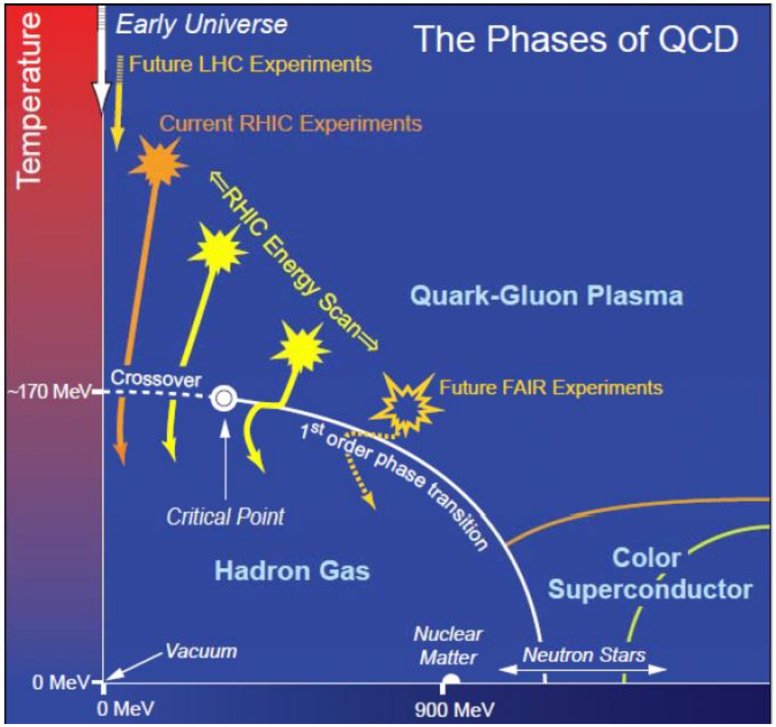
Физика столкновений тяжелых ионов

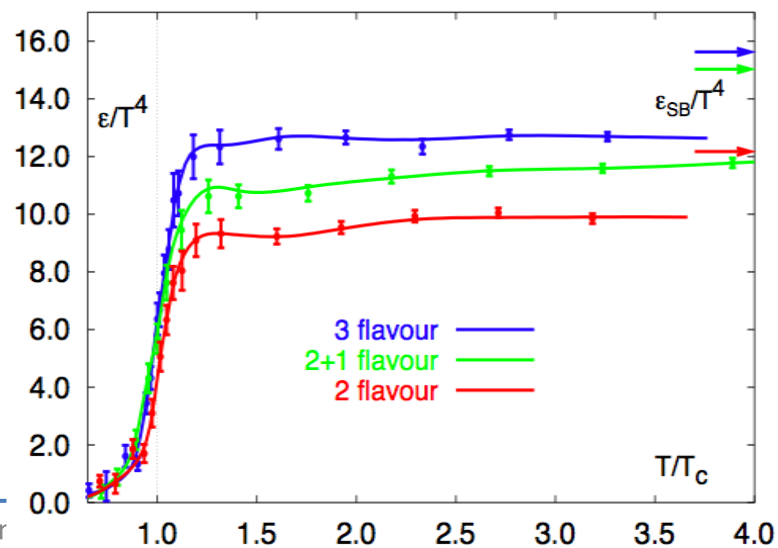
Е. Крышень

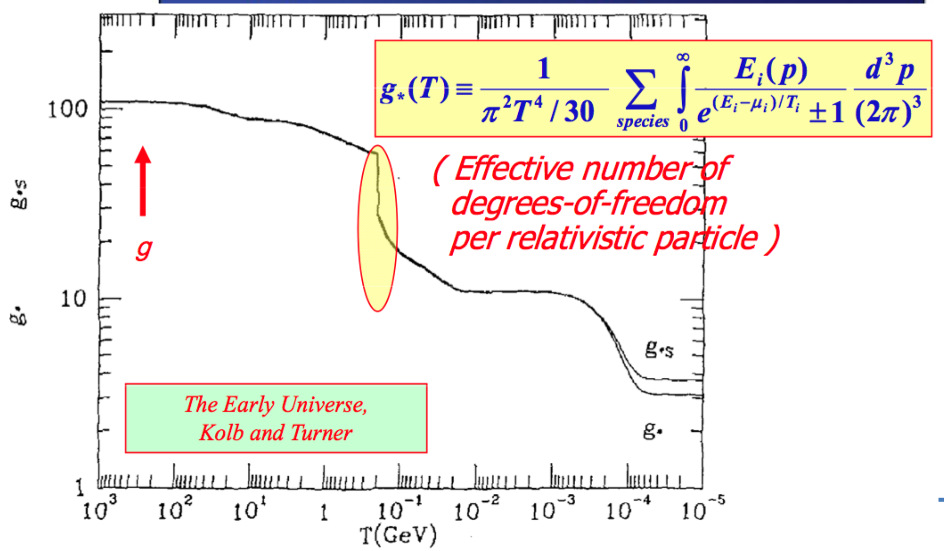
Научная сессия ОФВЭ
25 декабря 2012

Phase diagram

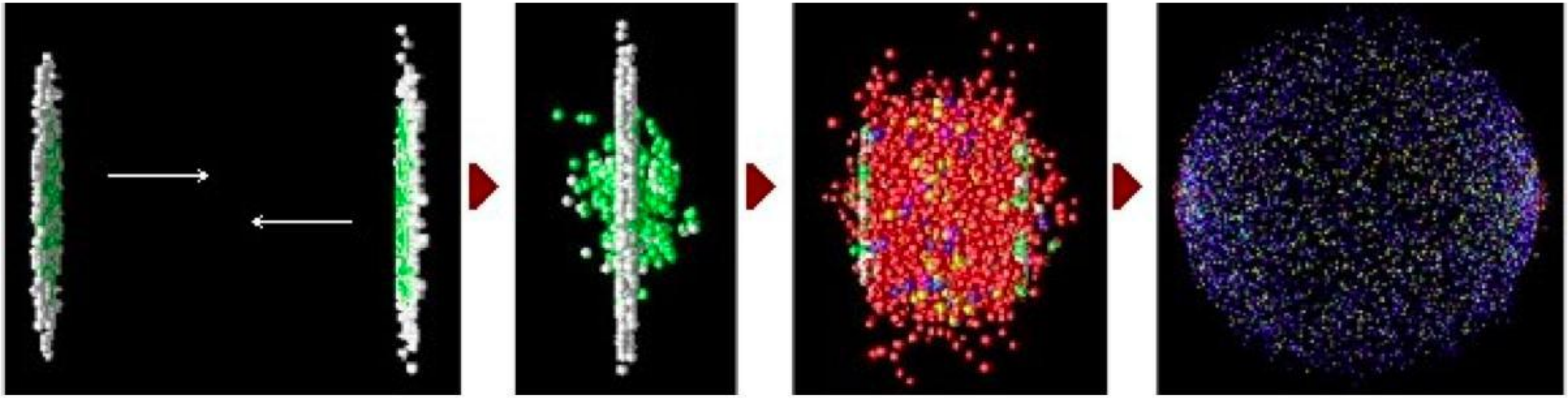
- Latice QCD: QCD matter undergoes a transition from a hadronic gas to a quark-gluon plasma at a temperature T_c ~170 MeV
- At small net baryon density, the transition is a smooth cross-over spanning a temperature range of 20-30 MeV
- much reduced condensate of light quarks $\rightarrow$ approximate restoration of chiral symmetry
- screening of chromo-electric force between heavy quarks $\rightarrow$ absence of quark confinement

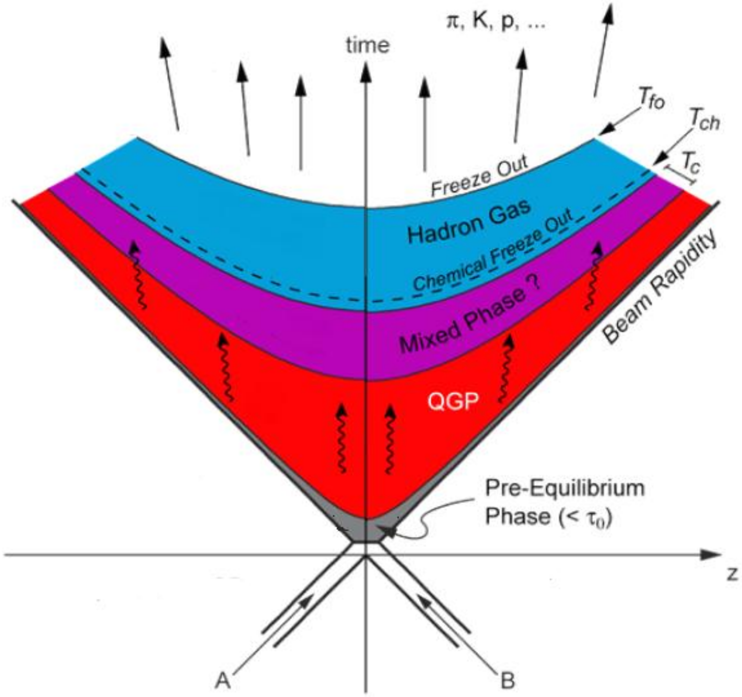






HIC: physics motivation

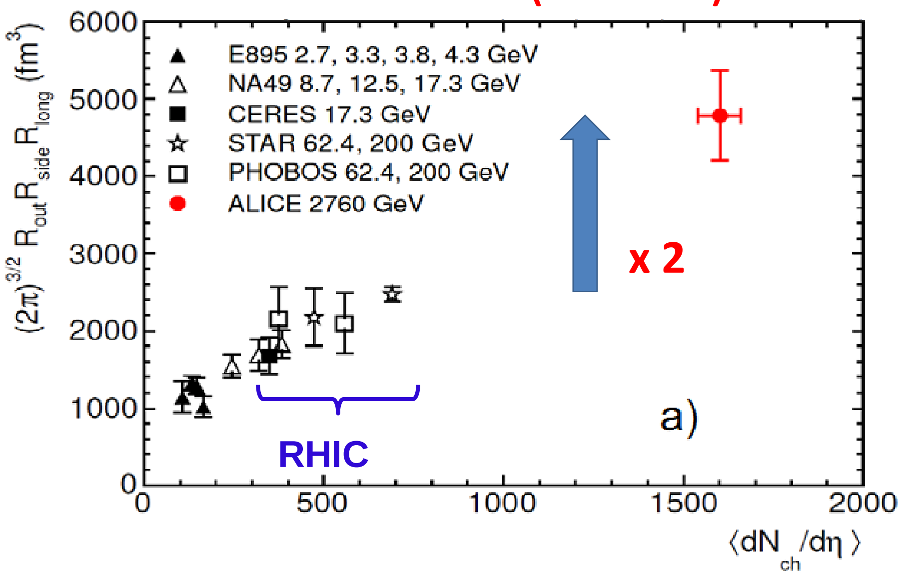




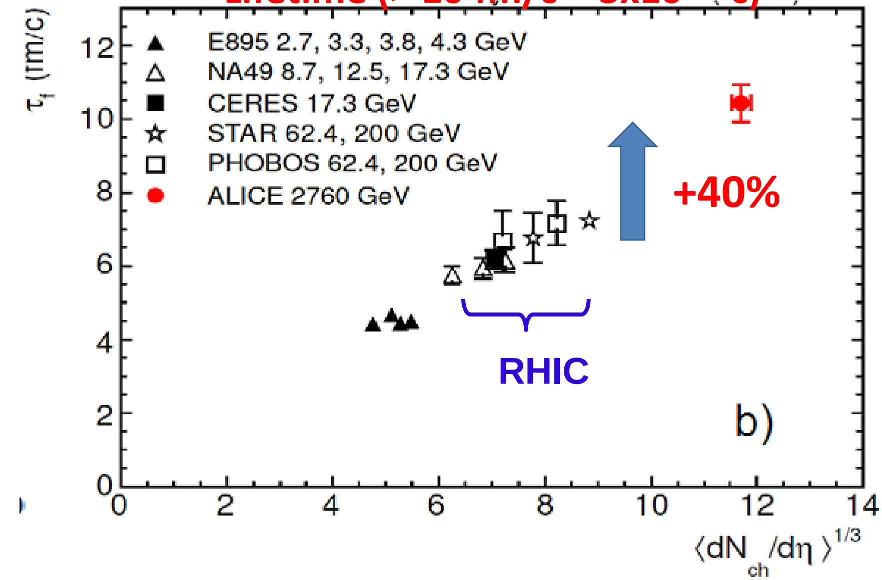
- Goal: study nuclear matter at extreme conditions of temperature and density
- Heavy ion collisions studied since AGS, SPS & RHIC
- Produced QCD matter initially thought as weakly interacting gas of quarks and gluons but
- found as strongly interacting matter:
  - short mean free path
  - high collectivity and flows
  - large parton energy-loss
  - almost perfect liquid ($\eta/s \sim 1/4\pi$)

Global properties

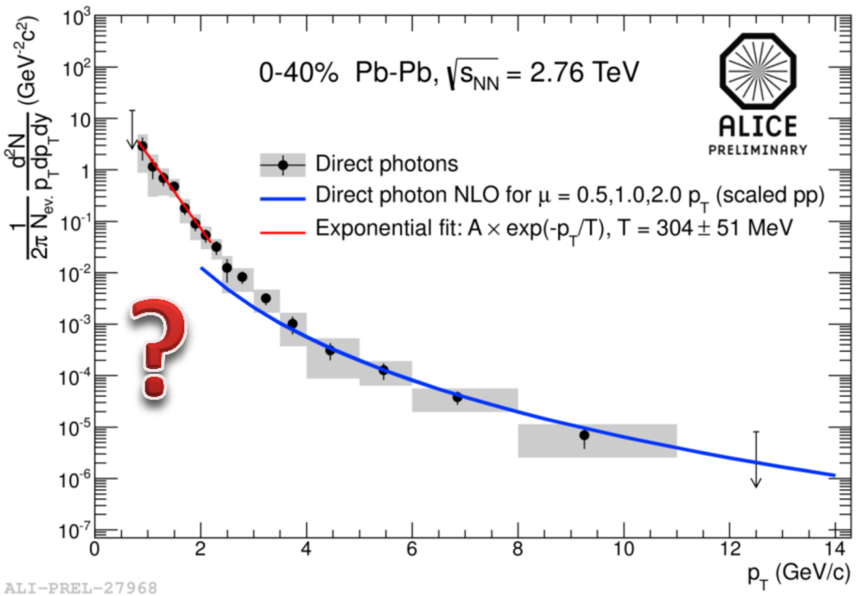
Volume ≈ 2 x RHIC (≈ 300 fm³)



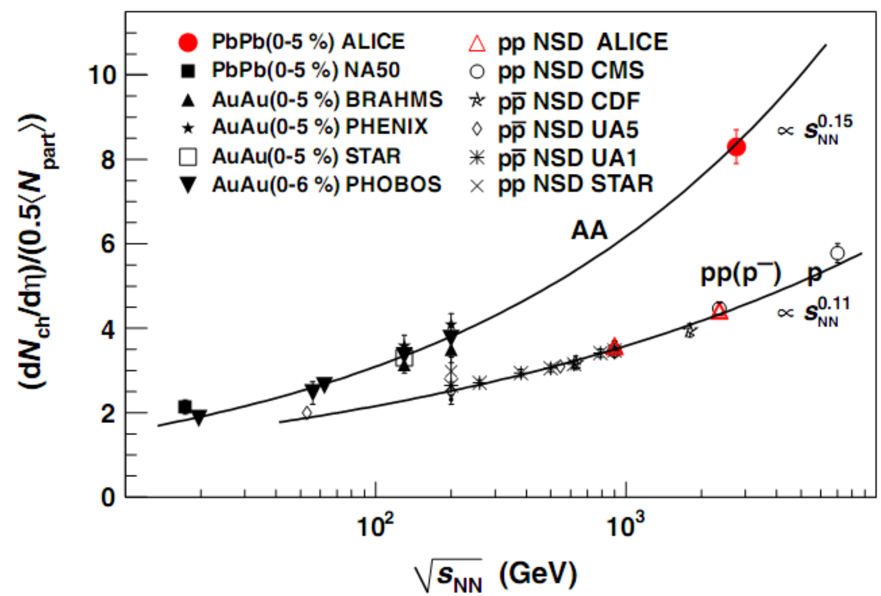
Lifetime (> 10 fm/c ~ 3x10⁻²³ c)



Photon T = 304±51 MeV ~ 1.4 x RHIC



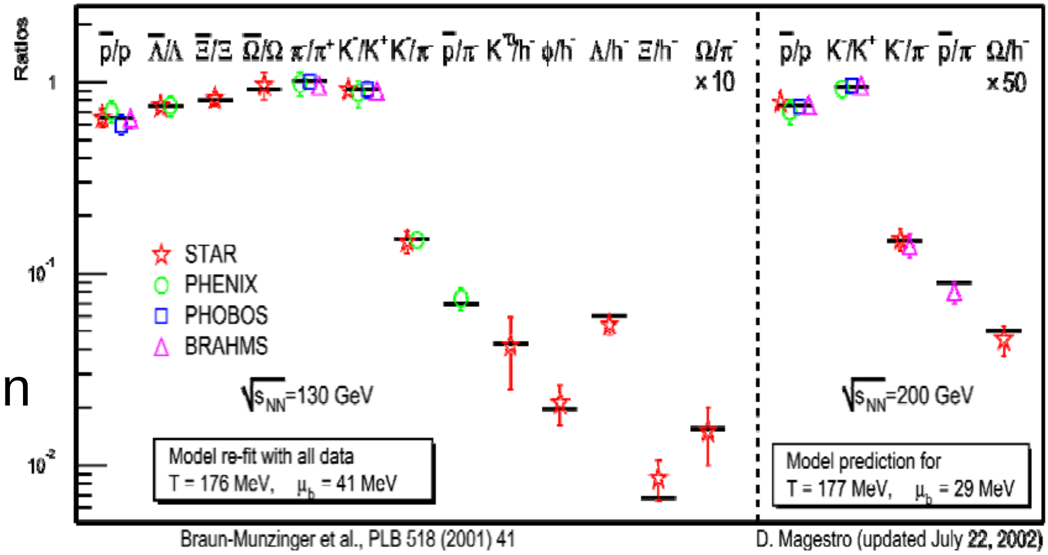
Energy density ~ 3 x RHIC ~ 10 GeV/fm3

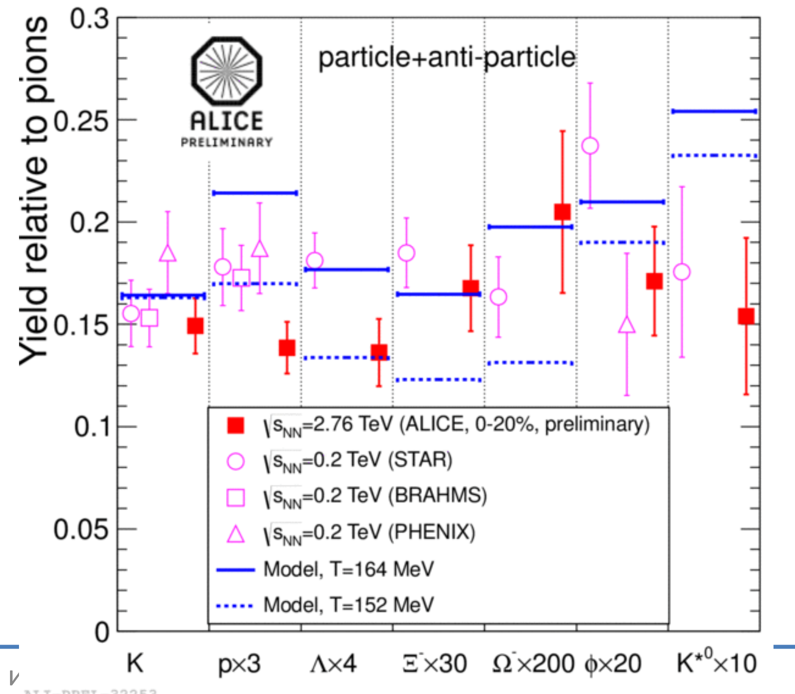


ікновений тя

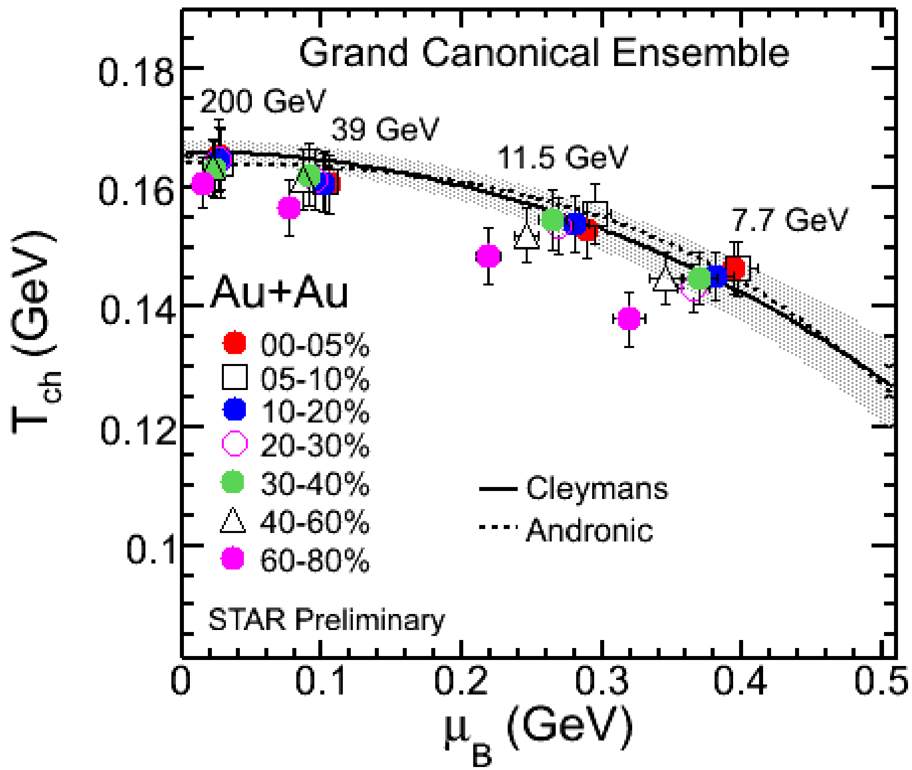
Hadrochemistry / thermal models

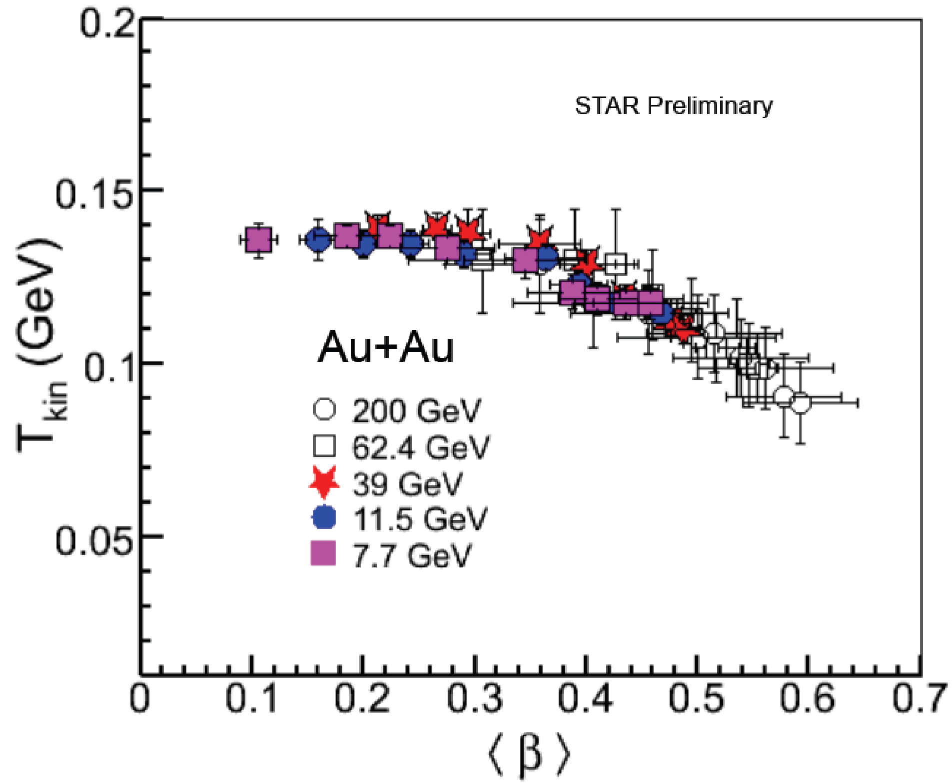
- Hadron yields and ratios **up to RHIC** energies well-fitted by statistical model in terms of T, μ_B
- Extracted (T, μ_B) in **good agreement** with transition curve in lattice QCD phase diagram
- Confirmed/refined by RHIC data on beam energy scan.
- **At LHC**, some tension with statistical description
  - Hadronic re-interactions?
  - Importance of charm contribution to strangeness production?





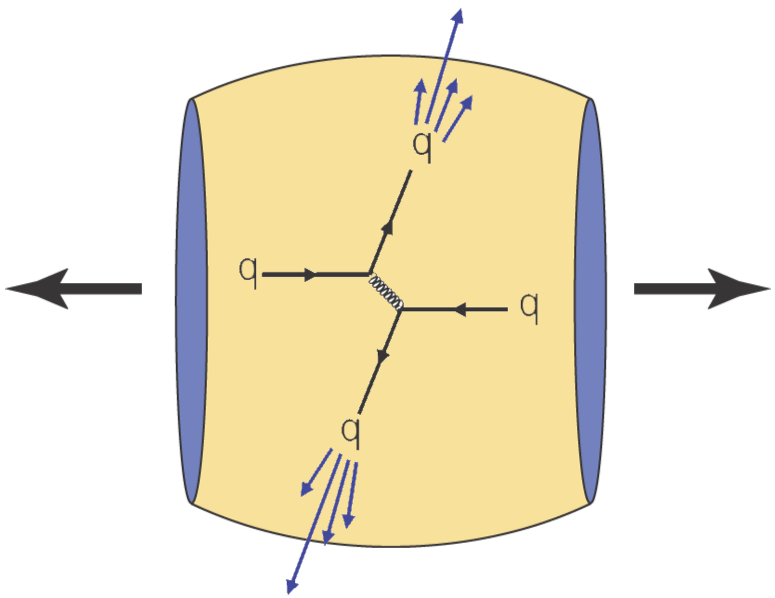
RHIC energy scan and statistical model

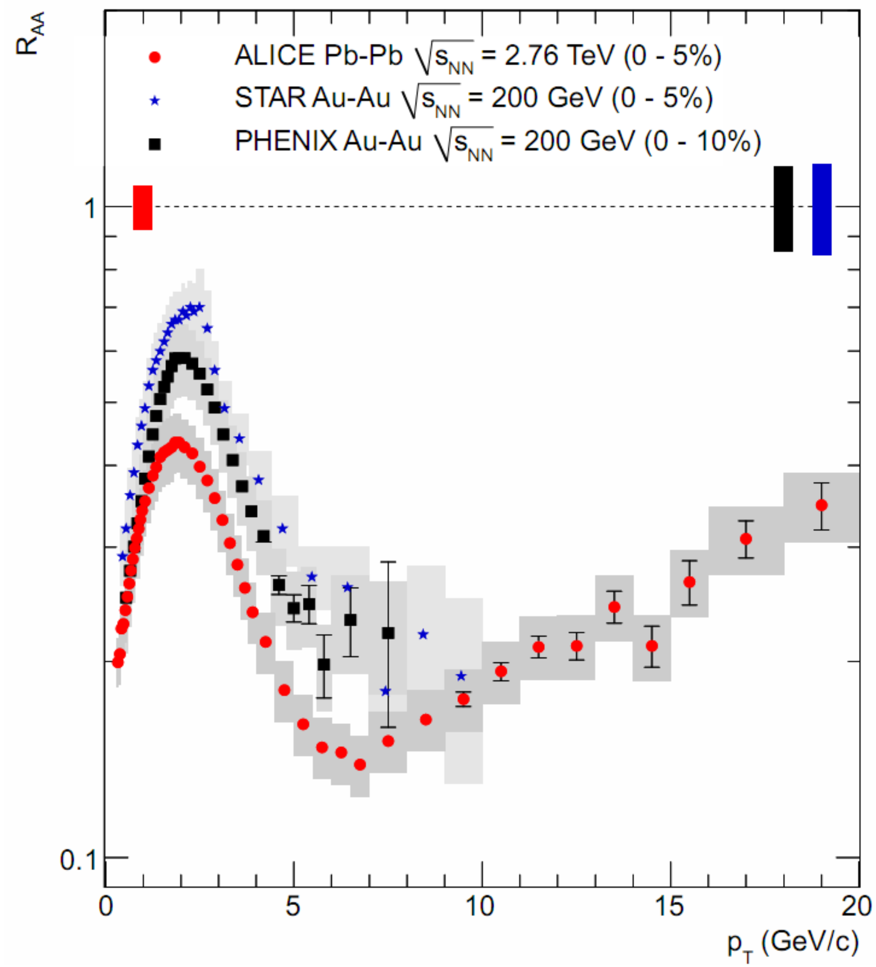




- Observation of a centrality dependence of the freeze-out temperature vs. baryon chemical potential (beam energy)
- Radial flow increase from most peripheral collisions at √sNN = 7.7 GeV to most central Au-Au events at √sNN = 200 GeV

Strong suppression for hadrons

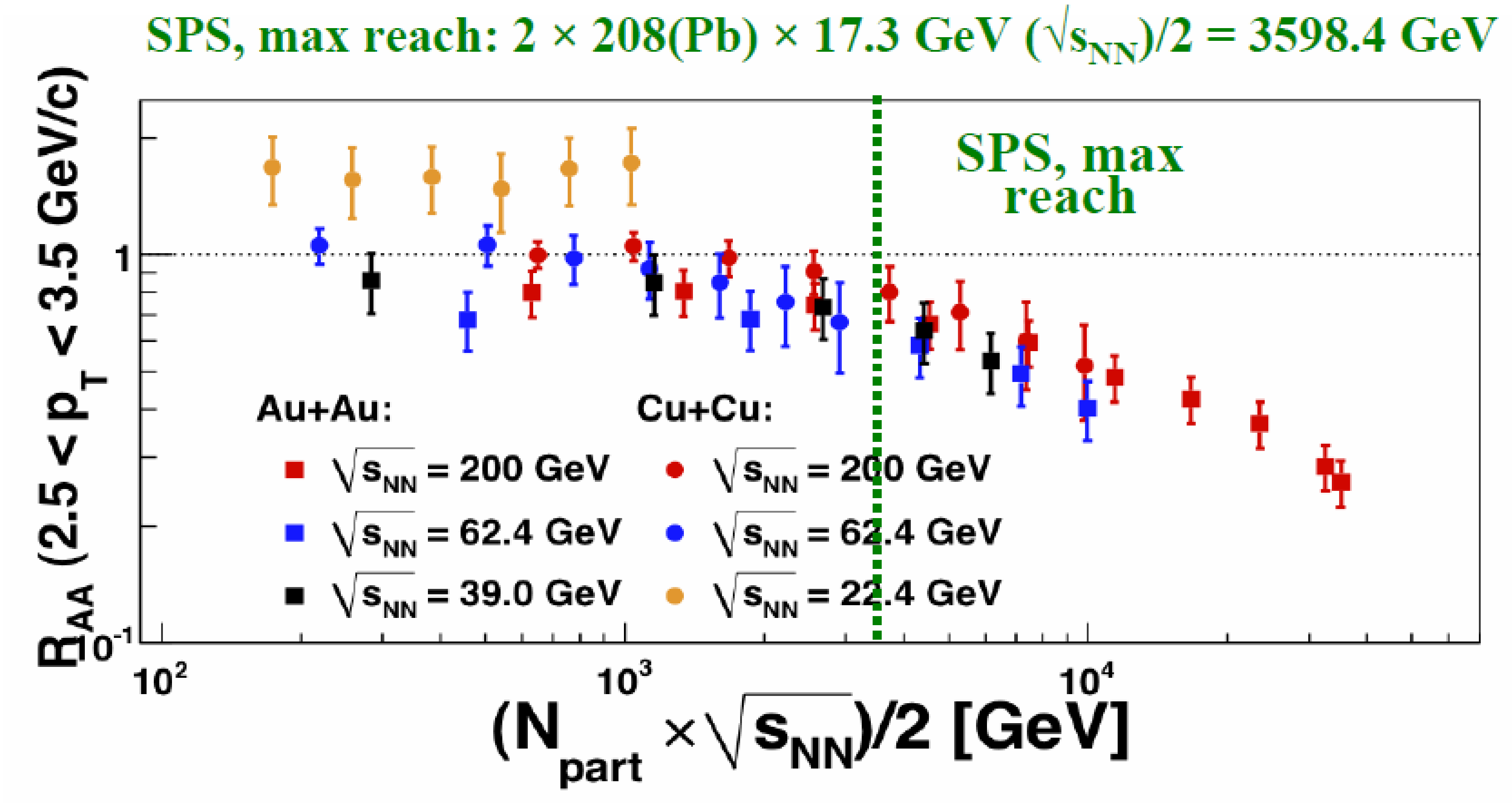




- Stronger suppression at LHC

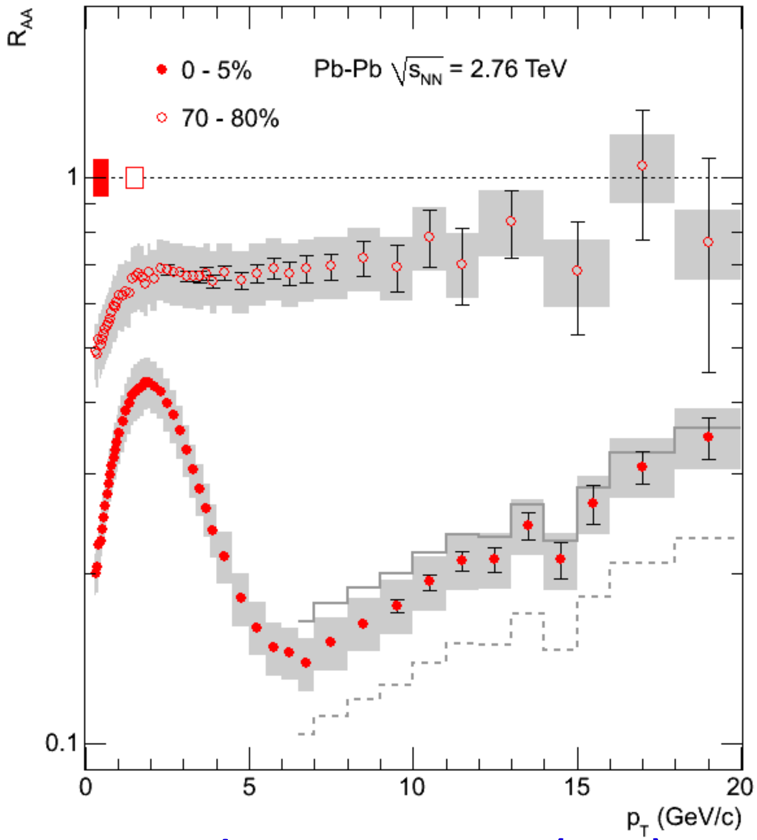
$$R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\langle N_{COLL} \rangle_{AA} \text{Yield}_{pp}(p_T)}$$

RHIC energy scan



полная накопленная энергия

3 regions in p_T



ALICE, Phys. Lett. B696, 30 (2011)

Low: p_T < 3-4 GeV/*c*

- Bulk properties and collective radial flow

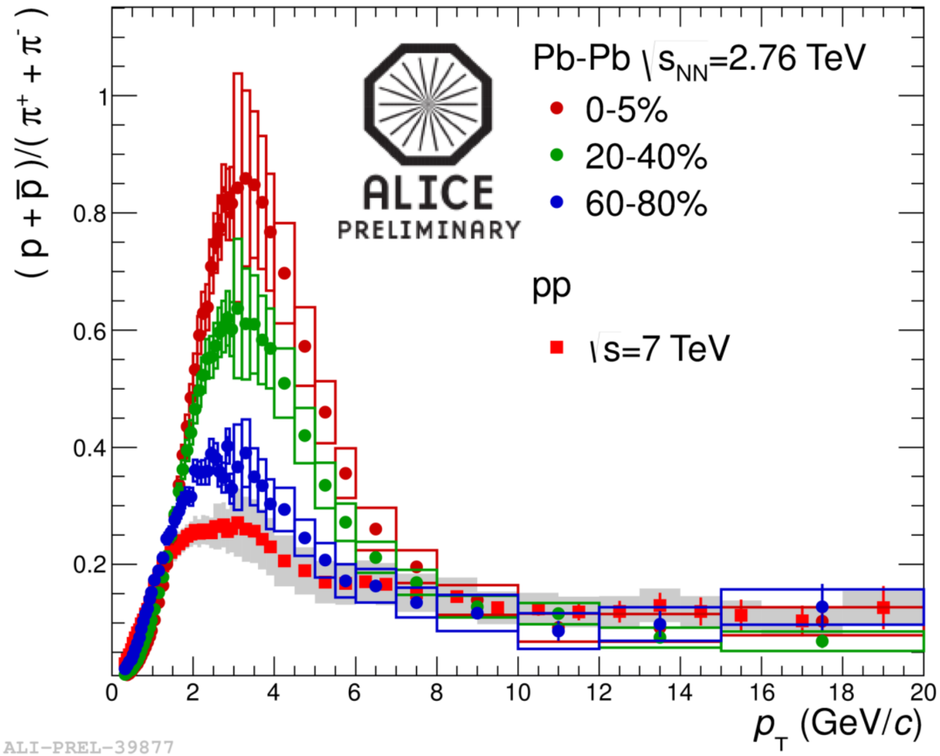
Intermediate: 3 < p_T < 7 GeV/*c*

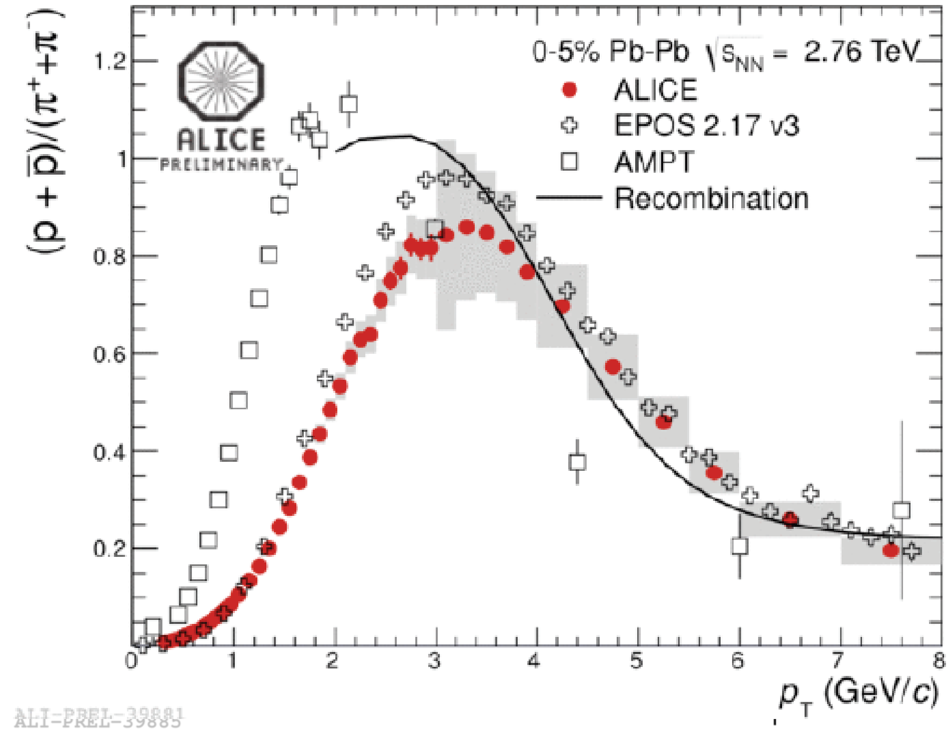
- Test of valence quark scaling
- Anomalous baryon enhancement and coalescence

High: p_T > 7 GeV/*c*

- Jet fragmentation, modification of fragmentation functions in medium

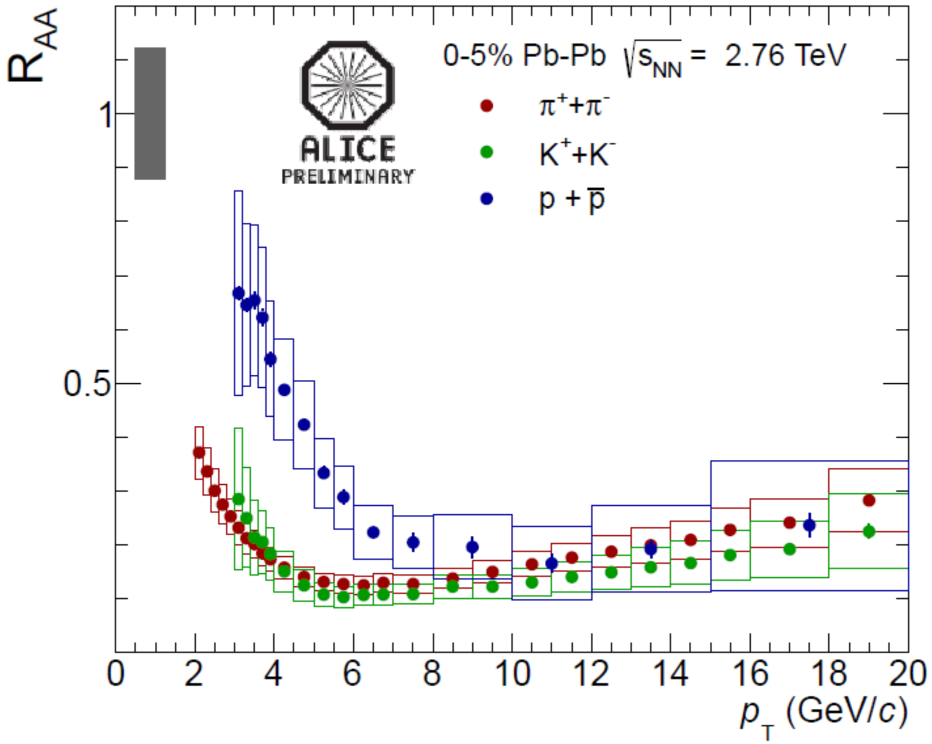
Baryon-to-meson ratio: p/π

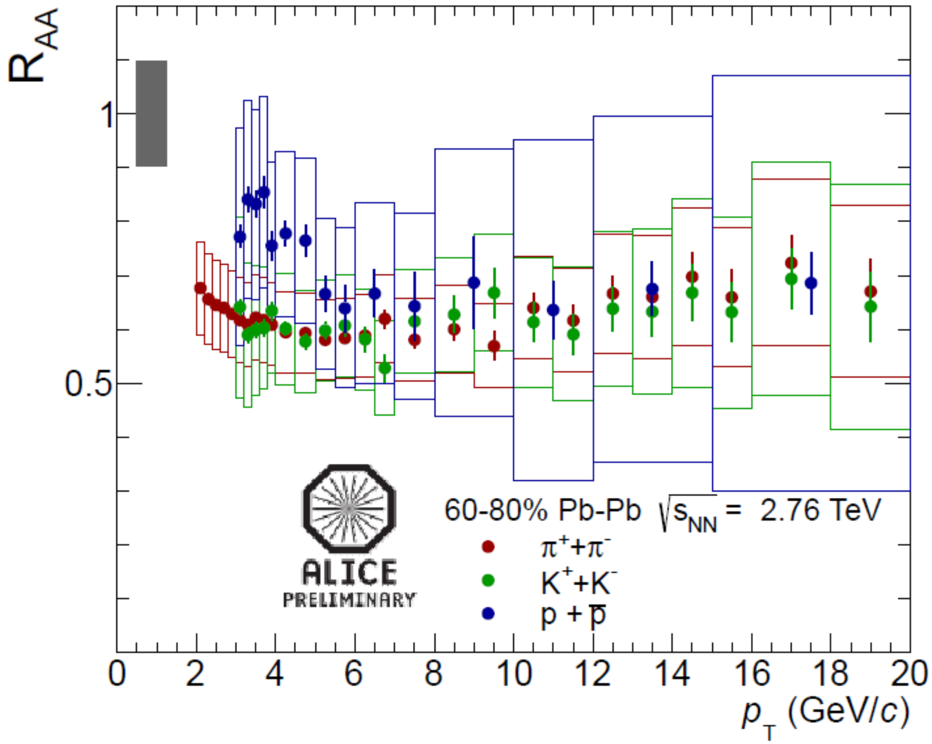




- p/π ratio at $p_T \approx 3$ GeV/c in 0–5% central Pb-Pb collisions factor ~3 higher than in pp
- the maximum of the ratio is shifted to higher p_T with respect to RHIC measurements
- at p_T above ~ 10 GeV/c back to the “normal” pp value
- recombination – radial flow?

Identified particles R_{AA}

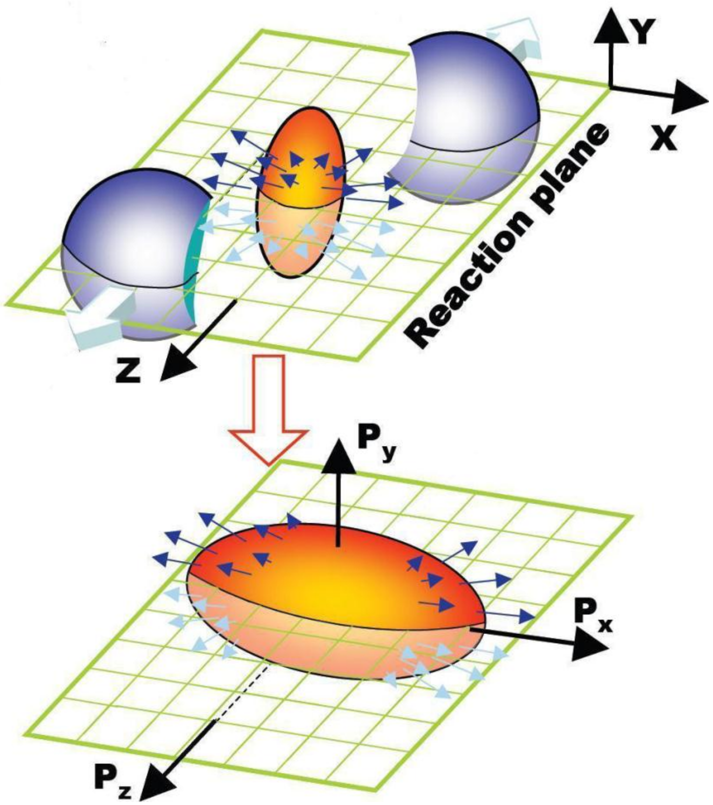




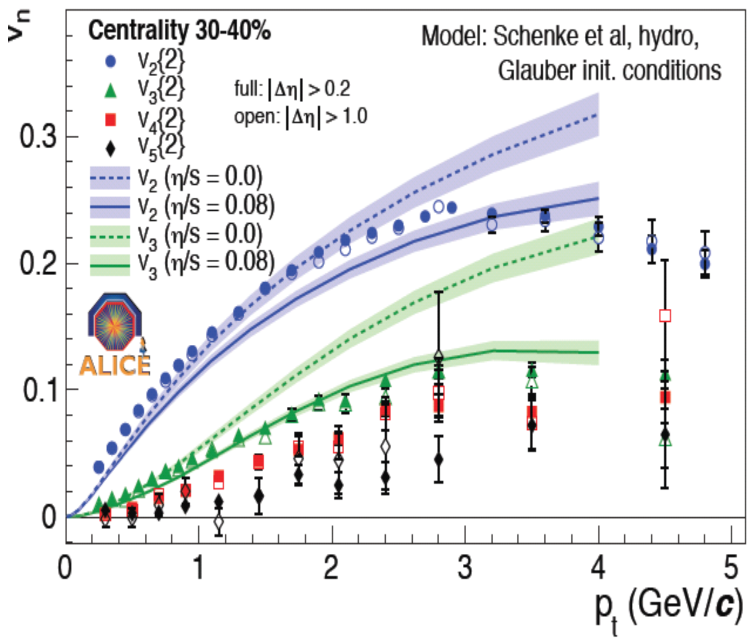
- Strong suppression confirming previous measurements for non-identified particles
- For p_T below ~ 7 GeV/c:
  - $R_{AA}(\pi) < R_{AA}(h^{\pm})$
  - $R_{AA}(\mathrm{K}) \approx R_{AA}(h^{\pm})$
  - $R_{AA}(\mathrm{p}) > R_{AA}(h^{\pm})$
- At higher p_T: R_{AA} are compatible $\rightarrow$ medium does not significantly affect the fragmentation.

Anisotropic flow

Spatial asymmetry transforms
into momentum space:



Phys. Rev. Lett. 107, 032301 (2011)



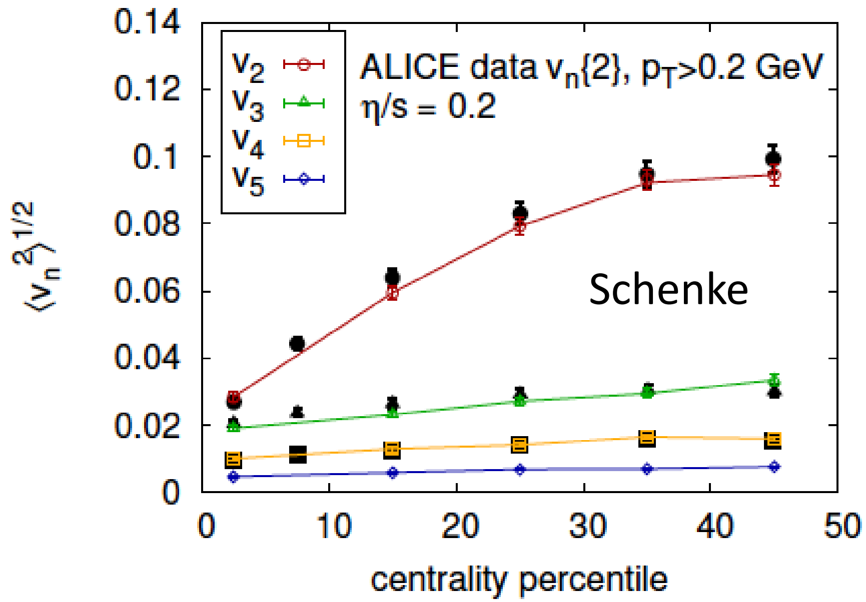
$$\frac{dN}{d(\varphi_i-\Psi_n)} \sim 1 + 2\sum_{n=1} v_n \cos[n(\varphi_i-\Psi_n)]$$

Hydrodynamics and flow

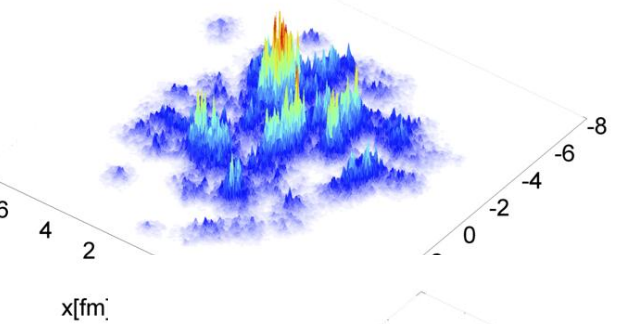
- 3+1 dim hydro dynamics reproduces v_2, v_3, v_4, v_5 in p_T and centrality for matter with same dissipative property
- Most conservative bound:

  $0.07 < \eta/s < 0.43$

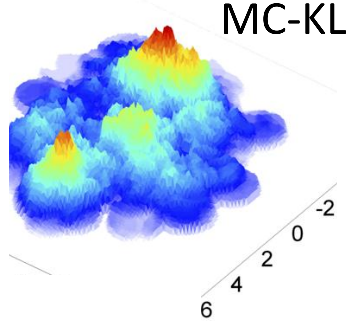
- Models increasingly sensitive to initial conditions and their (quantum) fluctuations

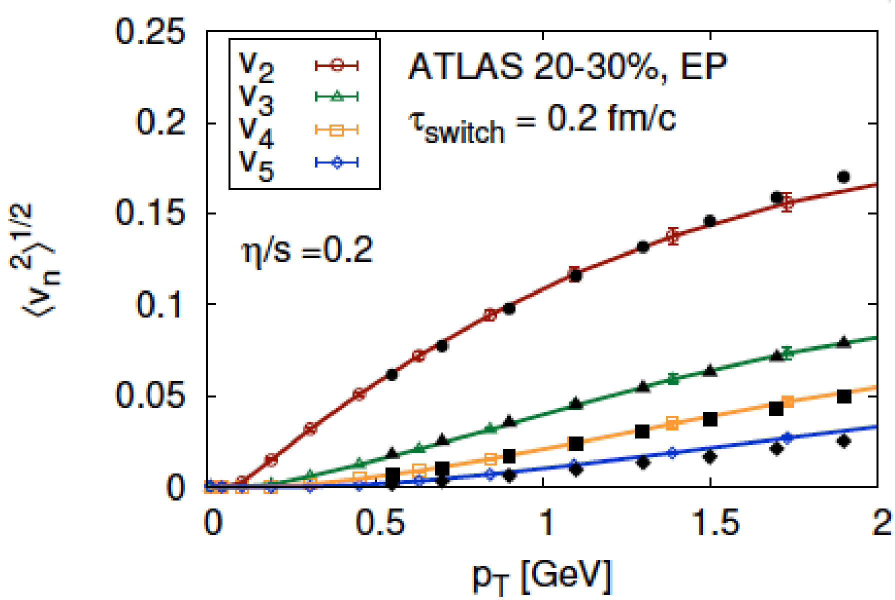


IP-Sat. Glasma

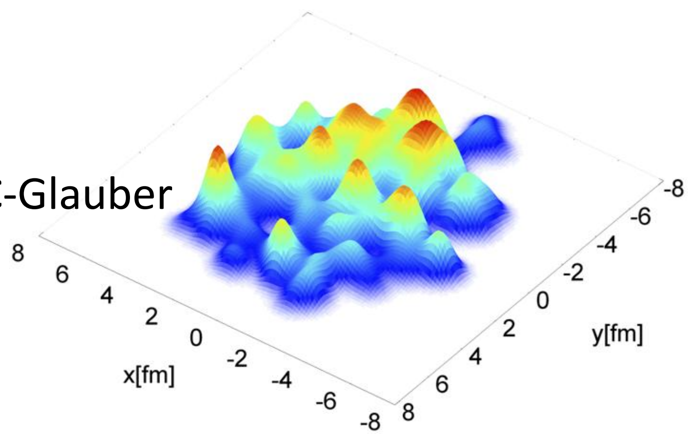


MC-KLN

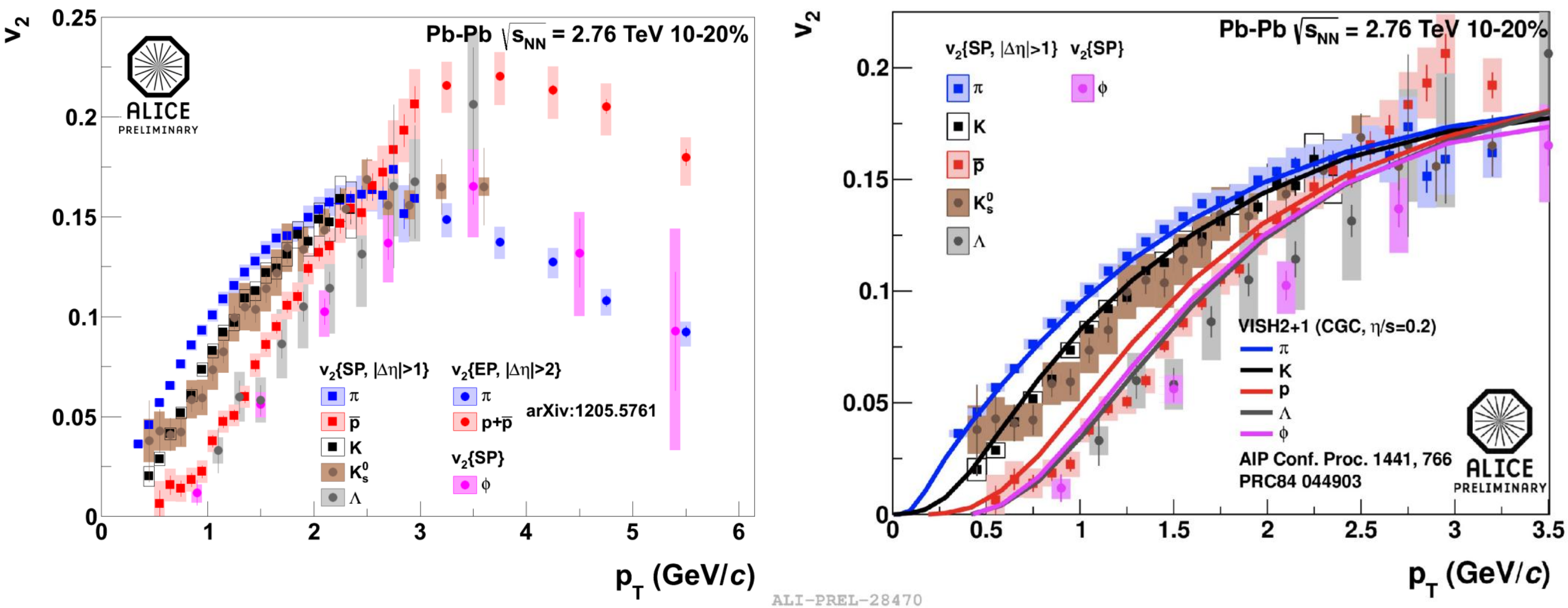




MC-Glauber



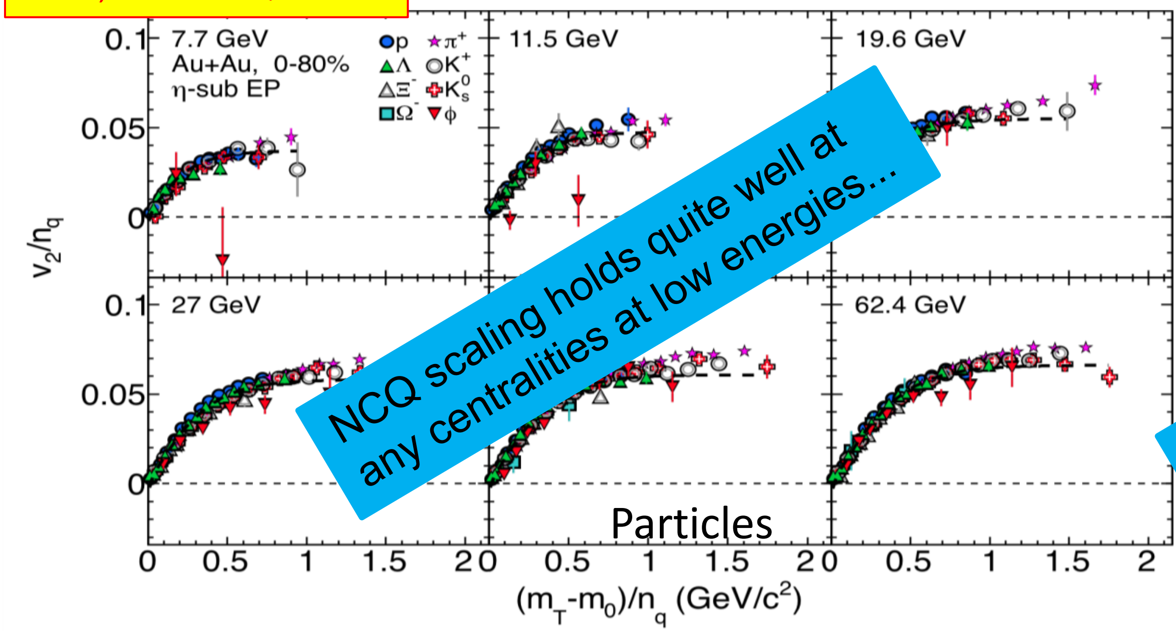
Identified particle v_2



- Mass ordering observed at low p_T for π, p, $K^{\pm}$, K^0_s, Λ, ϕ and (not shown) Ξ, Ω
- ϕ-meson follows mass dependence at $p_T < 3$ GeV/c and “meson band” at higher p_T
- Overall qualitative agreement with viscous hydro calculations at low p_T
- Hadronic rescattering phase improves agreement

NCQ scaling: RHIC

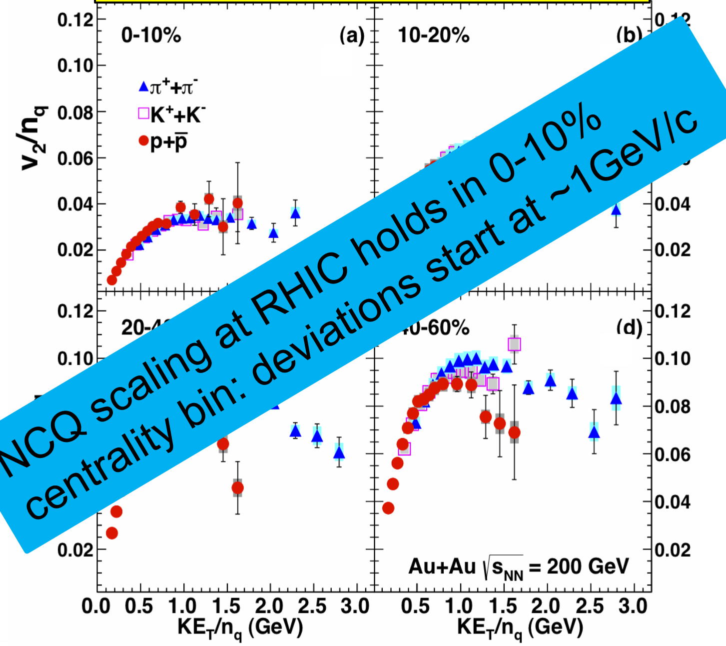
STAR, S.Shu at QM2012



NCQ scaling holds quite well at any centralities at low energies…

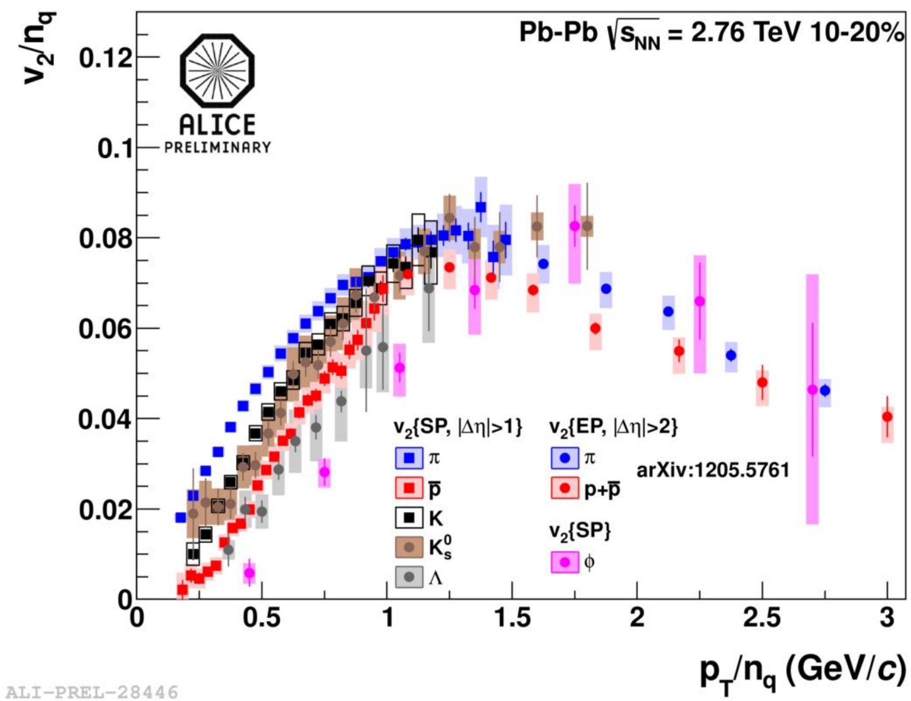
Particles

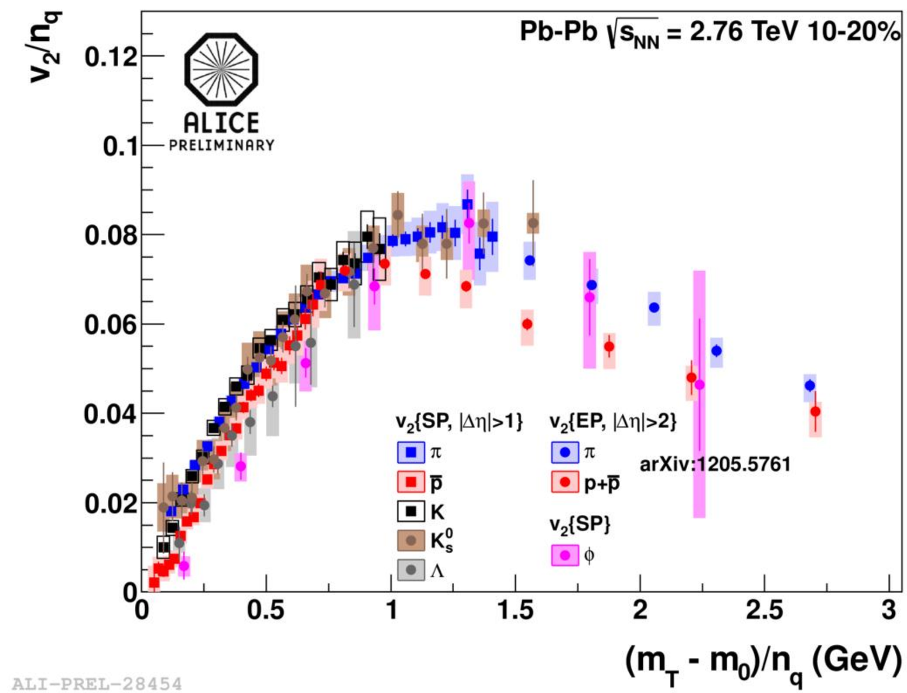
PHENIX Phys. Rev. C85 064914(2012)



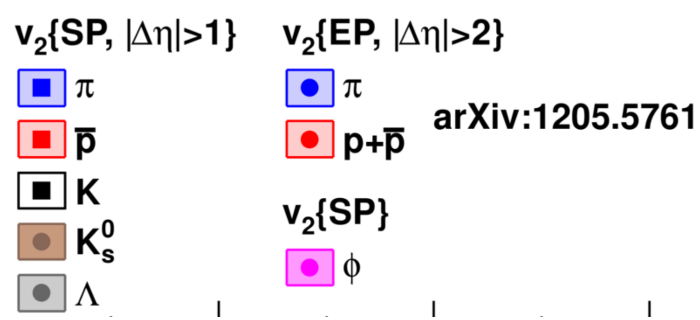
NCQ scaling at RHIC holds in 0-10% centrality bin: deviations start at ~1GeV/c

NCQ scaling breaking: LHC



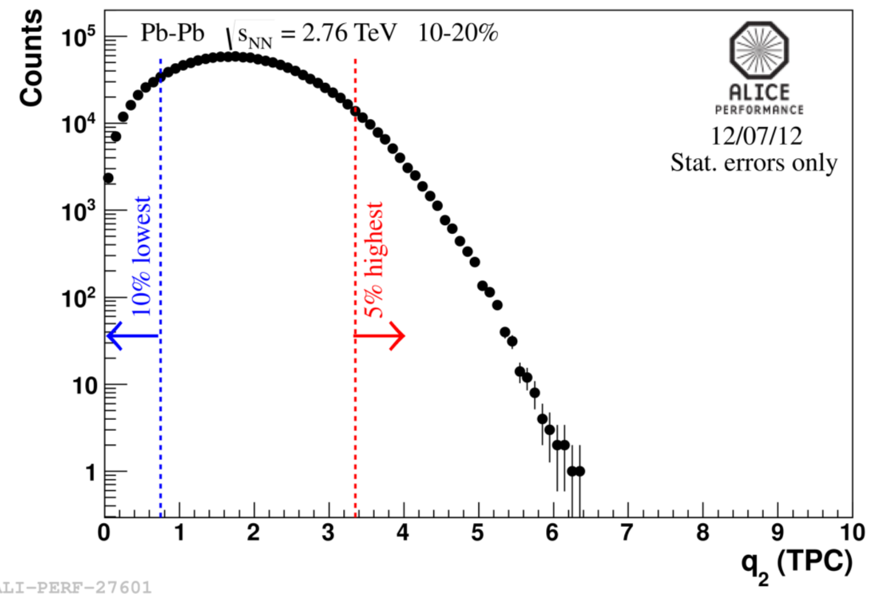


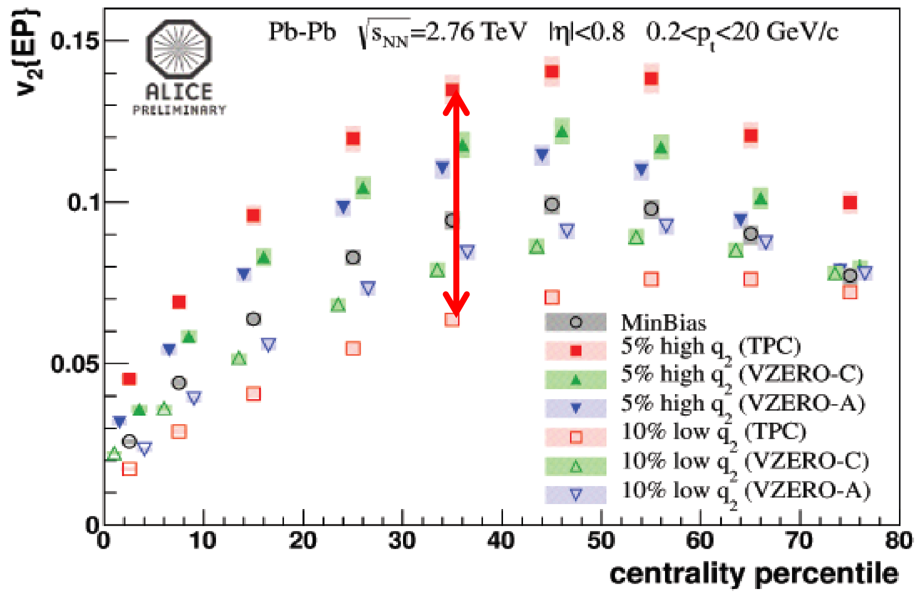
- scaling off by 10-20% at high p_T (where mass is negligible)
- stronger radial flow or jet quenching/ rescattering, more important than coalescence ?



Event Shape Engineering

New tool towards better understanding of elliptic flow





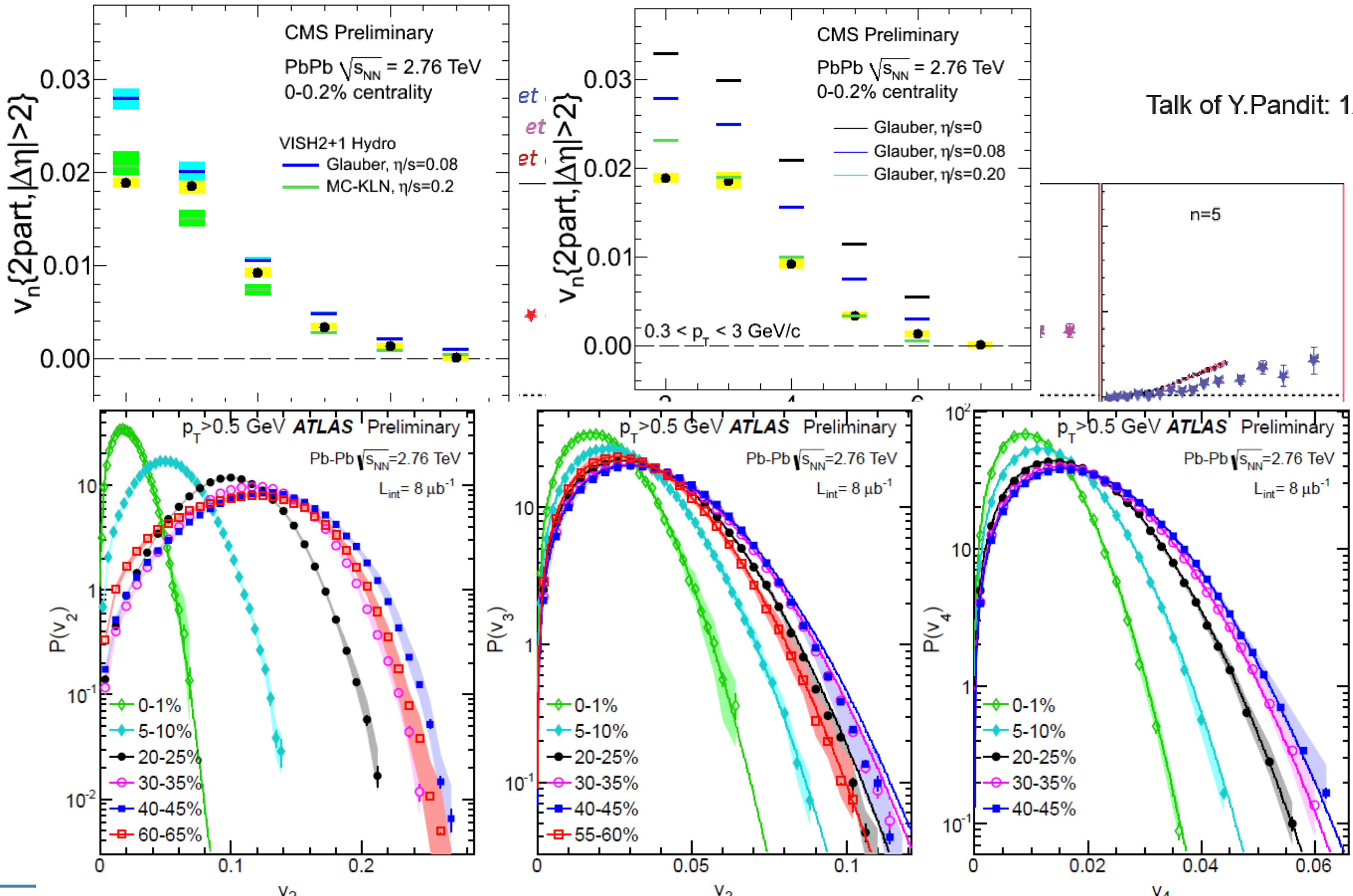
$$Q_{n,x} = \sum_{i=1}^{M} \cos n\varphi_i$$

$$Q_{n,y} = \sum_{i=1}^{M} \sin n\varphi_i$$

$$q_n = Q_n/\sqrt{M}$$

- At fixed centrality large flow fluctuations
- v_2 splits by factor of two for semi-central events (30–50%)

More flow…

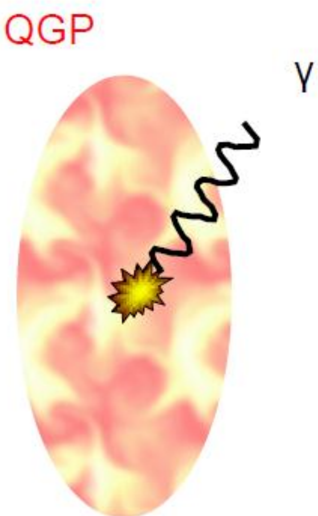

CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
0-0.2% centrality
VISH2+1 Hydro
Glauber, η/s=0.08
MC-KLN, η/s=0.2
$v_n\{2part,|\Delta\eta|>2\}$
0.3 < p_T < 3 GeV/c
Glauber, η/s=0
Glauber, η/s=0.08
Glauber, η/s=0.20
Talk of Y.Pandit: 1/
n=5
p_T>0.5 GeV ATLAS Preliminary
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
L_{int}= 8 μb^{-1}
$P(v_2)$
v_2
0-1%
5-10%
20-25%
30-35%
40-45%
60-65%
$P(v_3)$
v_3
55-60%
$P(v_4)$
v_4

Hard probes

Three types of hard probes

Electroweak probes

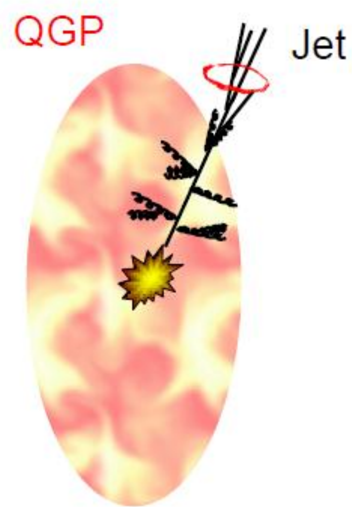
W/Z bosons, high p_T γ



Probe the initial state

Quarks and gluons

Jets



Probe the opacity of QGP

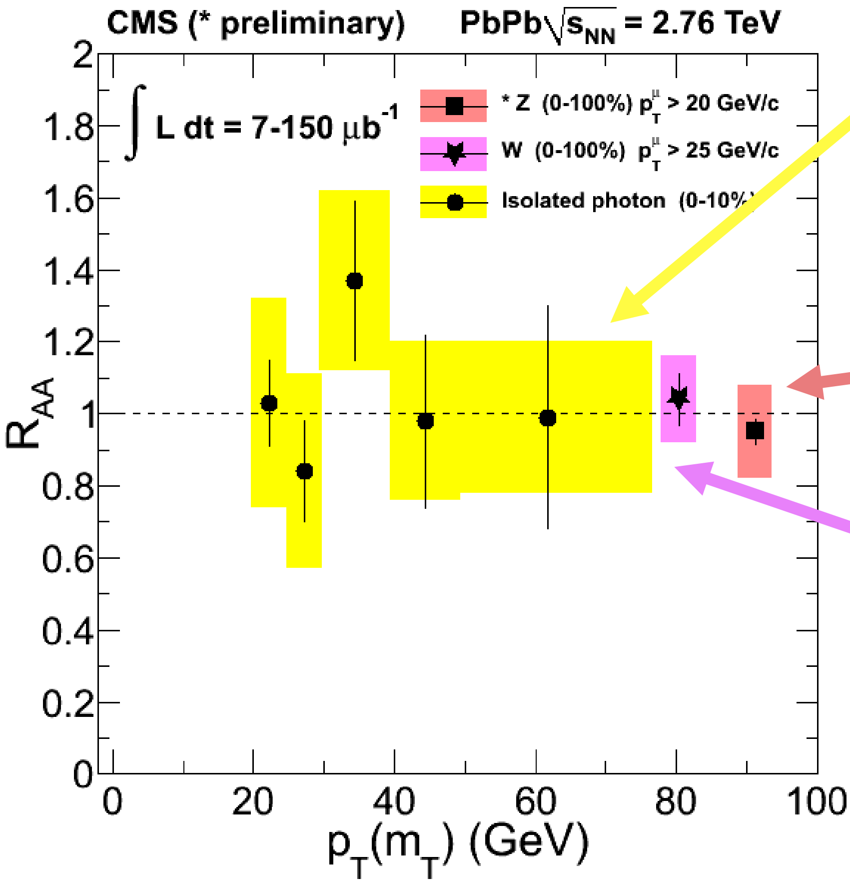
Quarkonium

J/ψ, ϒ family

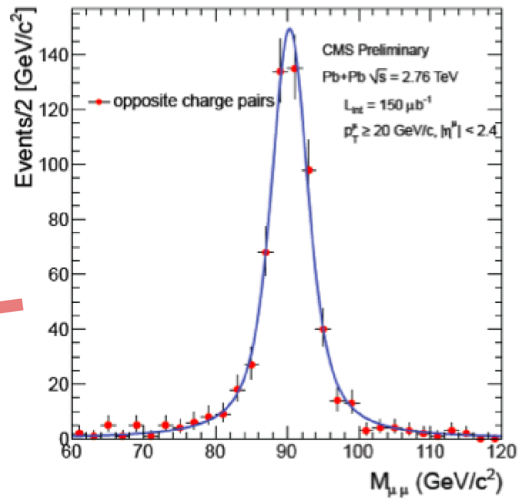
Sensitive to
the temperature of QGP

Electroweak probes

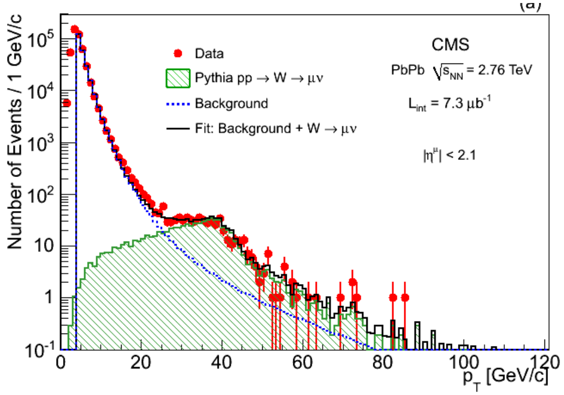
PLB 710 (2012) 256



CMS-PAS HIN-12-008



$Z^0 \rightarrow \mu^+\mu^-$

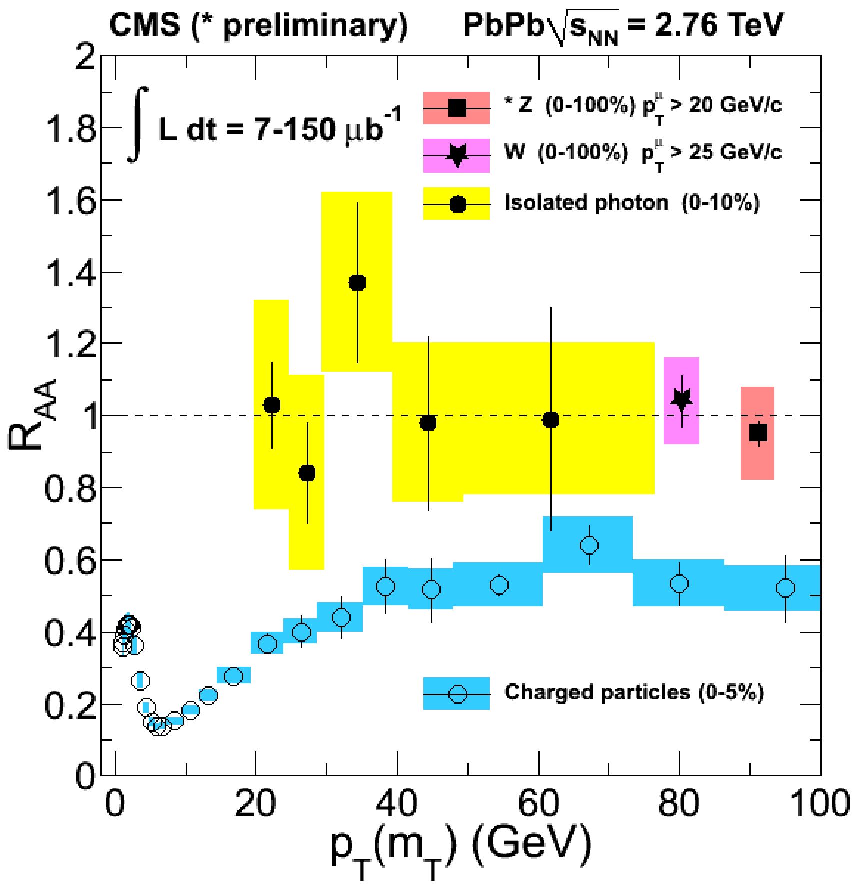


W→ μν using single muon recoil against missing p_T

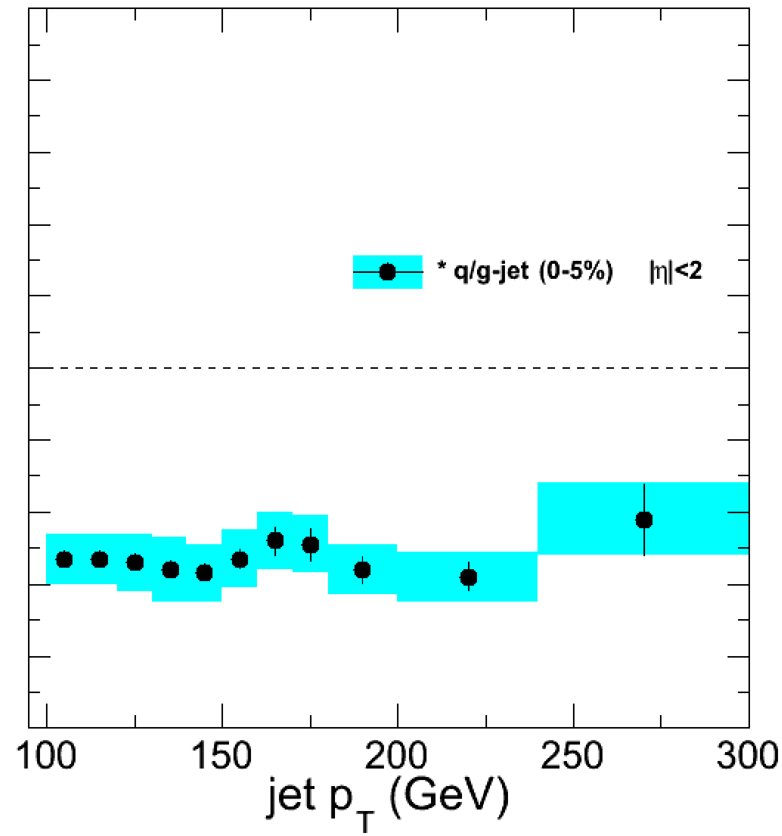
arXiv:1205.6334
Accepted by PLB

N_{coll} scaling confirmed

Suppression of charged particles



Fully unfolded inclusive jet R_{AA}
pp 2.76 TeV reference



Charged hadron R_{AA} flat for p_T = 30 - 100GeV

Like for charged particles, high-p_T jet R_{AA} flat at ≈ 0.5

Jet quenching

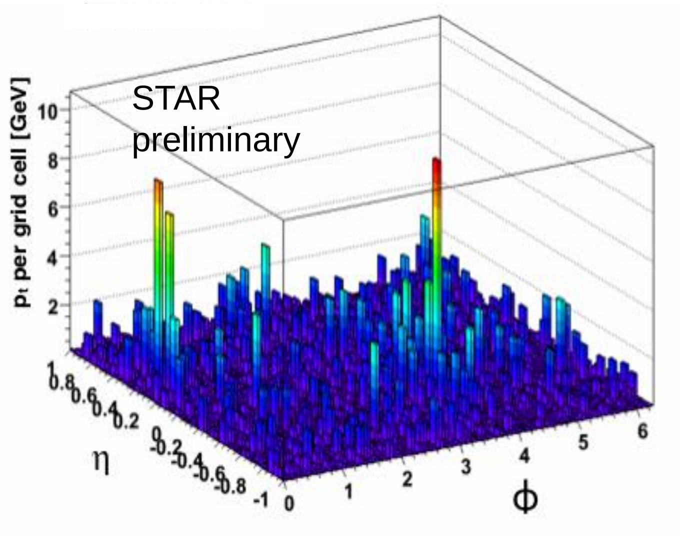
FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

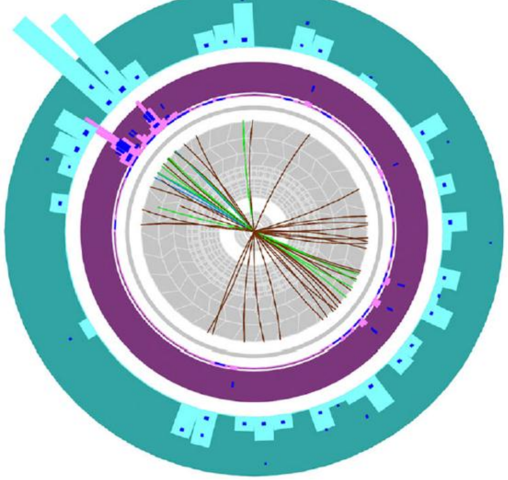
J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

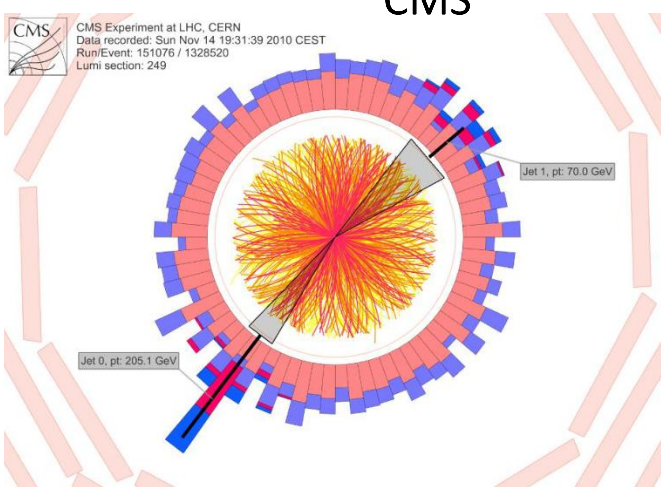
STAR



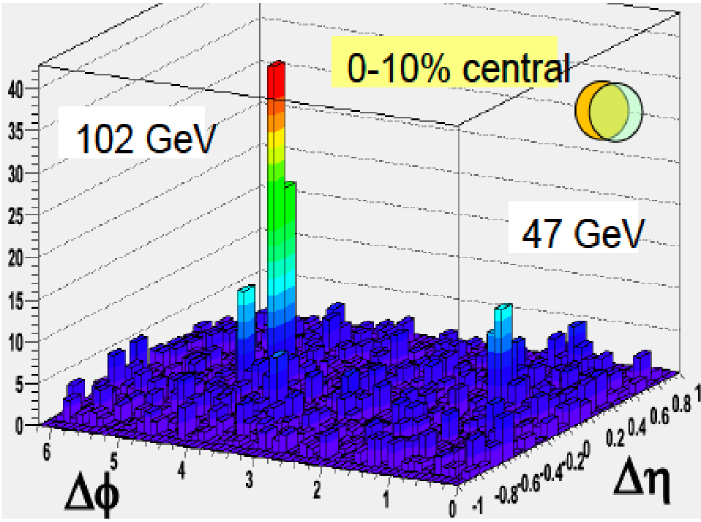
ATLAS



CMS

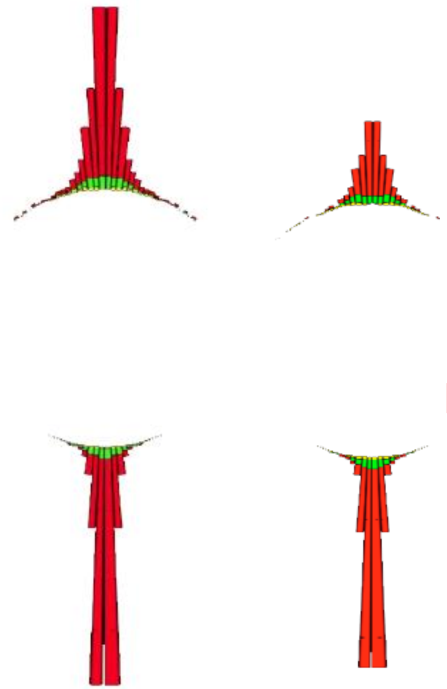


ALICE



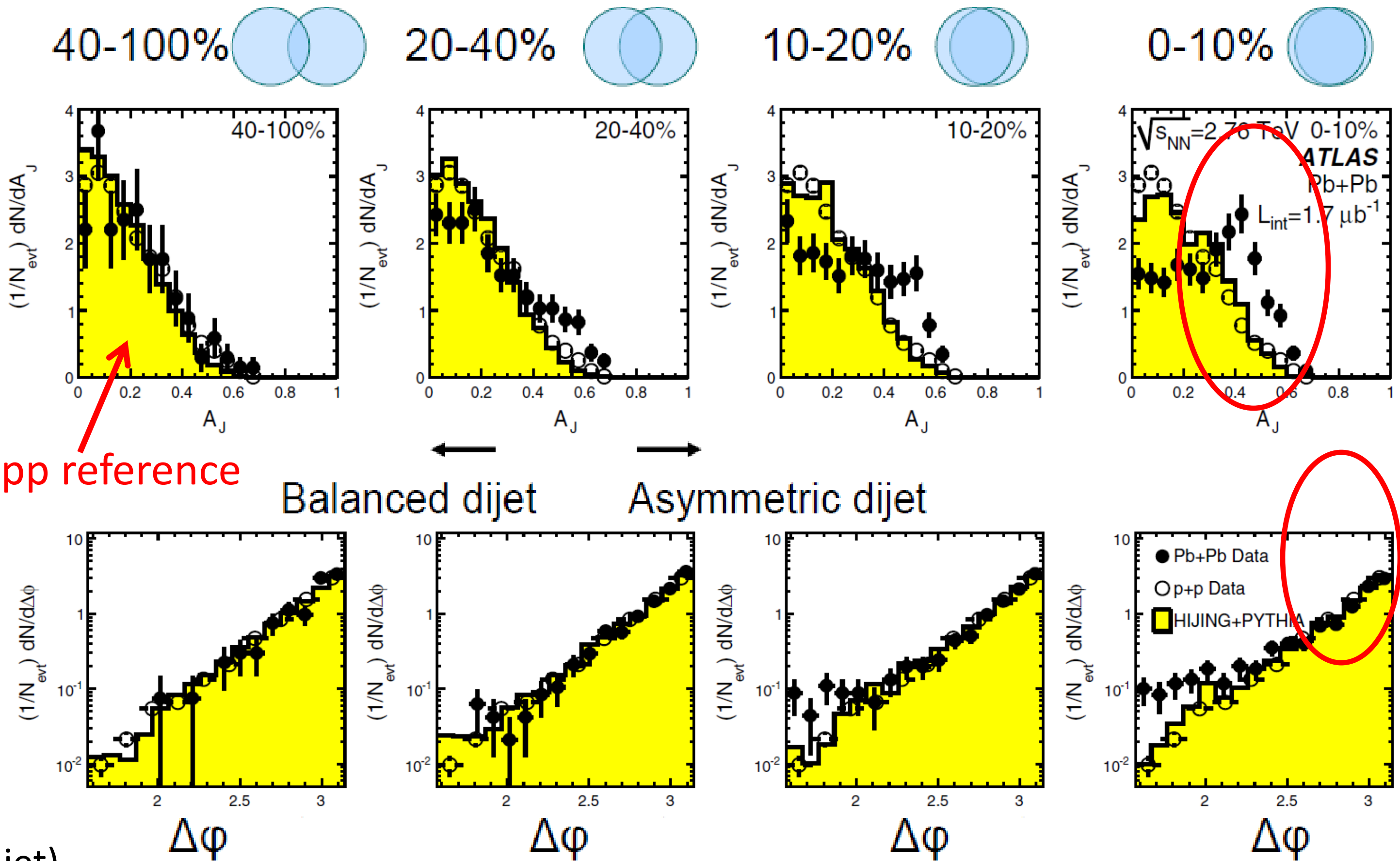
Dijet asymmetry

$A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2})$



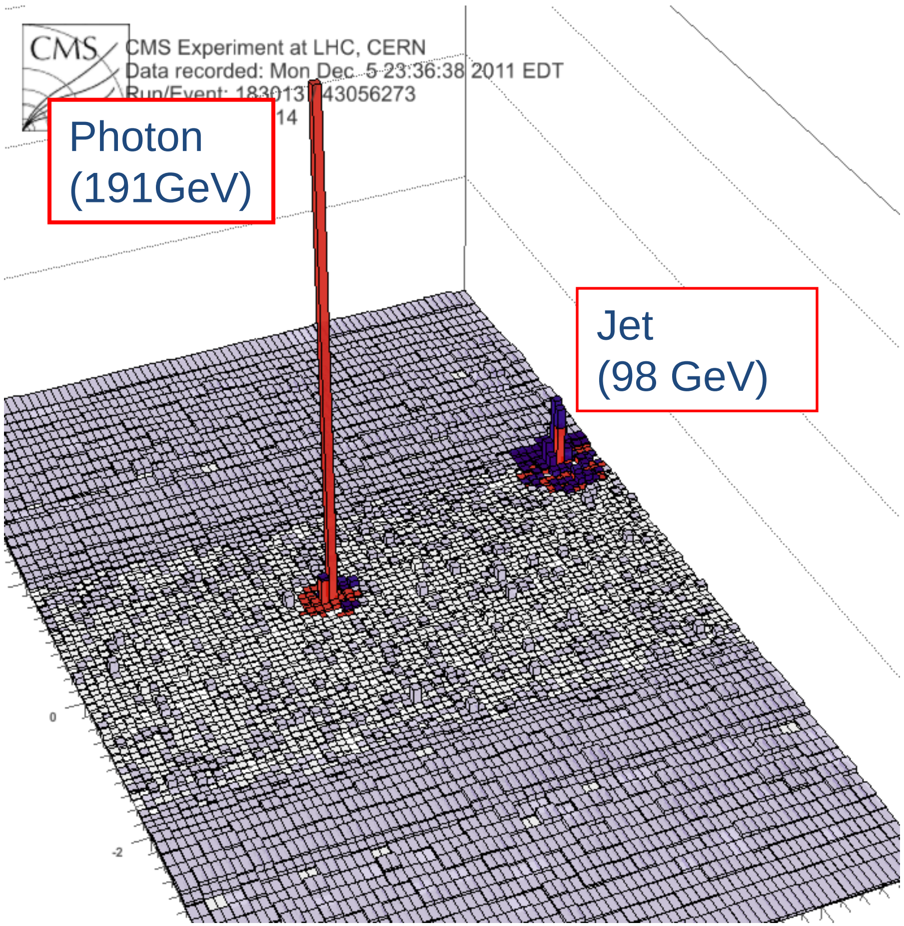
Small A_J
(Balanced jet)

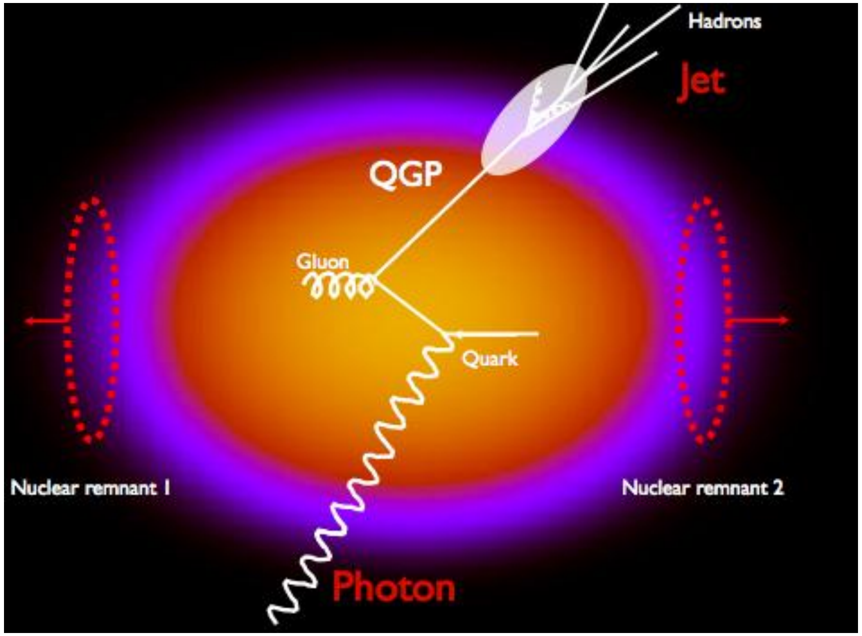
Large A_J
(Un-alanced jet)



- Parton energy loss is observed as a pronounced energy imbalance in central PbPb collisions
- No apparent modification in the dijet Δϕ distribution
  (Dijet pairs are still back-to-back in azimuthal angle)
- However information on initial jet momentum is missing + surface bias

γ+jet – “golden channel”





Photon tag:

- Identifies jet as u,d quark jet
- Provides initial quark direction
- Provides initial quark p_T

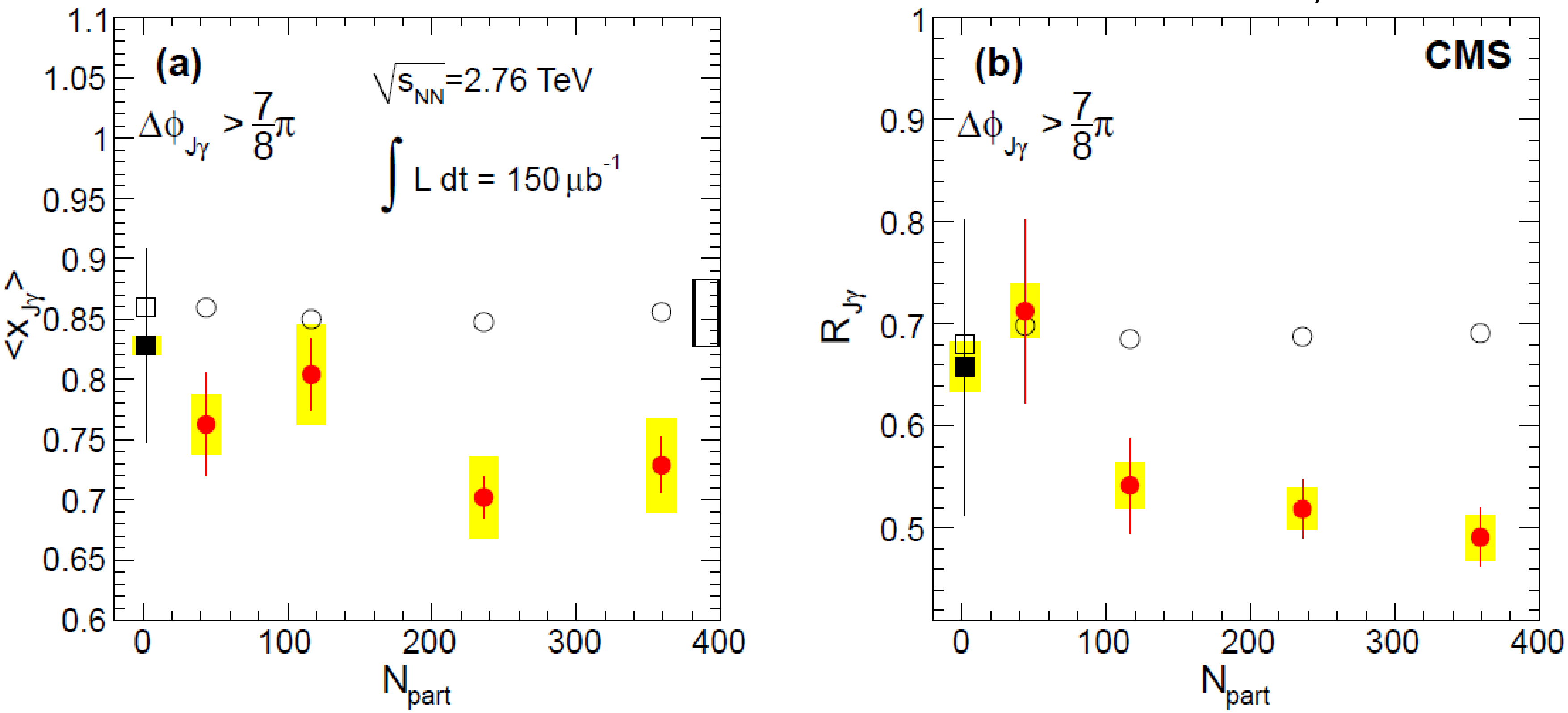
γ+jet: u,d quark energy loss

$p_T^{\gamma} > 60\,\mathrm{GeV}/c$

$p_T^{\mathrm{Jet}} > 30\,\mathrm{GeV}/c$

$x_{J\gamma} = p_T^{\mathrm{Jet}} / p_T^{\gamma}$

nucl-ex/1205.0206



Jet-photon p_T balance drops by 14%

20% of photons lose jet partner

D meson R_{AA}

Color factor → $\Delta E_g > \Delta E_q$

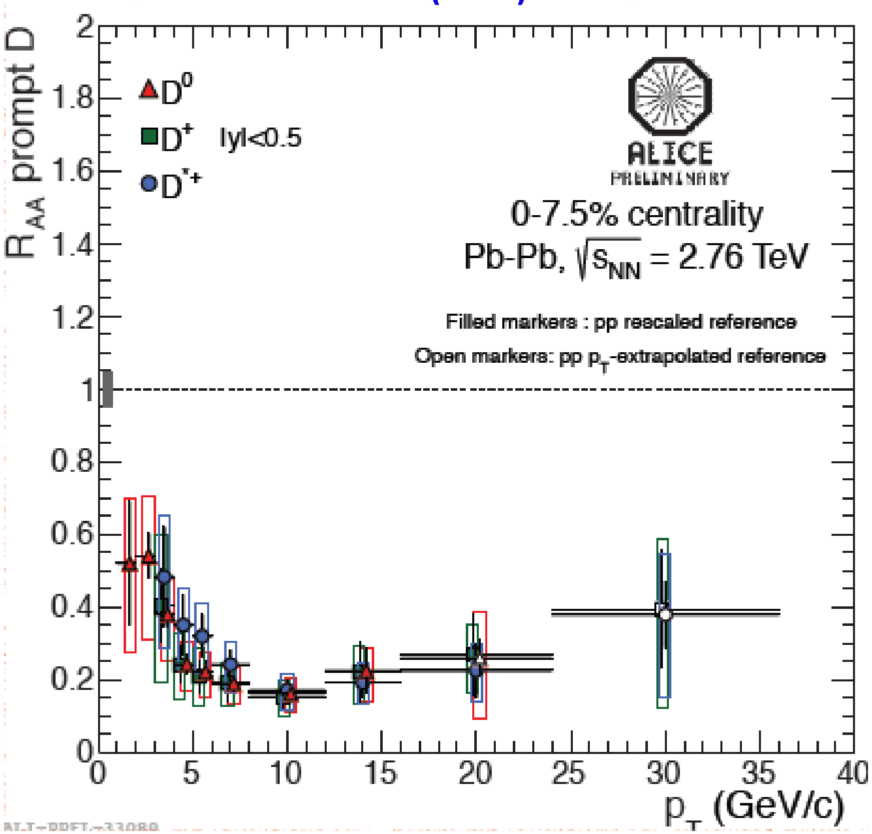
Dead cone effect → $\Delta E_q > \Delta E_Q$

$\Delta E_g > \Delta E_c > \Delta E_b$

Meson R_{AA}: π< D < B

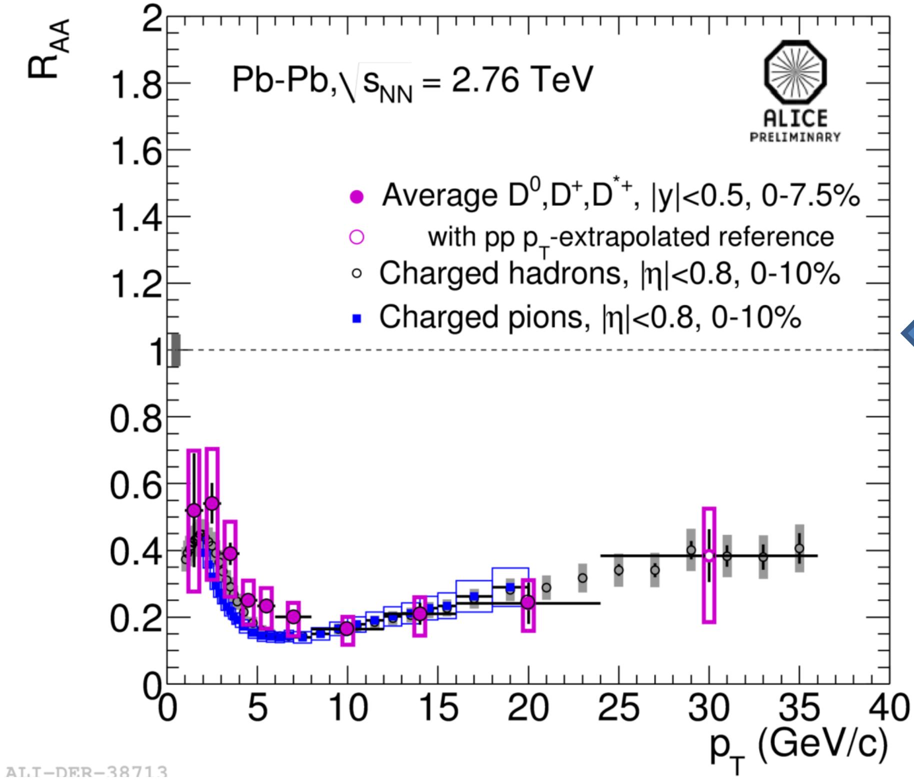
Jet R_{AA}: g < uds < c < b

JHEP 1209 (2012) 112



- D^0, D^+ and D^{*+} R_{AA} compatible within uncertainties.
- Suppression up to a factor 5 at p_T ~ 10 GeV/c.

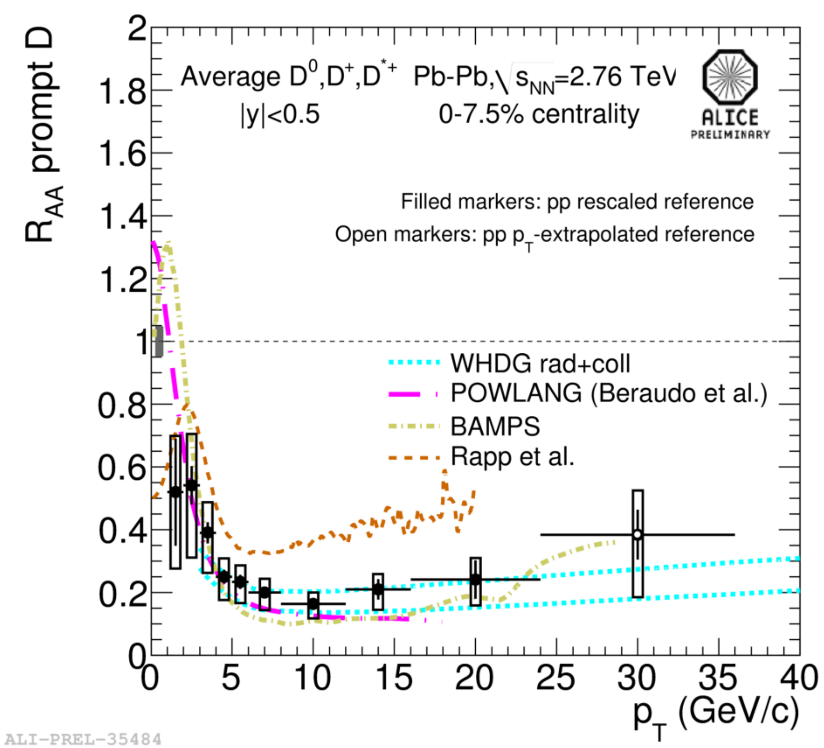
D meson R_{AA}: comparison to charged pions

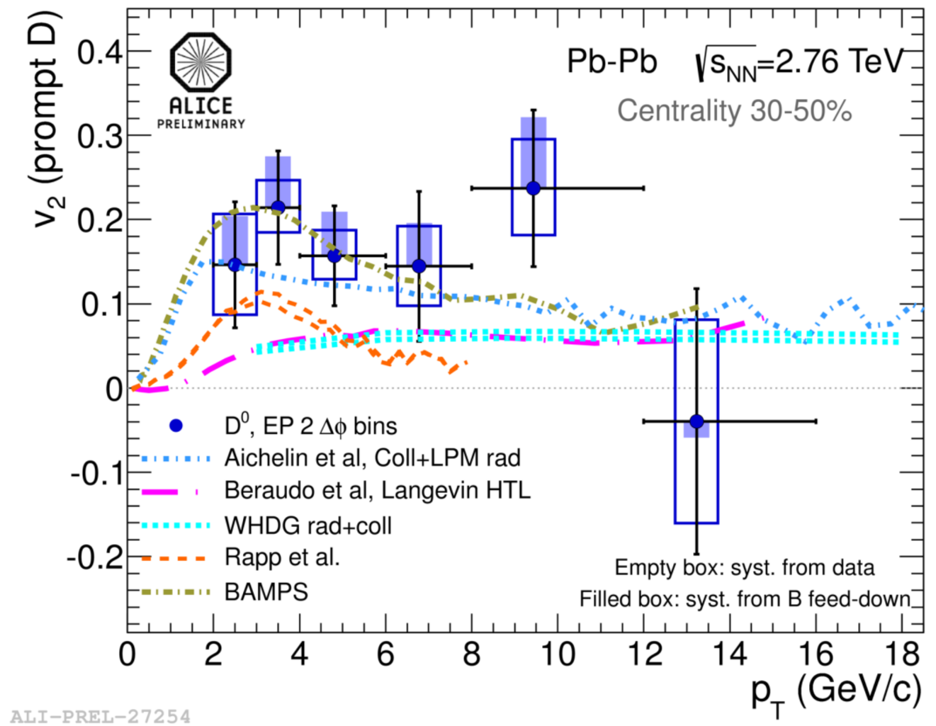


Average D-meson R_{AA}:

- – p_T < 8 GeV/*c* hint of slightly less suppression than for light hadrons
- – p_T > 8 GeV/*c* both (all) very similar: no indication of colour charge dependence

D meson v_2





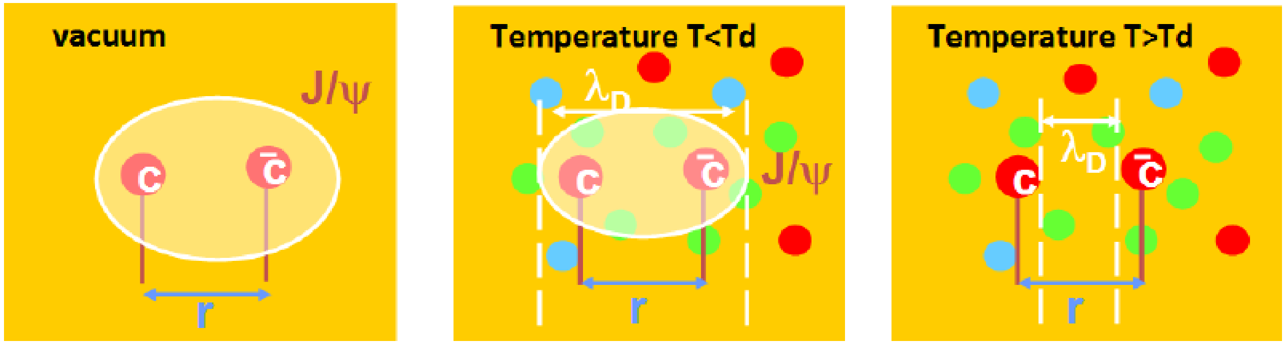
Non-zero D-meson elliptic flow observed:

- consistent among D-meson species (D^0, D^+, D^{*+})
- comparable to v_2 of light hadrons

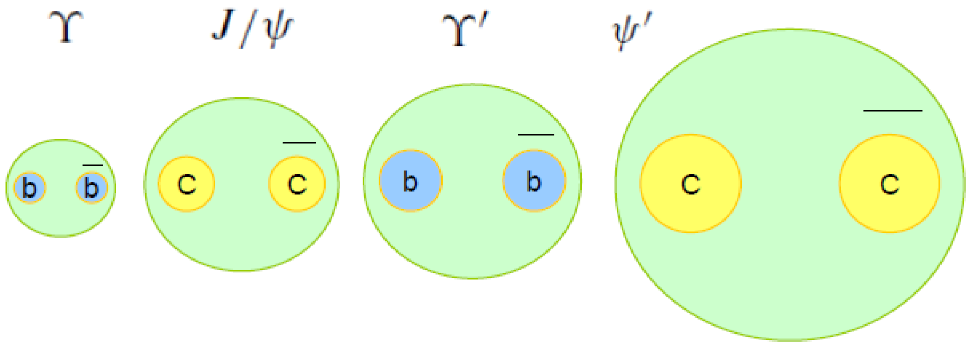
Simultaneous description of R_{AA} and v_2 – challenge for transport models

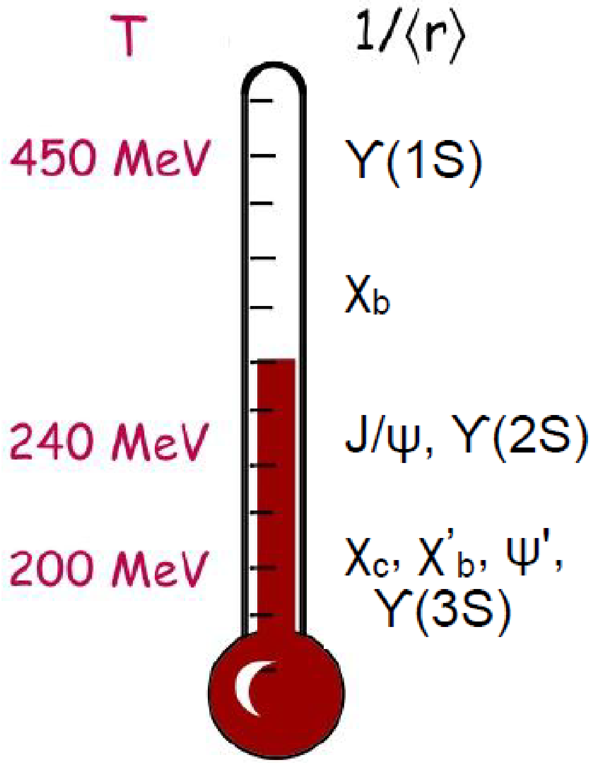
Quarkonia

Screening and initial temperature



Matsui & Satz, PLB168 (1986) 415



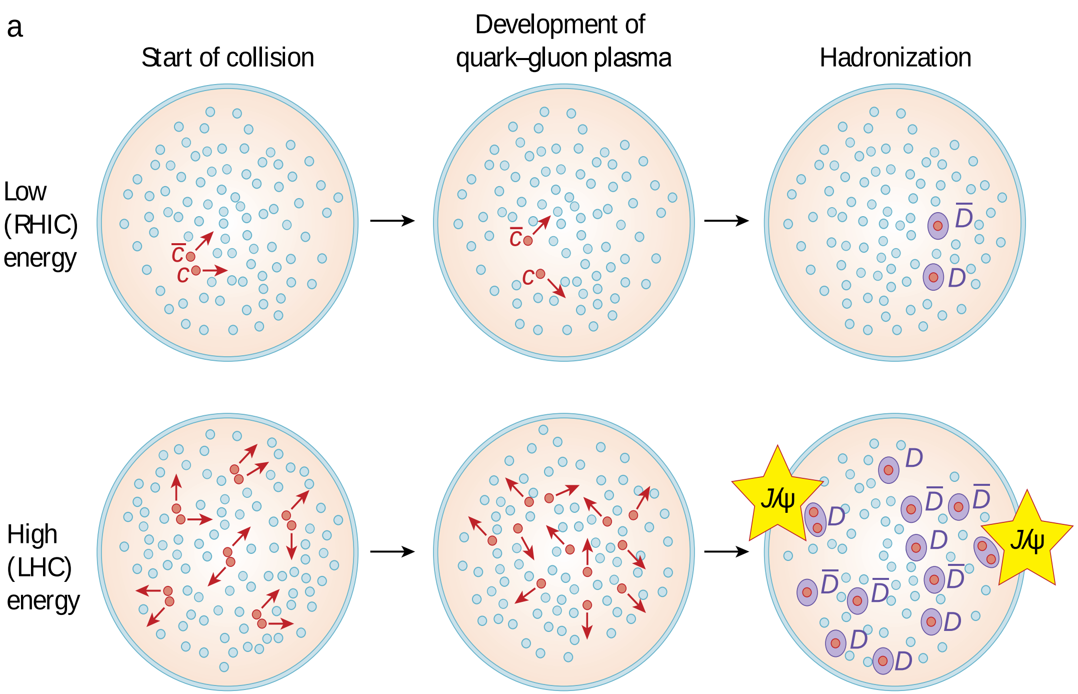


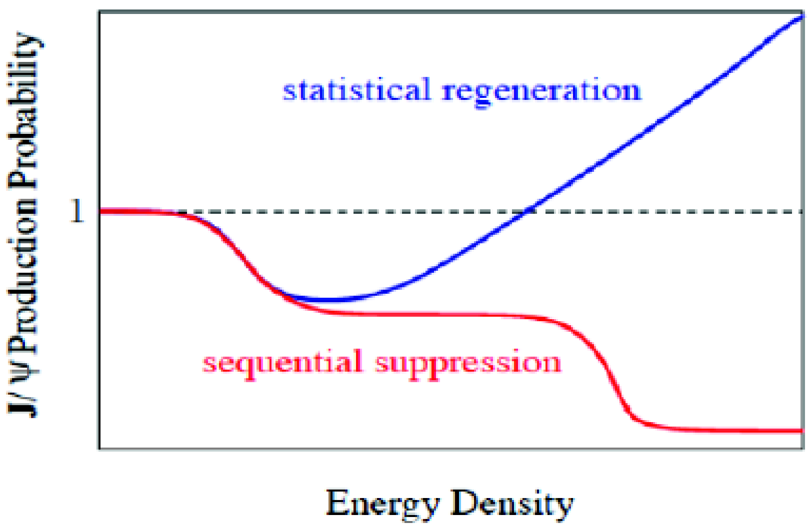
- Different states have different binding energies Loosely bound states melt first!
- Successive suppression of individual states provides a "thermometer" of the QGP

Suppression or enhancement?

- **LHC energies :** Enhancement via (re)generation of quarkonia, due to the large heavy-quark multiplicity (A. Andronic et al., PLB 571, 36 (2003))

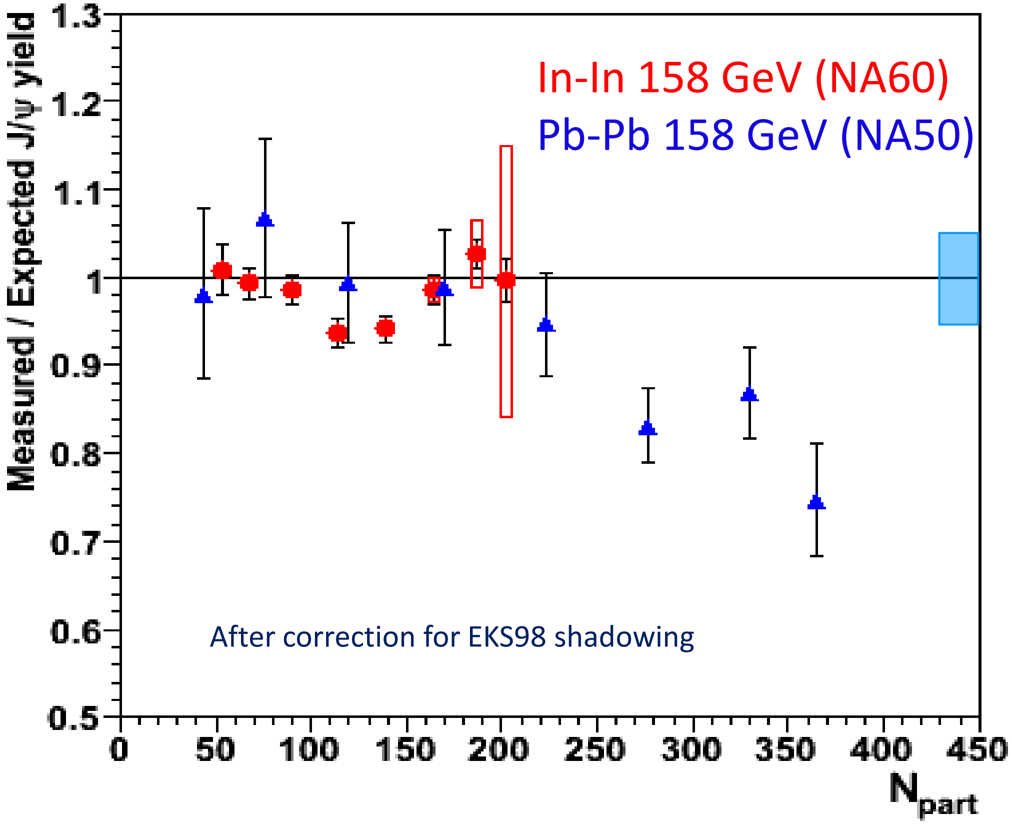
In most central A-A collisions	SPS 20 GeV	RHIC 200 Gev	LHC 2.76 TeV
N_{ccbar}/event	~0.2	~10	~60





SPS summary plot

NA50 (Pb-Pb) and NA60 (In-In) results:



B. Alessandro et al. (NA50), EPJC39 (2005) 335
R. Arnaldi et al. (NA60), Nucl. Phys. A (2009) 345

- Anomalous suppression for central Pb-Pb collisions
- Agreement between Pb-Pb and In-In in the common N_{part} region
- Pb-Pb data not precise enough to clarify the details of the pattern!

Anomalous suppression up to ~30%, compatible with $\psi(2S)$ and χ_c melting, i.e. with a sequential suppression scenario!

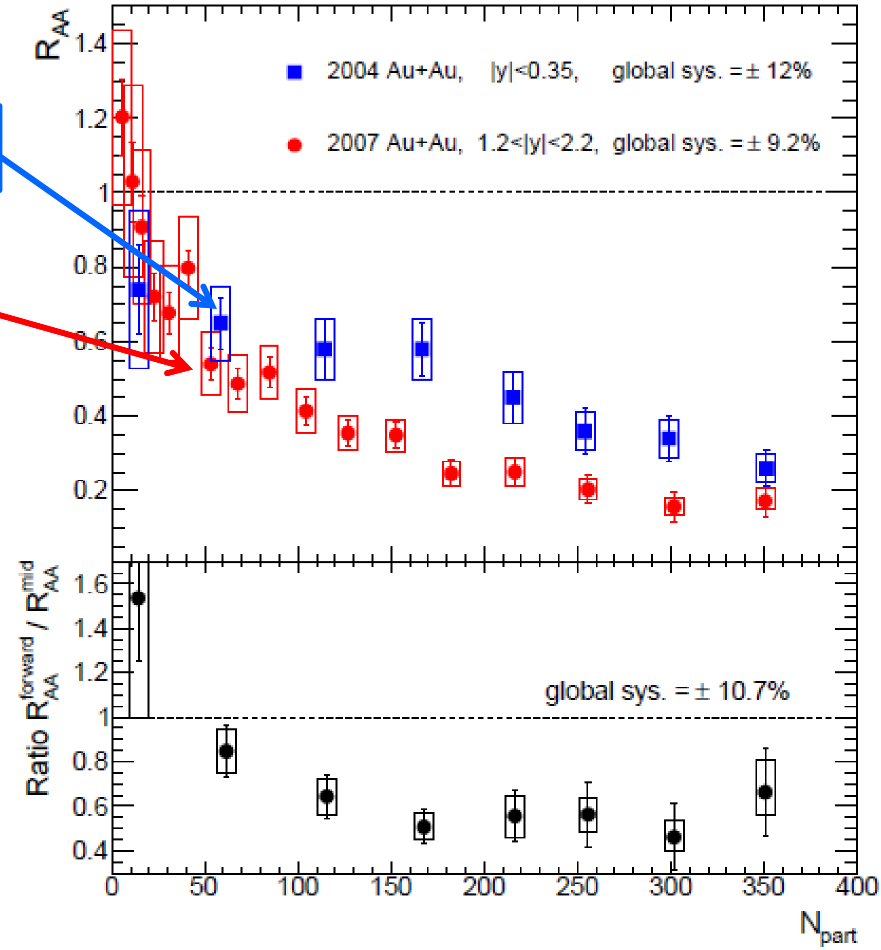
RHIC results

- Comparison of R_{AA} results obtained at different rapidities

Mid-rapidity

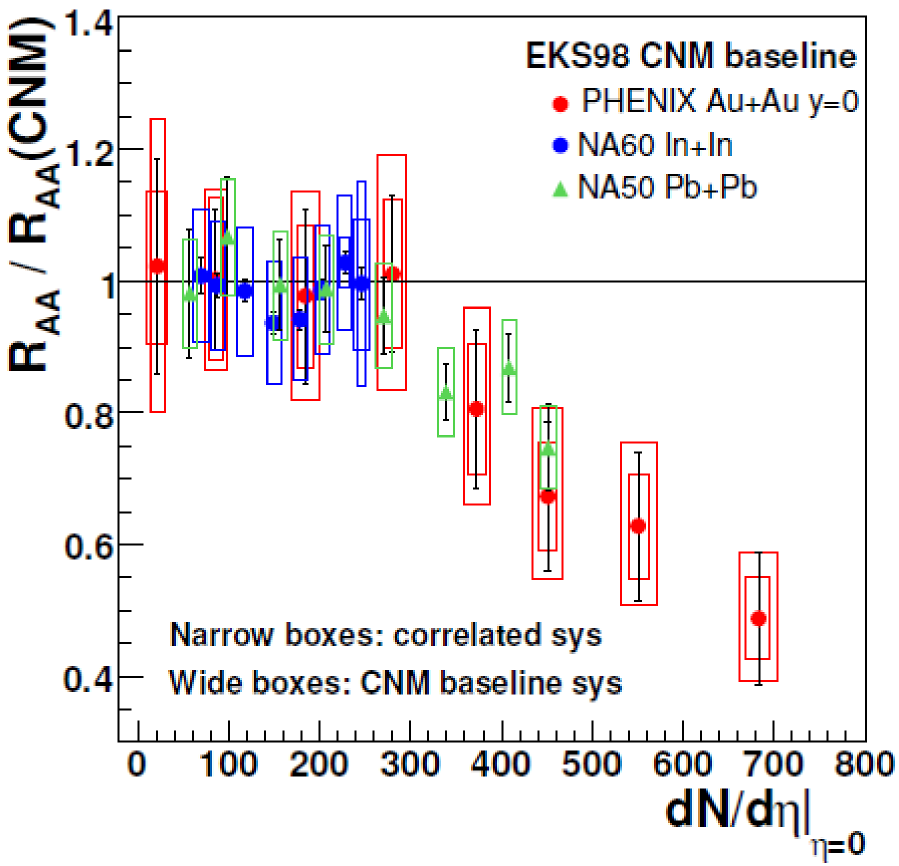
Forward-rapidity

- Stronger suppression at forward rapidities



- ❑ Not expected if suppression increases with energy density (which should be larger at central rapidity)
- ❑ Are we seeing a hint of (re)generation, since there are more pairs at y=0?
- ❑ Or may other effects (e.g. cold nuclear matter effects) explain this feature ?

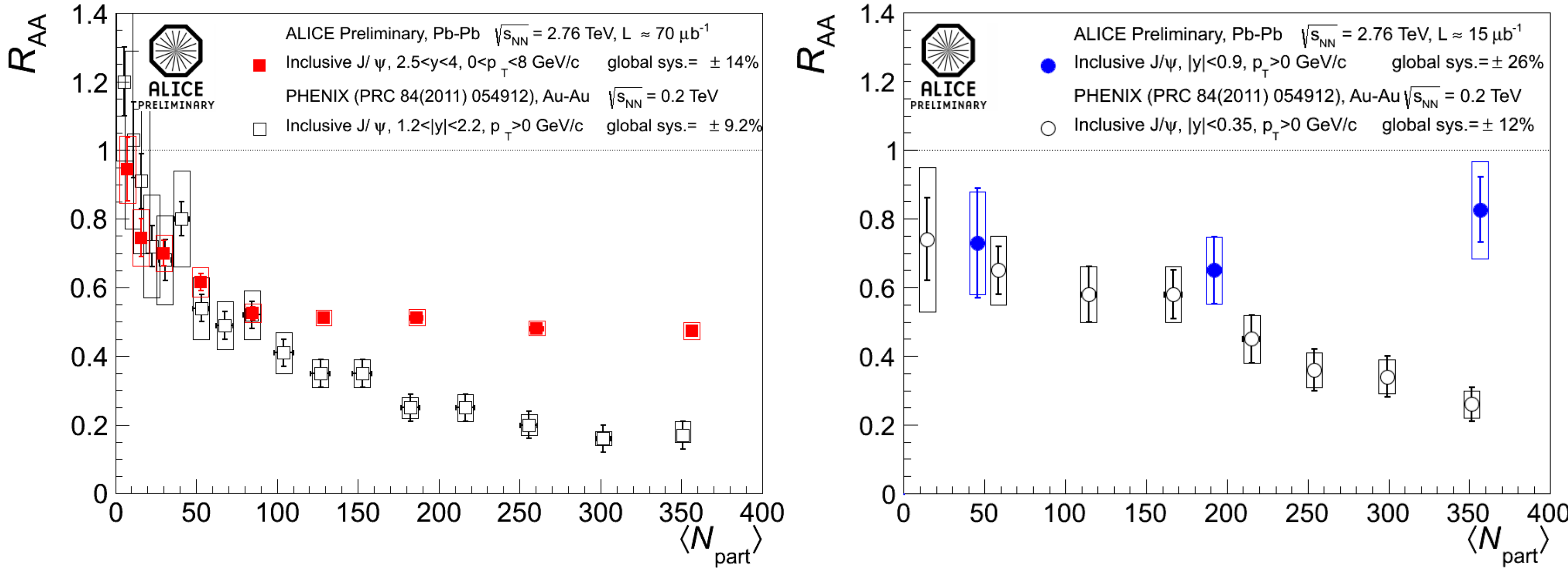
RHIC vs SPS



N.Brambilla et al., EPJ C71(2011) 1534

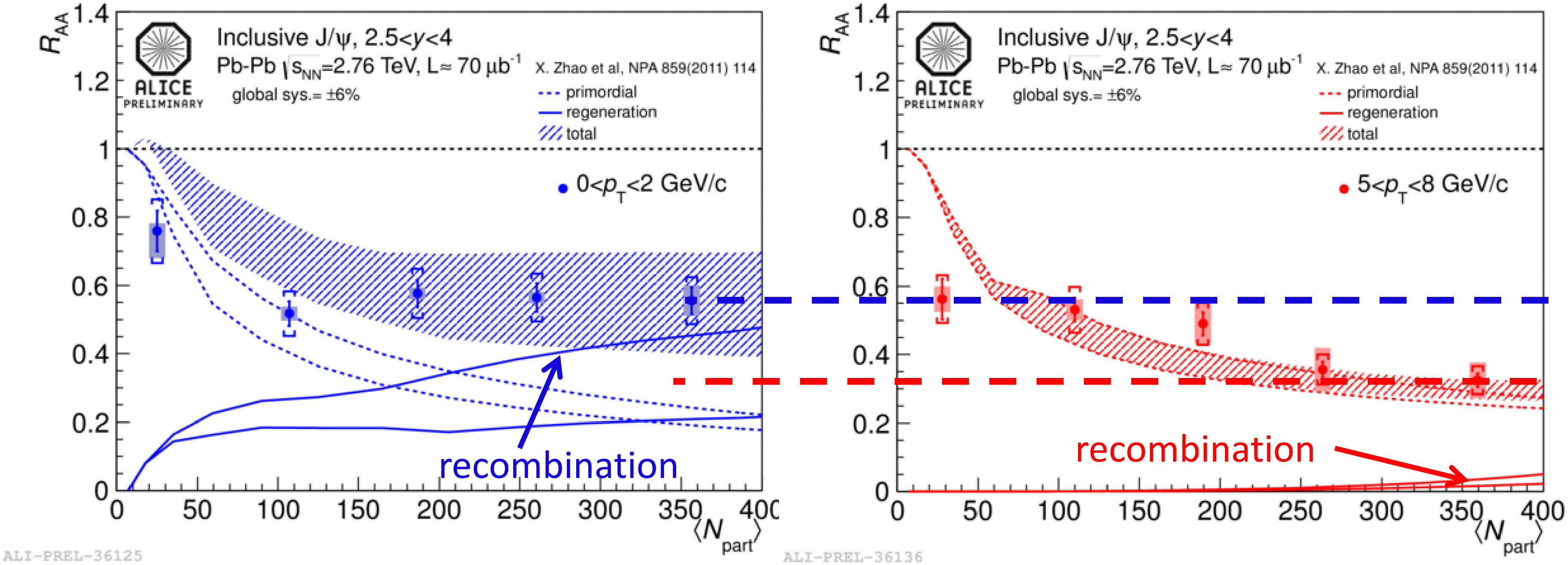
- Nice "universal" behavior
- Maximum suppression ~40-50%, still compatible with only $\psi(2S)$ and χ_c melting

J/ψ suppression at LHC: R_{AA} vs $\langle N_{part} \rangle$



- Comparison with PHENIX: stronger centrality dependence at lower energy
- Systematically larger R_{AA} values for central events in ALICE
- Behaviour qualitatively expected in a (re)generation scenario
  → Look at theoretical models

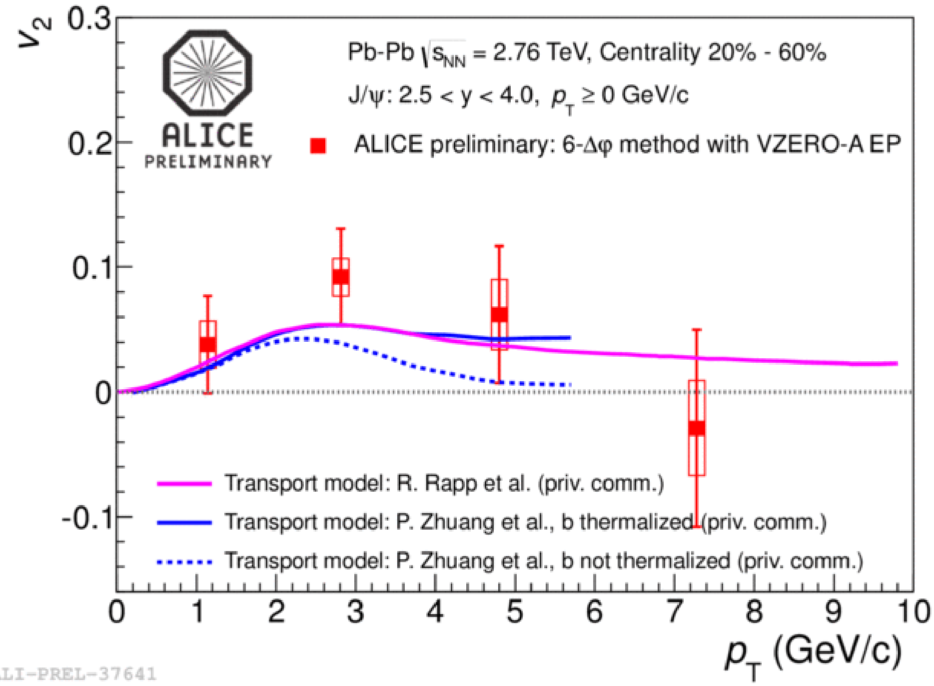
R_{AA} vs $\langle N_{part} \rangle$ in p_T bins

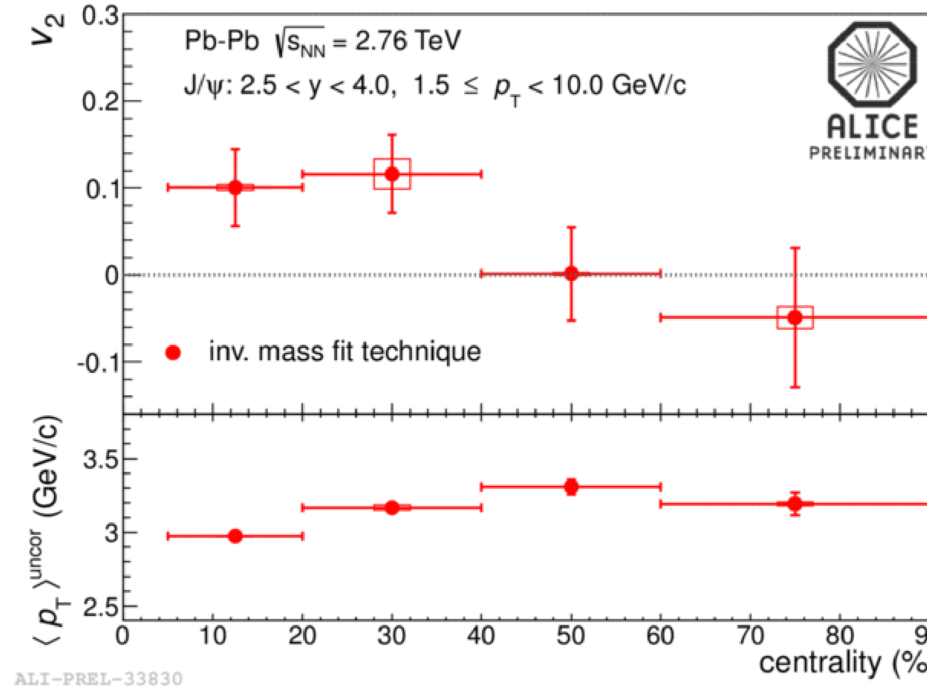


- Compare R_{AA} vs $\langle N_{part} \rangle$ for low-p_T (0<p_T<2 GeV/c) and high-p_T (5<p_T<8 GeV/c) J/ψ
- Different suppression pattern for low- and high-p_T J/ψ
- Smaller RAA for high p_T J/ψ
- In the models, ~50% of low-p_T J/ψ are produced via (re)combination, while at high p_T the contribution is negligible → fair agreement from N_{part}~100 onwards
- Need pA for cold nuclear matter effects

J/ψ v_2

The contribution of J/ψ from recombination should lead to a significant elliptic flow signal at LHC energy





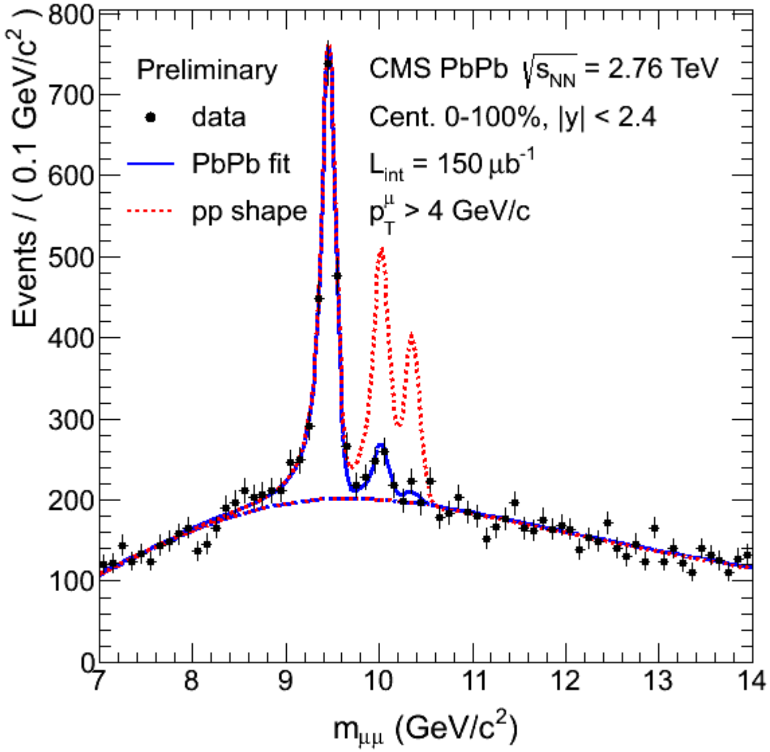
- STAR: v_2 compatible with zero everywhere
- ALICE: hint for non-zero v_2
- Significance up to 3.5 σ

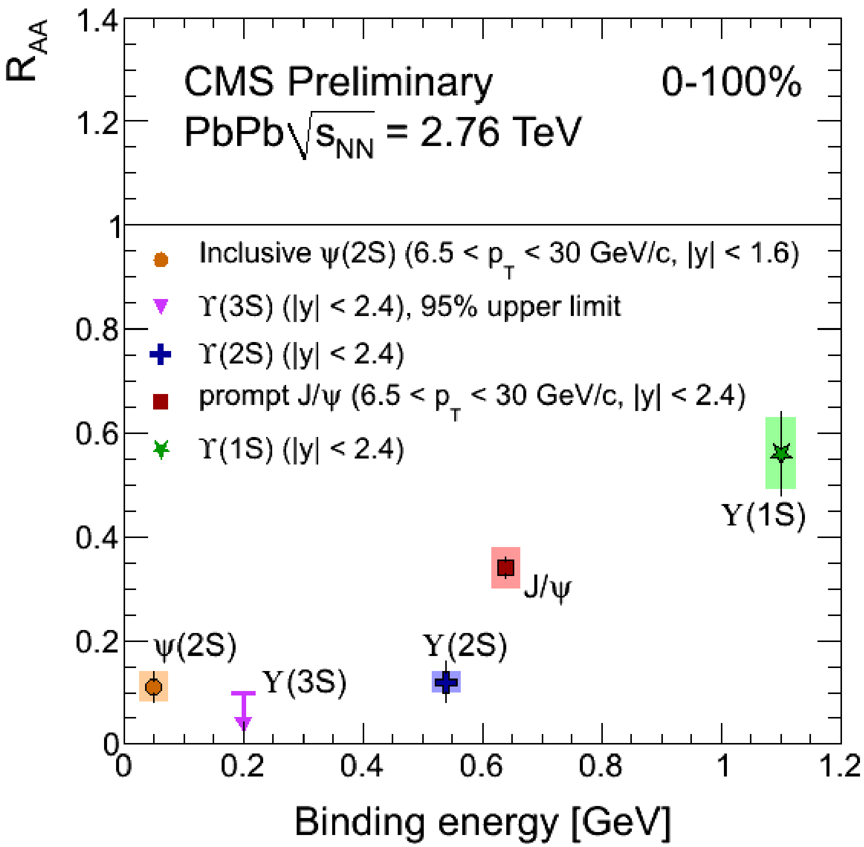
- Qualitative agreement with transport models including regeneration

Sequential suppression

2011 data

arXiv:1208.2826





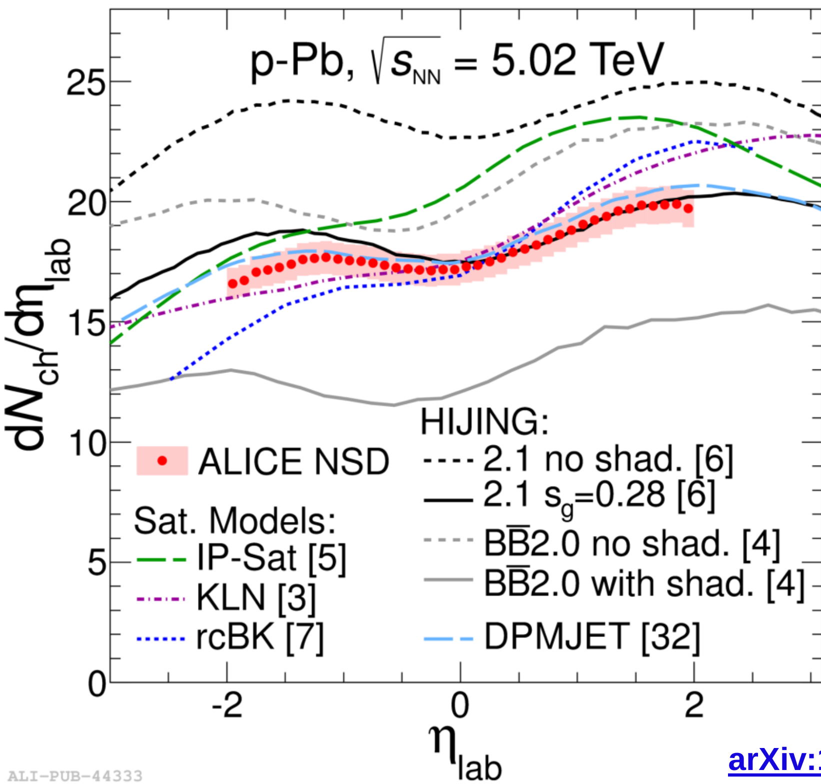
Observation of sequential suppression of ϒ family

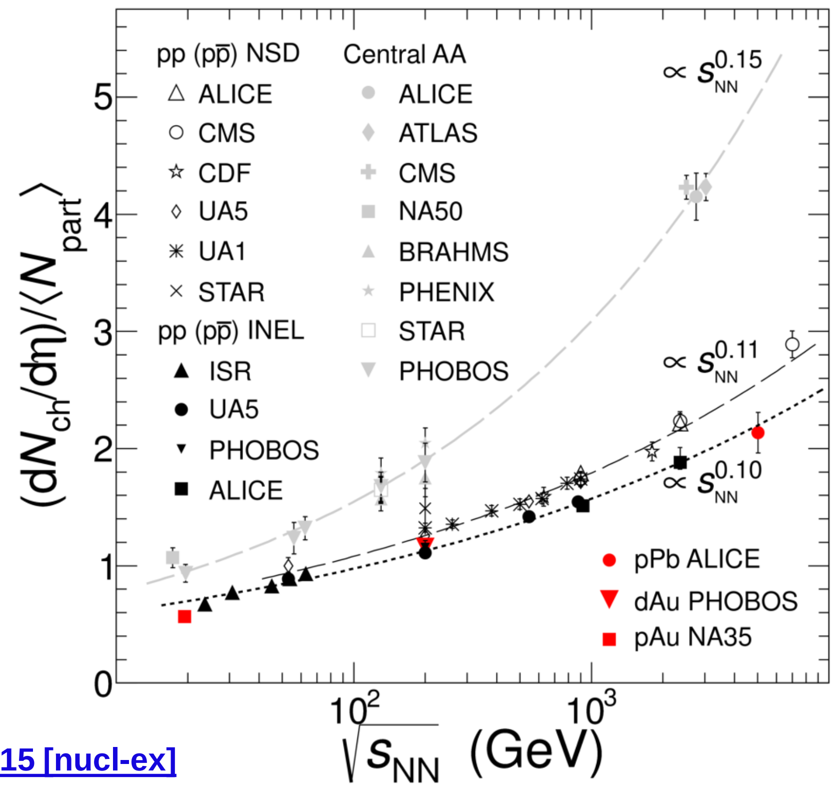
Expected in terms of binding energy

CMS-PAS HIN-12-014, HIN-12-007

pA highlights

$dN_{ch}/d\eta$ in p-Pb collisions

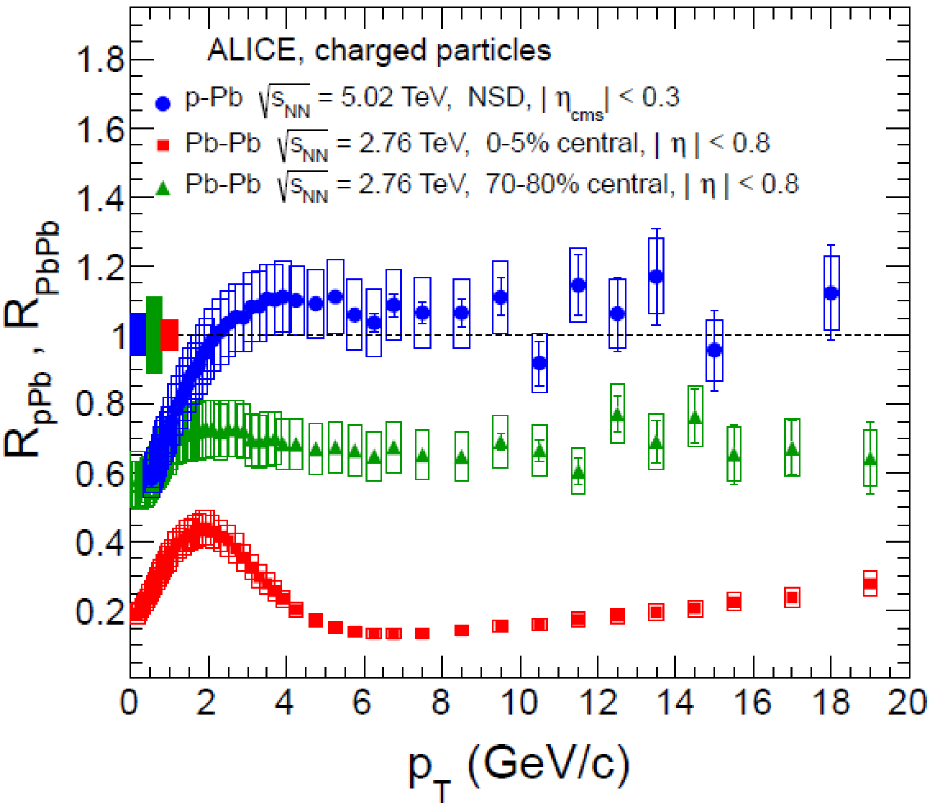


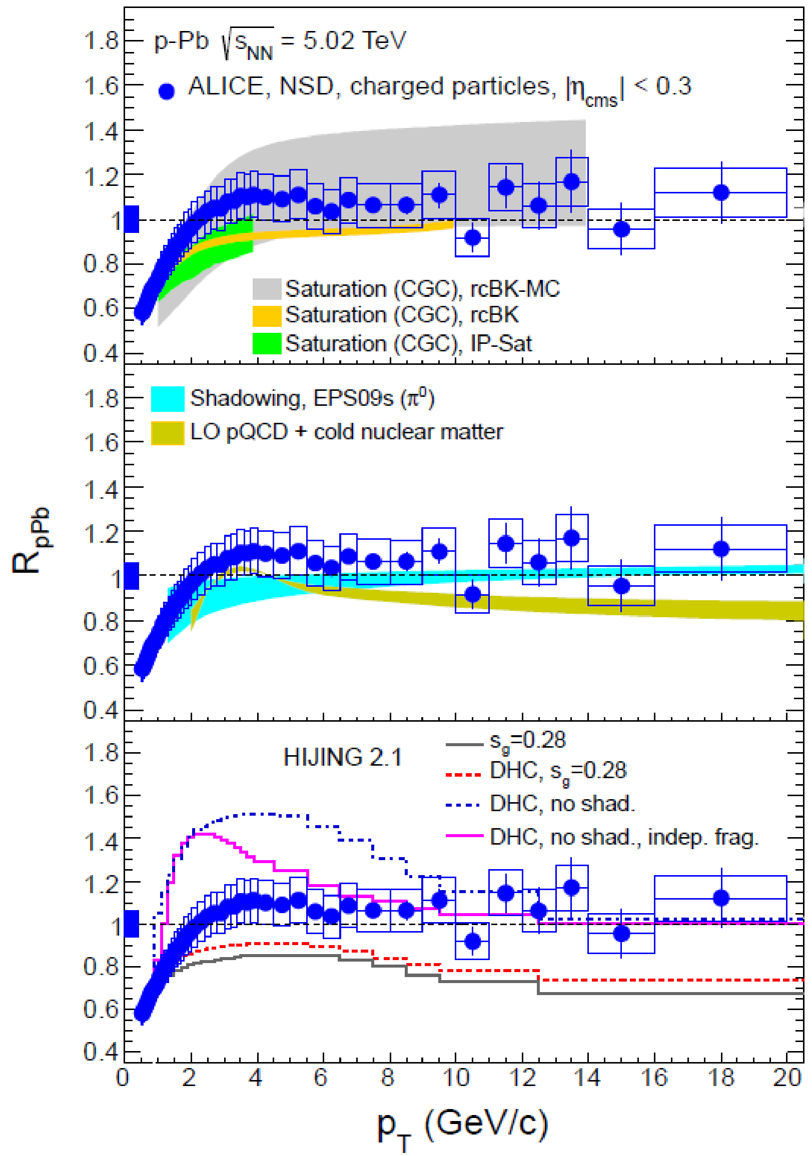


arXiv:1210.3615 [nucl-ex]

- pA crucial to discriminate between initial (cold nuclear matter) effects and QGP dynamics
- p-Pb at LHC → probe nuclear wave-function at low x → nuclear gluon shadowing
- CGC: steeper η_{lab} dependence than the data
- HIJING (with shadowing) and DPMJET: describe the η-shape rather well
- mid-rapidity ⟨Npart⟩ normalized $\langle dN_{ch}/d\eta \rangle$ p-Pb similar trend to pp

Charged particle R_{pA}





- consistent with unity for $p_T > 2$ GeV/c
- the strong suppression observed in Pb-Pb is NOT an initial-state but hot QCD matter effect

arXiv:1210.4520 [nucl-ex]

Conclusions

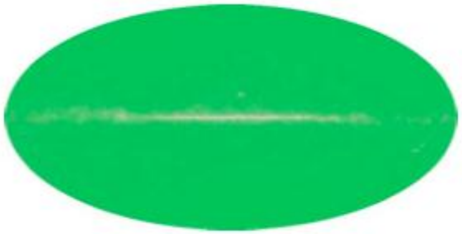
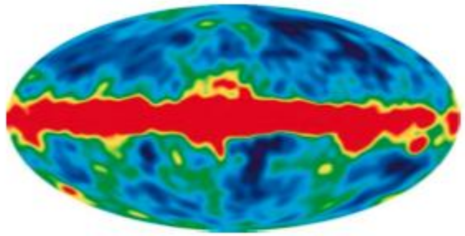
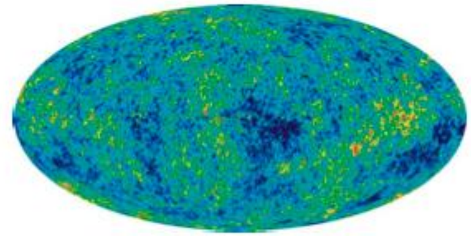
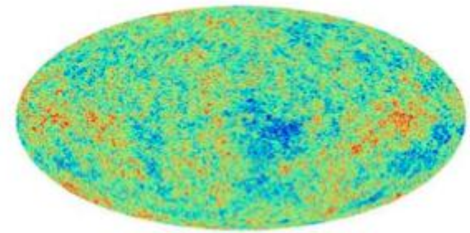
- Early to make conclusions…

- Wealth of physics results from RHIC and first two LHC heavy-ion runs:
  - bulk, soft probes: spectra and flow of identified particles, thermal photons
  - high-p_T probes: jet fragmentation, particle-type dependent correlations
  - heavy-flavour physics: suppression and flow of D mesons, quarkonia

- Entering the precision measurement era:
  - First studies of cold nuclear matter effects with p–Pb collisions, more next year

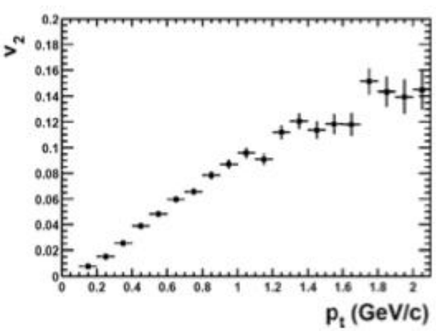
A (valid) analogy

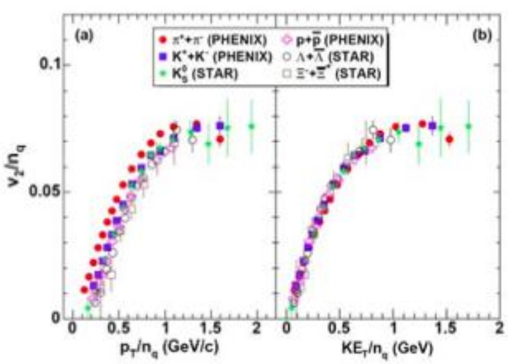
Penzias/Wilson 1965	COBE 2003	WMAP 2007	Planck 2012

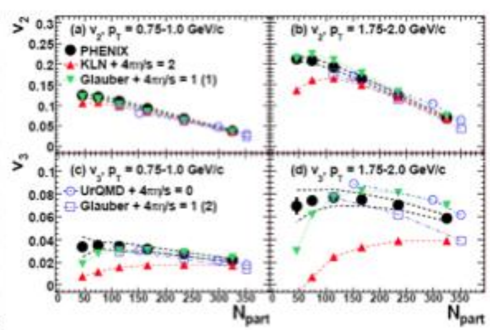





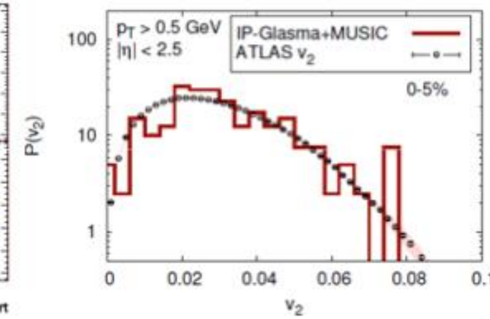
D I S C O V E R Y.....

..... P R E C I S I O N









2001	2004	2008	2012

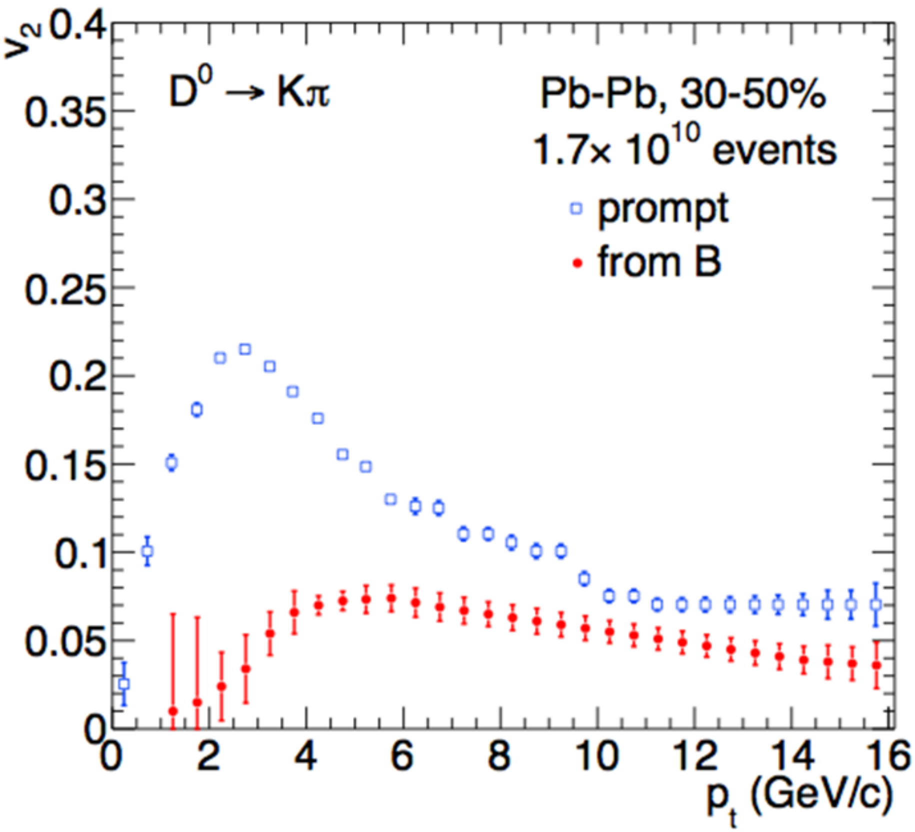
Backup

ALICE physics perspectives

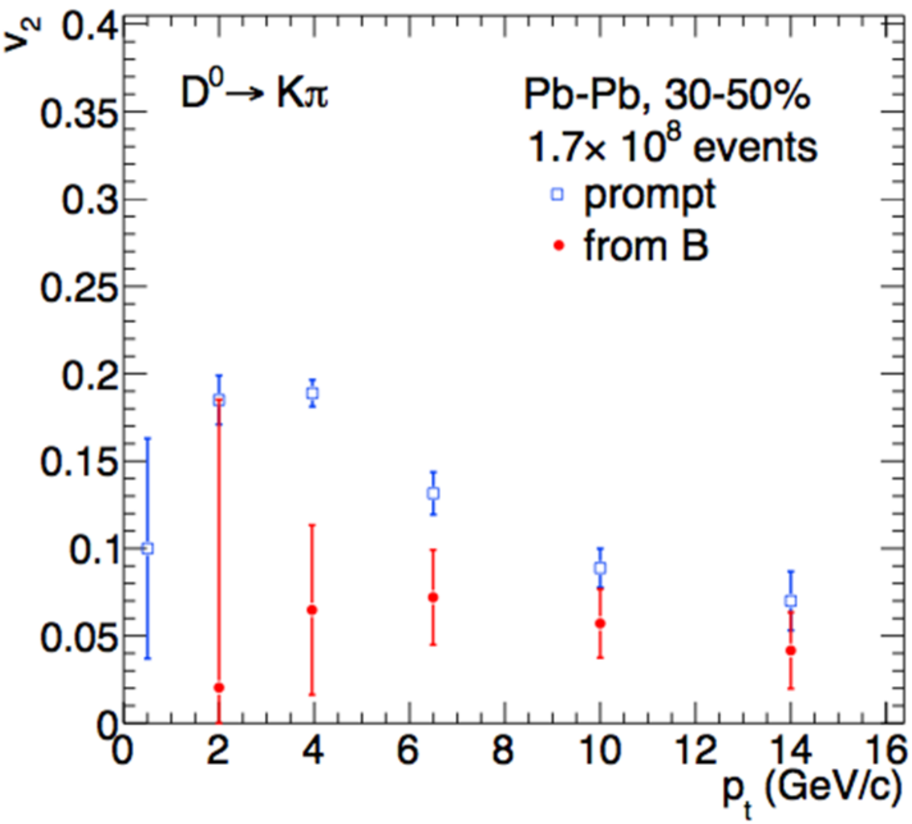
		Status as of today	Reachable for approved	Reach with the upgrade
Bulk production	light flavours, v_2, HBT	quantitative	precision	precision
Intermediate p_t	v_2, correlations, baryon-meson	quantitative	precision	precision
High-p_t – jets	R_{AA}, correlations, jet fragm.	quantitative	precision	precision
	heavy-flavour in jets		hint	quantitative
	PID fragmentation	hint	quantitative	precision
Heavy flavour	D-mesons, R_{AA}	quantitative		precision
	D-meson v_2	hint		precision
	beauty, D_s	hint	quantitative	precision
	charm baryons		hint	Quantitative
Charmonia	J/ψ forward, R_{AA}	quantitative	precision	Precision
	J/ψ v_2	hint	quantitative	precision
	ψ', χ_c			quantitative
	J/ψ central, Υ family	hint	quantitative	precision
Dileptons – γ	virtual γ	hint		quantitative
	ρ-meson			quantitative
Heavy nuclei	hyper(anti)nuclei, H-dibaryon	hint	quantitative	precision

Example: Heavy-flavour v_2

High rate, new ITS



No high rate, new ITS



- need >> 1 nb^{-1} for precise measurement of charm and beauty v_2
- systematic uncertainties and corrections mostly cancel in v_2
- Other key measurements: Λ_b, Ξ_c, B decays, virtual γ, ψ', χ_c, tagged jets…