Particle Production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV measured by the ALICE experiment

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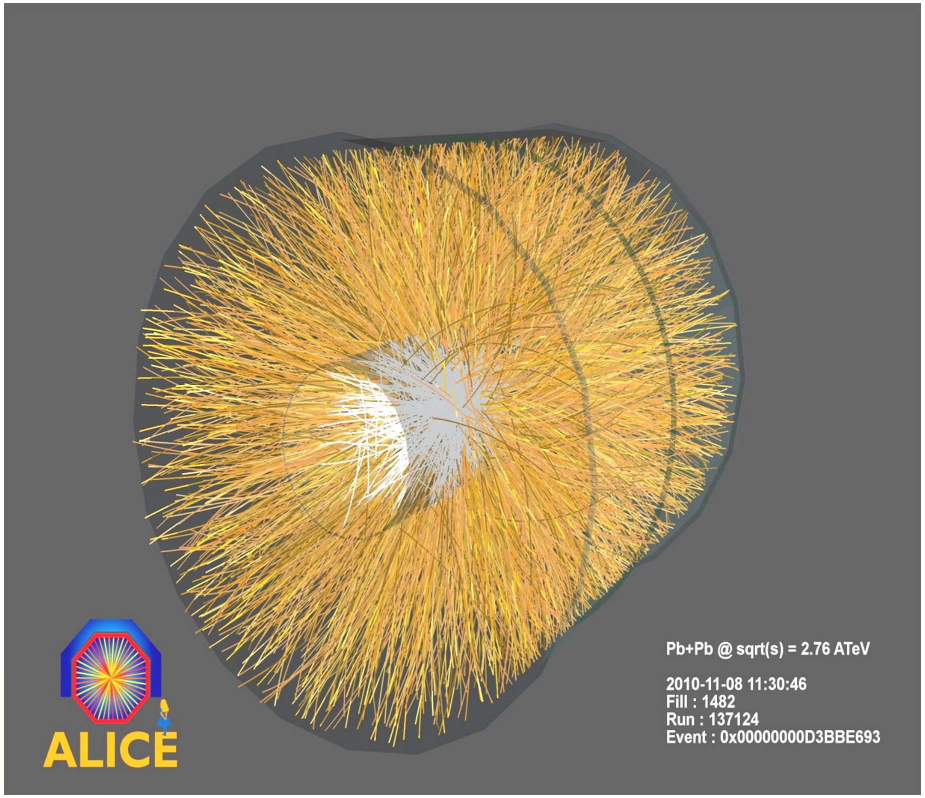
for the ALICE Collaboration

- Start of Heavy Ion Physics at LHC
  goal and observables
- Soft Physics
  particle production
- Hard processes
  probe of the QGP
- Conclusions & Outlook



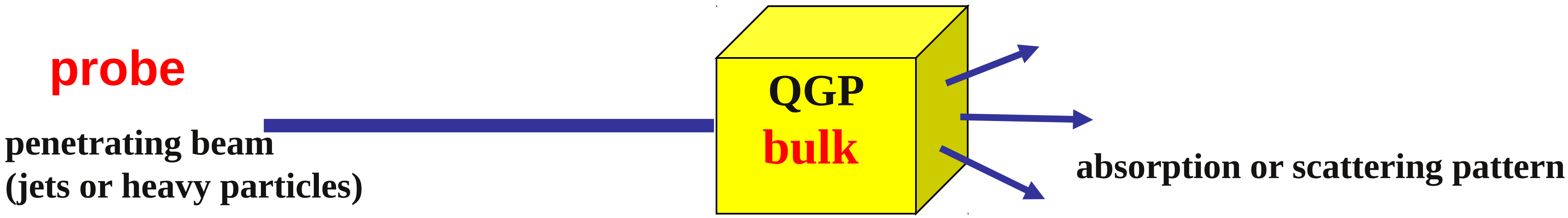
ÉCOLE DE PHYSIQUE des HOUCHES

Winter Workshop on Recent QCD Advances at the LHC

Les Houches, February 13th - 18th, 2011

Probing the QGP

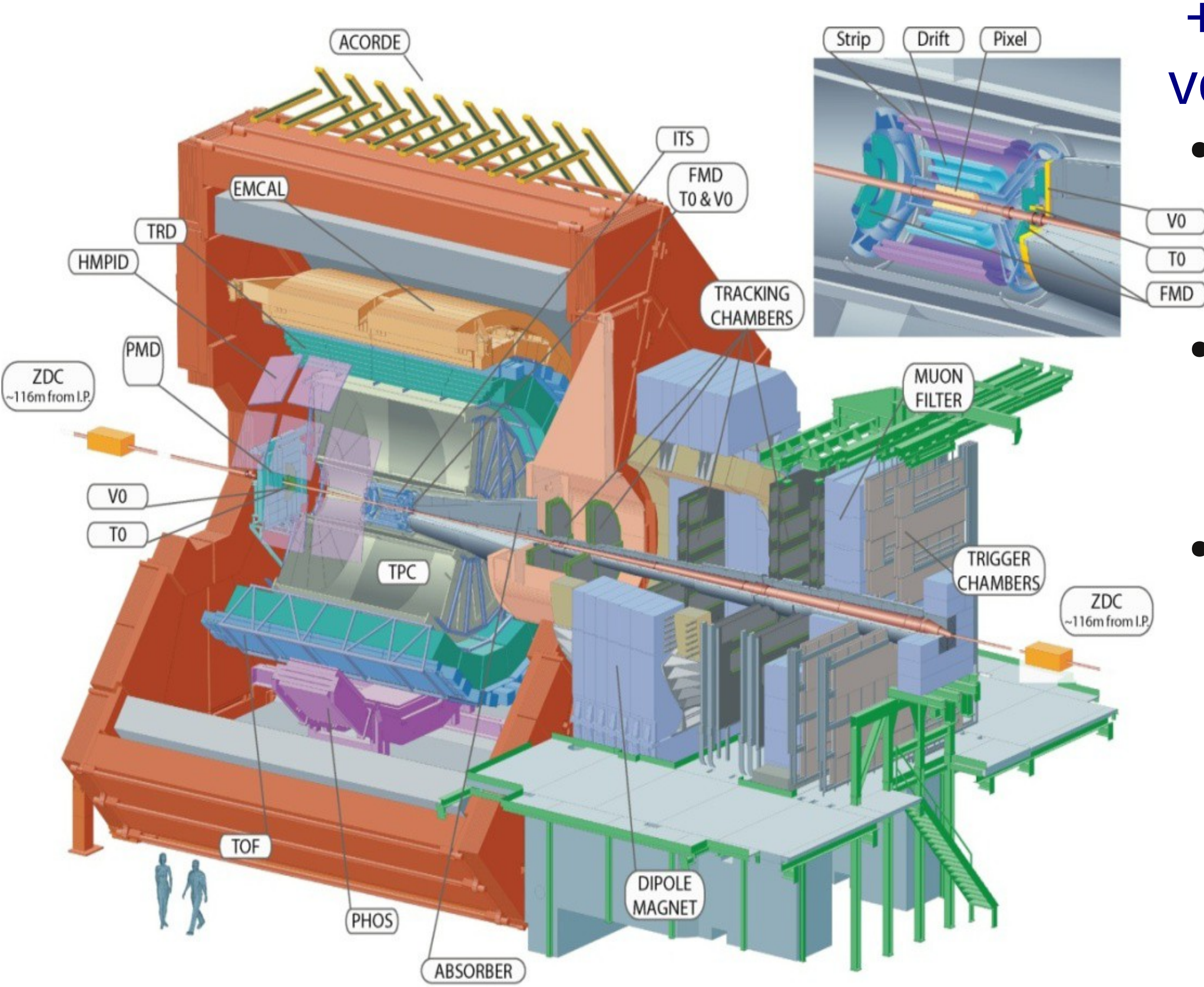
- Rutherford experiment α → atom discovery of nucleus
- SLAC electron scattering e → proton discovery of quarks



- Penetrating beams created by parton scattering before QGP is formed
  - High transverse momentum particles → jets
  - Heavy particles → open and hidden charm or bottom
- Probe QGP created in Au-Au collisions as transient state after ~ 1 fm
  - Calculable in pQCD (if no medium: $dN^{hard}_{AA} = N_{coll} \times dN^{hard}_{pp}$)
  - Calibrated in control experiments: pp (QCD vacuum), p(d)A (cold medium)
- Produced hadrons lose energy by multiple final state non-Abelian (gluon) radiation in the traversed medium
- QCD Energy loss → medium properties
  - Gluon density
  - Transport coefficient
- Phenomenological implications:
  - Suppression of leading hadron
  - Disappearence of away-side jet

ALICE detector and data taking

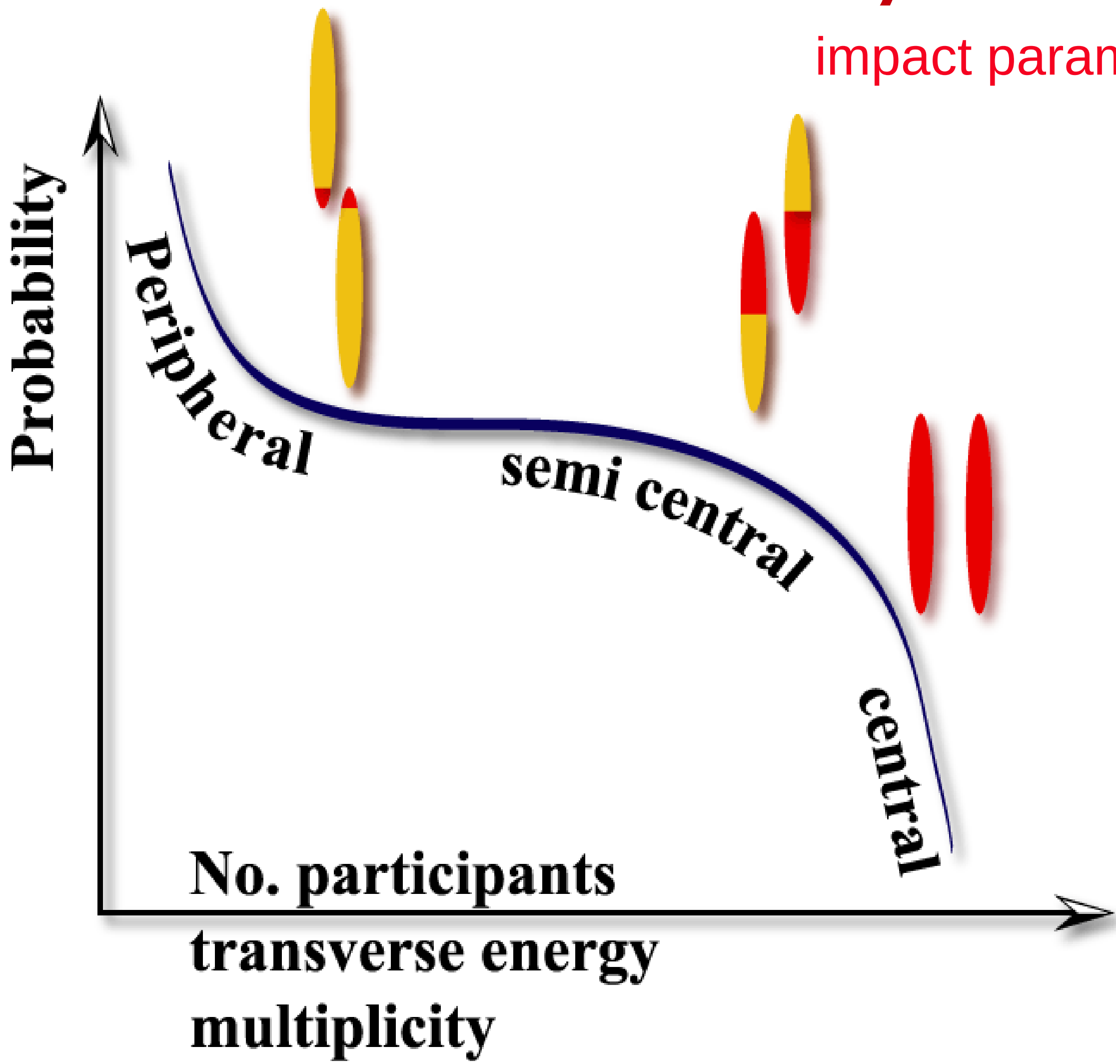
Pb-Pb @ 2.76 TeV, ~1month data taking, ~30M nuclear collisions
MB trigger with increasingly stronger conditions

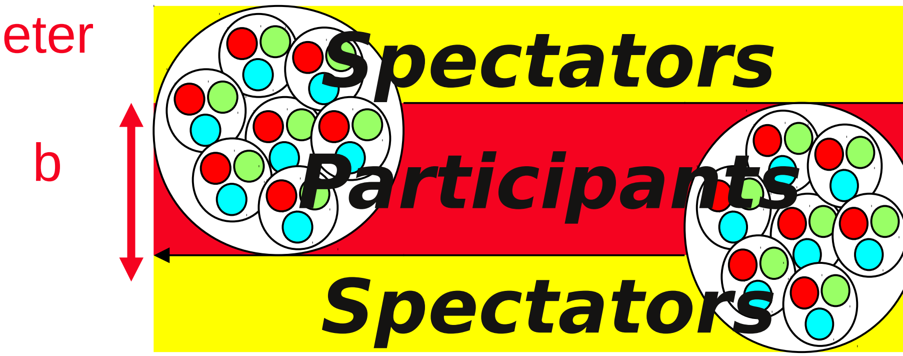


+ Ultraperipheral trigger
very large em cross sections:

- QED pair production:
  hundreds of kbarn e+e-
  very soft
- em dissociation ~ 200 barn
  one or several neutrons in ZDC, no central particles
- photonuclear reactions:
  tens of barns (kinematics very similar to pA)
  E_{γ} ~ several 100 GeV

Geometry of AA collision



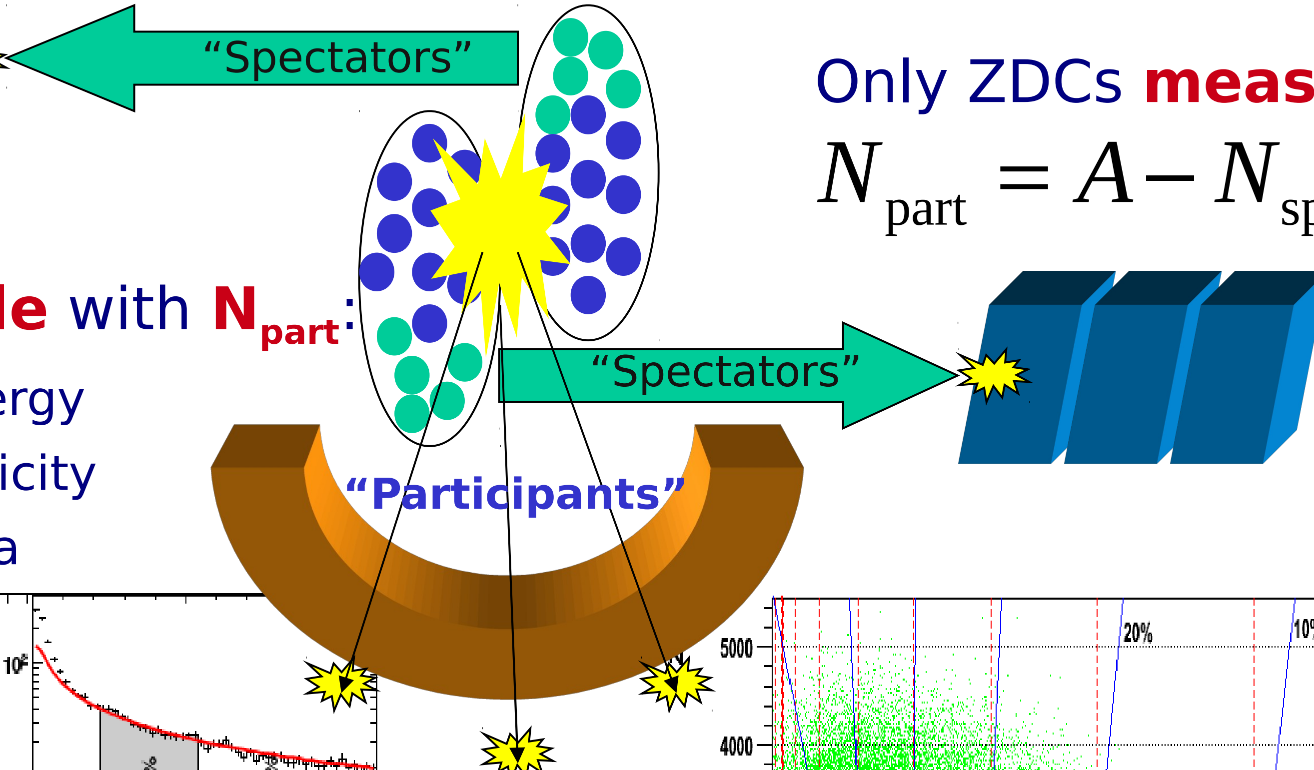


- small impact parameter (b~0)
  - high energy density
  - large volume
  - large number of produced particles
- measured as:
  - fraction of cross section "centrality"
  - number of participants
  - number of nucleon-nucleon collisions

From a Glauber Monte Carlo calculation (applies to: number of participants, number of nucleon-nucleon collisions)

Centrality experimentally

The collision geometry (i.e. the impact parameter) determines the number of nucleons that **participate** in the collision

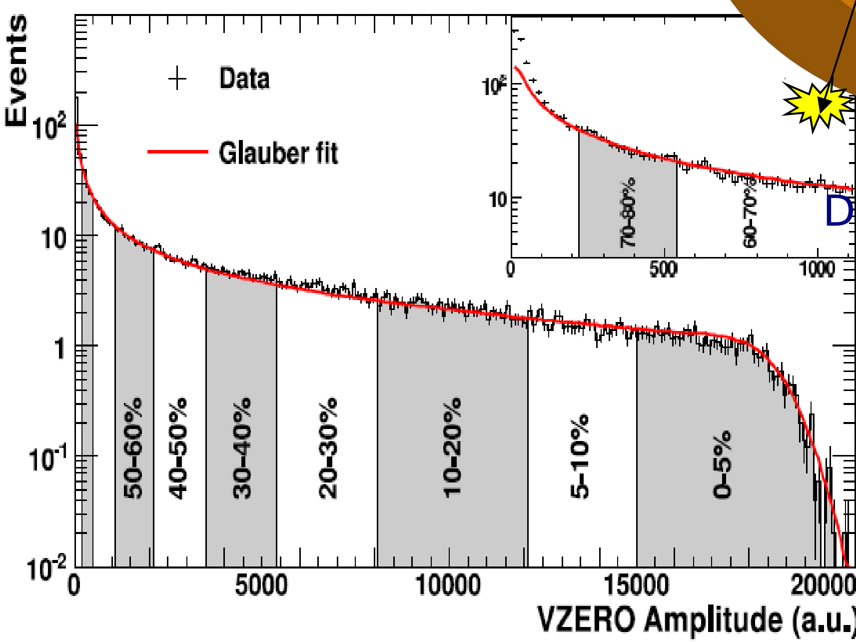


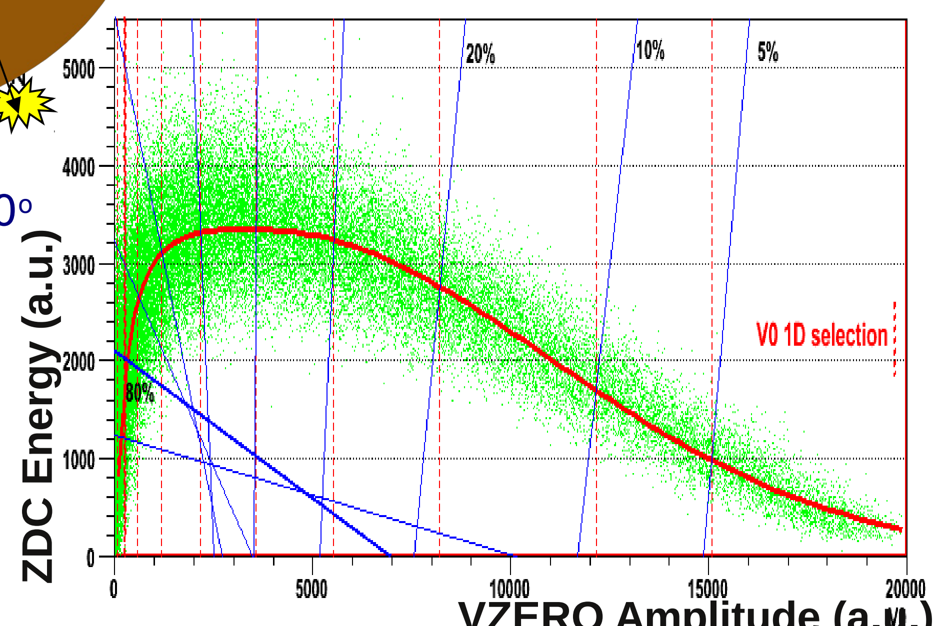
Only ZDCs **measure N_{part}**

$$N_{part} = A - N_{spec}$$

Many things **scale** with N_{part}:

- Transverse Energy
- Particle Multiplicity
- Particle Spectra





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Calculating Npart, Ncoll

- Glauber model approach: geometrical picture of a A+A collision
  - Straight−line nucleon trajectories
  - N-N cross−section independent of the number of collisions the nucleons have undergone before
- Parameters
  - Nuclear density profile (Woods−Saxon distribution)

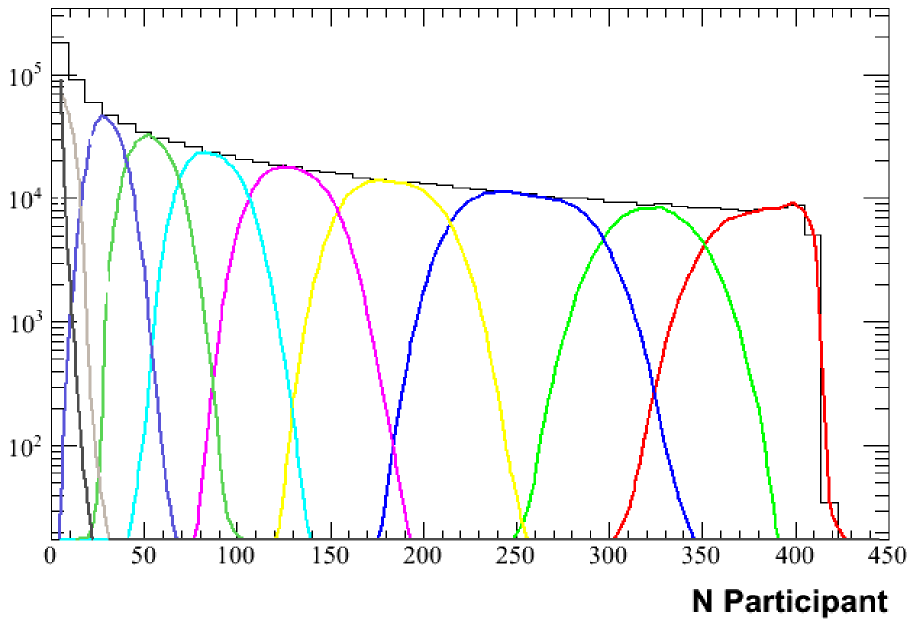
$$\rho(r)=\rho_0\cdot\frac{1}{1+\exp\left(\frac{r-R}{d}\right)}$$

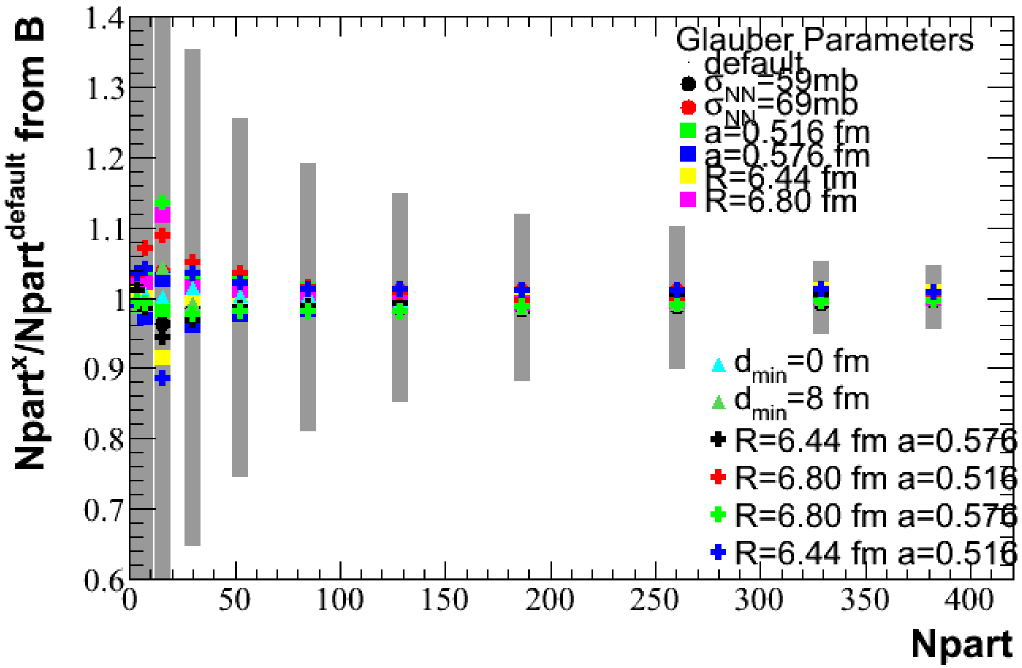
R=6.62 fm, d=0.546 fm,
collision occurs if distance between nucleons in transverse plane≤0.4 fm

  - Nucleon-Nucleon inelastic cross section σ_{NN} = 64±5 mb

Extracting Npart, Ncoll

- Define centrality classes as in analysis of real data
- Extract mean of N_{part} and N_{coll} distribution for each class

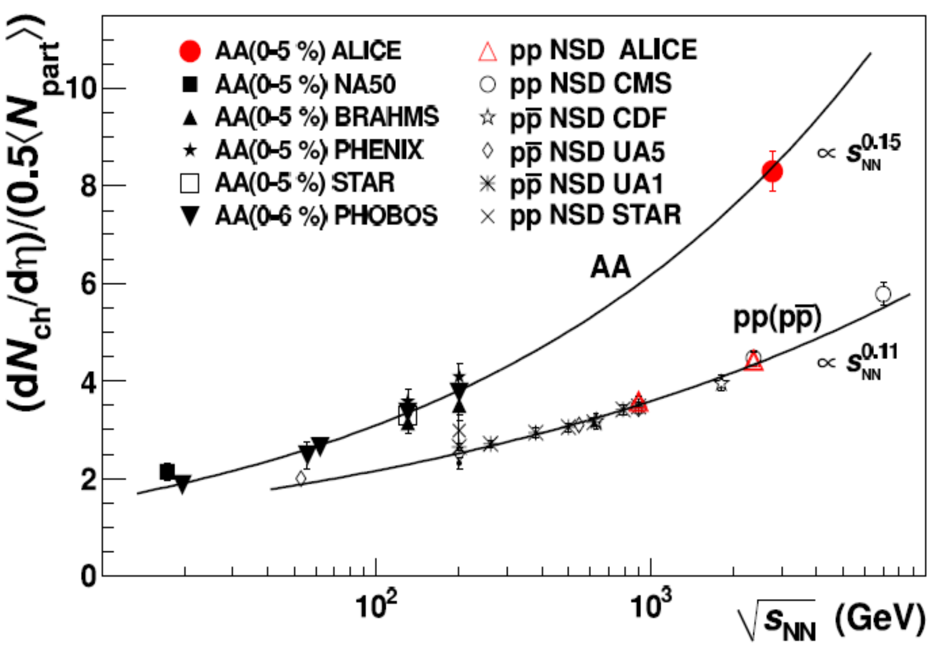




- N_{part}, N_{coll} agree well with true geometrical values
- Estimate uncertainty by varying model assumptions

How many particles are produced?

- Multiplicity of charged particles:
  per unit of pseudorapidity
  per pair of participants (i.e. nucleons taking part in collision)
  dNch/dη ~1600 for 0-5% most central
- Highest ever achieved, ~ 2 x higher than at RHIC
- growth with √s faster in AA than pp



- → the largest energy density e ever reached

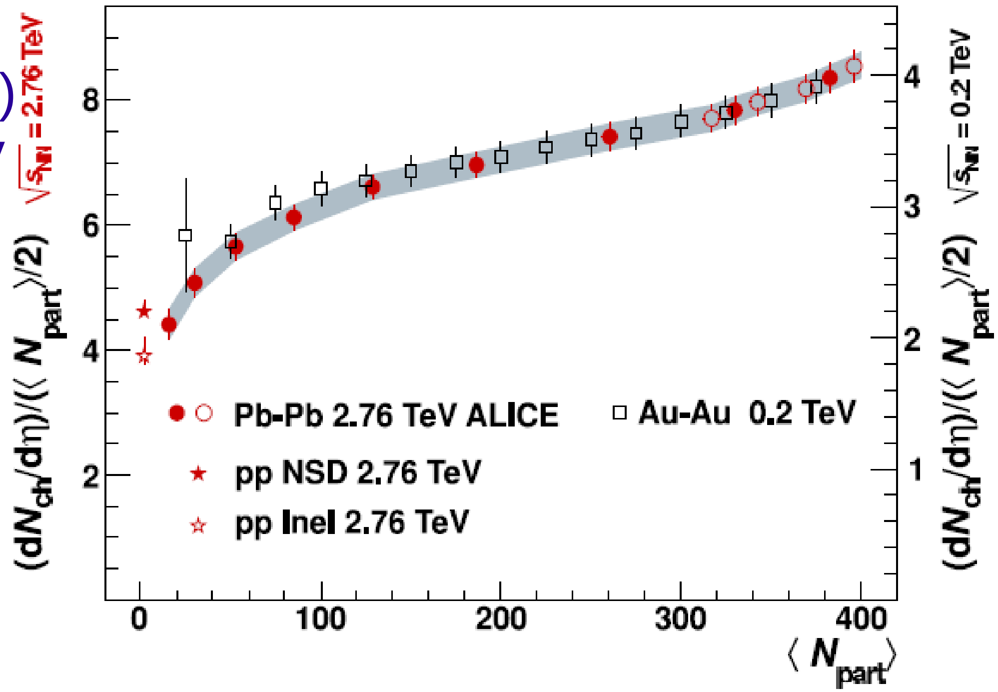
$$\varepsilon = \frac{E}{V} = A \cdot \frac{dN_{ch}}{d\eta} \cdot \left\langle \sqrt{m^2 + p_T^{\,2}} \right\rangle$$

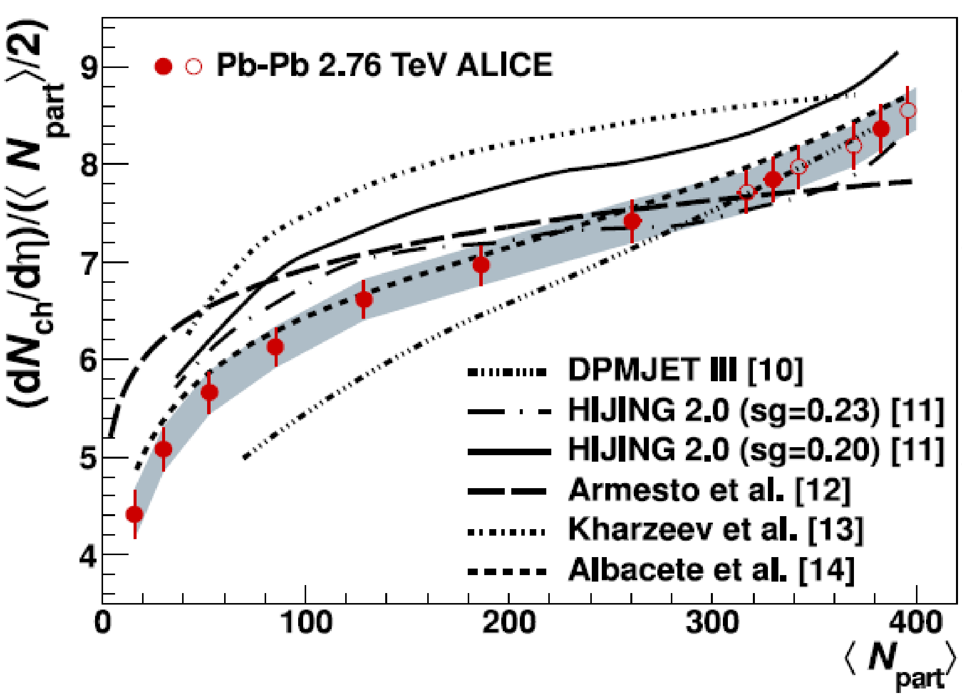
~ few GeV/fm3
3 x higher than at RHIC
(fixed t)

Multiplicity as function of centrality

- **soft process** $dN_{ch}/d\eta$ ~ number of scattered nucleons (strings, participants) 'nuclear amplification' should be energy independent
- **hard processes** $dN_{ch}/d\eta$ ~ number of nucleon-nucleon collisions

getting more important with √s **&** with centrality





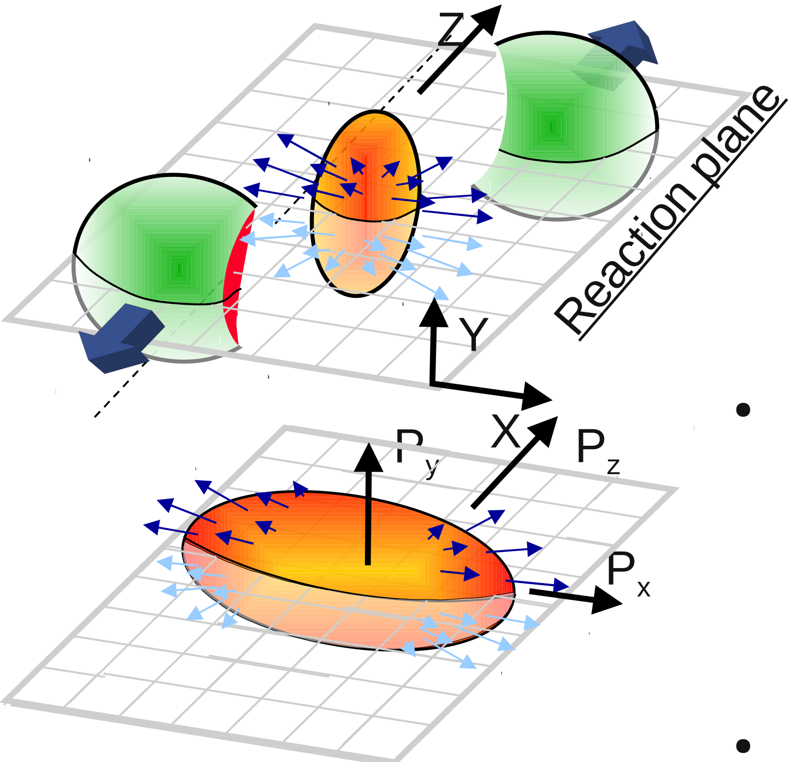
- DPMJET MC (2-component + string fusion) stronger rise than data
- HIJING MC
  strong centrality dependent
  gluon shadowing
- Other **saturation models:**
  Color Glass Condensate, 'geometrical scaling' from HERA/ photonuclear react.

Azimuthal Asymmetry

Almond-shape spatial anisotropy in non-central collisions translated into boosted momentum emission along reaction plane

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

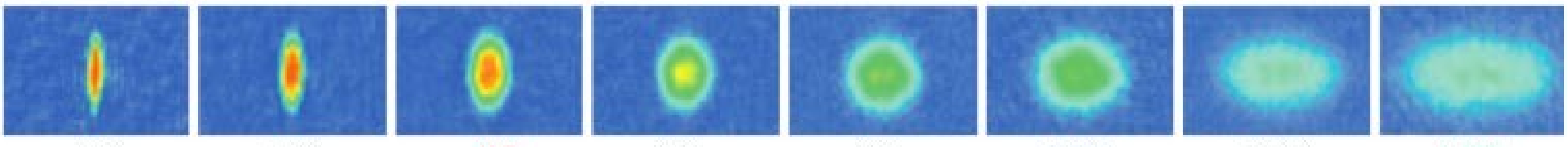
Elliptic flow v_2 = 2nd Fourier coefficient



→ The transfer of this asymmetry to momentum space provides a measure of the strength of collective phenomena

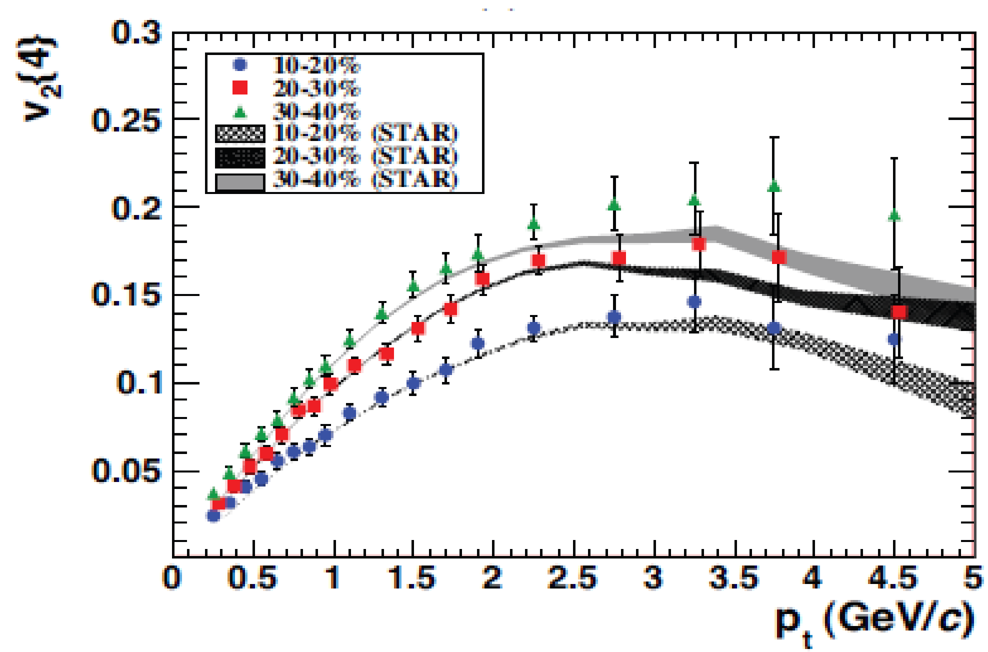
- Large mean free path
  - particles stream out isotropically, no memory of the asymmetry
  - extreme: ideal gas (infinite mean free path)
- Small mean free path
  - larger density gradient -> larger pressure gradient -> larger momentum
  - extreme: ideal liquid (zero mean free path,

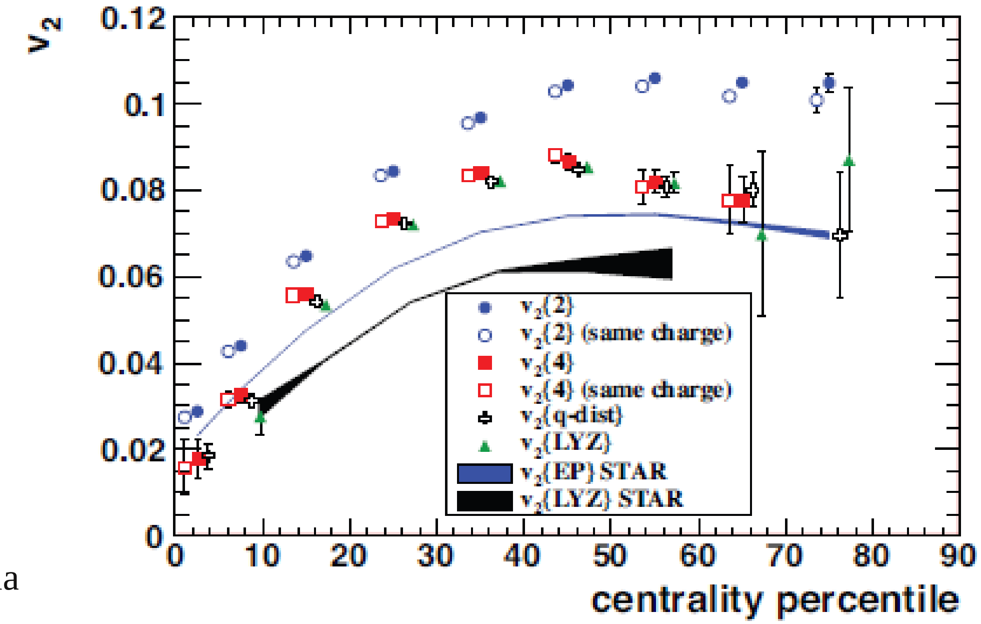
Liquid Li Explodes into Vacuum



Elliptic Flow Measurement

- v_2 as function of p_t
  - **no change with energy**
  - Consistent with hydro predictions
  - extends towards
    larger centrality/higher p_t ?
- v_2 integrated over pt
  - **30% increase from RHIC**
  - $<p_t>$ increases with √s
  - Hydro predicts increased
    ‘radial flow’
    very characteristic
    p_t and mass dependence



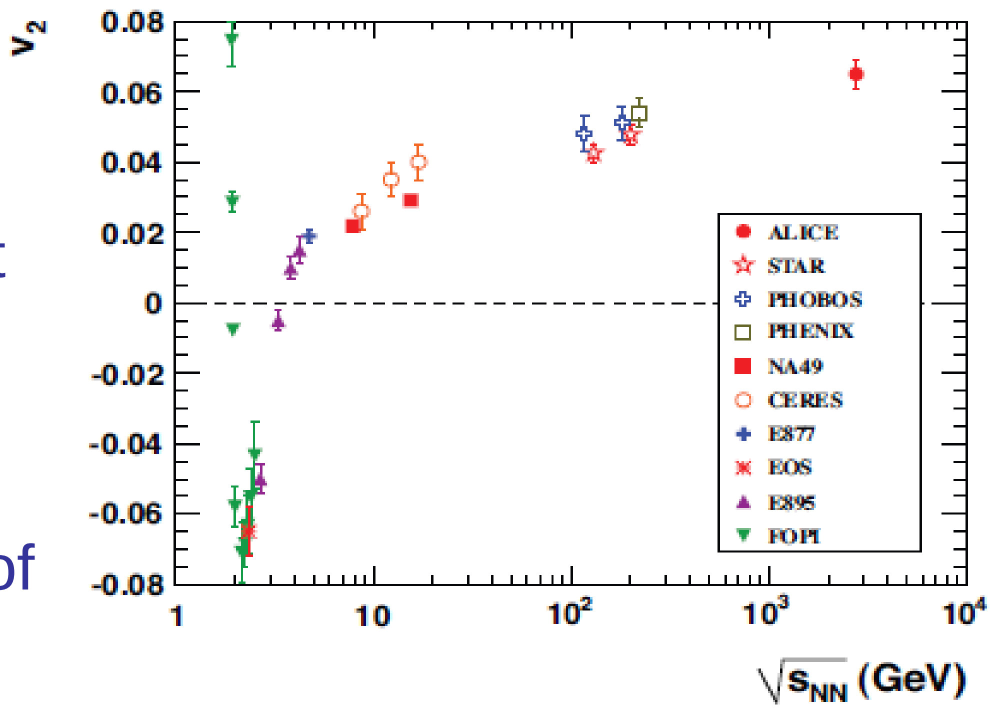


Towards the most perfect liquid?

- Large v_2 signal: reaches "hydro limit" (i.e. full thermalization)
  → Truly collective effect
- Strong partonic pressure gradient

large & fast parton scattering:
→ early thermalization

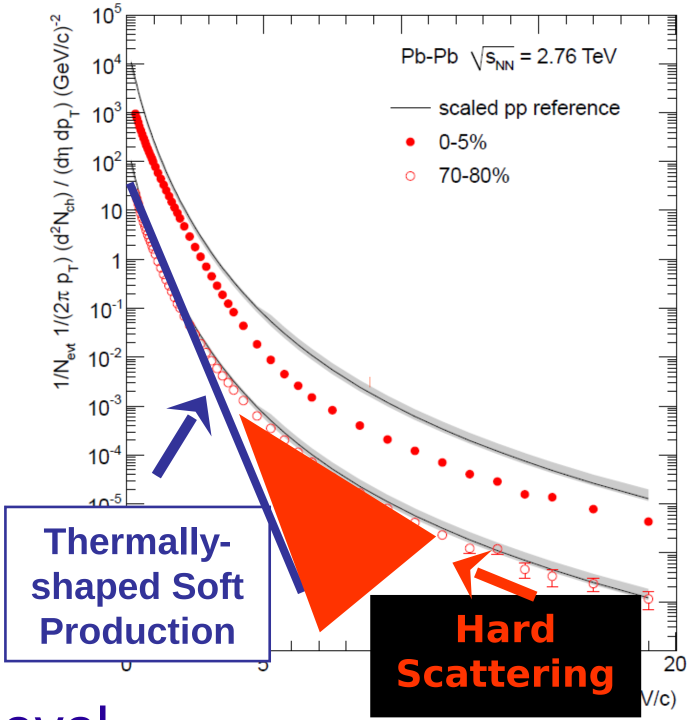
- Low viscosity:
  early hydrodynamic calculations of the medium at RHIC have assumed zero viscosity:
  $\eta = 0$, i.e. a "perfect fluid"
- AdS/CFT: conjectured lower quantum limit $1/4\pi$
- … but viscous corrections should be taken into account



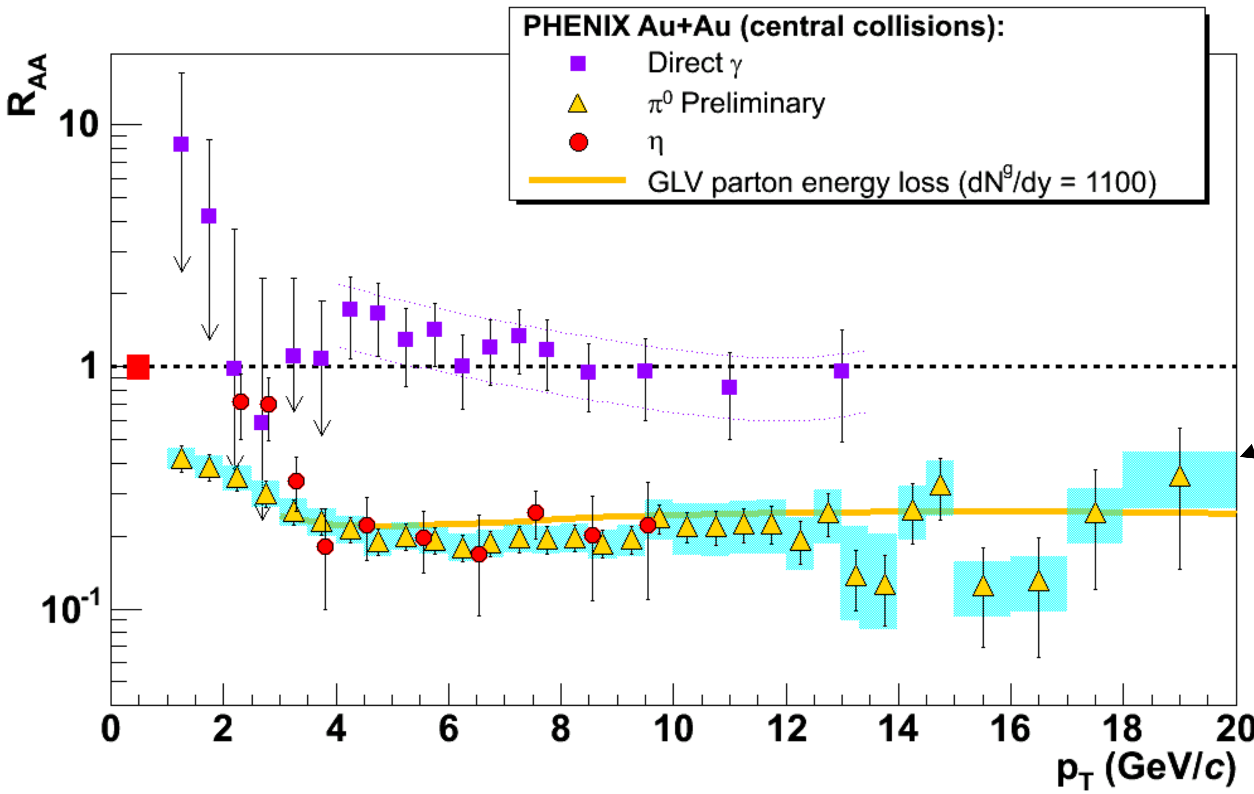
High p_T hadrons

Nuclear Modification Factor:

$$R_{AA} = \frac{Yield\ in\ Pb+Pb}{N_{coll} \times Yield\ in\ p+p}$$



- No suppression for direct photons: consistent with pQCD x N_{coll}
- Hadron suppression up to >20 GeV/c: Energy loss in dense medium
- Common suppression for π^0 and η; it is at partonic level

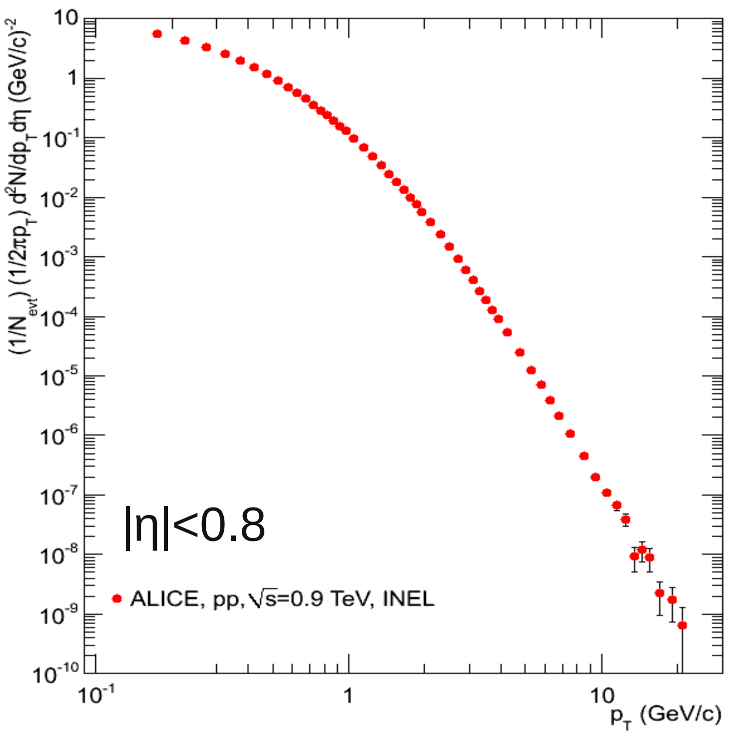


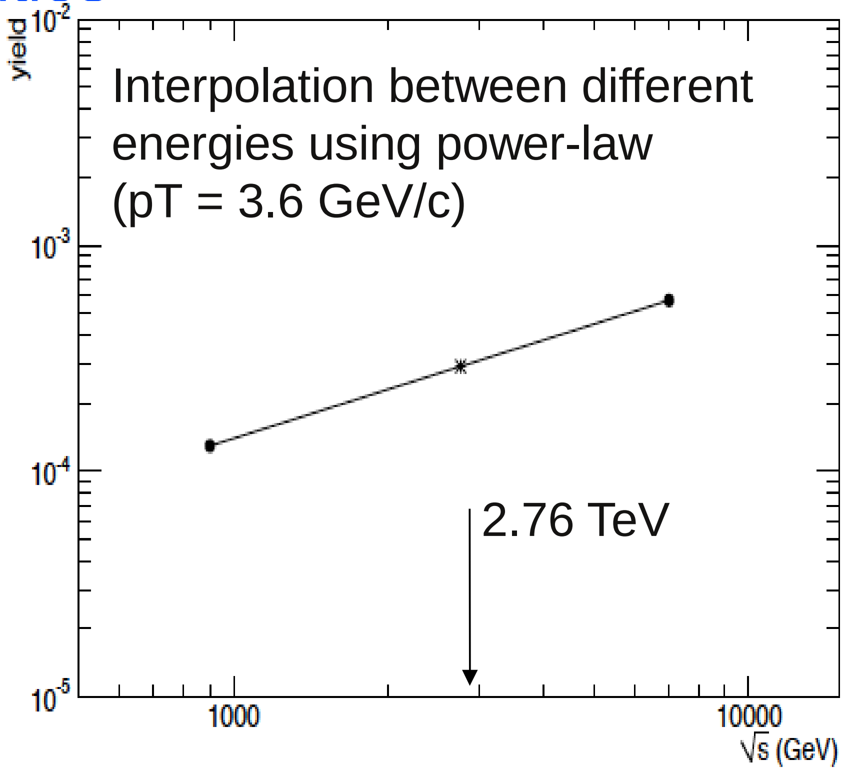
M. Gyulassy et al.

dN_g/dy > 1100

Extrapolation of the reference spectrum

- Use pQCD to extrapolate from existing data (0.9 → 2.76 TeV or 7 → 2.76 TeV)
  Arleo, d'Enterria, Yoon arXiv:1003.2963
  - Use only ALICE data
  - Parametrize p_T spectra to avoid fluctuations and increase p_T reach
    → reduces systematic scale uncertainties





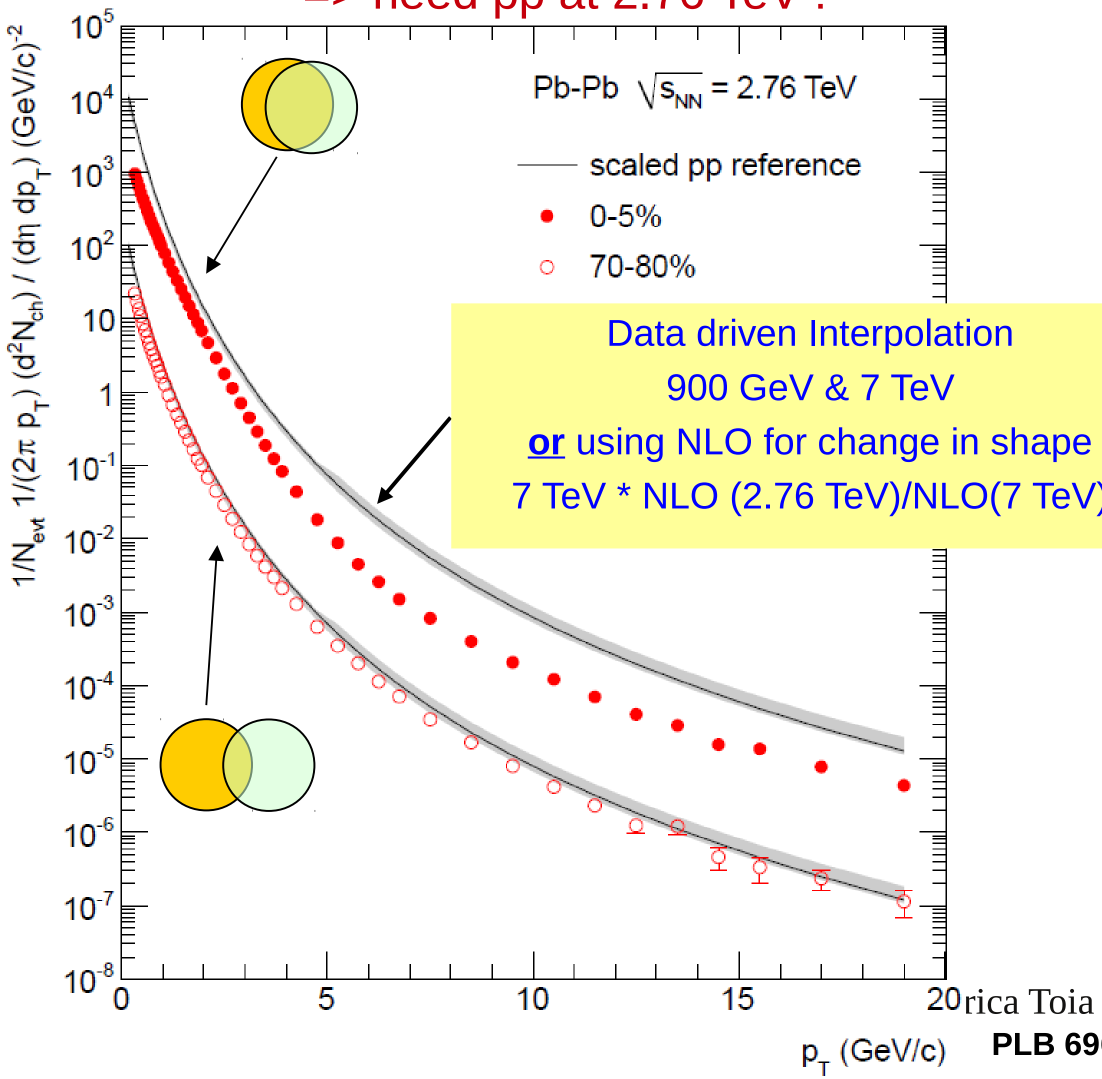
High pT suppression

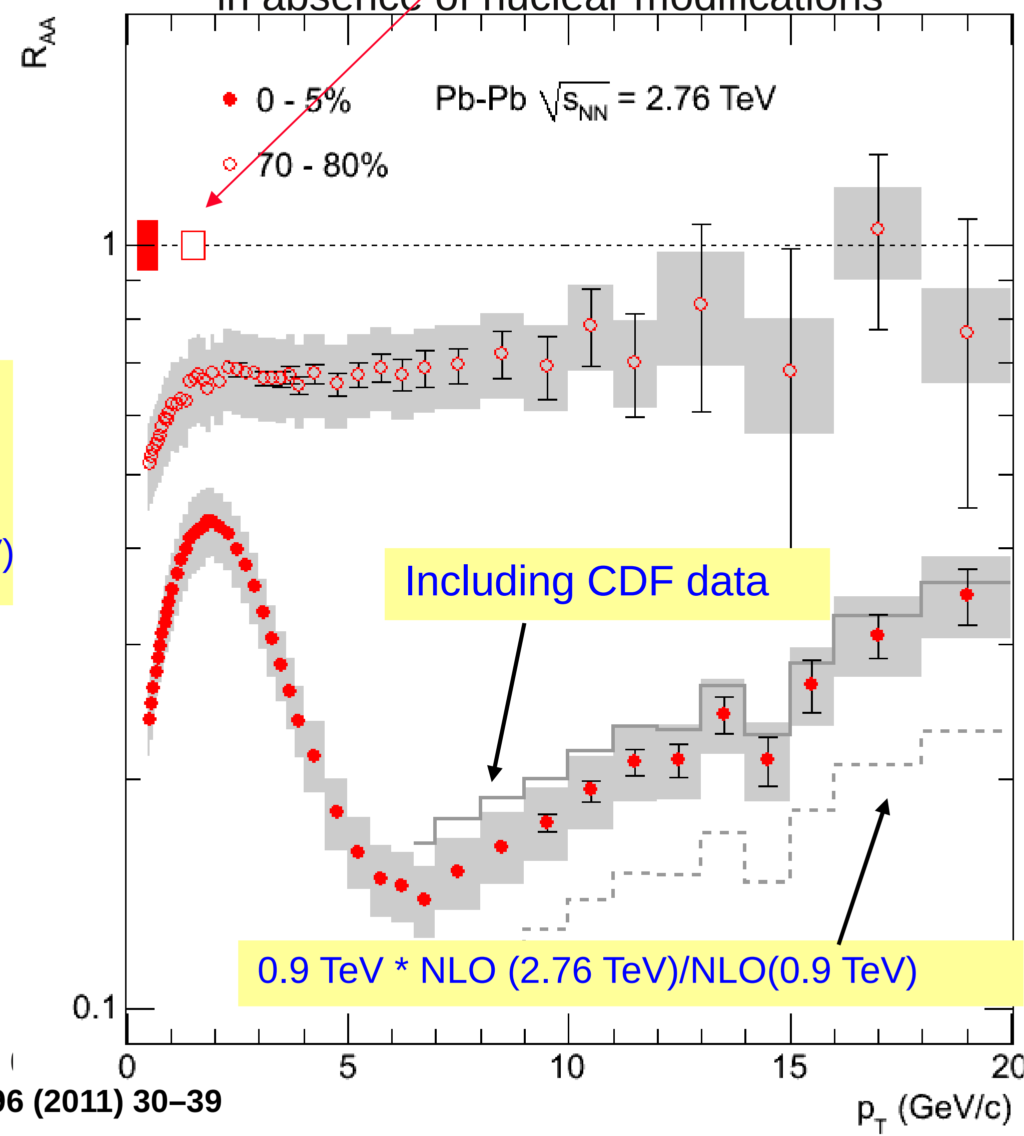
- suppression of high p_t particles (~ leading jet fragments)
  - Minimum R_{AA} ~ .15 at p_T= 6.5 GeV
  - Rising with p_t !
  - accuracy limited by pp reference

    => need pp at 2.76 TeV !

$$R_{AA} = \frac{Yield\ in\ Pb+Pb}{N_{coll} \times Yield\ in\ p+p}$$

R_{AA} = 1 for (very) hard QCD processes in absence of nuclear modifications





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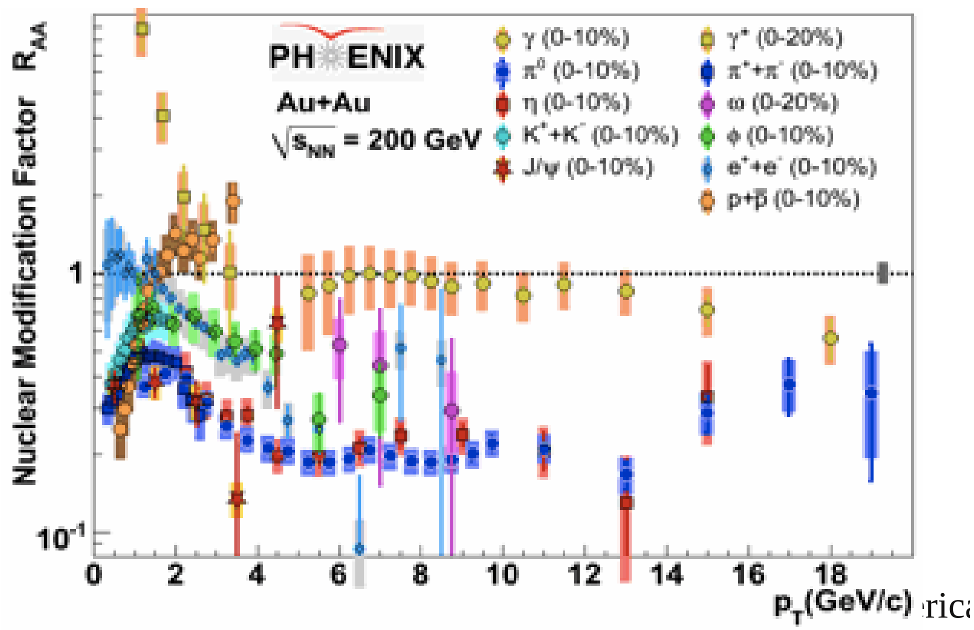
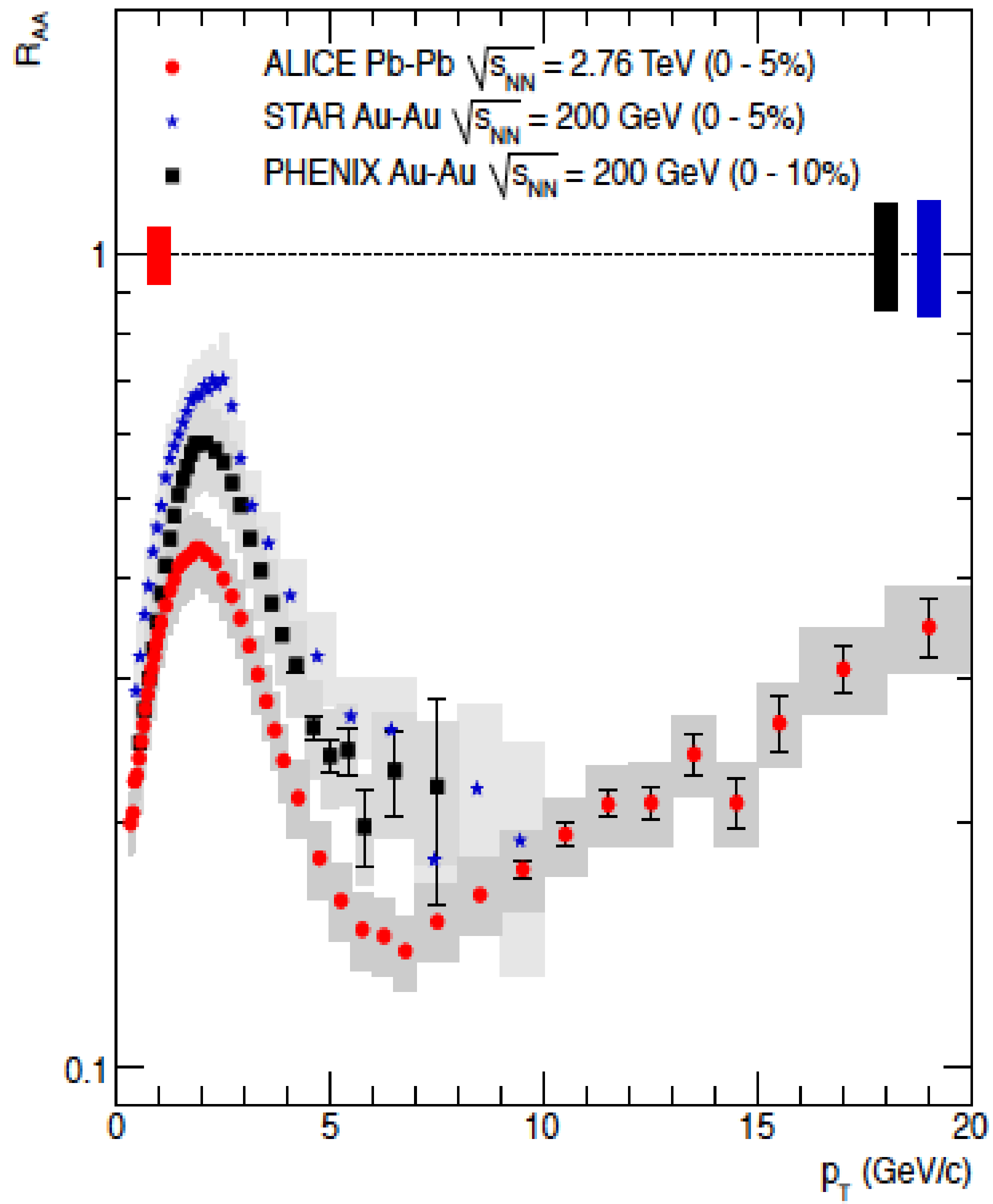
PLB 696 (2011) 30–39

Suppression is more complicated at higher p_T

- Larger suppression than at RHIC
- Steep R_{AA} rise from 6.5 – 20 GeV/c (ambiguous at RHIC)
- What happens at higher p_T?
  - ATLAS, CMS jet suppression...
- Enough Pb-Pb and p-p event statistics to reach p_T = 50 GeV/c





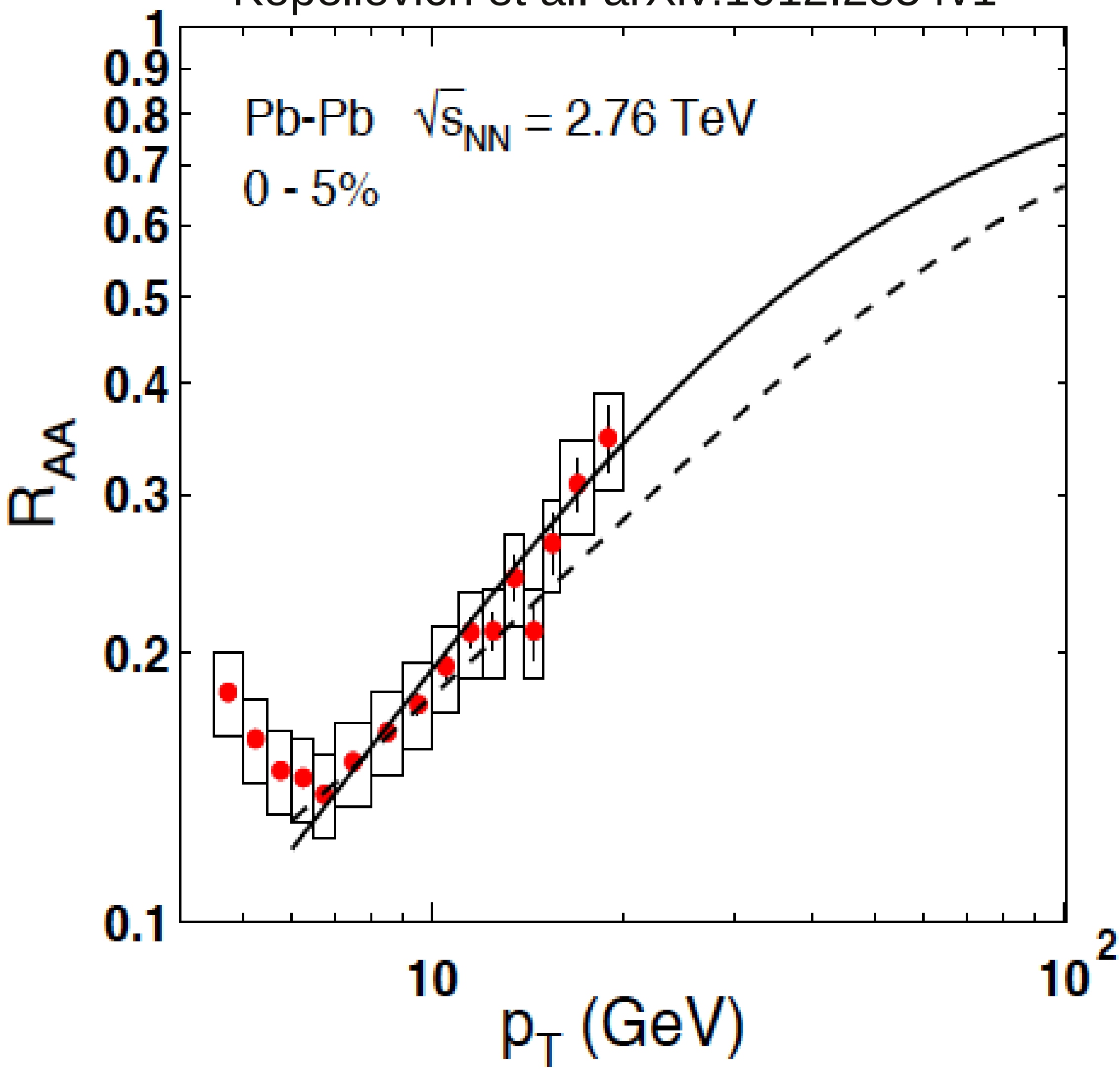
Conclusions & Outlook

- LHC and ALICE performed well in the first Pb-Pb run
- First look at collected data
  - Few weeks of data analysis
  - Small sample of data analyzed
- Results
  - Highest charged particle density ever reached
  - Its centrality dependence saturates
  - Hadrons flow close to hydro limit
  - High p_T Suppression stronger than at RHIC rises with p_T

Backup

High pT suppression

Kopeliovich et al. arXiv:1012.2854v1



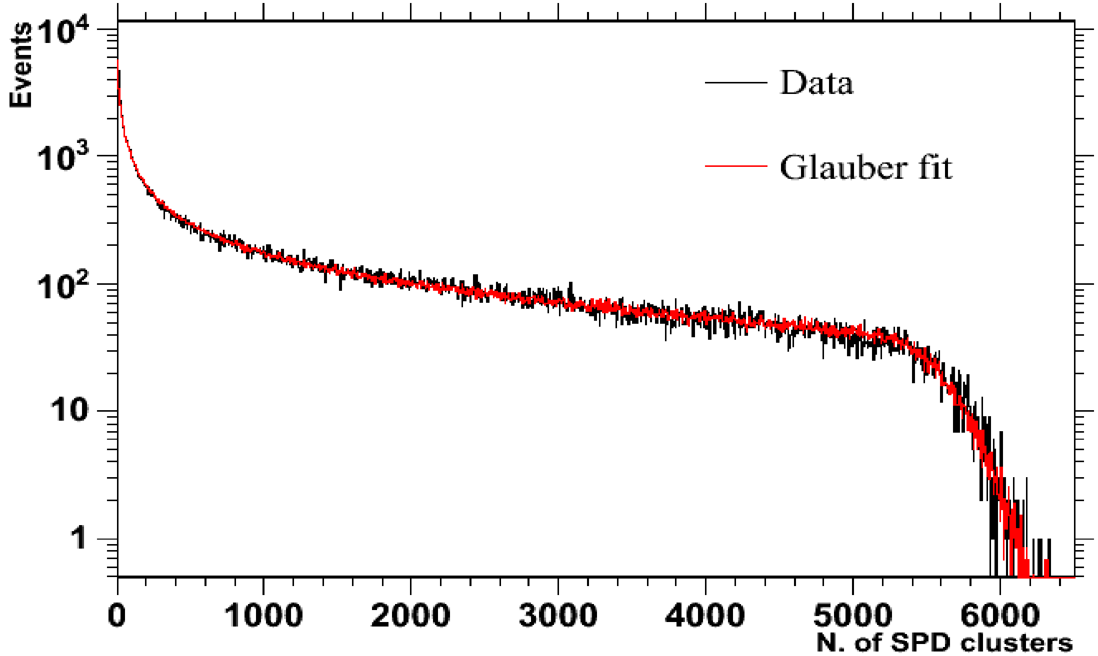
The production length of a leading hadron short because of vacuum gluon radiation and energy dissipation

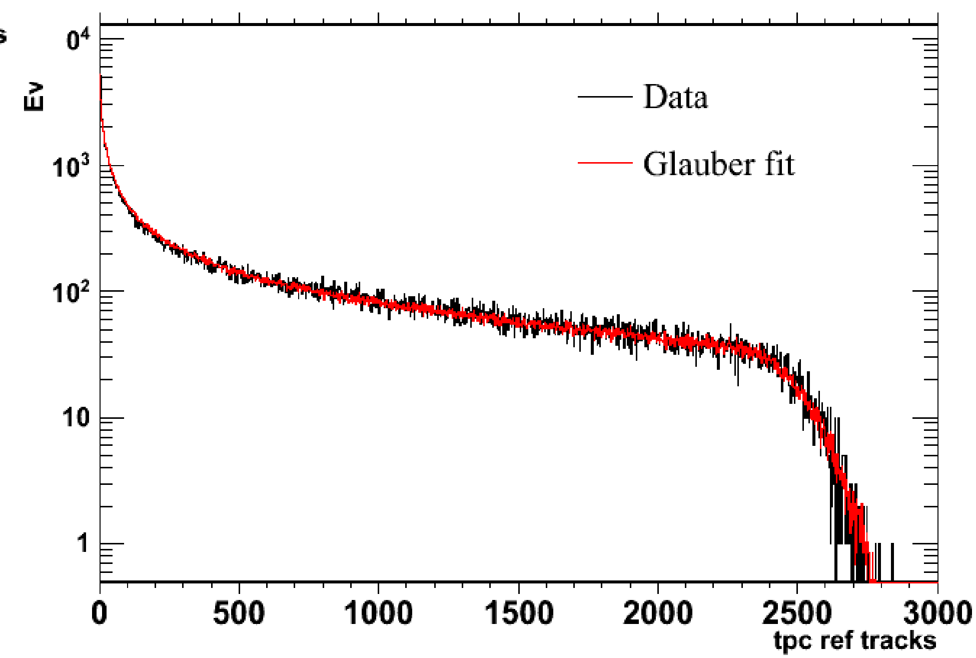
nuclear suppression of high-pT hadrons related to the survival probability of a colorless dipole

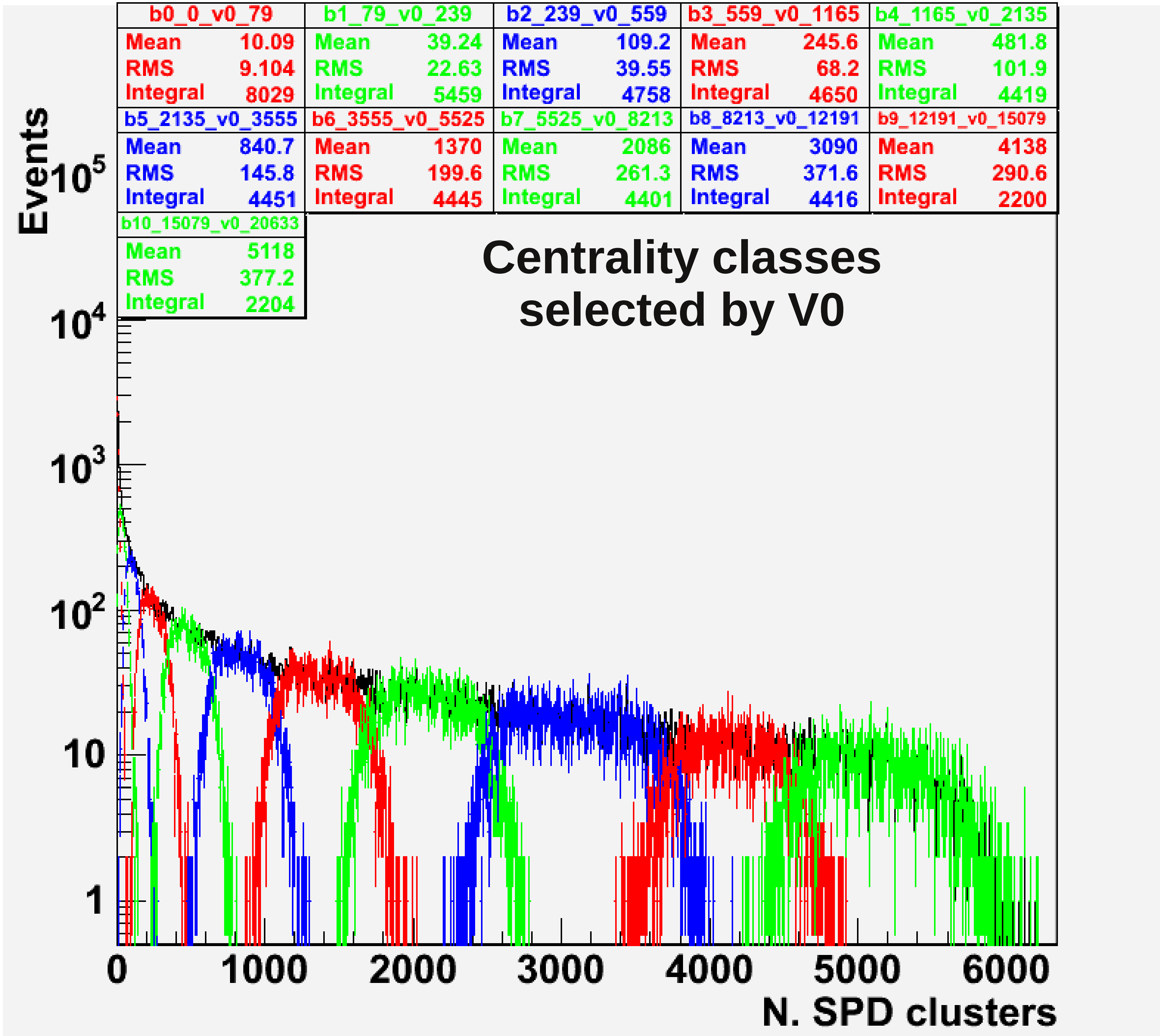
This is subject to color transparency, which leads to a steep rise with p

Enough Pb-Pb and p-p event statistics to reach pT = 50 GeV/c

Other centrality measures






b0_0_v0_79
Mean 10.09
RMS 9.104
Integral 8029
b1_79_v0_239
Mean 39.24
RMS 22.63
Integral 5459
b2_239_v0_559
Mean 109.2
RMS 39.55
Integral 4758
b3_559_v0_1165
Mean 245.6
RMS 68.2
Integral 4650
b4_1165_v0_2135
Mean 481.8
RMS 101.9
Integral 4419
b5_2135_v0_3555
Mean 840.7
RMS 145.8
Integral 4451
b6_3555_v0_5525
Mean 1370
RMS 199.6
Integral 4445
b7_5525_v0_8213
Mean 2086
RMS 261.3
Integral 4401
b8_8213_v0_12191
Mean 3090
RMS 371.6
Integral 4416
b9_12191_v0_15079
Mean 4138
RMS 290.6
Integral 2200
b10_15079_v0_20633
Mean 5118
RMS 377.2
Integral 2204
Centrality classes
selected by V0
Events
10^5
10^4
10^3
10^2
10
1
0
1000
2000
3000
4000
5000
6000
N. SPD clusters