# Heavy Ion Physics at ATLAS and CMS

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for

and

**Workshop on Physics at the LHC era**

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# Outline

- Heavy Ion Physics
- From RHIC to LHC
- Performance in ATLAS and CMS
- Outlook

# Why Heavy Ions at the LHC?

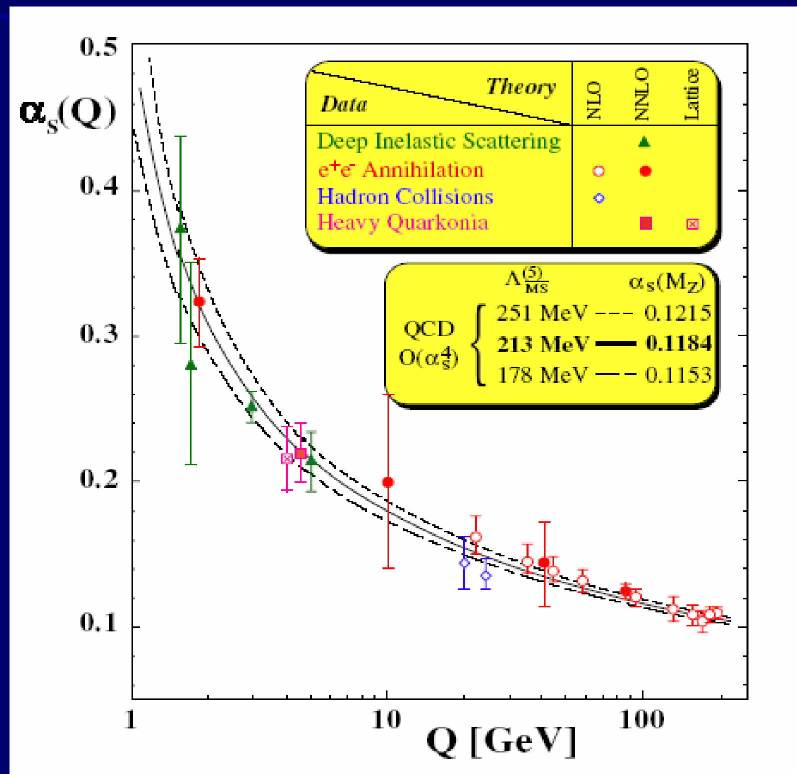
- QCD is the fundamental theory of strong interactions.

$$L_{QCD} = -\frac{1}{4} F^{\alpha}_{\mu\nu} F^{\mu\nu}_{\alpha} - \sum_{n} \overline{\psi}_{n} \left( \partial - ig\gamma^{\mu} A^{\alpha}_{\mu} t_{\alpha} - m_{n} \right) \psi_{n}$$

- QCD is well studied/tested in the few particles and large $Q^2$– i.e. in perturbative limit

- Heavy Ions provide a new opportunity to study **QCD in small** $Q^2$ **and many-particle regime**

# QCD Coupling Constant



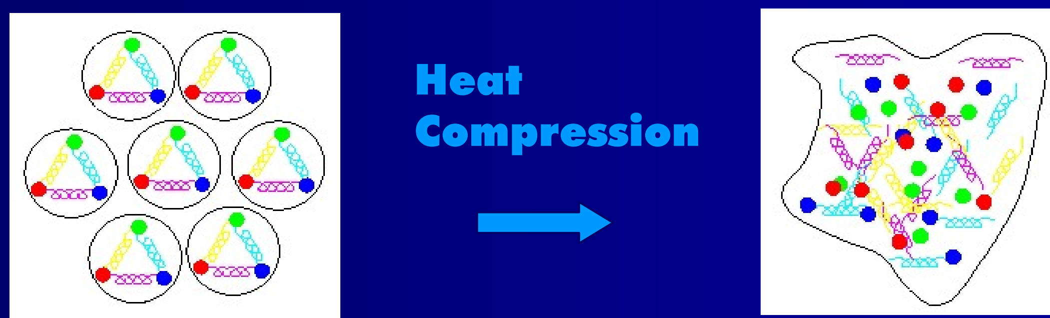

**NP**

**HEP**

**non perturbative at long range/low energy**

**asymptotic freedom at short range / high energy**

# Matter under Extreme conditions




Normal Nuclear Matter    Quark Gluon Plasma

- Quark-Gluon Plasma (QGP) is a state of QCD and is considered to be the primordial matter of the Universe
  - Quarks and gluons are deconfined
  - Chiral symmetry is restored (quarks are massless)

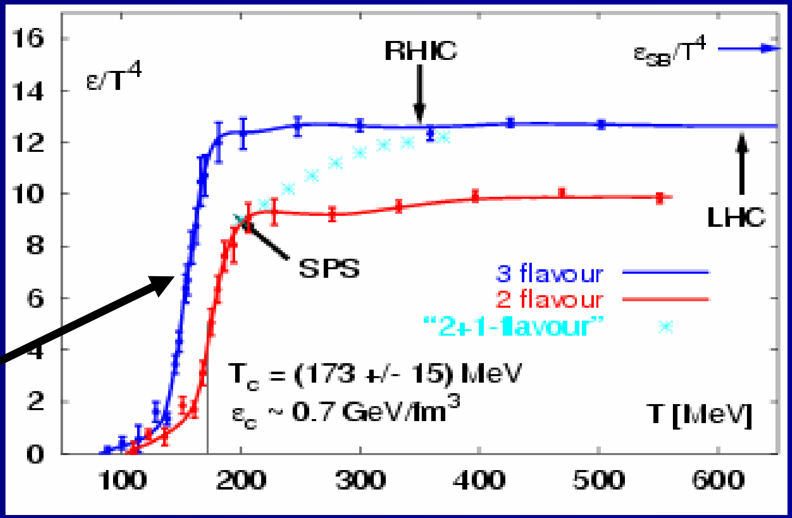
- HI collisions provide unique opportunity to study matter limit of QCD
  - Another calculable limit of QCD
    - Asymptotic freedom via high temperature
  - Only matter we can create in the laboratory whose properties are entirely determined by *fundamental*, *non-Abelian* interaction

# Lattice QCD calculations

- The nature of this bath of quarks and gluons cannot be calculated directly with Quantum Chromodynamics.
- Teraflop-scale computers simulate equilibrium QCD (assume thermal system)

- Predict phase transition:

$$T_c \sim 170\ MeV \quad or \quad 10^{12}\ F$$
$$\varepsilon_c \sim 0.7\ GeV / fm^3$$




**A fundamental "phase transition" that can be studied in the lab**

**Direct consequence of asymptotic freedom.**

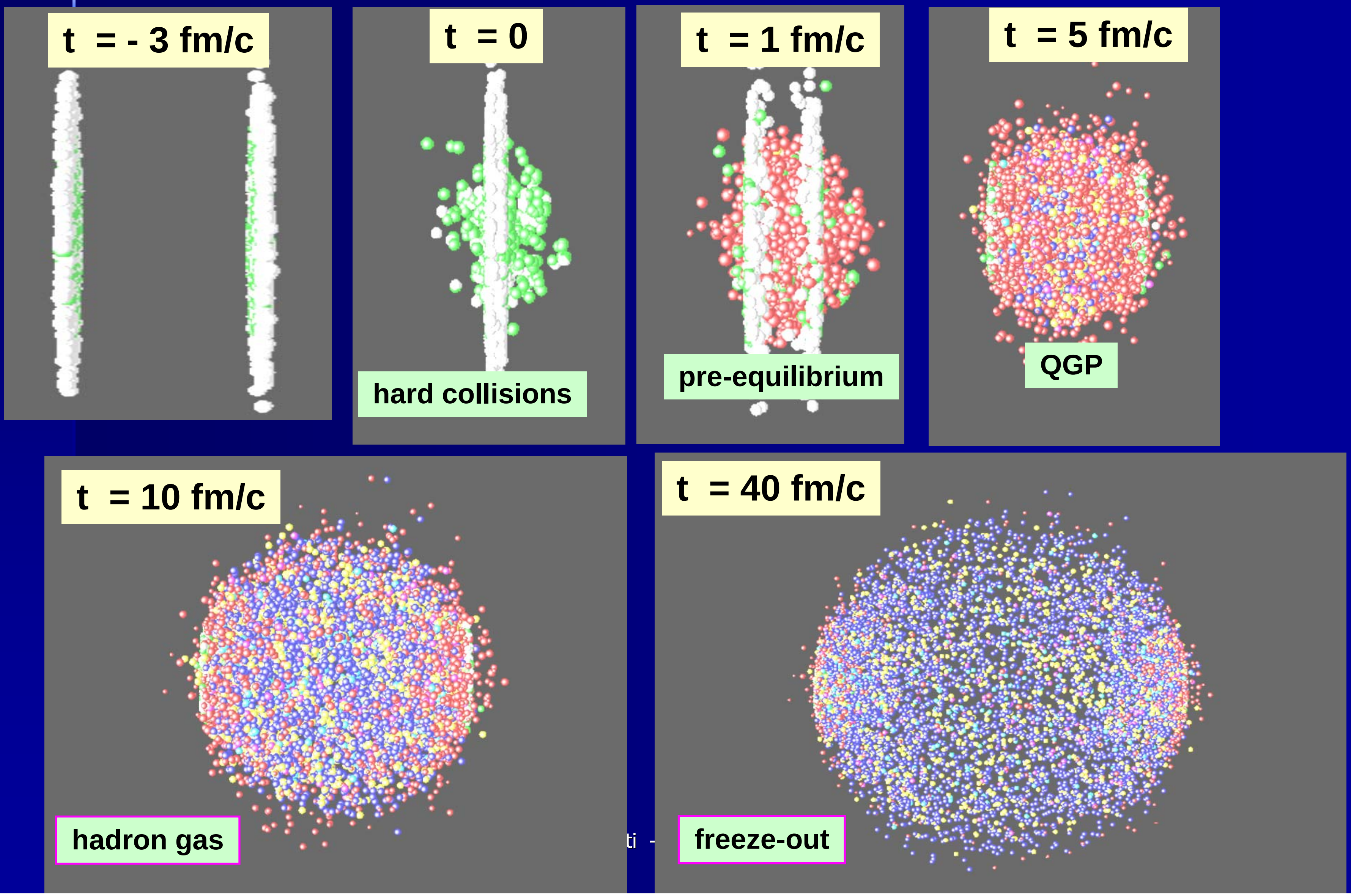
# LHC Heavy Ion Program

- Machine
  - Energy
    - E(beam)=7* Z/A→$\sqrt{s}$ = 5.5.TeV/A or 1.14 PeV for Pb-Pb
  - Heavy Ion Running
    - Typically 4 weeks/ year
    - Luminosity $10^{27}$ $cm^{-2}$ $s^{-1}$ (Pb)

      ⇨ 10 kHz rates
- Experiments
  - ALICE: experiment designed for HI
  - ATLAS and CMS: have a major and rich HI program

    ⮡ this talk

# Stages during HI Collision



# What Have We Learned from RHIC

- Au+Au collisions @ 200 GeV/N-N pair produce "matter" with energy density > 10 GeV/$fm^3$

  ~ 10x the critical energy density.

- This matter induces strong energy loss in hard-scattered quarks and gluons.
- This matter thermalizes rapidly and generates large pressures – much larger than expected
  - "Ideal Fluid"
- Initial conditions of a heavy ion collision are affected by strong coherent gluon fields in the incident nuclei (saturation).
- Discovering the Quark-Gluon Plasma is no longer the issue.

# Heavy Ion Physics at LHC

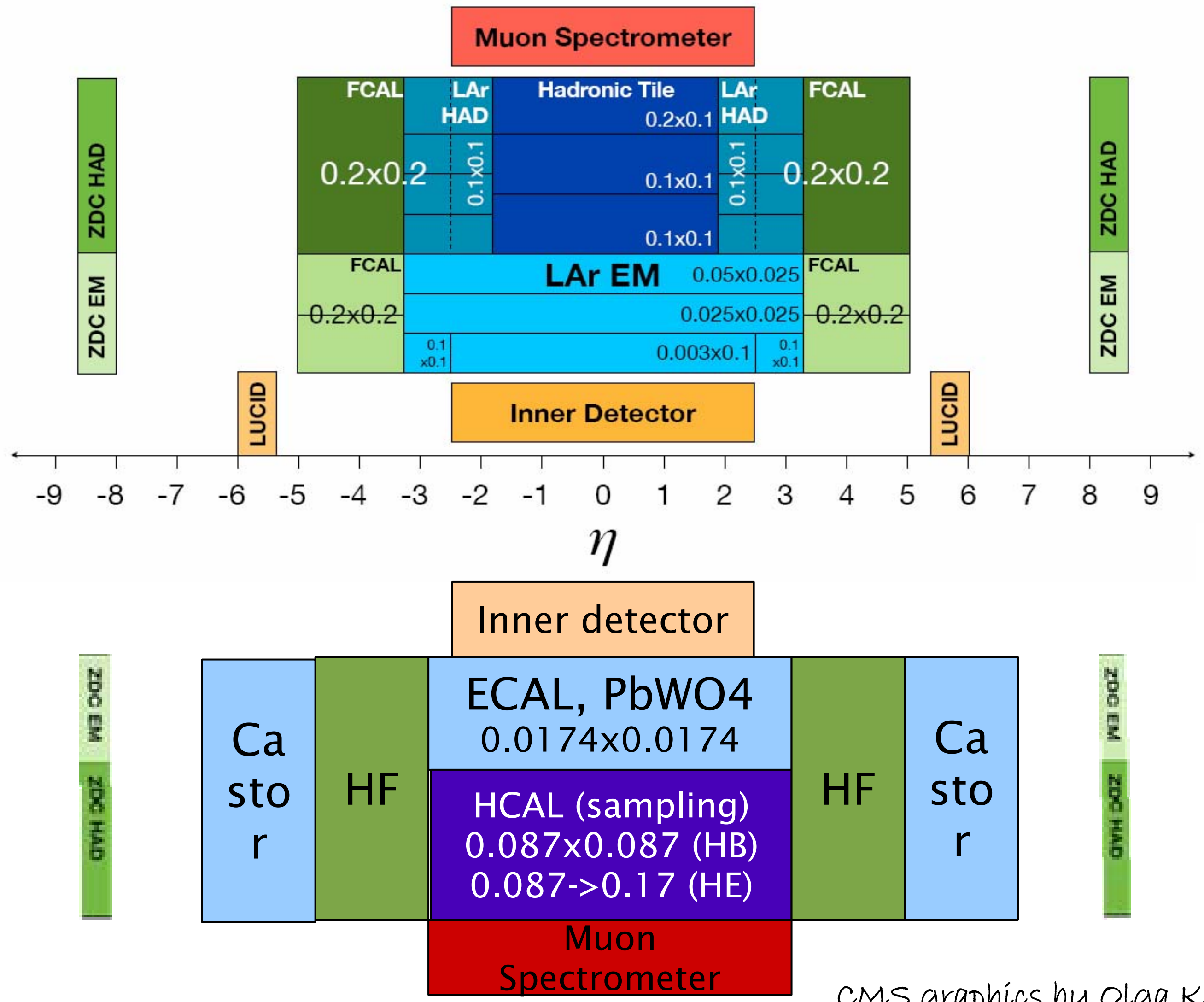
- LHC: factor 30 jump in center of mass energy with respect to RHIC

| Central collisions | SPS | RHIC | LHC |
|---|---|---|---|
| $s^{1/2}$(GeV) | 17 | 200 | 5500 |
| $dN_{ch}/dy$ | 430 | 700 | 2- 8 $x10^3$ |
| $\varepsilon$ (GeV/fm$^3$) | 2.5 | 3.5-10 (× 4 -10) | 15- 40 |
| $V_f$(fm$^3$) | $10^3$ | $7x10^3$ | $2x10^4$ |
| $\tau_{QGP}$ (fm/c) | < 1 | 1.5- 4.0 (× 3) | 4-10 |

# The ATLAS and CMS detectors

**Different technologies but close acceptances – cross-checks possible.**

**Unprecedented acceptance for A+A physics both in $p_T$ and rapidity, with full azimuth**




CMS graphics by Olga Kodolova

**ATLAS:**

**Inner detector (|η|<2.5)**
**ECAL (|η|<3.2)**
**HCAL (|η|<3.2)**
**HF (3.2<|η|<5)**
**Muon (|η|<2.7)**
**Lucid (5.5<|η|<6)**
**ZDC (|η|>8)**

**CMS:**

**Inner detector (|η|<2.5)**
**ECAL (|η|<3)**
**HCAL (|η|<3)**
**HF (3<|η|<5)**
**Muon (|η|<2.4)**
**Castor (5<|η|<6.7)**
**ZDC (|η|>8)**

# Heavy Ion Physics Program at LHC

- LHC will accelerate and collide heavy ions at energies far exceeding the range of existing accelerators:
  - A hotter and longer lived partonic phase
  - Extended kinematic reach for pp, pA, AA
  - New experimentally accessible hard probes
- Some examples of what we hope to do:
  - First 15 min of running at low luminosity ~ $10^5$ events:

    **global event properties and hadronic observables**
    - **multiplicity**
    - **elliptic flow**
  - first few days of running ~ $10^7$ events:

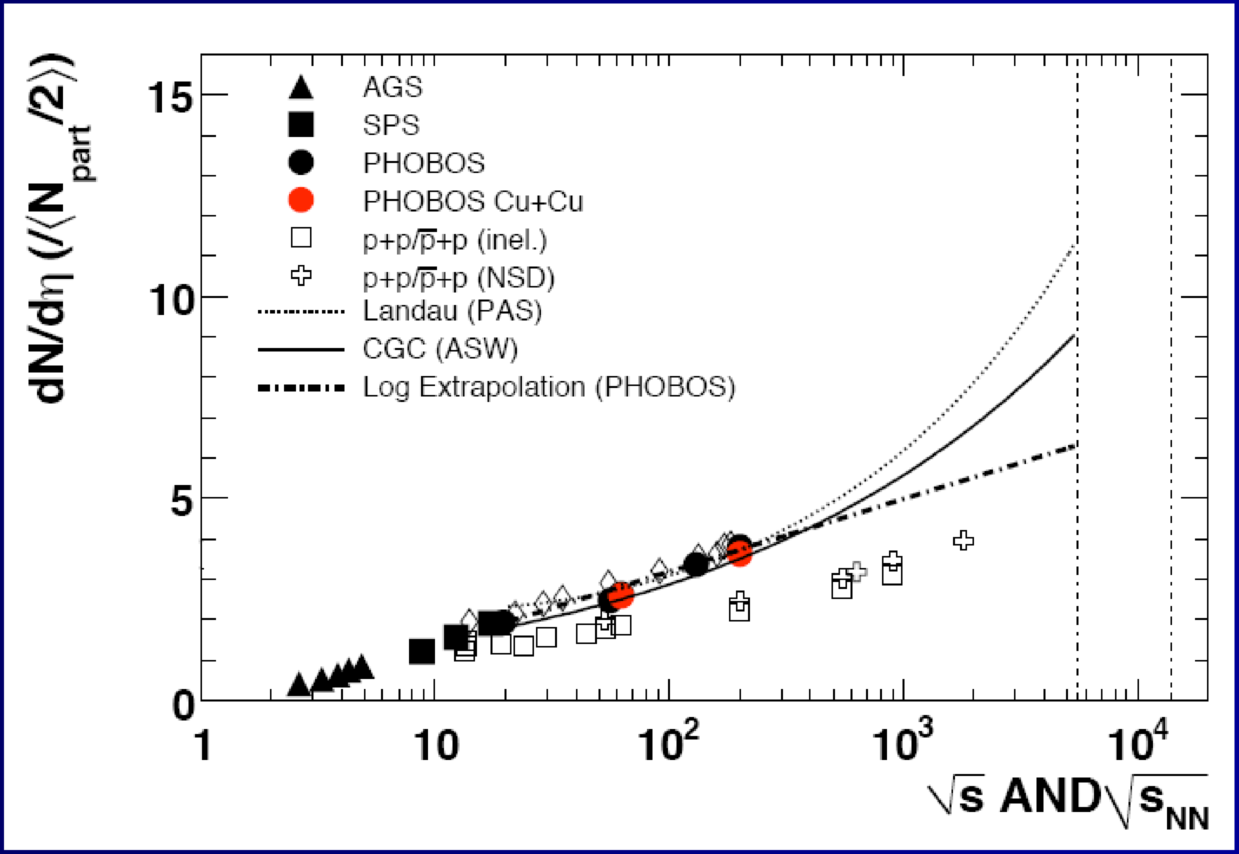
    **high-pt, heavy flavor**
    - **jet quenching, photon, heavy-flavour energy loss**
    - **quarkonium production**

# GLOBAL EVENT PROPERTIES:

- Characterize gross properties of initial state
- Test saturation predictions
- Probe early collective motion

# Charged Particle Density vs c.m. energy

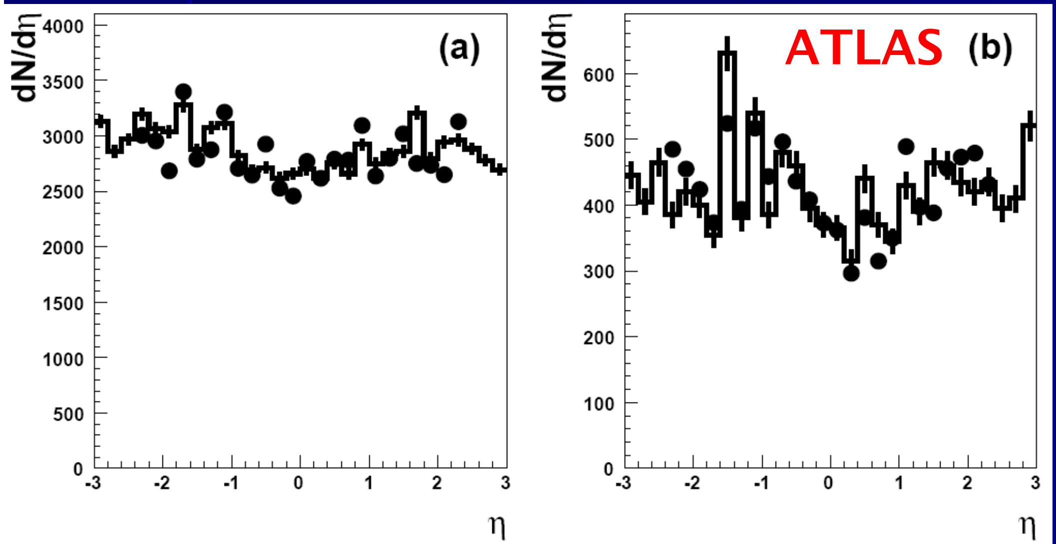
- First estimate of energy density
- Saturation, CGC ?



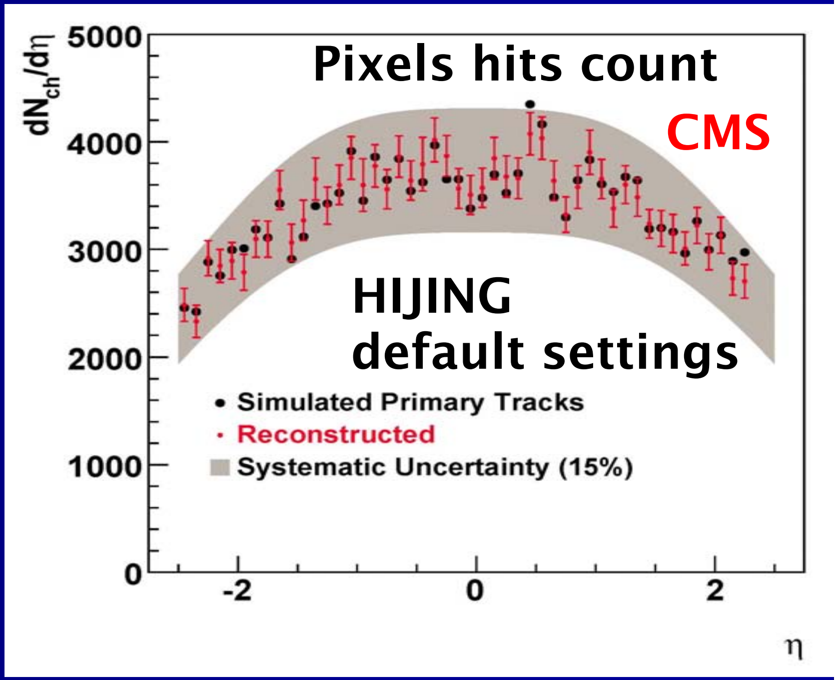
# Multiplicity measurements

One event

- **Silicon Hits**

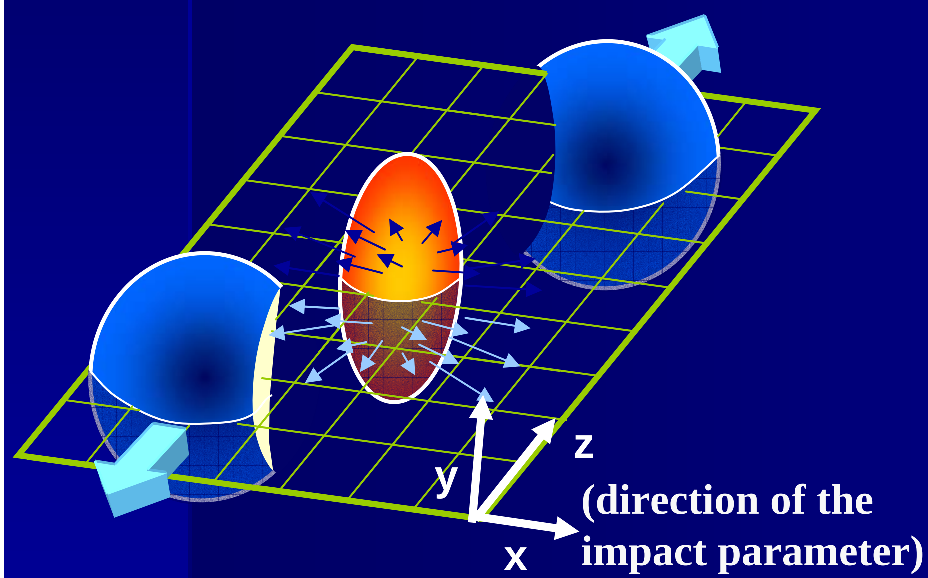


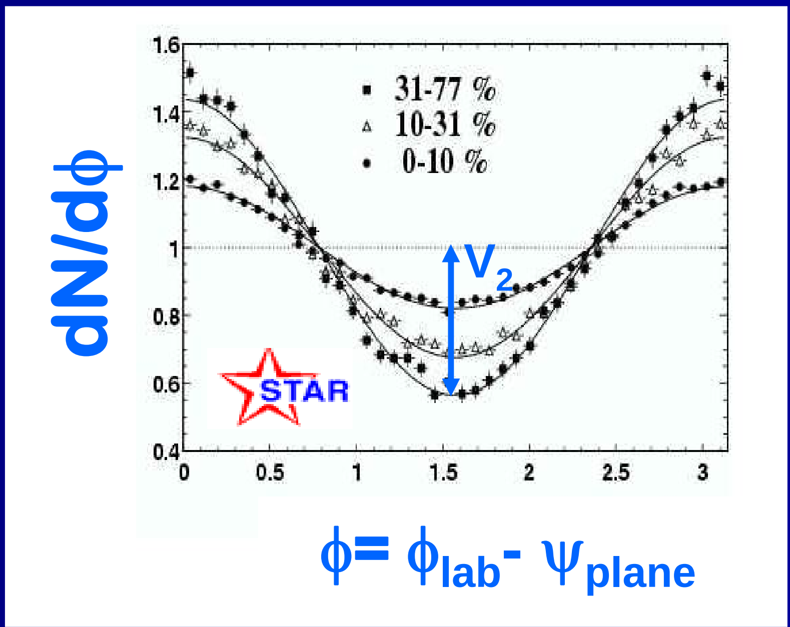

- **hit count in pixels using dE/dx cut**



# Collective flow in heavy ion collisions

In non central collisions there is large initial spatial anisotropy.
The degree to which this translates into momentum space is a measure of the pressure gradient



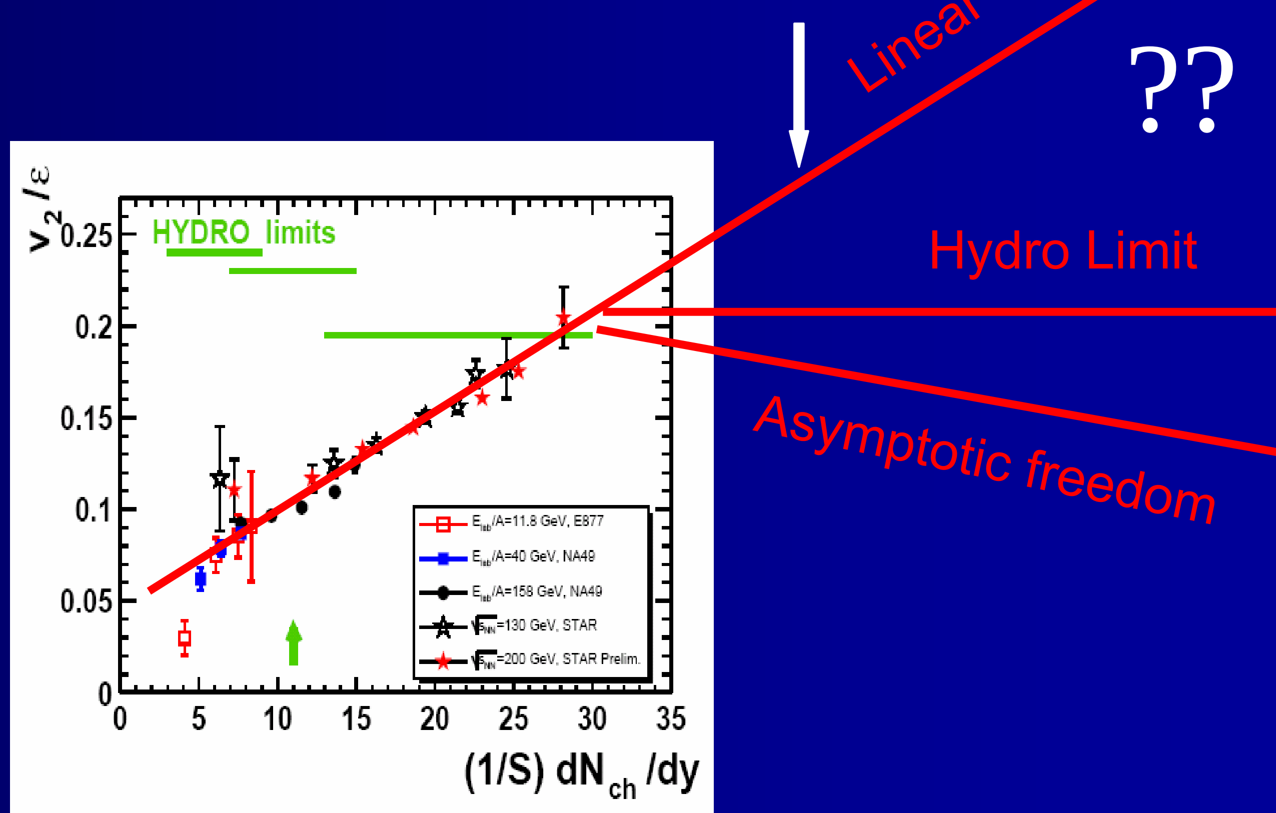




$dN/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

"elliptic flow"

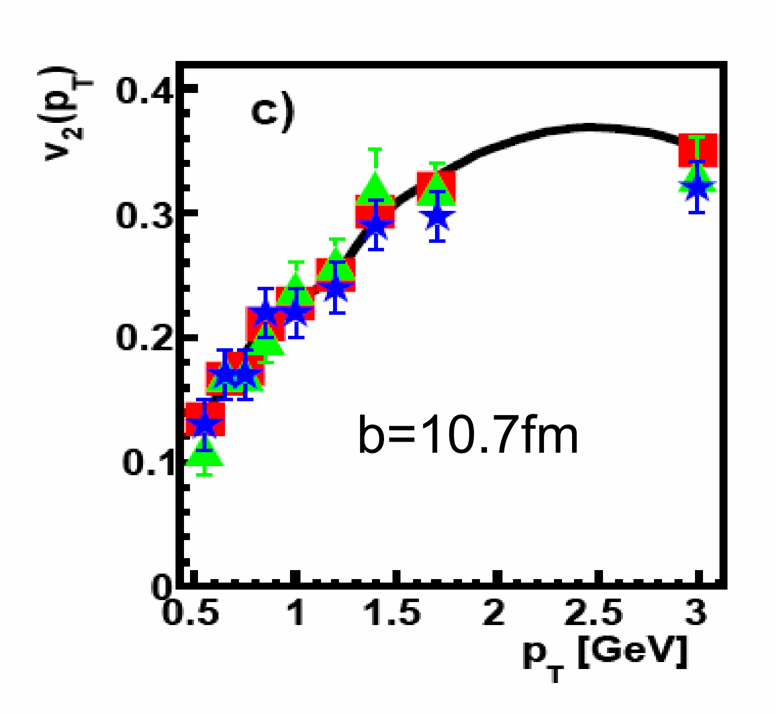
# Flow at RHIC

- Hydrodynamics with small viscosity describes heavy ion reactions

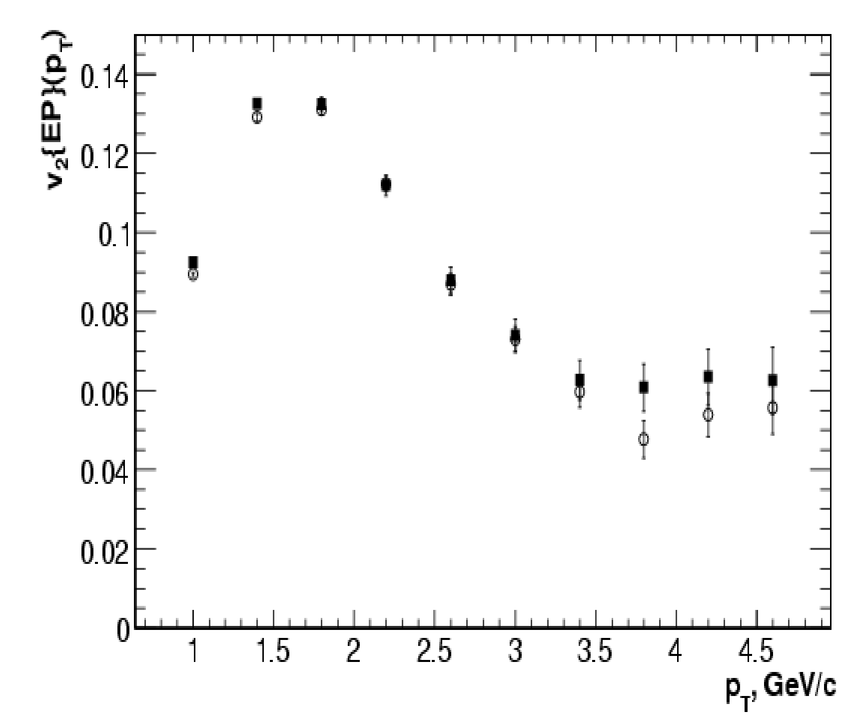


# Elliptic Flow in ATLAS and CMS

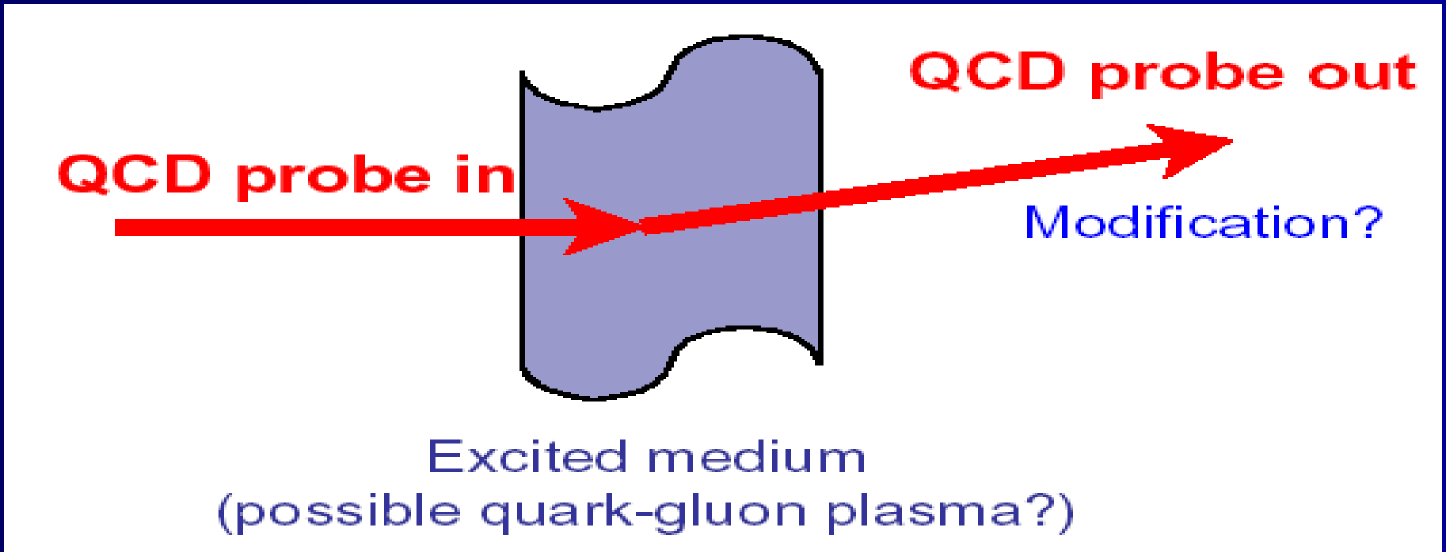
- **ATLAS**
  Flow included in HIJING using parametrization from RHIC
- 3 separate methods are shown




- **CMS**
  HYDJET
  Flow measured using reaction plane and tracker

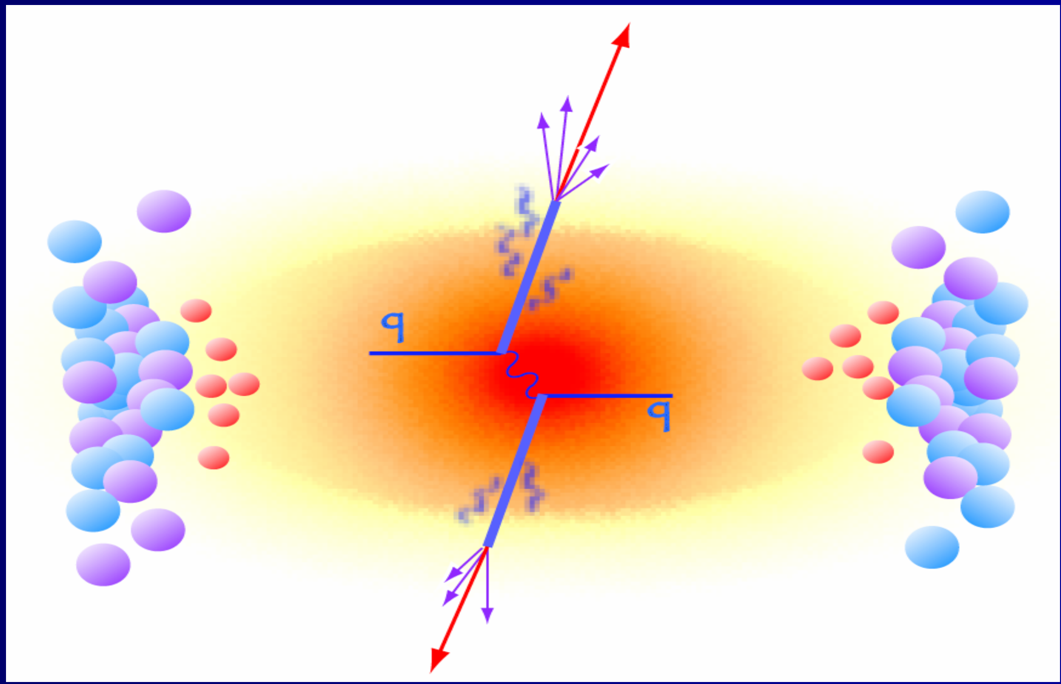


# Hard Probes




- Hard probe rates can be calculated with pQCD
- Results with no medium (pp) define the benchmark for the probe;
- Results in hot medium and their difference with defined expectation provides a **characterization of the medium.**

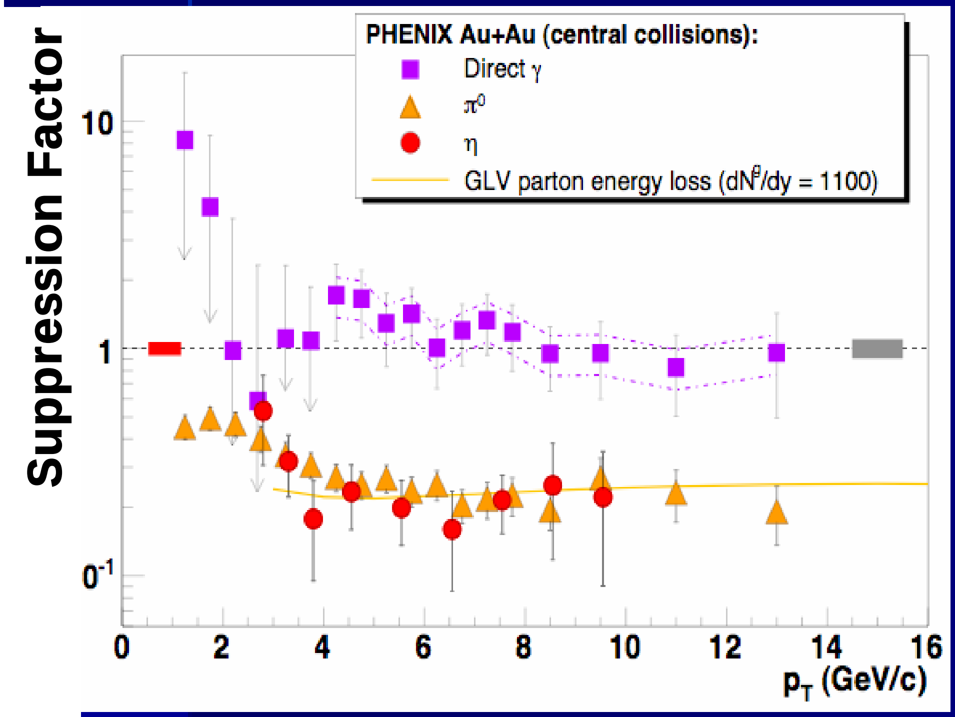
# Jet Tomography

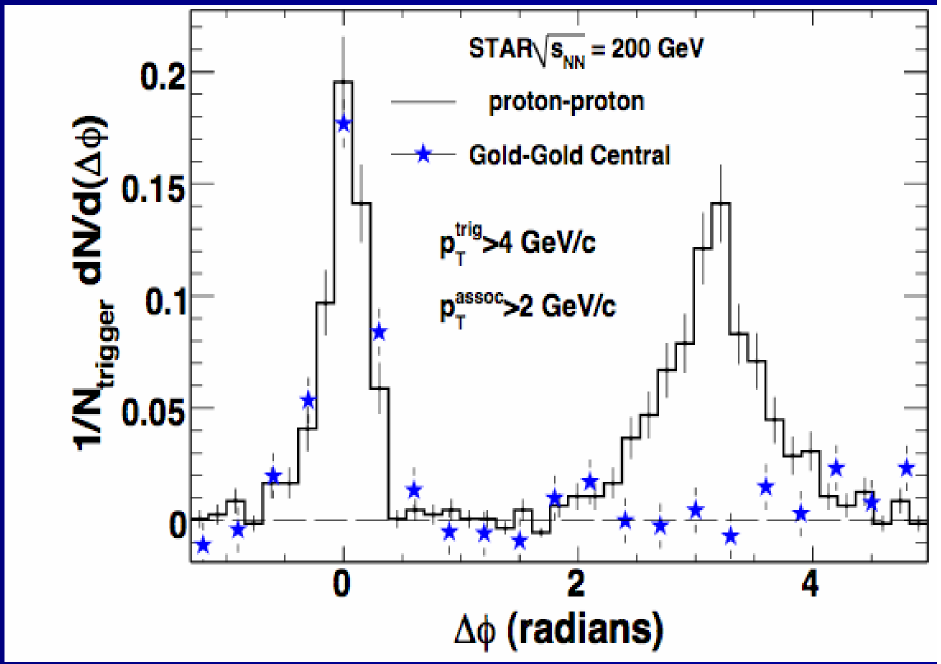



- Partons are expected to lose energy via induced gluon radiation in traversing a dense colored medium.

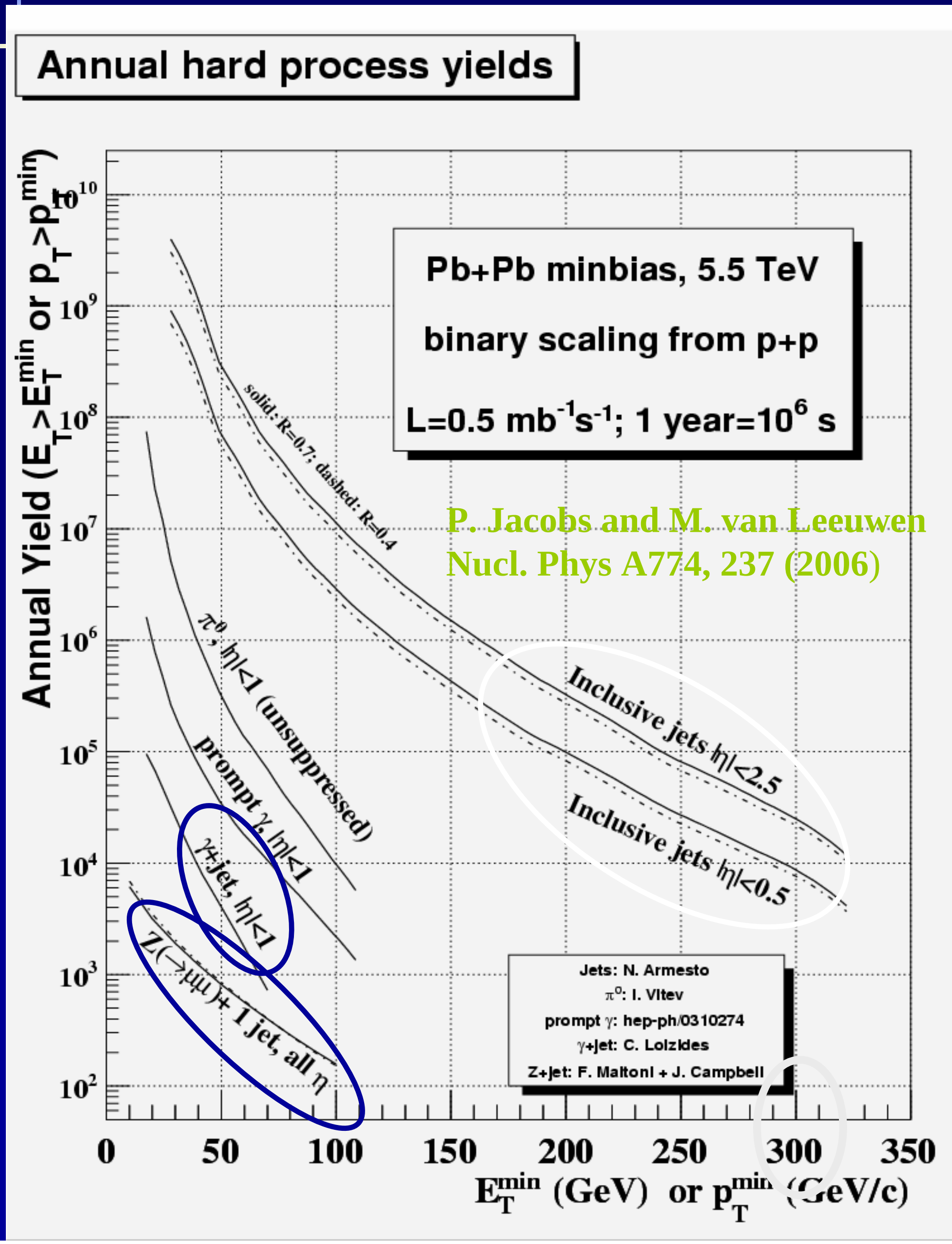
# Discovery of Jet Quenching at RHIC

- Measure using (Leading) high-$p_T$ hadrons and photons



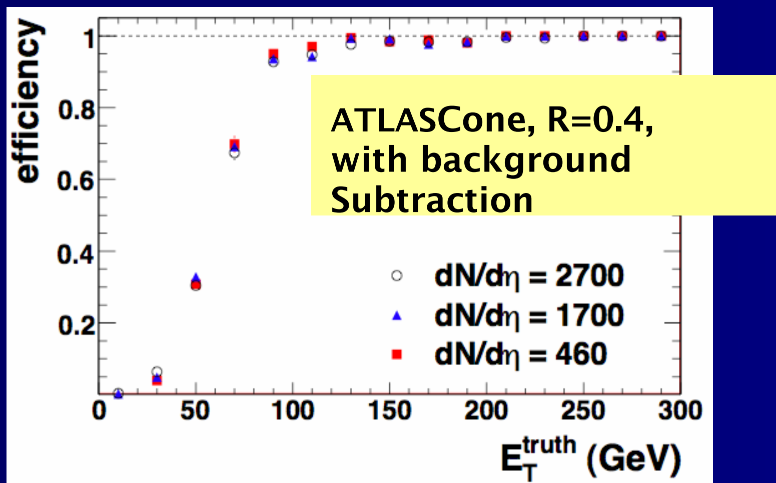
# Jet Rates at LHC

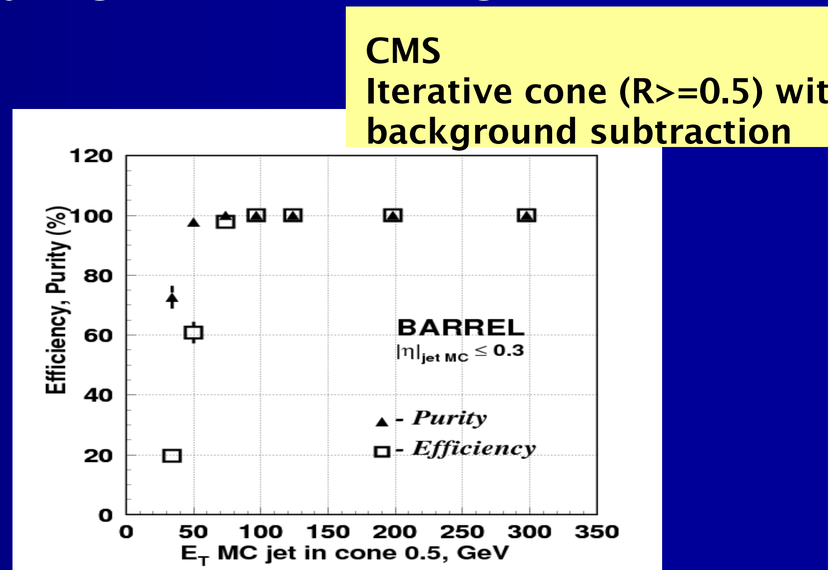


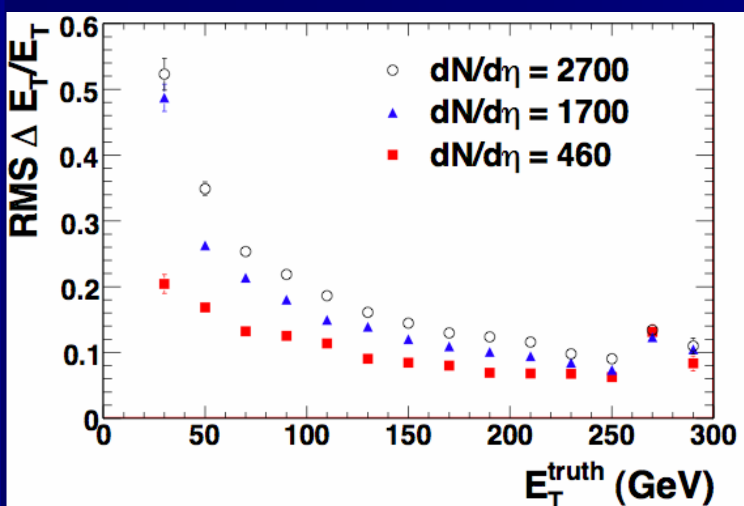

- High $p_T$, large rates
- b jets, di-jet, $\gamma$-jet
- Also full jet measurement not leading hadrons

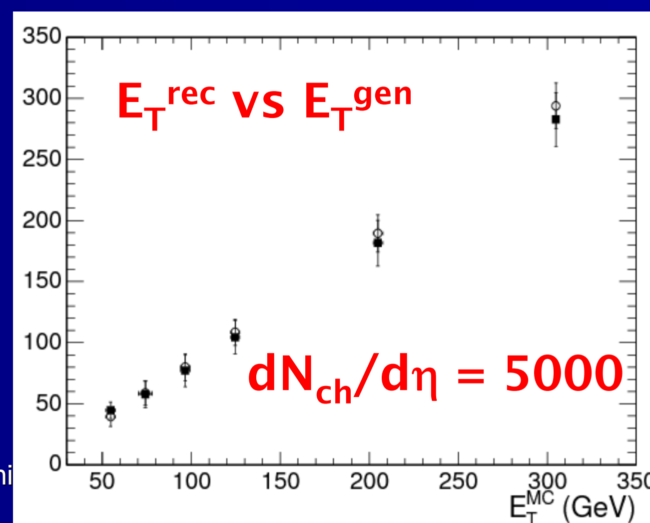
# "Full" Jet Measurements at LHC

After subtraction of the "underlying event" background



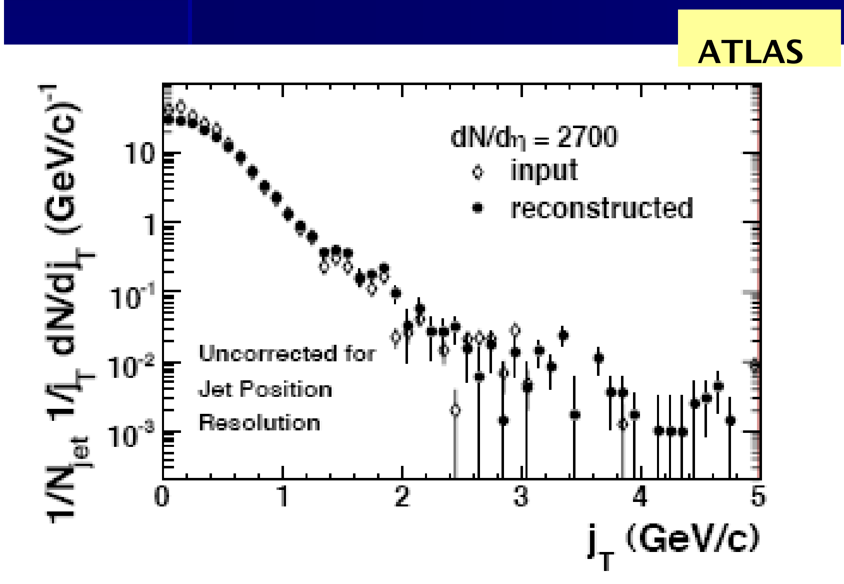



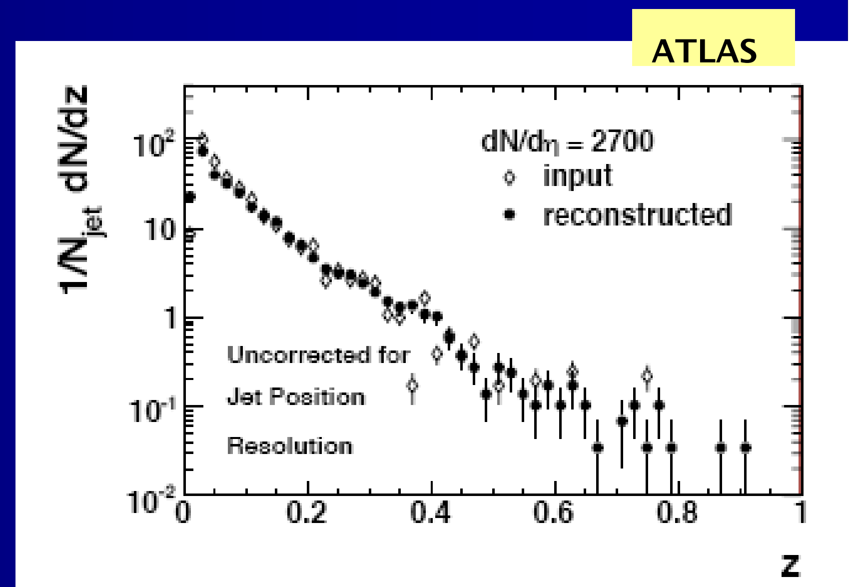



# Fragmentation Functions

- Well measured fragmentation function both in $j_T$ and z
- Will provide direct access to radiative energy loss

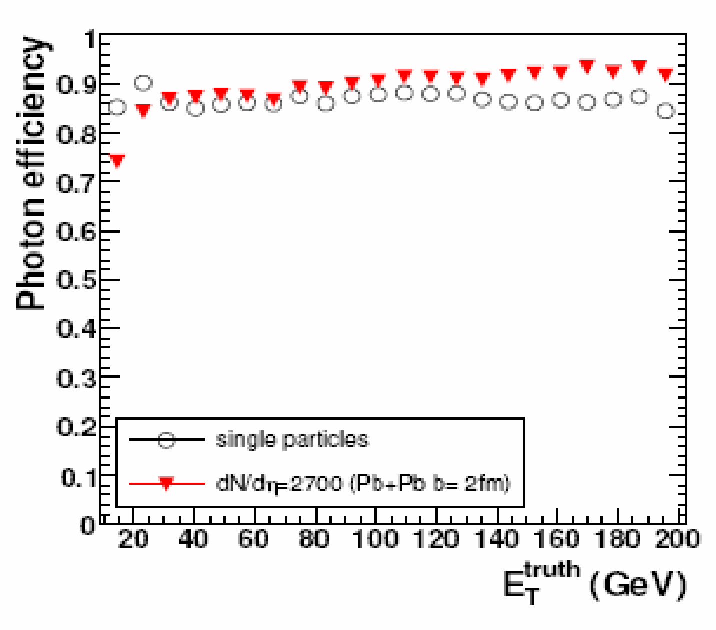


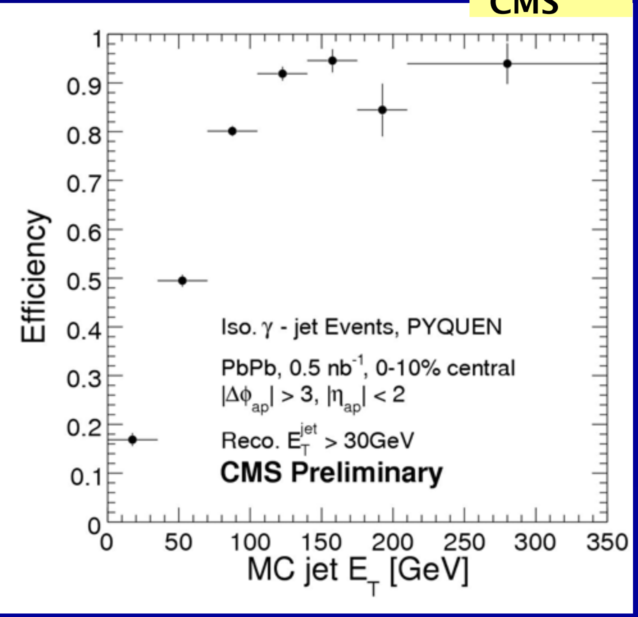
# Photon measurement at LHC

- Excellent photon reconstruction will allow direct photon and γ-jet measurements:
  - ATLAS uses **direct identification in first EM sampling layer through shower shape**
  - **CMS uses Photon reconstruction with Island Algorithm and Photon ID using Multi-Variate Analysis**

ATLAS

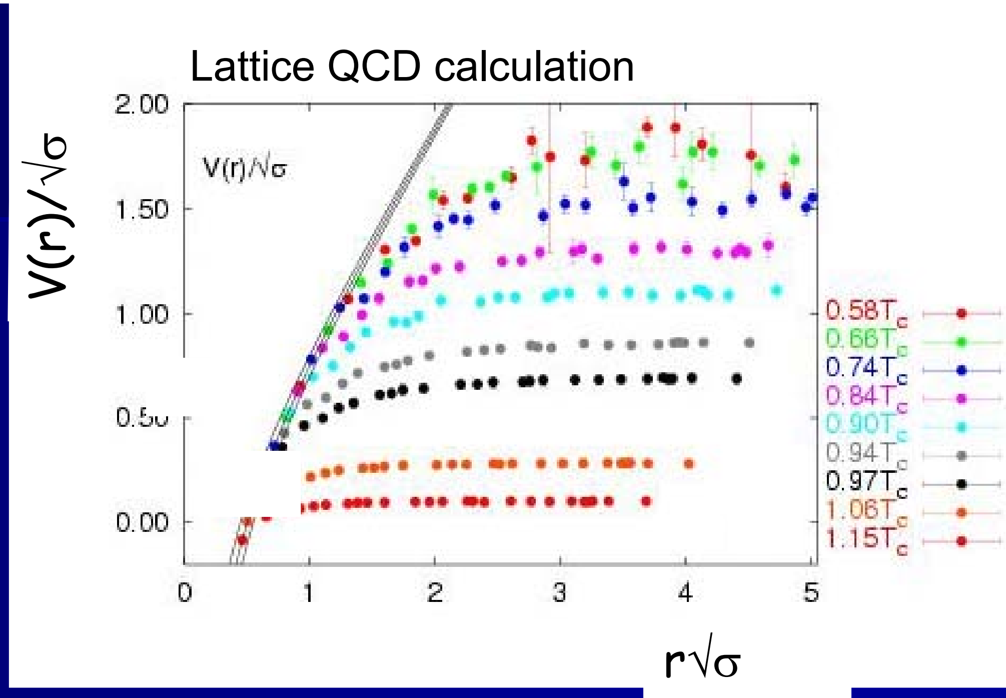


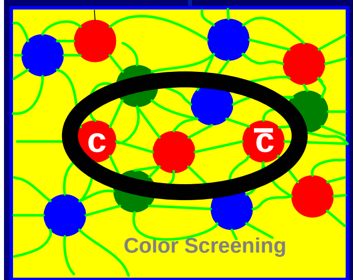

CMS



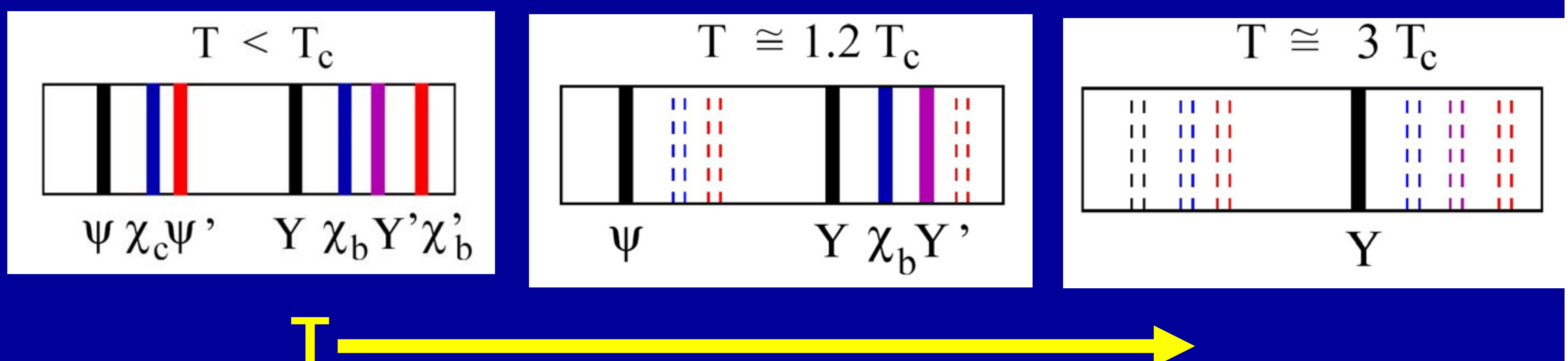
# Deconfinement

- Lattice QCD makes a clear prediction for the onset of deconfinement.

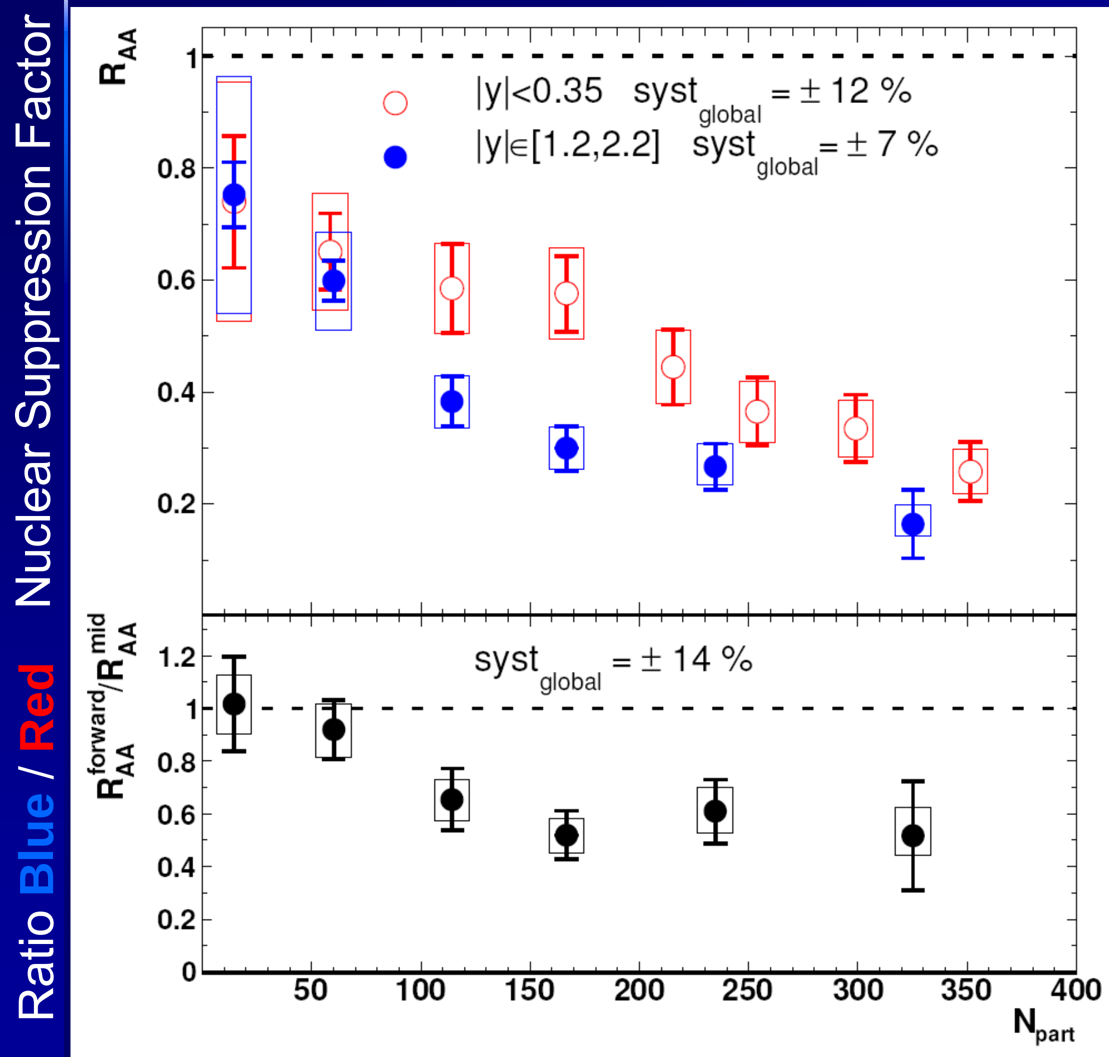



- Different Quarkonia states test the degree of color screening and measure the temperature.



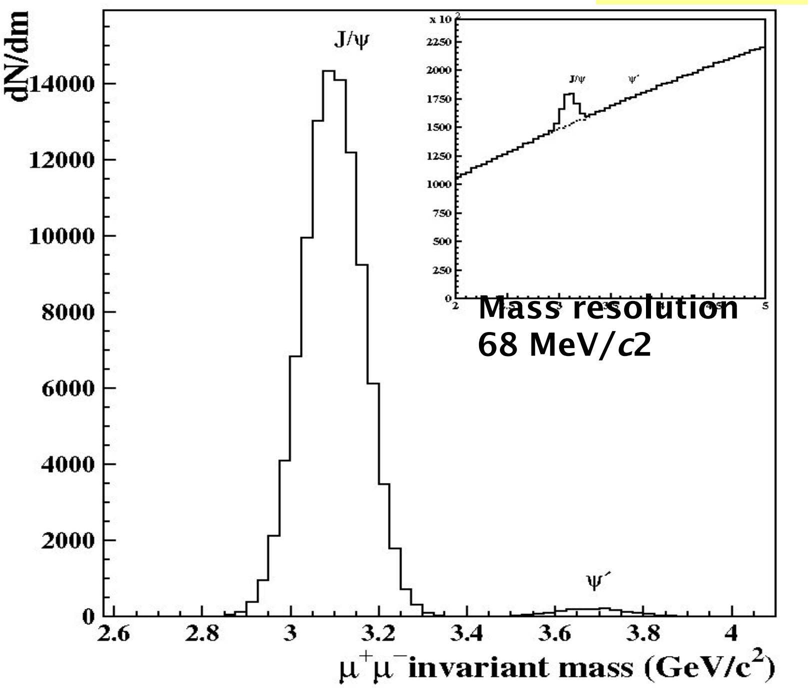
# J/ψ suppression at RHIC



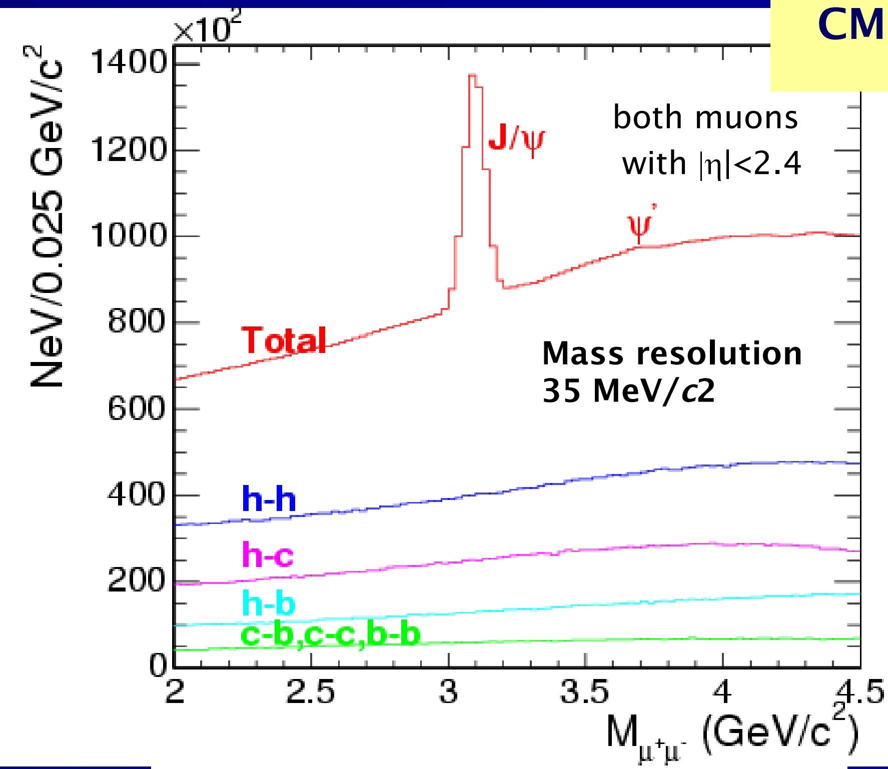

- Smooth suppression with increasing collision centrality
- Forward rapidity more suppressed than mid-rapidity
- very similar suppression at RHIC and SPS...

# J/ψ Measurement at the LHC

ATLAS



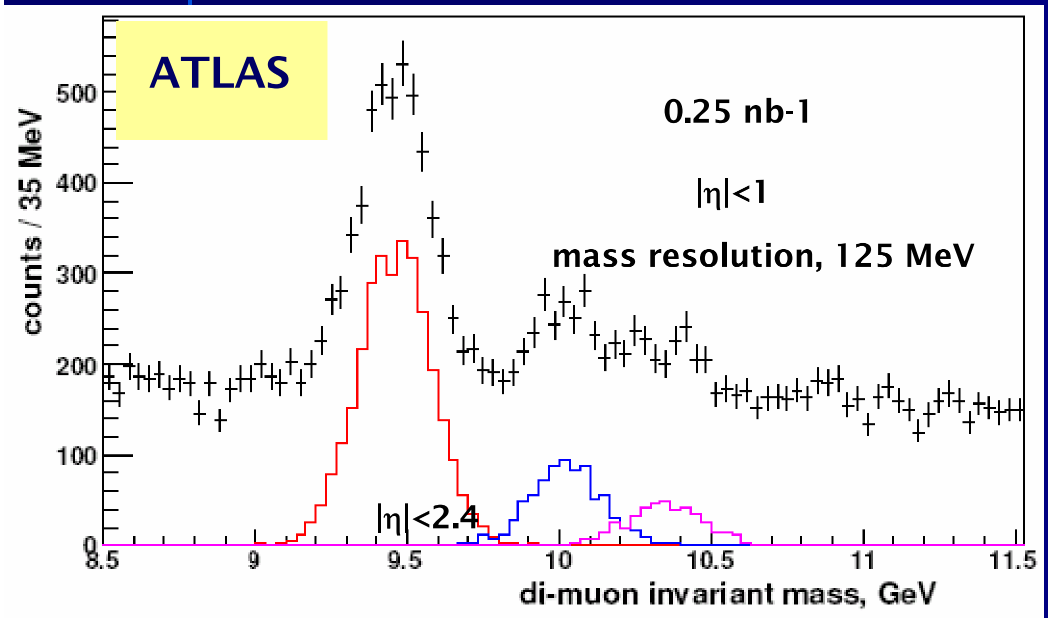

CMS

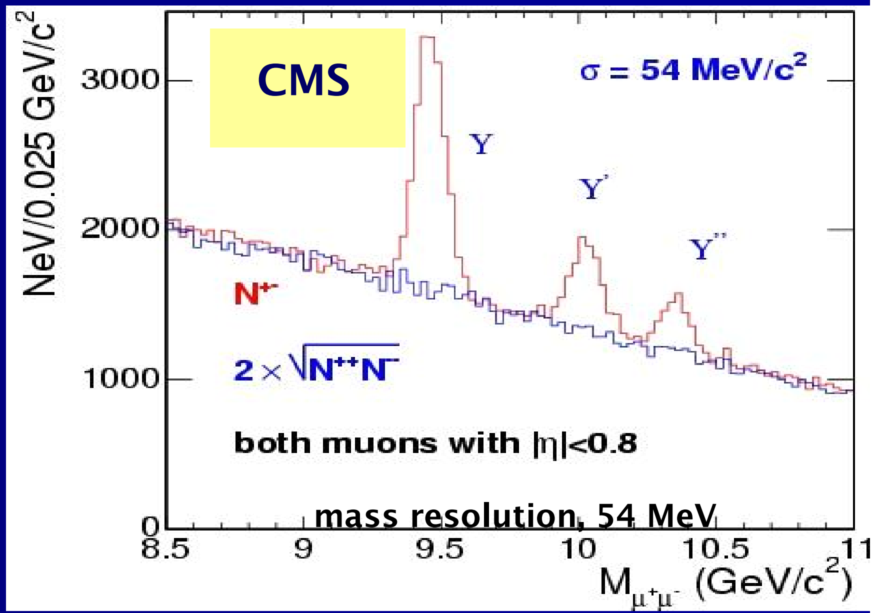



~100k J/ψ per month, tagging method

Expected rate (per month, $10^6$ s, 0.5 $nb^{-1}$):
J/ψ ~ 180 kevents

# Upsilon Measurement at LHC




Upsilon rates in 1 month of running:
(at nominal luminosity)

- Y ~ 25 kevents,
- Y' ~ 7 kevents,
- Y" ~ 4 kevents

# Conclusions

- The LHC with Heavy Ions is a fantastic discovery machine with a very rich Physics program:
  - The first 15 minutes; $L_{int}=1\mu b^{-1}$
    - Event multiplicity, elliptic flow
  - The first month; $L_{int}=0.1\text{-}1nb^{-1}$
    - Rare high $p_t$ processes: jets, quarkonia

- ATLAS and CMS have unprecendented capabilities to make measurements over a large kinematic range for important signatures of the Quark Gluon Plasma

- The experiments will be commissioned and ready (thanks to the proton run)

➡ Important results already from the very start of running with nuclear beams