Probing the QCD matter with ALICE

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on behalf of the ALICE Collaboration

Disclaimer: This is a biased Selection of ALICE results

– XLII International Meeting on Fundamental Physics –

Outline

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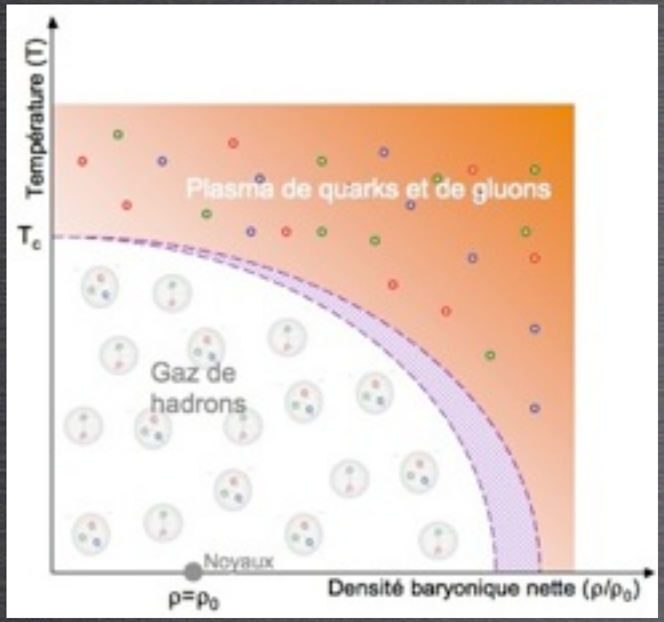

Probing the QCD matter, why and how?

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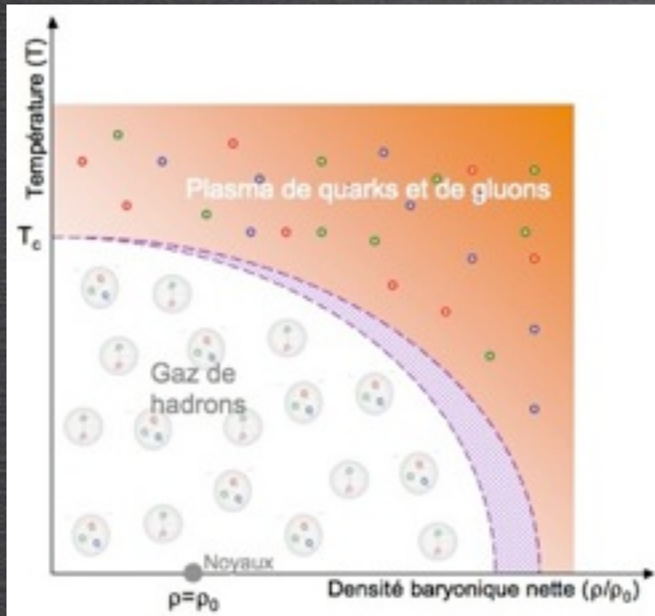

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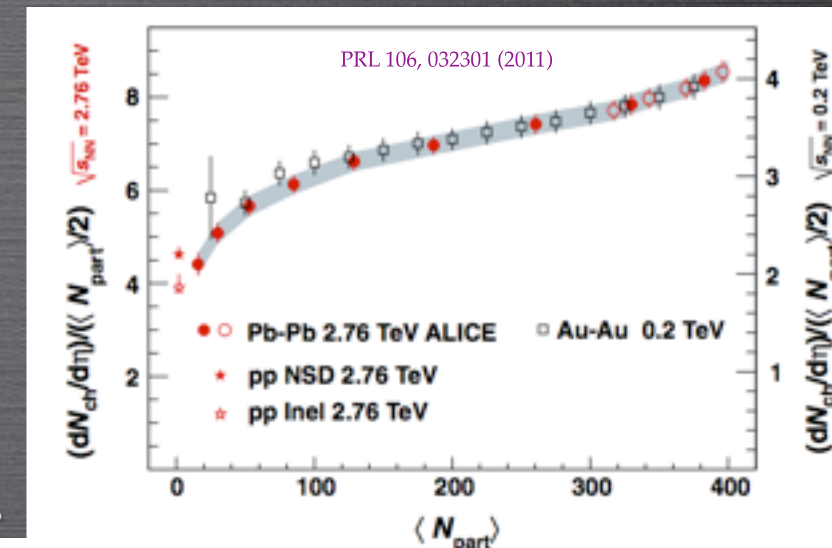
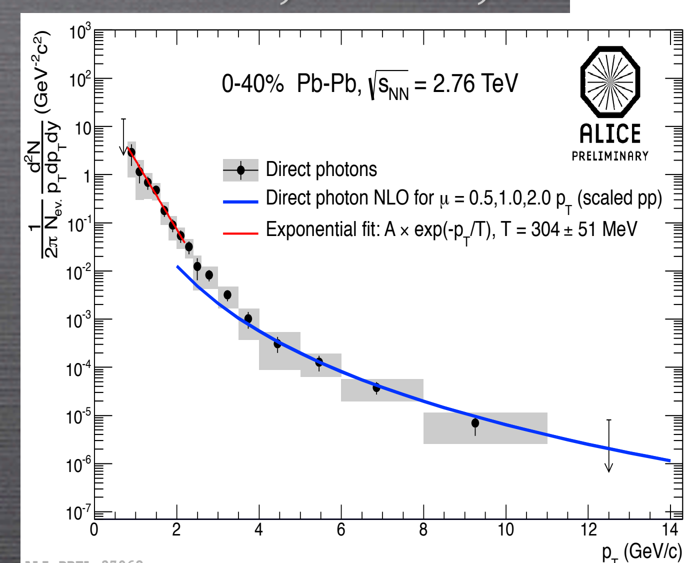
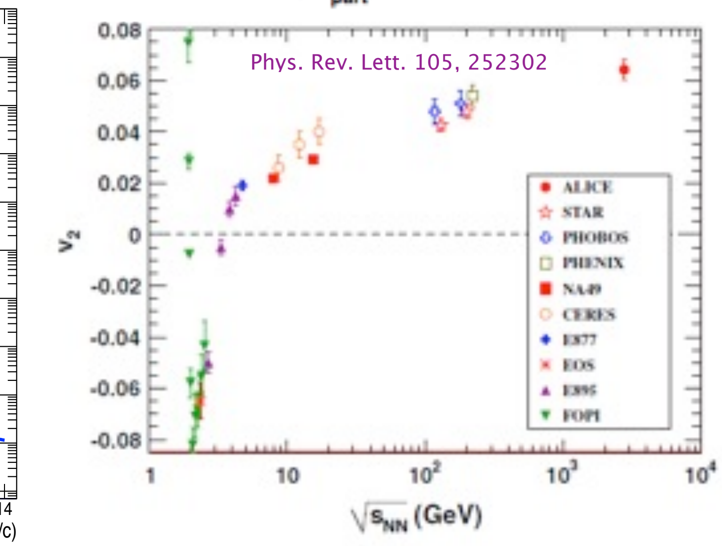


Studying the bulk properties

Charged Particles, Transverse energy, Flow,...





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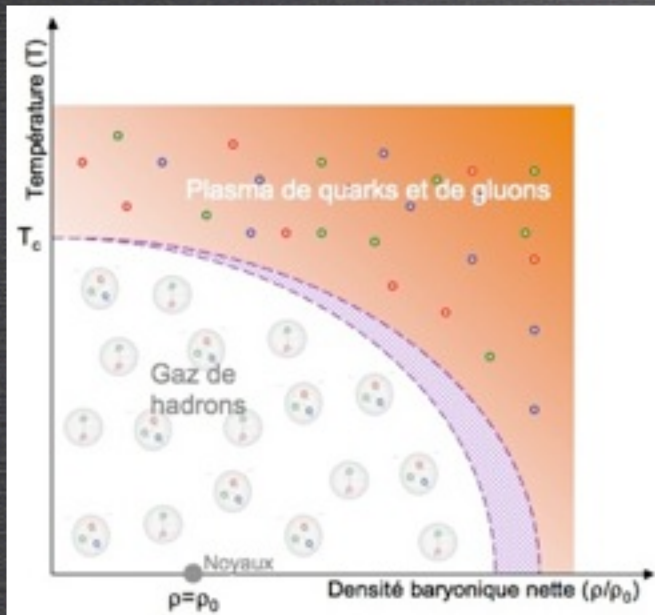

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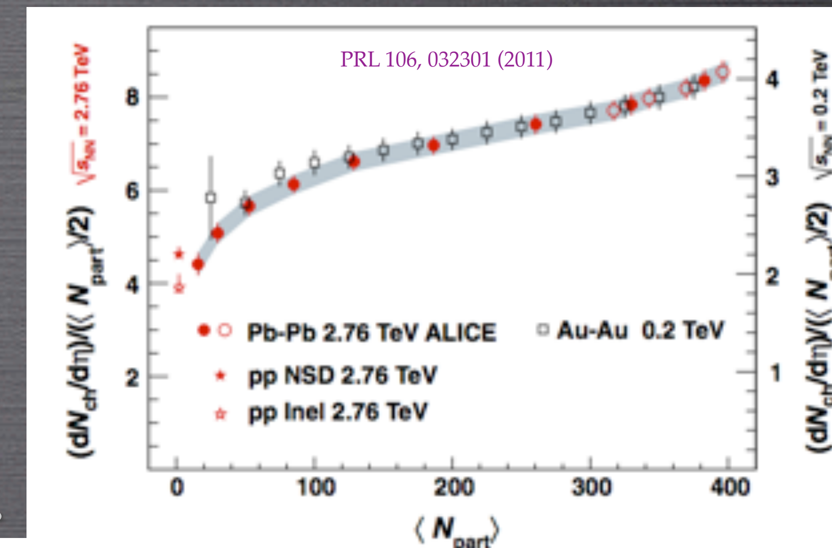

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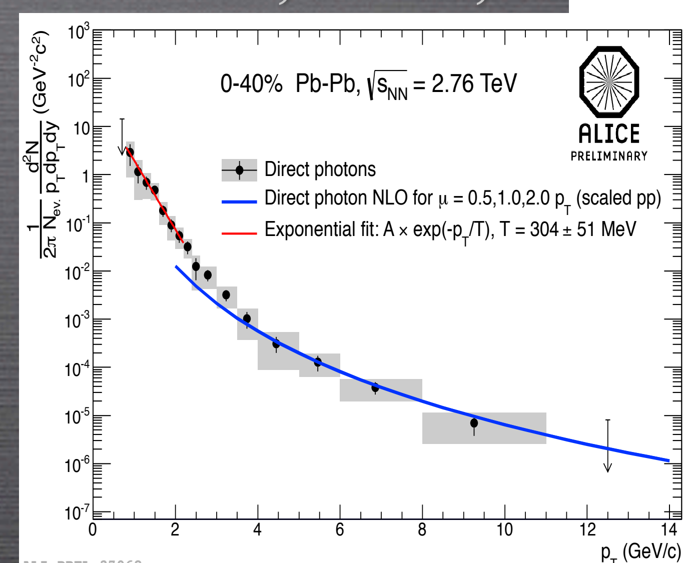
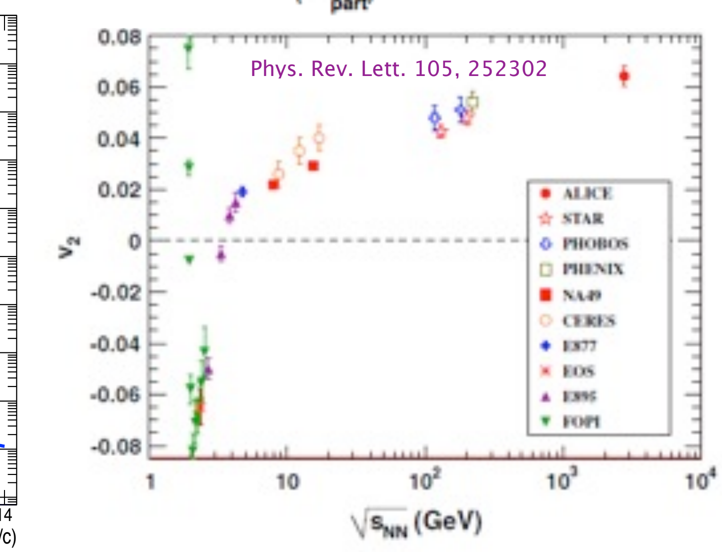
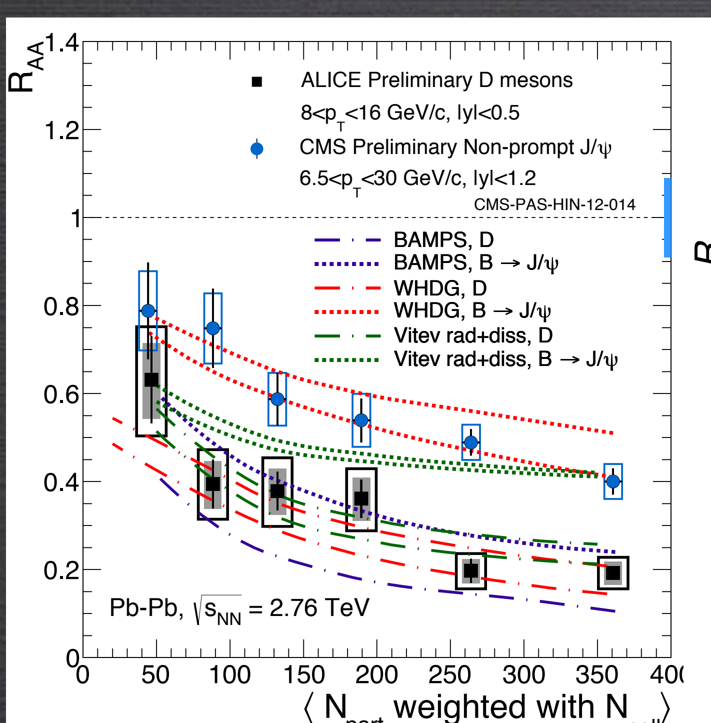
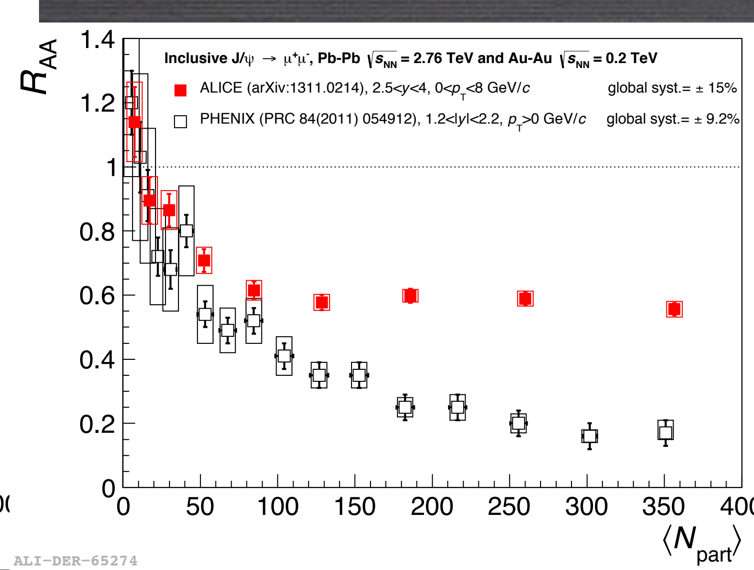




Heavy Flavor & Quarkonia



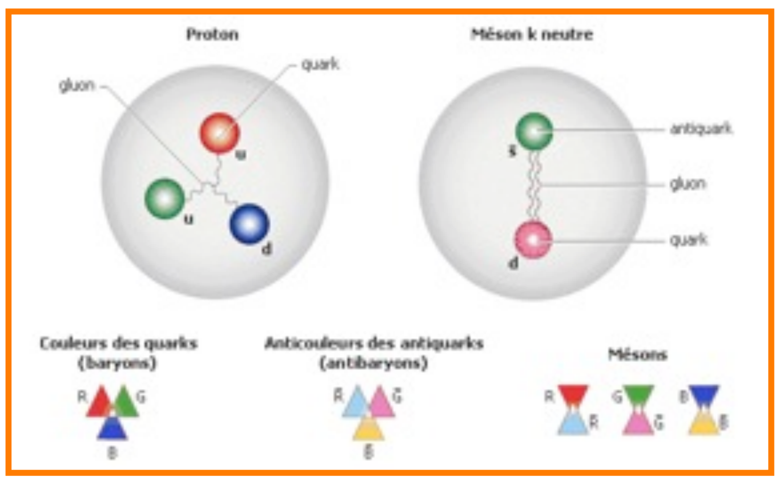


Probing the QCD matter: Why and How ?

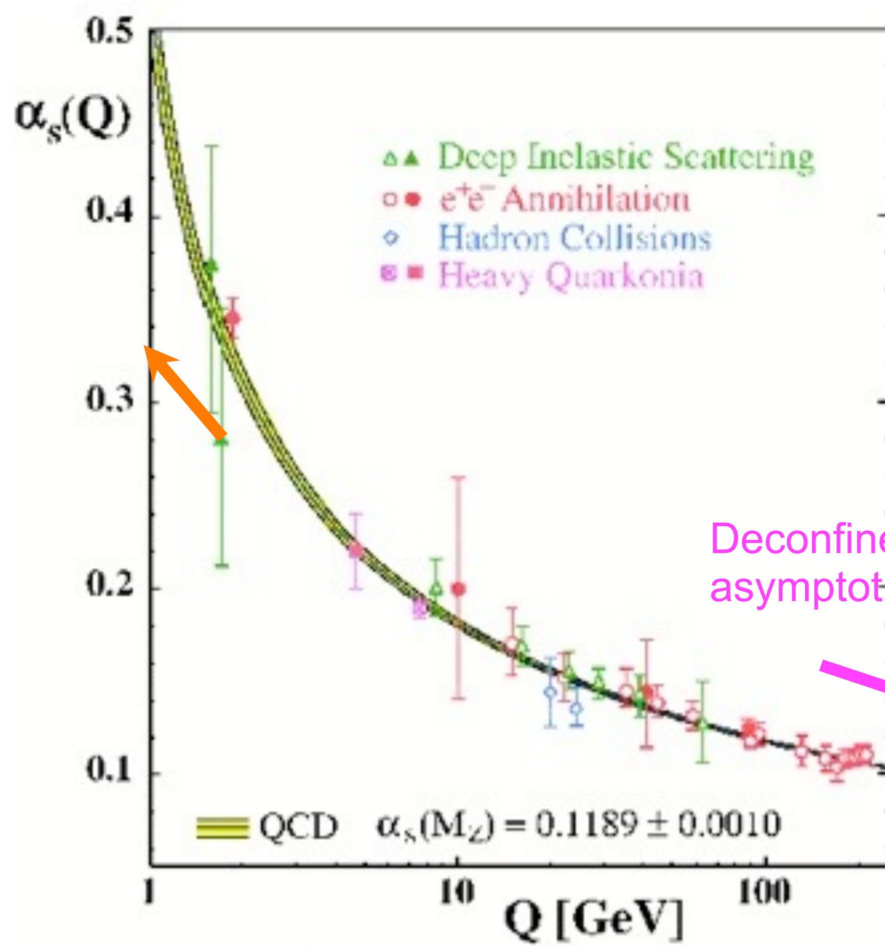
- Quantum ChromoDynamics vs Quantum ElectroDynamics
  - Mediator: gluon (color charge) vs photon (no charge)
  - Asymptotic freedom, vacuum polarization: in QED there is screening, and in QCD there is also anti-screening.
  - Confinement: In the nature, quarks and gluons are confined in neutral color states, the mesons and the baryons.

$$\alpha_{QED}(Q^2) = \frac{\alpha_{em}}{1 - \frac{\alpha_{em}}{3\pi}\ln(\frac{Q^2}{m^2})}$$

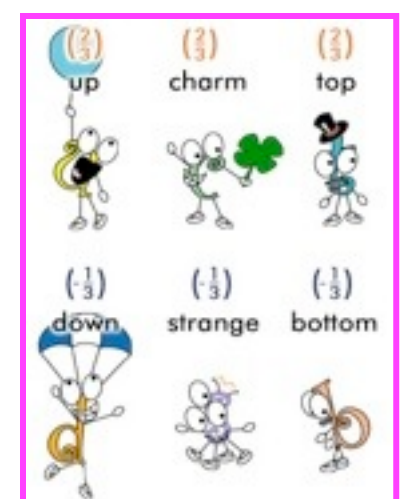
$$\alpha_{QCD}(Q^2) = \alpha_s(Q^2) = \frac{4\pi}{(11 - \frac{2}{3}n_f)\ln(\frac{Q^2}{\Lambda^2_{QCD}})}$$



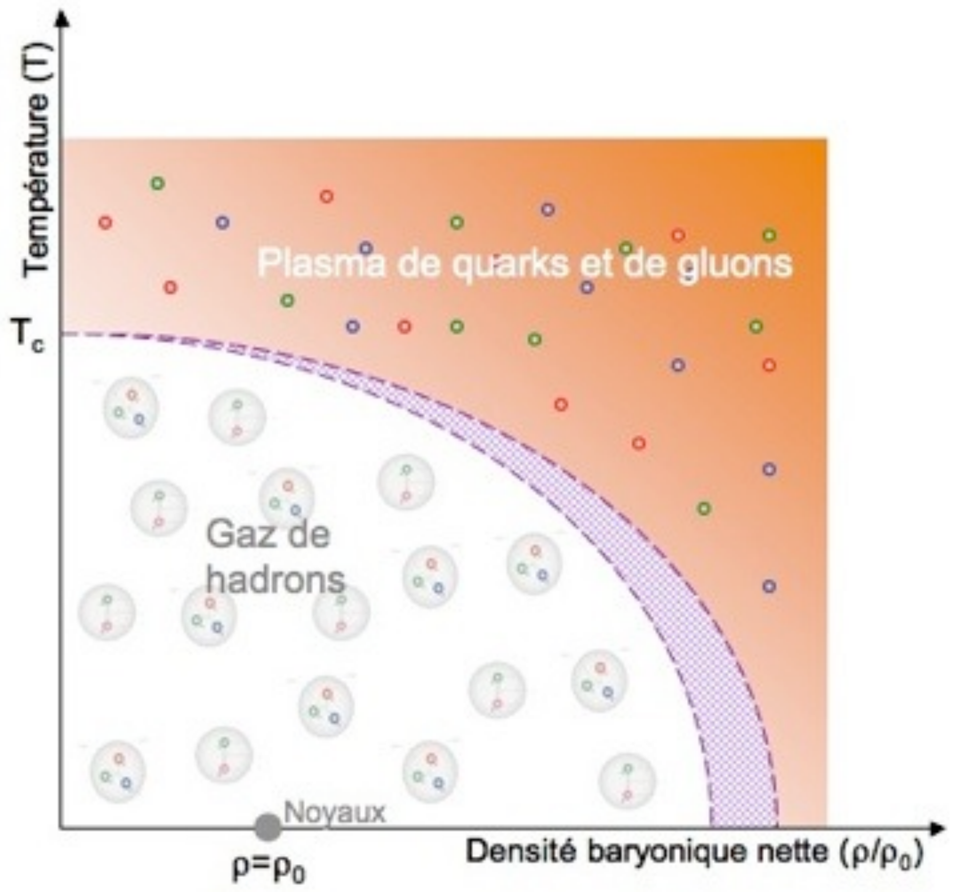
Confinement



Deconfinement: asymptotic freedom

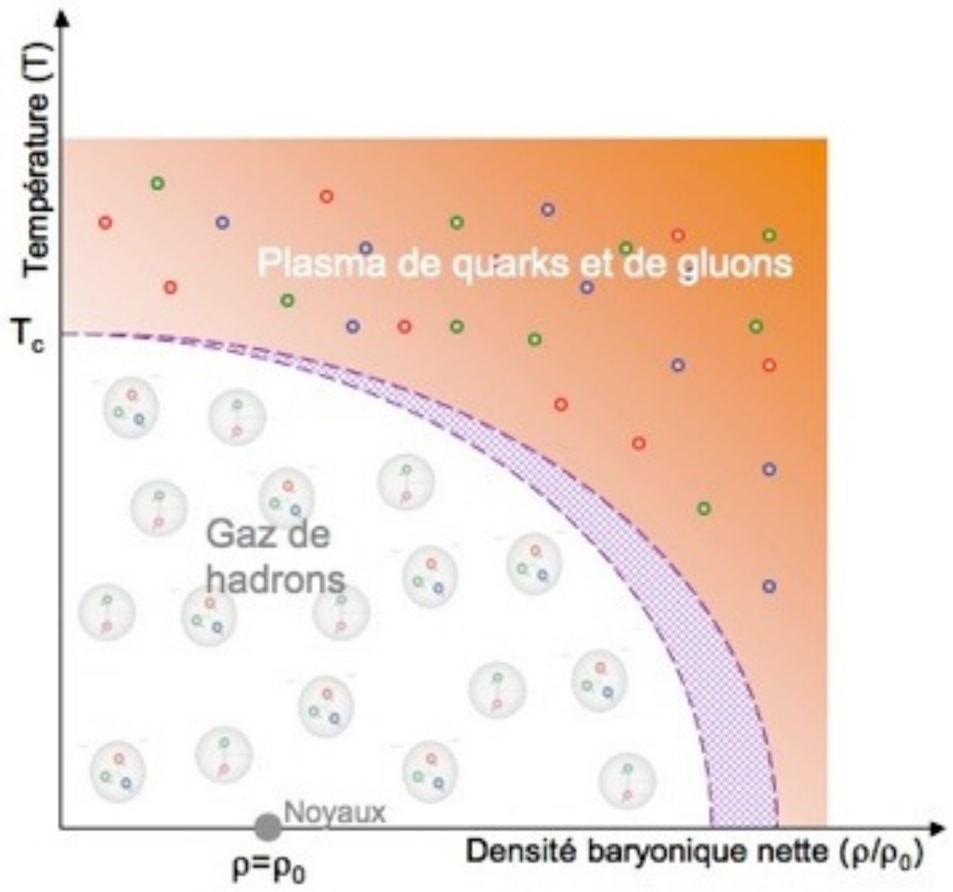


The Quark Gluon Plasma



- ρ_B = 1, T ~ 0
  - Nuclei
- $\rho_B \uparrow$, T ~ 0
  - Neutron star cores
- ρ_B = 0, T$\uparrow$
  - T_c~ 170-194MeV, ε_c~ 0.8GeV/fm^3
  - Cross-over transition
  - Quark gluon plasma

The Quark Gluon Plasma

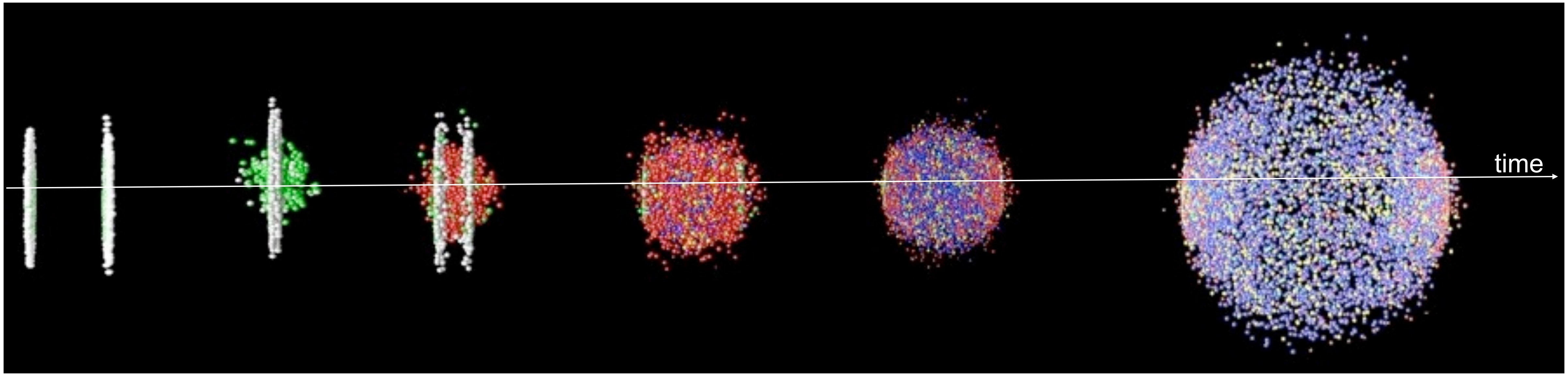


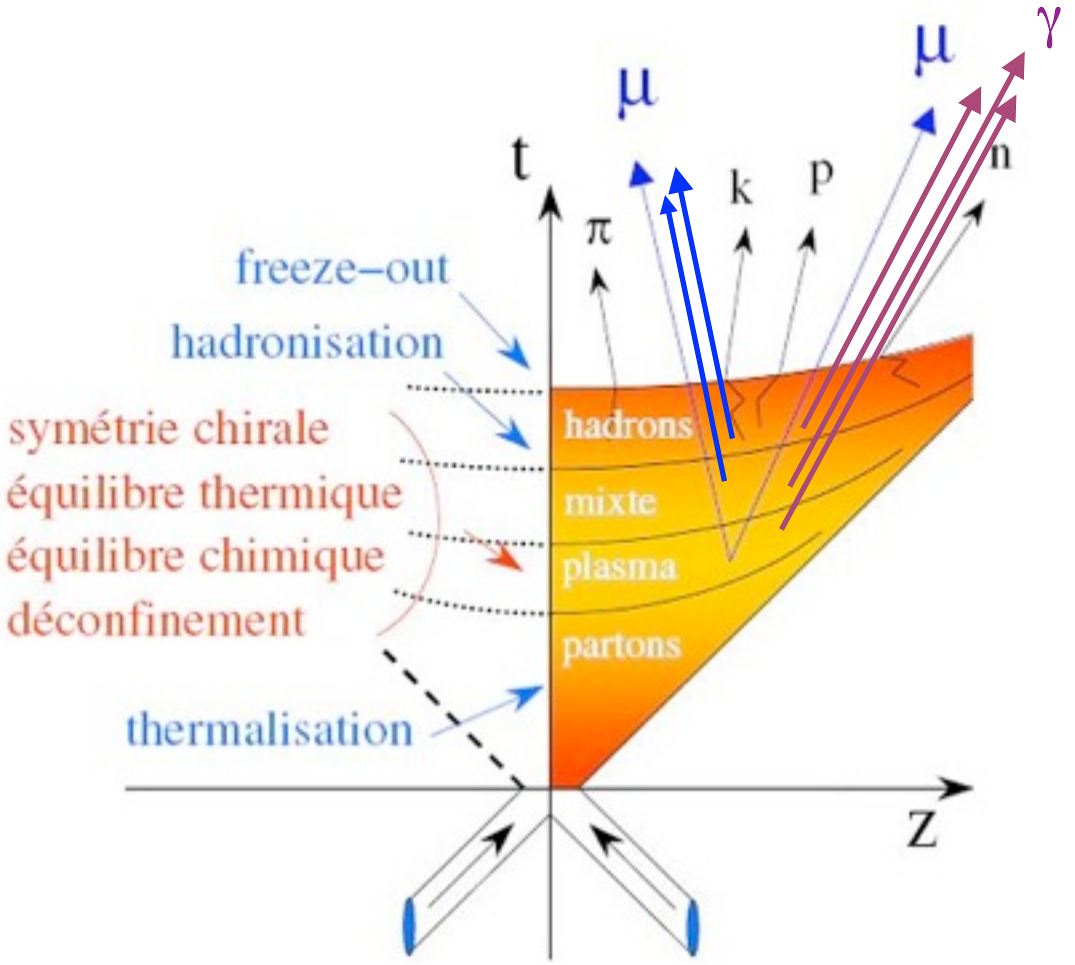
- $\rho_B = 1$, $T \sim 0$
  - Nuclei
- $\rho_B \uparrow$, $T \sim 0$
  - Neutron star cores
- $\rho_B = 0$, $T\uparrow$
  - T_c~ 170-194MeV, ε_c~ 0.8GeV/fm^3
  - Cross-over transition
  - Quark gluon plasma

"When the energy density ε exceeds some typical hadronic value (~ 1 GeV/fm^3), **matter no longer exists of separate hadrons (protons, neutrons, etc), but as their fundamental constituents, quarks and gluons**. Because of the apparent analogy with similar phenomena in atomic physics we may call this phase of matter the QCD (or Quark Gluon) plasma."
E.V. Shuryak, Phys. Rept. 61 (1980) 71

"Above Tc, the medium consists of deconfined quarks and gluons. We emphasize that **deconfinement does not imply the absence of interaction – it is only the requirement to form color neutral bound states that has been removed**." H. Satz, J.Phys.G32:R25 (2006)

Relativistic Heavy Ion Collisions





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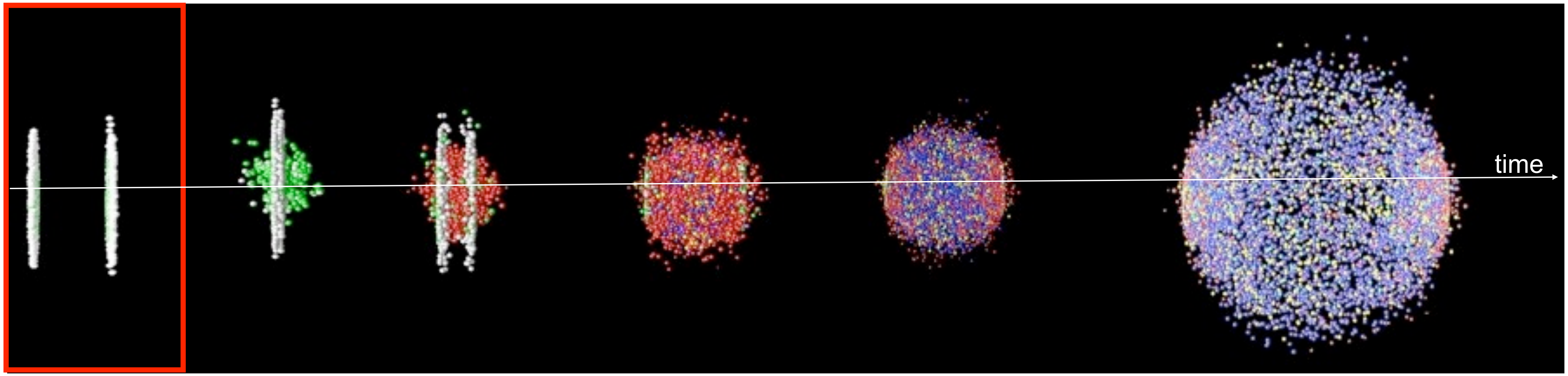

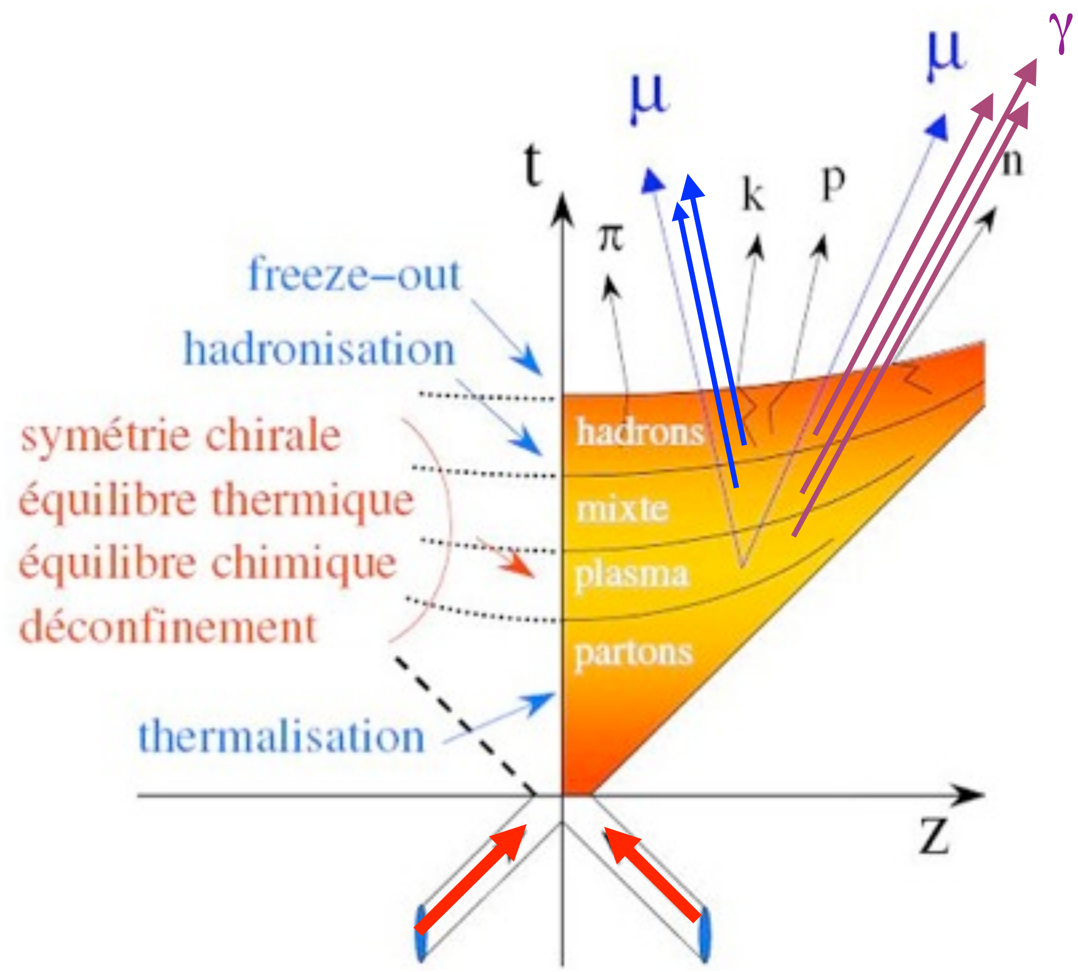

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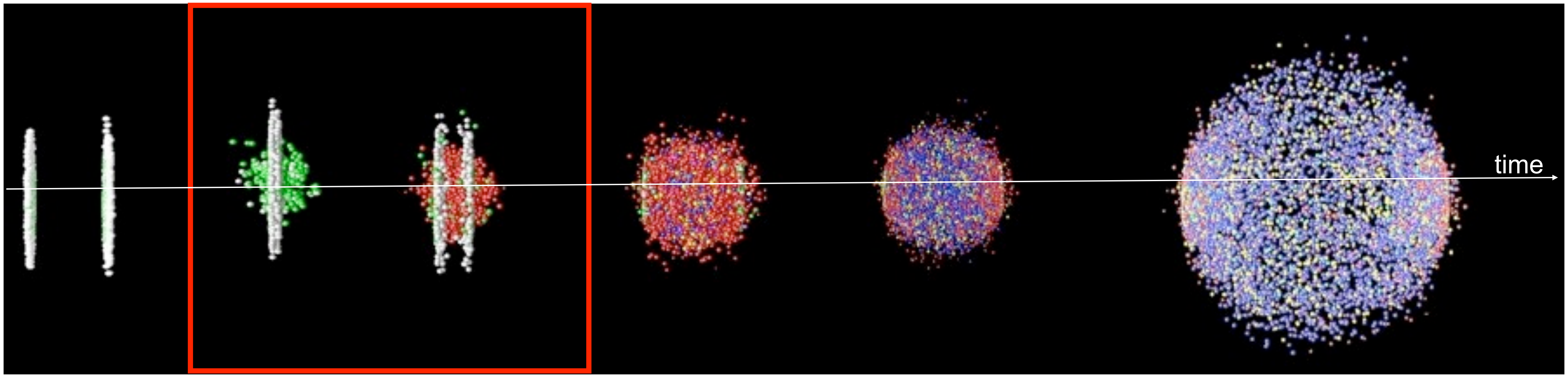

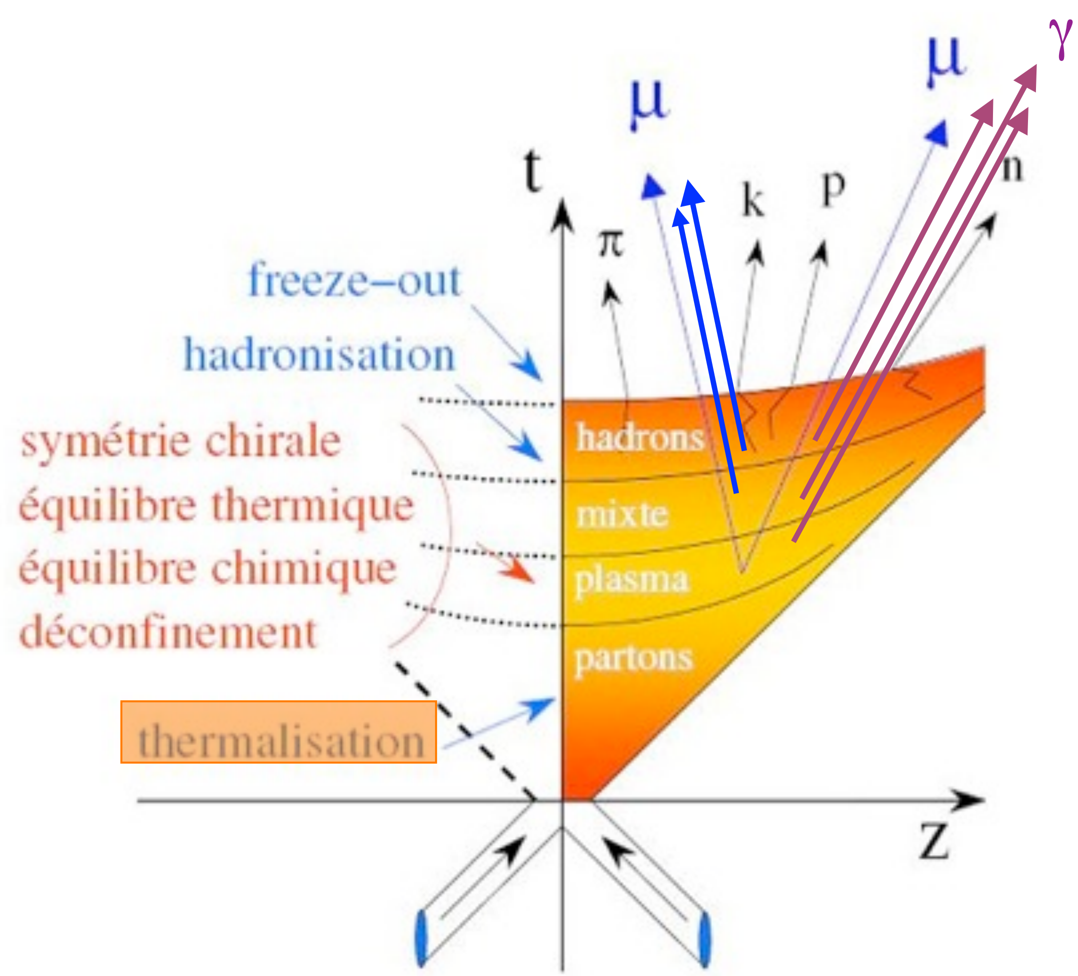

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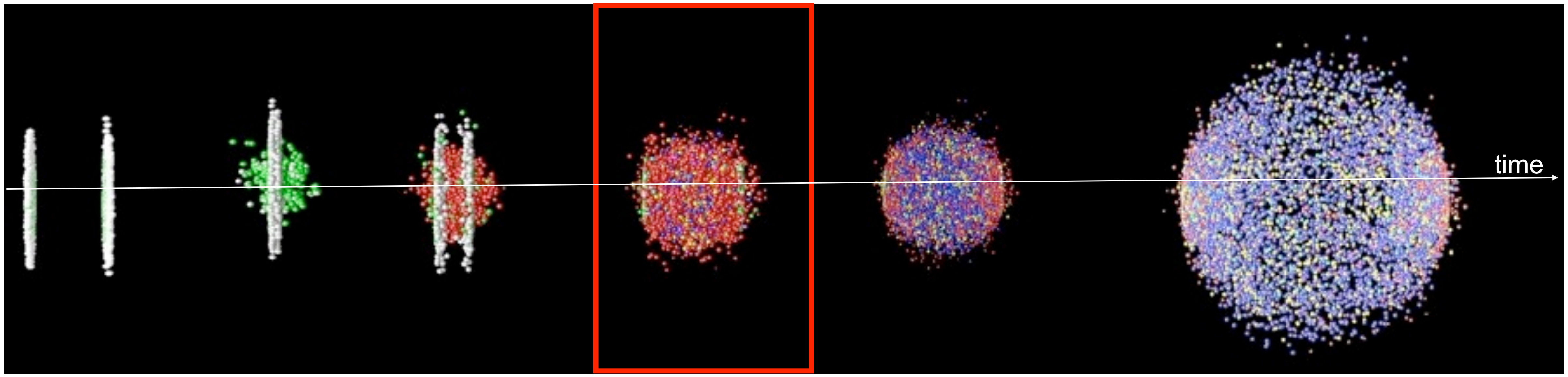

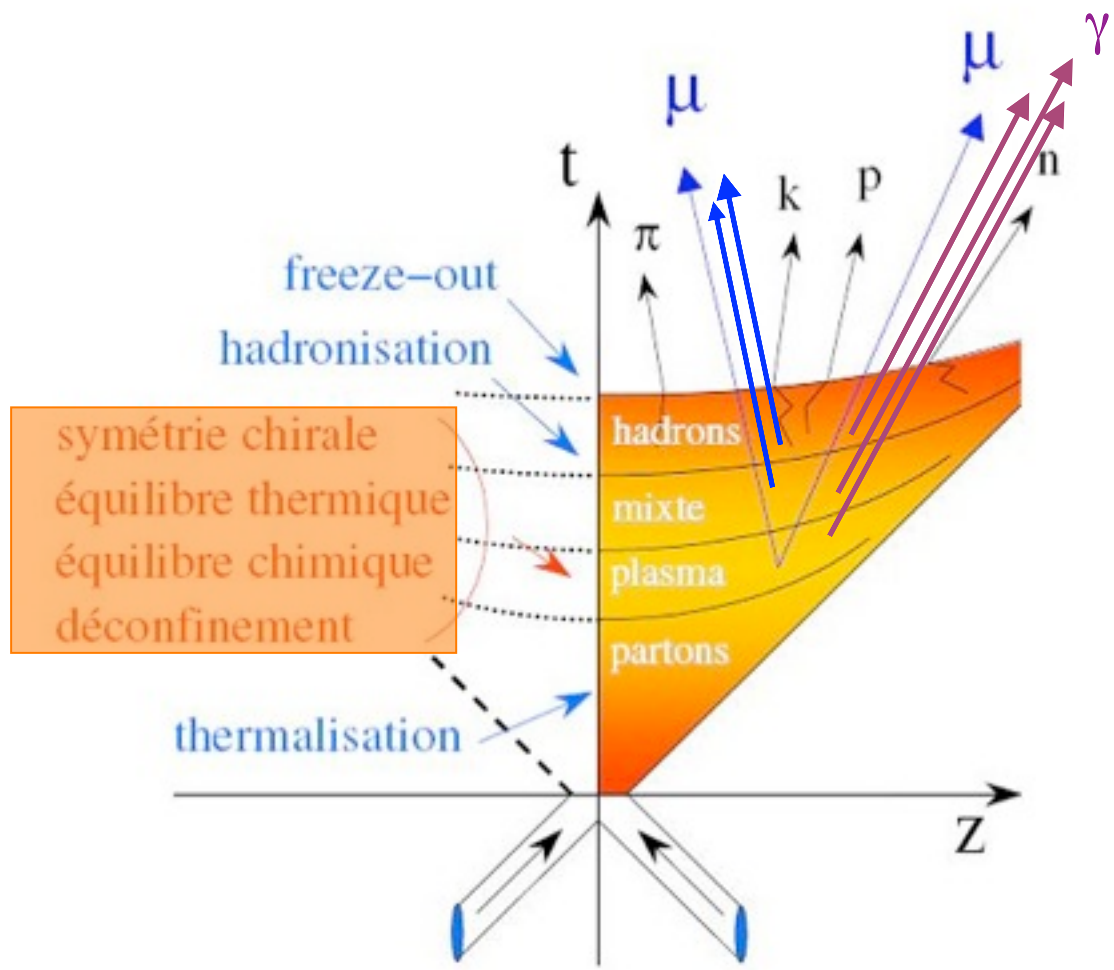

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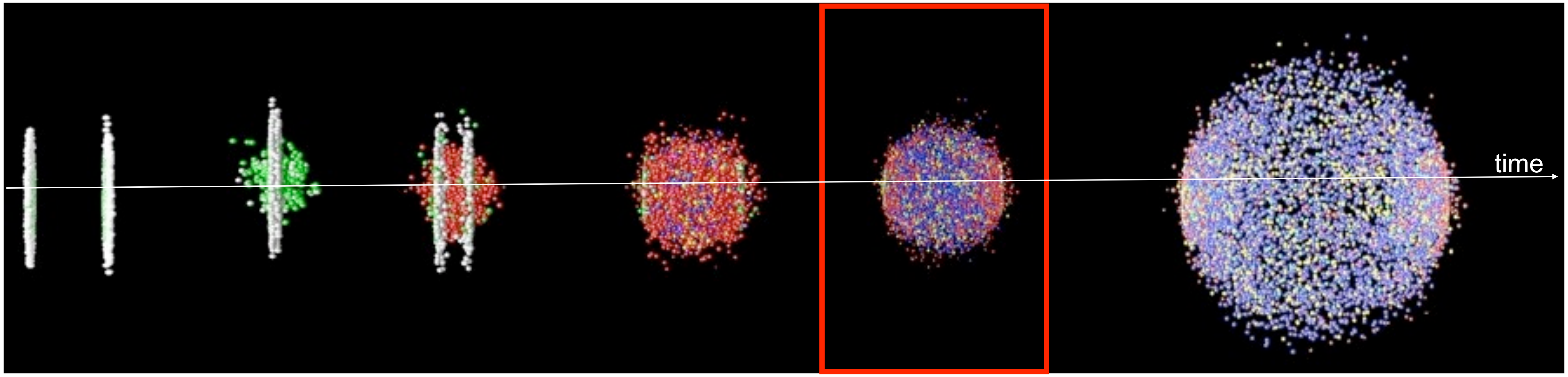

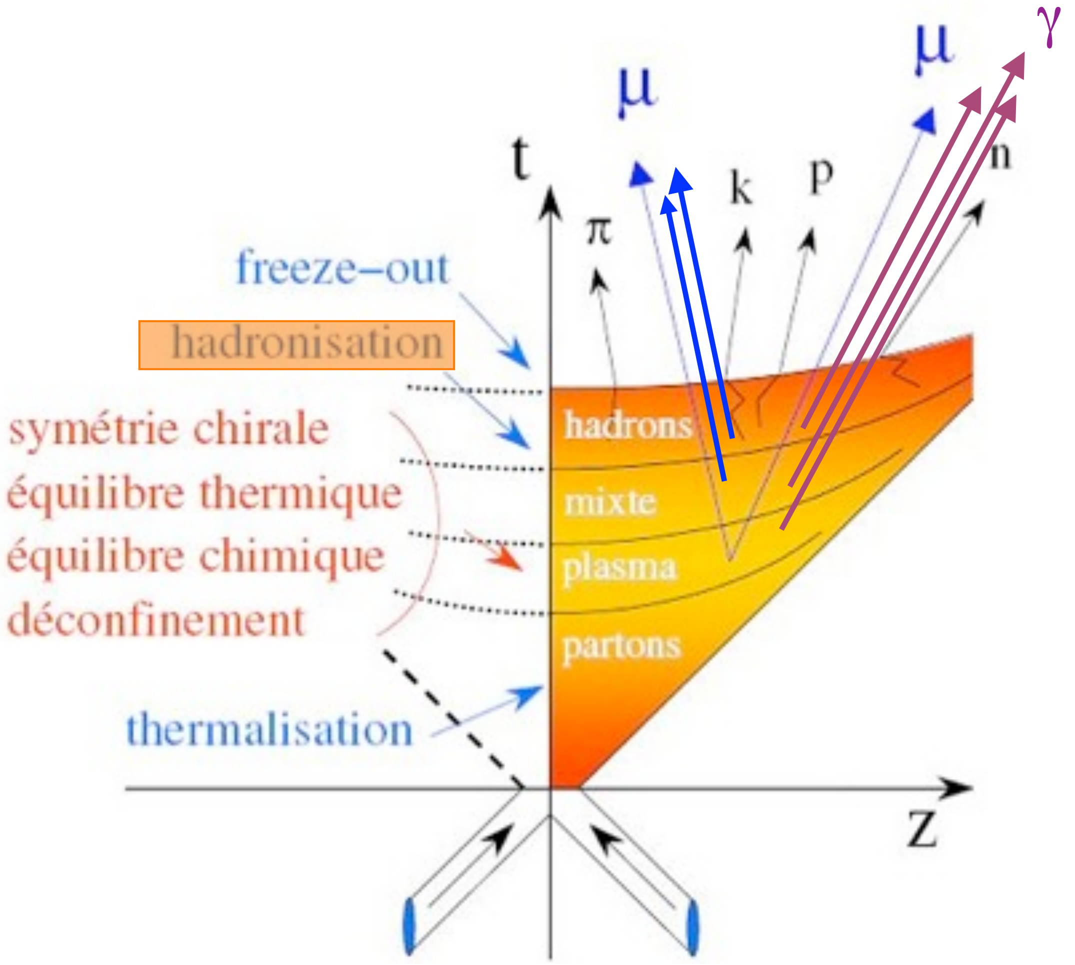

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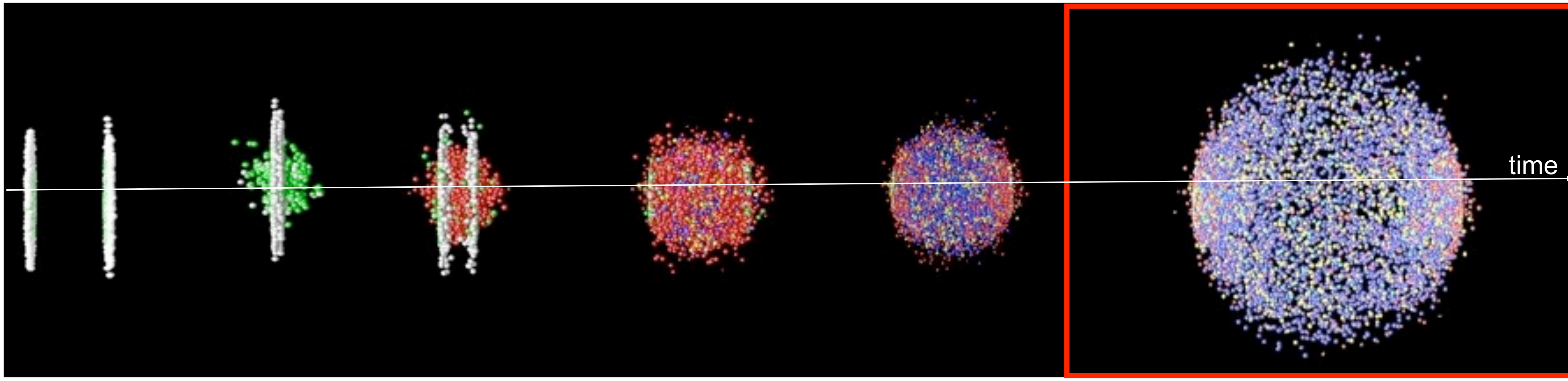

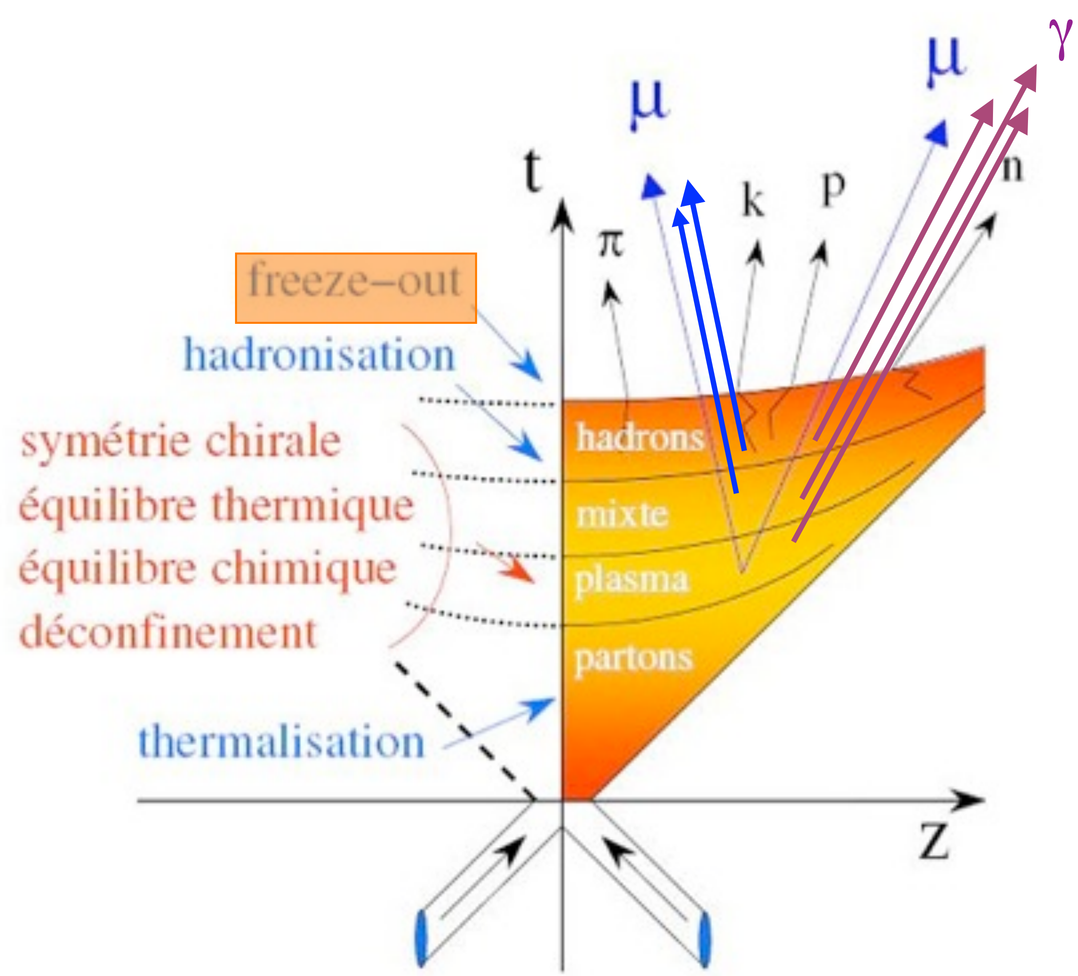

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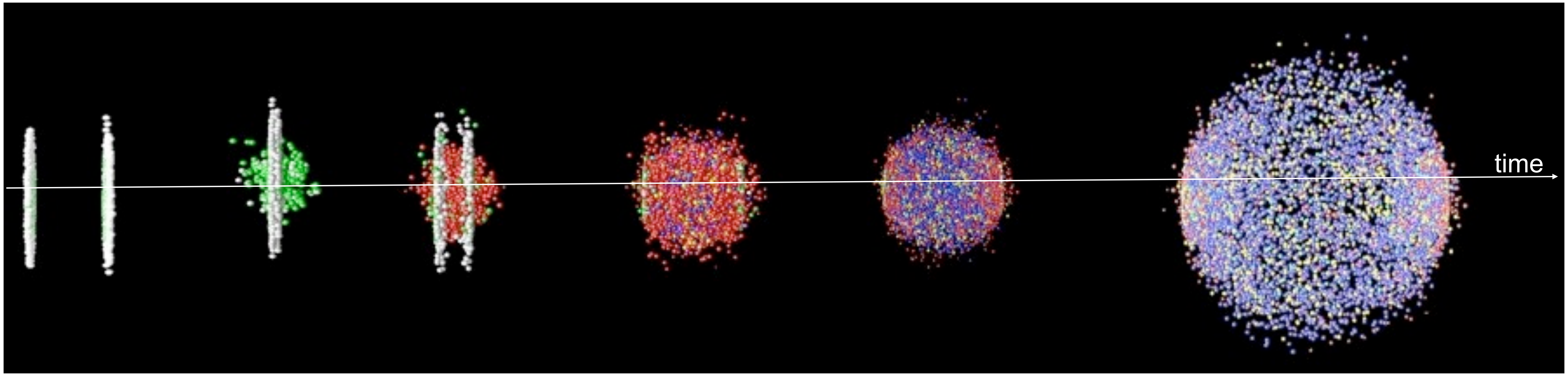
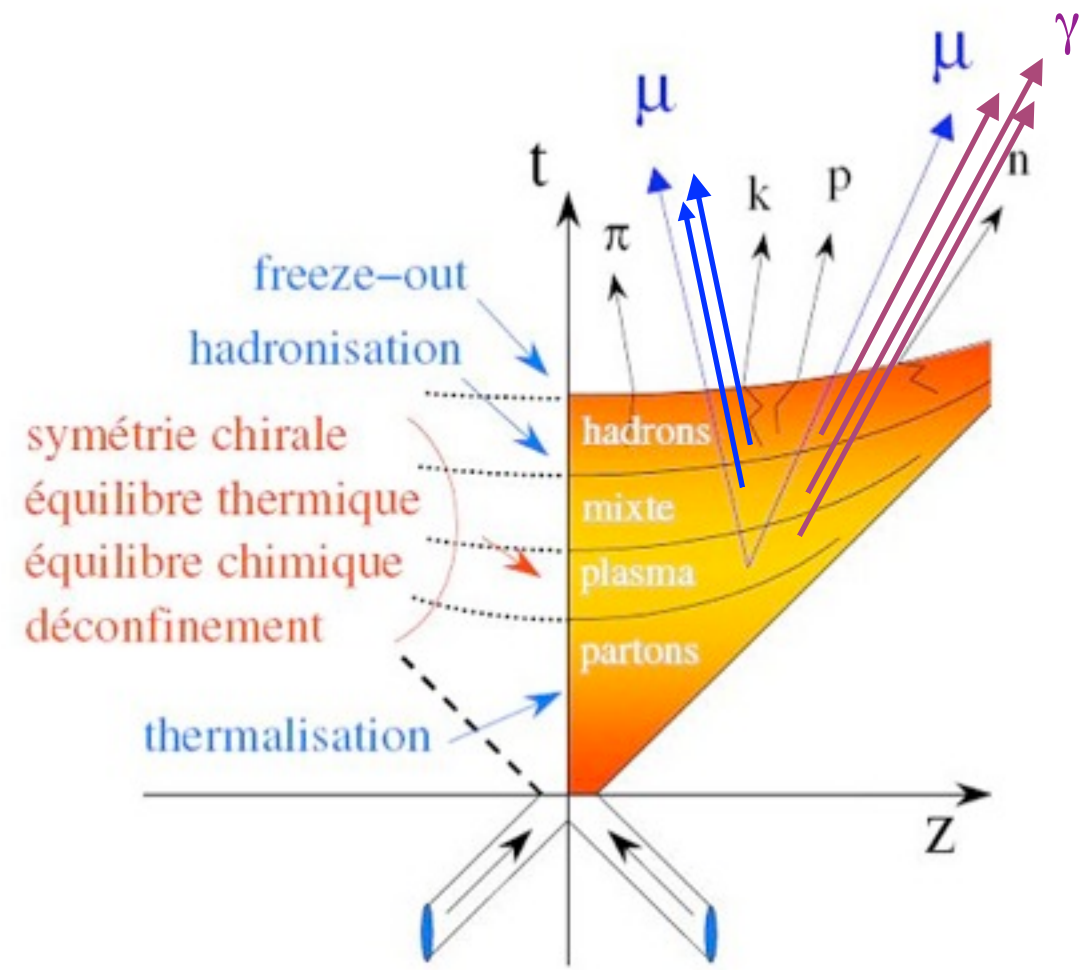


- Experimental observables:
  - Global: centrality, particle multiplicity, E_T,…
  - Initial state: high-p_T photons, weak bosons (W & Z),…
  - Final state:
    - Hadronic: p_T & η distributions, strange particles, particle correlations, the flow,…
    - Penetrating: vector mesons, quarkonia, jets,…



A rough How To Guide

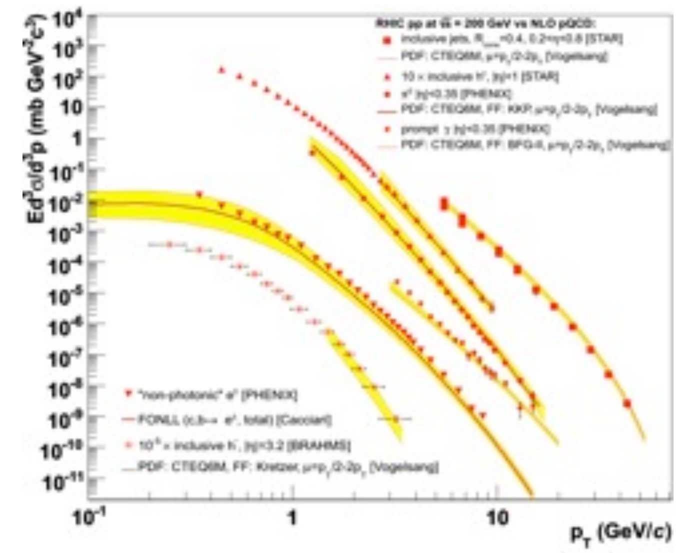
A rough How To Guide

$\varepsilon \ll \varepsilon_C$
$T \ll T_C$

① Identify an observable which might be modified in the presence of a QGP (by theoretical basis).

② Measure the observable in absence of medium effects, in p-p coll.

- The baseline. Confront with theoretical predictions: the QCD reference?



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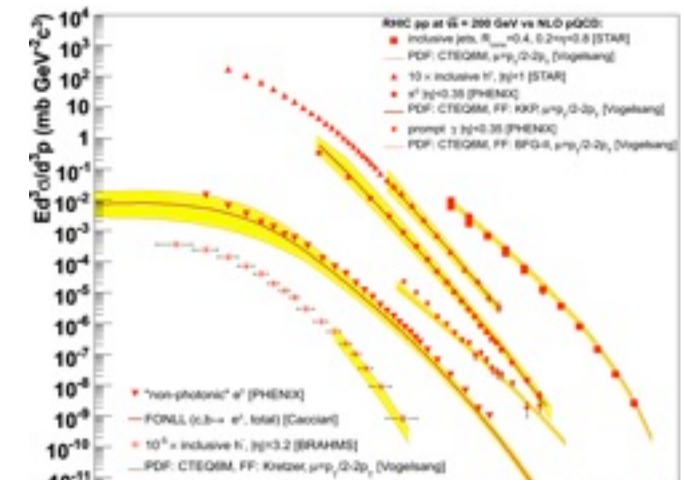
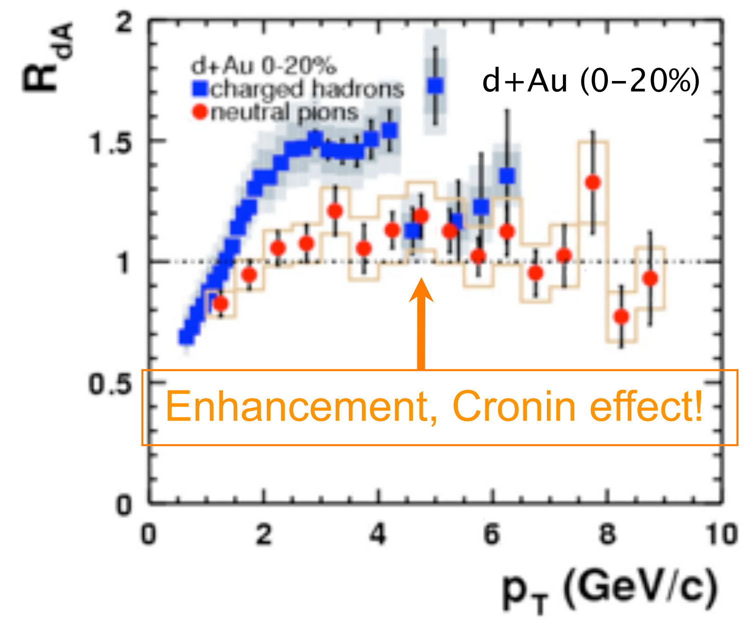


$\varepsilon < \varepsilon_C$
$T < T_C$

③ Measure it in the presence of a cold nuclear environment, in p-A and/or d-A coll.
- Need to elucidate (between others…):
  - Modification of PDFs
  - Gluon saturation
  - Colour charge screening



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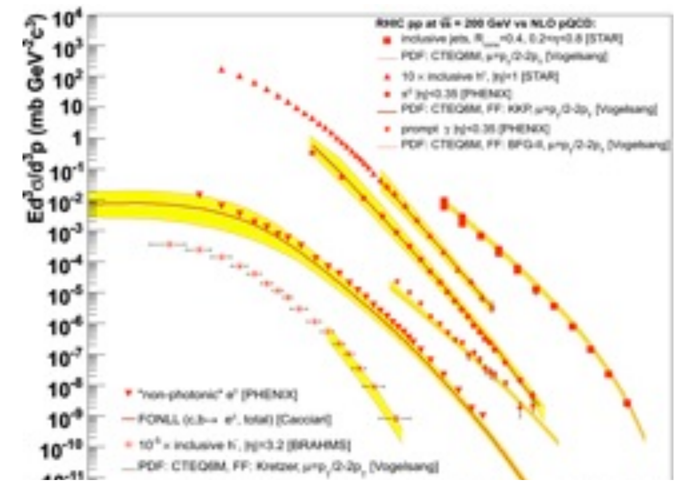

② Measure the observable in absence of medium effects, in p-p coll.
- The baseline. Confront with theoretical predictions: the QCD reference?

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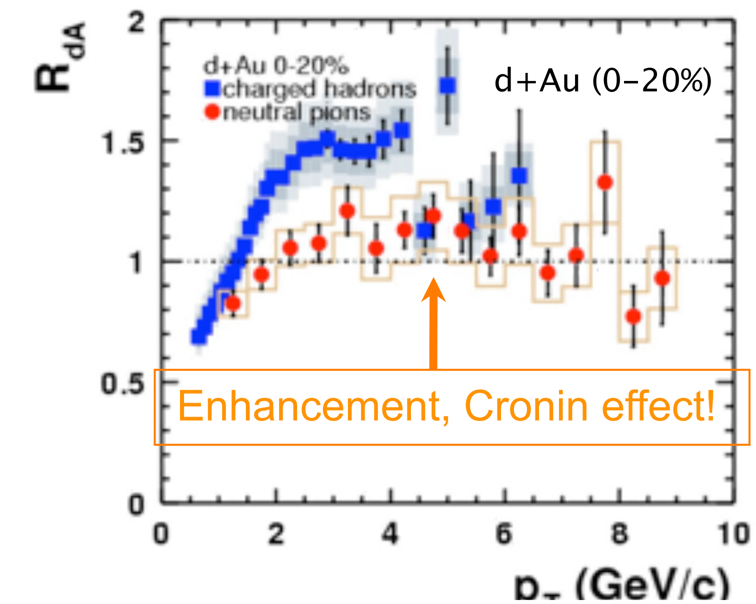
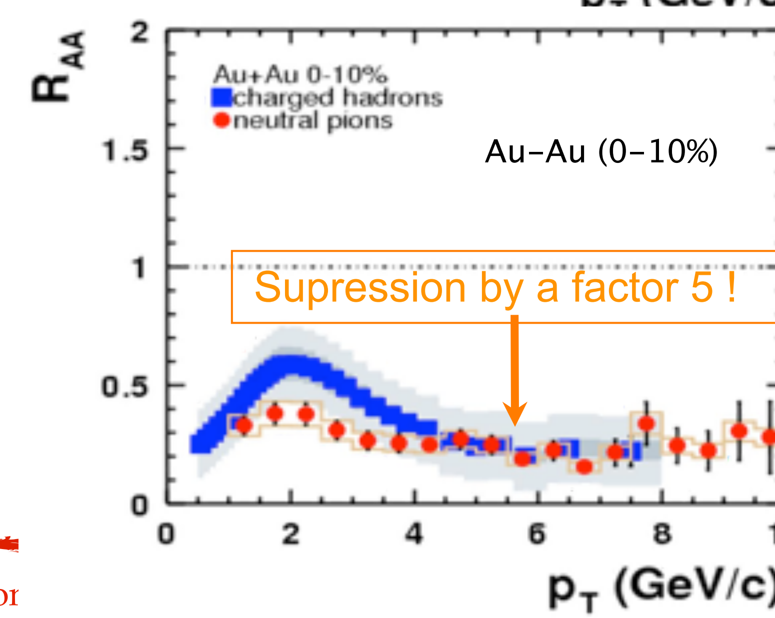


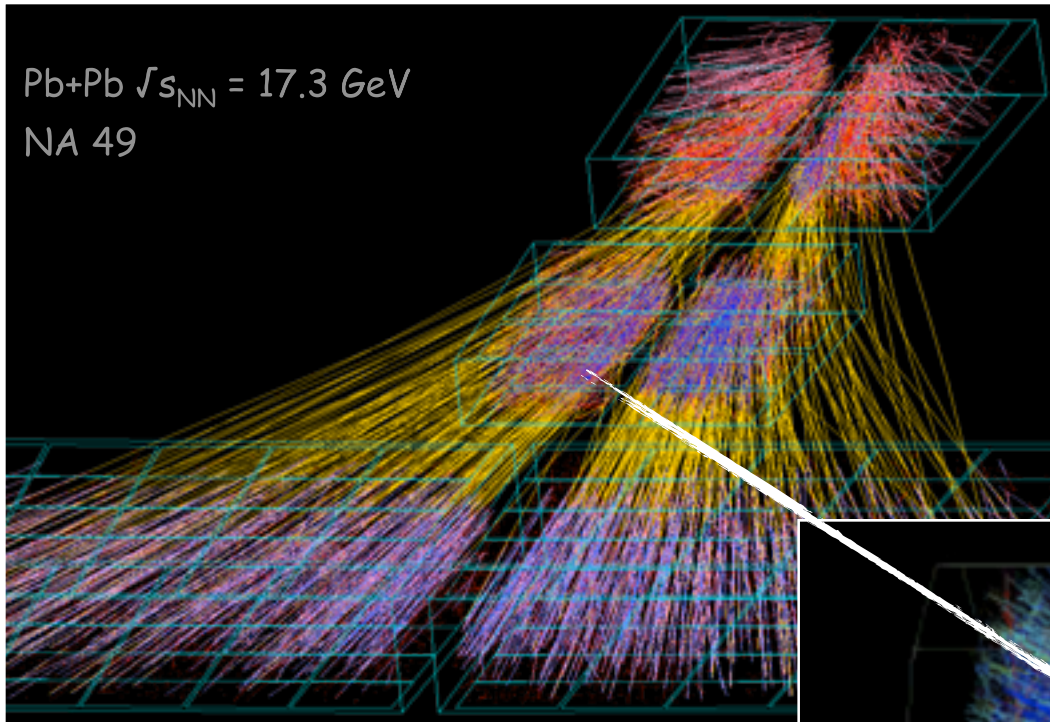
$\varepsilon > \varepsilon_C$
$T > T_C$

④ Measure it in the presence of a hot nuclear environment, in the most central A-B coll.
- Distinguish QGP effects, interpret them, confront with theory.



- Need to do all these systematically (nuclei, energy,…)
- Multiple observables are required to characterize the created matter
- Characteristic: huge particle multiplicity

A rough How To Guide



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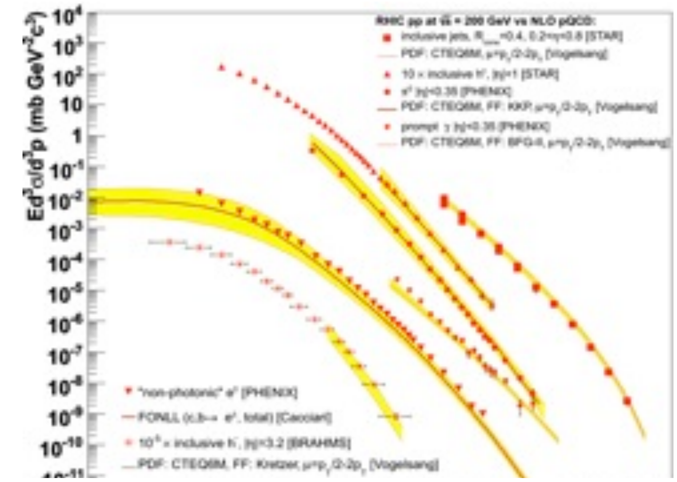
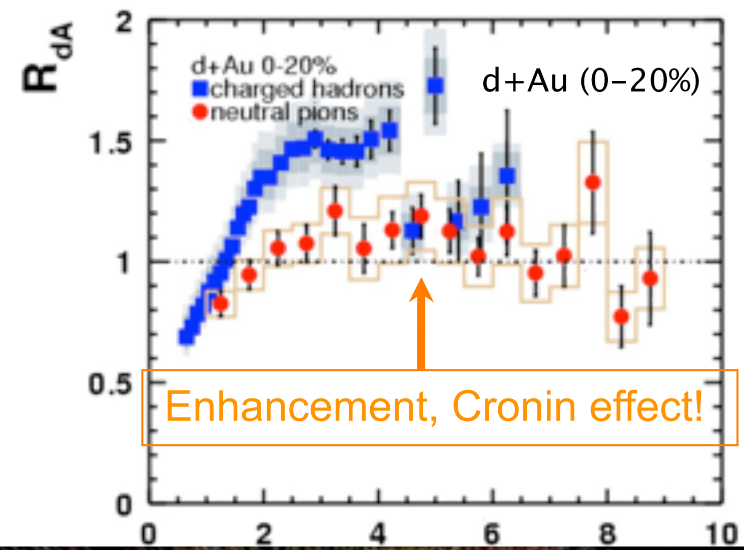


ence of medium effects, in p-p coll.
eoretical predictions: the QCD

-A



- Modification of PD
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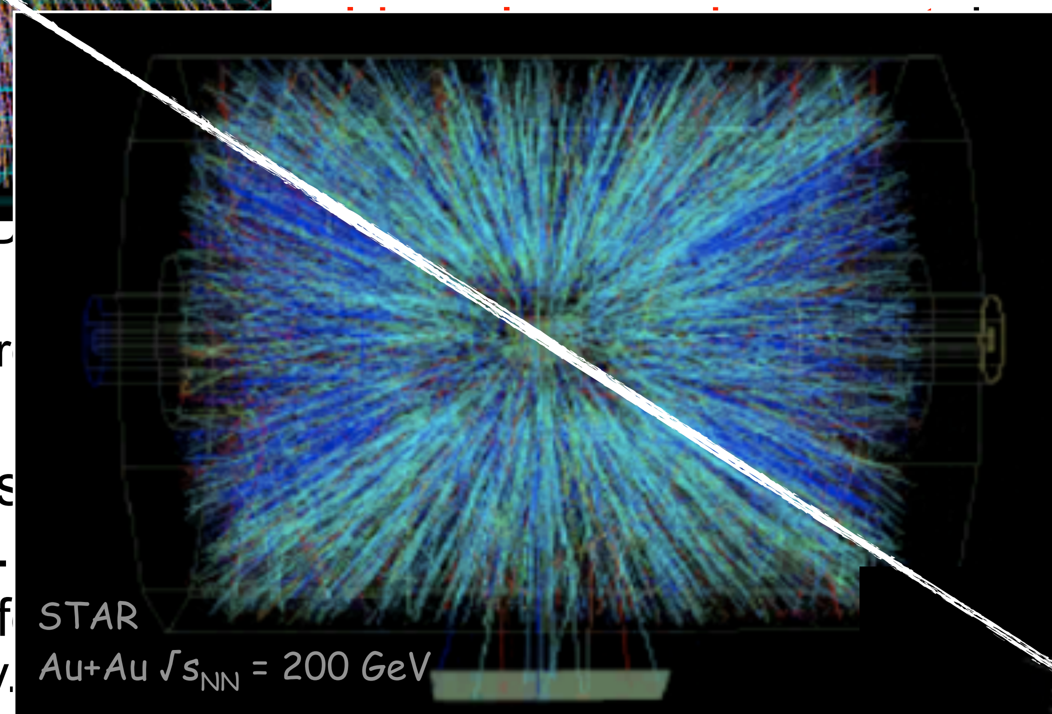
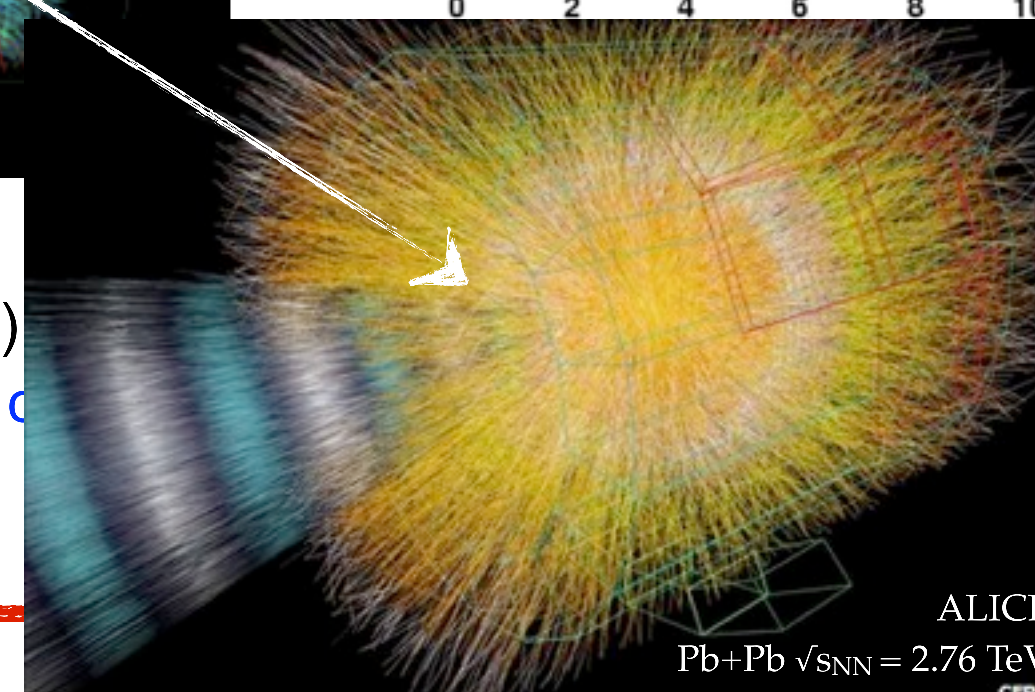


$\varepsilon > \varepsilon_c$
$T > T_C$

④ Measure it in the pres most central A-B coll.

- Distinguish QGP eff confront with theory.



- Need to do all these systematically (nuclei, energy,…)
- Multiple observables are required to characterize the matter
- Characteristic: huge particle multiplicity

"Few words" about what has been learned

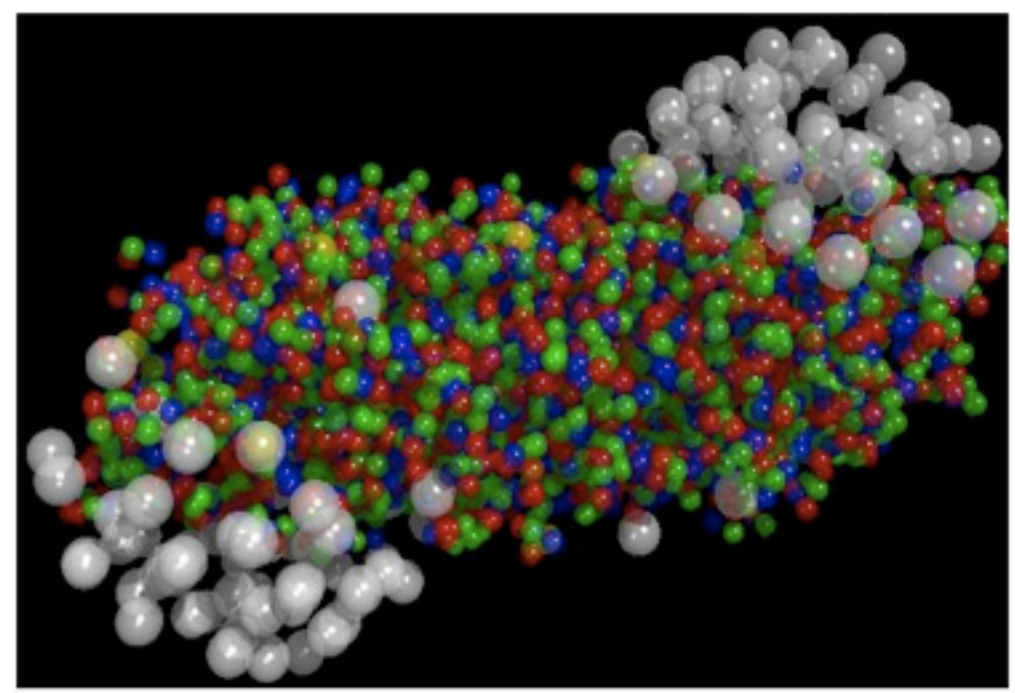
- SPS heavy-ion programme
  - Took data from p to Pb, from $\sqrt{s_{NN}}$ = 17 GeV to 30 GeV
  - Experiments: NA44, NA45, NA49, NA50, NA60, WA97, WA98,…
  - Observed (between others…):
    - Low-mass dilepton excess
    - Strangeness enhancement
    - Charmonium suppression
  - Concluded:
    there was "*experimental evidence for the formation of a new state of matter*", since their data could not be explained in terms of hadronic degrees of freedom alone.
    [Heinz & Jacob 2000] nucl-th/0002042
    [Gonin 2001] INPC 2001

http://info.web.cern.ch/Press/PressReleases/Releases2000/PR01.00EQuarkGluonMatter.html
10th February 2000

PRESS RELEASE

Organisation Européenne pour la Recherche Nucléaire
European Organization for Nuclear Research

New State of Matter created at CERN



At a special seminar on 10 February, spokespersons from the experiments on CERN* 's Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

"Few words" about what has been learned

- RHIC heavy-ion programme (from 2000 till today)
  - Takes data from p to Au, from $\sqrt{s_{NN}}$ = 22 GeV to 200 GeV
  - Experiments: PHENIX, STAR, PHOBOS, BRAHMS
  - Observe (between others):
    - High-p_T hadron suppression
    - Vanishing away-side-jet
    - Hydro and partonic flow
    - Charmonium suppression
    - Direct photon excess
  - Claim:
    that "a strongly interacting matter was formed" …
    "behaves more like a liquid"

[PHENIX] NP A757:184 (2005); nucl-ex/0410003
[STAR] NP A757:102 (2005); nucl-ex/0501009
[PHOBOS] NP A 757:28 (2005); nucl-ex/0410022
[BRAHMS] NP A757:1 (2005); nucl-ex/0410020

http://www.bnl.gov/bnlweb/pubaf/pr/PR_display.asp?prID=05-38
18th April 2005

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

Secretary of Energy Samuel Bodman

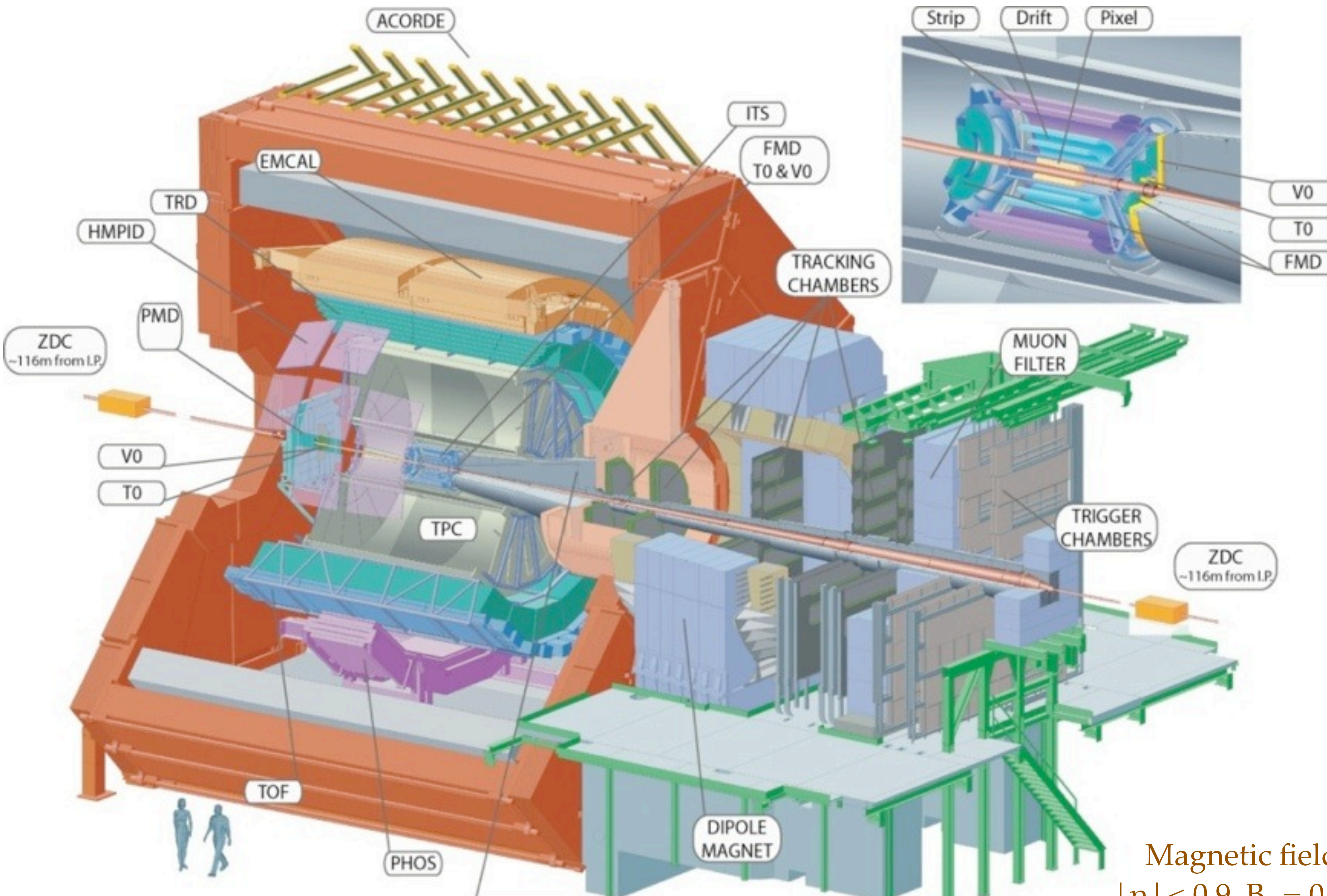
"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain fundamental properties of the universe using 10 dimensions instead of the usual three spatial dimensions plus time.

ALICE Results @ Pb-Pb 2.76TeV

Some Global Observables, the Bulk

THE ALICE EXPERIMENT



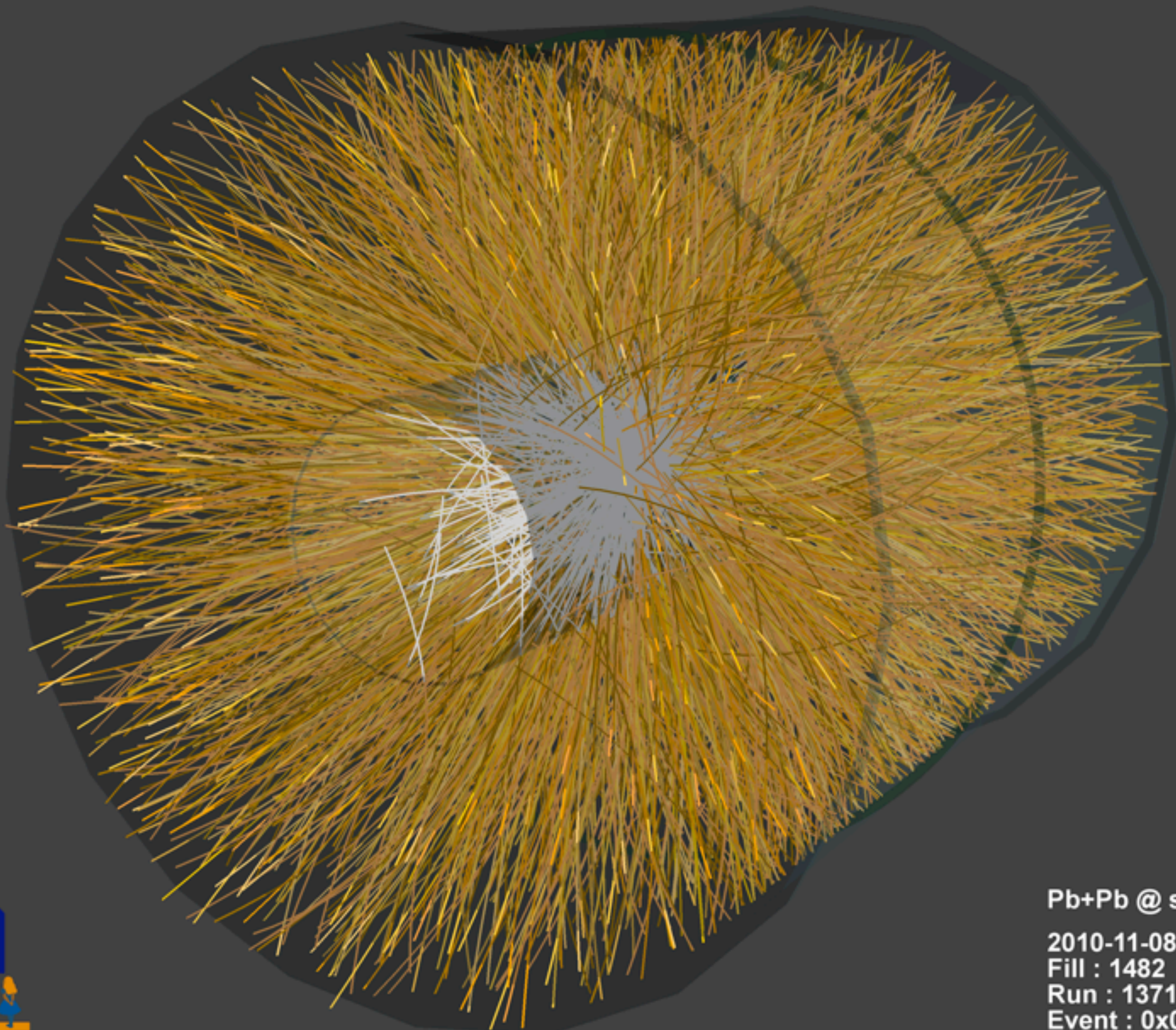
ZDC, V0: beam background rejection, centrality determination

Magnetic field

$|\eta| < 0.9$, $B_z = 0.5$ T

$-4.0 < \eta < -2.5$, $B_y \leq 0.7$ T

Event Display @ Pb-Pb 2.76TeV



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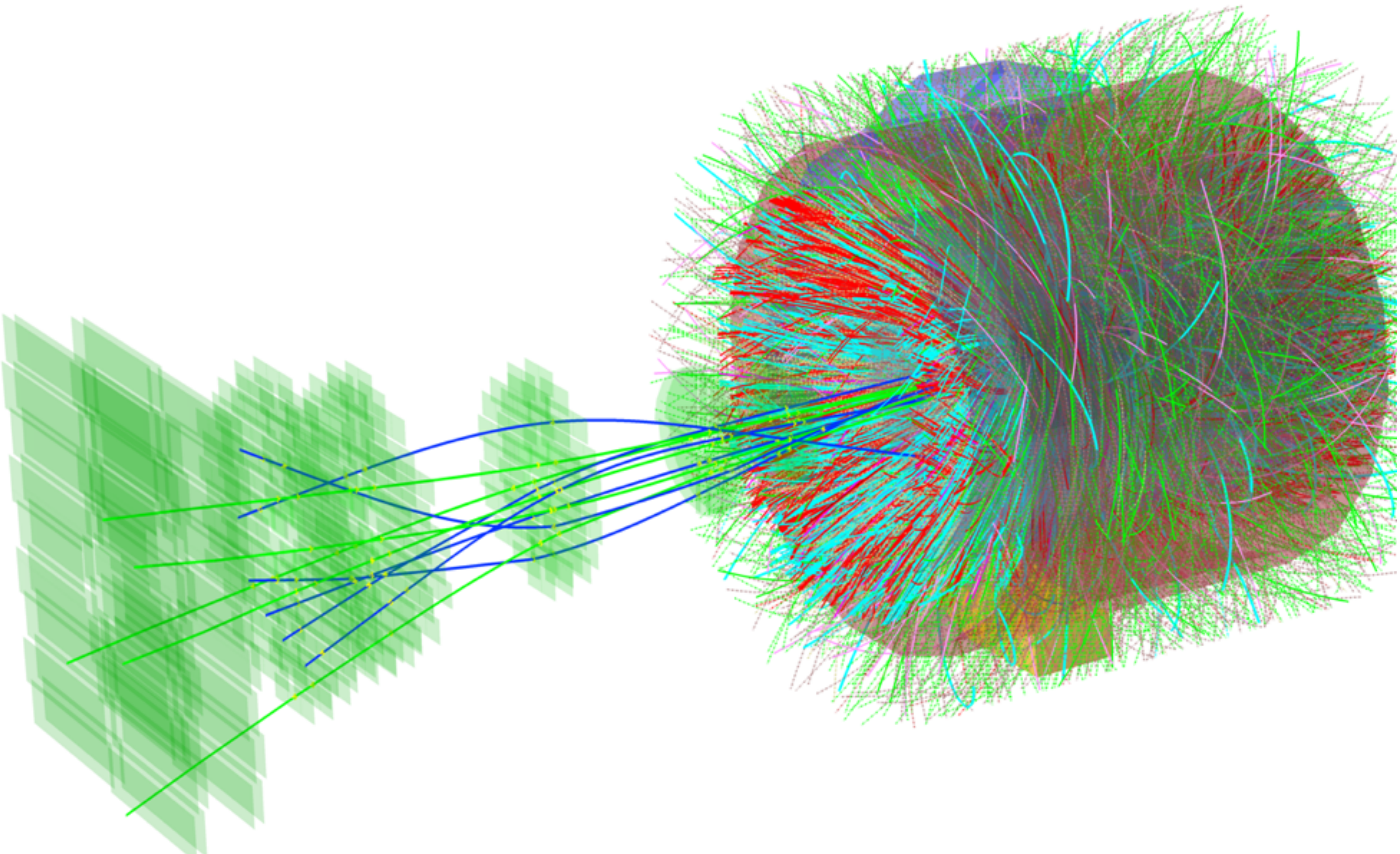
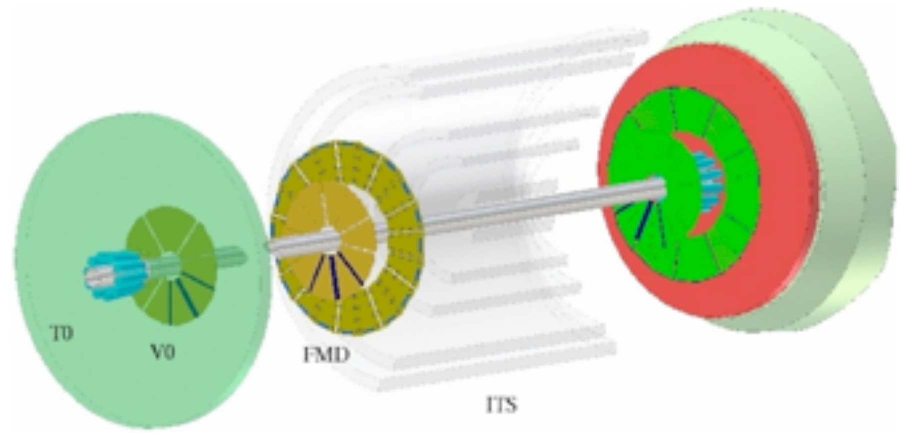


Data Taking

- In proton proton collisions (2009, 2010, 2011, 2012)
  - MB trigger (V0, SPD) was favored on 2010 and 2011 data-taking
  - Rare triggers: EMCAL, MUON, TRD, T0
- In Pb-Pb collisions (2010, 2011)
  - MB (V0and) + MUON were the main triggers on 2010 data-taking
  - On the 2011 campaign, in addition to the MB trigger :
    - Centrality (0-10%, 10-50%) selection
    - MUON + EMCAL triggers
    - Data compression with the High Level Trigger
- In p-Pb collisions (2013)
  - MB (V0and) + MUON + EMCAL triggers
  - Data compression with the High Level Trigger



V0: $2.8<\eta<5.1$, $-3.7<\eta<-1.7$
beam background rejection, centrality determination

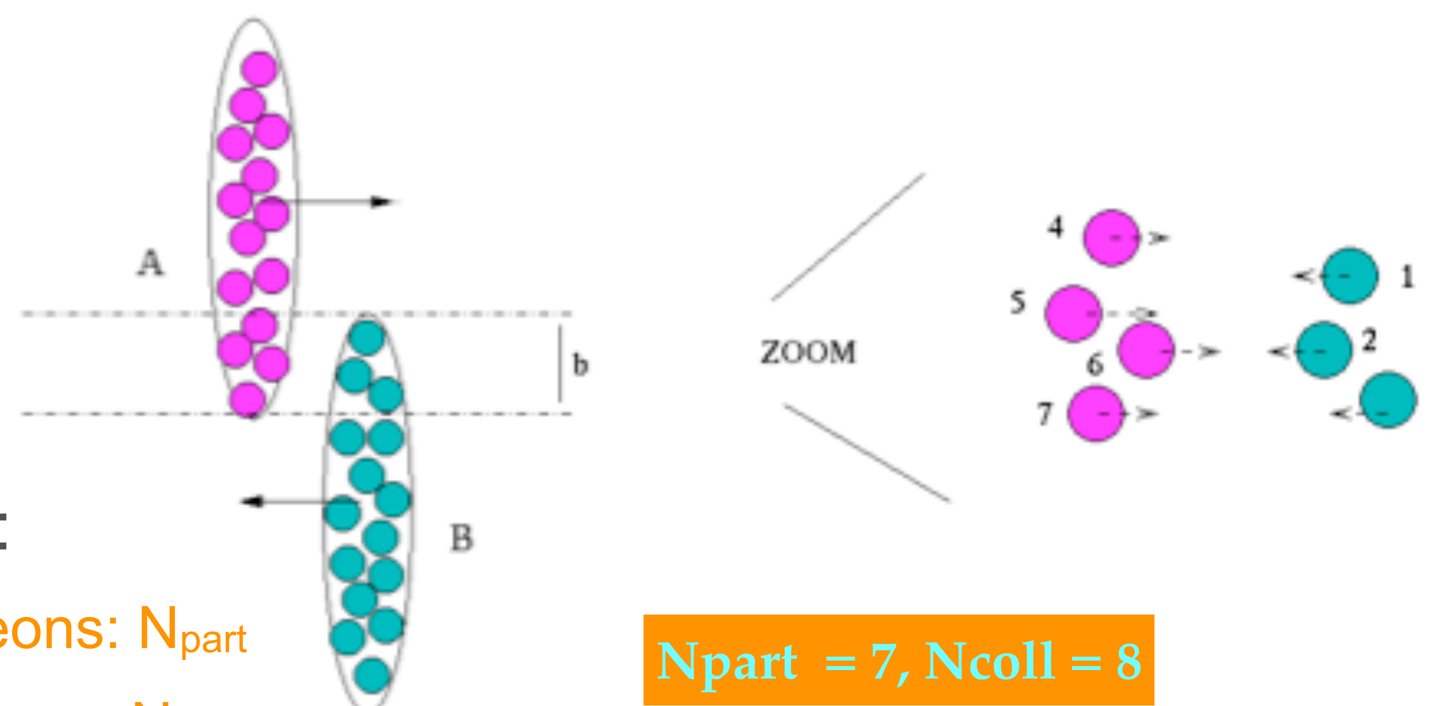
Note: the values reported in this table illustrate the analyzed statistics for now

System	pp	pp	pp	pp	Pb-Pb	Pb-Pb	p-Pb
$\sqrt{s_{NN}}$ [TeV]	7	7	2,76	2,76	2,76	2,76	5.02
trigger	MB	μ-trigger	MB	μ-trigger	MB	MB+Ctr+SM	MB
Data-taking	April-Aug 10	April-Sept 10	March 11	March 11	Nov 10	Nov 11	Jan 2013
<L>	1.6 (5) nb^{-1}	16 nb^{-1}	1.1 nb^{-1}	20 nb^{-1}	2.7 μb^{-1}	23 - 6 μb^{-1}	49 μb^{-1}

Centrality, the Glauber Model

- Glauber model : geometrical picture of the collision
  - The nucleons are distributed following a known density distribution function ρ(r) (Wood-Saxon), as a function of their radius, usually measured experimentally;
  - The nucleons travel in straight-line trajectories and their trajectory does not change while passing through the nucleus;
  - The nucleons interact with a nucleon-nucleon inelastic cross section, $\sigma_{NN}(\sqrt{s_{NN}})$, measured in pp collisions, where $\sqrt{s_{NN}}$ is the energy available in the nucleon-nucleon (NN) center of mass. At 2.76 TeV $\sigma_{NN} = 64 \pm 5$ mb.

$$\rho(r) = \frac{\rho_0}{1 + \exp(\frac{r-R}{a})},$$
$$R = 1.19\, A^{\frac{1}{3}} - \frac{1.61}{A^{\frac{1}{3}}}(\mathrm{fm}),$$

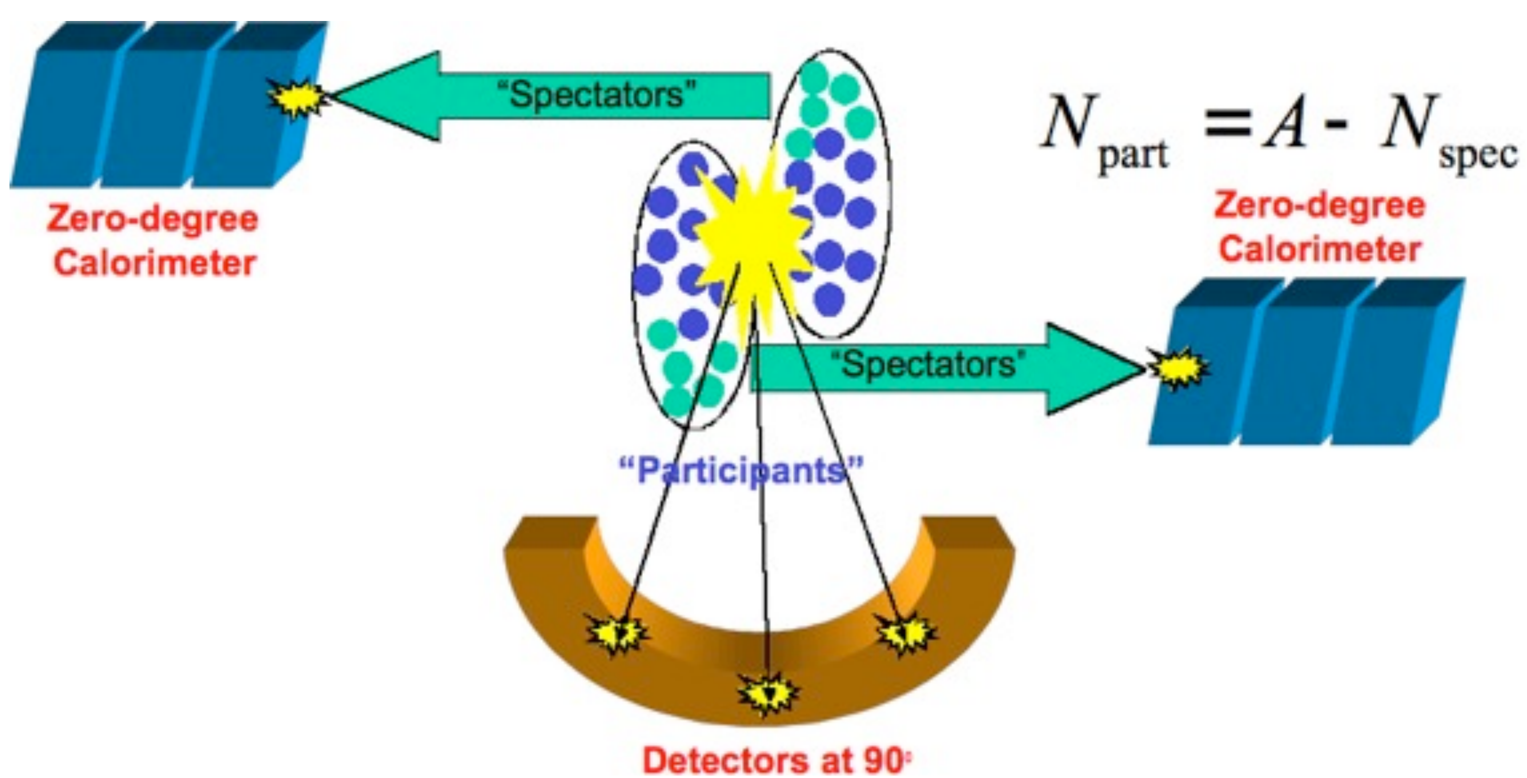


- Characteristic parameters:
  - Number of participant nucleons: N_{part}
  - Number of binary NN collisions: N_{coll}

Npart = 7, Ncoll = 8

Centrality measurement

- The collision centrality determines the number of nucleons participating on the collision and the remaining spectator nucleons
  - ZDCs (~116m from IP) measure the spectator nucleons
  - Other detectors (V0, SPD, TPC) are sensitive to the participating nucleons
- Experimental centrality determination
  - “Fit” the multiplicity distributions with a Glauber MC:
    V0 amplitude, SPD clusters, TPC tracks
  - Energy deposit on the ZDCs (z~116m) and ZEMs (z~7.5m)



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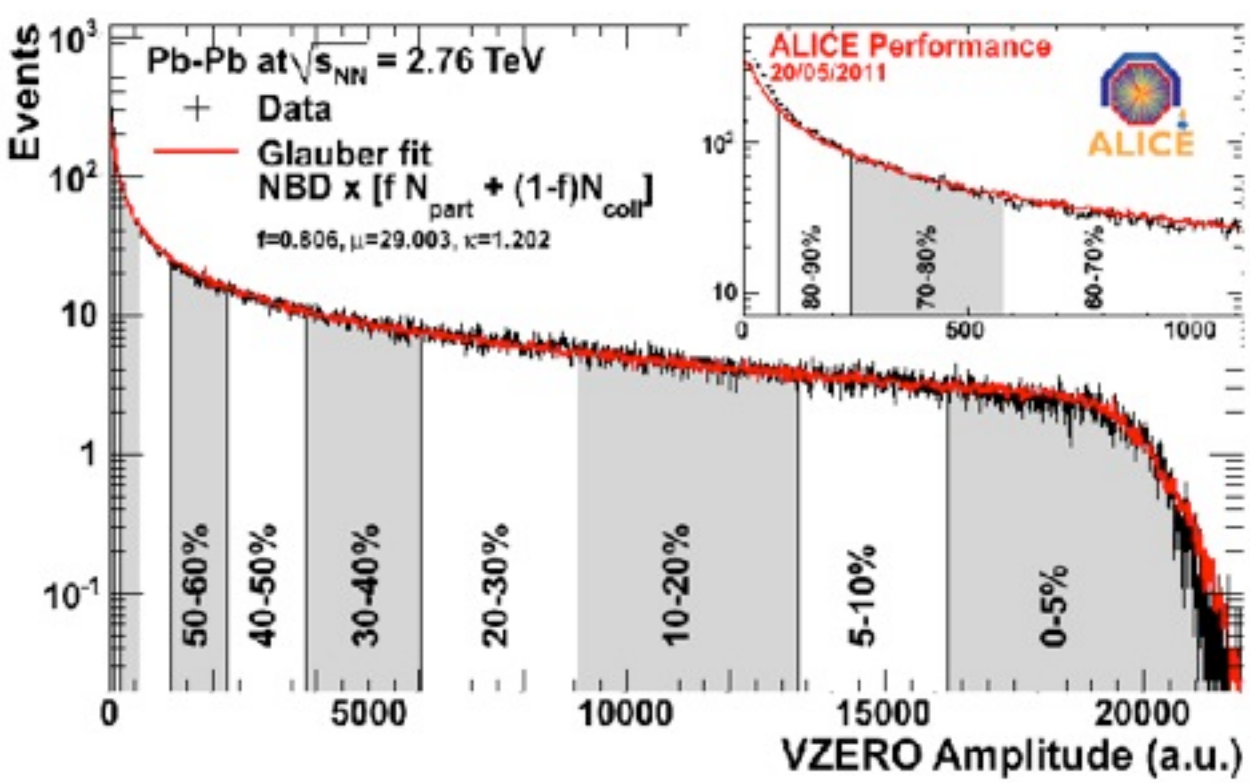
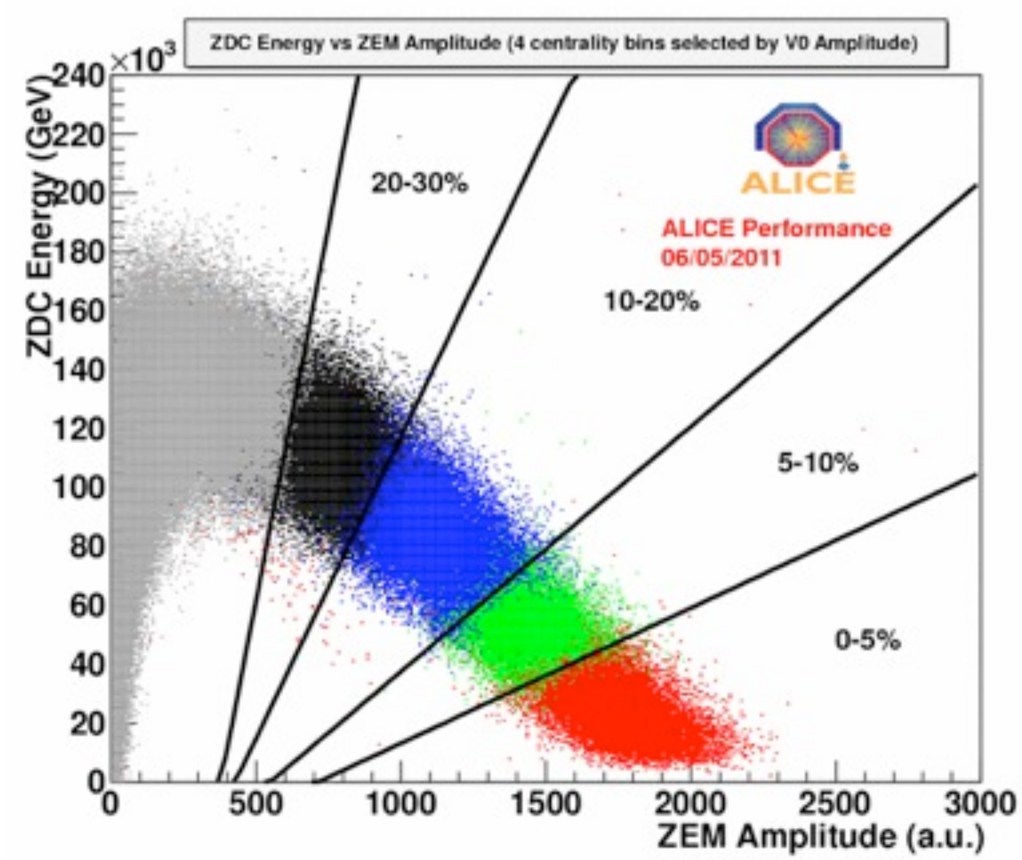
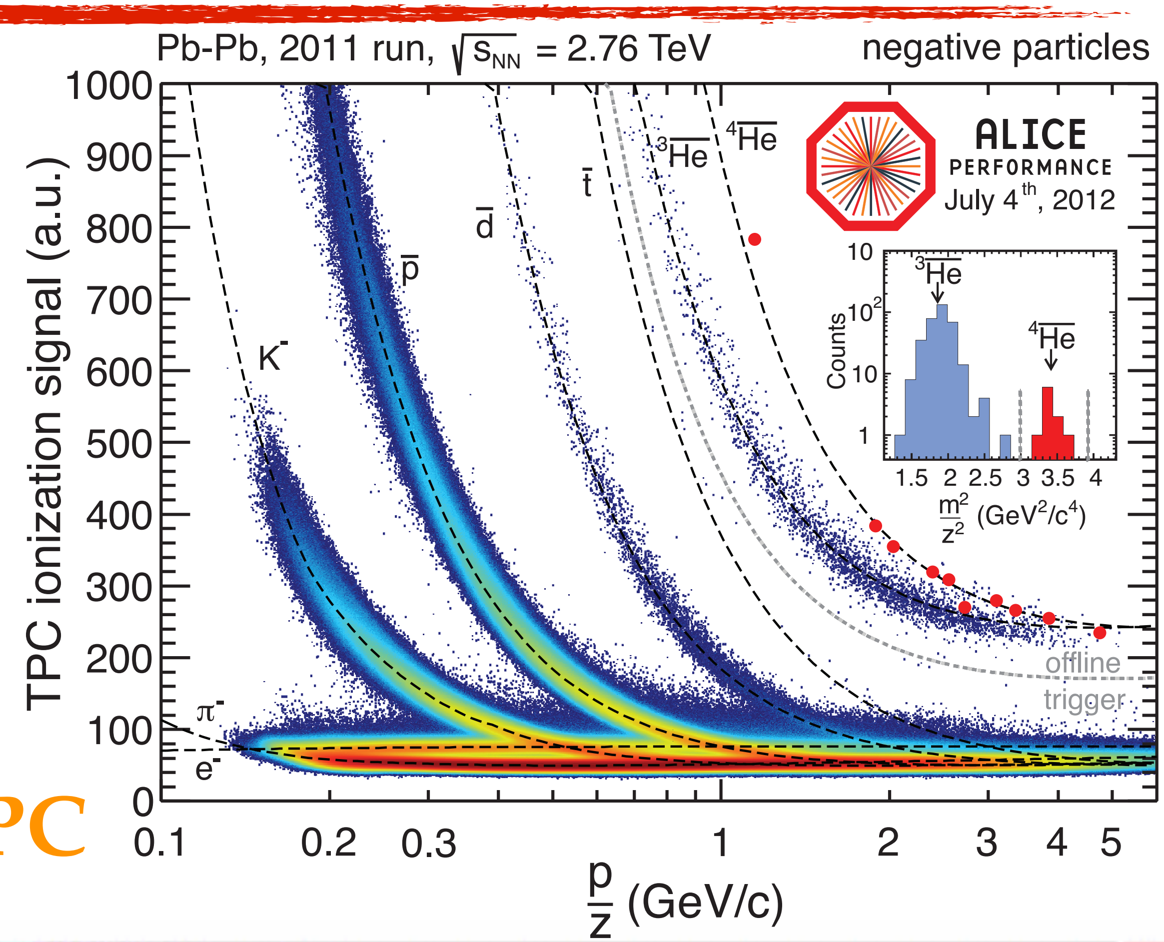




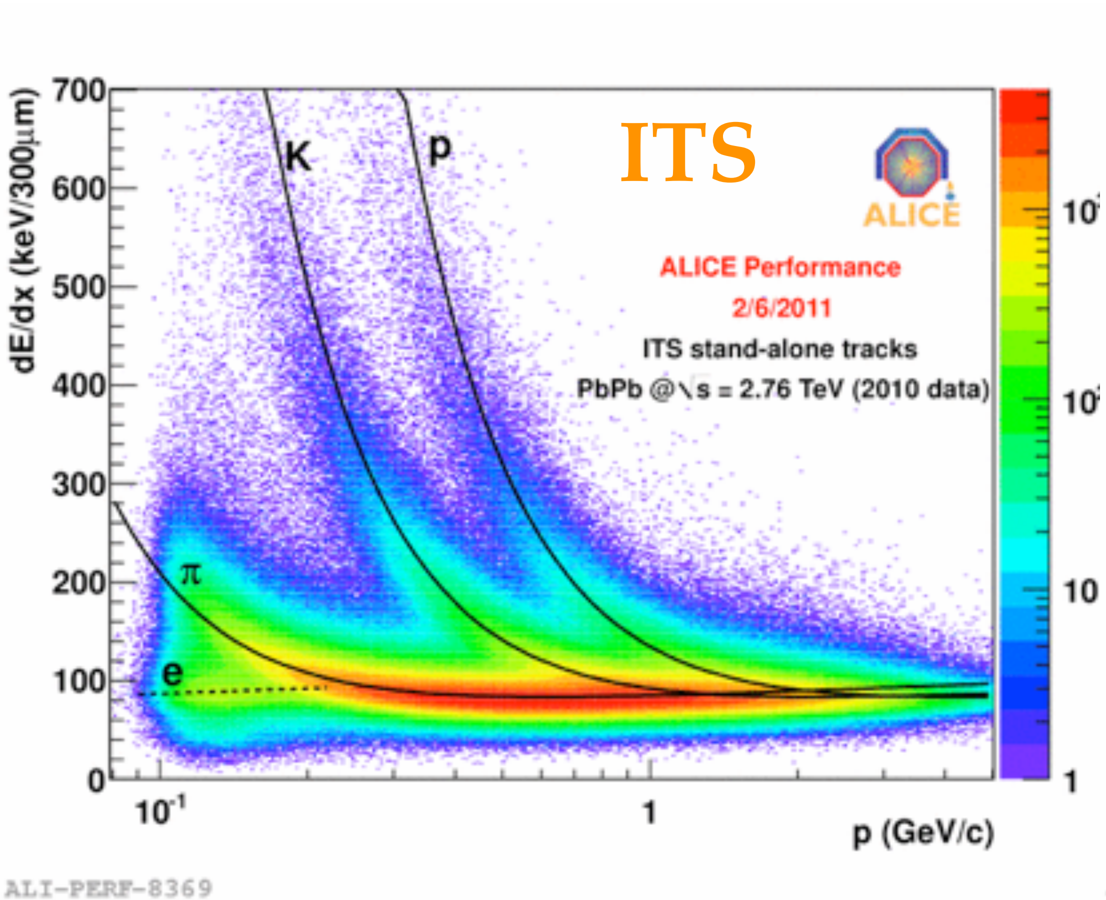
Particle Identification

- Diverse detectors for PID vs p
- TPC: Specific energy deposit
- ITS: energy deposit (SDD+SPD)
- TOF: time of flight (σ~85ps)

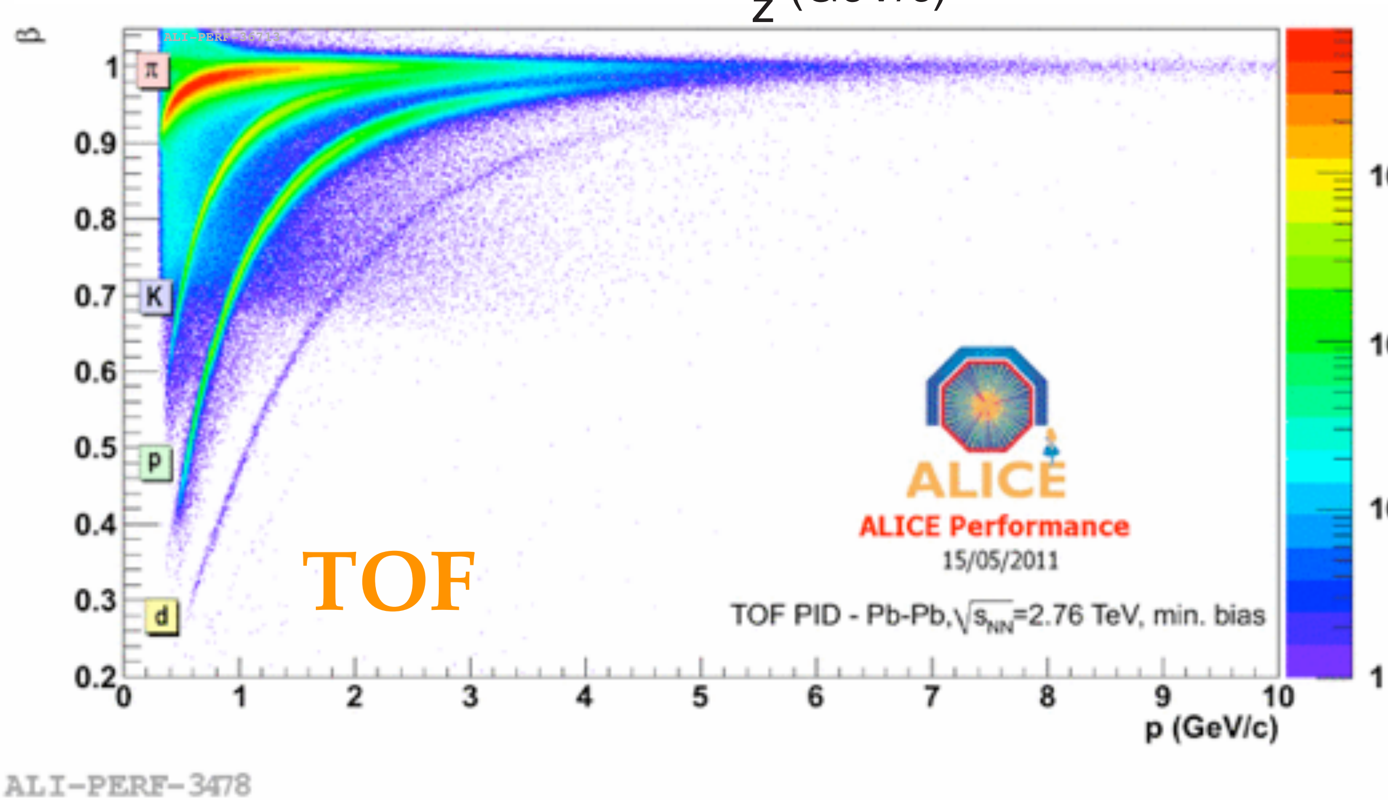
Observed 10 anti-alpha candidates in 2011 Pb-Pb data



TPC



ITS

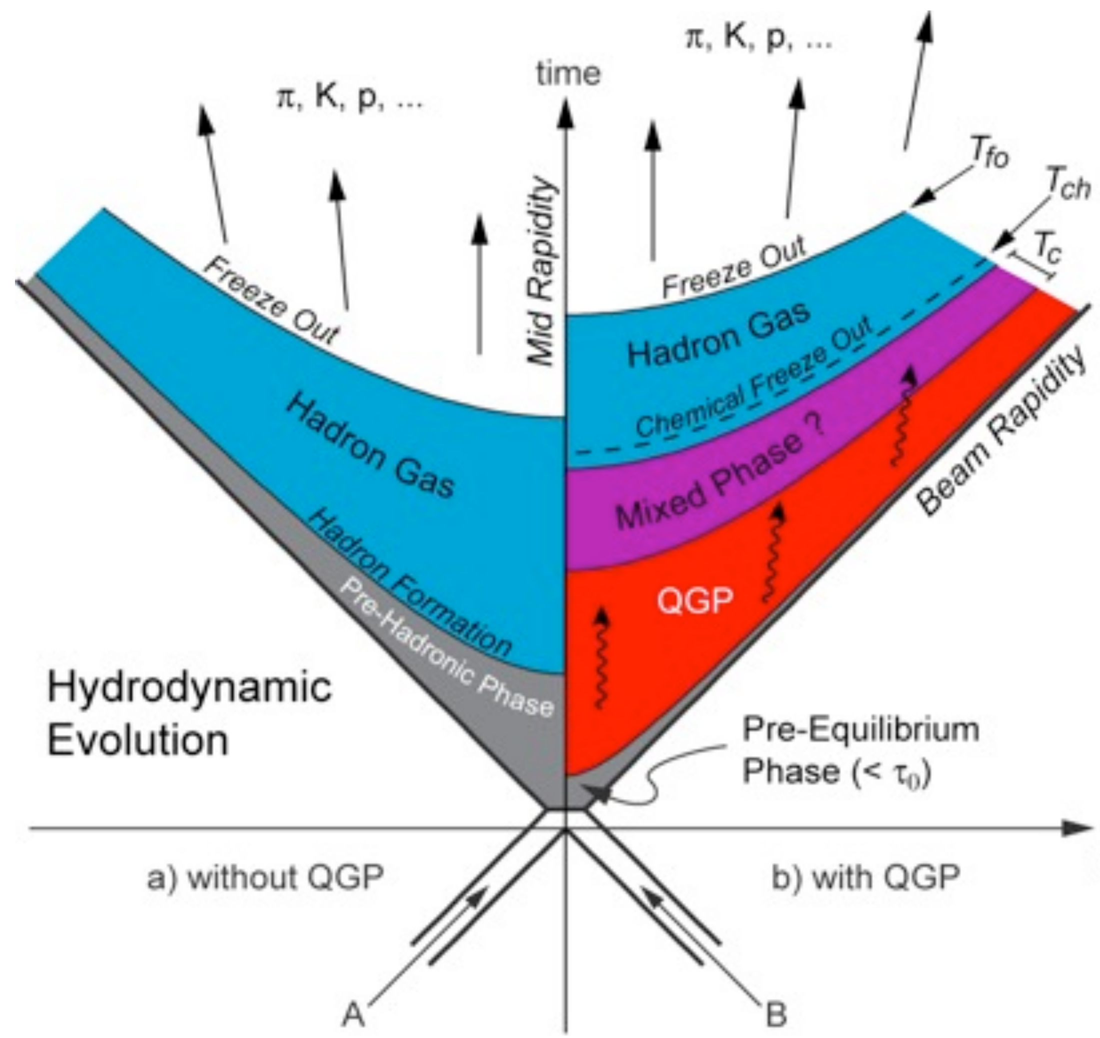


TOF

The Bulk of hadronic collisions

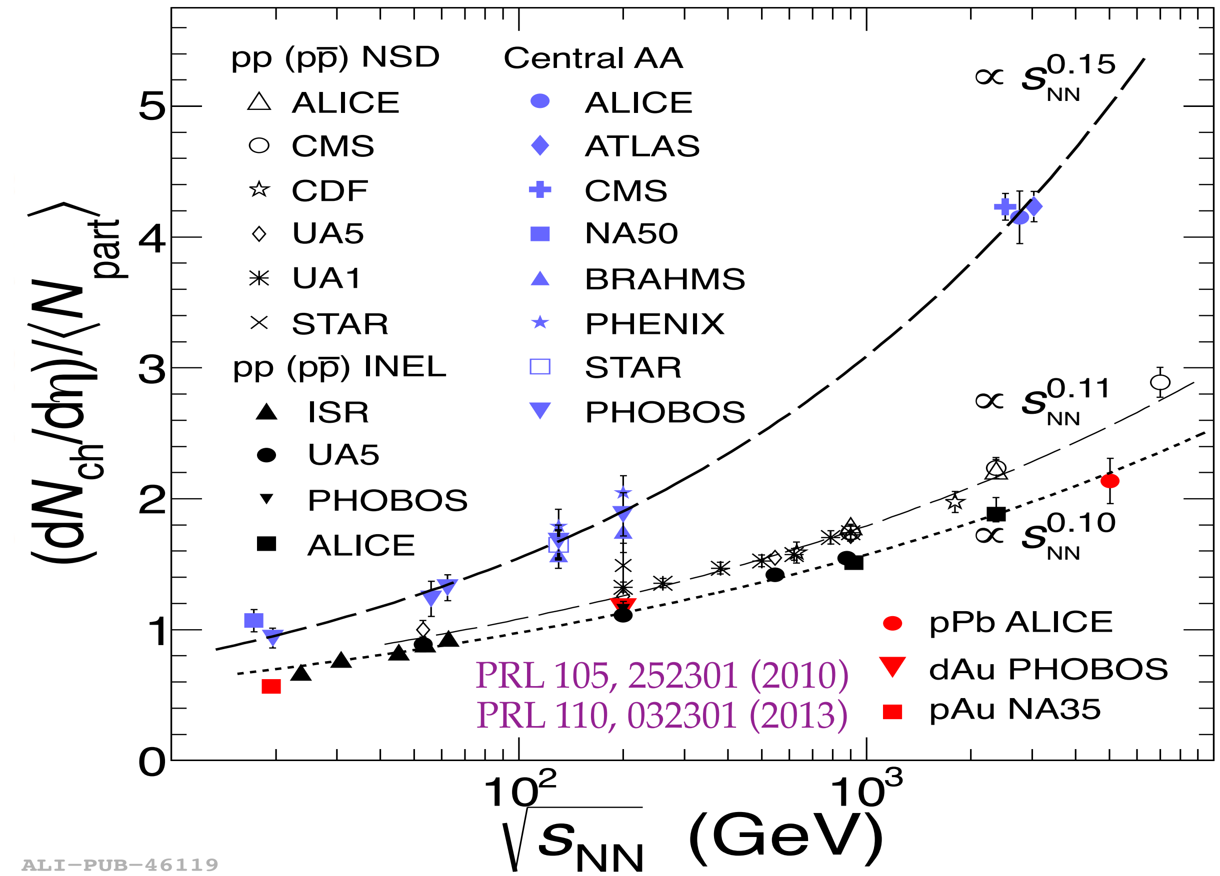
A. Toia, seminar Paris

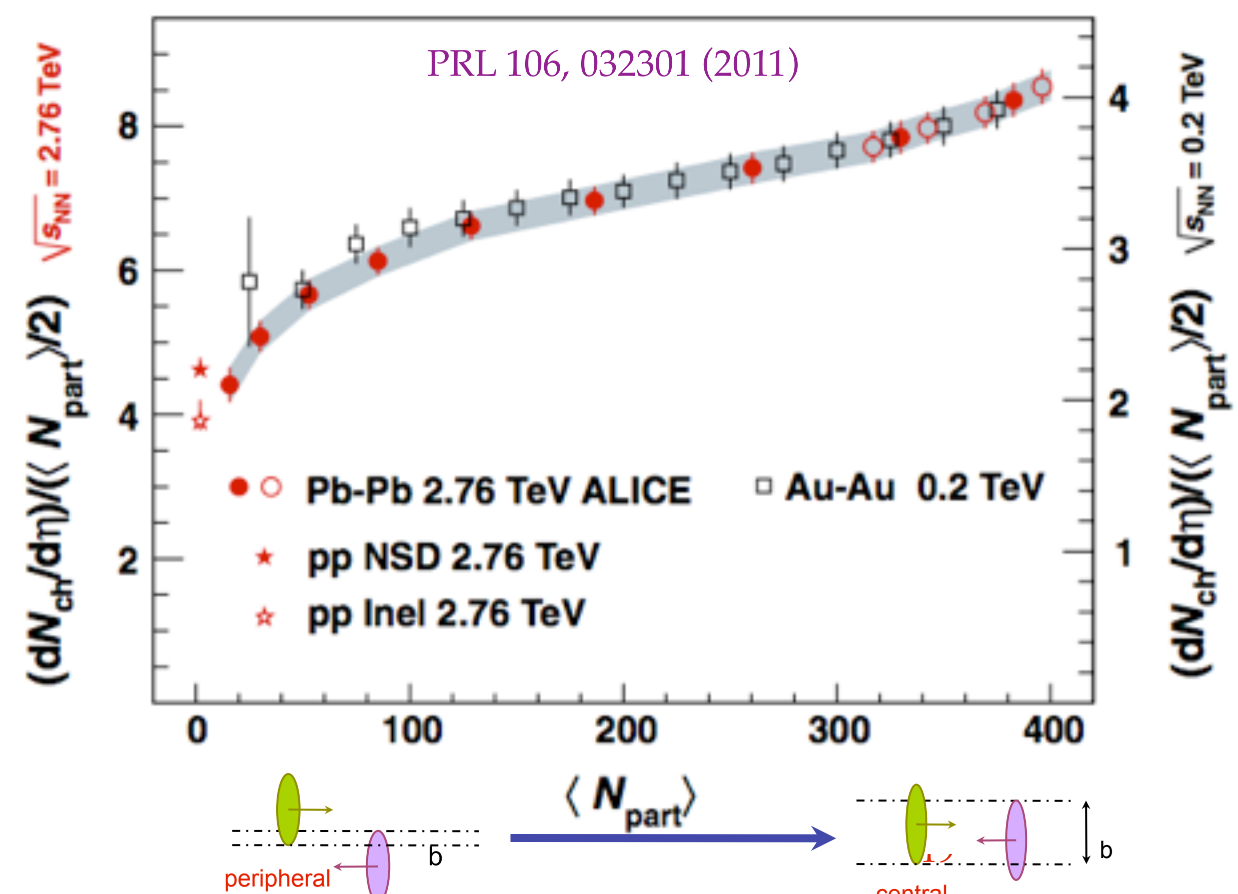
- Charged particle multiplicity and transverse energy
  - Information about initial conditions and dynamics of nucleus-nucleus collisions
    - energy density of the system
    - gluon saturation
  - Mechanisms of particle production
    - Soft: $N_{ch} \sim$ Npart
    - Hard: $N_{ch} \sim$ Ncoll
- Femptoscopy: system size and lifetime
- Soft light hadrons
  - Characterize the freeze-out
    - Chemical: $T_{ch} \leq T_c$ inelastic scattering ceases
    - Kinetic: $T_{fo} \leq T_{ch}$: elastic scattering ceases
  - Constrain the system dynamical evolution
- Elliptic Flow
  - Collective behavior
  - Early dynamics



Charged Particle Multiplicity

- Charged particle multiplicity measured from SPD tracklets
- Charged particle density at mid-rapidity in PbPb at 2.76 TeV
  - $dN_{ch}/d\eta$ ~ 1600 for 0-5% CC
  - 1.9 x p-p ($\sqrt{s_{NN}}$= 2.36 TeV) ⇒ nuclear amplification !
  - ~2.2 x RHIC (Au-Au, $\sqrt{s_{NN}}$= 0.2 TeV)
- The dependence on centrality
  - Similar trend at RHIC and LHC
  - Good "matching" to the pp reference
  - The shape indicates a different behavior for N_{part} > 100
  - It seems better reproduced by saturation models than models with pQCD processes with soft interactions.
    Note, that models are evolving...





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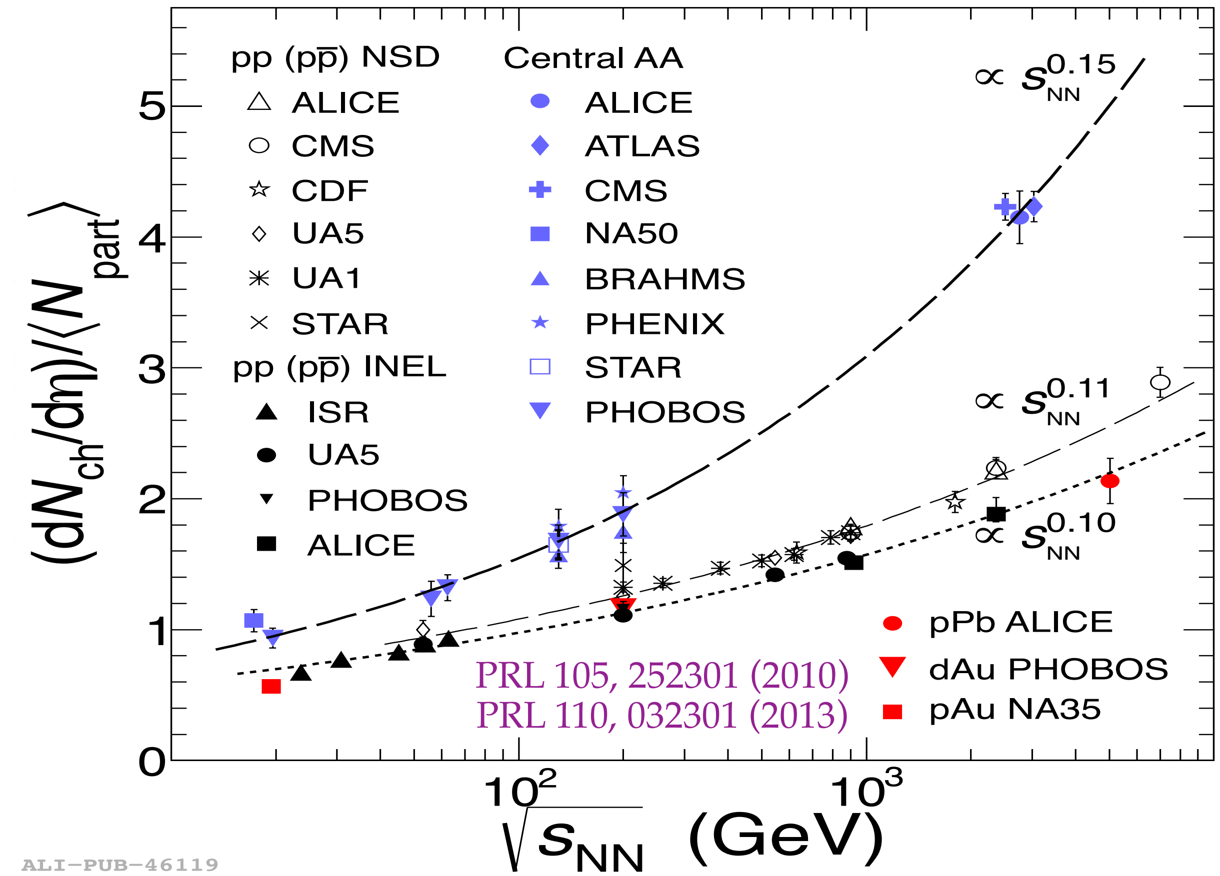
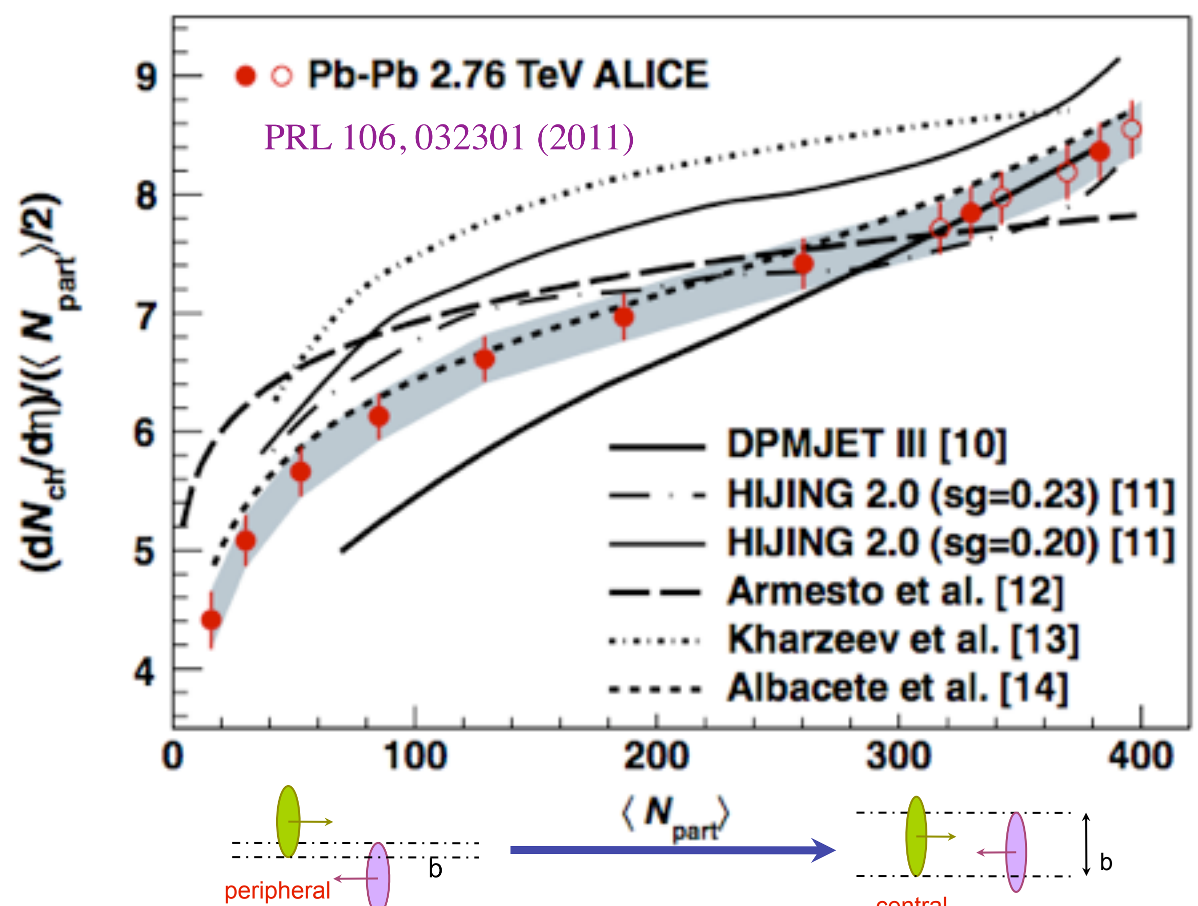
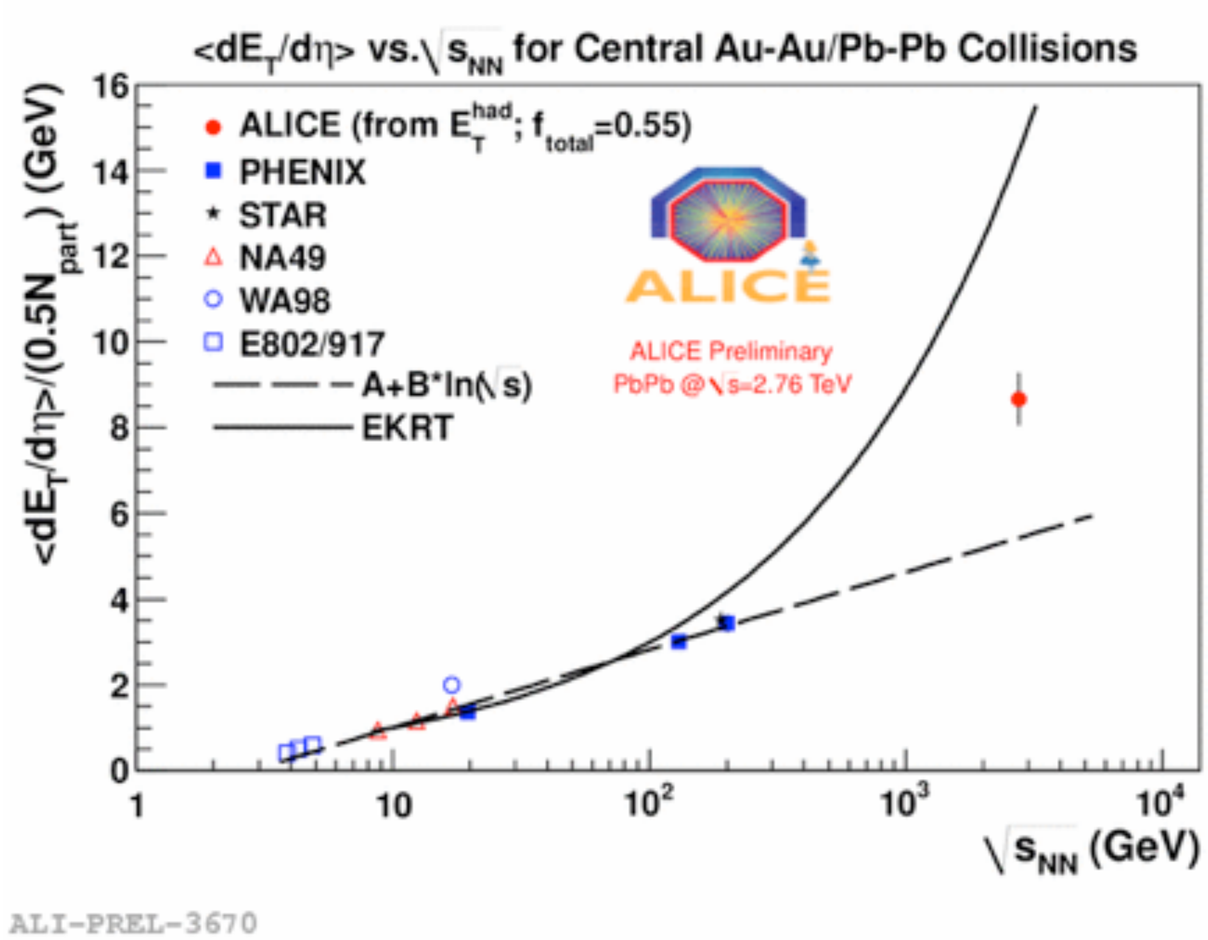
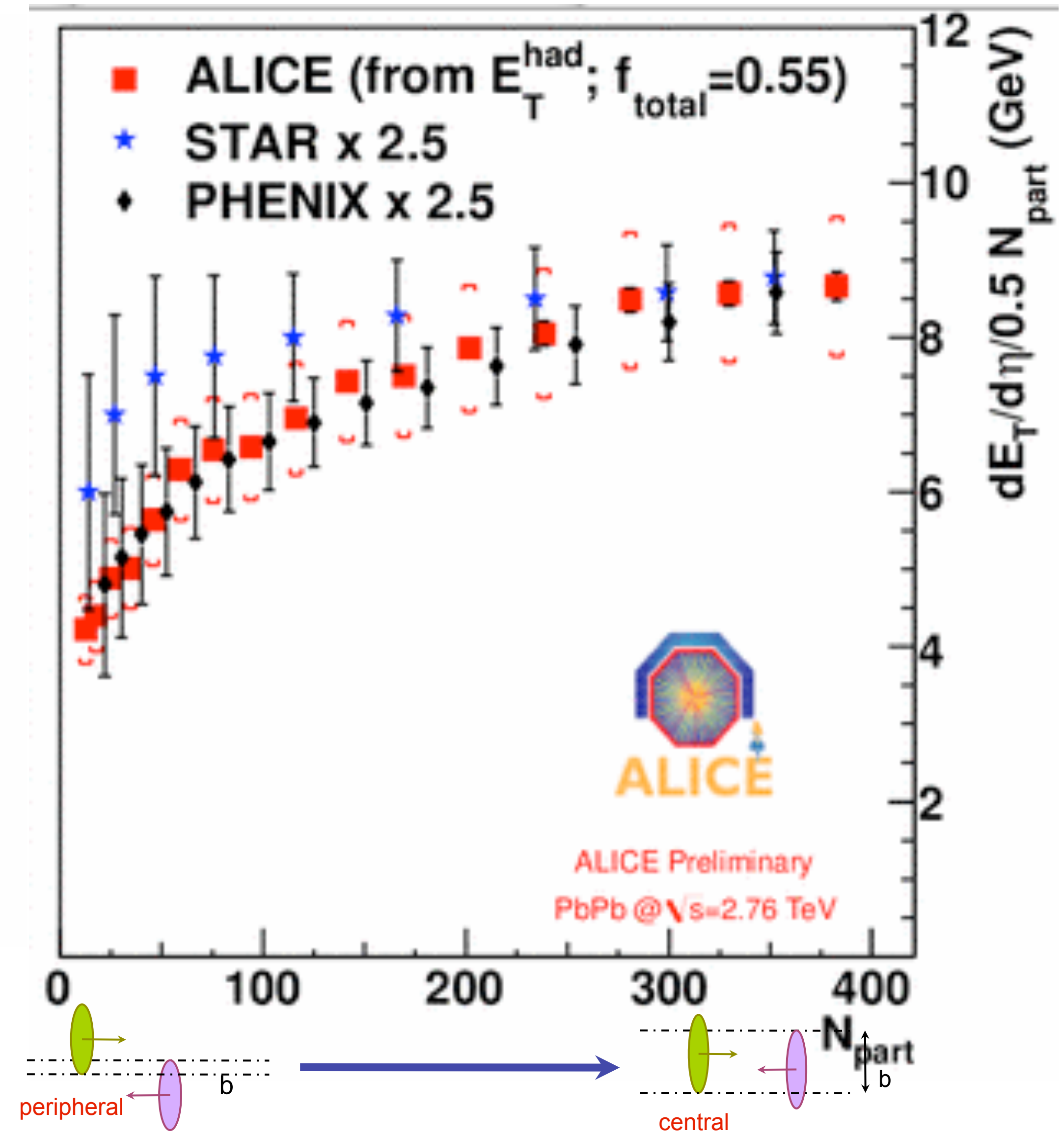




Transverse Energy

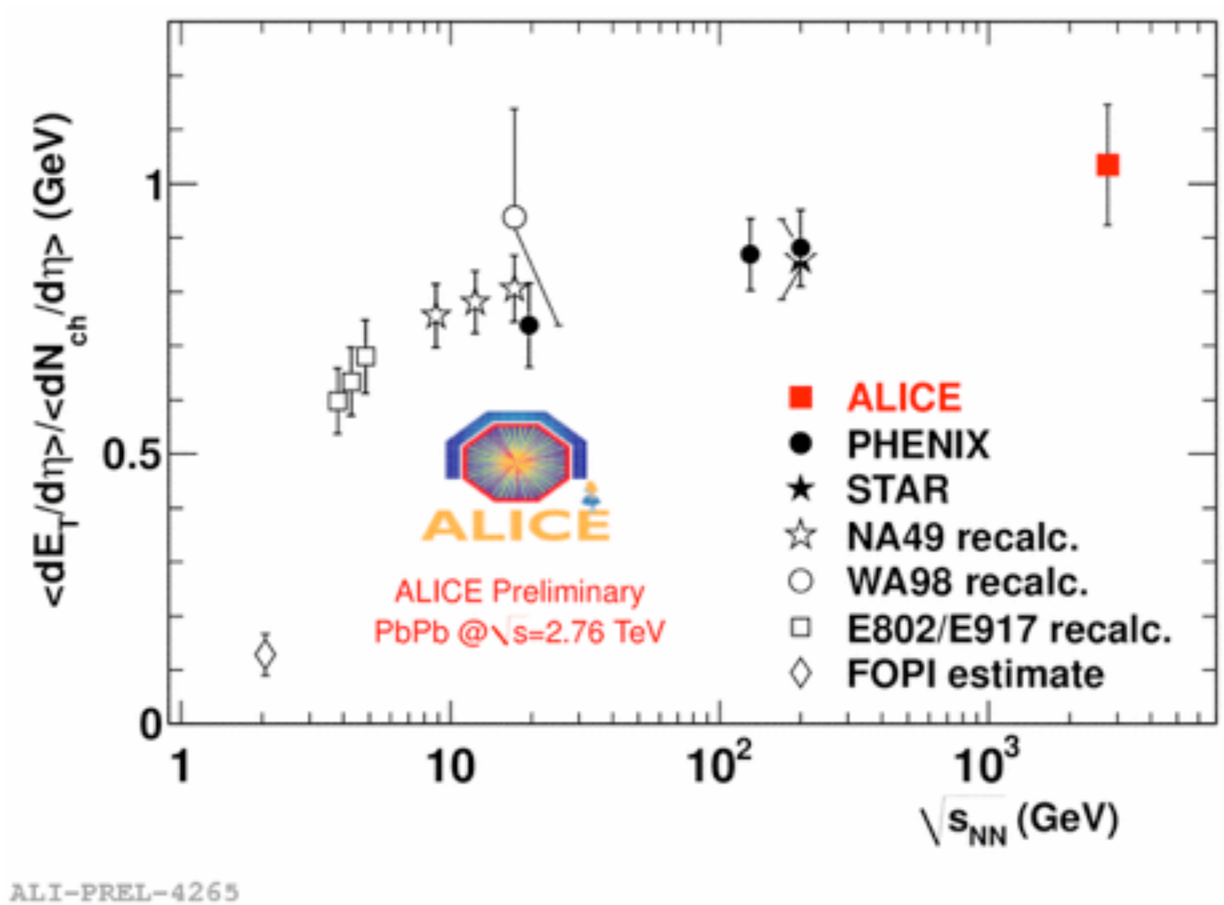


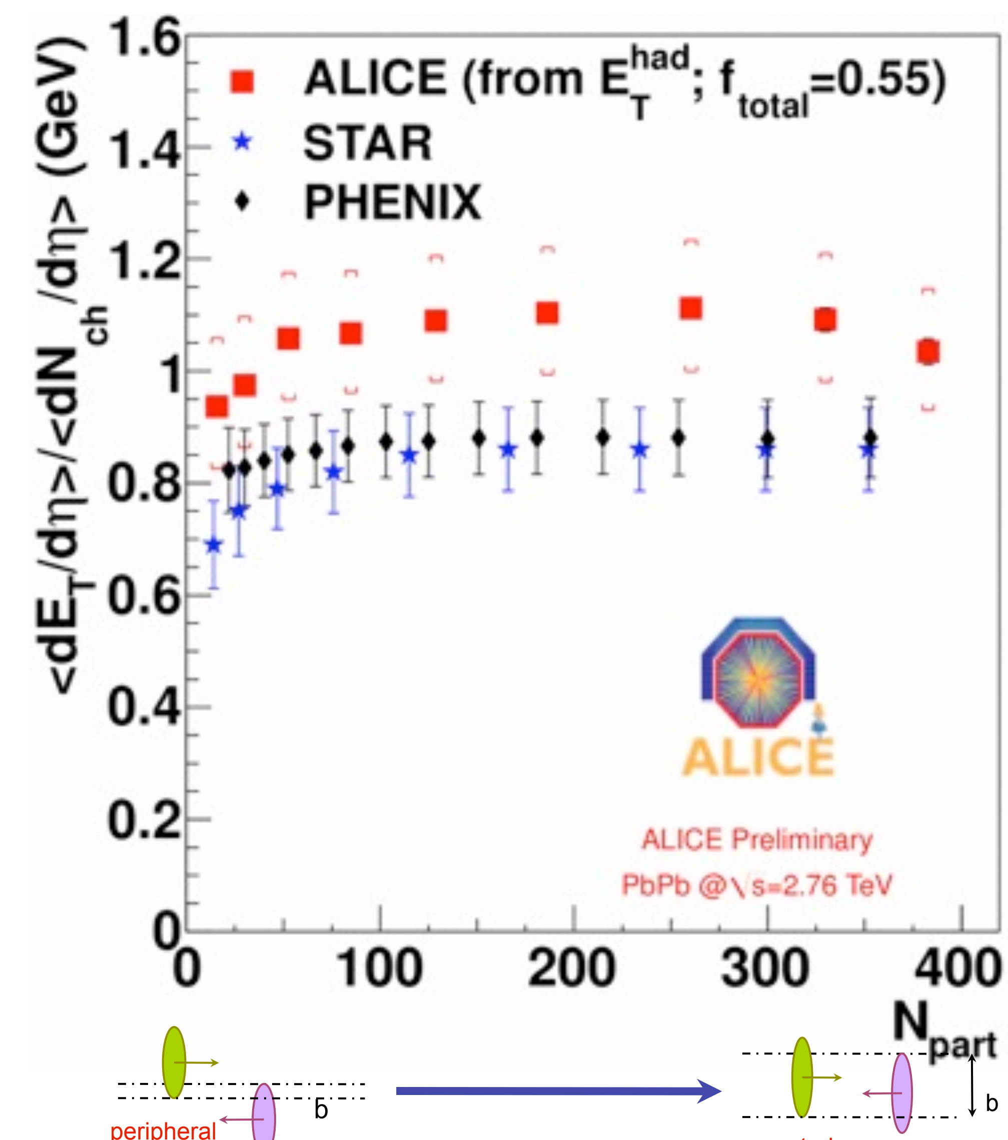


- Charged particles transverse energy measured by the tracking detectors
- Total transverse energy extrapolated from MC (factor 0.55)
- Comparing RHIC (Au-Au, $\sqrt{s_{NN}}$= 0.2 TeV) to LHC (Pb-Pb, $\sqrt{s_{NN}}$= 2.76 TeV)
  - Increase of about a factor 2.5 (2.7)
  - Grows faster than with a simple logarithmic law
  - Similar trend vs centrality at RHIC and LHC

Charged Particles and Transverse Energy

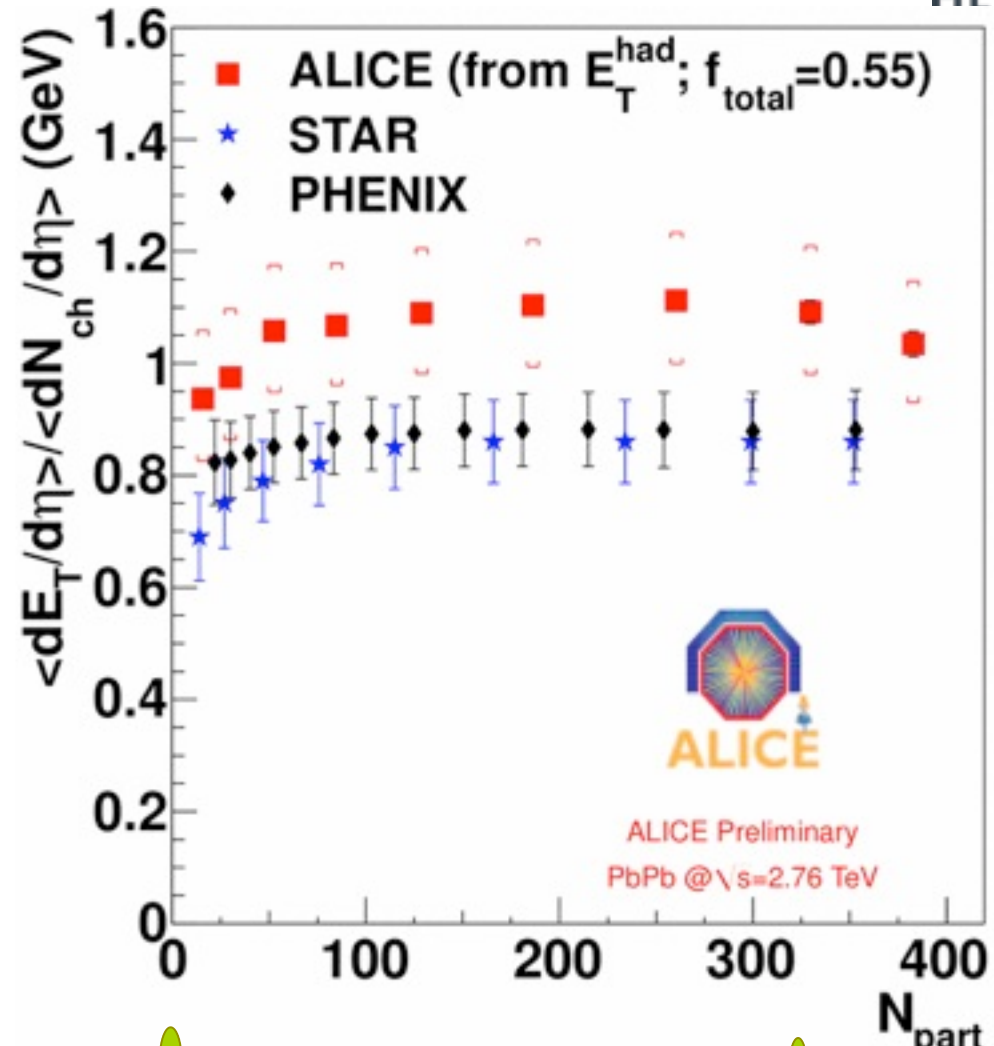
- Consistent behavior of $dE_T/d\eta$ and $dN_{ch}/d\eta$
- Both increase with $\sqrt{s_{NN}}$
- Show a steady rise from peripheral to central collisions
- E_T/N_{ch} independent of centrality
- E_T/N_{ch} slightly increases with energy

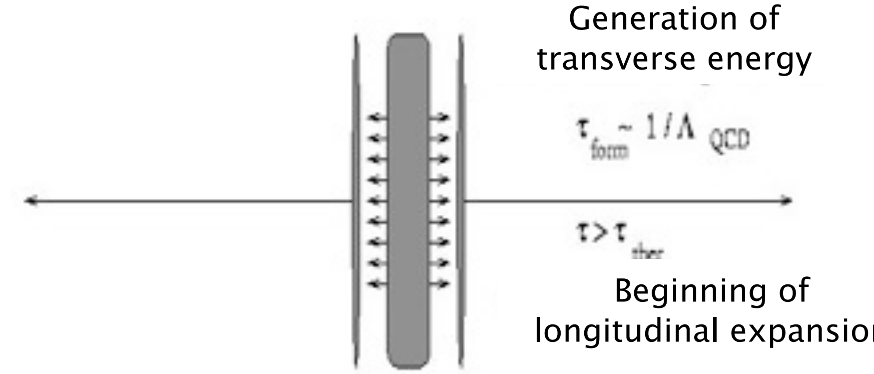




Charged Particles and Transverse Energy

- In the central collisions, at LHC
  - $dN_{ch}/d\eta \sim 1.9$ x p-p ($\sqrt{s_{NN}}$= 2.36 TeV)
    Grows faster than scaling from pp to AA
  - $dN_{ch}/d\eta \sim 2.2$ x RHIC
  - $dE_T/d\eta \sim 2.7$ x RHIC
    Grows faster than with a logarithmic law
- The energy density, Bjorken scenario
  - after the initial hard collisions, the partons are created in about $\tau_{strong} \approx 1/\Lambda_{QCD} \sim 1$ fm/c,
  - at that time the colliding nuclei have already passed through $\tau_{cross} = 2R/\gamma$;
  - that the system expands in a homogeneous and longitudinal manner, thus particle multiplicities present a plateau at mid-rapidity
- The energy density :
  at RHIC $\varepsilon_T \approx$ 5-10 GeV/(fm^{2}c)
  at LHC $\varepsilon_T \sim$ 15-30 GeV/(fm^{2}c)
  ⇒ The system is hotter and denser !



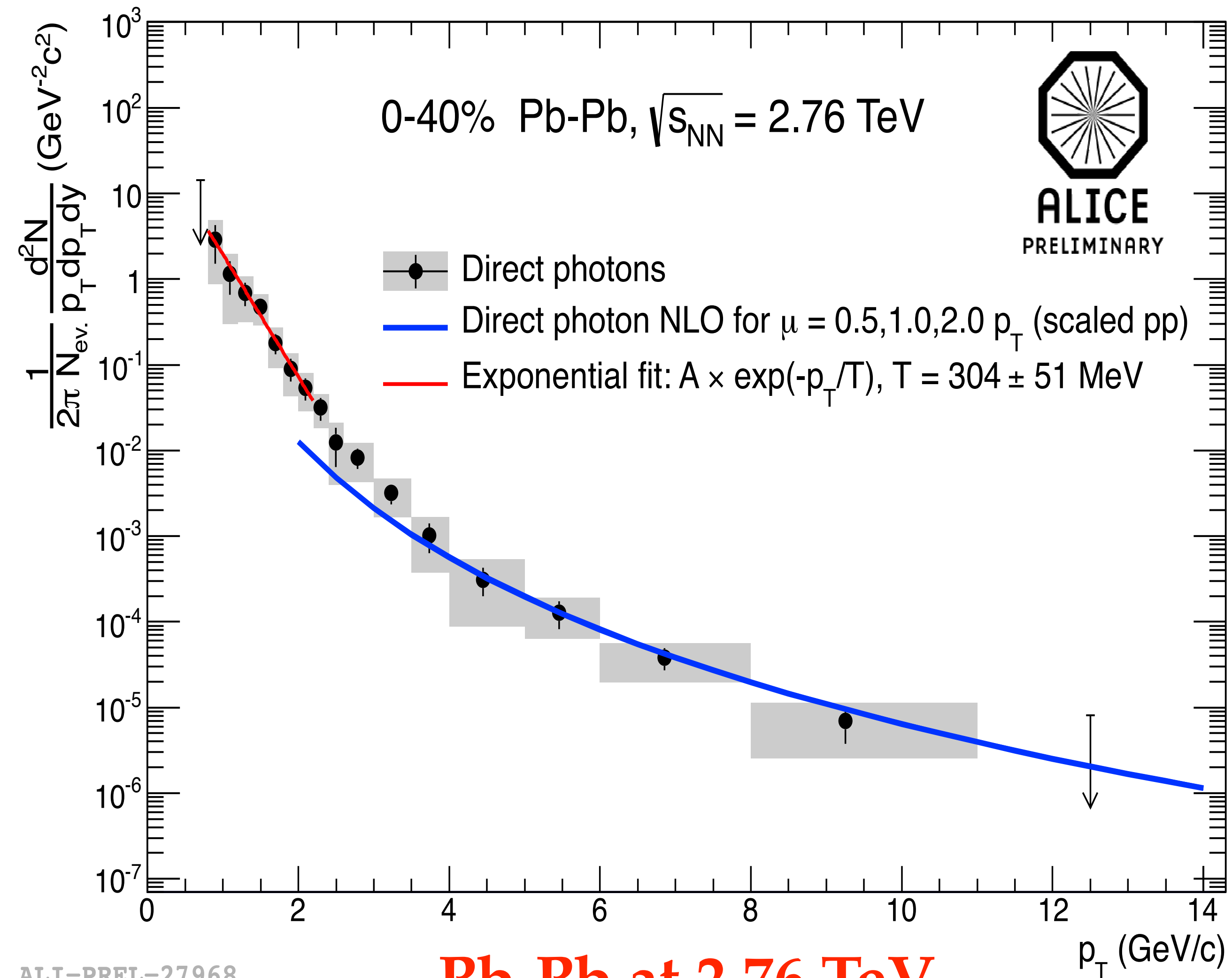


$$\epsilon = \frac{1}{\pi R^2 \tau}\frac{dE_t}{dy}, \qquad R = 1.12\, A^{1/3}\,\mathrm{fm}$$

Direct Photons

- Direct photons are those not produced by particle decays
  - Partonic hard interaction (prompt photons) are calculable by NLO pQCD
    ⇨ good reference (high p_T)
  - Jet medium interactions
    - qqbar annihilation in the QGP or hadron annihilation in hadronic phases
    - Parton bremsstrahlung or fragmentation processes
  - Thermal photons are exponentially decreasing, but dominant at low p_T

$$\gamma_{\rm direct} = \left(1 - \frac{\gamma_{\rm decay}}{\gamma_{\rm inclusive}}\right)\gamma_{\rm inclusive}$$

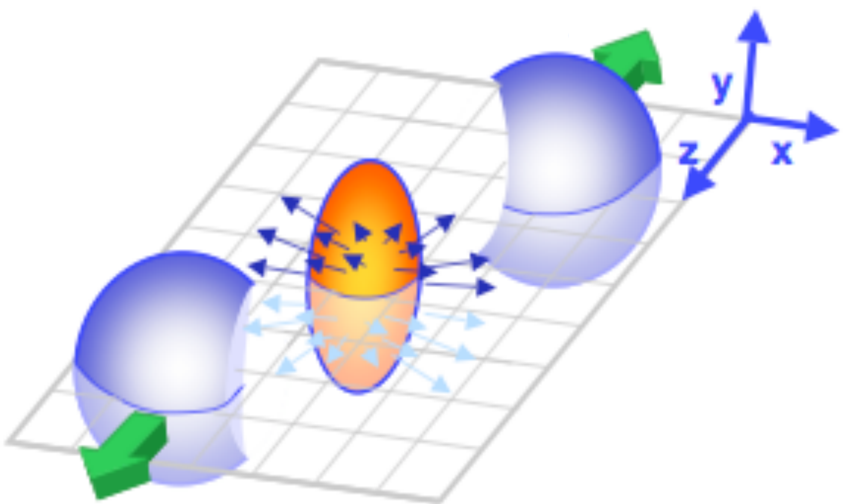


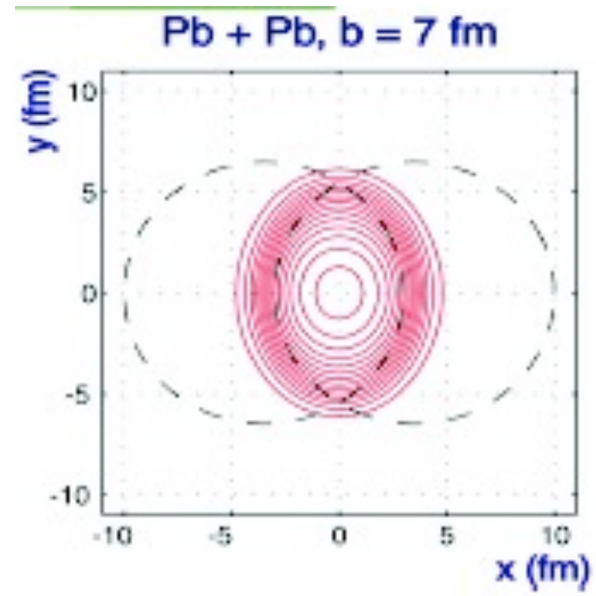
Pb-Pb at 2.76 TeV

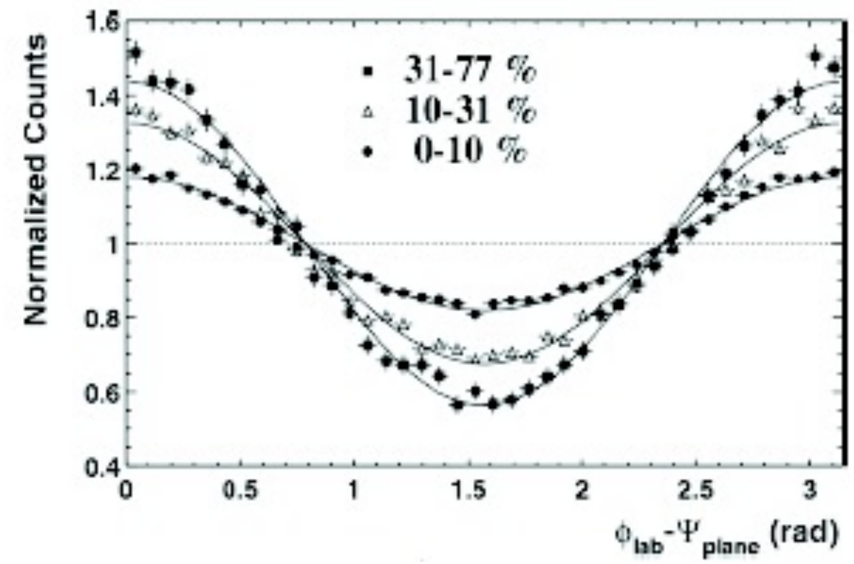
- NLO calculations in agreement with the spectrum for $p_T > 4$ GeV/c
- Low p_T part fit with exponential
  T = 304 ± 51 MeV for central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV.
  - That's **~1.4 x RHIC** or 3.4 trillion Kelvin.
  - That's 40x hotter than the core of a supernova, 250000x hotter than the center of the sun.

AZIMUTHAL ANISOTROPY

A. Toia, seminar Paris







Almond-shape spatial anisotropy in coordinate space → Interactions / Rescattering → Anisotropy in momentum space

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left(n\left(\phi - \Phi_{RP}\right)\right)\right)$$

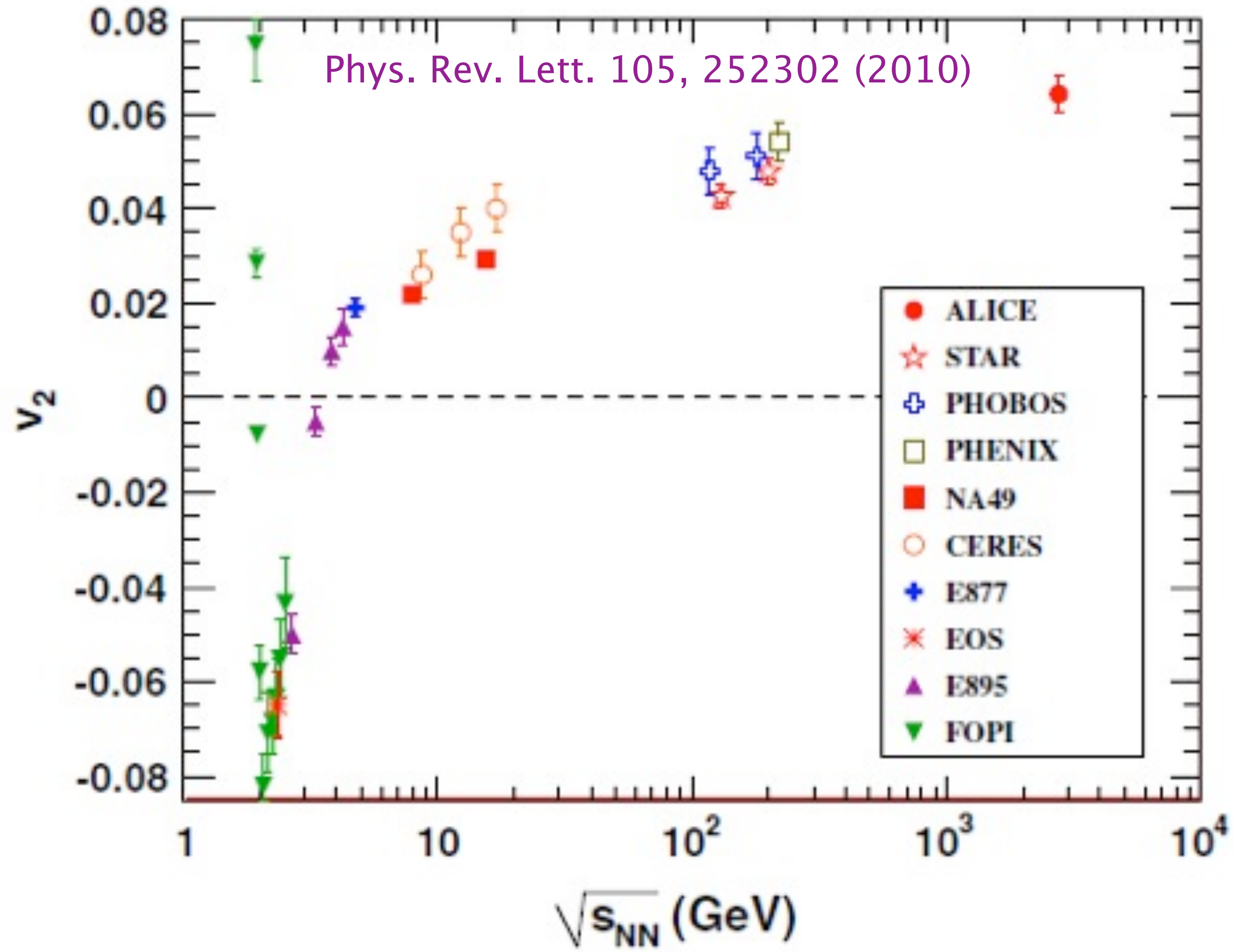
Elliptic flow ≡v_2 ≡ 2^{nd} Fourier component

- Boosted momentum emission wrt reaction plane
- Gases explode into vacuum uniformly in all directions.
- Liquids flow violently along the short axis and gently along the long axis.
- We can observe the medium and understand if it is more liquid-like or gas-like.

Elliptic Flow

Pb-Pb at 2.76 TeV

- At RHIC, it was concluded that the medium behaves as an ideal fluid with a shear viscosity over entropy ($1<4\pi(\eta/s)_{QGP} < 2.5$). Extremely strong interaction between partons in the QGP.
  Song H et al, Phys. Rev. Lett. 109, 192301 (2011), arXiv:1011.2783
- Hydrodynamic behavior continues at LHC
  v2 (p_T int.) LHC ~ 1.3 x (p_T int.) RHIC
- The overall increase is consistent with the increased radial expansion leading to a higher mean p_T



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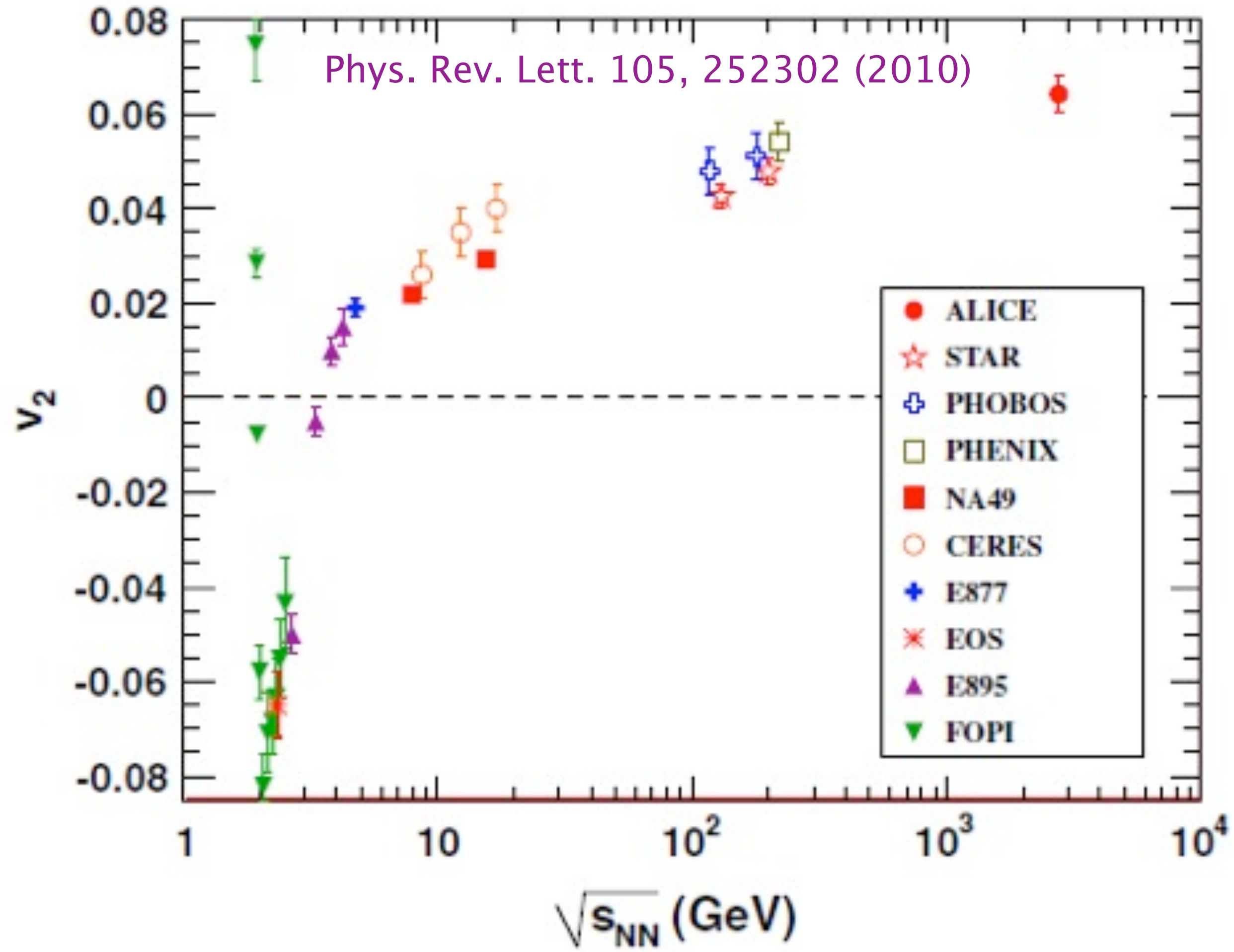
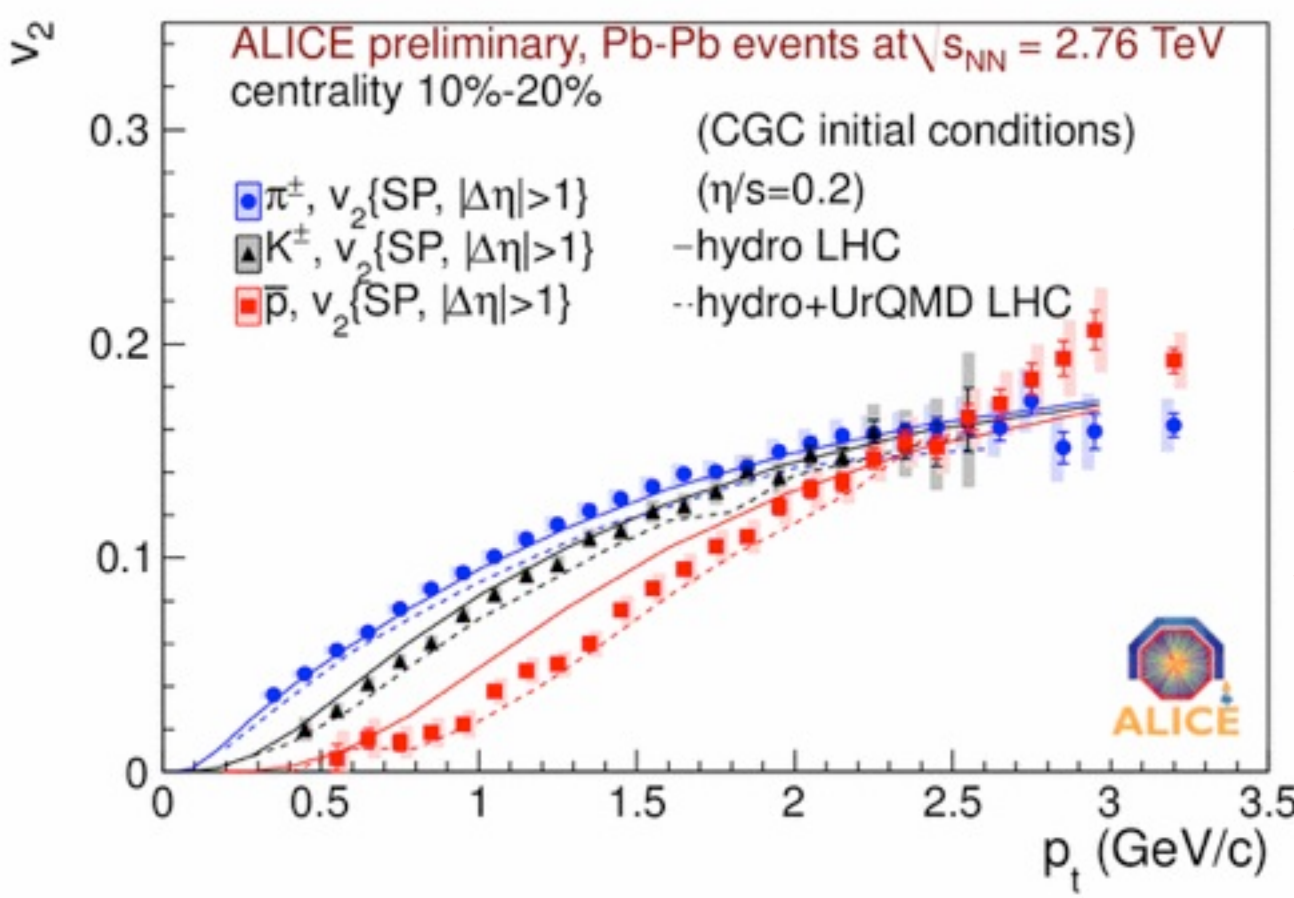
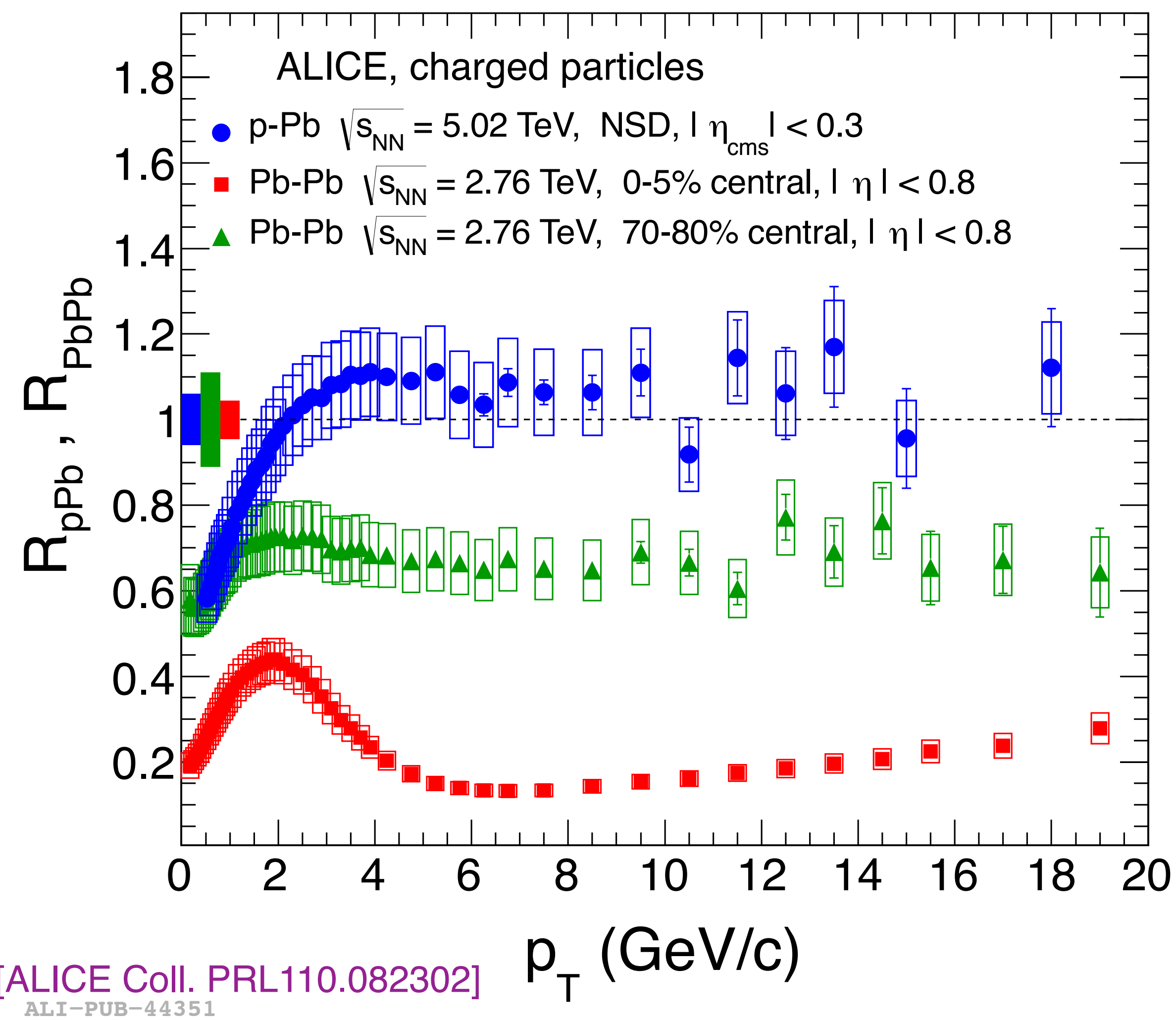




- Strong mass dependence, predicted by viscous hydro.
  (Heinz et. al, arXiv:1105.3226)
- Radial flow too small from hydro for protons
- Hadronic re-scatterings play an important role in flow development

High pt particle suppression



[ALICE Coll. PRL110.082302]

$$R_{AB} = \frac{1}{\langle T_{AB} \rangle} \frac{dN_{AB}/dp_T}{d\sigma_{pp}/dp_T} = \frac{1}{\langle N_{coll} \rangle_{AB}} \frac{dN_{AB}/dp_T}{dN_{pp}/dp_T}$$

p-Pb at 5.02 TeV
Pb-Pb at 2.76 TeV

- Strong suppression in the most central Pb-Pb collisions
- Consistent measurements of charged particles R_{AA} by CMS & ALICE
- Charged particles are more suppressed at LHC than at RHIC
  ⇒ Low pt bump likely due to initial state effects and collective flow
  ⇒ Evidence of strong parton energy loss and large medium density
  ⇒ High p_T behavior seemingly reproduced by pQCD elastic &/or inelastic energy loss

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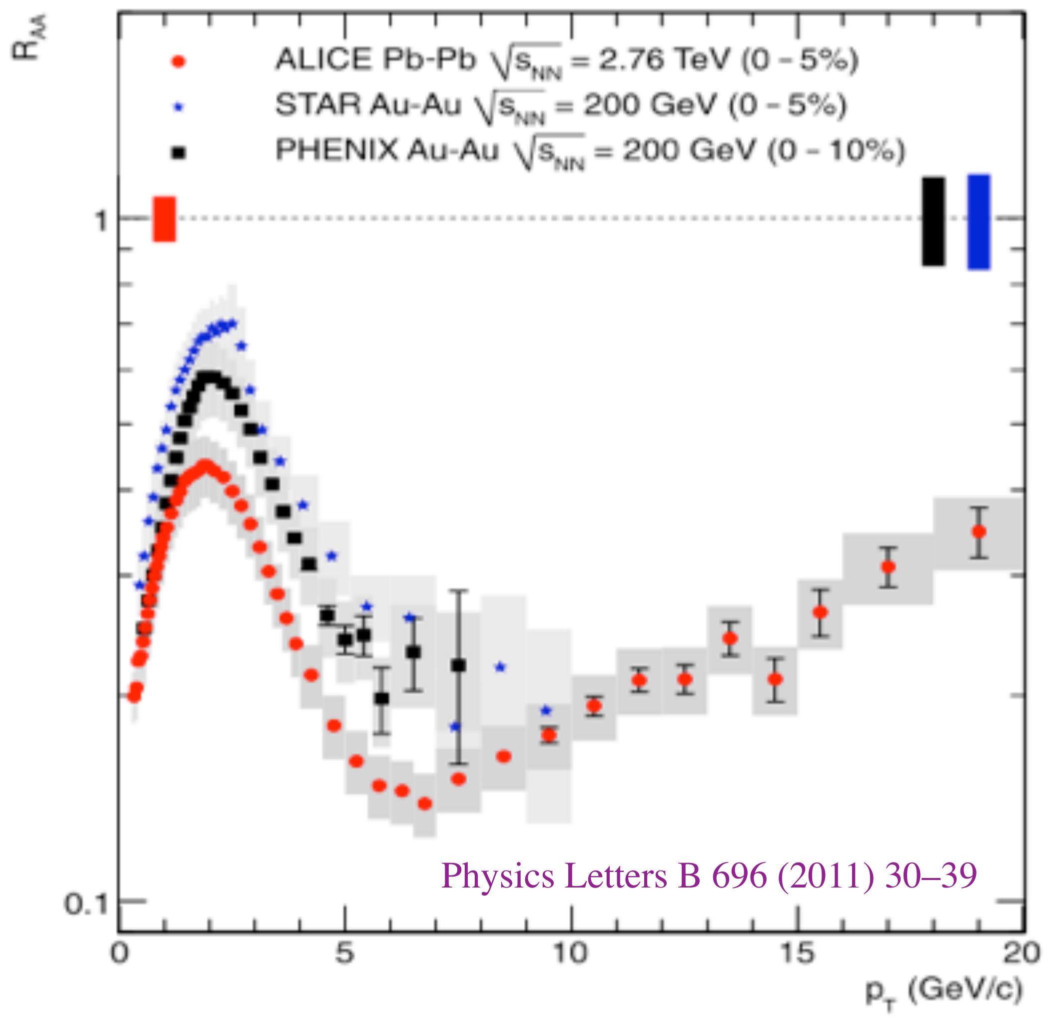

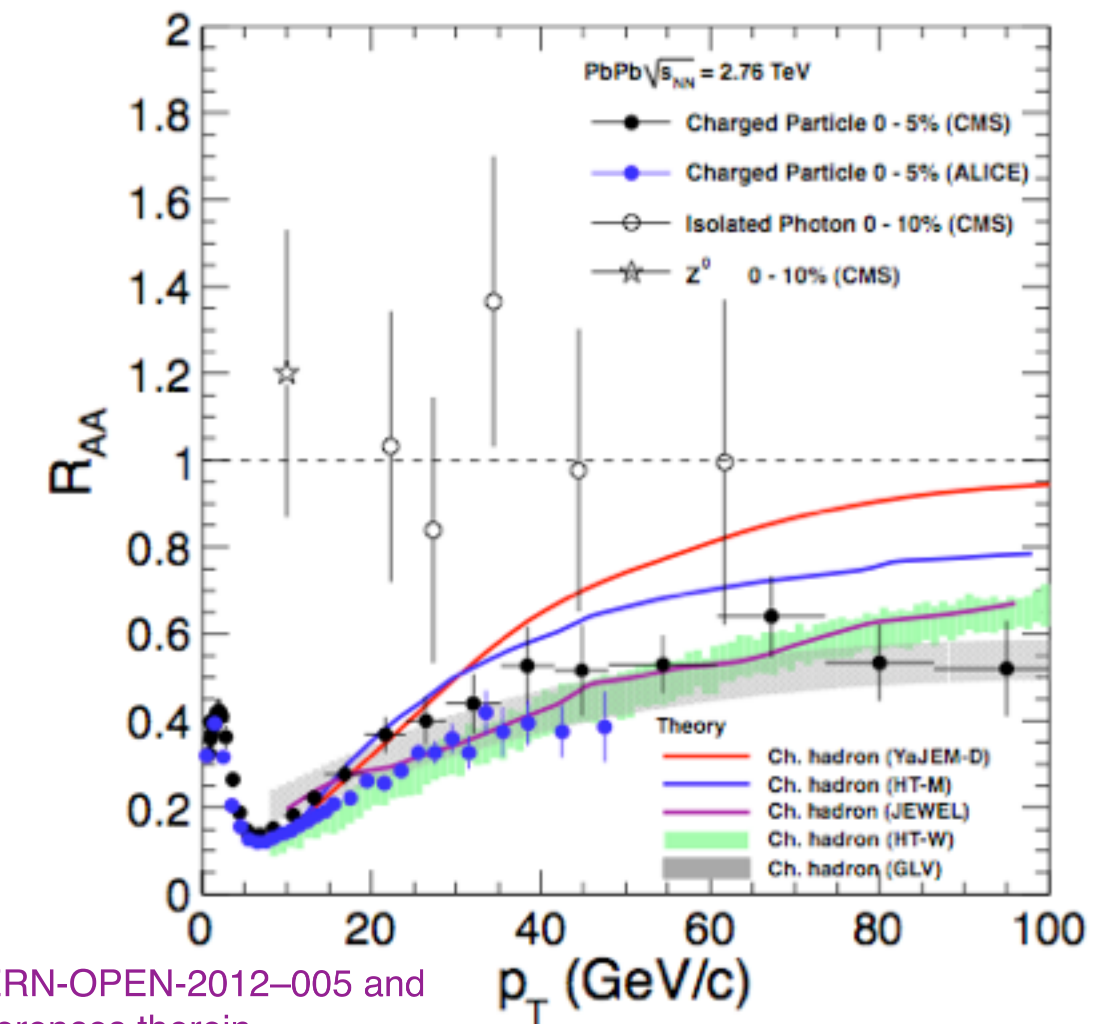

CERN-OPEN-2012–005 and references therein

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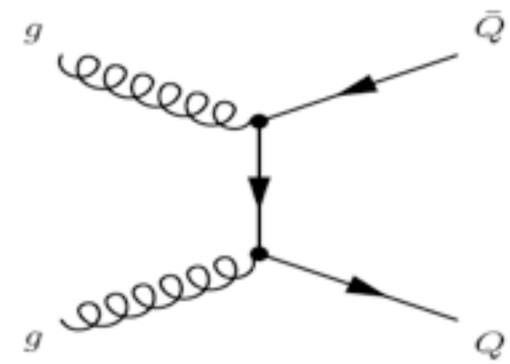
ALICE Results: pp & Pb-Pb

Focus on Heavy Flavor and Quarkonia

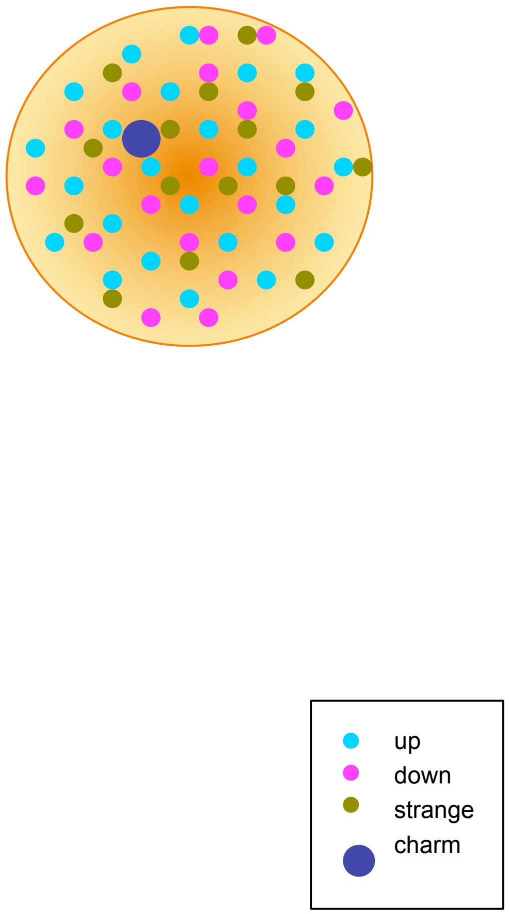
KeyWords: Heavy Quarks as QGP Probes

* Production in nucleon-nucleon collisions: pp collisions
  * Production time τ_p ~ 0.05 - 0.15 fm/c
  * ➡ **Tool to test pQCD calculations**



* Nuclear environment influence: p-A collisions
  * Shadowing (PDF modifications in nuclei) and Gluon saturation
  * ➡ **Tool to study high-density small-x gluons**

* Effects in a QGP: A-B collisions
  * Energy loss in the QGP (high p_T)
  * Thermalisation in the QGP (low p_T)
  * ➡ **Probe the QCD medium**



Cartoons just for illustration

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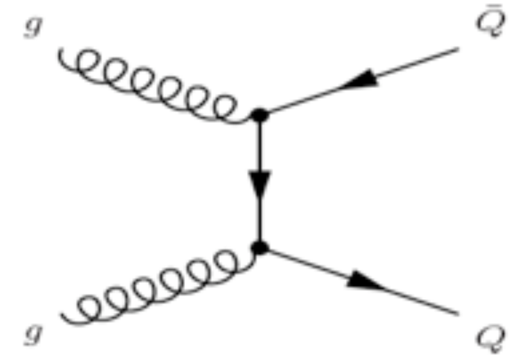

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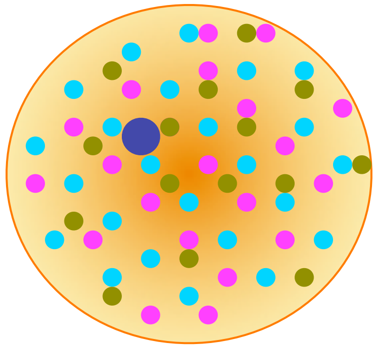

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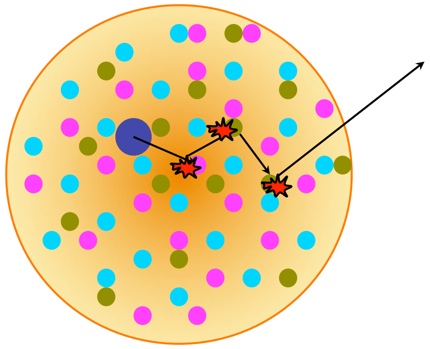

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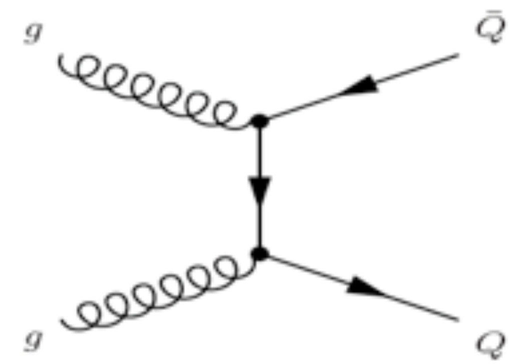

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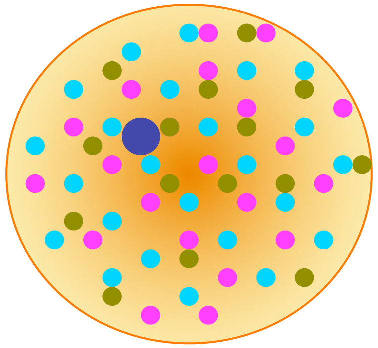

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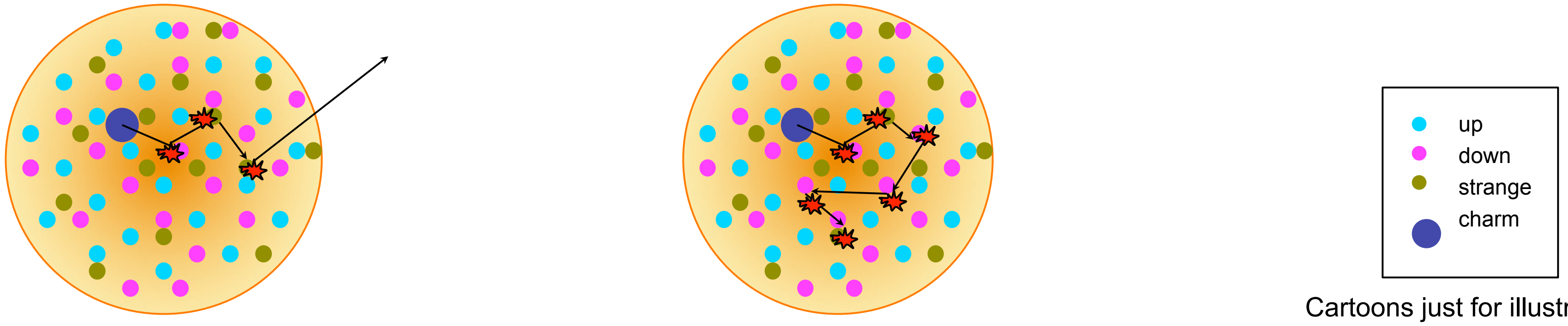
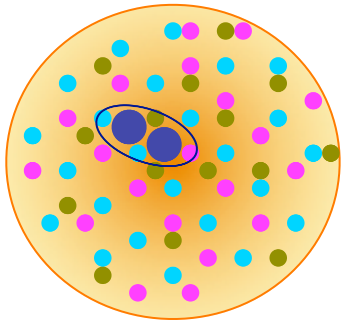


Cartoons just for illustration

KeyWords: Quarkonia as QGP Probes



- Production in nucleon-nucleon collisions
  - Ressonances formation time $\tau_f \sim 0.4 - 1.0$ fm/c
    Decay time $\tau_d \sim 1000$ fm/c
- Effects in QGP
  - Dissociation
    Example: by color screening, based on lQCD calculations that predict sequential states dissociation

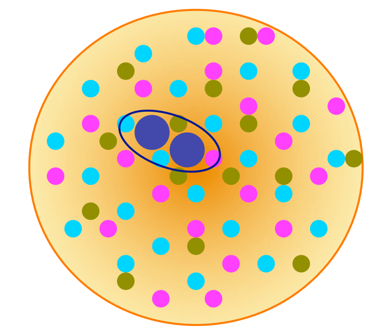
	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon'(2S)$	$\chi_b'(2P)$	$\Upsilon''(3S)$
M [GeV]	3.10	3.41	3.69	9.46	9.86	10.02	10.23	10.36
E_s^i [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
T_d/T_c	2.1	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

[Satz, JPG 32 R25 (2006)]

  - Regeneration
    Recombination of heavy quarks.
- Remarks:
  - Important feed-down
    - 40% for the J/Ψ from χ_c and Ψ'
    - 45% from higher ressonances for the Υ (30% for the Υ')
  - Charmonia are produced both in prompt and non-prompt (b-decays) processes

KeyWords: Quarkonia as QGP Probes

- Production in nucleon-nucleon collisions
  - Ressonances formation time τ_f ~ 0.4 - 1.0 fm/c
    Decay time τ_d ~ 1000 fm/c



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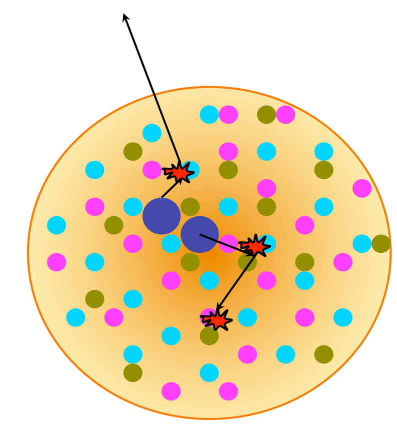

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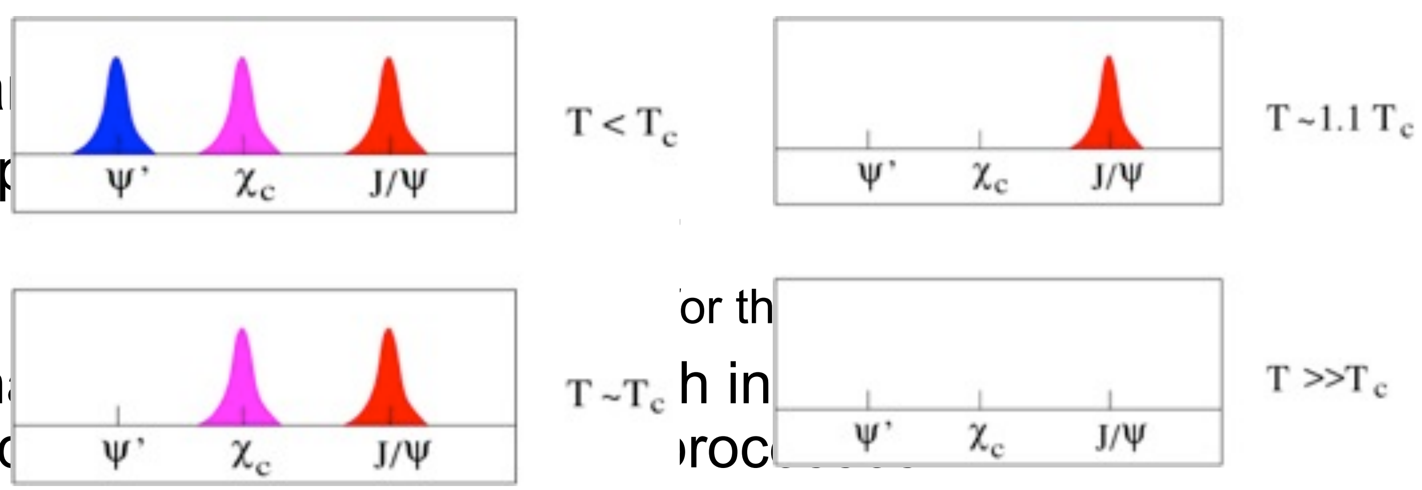

KeyWords: Quarkonia as QGP Probes

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  - Ressonances formation time $\tau_f \sim 0.4$ - 1.0 fm/c
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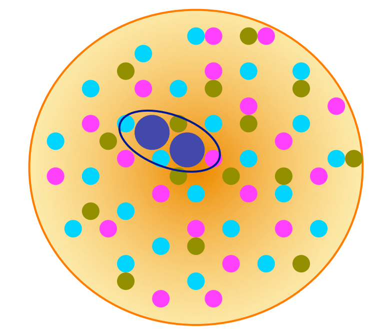
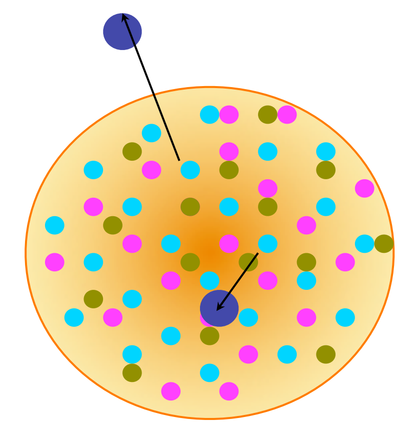


- Effects in QGP
  - Dissociation

    Example: by color screening, based on lQCD calculations that predict sequential states dissociation



	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon'(2S)$	$\chi_b'(2P)$	$\Upsilon''(3S)$
M [GeV]	3.10	3.41	3.69	9.46	9.86	10.02	10.23	10.36
E_s^i [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
T_d/T_c	2.1	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17

[Satz, JPG 32 R25 (2006)]

  - Regeneration

    Recombination of heavy quarks.

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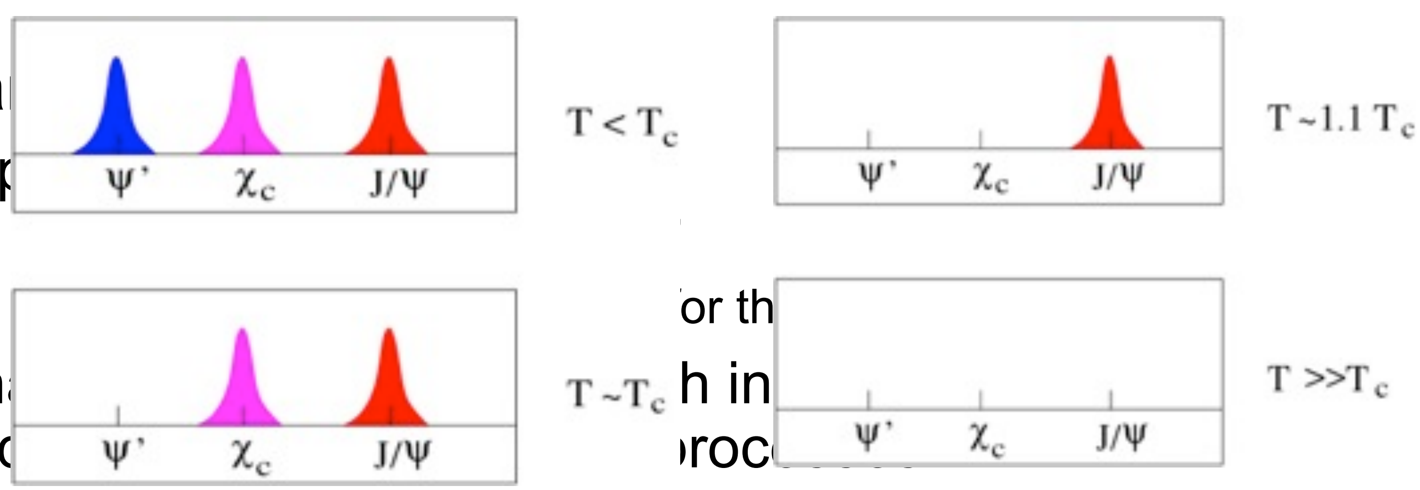
  and roc



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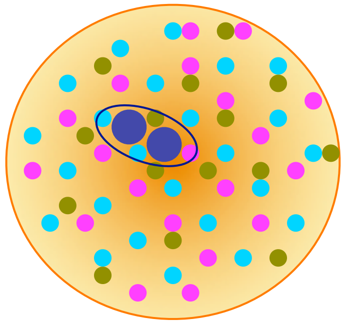

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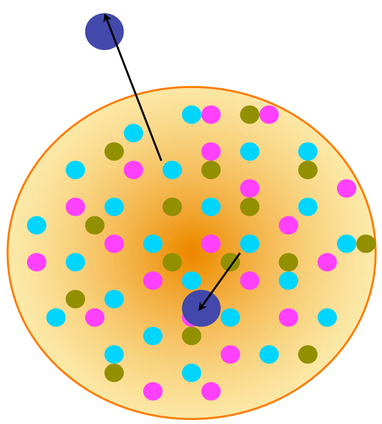

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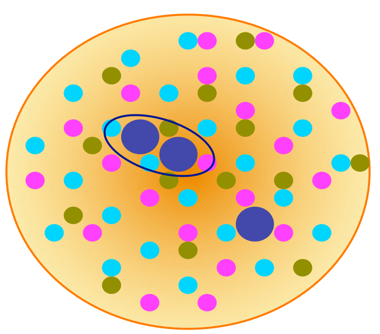
- Remarks:
  - Important feed-down
    - 40% for the J/Ψ from χ_c and Ψ'
    - 45% from higher ressonances for the Υ (30% for the Υ')
  - Charmonia are produced both in prompt and non-prompt (b-decays) processes



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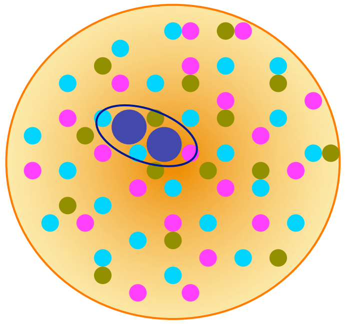

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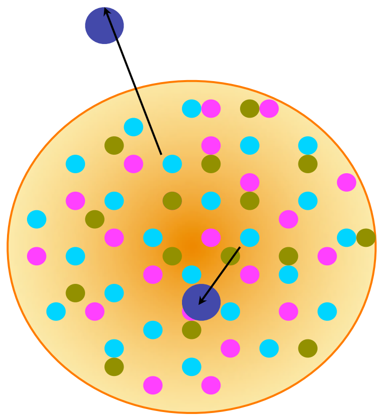

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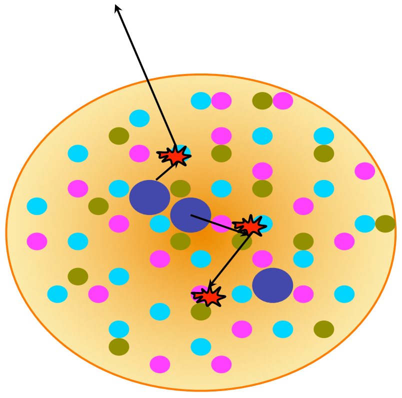

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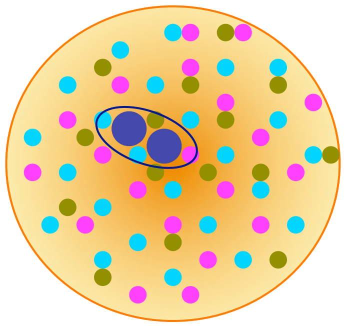

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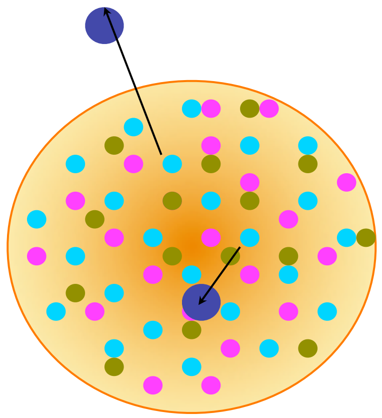

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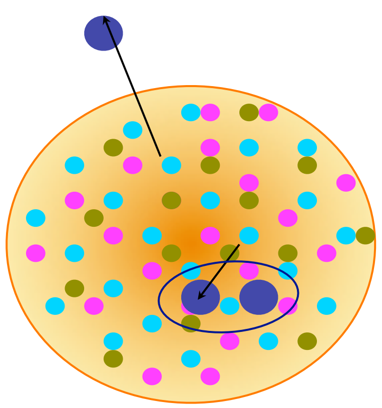

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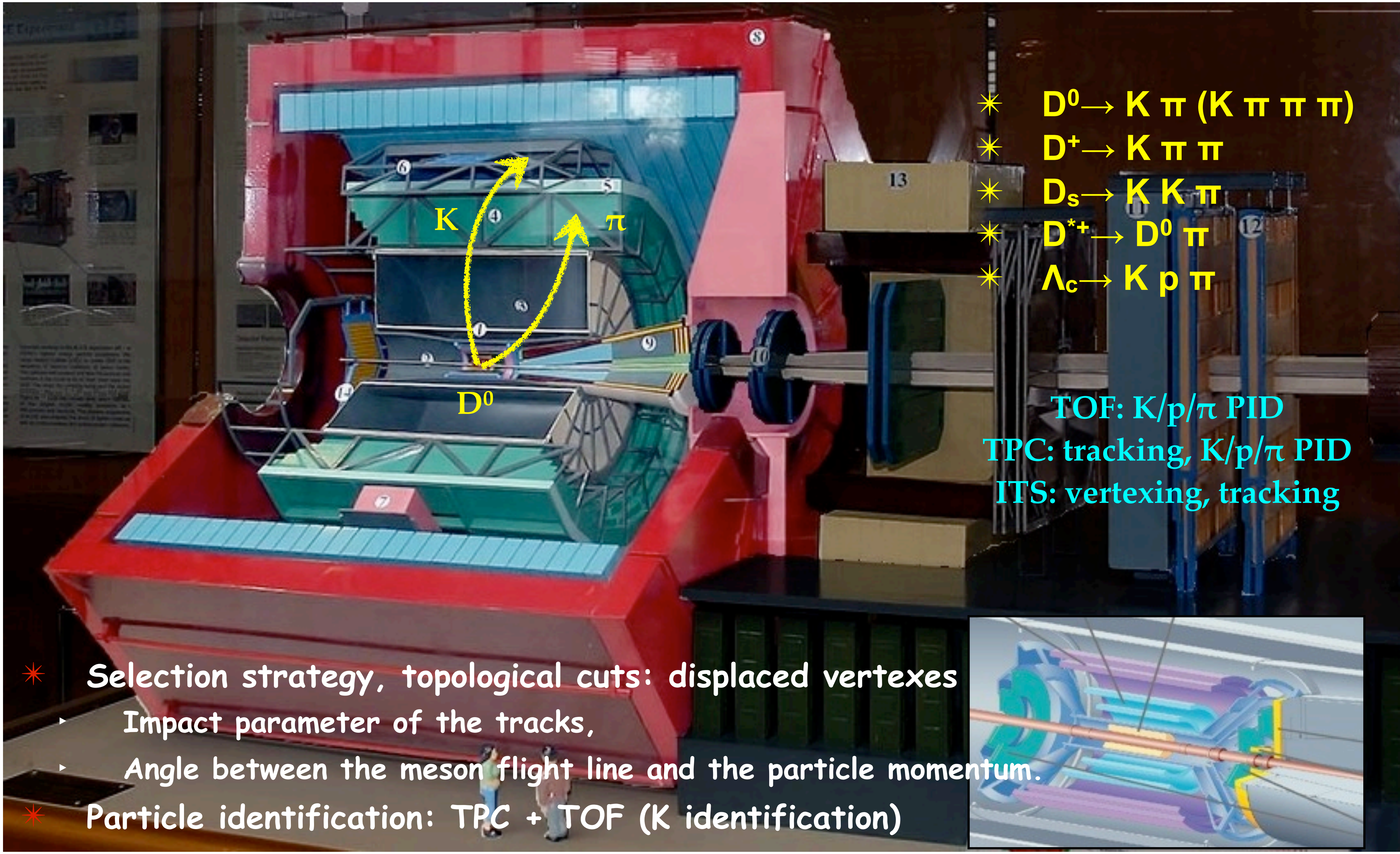
D mesons at |y|<0.8

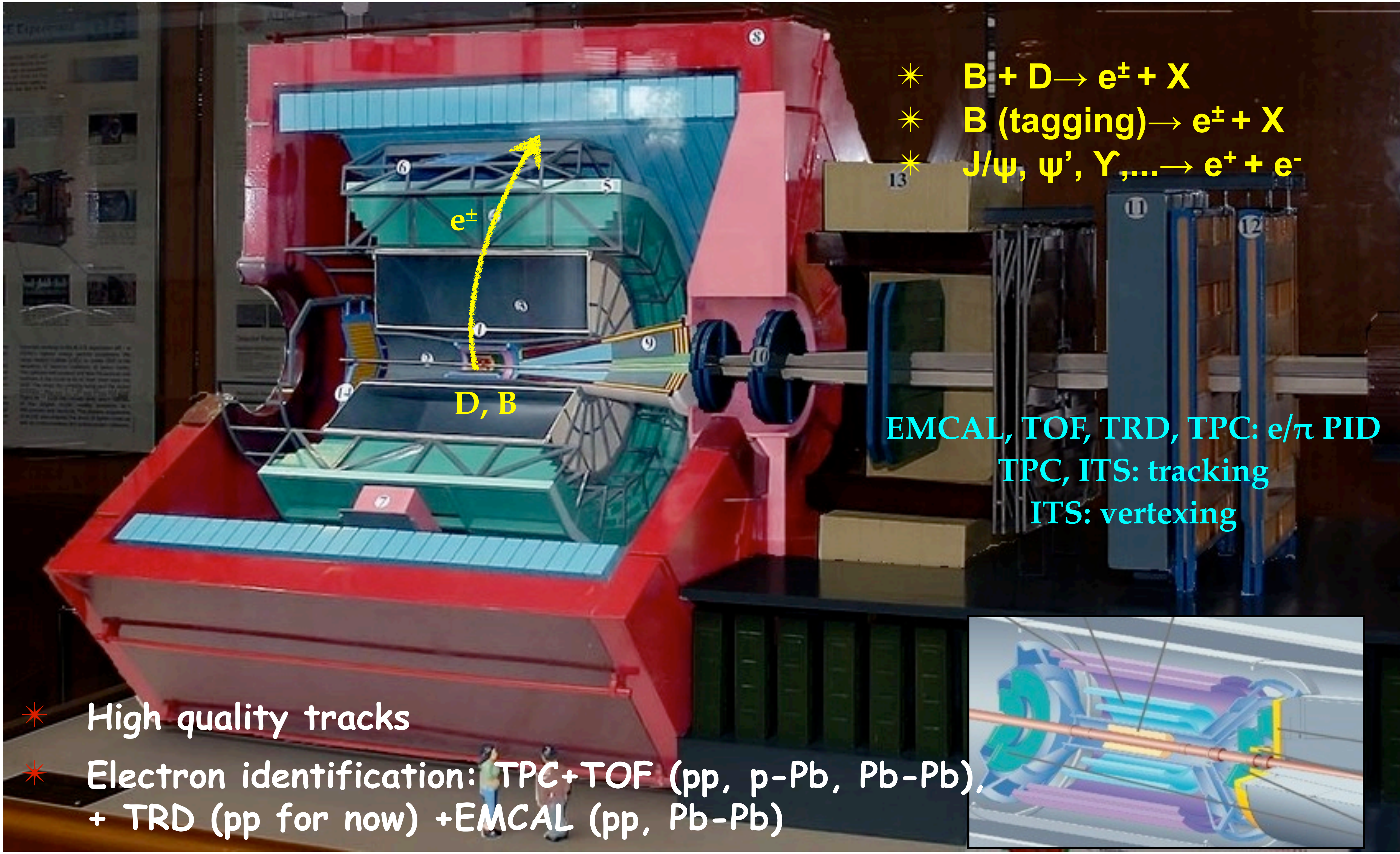


- $D^0 \rightarrow K\,\pi\ (K\,\pi\,\pi\,\pi)$
- $D^+ \rightarrow K\,\pi\,\pi$
- $D_s \rightarrow K\,K\,\pi$
- $D^{*+} \rightarrow D^0\,\pi$
- $\Lambda_c \rightarrow K\,p\,\pi$

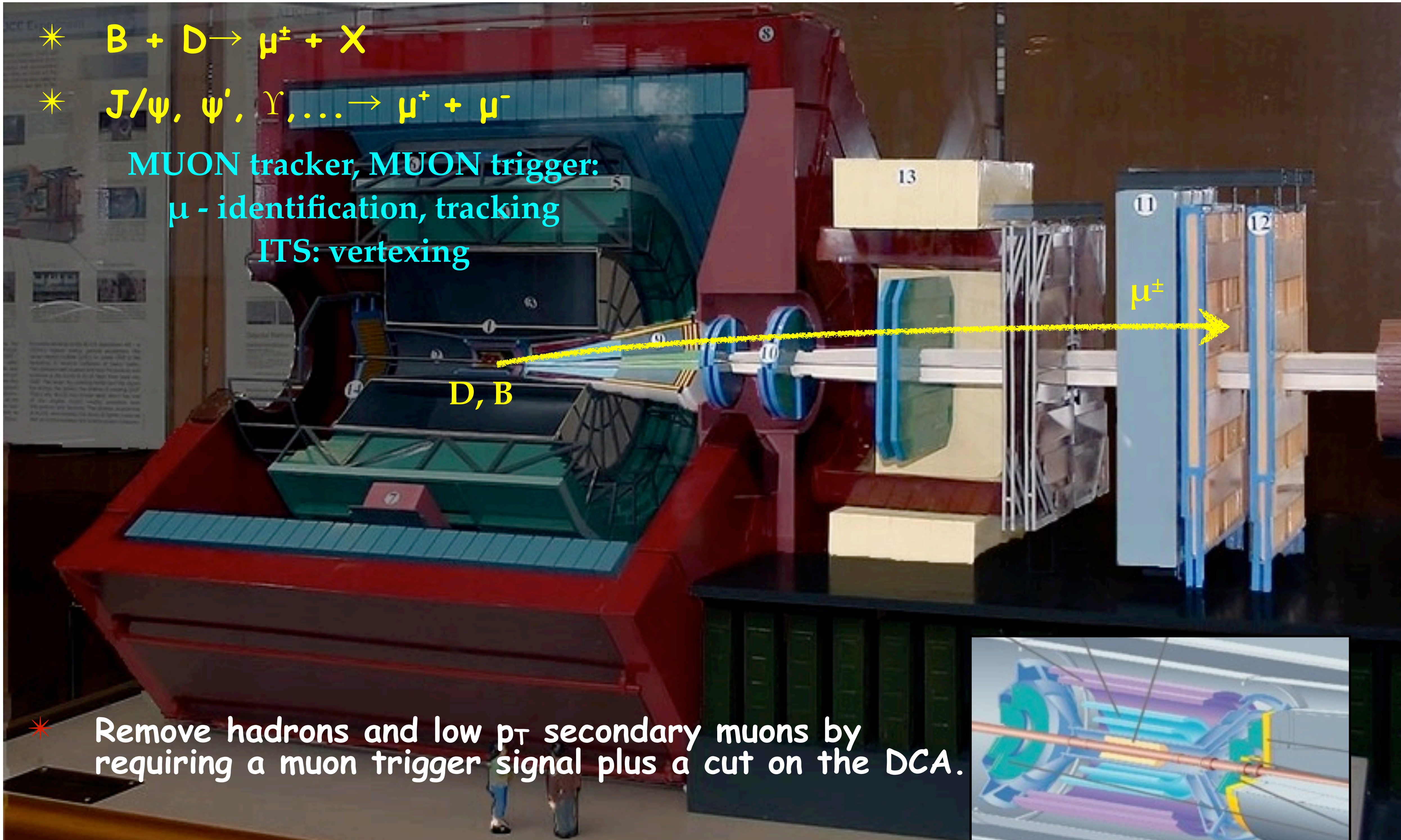
TOF: K/p/π PID
TPC: tracking, K/p/π PID
ITS: vertexing, tracking

- Selection strategy, topological cuts: displaced vertexes
  - Impact parameter of the tracks,
  - Angle between the meson flight line and the particle momentum.
- Particle identification: TPC + TOF (K identification)

HF & Onia, Electrons at $|\eta|<0.8$



HF & Onia, muons at $-4.0<\eta<-2.5$



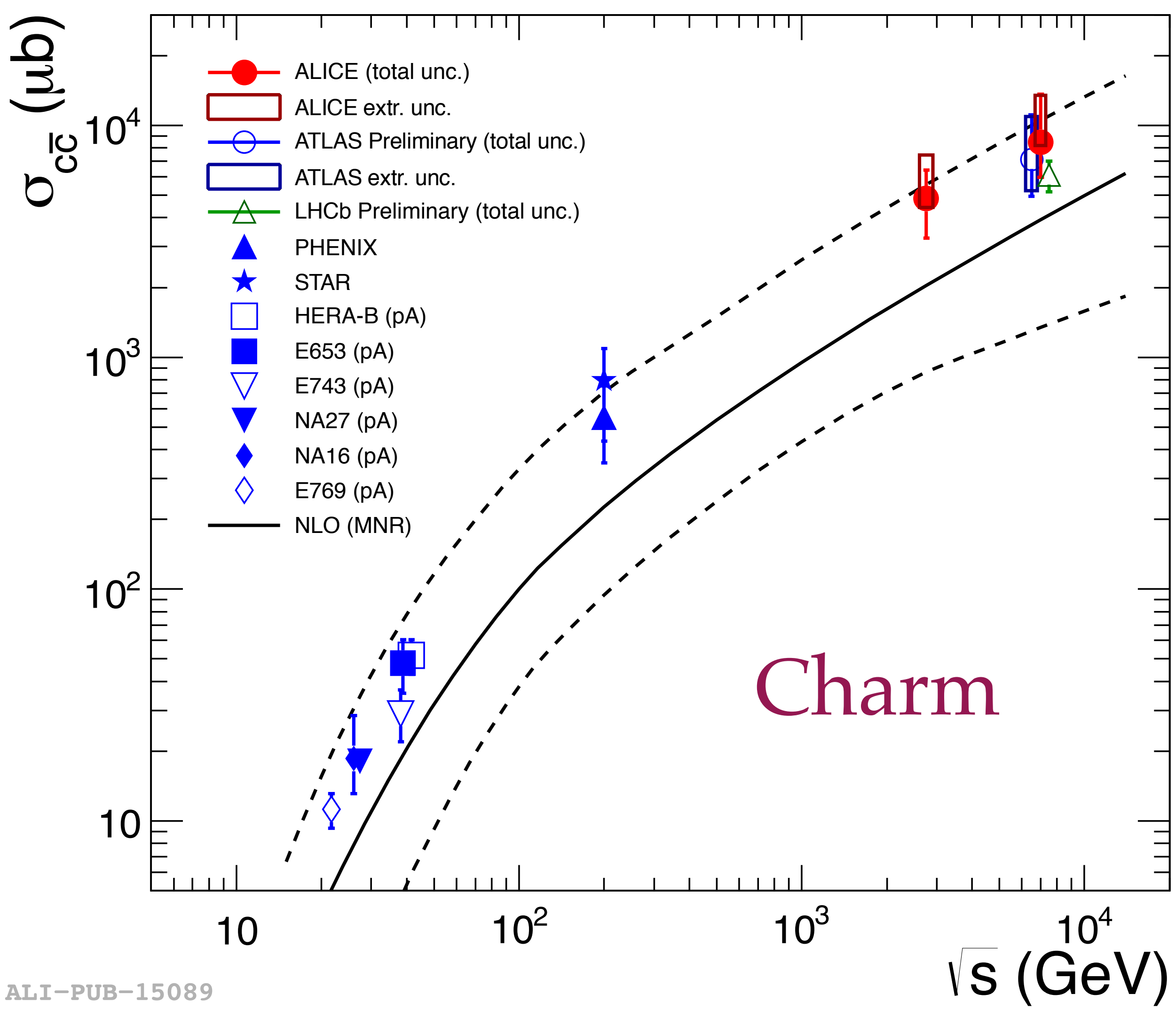
- $B + D \rightarrow \mu^{\pm} + X$
- $J/\psi,\ \psi',\ \Upsilon, \ldots \rightarrow \mu^{+} + \mu^{-}$

MUON tracker, MUON trigger:
μ - identification, tracking
ITS: vertexing

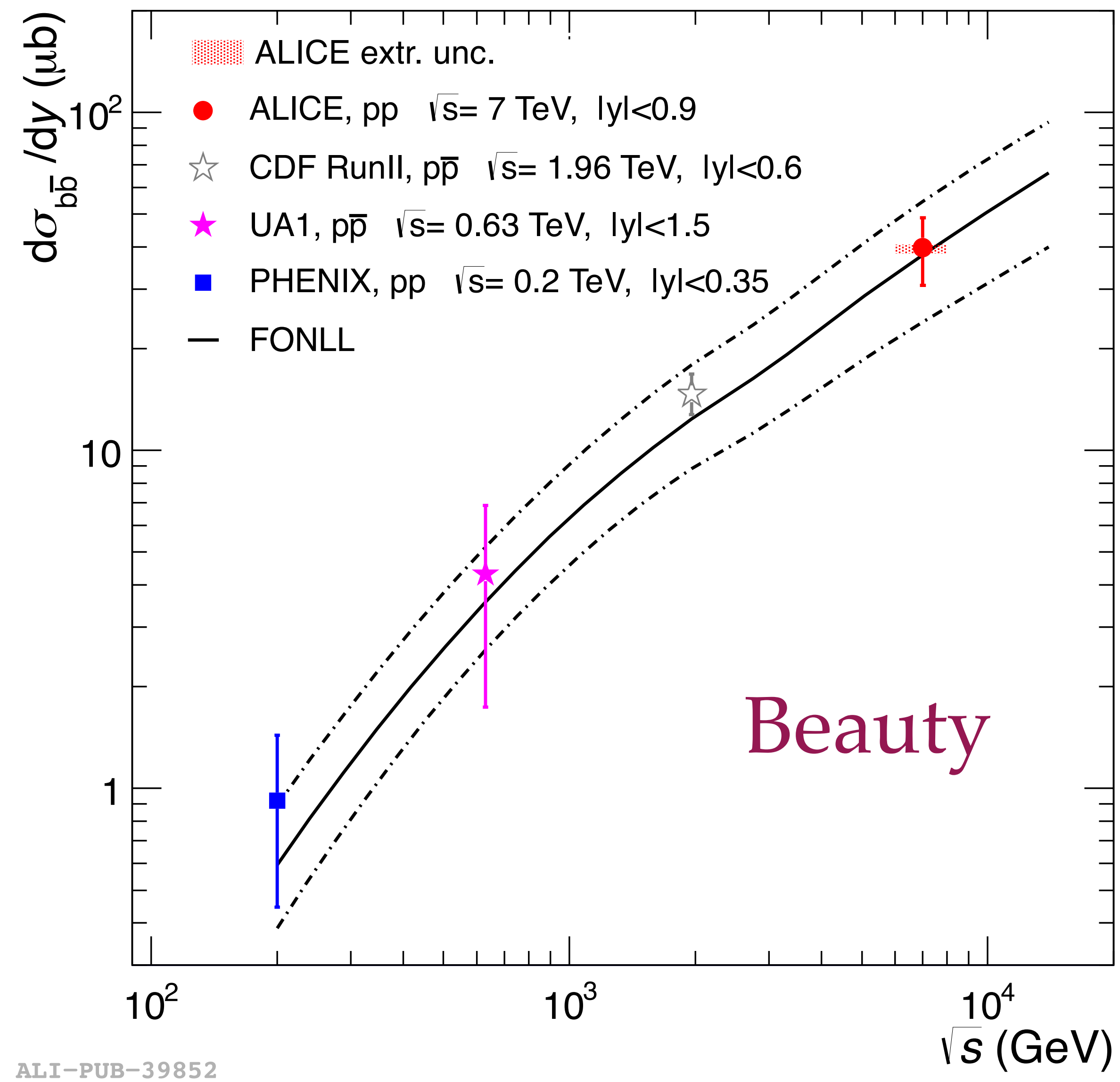
- Remove hadrons and low p_T secondary muons by requiring a muon trigger signal plus a cut on the DCA.

Charm and Beauty Cross Sections

[ALICE Coll. JHEP 07 (2012) 191]



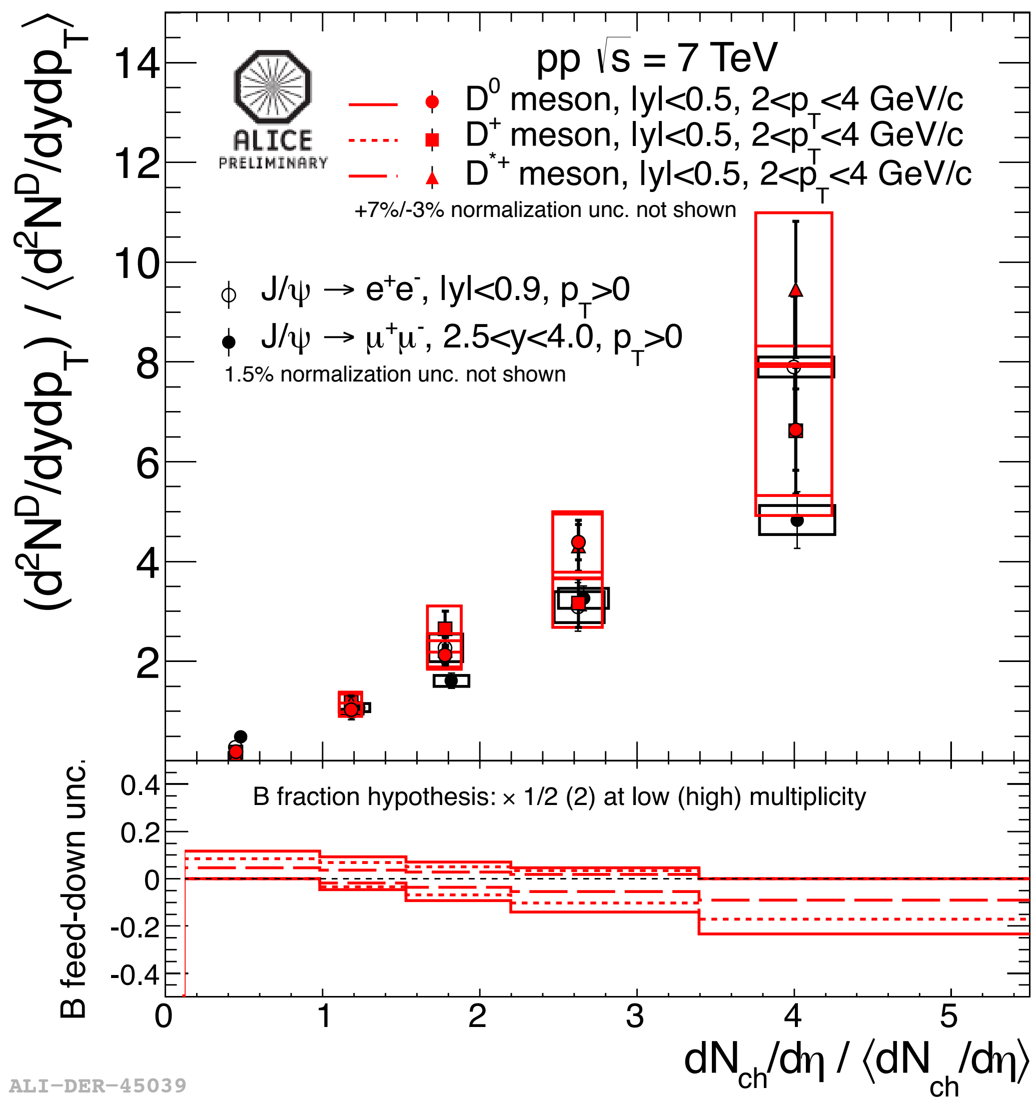
[ALICE Coll. arXiv: 1208.1902 (2012), JHEP1211 (2012) 065]

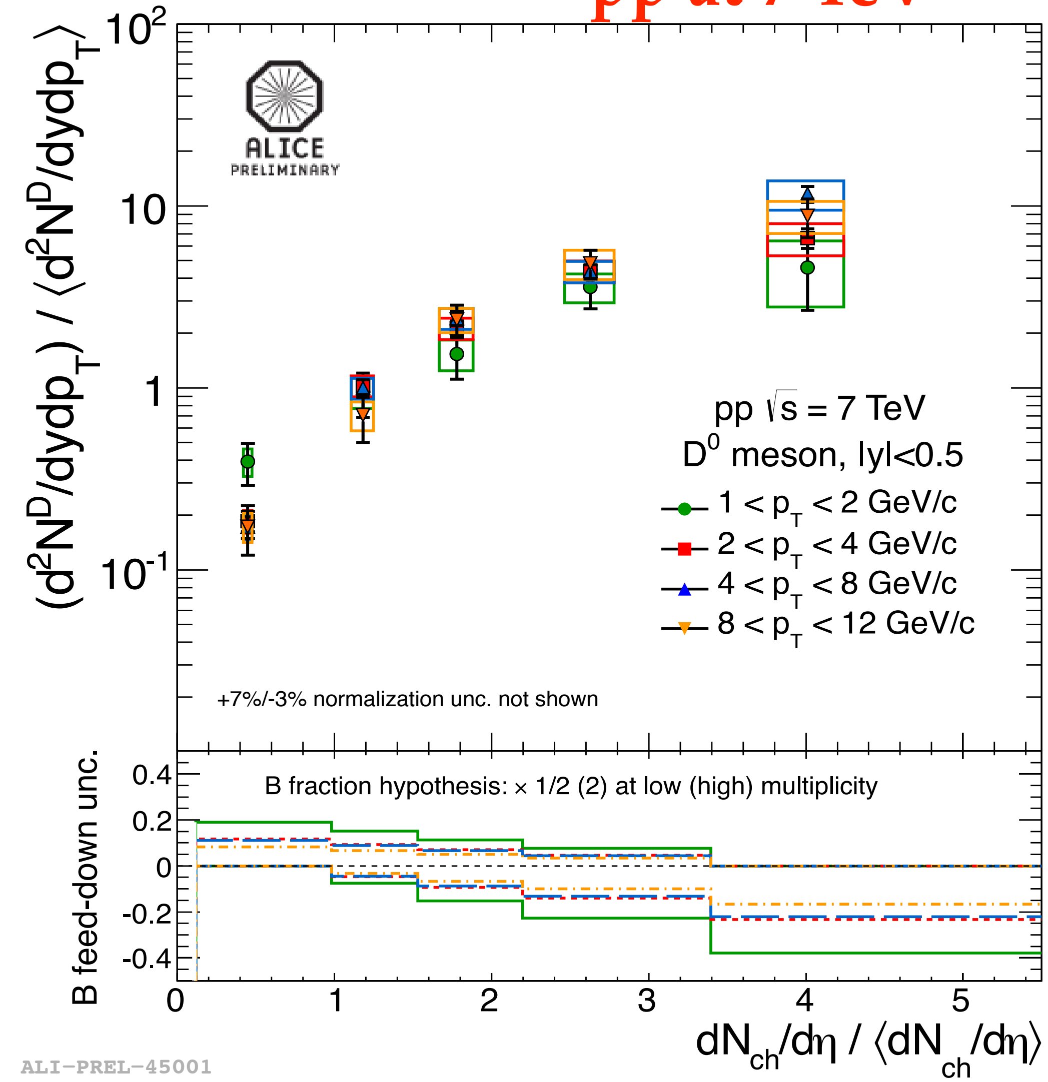


- **Their cross section evolution with √s is well described by pQCD.**
- ~560 μb × 950 collisions / 42mb ~ 13 cc pairs in 0-10% AuAu at 200 GeV
- ~5 mb × 1500 collisions / 65mb ~ 115 cc pairs in 0-10% PbPb at 2.76 TeV

Charm(onia) Multiplicity Dependence

pp at 7 TeV

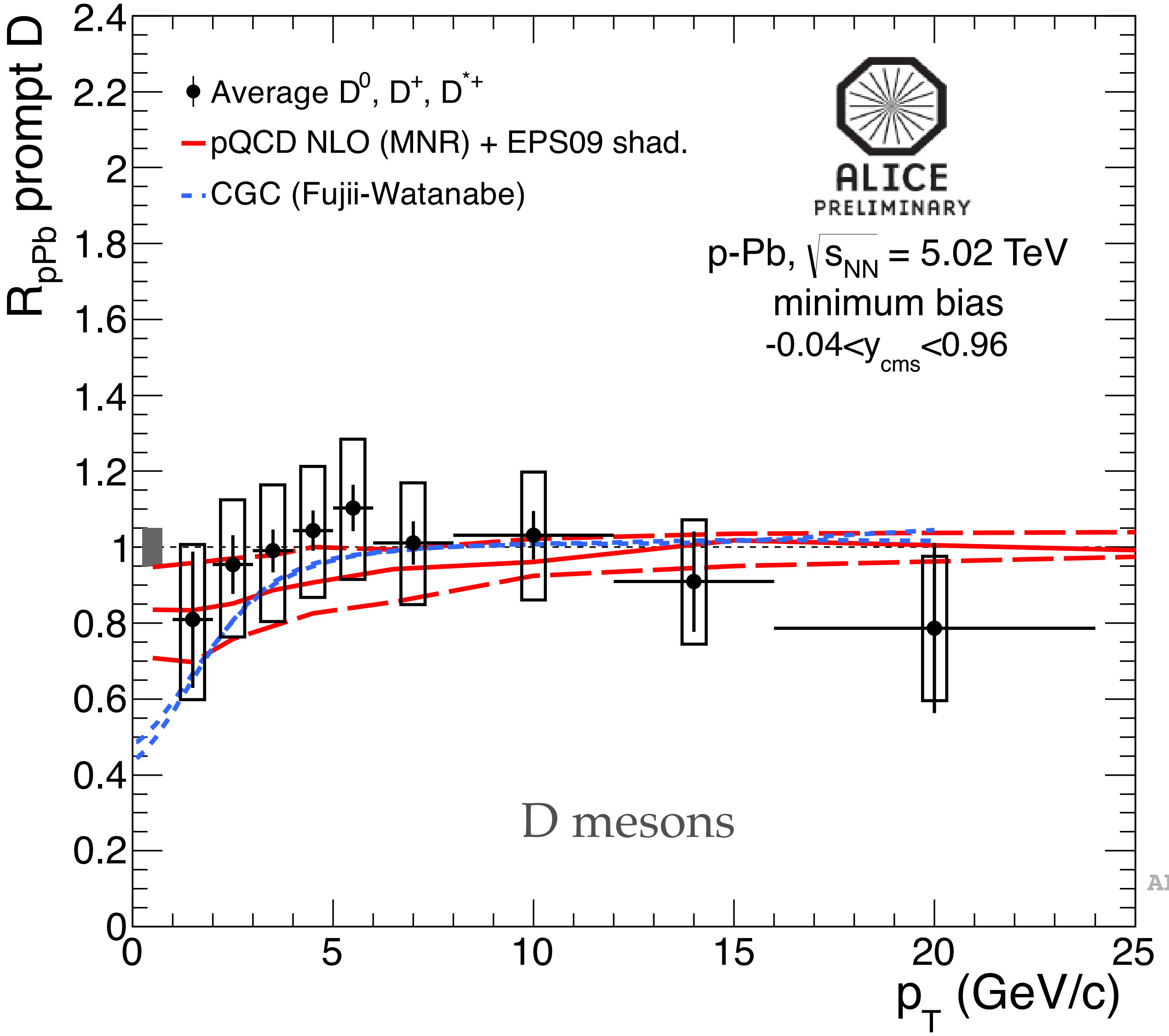


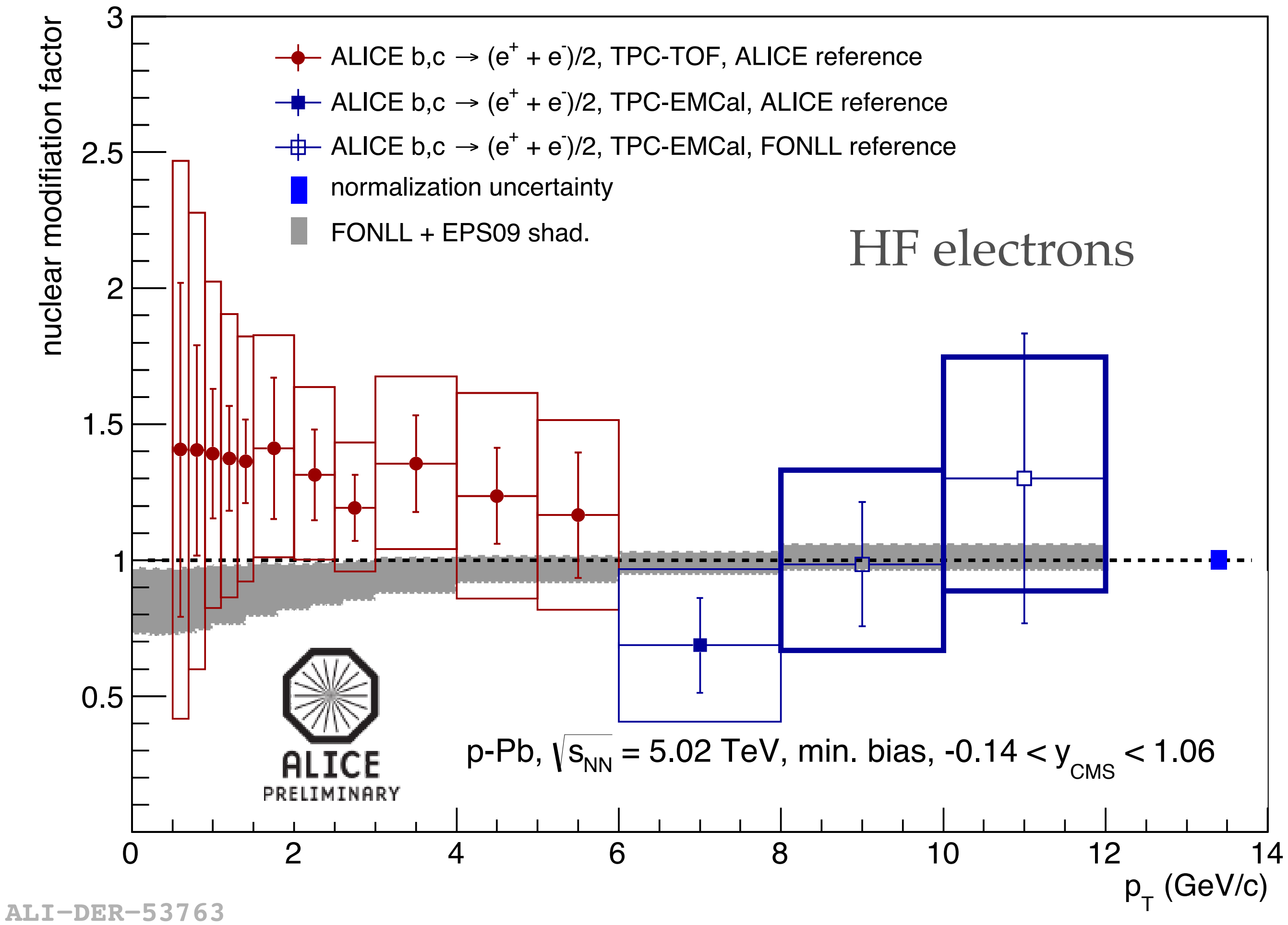


- ✳ Charged particle multiplicity in high-multiplicity pp collisions at 7 TeV is larger than the multiplicity in the peripheral CuCu collisions at 200 GeV
- ✳ **Similar increase of prompt-D and J/ψ production vs multiplicity**
- ✳ **No clear p_T dependence on the prompt-D relative yields vs multiplicity**
- ✳ **Hints for multi-parton interactions at a hard scale in pp collisions**

[ALICE Coll, Phys.Lett.B712 (2012) 165-175] [B.Alveretal (PHOBOS Coll.), Phys.Rev.C83,024913(2011).]

Open HF in p-Pb collisions





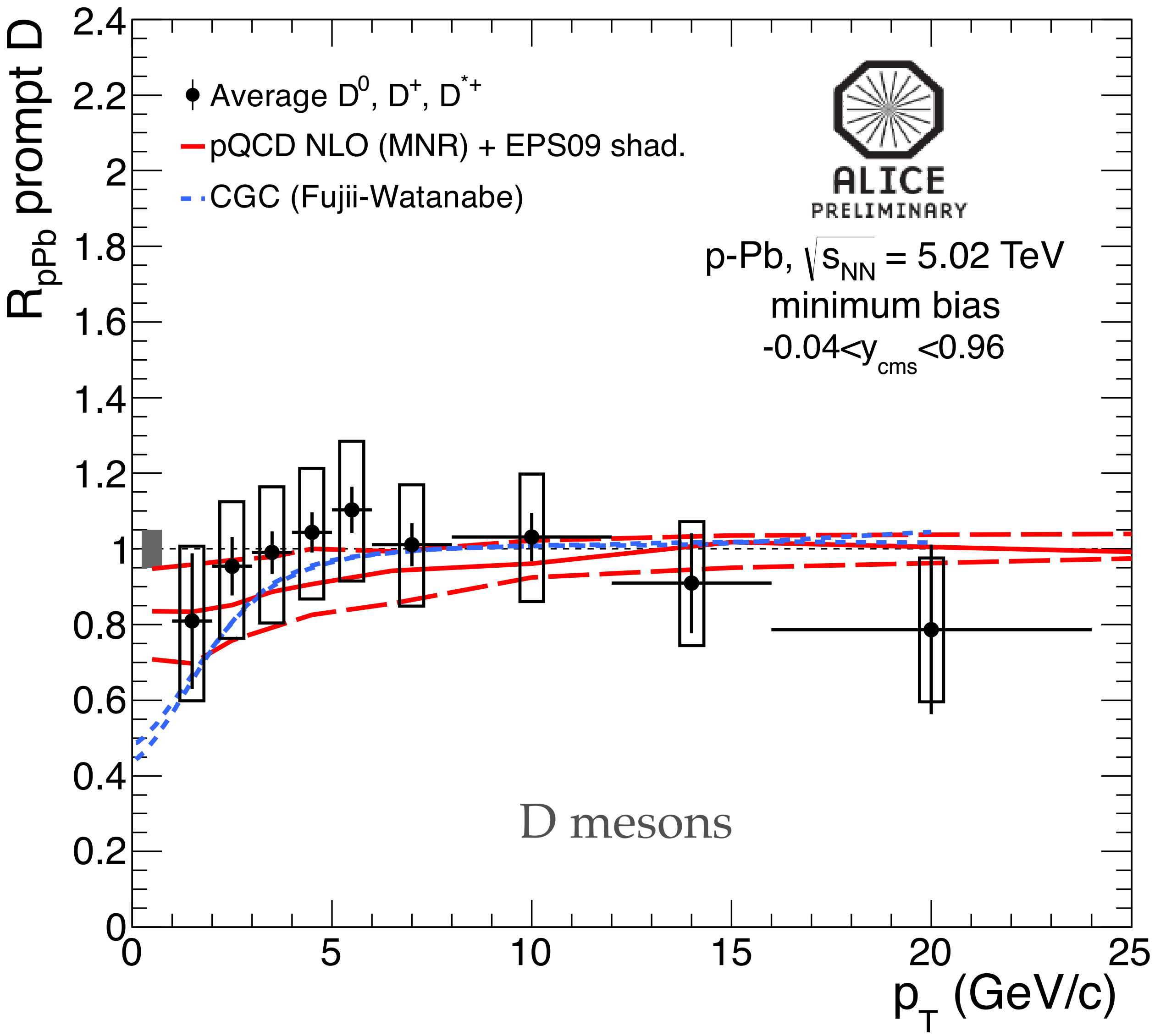
$$R_{\mathrm{AB}} = \frac{1}{\langle T_{\mathrm{AB}}\rangle}\frac{\mathrm{d}N_{\mathrm{AB}}/\mathrm{d}p_T}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_T} = \frac{1}{\langle N_{\mathrm{coll}}\rangle_{\mathrm{AB}}}\frac{\mathrm{d}N_{\mathrm{AB}}/\mathrm{d}p_T}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_T}$$

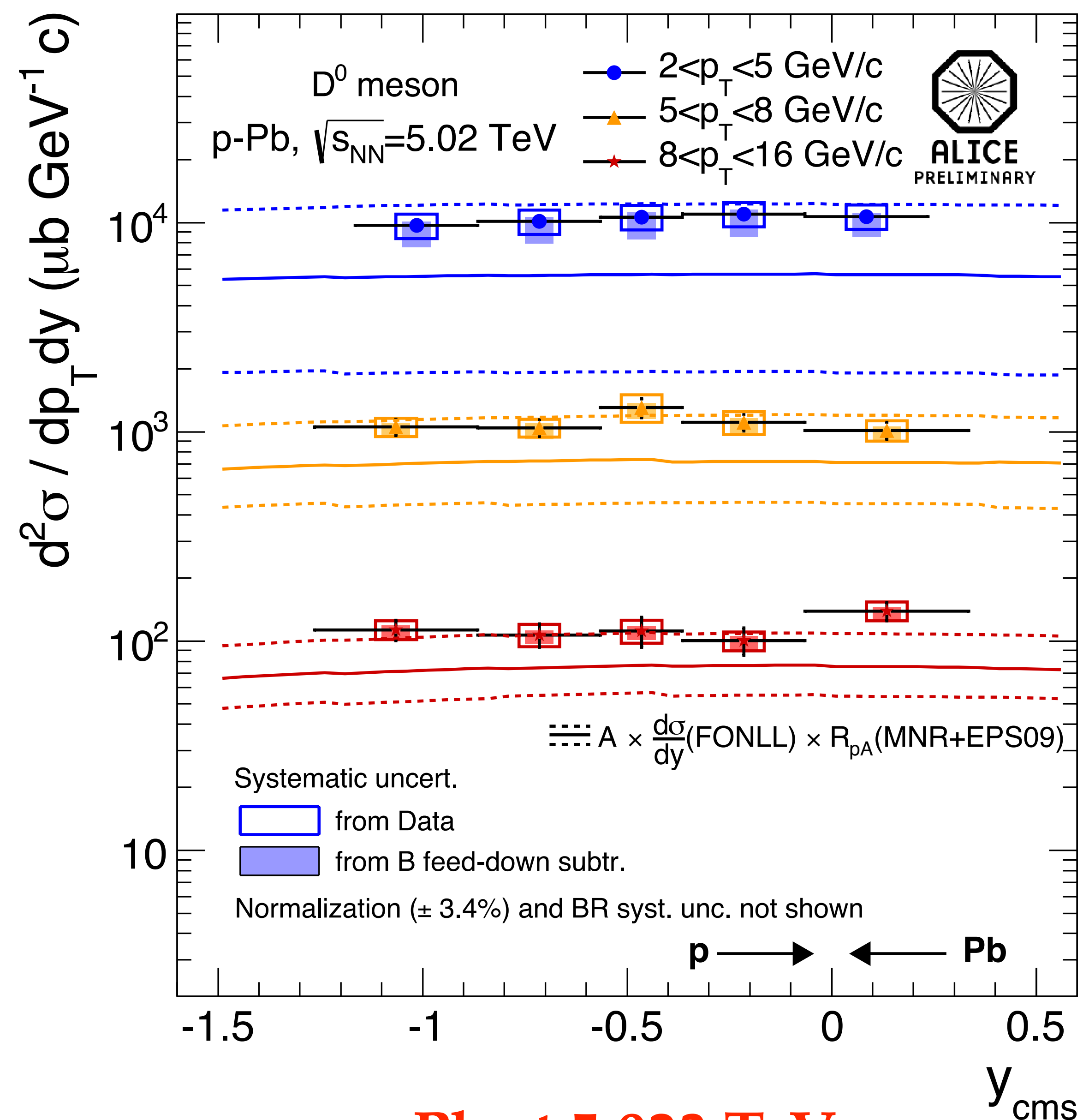
p-Pb at 5.023 TeV

D. Stocco, SQM13

- ➡ **Good agreement with MNR calculations with EPS09 shadowing**
- ➡ **Also well described by CGC predictions**
- ➡ **Nuclear effects expected to be small for high p_T Pb-Pb collisions**

Open HF in p-Pb collisions





$$R_{AB} = \frac{1}{\langle T_{AB} \rangle} \frac{dN_{AB}/dp_T}{d\sigma_{pp}/dp_T} = \frac{1}{\langle N_{coll} \rangle_{AB}} \frac{dN_{AB}/dp_T}{dN_{pp}/dp_T}$$

ALI-DER-61952

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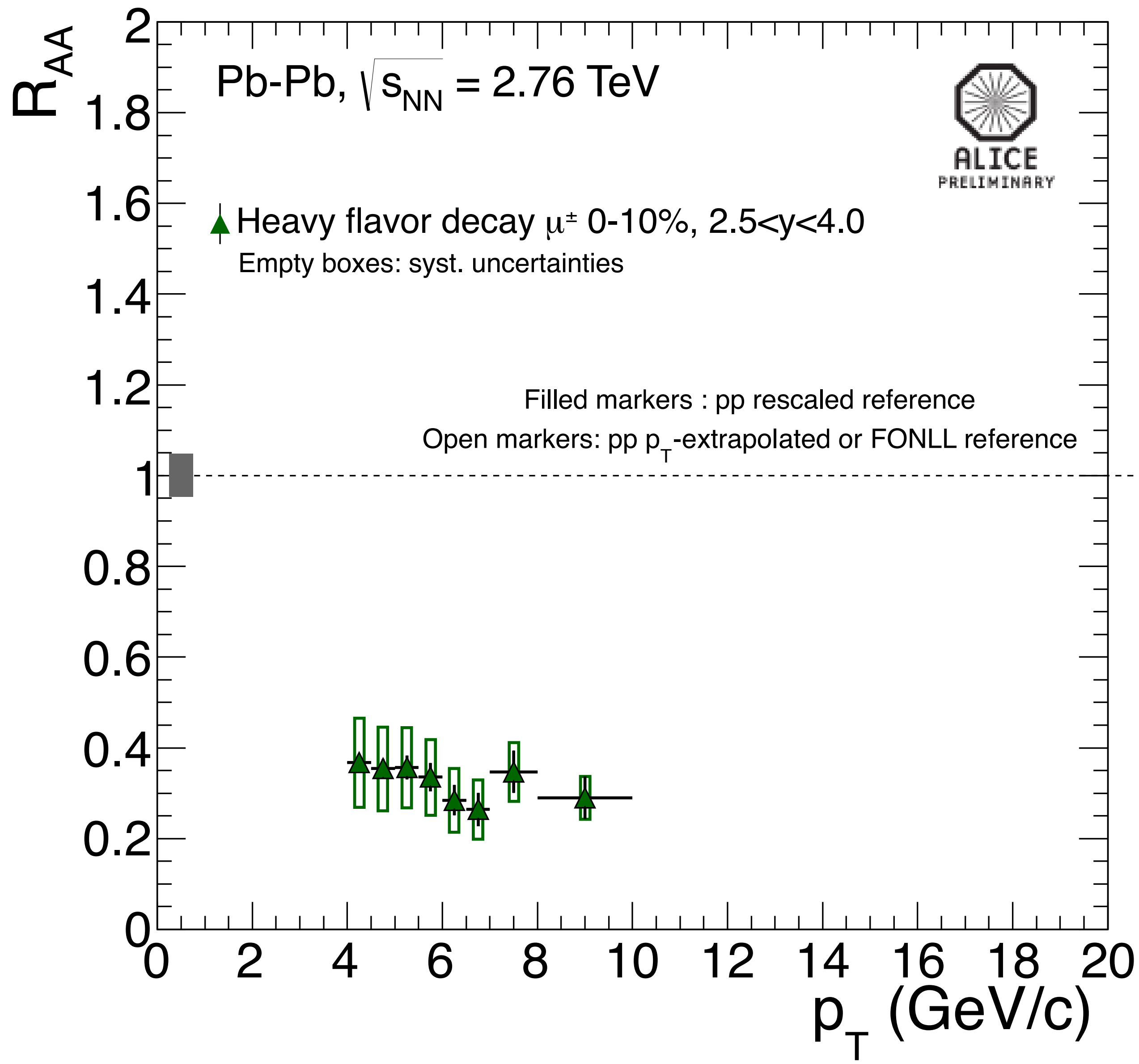
Heavy Flavor Suppression



Pb-Pb at 2.76 TeV

- ➡ **Strong heavy flavor suppression**
- ➡ **Similar HF decay e (|y|<0.6) and μ (2.5<y<4.0) R_{AA} in 0-10%**

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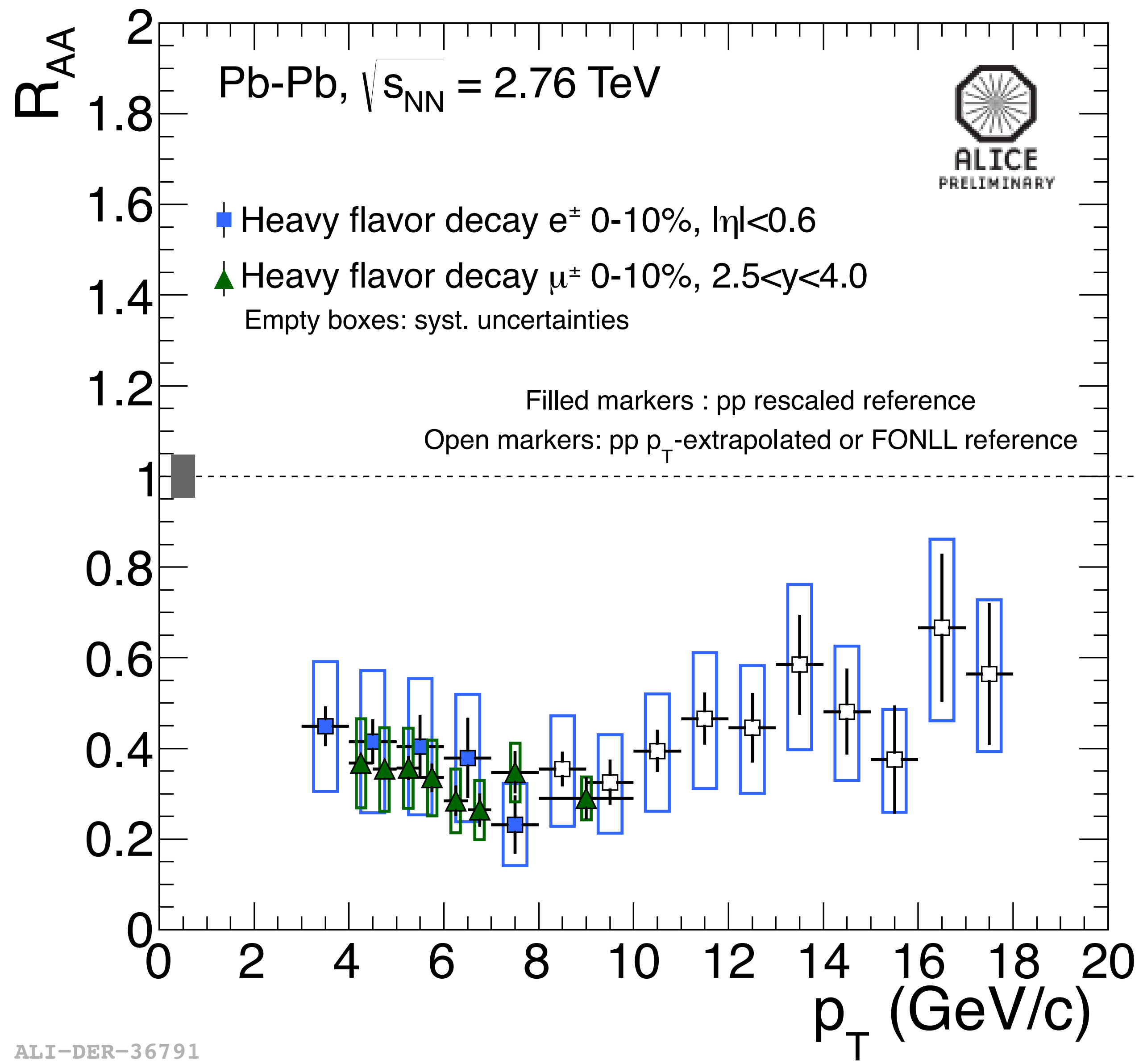

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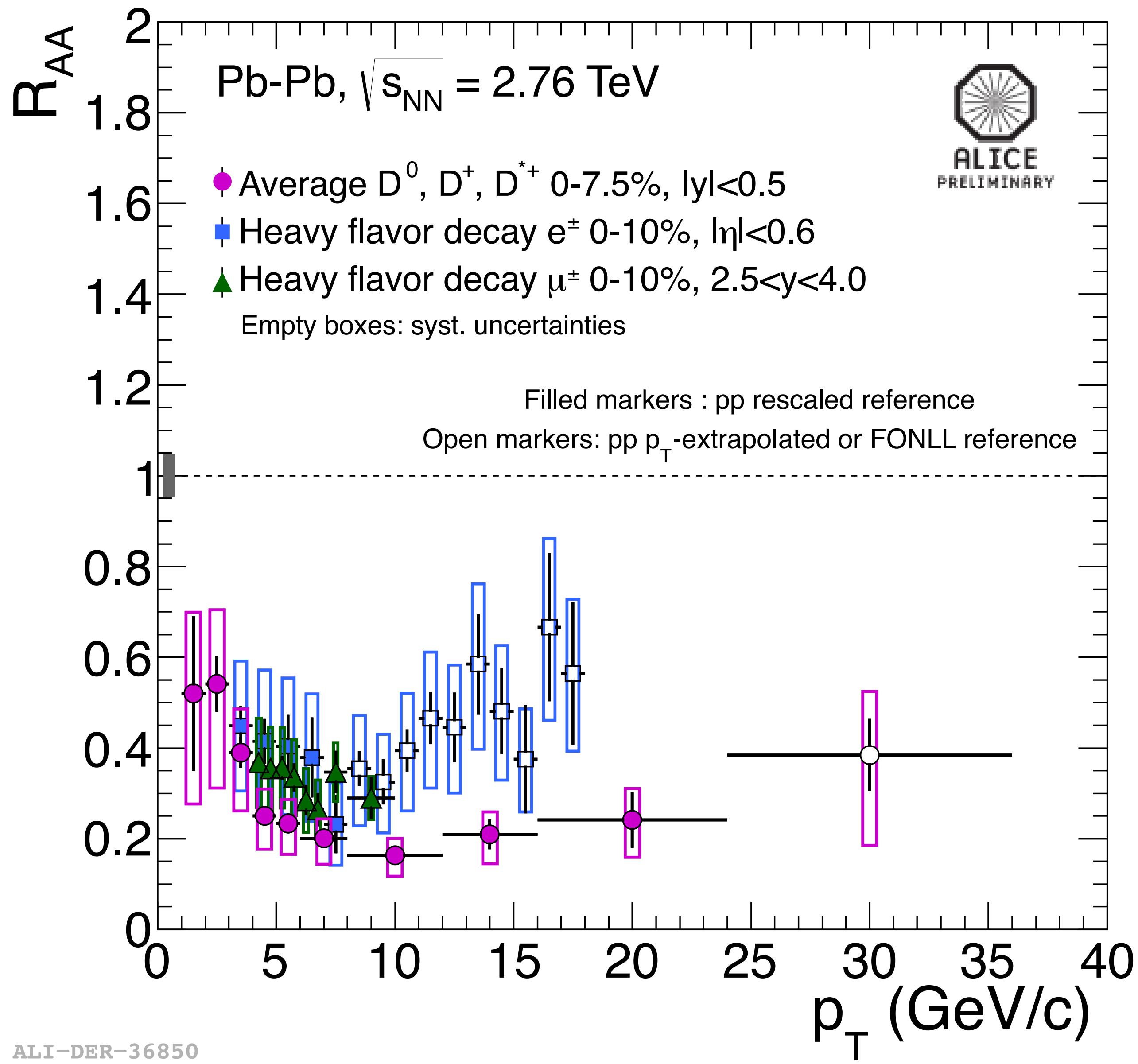

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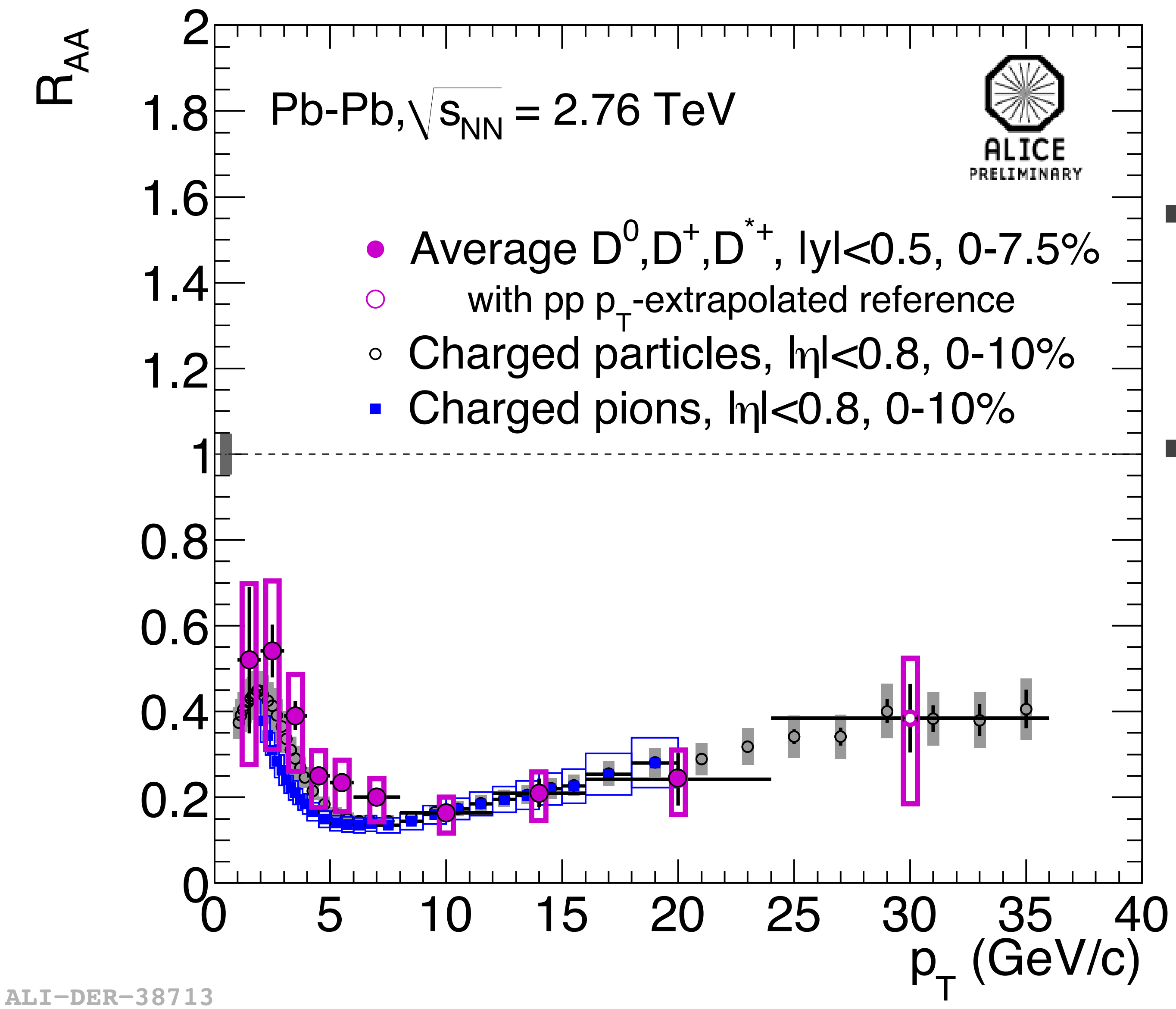
- ➡ **Strong heavy flavor suppression**
- ➡ **Similar HF decay e (|y|<0.6) and μ (2.5<y<4.0) R_{AA} in 0-10%**
- ➡ **they are also comparable with D mesons R_{AA} (|y|<0.5) in 0-7.5%** considering the semileptonic decay kinematics ($p_T^e \sim 0.5\ p_T^B$ at high p_T)



Pb-Pb at 2.76 TeV

- Theory: Parton energy loss depends on the color charge (Casimir factor): $\Delta E_{u,d,s} < \Delta E_g$
- D R_{AA} shows a similar trend as charged particles and $\pi^{\pm}$ for p_T>5 GeV/c
- What is up at low p_T ?
  - Hint of D>π for 2<p_T<5 GeV/c?
  - For p_T<2 GeV/c, no direct comparison, Ncoll-scale does not hold for low p_T pions

Heavy & Light Flavor Suppression

- ➡ Theory: Parton energy loss depends on the color charge (Casimir factor): $\Delta E_{u,d,s} < \Delta E_g$
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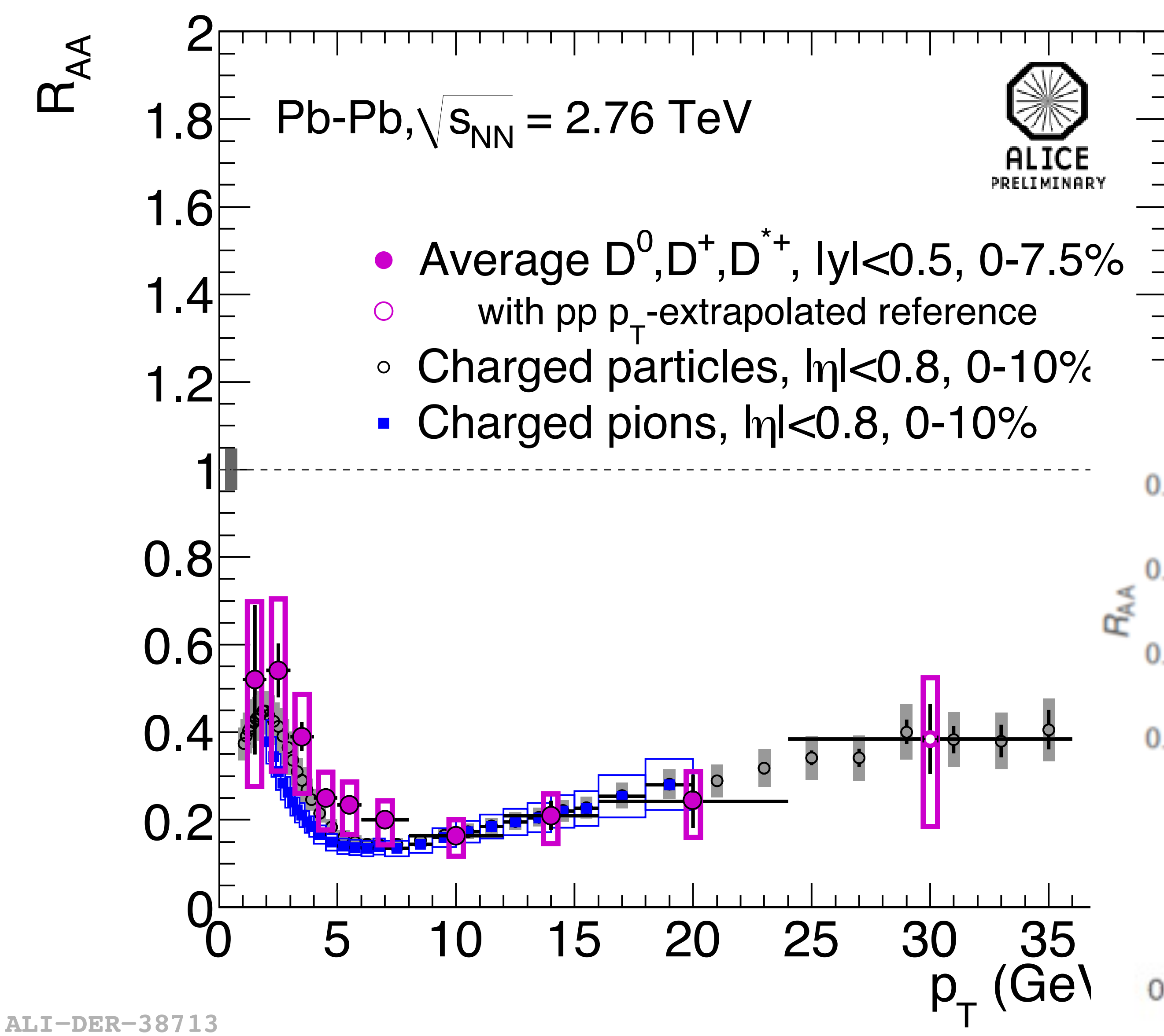

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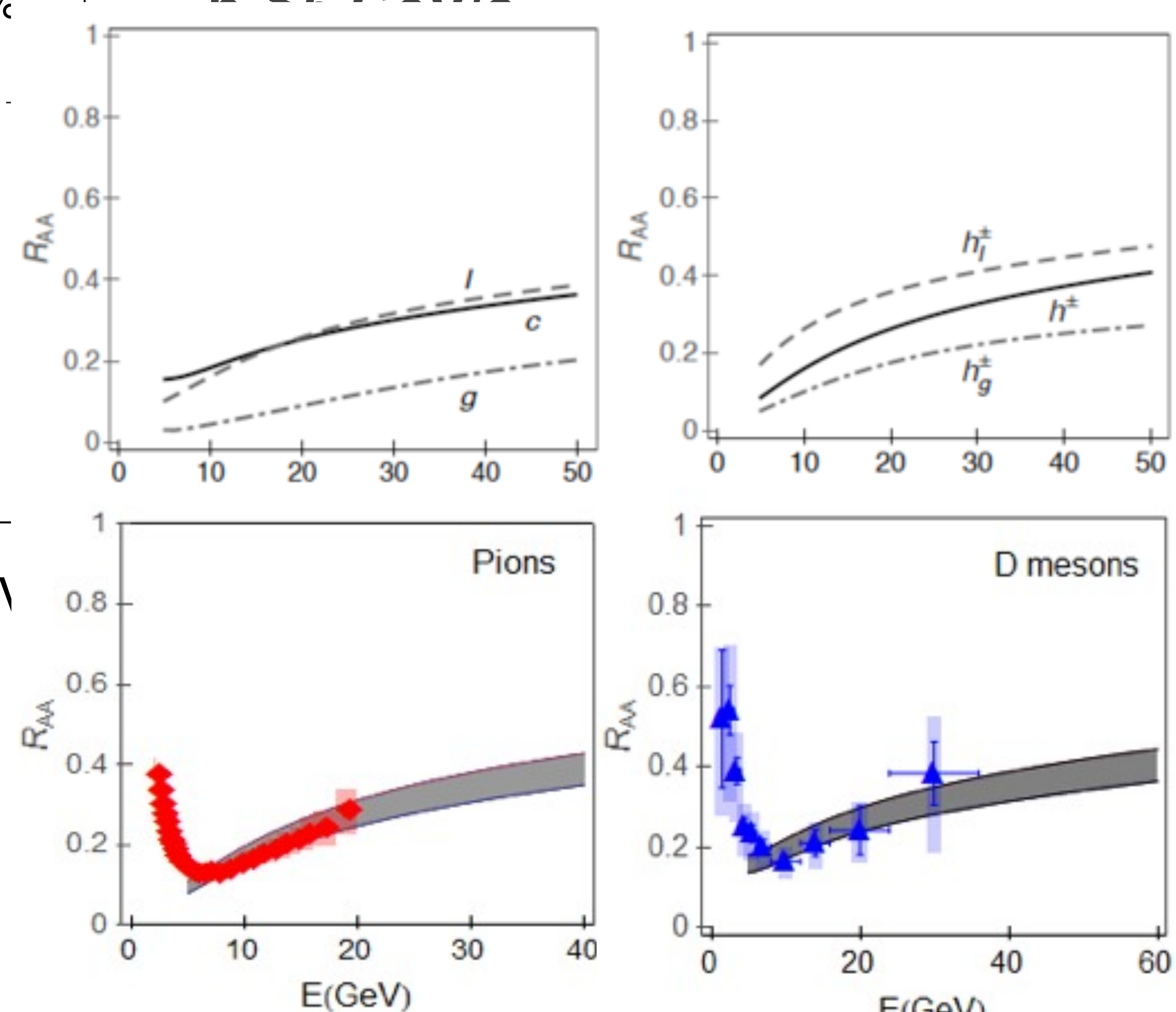
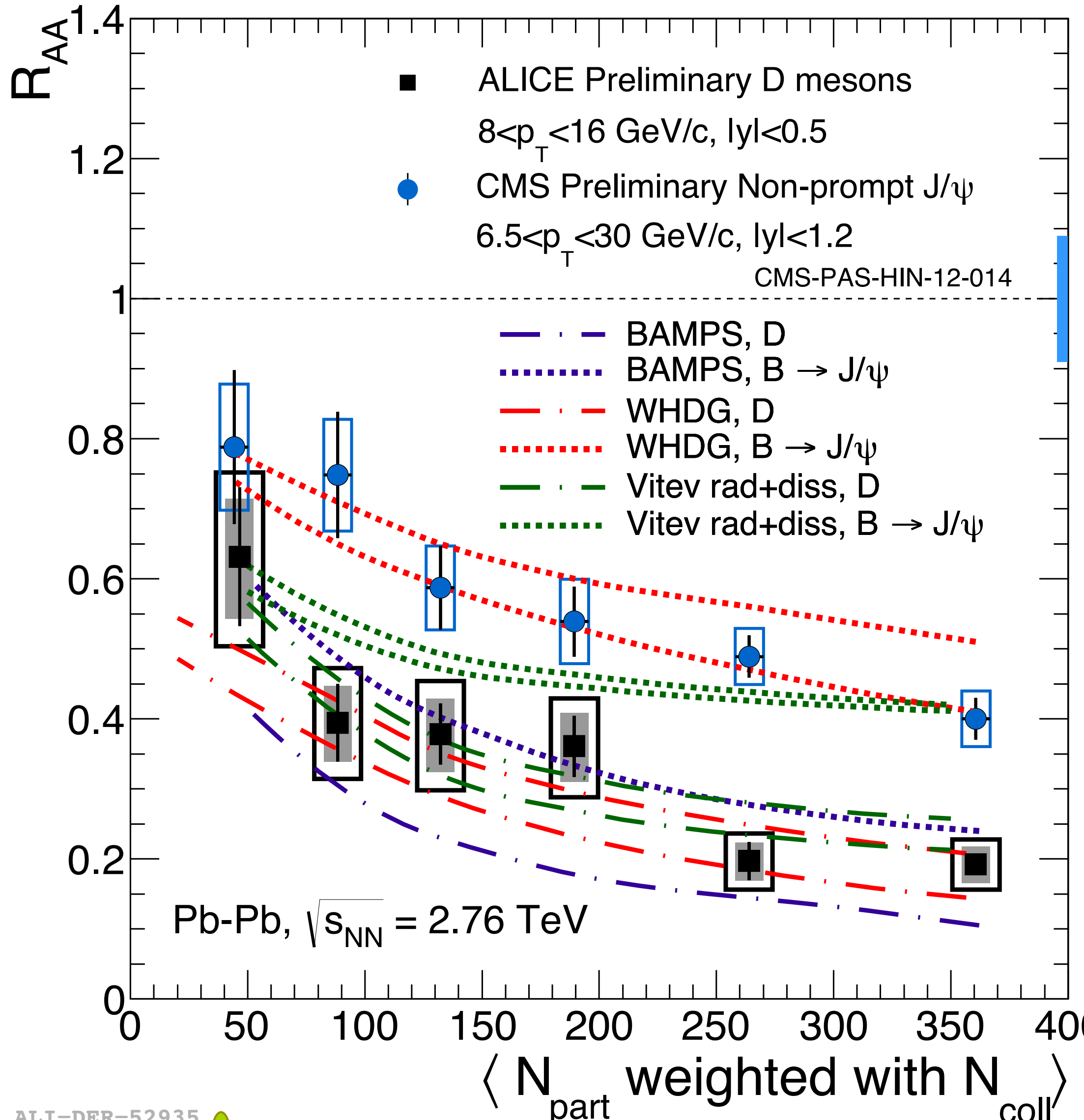


[M.Djordjevic, arXiv: 1307.4702, arXiv:1307.4098]

Charm and Beauty Suppression

Pb-Pb at 2.76 TeV



- ➡ **Theory: Parton energy loss depends on the parton mass (dead cone effect), so it suggests $\Delta E_b < \Delta E_c$**
- ➡ **In central collisions, for p_T>6 GeV/c, non-prompt J/ψ (CMS) are less suppressed than prompt D mesons, albeit the difference on the b/c average p_T.**

Caveats:
<p_T> B/D hadrons ≠ b/c quarks
fragmentation of b/c
⇨ Need models

With this selection:
•B <p_T> ~ 11 GeV
•D <p_T> ~ 10 GeV

BAMPS - collisional energy loss in an expanding medium

It tends to predict larger suppression for both D mesons and non-prompt J/ψ.

WHDG - collisional + radiative energy loss in anisotropic medium

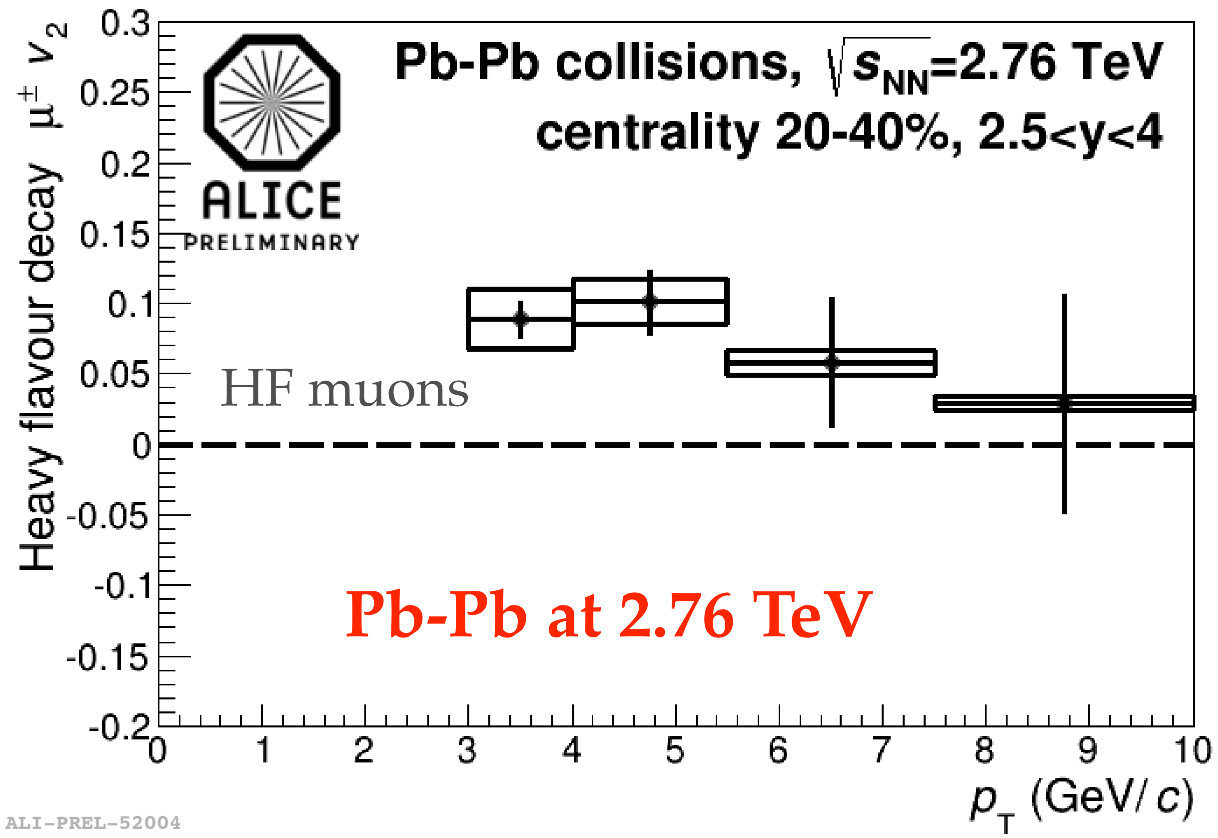
Good agreement with both measurements.

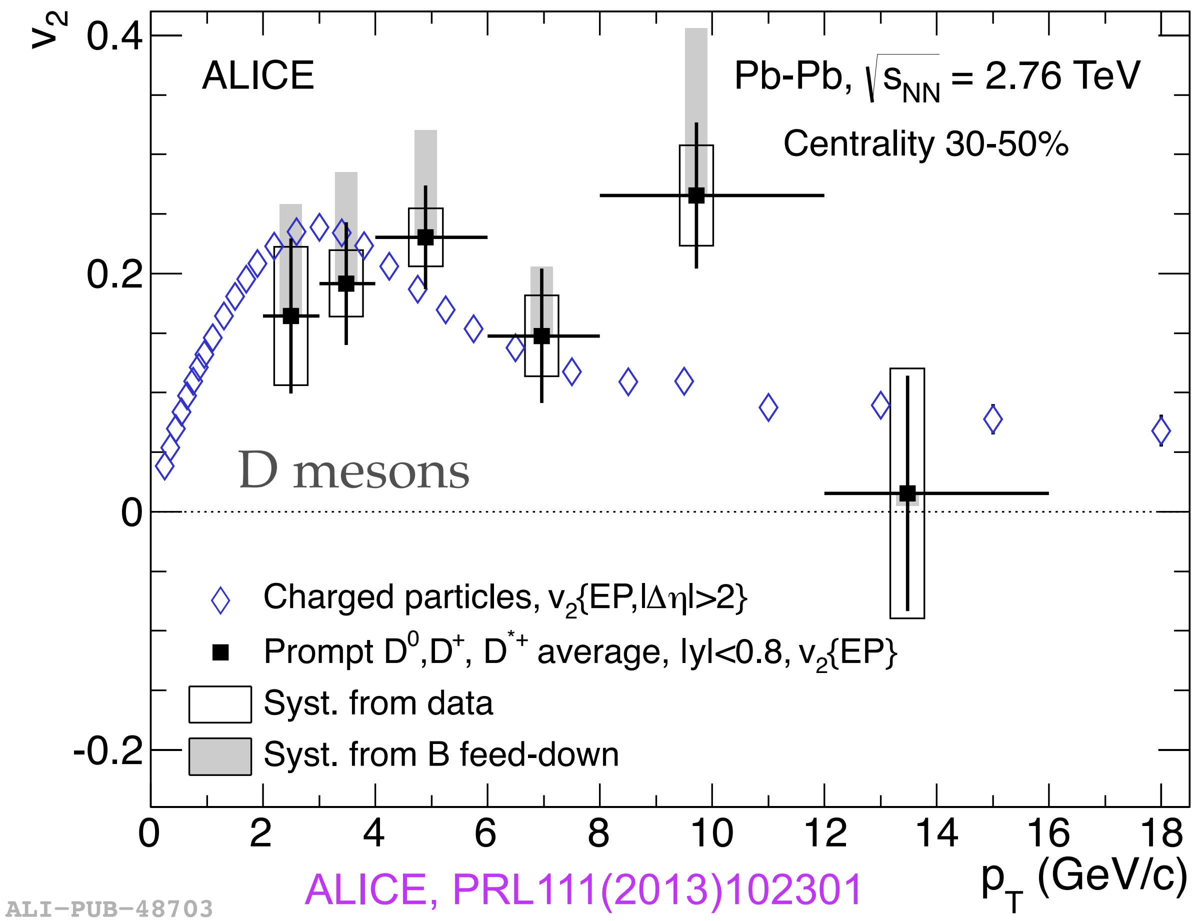
Vitev – radiative + dissociation

Relative good description, but underestimates non-prompt J/ψ for peripheral classes.

[BAMPS: J. Phys. G 38 (2011) 124152; Phys. Lett. B 717 (2012) 430] [WHDG: J. Phys. G 38 (2011) 124114]
[Vitev: R. Sharma, I. Vitev and B. W. Zhang, Phys. Rev. C80 (2009) 054902; Y. He, I. Vitev and B. -W. Zhang, Phys. Lett. B 713 (2012) 224]

Heavy Flavor Flow (v_2)



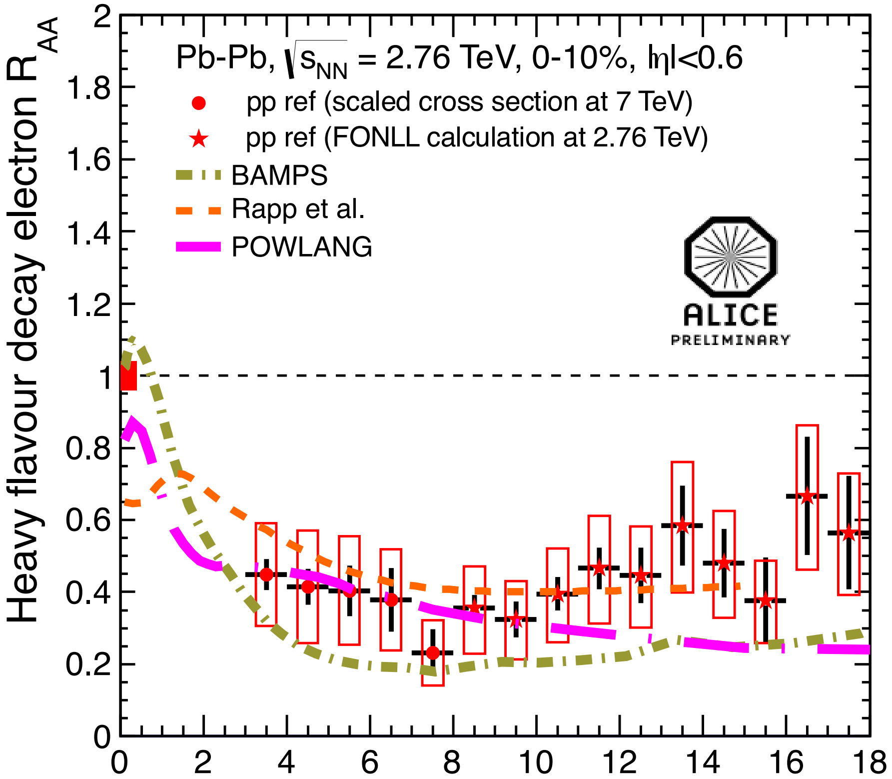


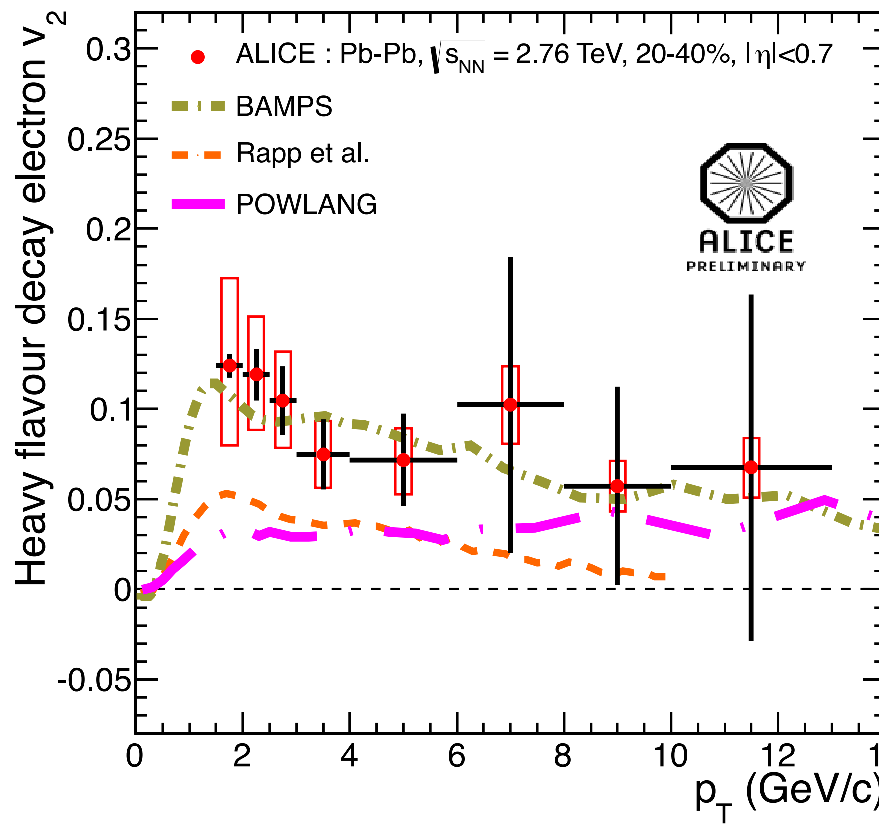
- ➡ Indication of non-zero v_2
  - D meson v_2 (5.7σ effect in $2<p_T<6$ GeV/c)
  - HF electron $v_2>0$ at low p_T (>3σ effect in $2<p_T<3$ GeV/c)
- ➡ Similar to that of charged particles

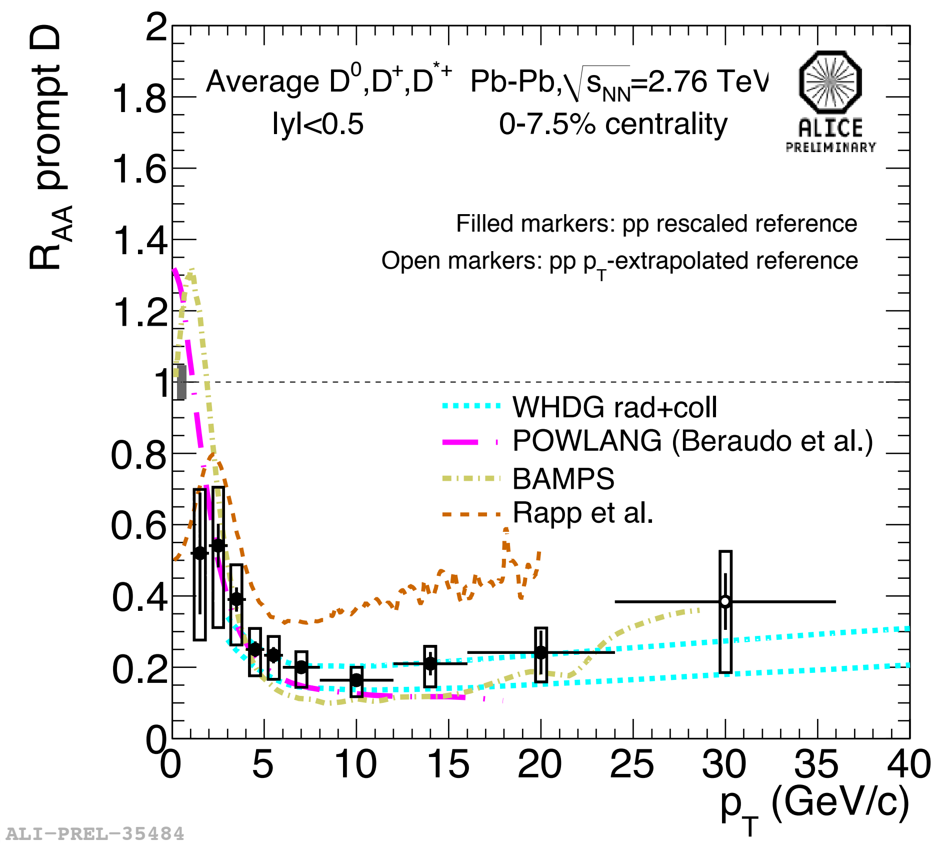
Suggesting:
⇨ low p_T charm quarks take part in the collective motion of the system
⇨ can constrain path length dependence of energy loss at high p_T, but not sufficient precision with the current statistics

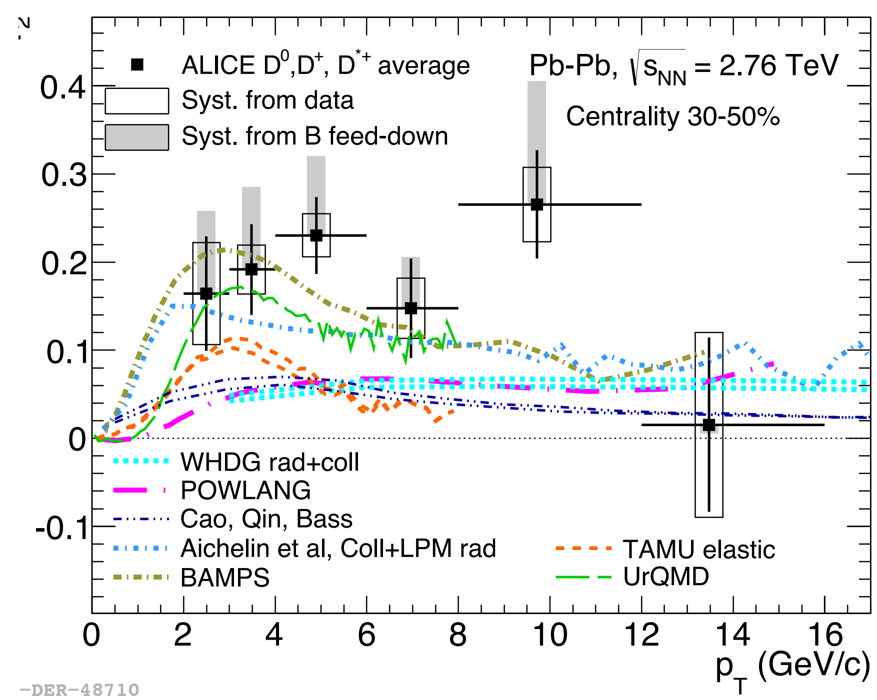
HF R_{AA} and v_2 vs Models

Pb-Pb at 2.76 TeV





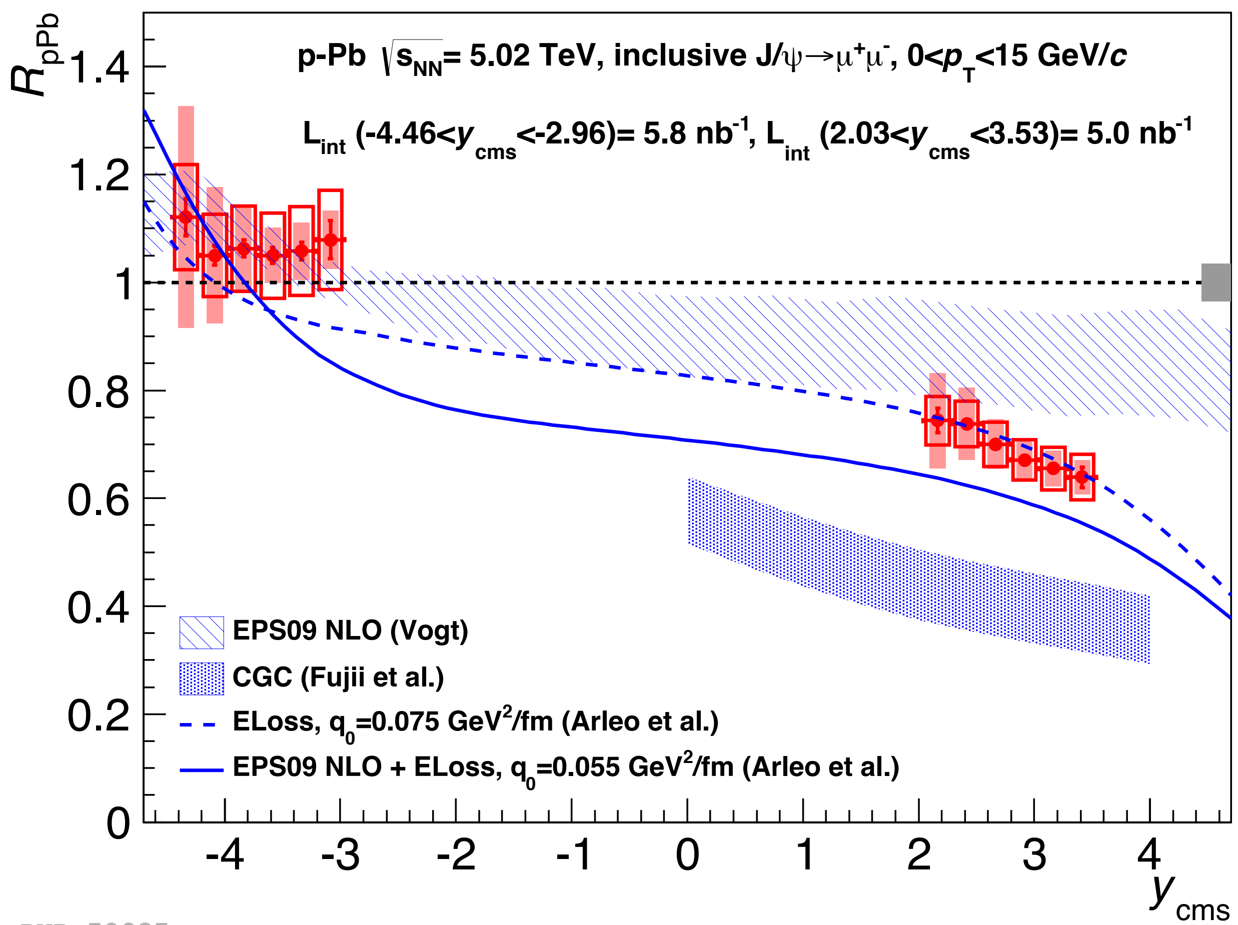




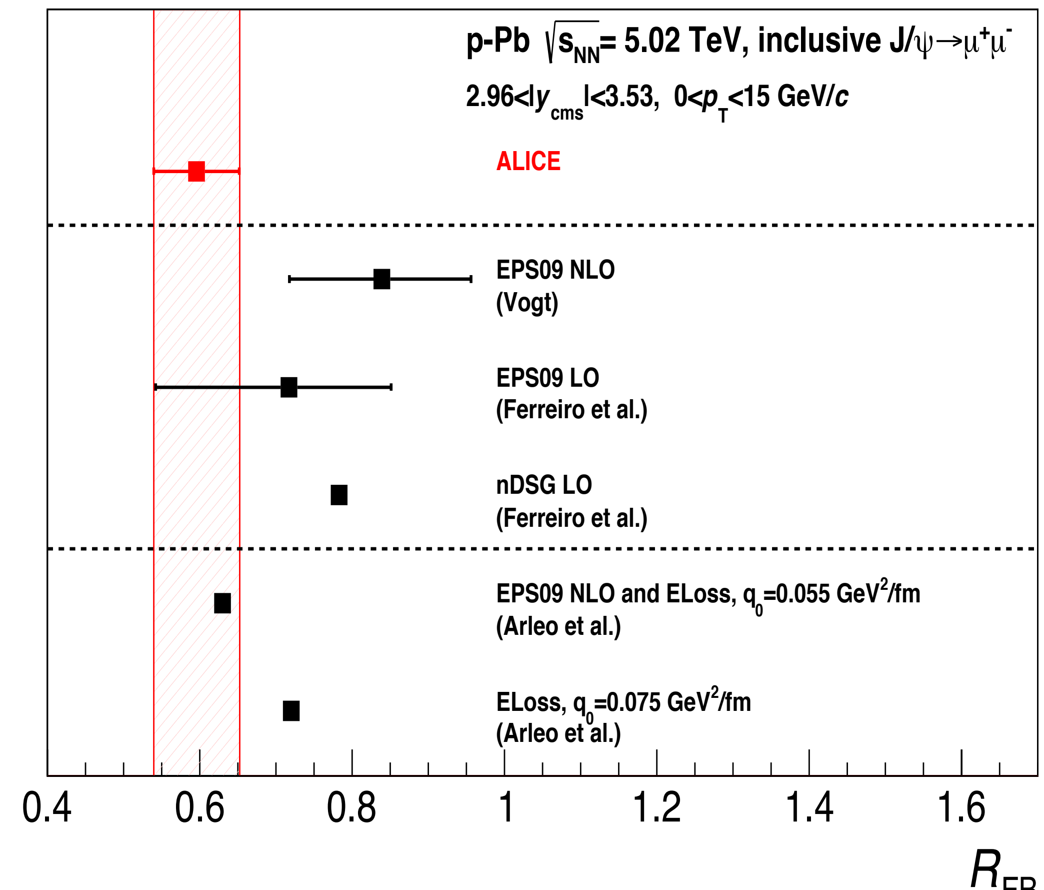
➡ **The simultaneous description of HFe and D-meson R_{AA} and v_2 is challenging**

⇨ Many models appearing. A more systematic data/ theory comparison might help the interpretation

J/ψ production in p-Pb



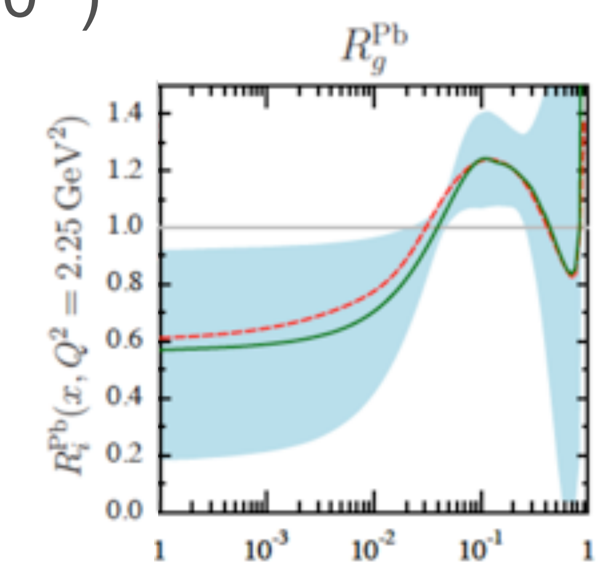
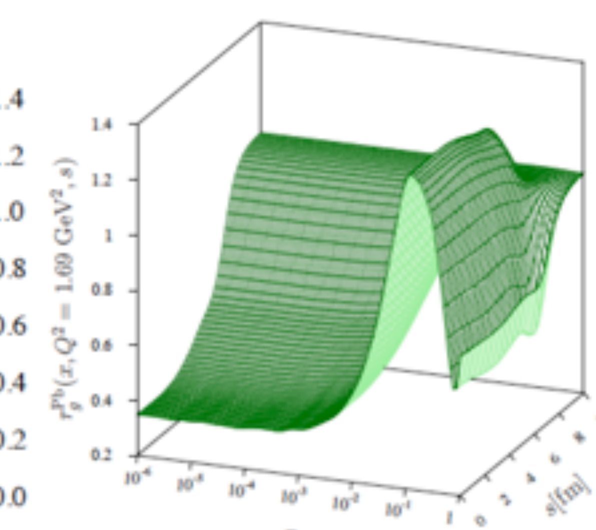
ALI-PUB-59027



ALI-PUB-59035

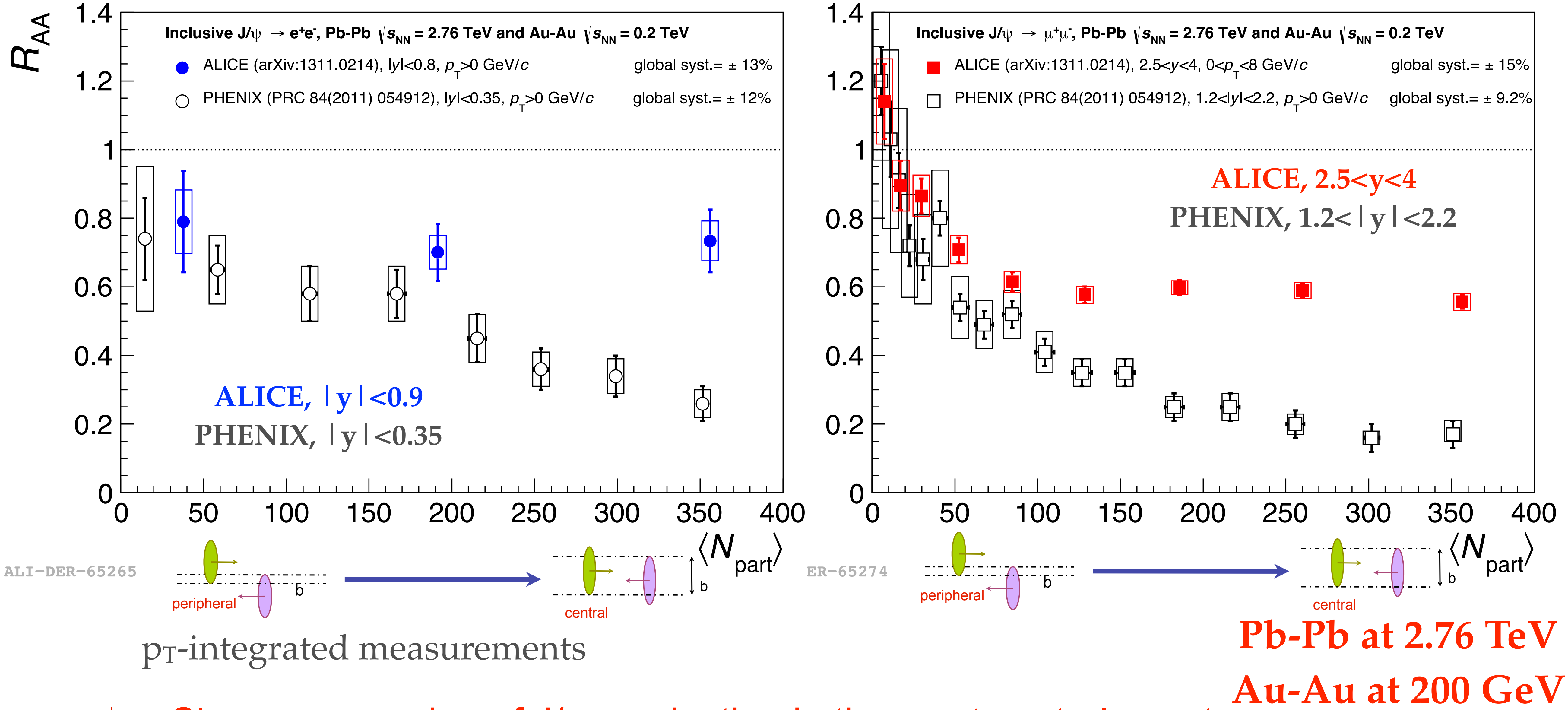
p-Pb at 5.02 TeV

- Larger suppression at forward (x~ 10^{-4}-10^{-5}) than backward (10^{-1}-10^{-2}) rapidity
- Results in agreement with models
  - Incorporating EPS09 shadowing with/wo contribution from energy loss
  - CGC calculations disfavoured

K.J Eskola et al,JHEP04 (2009) 065. I.Helenius et al, arXiv:1205.5359 [hep-ph]

J/ψ R_{AA} vs $\sqrt{s_{NN}}$ and Centrality

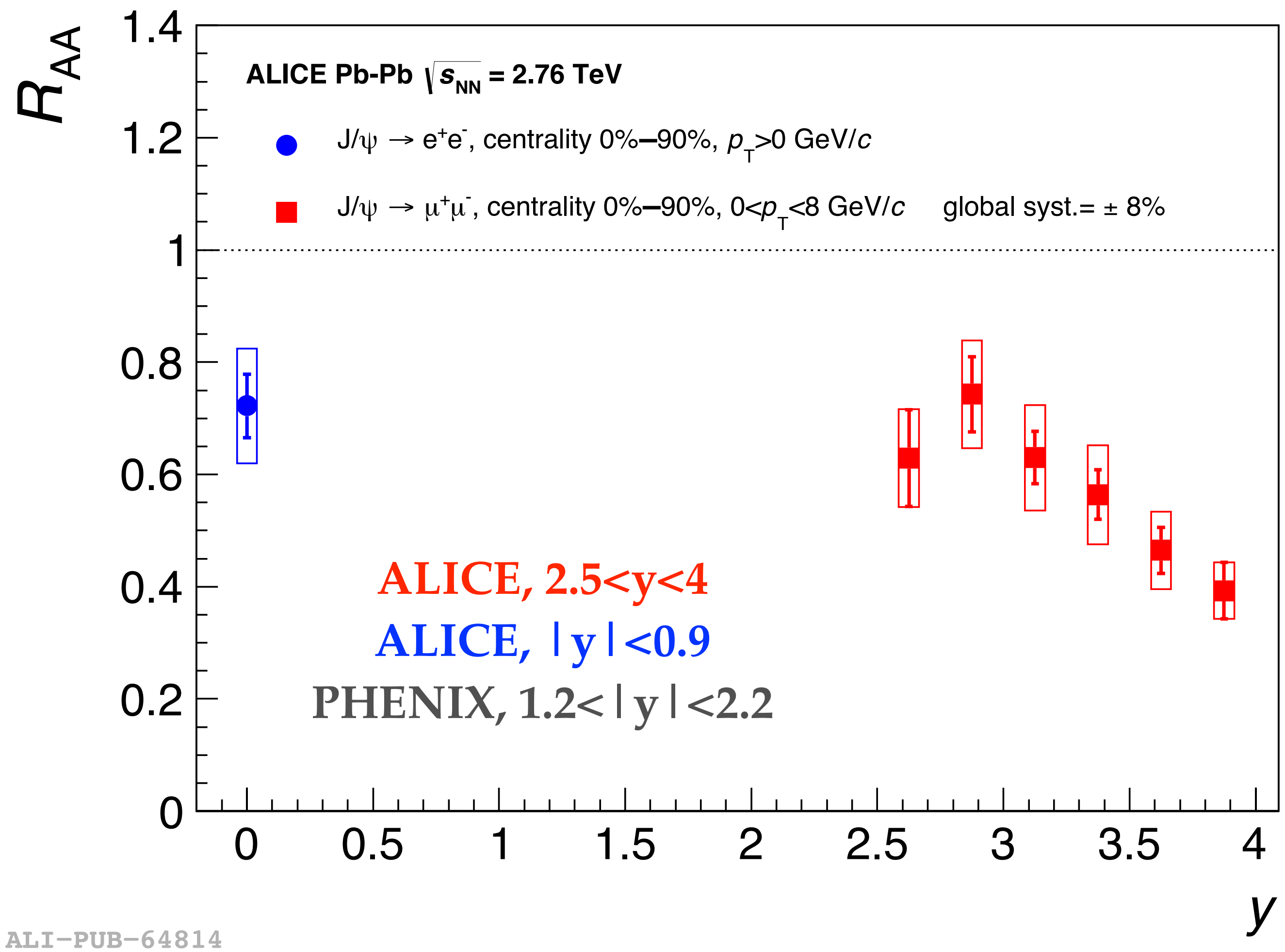


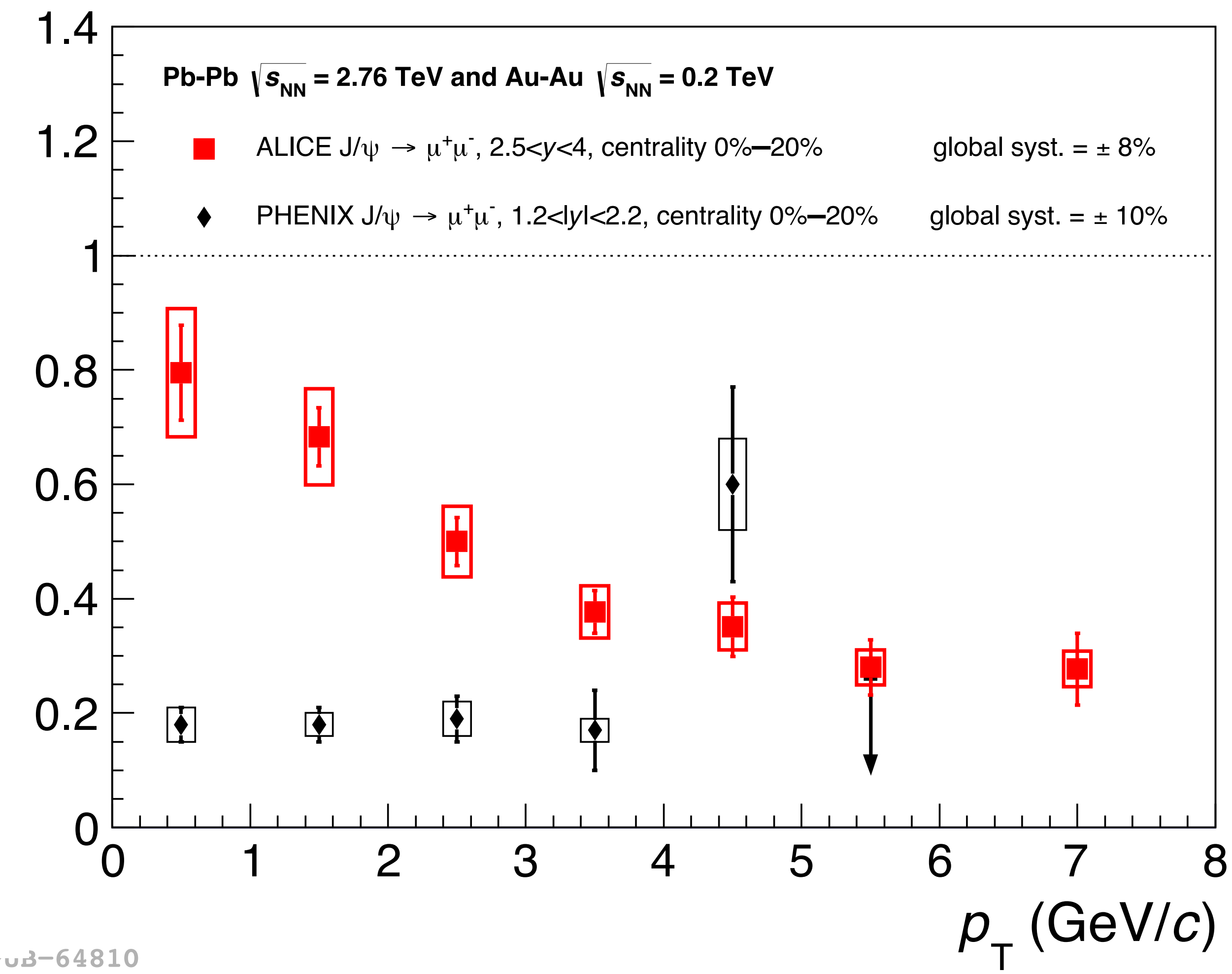
p_T-integrated measurements

- Clear suppression of J/ψ production in the most central events
- Inclusive J/ψ $R_{AA}(p_T>0)$ at LHC does not show a centrality dependence
- LHC J/ψ $R_{AA}(p_T>0)$ in the most central class is higher than at RHIC
  - but the rapidity ranges and centre of mass energy are different,
  - thus cold nuclear matter effects are expected to be different

arXiv: 1202.1383 (2012); arXiv: 1103.6269; arXiv: nucl-ex/0611020; arXiv: 1311.0214

J/ψ R_{AA} VS P_T AND RAPIDITY

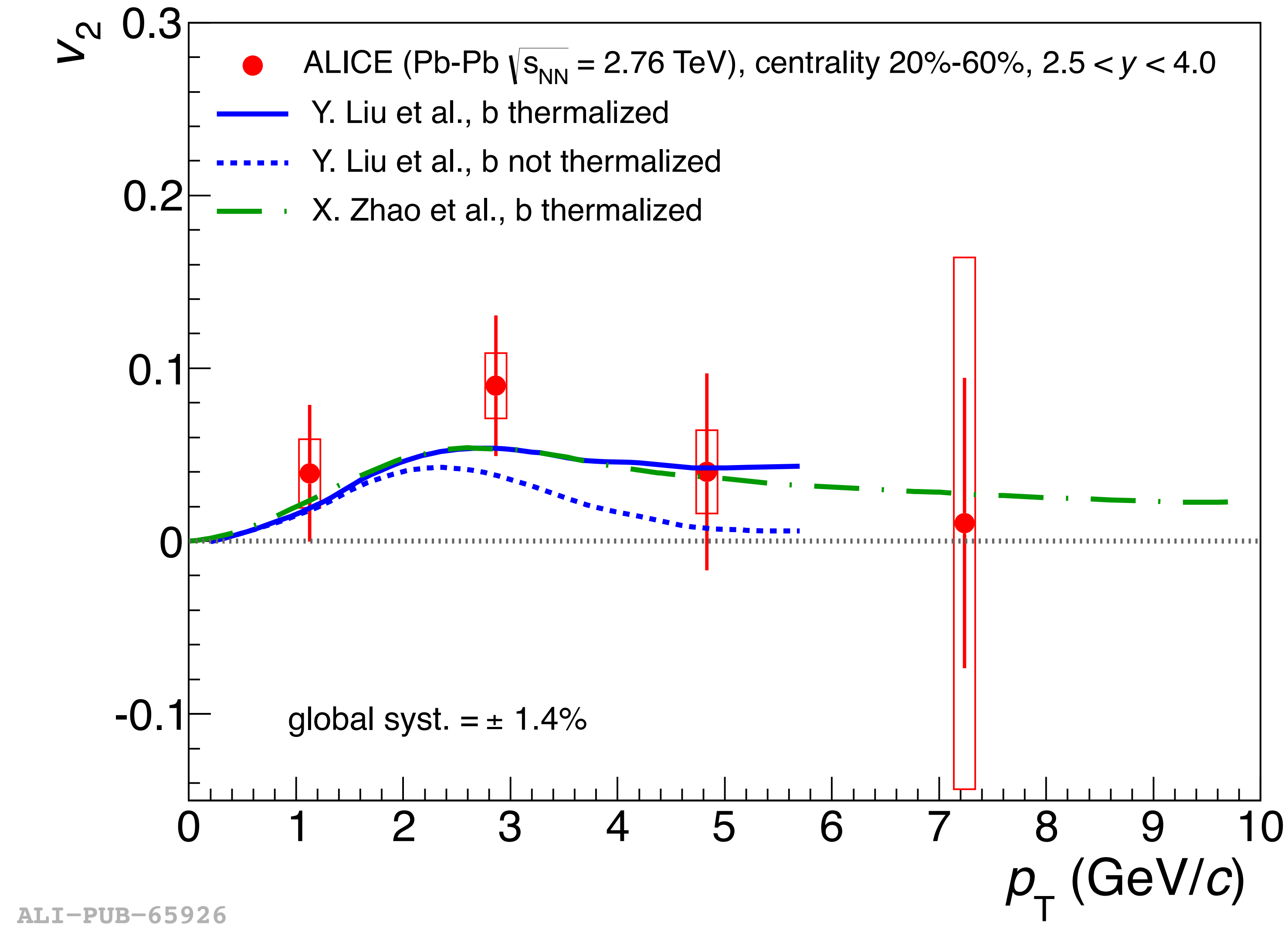




arXiv: 1202.1383 (2012); arXiv: 1311.0214

- J/ψ R_{AA} shows a larger suppression at forward than at mid-rapidity
- Different trend of J/ψ R_{AA} vs p_T
  - Clear suppression at high p_T
  - Hint of J/ψ regeneration at low p_T ?
  - Note, data belong to different rapidity ranges.
    Need a precise measurement of the total charm cross section and of the cold nuclear matter effects (pPb+Pbp)

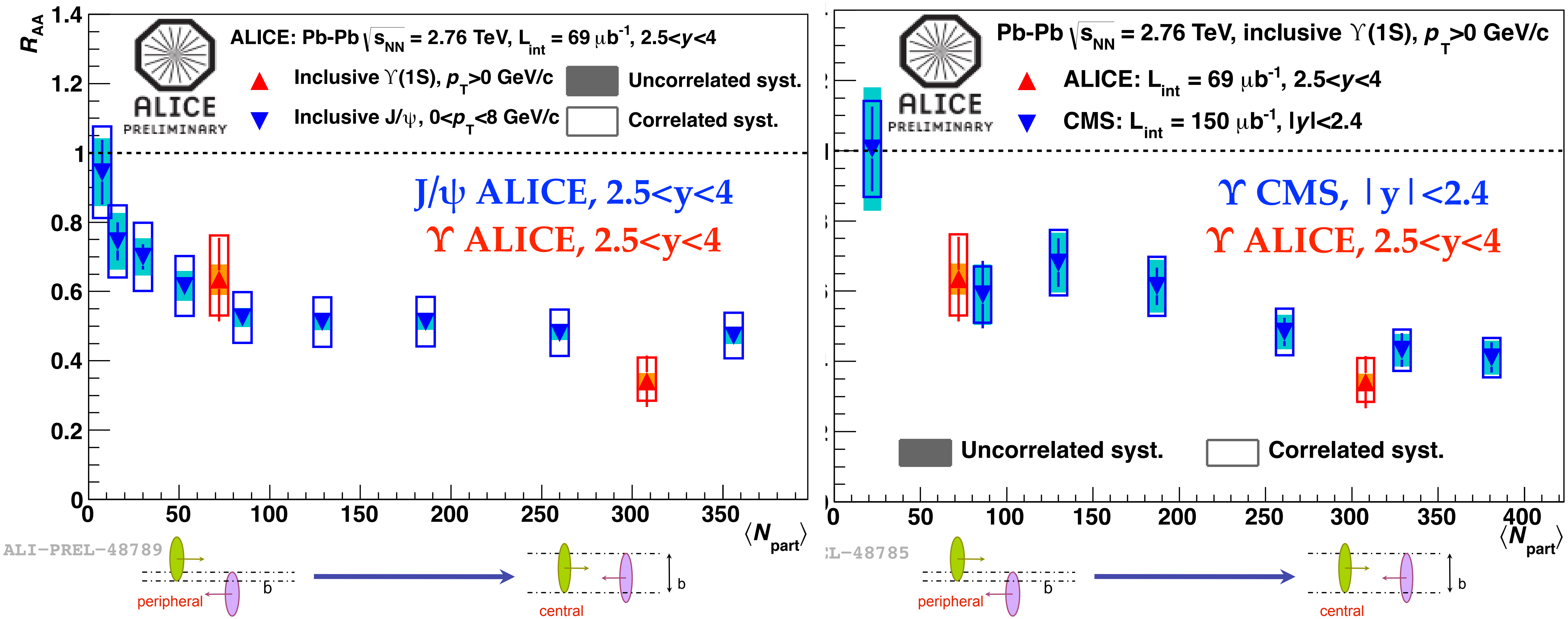
Pb-Pb at 2.76 TeV
Au-Au at 200 GeV



Pb-Pb at 2.76 TeV

- Hint of non-zero v_2 at intermediate p_T in semi-peripheral reactions
- In agreement with transport models including suppression and regeneration mechanisms
  ⇨ favors scenario with a significant fraction of J/ψ production originated in the deconfined phase

A Glimpse at Upsilon



p_T-integrated measurements

Pb-Pb at 2.76 TeV

- Similar J/ψ and Y suppression pattern with centrality (p_T-integrated)
- Consistent ALICE and CMS results, small rapidity dependence
- In agreement with model calculations within uncertainties

Summary

- The bulk properties of the system show a smooth transition from RHIC → LHC
  - Energy density > 15 GeV/fm^3 → x2.5 RHIC
  - Temperature = 304 ± 51 MeV → x1.4 RHIC
  - Elliptic flow → x1.3 RHIC as expected from hydro-dynamical calculations with viscous corrections and hadronic re-scattering

- The penetrating probes of the interaction :
  Heavy flavor production is suppressed in the most central collisions
  - Both at RHIC and LHC ⇨ Suffer from parton energy loss
  - Similar for pions and D mesons for p_T >5 GeV/c
    ⇨ Consistent with colour charge dependence
  - Larger for D mesons than for non-prompt J/ψ for p_T >6 GeV/c
    ⇨ Consistent with expected parton mass dependence
  - Positive v_2 for p_T>2. D-meson v_2 similar to that of light hadrons
    ⇨ low p_T c-quarks participate to the system collective motion

- Quarkonia production
  - Low p_T J/ψ R_{AA} does not show a centrality dependence, which differs from RHIC data
  - High p_T J/ψ are more suppressed in the most central events wrt the most peripheral
  - Hint of non-zero v_2 at intermediate p_T ⇨ Regeneration is at play ?
  - Υ R_{AA} presents a similar pattern to the J /ψ one

➡ **Need precise measurements down to p_T~0 both in pA and AA over a wide y-range**

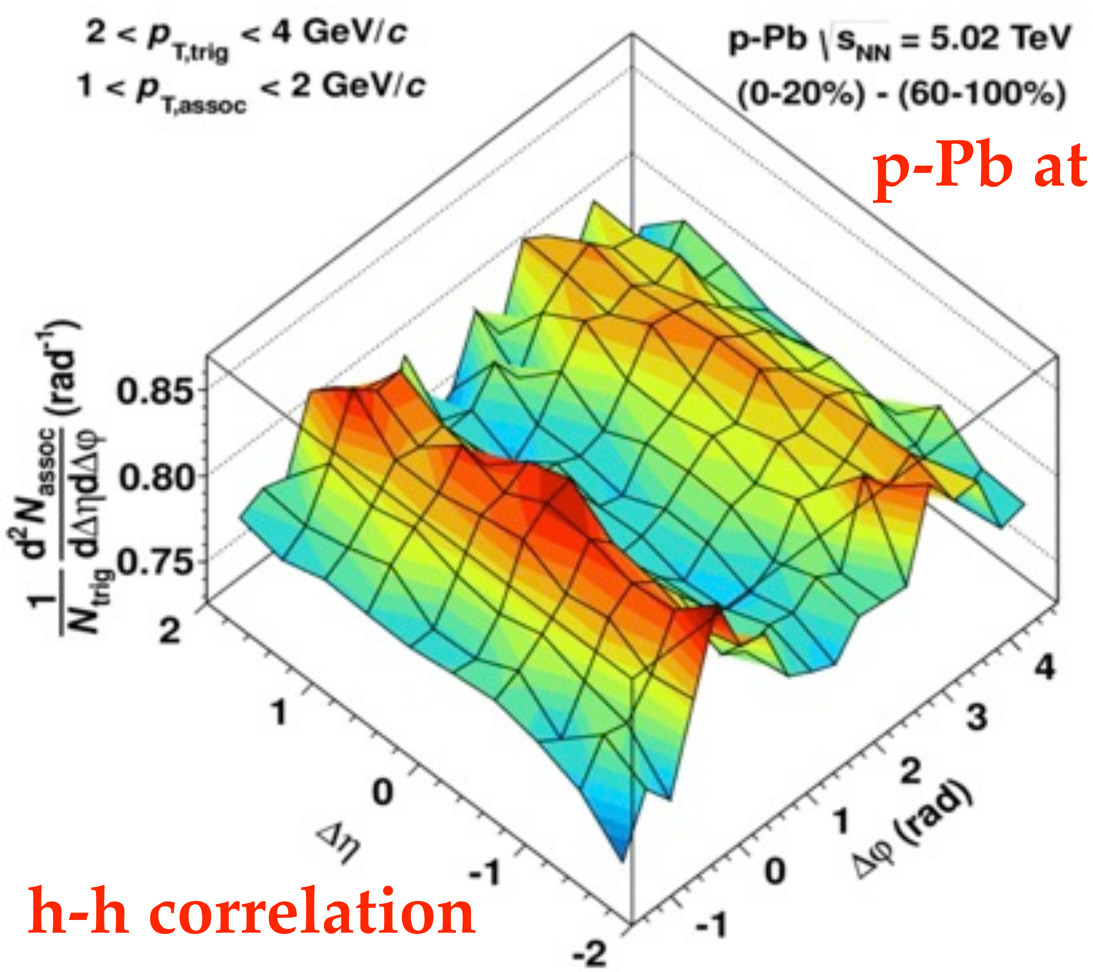
➡ **Require models describing both pA and AA measurements: p_T, y, v_2 and their centrality dependence. Quarkonia models should also be able to reproduce HF.**

Back Up

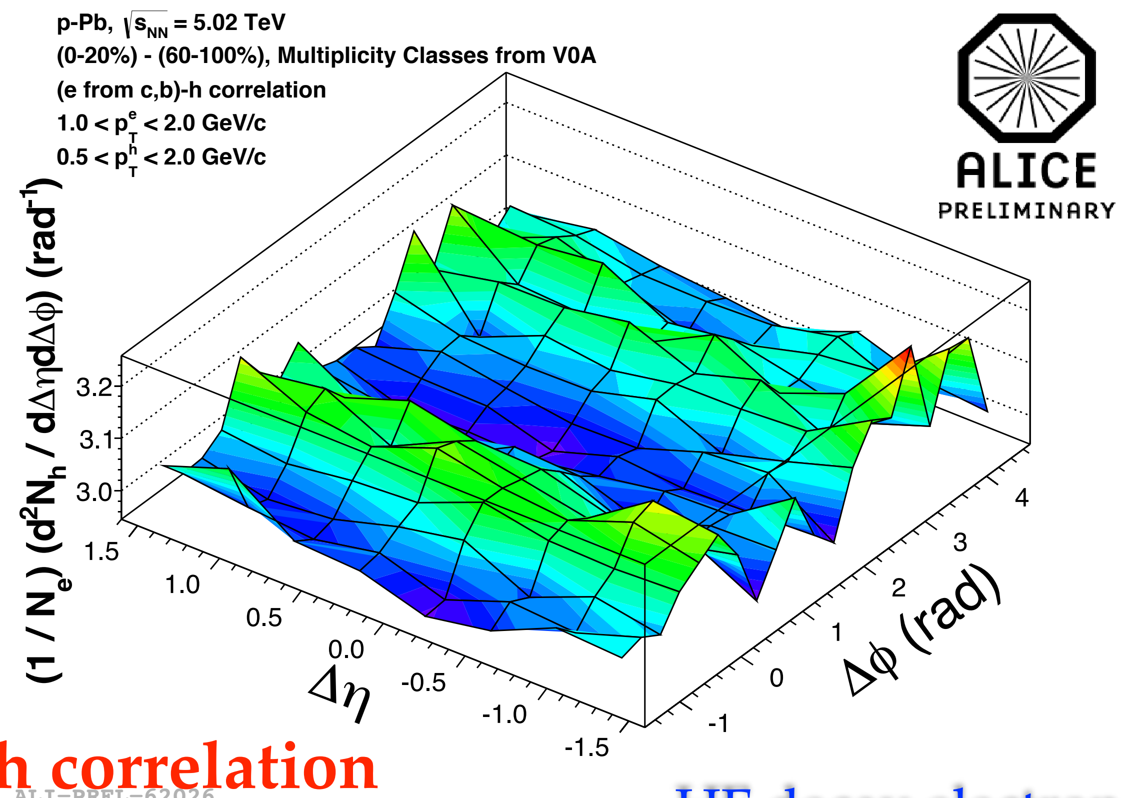
HFe-Hadron correlations in p-Pb

Correlations of the (0-20)% - (60-100)%

p-Pb at 5.023 TeV

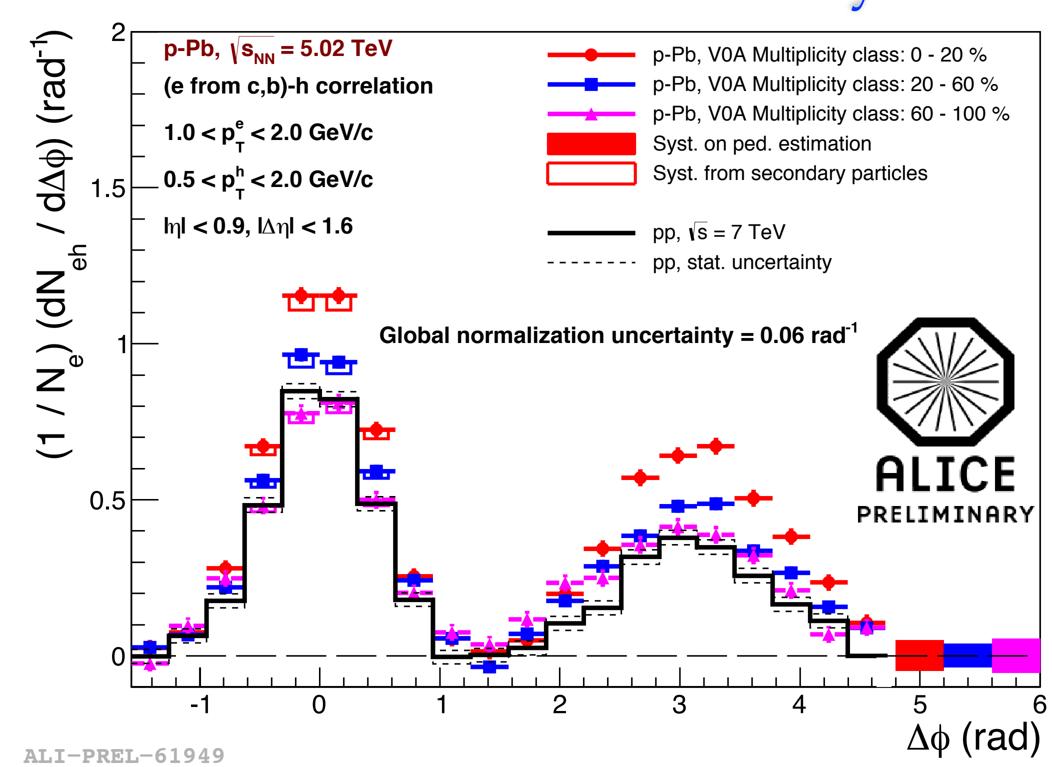


h-h correlation



HFe-h correlation

HF decay electrons



➡ Correlation within HF electrons and hadrons in p-Pb collisions resemble the double-ridge of hadron-hadron correlation

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