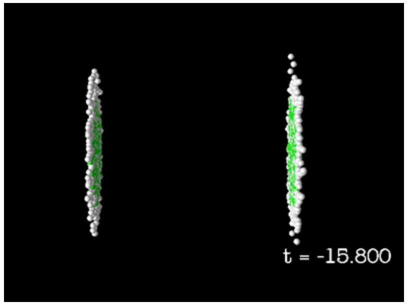
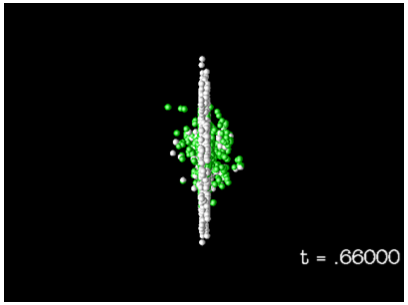
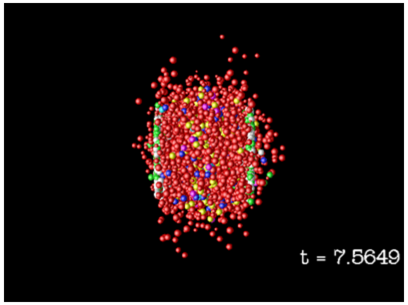
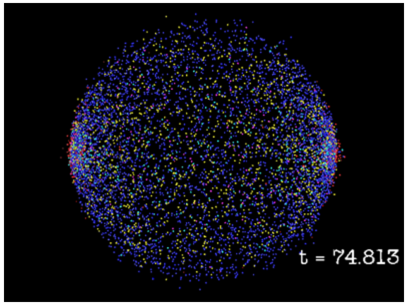
XLVIIIth Rencontres de Moriond: QCD and High-Energy Interactions


Lorentz contracted heavy ions


initial conditions


QGP


hadronisation

HEAVY-ION SESSION: A (QUICK) INTRODUCTION

Boris HIPPOLYTE (IPHC, Université de Strasbourg)

Moriond 2013 | La Thuile, Aoste Valley | Friday March the 15th

OUTLINE

- Precision measurements of the Quark-Gluon Plasma properties
  - ➡ results at the Large Hadron Collider and Relativistic Heavy Ion Collider
    - at the LHC (Pb-Pb): $\sqrt{s_{NN}}$ = 2.76 **TeV**
    - [at RHIC (Au-Au): $\sqrt{s_{NN}}$ = 7.7 - 11.5 - 19.6 - 27 - 39 - 62.4 - 200 **GeV** (Beam Energy Scan: BES)]
    - comparisons with “**reference**” colliding systems: pp and p-Pb at the LHC, pp, d-Au, Cu-Cu at RHIC
  - ➡ in fact, not only properties: studying the whole evolution of the QGP
    - initial state conditions, including **fluctuations**
    - “perfect” fluid: **dissipative fluid dynamic** works amazingly well (for soft particle emission)
    - “opaque”: hard hadronic processes are **strongly quenched** (high-p_T hadron, jet production, correlations)
    - [“hot”: photon spectrum and sequential melting of quarkonia]

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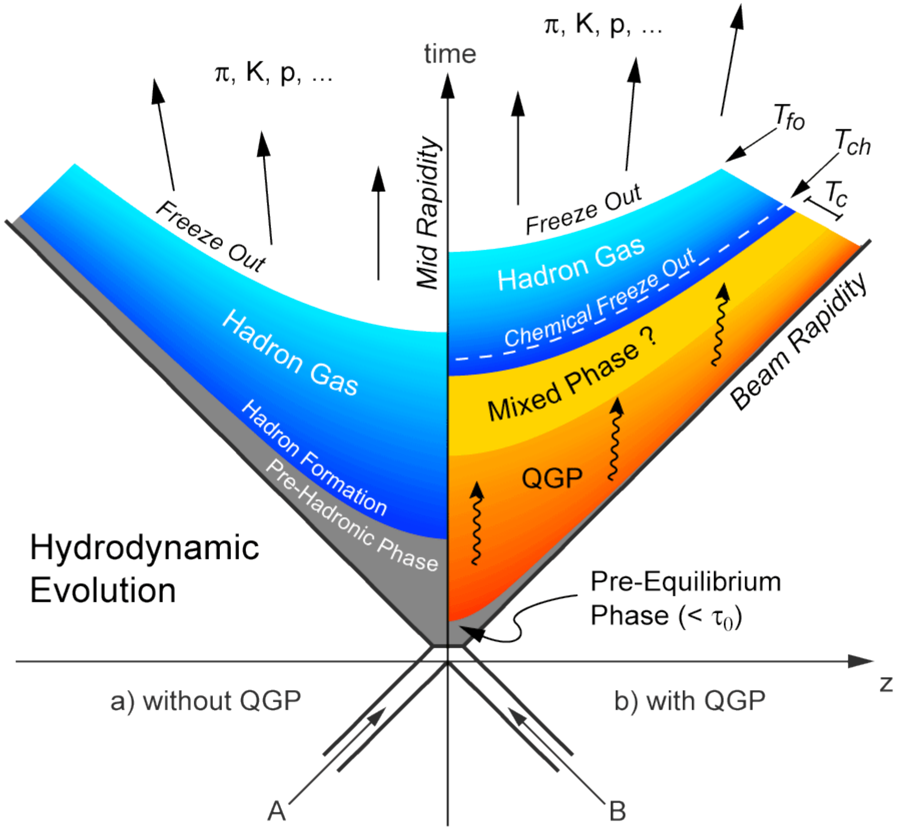
- Only an "introduction" (obviously, for it to fit in ~20 mins...)
  - ➡ focus on global pictures describing the Heavy-Ion (HI) collision
    - more precise understanding of the initial conditions
    - Lattice QCD and hydrodynamics: Equation of state (EOS) and transport coefficients
    - several definitions and keys questions related to global observables
  - ➡ leave highlights and latest developments / results to following talks

EVOLUTION OF THE SYSTEM CREATED IN H-I COLLISIONS

- ➡ Initial pre-equilibrium state
- ➡ parton scattering & jet production
  - gluonic fields (Color Glass Condensate)
  - heavy flavour production
- ➡ Thermalization (hydrodynamics)
- ➡ QGP expansion and cooling
- ➡ Phase transition (T_c)
  - hadronisation mechanism(s) (partons→ hadrons)
  - chemical freeze-out (abundances fixed at T_{ch})
- ➡ Hadronic phase
  - rescattering and kinetic freeze-out (stop interacting at T_{fo})

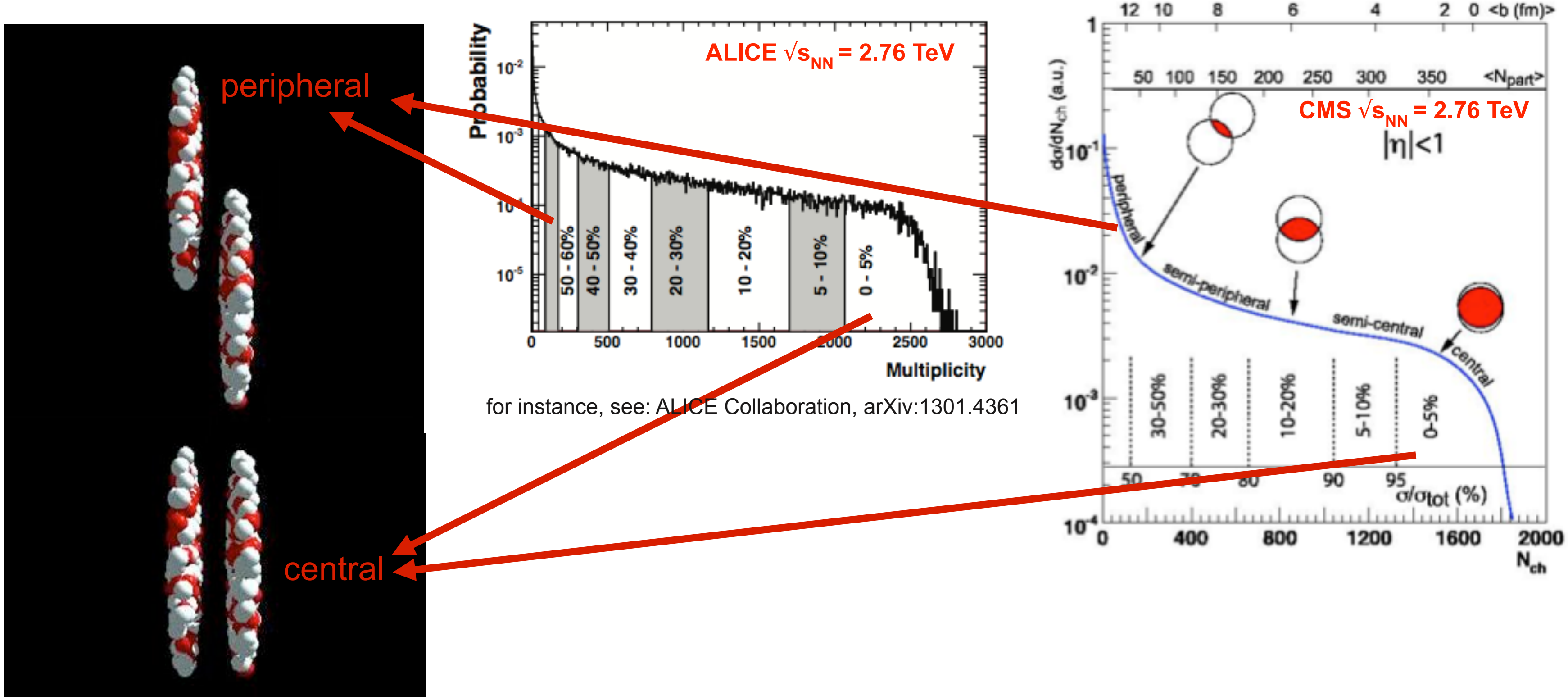


SIMPLIFIED (PEDAGOGICAL) PICTURE:

- “guidelines” used to separate **hard** and **soft** probes of the QGP
- devil is at the **interfaces**
- measurements often correspond to **“integrated-over-time”** observables

DEFINING CENTRALITY IN A HEAVY-ION COLLISION

- correlate the multiplicity of produced particles with the geometry of the system i.e. impact parameter, volume and (roughly) the shape...



for instance, see: ALICE Collaboration, arXiv:1301.4361

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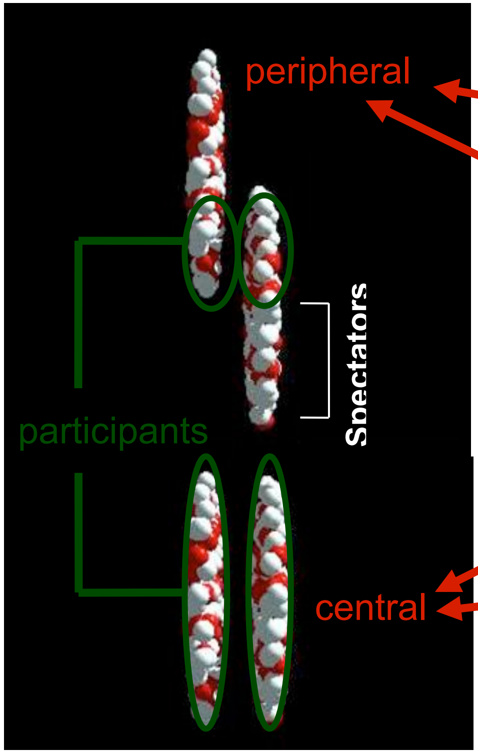

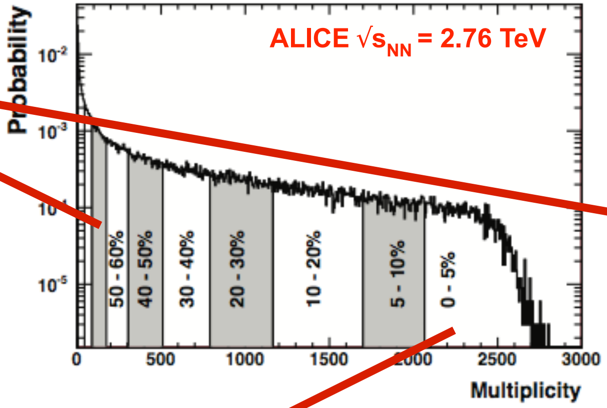

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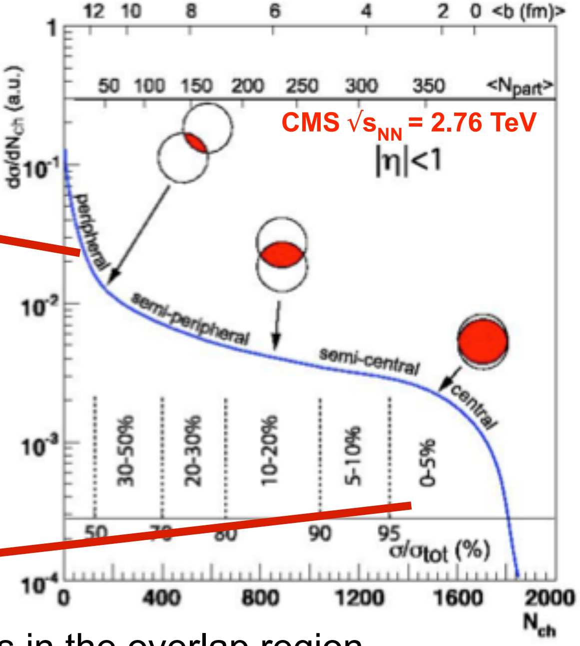

Number of participants (N_{part}): nucleons in the overlap region

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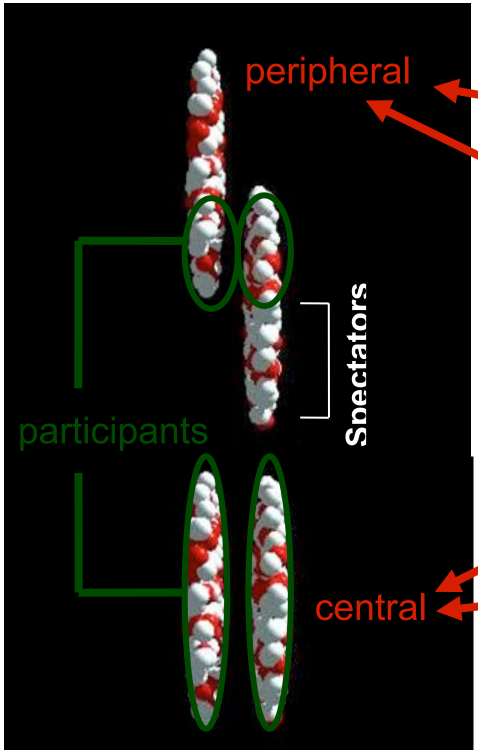

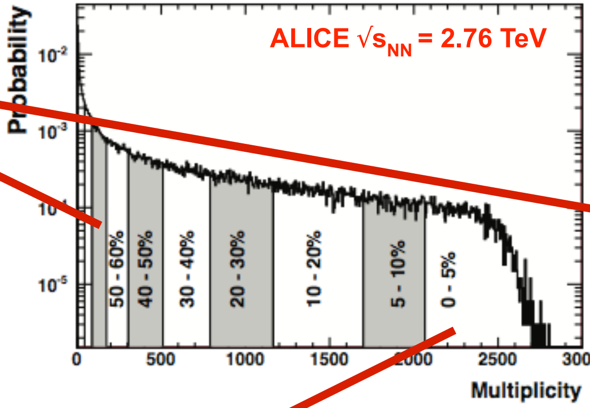

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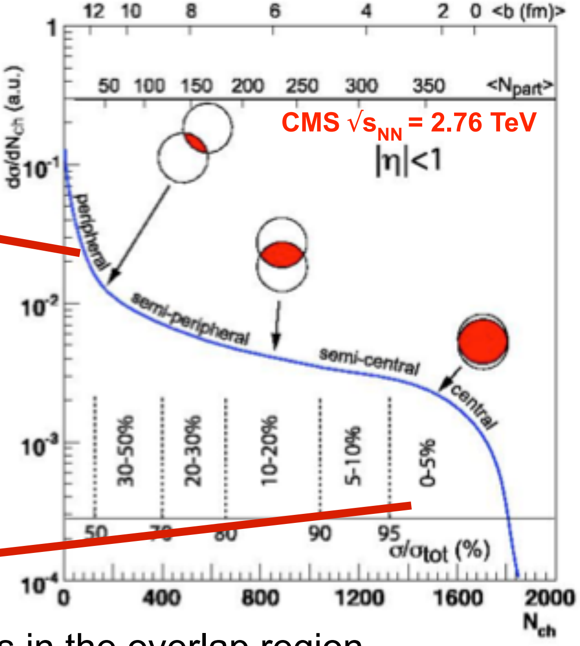

Number of participants ($N_{\rm part}$): nucleons in the overlap region

Number of binary collisions ($N_{\rm coll}$): nucleon-nucleon inelastic collisions

Geometric nuclear overlap function: $T_{\rm AA} = N_{\rm coll}/\sigma_{\rm NN}^{\rm inel}$

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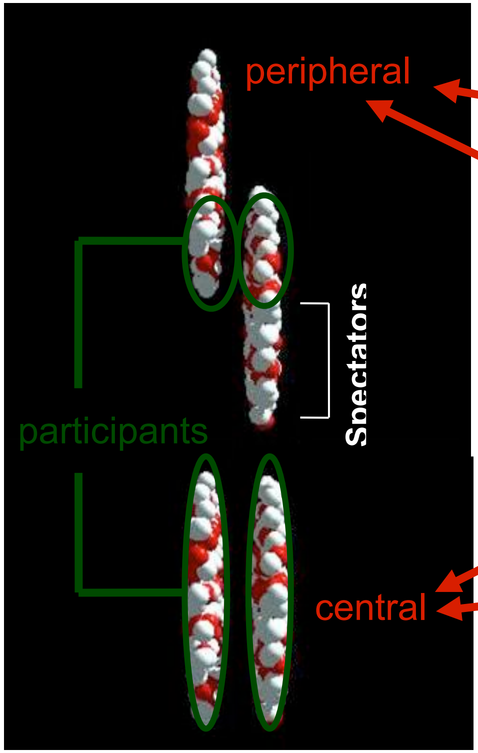

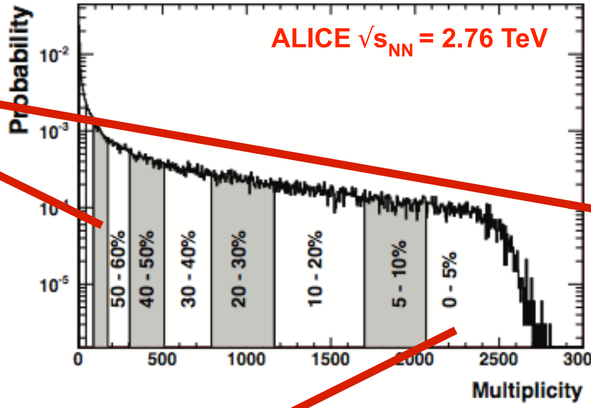

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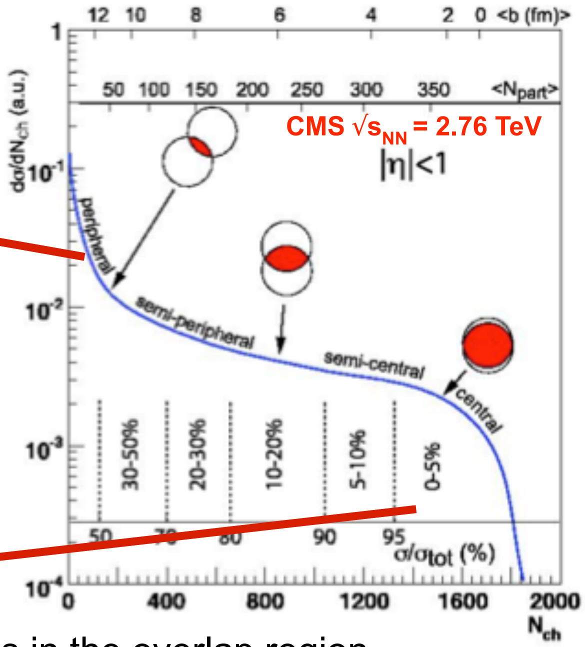

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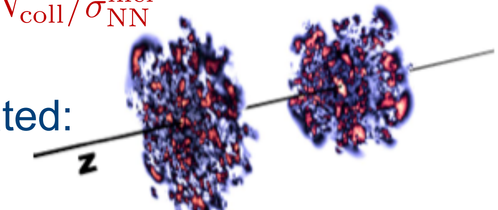
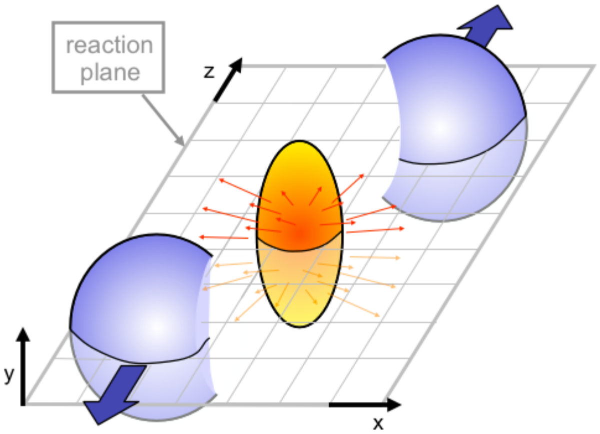
In the details, the situation is “slightly” (;-)) more complicated:
→ after centrality, fluctuations play an important role



ECCENTRICITY, FLOW COEFFICIENTS AND FLUCTUATIONS

non-central collisions



Initial **coordinate** space anisotropy

Anisotropy in azimuthal angle described by a Fourier series:

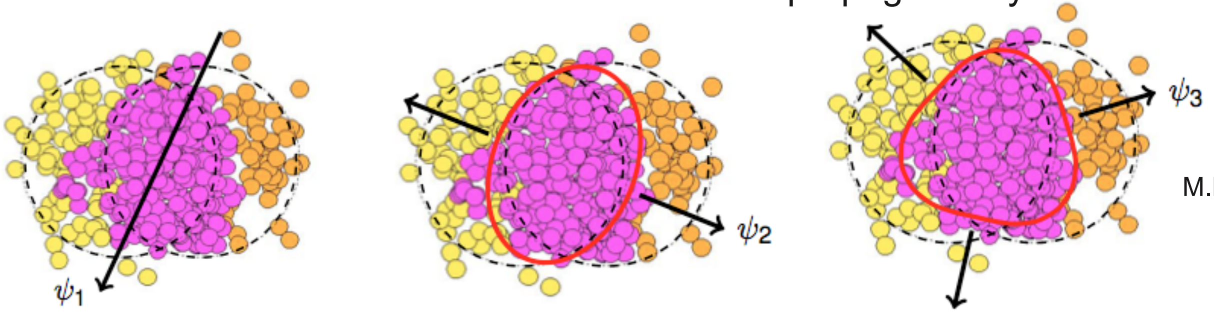
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Phi_n)$$

EXPERIMENTAL RESULTS

- ➡ 2nd order (v_2) dominates in non-central collisions
- ➡ Higher flow harmonics: sizable, own event plane angle
- ➡ v_n decreases with increasing n: typical of viscous fluid (damping)
- ➡ Odd harmonics with weak centrality dependence: **fluctuations**

CLEAR PICTURE

- ➡ $v_n \propto \varepsilon_n$
- ➡ Initial fluctuations propagated by a viscous fluid



M.Luzum, arXiv:1107.0592

Importance of the description of the initial conditions

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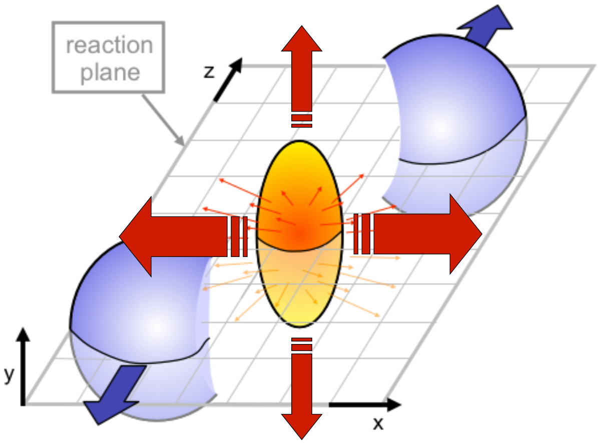

Initial **coordinate** space anisotropy
→ **momentum** space anisotropy

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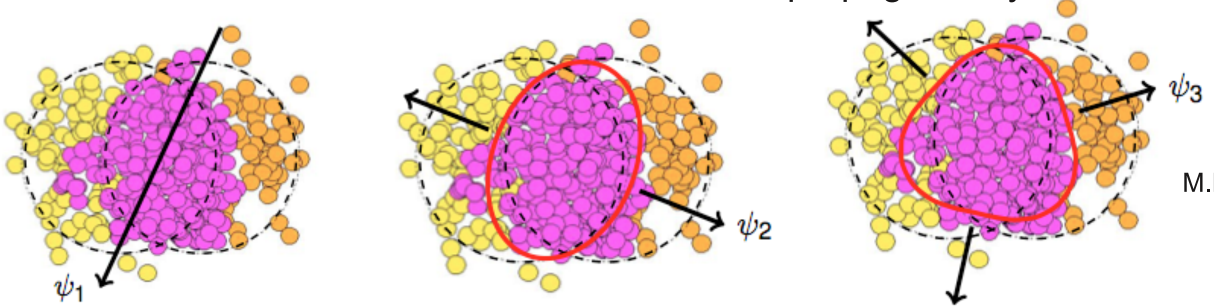

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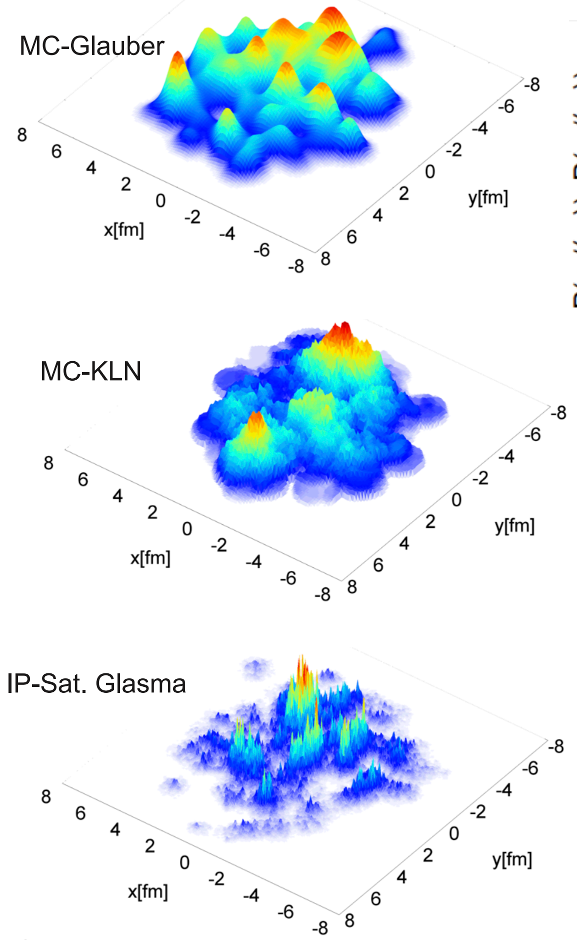
Importance of the description of the initial conditions

INITIAL CONDITIONS AND FLUCTUATIONS...

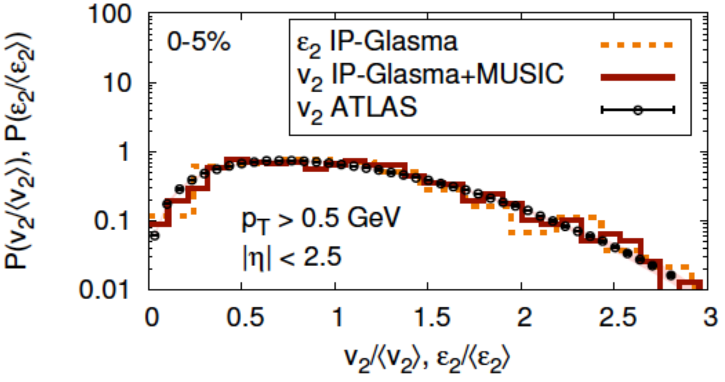
- cross roads: state-of-the-art modeling of initial conditions meets extremely precise experimental measurements of fluctuations !

Initial energy density (arb. units)



B.Schenke, P.Tribedy and R.Venugopalan,
Phys. Rev. Lett.108, 252301 (2012)

Spectacularly good level of agreement:



B.Schenke *et al.*, QM'12 arXiv:1210.5144

Fact: initial state conditions survive up to final state observables.
Weapon: 3+1D CYM dynamics + viscous hydro !

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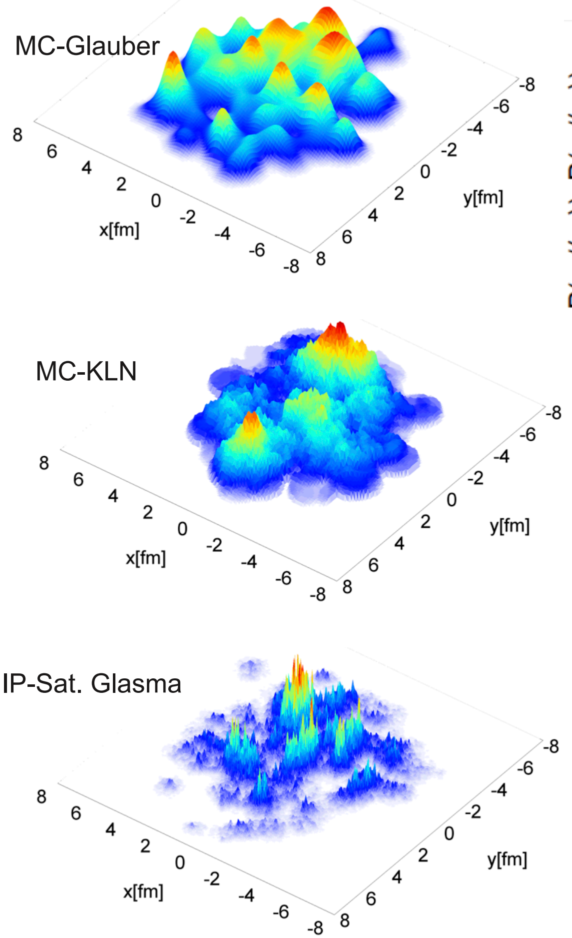

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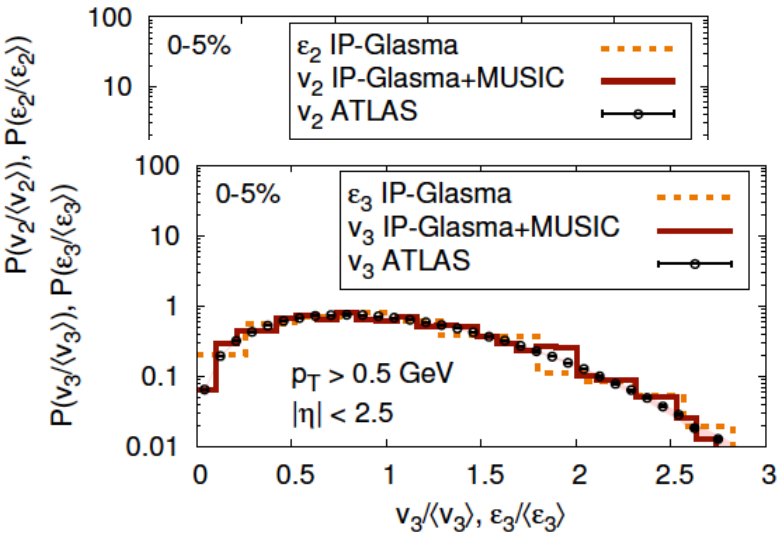

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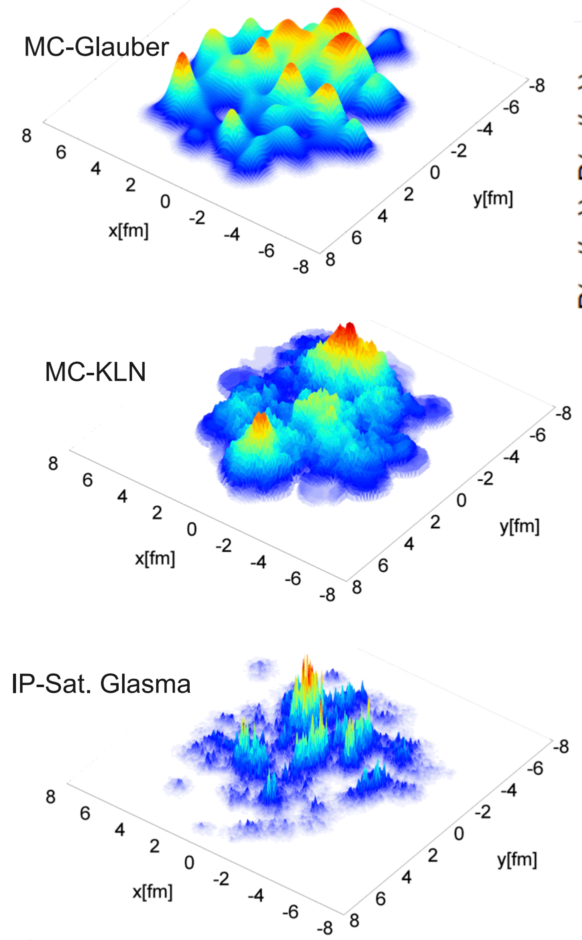

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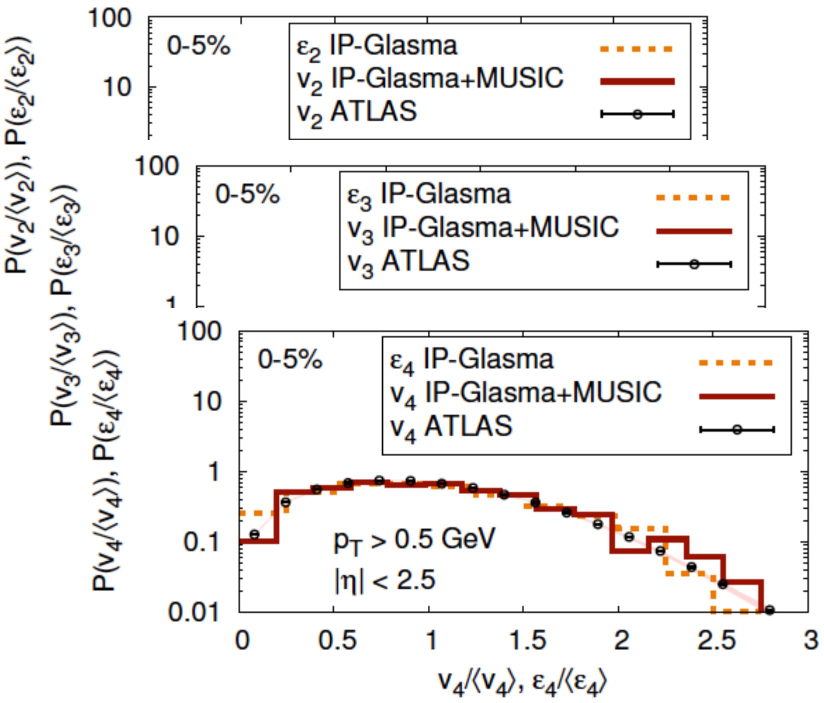

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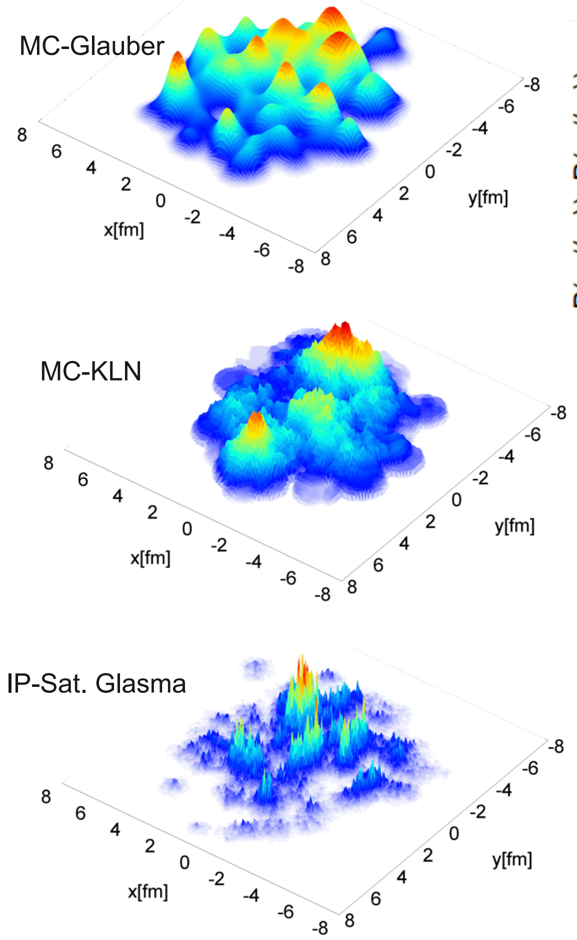

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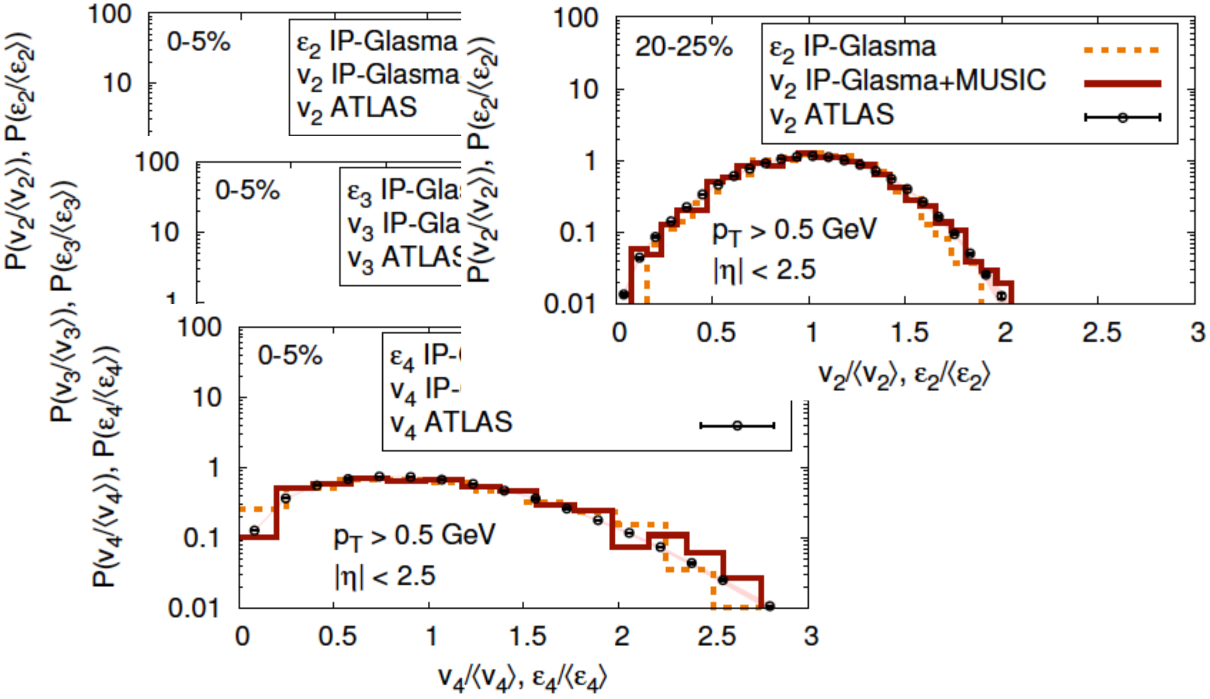

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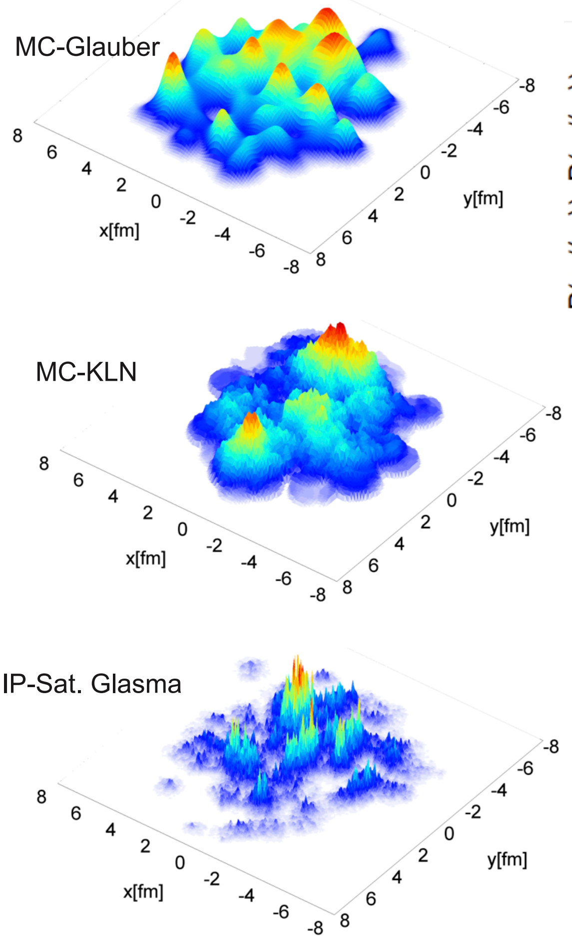

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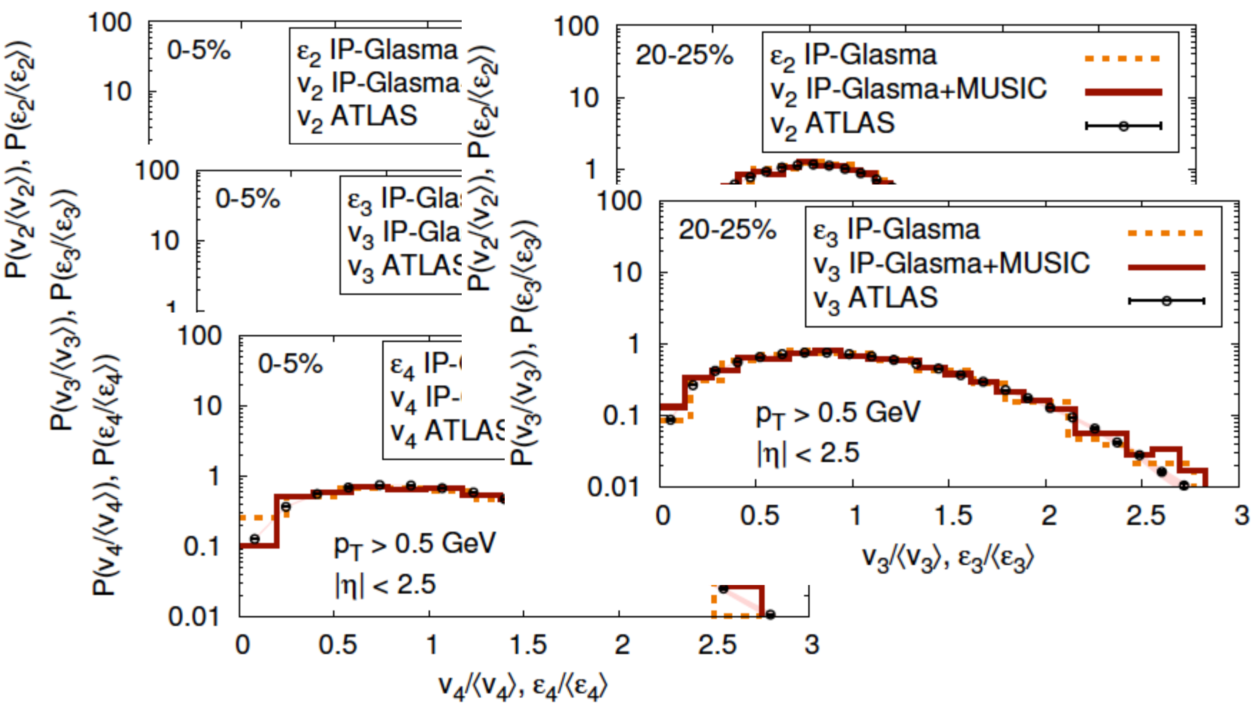

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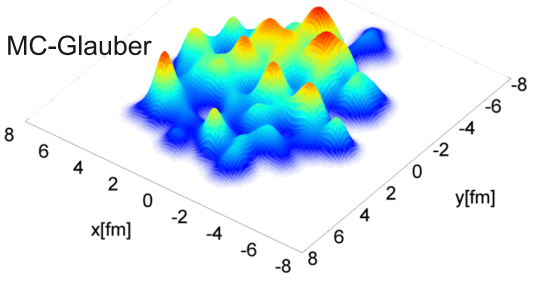
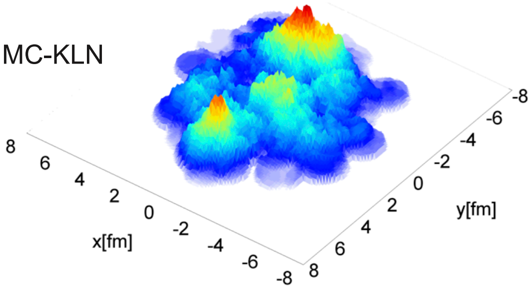
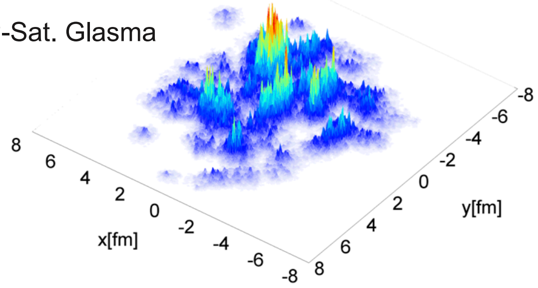
MC-Glauber



MC-KLN



IP-Sat. Glasma



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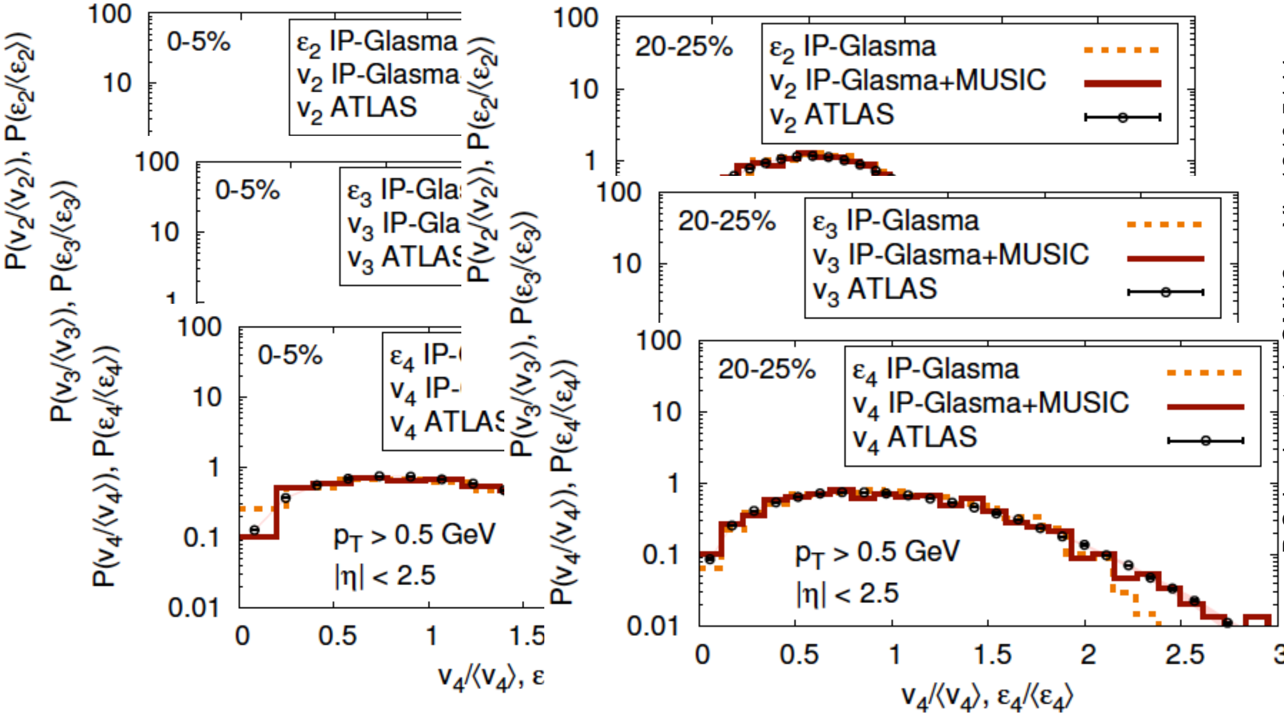

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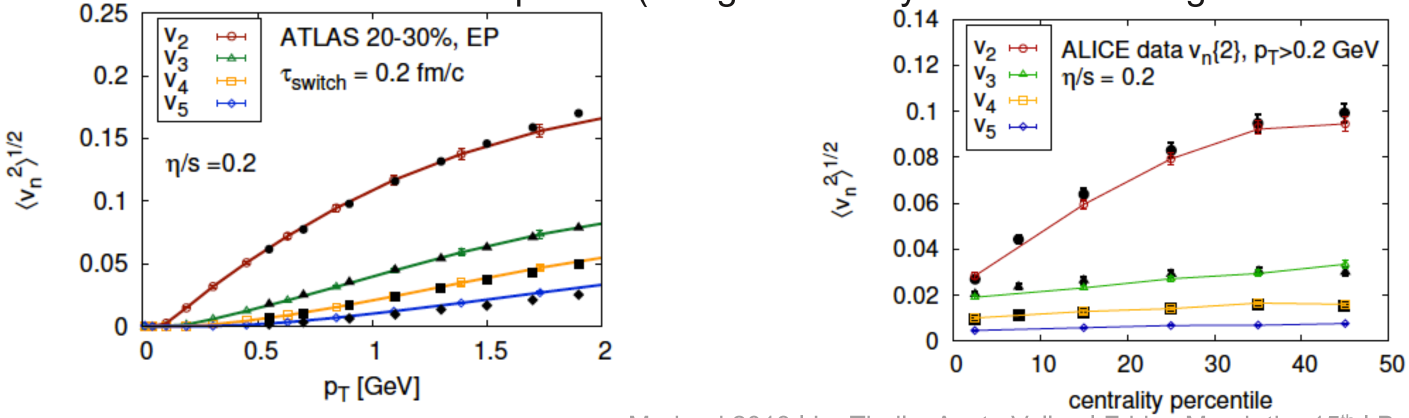
DISSIPATIVE FLUID DYNAMIC DESCRIPTION

- hydrodynamic description based on
    - ➡ basic conservation equations
        - energy-momentum tensor and net baryon current: $\partial_\mu T^{\mu\nu} = 0, \ \partial_\mu J^\mu_B = 0$
    - ➡ equilibrium Equation Of State (EOS)
        - pressure, energy density and baryon density: $\mathcal{P} = \mathcal{P}(\varepsilon, \rho_B)$
    - ➡ viscosity using stress energy tensor $S^{\mu\nu}$
        - Navier-Stokes formalism (1st order)
        - Israel-Stewart formalism (2nd order)
- sensitive to properties of matter calculated from 1st principles in QFT
    - ➡ EOS $\varepsilon = \varepsilon(\mathcal{P}, n)$ and sound velocity $c_s = \partial\mathcal{P}/\partial\varepsilon$
    - ➡ transport coefficients: shear η and bulk ξ viscosities, conductivities...
    - ➡ relaxation times: τ_π , τ_Π , ...
- allow for quantitative comparisons with experimental measurements

η/s=0.2 (using MUSIC hydro and matching ATLAS & ALICE v_n)



C.Gale *et al.*, arXiv:1209.6330

LATTICE QCD

- local thermodynamical equilibrium is needed for the applicability of the aforementioned fluid dynamics.

➡ establishing Equation Of State (EOS)

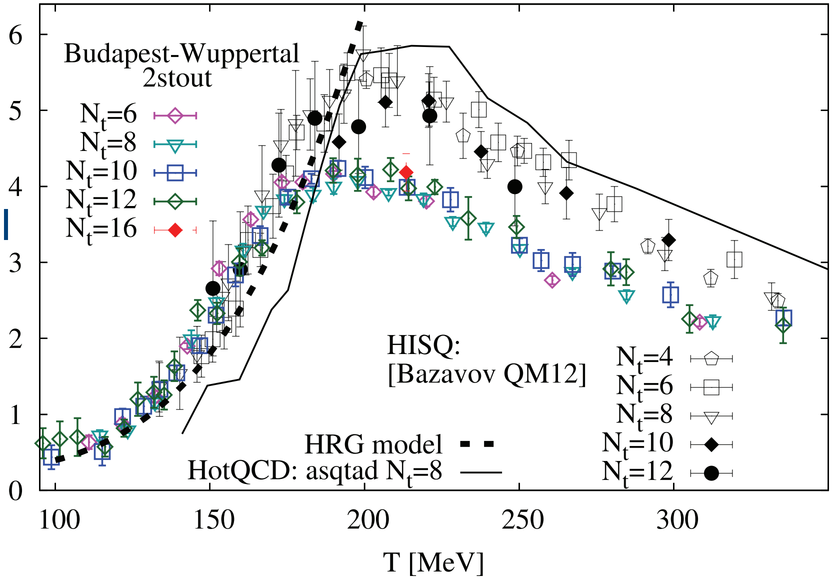
  - important input for the whole evolution
  - little constraint from experimental flow data...
  - still not clear thermalization is reached so fast !

➡ LQCD provides quantitatively reliable input

- Now agreement between Budapest-Wuppertal and HotQCD Collaborations for T_c value:

T_c= 155 ± 3 (stat.) ± 3 (syst.) MeV (**)
T_c= 154 ± 8 (stat.) ± 1 (syst.) MeV (°°)

➡ in fact very good agreement below T_c whereas differences remain above with HotQCD being ~25% higher

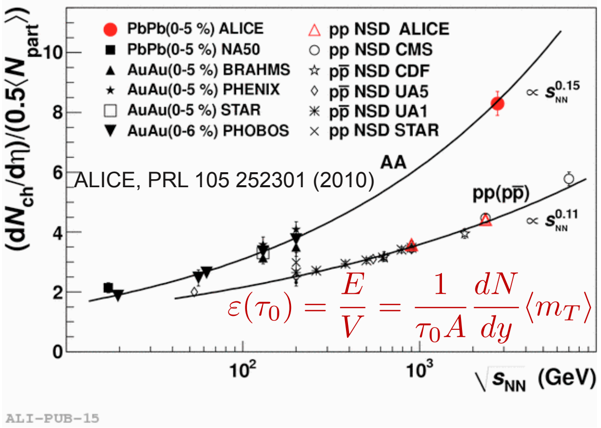


** S. Borsanyi *et al.*, JHEP 1009, 073 (2010)
°° A. Bazavov *et al.*, Phys. Rev. D 85, 054503 (2012)

FINAL STATE AND GLOBAL PROPERTIES OF THE MEDIUM

- the fireball at the LHC is **denser**, **larger** and **longer** lived than at RHIC

➡ energy density is ~10 GeV/fm^3 (3x RHIC)



ALICE, PRL 105 252301 (2010)

$$\varepsilon(\tau_0) = \frac{E}{V} = \frac{1}{\tau_0 A}\frac{dN}{dy}\langle m_T\rangle$$

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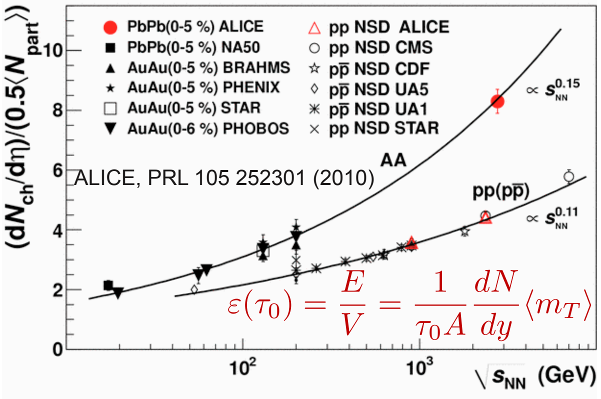
➡ volume is ~4800 fm^3 (2x RHIC)



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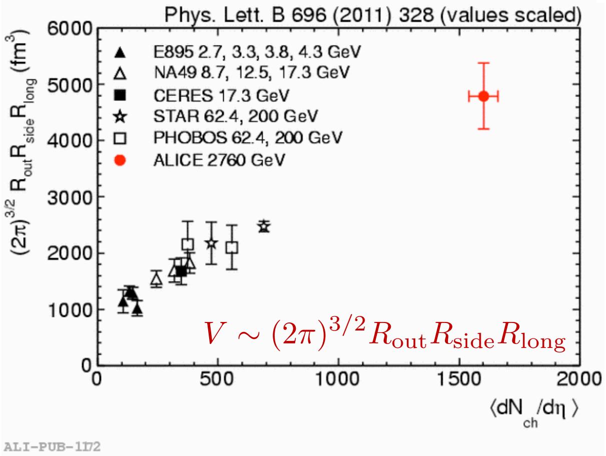
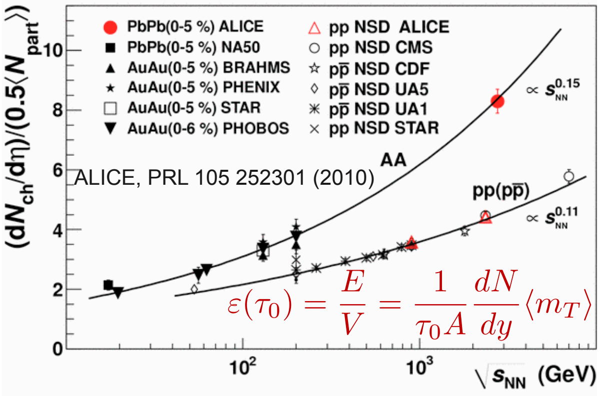


Phys. Lett. B 696 (2011) 328 (values scaled)

$$V \sim (2\pi)^{3/2} R_{\rm out} R_{\rm side} R_{\rm long}$$

FINAL STATE AND GLOBAL PROPERTIES OF THE MEDIUM

- the fireball at the LHC is **denser**, **larger** and **longer** lived than at RHIC
  - ➡ energy density is ~10 GeV/fm^3 (3x RHIC)
  - ➡ volume is ~4800 fm^3 (2x RHIC)
  - ➡ lifetime is ~10 fm/*c* (+20% RHIC)



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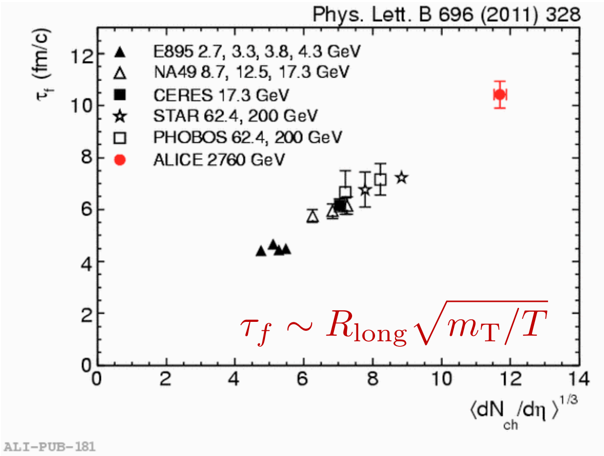
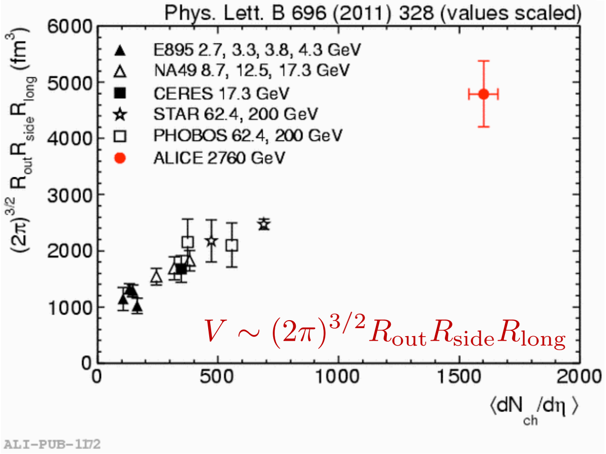


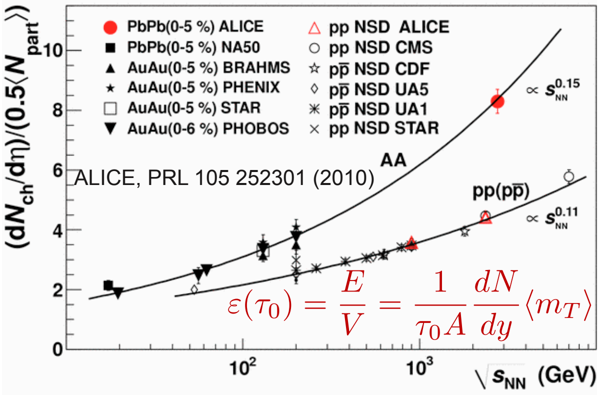
Phys. Lett. B 696 (2011) 328



Phys. Lett. B 696 (2011) 328 (values scaled)

FINAL STATE AND GLOBAL PROPERTIES OF THE MEDIUM

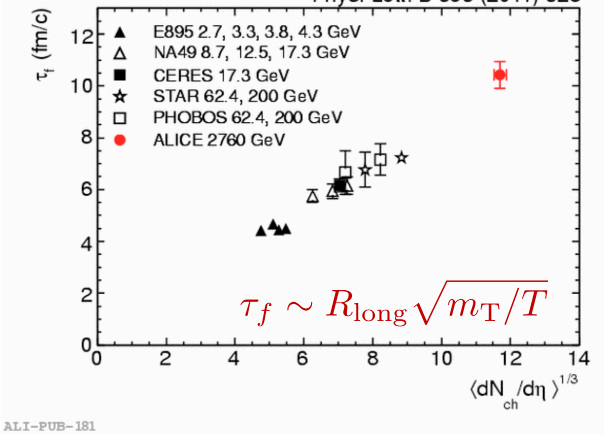
- the fireball at the LHC is **denser**, **larger** and **longer** lived than at RHIC
  - ➡ energy density is ~10 GeV/fm^3 (3x RHIC)
  - ➡ volume is ~4800 fm^3 (2x RHIC)
  - ➡ lifetime is ~10 fm/*c* (+20% RHIC)
  - ➡ temperature is ~300 MeV (+30% RHIC)



ALICE, PRL 105 252301 (2010)

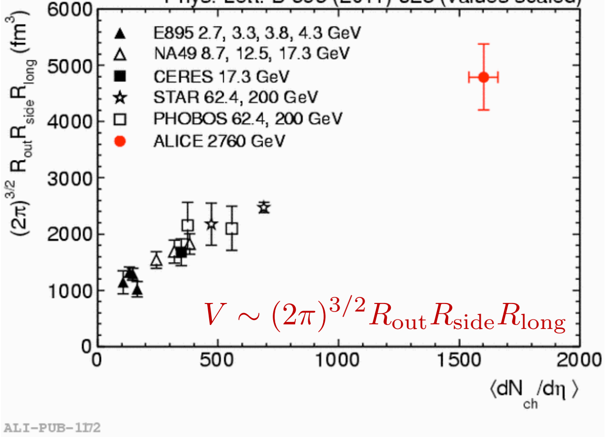
$$\varepsilon(\tau_0) = \frac{E}{V} = \frac{1}{\tau_0 A}\frac{dN}{dy}\langle m_T\rangle$$

Phys. Lett. B 696 (2011) 328

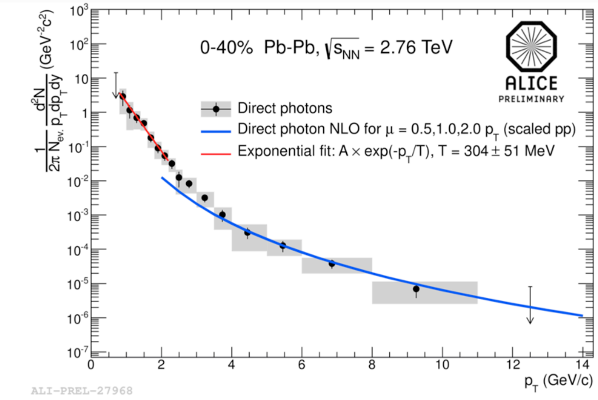


$$\tau_f \sim R_{\mathrm{long}}\sqrt{m_{\mathrm{T}}/T}$$

Phys. Lett. B 696 (2011) 328 (values scaled)

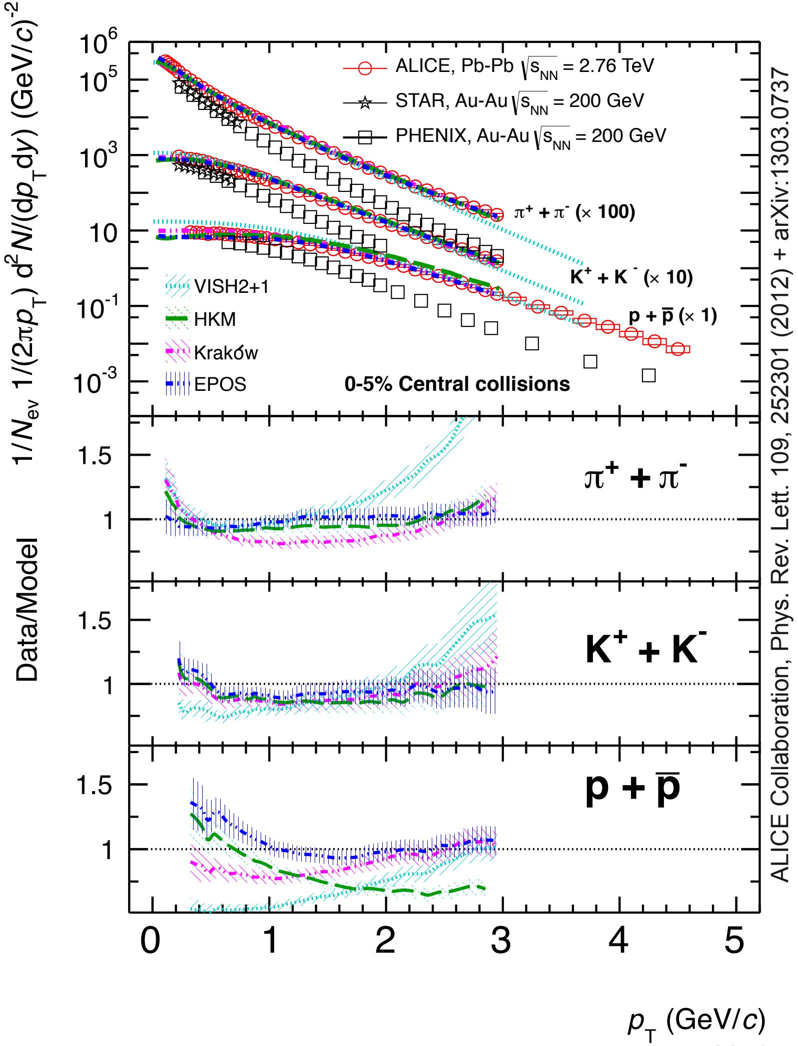


$$V \sim (2\pi)^{3/2} R_{\mathrm{out}} R_{\mathrm{side}} R_{\mathrm{long}}$$



IDENTIFIED P_T SPECTRA AND HADRONIC RESCATTERING

- Comparison with hydro models: radial flow and kinetic freeze-out temperature T_{kin}



Large radial flow in top central events:
$\langle\beta_T\rangle = 0.65 \pm 0.02$ (~10% higher w.r.t. RHIC)
increases with centrality

T_{kin}= 95 MeV (same as RHIC within errors)
decreases with centrality

model comparisons:
- VISH2+1 (viscous hydro)
- HKM (hydro+UrQMD)
- Kraków (viscous corr., lower the effective T_{ch})
- EPOS (hydro+UrQMD)

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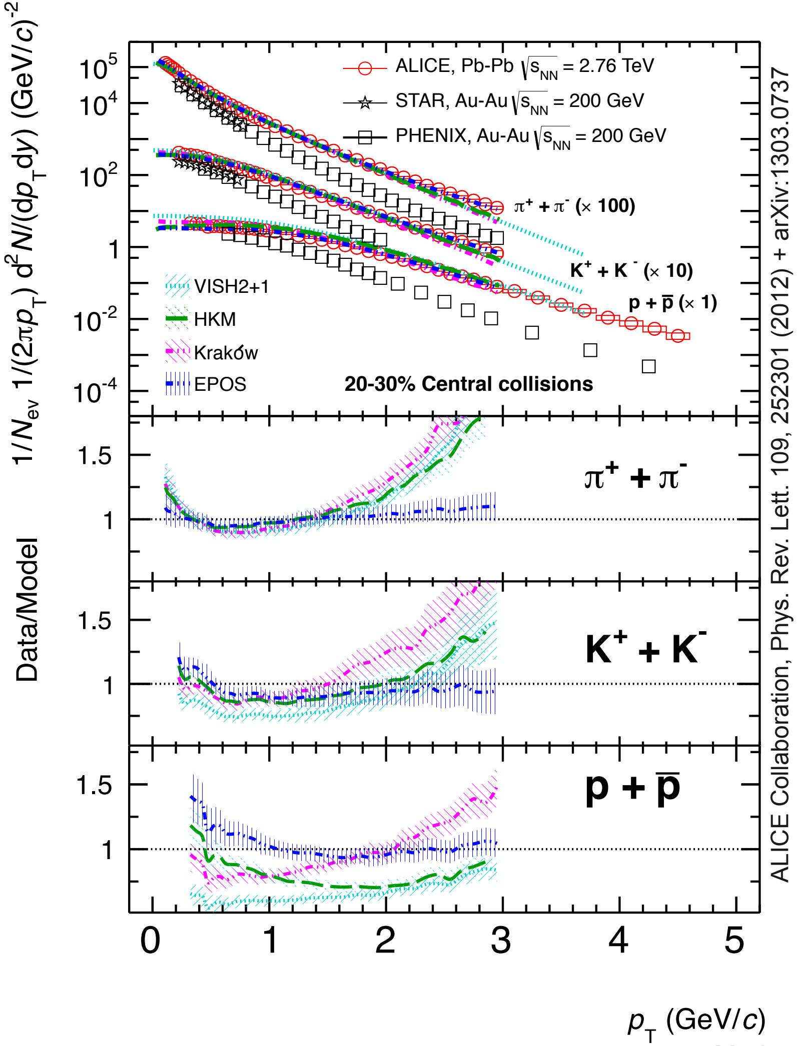

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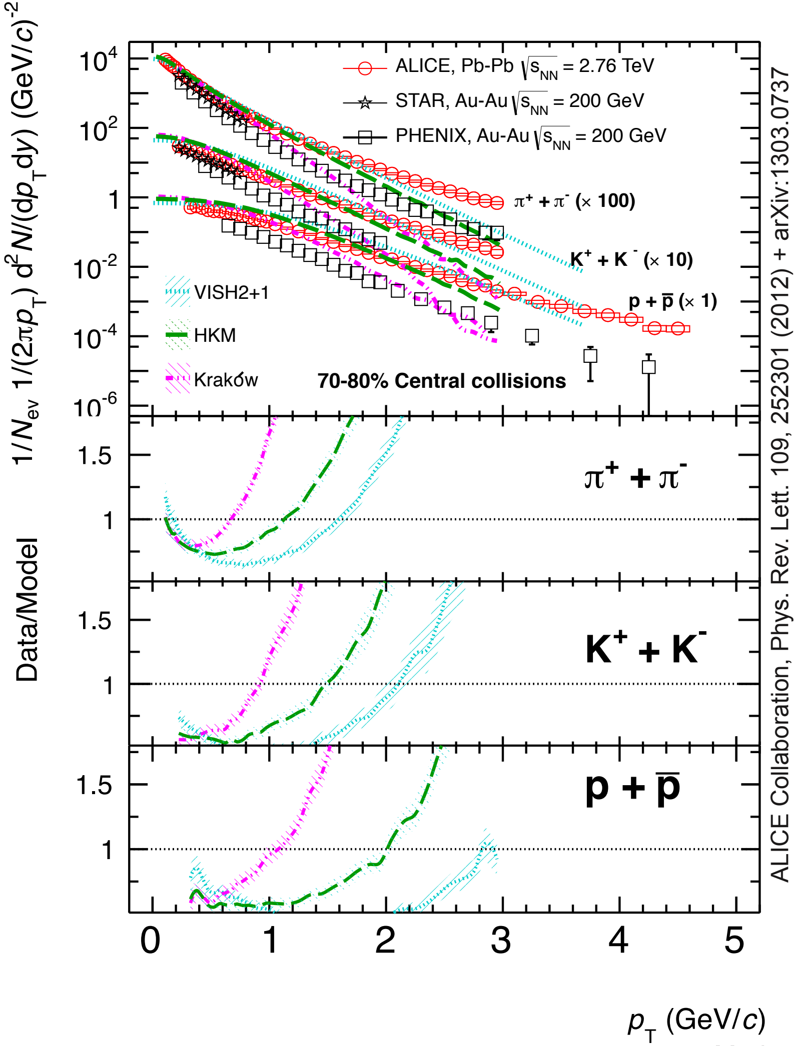

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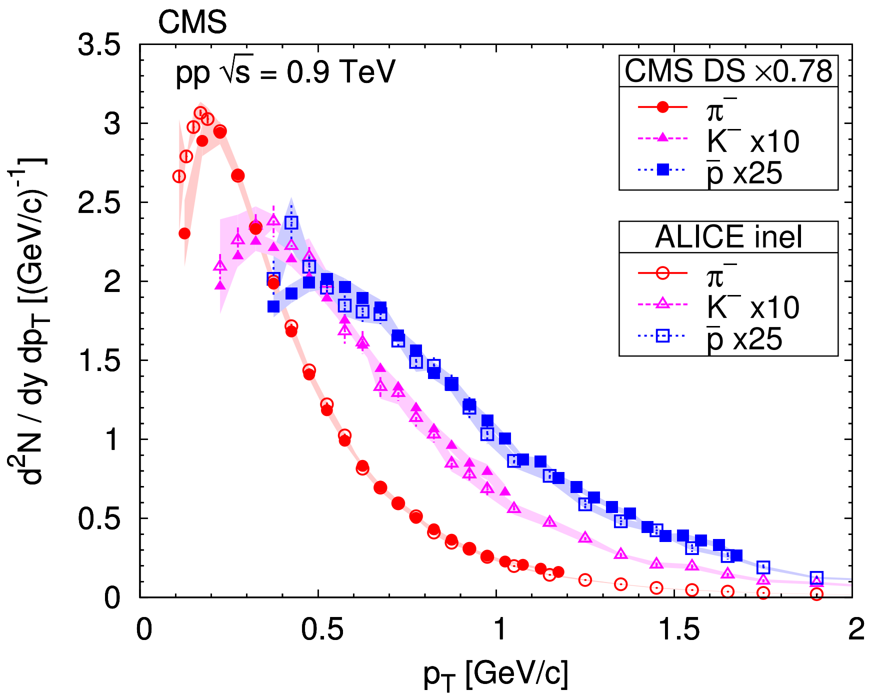
➡ the more peripheral the events are, the more challenging for the models !

Expect more comparison with models especially for identified particle v_n

REFERENCE COLLIDING SYSTEM(S) AND COMPARISONS

- the shapes of p_T spectra in AA are compared to pp collisions
  - ➡ check consistency for ranges with overlapping PID capabilities



➡ within the same experiment when several PID detectors are available

➡ between different experiments, e.g. CMS and ALICE for light-flavour hadrons at very low p_T

Excellent agreement between the different measurements !

REFERENCE COLLIDING SYSTEM(S) AND COMPARISONS

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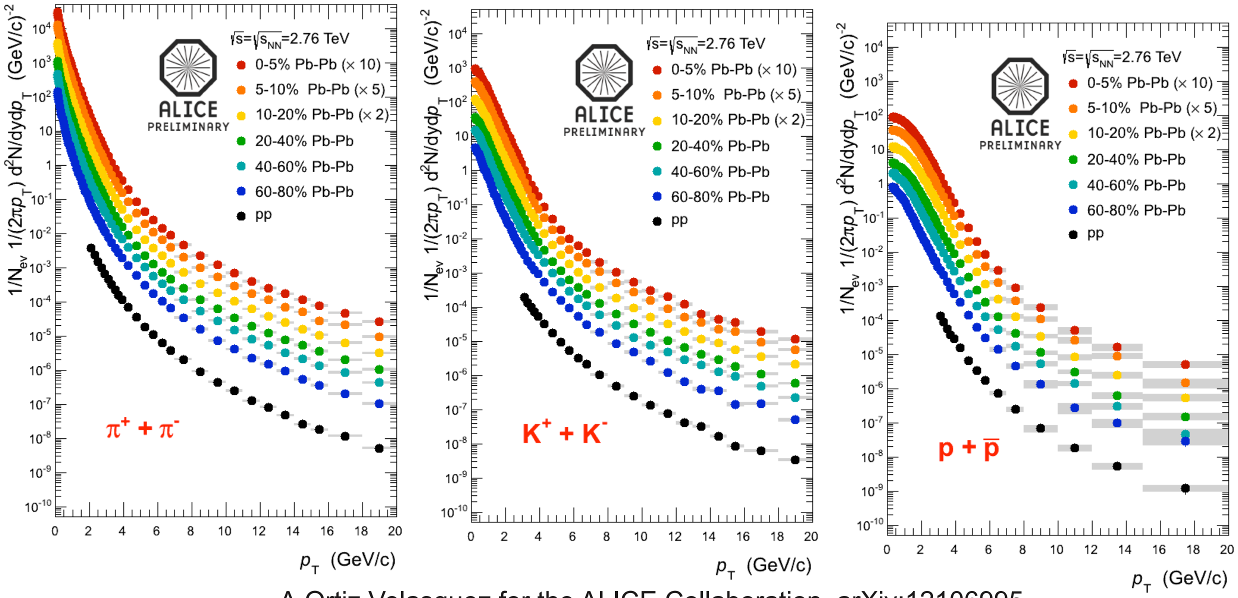
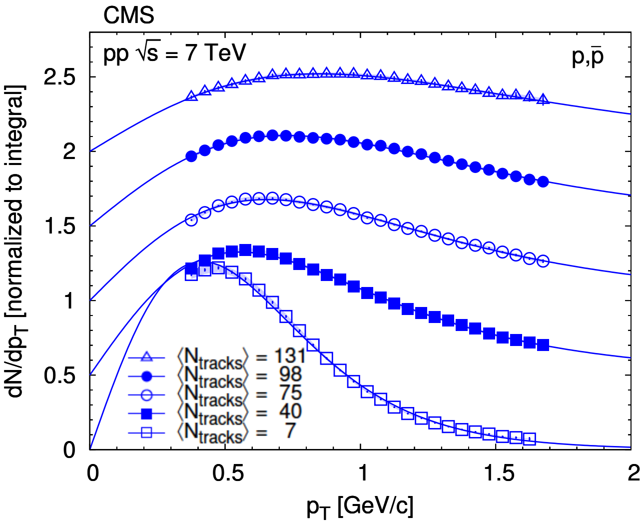
  - ➡ minimum bias pp often used as one reference for Pb-Pb



A.Ortiz Velasquez for the ALICE Collaboration, arXiv:12106995



CMS Collaboration, CMS-FSQ-12-014, arXiv:1207.4724

Caution: in pp, the p_T spectra shape changes more as a function of multiplicity than as a function of colliding energy...

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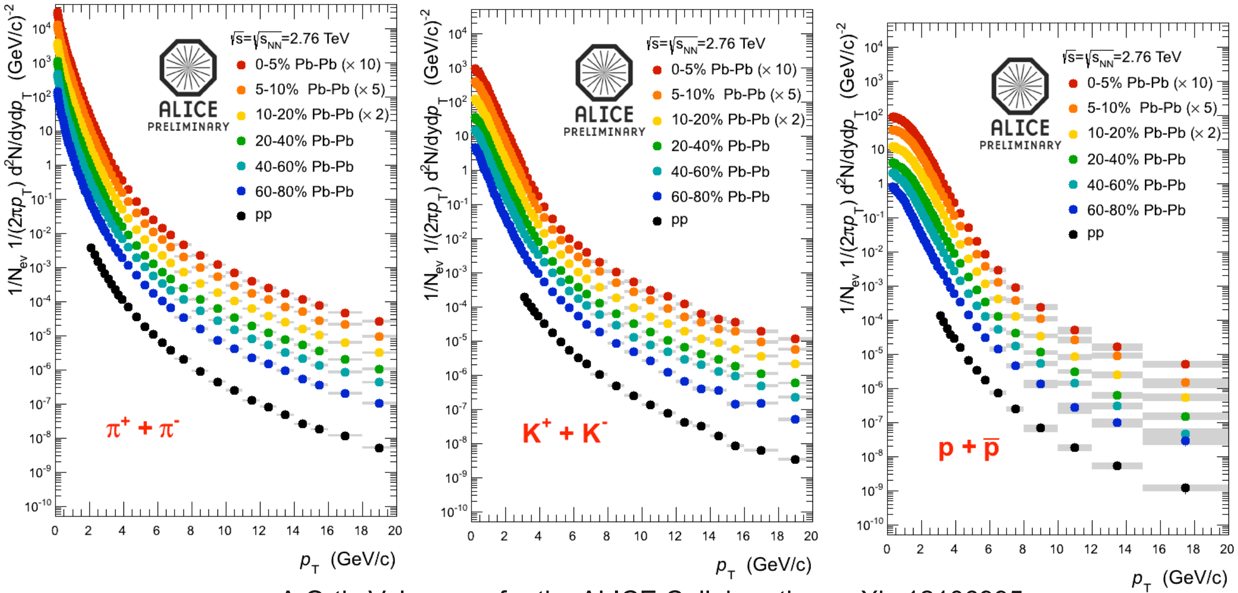

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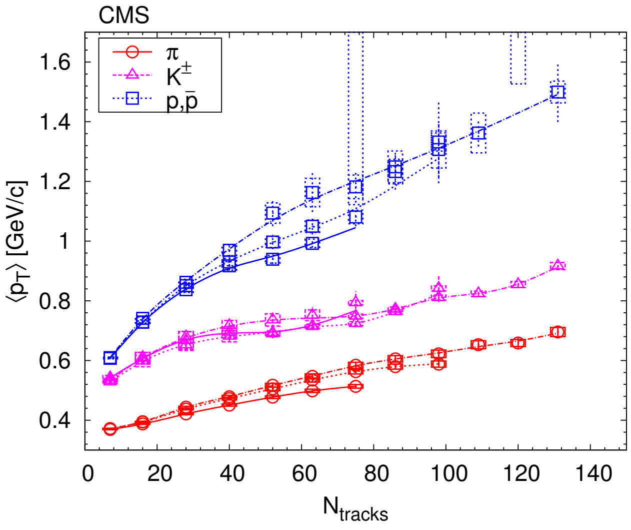

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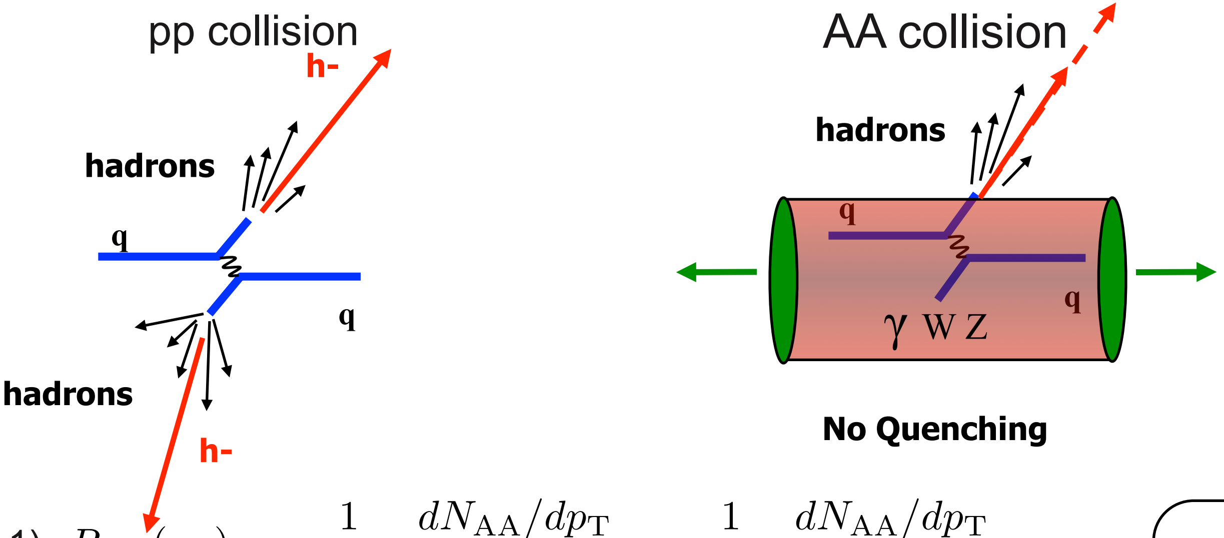
- the shapes of p_T spectra in AA are compared to pp collisions
- quenching at high p_T is obvious when the ratio is performed
  - ➡ principle and definitions: probing the density of the created medium



➡ 1) $$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{1}{\langle N_{\mathrm{coll}}\rangle}\frac{dN_{\mathrm{AA}}/dp_{\mathrm{T}}}{dN_{\mathrm{pp}}/dp_{\mathrm{T}}} = \frac{1}{\langle T_{\mathrm{AA}}\rangle}\frac{dN_{\mathrm{AA}}/dp_{\mathrm{T}}}{d\sigma^{\mathrm{inel}}_{\mathrm{pp}}/dp_{\mathrm{T}}}$$

reminder
$$T_{\mathrm{AA}} = N_{\mathrm{coll}}/\sigma^{\mathrm{inel}}_{\mathrm{NN}}$$

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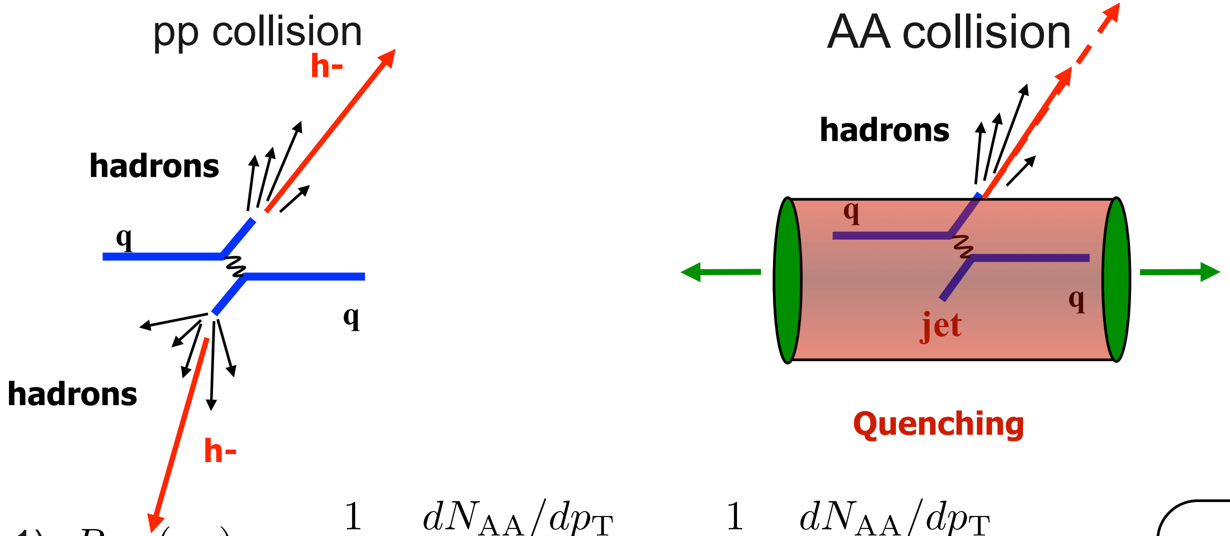
pp collision

AA collision

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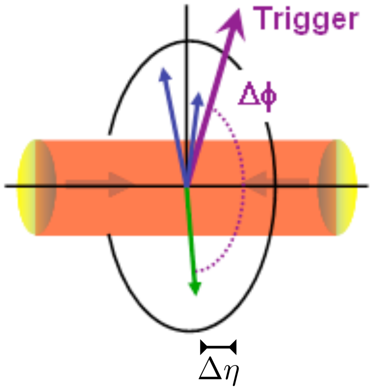

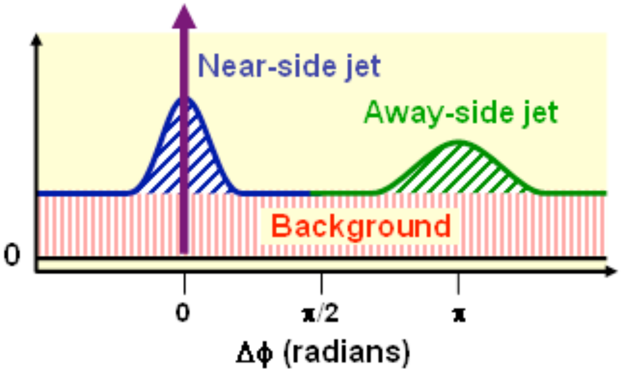

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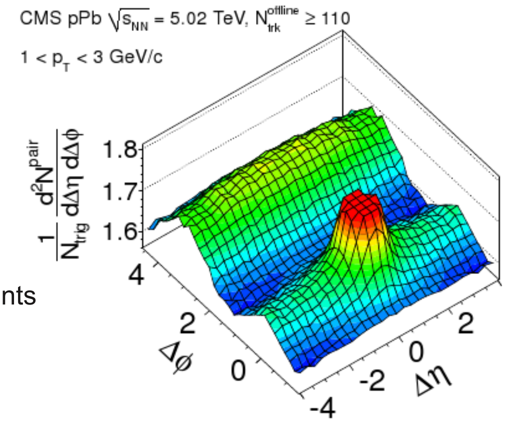
➡ 2) Hadron angular correlations:

$$\frac{1}{N_{\mathrm{trig}}}\frac{d^2N_{\mathrm{assoc}}}{d\Delta\eta\, d\Delta\varphi} = \frac{S(\Delta\eta\Delta\varphi)}{B(\Delta\eta\Delta\varphi)}$$

(S) same event and (B) different events

➡ 3) Gamma-jet angular correlations



CMS Collaboration, PLB 718 (2013)

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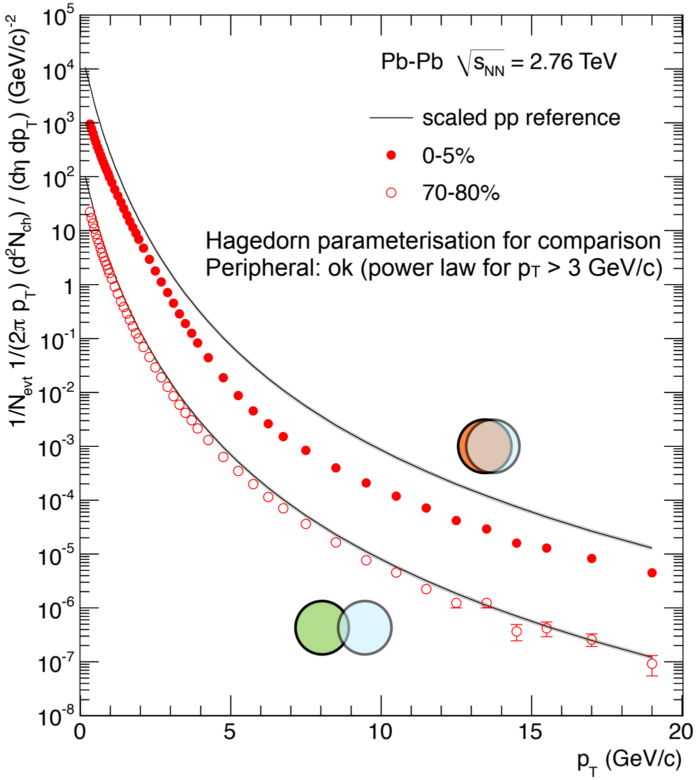

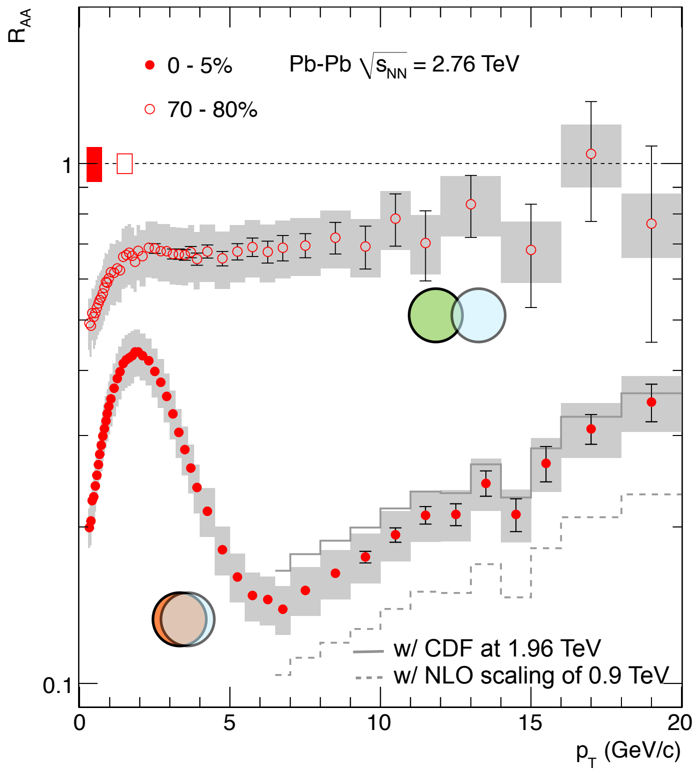

ALICE Collaboration, Phys. Lett. B696 (2011) 30

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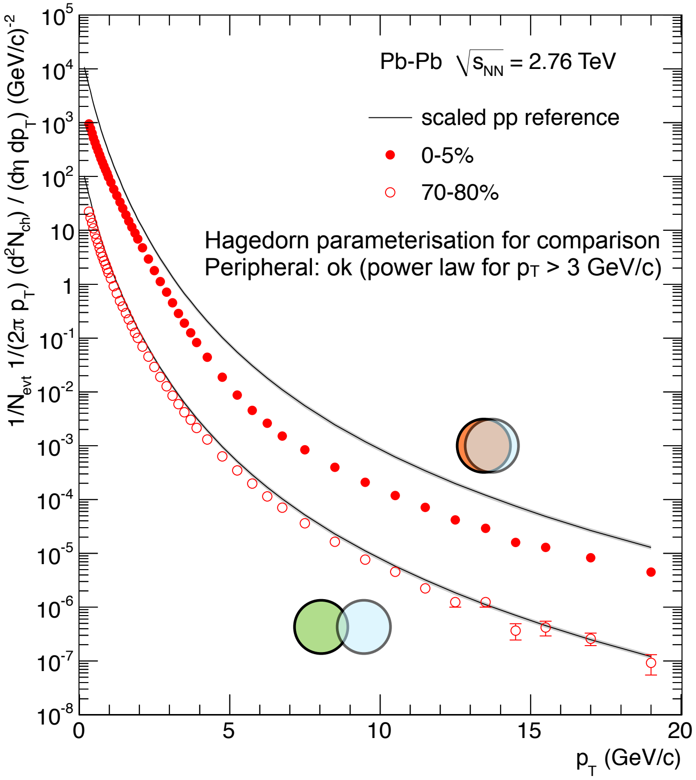
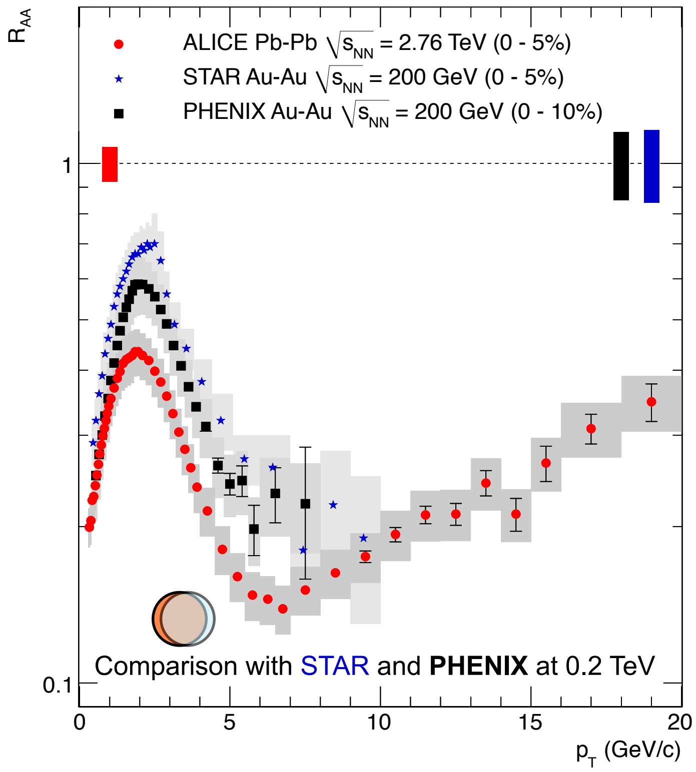


Hagedorn parameterisation for comparison
Peripheral: ok (power law for p_T > 3 GeV/c)



Comparison with STAR and **PHENIX** at 0.2 TeV

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

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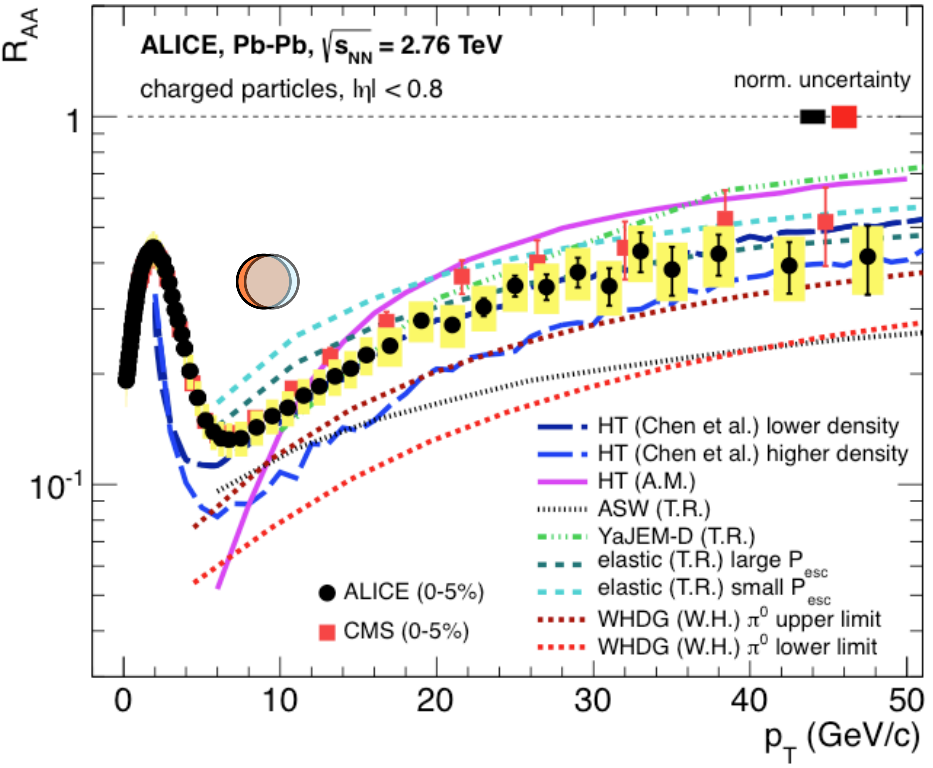
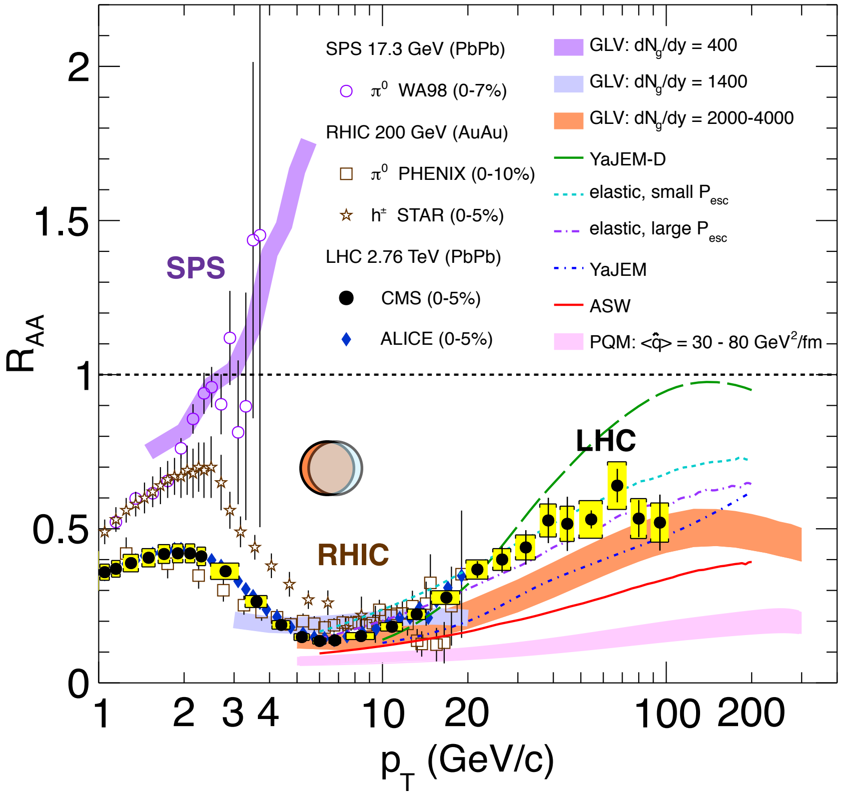


ALICE Collaboration, arXiv:1208.2711



CMS Collaboration, arXiv:1202.2554

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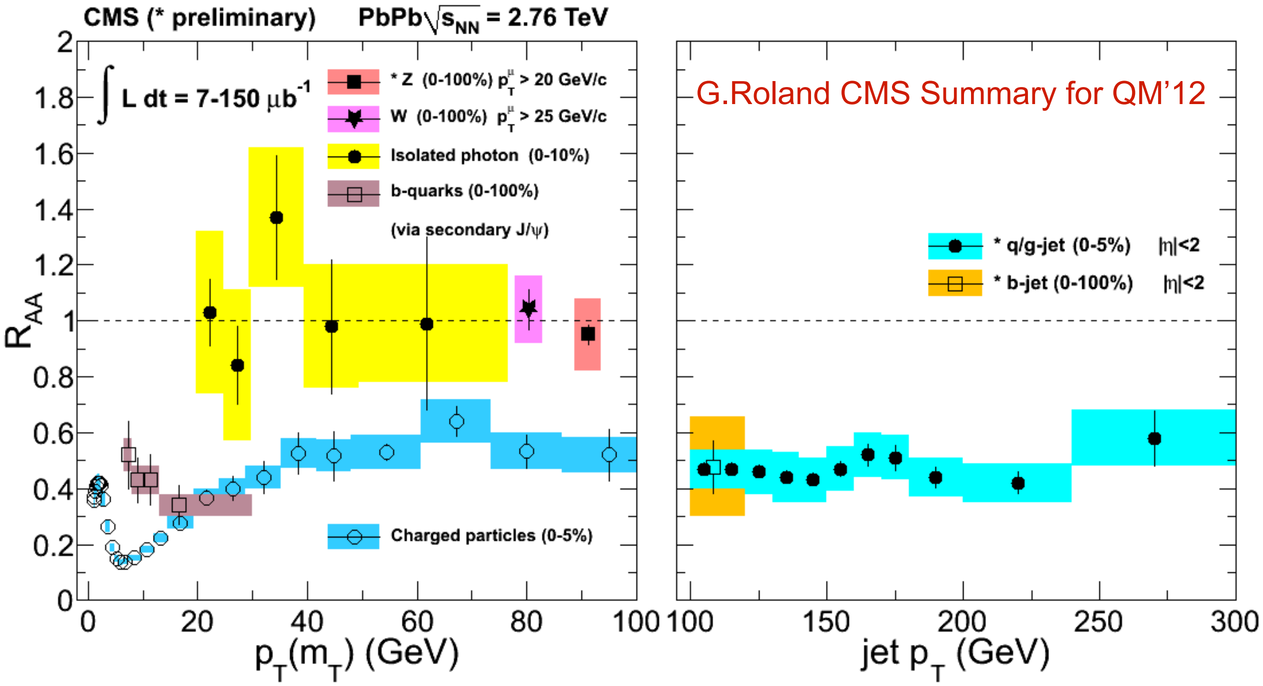
  - ➡ principle and definitions: probing the density of the created medium
  - ➡ non-identified hadrons
  - ➡ opacity and flavour dependence



"control" probes: γ, W, Z

strongly quenched:
h±, b-quarks, jets, b-jets

Not discussed in 15': models (e.g. K.C. Zapp, F. Kraus and U.A.Wiedemann, arXiv:12121599), gamma-jet angular correlations (afternoon + models e.g. G.-L. Ma, arXiv:1302.5873, X.-N. Wang and Y. Zhu, arXiv:1302.5874)

PRESENT (SEE NEXT TALKS) AND FUTURE...

- Precision era for measuring the properties of the Quark-Gluon Plasma:
  - ➡ results from the LHC experiments but also at RHIC
  - ➡ validity of models/descriptions from 7.7 GeV to 2.76 TeV
  - ➡ more comparisons to isolate genuine Heavy-Ion collective effects
  - ➡ question: are pp (multiplicity), p-A good reference systems ?

- Even more systematic studies:
  - ➡ Beam Energy Scan at RHIC for turning on/off key features
  - ➡ upgrade of the experiments (after LS1 and LS2) at the LHC
  - ➡ additional statistics for further differential measurements