XII Latin American Symposium on High Energy Physics

Pontificia Universidad Católica
del Perú,
Lima, November 26, 2018

ALICE: Recent Results and Future Perspectives

Edmundo J. García Solís
Chicago State University

For the ALICE Collaboration

Outline

- Introduction
- The Detector
- Collective Behavior
- Particle Production
- Jet-medium Interactions
- ALICE Upgrade

Other ALICE talks

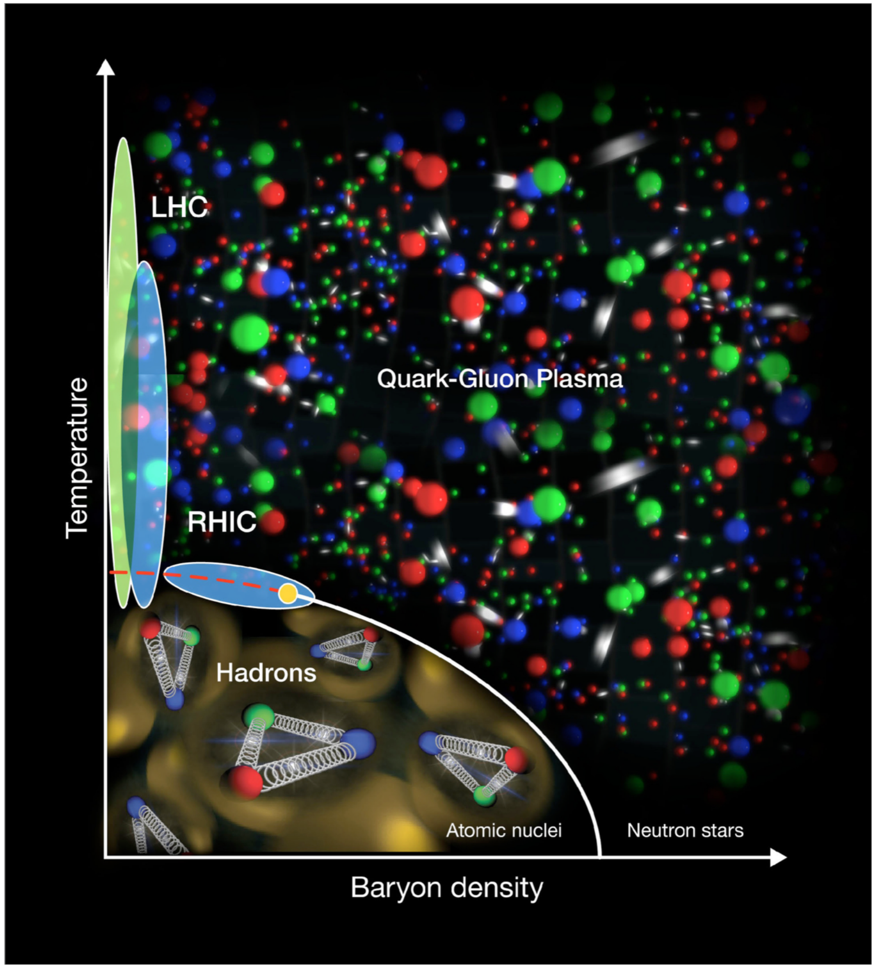
- Investigating diffractive processes in the ALICE experiment at the LHC

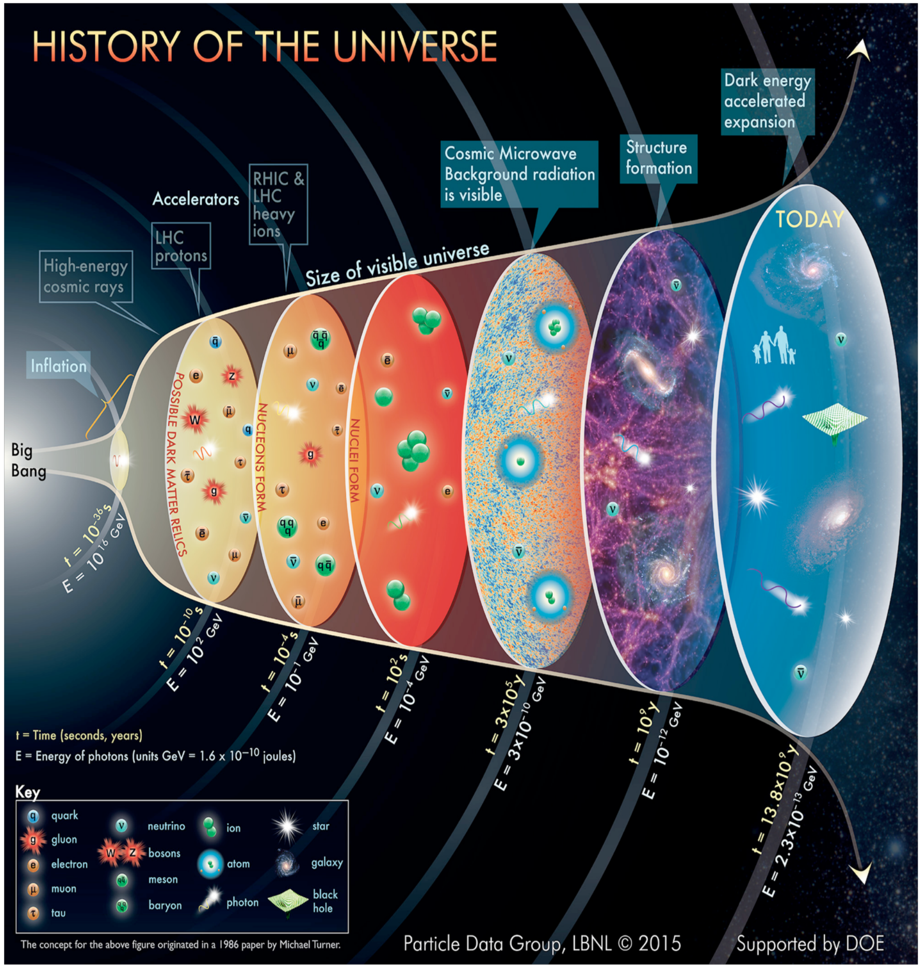
Ernesto Calvo Villar – 27/11 15:00

- Coherent J/ψ photo-production in ultra-peripheral Pb-Pb collisions with ALICE at the LHC

Roman Lavicka – 27/11 15:20

Heavy-Ion Physics at the Large Hadron Collider





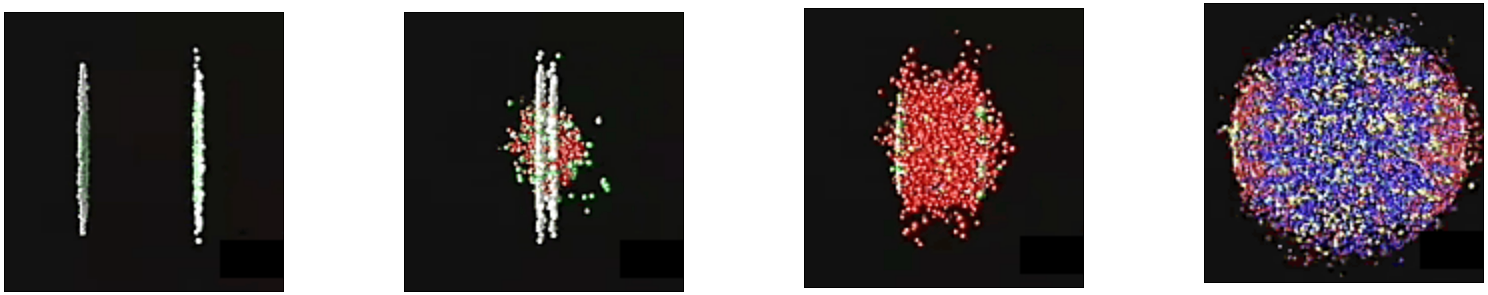
The concept for the above figure originated in a 1986 paper by Michael Turner.

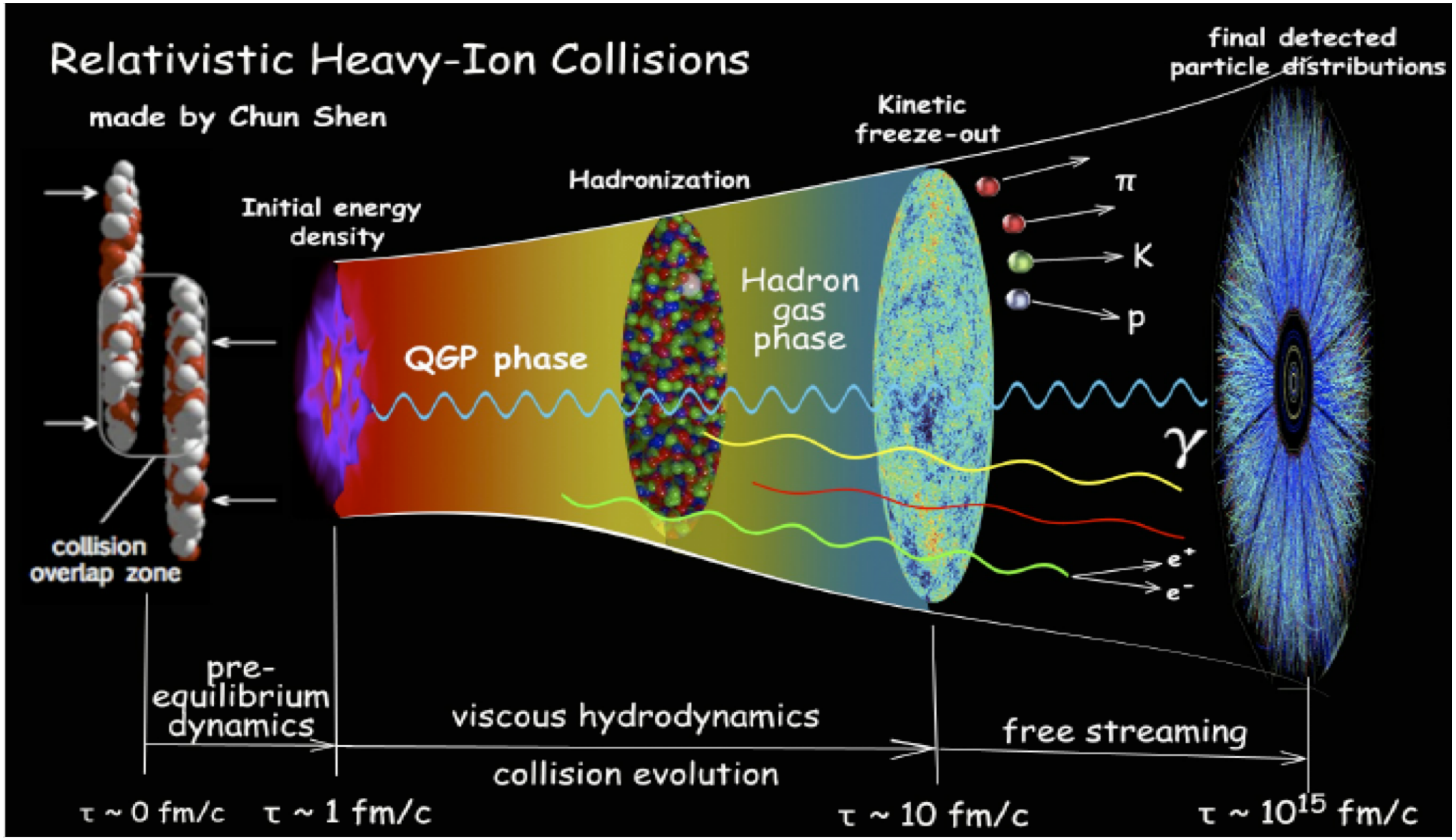
Particle Data Group, LBNL © 2015

Supported by DOE

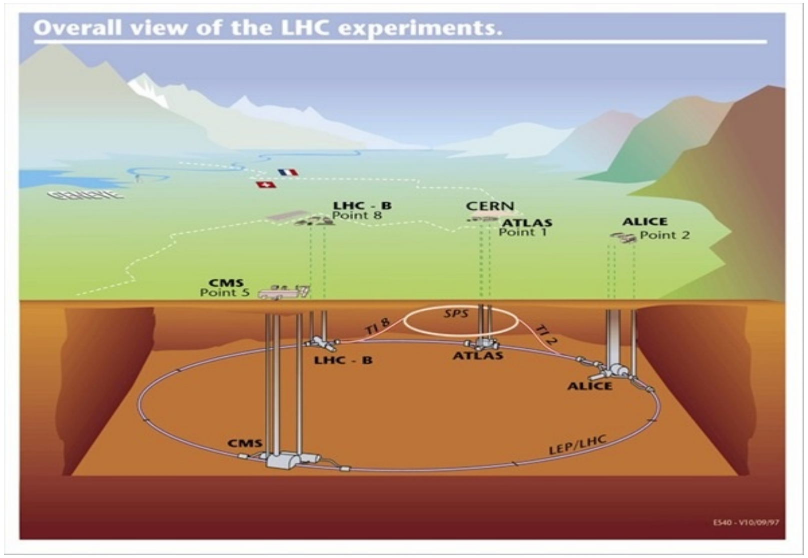
- What are the phases of strongly interacting matter and what roles do they play in the cosmos?
- How the quarks behave when they are “freed”?

Heavy-Ion Collisions



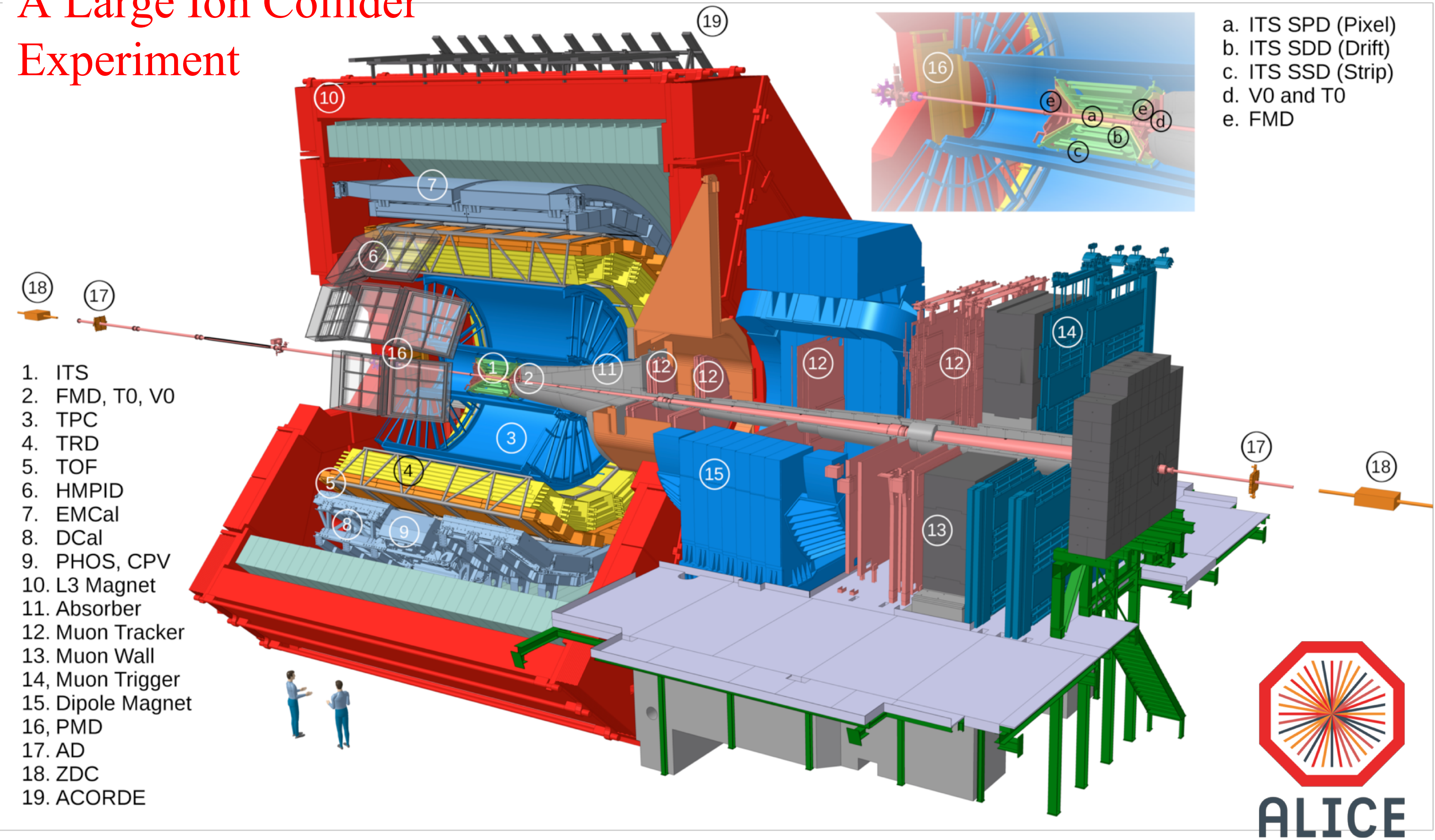


The Large Hadron Collider (LHC) at CERN (European Center of Nuclear Research)



- Energy 13 TeV (pp), 5.02 TeV (Pb-Pb)
- Located in Switzerland/France Border
- Circumference (27 km) 16.8 miles
- Four detectors used to study the collisions

A Large Ion Collider Experiment



a. ITS SPD (Pixel)
b. ITS SDD (Drift)
c. ITS SSD (Strip)
d. V0 and T0
e. FMD

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE

- 26 m long, 16 m high, 16 m wide, 10,000 tons, 15 subsystems
- Central barrel $|\eta|<0.9$, plus single arm and forward muon spectrometer - 4< $|\eta|$< -2.5
- PID in the p_T range 0.1-20 GeV/*c*, $\Delta p/p$ ~1-5% for p_T = 0.1-50 GeV/*c*

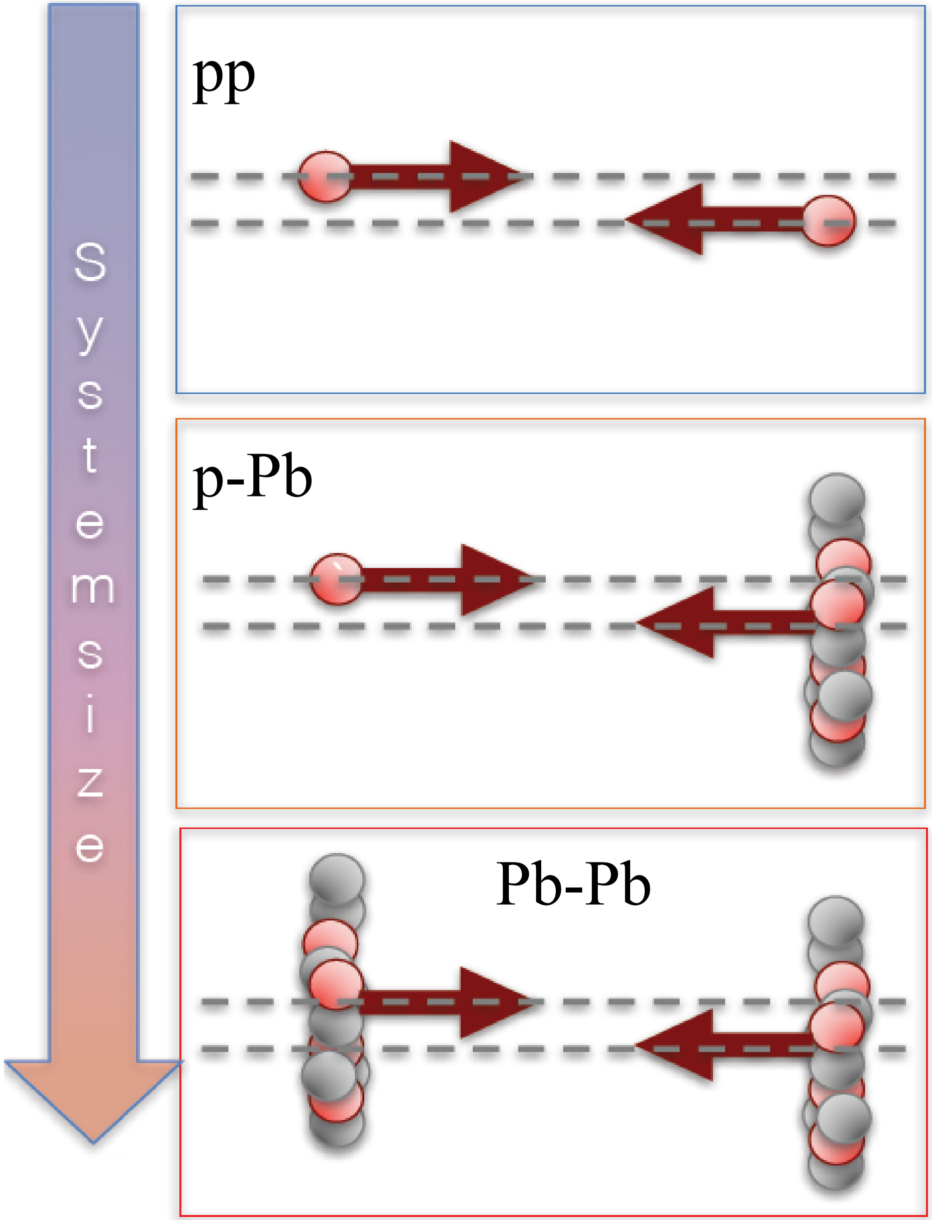
ALICE Collisions

Run 1 (2009-2013)

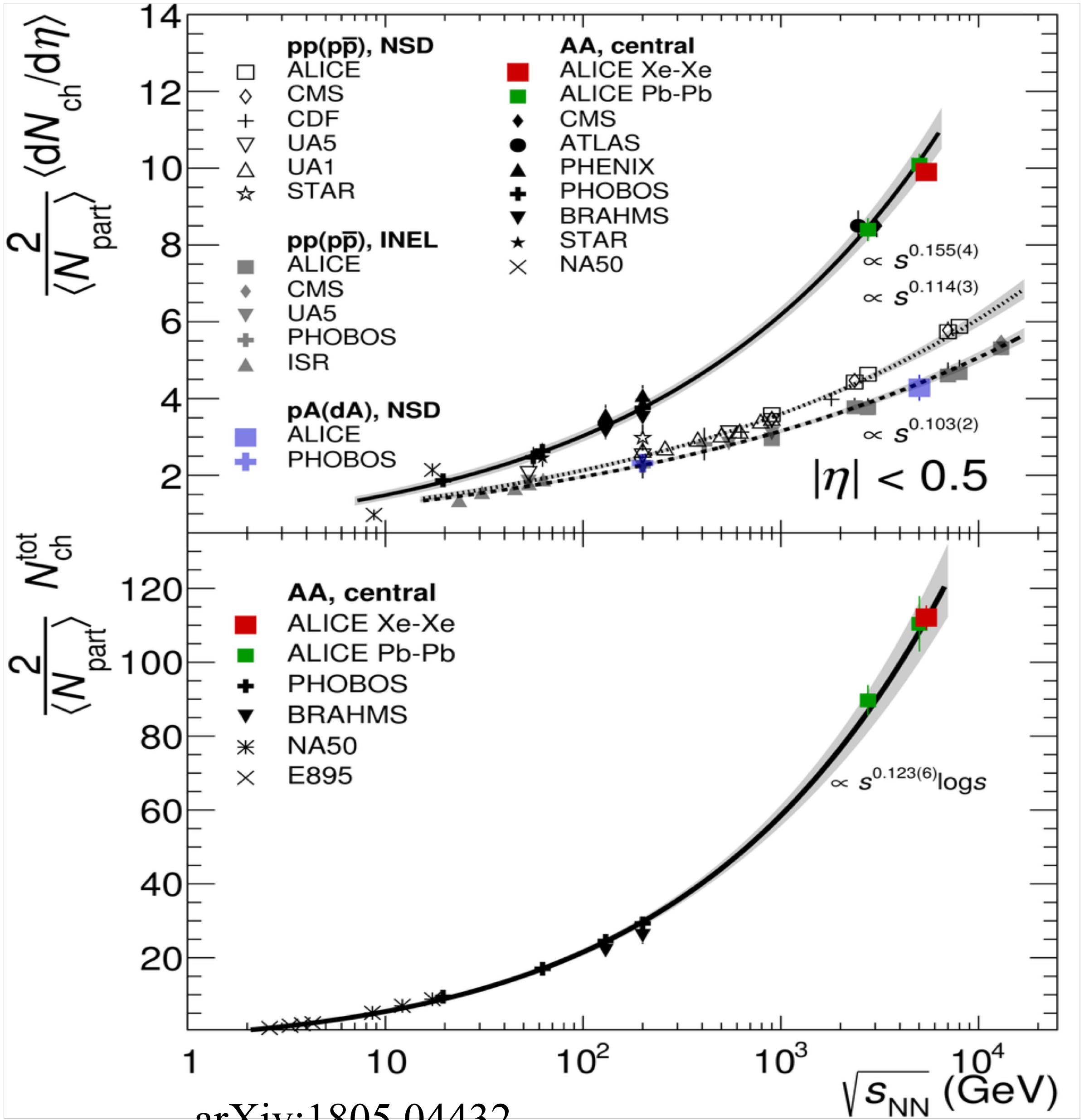
System	Energy	L_{INT}
pp	0.9 TeV	~ 200 mb^{-1}
	2.76 TeV	~ 100 nb^{-1}
	7.0 TeV	~ 1.5 pb^{-1}
	8.0 TeV	~ 2.5 pb^{-1}
p-Pb	5.02 TeV	~ 15 nb^{-1}
Pb-Pb	2.76 TeV	~ 75 mb^{-1}

Run 2 (2015-2018)

pp	5.02 TeV	~ 1.3 pb^{-1}
	13 TeV	~ 25 pb^{-1}
p-Pb	5.02 TeV	~ 3 nb^{-1}
	8.16 TeV	~ 25 nb^{-1}
Xe-Xe	5.44 TeV	~ 0.3 mb^{-1}
Pb-Pb	5.02 TeV	~ 1 nb^{-1}



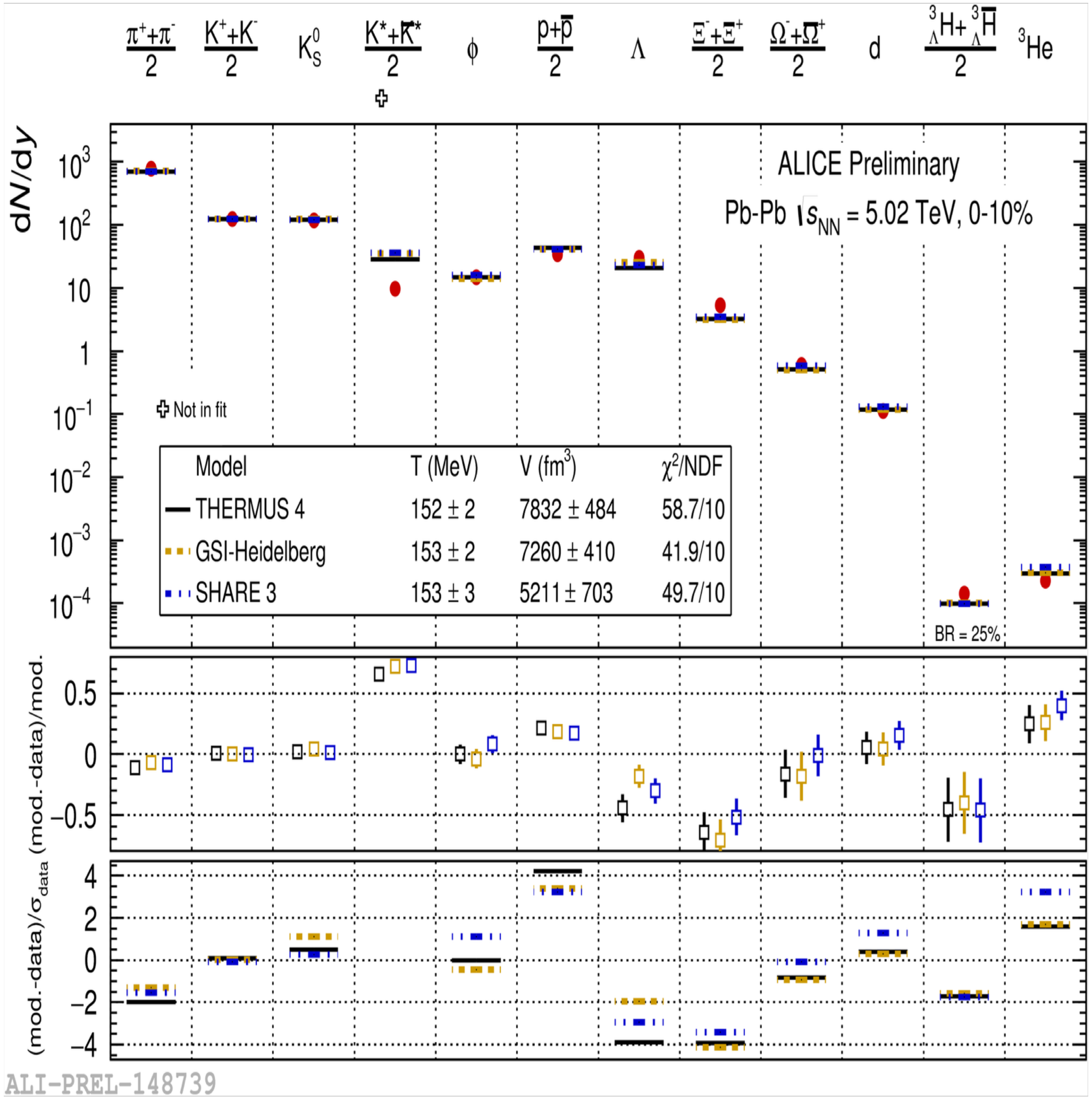
Multiplicity



arXiv:1805.04432

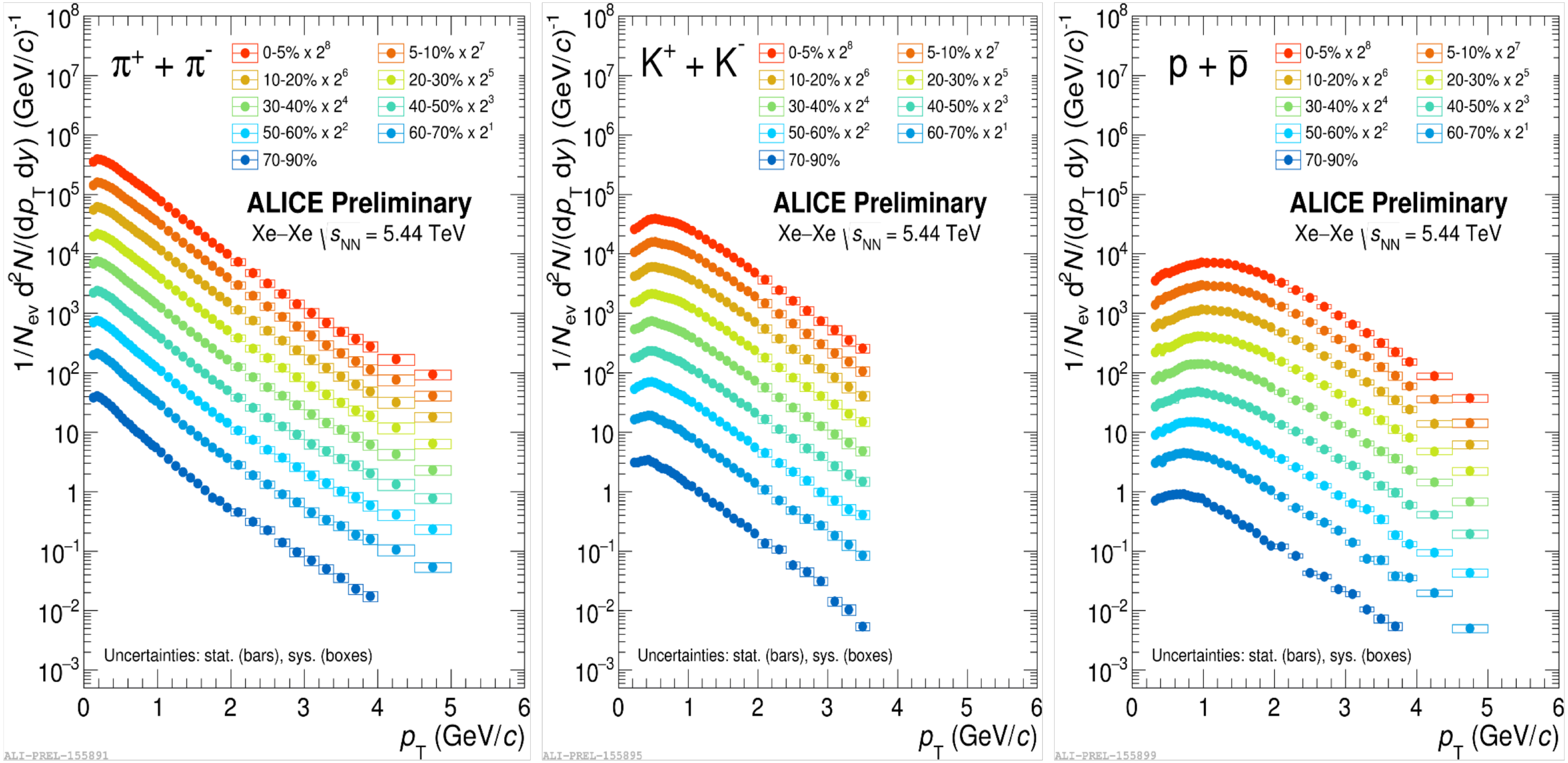
- Collection of pp, p-A and A-A multiplicity data at different energies
- Densities 100 times cold nuclear matter density, $\varepsilon \approx$ 15 GeV/fm^3
- Stronger rise with $\sqrt{s}$ for A-A particle production per participant pair than for p-A and pp collisions

Local Thermal Equilibration



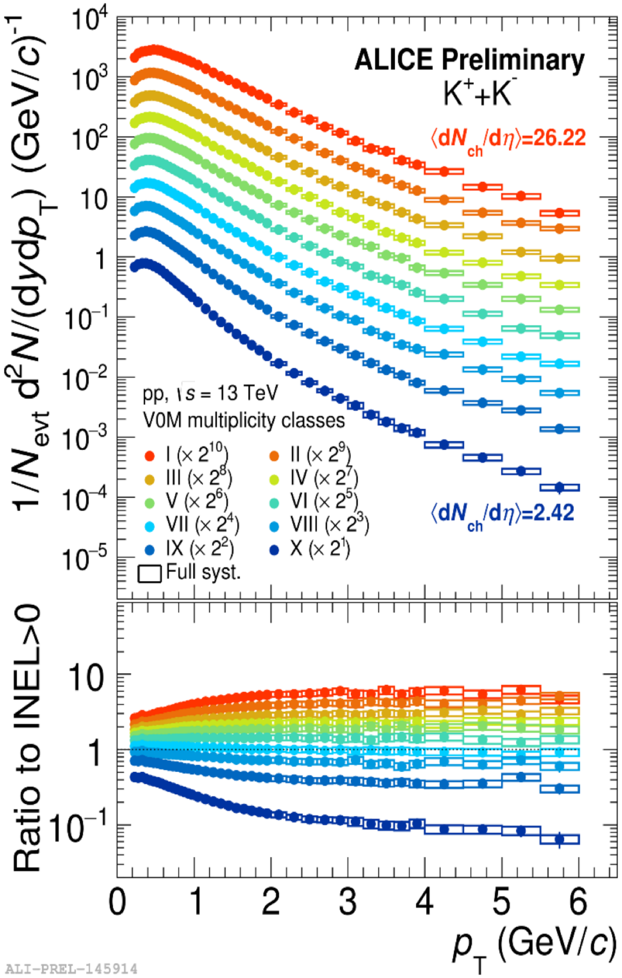
- Thermal model $yield \sim e^{-m/T}$
- Thermal fit of 0-10% central Pb-Pb collisions at 5.02 TeV, with 3 models
- Yields of light flavor hadrons are qualitatively well described by equilibrium thermal models over seven orders of magnitude.
- We see also nuclei as shown later in the talk

Radial Flow

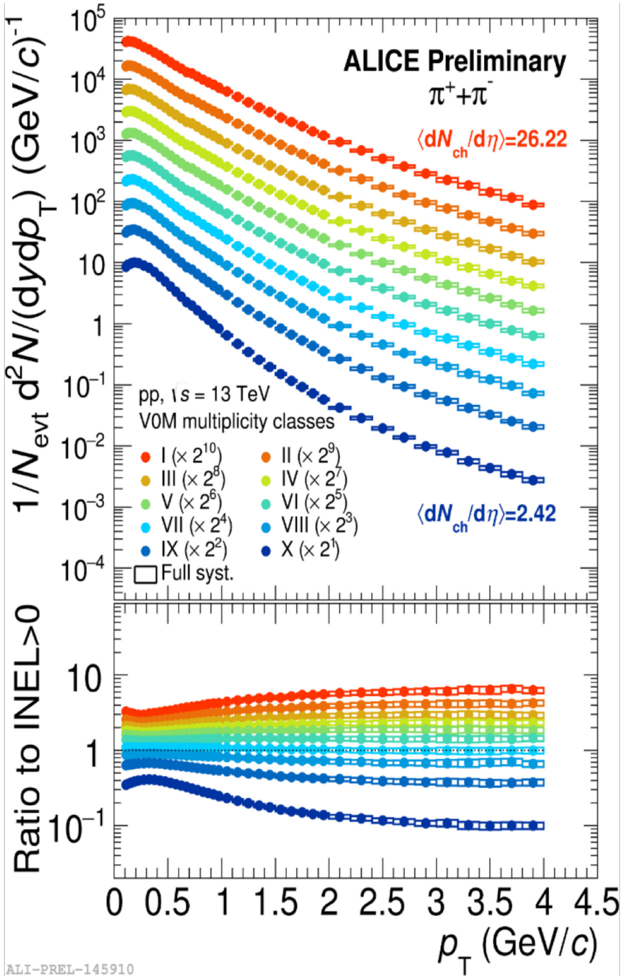


- Transverse momentum (p_T) spectra becomes harder for central collisions, hardening is also mass-dependent
- At low p_T behavior consistent with underlying collective expansion (hydrodynamic radial flow) in local thermal equilibrium

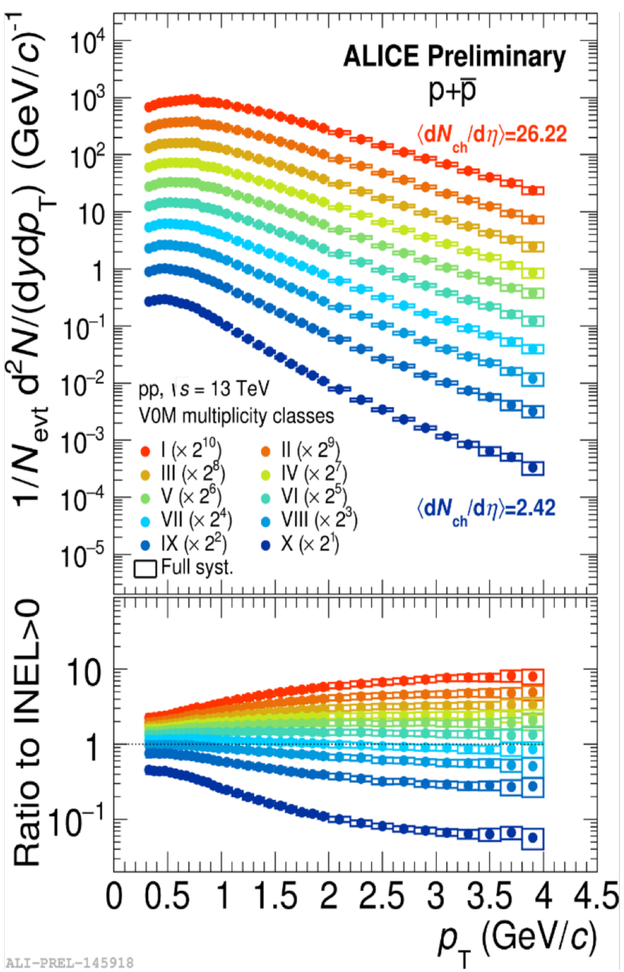
Radial Flow in pp spectra



ALI-PREL-145914



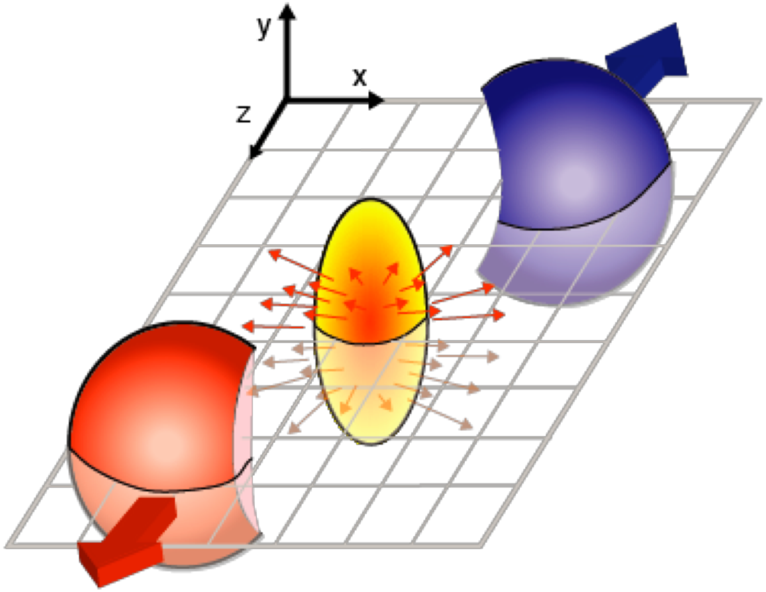
ALI-PREL-145910



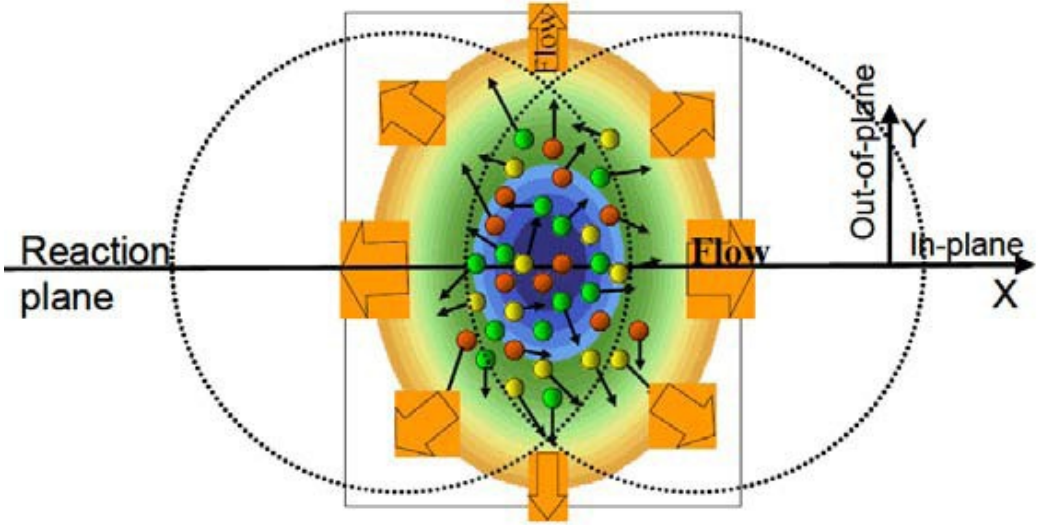
ALI-PREL-145918

- Hardening of spectra observed in pp collisions with increasing multiplicity and mass

Elliptic Flow

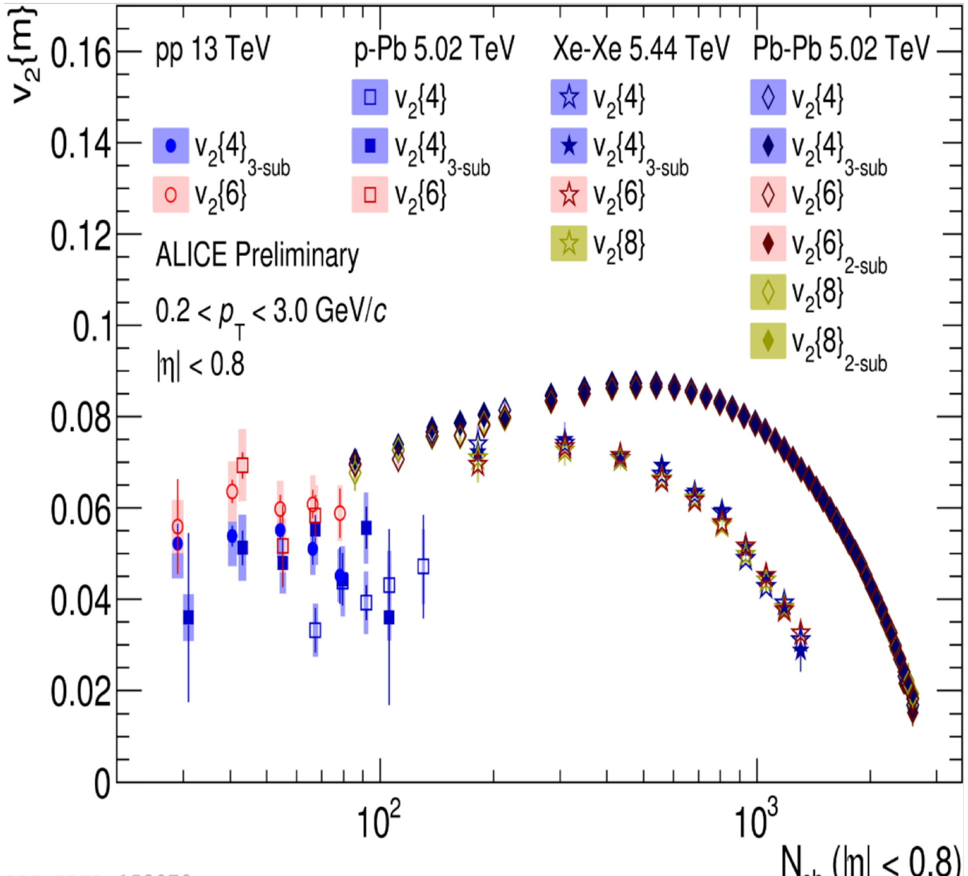


$$\frac{dN}{d\varphi} = 1 + v_2 \cos(2(\varphi - \Psi_{RP}))$$

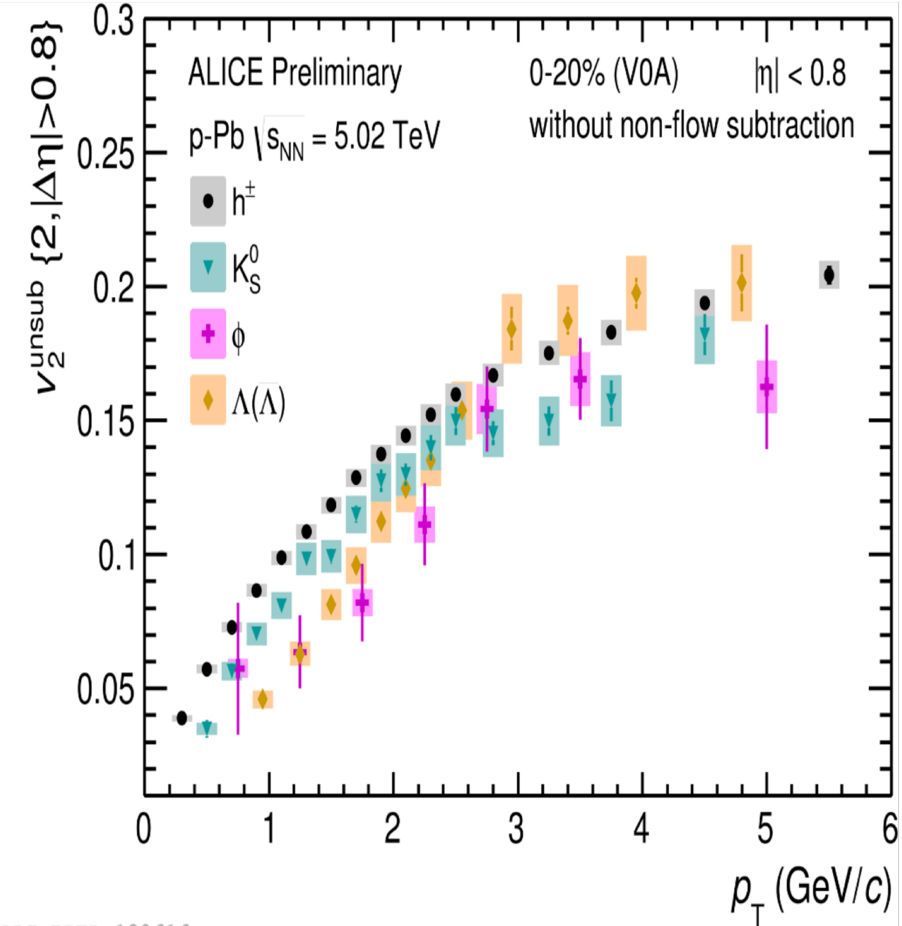


- The v_2 coefficients of the azimuthal distribution of particles is known as elliptic flow
- The elliptic flow provides information on the transport properties the matter created in a heavy-ion collision.
- The presence of elliptic flow is a signature of multiple interactions between the constituents of the created matter and the initial state of a non-central collision

Elliptic Flow



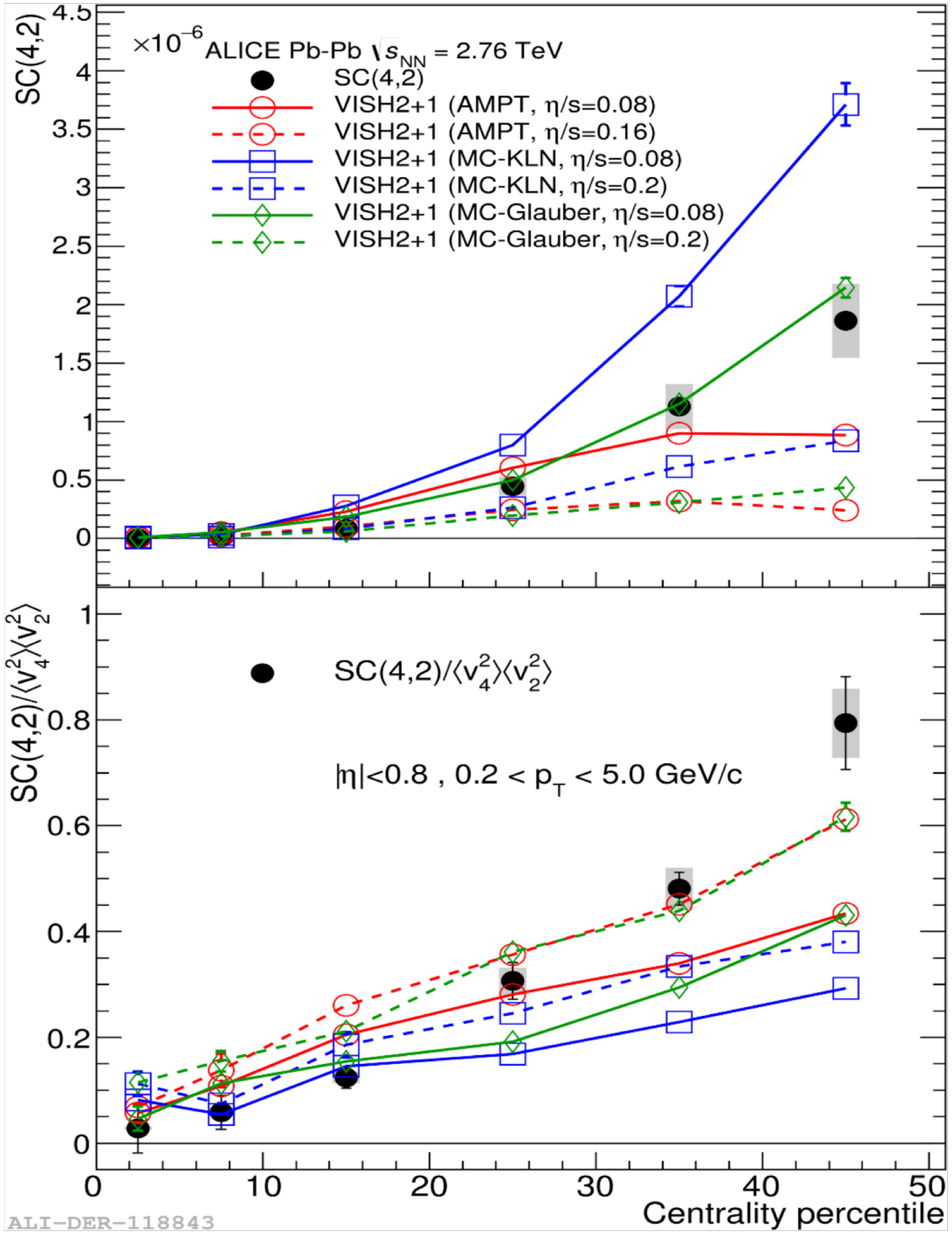
ALI-PREL-153079



ALI-PREL-132616

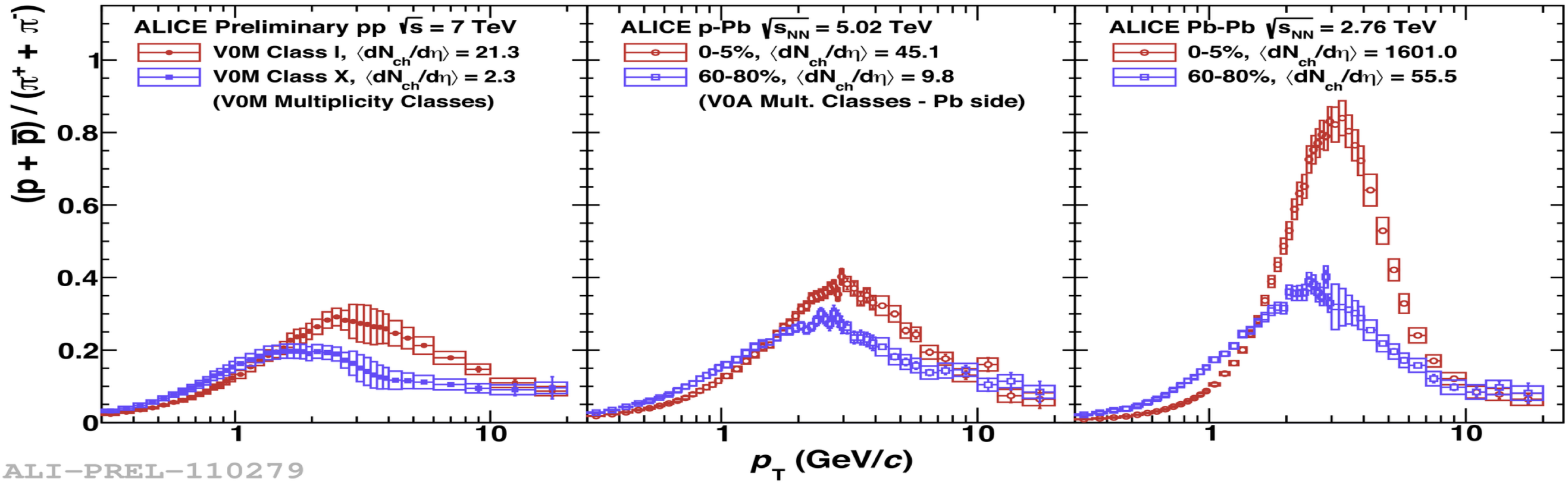
- The matter created in the heavy ion collision flows as a fluid with almost no friction.
- Elliptic flow coefficients in pp and p–Pb collisions exhibit similar features as in Pb–Pb collisions, a surprising and puzzling result, as it requires some collectivity to be developed in the absence a large size of strong coupled matter as QGP

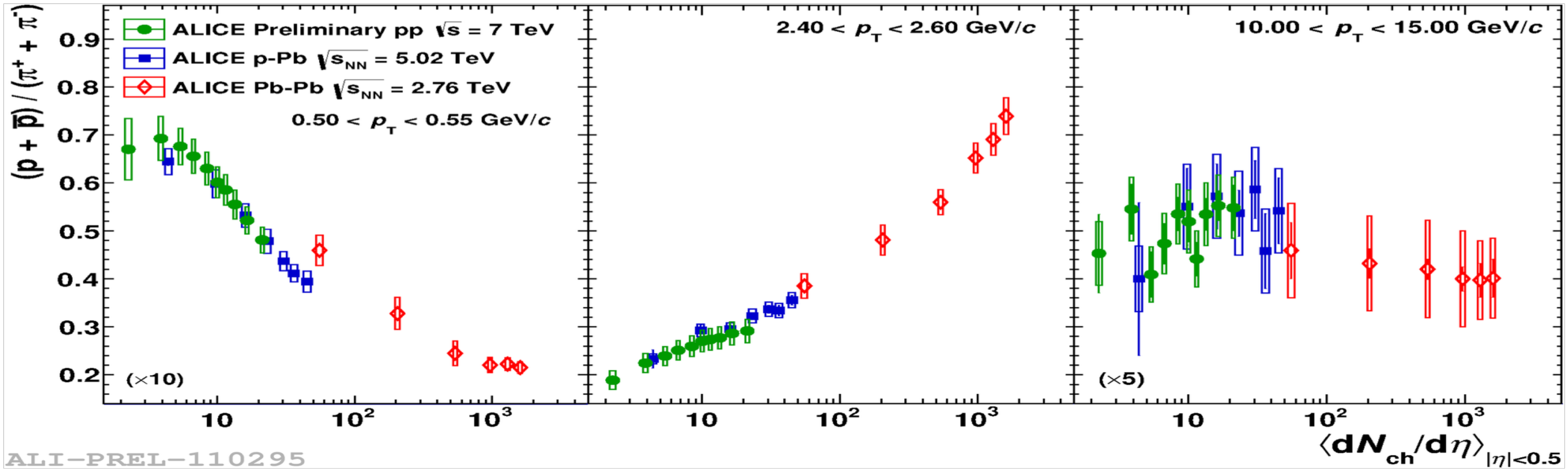
Flow Viscocity η/s



- Measurements of SC(4,2) in Pb-Pb collisions are compared to various VISH2+1 calculations.
- The η/s parameters are shown as different line styles, the small shear viscosity (η/s=0.08) are shown as solid lines, and large shear viscosities (η/s=0.2 for MC-KLN and MC-Glauber, 0.16 for AMPT)

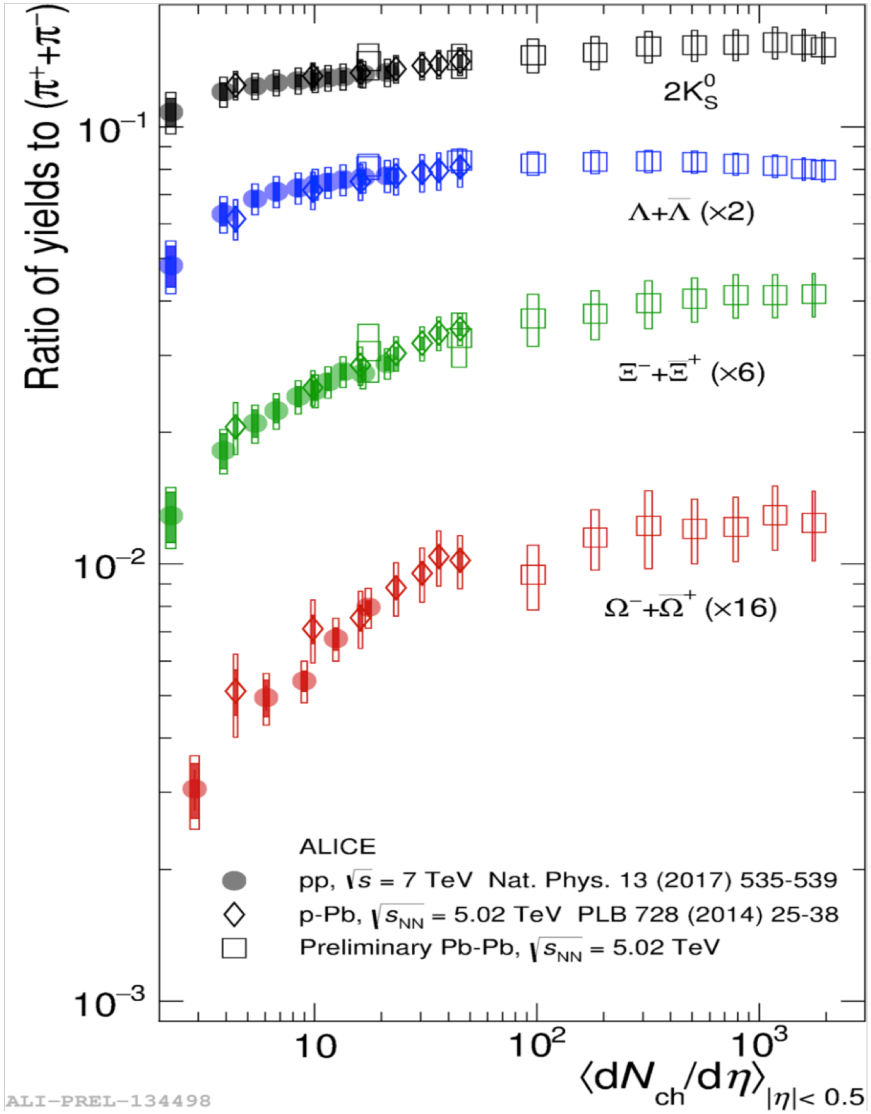
Baryon vs. Mesons



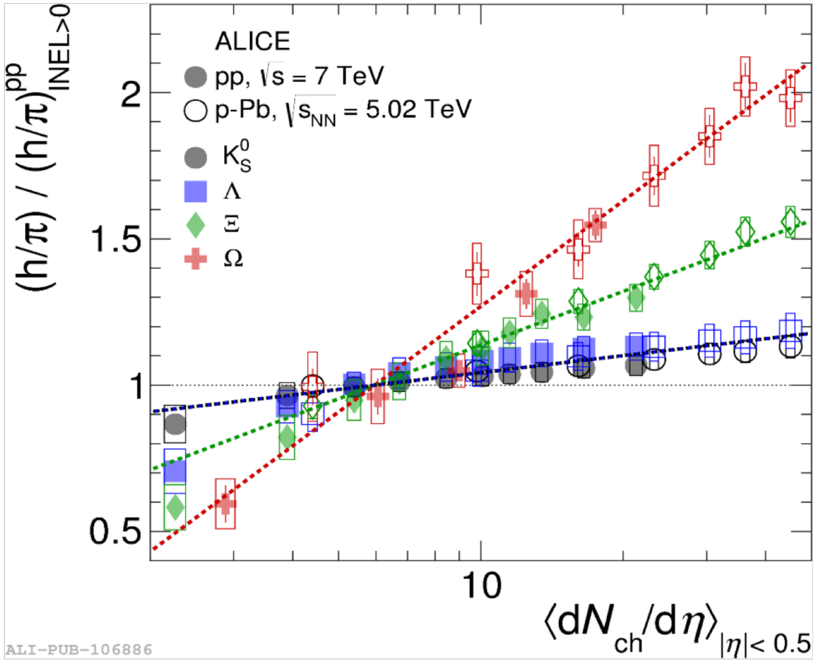


- Consistency versus multiplicity across all systems points to common driving mechanism(s) (recombination and/or radial flow)

Strangeness Production

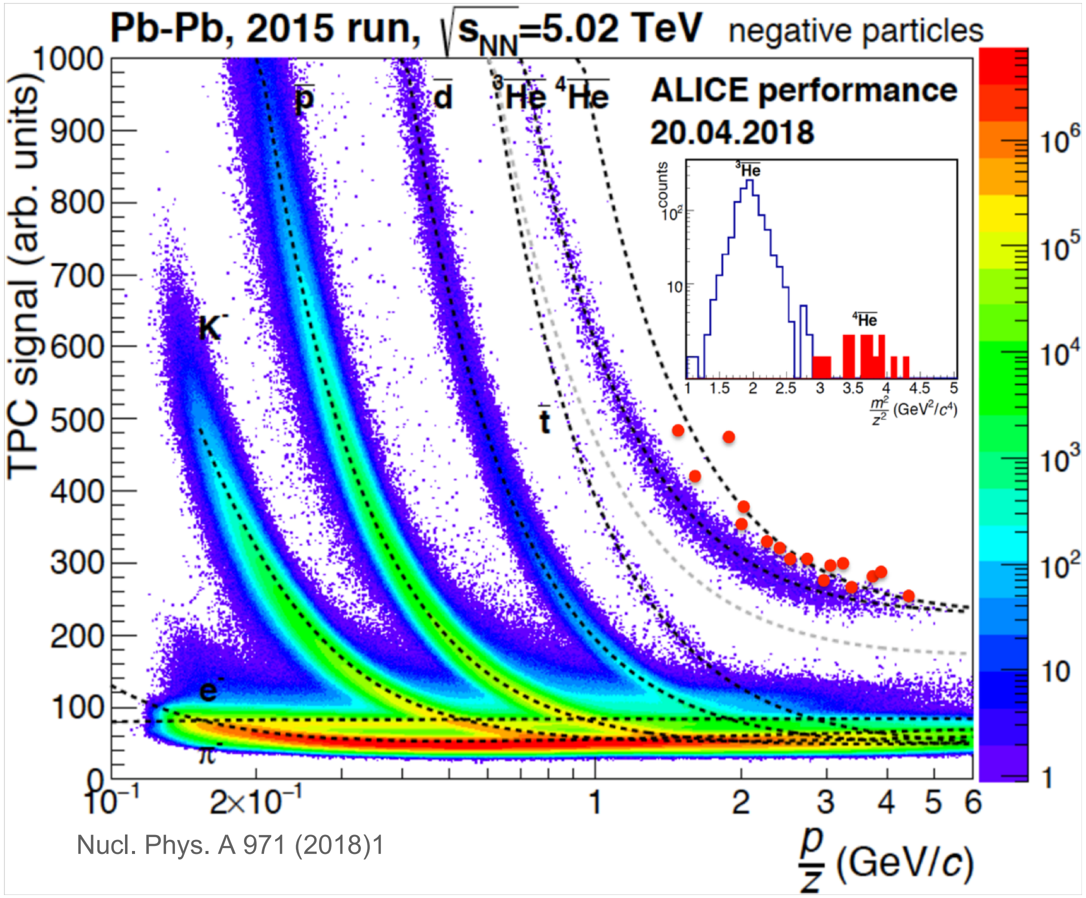


Nature Physics 13, 535 (2017)

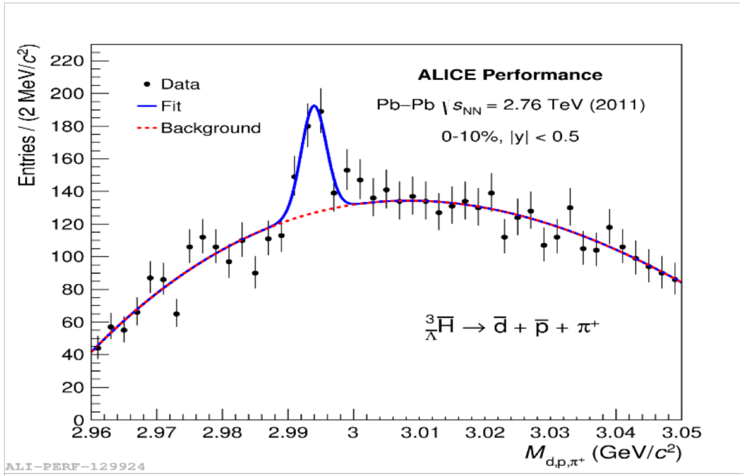


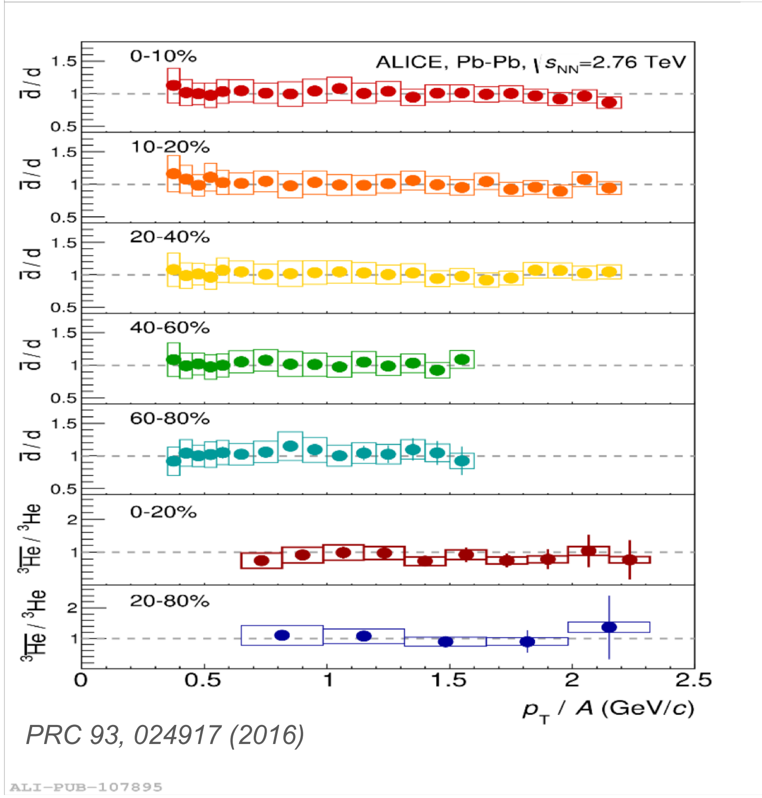
- Observation of strangeness enhancement in large and small collision systems as function charged particle multiplicity
- Smooth evolution from small to large systems
- Common origin in all systems?

Anti-Nuclei



Nucl. Phys. A 971 (2018)1

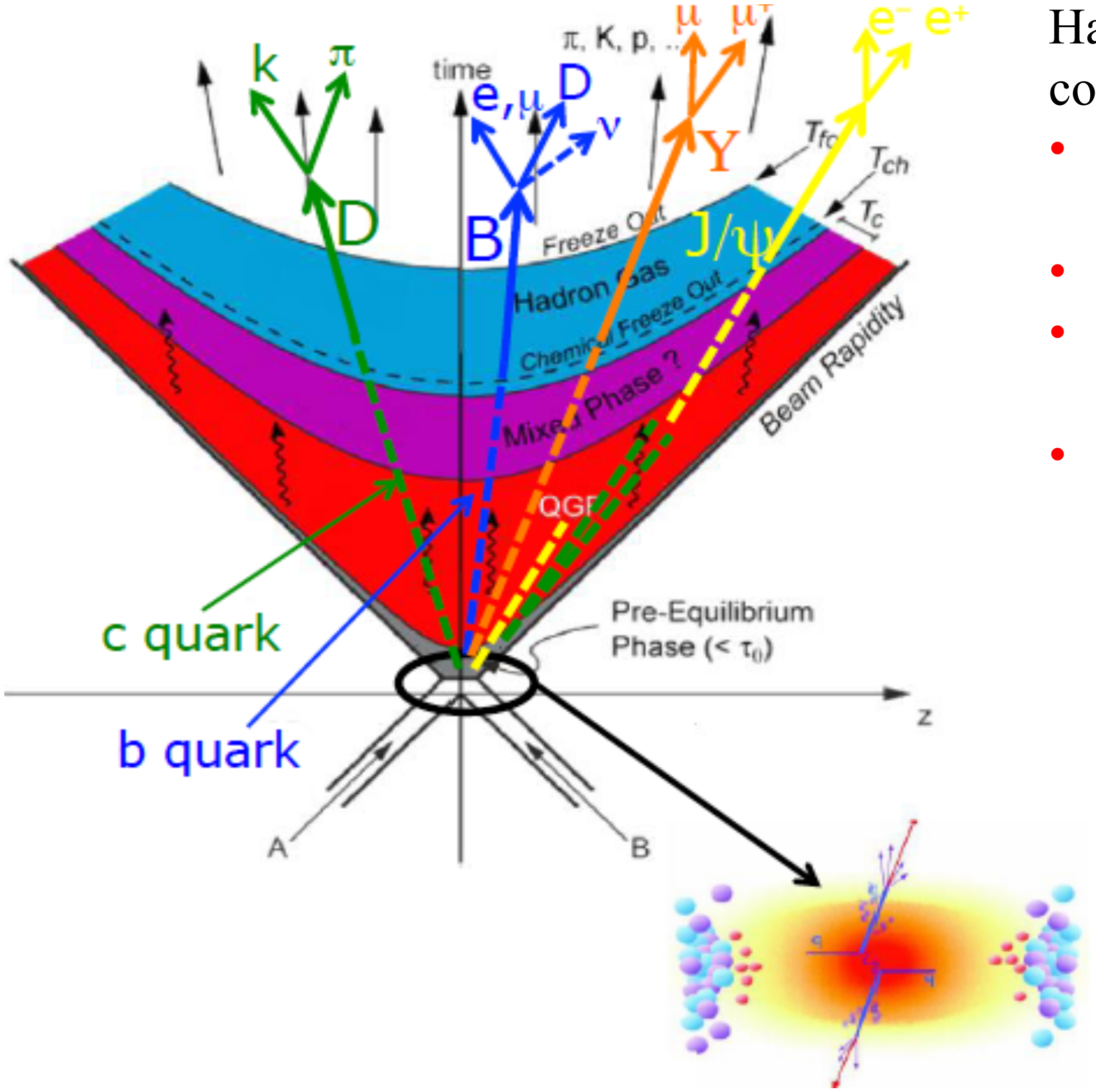




PRC 93, 024917 (2016)

- Ratios are consistent with unity and in agreement with the coalescence and thermal model expectations

Heavy Flavours: Hard probes of QGP



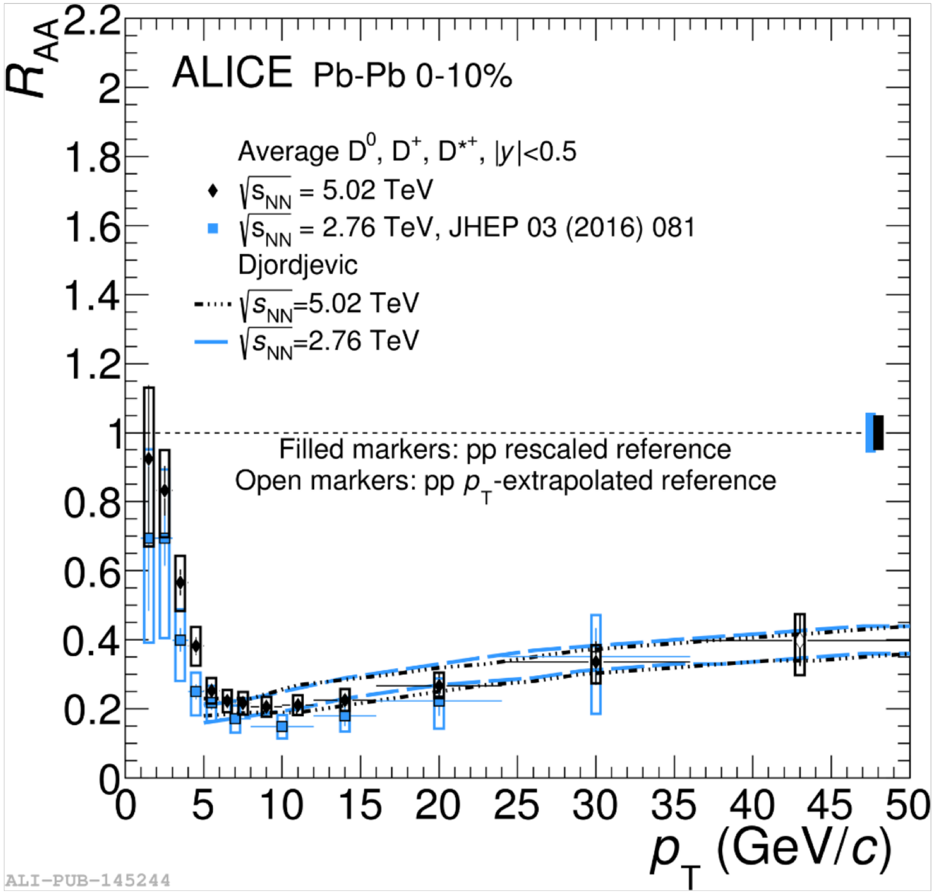
Hard probes in nucleus-nucleus collisions:

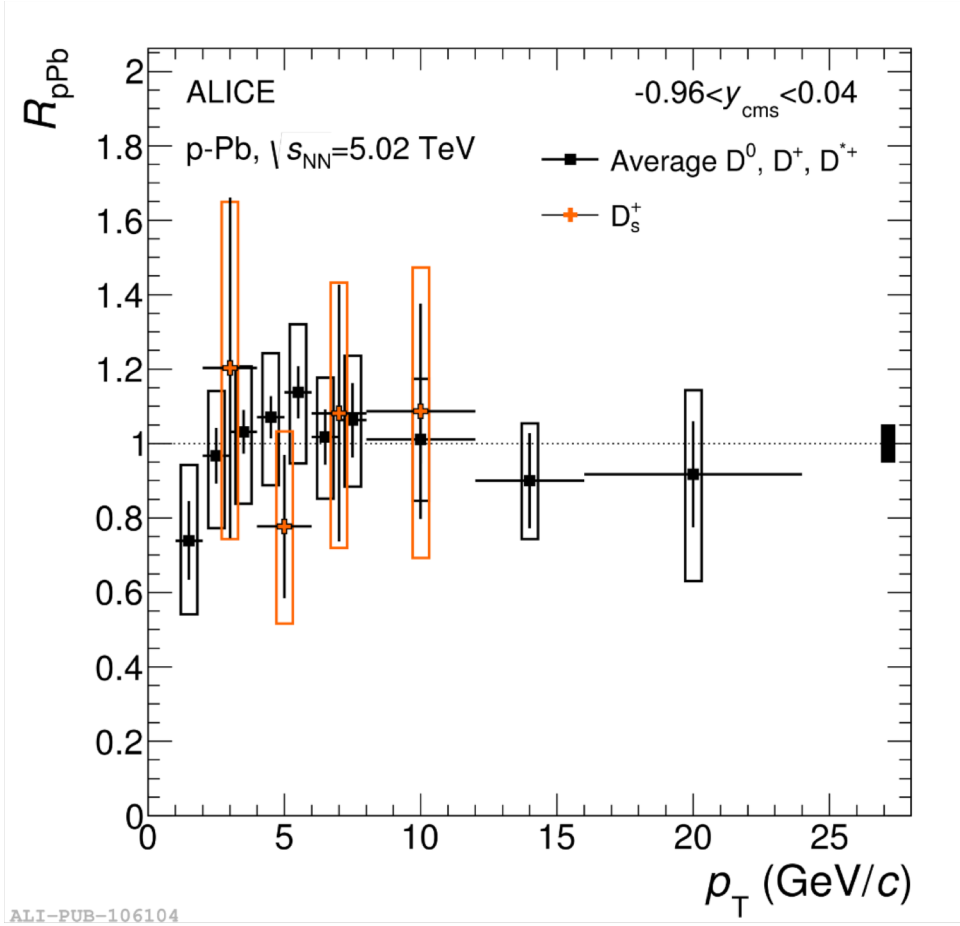
- Produced at the very early stage of the collisions in partonic
- processes with large Q^2
- pQCD can be used to calculate initial cross sections
- Traverse the hot and dense medium so can be used to probe the properties of the medium

Nuclear Modification Factor

$$R_{AA} = \frac{\frac{d^2N^{AA}}{dp_T dy}}{\langle N_{bin}\rangle \frac{d^2N^{AA}}{dp_T dy}}$$

D-Mesons

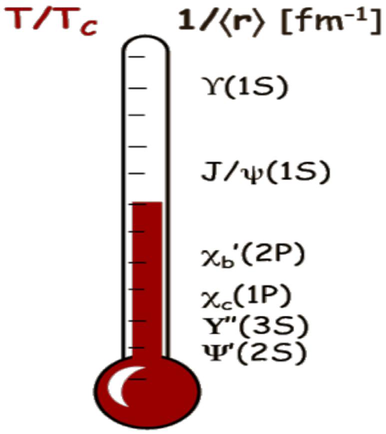


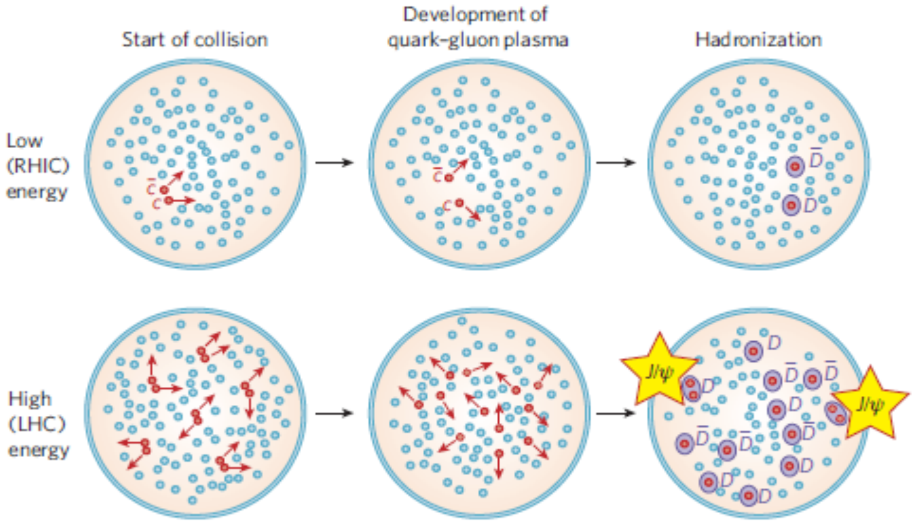


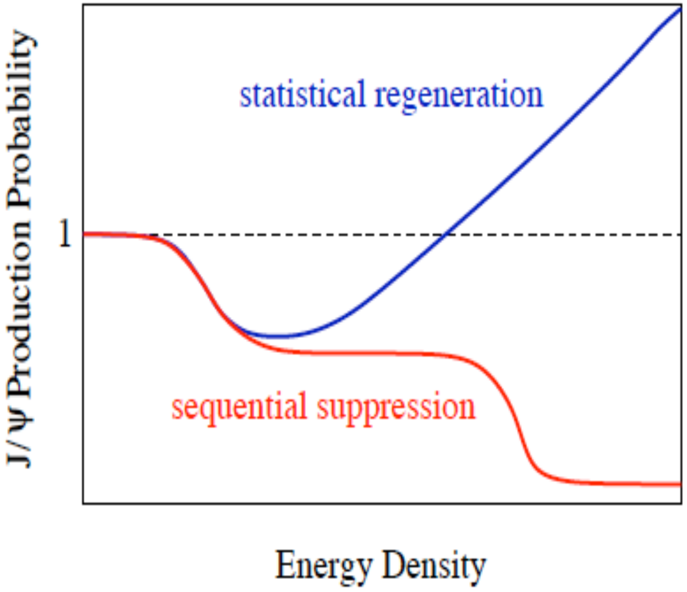
- Strong suppression of D mesons, heavy quarks undergo strong energy loss in the QGP
- R_{pPb} of D mesons consistent with unity, cold nuclear matter effects small, no large suppression in the measured p_T range

Charmonium in Heavy-Ion Collisions

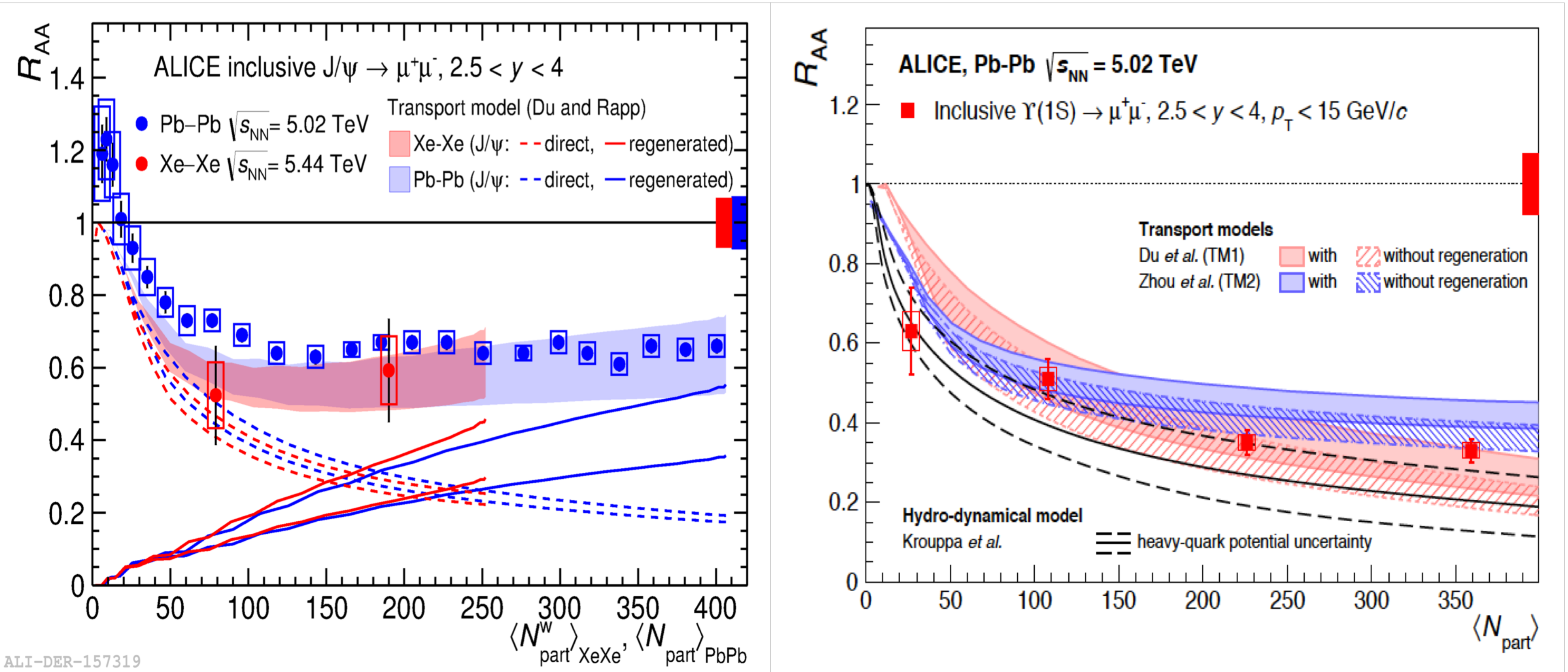
- Suppression due to Debye-like screening of $c\bar{c}$ QCD potential ("melting" of bound states color screening)
- Different binding energies results in sequential suppression of charmonium states
- Charmonium production via coalescence of deconfined quarks (recombination)





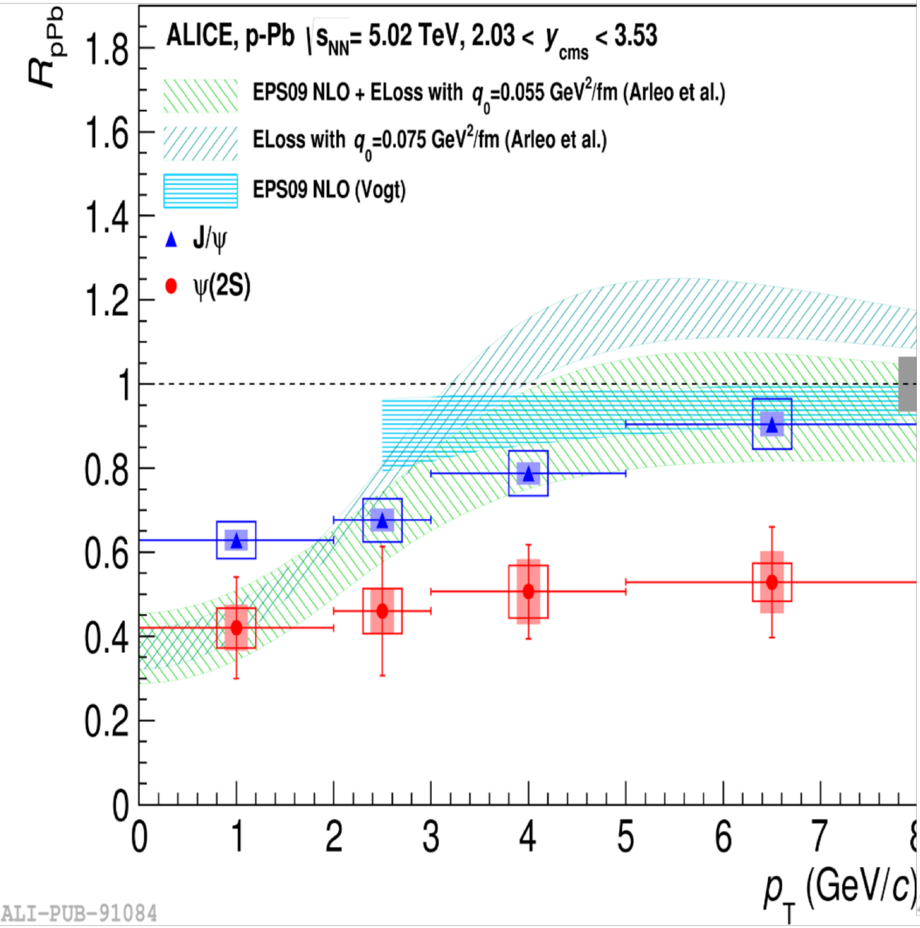


Charmonium

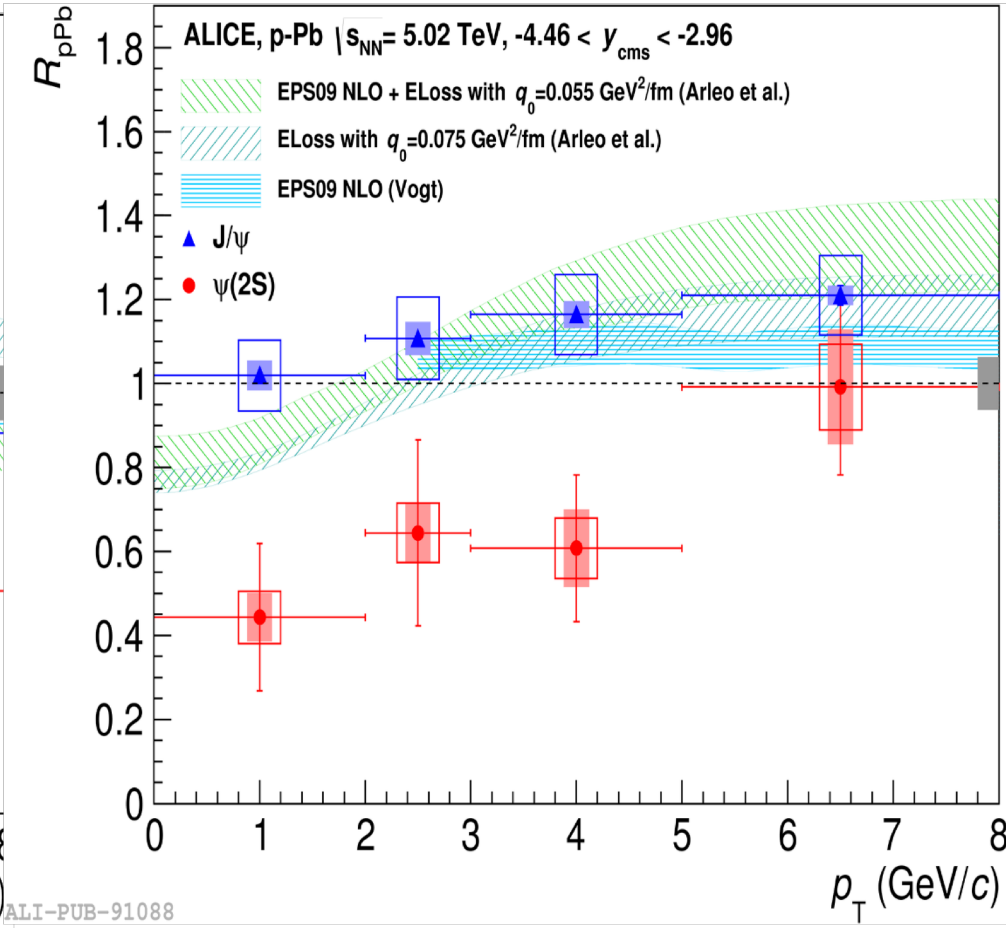


- Comparison to transport model: predicts larger suppression at higher energy with an increase effect of regeneration
- Evidence for re-combination as production mechanism present with increasing beam energy and system size

Charmonium Cont.



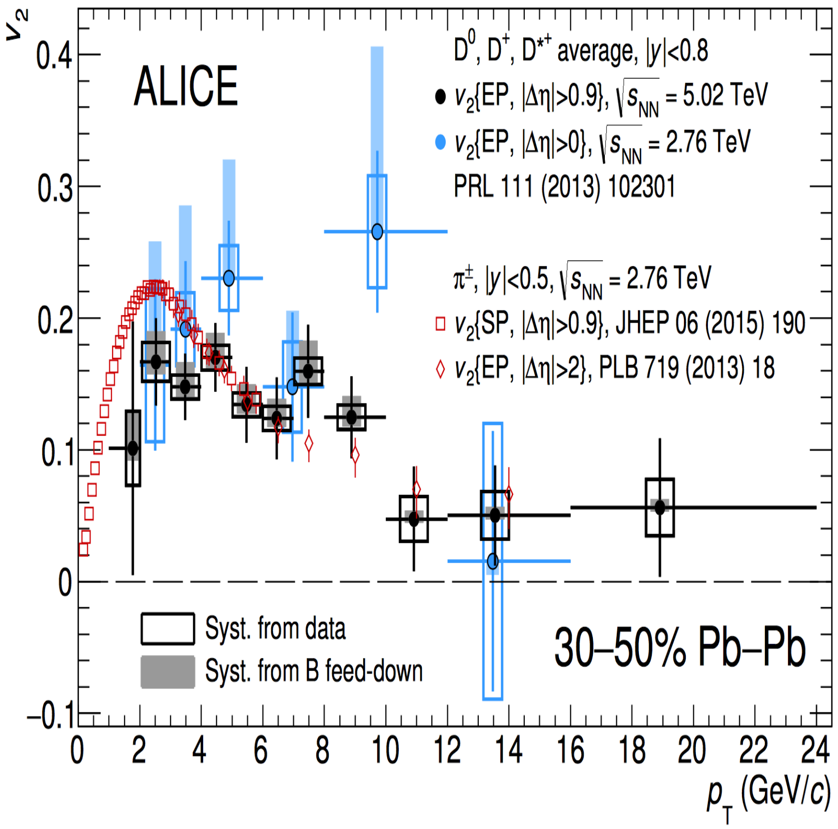
ALI-PUB-91084

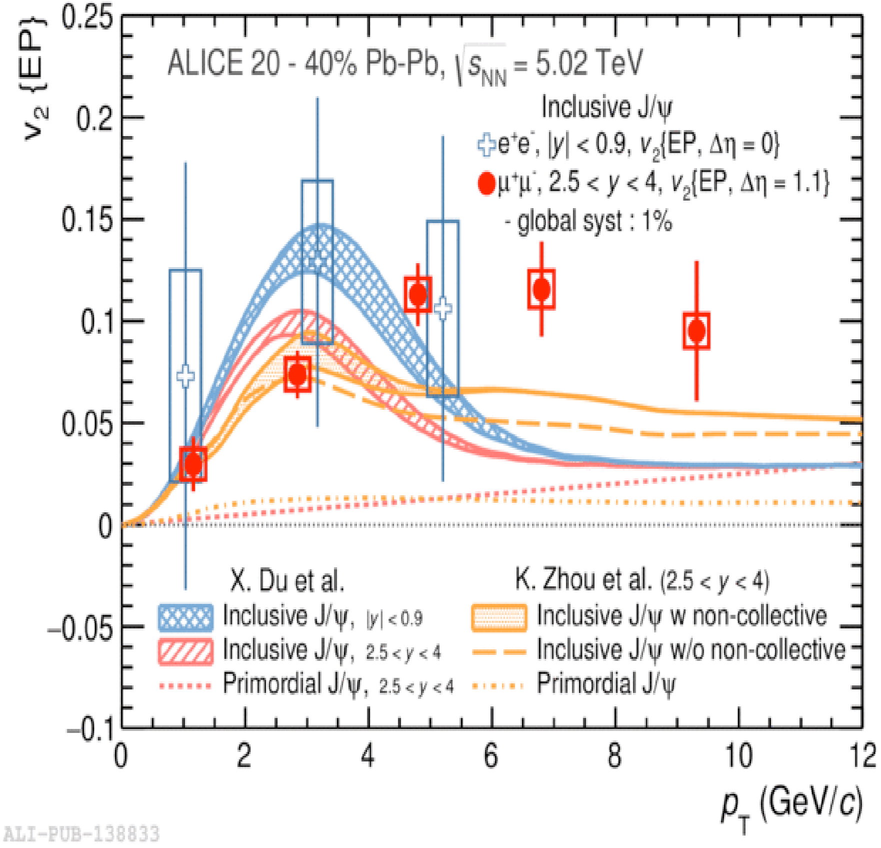


ALI-PUB-91088

- ψ(2S) results show stronger suppression w.r.t. to J/ψ in the Pb-going direction
- ψ(2S) results show suppression in the p-going direction

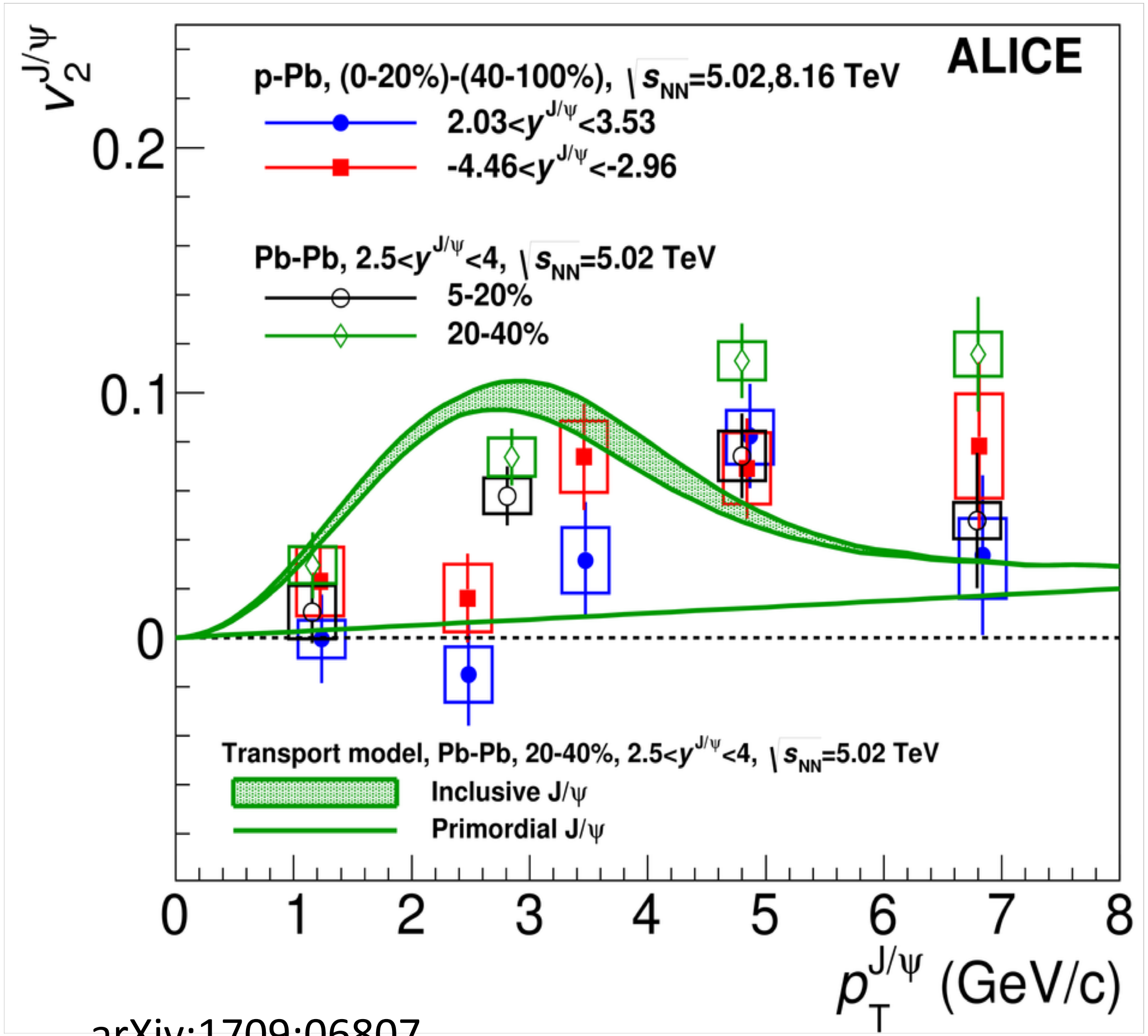
Elliptic Flow in Heavy Flavours





- v_2 of J/ψ production corroborates the significant contribution of (re)generation as source of J/ψ production in Pb–Pb
- D-meson v_2 points to the participation of the charm quarks in thermalization and recombination
- D-meson v_2 indicates that charm participates in collective motion

Elliptic Flow in Heavy Flavours cont.

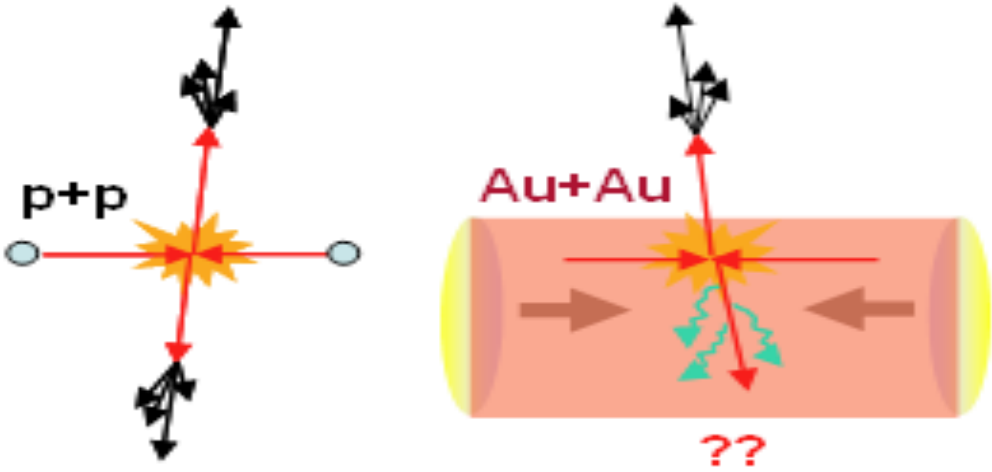


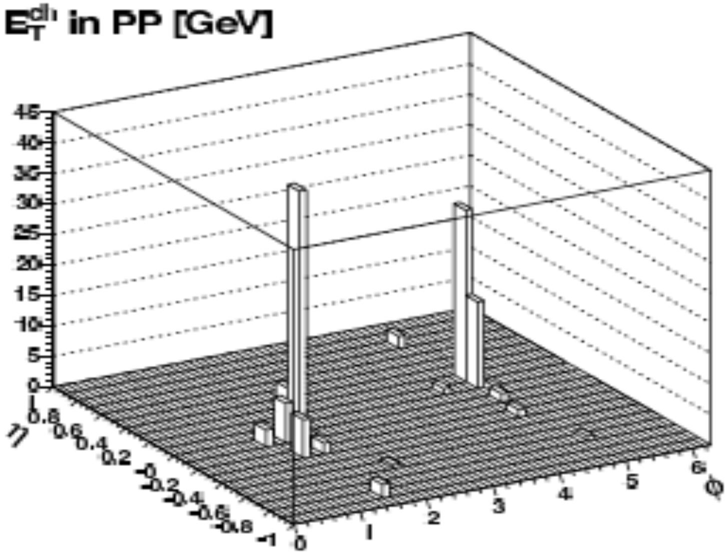
arXiv:1709:06807

- p-Pb
- At p_T<3 GeV/c v_2 compatible with 0
- At p_T>3 GeV/c v_2>0
- Charm quarks participate in collective effects? Flow p-Pb? Rescattering of charm?

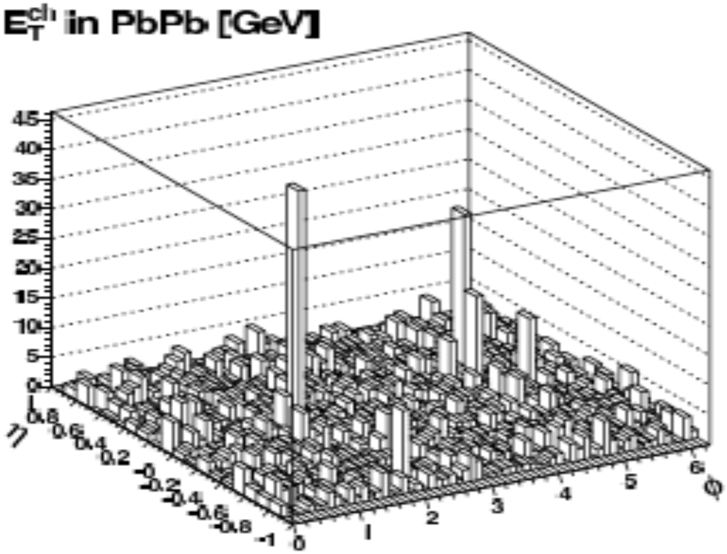
Probing the QGP Medium with Jets

- Study QGP by the way particles interact while crossing the plasma



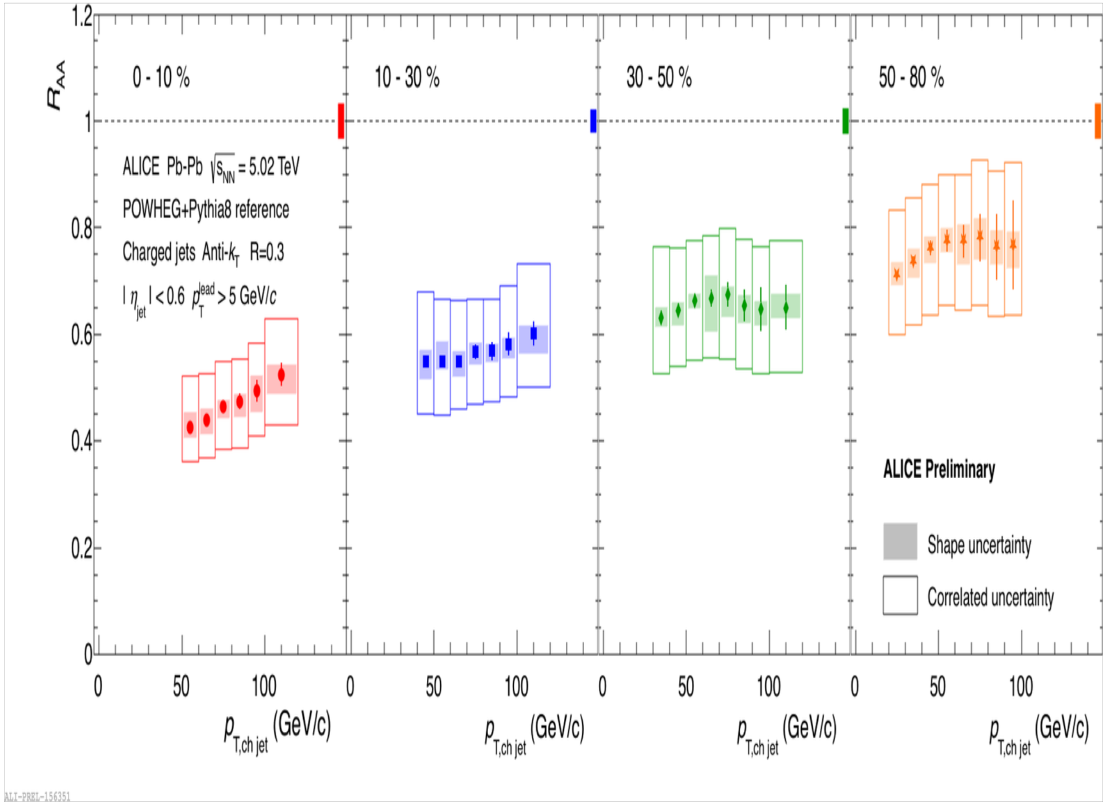


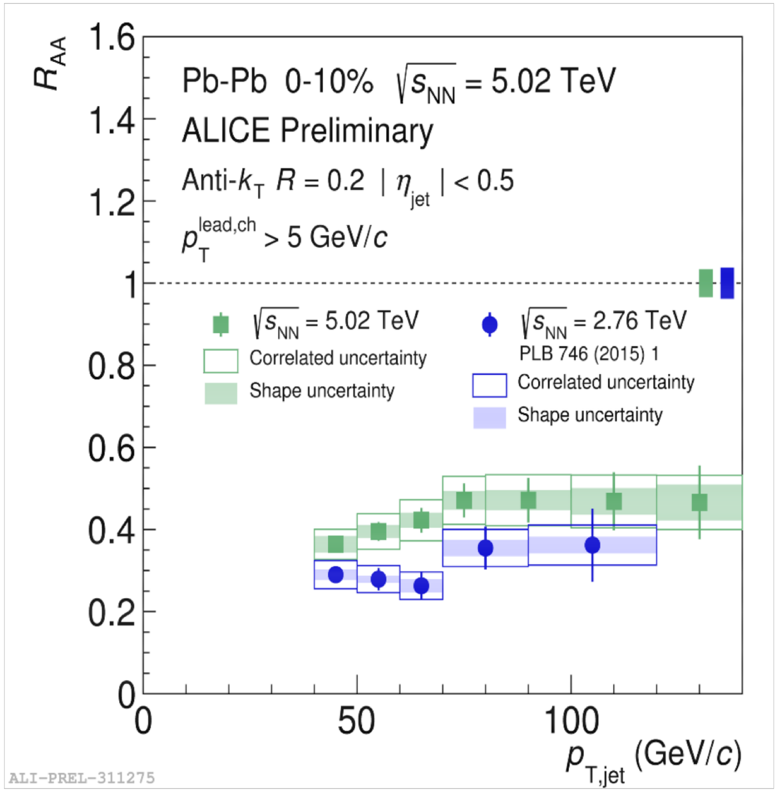
Jet event pp collision



Jet event Pb-Pb collision

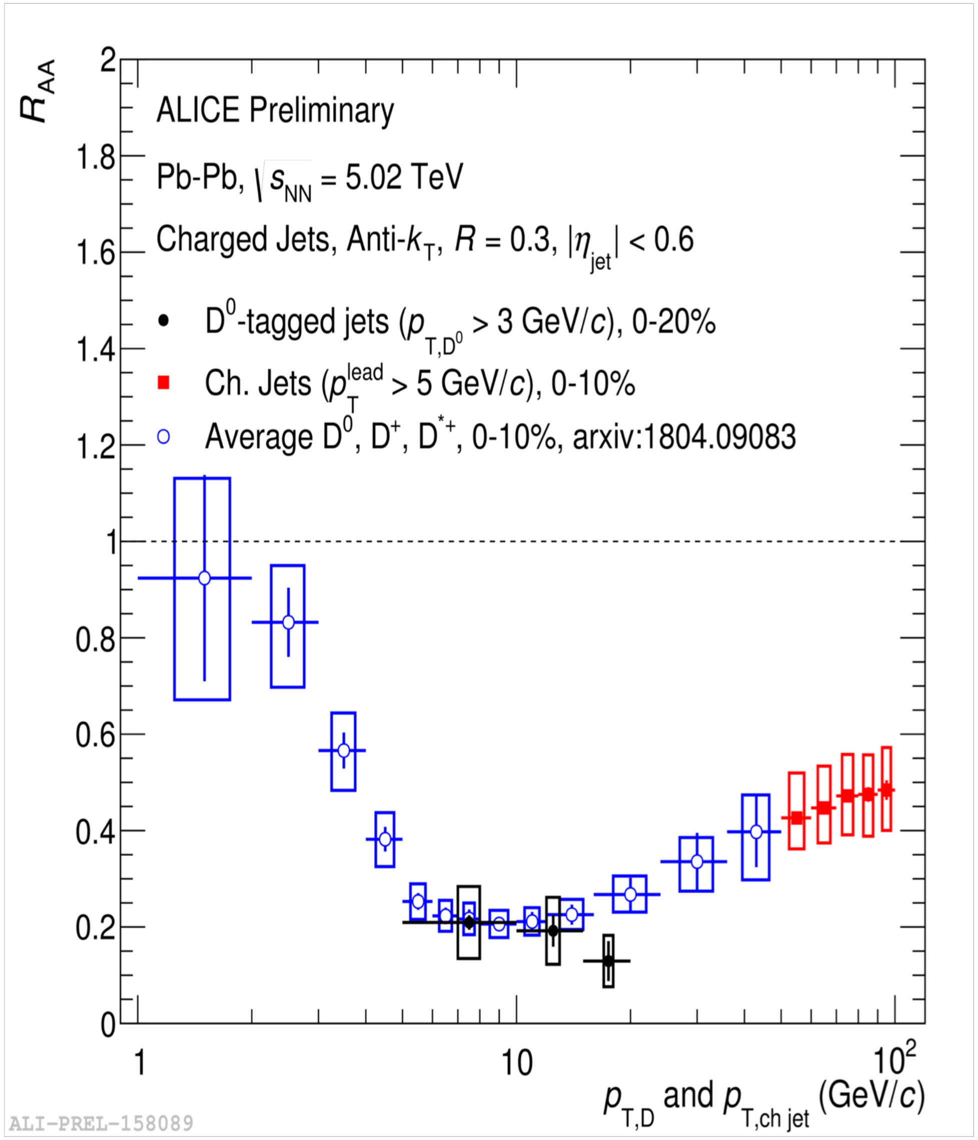
Nuclear modification factor of Jets Pb-Pb





- Charged Jet R_{AA} in Pb-Pb 5.02TeV for four centrality classes.
- POWHEG+Pythia8 predictions is used as pp reference.

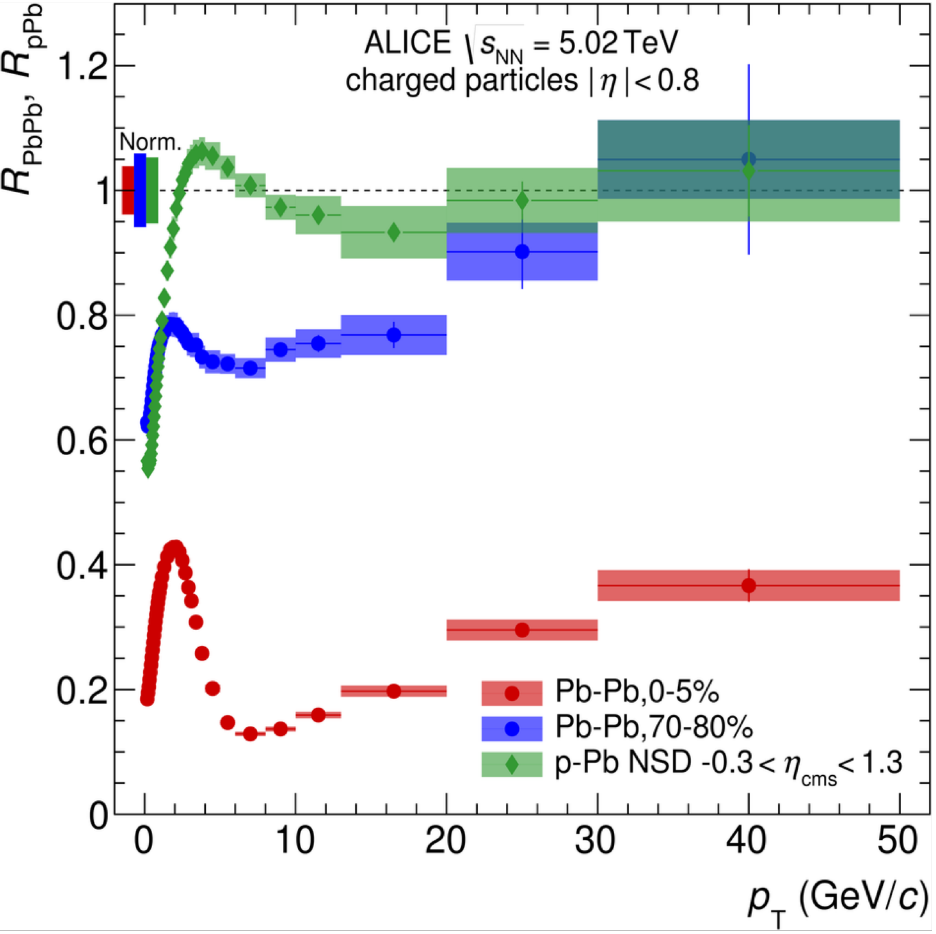
D-meson tagged jets vs inclusive full Jets (Pb-Pb)

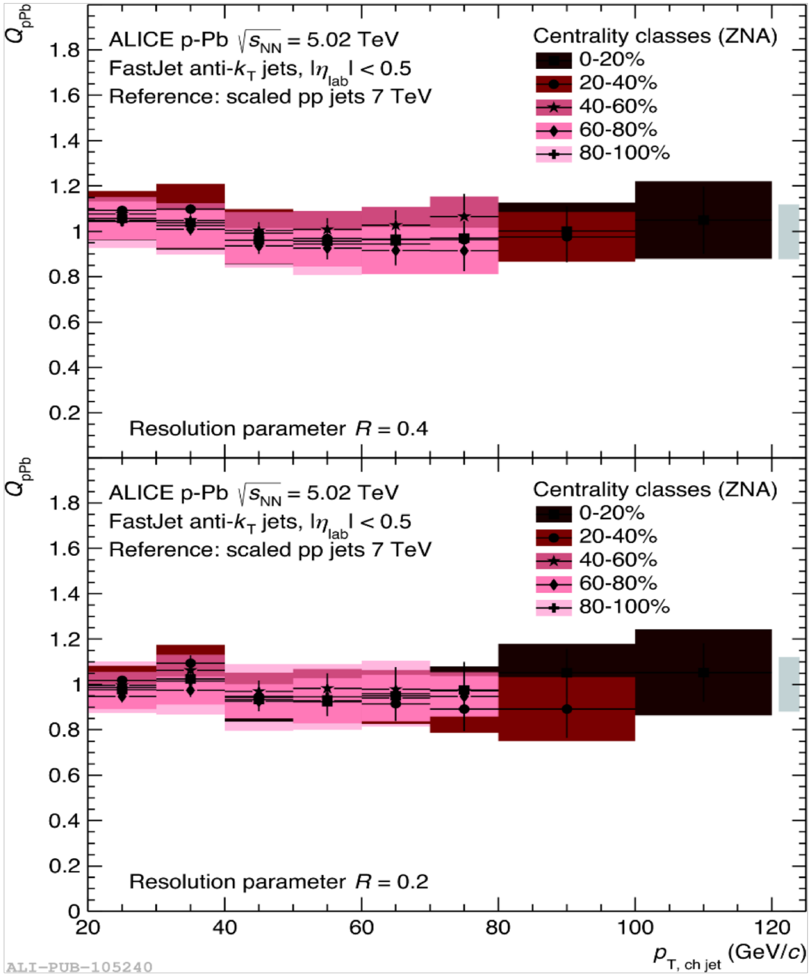


- Suppression of full jets observed up to 130 GeV/c

- Similar suppression found for D^0-tagged jets as for D^0-mesons at lower p_T

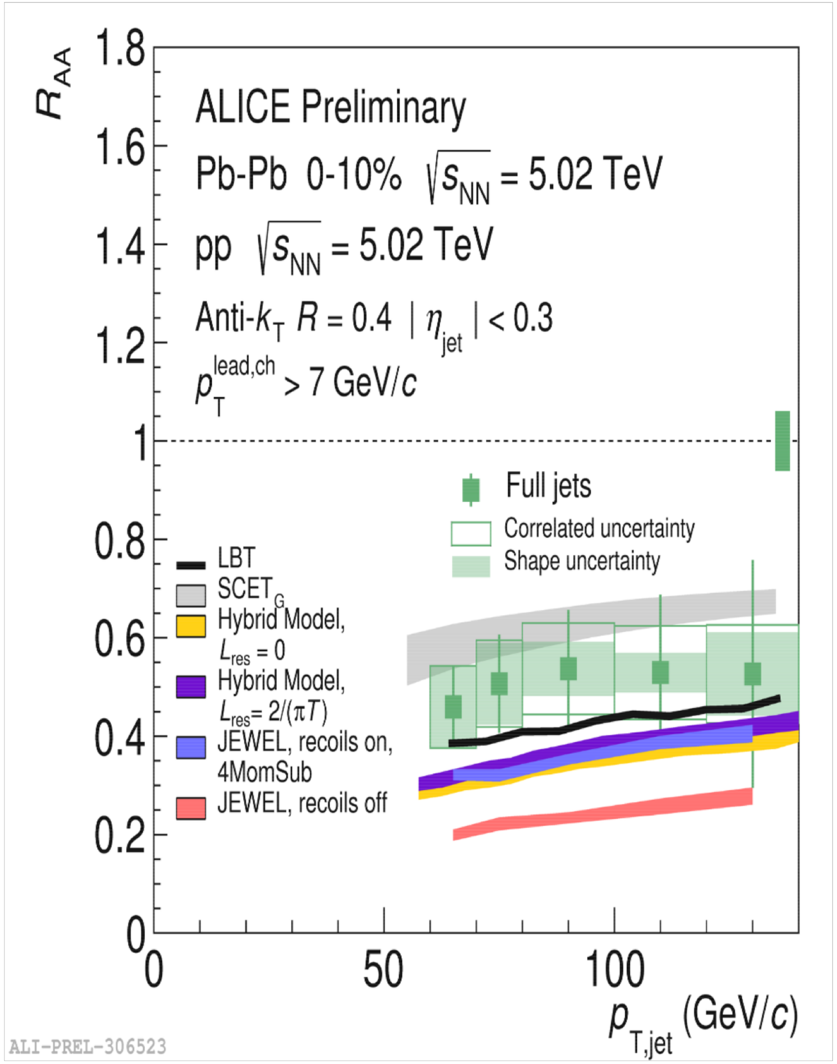
Nuclear modification factor of Jets p-Pb





- Suppression still significant in peripheral Pb-Pb
- No suppression in p-Pb collisions
- Qualitatively final state effects would cause not only flow and energy loss, quantitatively the energy loss effects may be small

R_{AA} and Model Calculations



- JEWEL[arXiv:1212.1599] predictions are provided with and without recoils
- Linear Boltzmann Transport (LBT) model [arXiv:1503.03313] initial jet shower is produced by Pythia 8, neglecting nuclear modification of the PDF
- Soft Collinear Effective Theory with Glauber gluons (SCETG) [arXiv:1701.05839], pp jet crosssection is computed to NLO in α_s, and with a LL resummation in jet R. Medium effects are computed at NLO, but without a resummation in jet
- In the Hybrid model [arXiv:1405.3864], The parameter κ_{sc} is the main free parameter in the model, and is fit to ATLAS and CMS hadron and jet data

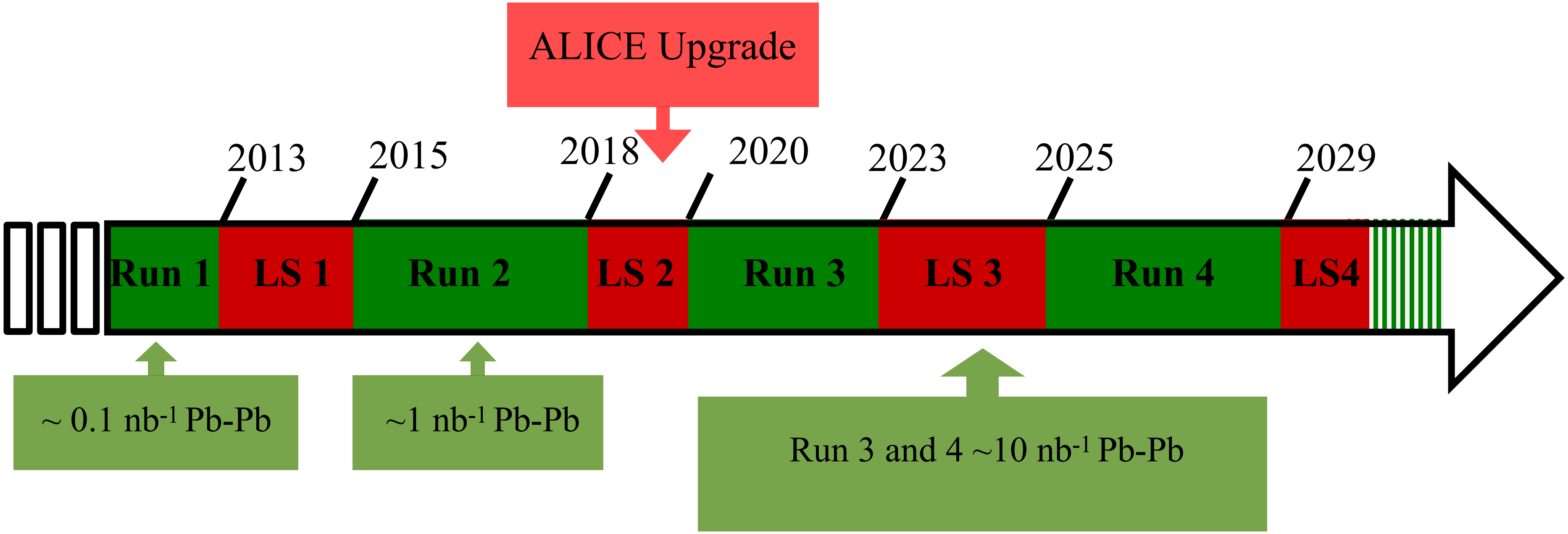
Conclusion Before Upgrade Review

- Better understanding of QGP development in heavy-ion collisions via soft and hard probe observables, including heavy-flavour measurements
- Signs of collective behavior in p-Pb collisions with origin to be clarified
- No energy loss observable detected in p-Pb collisions
- Upgrade will give us the opportunity to clarify further these and other open questions

LHC Schedule for Heavy Ions

Heavy-ion program at LHC extended to Run 3 and Run 4

- Energy Pb-Pb 5.5 TeV, p-Pb 8.8 TeV, pp all energies
- LHC target luminosity Pb-Pb $\mathcal{L}=6\times10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Participation of ALICE, ATLAS, CMS, LHCb (p-Pb)



ALICE Upgrade

2013 2015 2018 2020 2023 2025 2029

Run 1 | LS 1 | Run 2 | LS 2 | Run 3 | LS 3 | Run 4 | LS4

~ 0.1 nb^{-1} Pb-Pb

~1 nb^{-1} Pb-Pb

Run 3 and 4 ~10 nb^{-1} Pb-Pb

ALICE Physics Goals for Run 3 &4

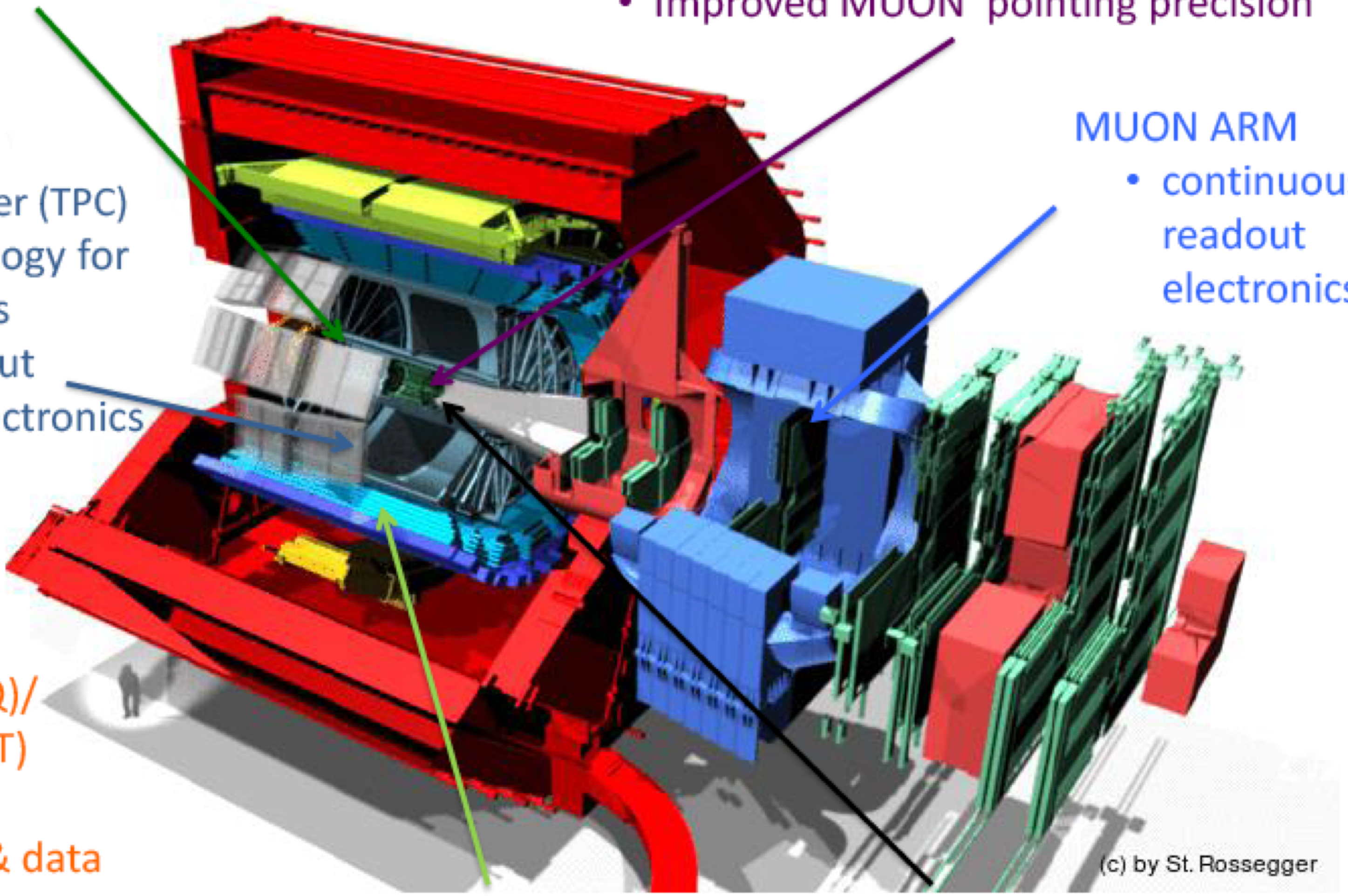
Probe	Physics	Measurement
Heavy-flavor (charm & bottom)	Thermalization, EoS Transport coefficient, Energy loss	v_2 and R_{AA}
Quarkonia (J/ψ, ψ’)	Production mechanisms, dissociation and regeneration	Yield, v_2 and R_{AA}
Low mass di-leptons	Initial temperature, EoS Chiral phase transition	Yield, v_2 , vector meson spectral function
Jet Probes	Parton energy loss, jet composition, jet tagging	PID fragmentation function, heavy flavor in jets, γ-jet correlation
Heavy nuclear states	Search for exotic bound states, anti-hyper nucleus, H-Dibaryon	Yield

- High precision in a wide momentum range down to very low p_T

ALICE for Run 3 and 4

- Requirements
  - Minimum bias trigger selection (very low signal/background ratio for most of the physics signals)
  - High Rate: 50 kHz
  - Large data sample: $L_{int} > 10\ nb^{-1}$
  - Improve (add) heavy flavour vertexing at central (forward) rapidity
  - Improve low p_T tracking efficiency
- Strategy
  - Forward trigger detectors upgrade
  - Integrated online & offline structure (O^2 project)
  - New Inner Tracking System at midrapidity
  - New Muon Forward Tracker in front of the muon absorber
  - TPC with GEM readout + new pipelined electronics (dead-time free)

ALICE Upgrade



New Inner Tracking System (ITS)
- improved pointing precision
- less material -> thinnest tracker at the LHC

Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

Time Projection Chamber (TPC)
- new GEM technology for readout chambers
- continuous readout
- faster readout electronics

MUON ARM
- continuous readout electronics

al

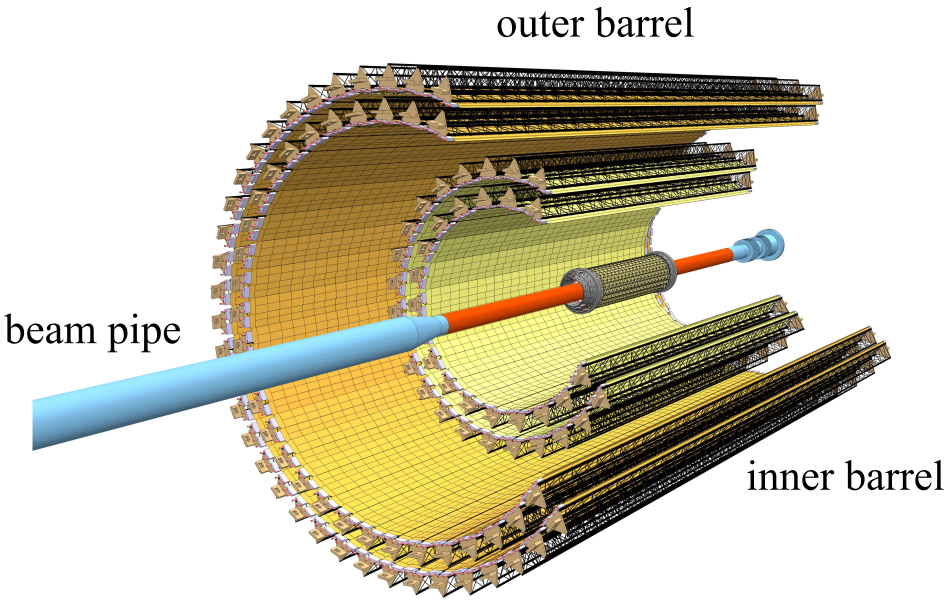
Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

TOF, TRD
- Faster readout

New Trigger Detectors (FIT)

(c) by St. Rossegger

New Inner Tracking System (ITS)

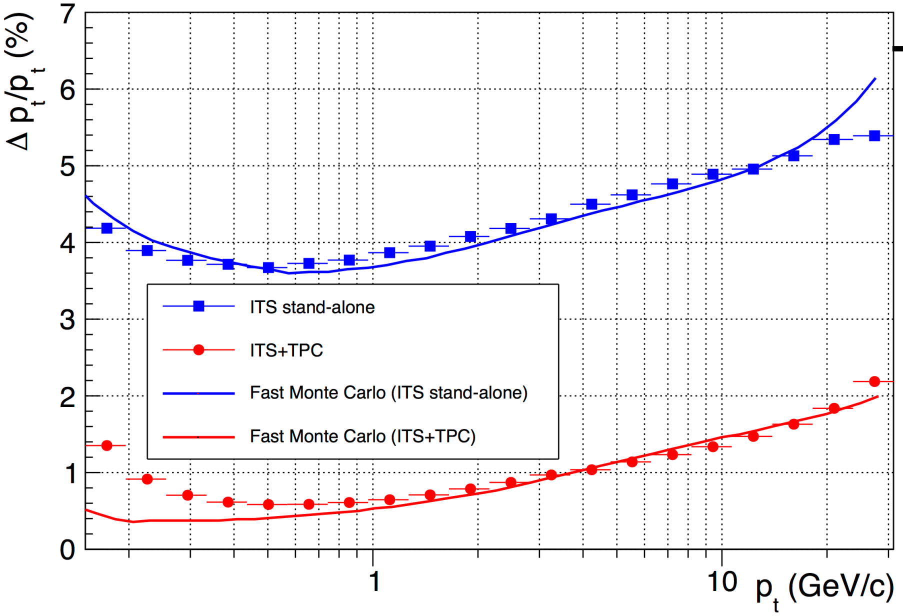


CERN-LHCC-2013-024;ALICE-TDR-17

	Present	Upgrade
Pseudorapidity	$\lvert \eta \rvert < 0.9$	$\lvert \eta \rvert < 1.22$
Radius inner most layer	39 mm	~ 23 mm
Si thickness	~ 350 µm	~ 50 µm
Pixel Size	50 µm by 425 µm	~ 30 µm by 30 µm
Material Budget per layer	~1.1 % X_o	~ 0.3 – 0.8 % X_o
Max. Rate Pb-Pb	~1 kHz	~100 kHz

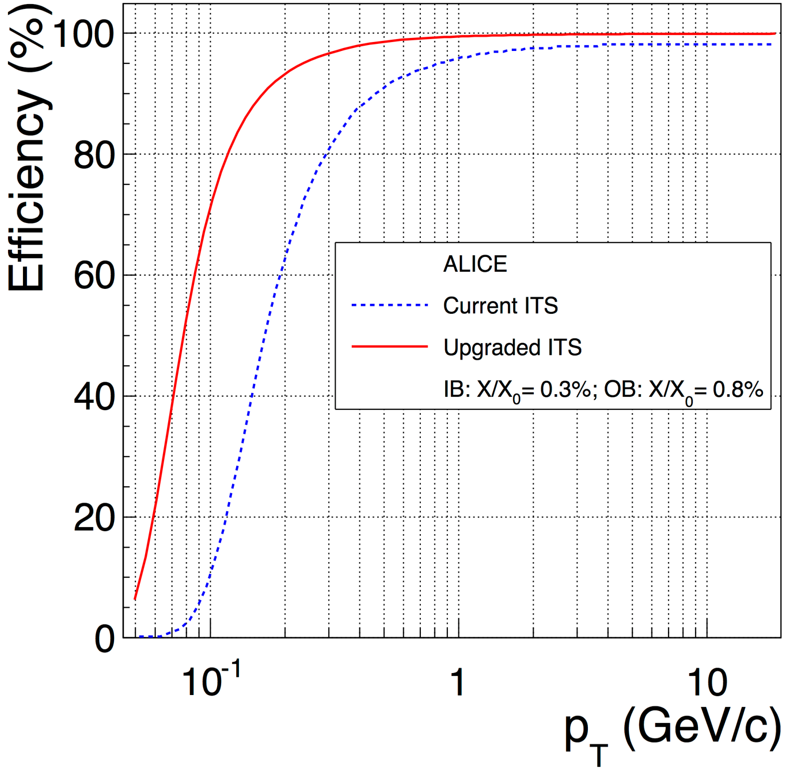
- 7 layers of Monolithic Active Pixel Sensors (MAPS)
- Improve impact parameter resolution by a factor ~3 to 5 in rϕ (z)
- Better tracking efficiency and p_T resolution at low p_T
- Accessible for maintenance during winter shutdowns

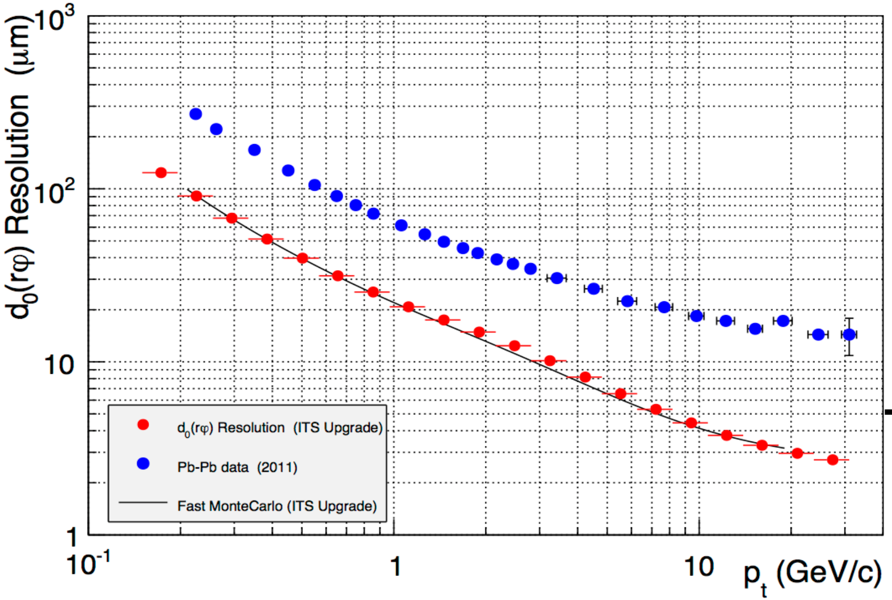
ITS Expected Performance



Transverse momentum resolution

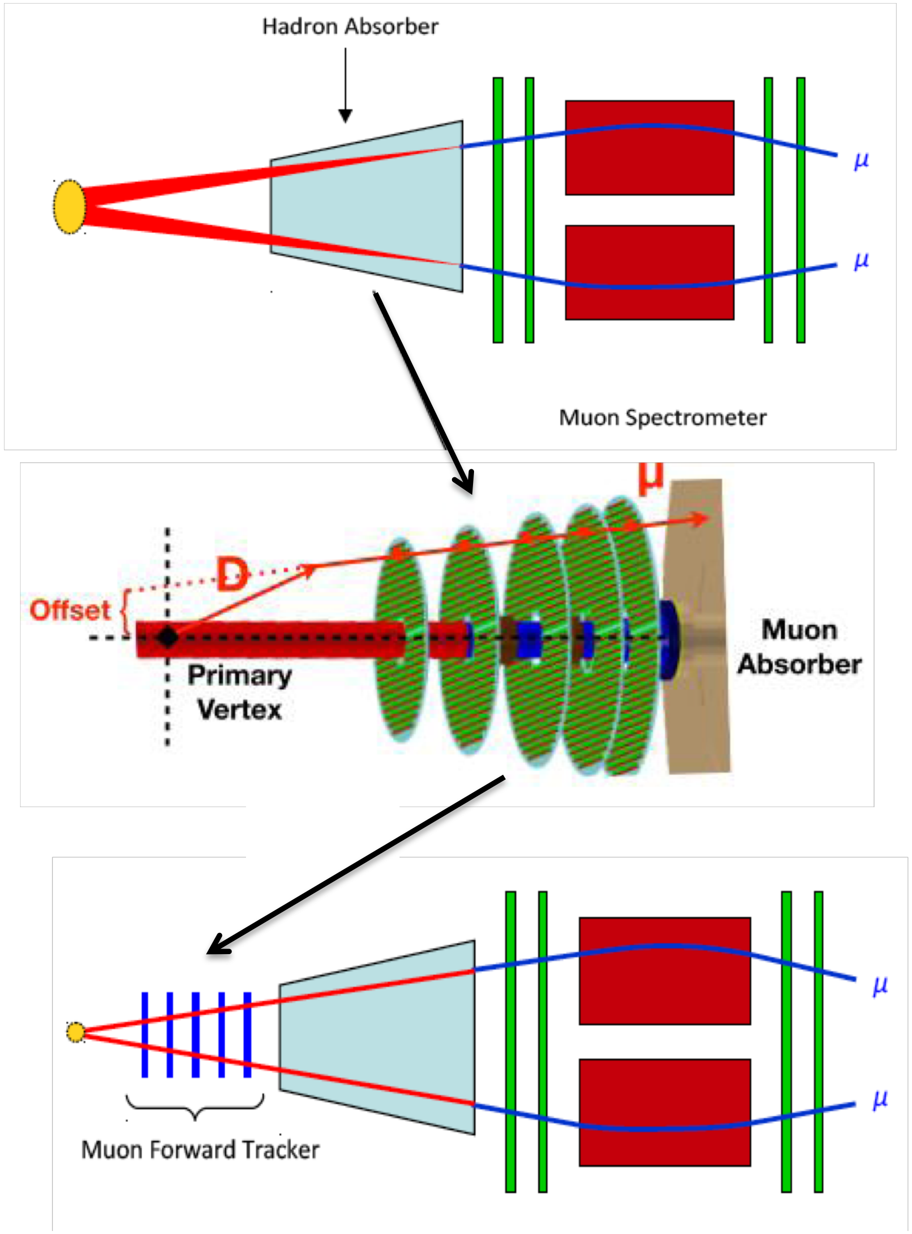
Tracking efficiency





Impact parameter resolution

Muon Forward Tracker

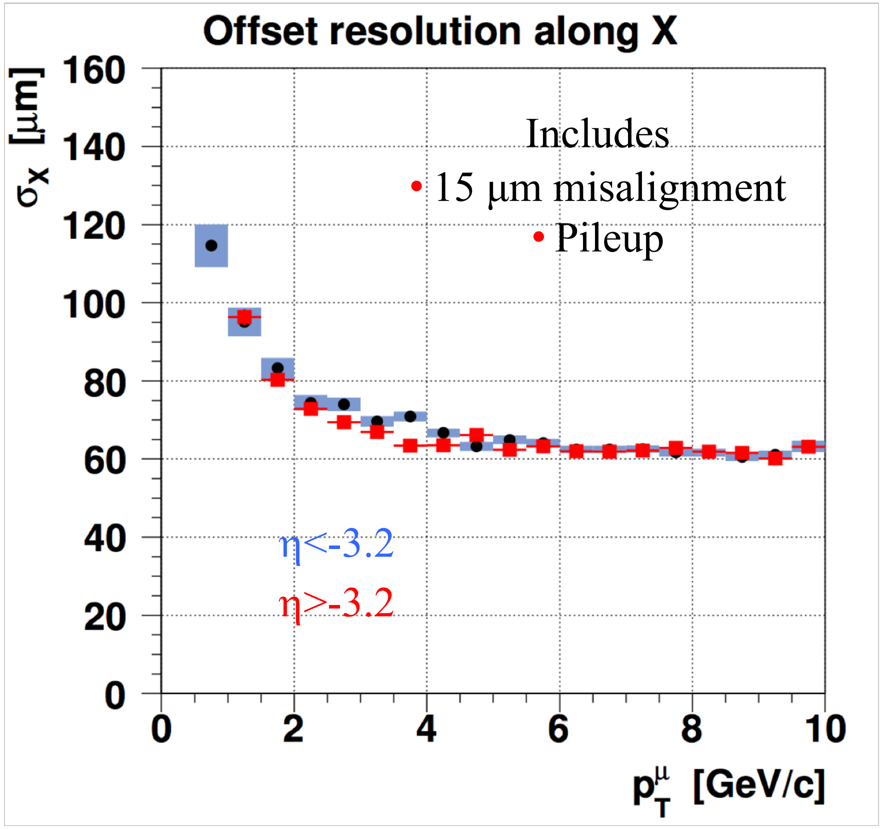


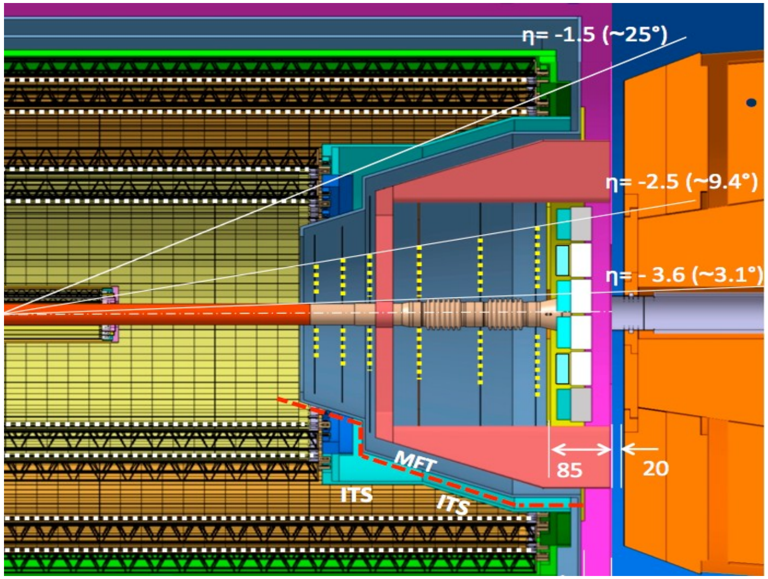
- Extrapolating back degrades the information on the kinematics and trajectory
- Cannot separate prompt and displaced muons

Upgrade

- Muon tracks are extrapolated and matched to the MFT clusters before the absorber
- High pointing accuracy
- Separation of charm and beauty signals (single μ, J/ψ)

Muon Forward Tracker Performance

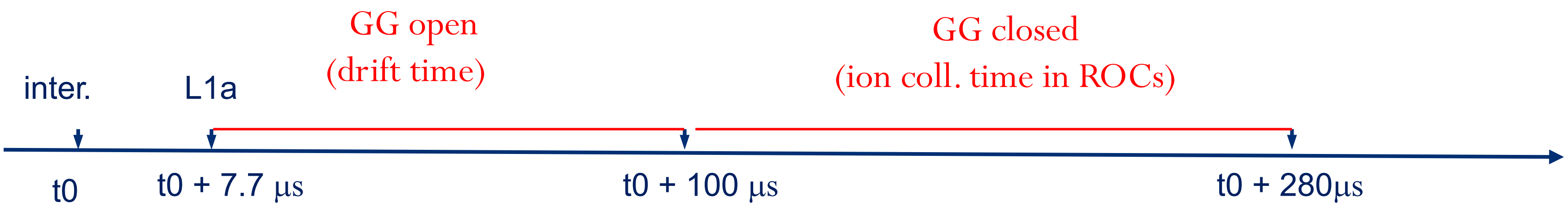


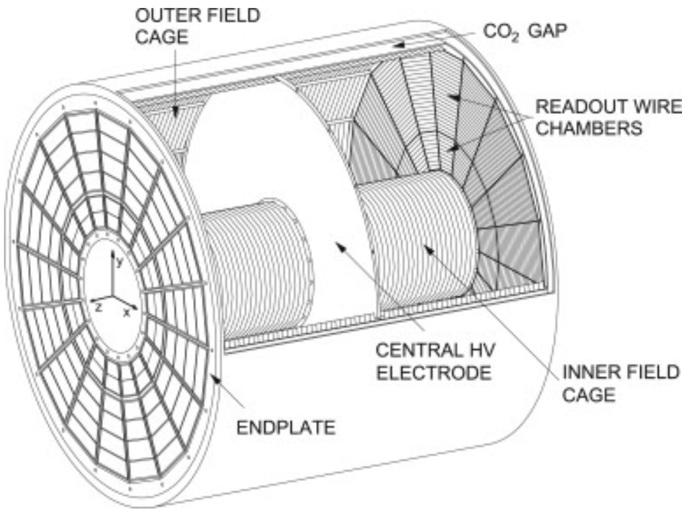


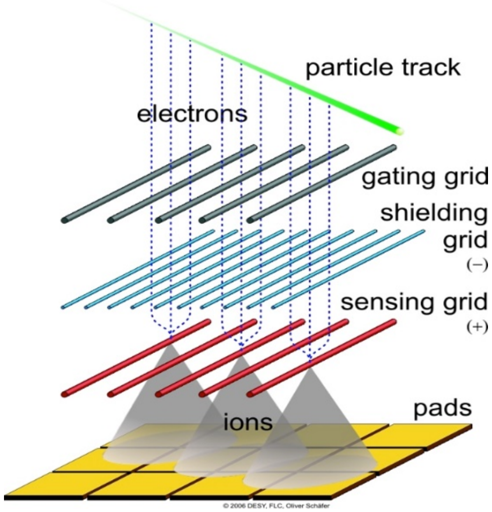
CERN-LHCC-2013-014 ; LHCC-I-022-ADD-1

- 5-6 planes of MAPS pixel size 30 by 30 µm^2 (same as ITS)
- $50 < z < 80$ cm
- $R_{min} \approx 2.5$ cm, $11 < R_{max} < 16$ cm
- $X/X_0 = 0.4\%$ per plane

TPC Current Limitations

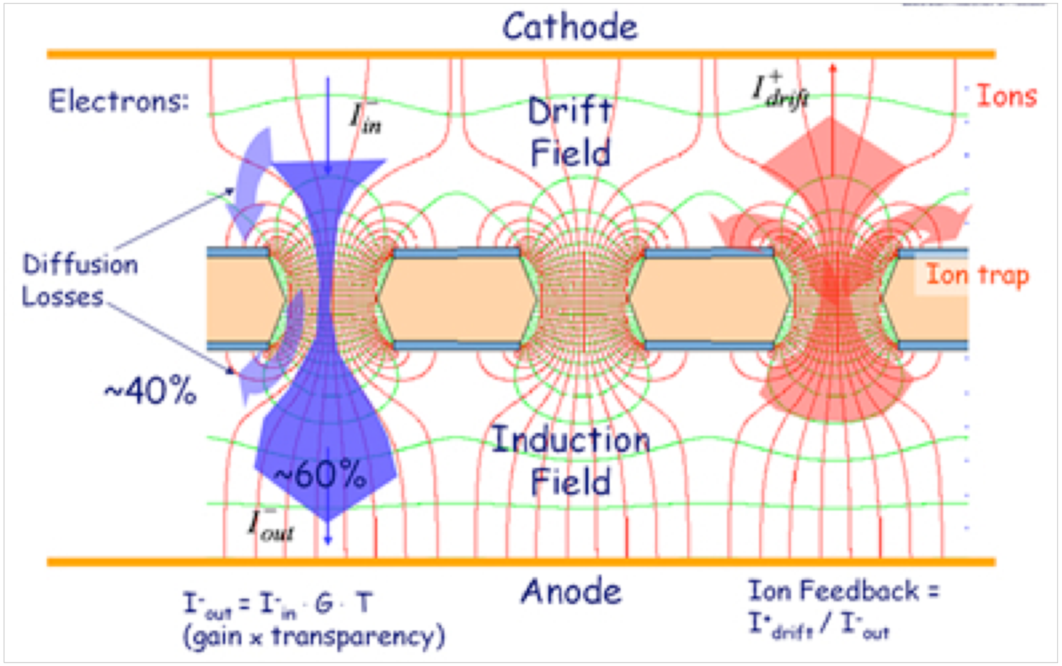

GG open
(drift time)
GG closed
(ion coll. time in ROCs)
inter.
L1a
t0
t0 + 7.7 μs
t0 + 100 μs
t0 + 280μs



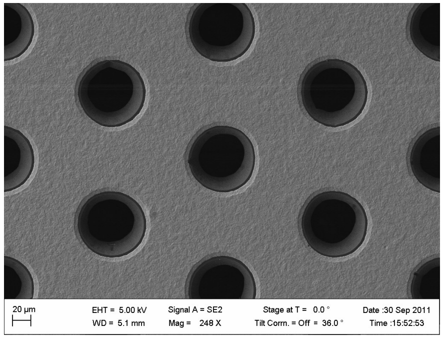


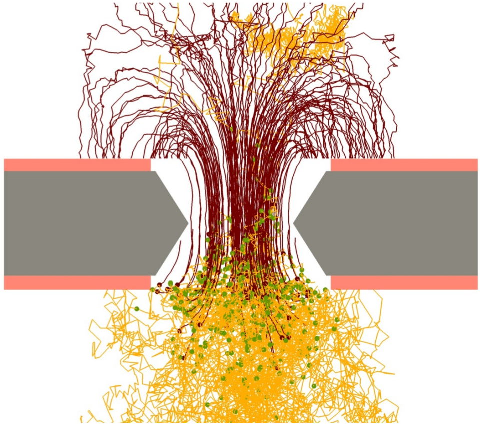
- Gating grid of readout of MWPCs closed to avoid ion feedback (IFB) and keep space charge at tolerable levels
- Effective dead time ~280 μs, maximum effective readout rate 3.5 kHz

TPC Upgrade



F.Sauli, NIM A386 531 (1997)

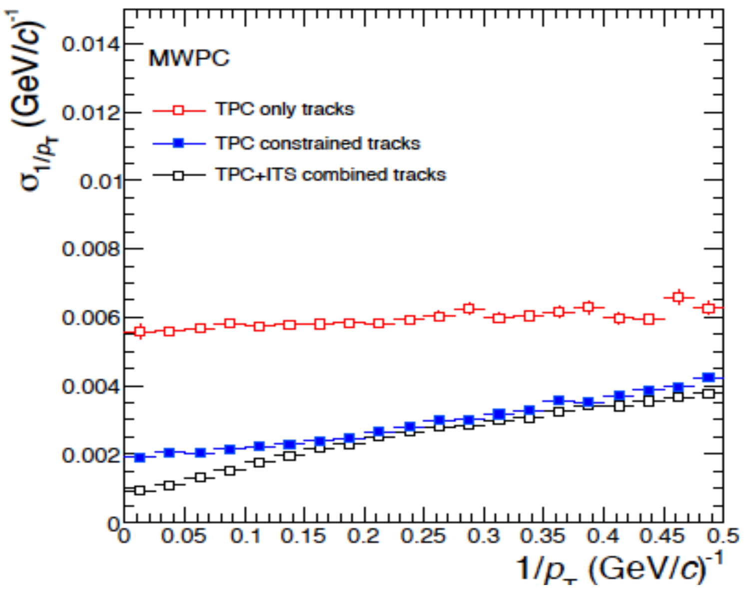


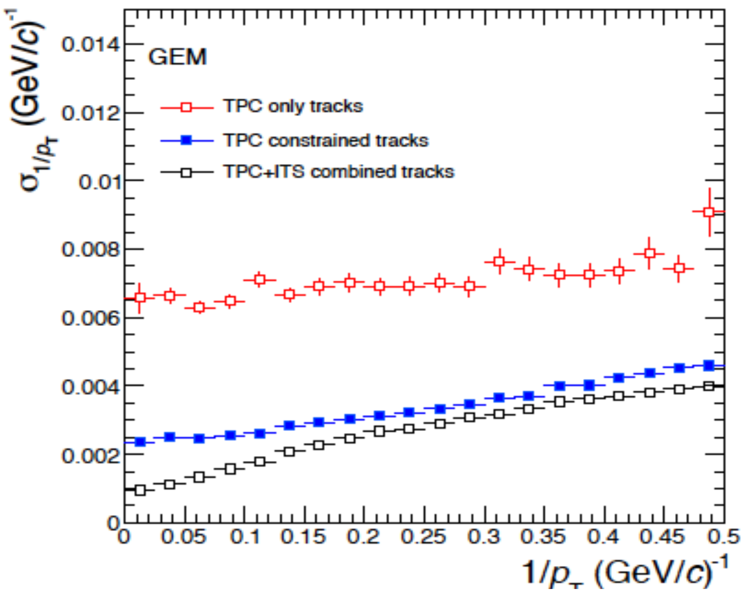


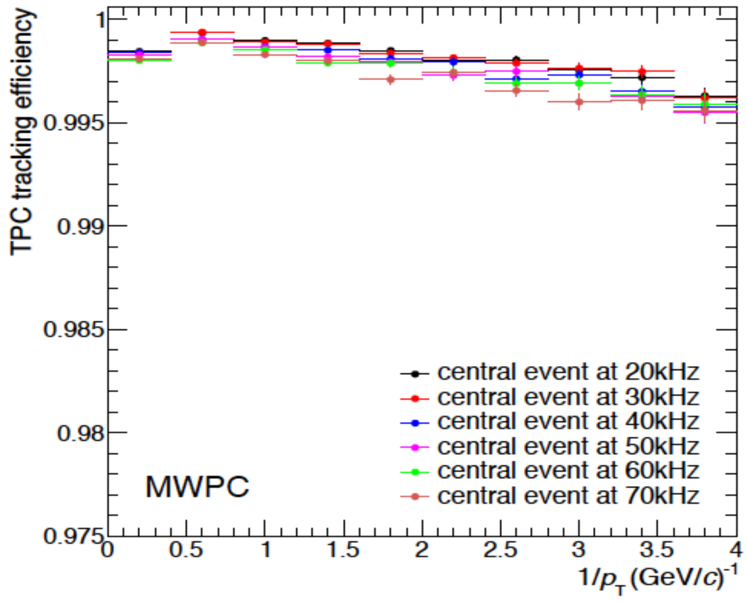
- Continuous readout: redesign of FE and readout electronics
- Use of Gas Electron Multiplier (GEM)
  - IBF < 1% at gain = 2000
  - Cluster energy resolution <12% for ^{55}Fe
  - Stable operation at high rate

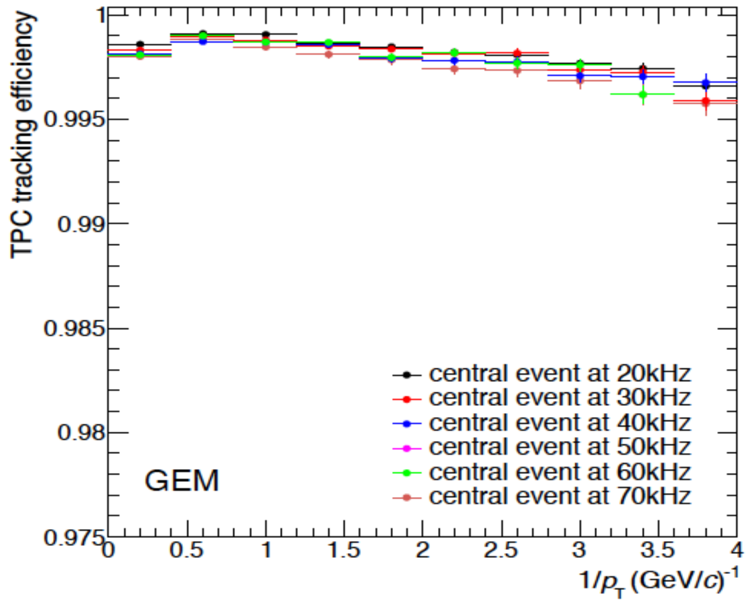
CERN-LHCC-2013-020 ; ALICE-TDR-016

Expected performance





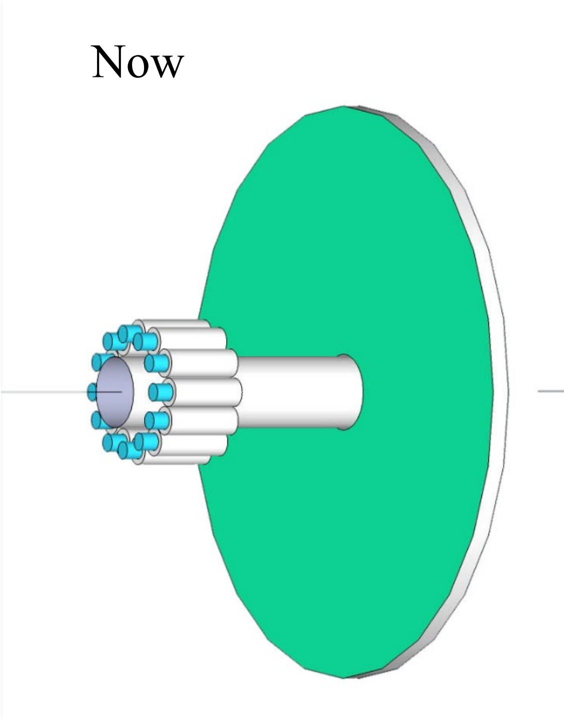




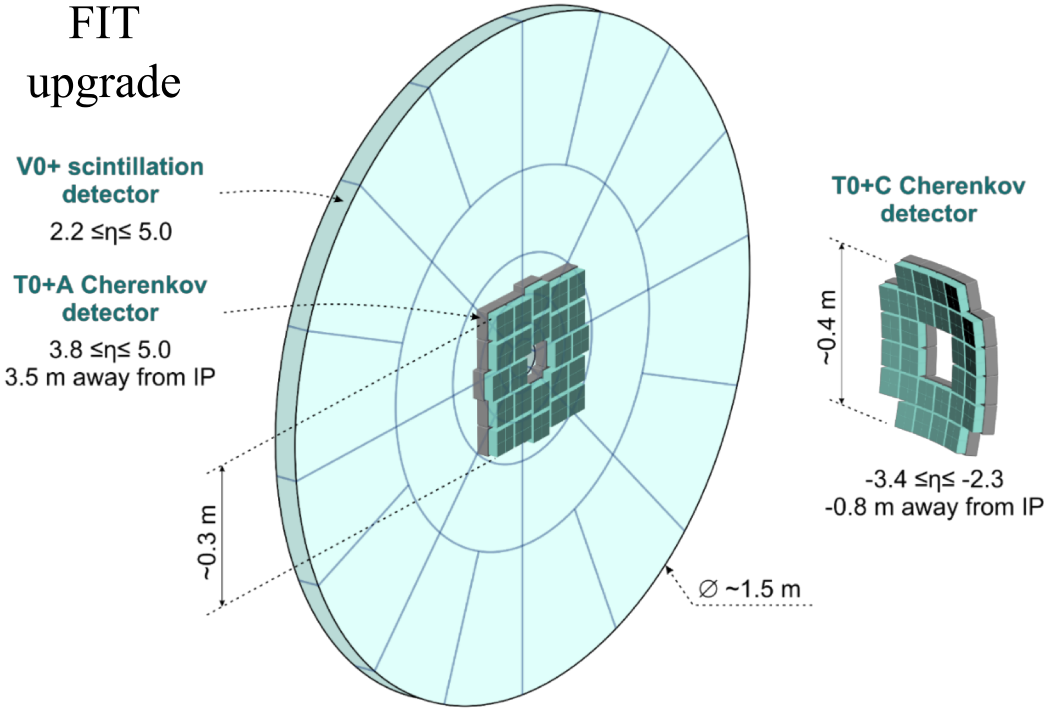
CERN-LHCC-2013-020 ; ALICE-TDR-016

Fast Interaction Trigger (FIT)

Now

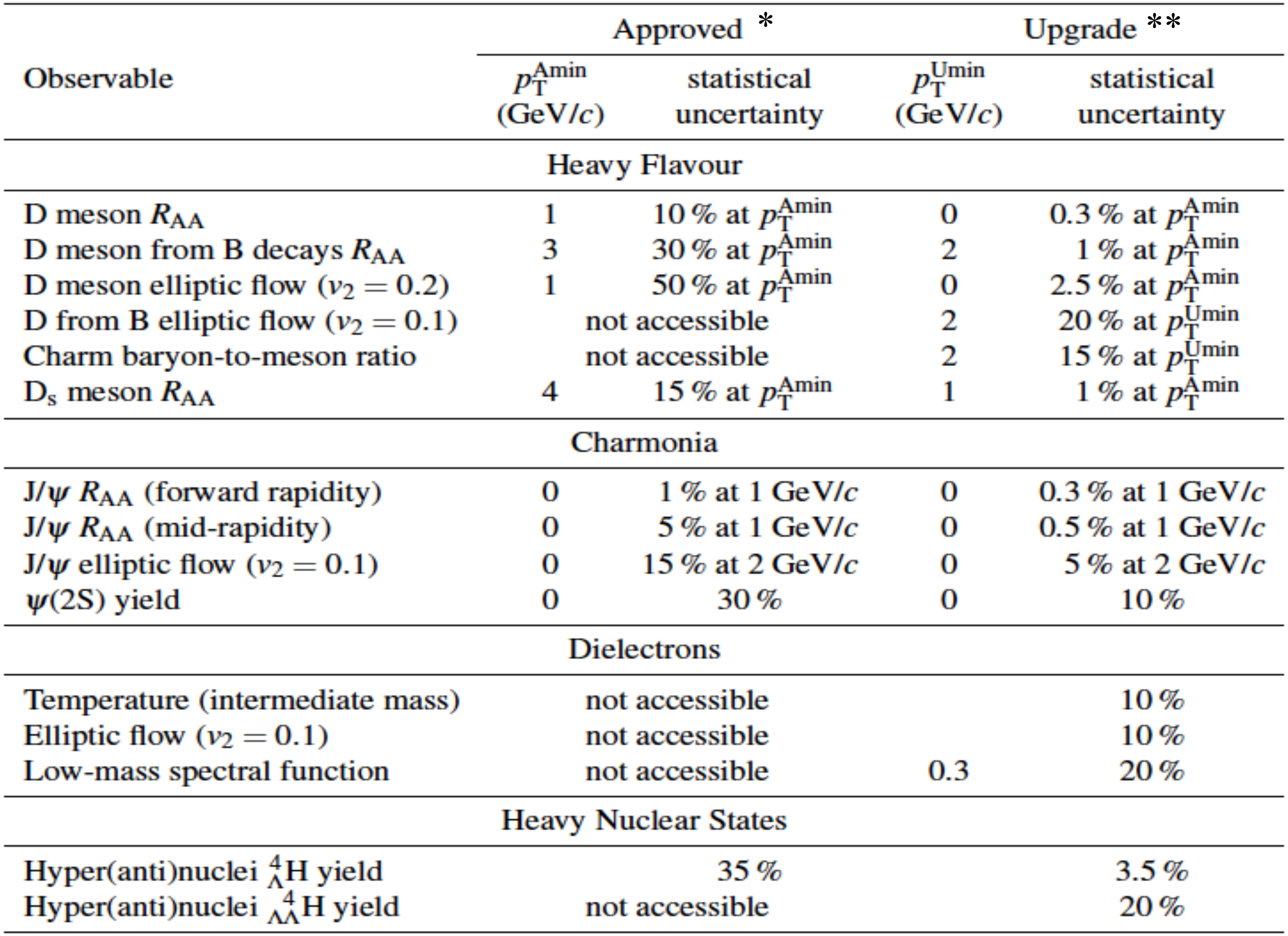


FIT upgrade



- New sensors, MCP-PMT (same for V0-Plus and T0-Plus)
- Larger acceptance
- Larger segmentation
- Improved frontend electronics and readout

Upgrade Physics Reach



Observable	Approved *		Upgrade **	
	p_T^{Amin} (GeV/c)	statistical uncertainty	p_T^{Umin} (GeV/c)	statistical uncertainty
Heavy Flavour				
D meson R_{AA}	1	10 % at p_T^{Amin}	0	0.3 % at p_T^{Amin}
D meson from B decays R_{AA}	3	30 % at p_T^{Amin}	2	1 % at p_T^{Amin}
D meson elliptic flow ($v_2 = 0.2$)	1	50 % at p_T^{Amin}	0	2.5 % at p_T^{Amin}
D from B elliptic flow ($v_2 = 0.1$)	not accessible		2	20 % at p_T^{Umin}
Charm baryon-to-meson ratio	not accessible		2	15 % at p_T^{Umin}
D_s meson R_{AA}	4	15 % at p_T^{Amin}	1	1 % at p_T^{Amin}
Charmonia				
J/ψ R_{AA} (forward rapidity)	0	1 % at 1 GeV/c	0	0.3 % at 1 GeV/c
J/ψ R_{AA} (mid-rapidity)	0	5 % at 1 GeV/c	0	0.5 % at 1 GeV/c
J/ψ elliptic flow ($v_2 = 0.1$)	0	15 % at 2 GeV/c	0	5 % at 2 GeV/c
ψ(2S) yield	0	30 %	0	10 %
Dielectrons				
Temperature (intermediate mass)	not accessible			10 %
Elliptic flow ($v_2 = 0.1$)	not accessible			10 %
Low-mass spectral function	not accessible		0.3	20 %
Heavy Nuclear States				
Hyper(anti)nuclei $^{4}_{\Lambda}$H yield		35 %		3.5 %
Hyper(anti)nuclei $^{4}_{\Lambda\Lambda}$H yield	not accessible			20 %

Luminosity for minimum bias data

* 0.1 nb^{-1} out of 1 nb^{-1} delivered luminosity

** 10 nb^{-1} integrated luminosity

ALICE upgrade LOI, http://cds.cern.ch/record/1475243/

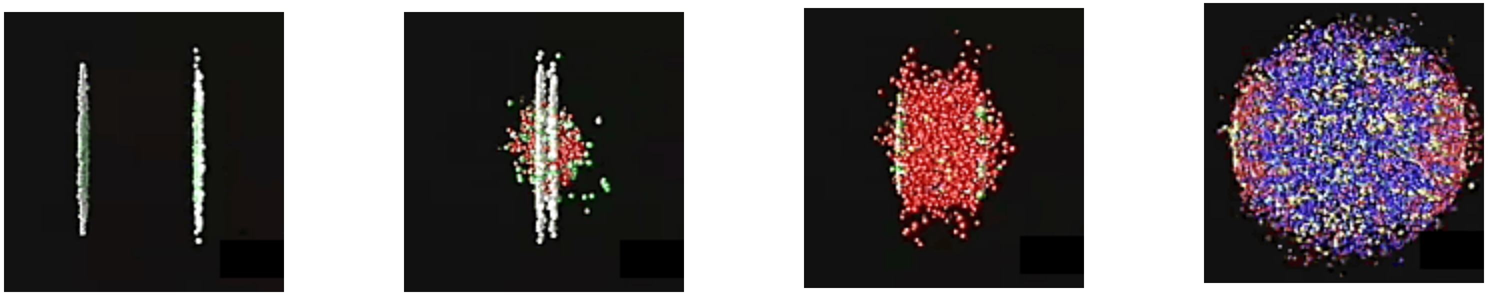
Final Notes

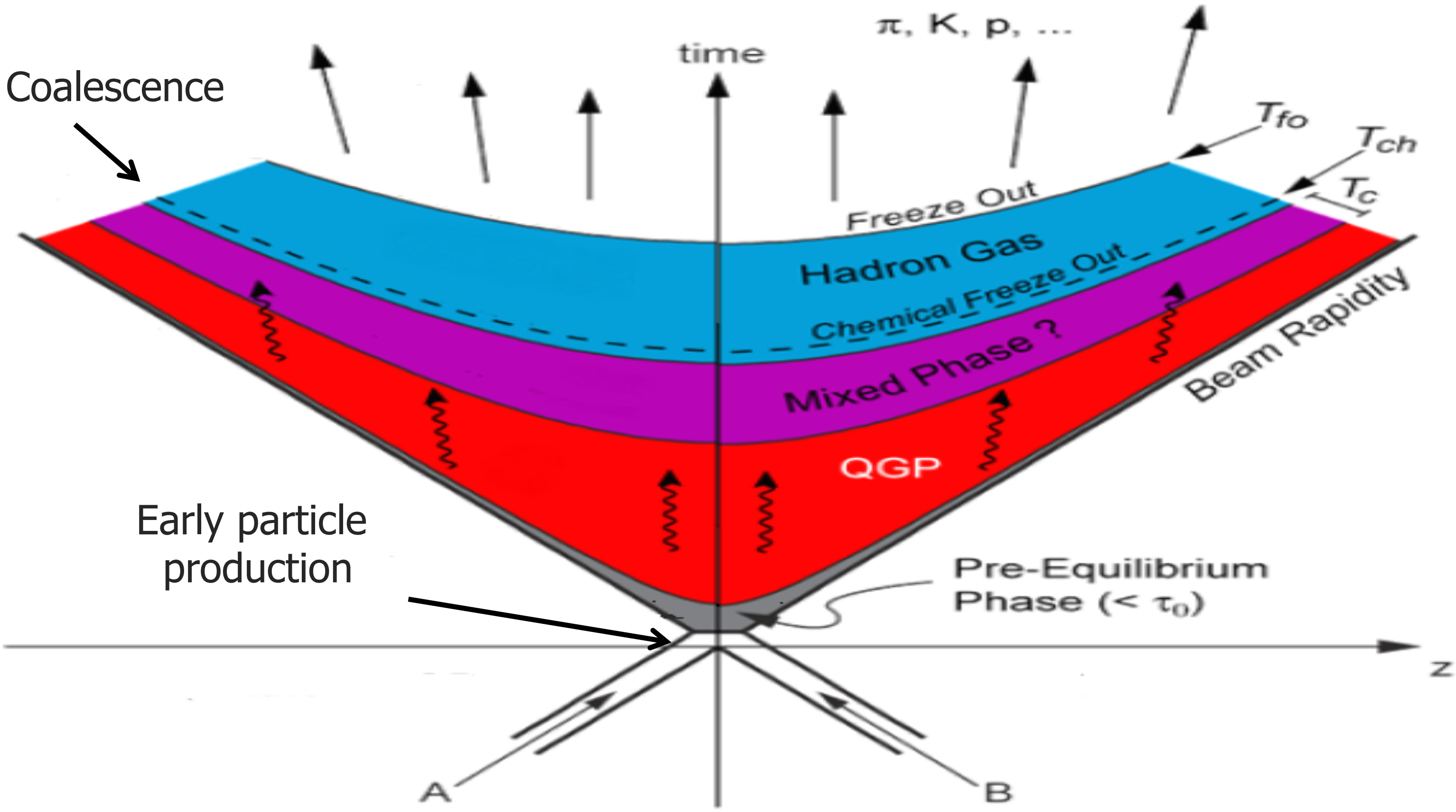
- ALICE covers a broad program of QGP physics: soft and hard probes, light, heavy flavors, photons and jets probe the QGP directly and via interactions
- Moving from qualitative to quantitative constraints on the QGP properties
- ALICE upgrade: improved precision and up to 100 times more events, to e.g. determine heavy flavor transport coefficient, investigate hadronization and gluon radiation in jets
- Upgrade is starting in a week! (after Pb-Pb run)

For Chicago State University, this material is based upon work supported by the National Science Foundation under grants NSF-PHY-1613118, NSF-PHY-1625081 and NSF-PHY-1719759

BACKUP SLIDES

Particles Produced in the Heavy-Ion Collision

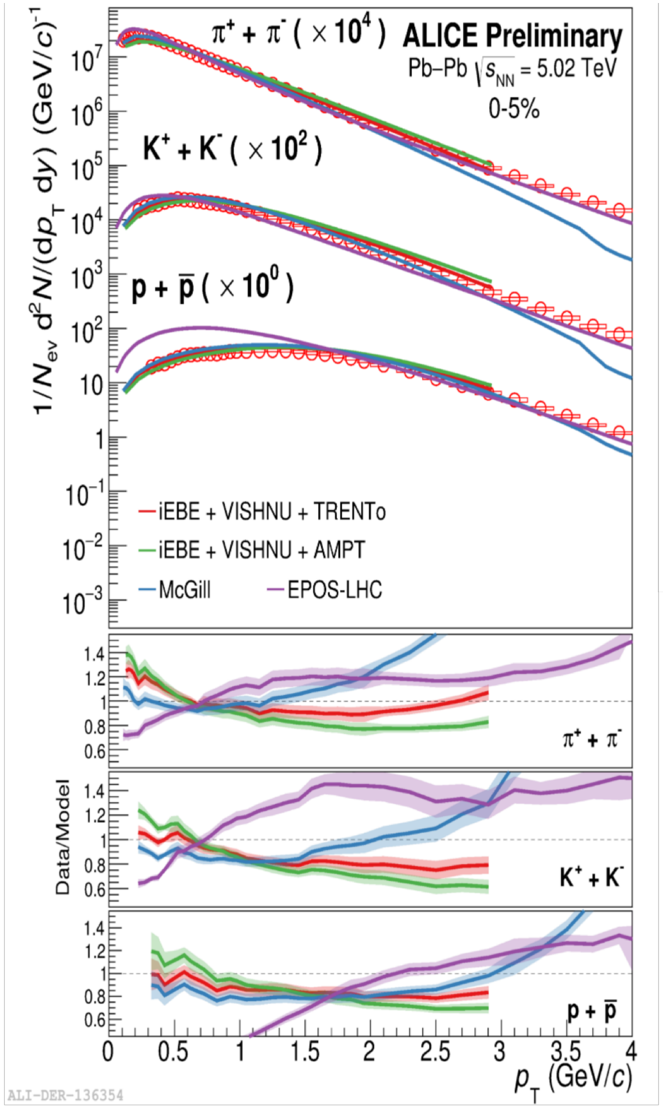




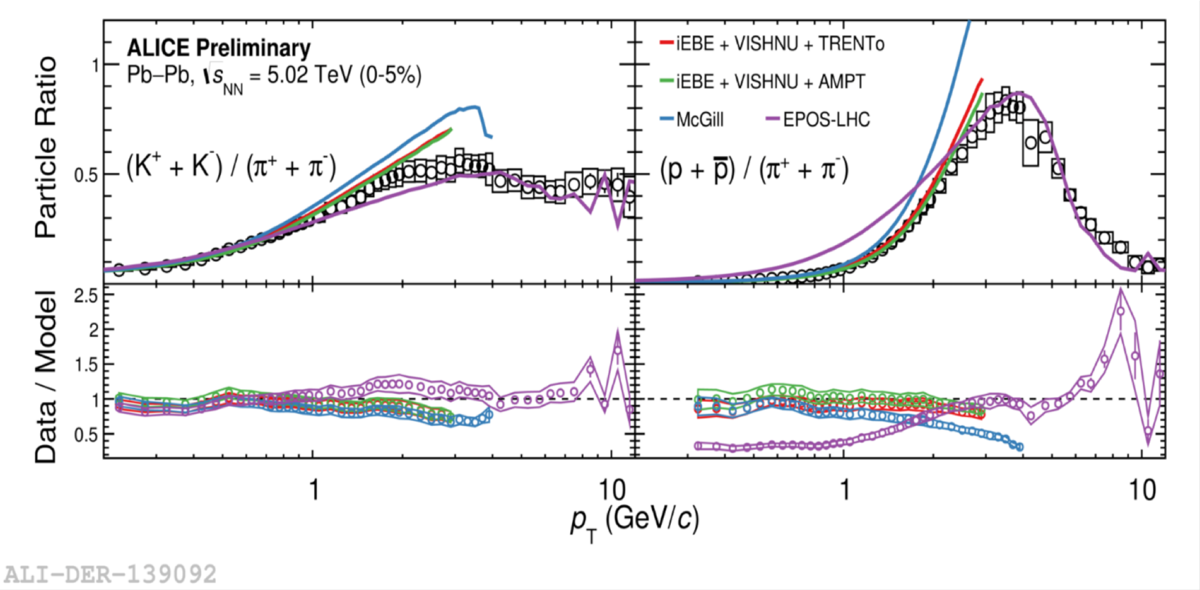
Coalescence

Early particle production

Hydro model comparison – Pb-Pb 0-5%



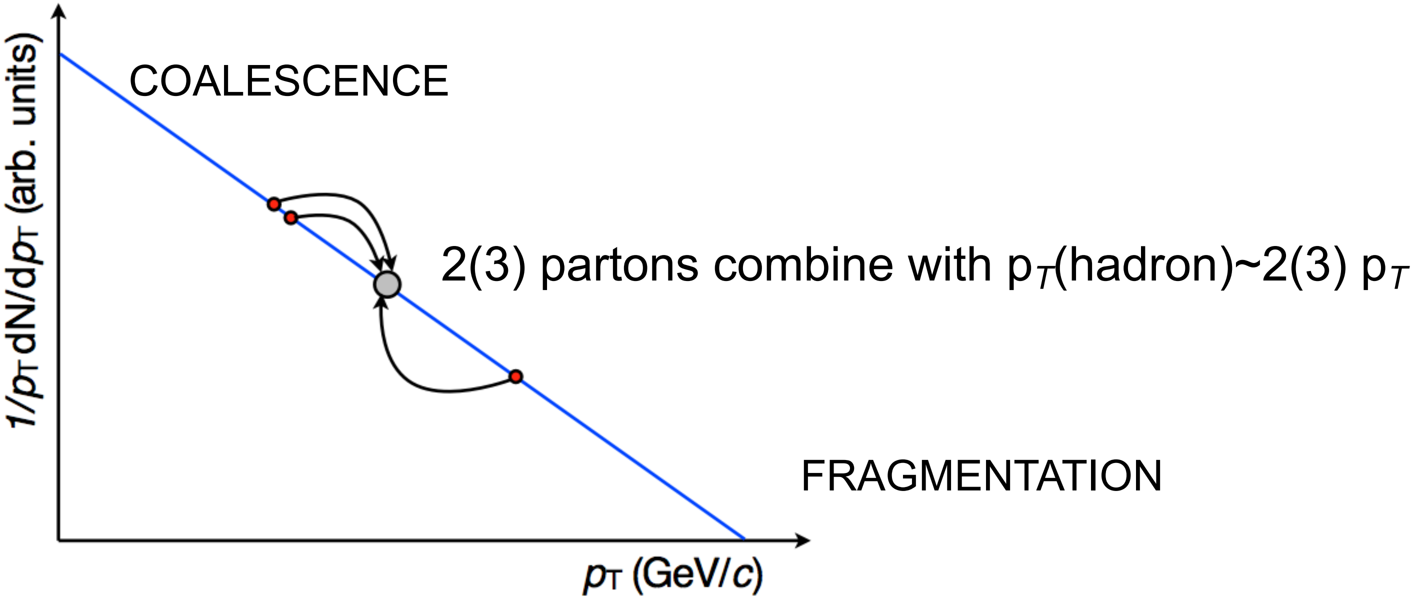
ALI-DER-136354



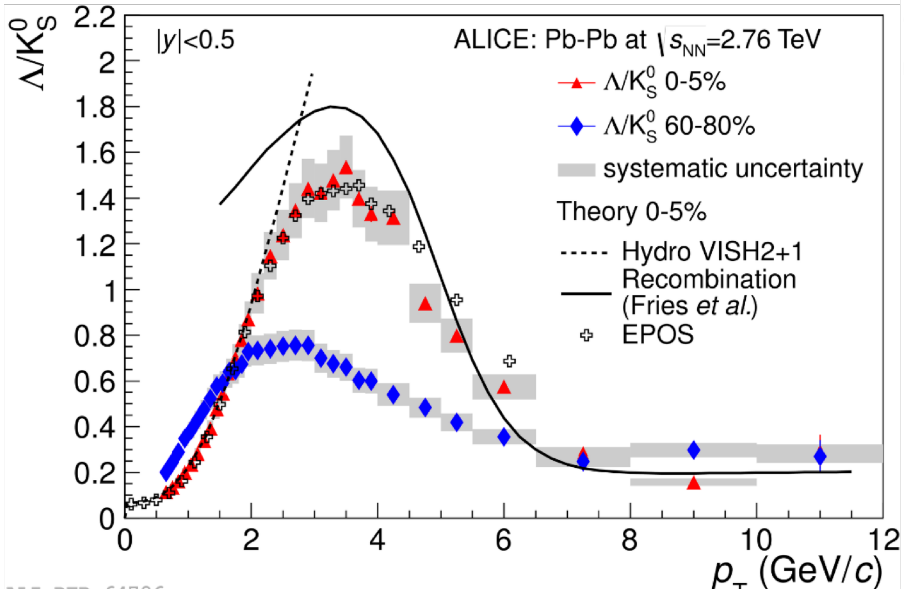
ALI-DER-139092

- iEbyE + VISHNU + Trento/AMPT: viscous hydro with different initial conditions [*PRC 92 (2015) 011901(R)]*
- McGill: MUSIC viscous hydro with IP-Glasma initial conditions *[PRC 95 (2017) 064913]*
- Full-hydro models reproduce features of particle spectra and particle ratios below 2 GeV/*c* at 20-30% level

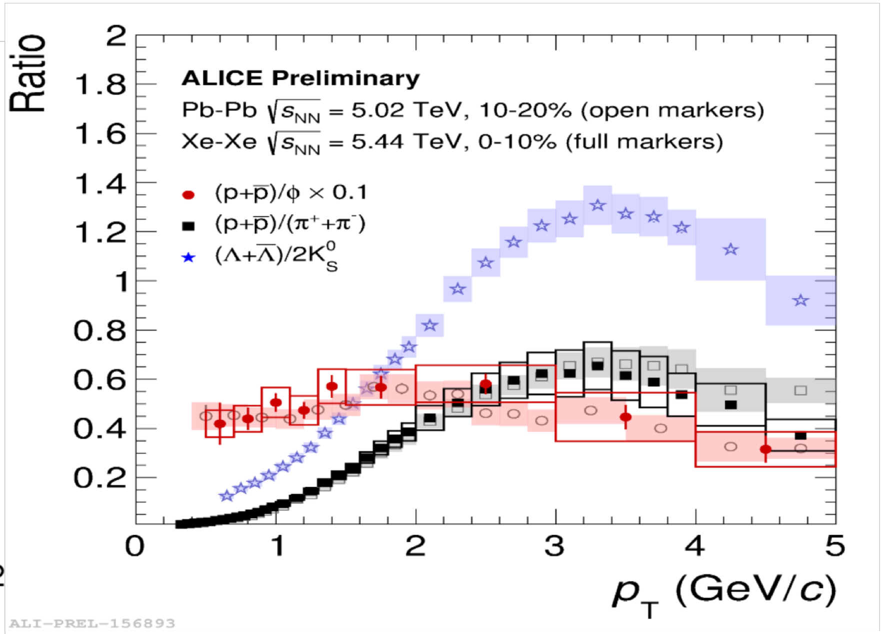
Recombination



2(3) partons combine with p_T(hadron)~2(3) p_T

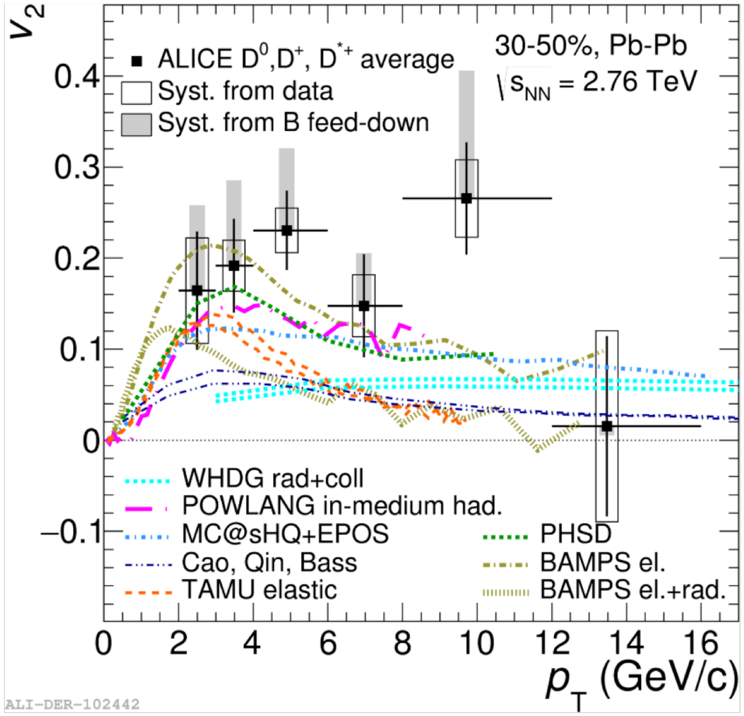


ALI-DER-64786

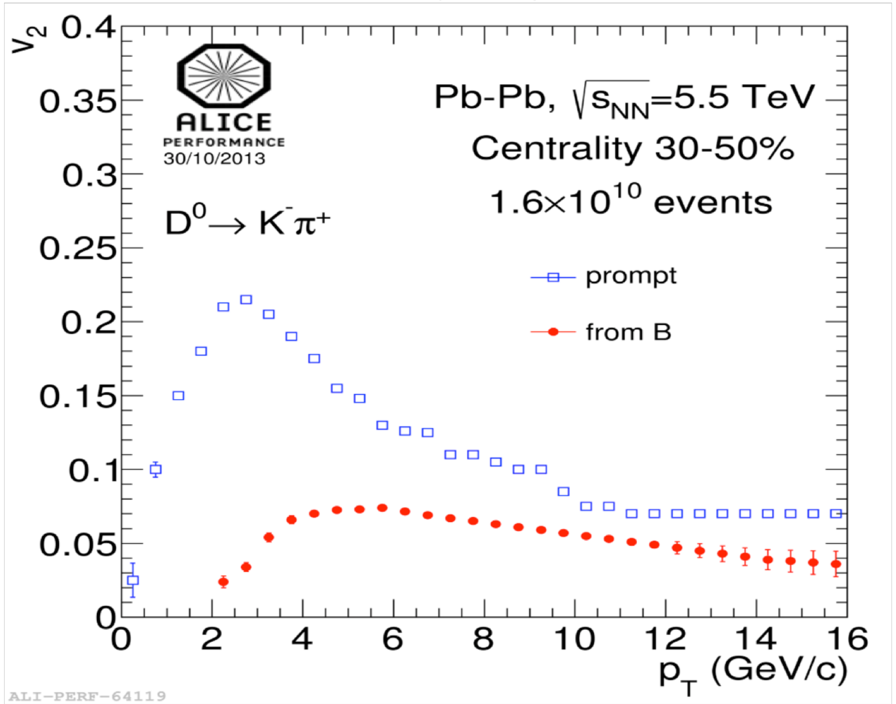


ALI-PREL-156893

Heavy Flavor Flow



New ITS



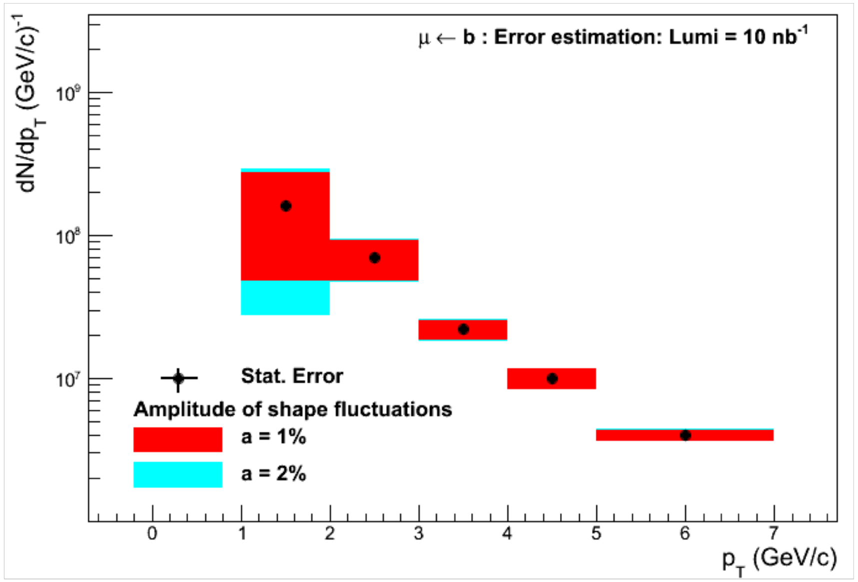
(GeV/c
)

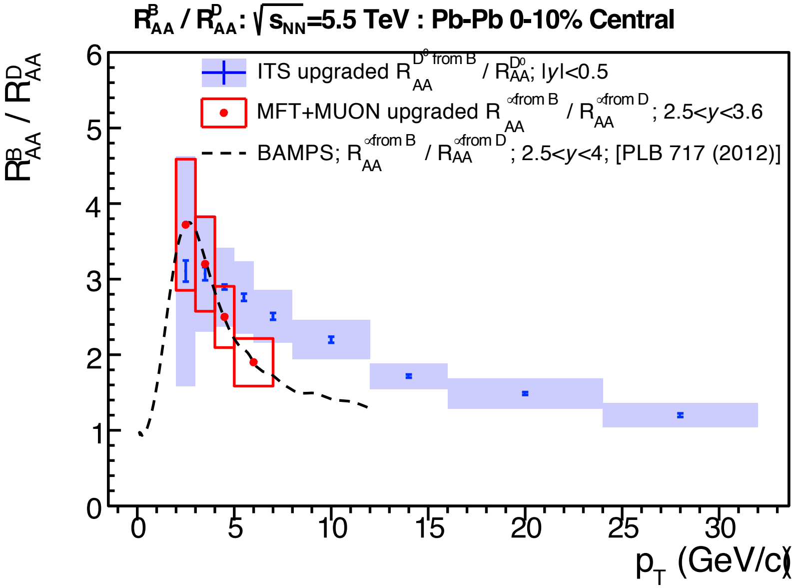
CERN-LHCC-2013-024;ALICE-TDR-17

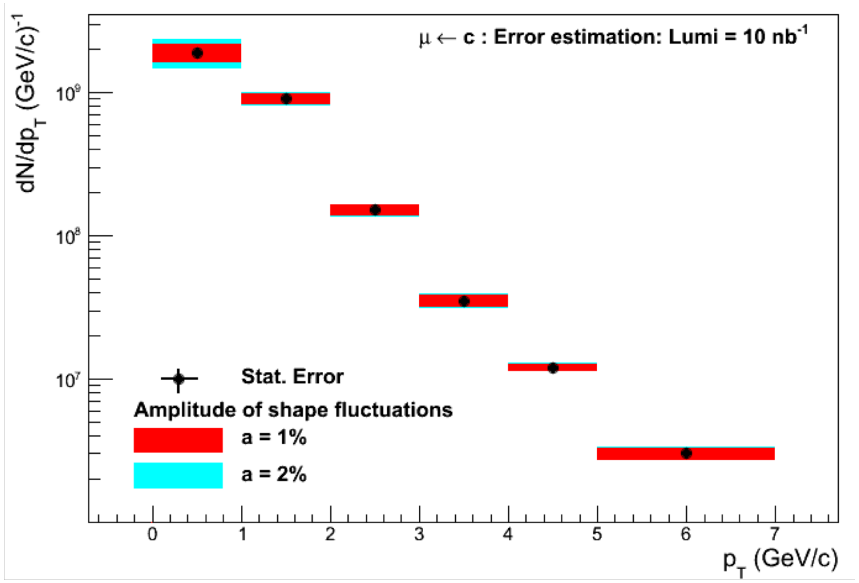
- Charm v_2 measurement down to $p_T \sim 0$ with prompt D^0
- Beauty v_2 also measured down to $p_T \sim 0$ with B-decay D^0

Expected Physics Performance for Run 3

Heavy Flavour from Single Muons



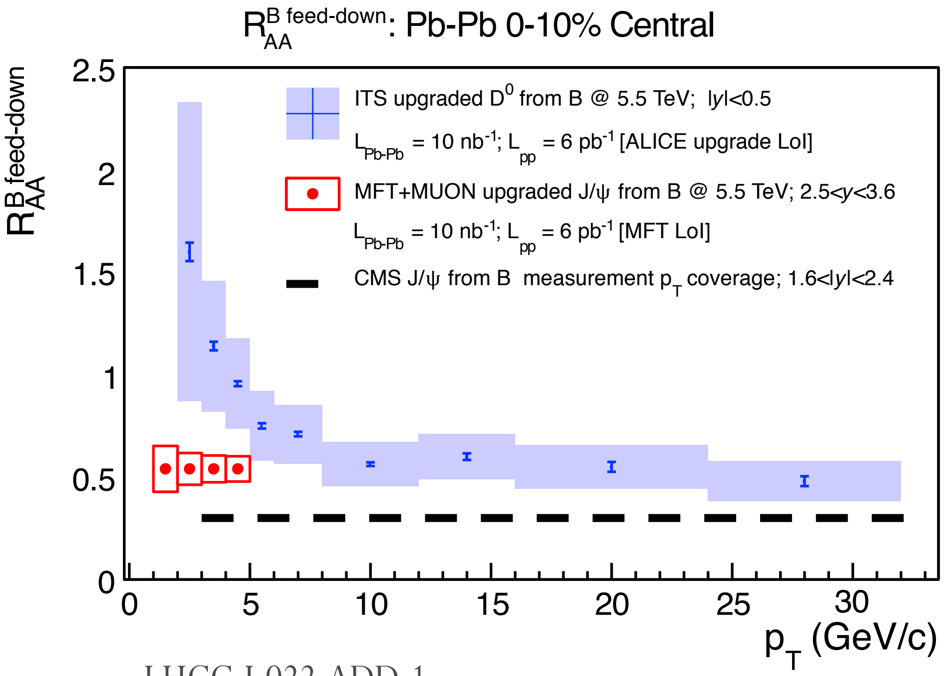




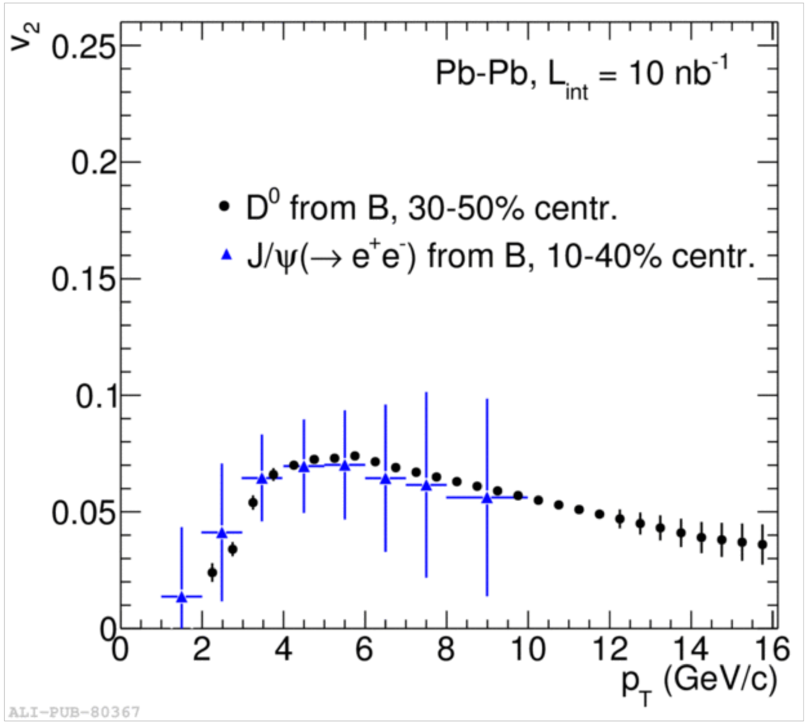
LHCC-I-022-ADD-1

- p_T distributions of single muons from beauty and charm decay (left) with statistical and systematical uncertainties
- Ratio of the nuclear modification factors of open charm and beauty (top)

Open Beauty



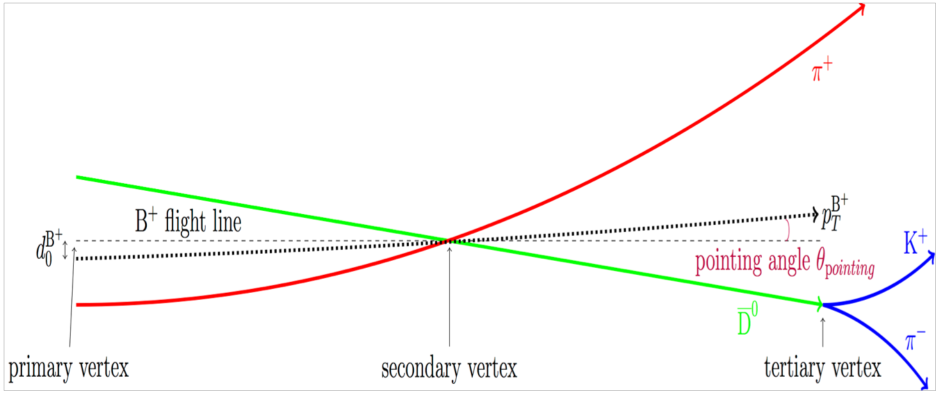
LHCC-I-022-ADD-1



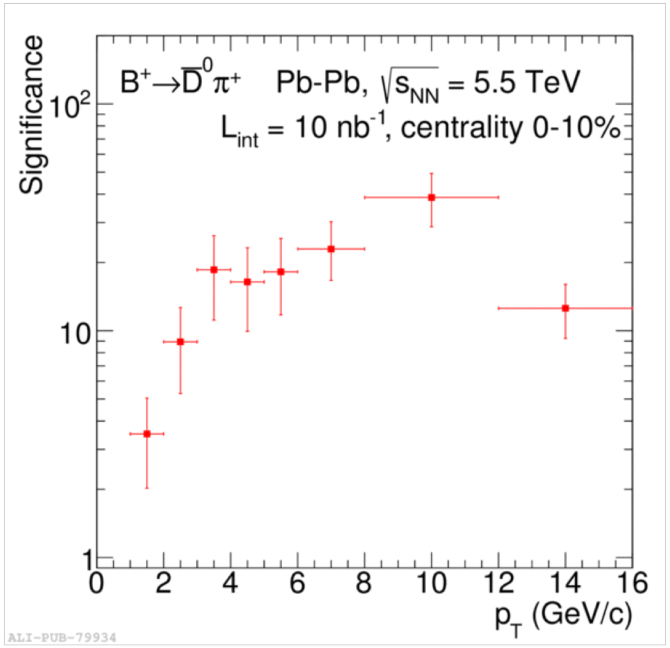
CERN-LHCC-2013-024; ALICE-TDR-17

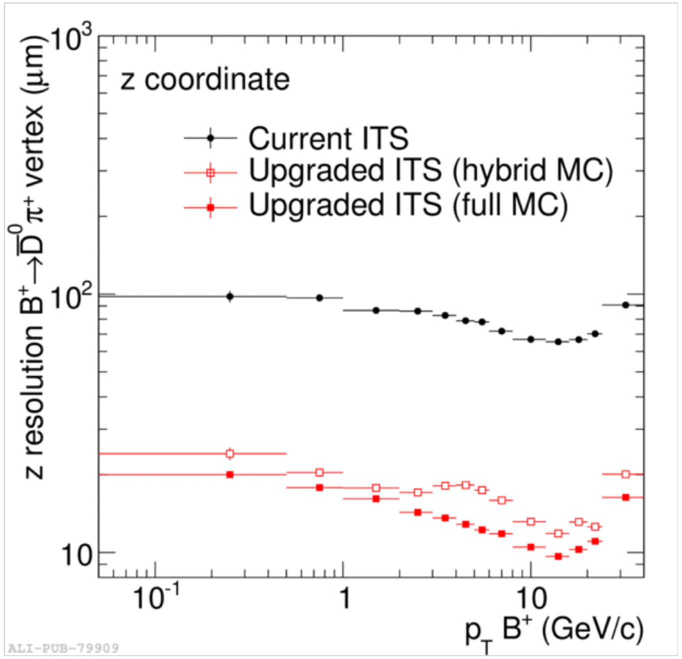
- Access to beauty at low p_T via
  - Displaced J/ψ → e^+e^- at mid –rapidity
  - Displaced J/ψ → $\mu^+\mu^-$ at forward rapidity
  - Displaced D mesons

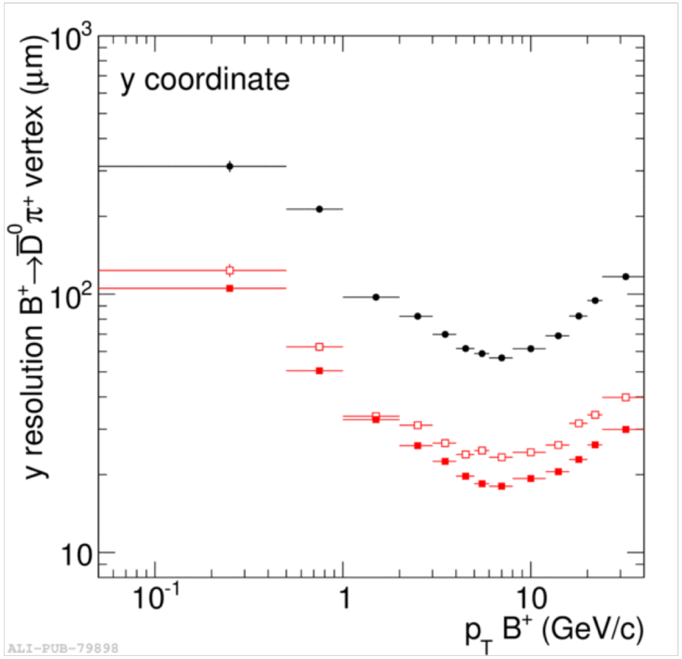
$B^+ \rightarrow D^0 + \pi^+$



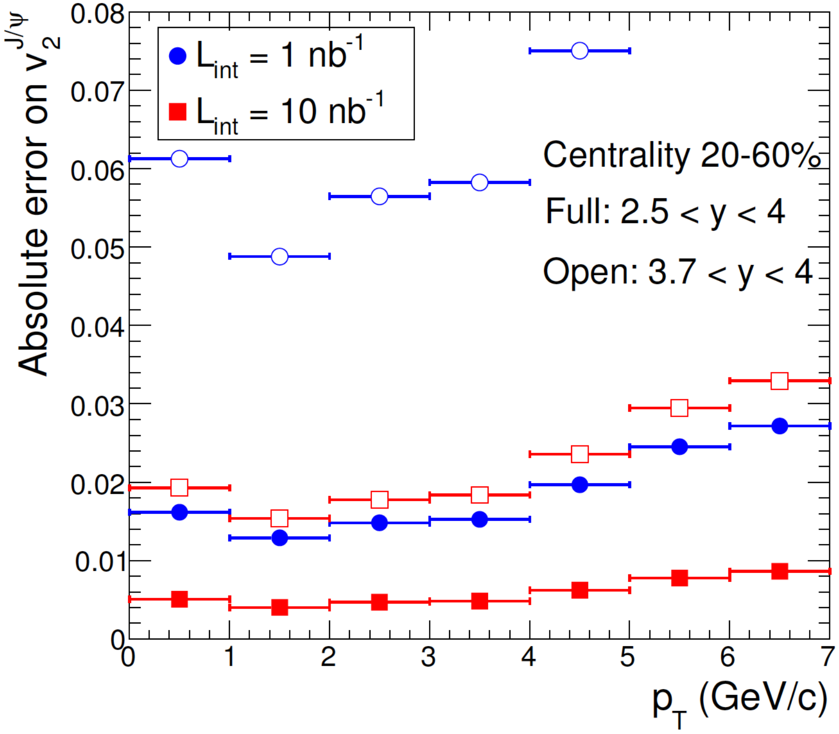
CERN-LHCC-2013-024; ALICE-TDR-17

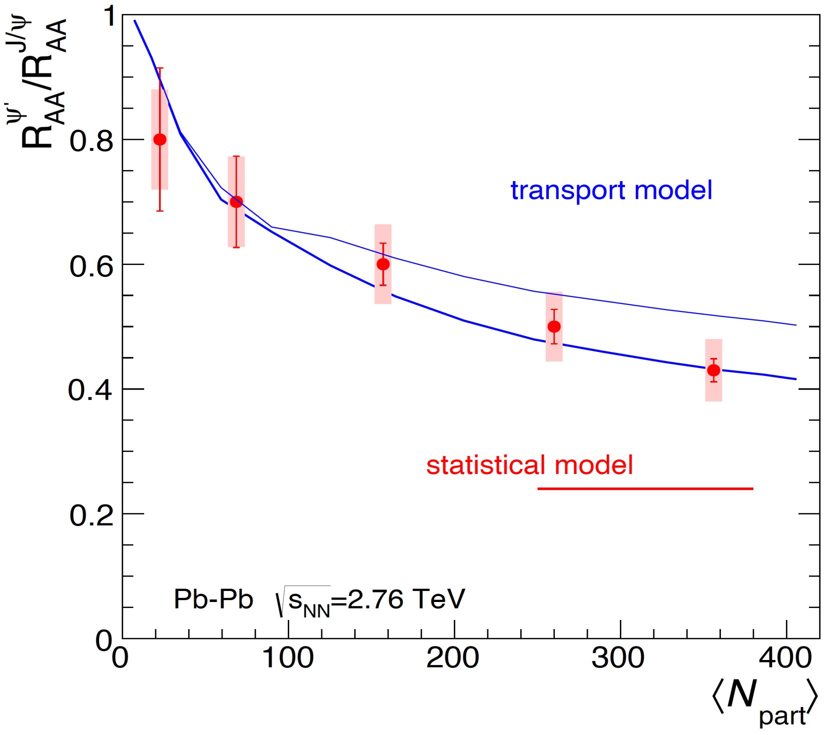






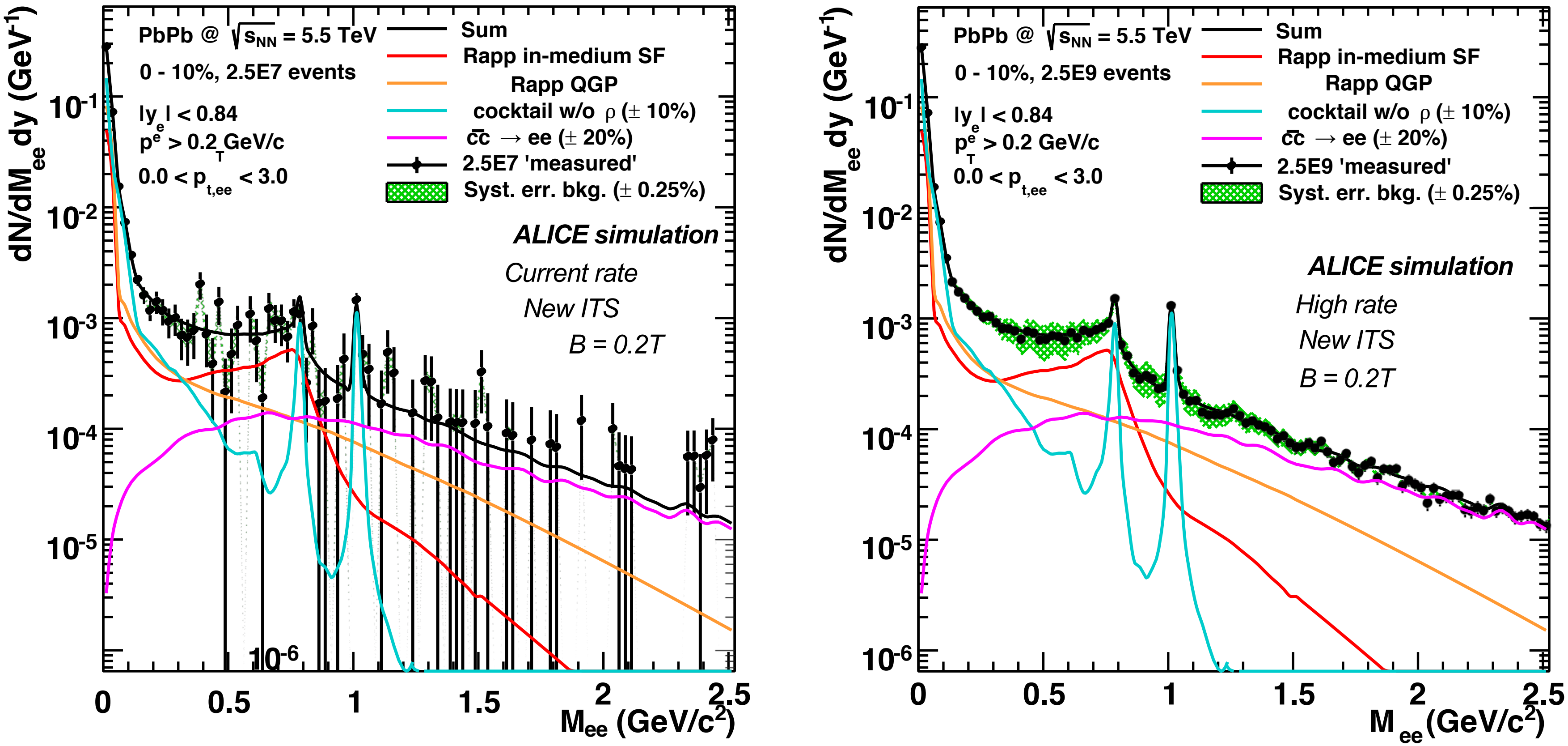
Quarkonia





- Precise J/ψ v_2 measurement
- Improvement by a factor of 10 of the expected errors with the upgrade of the central barrel detector
- Comparison of the expected MFT/MUON performance with two charmonium production models (statistical and transport models)

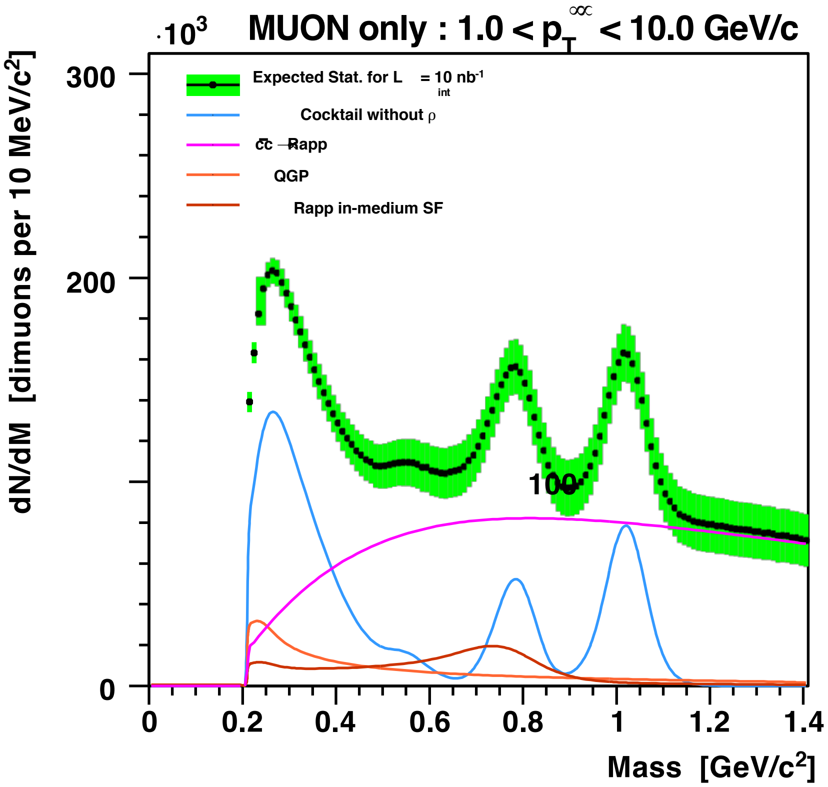
Low Mass Di-leptons

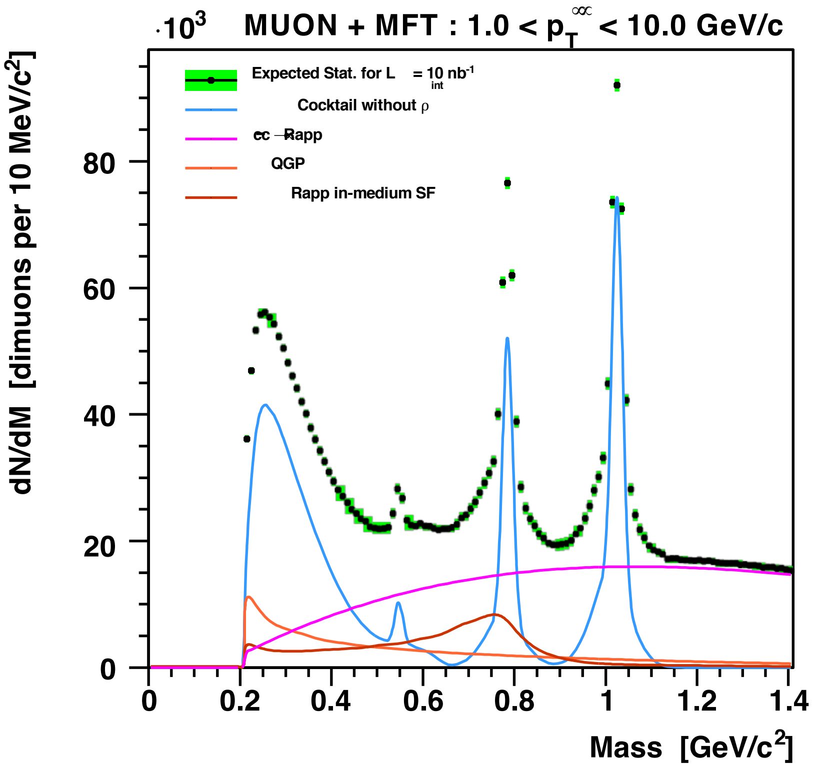


CERN-LHCC-2012-005, LHCC-G-159, 2012

- High readout rate will provide a large sample with a single dedicated run with reduced magnetic field (larger acceptance for low-mass low-p_T dielectrons)
- Dalitz decay, conversion and charm rejection with ITS
- Electron ID by TPC + TOF, reduction of systematic uncertainty

Low Mass Di-muons





- Expected low mass dimuon spectrum after combinatorial background subtraction, without and with the MFT
- The dramatic increase of the mass resolution (and a decrease of the background) is due to the extrapolation of muon tracks to MFT clusters

FIT Test Beam Performance