ALICE Experiment

-- Topics & upgrade plan --

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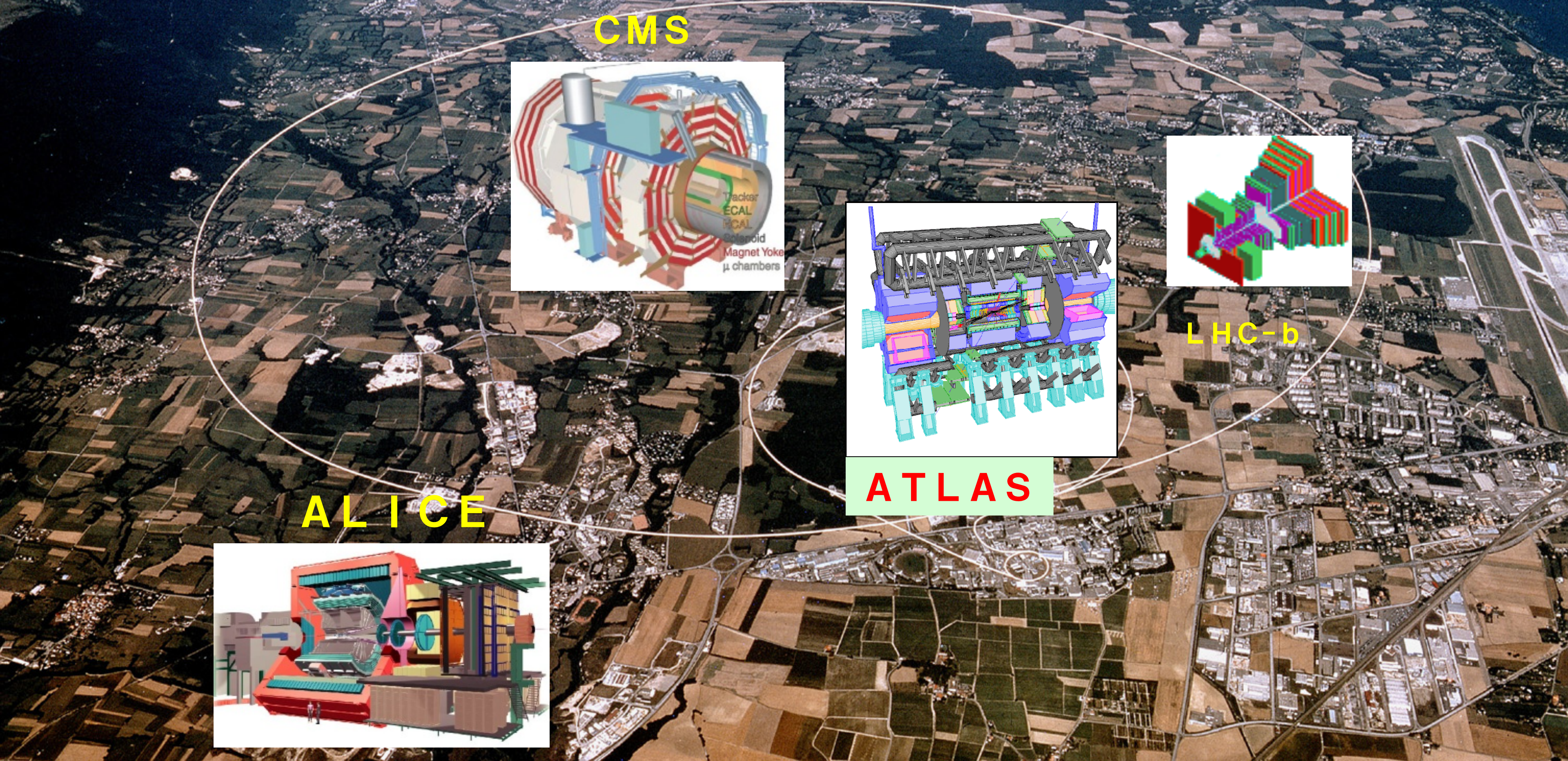
INTRODUCTION

LHC at CERN

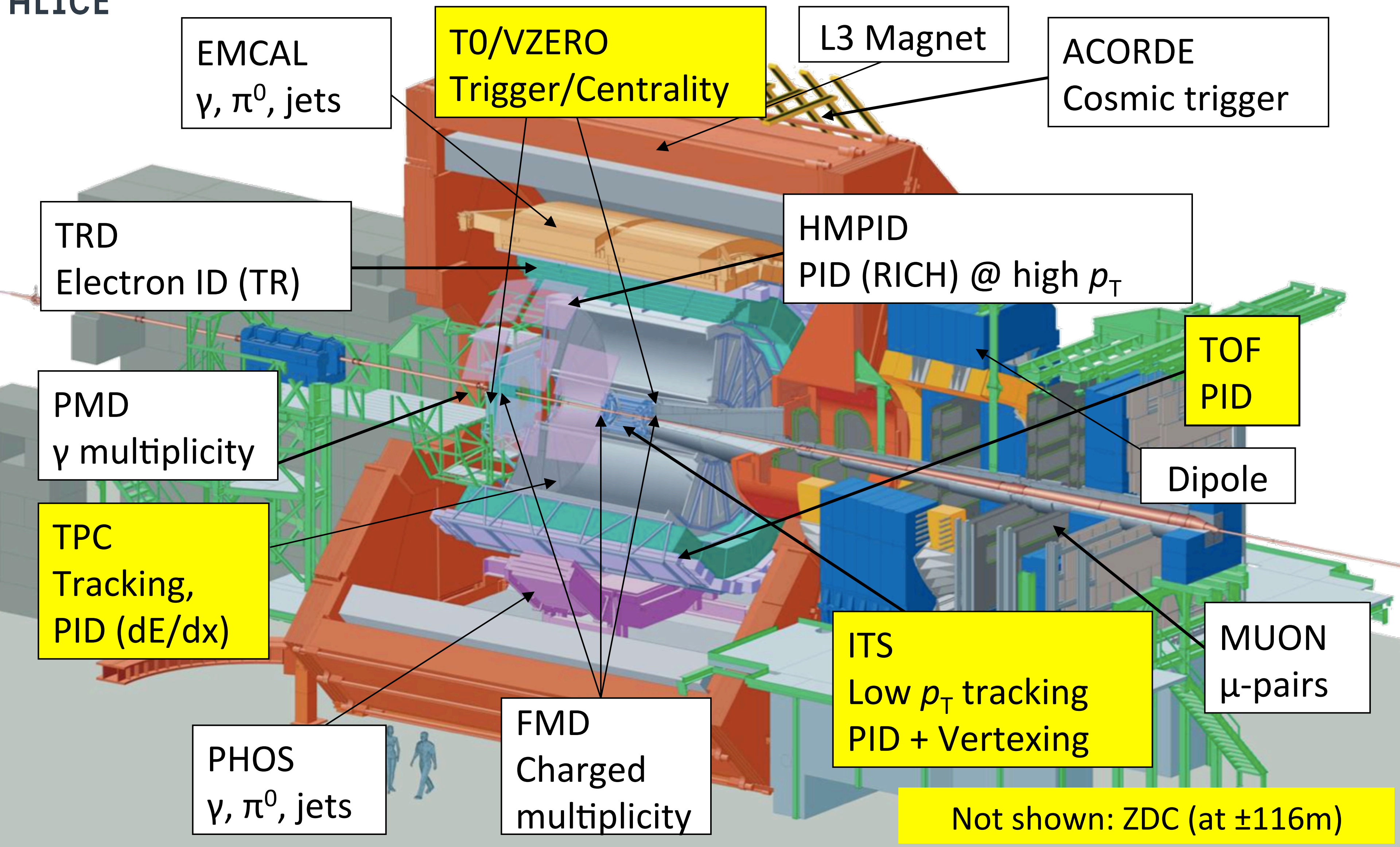
circumference = 27 km (Yamanote-line = 35 km)

$\sqrt{s}$ = 14 TeV for p + p $\sqrt{s_{NN}}$ = 5.5 TeV for Pb + Pb

$\sqrt{s_{NN}}$ at LHC = 28 x RHIC =320 x SPS = 1000 x AGS



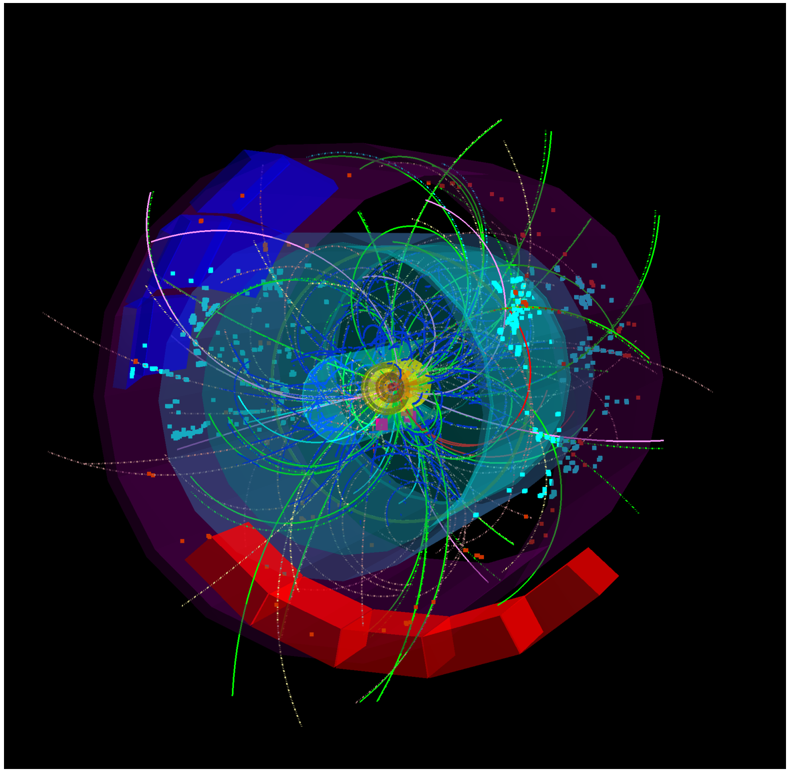
A Large Ion Collider Experiment



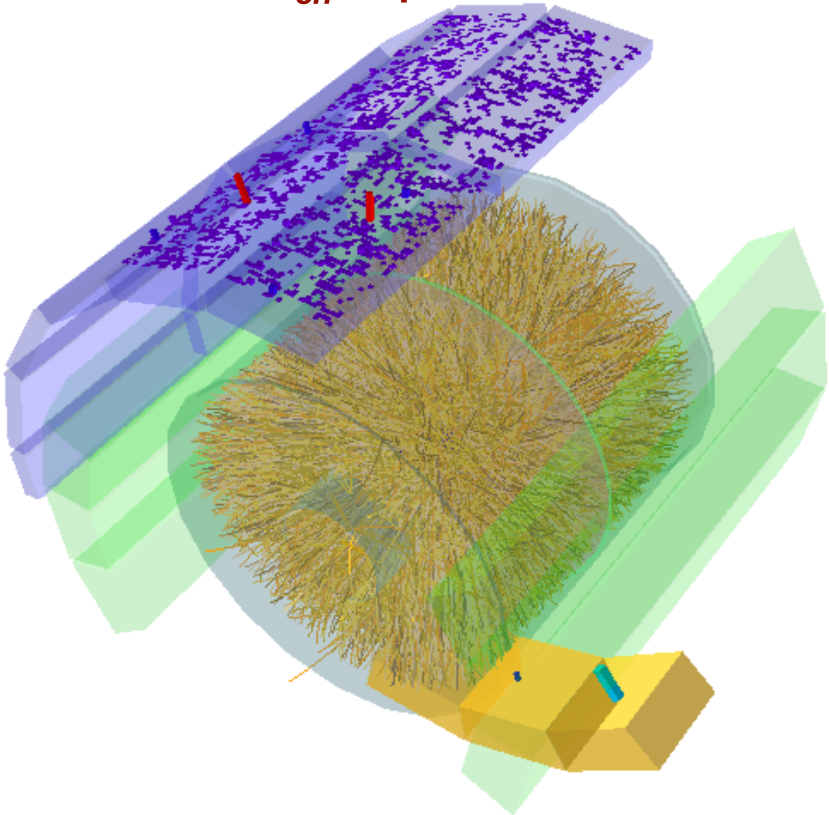
Startup of ALICE

- 2009/11/23: First pp collisions at 900 GeV
- 2010/3/31: pp collisions at 7 TeV
- 2010/11/8: Pb-Pb collisions at 2.76 TeV/A

$dN_{ch}/d\eta \sim 6.0$



$dN_{ch}/d\eta \sim 1600$

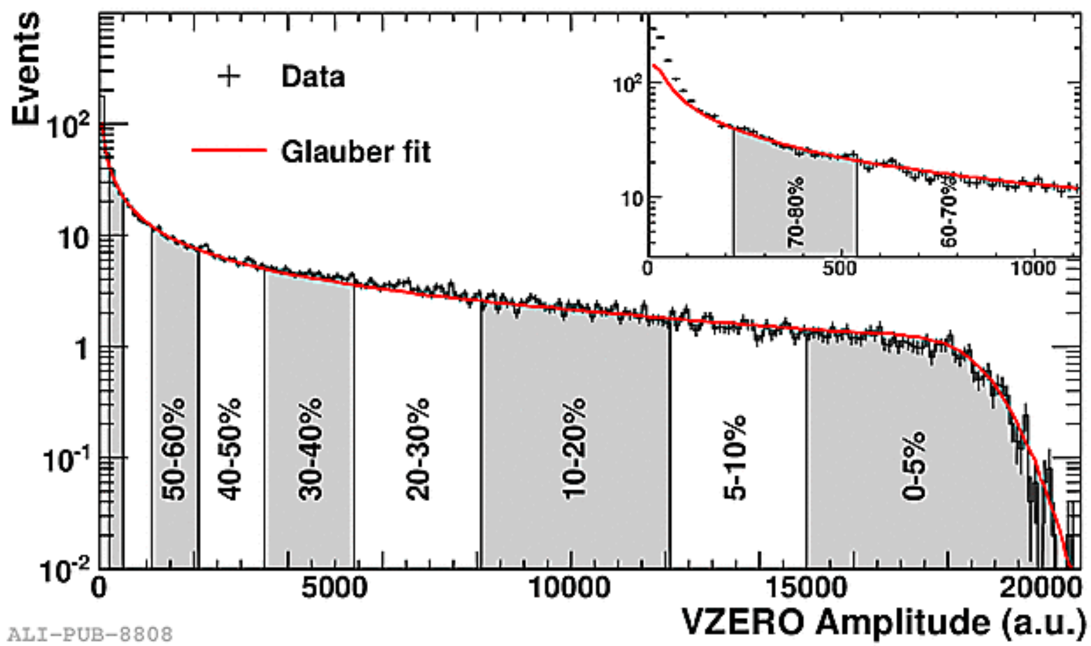


ALICE Run Summary

- pp collisions at $\sqrt{s}$ = 7 TeV in 2010– 2011
  - Int L = 16 nb^{-1} (with INT trigger)
  - Int L = 4.9 pb^{-1} for rare-event triggers with EMCAL, PHOS and MUON
- pp collisions at $\sqrt{s}$ = 0.9 and 2.76 TeV
  - Int L = 0.14 and 1.3 nb^{-1}, respectively.
- Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV in 2010 and 2011
  - Int L = 10 μb^{-1} in 2010
  - An order of magnitude higher in 2011
  - Triggers in 2011
    - Most central and semi-central events, and rare event selection with EMCAL, MUON, and ultra-peripheral collisions
- p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV in 2013
  - 4 TeV for the proton beam and 1.58 TeV per nucleon for *Pb* beam 1.7×10^8 events

Centrality Determination

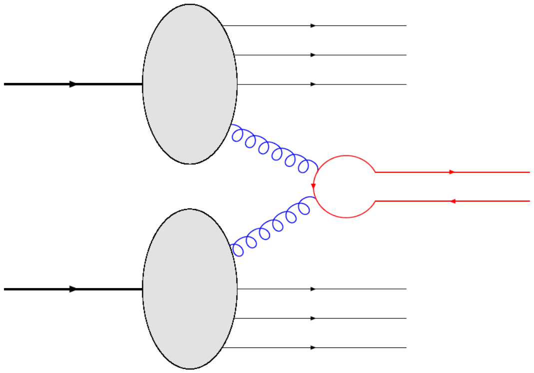
- In Pb-Pb, clear correlation between collision geometry (impact parameter) and experimental observables
  - Centrality measure, based on forward detectors
- ALICE
  - VZERO scintillator detectors
  - VZERO-A: $2.8 < \eta < 5.1$ and VZERO-B: $-3.7 < \eta < -1.7$

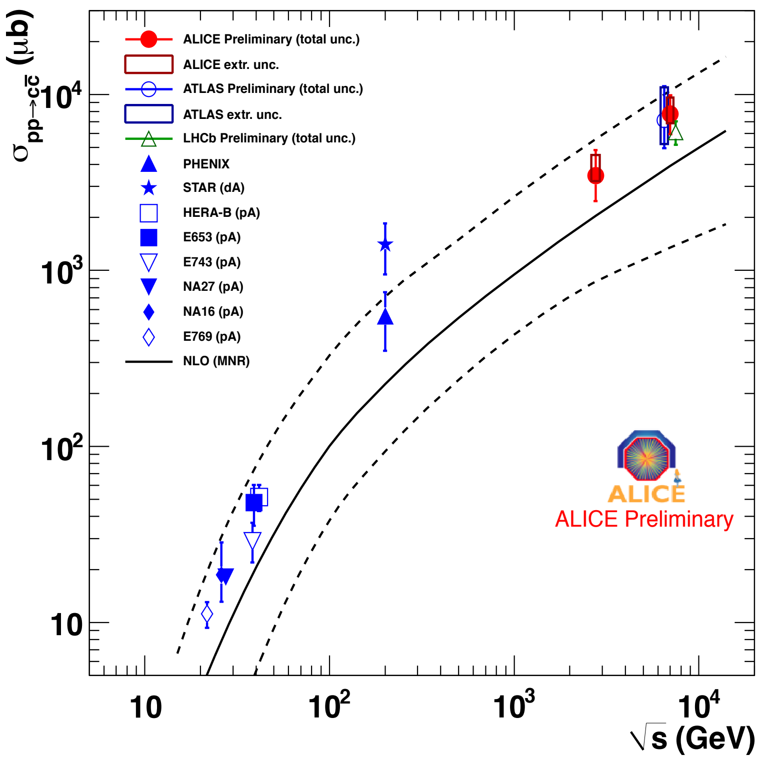


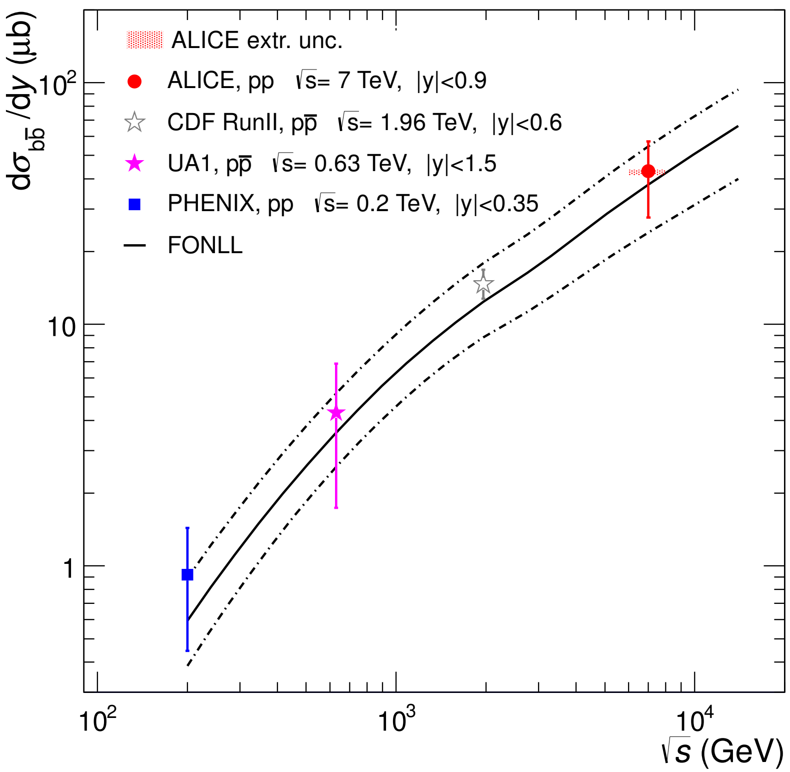
HEAVY FLAVOR IN PP & PB-PB COLLISIONS

Heavy Quark Production in pp

- Two-gluon fusion process
- Copious production at LHC
  - Charm: ~5mb@2.76TeV (8.5mb@7TeV)
  - Bottom: ~0.3mb@7TeV



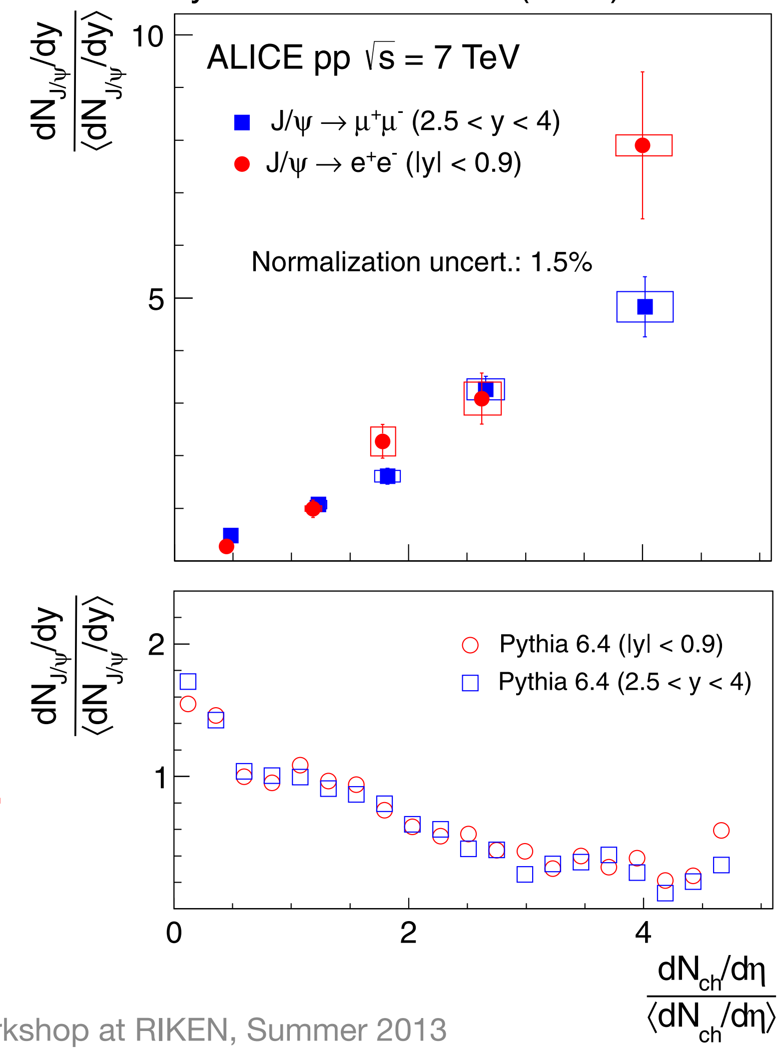




J/ψ production as a function of dN_{ch}/dy in pp collisions at $\sqrt{s}$ = 7 TeV

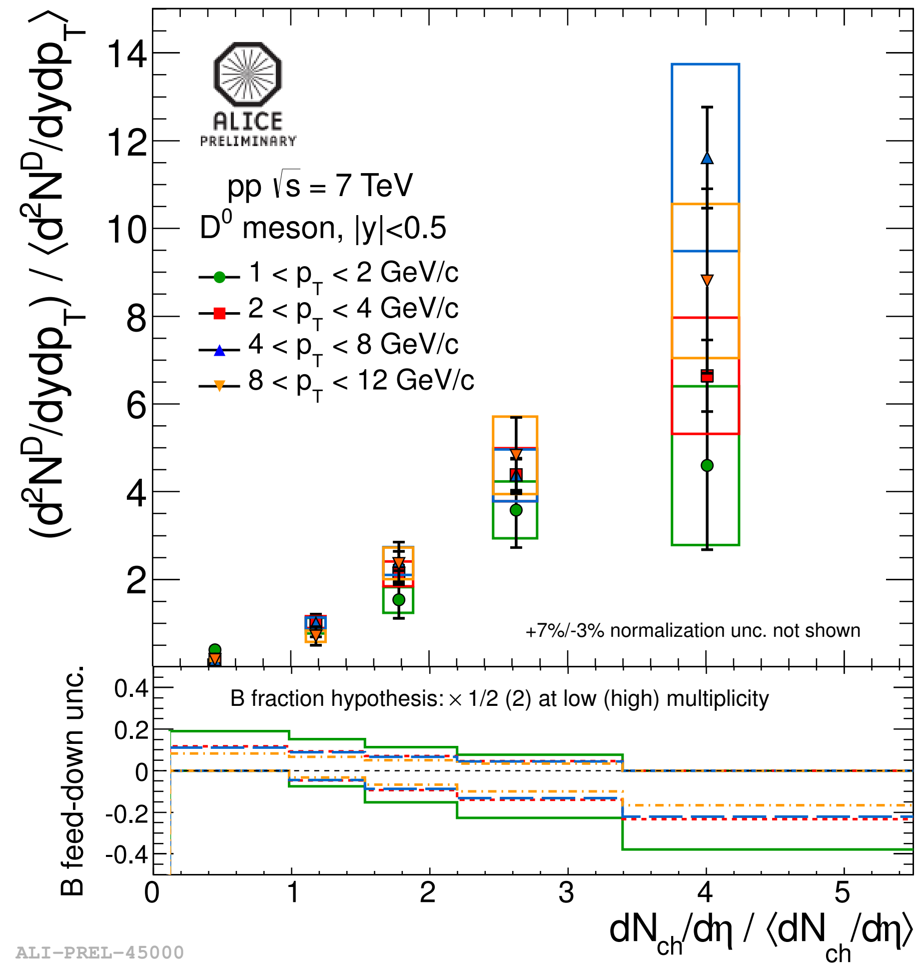
- $dN_{J/\psi}/dy$ depends almost linearly on dN_{ch}/dy
- Not accounted for by the direct hard process, as implemented in Phythia 6.4
- Suggesting the effect of MPI (multi parton interaction) in c-cbar production
  - c-cbar production is *NOT* be a very hard process at LHC?
- Further studies are interesting for Υ, open charm, …

Physics Letters B 712 (2012) 165–175



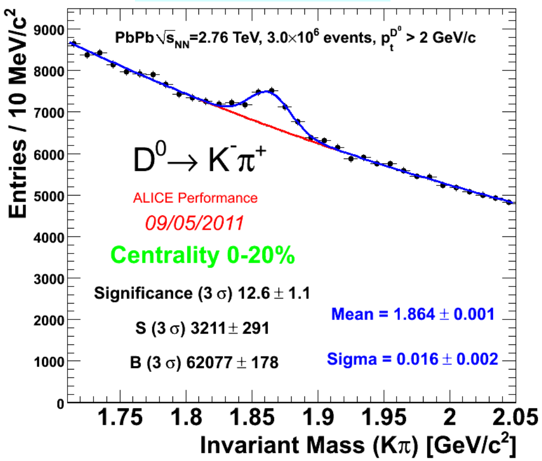
D Yield in pp Collisions

- dN_D/dy is almost linearly dependent on dN_{ch}/dy
- Similar trend to that for J/ψ

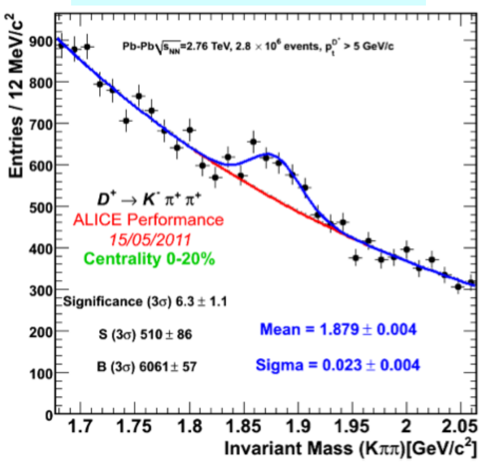


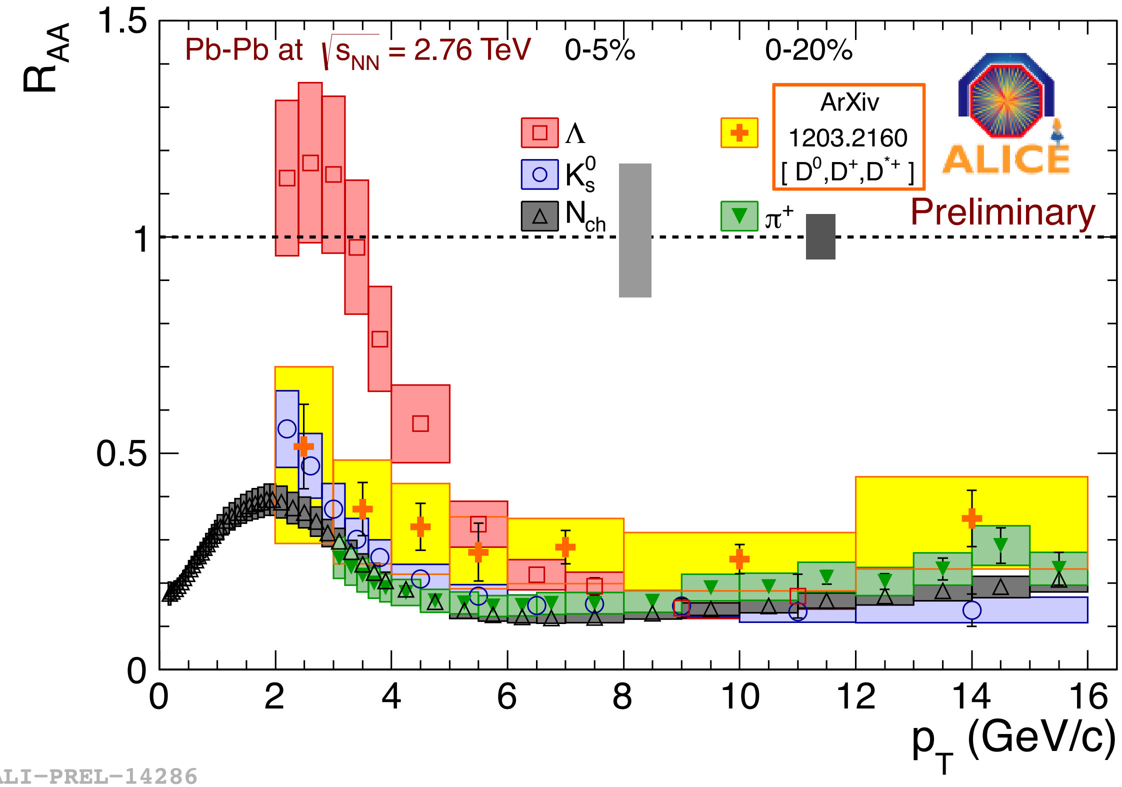
Exclusive D Meson Measurement

$D^0 \rightarrow K\pi$



$D^+ \rightarrow K\pi\pi$



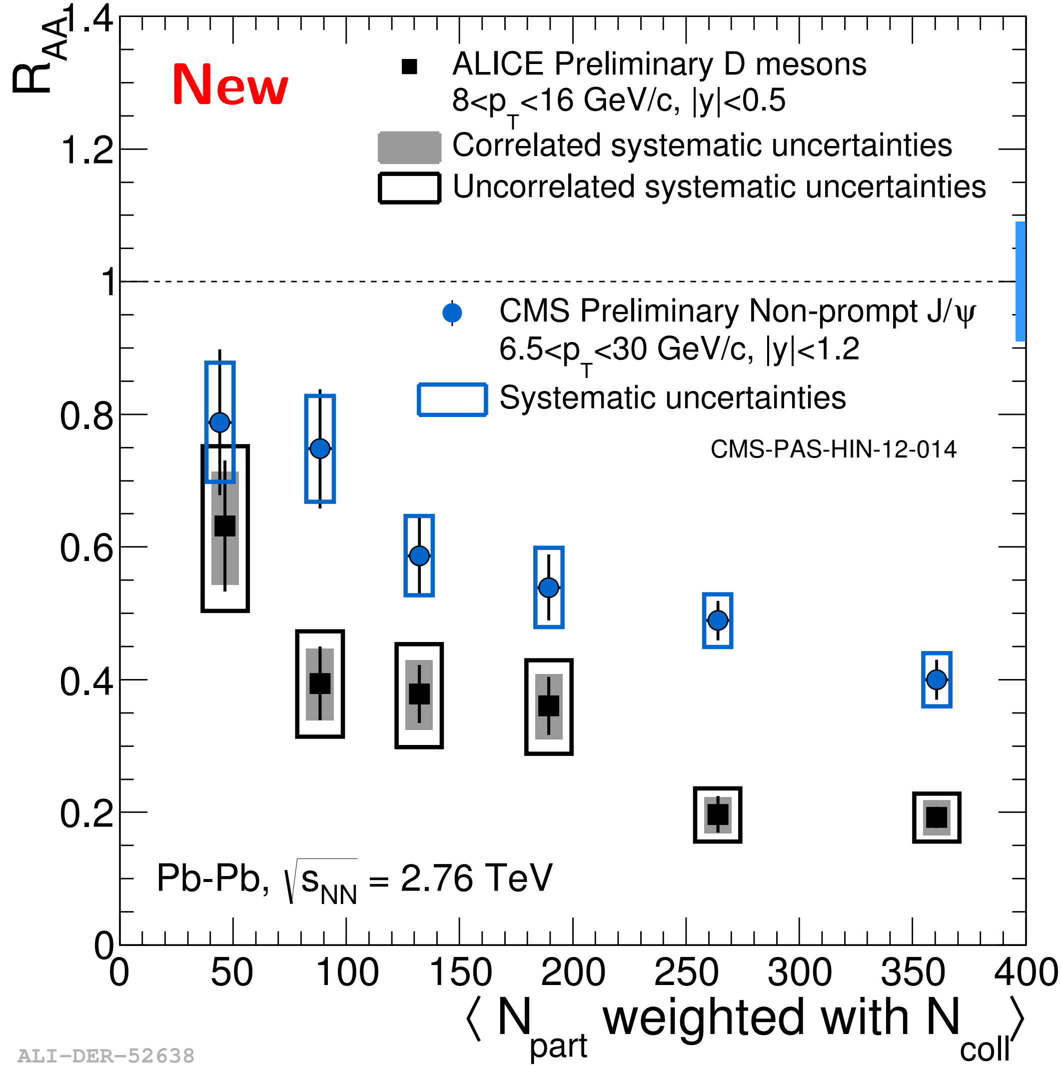


- D has slightly larger R_{AA} over π and K in all p_T range, while behavior is similar
- Different behavior between Λ and mesons at $p_T < 8$ GeV/c, consistent with the quark recombination picture

R_{AA} of D and non-prompt J/ψ

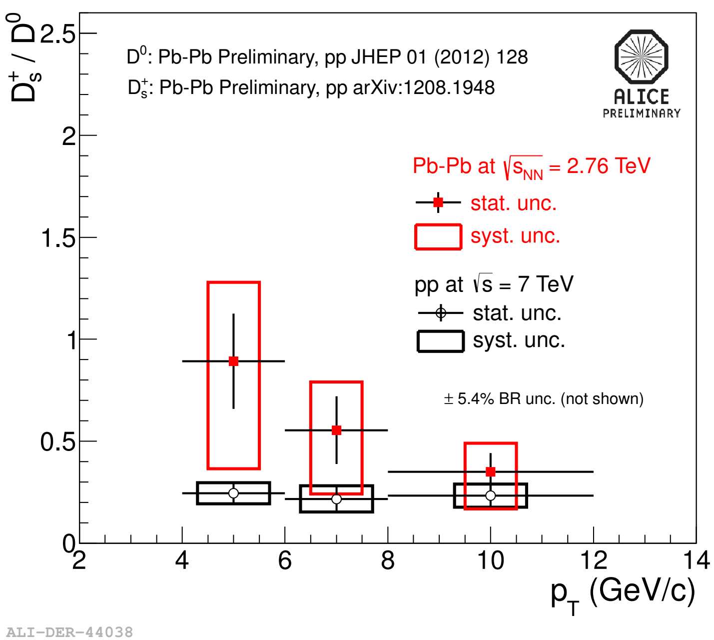
- Non-prompt J/ψ from B decay
- Previous comparison in 2012: $\langle p^D_T \rangle \neq \langle p^B_T{}^{(\to J/\psi)} \rangle$
- New comparison: compatible p_T range for D and the parent B of non-prompt J/ψ

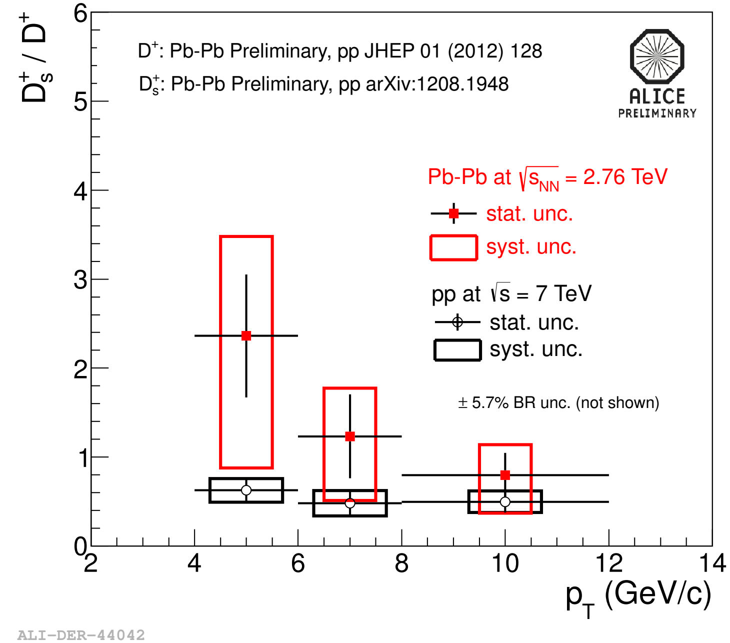
- ***R_{AA}(np-J/ψ) > R_{AA}(D)***
  - Getting clear in the new comparison
  - Mass hierarchy in energy loss process



D_s^+ vs $D^{0,+}$

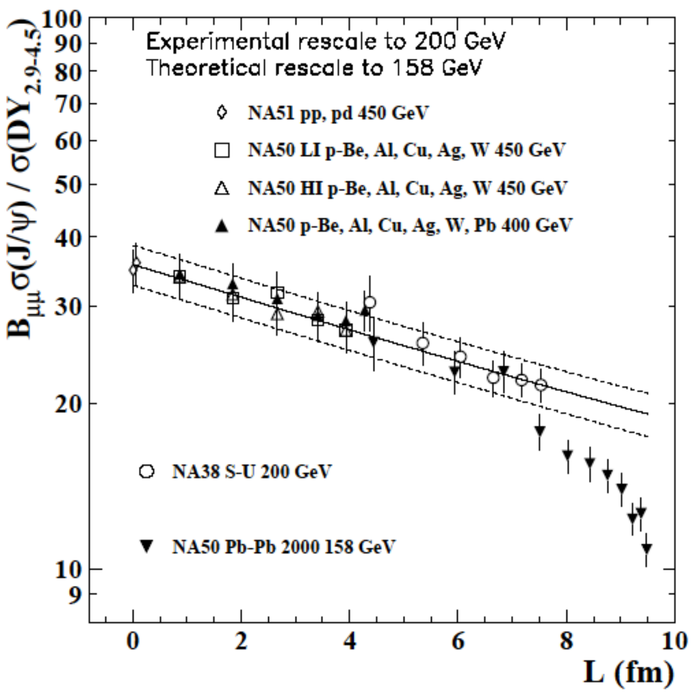
- Larger D_s/D ratio in Pb-Pb than in pp for p_T < 8 GeV/c
- Qualitatively consistent with the **quark recombination picture**; additional D_s production in Pb-Pb collisions

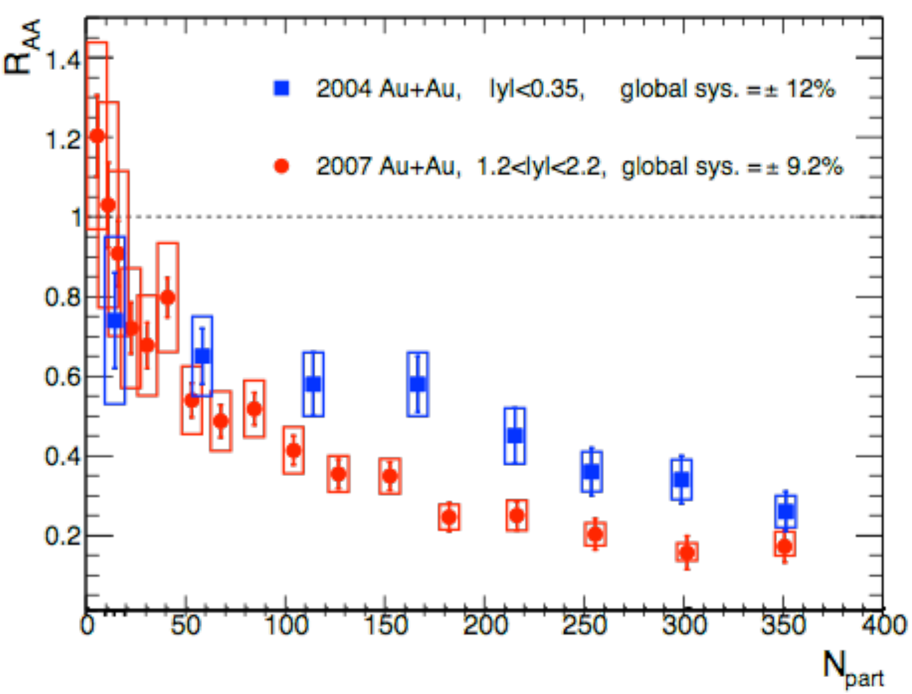




J/ψ at SPS & RHIC

- J/ψ suppression; proposed as a probe of deconfinement by T. Matsui and H. Satz (1985)
- Anomalous suppression was observed in Pb-Pb at SPS
- Suppression with a similar magnitude to SPS was observed at RHIC

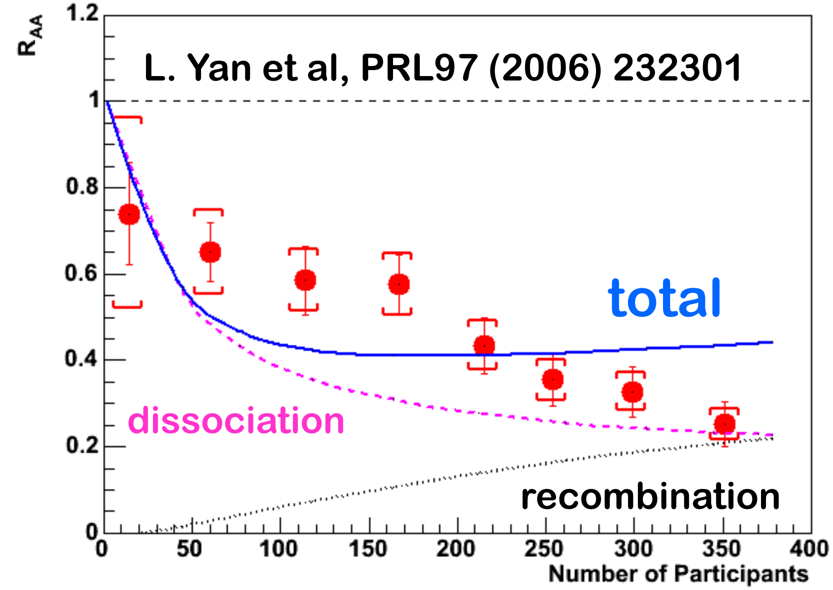




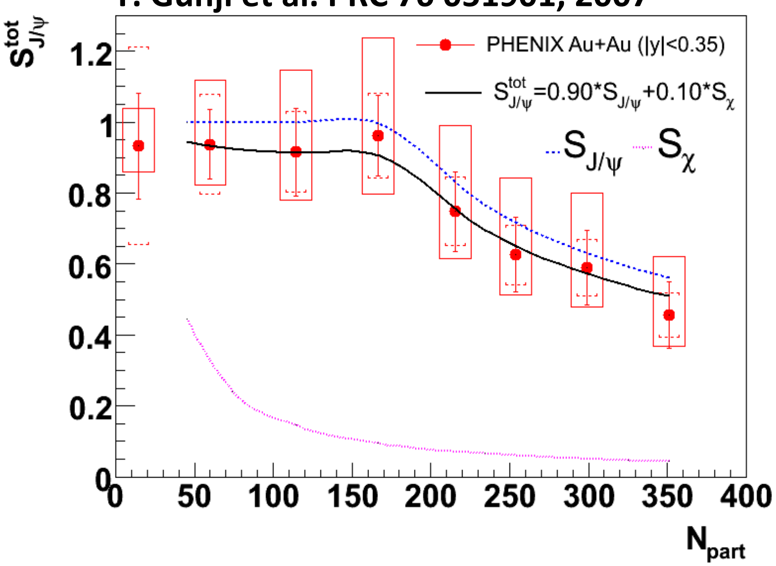
Comparison with Models

- Sequential melting
- Dynamical dissociation
- Quark recombination

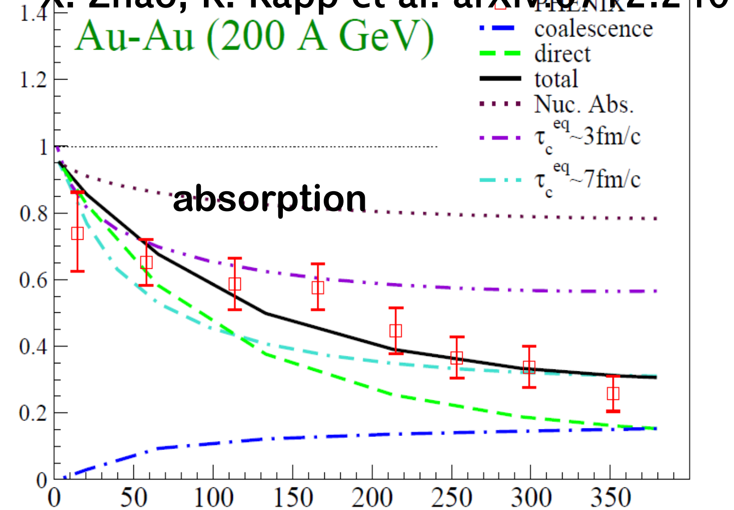
- Not significant contribution from recombination process at RHIC



T. Gunji et al. PRC 76 051901, 2007

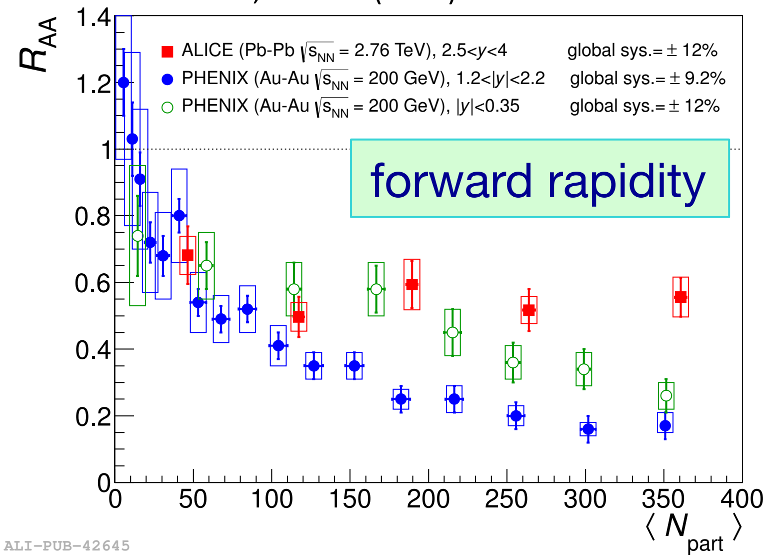


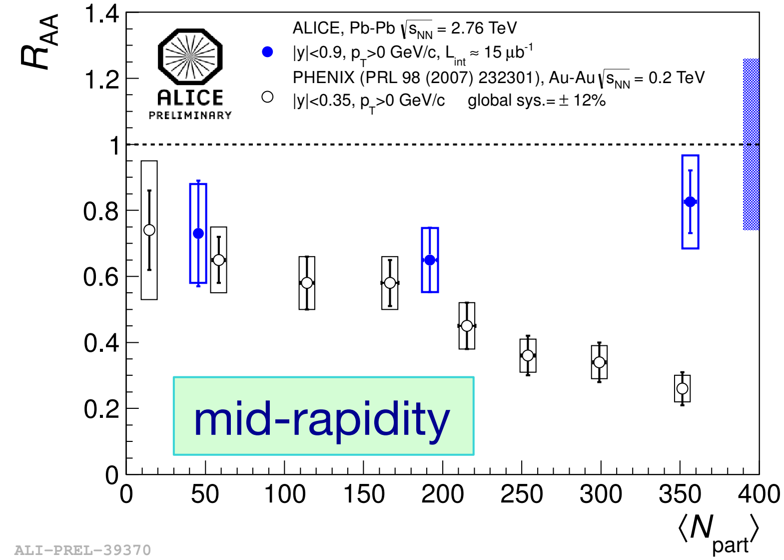
X. Zhao, R. Rapp et al. arXiv:0712.2407



$R_{AA}(J/\psi)$ at LHC

PRL109, 072301 (2012)

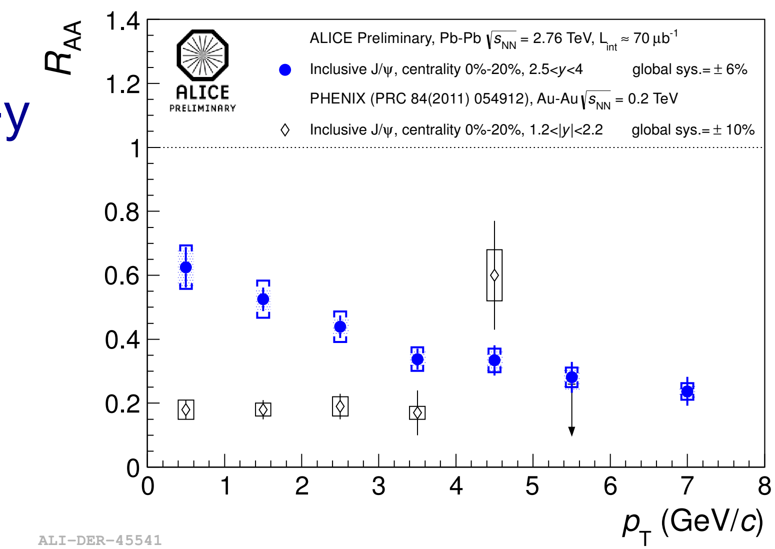




- $R_{AA}(J/\psi)$ is large at LHC
  - $R_{AA}(J/\psi)$ at mid-y > $R_{AA}(J/\psi)$ at forward-y
- $R_{AA}(J/\psi)$ is large at low p_T

  is small at high p_T

Consistent with large contribution from recombination process



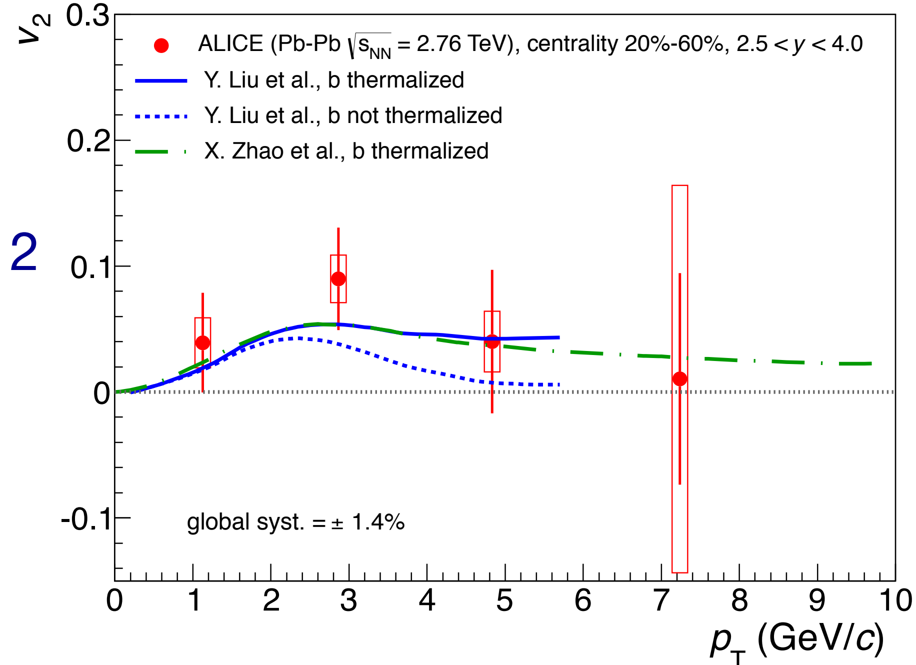
ALICE

$v_2(J/\psi)$ at LHC

- Sizable $v_2(J/\psi)$ at LHC, in contrast to the case at RHIC
  - Non-prompt-J/ψ is ~7 % for p_T < 12 GeV/c from bottom decay
- Condition for finite $v_2(J/\psi)$ = Recombination of charms with finite v_2
- Consistent with the two model calculations
  - Both models assume charm is thermalized (and flows)
  - Two cases for bottoms: thermalized, and NOT thermalized

    -> need more statistics to judge

arXiv:1303.5880



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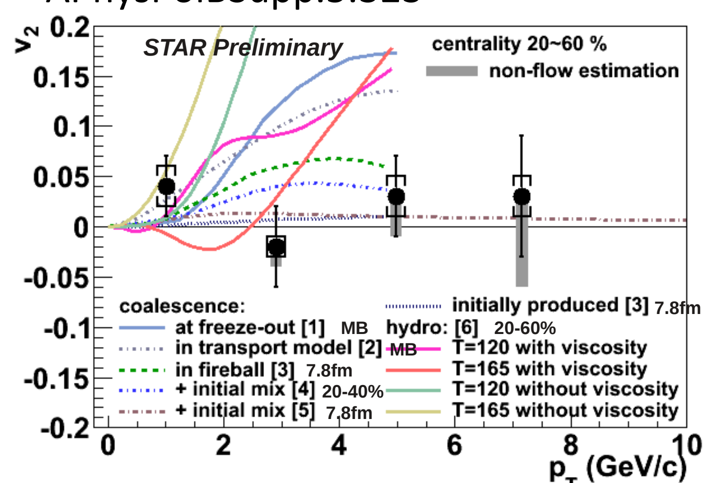
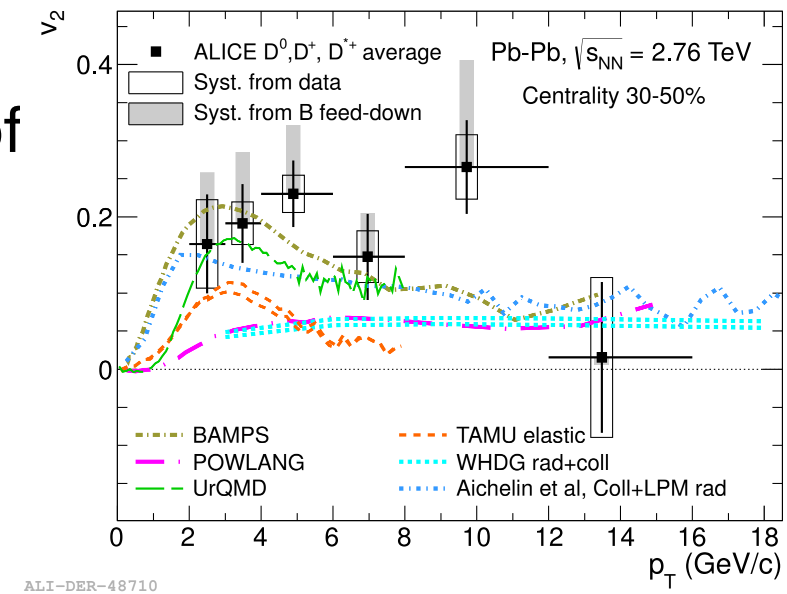


Open Charm v_2

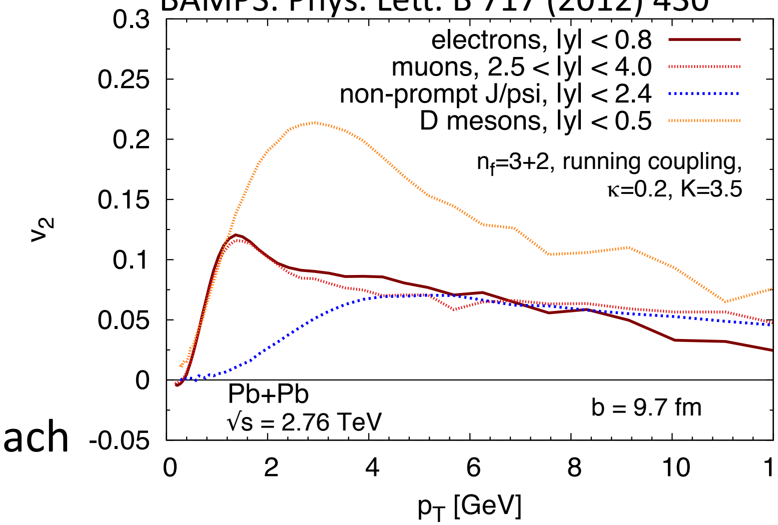
- Sizable v_2 of D mesons at LHC, suggesting rapid thermalization of charm
  - It also serves as a strong backup of the finite $v_2(J/\psi)$

- *Non-prompt J/ψ and D for investigating bottom thermalization will be the key measurement*

arXiv:1207.7239



BAMPS: Phys. Lett. B 717 (2012) 430



BAMPS: transport model, named as Boltzmann Approach to Multi-Parton Scatterings

RESULTS FROM P-PB COLLISIONS

p-A Collisions

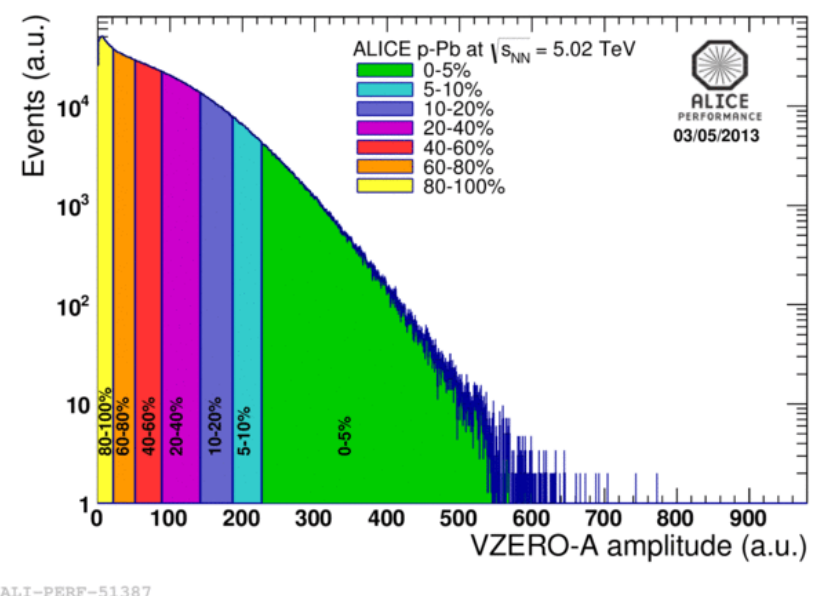
- Reference of the initial state of A-A collisions
  - Cold nuclear matter (CNM) effect
  - nPDF; possible gluon saturation

- Recent findings indicate that p-A may provide *a unique circumstance to study early stage, the least known stage, in heavy ion collisions*
  - Origin of fluctuations
  - Thermalization process; highly non-perturbative & non-equilibrium process
  - *TO MY SURPRISE: Space-time evolution as an thermalized system??*

p-Pb Runs at LHC

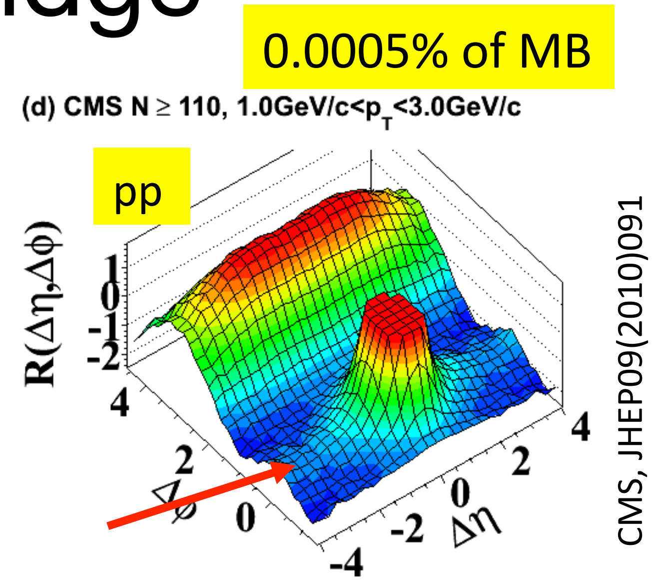
- $\sqrt{s_{NN}}$ = 5.02 TeV
  - 4 TeV p beam / 1.58 TeV per nucleon Pb beam
  - Rapidity shift of 0.465 (in proton-going direction)
- 2013 Feb./March run with both beam directions (p-Pb and Pb-p)
  - Low luminosity running; ~130 million MB events (50 μb^{-1})
  - High luminosity running; ~30 nb^{-1} (muon trigger -> J/ψ)

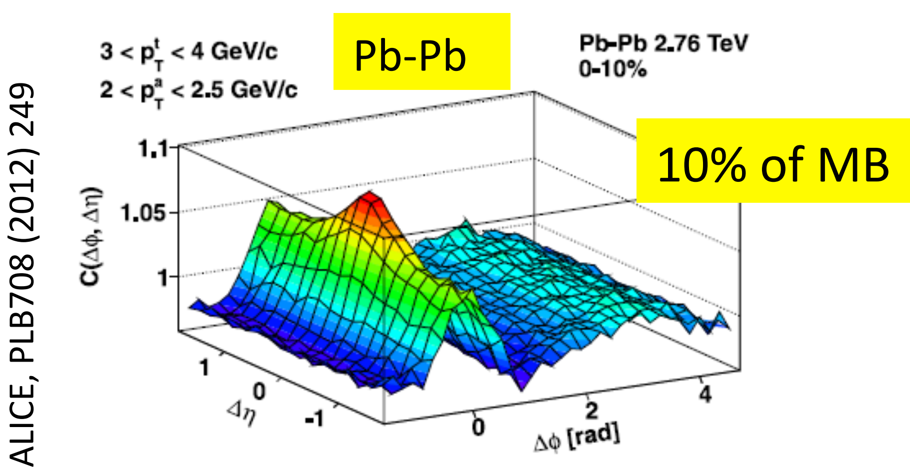
- A straightforward correlation between collision geometry and multiplicity is not found in p-Pb collisions
- Event classes are defined as percentiles of the measured sample
  - VZERO scintillator detectors to measure particle multiplicity; 2.8 < η < 5.1 and -3.7 < η < -1.7
  - Only Pb direction (2013 analysis)

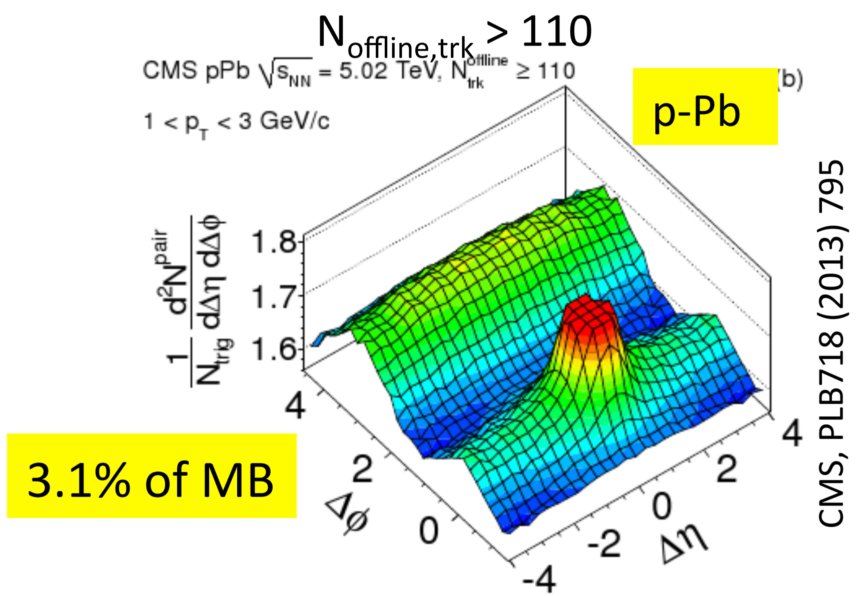


The Near-Side Ridge

- Well known feature in Pb-Pb collisions (→ collective flow)
- Observed in extremely high-multiplicity pp collisions by CMS
- Somehow expected in p-Pb, but still surprising, in particular, because of its amplitude



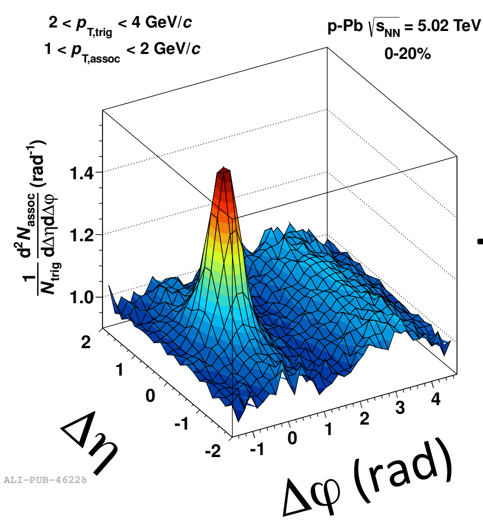




The Double Ridge

- No ridge seen in 60-100% and similar to MB pp collisions
- Subtraction of (peripheral yield) from (central yield) to "isolate" ridge contribution from jet correlations

0-20%



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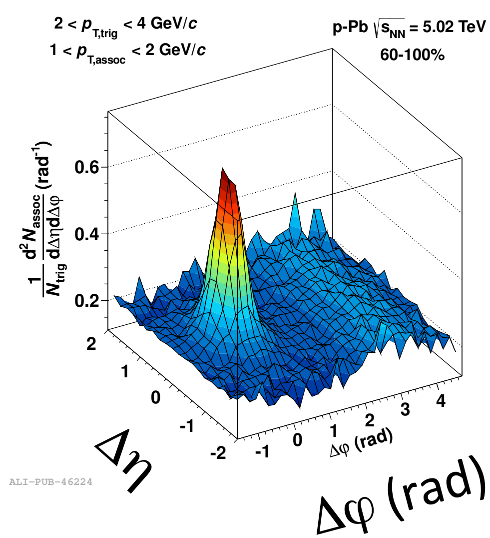
60-100%



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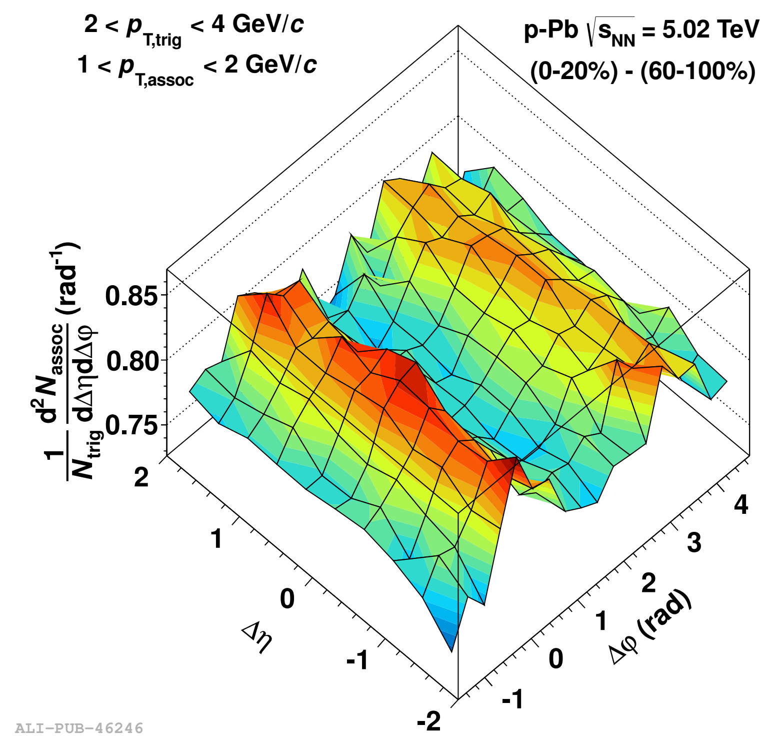


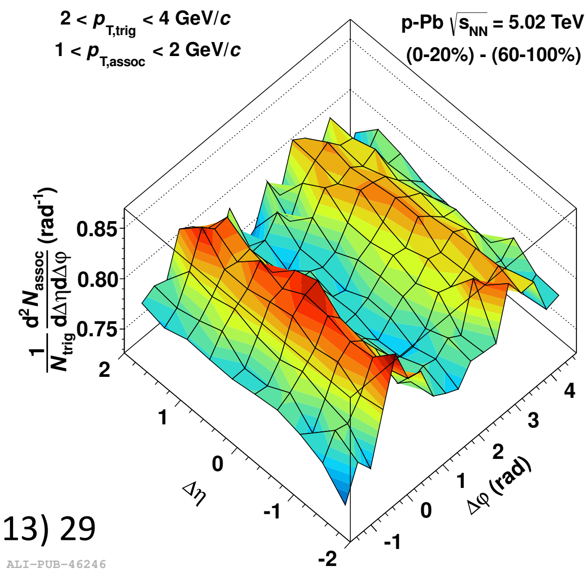
ALICE, PLB719 (2013) 29

Projections to $\Delta\varphi$

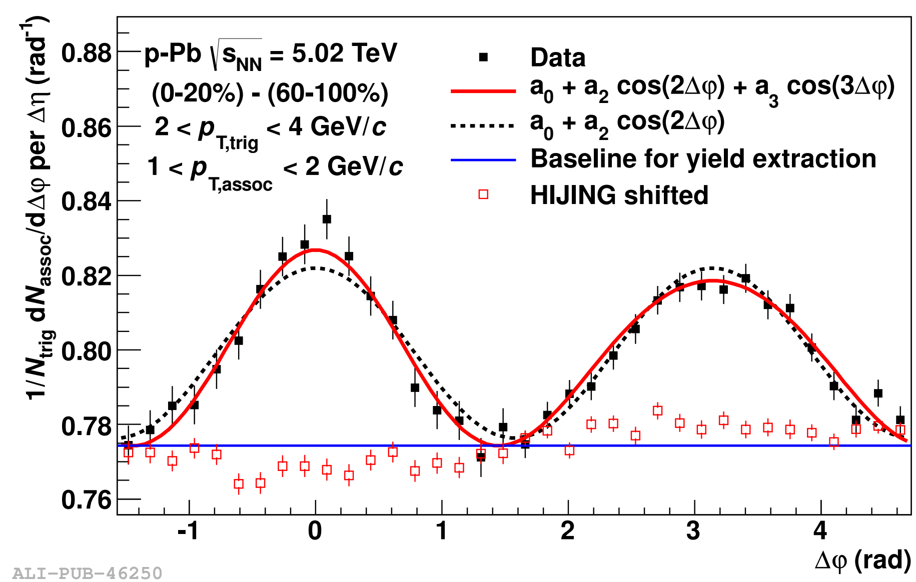
- Modulation mostly of cos $2\Delta\varphi$ type
- Small but significant cos $3\Delta\varphi$ term needed

$$v_n = \sqrt{a_n / b}$$

- Same procedure applied on HIJING simulated events → no significant modulation remains



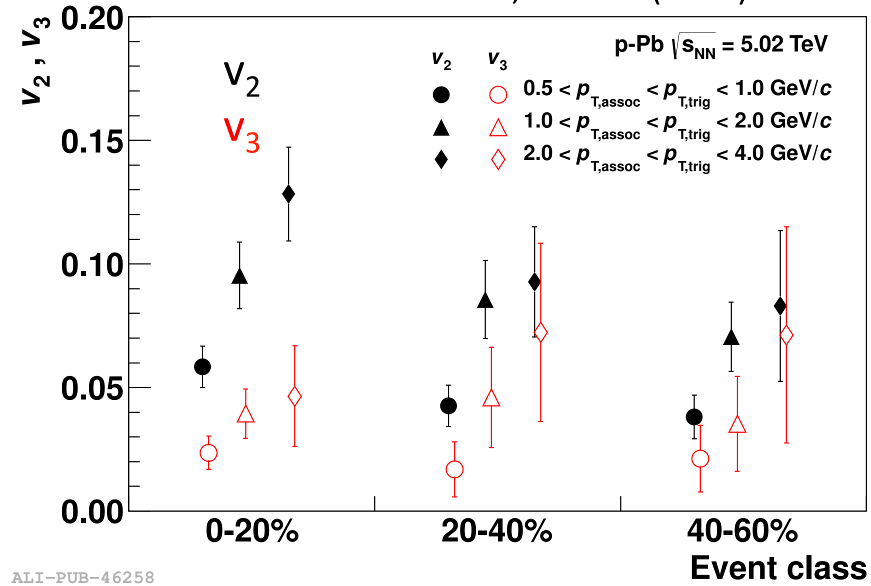
ALICE, PLB719 (2013) 29

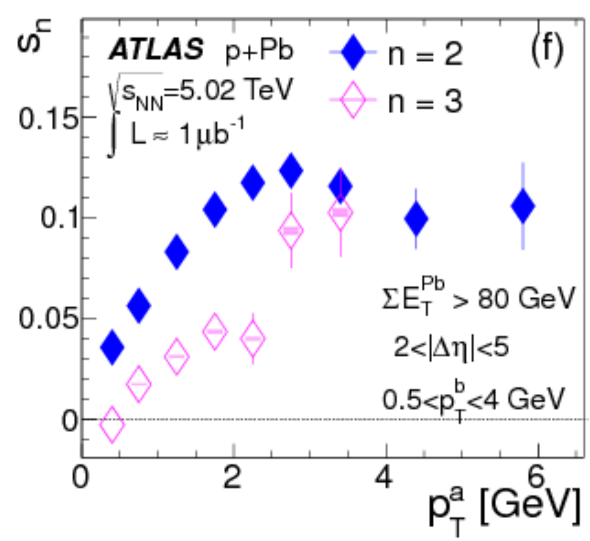


v_2 and v_3 Coefficients

- v_2 and v_3 as a function of p_T for different event classes (each 60-100% subtracted)
- v_2
  - Strong increase with p_T
  - Mild increase with multiplicity
- v_3
  - Increase with p_T within large uncertainties
- Similar results by ATLAS
- PHENIX reports similar v_2 values in d-Au at 200 GeV (arXiv: 1303.1794)

ALICE, PLB719 (2013) 29



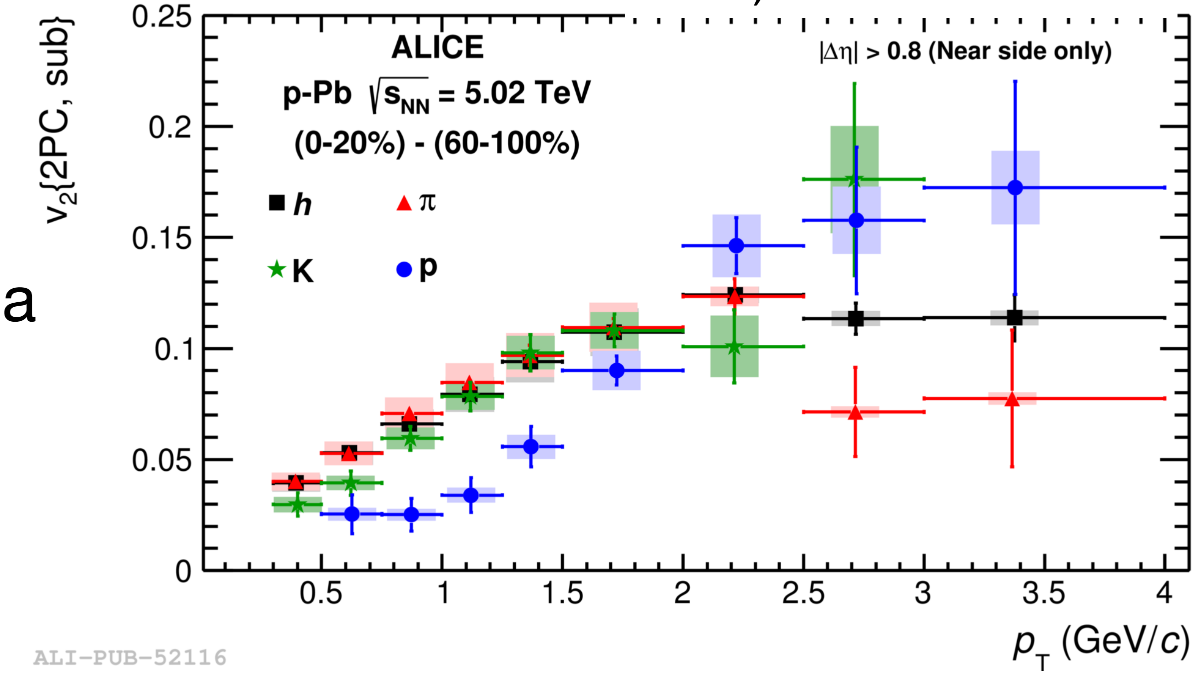


ATLAS, PRL110, 182302 (2013)

v_2 of π, K, p

ALICE, arXiv:1307.3237

Mass ordering in v_2 suggests collective flow in the hadronic phase, where mass is a factor to make v_2 different



- Question is whether hydro is still applicable in a system with a transverse extension of a few fm?
  - Maybe so, since the effective interacting range in sQGP is less than 1 fm
  - Maybe NOT, since surface effect should be dominant …

ALICE UPGRADE PLAN

Present ALICE program

2013–14: Long Shutdown 1 (LS1)

- completion of TRD and CALs

- 2015: Pb–Pb at $\sqrt{s_{NN}}$ = 5.1 TeV
- 2016–17: (maybe combined in one year) Pb–Pb at $\sqrt{s_{NN}}$ = 5.5 TeV

2018: Long Shutdown 2 (LS2)

- 2019: probably Ar–Ar high-luminosity run
- 2020: p–Pb comparison run at full energy
- 2021: Pb–Pb run to complete initial ALICE program

2022 Long Shutdown 3 (LS3)

- Physics reach extended by the new energy and completion of TRD and CALs
- Improvement of statistical significance of our main results by a factor about 3 --- ***this is enough?***

Scope of Upgrade

- Run ALICE at high rate, and inspect all events, in accord with the LHC luminosity upgrade; targeting 50 kHz minimum bias rate for Pb–Pb

- Upgrade detectors and electronics by the end of LS2 (2018), and run with upgraded program after LS2
  - Target: more than 10 nb^{-1} of integrated luminosity, which implies running with heavy ions a few years after LS3 (2022)
  - A factor of >100 increase in statistics; (maximum readout with present ALICE ~ 500 Hz) for core physics programs
  - For triggered probes increase in statistics by factor > 10

ALICE

Core physics motivation

- Main physics topics, uniquely accessible with the ALICE detector:
- Heavy-flavor transport parameters:
  - diffusion coefficient – azimuthal anisotropy and R_{AA}
  - in-medium thermalization and hadronization – meson-baryon
  - mass dependence of energy loss – R_{AA}
- Low-mass and low-pt di-leptons
  - chiral symmetry restoration – vector-meson spectral function
  - space-time evolution of the QGP – radial and elliptic flow of emitted radiation
- J/ψ , ψ', and cc states down to zero p_T in wide rapidity range
  - charm and bottom thermalization – R_{AA}, elliptic flow
  - regeneration process – central vs. forward production
- Jet quenching and fragmentation
- Heavy-nuclei, hyper-nuclei & exotics

ALICE detector upgrade

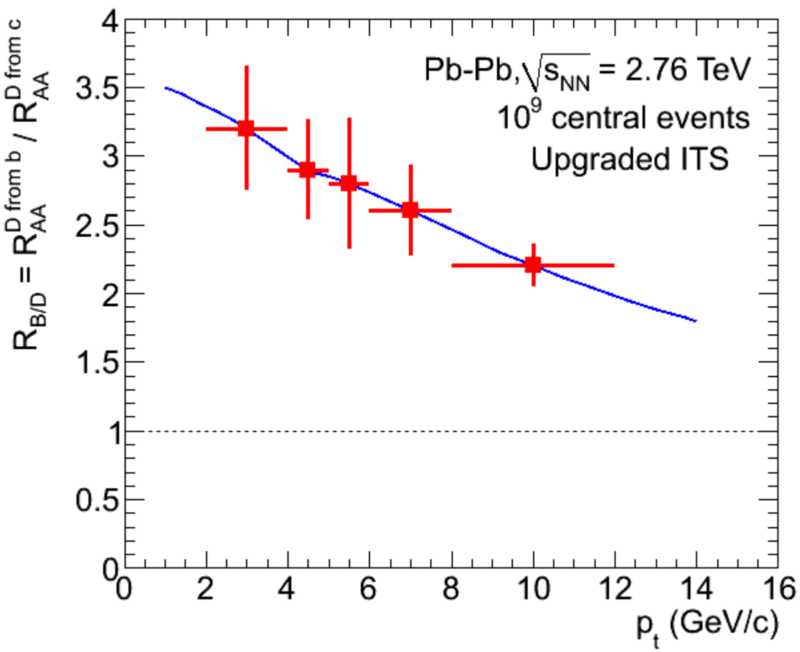
- High-luminosity operation without dead-time
  - Improved vertexing and tracking at low p_T
  - Preserve particle-identification capability
- Target for installation and commissioning LS2 (2018)

- LOI approved by LHCC, TDR in preparation:
  - New, smaller radius, beam pipe
  - Performance and rate upgrade of inner tracker (ITS)
  - Non–stop operation of TPC without gating grid; MWPC --> GEM
  - High-rate upgrade for the readout of the TPC, TRD, TOF, CALs, DAQ-HLT, Muon-Arm and Trigger detectors
- LOI in preparation:
  - MFT: b-tagging for J/ψ, low-mass di-muons

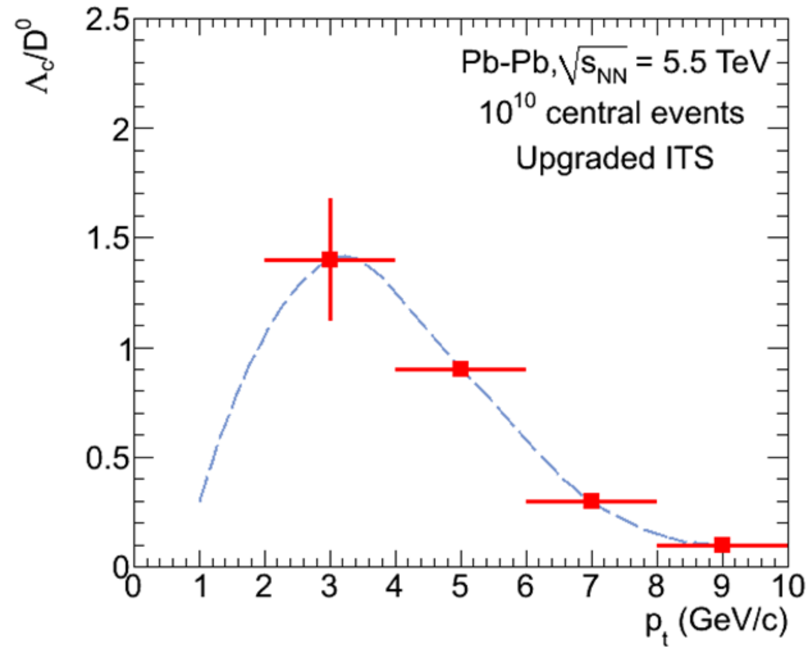
Example: Heavy flavor production

- Bottom via non-prompt D^0 -> $K + \pi$ = mass dependence of energy loss
  - needs precision of the new ITS
- Λ_c = hadronization process; baryon-meson universality
  - needs both: the new ITS and luminosity ~ 10 nb^{-1}

B/D R_{AA} suppression

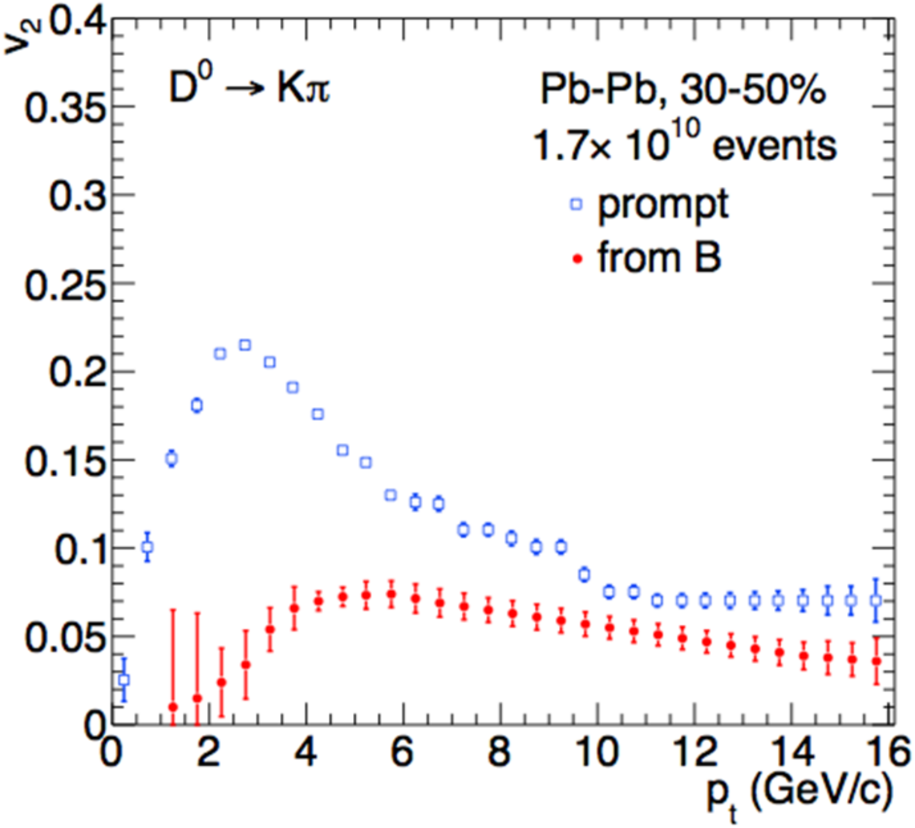


Λ_c/D enhancement

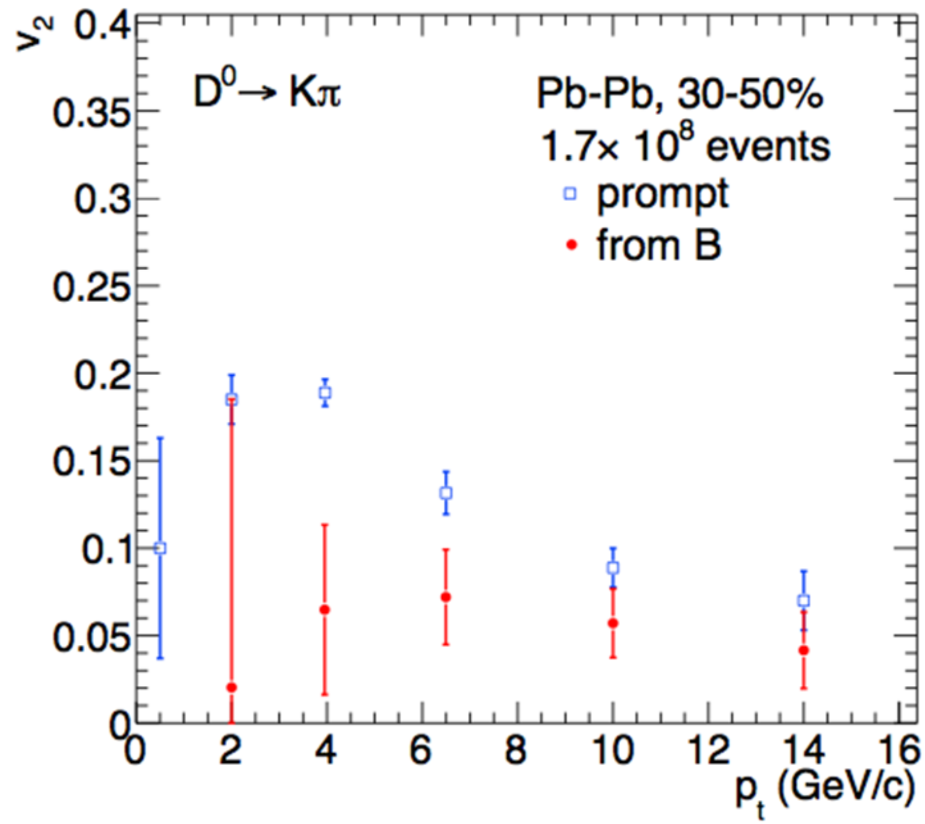


Example: Heavy flavor v_2

L_{int}=10 nb^{-1}



L_{int}=0.1 nb^{-1}



- Need >> 1 nb^{-1} for precise measurement of charm and beauty v_2
- Other key measurements: Λ_b, Ξ_c, B decays, virtual γ, ψ', χ_c, tagged jets…

SUMMARY & OUTLOOK

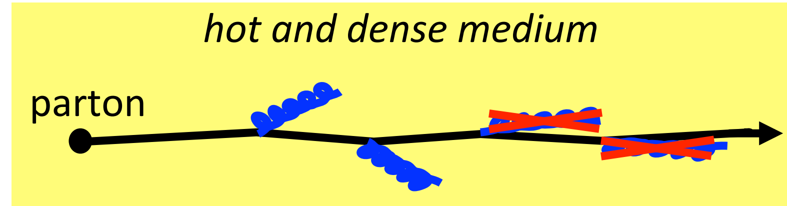
Summary & Outlook

- ALICE has been producing rich results at full speed
- Various results on Open heavy flavor and Quarkonia
  - Exclusive D meson reconstruction
  - Energy loss and thermalization of heavy quarks in Pb-Pb
  - Recombination process for J/ψ production in Pb-Pb
- Interesting results in p-Pb collisions
  - p-Pb May NOT be a mere reference of initial state in Pb-Pb
  - Double ridge structure is an example
- Importance of data with higher statistics
- A major upgrade
  - Pb-Pb data with 50 kHz (= MB Pb-Pb rate after LHC intensity upgrade); ~100 times more than current (-500Hz)
  - New ITS (inner tracking system), GEM TPC with no gating grid, faster electronics and wider bandwidth …

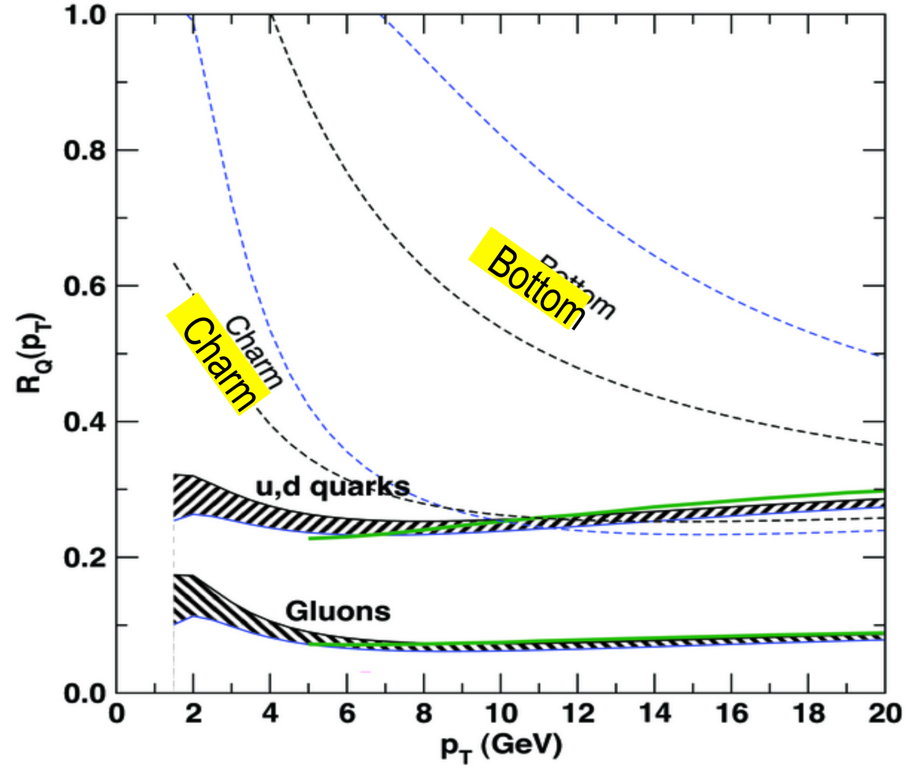
BACKUP

Heavy Flavor as Probes

- Production = initial stage; pQCD
- High p_T → energy loss
  - Dead-cone effect
    gluon radiation suppressed at small angles ($q < m_Q/E_Q$)
    Y. Dokshitzer, D. Kharzeev, PLB 519, 199 (2001), hep-ph/0106202
- Low to medium p_T → thermalization



Wicks et al., Nucl. Phys. A784, 426 (2007)

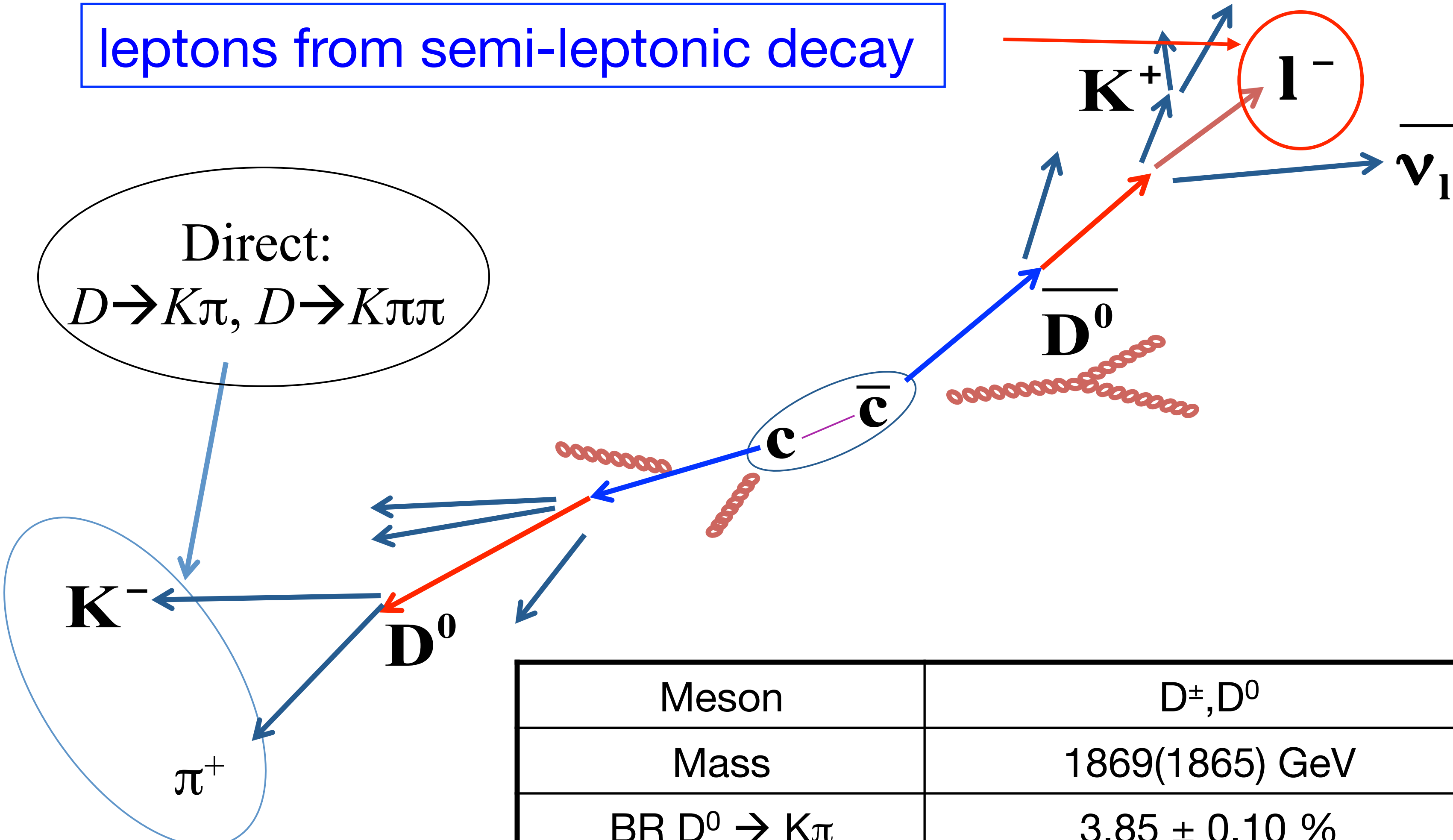


Gluon radiation probability:

$$\omega \frac{dI}{d\omega}\bigg|_{HEAVY} = \frac{\omega \frac{dI}{d\omega}\Big|_{LIGHT}}{\left(1 + \left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^2}$$

How to Measure Heavy Quarks?

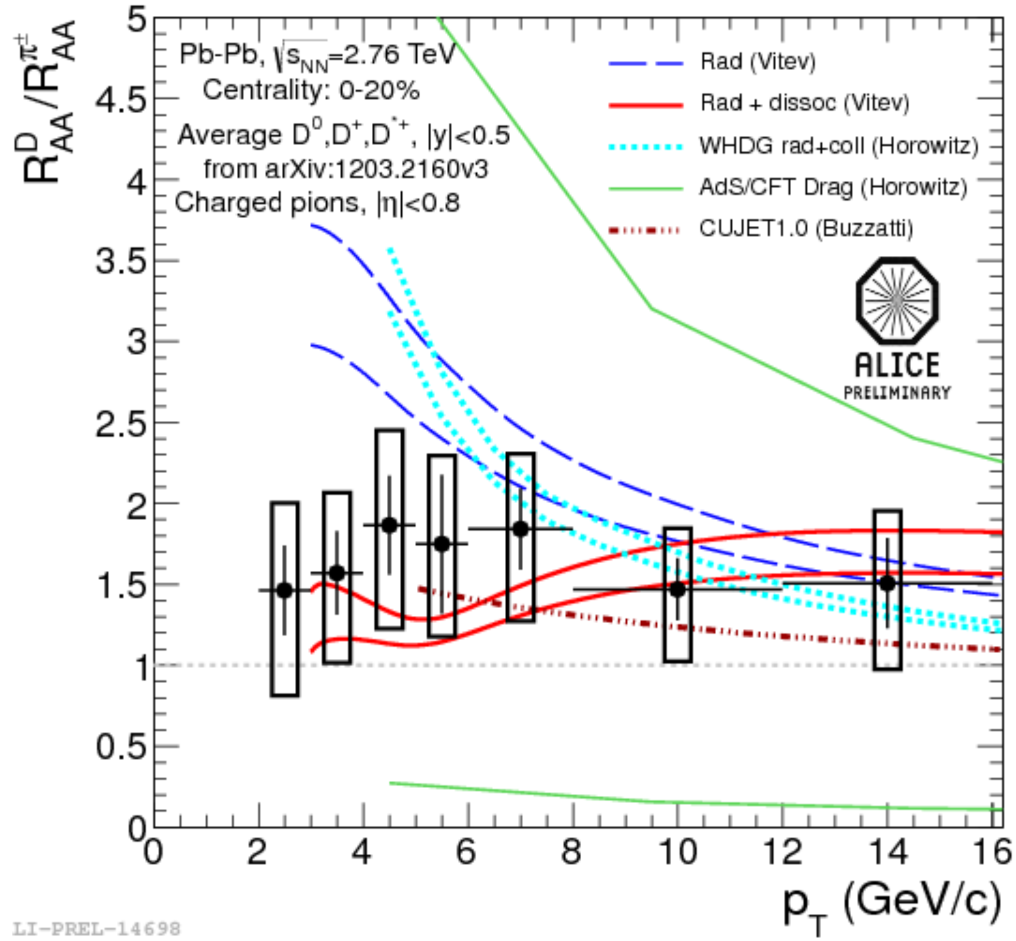
leptons from semi-leptonic decay



Meson	$D^{\pm}, D^0$
Mass	1869(1865) GeV
BR $D^0 \rightarrow K\pi$	3.85 ± 0.10 %
BR $D \rightarrow e + X$	$D^{\pm}$: 17.2, D^0: 6.7 %

R^{D}_{AA}/R^{π}_{AA} at LHC

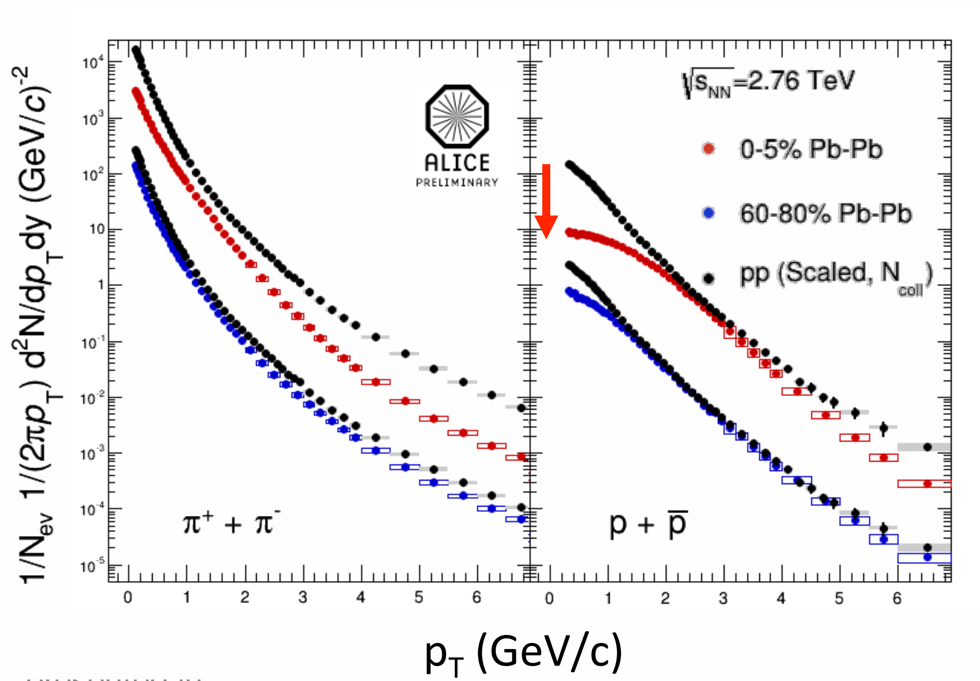
- No large variation with p_T
- $\delta p_T/p_T$ will be interesting to see



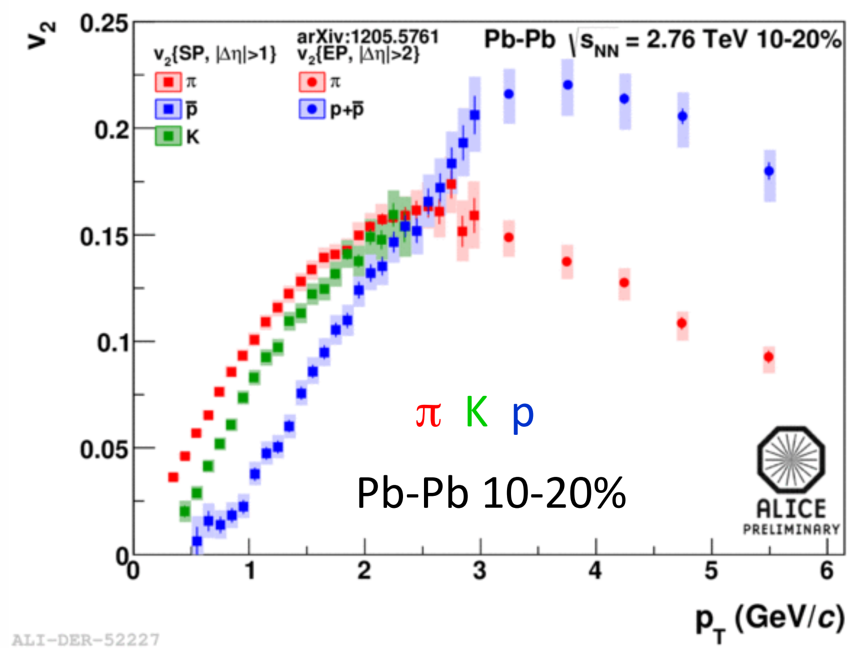
Flow Patterns in Pb-Pb

- For many it smells like flow, but does it flow?
- Particle identification allows further tests
- Particle-mass dependent effects emerge

Radial Flow



Elliptic Flow



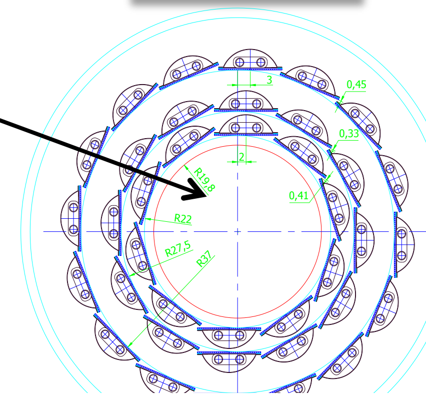
New Inner Tracking

seven layers silicon tracker

pointing resolution improved ~ 3 times

- very close to the interaction point – innermost layer 22 mm

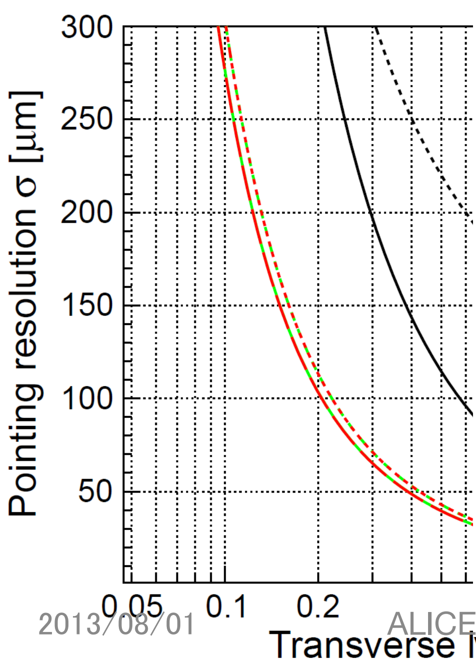
inner barrel

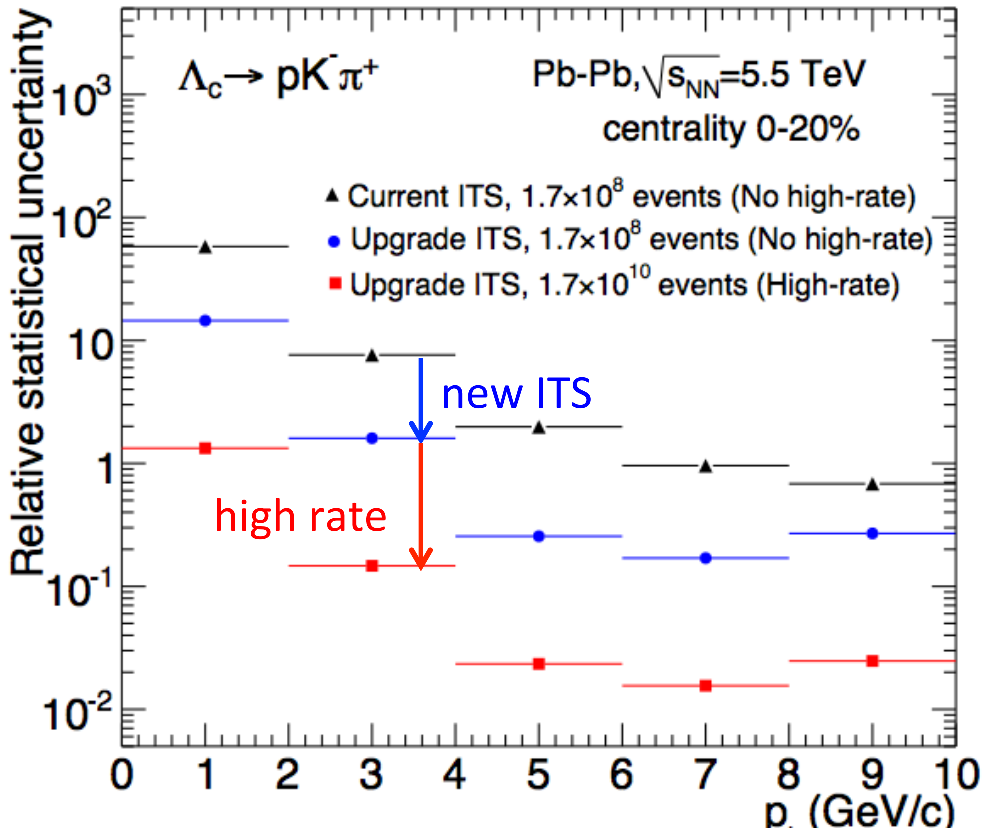


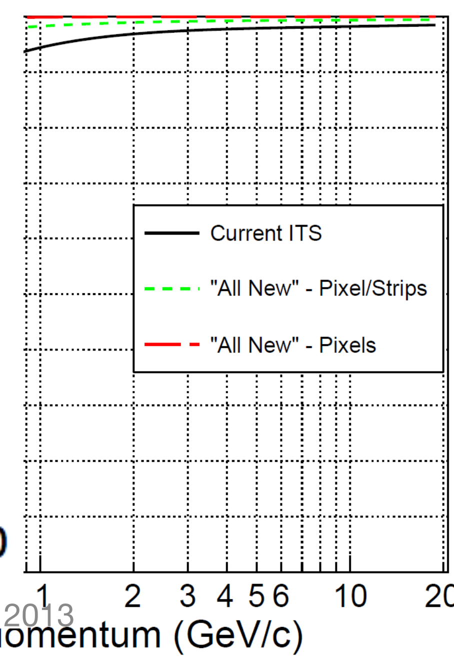
low material bu

substantially im

and p_t resolutio



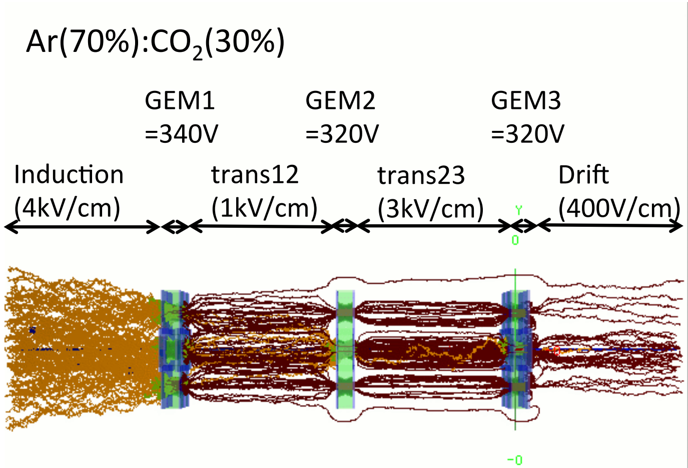




TPC upgrade

- TPC continuous readout without gating grid
  - minimize ion feedback from amplification region
  - change MWPC readout to GEM readout
  - preserving tracking and particle identification capabilities
  - online calibration and data reduction in HLT
  - at 50 kHz of Pb–Pb interaction: reduction factor of ~ 25, event rate tape 25 kHz, throughput to mass storage 20 GB/s

- Event display



- 7 holes/layer are drawn for display (TGeoManager).

```
---- Event Summary 0 ----
*** ElectronsTotal = 238
***** ElectronsDrift = 0
***** ElectronsGEM3UpperMetal = 0
***** ElectronsGEM3Plastic = 1
***** ElectronsGEM3LowerMetal = 15
***** ElectronsTransfer23 = 0
***** ElectronsGEM2UpperMetal = 0
***** ElectronsGEM2Plastic = 2
***** ElectronsGEM2LowerMetal = 17
***** ElectronsTransfer12 = 0
***** ElectronsGEM1UpperMetal = 0
***** ElectronsGEM1Plastic = 14
***** ElectronsGEM1LowerMetal = 87
***** ElectronsInduction = 102
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***** IonsDrift = 33
***** IonsGEM3UpperMetal = 85
***** IonsGEM3Plastic = 9
***** IonsGEM3LowerMetal = 2
***** IonsTransfer23 = 0
***** IonsGEM2UpperMetal = 1
***** IonsGEM2Plastic = 3
***** IonsGEM2LowerMetal = 0
***** IonsTransfer12 = 0
***** IonsGEM1UpperMetal = 76
***** IonsGEM1Plastic = 29
***** IonsGEM1LowerMetal = 0
***** IonsInduction = 0
```
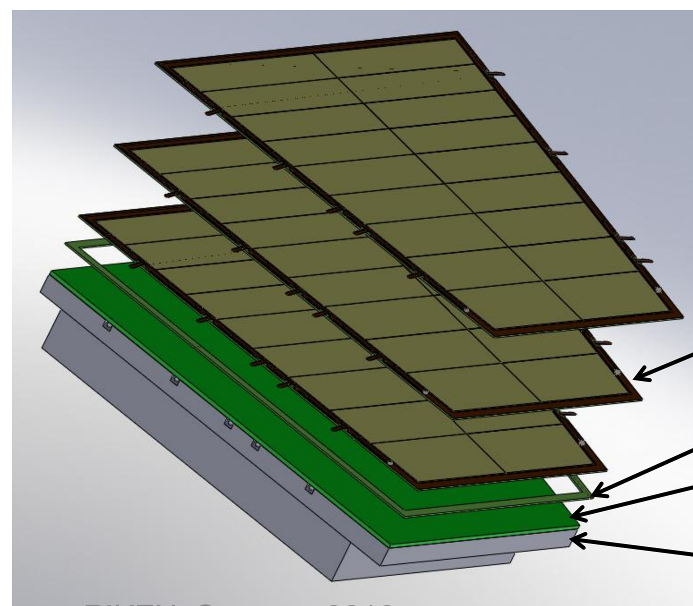
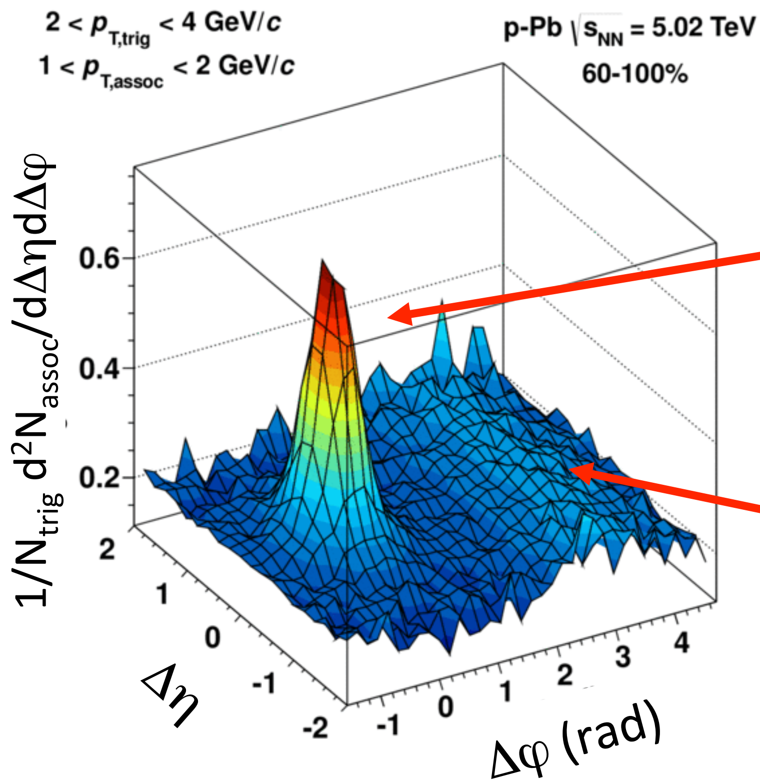



Typical Two-Particle Correlation in p-Pb Collisions



$2 < p_{T,trig} < 4$ GeV/c
$1 < p_{T,assoc} < 2$ GeV/c
40% lowest multiplicity p-Pb

Near-side jet
+ resonances, ...
($\Delta\varphi \sim 0$, $\Delta\eta \sim 0$)

Away-side jet
($\Delta\varphi \sim \pi$, elongated in $\Delta\eta$)

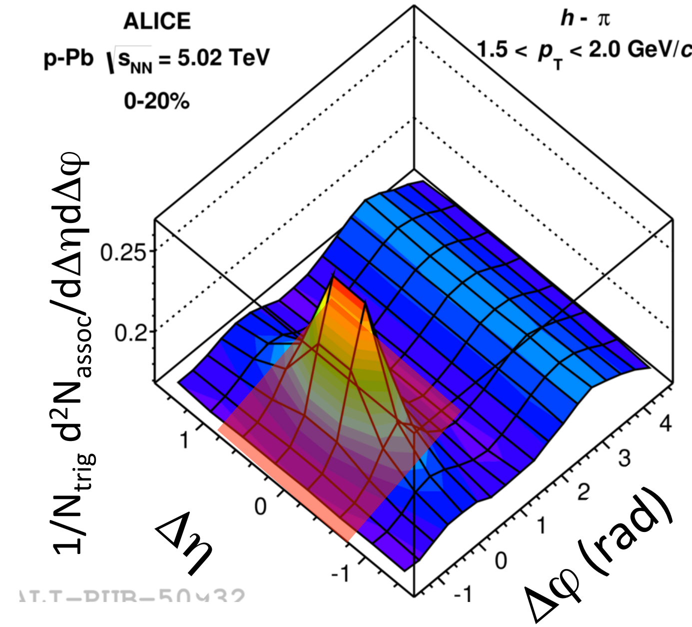
There is some thing more … interesting

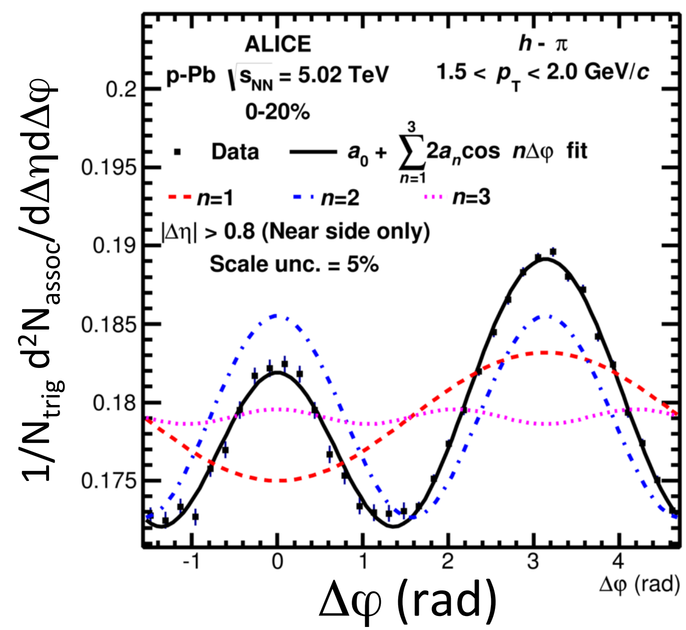
h-ID Correlations

- Typical features (NS + AS jet, ridge) also in h-π, h-K, h-p correlations
- Project to Δφ with η-gap on NS
- Fit with 3 Fourier coefficients gives good description
  - Large first component due to recoil jet
- Near side: mostly ridge
- Away side: jet + ridge
  - affects also v_2
- Allows to extract v_n coefficients

$$v_n = \sqrt{a_n / a_0}$$

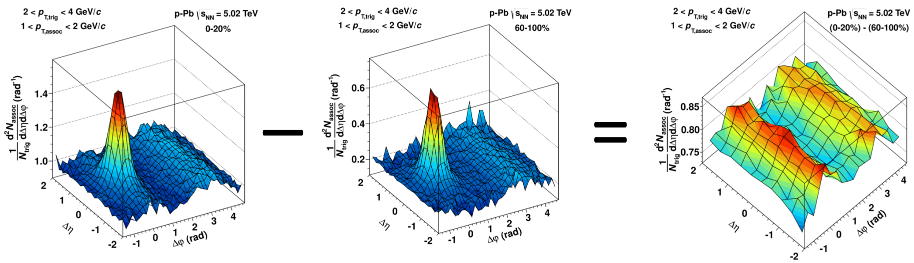
ALICE, arXiv:1307.3237



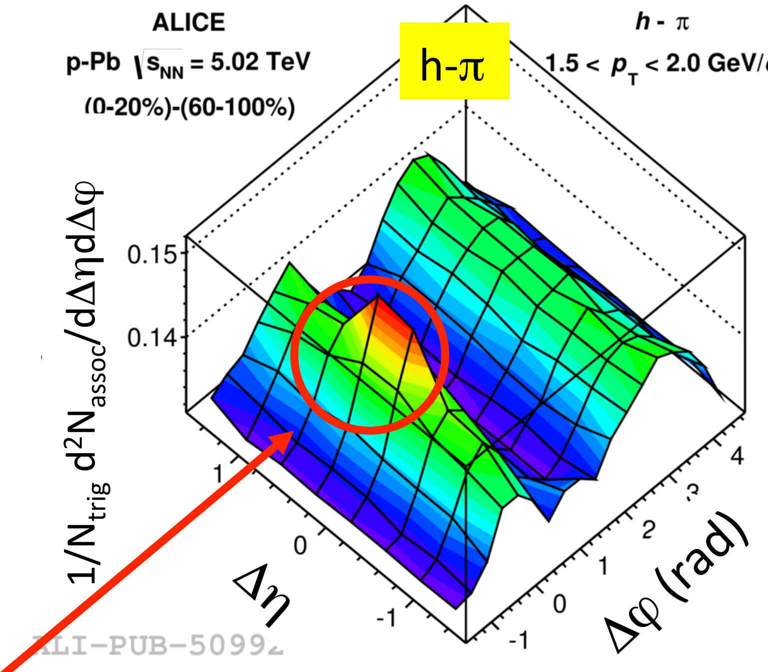


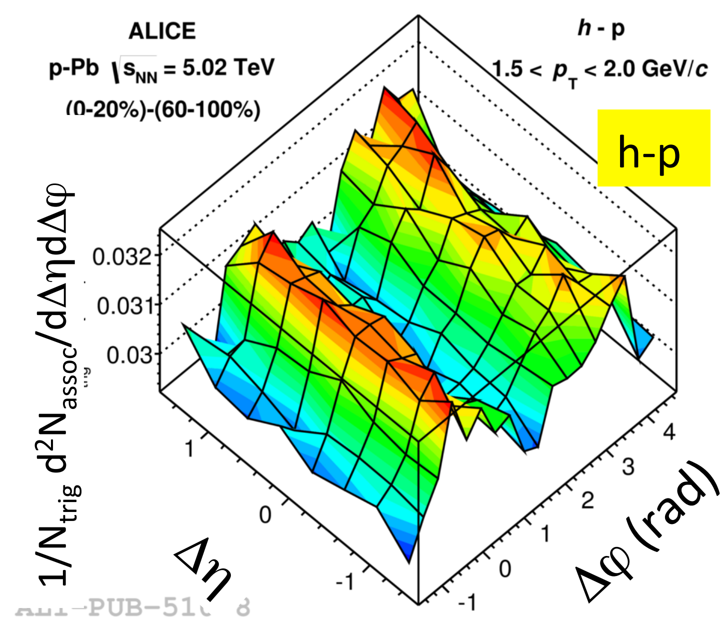
Subtraction

- Subtract jet component by (0-20%) – (60-100%)



- Residue of jet, in particular for pions
  - Most likely event-selection bias on jet fragmentation
  - Excluded due to near-side η-gap
  - Away-side contribution assessed in various ways (ask for details)





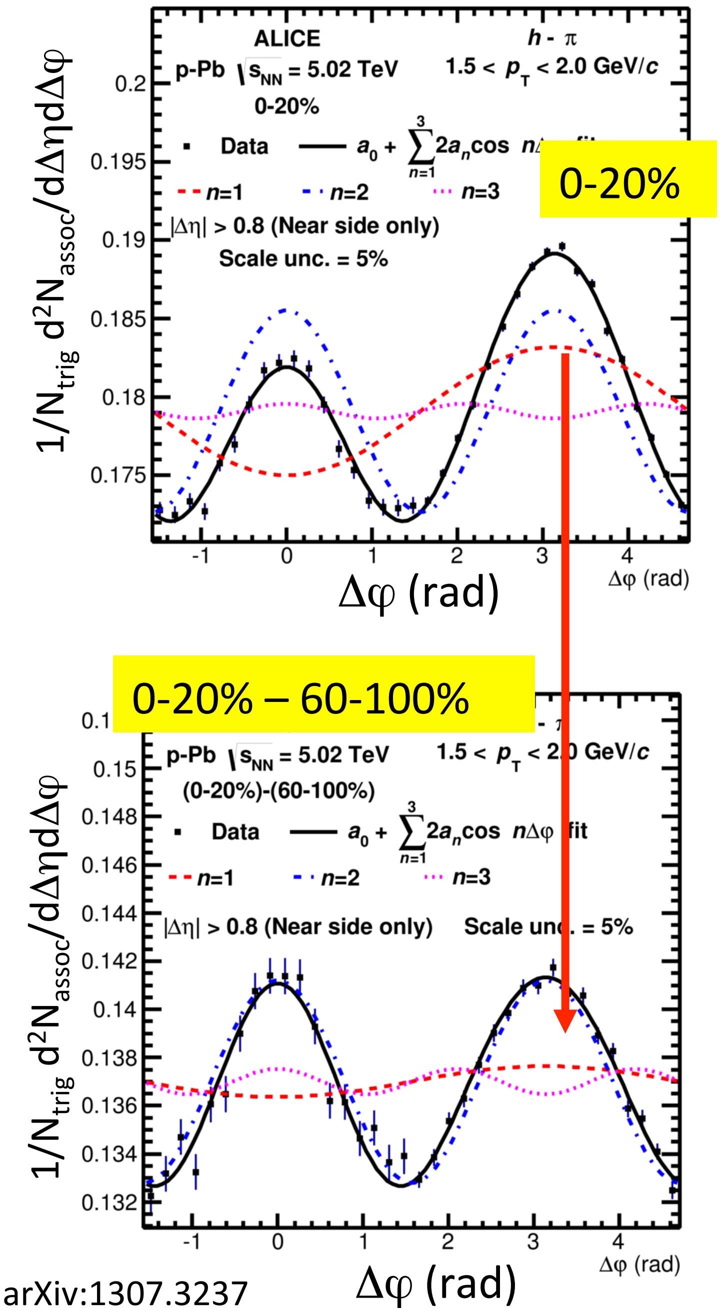
ALICE, arXiv:1307.3237

here: $\eta = \eta_{lab}$

v_n Coefficients

- First Fourier coefficients is mainly driven by recoil jet
  - Significant change in magnitude with subtraction (up to 10 times smaller)
- Second Fourier coefficient changes with subtraction by 20-40%
- NB. Subtraction removes also baseline (b) from 60-100%

$$v_2 = \sqrt{a_2/(a_0 + b)}$$

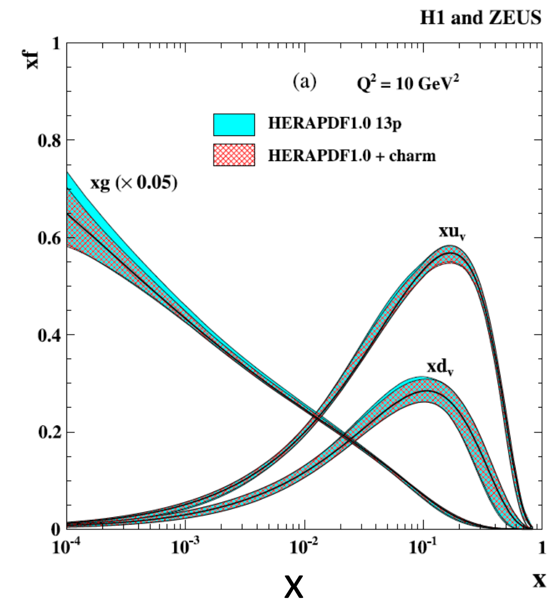


ALICE, arXiv:1307.3237

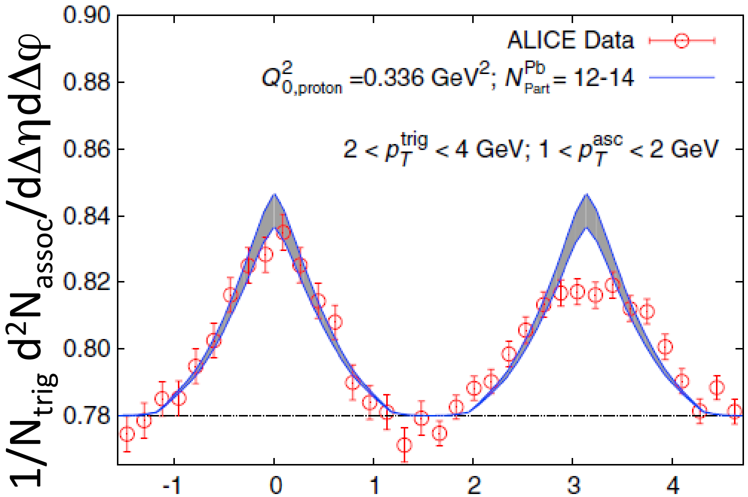
here: $\eta = \eta_{lab}$

Color Glass Condensate

- Gluon saturation at low x
  - New scale: saturation scale
- Enhancement of "glasma" graph
- Calculation for p-Pb LHC by Dusling and Venugopalan (PRD 87, 094034 (2013))
  - Good agreement, no v_3 component, though



HERA, EPJC (2013) 73:2311



PRD 87, 094034 (2013)