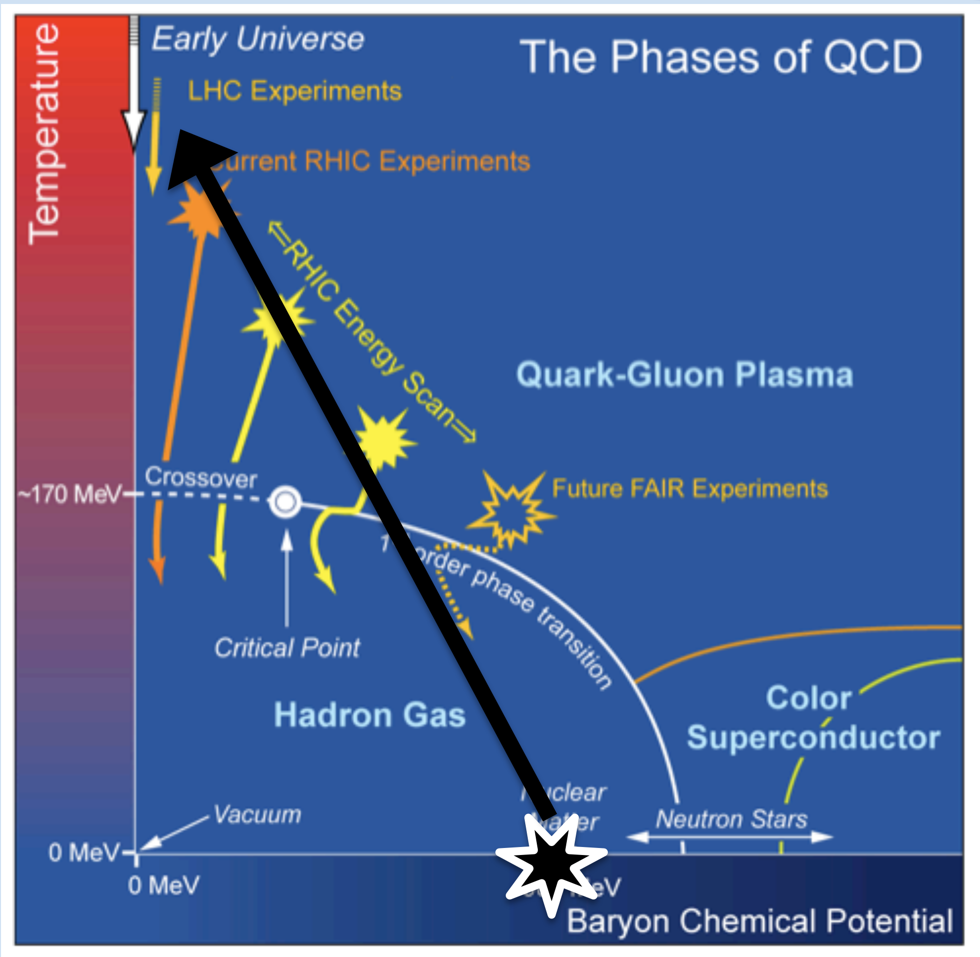
For the ALICE Collaboration
SLAC Summer Institute
August 15, 2016

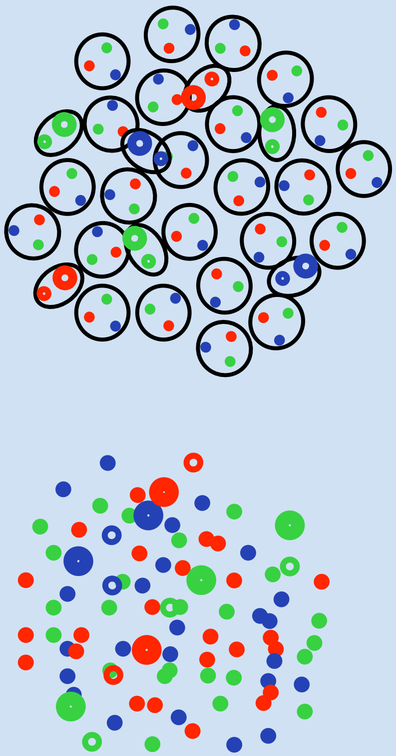
Outline

- Heavy ion / QGP Primer
- The ALICE Detector
- Recent Results
  - Various collision systems and energies
    - pp, p-Pb, Pb-Pb
    - 2.76 TeV, 5.02 TeV, 7 TeV and 13 TeV
  - Bulk Observables
    - Multiplicity, Flow
  - Hard Probes
    - Jets, Heavy Flavor
- ALICE Upgrades

Quark Gluon Plasma

Nuclear Matter under extreme conditions





Normal nuclear matter (confined)

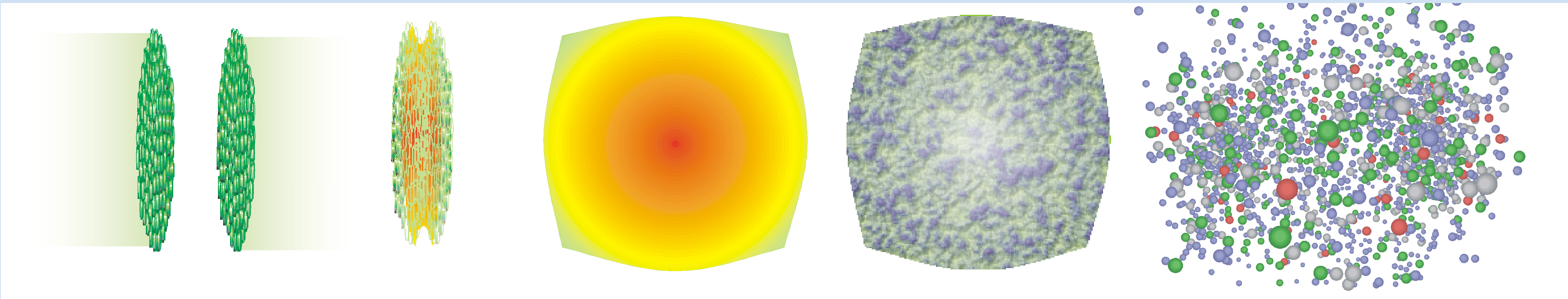
QGP (deconfined)

170 MeV ➔ $2 \cdot 10^{12}$K 100,000 times hotter than the sun's core!

Evolution of the Collision

Initial State

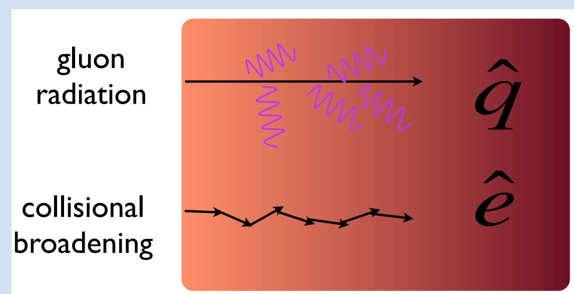
Hadronization



Incoming Nuclei

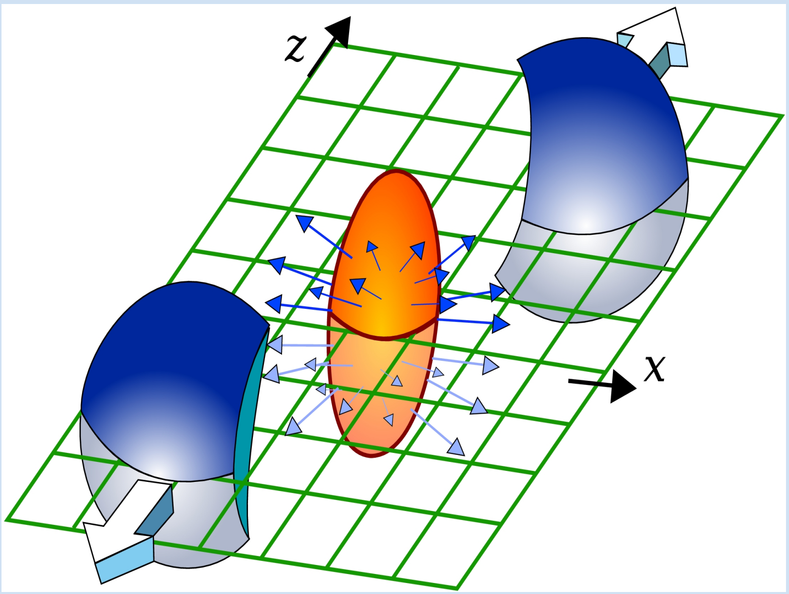
QGP
Hydrodynamic expansion

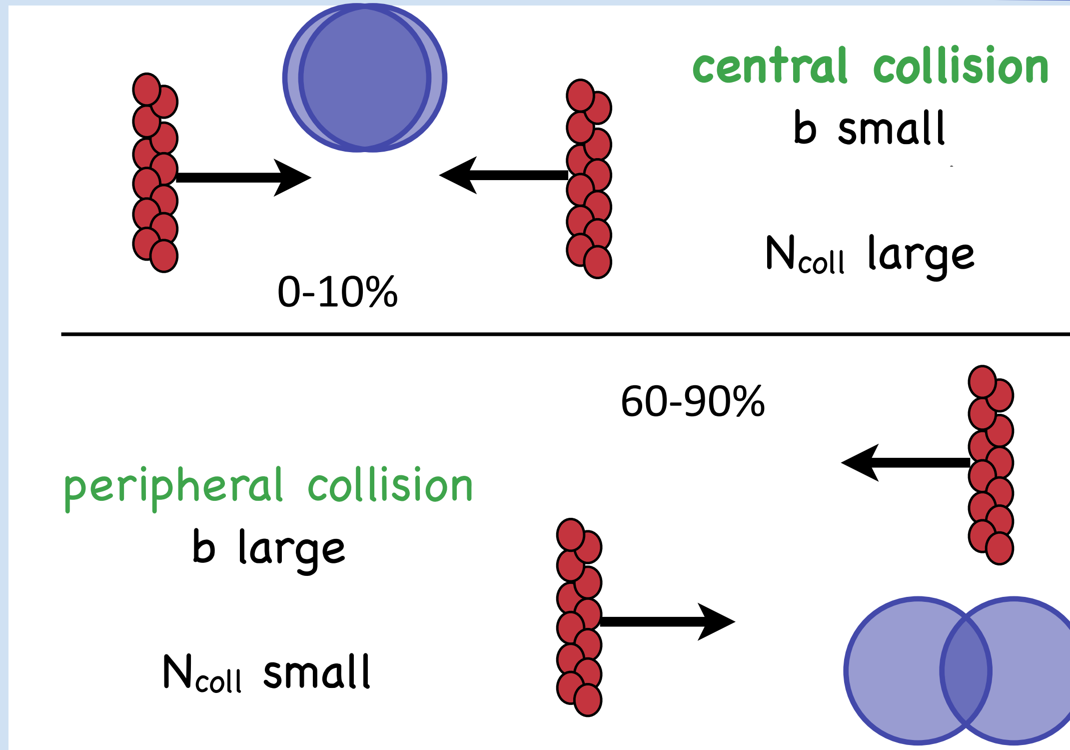
Freeze-out



- 2 classes of observables
  - Hard probes (jets, high p_T hadrons, heavy flavor)
  - Bulk measurements (multiplicity, elliptic flow)

Event Categorization

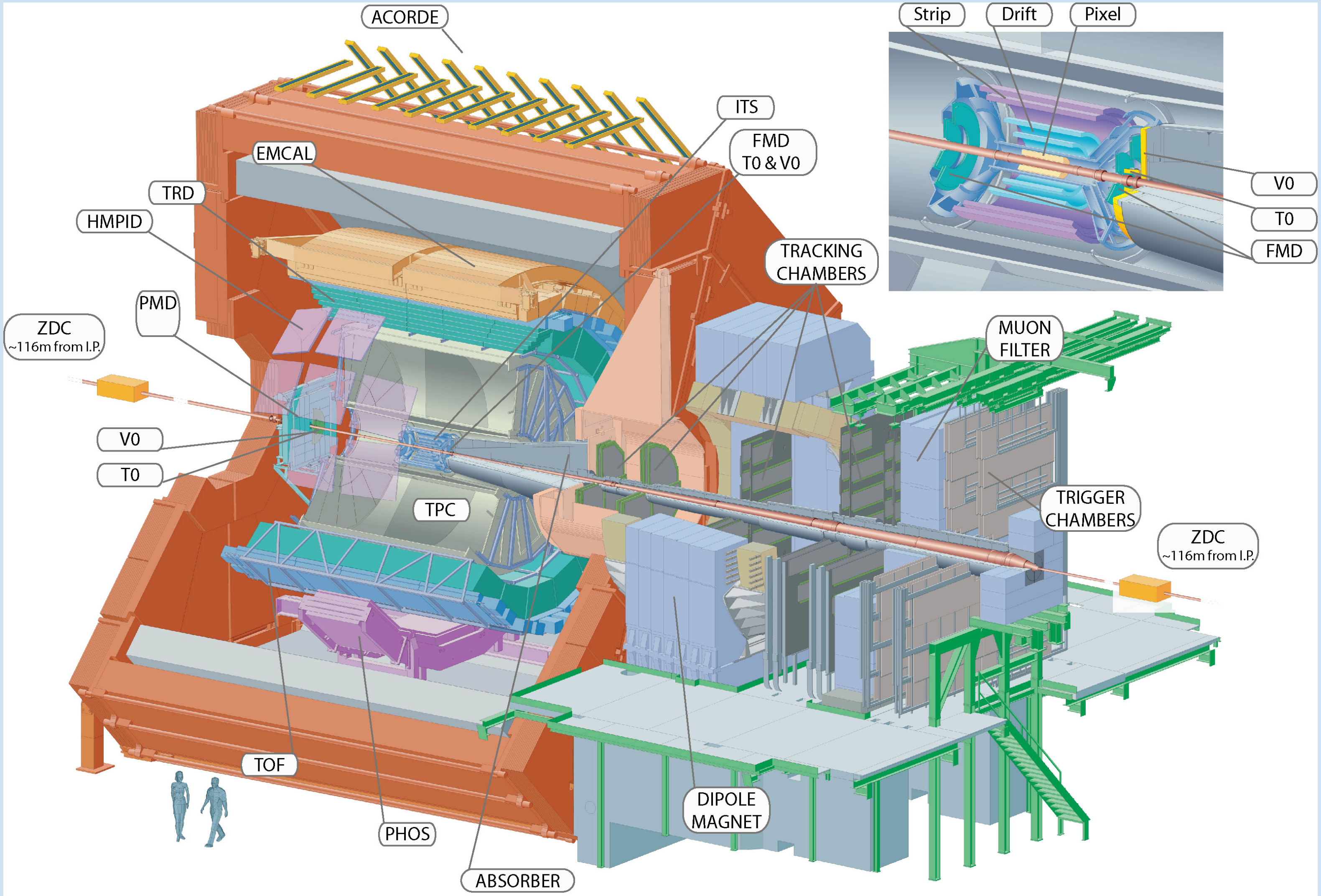




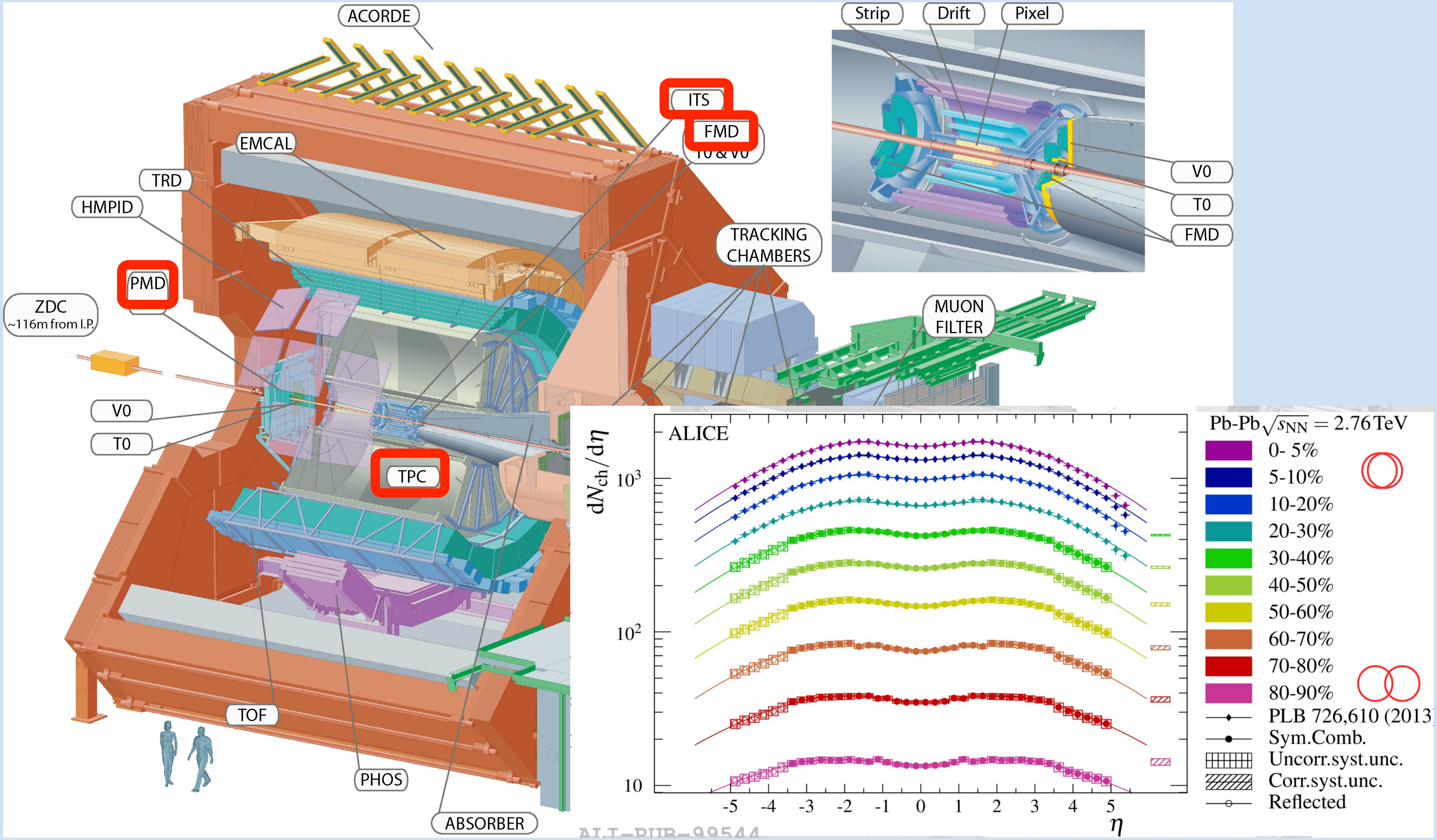
- Centrality relates to impact parameter (b) or amount of overlap
- % refers to total cross-section

- Multiplicity increases with centrality
- N_{coll} = number of binary collisions

The ALICE Detector

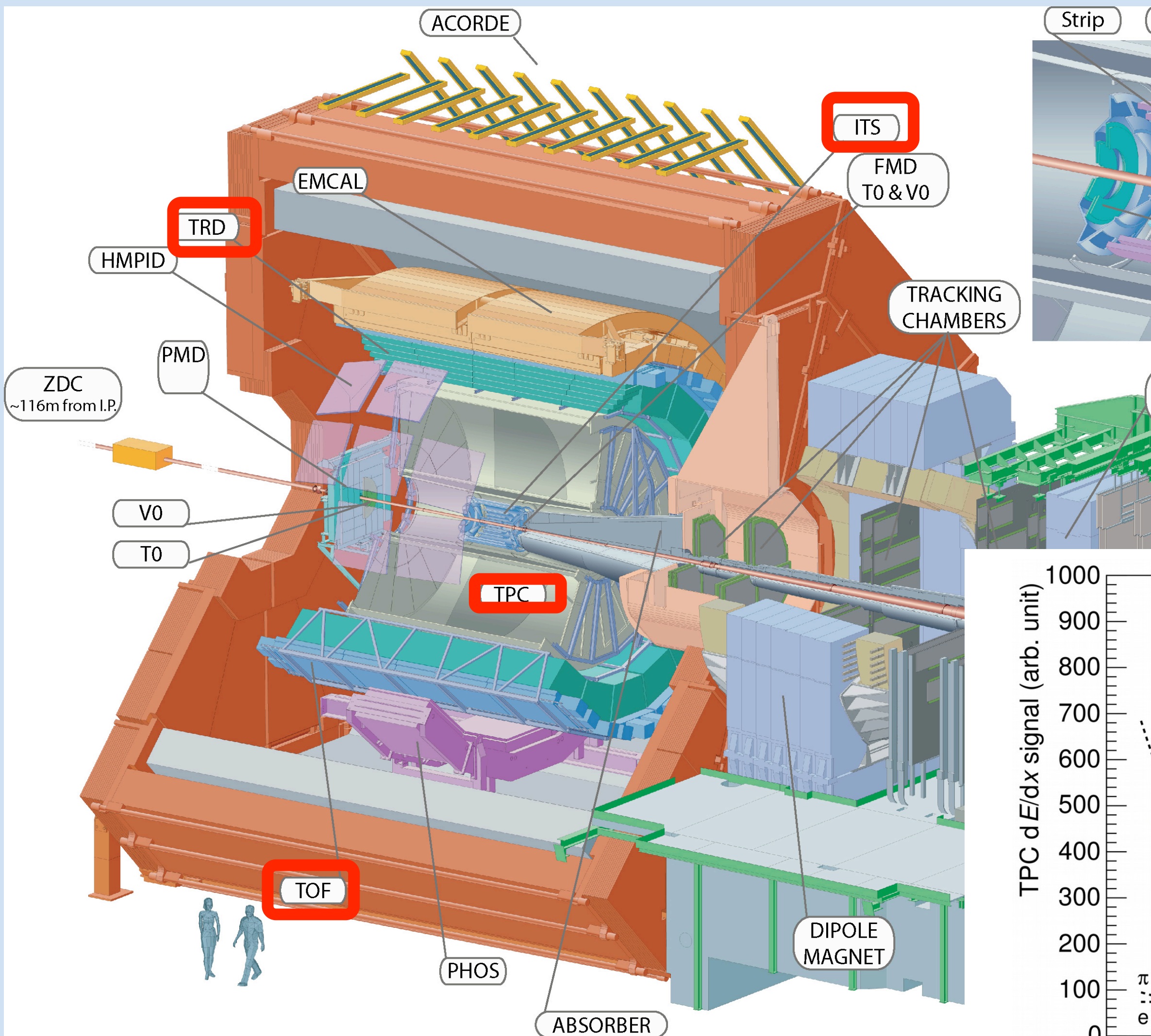


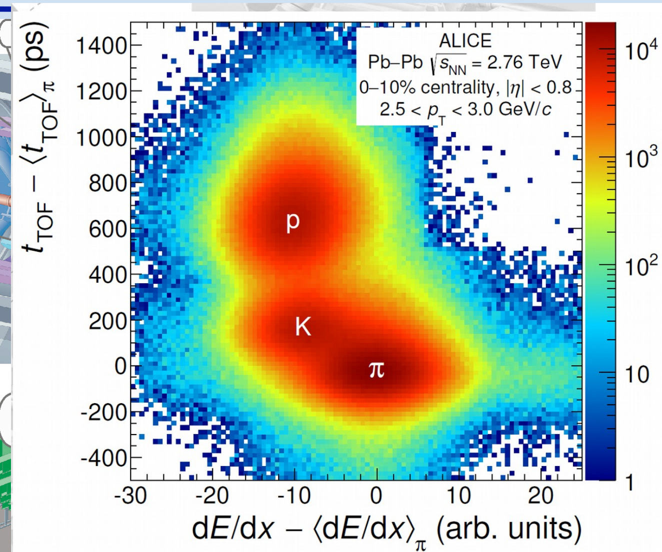
Tracking



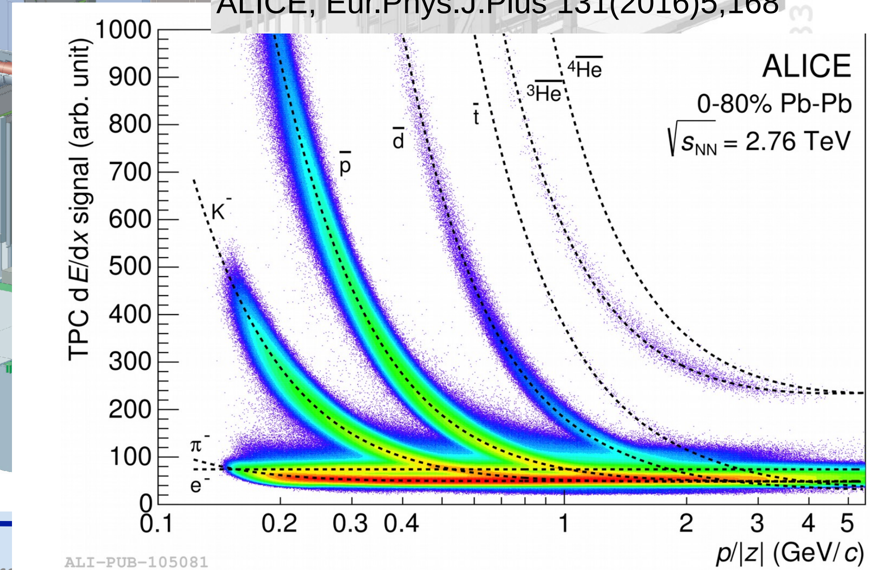
ACORDE
ITS
FMD
T0 & V0
EMCAL
TRD
HMPID
PMD
ZDC
~116m from I.P.
V0
T0
TPC
TOF
PHOS
ABSORBER
TRACKING CHAMBERS
MUON FILTER
Strip
Drift
Pixel
V0
T0
FMD
ALICE
$dN_{ch}/d\eta$
10^3
10^2
10
-5 -4 -3 -2 -1 0 1 2 3 4 5
η
Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV
0- 5%
5-10%
10-20%
20-30%
30-40%
40-50%
50-60%
60-70%
70-80%
80-90%
PLB 726,610 (2013)
Sym.Comb.
Uncorr.syst.unc.
Corr.syst.unc.
Reflected
ALI-PUB-99544

Particle Identification



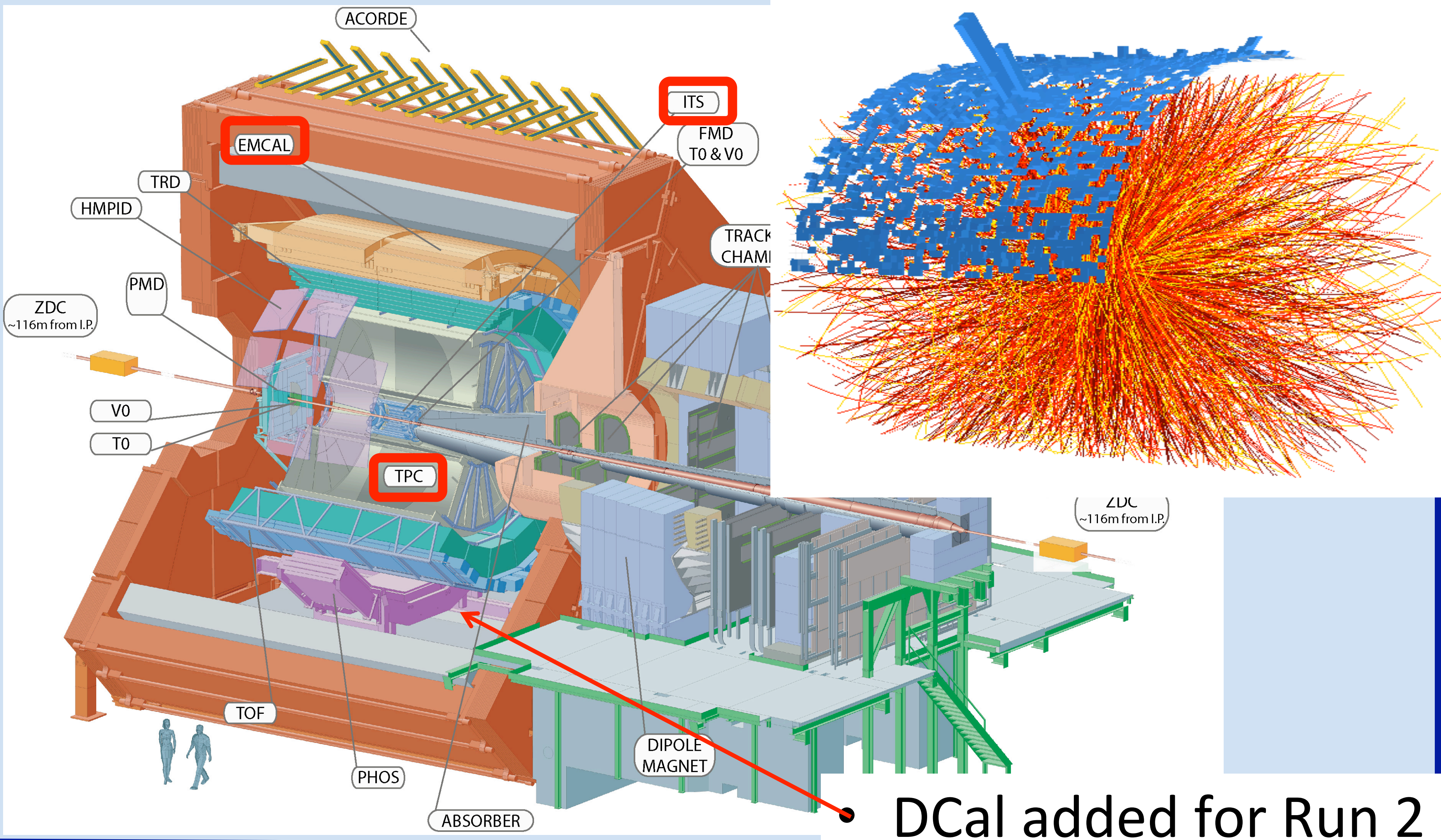


ALICE, Eur.Phys.J.Plus 131(2016)5,168



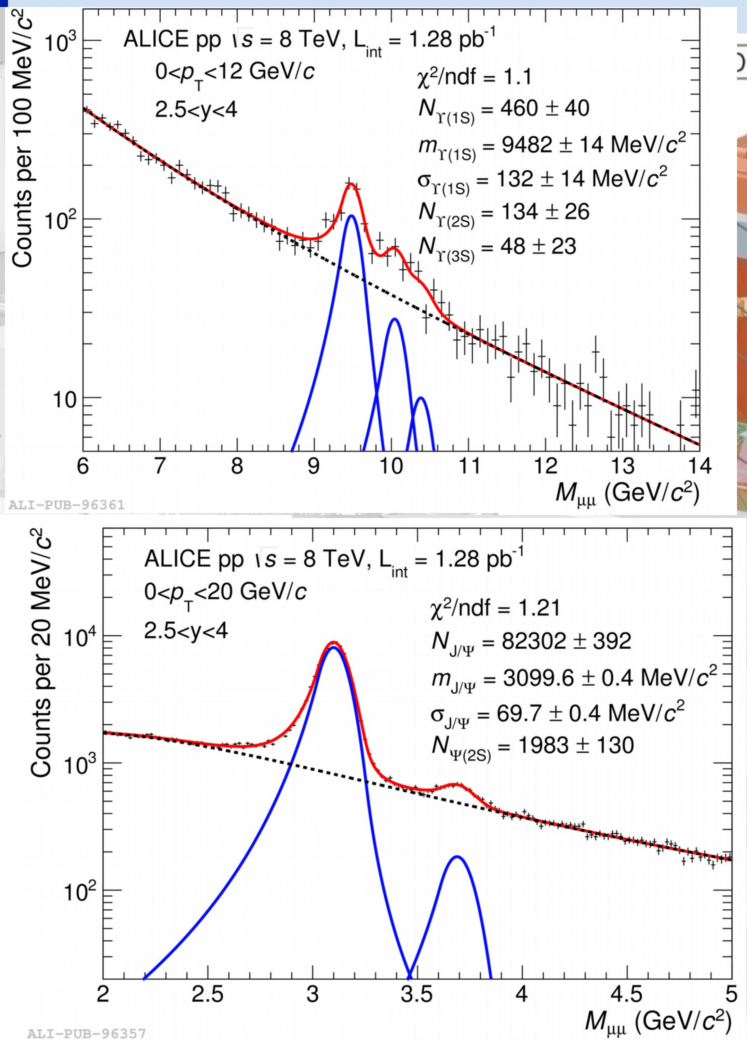
ALICE, PLB752 (2016) 267

Jet reconstruction

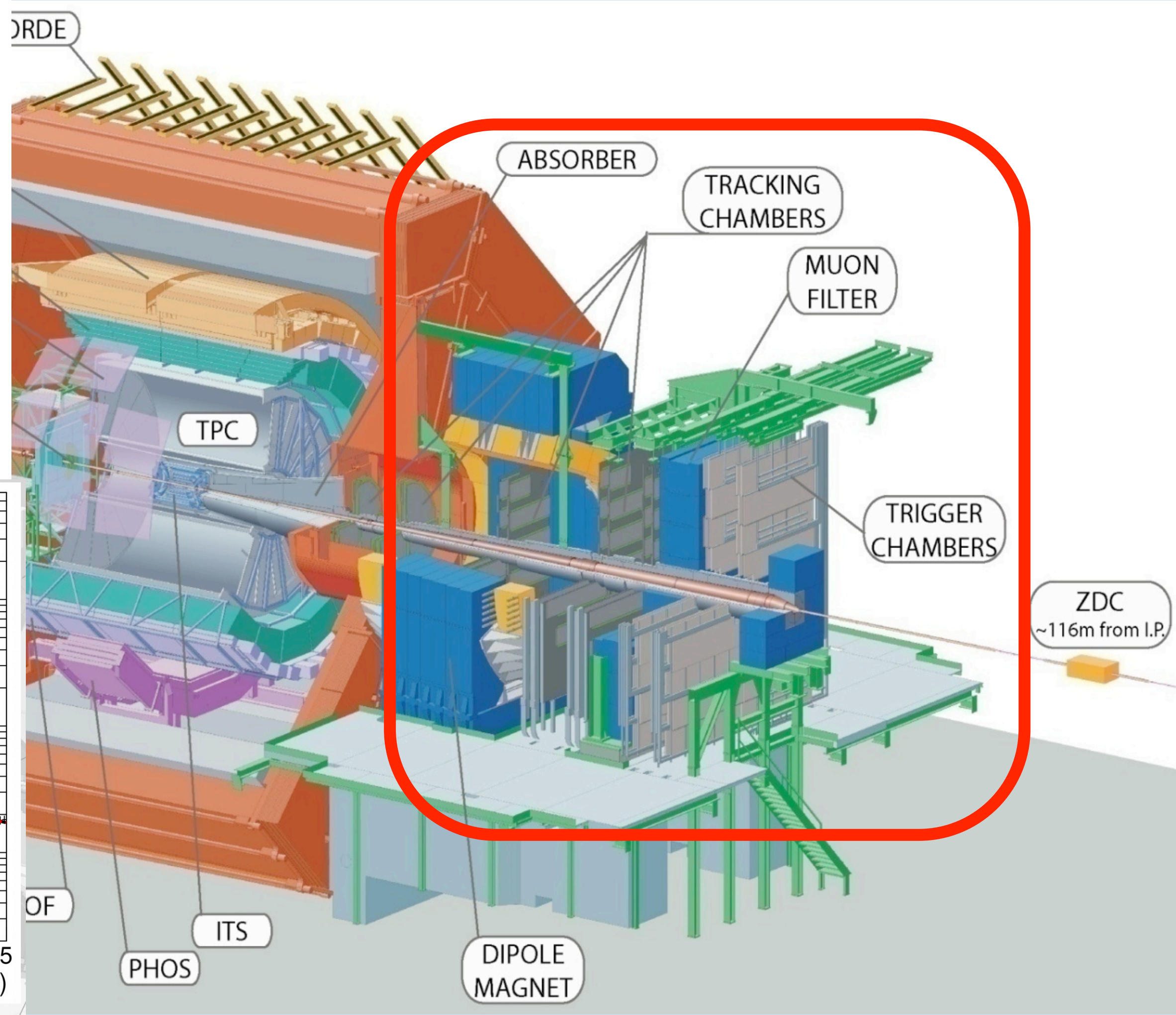


- DCal added for Run 2

Muon Identification



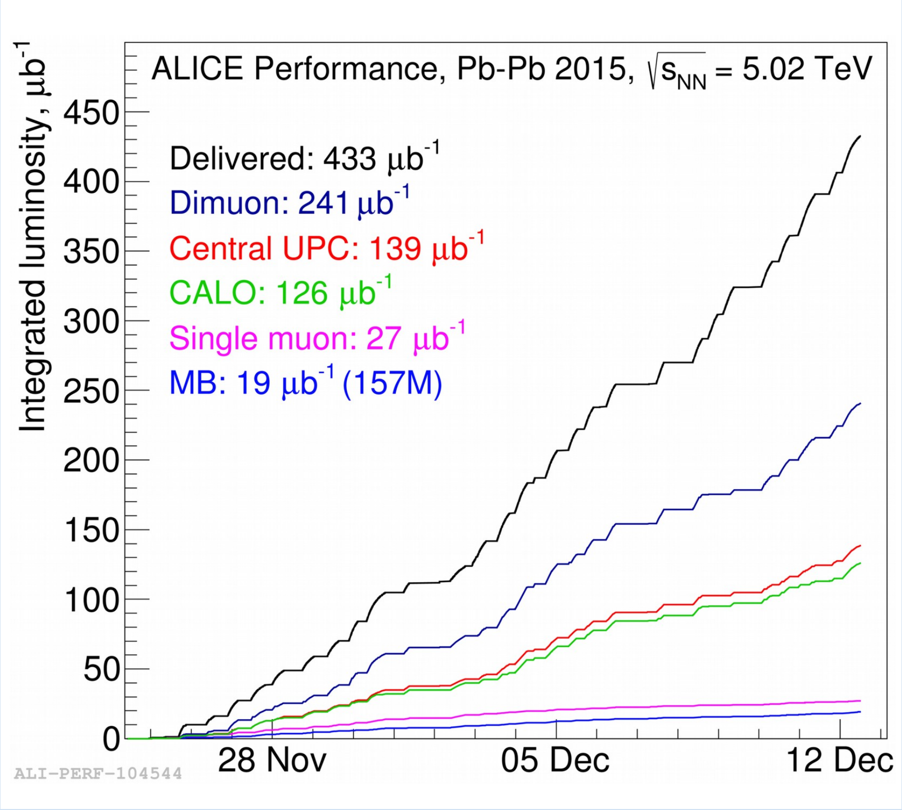
ALICE, EPJ C76 (2016) 4, 184



ALICE Data: Run 1

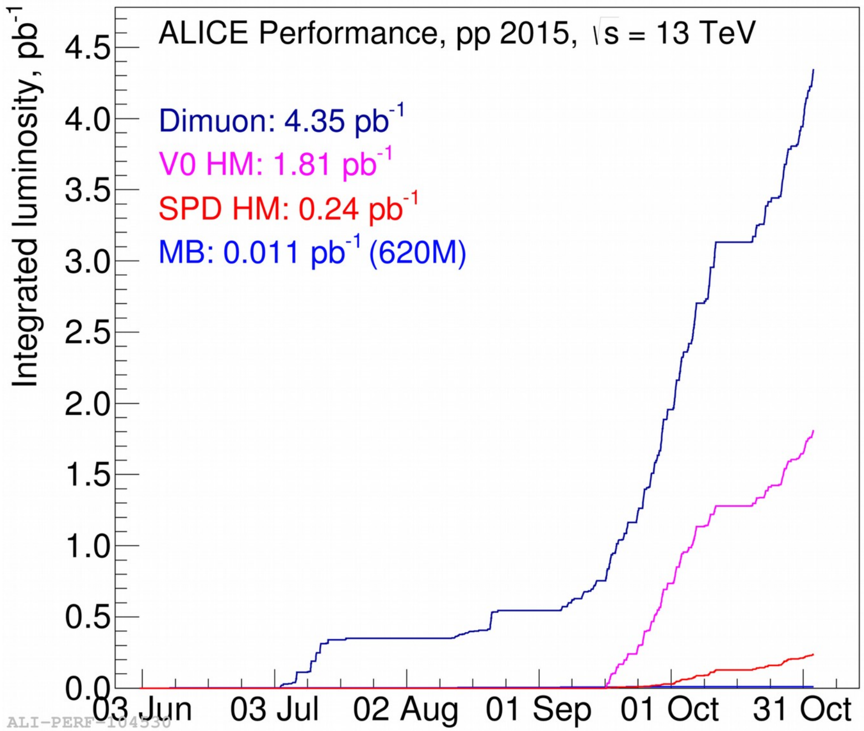
System	Energy $\sqrt{s_{NN}}$ (TeV)	Year	Integrated luminosity	Main Goal
Pb-Pb	2.76	2010	10 μb^{-1}	First Pb-Pb data taking at LHC
Pb-Pb	2.76	2011	0.1 nb^{-1}	Study hot & dense QCD matter
p-Pb & Pb-p	5.02	2013	15 nb^{-1} 15 nb^{-1}	Study Cold Nuclear Matter effects
pp	0.9	2009-10	0.15 nb^{-1}	Commissioning
pp	7	2010	7 nb^{-1}	Reference for Pb-Pb and p-Pb
pp	2.76	2011	1.1 nb^{-1}	
pp	7	2011	4.8 pb^{-1}	
pp	8	2012	9.7 pb^{-1}	

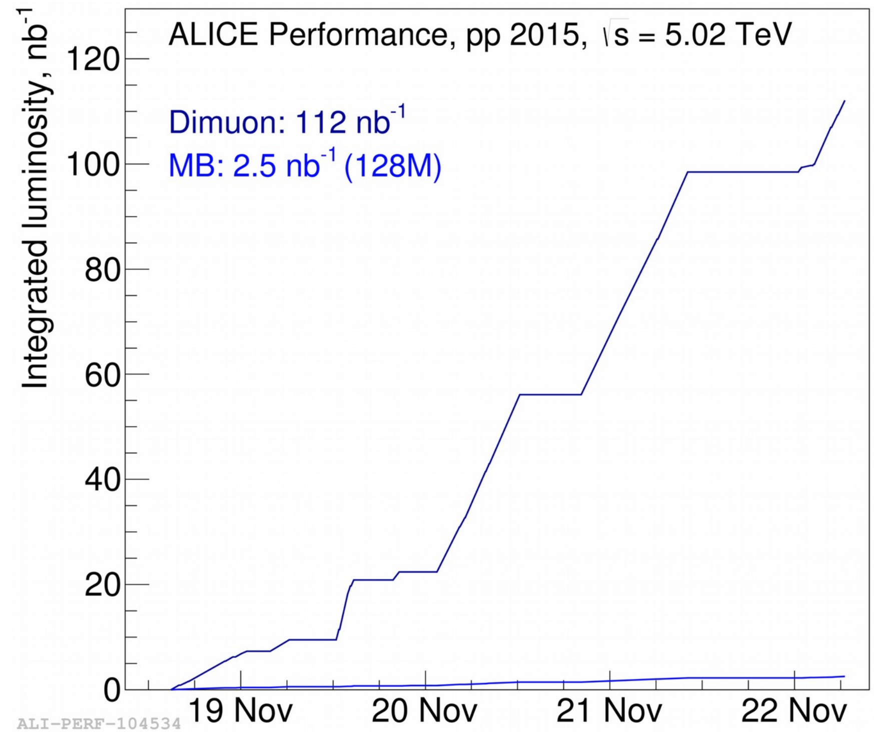
ALICE Data: Run 2 Heavy Ion



- From 2015 Pb-Pb collisions at 5.02 TeV
- Data Collected:
  - Minimum Bias: 19 μb^{-1}
  - EMCal: 126 μb^{-1}
  - Dimuons: 241 μb^{-1}
  - Ultra-peripheral: 139 μb^{-1}

ALICE Data: Run 2 pp





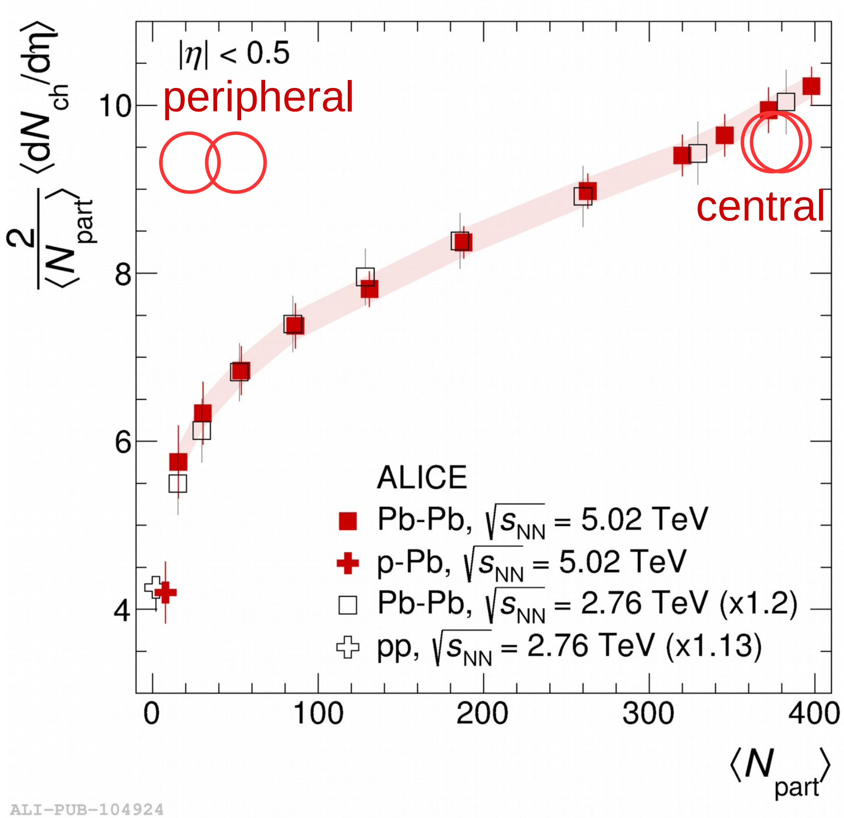
- pp collisions at 13 TeV
- High multiplicity trigger
  - Look for onset of collectivity in small systems

- pp collisions at 5.02 TeV
  - Important reference for p-Pb and Pb-Pb data!

Results: Bulk Properties

Multiplicity in 5.02 TeV Pb-Pb Collisions
Particle density of the medium created

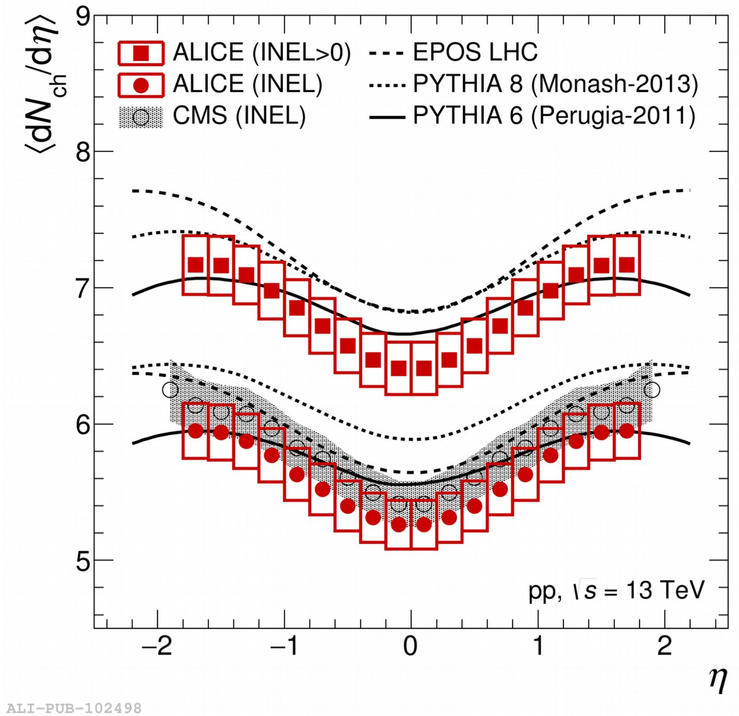
ALICE, PRL116(2016)222302

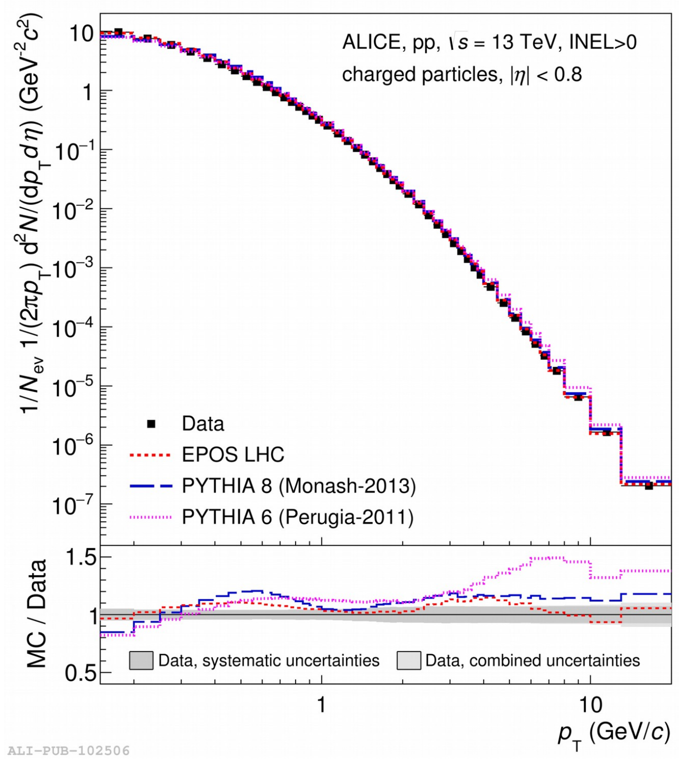


- Centrality dependence similar to 2.76 TeV trend
- Central (0-5%) Pb-Pb multiplicity, 1943±54, is ~ 2.5 times larger than pp collisions
- Peripheral collisions approach pp and p-Pb multiplicities

Multiplicity in 13 TeV pp collisions
Particle density achieved in pp

ALICE, PLB753 (2016) 319





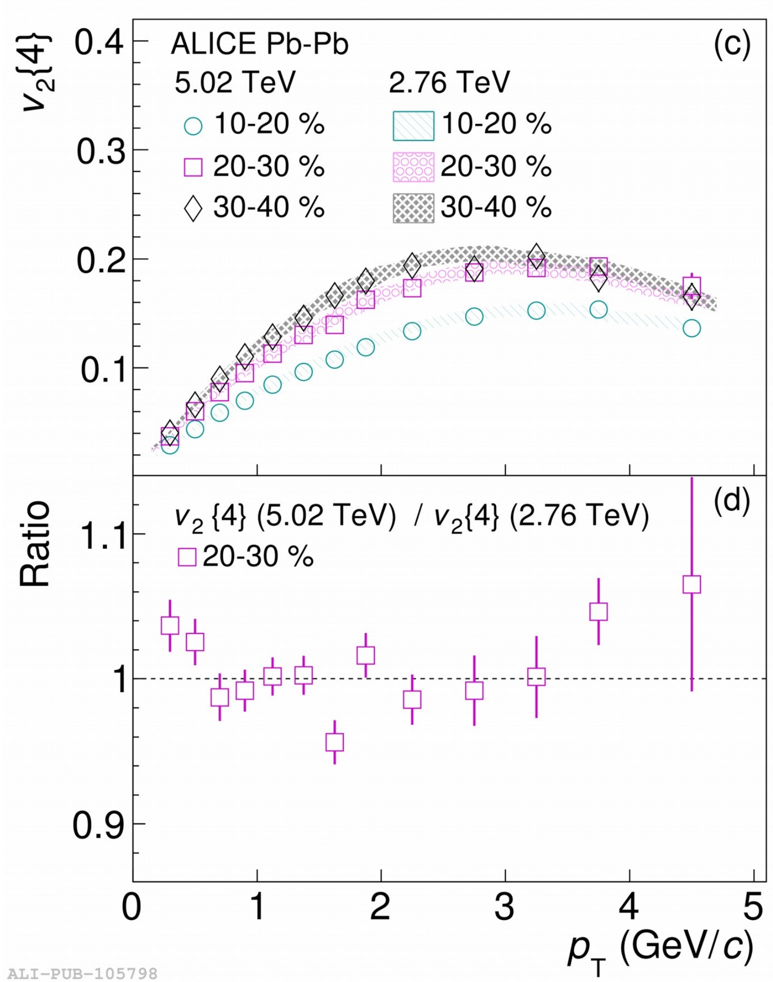
- $dN_{ch}/d\eta$ ($|\eta|<0.5$, INEL) = 5.31±0.18

- Good agreement with PYTHIA and EPOS expectations

Anisotropic flow in Pb-Pb at 5.02 TeV *Bulk motion in the QGP*

ALICE, PRL116(2016)132302

$$\frac{dN}{d\varphi} \propto 1+2v_1\cos(\varphi-\Psi)+2v_2\cos[2(\varphi-\Psi)]+2v_3\cos[3(\varphi-\Psi)]+\ldots$$

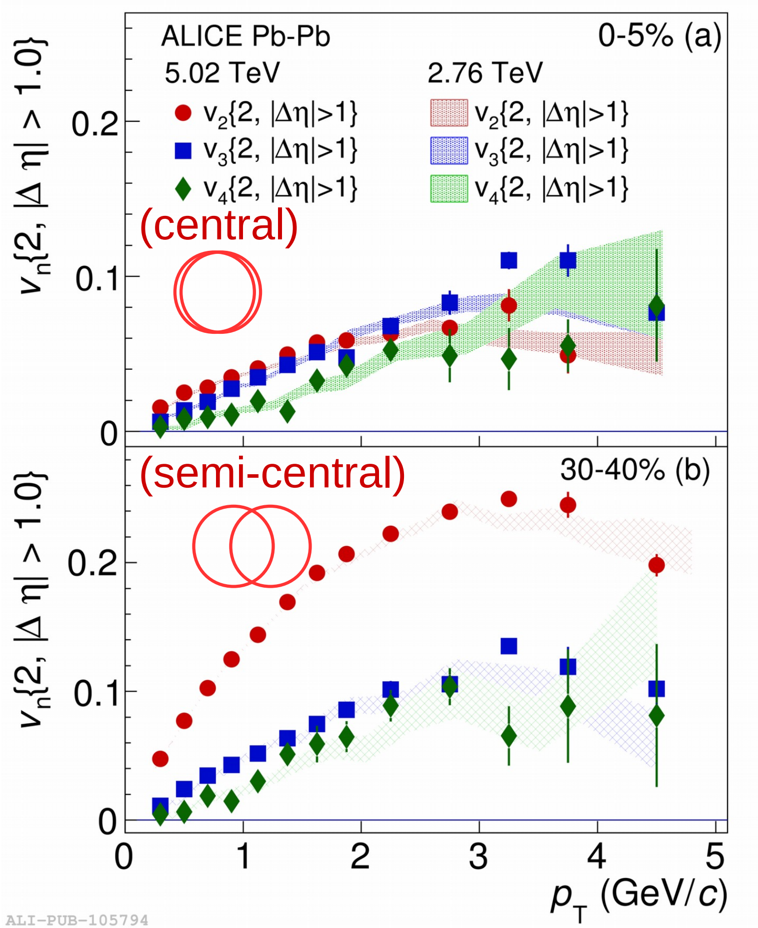


- Flow measured with 4 particle cumulants
- Elliptic flow (v_2) in Pb-Pb collisions at 5.02 TeV similar to 2.76 TeV
  - Recent 2.76 TeV publication: arXiv:1606.06057

Anisotropic flow in Pb-Pb at 5.02 TeV
Bulk motion in the QGP

ALICE, PRL116(2016)132302

$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos(\varphi - \Psi) + 2v_2\cos[2(\varphi - \Psi)] + 2v_3\cos[3(\varphi - \Psi)] + \ldots$$

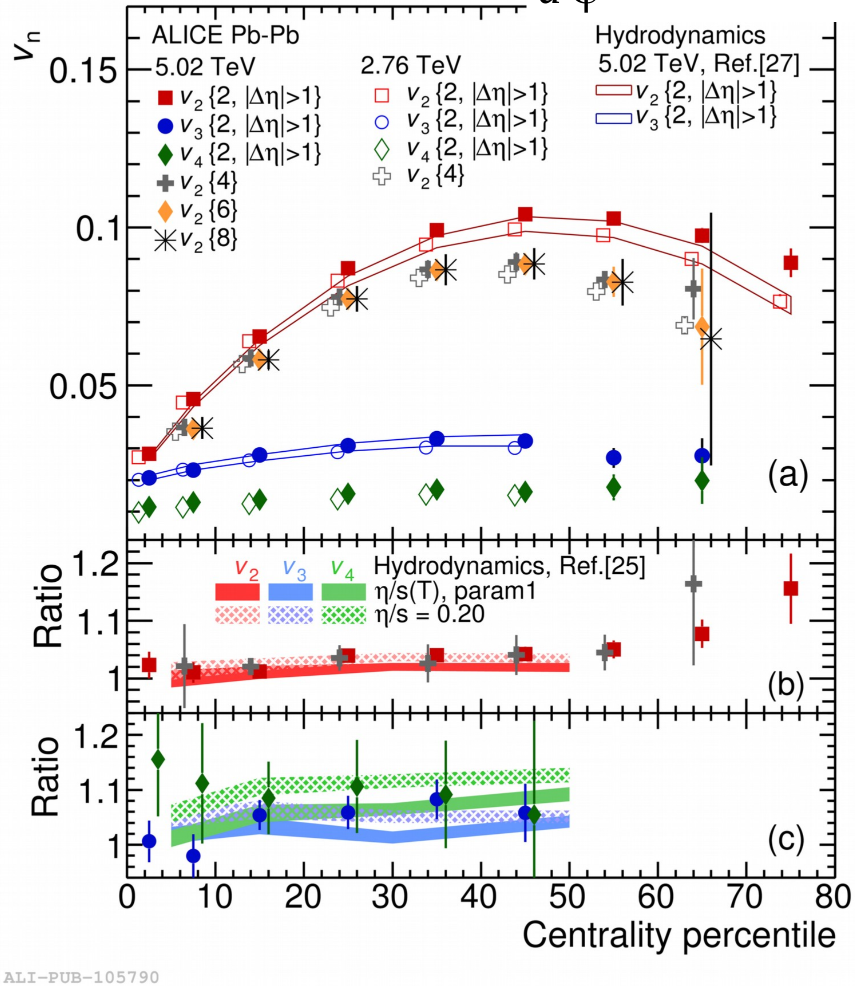


- Flow measured with 2 particle cumulants
- Higher order harmonics in Pb-Pb collisions at 5.02 TeV similar to 2.76 TeV

Anisotropic flow in Pb-Pb at 5.02 TeV
Bulk motion in the QGP

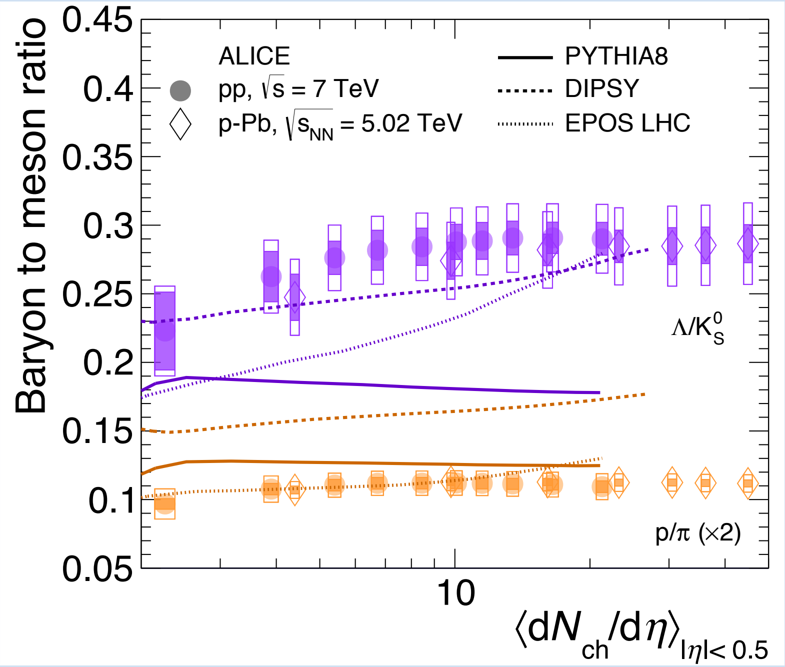
ALICE, PRL116(2016)132302

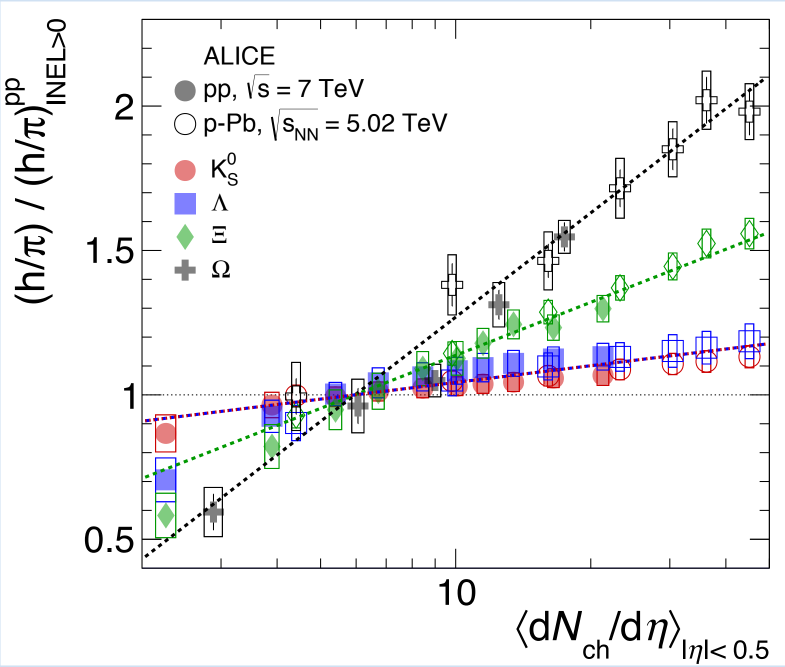
$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos(\varphi - \Psi) + 2v_2\cos[2(\varphi - \Psi)] + 2v_3\cos[3(\varphi - \Psi)] + \ldots$$



- Mild increase with collision energy for p_T integrated attributed to increase in <p_T>
- Hydrodynamical calculations
  - Supports a low shear viscosity to entropy density ratio (η/s)

Multiplicity dependence of *Strangeness in 7 TeV pp collisions*

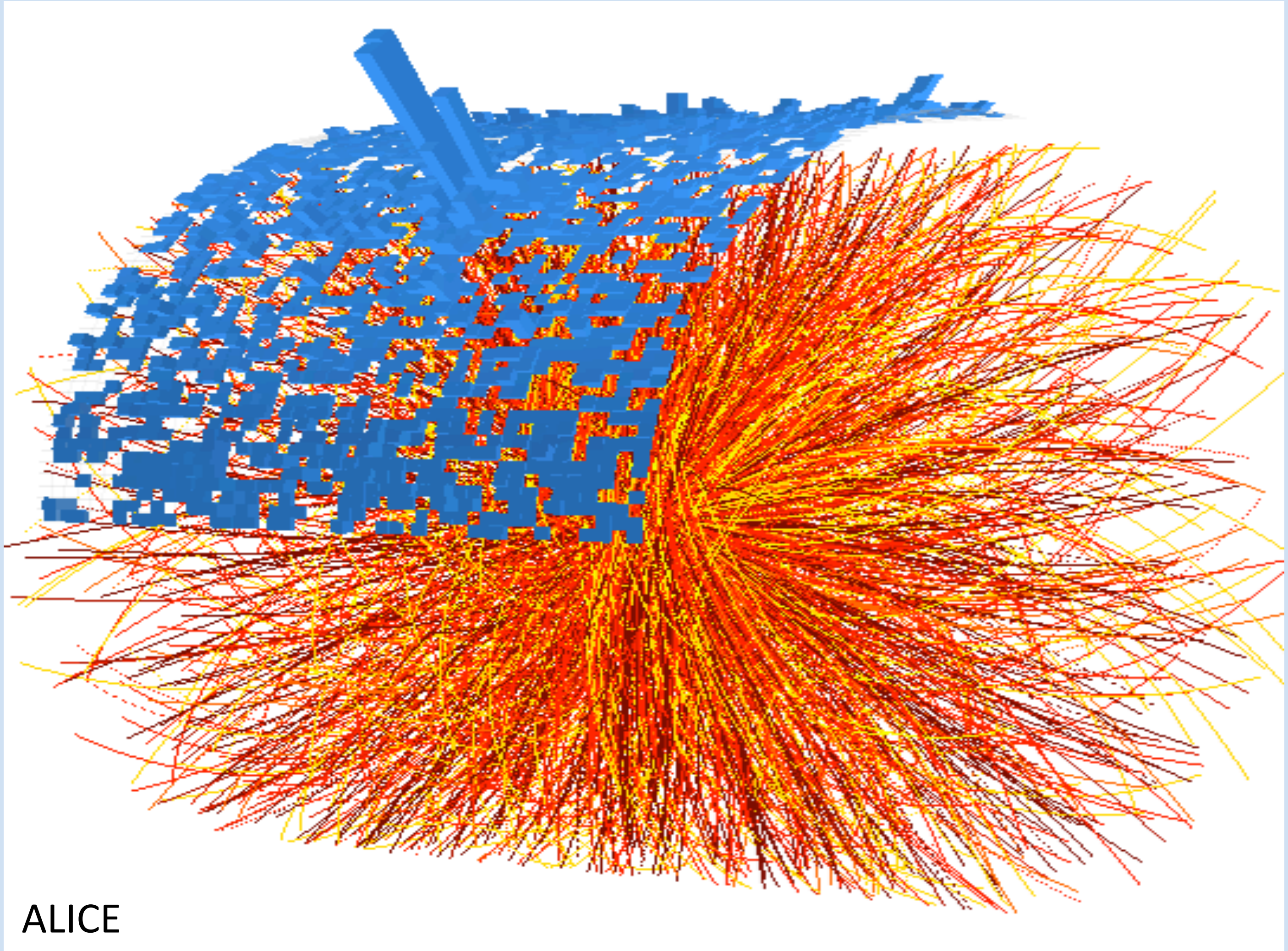




arXiv:1606.07424

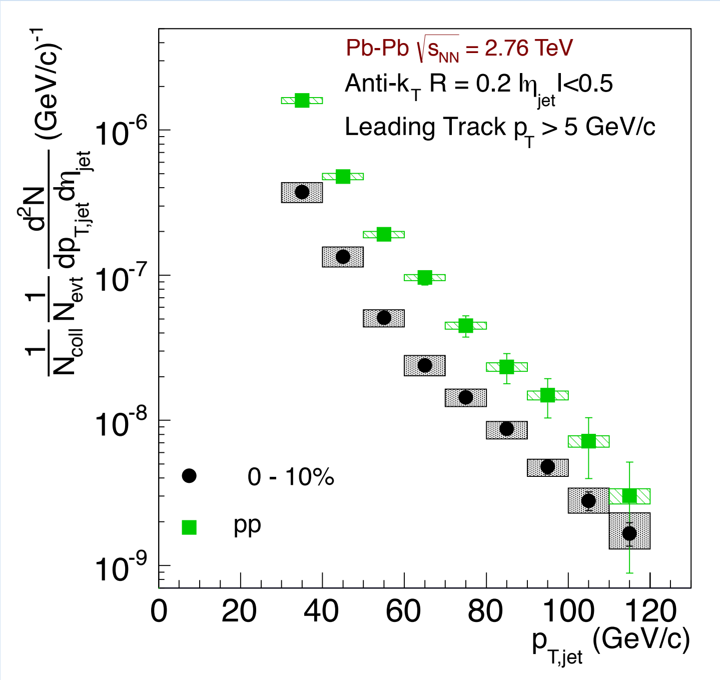
- Strange particle production increases vs multiplicity faster than non-strange particles
- First observation of an enhanced production of strange particles in high multiplicity pp collisions
- Not reproduced in MC

Results: Jets



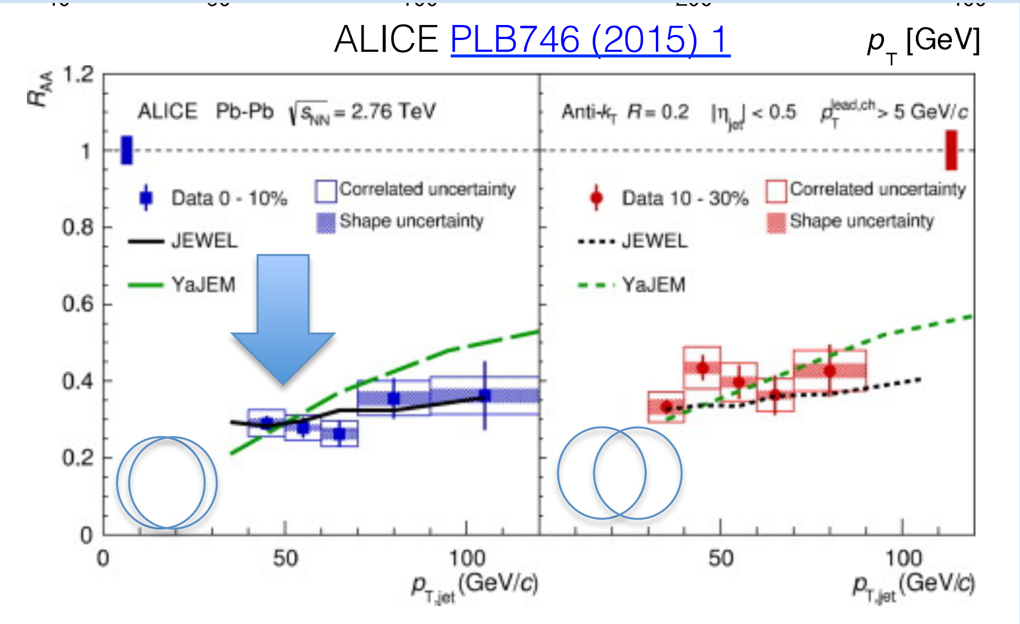
Jets in Pb-Pb at 2.76 TeV

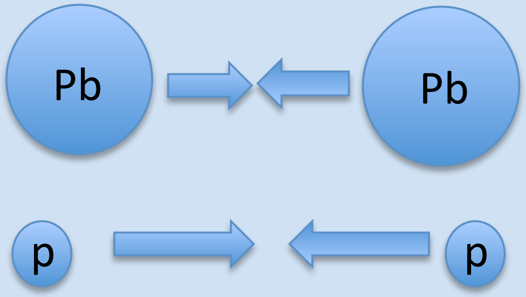
Partonic energy loss



$$R_{AA} = \frac{dN_{jet}^{AA} / dp_T}{\langle N_{coll} \rangle dN_{jet}^{pp} / dp_T} \frac{N_{evt}^{pp}}{N_{evt}^{AA}}$$

Jet Quenching!

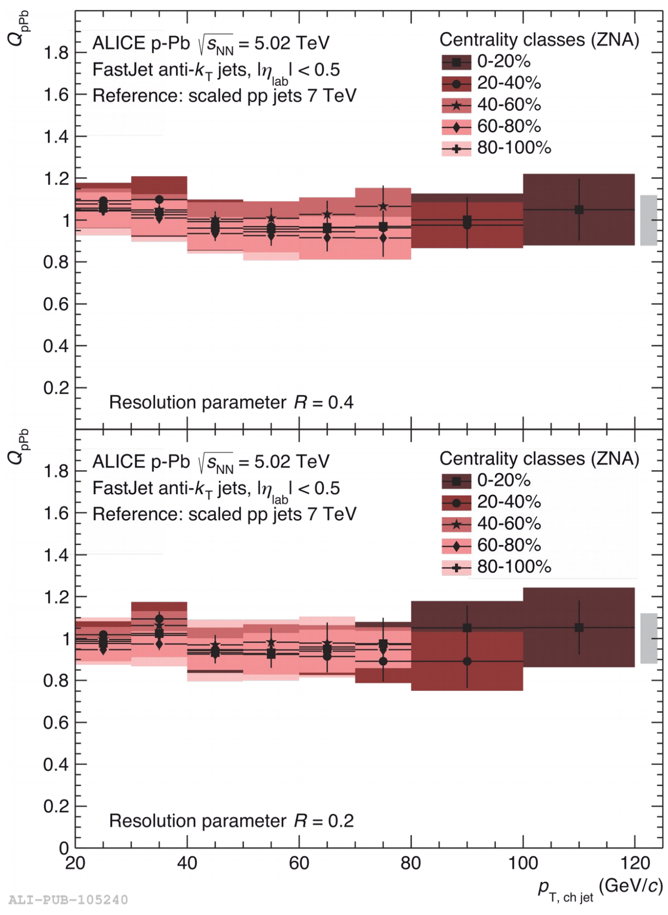




- Jet suppression observed in Pb-Pb
  - Energy loss in QGP

Charged Jets in p-Pb at 5.02 TeV
Cold Nuclear Matter Effects

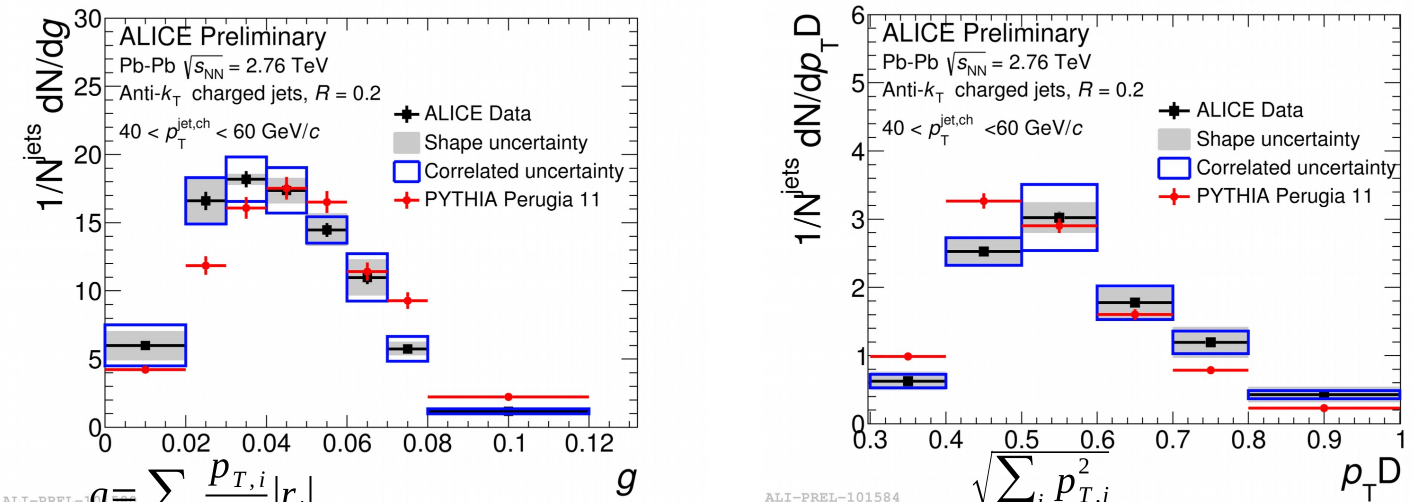
ALICE, EPJ C76 (2016) 5, 271



$$Q_{pPb} = \frac{d^{2N}_{pPb}/d\eta\, dp_T}{\langle N_{coll} \rangle d^2 N_{pp}/d\eta\, dp_T}$$

- Charge jets utilize the tracking system only = more statistics
- Q_{pPb} ~ 1 for all centrality classes
  - No or very little cold nuclear matter effect in this kinematic range
  - Suppression in Pb-Pb is a QGP effect

Jet Shapes in Pb-Pb at 2.76 TeV
How are jets modified in the QGP?



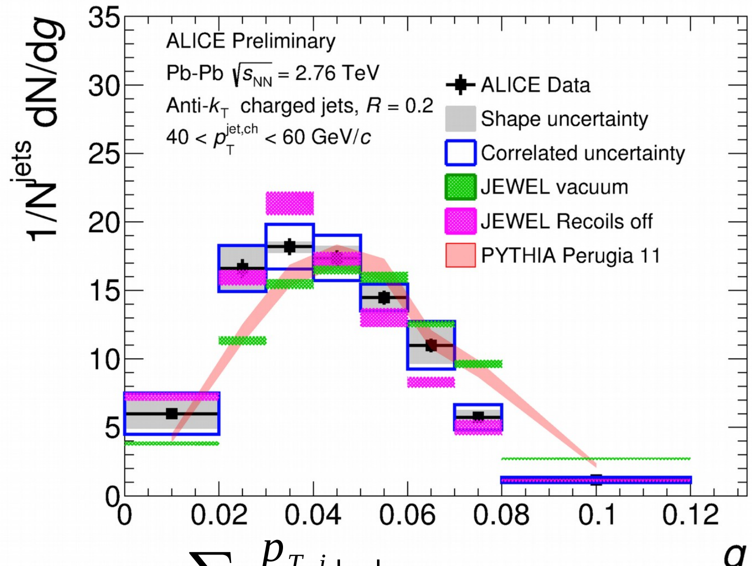
$$g = \sum_{i \in jet} \frac{p_{T,i}}{p_T^{jet}} |r_i|$$

$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

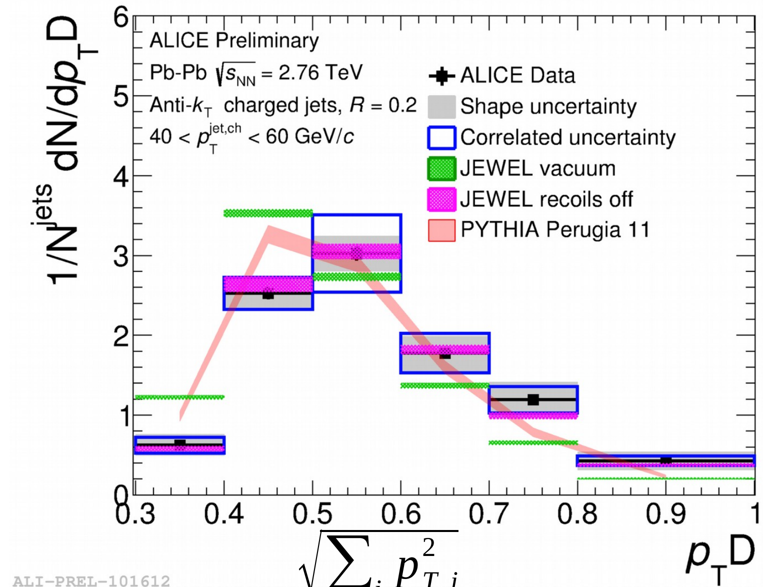
- Radial moment, g, is lower in Pb-Pb data compared to PYTHIA
  - The jet core is more collimated in Pb-Pb
- p_T dispersion $p_T D$ is higher in Pb-Pb than PYTHIA
  - Fewer jet constituents and/or larger p_T dispersion
- Be aware of jet definitions: These are R=0.2 jets

Jet Shapes in Pb-Pb at 2.76 TeV

How are jets modified in the QGP?



$$g = \sum_{i \in jet} \frac{p_{T,i}}{p_T^{jet}} |r_i|$$



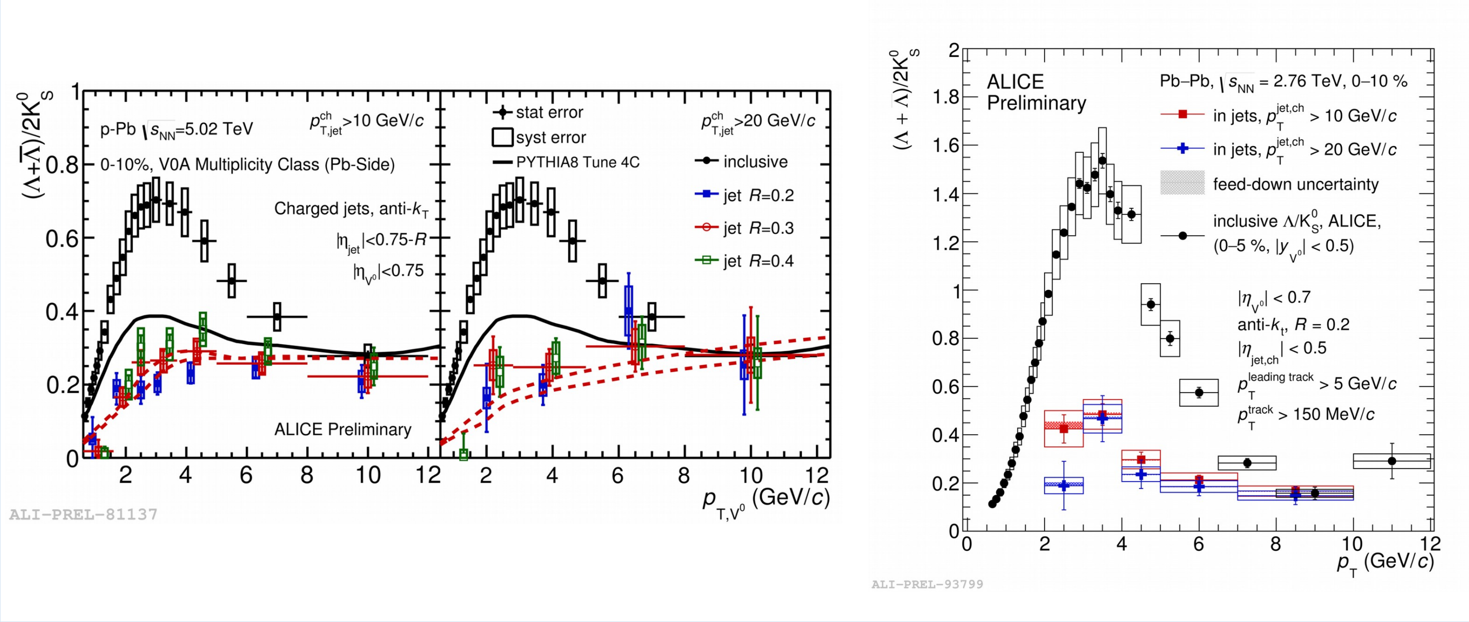
$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

- JEWEL (model with QGP effects) gives qualitative agreement with the data
  - JEWEL jets are collimated due to soft particle emission at large angles (outside of R=0.2 jet cone)

Strange Hadron Production in Jets

Is there a baryon enhancement in jets?

- Baryon enhancement has been observed in Pb-Pb and p-Pb for inclusive particles



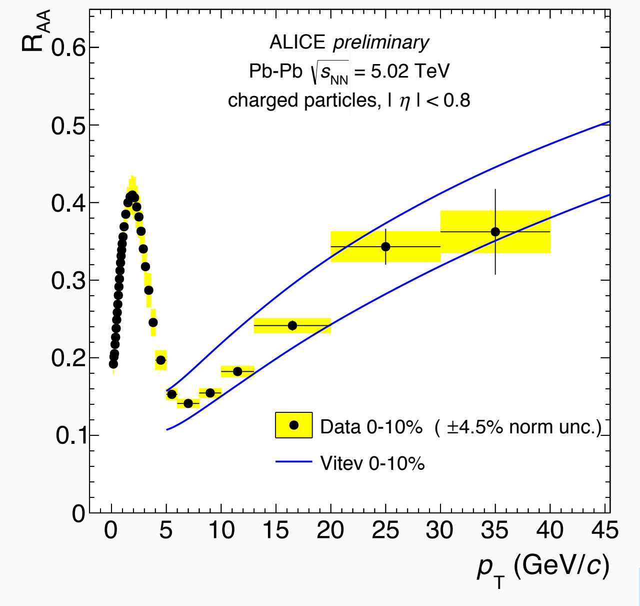
- Λ/K^0_s ratio in jets is significantly lower than the inclusive measurement in both p-Pb and Pb-Pb
- Λ/K^0_s ratio in jets is consistent with PYTHIA
- Baryon enhancement in p-Pb & Pb-Pb collisions not from jets

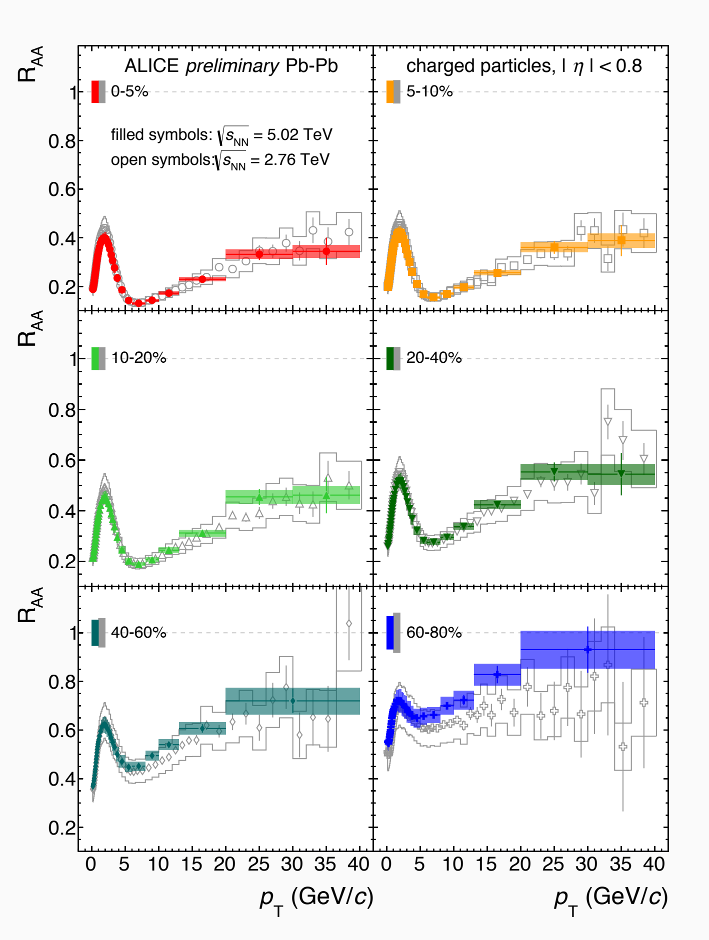
High p_T Particle Production in 5.02 TeV Pb-Pb
Suppression in a hotter/denser QGP

- Pb-Pb 5.02 TeV suppression similar to 2.76 TeV (common systematics not yet cancelled)
- Well described by models
- Additional constraints on medium properties ($\hat{q}$)

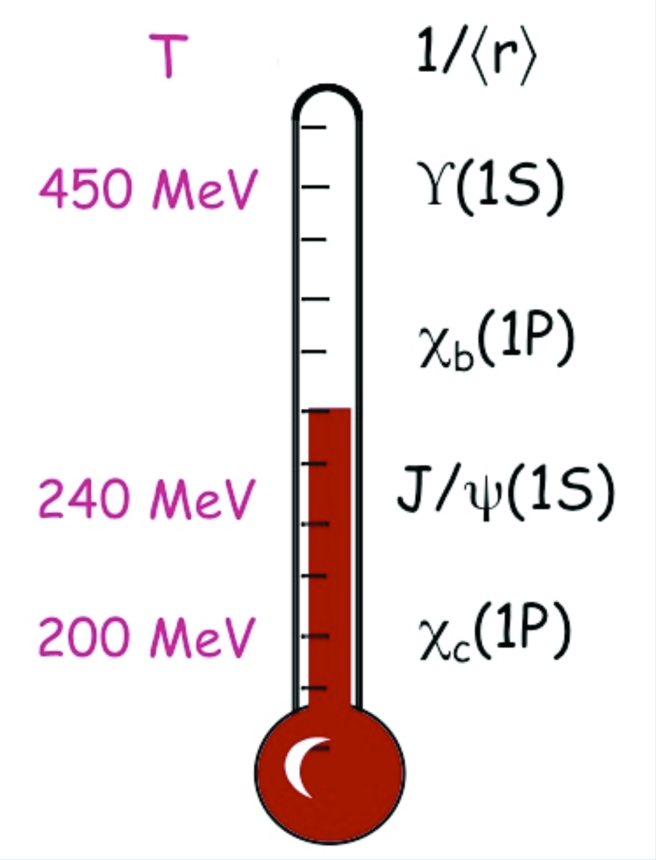
$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN^{AA}_{ch}/dp_T}{d\sigma^{pp}_{ch}/dp_T}$$

Vitev et al., Phys. Rev. D **93** (2016) no.7 | arXiv:1509.02936
Djordjevic et al., arXiv:1601.07852
Majumder et al., Phys. Rev. Lett. **109** (2012)| arXiv:1103.0809

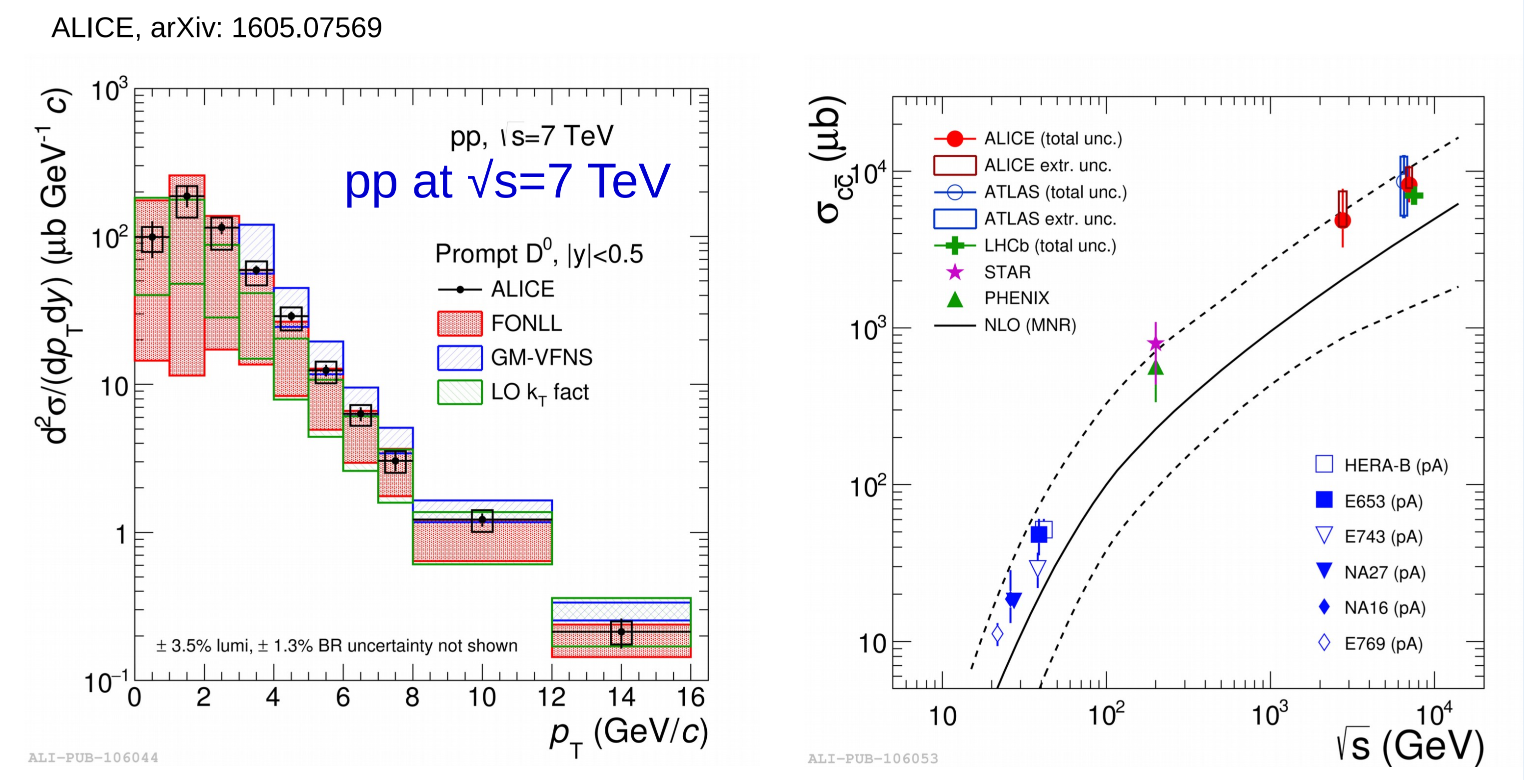




Results: Heavy Flavor



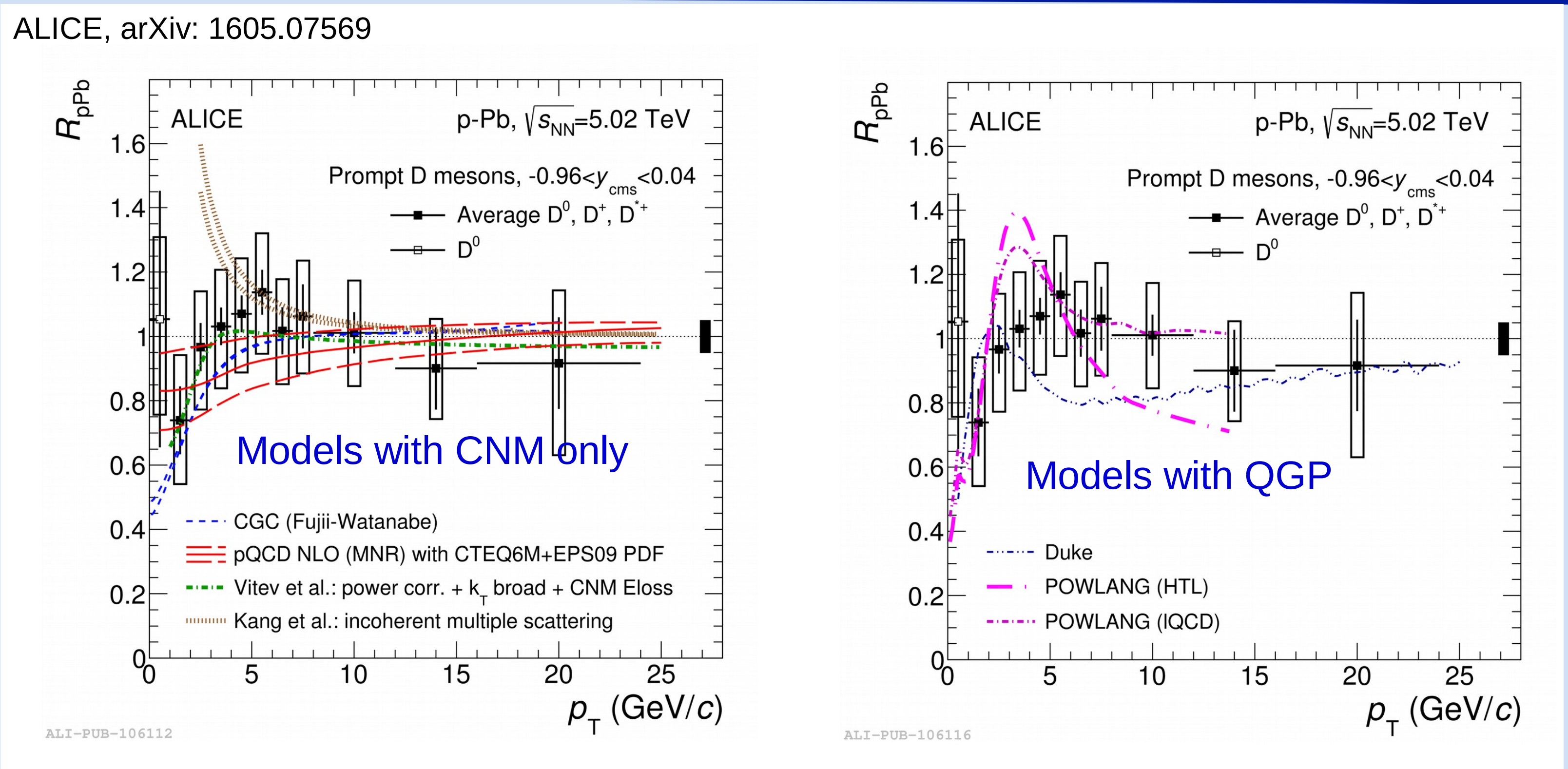
D^0 meson production in pp at 7 TeV
Baseline measurement & constrain theory



- Theories agree with Data
  - Theory uncertainties currently larger than the experimental uncertainties

D^0 meson production in p-Pb

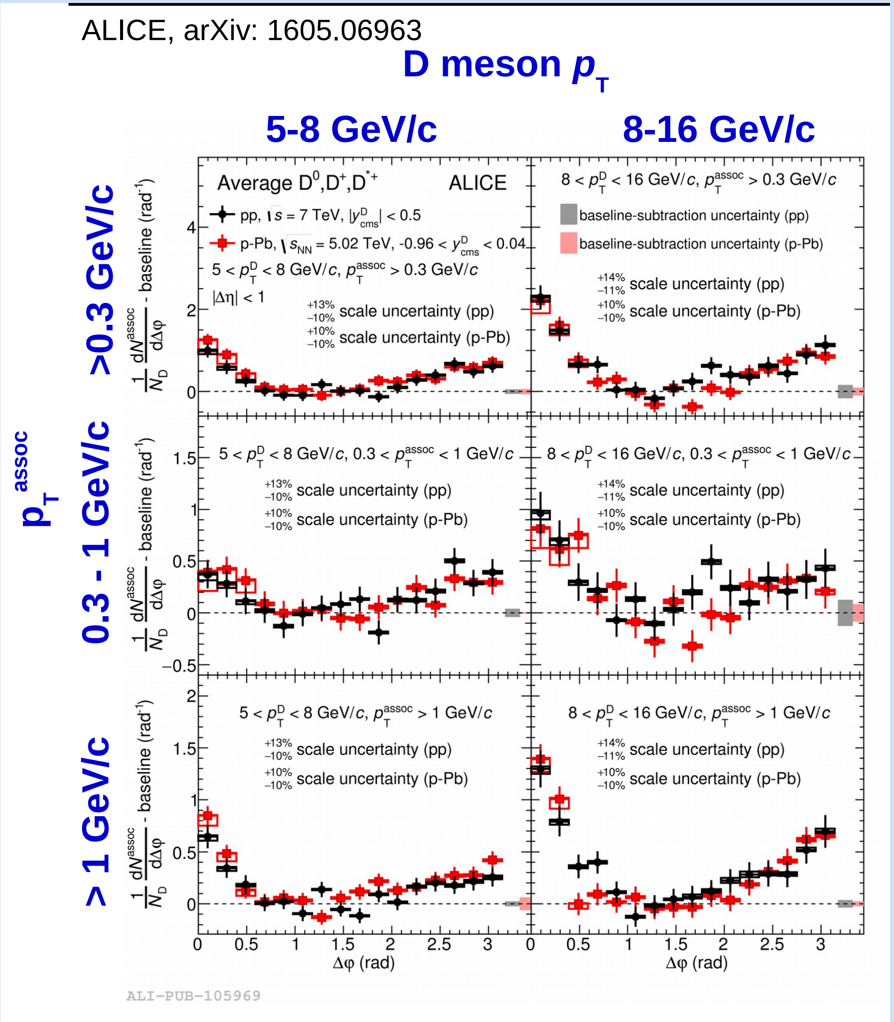
CNM effects on D^0 meson production



- Compatible with no CNM effects
- Cannot yet distinguish between models due to experimental uncertainties
  - More p-Pb data and pp reference coming soon!

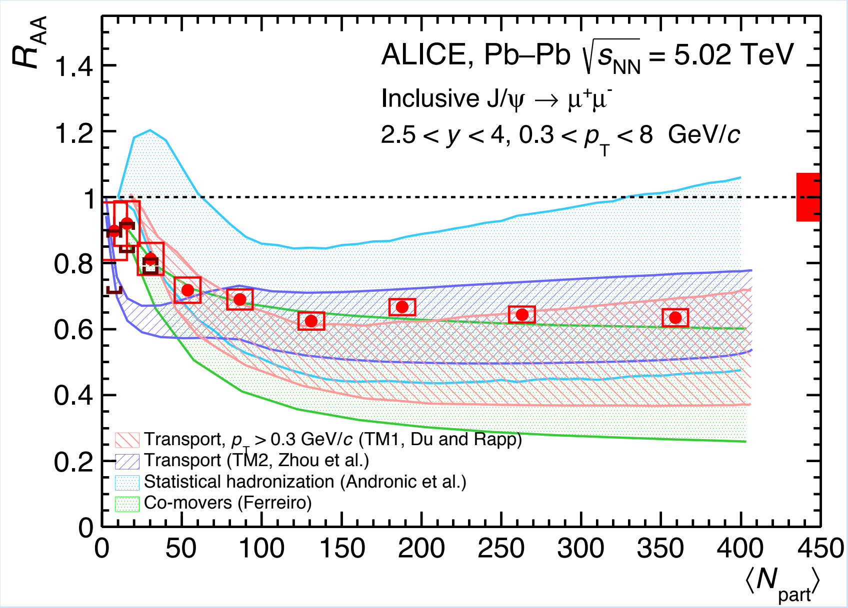
D-h correlations in pp and p-Pb

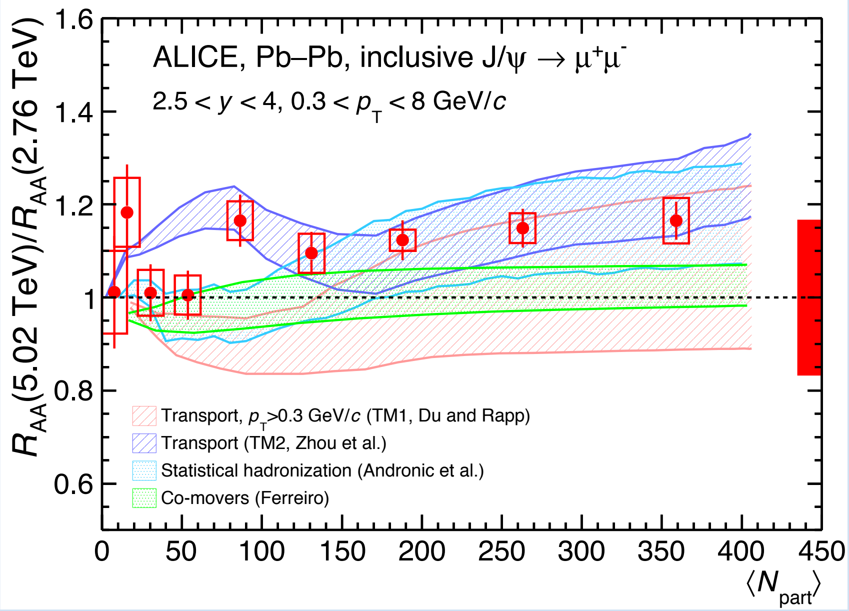
CNM effects on c-quark fragmentation



- Measure hadron yield on near and away side of D-meson momentum vector
- Similar correlation functions in both pp and p-Pb for full kinematic range measured
- Charm quark fragmentation appears unmodified by CNM effects

J/Psi suppression in 5.02 TeV Pb-Pb
Heavy flavor suppression in the QGP

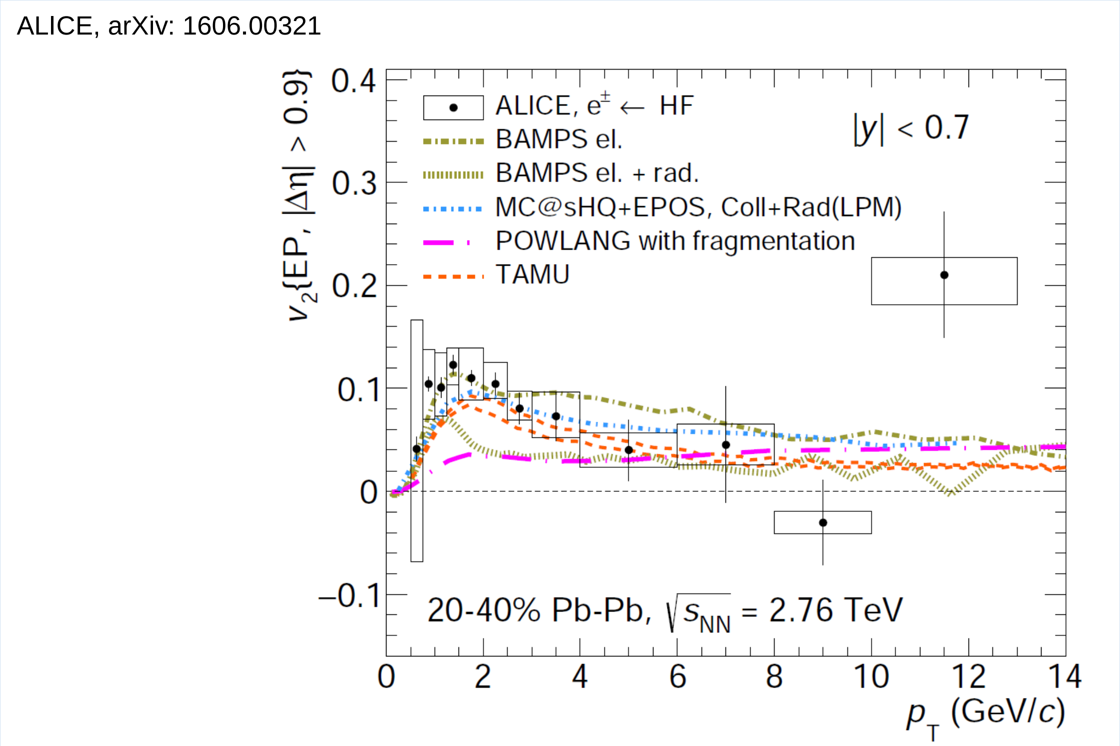




arXiv:1606.08197

- Suppression observed in 5.02 TeV Pb-Pb
- 15% above 2.76 TeV suppression
- Described by models

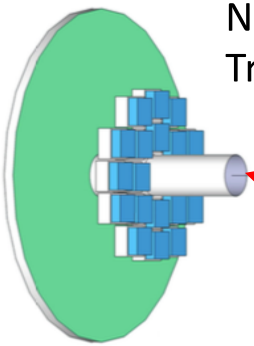
Heavy Flavor v_2 in Pb-Pb at 2.76 TeV
Do heavy quarks thermalize and flow?



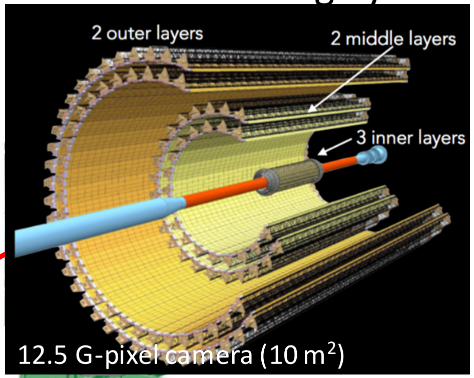
- Significant non-zero elliptic flow observed
- Sensitive to transport properties of the QGP
- Models including collisional energy loss and hadronization via coalescence agree with the data

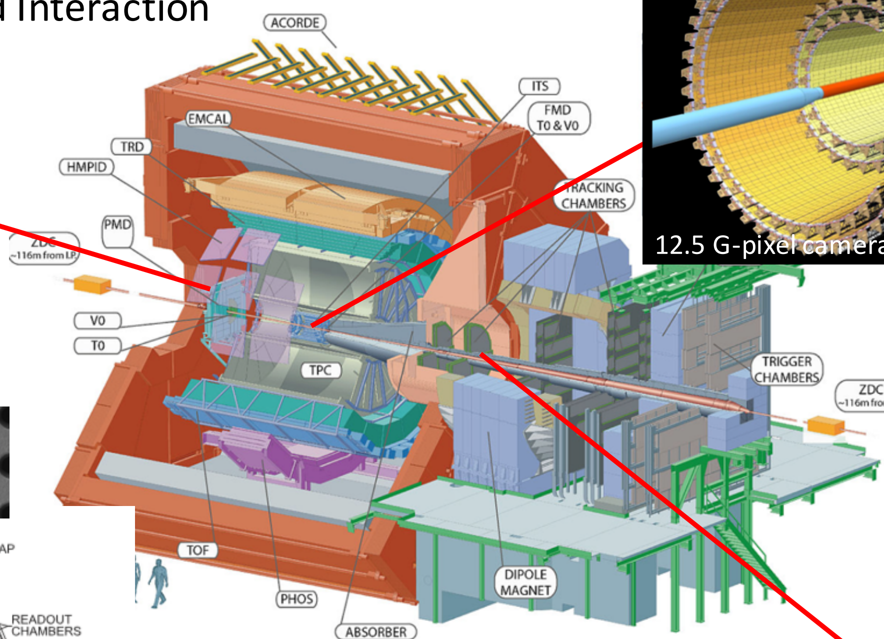
Future Upgrades

New Forward Interaction Trigger (FIT)



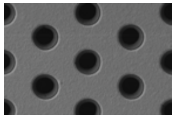
New Inner Tracking System (ITS)

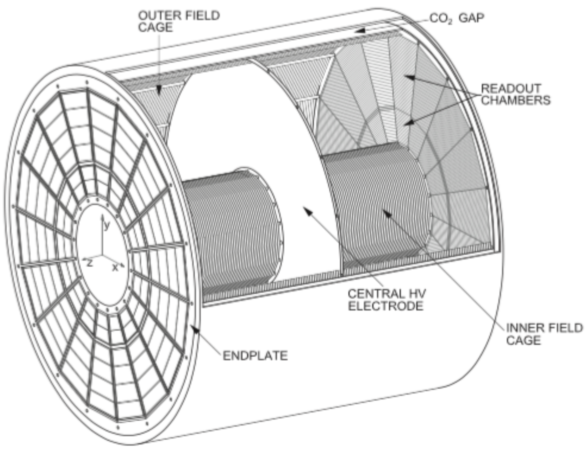




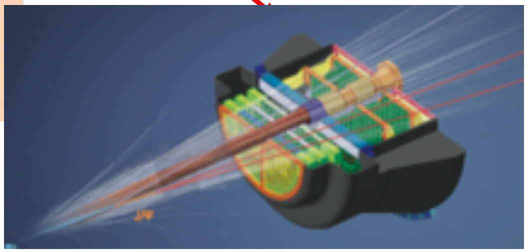
Both based on Monolithic Active Pixel Sensors (MAPS)

TPC with GEM based readout





New Muon Forward Tracker (MFT)



+ improved readout for TOF, ZDC, TRD, MUON ARM
+ new Central Trigger Processor
+ new DAQ/Offline architecture

Summary

- ALICE has a rich physics program with many important measurements in pp, p-Pb and Pb-Pb collisions. This talk only highlighted a few:
  - The QGP flows
  - Jets are quenched in the QGP (no/small CNM effects) and appear more collimated with in an R=0.2 cone. Jet fragmentation appears pp like in both p-Pb and Pb-Pb.
  - Heavy quarks are suppressed and have non-zero v_2 in Pb-Pb collisions. No or little CNM effects observed.
  - Suppression in 5.02 TeV similar to 2.76 TeV Pb-Pb
- ALICE upgrades underway to continue strong data taking performance in the future