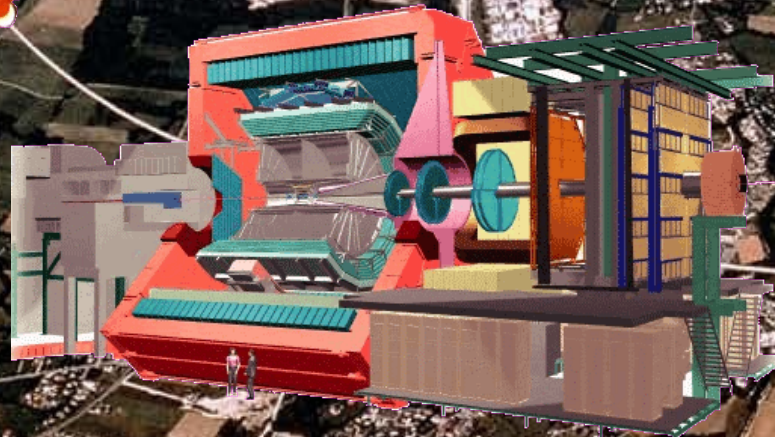
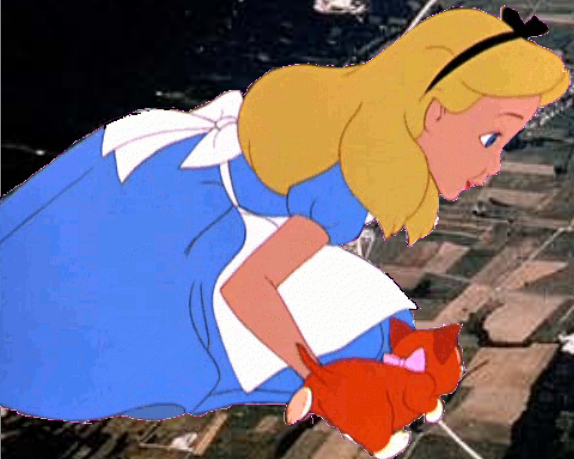
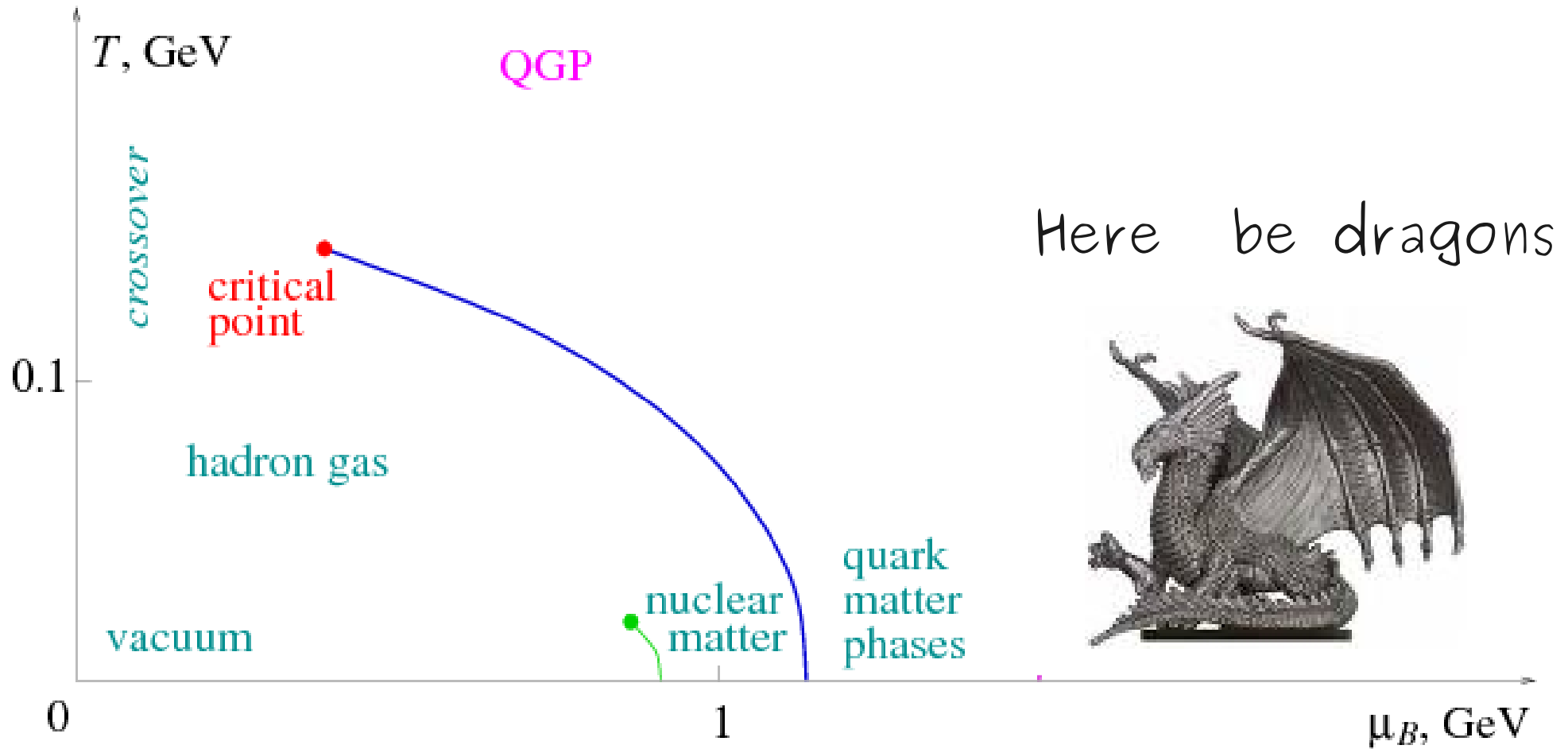


Understanding the Quark Gluon Plasma

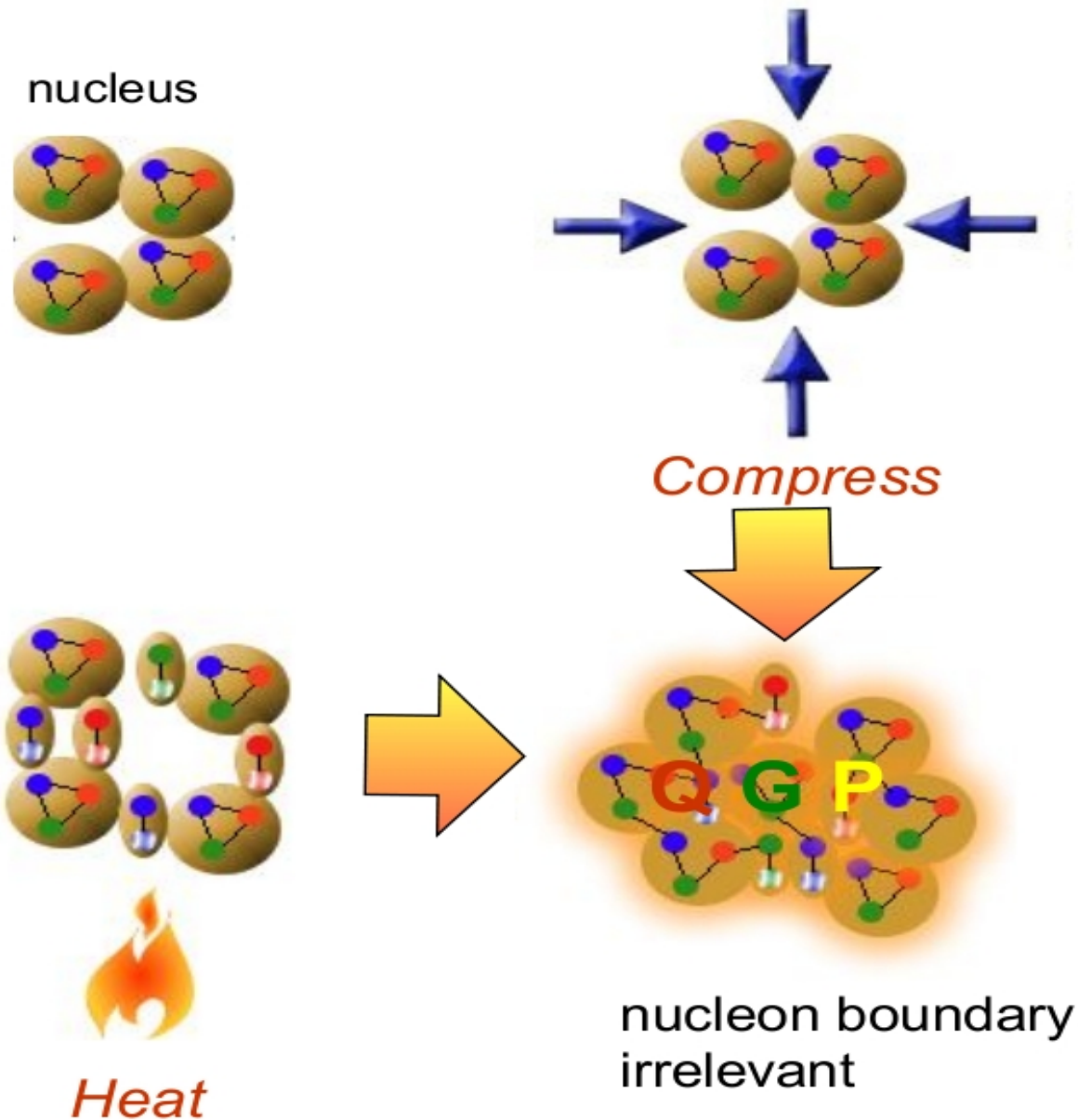
*Christine Nattrass
University of Tennessee at Knoxville*



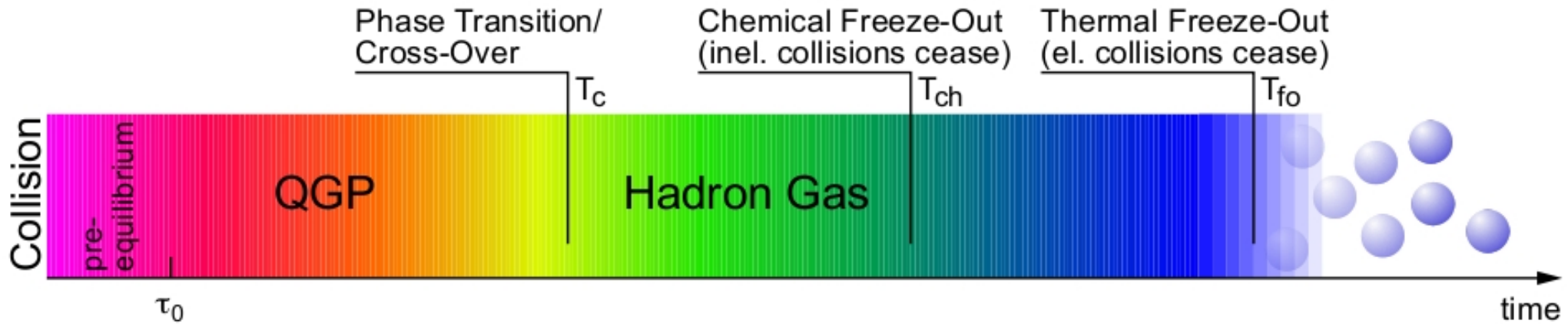
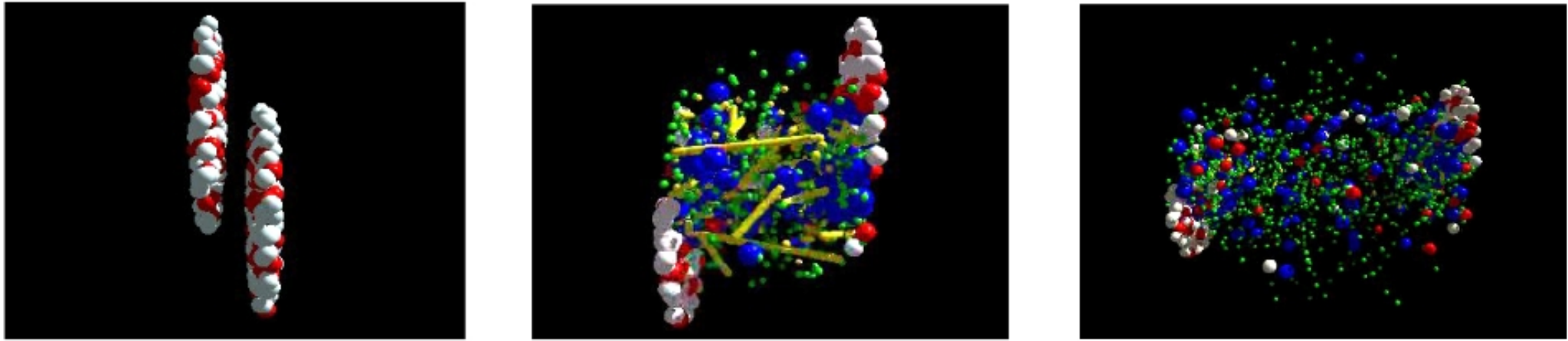
Phase diagram of nuclear matter



How to make a Quark Gluon Plasma



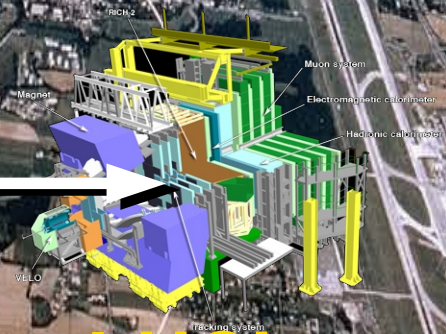
The phase transition in the laboratory





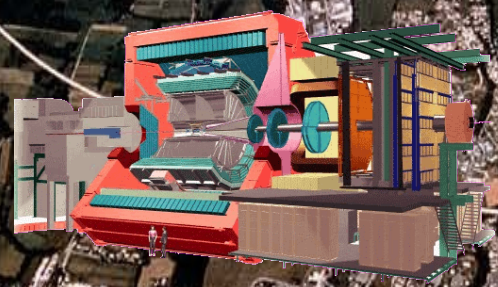
CMS

8.6 km

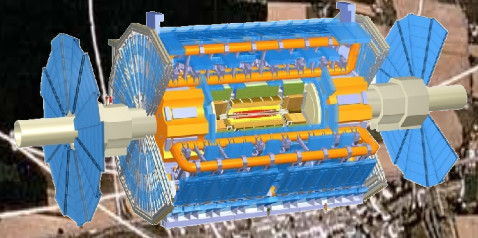


LHCb

2.2 km

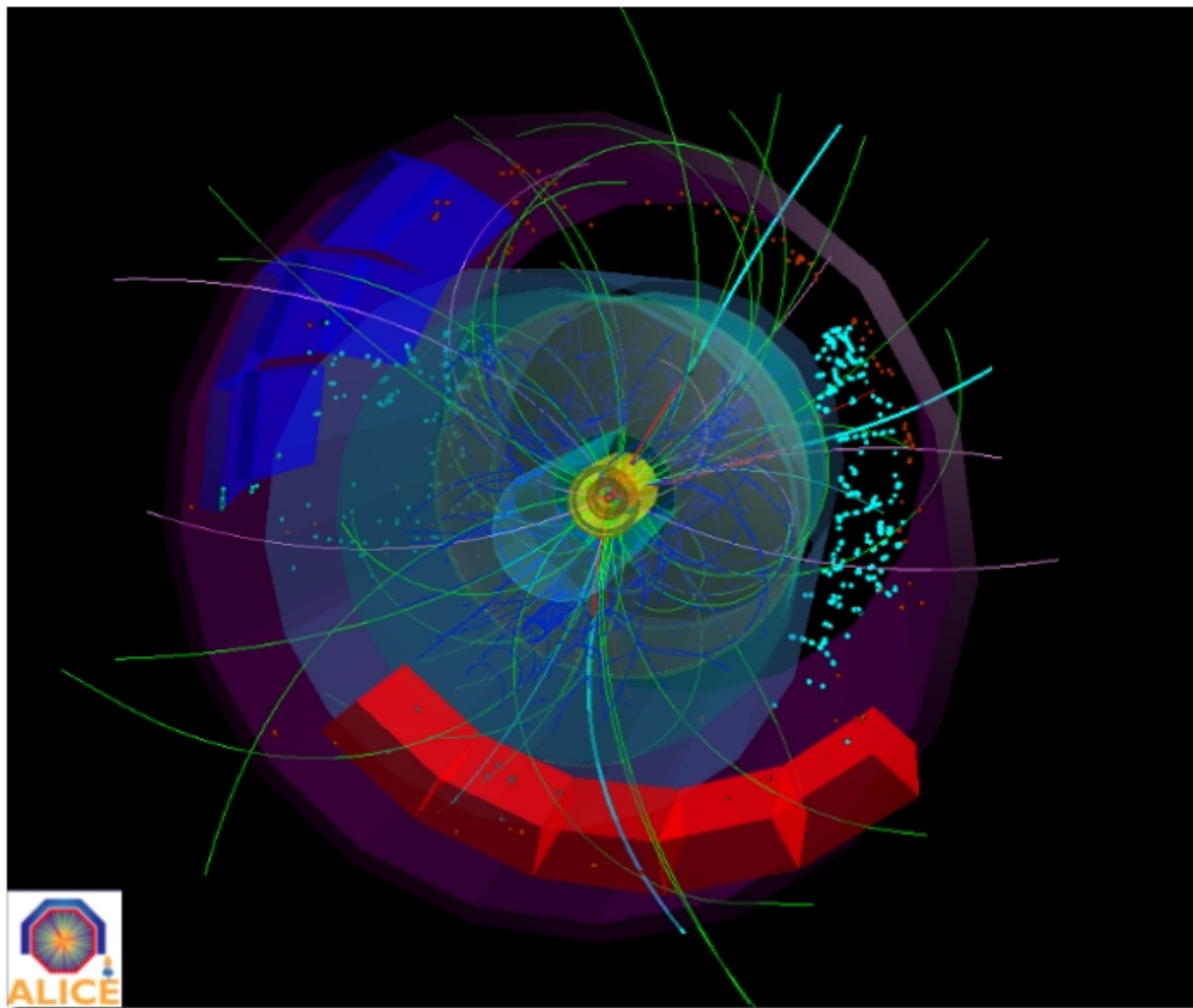


ALICE

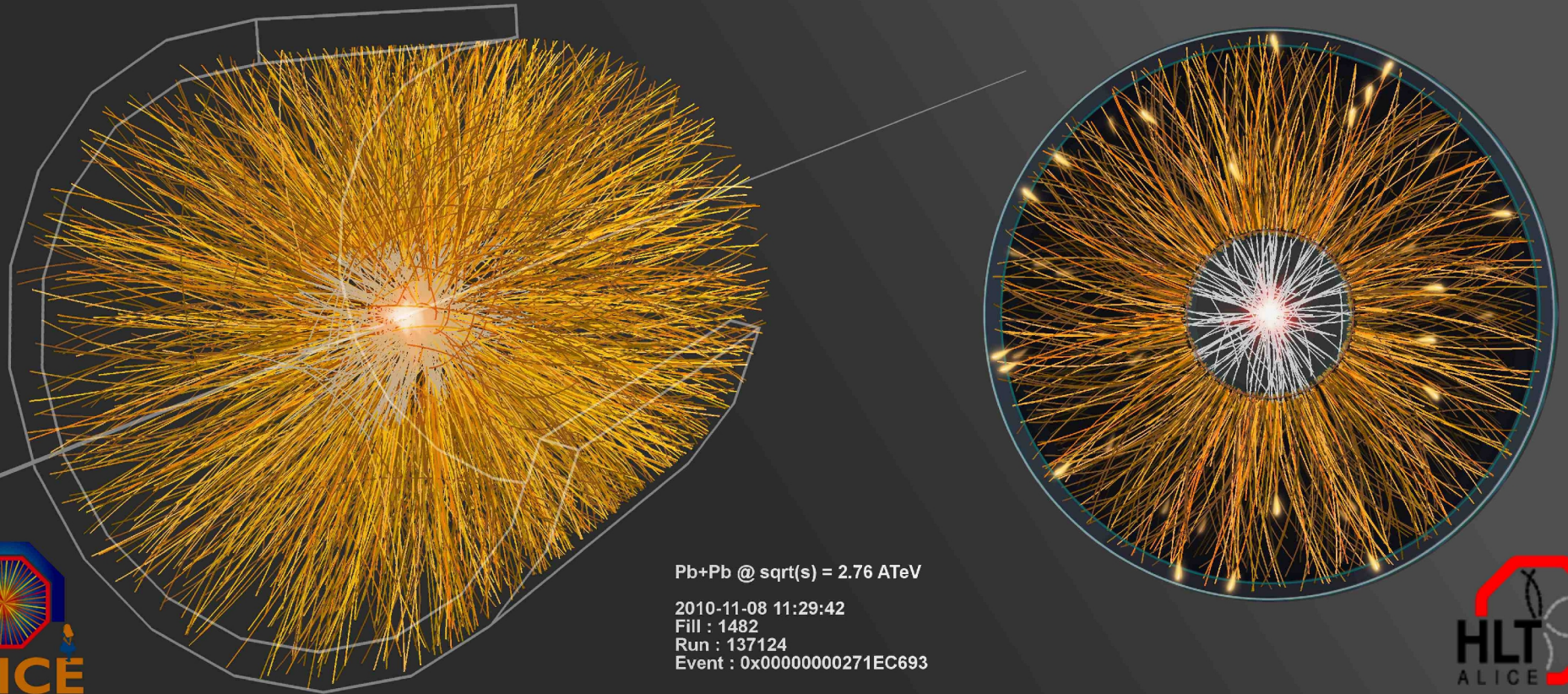


ATLAS
LHCf

$p+p$ collisions

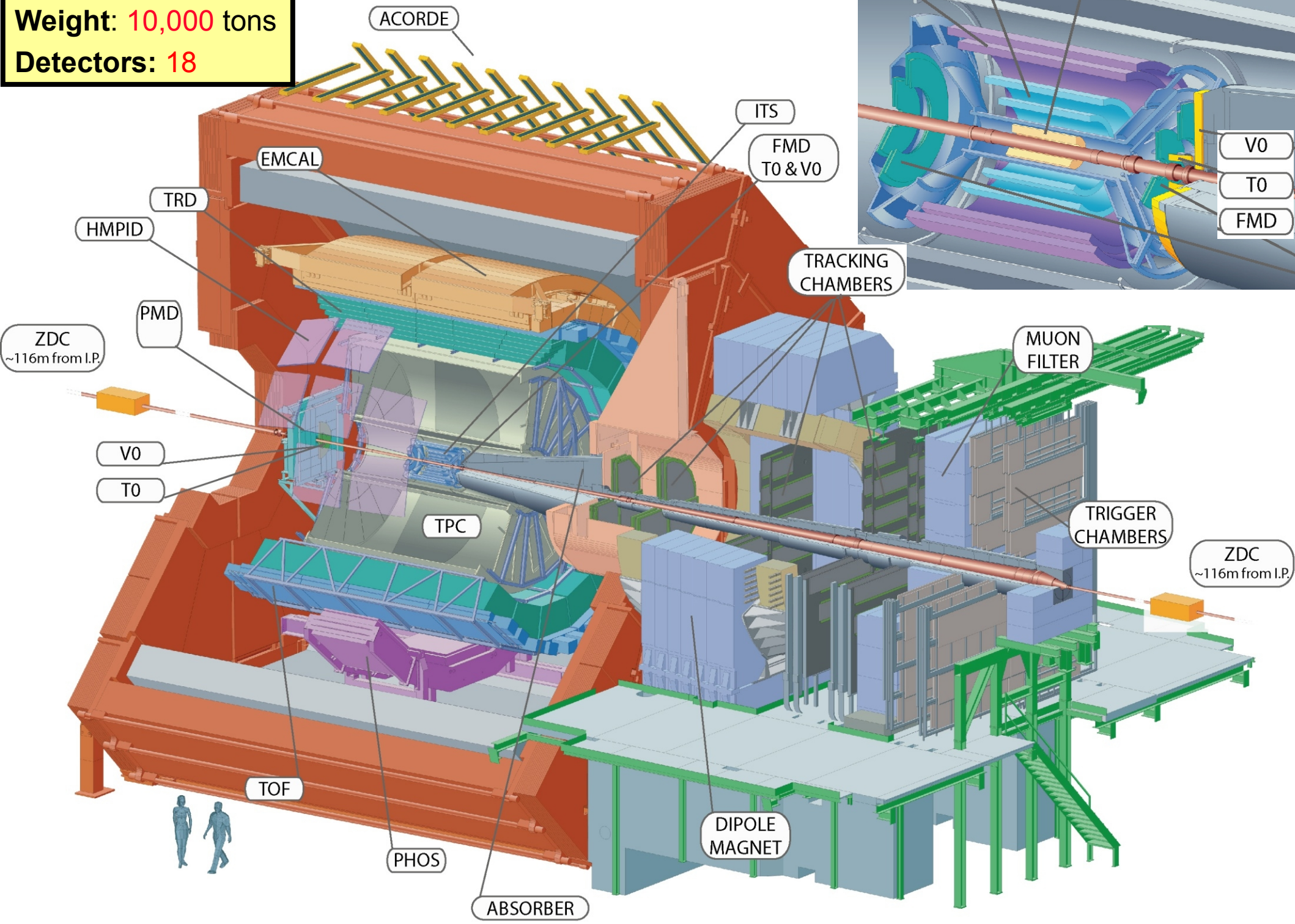


Pb+Pb collisions

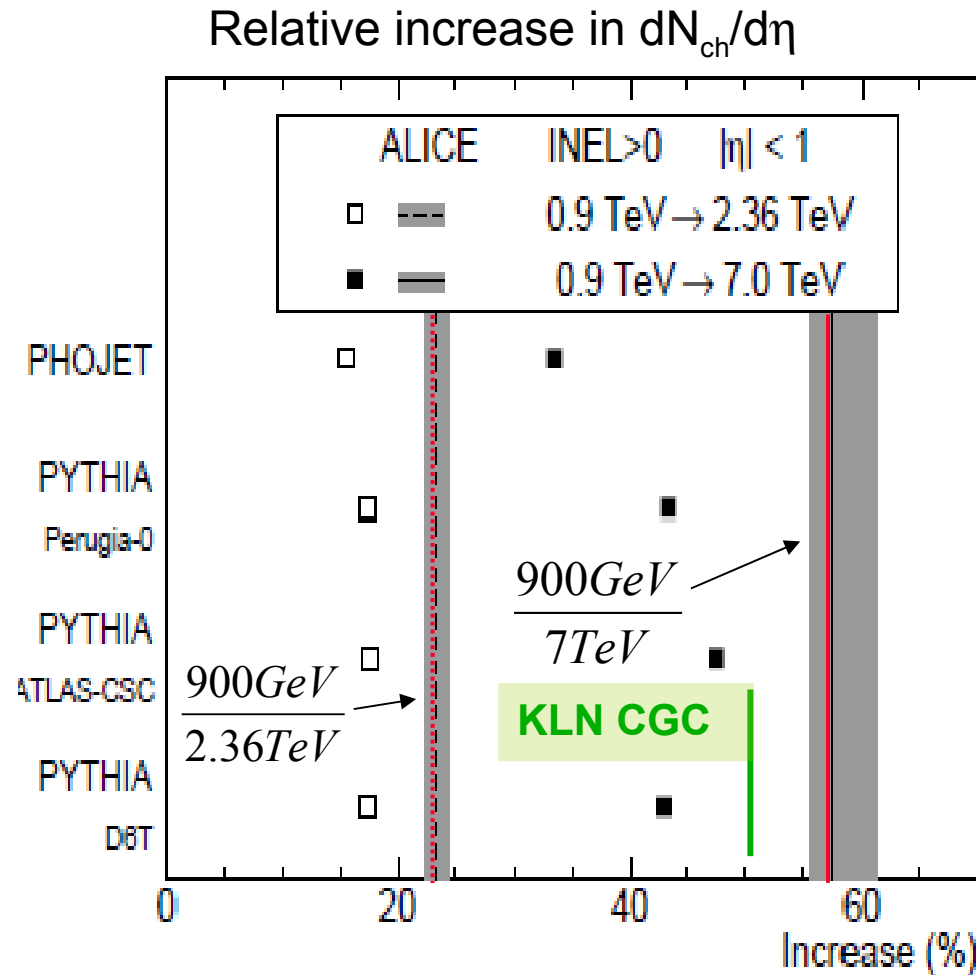
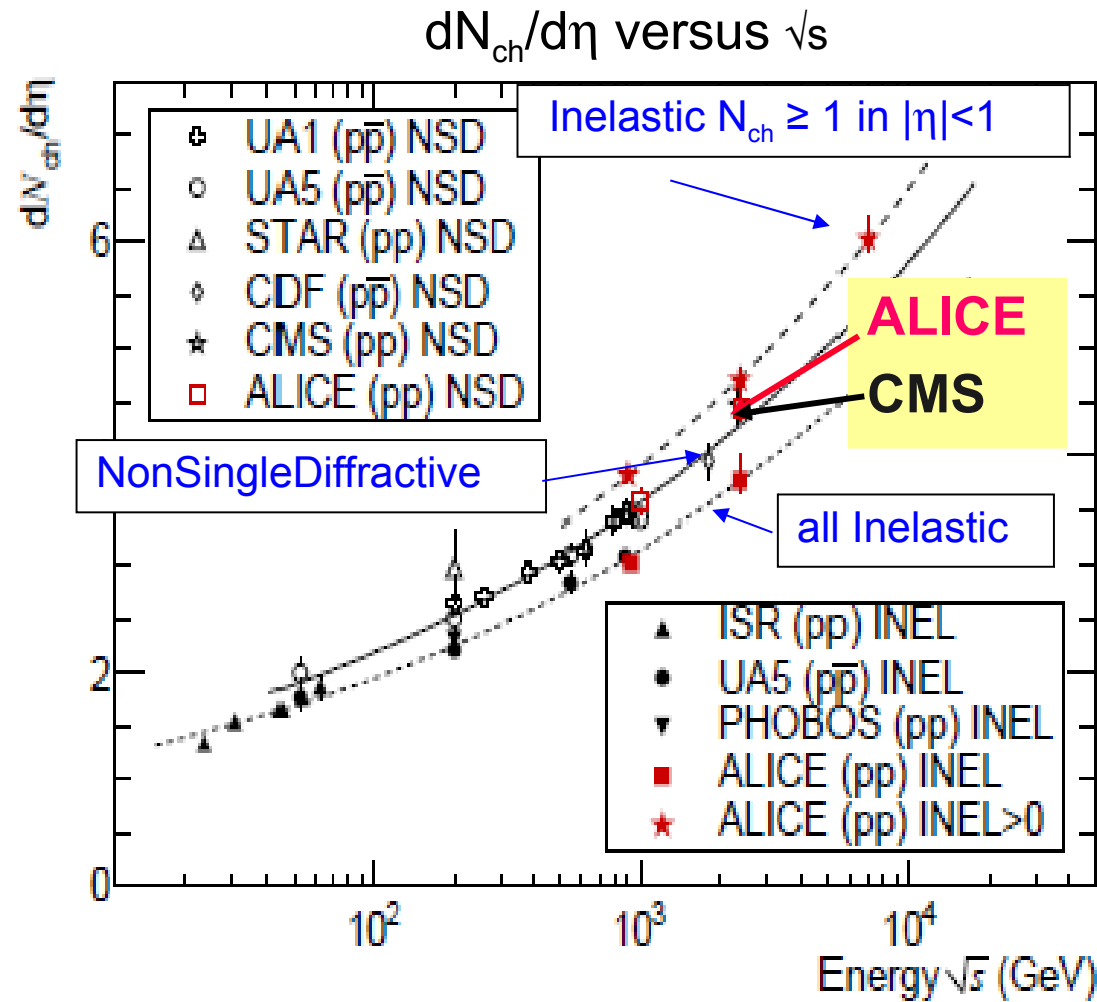


contactniko@yahoo.de
ageiki13@gmail.com
NIKOS EMMANOULIDIS
AGEIKI MANTA

Size: 16 x 26 meters
Weight: 10,000 tons
Detectors: 18



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

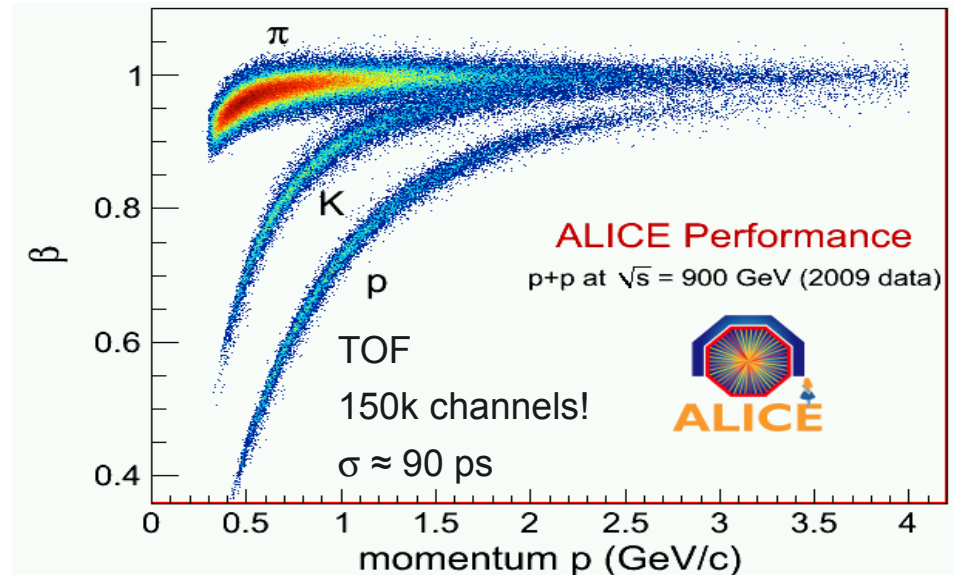
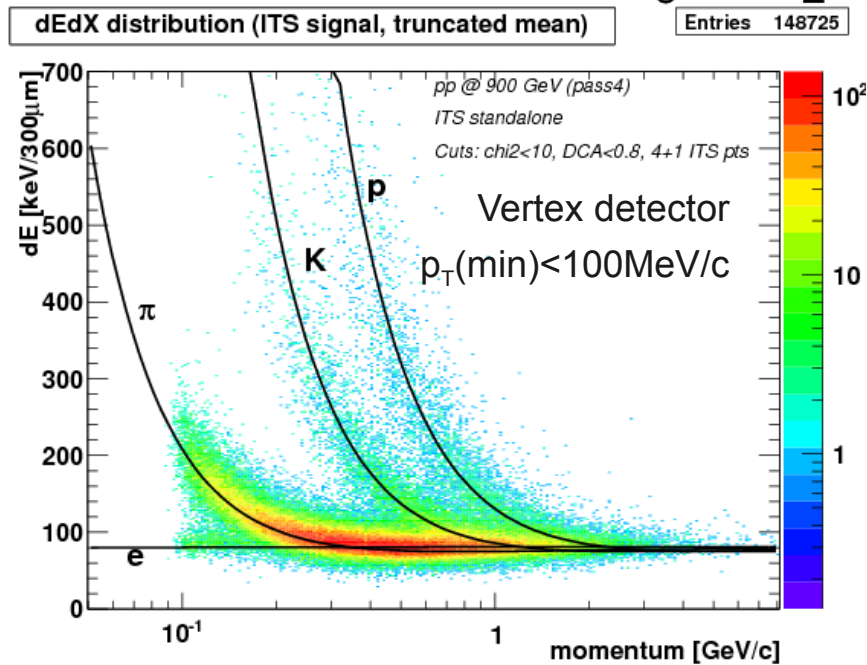
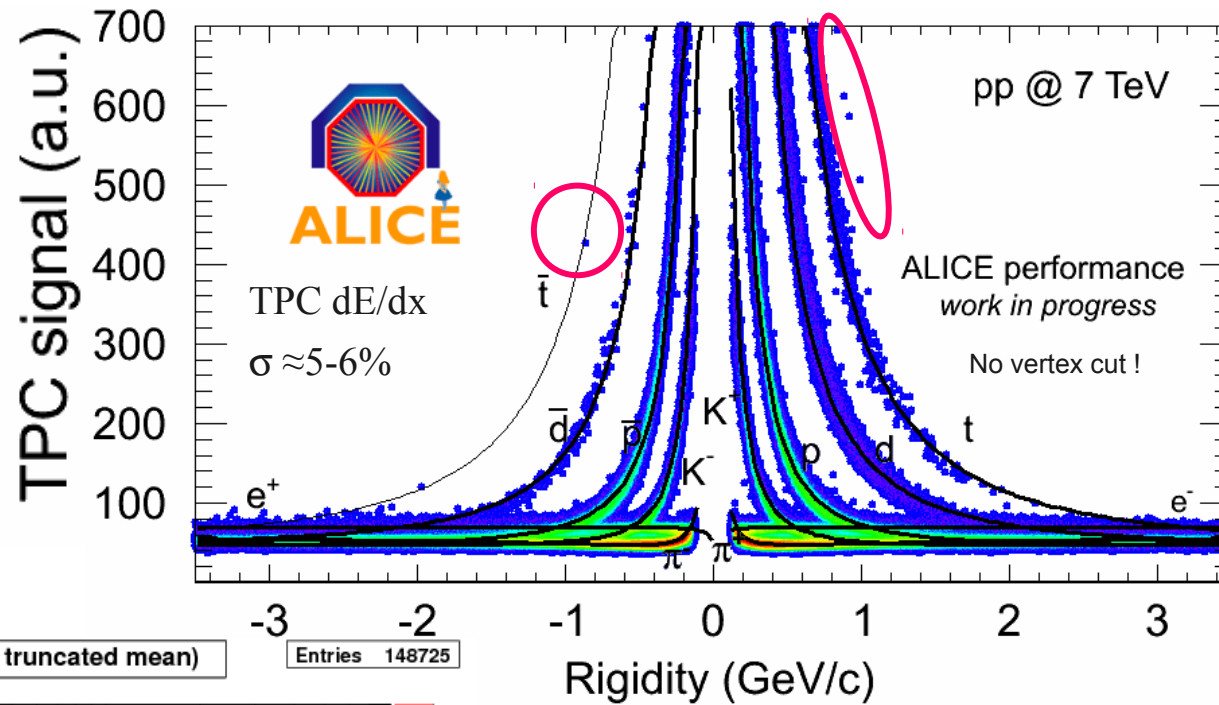


Eur. Phys. J. C (2010) 68: 345–354
 Eur. Phys. J. C (2010) 68: 89–108
 Eur. Phys. J. C (2010) 65: 111-125

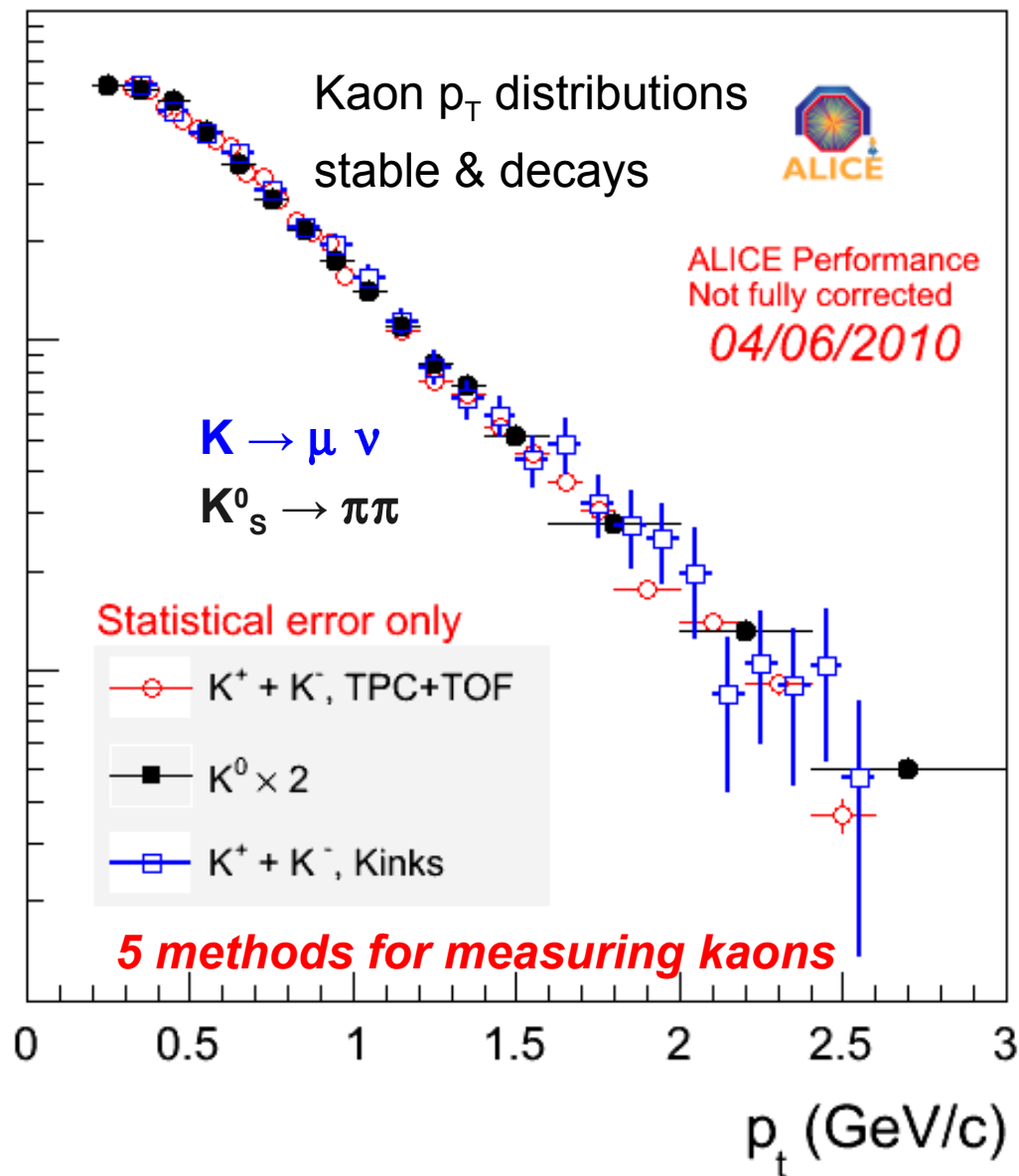
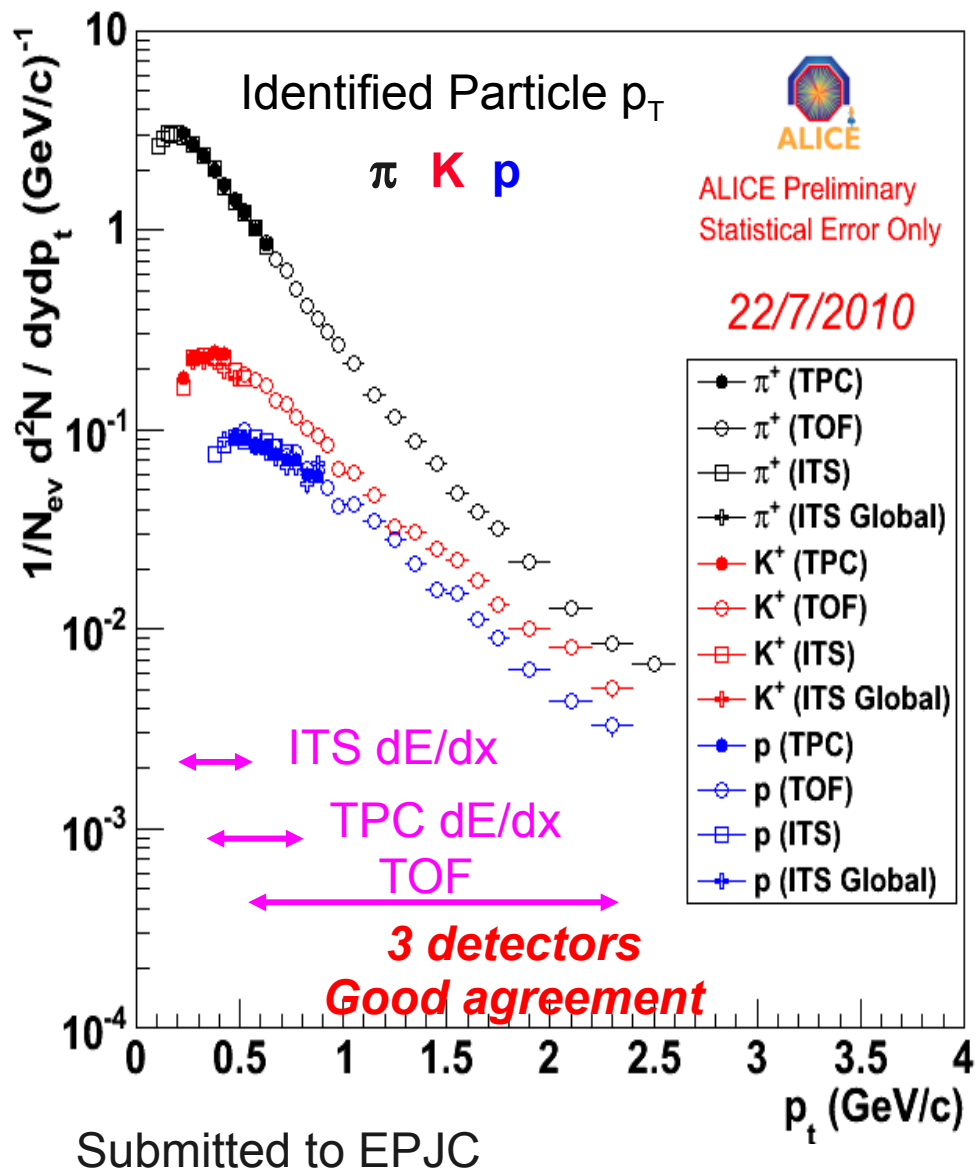
Results:

- increase with energy significantly stronger in data than MC's
- ALICE & CMS agree to within 1σ ($< 3\%$)

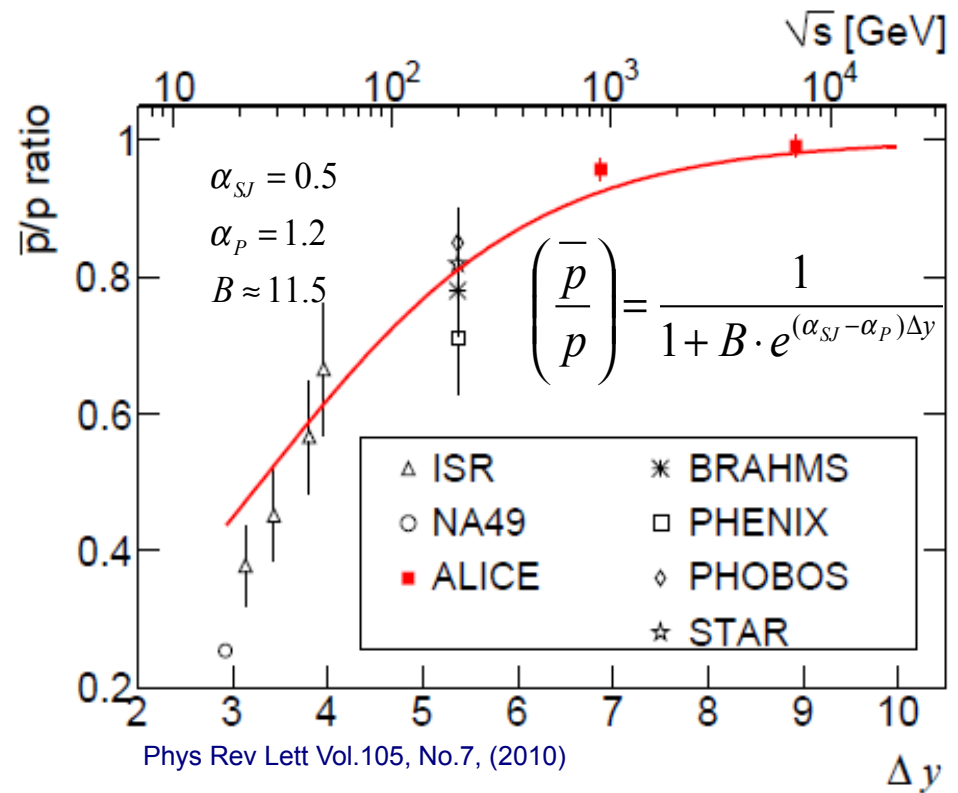
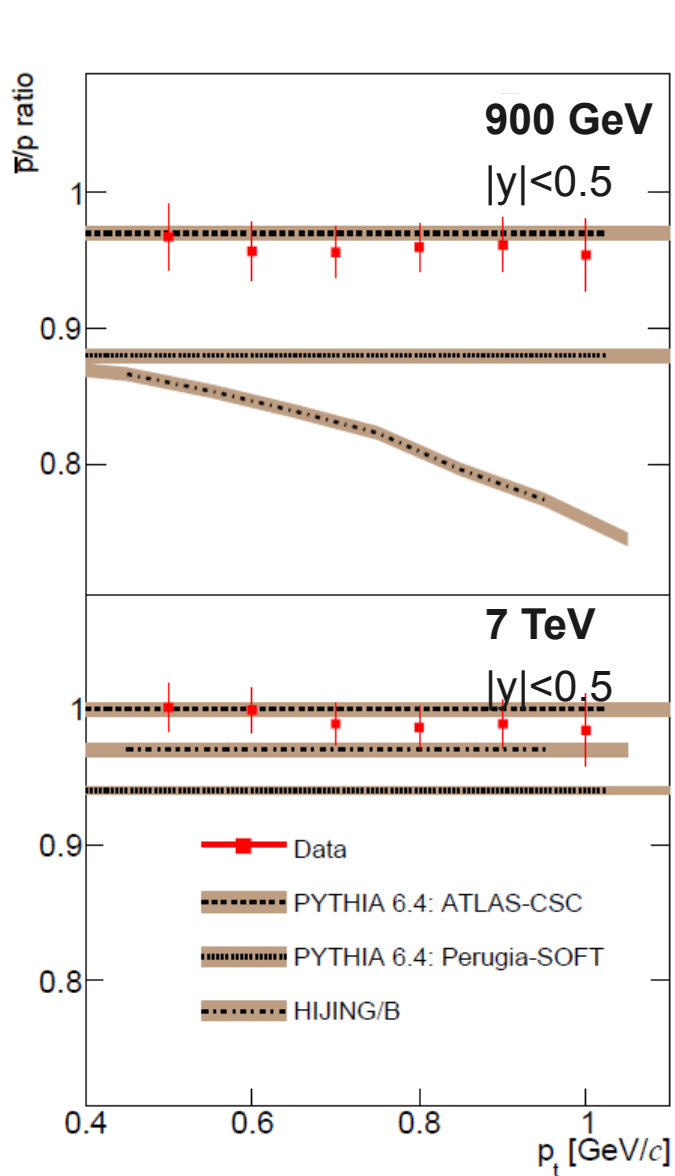
Particle identification



Identified particle spectra

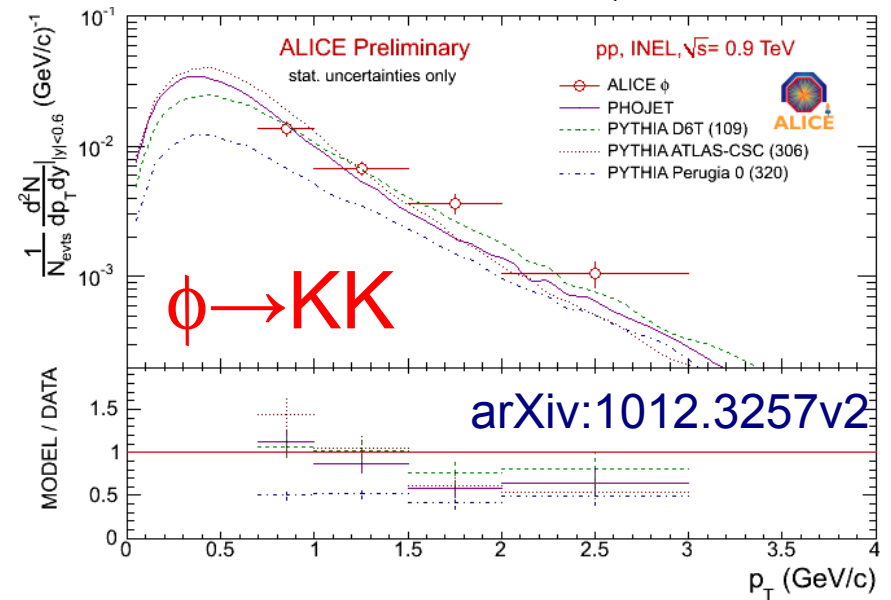
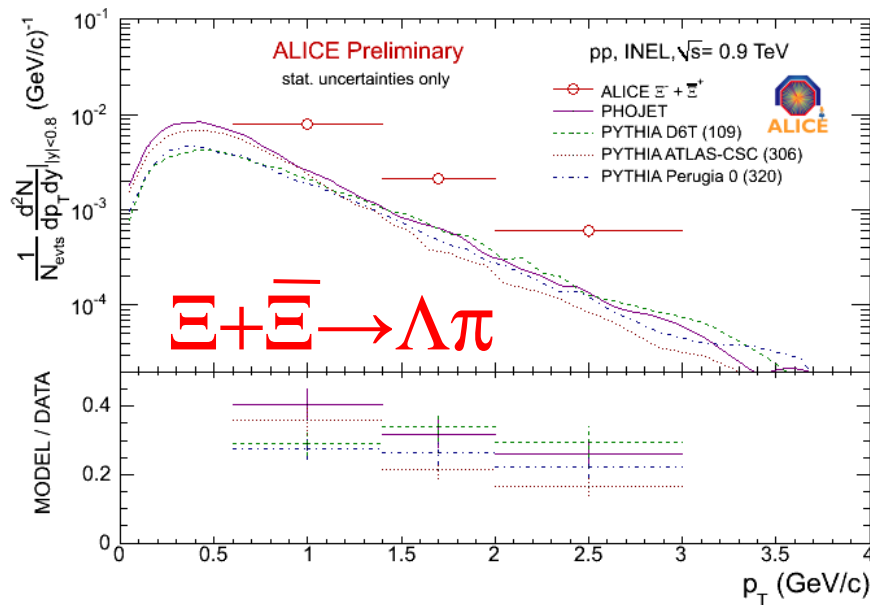
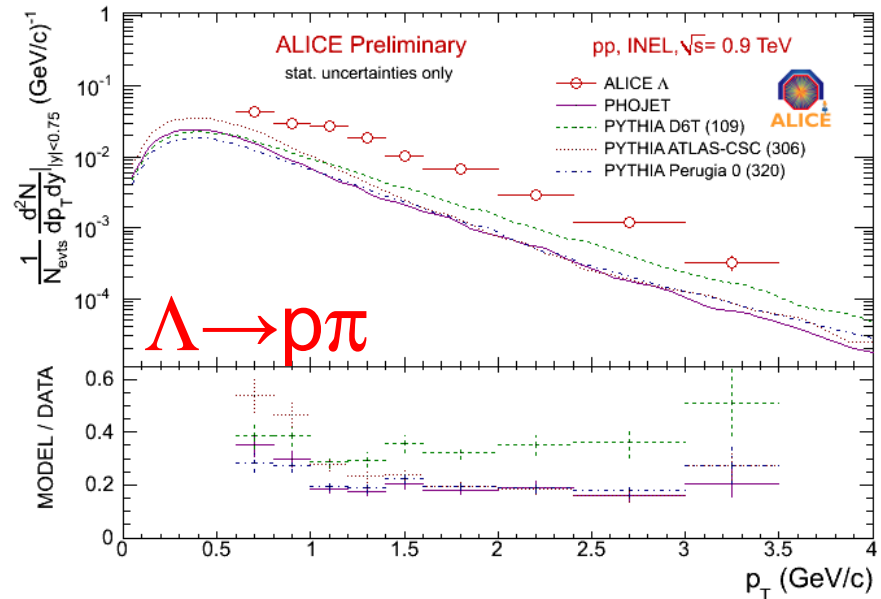
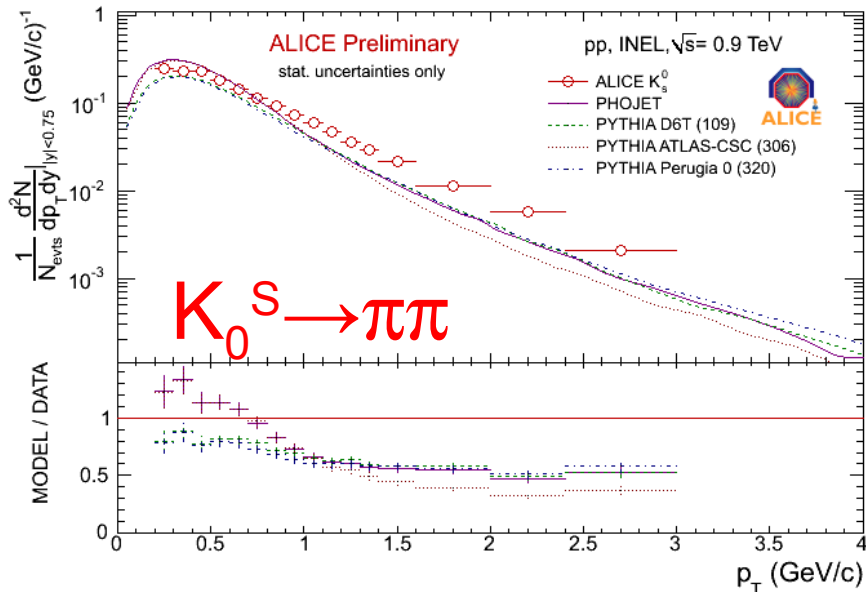


\bar{p}/p ratio



0.9 TeV: $\bar{p}/p = 0.957 \pm 0.006(\text{stat}) \pm 0.014(\text{syst})$
7 TeV: $\bar{p}/p = 0.990 \pm 0.006(\text{stat}) \pm 0.014(\text{syst})$

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
	$\langle p_T \rangle$				$p_T > 1$ GeV/c
	$K_s^0, \Lambda, \bar{\Lambda}$				
	ϕ				
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 \approx Data

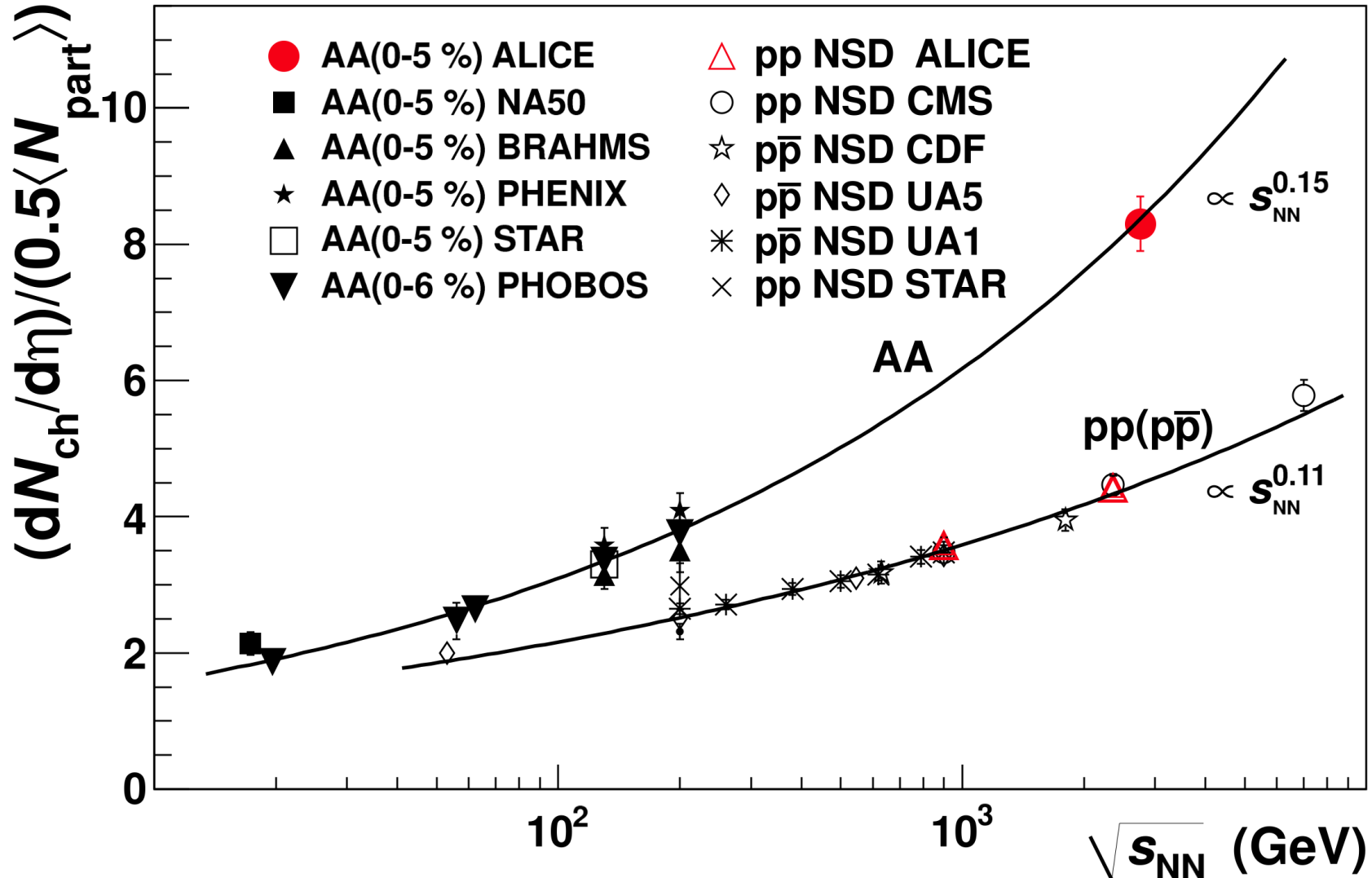
MC >> Data

Conclusion:

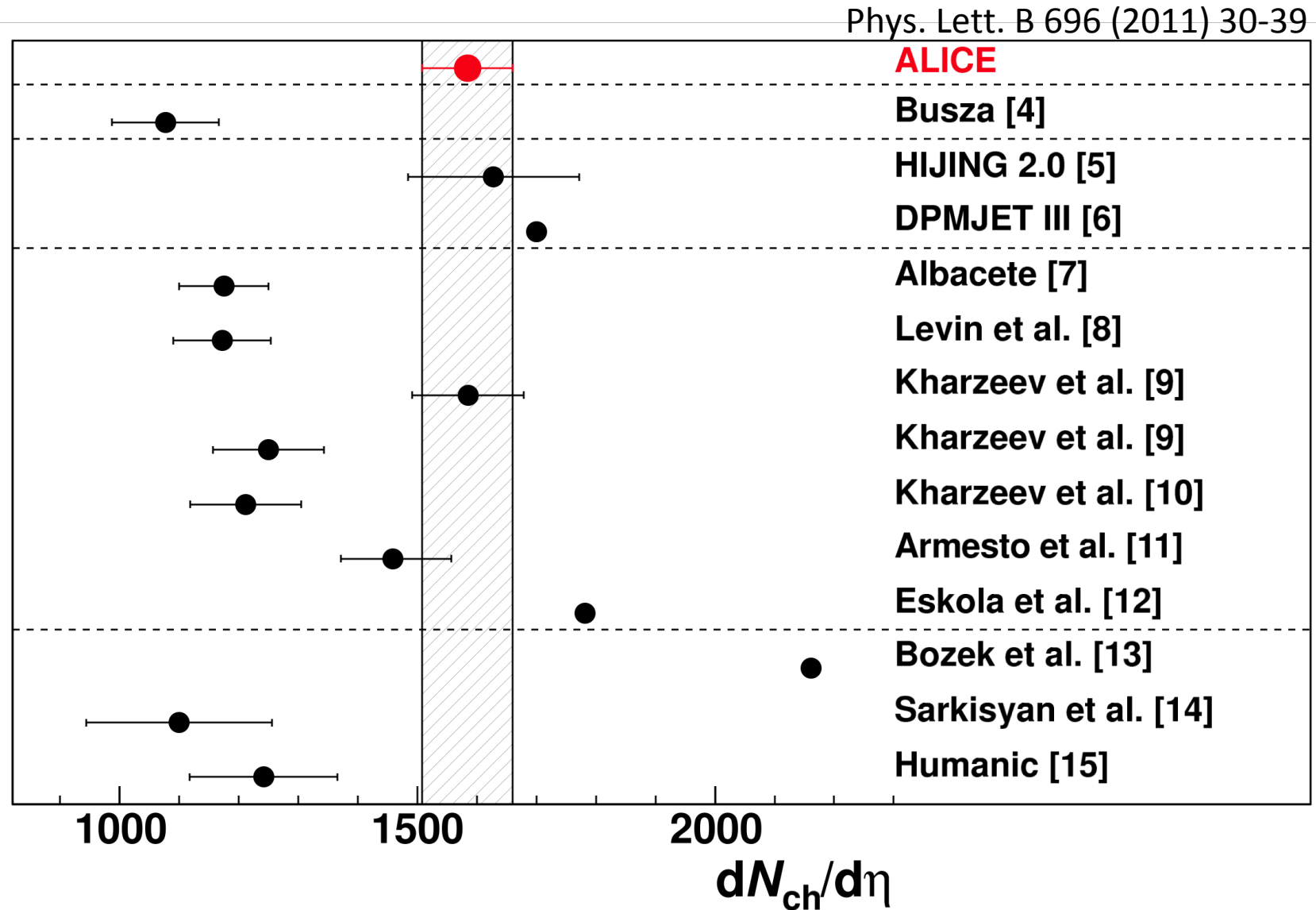
- None of the tested MC's (adjusted at lower energy) does really well
- Tuning one or two results is doable, getting everything right will require more effort (and may, with some luck, actually teach us something on soft QCD rather than only turning knobs).

Charged particle multiplicity in central Pb+Pb

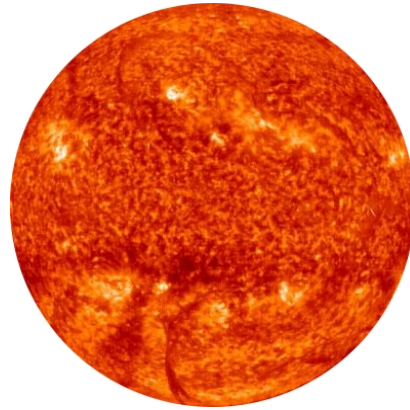
Phys. Lett. B 696 (2011) 30-39



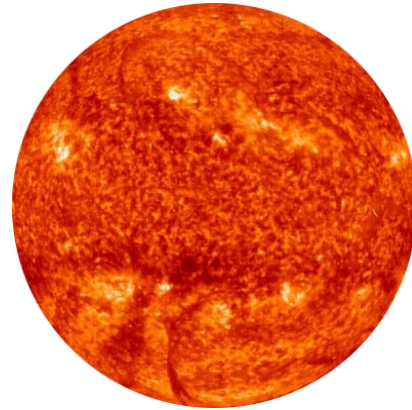
How do the models compare?



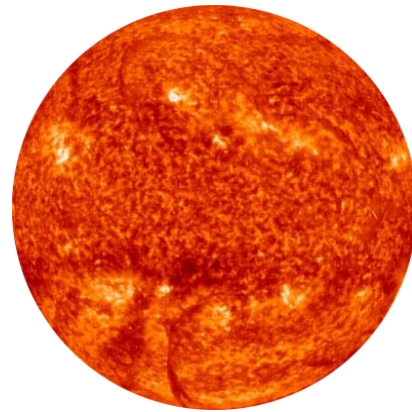
A simple picture of a heavy ion collision



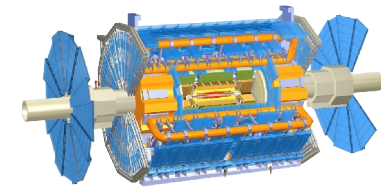
Jets as a probe of the quark gluon plasma



One jet “absorbed” by the medium

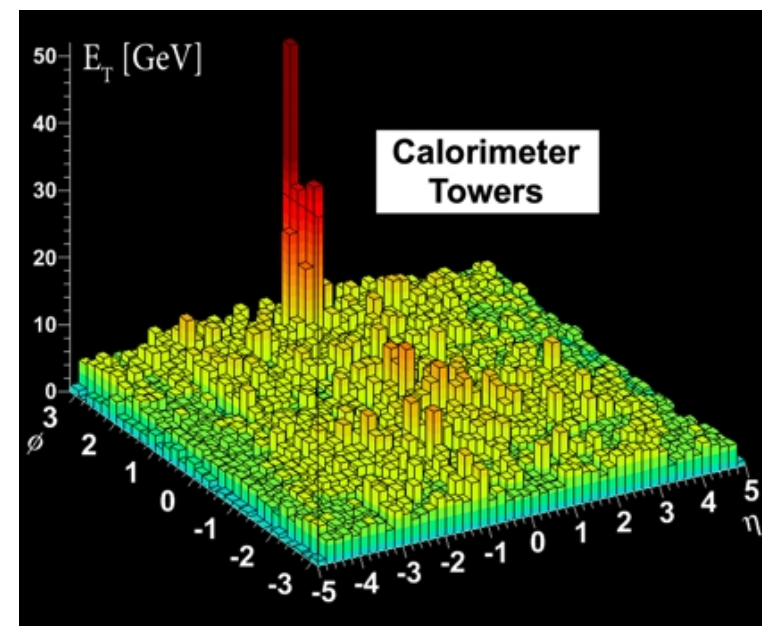
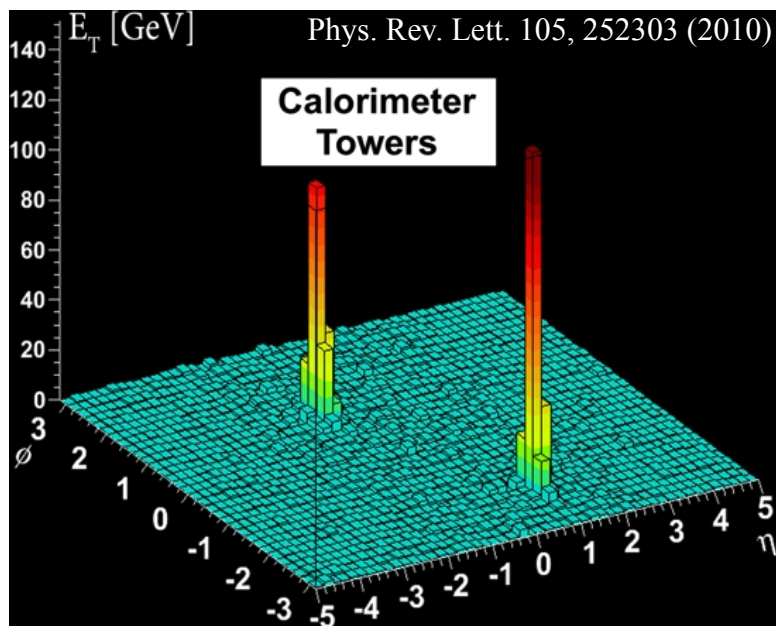
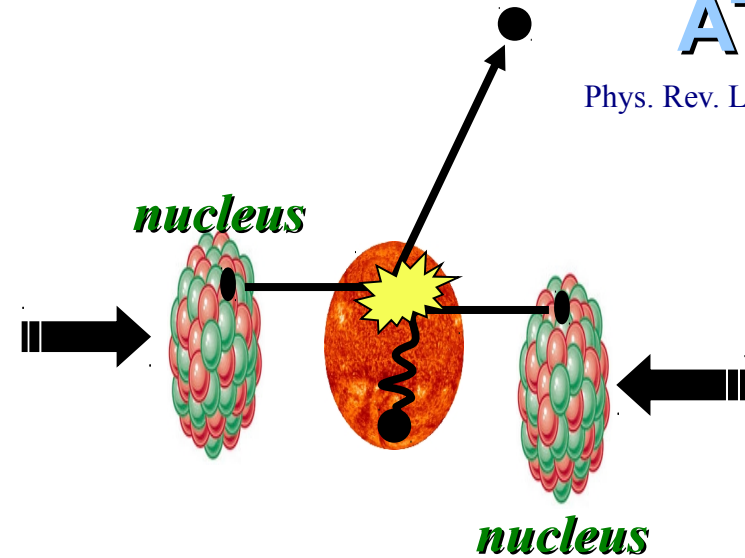
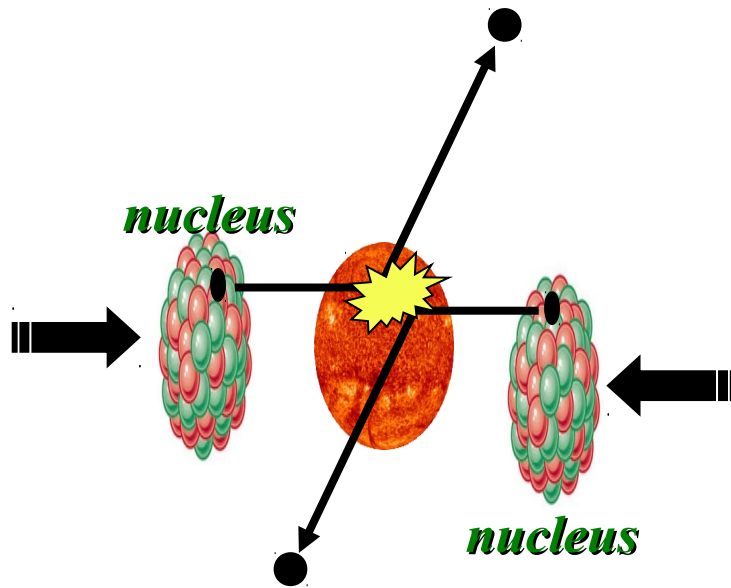


Jet quenching



ATLAS

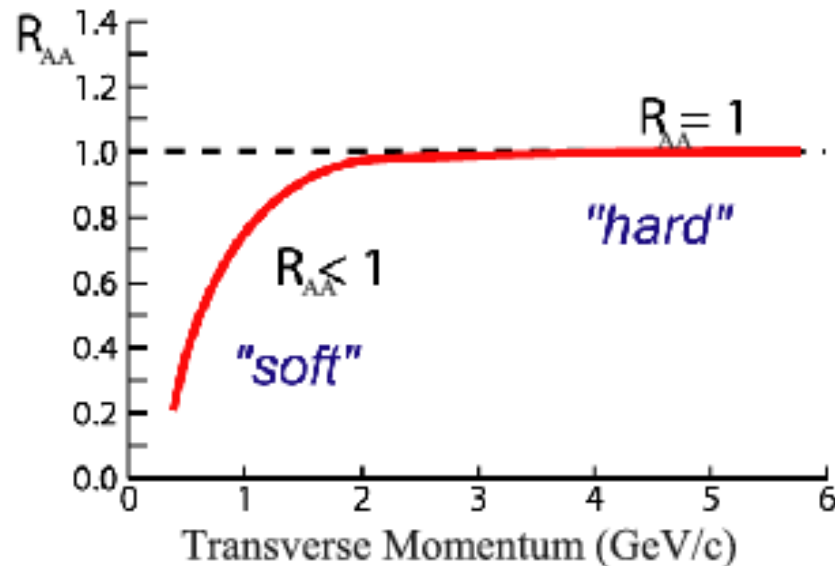
Phys. Rev. Lett. 105, 252303



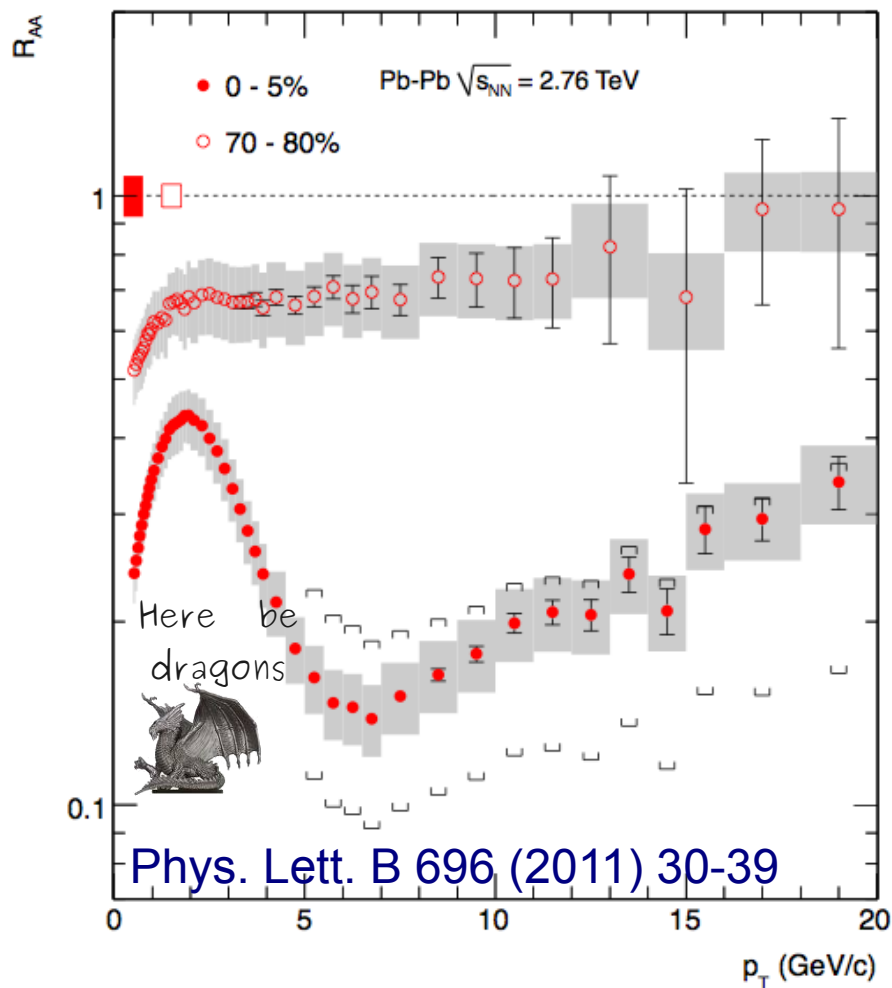
Single particles

- 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:

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

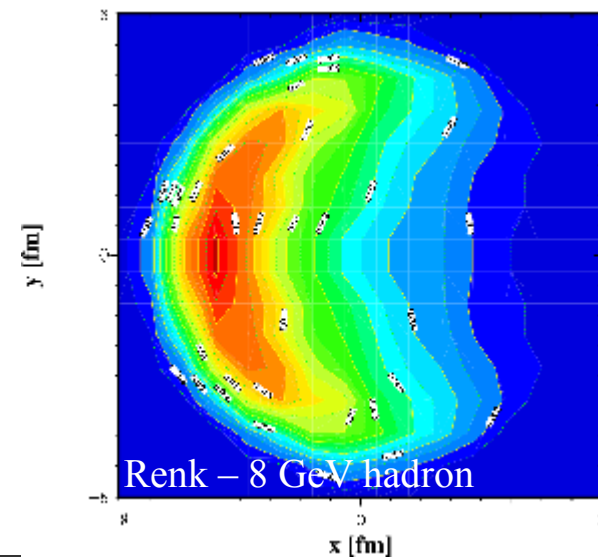


Experimental results

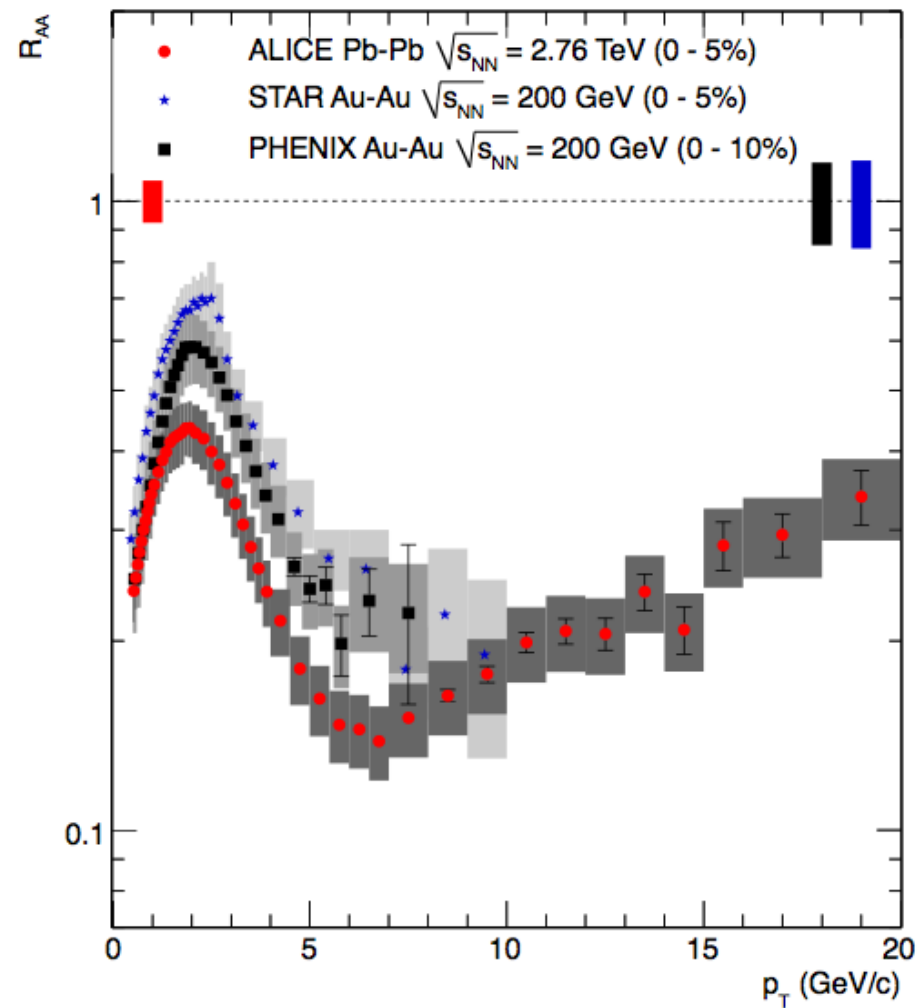
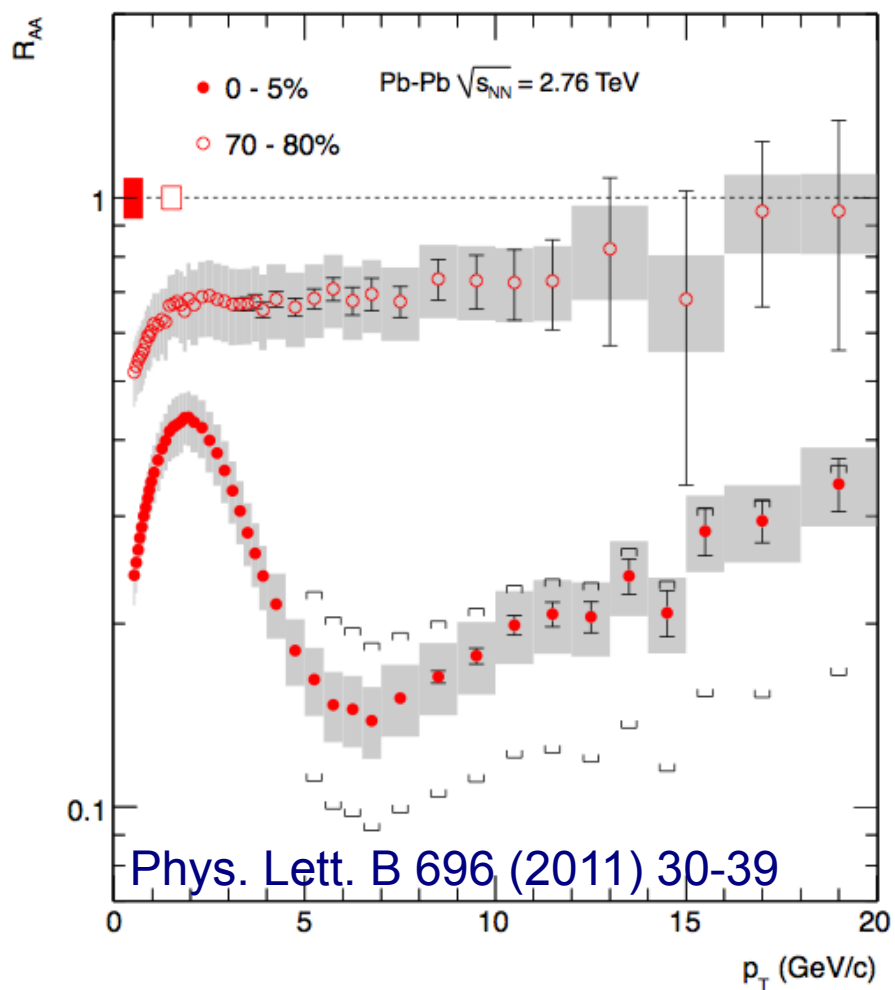


← No suppression

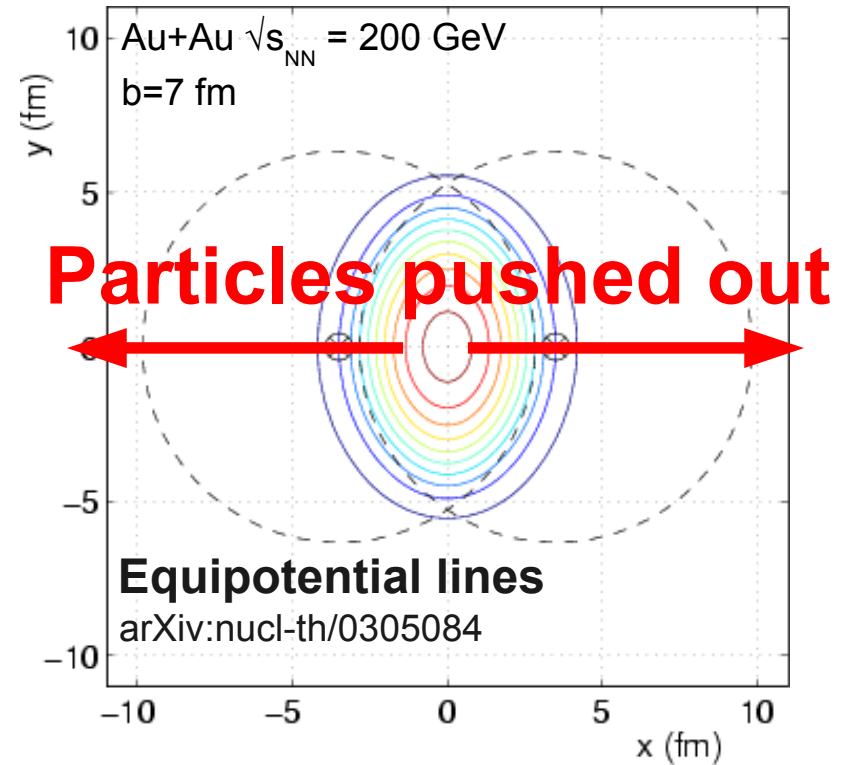
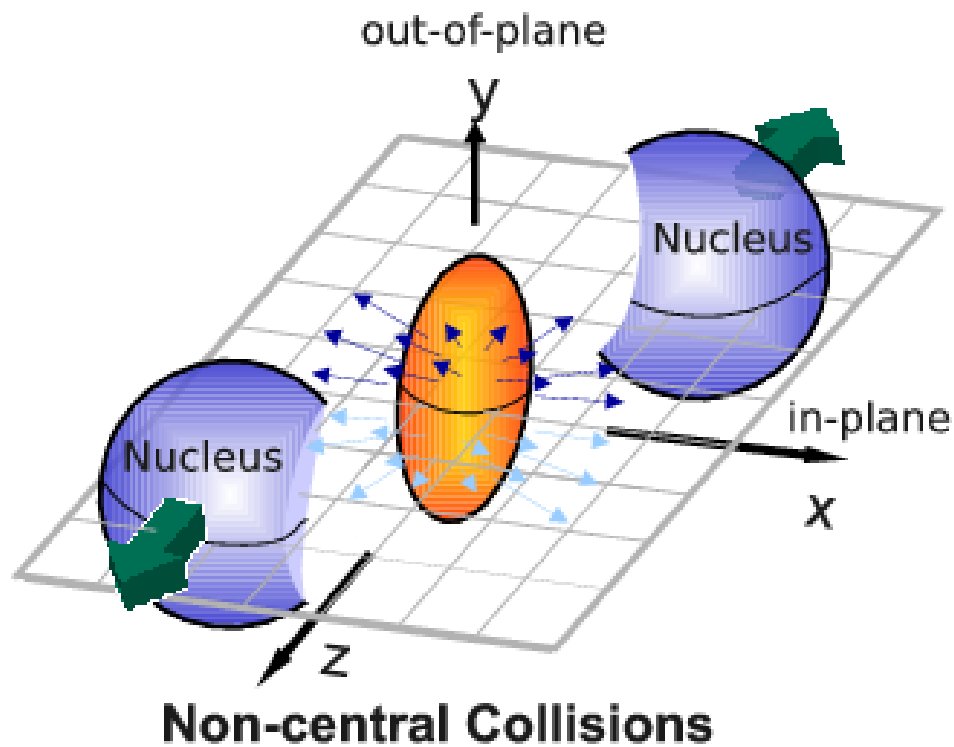
← Observed



Experimental results



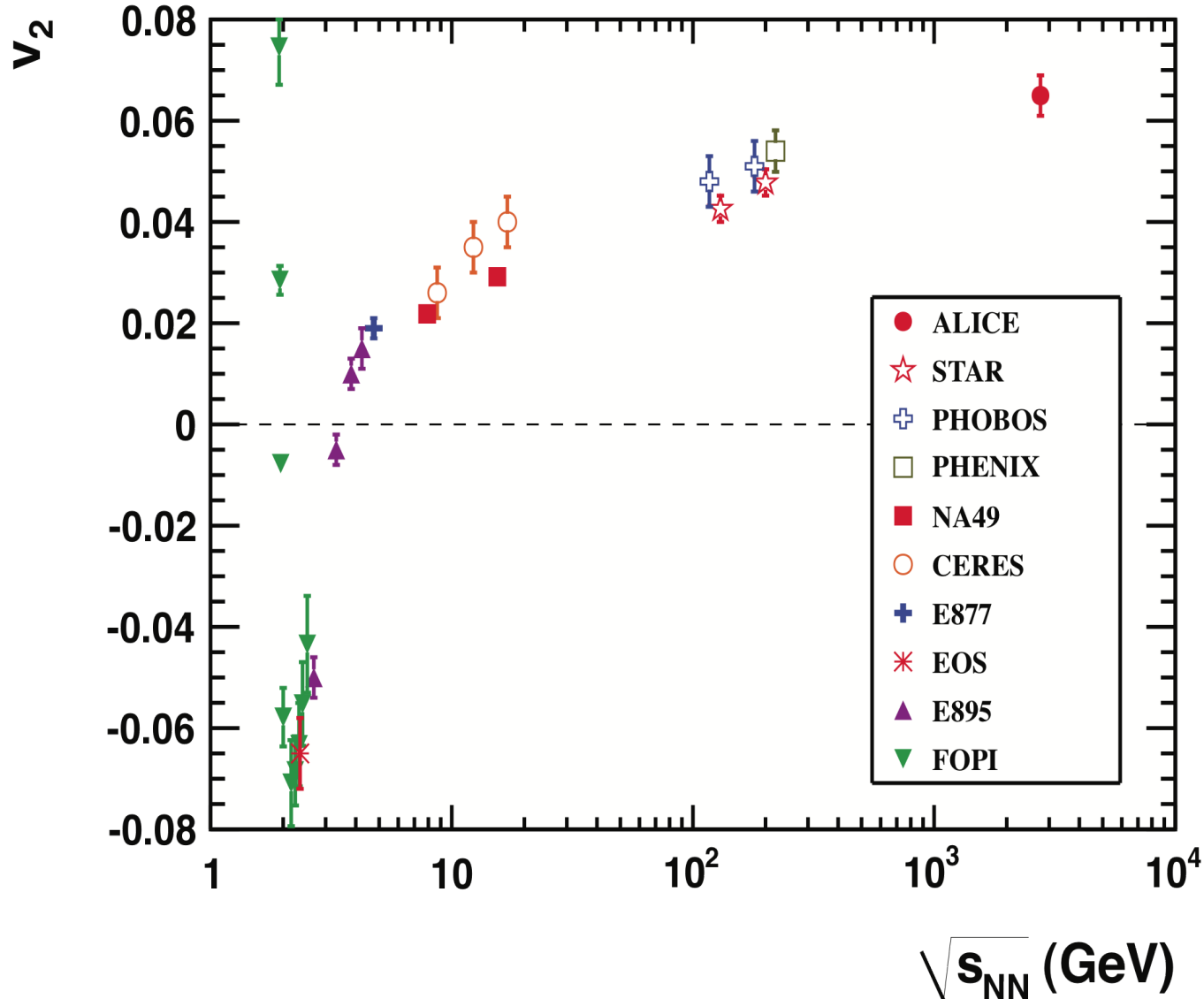
Hydrodynamical flow



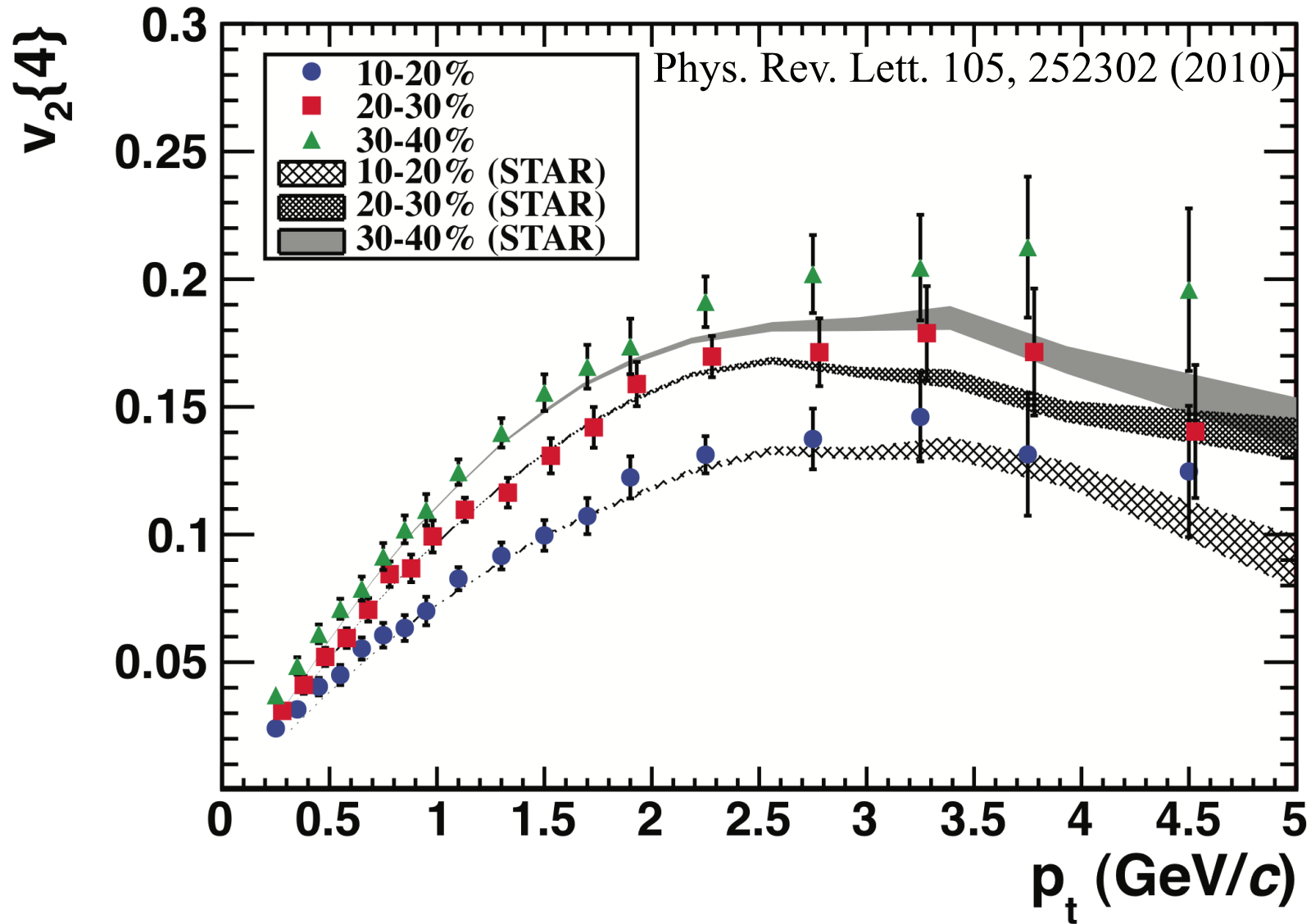
- When nuclei collide, the overlap region is roughly elliptical
- If we have a fluid when we collide nuclei, there will be pressure gradients, pushing particles out

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

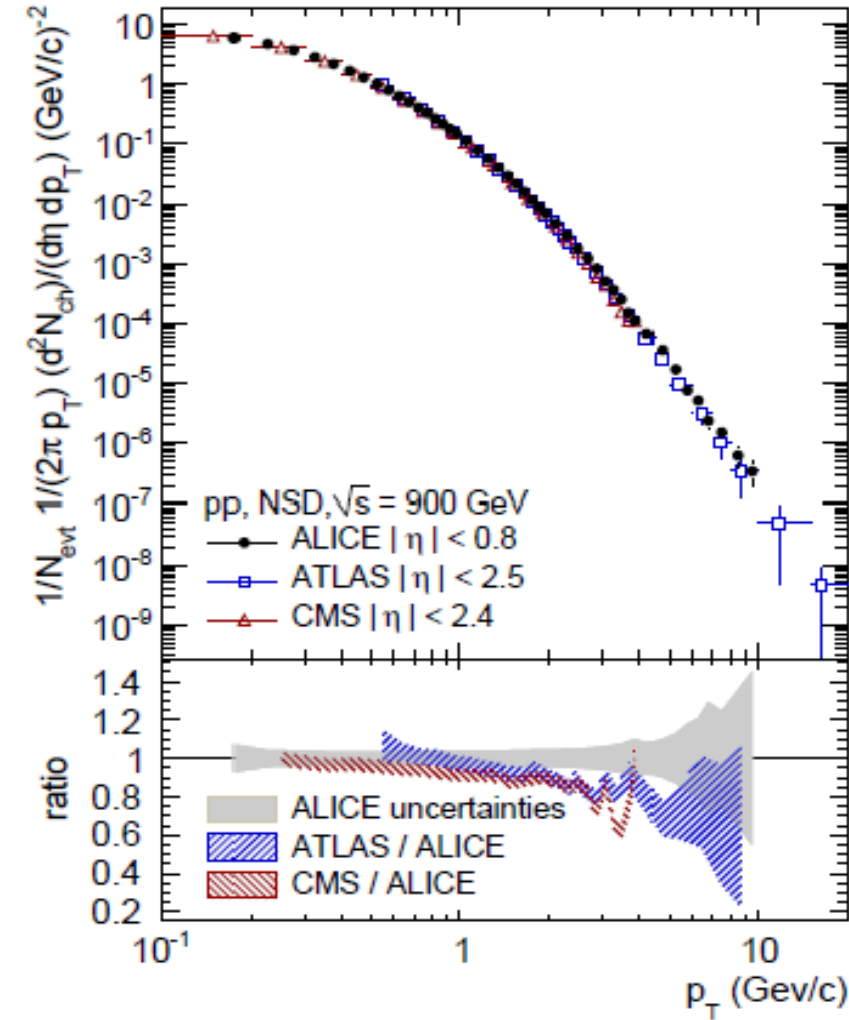
Backup slides

How do we know it's a QGP?

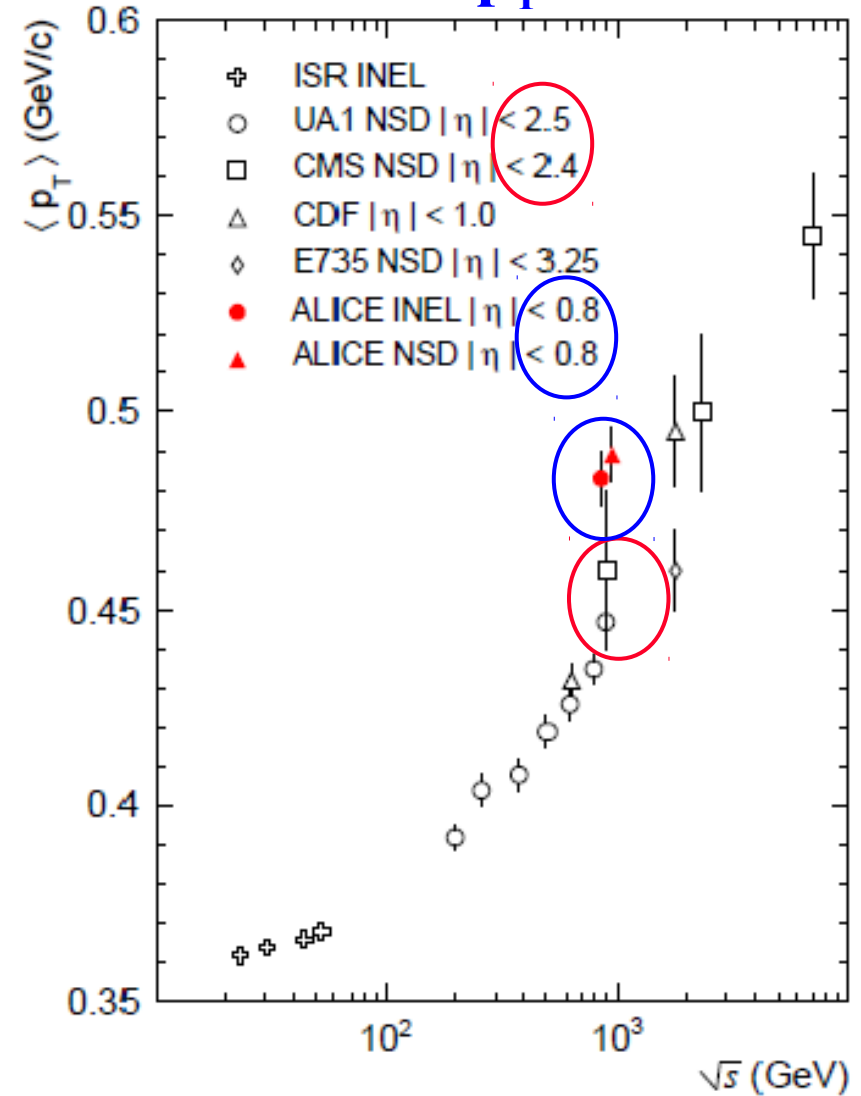
- Temperature – it is hot enough to match where we think it should be
- Jet quenching – high momentum quarks and gluons get stopped in the medium
- Hydrodynamical flow – it moves like a fluid of quarks and gluons
- Chemistry – what we produce is roughly at equilibrium

Momentum distributions at 900 GeV

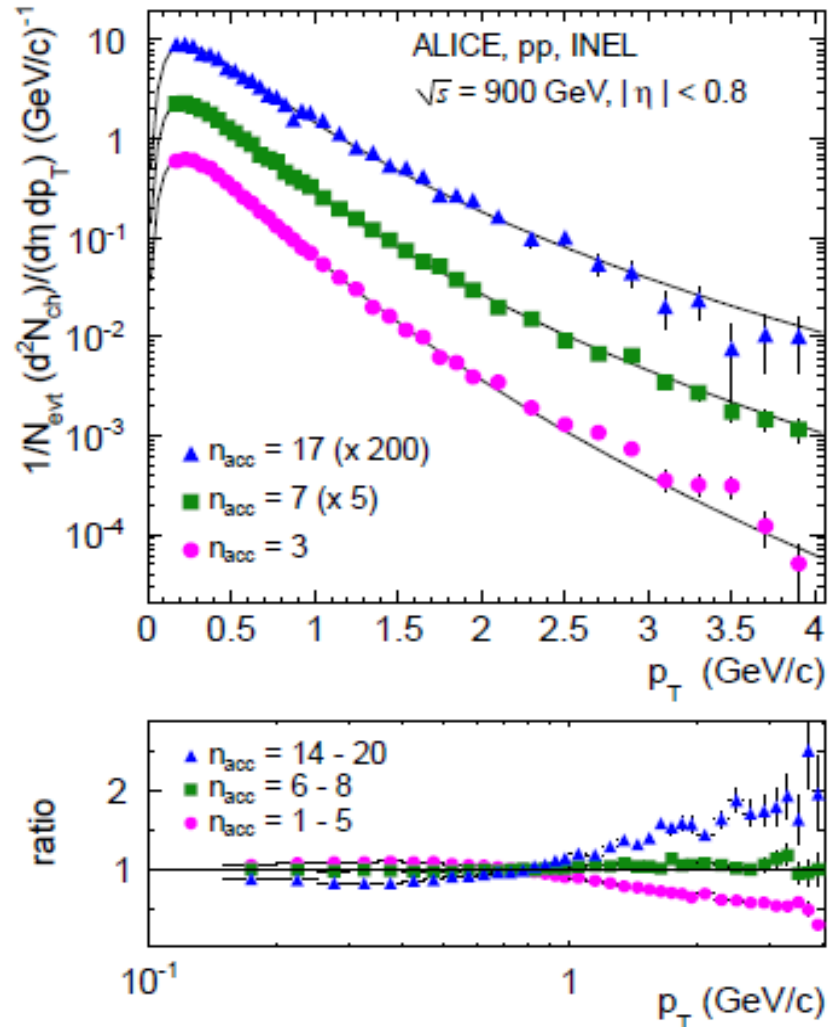
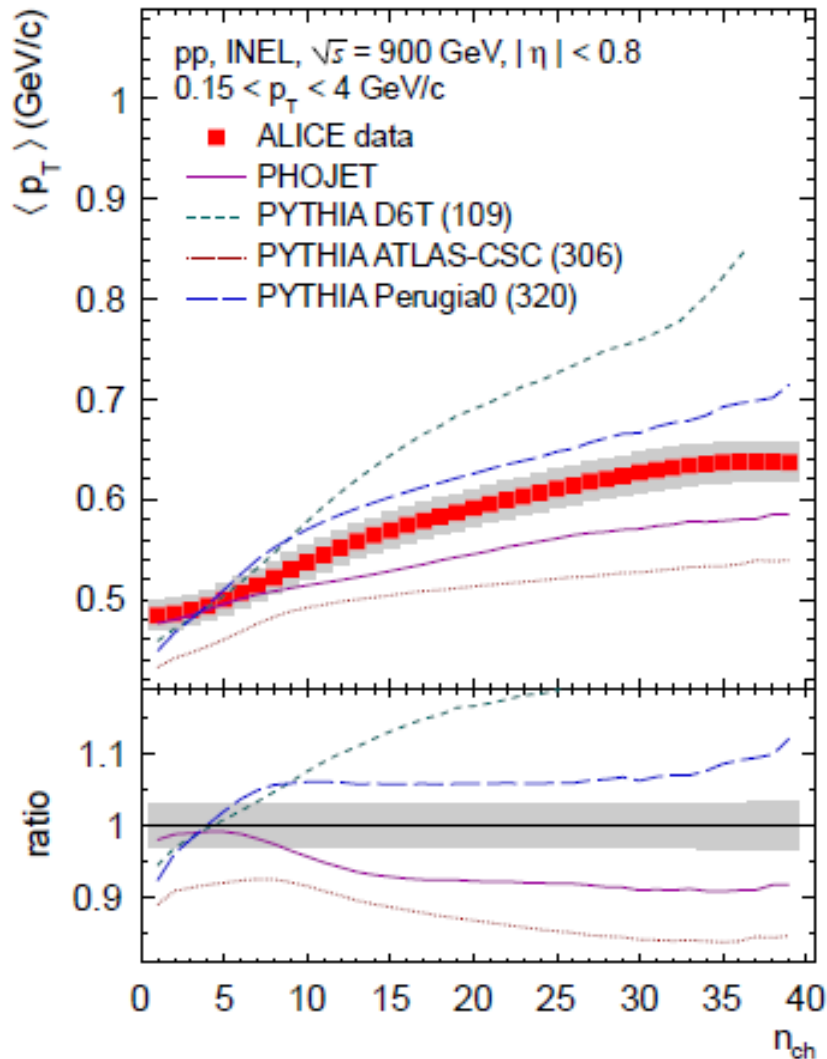
p_T distribution



$\langle p_T \rangle$

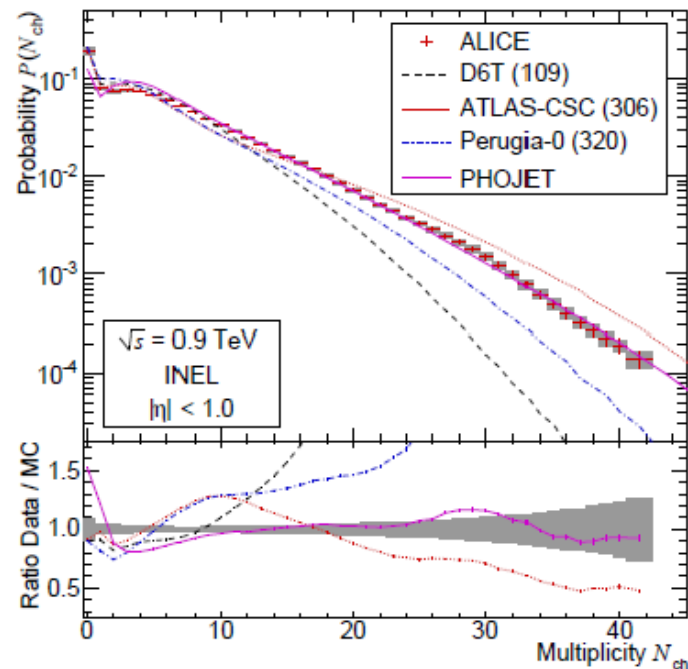


$\langle p_T \rangle$ versus multiplicity

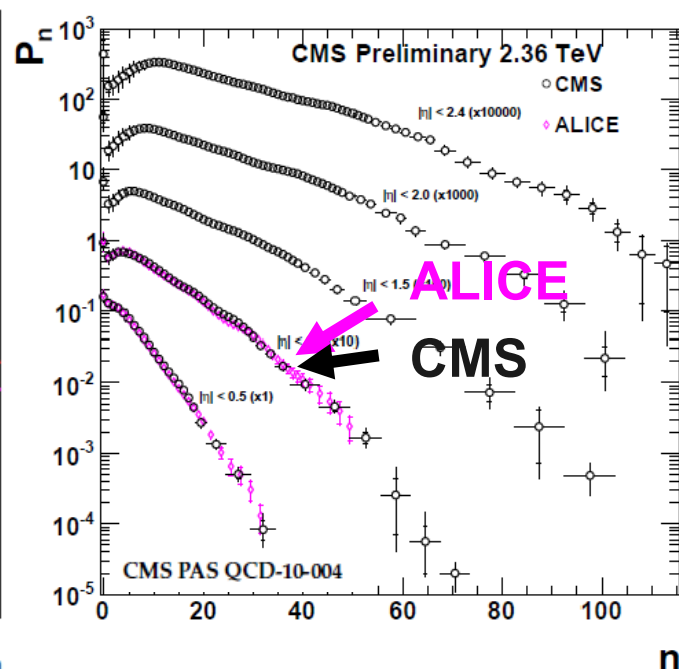


- Substantial discrepancies between Monte Carlo and the data

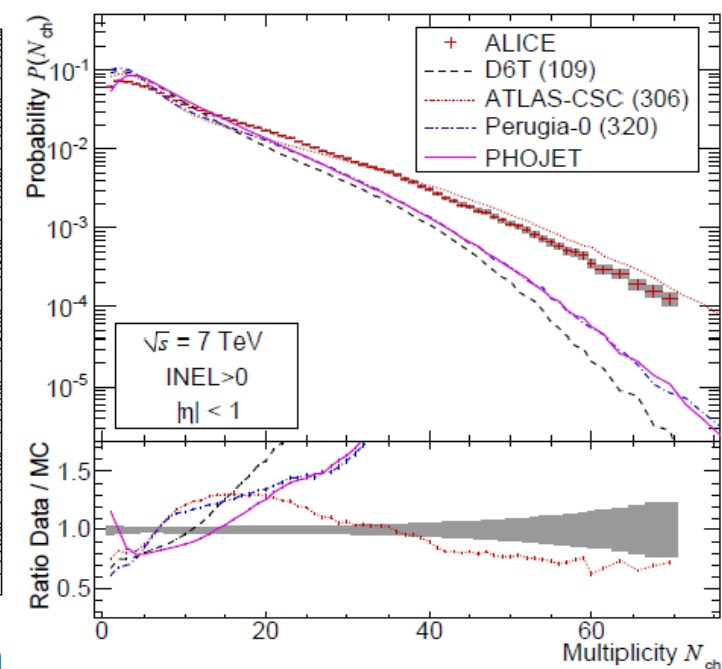
Multiplicity distributions



900 GeV



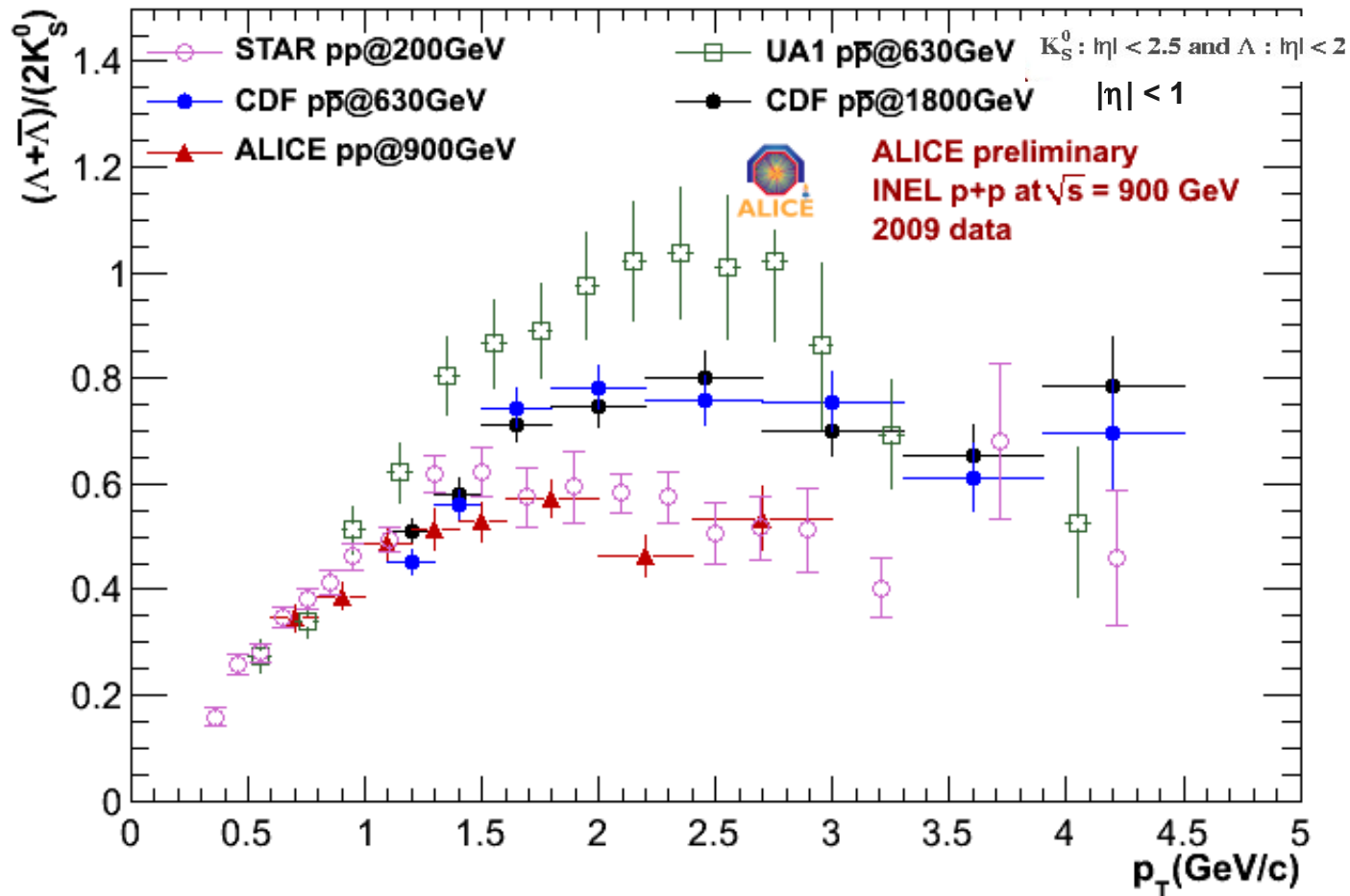
2.36 TeV



7 TeV

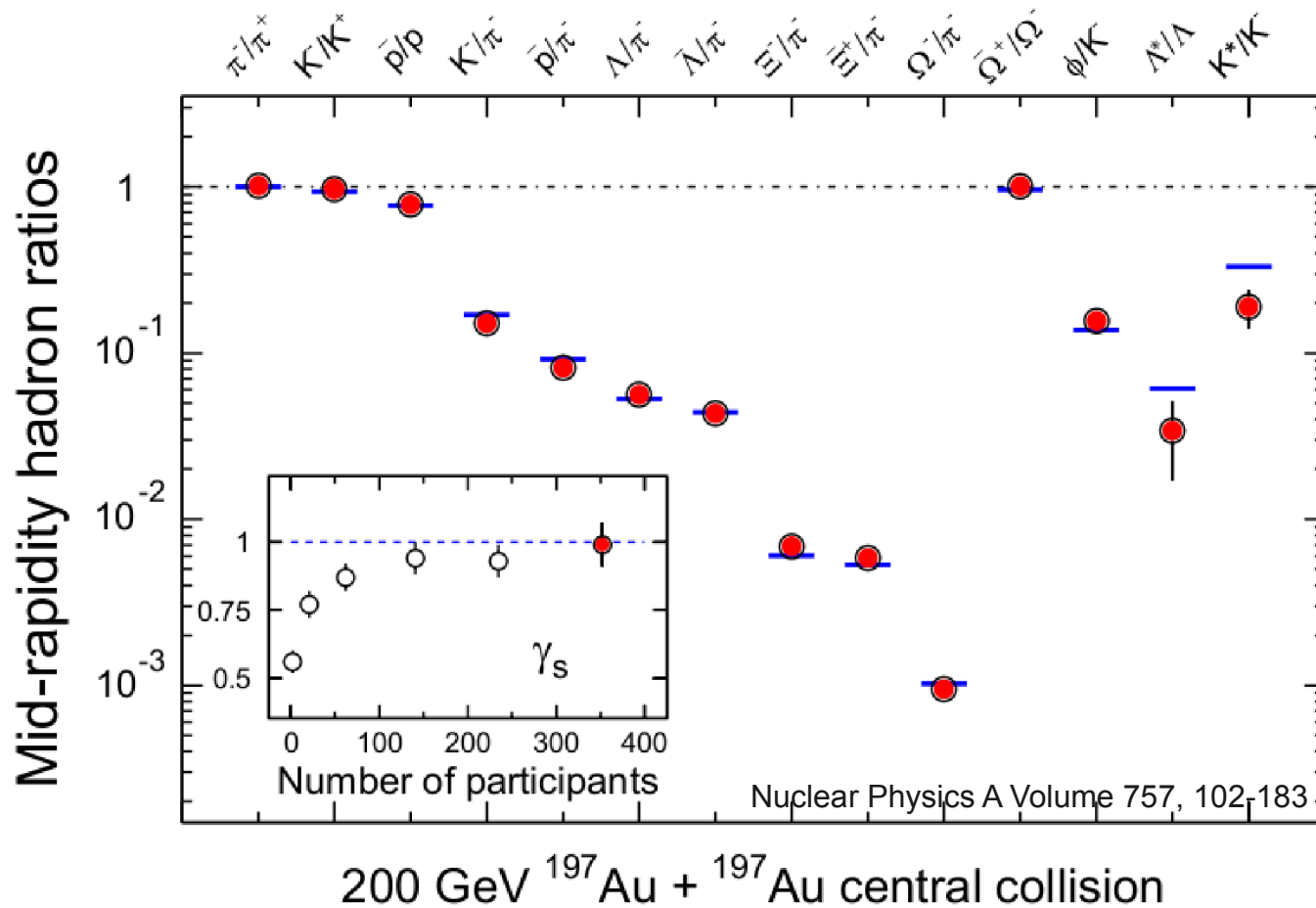
- Data from 900 GeV, 2.36 TeV, and 7 TeV
- Substantial discrepancies between Monte Carlo and the data
- Agreement between ALICE & CMS

$\Lambda/\bar{\Lambda}$ ratio at 000 GeV



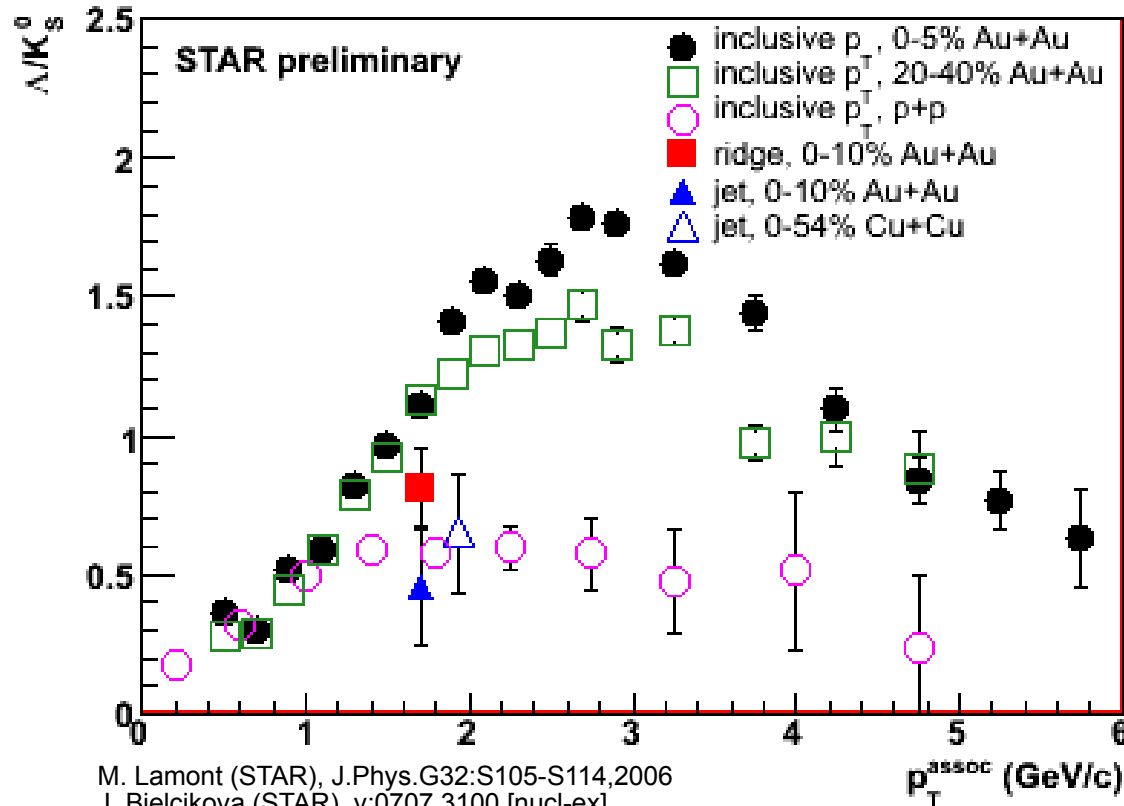
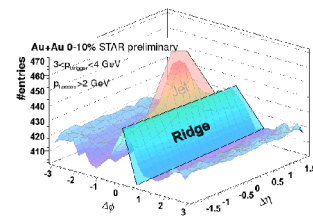
- Very good agreement between STAR (200 GeV) and ALICE (900 GeV)
- Very different from CDF (630/1800) and UA1 (630) for $p_T > 1.5$ GeV

Chemistry - equilibrium

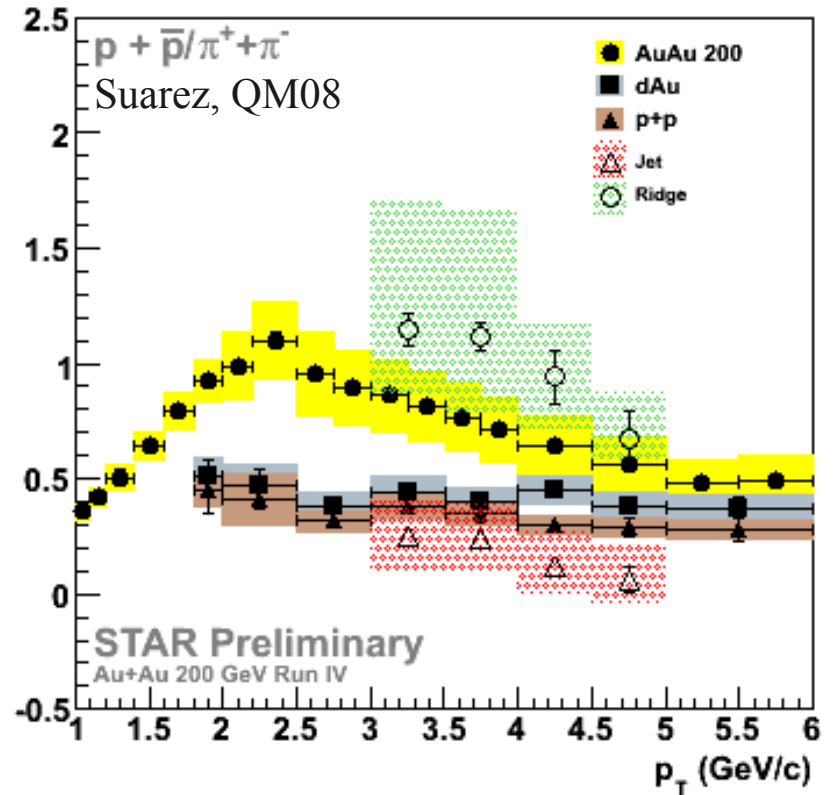


- Ratios of particles expected from a model
- Even strange quarks are at equilibrium!

Ridge composition

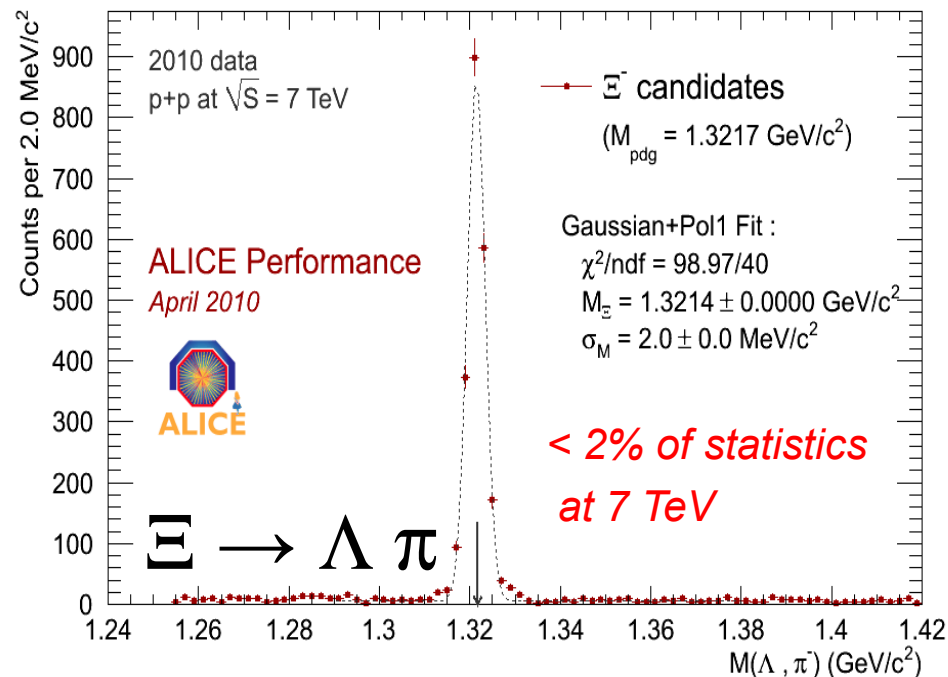
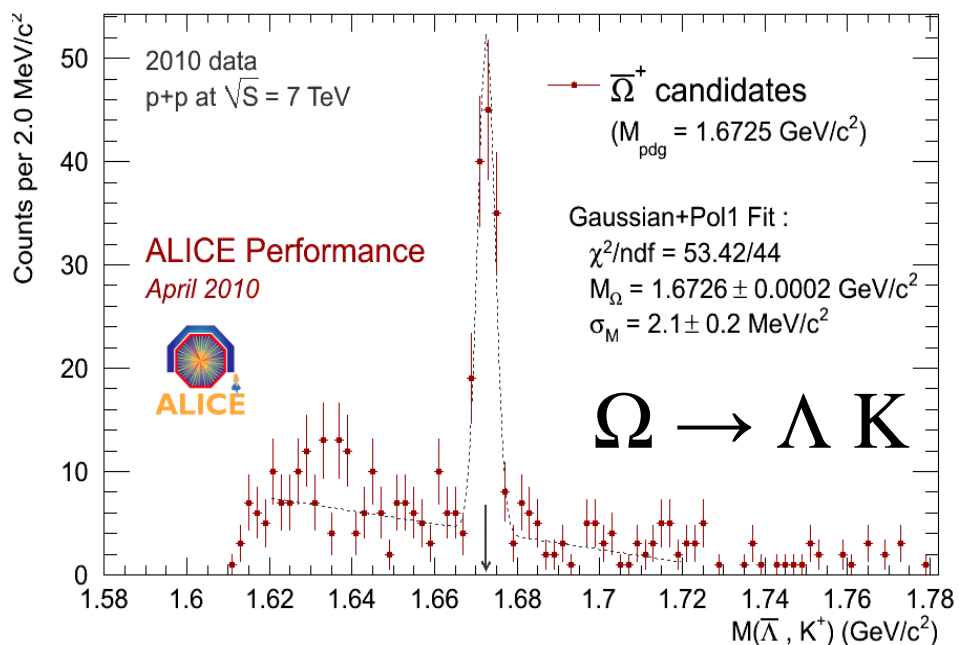
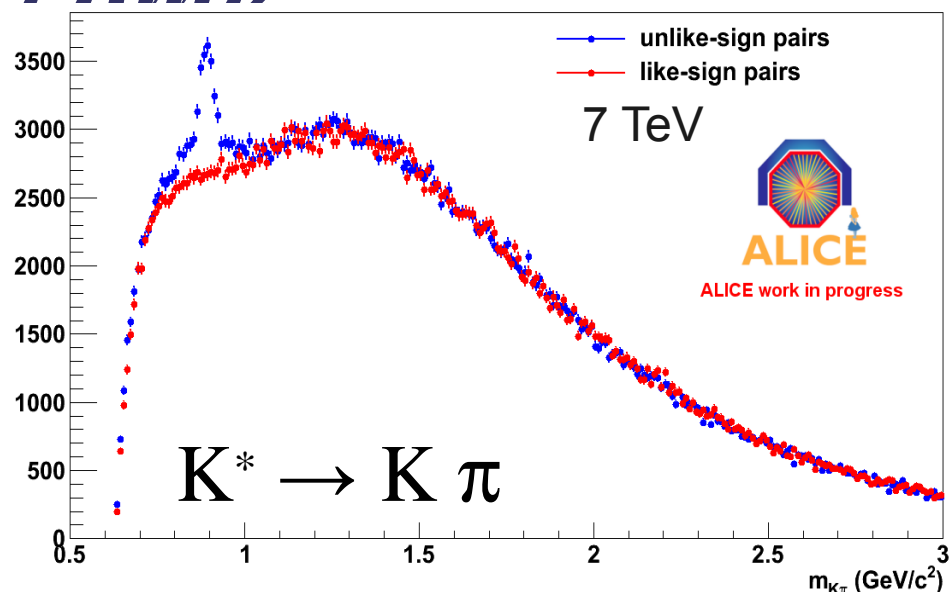
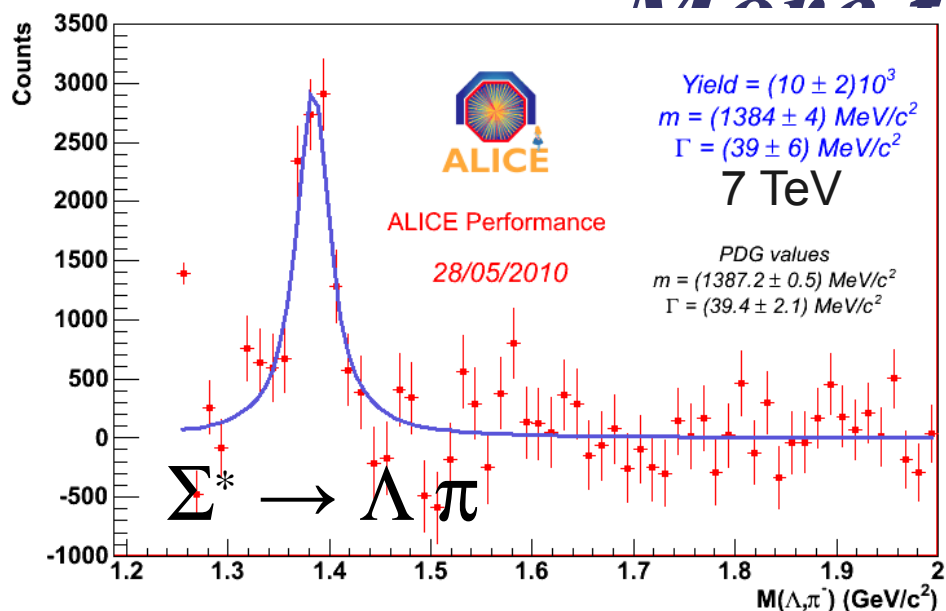


M. Lamont (STAR), J.Phys.G32:S105-S114,2006
 J. Bielcikova (STAR), v:0707.3100 [nucl-ex]
 C. Nattrass (STAR), arXiv:0804.4683/nucl-ex



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

More to come



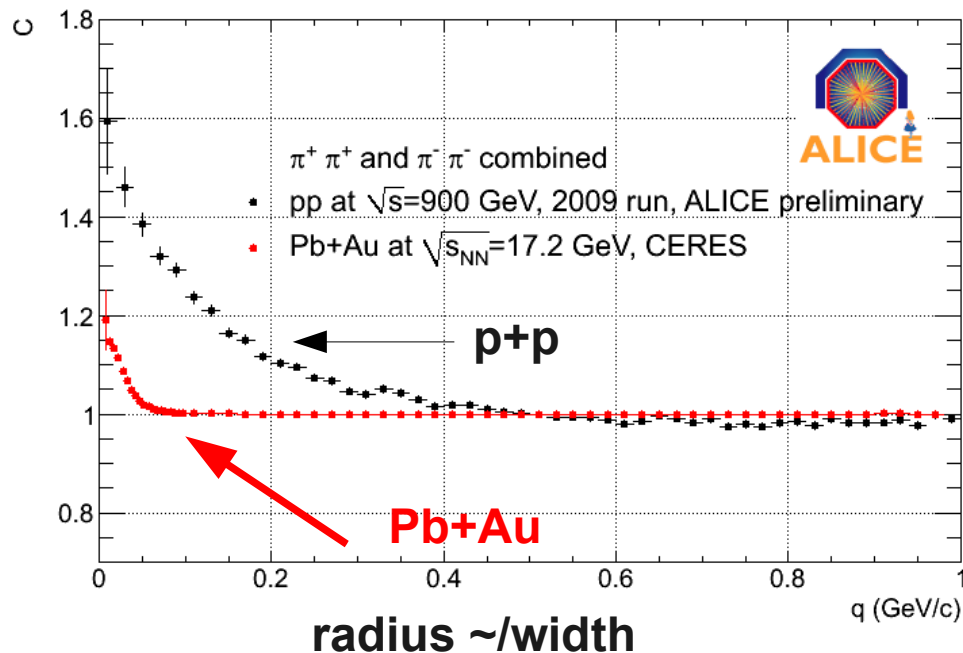
Bose-Einstein correlations

QM enhancement of identical Bosons at small momentum difference:

- Enhancement of e.g. like-sign pions at low momentum difference $q_{inv} = |\mathbf{p}_1 - \mathbf{p}_2|$

→ 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...

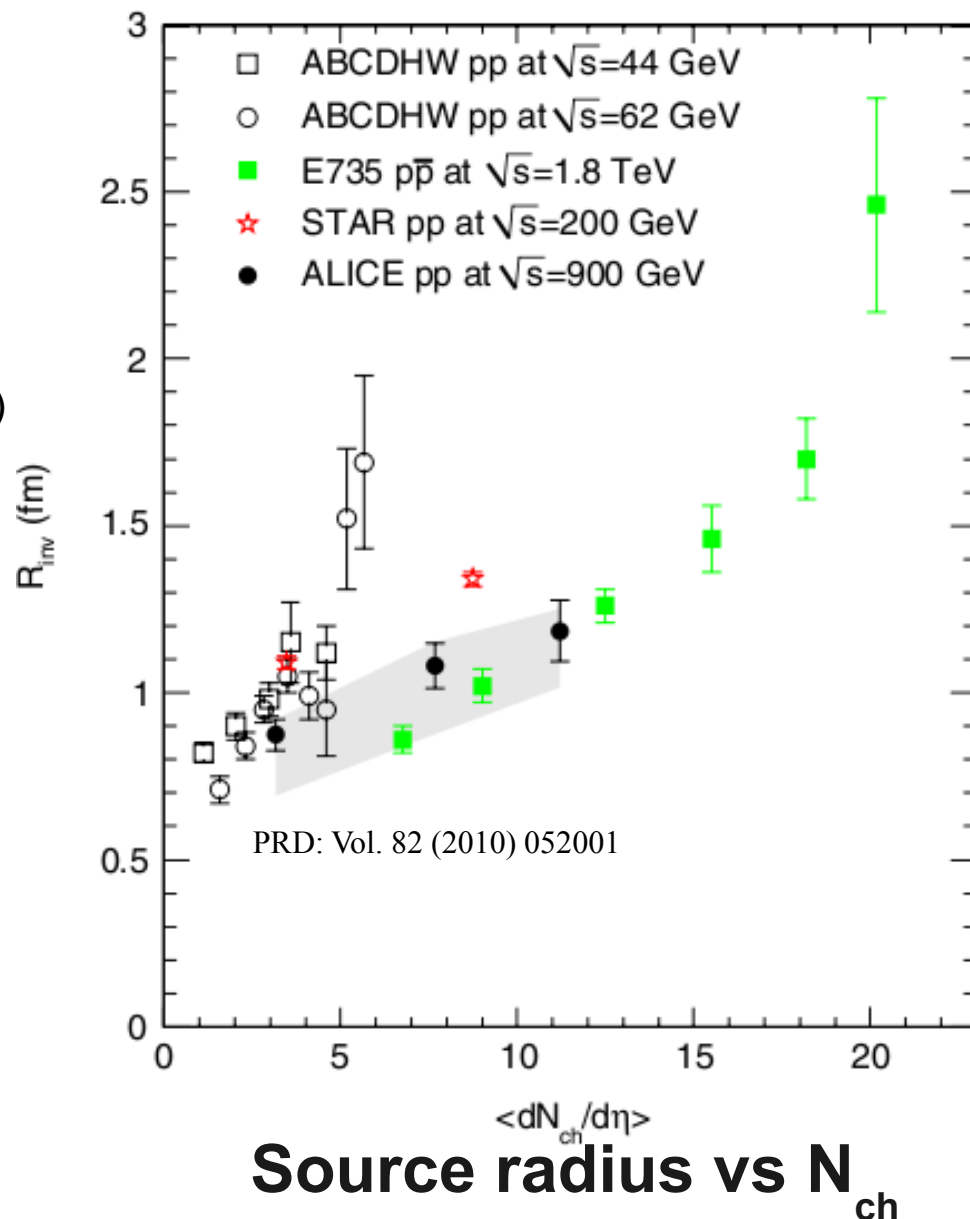
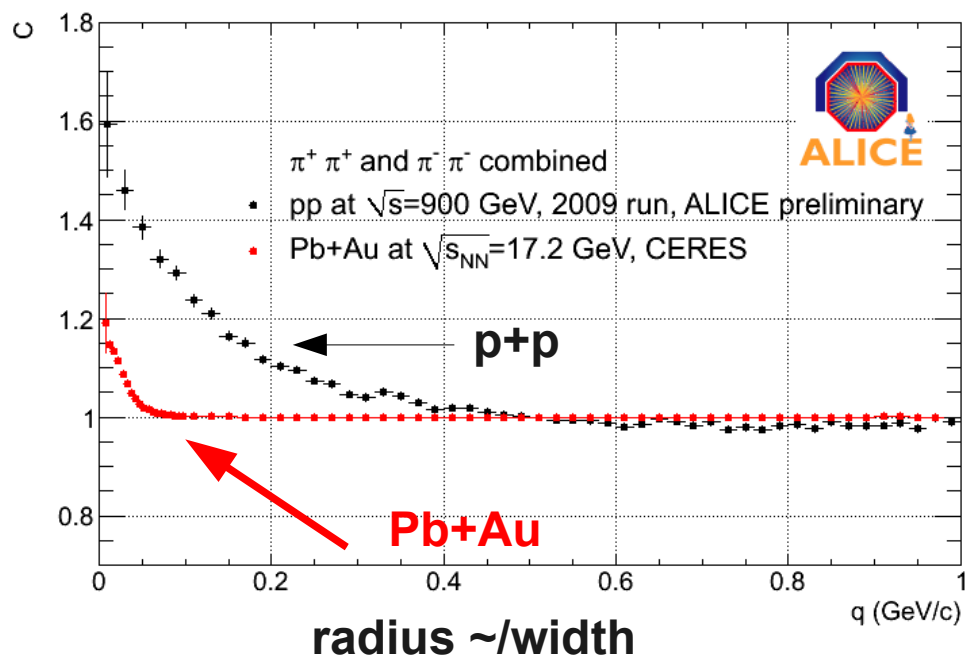


Bose-Einstein correlations

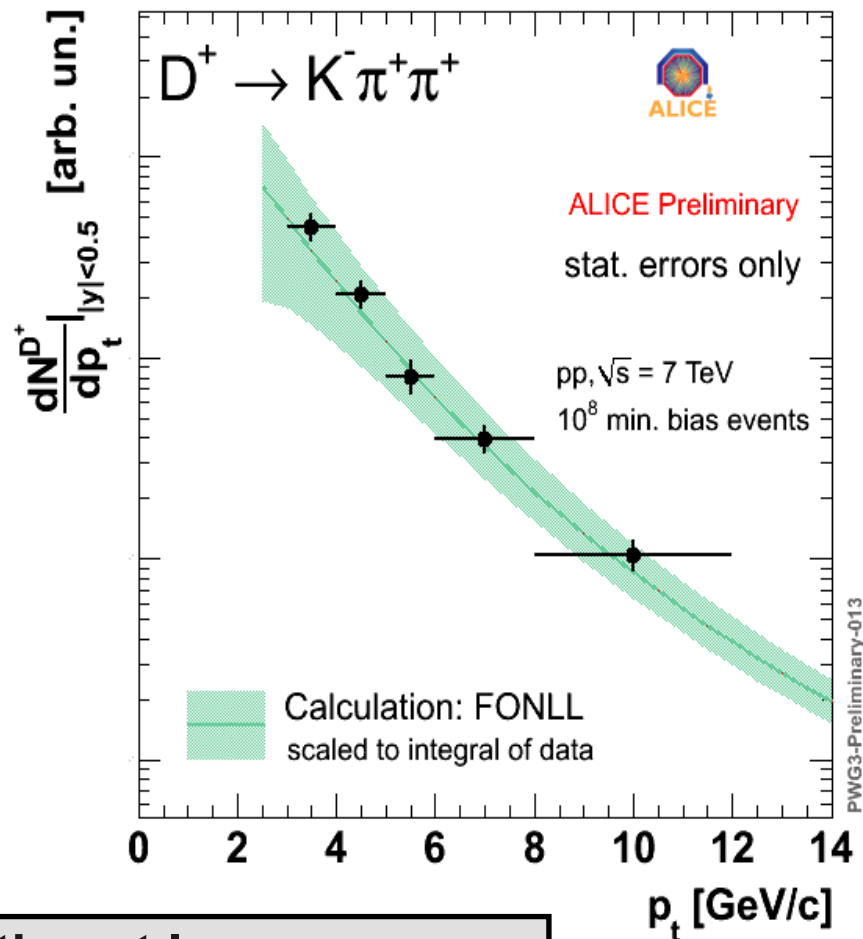
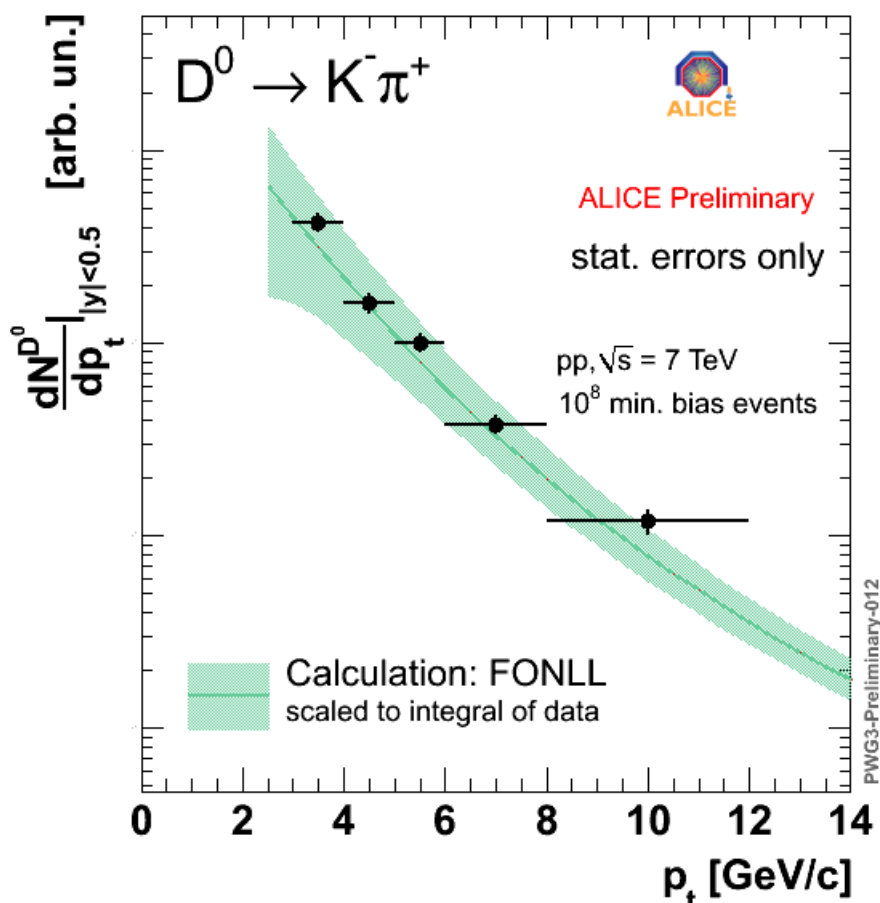
QM enhancement of identical Bosons at small momentum difference:

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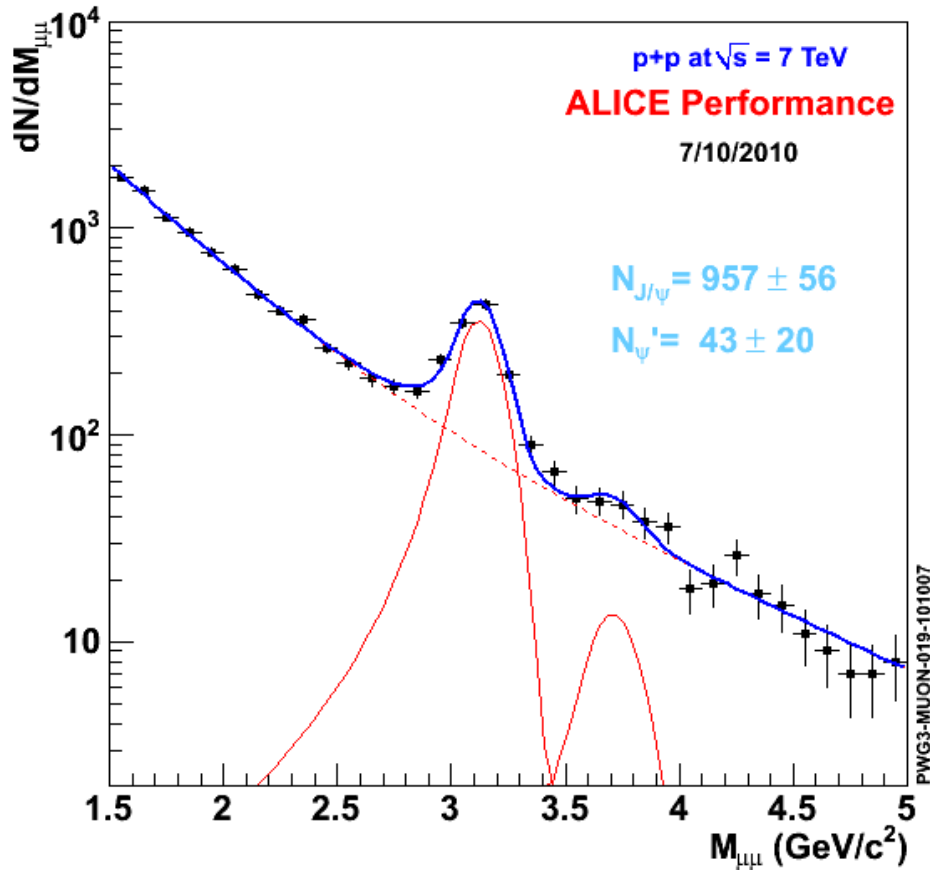
D^0 and D^+ dN/dp_t



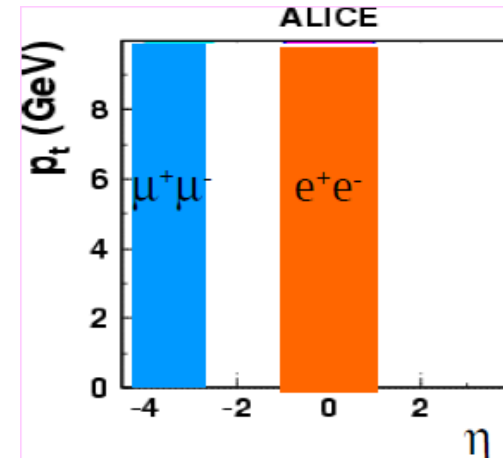
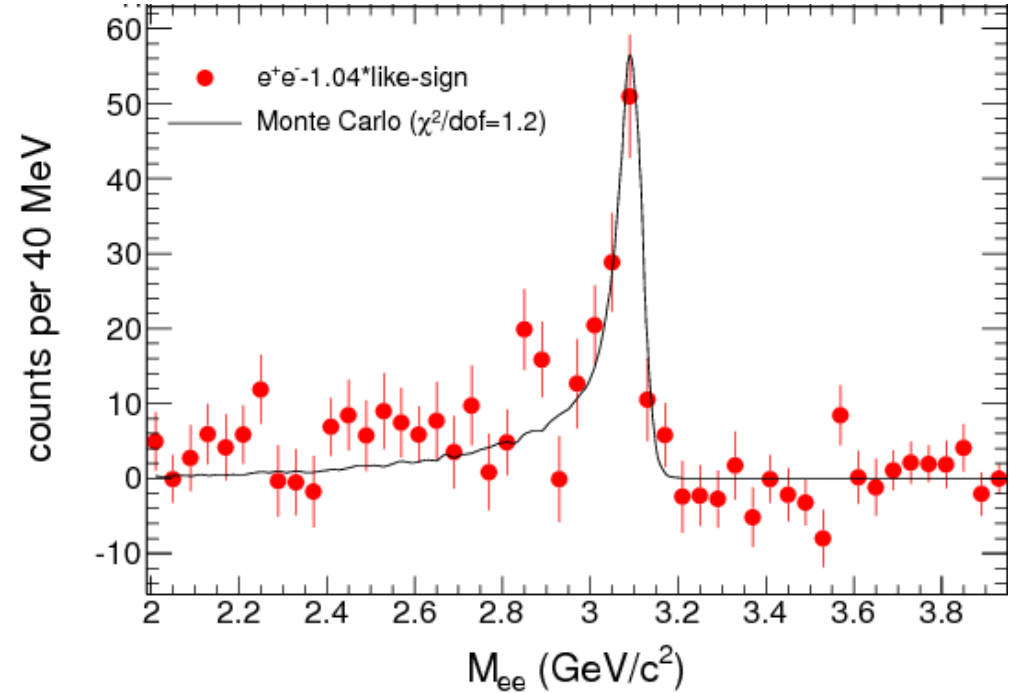
- Most of the cross section at low p_T
- Shape at low p_T very uncertain
- 10^9 MB events \Rightarrow measure below 1 GeV
(PID important at low p_T !)

J/ψ production at 7 TeV

$J/\psi \rightarrow \mu^+\mu^-, y = 2.5-4.0$



$J/\psi \rightarrow e^+e^- |y| < 1$



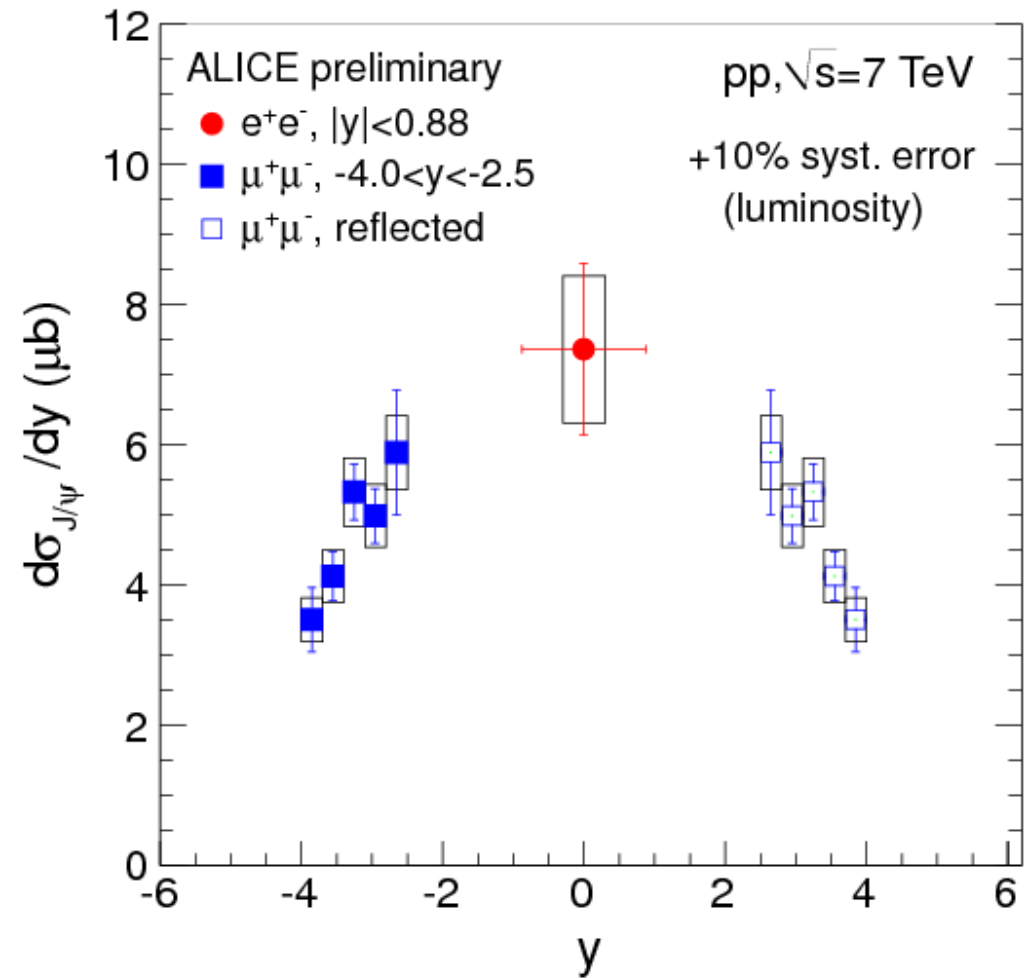
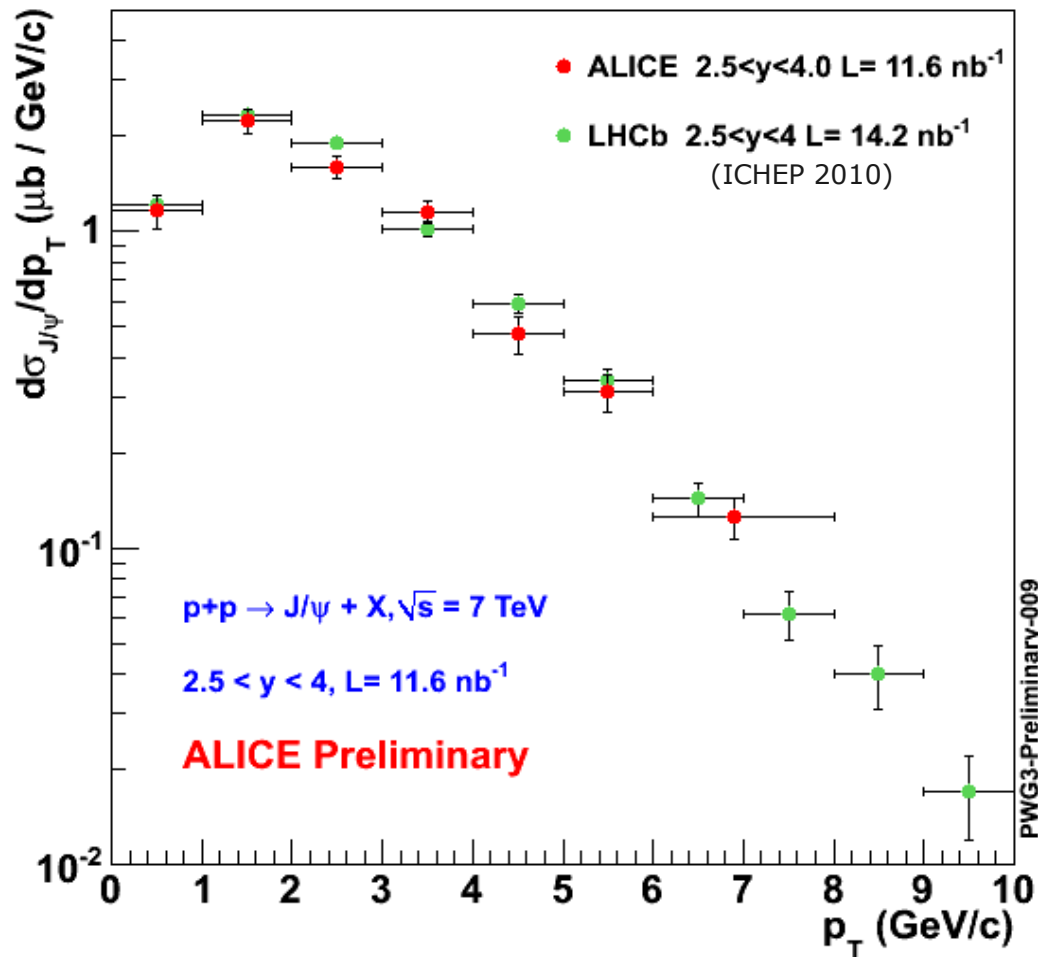
Measurement of J/ψ over wide pseudorapidity range

Rapidity spectra

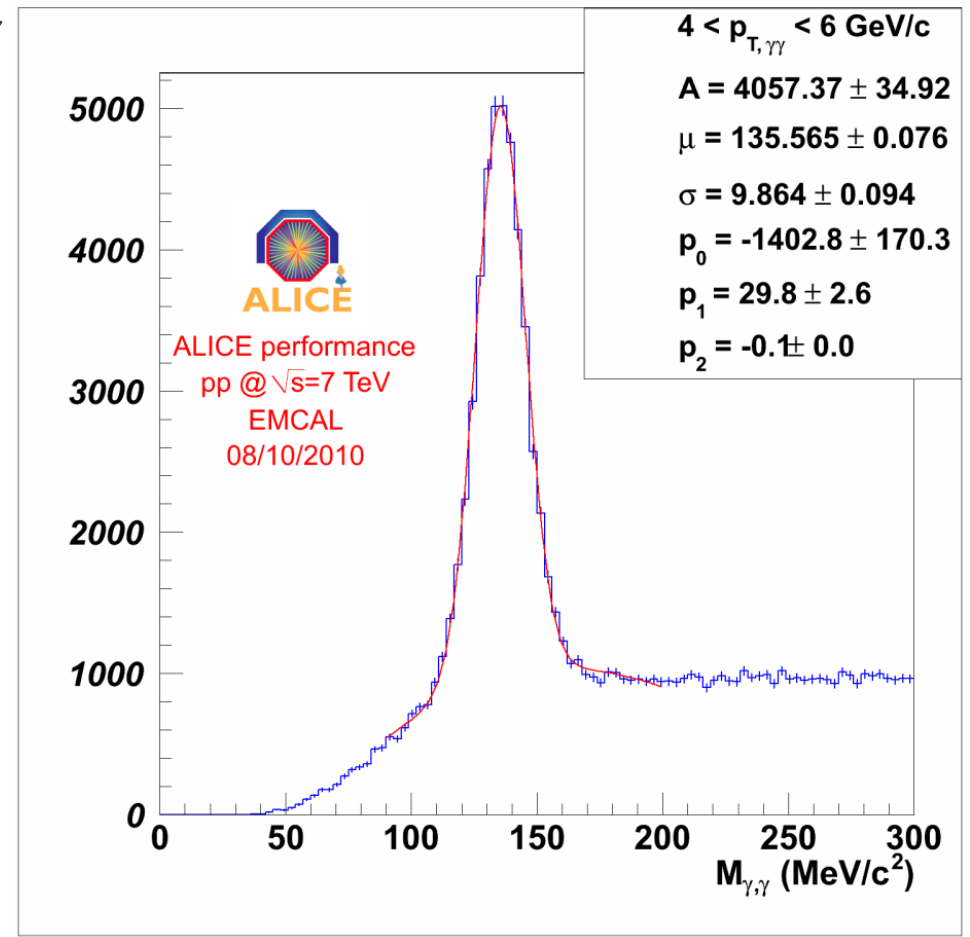
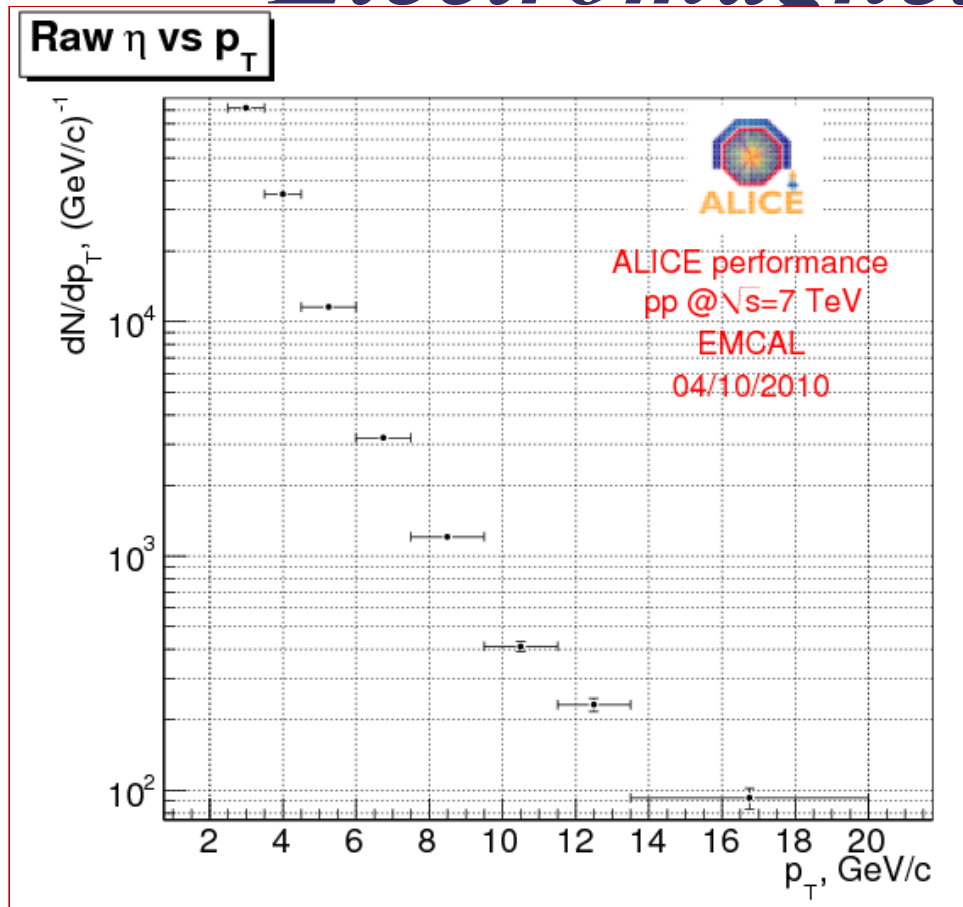
Transverse-momentum spectra

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

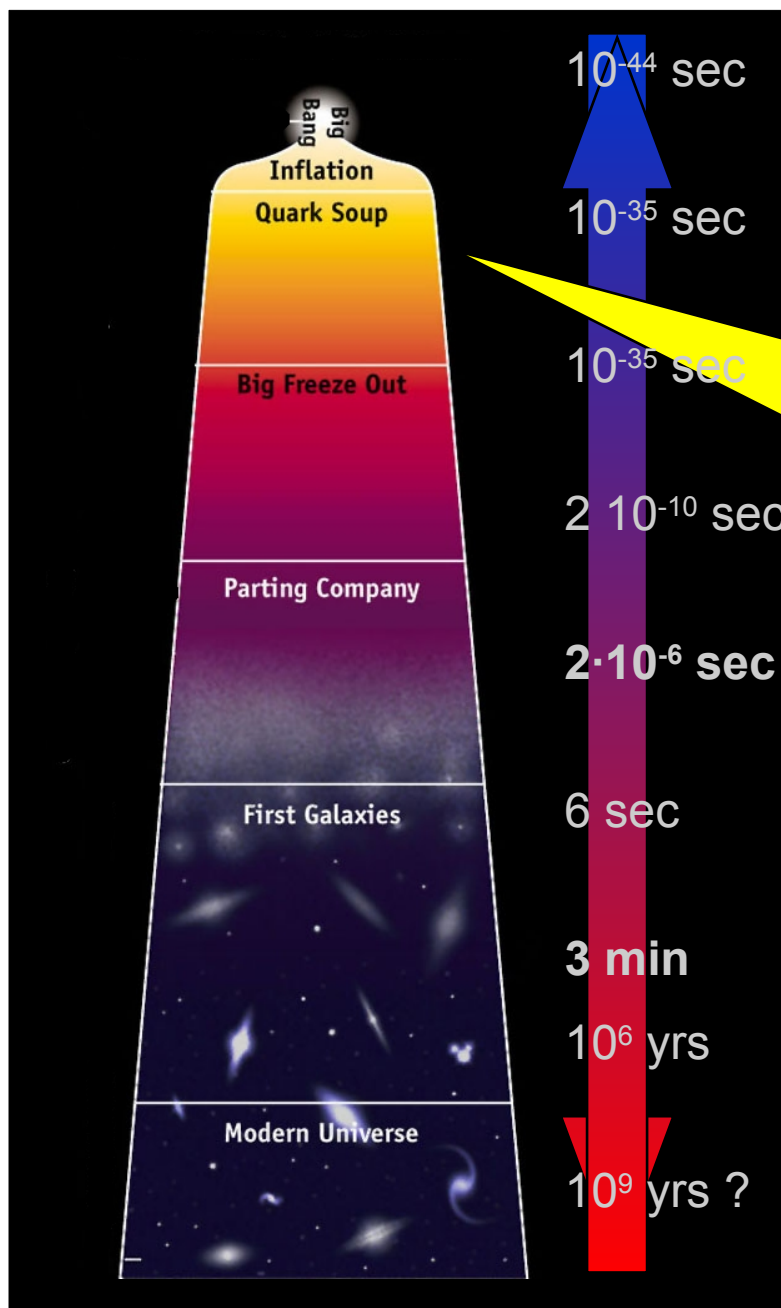


- EMCAL: $-0.7 < \eta < 0.7$, $80^\circ < \varphi < 120^\circ$ in 2010
 $\rightarrow 80^\circ < \varphi < 180^\circ$ in January 2011 – Ahead of schedule!

Physics papers submitted/published: 2010

- Strange particle production at central rapidity in proton-proton collisions at $\sqrt{s} = 0.9$ TeV with ALICE at LHC (Submitted?)
- Transverse momentum spectra of charged particles in proton-proton collisions at $\sqrt{s}=900$ GeV with ALICE at the LHC (Physics Letters B 693 (2010) 53–68)
- Two-pion Bose-Einstein correlations in pp collisions at $\sqrt{s}=900$ GeV (Phys. Rev. D 82, 052001 (2010))
- Midrapidity Antiproton-to-Proton Ratio in pp Collisions at $\sqrt{s}=0.9$ 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 $\sqrt{s}=7$ TeV with ALICE at LHC (Eur. Phys. J. C (2010) 68: 345–354)
- Charged-particle multiplicity measurement in proton-proton collisions at $\sqrt{s}=0.9$ 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 $\sqrt{s}=900$ GeV (Eur. Phys. J. C (2010) 65: 111-125)

Evolution of the Universe

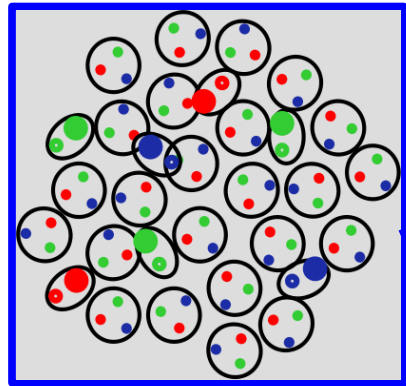


The universe gets cooler !

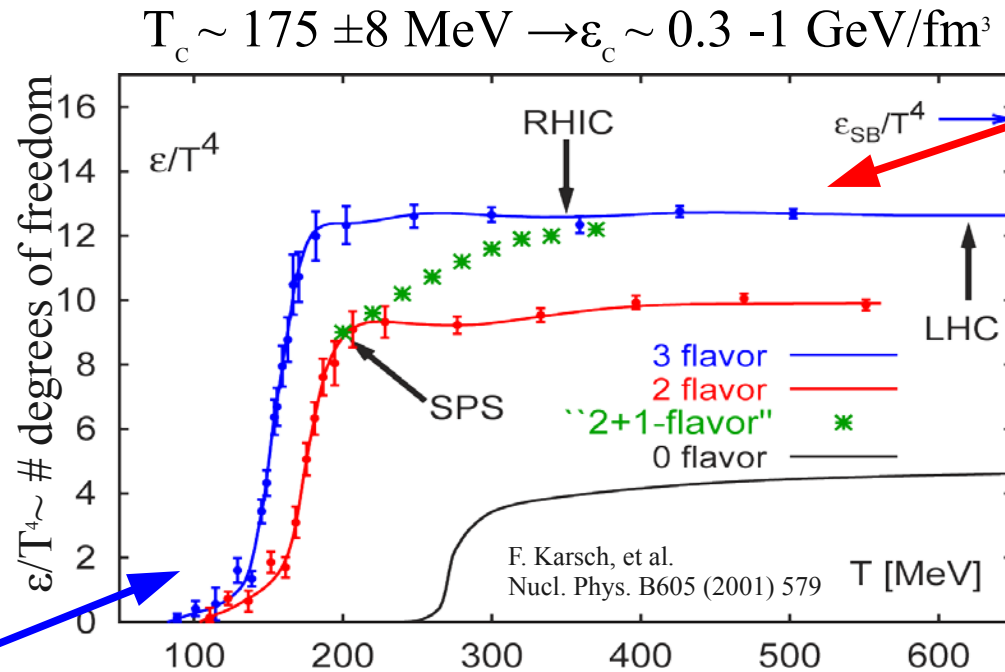
?

Need temperatures around
 $1.5 \cdot 10^{12}$ K
 $\sim 10^5$ times hotter than the core of the sun

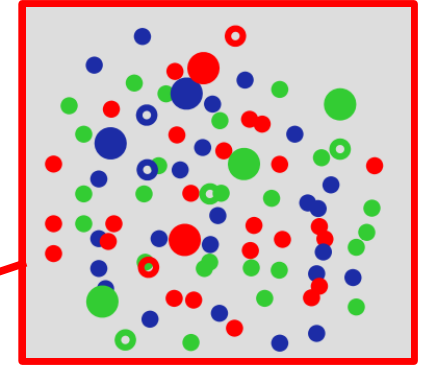
Exploring QCD at high temperatures



Confined - fewer degrees of freedom

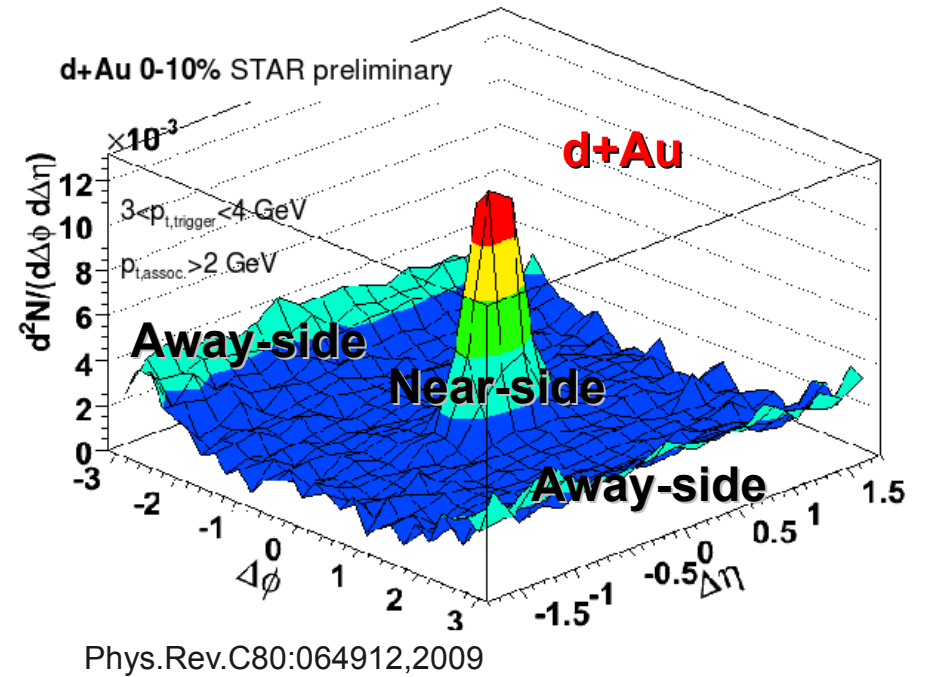
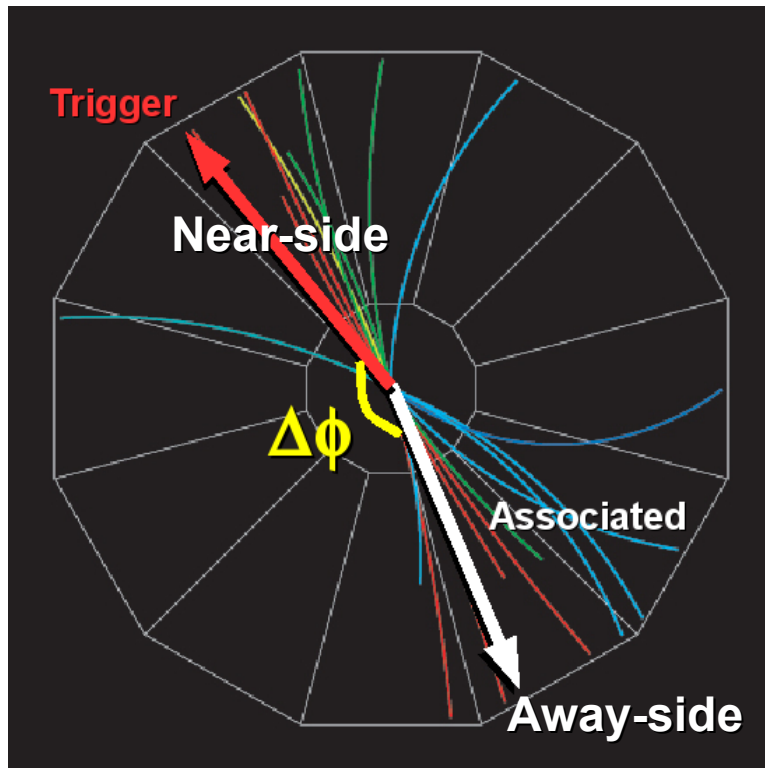


Quark-gluon plasma

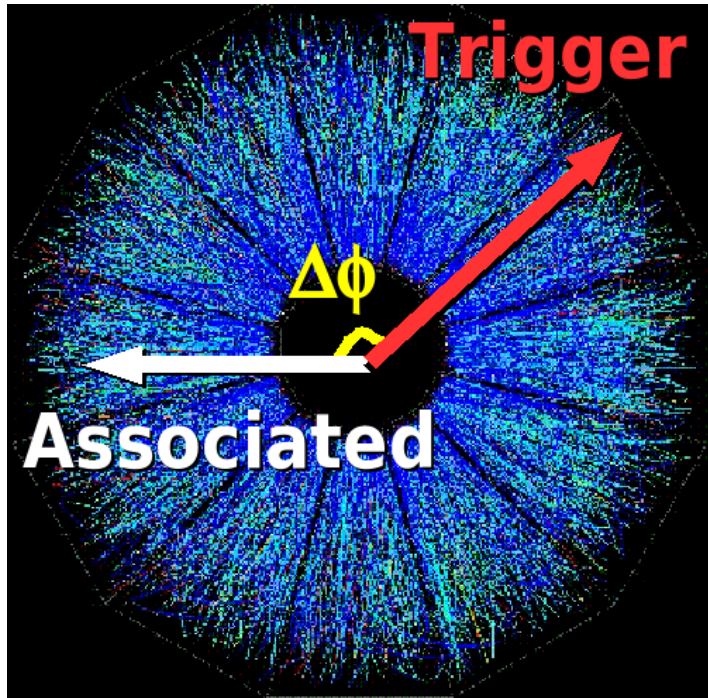


Deconfined - more degrees of freedom

$d+Au$



In two dimensions in Au+Au



Phys.Rev.C80:064912,2009

