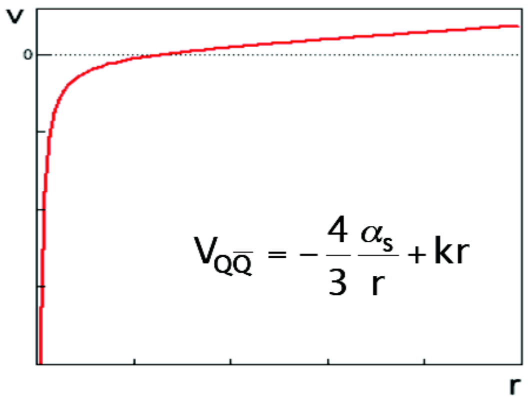
Heavy-Ion Physics and the ALICE experiment at the LHC

Plamen R. Petrov

26/03/2014

CP3 - Université catholique de Louvain

- **Confinement**
  - At large distances the effective coupling between quarks is large resulting in confinement.
  - Free quarks are not observed in nature.



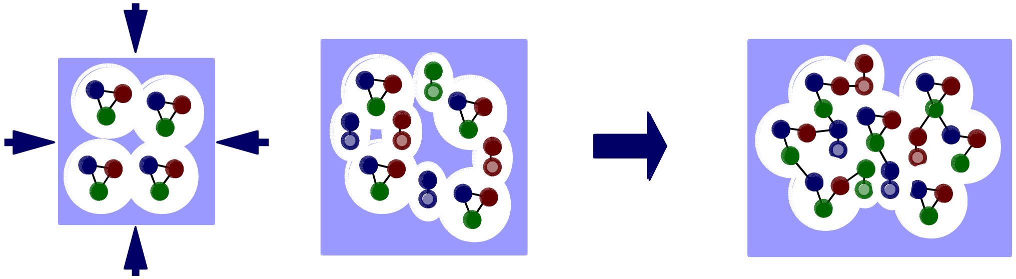
$$\alpha_s(|q^2|) = \frac{12\pi}{\beta \ln |q^2|/\Lambda^2}$$

$$\beta = 2f - 11n$$

- **Asymptotic freedom**
  - At short distances the effective coupling between quarks decreases logarithmically.
  - Under such conditions quarks and gluons appear to be quasi-free.

However, in the context of a QGP, it implies a medium of quarks and gluons where individual partons can move freely over distances larger than the typical size of hadronic states.

- **In plasma, presence of other mobile charges can screen long range interactions (Debye screening)**
- **High colour charge densities achieved by colliding heavy nuclei:**
  - Compression
  - Heating = creation of pions



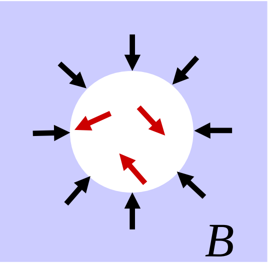
Compression + Heating *Quark-Gluon Plasma*

- **Mapping out the QCD matter phase diagram:**
  - pQCD only applicable for very hard processes
  - Two solutions:

1. Phenomenological models
2. Lattice QCD calculations

MIT bag model

- At first approximation treat hadron gas/ QGP as an ideal gas



$$P = g\frac{\pi^2}{90}T^4$$

$g_{HadronGas} \sim 3$

$g_{QGP} \sim 48$

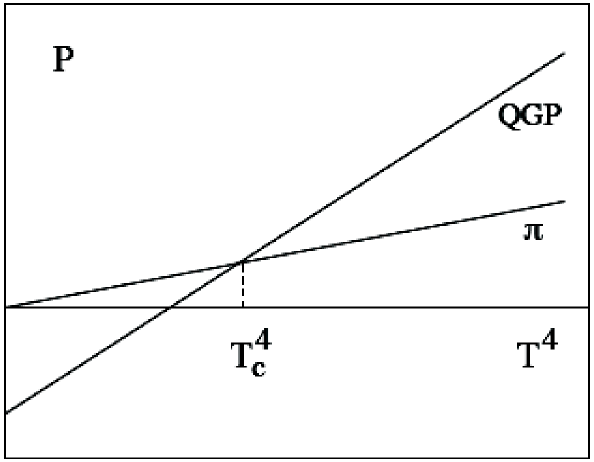
- A deconfined state can be attained if the QGP pressure is greater than the Bag pressure and the Hadron Gas pressure

- High T, low density limit – the early Universe
  - Two terms contribute to the total energy density

$$\varepsilon_{qg} = 37\frac{\pi^2}{30}T^4 = 1.3\ \mathrm{GeV/fm^3}$$

  - For a relativistic gas $P_{qg} = \frac{1}{3}\varepsilon_{qg}$
  - For stability $P_{net} = P_{qg} - B \geq 0$

$$T_c = \left[\frac{90}{37\pi^2}B\right]^{1/4} = 100-170\ \mathrm{MeV}$$



Satz, Helmut arXiv:0903.2778

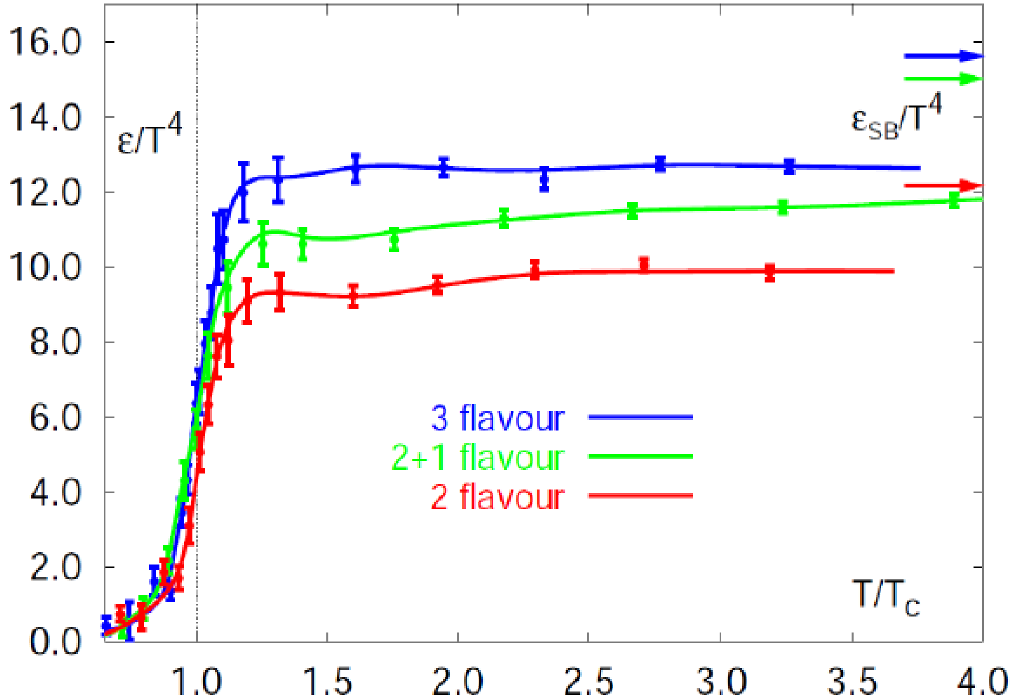
- Low T, high density limit – neutron stars
  - Only one term contributes to the total energy density

$$e_q = \frac{3}{2p^2}m_q^4$$

$$m_c = \left(2p^2 B\right)^{1/4} = 300-500\mathrm{MeV}$$

- Quarks and gluons are studied on a discrete space-time lattice
- Solves problems of divergences in pQCD calculations (which arise due to loop diagrams)

F. Karsch, Lect. Notes Phys. 583 (2002) 209, hep-lat/0106019



$$\frac{\epsilon}{T^4} = \left[2(n_c^2 - 1) + 2n_c n_f \frac{7}{4}\right] \frac{\pi^2}{30}$$

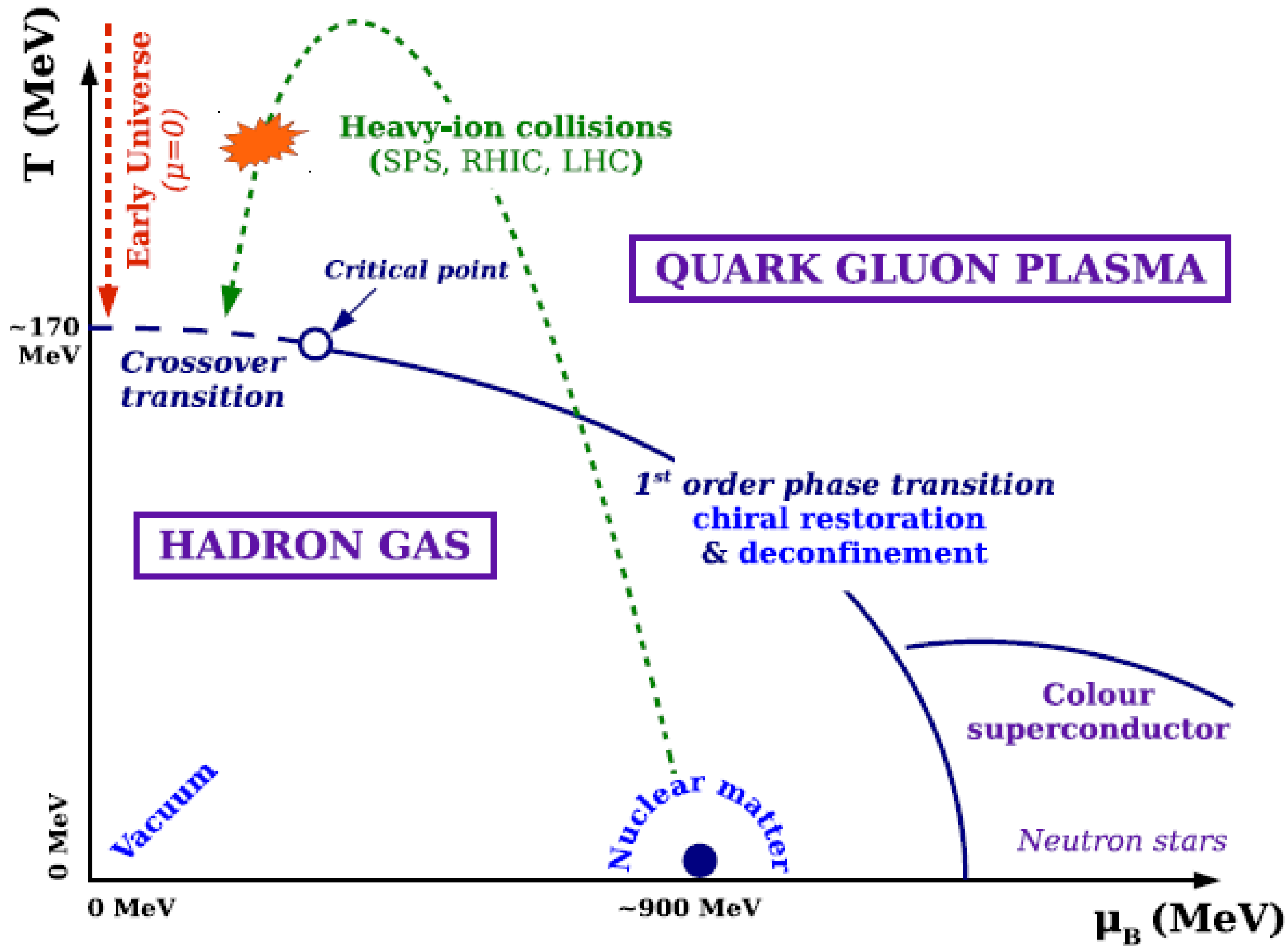
For ideal quark-gluon gas

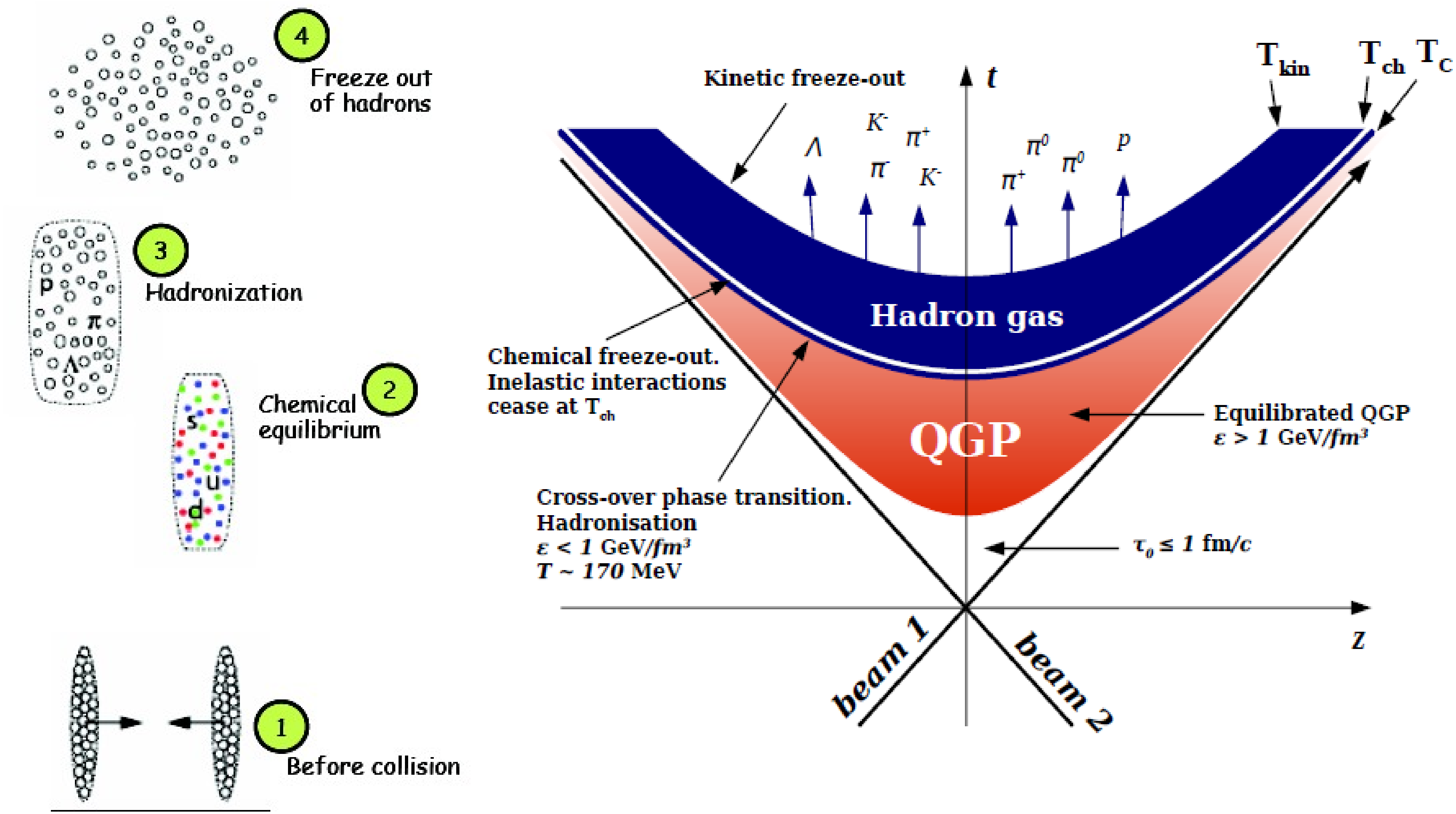
Critical Temp.: T_c = 173 MeV @ μ_B = 0

Critical Energy Density: ρ_c = 0.7 GeV/fm3

Nuclear Density: ρ = 0.15 GeV/fm^3

Inside Nucleon: ρ = 0.5 GeV/fm^3

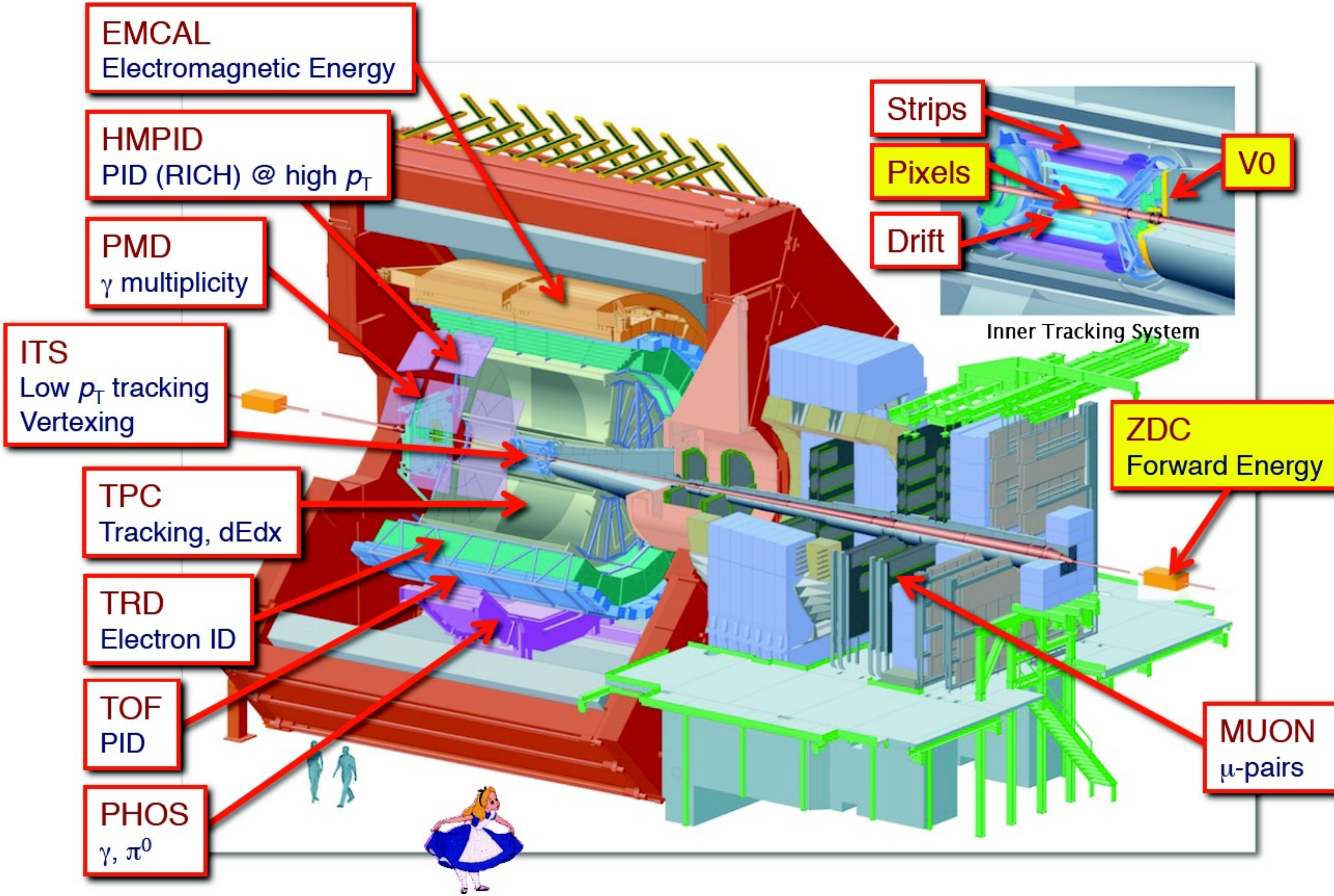

T (MeV)
Early Universe
(μ=0)
Heavy-ion collisions
(SPS, RHIC, LHC)
Critical point
QUARK GLUON PLASMA
~170
MeV
Crossover
transition
1st order phase transition
chiral restoration
& deconfinement
HADRON GAS
Colour
superconductor
0 MeV
Vacuum
Nuclear matter
Neutron stars
0 MeV
~900 MeV
μB (MeV)

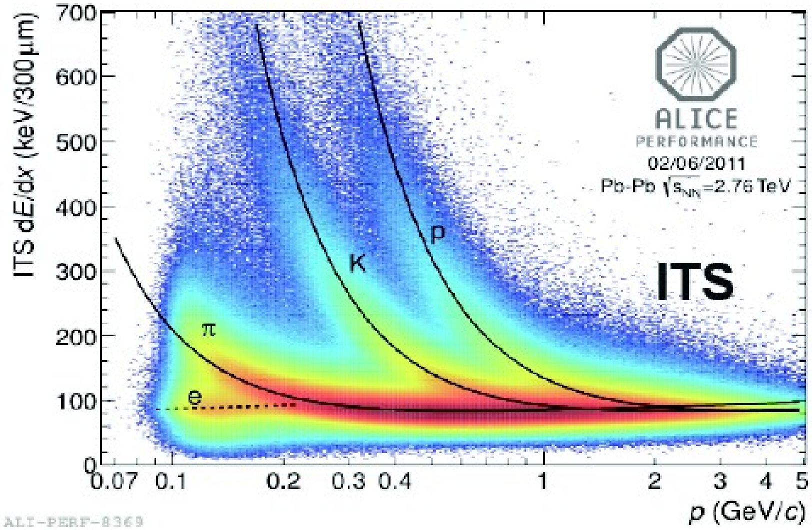

4
Freeze out of hadrons
3
Hadronization
p
π
Λ
2
Chemical equilibrium
s
u
d
1
Before collision
Kinetic freeze-out
t
T_{kin}
T_{ch}
T_C
Λ
K^-
π^+
π^-
K^-
π^0
π^0
π^+
p
Hadron gas
Chemical freeze-out. Inelastic interactions cease at T_{ch}
QGP
Equilibrated QGP
$\varepsilon > 1$ GeV/fm^3
Cross-over phase transition. Hadronisation
$\varepsilon < 1$ GeV/fm^3
$T \sim 170$ MeV
$\tau_0 \leq 1$ fm/c
z
beam 1
beam 2

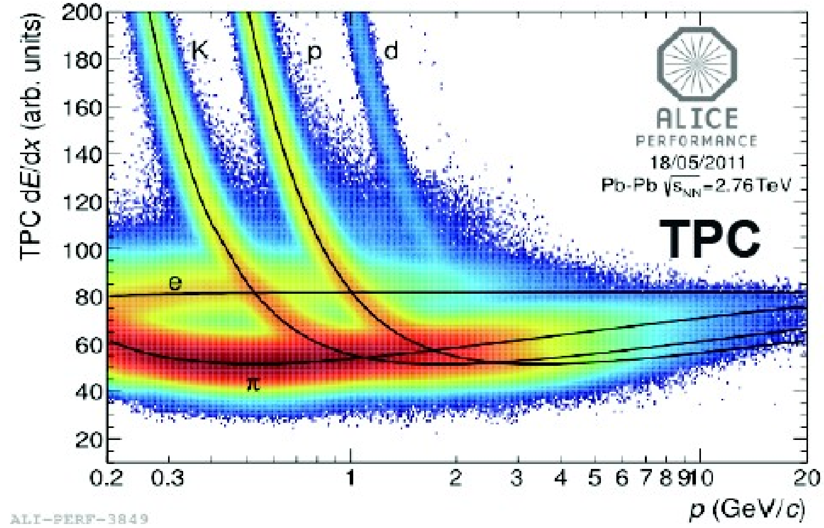
Experimental facilities

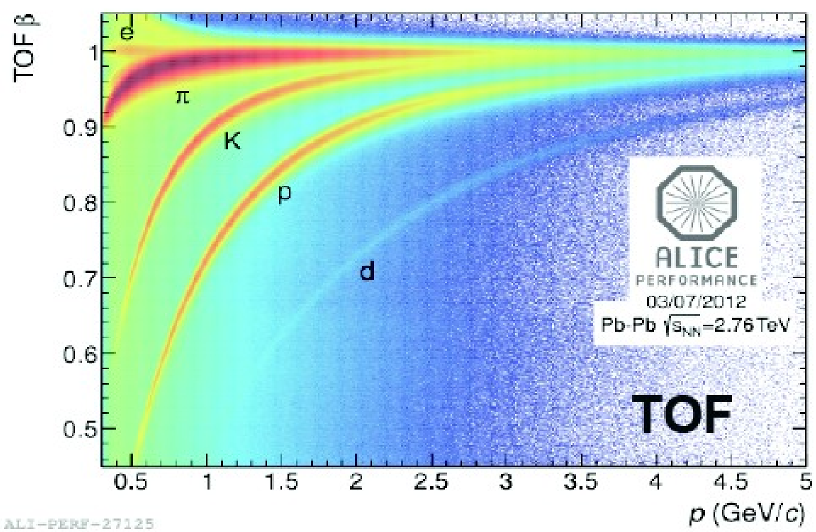
Facility	Beam	Beam Energy (GeV/A)	CMS Energy $\sqrt{s}$	
AGS	^{28}Si	14.6	5.4	1986
	^{197}Au	11.6	4.8	1994
SPS	^{16}O	200	19	1986
	^{32}S	200	19	1987
	^{208}Pb	158	17	1994
RHIC	**^{197}Au**	**100**	**200**	**2000**
LHC	^{208}Pb	3000	6000	2008

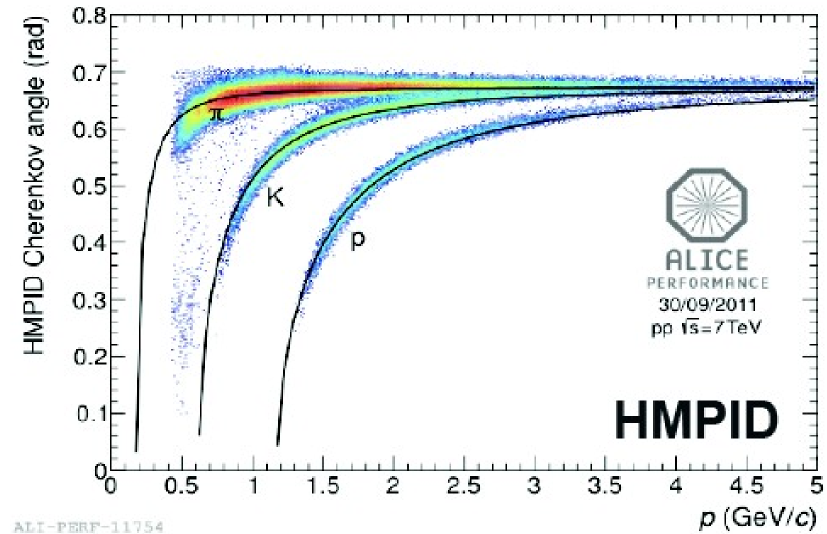
AGS	Alternating Gradient Synchrotron (BNL)
SPS	Super Proton Synchrotron (CERN)
RHIC	Relativistic Heavy-Ion Collider (BNL)
LHC	Large Hadron Collider (CERN)


EMCAL
Electromagnetic Energy
HMPID
PID (RICH) @ high p_T
PMD
γ multiplicity
ITS
Low p_T tracking
Vertexing
TPC
Tracking, dEdx
TRD
Electron ID
TOF
PID
PHOS
γ, π^0
Strips
Pixels
Drift
V0
Inner Tracking System
ZDC
Forward Energy
MUON
μ-pairs


ITS dE/dx (keV/300µm)
p (GeV/c)
π
e
K
p
ITS
ALICE PERFORMANCE
02/06/2011
Pb-Pb √sNN=2.76 TeV
ALI-PERF-8369


TPC dE/dx (arb. units)
p (GeV/c)
K
p
d
e
π
TPC
ALICE PERFORMANCE
18/05/2011
Pb-Pb √sNN=2.76 TeV
ALI-PERF-3849

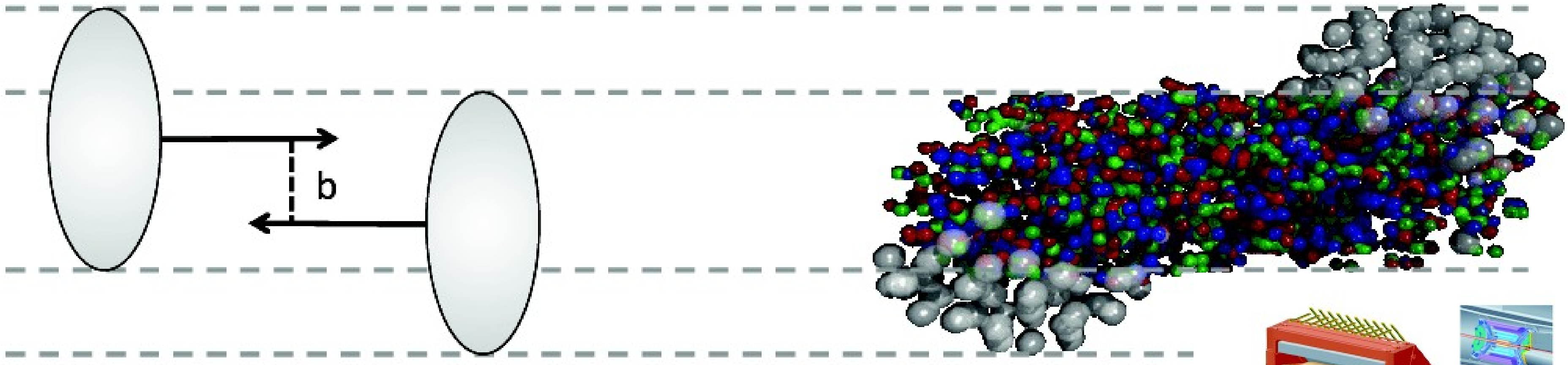

TOF β
p (GeV/c)
e
π
K
p
d
TOF
ALICE PERFORMANCE
03/07/2012
Pb-Pb √sNN=2.76 TeV
ALI-PERF-27125

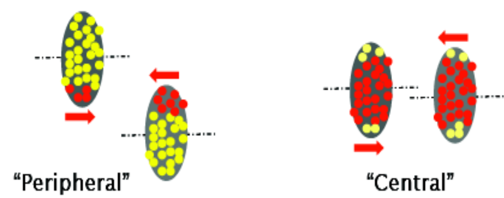

HMPID Cherenkov angle (rad)
p (GeV/c)
π
K
p
HMPID
ALICE PERFORMANCE
30/09/2011
pp √s=7 TeV
ALI-PERF-11754

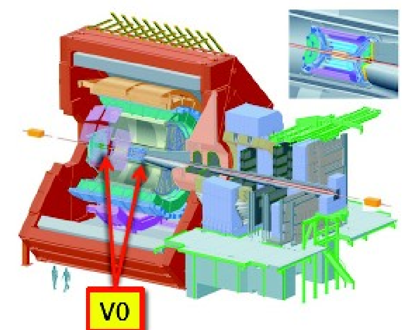
Year	System	Energy $\sqrt{s_{NN}}$ (TeV)	Delivered Integrated luminosity
2010	Pb-Pb	2.76	10 μb^{-1}
2011	Pb-Pb	2.76	0.1 nb^{-1}
2013	p-Pb Pb-p	5.02	15 nb^{-1} 15 nb^{-1}

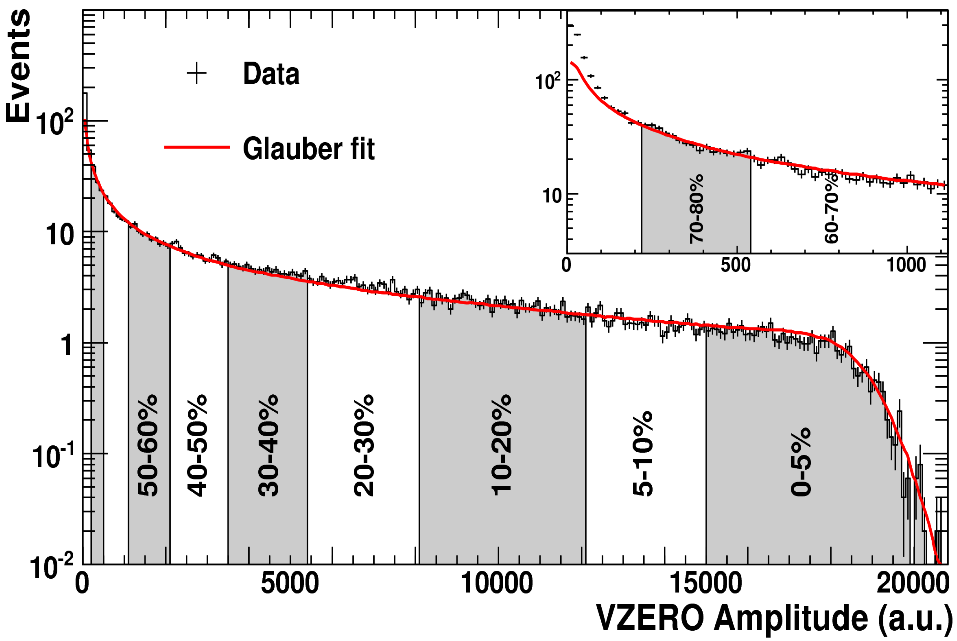
- Two Pb-Pb runs:
  - In 2010 - Commissioning and first data taking
  - In 2011 – factor 10 increase in luminosity
- p-Pb run in 2013:
  - LHC delivered target luminosity
- In addition p-p runs at √sNN = 0.9, 2.76, 7 and 8 TeV
- At present: still in long shut down (LS1)
  - Various upgrades and maintenance

Geometry of the collision is essential to the study of any physics observable in A-A





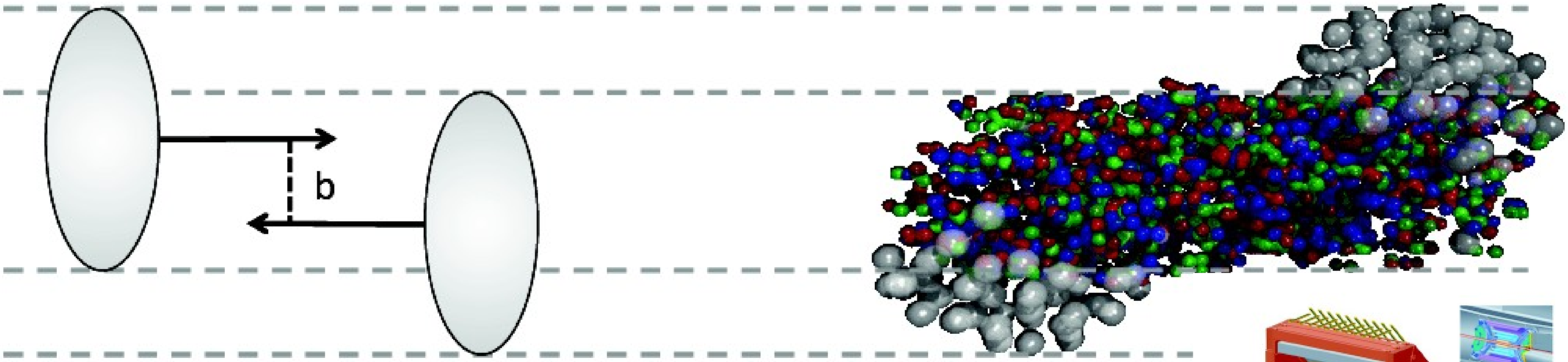


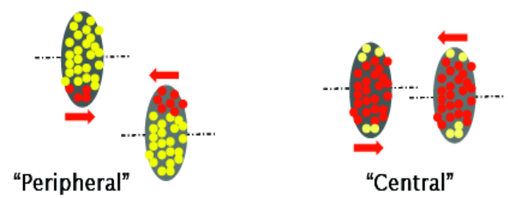


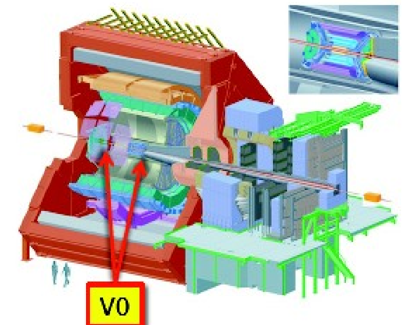
ALICE Collab., PRL 106, 032301(2011)

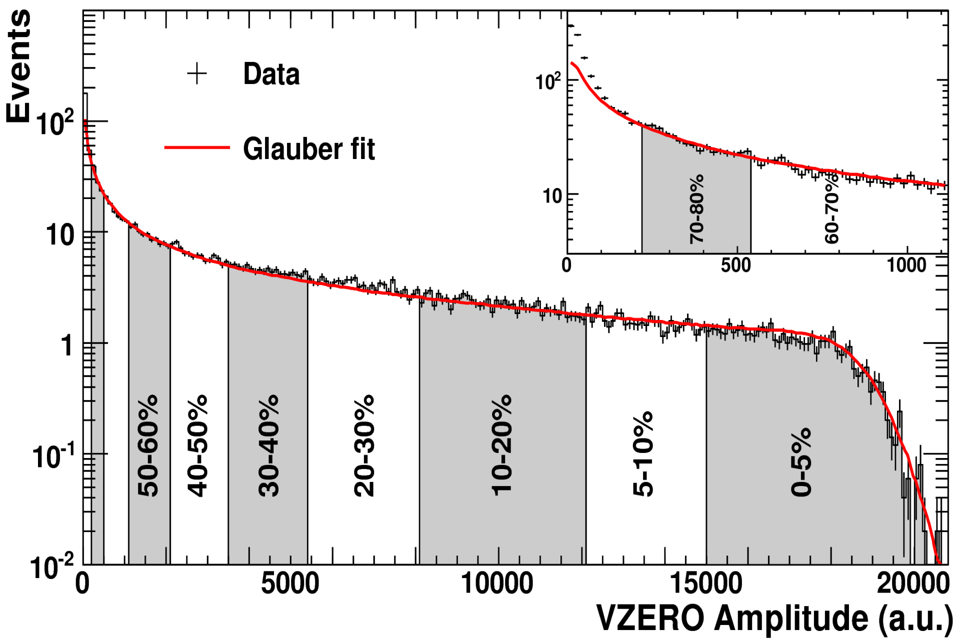
- Events are classified by their centrality – a % of the total nuclear interaction cross section
- The number of charged particles produced in a collision is dependent on both $N_{participants}$ and $N_{collisions}$
- The number of charged particles seen at the VZERO is fitted with a prediction from MC, and split into centrality regions

Geometry of the collision is essential to the study of any physics observable in A-A









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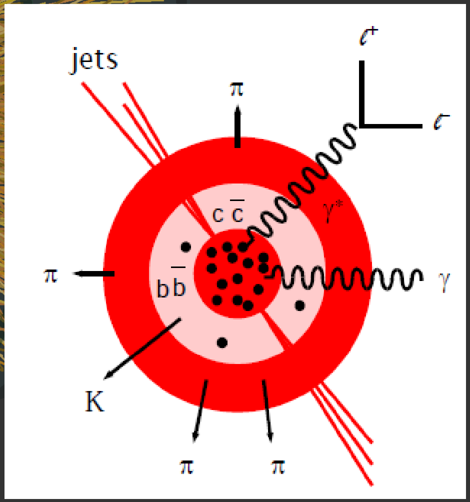
Final hadrons at freeze-out can give information on intermediate state...

- **Is initial state dense enough?**
  - → **Energy density**
  - → **Particle multiplicity**
- **What is the size of the initial state?**
  - → **Bose-Einstein correlation (HBT)**
- **Is initial state in equilibrium (thermalised)?**
  - → **Hadronic yields (thermal models)**
  - → **Hydrodynamic collective motion – elliptic flow**
- **Does initial state behave like QGP?**
  - → **J/Psi production – suppression or enhancement**
  - → **R_{AA} – suppression of high pT particles**

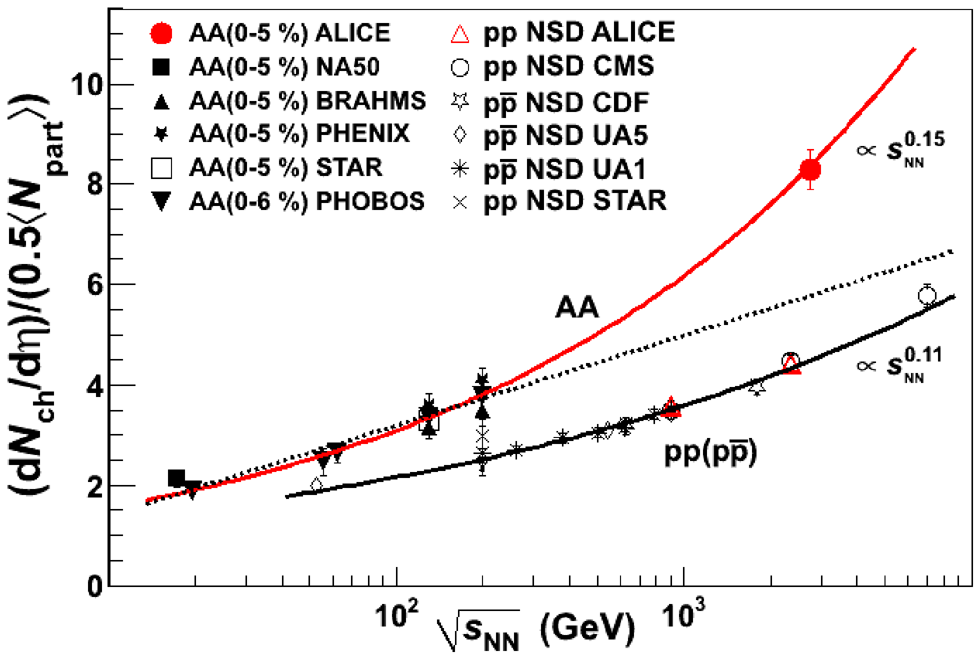


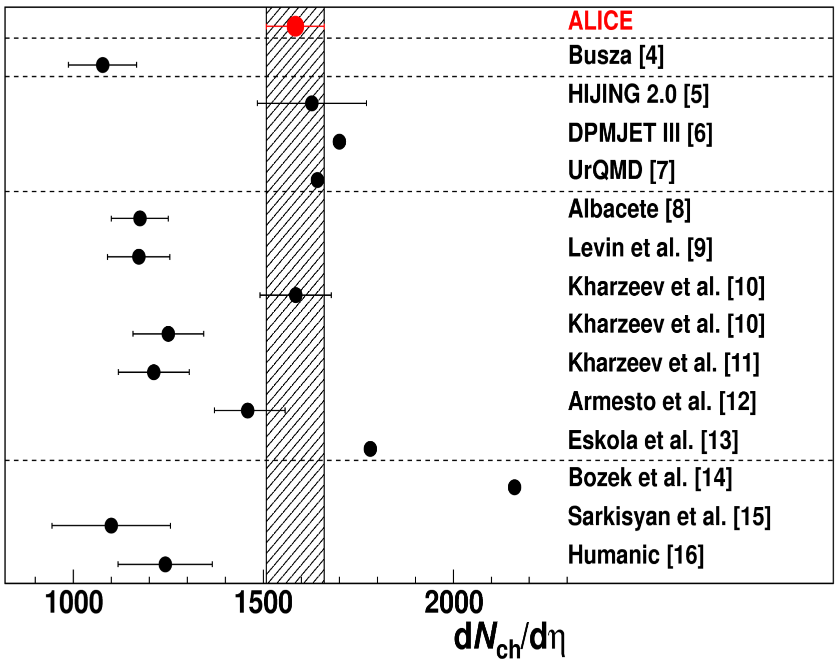
Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

ALICE

Multiplicity



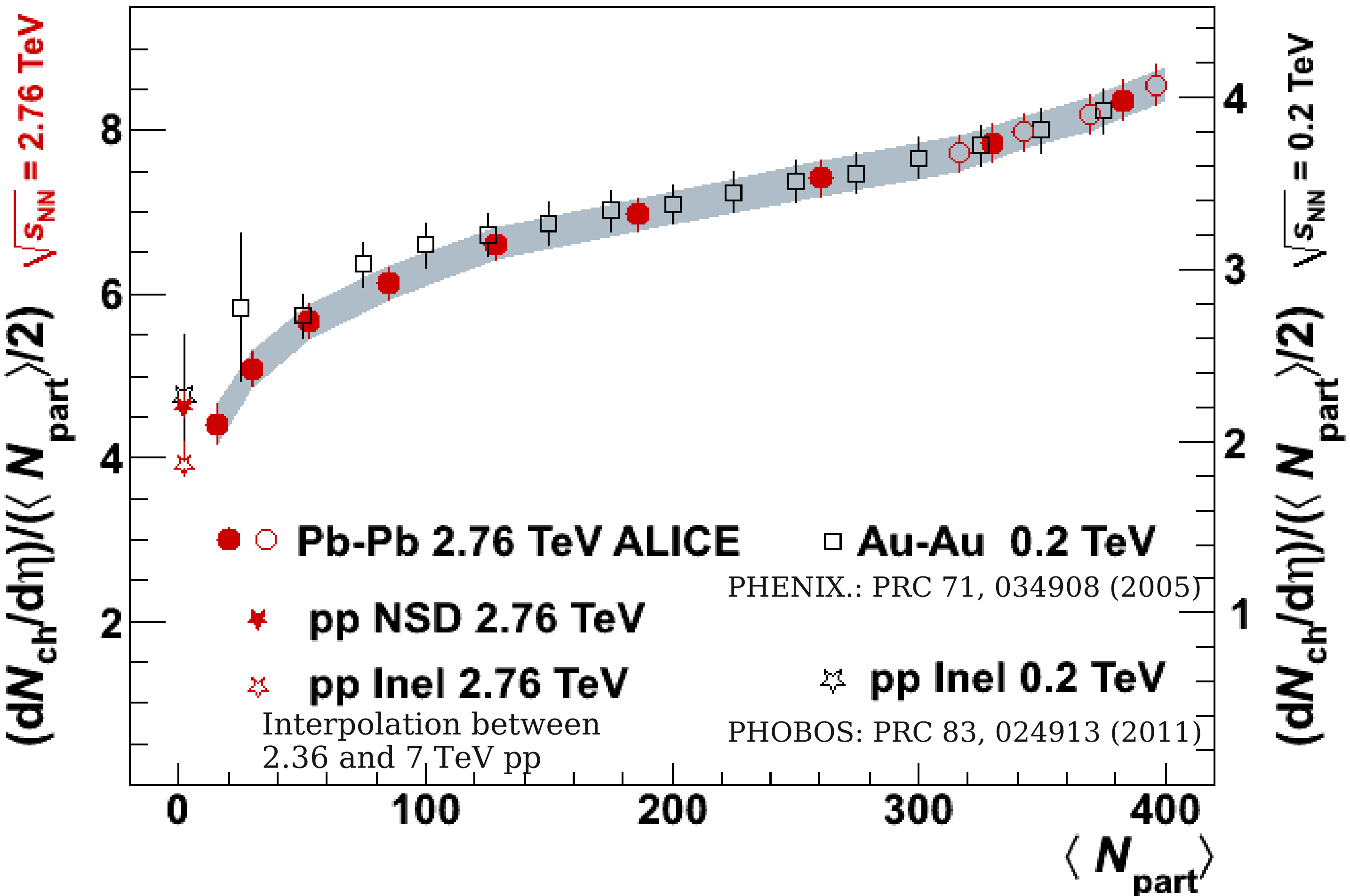


- **Pb-Pb @ 2.76 TeV, 0-5% central, $|\eta|<0.5$**
  - **$dN_{ch}/d\eta = 1584 \pm 76$**
  - **$2\ dN_{ch}/d\eta\ /\ N_{part} = 8.3 \pm 0.4$**

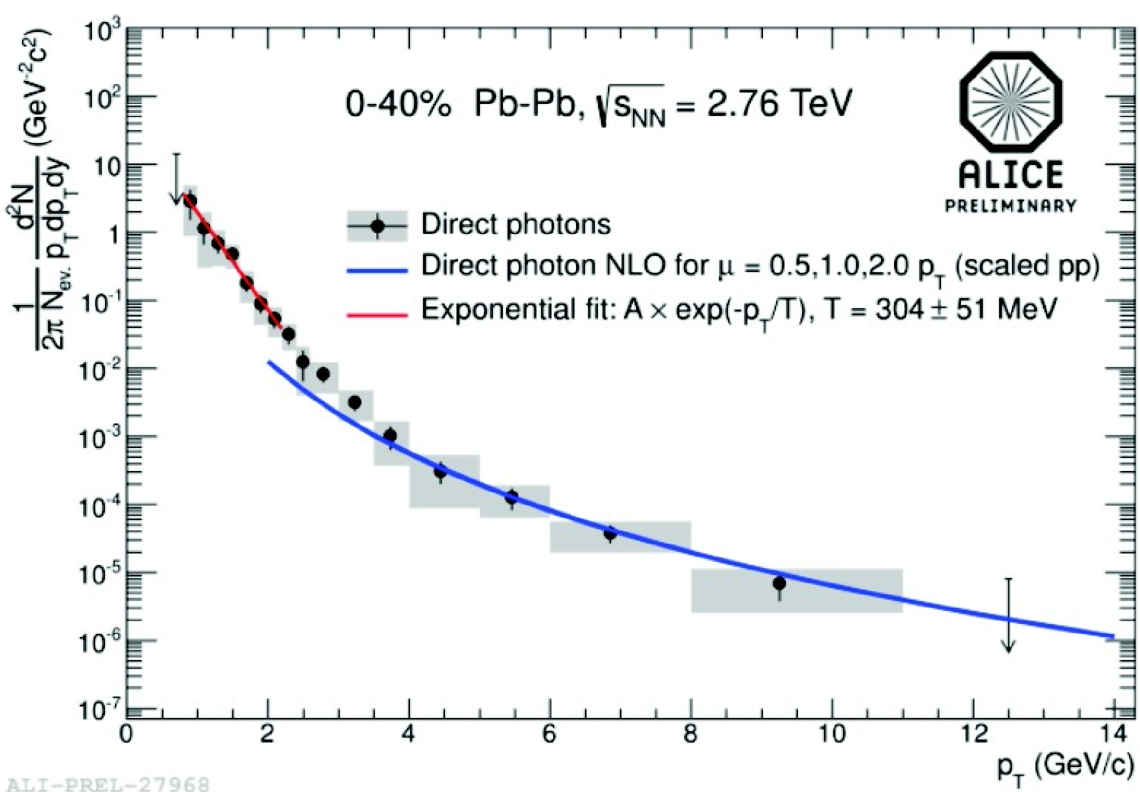
ALICE Collab., PRL 105, 252301 (2010)

- **1.9 x pp @ 2.36 TeV (NSD)**
- **2.1 x central Au-Au @ 0.2 TeV**
- **Growth with √s faster in AA than in pp**
- **Growth with power of CM energy faster than log scaling extrapolated from lower energies**

ALICE Collab., PRL 106, 032301(2011)



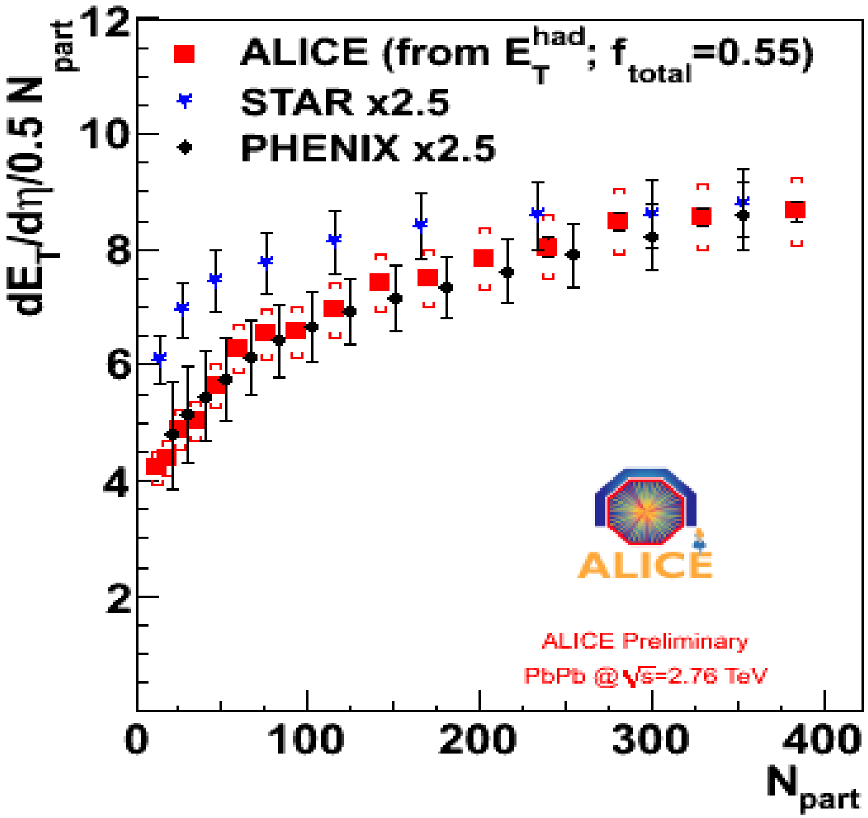
- **RHIC data scaled by 2.1**
- **Centrality evolution at LHC similar to RHIC (N_{part}>100)**



The famous Guiness Book of Records entry: T_{LHC} = 1.4 T_{RHIC}

T_{av} for thermal photons = 304+-51 MeV ⇨ T_{init} = 500-600 MeV

Energy density



STAR Collab.: PRC70, 054907 (2004)
PHENIX Collab.: PRC71, 034908 (2005)

$\tau\varepsilon_{LHC} \sim 2.7 \times \tau\varepsilon_{RHIC}$

- E_t^{had} from charged hadrons measured by the barrel tracking detectors
- f~0.55 to convert to total energy
  - From MC – model dependent
- From RHIC to LHC
  - Similar centrality dependence
  - **~ 2.5 increase in 2dE$_T$/dη/N$_{part}$**
- Energy density estimate (Bjorken)

$$\varepsilon = \frac{1}{\pi R^2 \tau}\frac{dE_t}{dy} \qquad R = 1.2A^{1/3} fm$$

  - $\tau\varepsilon_{LHC} \sim 15$ GeV/(fm^{2}c)
  - $\tau\varepsilon_{RHIC} = 5.4 \pm 0.6$ GeV/(fm^{2}c)

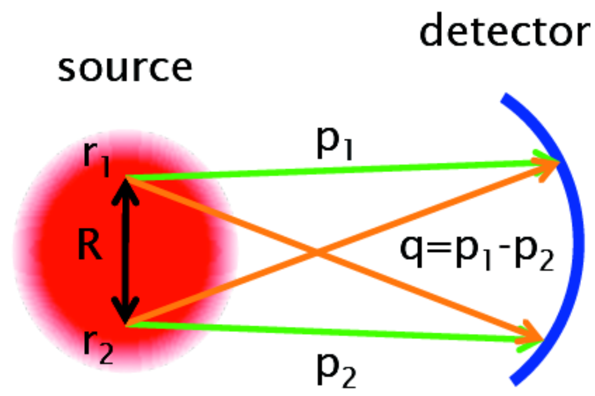
System syze

- Brief description of method

Hanbury Brown and Twiss first used it in 1956 to measure the angular size of stars

Goldhaber, Goldhaber, Lee and Pais used it in 1965 to measure size of proton-antiproton collisions

For each pair of identical pions there are two indistinguishable processes



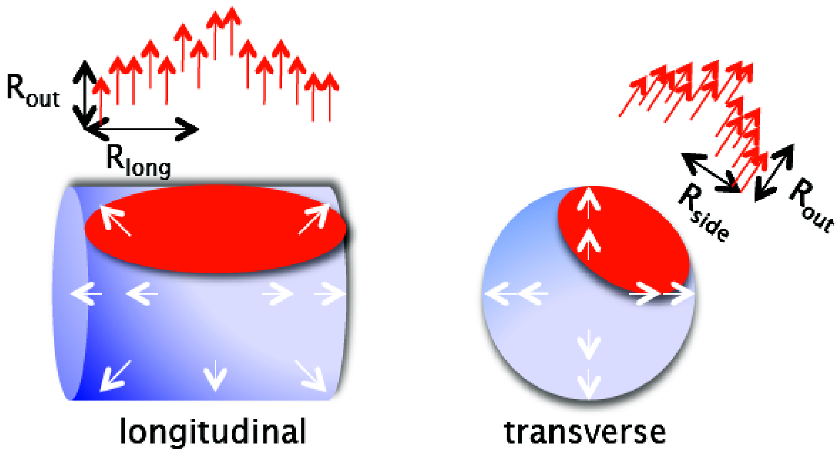
$$\Psi(p_1,r_1,p_2,r_2) \sim e^{i(p_1 \cdot r_1 + p_2 \cdot r_2)} \pm e^{i(p_1 \cdot r_2 + p_2 \cdot r_1)}$$

Enhancement at small momentum difference, q

$$P(p_1,p_2) \sim 1 + \cos((p_1 - p_2)\cdot(r_1 - r_2)) = 1 + \cos(q \cdot R)$$

By measuring P as a function of q we can extract R

- Experimental correlation



$$C(q) = \frac{f(p_1, p_2)}{f(p_1) f(p_2)} \qquad R \approx \frac{\hbar}{\Delta q} = 7 - 8 \text{ fm}$$

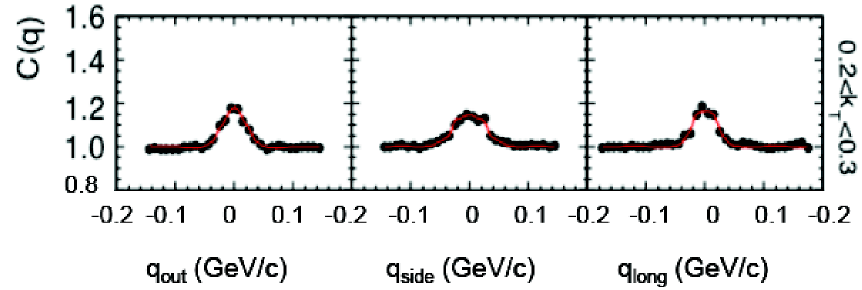
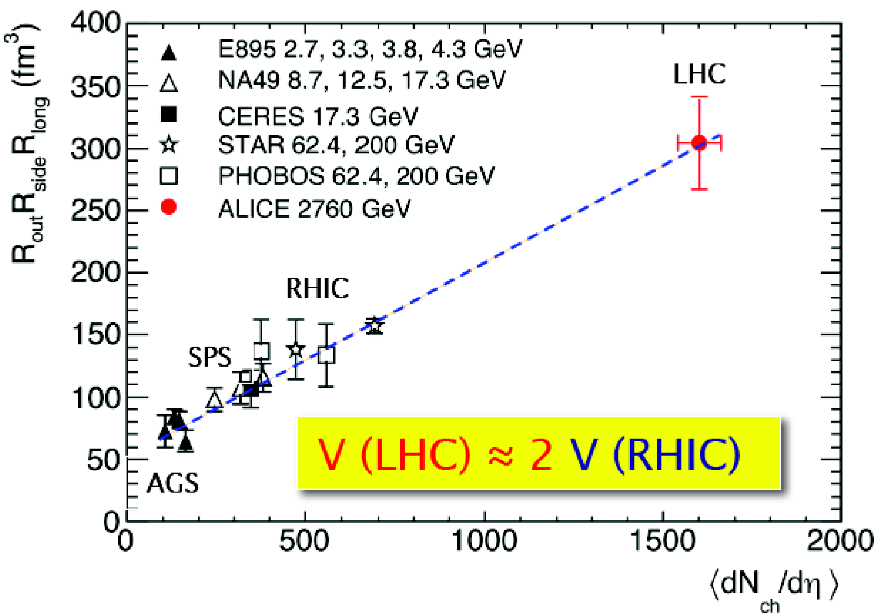
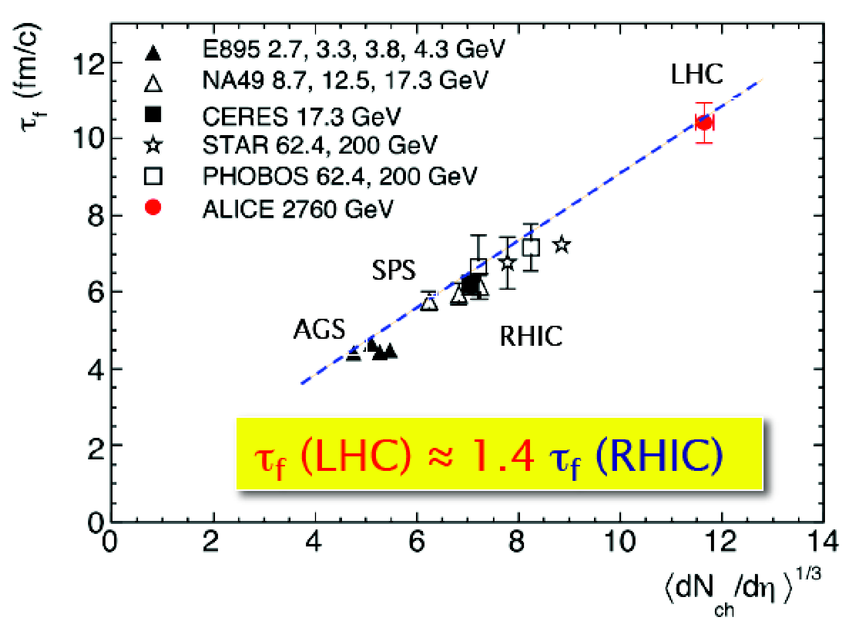


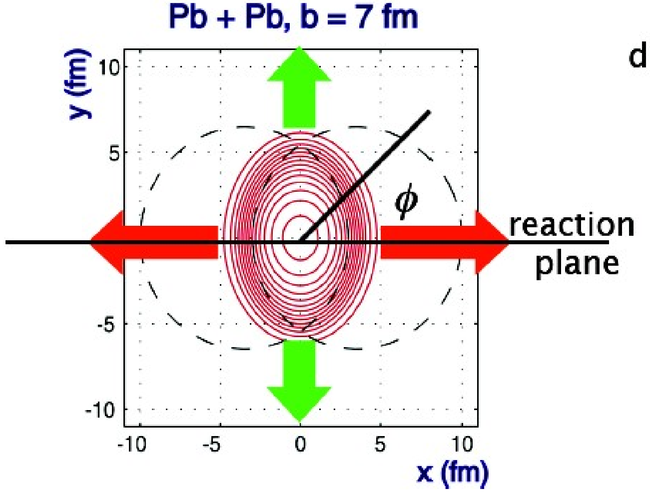
Figure adapted from Lisa et al., Ann. Rev. Nucl. Part. Sci. 2005. 55:357-402



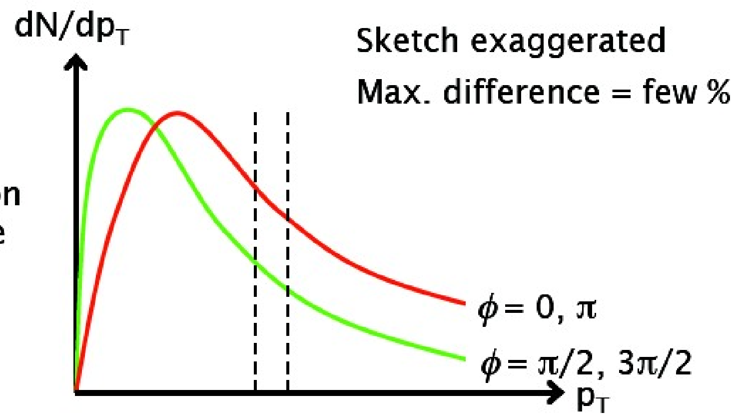


Collective behaviour: FLOW

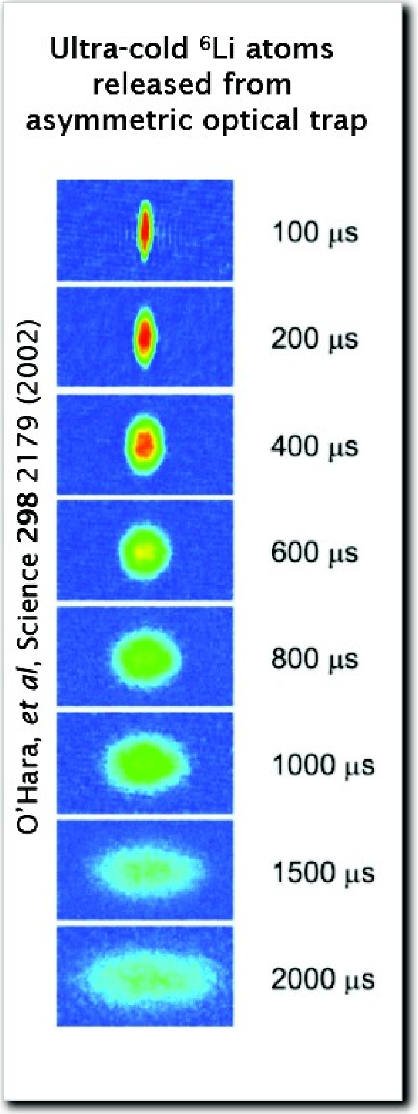
Particle flows are generated by pressure gradients



Initial-state spatial anisotropy



Final-state momentum anisotropy



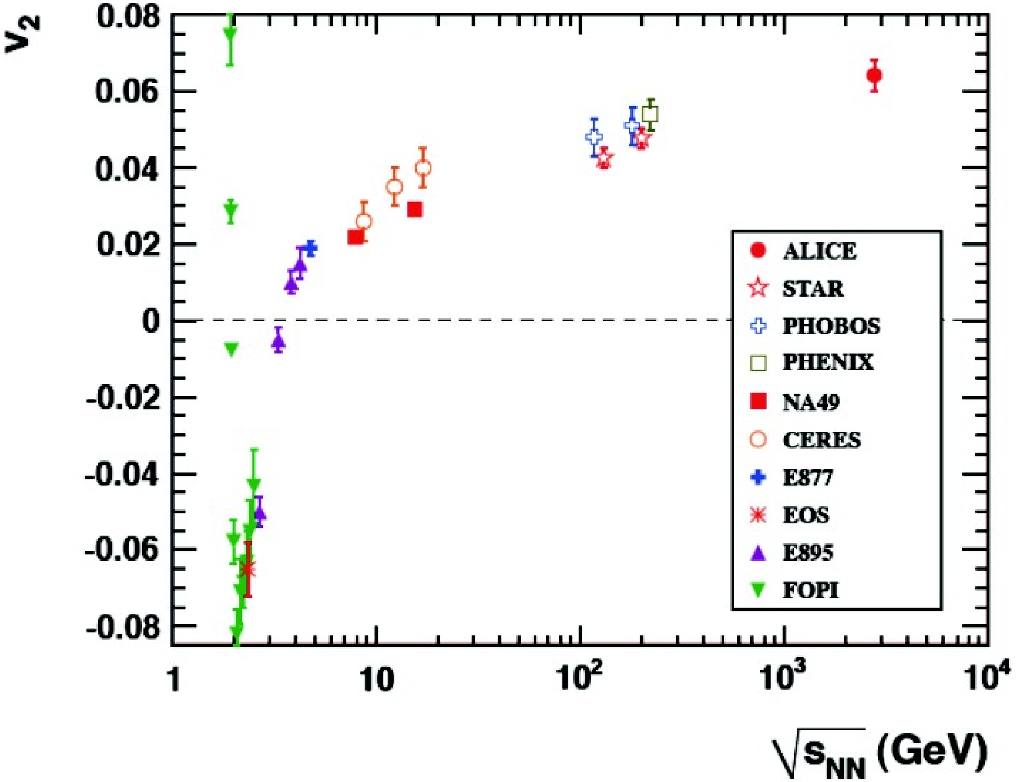
Fourier coefficient

Angle of reaction plane

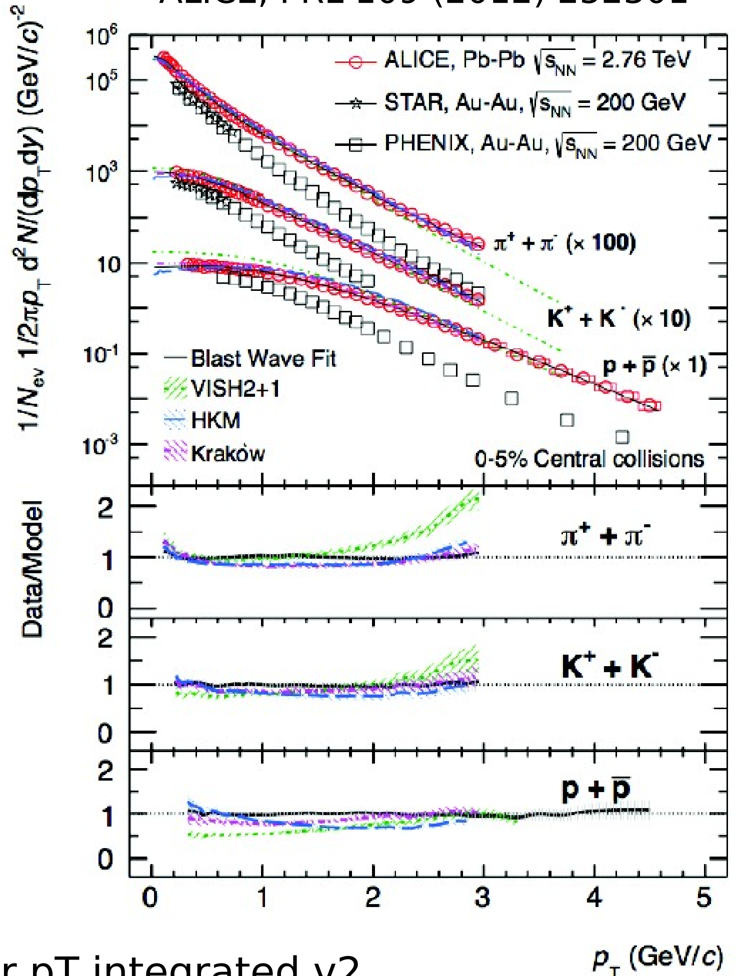
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos\left[n\left(\phi - \Psi_r\right)\right]\right)$$

$$v_2 = \left\langle \cos\left[2\left(\phi - \Psi_r\right)\right]\right\rangle$$

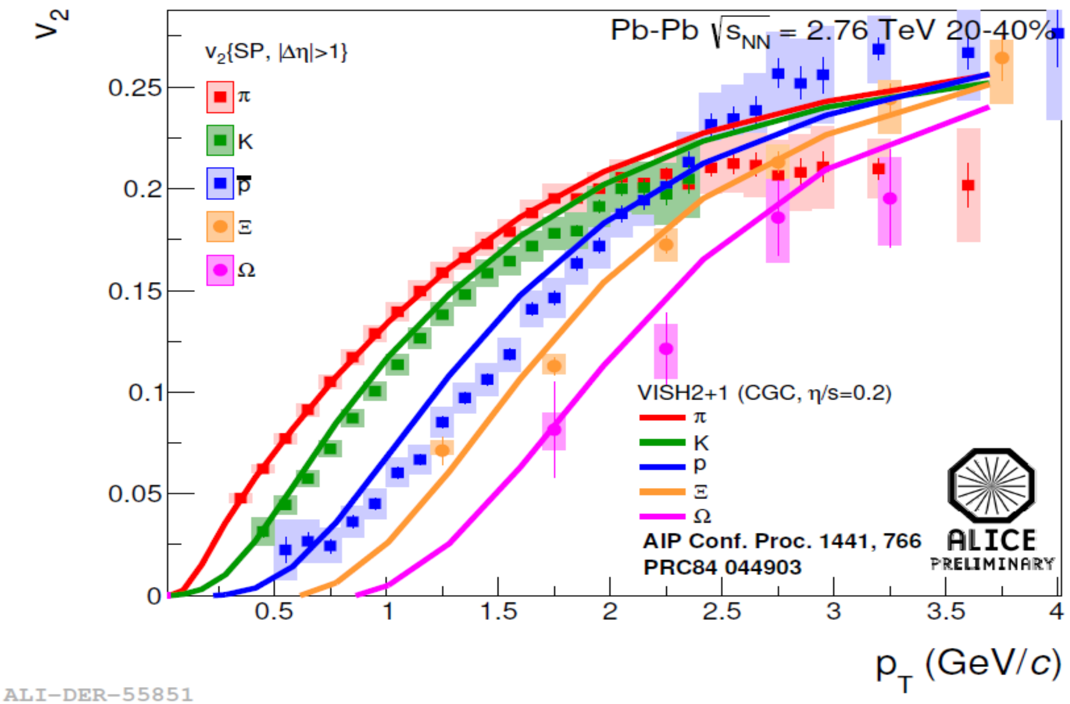
ALICE, PRL 105 (2010) 252302

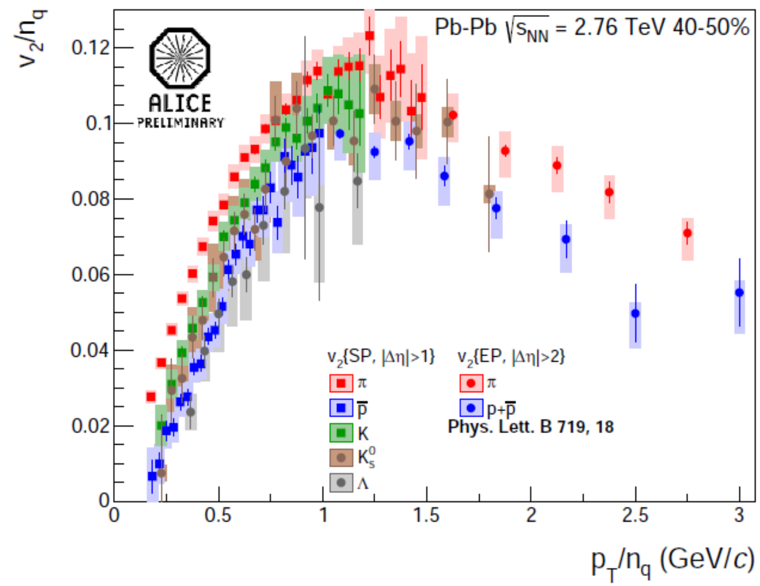


ALICE, PRL 109 (2012) 252301



- Larger flow than at RHIC
- For anisotropic flow (peripheral coll. 20-30%): larger pT integrated v2
- For radial flow (central coll. 0-5%): 10% larger expansion velocity (**$\langle\beta_T\rangle$ = 0.65c, T_{kin} = 80–95 MeV**)





- Mass ordering at low pT described by hydrodynamics (VISH2+1): Viscous hydrodynamic model using CGC initial condition with η/s = 0.20

- Better agreement in peripheral collisions. In central collisions, hydrodynamic calculations overestimate the proton v2, indicating that proton might freeze out later (with larger radial flow) compared to pion and kaon.

- Validity of NCQ scaling (observed at lower energies) less obvious at the LHC (within ~20%)

- Changes in dominant production mechanisms with beam energy?

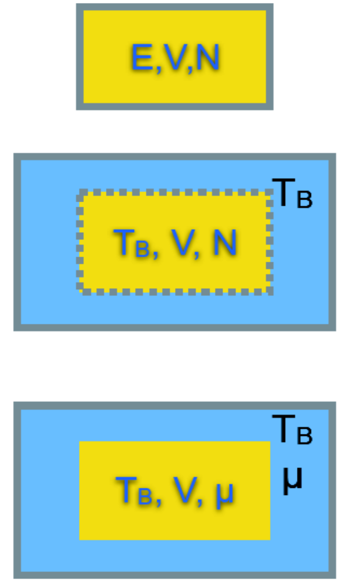
Bulk particle production: Thermal fits

Thermal models for particle production
Three different statistical ensembles:

(i) micro-canonical: E, V, N fix

(ii) canonical: T, V, N fix
➔ given volume element is coupled to a heat bath

(iii) grand-canonical: T, V, μ fix
➔ given volume element can also exchange particles with its surrounding (heat bath and particle reservoir)



Statistical model for e^+e^- collisions.

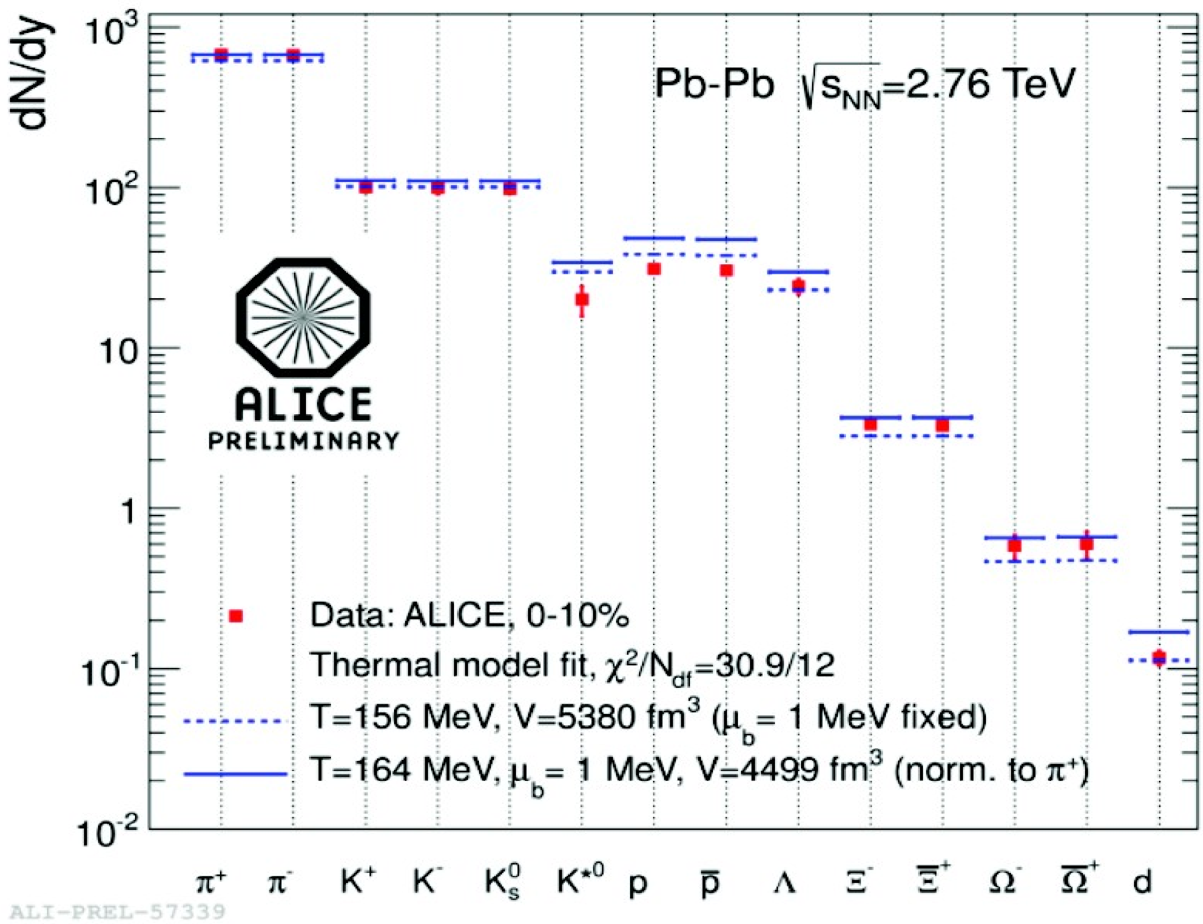
Strangeness conservation in peripheral HI collisions.

Central relativistic heavy-ion collisions.

$P(m) \sim e^{-(m/T)}$

T Temperature
μ_b Baryo-chemical potential
γ_s Strangeness suppression

$$\boxed{N_i/V = \frac{g_i}{(2\pi)^3}\gamma_S^{S_i}\int \frac{1}{\exp\left(\frac{E_i-\mu_B B_i-\mu_S S_i}{T_{\rm chem}}\right)\pm 1}d^3p,}$$

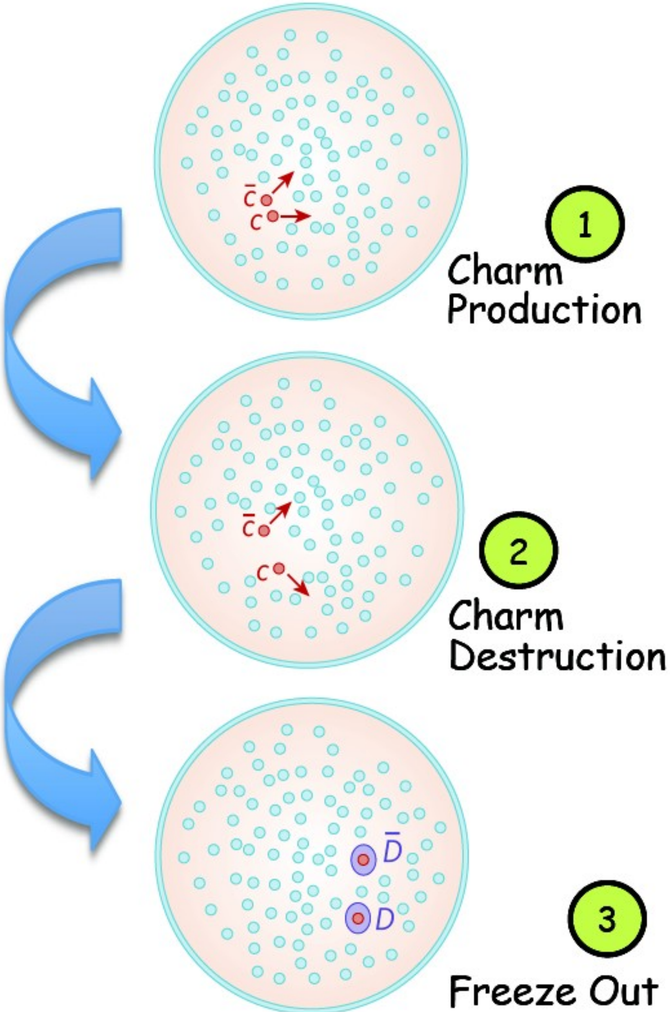


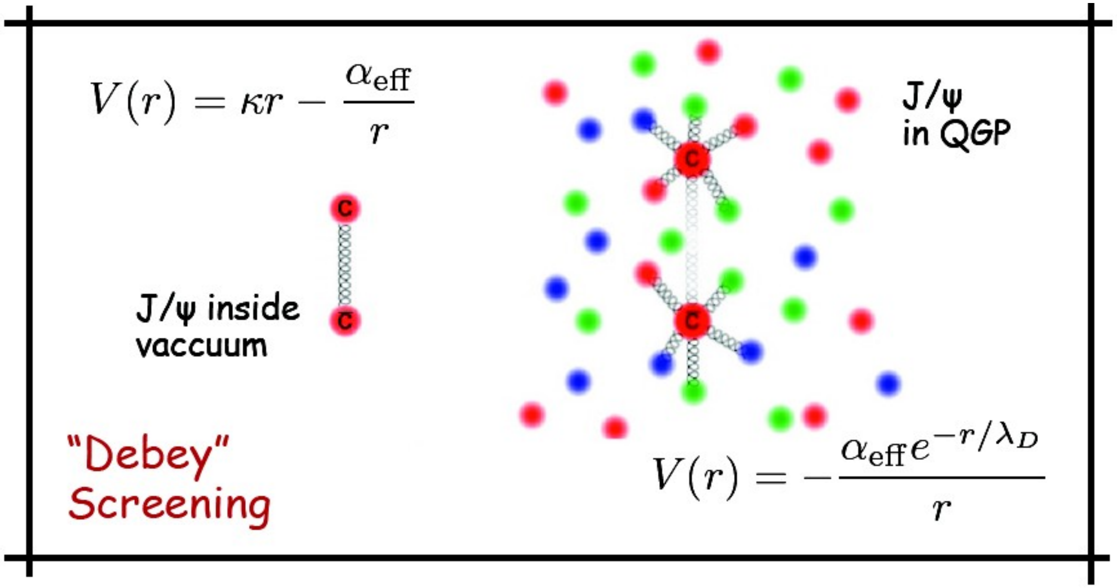
Final results of a thermal model calculation depend on the used hadron list (resonance spectrum)!

- Proton yield does not follow the results from statistical hadronisation model when assuming a common freeze-out temperature
  - ➔ Late stage p-pbar annihilation
  - ➔ Non equilibrium freeze-out conditions
  - ➔ Unknown/unmeasured baryon resonance spectrum

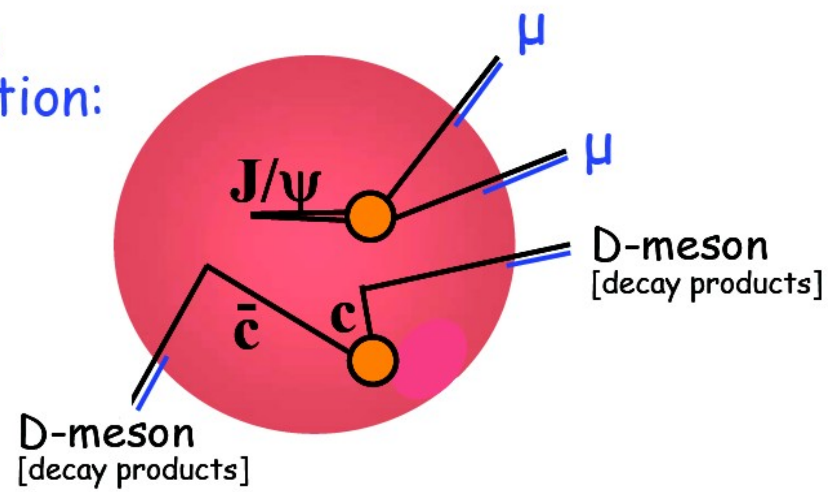
Charmonium production: suppression or enhancement?

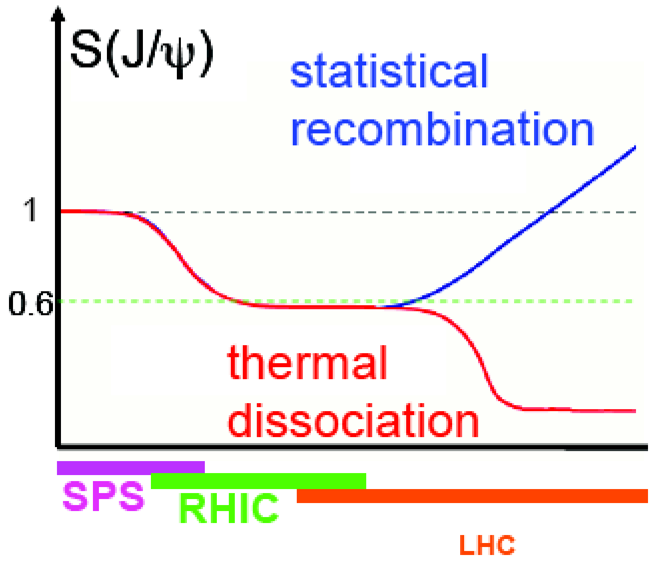
J/ψ in QGP:

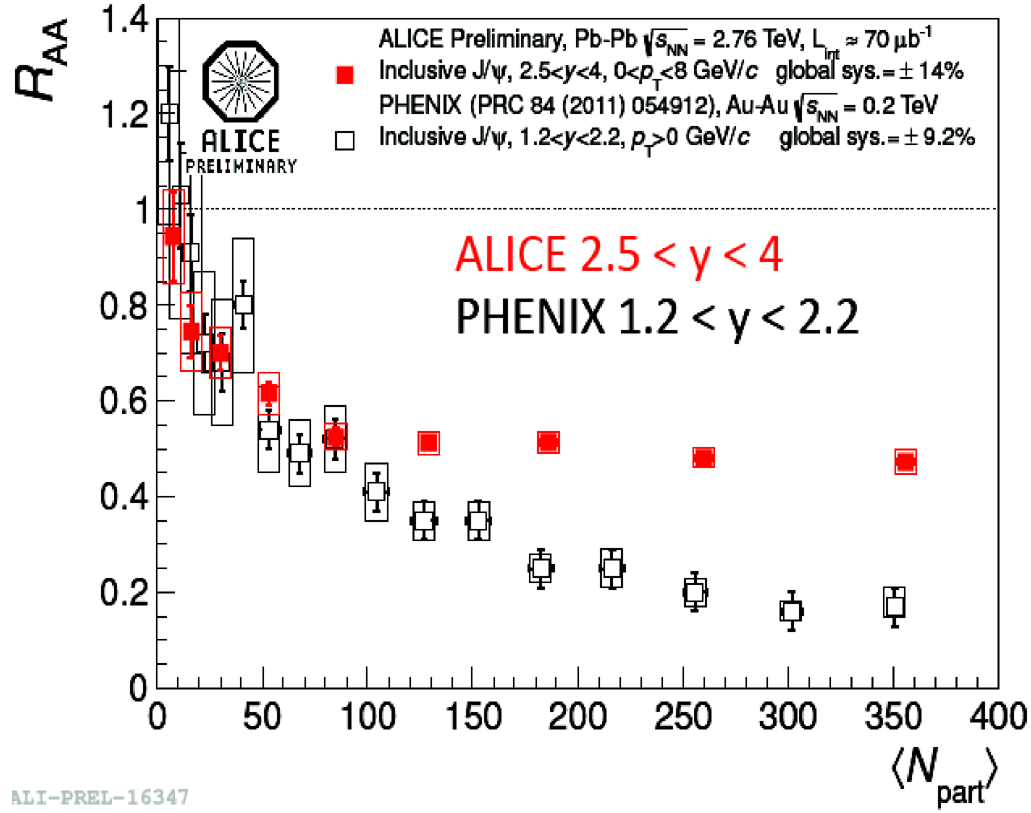




Charm
Detection:



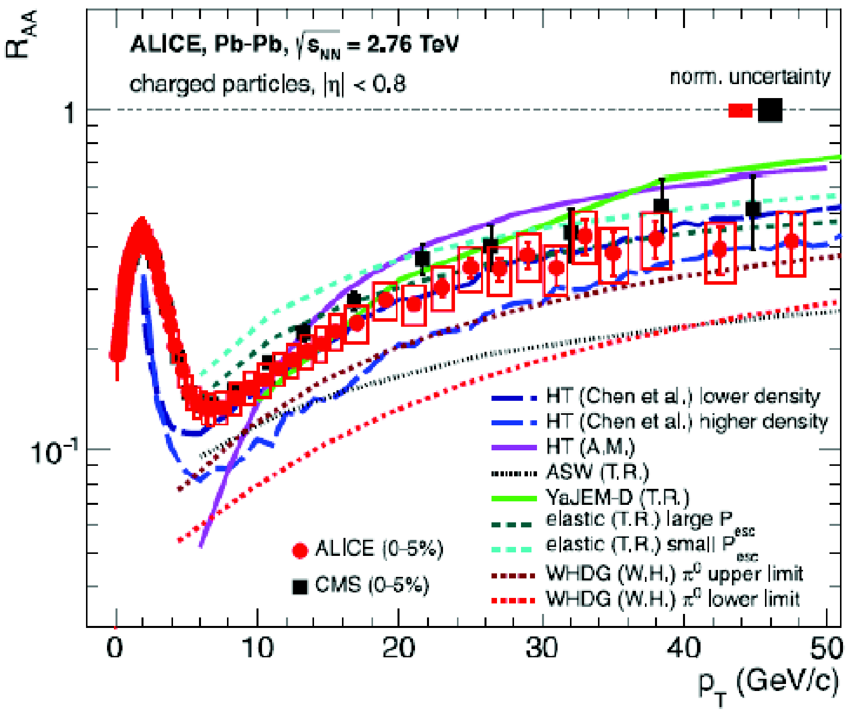


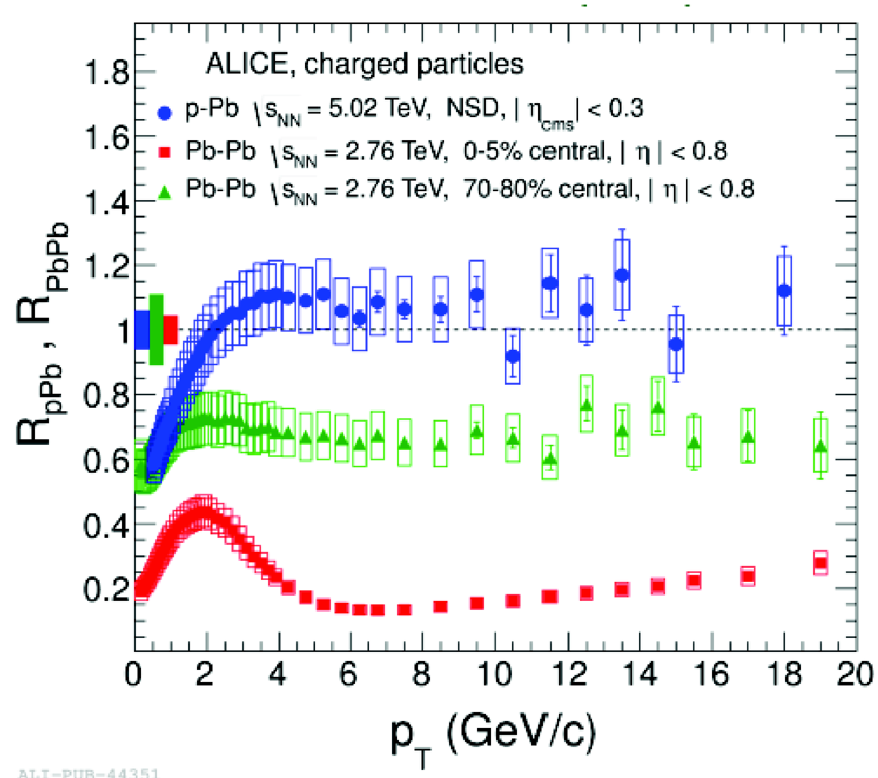


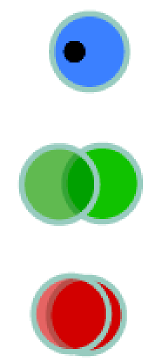
- Different suppression patterns as compared to RHIC
- Much less suppression in central events
  - ➔ Recombination?

Hard probes

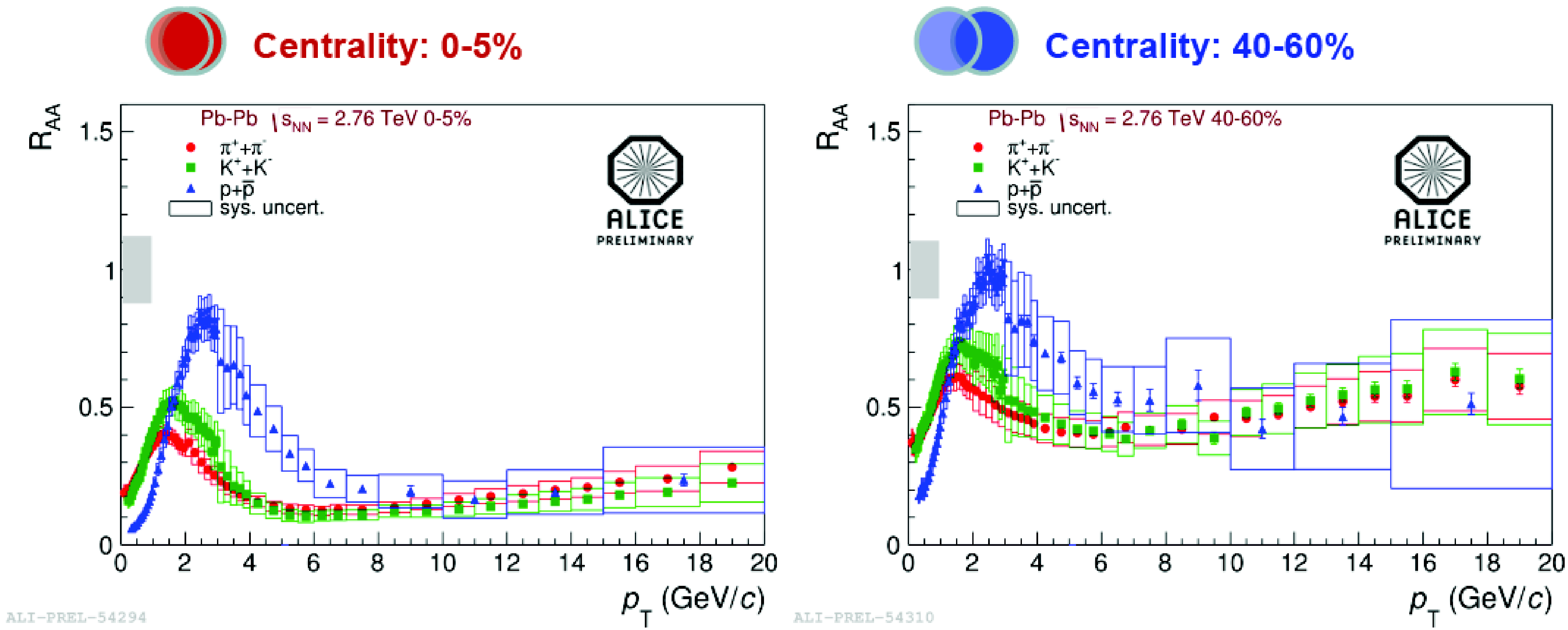
$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$





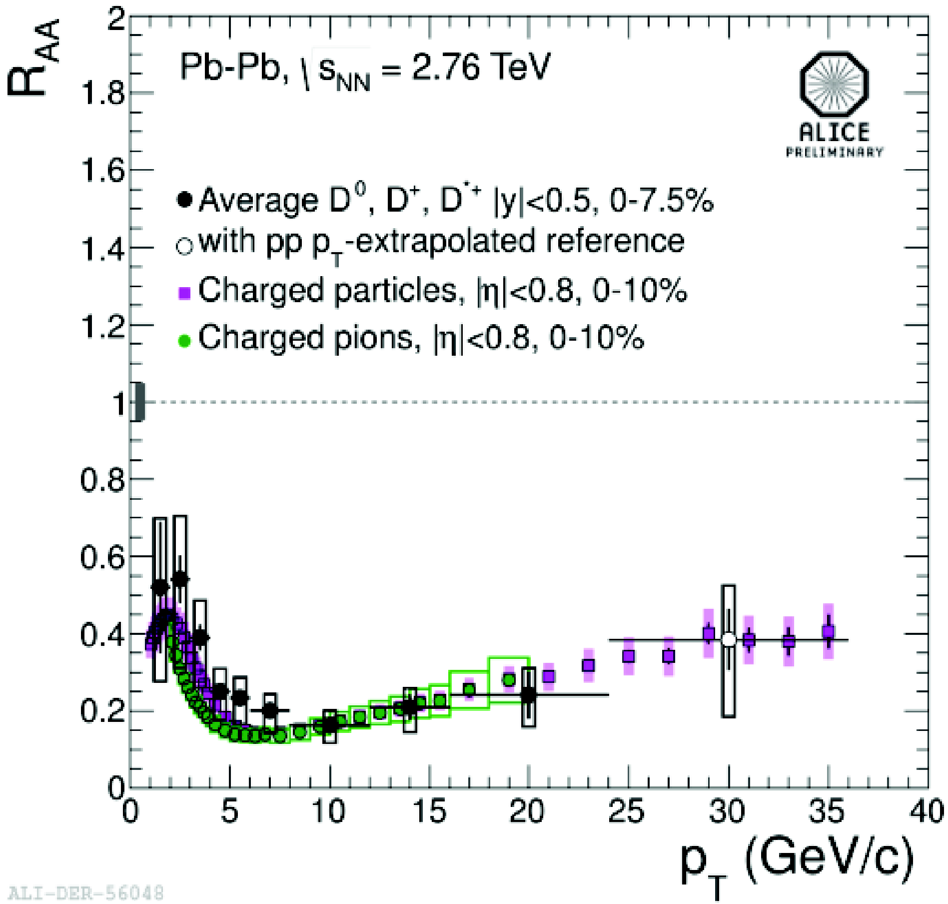


- Charged particle spectra strongly modified in PbPb compared to pp
- p-Pb results confirm that jet-quenching is a final state result

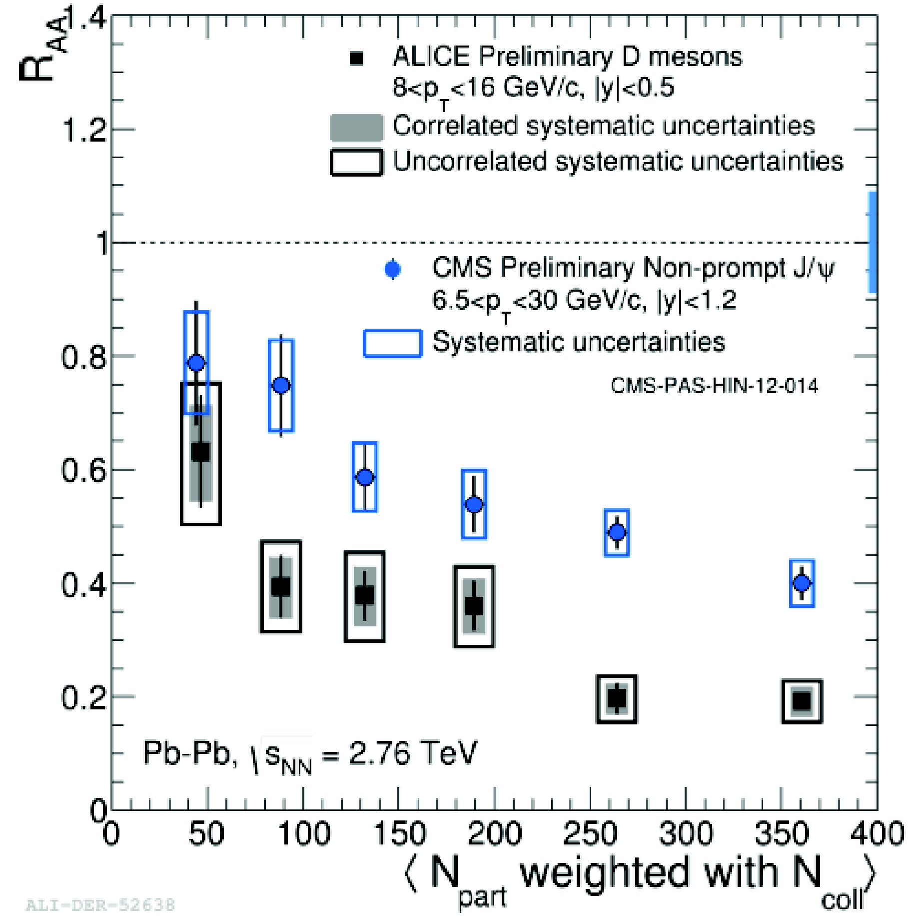


- For pT > 8 GeV/c pion, kaon , proton are equally suppressed within uncertainties
  - ➔ Particle composition at high pT not affected by the medium

- Expectation from radiative energy loss: $\mathbf{\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b}$
- Could be reflected in hierarchy of R_{AA}: $\mathbf{R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)}$



$R_{AA}(D) \sim R_{AA}(\pi)$



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

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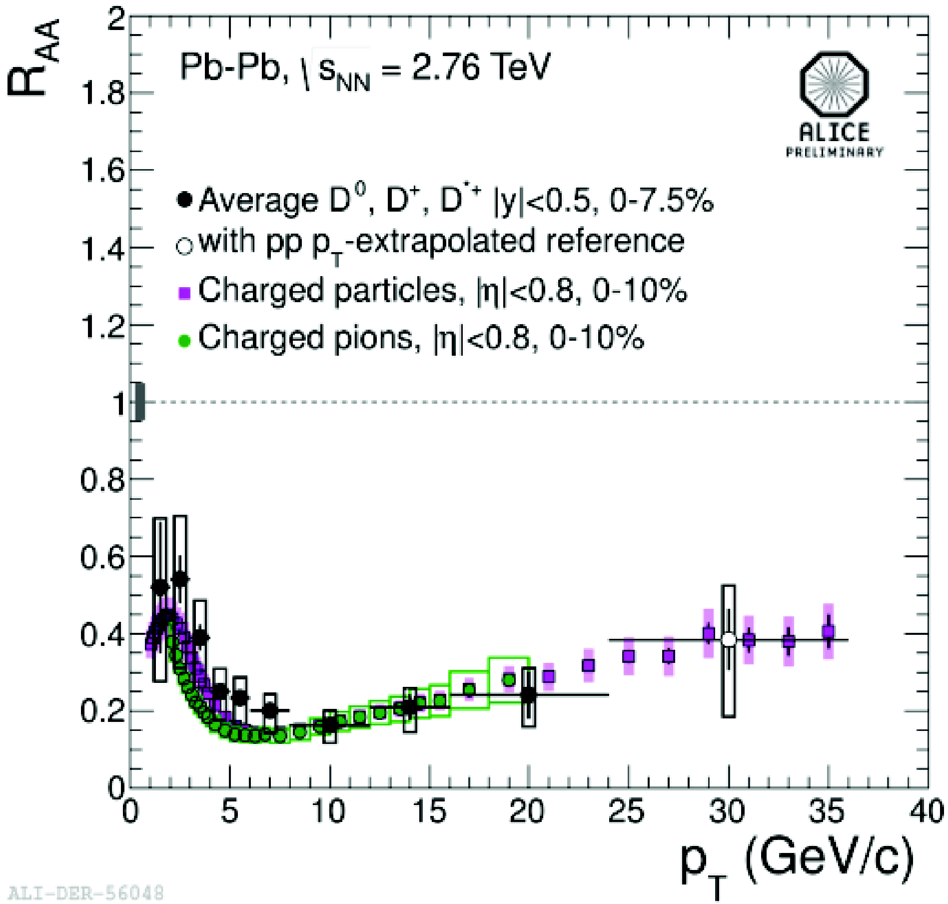

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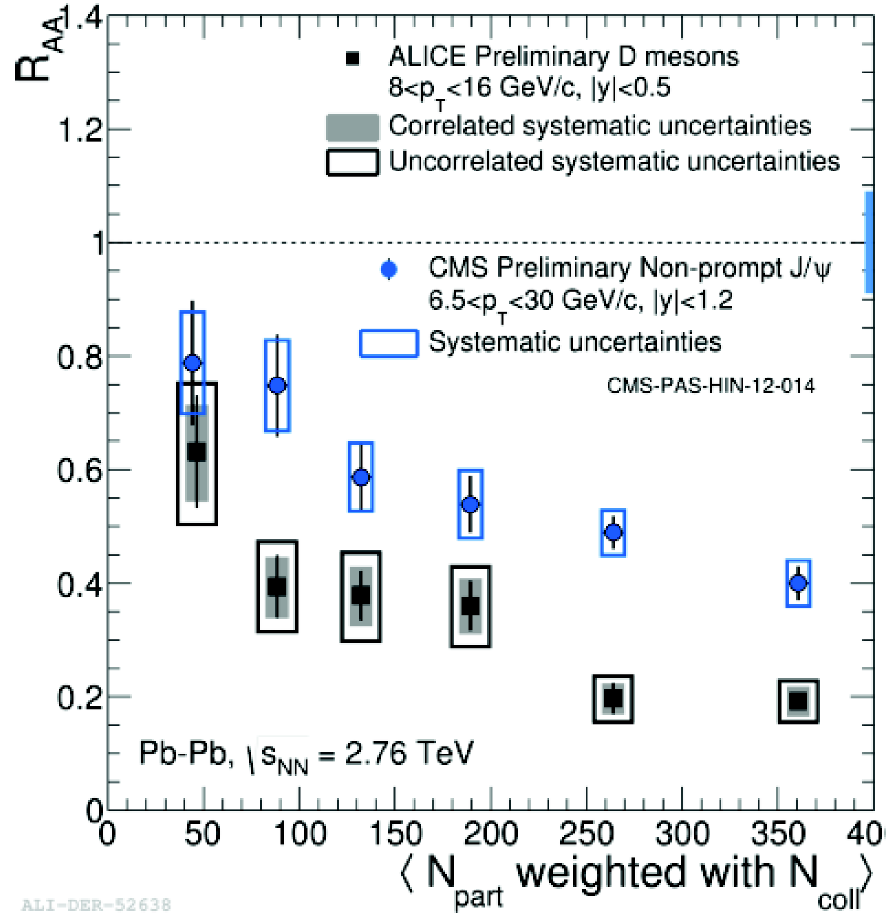
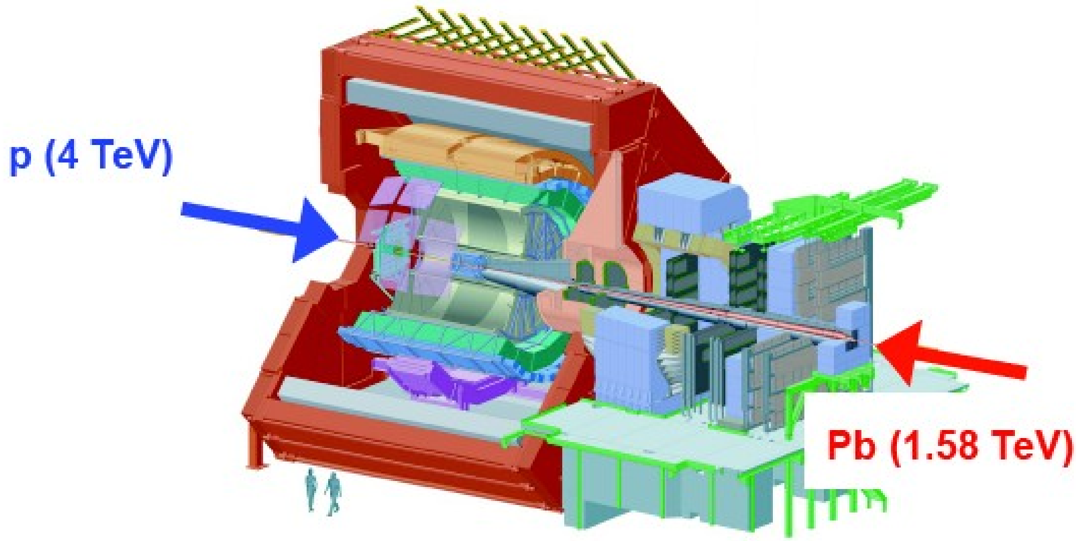
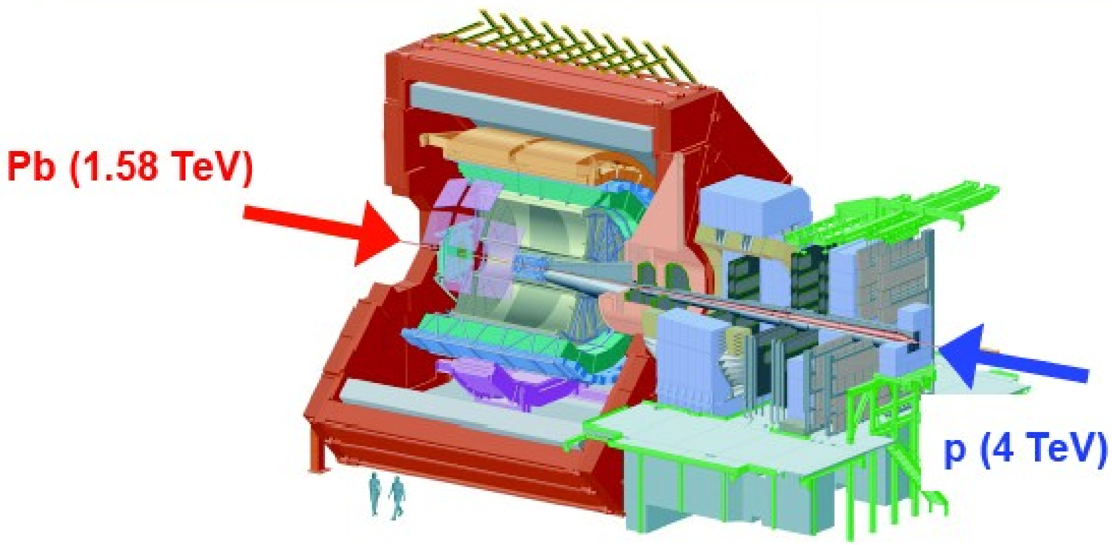


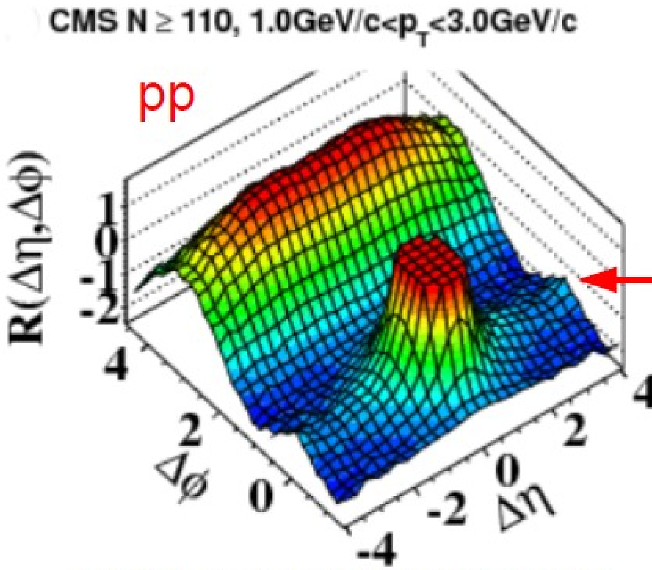
$R_{AA}(B) > R_{AA}(D)$

p-Pb: control sample



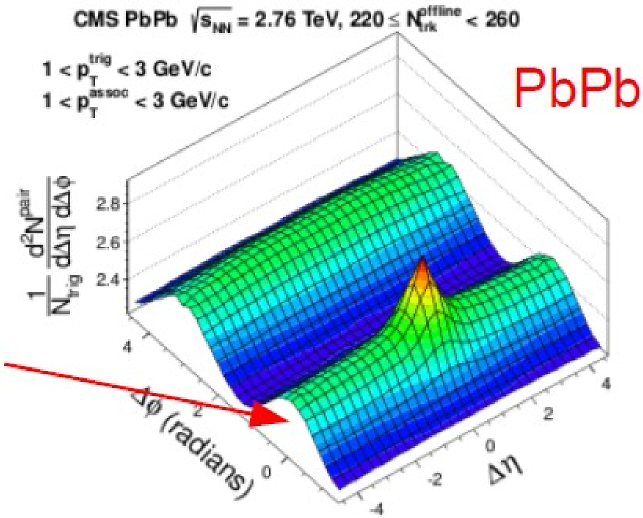
y_{CM} = 0.465 in the p-beam direction



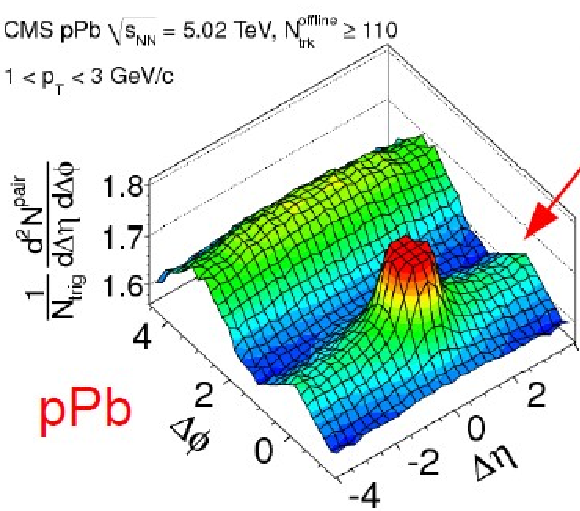


CMS, JHEP 1009 (2010) 91

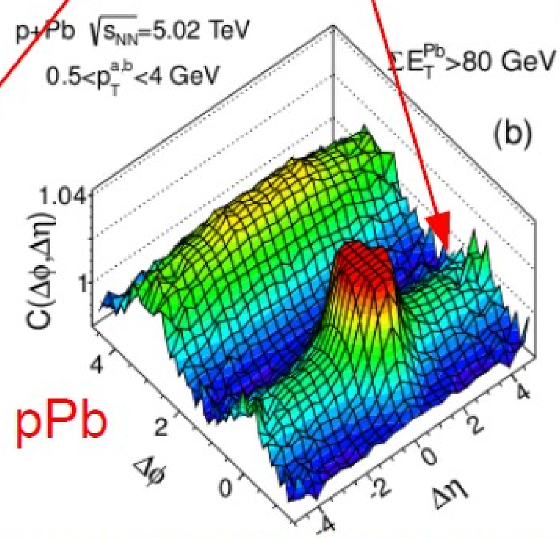
Near-side ridges apparent in high multiplicity events at LHC energies



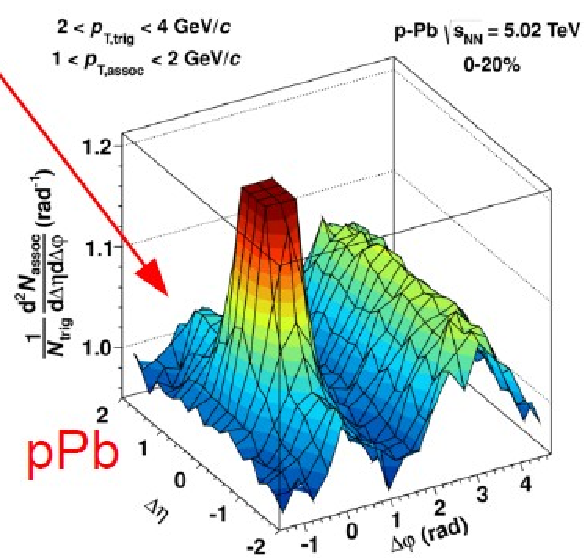
CMS, PLB 724 (2013) 213



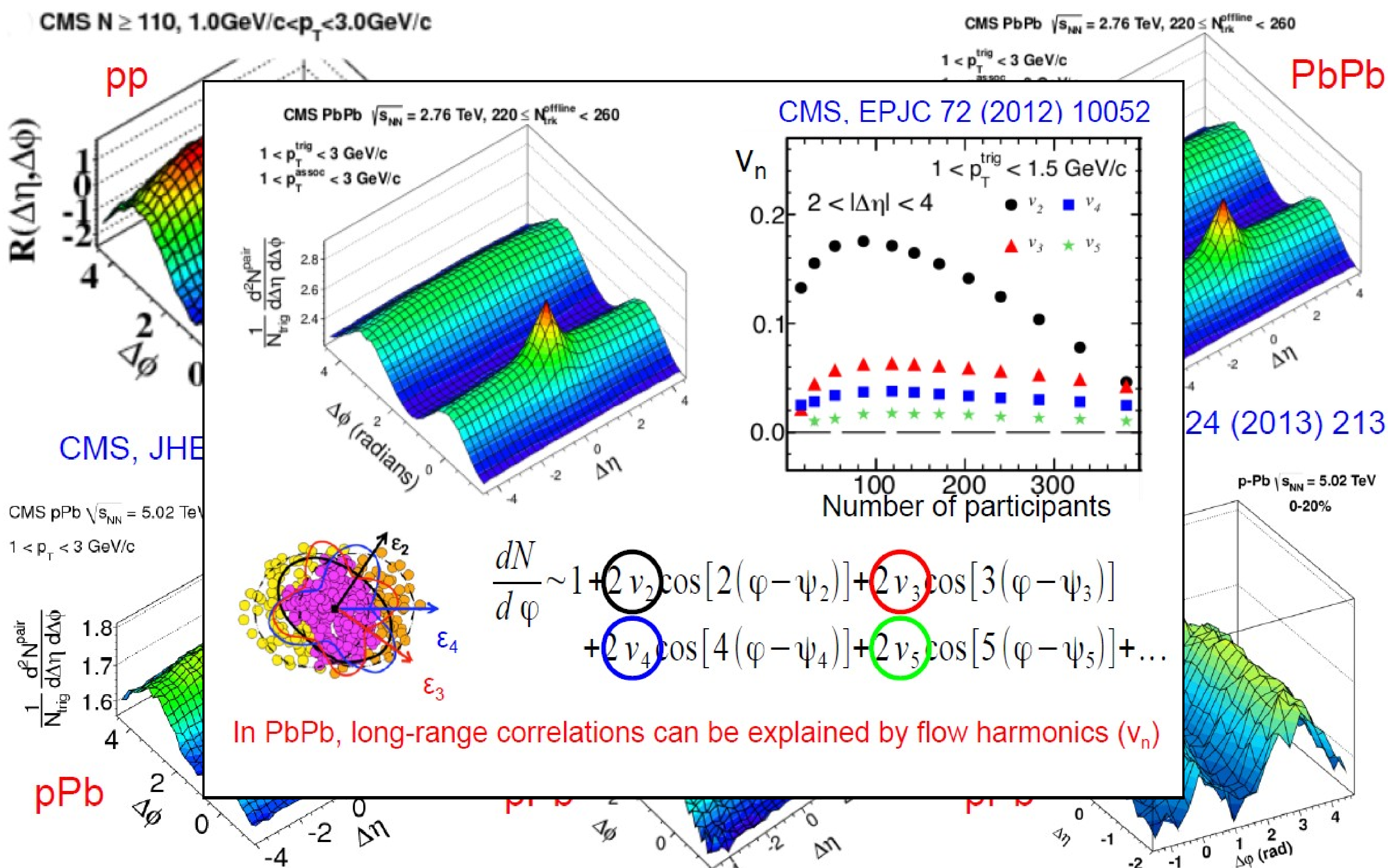
CMS, PLB 718 (2012) 795



ATLAS, PRL 110 (2013) 182302



ALICE, PLB 719 (2013) 29

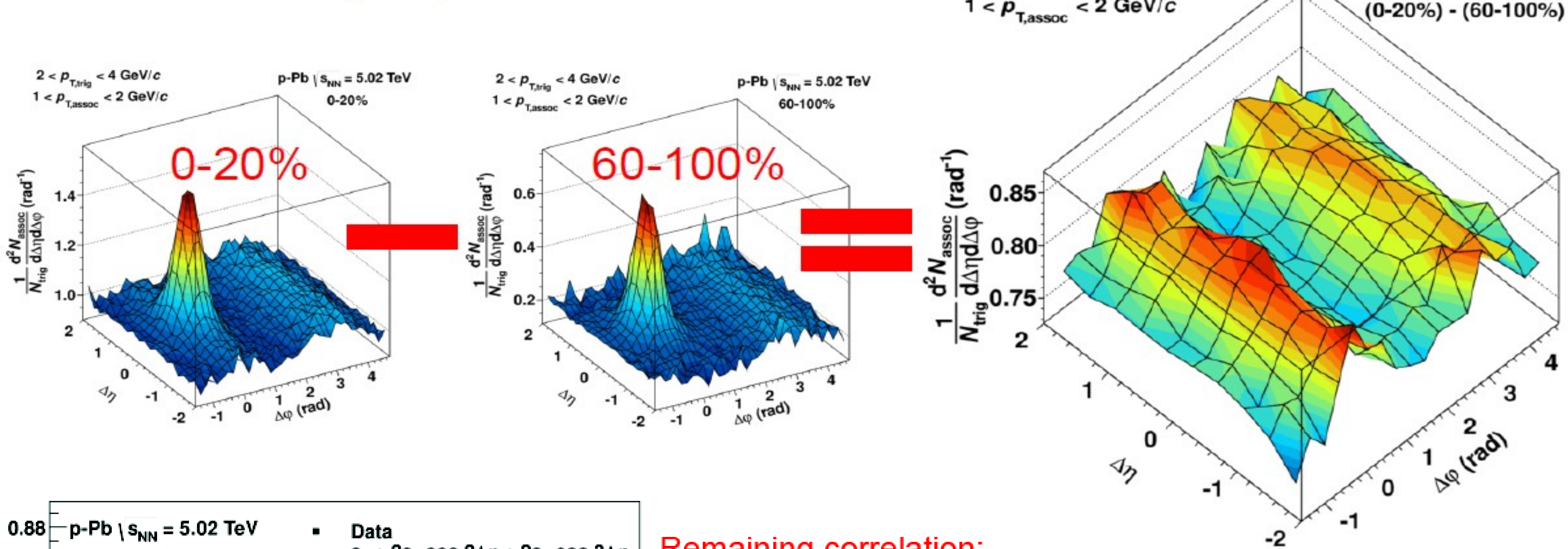


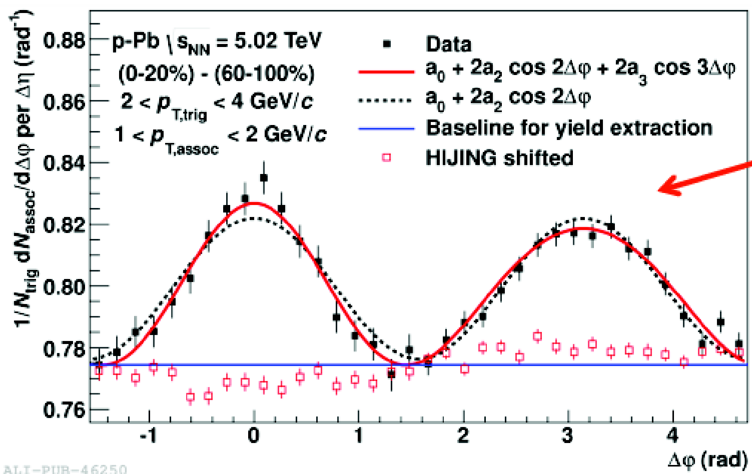
$$\frac{dN}{d\varphi} \sim 1 + 2v_2 \cos[2(\varphi-\psi_2)] + 2v_3 \cos[3(\varphi-\psi_3)] + 2v_4 \cos[4(\varphi-\psi_4)] + 2v_5 \cos[5(\varphi-\psi_5)] + \ldots$$

In PbPb, long-range correlations can be explained by flow harmonics (v_n)

CMS, PLB 718 (2012) 795 ATLAS, PRL 110 (2013) 182302 ALICE, PLB 719 (2013) 29

ALICE, PLB 719 (2013) 29





Remaining correlation: two twin long-range structures (**double ridge**)

- The near-side ridge is accompanied by an almost identical ridge structure on the away-side.
- Sizable values for v2 reached for high-multiplicity events
- Results qualitatively consistent with viscous hydrodynamic calculations

Backup

Grand Canonical Ensemble

Quantum Statistics:

[Thermodynamics & Statistical Physics]

Partition function
for fermions/bosons

describes system
in equilibrium

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int p^2 dp \ln\left(1 \pm e^{-\frac{E_i - \mu_i}{T}}\right)$$

with $\mu_i = \mu_b B_i + \mu_S S_i + \mu_{I_3} I_{3,i}$

Each conserved quantum number
has chemical potential μ:

B_i : Baryon Number
S_i : Strangeness
$I_{3,i}$: Charge (only 3 quarks)

→

conservation
laws

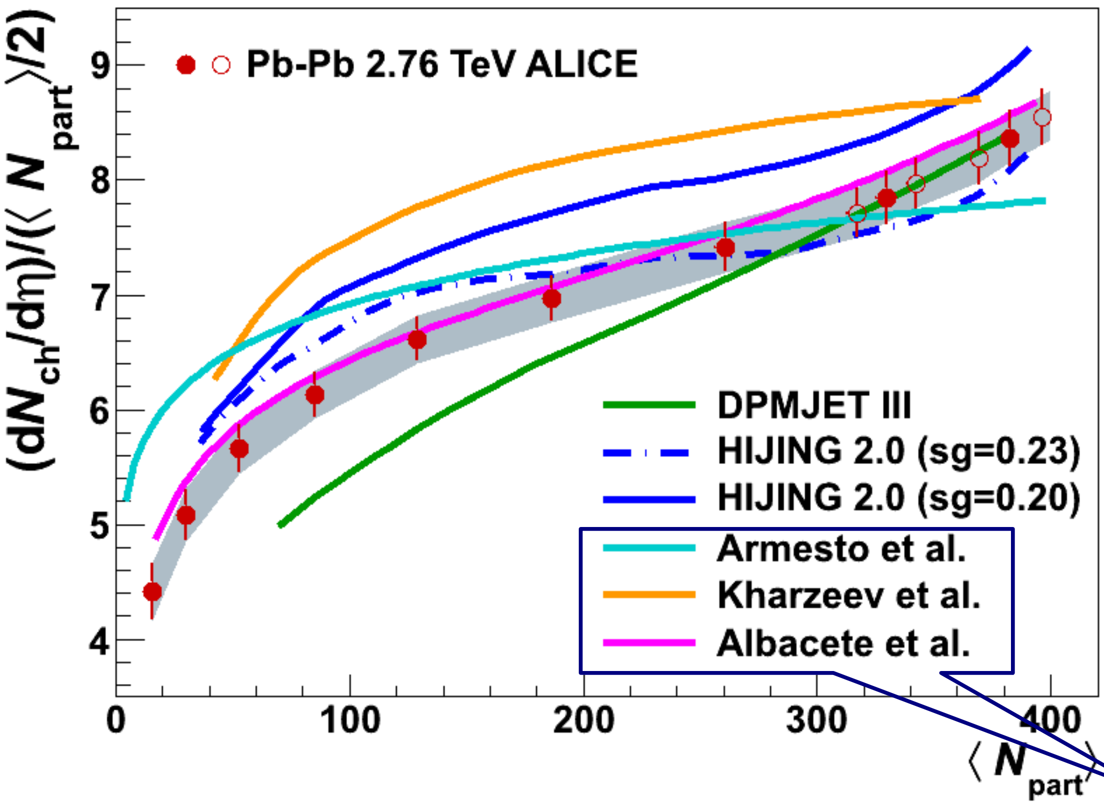
$$\left[\begin{array}{lll} V \sum_i n_i B_i = Z + N & \rightarrow & V \\ V \sum_i n_i S_i = 0 & \rightarrow & \mu_S \\ V \sum_i n_i I_{3,i} = \frac{1}{2}(Z - N) & \rightarrow & \mu_{I_3} \end{array}\right.$$

number
density

$$n_i = N_i / V = -\frac{T}{V}\frac{\partial ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int \frac{p^2 dp}{e^{\frac{E_i - \mu_i}{T}} \pm 1}$$

→ particle multiplicities yield T and μ_B !

ALICE Collab., PRL 106, 032301(2011)



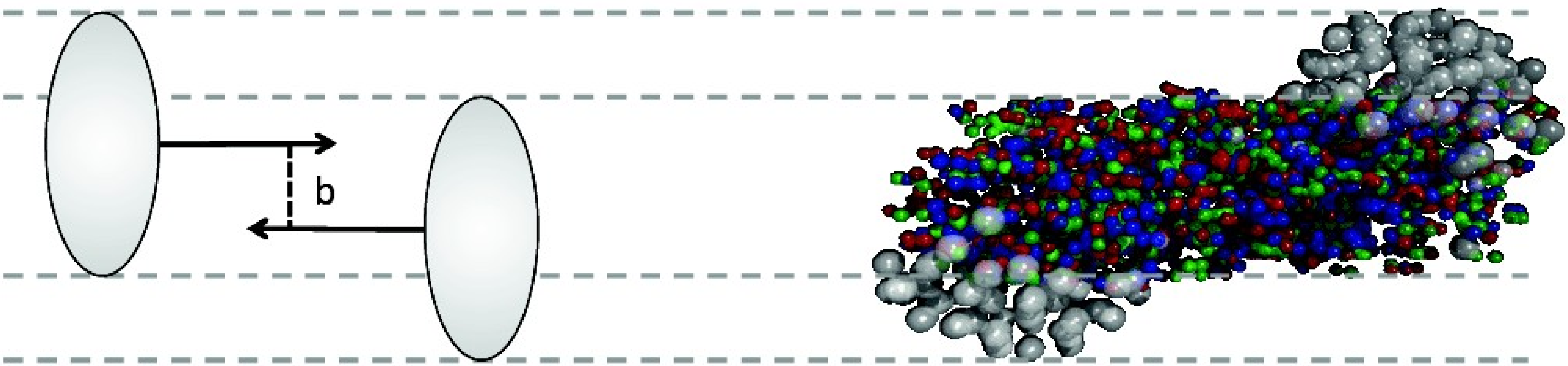
- **Two-component models** (DPMJET, HIJING)
  - Soft ($\sim N_{part}$) and hard ($\sim N_{coll}$) components
  - **DPMJET** (2-component + string fusion) – stronger rise than the data
  - **HIJING** (no quenching) – strong centrality dependent gluon shadowing
- **Saturation models**
  - parametrisation of the parton saturation scale with energy and centrality

Most models reproduce some of the data but not all.

Saturation models favoured by the data.

Centrality

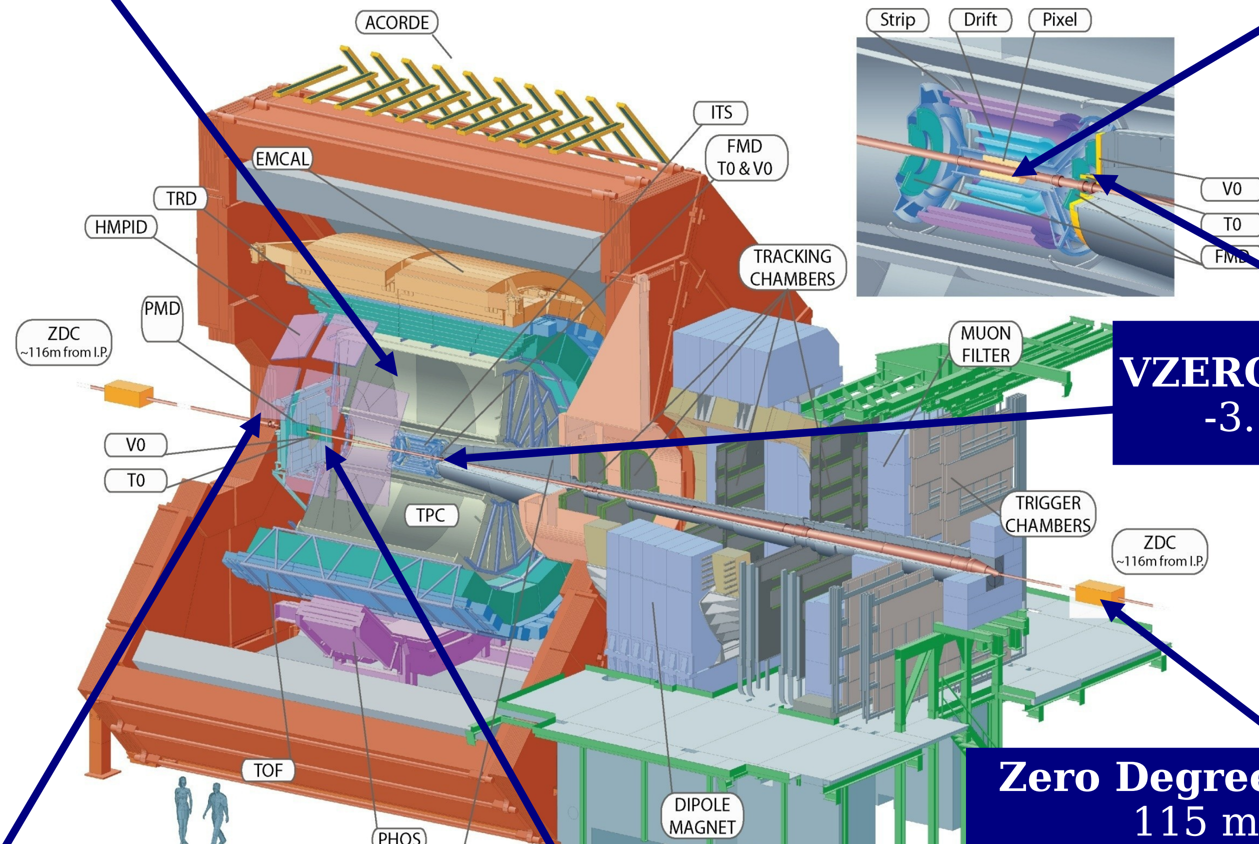
- Multiplicity - fundamental “day-1” observable:
  - Density of the system
  - Constraints on models
  - Background for hard-probe signals
- Centrality
  - Geometry of the collision. Essential to the study of any physics observable in A-A
- Multiplicity vs centrality - sensitive to the soft and hard nature of the particle production
  - Soft: N ~ N



The ALICE detector

Time Projection Chamber
$|\eta| < 0.9$

Silicon Pixel Detector
Layer 1: $|\eta| < 2$
Layer 2: $|\eta| < 1.4$



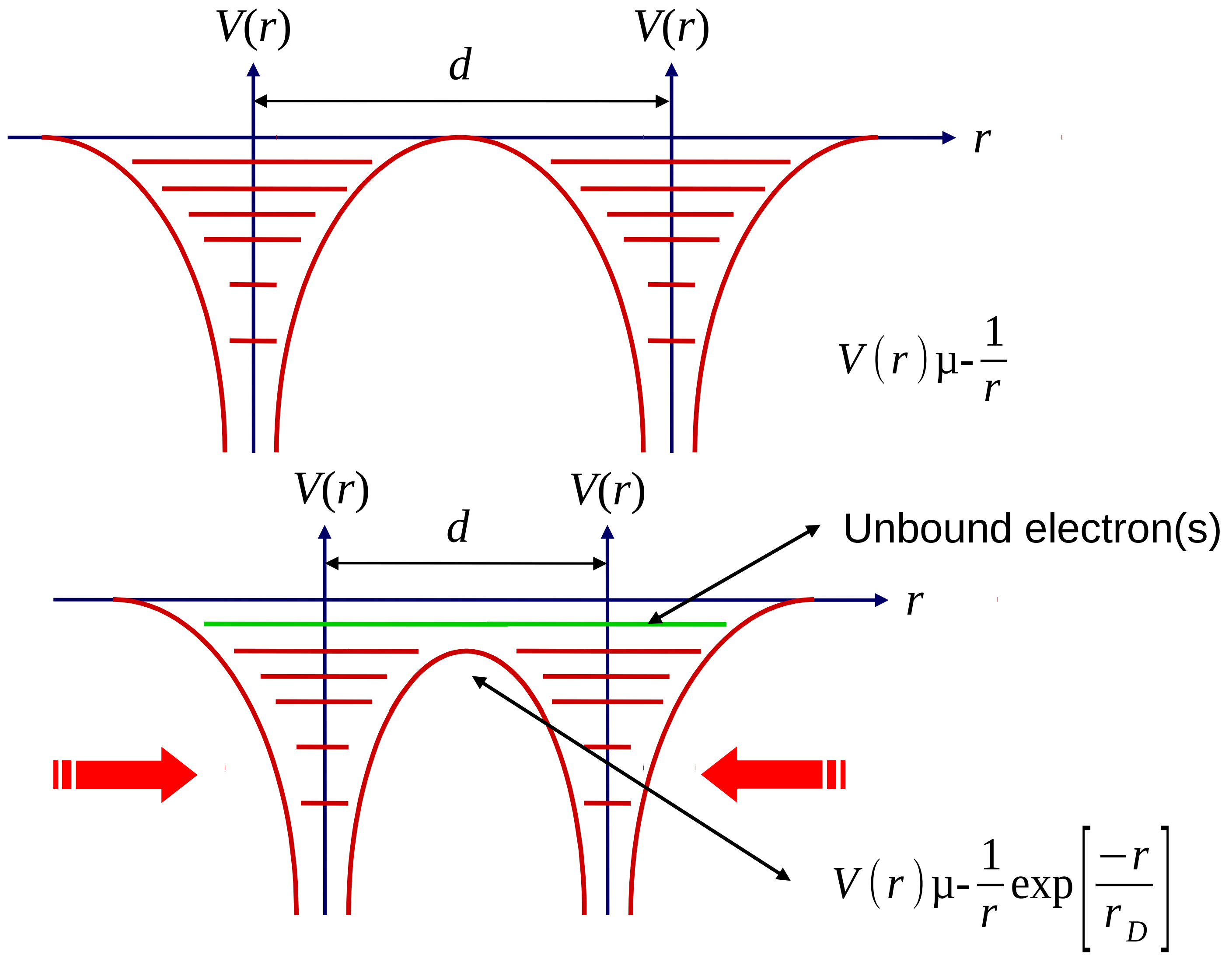
VZERO C scintillator
$-3.7 < \eta < -1.7$

Zero Degree Calorimeter
115 m from IP
very forward

ZEM – EM calorimeter
$4.8 < \eta < 5.7$

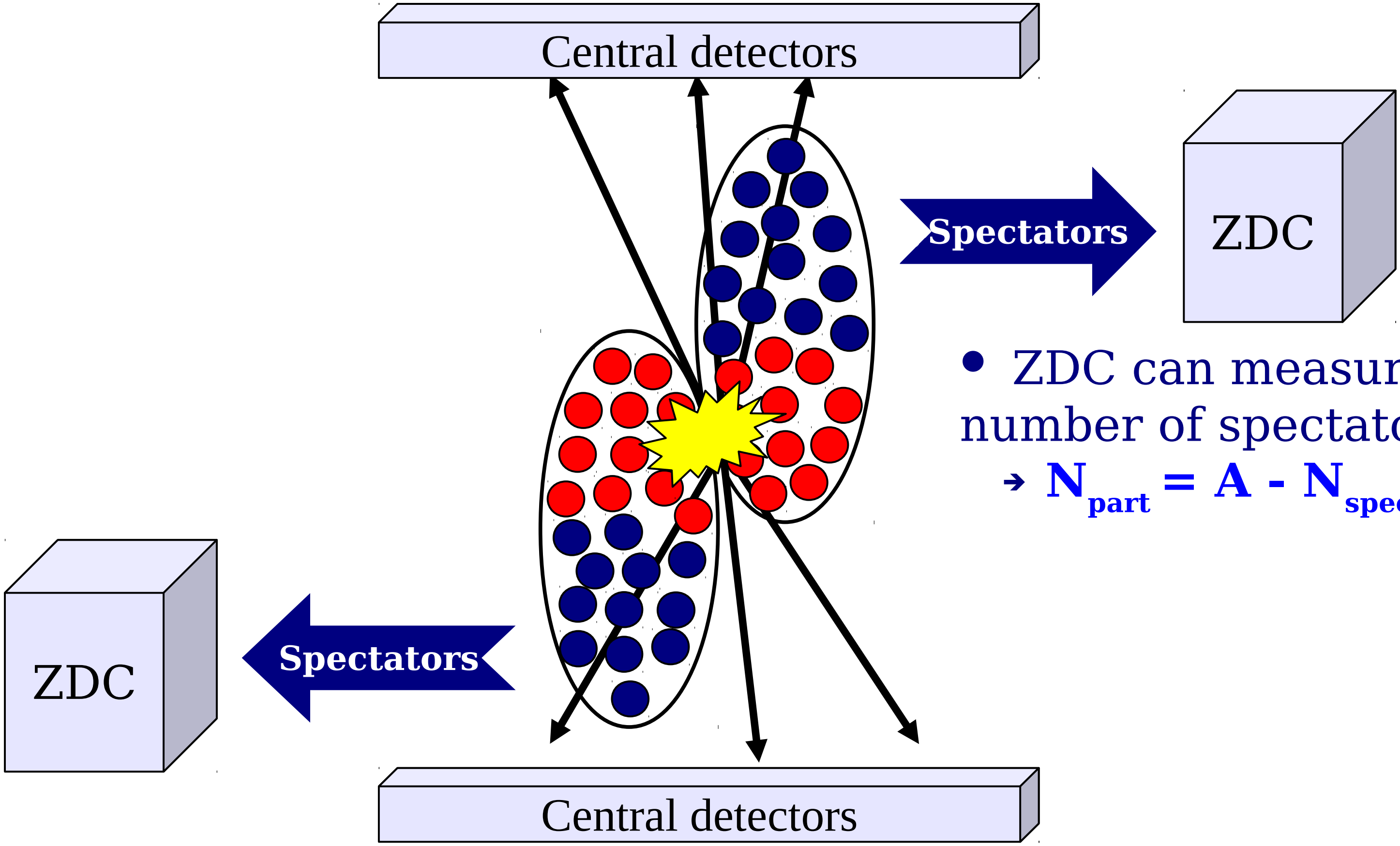
VZERO A scintillator
$2.8 < \eta < 5.1$

However, in the context of a QGP, it implies a medium of quarks and gluons where individual partons can move freely over distances larger than the typical size of hadronic states.



Centrality

- The number of participating nucleons N_{part} is determined by the collision geometry (*impact parameter*)
- Particle multiplicity and transverse energy scales with N_{part}



- ZDC can measure the number of spectators:
  - → $\mathbf{N_{part} = A - N_{spec}}$

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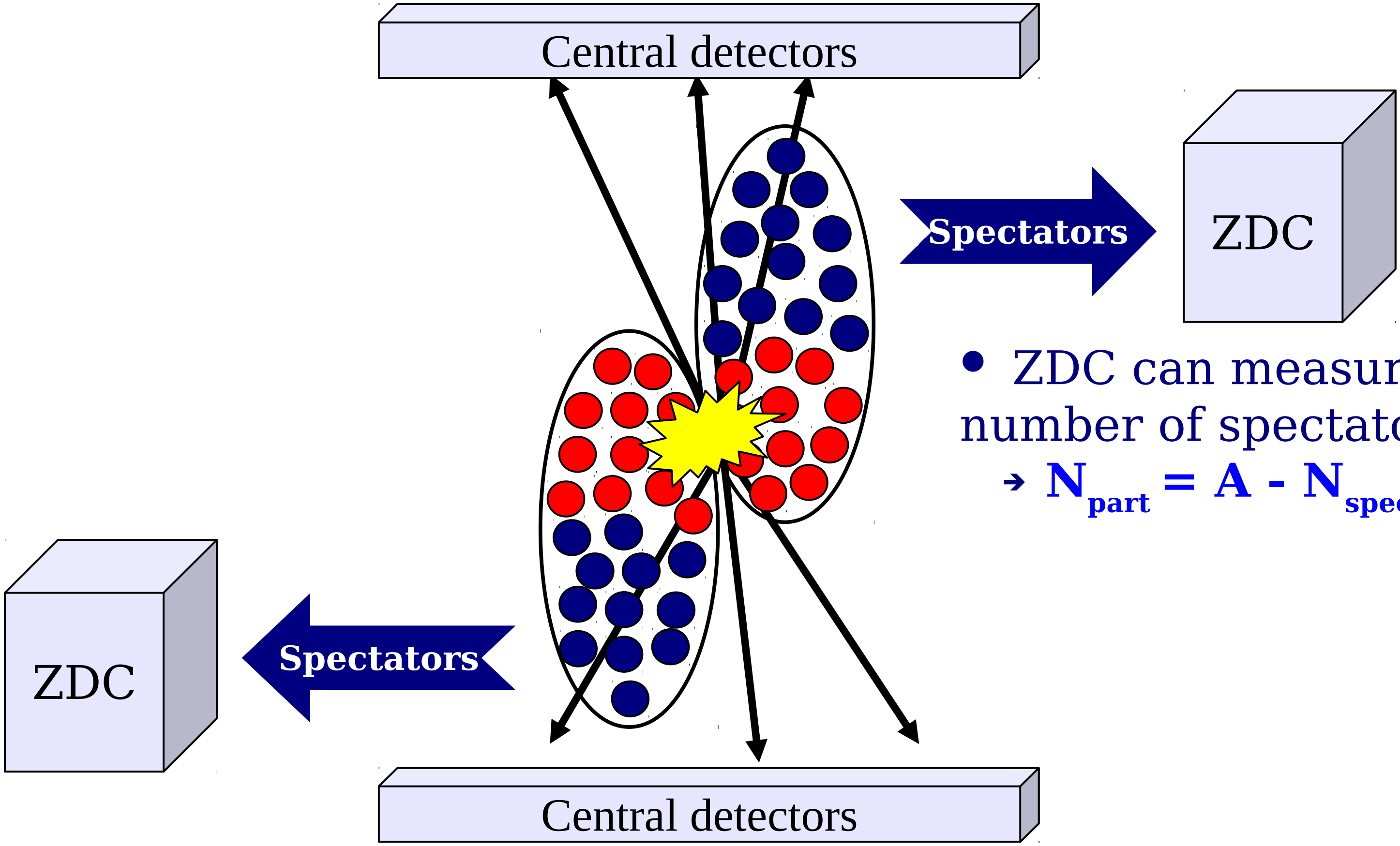


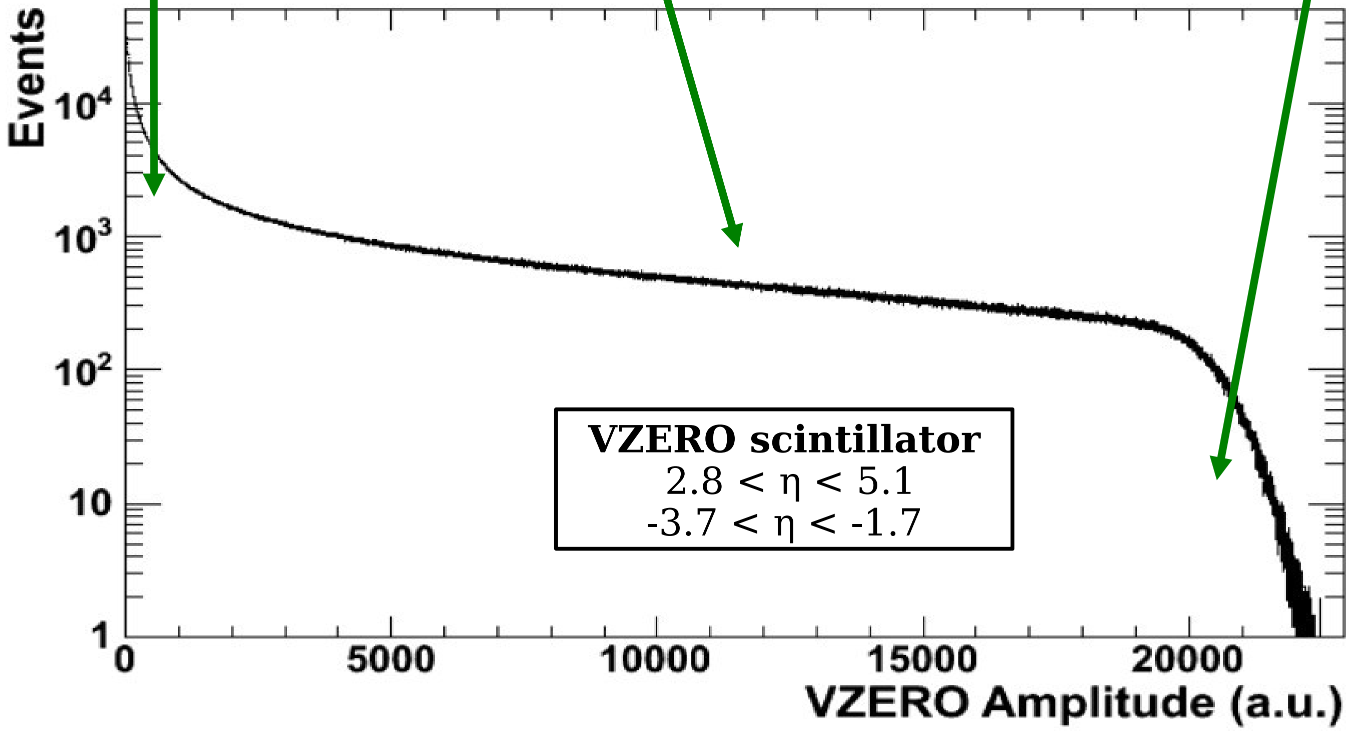
- ZDC can measure the number of spectators:
  - ➔ $\mathbf{N_{part} = A - N_{spec}}$

Example VZERO amplitude distribution

- **Peak:**
  - Most peripheral events
  - Trigger inefficiency
  - Strong EM background

- **Plateau:**
  - Mid-central collisions

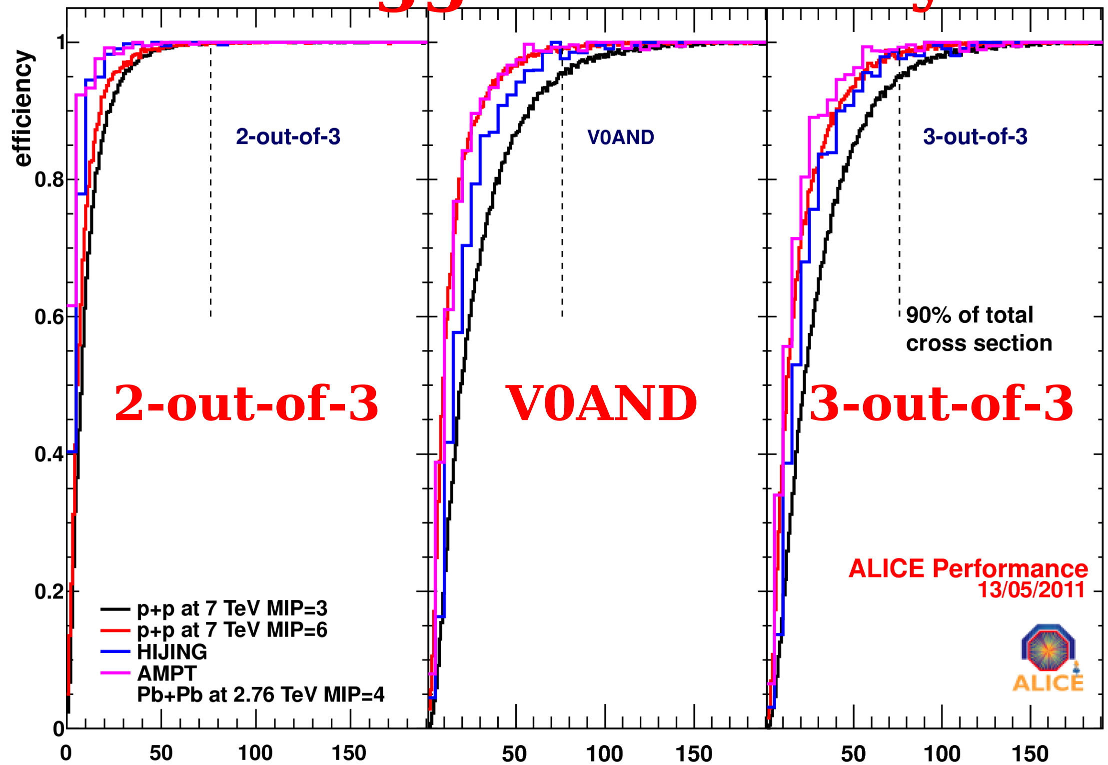
- **Edge:**
  - Most central collisions
  - The shape is a consequence of intrinsic fluctuations and detector acceptance and resolution



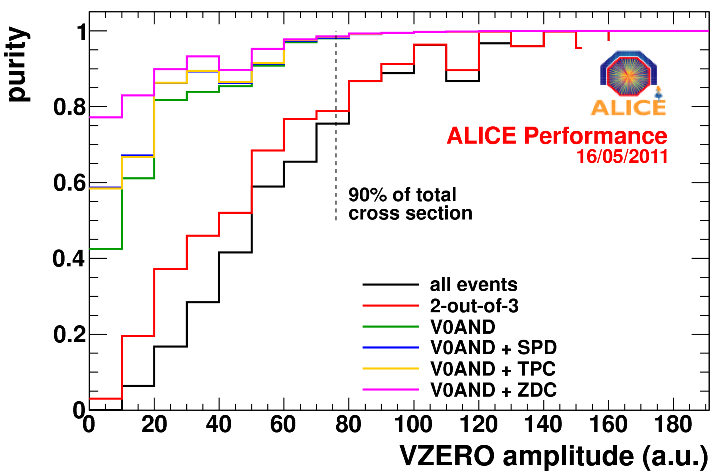
Trigger and background

- Min bias triggering: coincidence of
  - ➔ **SPD** (≥ 2 pixel hits)
  - ➔ **VZERO** (A side)
  - ➔ **VZERO** (C side)

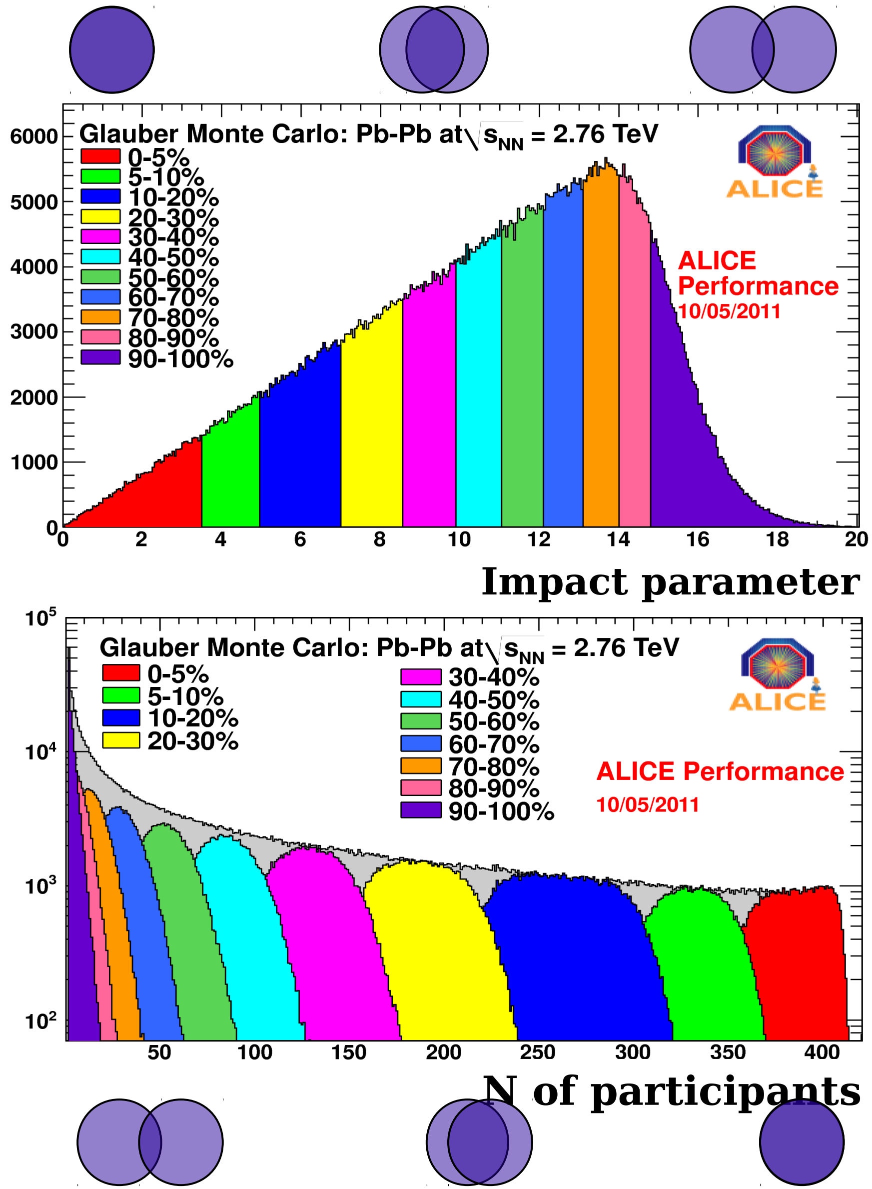
Trigger efficiency



VZERO Amplitude



- **Background: σ_{EM} large at the LHC**
  - ➔ e^+e^- pair production
  - ➔ EM dissociation
  - ➔ photo-nuclear reactions
  - ➔ Purity < 1 in the most peripheral region



- Centrality
  - Impact parameter
- Glauber model:
  - Geometrical picture of AA collision
  - Assume straight-line nucleon trajectories
  - N-N cross-section (next slide) independent of the number of collisions the nucleons have undergone
  - Woods-Saxon nuclear density profile

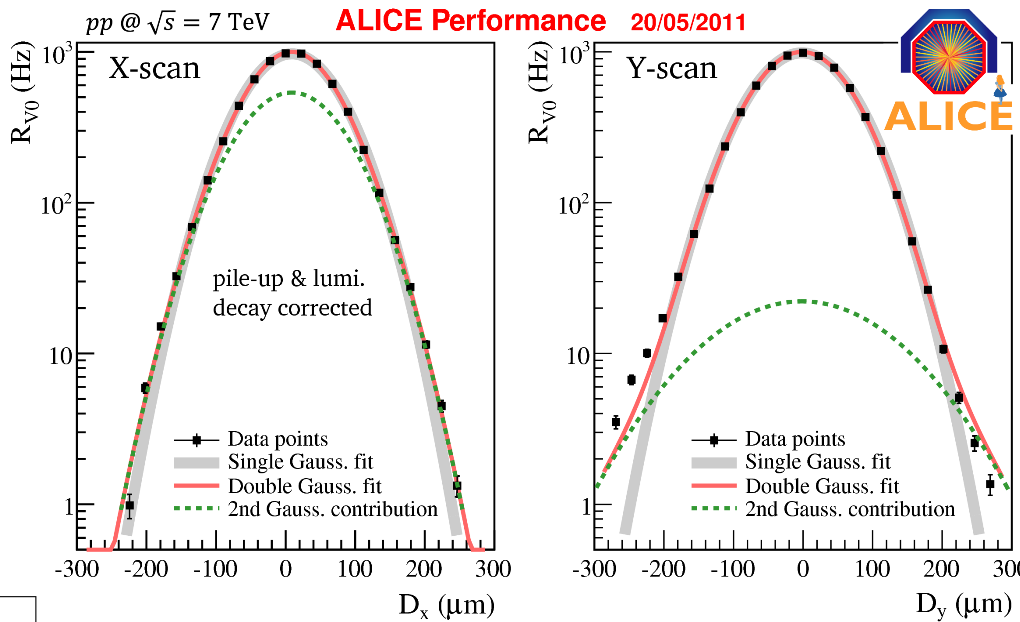
$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r - R}{a}\right)}$$

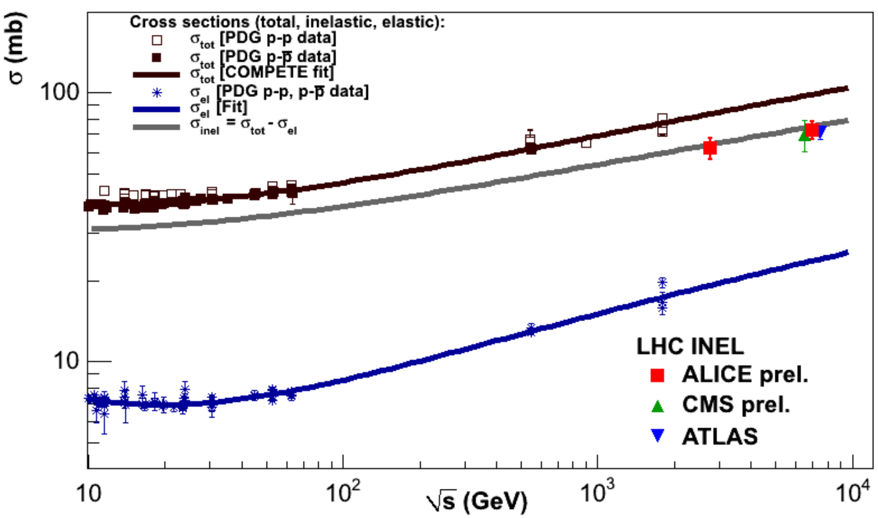
radius R = 6.62 ± 0.06 fm
skin depth a = 0.546 ± 0.010 fm
intra-nucleon distance = 0.4 ± 0.4 fm

pp cross-section

Details: [CERN-Proceedings-2011-001 (ISSN 2078-8835, ISBN 978-92-9083-361-1)]

- σ_{NN} measured in Van der Meer scans
  - ➔ 62.1 ± 1.6 ± 4.3 mb @ 2.76 TeV



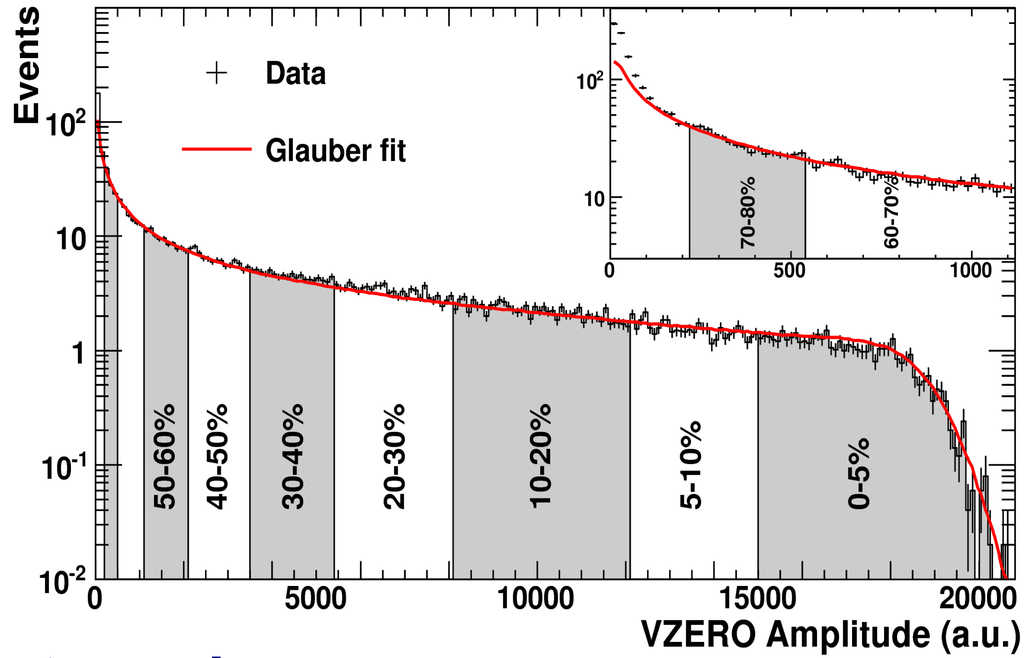


- Extrapolation to σ_{INEL}
  - ➔ 64 ± 5 mb

σ_{INEL} pp @ 7 TeV
ALICE: 72.7 ± 1.1 ± 5.1 mb
ATLAS: 69.4 ± 2.4 ± 6.9 mb (arXiv:1104.0326)
CMS: 70.4 ± 1.1 ± 3.5 mb (M.Marone, DIS'11)
σ_{INEL} pp @ 2.76 TeV:
ALICE: 62.1 ± 1.6 ± 4.3 mb

Centrality definition

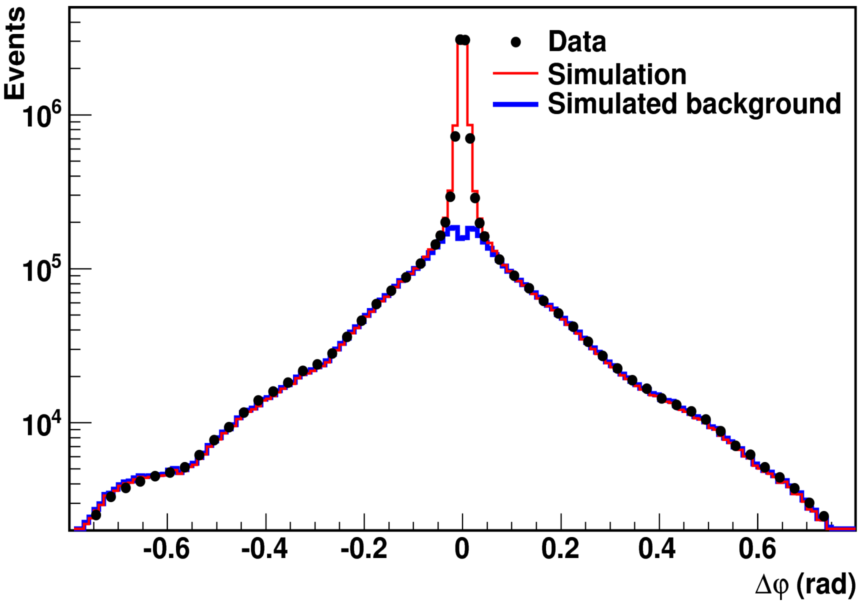
ALICE Collab., PRL 106, 032301(2011)



- Glauber fit to find anchor point
- Number of ancestors given by:
  $fN_{part} + (1-f)N_{coll}$
- Particle production per ancestor according to Negative binomial distribution **NBD(μ,k)**
- Fit Glauber multiplicity to experimental one
  - fit restricted to ~88% of the cross-section (above VZERO = 100)
  - 100% trigger efficiency
  - Negligible background
- **$\langle N_{part} \rangle$** from Glauber fits agree with the geometrical values better than 1% except for 70-80% where the difference is 3.5%

Multiplicity measurement

- Based on SPD tracklets:
  - tracklet – pair of hits, one on each SPD layer
  - $dN_{ch}/d\eta=\alpha(1-\beta)dN_{tracklets}/d\eta$
  - **α:** acceptance and efficiency
    dominated by acceptance
    little variation with centrality

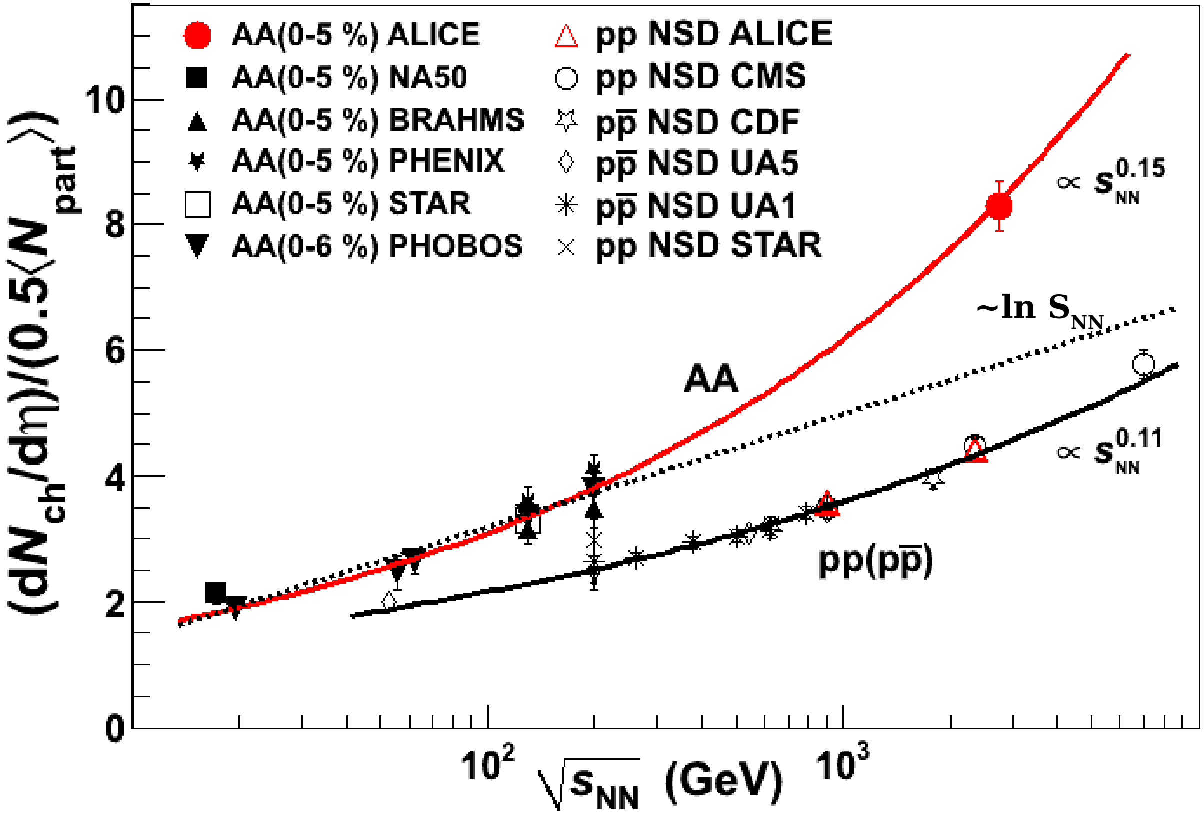


ALICE Collab., PRL 105, 252301 (2010)

Sources of error	Relative uncertainty
Background subtraction	0.1% to 2.0%
Particle composition	1.0%
Contamination of weak decays	1.0%
Zero-p_t extrapolation	2.0%
Event generator	2.0%
Centrality	6.2% to 0.4%
Tracklet + vertex cuts	negl.
Material budget	negl.
Detector efficiency	negl.
Background events	negl.
Total	7.0% to 3.8%
Correlated	5.0% to 2.5%

- **β:** combinatorial background frac.
  varies from 1% in most peripheral to 14% in the most central

Multiplicity in central Pb-Pb @ 2.76 TeV

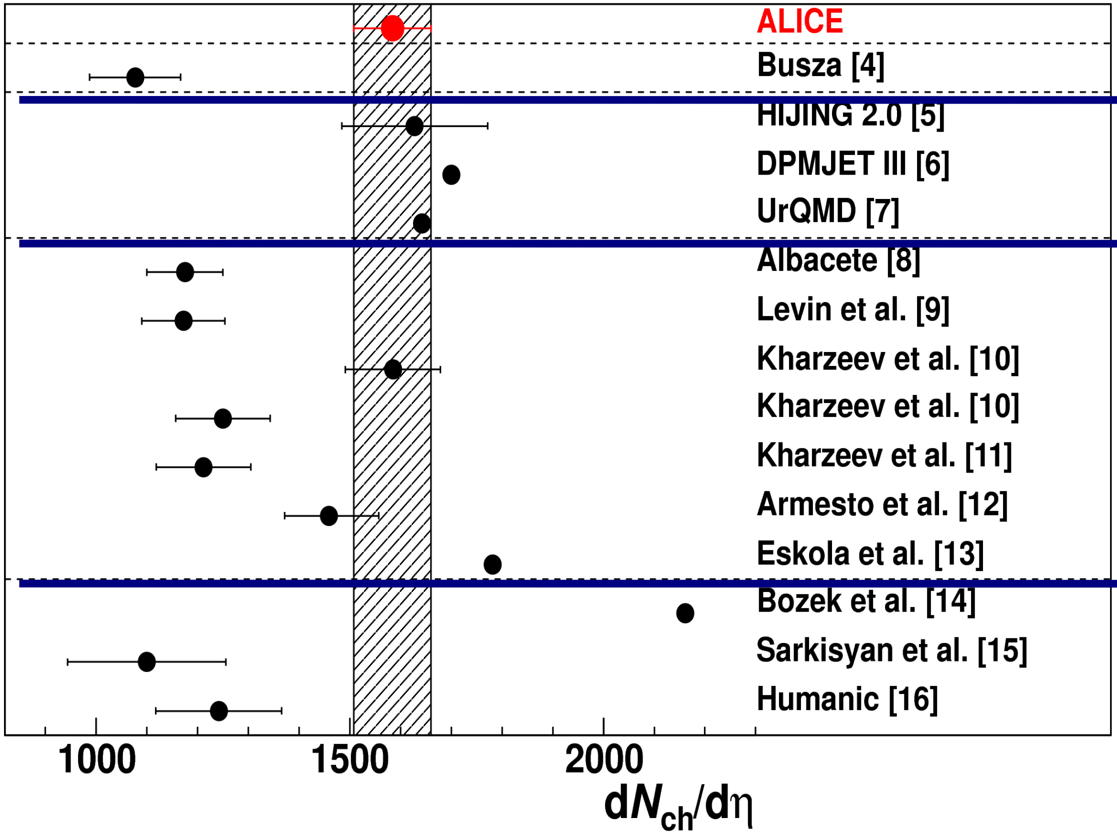


- **Pb-Pb @ 2.76 TeV, 0-5% central, |η|<0.5**
  - **$dN_{ch}/d\eta = 1584 \pm 76$**
  - **$2\ dN_{ch}/d\eta\ /\ N_{part} = 8.3 \pm 0.4$**

ALICE Collab., PRL 105, 252301 (2010)

- **1.9 x pp @ 2.36 TeV (NSD)**
- **2.1 x central Au-Au @ 0.2 TeV**
- **Growth with √s faster in AA than in pp**
- **Growth with power of CM energy faster than log scaling extrapolated from lower energies**

ALICE Collab.: dN/dη = 1584 ± 76   PRL 105, 252301 (2010)



data-driven, limiting frag.

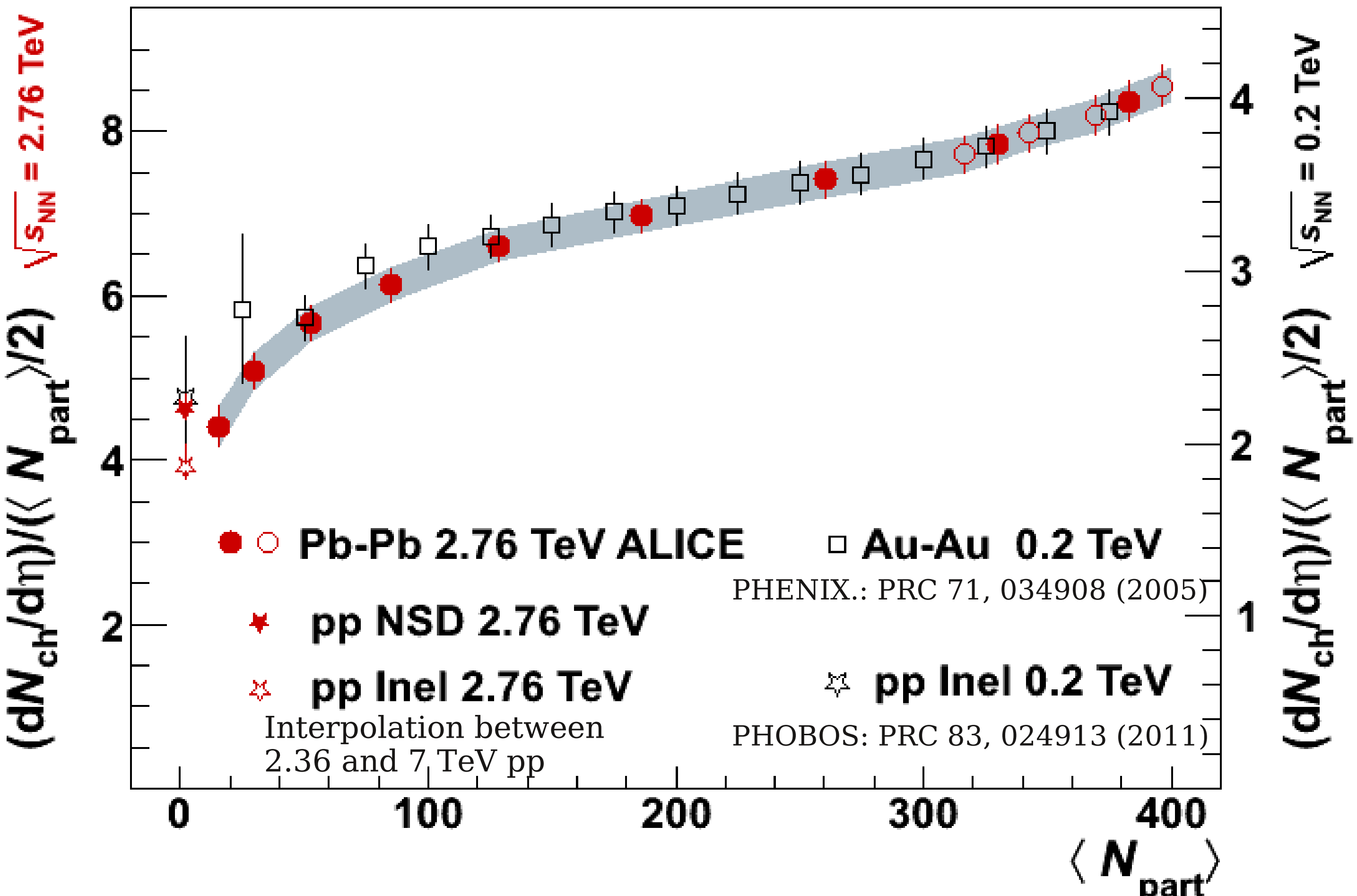
pQCD-inspired models

saturation models (different implementation)

hydro, tuned with pp data
Landau hydro
NN superposition & hadronic rescatering

Centrality dependence

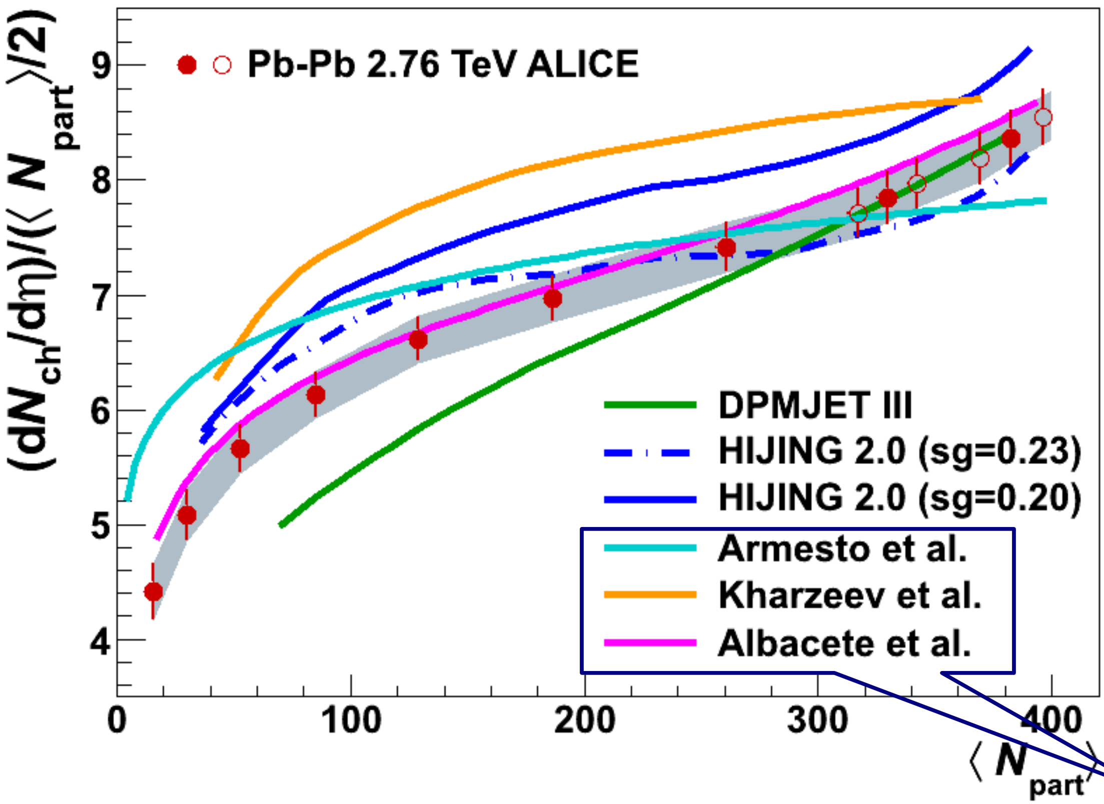
ALICE Collab., PRL 106, 032301(2011)



- **RHIC data scaled by 2.1**
- **Centrality evolution at LHC similar to RHIC (N_{part}>100)**

Centrality vs models

ALICE Collab., PRL 106, 032301(2011)



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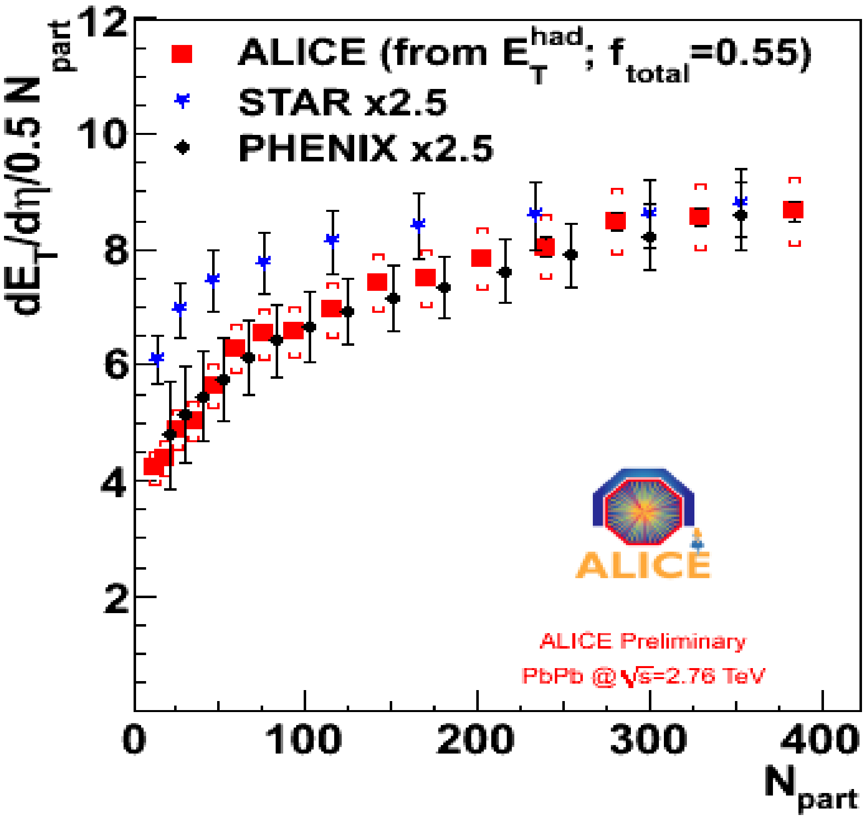
Transverse energy vs centrality



STAR Collab.: PRC70, 054907 (2004)
PHENIX Collab.: PRC71, 034908 (2005)

- E_t^{had} from charged hadrons measured by the barrel tracking detectors
- f~0.55 to convert to total energy
  - From MC – model dependent
- From RHIC to LHC
  - Similar centrality dependence
  - **~ 2.5 increase in $2dE_T/d\eta/N_{part}$**
- Energy density estimate (Bjorken)

$$\varepsilon = \frac{1}{\pi R^2 \tau} \frac{dE_t}{dy} \qquad R = 1.2A^{1/3} fm$$

  - $\tau\varepsilon_{LHC}$ ~ 15 GeV/(fm^{2}c)
  - $\tau\varepsilon_{RHIC}$ = 5.4 ± 0.6 GeV/(fm^{2}c)

$\tau\varepsilon_{LHC} \sim 2.7 \times \tau\varepsilon_{RHIC}$

Summary

- ALICE has measured the charged particle multiplicity of Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

- $dN_{ch}/d\eta$ per participant increased from RHIC to LHC by a factor of 2.1
  - Rise with collision energy is stronger than the *ln* extrapolation from lower energies
  - $\boldsymbol{\tau\varepsilon_{LHC} \sim 2.7 \times \tau\varepsilon_{RHIC}}$

- Centrality dependence similar to RHIC

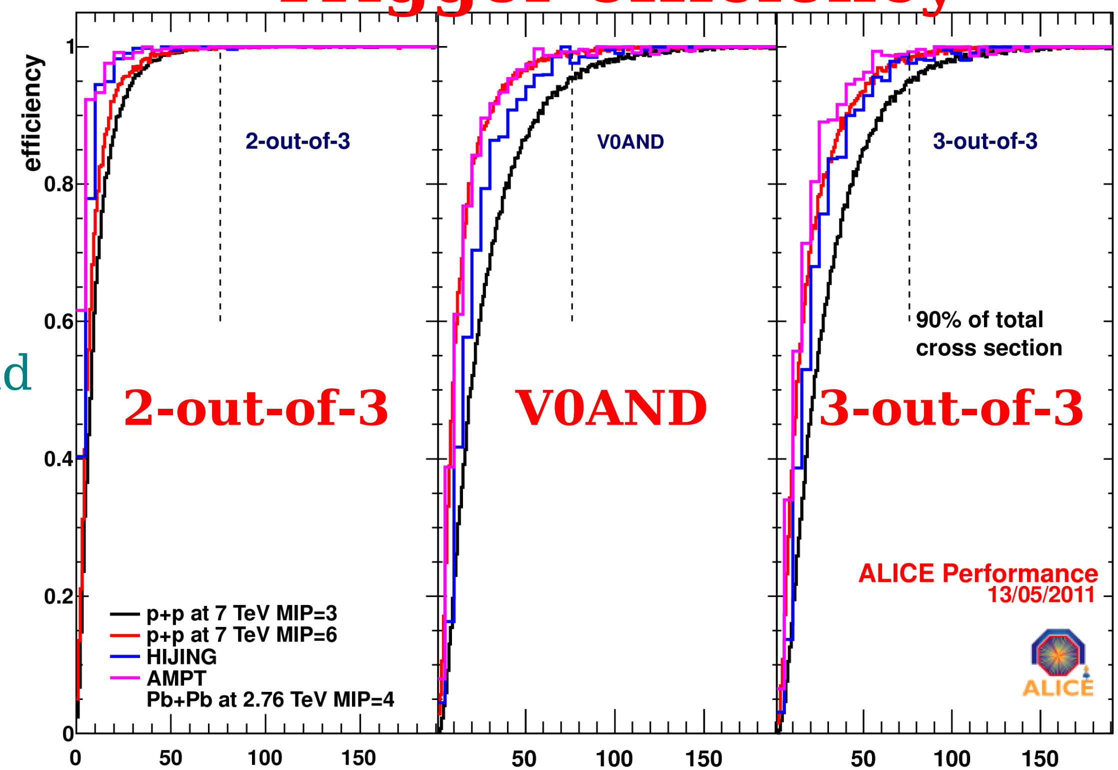
- Models have a hard time to describe the centrality dependence and predict the increase with $\sqrt{s}$

Backup

Trigger and event selection

- Triggering detectors:
  - ➔ **SPD** (≥ 2 pixel hits)
  - ➔ **VZERO** (A side)
  - ➔ **VZERO** (C side)
- Online triggers:
  - ➔ Coincidence of VZERO and SPD signals.
  - ➔ Definition tightened throughout the run
    - 2 out of 3
    - V0 AND
    - 3 out of 3

Trigger efficiency

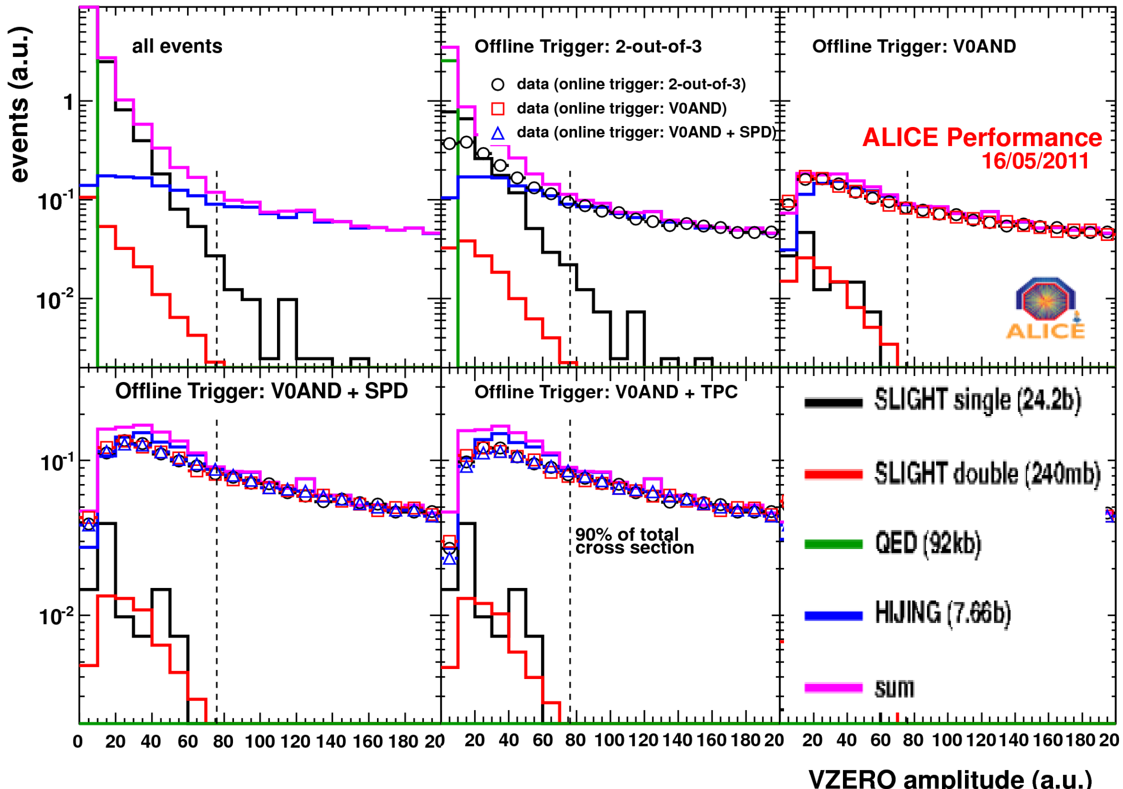


VZERO Amplitude

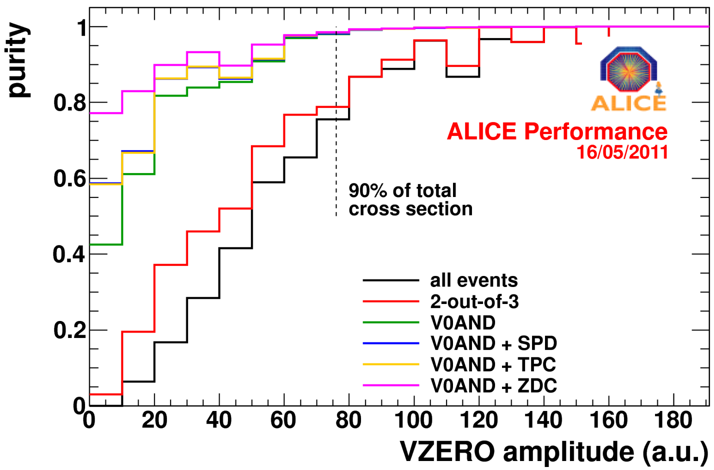
- Offline triggers and vertex cut:
  - ➔ VZERO A and C timing coincidence to remove beam gas background
  - ➔ ZDC timing coincidence to remove debunching
  - ➔ $|z_{SPD}| < 7$ cm around the center of the interaction region

- e^+e^- pair production (QED)
  - Very soft
  - O(100 kbarn)
- EM dissociation
  - One or several neutrons in ZDC
  - No central particles
  - O(100 barn)

cross-sections



purity

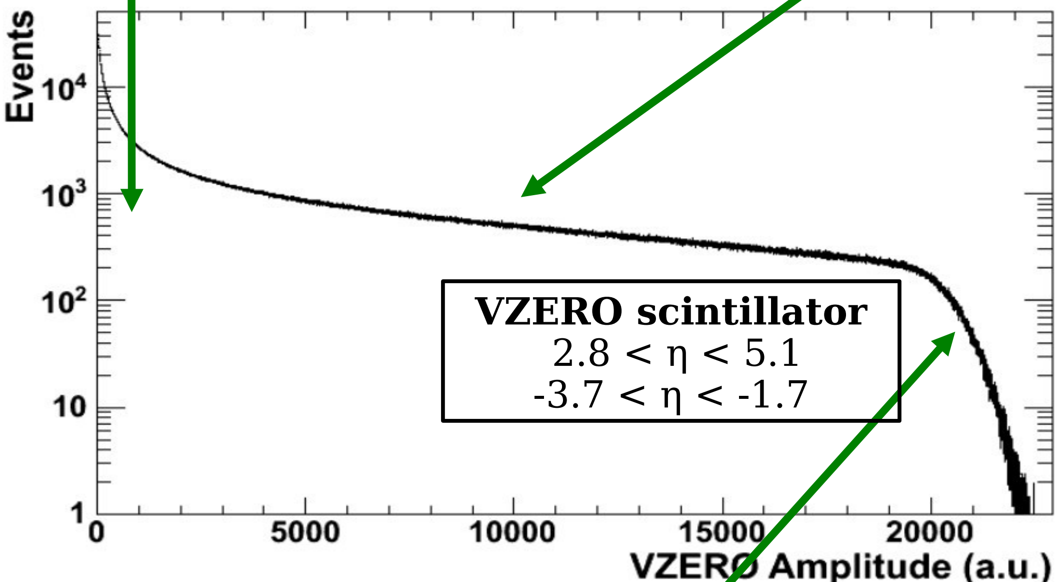


- Photo-nuclear reactions
  - Kinematics similar to pA
  - $E_\gamma \sim 100$ GeV
  - O(10 barn)

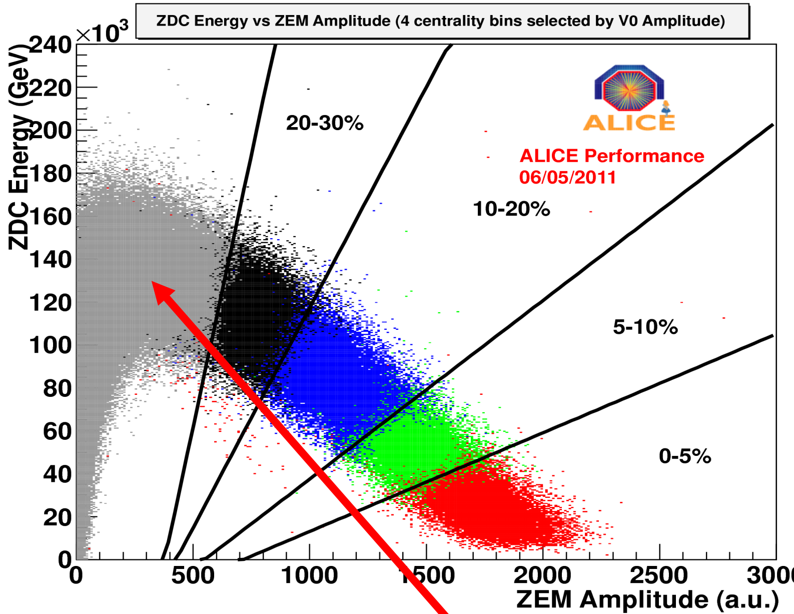
Example VZERO and ZDC distribution

- **Peak:**
  - Most peripheral events
  - Trigger inefficiency
  - Strong EM background

- **Plateau:**
  - Mid-central collisions



- **Edge:**
  - Most central collisions
  - The shape is a consequence of intrinsic fluctuations and detector acceptance and resolution



- **ZDC energy correlated to ZEM:**
  - nuclear fragmentation breaks relation in the measured variables
  - correlate with another detector (ZEM)

Negative binomial

The negative binomial is a probability distribution of the number of trials which are necessary to get a number of successes.

$P(n,\mu,k) = \Gamma(n+k)/(\Gamma(k)n!)\ (\mu/k)^{n}/(1+\mu/k)^{n+k}$

where k is related to the width of the distribution σ like:

$(\sigma/\mu)^2 = 1/k + 1/\mu$