Workshop on the Standard Model and Beyond

August 31 - September 9

Characterising the quark-gluon plasma with the ALICE experiment at the LHC

Tapan Nayak (ALICE Collaboration)

1 September 2018

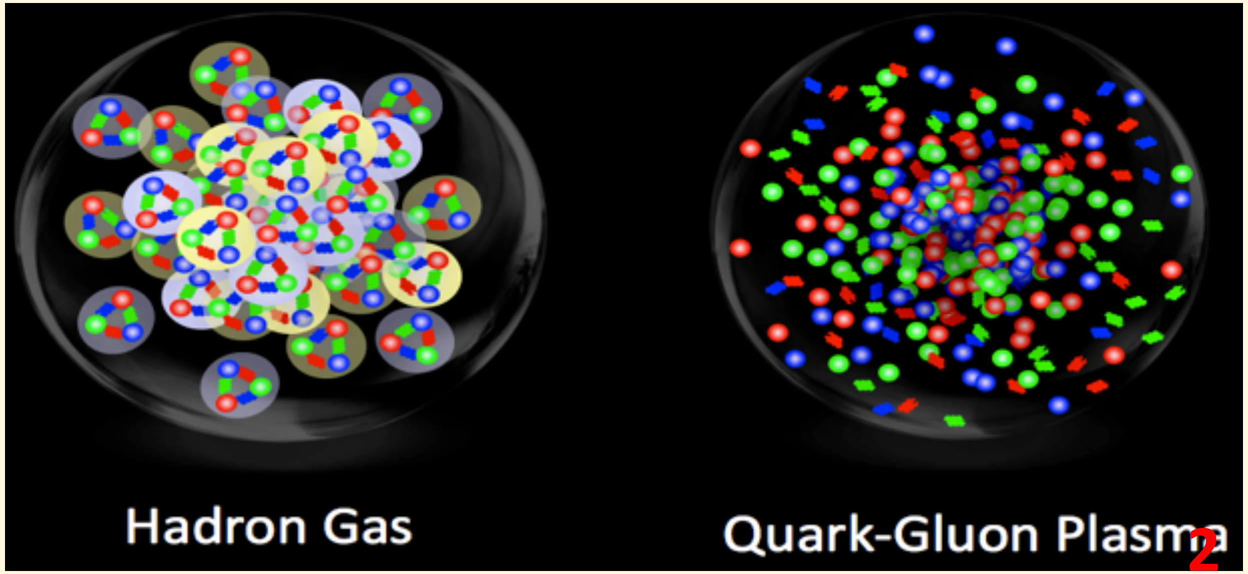
Quark Gluon Plasma

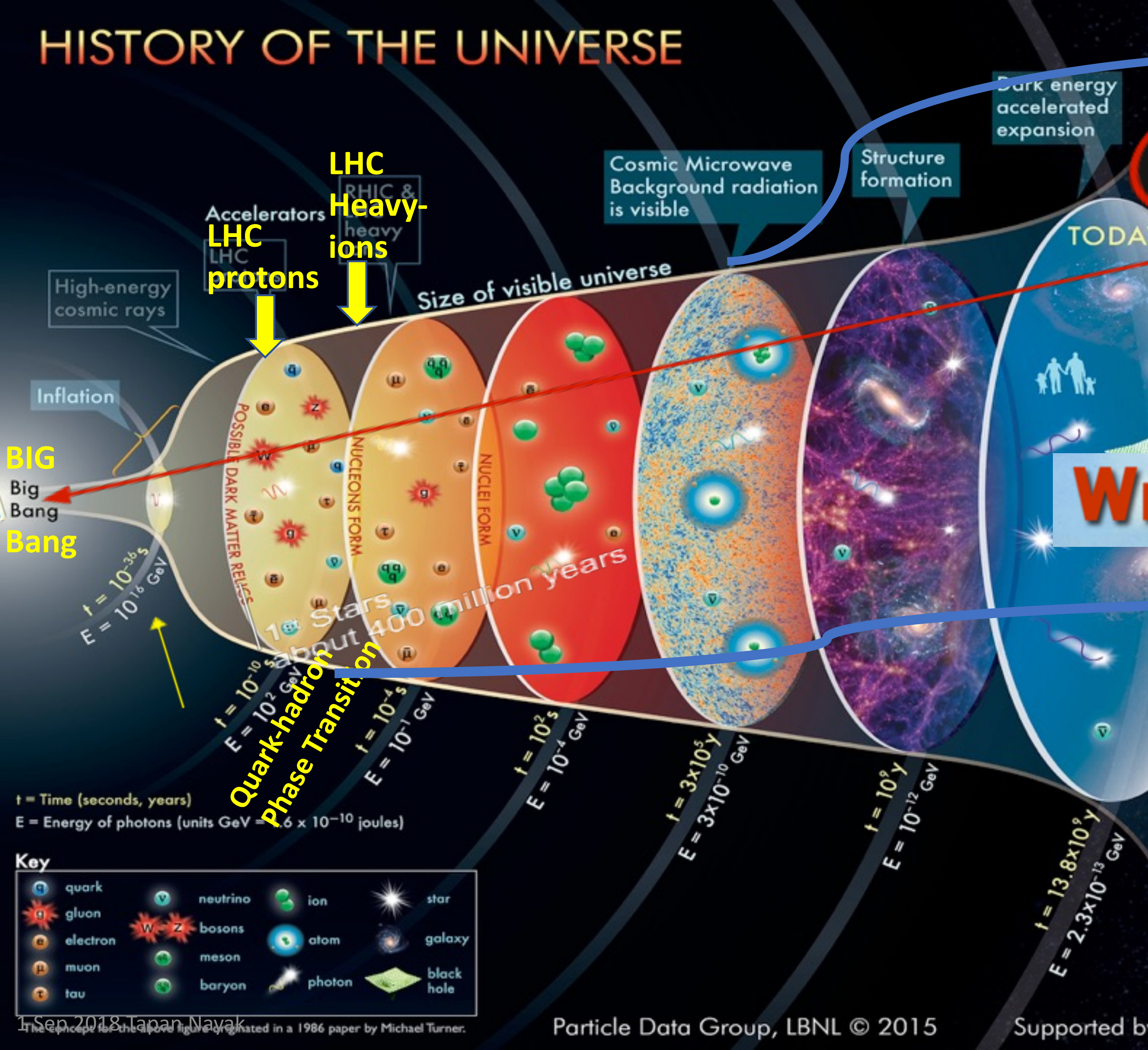
Hadrons are composite objects made of quarks and gluons. q-q interactions become weaker as the inter-quark distance becomes shorter (asymptotic freedom). The system behaves like free quarks and gluons.

QCD is a "confining" gauge theory, with an effective potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

Quark Gluon Plasma (QGP): (locally) thermally equilibrated state of matter in which quarks and gluons are deconfined from hadrons, so that color degrees of freedom become manifest over nuclear, rather than merely nucleonic, volumes.





Astrophysical Probes

Takes us back to 380,000 years after the Big Bang

Windows on the Universe

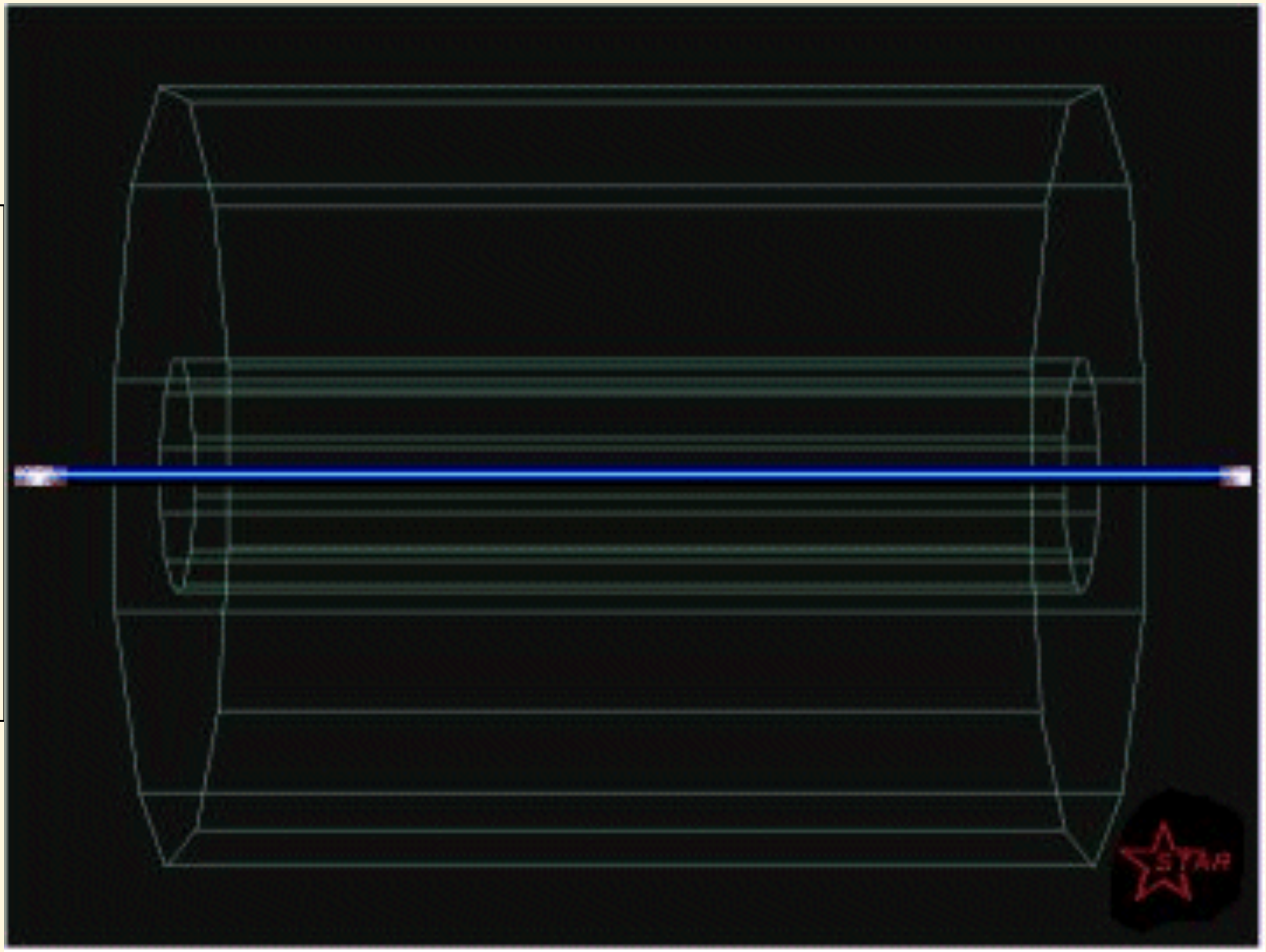
ALICE @ LHC

- Quark-hadron Phase Transition
- Quark Gluon Plasma

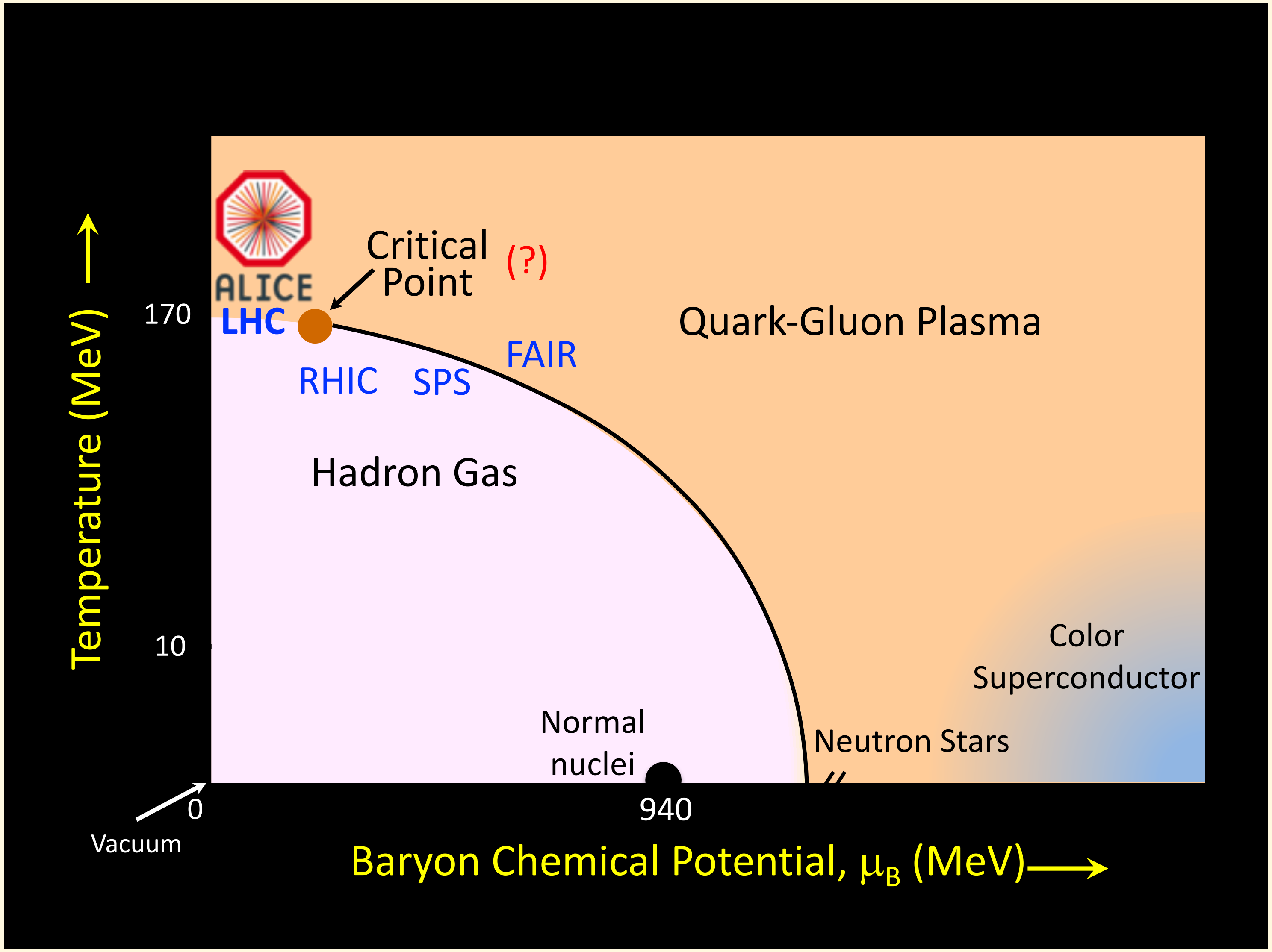
Takes us back to within few Microseconds of the Big Bang

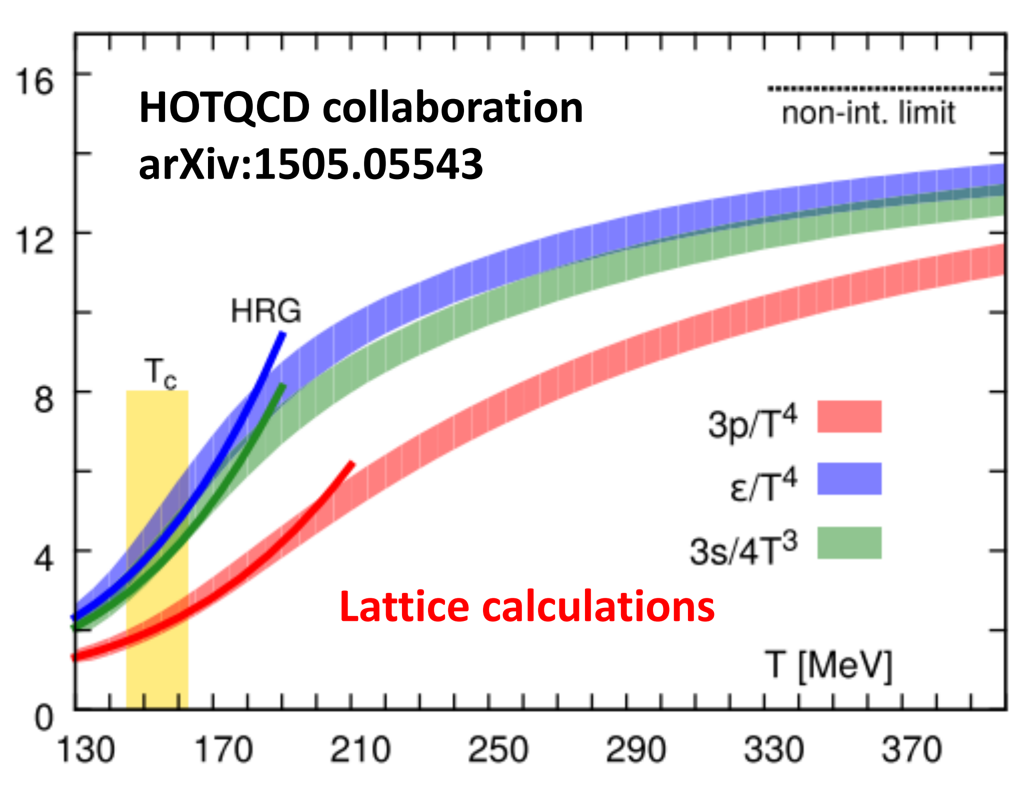
Heavy-ion collisions: Creating the QGP state

- Take a high-mass atom like Au or Pb
- Take away the electron => Ion (***Heavy-ion***)
- ***Accelerate the Ion*** to almost the speed of light
- ***Collide the Ions => Create the Little Bang***
- Study the aftermath by specialized detector systems which surround the collision point ***=> Experiment***



Phase Diagram





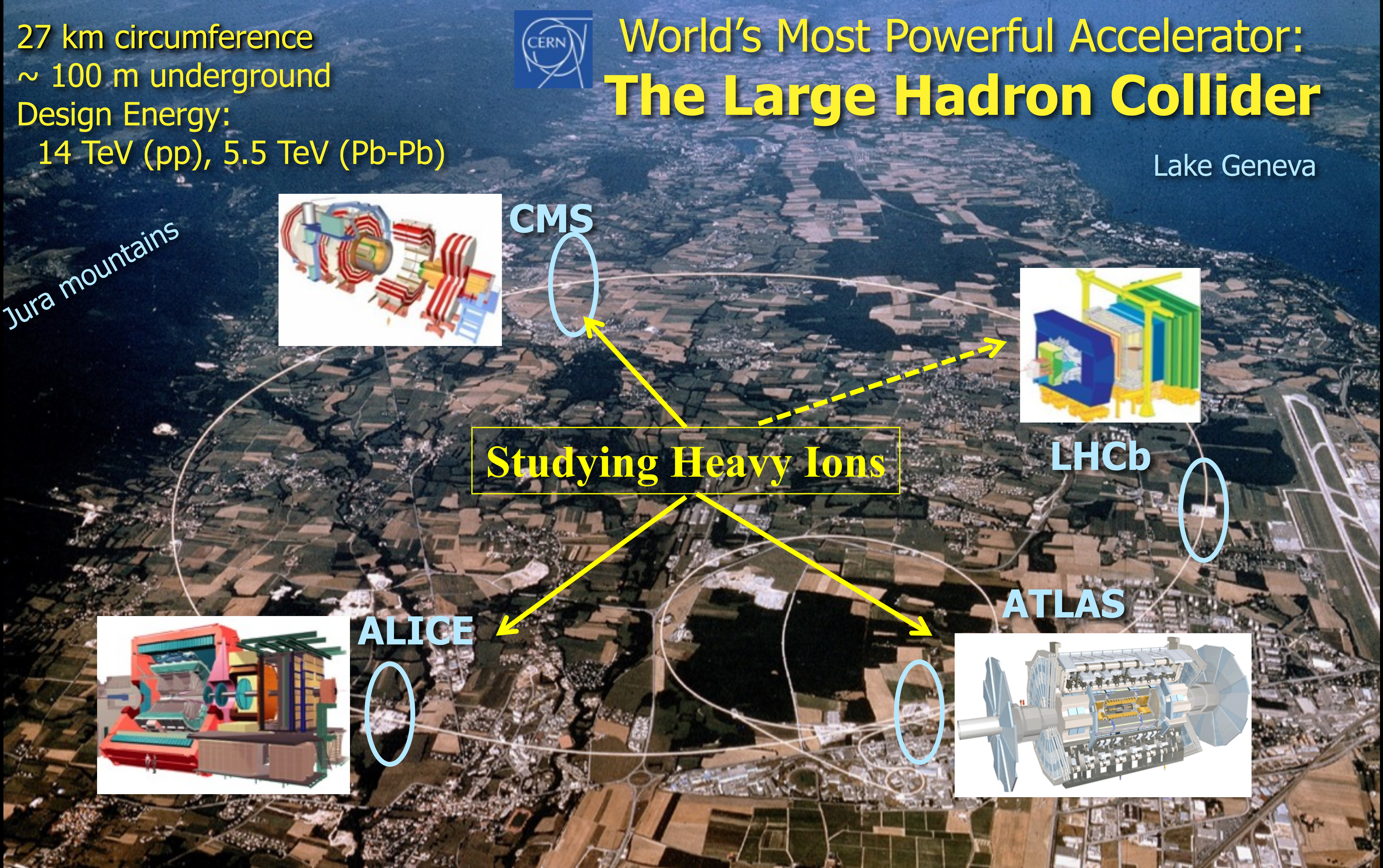
$T_C \approx 155$ MeV and $\varepsilon_C \approx 0.5$ GeV/fm^3

$$\varepsilon = g \frac{\pi^2}{30} T^4$$

- **For hadronic matter, g=3**
- **For QGP: degrees of freedom increases by a factor of about 10**
  (8 gluons, 2 quark flavours, 2 antiquarks, 2 spins, 3 colors)

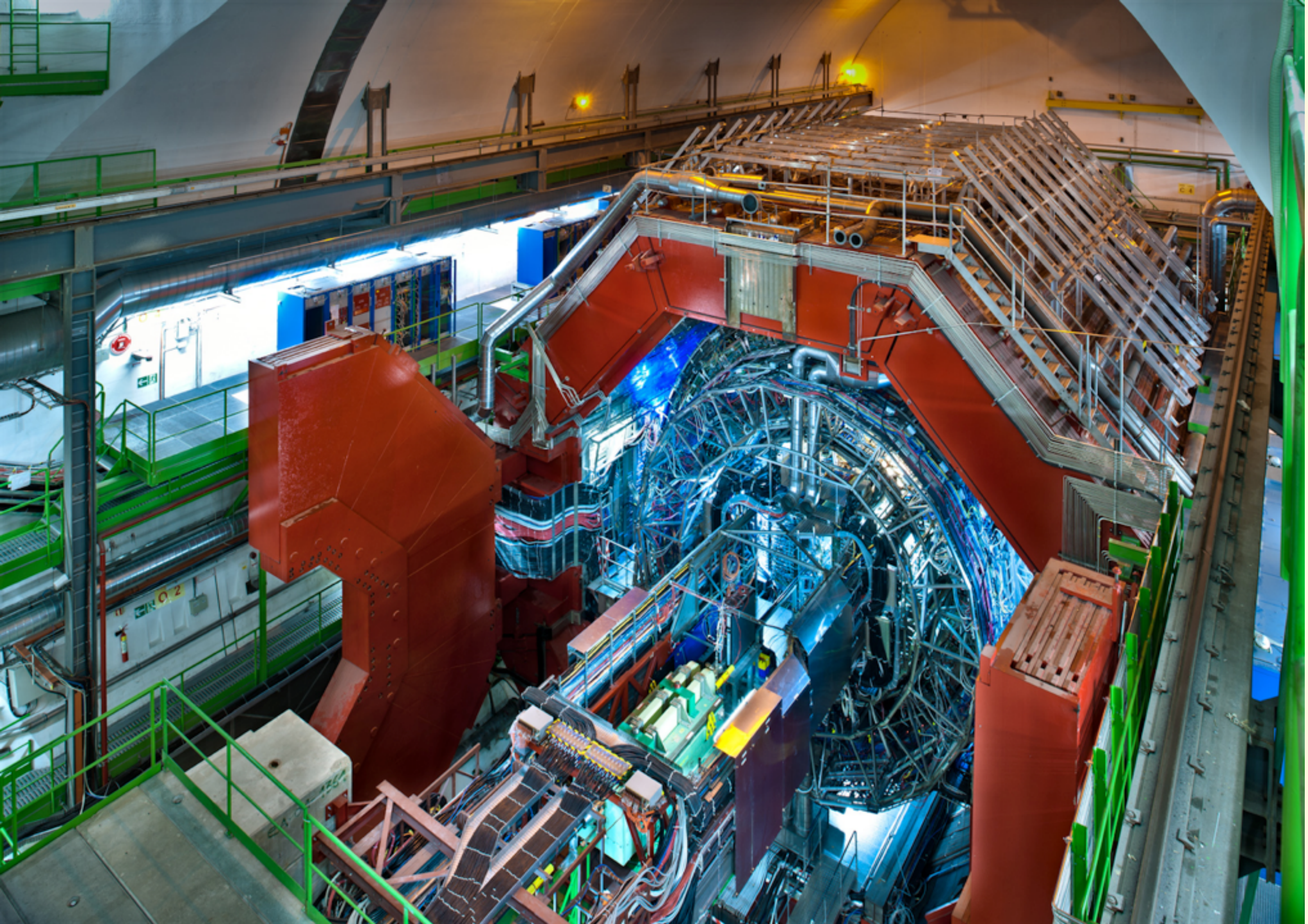
World's Most Powerful Accelerator:
The Large Hadron Collider

27 km circumference
~ 100 m underground
Design Energy:
14 TeV (pp), 5.5 TeV (Pb-Pb)



THE ALICE COLLABORATION

41 Countries – 177 Institutes – 1994 Scientists



ALICE at Point-2 of the LHC

- Excellent track and vertex reconstruction capabilities in high multiplicity environment over a wide p_T range
- Particle identification over a wide momentum range

The ALICE program

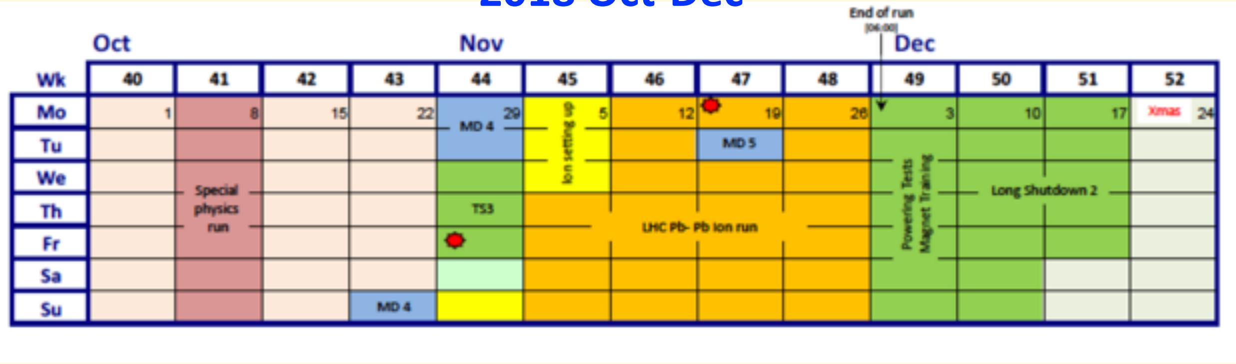
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010-2011	2.76	~75 μb^{-1}
	2015	5.02	~250 μb^{-1}
	by end of 2018	*5.02*	*~1 nb^{-1}*
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013	5.02	~15 nb^{-1}
	2016	5.02, 8.16	~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013	0.9, 2.76, 7, 8	~200 μb^{-1}, ~100 nb^{-1}, ~1.5 pb^{-1},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

Past and Present:

LHC Run-1: 2009 – 2013

LHC Run-2: 2015 – 2018 (Ongoing)

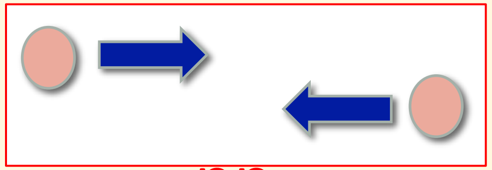
2018 Oct-Dec



Future: major upgrade

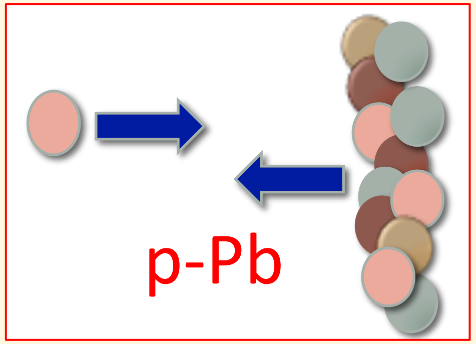
LHC Run-3: 2021 – 2023

LHC Run-4: 2016 – 2029

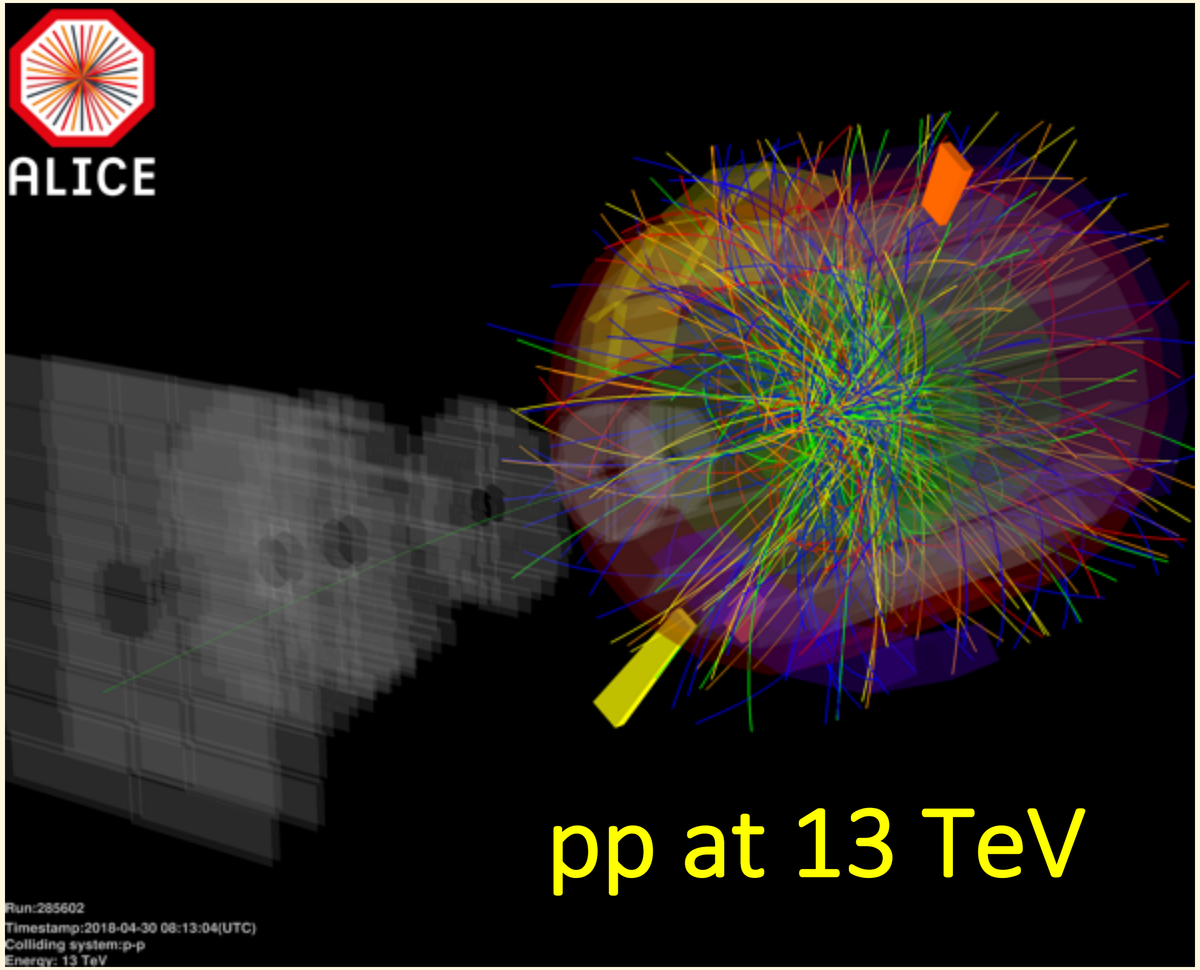


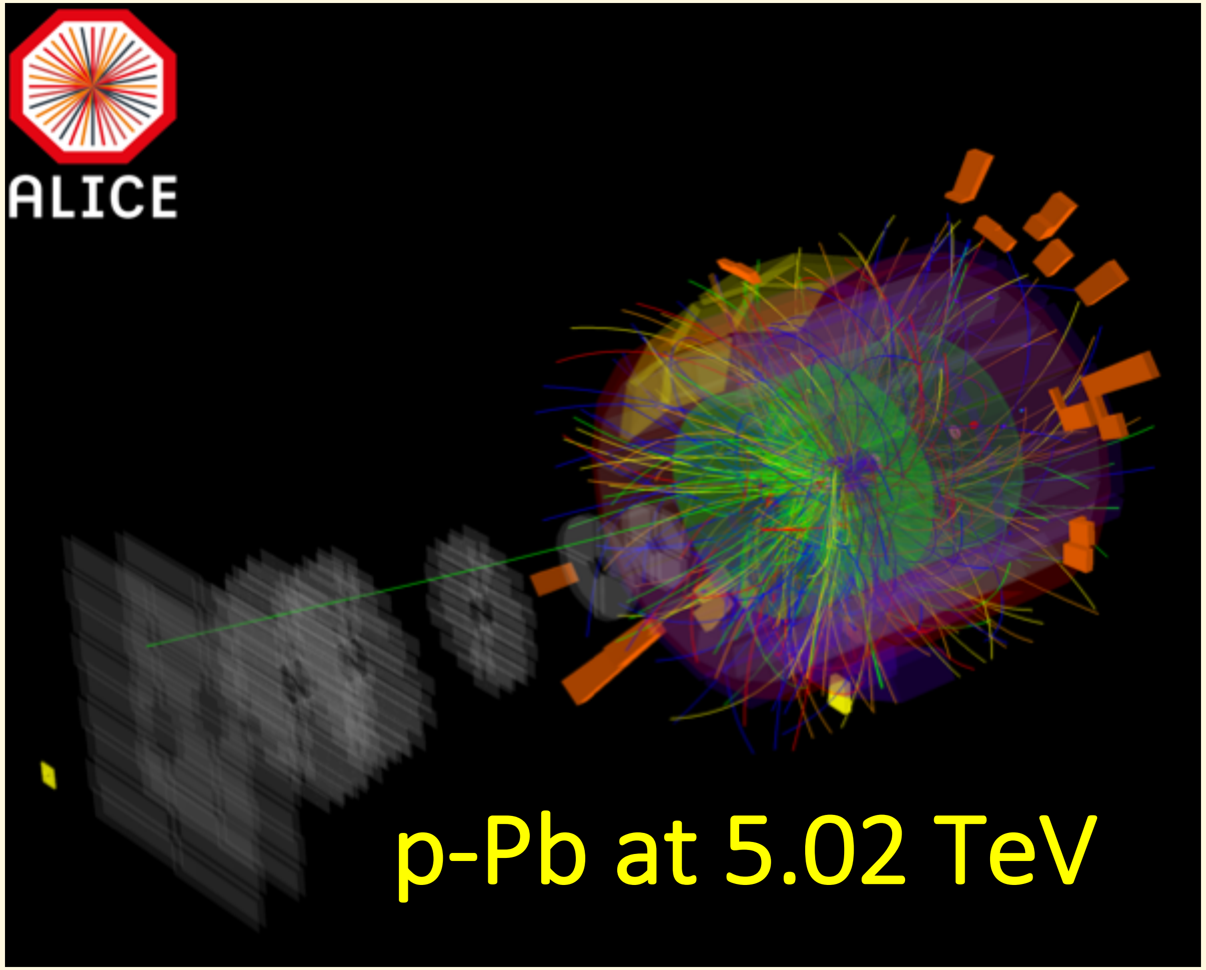
pp

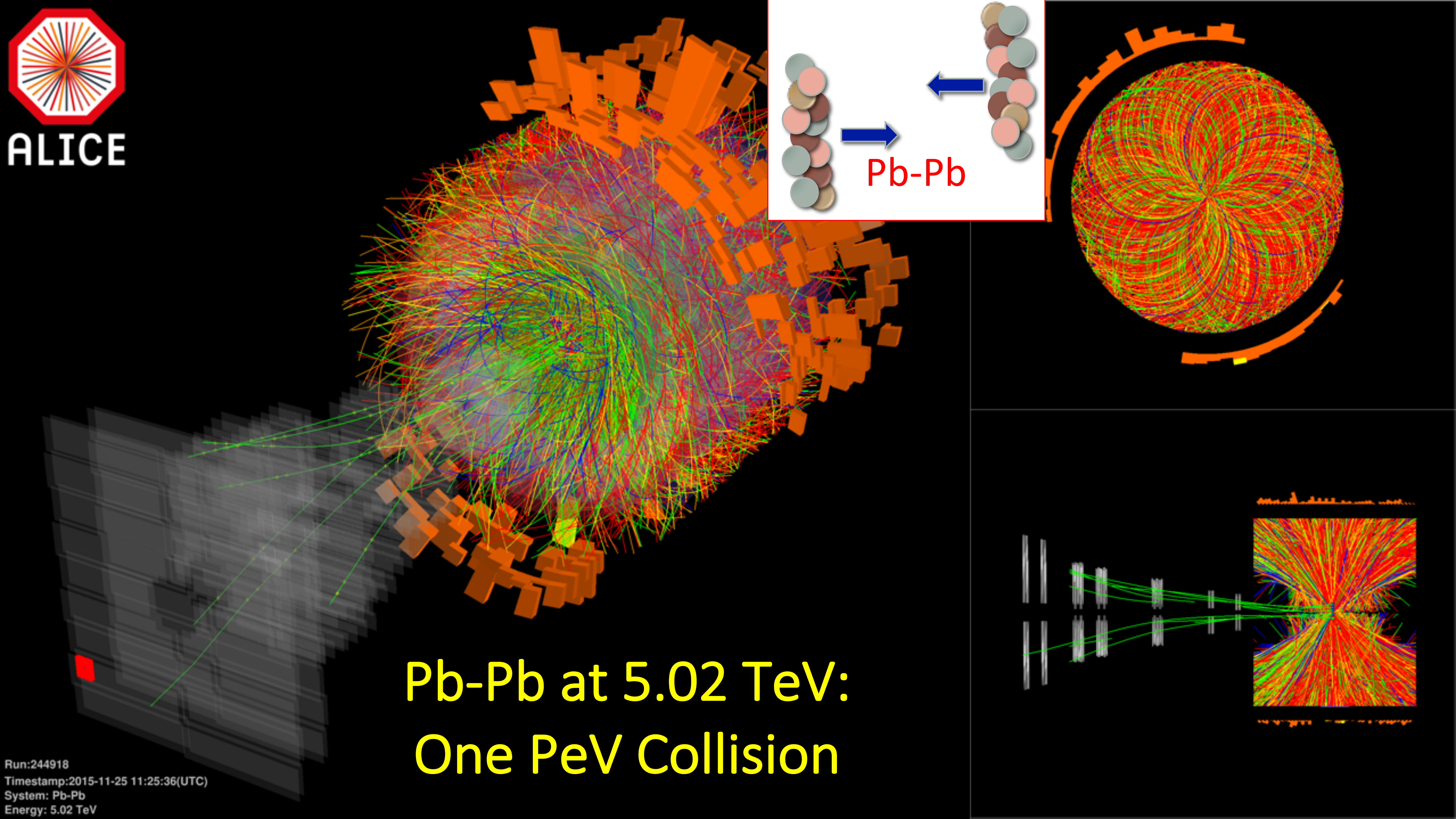
- Test of pQCD calculations from cross section measurements
- Provide reference for p-Pb and Pb-Pb collisions
- High multiplicity pp: what's the behaviour?



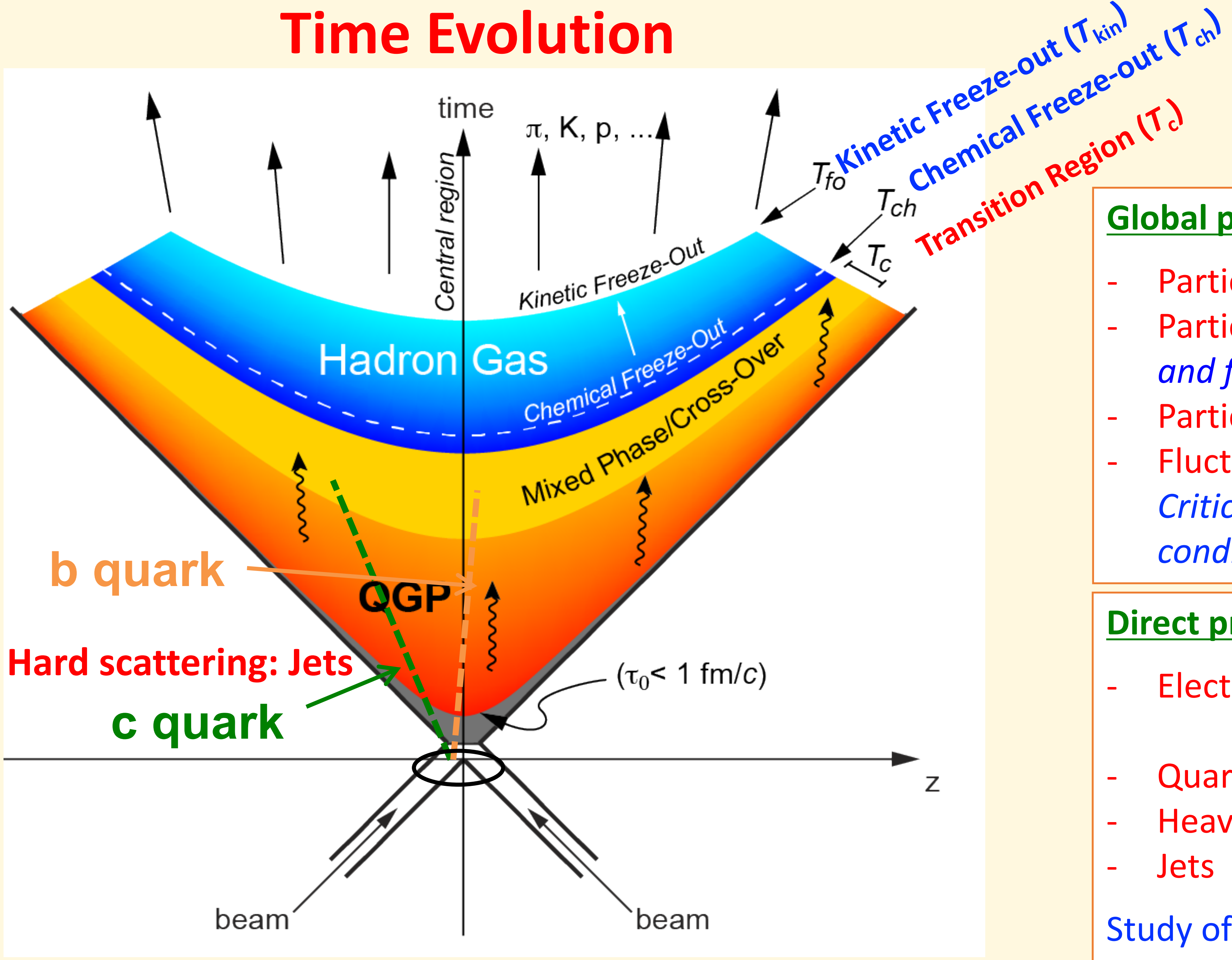
- Intermediary reference
- Address cold nuclear matter effects in initial and final states






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

Time Evolution



Global properties & freezeout conditions

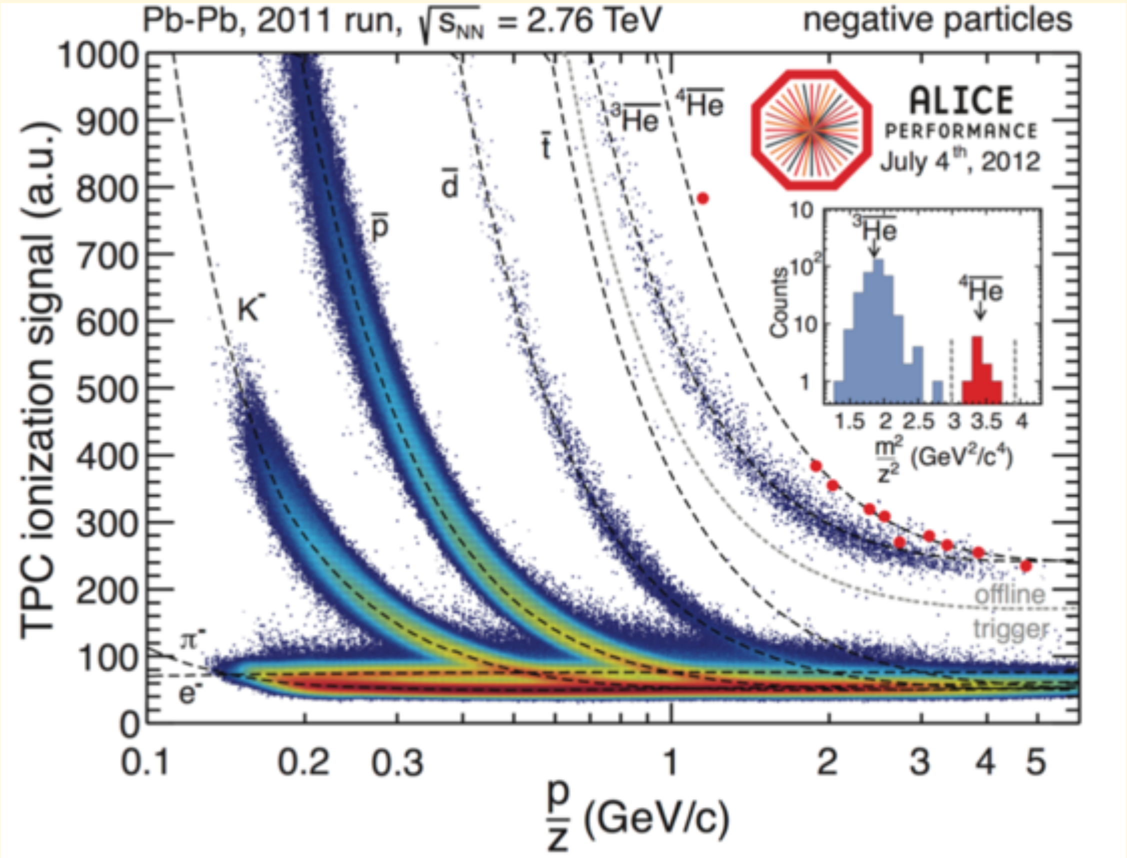
- Particle multiplicities: *energy densities*
- Particle spectra: *radial flow, expansion and freeze-out Temperatures*
- Particle flow: *Nature of matter*
- Fluctuations and correlations: *Access to Critical Phenomena, T_c and freeze-out conditions, shape and size of the system*

Direct probes of QGP

- Electromagnetic Probes: photons and dileptons
- Quarknonia
- Heavy Flavour
- Jets

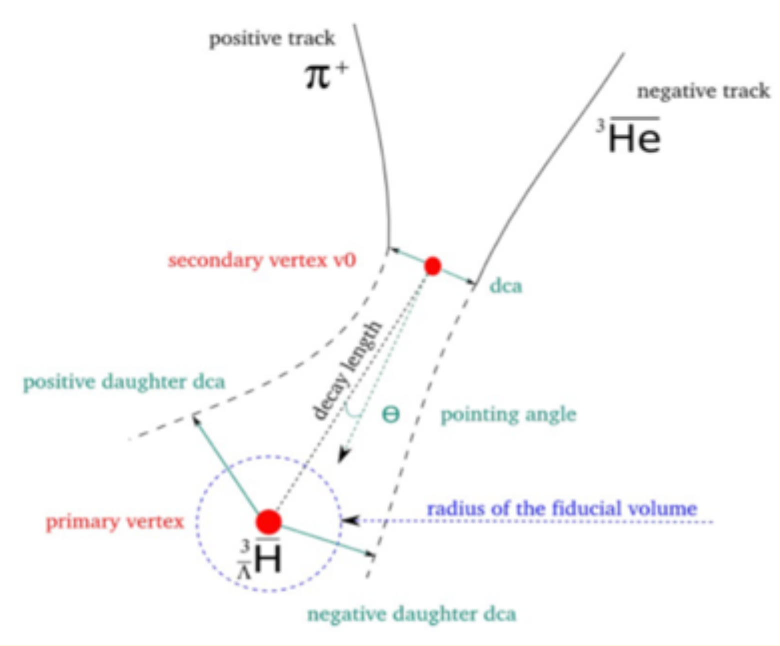
Study of energy loss and nuclear modification factors

Particle identification in ALICE



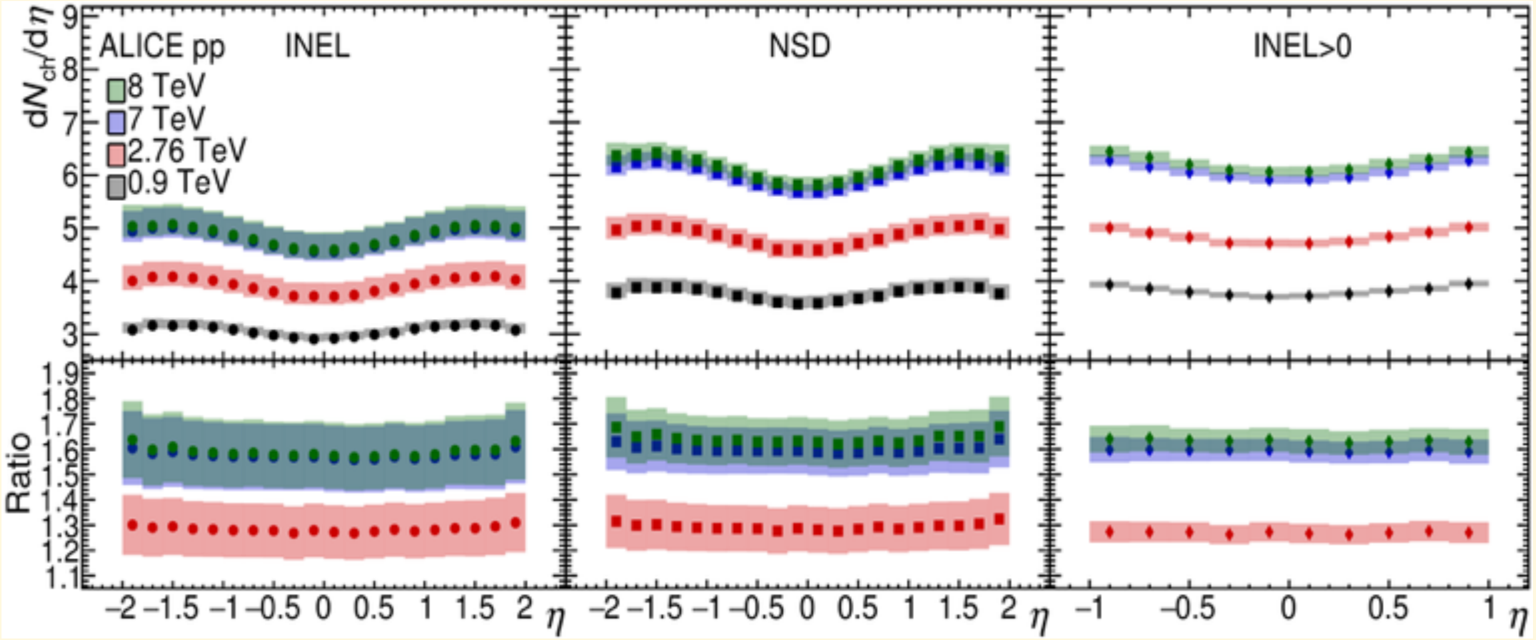
- Pions, kaons, protons and light nuclei identified using dE/dx measurement with the TPC
- Deuterons below $p_T \leq 1.4$ GeV/c, and ^{3}He between $1.5 < p_T < 7$ GeV/c are also identified with the TPC
- Deuterons above 1.4 GeV/c are identified using velocity measurement with the TOF and extracting the yield from the Δm^2 distribution:

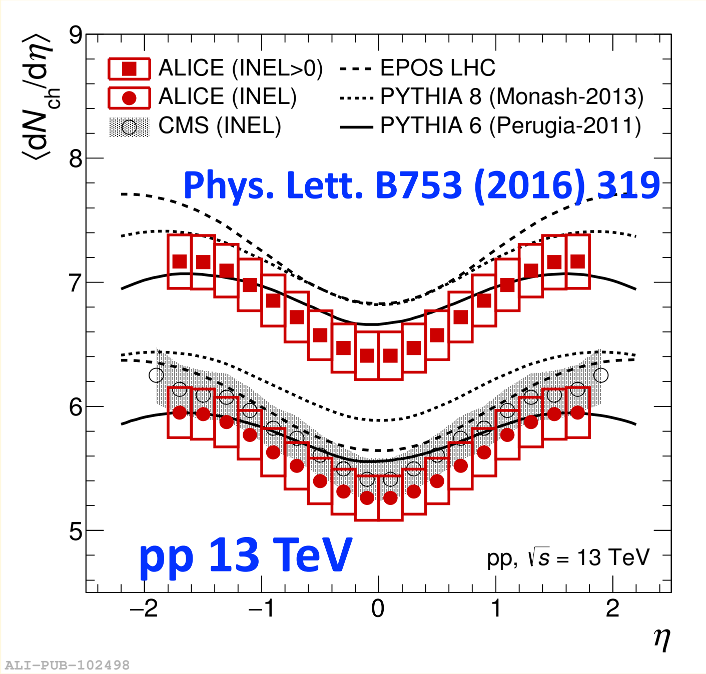
$$m_{TOF}^2 = \frac{p^2}{c^2}\left(\frac{c^2 t_{TOF}^2}{l_{track}^2} - 1\right)$$



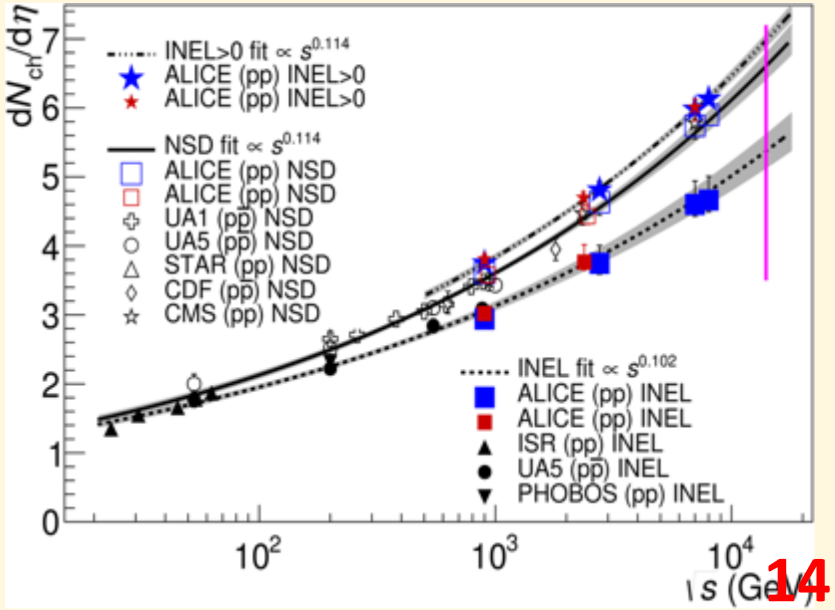
Charged particle multiplicity density (pp)

pp 0.9 TeV, 2.76 TeV, 7 TeV and 8 TeV





Eur. Phys. J. C (2017) 77

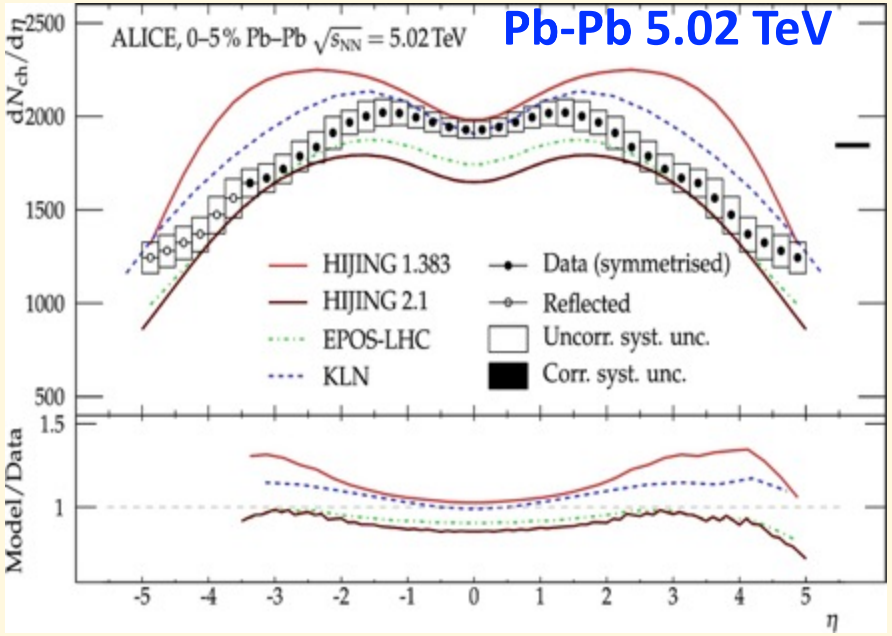


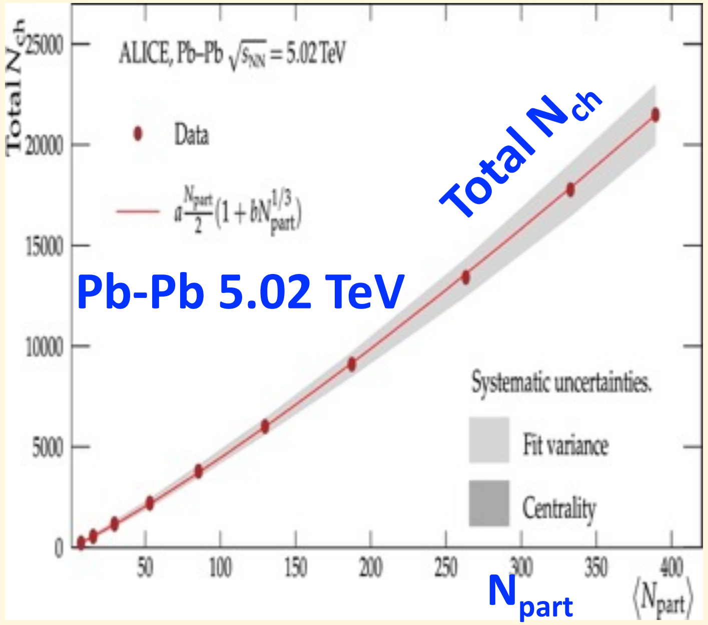
$dN_{ch}/d\eta$ measured for three normalisation classes:

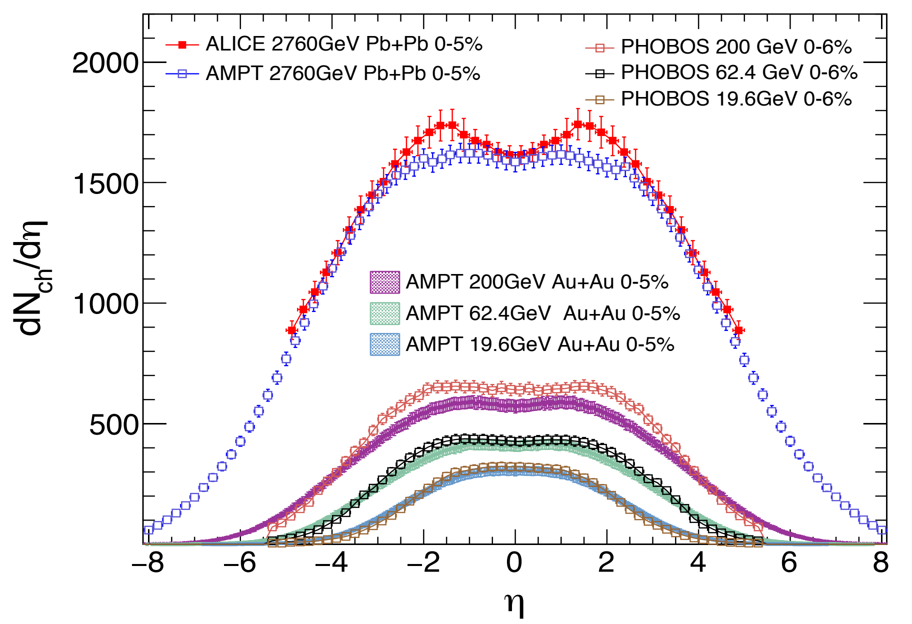
- NSD
- INEL: inelastic events
- INEL>0: events having at least one charged particle in $|\eta|<1$

Collision energy dependence of $dN_{ch}/d\eta$ at $\eta=0$ (integral of data over $\eta<0.5$) for INEL, NSD and INEL>0

Charged particle multiplicity density (Pb-Pb)



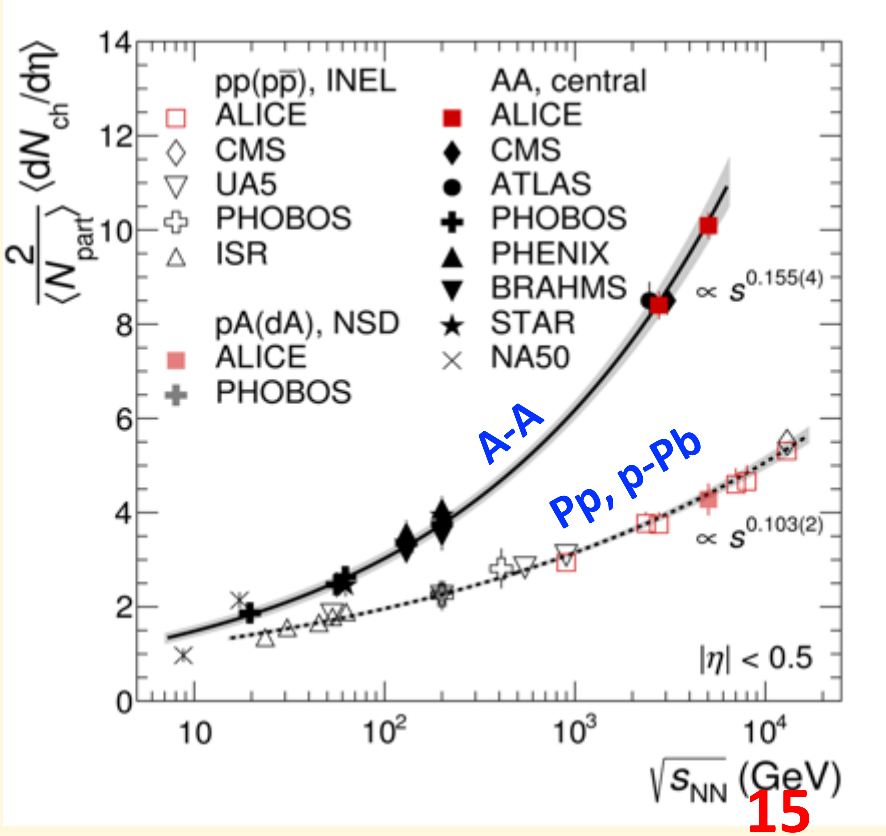




- $dN_{ch}/d\eta$ measured by SPD and FMD
- Total number of charged particles estimated by integrating over full η

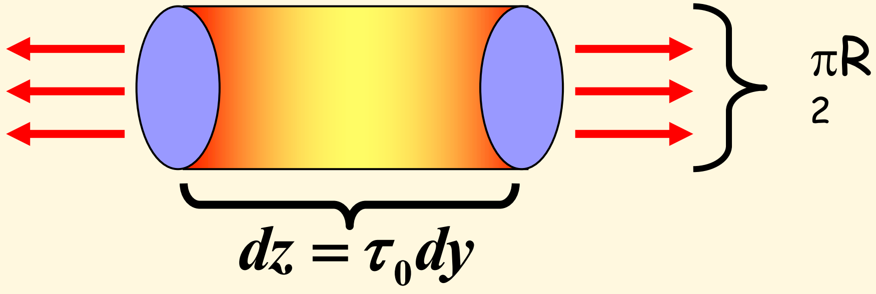
Phys.Lett. B 772 (2017) 567577
Phys. Rev. Lett. 116 (2016) 222302

Collision energy dependence of $dN_{ch}/d\eta$ at $\eta=0$ normalised by averge number of participant pair: Charged particle per participant pair in Pb-Pb rises faster ($s^{0.15}$) and stronger than in pp($s^{0.11}$).



Estimated energy density

J. D. Bjorken, Phys. Rev. D 27, 140 (1983).



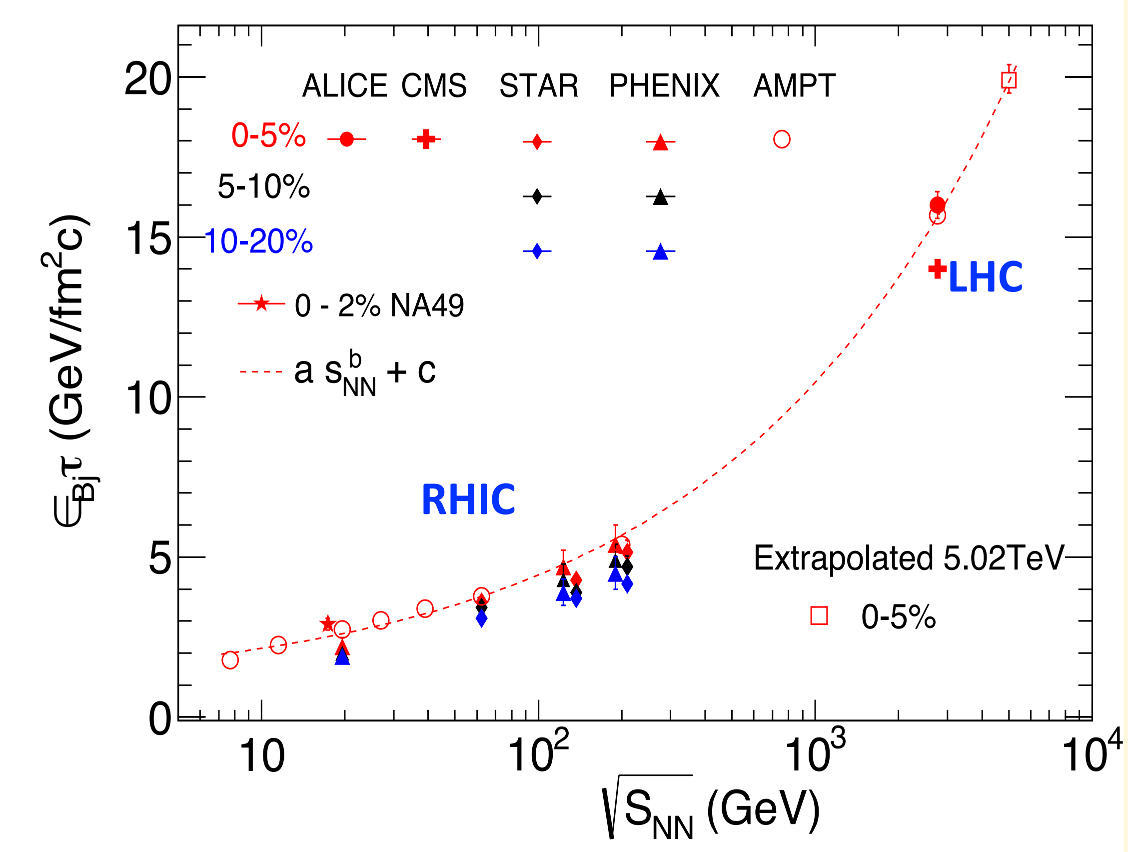
$$dz = \tau_0 dy$$

$$\varepsilon_{Bj}(\tau) = \frac{1}{\pi R^2 \tau} \frac{dE_T}{dy}$$
$$\approx \frac{1}{\pi R^2 \tau} < m_T > \frac{3}{2} \frac{dN_{ch}}{d\eta}$$

ε.τ ~ 16 GeV/fm²c

Energy Density at LHC: More than what had been predicted for the formation of QGP (depending on the formation time)

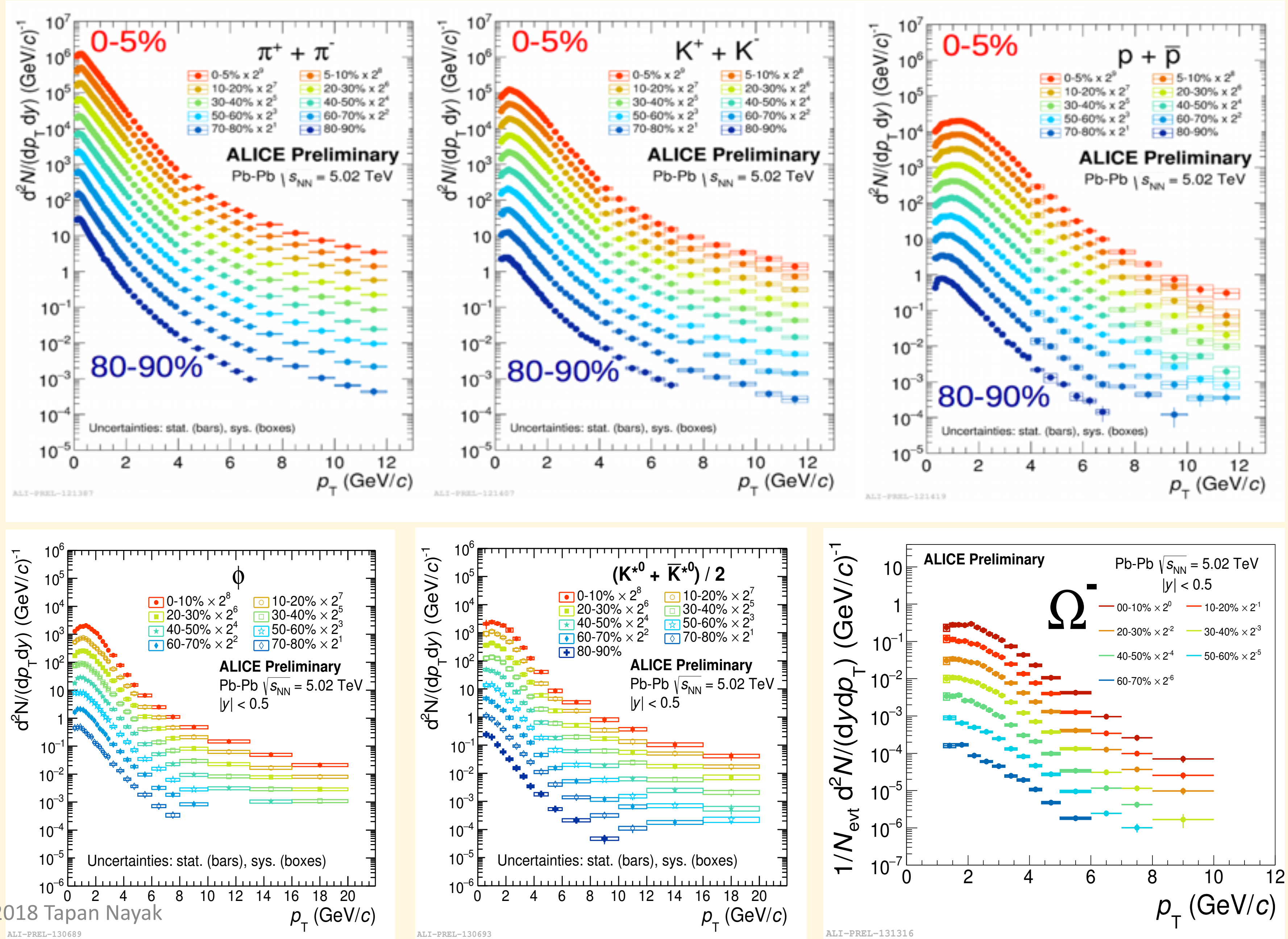
Collision energy dependence of energy density



S. Basu et al. PRC 93 (2016) 064902

R. Sahoo et al. Adv. in High Energy Physics, Vol. 2015

Particle spectra (Pb-Pb 5.02 TeV)



Spectra for pions, kaons, protons …

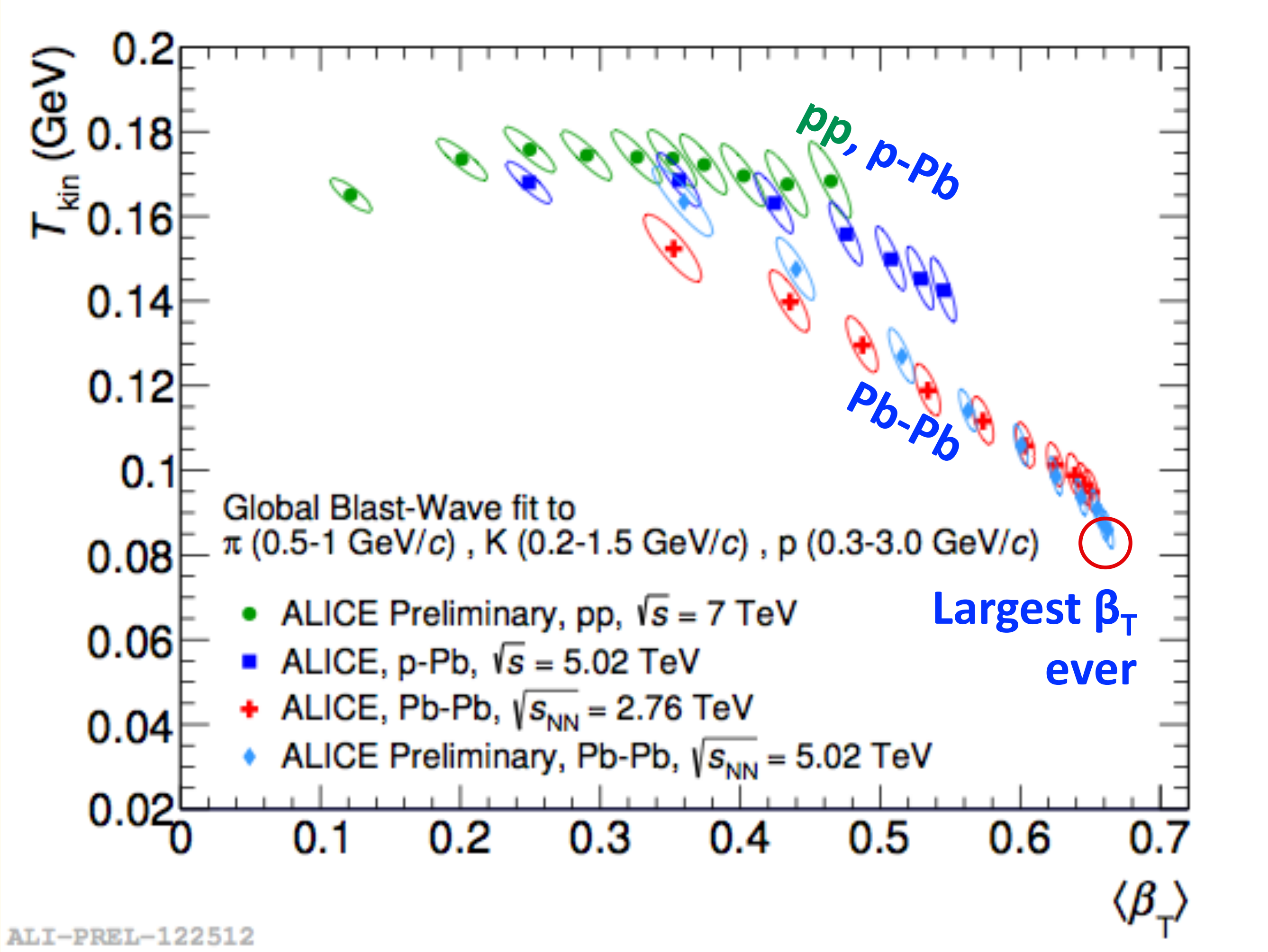
as well as resonances …

Fits to the spectra give information of

QGP hadronisation, radial expansion, freeze-out, …

Blast wave fits to particle spectra: T_{kin} vs. $\langle\beta_T\rangle$

Radial expansion



Boltzmann-Gibbs Blast wave model:

A simplified thermodynamic model with 3 fit parameters:

- T_{kin} : Kinetic freeze-out temperature
- $<\beta_T>$: Radial Flow velocity
- n : velocity profile

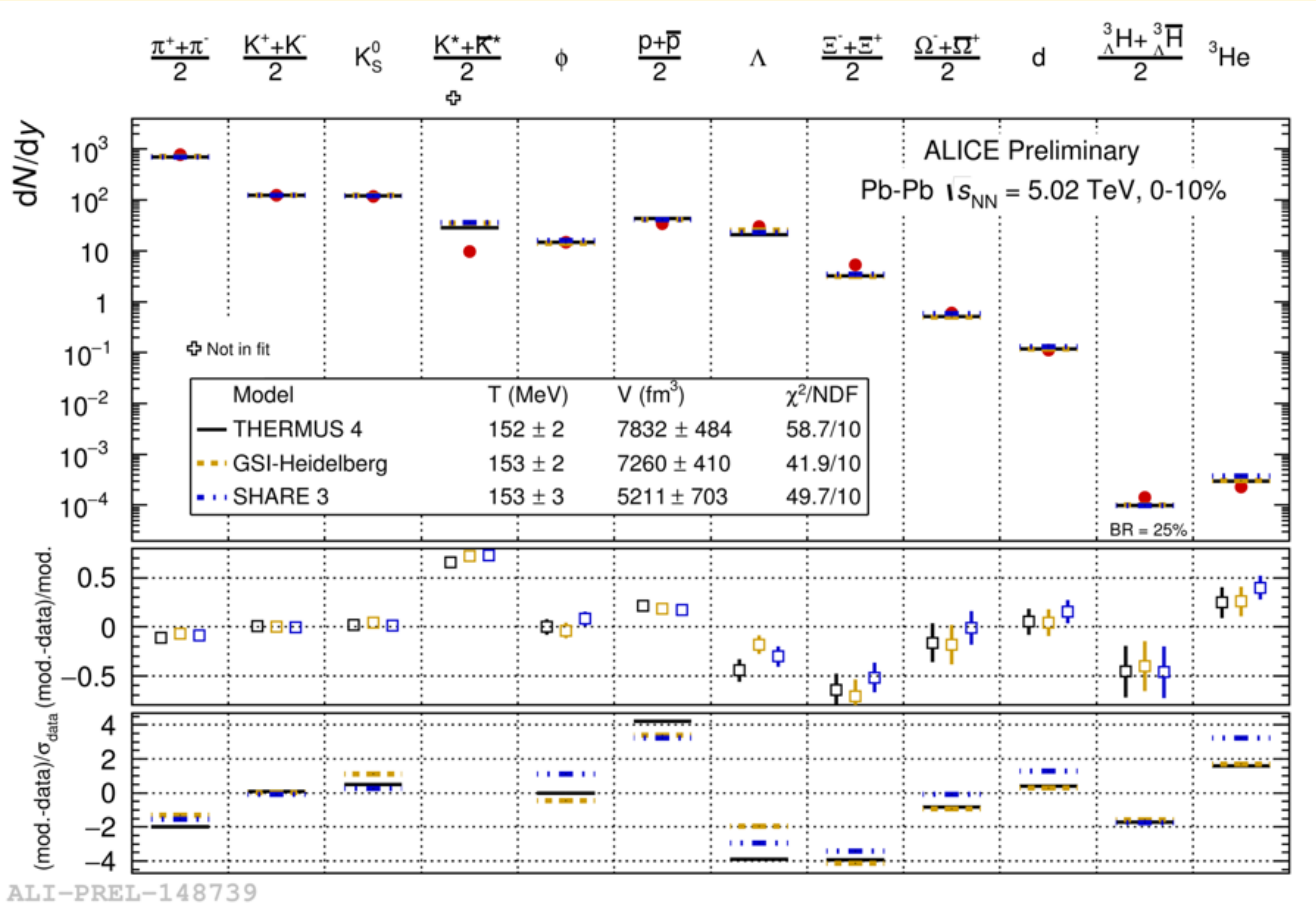
Describes the particle production from a thermalized source + a radial flow boost

Simultaneous fits to π,*K*,*p* spectra gives:

- increase of $<\beta_T>$ with centrality
- Similar evolution of fit parameters in case of pp and p-Pb collisions
- At similar multiplicities, $<\beta_T>$ is larger for smaller systems

Thermal model fits to particle yield

Pb-Pb at 5.02 TeV



Thermal models:

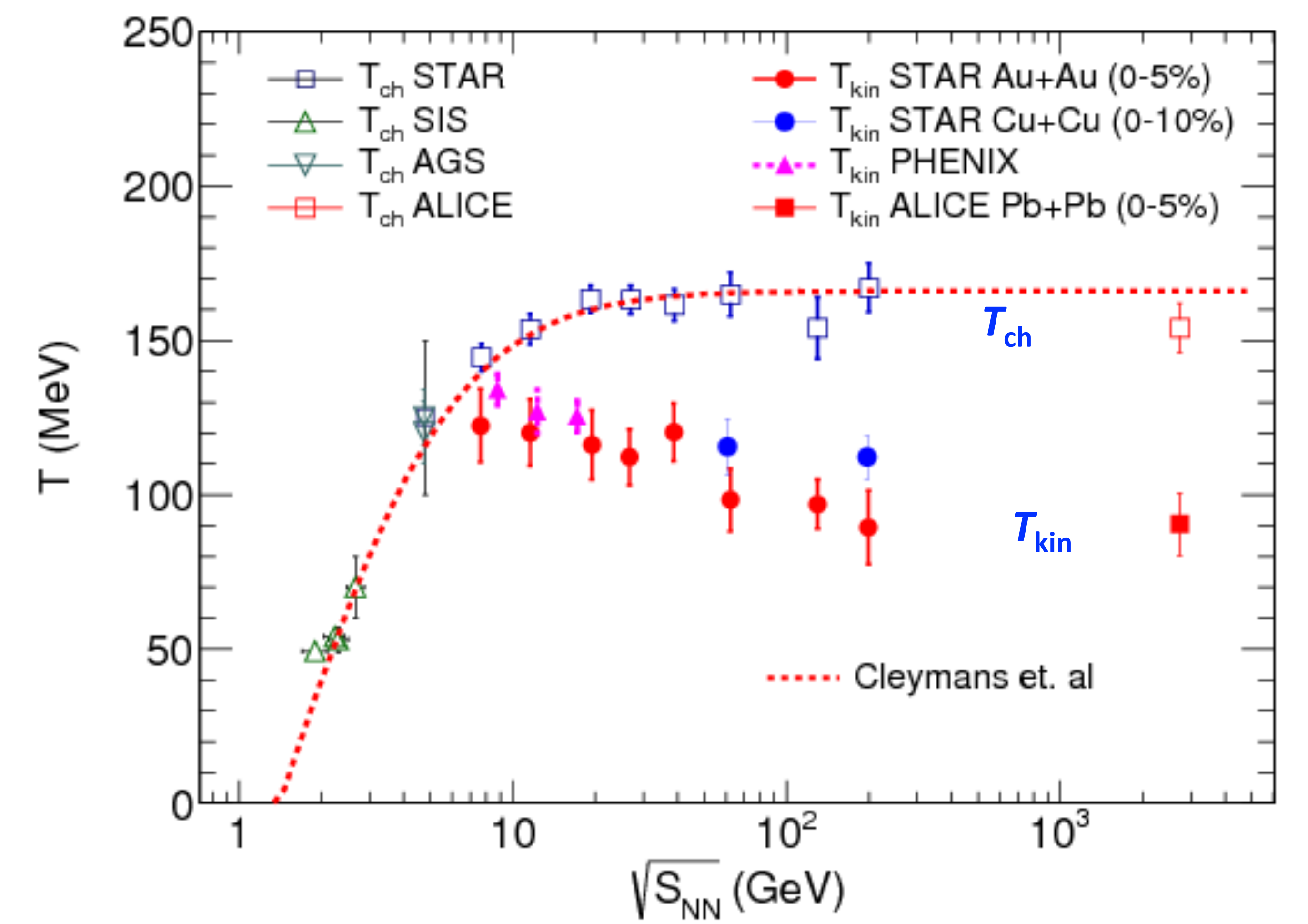
- At Chemical freeze-out => Particle yields get fixed.
- Abundance is determined by thermodynamic equilibrium:

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

T_{ch} : 153 MeV

Chemical and kinetic freeze-out temperatures

Collision energy dependence of T_{kin} and T_{ch}



the difference between T_{kin} and T_{ch} increases with the increase of collision energy.

Sumit Basu et al. PRC 94 (2016) 044901
STAR Collaboration PRC 79 (2009) 034909
ALICE Collaboration PRD 88 (2013) 044910
Cleymans et al. PRC 73 (2006) 034905

Hyperon lifetime

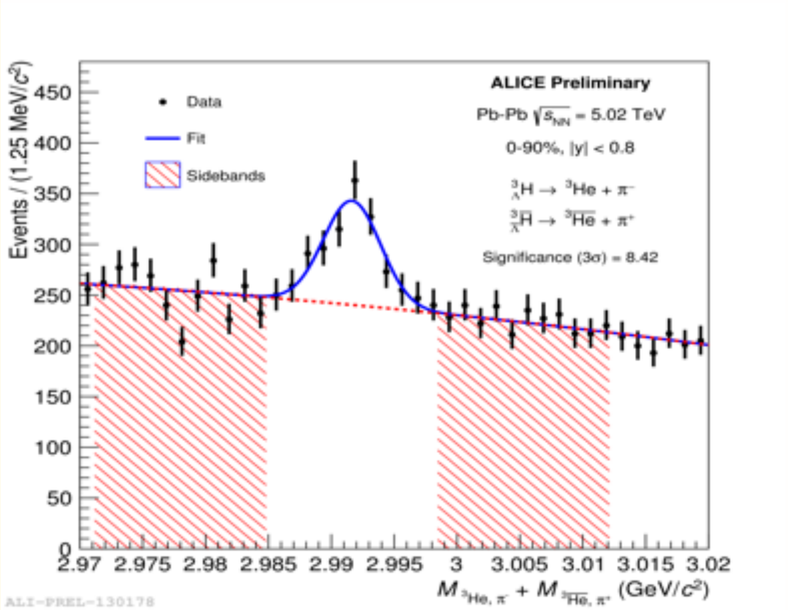
$^{3}_{\Lambda}$H: pnΛ bound state

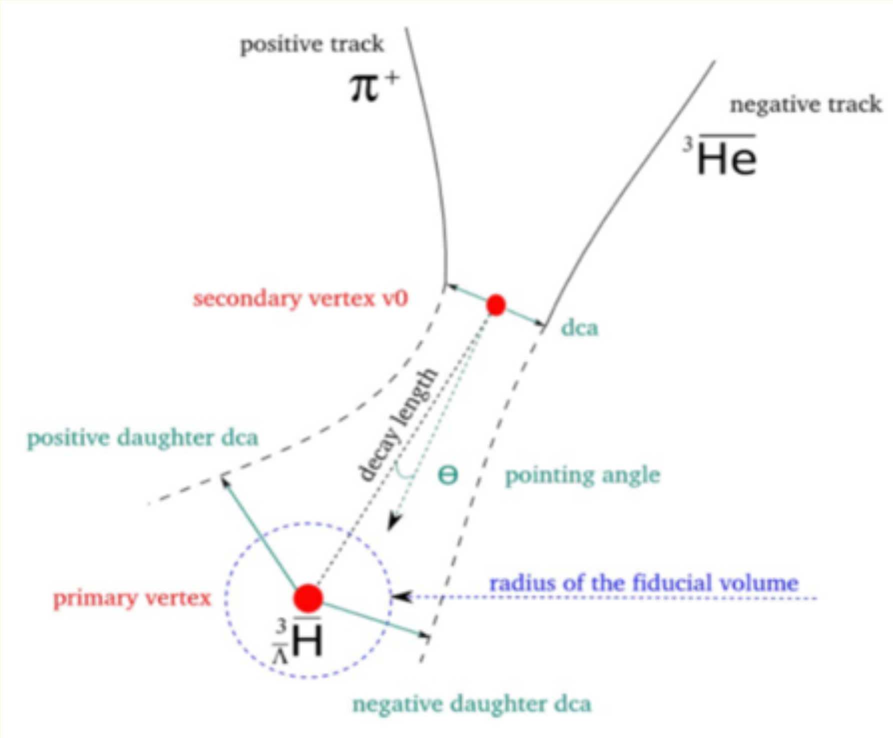
$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$

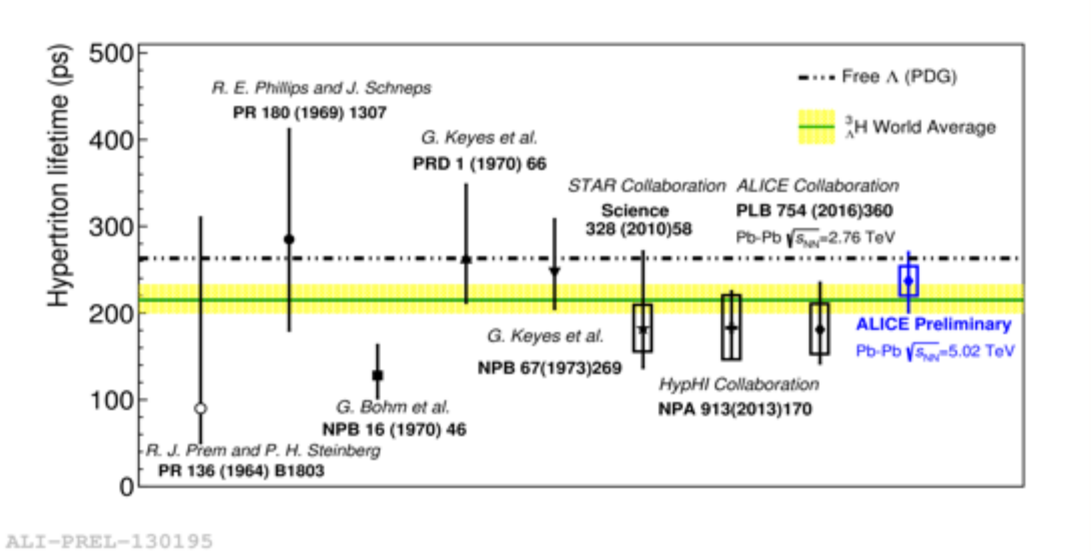
Hypertriton (M = 2.991 GeV/c^2) signal extracted using invariant mass of $^{3}He + \pi^{-}$

Applied topological cuts in order to:

- identify secondary decay vertex and
- reduce combinatorial background.





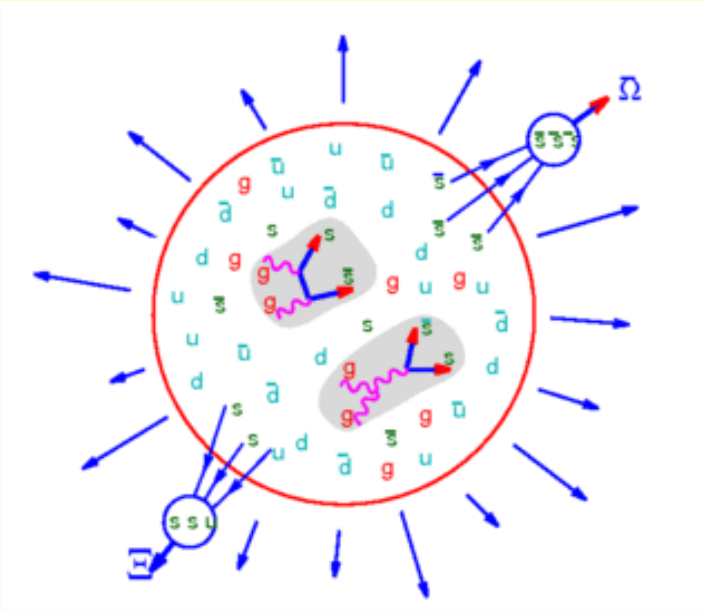


Consistent with world data and with free Λ lifetime

Strangeness enhancement

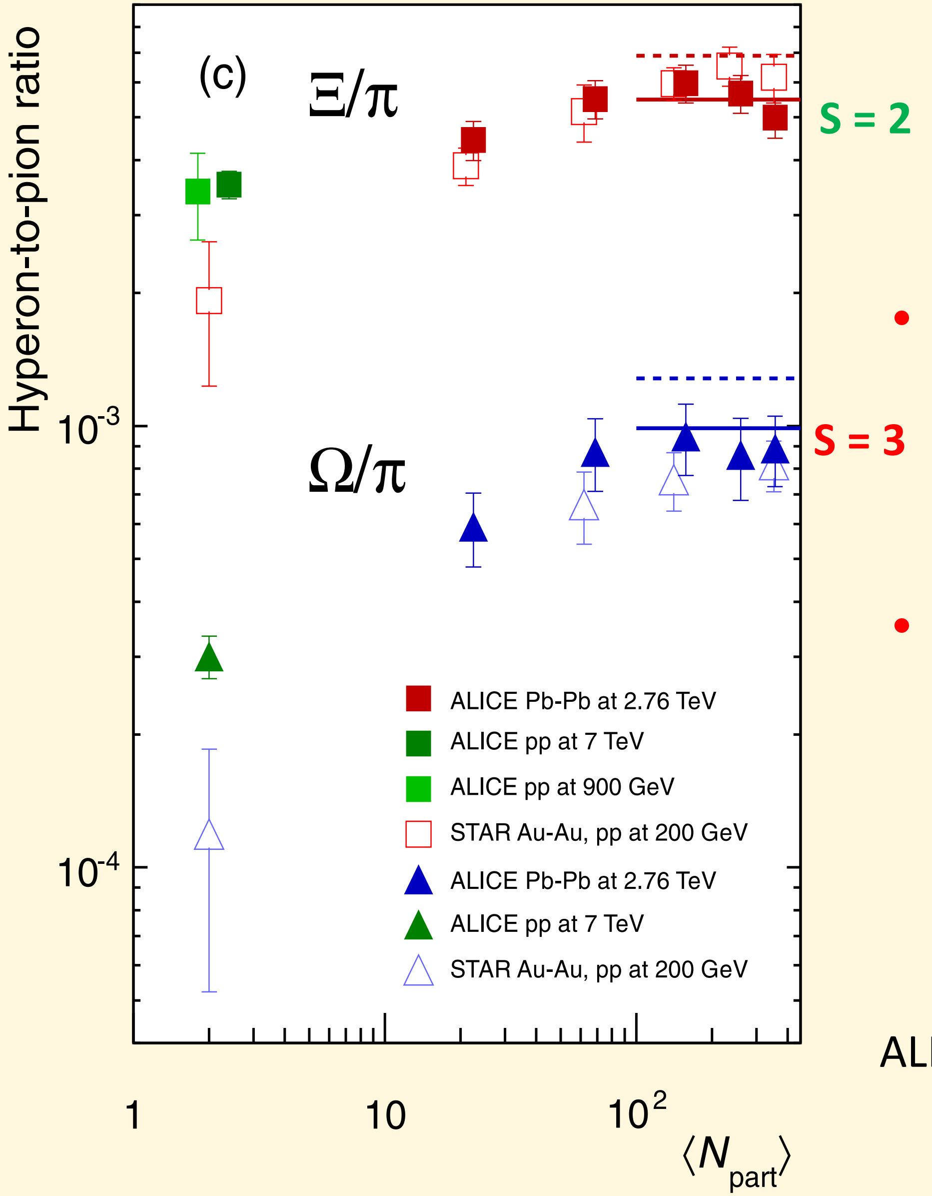
Ordinary nuclear matter is composed of *u* and *d* quarks. Strange quarks are produced in the collision

$$m_{u,d,s} < \Lambda_{QCD} < m_{c,b,t}$$



J. Rafelski and B. Müller, PRL48, 1066 (1982)
P. Koch, B. Müller, J. Rafelski, Phys. Rep. 142, 167 (1986)

The enhanced production of strangeness relative to u and d quarks was proposed as one of the QGP signals.



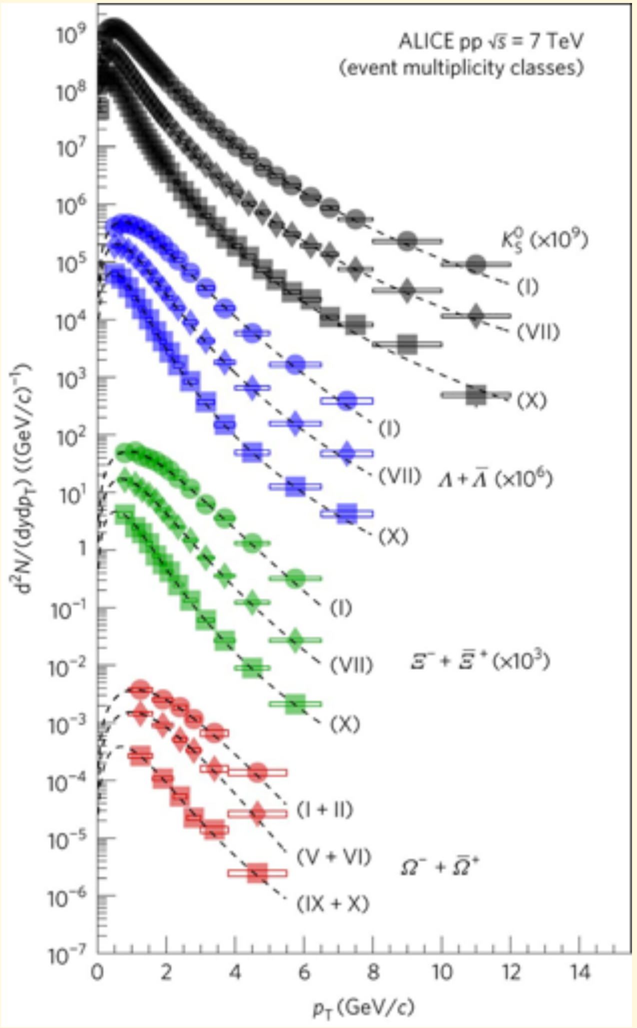
pp **Pb-Pb/Au-Au**

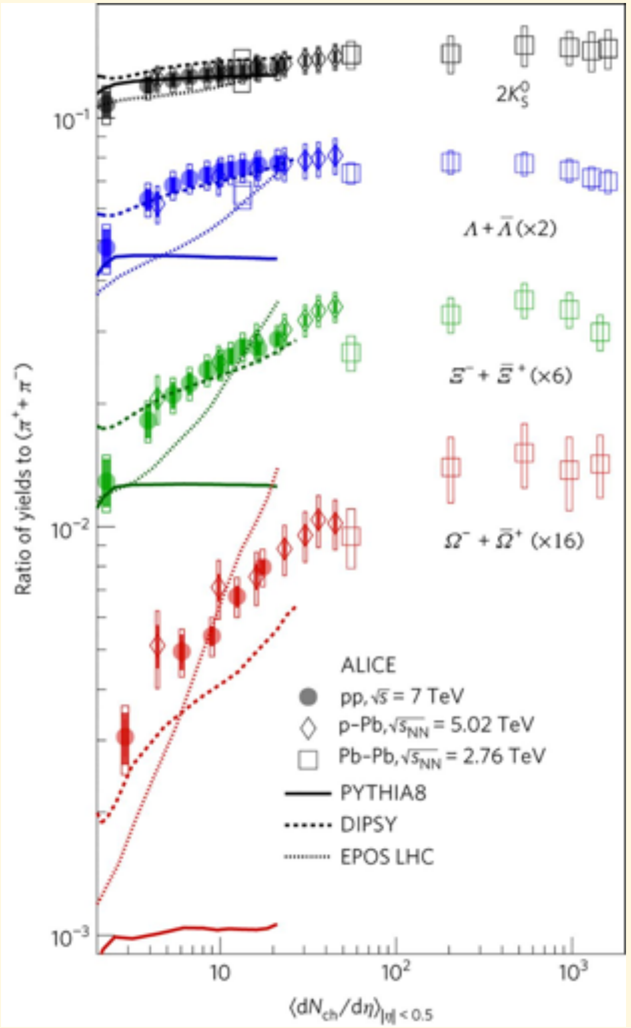
- Strangeness production increases from pp to Pb+Pb collisions.
- Can the gap between minimum bias pp and Pb-Pb be filled with high multiplicity pp and p-Pb events?

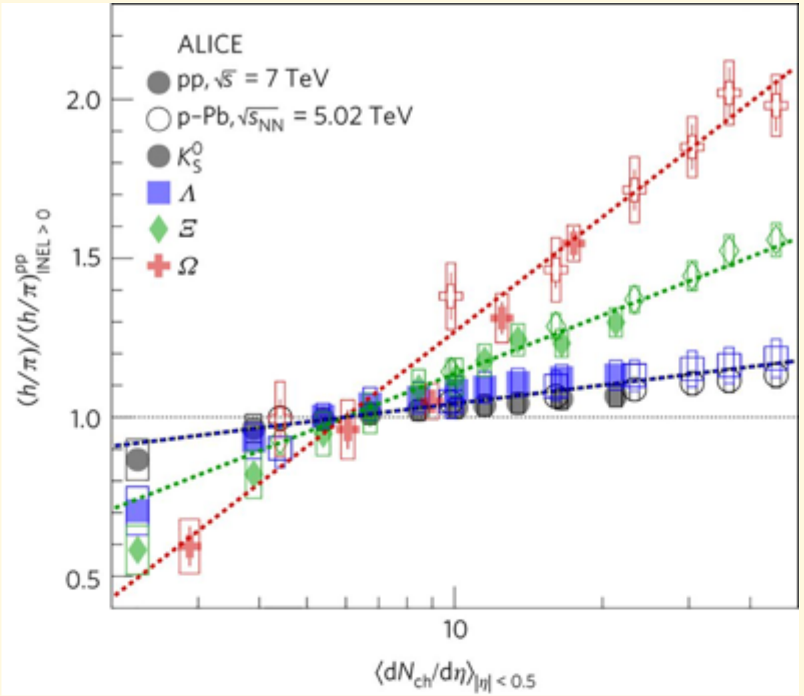
ALICE, PLB 728 (2014) 216
PLB 734 (2014) 409

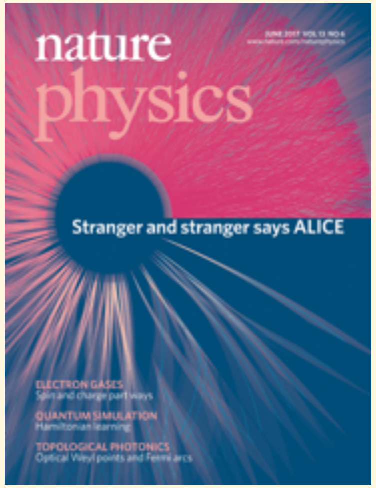
Strangeness enhancement

ALICE Coll., *Nature Physics* **13**, 535–539 (2017)





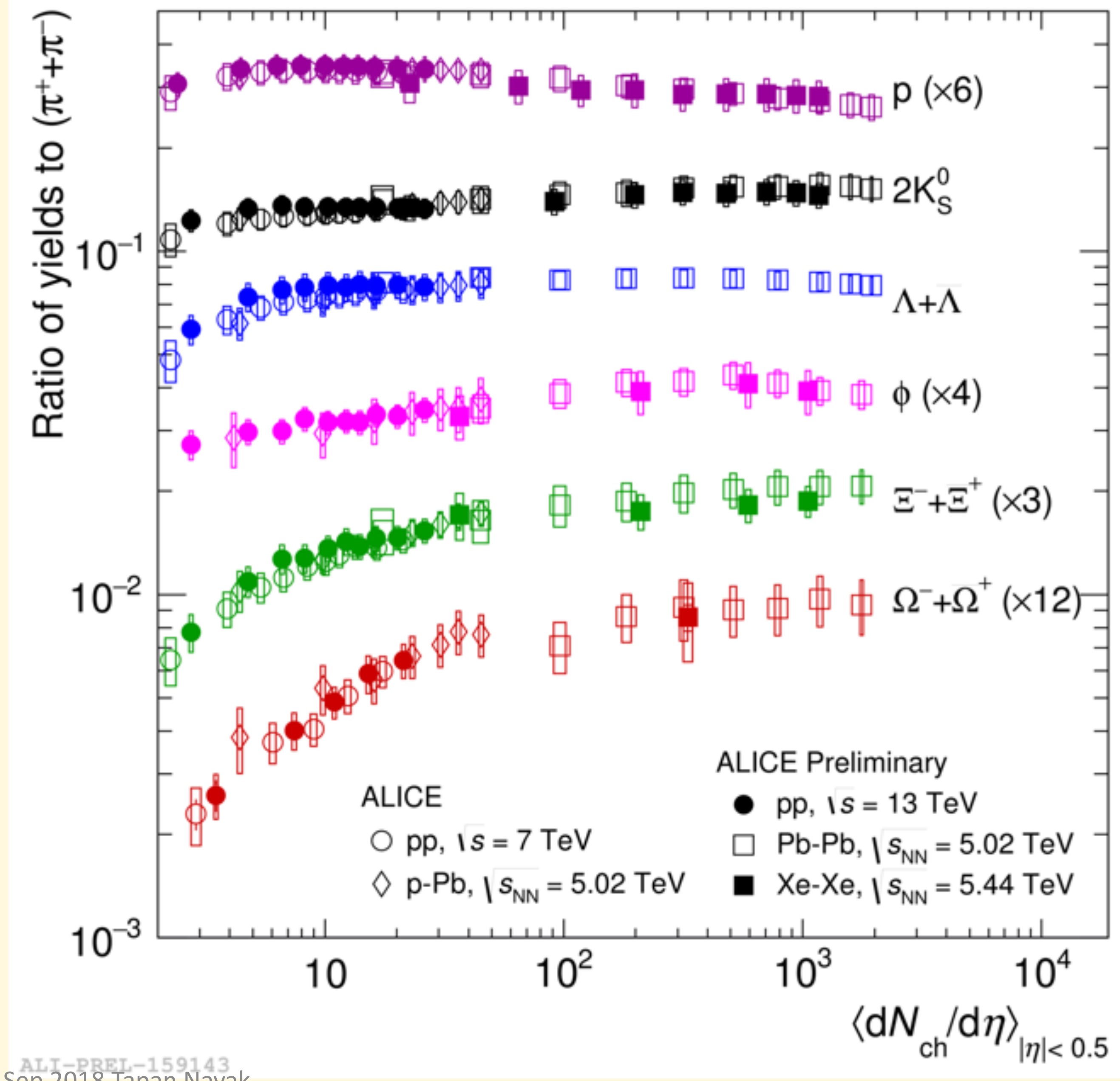




Pb-Pb-like features in pp, p-Pb

- strangeness enhancement:
- enhancement only dependent on multiplicity
- underlying mechanism?
- Strangeness enhancement increases with strangeness content.

Strangeness enhancement in small systems



S = 0

S = 1

S = 1

S = 0

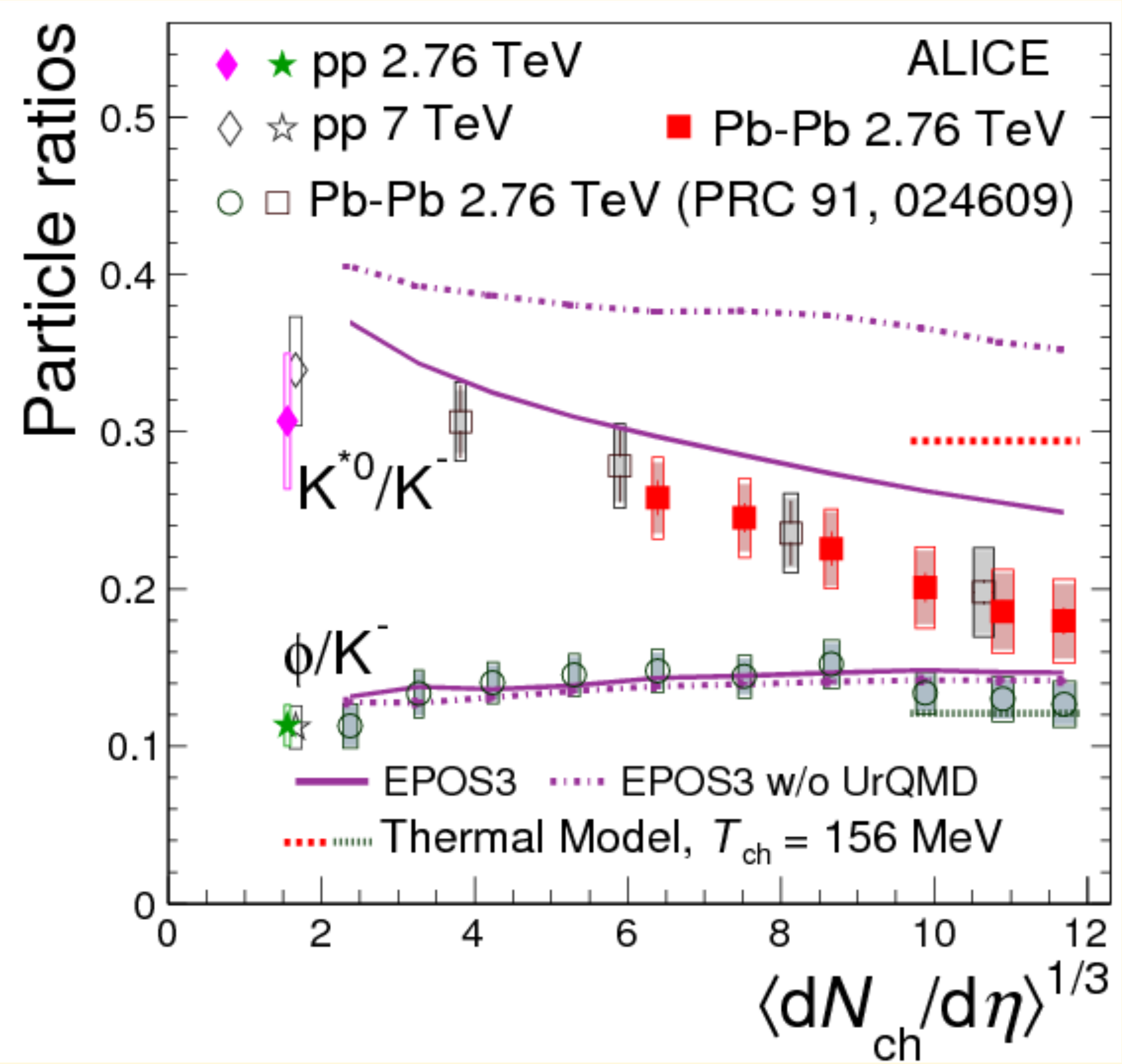
S = 2

S = 3

- Smooth evolution as a function of event multiplicity (in pp, p-Pb and Pb-Pb collisions)
- Measurement at different energies as a function of multiplicity indicate that the hadron chemistry is driven by multiplicity regardless of the collision energy
- Ratios increase from low to high multiplicity in small systems and reach values similar to those observed in Pb-Pb collisions.
- Strangeness enhancement increases with strangeness content.

Resonance production – access to freeze-out times

ALICE: Phys. Rev. C. 95 064606



$K^{*0}(892)$

	Life time (fm/c)
K^{*0}	~ 4.16
ϕ	~ 46.3

- The shorter lifetime of the K^{*0} means that it decays within the medium, enabling its decay products (π,K) to re-scatter with other hadrons.
- The process depends on the time interval between chemical and kinetic freeze-outs, in addition to the source size and the interaction cross-sections of the daughter hadrons.
- In contrast, due to the longer lifetime of the ϕ meson, both the re-scattering and regeneration effects are expected to be negligible.
- Indicates the existence of re-scattering effects on resonances in the last stages of heavy-ion collisions.

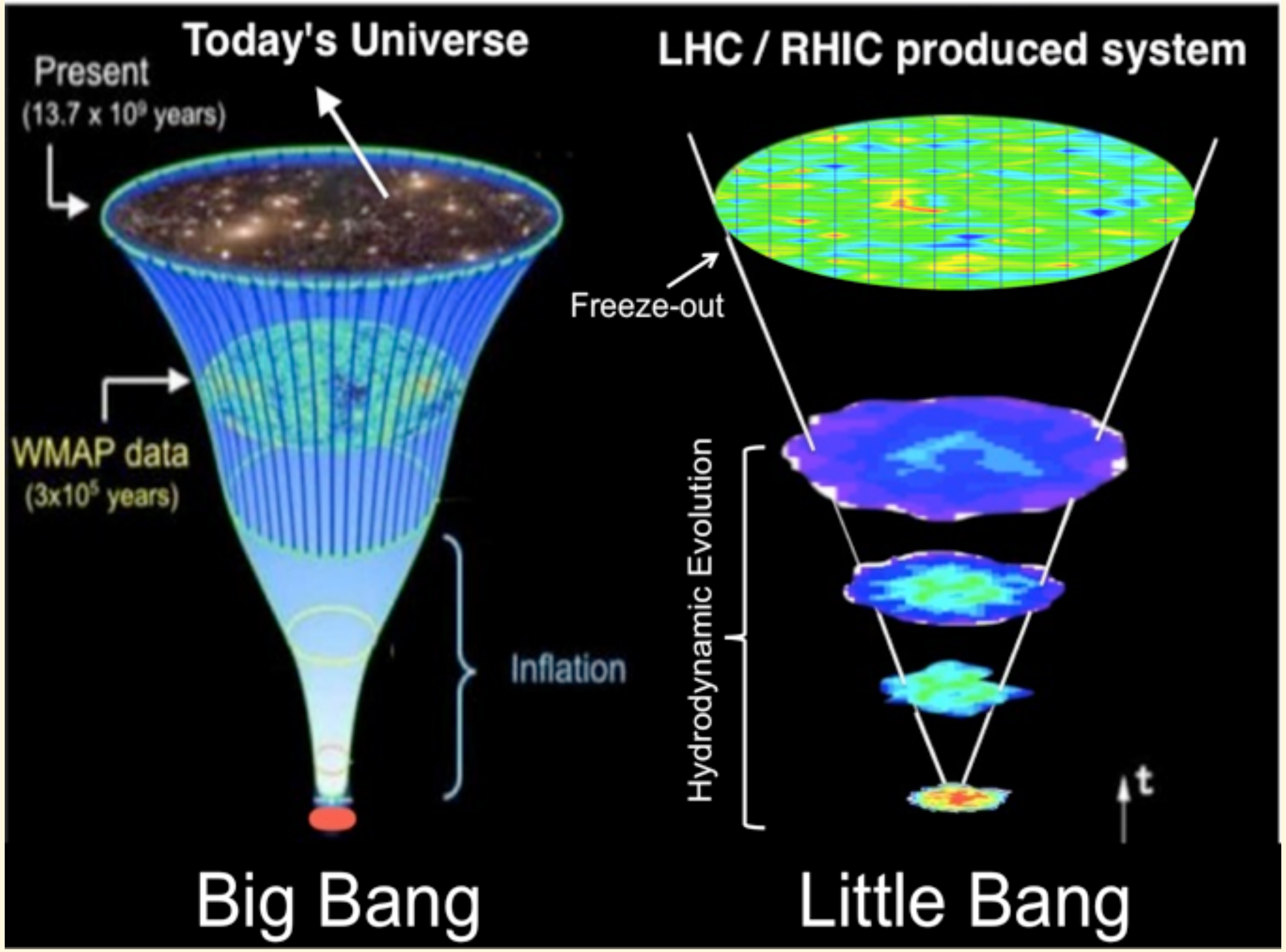
Fluctuation measures

- **Fluctuations of Conserved Quantities**
  - Access to critical phenomena
  - Obtaining freeze-out parameters
  - Bridge between THEORY and EXPERIMENT

Thermodynamic susceptibility ←→ Moments of the conserved charge distribution

$$\begin{bmatrix} \sigma_Q^2 & \sigma_{QB} & \sigma_{QS} \\ \sigma_{BQ} & \sigma_B^2 & \sigma_{BS} \\ \sigma_{SQ} & \sigma_{SB} & \sigma_S^2 \end{bmatrix}$$

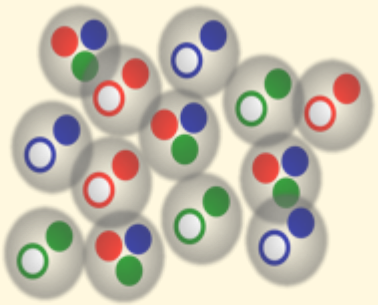
Higher moments
Diagonal and Off-diagonal Susceptibilities



Net-charge fluctuations

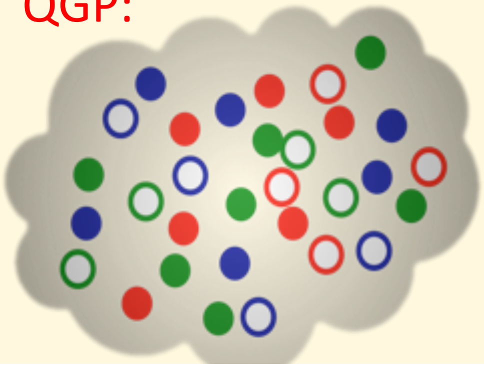
Net charge fluctuations:

Hadron gas:



Confined: few d.o.f.

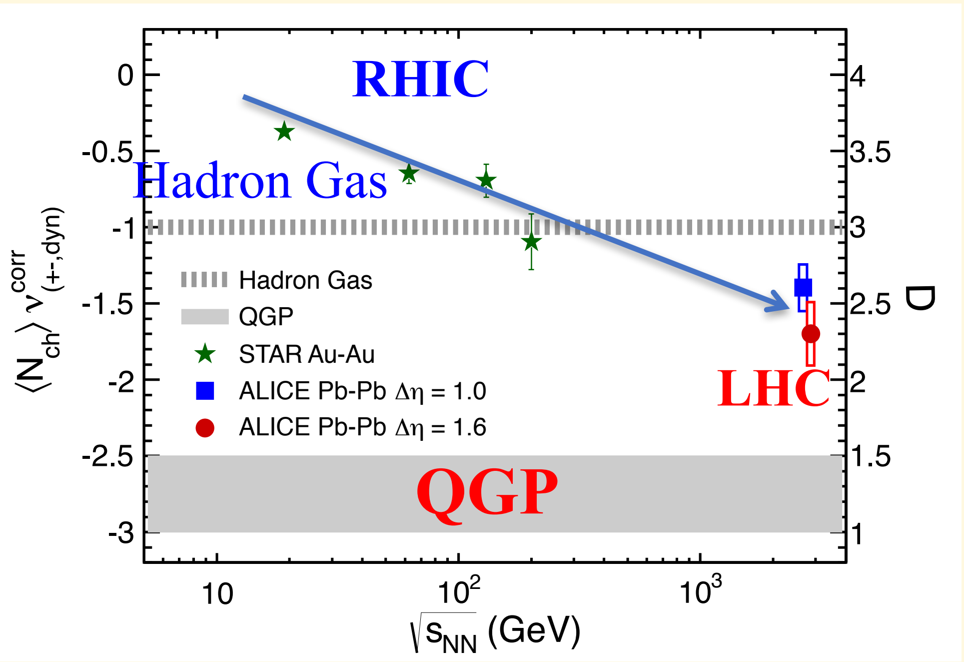
QGP:



Deconfined: many d.o.f.

Jeon, Koch. PRL 85 (2000)
Asakawa, Heinz, Müller, PRL 85 (2000)

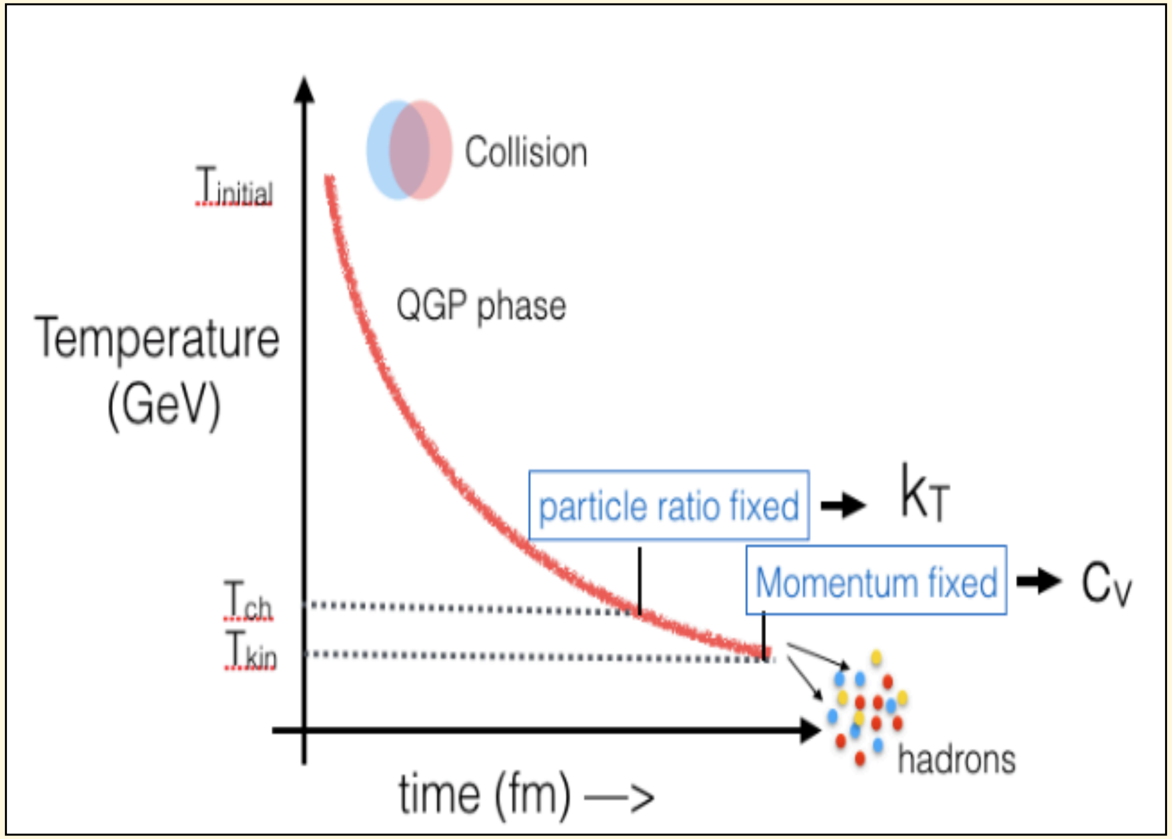
PRL 110 (2013)



$$\nu_{(+-,dyn.)} = \frac{\langle N_+(N_+-1)\rangle}{\langle N_+\rangle^2} + \frac{\langle N_-(N_--1)\rangle}{\langle N_-\rangle^2} - 2\frac{\langle N_+N_-\rangle}{\langle N_+\rangle\langle N_-\rangle}$$

$$D = 4\frac{\langle(\delta Q)^2\rangle}{N_{ch}} \approx \langle N_{ch}\rangle\langle \nu_{dyn}\rangle - 4 \approx \begin{cases} 4(HG) \\ 3(HRG) \\ 1-1.5(QGP) \end{cases}$$

Thermodynamic response functions: using fluctuation measures



- **Heat capacity:**

$$C = \left(\frac{\partial E}{\partial T}\right)_v$$

A heat capacity is a response function expressing how much a system's temperature changes when heat is transferred to it, or equivalently how much δE is needed to obtain a given dT

- **Isothermal compressibility:**

$$k_T = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T$$

Isothermal compressibility expresses how a system's volume responds to a change in the applied pressure.

Critical behavior → power law scaling k_T

$$k_T \propto \left(\frac{T - T_C}{T_C}\right)^{-\gamma} \propto \varepsilon^{-\gamma}$$

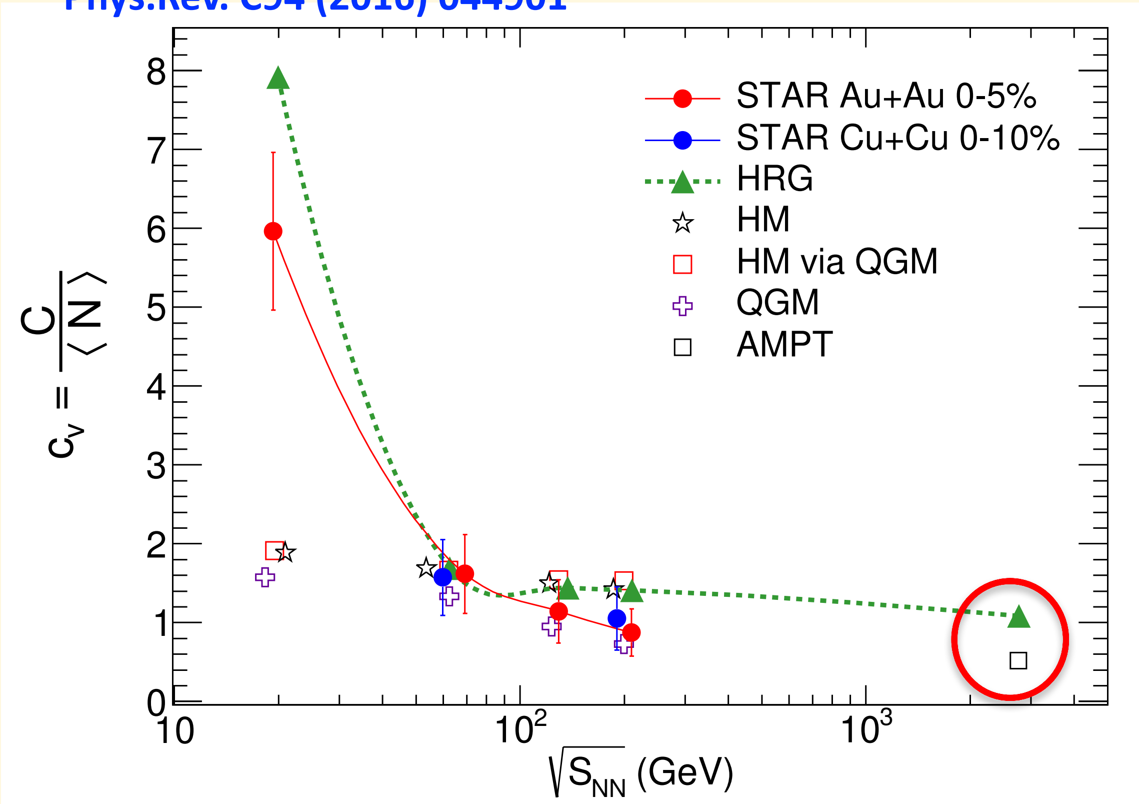
Beam Energy Dependence of C_v and k_T

C_v from mean p_T fluctuations

$$\frac{1}{C_v} = \frac{(\langle T^2 \rangle - \langle T \rangle^2)}{\langle T \rangle^2}.$$

$$\frac{1}{C_v} = \frac{(\langle T_{\rm kin}^2 \rangle - \langle T_{\rm kin} \rangle^2)}{\langle T_{\rm kin} \rangle^2} \approx \frac{(\langle T_{\rm eff}^2 \rangle - \langle T_{\rm eff} \rangle^2)}{\langle T_{\rm kin} \rangle^2}$$

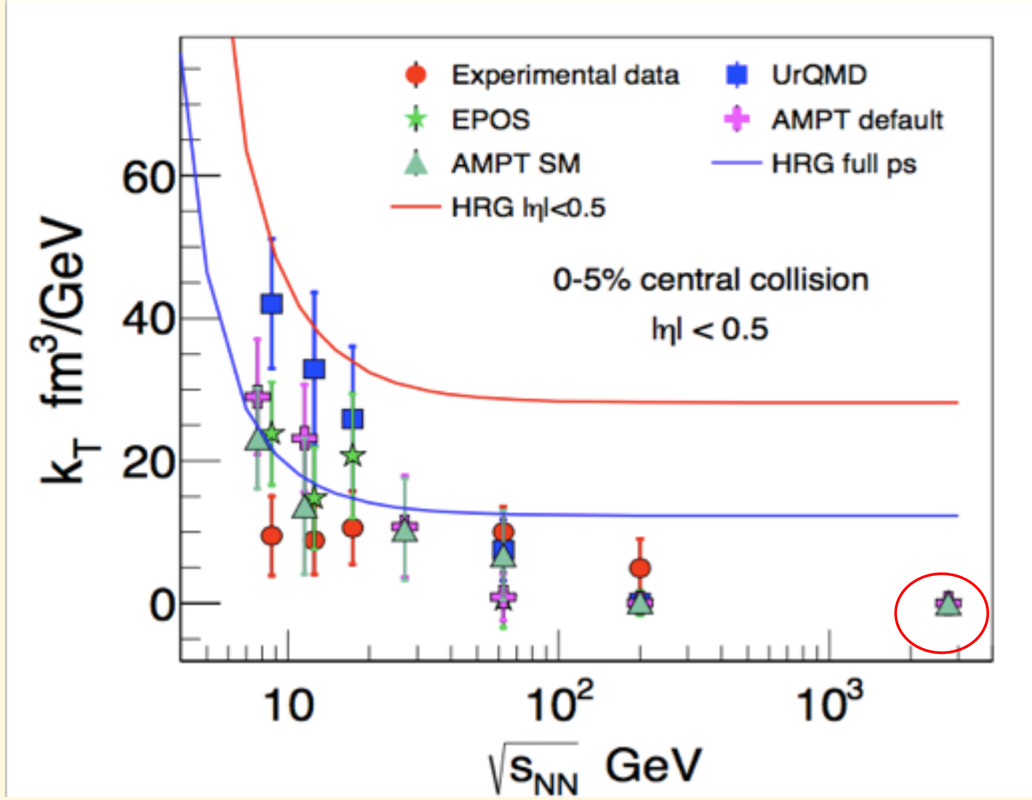
Phys.Rev. C94 (2016) 044901



k_T from multiplicity fluctuations

$$k_T = \frac{\sigma^2}{< N >^2} \frac{V}{k_B T}$$

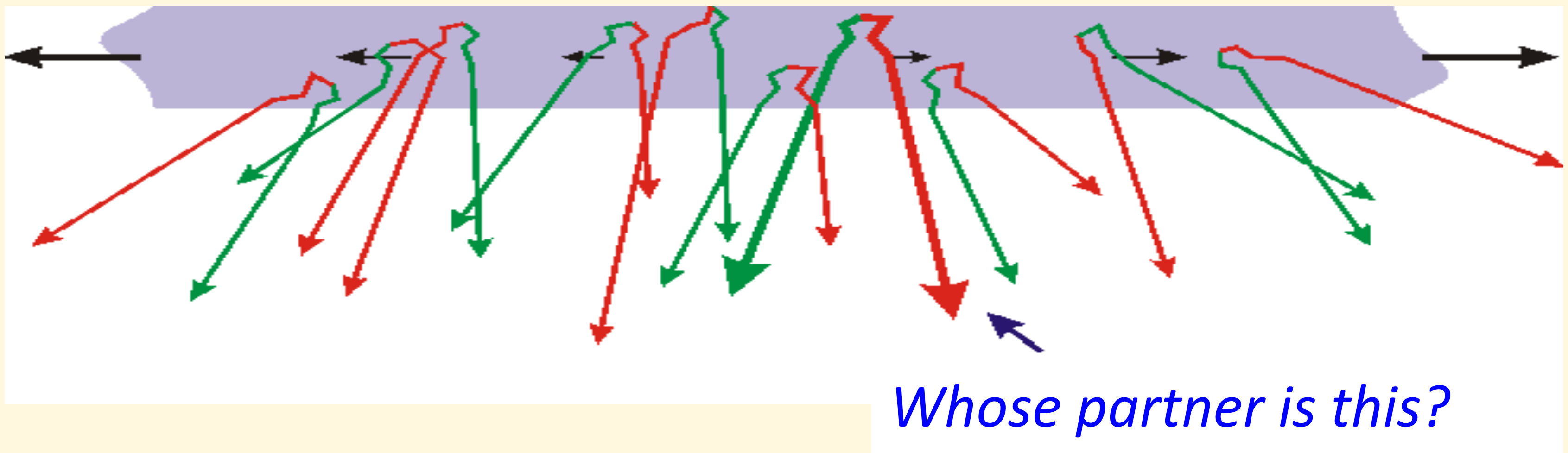
Phys.Lett. B784 (2018) 1



ALICE data analysis in progress

Balance Functions

Bass, Danielewicz, Pratt PRL 85 (2000)



Balance Function quantifies the degree of the separation of pairs of particles and relates that with the time of hadronization.

Conditional probability of detecting a particle of type b in the bin P_2 whilst there is a particle of type a in the bin P_1.

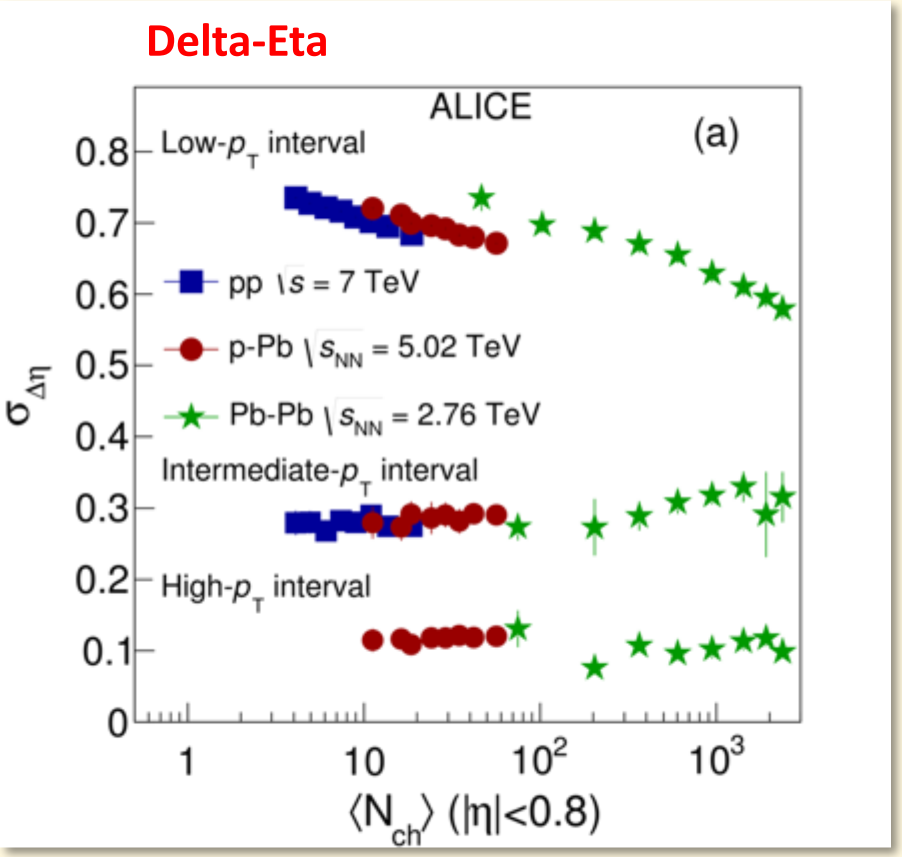
$$\rho(b,P2|a,P1)=\frac{N(b,P2|a,P1)}{N(a,P1)}$$

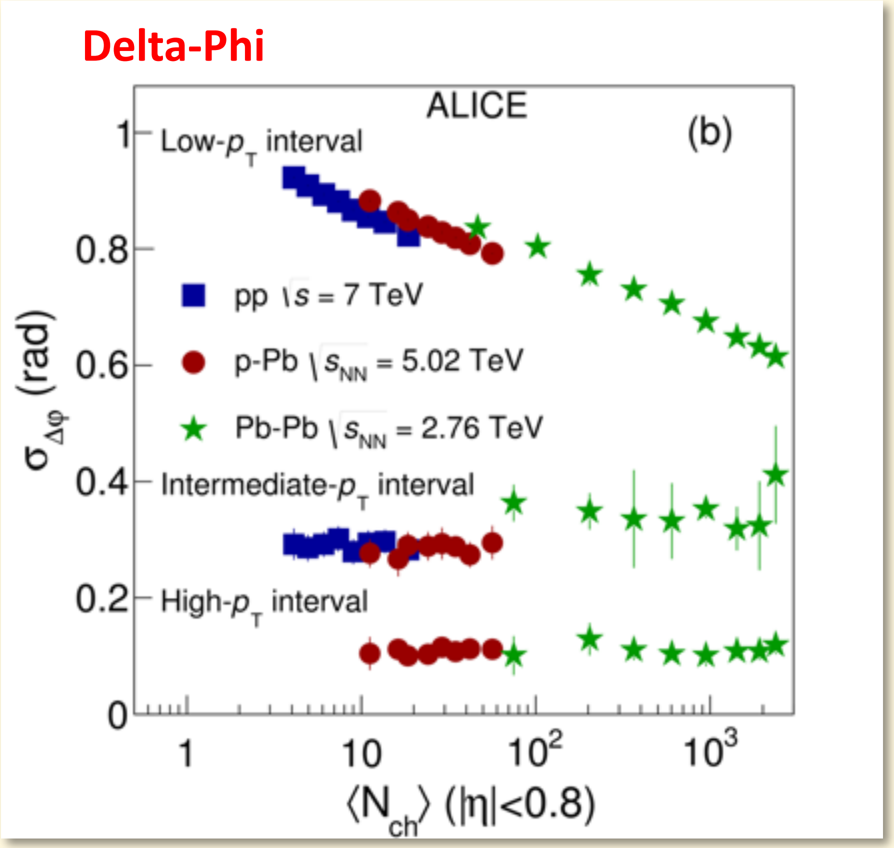
$$B(\Delta\eta)=\frac{1}{2}\left(\frac{N_{(+-)}(\Delta\eta)-N_{(--)}(\Delta\eta)}{N_{-}}+\frac{N_{(-+)}(\Delta\eta)-N_{(++)}(\Delta\eta)}{N_{+}}\right)$$

Width of the BF is a combination of thermal spread and diffusion

BF in pp, p-Pb and Pb-Pb: (pT window)

ALICE Collaboration, EPJC (2016)

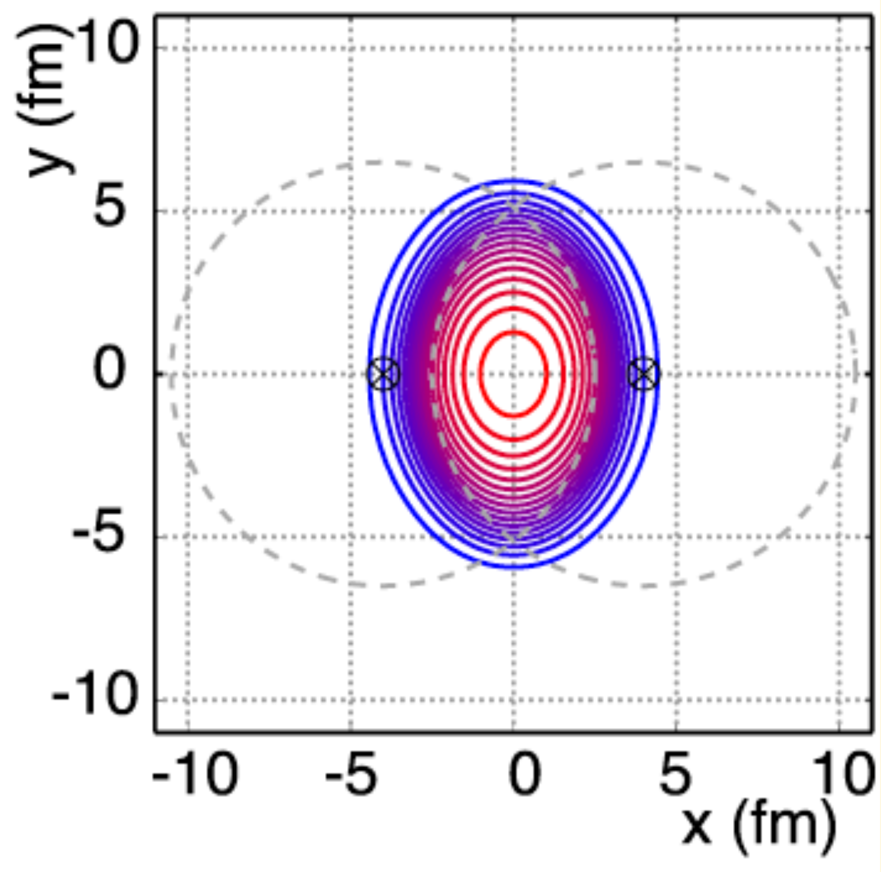




- The widths of the BF in Δη and Δϕ are found to decrease with increasing multiplicity for all systems only in the low-*p*T region (for *p*T < 2.0 GeV/*c*).
- For higher values of *p*T, the multiplicity dependence is significantly reduced, and the correlations of balancing partners are stronger with respect to the low-*p*T

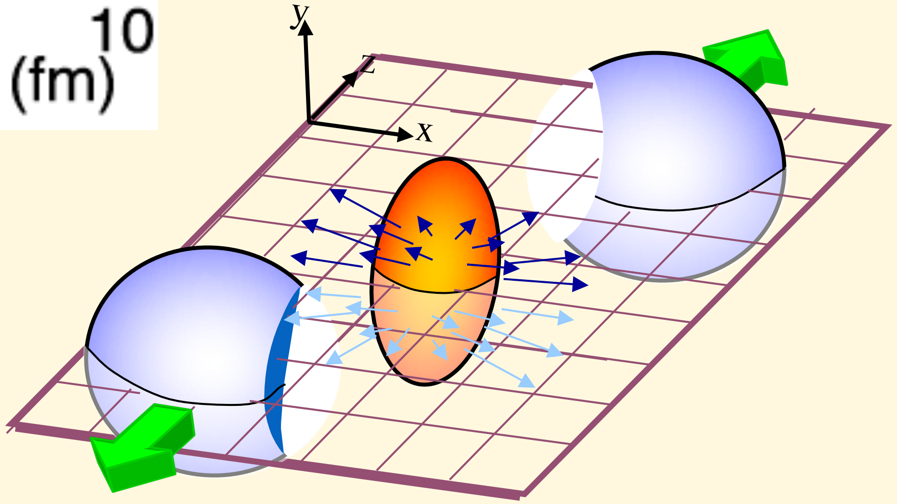
Azimuthal asymmetry:

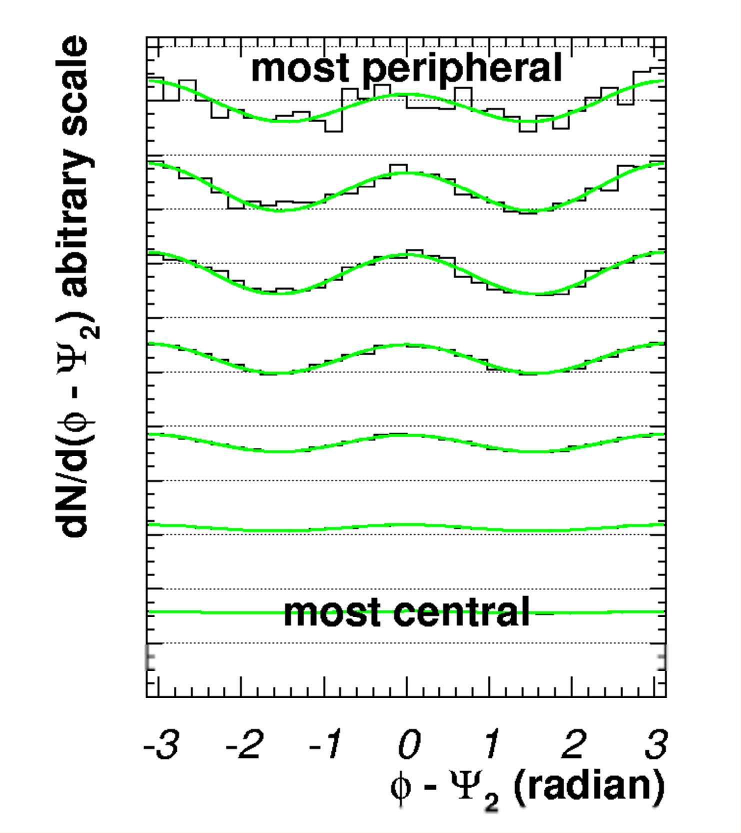
Non-central A-A collisions



$$\frac{dN}{p_T dp_T dy d\varphi}(p_T, \varphi; b) = \frac{dN}{2\pi p_T dp_T dy}\left(1 + 2v_2(p_T; b)\cos(2\varphi) + \ldots\right)$$

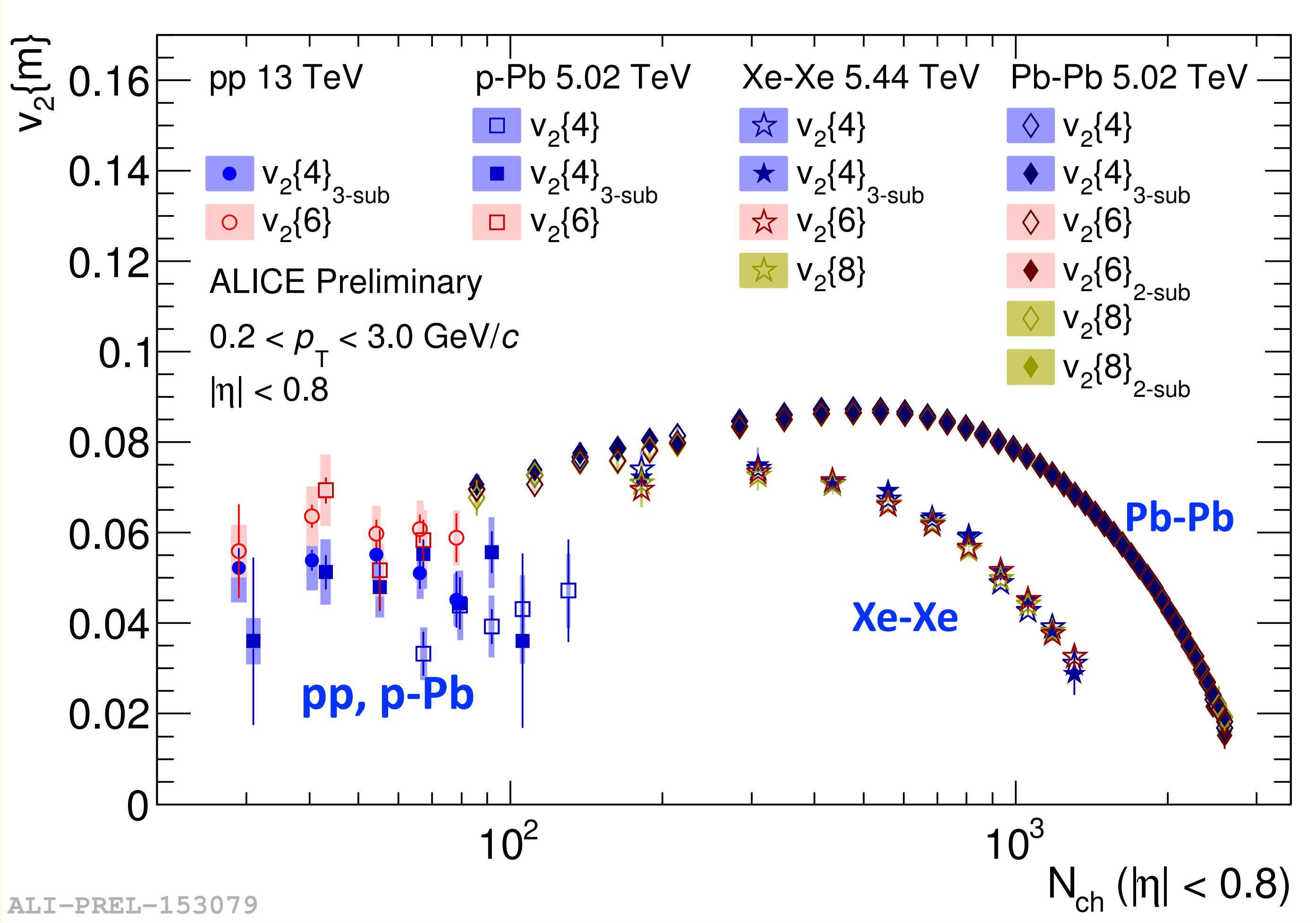
v_2 = "elliptic flow"





Study angular dependence of emitted particles

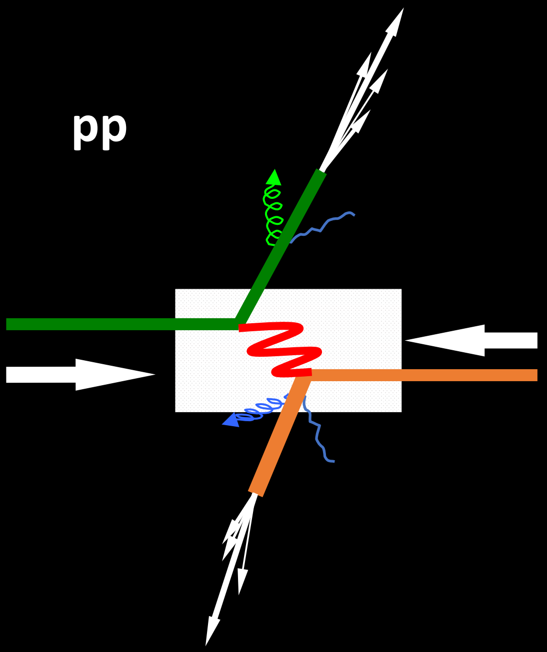
Elliptic flow in different collision systems



Detailed measurement of *v2{m}* as a function of charged particle density for **different geometries.**

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

Nuclear modification factor: probing the dense matter



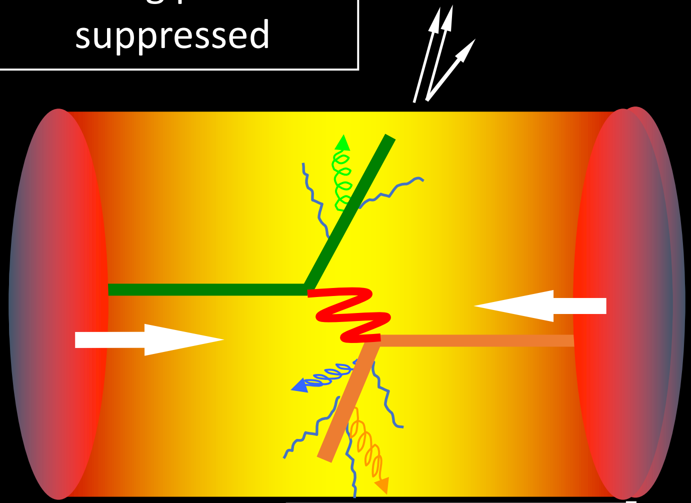
$$R_{AA} = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

Nuclear overlap function:

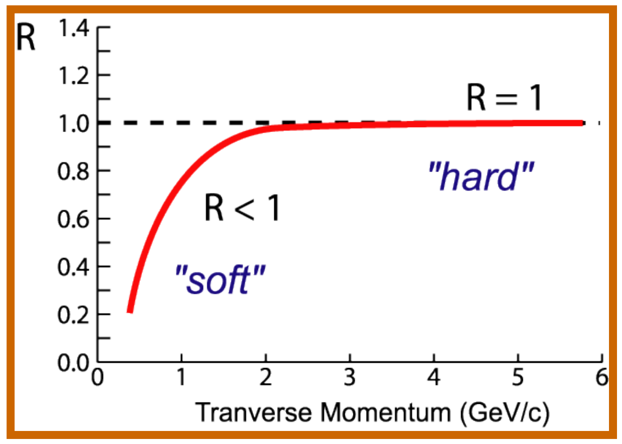
$$\langle T_{AA} \rangle = \langle N_{coll} \rangle / \sigma_{inel}^{NN}$$

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

leading particle suppressed



back-to-back jets disappear



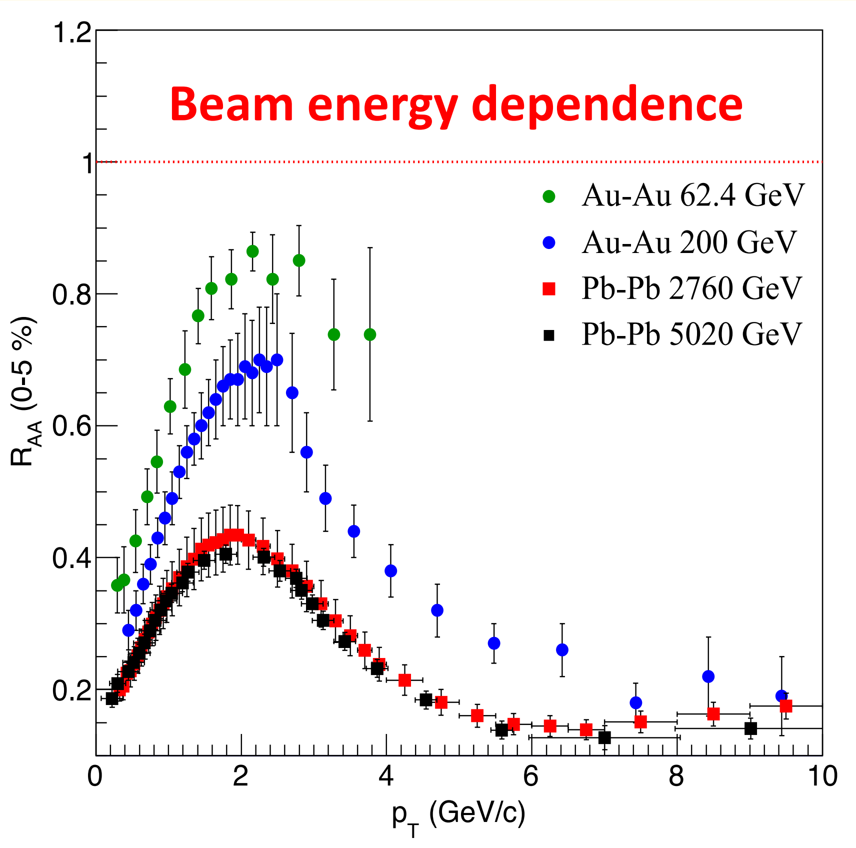
$R_{AA} > 1$: enhancement

$R_{AA} = 1$

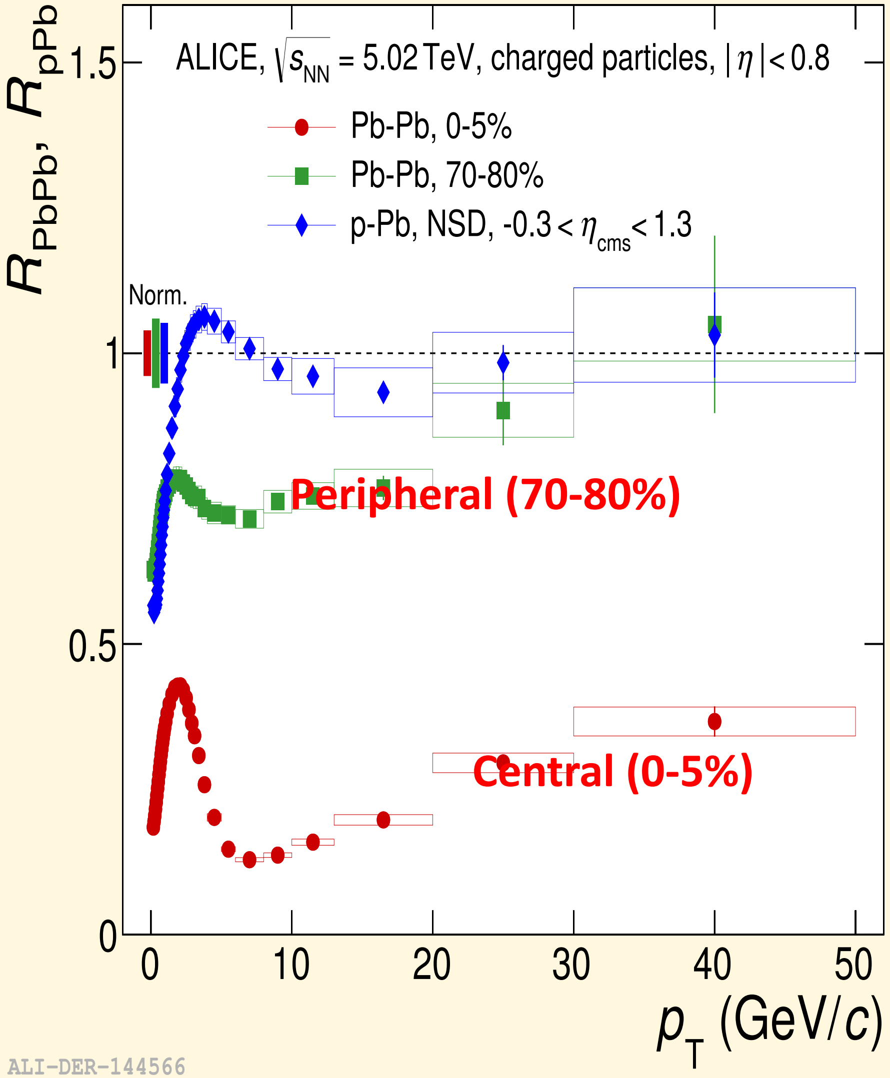
$R_{AA} < 1$: suppression

⇒ **Disentangle INITIAL (Cronin effect, Nuclear PDF …) and FINAL (Energy loss, Rescattering …) state effects**

Charged particle energy loss



$$R_{AB} = \frac{dN_{AB}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$



arXiv:1802.09145

- **p-Pb:** no evidence of jet quenching for NSD events. Small system size – hence effect is very small.

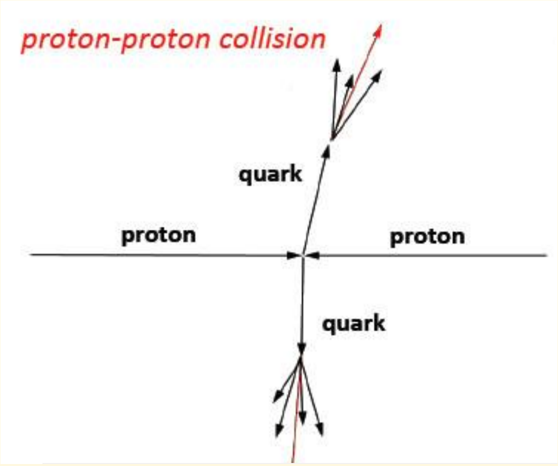
  To check: dependence on event activity.

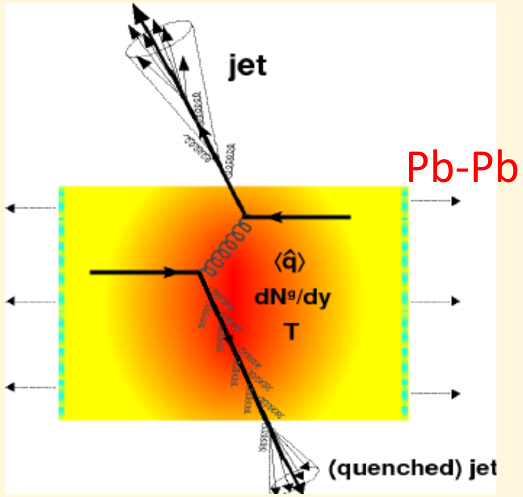
- **Pb-Pb**: Strong suppression with increasing centrality.

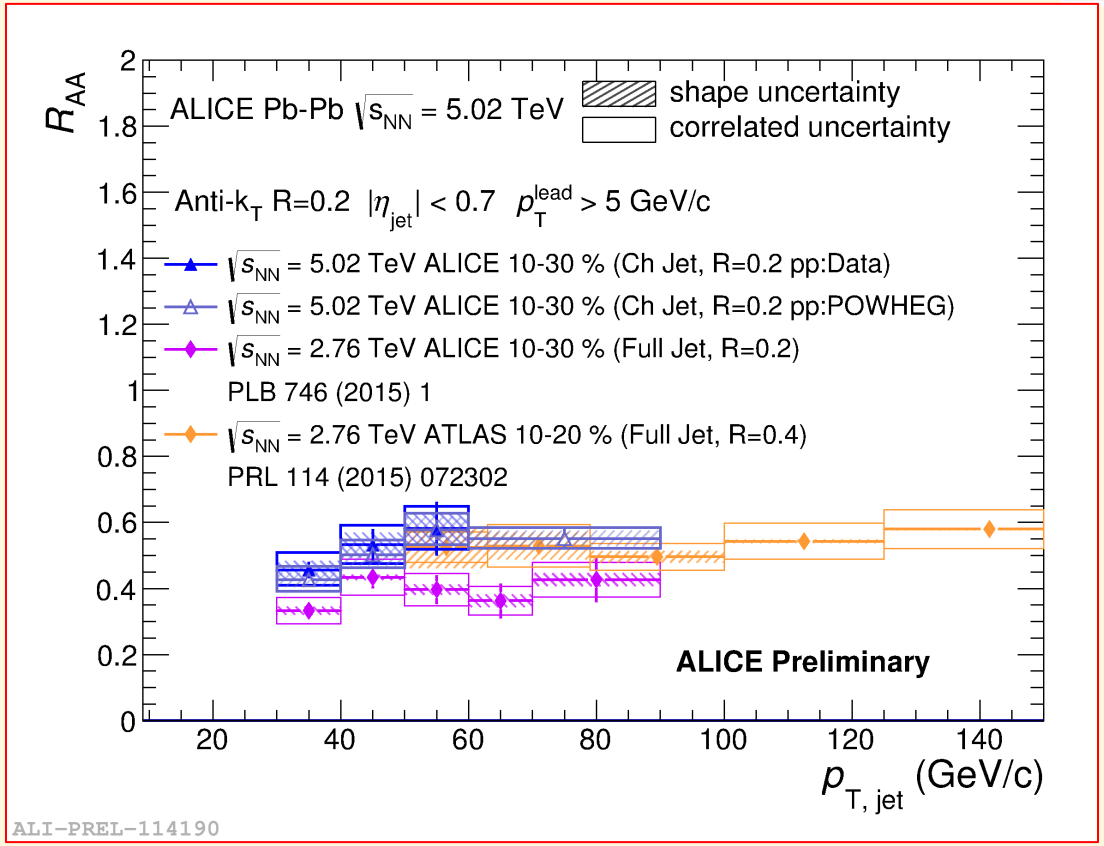
  Strong suppression at intermediate p_T ; stronger in more central (.. not due to initial state effects)

Jets in medium

$$R_{AA}^{jet} = \frac{dN/dp_T|_{PbPb}}{N_{coll}\, dN/dp_T|_{pp}}$$





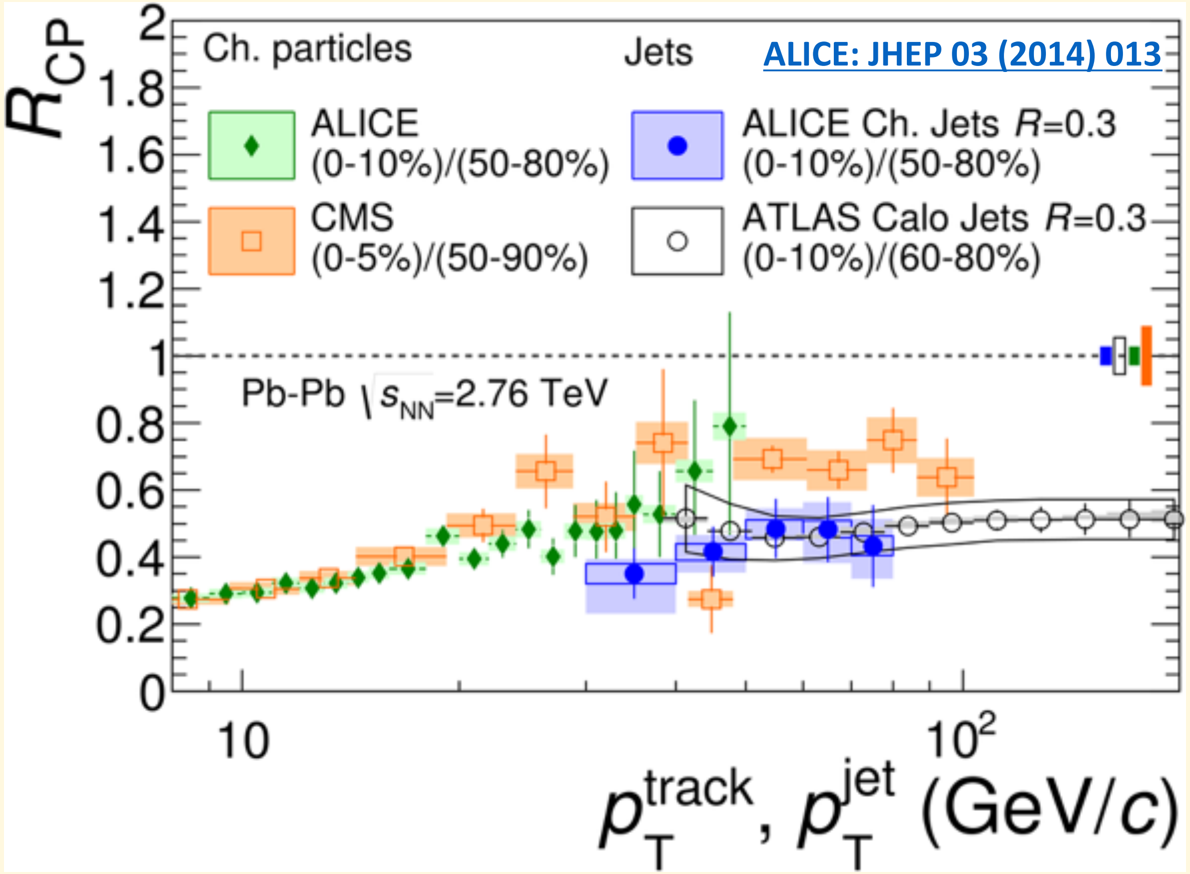


- Jet: hadrons and other particles produced by the hadronization of a quark or gluon in a narrow cone
- Hard partons in the presence of dense coloured medium lose energy via elastic scattering and multiple gluon radiation.
- Energy loss => medium properties

- Large jet suppression in Pb-Pb collisions with respect to pp

Energy loss of charged particles and of jets

Pb-Pb 2.76 TeV



R_{CP} is the ratio of the yield of central to peripheral

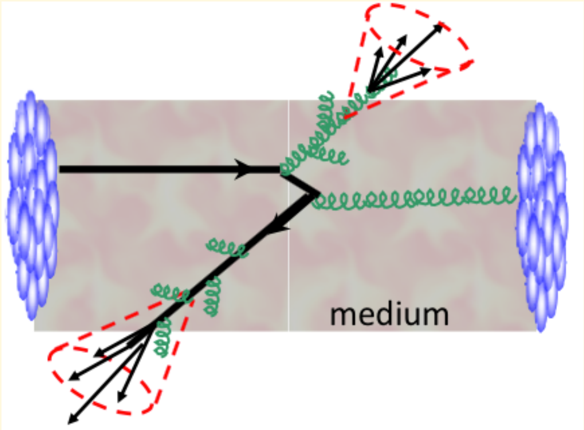
R_{CP} of charge jets is similar to that observed for single hadrons over a broad momentum range.

This is contrary to the expectation that the suppression for jets to be smaller than for hadrons, since jet reconstruction collects multiple jet fragments into the jet cone, thus recovering some of the medium-induced fragmentation.

=> the momentum is redistributed to angles larger than R = 0.3 by interactions with the medium.

Heavy flavours: probes of strongly interacting medium

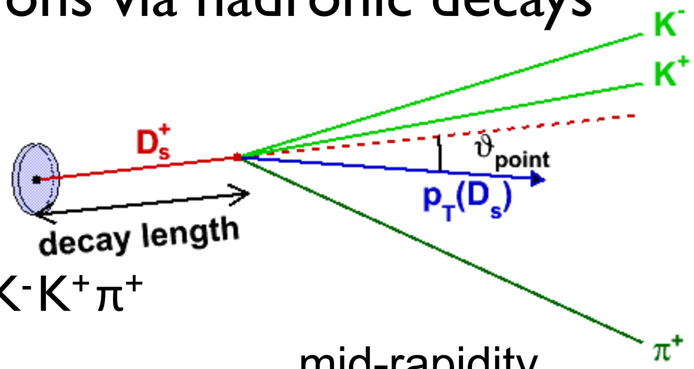
- c and b quarks are produced in initial high-Q^2 processes (calculable with pQCD)
- Large mass => short formation time => experience medium evolution
  $1/2m_c$ (~0.07 fm/c) < QGP formation time (~0.1-1fm/c) << QGP life time (10 fm/c)
- Small rate of thermal production in the QGP ($m_{c,b}$>>T)
- Traverse the QCD medium undergoing elastic and inelastic collisions in the medium



Open Heavy Flavours

Full reconstruction of charmed mesons and baryons via hadronic decays

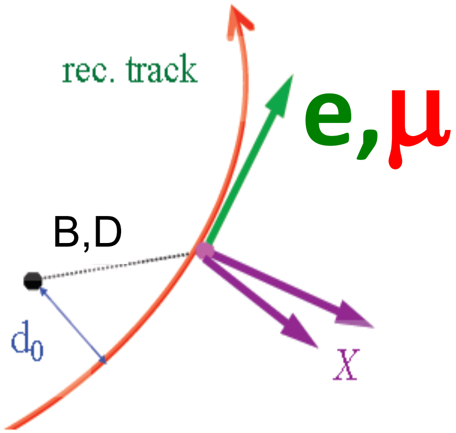
$D^0 \rightarrow K^-\pi^+$
$D^+ \rightarrow K^-\pi^+\pi^+$
$D^{*+} \rightarrow D^0\pi^+$
$D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$
$\Lambda_c^+ \rightarrow pK^-\pi^+$
$\Lambda_c^+ \rightarrow pK^0_s$



mid-rapidity
|y|<0.5

Semi-leptonic decays

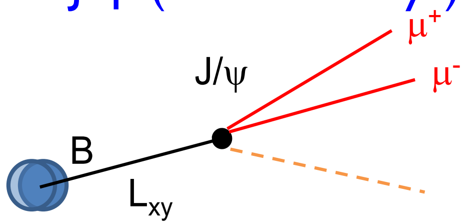
Electrons:
|y|<0.8
Muons:
2.5|y|<4



$D, B \rightarrow e,\mu\ X$
$B \rightarrow e\ X$ (via displaced impact parameter)
$\Lambda_c^+ \rightarrow e^+\nu_e\Lambda$
$\Xi_c^0 \rightarrow e^+\nu_e\ \Xi^-$

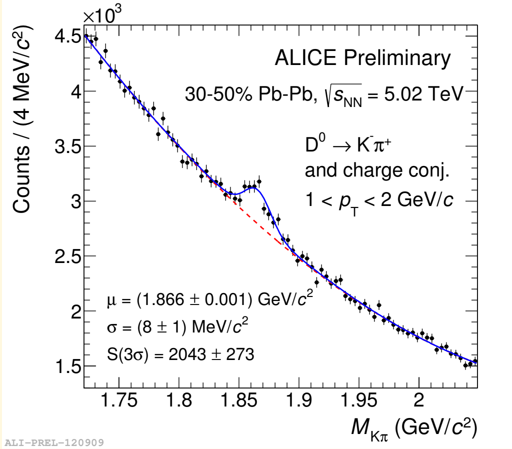
Displaced J/ψ (from B decays)

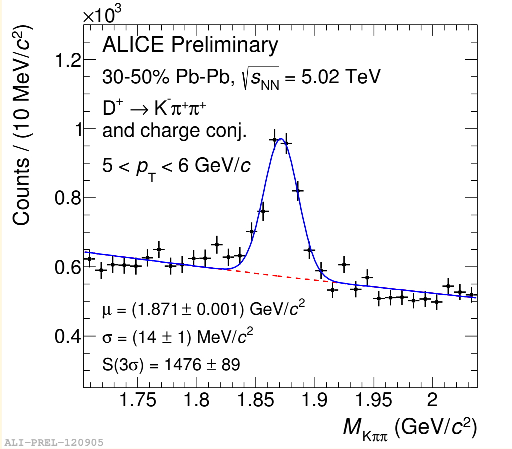
mid-rapidity
|y|<0.9

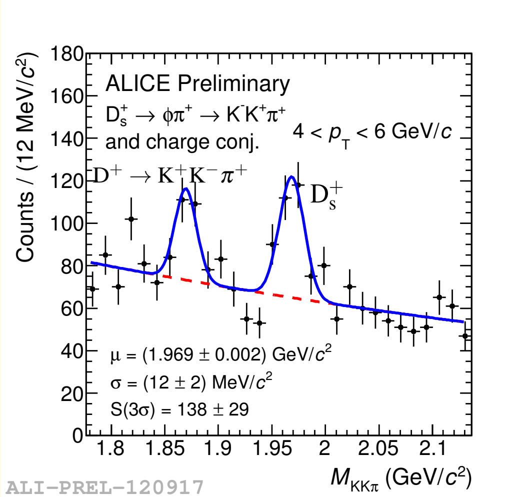


Probe with charmed mesons:

Measurement of D^0, D^+, D^{*+} and D_s^+







D^+: $c\bar{d}$

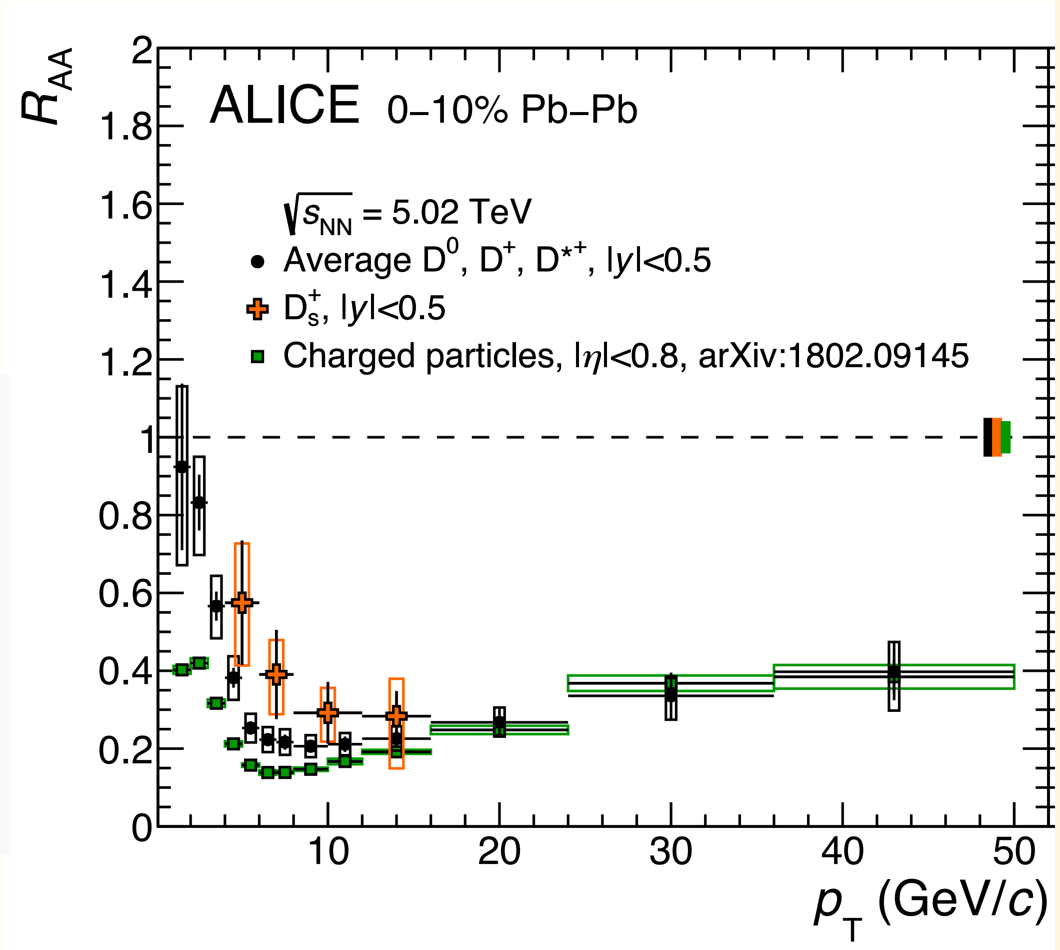
D^-: $d\bar{c}$

D^0: $c\bar{u}$

$\bar{D}^0$: $u\bar{c}$

D_s^+: $c\bar{s}$

D_s^-: $s\bar{c}$



$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

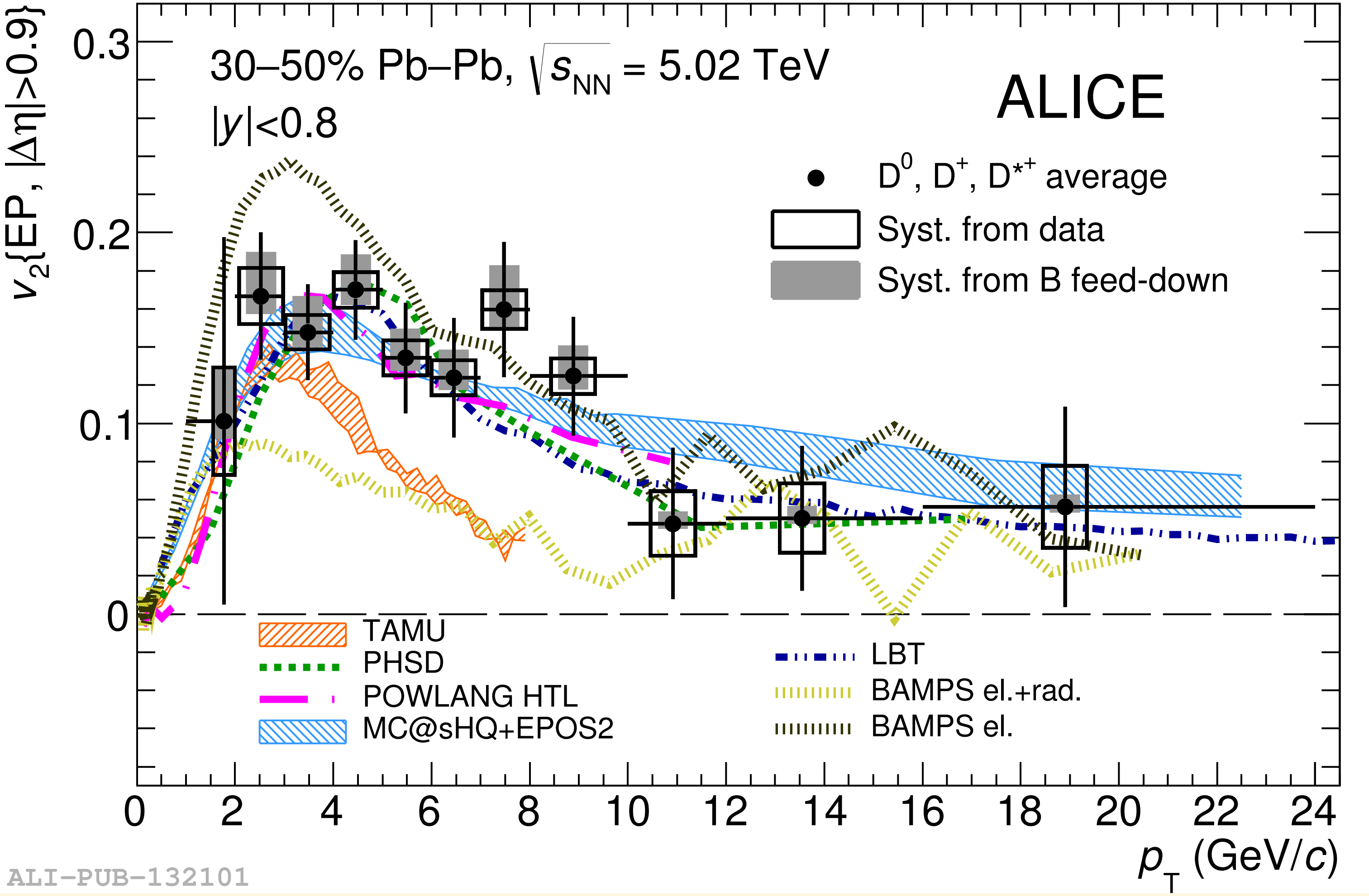
Strong suppression of open heavy-flavour mesons in central Pb-Pb @ 5.02 TeV

- A minimum of 0.2 for 5-6 GeV/c indicates significant energy loss
- R_{AA} compatible with charged particles for $p_T > 8$ GeV
- Non-strange D mesons are more suppressed compared to D_s^+

D meson strongly interacting with the medium.

Does that mean **it flows too?**

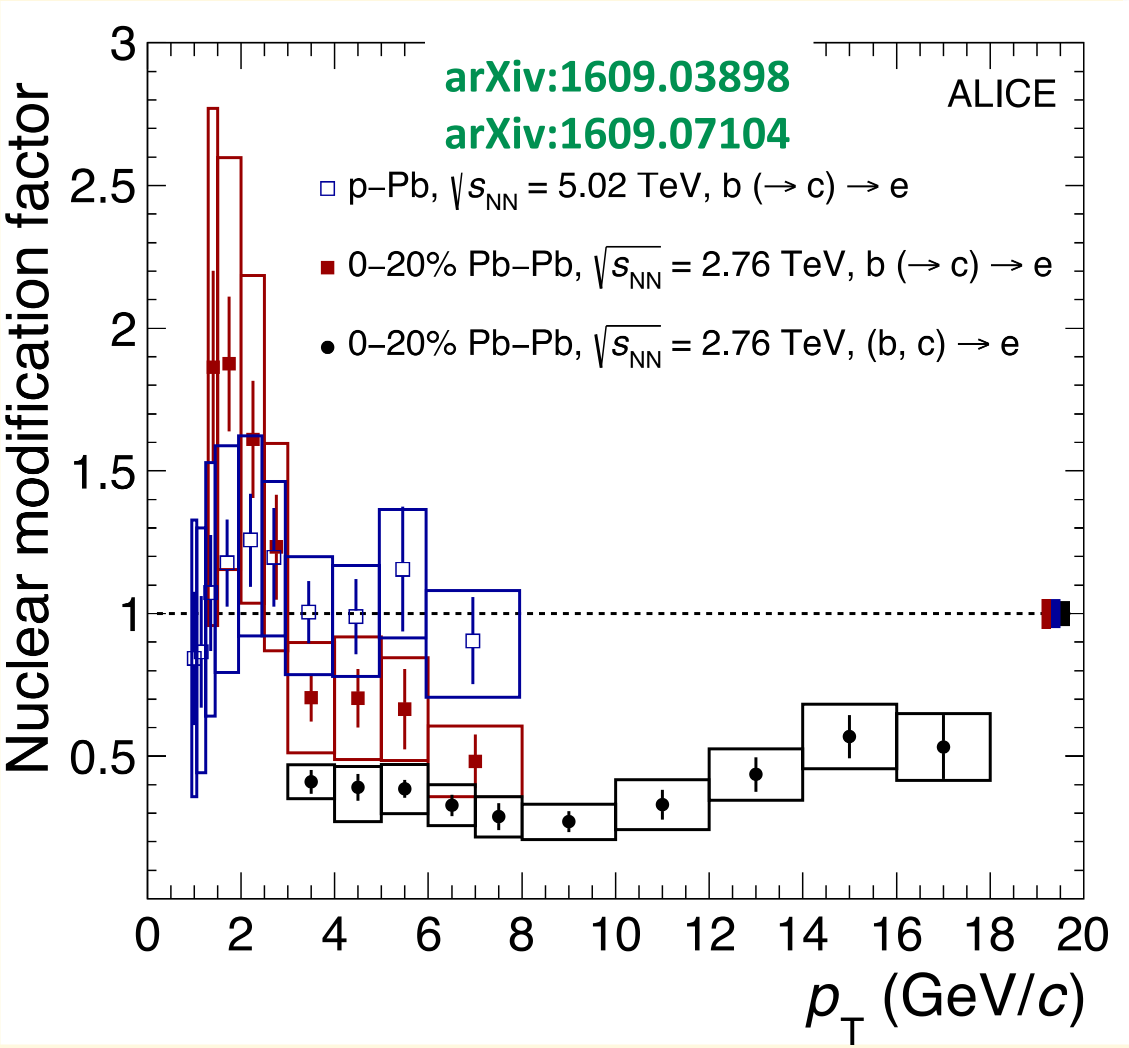
D-meson elliptic flow



The results of the D meson elliptic flow v2 show non-zero value for 2 < p_T < 10 GeV/c in 30–50% centrality class, which provide information of the collective expansion of the system.

Beauty-hadron decays in mid-rapidity:

- Electrons from heavy-flavour hadron decays in p-Pb collisions show no indication of modification of the production with respect to pp collisions, indicating that cold nuclear matter effects are small.
- The observed reduction in central Pb-Pb relative to pp can be attributed to the presence of the hot and dense medium formed in Pb-Pb collisions => beauty quarks interact with the medium.
- The larger suppression of electrons from both charm- and beauty-hadron decays compared with the beauty-only measurement (within large uncertainties) is consistent with the ordering of charm and beauty suppression as seen in the comparison of prompt D mesons (ALICE) and J/Ψ from B meson decays (CMS).



Nuclear modification factors of electrons from beauty-hadron decays at mid-rapidity for p-Pb and central Pb-Pb collisions.

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

J/Ψ suppression

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

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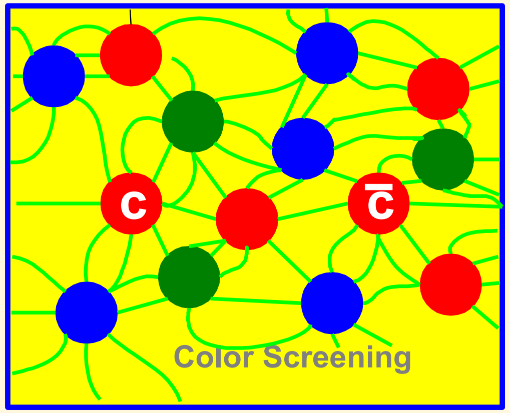
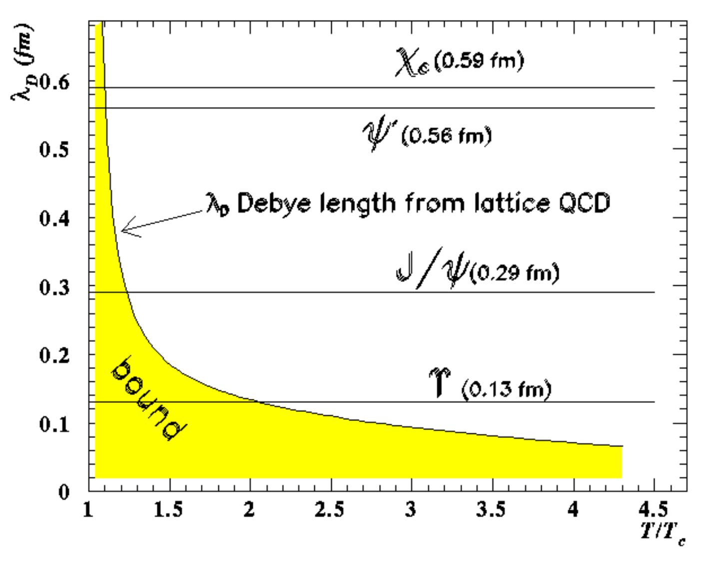
Received 17 July 1986

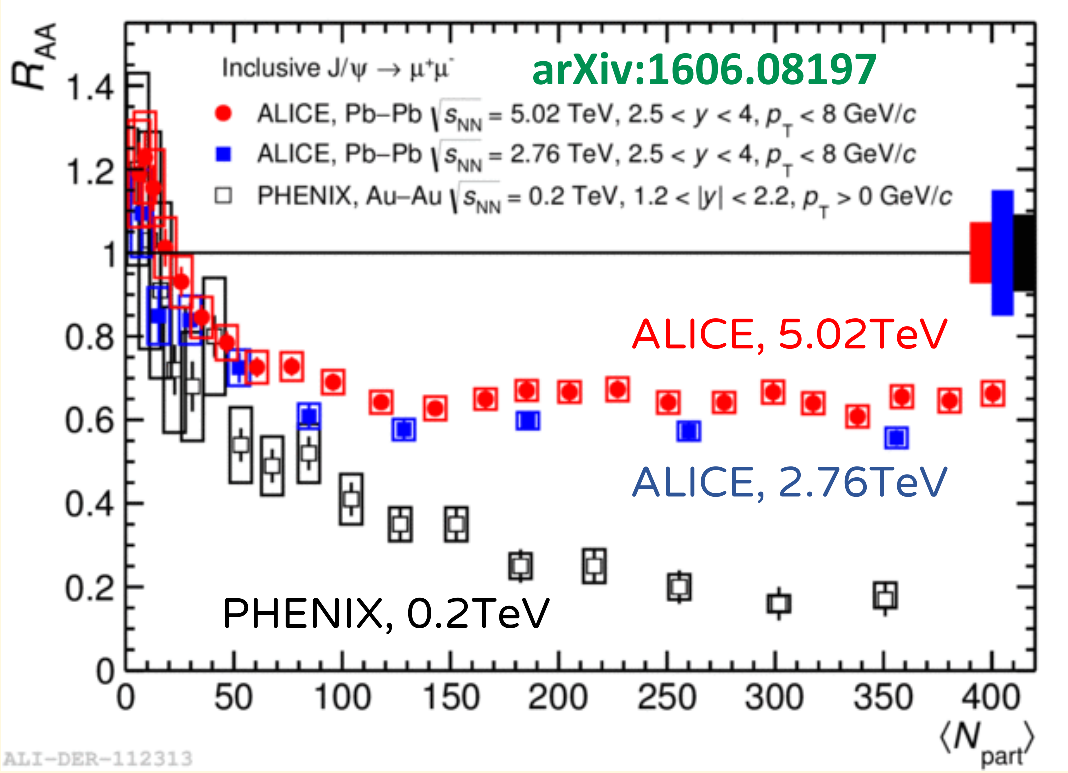
If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

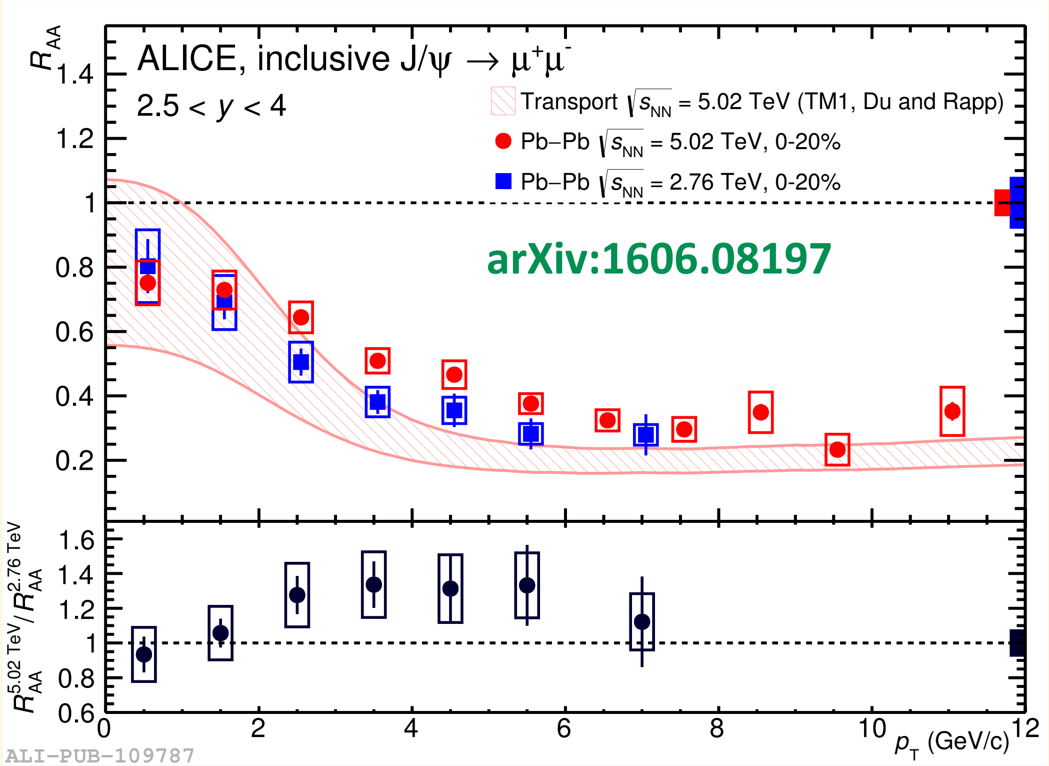




- In the plasma phase the interaction potential is expected to be screened beyond the Debye length λ_D (analogous to e.m. Debye screening):
- Charmonium (cc) and bottonium (bb) **states with r > λ_D will not bind**; their production will be suppressed

J/Ψ production in forward rapidity

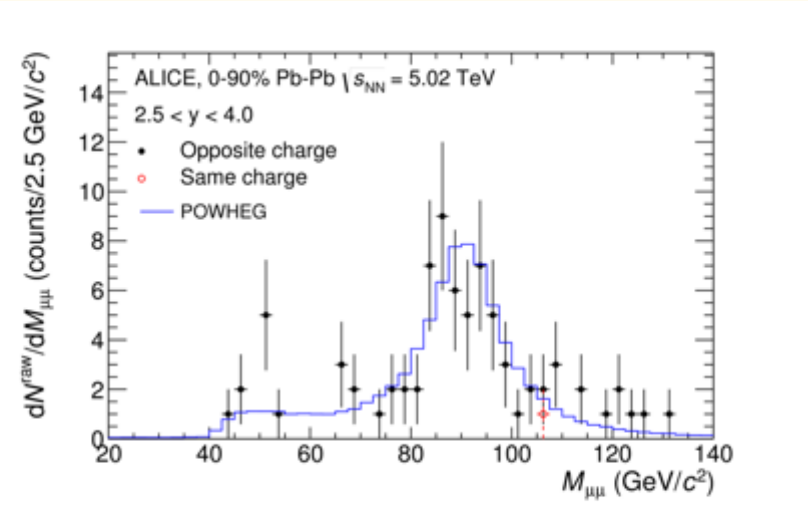




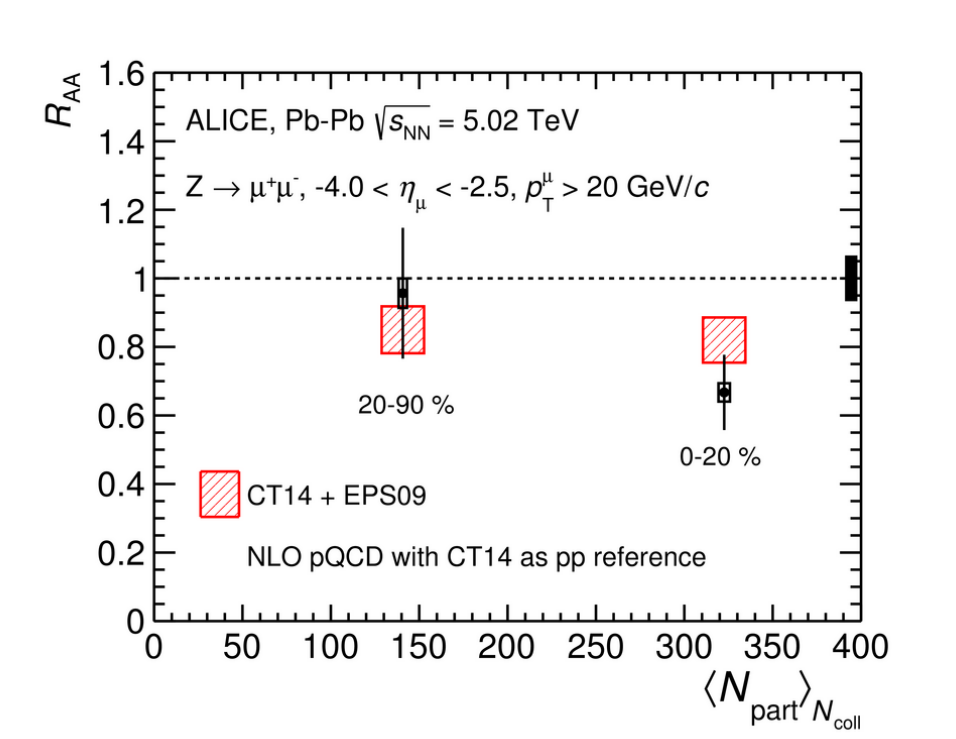
- R_{AA} *vs* centrality: increasing suppression with centrality up to Npart ~ 100, followed by a constant R_{AA}
- Stronger suppression at RHIC energies (PHENIX) compared to LHC => role of recombination
- J/Ψ at Pb-Pb 5.02 TeV is less suppressed (by ~15%) compared to 2.76 TeV
- R_{AA} *vs* p_T has been compared to different models. Models with dissociation and regeneration are consistent with data within the uncertainties.

Z^0 boson production in Pb-Pb

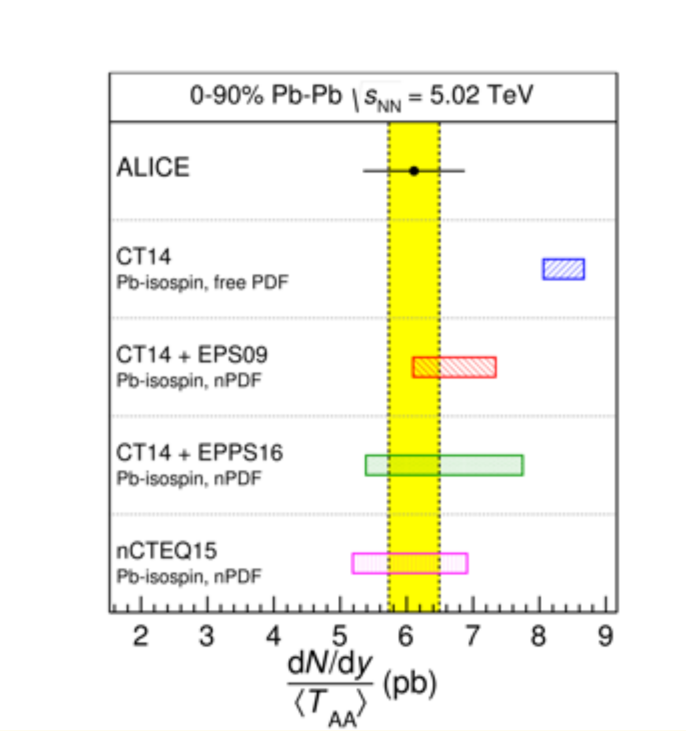
ALICE, Phys. Lett. B 780, 372



Nuclear modification factor

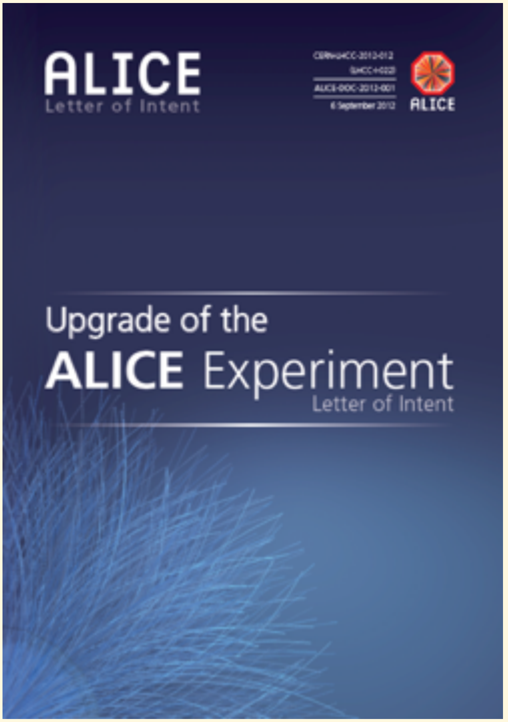


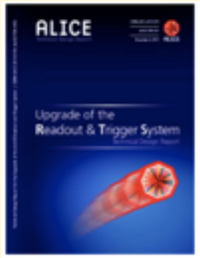
- insensitive to QGP
- sensitive to quark, gluon density in the nucleus
- yield suppressed by ~30%
  - in agreement with nuclear PDFs



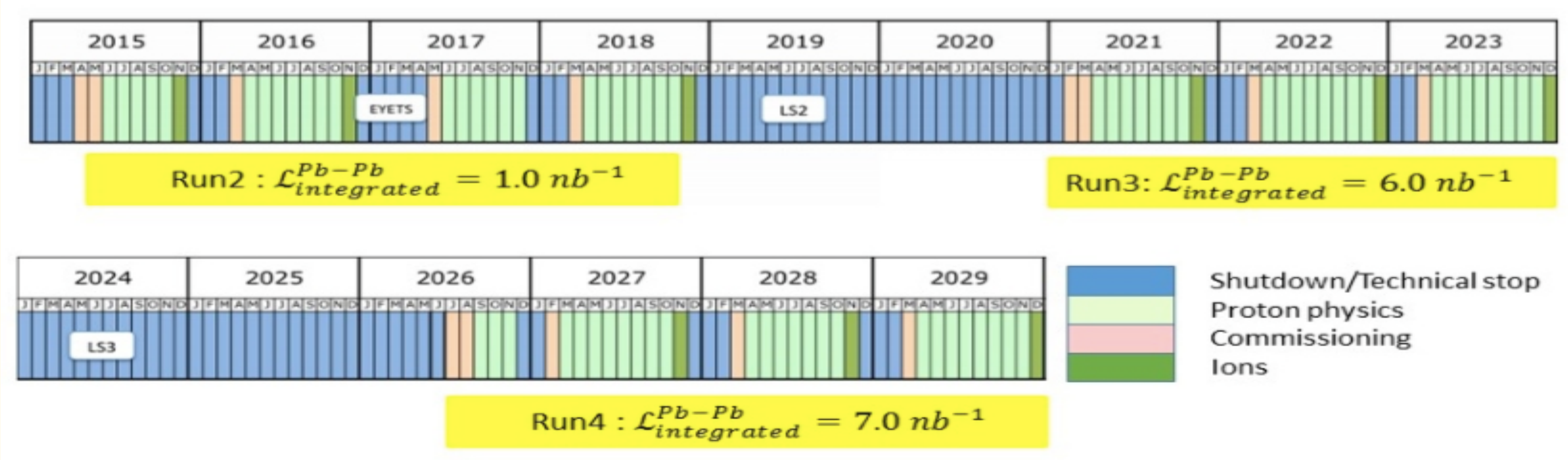
comparison to theory (with/without shadowing)

ALICE LS2 upgrades





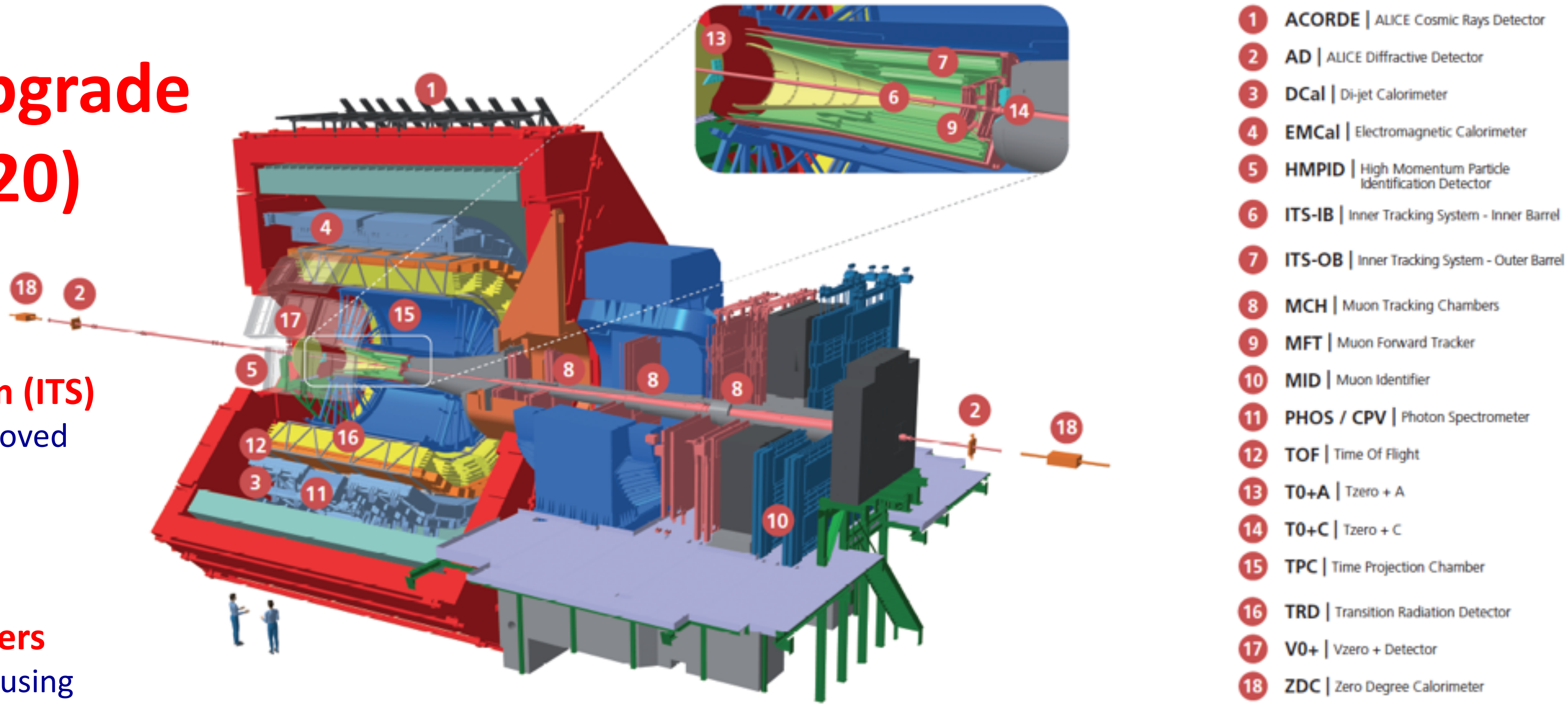
LHC timeline



→ 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

ALICE LS2 Upgrade (2019-2020)



New Inner Tacking System (ITS)

- MAPS technology: improved resolution
- Less material,
- Faster readout

New TPC Readout Chambers

- New readout chambers using 4-GEM technology
- New electronics for continuous readout (SAMPA)

New Forward Muon Tracker (MFT)

- Vertex tracker at forward rapidity

Muon Arm

- New electronics (SAMPA)
- New electronics for Muon Trigger

Online Offline (O2) system

- new computing facility
- on line tracking & data compression
- 50kHz Pb-Pb event rate

Common Projects:

Common Readout Unit (CRU)

SAMPA common FE chip

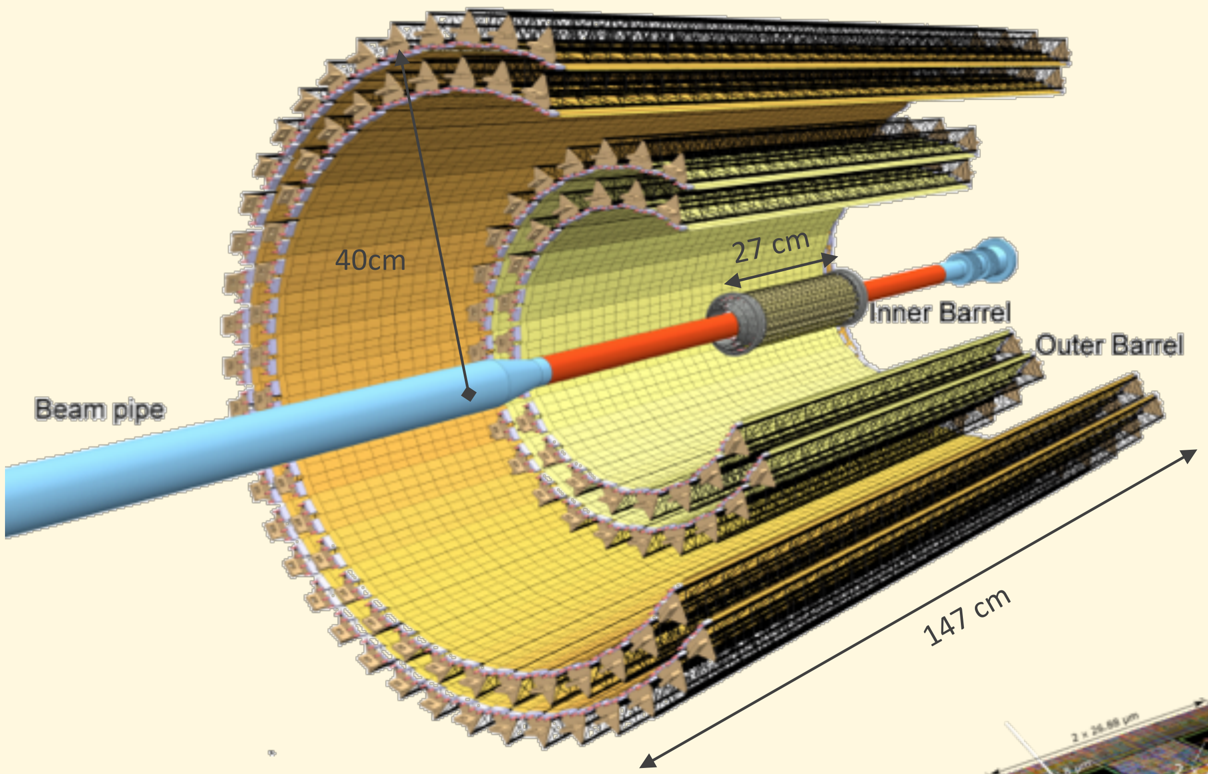
New Trigger Detectors (FIT, AD)

- + centrality, event plane

New Central Trigger Processor (CTP)

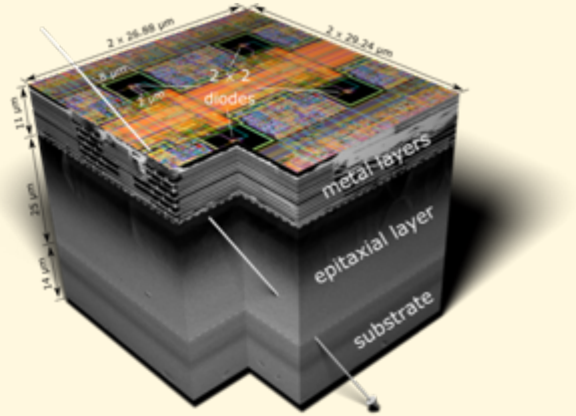
Upgraded readout for TOF, TRD, PHOS, EMCAL, CPV, HMPID

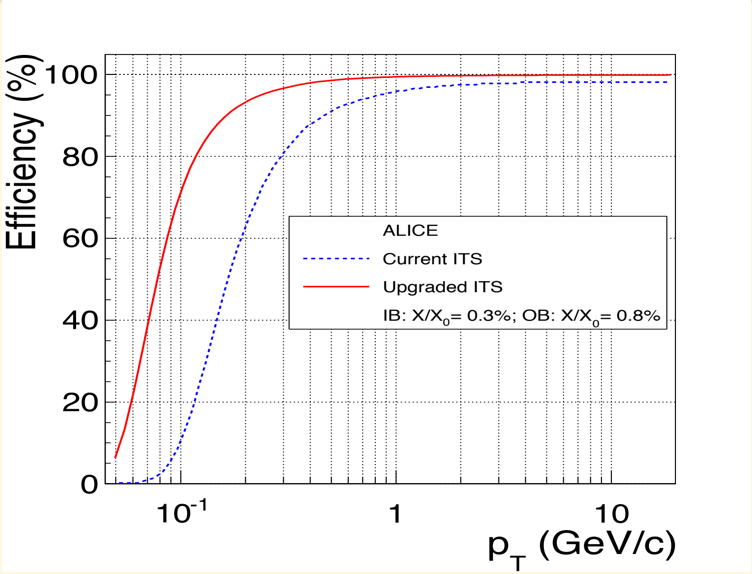
ITS Upgrade



- 7-layer geometry (23 – 400mm), $|\eta| \leq 1.5$)
- 10 m^2 active silicon area (**12.5 G-pixels**)
- Pixel pitch 28 x 28 μm^2
- Spatial resolution ~5μm
- Power density < 40mW / cm^2
- Material thickness: ~0.3% / layer (IB)
- Maximum particle rate: 100 MHz / cm^2

Based on CMOS Monolithic Active Pixel Sensors (MAPS)

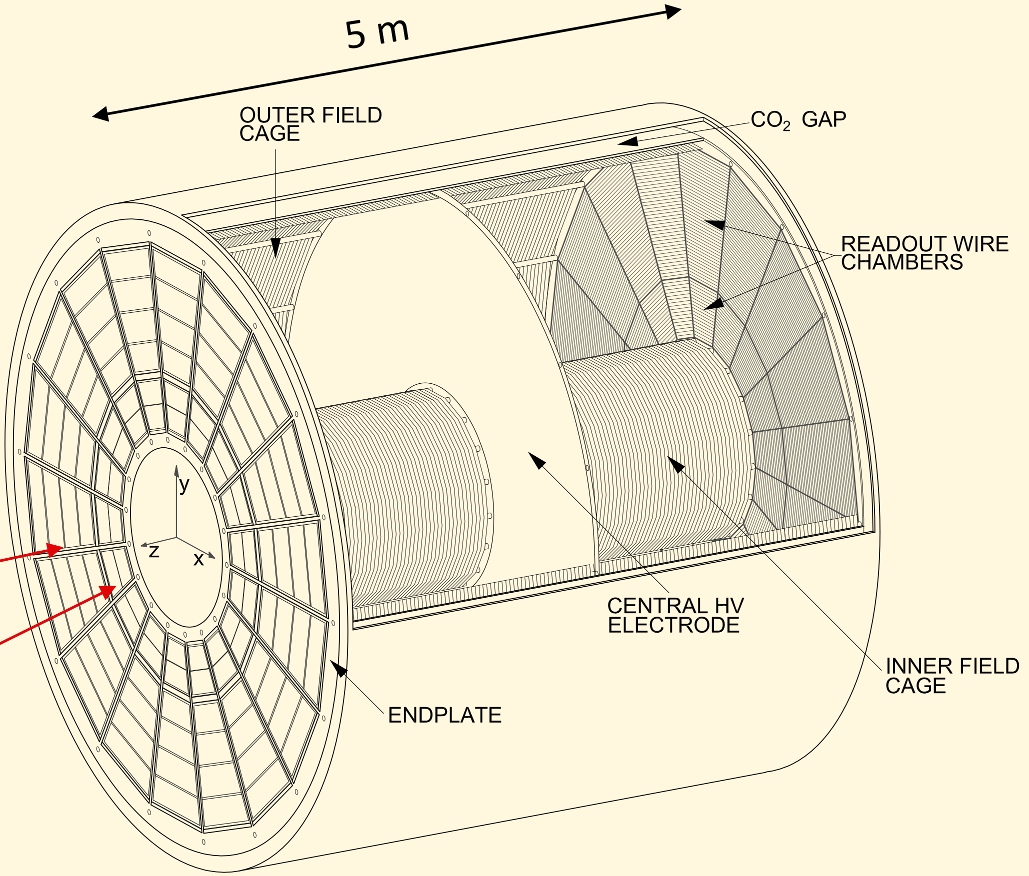


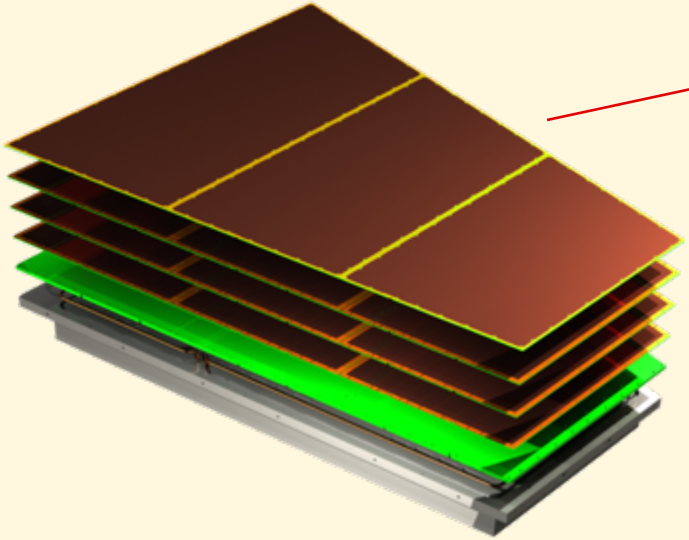


TPC Upgrade with GEMs

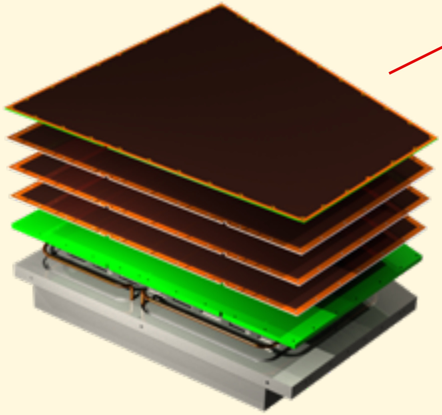
World's Largest TPC: key tracking and PID instrument with 275 million pixels

- **Goal:** replace existing MWPC-based Readout Chambers and Front-End Electronics in LS2 to allow **continuous readout** of Pb-Pb collisions at **50 kHz** in RUN3 and 4
- **Technical solution: 4-layer GEM** detectors

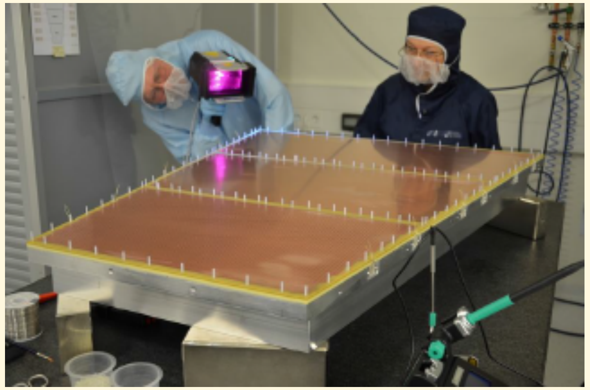




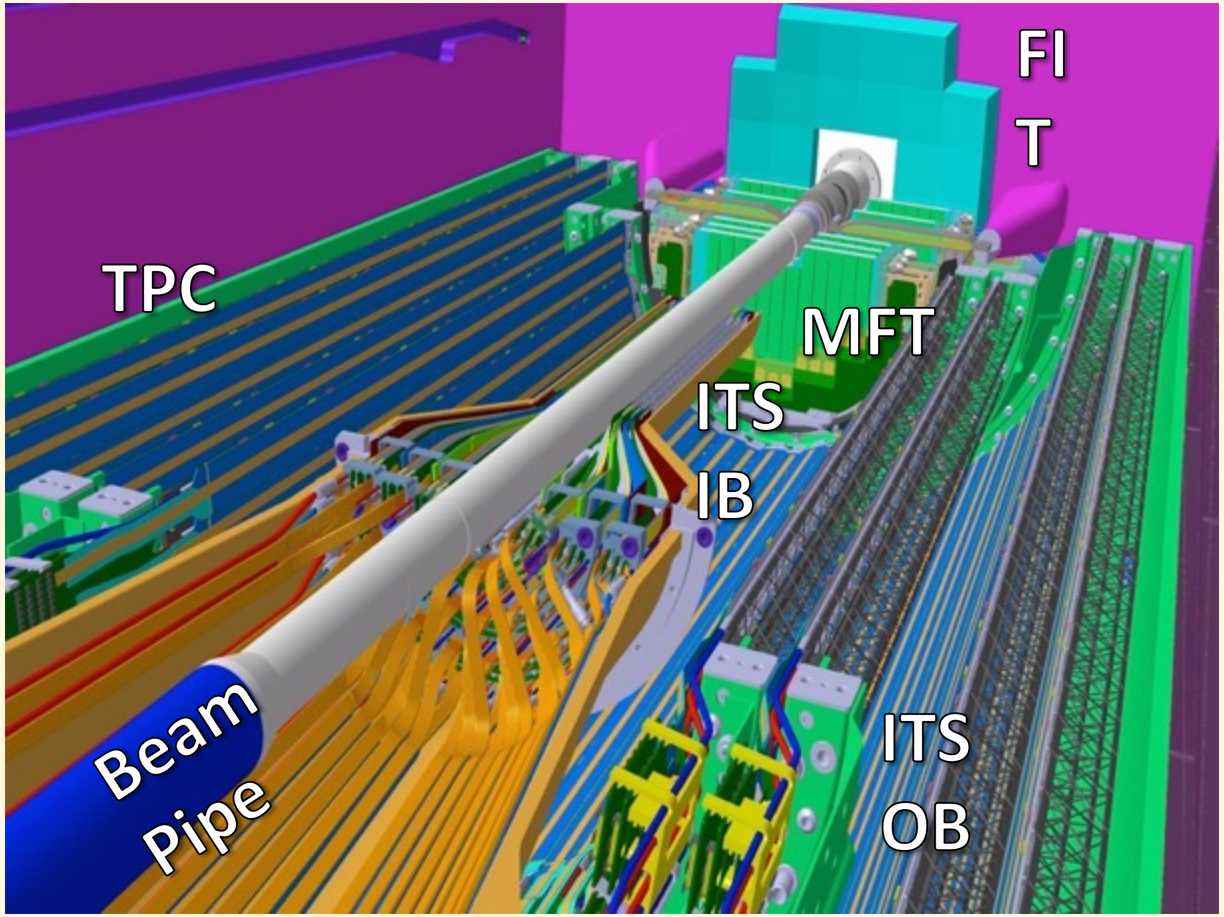
OROC (18+18)



IROC (18+18)

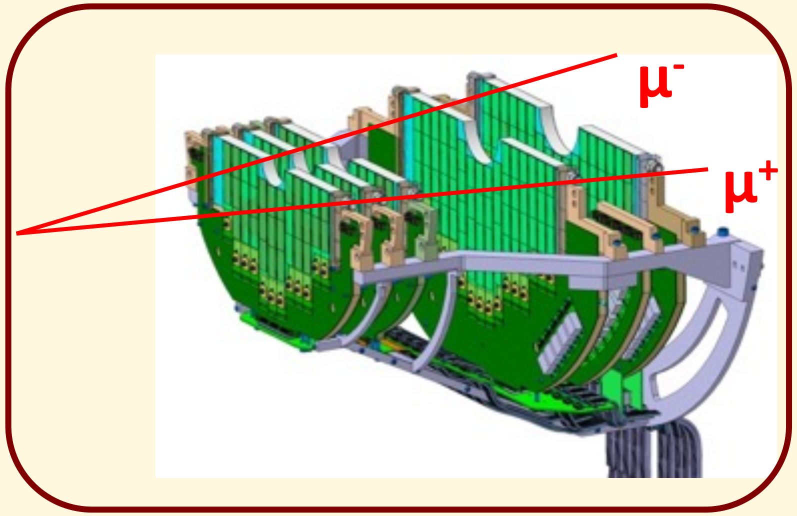


Muon Forward Tracker



Goals:

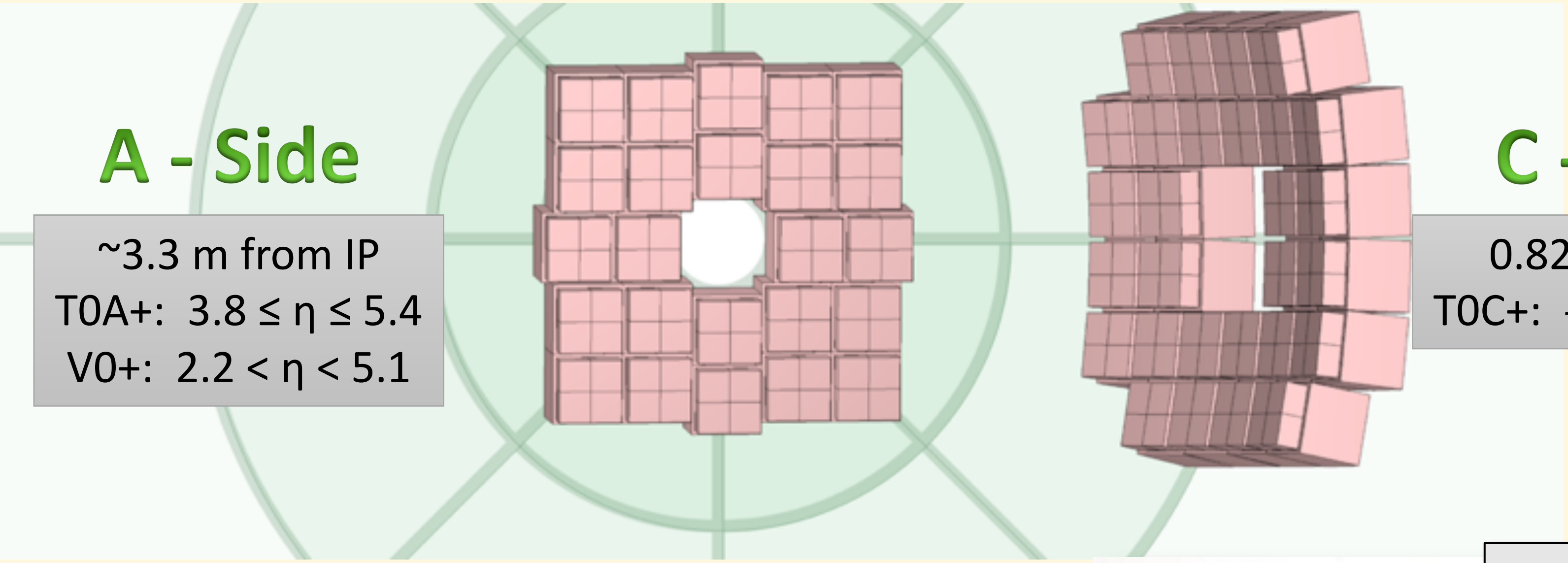
- HF decay vertices
  - forward y → Lorentz boost
- μ from c and b down to p_T > 1 GeV
- b → J/ψ down to zero p_T



Muon tracks are extrapolated and matched to the MFT tracks before the absorber.

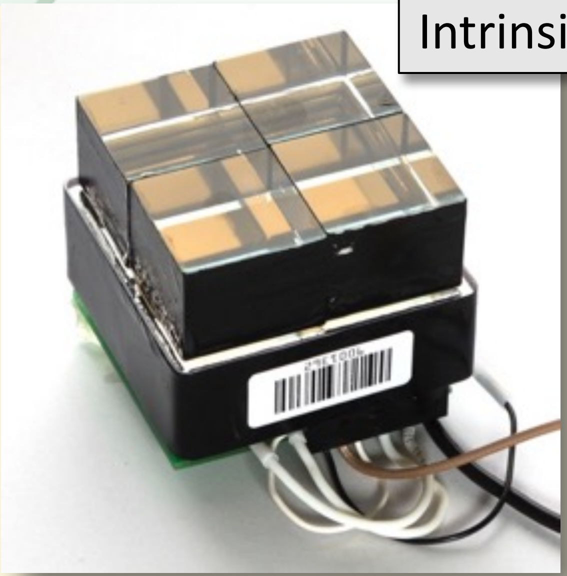
Silicon Pixel tracker with ALPIDE → **High pointing accuracy**

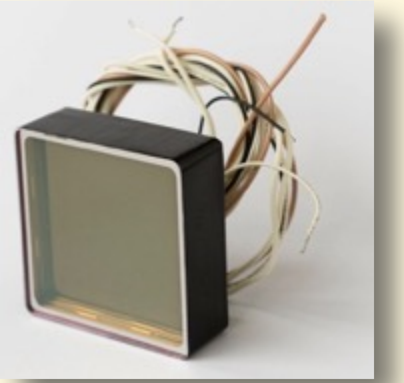
Fast Interaction Trigger (FIT)



- Luminosity monitoring & feedback to LHC
- Fast Interaction Trigger with LM latency < 425 ns
  - Online Vertex determination
  - Minimum Bias and centrality selection
  - Rejection of beam/gas events
  - Veto for Ultra Peripheral Collisions
- Collision time for Time-Of-Flight particle ID
- Multiplicity → Centrality and Event Plane

Intrinsic resolution < 20 ps





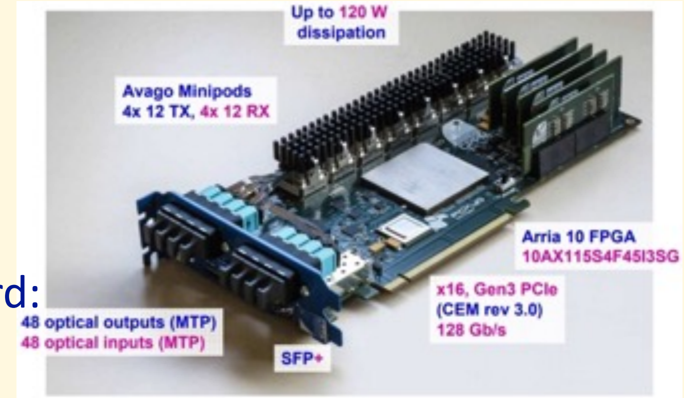
PLANACON® XP85012 + quartz radiators

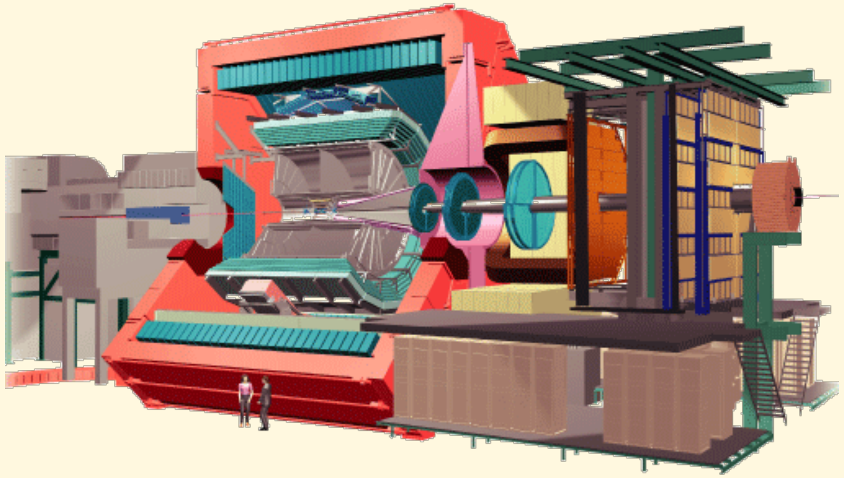
Read-out Architecture

	Before LS2	RUN3
Luminosity	10^{27} cm^{-2} s^{-1}	**6 x 10^{27} cm^{-2} s^{-1}**
Collision rate	8 kHz (PbPb)	**50 kHz (PbPb)**
Max Readout rate	500 Hz (PbPb)	**PbPb: 50 kHz pp & pPb: 200 kHz**

- Several detectors will have continuous readout to address pileup and avoid trigger-generated dead-time.
- Online/Offline (O2) Facility: to reduce recorded data volume by doing the online reconstruction.
- Common Readout Unit (CRU) of O2: tasked to perform data concentration, reconstruction and multiplexing.

CRU FPGA Board:





50 kHz (70 MB/event)
3.3 TB/s

Online
Offline
(O2)

CRU

50 kHz (1.5 MB/event)

Storage

80 GB/s (peak)

Summary

Accelerator and detector technology:

- Excellent performance of the LHC
- Excellent heavy-ion physics program involving all four experiments
- New detector technologies, electronics as well as new data taking and computing models developed. Fully ready for the upgrades ..

Physics harvest continues:

QGP properties:

- Energy density, temperatures
- Freeze-out parameters
- Hadron chemistry
- Energy loss, nuclear modification factors
- Jet quenching
- Precision on QGP parameters

Collective effects in small systems:

- System-size dependence of observables
- Collective effects in small systems
- Medium effects in small systems
- Rich input for proton-proton modelling

Looking forward:

- Even after 25 years, it seems to back to the beginning with an aggressive upgrade program
- ALICE will continue to take data until 2028 (LS 4) and continue to address fundamental questions