Probing the QCD matter with ALICE at the LHC

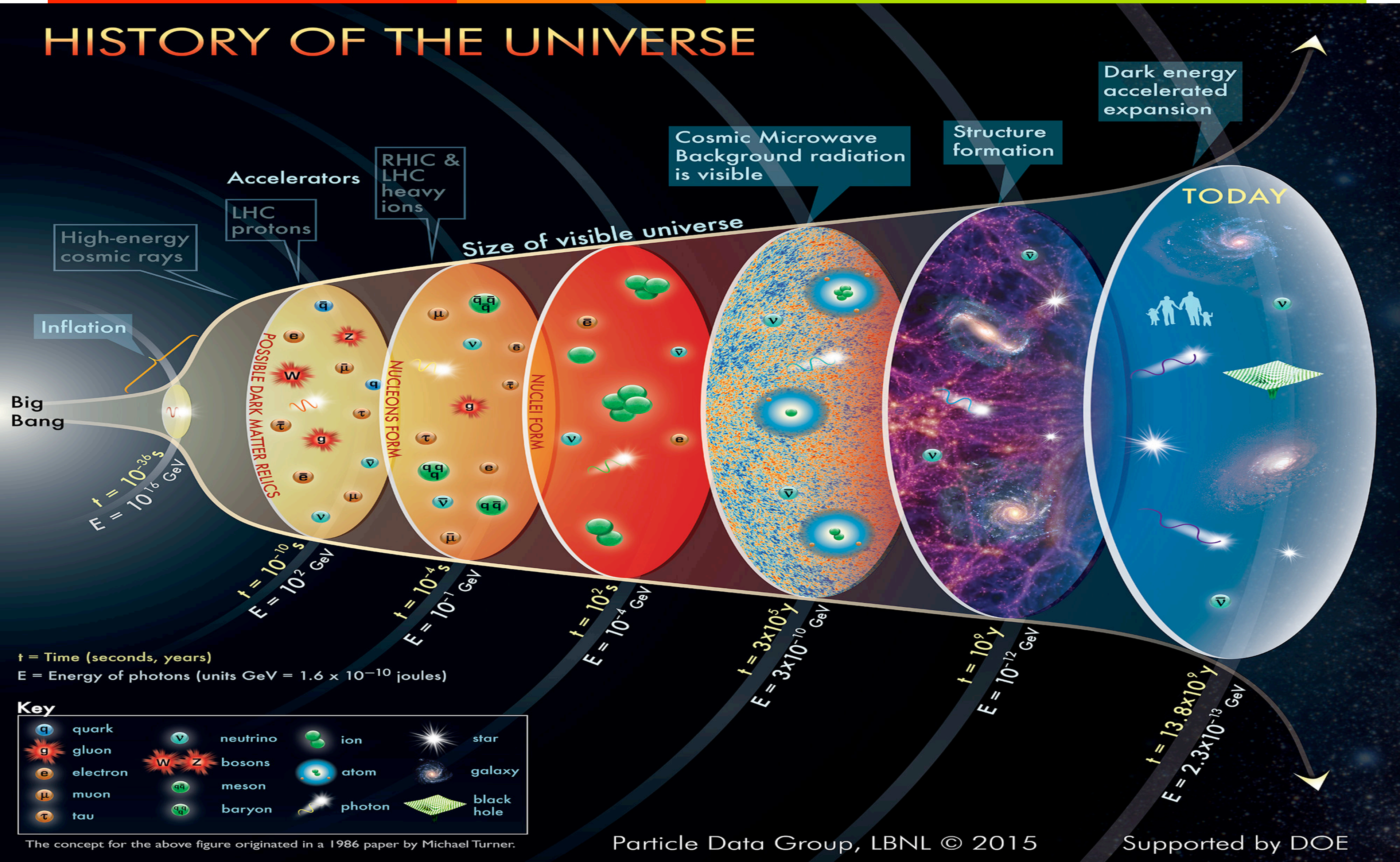
Sudipan De for the ALICE collaboration

National Institute of Science Education and Research (NISER), India

EISA

European Institute for Sciences and Their Applications

Big Bang


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Size of visible universe
Inflation
Big Bang
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s E = 10^16 GeV
t = 10^-10 s E = 10^2 GeV
t = 10^-4 s E = 10^-1 GeV
t = 10^2 s E = 10^-4 GeV
t = 3x10^5 y E = 3x10^-10 GeV
t = 10^9 y E = 10^-12 GeV
t = 13.8x10^9 y E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

Introduction

What do we study?

De-confined state of quarks and gluons which is believed to similar state just after few microseconds of the big bang. This state is known as Quark-Gluon Plasma (QGP) where quarks and gluons are free

How to create such state?

By colliding heavy-ions (such as Pb-Pb, Xe-Xe, Au-Au, U-U) in the laboratory at ultra-relativistic energies

Signatures of the QGP:

- ✓ Strangeness enhancement
- ✓ Anisotropic flow
- ✓ Direct photon emission
- ✓ J/ψ suppression
- ✓ Jet quenching

Confinement and asymptotic freedom

Nobel Prize 2004 in Physics:

David J. Gross, H. David Politzer and Frank Wilczek

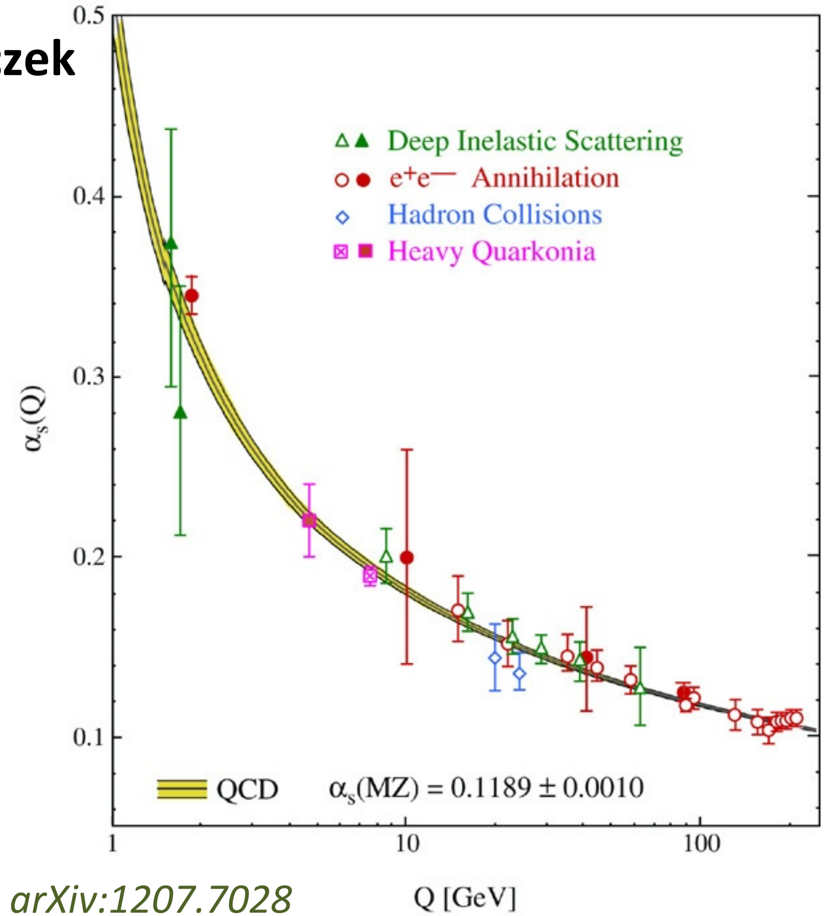
Confinement:

At low energies (or far apart) the effective coupling between quarks are large, resulting in confinement -> no free quarks exist

Asymptotic freedom:

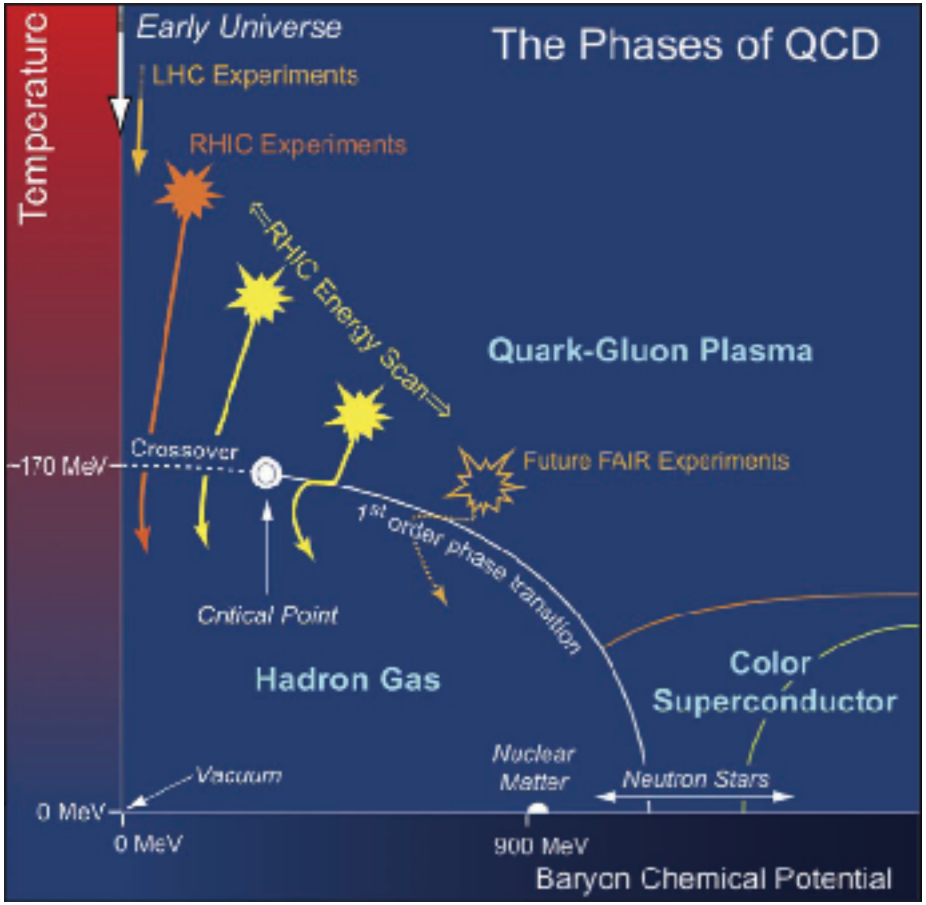
At high energies (or short distance) the effective coupling between quarks decreases logarithmically->asymptotically free quarks and gluons -> Quark Gluon Plasma (QGP)

Running of the strong coupling



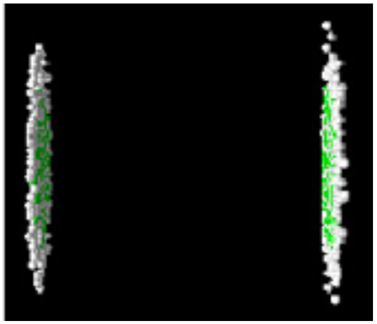
arXiv:1207.7028

QCD phase diagram

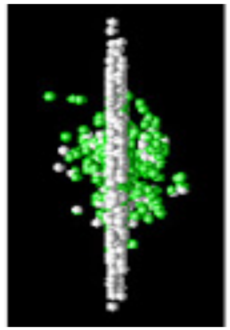


- **At vanishing net baryon density: (LHC experiments)**
- Cross-over from hadron phase to QGP Phase according to lattice QCD
- Tc ~ 155 MeV and ε_c = 0.5 GeV/fm^3 (*Bazavov et al. Phys. Rev. D90 (2014) 094503*)
- **At non-zero net baryon density: (RHIC, FAIR, NICA experiments)**
  First order phase transition

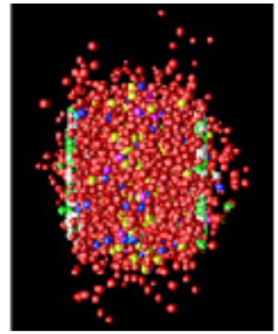
Collision process



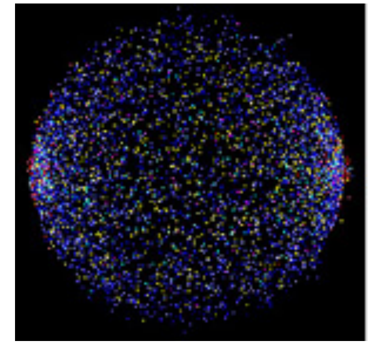
t = -10 fm



t = 0 fm

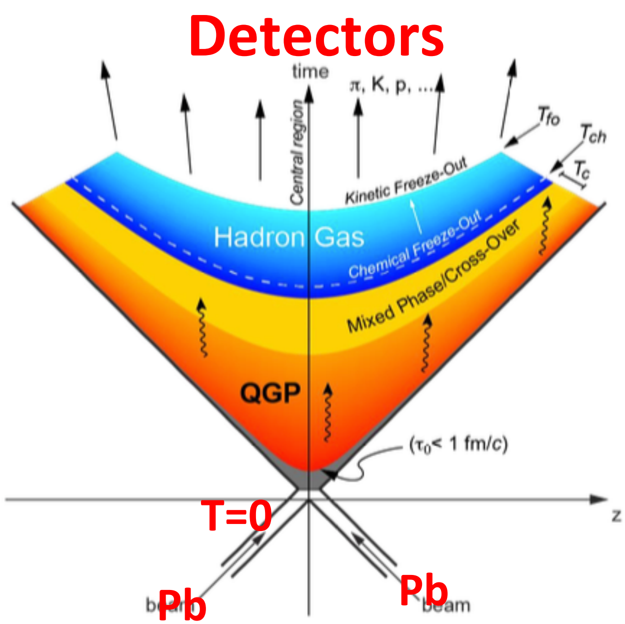


t = 3 fm



t = 10 fm

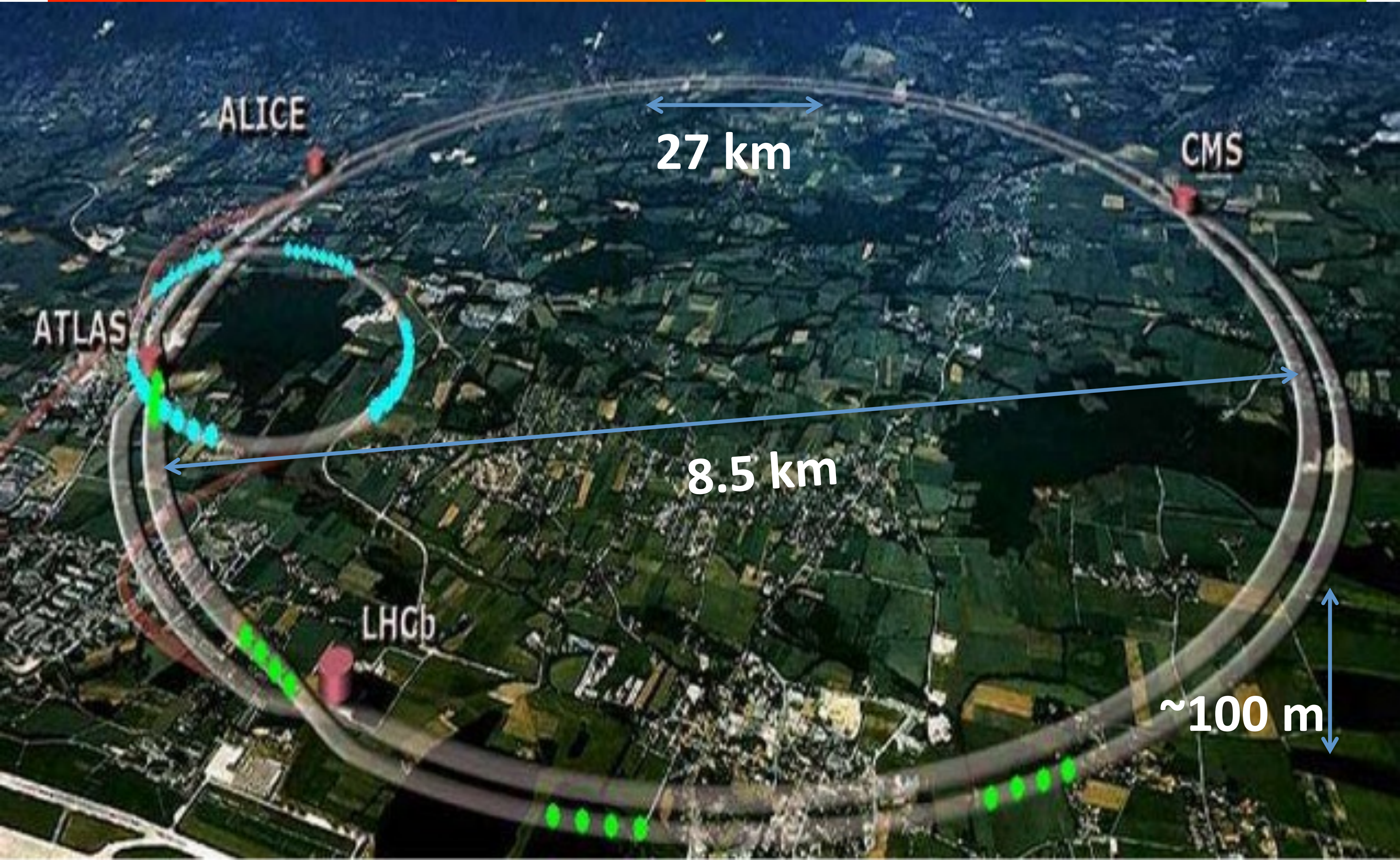
MADAI.us



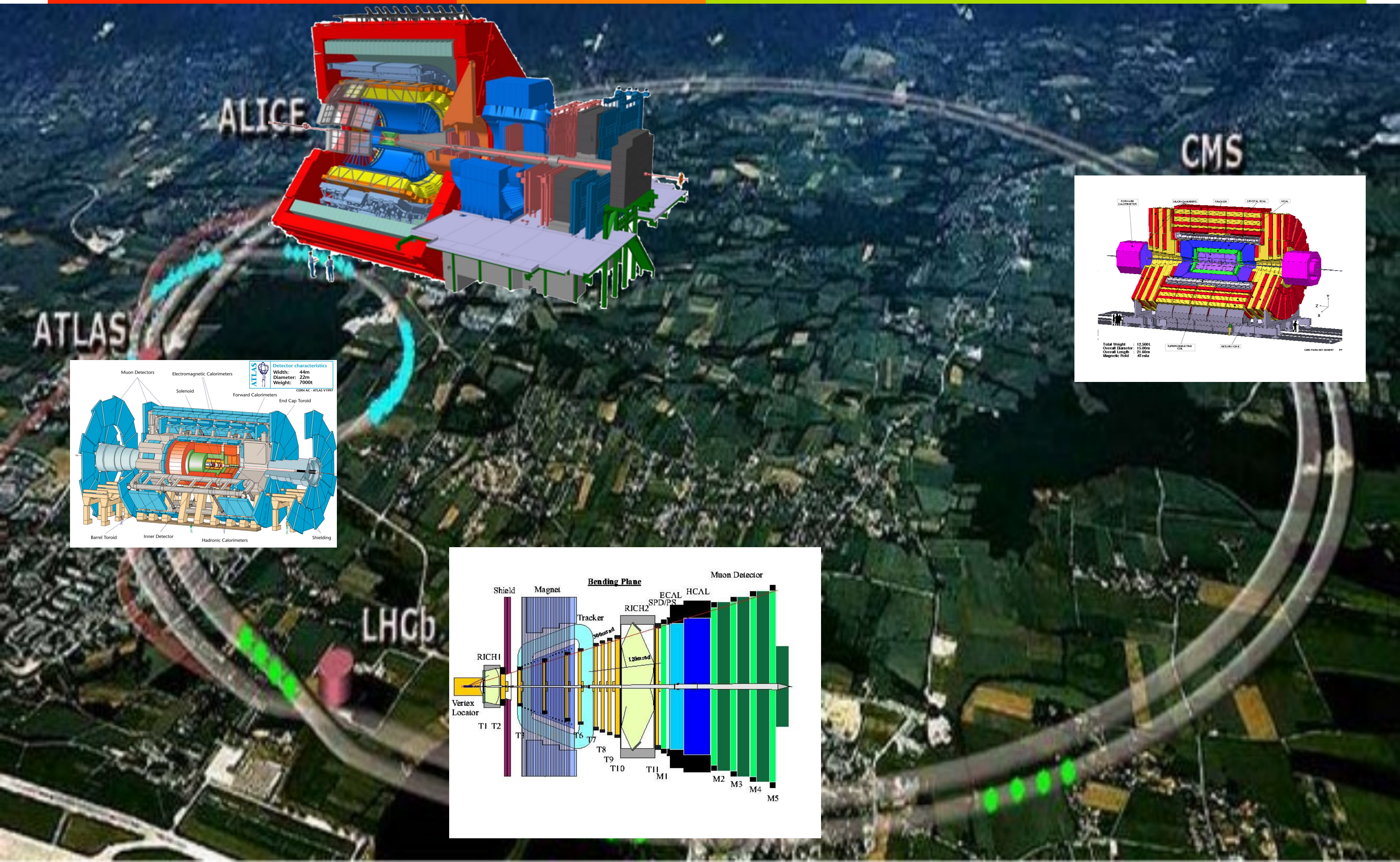
- The **chemical** freeze out (the moment when the inelastic scatterings cease) fixes the particle yields

- The **kinetic** freeze out (the moment when the elastic scatterings stop) affects particle momenta.

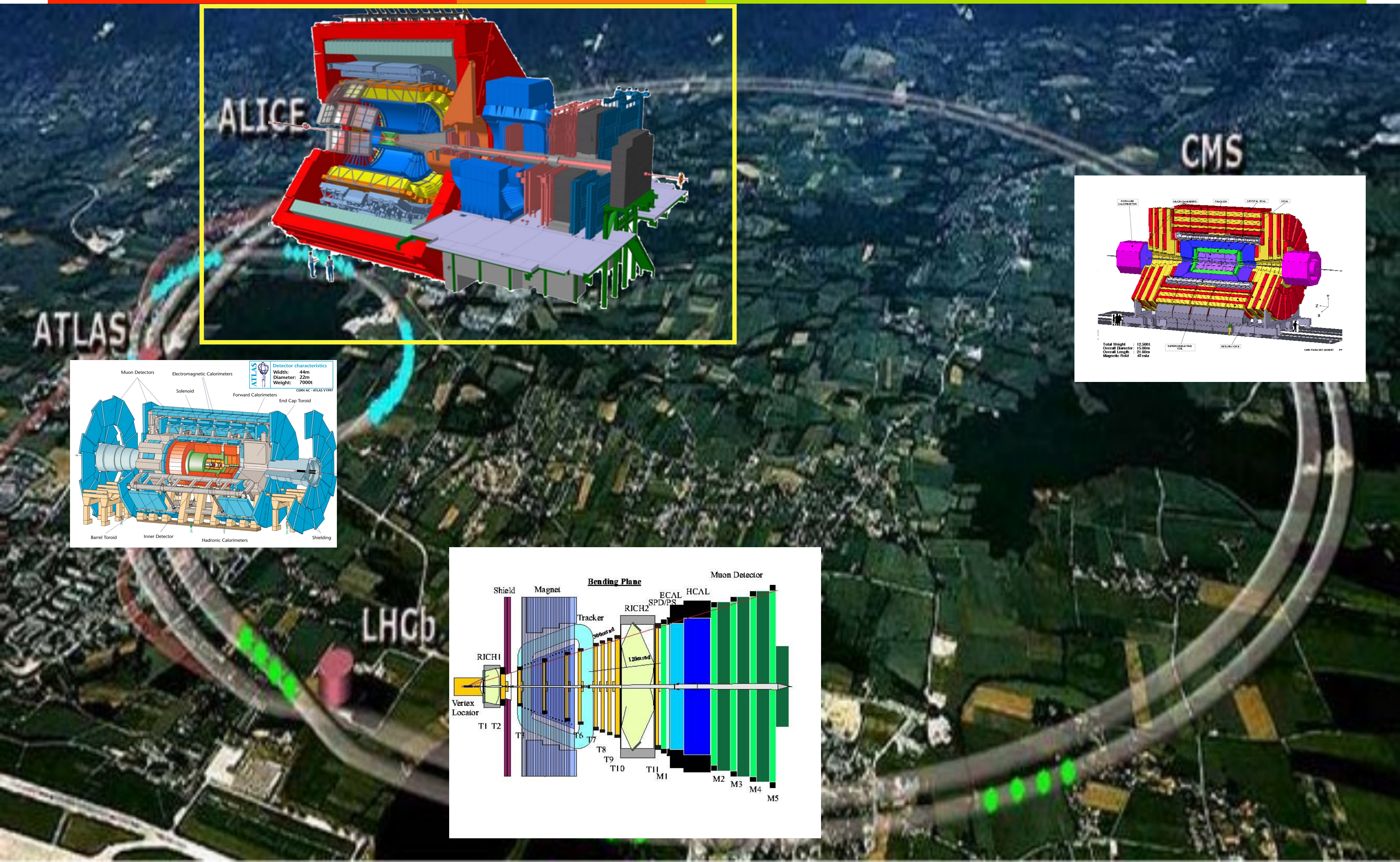
The Large Hadron Collider (LHC)



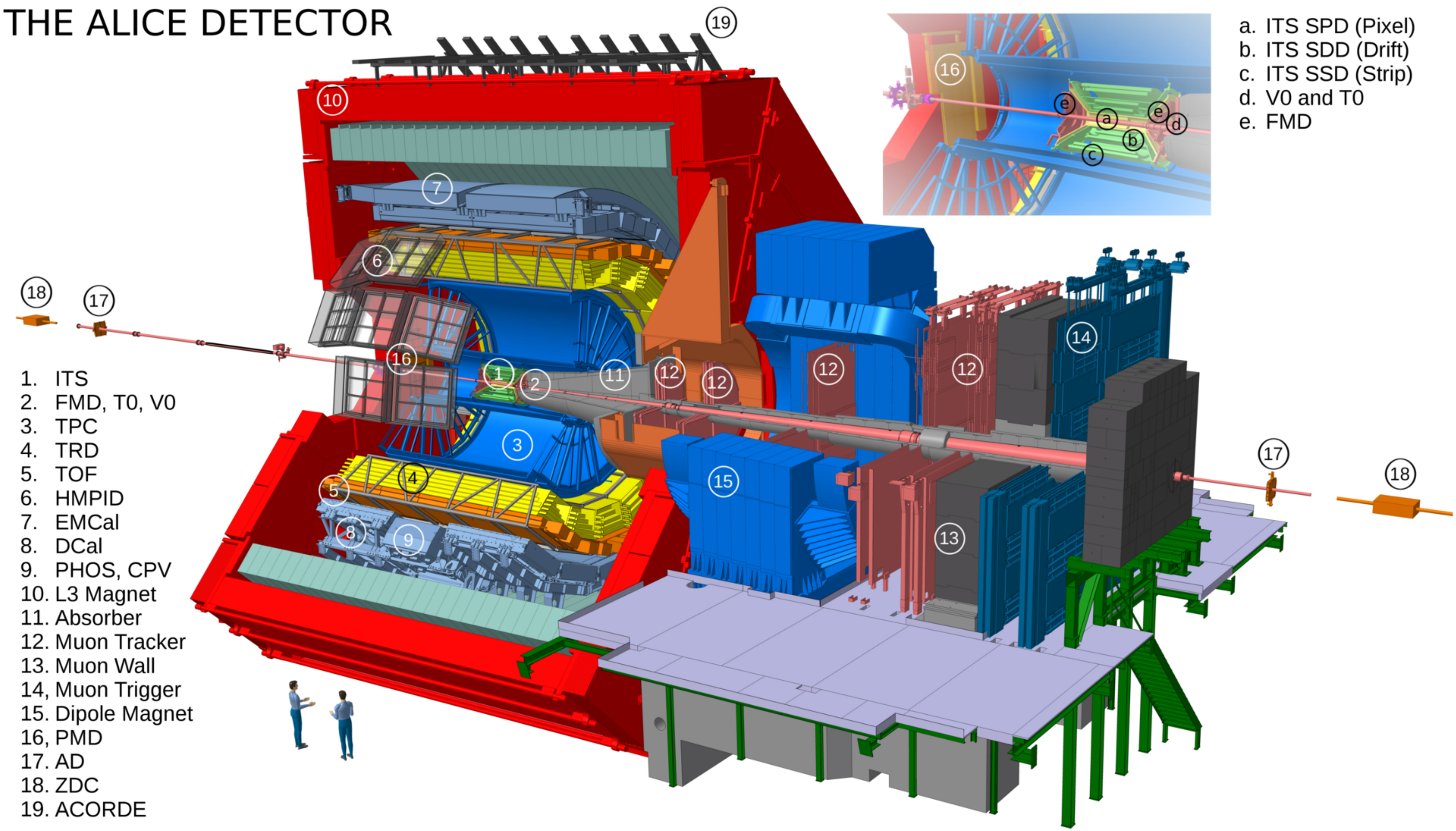
The Large Hadron Collider



The Large Hadron Collider

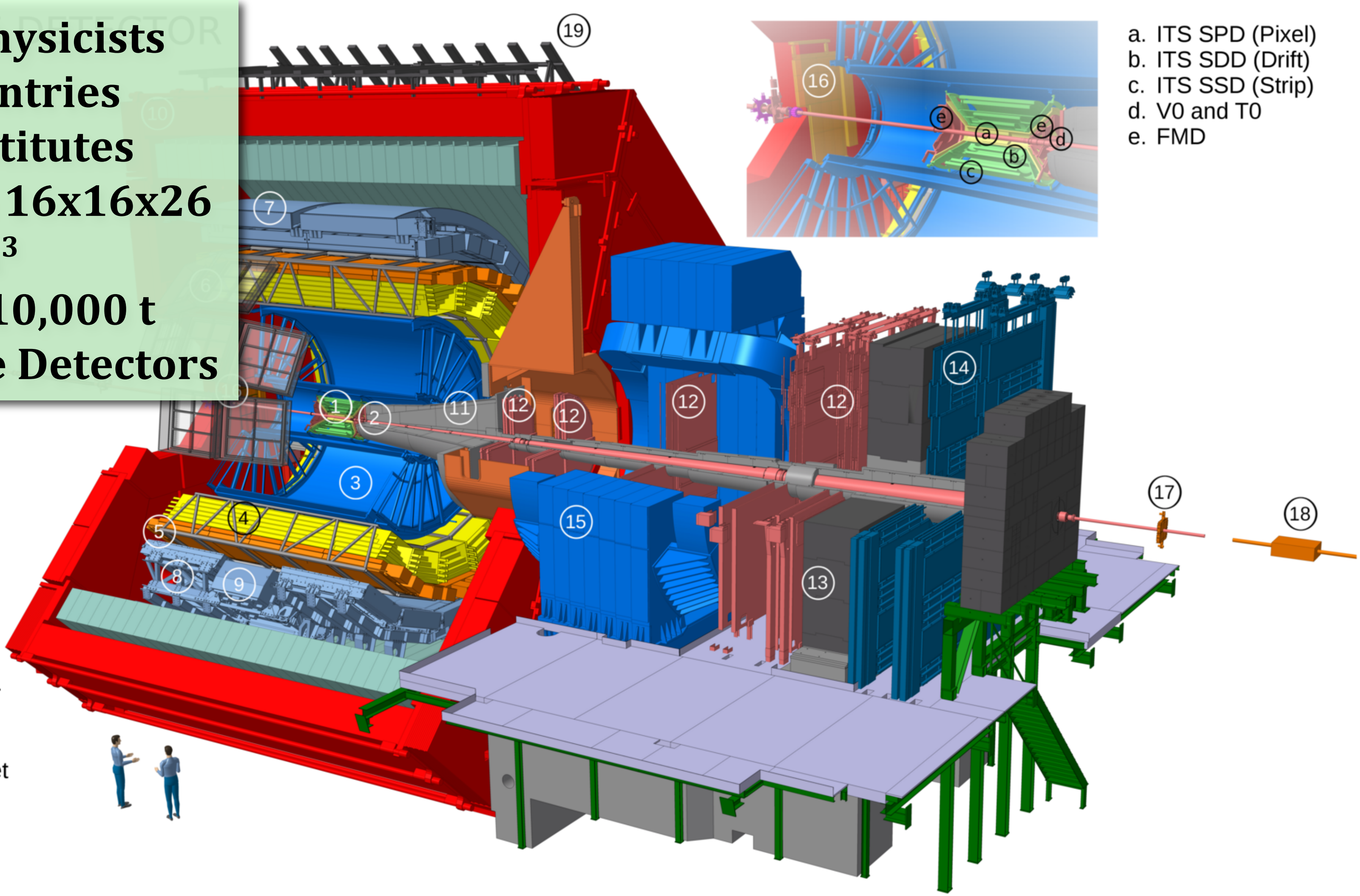


The ALICE detector



The ALICE detector

~2000 physicists
41 countries
177 institutes
Dimension 16x16x26 m^3
Weight 10,000 t
19 seperate Detectors

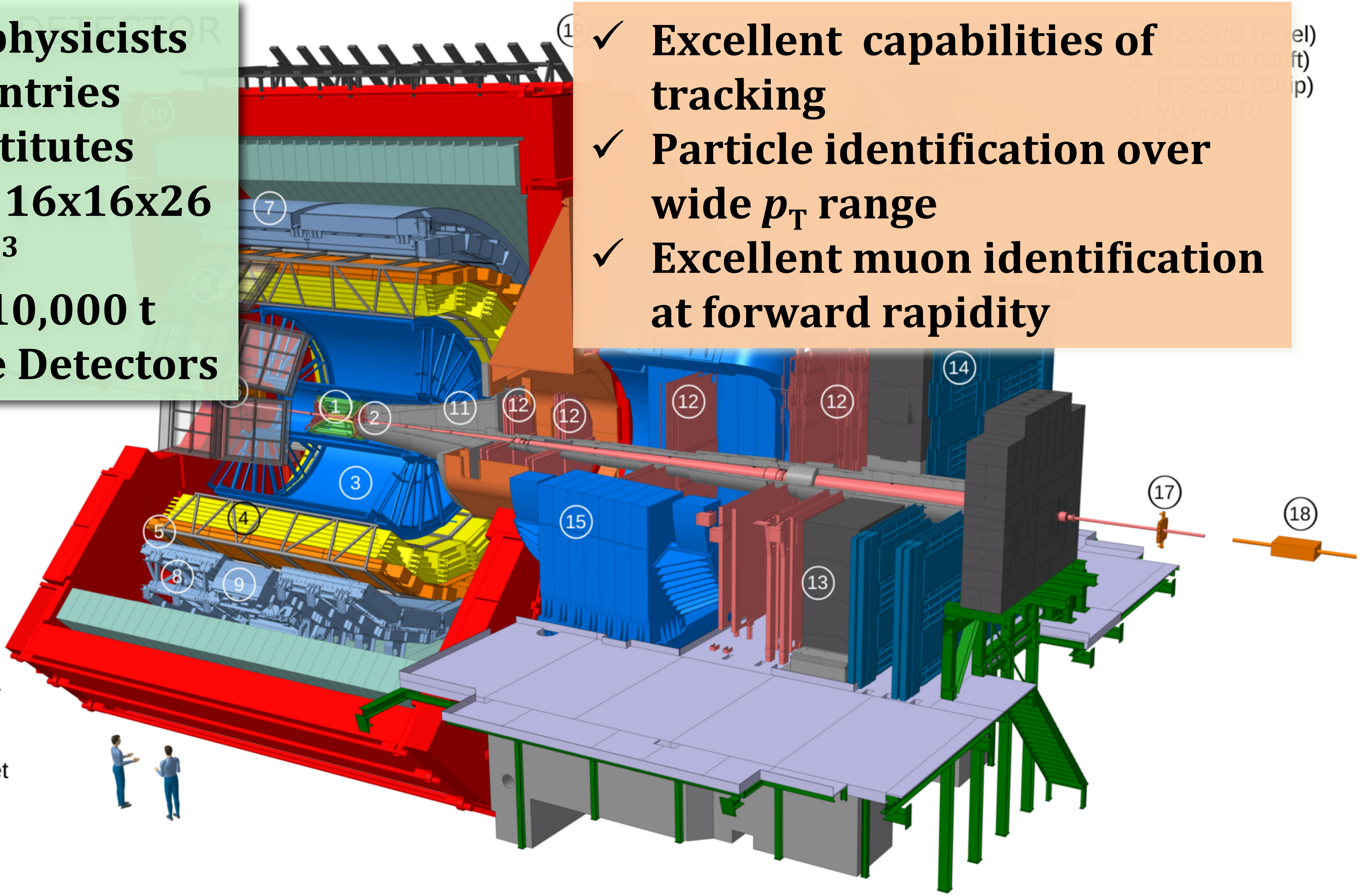


1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE

The ALICE detector

1000s of physicists
41 countries
177 institutes
Dimension 16x16x26 m^3
Weight 10,000 t
19 seperate Detectors

- ✓ **Excellent capabilities of tracking**
- ✓ **Particle identification over wide p_T range**
- ✓ **Excellent muon identification at forward rapidity**



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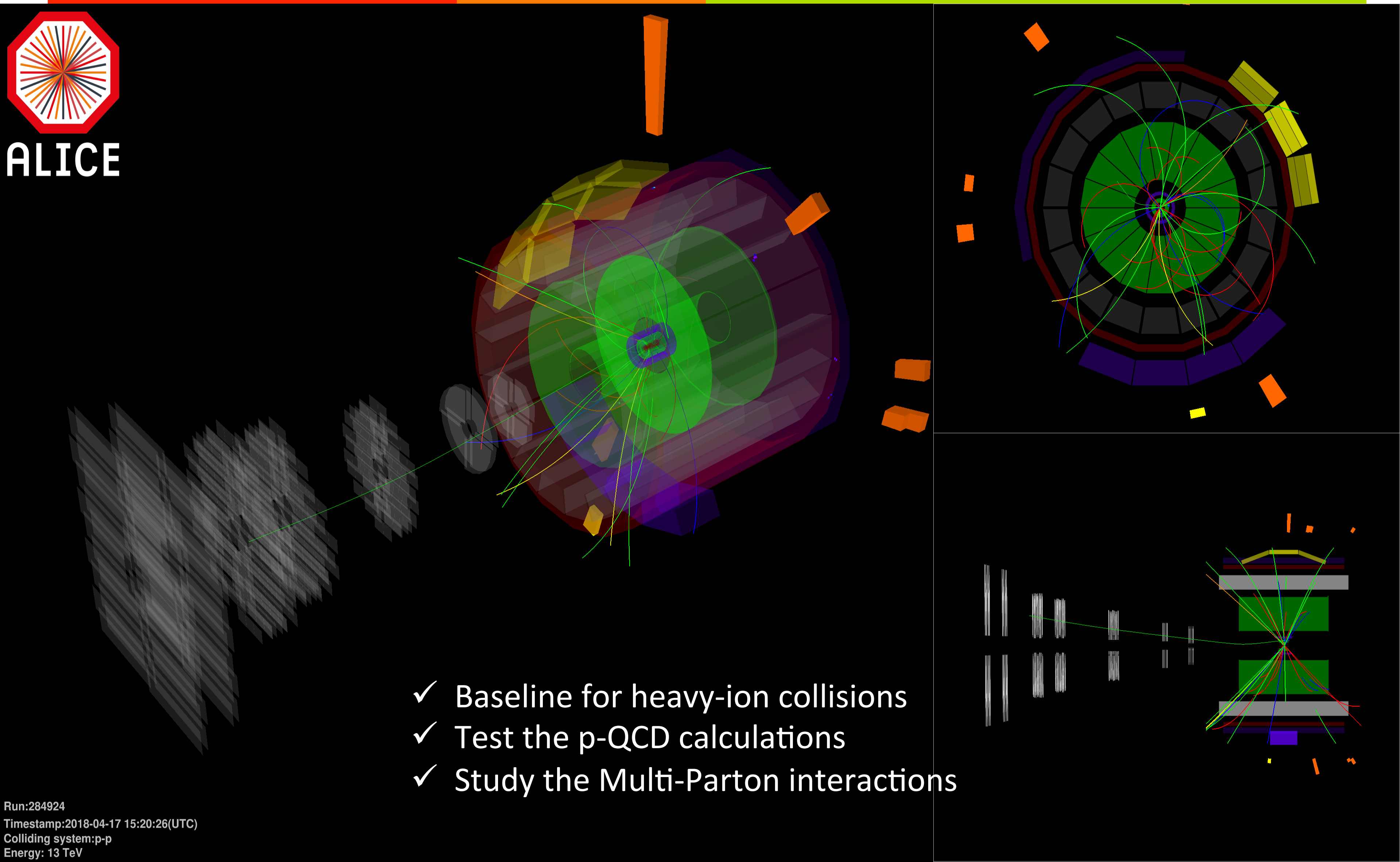
The ALICE program

- Almost 10 years of successful running
- Run 2 just finished in December 2018
- Run 3 will start from 2021 after major upgrade

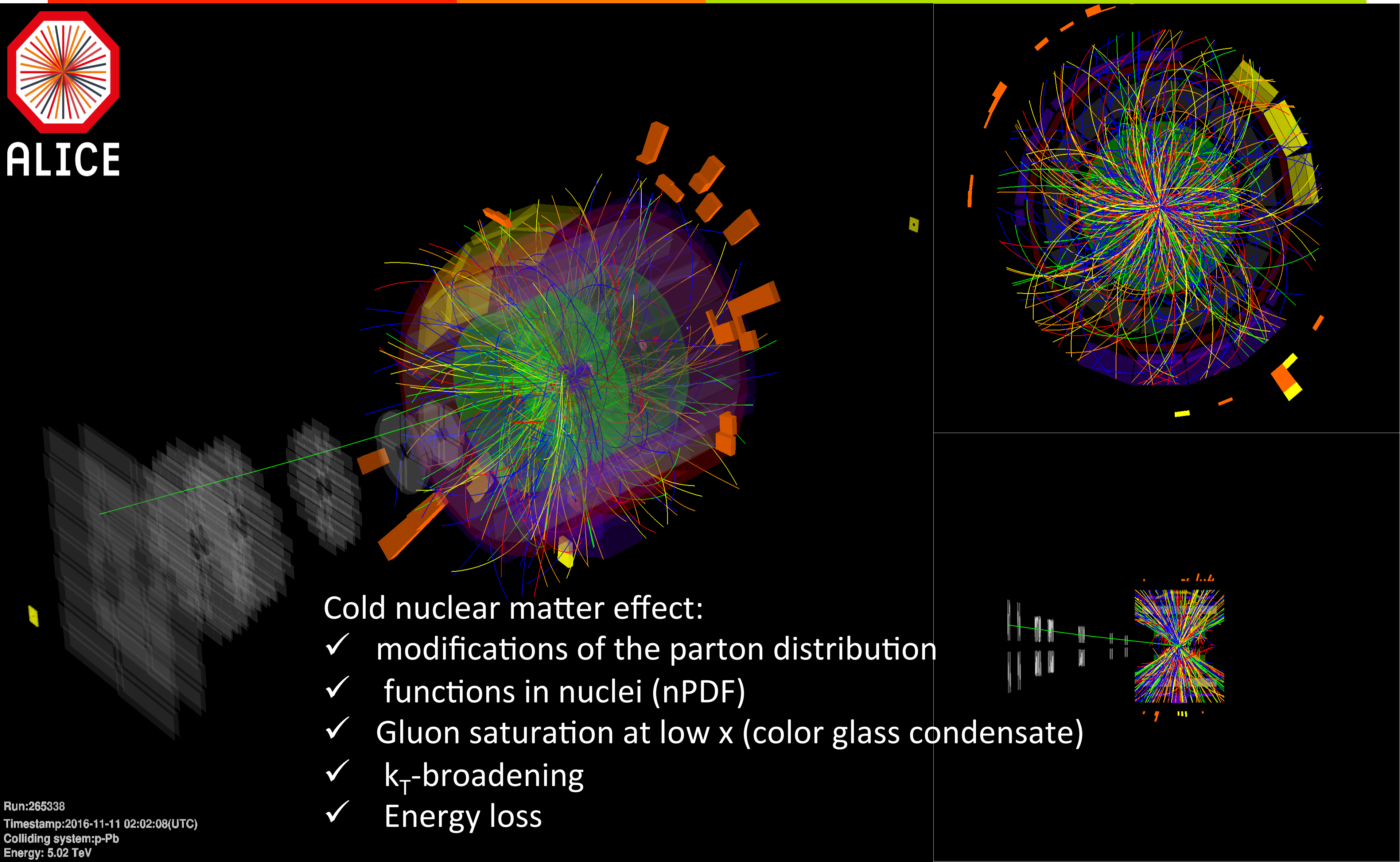
System	years	$\sqrt{s_{NN}}$ (TeV)	L_{int}
pp	2009-20013 2015,2017 2015-2018	0.9, 2.76 7, 8 5.02 13	~200 μb^{-1}, ~100 nb^{-1} ~1.5 nb^{-1}, ~ 2.5 nb^{-1} ~1.3 nb^{-1} ~25 nb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	~15 nb^{-1} ~ 3 nb^{-1}, ~25 nb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
Pb-Pb	2010-2011 2015-2018	2.76 5.02	~75 μb^{-1} ~250 μb^{-1}, ~1 nb^{-1}

Event display in pp collisions



- ✓ Baseline for heavy-ion collisions
- ✓ Test the p-QCD calculations
- ✓ Study the Multi-Parton interactions

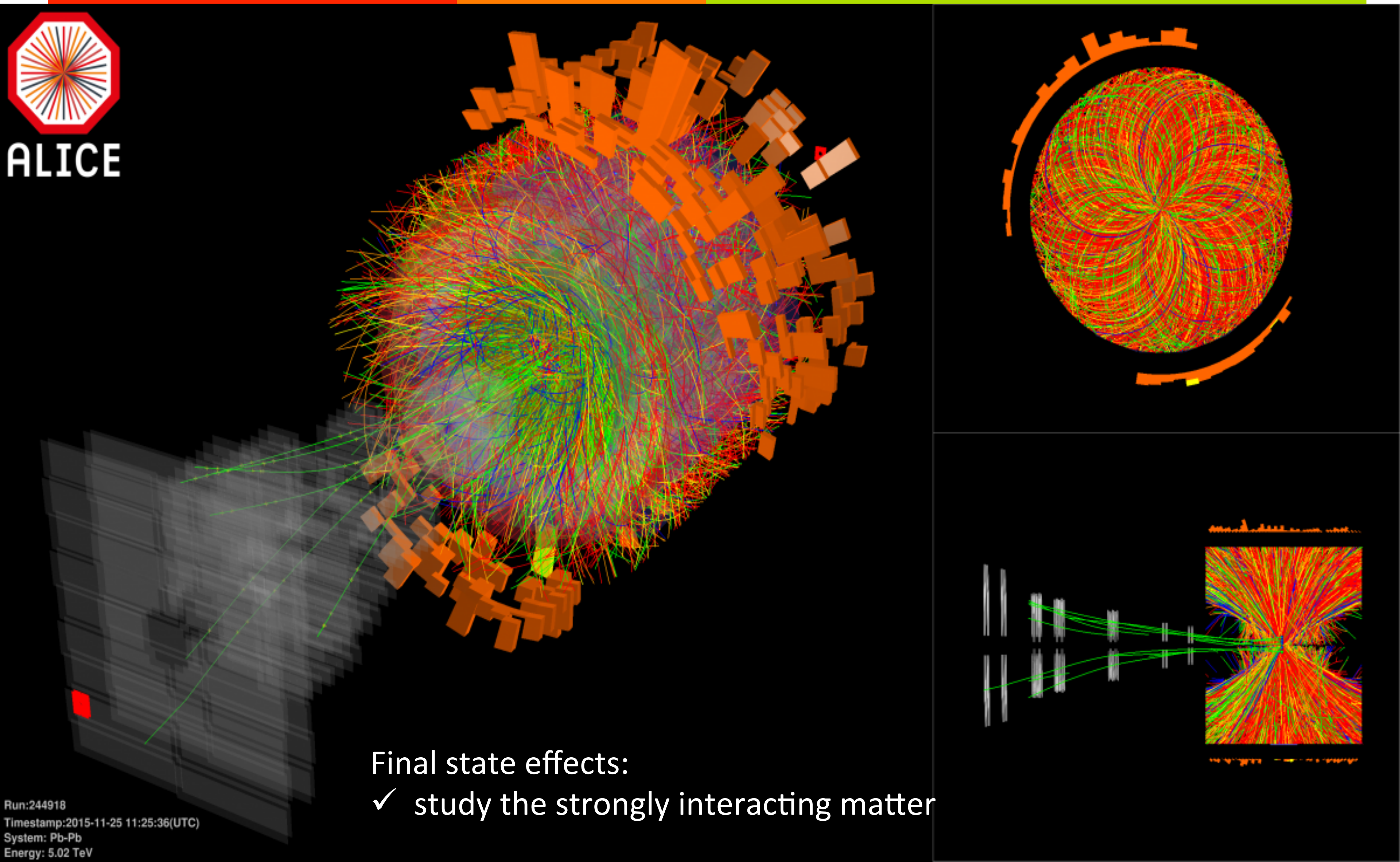
Event display in p-Pb collisions



Cold nuclear matter effect:

- ✓ modifications of the parton distribution
- ✓ functions in nuclei (nPDF)
- ✓ Gluon saturation at low x (color glass condensate)
- ✓ k_T-broadening
- ✓ Energy loss

Event display in Pb-Pb collisions



Final state effects:
✓ study the strongly interacting matter

Probes of QGP

Soft probes:

- ✓ Particles multiplicities → energy density
- ✓ Particle spectra → radial flow, freeze-out parameters, thermal properties
- ✓ Particle flow → dynamics of matter
- ✓ Fluctuations and correlations → probe the initial state, shape and size of the system, critical phenomena

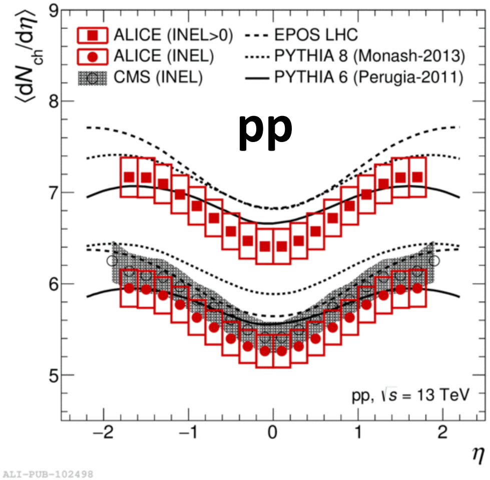
Hard probes:

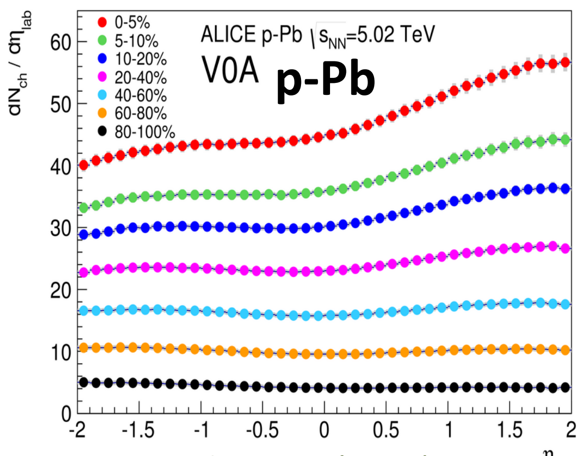
- ✓ Heavy-flavour particles, Jets → energy loss, modification of the medium

Electromagnetic probes:

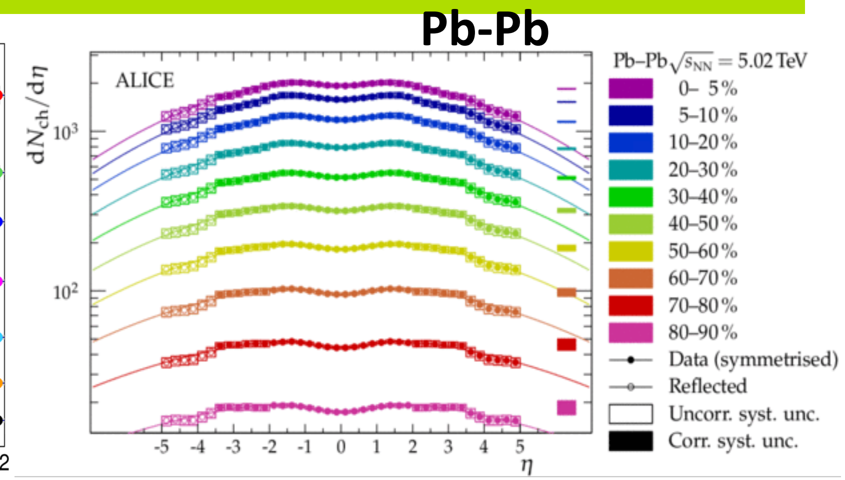
- ✓ photons and dilepton → direct information of the OGP, initial temperature

Charged particle measurements





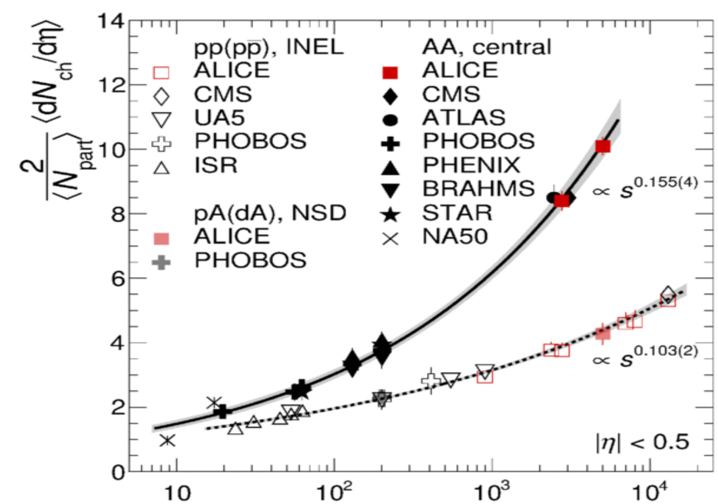
Eur. Phys. J. C (2019) 79: 307



ALI-PUB-115086

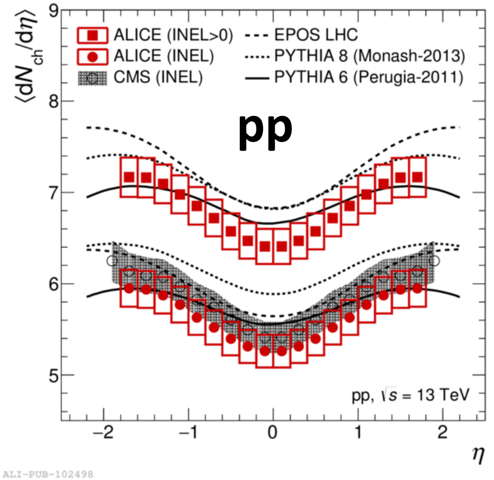
Phys.Lett. B 772 (2017) 567-577

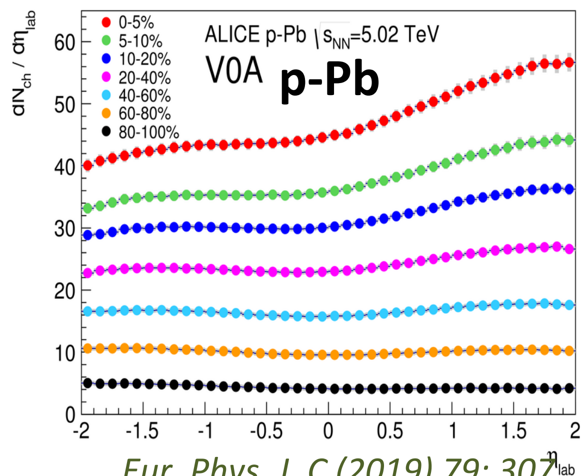
- ➢ This results put constrain to the existing model → help to tune the models
- ➢ Highest multiplicity reach so far for top central (0-5%) Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- ➢ Energy dependence of produced particles is faster ($\sim s^{0.15}$) than that of pp (p-Pb) collisions ($\sim s^{0.11}$)
- ➢ $dN_{ch}/d\eta$ is the input to measure the Bjorken energy density *(J. D. Bjorken, Phys. Rev. D 27, 140 (1983))*



Phys. Rev. Lett. 116 (2016) 222302

Charged particle measurements





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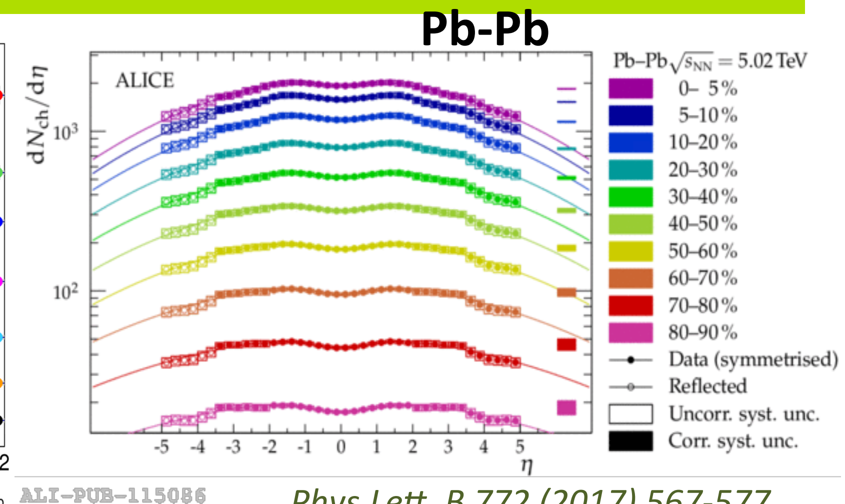

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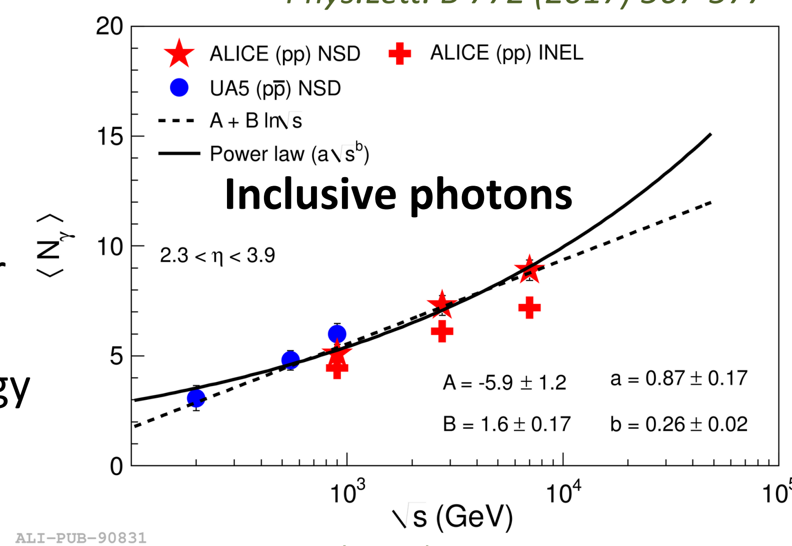
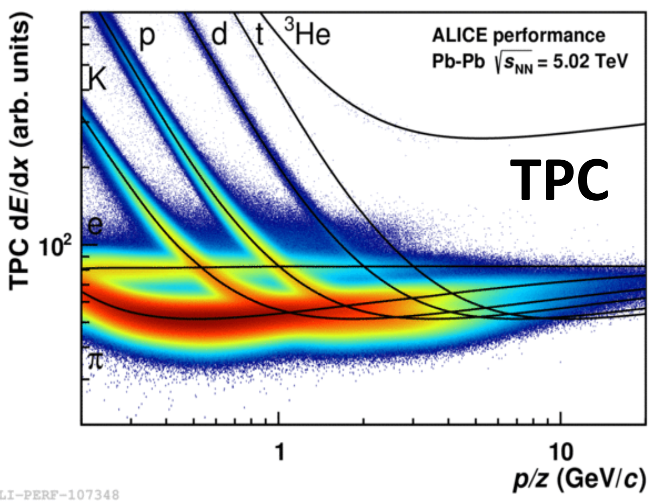
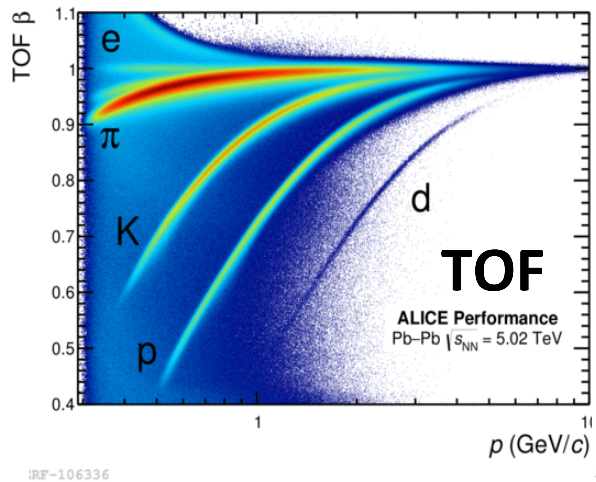
- $dN_{ch}/d\eta$ is the input to measure the Bjorken energy density *(J. D. Bjorken, Phys. Rev. D 27, 140 (1983))*
- $\langle N_\gamma \rangle$ at forward rapidity shows power law as well as logarithmic increase with $\sqrt{s}$

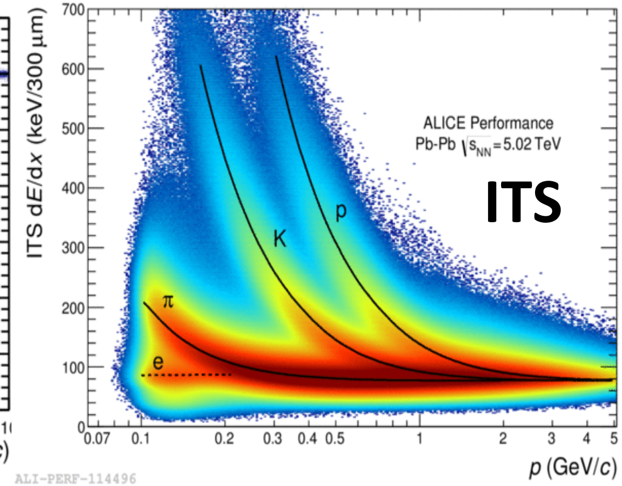


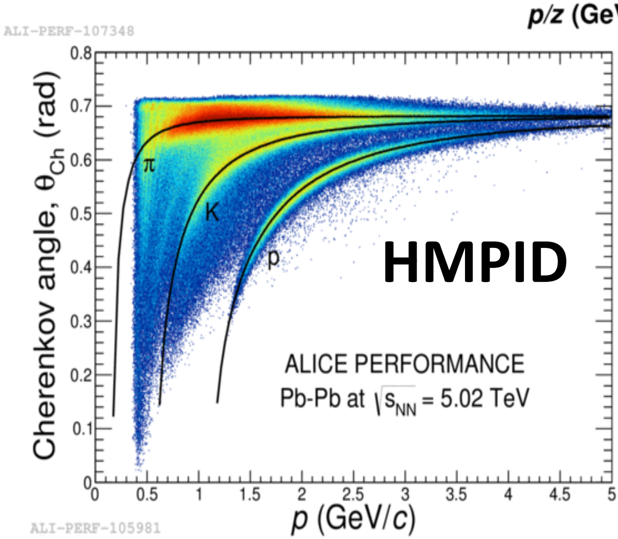
EPJC 75 (2015) 146

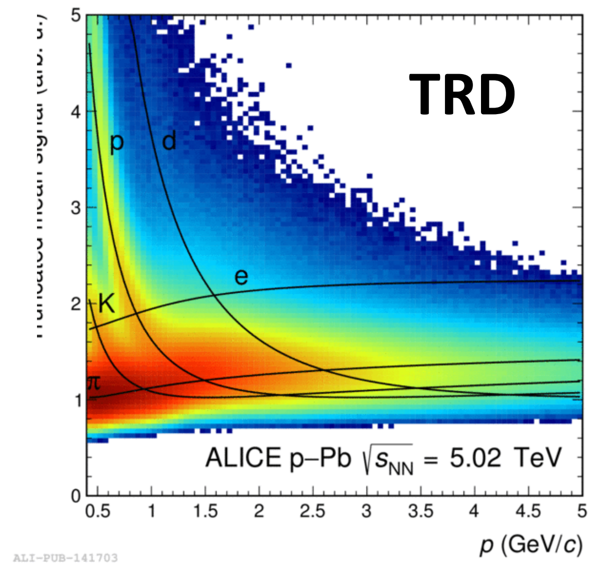
Excellent particle identification





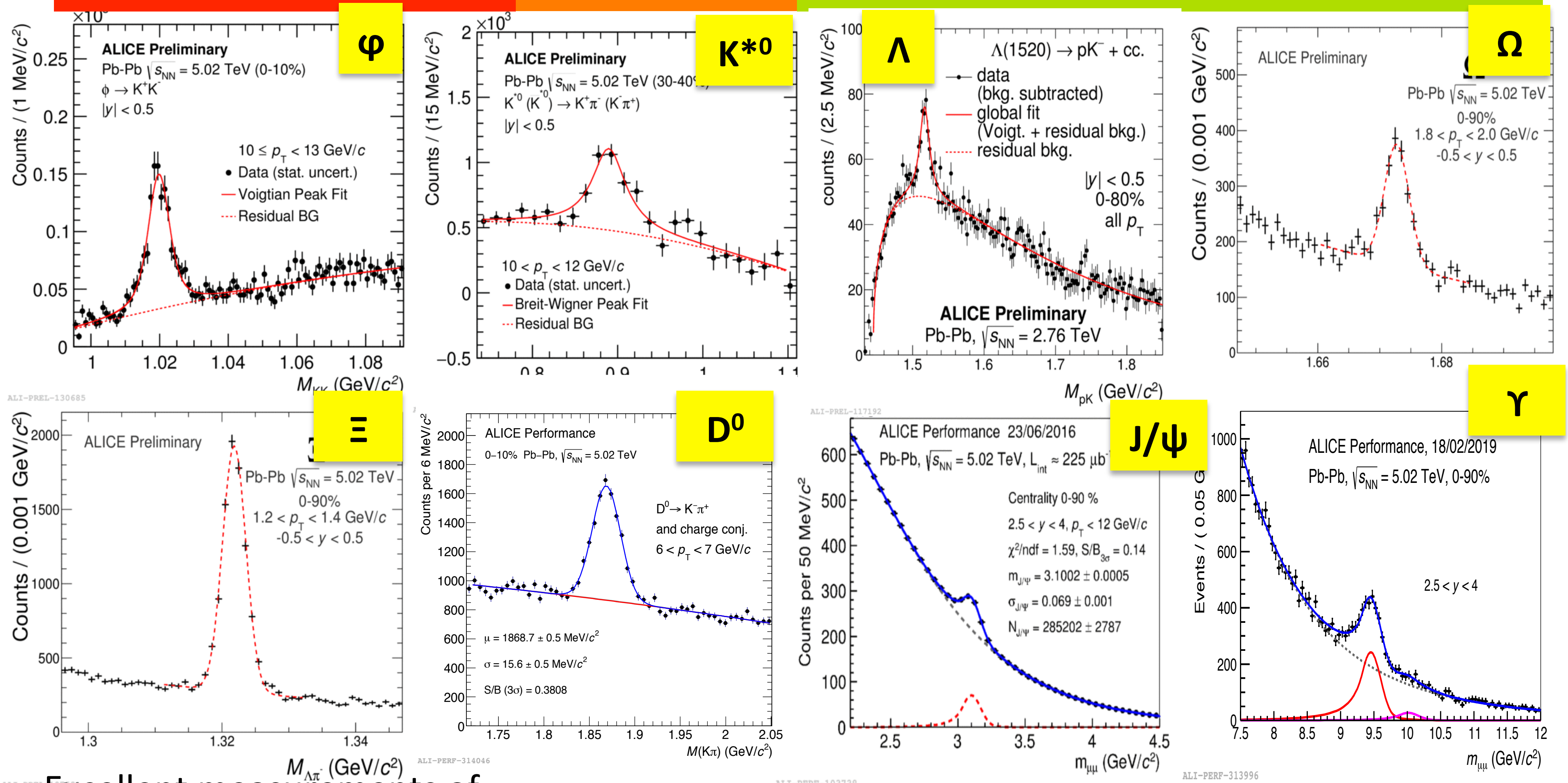






- ➢ Excellent particle identification using different detectors
- ➢ Particle identification over a wide p_T range

Excellent particle identification

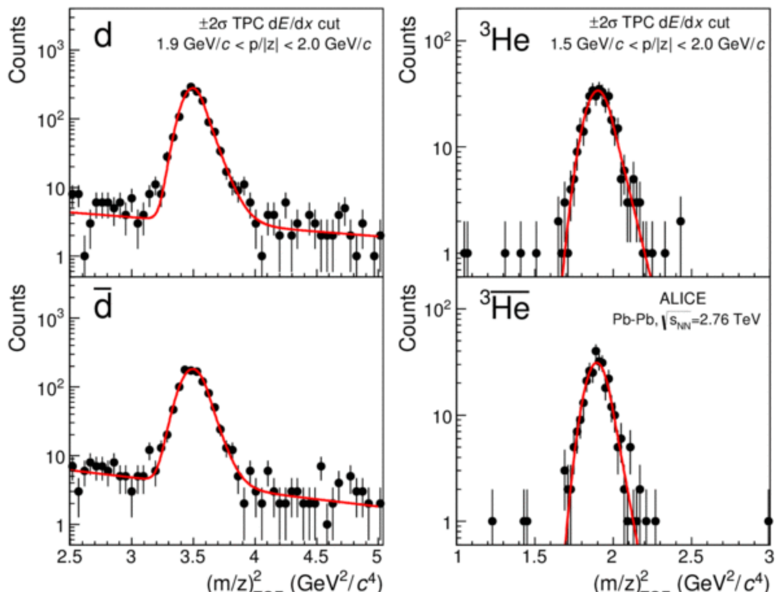


Excellent measurements of:

✓ resonance particles (Φ, k*, Λ, k^0_s, Ω, Ξ, Δ .... etc.), quarkonia (J/Ψ, Ψ(2s), ϒ), open heavy flavours (D mesons, electrons)

Nuclei measurements

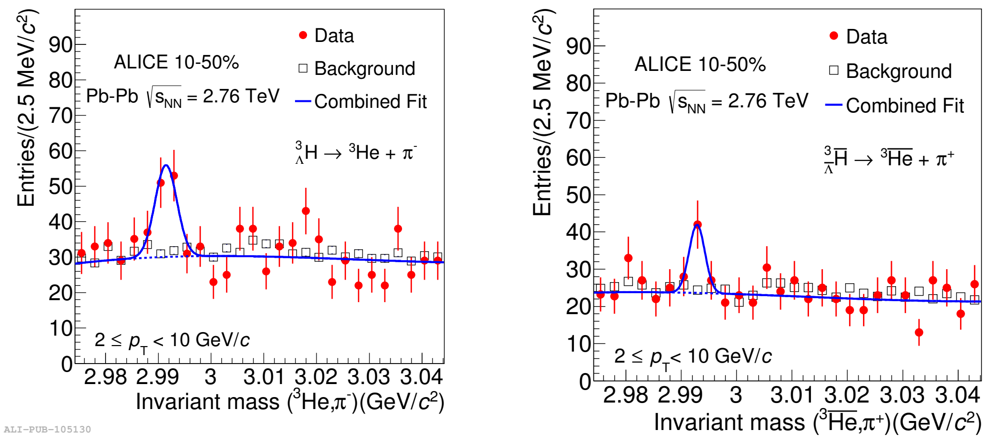
Deuterons (d) and Helium (^{3}He)



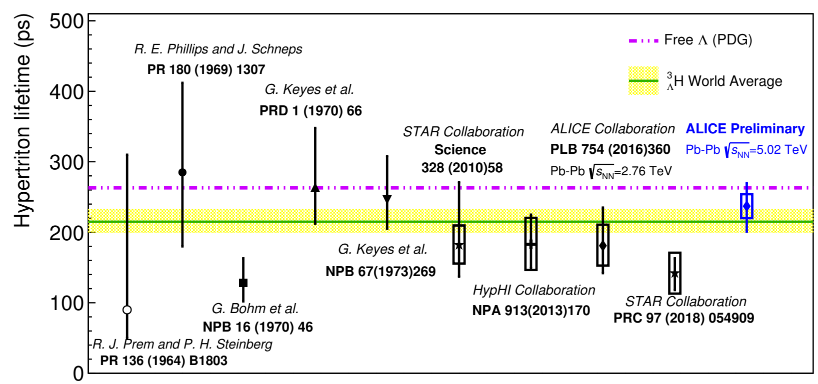
ALI-PUB

nature physics LETTERS
PUBLISHED ONLINE: 17 AUGUST 2015 | DOI: 10.1038/NPHYS3432

Hypertriton ($^3_\Lambda$H)



Phys. Lett. B 754 (2016) 360-372



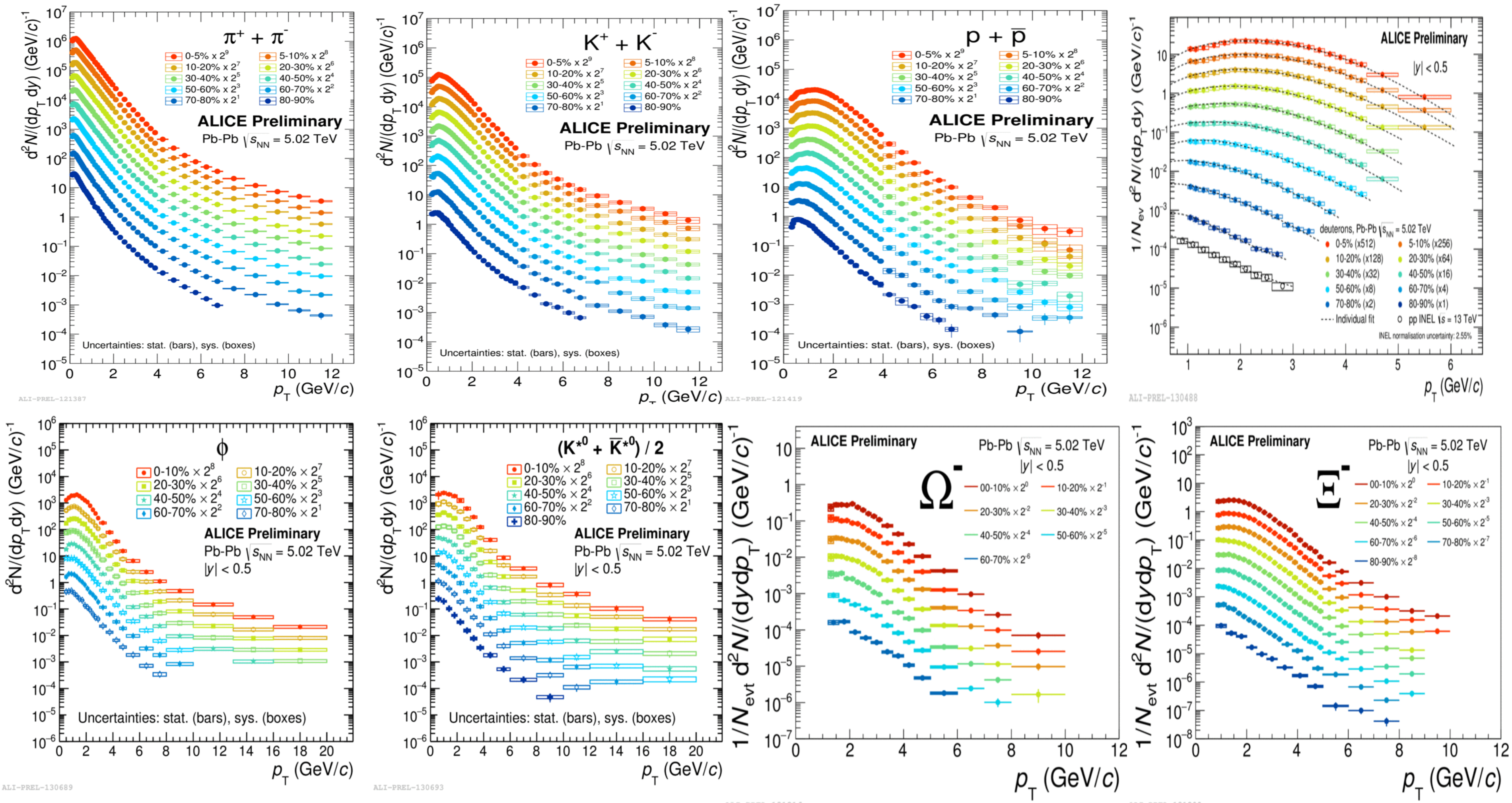
ALI-DER-161043

Excellent measurements of:

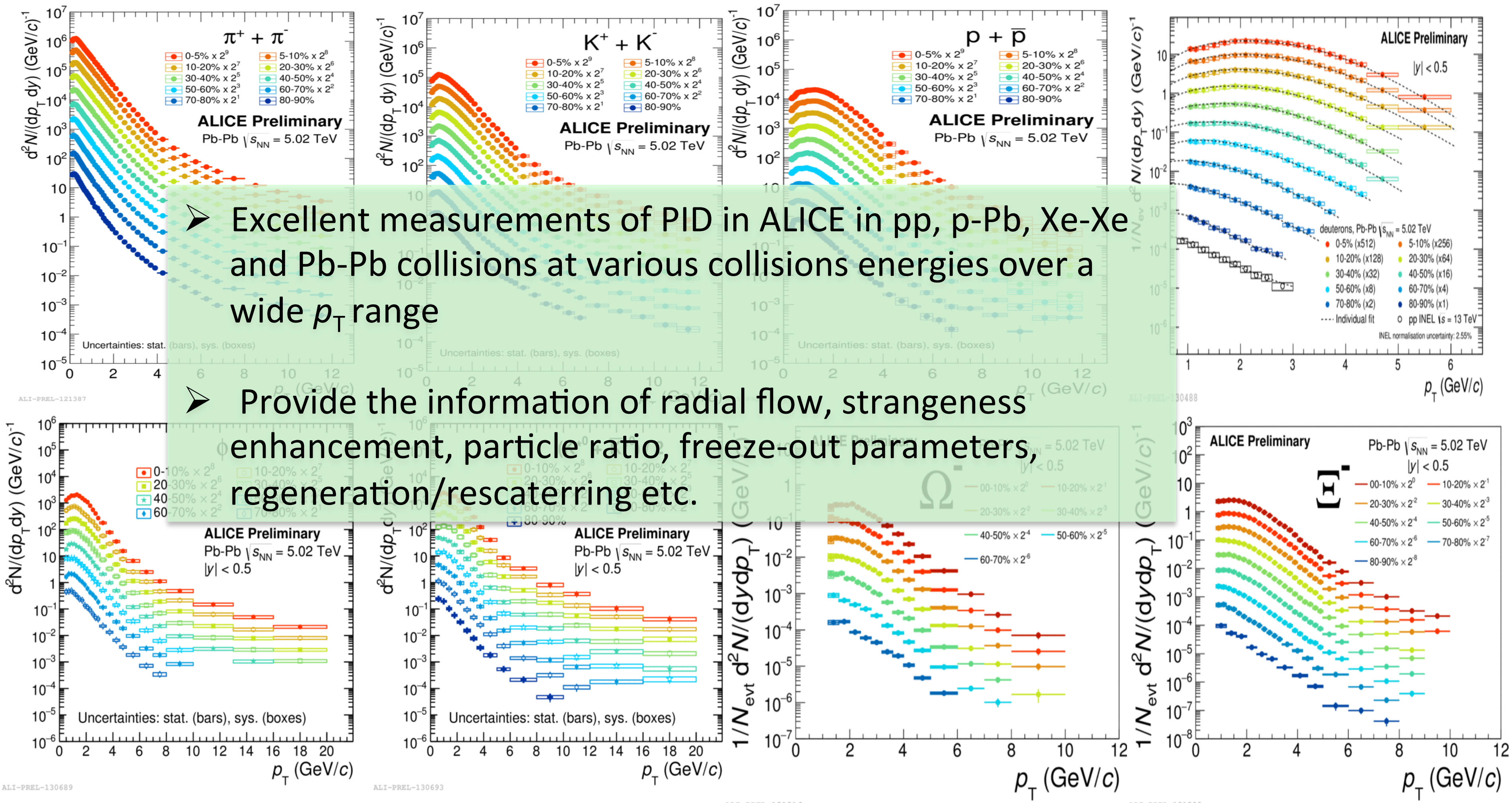
✓ light nuclei (d, ^{3}He) and Hyper-nuclei ($^3_\Lambda$H)

$^3_\Lambda$H lifetime is consistent with world data

Particle spectra

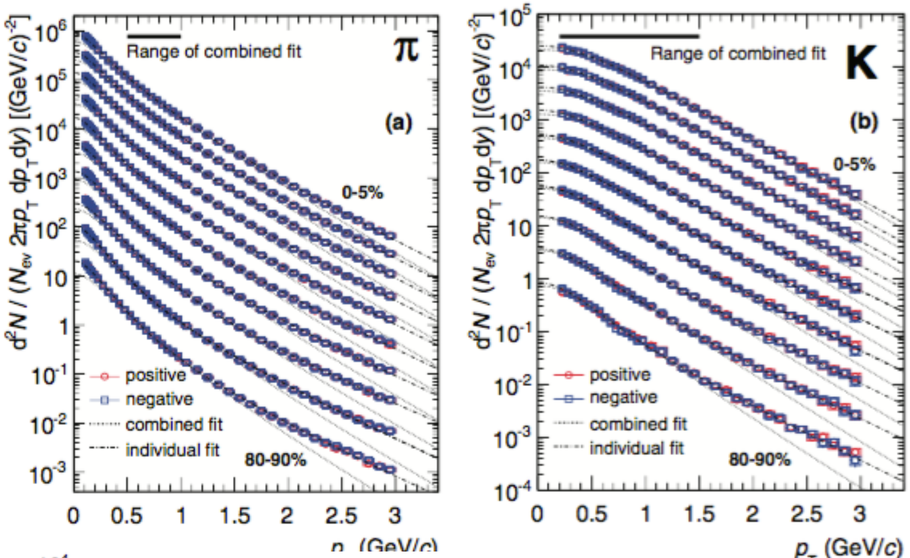


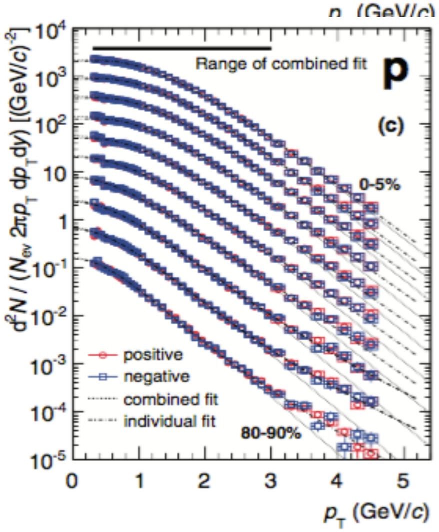
Particle spectra



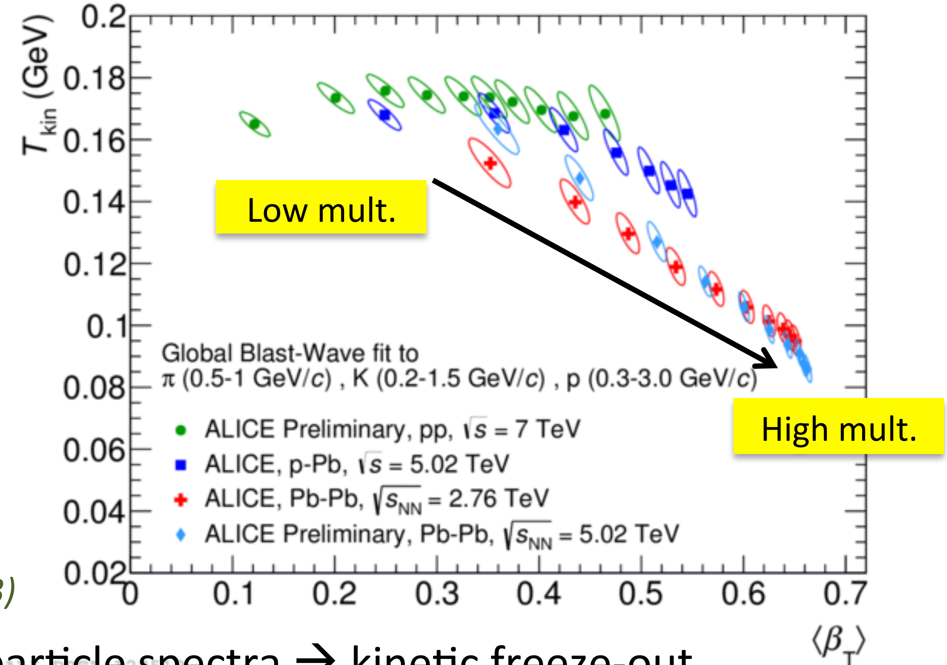
- Excellent measurements of PID in ALICE in pp, p-Pb, Xe-Xe and Pb-Pb collisions at various collisions energies over a wide p_T range
- Provide the information of radial flow, strangeness enhancement, particle ratio, freeze-out parameters, regeneration/rescaterring etc.

Kinetic freeze-out parameters





Phys. Rev. C 88 044910 (2013)



- ➢ Blast wave fits to particle spectra → kinetic freeze-out temperature (T_{kin} and radial flow ($<\beta_T>$) → **highest $<\beta_T>$ has been reached so far**

$$\frac{1}{p_T}\frac{dN}{dp_T} \propto \int_0^R r\,dr\, m_T\, I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right)$$

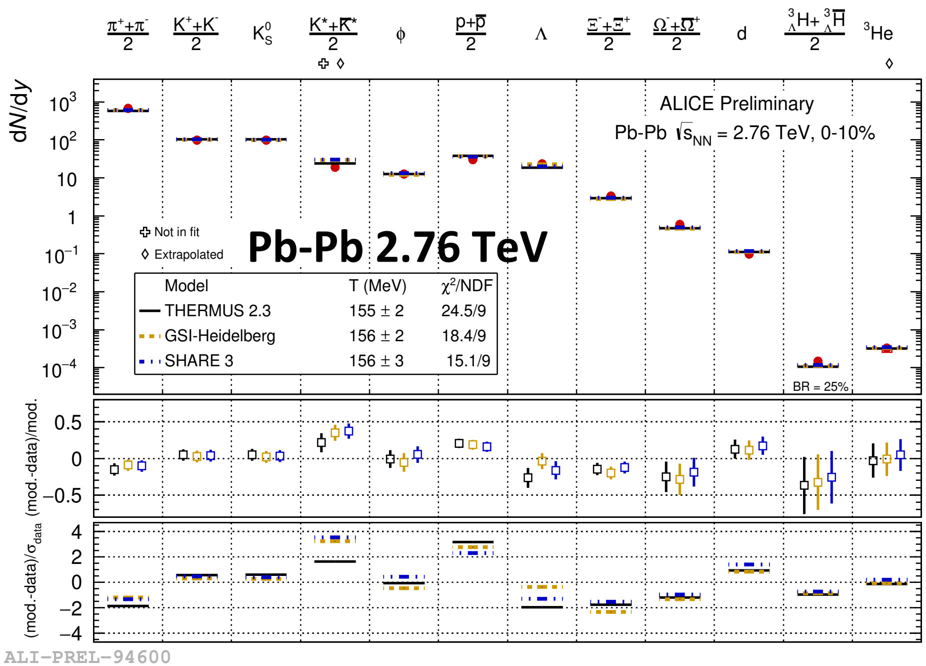
Phys. Rev. C48 (1993) 2462

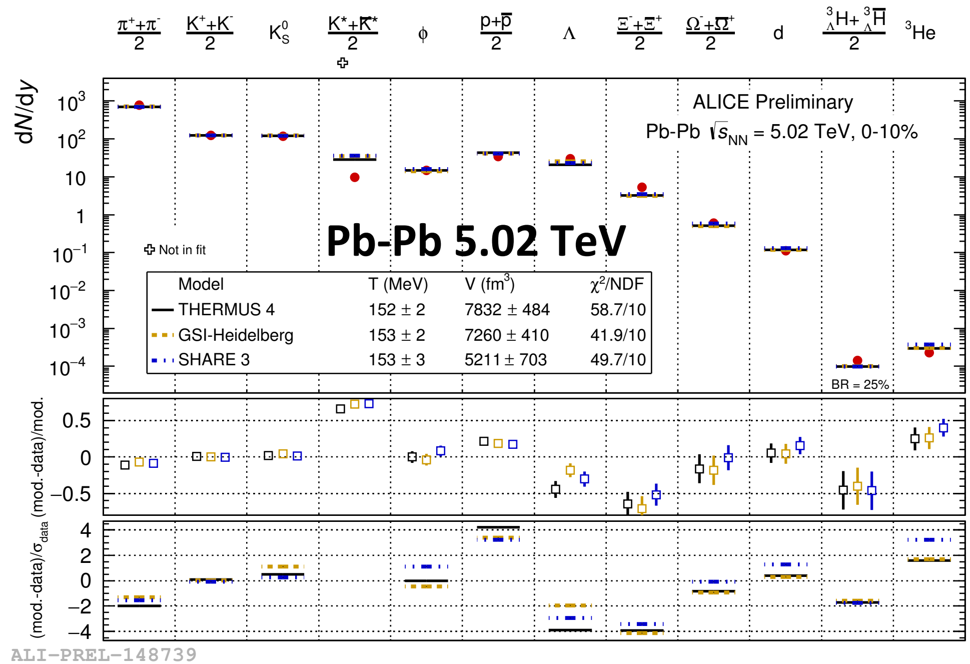
$$\rho = \tanh^{-1}\beta_T = \tanh^{-1}\left(\left(\frac{r}{R}\right)^n \beta_s\right)$$

Three fit parameters: $<\beta_T>$, T_{kin} and n

ρ → Velocity profile;

Chemical freeze-out parameter





- Fit the particle yield using thermal model to extract the chemical freeze-out temperature (T_{ch})

$$\frac{dN}{dy} \propto \exp\left(\frac{-m}{T_{chem}}\right)$$

- T_{ch} found slightly lower at 5.02 TeV (T_{ch} = 153 MeV) than T_{ch} (=156 MeV) at 2.76 TeV

*Phys. Lett. **B 673** (2009) 142*

QGP temperature

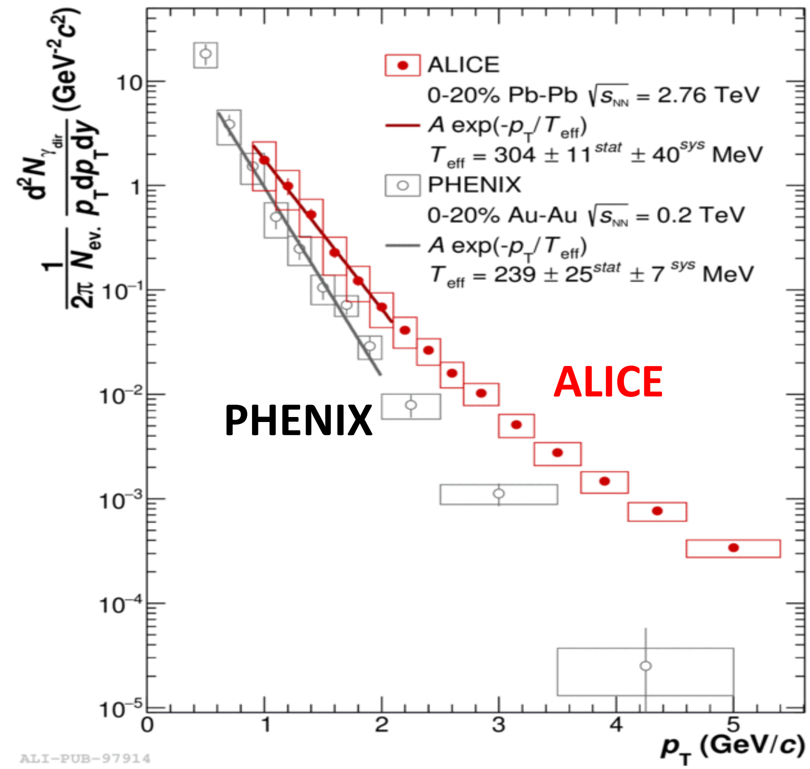
- QGP temperature is measured via “**direct photon (not originating from hadrons)** ” measurement

- produced at all stages of the collision and escape from the hot nuclear matter basically unaffected
- Promt direct photons (p_T > 5 GeV/c) are produced via initial hard scattering of quarks and gluons

- Thermal direct photons (p_T < 4 GeV/c) are emitted from the QGP as well as hadronic matter → provide information about the temperature, collective flow etc.

- Significant contribution from blueshifted photons from the late rom the late stages of the collision evolution

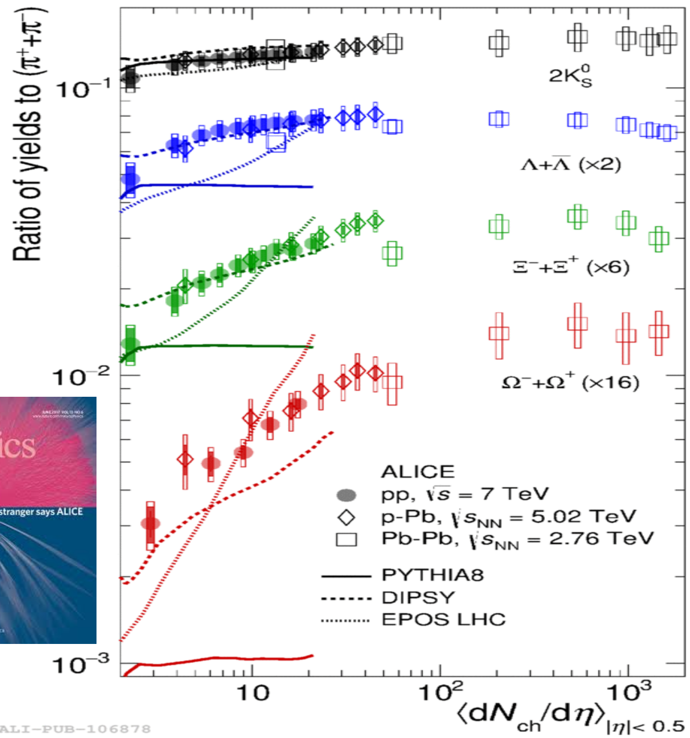
Phys. Lett. B 754 (2016) 235–248

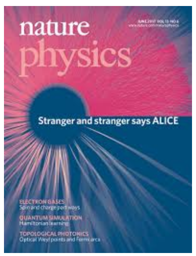


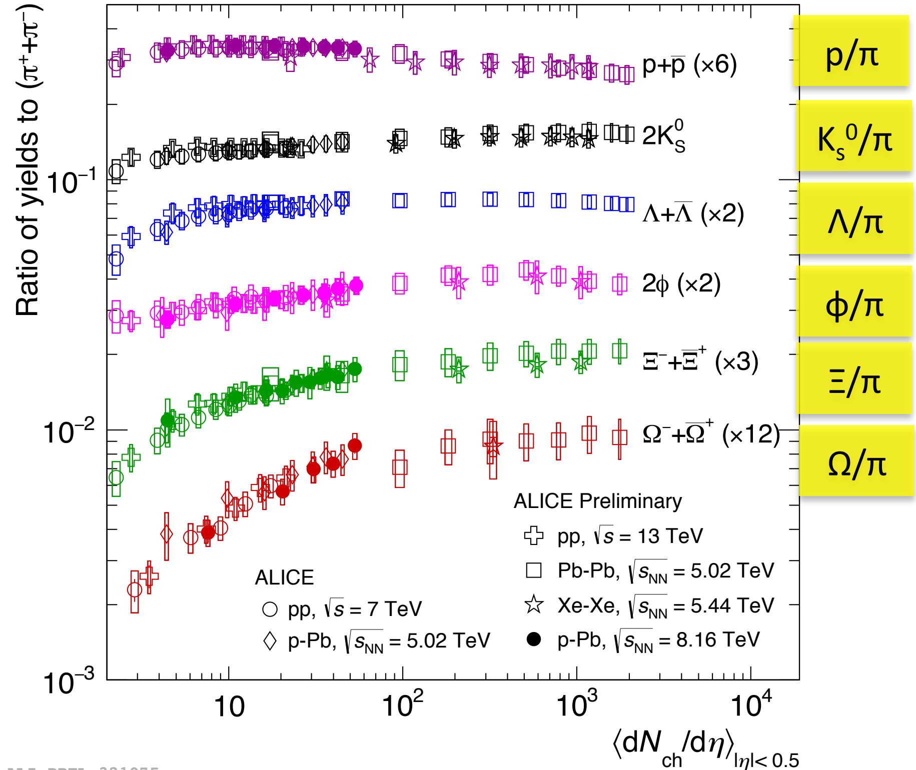
T_{eff} (average)= 304 ± 11^{stat} ± 40^{sys} MeV

Highest temperature ever achieved

Strangeness enhancement







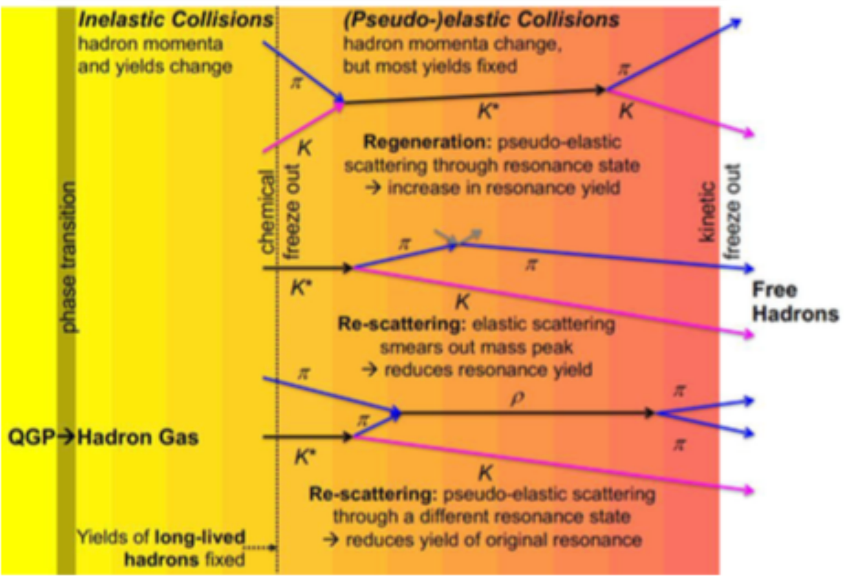
- Strangeness enhancement is considered as a sign of QGP *(Rafelski, Müller, PRL 48, 1066 (1986))*
- strangeness production governed by mass of the strange quarks, strangeness conservation
- Strangeness enhancement is also observed in small systems like pp and p-Pb for the first time
- No significant energy and system dependence at given multiplicity

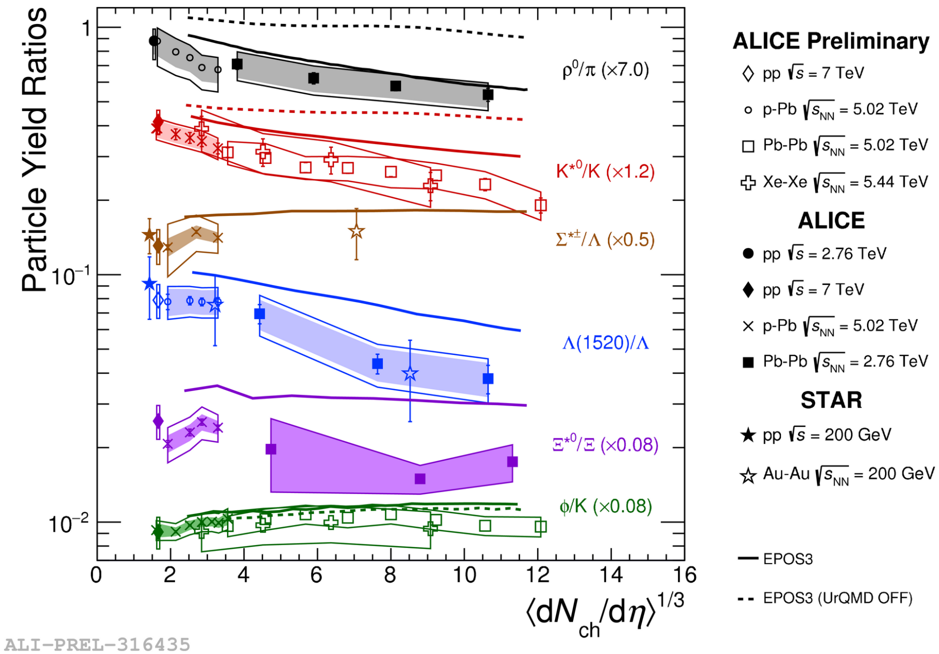
Resonances

increasing lifetime →

	ρ(770)	K*(892)	Λ(1520)	Ξ(1530)	φ(1020)
cτ (fm/c)	1.3	4.2	12.7	21.7	46.2

Re-scattering and regeneration





- Suppression of short lived resonances → re-scattering effects in the hadronic medium
- Ratio with longer life-time remains constant → decay outside the fireball

Spin alignment

➢ Non central heavy-ion collisions: large angular momentum

➢ In presence of QGP, vector mesons (spin=1) can be polarized due to spin-orbit interaction

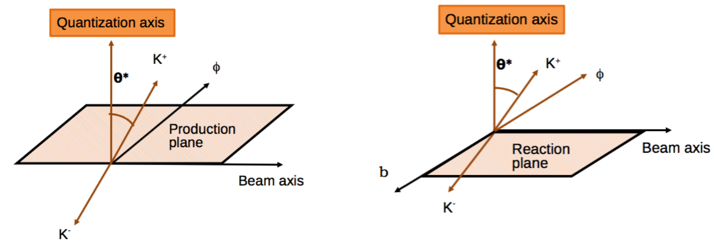
➢ Spin alignment can be studied through angular distribution of the decay daughters of vector mesons (K^* and ϕ) along the quantization angle

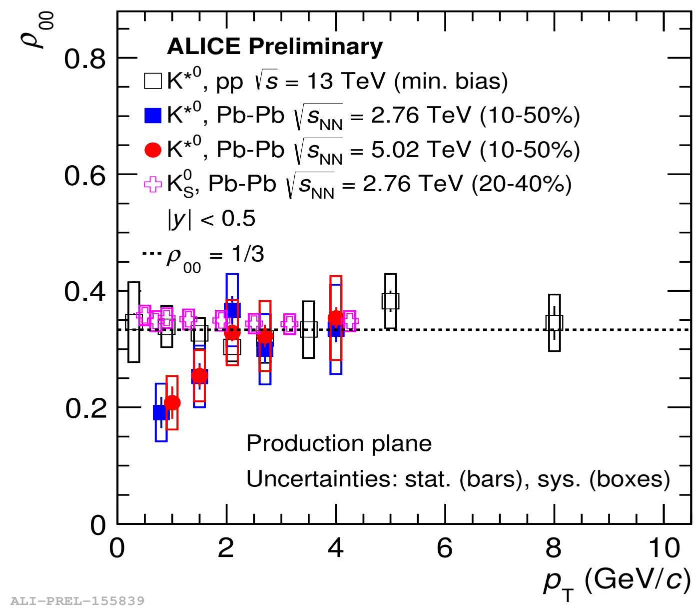
$$\frac{dN}{d\cos\theta^*} \propto [1-\rho_{00}+\cos^2\theta^*(3\rho_{00}-1)]$$

ρ_{00} → is the element of spin density matrix

➢ If ρ_{00} = 1/3 → No spin alignment
Deviation from 1/3 → preferring spin state

Nucl. Phys. B 15, 397 (1970)





➢ ρ_{00} = 1/3 in pp collisions

➢ ρ_{00} < 1/3 for p_T < 2 GeV/c in Pb-Pb collisions

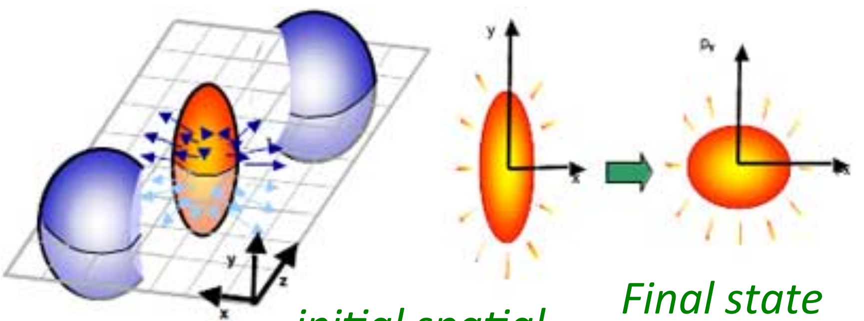
Anisotropic flow

- measures the momentum anisotropy of the final-state particles
- created due to the initial spatial anisotropy of the overlap region

- Fouriar expansion of azimutal distribution of produced particles:

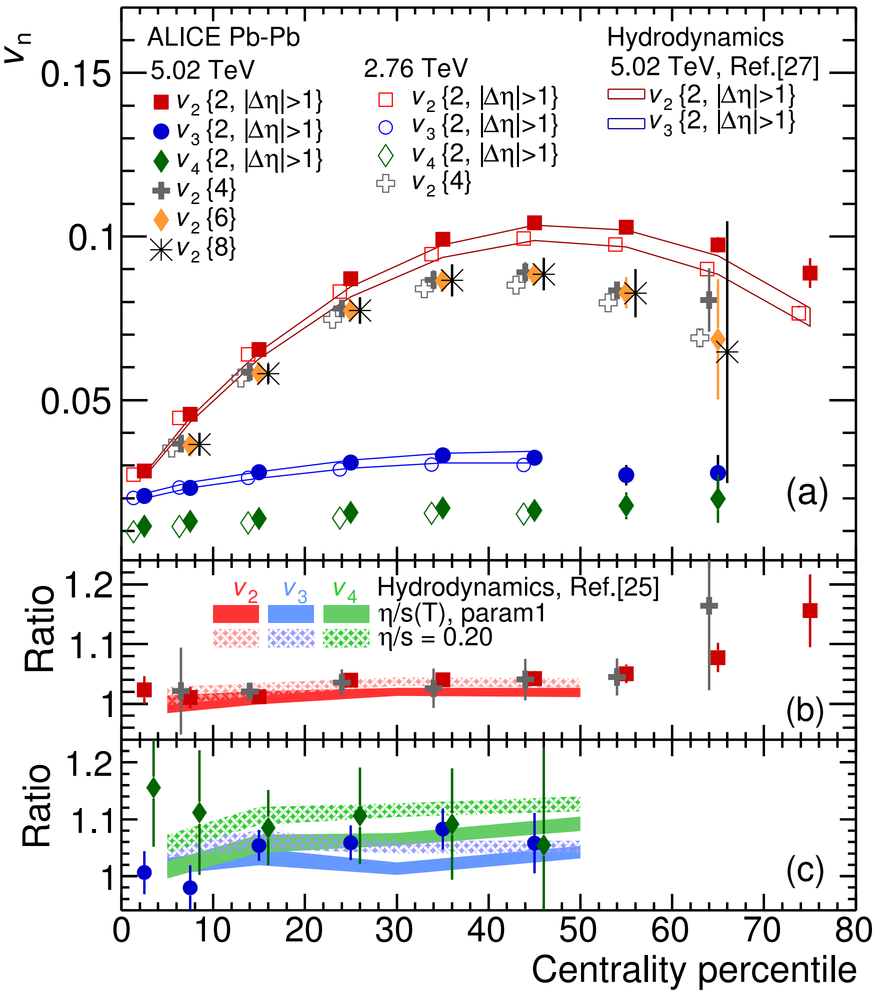
$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_{RP})]$$

- quantified as the v_n, Ψ_{RP} is the reaction plane angle
- ✓ v_1 → directed flow
- ✓ v_2 → elliptic flow
- ✓ v_3 → triangular flow



- Elliptic flow of produced particles provides information on:
- ✓ Collective expansion and possible thermalization (low and intermediate p_T)
- ✓ Parton energy loss (high p_T)
- Non-zero elliptic flow in small system → collectivity in small system?

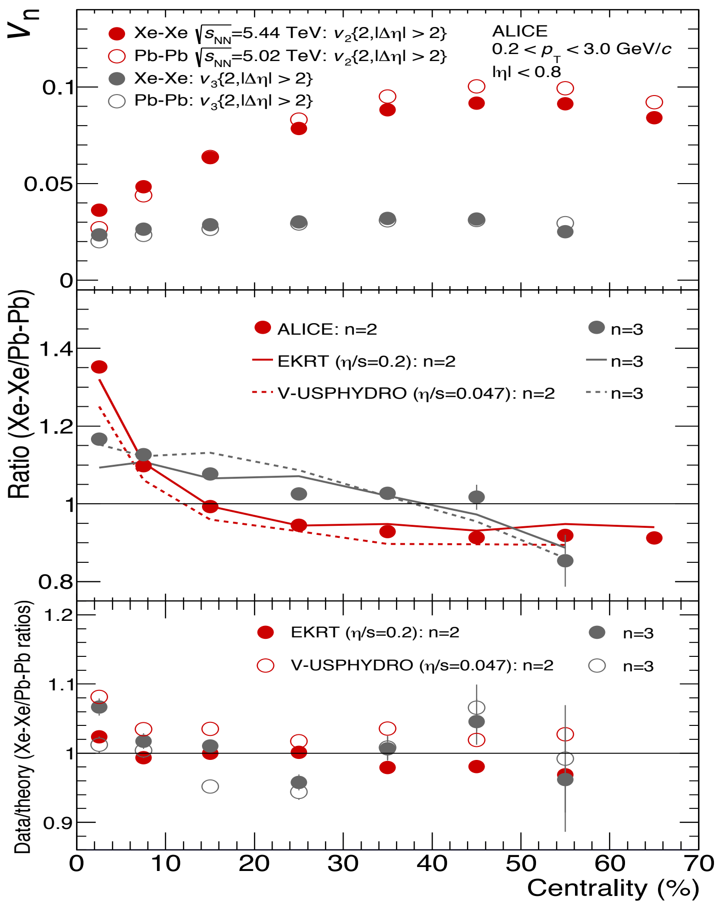
Anisotropic flow of charged particles



ALI-PUB-105790 *Phys. Rev. Lett. 116 (2016) 132302*

- Anisotropic flow coefficient (v_n) integrated over $0.2 < p_T < 5$ (GeV/c) is presented for Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV
- Only a small change of v_n between two different centre of mass energies
- Results are compared with the 3D + 1 e-by-e relativistic hydrodynamics
- Model comparison suggests that the viscosity of the medium is very low → almost perfect liquid

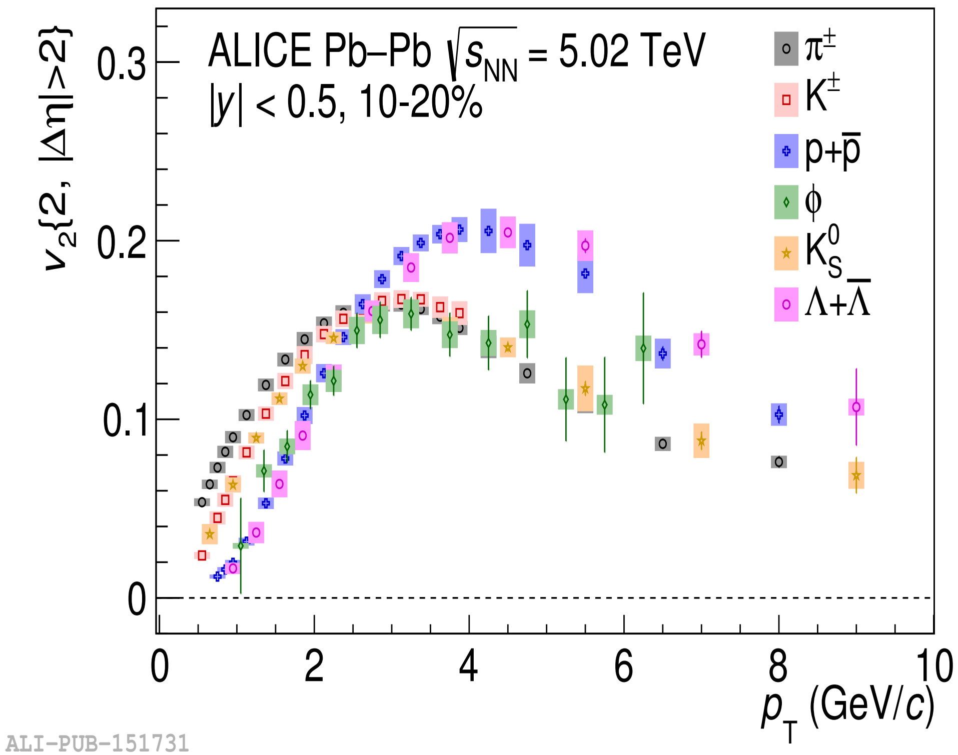
Anisotropic flow of charged particles



Phys Lett. B 784 (2018) 82-95

- Anisotropic flow coefficient (v_n) integrated over $0.2 < p_T < 5$ (GeV/c) is presented for Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 and 5.02 TeV
- Only a small change of v_n between two different centre of mass energies
- Results are compared with the 3D + 1 e-by-e relativistic hydrodynamics
- Model comparison suggests that the viscosity of the medium is very low → almost perfect liquid
- v_n of Xe-Xe found higher than Pb-Pb in central collisions → explained by hydro by taking care of nuclear deformation of Xe nuclei

Anisotropic flow of identified particles



JHEP09(2018)006

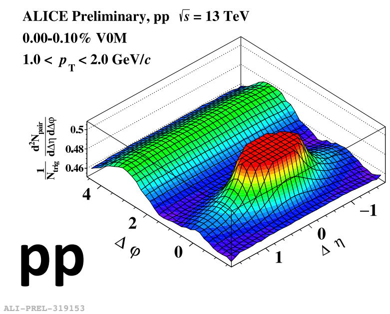
- v_n are sensitive to different stages of the collisions:
  ✓initial state
  ✓QGP
  ✓hadronic phase

- **At low p_T:** hadron mass ordering

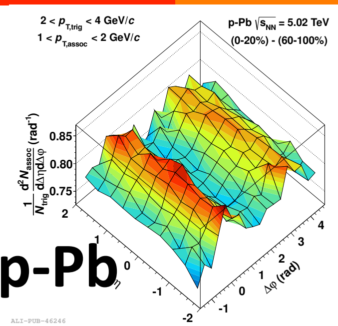
- **At intermediate p_T:** splitting for baryons and mesons → ordering by NCQ

- **At high p_T:** parton energy loss dominate

Collectivity in small systems

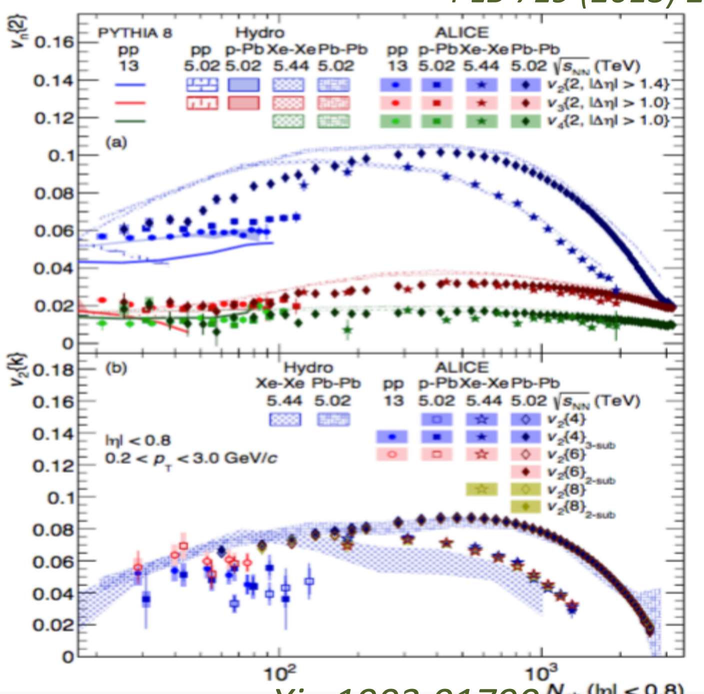


pp



p-Pb

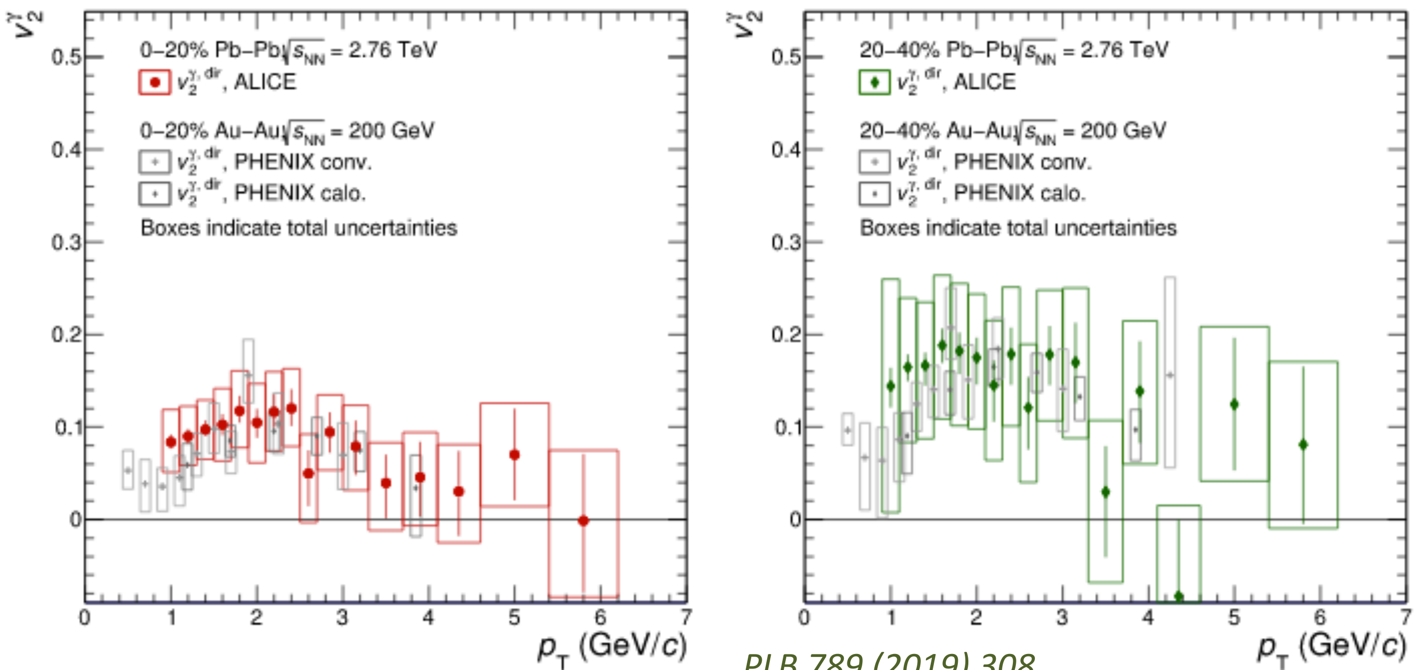
PLB 719 (2013) 29



arXiv:1903.01790

- Near side, long range correlations also observed in pp and p-Pb systems → collectivity in small systems
- An ordering of the coefficients $v_2 > v_3 > v_4$ are observed in small system as well
- At higher multiplicity v_2 does not scale with N_{ch} → different initial geometries for small and large systems
- Model description (PYTHIA8 and IP-Glasma+MUSIC+UrQMD) in small systems (pp and p-Pb) is not satisfactory
- A better understanding of the initial conditions in small collision systems may be helpful

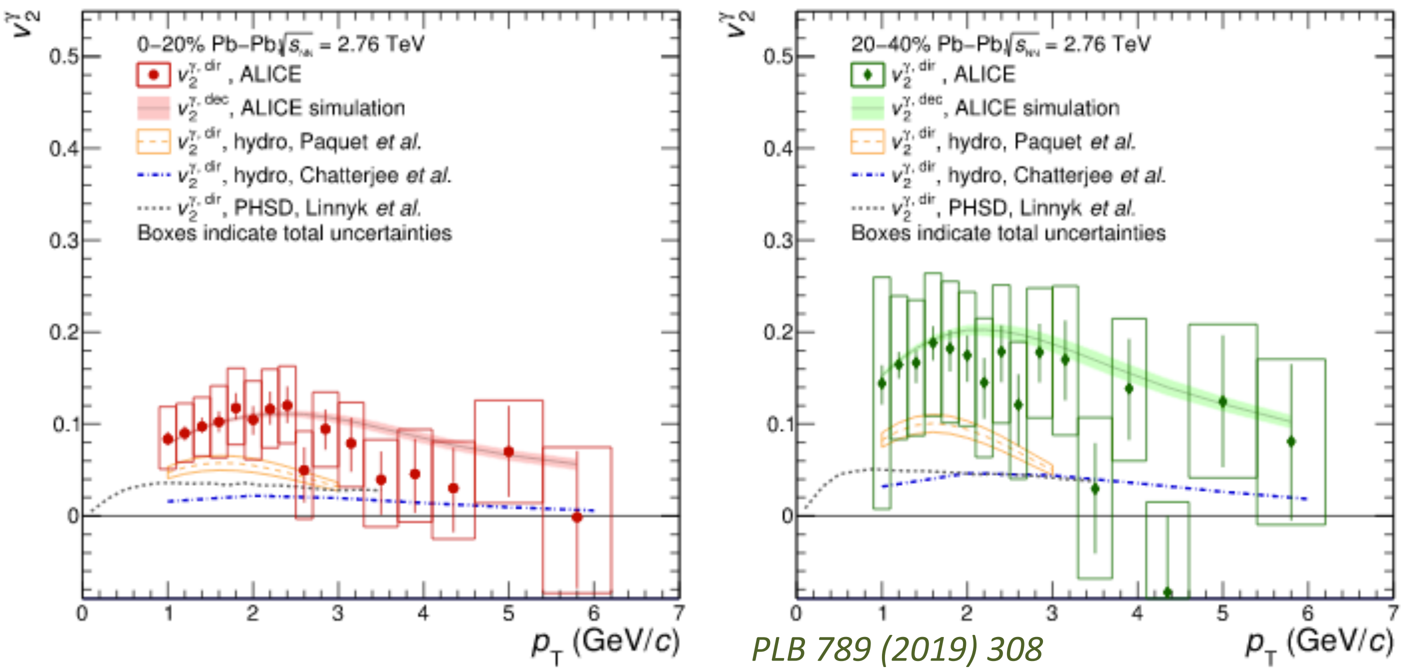
Direct photon flow



PLB 789 (2019) 308

- ➢ Direct photon (mostly thermal photons) flow is comparable with the decay photon flow (final state) → no initial state effects?
- ➢ ALICE results consistent with the PHENIX results → no strong energy dependence of photon v_2

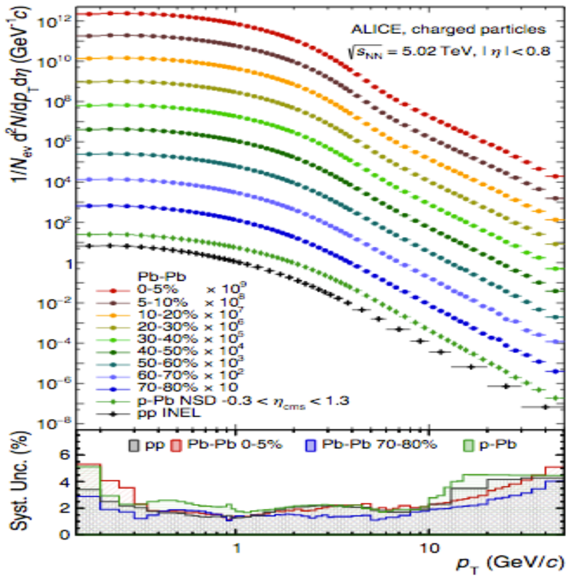
Direct photon flow

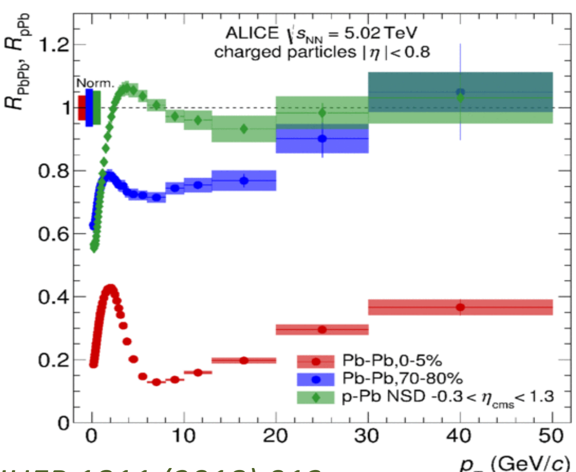


PLB 789 (2019) 308

- ➢ Direct photon (mostly thermal photons) flow is comparable with the decay photon flow (final state) → no initial state effects?
- ➢ ALICE results consistent with the PHENIX results → no strong energy dependence of photon v_2
- ➢ Existing models (hydro, transport) could not explain the data well

Nuclear modification factor





JHEP 1811 (2018) 013

- Defined as :

$$R_{\mathrm{AA}} = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

- Quantify the energy loss in medium by collisional and radiative processes :
  - ✓ Colour-charge dependence
  - ✓ Dead-cone effect -> expected mass-dependent energy loss:

ΔE (g) > ΔE (u,d,s) > ΔE (c) > ΔE (b) *PLB 519 (2001) 199*

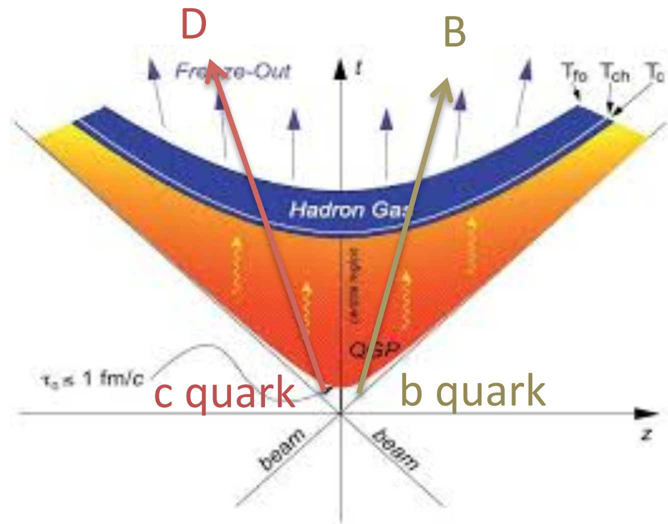
R_{AA} (π) < R_{AA} (D) < R_{AA} (B) ?

- R_{AA} = 1 at high transverse momentum (p_T) indicates no medium effects

- R_{AA} < 1 at high p_T indicates a modification/softening of the spectra which can be related to parton energy loss.

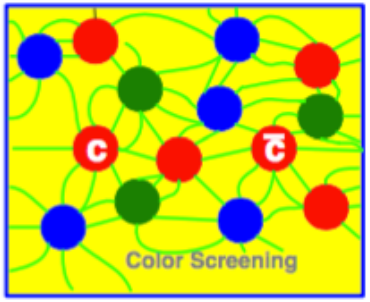
Probes with heavy flavours

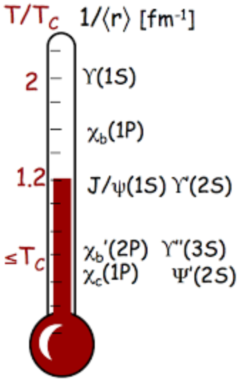
- ✓ Produced in the early stages of the collisions
- ✓ Witness entire space-time evolution of the system
- ✓ Parton energy loss by radiative and elastic processes



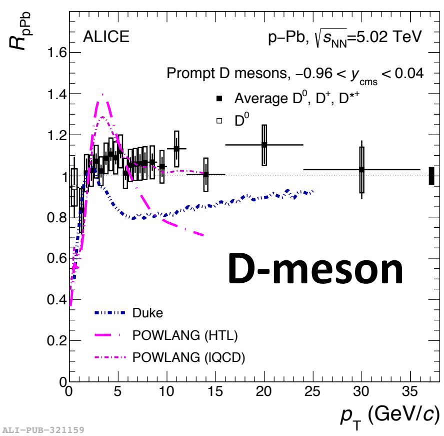
Open heavy-flavour:
- ✓ Access to transport properties of the system
- ✓ Flavour dependent hadronization
- ✓ Penetrating probe down to very low momenta

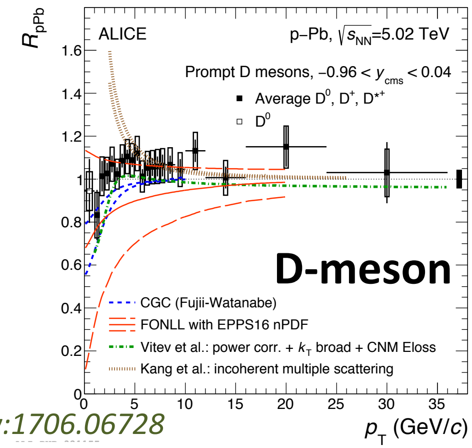
Quarkonia:
- ✓ Dissociation and regeneration in the QGP
- ✓ Debye screening
- ✓ Sequential melting of different states depending on their binding energy → QGP thermometer



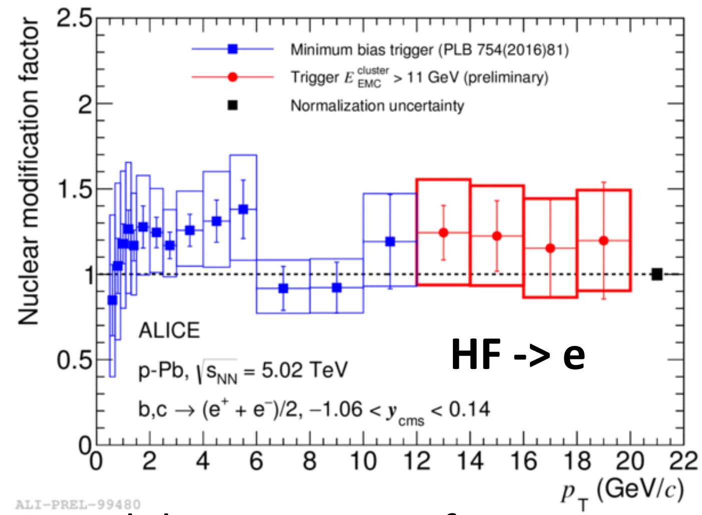


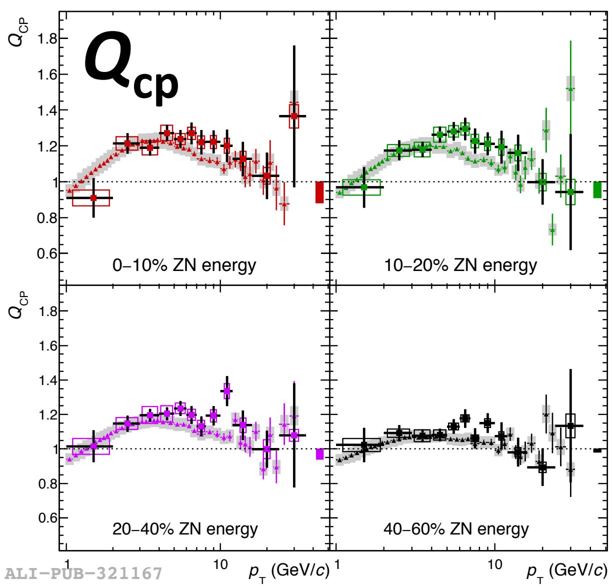
Nuclear modification factor of open charms in p-Pb collisions

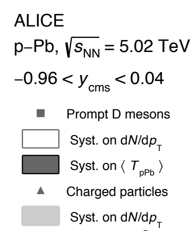




arXiv:1706.06728

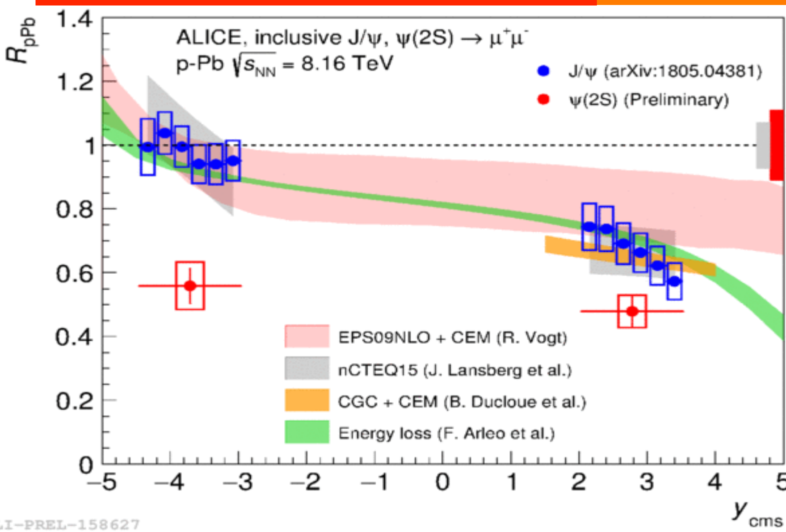


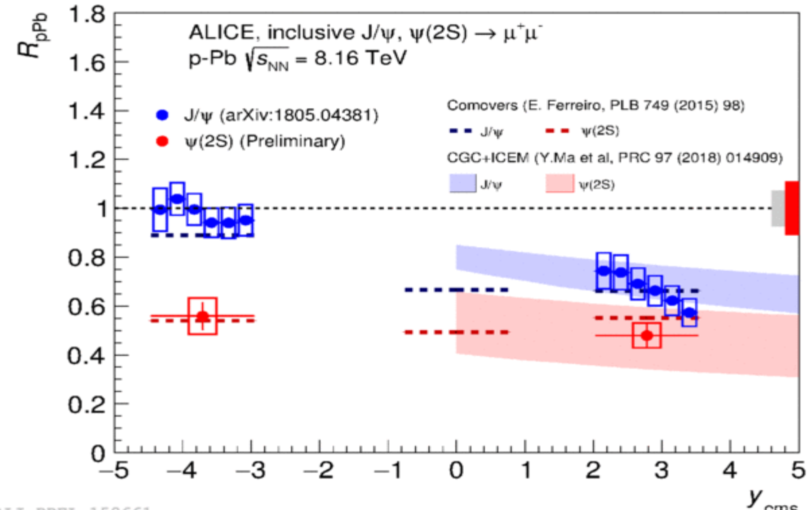


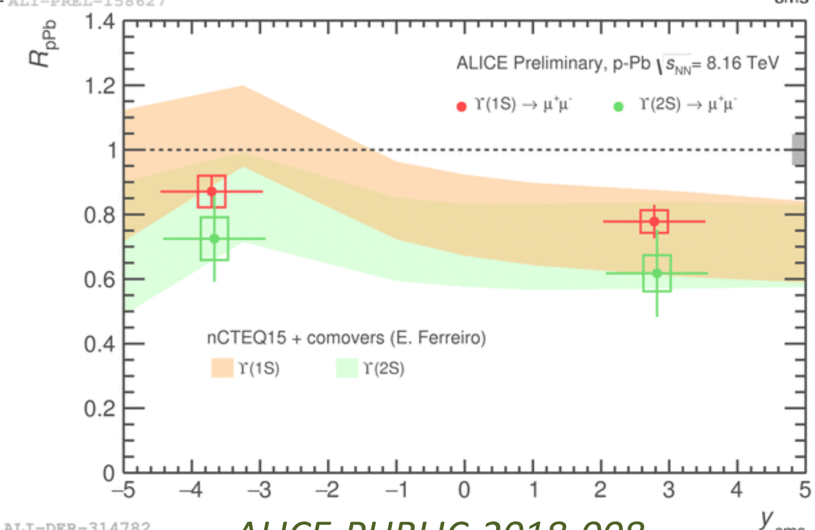


- ➢ R_{pPb} is measured down to p_T ~ 0 for D-meson
- ➢ R_{pPb} is consistent with unity within the uncertainties
- ➢ Results are well described by the models include initial state effects (CGC, FONLL, Vitev)
- ➢ The models include strong final state interactions can not explain the data well (Duke, POWLANG)
- ➢ Hint of $Q_{cp} > 1$ for central collisions in $3 < p_T < 8$ GeV/c with 1.5σ
- ✓ Radial flow?
- ✓ Initial or final-state effect?

Quarkonia suppression in p-Pb





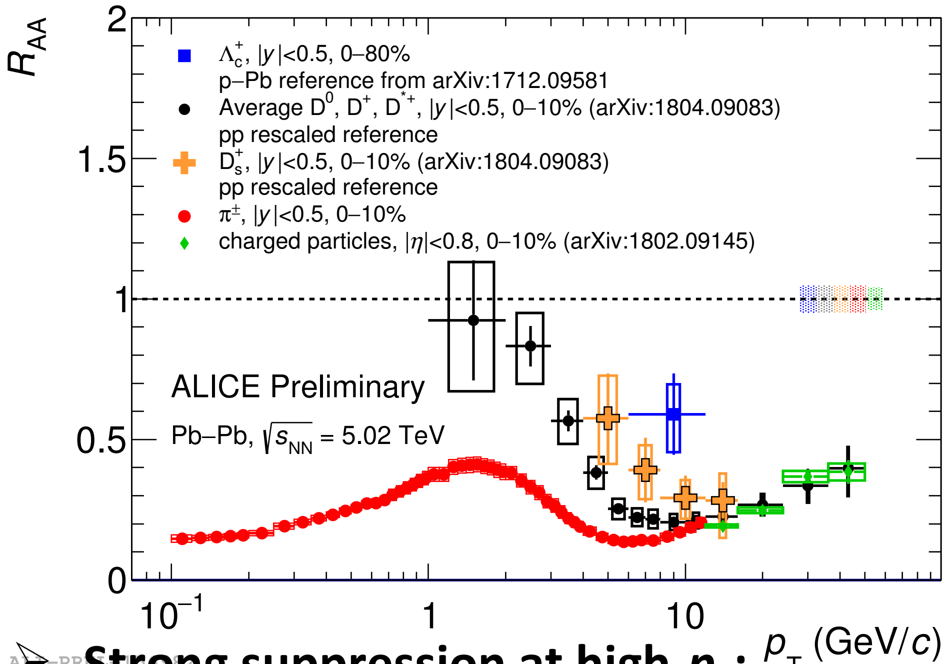


ALICE-PUBLIC-2018-008

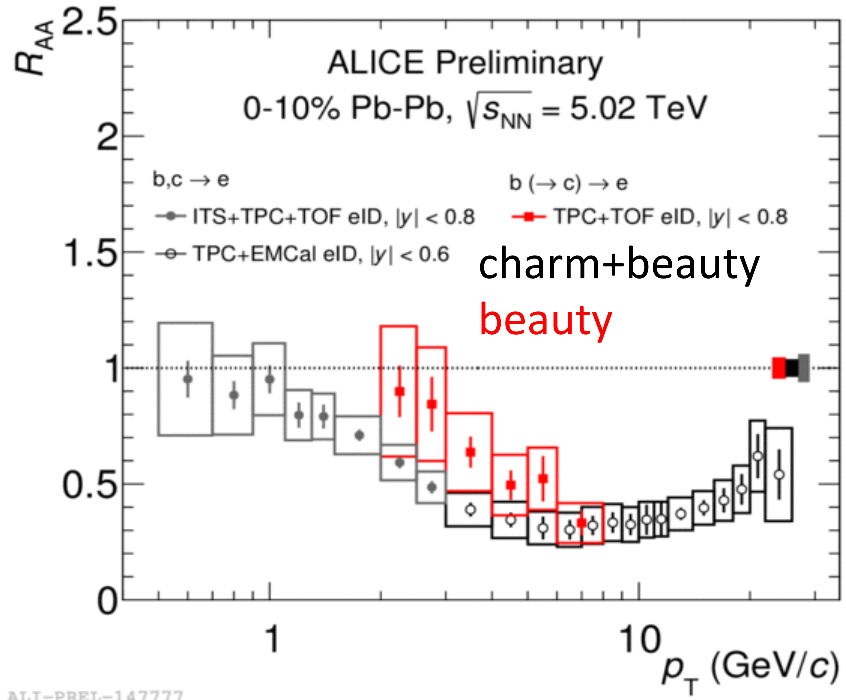
- J/ψ suppression is reproduced by the model with initial state effects
- ψ(2S) shows larger suppression than J/ψ especially at backward rapidity
- Model includes final state effect can explain the ψ(2S) suppression
- Two resonance of ϒ shows similar suppression, ϒ(2S) shows slightly higher
- A Model which includes shadowing + interaction with comoving particles describes the data

Heavy-flavour energy loss in Pb-Pb collisions

Charm family portrait

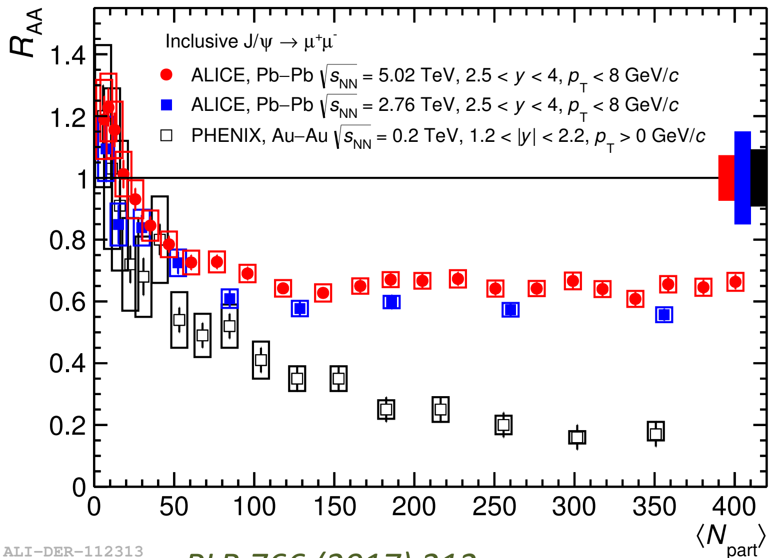


HF → e

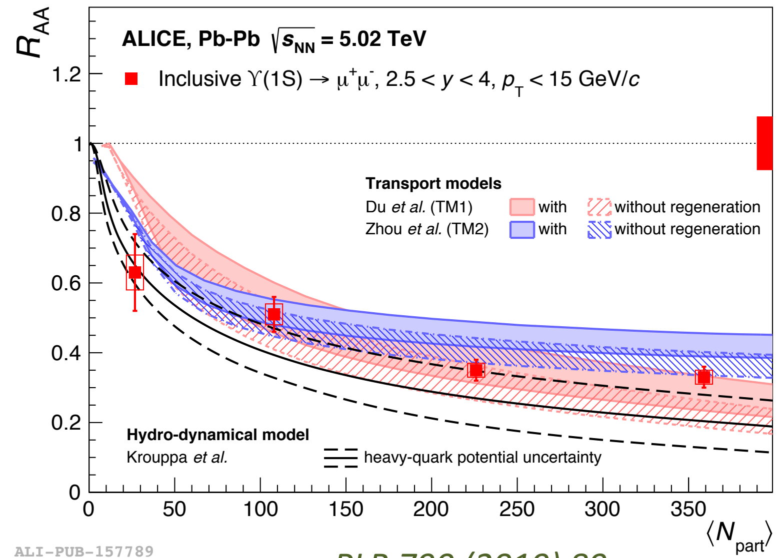


- **Strong suppression at high-p_T:**
  Charm is suppressed similarly as light quarks → No mass ordering at high-p_T
- **Hints of mass ordering at low-p_T:**
  Different fragmentation and initial spectra shapes, coalescence and radial flow, mass dependent energy loss
- **Hints of mass ordering in beauty sector as well**

Quarkonia suppression



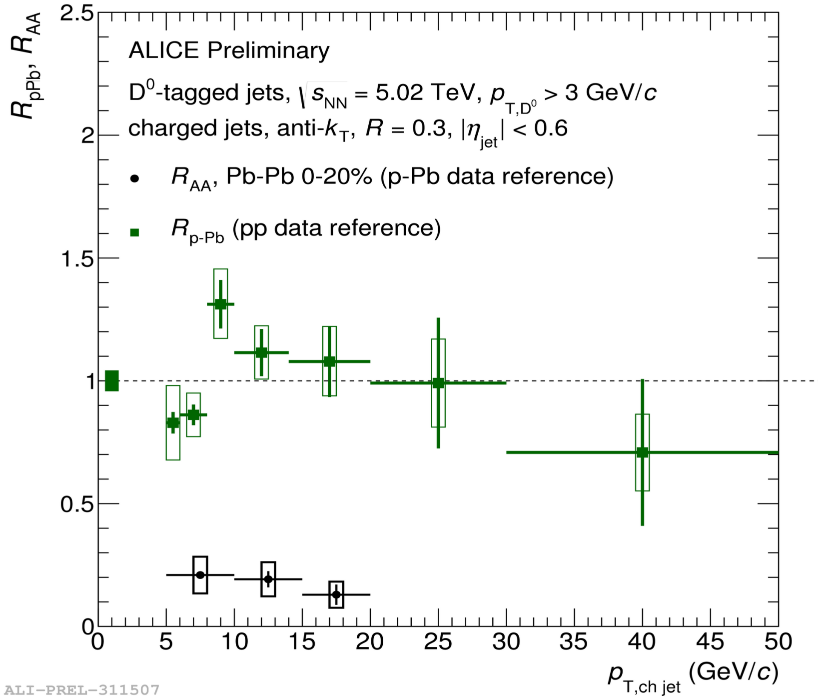
PLB 766 (2017) 212

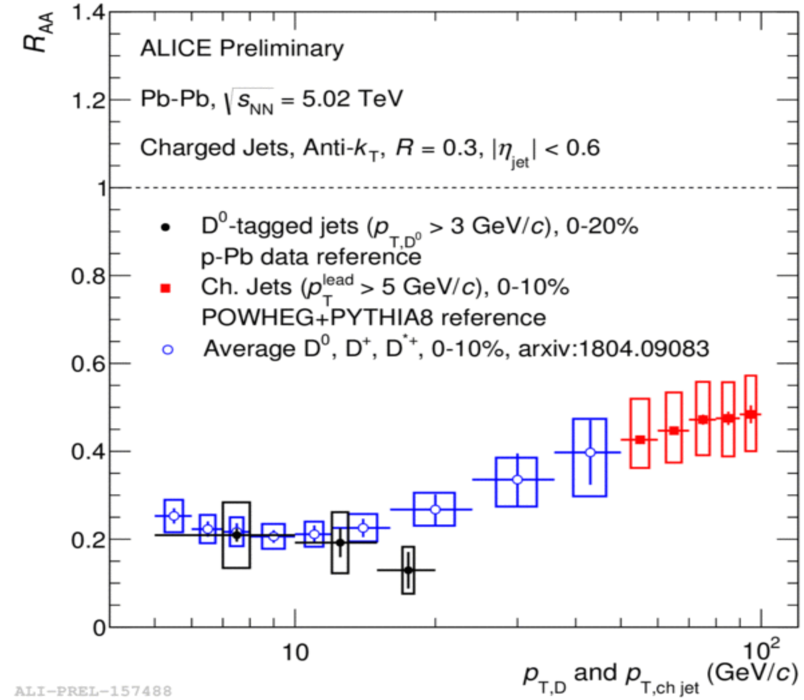


PLB 790 (2019) 89

- Quarkonium suppression due to dissociation of bound state in colored medium
- Clear J/ψ suppression with almost no centrality dependence
  Less suppression at LHC than at RHIC → later recombination of c-cbar pairs
- Strong suppression for ϒ is observed → regeneration effect is small
  Transport models describe the data within uncertainties

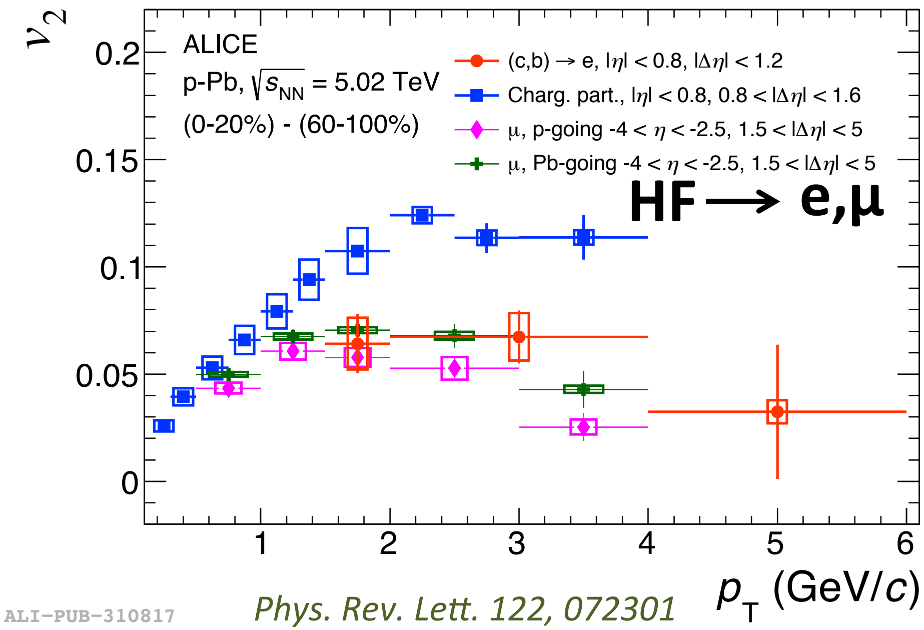
HF-tagged jet



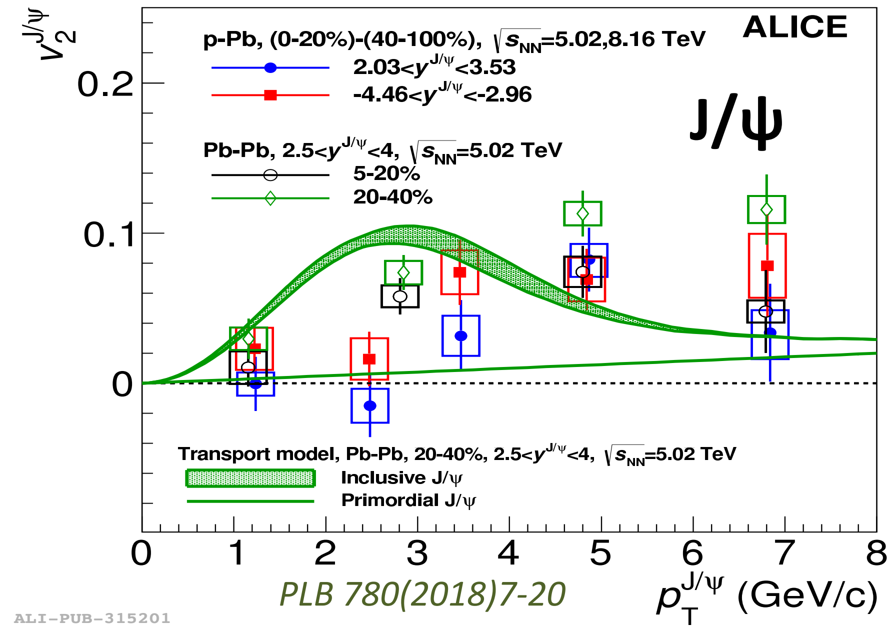


- No suppression in p-Pb and strong suppression in Pb-Pb → Signature of HF jets energy loss in hot and dense matter
- R_{AA} of D^0-tagged jet in $5 < p_T$ (jet) < 20 GeV/c is lower than that of charged-jets in $p_T > 50$ GeV/c
- D^0-tagged jet R_{AA} is compatible with D-meson R_{AA} -> jet R_{AA} dominated by leading particle energy loss?

Collectivity in small system



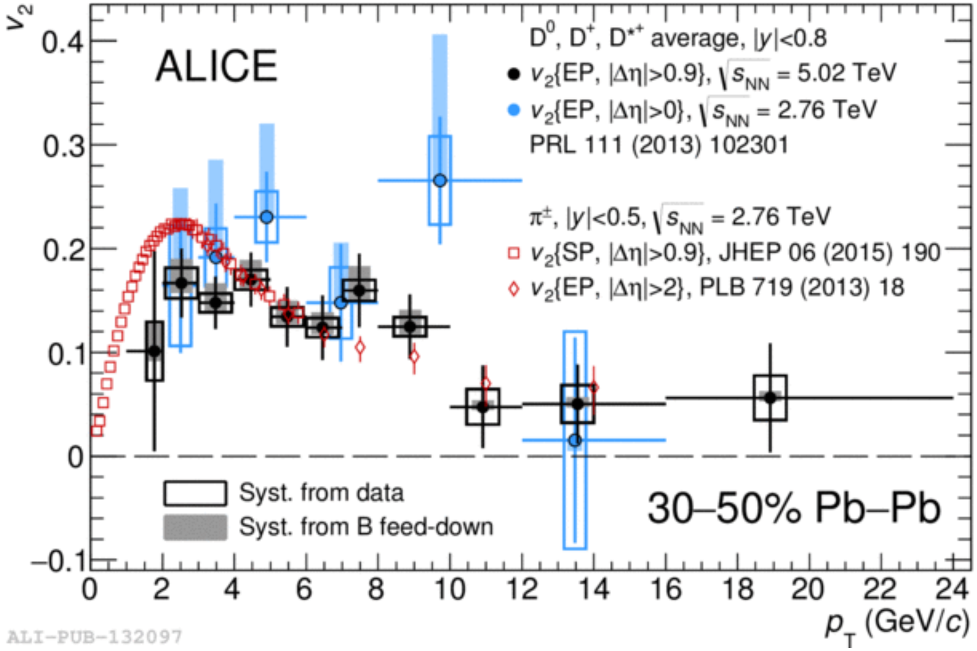
Phys. Rev. Lett. 122, 072301



PLB 780(2018)7-20

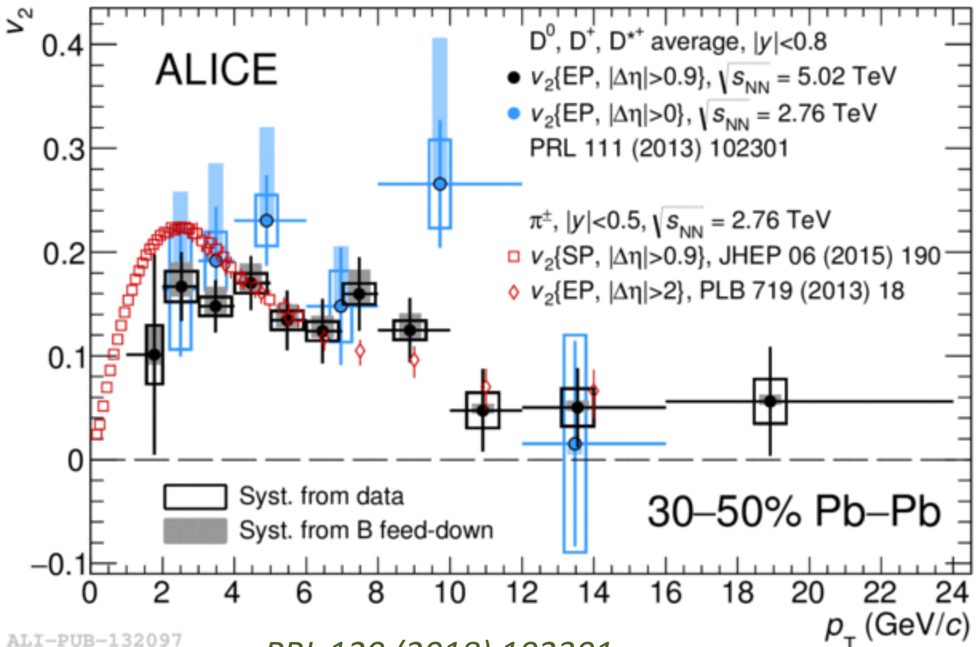
- HFE v_2 and μ-v_2 are compatible with each other within the uncertainties
- HF-leptons v_2 are lower than the charged particles v_2 → Initial-state, final state effects, collective effect -> need model predictions!
- J/ψ v_2 in p-Pb collisions is compatible with same in Pb-Pb collisions
- Model comparison suggests charm quark participation to the collective expansion
- Same mechanism in p-Pb and Pb-Pb?

v_2 of D mesons in Pb-Pb collisions

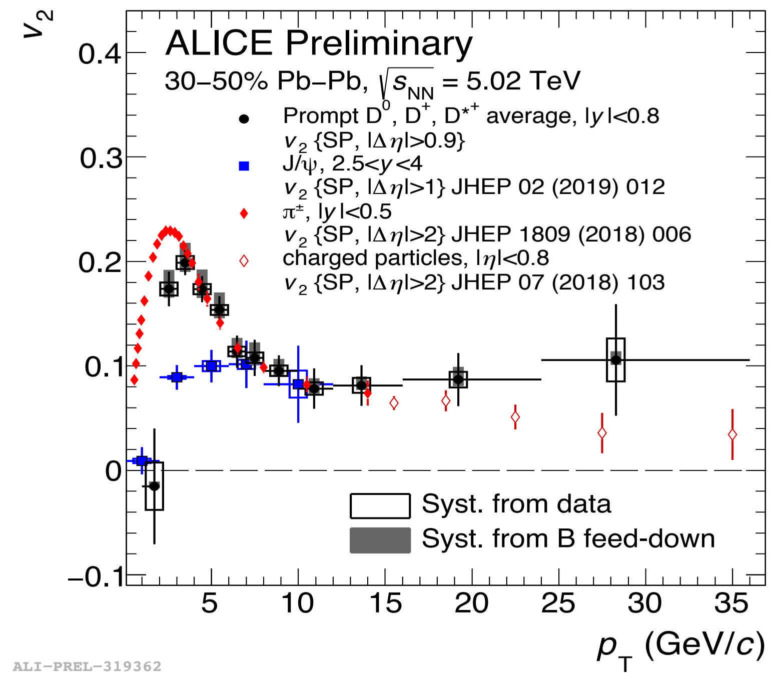


- Significantly large D-meson average v_2 → charm quarks are sensitive to medium collective motion->charm thermalization?

v_2 of D mesons in Pb-Pb collisions

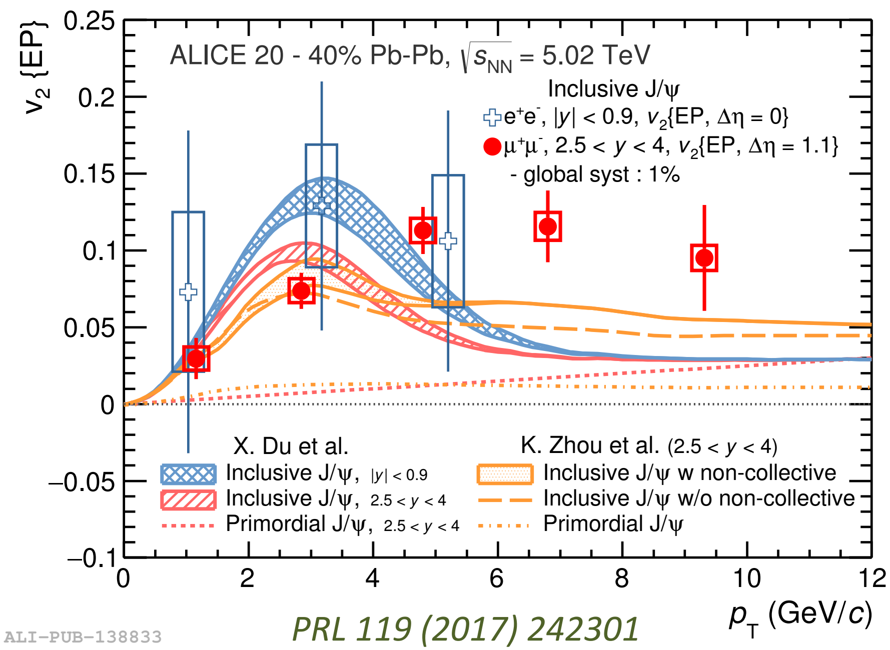


PRL 120 (2018) 102301

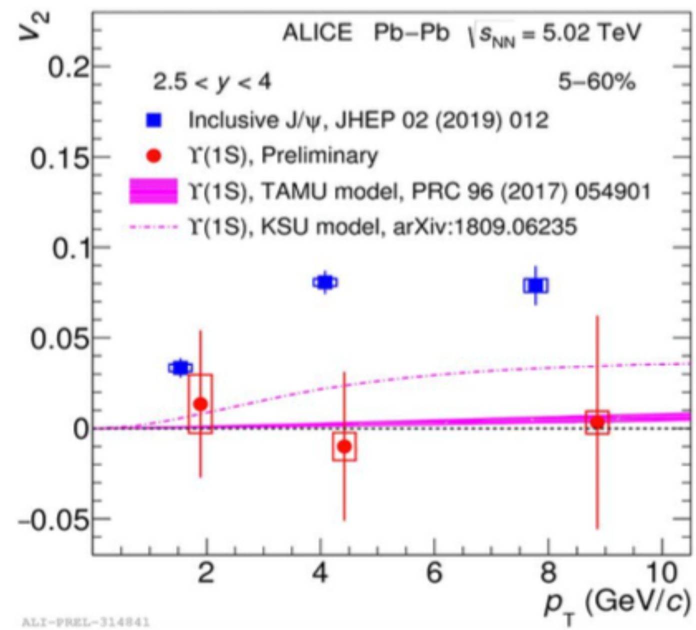


- Significantly large D-meson average v_2 → charm quarks are sensitive to medium collective motion->charm thermalization?
- Ordering at low and intermediate p_T → $v_2(J/\Psi) < v_2(D) < v_2(\pi^{\pm})$
  Light quarks contribute to the open charm v_2?
- Elliptic flow for different particles converges at high-p_T
  Path length dependent energy loss

Anisotropic flow of J/ψ and ϒ(1S)

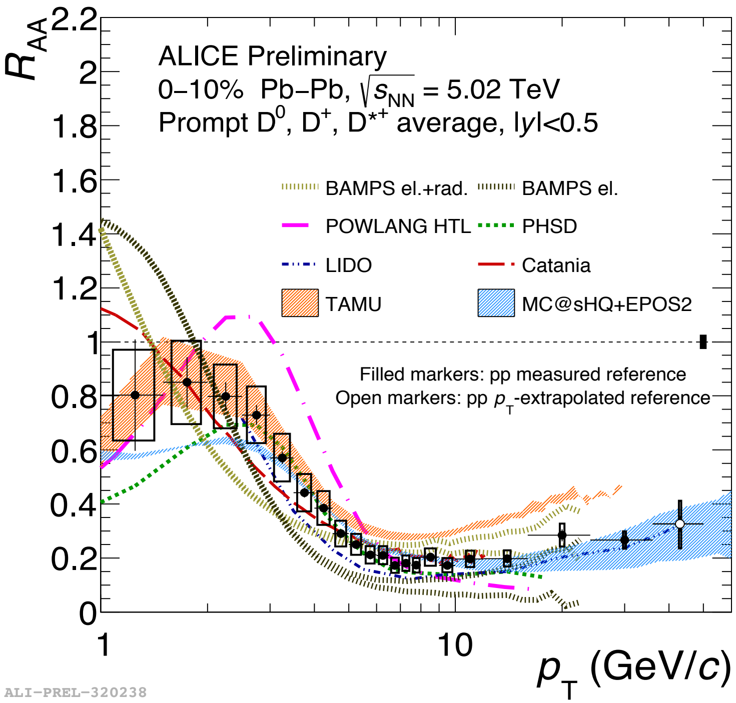


PRL 119 (2017) 242301

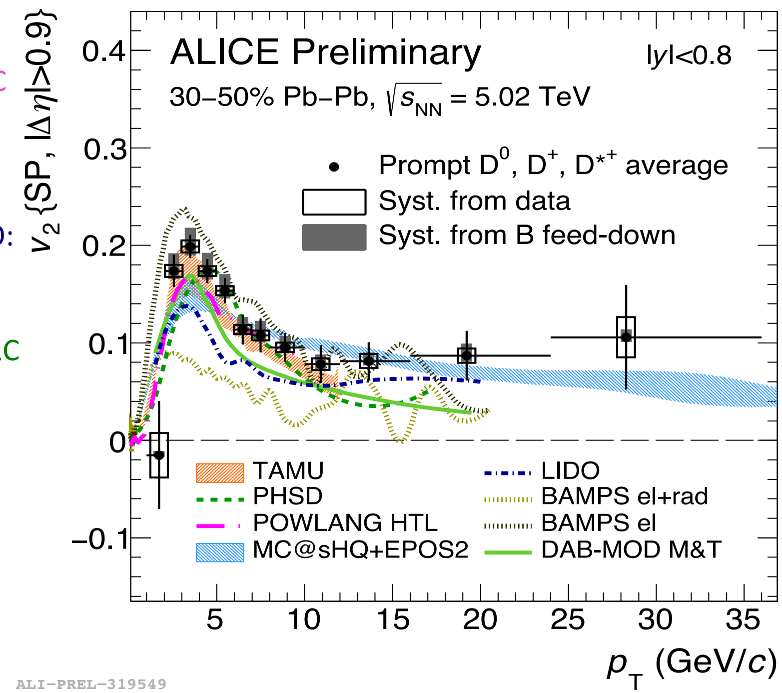


- Substantial amount of J/ψ v_2
- v_2 measured at forward rapidity consistent with v_2 measured a mid rapidity within uncertainties
- Consistent with strong charmonium recombination
- ϒ(1S) v_2 is comparable to zero → early production decoupled from medium
- Data are compatible with the existing models

Simultaneous description of R_{AA} and v_2

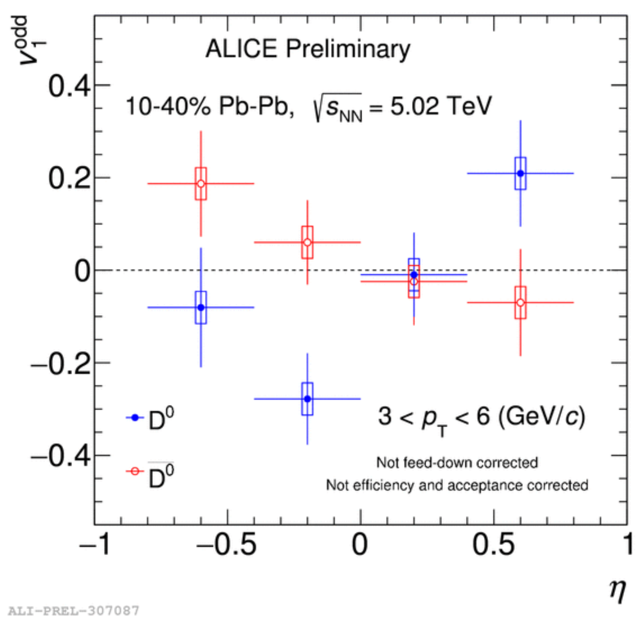


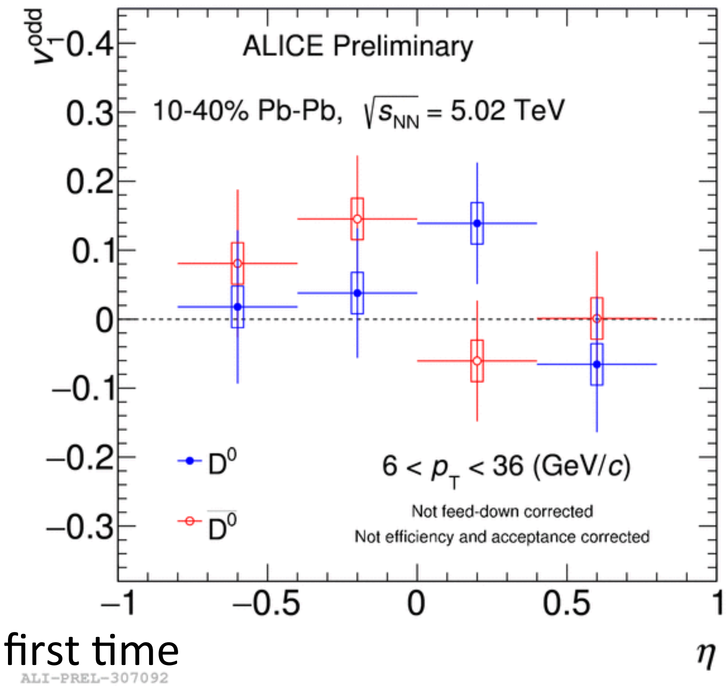
TAMU: PLB 735 (2014) 445 POWLANG: EPJC 75 (2015) 121 PHSD: PRC 92 (2015) 014910 MC@sHQ+EPOS: PRC 89 (2014) 014905 LIDO: PRC 98 (2018) 064901 BAMPS: JPG 42 (2015) 115106 DAB-MOD: PRC 96 (2017) 064903 CATANIA: Eur. Phys. J. C78 no. 4, (2018) 348



- Precise measurement of data constrains the model predictions
- Simultaneous description of R_{AA} and v_2 for D mesons
- Interplay of nuclear shadowing, collisional and radiative energy loss, coalescence, flows required to describe the data

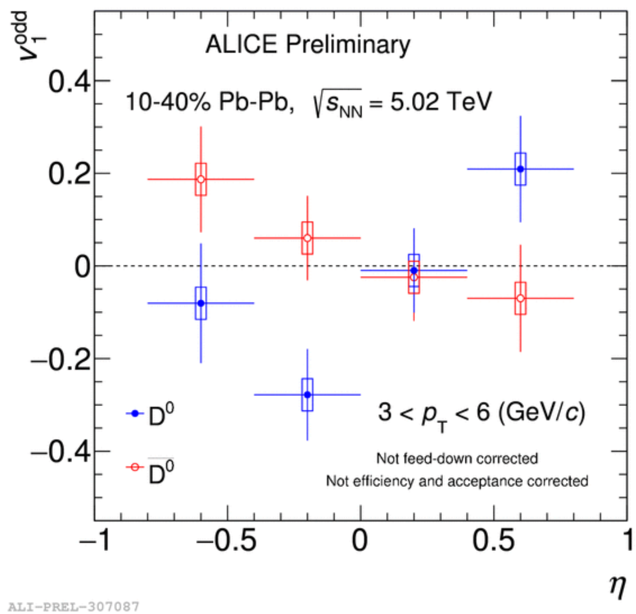
Directed flow (v_1) of D meson

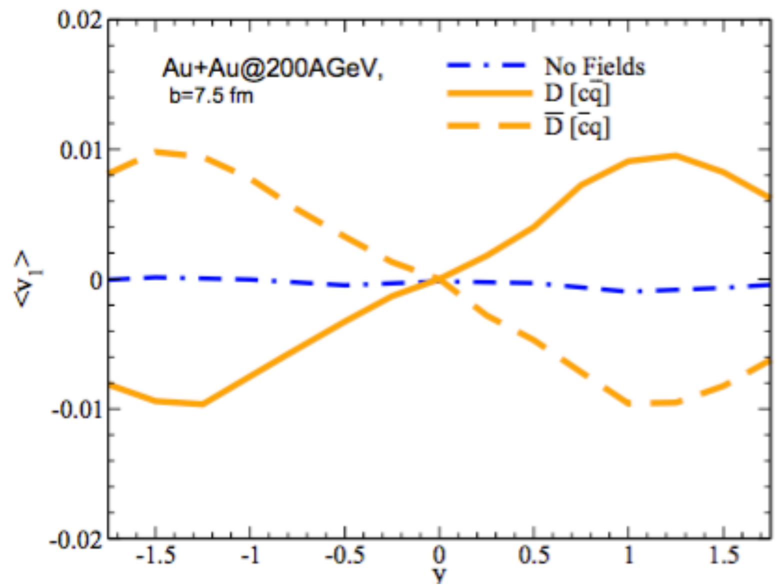




- ALICE has measure directed flow of D^0-meson for first time
- Results are not feed down corrected or efficiency corrected
- Indication of opposite trend of directed flow of D^0 and D^0 mesons at low-p_T ($3 < p_T < 6$ GeV/c)
- Similar trend for both particle and anti-partile at high-p_T ($6 < p_T < 36$ GeV/c)

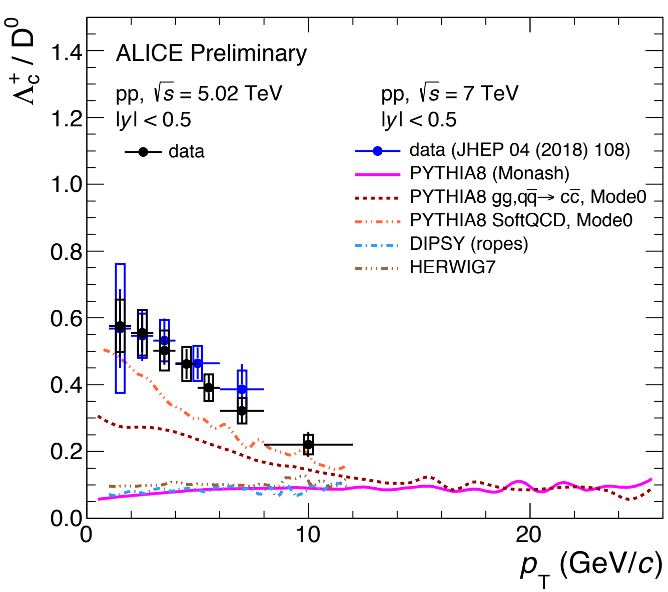
Directed flow (v_1) of D meson

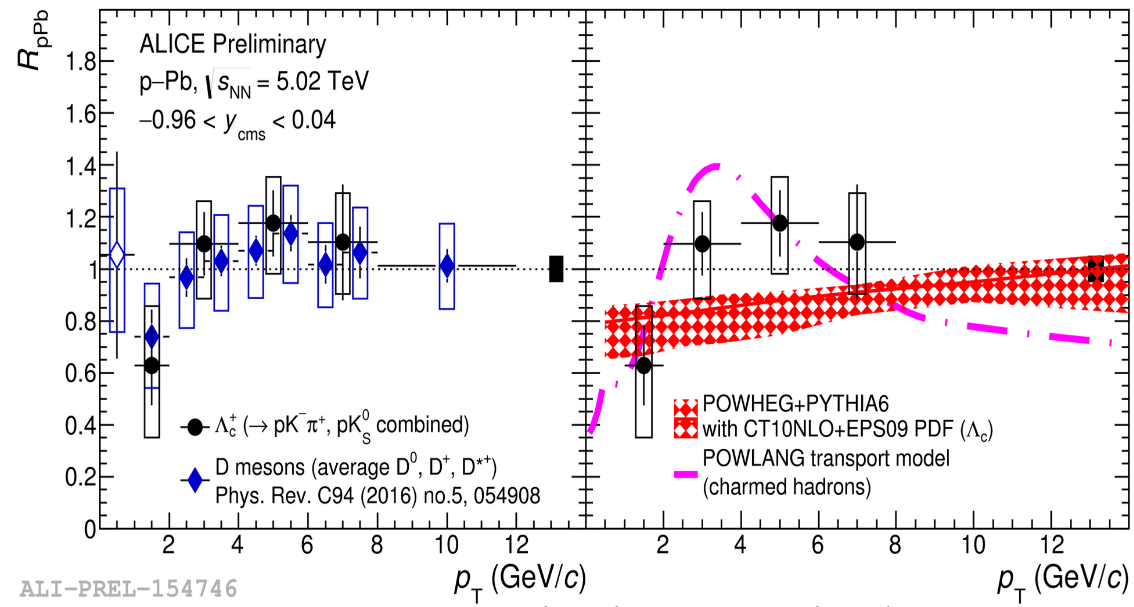




- ALICE has measure directed flow of D^0-meson for first time
- Results are not feed down corrected or efficiency corrected
- Indication of opposite trend of directed flow of D^0 and D^0 mesons at low-pT (3 < pT < 6 GeV/c)
- Similar trend for both particle and anti-partile at high-pT (6 < pT < 36 GeV/c)
- Indication of initial Electromagnetic effects *(EPJ Web of Conferences **171**, 18014 (2018), PLB 768 (2017) 260)*

Charm baryon (Λ_c^+) production



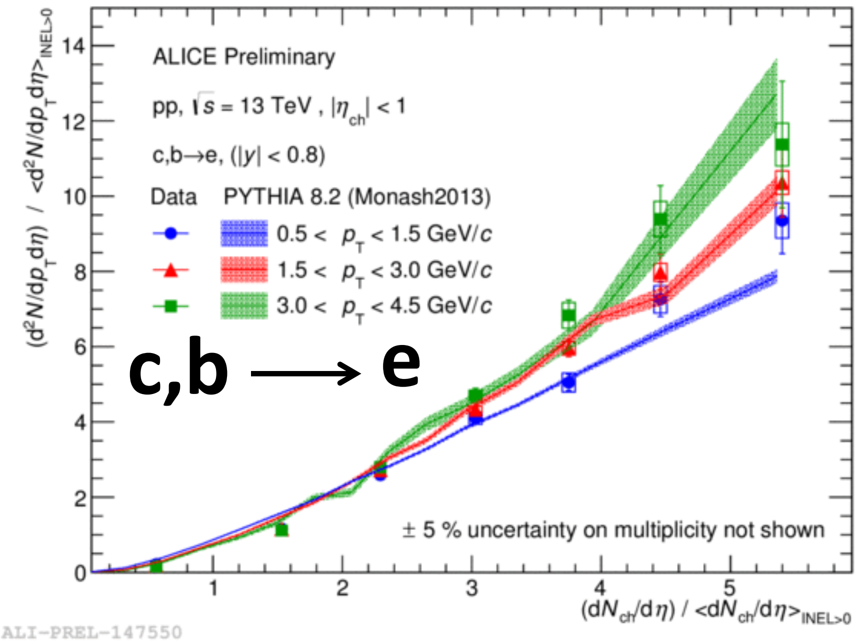


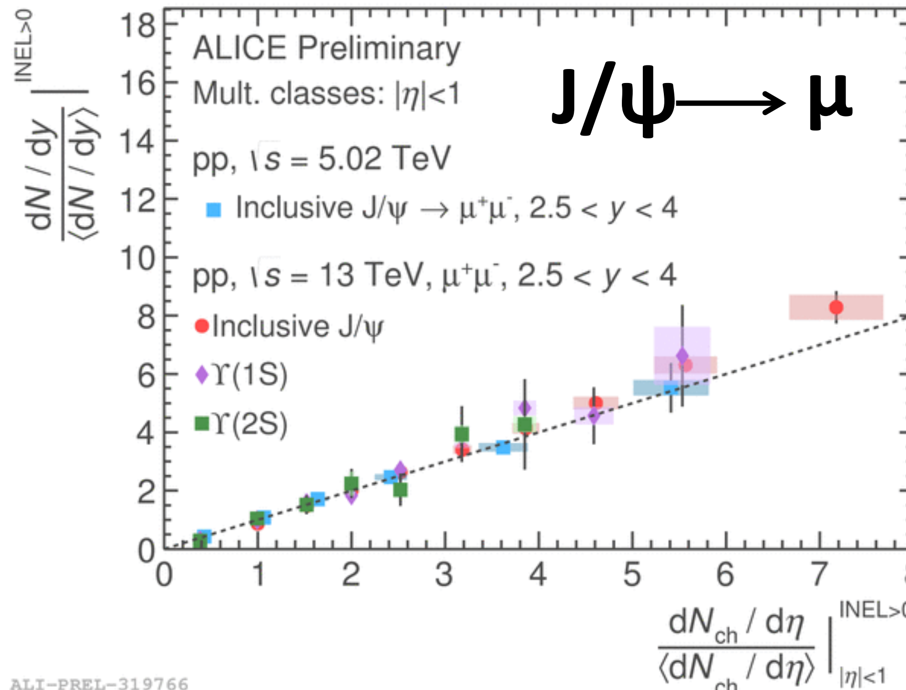
JHEP 09 (2007) 126, Phys. Rev. D82 (2010) 074024,

JHEP 04 (2009) 065, JHEP 03 (2016) 123

- Λ_c^+/D^0 production is compatible in both pp and p-Pb collisions
- Existing models with e+e- fragmentation functions underestimate the results → charm hadronization not fully understood in small system
- R_{pPb} of Λ_c^+ is consistent with unity as well as with D mesons R_{pPb}
- R_{pPb} of Λ_c^+ seems more compatible with the model includes CNM effects rather than the model includes final state effect
- Large uncertainties in data point do not allow any conclusive statement

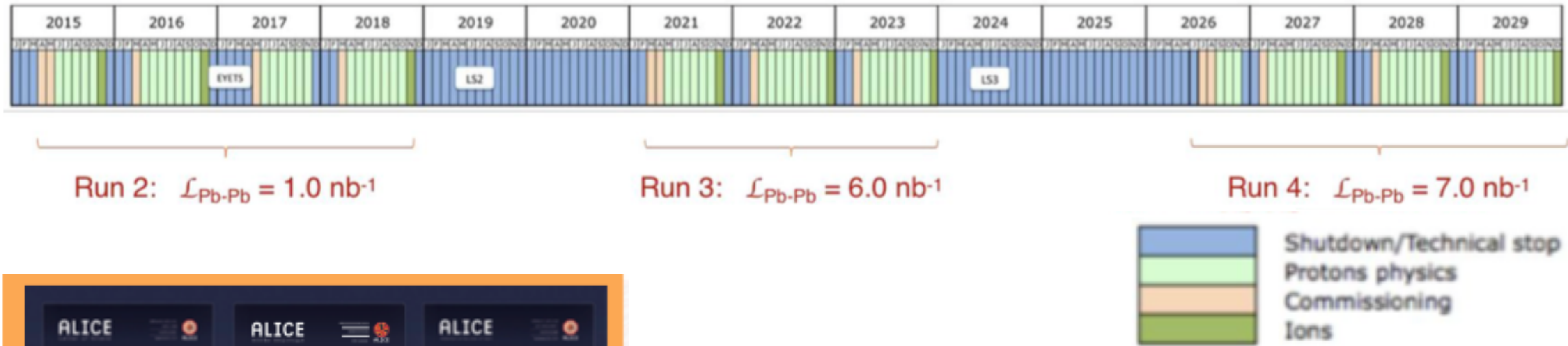
Results in pp collisions





- Charged particle multiplicity dependence of heavy-flavour production (self normalized yield) is sensitive to production mechanism, Multiparton interaction (MPI), interplay between soft and hard process
- Faster than the linear increase of heavy-flavour decay electrons → reproduced by the PYTHIA with MPI
- Linear increase with multiplicity for different quarkonium states and energy independent

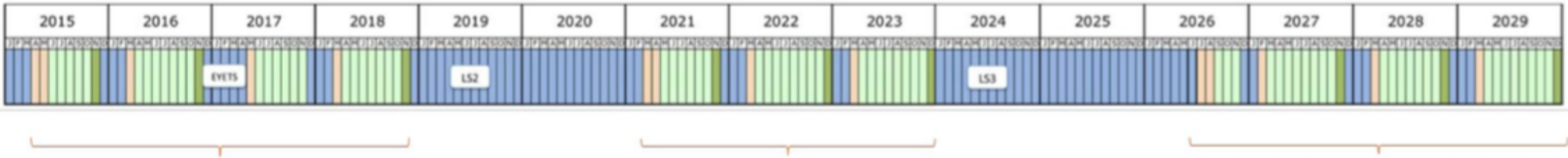
ALICE Upgrade



Main physics goals:

- study heavy quark interaction in QCD medium
- study charmonium regeneration in QGP
- chiral symmetry restoration and QGP radiation
- production of nuclei in QGP
- Probing the low-x by measuring photons at forward rapidity

ALICE Upgrade



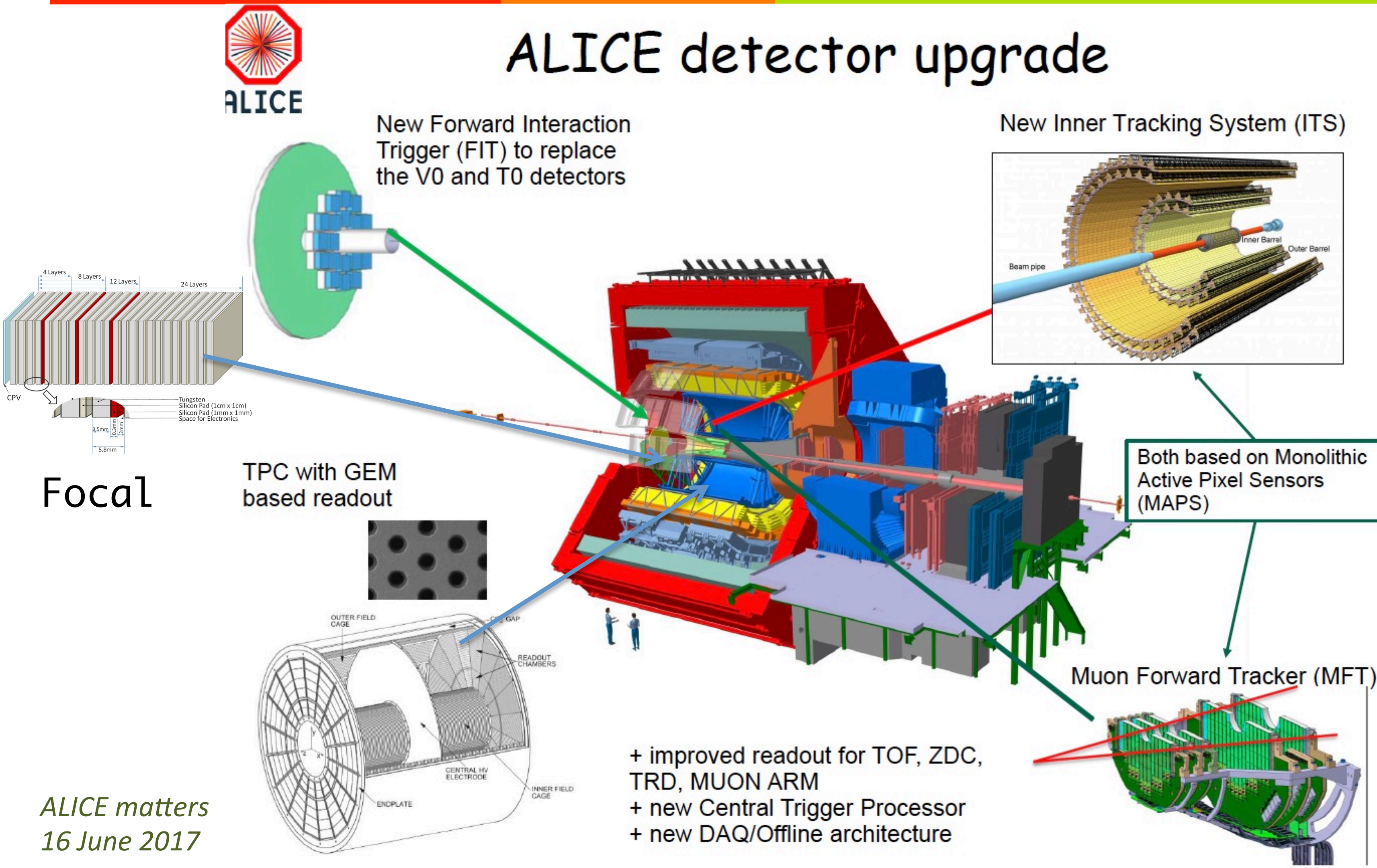
Run 2: $\mathcal{L}_{Pb\text{-}Pb} = 1.0\ nb^{-1}$

Run 3: $\mathcal{L}_{Pb\text{-}Pb} = 6.0\ nb^{-1}$

Run 4: $\mathcal{L}_{Pb\text{-}Pb} = 7.0\ nb^{-1}$

- Upto 50 kHz Pb-Pb interaction rate
- Expected Pb-Pb luminosity about 6 times higher than the Run2 Pb-Pb
- Improved tracking efficiency and resolution at low p_T
- Detector upgrades: ITS, TPC, MFT, FIT and FoCal
- Faster, continuous readout

ALICE Upgrade



ALICE matters
16 June 2017

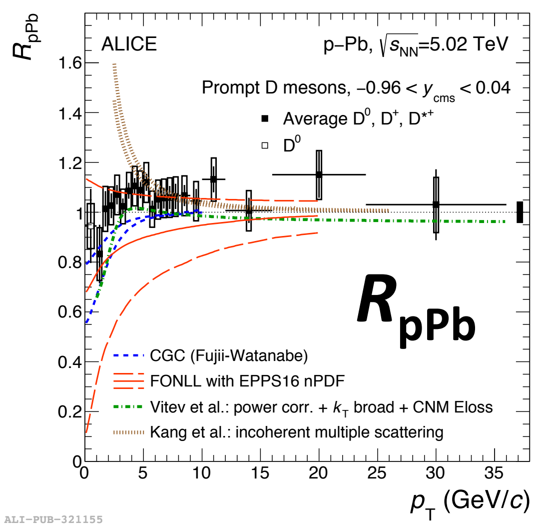
Summary

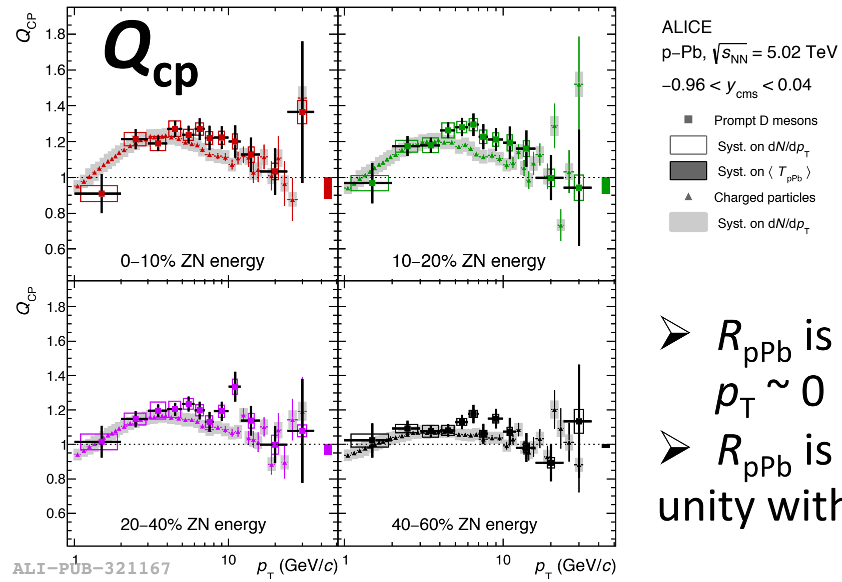
- We have created a deconfined state of matter called QGP.
- The effective temperature of the system is 304 ± 11^{stat} ± 40^{sys} MeV and the initial energy density is ~ 15 GeV/fm^3 (about 3 times larger than RHIC)
- This QGP is a fluid with very small viscosity
- LHC has also produced QGP like signatures in small systems
- Medium density of the QGP is so high that quarks loose their energy inside the medium
- This energy loss depends on masses of the quarks

- **Next Run will be performed in 2021 with 6 times higher luminosity and upgraded detectors which will lead to more precise measurement of heavy-flavour particles**

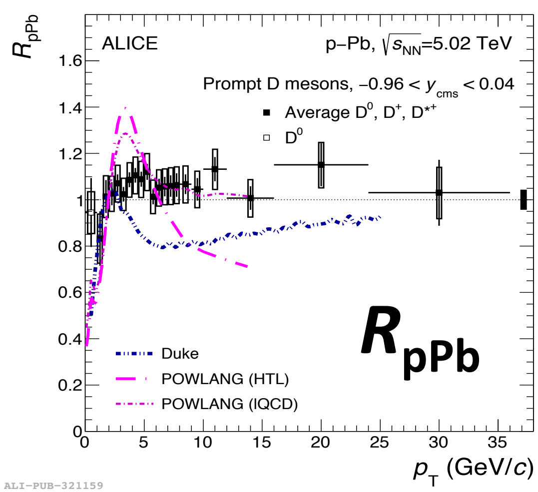
Back up

D-meson production in p-Pb collisions





- R_{pPb} is measured down to p_T ~ 0
- R_{pPb} is consistent with unity within the uncertainties



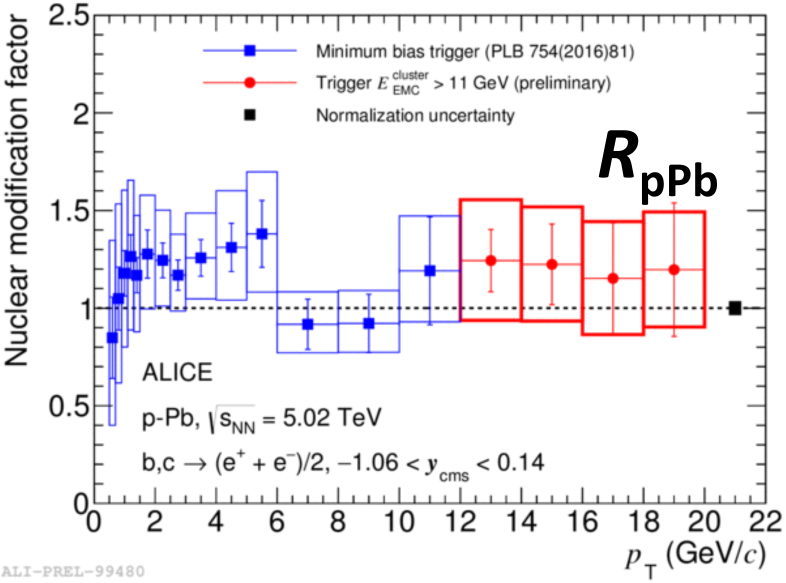
- Results are well described by the models include initial state effects (CGC, FONLL, Vitev)
- The models include final state effects can not explain the data well (Duke, POWLANG)
- Hint of $Q_{cp} > 1$ for central collisions in $3 < p_T < 8$ GeV/c with 1.5σ

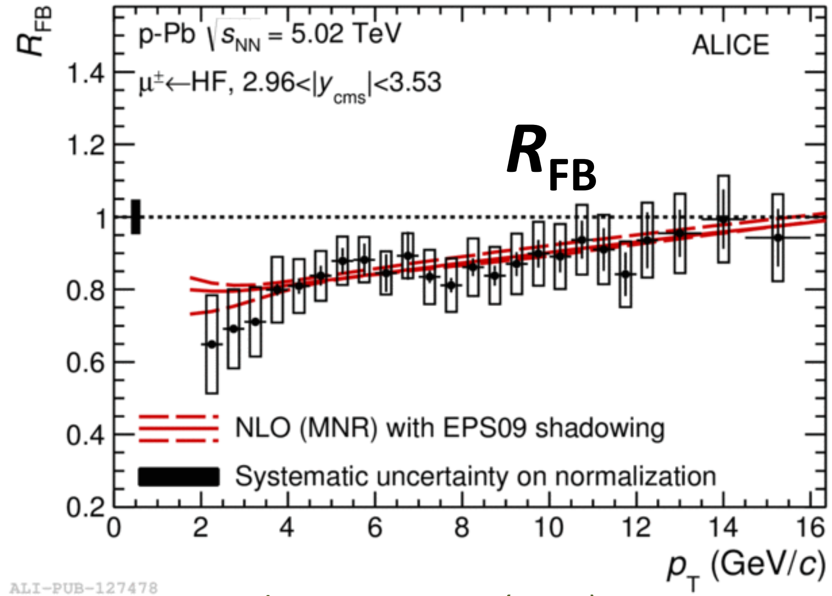
✓ Radial flow?

✓ Initial or final-state effect?

arXiv:1706.06728

Leptons from HF decays in p-Pb colllisions





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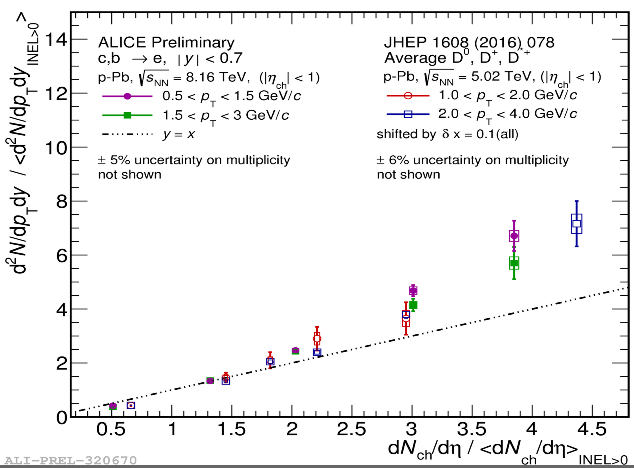

- ➢ Heavy-flavour hadrons decay electrons R_{pPb} is consistent with unity within the uncertainties
- ➢ Forward to backward ratio of heavy-flavour hadrons decay muons shows a tendency to below 1 → nature is reproduced by NLO pQCD calculation with shadowing
- ➢ Faster than the liner increase is observed for HF→e as well as D mesons