The quest for the QGP with ALICE: overview of recent results and prospects for the future

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Dipartimento di Fisica and INFN – Bari –Italy
CERN - Switzerland

31 Ottobre 2016, *Genova, Italy*

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Outline:

- ALICE: scope of the experiment and overview of recent results
  - focus on heavy flavour probes
- perspective for the LHC phase2

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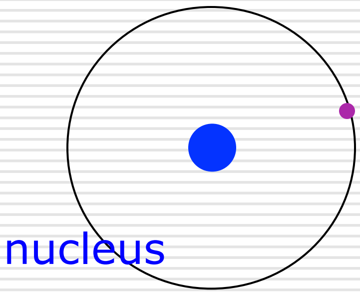
Confinement: a crucial feature of QCD

electron



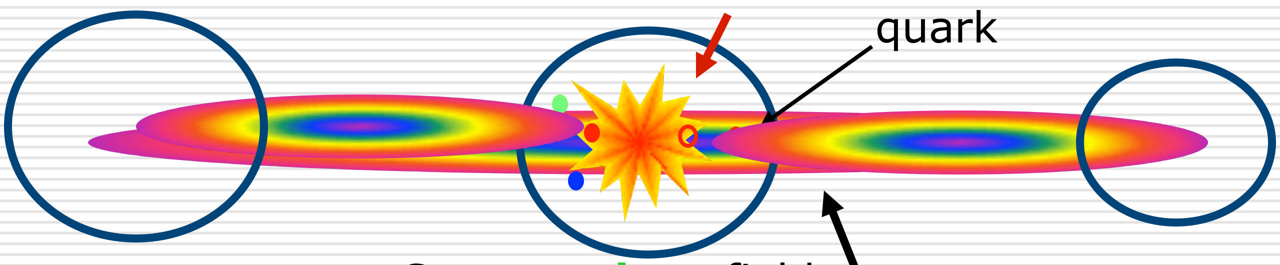
neutral atom

We can extract an electron from an atom by providing energy

But we cannot get free quarks out of hadrons: **“colour confinement”**

•

quark-antiquark pair created from vacuum



“white” proton
(confined quarks)

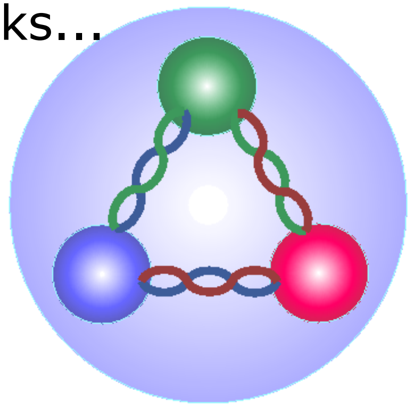
Stror ld
Ener separation!

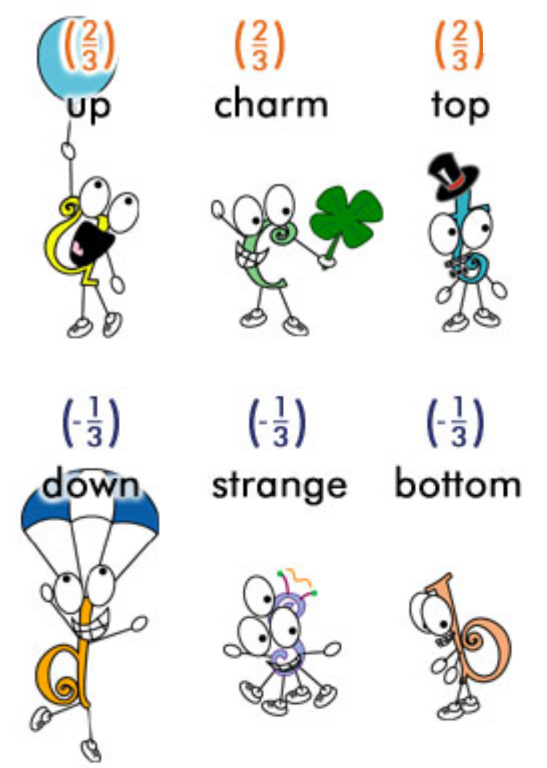
E = mc²

“white” proton

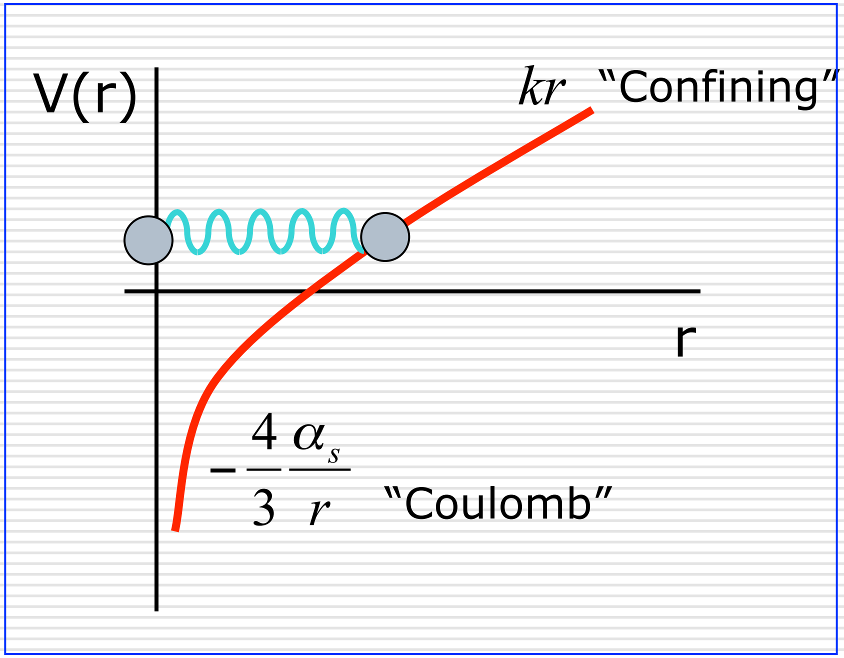
“white” π^0
(confined quarks)

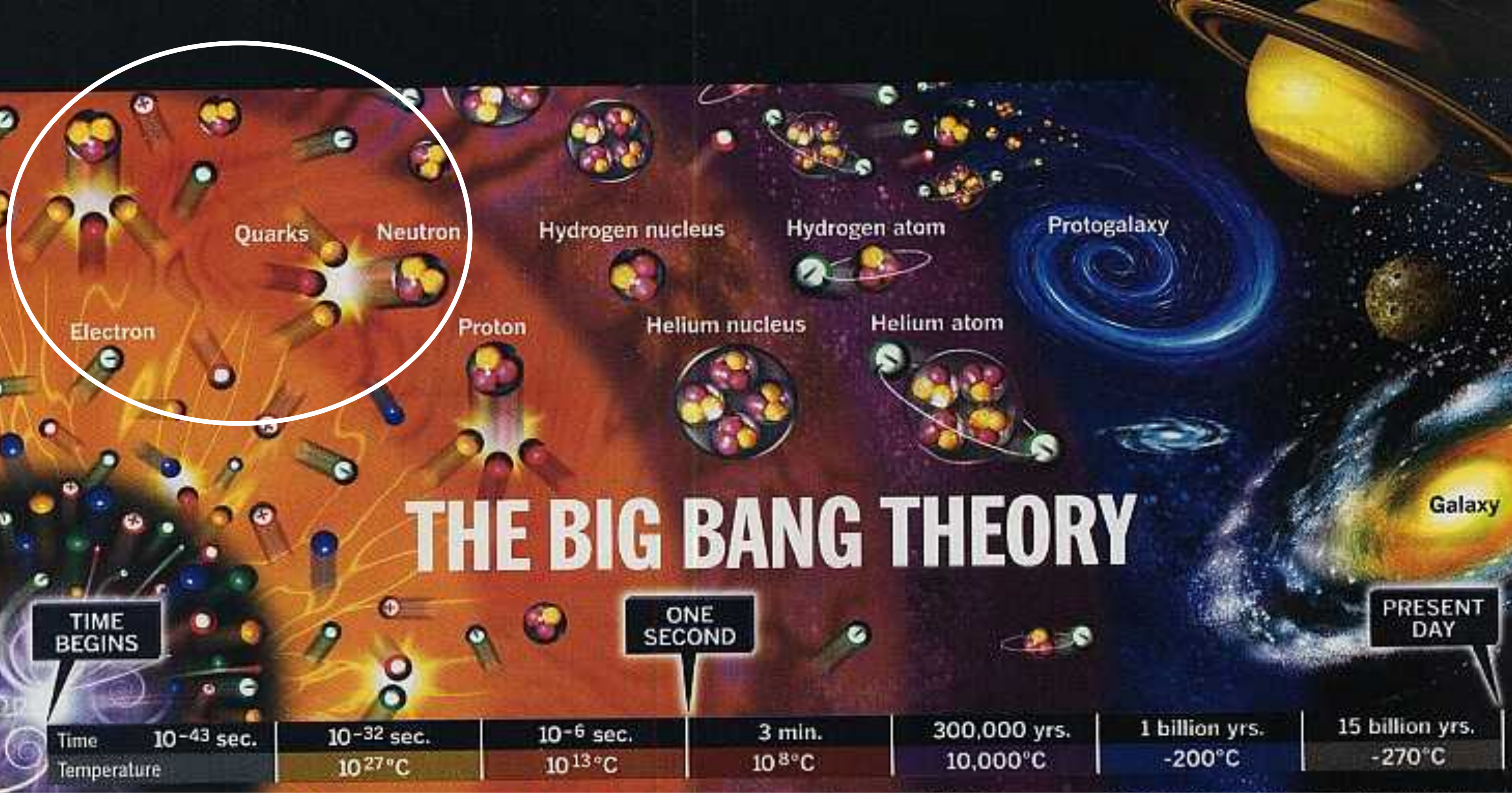
A proton is a composite object made of quarks… and gluons





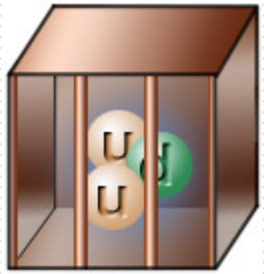
No one has ever seen a free quark; QCD is a “confining gauge theory”





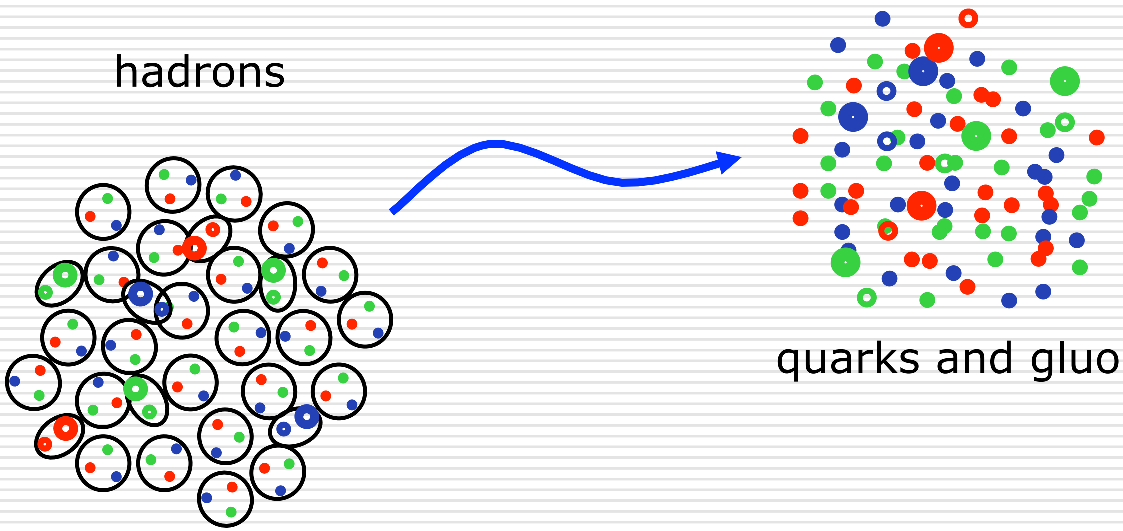
A very very long time ago... quarks and gluons were "free".

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



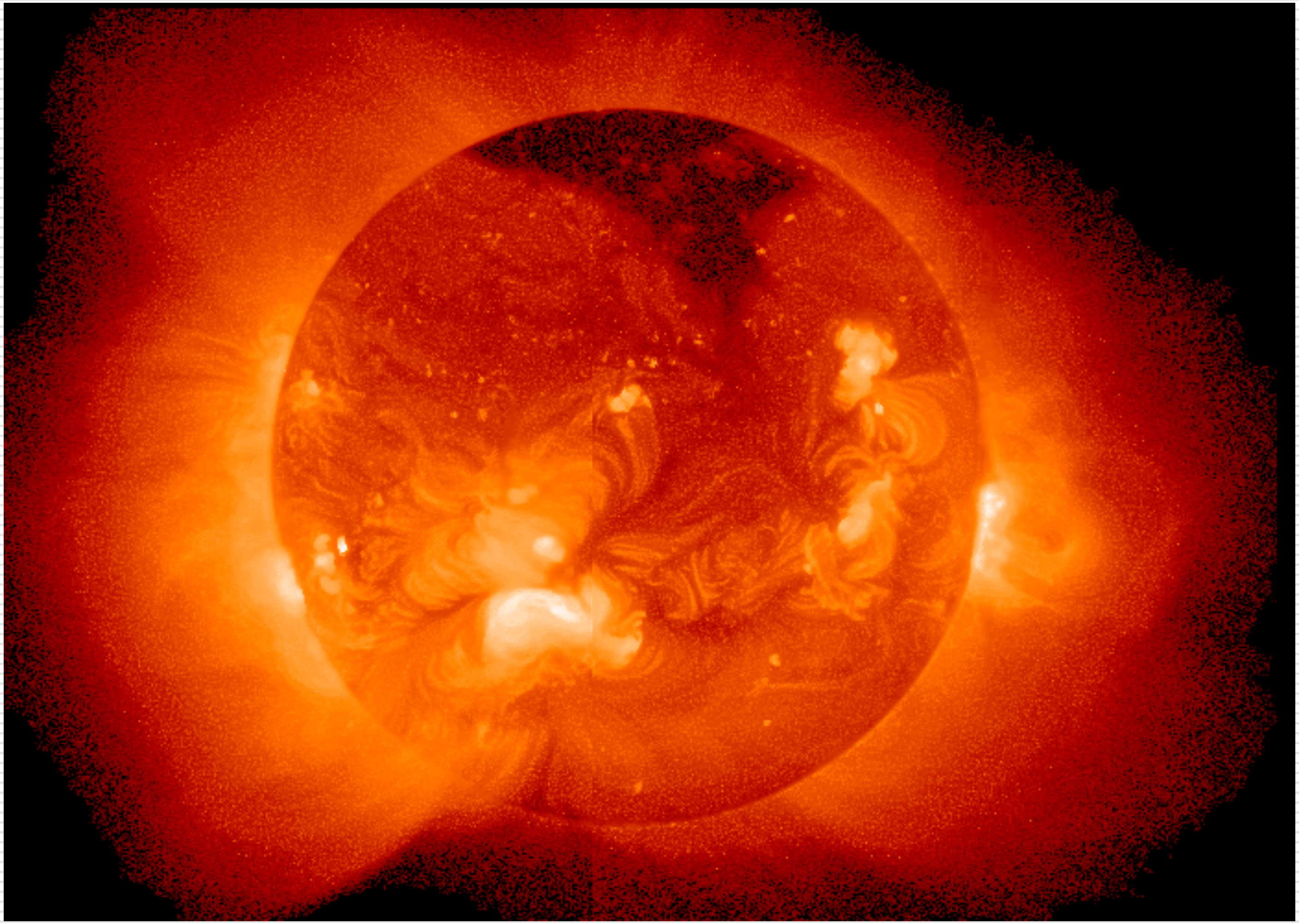
The QCD phase transition

QCD calculations indicate that, at a *critical* temperature around 170 MeV, strongly interacting matter undergoes a phase transition to a new state where the quarks and gluons are no longer confined in hadrons



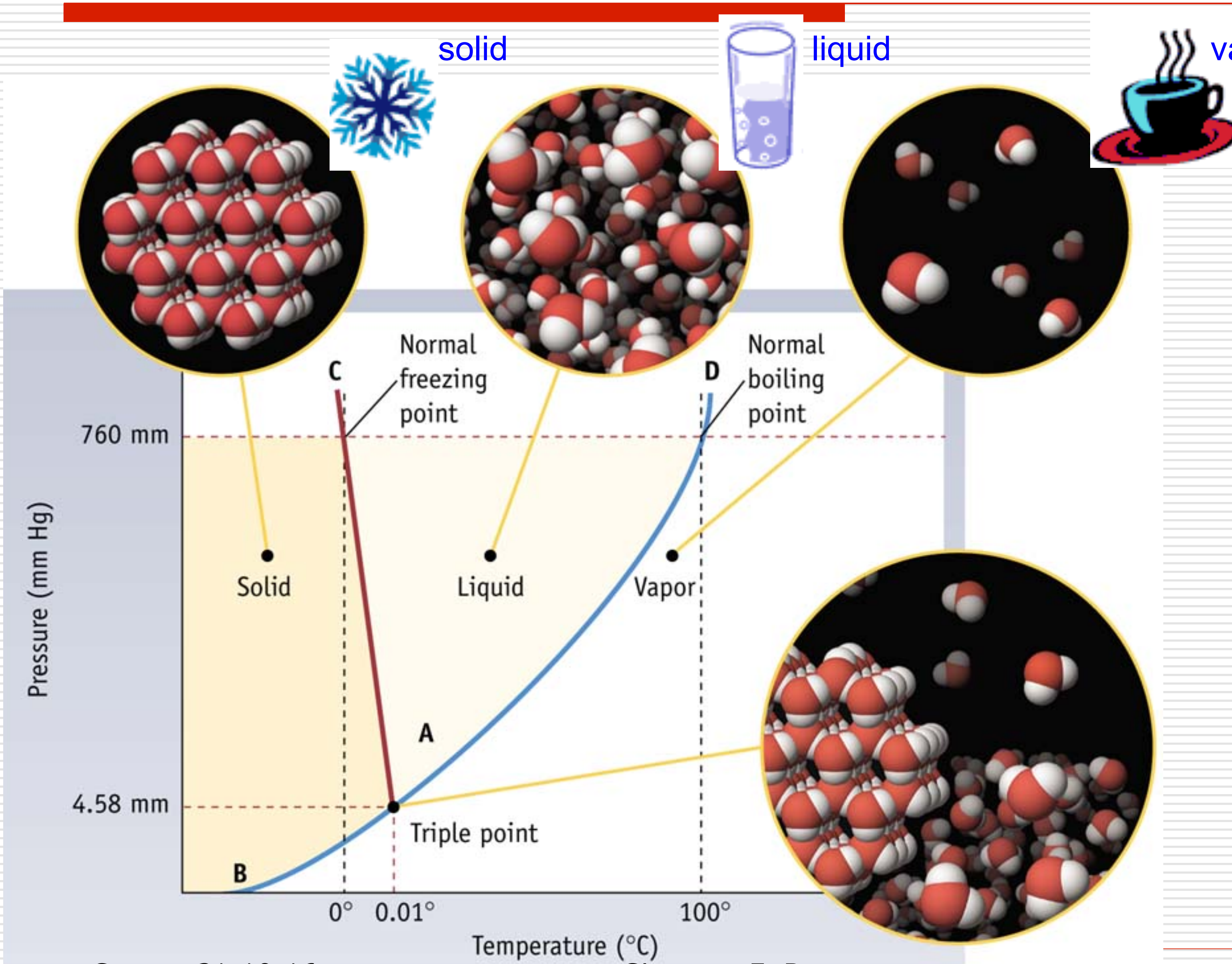
How hot is a medium of T ~ 170 MeV?

Temperature at the centre of the Sun ~ 15 000 000 K



A medium of 170 MeV is more than 100 000 times hotter !!!

The phase diagram of water



The phase diagram of QCD, in 1975

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. Cabibbo and G. Parisi, Phys. Lett. B59 (1975) 67

The exponentially increasing spectrum proposed by Hagedorn is not necessarily connected with a limiting temperature, but it is present in any system which undergoes a second order phase transition. We suggest that the "observed" exponential spectrum is connected to the existence of a different phase of the vacuum in which quarks are not confined.

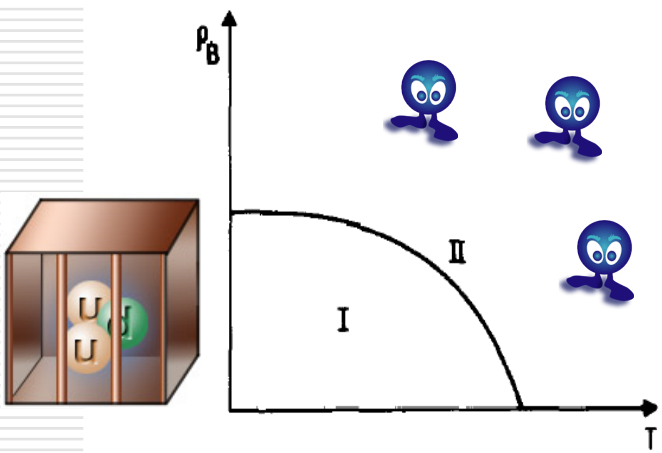
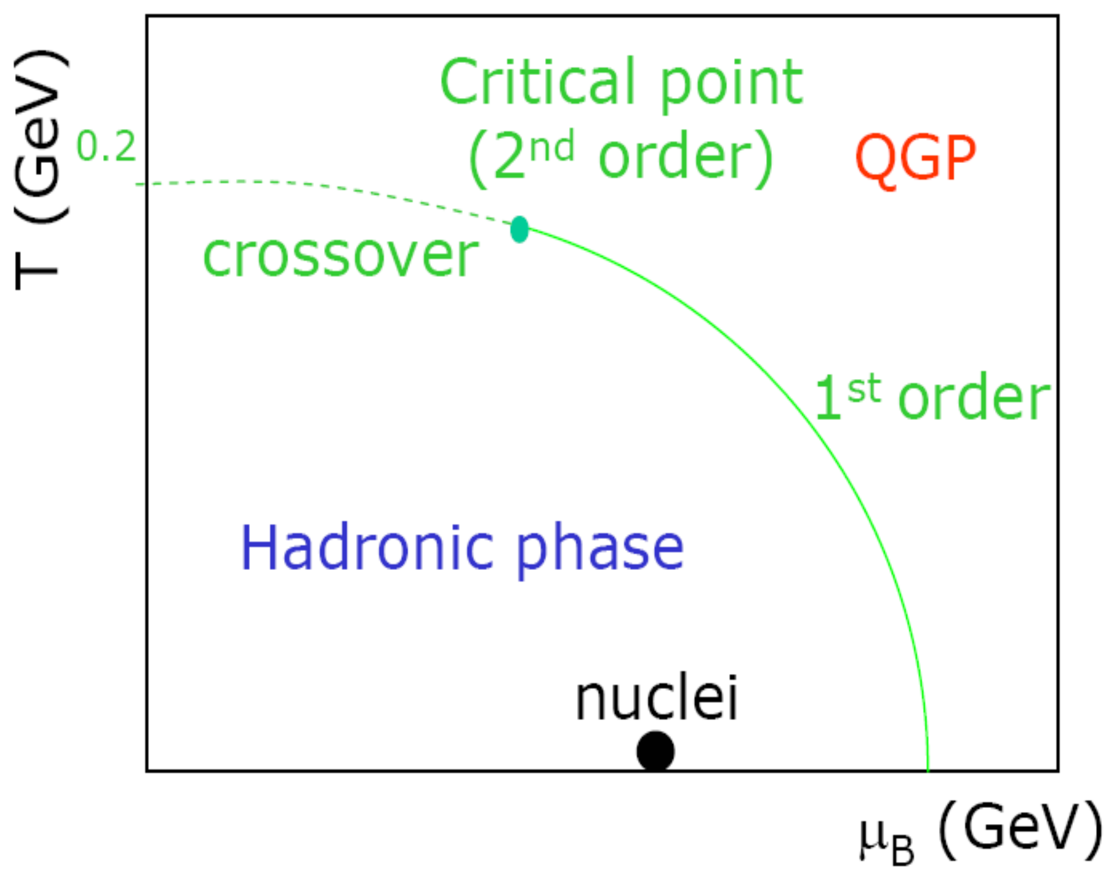


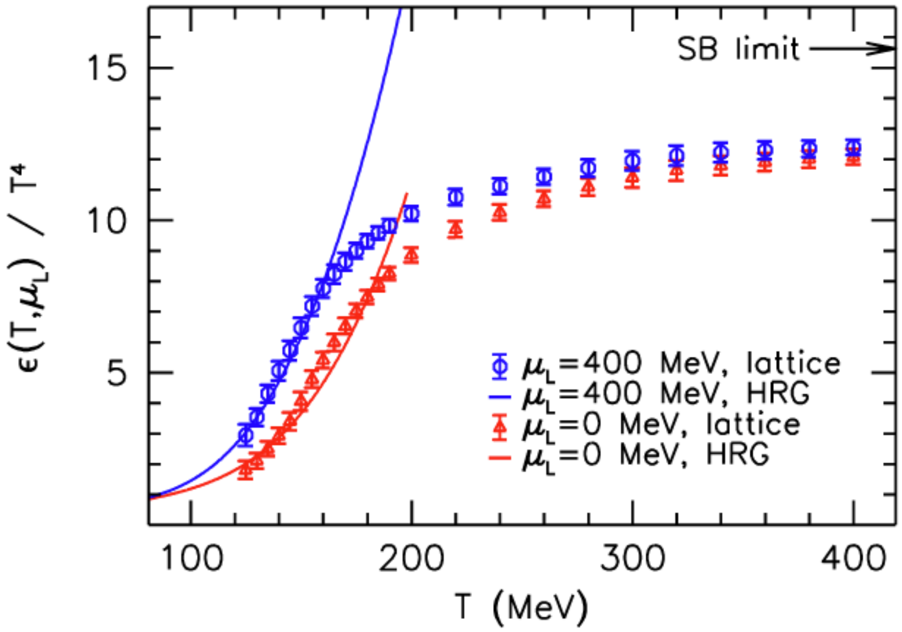
Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

The phase diagram of QCD, today



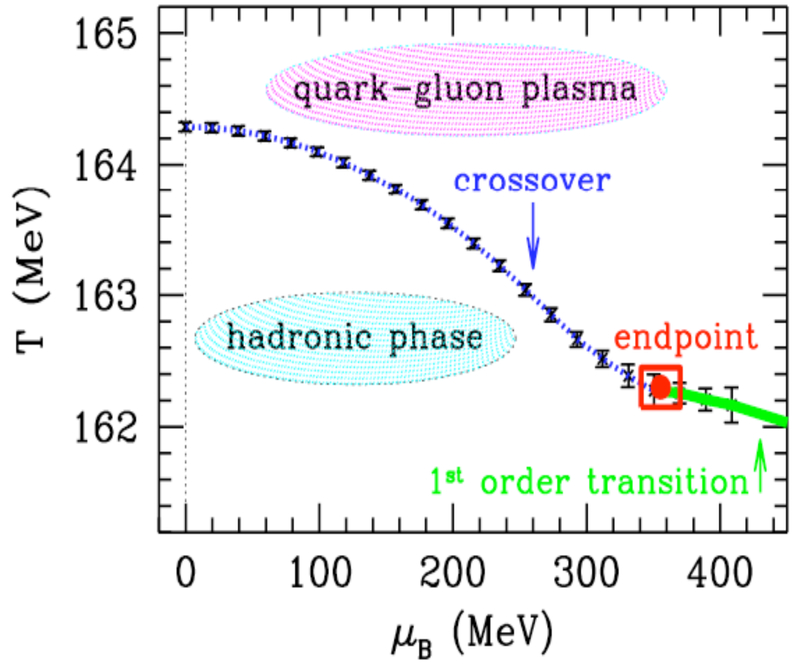
Lattice QCD: results

- Transition to QGP phase is a prediction of the lattice QCD
  - the order of the transition depends on μ_B



S. Borsanyi et al., JHEP (2012)

Z. Fodor, S. Katz, JHEP04 204 (2004)



"Most importantly one has to extrapolate to the continuum limit"

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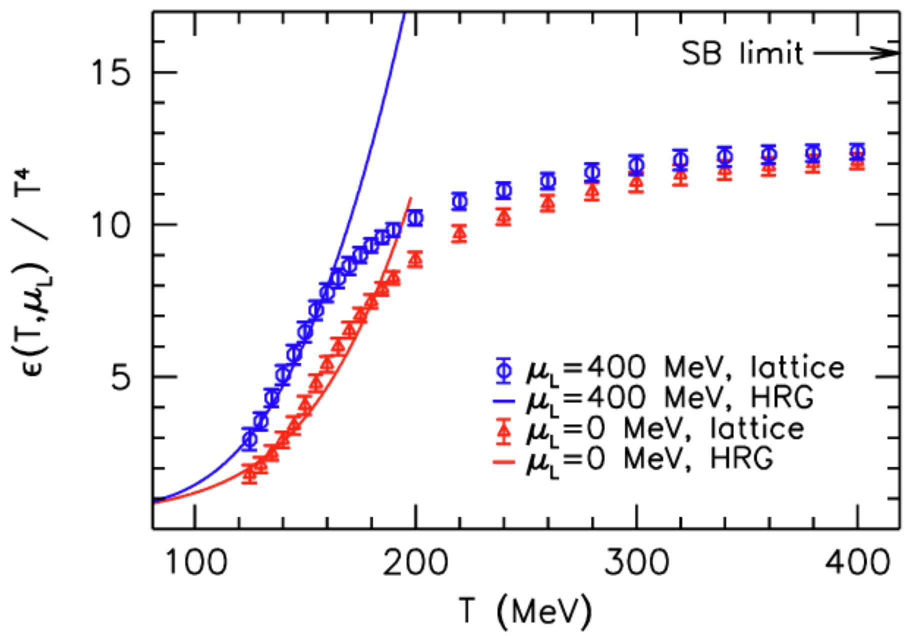
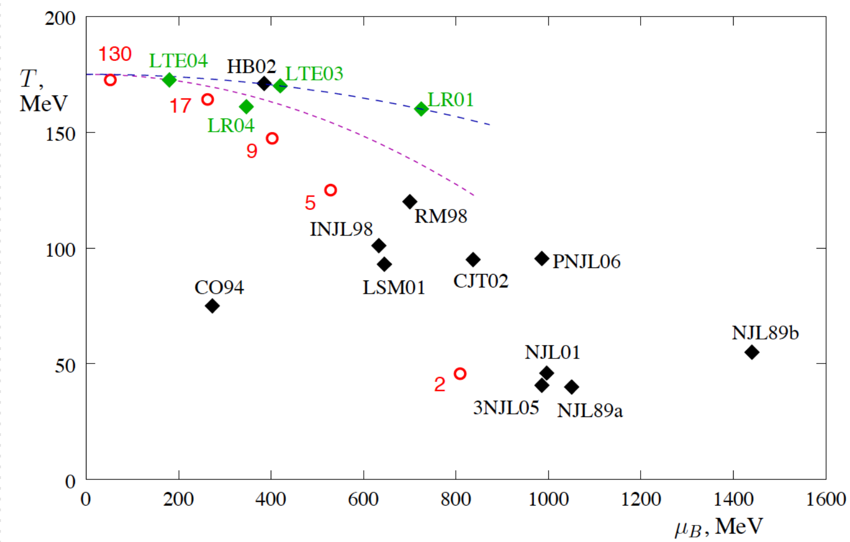


S. Borsanyi et al., JHEP (2012)

M. Stephanov, PoS LAT2006 (2006)



"… predictions for the location of the QCD critical point"

Lattice QCD: results

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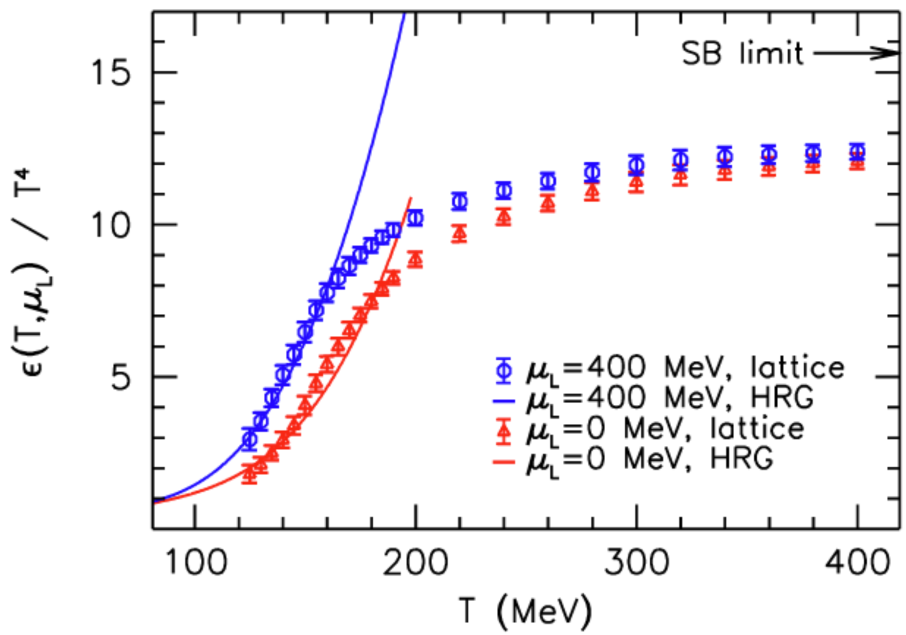
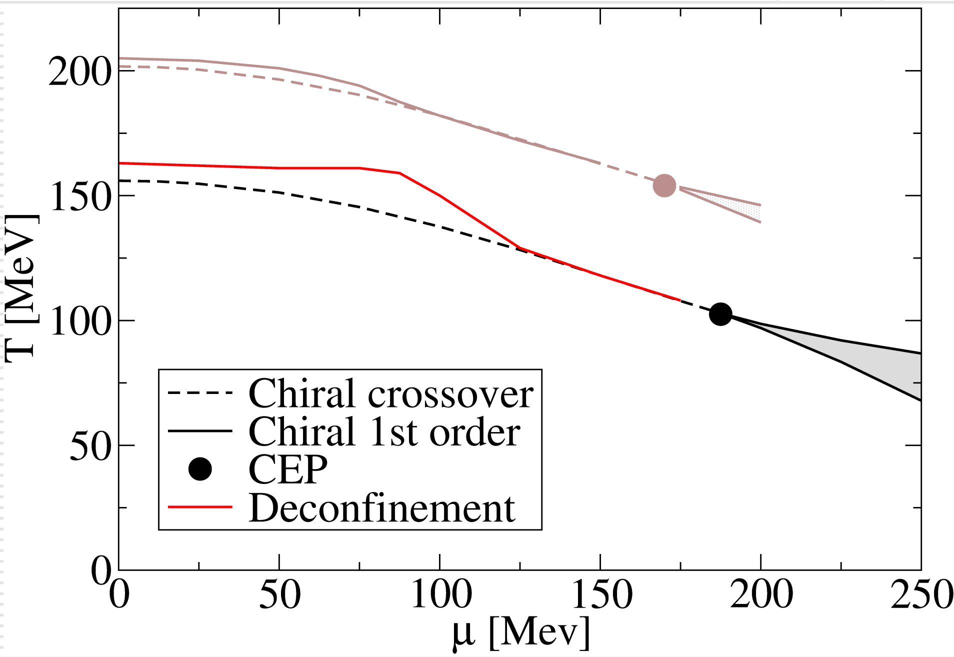


S. Borsanyi et al., JHEP (2012)

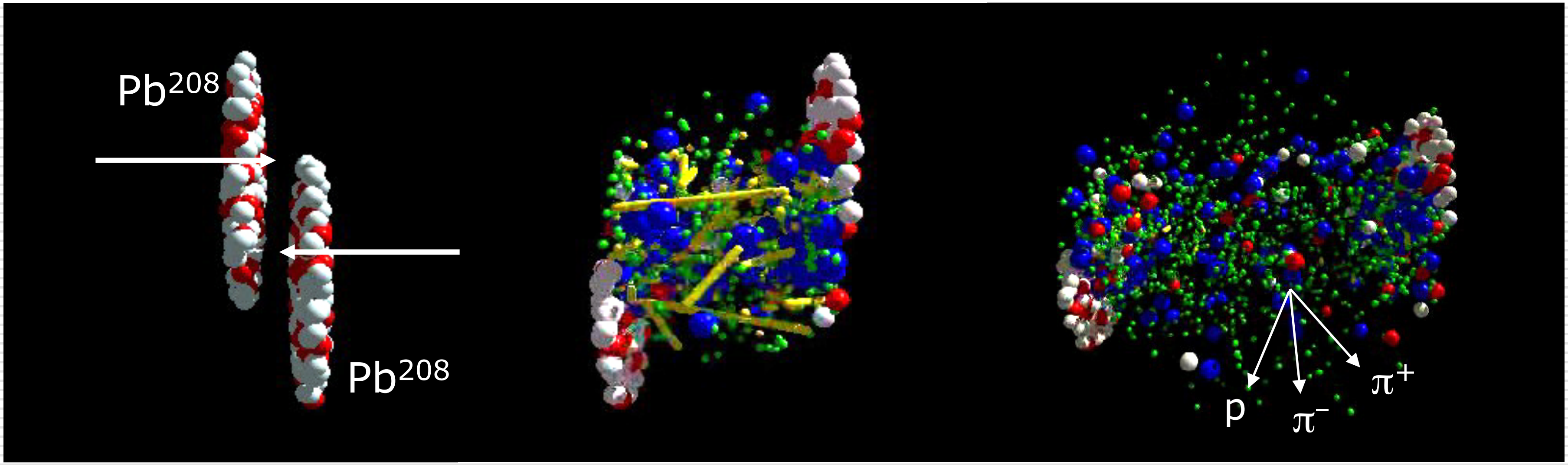
C. Fischer, J. Luecker, PLB718 (2013)



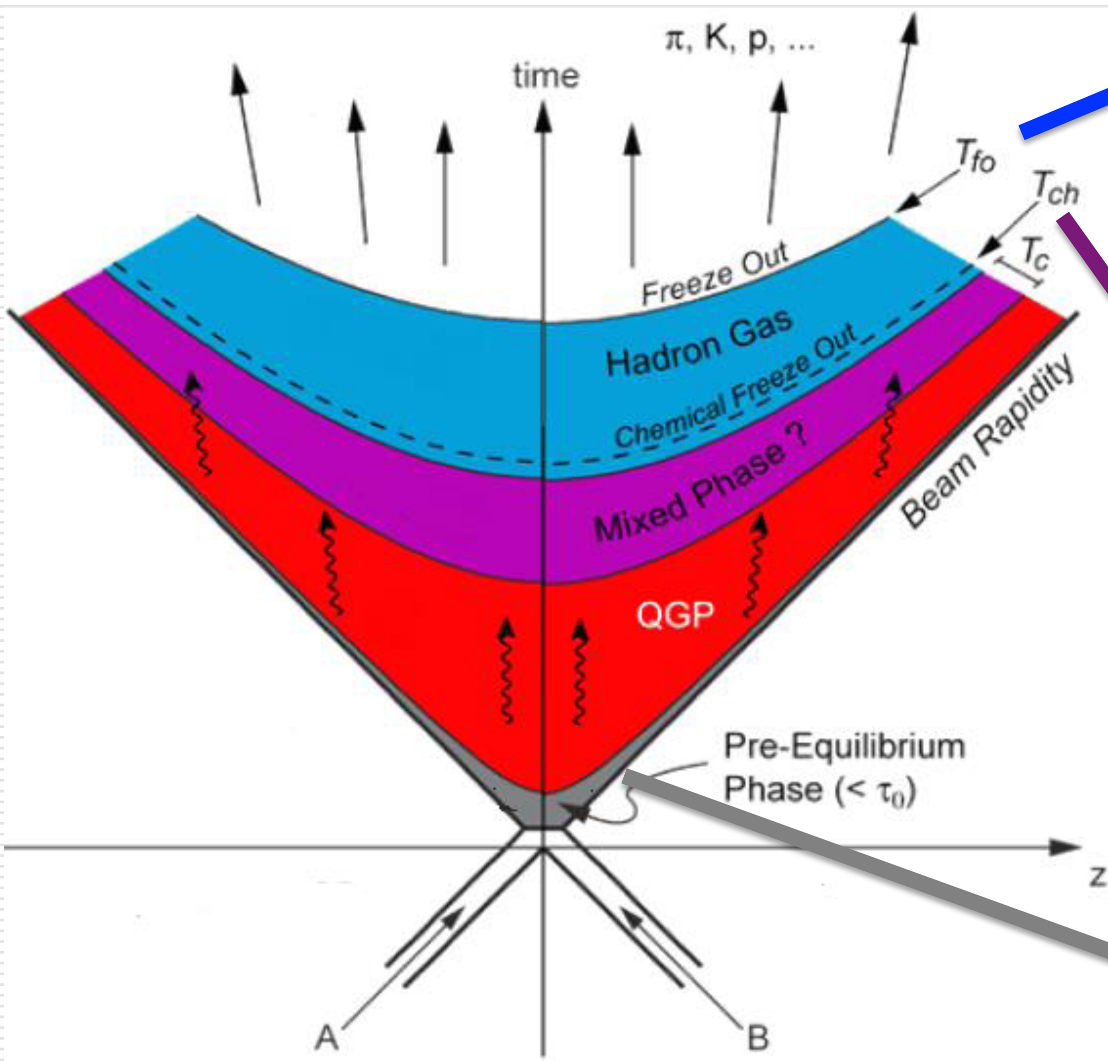
"We ... find a potential critical endpoint..."

How do we study *bulk* QCD matter?

- We can heat and/or compress a large volume of QCD matter
- Done in the lab by colliding heavy nuclei at high energies



Space time evolution of A-A collision

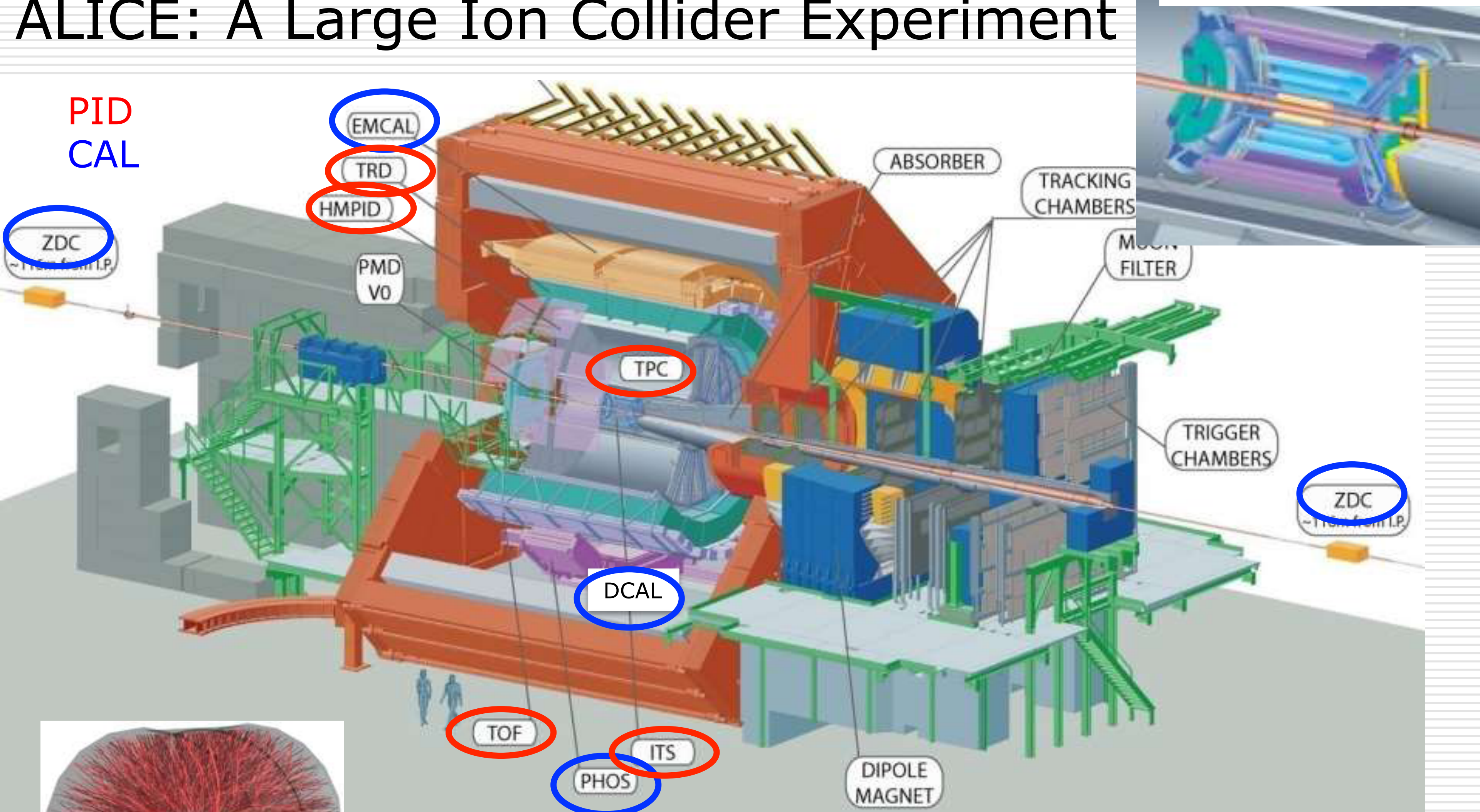


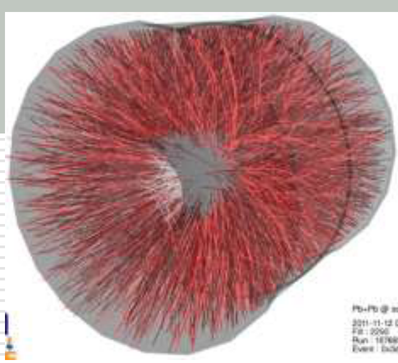
- Thermal freeze-out
  - Elastic interactions cease
  - Particle dynamics ("momentum spectra") fixed
  - T_{fo} ~ 100-110 MeV
- Chemical freeze-out
  - Inelastic interactions cease
  - Particle abundances ("chemical composition") are fixed
  - T_{ch} ~ 155 MeV
- Thermalization time
  - System reaches local equilibrium
  - τ_{eq} ~ 0.5 fm/c

ALICE: A Large Ion Collider Experiment

ITS : SPD, SDD, SSD

PID
CAL

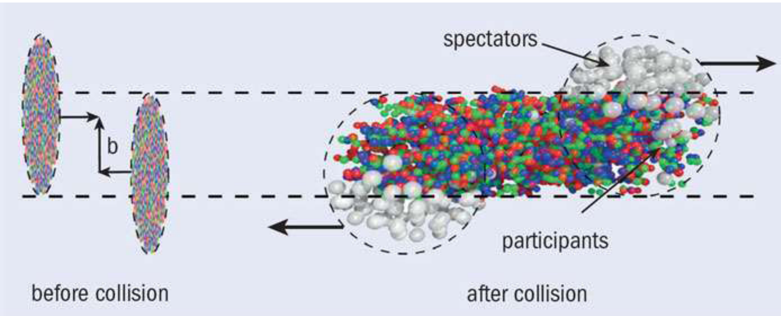




- Optimized for Heavy Ions Physics (dn/dy up to 2000 !) → high performances tracking and PID
- Complementary to the other LHC experiments

Global characterization of the system

Centrality definition

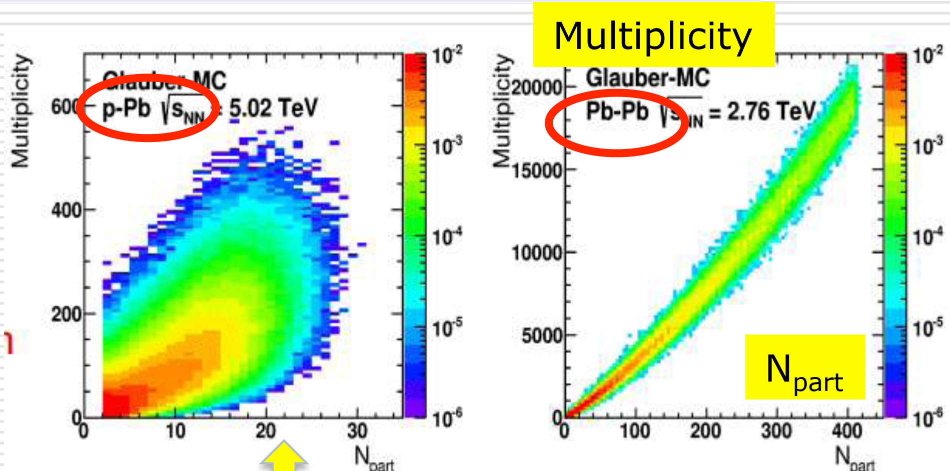


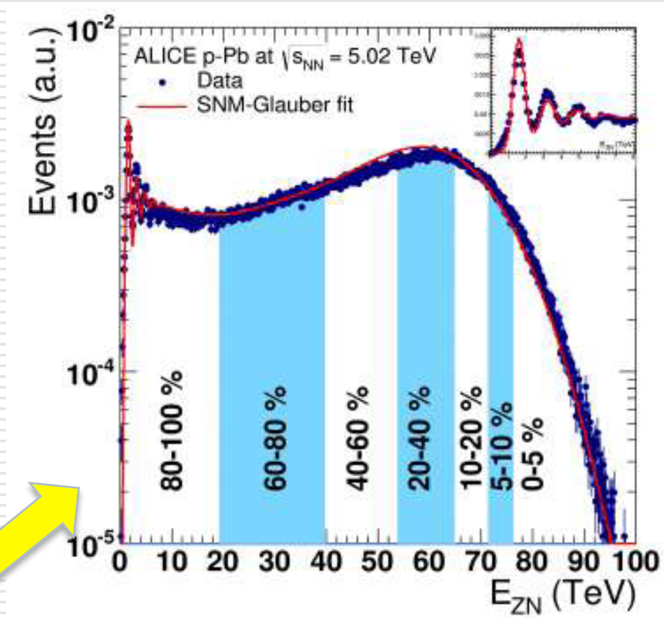
N_{part} :Number of nucleons participating to the collision

N_{coll} : Average number of binary collisions between nucleons

Example LHC:
Centrality 0-1%
Npar = 403
Ncoll = 1681

Centrality = fraction of σ_{PbPb}



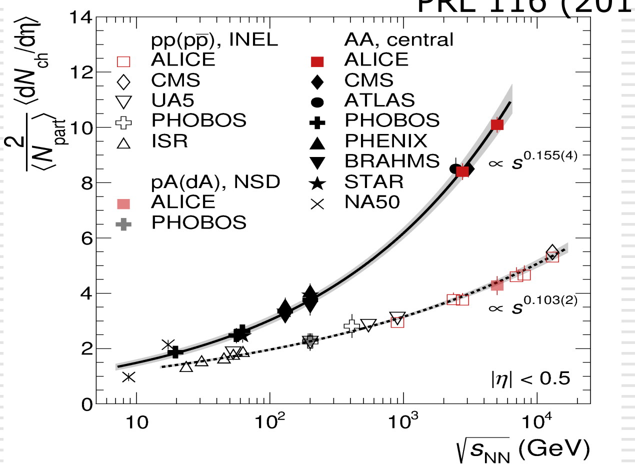


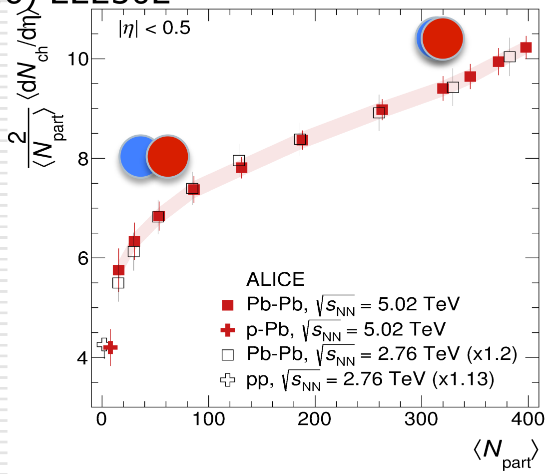
Centrality estimators

- Multiplicity : bias on the hardness of the pN collisions (quantified by the number of hard scatterings per pN collision).
- ZDC : expected to be insensitive to bias. Establish a geometry-related particle scaling with a better than 10% precision

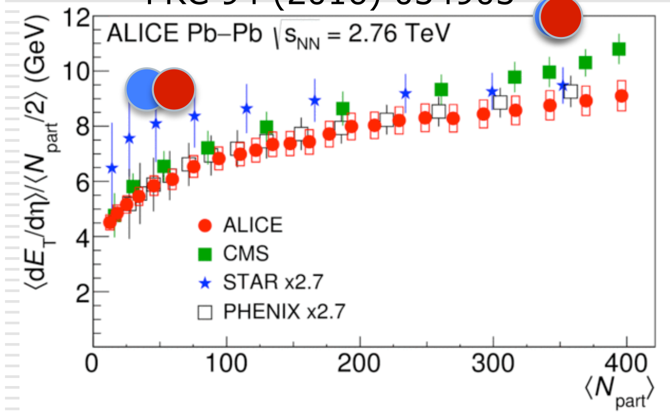
Charged multiplicity & energy density

PRL 116 (2016) 222302





PRC 94 (2016) 034903



- dNch/dη / (Npart/2) increases with √s
  - pp: $\sim s^{0.103}$ in
  - central A+A: $\sim s^{0.155}$
  - ~20% increase going from 2.76 to 5.02 TeV
- similar centrality dependence as at RHIC

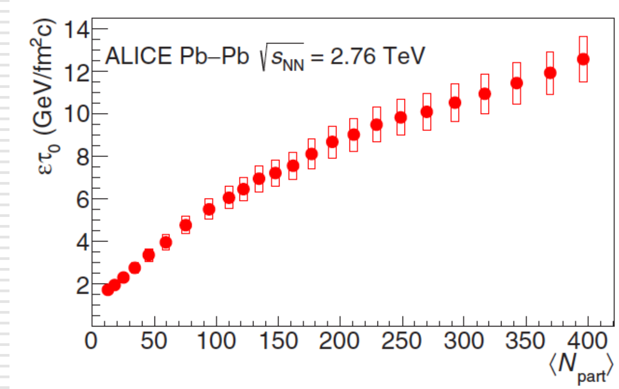
$$\varepsilon\tau_0 = \frac{J\langle dE_T / d\eta\rangle}{c\pi R^2}$$

J = 1.12 ±0.06

central collisions

$$\varepsilon\tau_0 \approx 12.5 \pm 1.0 \text{ GeV/fm}^2/c$$

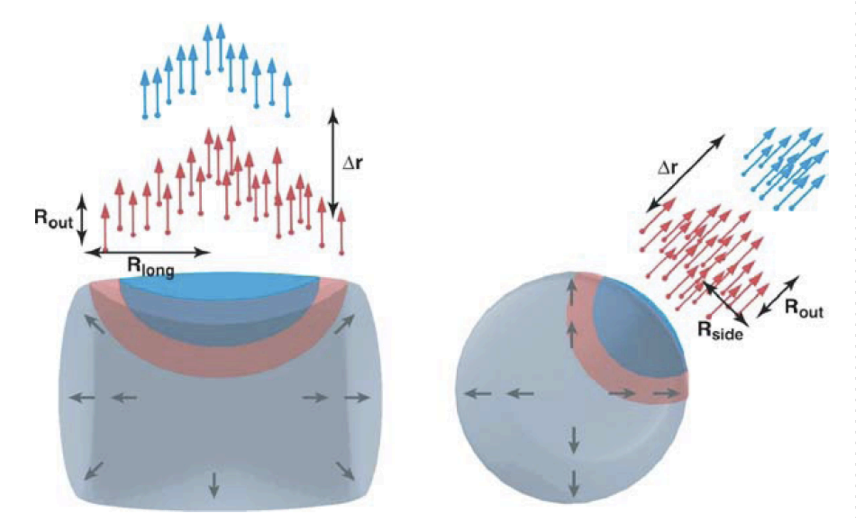
$$\varepsilon_c\tau_0 \approx 21 \pm 2 \text{ GeV/fm}^2/c$$

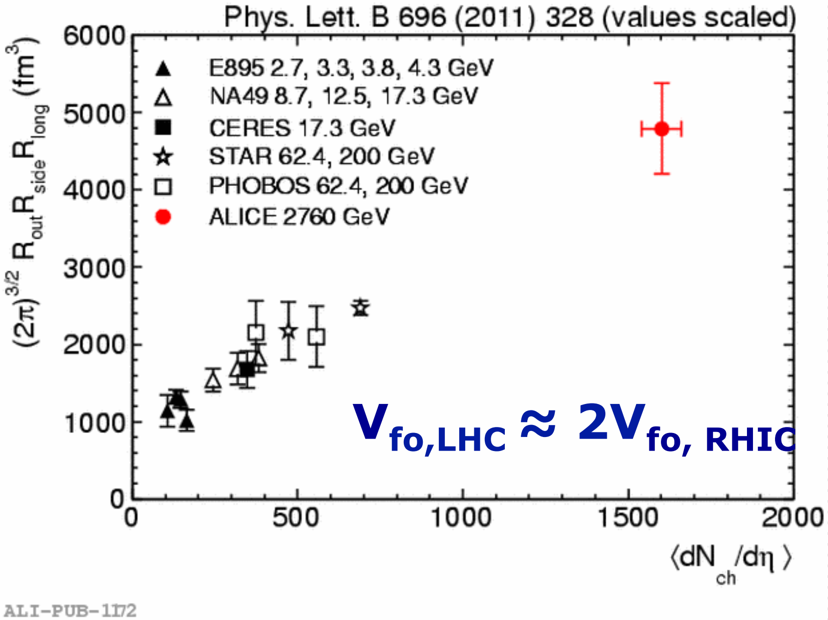


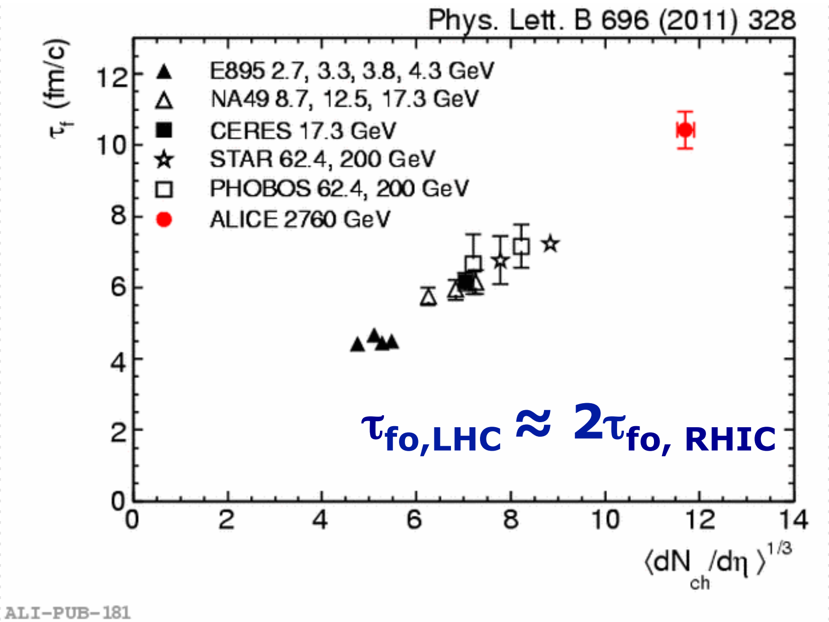
Initial energy density at LHC (and RHIC) well above $\varepsilon_{crit} \approx 0.5$ GeV/fm^3

System size

- Space-time evolution of the system from two-pion Bose-Einstein Correlations (HBT)

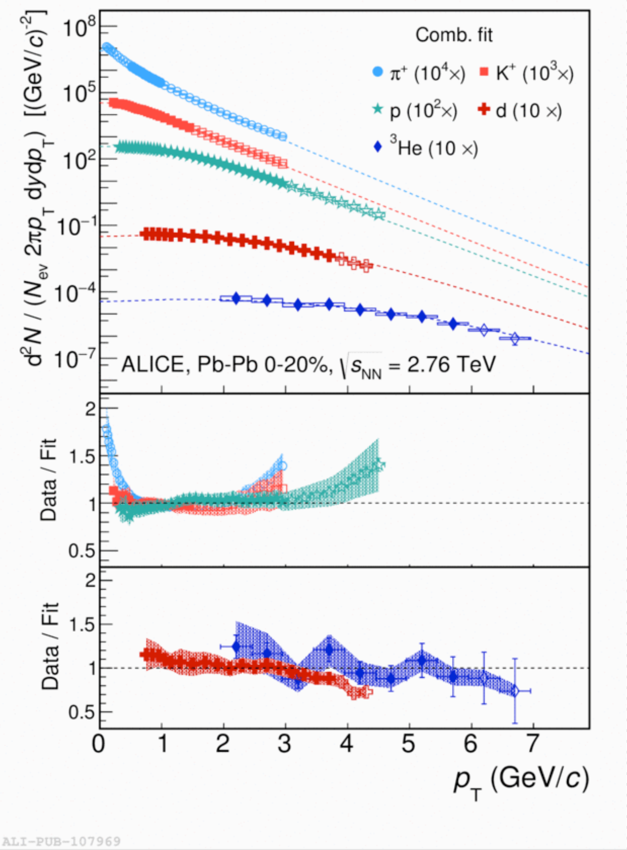




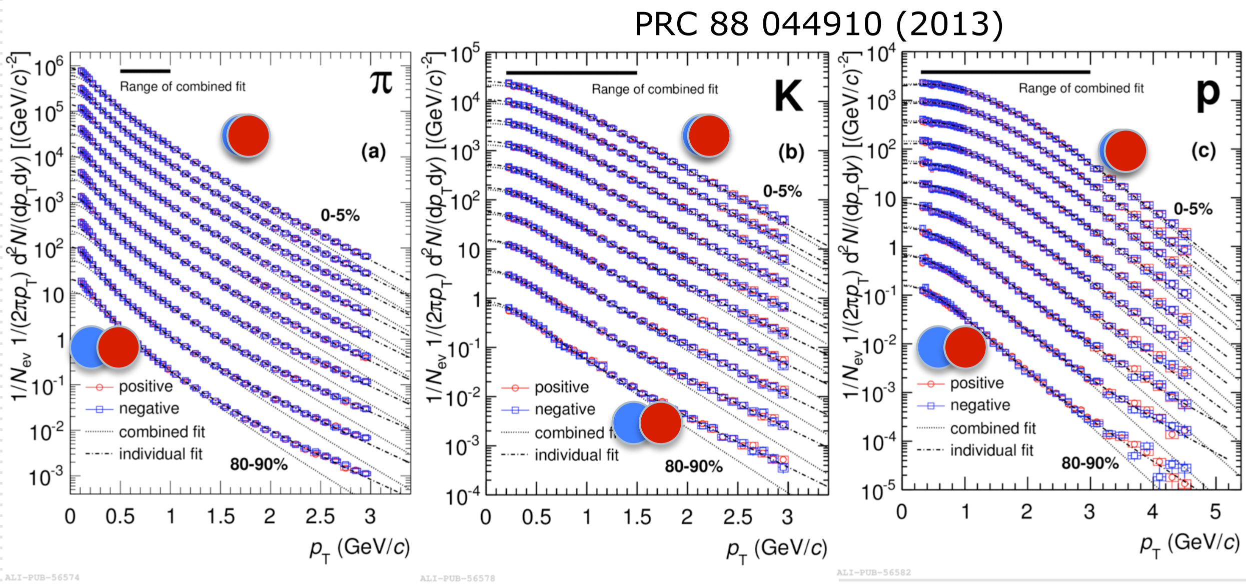


Identified particle spectra

PRC 93 (2015) 024917



PRC 88 044910 (2013)



- spectra get flatter for more central collisions
- stronger effect for heavier particles
- consistent with a hydrodynamic description
- even nuclei described by hydro

Collective Transverse Expansion

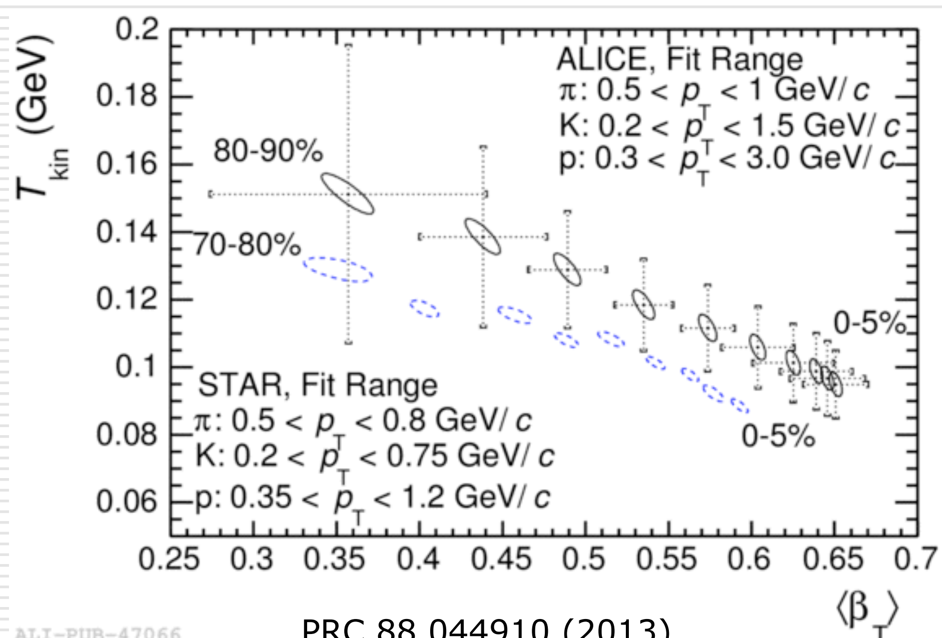
$$m_T = \sqrt{m^2 + p_T^2}$$

- p_T distributions described as combined result of thermal motion (**T**) and collective transverse expansion (β_T) at freeze-out

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

$$\rho(r) = \tanh^{-1} \beta_\perp(r) \qquad \beta_\perp(r) = \beta_S \left[\frac{r}{R_G}\right]^{n(=1)} \qquad r \le R_G$$

Schnedermann, Sollfrank, Heinz, PRC48 (1993) 2462



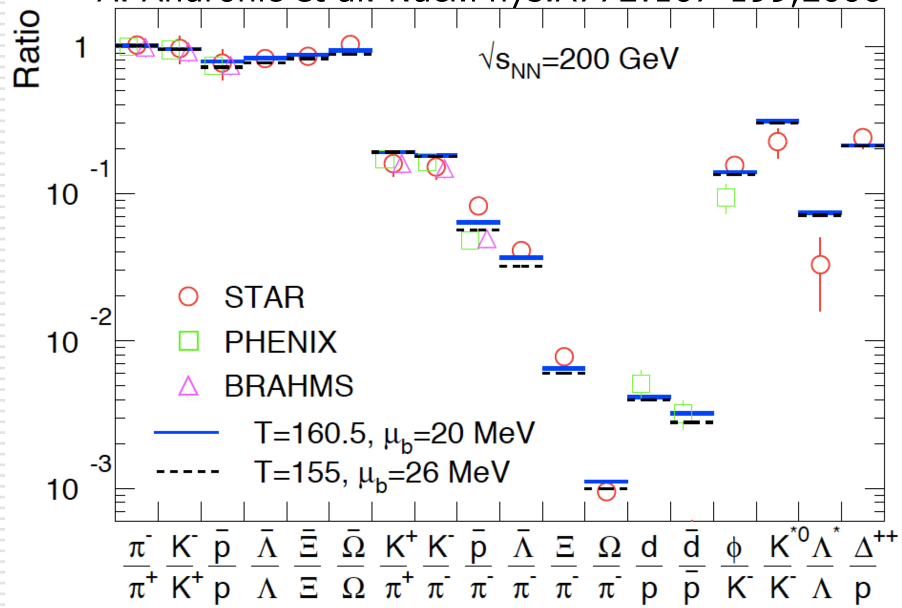
PRC 88 044910 (2013)

- Strong radial flow: $\beta \approx 0.65$ for most central collisions, 10% higher than at RHIC
- Freeze-out temperature of about 100 MeV

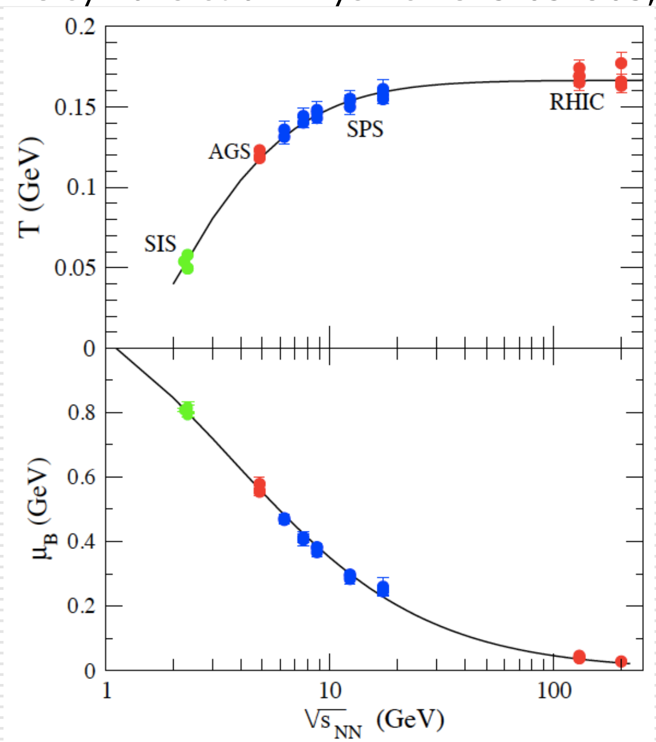
Hadro-chemistry

- relative abundances of hadron species can be described by statistical distributions

A. Andronic et al. Nucl.Phys.A772:167-199,2006



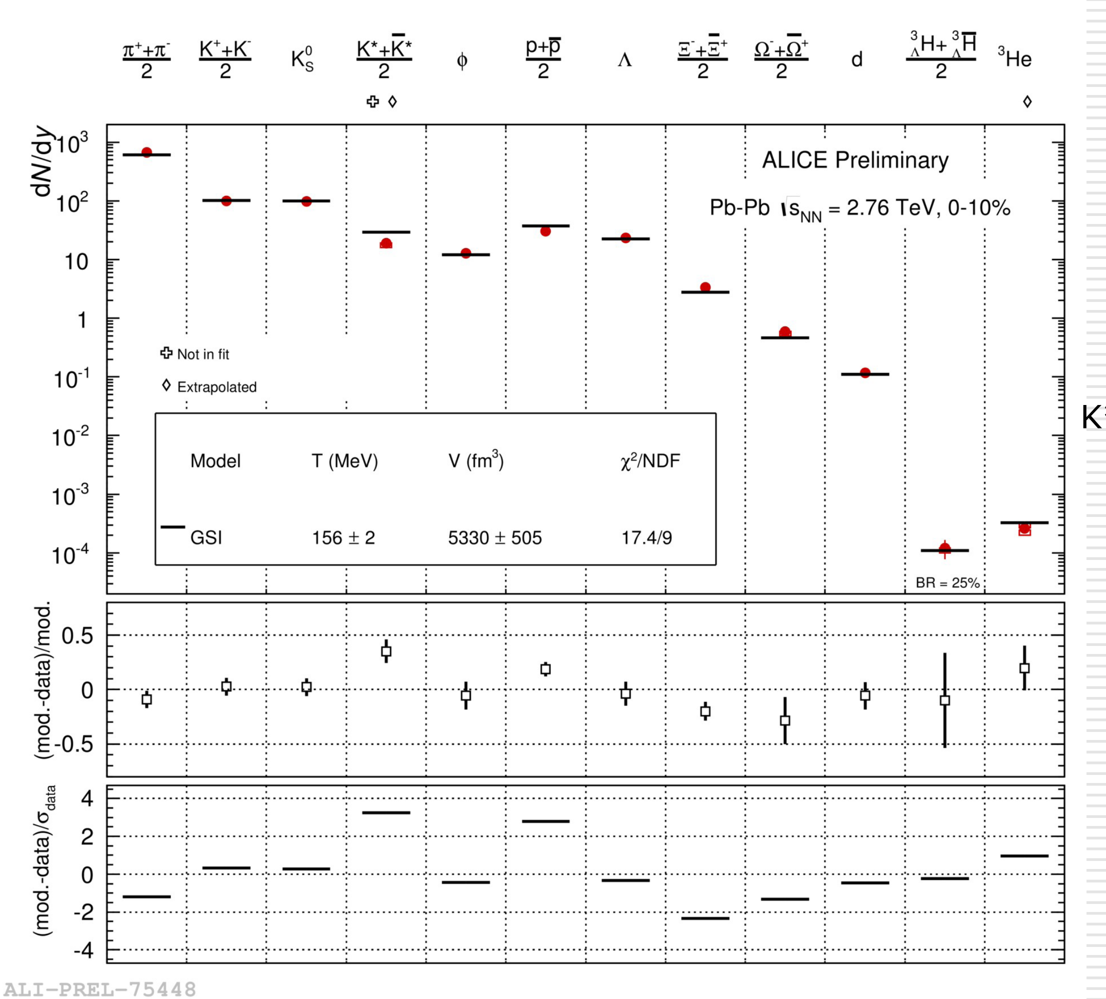
J. Cleymans et al. Phys.Rev.C73:034905,2006



- thermodynamic interpretation of model parameters in high energy A+A collisions:

$$T_{chem} = T_C$$

Chemical Equilibrium at LHC?



K* not include in the fit

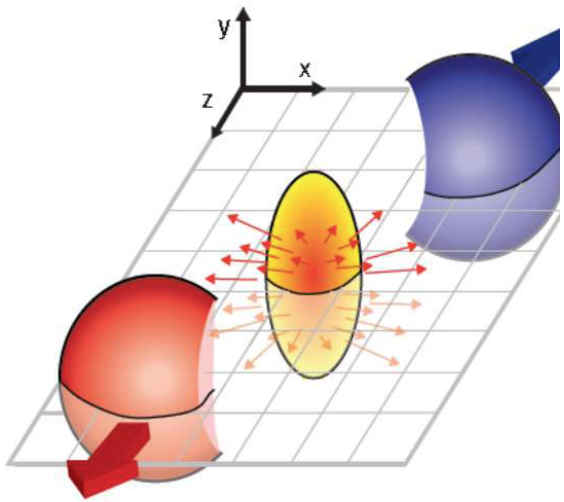
- hadrons (including nuclei) are described with a common chemical freeze-out temperature
  - T_{ch} = 156 (2) MeV → T_{ch} (LHC) ~ T_{ch} (RHIC) ~ T_c

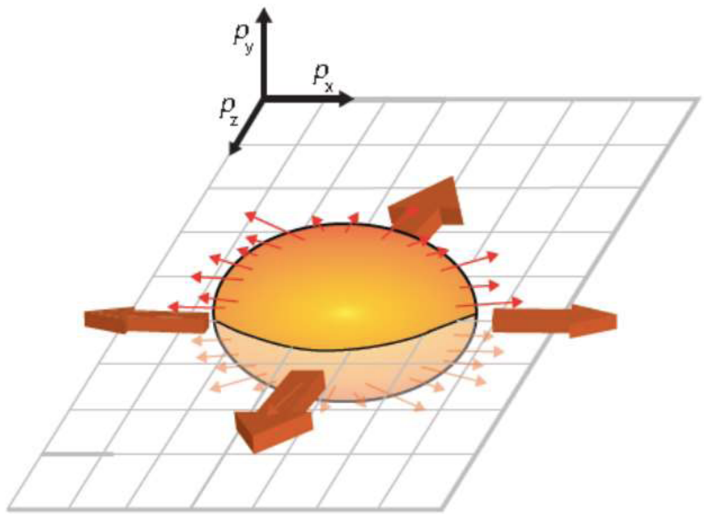
Azimuthal Anisotropy

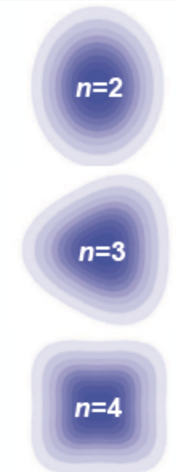
- Quantify anisotropy: Fourier decomposition of particle azimuthal distribution relative to the reaction plane (Ψ_{RP}) → coefficients v_2, v_3, v_4, …, v_n
- Elliptic flow ($v2$): spatial anisotropy — pressure gradients leads to momentum anisotropy — hydrodynamics
- Higher order flow: bring additional constraints on the initial conditions, η/s, EoS, freeze-out conditions…

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

$$v_n = \langle \cos n(\varphi - \psi_{RP}) \rangle$$

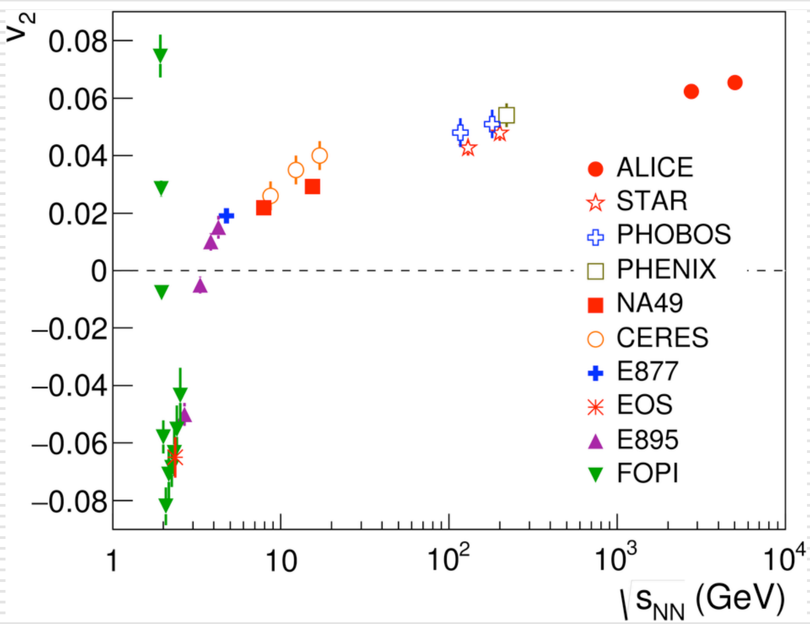


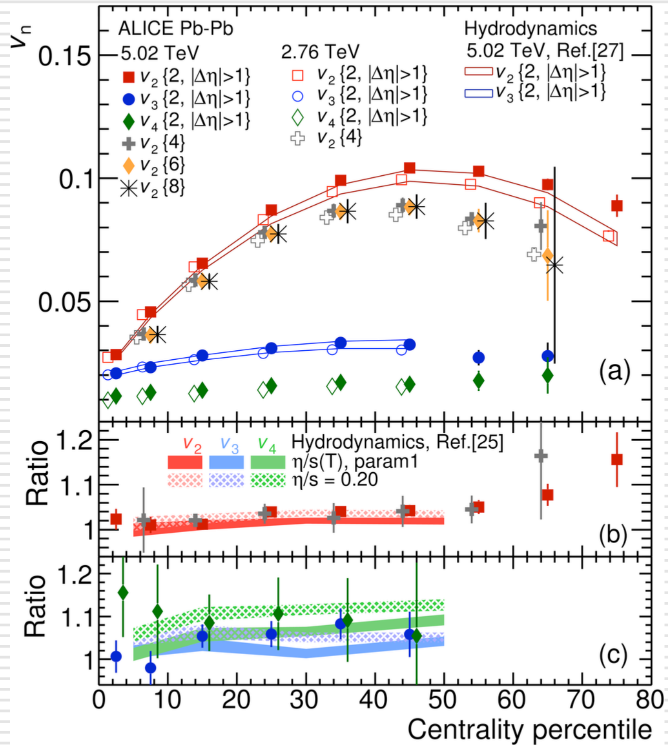




Flow of unidentified charged particles

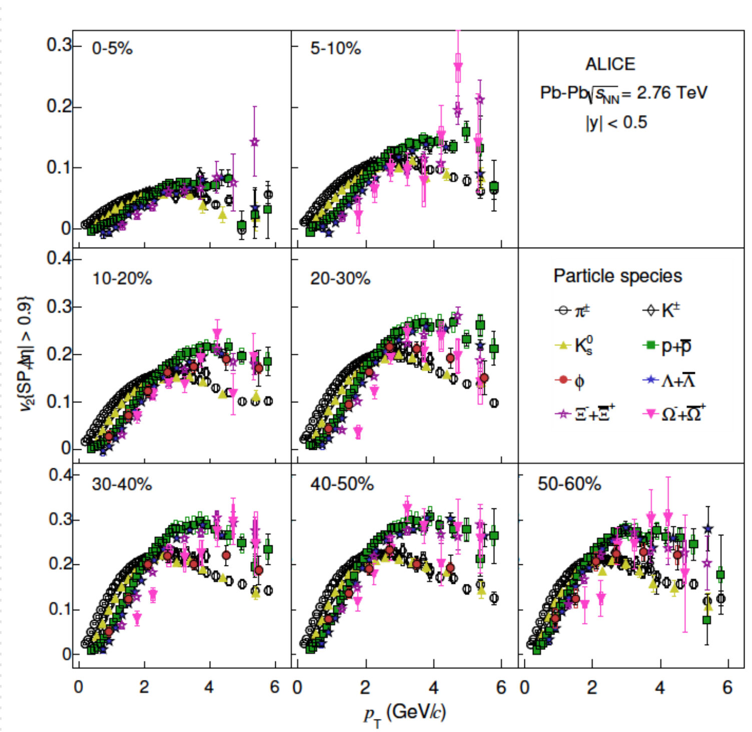
PRL 105 25230 (2010) ; PRL 116, 132302 (2016)

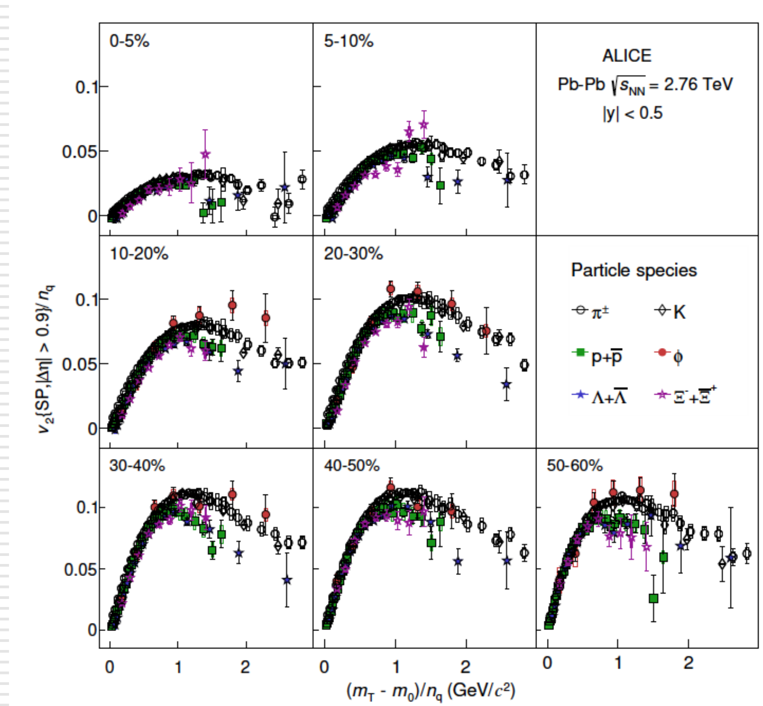




- The flow increases by about 30% w.r.t. RHIC. The system produced at the LHC behaves as a very low viscosity fluid (a perfect fluid)
  - constraints dependence of η/s versus temperature

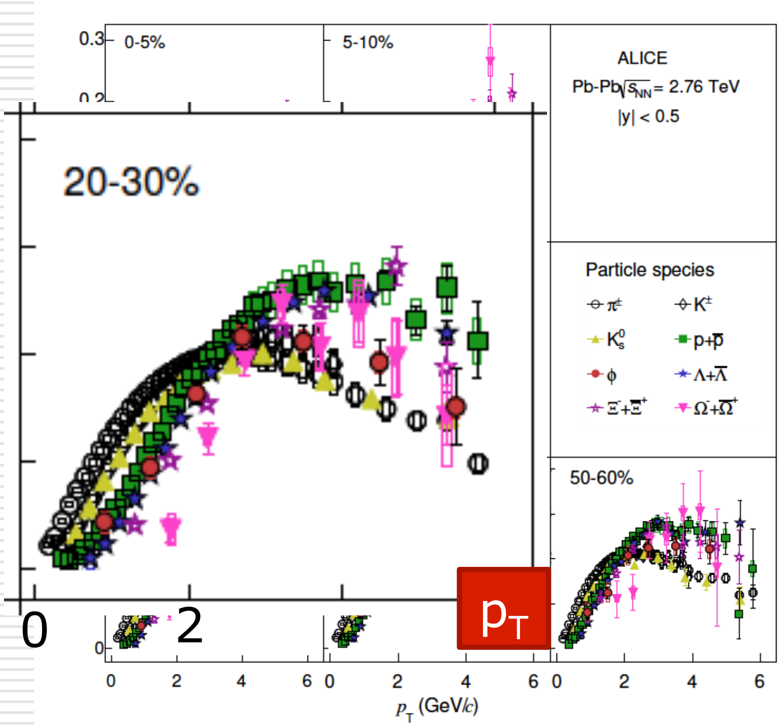
Elliptic flow of identified particles

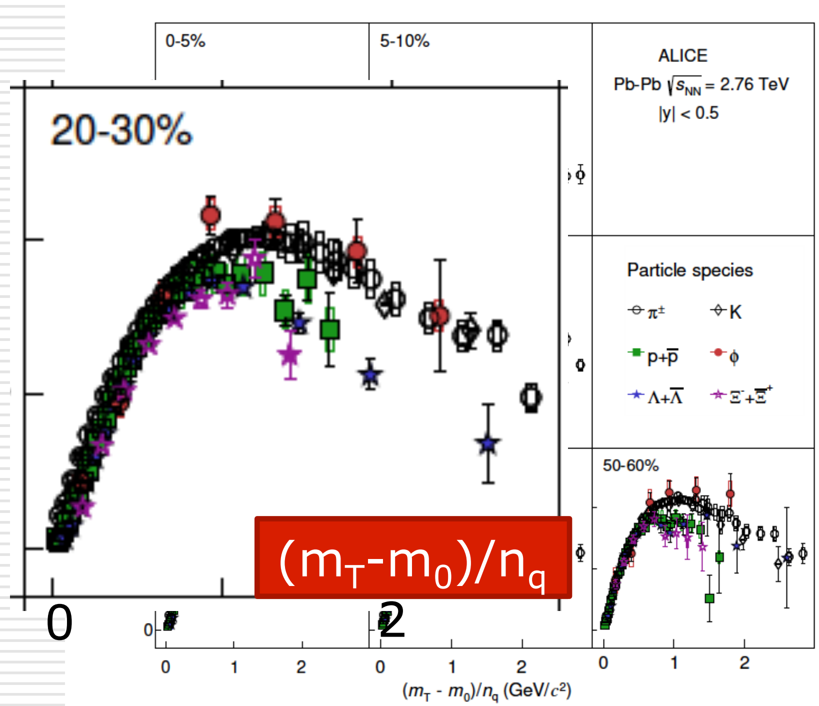




- main scaling with constituent quark number
  - at small $(m_t-m_0)/n_q$ the scaling in the data resemble the scaling as observed in hydrodynamics
- pion, kaon (and strange baryons) v_2 are described rather well with hydrodynamic predictions
  - for protons hadronic cascade important

Elliptic flow of identified particles





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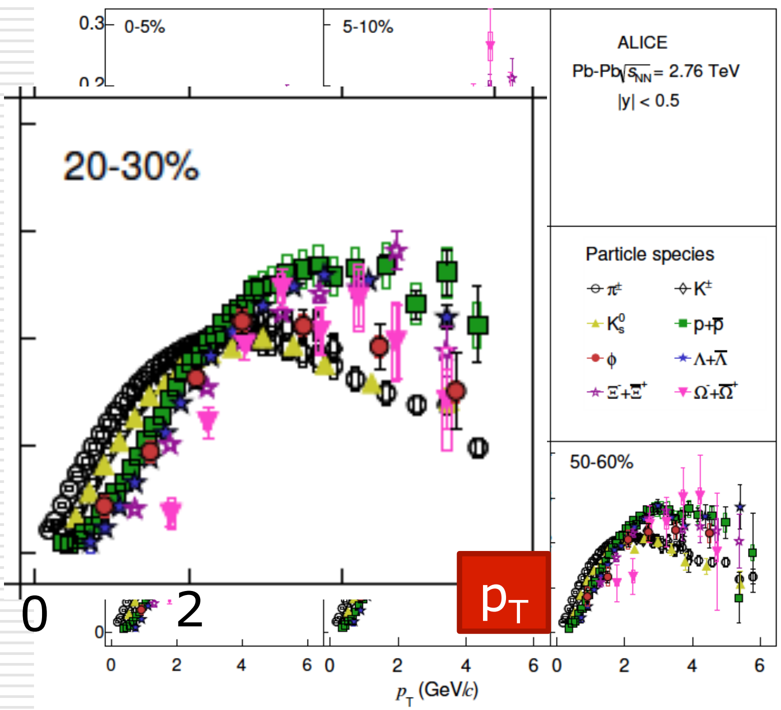

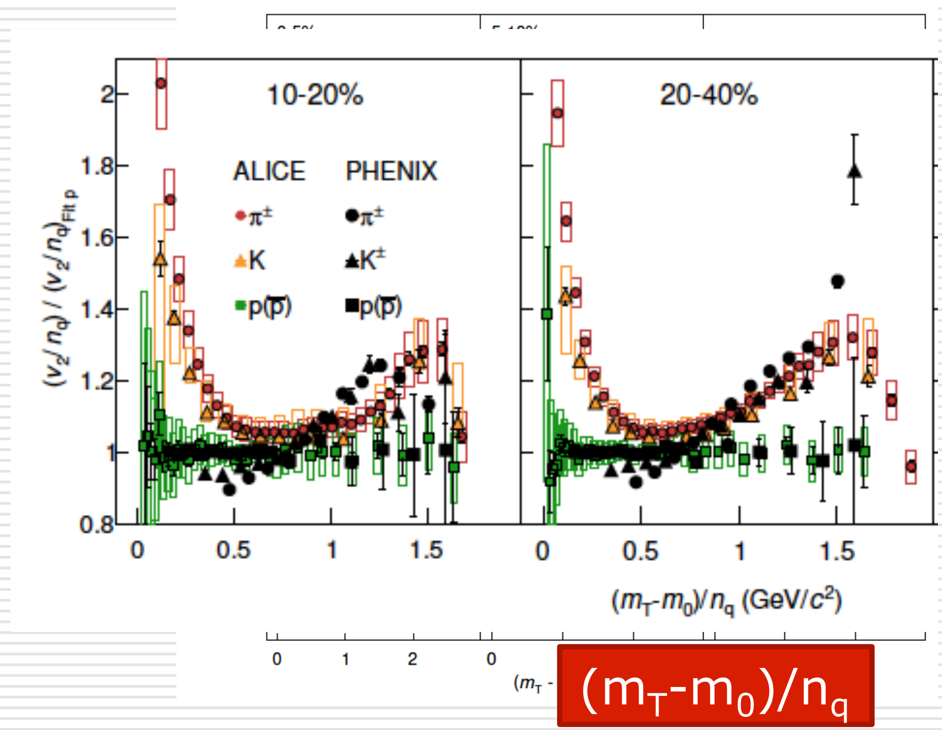

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The "Fireball" at LHC

- system created at LHC is consistently larger, denser, more excited than at lower energy (RHIC)
- multiplicity, transverse energy: "initial" energy density

$$\left(\varepsilon_i \cdot \tau_i\right)_{2.76\ \mathrm{TeV}} \approx 15\ \mathrm{GeV/fm}^2 c \approx 3\left(\varepsilon_i \cdot \tau_i\right)_{0.2\ \mathrm{TeV}}$$

- pion interferometry: freeze-out size and lifetime

$$V_{fo}(2.76\ \mathrm{TeV}) \approx 2V_{fo}(0.2\ \mathrm{TeV})$$

$$\tau_{fo}(2.76\ \mathrm{TeV}) \approx 1.4\tau_{fo}(0.2\ \mathrm{TeV})$$

- identified transverse momentum spectra: transverse expansion

$$\left\langle \beta_{fo} \right\rangle_{2.76\ \mathrm{TeV}} \approx 1.15 \left\langle \beta_{fo} \right\rangle_{0.2\ \mathrm{TeV}}$$

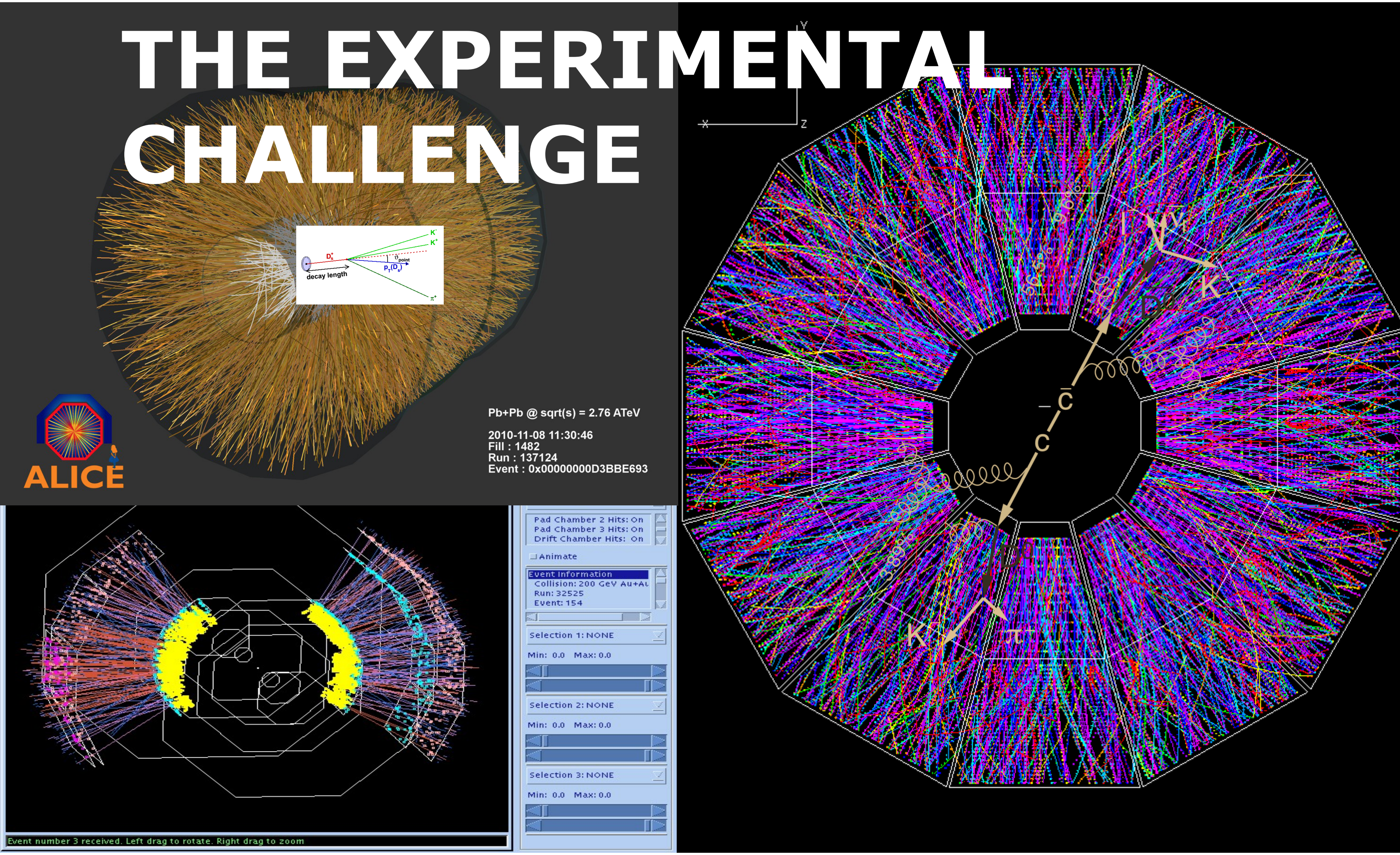
Heavy flavour

- From “discovery phase” to detailed characterization of the QGP properties

- ***Hard probes*** (jets, heavy-quarks, quarkonia)
  → “resolve” medium constituents

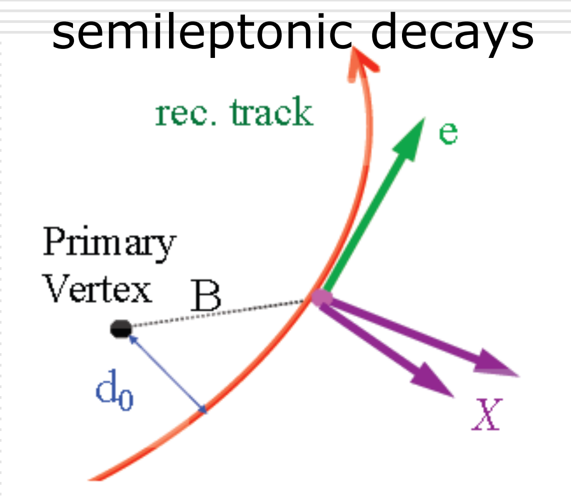
- **Microscopic description of the medium**

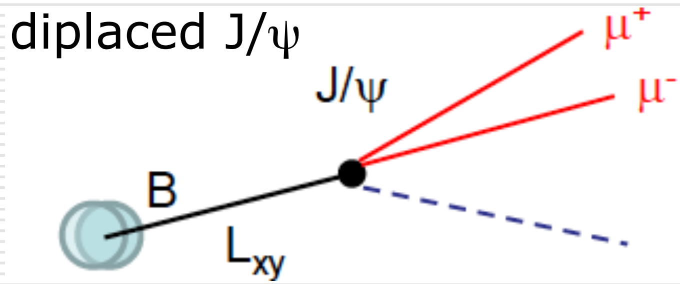
THE EXPERIMENTAL CHALLENGE

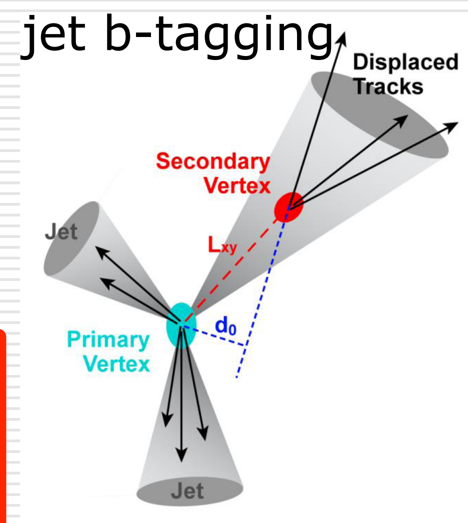


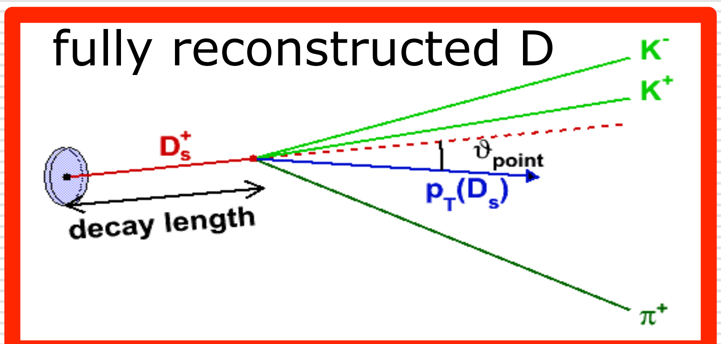
Heavy Flavour in Heavy Ion

- How can we measure it ?









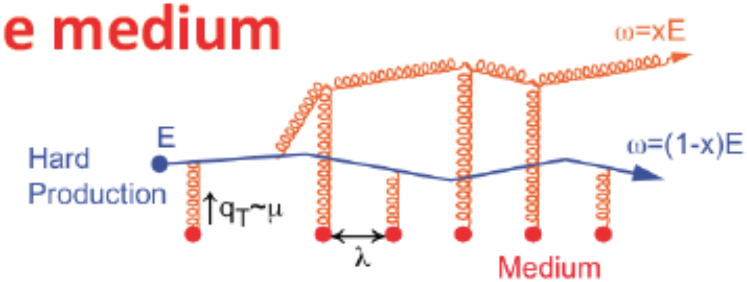
- I will show mainly the results on fully reconstructed D mesons

QGP tomography with high-energy partons

- Early production in hard-scattering processes with high Q^2
- Production cross sections calculable with pQCD
- Strongly interacting with the medium

⇨ **"Calibrated probes" of the medium**

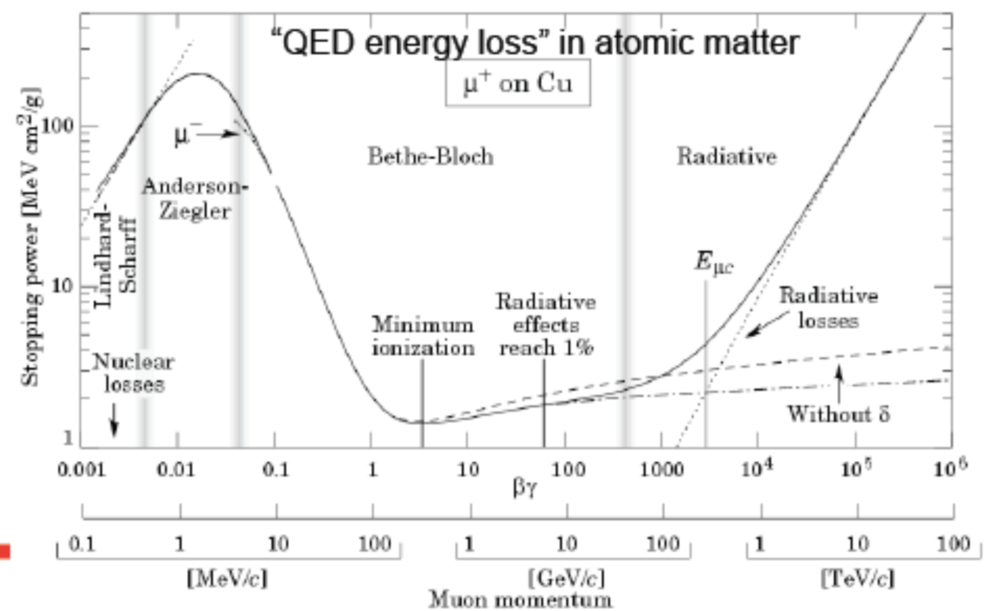
Study parton interaction with the medium
- **energy loss via radiative** ("gluon Bremsstrahlung")
  collisional processes



~ Study QCD "Bethe-Block" curve for partons in the QGP

⇩

Connection of "local" interactions with global medium properties



QGP tomography with heavy quarks

- Early production in hard-scattering processes with high Q^2
- Production cross sections calculable with pQCD
- Strongly interacting with the medium
- Hard fragmentation ➜ measured meson properties closer to parton ones

at all p_T for charm and beauty (large masses >> Λ_{QCD})

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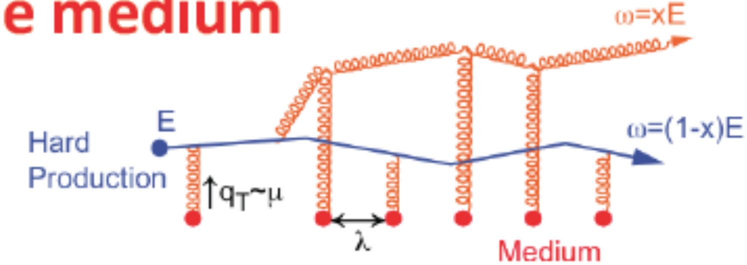

Study parton interaction with the medium

- **energy loss via radiative** ("gluon Bremsstrahlung")
  collisional processes
  - path length and medium density
  - **color charge** (Casimir factor)
  - **quark mass** (e.g. from dead-cone effect)

Gluonsstrahlung probability

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

Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

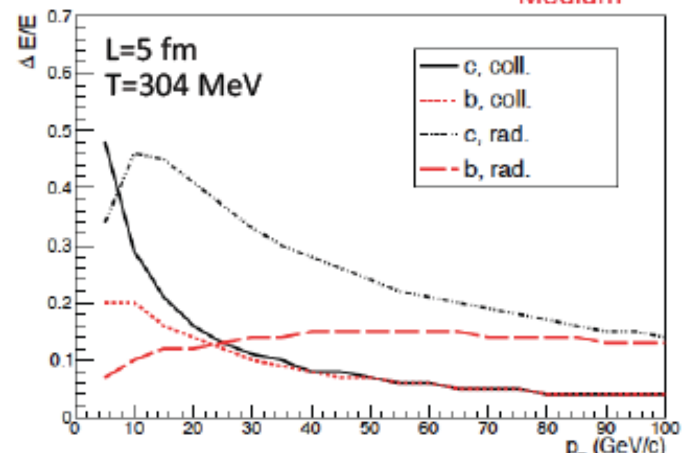

Figure from A. Andronic *et al.*, EPJC C76 (2016)
M. Djordjevic, Phys. Rev. C80 064909 (2009),
Phys. Rev. C74 064907 (2006).

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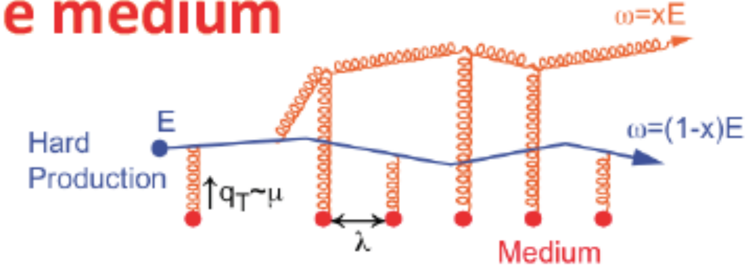

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$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

QGP tomography with heavy quarks

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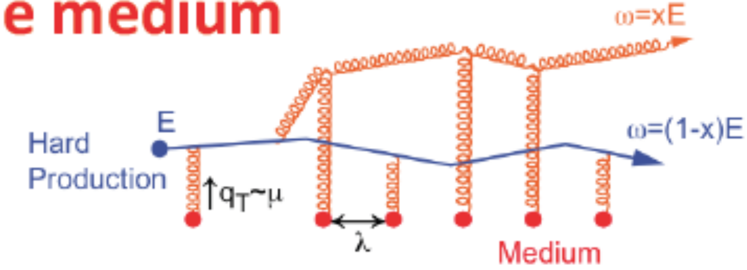

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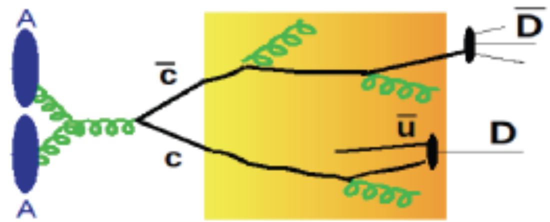
$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

- medium **modification to HF hadron formation**
  - hadronization via quark coalescence



- participation in collective motion ➜ azimuthal anisotropy of produced particle

How can we measure medium effects?

Nuclear modification factor (R_{AA}): compare particle production in Pb-Pb with that in pp scaled by a "geometrical" factor (from Glauber model)

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

Pb-Pb

pp

Nuclear overlap function, encodes collision geometry

If $R_{AA}=1$ → no nuclear effects
If $R_{AA}\neq 1$ → nuclear effects

Trivial but important caveat:

(simplistic scheme)

What we want to probe

$$\frac{dN_{AA}}{dp_T} = \text{"vacuum" parton spectra} \otimes \text{initial-state effects} \otimes \text{parton interaction with the medium} \otimes \text{(modified?) hadronization} \otimes \text{hadronic phase} \left(\otimes \text{decay e.g. for leptons} \right)$$

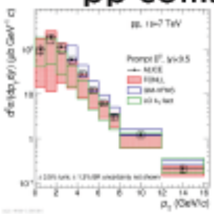
Measured spectra in AA collisions result from a convolution of many pieces
→interpretation of the results requires comparison with models
→must measure observables with different sensitivity to the various ingredients

A rather long shopping list

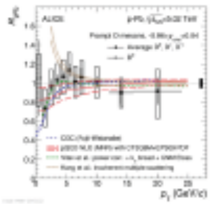
What we want to probe

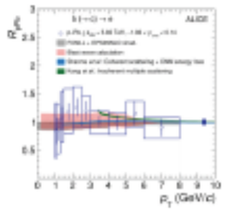
$$\frac{dN_{AA}}{dp_T} = \text{"vacuum" parton spectra} \otimes \text{initial-state effects} \otimes \text{parton interaction with the medium} \otimes \text{(modified?) hadronization} \otimes \text{hadronic phase} \left(\otimes \text{decay e.g. for leptons} \right)$$

pp collisions



Constrain models with measurements from p-Pb collisions





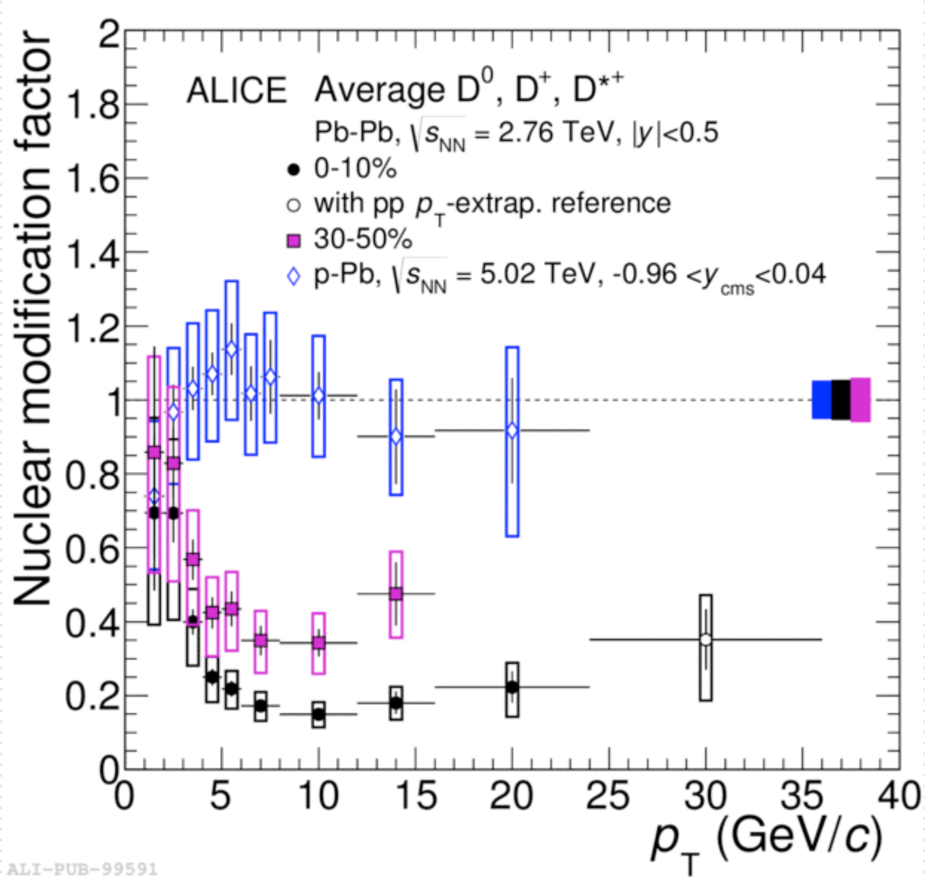
Charm and beauty lose energy

Via radiative and collisional processes

- quark mass (e.g. from dead-cone effect)
- color charge (Casimir factor)
- path length and medium density

Hadronization via coalescence with medium quarks?

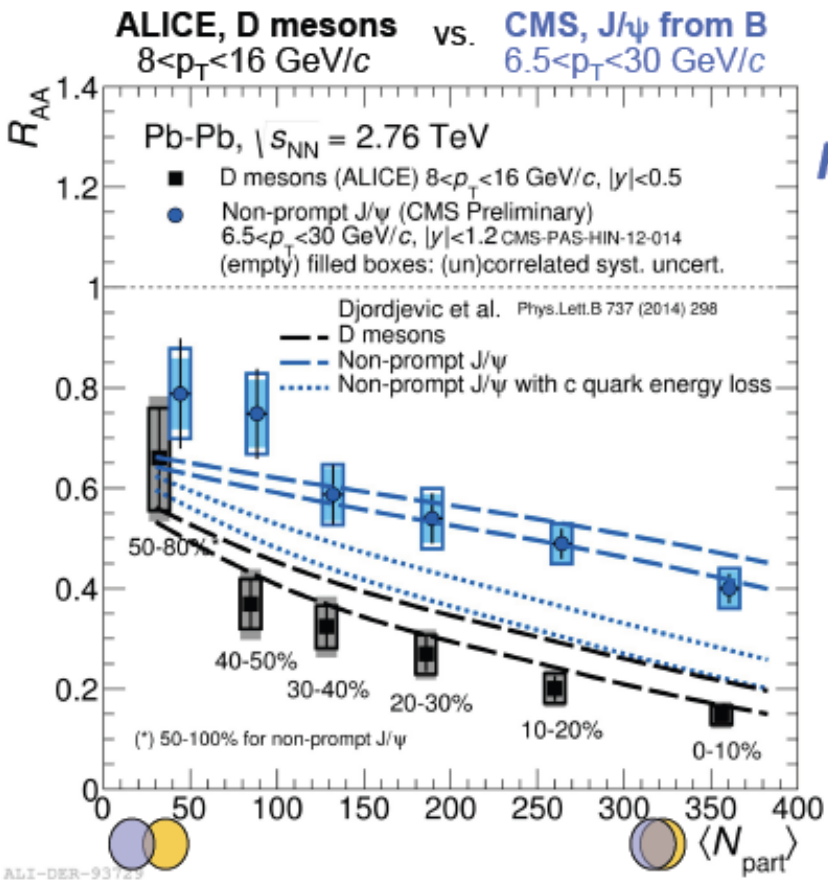
D-meson suppression at $\sqrt{s_{NN}}$=2.76 TeV



- D meson production suppressed up to a factor ~6 (p_T~10 GeV/c) in central Pb-Pb collisions
- Comparison with R_{pPb}~1 → **final-state effect due to in-medium charm-quark energy loss**

ALICE, JHEP 1511 (2015) 205
CMS-PAS-HIN-12-014
CMS-PAS-HIN-15-005

Charm vs. beauty



R_{AA} (J/ψ from B) > R_{AA}(D) in central collisions

p_T interval tuned to have p_T(D)~p_T(B):
~70% of J/ψ from B mesons with 8<p_T<16 GeV/c
(median ~11 GeV/c vs. ~10 for D mesons)

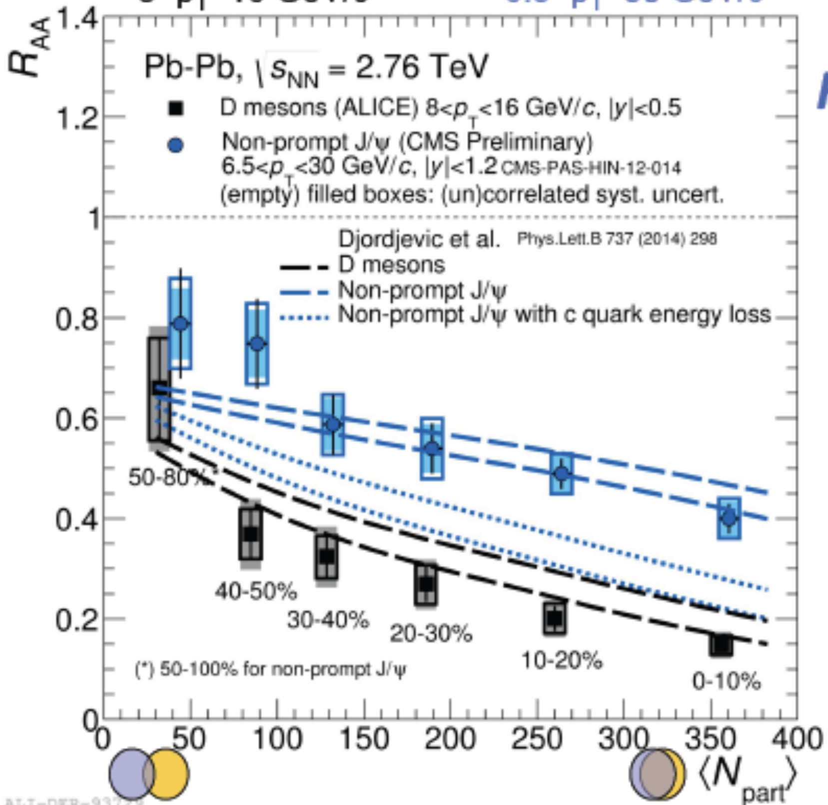
⇩

Indication of R_{AA} (B) > R_{AA}(D)

ALICE, JHEP 1511 (2015) 205
CMS-PAS-HIN-12-014
CMS-PAS-HIN-15-005

Charm vs. beauty

ALICE, D mesons vs. **CMS, J/ψ from B**
$8<p_T<16$ GeV/c — $6.5<p_T<30$ GeV/c



M. Djordjevic et al.
(Phys. Lett. B 737 (2014) 298; priv. comm.)

Radiative (DGLV formalism) + collisional energy loss, dynamical scattering centres in the medium

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The different suppression and the centrality dependence are **described by models with quark-mass dependent energy loss ($\Delta E_g > \Delta E_{lq} \geq \Delta E_c > \Delta E_b$)**

Comparison to other models (WHDG, MC@HQs +EPOS2, BAMPS, TAMU, Vitev et al.) shown in extra slides

ALICE, JHEP 1511 (2015) 205
CMS-PAS-HIN-12-014
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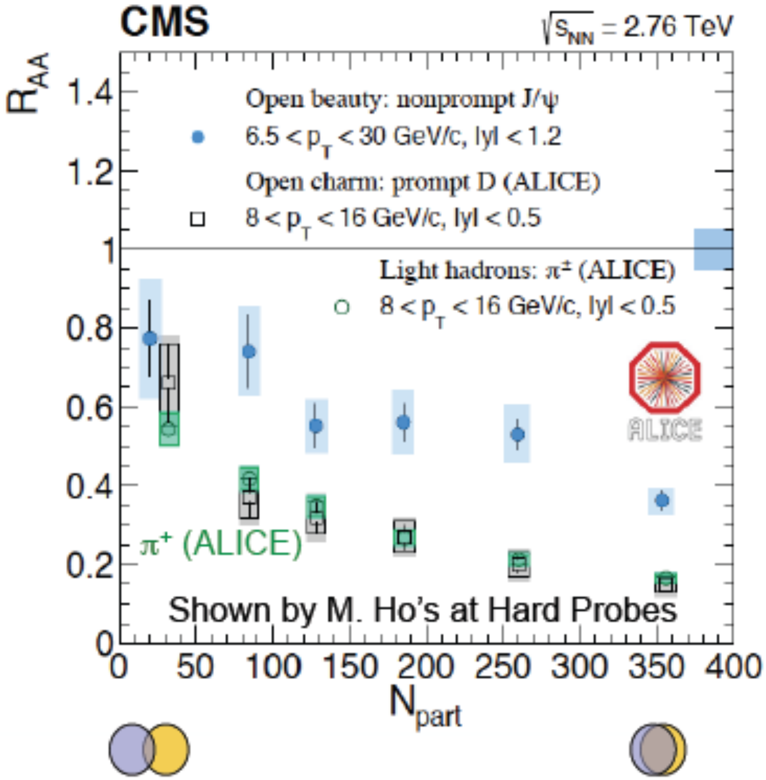
ALICE, D mesons $8<p_T<16$ GeV/*c* vs. **CMS, J/ψ from B** $6.5<p_T<30$ GeV/*c*



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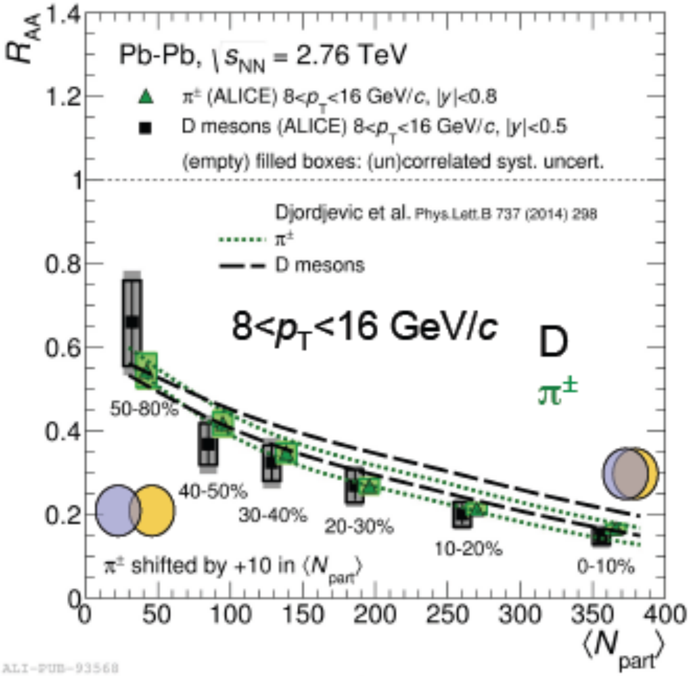
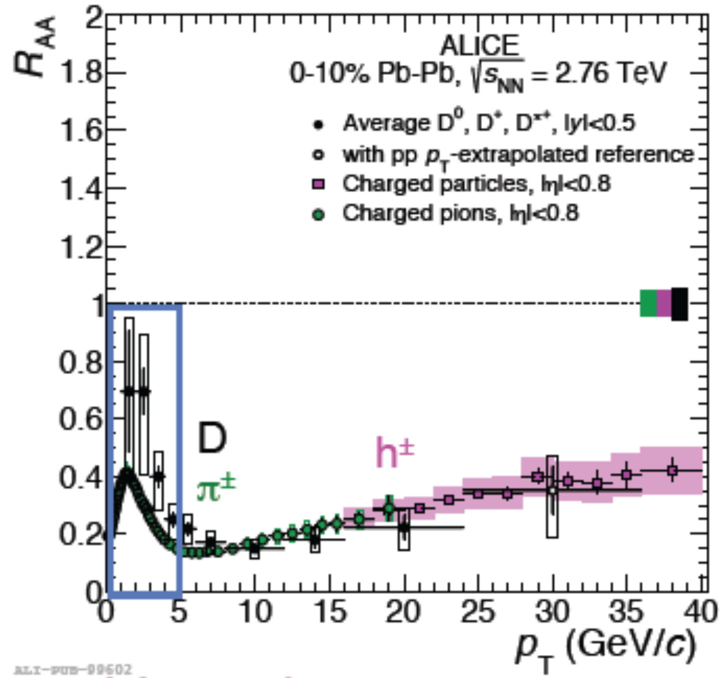
Same conclusion with final CMS results

Charm vs. light quarks/gluons





D-meson and pion R_{AA} compatible within uncertainties

Described by models (e.g. **M. Djordjevic, PRL112 (2014) 042302, see extra slides**) including:

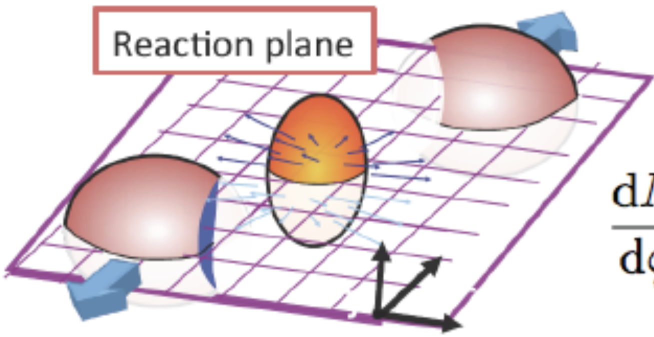
- Mass and colour charge dependent energy loss
- Different p_T spectra of charm quarks, light quarks and gluons
- Different fragmentation functions (harder for charm than light quarks and gluons)

What about low p_T (<5 GeV/*c*)?

- More data needed to study the (small?) effect of charm quark mass at low p_T
- N.B. for p_T<2 GeV/*c* not all pions come from hard scattering (yield does not scale with N_{coll})!

Elliptic flow (azimuthal anisotropy)

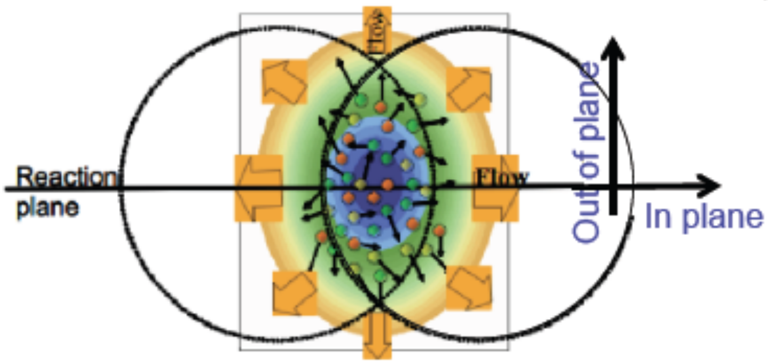
Study azimuthal distribution of produced particles w.r.t. the reaction plane (Ψ_{RP})



Initial spatial anisotropy → momentum anisotropy

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \dots\right)$$

$$v_n = \langle \cos(n[\varphi - \psi_n]) \rangle$$



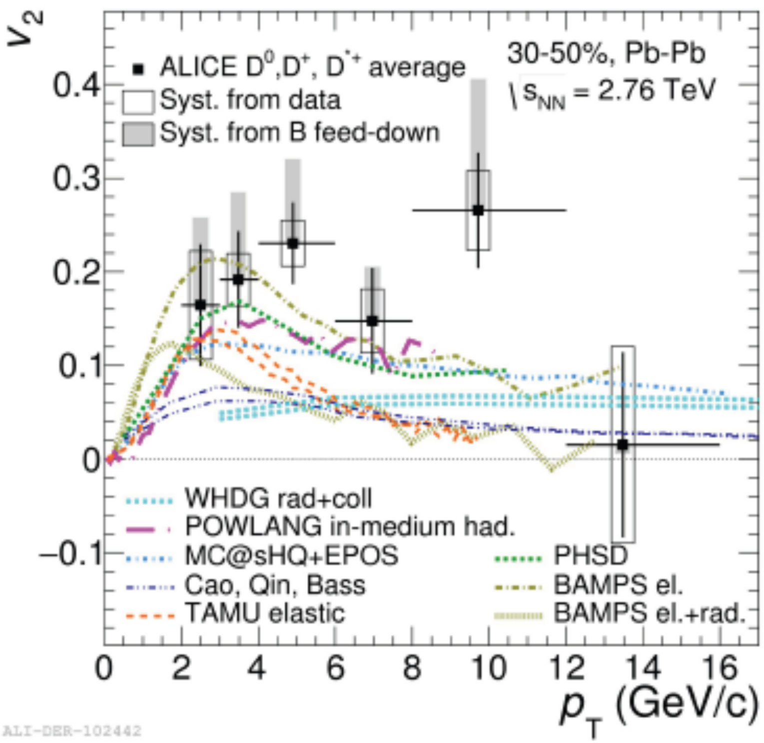
$v_2 > 0$ →

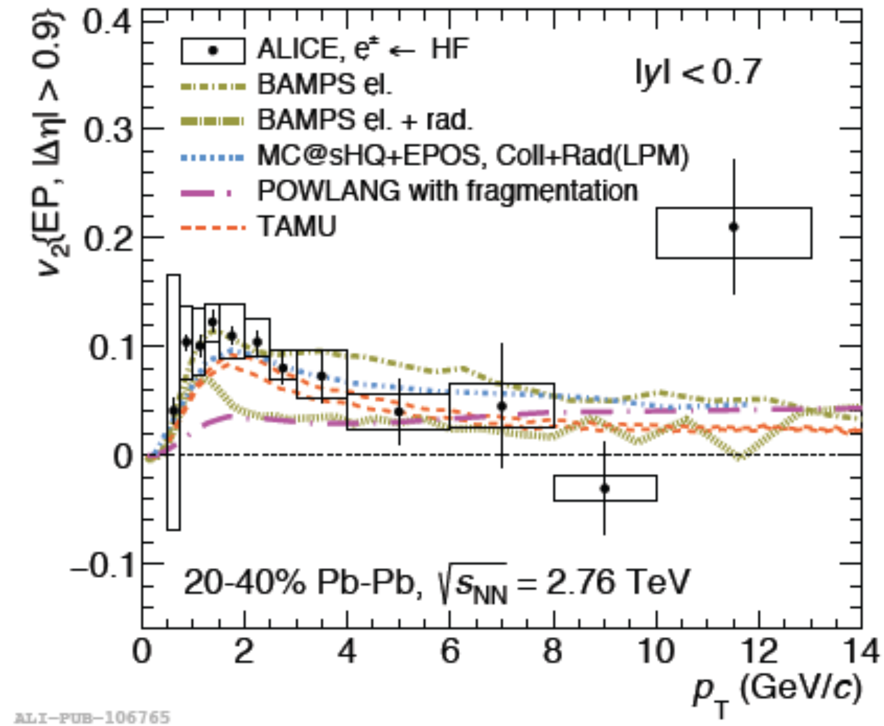
- Thermalization/collective motion (at low p_T)
- Path length dependence of energy loss (at high p_T)

v_2+ R_{AA}: complementary information → improve sensitivity to relative contribution of collisional and radiative energy losses and to coalescence

v_2: comparison with models

Model references in backup

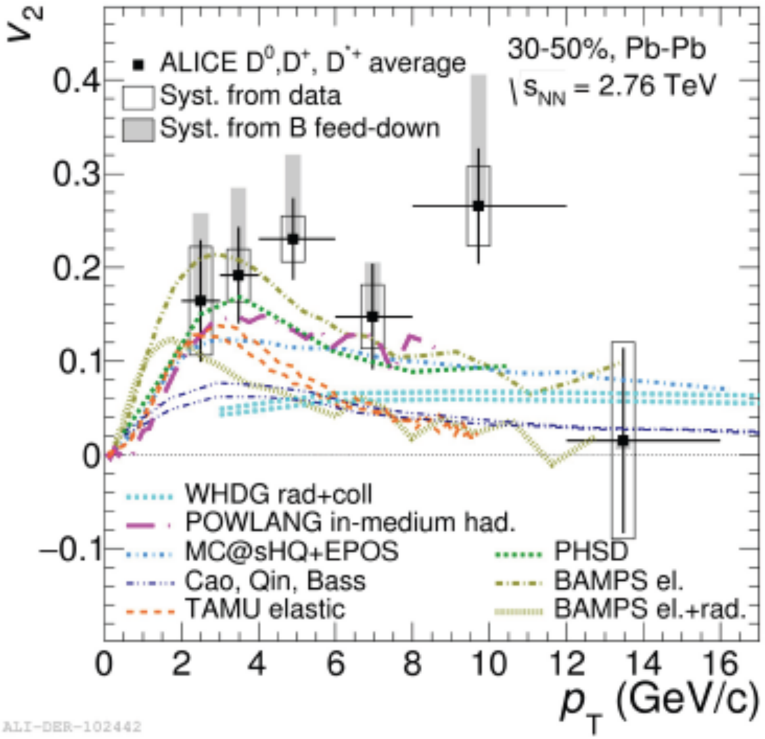


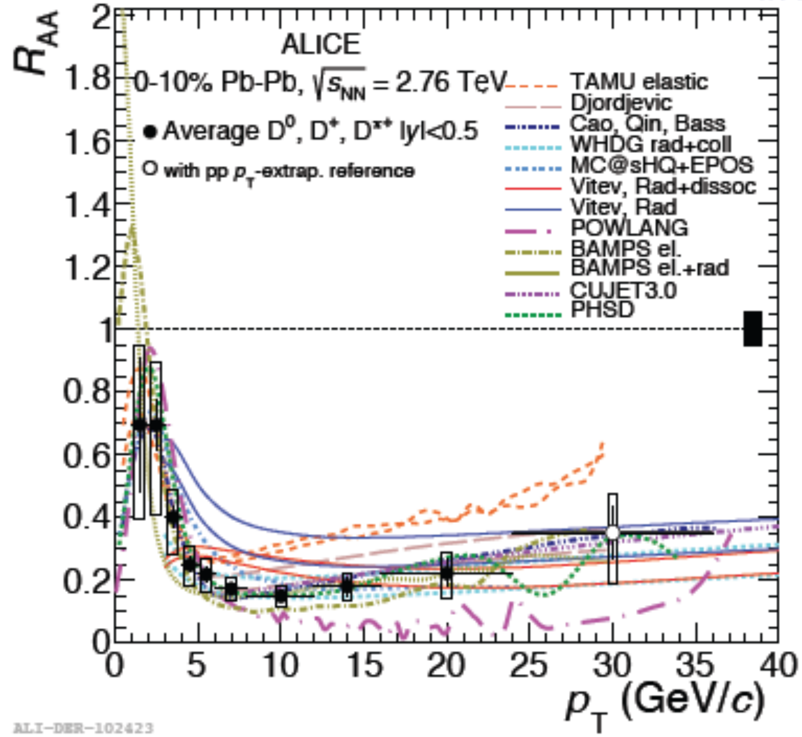


- v_2 at low p_T better described by models including mechanisms that transfer to charm quarks the elliptic flow induced during the system expansion of the medium (collisional energy loss, recombination)
- Highlight importance that models include a realistic description of the medium evolution and of initial conditions

v_2 and R_{AA}: comparison with models

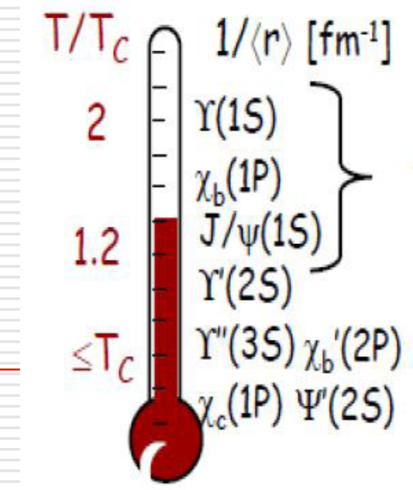
Model references in backup



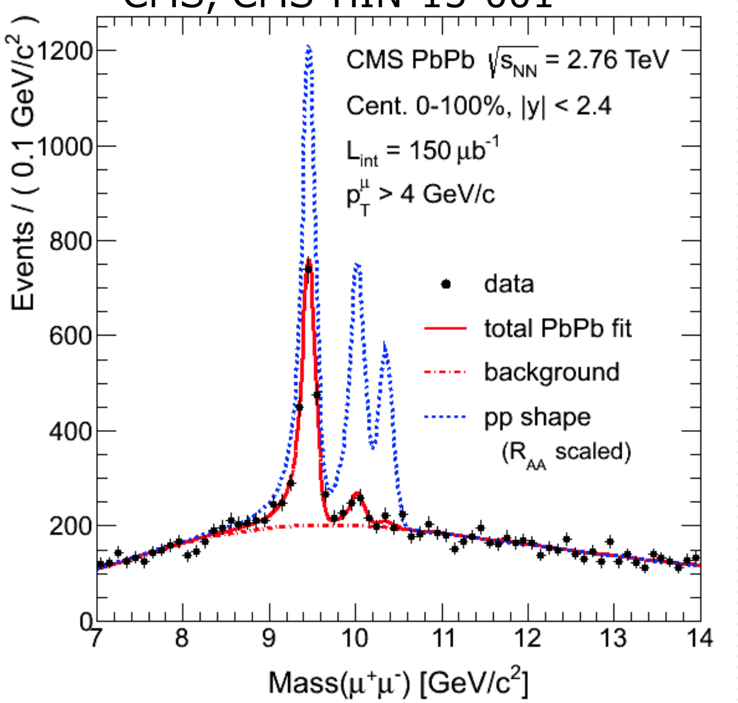


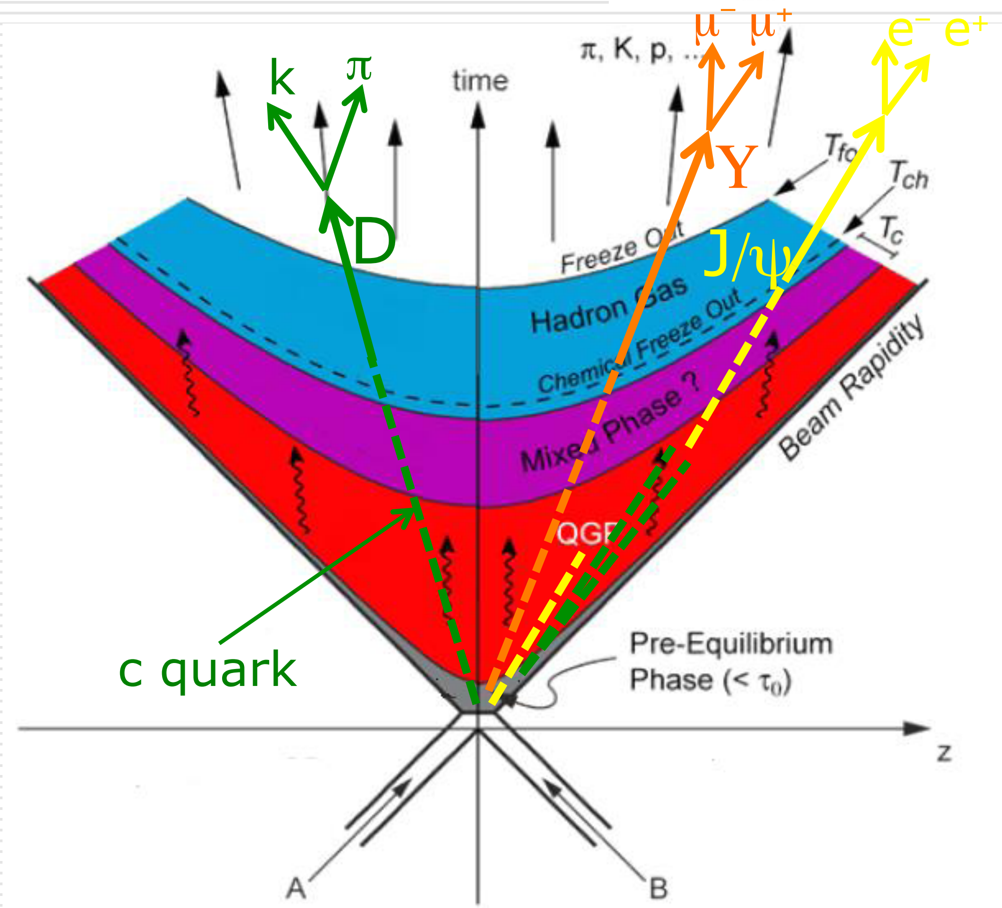
- v_2 at low p_T better described by models including mechanisms that transfer to charm quarks the elliptic flow induced during the system expansion of the medium (collisional energy loss, recombination)
- Highlight importance that models include a realistic description of the medium evolution and of initial conditions
- v_2 and R_{AA} measurements over a wide p_T range can set stringent constraints to model

Heavy Flavour: quarkonia



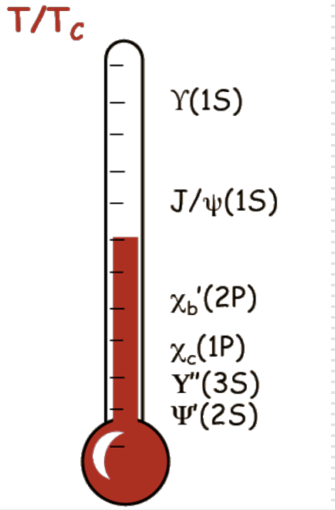
CMS, CMS-HIN-15-001



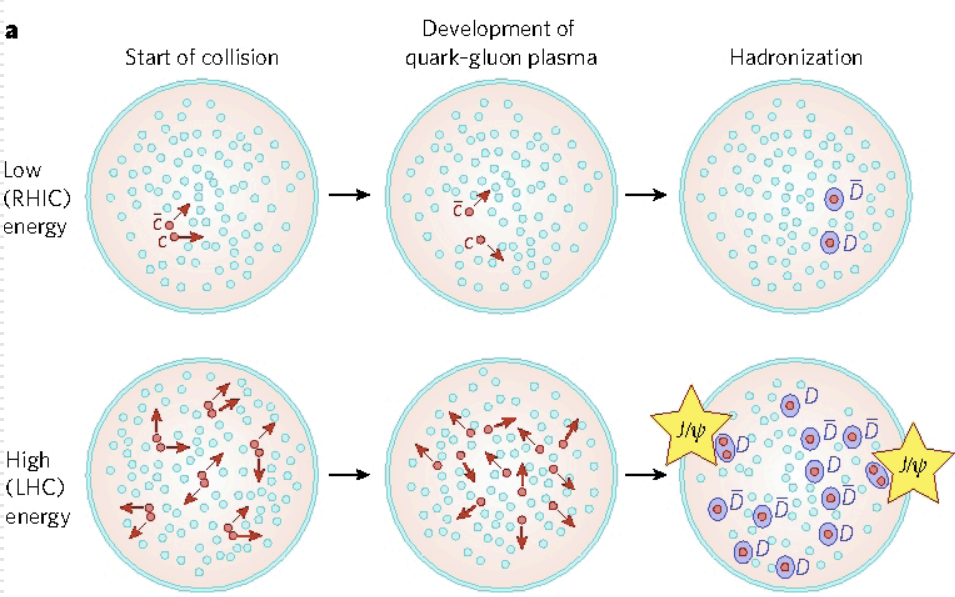


Charmonium as QGP Signature

- Charmonium suppression:
  - Color screening prevent *c* anti-*c* (and *b* anti-*b*) binding in deconfined matter
  - Dissociation temperature depends on binding energy → "QGP thermometer"



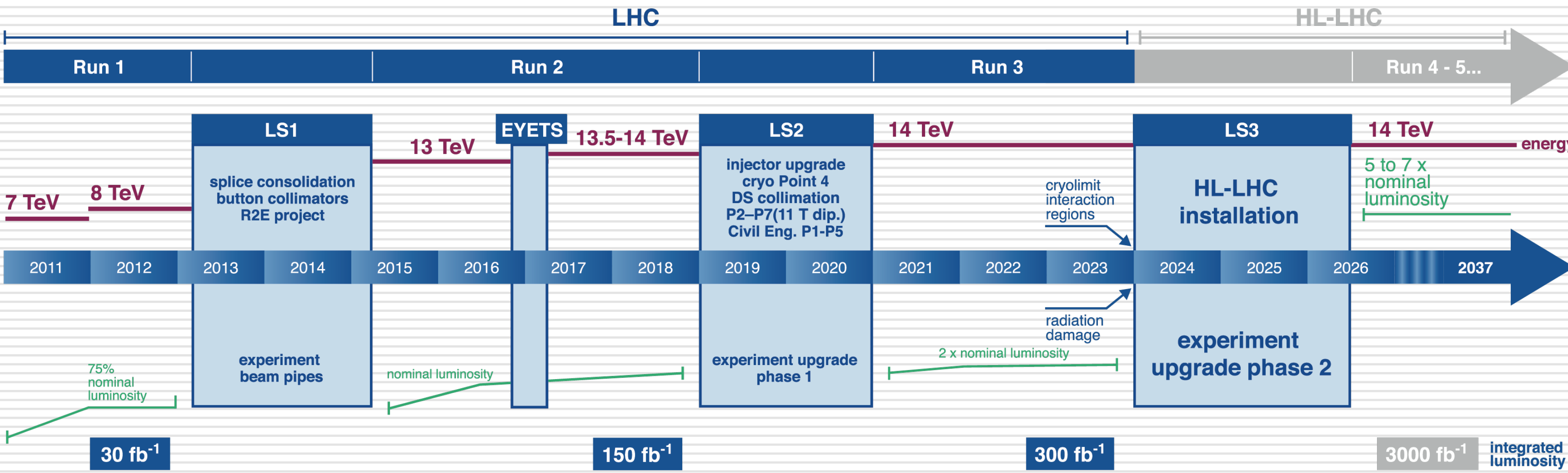
- J/ψ recombination:
  - J/ψ's from quark recombination at phase boundary ?



Suppression at low $\sqrt{s_{NN}}$ and J/ψ enhancement at high $\sqrt{s_{NN}}$?

ALICE Upgrade

LHC / HL-LHC Plan



- Main upgrades relevant for the Heavy-Ion physics (LS2:2019-2020)
  - LHC collimator upgrades: target L ≈ $6x10^{27}$ cm^{-2} s^{-1} for Pb-Pb
  - Major ALICE and LHCb upgrades, important upgrades for ATLAS and CMS

A quali domande si vuole rispondere con l'upgrade?

- In che maniera interagiscono i quark col mezzo creato nella collisione ?
  - studio della QCD in un sistema mesoscopico a multi-particelle
- Qual è la temperatura iniziale del mezzo e, più in generale, la sua equazione di stato ? Qual è la natura chirale della transizione di fase ?
- Come sono collegate la soppressione e la rigenerazione del quarkonio al deconfinamento ed alla temperatura del QGP ?

A quali domande si vuole rispondere con l'upgrade? Con quali osservabili?

- In che maniera interagiscono i quark col mezzo creato nella collisione ?
  - studio della QCD in un sistema mesoscopico a multi-particelle

  → la dinamica dei quark pesanti (charm e beauty) e la loro adronizzazione

- Qual è la temperatura iniziale del mezzo e, più in generale, la sua equazione di stato ? Qual è la natura chirale della transizione di fase ?

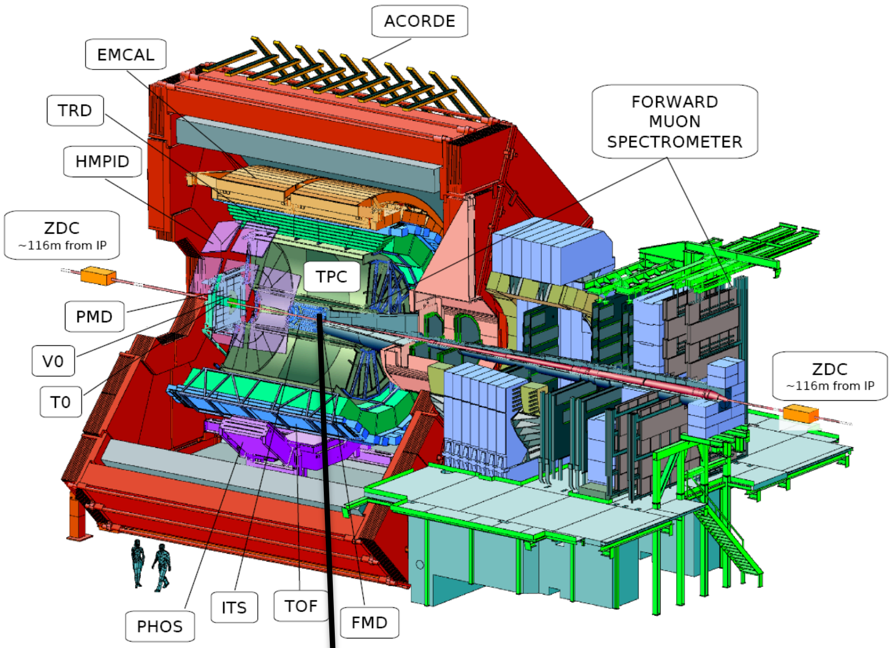
  → la produzione di fotoni termici e di coppie di leptoni di bassa massa invariante

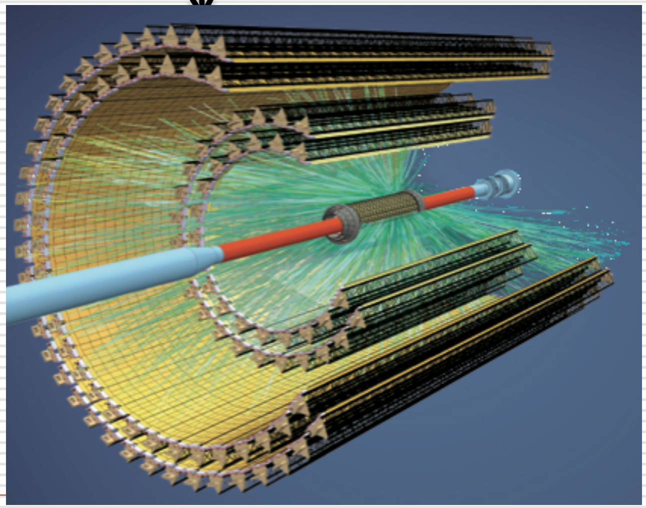
- Come sono collegate la soppressione e la rigenerazione del quarkonio al deconfinamento ed alla temperatura del QGP ?

  → la produzione degli stati di charmonio a bassi p_t

ALICE after 2020

- New Inner Tracking System (ITS)
  - Improved resolution, less material, faster readout





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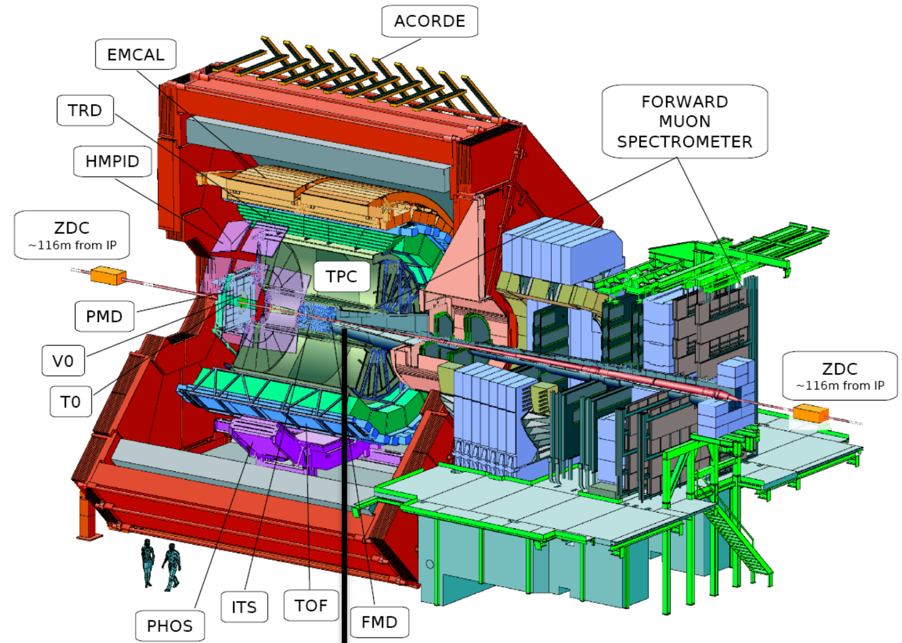
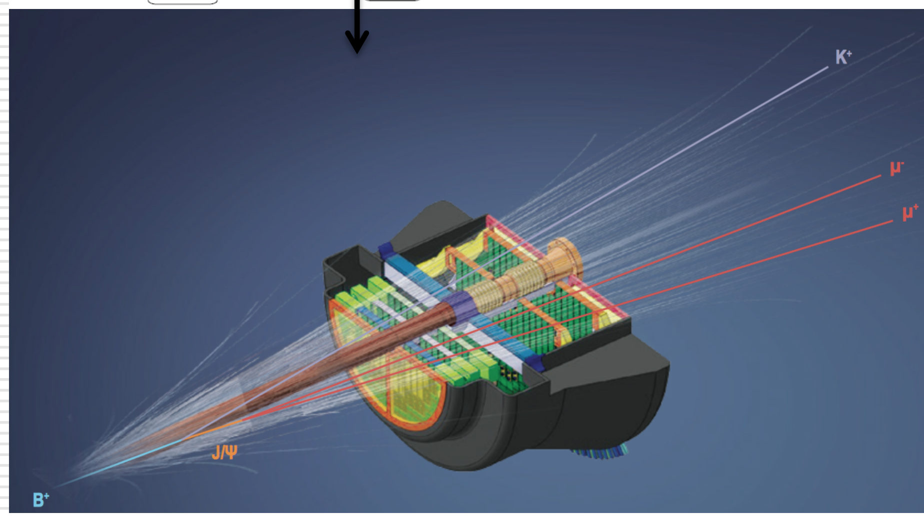
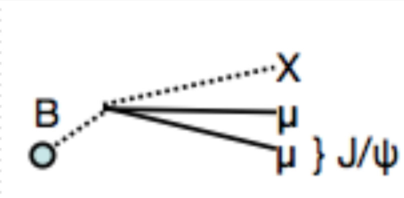
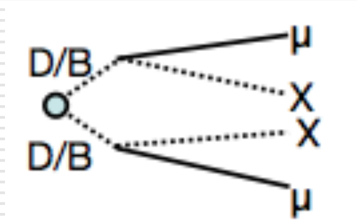
  - HF vertices also at forward rapidity



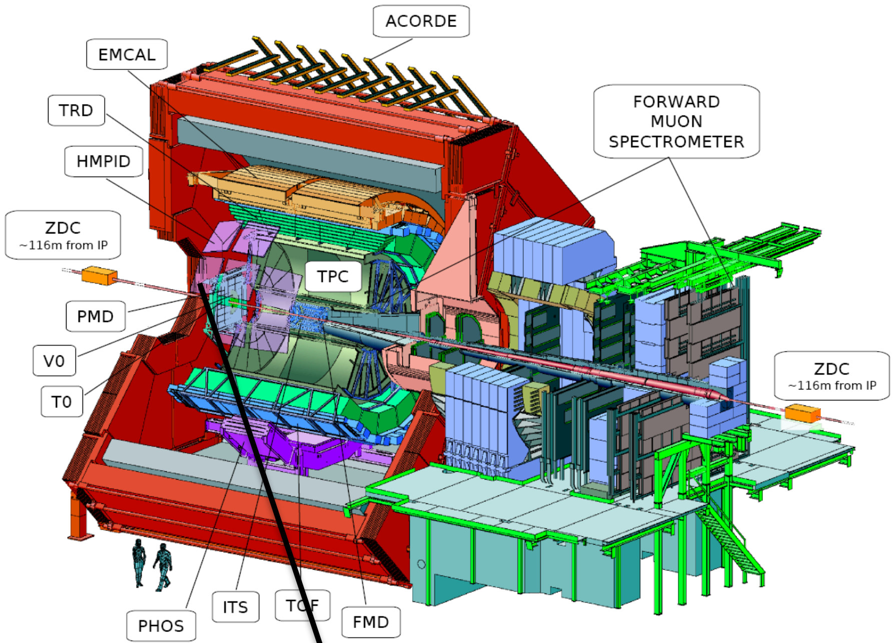


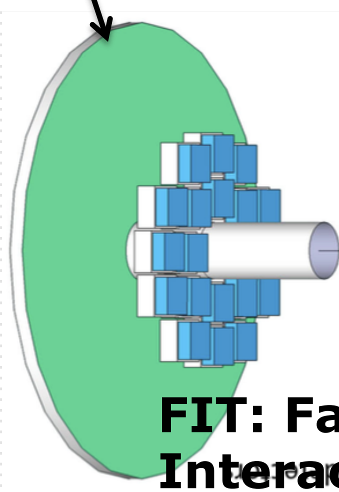




ALICE after 2020

- New Inner Tracking System (ITS)
  - Improved resolution, less material, faster readout
- New Forward Muon Tracker (MFT)
  - HF vertices also at forward rapidity
- Upgraded read-out for TPC, TOF, TRD, MUON, ZDC, EMCal, PHOS, new trigger detector (FIT), integrated
- Online-Offline system (O2)
  - Record minimum-bias Pb-Pb data at 50 kHz (currently <1 kHz)



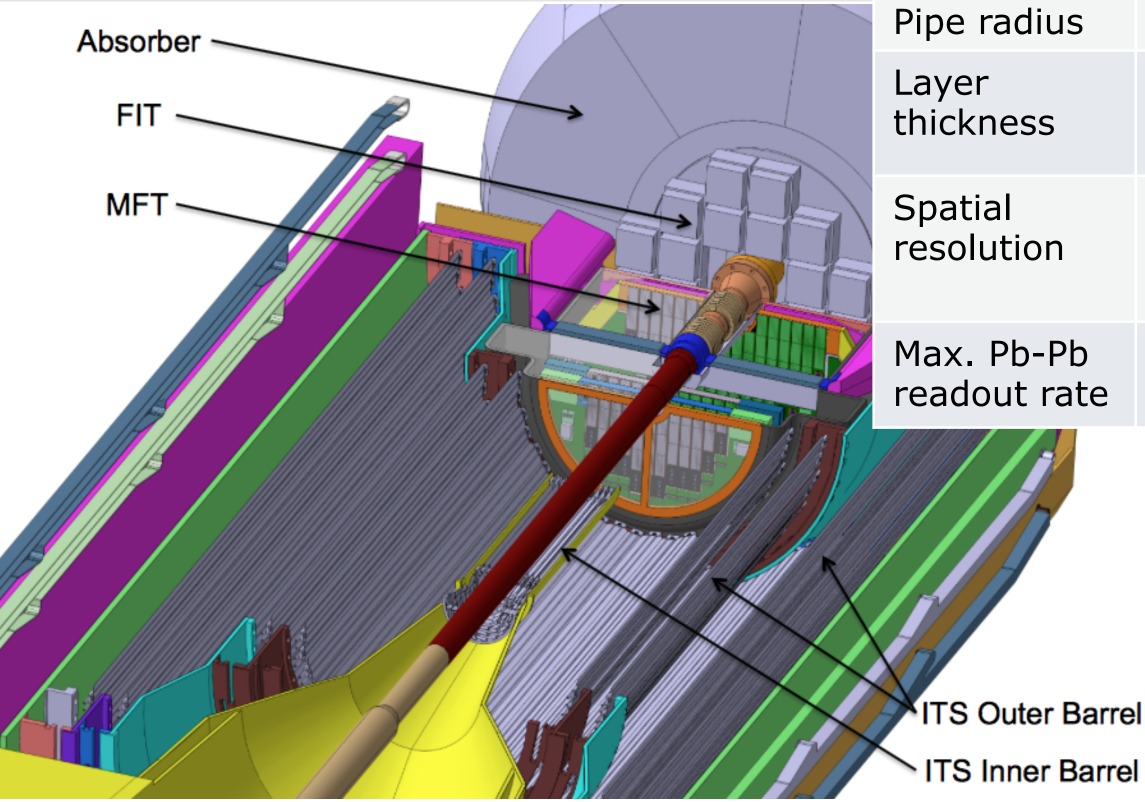


FIT: Fast Interaction Trigger

New all-pixel trackers: ITS and MFT

- Both trackers fully based on Monolithic Active Pixel Sensors (MAPS)

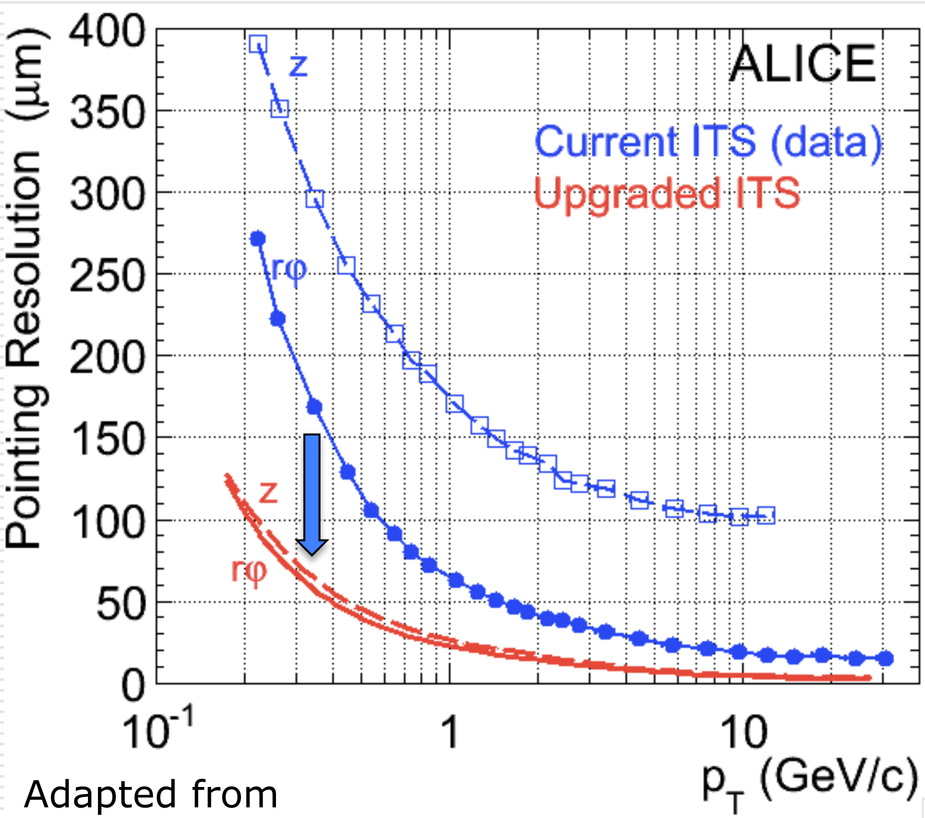
	Pres. ITS	New ITS	MFT
Acceptance	|η|<0.9	|η|<1.5	-3.6<η<-2.3
N Layers	6	7	5
Inner radius	3.9 cm	2.3 cm	/
Pipe radius	2.94 cm	1.86 cm	/
Layer thickness	~1.1%X_0	0.3-0.8% X_0	0.6%X_0
Spatial resolution	12x100 μm^2 35x20 μm^2 20x830 μm^2	~5x5 μm^2	~5x5 μm^2
Max. Pb-Pb readout rate	1 kHz	100 kHz	100kHz



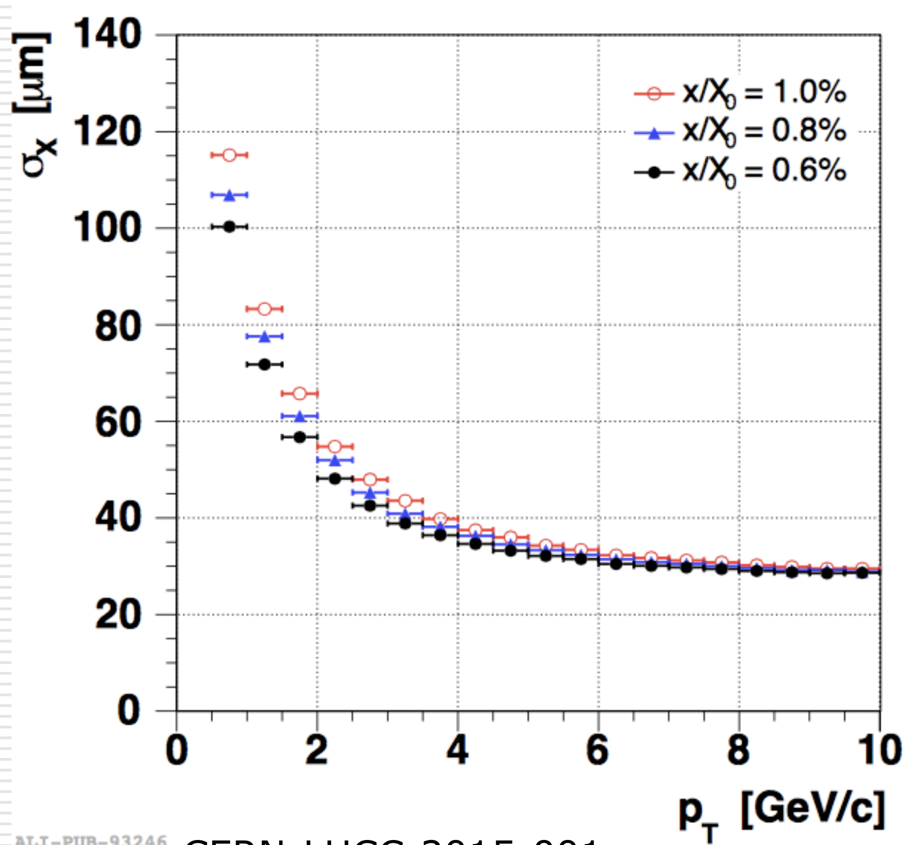
ITS: CERN-LHCC-2013-024
MFT: CERN-LHCC-2015-001

Tracking precision

- ITS: pointing resolution x3 better in transverse plane (x6 along beam)
- MFT: pointing resolution better than 100 μm for *p*T > 1 GeV/*c*



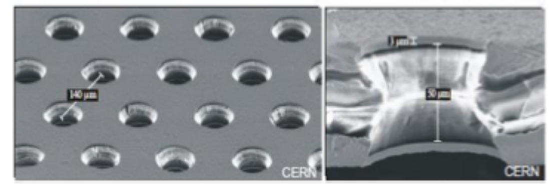
Adapted from CERN-LHCC-2013-024



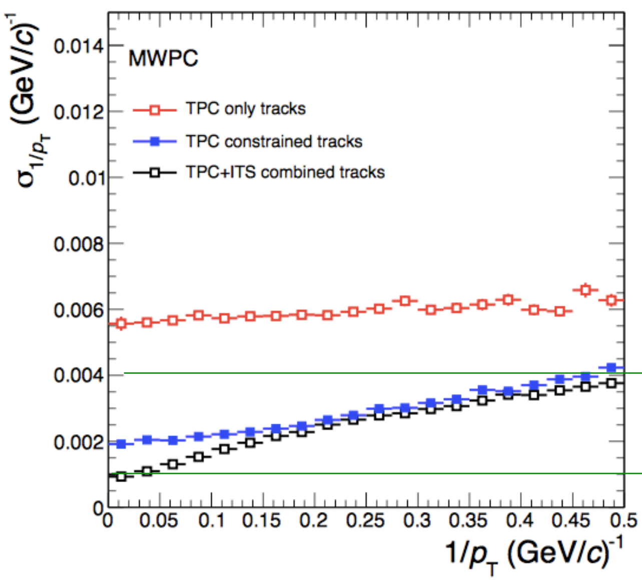
CERN-LHCC-2015-001

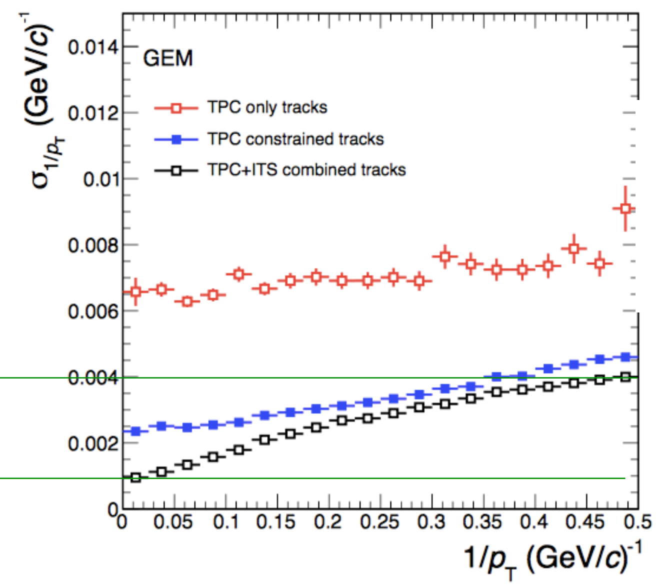
TPC with GEM readout chambers

- Current MWPC: readout limited by ion backflow
- New readout chambers (GEM): readout up to 50 kHz
  - preserve momentum resolution for TPC + ITS tracks
  - preserve particle identification via dE/dx

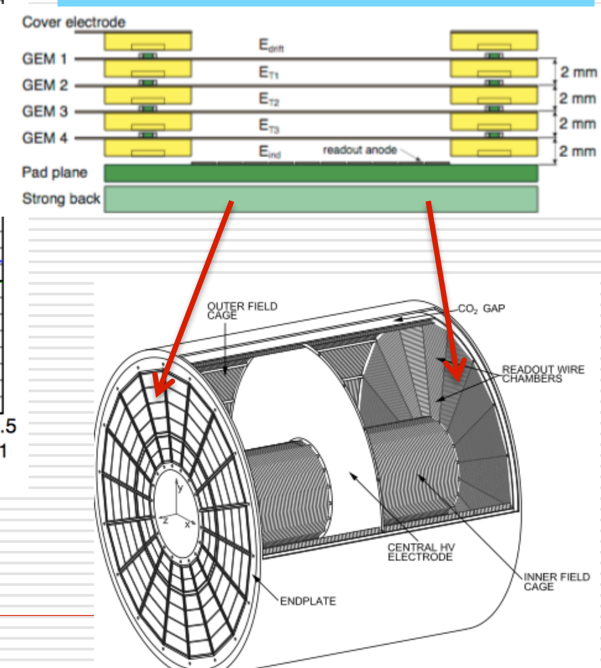


Electron microscope photograph of a GEM foil



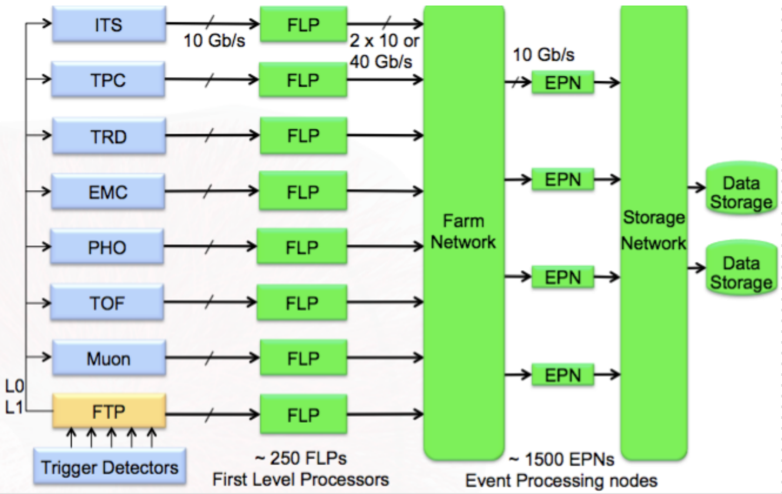


Stack of 4-GEM-foils



Online-Offline (O^2) System

- Pb-Pb at 50 kHz → 1.1 TB/s of data (90% from the TPC)
- The O^2 will integrate in a single infrastructure the present DAQ, HLT and Offline (reconstruction) systems
- A large computing farm close to the detector will process the data online, calibrate the TPC, and reject detector noise
- The overall reduction factor is ~13 → ~85 GB/s to tape
  - Projection based on experience with present HLT system



Detector	Data rate for Pb-Pb @ 50 kHz (GB/s)	Compressed data rate (GB/s)	Data reduction
TPC	1012	50	20.2
ITS	40	26 (8)	1.5 (5)
TRD	20	3	6.7
MFT	10	5	2
Total	**1082**	**84 (66)**	**12.9 (16.4)**

A quali domande si vuole rispondere con l'upgrade? Con quali osservabili?

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  - studio della QCD in un sistema mesoscopico a multi-particelle

  → la dinamica dei quark pesanti (charm e beauty) e la loro adronizzazione

- Qual è la temperatura iniziale del mezzo e, più in generale, la sua equazione di stato ? Qual è la natura chirale della transizione di fase ?

  → la produzione di fotoni termici e di coppie di leptoni di bassa massa invariante

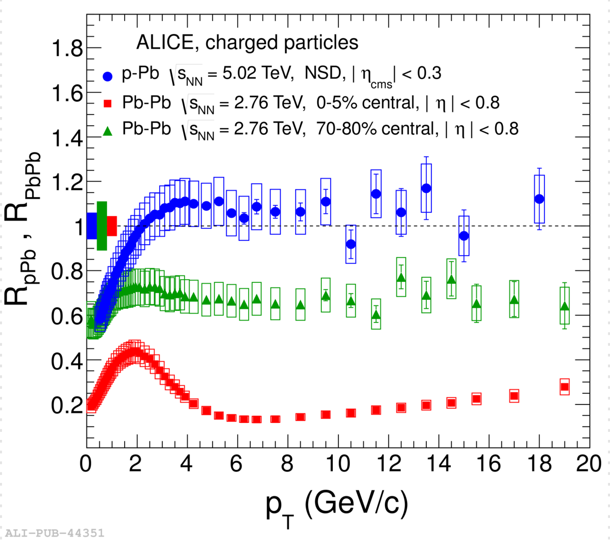
- Come sono collegate la soppressione e la rigenerazione del quarkonio al deconfinamento ed alla temperatura del QGP ?

  → la produzione degli stati di charmonio a bassi p_t

Heavy flavor: perdita di energia

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dydp_T}{N_{coll} \cdot d^2N^{pp}/dydp_T}$$

- Forte soppressione in collisioni Pb-Pb nella produzione di particelle di alto p_t rispetto alle collisioni pp (scoperta a RHIC)

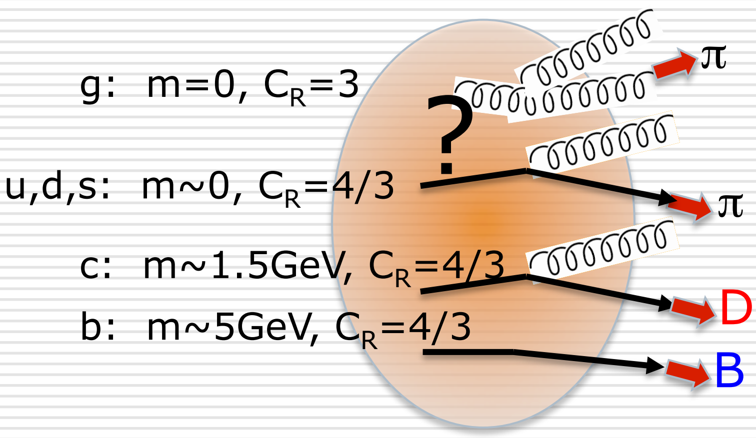


- Interpretazione: perdita di energia del *leading parton* nel mezzo, attraverso due meccanismi:
  - gluonstrahlung
  - perdita di energia per collisioni

- attese della QCD:
  - diverso accoppiamento (fattore di Casimir per quark e gluoni)
  - effetto “dead cone” per quark b

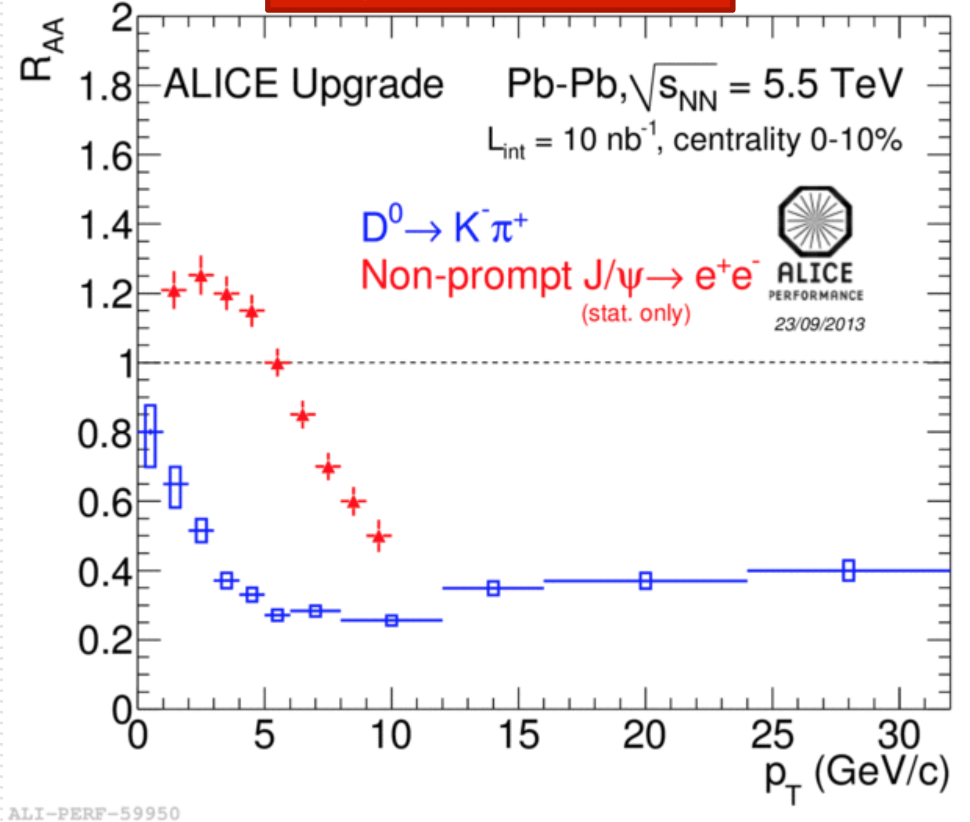
u,d,s,**c** **b**

$\Delta E^g > \Delta E^q > \Delta E^Q$ ⇒ $R_{AA}^{\pi} \overset{?}{<} R_{AA}^{D} < R_{AA}^{B}$

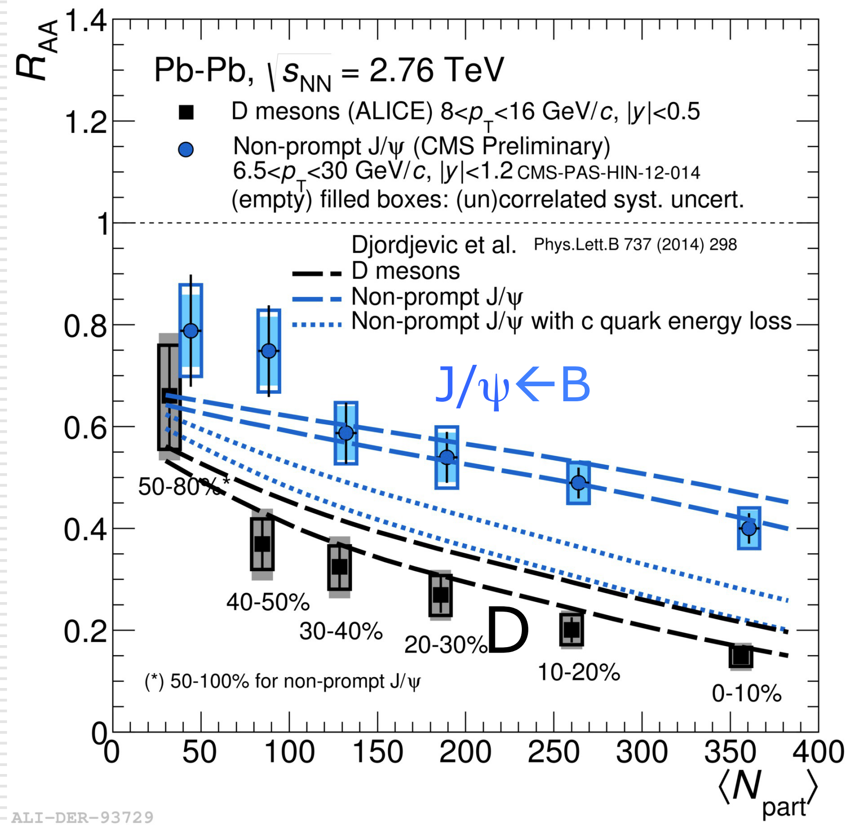


Heavy flavor: perdita di energia

Upgrade di ALICE

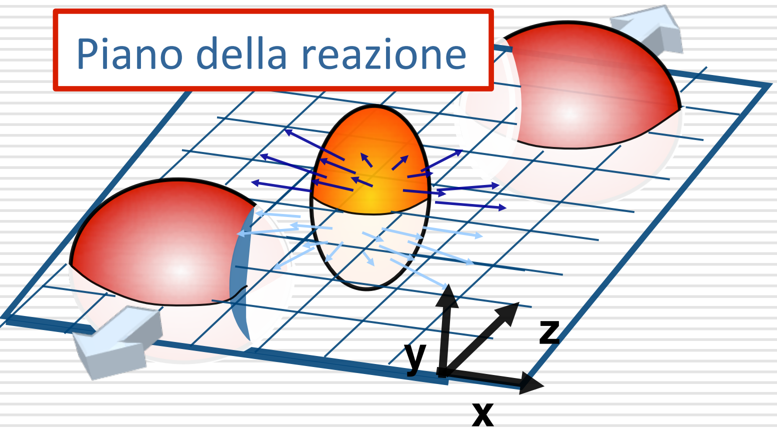


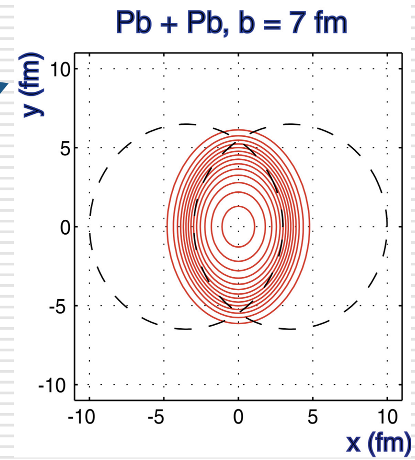
dati attuali: $p_t \sim$ 10 GeV/c

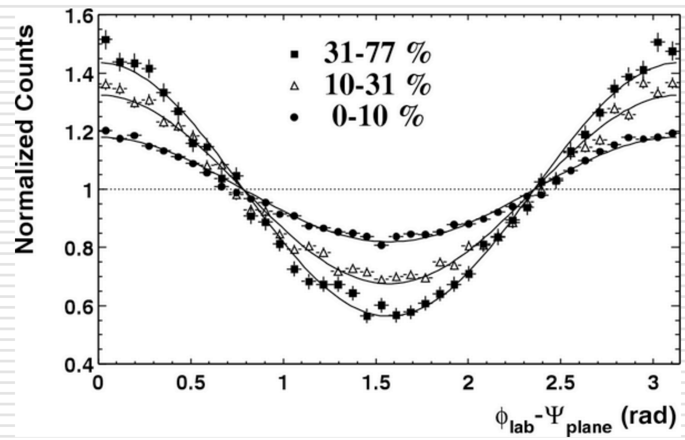


- R_{AA} di charm e beauty sino a p_t=0 con i mesoni D e i decadimenti di B in J/ψ
  - e con decadimenti esclusivi del B
- Prima indicazione dell'effetto della massa
  - misura limitata ad alti p_t
  - incertezza nella dipendenza dalla centralità

Il flusso ellittico: coefficiente v_2



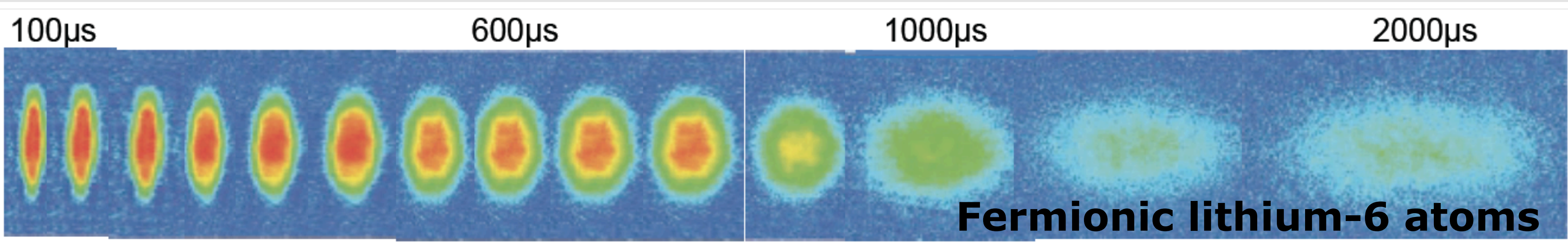




Almond shaped overlap region in geom. space → strong in-plane expansion due to pressure gradients → anisotropy in momentum space

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

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

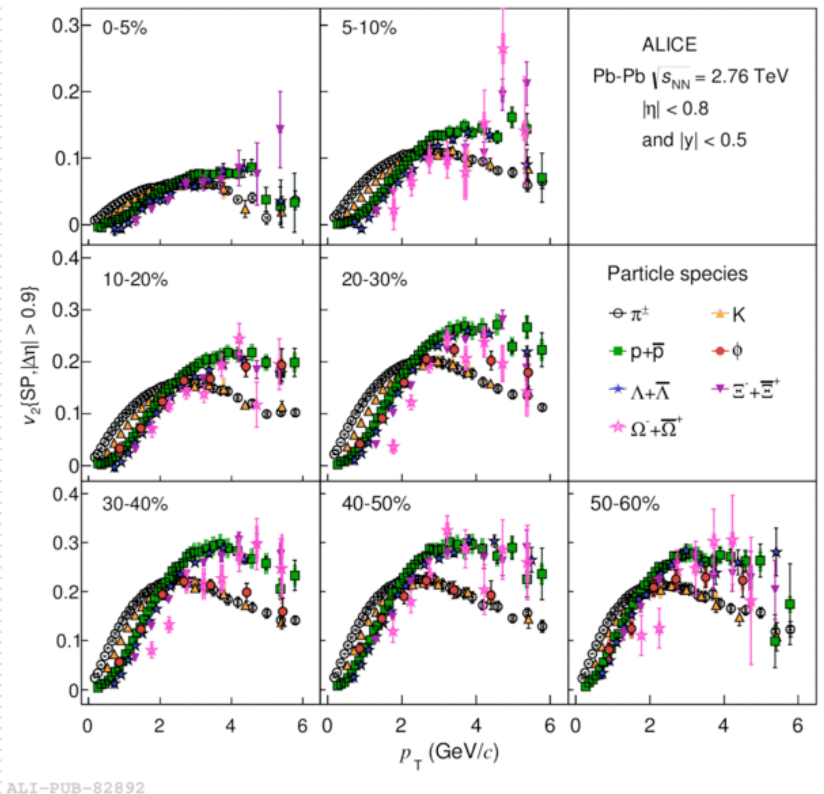


M. Gehm, S. Granade, S. Hemmer, K, O'Hara, J. Thomas - **Science** 298 **2179 (2002)**

Heavy flavor: il flusso ellittico

- la dipendenza di v_2 dalla specie e dal p_t segue le predizioni dei modelli idrodinamici, in cui v_2 è il risultato di una espansione collettiva (nelle diverse fasi, caratterizzate dalle diverse equazioni di stato)
- in che modo i quark pesanti prendono parte all'espansione collettiva ?

JHEP06(2015)190



Heavy flavor: il flusso ellittico

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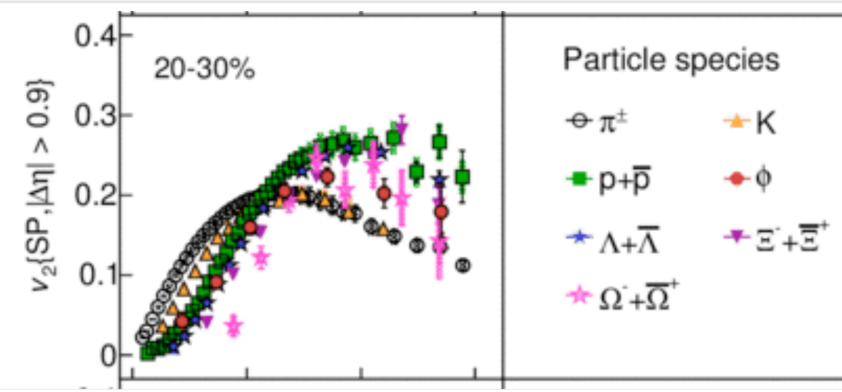
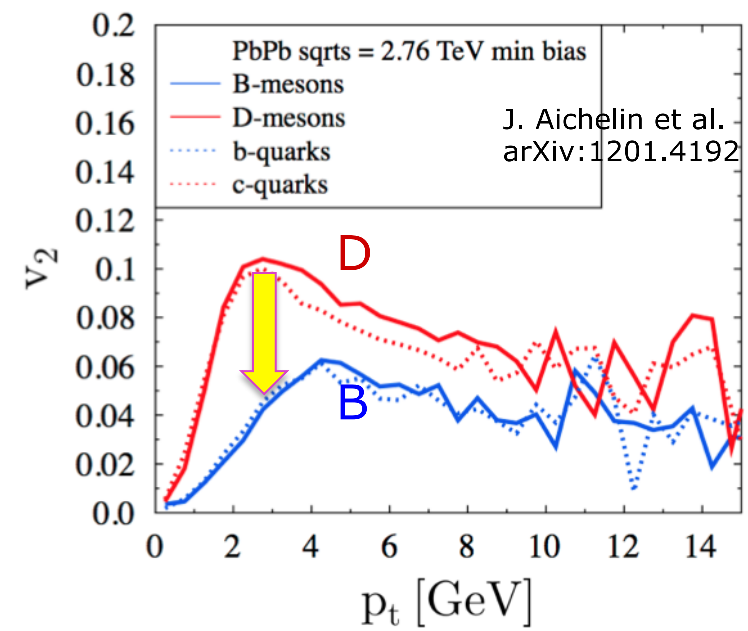
- in che modo i quark pesanti prendono parte all'espansione collettiva ?
  - sonde del meccanismo di interazione
  - sensibili alla viscosità del mezzo
- I modelli prevedono valori elevati di v_2 per il charm ed un sostanziale effetto di massa per il beauty

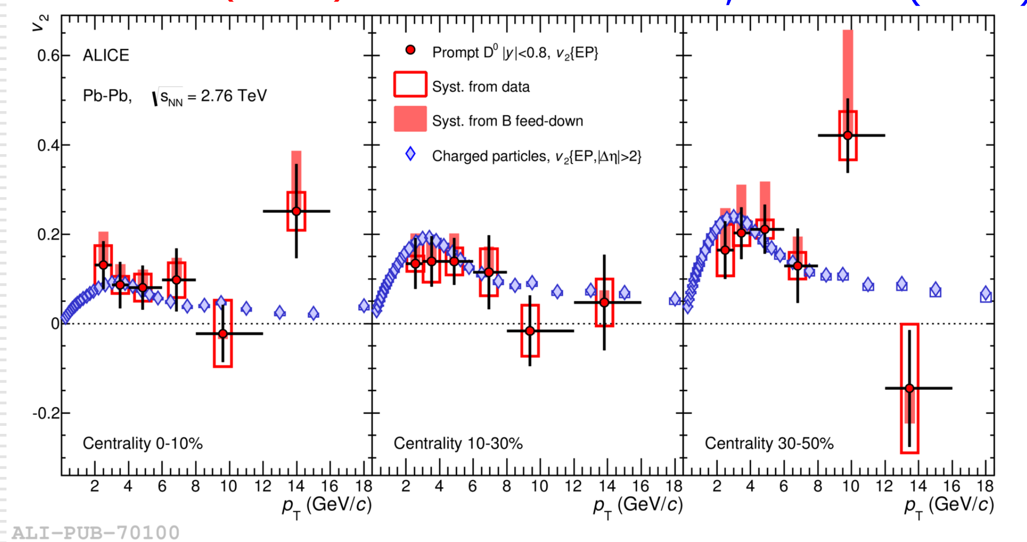
JHEP06(2015)190

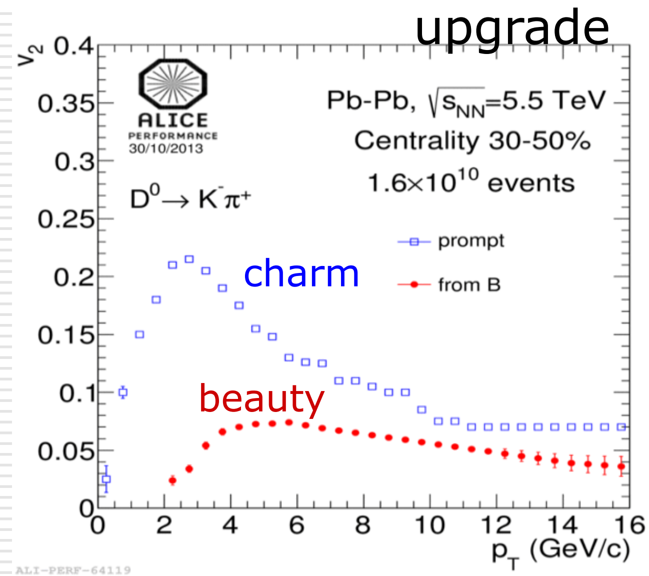




Heavy flavor: il flusso ellittico

- le misure indicano un valore di $v_2 > 0$, confrontabile con gli adroni leggeri
  - indicazioni ancora qualitative per il charm
  - misure non possibili per il beauty
- l'upgrade permetterà una misura dell'effetto di massa atteso per il beauty

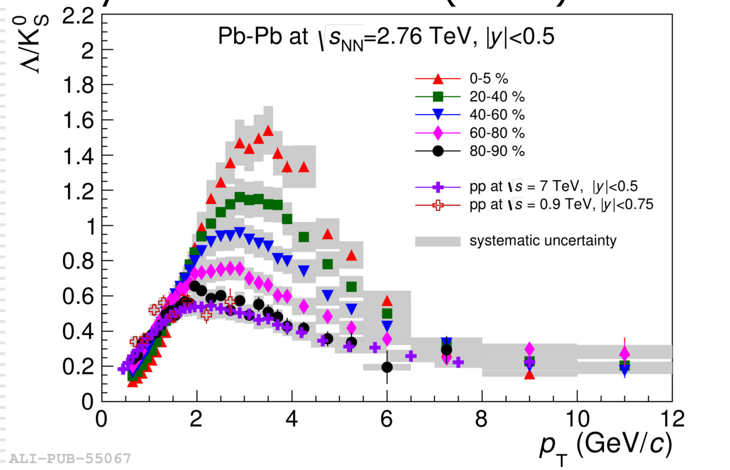




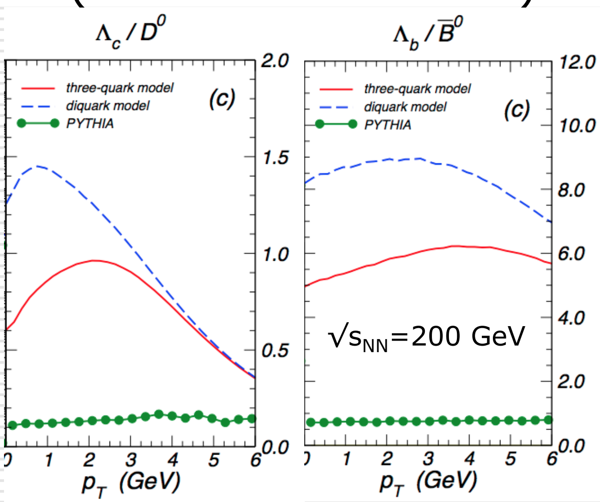
Heavy flavor: come adronizzano ?

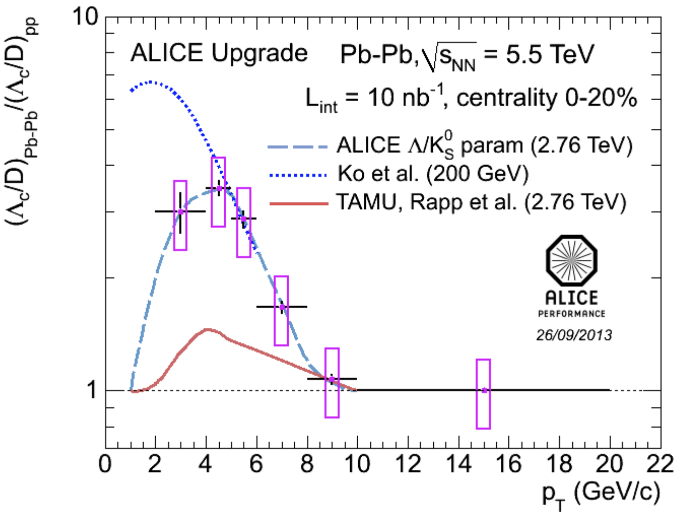
- Il rapporto barione/mesone mostra un incremento in collisioni Pb-Pb a p_t intermedi nel settore light (p/π, Λ/K)
  - non osservato all'interno dei jets
- Interpretazione: ricombinazione di 3 quark (quark anti-quark) dal plasma per formare un barione (mesone)

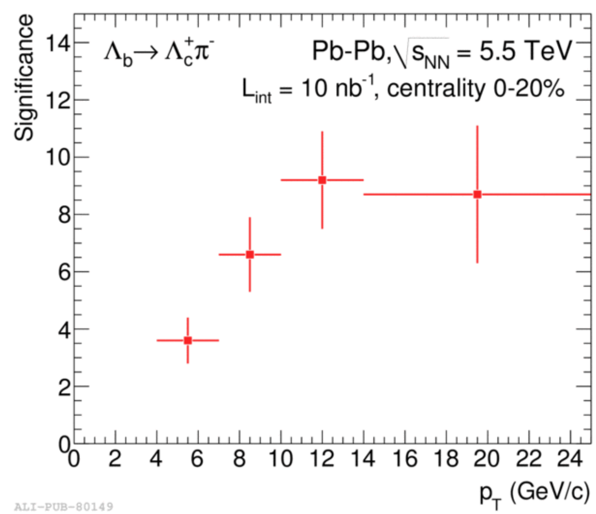
Phys. Rev. Lett. 111 (2013) 222301



(C.M.Ko et al. PRC79)







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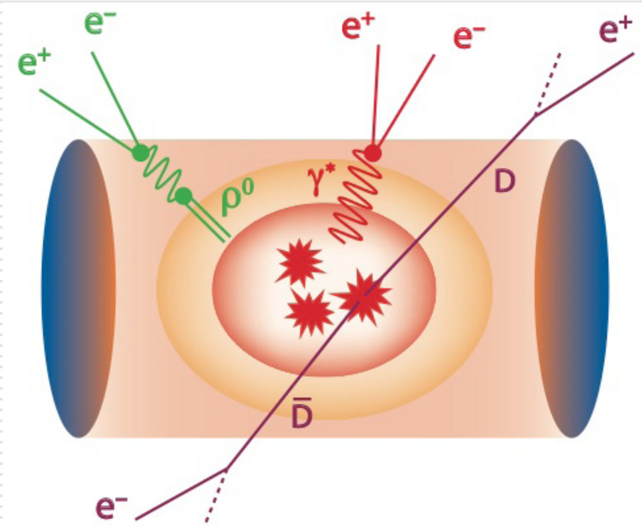
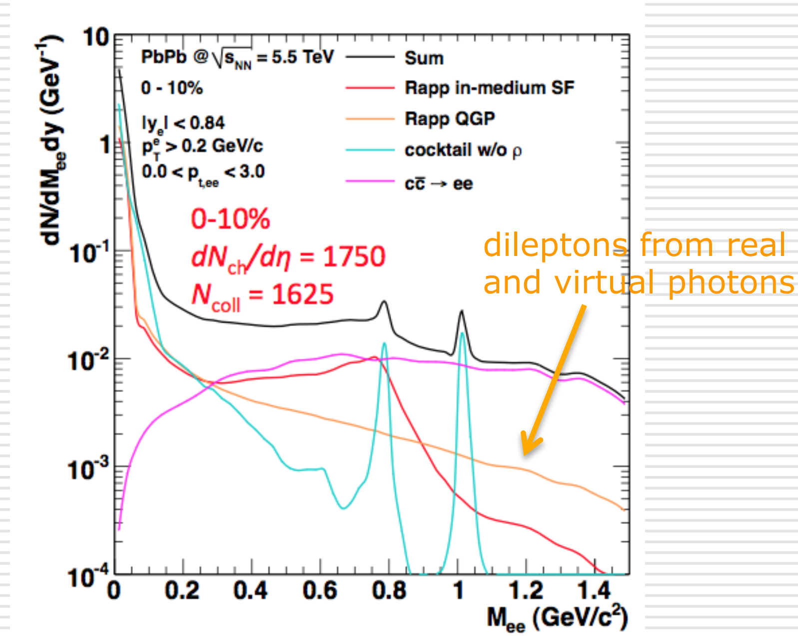
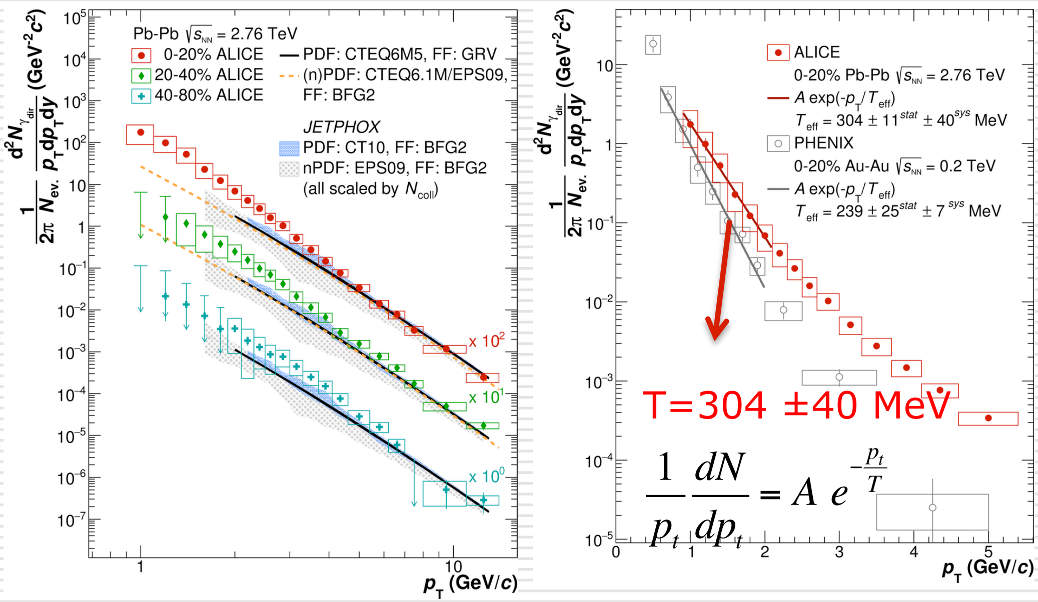
Una sonda penetrante: i dielettroni

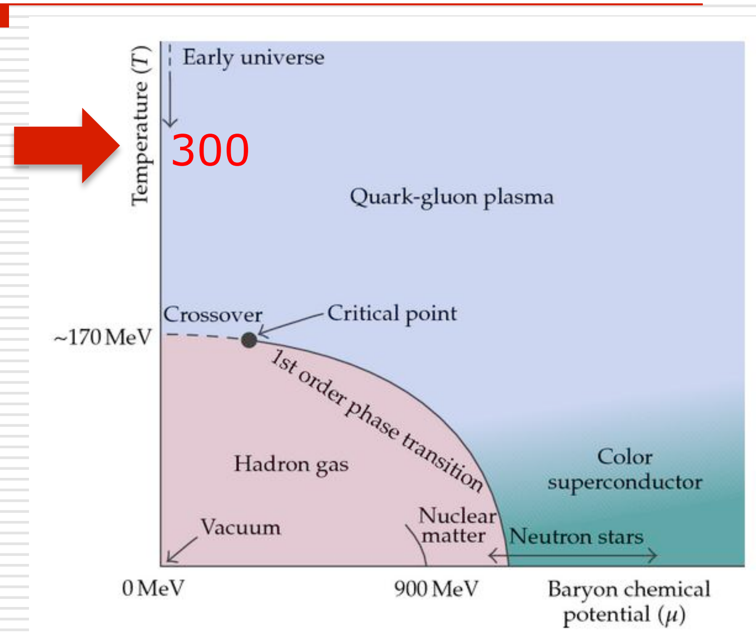




- La produzione di dielettroni riflette l'intera evoluzione del mezzo
- Sonde *elettromagnetiche*: una volta prodotte non risentono del mezzo
- diversi contributi nello spettro di massa invariante:
  - fotoni diretti (radiazione termica) → temperatura del QGP
  - mesoni vettoriali leggeri (ρ, ω, φ) → restaurazione della simmetria chirale
  - open charm ed open beauty

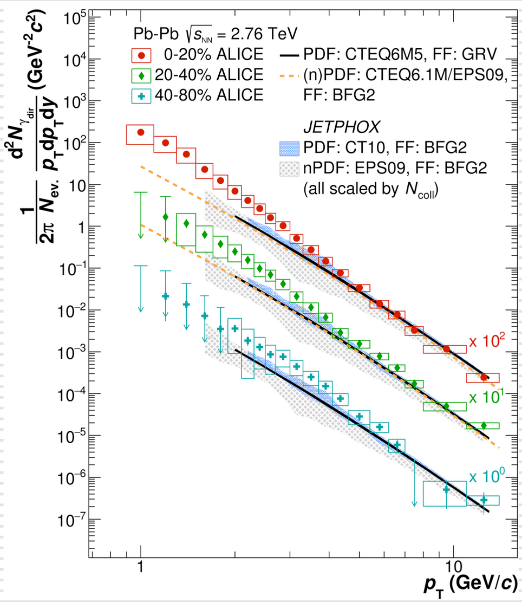
I γ diretti: la "temperatura" del QGP

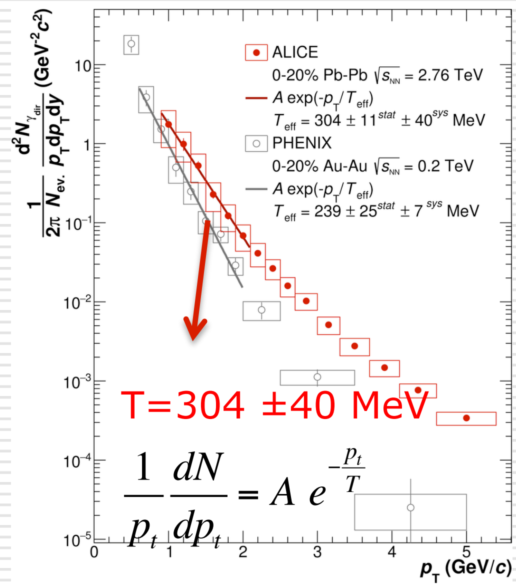


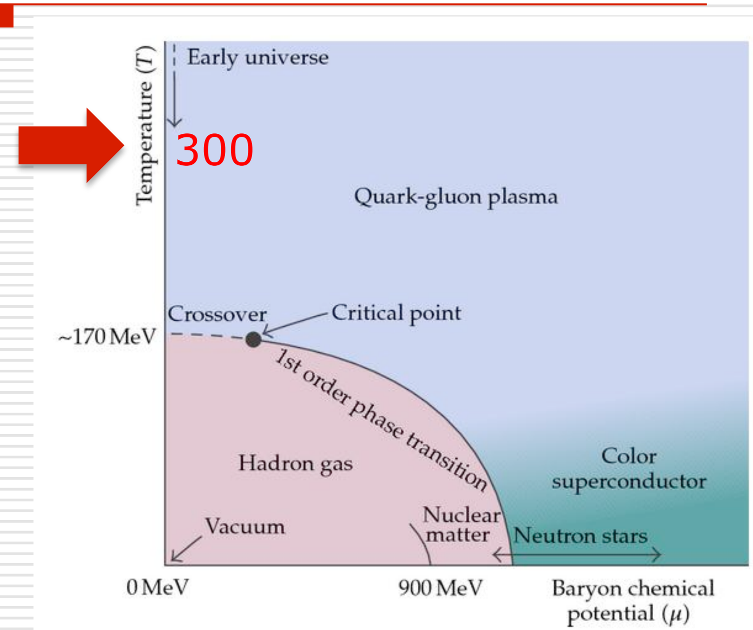


- La produzione di dielettroni riflette l'intera evoluzione del mezzo
- prima misura ad LHC → T~300 MeV è una temperatura effettiva

I γ diretti: la "temperatura" del QGP







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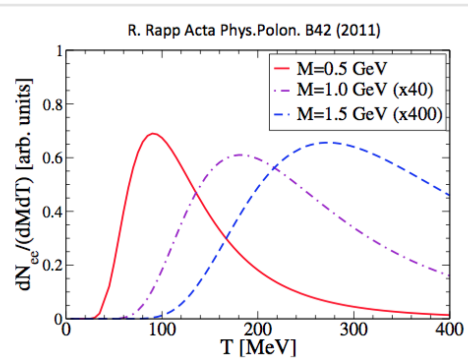
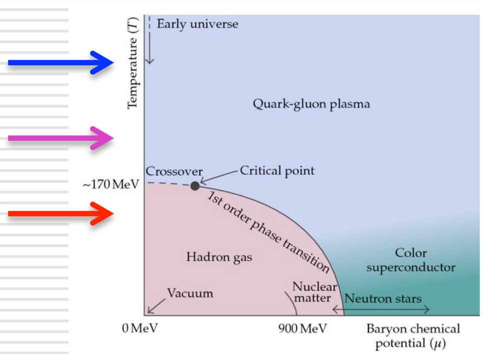
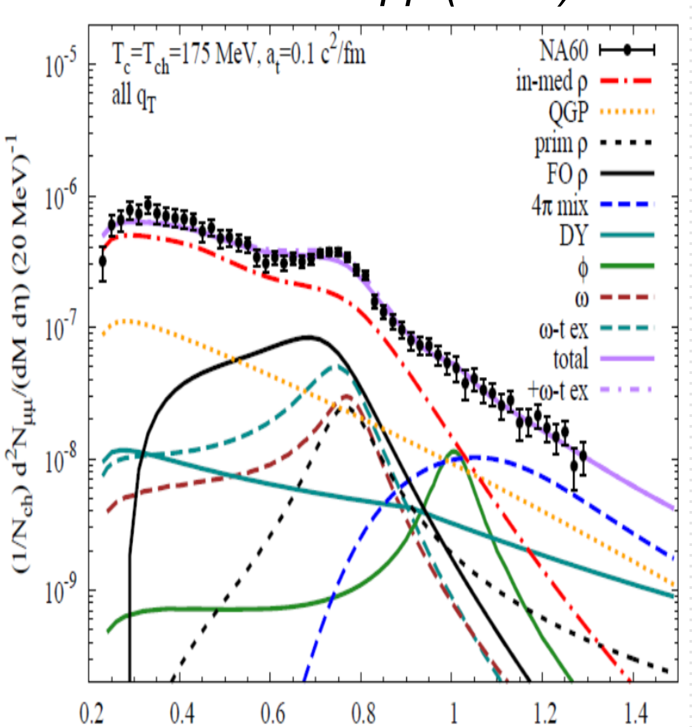




- Gamma virtuali → Studio in funzione di m_{ee}:
  - masse elevate, elevate temperature, primi istanti
  - masse intermedie
  - masse basse, basse temperature, ultime fasi

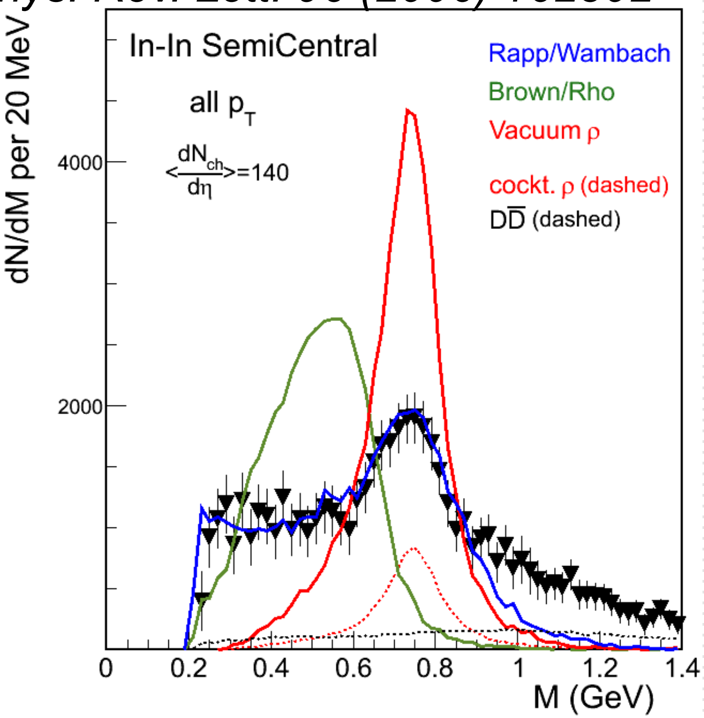
Il mesone ρ: la restaurazione della simmetria chirale

van Hees+Rapp (2008)



data acceptance-corrected
'spectrum directly reflects thermal emission rate' (Rapp)

Phys. Rev. Lett. 96 (2006) 162302

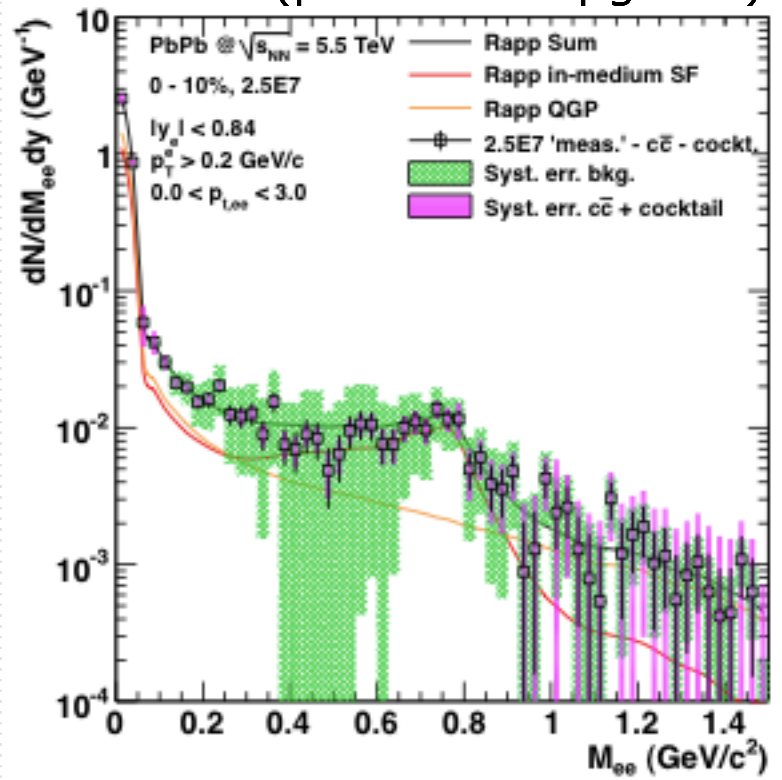


before acceptance correction:
underlying space-time averaged ρ spectral function (purely accidental)

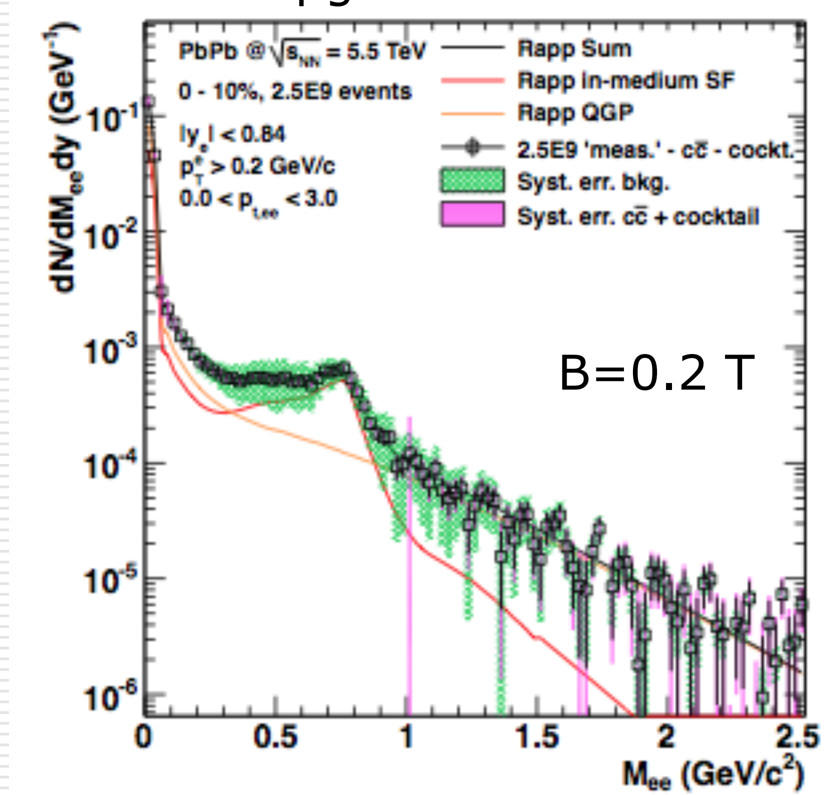
- la miglior misura mai eseguita: NA60 all'SPS
  - si osserva un allargamento della distribuzione di massa invariante della ρ ma non uno shift

I dielettroni di bassa massa

run2 (prima dell'upgrade)



upgrade con 3 nb^{-1}



- con l'upgrade dell'ITS (ed un run dedicato a 0.2 T):
  - precisione sulla "temperatura" del 10%, in funzione di m_{ee}
  - studio della modificazione della ρ

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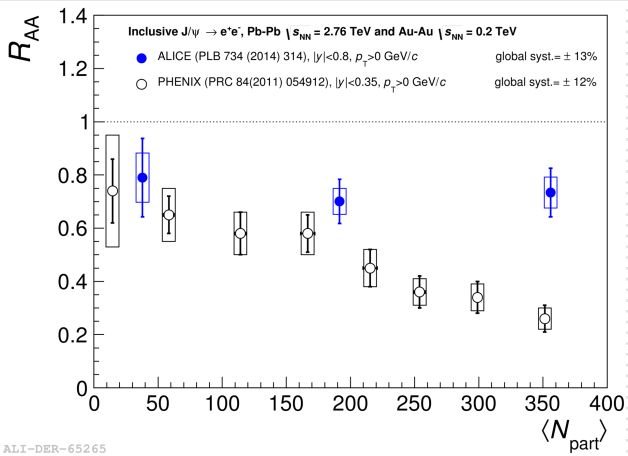
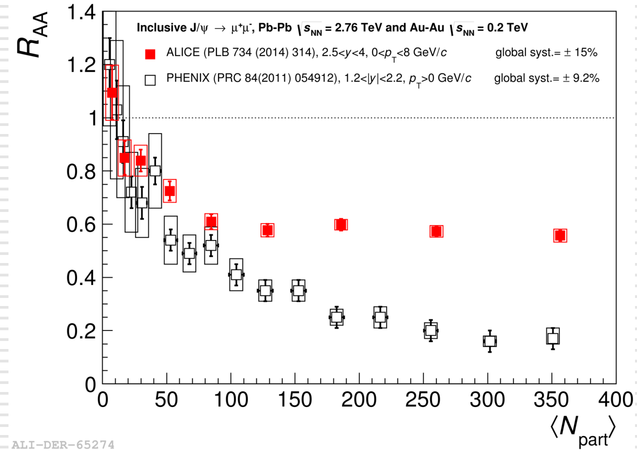
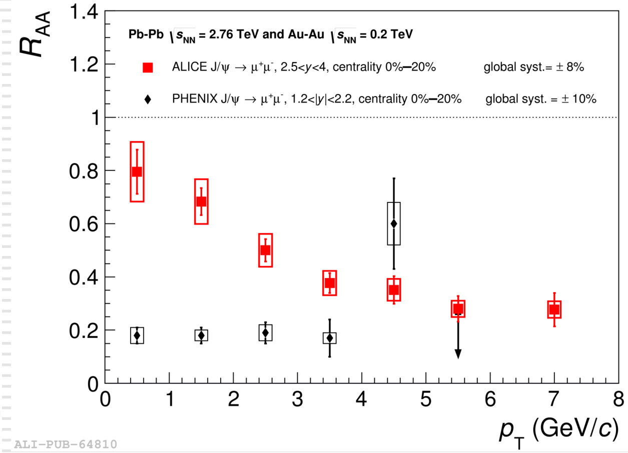
Produzione di charmonio a basso p_t

PLB 743 (2014) 314-327

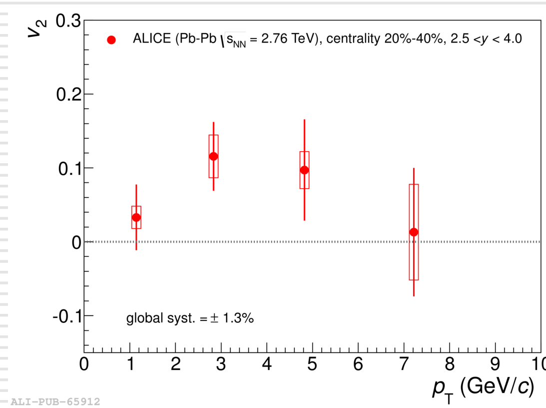






- ☐ In sintesi:
  - ■ ad alti p_t: conferma della soppressione come a più bassa energia
  - ■ a bassi p_t: una frazione sostanziale di J/ψ è prodotta per (ri)combinazione di coppie cc nel QGP o direttamente all'adronizzazione (phase boundary)
- ☐ Sono necessari:
  - ■ uno studio dettagliato di v_2
  - ■ studio del rapporto ψ(2S)/J/ψ
  - ■ studi analoghi a rapidità centrale

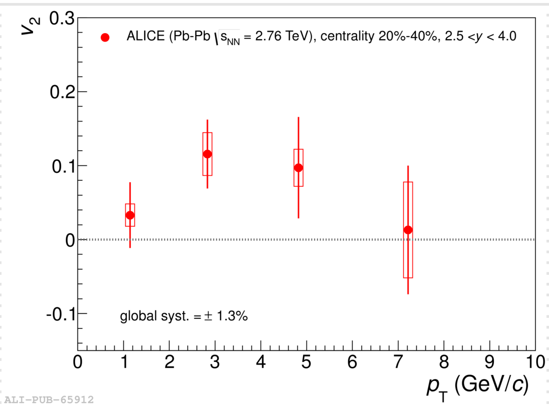
PRL 111 (2013) 162301



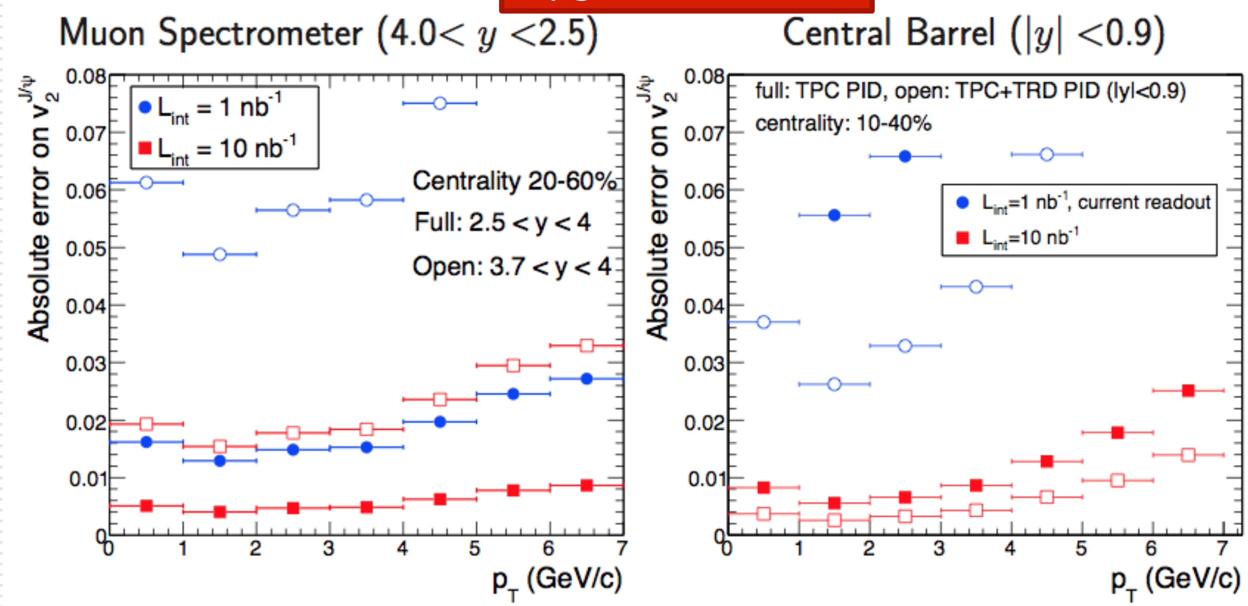
Produzione di charmonio a basso p_t

Misura del coefficiente v_2 per la J/ψ

PRL 111 (2013) 162301



Upgrade di ALICE



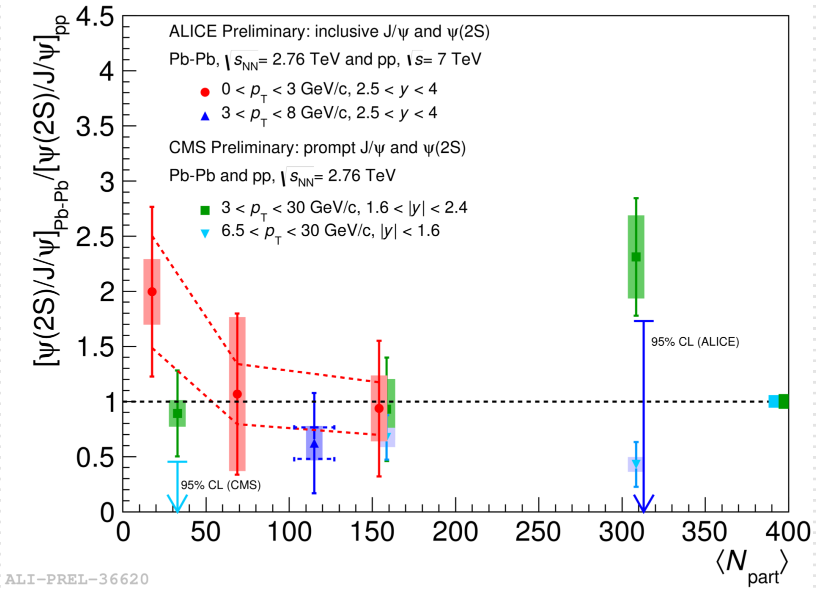
- run1: $v_2>0$? (2.7 σ)

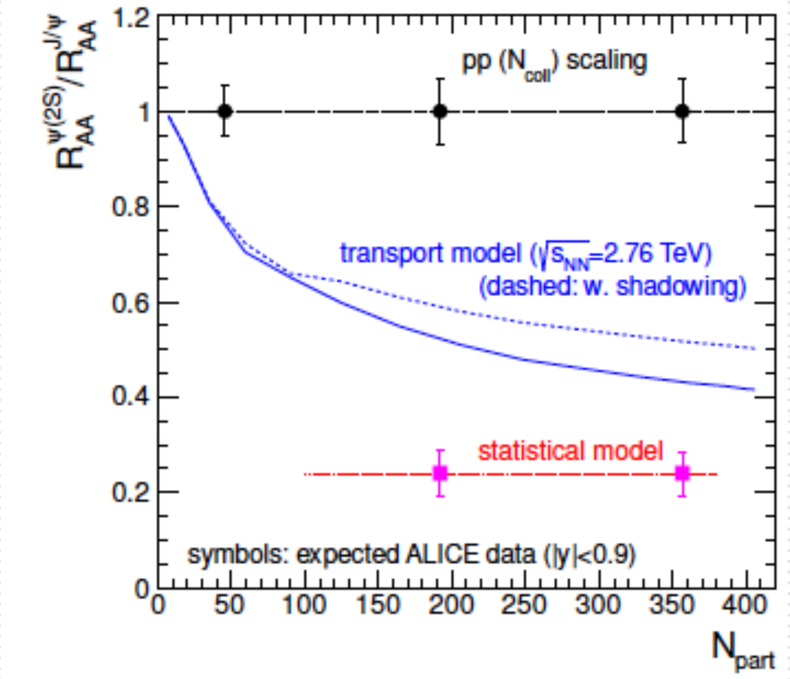
- In assenza di ricombinazione, la J/ψ non dovrebbe presentare flusso ellittico. Le J/ψ ricombinate ereditano il flusso dei quark c
  - con l'upgrade: $v_2(p_t, N_{part}, y)$

→ caratterizzazione dettagliata del meccanismo di ricombinazione

Produzione di charmonio a basso p_t

Misura del (doppio) rapporto ψ(2S)/J/ψ (Pb-Pb/pp) a p_t~0





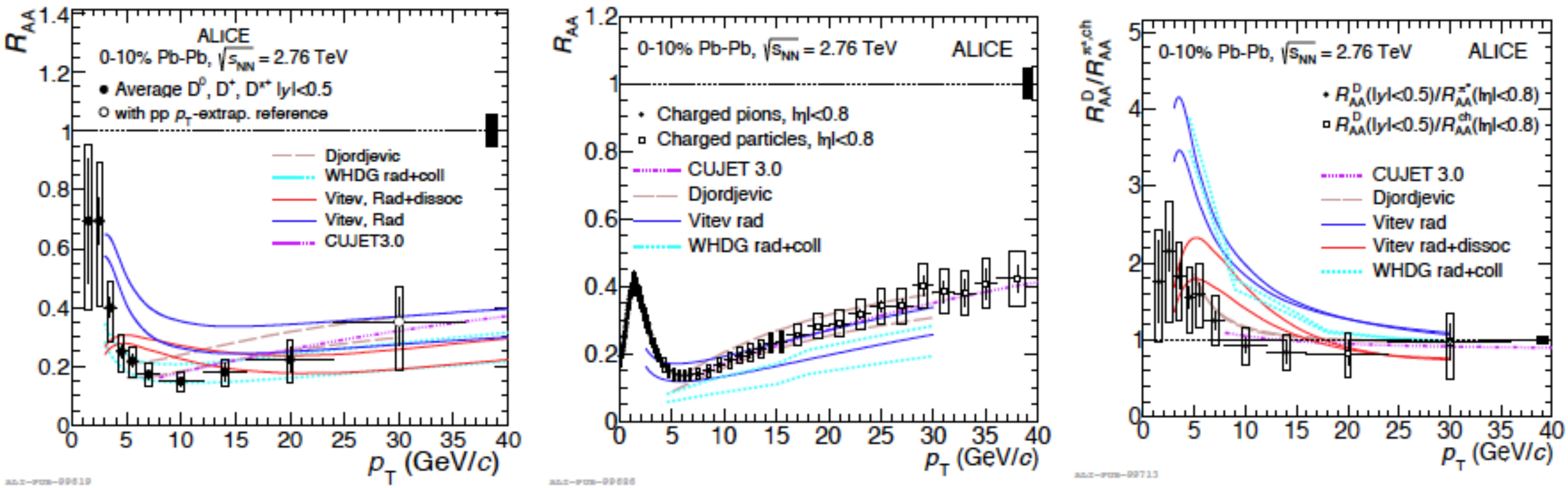
- Situazione attuale caratterizzata da ampie incertezze
- R<1 sia nel modello in cui le J/psi si combinano solo all'adronizzazione (statistical) che nel modello dinamico di trasporto nel QGP
  - l'upgrade permetterà di distinguere tra i due modelli

Conclusioni

- With LHC run2 Heavy Ion physics has entered into the precision era
- 2nd phase of LHC intended to characterize the medium with hard (penetrating) rare probes
- ALICE is upgrading its detector for this aim

Spares

Charm vs. light quarks/gluons



Not trivial to describe both D meson and pion/charged-particle R_{AA} within the same model

- in the ratio of R_{AA} predictions, uncertainties on the medium density/temperature cancel
- the model by Djordjevic and CUJET 3.0 do it over the whole momentum range they cover
- the version of Vitev model with radiative-only energy loss does not describe the data

Model references

– POWLANG: EPJ C 75 (2015) 121;
– TAMU: arXiv:1401.3817;
– MC@HQ+EPOS: PRC 89 (2014) 014905;
– WHDG: Nucl. Phys. A 872 (2011) 256;
– BAMPS: PLB 717 (2012) 430;
arXiv:1310.3597v1[hep-ph];
– Cao,Quin, Bass: PRC 88 (2013);
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arXiv:1411.3673 [hep-ph].
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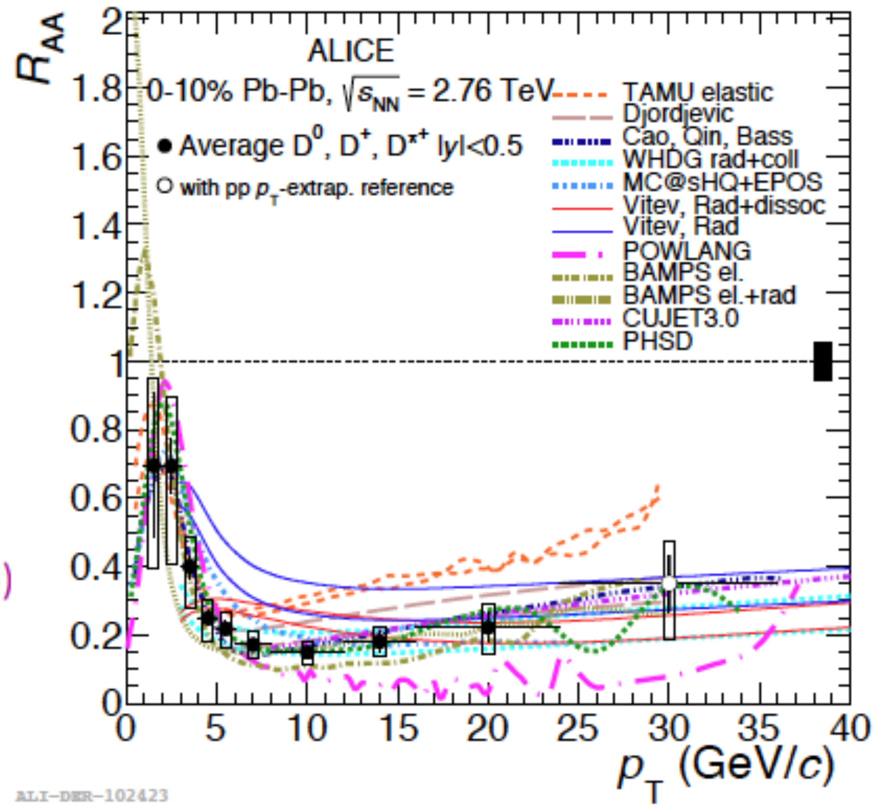
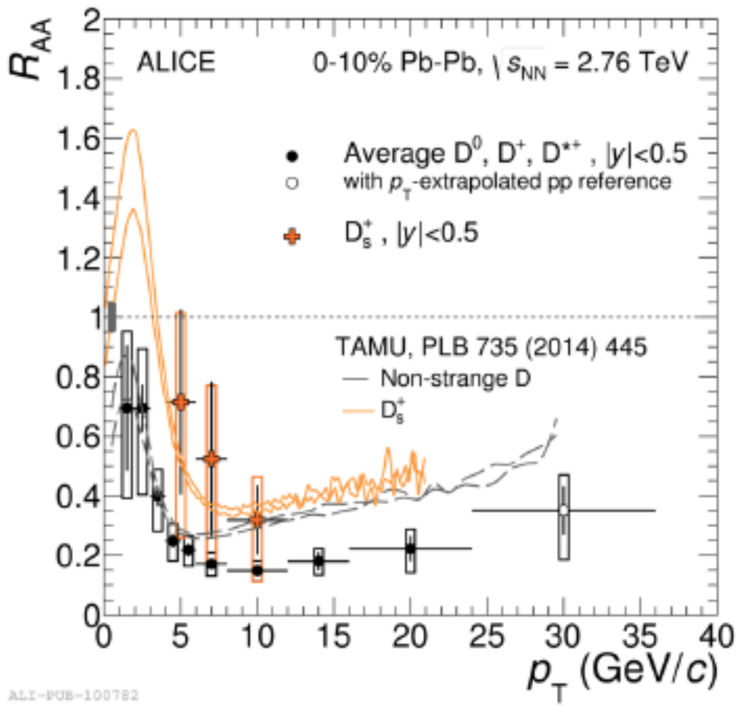


D_s vs. non-strange D mesons

ALICE, JHEP1603 (2016) 081
ALICE, JHEP1603 (2016) 082



- D_s in Pb-Pb: similar suppression than non-strange D mesons in 8-12 GeV/*c*
- **$R_{AA}(D_s) > R_{AA}(D^0, D^+, D^{*+})$ at low p_T? More statistics needed**
  - Important for constraining quark coalescence models

Kuznetsova, Rafelski, EPJ C 51 (2007) 113
He, Fries, Rapp, PLB 735 (2014) 445

Key measurement for run 2 and run 3.