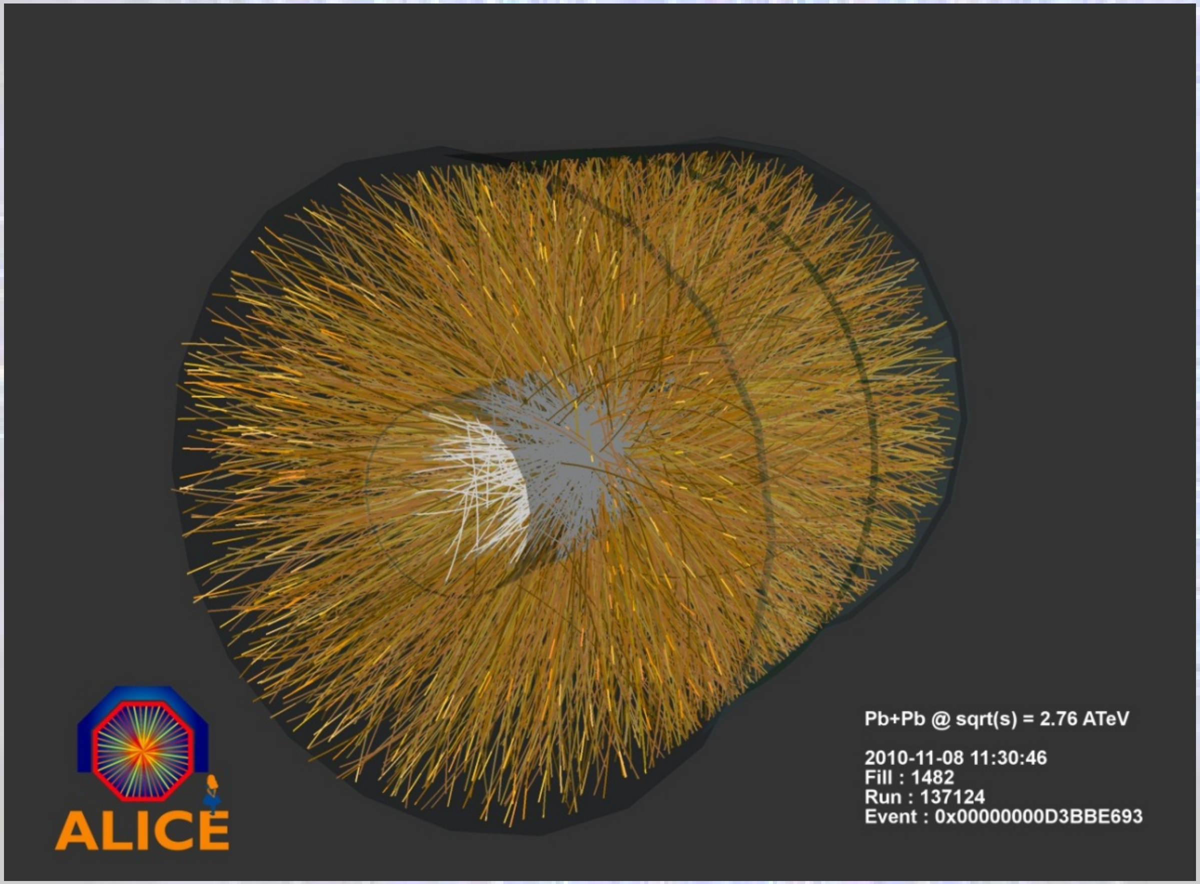
NEW RESULTS FROM THE ALICE EXPERIMENT



University of Birmingham
September 26th 2012

O. Villalobos Baillie
University of Birmingham

Plan of Talk

- Introduction
    - QGP properties
- ALICE Detector
- Reminder
    - System Size
    - Radial and Elliptic Flow
    - Jet Quenching
- New Results
- Future Plans
- Summary

Slides often "stolen" from Quark Matter 2012.

INTRODUCTION

Early Ideas

- It was realized fairly early in the development of Quantum Chromodynamics that at sufficiently extreme conditions, quarks and gluons would become deconfined. Two papers appeared on this topic in 1975.

Superdense Matter: Neutrons or Asymptotically Free Quarks?

J. C. Collins and M. J. Perry
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 9EW, England
(Received 6 January 1975)

We note the following: The quark model implies that superdense matter (found in neutron-star cores, exploding black holes, and the early big-bang universe) consists of quarks rather than of hadrons. Bjorken scaling implies that the quarks interact weakly. An asymptotically free gauge theory allows realistic calculations taking full account of strong interactions.

PRL **34** (1975) 1353

Early Ideas

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. CABIBBO
Istituto di Fisica, Universitá di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy

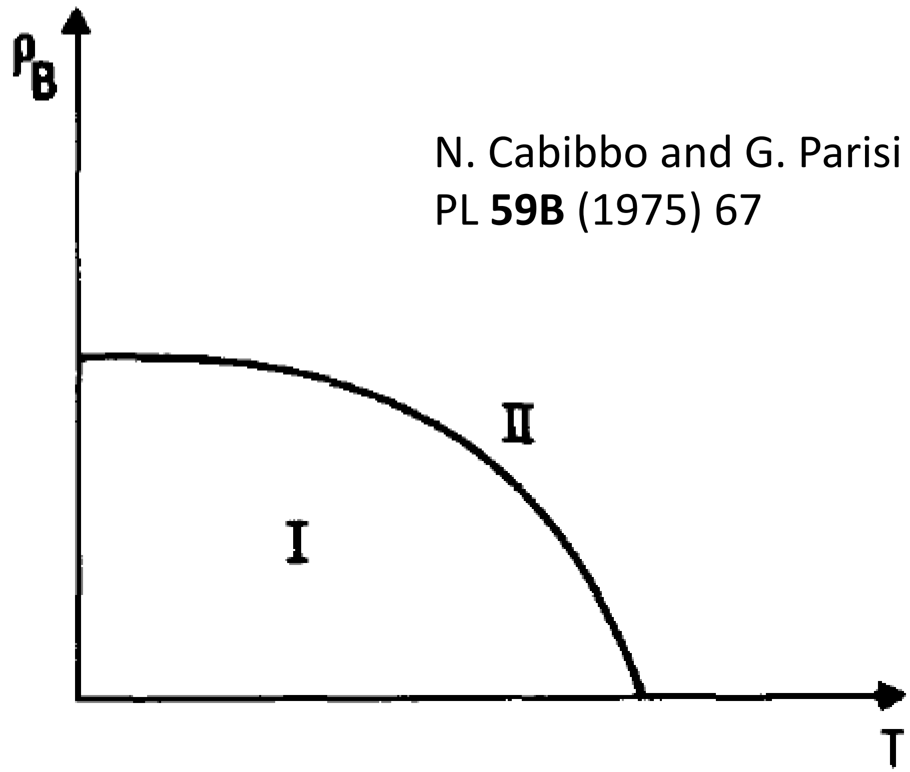
G. PARISI
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

Received 9 June 1975

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.

PLB59B (1975) 67

Early Ideas

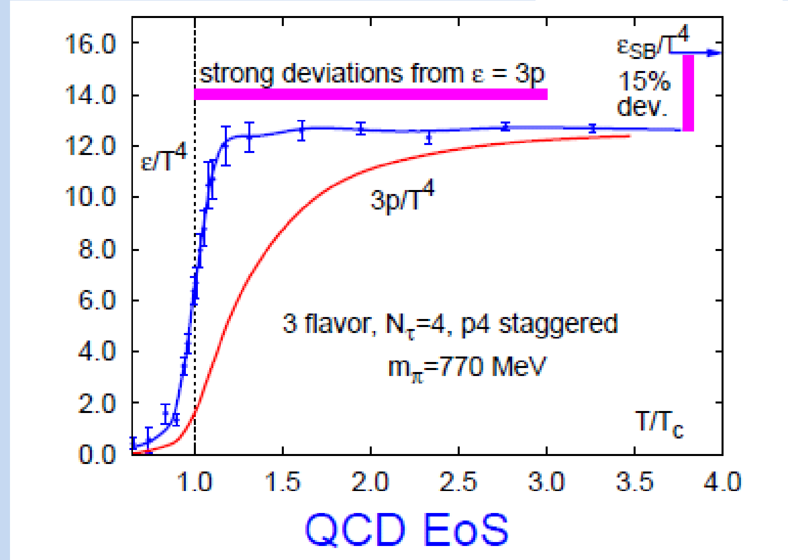


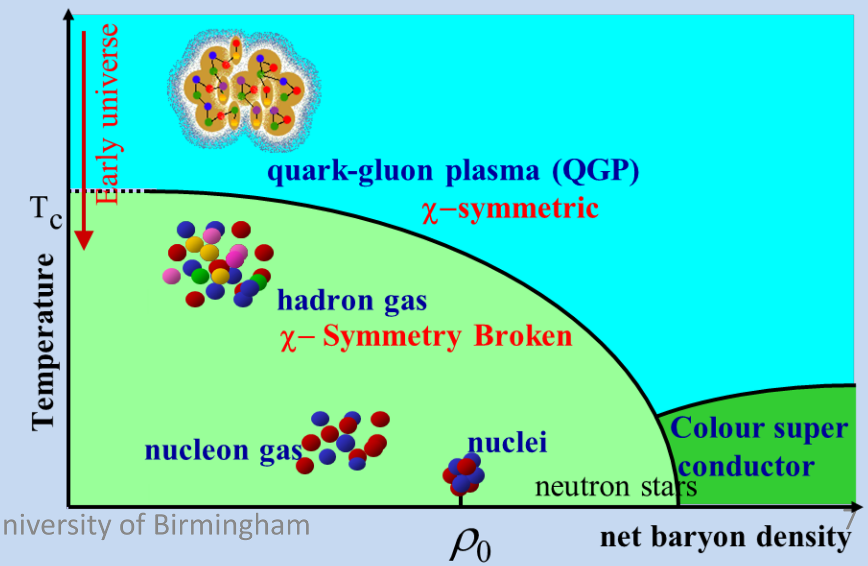
N. Cabibbo and G. Parisi
PL **59B** (1975) 67

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.

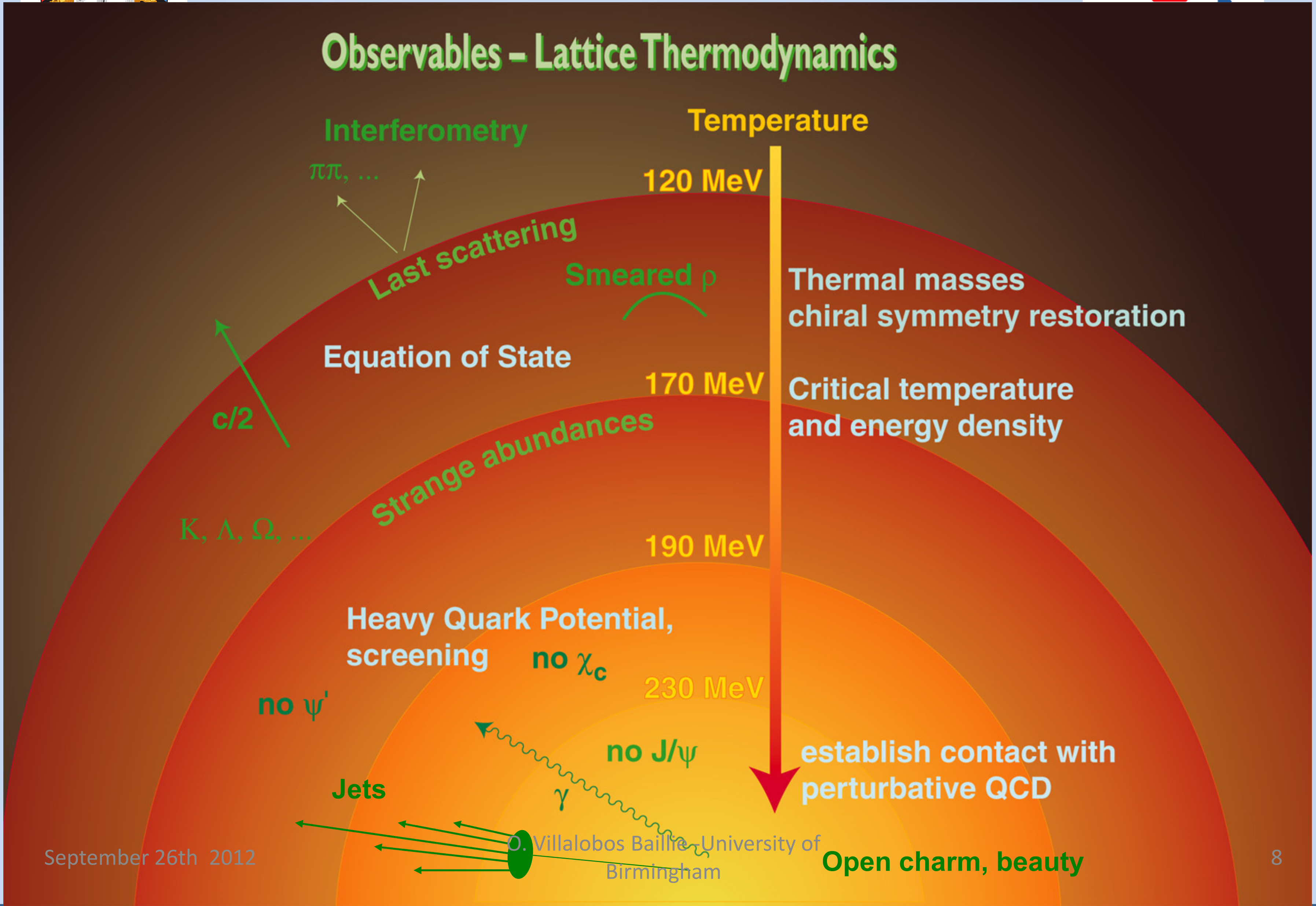
Quark-Gluon Plasma

- At high temperature, or at high net baryon density, QCD indicates that matter undergoes a phase transition to a phase in which quarks and gluons can move freely (QGP).
- Lattice QCD indicates that a fairly rapid transition occurs, which does not appear to be first order for ρ_0~0.
- Lattice calculations also show plateau comes about 15% below Stefan-Boltzmann limit – QGP does not behave like an ideal gas.
- Current estimates are that phase transition occurs for T~170 MeV and ϵ~1 GeV fm^{-3}





Observables



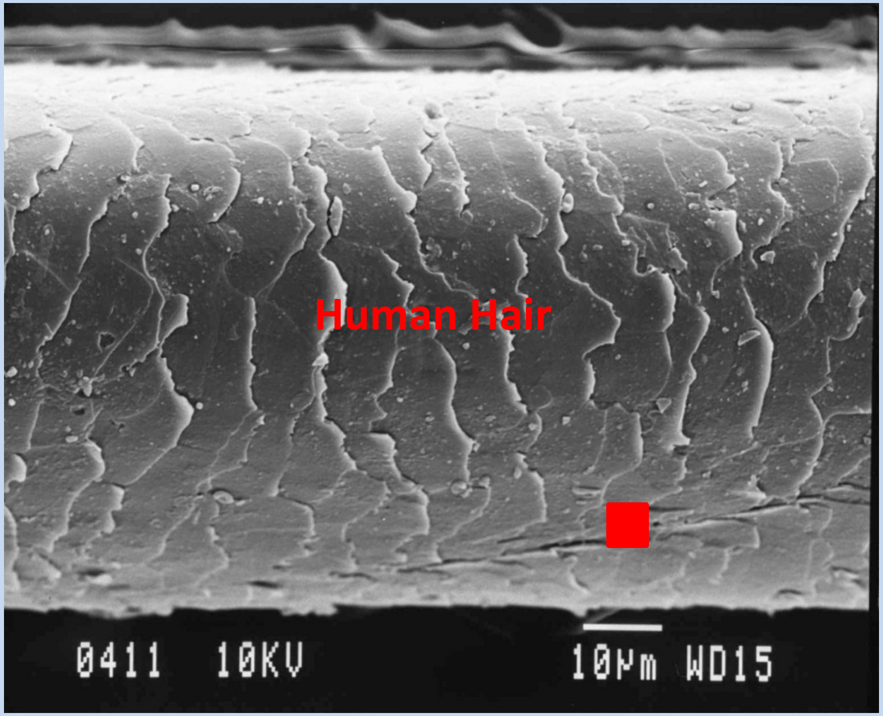
What is “extreme”?

- T of 170 MeV corresponds (in Kelvin) to around 2×10^{12}K (10^5 times hotter than sun).
- Heavy ion QGPs created at the LHC are estimated to reach an energy density $\epsilon \sim 5$ GeV fm^{-3}, well above the transition temperature.
- EXAMPLE Given that the annual energy consumption of the U.S. is about 10^{17} BTU, how much QGP would we need to hold this amount of energy?

Extreme conditions!

- 10^{17} BTU = 6.6 $\times 10^{29}$ GeV , so this fits in a cube of size

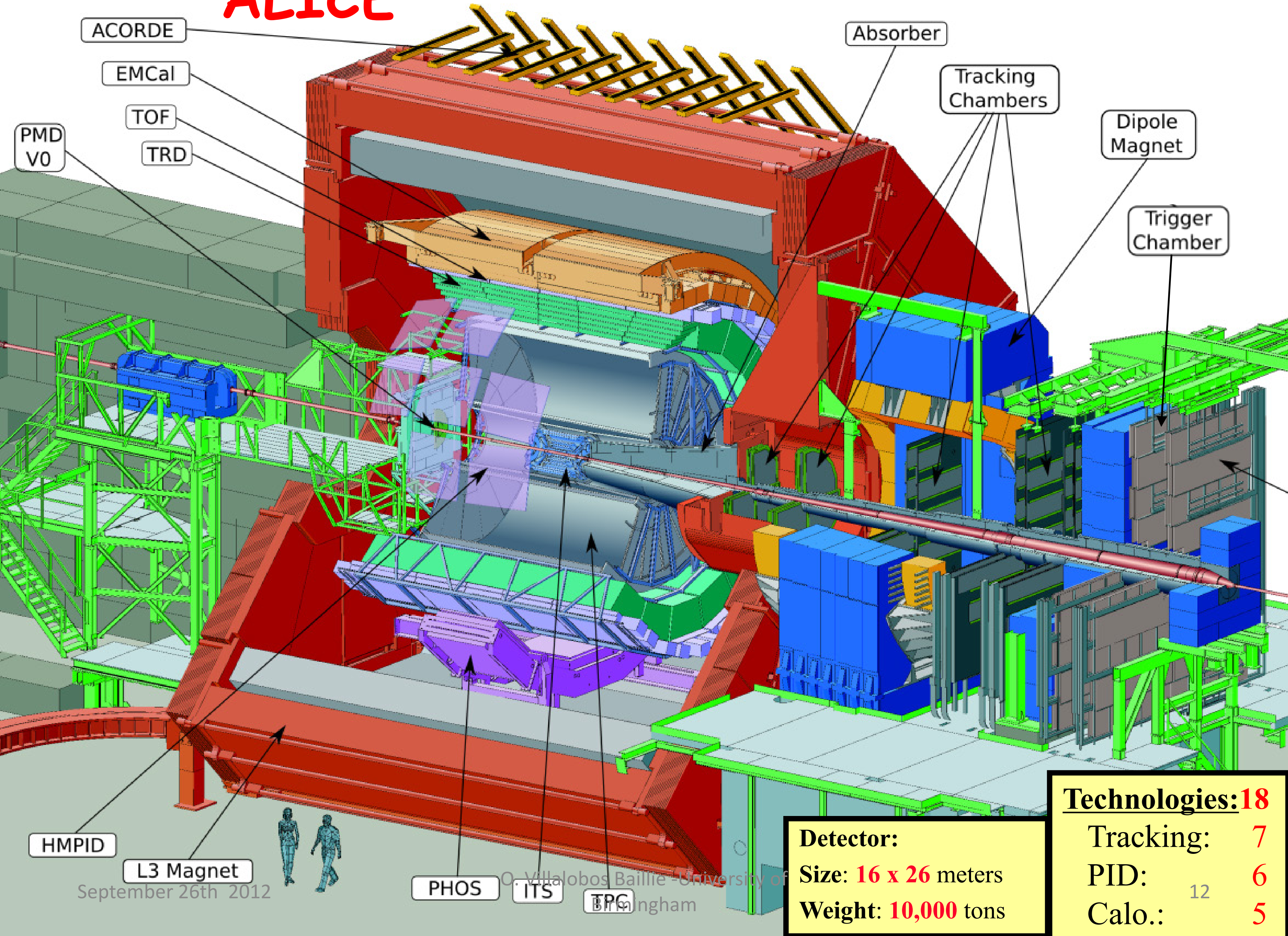
$$\sqrt[3]{\frac{6.6\times 10^{29}}{5}} = 5.09\times 10^{9}\ \text{fm} = 5.09\ \mu\text{m}$$



ALICE

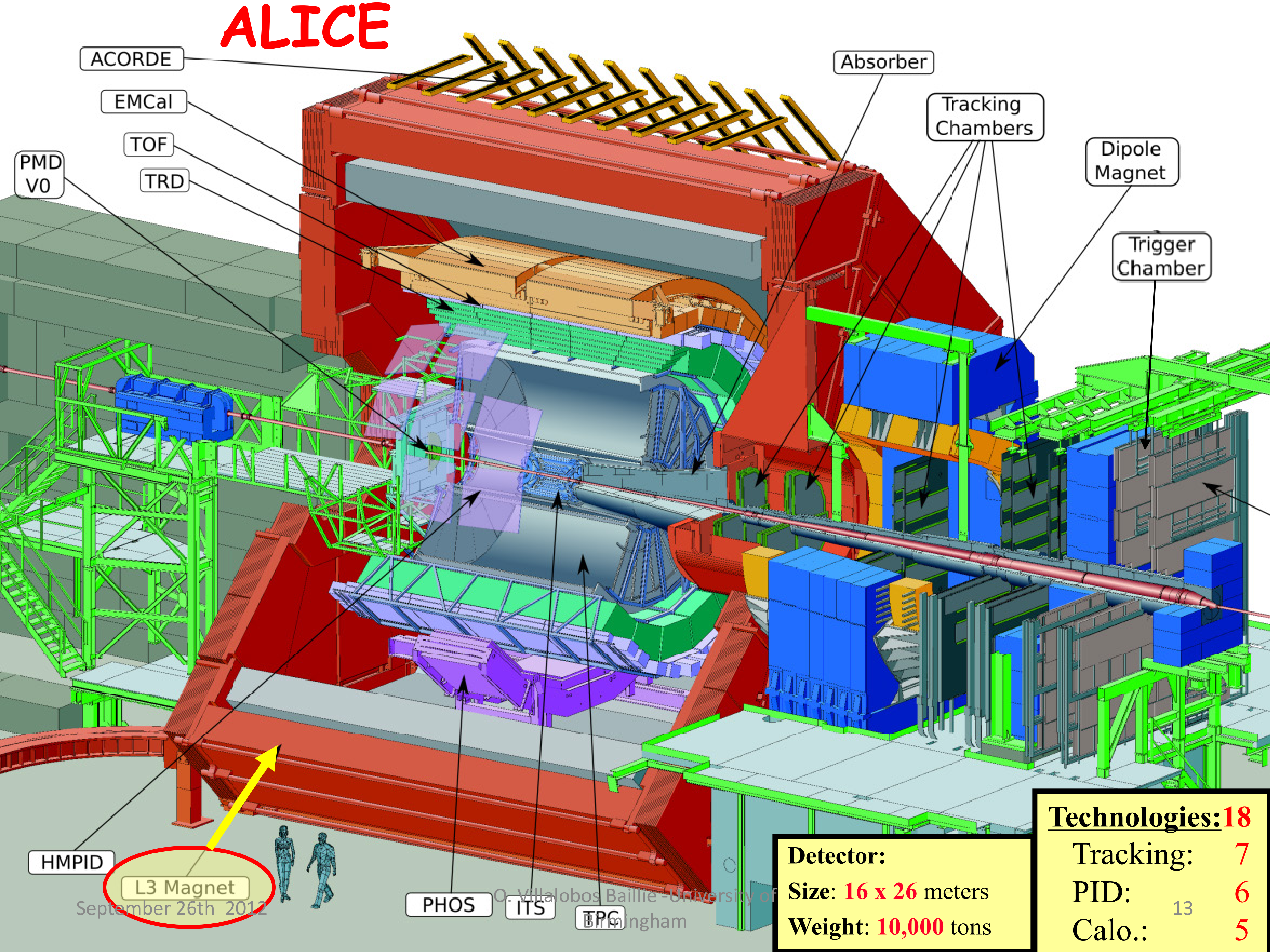
- The ALICE collaboration (A Large Ion Collider Experiment) is dedicated *principally* to the study of heavy ion collisions.
- The design of the detector is strongly based on *tracking*, and aims to be able to track *and identify* charged particles even in central ion-ion collisions.
    - (dN/dy thought to be ~8000 at time design was made.)
- Also electromagnetic calorimetry

ALICE



Detector:	
Size:	16 x 26 meters
Weight:	10,000 tons

Technologies:	18
Tracking:	7
PID:	6
Calo.:	5


ALICE
ACORDE
EMCal
TOF
TRD
PMD
V0
Absorber
Tracking Chambers
Dipole Magnet
Trigger Chamber
HMPID
L3 Magnet
PHOS
ITS
TPC
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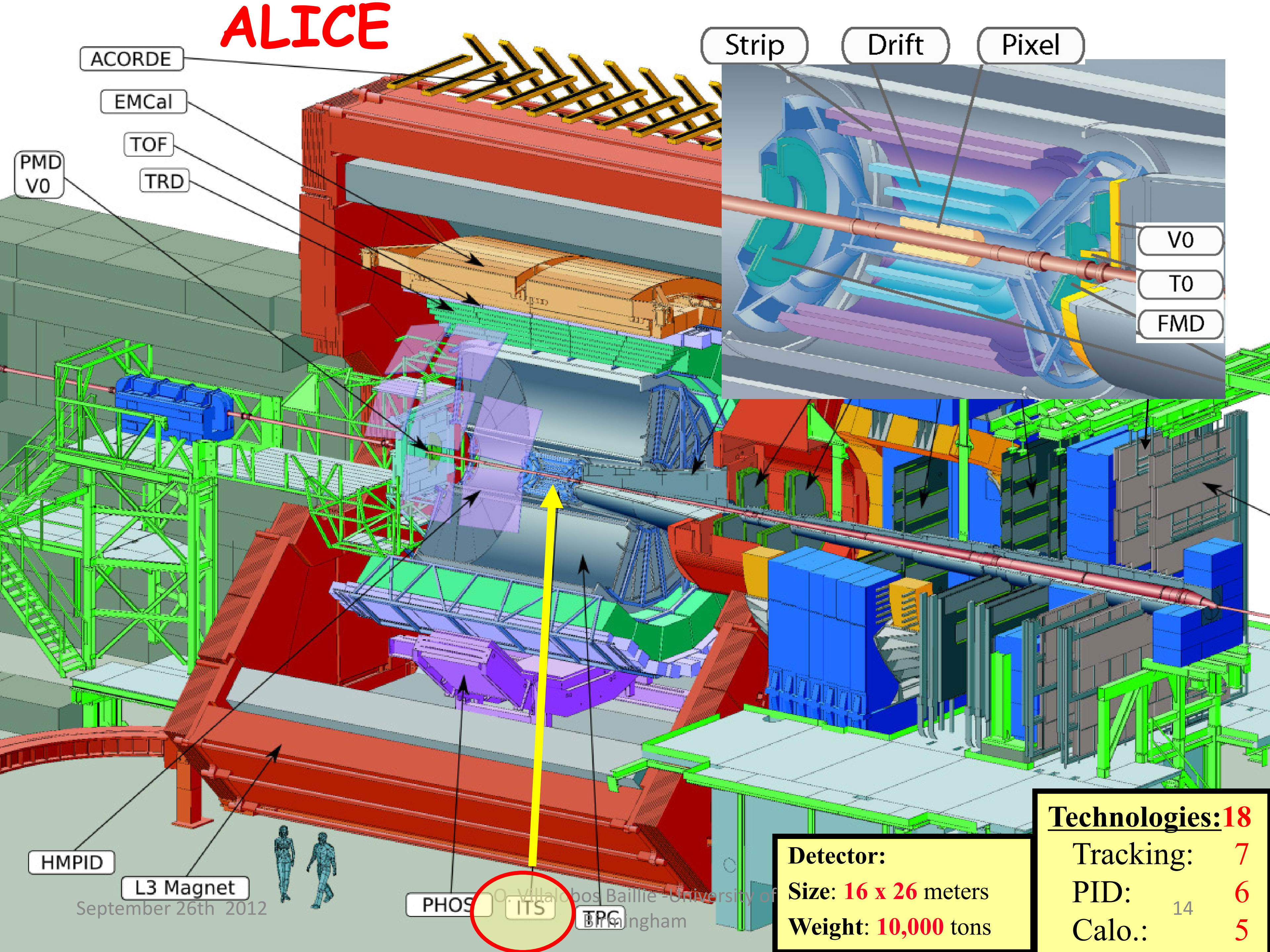
ALICE
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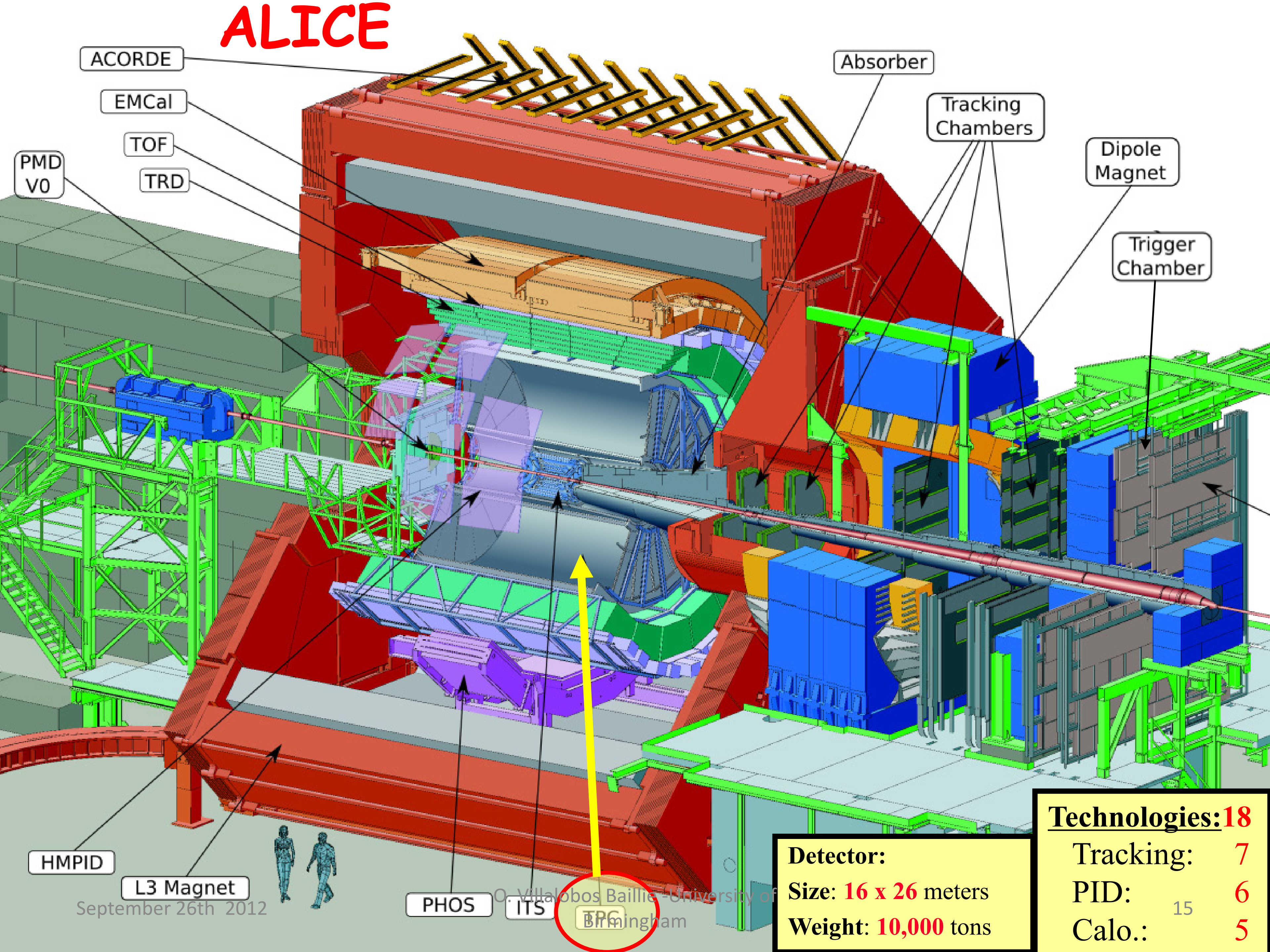

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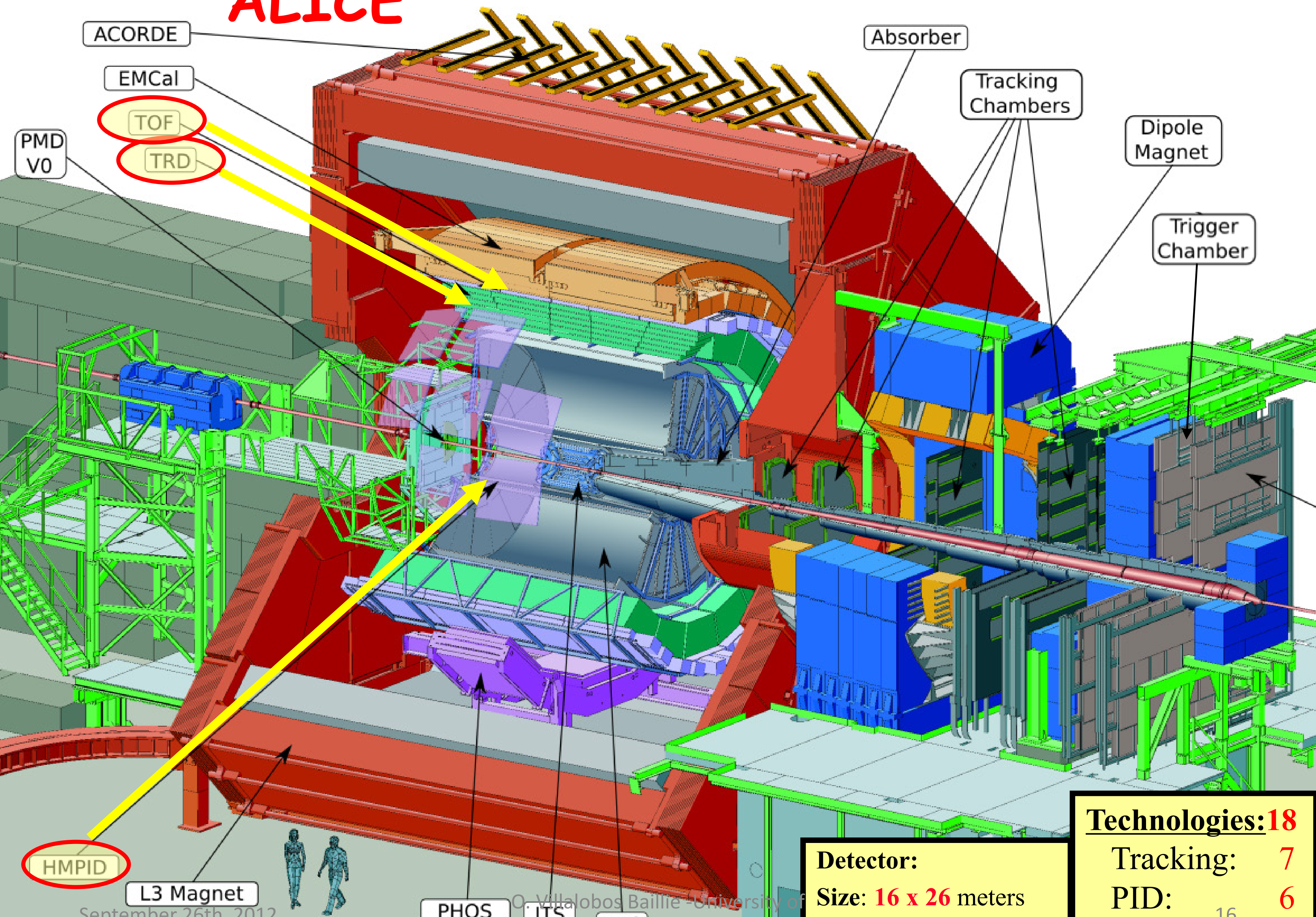

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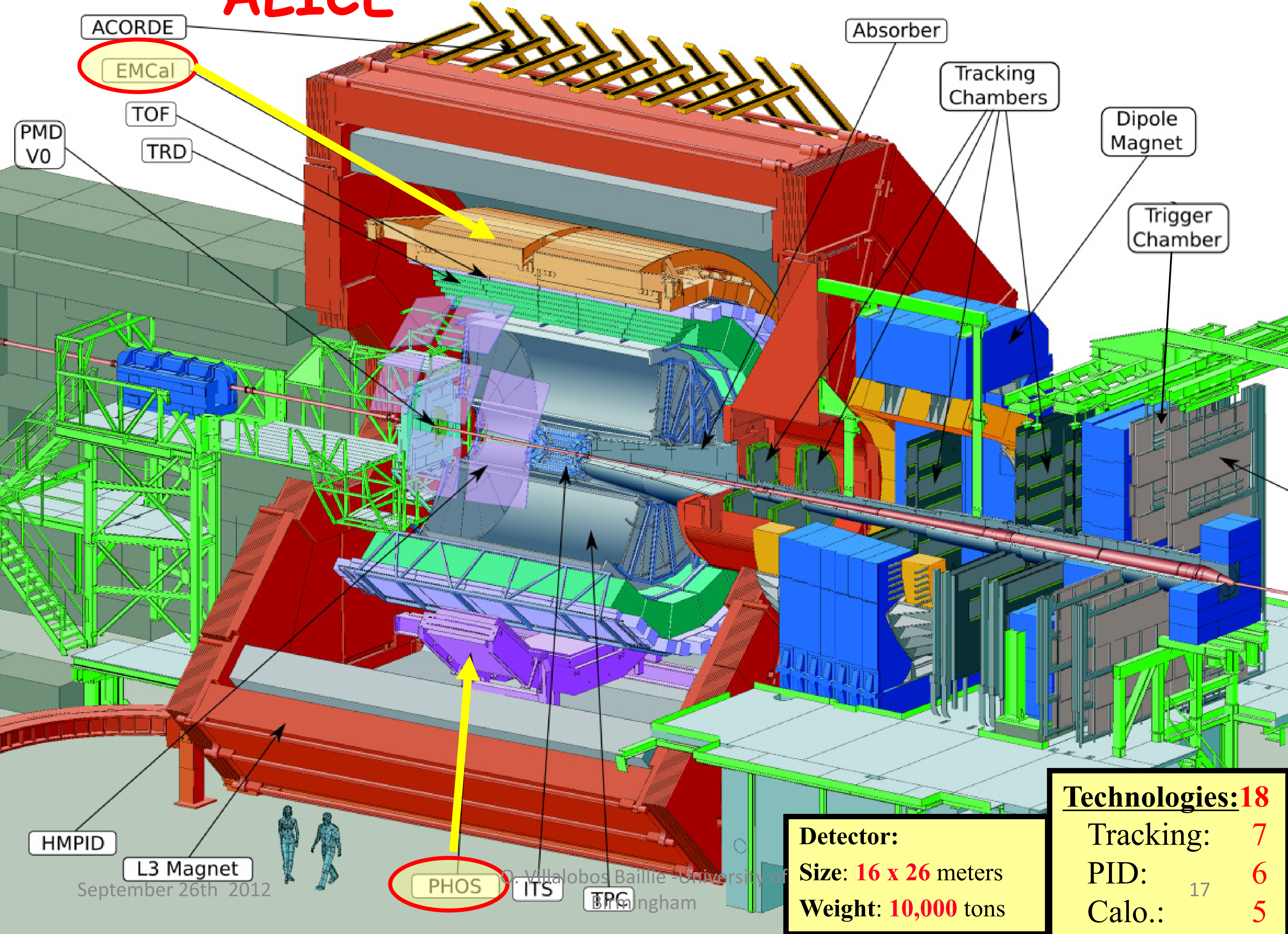

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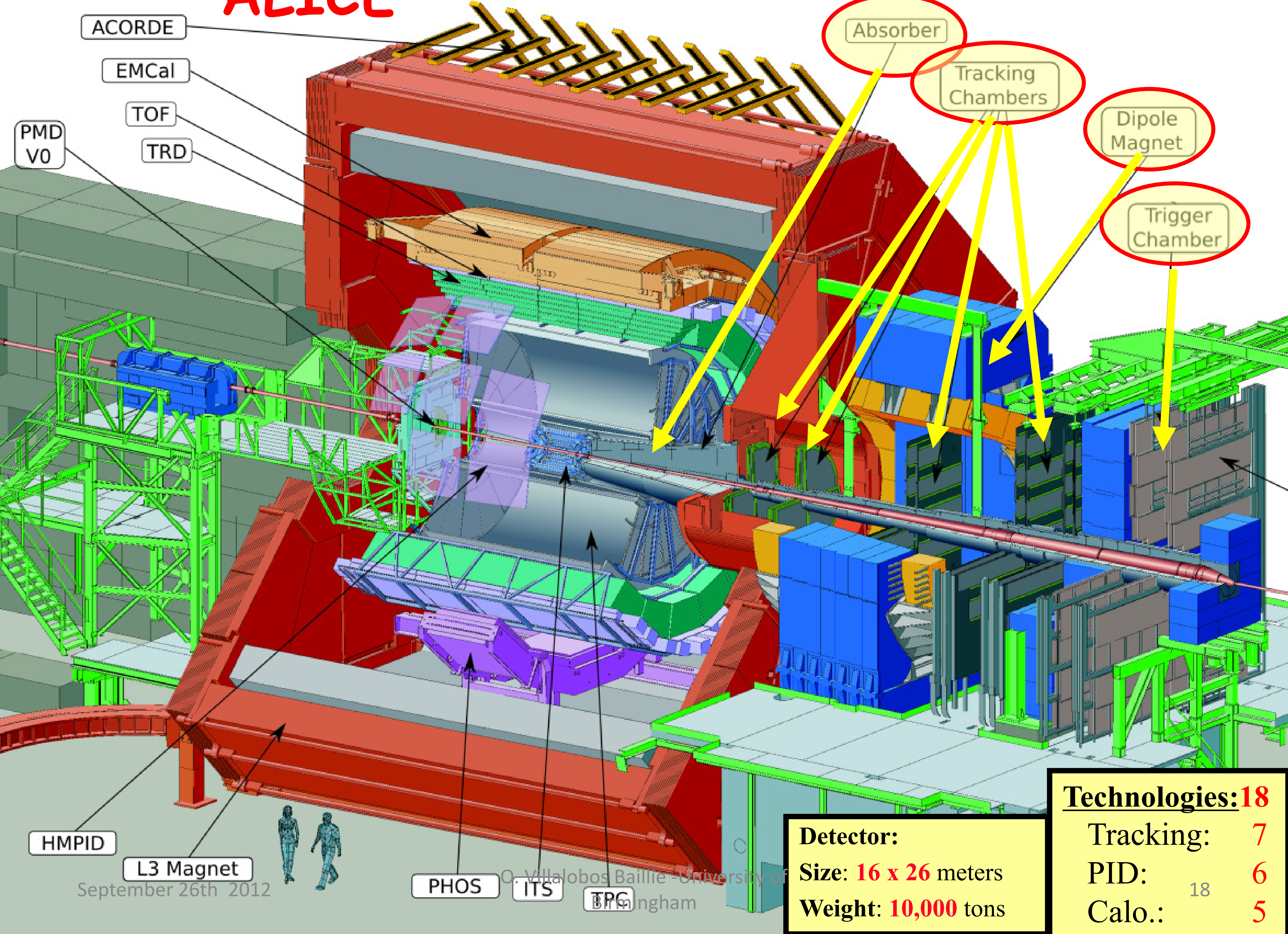

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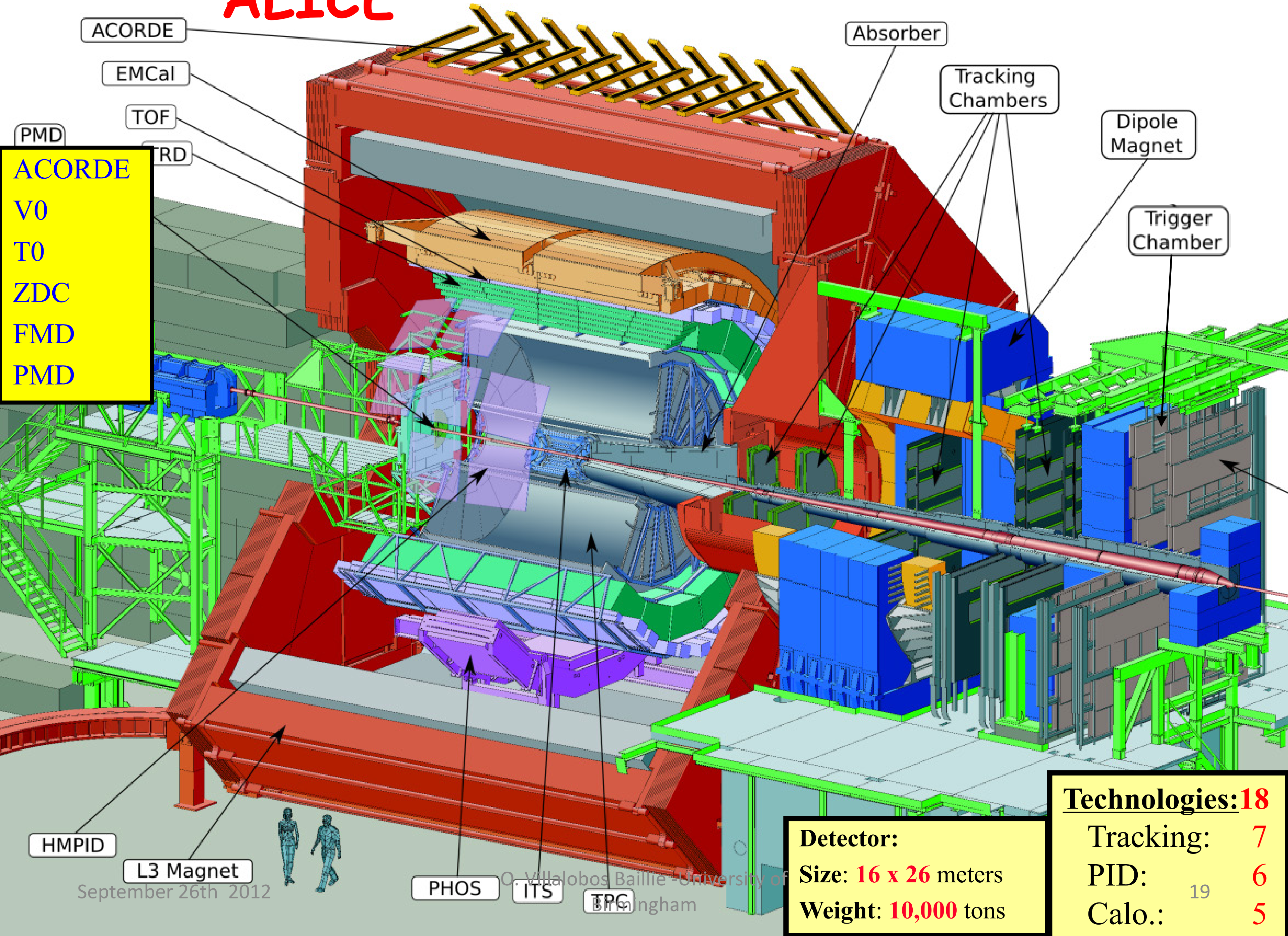

ACORDE
V0
T0
ZDC
FMD
PMD

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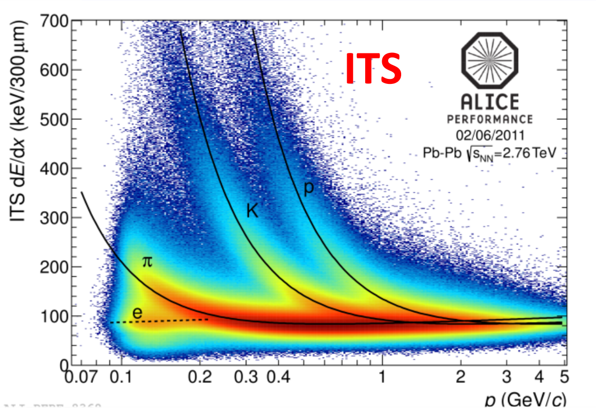
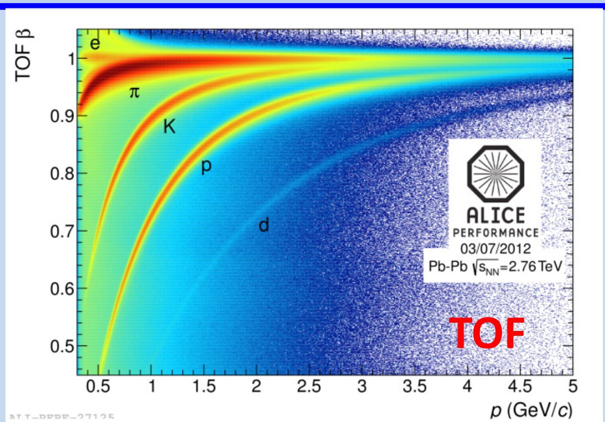
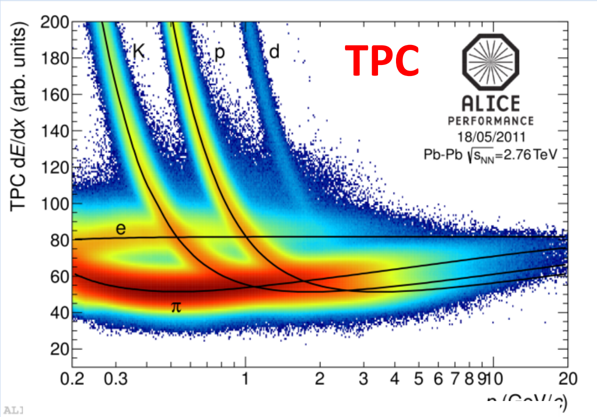
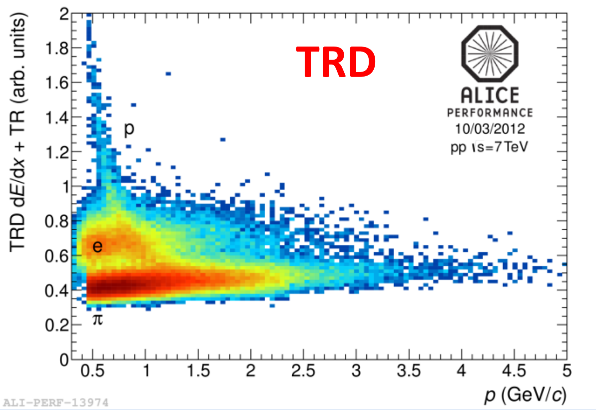
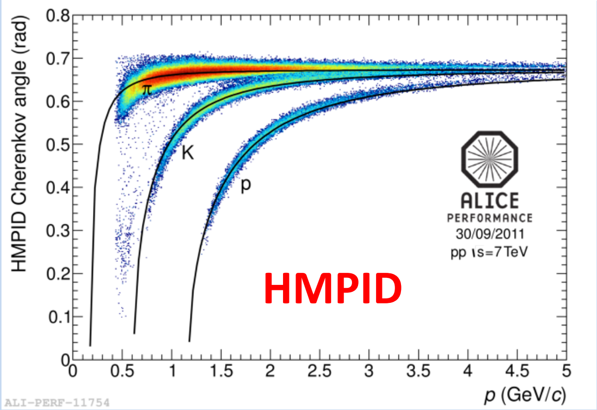
ALICE – dedicated heavy-ion experiment at the LHC

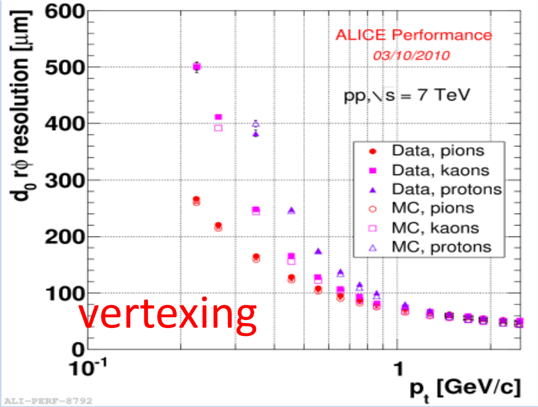












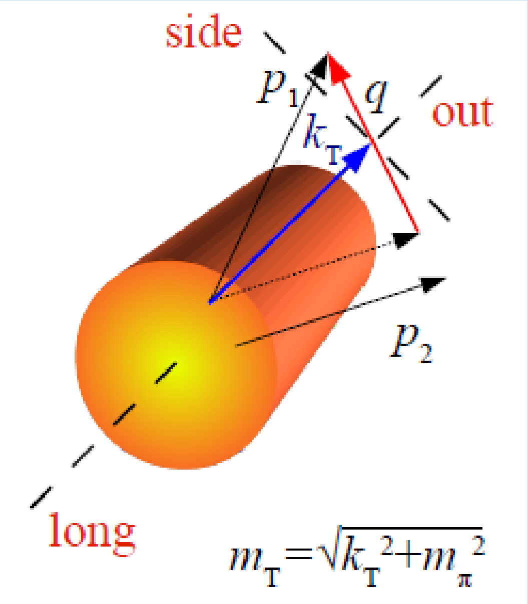
- particle identification (practically all known techniques)
- extremely low-mass tracker ~ 10% of X_0
- excellent vertexing capability
- efficient low-momentum tracking – down to ~ 100 MeV/*c*

REMINDER

Previous Results

System Size?

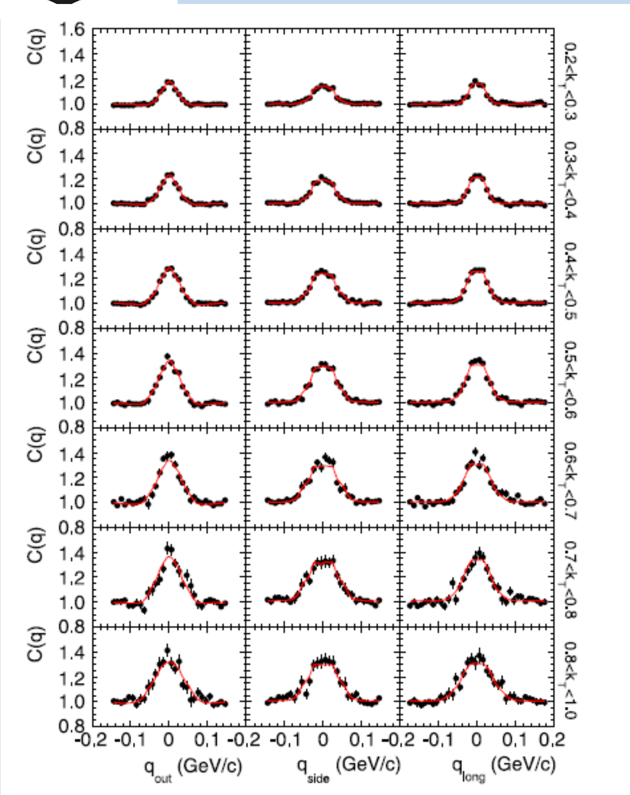
- Use *boson interferometry* (HBT) to estimate system size.
- Measure $C(q) = A(q) / B(q)$
  - A(*q*) is distribution in momentum difference $q=p_1-p_2$ for identical bosons
  - B(*q*) is the same, but measured for track pairs that cannot be correlated (e.g. from different events)

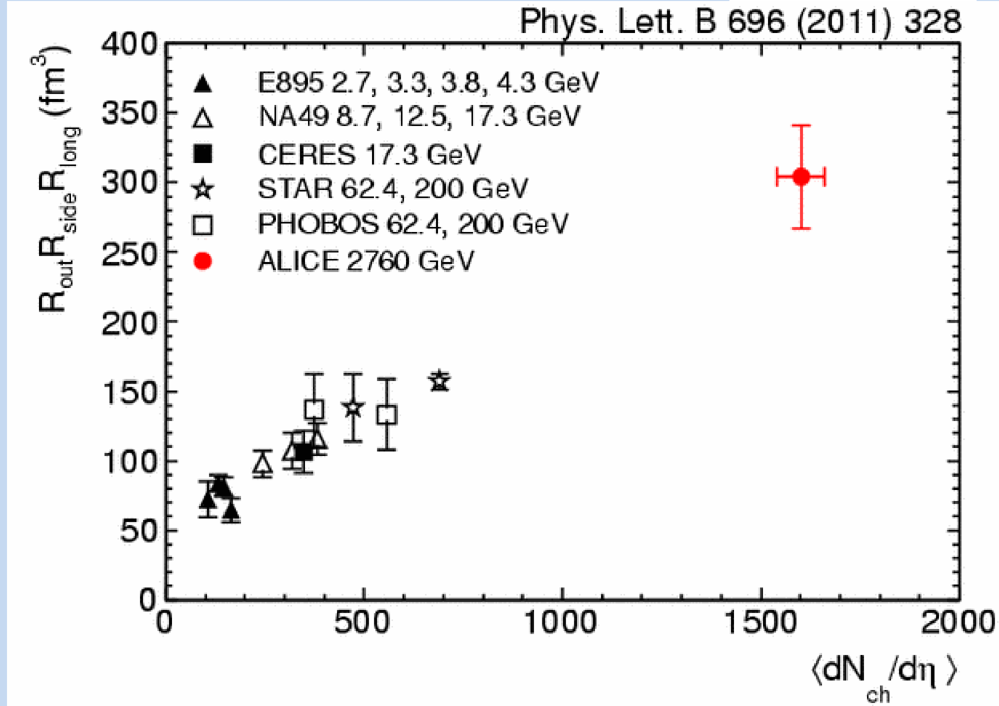


$$C(\mathbf{q}) = N[(1-\lambda) + \lambda K(q_{\text{inv}})(1+G(\mathbf{q}))]$$

$$G(\mathbf{q}) = \exp(-(R_{\text{out}}^2 q_{\text{out}}^2 + R_{\text{side}}^2 q_{\text{side}}^2 + R_{\text{long}}^2 q_{\text{long}}^2 \\ +2|R_{\text{ol}}|R_{\text{ol}} q_{\text{out}} q_{\text{long}}))$$

System size



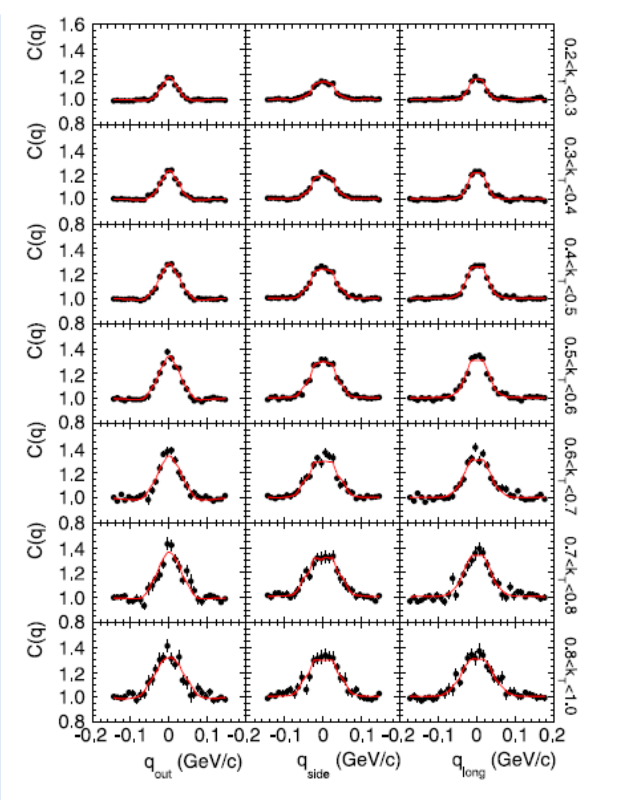


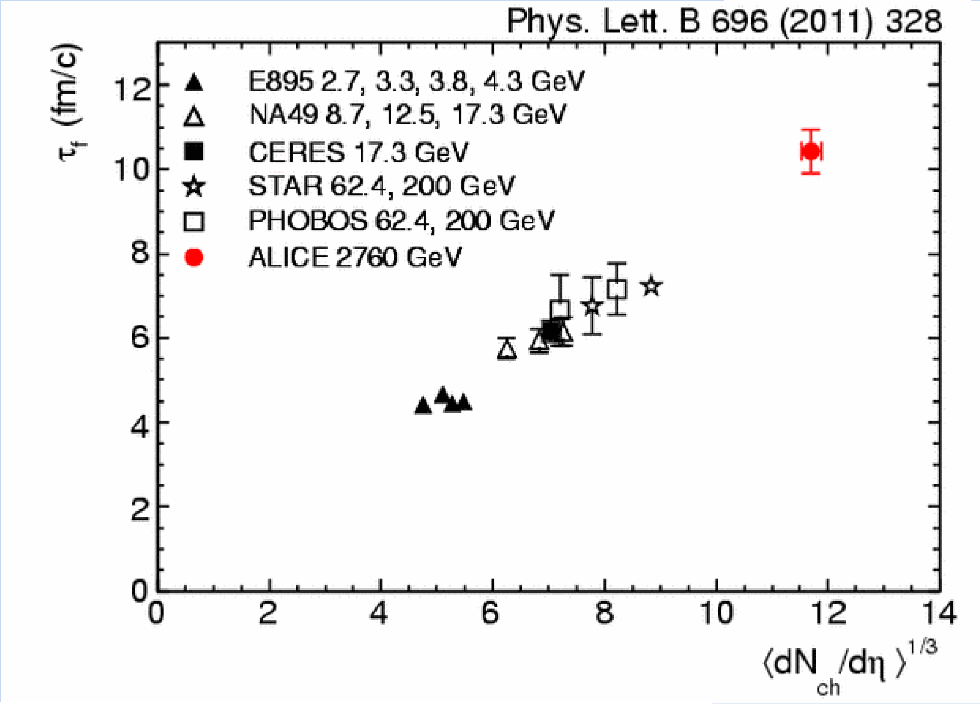
A. Aamodt et al. Phys. Lett. B696 (2011) 328

- Both radii (and therefore volume) and the decoupling time (τ_f) for the system (measure of "lifetime") can be extracted.
- Shows LHC collisions give rise to an interacting system that is larger (3×RHIC) and longer-lived (140% RHIC) than any previously.

V ~ 4500 fm^3, τ~10 fm/c

System size





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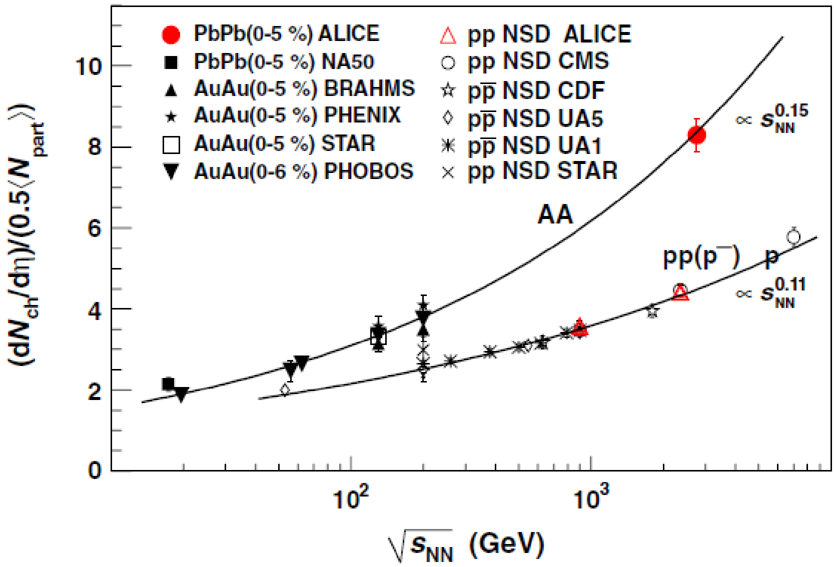
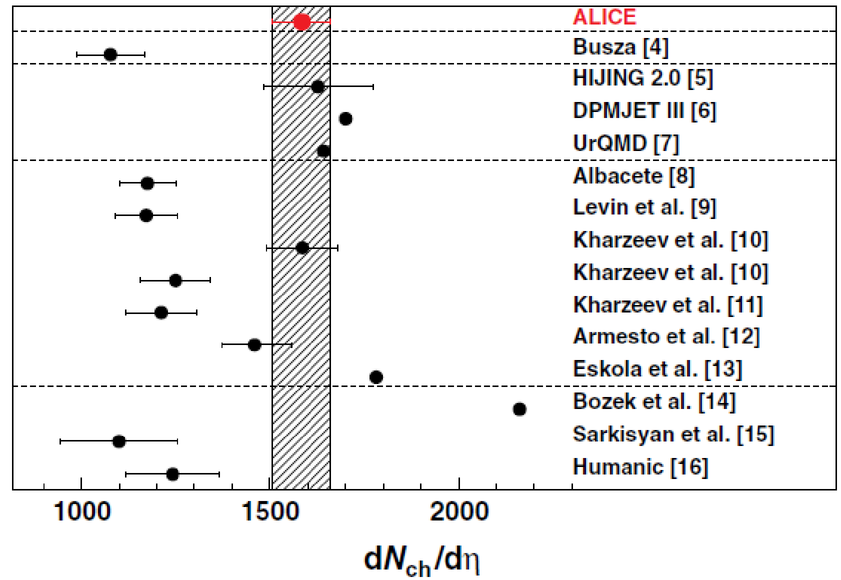
Rapidity Density





- The minimum bias rapidity density <d*N*/dη> at mid-rapidity rises with √s, both in pp and in PbPb.
- pp multiplicity density was not described by Monte Carlo generators without tuning, and initially underpredicted the result.
- Production per participant greater by factor 1.9 in PbPb
- Monte Carlo generators tuned to pp reproduce PbPb well
- Models based on initial-state gluon saturation density have mixed success, depending on specific assumption. (Parton production in a QGP is dominated by gg interactions.)

ALICE Collaboration EPJ C(2010) **65** 111
EPJ C(2010) **68** 89
EPJ C(2010) **68** 345
PRL (2010)**105** 252301

Rapidity Density

$$\frac{\mathrm{dN}}{\mathrm{d}\eta} = 1600 \pm 75$$

$$\varepsilon = \frac{1}{A\tau}\left(\frac{\mathrm{d}N}{\mathrm{dy}}\right)\langle m_{\mathrm{T}}\rangle \quad \text{(Bjorken)}$$

$$\varepsilon\tau \approx \frac{1}{\pi \times 6^2} \times (1600) \times 0.35\ \text{GeV fm}^{-3}$$

$$\square\ 5\ \text{GeV fm}^{-3}$$

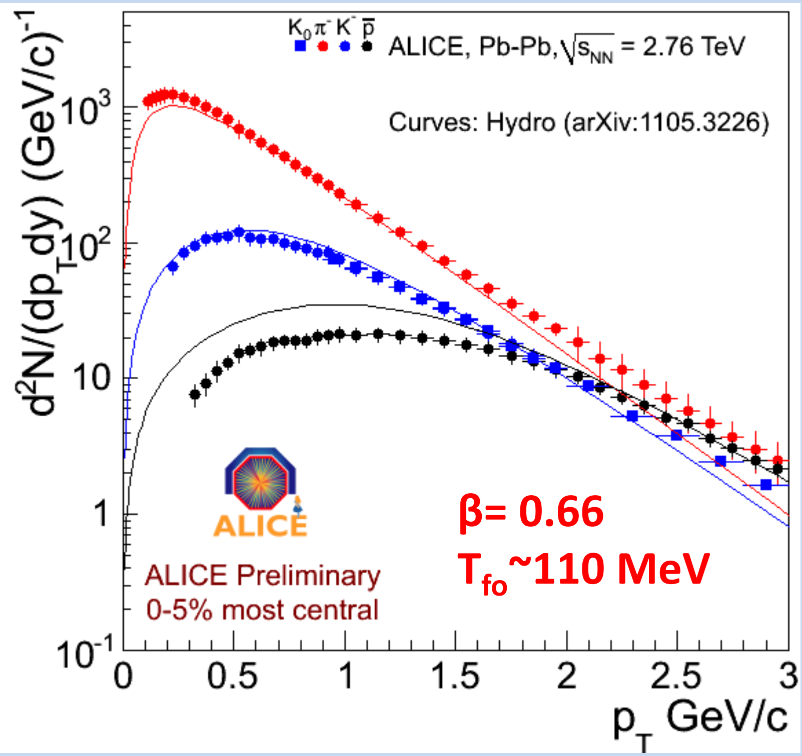
Summary on Bulk Properties

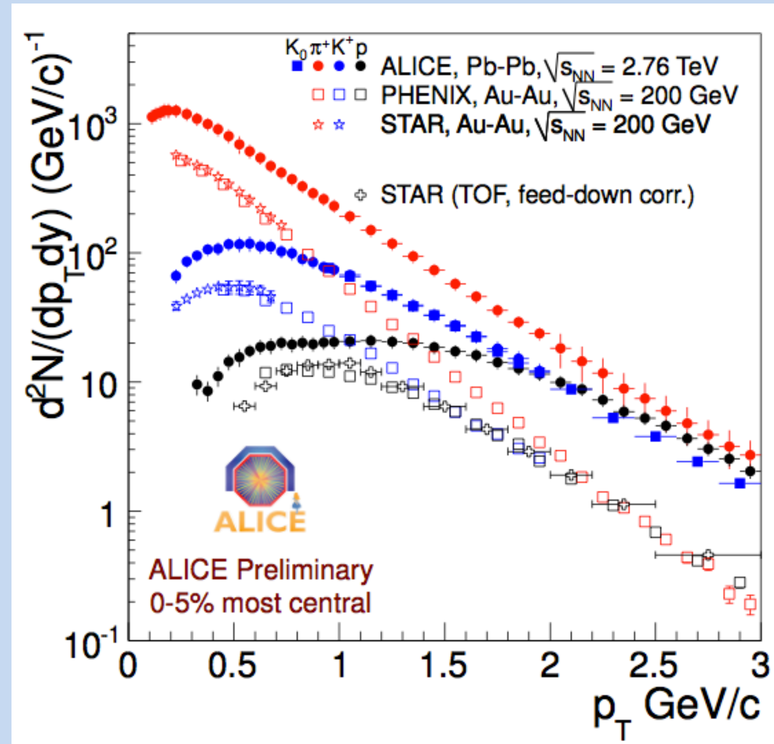
- Measurements of global variables of the PbPb system lead to information on the size and energy density of the system.
- They indicate that the system created at the LHC has a volume considerably larger than that at RHIC, and lives longer. ($R_{out} \approx R_{side} \approx 6$ fm, $R_{long} \approx 8$ fm for low p_T)
- The energy density is also larger. The exact size depends on the value given for the "formation time" τ in the Bjorken formula. As the correct value for this parameter is difficult to ascertain, the results are often given for the product $\epsilon\tau$. The other parameters in the formula are all unambiguous.

Flow Measurements

- The system produced in a heavy ion collision is far from static, and is in a process of very rapid expansion. The way in which this takes place is described by “flow”.
- *Radial* flow determines the modifications to the p_T spectra coming from the expansion of the system. This gives an additional “boost” to the p_T and leads to a hardening of the spectrum.
- It is described by a “blast-wave” analysis.

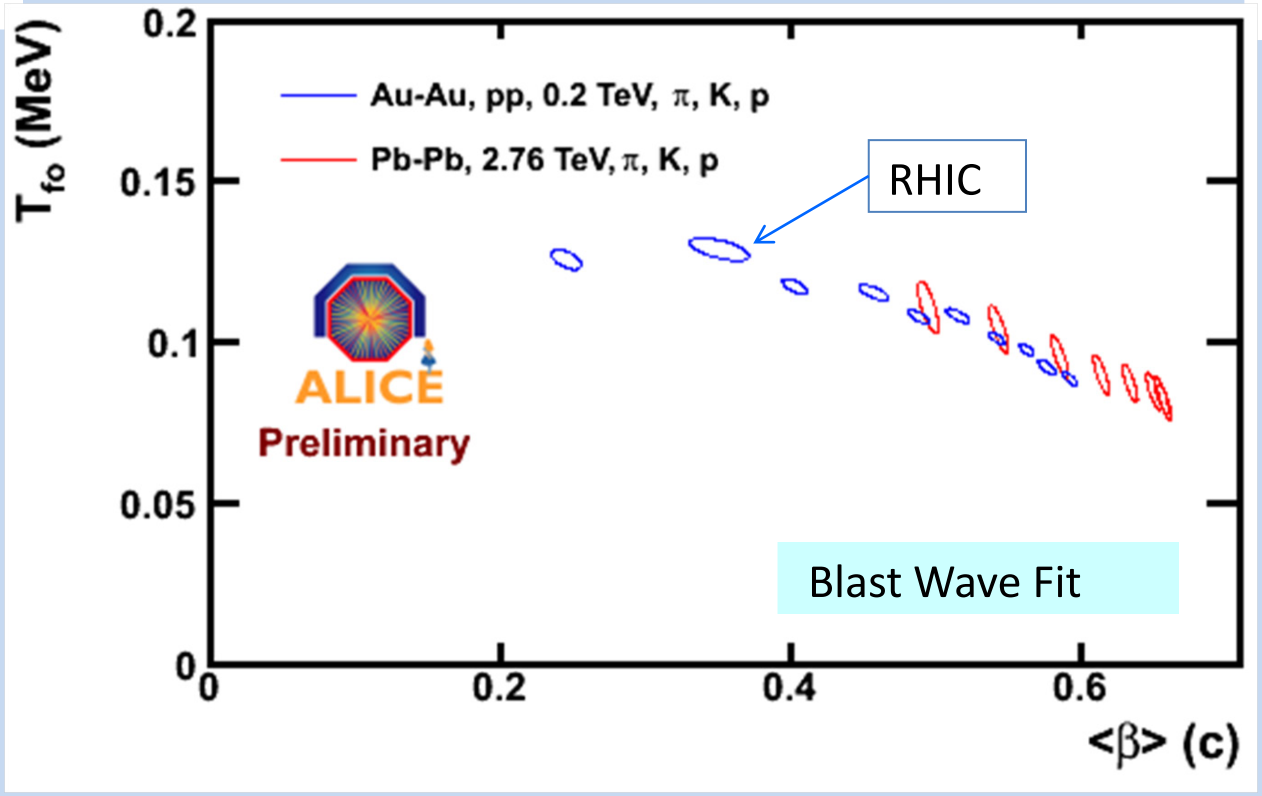
Radial Flow





- Blastwave fit using hydrodynamic model gets expansion velocity and freeze-out temperature.
- Comparison with RHIC spectra shows flow effects are stronger at the LHC.

Radial Flow



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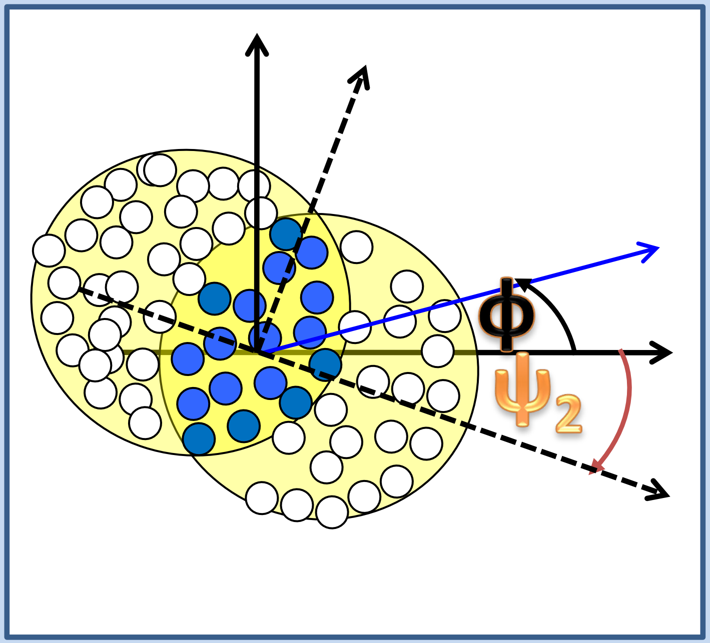
Anisotropic Flow

$$\frac{dN}{p_T dp_T dy d\phi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T dy}\left(1 + 2v_1 \cos(\phi - \psi_1) + 2v_2 \cos(2(\phi - \psi_2)) + \ldots\right)$$



Collision plane normal: $\mathbf{p} \times \mathbf{b}$

Impact parameter: $\mathbf{b}$

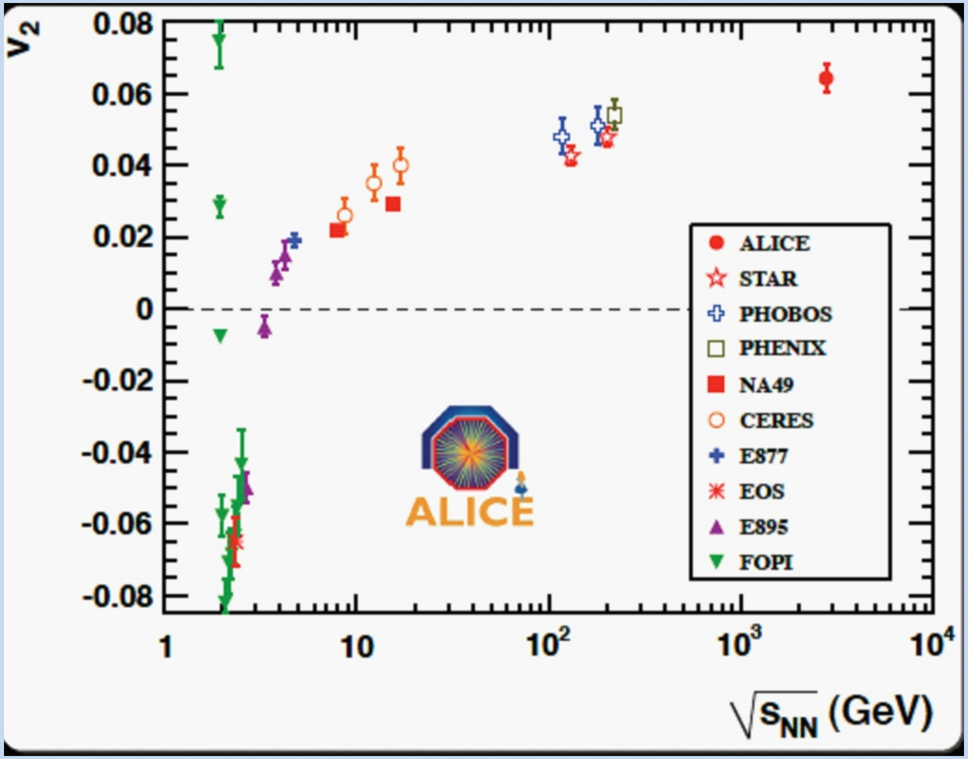
beam direction: $\mathbf{p}$

- For *non-central* collisions, the collision geometry is not azimuthally symmetric.
- This gives rise to an asymmetry in azimuthal distribution of particle production
- Parameterise in terms of Fourier coefficients of ϕ distribution
- "Elliptic flow" described by v_2.

Elliptic Flow

- Most straightforward distortion of system is that the overlap volume of the colliding nuclei is not spherical but (approximately) oval shaped, so better described by an ellipsoid.
- The Fourier coefficient v_2 is well suited for describing the distortion of a sphere into an ellipsoid.
- Real fluids do not distort instantaneously. Degree of distortion depends on equation of state of the medium (EOS) and on the shear viscosity of the fluid η.
- Hydrodynamic model represents the transformation of the intial state geometric azimuthal asymmetry into the final state momentum azimuthal asymmetry.
- Fits in terms of such a model yield values of η.

Hydrodynamic Limit



v_2 vs √s for unidentified charged particles

2011

- The lower the viscosity, the higher the limiting value of v_2.
- Claim that QGP behaves like a "perfect fluid" comes from fact that as √s increases, the value approaches that from ideal hydrodynamics.

Perfect Fluid?

- Relevant quantity is not η but η/S, where S is the entropy of the system.
- AdS/CFT sets lower limit on η/S
  - $\eta/S \geq \hbar/(4\pi k_B)$ ~ 0.02 Starinets 2002

$\eta \,\square\, \rho v l$ shear viscosity (Maxwell relation)

$S \,\square\, n \,\square\, \rho / m$ entropy

$\frac{\eta}{S} \sim m v l \geq \hbar$ η/s

Relativistic treatment gives η/S ~ <p>/σ, so small η/S implies large σ - strongly interacting fluid

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$S \sim n \sim \rho / m$ entropy

$\frac{\eta}{S} \sim m v l \geq \hbar$ η/s

water	$\eta = 1$	kPa s
Liquid Helium	$\eta = 1.7 \times 10^{-6}$	kPa s
QGP	$\eta \sim 5 \times 10^{11}$	kPa s

Relativistic treatment gives $\eta/S \sim \langle p \rangle/\sigma$, so small η/S implies large σ - strongly interacting fluid

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$S \;\square\; n \;\square\; \rho / m$ entropy

$\frac{\eta}{S} \sim mvl \geq \hbar$ η/s

water	
Liquid Helium	η/S = 0.8
QGP	η/S = 0.5

Relativistic treatment gives η/S ~ <p>/σ, so small η/S implies large σ - strongly interacting fluid

η and η/S

- Result is that for QGP η is in fact quite large
- BUT η/S is very small.

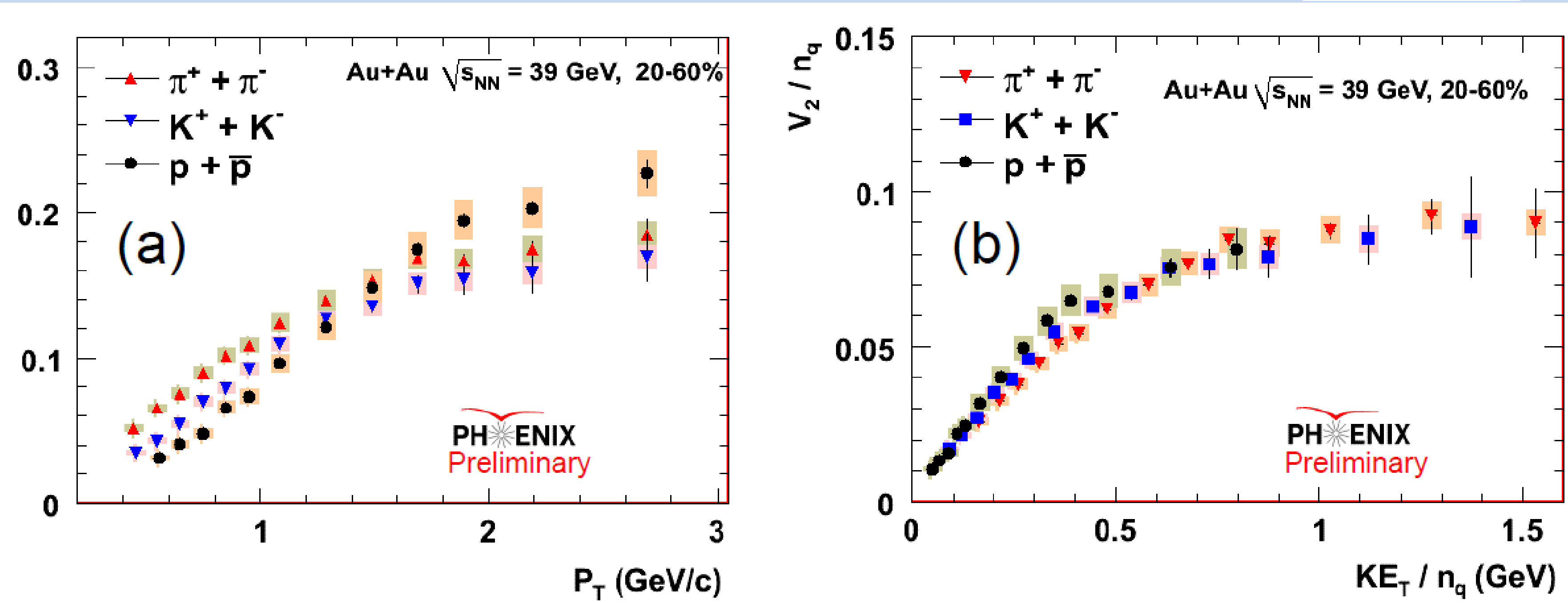
University of Queensland "pitch drop" experiment where eight drops have been recorded since 1927, gives an η ~ 10^5-10^9 kPa s depending on temperature

QGP η is even larger (10^{11} kPa s)

BUT η/S is a bit smaller than liquid Helium – very close to "perfect fluid".

http://www.physics.uq.edu.au/physics_museum/pitchdrop.shtml

n_q scaling?

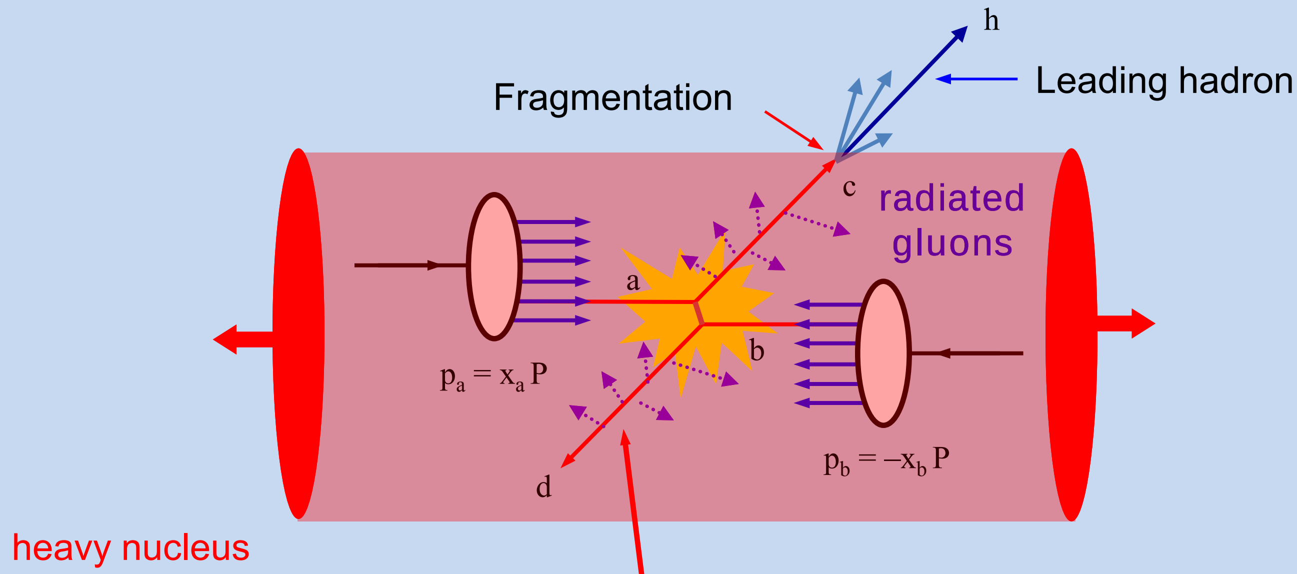


- RHIC – relatively small differences in v_2 by species – scaling in v_2/n_q
- Quoted as key evidence for partonic flow

Flow Summary

- At RHIC, flow effects were a very important part of the analysis.
    - "perfect fluid" and constituent quark scaling two very important arguments in partonic picture of medium.
- Good hydrodynamic model essential to interpret results
    - Gives bridge from v_2 to η
- LHC results show even stronger flow effects than RHIC
    - Very low η/S seems to be confirmed. Strongly interacting QGP

Jet Quenching



Key prediction: jets are *quenched*
- collisional energy loss (Bjorken)
- radiative energy loss (Wang and Gyulassy)

J.D. Bjorken Fermilab preprint PUB-82/59-THY (August 1982).
X.-N. Wang and M. Gyulassy, Phys. Rev. Lett. **68** (1992) 1480

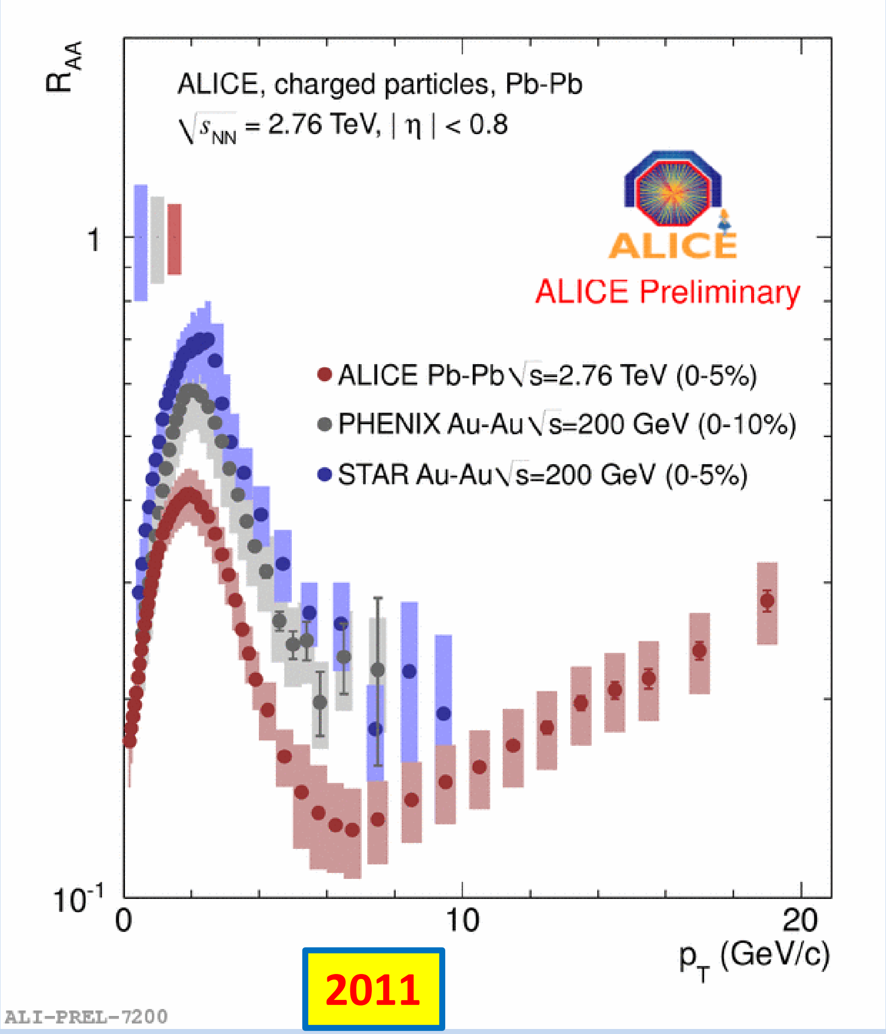
Nuclear Modification Factor R_{AA}

- One way to parameterise the absorption of jets in the medium is through R_{AA}

$$R^h_{AA}(p_T) = \frac{d\sigma^h_{AA} / dp_T}{< N_{coll} > \times d\sigma^h_{pp} / dp_T}$$

- Ratio gives 1 if production of given hadron in AA is described by scaling by number of collisions from production in pp – no absorption.
- Differences from one indicate the jets have been absorbed (quenched).

R_{AA} for charged particles



2011

- Effects at LHC are stronger than at RHIC as already seen for other phenomena
- Strongest suppression for p_T~7 GeV/c (R_{AA} ~1/7)
- For higher p_T, R_{AA} starts to rise again – energetic enough jets have a chance to break through.

UPDATES 2012

LHC Heavy-Ion running

- Two heavy-ion runs at the LHC so far:
  - in 2010 – commissioning and the first data taking
  - in 2011 – already above nominal instant luminosity!
- p–Pb run moved to beginning of next year
  - plan for ~ 30 nb^{-1}
    - (for rare-probe statistics equivalent to ~0.15 nb^{-1} of Pb–Pb)
- Followed in 2013 by Long Shutdown–1 (LS1)

year	system	energy $\sqrt{s_{NN}}$ TeV	integrated luminosity
2010	Pb – Pb	2.76	~ 10 μb^{-1}
2011	Pb – Pb	2.76	~ 0.1 nb^{-1}
2013	p – Pb	5.02	~ 30 nb^{-1}

QM11

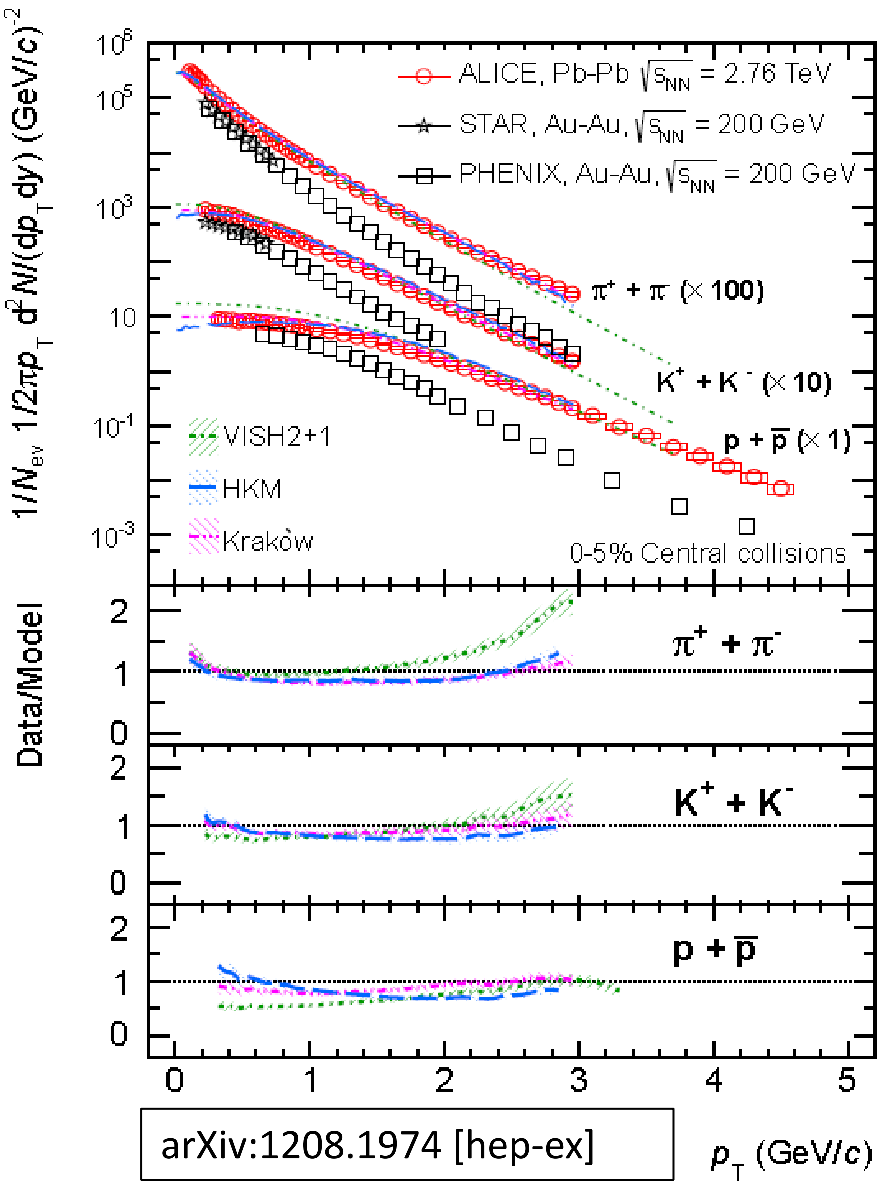
QM12

HADROCHEMISTRY

Hadron Production

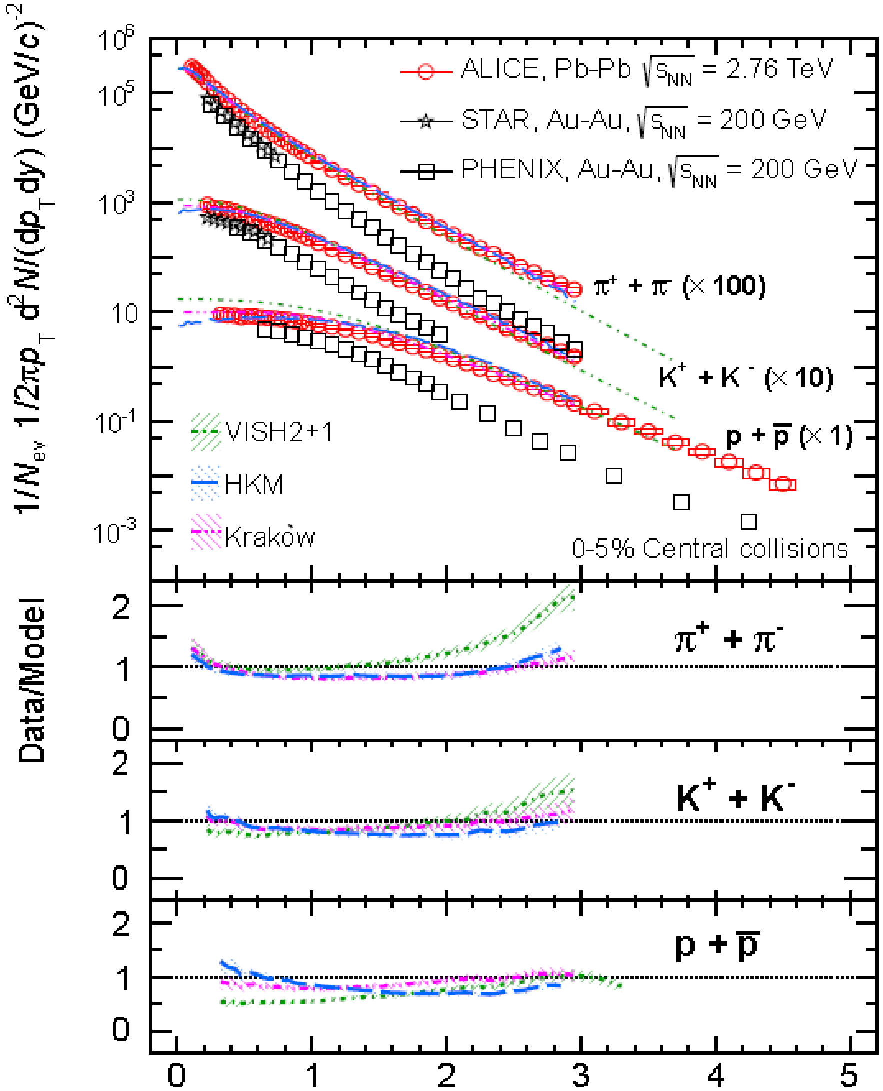
- ALICE has now measured the spectra and yields in Pb-Pb collisions at $\sqrt{s}$=2.76 TeV for a large number of hadron species
  - $\pi^{\pm}$, K, p, Λ, Ξ, Ω, ϕ - π^0, η, $D^{\pm}$, D^0, D^*, D_s, J/ψ, ψ'
- These allow a check to be made of the thermal nature of hadronic production, and also of the influence of particle flow.

Low-p_T particle production

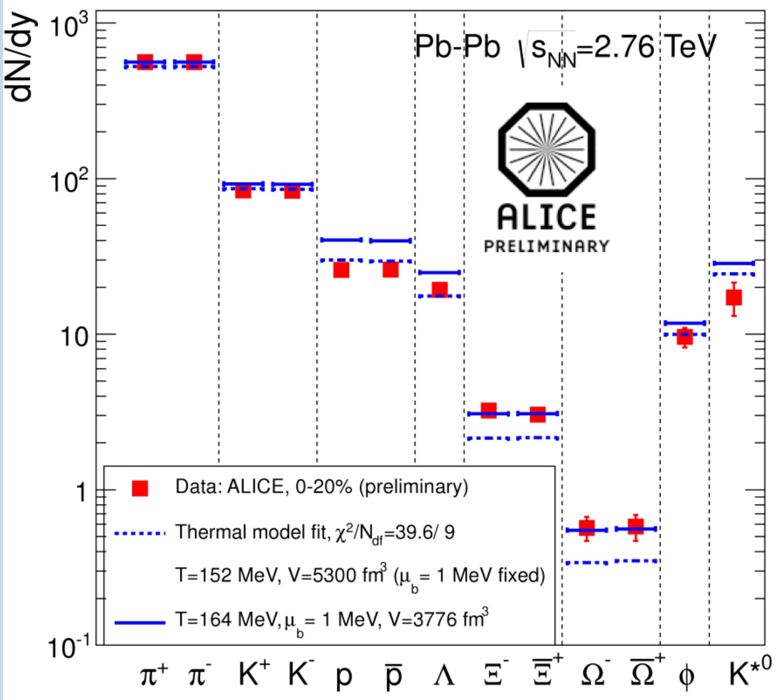


arXiv:1208.1974 [hep-ex]

Low-p_T particle production

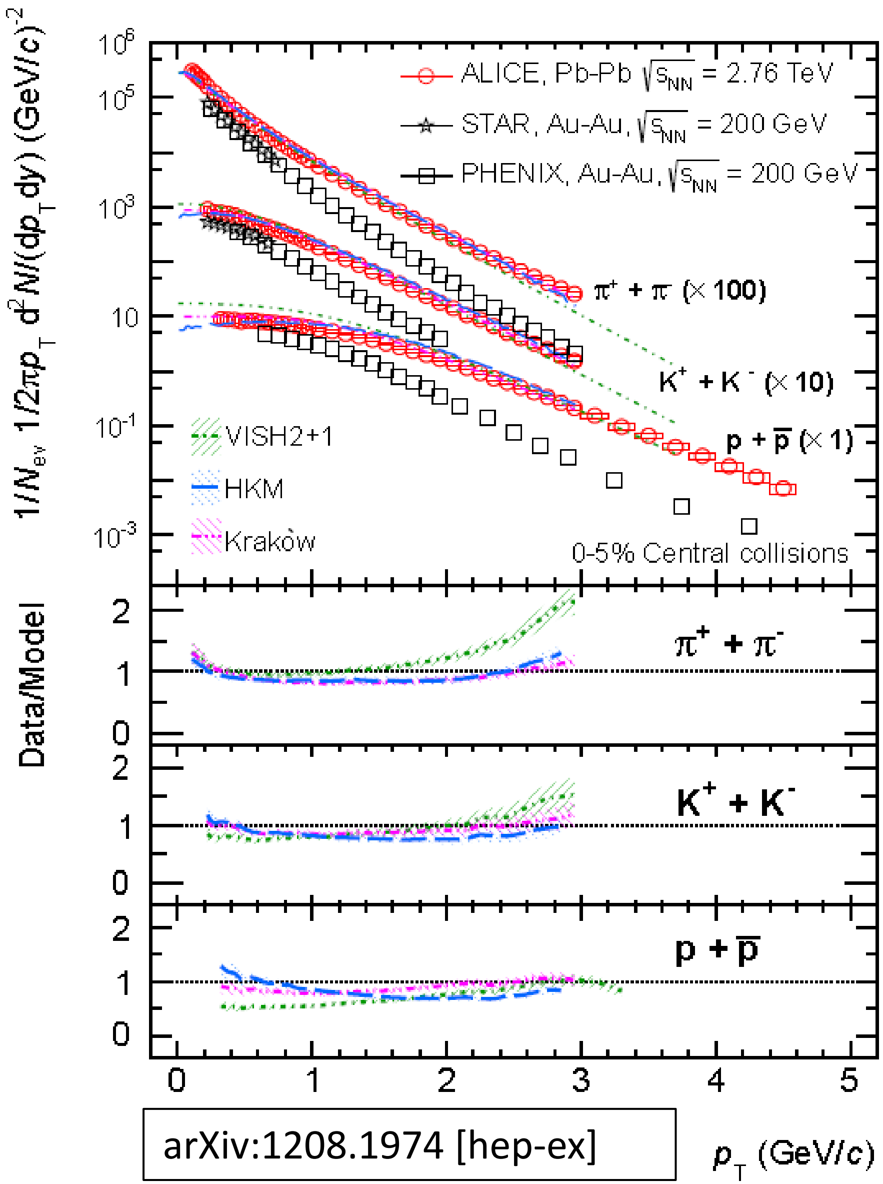


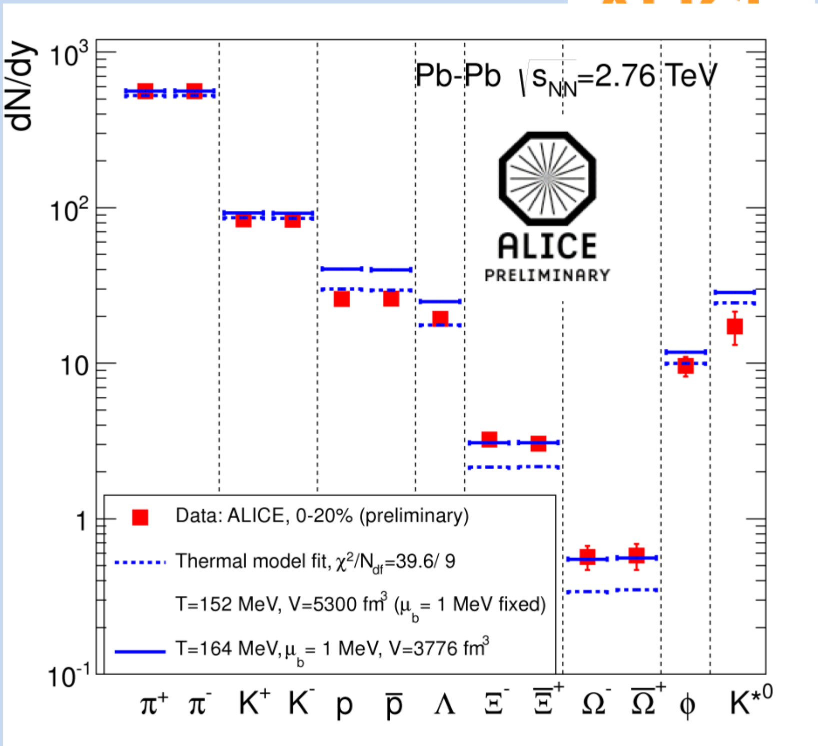
arXiv:1208.1974 [hep-ex]



Predicted temperature T=164 MeV
A.Andronic, P.Braun-Munzinger, J.Stachel NP A772 167
Thermal fit (w/o res.): T=152 MeV (χ^2/ndf = 40/9)
Ξ and Ω significantly higher than statistical model

Low-p_T particle production



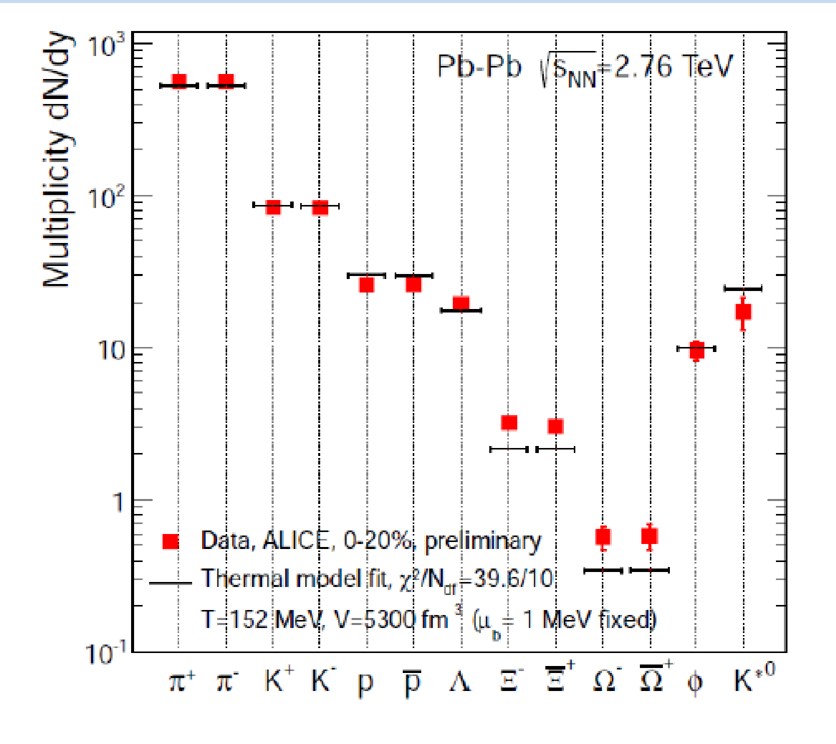


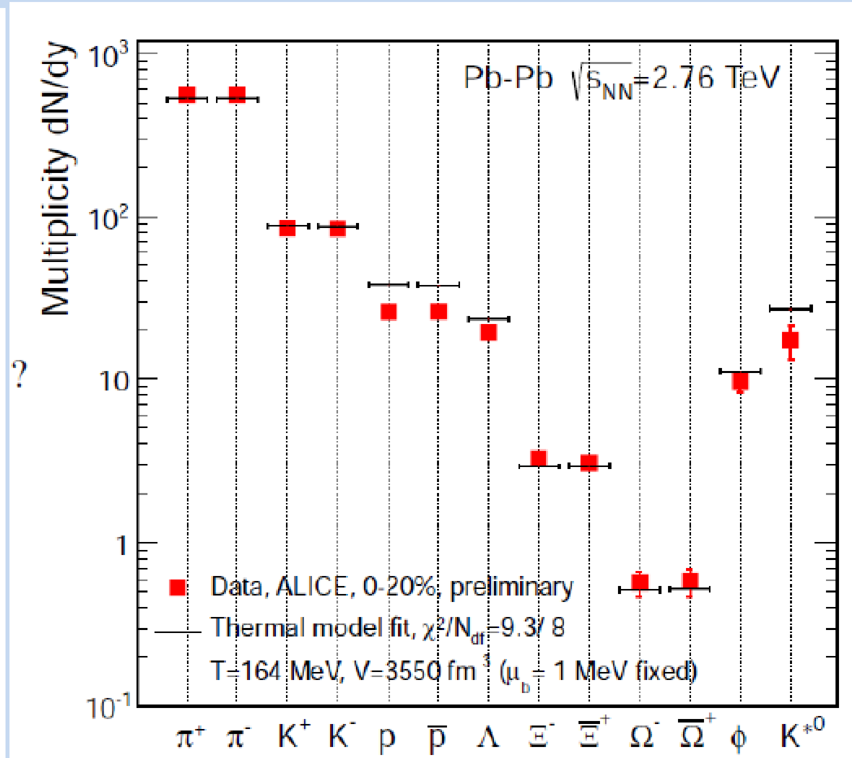
p/π and Λ/π ratios at LHC lower than at RHIC

Hadronic re-interactions ?

F.Becattini et al. 1201.6349 J.Steinheimer et al. 1203.5302

Two Thermal Fits



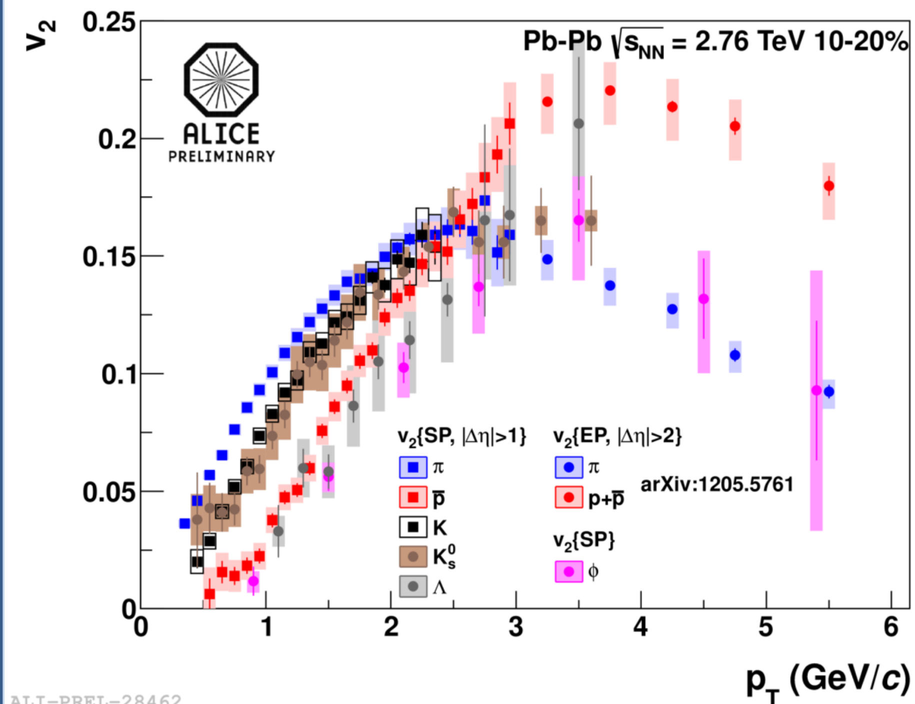


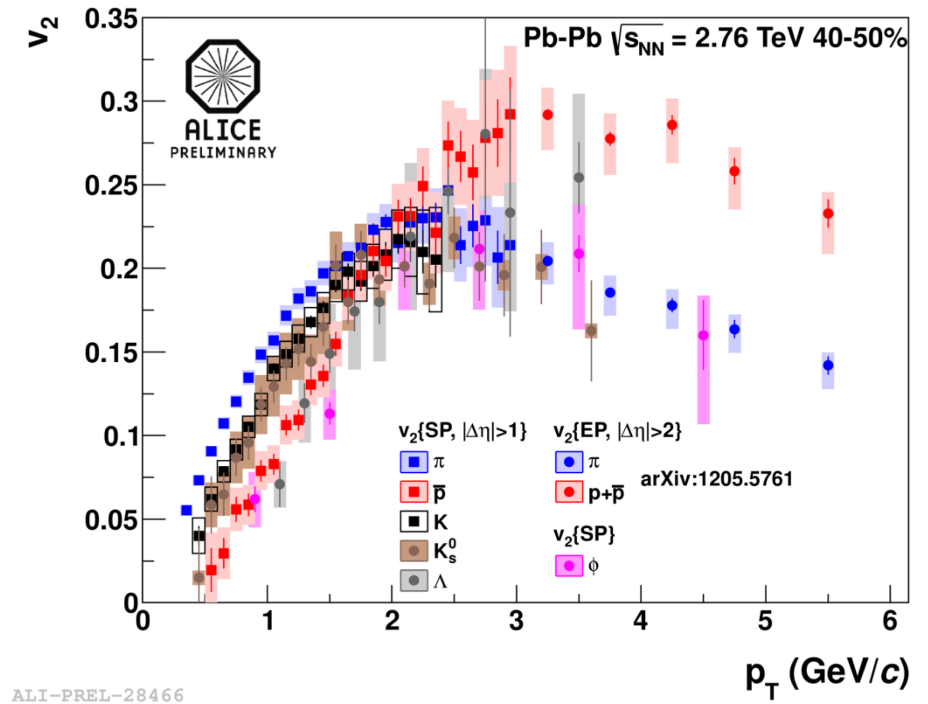
K* excluded: Bad fit (χ^2/NDF = 39/10)

p excluded: good fit (χ^2/NDF = 9.3/8)

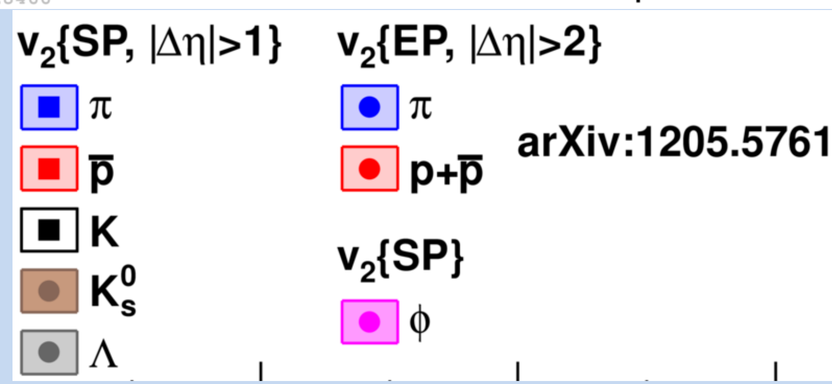
Not enough p: absorption?

Identified-particle v_2

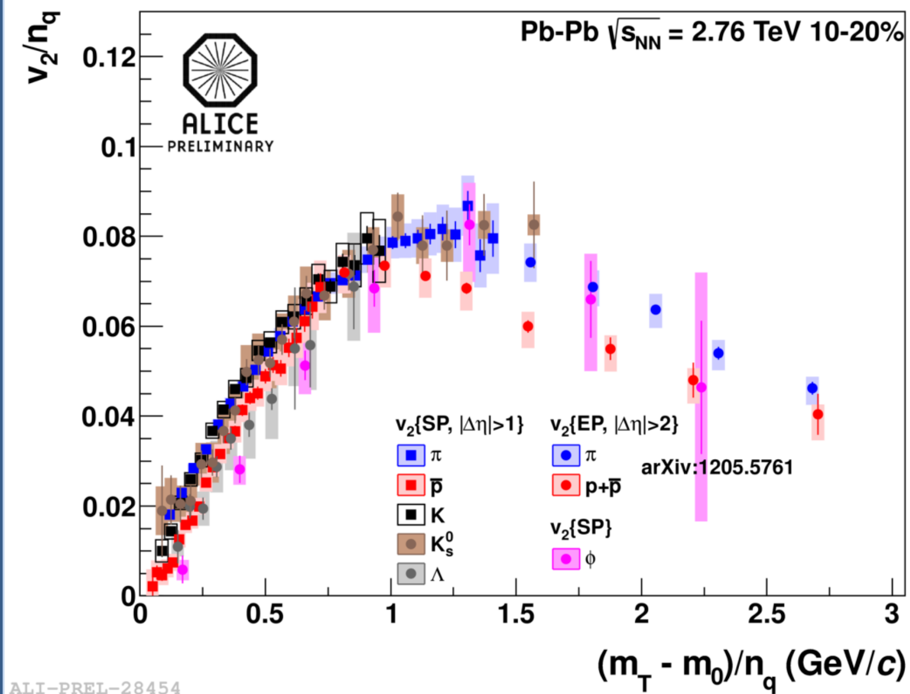


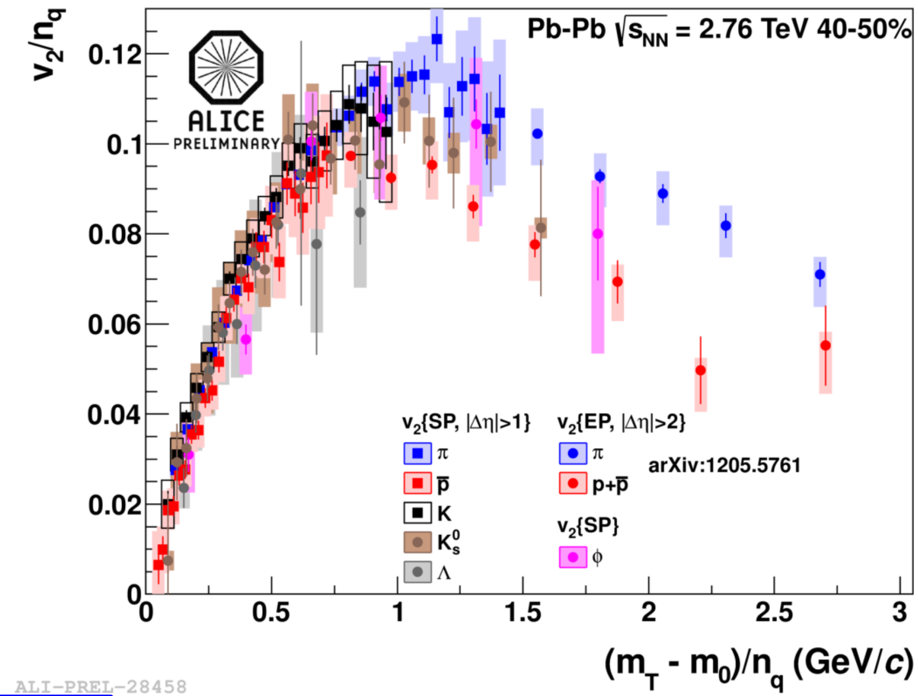


v_2 for π, p, $K^{\pm}$, K^0_s, Λ, ϕ (not shown for Ξ, Ω)
ϕ at low p_T (<3 GeV/c) follows mass hierarchy
– at higher p_T joins mesons
overall qualitative agreement with hydro up to p_T 1.5–3 GeV/c (π–p); quantitative precision needs improvements – hadronic afterburner

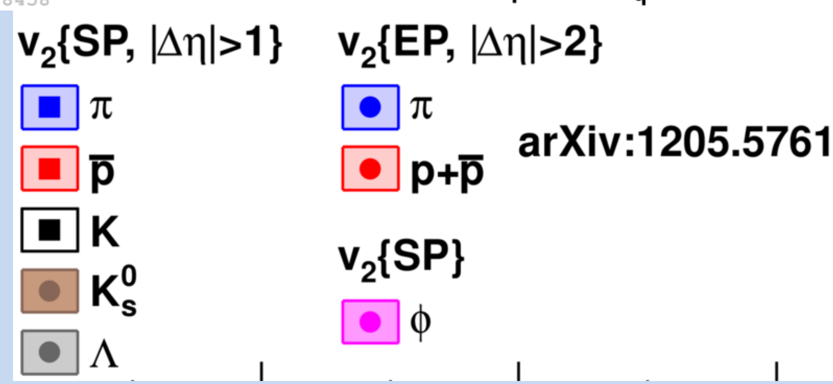


Identified-particle v_2



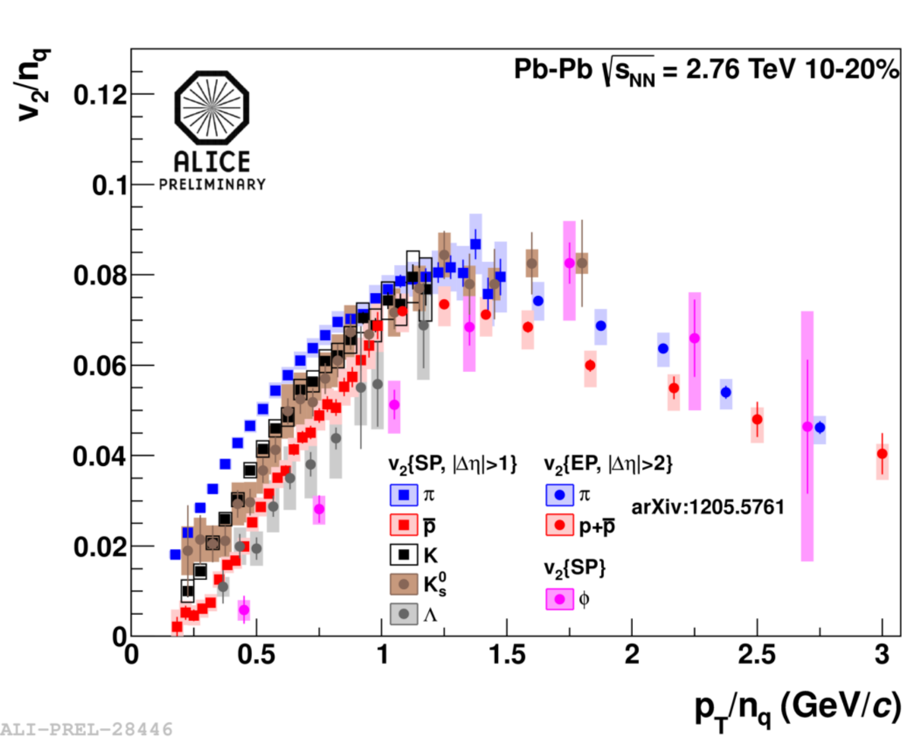


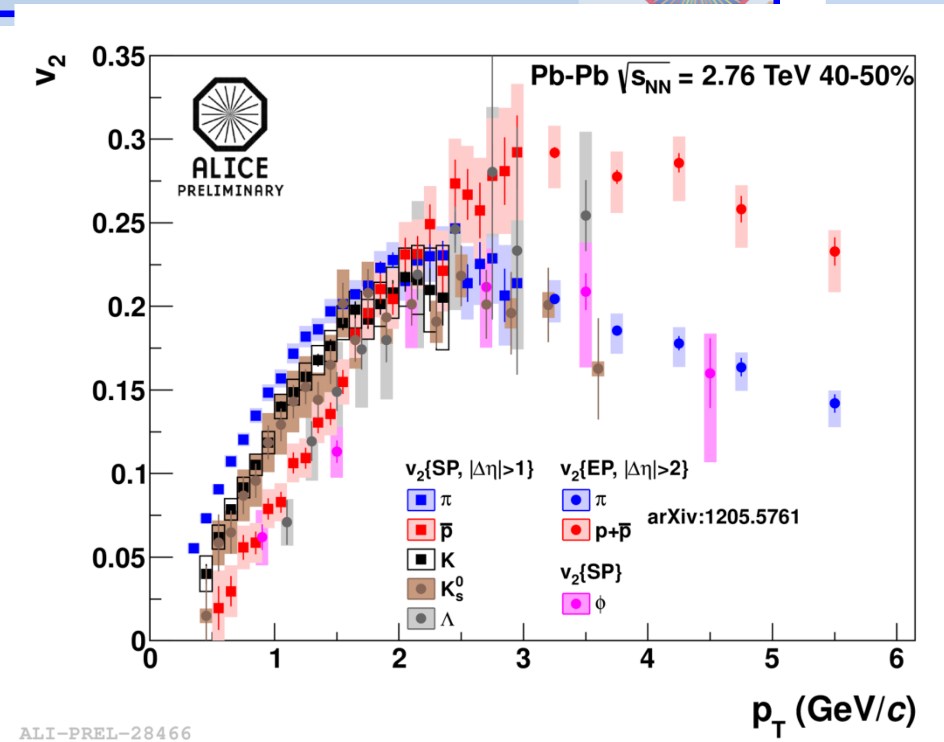
v_2 for π, p, $K^\pm$, K^0_s, Λ, φ (not shown for Ξ, Ω)
φ at low p_T (<3 GeV/c) follows mass hierarchy
– at higher p_T joins mesons
overall qualitative agreement with hydro up to p_T 1.5–3 GeV/c (π–p); quantitative precision needs improvements – hadronic afterburner



$n_q(m_T)$-scaling worse than at RHIC

Identified-particle v_2





- v_2 for π, p, $K^{\pm}$, K^0_s, Λ, ϕ (not shown for Ξ, Ω)
- ϕ at low p_T (<3 GeV/c) follows mass hierarchy
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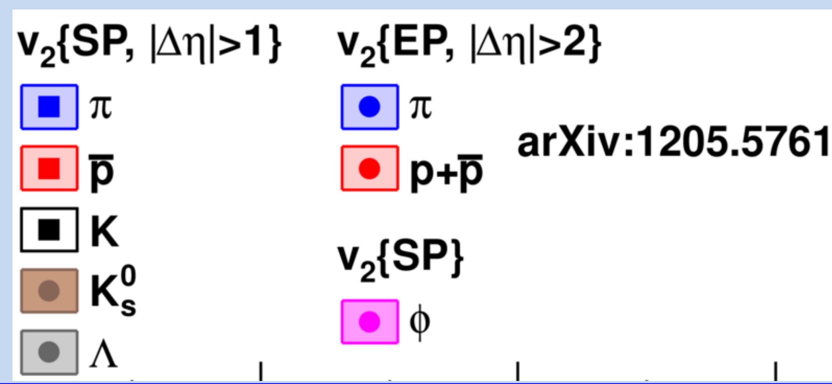
- overall qualitative agreement with hydro up to p_T 1.5–3 GeV/c (π–p); quantitative precision needs improvements – hadronic afterburner

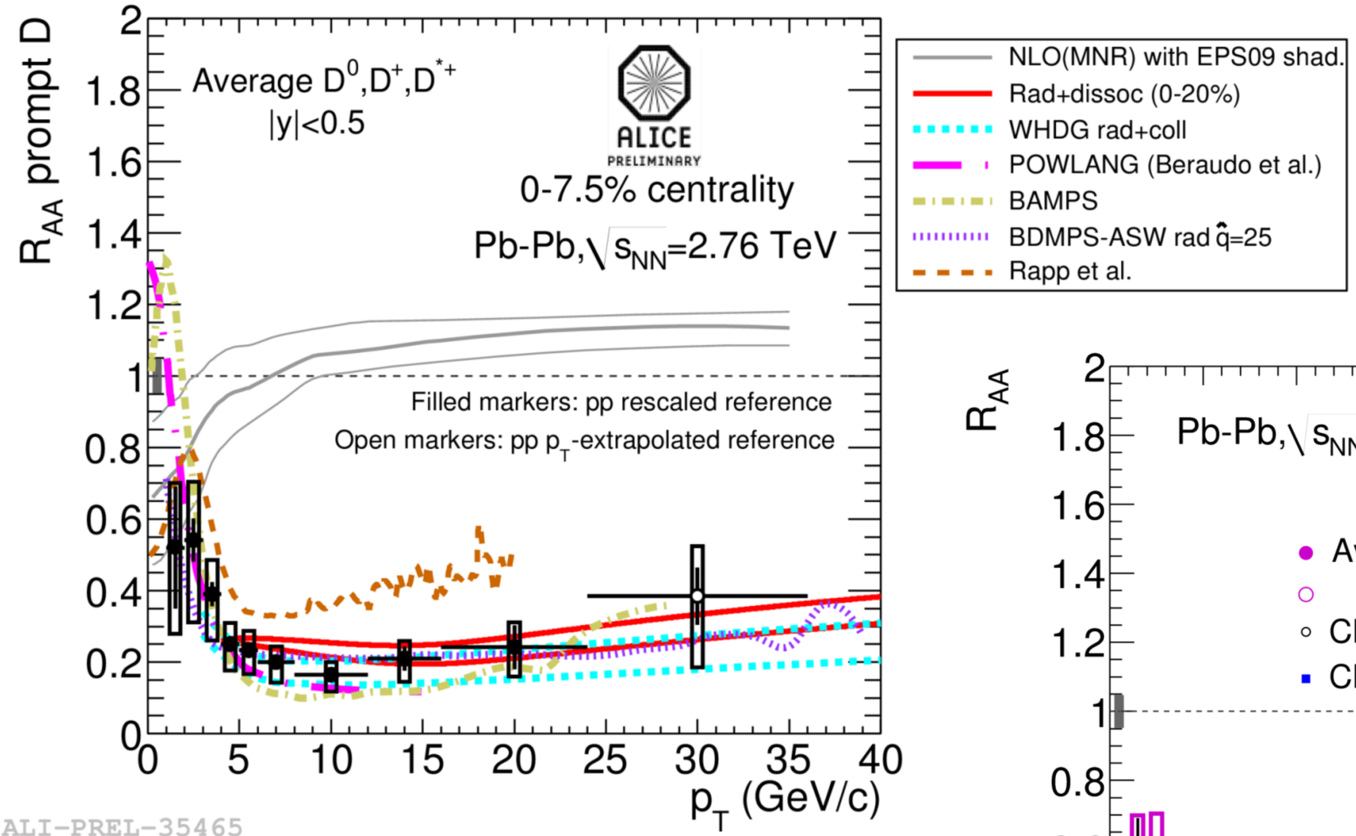


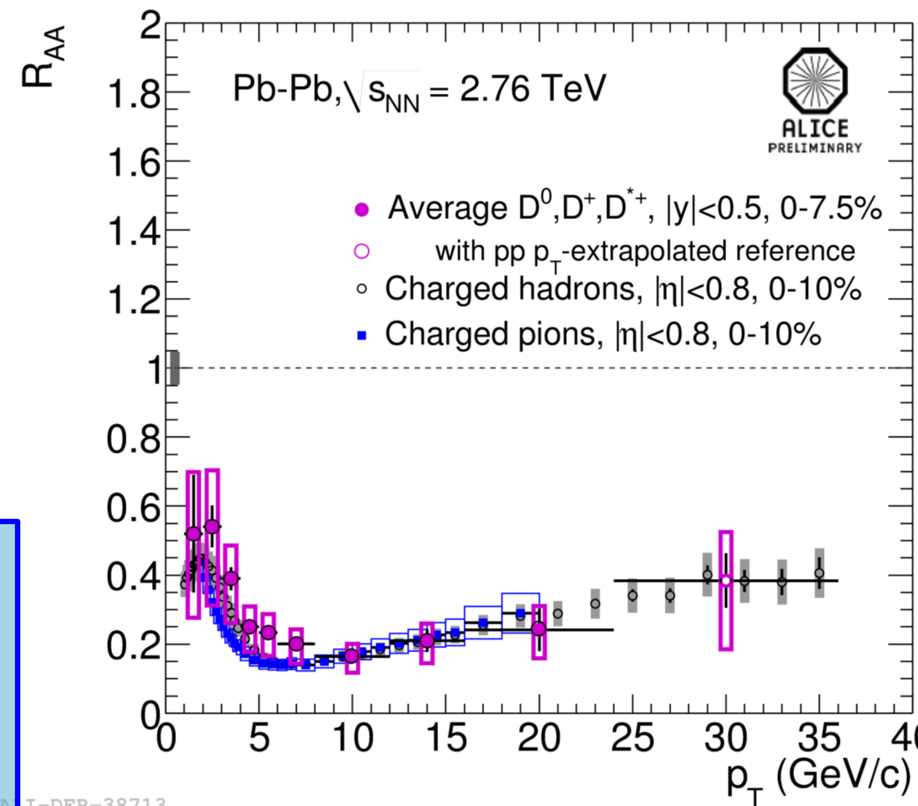
$n_q(m_T)$-scaling wose than at RHIC

$n_q(p_T)$-scaling at p_T > 1.2 GeV/c violation 10–20%

HEAVY FLAVOUR

D meson R_{AA}





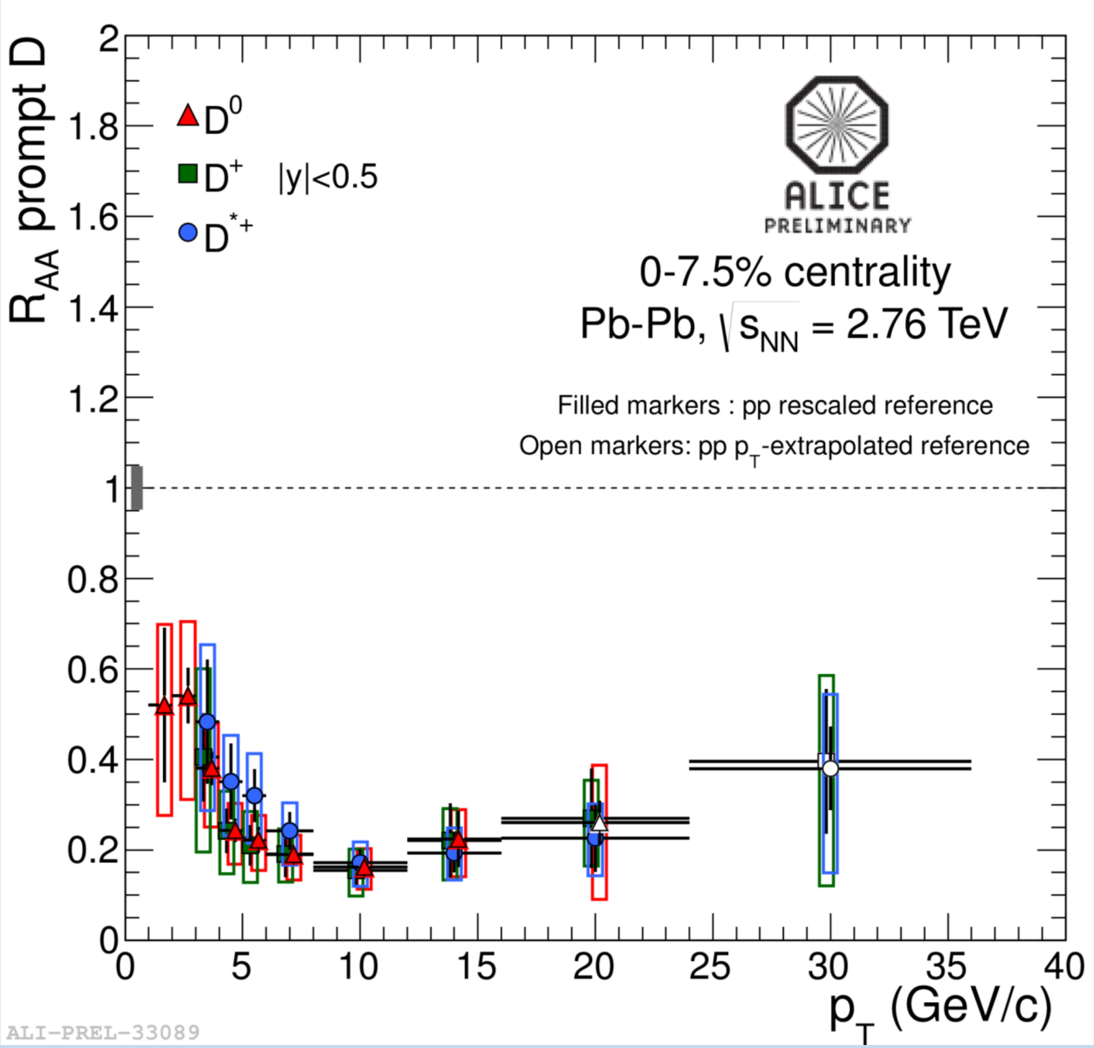
Average D-meson R_{AA}:

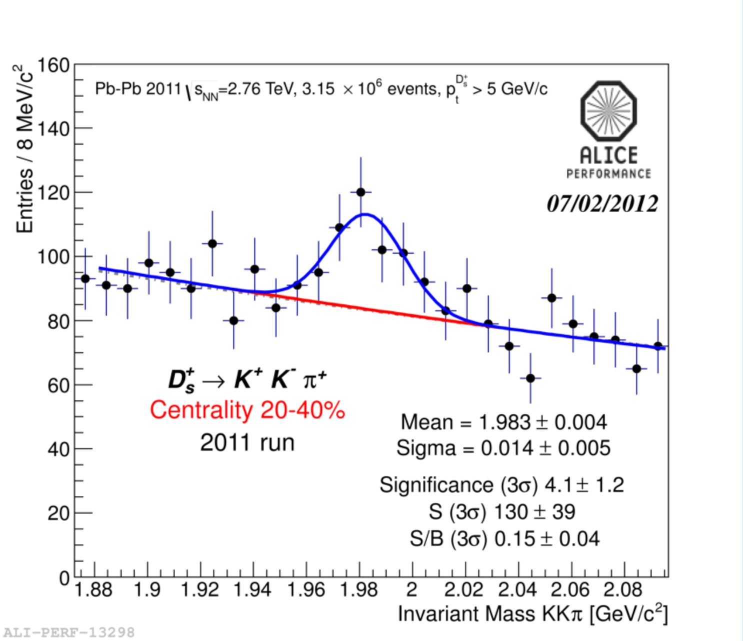
– p_T < 8 GeV/c hint of slightly less suppression than for light hadrons

– p_T > 8 GeV/c both (all) very similar

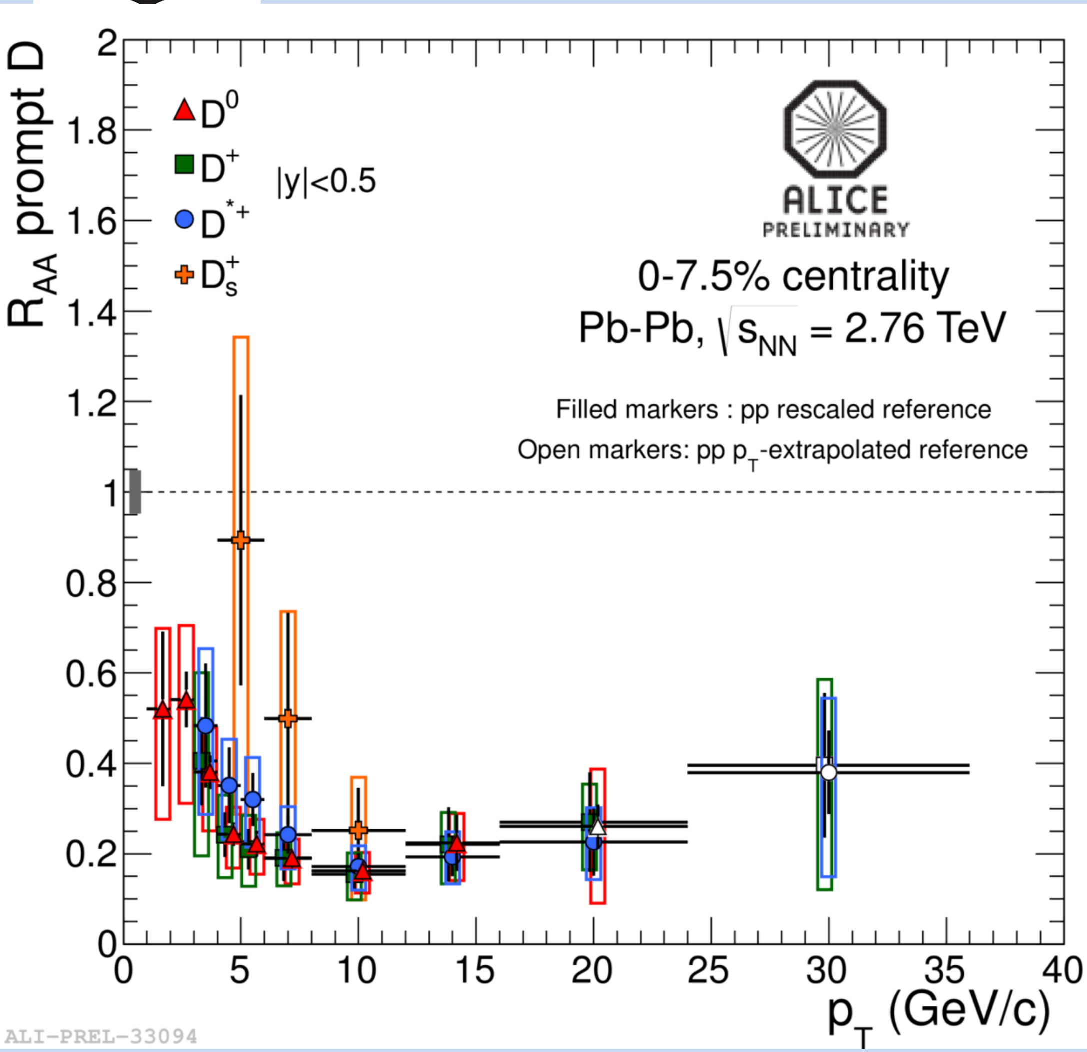
no indication of colour charge dependence

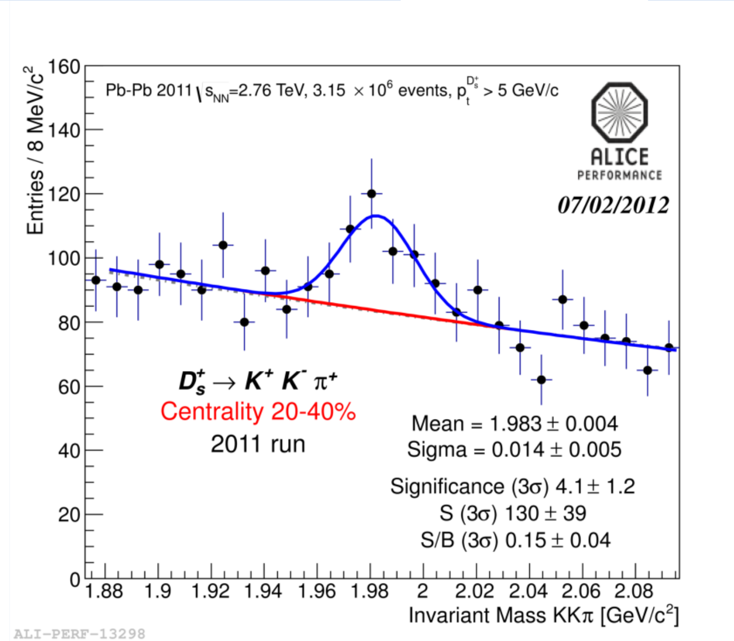
… adding D_s to charm R_{AA}





… adding D_s to charm R_{AA}

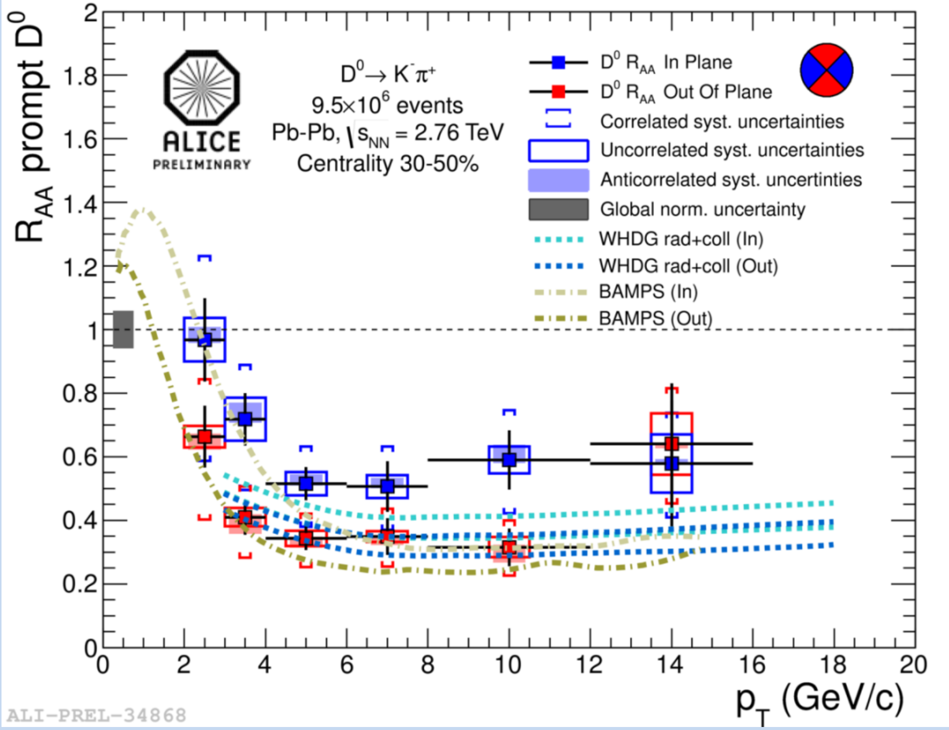


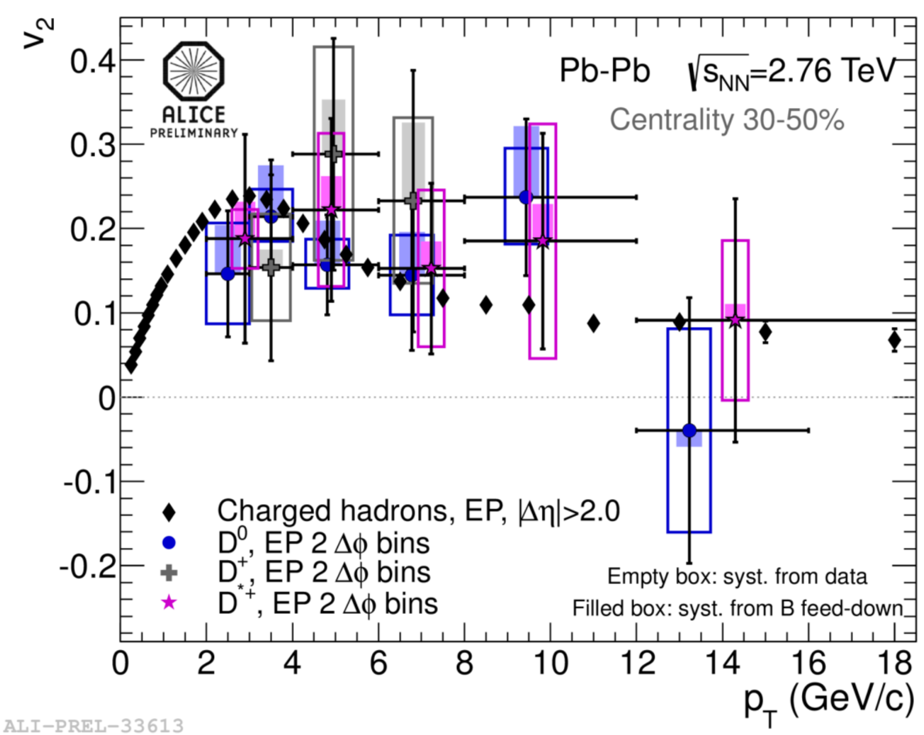


Strong suppression (~ 4–5)
at p_T above 8 GeV/c

Uncertainty will improve with
future pp and Pb–Pb data taking

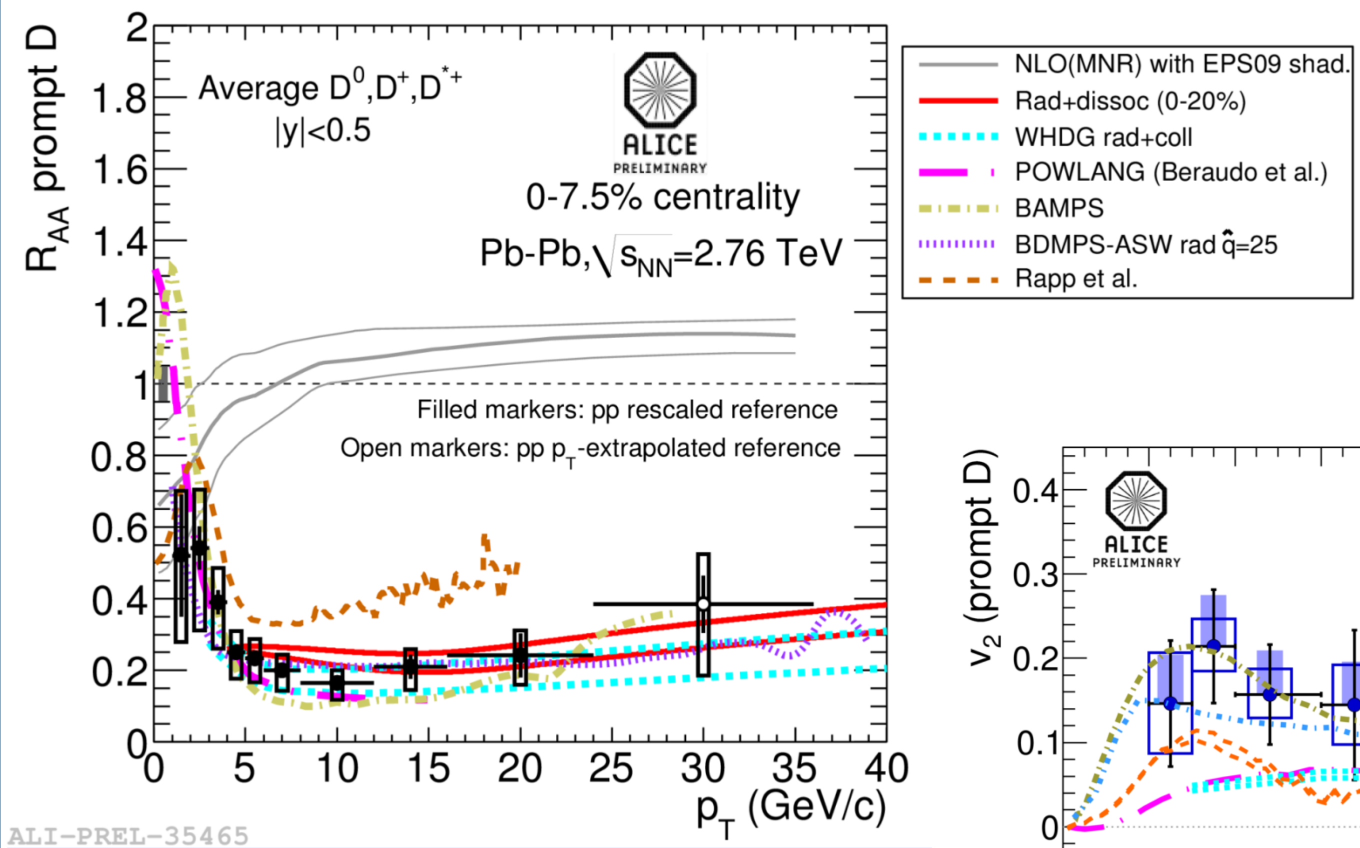
D meson v_2

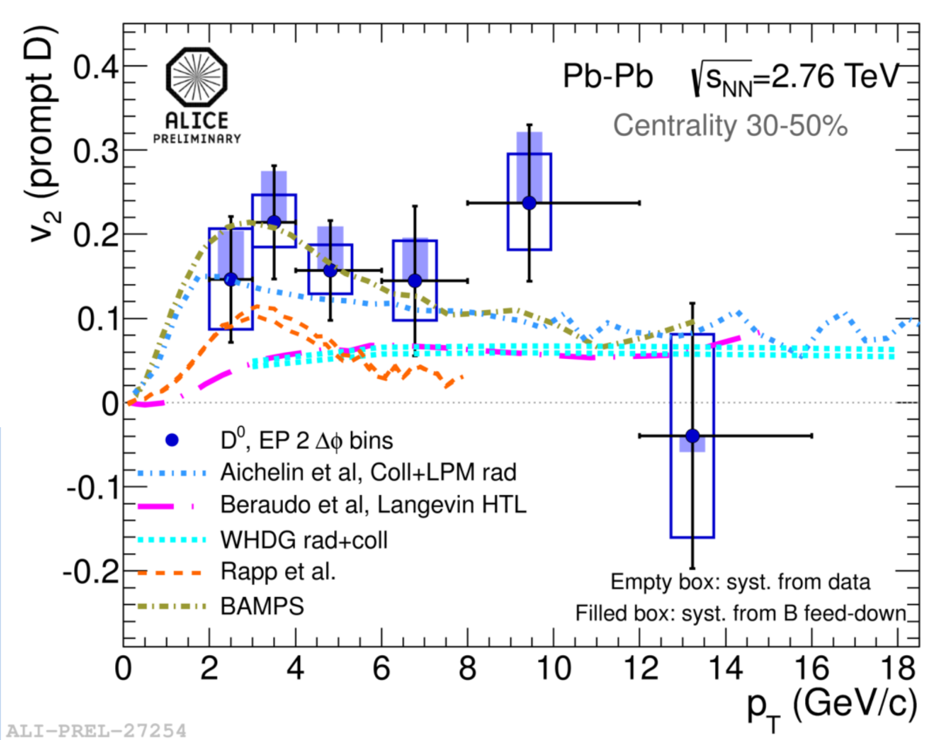




- Non-zero D meson v_2 observed
- Comparable to that of light hadrons
- Expressed as event-plane dependent R_{AA}

D meson v_2





Non-zero D meson v_2 observed
Comparable to that of light hadrons
Expressed as event-plane dependent R_{AA}

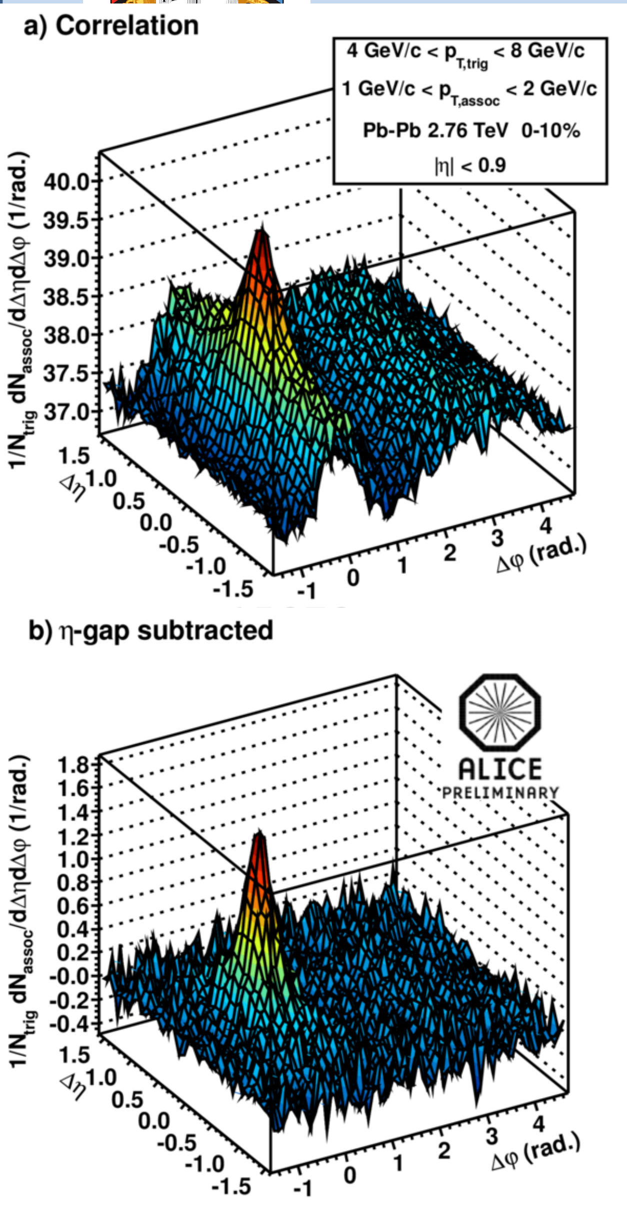
Simultaneous description of R_{AA} and v_2
c-quark transport coefficient in medium

D Meson Behaviour

- Case of D meson (or any other identified charmed hadron) is of interest.
- In heavy ions, created isotropically
  - non-zero v_2 indicates (calculable) interaction with medium, leading to anisotropy
  - R_{AA} expected to be *less* than for light particles because of dead cone effect (gluon radiation suppressed at small angles because of destructive interference) NOT SEEN.
- Heavy flavour case is a good test, as initial production is describable by pQCD (certainly for *b*, probably for *c*, though *c* may have thermal component at LHC energies.

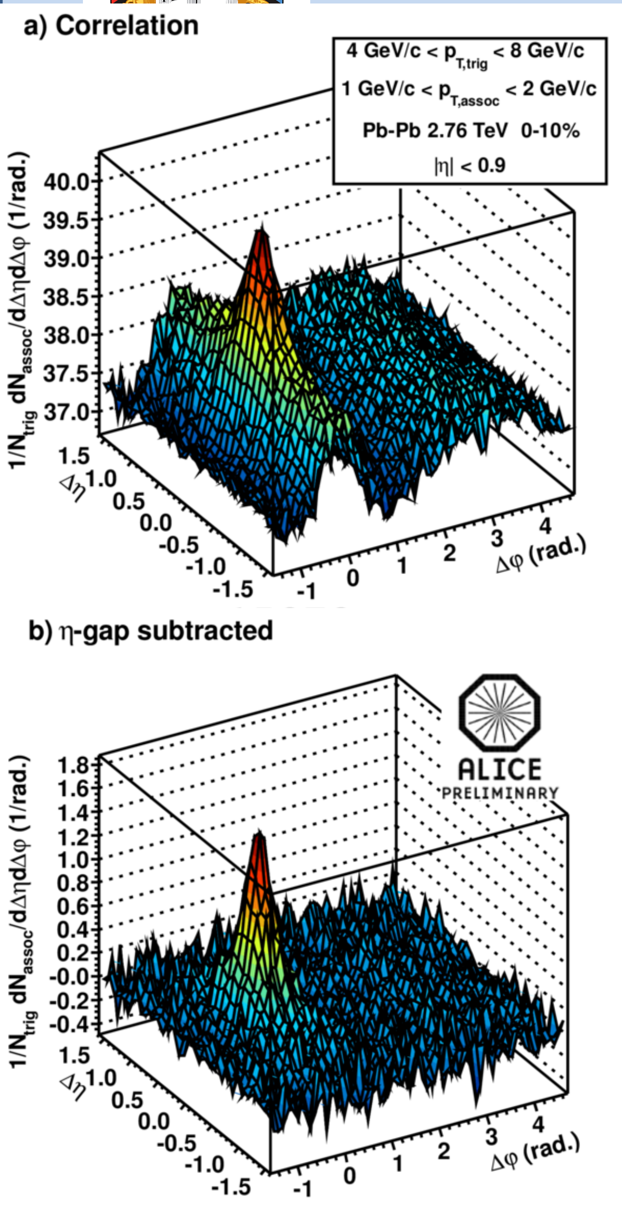
JETS AND JET-QUENCHING

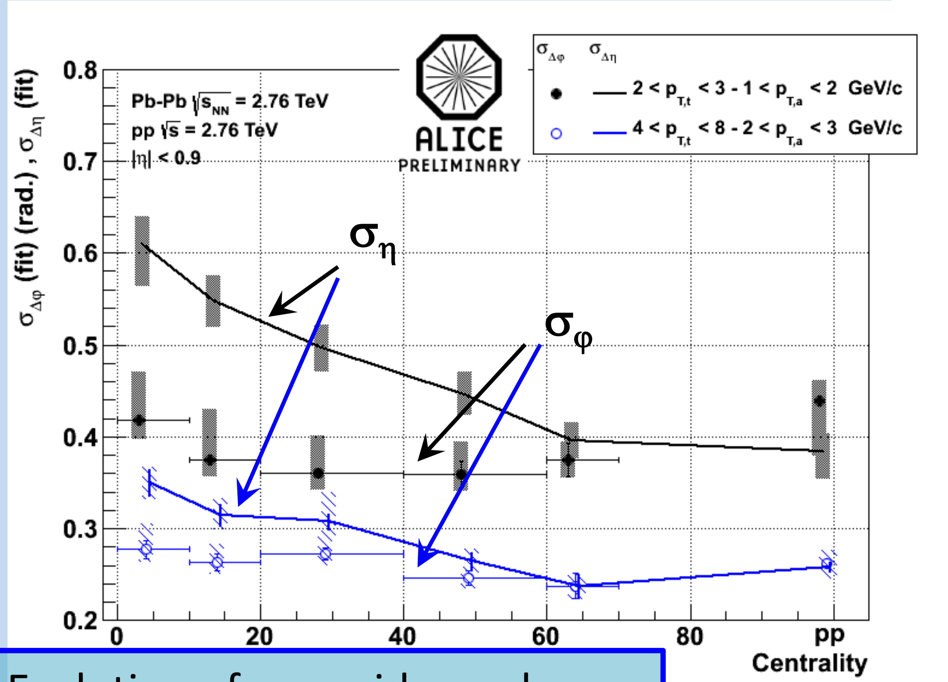
Near-side (jet-like) structure



Isolation of near-side peak:
Δη–Δφ correlation with trigger
Long-range (large Δη) correlation used as proxy for background

Near-side (jet-like) structure

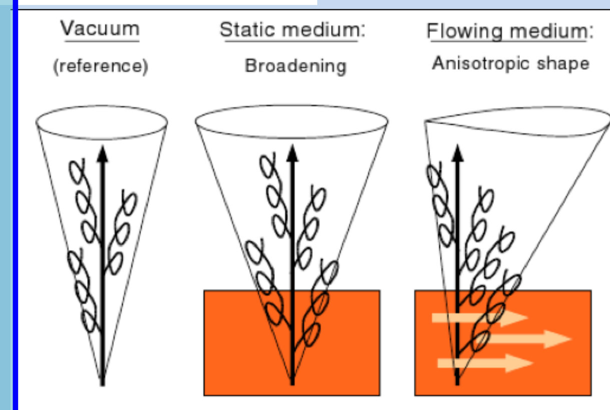




Evolution of near-side-peak σ_η and σ_φ with centrality:
Strong σ_η increase for central collisions

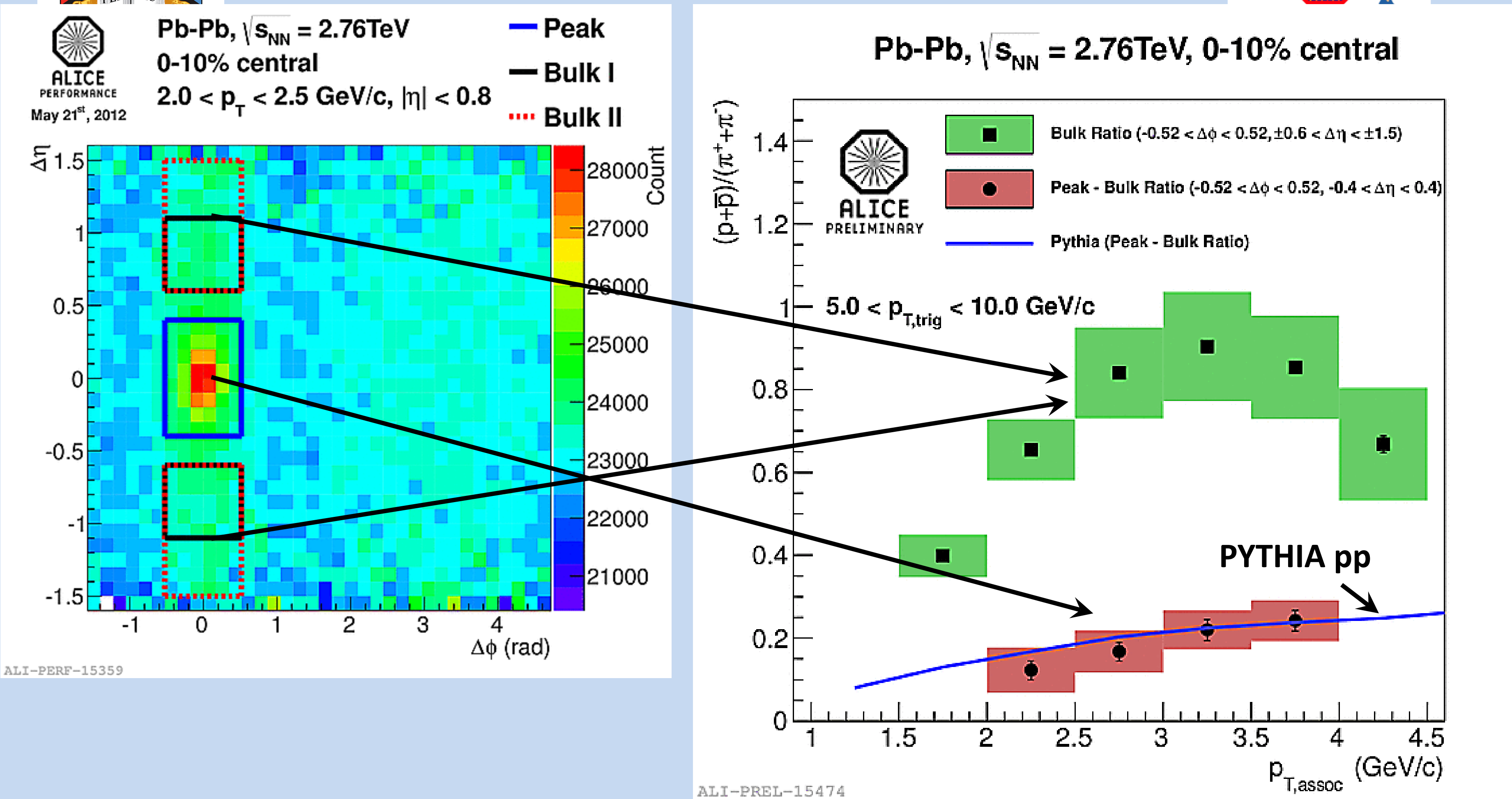
Interestingly: AMPT describes the data very well

Influence of flowing medium?



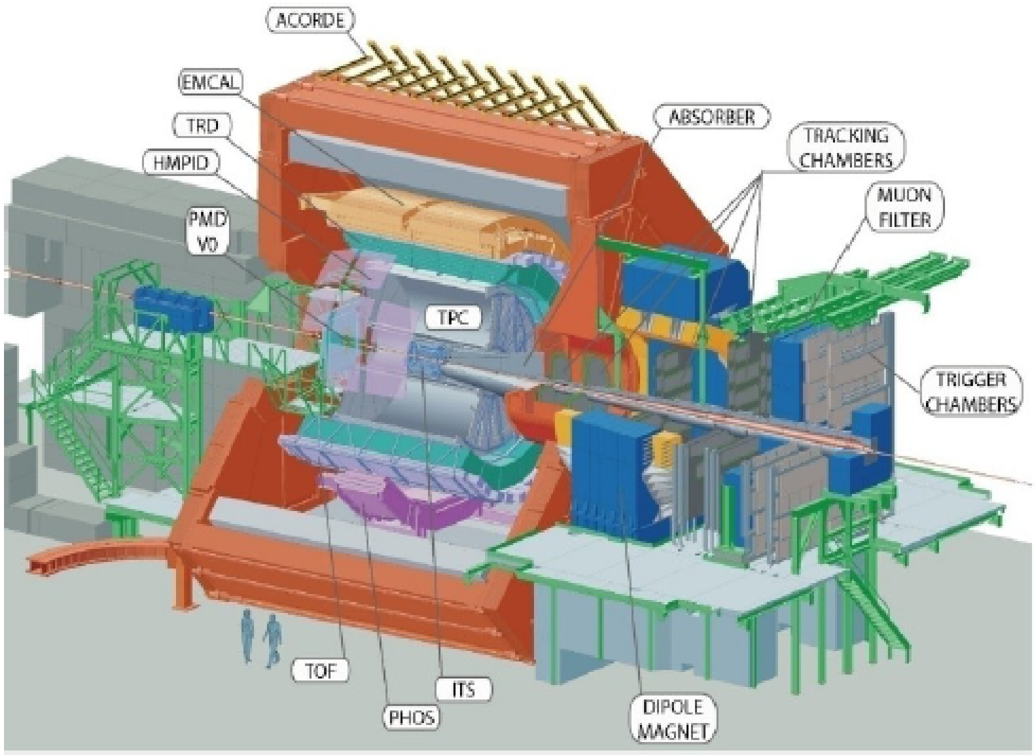
N.Armesto et al., PRL 93, 242301

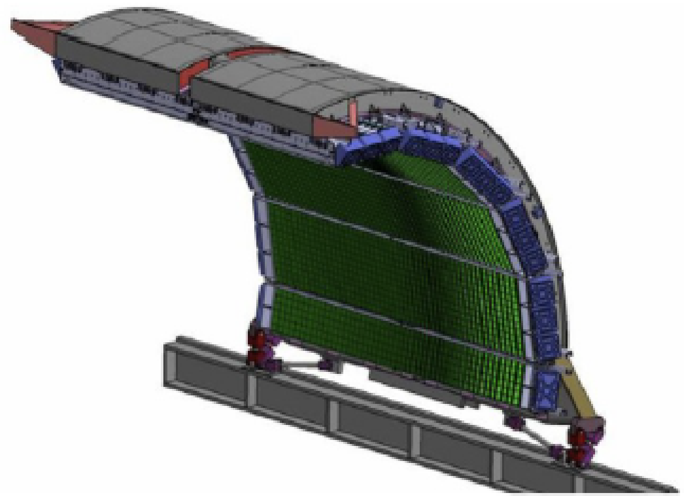
PID in jet structures



Near-side peak (after bulk subtraction): p/π ratio compatible with that of pp (PYTHIA)
Bulk region: p/π ratio strongly enhanced – compatible with overall baryon enhancement
Jet particle ratios not modified in medium? Could this still be surface bias?

Jet Reconstruction in ALICE





Energy and direction of neutral particles

EMCal: Pb-scintillator sampling calorimeter which covers:

$$|\eta| < 0.7,\ 80° < \varphi < 180°$$

- 11520 towers with each covers

$$\Delta\eta \times \Delta\varphi \sim 0.014 \times 0.014$$

4-momenta of charged particles

Tracking: $|\eta| < 0.9,\ 0 < \varphi < 360°$

TPC: gas detector

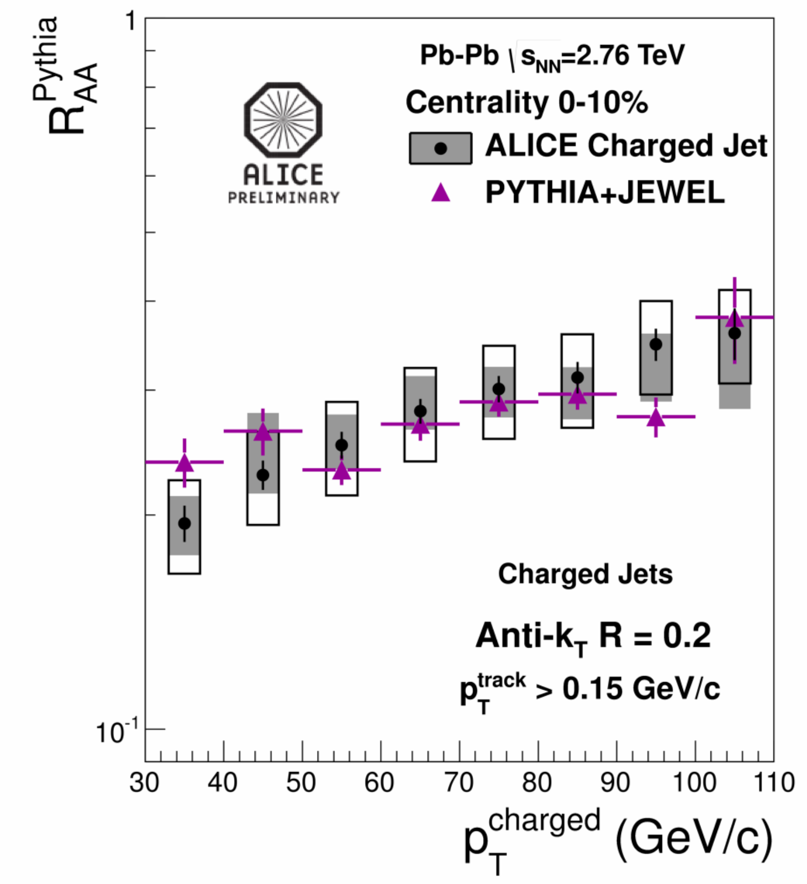
ITS: silicon detector

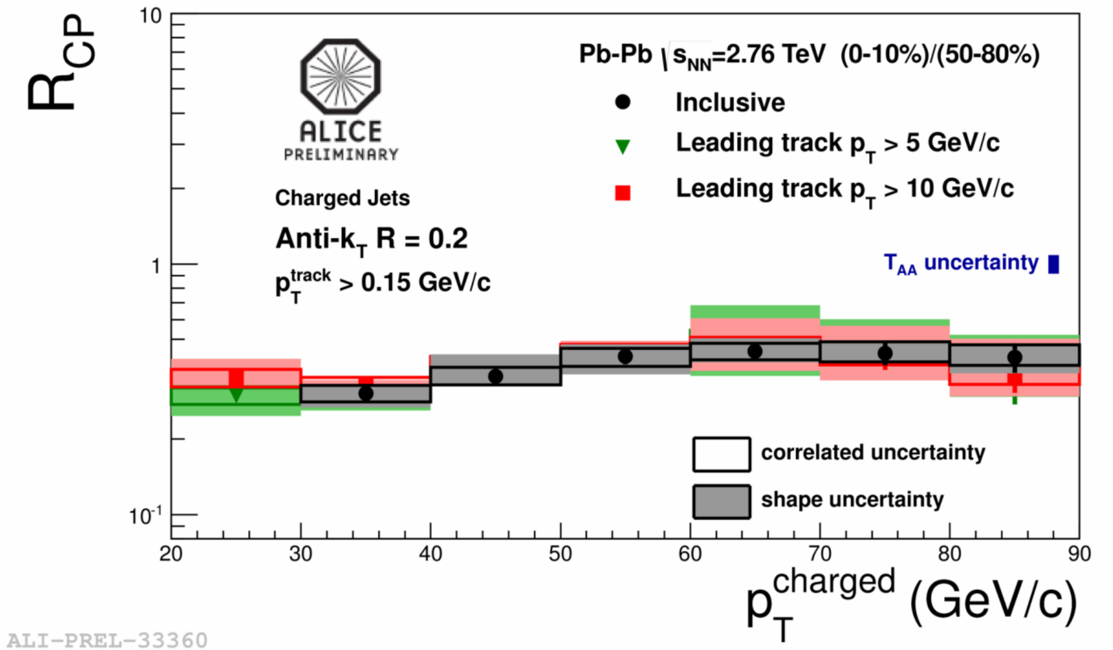
Charged constituents

Neutral constituents

JET

Charged jet R_{AA} and R_{CP}



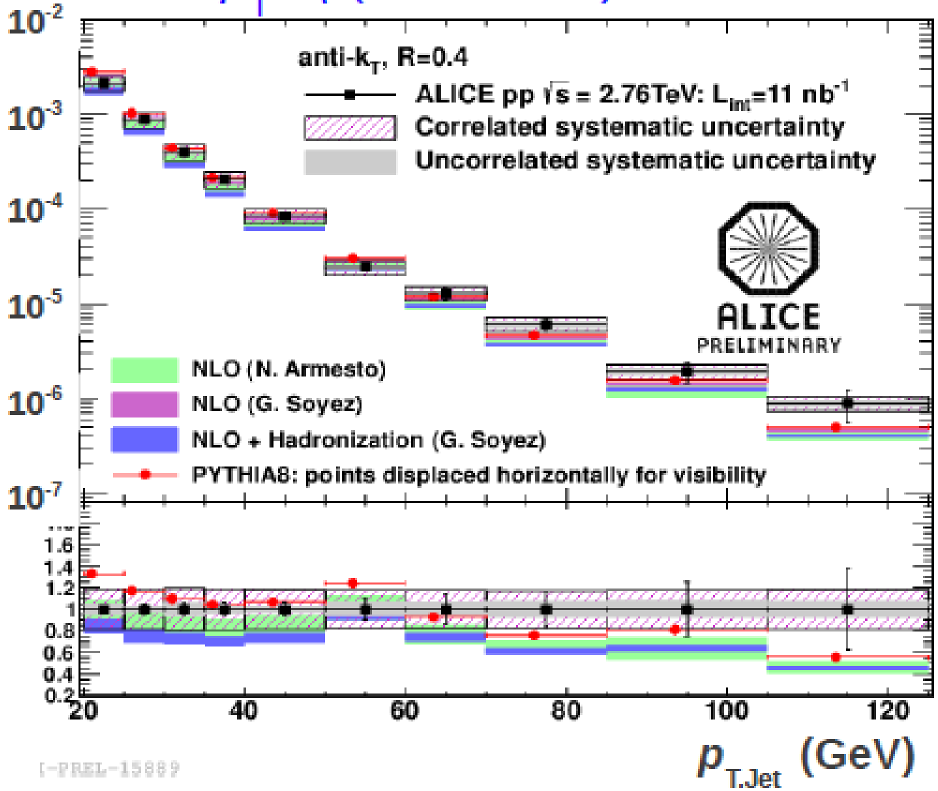


Strong jet suppression observed for jets reconstructed with charged particles
– R_{AA} (jet) is smaller than inclusive hadron $R_{AA}(h^{\pm})$ at similar parton p_T
– data are reasonably well described by JEWEL model
K. Zapp, F. Krauss, U. Wiedemann, arXiv:1111.6838

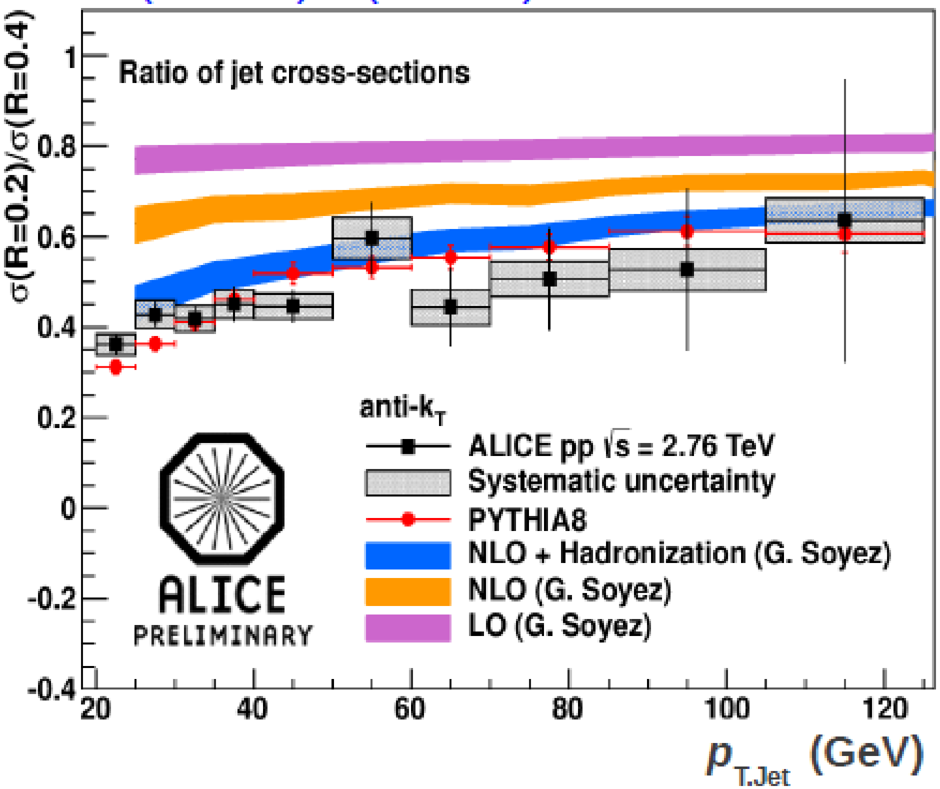
Jets in pp at $\sqrt{s}$ = 2.76 TeV :
Jet shape information by varying R

anti k_T : R = 0.4

$d^2\sigma/dp_Td\eta$ (mb c/GeV)



$\sigma(R=0.2)/\sigma(R=0.4)$

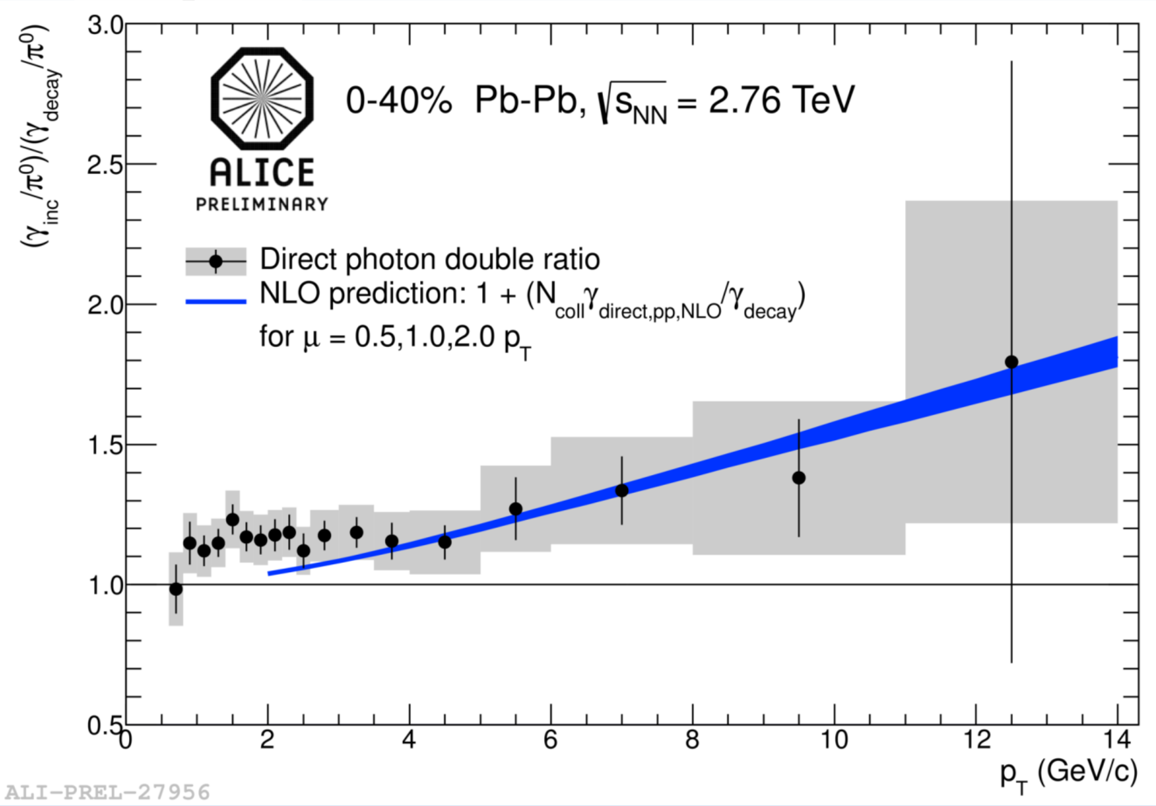


Good agreement with NLO pQCD and Pythia8

Increase of $\sigma(R=0.2)/\sigma(R=0.4)$: Higher p_T jets are more collimated

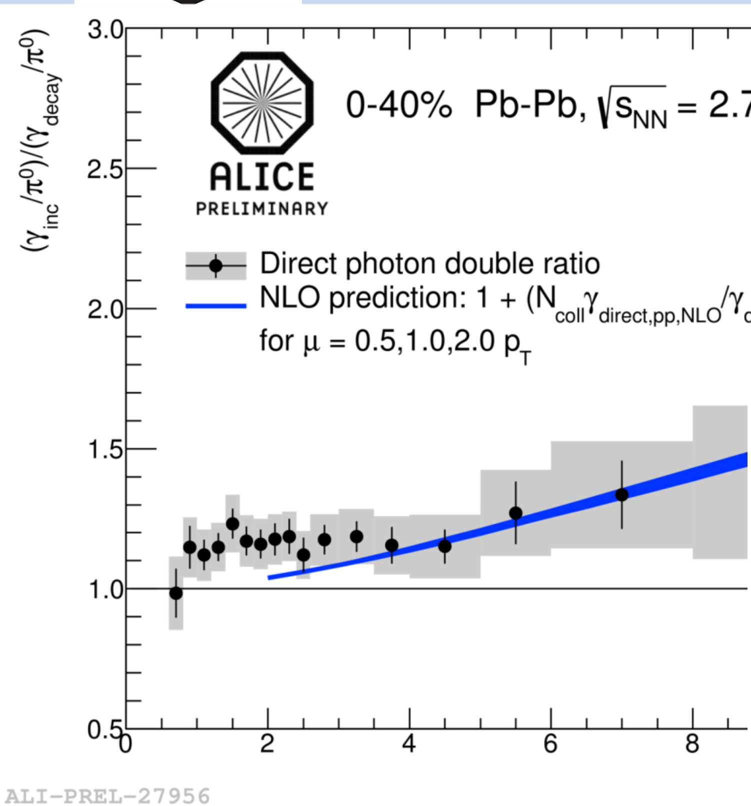
THREE MORE THINGS

Direct photon production

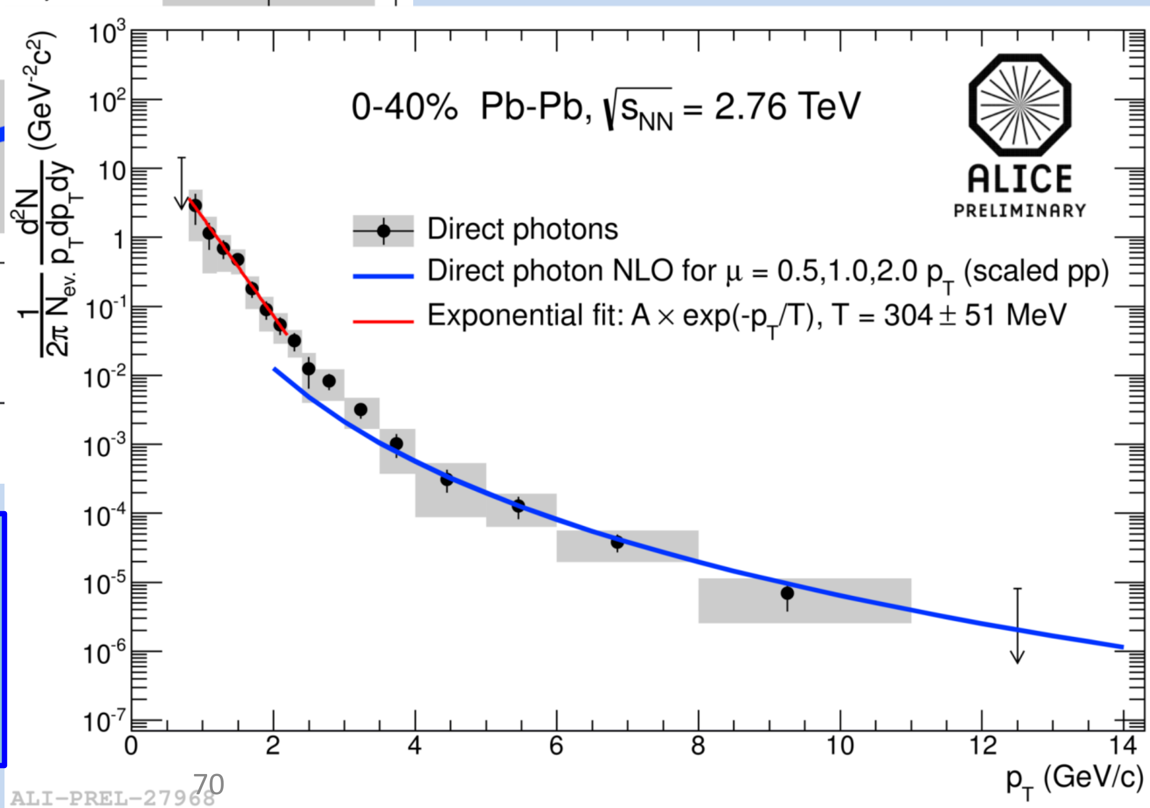


$p_T < 2$ GeV/c
~20% excess of direct photons
$p_T > 4$ GeV/c
agreement with N_{coll}-scaled NLO

Direct photon production



Exponential fit for p_T < 2.2 GeV/c
inv. slope T = 304±51 MeV
for 0–40% Pb–Pb at √s 2.76 TeV
PHENIX: T = 221±19±19 MeV
for 0–20% Au–Au at √s 200 GeV



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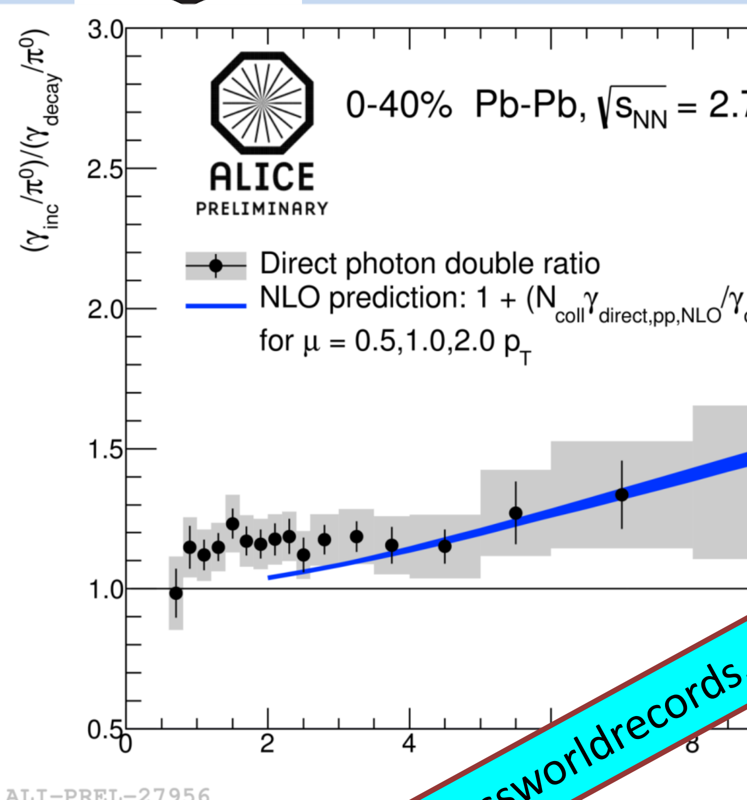
Direct photon production



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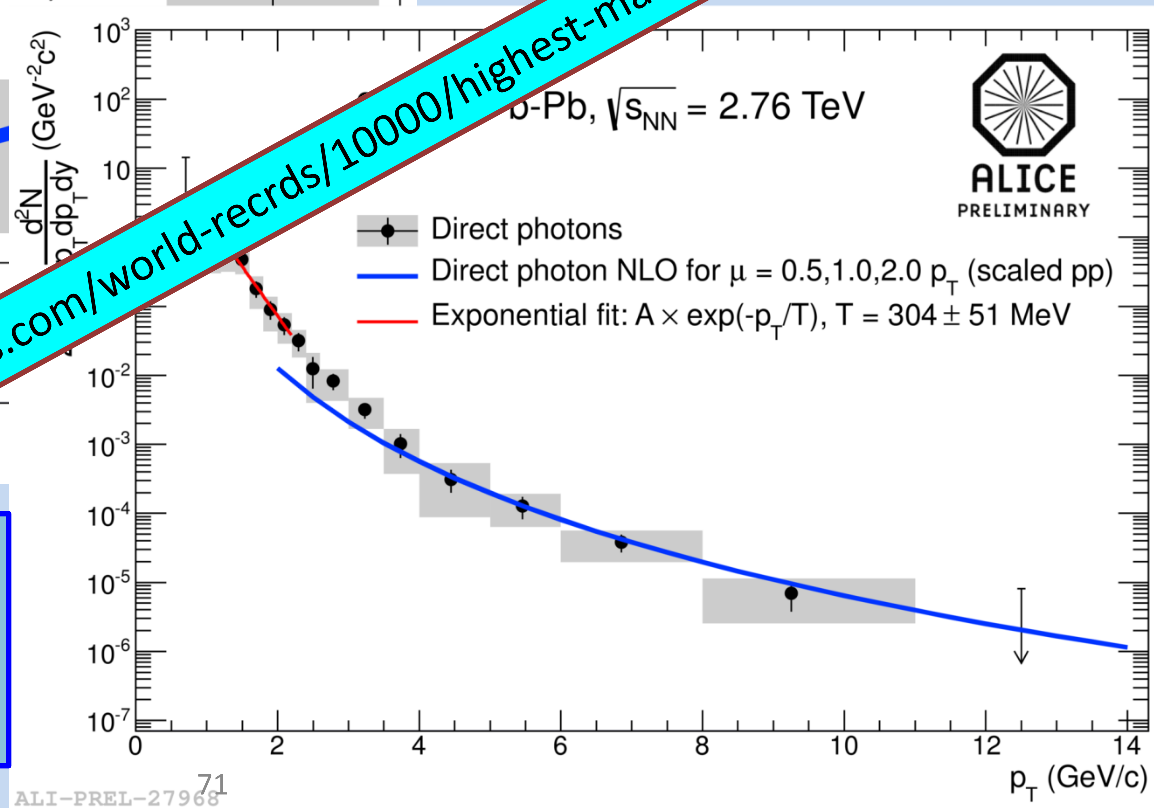
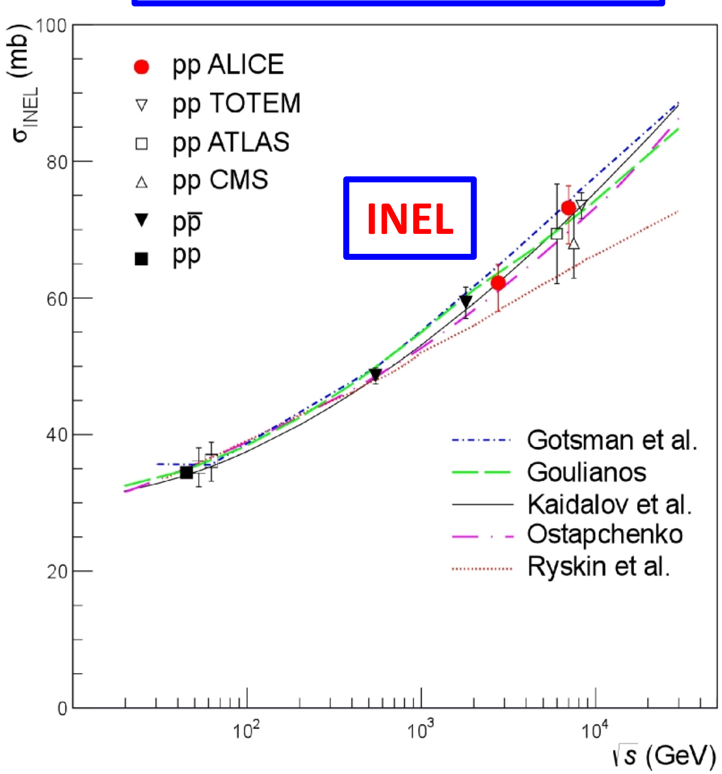
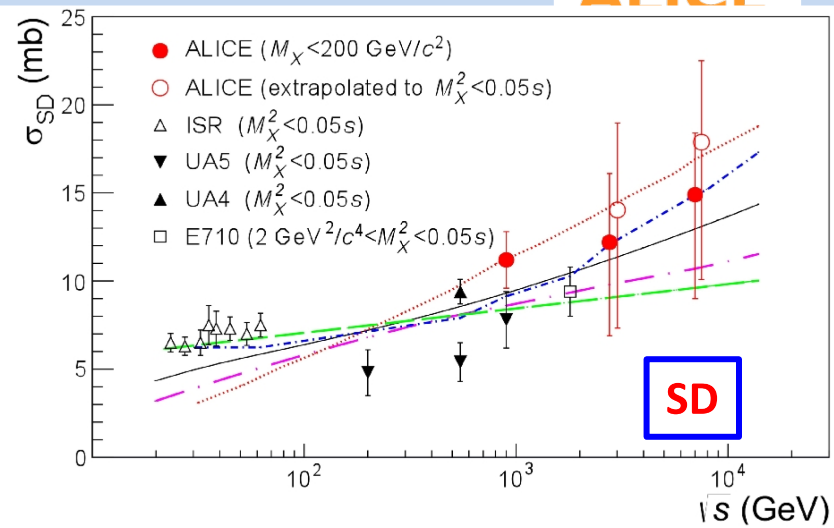


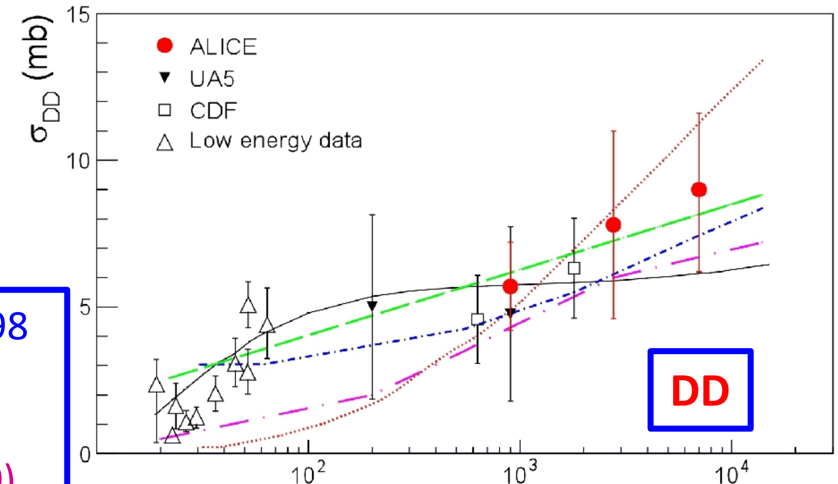
p_T < 2 GeV/c
~20% direct photons
p_T > V/c
agreement with N_{coll}-scaled NLO

Comparison with other experiments and models

From van-der-Meer scan



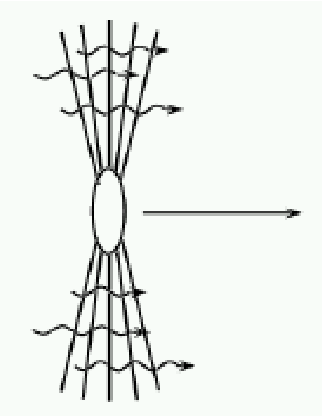




Gotsman et al. Phys. Rev. **D85** (2012), arXiv:1208:0898
Goulianos Phys. Rev. D80 (2009) 111901
Kaidalov et al., arXiv:0909.5156, EPJ **C67** 397 (2010)
Ostapchenko, arXiv:1010.1869, PR **D81** 114028 (2010)
Ryskin et al., EPJ **C60** 249 (2009), **C71** 1617 (2011)

Diffraction 2012 - Lanzarote

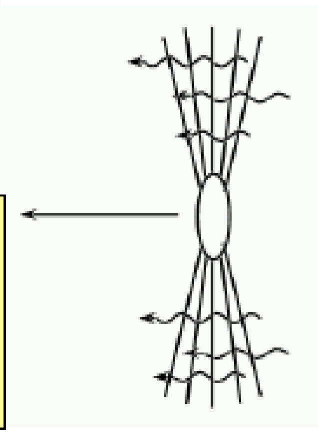
Why ultra-peripheral heavy-ion collisions



Two ions (or protons) pass by each other with impact parameters b > 2R. **Hadronic interactions are strongly suppressed**

Number of photons scales like Z^2 for a single source ⇒ exclusive particle production in heavy-ion collisions dominated by electromagnetic interactions.

The virtuality of the photons → 1/R ~ 30 MeV/*c*



See talks by W. Schaefer, and M. Melo Machado

Coherent production:

Photon couples coherently to all nucleons

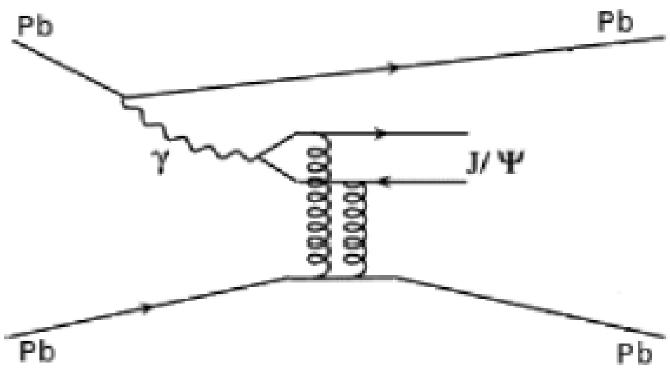
$\langle p_T \rangle$~60MeV/*c*; target nucleus normally does not break up

Incoherent production

Photon couples to a single nucleon

Quasi-elastic scattering off a single nucleon

$\langle p_T \rangle$~500 MeV/*c*



$\gamma + p \rightarrow J/\psi + p$

modelled in pQCD: exchange of two gluons with no net-colour transfer

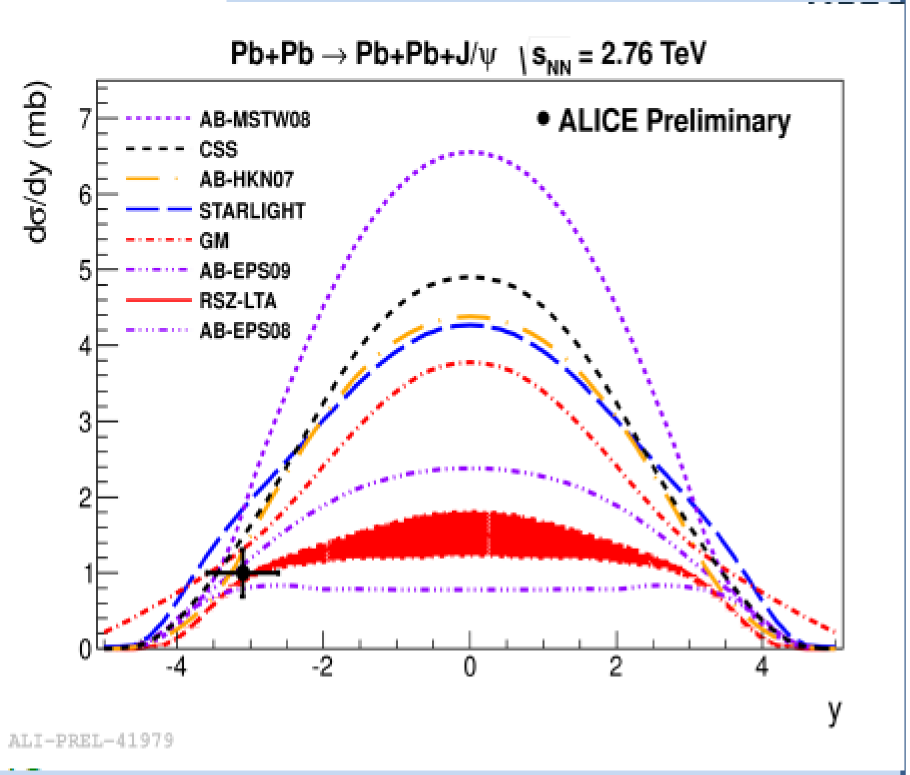
A big jump in energy ...

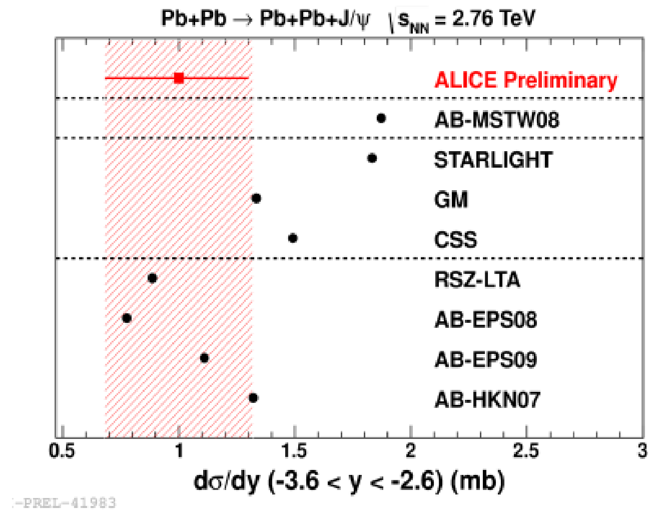
RHIC: $W_{\gamma N,max}$ ~ 34 GeV

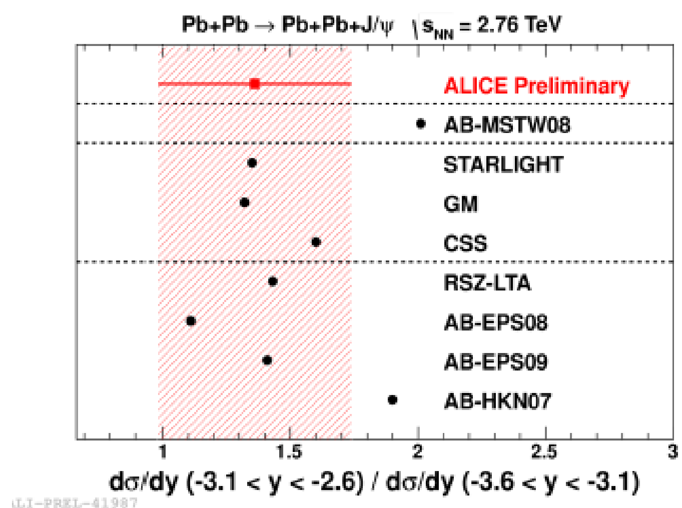
HERA: $W_{\gamma N,max}$ ~ 300 GeV

LHC: $W_{\gamma N,max}$ reaches up to 950 GeV !

Ultraperipheral J/ψ







J.D. Tapia Takaki Diffraction 2012 Lanzarote
arXiv:1209.3715

FUTURE PLANS

ALICE programme

- ALICE heavy-ion programme approved for ~ 1 nb^{-1}:
  - 2013–14 Long Shutdown 1 (LS1)
    - completion of TRD and CALs
  - 2015 Pb–Pb at $\sqrt{s_{NN}}$ = 5.1 TeV
  - 2016–17 (maybe combined in one year) Pb–Pb at $\sqrt{s_{NN}}$ = 5.5 TeV

  - 2018 Long Shutdown 2 (LS2)
  - 2019 probably Ar–Ar high-luminosity run
  - 2020 p–Pb comparison run at full energy
  - 2021 Pb–Pb run to complete initial ALICE programme
  - 2022 Long Shutdown 3 (LS3)

Order/choice of nuclei may change

- This will improve statistical significance of our main results by a factor about 3
  - physics reach extended by the new energy and completion of TRD and CALs

ALICE UPGRADE

ALICE future plans

Precision measurement of the QGP parameters at $\mu_b = 0$ to fully exploit scientific potential of the LHC – unique in:

- large cross sections for hard probes
- high initial temperature

- Main physics topics, uniquely accessible with the ALICE detector:
  - measurement of heavy-flavour transport parameters:
    - study of QGP properties via transport coefficients (η/s, $\hat{q}$)
  - measurement of low-mass and low-p_T di-leptons
    - study of chiral symmetry restoration
    - space-time evolution and equation of state of the QGP
  - J/ψ , ψ', and χ_c states down to zero p_T in wide rapidity range
    - statistical hadronization versus dissociation/recombination

ALICE upgrade

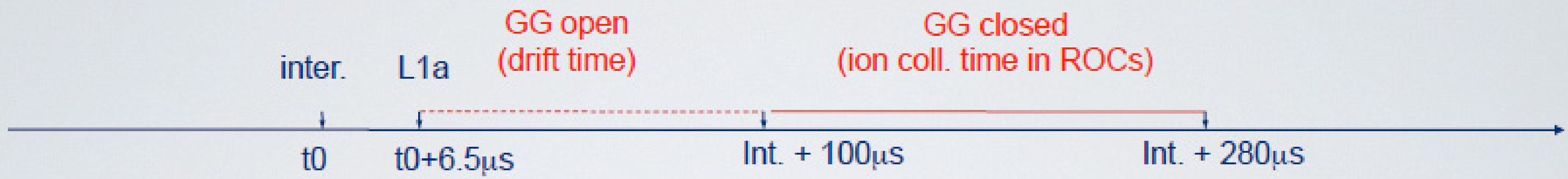
- luminosity upgrade – 50 kHz target minimum-bias rate for Pb–Pb
- run ALICE at this high rate, inspecting *all* events

- improved vertexing and tracking at low p_T
- preserve particle-identification capability
- high-luminosity operation without dead-time

- new, smaller radius beam pipe
- new inner tracker (ITS) (performance and rate upgrade)
- high-rate upgrade for the readout of the TPC, TRD, TOF, CALs, DAQ-HLT, Muon-Arm and Trigger detectors

- target for installation and commissioning LS2 (2018)
- collect more than 10 nb^{-1} of integrated luminosity
    - implies running with heavy ions for a few years after LS3
- for core physics programme – factor > 100 increase in statistics
    - (maximum readout with present ALICE ~ 500 Hz)
- for triggered probes increase in statistics by factor > 10

Limits of Current TPC

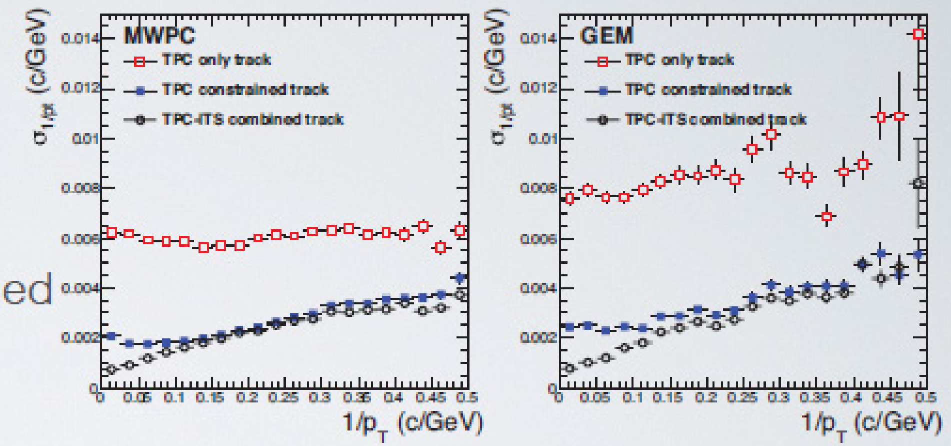


- gating grid of readout chambers closed to avoid ion feedback
  - limit space charge to tolerable level
  - effective dead time ≈280 μs, maximum readout rate: ≈3.5 kHz
- alternative: gating grid always open
  - ion feedback ≈ 10^3 x ions generated in drift volume
  - large space charge effects (of the order of electrical field)
    - space point distortions of order of 1 m - not tolerable!

TPC Upgrade

new readout chambers

- replace MWPC with GEMs
- no gating, small ion feedback
- usage of existing pad-planes possible
  - momentum resolution for constrained tracks not affected



continuous sampling at 10 MHz, ship data unsuppressed off detector

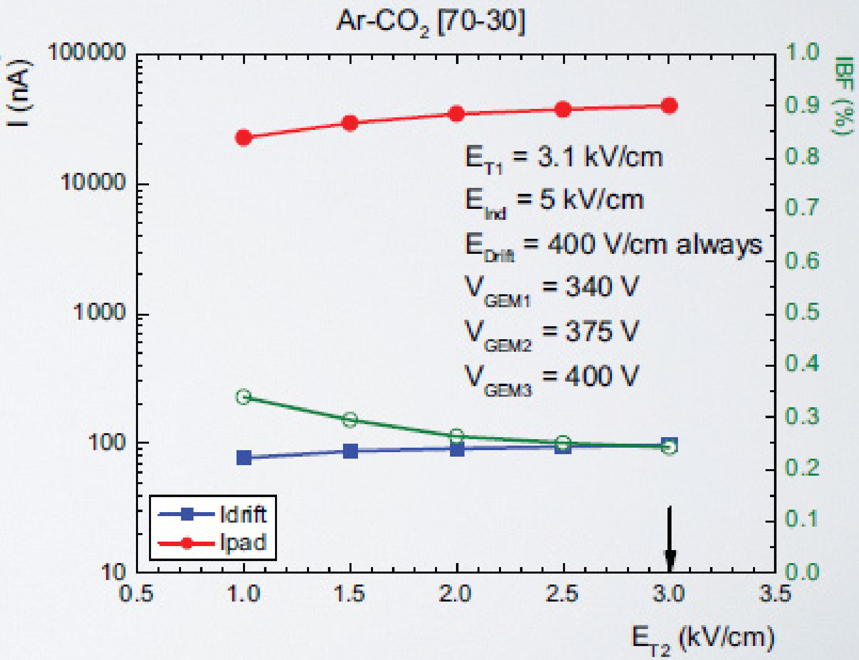
- needs new electronics

extensive R&D program ongoing with lab tests

- confirm low ion feedback
  - goal: 0.25% at gain of 2000
- gain stability?

... and in ALICE cavern (November)

- performance under LHC conditions?



poster by T. Gunji (ID 496)

Event Size and Rates

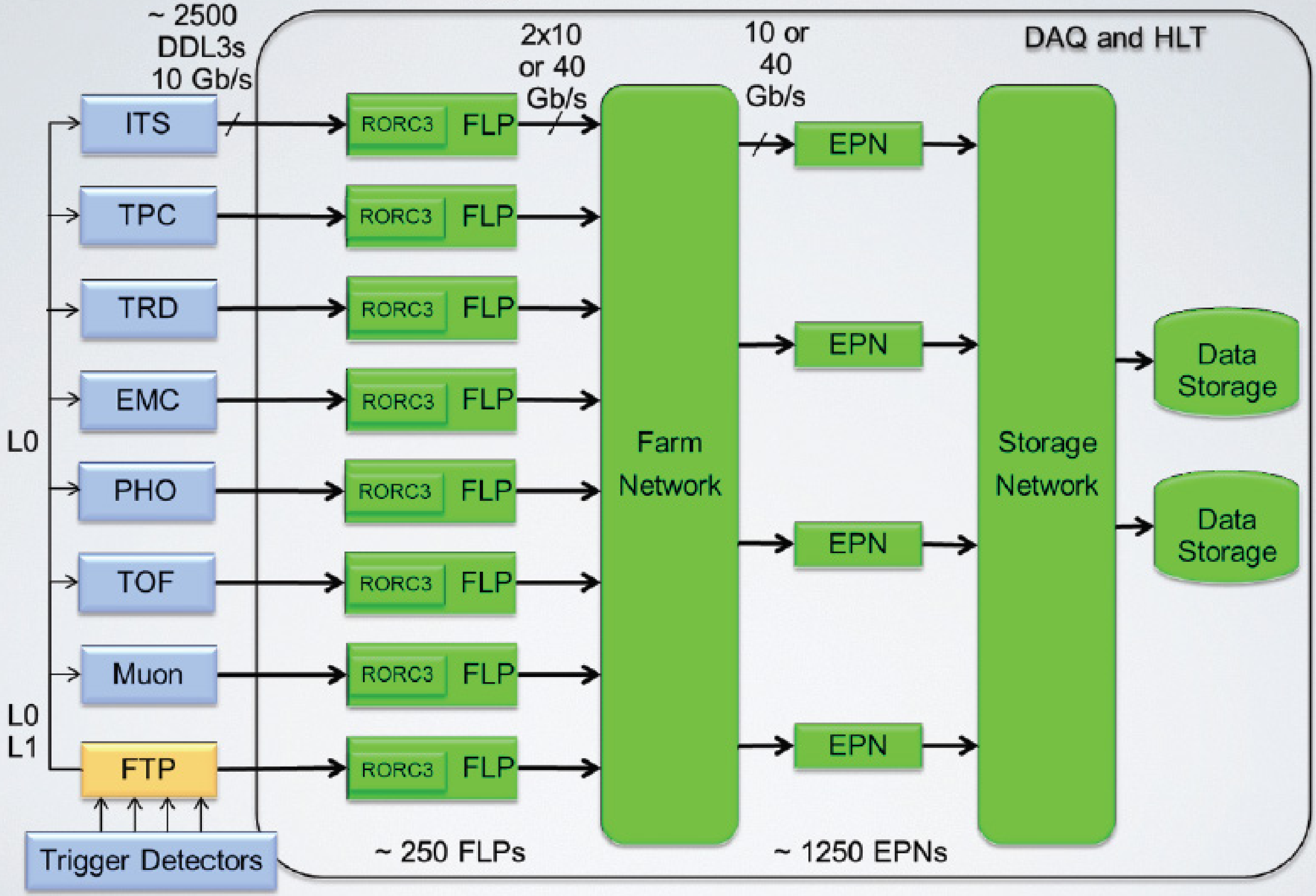
- event size of major systems, I/O rates of online system
  - assume average minbias rate to tape of 20 kHz

Detector	Event Size (MByte) After Zero Suppression	Event Size (MByte) After Data Compression	Input to Online System (GByte/s)	Compressed Output to data storage (GByte/s) Peak	Compressed Output to data storage (GByte/s) Average
ITS	0.8	0.2	40	10.0	4.0
TPC	20.0	1.0	1000	50.0	20.0
TRD (20 kHz)	0.3	0.1	6	2.0	2.0
Others (1)	0.5	0.25	25	12.5	5.0
Total	**21.6**	**1.55**	**1071**	**74.5**	**31.0**

- data reduction for TPC: clustering, reconstruction

Data Format	Data Reduction Factor	Event Size (MB Pb-Pb) (MByte)
Raw data	1	700
Zero suppression (FEE)	35	20
Clustering (HLT)	5-7	~3
Remove clusters not associated to relevant tracks (HLT)	2	~1.5
Data format optimization (HLT)	2-3	< 1

Online Upgrade Architecture



FTP: Fast Trigger Processor FLP: First-Level Processor EPN: Event-Building and Processing Nodes

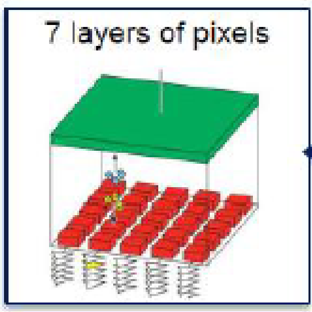
Upgrade Options

Poster on Sensor R&D – Giacomo Contin

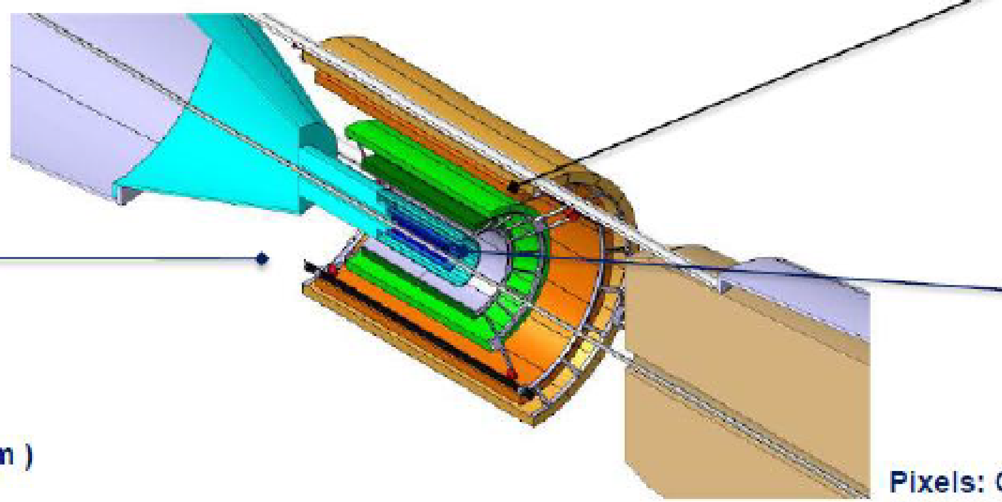
Two design options are being studied:

- 7 layers of pixel detectors
  - better standalone tracking efficiency and p_T resolution
  - worse PID
- 3 inner layers of pixel detectors and 4 outer layers of strip detectors
  - worse standalone tracking efficiency and momentum resolution
  - better PID

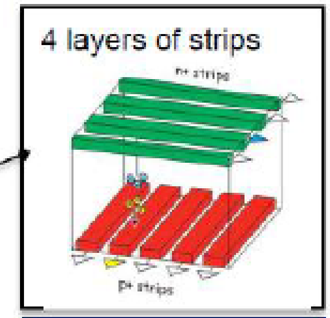
Option A

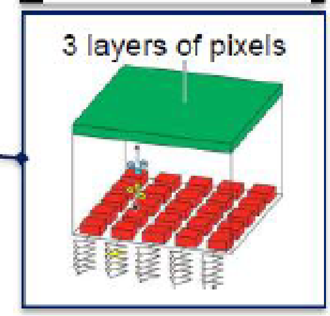


Pixels: O(20 µm x 20 µm)



Option B





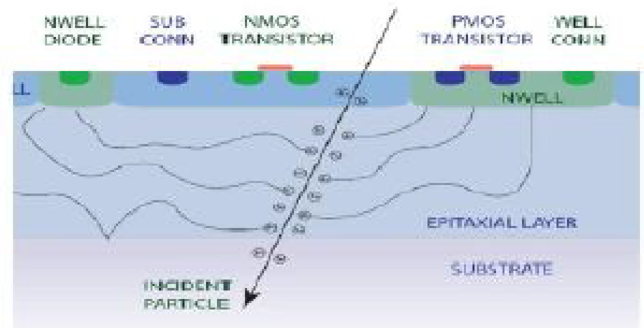
Pixels: O(20x20µm² - 50 x 50 µm²)
Strips: 95 µm x 2 cm, double sided

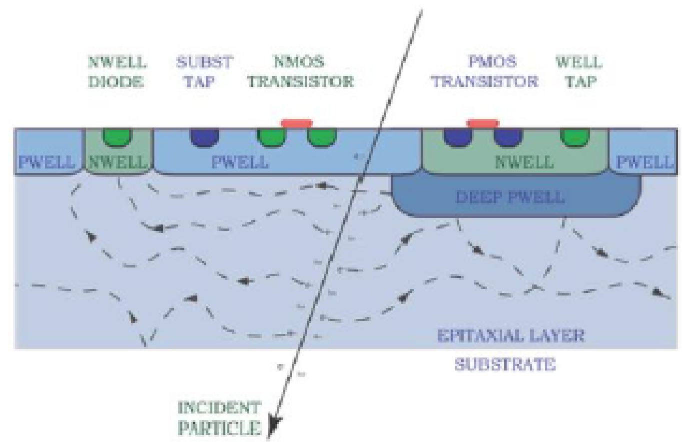
Radiation levels for layer 1:
- 1 Mrad/1.6 x 10^{13} $n_{eq}cm^{-2}$ per year
- with safety factor 4

Monolithic Active Pixel Detectors (MAPS)

MAPS features:
- all-in-one: detector-connection-readout
- sensing layer included in CMOS chip
- small pixel size: 20 μm x 20 μm
- small material budget: 50 μm or less

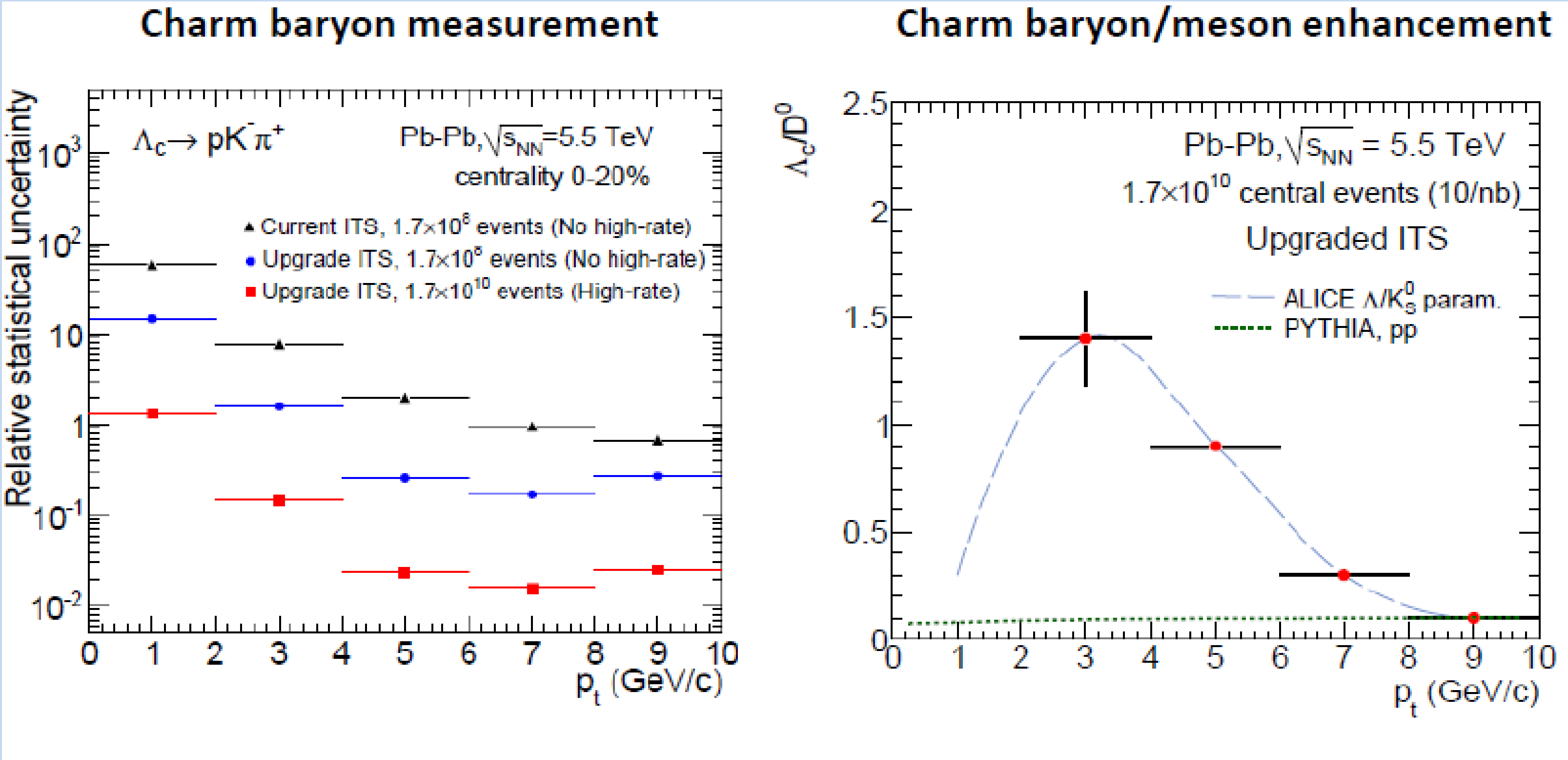
Development for monolithic detectors using Tower/Jazz 0.18 μm CMOS technology:
- improved TID resistance due to smaller technology node
- available with high resistivity (~ 1kΩcm) epitaxial layer up to 18 μm
- special quadruple-well available to shield PMOS transistors (allows in-pixel truly CMOS circuitry)
- study radiation hardness and SEU
- study charge collection performance
- use existing structures/sensors (STFC Rutherford/Daresbury)
- design new prototype chips in Tower/Jazz 0.18 μm (IPHC, CERN, STFC Rutherford/Daresbury)





M. Stanitzki et al., Nucl. Instr. Meth. A 650 (2011) 178.

Λ_C Measurement



- Λ_C benchmark for ITS upgrade as regards heavy flavour. Currently not accessible
- Both improvement in ITS precision *and* increase in statistics bring benefits.
- Having both baryons and mesons in charm sector allows more detailed comparisons to be made.

Summary

- First results from Pb-Pb running (2011) showed that the main features of RHIC running are seen again, but are seen more strongly in LHC data
  - energy density higher than at RHIC
  - volume from HBT larger than at RHIC (~4500 fm^3)
  - strong flow effects seen
  - Fluctuations are important. Understanding them may lead to re-assessment of some phenomena (Mach cone, “ridge”)
- Higher statistics uncovers more detail. Some anomalies now clearly seen (proton yields, no “dead cone”, charm flow,…)
- Starting to make sense. RHIC/LHC comparisons very fruitful
- Time to plan for the future. 10-fold increase in statistics, focussing principally on heavy flavour to exploit ALICE advantages of good low p_t coverage and excellent PID