



Technical University of Dresden, 11° of May 2017

*An introduction to ALICE at the  
LHC: physics goal and experimental  
apparatus*

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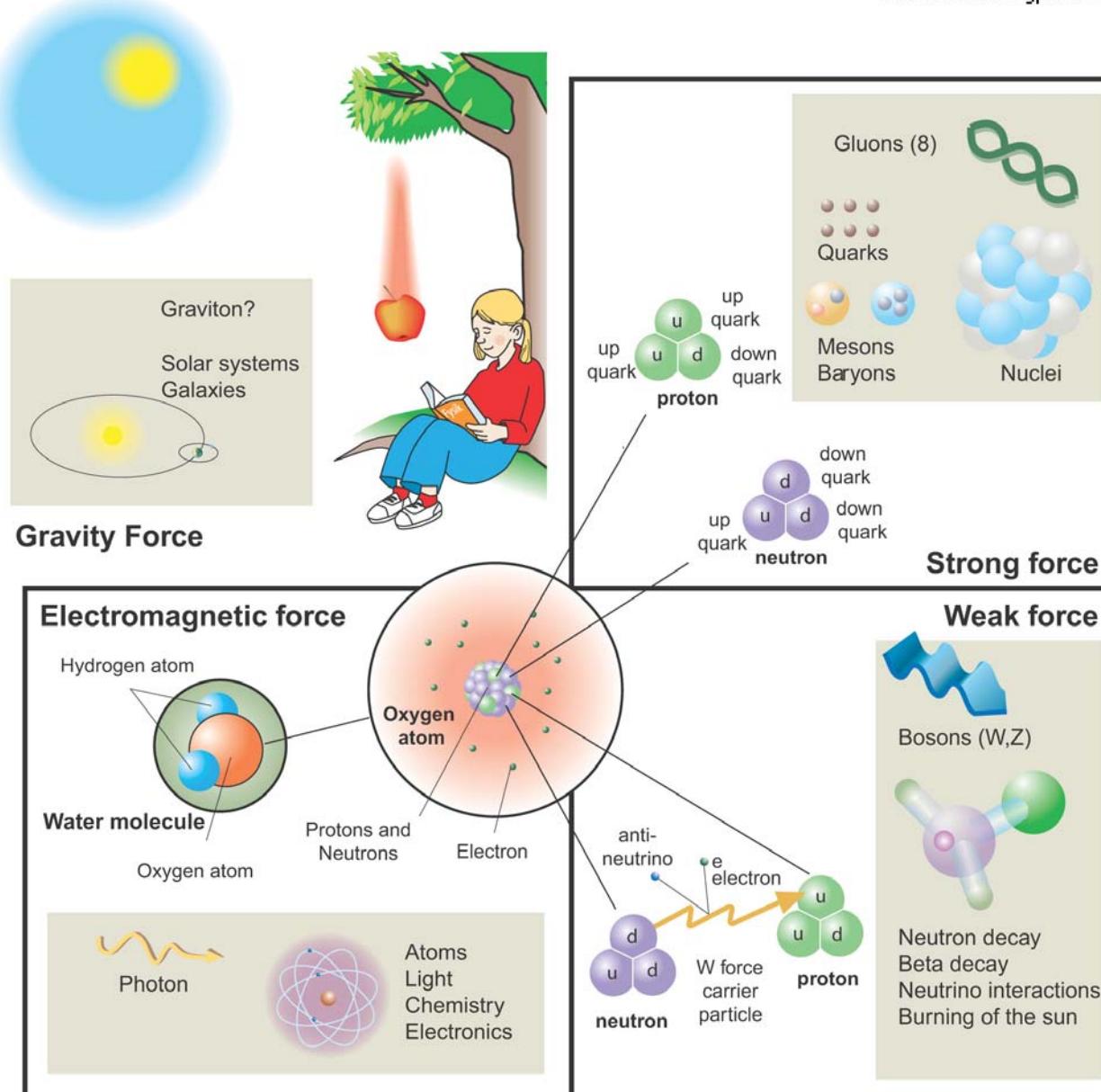
# Outline

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- Introduction
  - Quantum Chromodynamics
  - Quark-Gluon Plasma
  - Relativistic Heavy-ion Collisions
- ALICE at LHC
  - Experimental apparatus
  - Results overview from Pb-Pb collisions (**personal selection**)
    - Soft probes
    - Hard probes
  - Some results from small colliding systems (**personal selection**)
- ALICE upgrade
- Conclusions

# Fundamental interactions

Illustration: Typoform



# Costituents of matter

**FERMIIONS**

matter constituents  
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ electron neutrino	$<1 \times 10^{-8}$	0	<b>u</b> up	0.003	2/3
e electron	0.000511	-1	<b>d</b> down	0.006	-1/3
$\nu_\mu$ muon neutrino	<0.0002	0	<b>c</b> charm	1.3	2/3
$\mu$ muon	0.106	-1	<b>s</b> strange	0.1	-1/3
$\nu_\tau$ tau neutrino	<0.02	0	<b>t</b> top	175	2/3
$\tau$ tau	1.7771	-1	<b>b</b> bottom	4.3	-1/3

**BOSONS**

force carriers  
spin = 0, 1, 2, ...

Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge	Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0	<b>g</b> gluon	0	0
$W^-$	80.4	-1			
$W^+$	80.4	+1			
$Z^0$	91.187	0			

Ordinary matter

# Hadrons

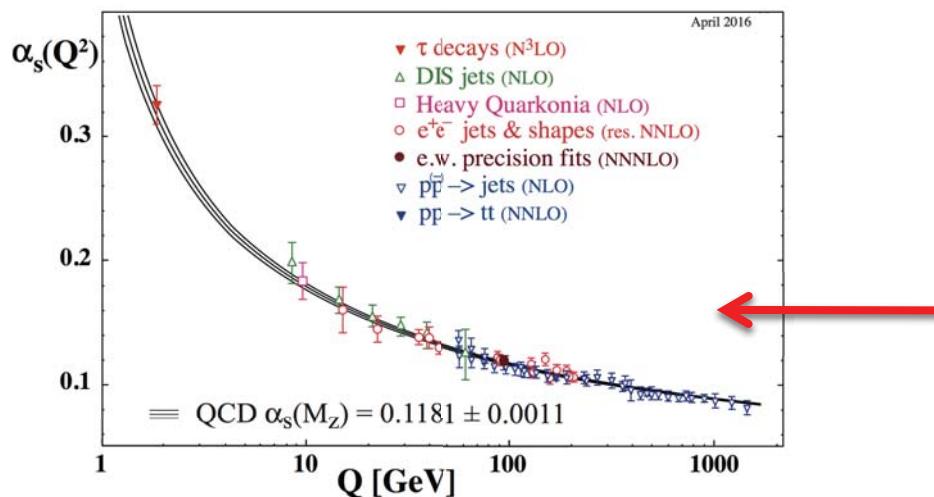
Not fundamental particles made up of quarks

Baryons $qqq$ and Antibaryons $\bar{q}\bar{q}\bar{q}$						Mesons $q\bar{q}$					
Baryons are fermionic hadrons. There are about 120 types of baryons.						Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass $\text{GeV}/c^2$	Spin	Symbol	Name	Quark content	Electric charge	Mass $\text{GeV}/c^2$	Spin
p	proton	uud	1	0.938	1/2	$\pi^+$	pion	u $\bar{d}$	+1	0.140	0
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2	K $^-$	kaon	s $\bar{u}$	-1	0.494	0
n	neutron	udd	0	0.940	1/2	$\rho^+$	rho	u $\bar{d}$	+1	0.770	1
$\Lambda$	lambda	uds	0	1.116	1/2	B $^0$	B-zero	d $\bar{b}$	0	5.279	0
$\Omega^-$	omega	sss	-1	1.672	3/2	$\eta_c$	eta-c	c $\bar{c}$	0	2.980	0

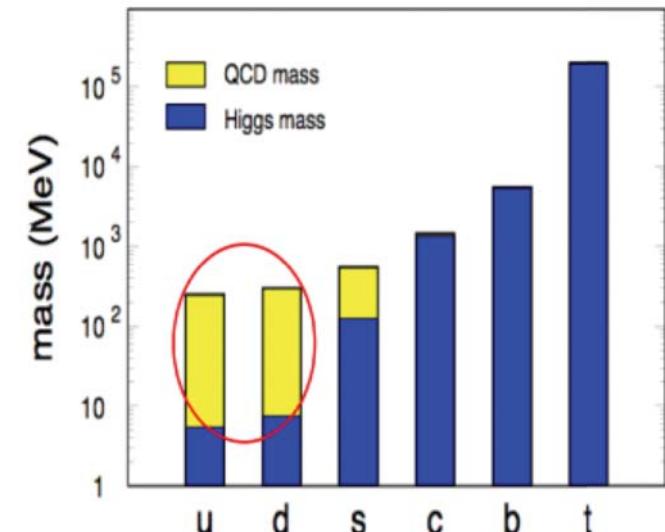
# Quantum Cromodynamics

- Quantum Cromodynamics (QCD) → theory of the **strong interaction**.
  - Quarks and gluons confined in hadrons → **confining property of QCD**
    - Coupling constant  $\alpha_s$  is large
    - QCD not perturbative
  - Chiral symmetry spontaneously broken: **largest contribution to nucleons mass** → generated as a consequence of the interaction among constituent quarks
  - $\alpha_s$  becomes weak for processes involving large momentum transfers → **asymptotic freedom**
    - small  $\alpha_s$
    - perturbative approach to QCD

C. Patrignani et al. (PDG), Chin. Phys. C, 40, 100001 (2016)



Nucl. Phys. A750 (2005) 84–97

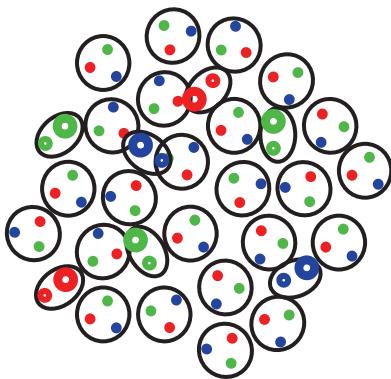


Masses of the six quark flavors. The masses generated by electroweak symmetry breaking (current quark masses) are shown in dark blue; the additional masses of the light quark flavors generated by spontaneous chiral symmetry breaking in QCD (constituent quark masses) are shown in light yellow. Note the logarithmic mass scale.

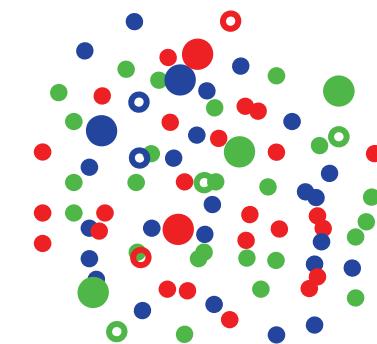
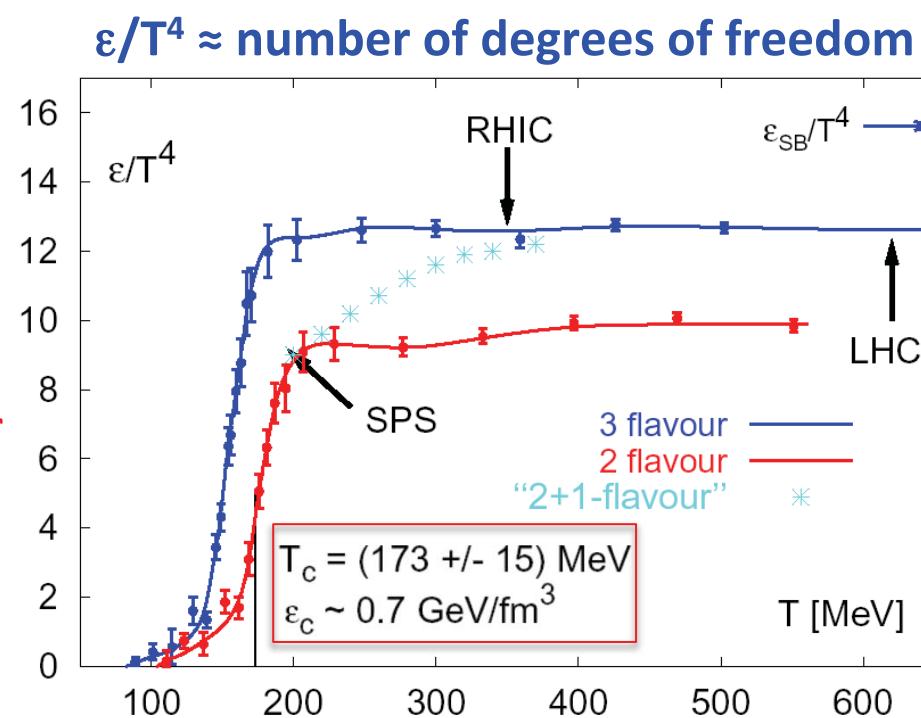
Summary of measurements of  $\alpha_s$  as a function of the energy scale  $Q$ . The respective degree of QCD perturbation theory used in the extraction of  $\alpha_s$  is indicated in brackets (NLO: next-to-leading order; NNLO: next-to-next-to leading order; res. NNLO: NNLO matched with resummed next-to-leading logs; NNNLO (N3LO): next-to-NNLO).

# Quantum Chromodynamics

- Open questions:
  - hadrons-partons transition.
  - Nuclear matter behaviour at high temperature and energy density condition.
- It is foreseen that, above a critical temperature,  $T_c$ , or energy density,  $\epsilon_c$ , strongly interacting matter undergoes a phase transition to a new state where the quarks and the gluons are no longer confined in hadrons → **Quark-Gluon Plasma (QGP)**
  - Chiral symmetry restoration.
  - From QCD lattice calculation →  $T_c \approx 170,  $\epsilon_c \approx 1\text{ GeV/fm}^3$$

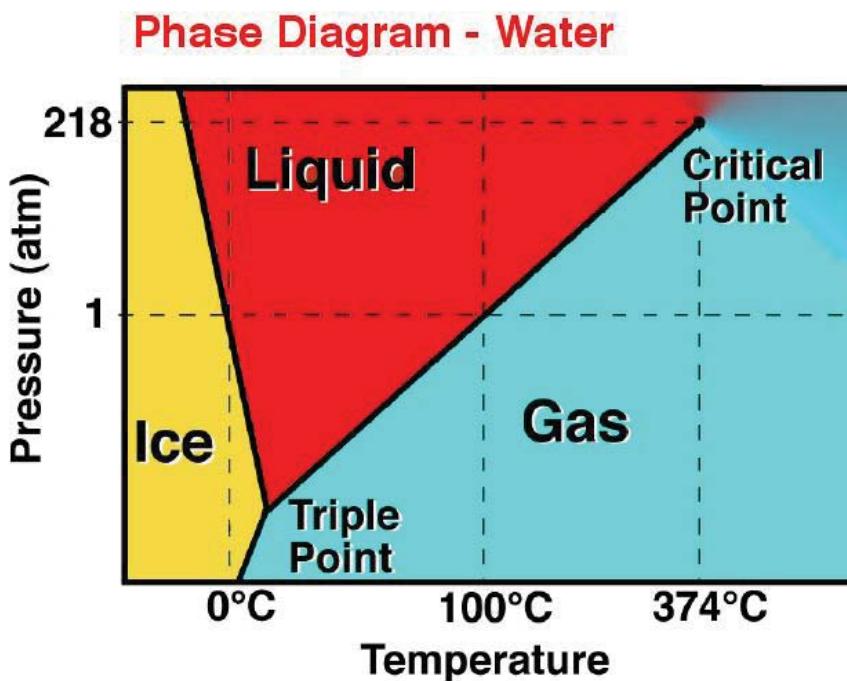
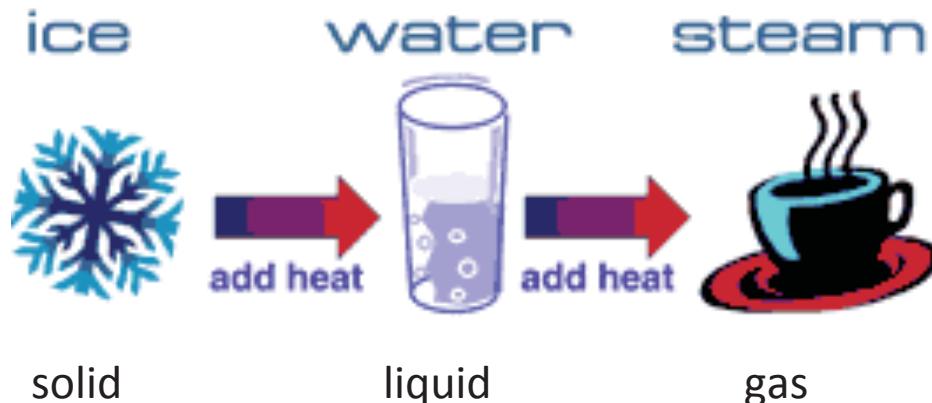


Ordinary nuclear matter: quarks are confined in the nucleons

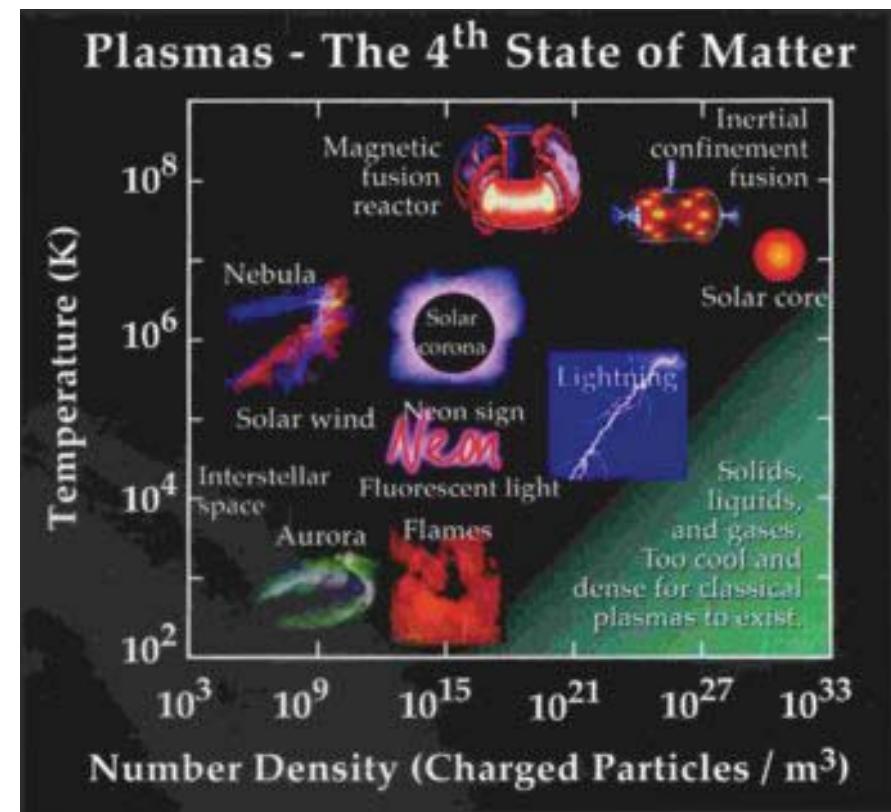


QGP: quarks and gluons deconfined are free

# Phases of Normal Matter



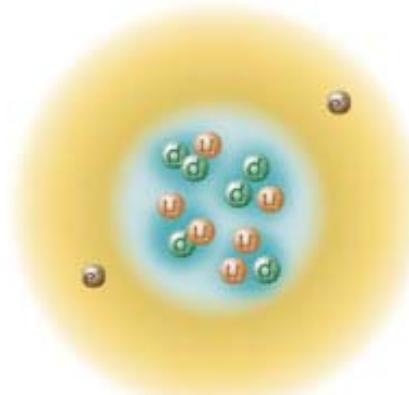
## Electromagnetic plasma



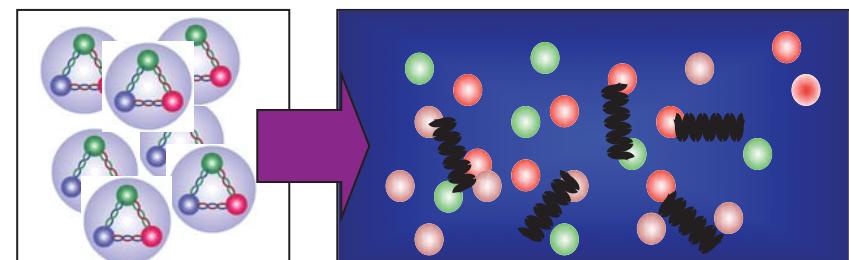
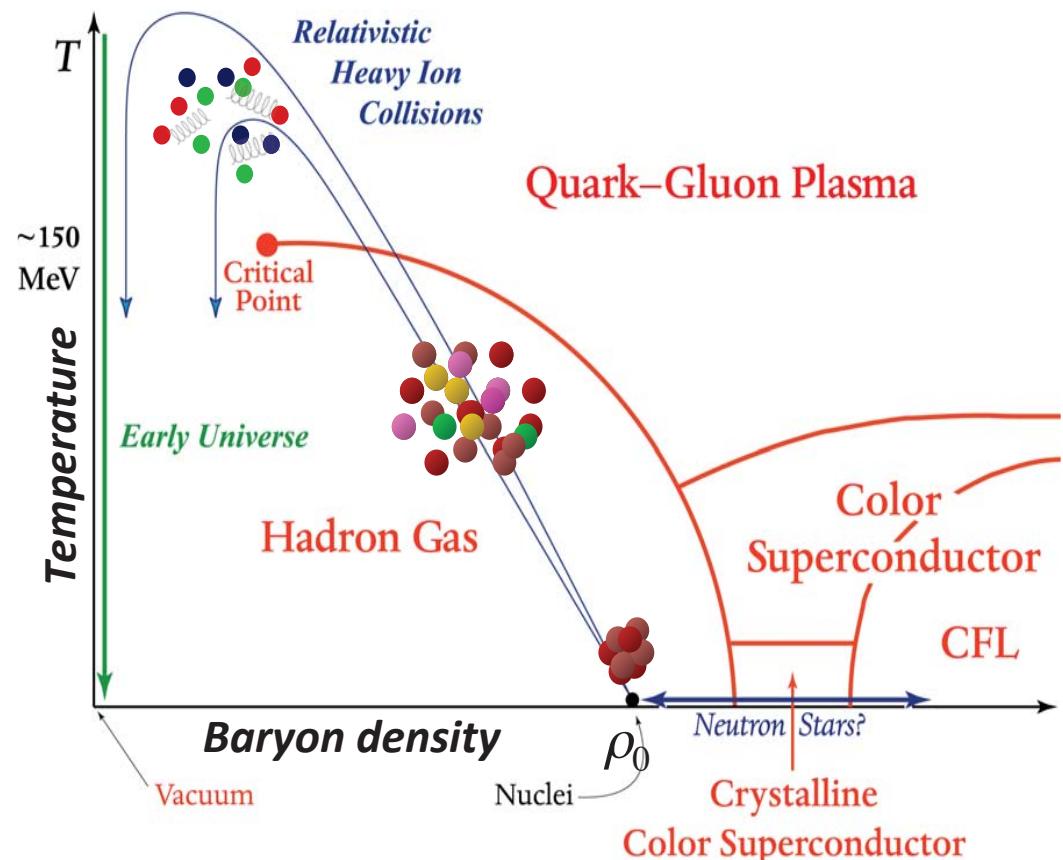
- Electromagnetic interactions determine phase structure of **normal matter**

# Phases diagram of QCD Matter

- We have strong interaction analogues of the familiar phases

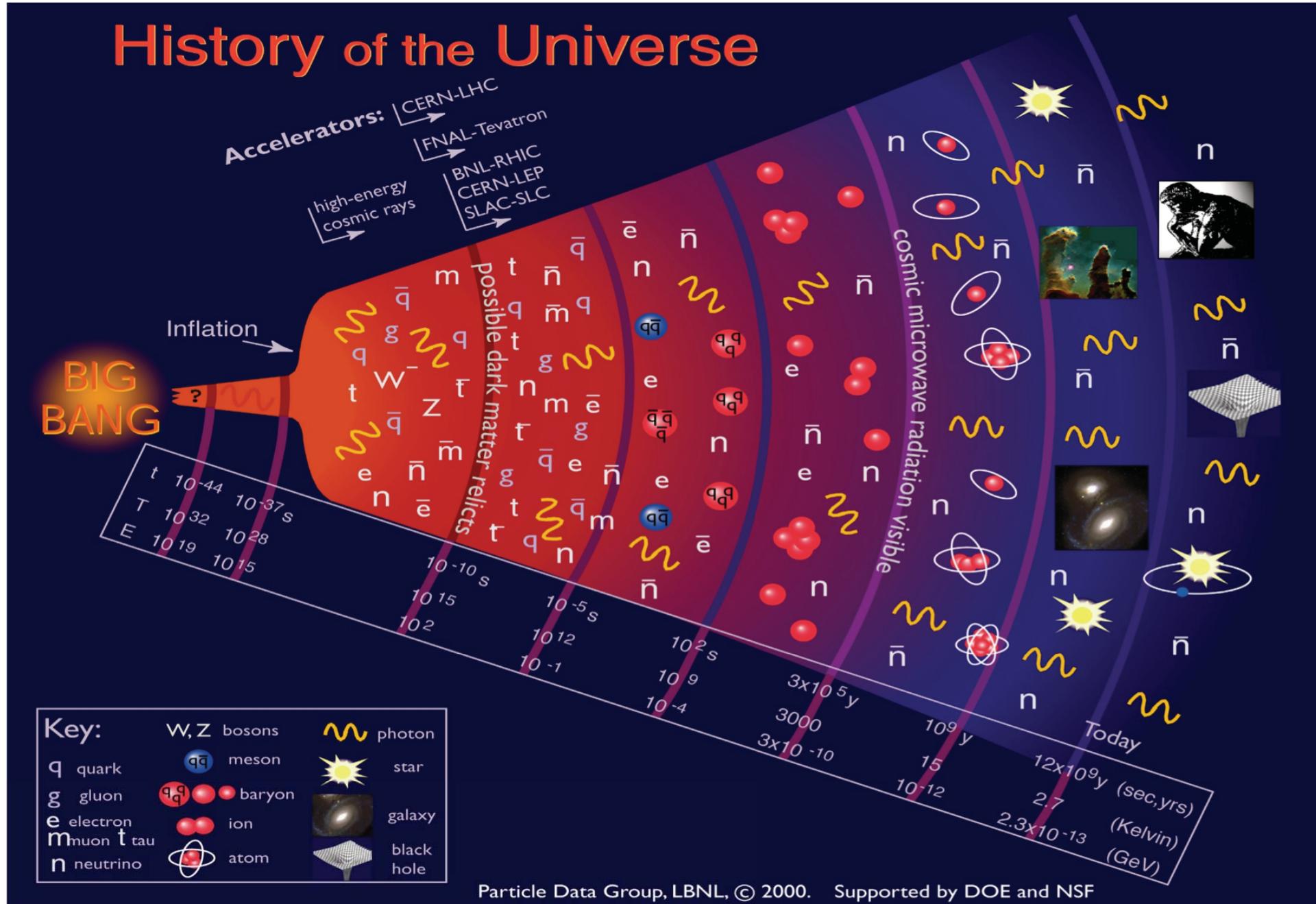


- Nuclei behave like a liquid
  - Nucleons are like molecules
- **Quark Gluon Plasma**
  - “Ionize” nucleons with heat
  - “Compress” them with density
- **New state of matter!**



# QGP in the Universe

## History of the Universe

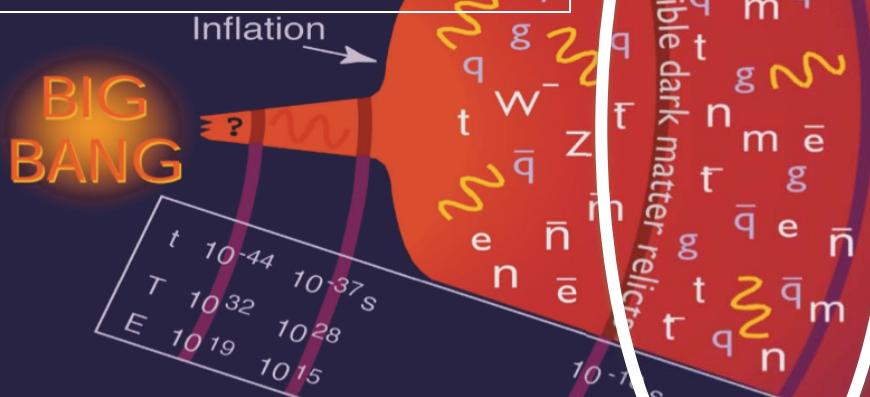


# QGP in the Universe

## History of the Universe

In the early stages of the Universe, Quarks and gluons were free

Accelerators:  
high-energy cosmic rays  
CERN-LHC  
FNAL-Tevatron  
BNL-RHIC  
CERN-LEP  
SLAC-SLC

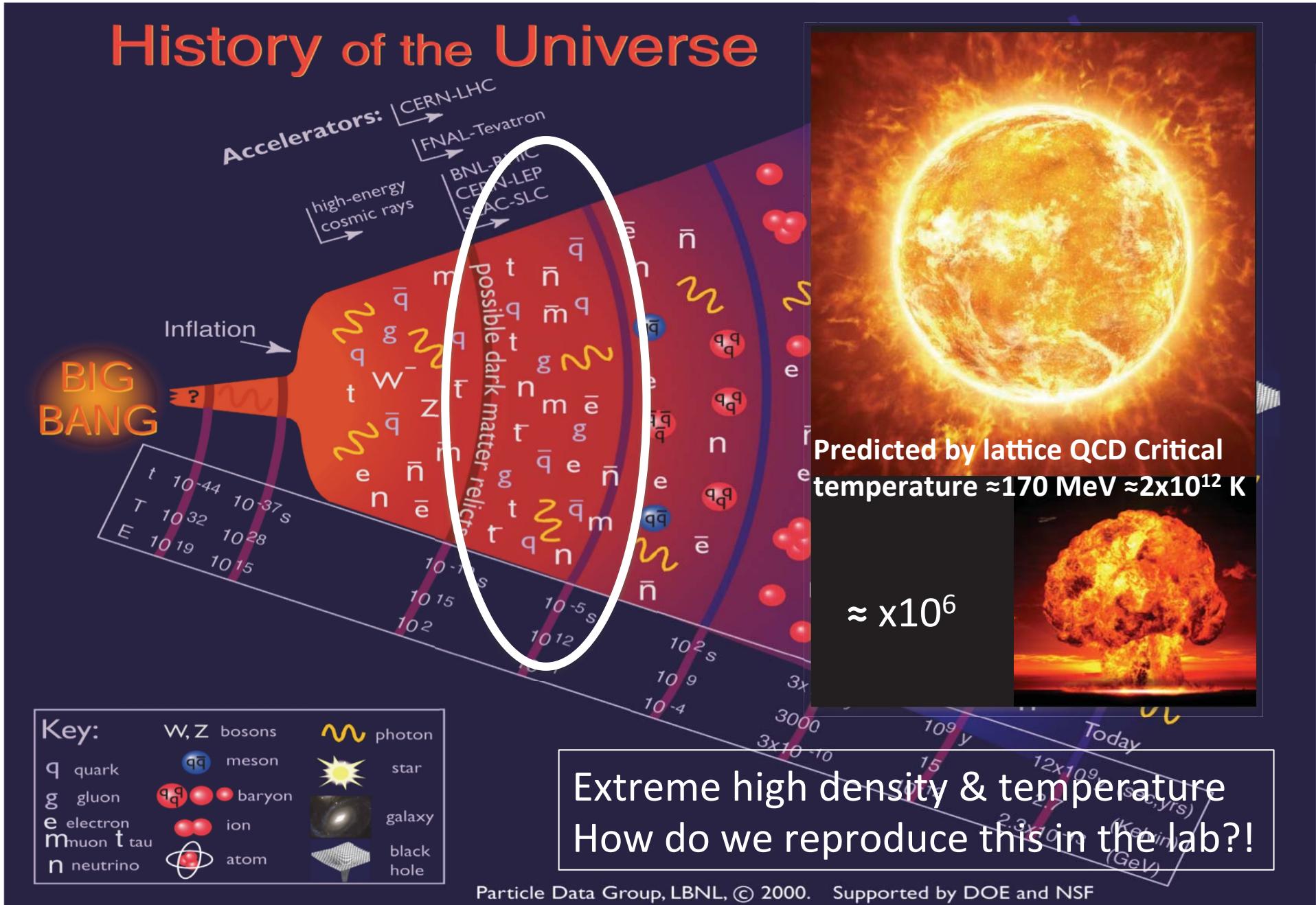


As the universe cooled down, they got confined and have remained imprisoned ever since.....

Key:	
W, Z bosons	photon
q quark	
g gluon	
e electron	
m muon	
t tau	
n neutrino	
meson	
baryon	
ion	
atom	
star	
galaxy	
black hole	

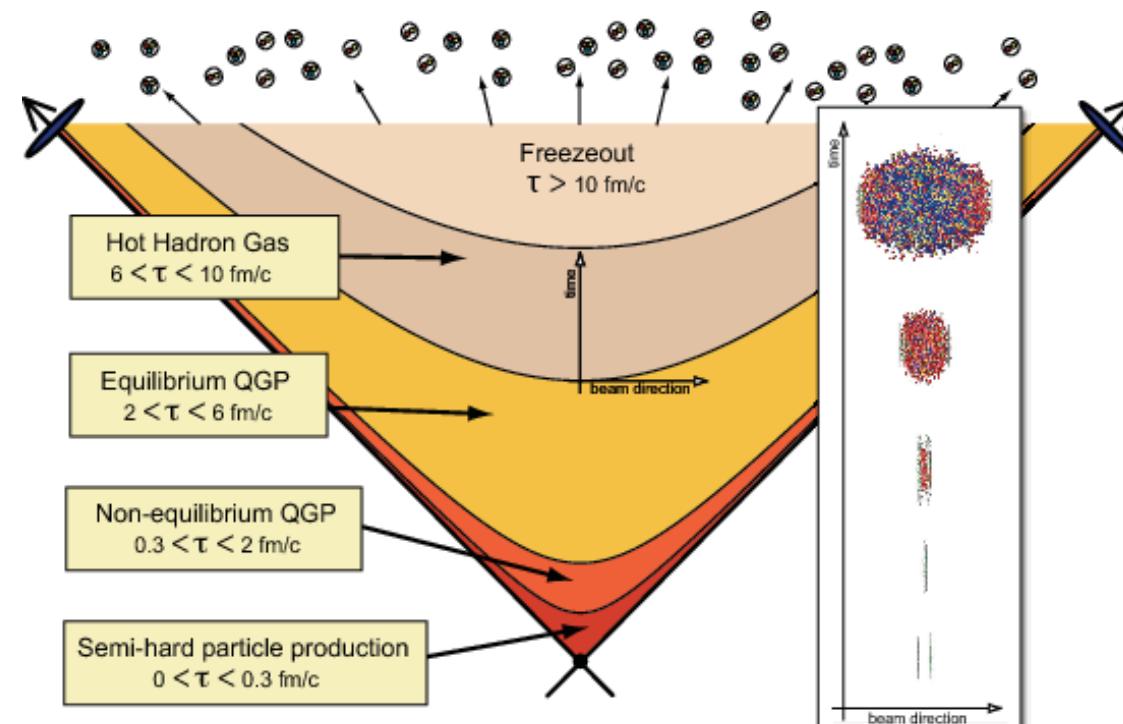
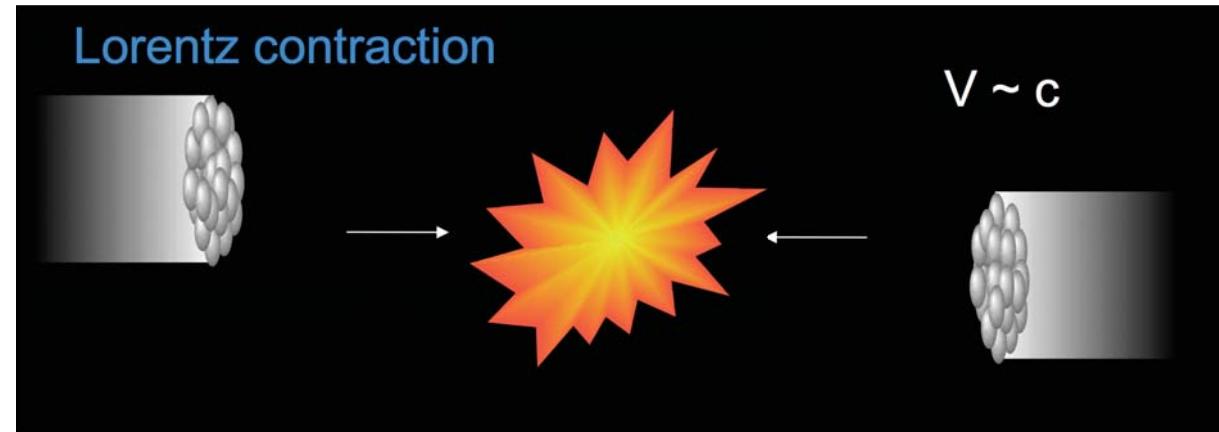
# QGP in the Universe

## History of the Universe

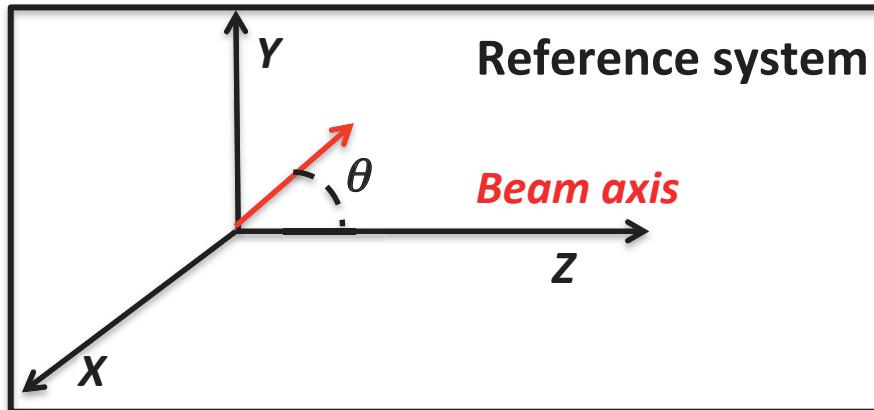


# How can we “melt” nuclear matter in the laboratory?

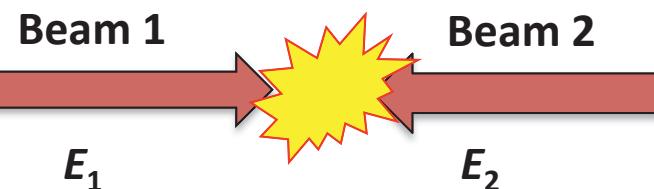
## Collisions of relativistic, large nuclei



# Before to continue....same basic concepts!



AT COLLIDERS



**Center of mass energy** = energy available  
to create particles =  $\sqrt{s} \approx 2*(E_1 * E_2)^{1/2}$   
If  $E_1 = E_2 = E$ ,  $\sqrt{s} \approx 2E$

**Rapidity**

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

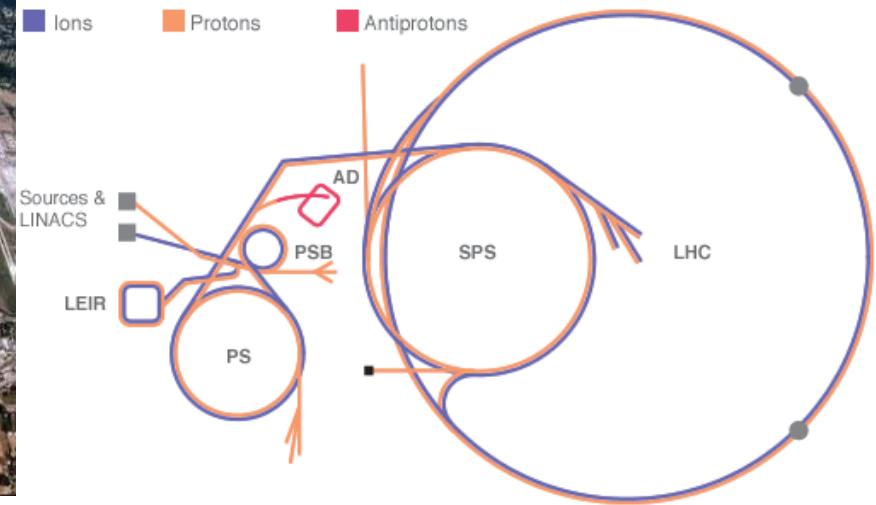
**Pseudorapidity**

$$\eta = -\ln(\tan(\theta/2))$$

For relativistic particles  $\eta \approx y$



# LHC



CERN

**Beam pipe**

Bunch  $10^{11}$  protoni      Bunch  $10^{11}$  protoni

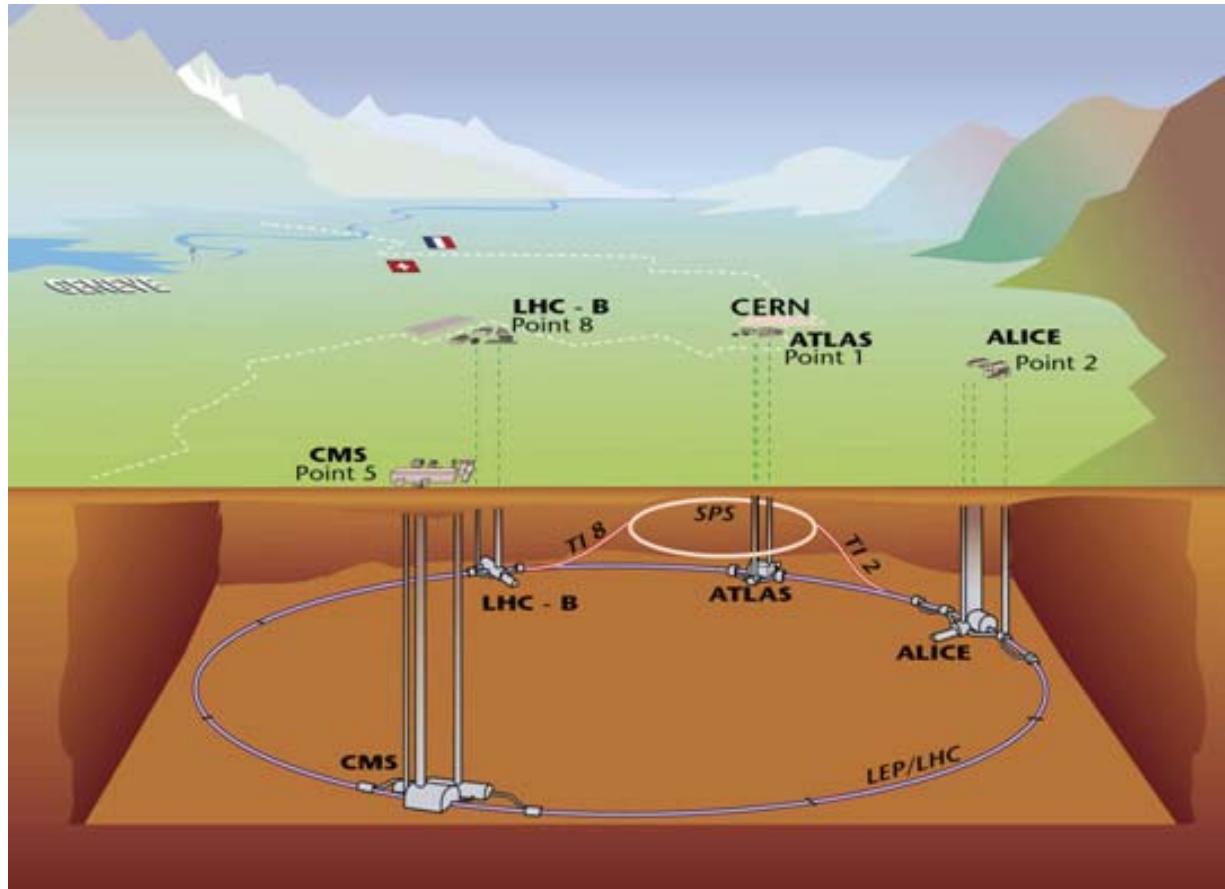
2010:  $3 \cdot 10^6$  collisions/s

$E = 7 \text{ TeV}$  (~ eurostar at 200 km/h)

$1 \text{ TeV} = 10^{12} \text{ eV}$



# LHC



- 4 gigantic caverns host 4 huge detectors
- Maximum center of mass energy of 14 TeV, never reached before
- beam intensity orders of magnitude higher than before
- almost 40.000 ton of material at **1.9 K**, a temperature **lower than the cosmic background**

# LHC

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- In addition to protons, LHC accelerates and collides **lead ions**
- isotope Pb <sup>208</sup> with 82 protons and 126 neutrons in the nucleus
- LHC RUN1 (2009-2013) →  $\sqrt{s_{NN}} = 2.76 \text{ TeV}$
- LHC RUN2 (2015-2018) →  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$
- Before LHC the most powerful accelerator for ions → **RHIC at BNL (USA)**:
  - **Au-Au collision at  $\sqrt{s_{NN}} = 200 \text{ GeV}$**

$\sqrt{s_{NN}}$  = energy in the center of mass system per nucleon pair

temperature evolution

the cosmic background

# A Large Ion Collider Experiment

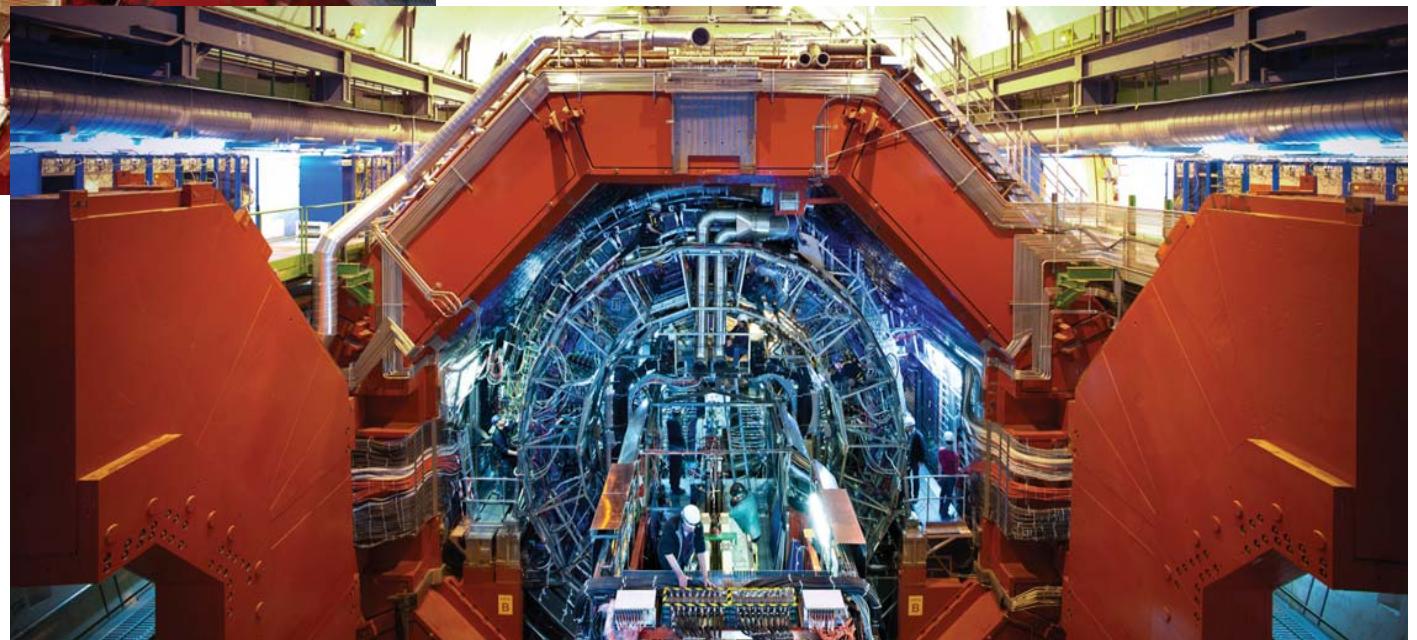


**Detector:**  
**Size:** 16x26 meters  
**Weight:** 10000 tons

**Collaboration:**  
-> 1300 Members  
-> 100 Institutes  
-> 30 Countries



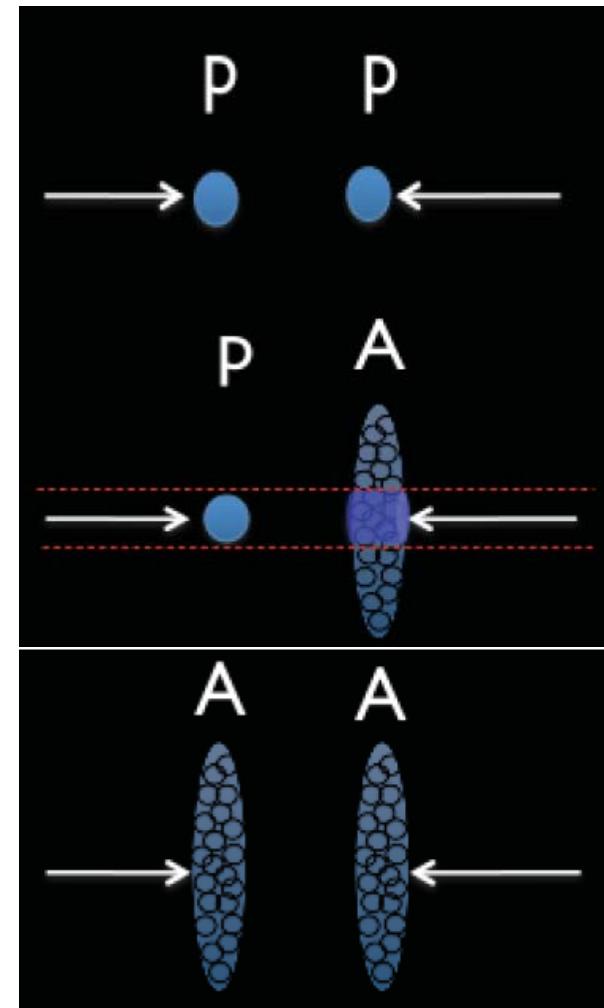
# ALICE



# The goal of ALICE

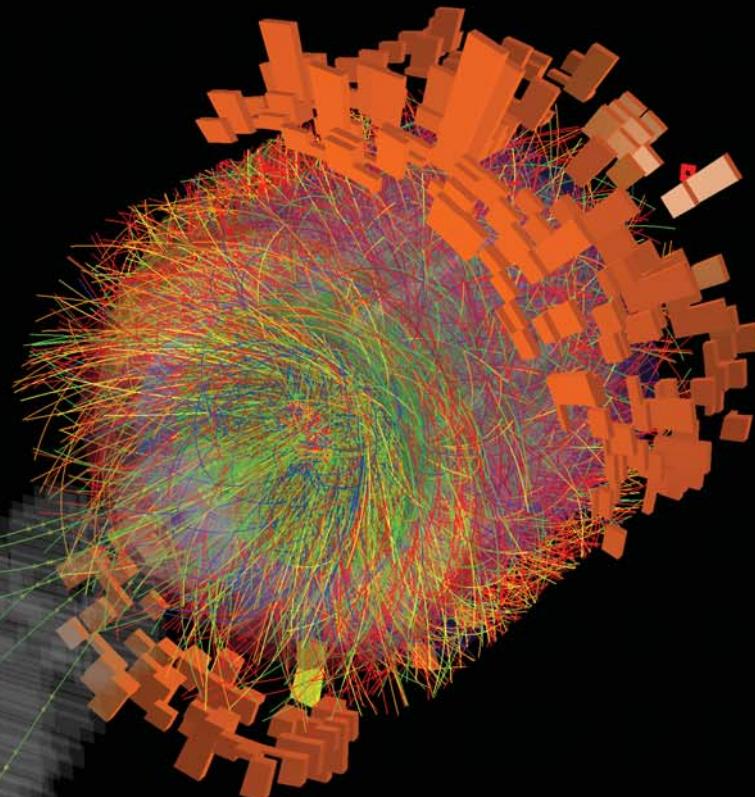
ALICE is designed to study the physics of strongly interacting matter under extremely high temperature and energy densities to investigate the properties of the **quark-gluon plasma**.

- proton-proton collisions:
  - **high energy QCD reference.**
  - collected pp data at  $\sqrt{s} = 0.9, 2.76, 7, 8, 13 \text{ TeV}$  (2009-2012, 2015, 2016)
- proton-nucleus collisions:
  - **initial state/cold nuclear matter.**
  - collected p-Pb data at  $\sqrt{s_{\text{NN}}} = 5.02, 8.16 \text{ TeV}$  (2012, 2013, 2016)
- nucleus-nucleus collisions:
  - **quark-gluon plasma formation!**
  - collected Pb-Pb data at  $\sqrt{s_{\text{NN}}} = 2.76, 5.02 \text{ TeV}$  (2010, 2011, 2015)



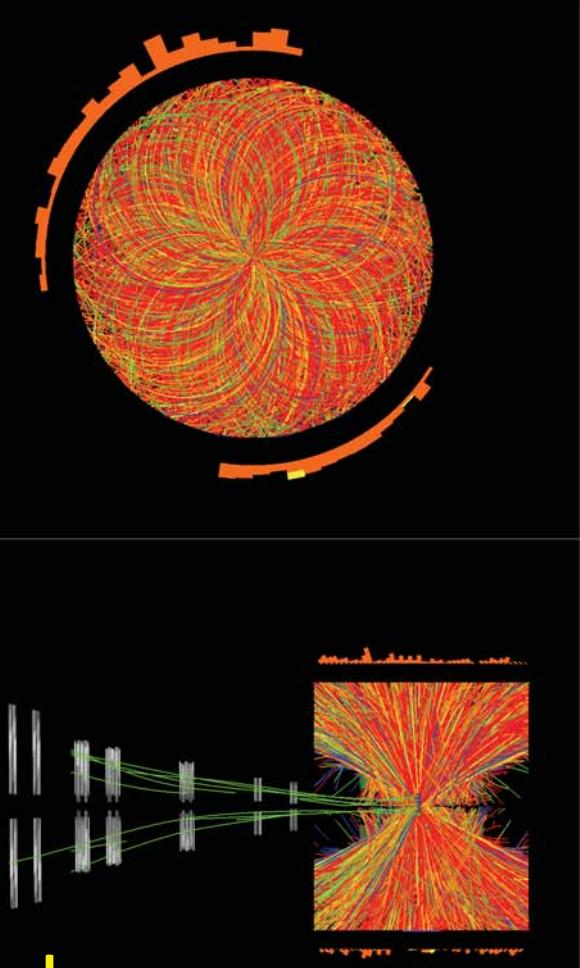


ALICE



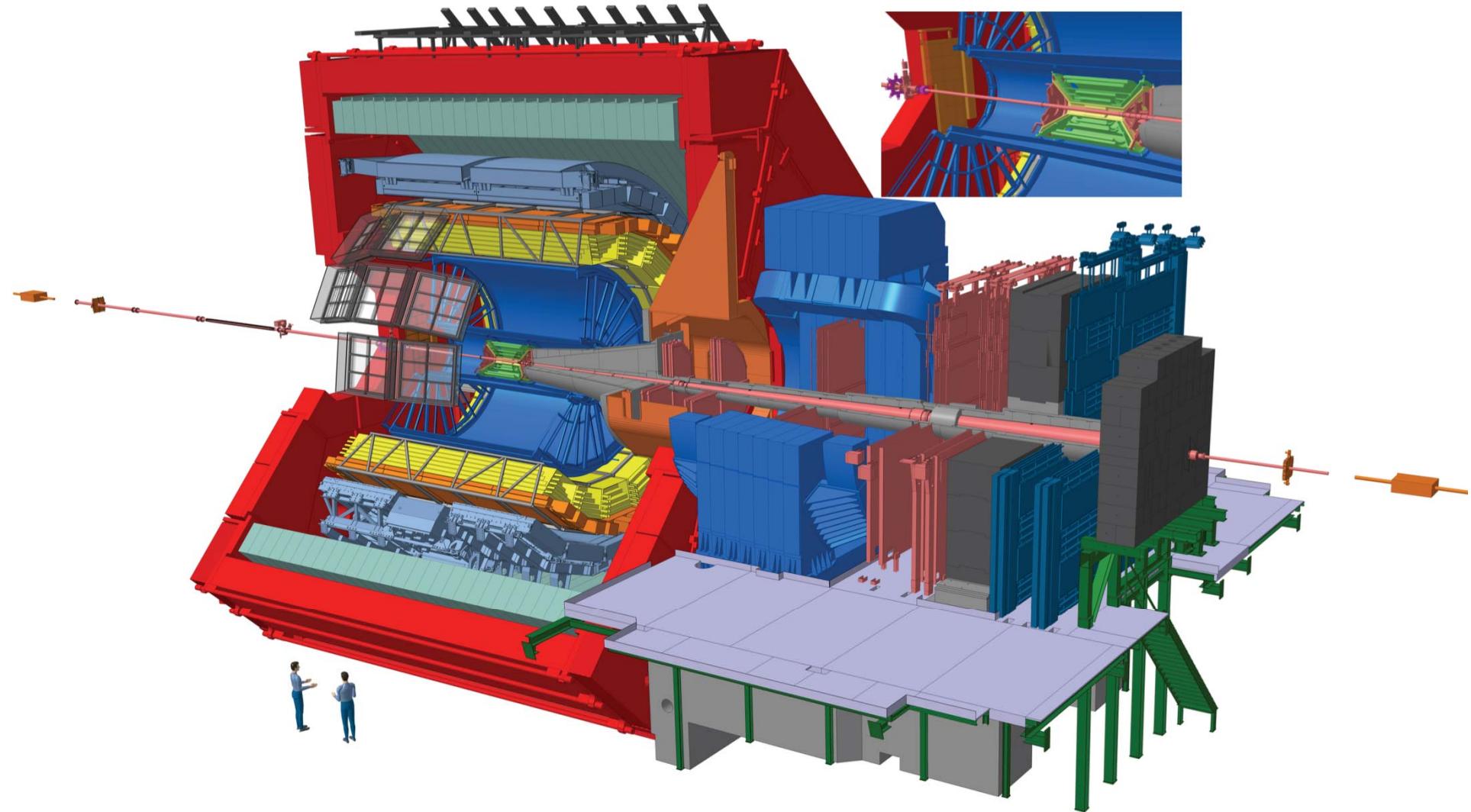
Run:244918  
Timestamp:2015-11-25 11:25:36(UTC)  
System: Pb-Pb  
Energy: 5.02 TeV

## 2015 Pb-Pb event display

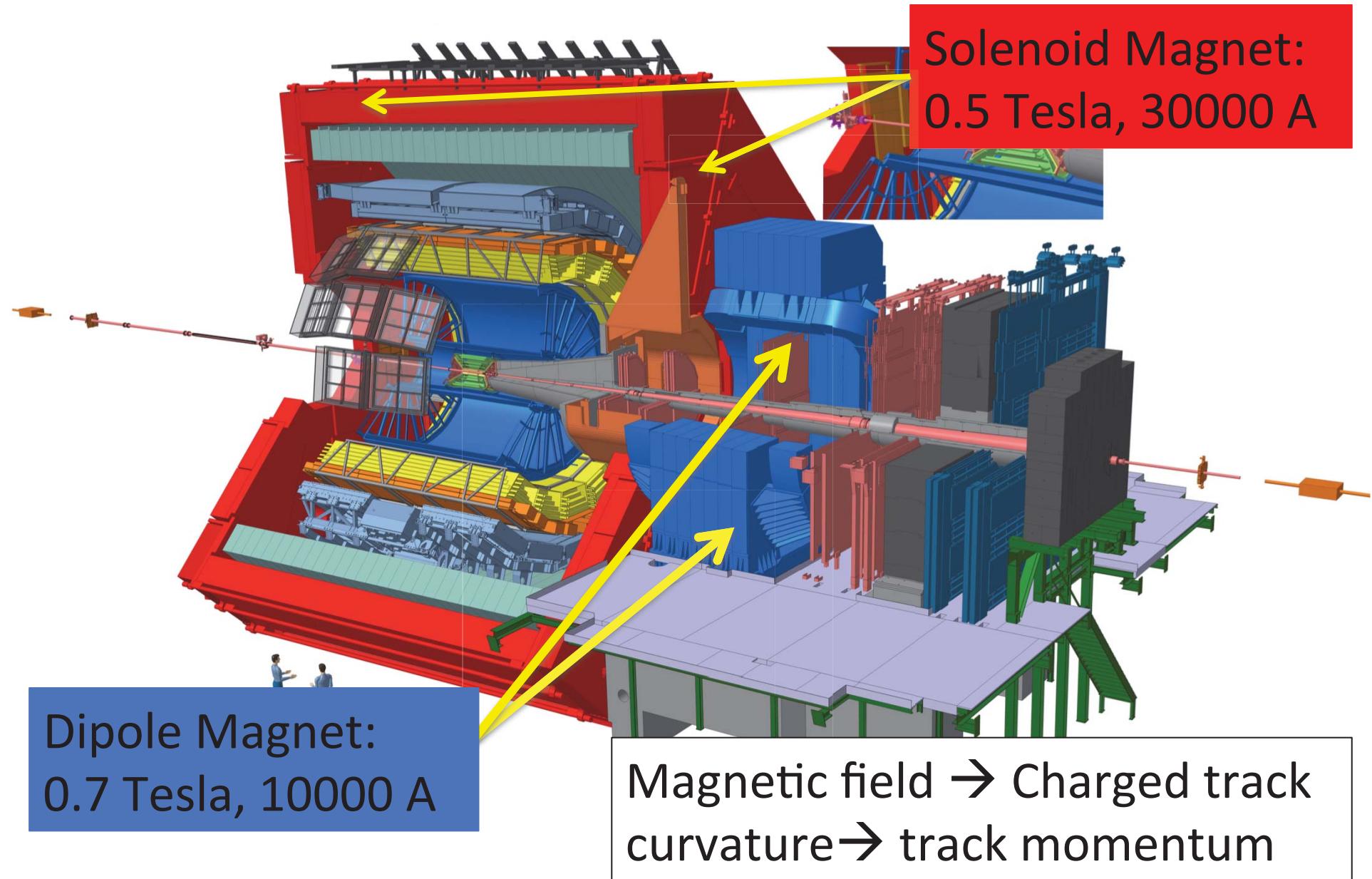


# ALICE apparatus

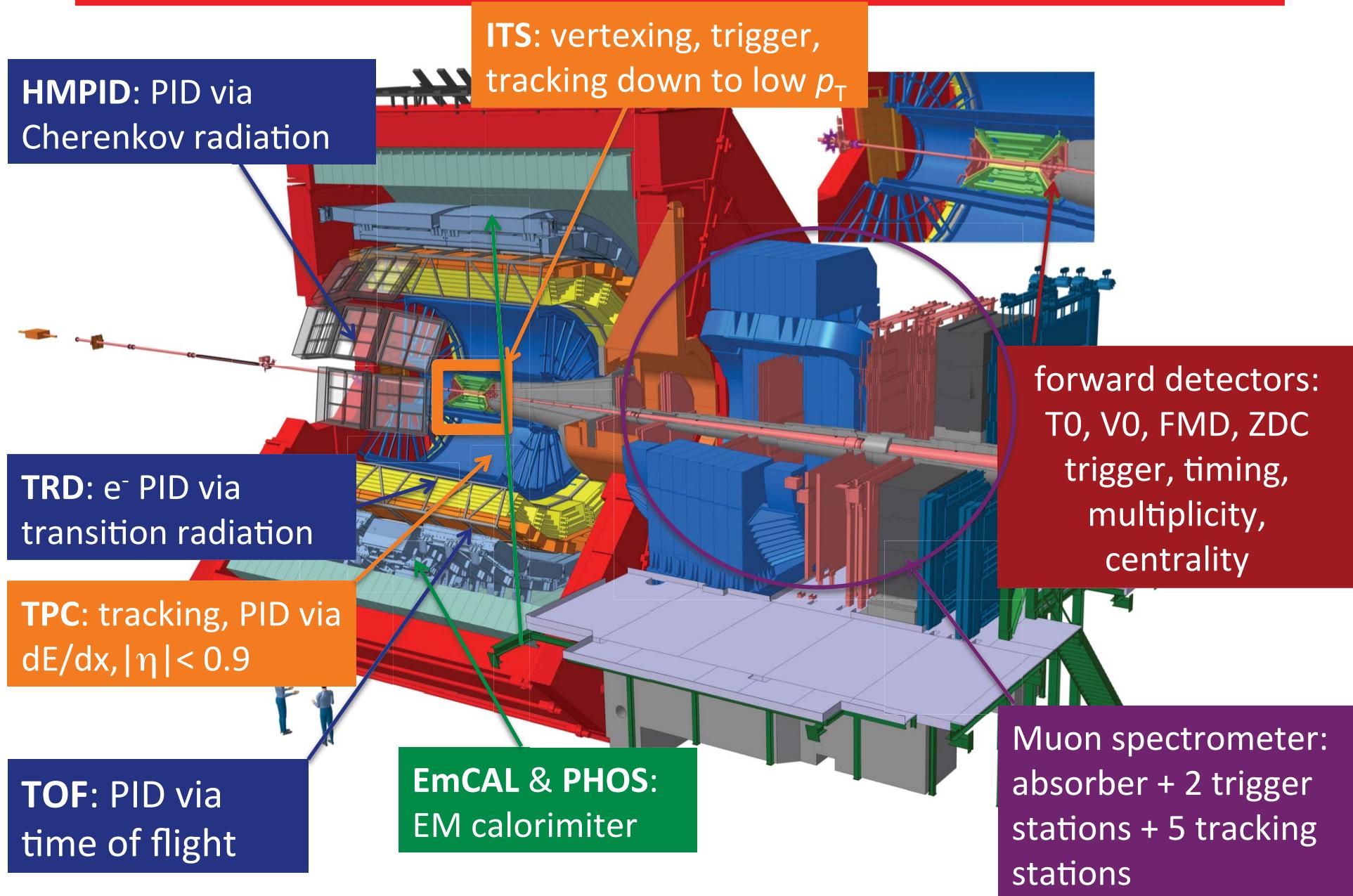
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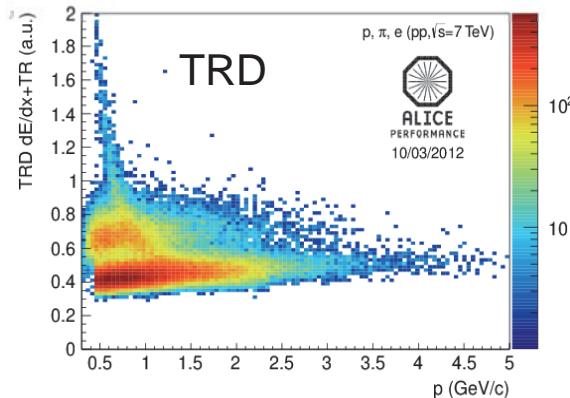
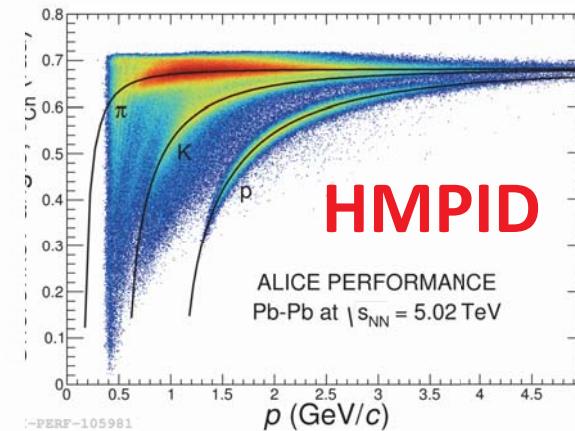
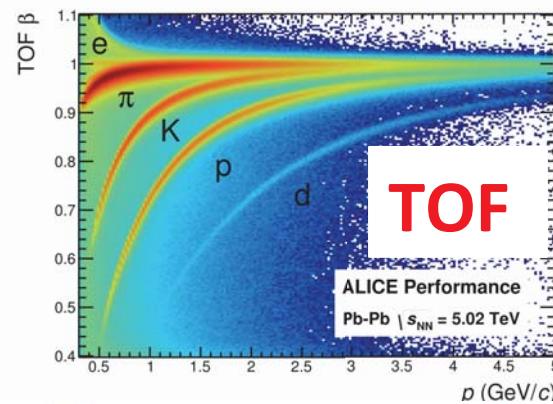
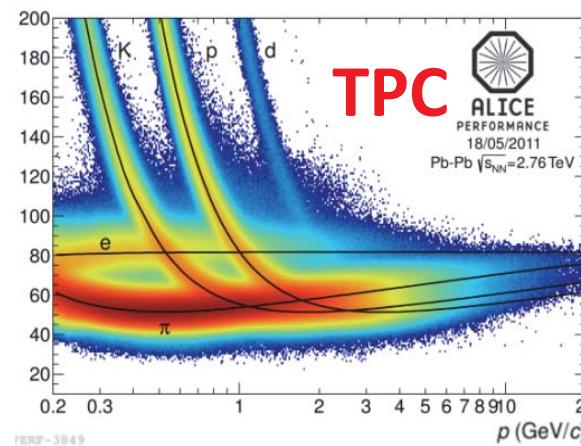
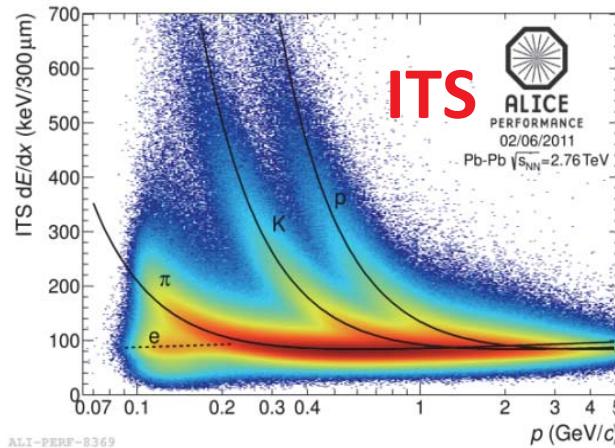
# ALICE apparatus



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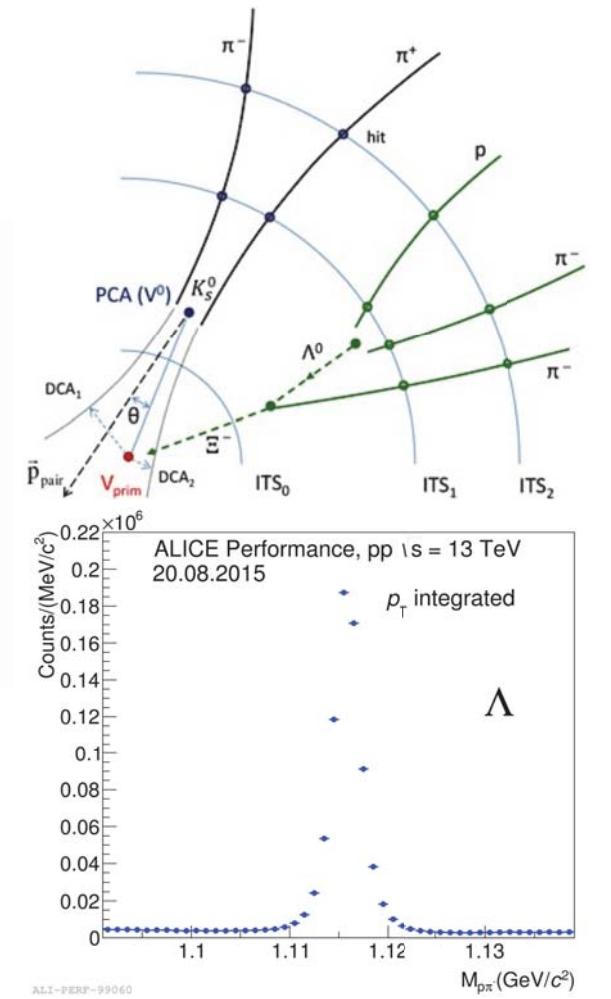


# Particle identification in ALICE



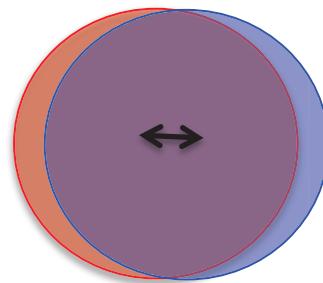
**Particle identification via all known PID techniques in  $0.1 \text{ GeV}/c < p_T < 30 \text{ GeV}/c$**

**Topological PID**  
secondary vertex reconstruction + invariant mass analysis



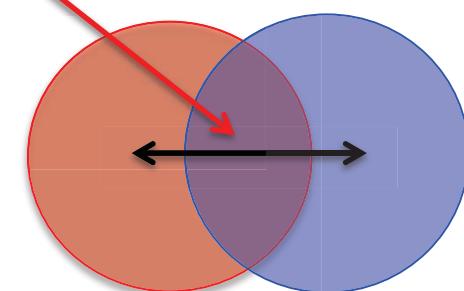
# Collision Geometry (centrality)

- Centrality: amount of overlap between nuclei
- Impact parameter: distance between centers of nuclei
- Impact parameter cannot be measured directly; measure
  - Charged-particle multiplicity (mostly  $\pi^\pm$ ,  $K^\pm$ , p e anti-p)
  - Number of spectator neutrons (unaffected by collision)
  - Use models to map these measurements into impact parameter



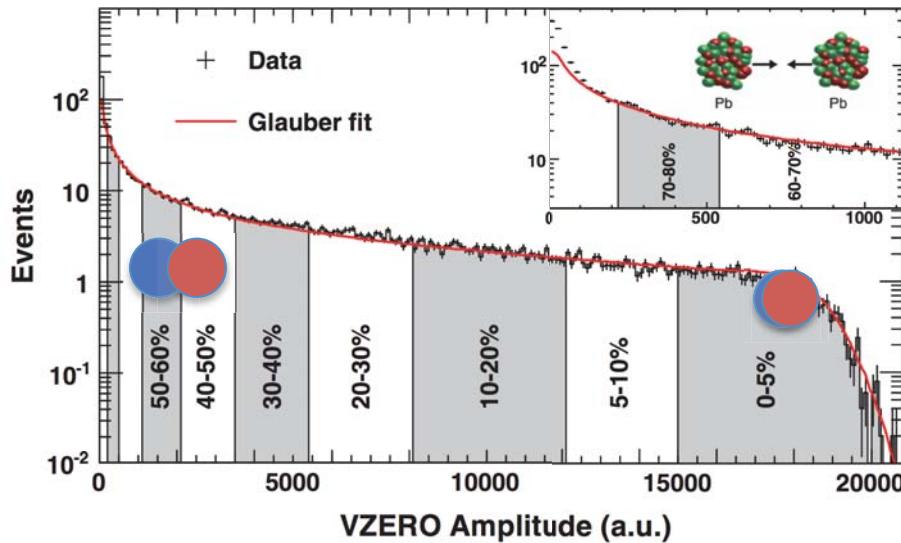
**“Central”**  
**Small impact parameter**  
**Large system volume**  
**Large charged-particle multiplicity**

*Parametro d'impatto*

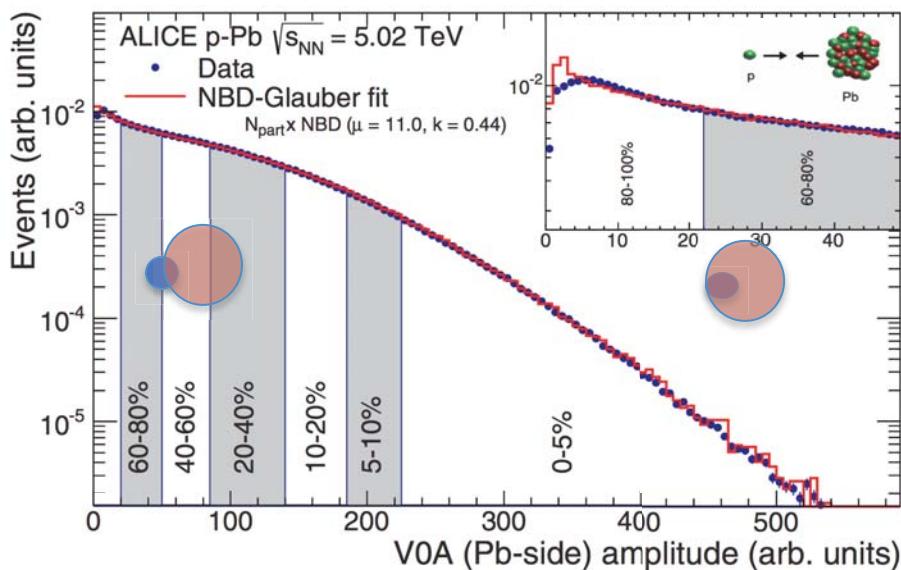


**“Peripheral”**  
**Large impact parameter**  
**Small system volume**  
**Small charged-particle multiplicity**

# Multiplicity measurement in ALICE



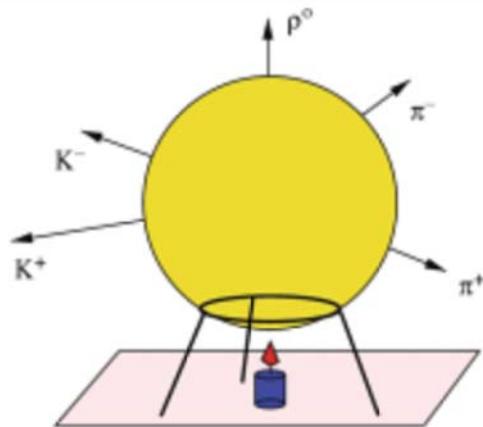
Phys. Rev. Lett. 106, 032301 (2011)



Phys. Rev. C 91 (2015) 064905

- Multiplicity is defined as the number of charged particles per event in  $|\eta| < 0.5$
- Linked through the impact parameter to the collision centrality in Pb–Pb (**Glauber model**)
- ALICE measures the event activity at forward rapidity with the **V0 scintillators** placed at:  $2.8 < \eta < 5.1$  (V0A) and  $-3.7 < \eta < -1.7$  (V0C)
- Wide range of measured multiplicities
  - from  $\langle dN_{ch}/d\eta \rangle \approx 2$  in low multiplicity pp collisions
  - to  $\langle dN_{ch}/d\eta \rangle \approx 1600$  in central Pb–Pb collisions

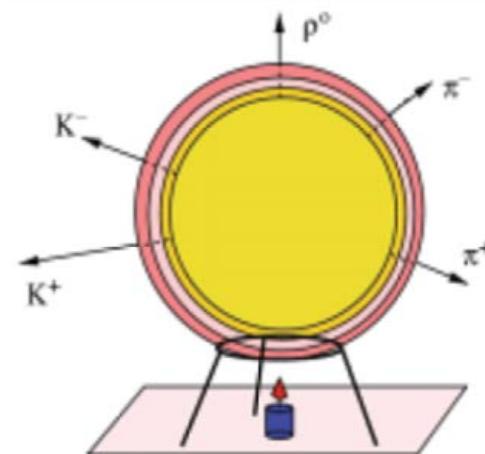
# Techniques to study the plasma



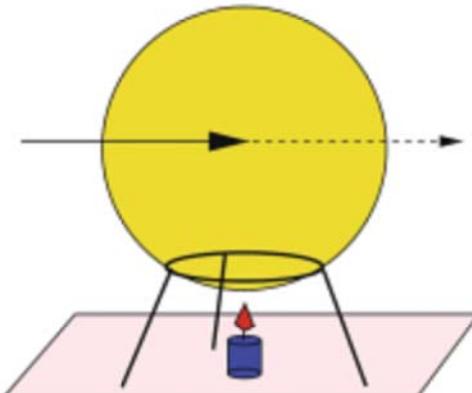
**Soft probes**  
(Low energy process)

**Radiation of hadrons and photons**

- Multiplicity, momentum spectra, particle composition.....

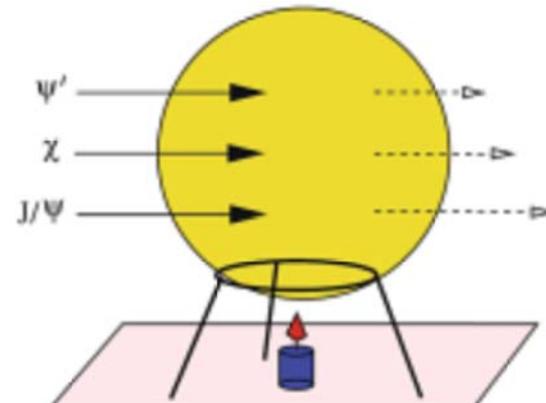


**Azimuthal asymmetry and radial expansion**



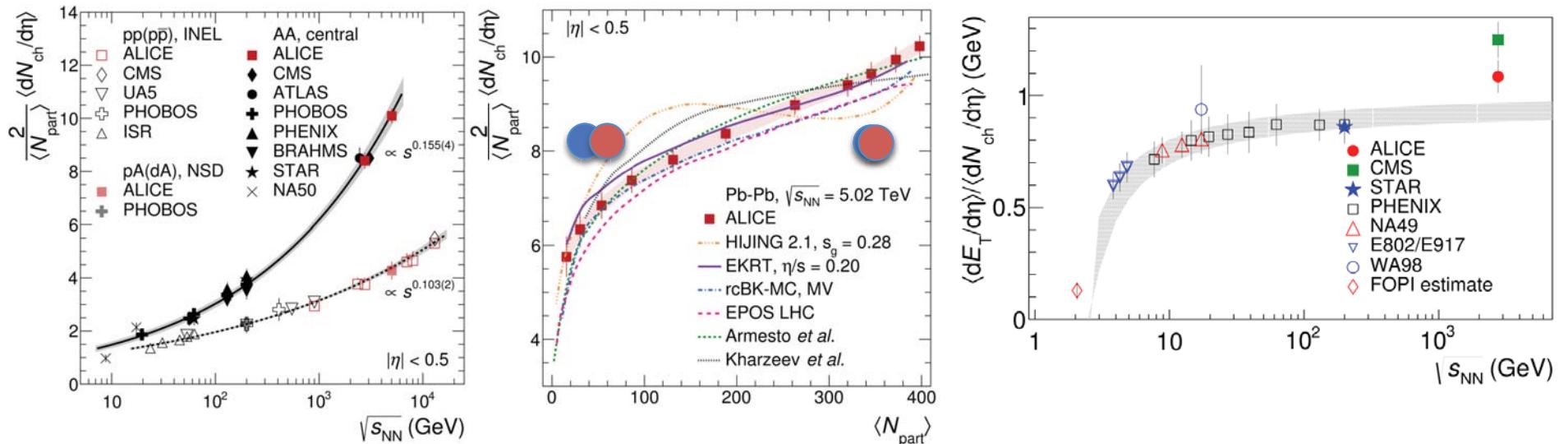
**Hard probes**  
(High energy process)

**Energy loss by quarks, gluons and other particles**



**Suppression of quarkonia and heavy flavour**

# Charged particle multiplicity and energy density



- $dN_{\text{ch}} / d\eta / (N_{\text{part}} / 2)$  increases with  $\sqrt{s}$ 
  - pp:  $\approx s^{0.103}$
  - central A+A:  $\approx s^{0.155}$
- same centrality dependence as at RHIC

Bjorken formula  
(Phys. Rev. D27, (1983) 140)

$$\varepsilon = \frac{dE_T / dy}{\tau_0 \pi R^2} \approx \frac{3}{2} \langle m_T \rangle \frac{dN_{\text{ch}} / d\eta}{\tau_0 \pi R^2} \rightarrow \varepsilon \approx 15 \text{ GeV/fm}^3$$

Initial energy density at LHC (and RHIC) well above  $\varepsilon_c \approx 1 \text{ GeV/c}$

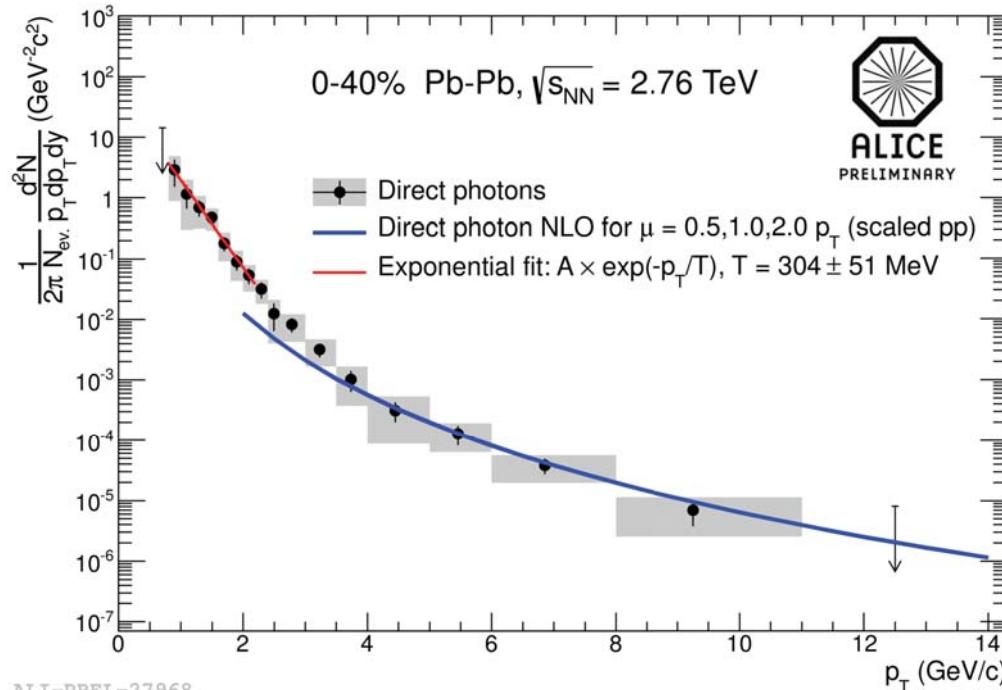
# Direct photons and QGP temperature

Hot Objects produce thermal spectrum of EM radiation.



## Direct Photons - Definition

Photons that are not produced by particle decays



- Two major domains:
  - Prompt photons**
    - Hard scattering process
    - High  $p_T$
    - information on PDFs, QCD, etc.
  - Thermal photons**
    - thermal production
    - Low/medium  $p_T$
    - information on early thermal state (QGP?)

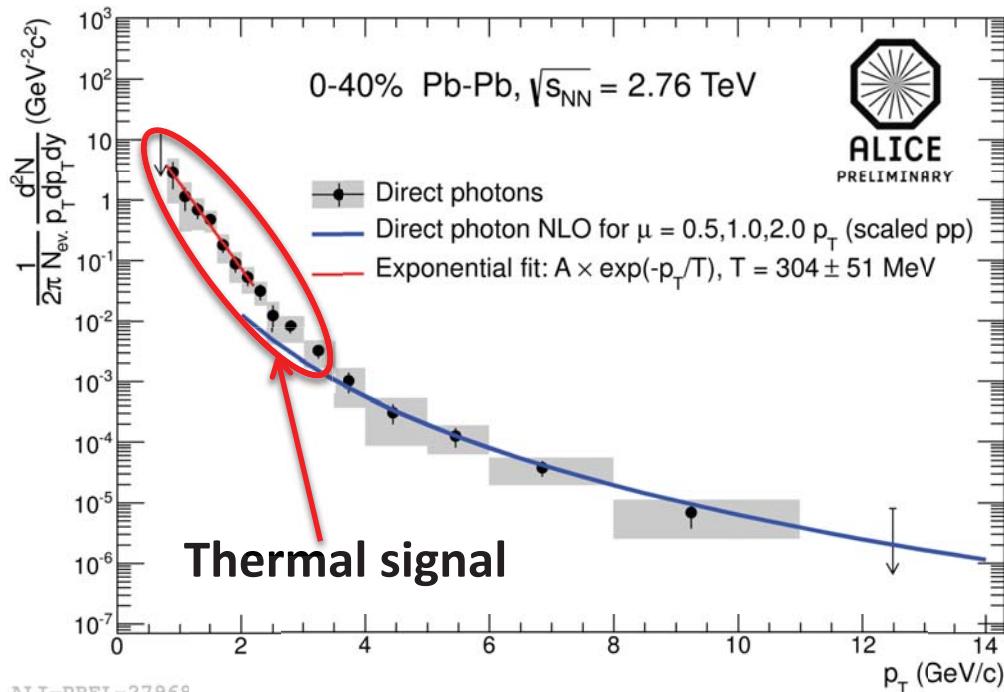
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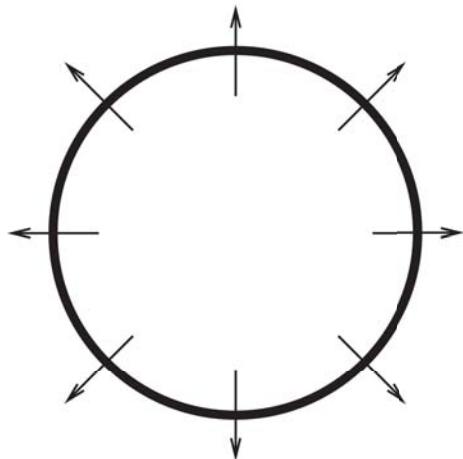
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$$T_{LHC} = 304 \pm 51 \text{ MeV}_{50}$$

# Radial flow

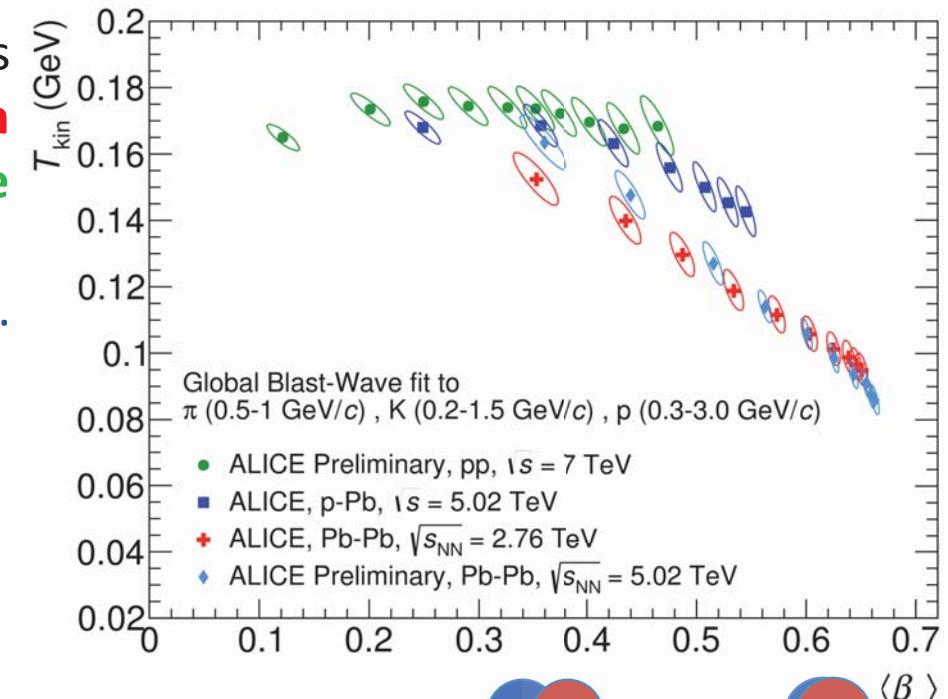


$$m_T = \sqrt{m^2 + p_T^2}$$

$$\frac{d^2N_j}{m_T dy dm_T} = \int_0^{R_G} A_j m_T \cdot K_1\left(\frac{m_T \cosh \rho}{T}\right) \cdot I_0\left(\frac{p_T \sinh \rho}{T}\right) r dr$$

$$\rho(r) = \tanh^{-1} \beta_{\perp}(r) \quad \beta_{\perp}(r) = \beta_s \left[ \frac{r}{R_G} \right]^{n(=1)} \quad r \leq R_G$$

- $p_T$  distributions described as combined result of **thermal motion ( $T$ )** and **collective transverse expansion velocity ( $\beta_T$ )** at freeze-out
- (Hydrodynamic description, Phys. Rev. C48, 2462 (1993))
- Radial flow larger in the central collisions ( $\beta \approx 0.67$ ).
- Kinetic freeze-out temperature below 100 MeV.

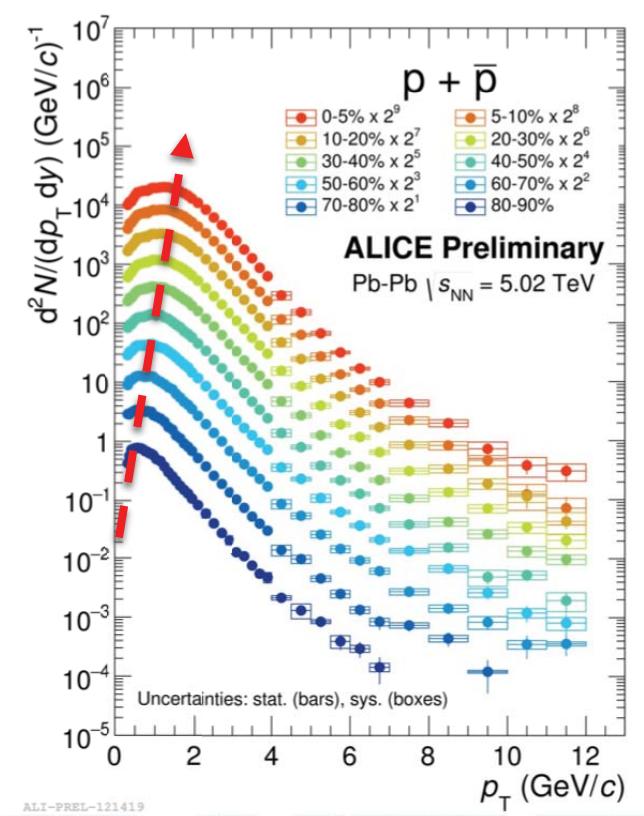
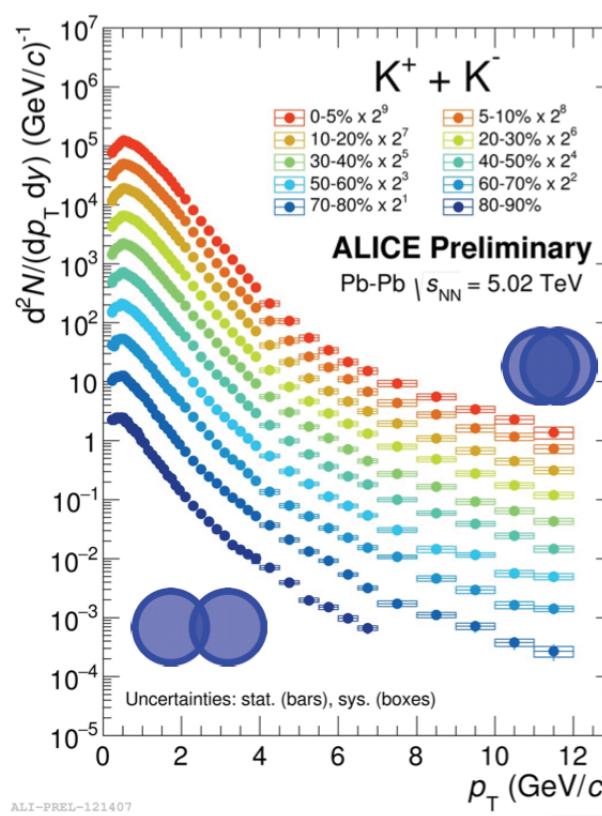
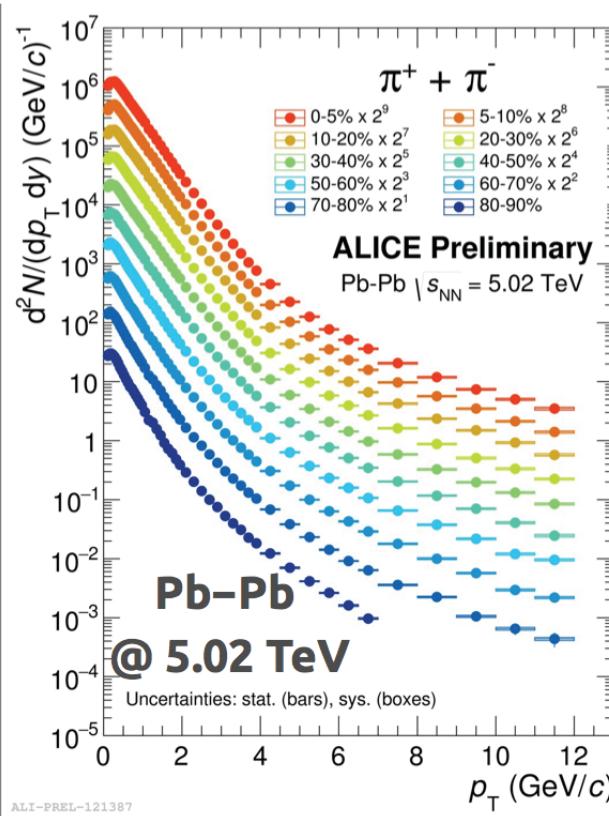


ALI-PREL-122512



$\langle \beta_T \rangle$

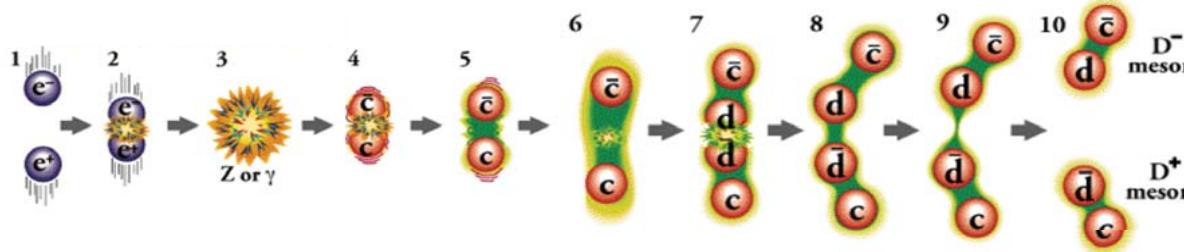
# $p_T$ spectra of charged particles



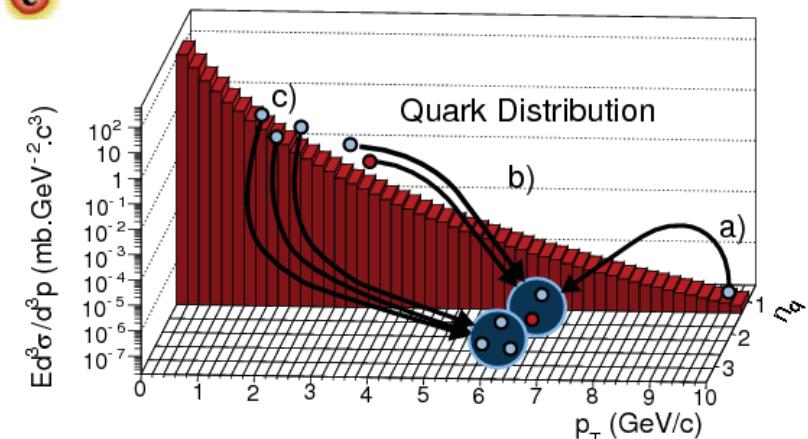
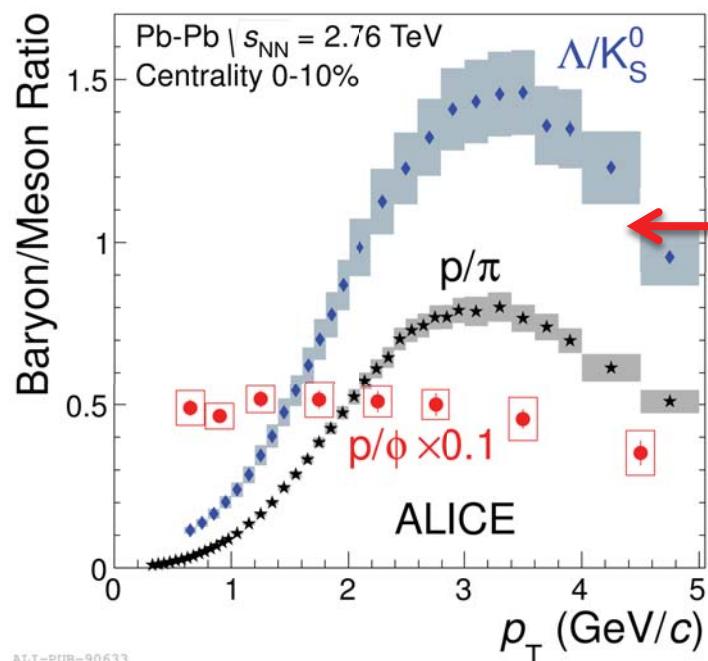
- spectra get flatter for more central collisions
- stronger effect for heavier particles
- consistent with a collective hydrodynamic expansion
  - Heavier particles have larger momenta than lighter ones with the same velocity

# Particle production mechanisms - baryon/meson

- Partons fragmentation → baryon suppression



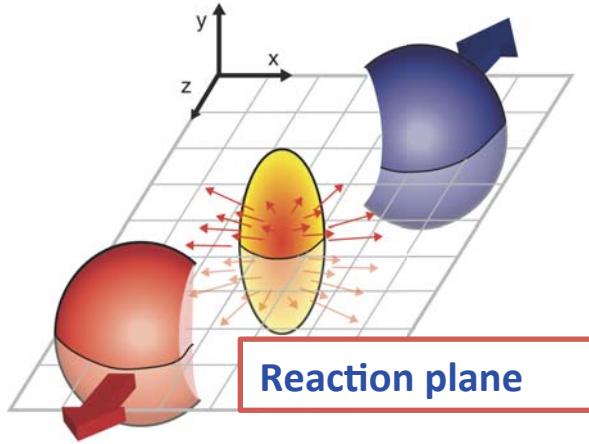
- Recombination/coalescence: quarks close in the phase space , recombine to create baryons and mesons [Phys. Rev. Lett. 90,202303,Phys. Rev. Lett. 90, 202302] → baryon enhancement



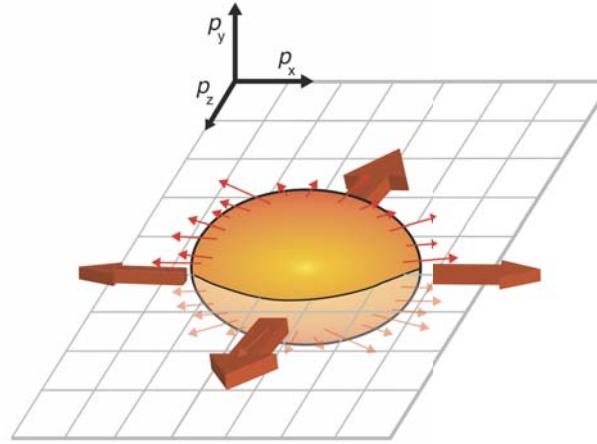
In central Pb-Pb collisions the baryon/meson ratios shows a peak at intermediate  $p_T$

- Particle type ordering → recombination
- Mass ordering → hydrodynamic (radial flow)
- $p/\phi$  flat: a meson and a baryon with the same mass → explained by hydro but also by models with recombination [V. Greco *et al*, Phys.Rev. C 92 (2015) 054904]

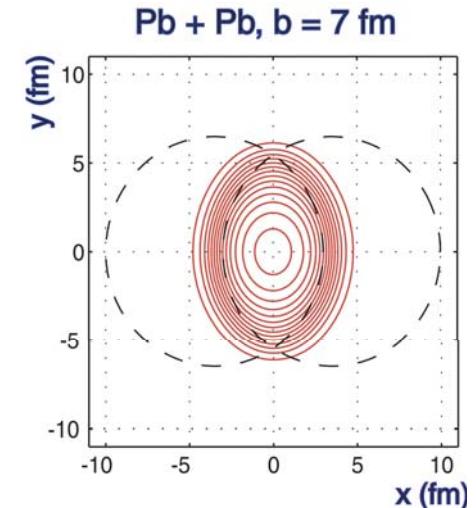
# Elliptic flow



No central collisions  
present spatial  
anisotropy



Hot fireball pressure  
influence the momentum  
distribution of the produced  
particles



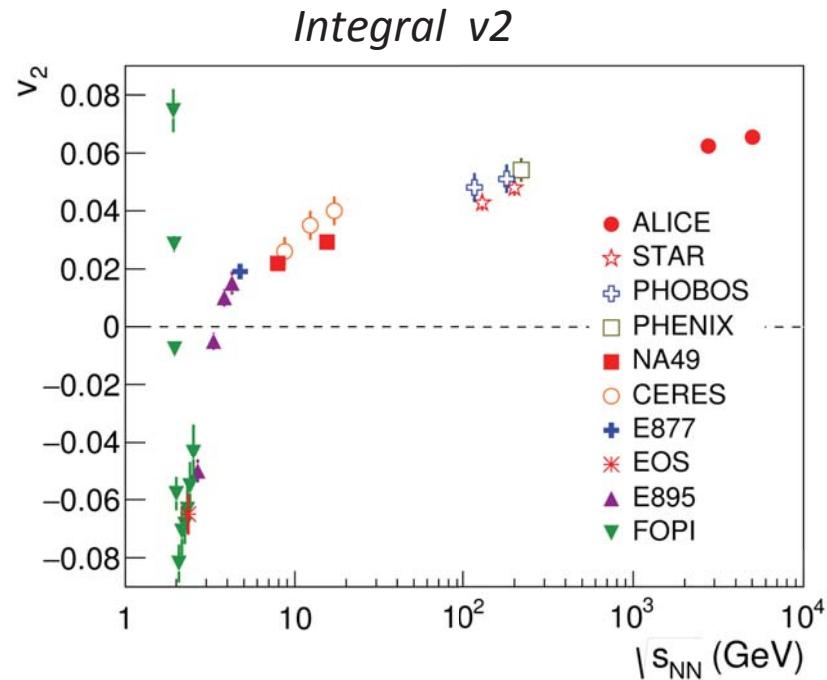
Anisotropy in the  
momentum space

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

$$v_2 = \langle \cos[2(\varphi - \psi_{RP})] \rangle$$

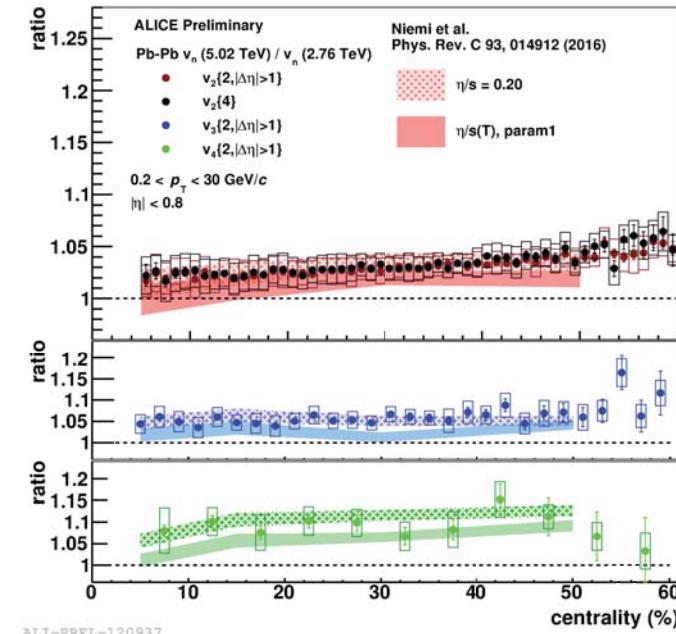
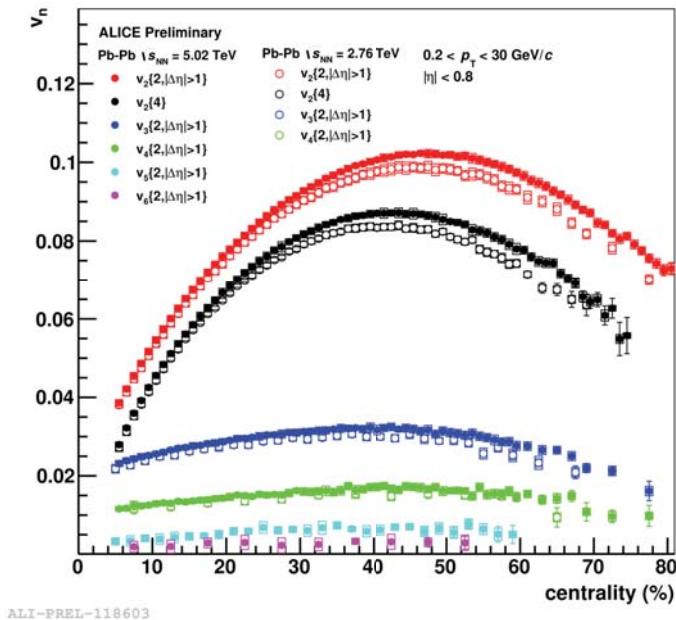
- One quantifies this anisotropy in terms of the **azimuthal Fourier coefficients of the transverse momentum spectrum**
- The Fourier coefficient of 2<sup>nd</sup> order,  $v_2$ , is called elliptic flow

# Flusso ellittico



ALI-PUB-105802

- Elliptic flow at LHC  $\approx 30\%$  larger than at RHIC
- The transfer of the spatial coordinate anisotropy to the momentum space brings information about the viscosity of the fluid,  $\eta$ .
  - $\eta/s$  is the relevant parameter of the hydrodynamic theory ( $s$  = entropy density).
  - The system created at LHC has a very low viscosity  $\eta/s = 0.2$  (perfect fluid).



# Strangeness enhancement

---

- Strangeness is one of the “historic” observables in ultra-relativistic nucleus-nucleus collisions
- In elementary collisions (pp), strangeness production is suppressed relative to the production of light flavors (no strange quarks present the the nucleons, strange mass > up and down mass).
- For a large system, this suppression is expected to be removed, strangeness enhancement, provided the correlation volume is large, as expected if partons are freed in a quark-gluon plasma.

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How do we quantify the  
enhancement/suppression?!

# Strangeness enhancement

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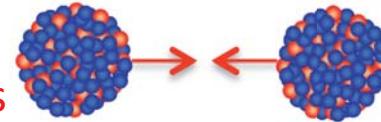
## Nuclear modification factor

$$R_{AA} = \frac{Y(A-A)}{Y(pp) \times \langle N_{coll} \rangle}$$

particle yield in  
nucleus-nucleus collisions

particle yield in  
proton-proton collisions (baseline)

number of binary nucleon-nucleon collisions in  
nucleus-nucleus collisions  
(calculated from models)



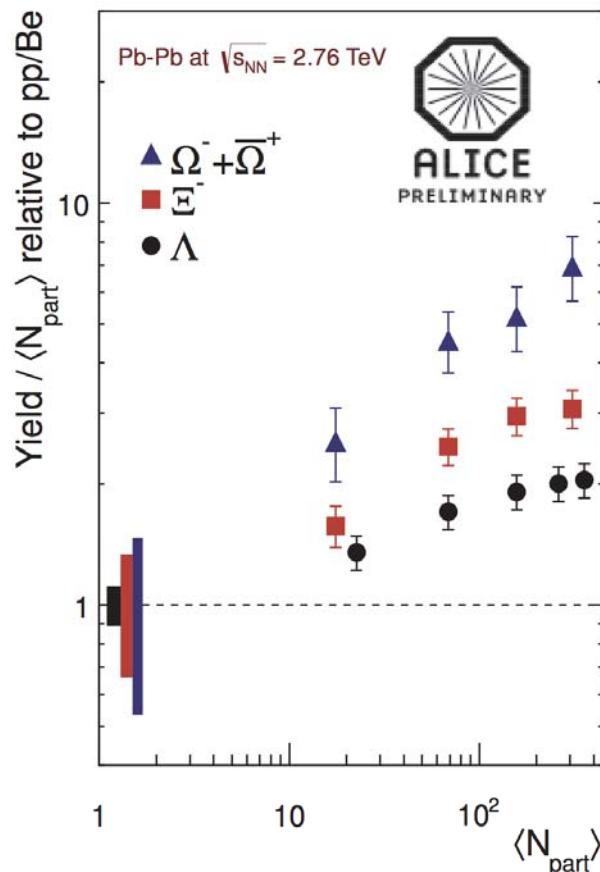
$R_{AA} > 1$ : nuclear effects (enhancement)

$R_{AA} = 1$ : A–A is incoherent superposition of nucleon-nucleon collisions

$R_{AA} < 1$ : nuclear effects (suppression)

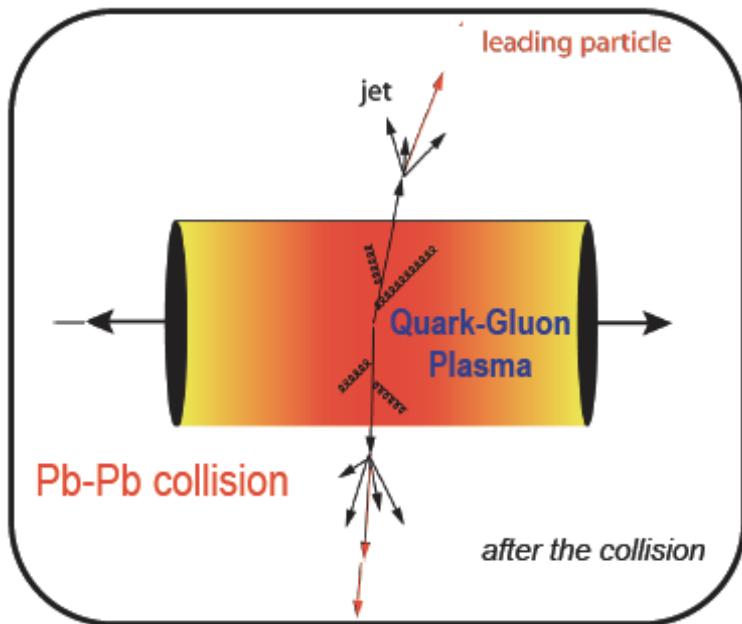
# Strangeness enhancement

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- In elementary collisions (pp), strangeness production is suppressed relative to the production of light flavors (no strange quarks present in the nucleons, strange mass > up and down mass).
- For a large system, this suppression is expected to be removed, strangeness enhancement, provided the correlation volume is large, as expected if partons are freed in a quark-gluon plasma.



Enhancement increases with number of strange quarks in the hadron ( $\Omega$  has 3,  $\Xi$  has 2,  $\Lambda$  has 1)

# Hard probes



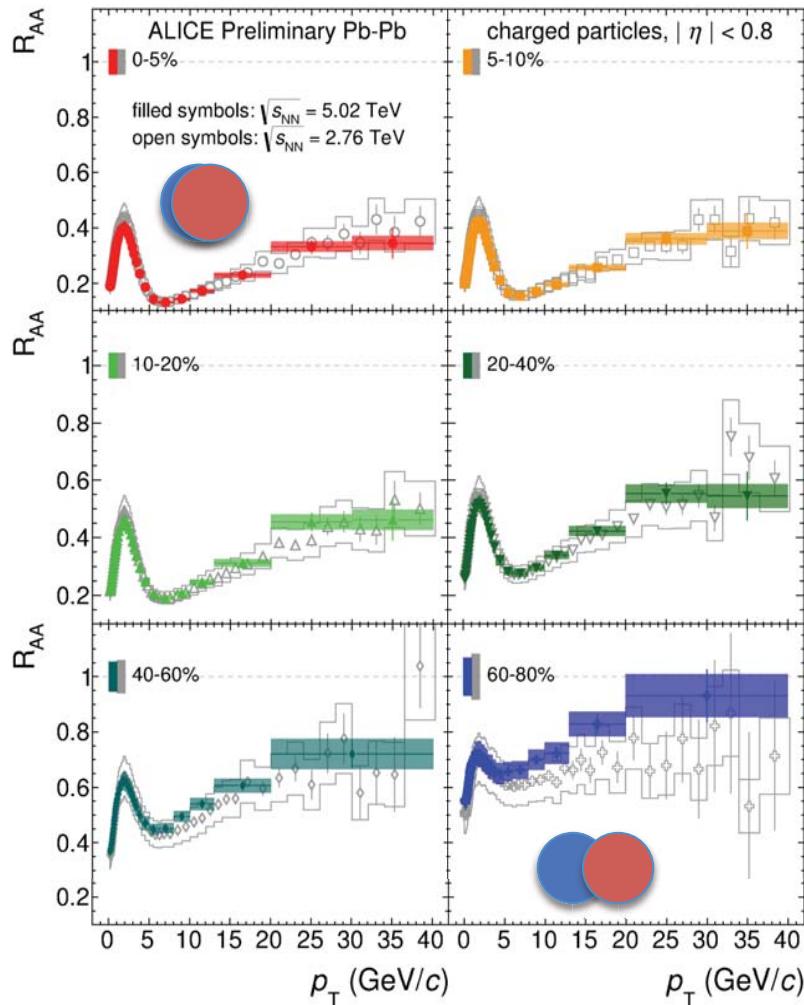
- hard processes serve as calibrated probe (pQCD)
- traversing through the medium and interact strongly
- suppression provides density measurement
- general picture: energy loss via medium induced gluon radiation and collisional energy loss (gluonstrahlung)

- particles (hadrons or partons) that are characterized by a **hard scale** (mass or momentum)
- produced in **the first instants of the nucleus–nucleus collision** in hard partonic scatterings
- affected by the presence of the strongly-interacting QGP, which they cross after their production.
  - High  $p_T$  particles
  - Quarkonia
  - Heavy quarks (*charm and beauty*)
  - *jet*

Simplest observable: **nuclear modification factor ( $R_{AA}$ ) of the jet leading particles**

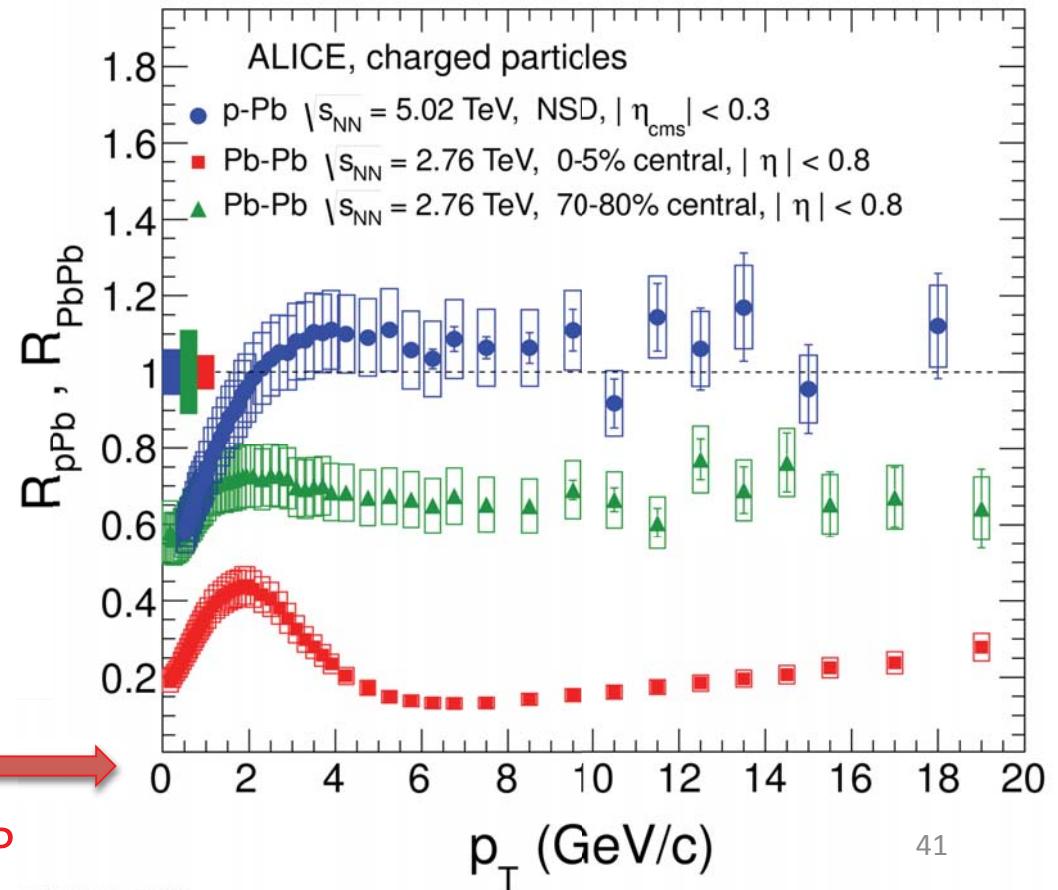
$$R_{AA}(p_T) = \frac{d^2 N^{AA} / dy dp_T}{\langle N_{coll} \rangle d^2 N^{pp} / dy dp_T}$$

# Charged particle $R_{AA}$ – jet quenching

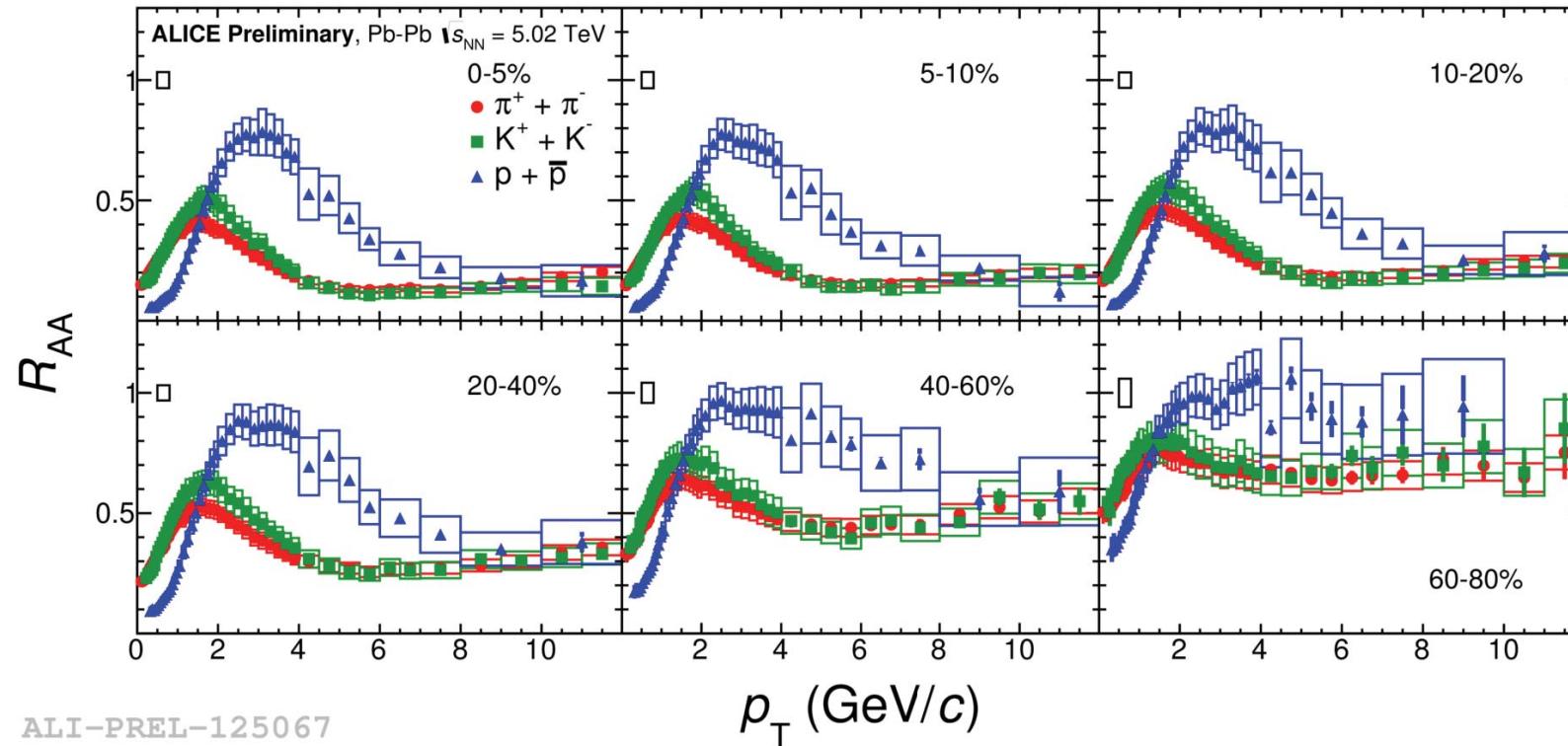


- Suppression not present in p-Pb collisions
- Due to hot and dense medium, QGP

- High  $p_T$  particle suppression increase with collisions centrality (**jet quenching**).
- No relevant evolution with collision energy
- Minimum at 6-8 GeV/c
- Rise and flattening at very high  $p_T$



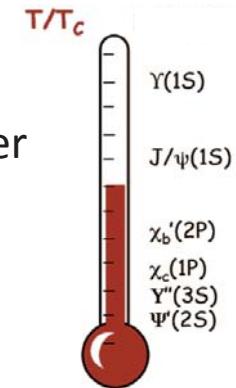
# Charged particle $R_{AA}$ – jet quenching



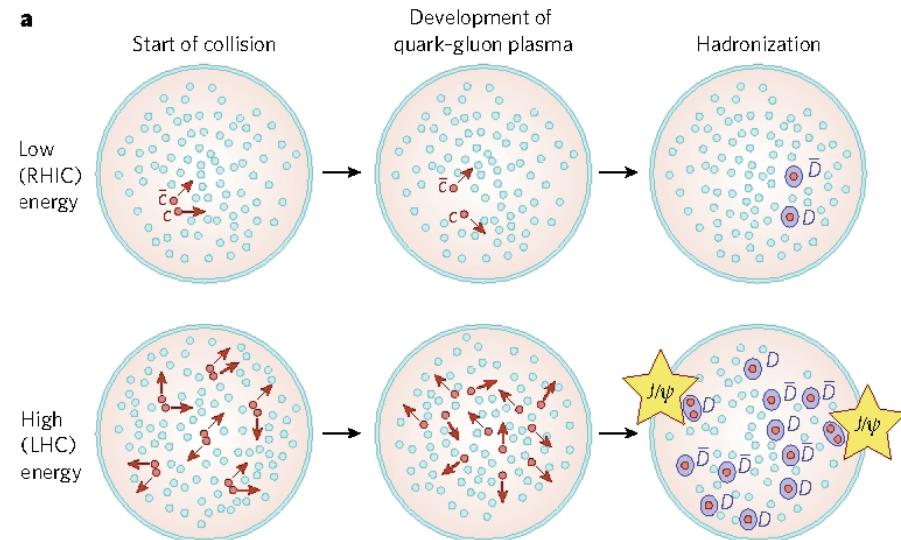
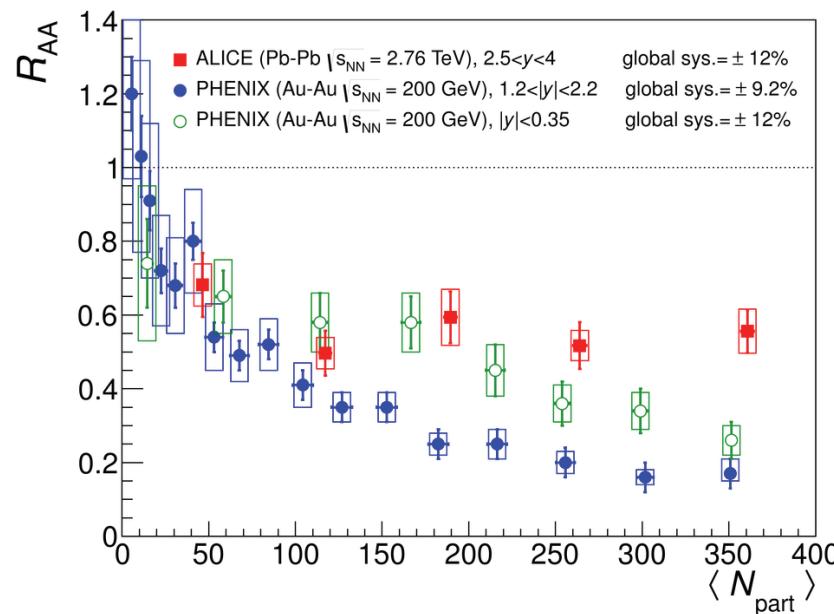
- For  $p_T < \approx 8 - 10$  GeV/c:  $R_{AA}$  for  $\pi$  and  $K$  are compatible and are smaller than  $R_{AA}$  for  $p$ .
- At high  $p_T$ :  $R_{AA}$  for  $\pi$ ,  $K$  and  $p$  are compatible. Three particles species equally suppressed at very high  $p_T$ .

# Quarkonia as QGP signature

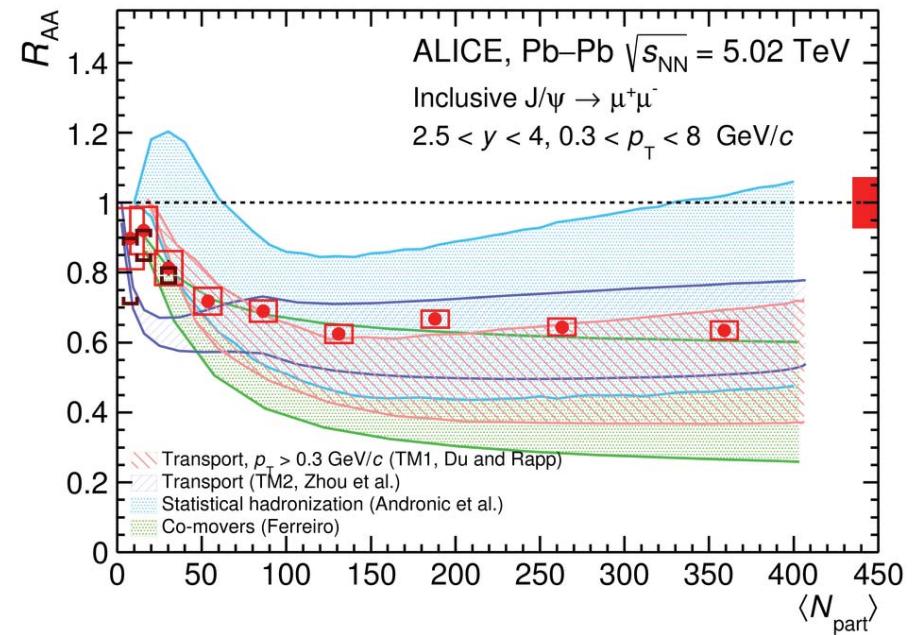
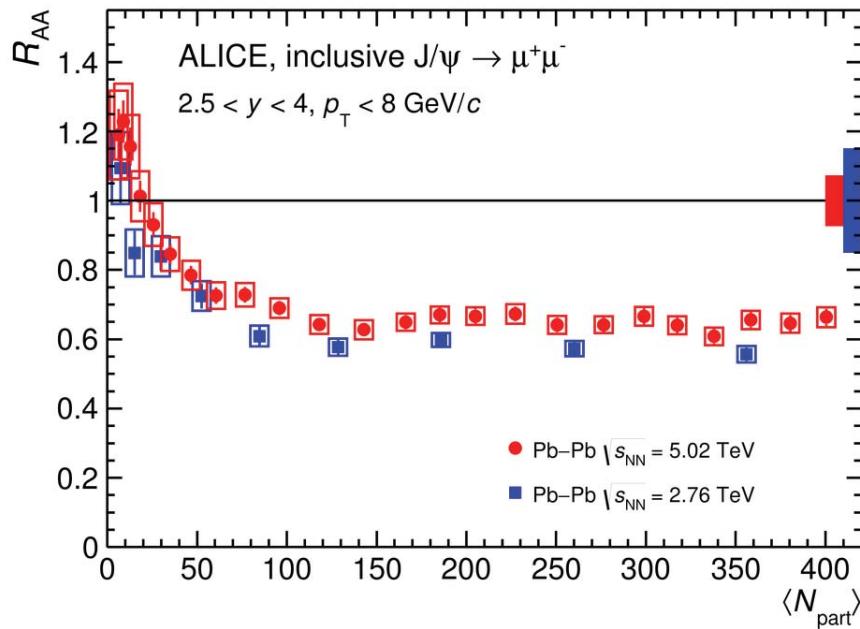
- **J/ψ (charmonium):** bound state of a c quark and a c anti-quark (3 GeV mass)
- Charmonium suppression:
  - Inside the QGP, due to the high number of free colour charges, the binding between c-quark and c-antiquark becomes weaker, the pair disintegrates and the J/ψ disappears
  - Temperature dissociation depends on bound energy → QGP thermometer
- Charmonium **regeneration:**
  - J/ψ from quarks recombination?



Suppression at LHC smaller than at RHIC

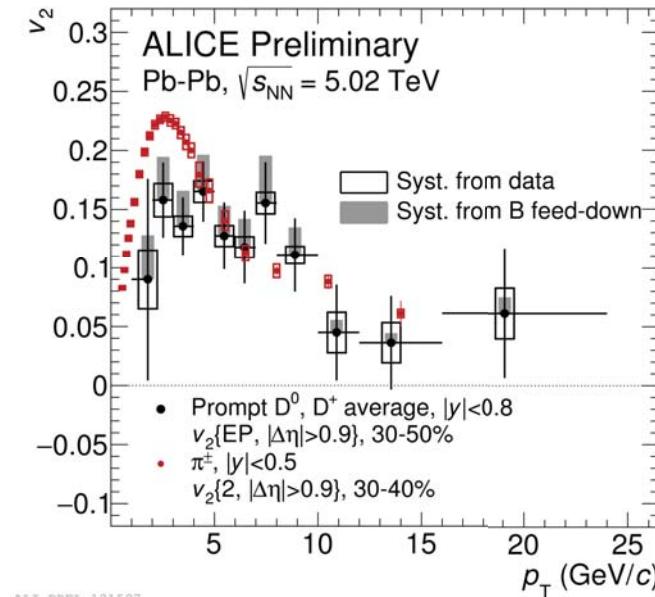
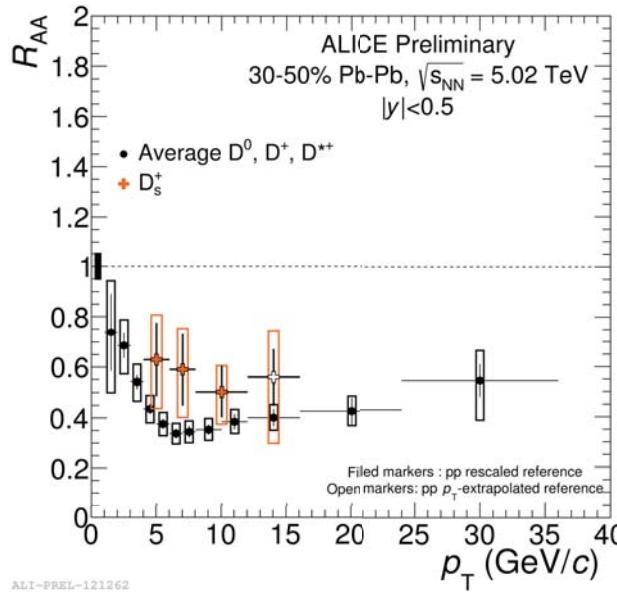


# J/ $\Psi$ suppression

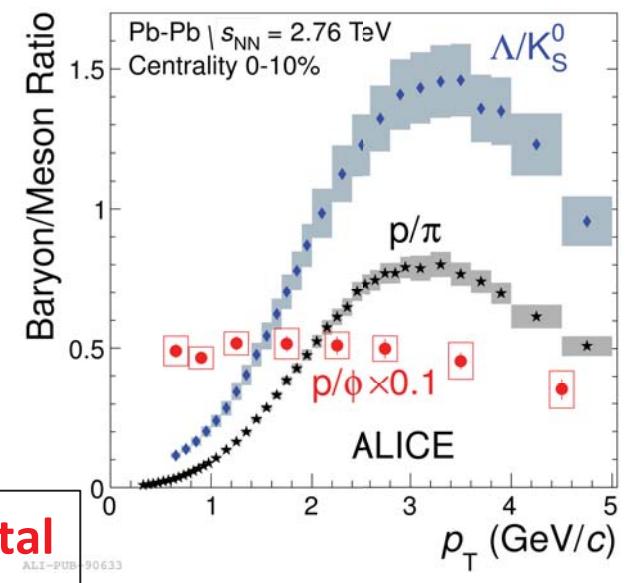


- Suppression independent on centrality.
- Measurement at  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$  more precise than that at  $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ .
- Good agreement with recombination model
- Largest contribution to model uncertainty is due to the uncertainty on the total amount of charm produced→
  - **Important to measure the total charm production cross section down to  $p_T \approx 0 \text{ GeV}/c$ !**

# Heavy flavour (charm e beauty)



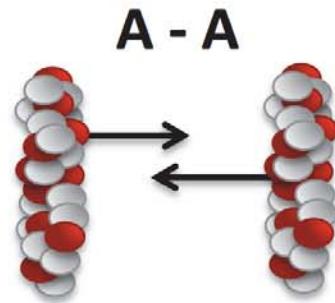
- For a more precise QGP characterization is necessary to study the thermalization and the energy loss of the heavy quarks c and b
- It is important to measure
  - V2 of barions and mesons with charm and beauty down to very low  $p_T$
  - D mesons at  $p_T \approx 0$ ;
  - barion/meson ratio for charm ( $\Lambda_c/D$ ) and beauty ( $\Lambda_b/B$ ).



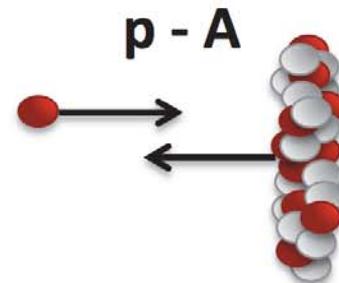
Quantities not measurable with the current experimental apparatus!!

# “Small” systems as reference for “large” systems

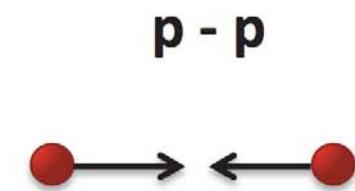
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**Nuclear** initial state  
**Hot matter** in the final state



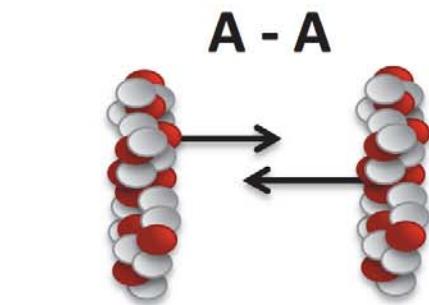
**Nuclear** initial state  
**Cold matter** in the final state



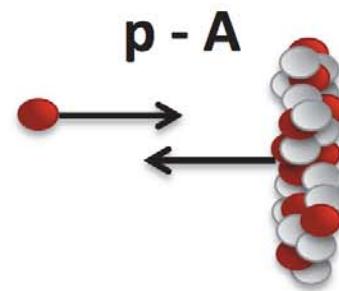
**Hadronic** initial state  
**Hadronic** final state

In **p-A** and **pp** no phase transition is expected to occur, thus they have been **used as reference** for the measurements in **A-A** collisions, where **QGP** is formed

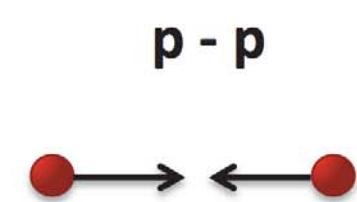
# “Small” systems as reference for “large” systems



Nuclear initial state  
**Hot matter** in the final state



Nuclear initial state  
**Cold matter** in the final state



**Hadronic** initial state  
**Hadronic** final state

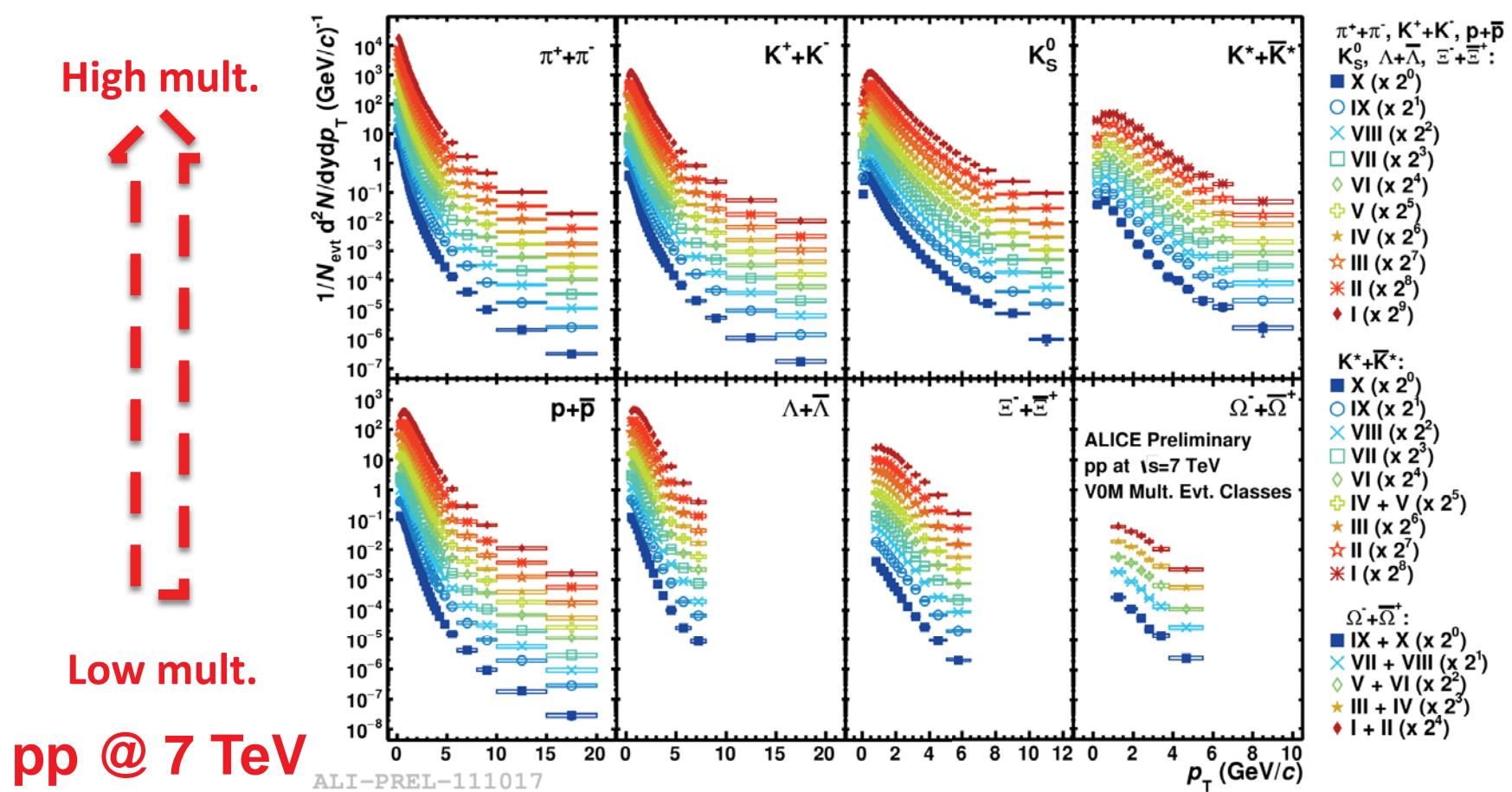
In **p-A** and **pp** no phase transition is expected to occur, thus they have been used as **reference** for the measurements in **A-A** collisions, where **QGP** is formed

Recent measurements have revealed **striking similarities across different systems**

- Hints for **collectivity in small systems**
  - What is its origin (radial flow, QCD effects, ...)?
- Smooth **evolution of particle production as a function of multiplicity** across different systems
  - What drives particle composition in different systems?
- **Enhancement of strangeness production** in high-multiplicity pp and p-Pb

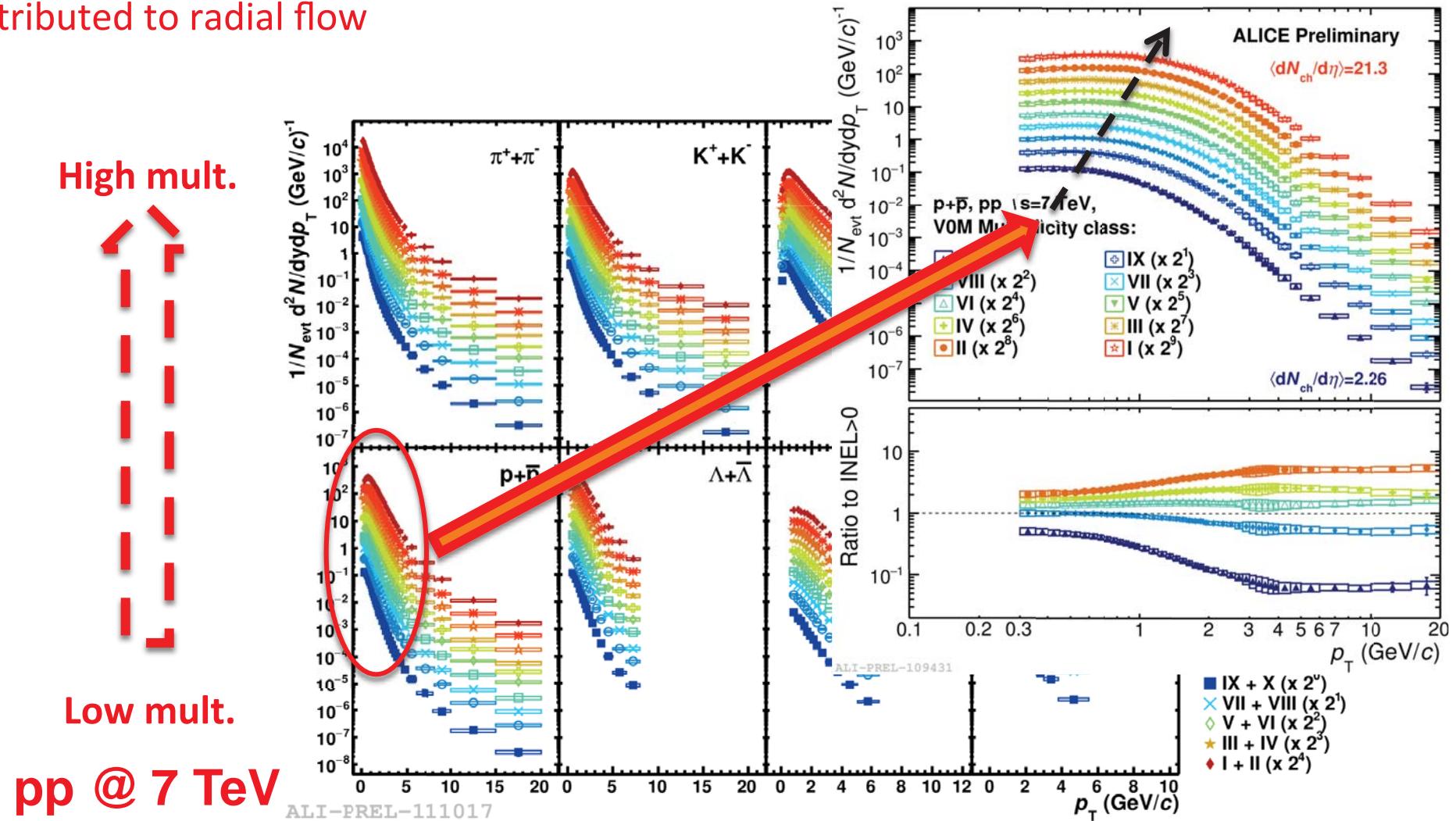
# Collectivity in small system: $p_T$ spectra

- Hardening with multiplicity and particle mass at low  $p_T$  ( $< 2 \text{ GeV}/c$ )
- Indication for collective effects, reminiscent of observed effects in Pb-Pb → attributed to radial flow



# Collectivity in small system: $p_T$ spectra

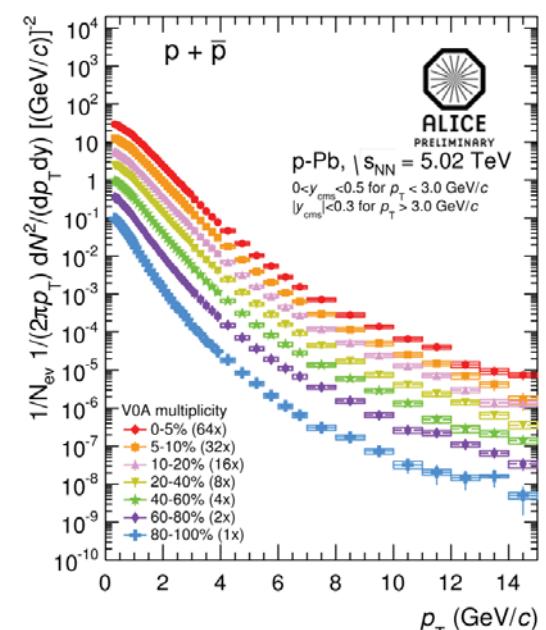
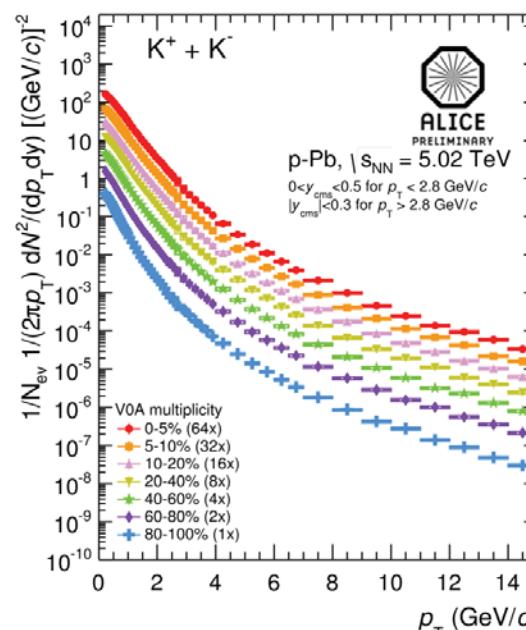
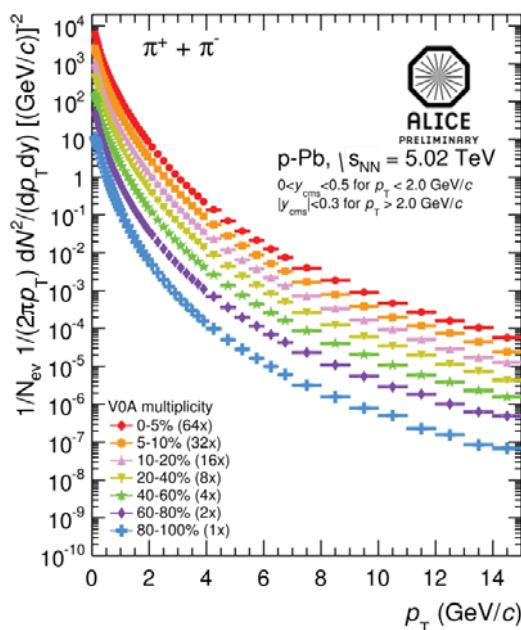
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High mult.



Low mult.

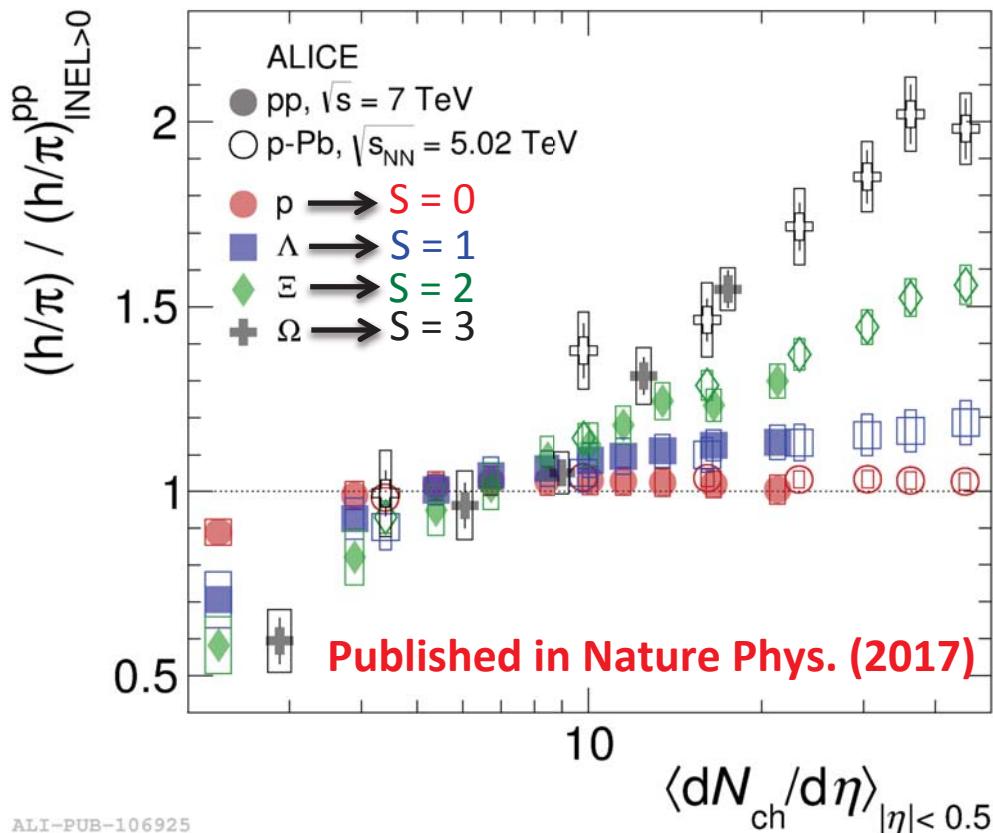
**p-Pb @ 5.02 TeV**

# Strangeness enhancement in small system

Enhancement definition  
modified to be used →  
also in pp and p-Pb

$$En = \left( \frac{Y(h)}{Y(\pi)} \right)_{ppMinBias} / \left( \frac{Y(h)}{Y(\pi)} \right)$$

$Y(h)$  = hadron yield  
 $Y(\pi)$  = pion yield



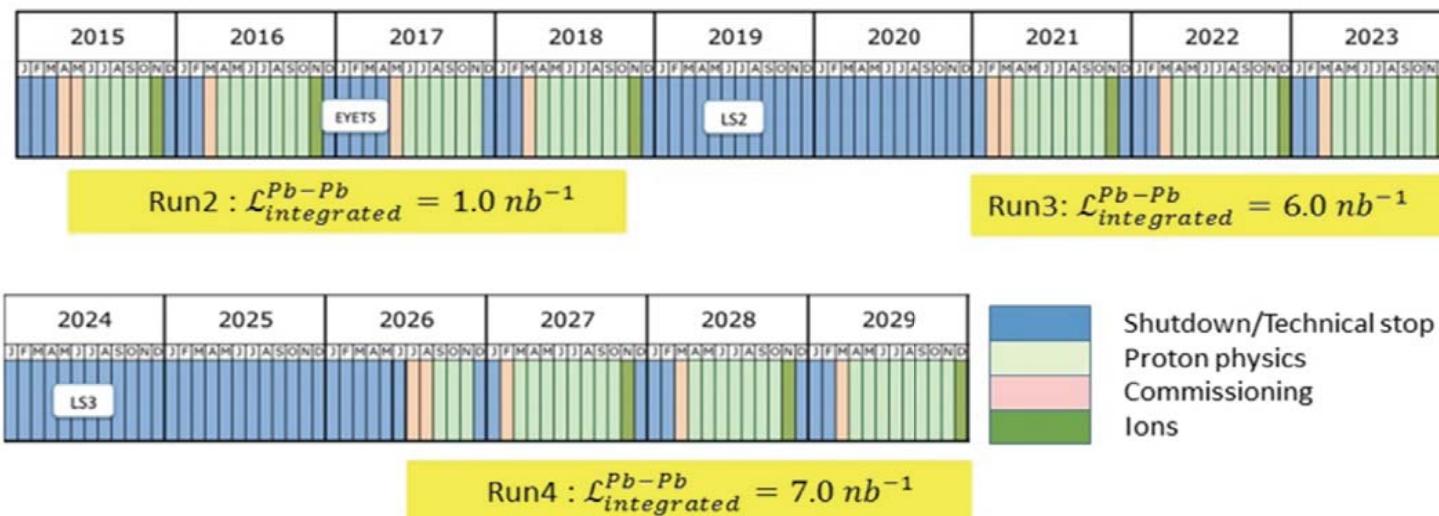
- Double-ratio in pp collisions (and p-Pb, also shown) evolves smoothly with multiplicity density.
- Proton ( $S=0$ ) is consistent with unity up to highest  $\langle dN_{ch}/d\eta \rangle$
- Hyperon production increases from low to high multiplicity in pp and p-Pb
- The larger the valence strange quark content, the steeper the slope

→ the effect is due to strangeness

# Future scenario: heavy-ion program at LHC

- Run3 e Run4: 2021- 2029
  - $\sqrt{s}_{\text{NN}} = 5.5 \text{ TeV}$
  - $L_{\text{int}} > 10 \text{ nb}^{-1}$
  - Experiments upgrade
- Accelerator upgrade during LS2 (2019-2020)
  - Pb-Pb interaction rate from 8 kHz → 50 kHz

LHC roadmap: ion runs



# ALICE upgrade

---

## LHC upgrade → New Physics Opportunities for ALICE

- Study the **thermalization of partons** in the QGP, with focus on **charm and beauty** quarks at **low  $p_T$** 
  - secondary vertices
- Low-momentum charmonium ( $J/\Psi$ ) dissociation (and regeneration?) to study deconfinement and medium temperature
- Production of **thermal photons** and **low-mass dileptons** emitted by QGP to study initial temperature and equation of state of the medium
  - exploit low  $p_T$  reach & PID of ALICE

*Processes of interest cannot be selected at trigger level*

Move from **1 kHz triggered** running in ALICE to **50 kHz Pb-Pb**

*Record Everything!*

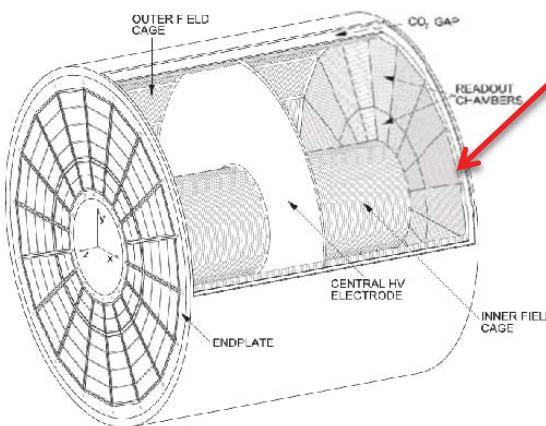
# ALICE upgrade

## Fast Interaction Trigger detector

- Luminosity monitoring
- Online vertex determination
- Minimum Bias trigger
- Centrality
- beam/gas events rejection
- Veto for Ultra Peripheral Collisions without forward particles
- Collision time → Time-Of-Flight → Particle ID

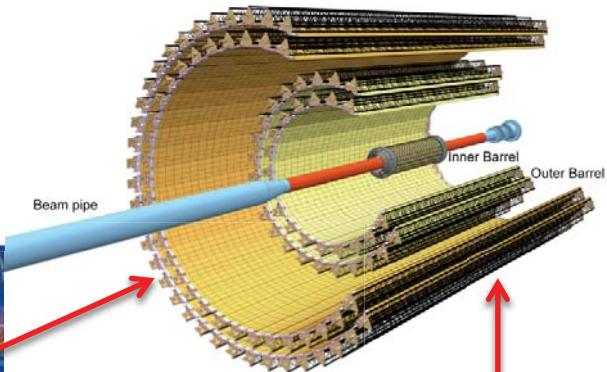


TPC with  
GEM based  
readout



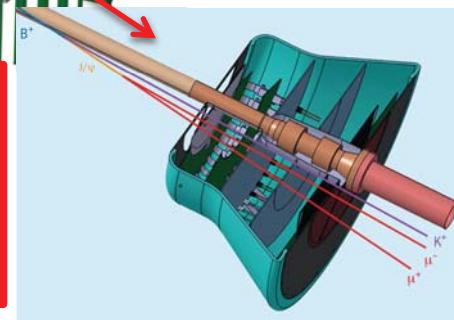
- + new readout for TOF, ZDC, TRD, MUON ARM
- + new Central Trigger Processor
- + new DAQ/offline architecture

## Nuovo Inner Tracking System



Both based on  
Monolithic  
Active Pixel  
Sensor (MAPS)

## Muon Forward Tracker



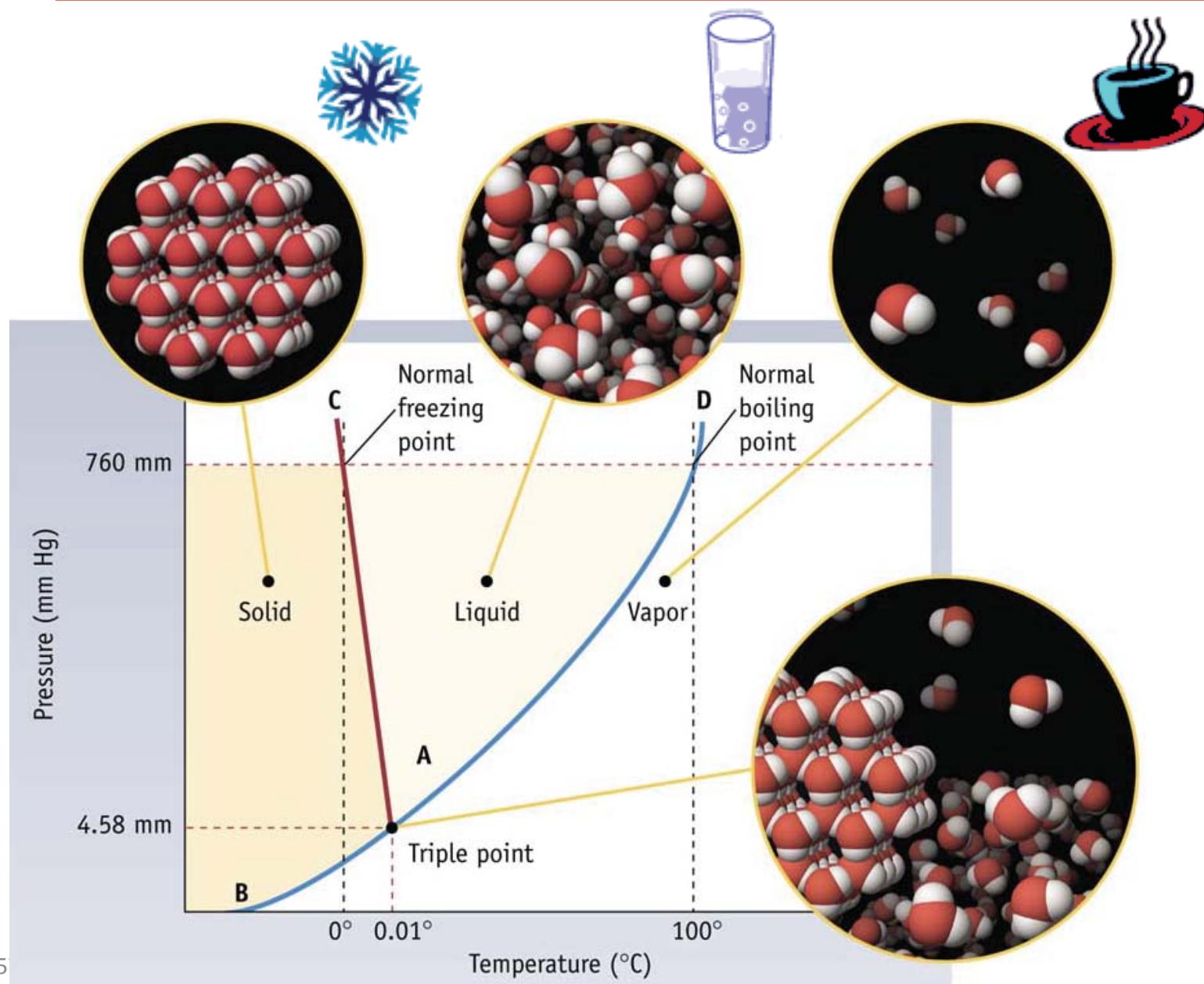
# Conclusion

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- ALICE has studied the heavy-ion collisions provided by LHC during RUN1 and RUN2 periods, this represents an important step forward in our understanding of QGP
  - Energy density  $\varepsilon \approx 15 \text{ GeV/fm}^3 \gg \varepsilon_c$
  - Temperature  $T \approx 300 \text{ MeV}$
  - Elliptic flow as expected from hydro-dynamical calculations
    - QGP behaves as a **perfect fluid**
    - **J/Ψ** suppression smaller than at RHIC → **dissociation + recombination**.
- Interesting similarities among different systems (pp, p-Pb, Pb-Pb) are observed:
  - Hints for the presence of **collectivity in small systems**, whose origin and phenomenology is under investigation.
  - **Enhancement of strangeness** production observed from low to high-multiplicity pp collisions
- A better description of QGP needs high precision measurements of the **production of heavy quarks, quarkonia , jet and di-leptons over a large momentum range**.
- ALICE will be upgraded for LHC RUN2 and RUN4
  - **Tracking performance improvement** (precision and efficiency), in particular for **low  $p_T$  particles**;
  - **50 kHz readout rate** for Pb-Pb collisions (minimum bias trigger);
  - **New ITS**, a Moun Forward Tracker , **TPC with GEM**, a Fast Interaction Trigger (FIT);
  - New readout electronics for TOF, MUON e ZDC (50 kHz rate);
  - New DAQ/offline architecture.

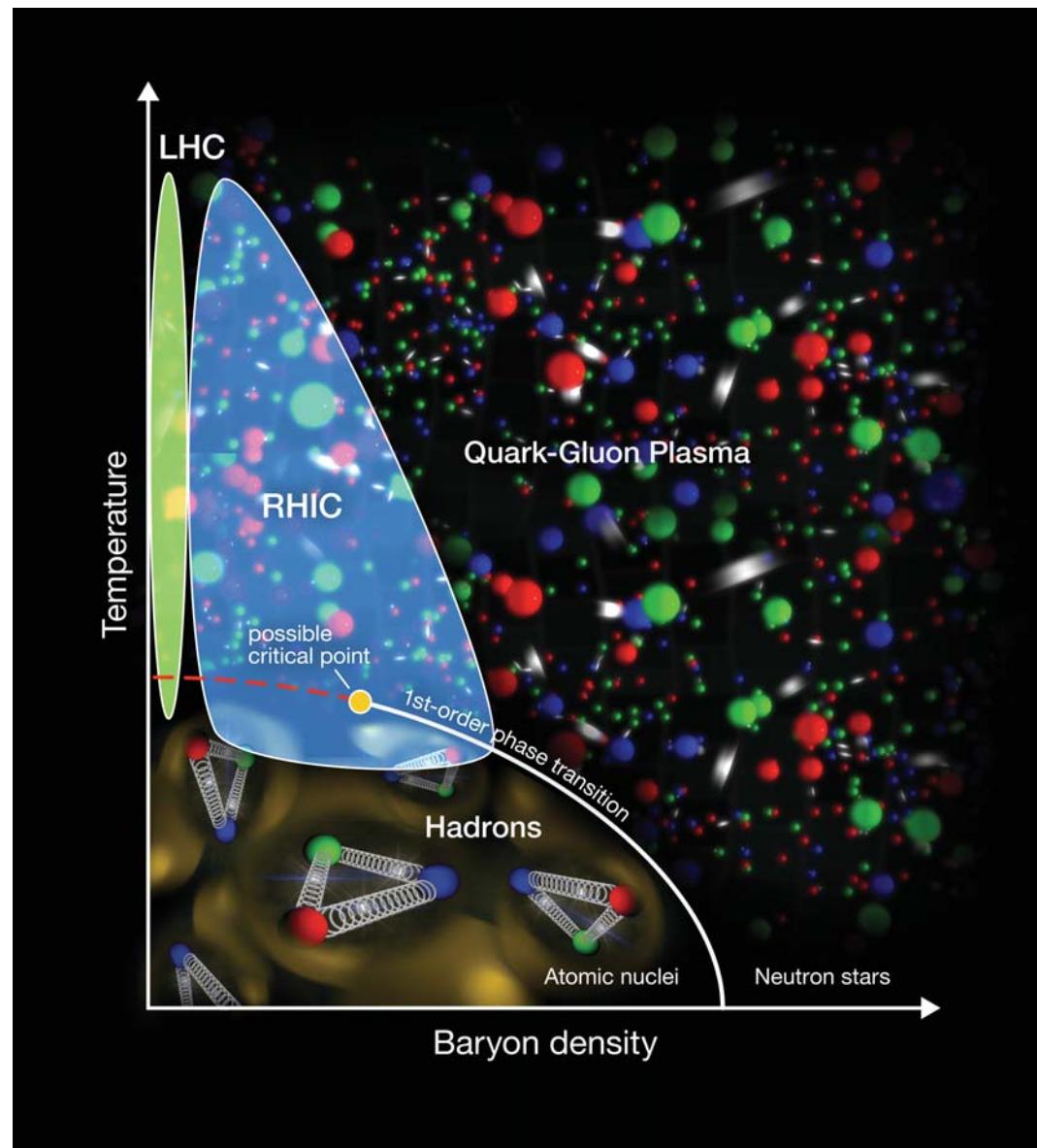
# Backup

# The phase diagram of water



# Phase diagram of hadronic matter

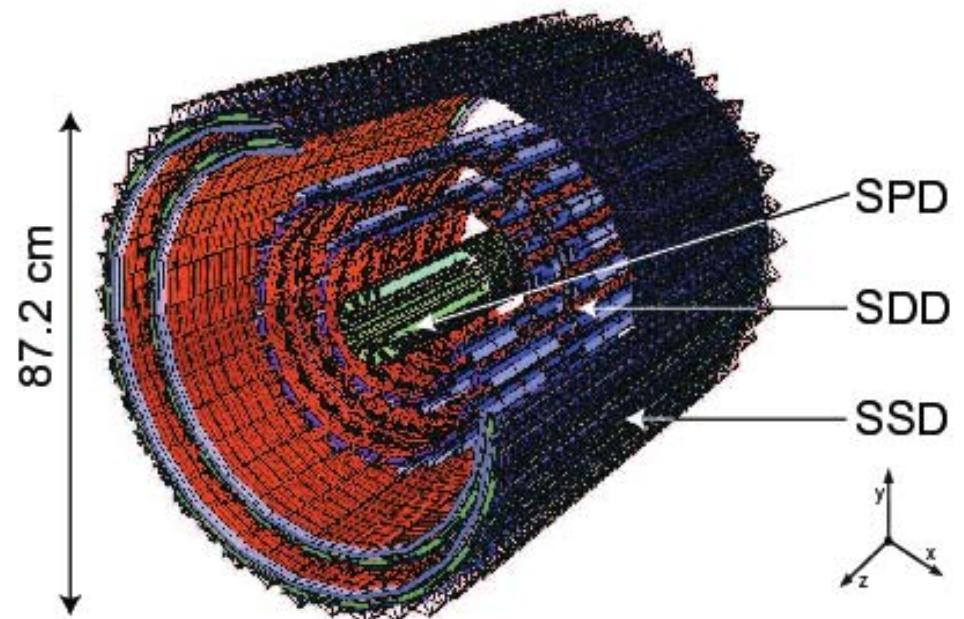
- Schematic phase diagram of strongly interacting matter for temperature and baryon chemical potential
- At LHC energies: most particles produced during the collision  
→ very low baryon chemical potential



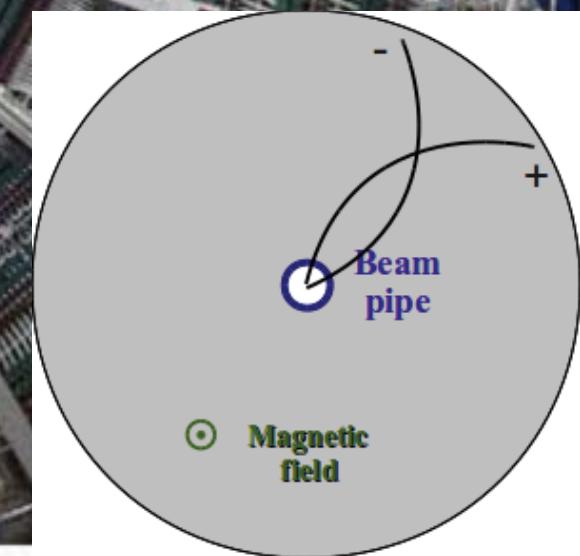
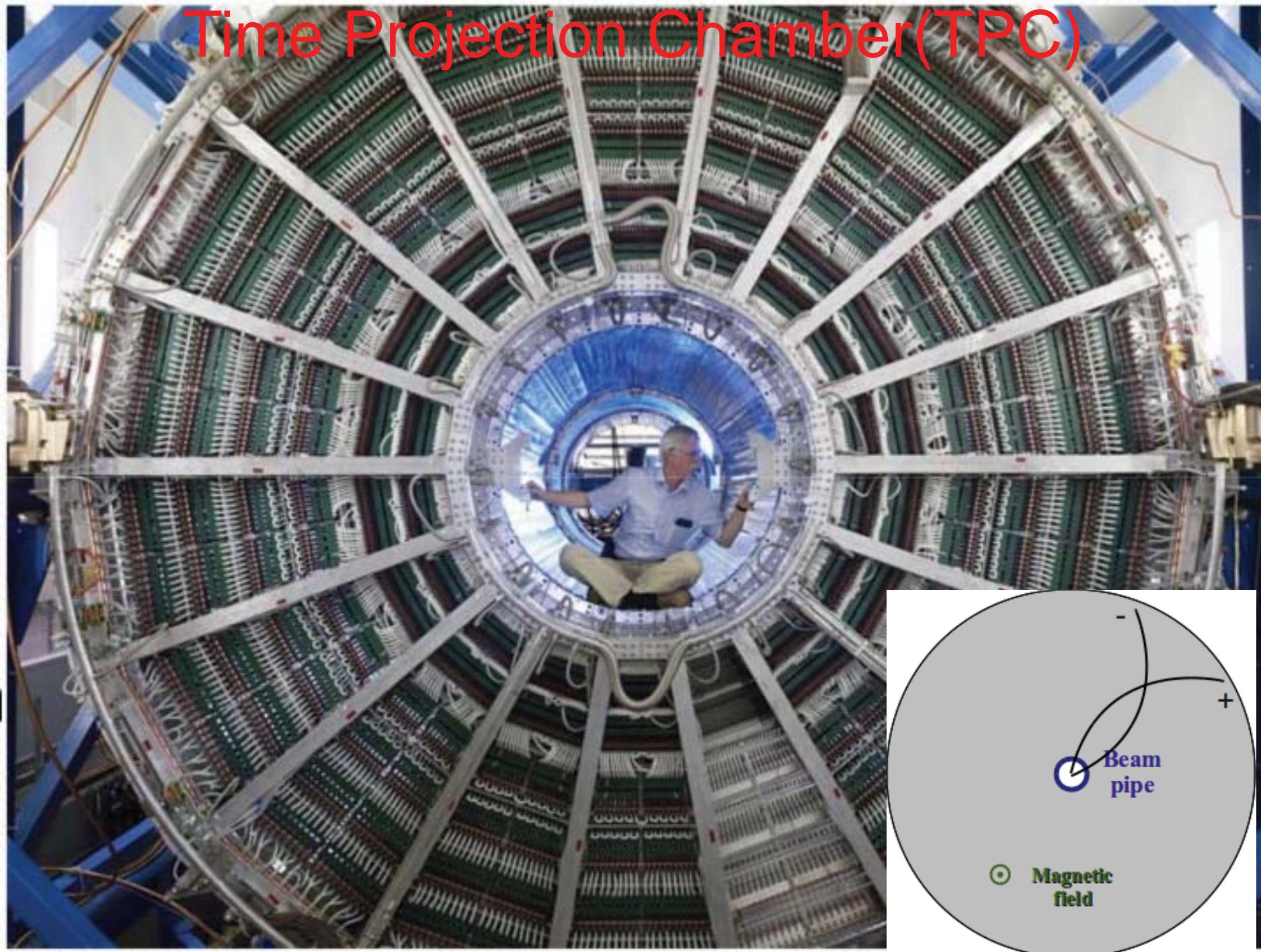
# Inner tracking System (ITS)

## Tracking/PID

- Six cylindrical layers of silicon detectors
  - Two layers of pixels
  - Two layers of strips
  - Two layers of drifts
- Surrounds the collision point and measure the properties of the emerging particles
- Contributes to the tracking.
- **Secondary vertex detector:** resolution  $\approx$  tenth of millimetres.
- Charged hadrons PID by means of energy loss  $dE/dx$  measurements

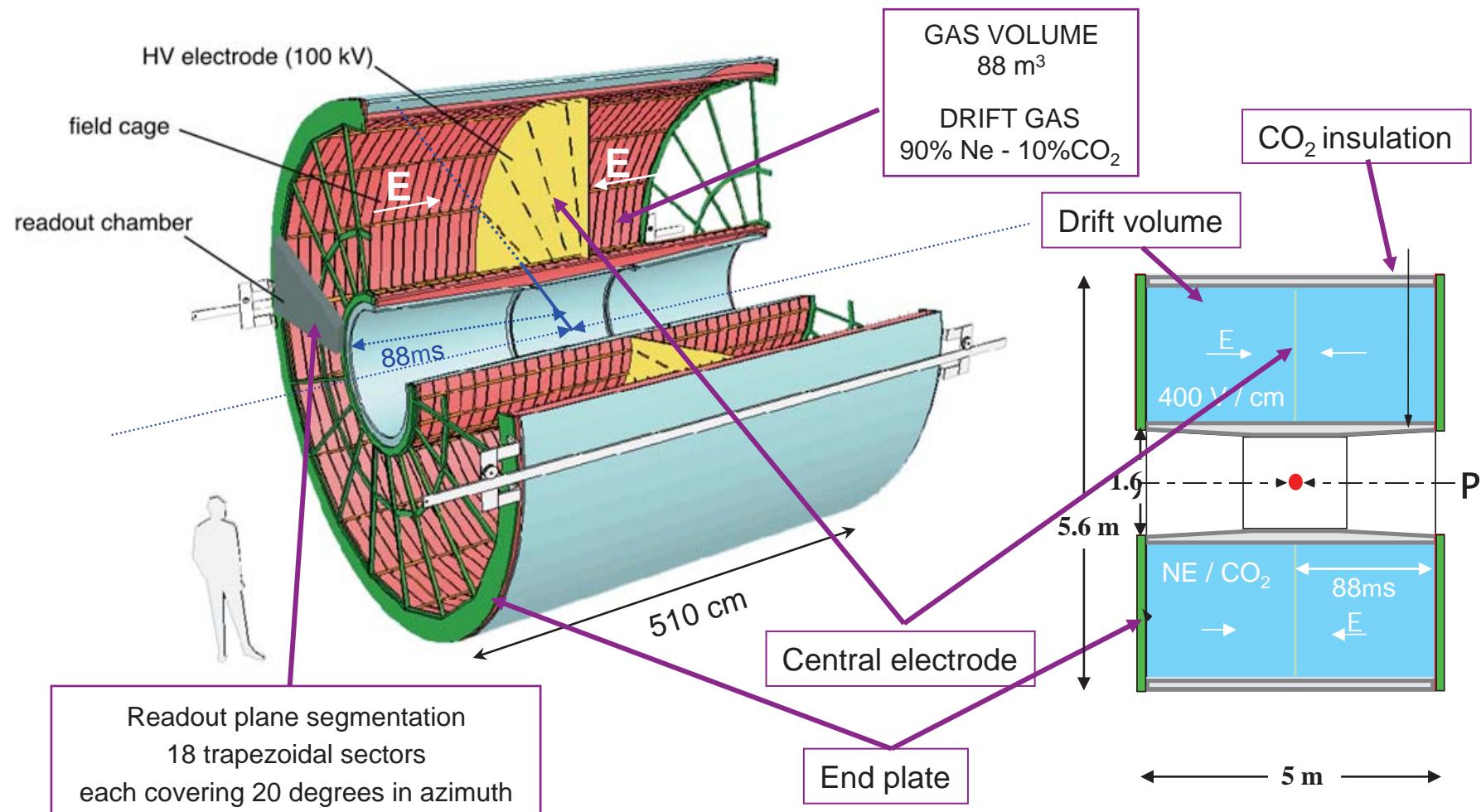


# Time Projection Chamber(TPC)

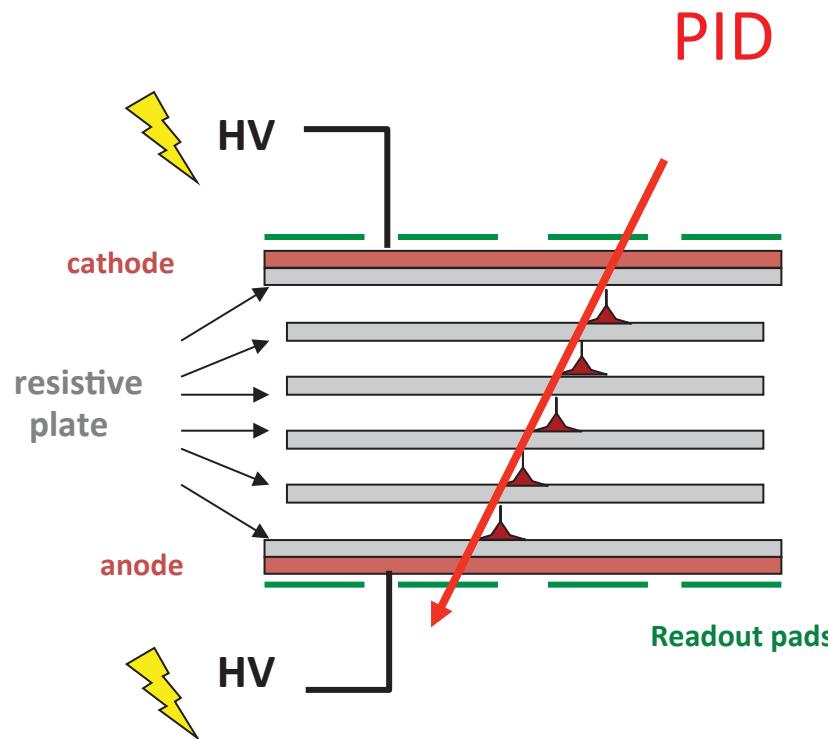


# Time Projection Chamber(TPC)

## Tracking/PID



# Time of Flight (TOF) detector

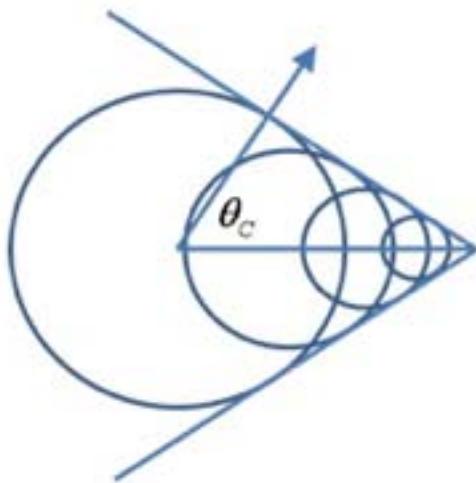


- It measures the time of flight (from the interaction point to the detection one) of charged particles with a resolution of 60 ps
- The time and the track length (measured by tracking devices) provides particle velocity
- From the tracking detector we have the track curvature so the track momentum
- Momentum and velocity allow to evaluate the particle mass, that univocally identifies the particle.

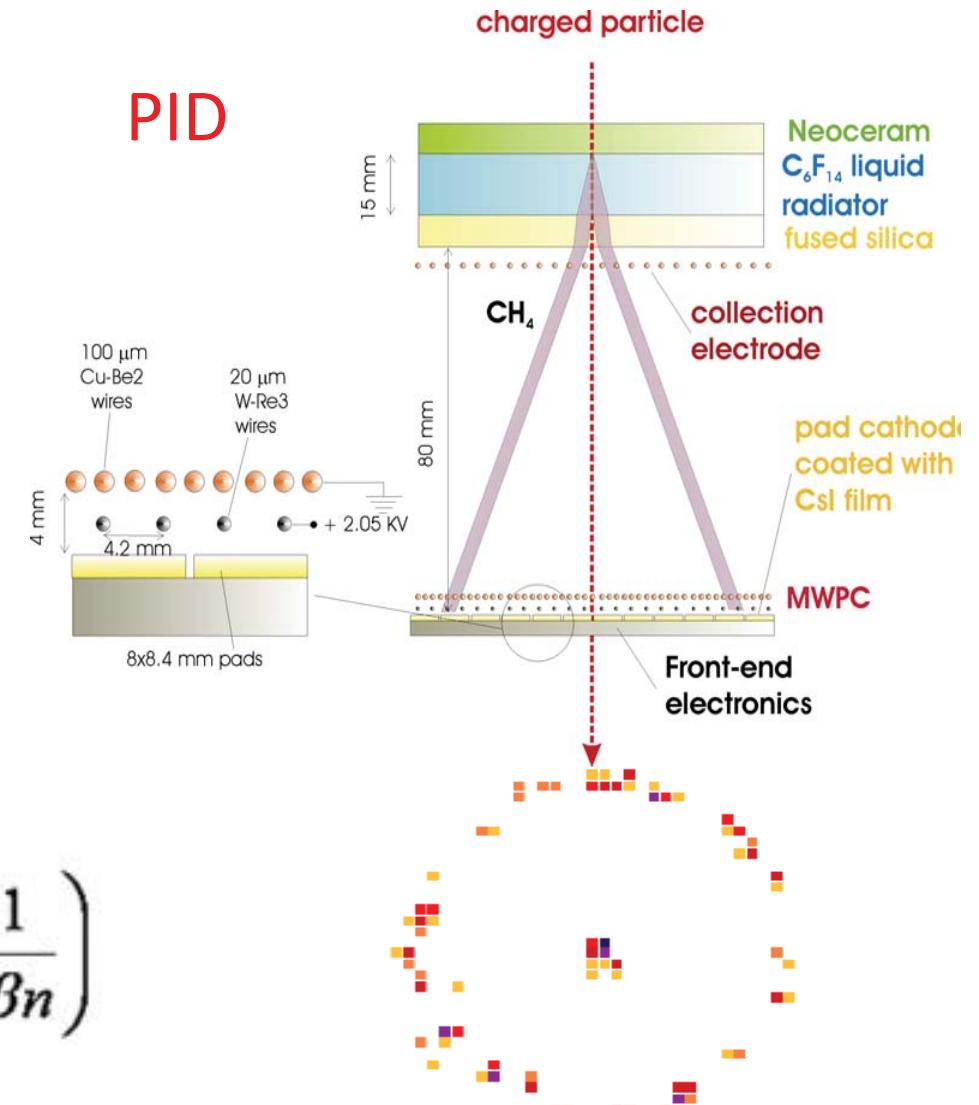
## Multigap Resistive Plate Chamber

# High Momentum Particle Identification (HMPID)

- **Cherenkov effect:** a charged particle that travel in a dielectric medium I with a speed lager than the speed of light in that medium, produce EM radiation
- The HMPID measure the emission angle of the Cherenkov photons with a resolution of  $\approx 4$  mrad.
- From the emission angle is possible to evaluate the particle velocity



$$\theta_C = \cos^{-1}\left(\frac{1}{\beta n}\right)$$

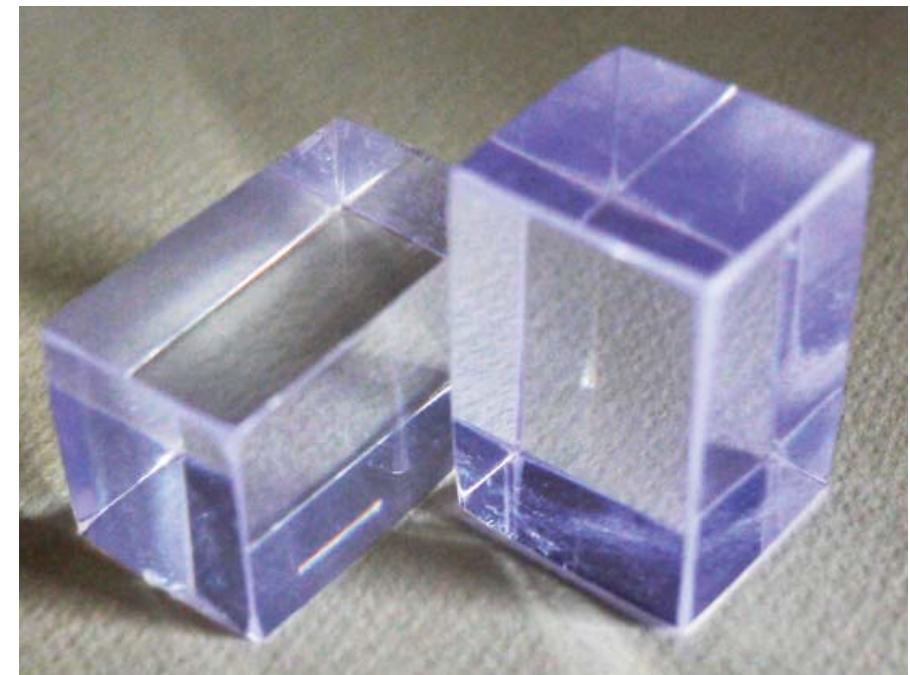
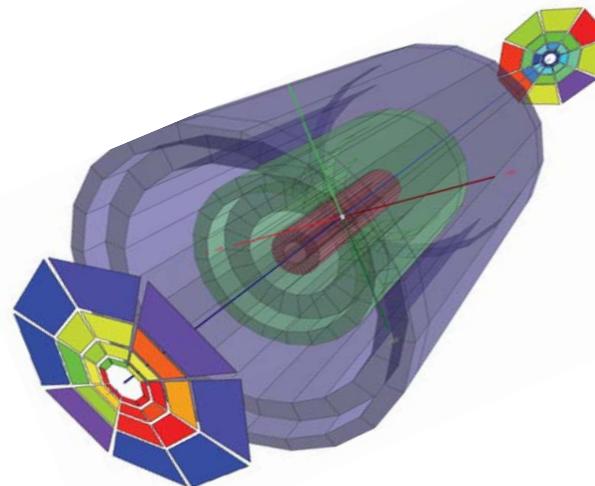


# V0 detector

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## *Trigger*

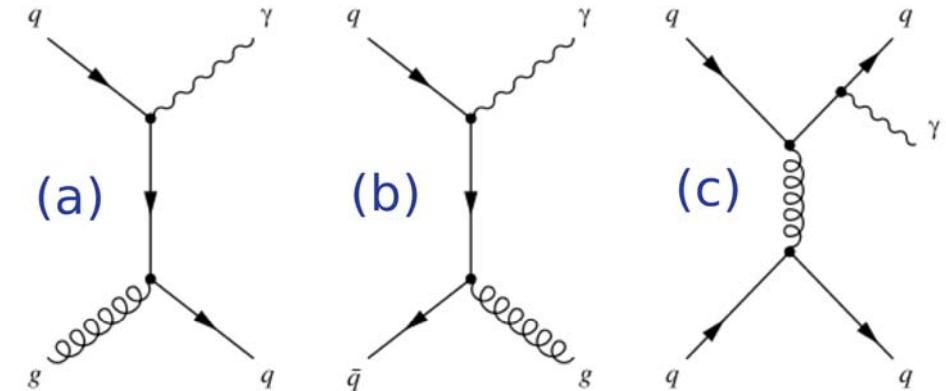
- The V0 detector consists of two plates made of plastic scintillator material, placed on both side of the collision point
- It provides the **Minimum Bias trigger** (MB) for the central barrel detectors, in pp, P-Pb and Pb-Pb collisions
- V0 is able to select the centrality in Pb-Pb collisions



# Direct Photons in pp and Pb-Pb Collisions

## Prompt Photons: In pp and Pb-Pb

- Calculable within NLO pQCD
- Predominant source in pp
- Signal expected to scale with number of binary collisions in Pb-Pb
- Fragmentation photons may be modified by parton energy loss in the medium



- a) Quark-gluon Compton scattering
- b) Quark anti-quark annihilation
- c) Fragmentation photons (bremsstrahlung)

Measurement of direct photons in pp is an ideal test for pQCD

# Direct Photons in Pb-Pb Collisions

## Additional sources of direct photons in Pb-Pb collisions

### Jet-Medium Interactions:

- Scattering of hard partons with thermalized partons
- In medium (photon) bremsstrahlung emitted by quarks

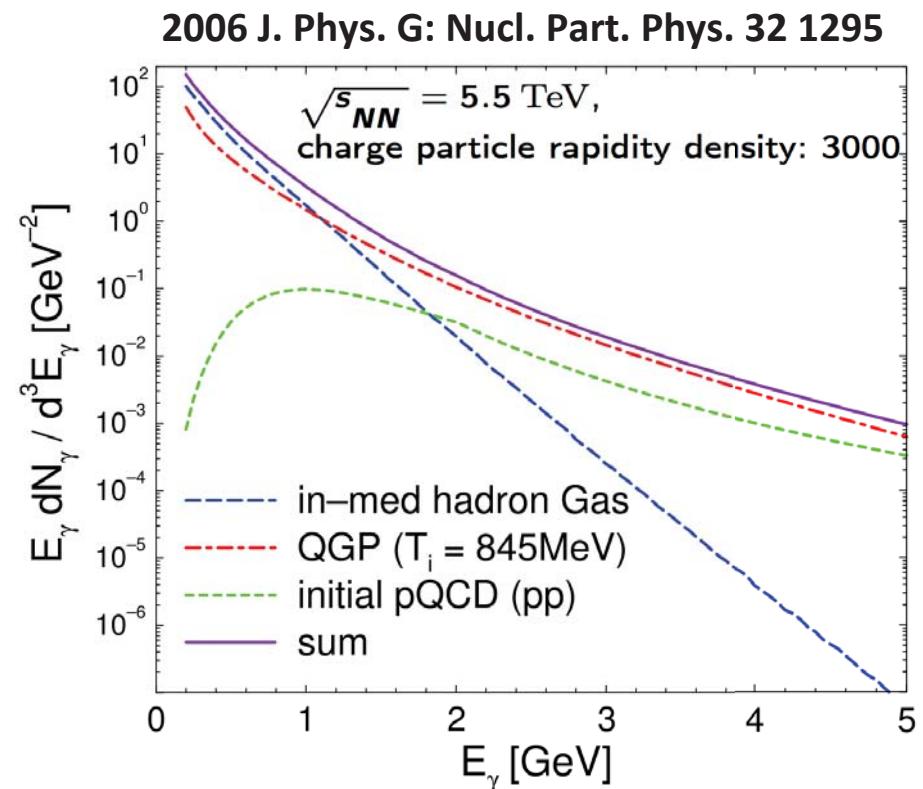
### Thermal Photons:

- Scattering of thermalized particles

QGP:  $q\bar{q} \rightarrow g\gamma$  and  $qg \rightarrow q\gamma$  (+NLO)

HHG (hot hadronic gas): Hadronic interactions  
(e.g.  $\pi^+\pi^- \rightarrow \gamma\rho_0$ )

- Exponentially decreasing but dominant at low  $p_T$



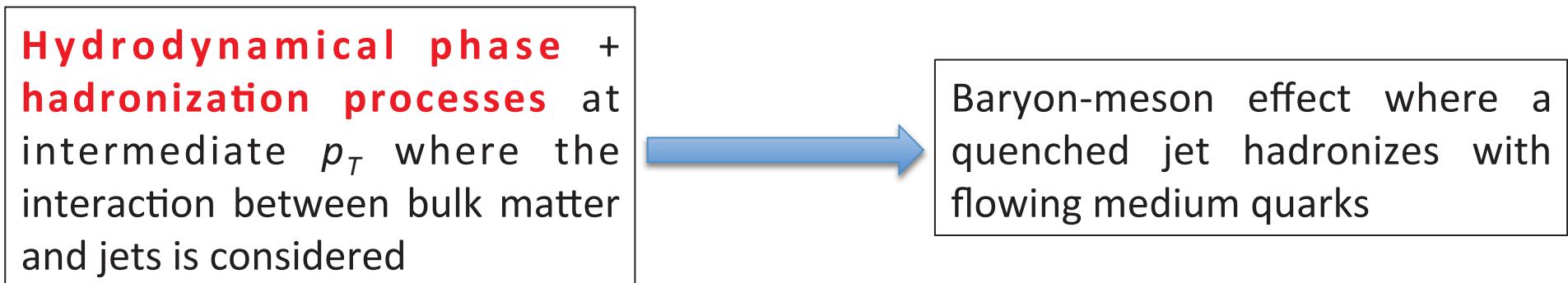
Photons leave the medium unaffected, an ideal probe to study HI collisions

# EPOS model

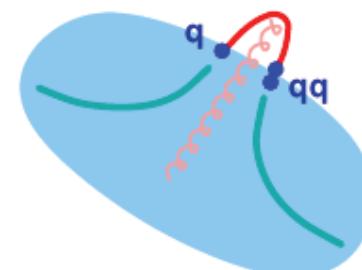
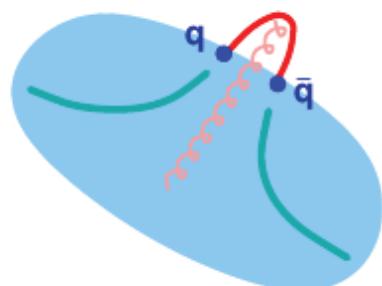
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*Phys. Rev. C* **93** 014911 (2016) “fluid-jet interaction”

Describes pp, p–A ,and A–A collisions with common framework



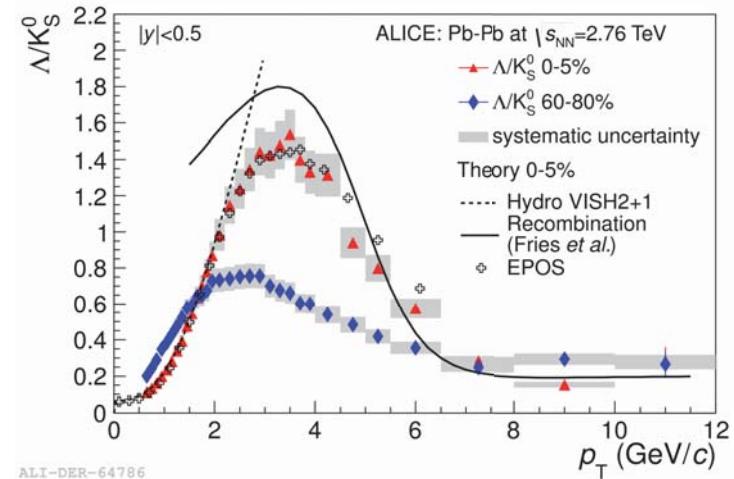
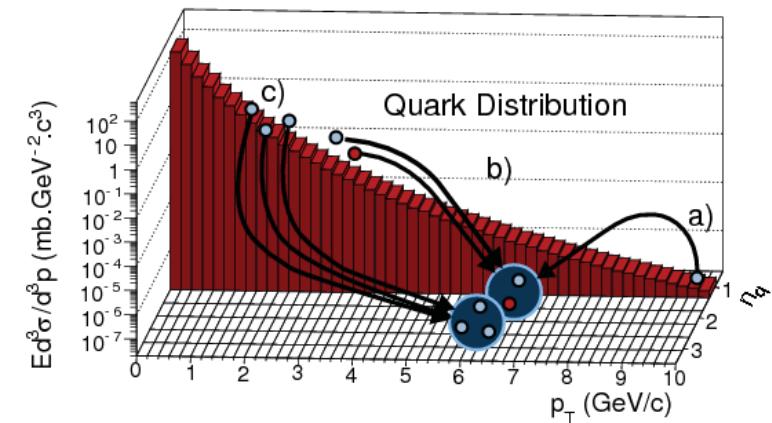
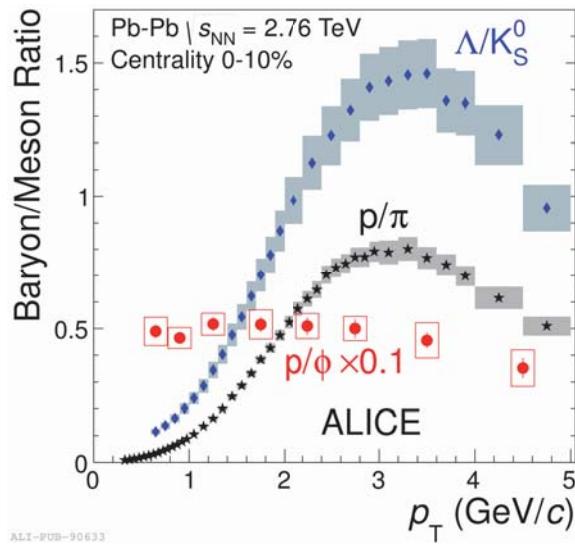
“Considering transverse fluid velocities up to  $0.7c$ , and thermal parton momentum distributions, one may get a “push” of a couple of  $\text{GeV}/c$  to be added to the transverse momentum of the string segment. This will be a crucial effect for intermediate  $p_T$  jet hadrons.”



# Barion/meson ratio

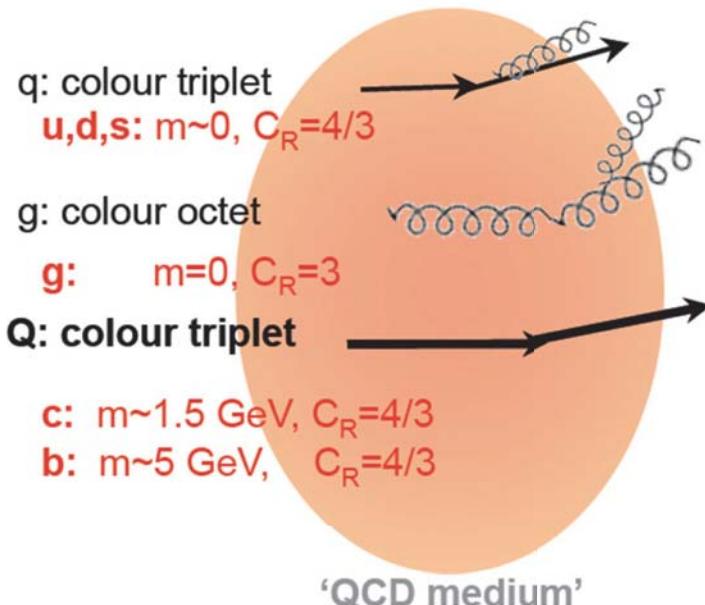
## Particles production models:

- Partons fragmentation → barion suppression
- Recombination/coalescence: quarks close in the phase space , recombine to create barions and mesons [Phys. Rev. Lett. 90,202303,Phys. Rev. Lett. 90, 202302].  
→ barion enhancement



- Hydro** describes only the rise  $p_T < 2 \text{ GeV}/c$  [H. Song, U. Heinz, PLB 658 (2008) 279]
- Recombination** reproduces effect but overestimates [Fries et al., ARNPS 58 (2008) 177]
- EPOS** (with flow) gives good description of the data [PRL 109, 102301 (2012)]  
 $p/\phi$  can be explained **by hydro** (radial flow), since similar mass drives similar spectral shapes  
 → also by models with recombination [V. Greco et al, Phys.Rev. C 92 (2015) 054904]

# Heavy quarks energy loss

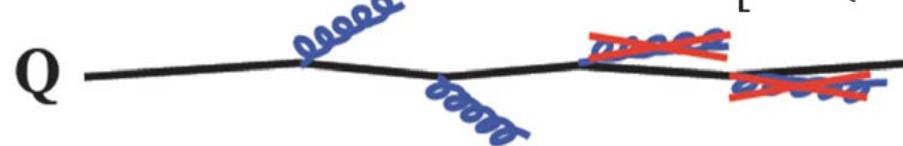


- The energy loss  $\Delta E$  depends on:
  - Medium properties: density, temperature, mean free path.
  - Path length in the medium ( $L$ )
  - Properties of the parton:
    - ✓ **Casimir coupling factor ( $C_R$ )**
    - ✓ **Quark mass (dead cone effect)**



Gluonstrahlung probability  $\propto$

$$\frac{1}{[\theta^2 + (m_Q/E_Q)^2]^2}$$



Dokshitzer and Kharzeev, PLB 519 (2001) 199

$$\Delta E_{\text{quark}} < \Delta E_{\text{gluone}} , \quad \Delta e_{\text{heavy quark}} < \Delta e_{\text{light quark}}$$



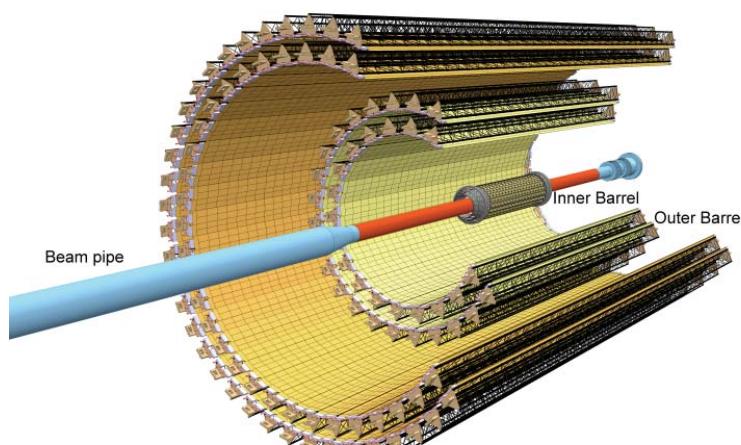
$$R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$$

# ALICE upgrade: ITS

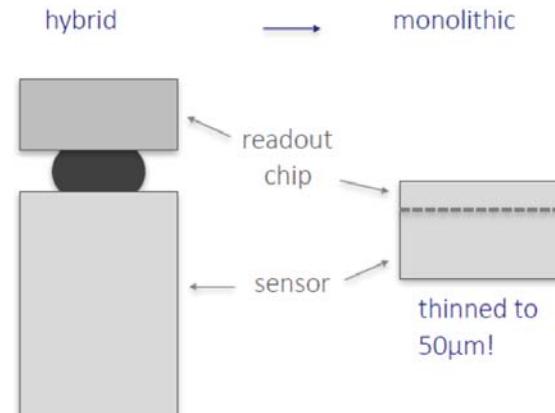
- Improve impact parameter resolution by a factor of 3 (5) in  $r_j(z)$  @  $p_T = 500 \text{ MeV}/c$ 
  - Get closer to IP (position of first layer):  $39 \text{ mm} \rightarrow 23 \text{ mm}$
  - Reduce  $x/X_0$  /layer:  $\approx 1.14\% \rightarrow 0.3\%$  (for the 3 innermost layers)
  - Spatial resolution : current SPD  $12\text{mm} \times 100\text{mm} \rightarrow 5\text{mm} \times 5\text{mm}$ .
- Improve tracking efficiency and  $p_T$  resolution at low  $p_T$ 
  - Increase granularity:
    - $6 \text{ layers} \rightarrow 7 \text{ layers}$
    - Pixel, drift and strip  $\rightarrow$  all-pixels

7-layer barrel geometry, fully equipped ( $\sim 24000$  chips) with dedicated **MAPS**:

R-coverage:  $23 - 400 \text{ mm}$ ;  $\eta$ -coverage:  $|\eta| < 1.3$



## Monolithic Active Pixel Sensor (MAPS)



# ALICE upgrade: TPC

Present TPC: Wire chamber end plates

Goal: to record **50 kHz Pb-Pb** collision rate and maintain the current performance

- **Momentum Resolution** :  $\sigma_{p_T}/p_T \leq 3.5\%$  a  $p_T = 50 \text{ GeV}/c$ ;  $\sigma_{p_T}/p_T \leq 1\%$  a  $p_T = 1 \text{ GeV}/c$
- **dE/dx resolution** : 5% pp; 6% central Pb-Pb collisions

Current limitations:

- Drift time for ionization electrons from central electrode to end plate is  $\approx 100 \mu\text{s}$
- Drift time for ions from end plate to central electrode is  $\approx 160 \text{ ms}$
- **positive ions** in the drift volume  $\rightarrow$  electric field distortion  $\rightarrow$  distortion of the ionization electron tracks as they drift to the end plates

Solution: use 4 **GEM (Gas Electron Multipliers)**

instead of multi-wire chambers

- Different GEM hole patterns on each GEM helps to block ion **backflow (IBF)**
- Tradeoff between energy resolution (large gain in first foil) and ion backflow (small gain in first foil)

