# Heavy Ion Physics at the LHC
## What's new ? What's next ?


- **Short pre-LHC history**
  - **Reminder of main SPS/RHIC results**
- **Selected Results from the LHC**
  - **New light on old puzzles**
  - **Towards measuring QGP properties**
  - **Discoveries**
- **Open Issues/Questions**


**SPS : 1986 - 2003**

S and Pb ; up to $\sqrt{s}$ =20 GeV/nucl pair

$E_{cm}$* = 3200 GeV - 2500 prod. hadrons

**LHC : starting 2009**

Pb ; up to $\sqrt{s}$ = 5.5 TeV/nucl pair

od. hadrons

## QGP: Matter under extreme conditions

- Macroscopic partonic matter ('QCD thermodynamics')
- Deconfinement/Color Conductivity
- Chiral Symmetry Restoration

**AGS : 1986 - 2000**

- Si and Au ; up to $\sqrt{s}$ =5 GeV /nucl pair

$E_{cm}$* = 600 GeV - 1000 prod. hadrons

**RHIC : 2000**

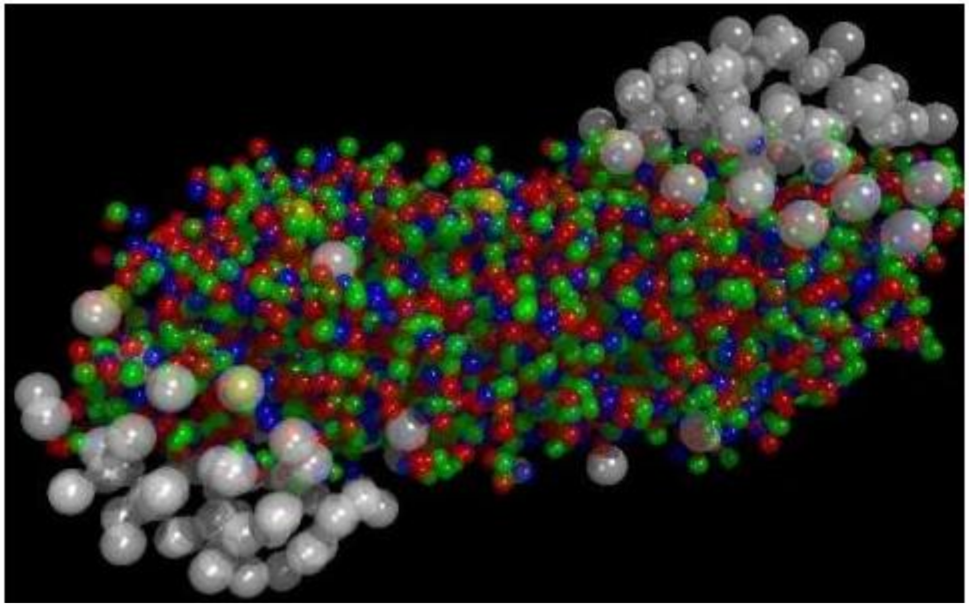
Au ; up to $\sqrt{s}$ = 200 GeV /nucl pair

$E_{cm}$* = 40 TeV - 7500 prod. hadrons

# New State of Matter created at CERN

10 Feb 2000

http://press.web.cern.ch/press-releases/2000/02/new-state-matter-created-cern



Based on a (unpublished)

**'common assessment'** of

results from ~ half dozen experiments

collected & published over the course of the SPS Pb program (1994 - 2000)

http://arxiv.org/abs/nucl-th/0002042v1

The collected data from the experiments gives compelling evidence that a new state of matter has been created. This state of matter found in heavy ion collisions at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma..

in today's LHC speak:

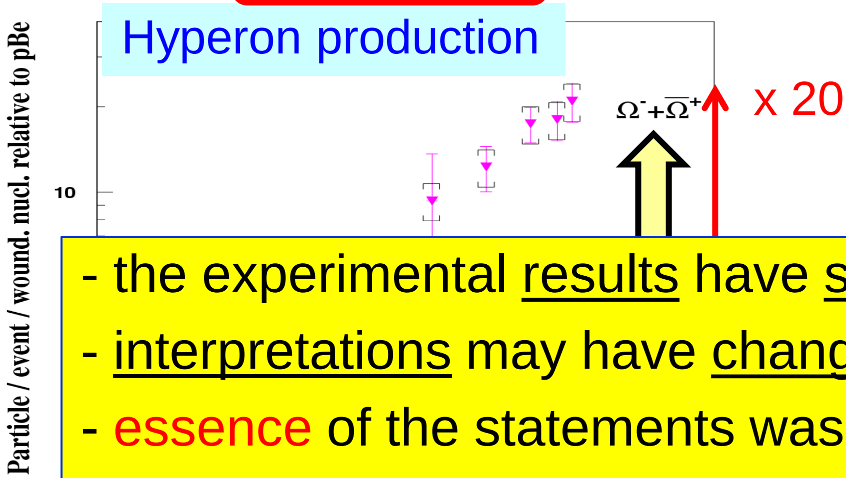
**'.. a QGP-like state ..'**

# Main Results from SPS

- strangeness enhancement

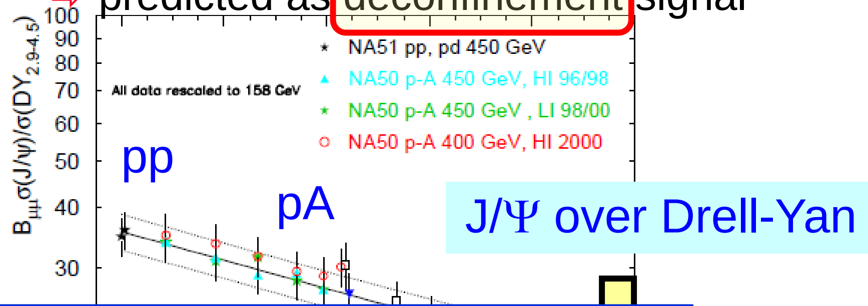
⇨ in general: thermal particle production

⇨ predicted for thermal system (partonic ?)




- 'anomalous' J/Ψ suppression

⇨ predicted as deconfinement signal



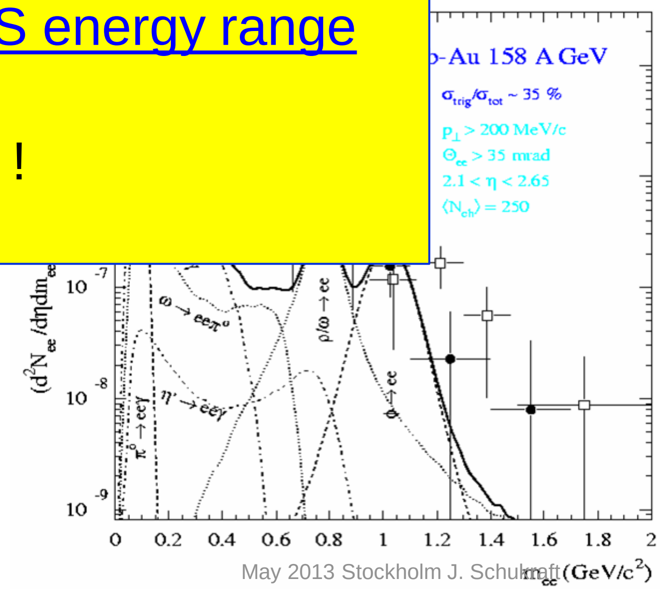

- the experimental results have stood the test of time
- interpretations may have changed over time
- essence of the statements was & is correct (in my view)

evidence for a new state of matter at the SPS energy range

however, today more 'compelling' than in 2000 !
(later SPS results, RHIC energy scan, LHC)

- low mass lepton pair enhancement

⇨'rho melting',
sign of chiral symmetry restoration ?

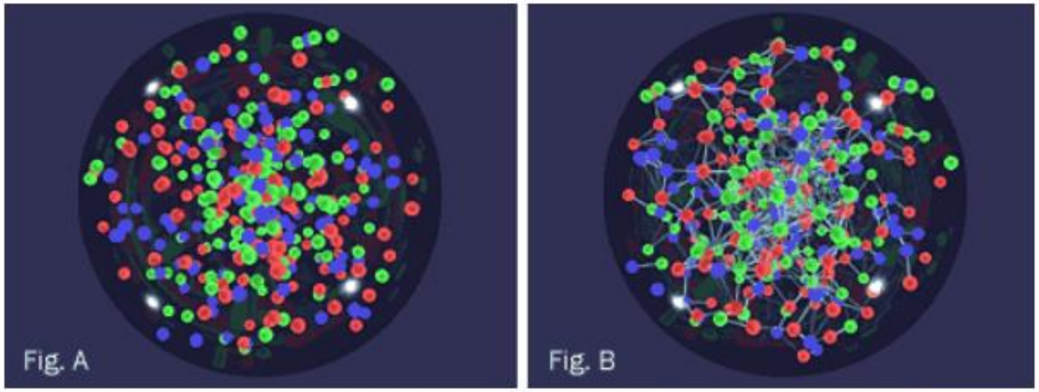


http://www.bnl.gov/newsroom/news.php?a=1303

# RHIC Scientists Serve Up "Perfect" Liquid

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

April 18, 2005




These images contrast the degree of interaction and collective motion, or "flow," among quarks in the predicted gaseous quark-gluon plasma state (Figure A, see mpeg animation) vs. the liquid state that has been observed in gold-gold collisions at RHIC (Figure B, see mpeg animation). The green "force lines" and collective

+ ENLARGE

Based on a (published) **comprehensive (re)analysis** of the first years of RHIC (2000 - 2004)

Nucl.Phys.A757:1-284,2005

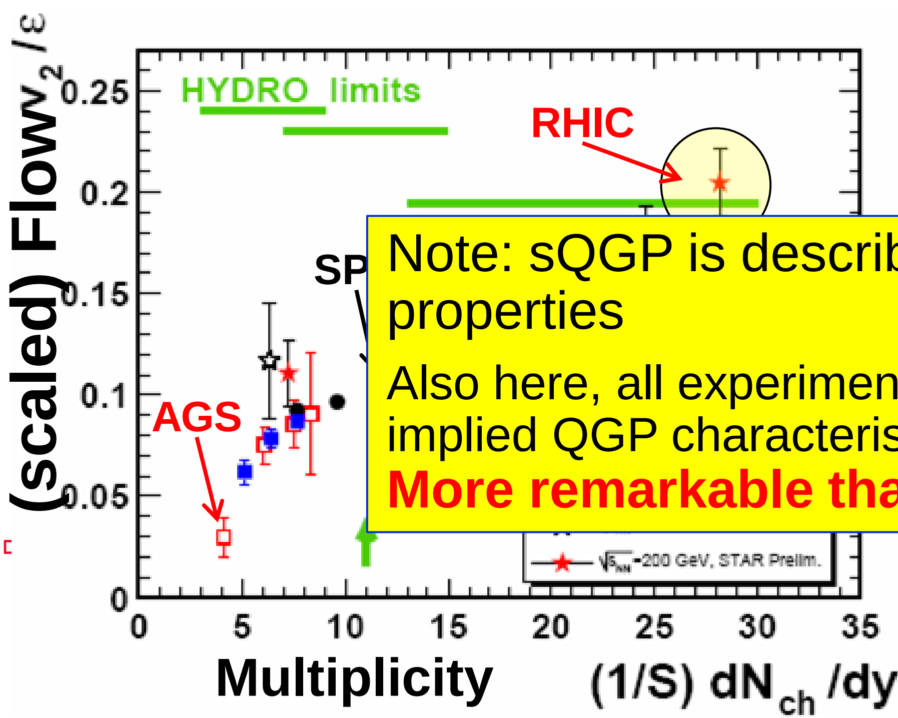
.. created a new state of hot, dense matter out of the quarks and gluons .., but it is a state quite different and even more remarkable than had been predicted.

in today's LHC speak:
**not**
**' ..the QGP ..'**
**but**
**'.. a QGP ..': sQGP**

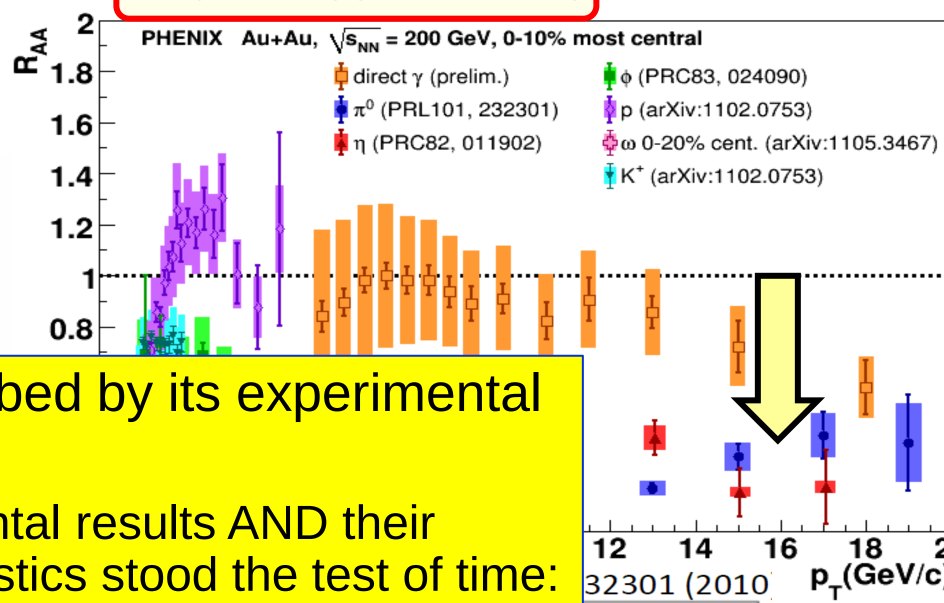
sQGP: strongly interacting QGP

# Main Results from RHIC

- strong elliptic flow
  - ⇨ ~ maximum possible i.e 'ideal liquid' ($\eta/s \approx 0$)
  - ⇨ mostly produced in the early phase (partonic?)

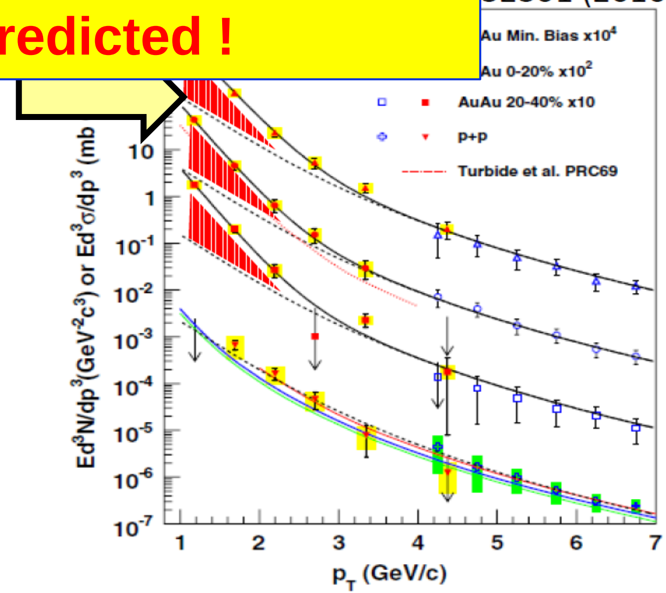



- high $p_T$ suppression 'jet-quenching'
  - ⇨ very strongly interacting (large energy loss)




Note: sQGP is described by its experimental properties

Also here, all experimental results AND their implied QGP characteristics stood the test of time:
**More remarkable than predicted !**

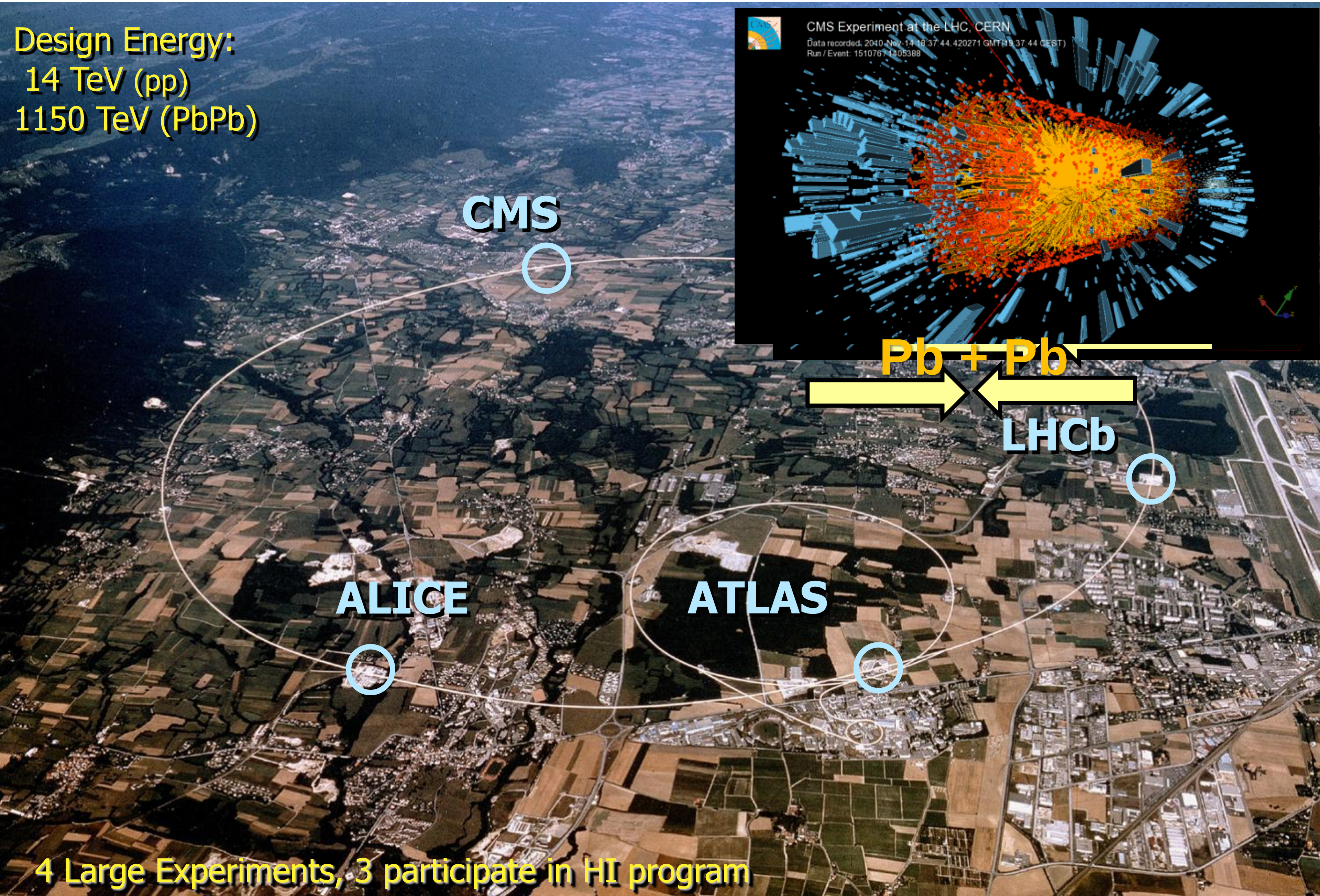



- direct 'thermal' photons => 'hot matter'
  - ⇨ data: inverse slope T ~ 220 ± 20 MeV
    model dependent $T_0$: 300 - 600 MeV

# Large Hadron Collider

# Collider of 'Large Hadrons'

Design Energy:
14 TeV (pp)
1150 TeV (PbPb)




4 Large Experiments, 3 participate in HI program

# What is left to do at LHC ?

- What is different ? Same physics with ..
  - ⇨ **different 'matter:'** increased energy (up to factor ~30 in √s )
    - ✪ QGP will be '**hotter - larger - longer living**'
    - ✪ large cross section for '**hard probes**' : high $p_T$, jets, heavy quarks,…
  - ⇨ **different experiments:** new generation, large acceptance state-of-the-art detectors
    - ✪ Atlas, CMS, Alice, [LHCb, for pA]

- Where is progress@LHC ? (very limited & personal selection)
  - ⇨ **New Light on Old Problems (NLOP)**
    - ✪ **hadronisation/**particle production ⇦ Q # 1
    - ✪ **quarkonia** suppression ⇦ Q # 2
  - ⇨ **Towards Precision Measurements (PM)** of QGP parameters
    - ✪ **elliptic flow**: viscosity $\eta$/s
    - ✪ **jet quenching**: opacity **q^**
  - ⇨ **Discoveries**
    - ✪ the '**Ridge**': long range correlations in pp & pA ⇦ Q # 3

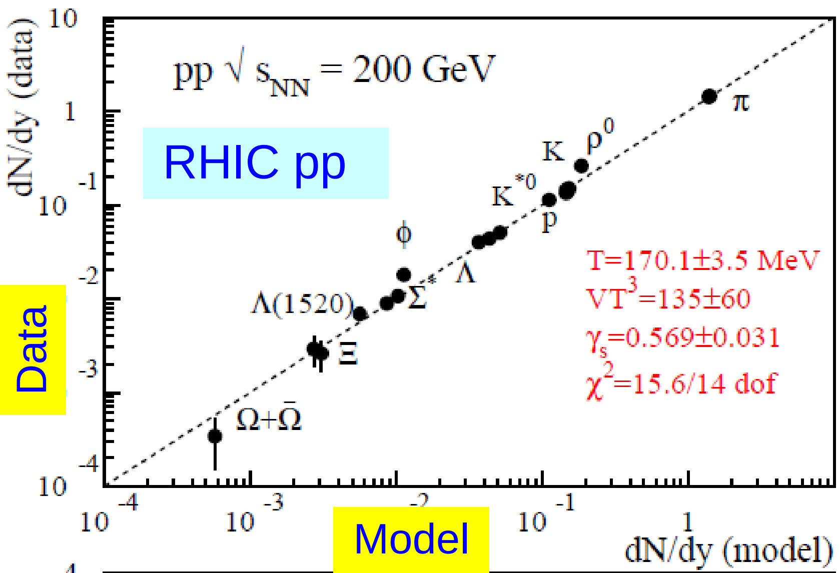
# NLOP I: Particle Production

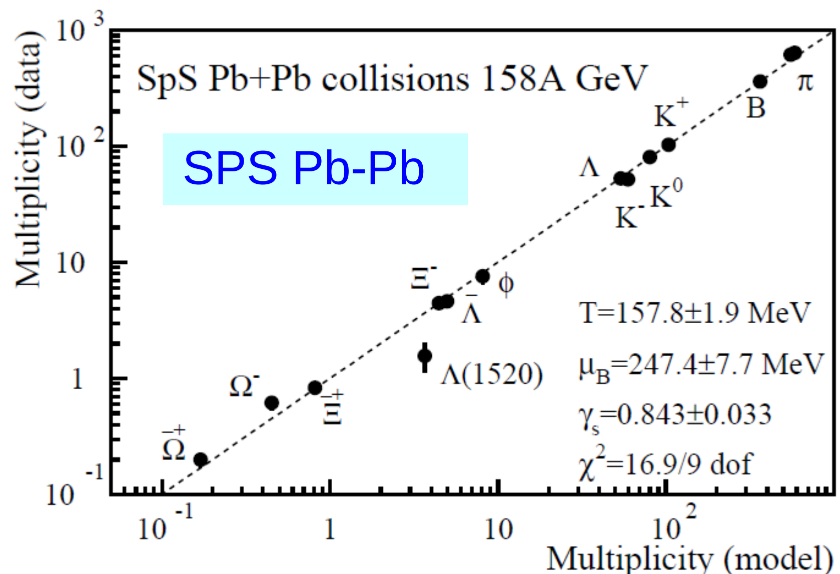
- Hadronisation is non-pertubative
  - ⇨ phenomenological models ('event generators') with many parameters
    - ✪ strings or clusters, PPAR(x), x=1,..n
- Statistical ('thermal') models: accurate to O(10%) (no 'a priori' justification)
  - ⇨ particle with mass *m* produced in 'heat bath T' according to phase space
  - ⇨ P(m) ~ $e^{-(m/T)}$

**$T_{ch}$: 160-170 MeV $\gamma_s$ : 0.9-1 (AA), 0.5-0.6 (pp)**
**strangeness enhancement = QGP signal ?**

$T_{ch}$ Temperature (ch='chemical')
$\mu_b$ Baryo-chemical potential (baryon conservation)
$\gamma_s$ Strangeness suppression

particles created per collision




kraft

# Dynamical Origin of Thermal Ratios ?

- 'born into equilibrium' ($e^+e^-$, pp, AA) — at the QCD phase boundary $T_c \approx T_{ch}$
  - ⇨ yields ~ QCD x (hadronic) phase space — many channels => PS dominates
  - ✪ **pp** $\gamma_s < 1$ : QCD, $m_s$
  - ✪ **AA** $\gamma_s \approx 1$ : thermo-dynamics in parton phase

⇨ **BUT:** **$e^+e^-$, pp:** why $T_c \approx T_{ch}$ **AA**: why don't we see parton equilibrium ?

- 'evolving into equilibrium' (AA) — thermodynamics in hadron phase
  - ⇨ arbitrary (eg pp-like) initial hadron ratios + **inelastic reactions**
  - ✪ reach equilibrium close to phase boundary ($T_{ch} < T_c$) A + B <=> C + D + E

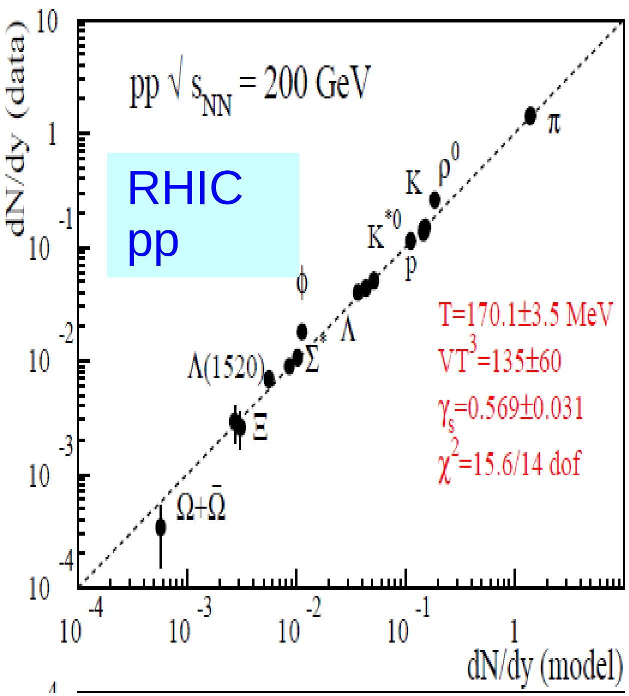
⇨ **BUT:** dynamic system (expansion & cooling) => **expect sequential freeze-out ?**

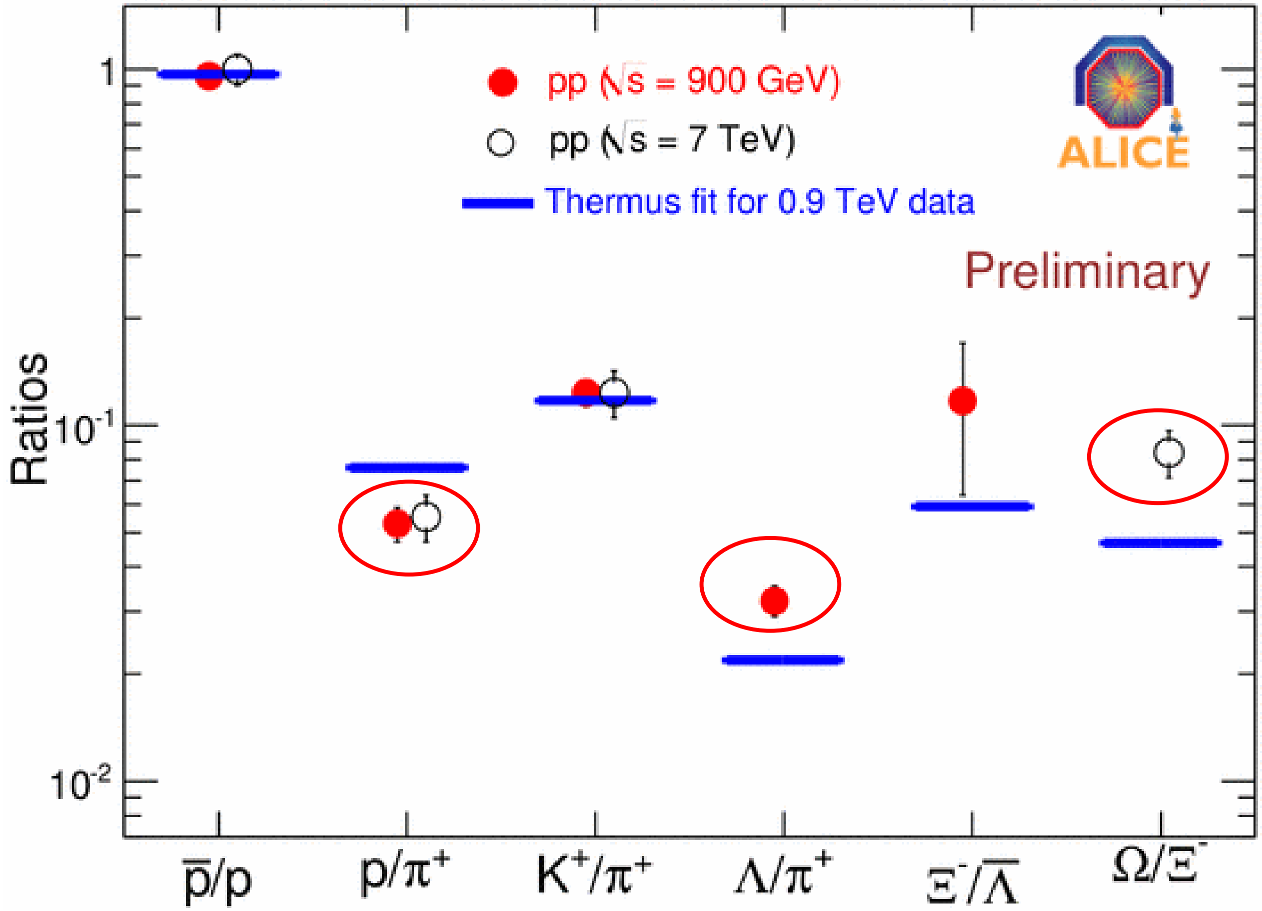
✪ hadrons with large inelastic $\sigma$ should freeze out later (lower T) !

**In this picture, statistical models work**
**- in AA by design (thermodynamics),**
**- in pp/$e^+e^-$ by accident (dominance of PS).**
**Conceivable, but limited direct evidence..**

# Particle Ratios at LHC

- pp: Less well described than at lower energies !
  - ⇨ fits 2 ratios with 2 parameters (T, $\mu_B$)
  - ⇨ maybe finally 'hard QCD processes' (ME, dynamics) become visible over PS ?



# Particle Ratios Pb-Pb

**Strangeness is enhanced**

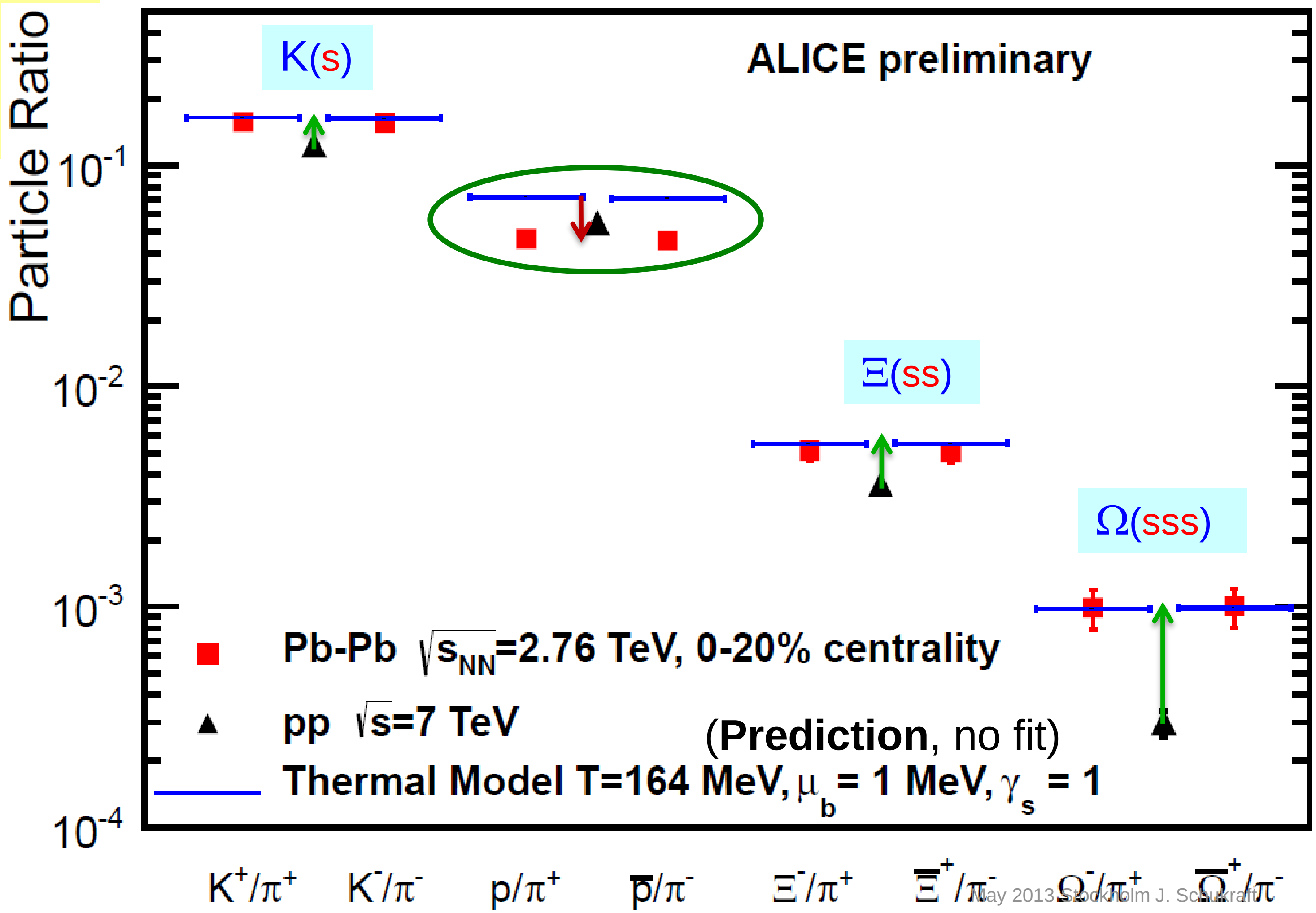
**+30% (K), > factor 3 (Ω)**

$\gamma_s$ **= 1,** like thermal model

**p/π off by factor > 1.5 from predictions !**

suspressed,
not enhanced,
compared to pp

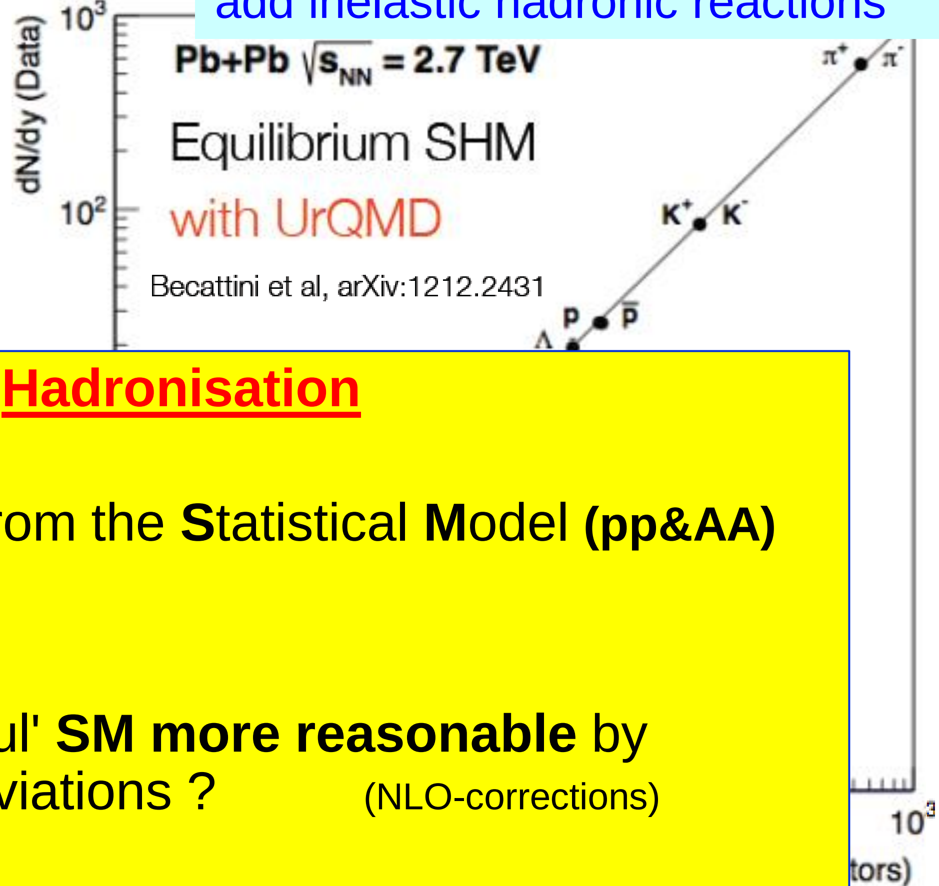
**initially very surprising result** (safest prediction for LHC !)



# NLOP I: Current Explanations

- Sequential Freeze-out
  - ⇨ hadronic final state reactions
  - ⇨ but: more art than science..
  - ✪ many unknown σ (e.g. $\Lambda + \Omega \to n\pi + m$K)
  - ✪ detailed balance (e.g. p + **p** <=> 5 π)

add inelastic hadronic reactions




**Questions 1: Hadronisation**

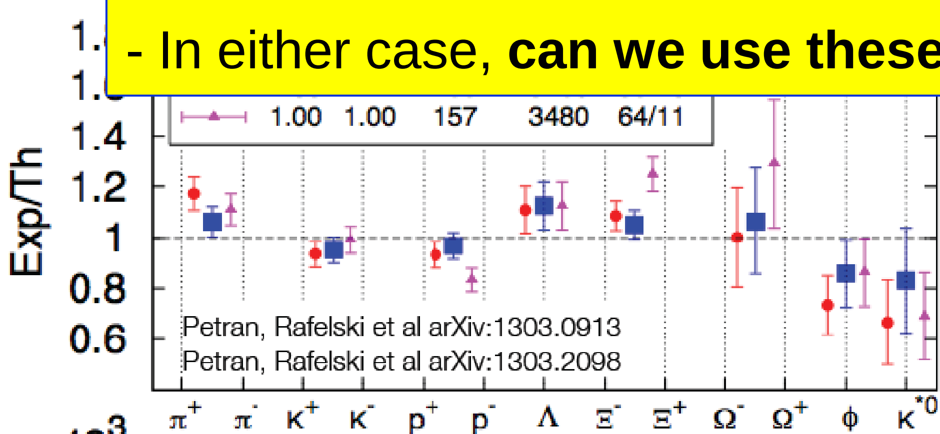
Unanticipated deviations at LHC from the **S**tatistical **M**odel **(pp&AA)**

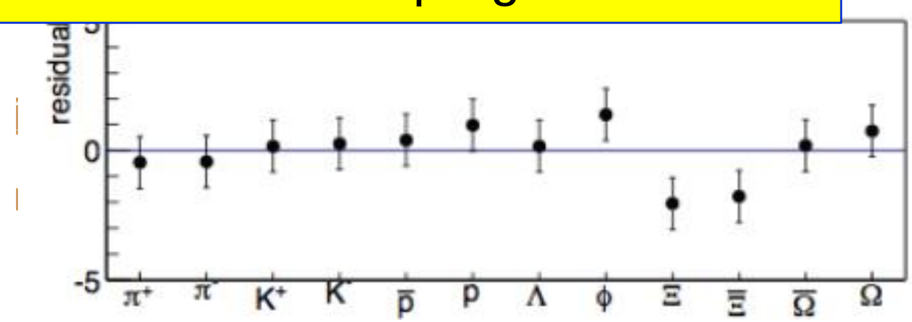
- Evidence **against the SM** ?

- Make the 'mysteriously successful' **SM more reasonable** by showing expected/conceivable deviations ? (NLO-corrections)

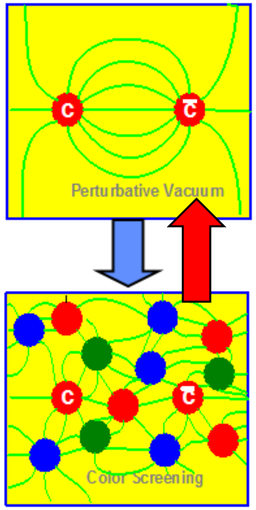
- In either case, **can we use these results** to make progress ?

- 'P
  - ⇨ 2
  - ✪ n
  - ⇨ w



# NLOP II: Quarkonia Suppression

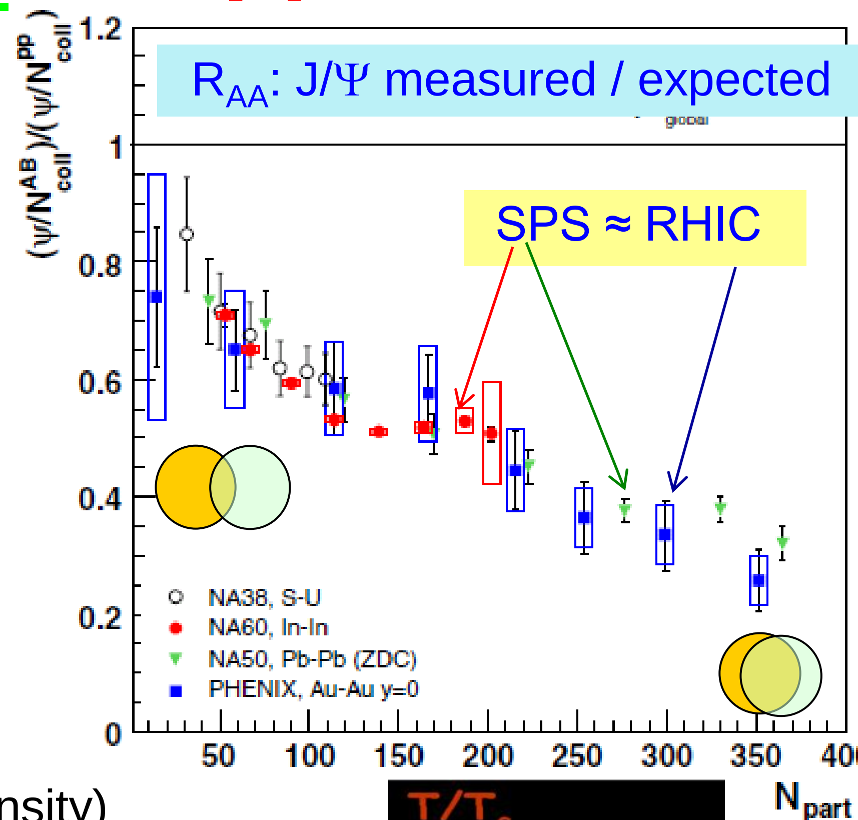



Heavy Flavor c**c** / b**b**

hard collisions (pQCD@$\tau \approx 0$)

'diffuse' (colour conductivity)

'melt' (deconfinement)

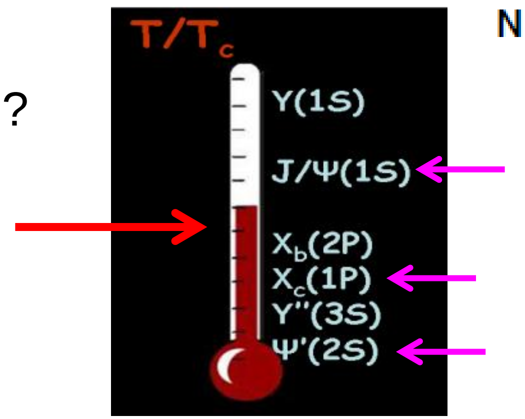



- J/Ψ suppression similar at RHIC and SPS !

⇨ should depend on Energy (Temperature/Density)

✪ 1) **No J/ Ψ melting** at both SPS & RHIC (T > 1.5 – 2 $T_c$ )?

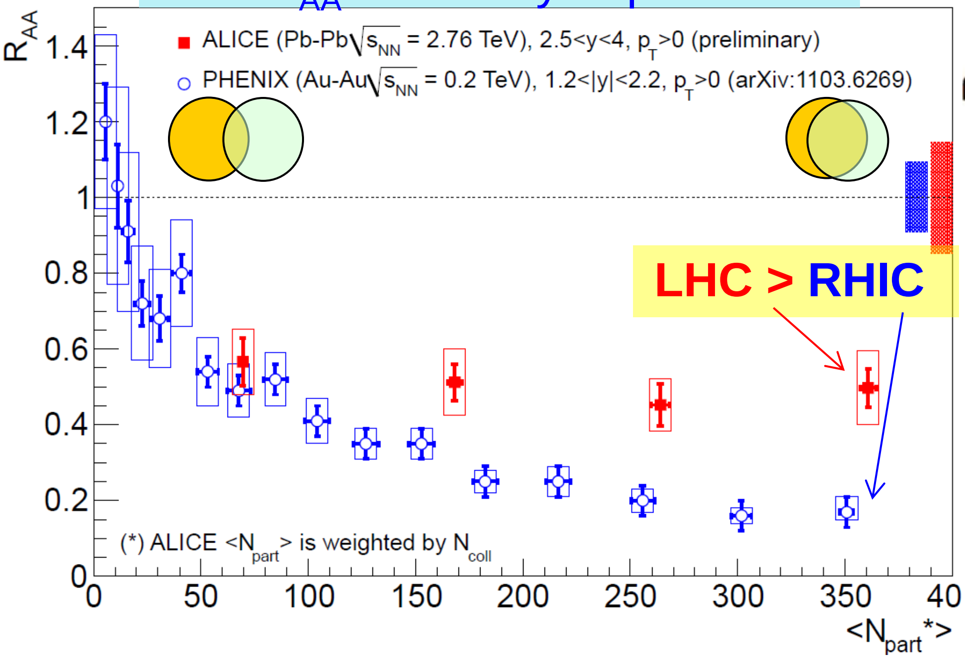
only weakly bound states (Ψ' & χ) melt.



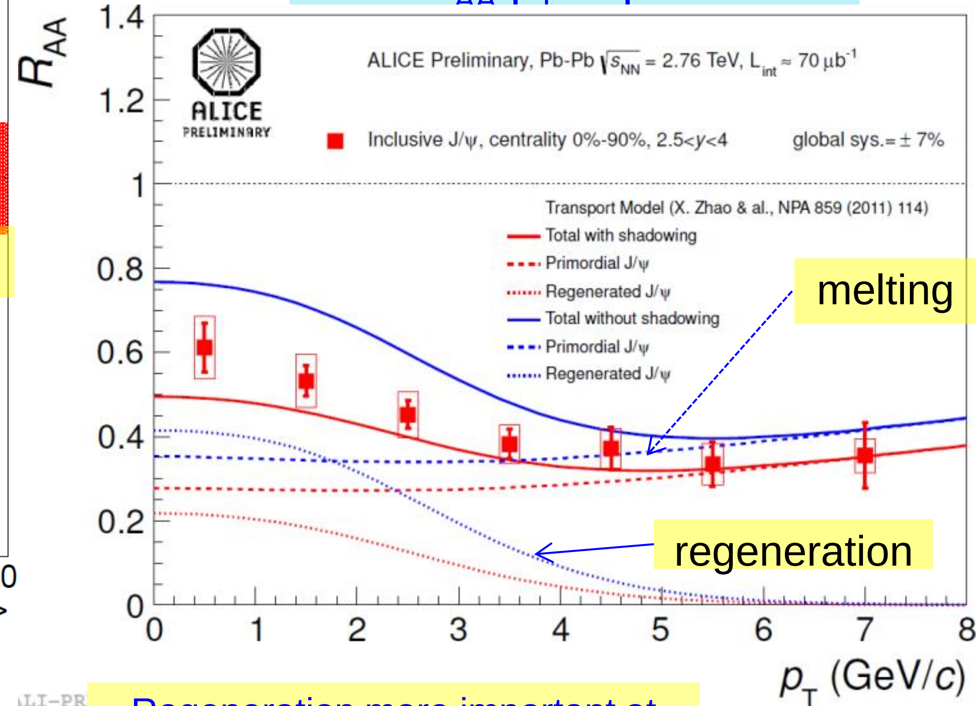

✪ 2) **More J/ Ψ melt** at RHIC than at SPS but 'by chance' cancellation from regeneration (c**c** recombination) ?

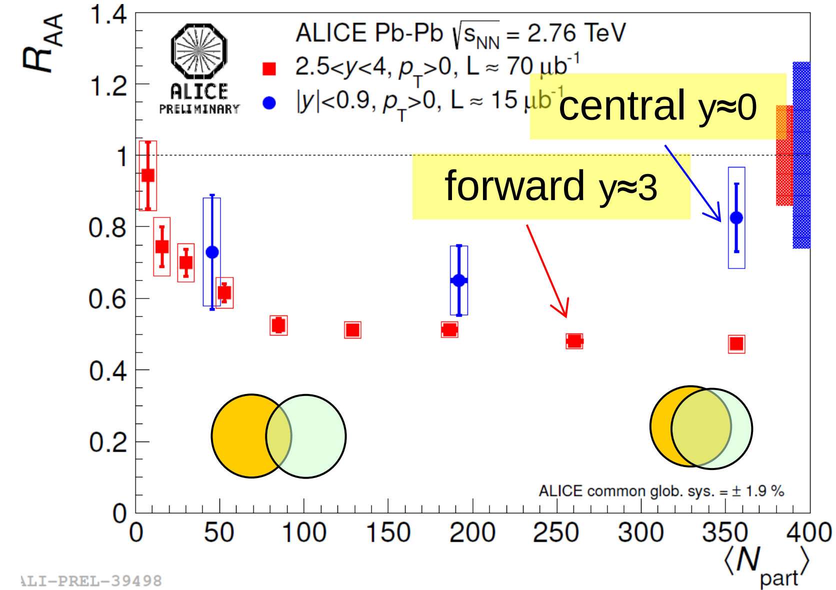
# J/Ψ: Consistent with Melting + Regeneration !

## J/Ψ $R_{AA}$: centrality dependence




## J/Ψ $R_{AA}$:$p_T$ dependence




Regeneration more important at
- **central**: ~ $N_c^2$
- **low $p_T$** : phase space

**Recombination/Coalesence:**

**Purist:** Dirt effect, obscures deconfinement

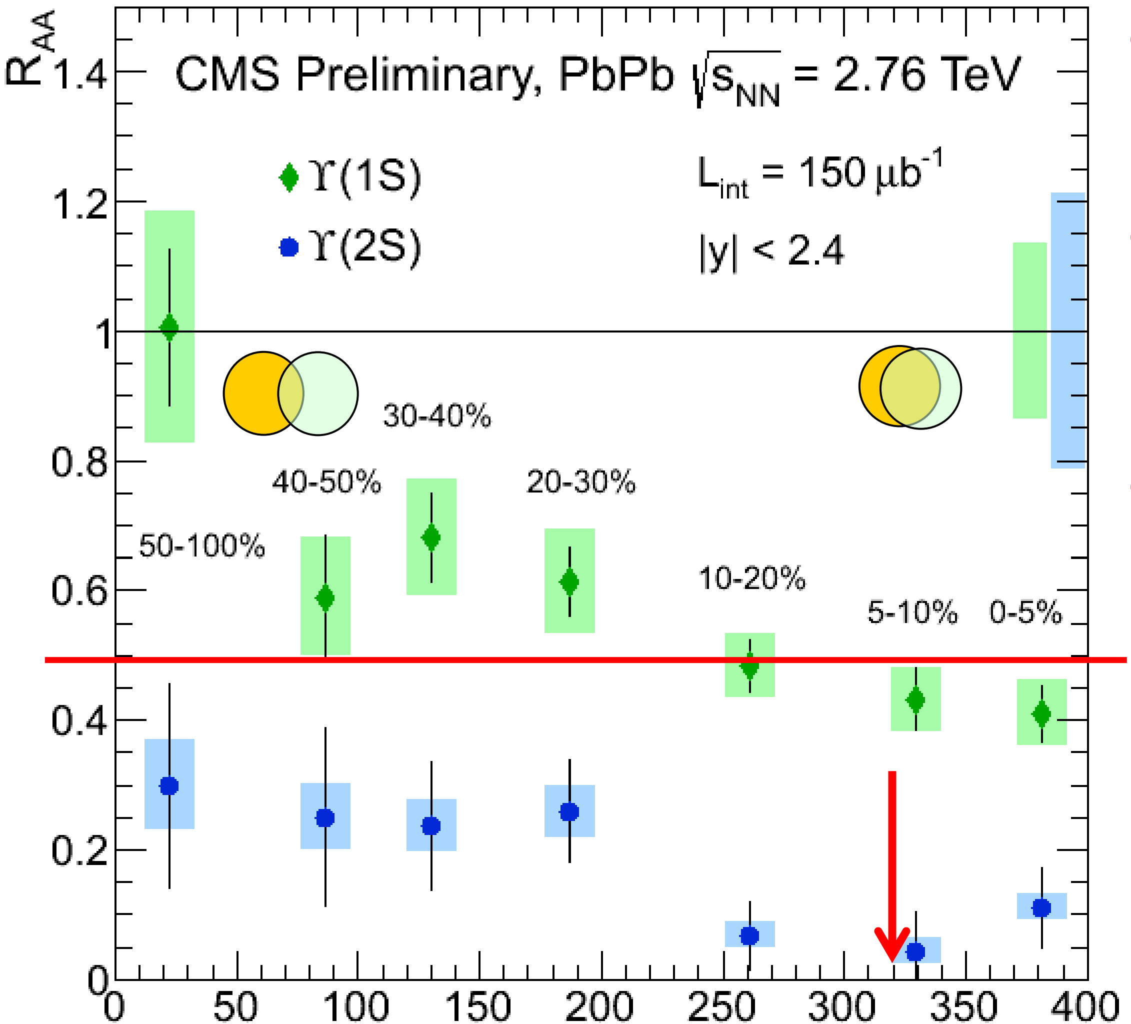
**Pragmatist**: Deconfinement signal !

Deconfinement ⇔ colour conductivity

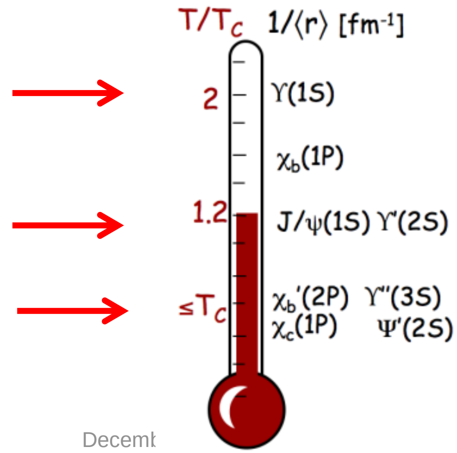
'partons roam freely over large distance'

That's what primordial charm quarks do to recombine

# Y suppression




- Y(1S), ~ 50% direct
  ⇨ direct Y not suppressed ?
- Y(2S) (~ J/Ψ)
  ⇨ up to 5 x stronger suppression than Y(1S)
- Y(3S) ~ gone
  ⇨ Y(3S)/Y(1S) < 0.1 (95%CL)




**<u>Sequential suppression as expected from deconfinement !!</u>** Caveats:

- **Feed-downs** from the many b**b** states to be sorted out
- **Initial State Effects** ( to be estimated from pA)

# NLOP II: Quarkonium ~~Suppression~~


- J/Ψ, the HP par excellence: 'well calibrated (pQCD) smoking gun'

**Matsui & Satz, 1986:**

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

**Question**s **2: Quarkonia Production**

- Regeneration (if confirmed): **Dirt** effect or **Deconfinement** signal ?
- Sequential Y suppression: **Settles** the deconfinement case ?

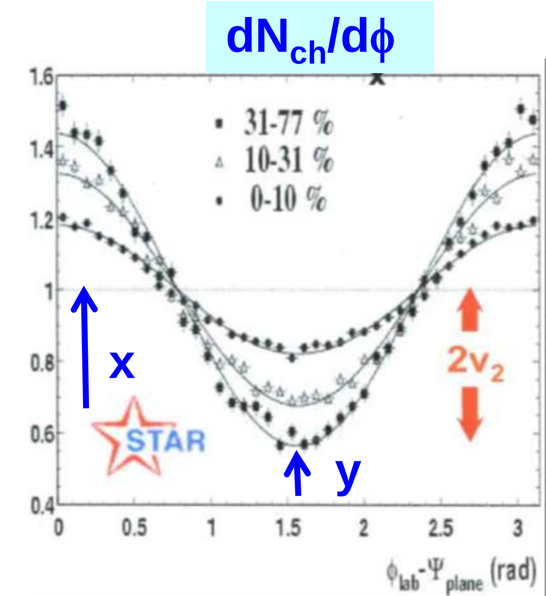
- If neither, **what else** would be needed from experiments ? (besides smaller errors)

# Flow in Heavy Ion Collisions

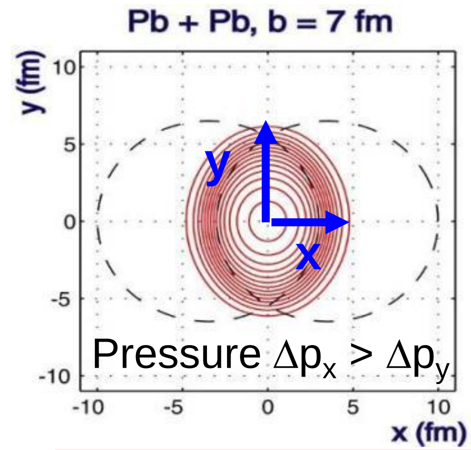
- Elliptic Flow $v_2$
  - ⇨ Initial Conditions
    - e.g. Geometry (eccentricity $\varepsilon_2 = (y^2-x^2)/(y^2+x^2)$)
  - ⇨ Fluid Properties
    - e.g. shear viscosity $\eta$

      usually use Viscosity/Entropy ($\eta/s$ dimensionless)

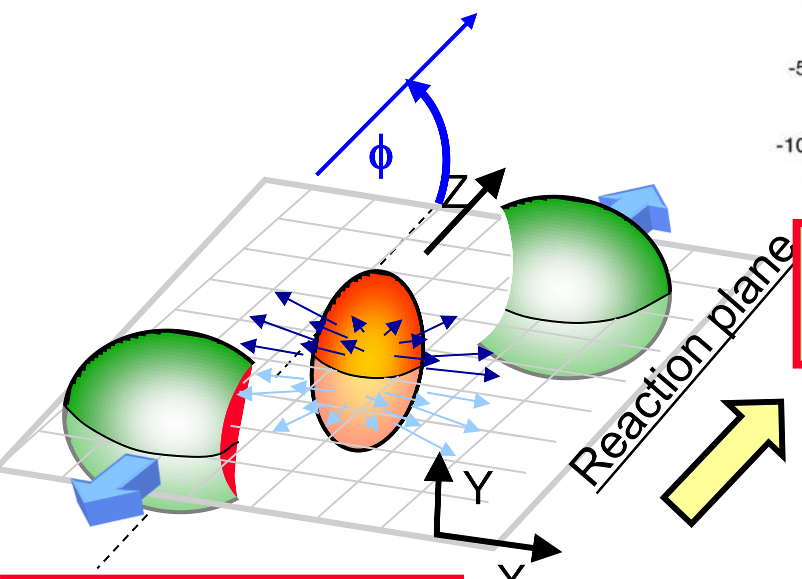
**Fourier analysis: $dN/d\phi = 1 + 2\, v_2 \cos(2\phi) + \ldots$**



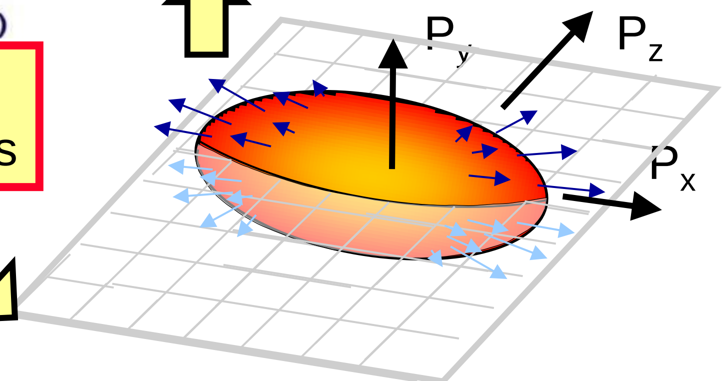

Anisotropic particle density




Azimuthal (φ) pressure gradients




Spatial deformation



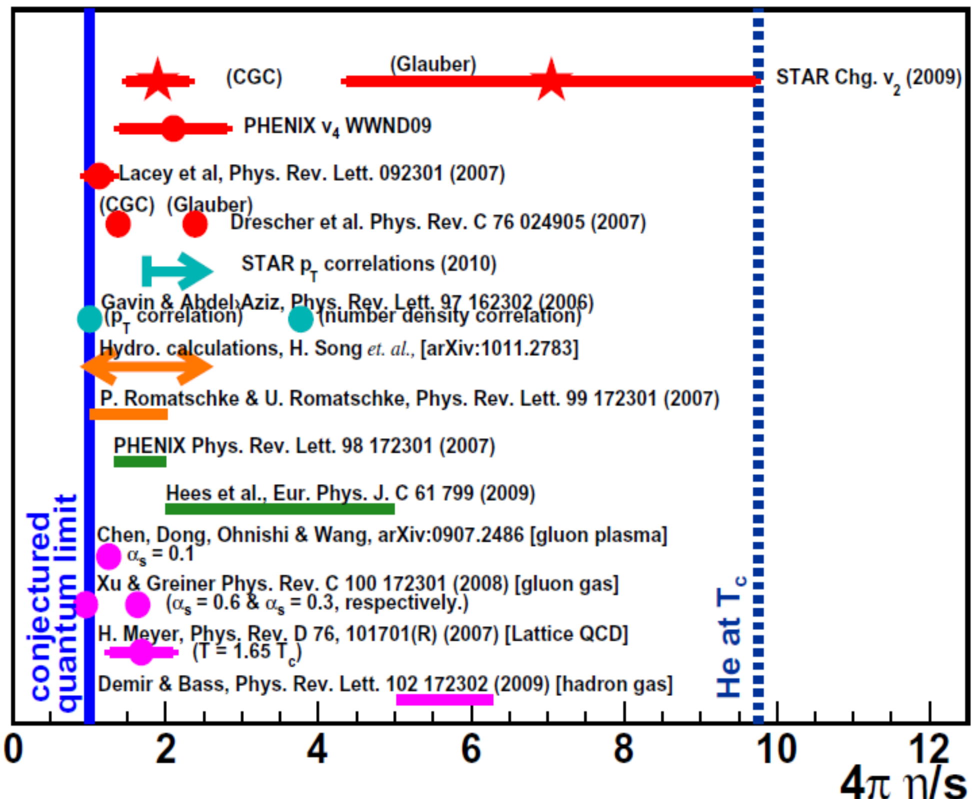

Anisotropic flow

# QGP: The 'perfect Liquid'

- **Perfect liquid → Viscosity** $\eta/s \approx 0$
  - ⇨ large interaction cross section $\sigma$ in the liquid

$$\eta = \frac{\sqrt{2mkT}}{\sigma}$$

- unexpected result
  - ⇨ QGP though to behave like a gas (i.e. weakly interacting)
  - ⇨ closest Theory prediction $\eta/s > 1/4\pi \approx 0.08$
    - ✪ AdS/CFT: ('QCD analogue')
      (Conformal Field Theory in Anti-de Sitter Space)
    - ✪ conjectured Quantum limit:
      $\eta/s = 1/4\pi$
      mfp $\lambda \approx$ Compton wavelength




- Pre-LHC limit: $\eta/s < (3\text{-}6) \times 1/4\pi$
  - ⇨ initial conditions
    (pressure/energy distribution)
    not known precisely enough

Kovtun, Son, Starinets,
PRL 94 (2005) 111601

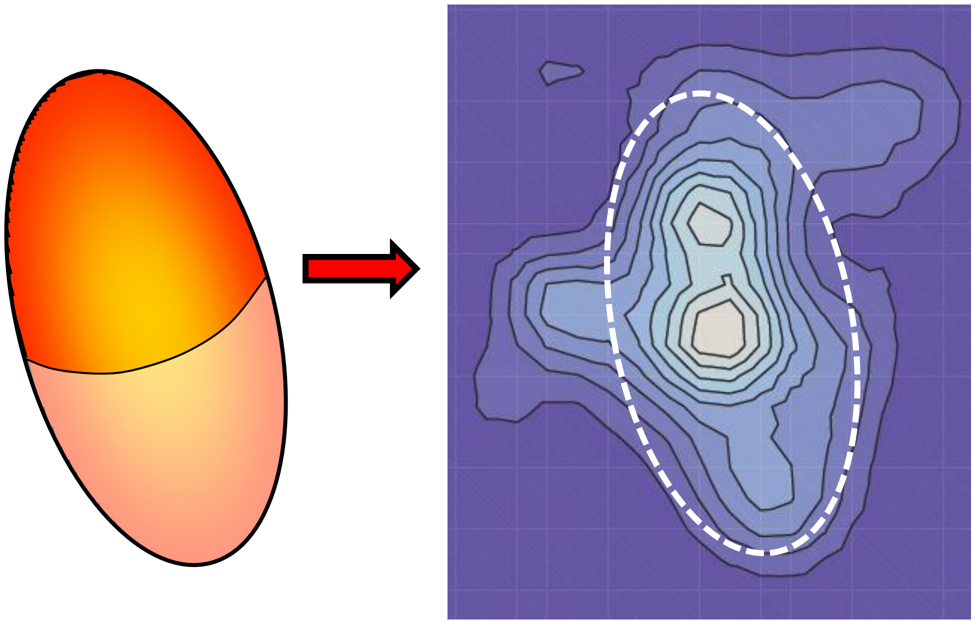
# Initial Conditions

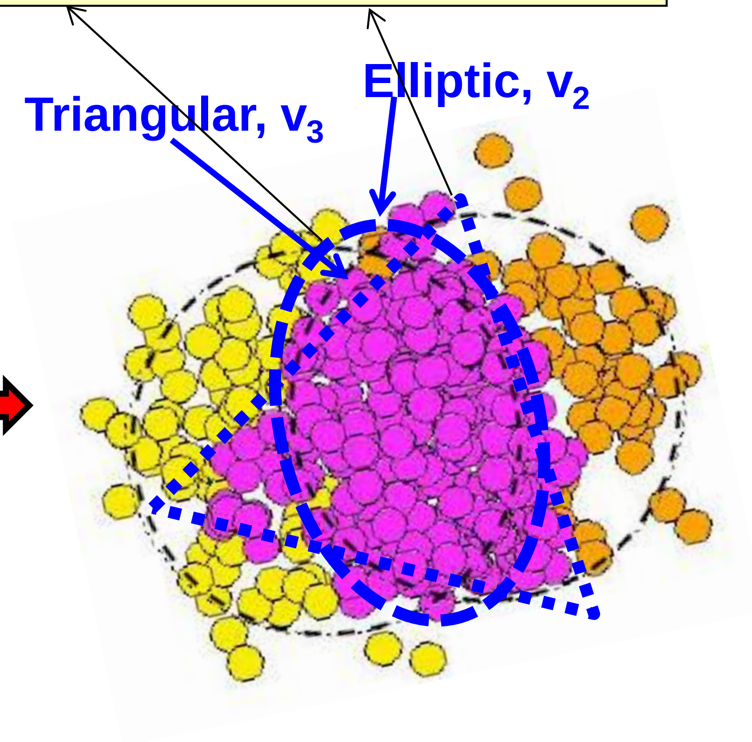
- Around 2010

⇨ 2) Event-by-Event fluctuations → more complicated shapes (higher order )

✪ suggested in 2010 but controversial, higher $v_n$ where not directly 'seen' in the data

**Fourier series: $dN/d\phi = 1 + 2\, v_1 \cos(\phi) + 2\, v_2 \cos(2\phi) + 2\, v_3 \cos(3\phi) + \ldots$**

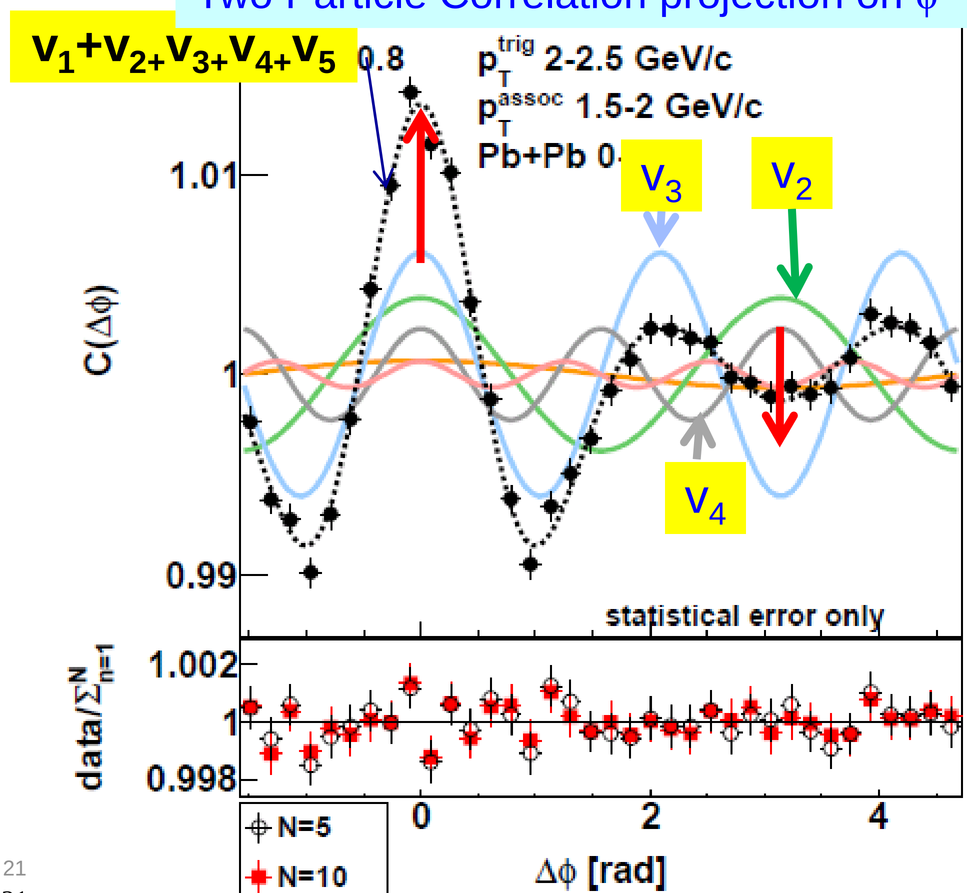




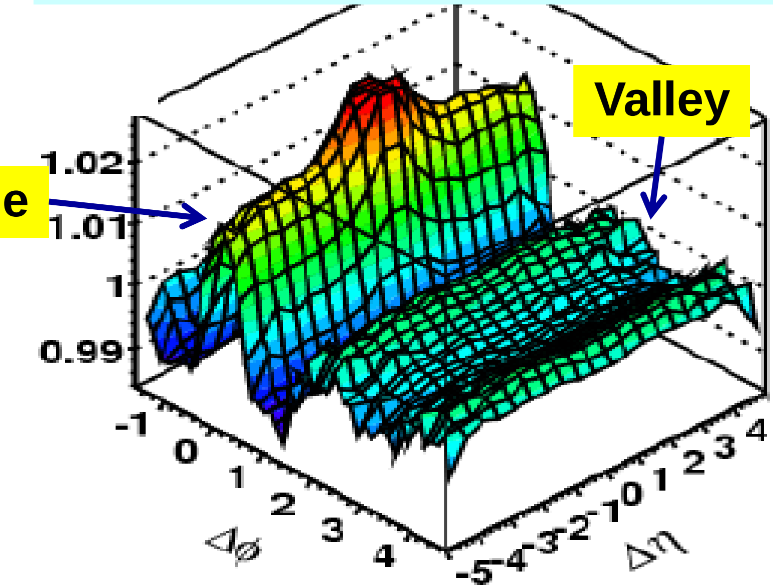
# 2011: First LHC (& new RHIC) data

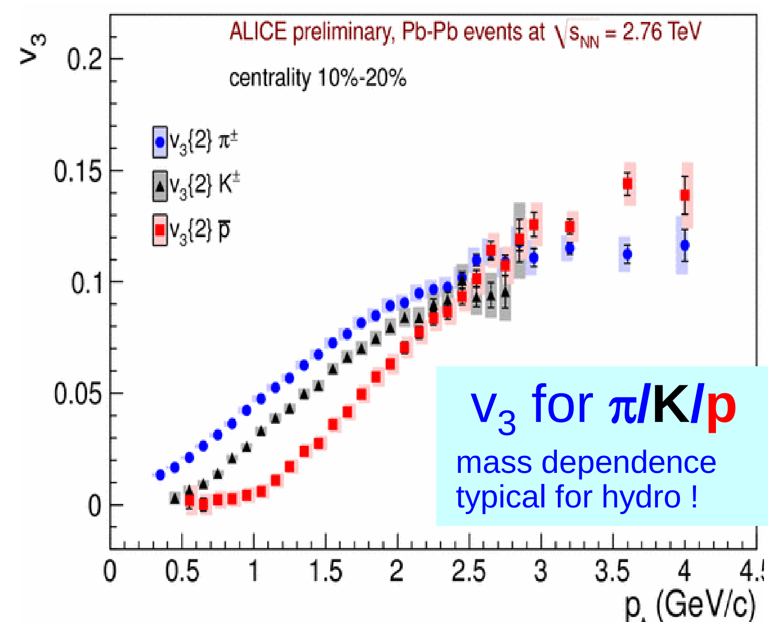
- overwhelming and unambiguous evidence: complex structures from E-b-E hydro flow
  - ⇨ interference of different harmonics
  - ⇨ all characteristics as expected from hydro:
    - ✪ strength, mass/centrality/momentum dependence

Two Particle Correlation projection on $\phi$



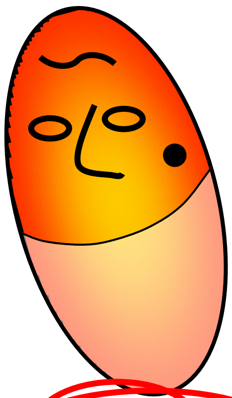

η–ϕ Two Particle Correlation (Atlas)

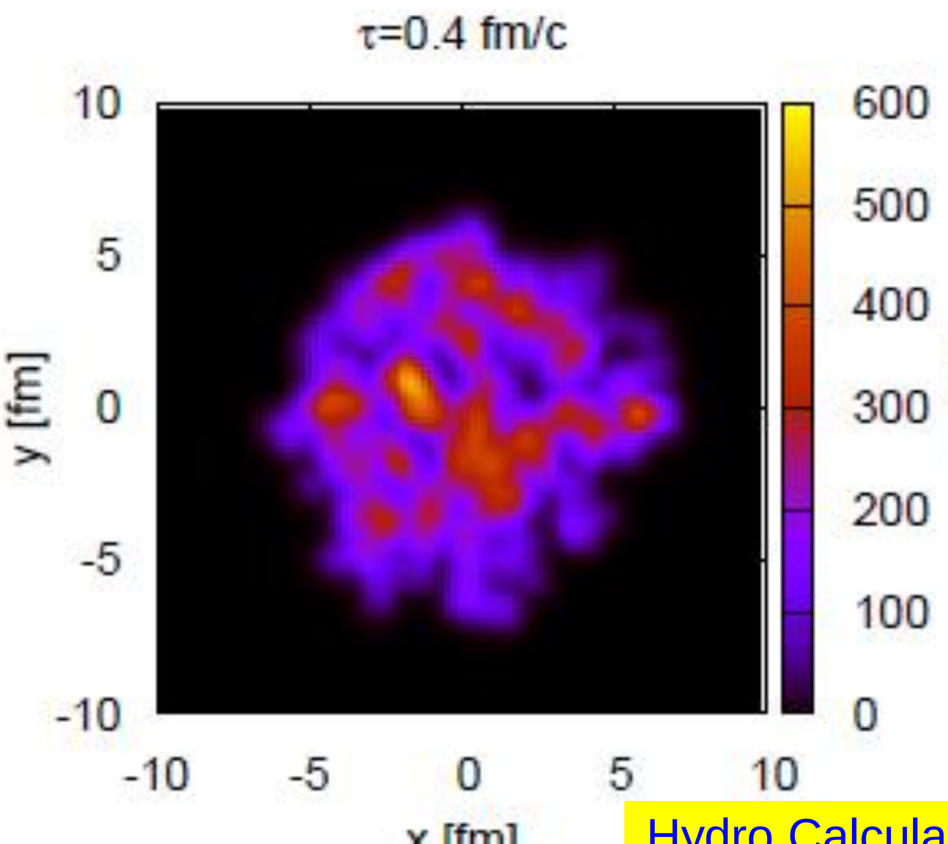


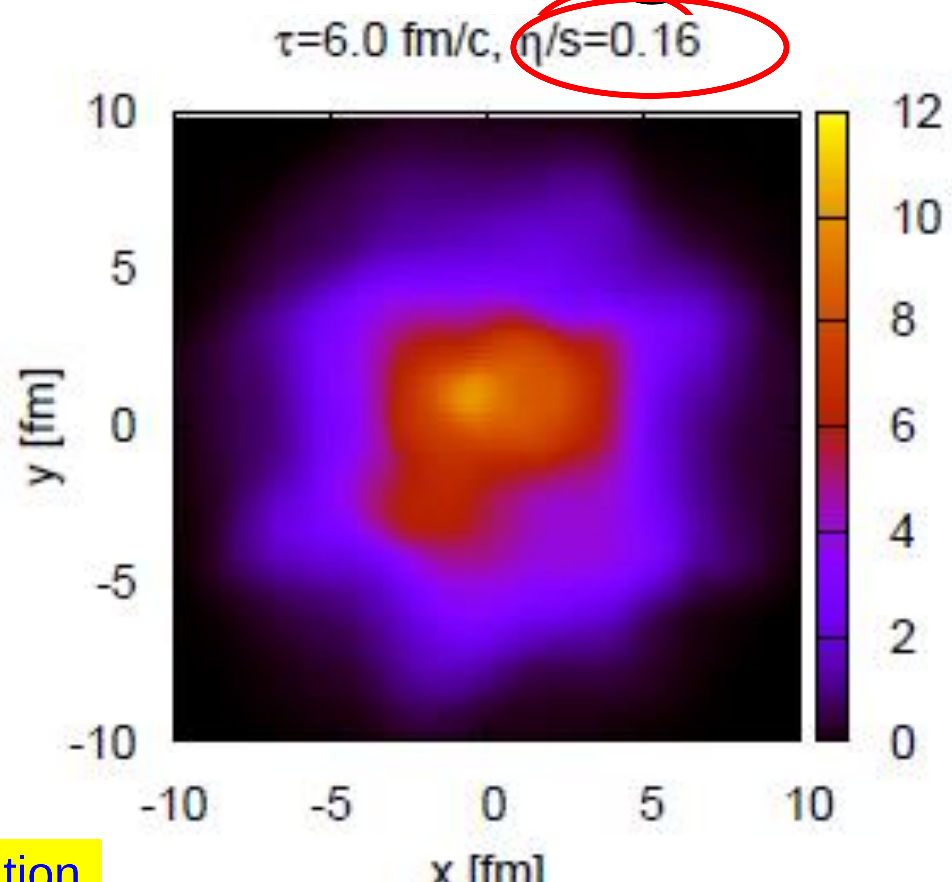



# A most amazing Discovery

- The 'face' of the collision zone, (state-of-art for 20 years) including 'warts & wrinkles' of each event
  - ⇨ progress in precision measurements of η/s
  - ✪ higher harmonics large sensitivity to viscosity
  - ✪ discriminate & constrain models & geometry






Hydro Calculation

# TPM-I: Quantum Jump in Exp. & Theory

- From Leading Order ..
  - ⇨ elliptic flow $v_2$
- .. to N
  - ⇨ high
- .. to
  - ⇨ corre
  - ⇨ via g
  - ⇨ via non-linear interactions in the hydro evolutic (mode mixing)

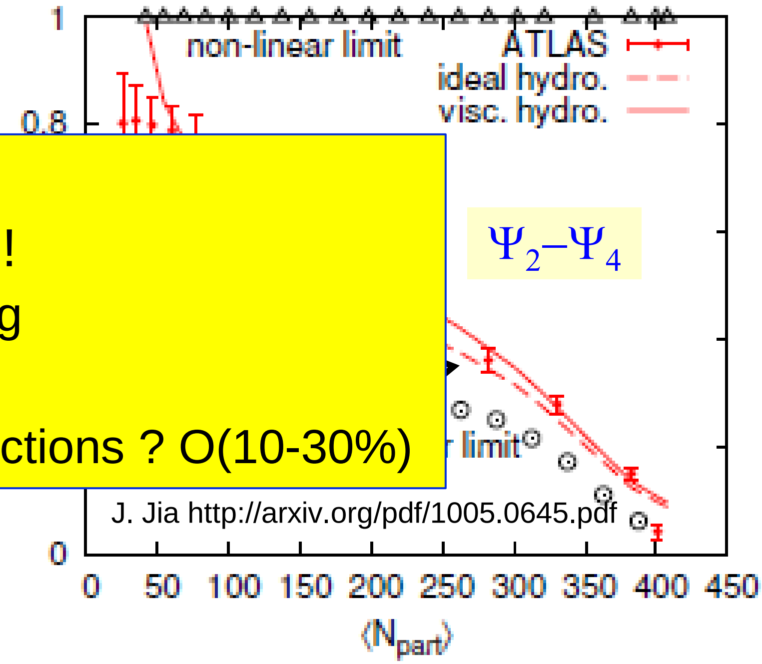
Better <u>limit</u>, but not yet good enough.

Aim for <u>measurement</u> (<30% ?) of $\eta/s$ !

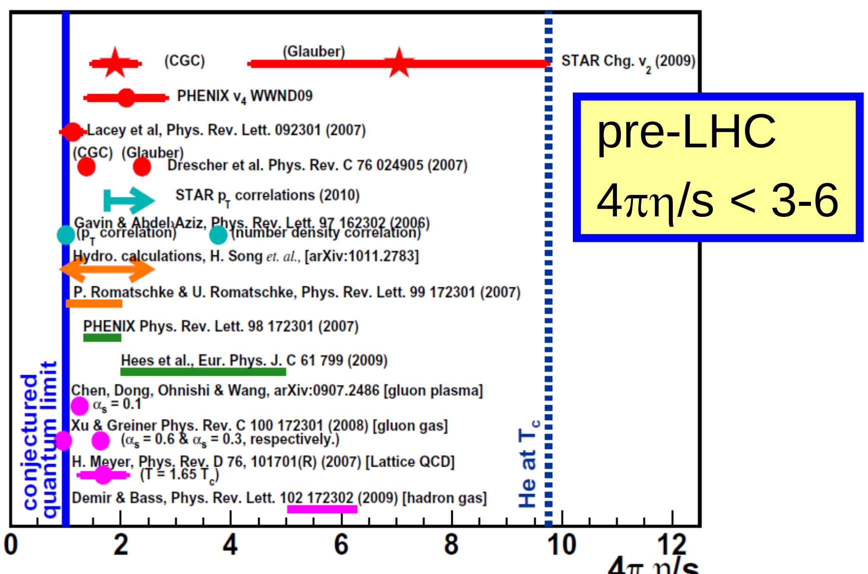
$\eta/S < 1/4\pi$ => conjectured limit is wrong

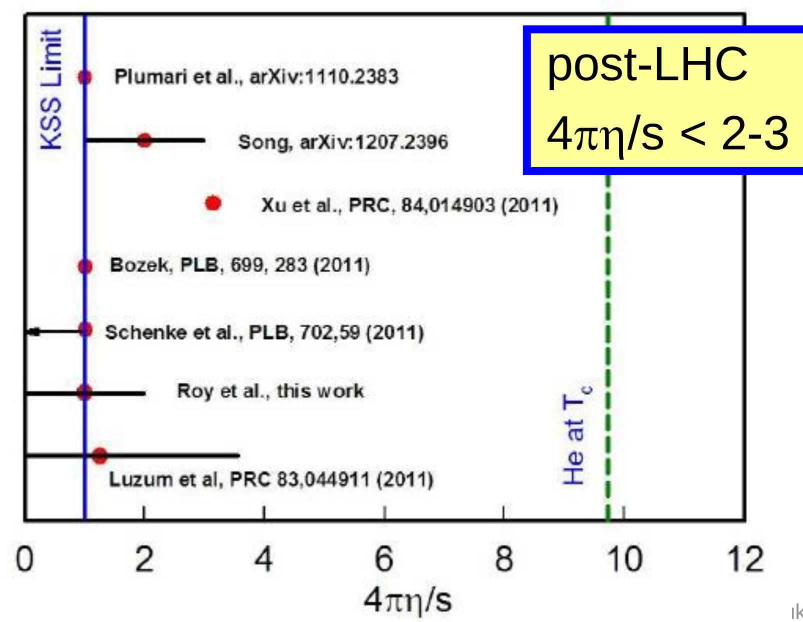
$\eta/S > 1/4\pi$ => measure $\sigma$ in QGP

$\eta/S \approx 1/4\pi$ => AdS/CFT quantum corrections ? O(10-30%)




- leading to better limits on $\eta/s$

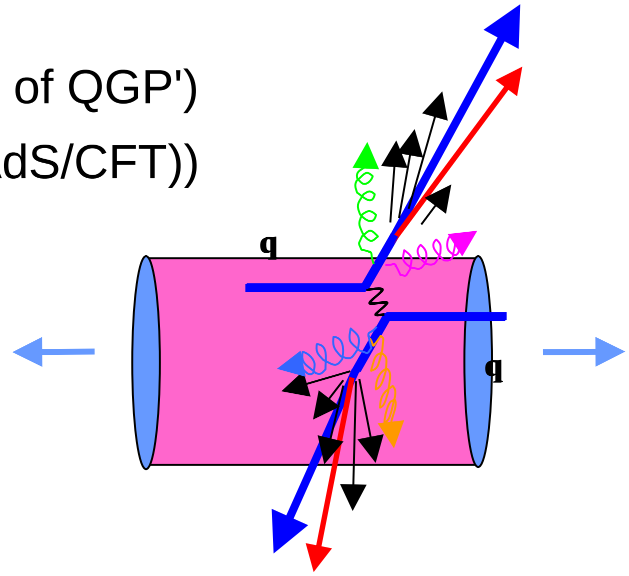



ıkraft

# TPM-II: Jets & 'Jet-quenching'

- partons loose energy **ΔE** when traversing a medium
  - ⇨ **Jet(E) → Jet (E' = E-ΔE) + soft particles(ΔE)**
  - ⇨ QCD energy loss **ΔE** expected to depend on:
    - ✪ $\hat{q}$ : 'opacity ' = property of medium ('radiation length of QGP')
    - ✪ **L**: size of medium (**~ L** (elastic) ~ $\mathbf{L^2}$(radiative), $\mathbf{L^3}$(AdS/CFT))
    - ✪ $\mathbf{c_q}$: parton type (gluon > quark)
    - ✪ **f(*m*)** : quark mass (light q > heavy Q)
    - ✪ **f(*E*)** : jet energy (ΔE = constant or ~ ln(E))



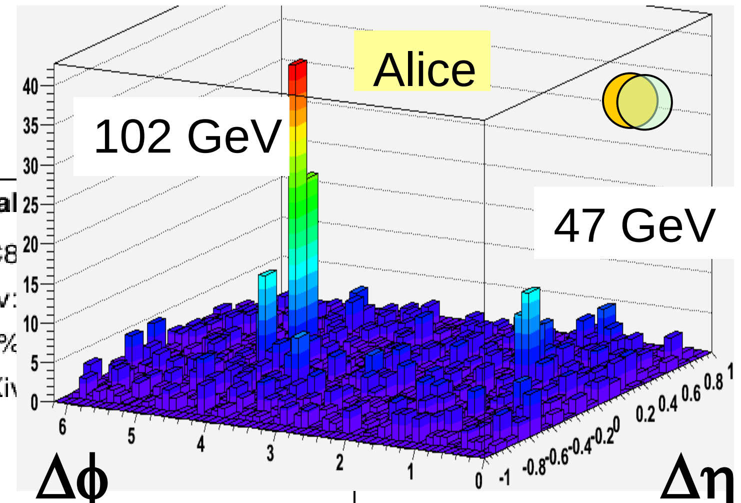

jet quenching measures
'stopping power' of QGP

$\Delta E \sim f(m) \times c_q \times \hat{q} \times L^n \times f(E)$

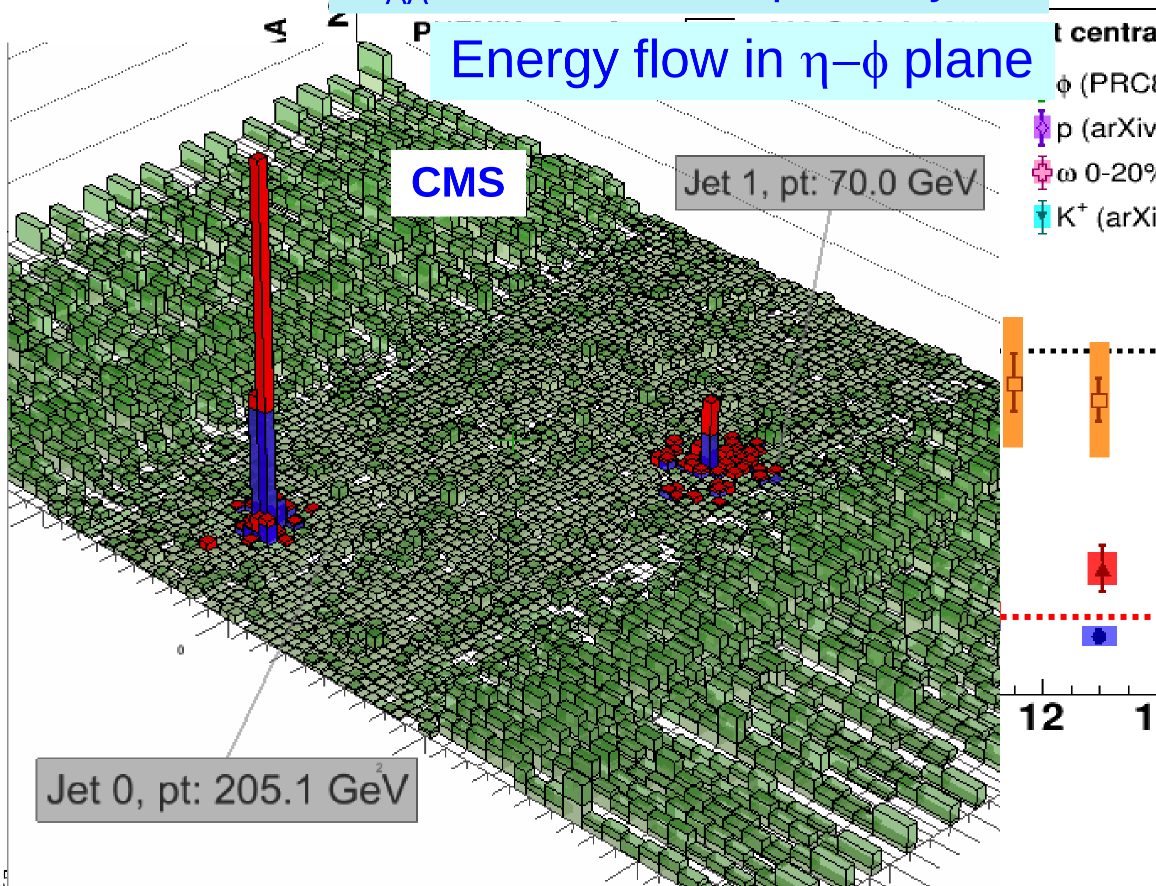
1) How much energy is lost ?
measure jet imbalance E - E'
2) Where (and how) is it lost ?
measure radiated energy ΔE
3) Shows expected scaling ?
vary L, m, E, ...

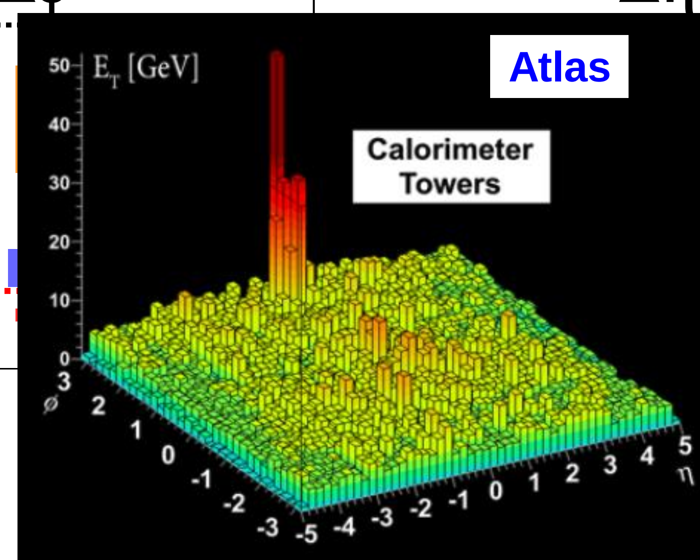
# Observation of Jet Quenching

- Observed at RHIC in 2001
  - ⇨ via suppression of 'leading fragments' (not enough energy to see jets)
    - ✪ qualitative clear effect, quantitative interpretation difficult & model dependent
- Very striking at LHC
  - ⇨ many unbalanced ($E_1 \neq E_2$) jets and 'monojets'




$R_{AA}$: measured / expected yield

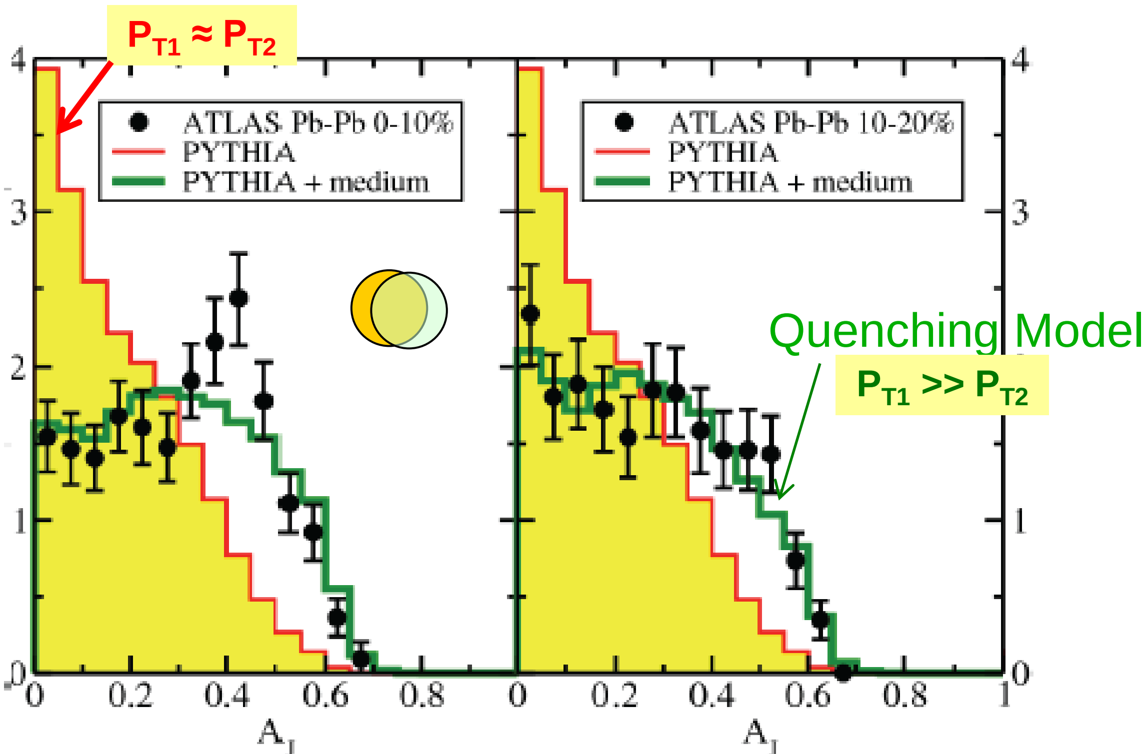


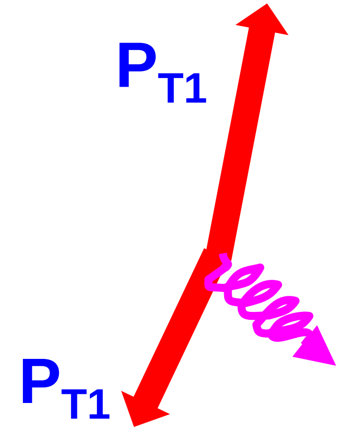



# 1) How much Energy is lost ?

- Di-Jet energy balance $A_j$

$A_j = (P_{T1}-P_{T2})/(P_{T1}+P_{T2})$




GY Qin & BM
PRL 106 (2011)
162302

**<ΔE> ≈ 20 GeV** (wide distribution)

Medium is VERY strongly **interacting** ('opaque')

(but within expectations)

jet quenching

$\Delta E \sim$ .....

## 2) Energy dependence

roughly as expected

(weak dep. on Energy)

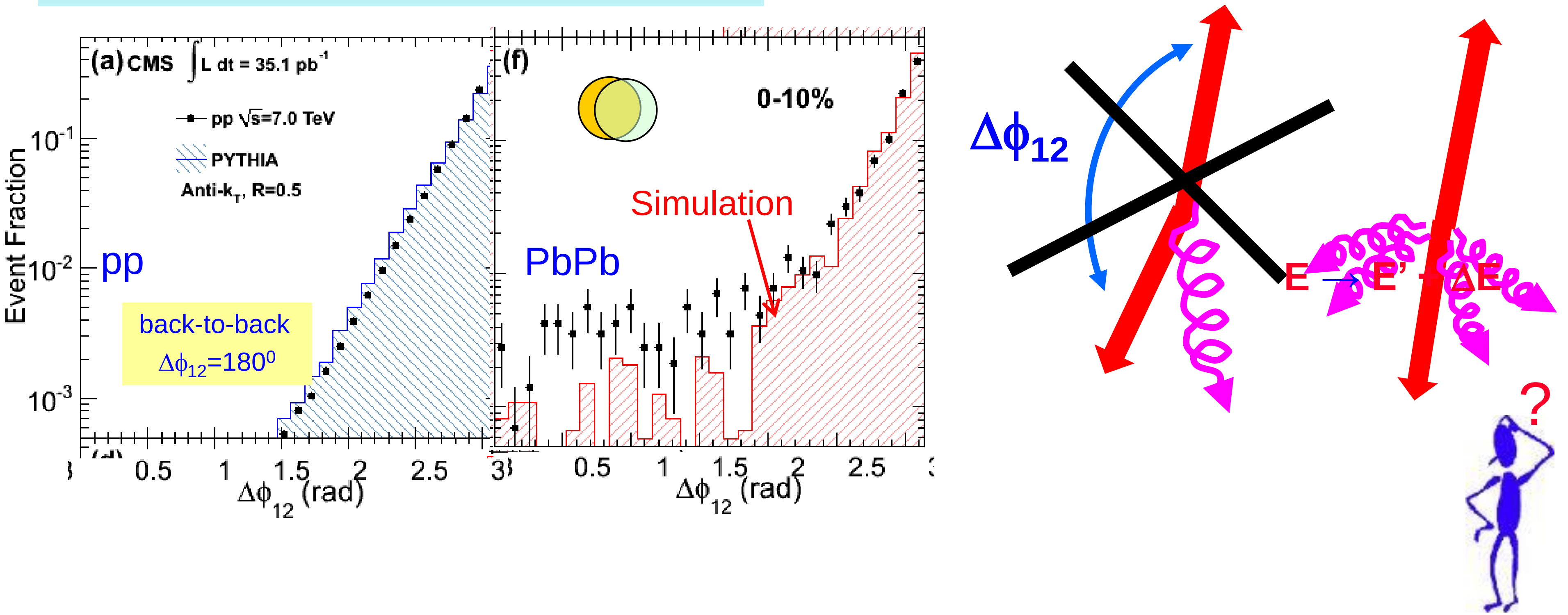
(CMS PLB 712 (2012) 176)

jet quenching

$\Delta E \sim f(m) \times c_q \times \hat{q} \times L^n \times f(E)$

# 2) Where (& how) is it lost ?

Di-jet angular correlation $\Delta\phi_{12}$




**<u>Unexpected Result :</u>**

**- jets remain back-to-back like in pp**
(little additional broadening from radiated Energy)

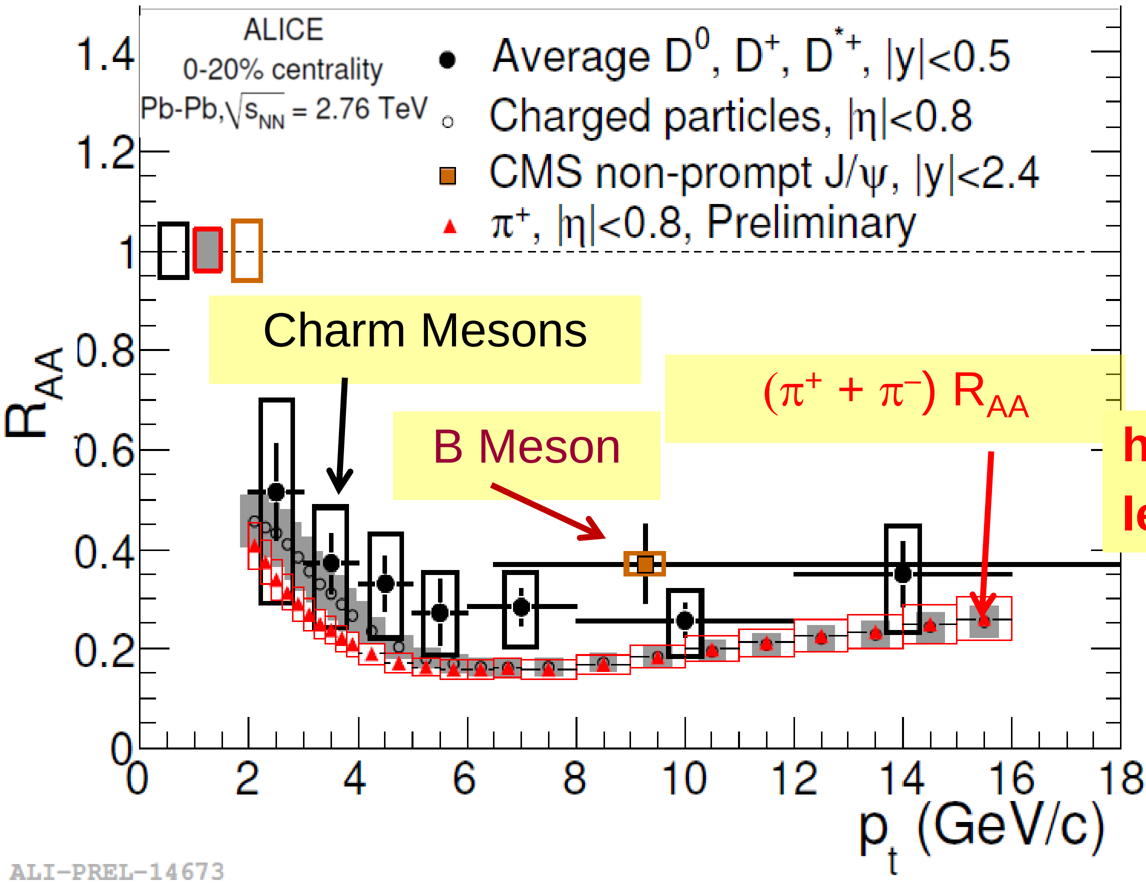
**- radiated energy appears in <u>low energy hadrons, far away from the jet</u>** (CMS PRC 84 (2011) 024906)

# 4) Mass & Color Charge Dependence

- Measure Heavy Quarks (c,b) versus $\pi$ (gluon fragmentation dominates $\pi$ at LHC)

$R_{AA}$ = measured/expected ~ AA/pp

jet quenching
$\Delta E \sim f(m) \times c_q \times \hat{q} \times L^n \times f(E)$




**Expectation:**

**$\Delta E(\pi) > \Delta E(D) > \Delta E(B)$**

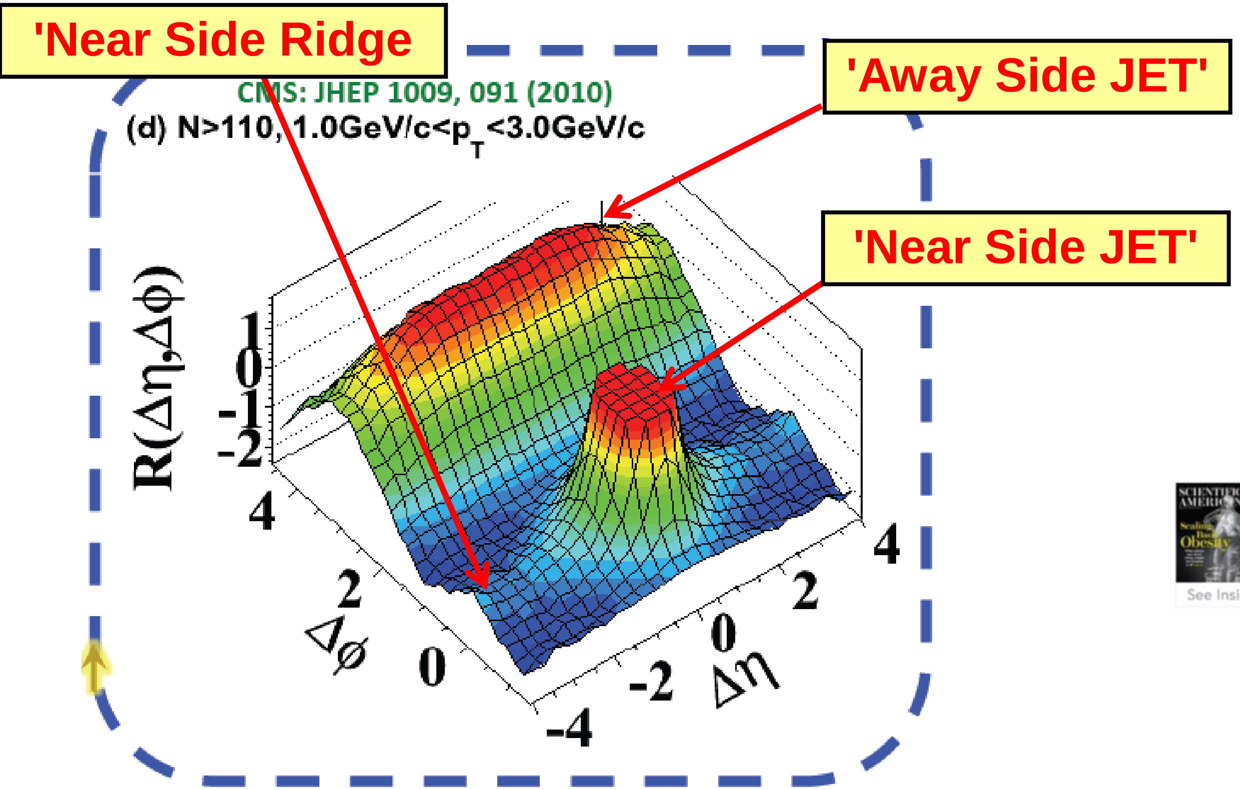
- gluon ↔ quark
- light ↔ heavy

**hints** for the expected hierarchy
**less strong** than naively expected

**Needs better statistics & quantitative comparison with models**

# Discovery

- The first LHC Discovery (pp, Sept 2010)
  - ⇨ long range rapidity 'ridge' in 2-particle correlations
    - ✪ visible in the highest multiplicity pp collisions
    - ✪ arguably still the most unexpected LHC discovery

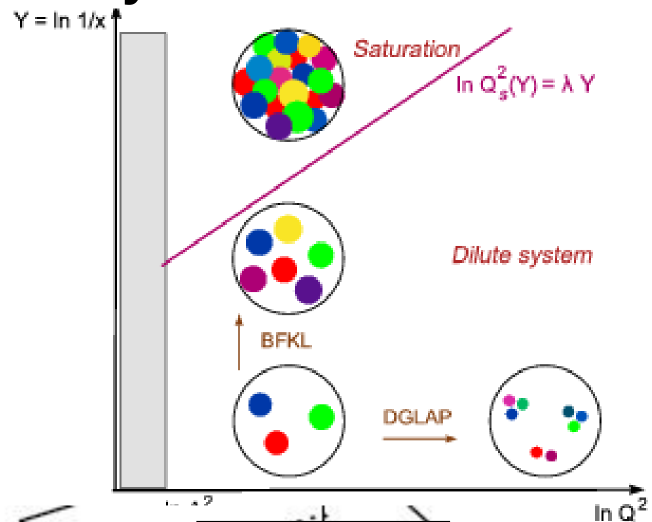




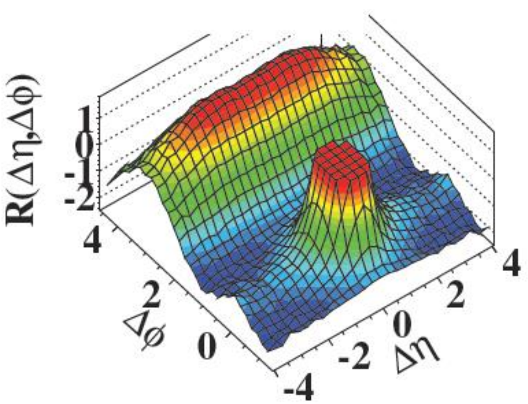
# Origin of the pp 'Ridge'

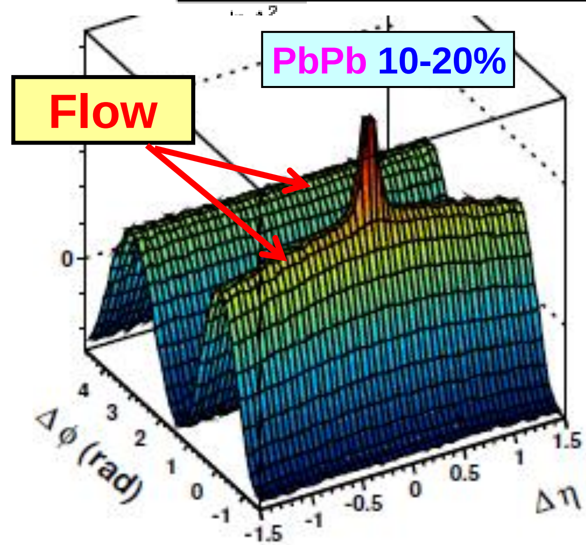
- Spawned a large number of different explanations
  - ⇨ mostly rather ad hoc, very speculative, or outright weird

- Color Glass Condensate CGC: **'first principles' theory**
  - ⇨ classsical FT in high density limit (small x, small $Q^2$)
  - ⇨ 'new state of cold & dense parton matter'
  - ⇨ some success describing aspects of ep, pp, eA:
    geometric scaling, low-x, particle production, ..
    - ✪ however, no 'smoking gun' so far…




- Collective flow (Hydro) ?
  - ⇨ vaguely similar correlations in nucleus-nucleus



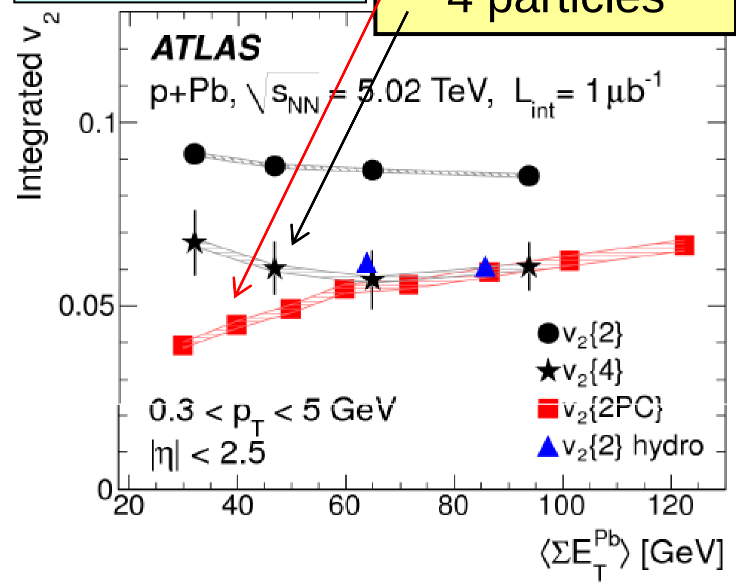
# Ridges everywhere..

- Ridge is much stronger in pPb (end 2012)!
  - ⇨ and is, in fact, a 'double ridge'
  - ⇨ even and odd components ($v_2$, $v_3$)
  - ⇨ collective multiparticle (i.e., not 'jet' like)
  - ⇨ now also seen in dAu at RHIC ! (tbc)
  - ⇨ strength ≈ as **predicted** by some hydro models

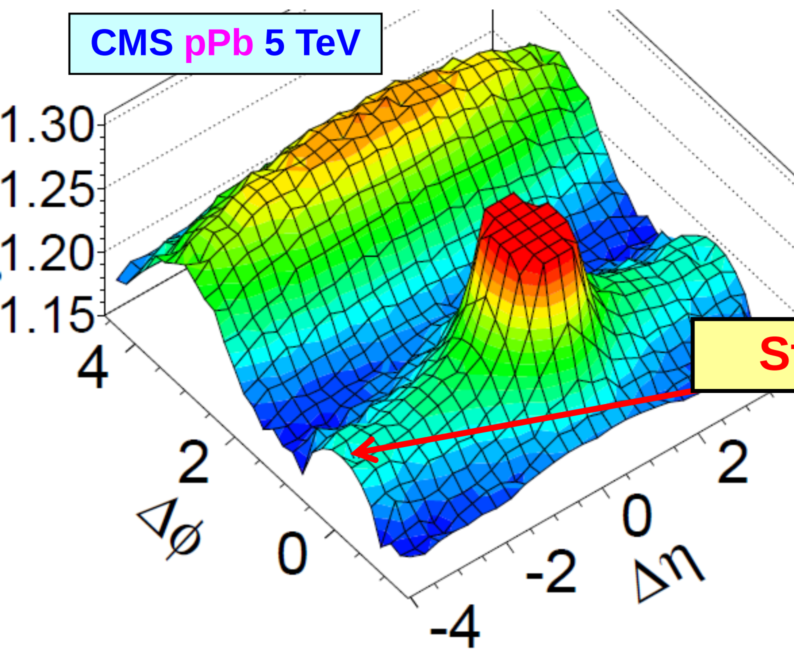
ATLAS pPb 5 TeV

2 particles

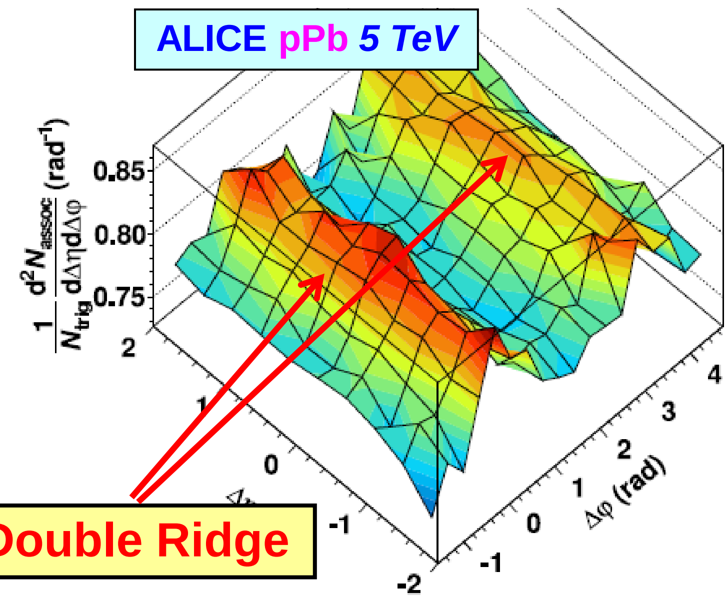
4 particles




CMS pPb 5 TeV




ALICE pPb 5 TeV



# Panta Rhei ?

- CGC in trouble ?
  - ⇨ mini-jet like correlation (4 part. << 2 part. ?), no odd harmonics ($v_3$), …
- Collective 'Hydro-like' flow in pA (& pp) ??
  - ⇨ energy/particle density quiet comparable to AA (eg high $N_{ch}$ pp@LHC ≈ Cu-Cu mid-central @RHIC)
  - ⇨ system size only few fm$^3$ ?? (presumably << 10 compared to >> 1000)
    - however, hydro has no intrinsic size, only ratio's: $\lambda$/r, and $\lambda \approx 0$ ! (from $\eta$/s)
    - a proton@LHC is more like a small nucleus (dozens of partons, MPI,..) !
  - ⇨ additional measurements should tell
    - mass dependence of ridge ($\pi$, K, p)
    - other collective signals (eg radial flow vi
- In either case, more than a curiosity
  - ⇨ **CGC**
    - discovered a 'new state of matter'
    - smoking gun for new 'first principle' limit of QCD
  - ⇨ **Hydro** stunning: a system the size of a single hadron behaves like 'macroscopic matter'
    - 'extra dimension' for QGP study: size !
    - finite size effects => correlation & coherence length, time scales, ….

**New State of Matter created at CERN** which features many of the characteristics of the theoretically predicted Colour Glass Condensate.

**RHIC Scientists found "Colorful Glass"** to serve the Perfect Liquid

**Rewrite the textbooks**

at least change the title from '**Heavy Ion** physics' to ..

**Questions 3:** (assuming hydro explanation for ridge)

Similar hadronisation (particle ratios), now signs of collectivity in pp ?

**pp, pA, AA: What, if anything, is qualitatively different ?**

- Does this make AA more pp-like ? (**no** 'new state of matter)
- Or pp more AA like ? (QGP 'matter' **everywhere** in dense systems > few $fm^3$)

How small can it get ?

- Is there **another smoking gun for CGC** in pA at LHC ? (should be, $x < 10^{-3}$-$10^{-5}$)
- If not, is there still a **science case for an electron-ion collider** ?

# The Questions:

**Questions 1: Hadronisation**

Unanticipated deviations at LHC from the Statistical Model **(pp&AA)**

- Evidence against the SM ?

- Make the 'mysteriously successful' SM more reasonable by showing expected/conceivable deviations ? (NLO-corrections)

- In either case, can we use this to make progress ?

**Questions 2: Quarkonia Production**

- Regeneration (if confirmed): Dirt effect or Deconfinement signal ?

- Sequential Y suppression: Settles the deconfinement case ?

- If neither, what else would be needed from experiments ? (besides smaller errors)

**Questions 3:** (assuming hydro explanation for ridge)

Similar hadronisation (particle ratios), now signs of collectivity in pA (& pp) ?

**pp, pA, AA: What, if anything, is qualitatively different ?**

- Does this make AA more pp-like (no 'new state of matter) ?

- Or pp more AA like (QGP 'matter' in all dense hadronic systems > few $fm^3$) ?

- Is there another smoking gun for CGC in pA at LHC (there should be, $x < 10^{-3}$-$10^{-5}$)?

- If not, is there still a science case for an electron-ion collider ?

# What's next for HI ?

- short/medium term at LHC ( ≈ 5 y)
  - ⇨ complete (& solve ?) the **quarkonia puzzle**(deconfinement)
    - ✪ quantify 'other effects' (pA), measure $\Psi$', better Y
    - ✪ theory: needs progress in calculating melting temperatures !
  - ⇨ **Hydro**: increased precision/sophistication (e.g. 30% in $\eta$/s ??)
  - ⇨ solve the **'ridge' mystery** (CGC vs Hydro vs ??)
    - ✪ any other sign of CGC in pA@LHC ? (e.g. monojets at large y => LHCb)
    - ✪ **pA at LHC could make (or break ?) the science case for eRHIC/EIC**

- medium/longer term LHC (≈ 10 y, including exp/LHC upgrades)
  - ⇨ comprehensive & precise **energy loss** ("jet-quenching') (needs HF,$\gamma$-jet)
  - ⇨ **chiral symmetry restoration** ? e.g. much better low mass lepton pairs(NA60)

- Outside LHC (not part of this presentation)
  - ⇨ 'Phase Transition Line' & 'Tri-critical Point' where starts the 'normal' (hadronic) matter ?
  - ⇨ matter at high baryon density (compression)
    - ✪ FAIR@GSI, NICA@DUBNA
    - ✪ RHIC energy scan, SPS fixed target

# The Questions:

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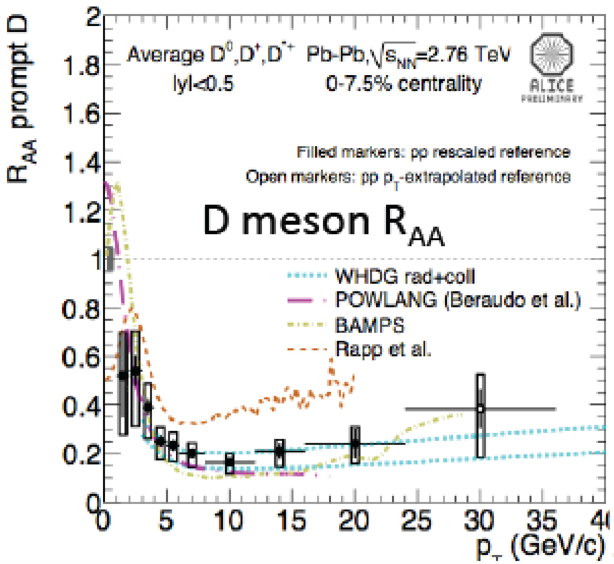
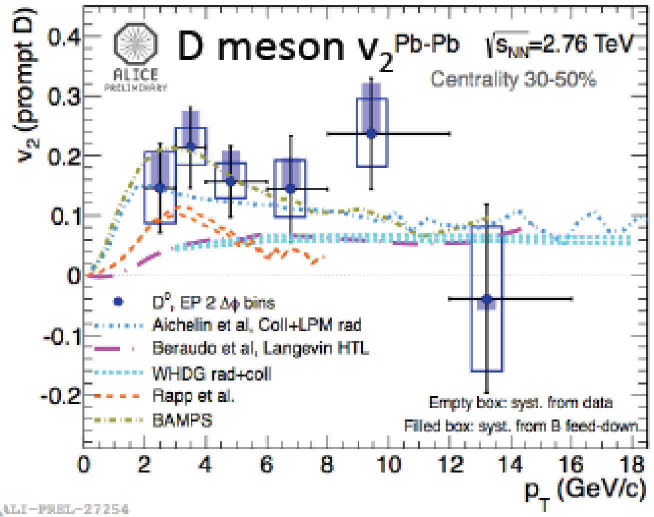
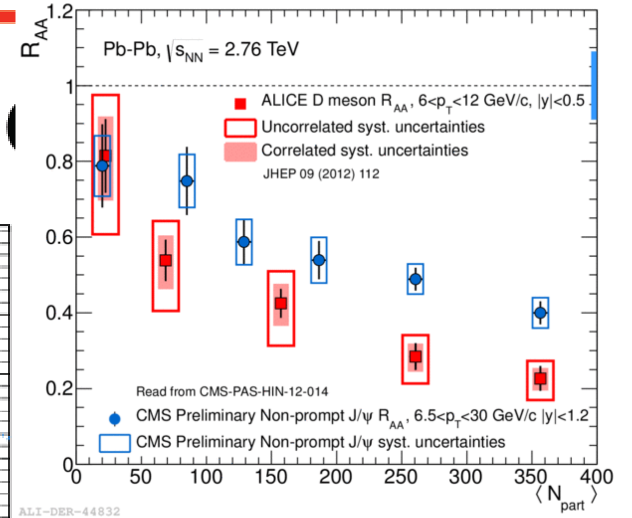
- If not, is there still a science case for an electron-ion collider ?

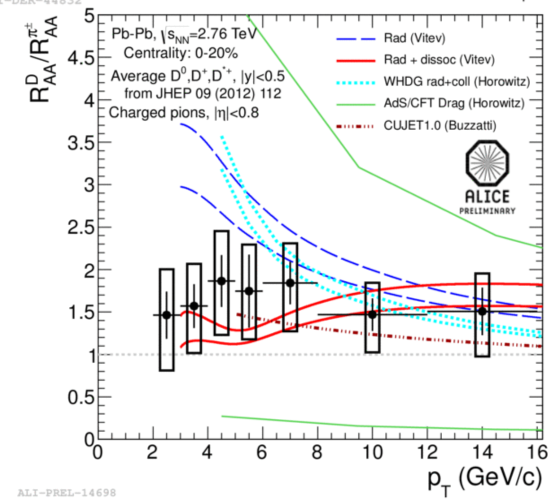
# Spares

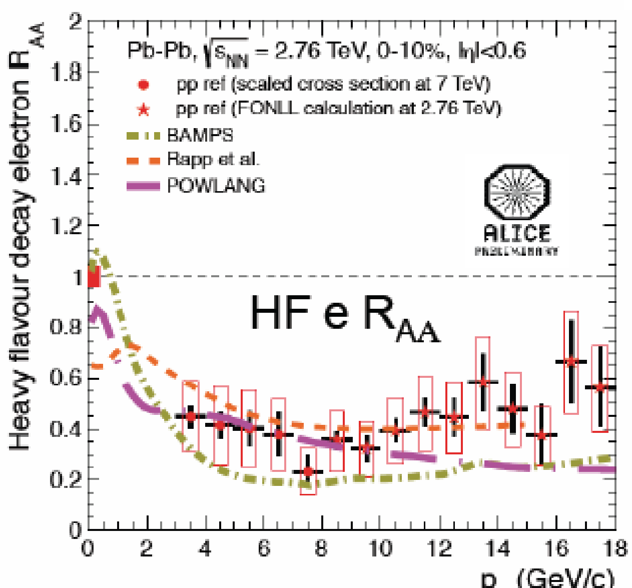
# A challenge for mode

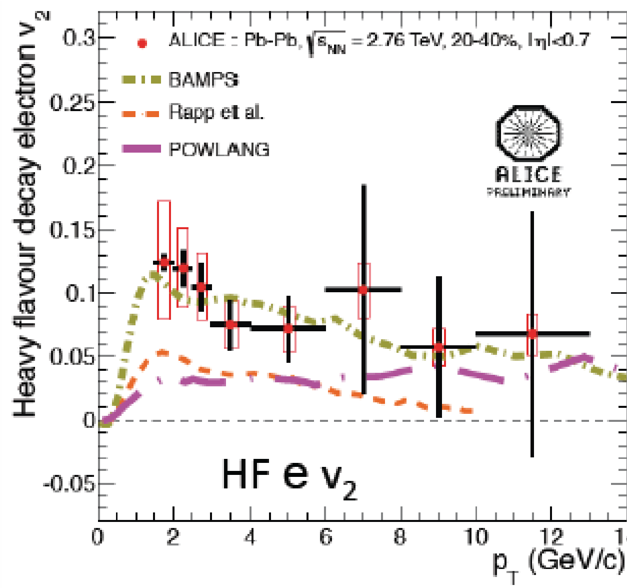


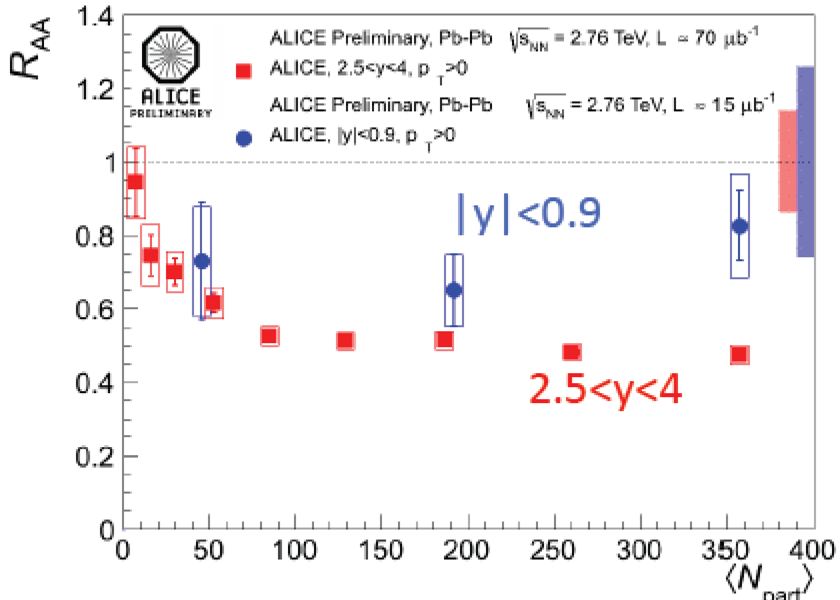



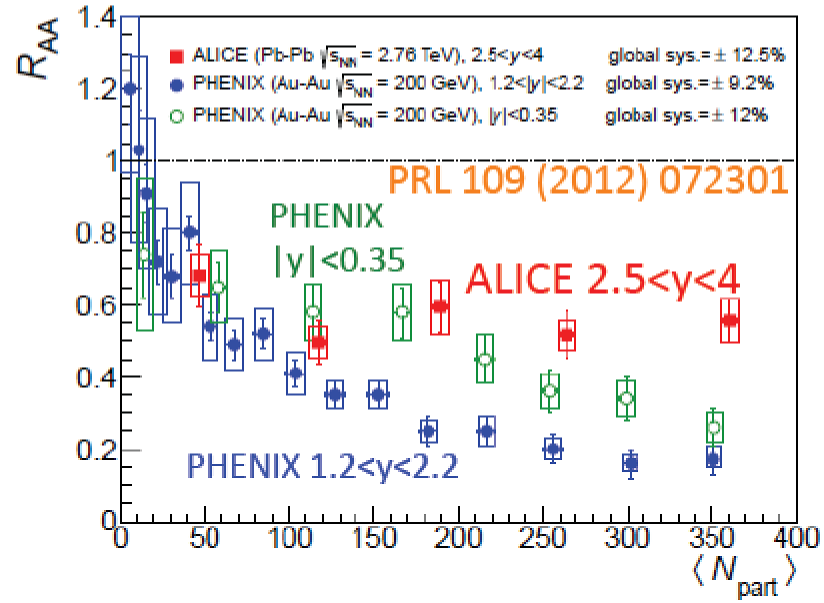




Armesto et al. PRD71 (2005) 054027
Horowitz et al., JPhys G38 (2011) 124114
Alberico et al., Eur.Phys.J C71 (2011) 1666
van Hees et al., PRC73 (2006) 034913
Fochler et al., J.Phys. G38 (2011) 124152
Sharma et al.,PRC80 (2009) 054902
He et al., PLB713 (2012) 224

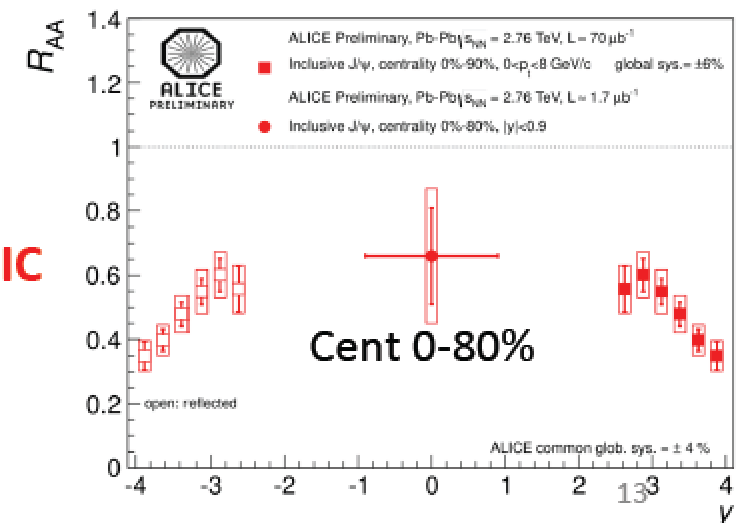
# J/ψ suppression & regeneration?

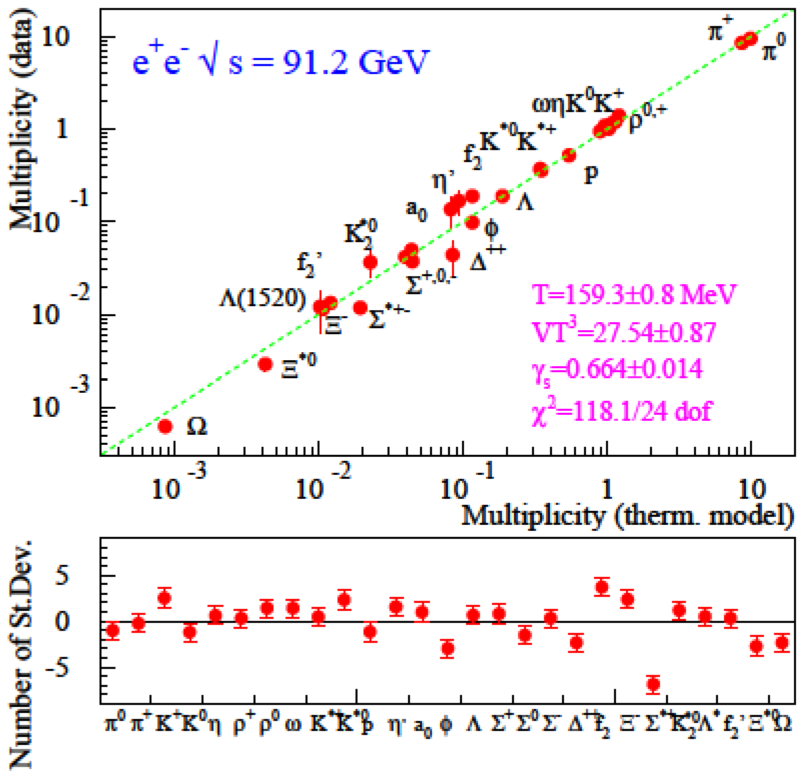



**Inclusive J/ψ** suppression measurements both in central and forward regions for $\mathbf{p_T>0}$:

- from $N_{part}$ > 100 suppression independent of centrality
- in central collisions, **less suppression than at RHIC**
- $R_{AA}$ decreases by 40% from $y$=2.5 to $y$=4





$e^+e^-$ $\sqrt{s}$ = 91.2 GeV
T=159.3±0.8 MeV
$VT^3$=27.54±0.87
$\gamma_s$=0.664±0.014
$\chi^2$=118.1/24 dof
Multiplicity (data)
Multiplicity (therm. model)
Number of St.Dev.

# Mapping the Phase Boundary