# Understanding the Quark Gluon Plasma

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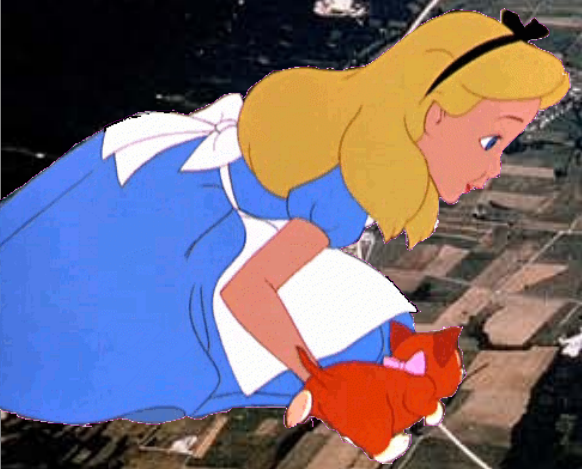
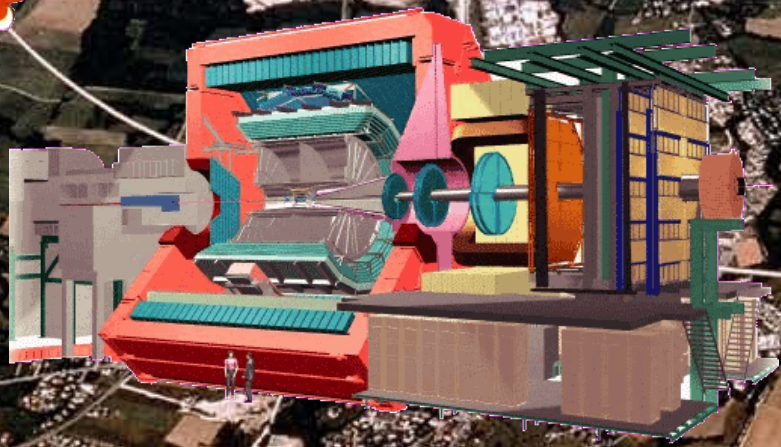
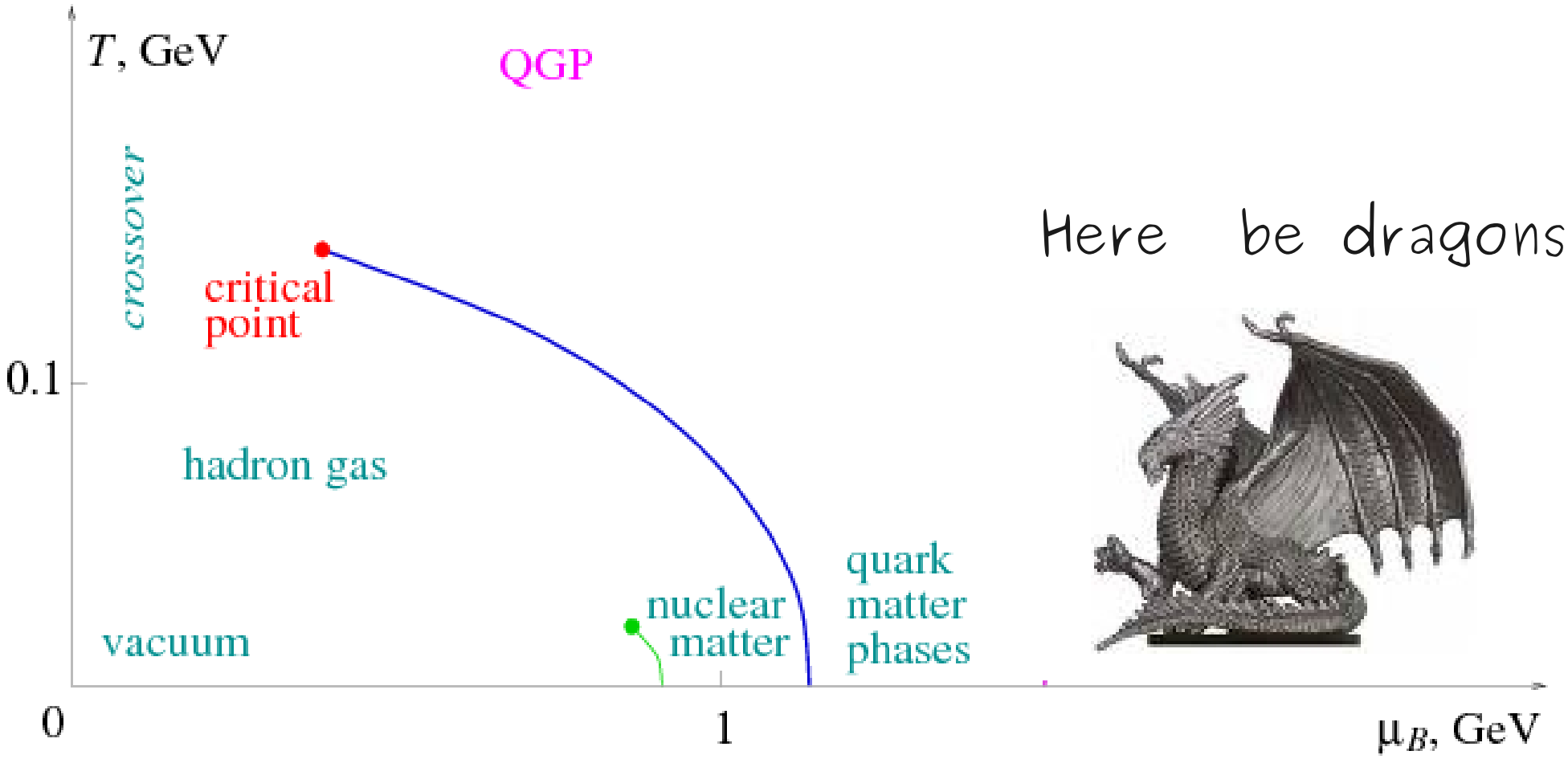
University of Tennessee at Knoxville

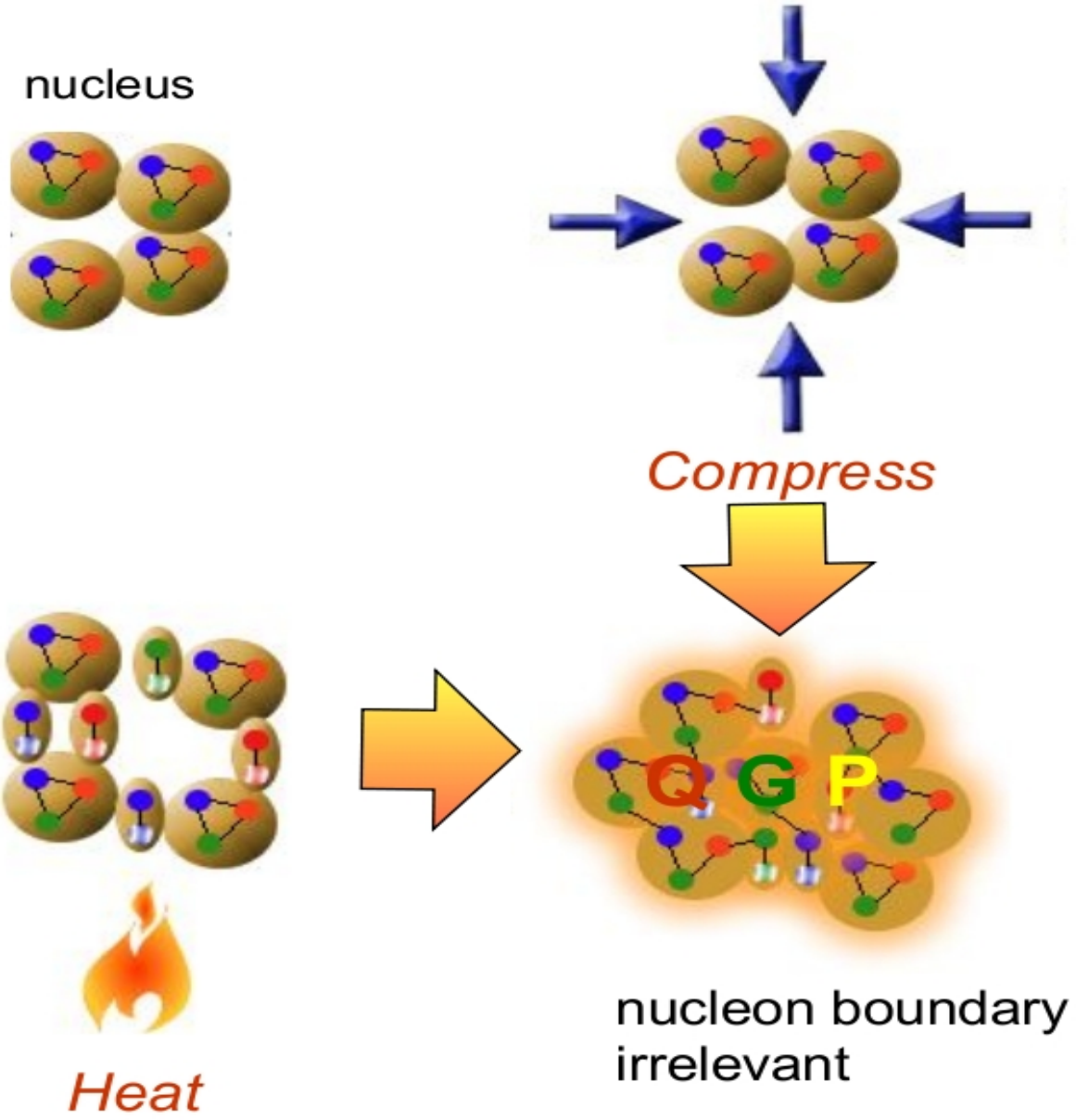




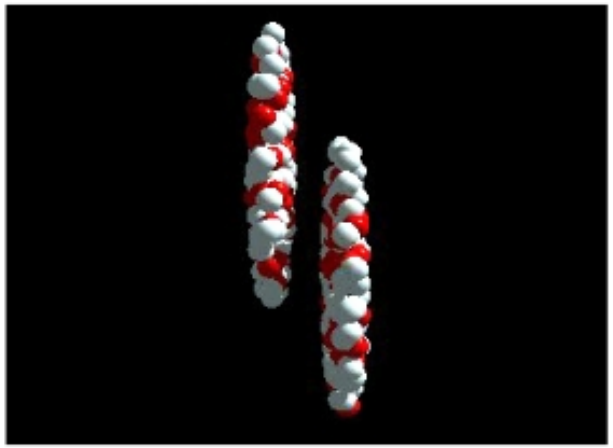
# *Phase diagram of nuclear matter*

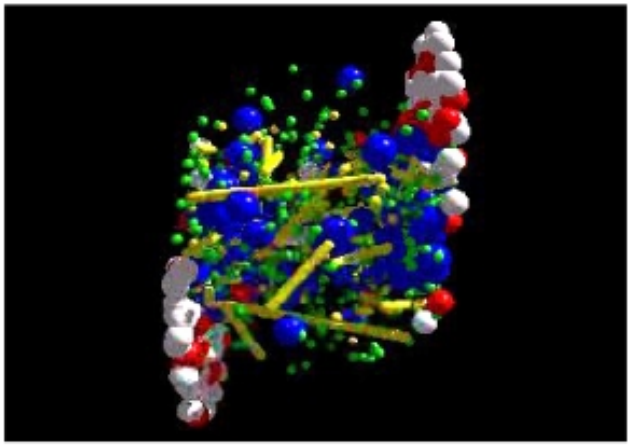


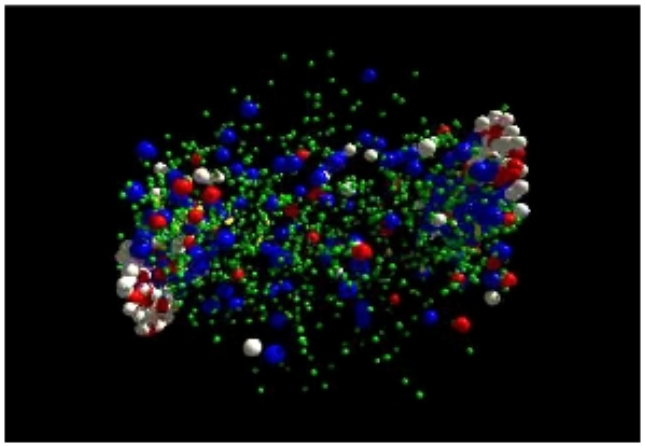
# How to make a Quark Gluon Plasma

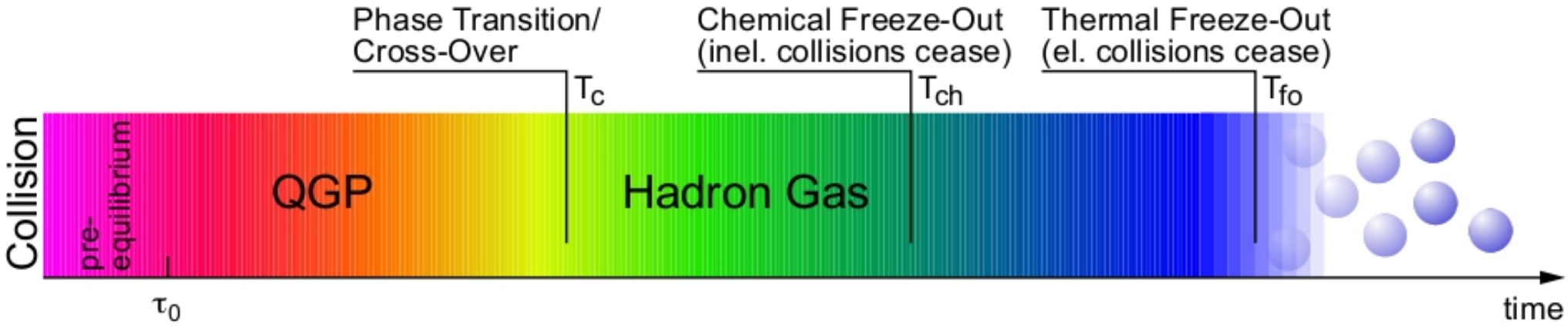


# *The phase transition in the laboratory*



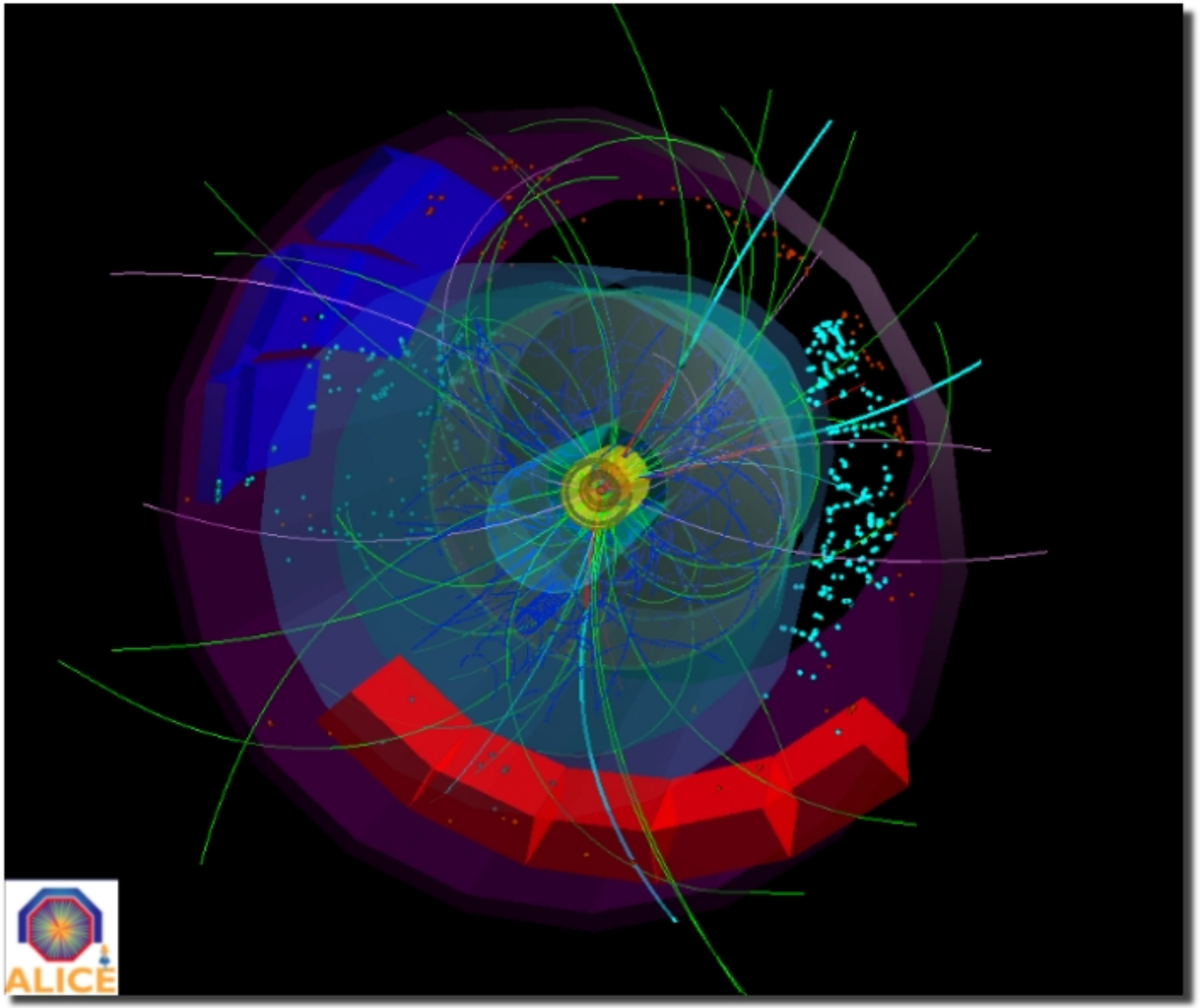




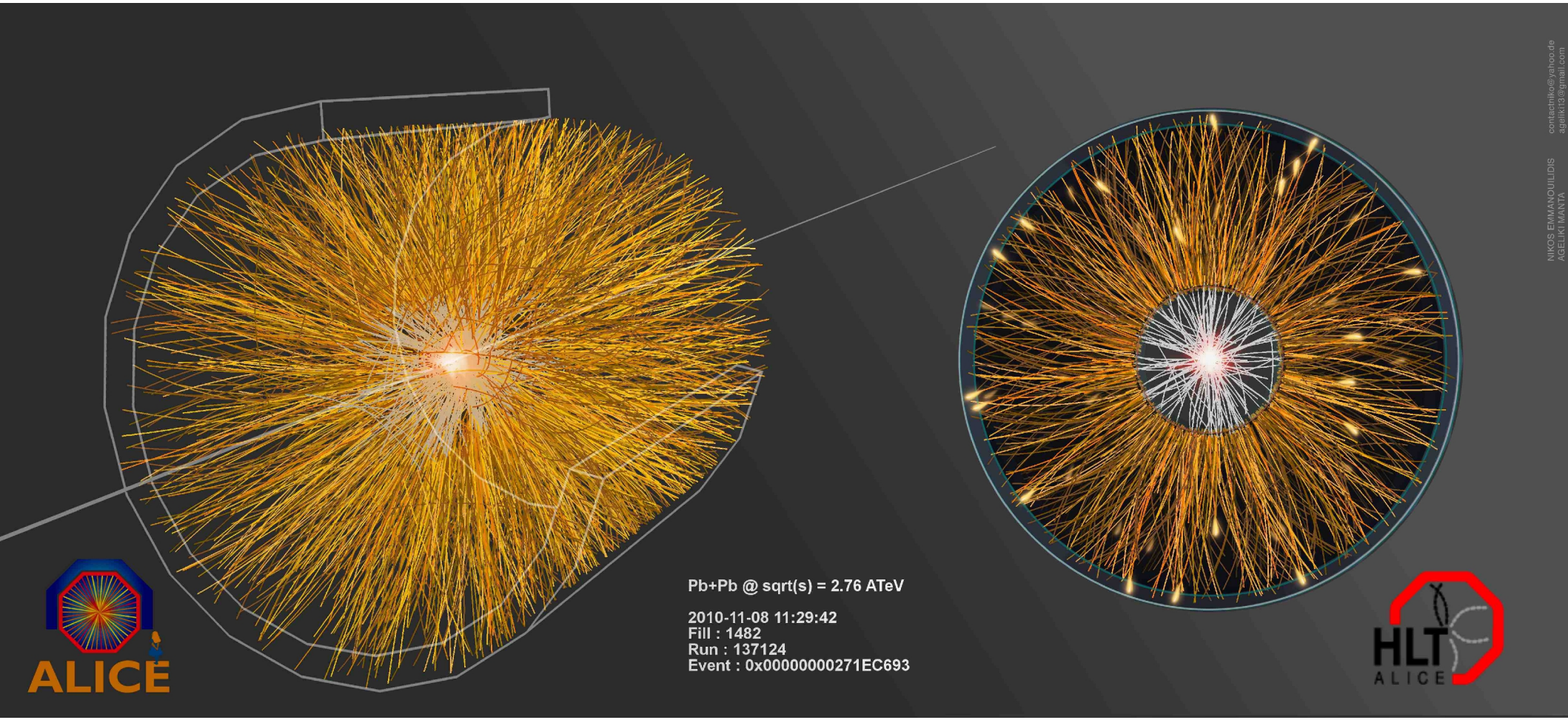


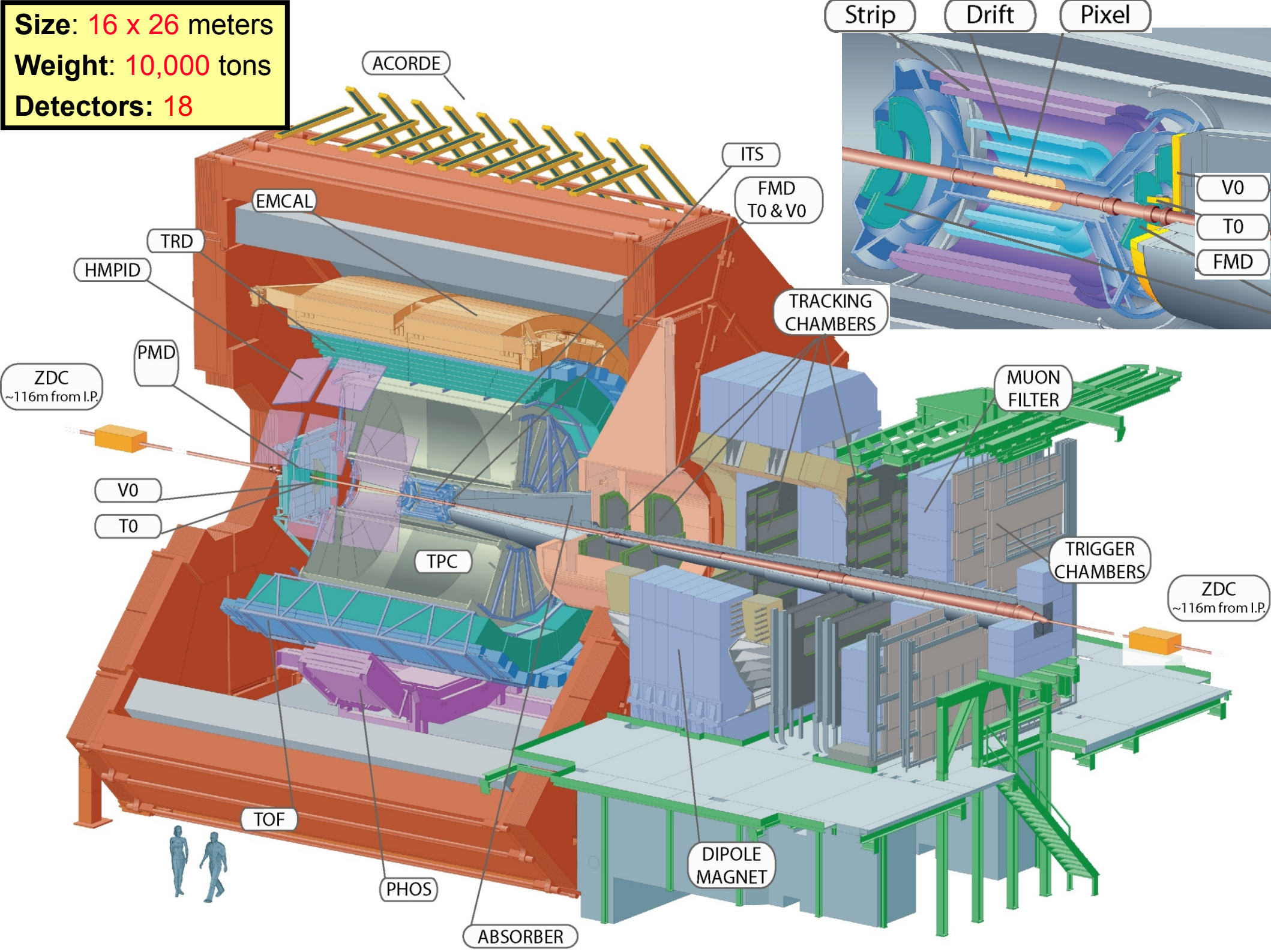

CMS
LHCb
RICH 2
Muon system
Magnet
Electromagnetic calorimeter
Hadronic calorimeter
RICH 1
VELO
Tracking system
ALICE
ATLAS
LHCf

# *p+p collisions*



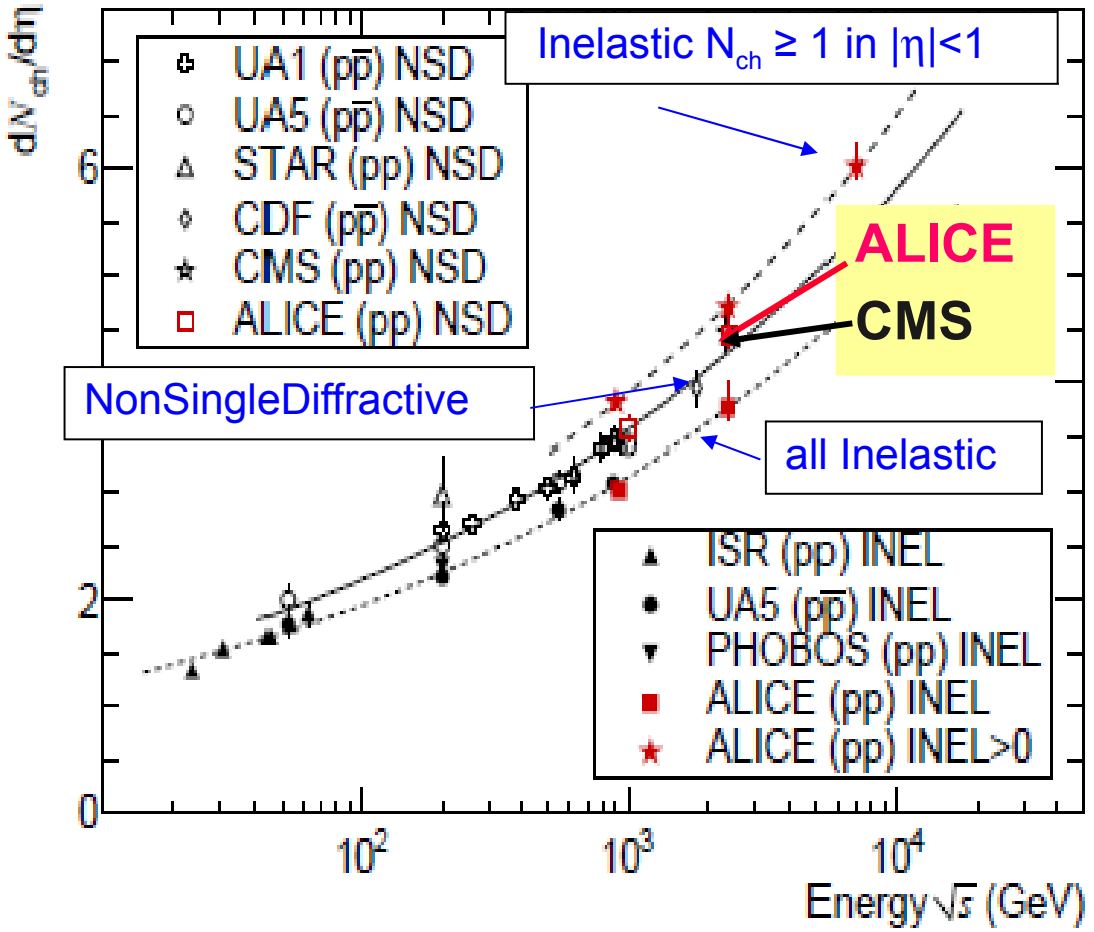
# *Pb+Pb collisions*



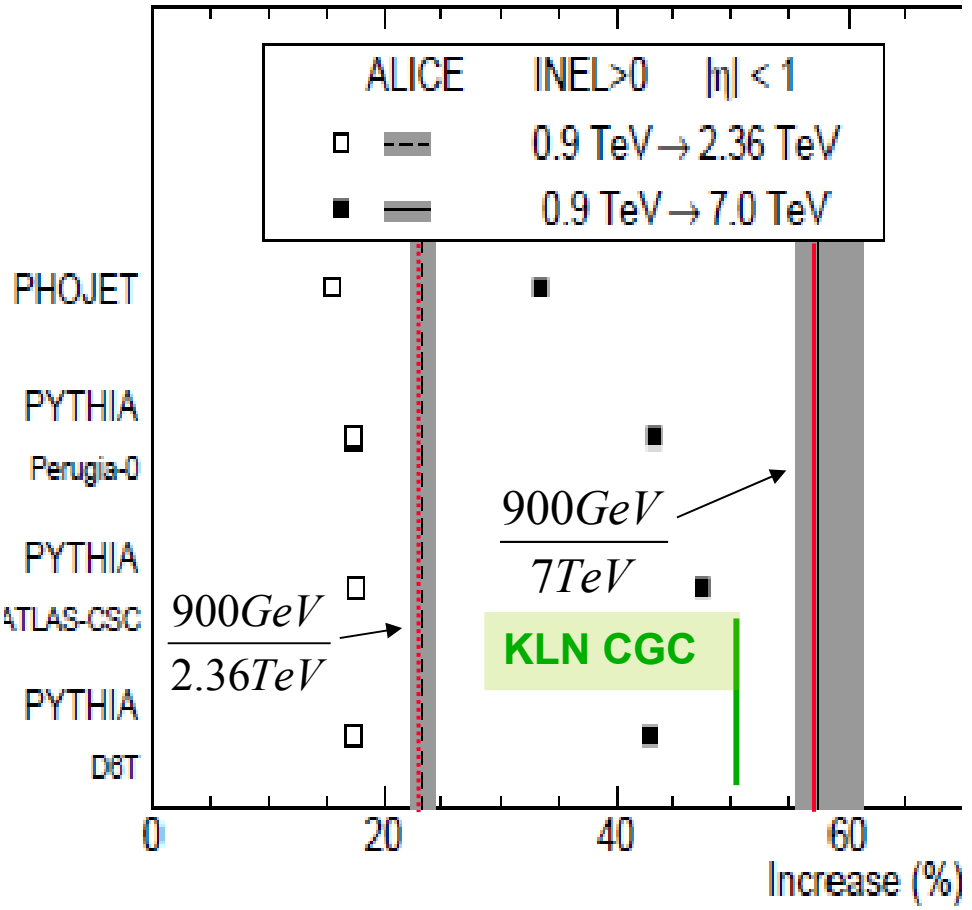

Size: 16 x 26 meters
Weight: 10,000 tons
Detectors: 18
ACORDE
ITS
FMD
T0 & V0
EMCAL
TRD
HMPID
TRACKING
CHAMBERS
PMD
ZDC
~116m from I.P.
MUON
FILTER
V0
T0
TPC
TRIGGER
CHAMBERS
ZDC
~116m from I.P.
TOF
PHOS
DIPOLE
MAGNET
ABSORBER
Strip
Drift
Pixel
V0
T0
FMD

# $dN_{ch}/d\eta$ versus $\sqrt{s}$

$dN_{ch}/d\eta$ versus $\sqrt{s}$




Relative increase in $dN_{ch}/d\eta$



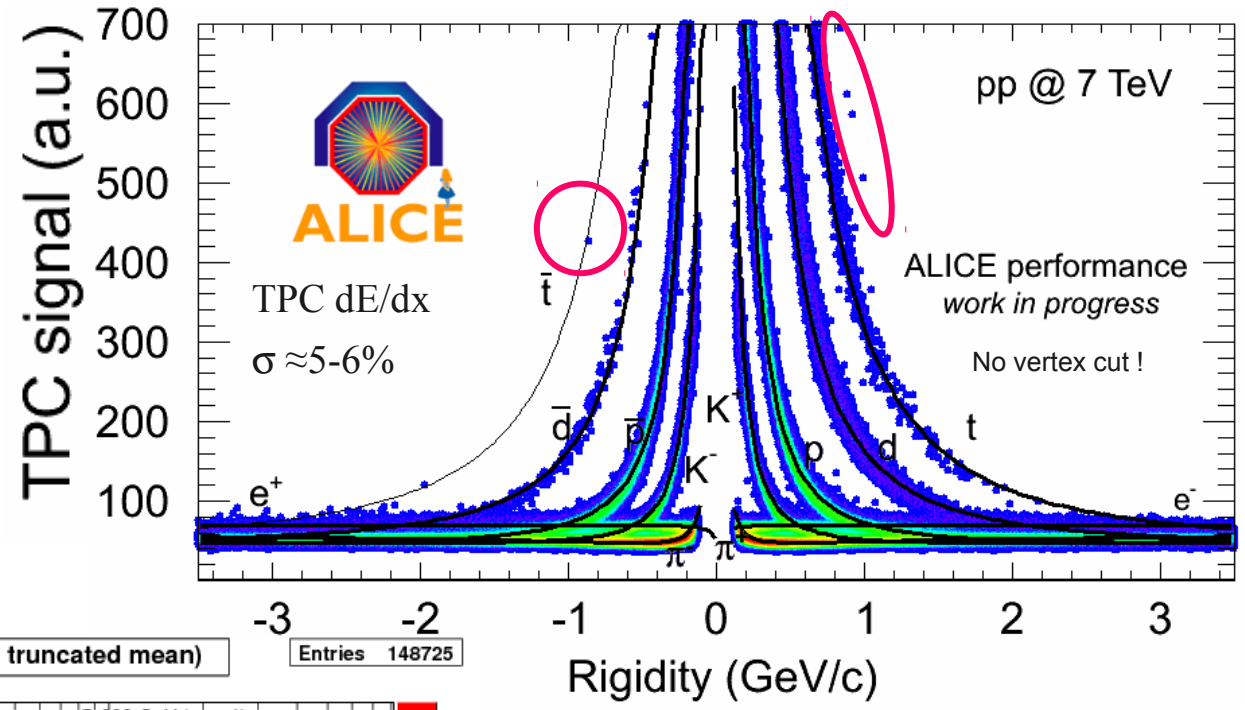

Eur. Phys. J. C (2010) 68: 345–354
Eur. Phys. J. C (2010) 68: 89–108
Eur. Phys. J. C (2010) 65: 111-125

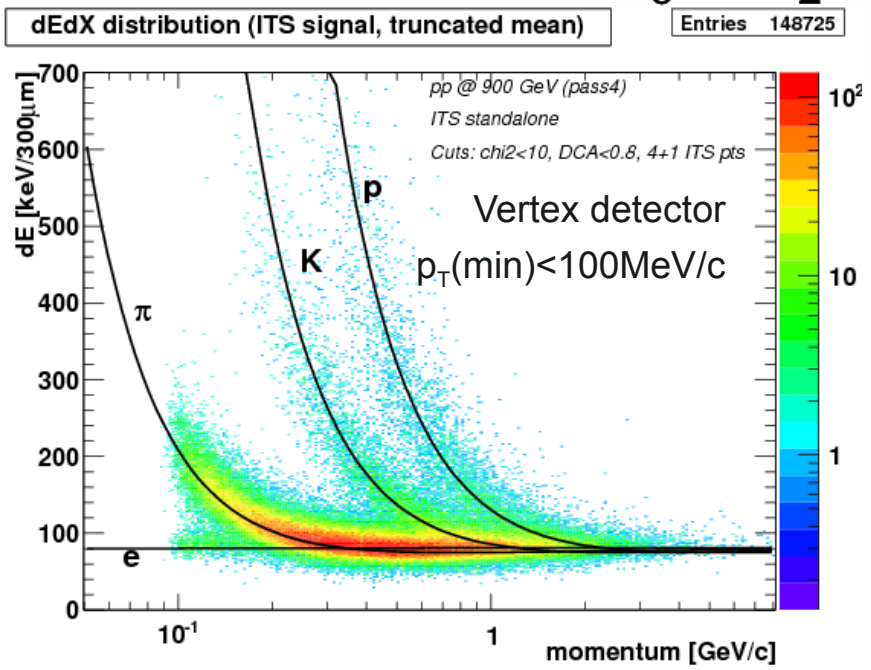
Results:

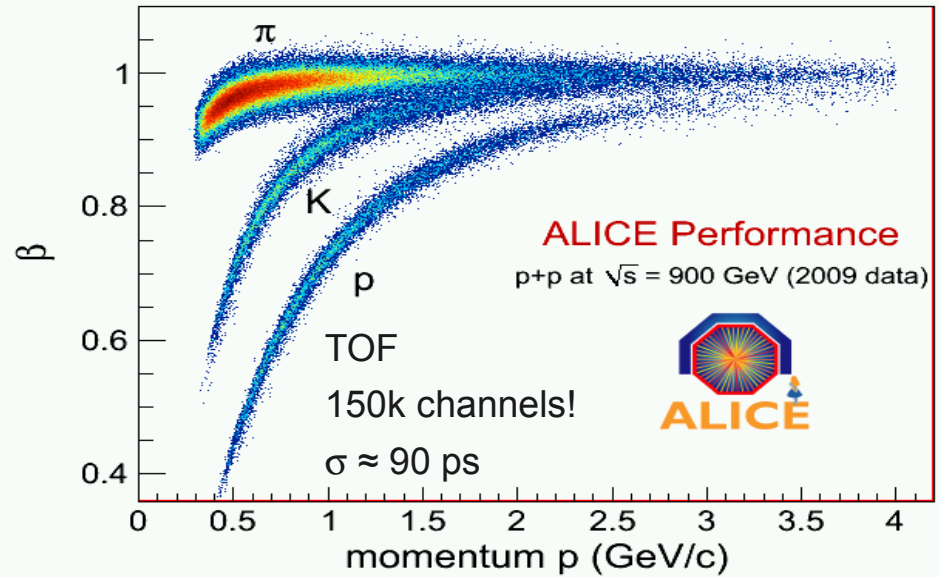
increase with energy significantly stronger in data than MC's

- ALICE & CMS agree to within 1 σ (< 3%)

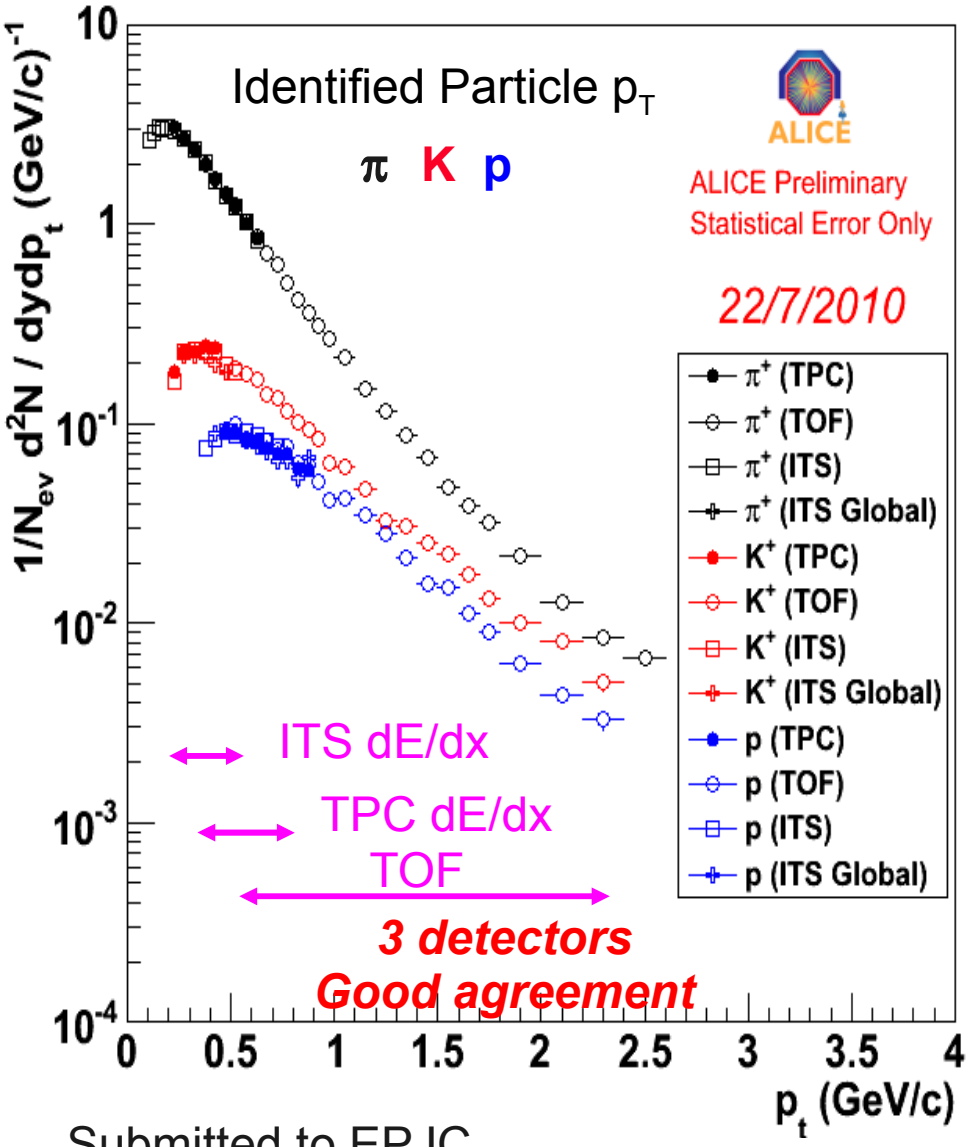
# Particle identification



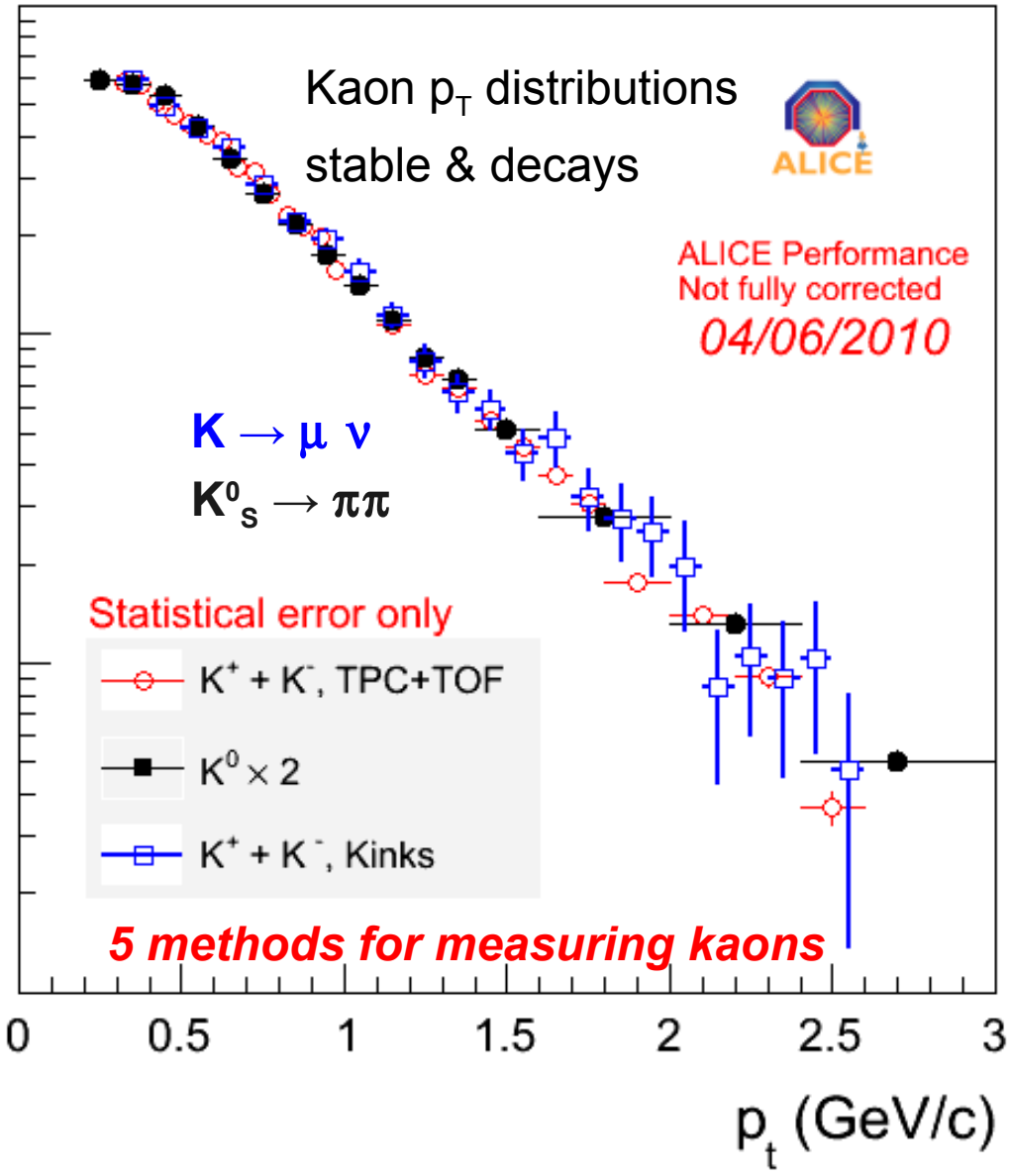



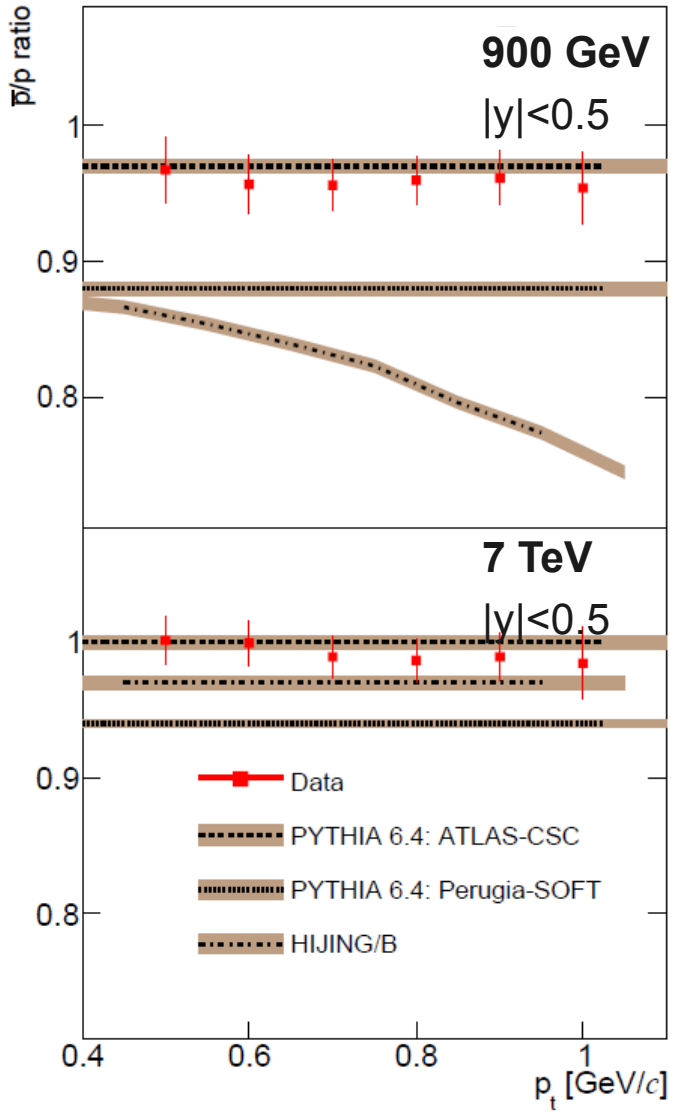
# Identified particle spectra

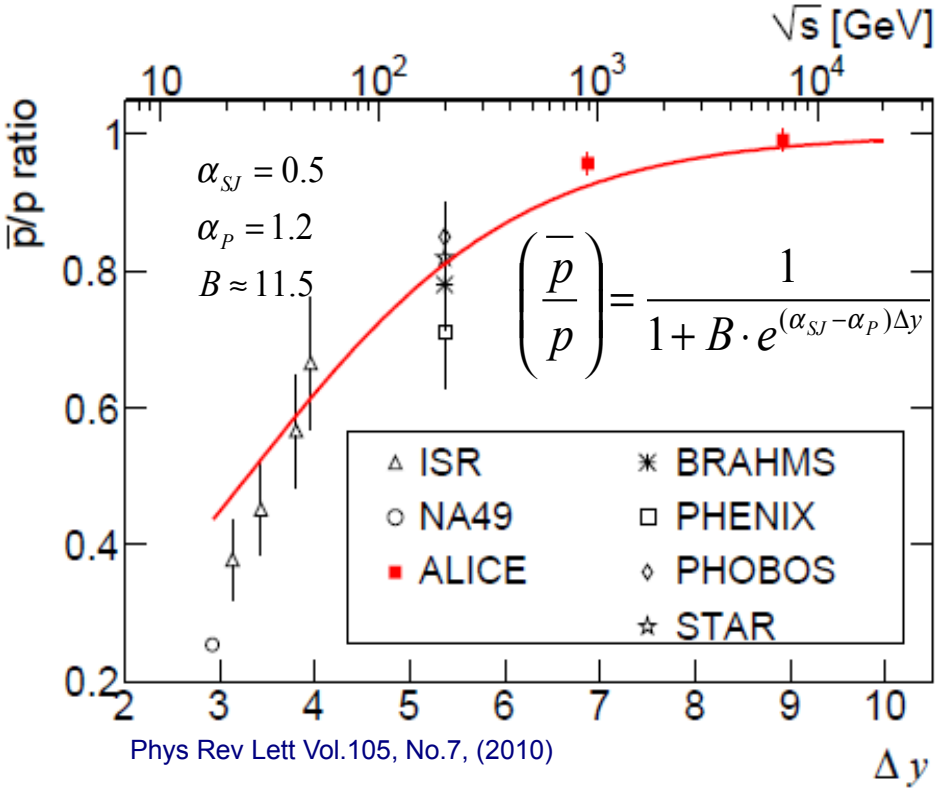



Submitted to EPJC



# $\bar{p}/p$ ratio

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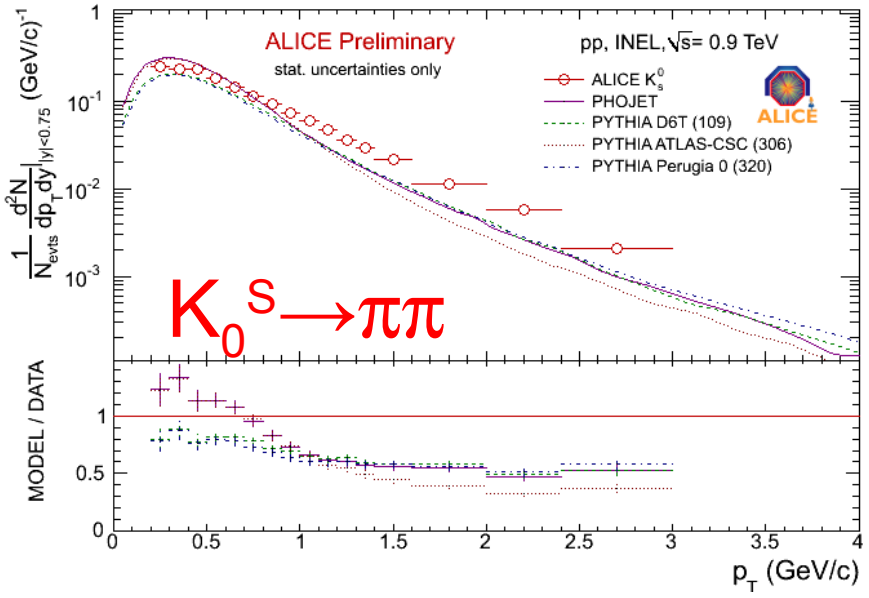
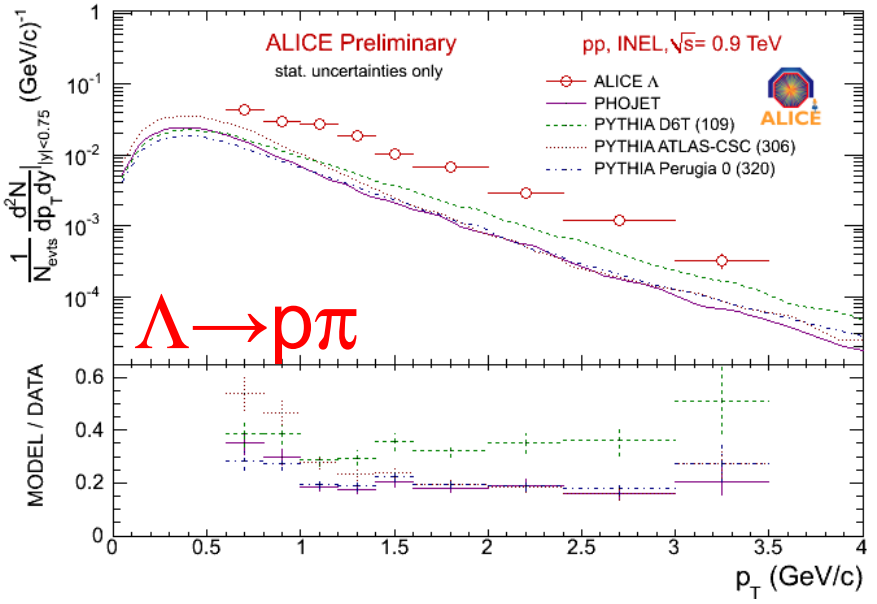
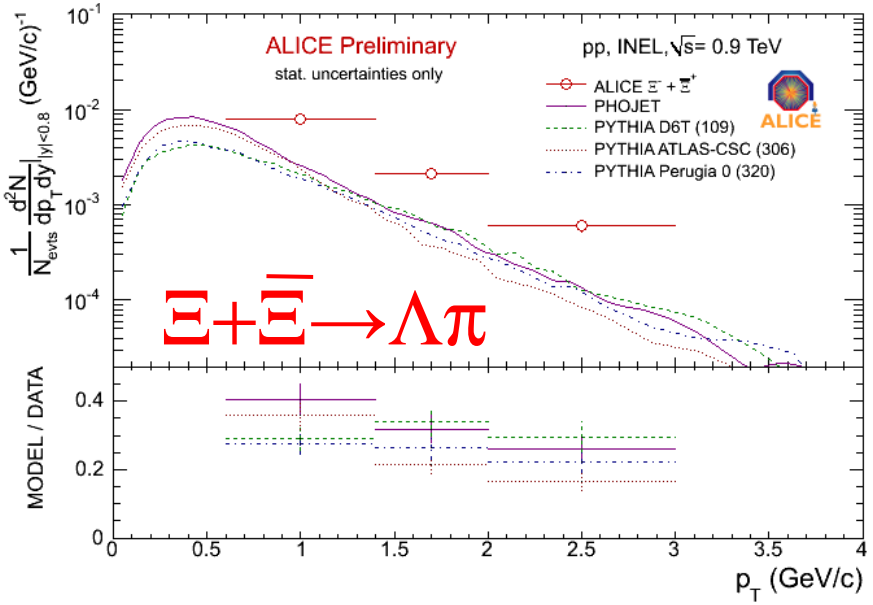
0.9 TeV: $\bar{p}/p$ = **0.957**±0.006(stat) ±0.014(syst)

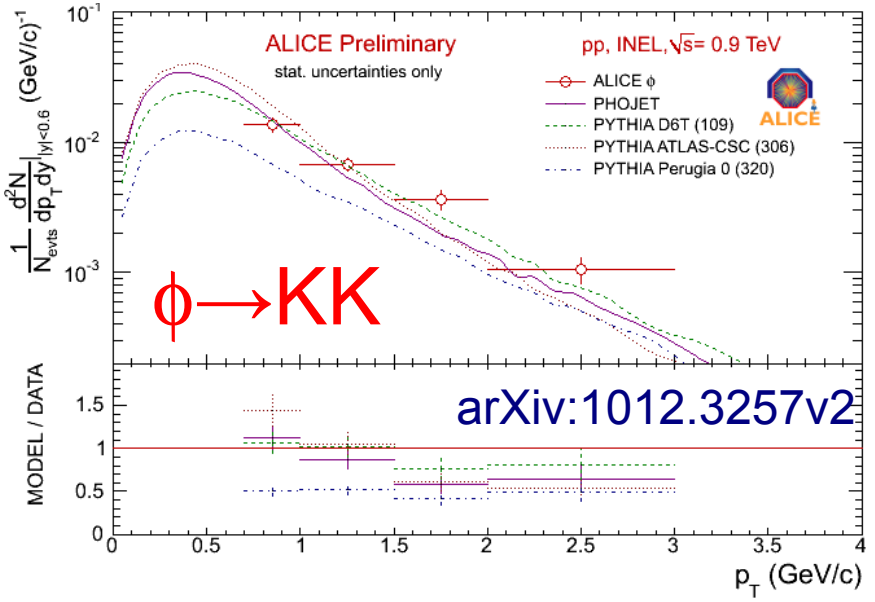
7 TeV: $\bar{p}/p$ = **0.990**±0.006(stat) ±0.014(syst)

# Strange particles at 900 GeV




- PYTHIA and PHOJET consistently below data

# Monte Carlo scoreboard

| | variable/tune | D6T | Perugia0 | CSC | PHOJET |
|---|---|---|---|---|---|
| 900 GeV | $dN_{ch}/d\eta$ | -20% | -17% | +3% | -2% |
| | $N_{ch}$ | $N_{ch}>10$ | $N_{ch}>5$ | $N_{ch}>15$ | $N_{ch}>10$ |
| | $p_T$ | | $p_T>4$ GeV/c | $p_T>1$ GeV/c | $p_T>1$ GeV/c |
| | $<p_T>$ | | | | $p_T>1$ GeV/c |
| | $K^0_S$, $\Lambda$, $\bar{\Lambda}$ | | | | |
| | $\varphi$ | | | | |
| 2.36 TeV | $dN_{ch}/d\eta$ | -24% | -21% | -2% | -8% |
| | $N_{ch}$ | $N_{ch}>10$ | $N_{ch}>5$ | $N_{ch}>20$ | $N_{ch}>15$ |
| 7 TeV | $dN_{ch}/d\eta$ | -27% | -24% | -4% | -17% |
| | $N_{ch}$ | | | $N_{ch}>30$ | |

MC <<<< Data | MC << Data | MC ≈ Data | MC >> Data

Conclusion:
- None of the tested MC's (adjusted at lower energy) does really well
- Tuning one or two results is doable, getting everything right will require more effort

(and may, with some luck, actually teach us something on soft QCD rather than only turning knobs).

# *Charged particle multiplicity in central Pb+Pb*

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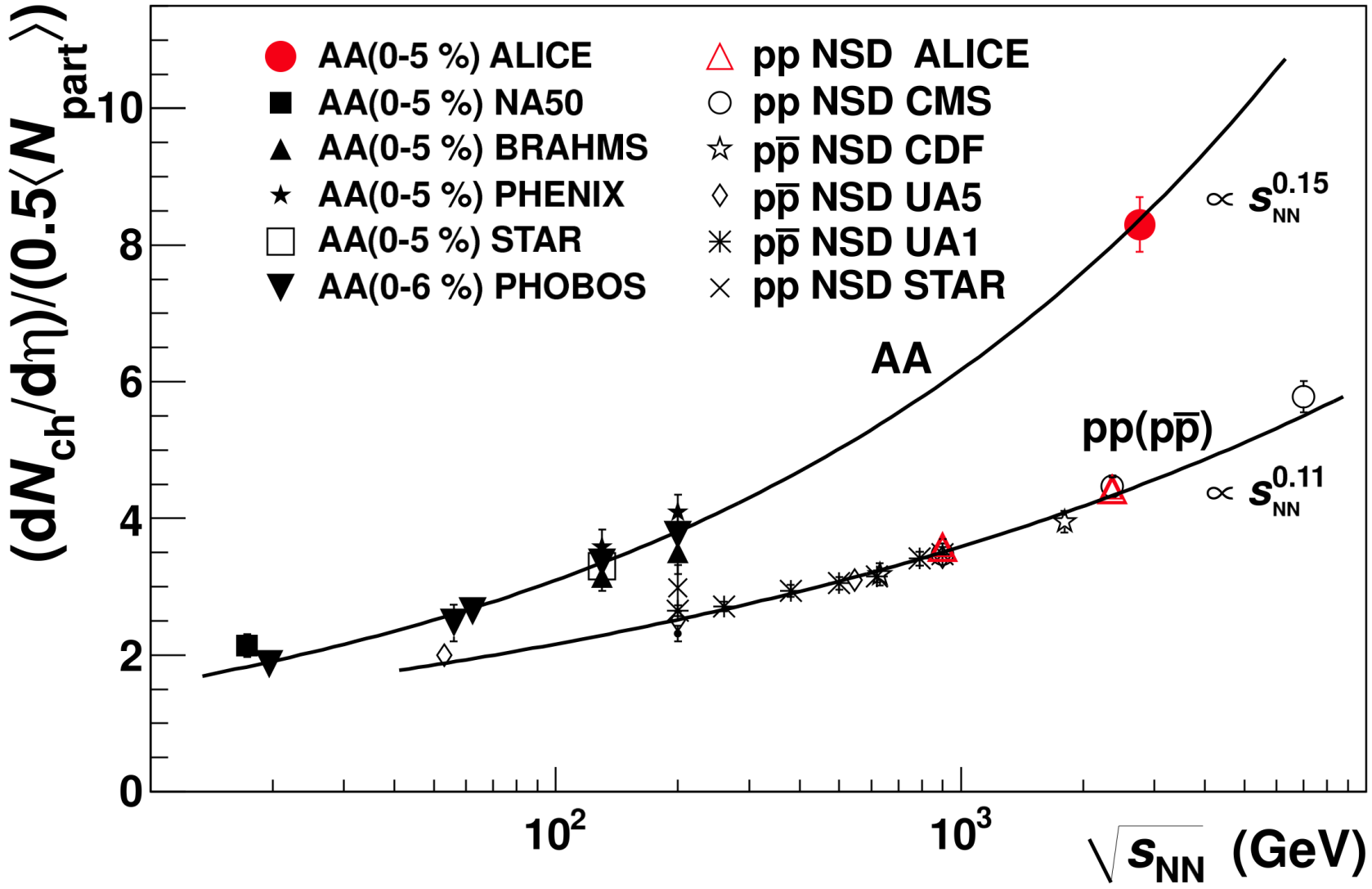
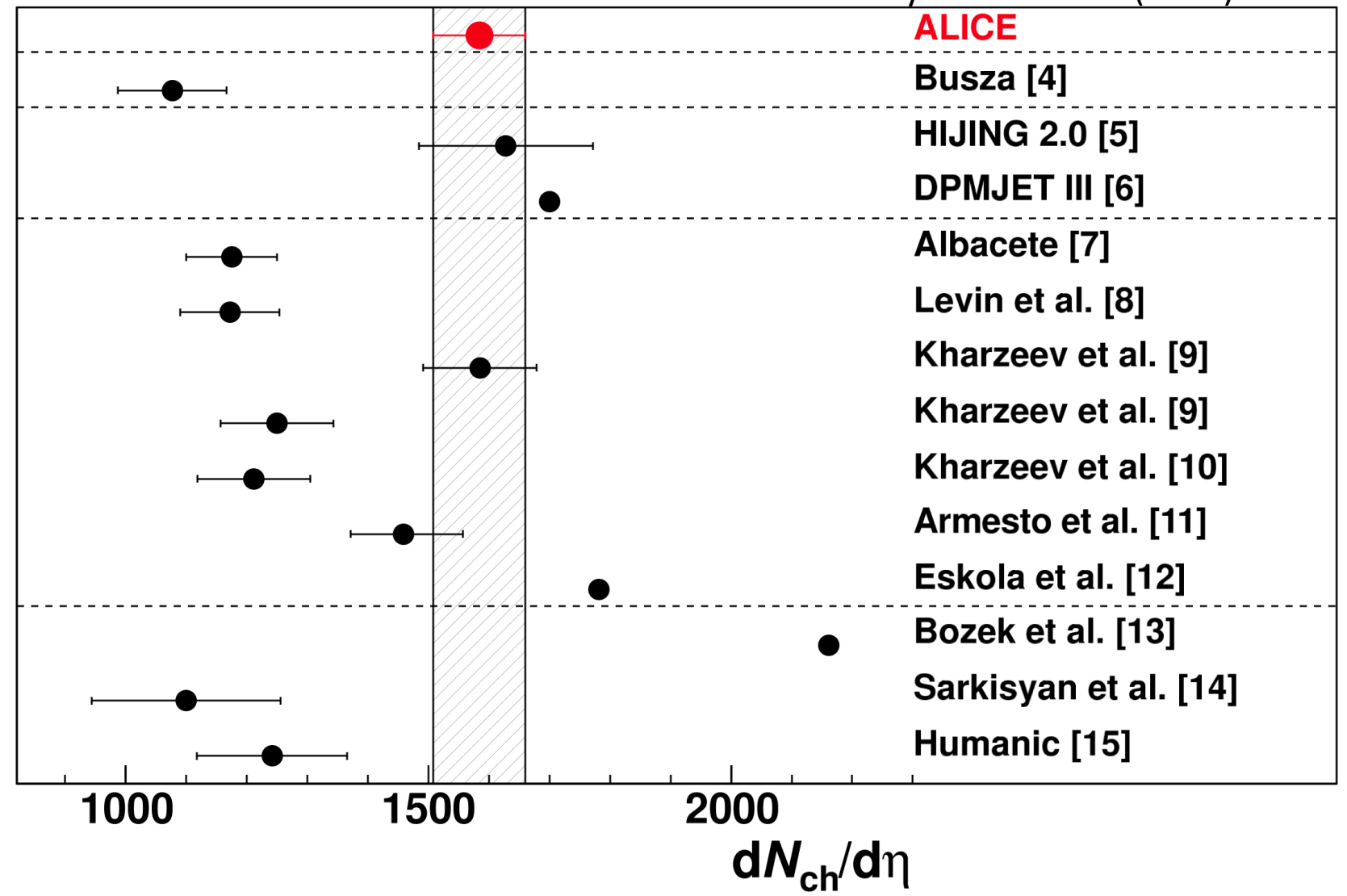
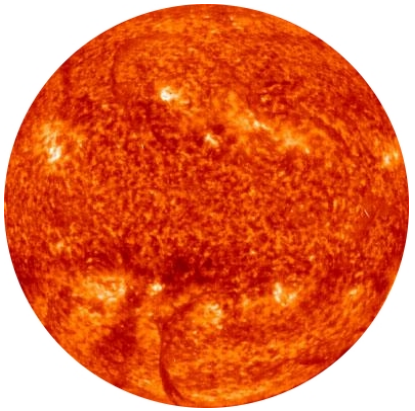


# *How do the models compare?*

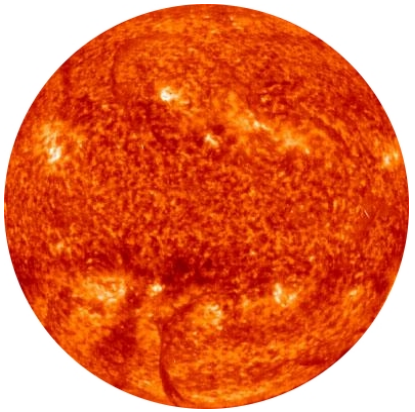
Phys. Lett. B 696 (2011) 30-39



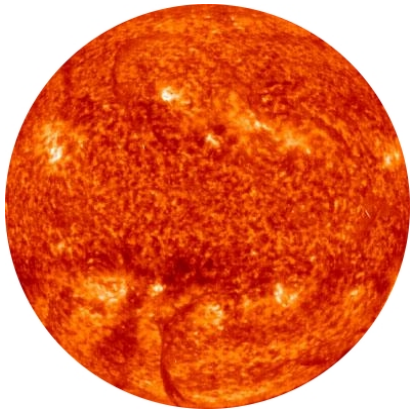
# *A simple picture of a heavy ion collision*



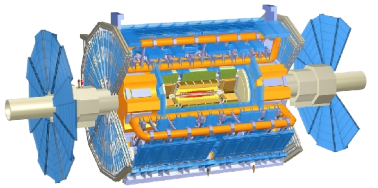
# *Jets as a probe of the quark gluon plasma*



# *One jet "absorbed" by the medium*

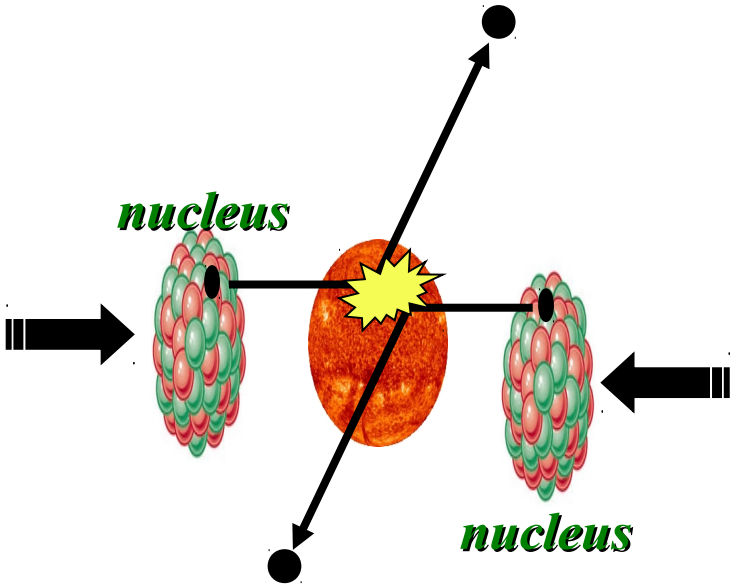


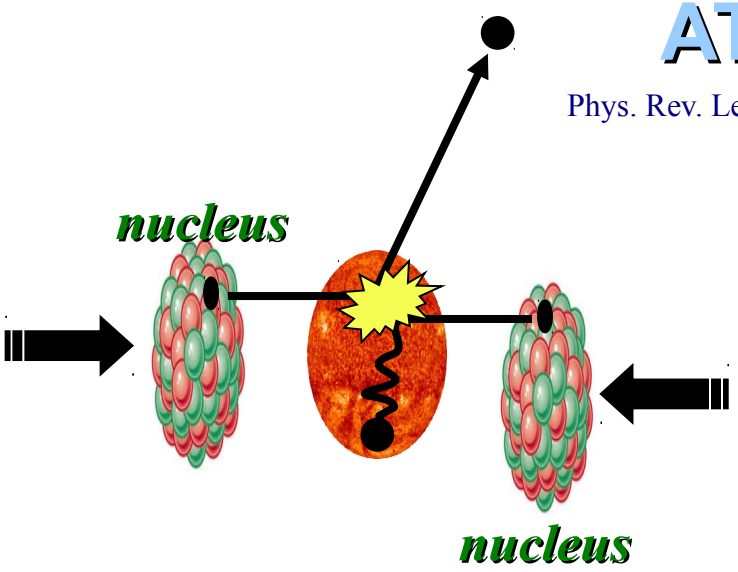
# Jet quenching

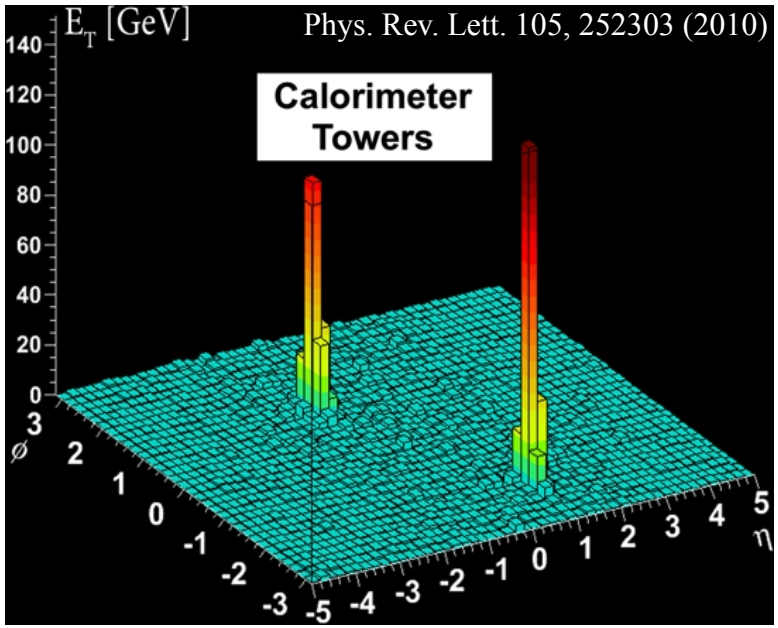


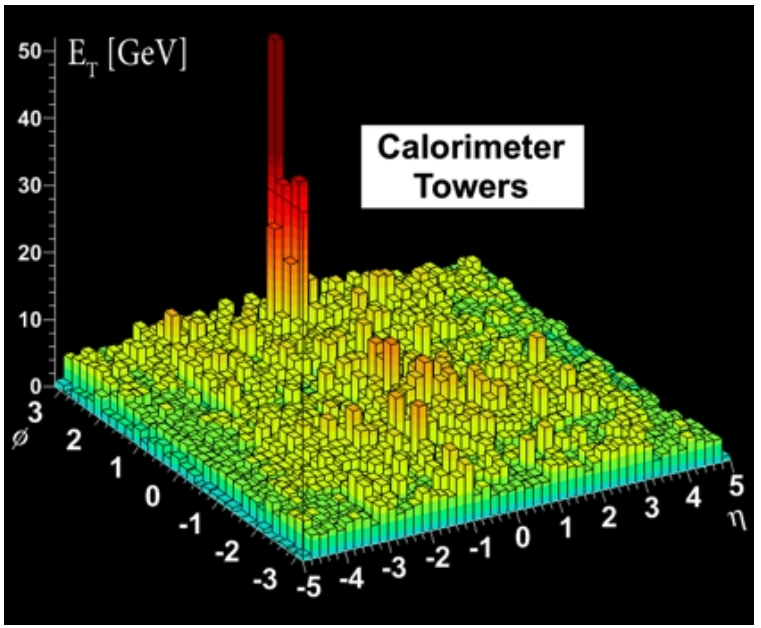
ATLAS

Phys. Rev. Lett. 105, 252303



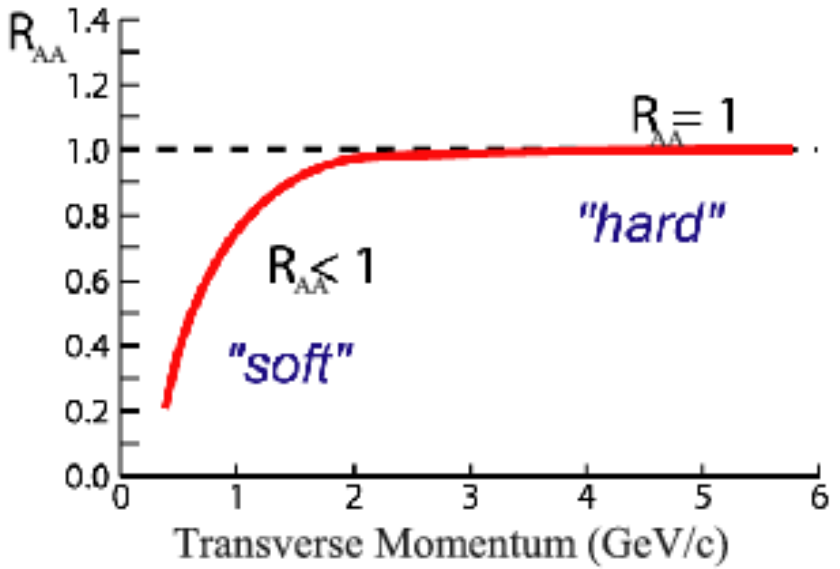



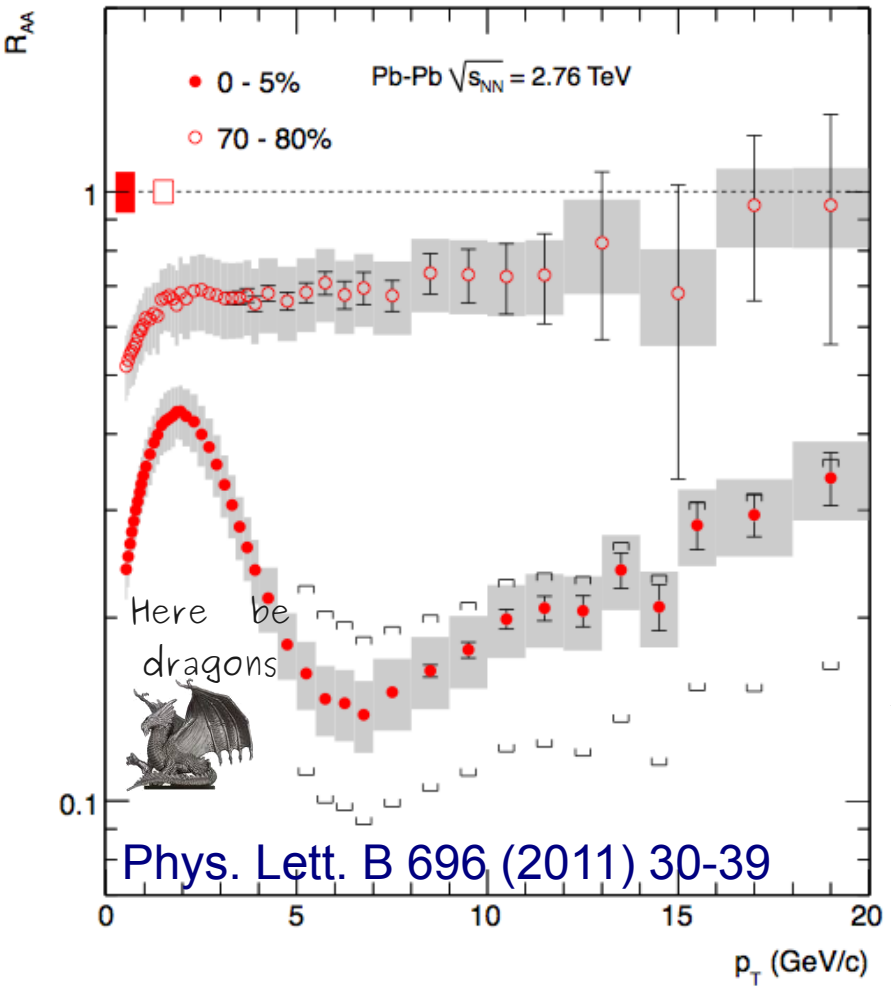
# *Single particles*

- Measure spectra of hadrons and compare to those in p+p collisions or peripheral A+A collisions
- If high-$p_T$ hadrons are suppressed, this is evidence of jet quenching
- Assumption: sufficiently high-$p_T$ hadrons mostly come from jets
- Unmodified spectra:

$$R_{AA} = \frac{d^2N_{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{pp}/dp_T d\eta}$$

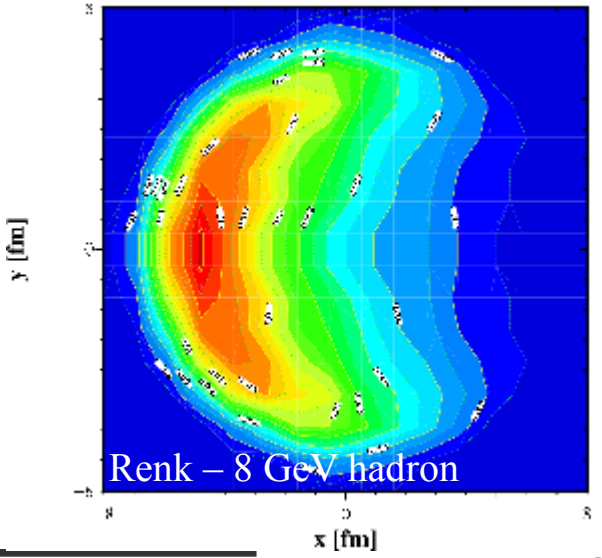


# *Experimental results*

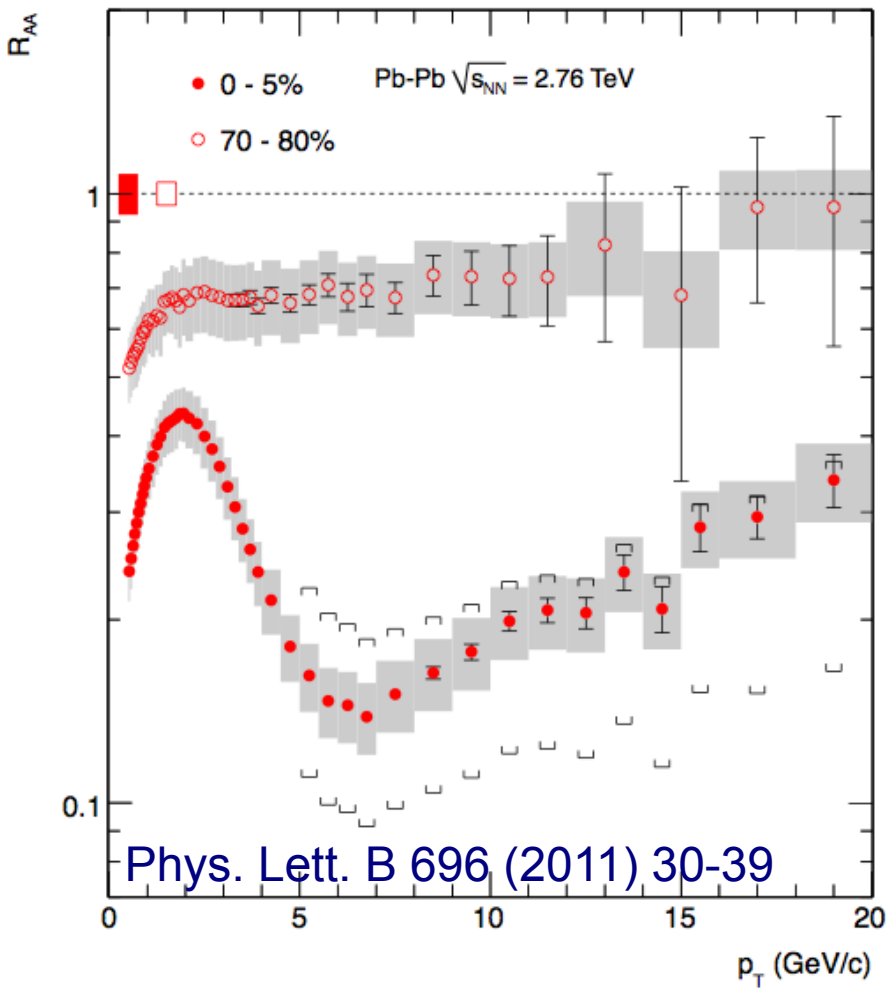



No suppression

Observed



# Experimental results

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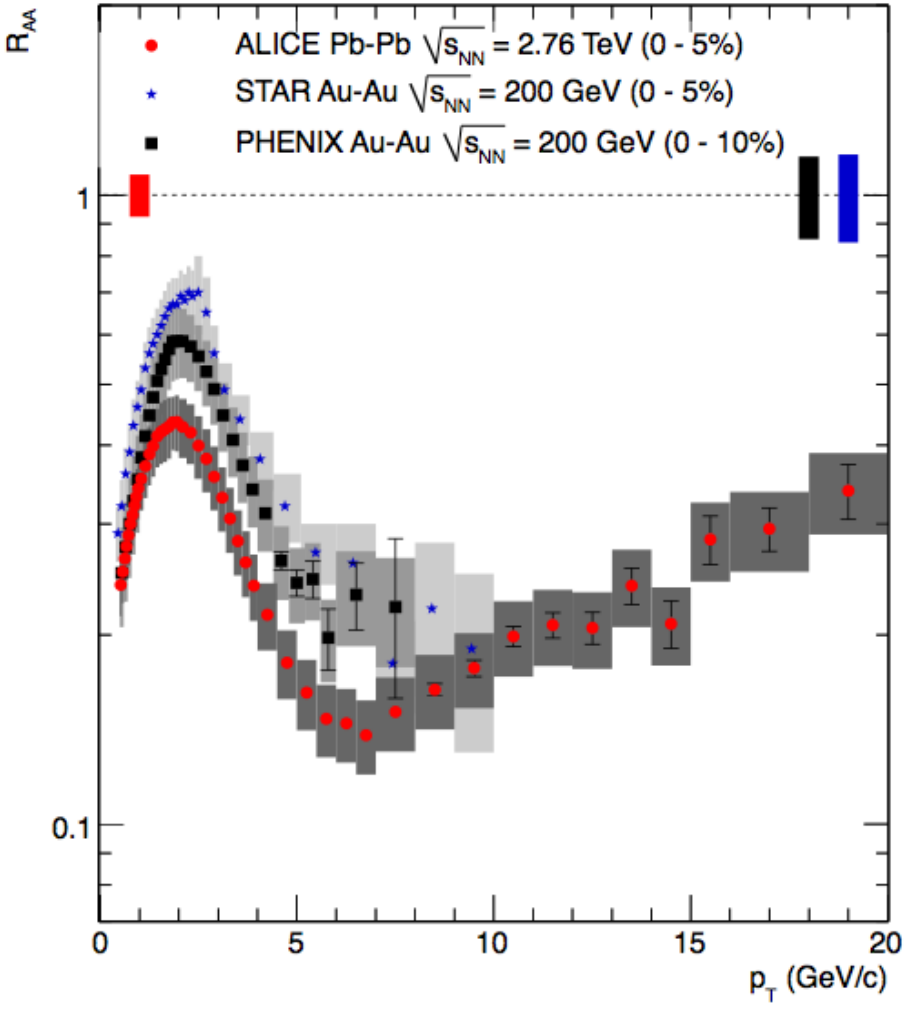
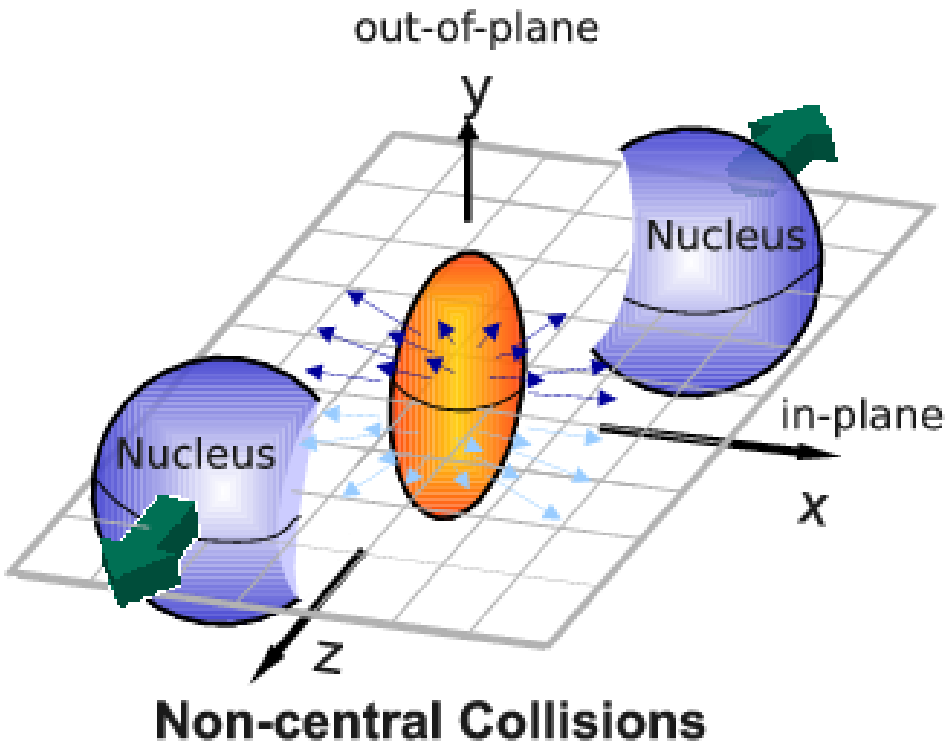
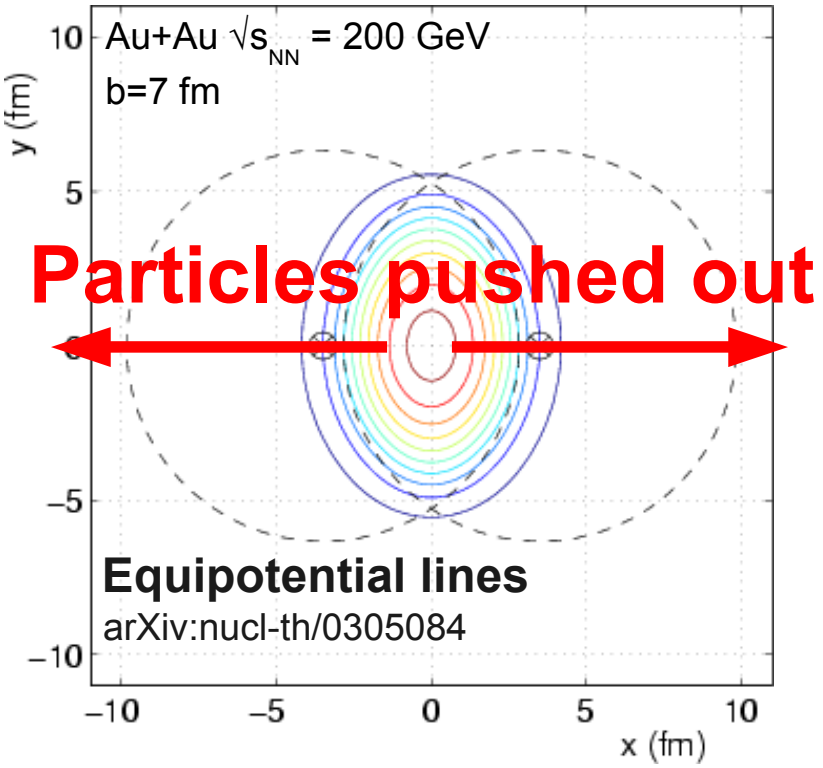


# *Hydrodynamical flow*

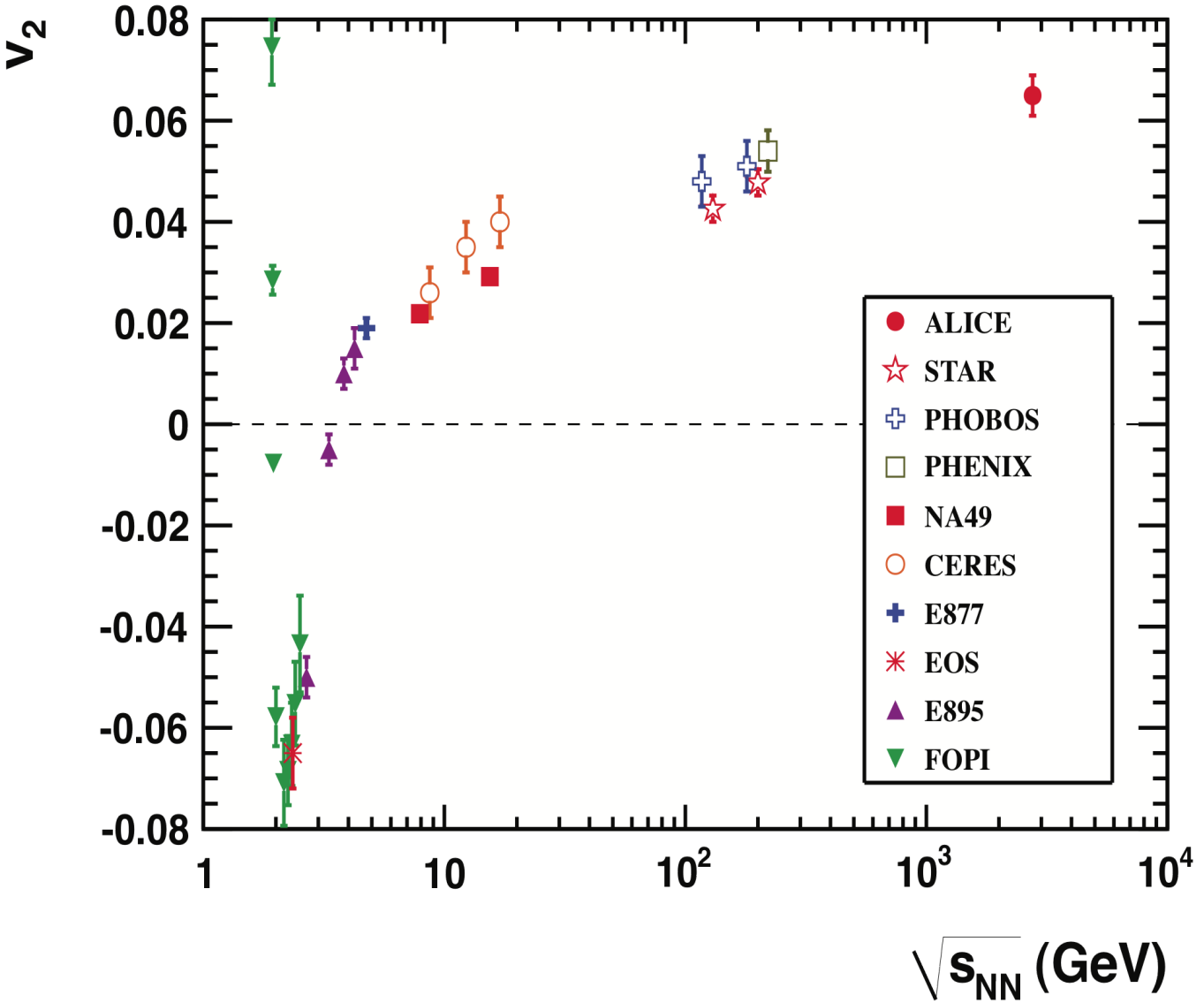


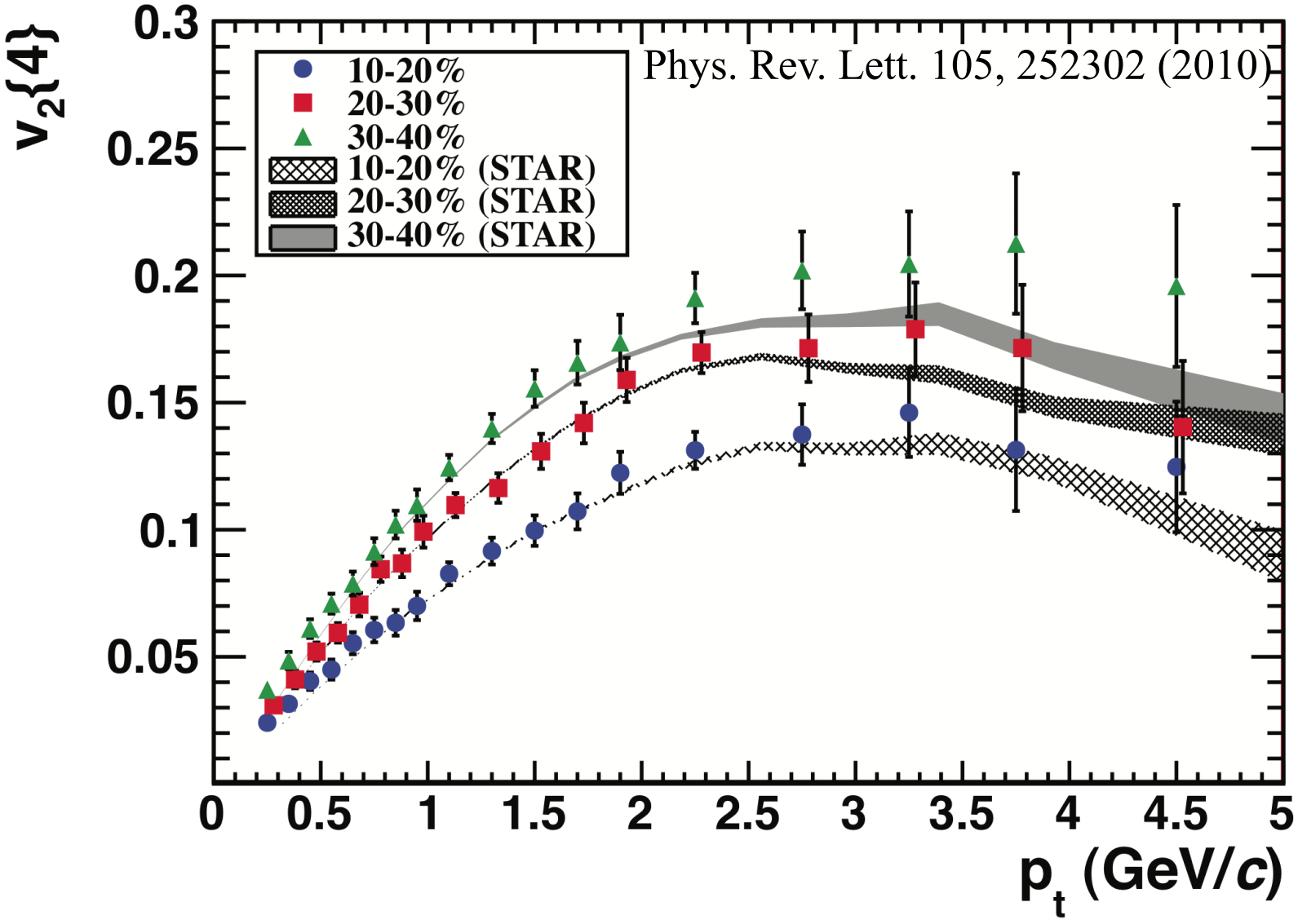

- When nuclei collide, the overlap region is roughly elliptical
- If we have a fluid when we collide nuclei, there will be pressure gradients, pushing particles out

# *Elliptic flow at 2.76 TeV*

Phys. Rev. Lett. 105, 252302 (2010)



# *Elliptic flow at 2.76 TeV*



# *Conclusions*

- ALICE is capable of precision measurements in p+p and Pb+Pb
- QGP at the LHC already appears to be hotter and denser than at RHIC
- We will have many, many more probes available at the LHC

***More information on ALICE***

- ALICE web site
- US LHC Blog posts

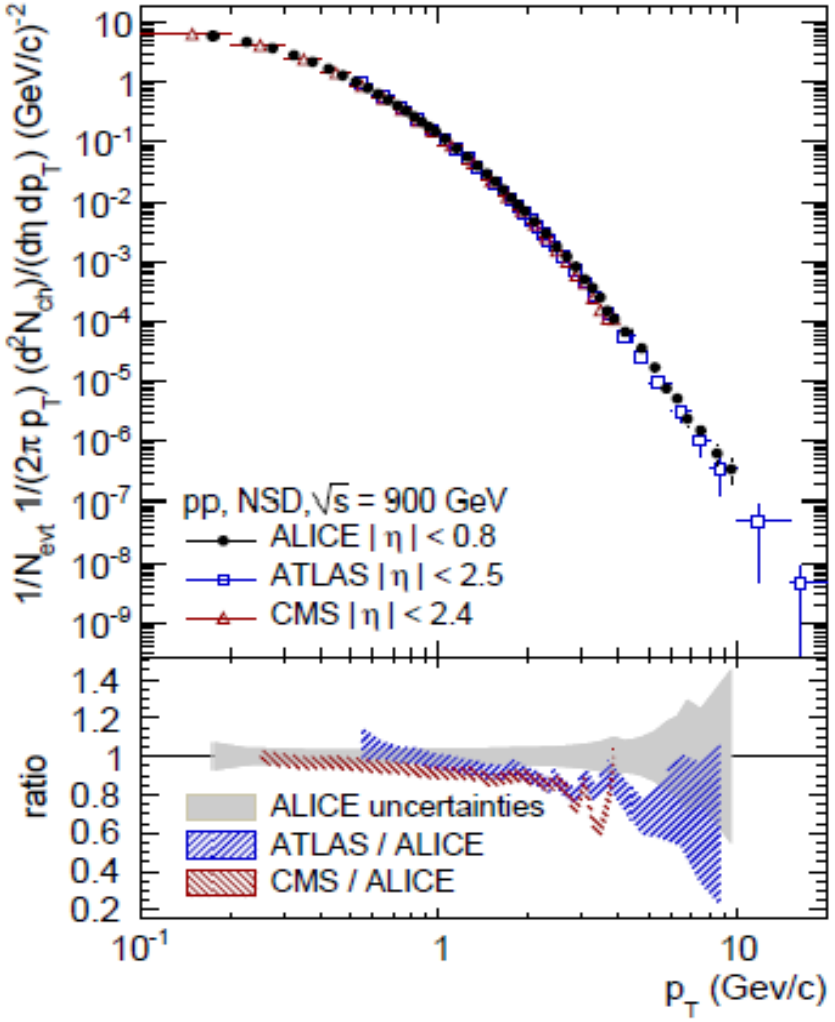
# *Backup slides*

# *How do we know it's a QGP?*

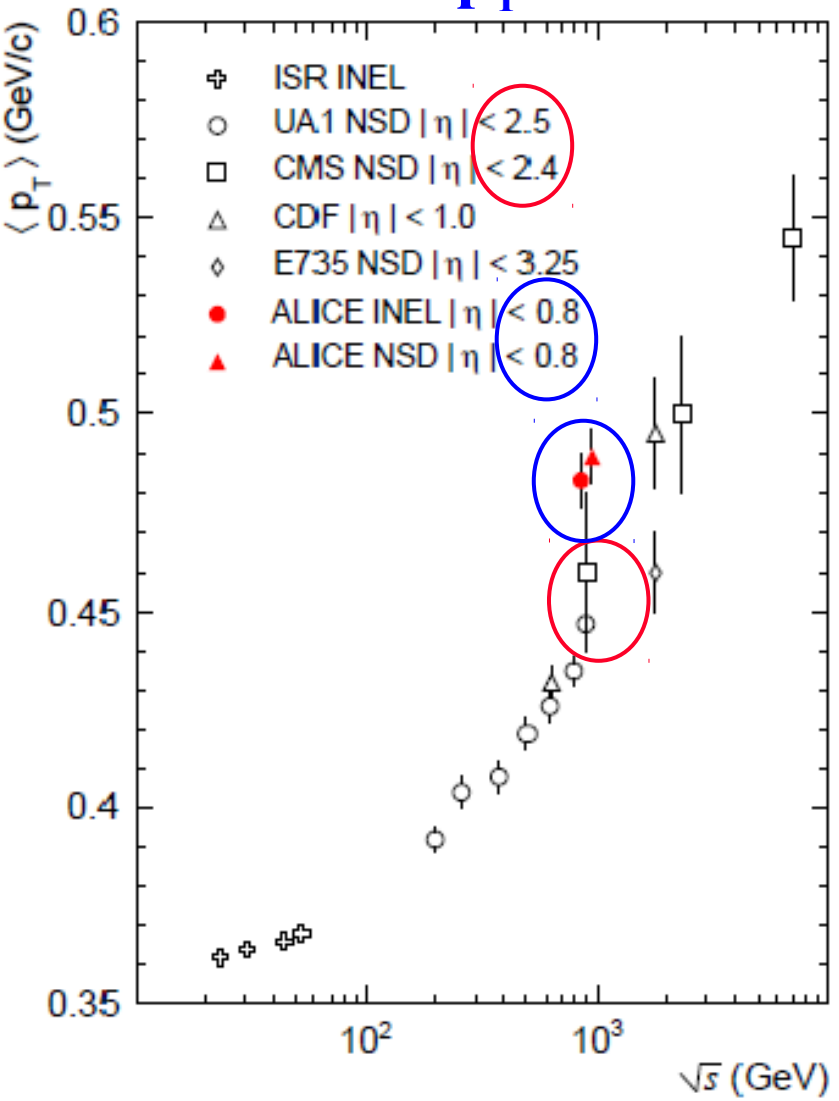
- Temperature – it is hot enough to match where we think it should be
- Jet quenching – high momentum quarks and gluons get stopped in the medium
- Hydrodynamical flow – it moves like a fluid of quarks and gluons
- Chemistry – what we produce is roughly at equilibrium

# Momentum distributions at 900 GeV

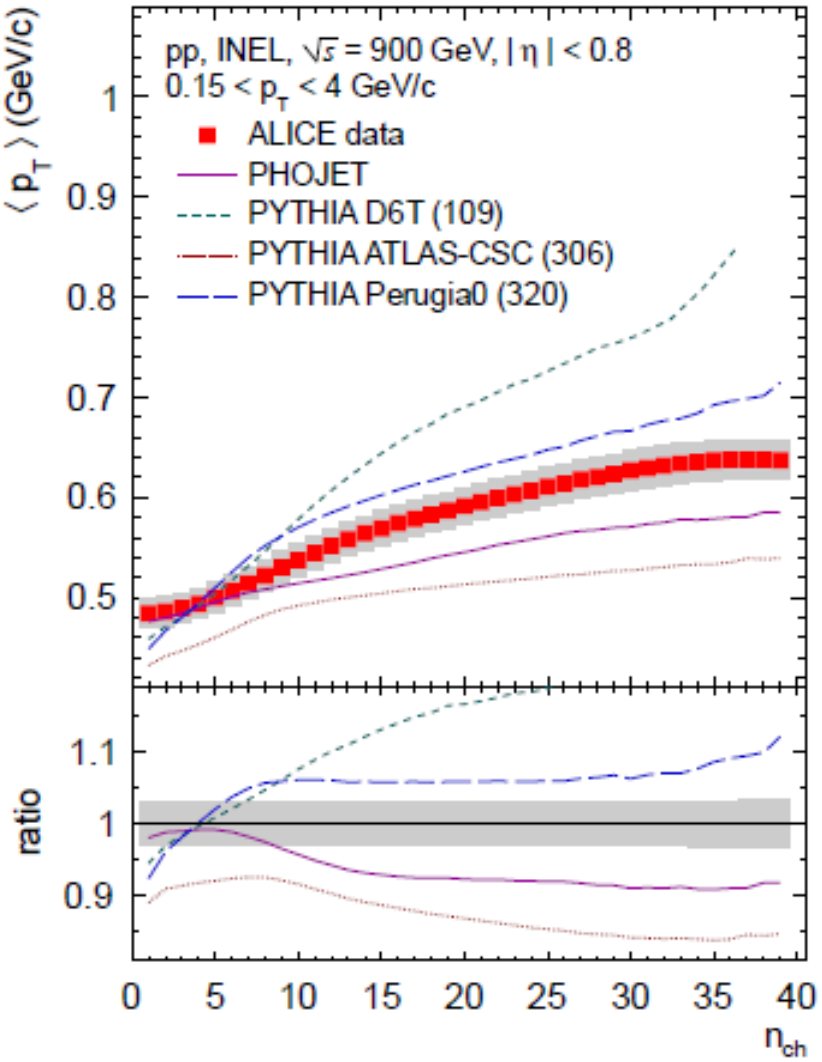
## $p_T$ distribution

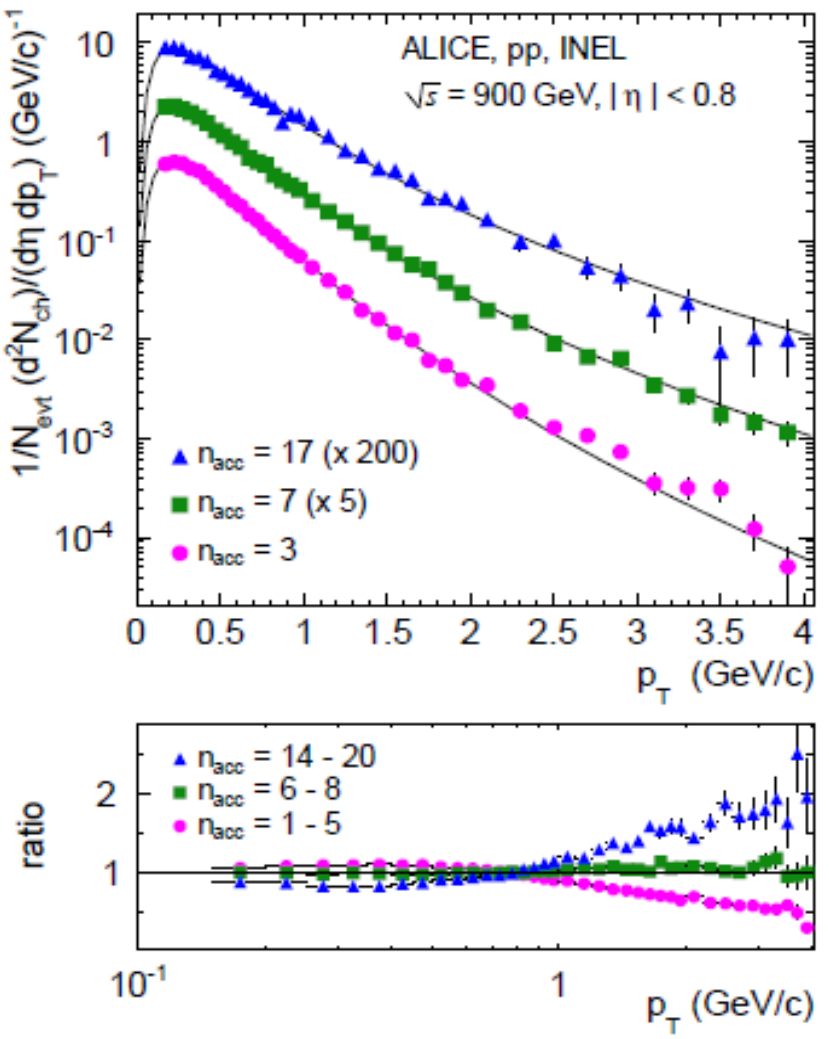



## $\langle p_T \rangle$



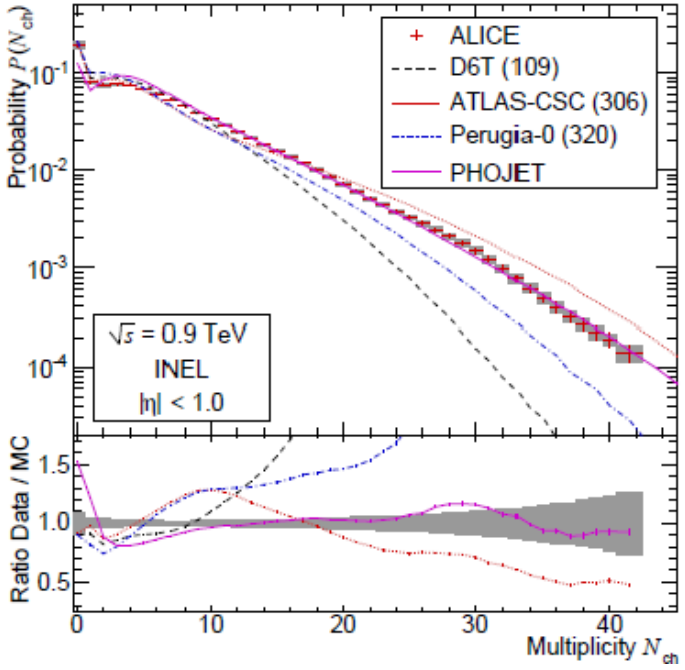
# $\langle p_T \rangle$ versus multiplicity

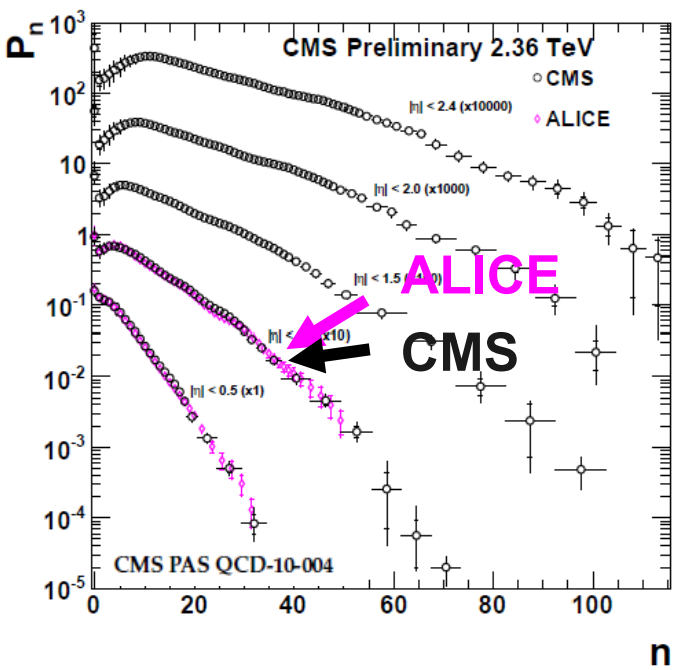


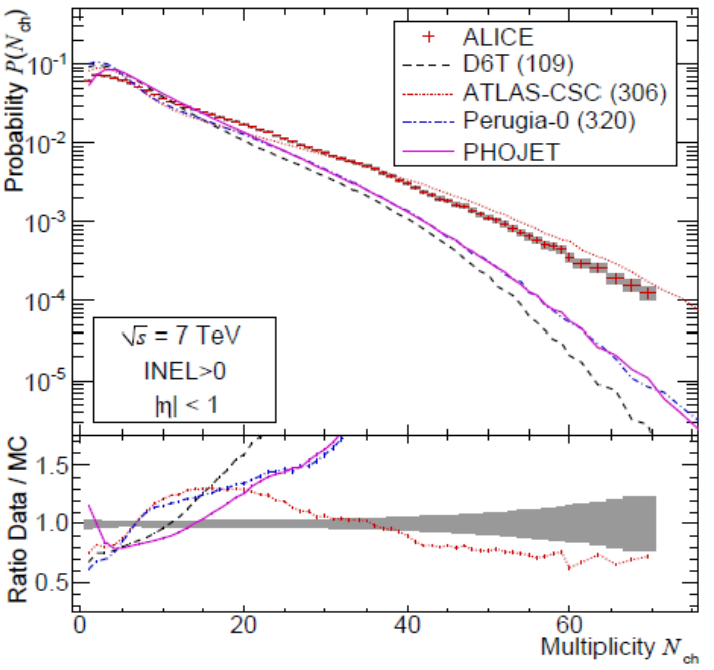




- Substantial discrepancies between Monte Carlo and the data

# *Multiplicity distributions*



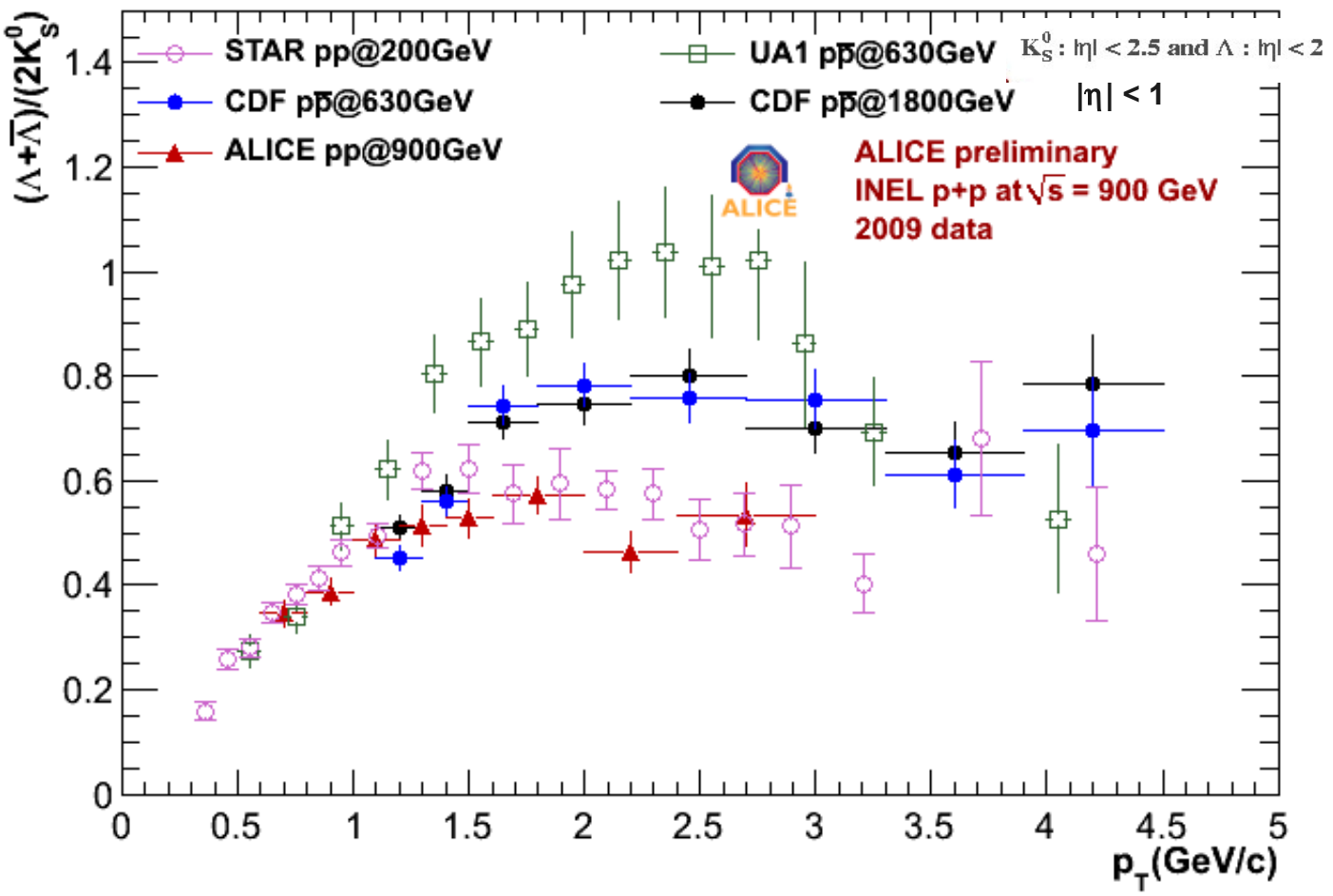




**900 GeV** **2.36 TeV** **7 TeV**

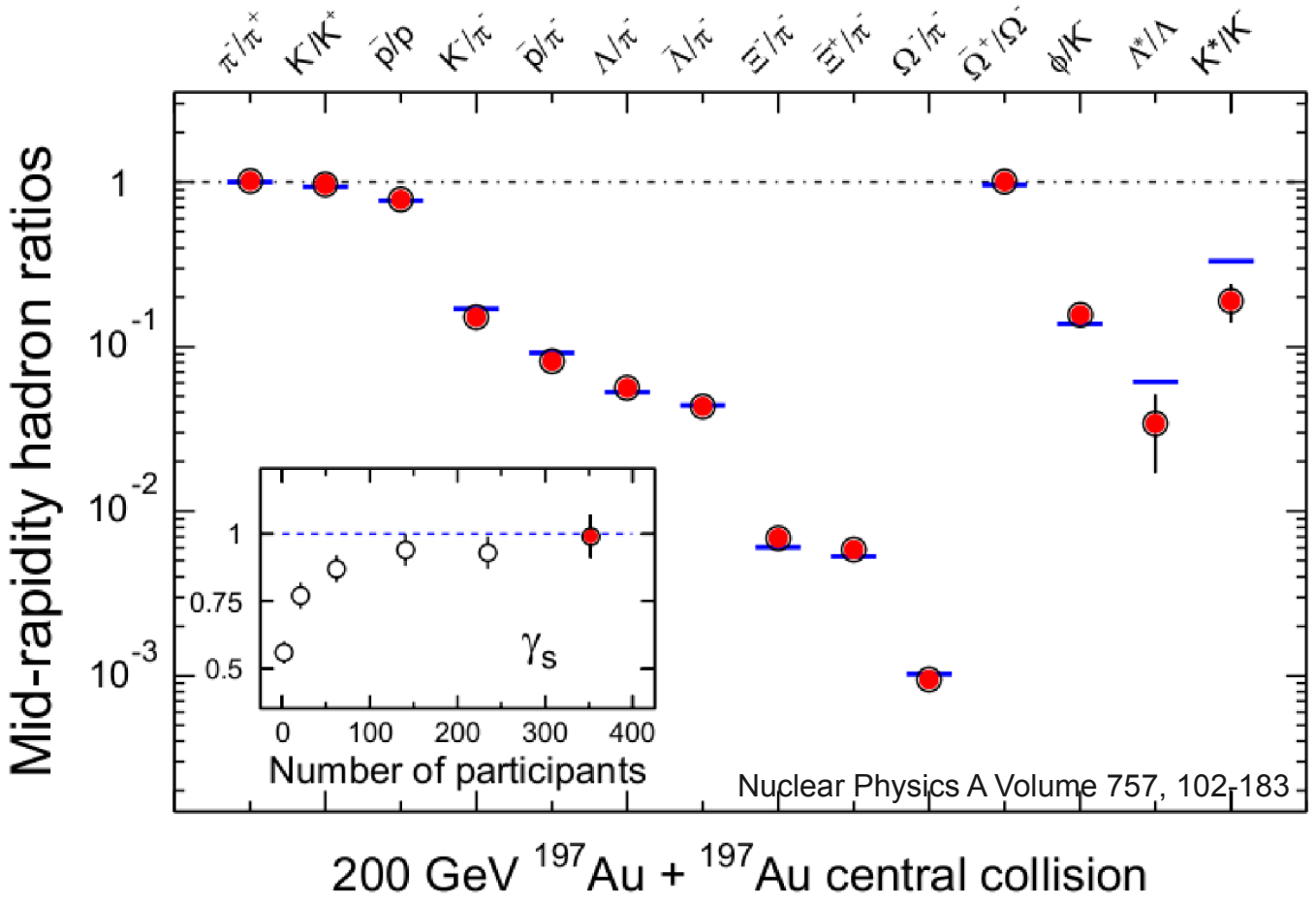
- Data from 900 GeV, 2.36 TeV, and 7 TeV
- Substantial discrepancies between Monte Carlo and the data
- Agreement between ALICE & CMS

# Λ/K⁰S ratio at 900 GeV

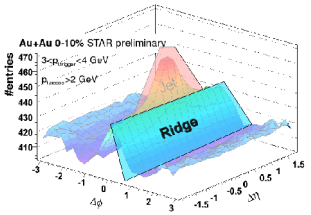



- Very good agreement between STAR (200 GeV) and ALICE (900 GeV)
- Very different from CDF (630/1800) and UA1 (630) for $p_T > 1.5$ GeV

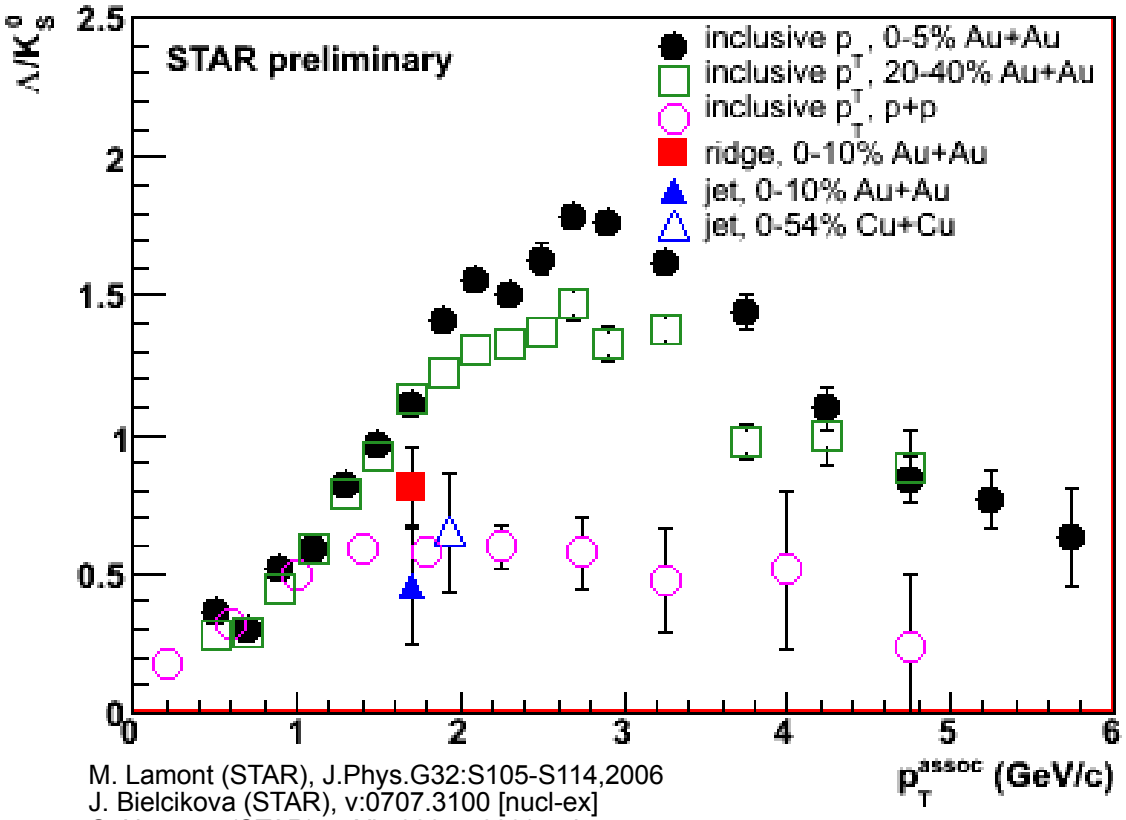
# Chemistry - equilibrium



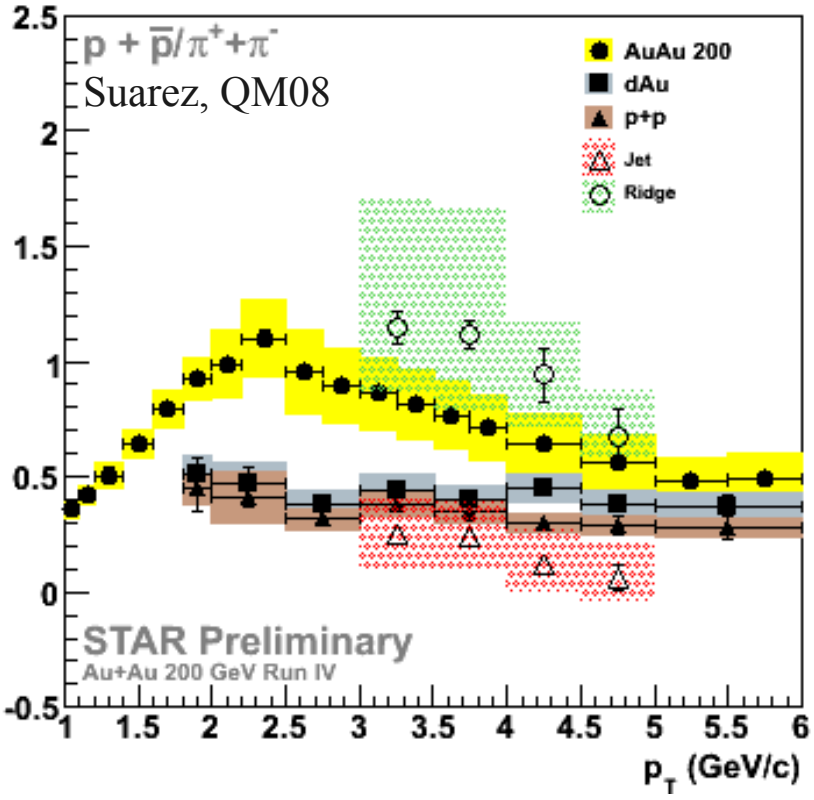

- Ratios of particles expected from a model
- Even strange quarks are at equilibrium!




# *Ridge composition*

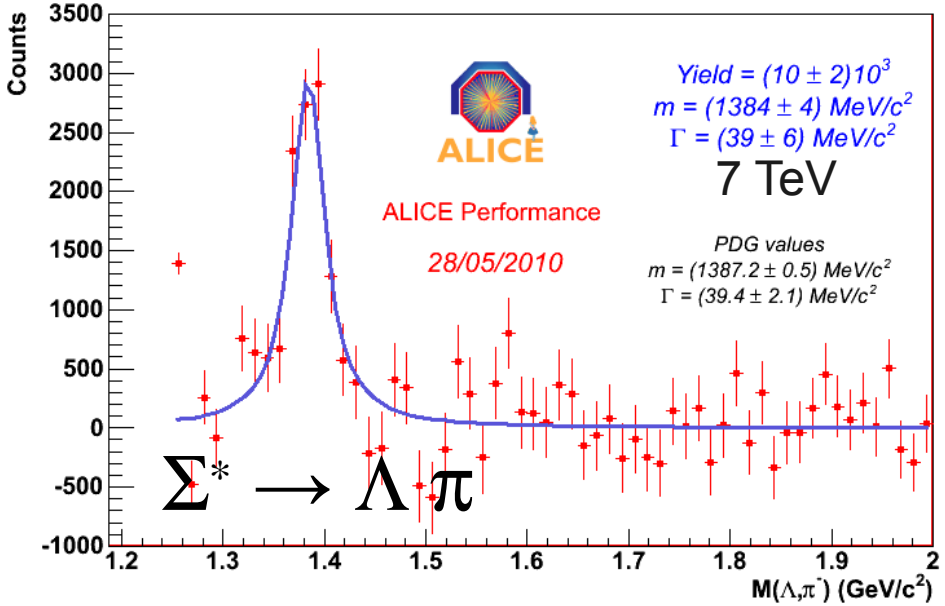


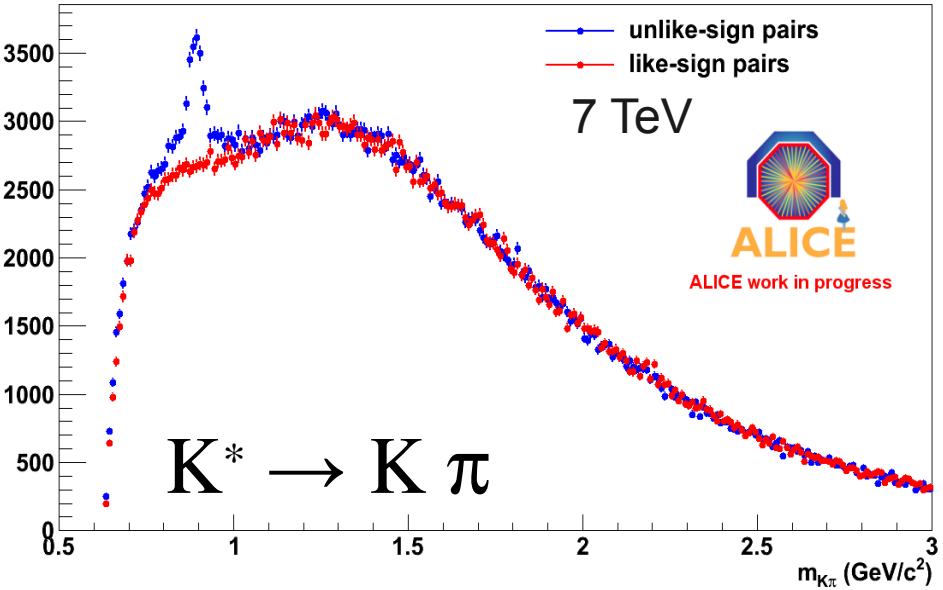

M. Lamont (STAR), J.Phys.G32:S105-S114,2006
J. Bielcikova (STAR), v:0707.3100 [nucl-ex]
C. Nattrass (STAR), arXiv:0804.4683/nucl-ex

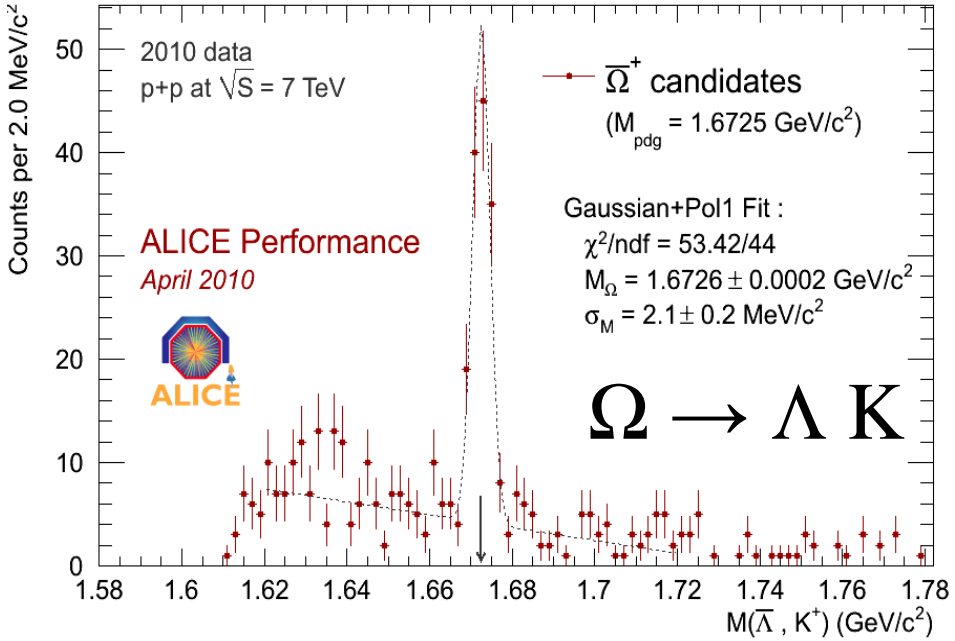


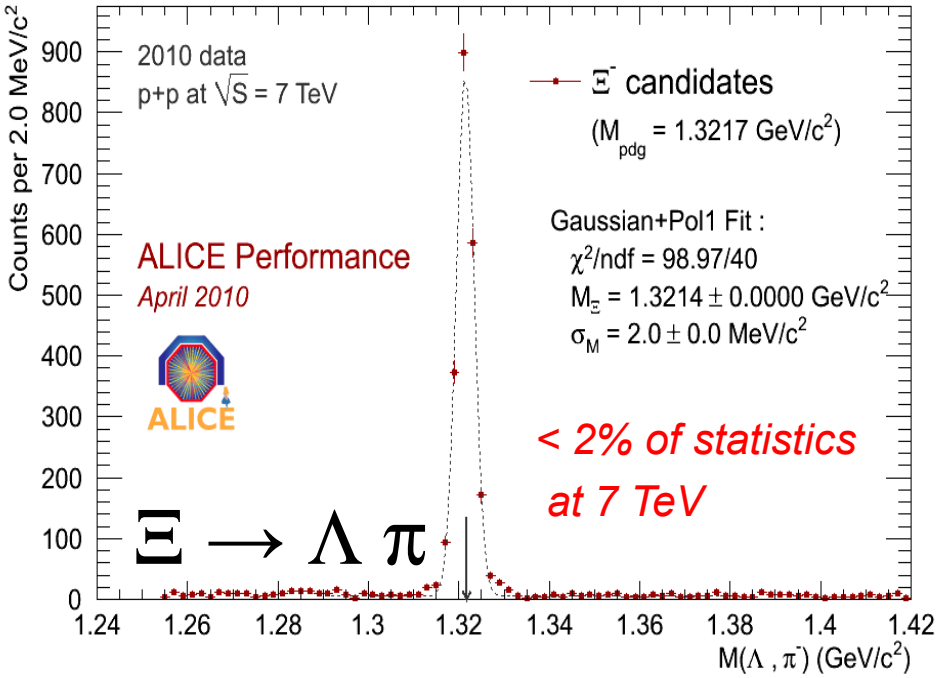

- Baryon/meson ratios in *Ridge* similar to bulk for both strange and non-strange particles

# More to come


Counts
Yield = (10 ± 2)10^3
m = (1384 ± 4) MeV/c^2
Γ = (39 ± 6) MeV/c^2
7 TeV
ALICE
ALICE Performance
28/05/2010
PDG values
m = (1387.2 ± 0.5) MeV/c^2
Γ = (39.4 ± 2.1) MeV/c^2
Σ* → Λ π
M(Λ,π^-) (GeV/c^2)


unlike-sign pairs
like-sign pairs
7 TeV
ALICE
ALICE work in progress
K* → K π
m_Kπ (GeV/c^2)


Counts per 2.0 MeV/c^2
2010 data
p+p at √S = 7 TeV
Ω̄^+ candidates
(M_pdg = 1.6725 GeV/c^2)
Gaussian+Pol1 Fit :
χ^2/ndf = 53.42/44
M_Ω = 1.6726 ± 0.0002 GeV/c^2
σ_M = 2.1 ± 0.2 MeV/c^2
ALICE Performance
April 2010
ALICE
Ω → Λ K
M(Λ̄ , K^+) (GeV/c^2)


Counts per 2.0 MeV/c^2
2010 data
p+p at √S = 7 TeV
Ξ^- candidates
(M_pdg = 1.3217 GeV/c^2)
Gaussian+Pol1 Fit :
χ^2/ndf = 98.97/40
M_Ξ = 1.3214 ± 0.0000 GeV/c^2
σ_M = 2.0 ± 0.0 MeV/c^2
ALICE Performance
April 2010
ALICE
< 2% of statistics
at 7 TeV
Ξ → Λ π
M(Λ , π^-) (GeV/c^2)

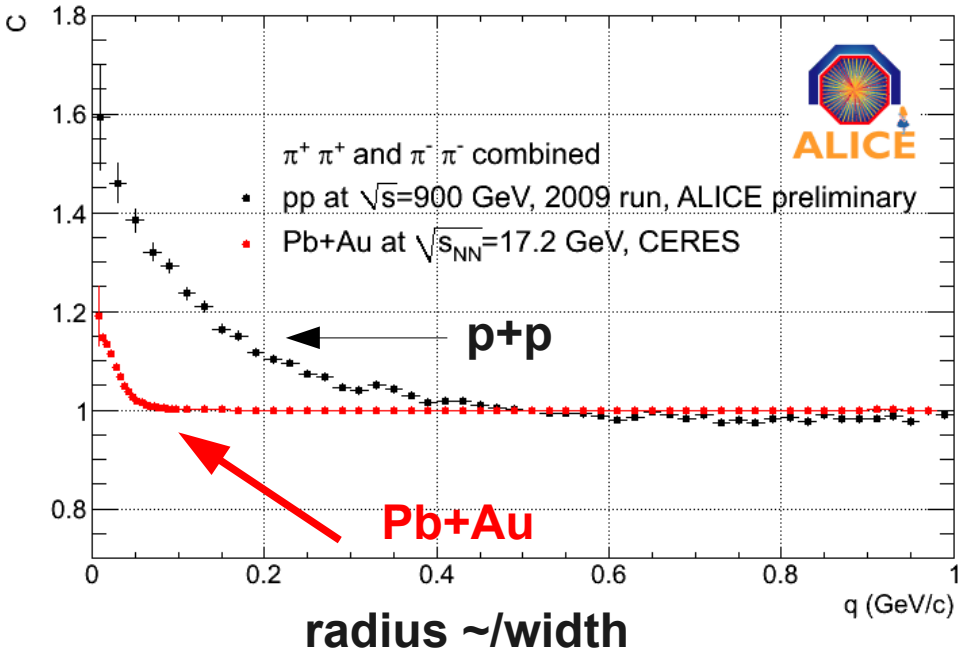
# Bose-Einstein correlations

QM enhancement of identical Bosons at small momentum difference:

- Enhancement of e.g. like-sign pions at low momentum difference $q_{inv}=|p_1-p_2|$

➡ Measure the space-time evolution of the dense matter formed in heavy-ion collisions.

➡ Interpretation for "small systems" (p+p, $e^+ + e^-$) is less obvious...



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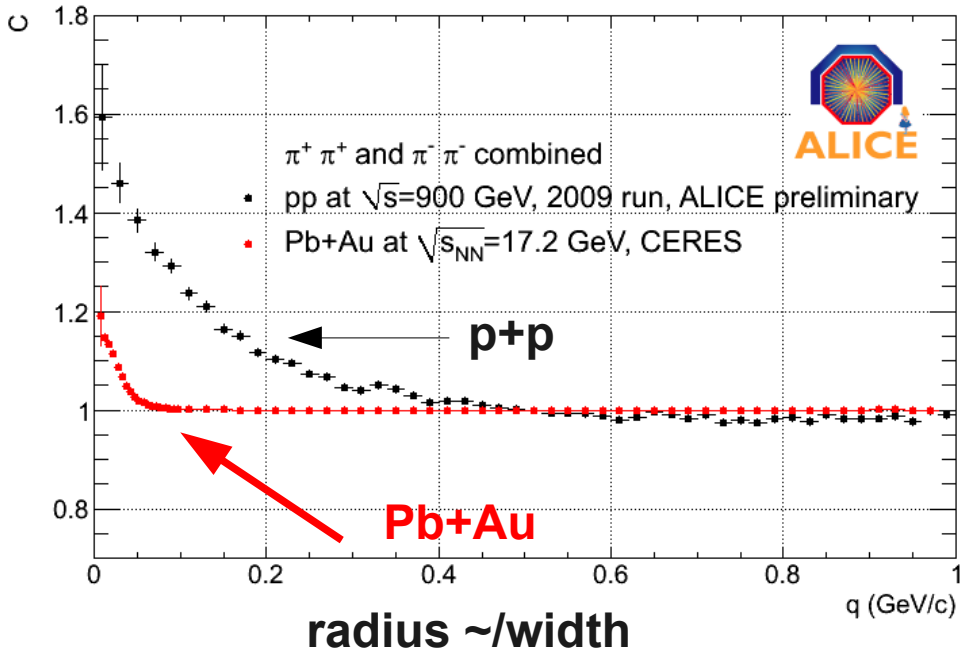
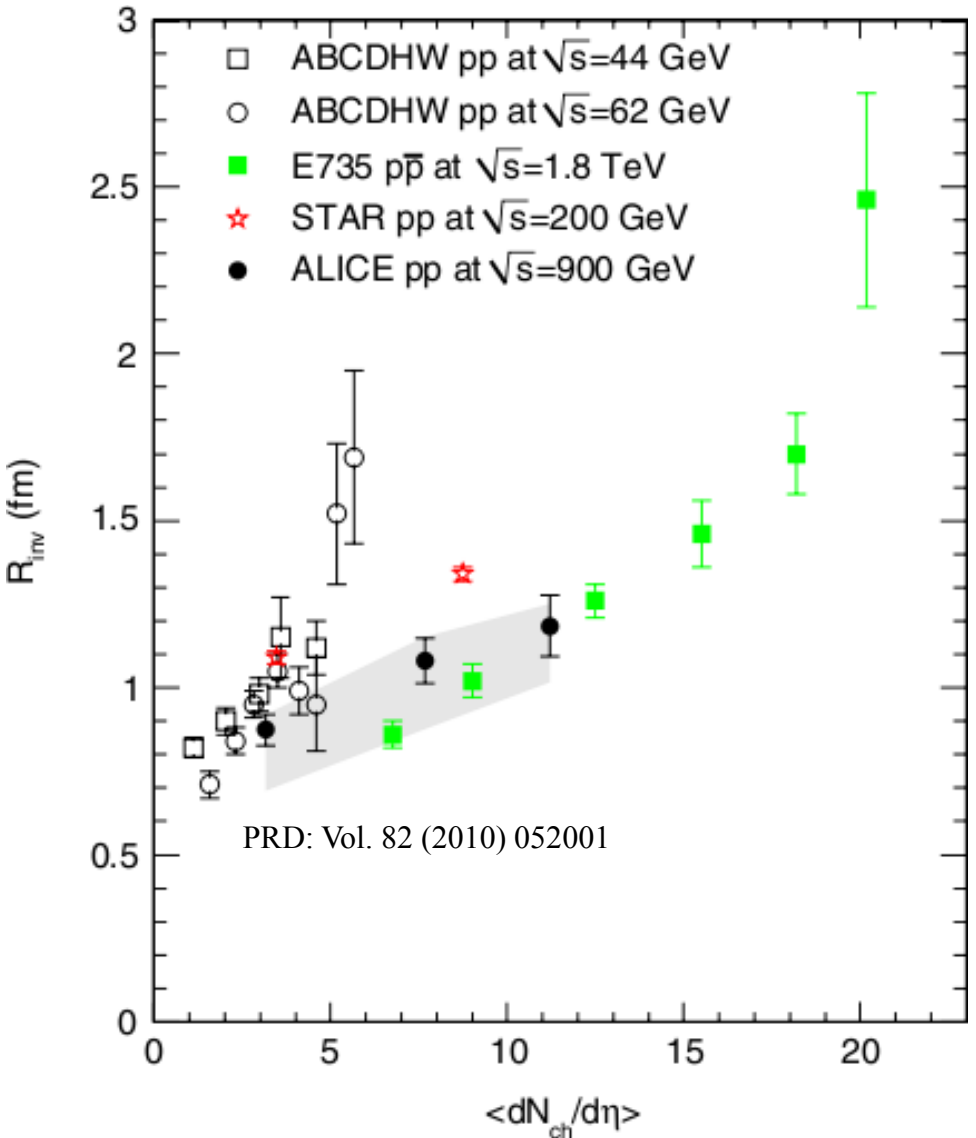
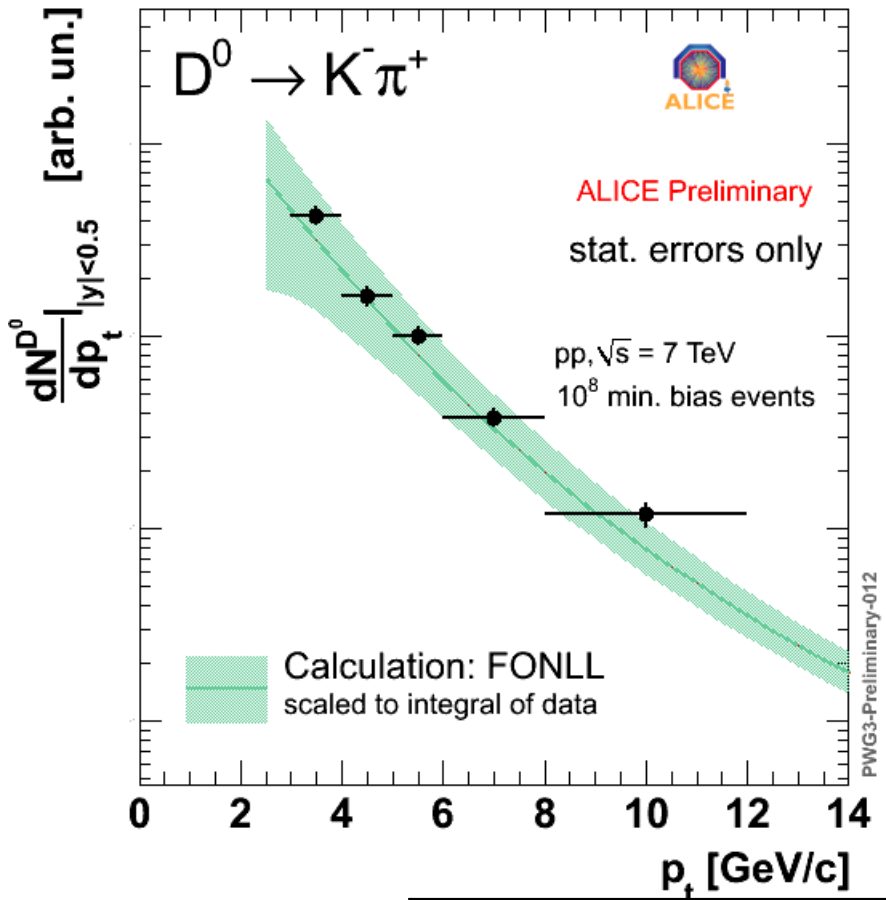


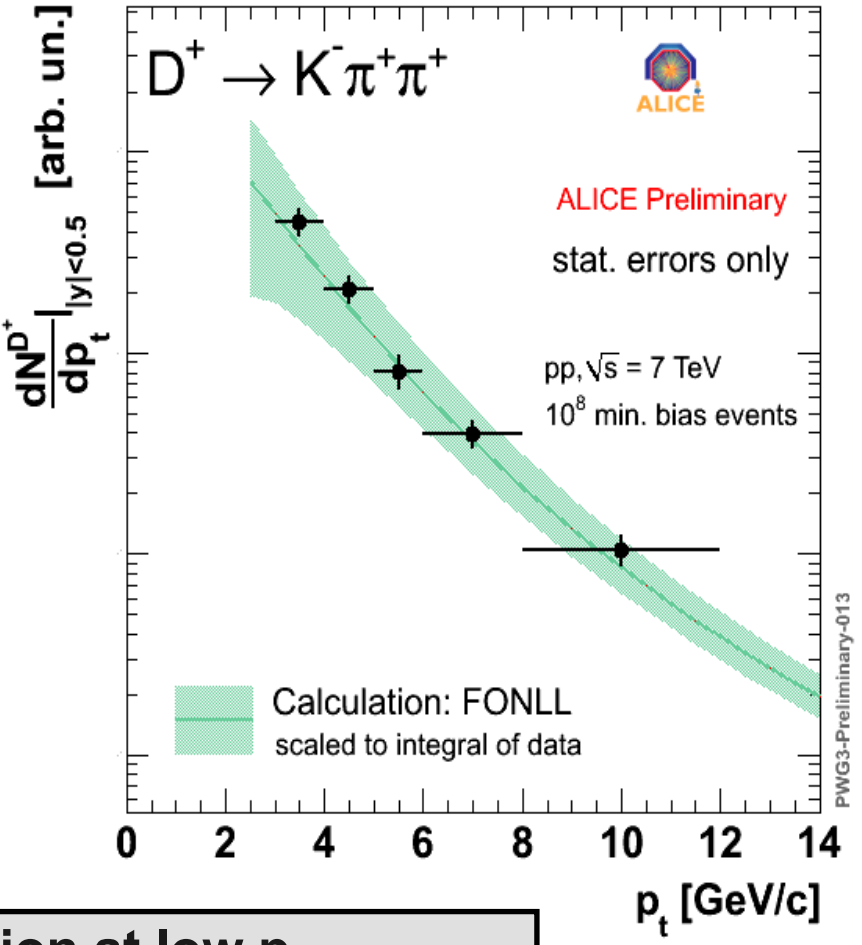

radius ~/width




Source radius vs $N_{ch}$

# $D^0$ and $D^+$ $dN/dp_t$



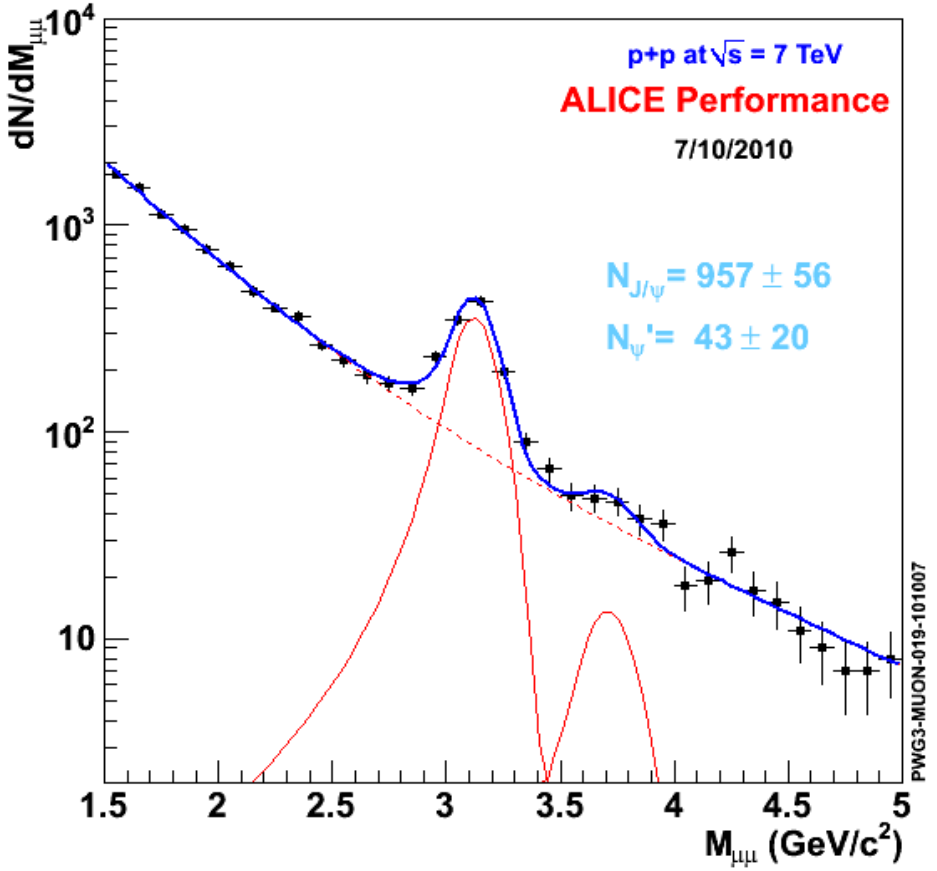




- Most of the cross section at low $p_T$
- Shape at low $p_T$ very uncertain
- $10^9$ MB events => measure below 1 GeV

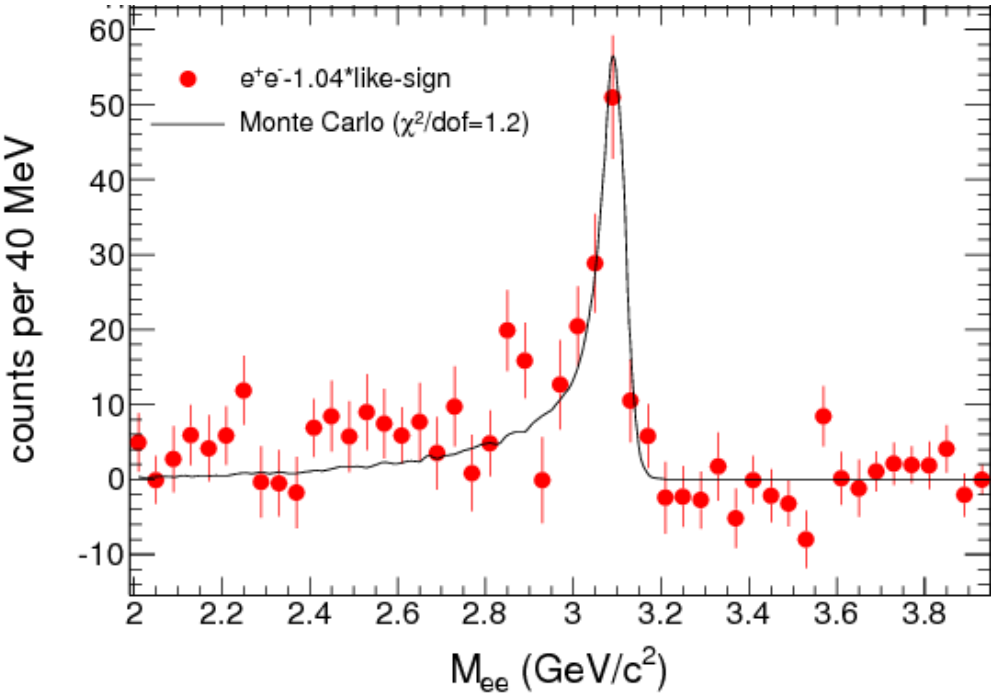
  (PID important at low $p_T$ !)

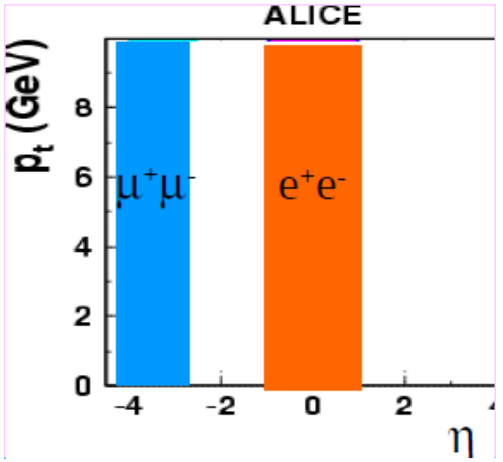
# J/ψ production at 7 TeV

**J/ψ → μ⁺μ⁻, y = 2.5–4.0**




**J/ψ → e⁺e⁻ |y| < 1**



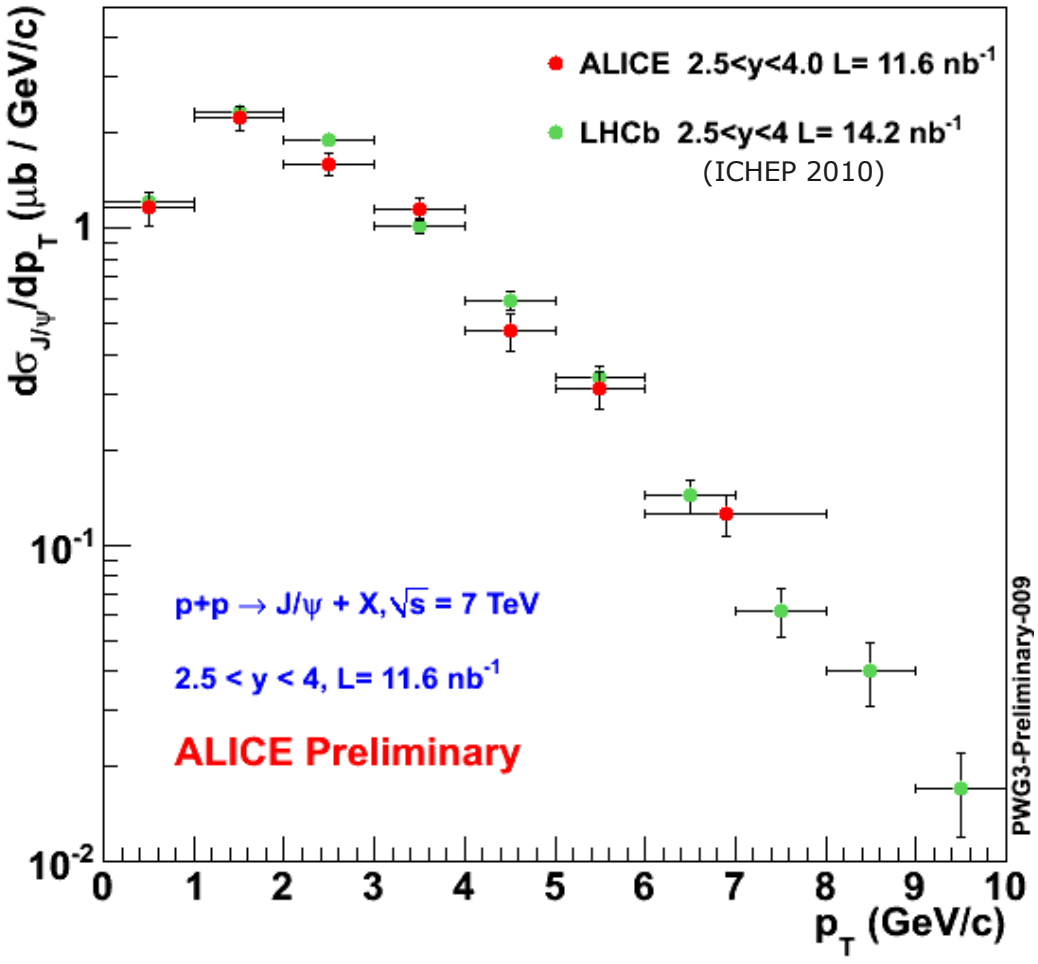



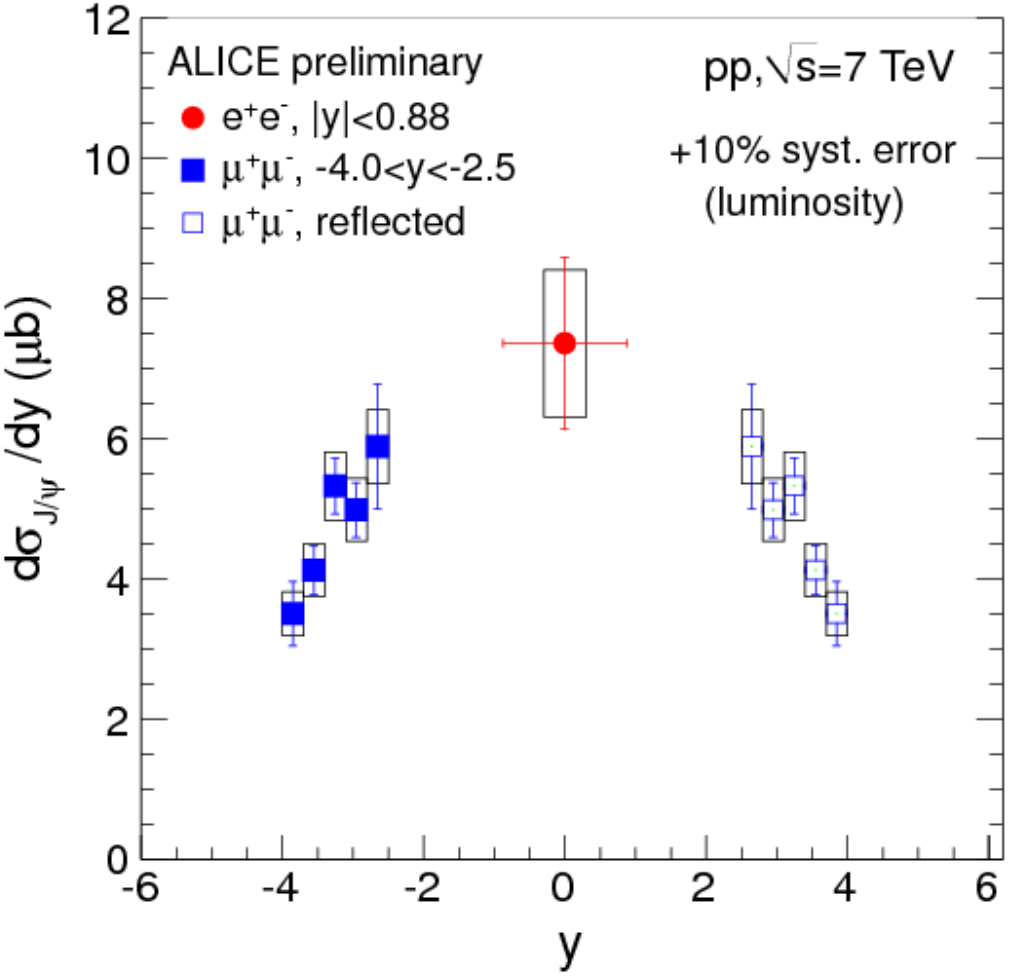

**Measurement of J/ψ over wide pseudorapidity range**

- **Rapidity spectra**
- **Transverse-momentum spectra**

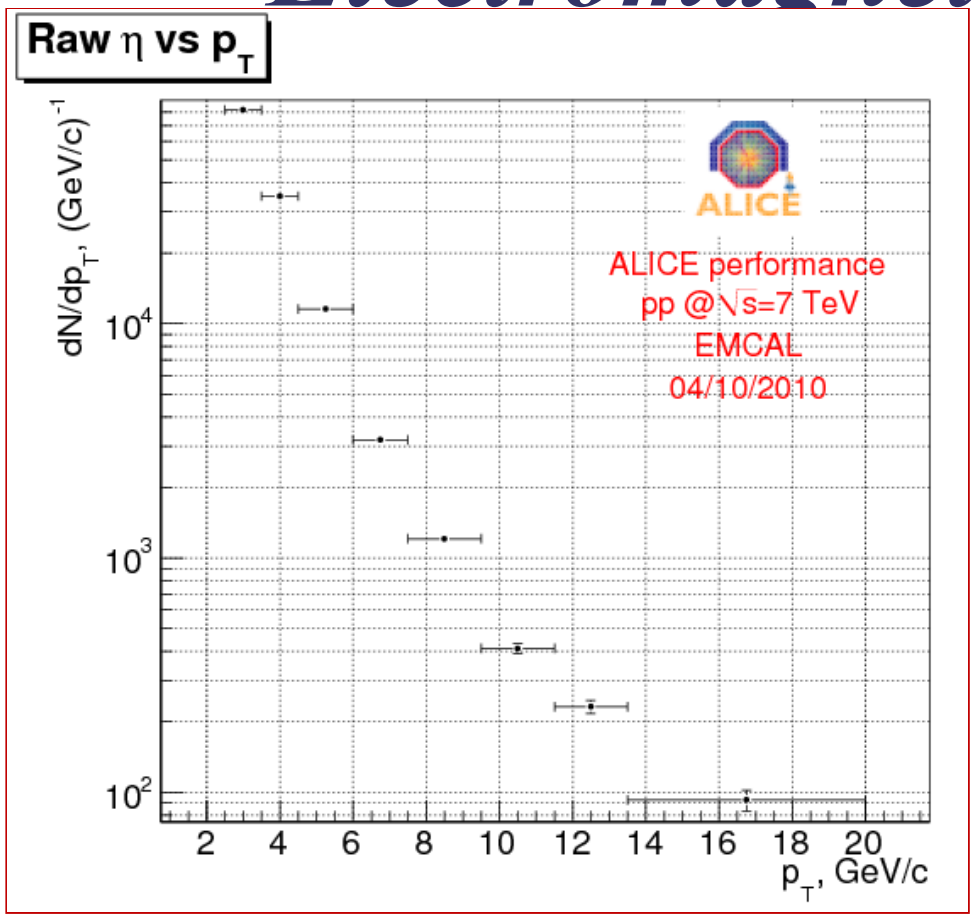
# J/ψ production at 7 TeV

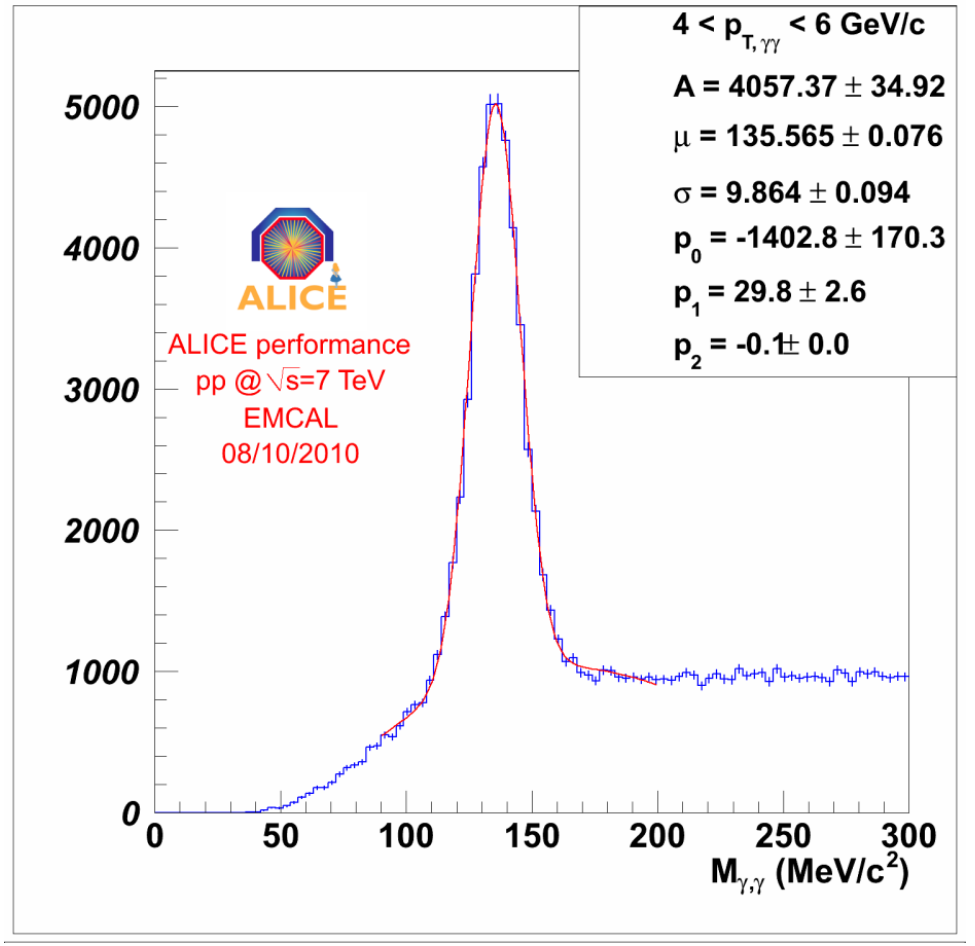
**very good agreement with LHCb pt spectra and cross section**
**cross-section measurement in central–forward regions match**



# Electromagnetic calorimeter



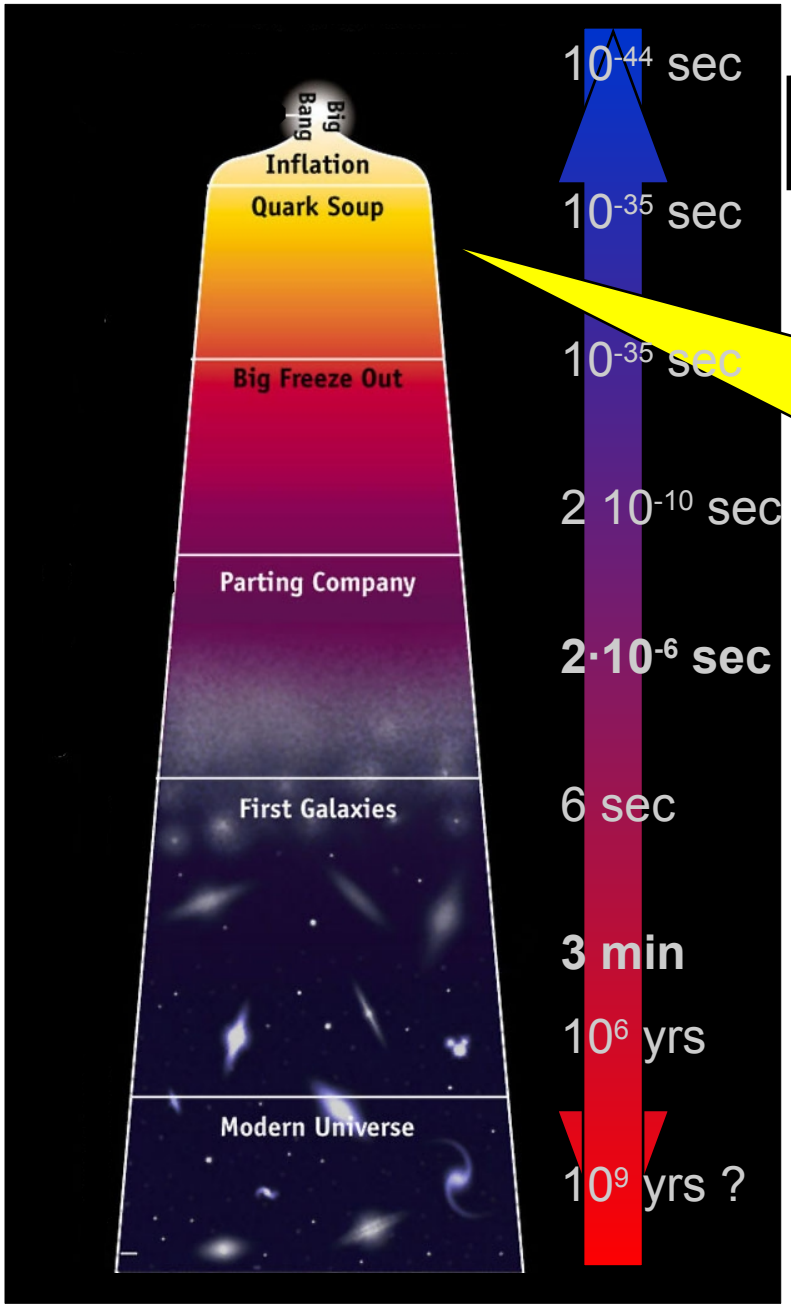




- EMCal: -0.7 <η< 0.7, 80°<φ< 120° in 2010
  → 80°<φ< 180° in January 2011 – Ahead of schedule!

# Physics papers submitted/published: 2010

- Strange particle production at central rapidity in proton-proton collisions at √s = 0.9 TeV with ALICE at LHC (Submitted?)
- Transverse momentum spectra of charged particles in proton–proton collisions at √s=900 GeV with ALICE at the LHC (Physics Letters B 693 (2010) 53–68)
- Two-pion Bose-Einstein correlations in pp collisions at √s=900 GeV (Phys. Rev. D 82, 052001 (2010))
- Midrapidity Antiproton-to-Proton Ratio in pp Collisons at √s=0.9 and 7 TeV Measured by the ALICE Experiment (Phys Rev Lett Vol.105, No.7, (2010))
- Charged-particle multiplicity measurement in proton–proton collisions at √s=7 TeV with ALICE at LHC (Eur. Phys. J. C (2010) 68: 345–354)
- Charged-particle multiplicity measurement in proton–proton collisions at √s=0.9 and 2.36 TeV with ALICE at LHC (Eur. Phys. J. C (2010) 68: 89–108)
- First proton–proton collisions at the LHC as observed with the ALICE detector: measurement of the charged-particle pseudorapidity density at √s=900 GeV (Eur. Phys. J. C (2010) 65: 111-125)

# *Evolution of the Universe*




**The universe gets cooler !**

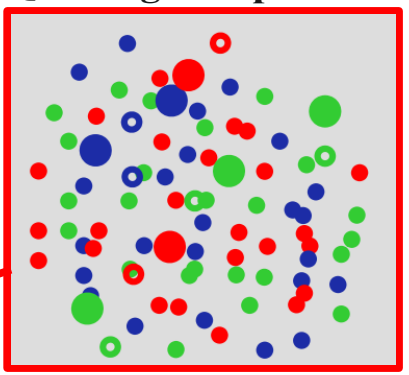
?

Need temperatures around $1.5 \cdot 10^{12}$ K

~$10^5$ times hotter than the core of the sun

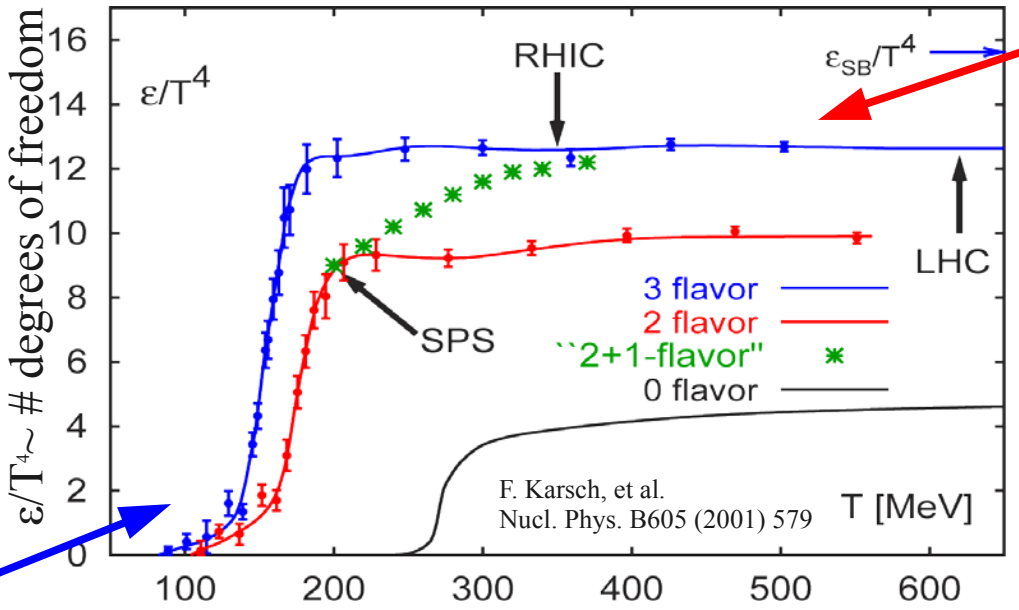
# Exploring QCD at high temperatures

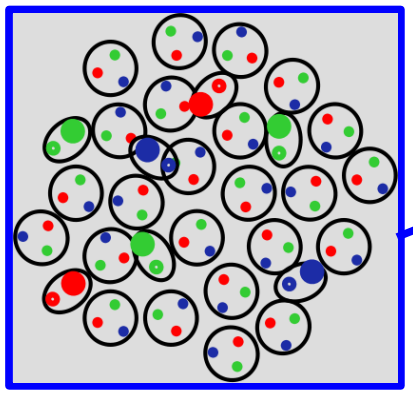
Quark-gluon plasma



Deconfined - more degrees of freedom

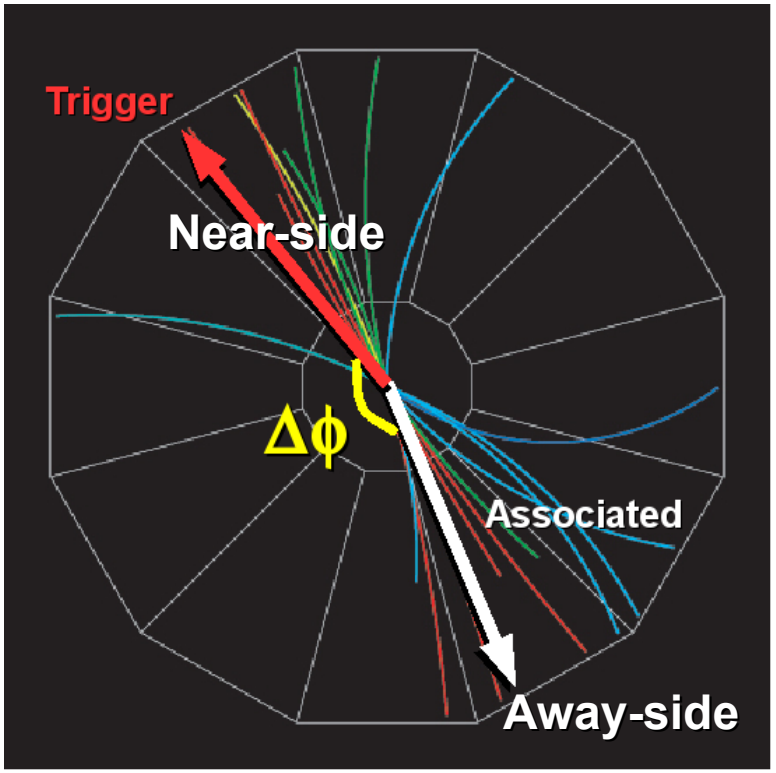
$T_c \sim 175 \pm 8$ MeV $\rightarrow \varepsilon_c \sim 0.3$ -1 GeV/fm$^3$

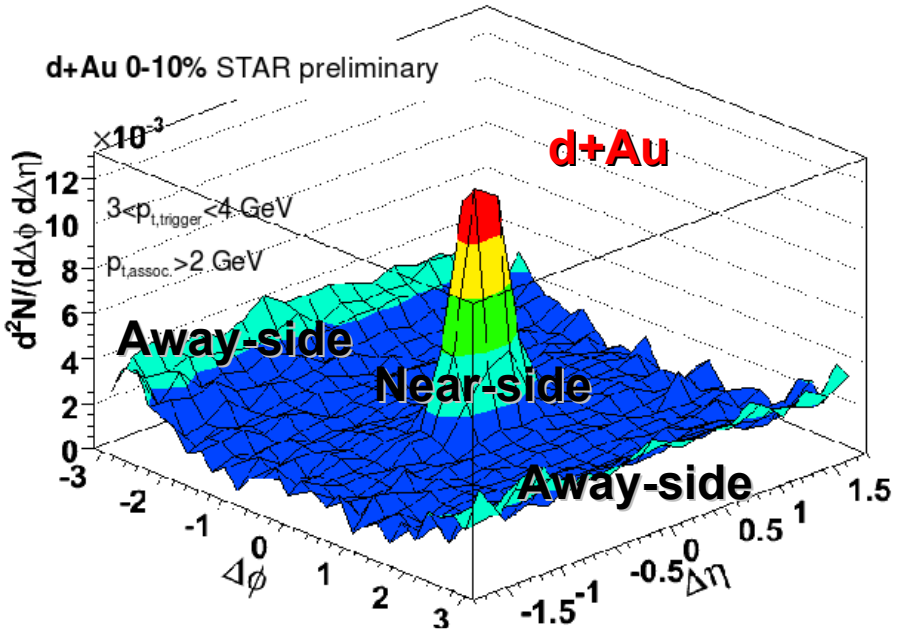


Confined - fewer degrees of freedom

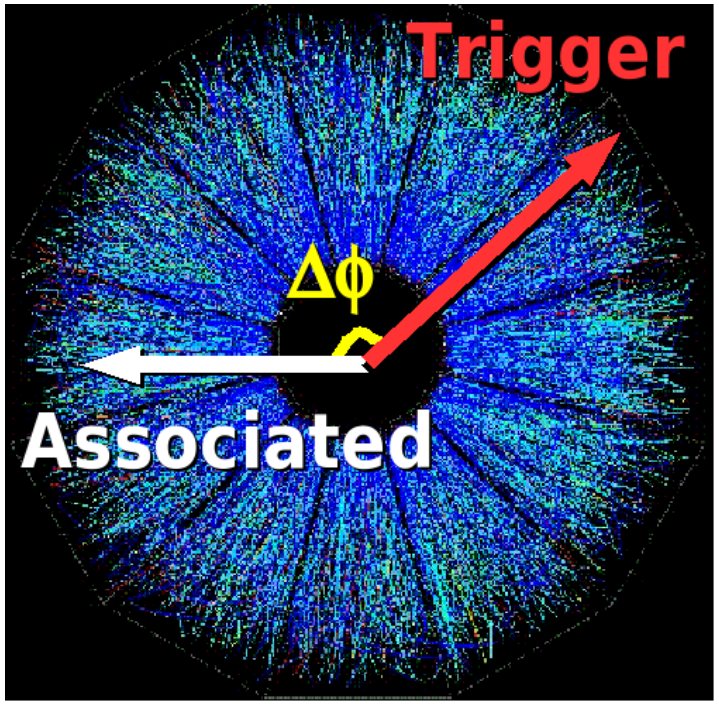
# *d+Au*




Phys.Rev.C80:064912,2009

# *In two dimensions in Au+Au*




Phys.Rev.C80:064912,2009