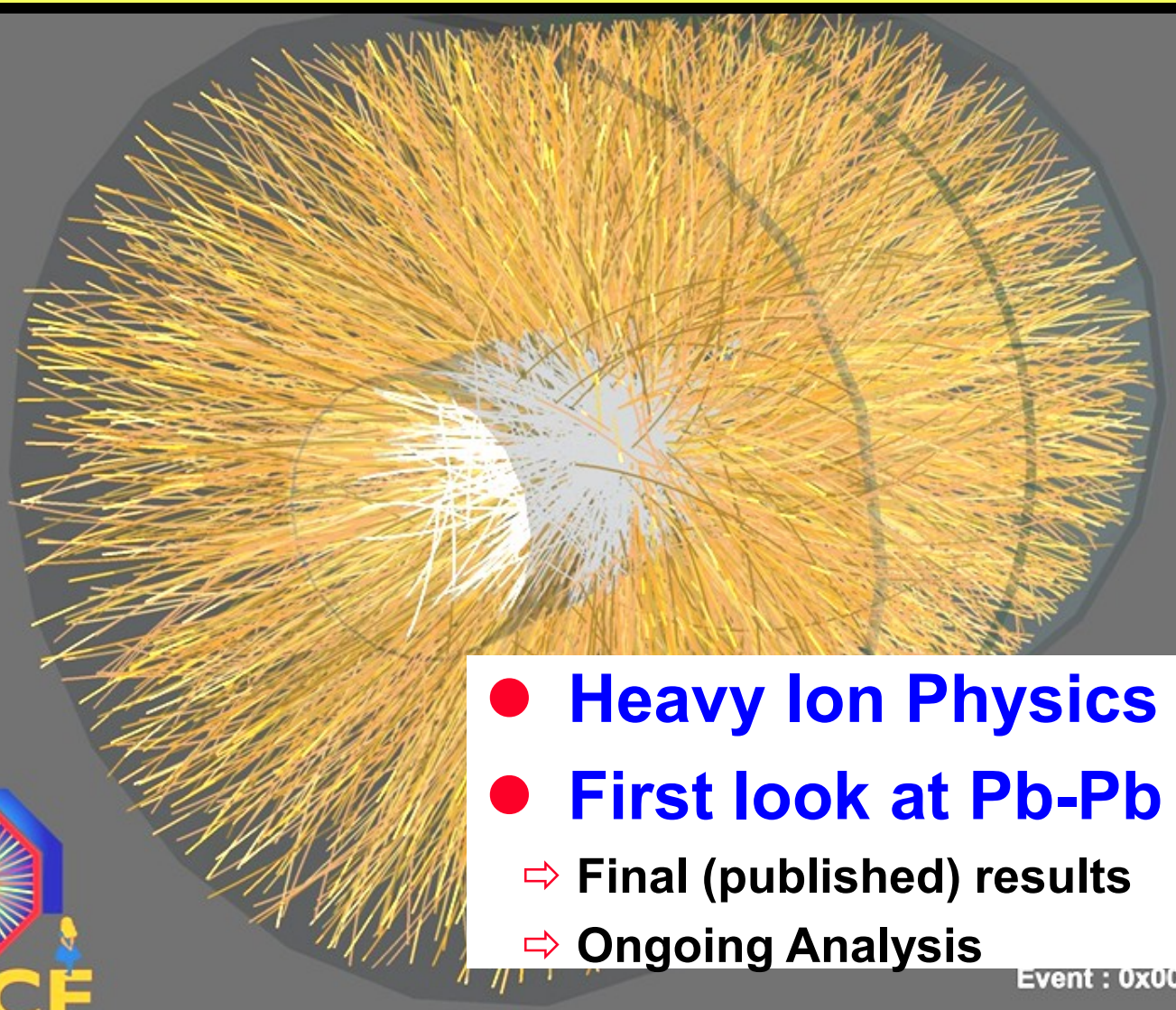
‘Little Bang’
The first 3 weeks …



- Heavy Ion Physics at LHC
- First look at Pb-Pb
  - ⇨ Final (published) results
  - ⇨ Ongoing Analysis

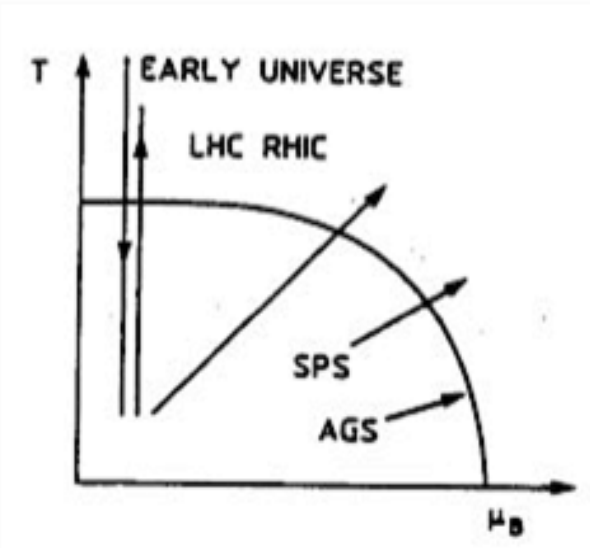
ALICE

Matter under Extreme Conditions

- 'state of matter' at high temperature & energy density: **'The QGP'**
  - ⇨ ground state of QCD & primordial matter of the Universe
    - ✪ partons are **deconfined** (not bound into composite particles)
    - ✪ **chiral symmetry** is restored (partons are ~ massless)
  - ⇨ **'the stuff at high T where ordinary hadrons are no longer the relevant d.o.f'**

Theory

- Mission of URHI
  - ⇨ **search** for the QGP phase
  - ⇨ **measure** its properties
  - ⇨ **discover** new aspects of QCD in the strongly coupled regime



Physics is QCD:
strong interaction sector of the Standard Model
(where its strong !)

Role of LHC after RHIC/SPS

- ⇨ **Search** for the 'QGP' is essentially over
- ⇨ **Discovery** of QGP is well under way (with fantastic results & surprises at RHIC)
- ⇨ **Measuring** QGP parameters has just begun

- 1) Quantitative differences
  - ⇨ significantly different state of QGP in terms of energy density, lifetime, volume
  - ⇨ large rate for 'hard probes' : jets, heavy quark states (b,c,Υ,J/Ψ),…

- 2) Test & validate the HI 'Standard Model' (< 10 years old !)
  - ⇨ Test predictio … st) perfect liquid
    - ✪ examples

> 10 year program

where are we after 3 weeks ?

- 3) 'Precision' measurements of QGP parameters
  - ⇨ Quantitative and systematic study of the new state of matter
    - ✪ **Equation-of-State** f(ε,p,T), **viscosity** η (flow), **transport coefficient** $\hat{q}$ (jet quenching), Debye **screening mass** (Quarkonia suppression), …
  - ⇨ Confront data with Theory and Models:
    - ✪ **standard tools:** Lattice QCD, pQCD, Thermo- and Hydrodynamics, …
    - ✪ **new tools:** AdS/CFT ('duality'), Classical QFT ('Colour Glass Condensate')

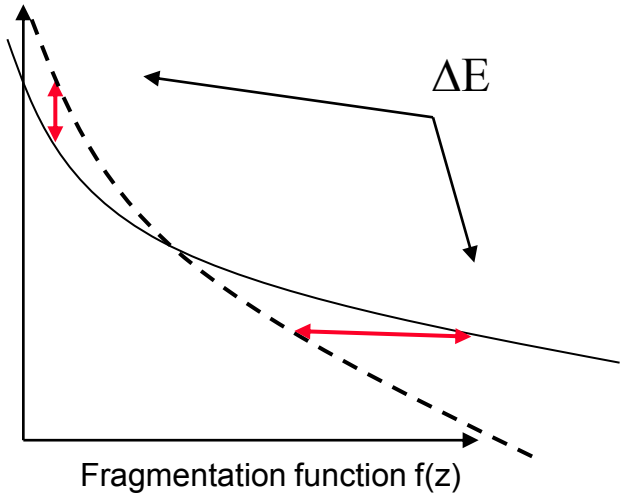
- 4) Surprises ?
  - ⇨ **we are dealing with QCD in the strong coupling limit !**

‘Jet Quenching’

- Jet quenching: **jet E -> jet E’ (=E-ΔE) + soft gluons (ΔE)**

  modified jet fragmentation function via matter induced gluon radiation/scattering

  => QGP properties



⇨ how much energy is lost ? (measures e.g. **q^**)

- ✪ most difficult question, may depend on jet cone R, p_t-cutoff, ..

⇨ how is it lost ? (e.g. multiple soft or few hard gluons ?)

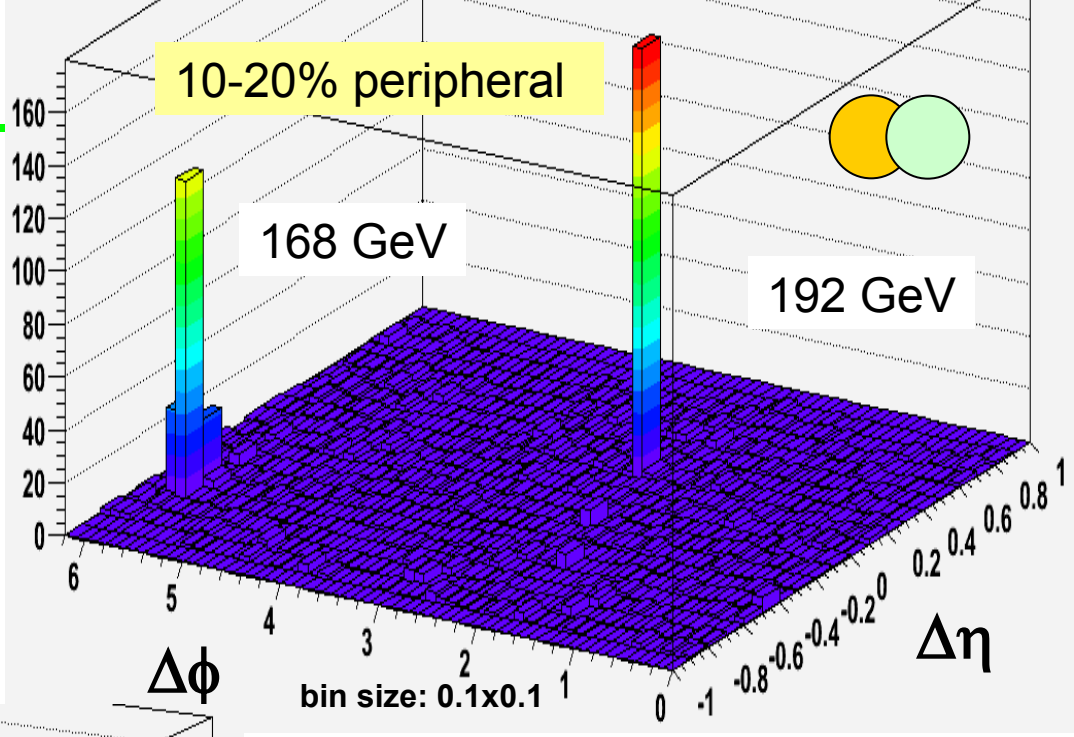
- ✪ look at soft part of f(z), p_t < 2-5 GeV

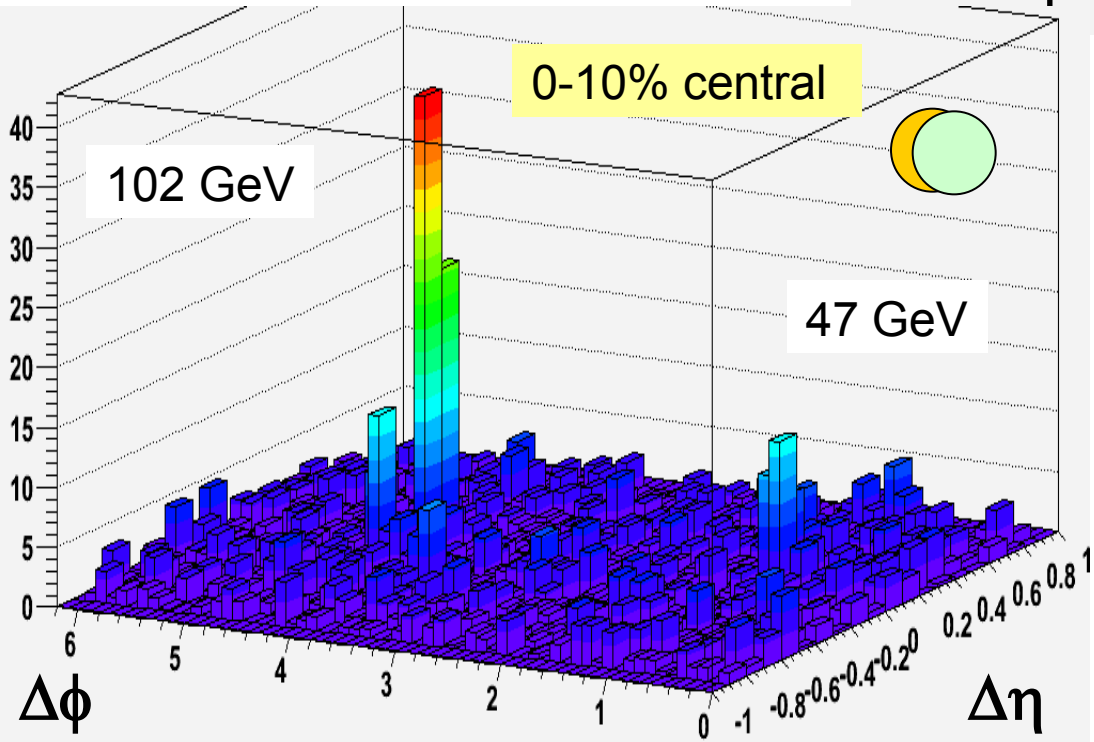
⇨ ‘response of QGP’ (shock waves, Mach cones ??)

- ✪ properties of bulk matter around jet, p_t ~ 1 GeV

Charged Jets

- Jets in ALICE (TPC)
  - ⇨ we see qualitatively a similar effect
  - ⇨ quantitative analysis is ongoing
    - ✪ small acceptance (statistics), => need full 2010 data
    - ✪ try to include low p_t (study p_t-cut off dependence of imbalance)

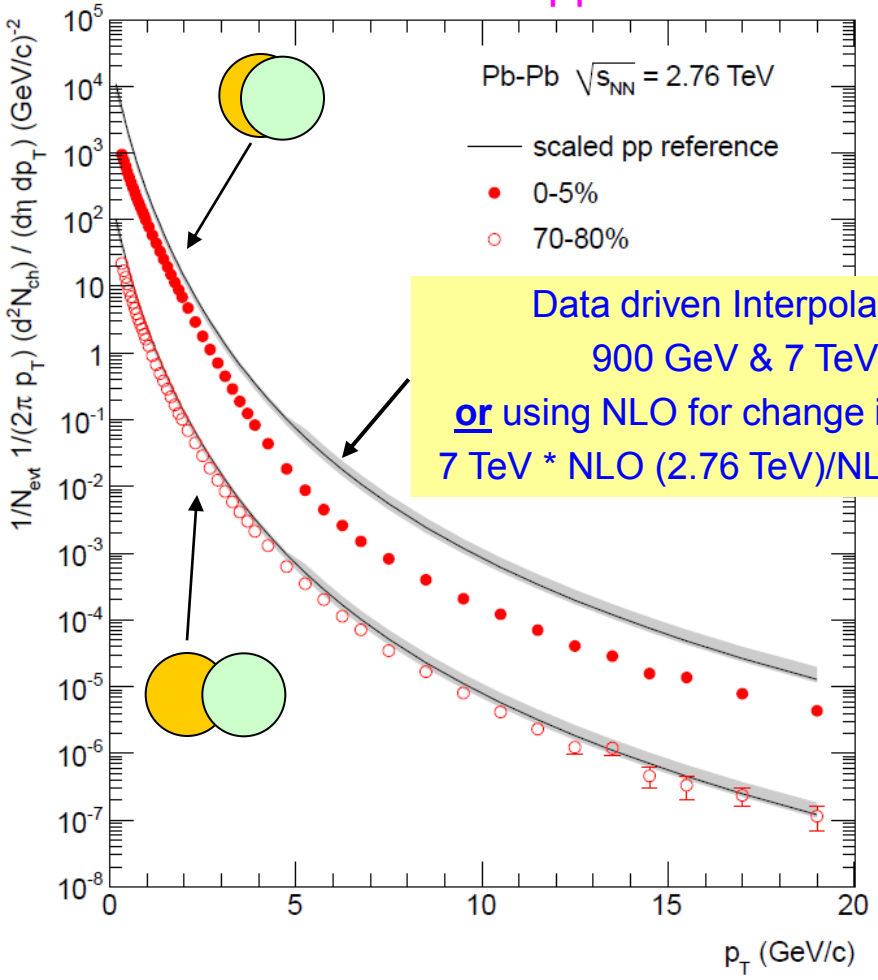




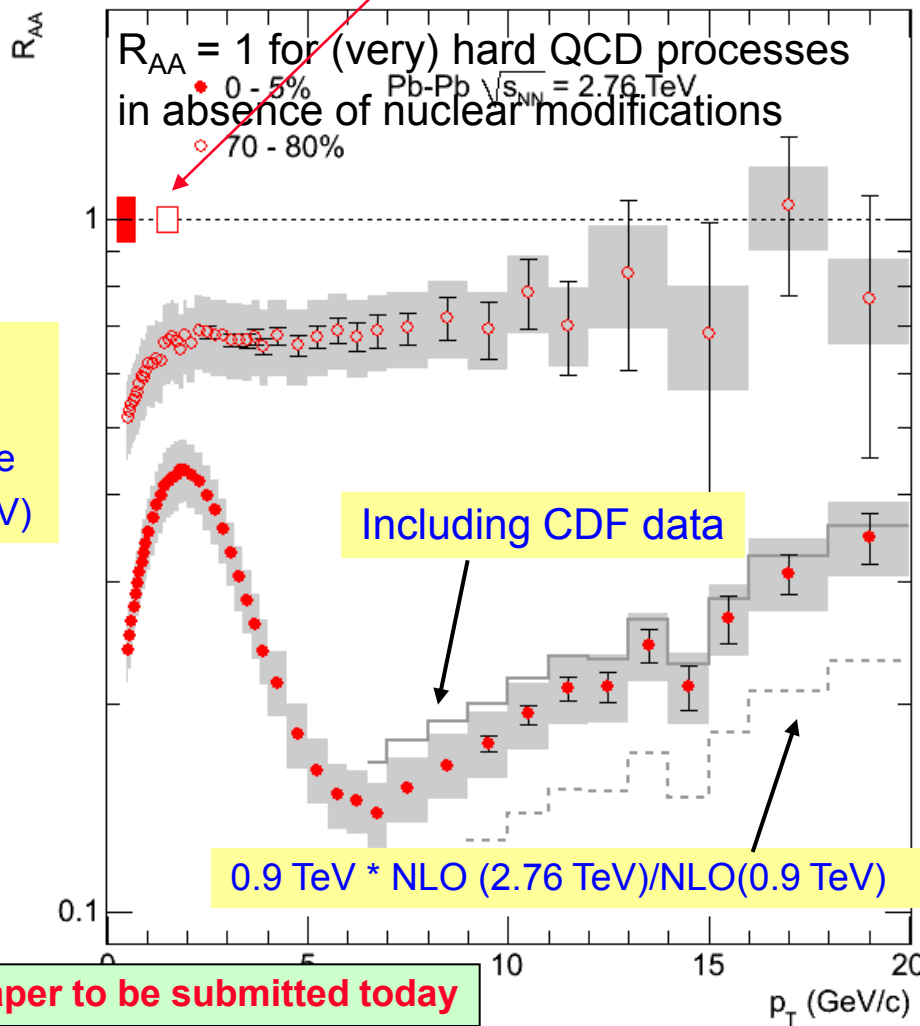
‘Jet Quenching’ as seen by p_t spectra

- Suppression of high p_t particles (~ leading jet fragments)
  - ⇨ Minimum R_{AA} ~ 1.5 – 2 x smaller than at RHIC
  - ⇨ Rising with p_t ! (ambiguous at RHIC !)
  - ⇨ accuracy limited by pp reference
    => need pp at 2.76 TeV !

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle\, (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$

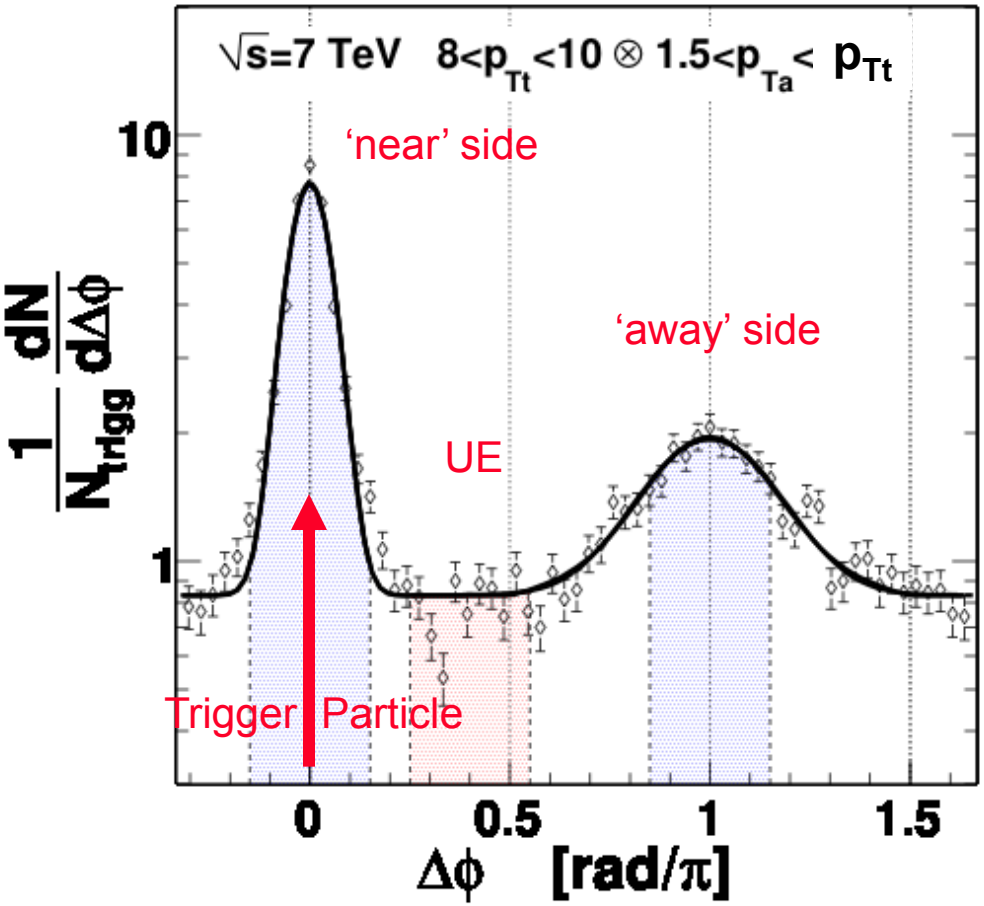


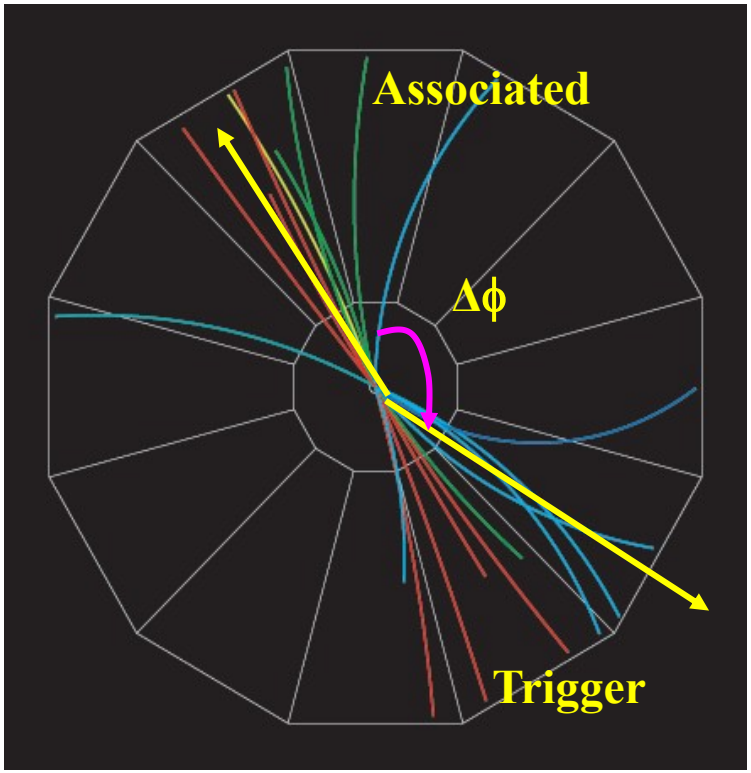
Data driven Interpolation
900 GeV & 7 TeV
or using NLO for change in shape
7 TeV * NLO (2.76 TeV)/NLO(7 TeV)



Paper to be submitted today

High p_T Particle Correlations



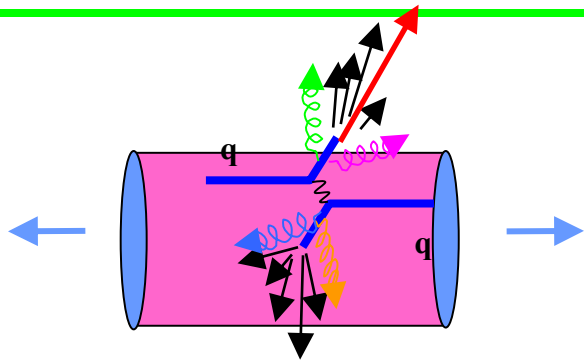


Trigger Particle: highest p_T particle in event (p_{Tt})

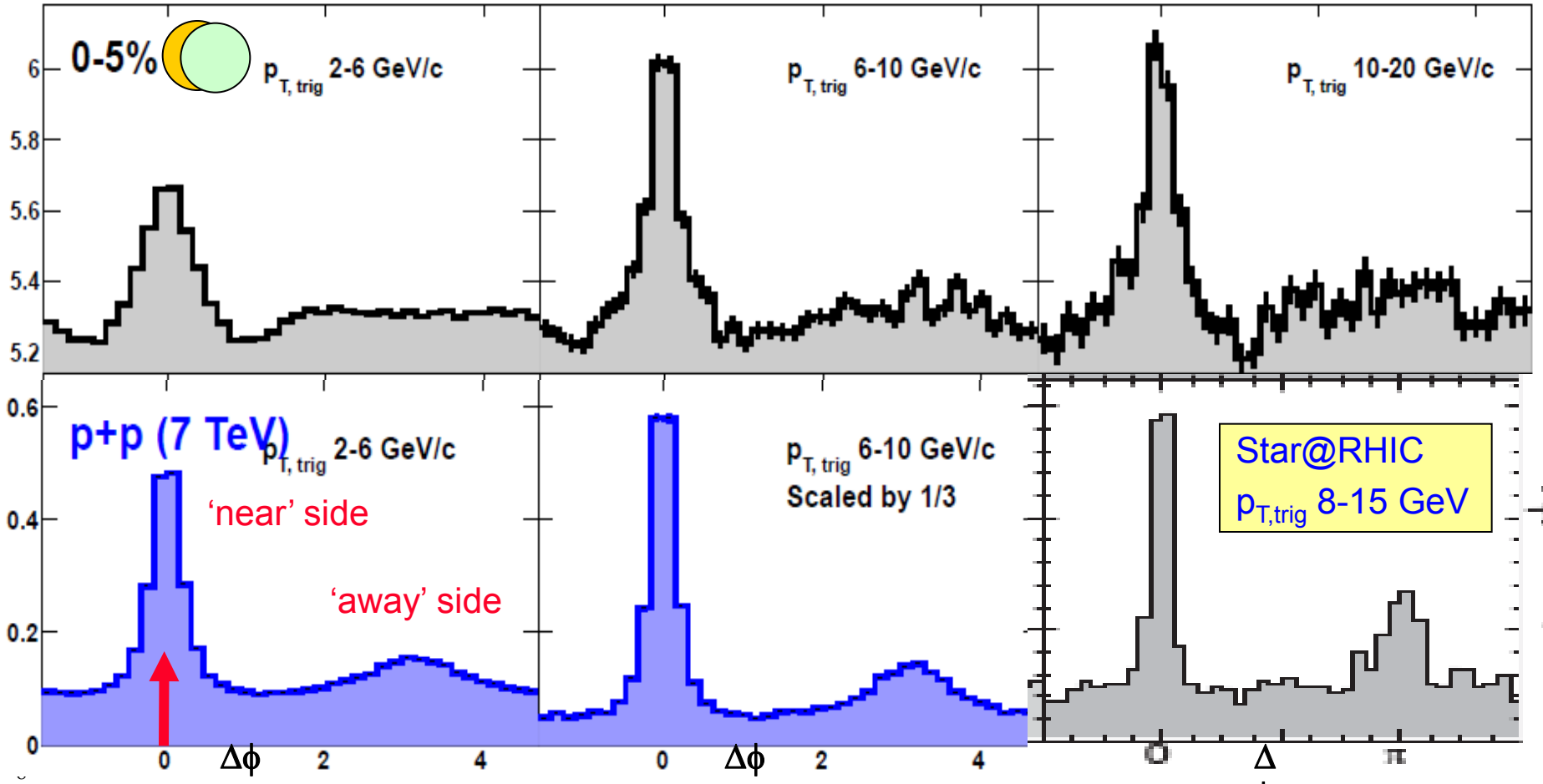
Associate Particle: all the others (p_{Ta})

Jet Quenching seen by High p_T Correlations

- classic 'jet quenching signal'
  - ⇨ away side correlation in central Pb-Pb washed out up to $p_{T,trig}$ > 10 GeV

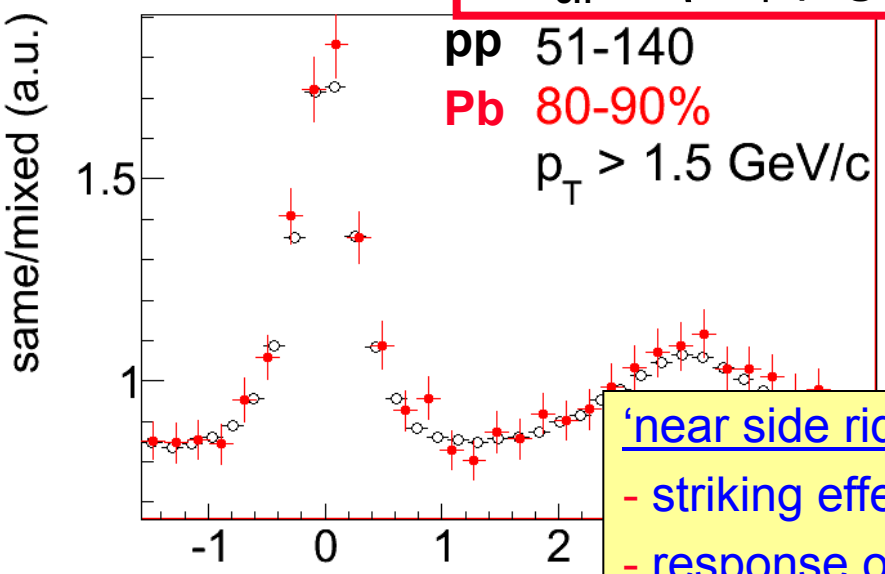


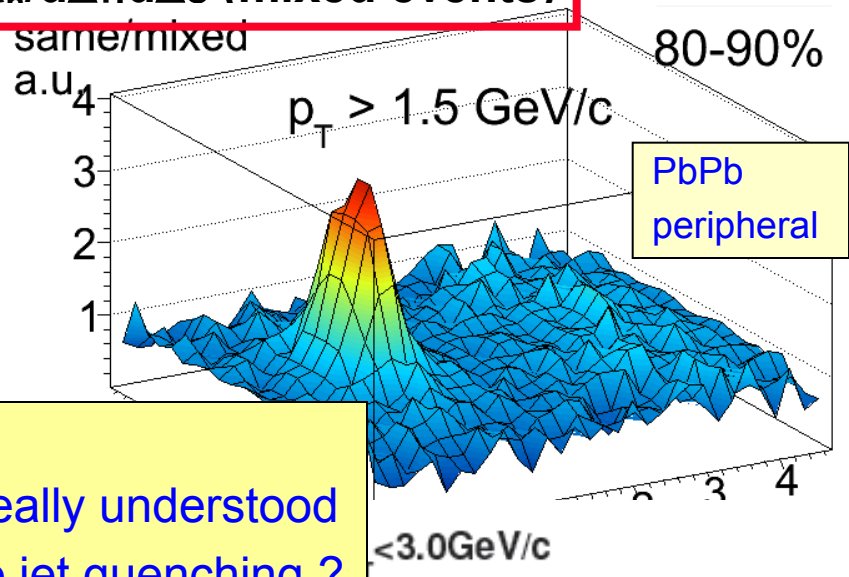
P_T associated 2 – 6 GeV



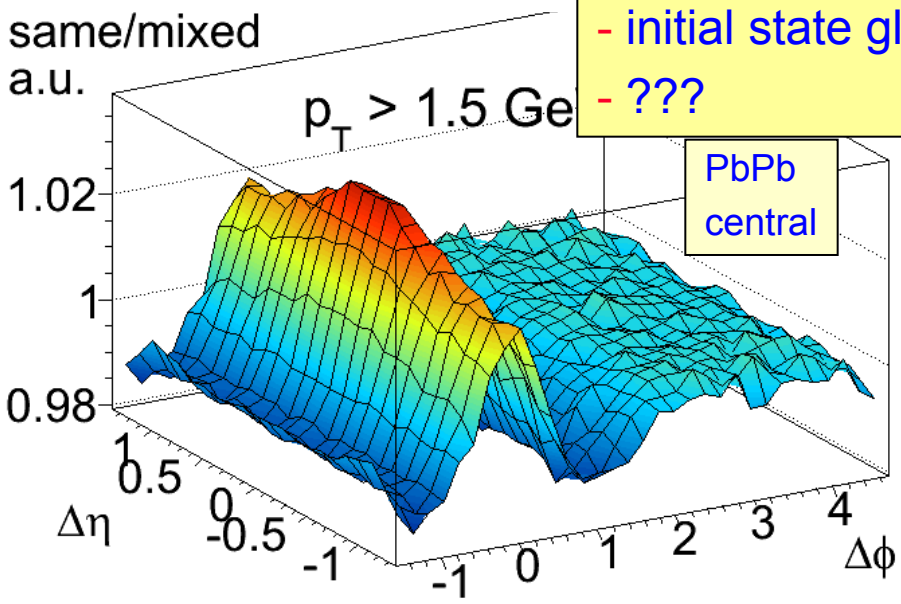
Jet Quenching (?) seen via Multiparticle Correlations

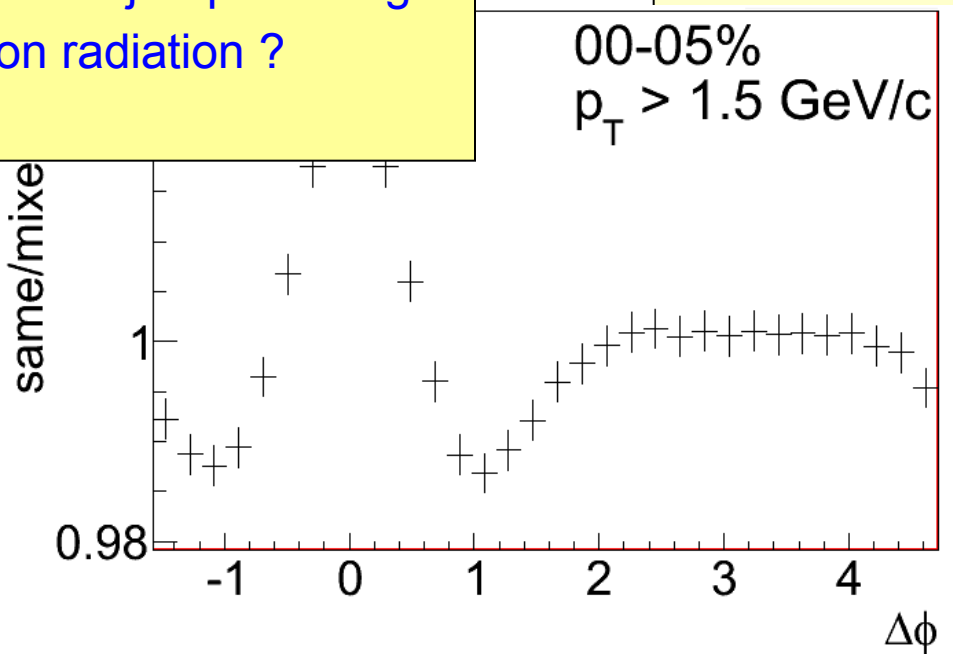
- 'Autocorrelation': $d^2N_{ch}/d\Delta\eta d\Delta\phi$ (signal)/$d^2N_{ch}/d\Delta\eta d\Delta\phi$ (mixed events)





'near side ridge':
- striking effect, not really understood
- response of QGP to jet quenching ?
- initial state gluon radiation ?
- ???





Role of LHC after RHIC/SPS

- 1) Quantitative differences
  - ⇨ significantly different state of QGP in terms of energy density, lifetime, volume
  - ⇨ large rate for 'hard probes' : jets, heavy quark states (b,c,Υ,J/Ψ),…

- 2) Test & validate the HI 'Standard Model'

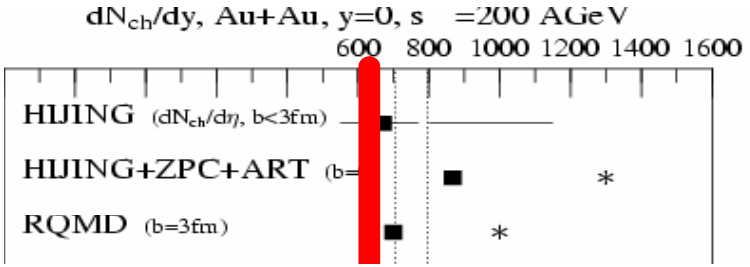
- 3) 'Precision' measurements of QGP parameters

- 4) Surprises ?

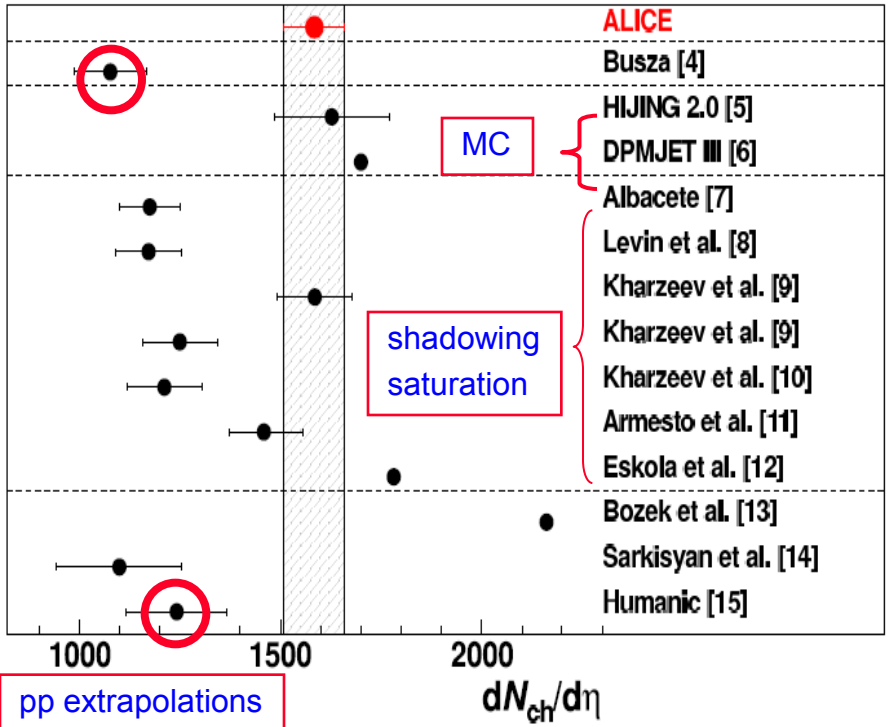
1) What's the Difference ?

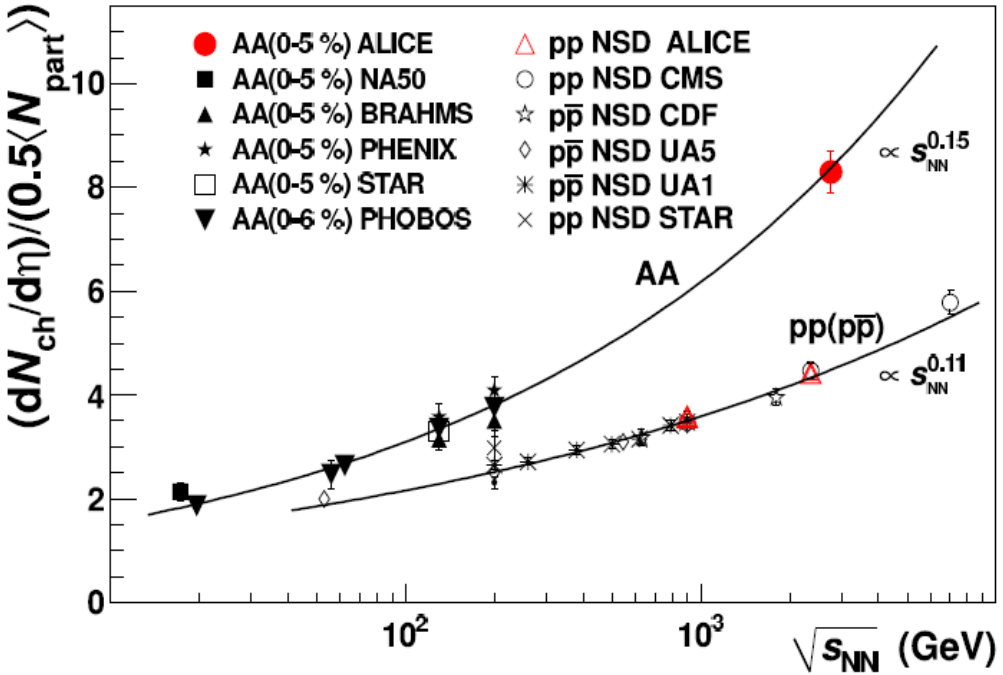
- Multiplicity and Energy density ε:
  - ⇨ **$dN_{ch}/d\eta \sim 1600 \pm 76$ (syst)**
    - somewhat on high side of expectations
    - growth with √s faster in AA than pp (√s dependent 'nuclear amplification')
  - ⇨ **Energy density ≈ 3 x RHIC** (fixed τ)
    - lower limit, likely τ_0(LHC) < τ_0(RHIC)

$$\varepsilon(\tau) = \frac{E}{V} = \frac{1}{\tau_0 A}\frac{dN}{dy} < m_t >$$



17 Nov: arXiv:1011.3916, acc. PRL

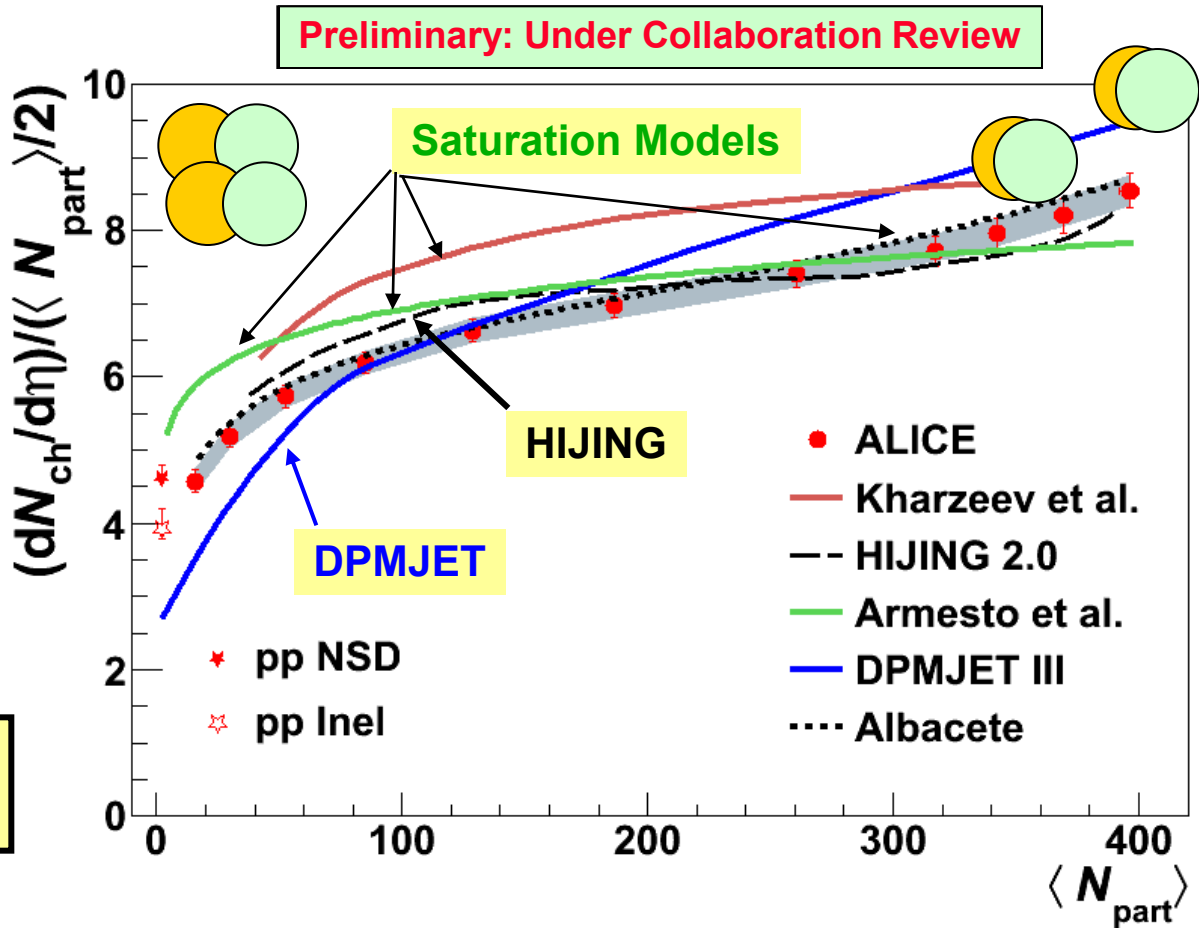




Who gets it right and why ?

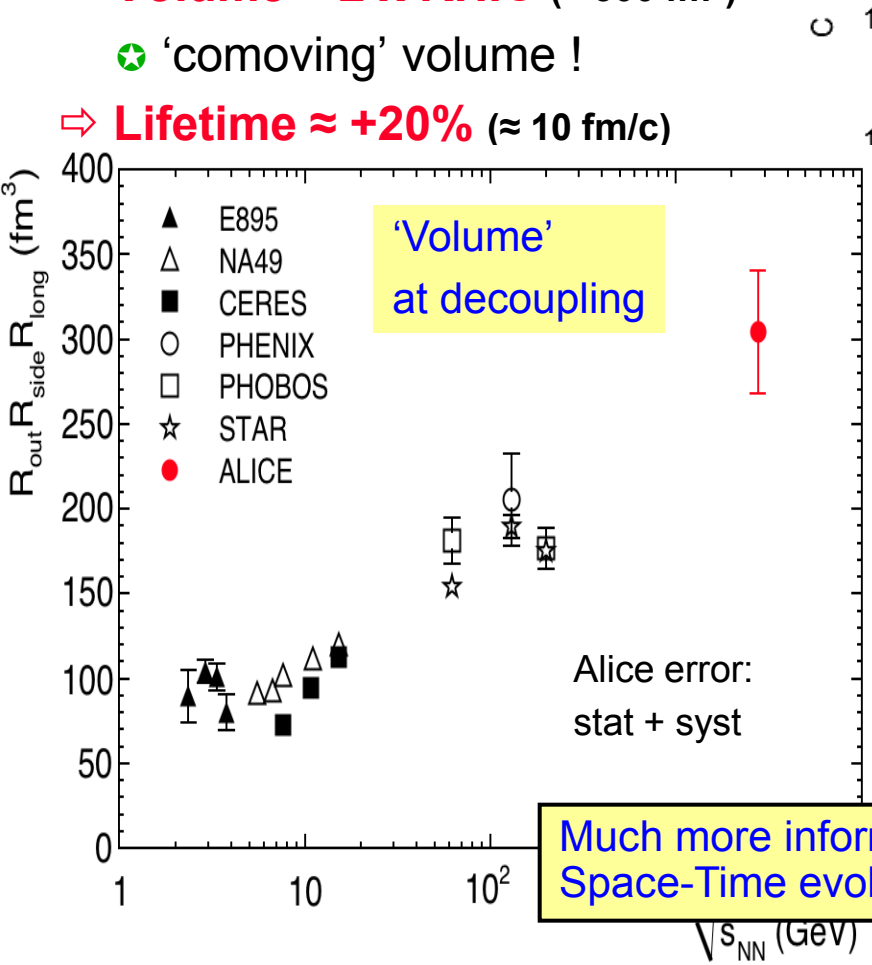
- $dN_{ch}/d\eta$ as function of centrality (normalised to 'overlap volume' ~ $N_{participants}$)
  - ⇨ soft process dN_{ch}/d_{η} ~ number of scattered nucleons (strings, participants, …)
    - ✪ 'nuclear amplification' should be energy independent
  - ⇨ (very) hard processes dN_{ch}/d_{η} ~ number of nucleon-nucleon collisions
    - ✪ getting more important with √s **&** with centrality
  - ⇨ DPMJET MC
    - ✪ gets it right for the wrong reason
  - ⇨ HIJING MC
    - ✪ strong centr. dependent **gluon shadowing**
  - ⇨ Others
    - ✪ **saturation models:** Color Glass Condensate, 'geometrical scaling' from HERA/ photonuclear react.

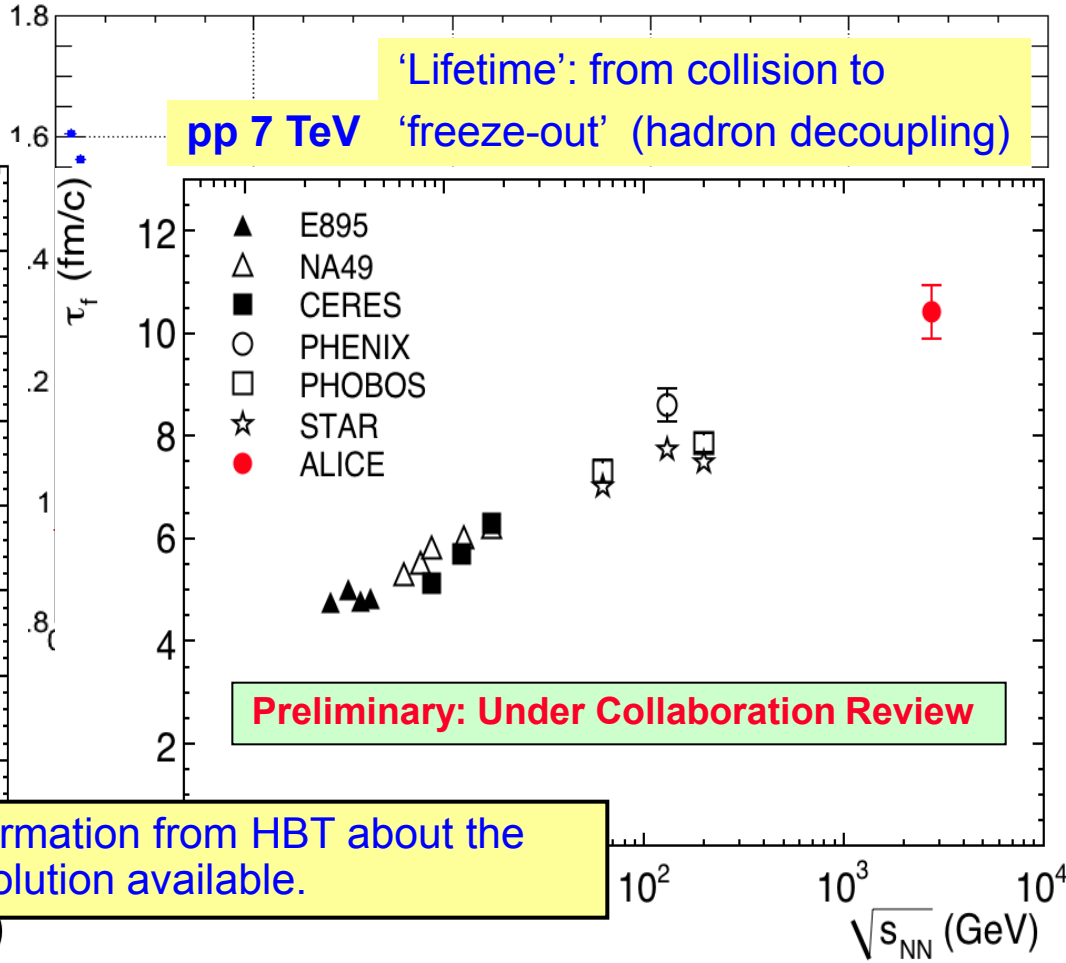
Important constraint for models sensitive to details of saturation



What's the Difference ?

- Volume and lifetime:
  - ⇨ Identical particle interferometry (HBT, Bose-Einstein correlations) $(E, \vec{\mathbf{p}}) \xrightarrow{\text{F.T.}} (\tau, \vec{\mathbf{X}})$
    - ✪ QM enhancement of identical Bosons at small momentum difference
    - ✪ measures Space-Time evolution of the 'dense matter' system in heavy ions coll.
  - ⇨ **Volume ≈ 2 x RHIC** (≈ 300 fm³)
    - ✪ 'comoving' volume !
  - ⇨ **Lifetime ≈ +20%** (≈ 10 fm/c)





Much more information from HBT about the Space-Time evolution available.

Role of LHC after RHIC/SPS

- 1) Quantitative differences

- 2) Test & validate the HI 'Standard Model'

QGP = very strongly interacting (almost) perfect liquid

⇨ Test predictions/extrapolations from RHIC to LHC

✪ examples: **flow** ('soft') **Quarkonia suppression** ('hard')

- 3) 'Precision' measurements of QGP parameters

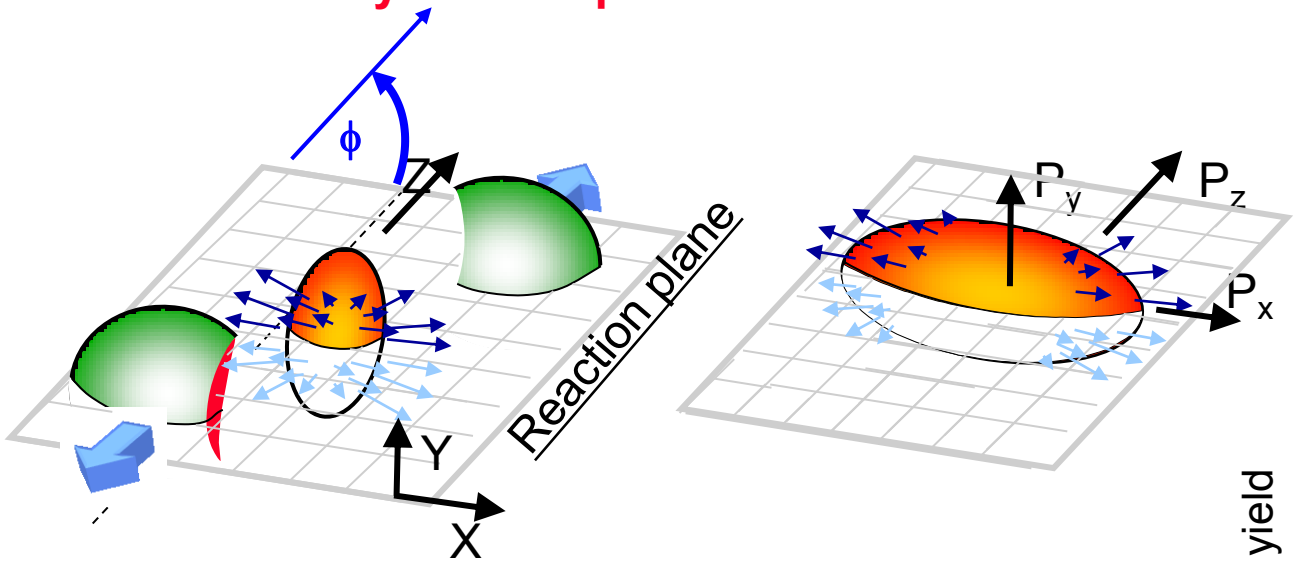
- 4) Surprises ?

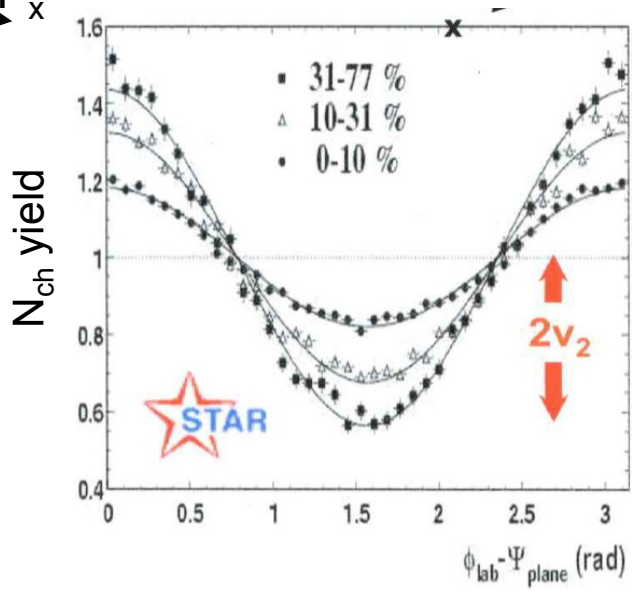
2) Testing the HI 'Standard Model'

- Elliptic Flow: one of the most anticipated answers from LHC

⇨ **experimental observation:** particles are distributed with azimuthally anisotropic around the scattering plane

⇨ **Are we sure Hydro interpretation is correct ?**





Elliptic Flow v_2 as interpreted by **Hydrodynamics**

Pressure gradient converts

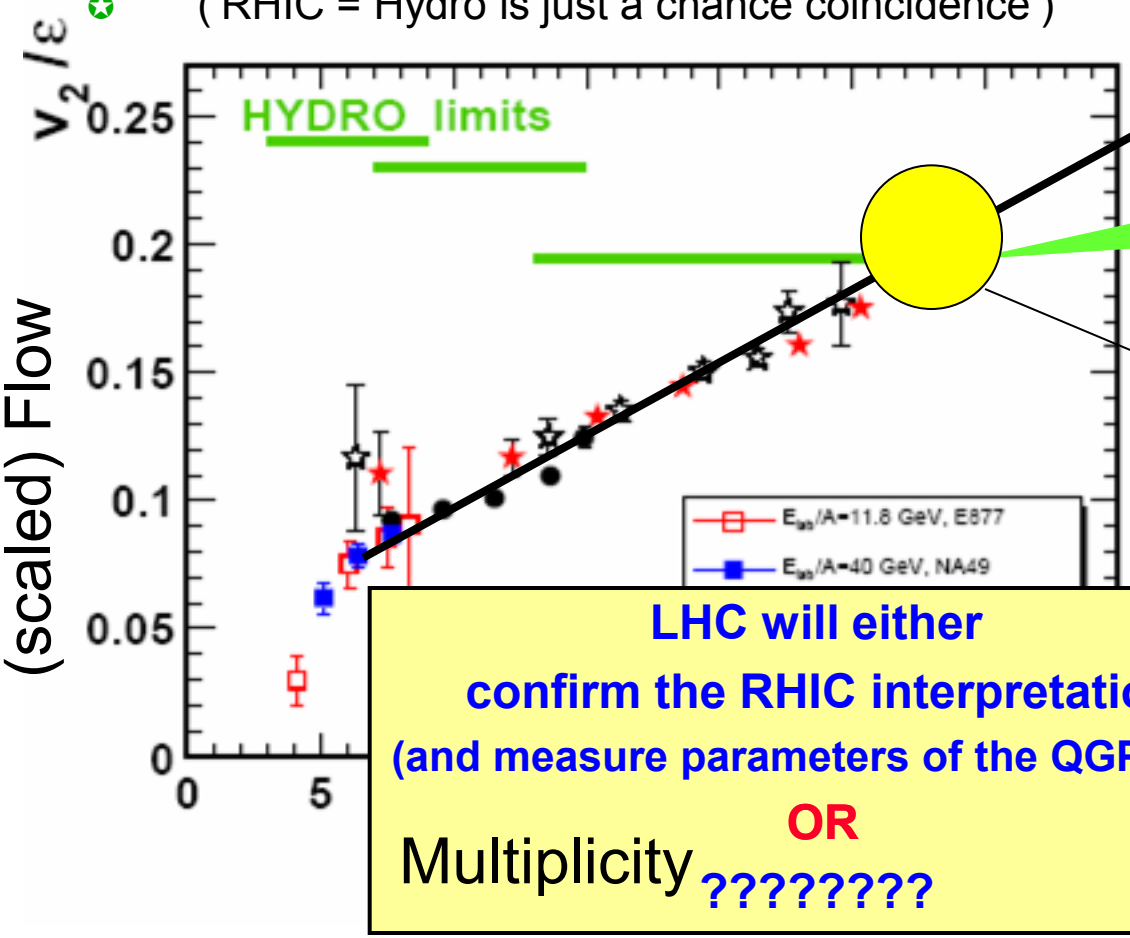
spatial anisotropy → momentum anisotropy

→ particle yield anisotropy

Testing the HI 'Standard Model'

- Hydro seems to work very well for first time at RHIC
  - ⇨ LHC prediction: modest rise (Depending on EoS, viscosity, speed of sound, $dN_{ch}/d\eta$, ..)
    - ('better than ideal is impossible')
  - ⇨ experimental trend & scaling predicts large increase of flow
    - ('RHIC = Hydro is just a chance coincidence')

LHC ?



BNL Press release, April 18, 2005:

Data = ideal Hydro

"Perfect" Liquid

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

LHC will either

confirm the RHIC interpretation

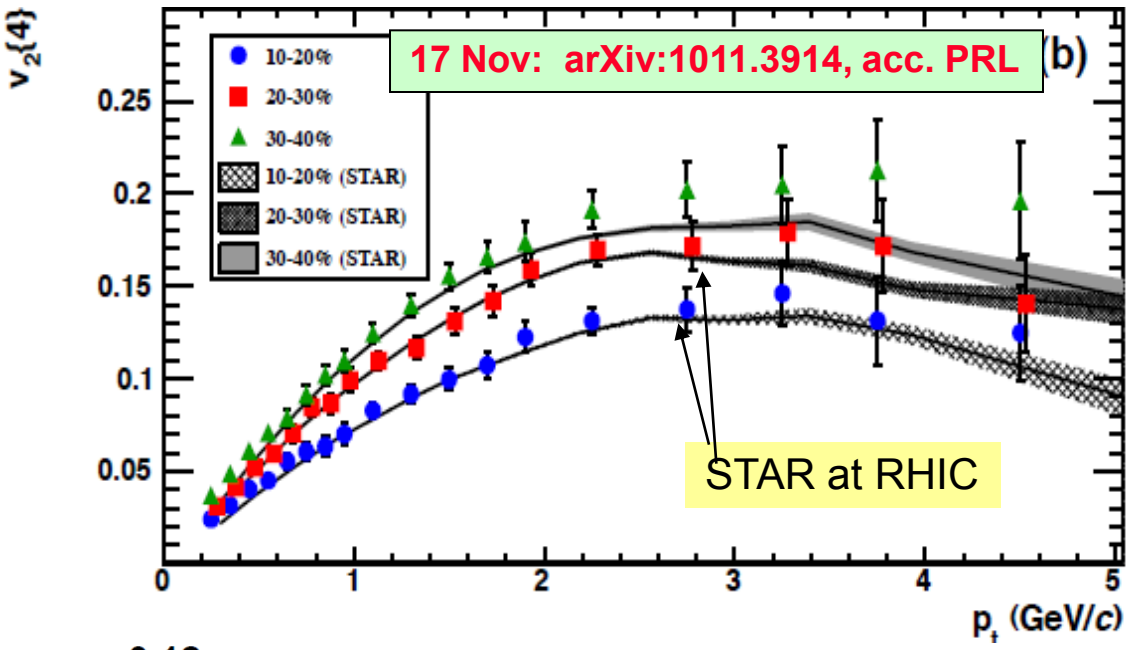
(and measure parameters of the QGP EoS)

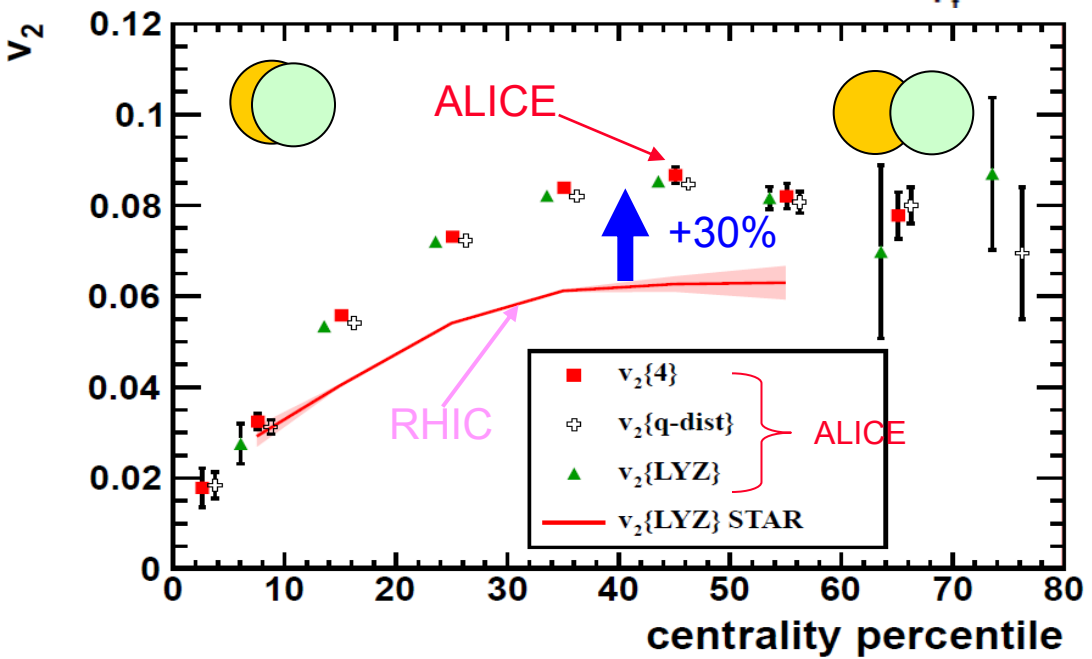
OR

Multiplicity **????????**

First Elliptic Flow Measurement at LHC

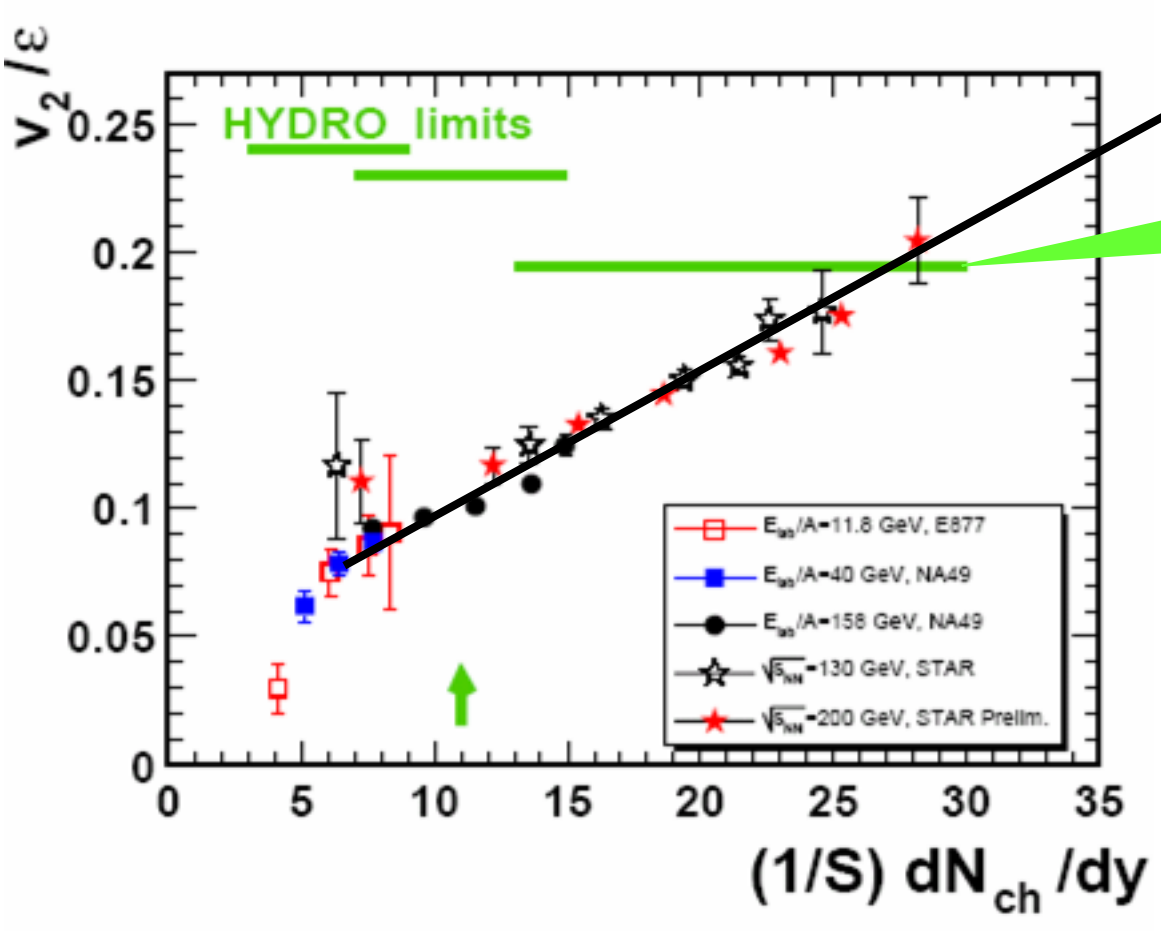
- v_2 as function of p_t
  - ⇨ **practically no change with energy !**
    - ✪ extends towards larger centrality/higher p_t ?
- v_2 integrated over pt
  - ⇨ **30% increase from RHIC**
  - ⇨ $\langle p_t \rangle$ increases with √s
    - ✪ pQCD powerlaw tail ?
  - ⇨ Hydro predicts increased 'radial flow'
    - ✪ very characteristic p_t and mass dependence; **to be confirmed !**





Testing the HI 'Standard Model'

- Hydro passed the first test !
  - ⇨ many more tests of Hydro and the HI-SM to come….



LHC !

CERN Press release, November 26, 2010:

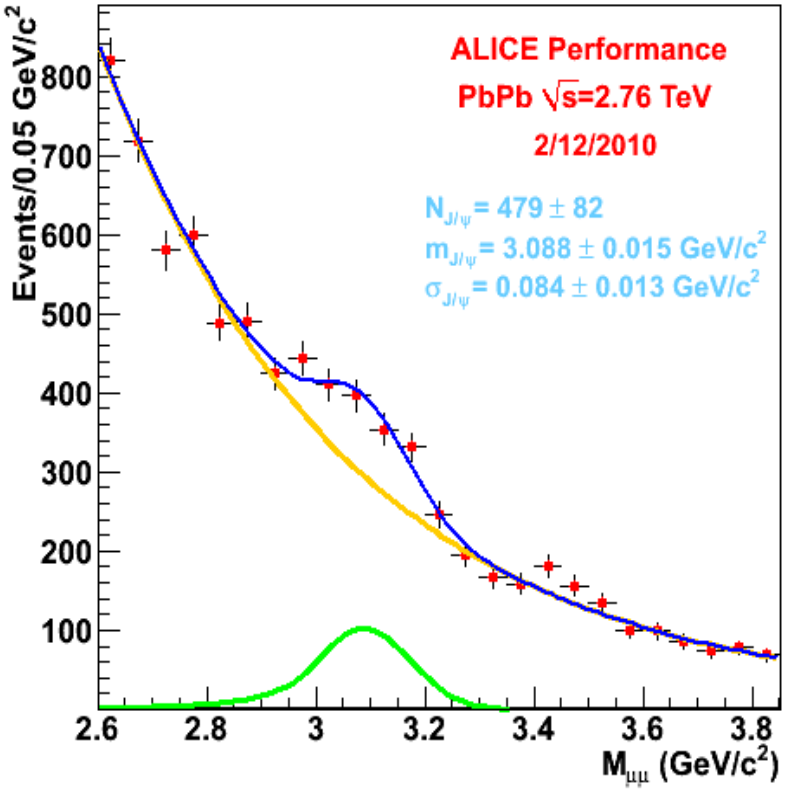
'confirms that the much hotter plasma produced at the LHC behaves as a very low viscosity liquid (a perfect fluid)..'

Testing Quarkonia Suppression

- Interpretation of SPS & RHIC results ambiguous
  - ⇨ **HI–SM :** J/Ψ (Υ', Υ'') suppression stronger at LHC, Υ suppression depends on T
  - ⇨ **extension** to HISM: J/Ψ enhancement, Υ', Υ'' suppression
    - ✪ recombination of charm pairs to J/Ψ may mask suppression at RHIC

- Partial answer expected from this vears data
  - ⇨ normalisation (measured/expected) ongoing
  - ⇨ Υ family will need integrated L ~ 1-2 nb^{-1}

Pb-Pb Min. Bias
fraction of data
expect few 1000 J/Ψ
total by end 2010



Role of LHC after RHIC/SPS

- 1) Quantitative differences
- 2) Test & validate the HI 'Standard Model'

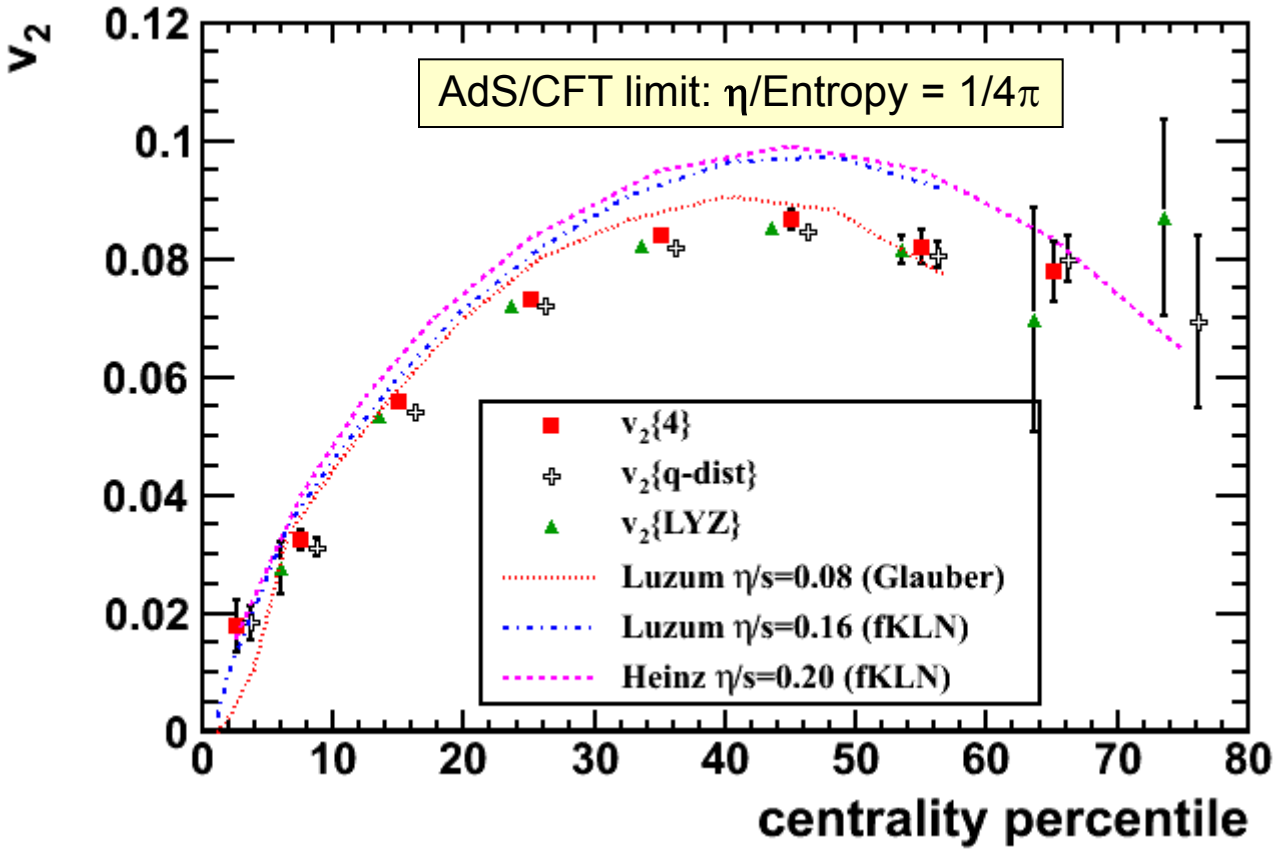
Precision measurements are still a long way ahead, but it looks like we will get there !

- 3) 'Precision' measurements of QGP parameters
  - ⇨ Quantitative and systematic study of the new state of matter
    - ✪ **Equation-of-State** f(ε,p,T), **viscosity** η (flow), **transport coefficient q** (jet quenching), Debye **screening mass** (Quarkonia suppression), …
  - ⇨ Confront with Theory and Models:
    - ✪ **standard tools:** Lattice QCD, pQCD, Thermo- and Hydrodynamics, …
    - ✪ **new tools:** AdS/CFT ('duality'), Classical QFT ('Colour Glass Condensate')

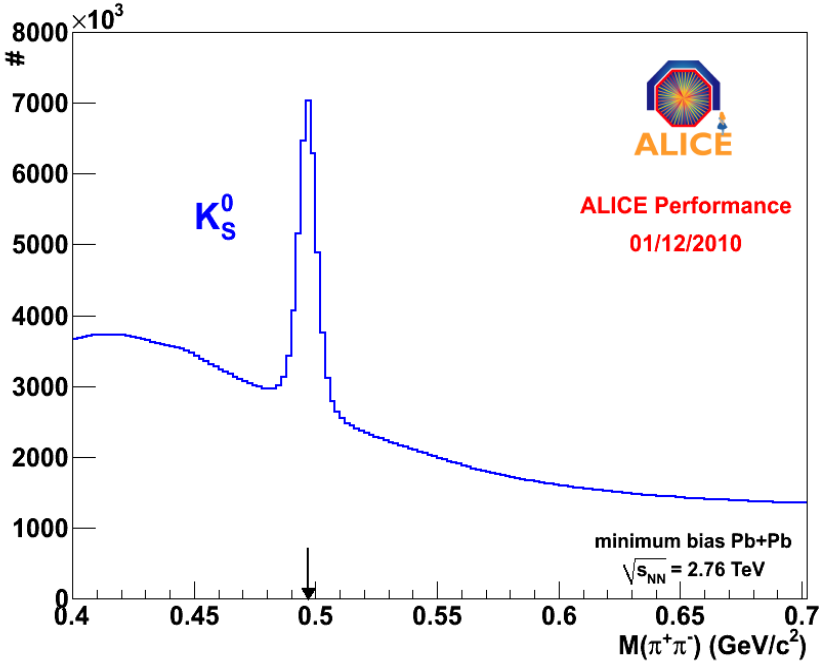
- 4) Surprises ?

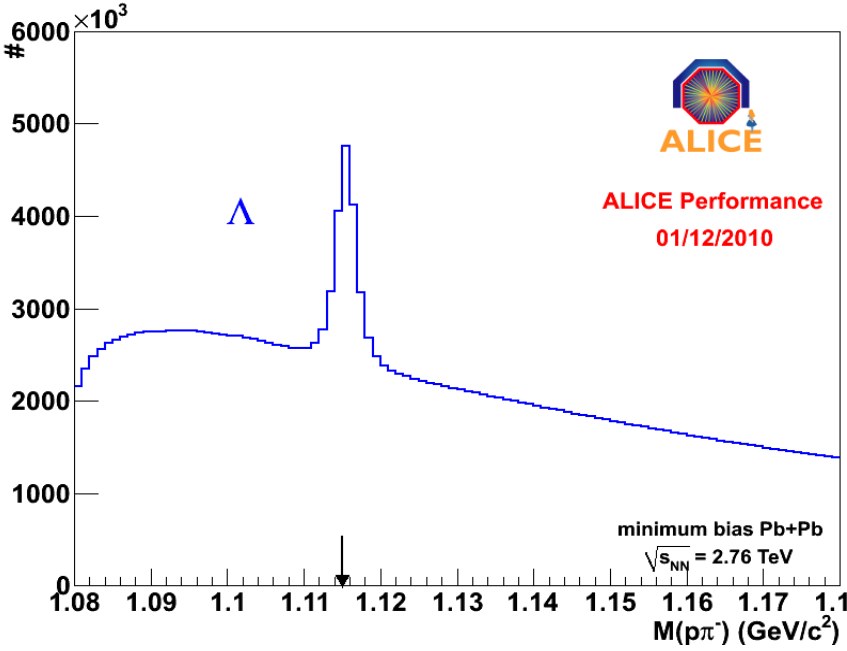
3) Towards Precision Measurements

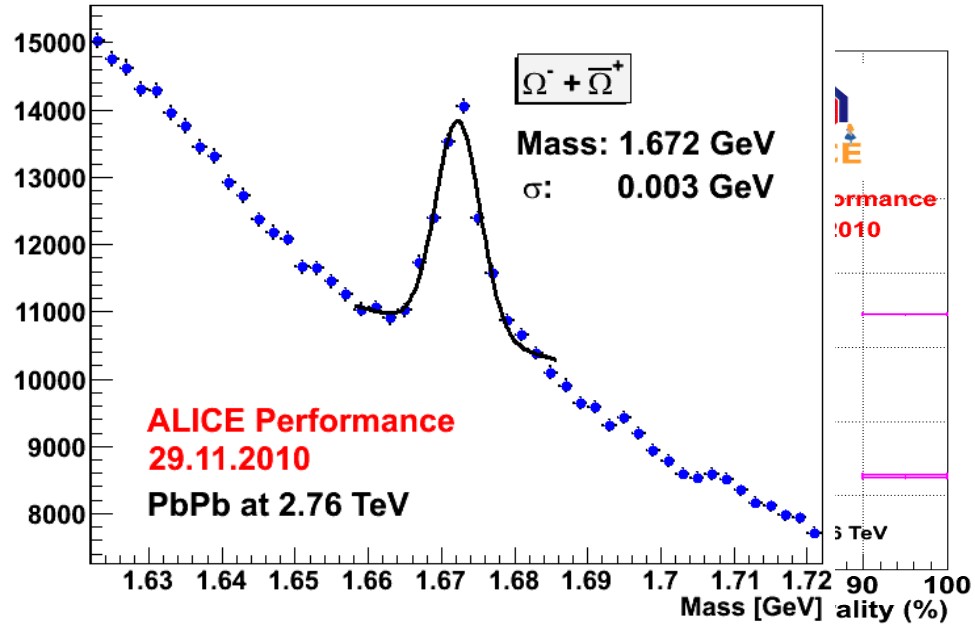
- Sensitivity to fluid viscosity η
  - ⇨ Quantitative results will need much more time and more experimental input …
    - ✪ elliptic flow with identified particles, radial flow ('radial expansion'), better determination of initial geometry, ……

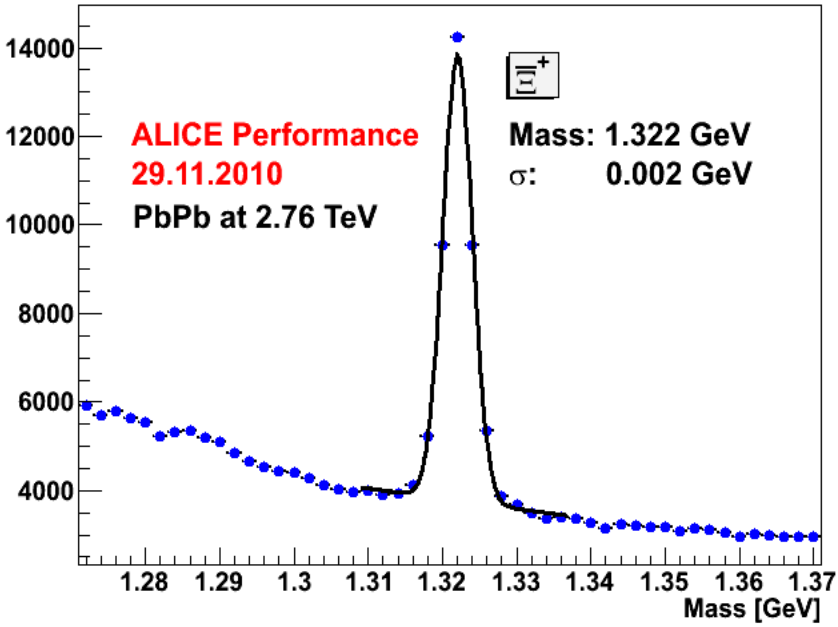


Strangeness in Pb-Pb

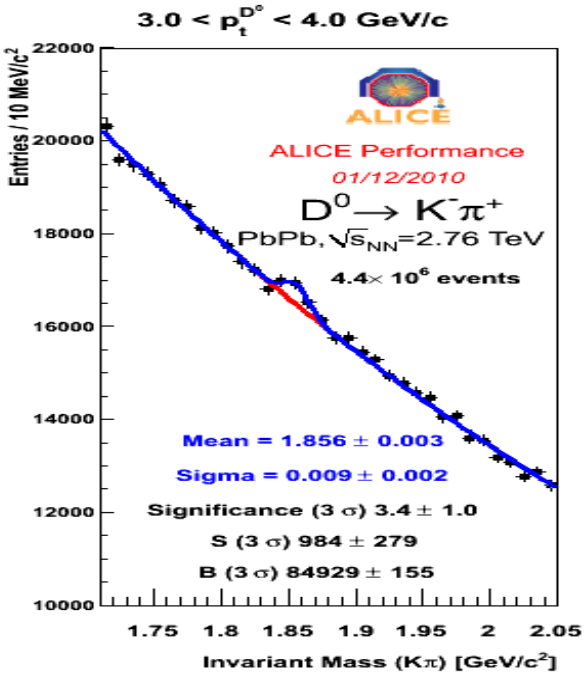


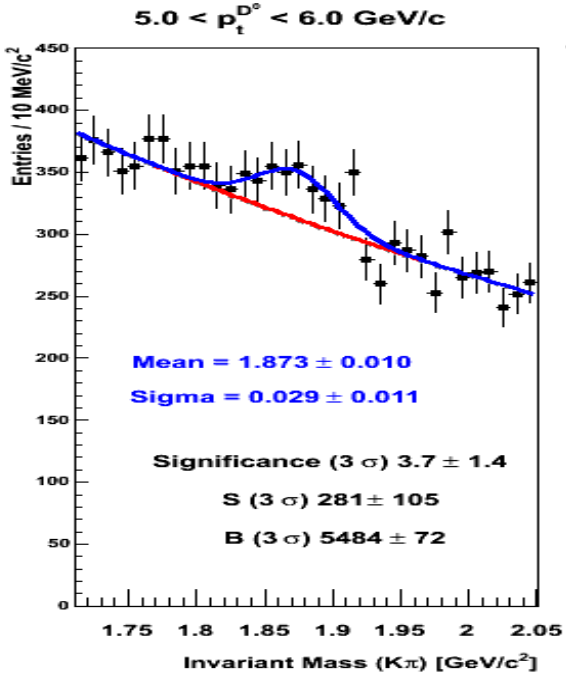


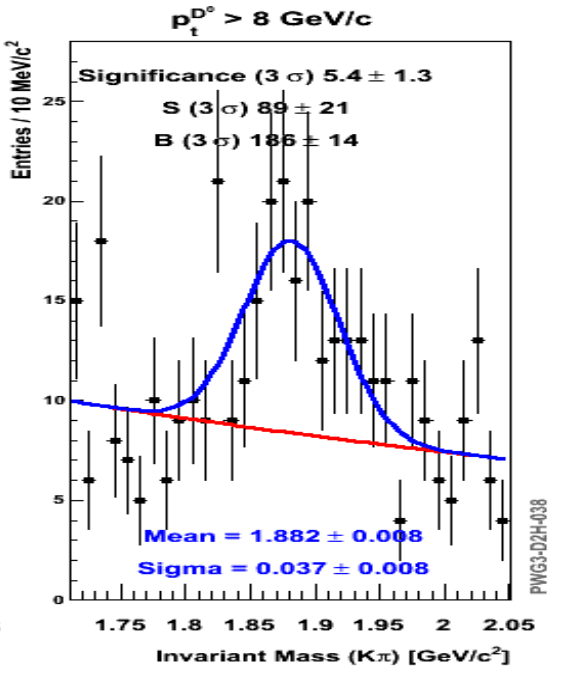




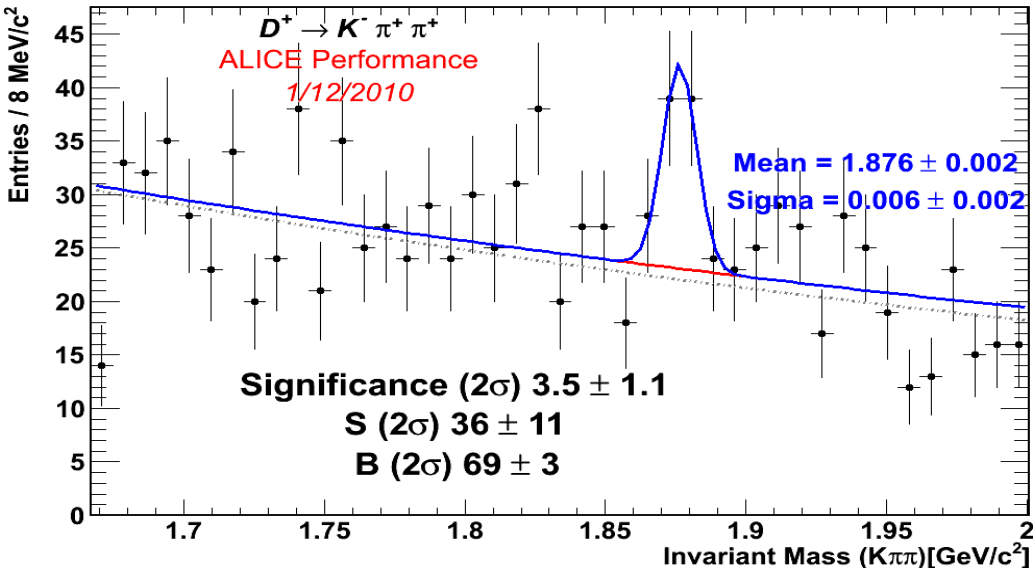
Charm in Pb-Pb







Pb-Pb $\sqrt{s}$=2.76 TeV, 1.7 × 10^6 events, $p_t^{D^+}$ > 6 GeV/c

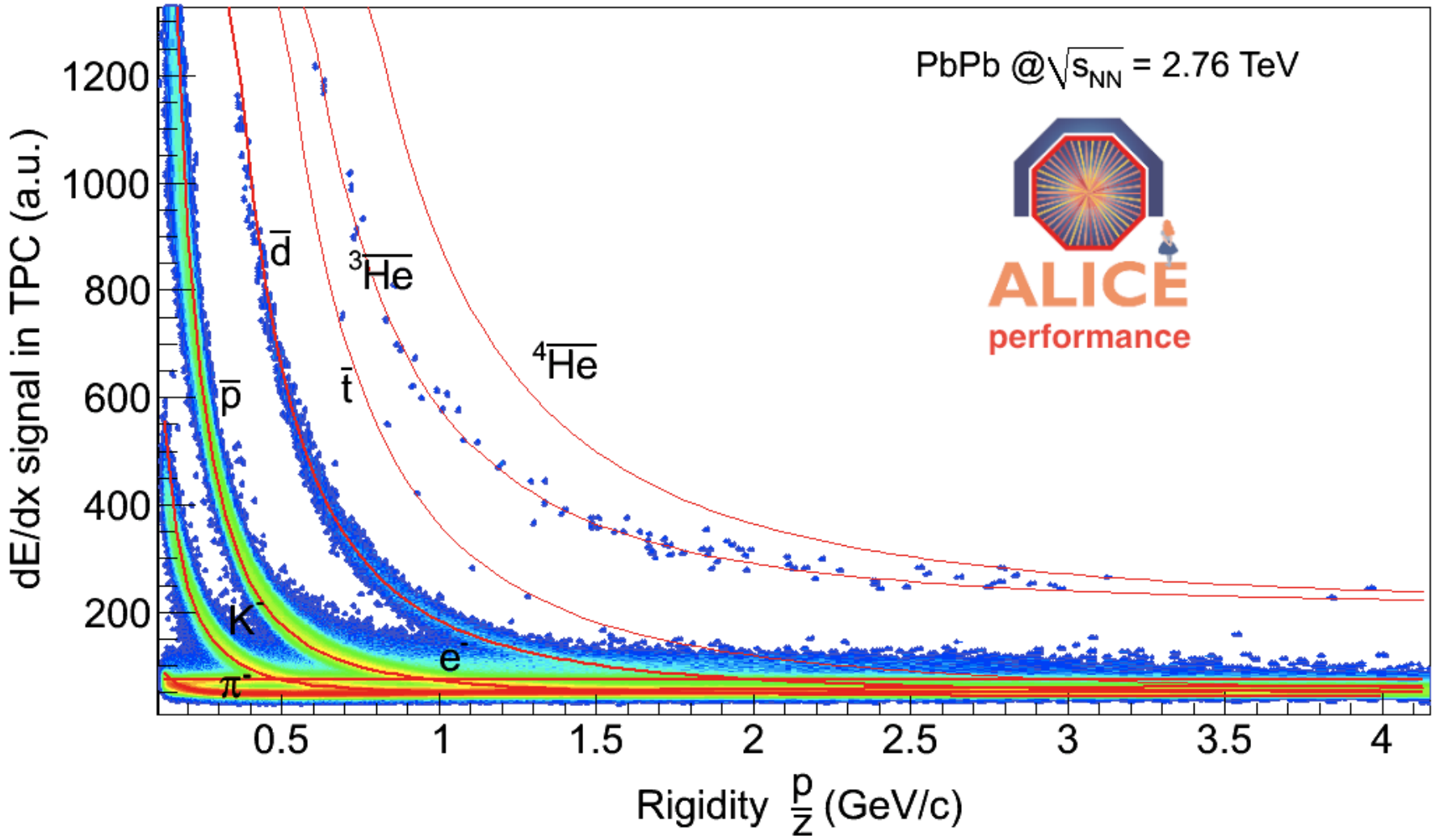


‘Jet quenching’ with heavy quarks:

Energy loss depends on

- color charge (quark/gluon)
- mass (light/heavy quarks)

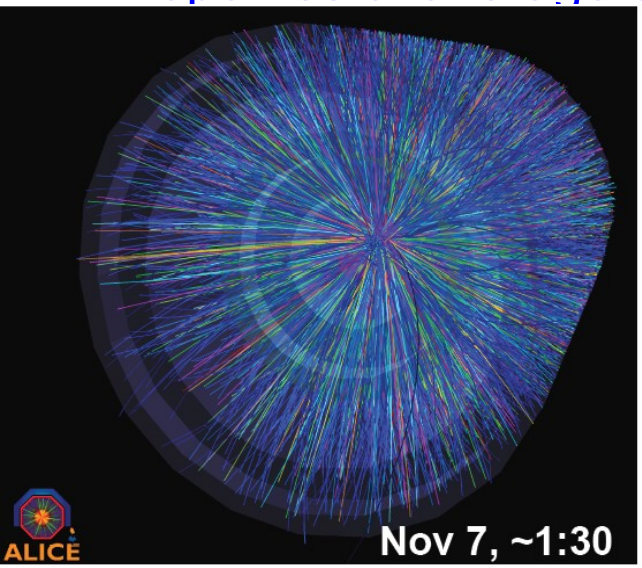
Anti-Nuclei

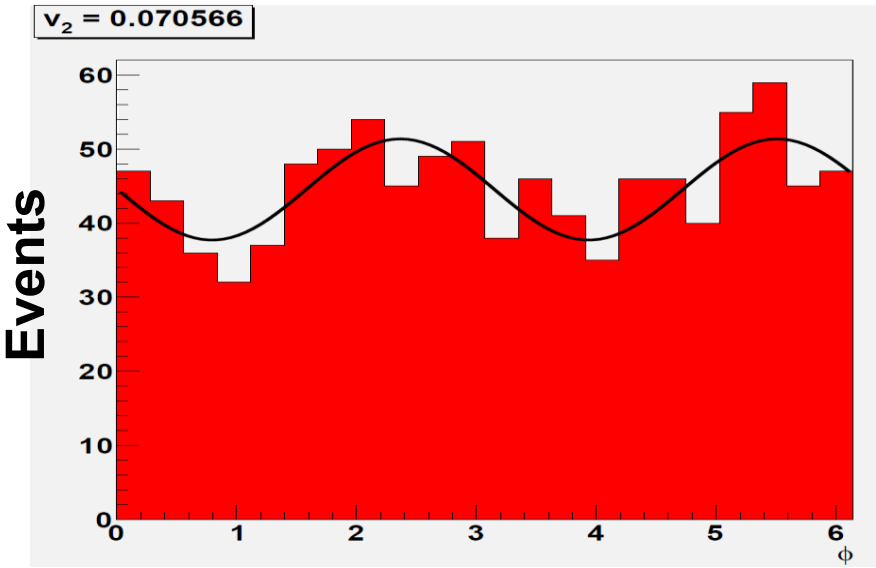


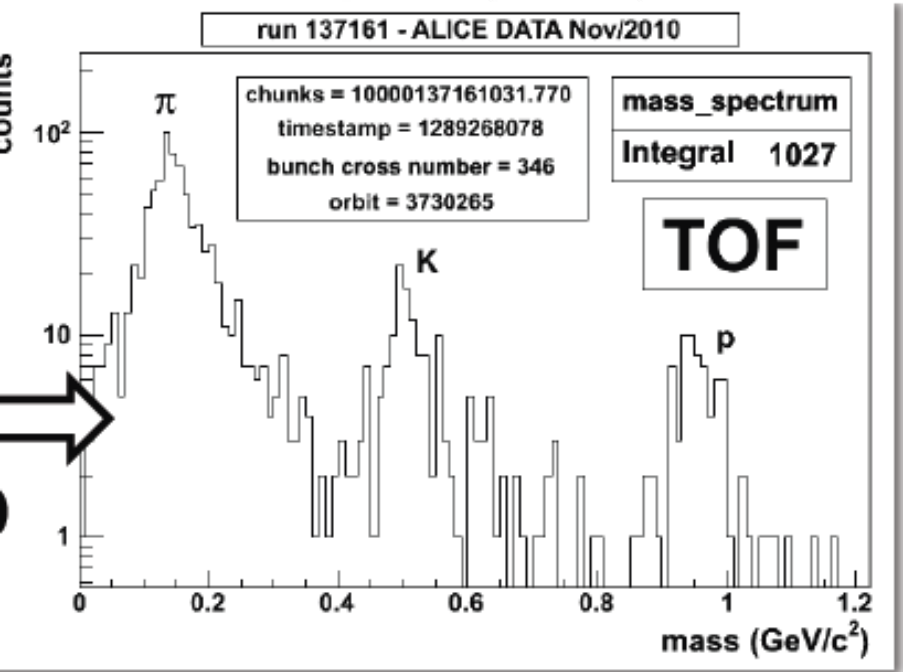
~ 2 M Pb-Pb Min Bias events

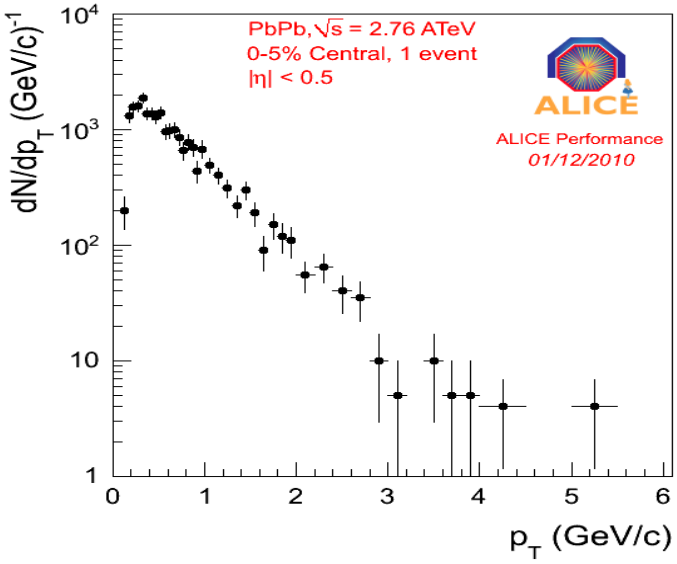
‘Single Events’

- ‘Properties of average events instead of average event properties’









Summary

- LHC is a fantastic 'Big Bang' machine
  - ⇨ even for LHC standards, speed and quality of ion run is outstanding
  - ⇨ unprecedented powerful and complementary set of detectors (LHCb, wanna join ?)
  - ⇨ physics looks to be even more interesting than anticipated

While waiting for Mr. Higgs and Ms. Susy,
there is plenty of exciting physics (and fun)
exploring QCD in a new domain,
where the strong interaction is really strong !

- Looking forward to the 'terra incognita' of HI at LHC

Big THANKS to the **CERN crew**
from ion source all the way to LHC

Hic sunt Leones !