FEMTOSCOPY DAY 2016

November 4.
Eszterházy University, Károly Robert Campus,
Gyöngyös, Hungary

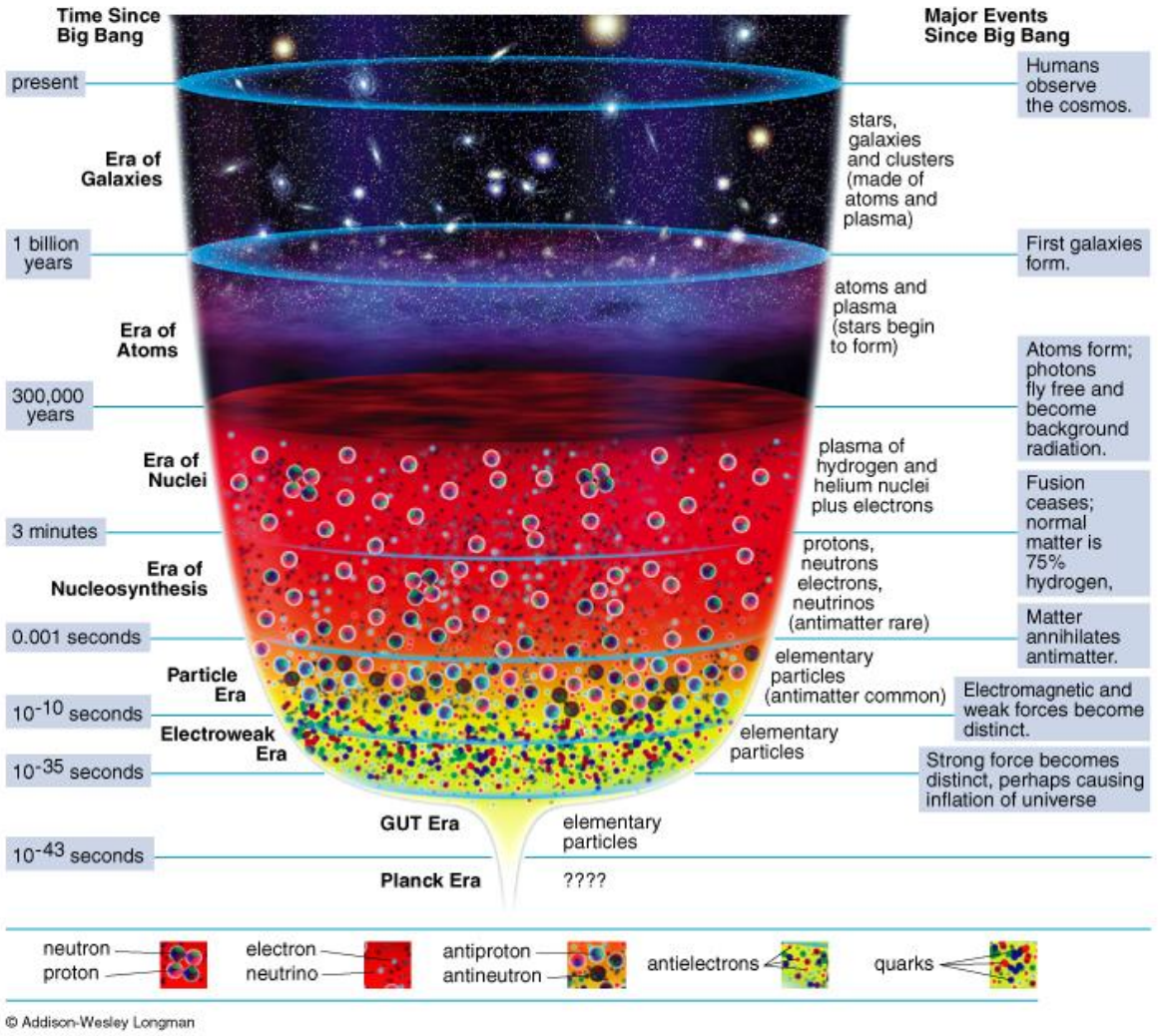
INITIAL ENERGY DENSITY IN LHC P+P COLLISIONS

04 Nov 2016

M. Csanád & the Hungarian femtoscopy group

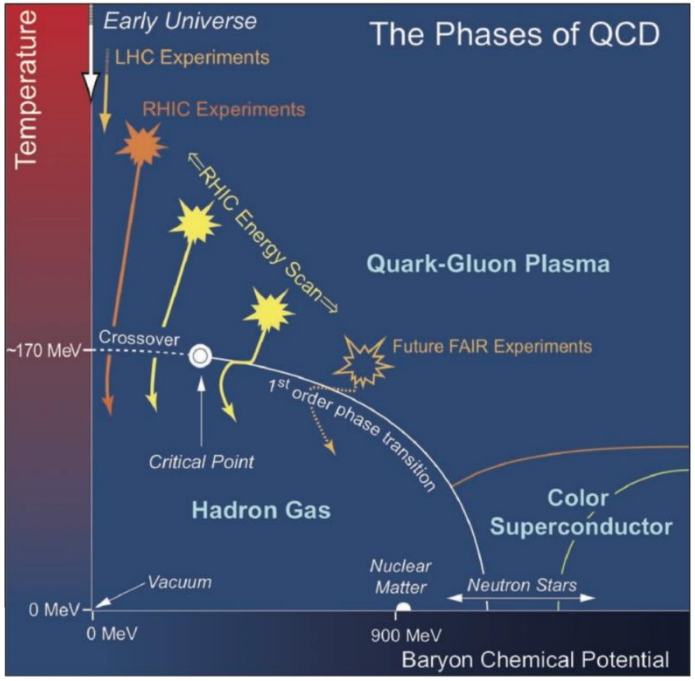
Heavy ion physics and the early Universe

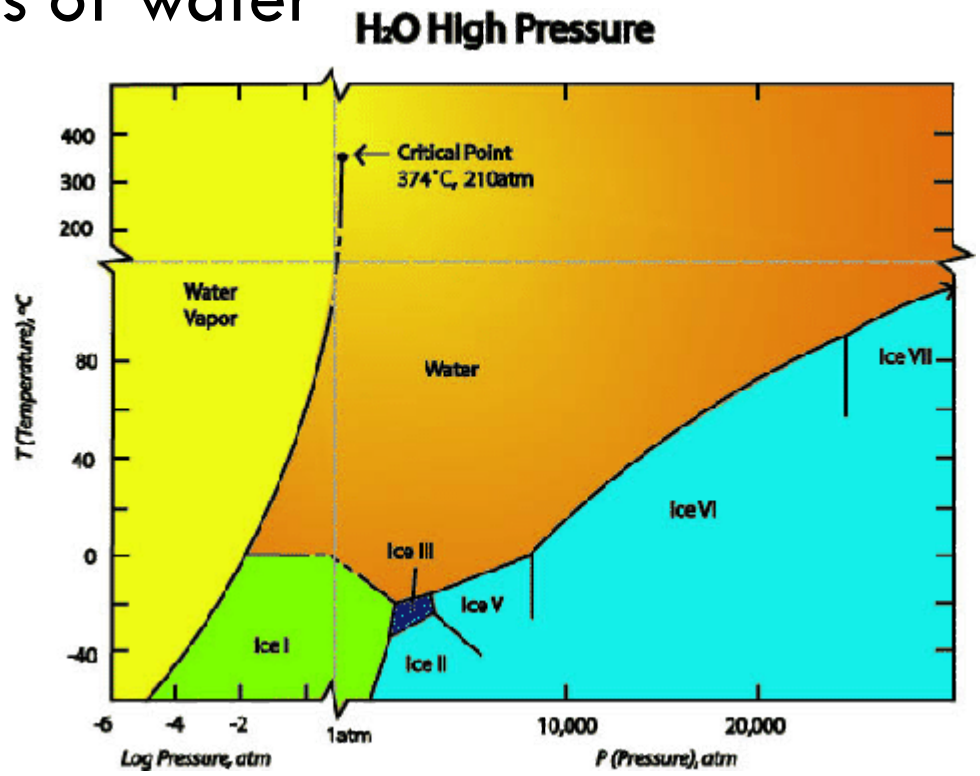
- Time evolution: → cooling
- Phase transitions crossovers
- Atoms ionize at: few 1000 K
- Nuclei melt at: million K
- Hadrons melt at: 10^{12} K



Phase diagram of the strongly interacting matter

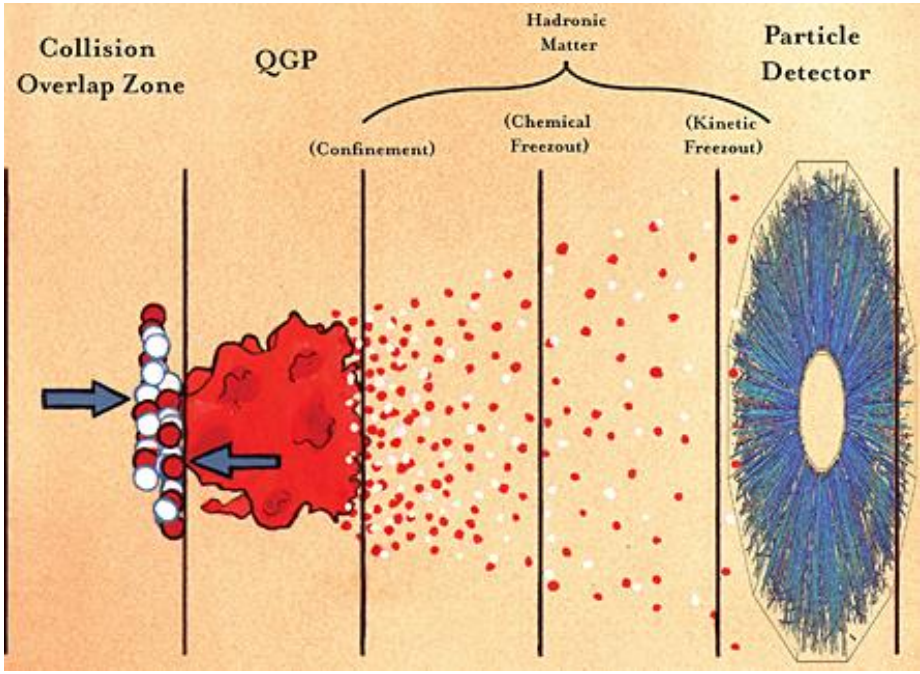
- Hadron gas, quark medium, many other phases
- Compare to the phases of water





Little Bangs

- How to investigate these phases? Particle accelerators!
- High initial energy density and pressure
- Quark matter recreated in A+A; how about p+p?



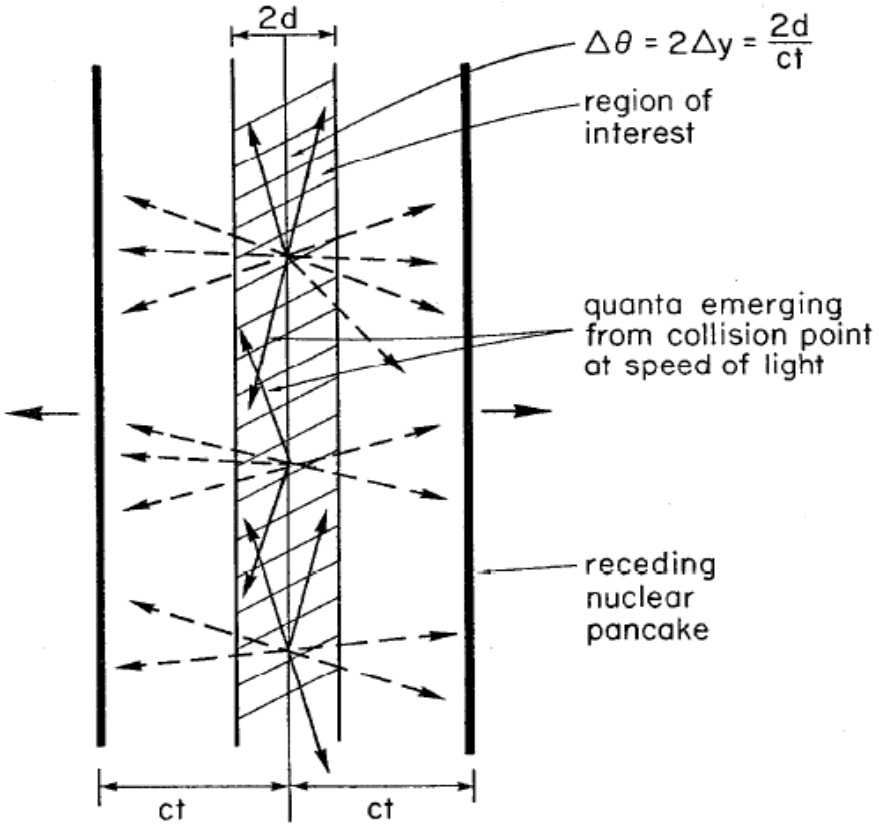
The Bjorken-estimate

- The original idea: energy density based on dE/dy
- QGP critical ε: $\leq$1 GeV/fm^3 (from $\varepsilon_c = 6\text{-}8 \times T_c^4$)
- Result (~2000x cited)

$$E = N\frac{dE}{dy}\Delta y = N\frac{dE}{dy}\frac{1}{2}\frac{2d}{t} = \epsilon A d$$

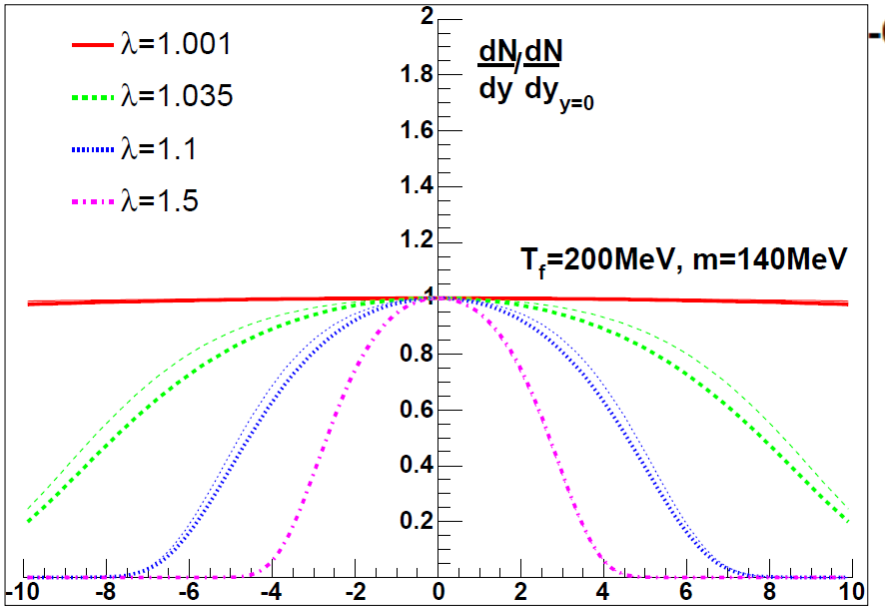
$$\epsilon_{\mathrm{Bj}} = \frac{1}{R^2\pi\tau_0}\frac{dE}{d\eta} = \frac{\langle E\rangle}{R^2\pi\tau_0}\frac{dN}{d\eta}$$

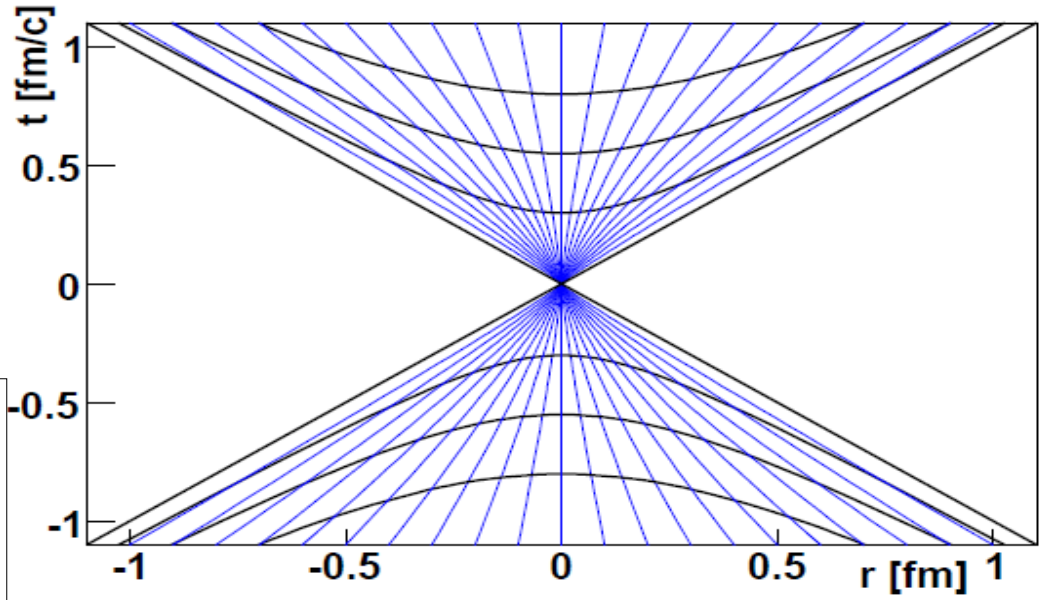
- Needs correction!
- Ref.: Phys.Rev. D27 (1983)



A solution of relativistic hydro

- Velocity: $\tanh(\lambda\eta)$
- Acceleration: $\lambda \neq 1$
- Density: $(\tau/\tau_0)^{\lambda}$
- dN/dy not flat!





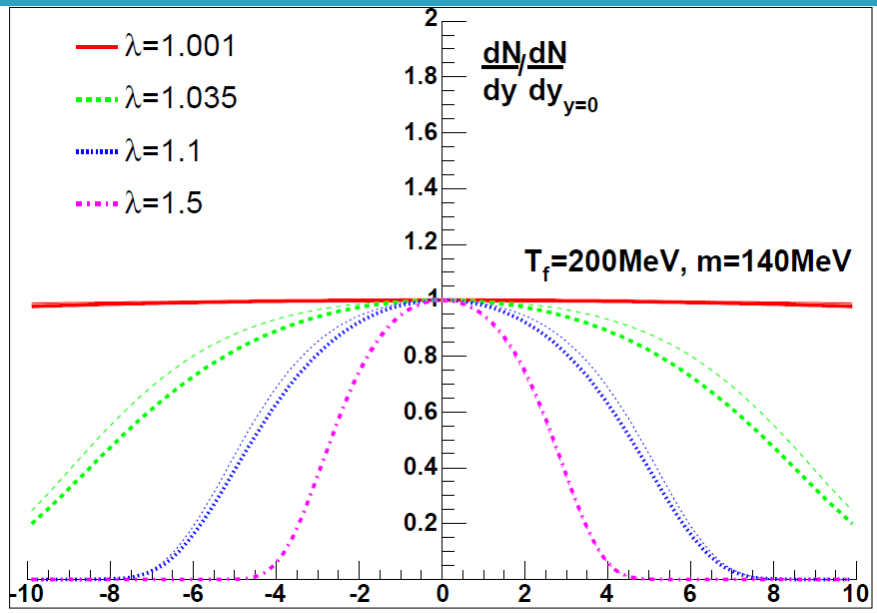
- Compare this to data!
- dN/dy measurement yields advanced initial ϵ estimate
- Significant correction at RHIC!

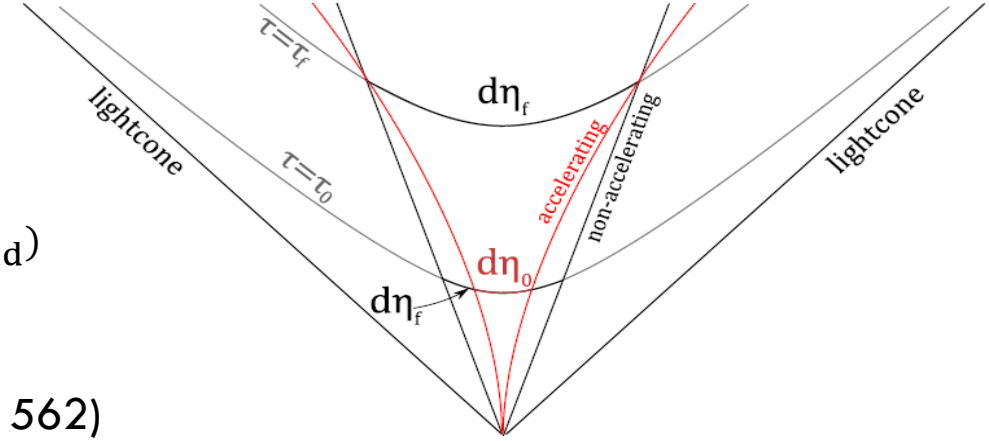
M. Nagy, T. Csörgő, M. Csanád: Phys.Lett. B663 (2008) 306-311 (nucl-th/0605070)

An advanced estimate

- Fact: dN/dy not flat
- Finiteness & acceleration
- Analytical investigation:
  - Acceleration parameter λ
- Two modifications:
  - $y \neq \eta$ & $\eta_{\text{final}} \neq \eta_{\text{initial}}$
- Work by acceleration!
- Correction w.r.t. EoS:

$$\epsilon = \epsilon_{\text{Bj}}(2\lambda - 1)\left(\frac{\tau_f}{\tau_i}\right)^{(\lambda-1)(2-c_{\text{sound}}^2)}$$





E.g.: J.Phys.G35 (2008) 104128 (arXiv:0805.1562)

Initial energy density at LHC

- Rough estimate via the Bjorken formula at 7 TeV
  - Number of particles at midrapidity: 1.5×5.89
  - Average energy: $\langle m_t \rangle = \langle E \rangle = 0.562\ \mathrm{GeV}$
  - Transverse size of the system $\mathrm{R}^2\pi = \sigma_{\mathrm{tot}}^2/4\sigma_{\mathrm{el}} = 9.8\ \mathrm{fm}^2$
  - Formation time $\tau_0 = 1\ \mathrm{fm}/c$ (conservative estimate)
- Energy density from this:

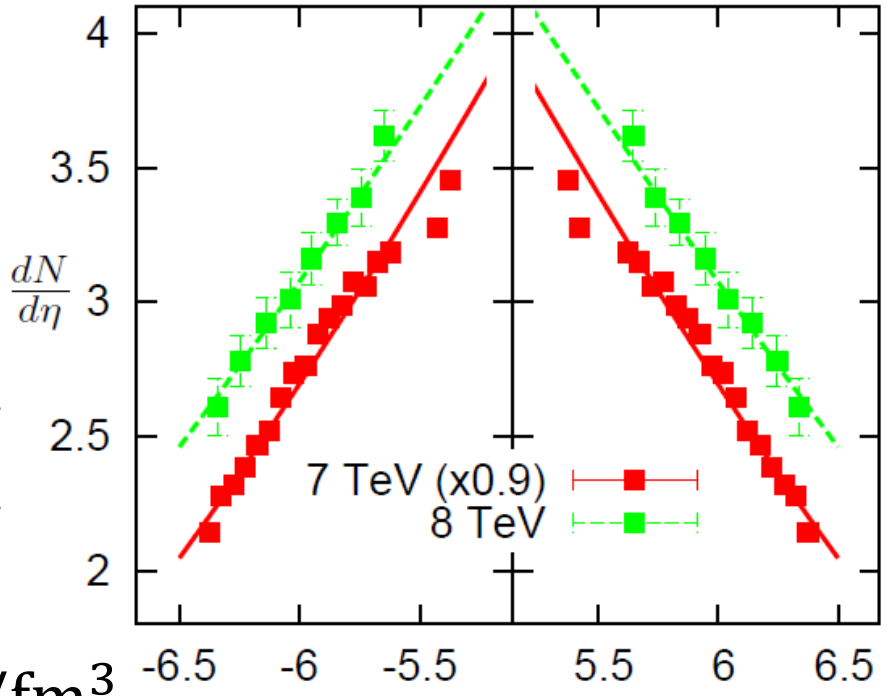
$$\epsilon_{\mathrm{Bj}}(7\ \mathrm{TeV}) = \frac{1}{R^2\pi\tau_0}\frac{dE}{d\eta} = \frac{\langle E \rangle}{R^2\pi\tau_0}\frac{dn}{d\eta} = \frac{0.562 \times 1.5 \times 5.89}{1.76^2\pi}\frac{\mathrm{GeV}}{\mathrm{fm}^3} = 0.507\frac{\mathrm{GeV}}{\mathrm{fm}^3}$$

$$\epsilon_{\mathrm{Bj}}(8\ \mathrm{TeV}) = \frac{1}{R^2\pi\tau_0}\frac{dE}{d\eta} = \frac{\langle E \rangle}{R^2\pi\tau_0}\frac{dn}{d\eta} = \frac{0.571 \times 1.5 \times 6.17}{1.80^2\pi}\frac{\mathrm{GeV}}{\mathrm{fm}^3} = 0.519\frac{\mathrm{GeV}}{\mathrm{fm}^3}$$

- Below critical? Important question!

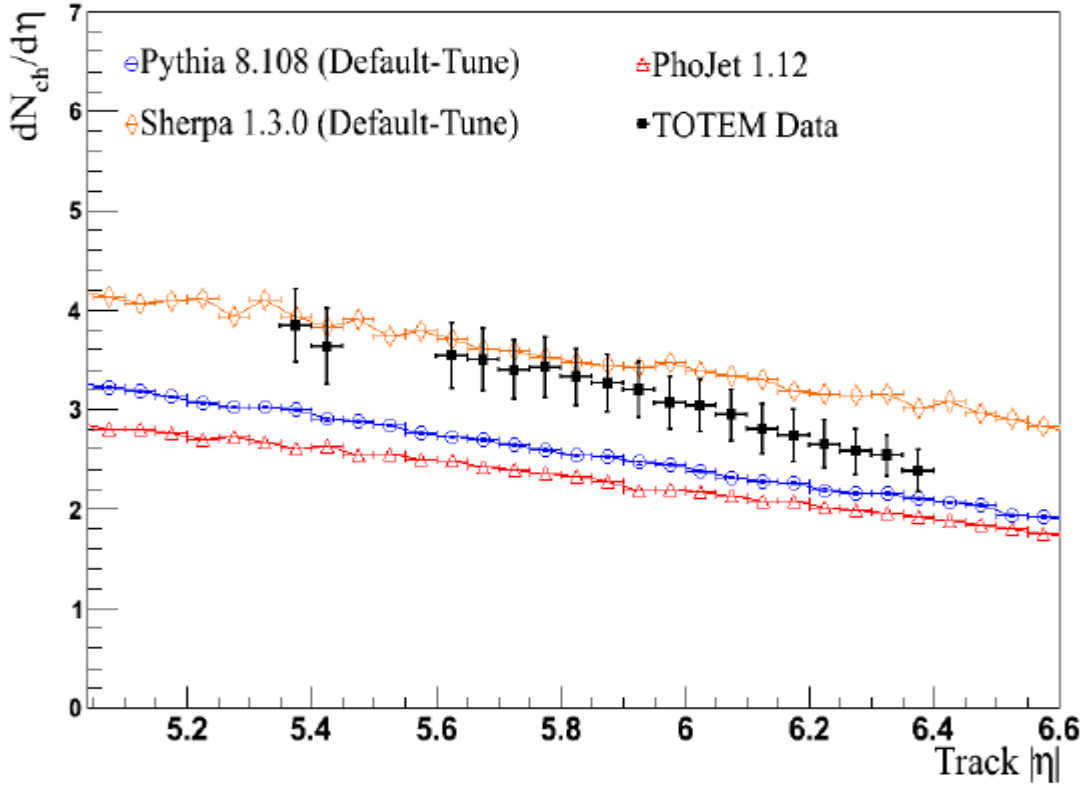
Correction from initial acceleration

- Initial acceleration pushes outer volume elements
- This modifies the $dN/d\eta$ distribution
- Estimate acceleration
- $\lambda = 1$: no acceleration
- TOTEM fit
  - 7 TeV: $\lambda = 1.073 \pm 0.001$
  - 8 TeV: $\lambda = 1.067 \pm 0.001$
- Corrected estimate:
  - 7 TeV: $\epsilon_{\mathrm{corr}} = 0.640\ \mathrm{GeV/fm^3}$
  - 8 TeV: $\epsilon_{\mathrm{corr}} = 0.644\ \mathrm{GeV/fm^3}$



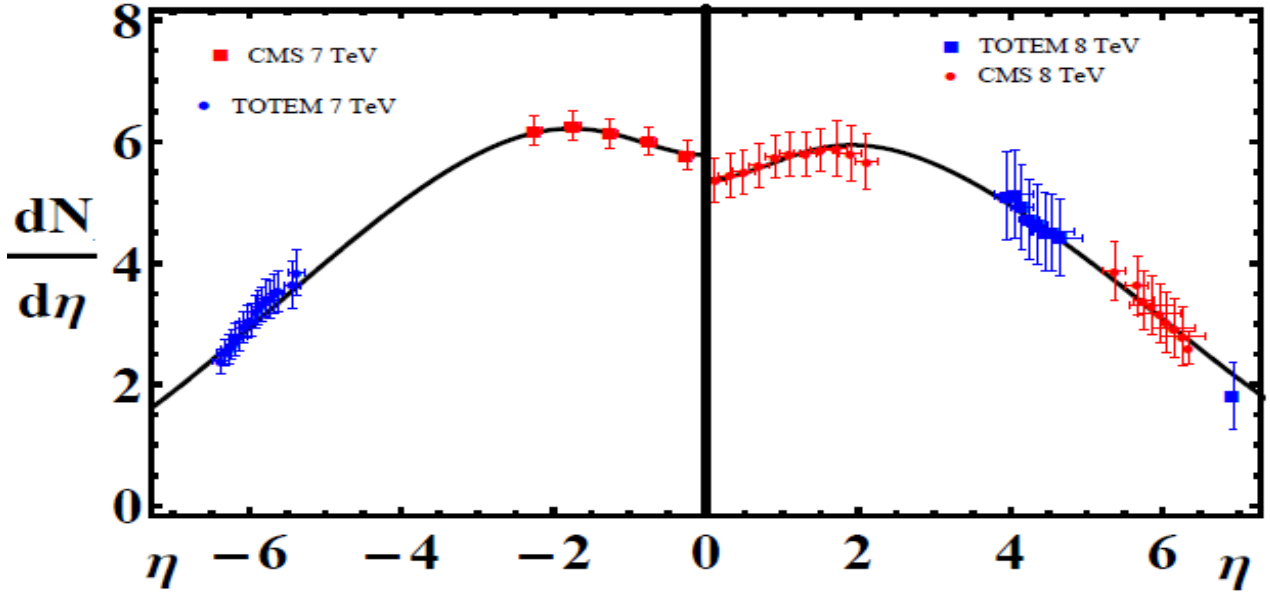
Comment: dN/dη @ LHC is not trivial

- Not trivial for MC models
- TOTEM Coll., EPL, 98 (2012) 31002



TOTEM & CMS data combined

- 7 TeV: $\lambda = 1.076$, 8 TeV: $\lambda = 1.066$

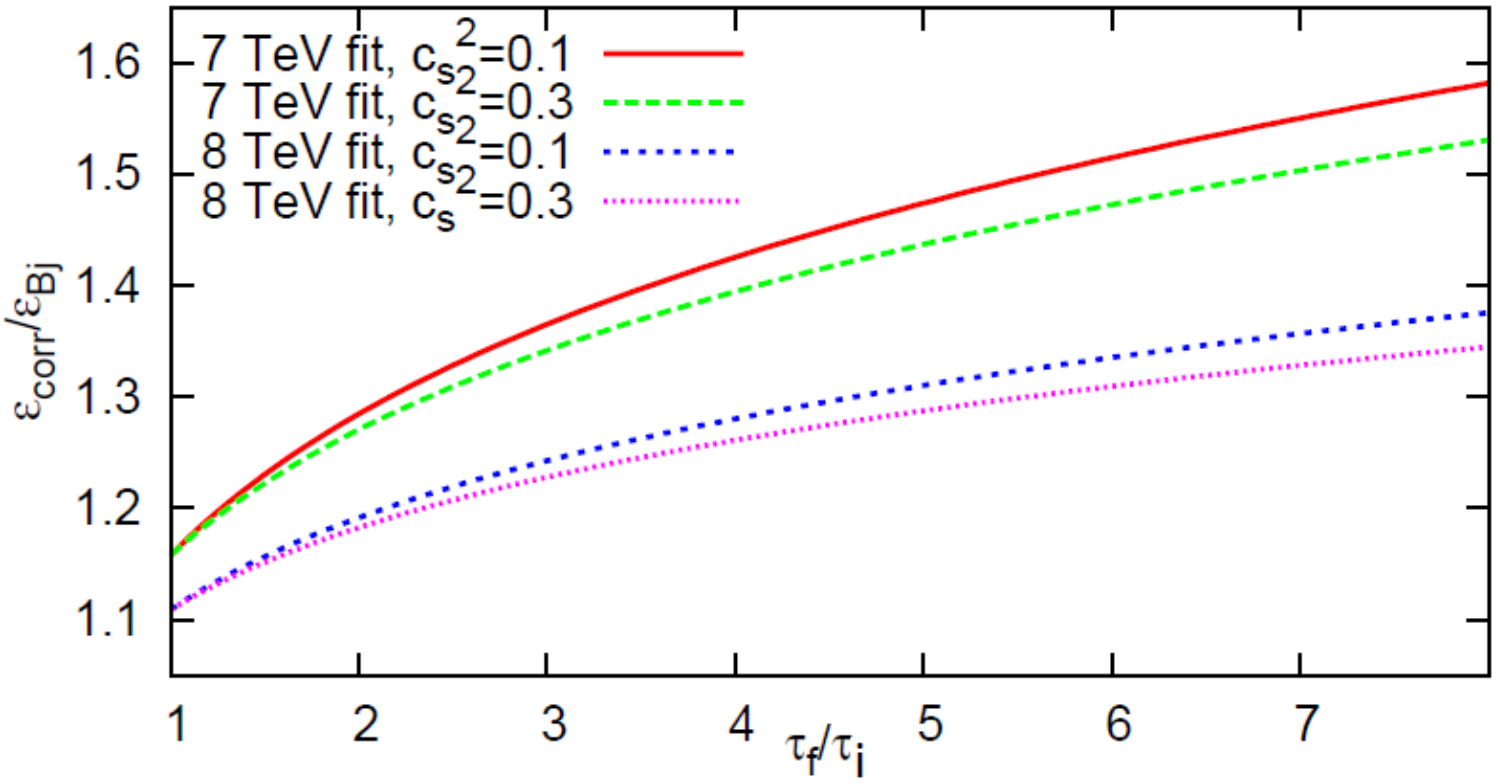


- Very small change compared to TOTEM only fit
- 7 TeV: $\epsilon_{\mathrm{corr}} = 0.645\ \mathrm{GeV/fm^3}$
- 8 TeV: $\epsilon_{\mathrm{corr}} = 0.641\ \mathrm{GeV/fm^3}$

Dependence on initial time speed of sound dependence

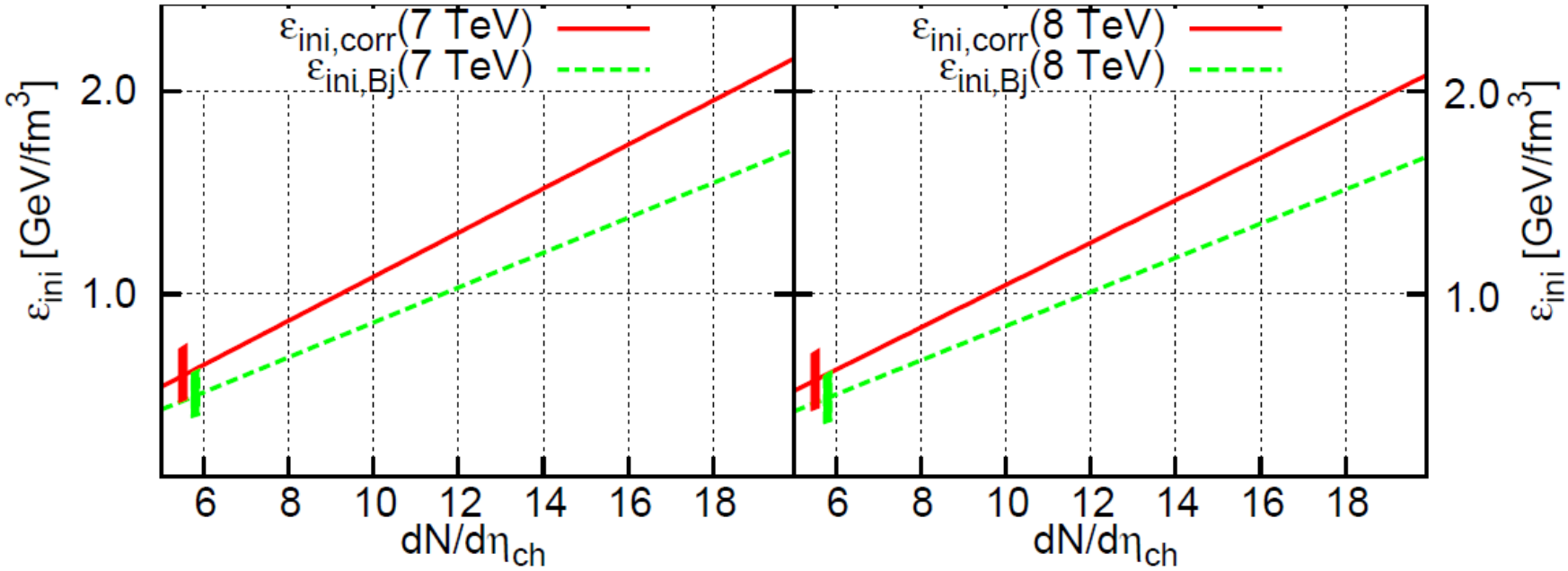
- Recall the correction factor:

$$\epsilon_{\mathrm{corr}} = \epsilon_{\mathrm{Bj}}(2\lambda - 1)\left(\tau_f/\tau_i\right)^{(\lambda-1)(2-c_{\mathrm{sound}}^2)}$$



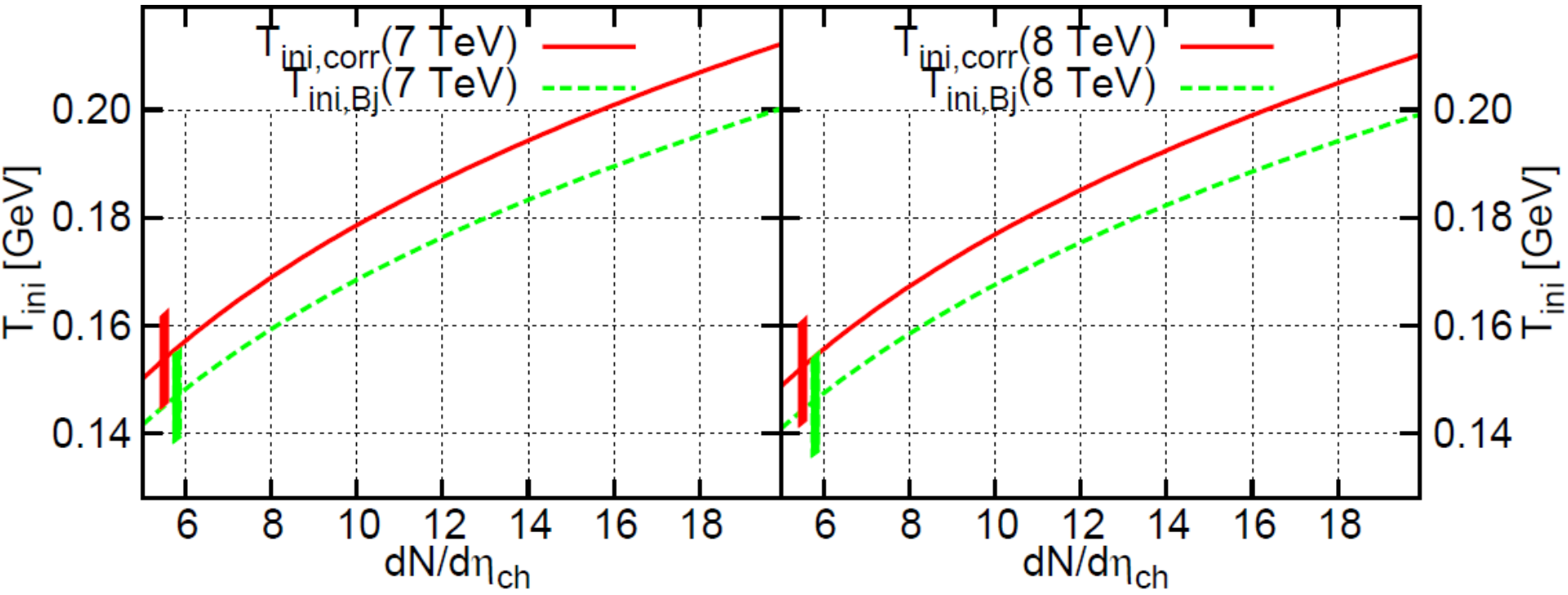
Dependence on multiplicity

- Several multiplicity classes, 6-20, even 40-50 seen!
- Initial energy density estimate above 1 GeV/fm^3, if:
  - Bjorken estimate: $dN_{\mathrm{ch}}/d\eta > 12$
  - Corrected estimate: $dN_{\mathrm{ch}}/d\eta > 9$



Initial temperature estimate

- Temperature from $\epsilon \sim T^4$
- Values above 150-170 MeV reached



Systematic uncertainties

- All sources of uncertainties at 7 TeV:

parameter	value	stat.	syst. eff. on ϵ
λ	1.073	0.1%	0.4% (from data)
c_s^2	0.1	-	-2%+0.2% (if $0.05 < c_s^2 < 0.5$)
τ_f/τ_0	2	-	-4%+10% (for τ_f/τ_0 in 1.5–4)
τ_0 [fm/c]	1	-	underestimates ϵ
R [fm]	1.766	-	1.3% (from σ_{tot})
$\langle E \rangle$ [GeV/c^2]	0.562	0.5%	3%
$dN/d\eta$ (7 TeV)	5.895	0.2%	3%

- Conclusion at 7 TeV:
  - $\epsilon_{\mathrm{corr}} = (0.64 \pm 0.01(\mathrm{stat})^{+0.14}_{-0.10}(\mathrm{syst}))\ \mathrm{GeV/fm^3}$

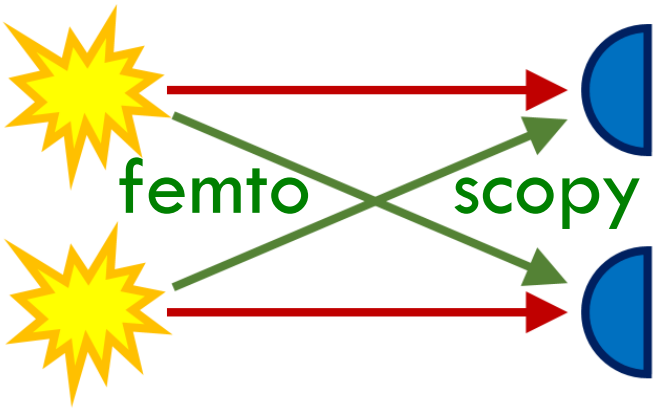
Is it unprecedented? Consequences?

- Bjorken and Landau worked out hydro for pp and pA
- Success of hydro to describe h+p, with <n> = 7-8...
  Phys.Lett. B422 (1998) 359-368
- Bjorken: it is not hadrons that play billiard balling
- If p+p is a complex system:
  - Gamma/pi0 ratio
  - Radial flow
  - Elliptic flow, scaling
  - HBT radii, scaling
  - Low mass dilepton enhancement
  - Direct photon enhancement
- R_{AA} might not be the best measure: divide by length scale?

Summary

- Experimentally widely used Bjorken est. at 7-8 TeV
- Advanced estimate: acceleration work, from $dN/d\eta$
- From TOTEM and CMS data, approximately:
  - $\epsilon_{\mathrm{corr}} = (0.64 \pm 0.01(\mathrm{stat}) \pm 0.1(\mathrm{syst}))\ \mathrm{GeV/fm^3}$
  - This at dN/dy=6 & linearly rises with multiplicity, up to 60!
- Critical energy density: $1\ \mathrm{GeV/fm^3}$
- Not incompatible with sQGP phase in high multiplicity p+p

Thank you for your attention



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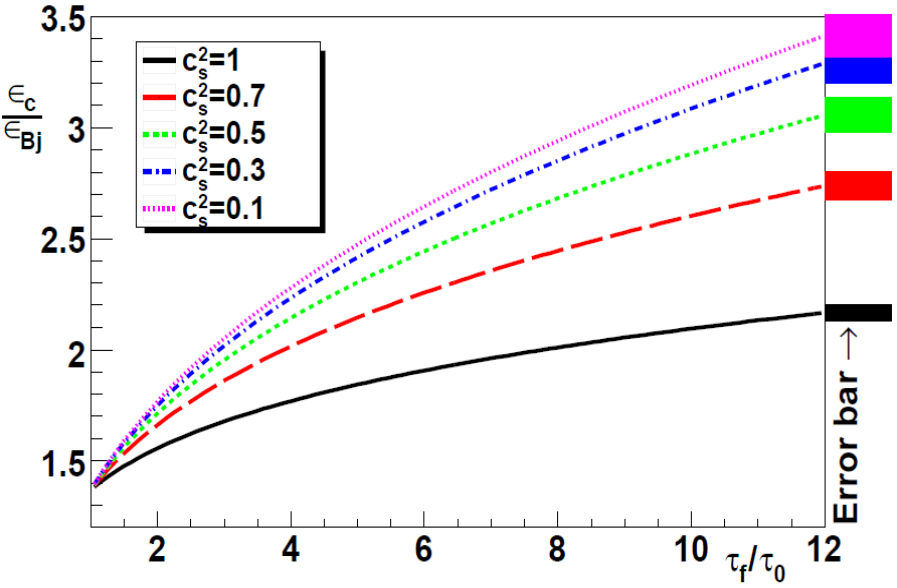
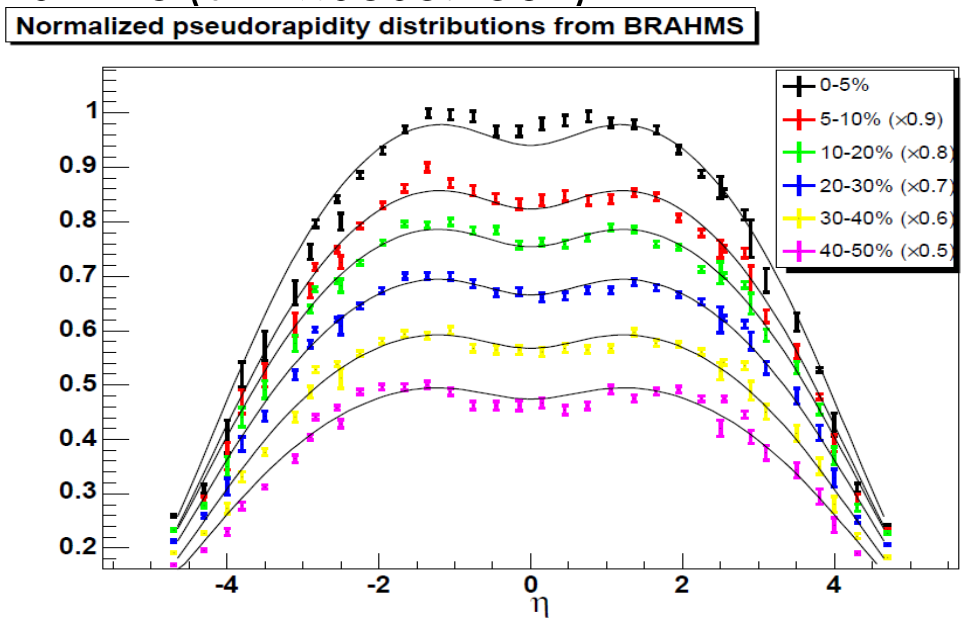
ESZTERHÁZY KÁROLY EGYETEM

Initial energy density at RHIC

- Bjorken estimate from BRAHMS: 5 GeV/fm^3
- Advanced estimate gives: $\varepsilon = \varepsilon_{Bj}(2\lambda - 1)\left(\frac{\tau_f}{\tau_i}\right)^{(\lambda-1)(2-c_{\text{sound}}^2)}$
- Correction: 2-3x, result 15 GeV/fm^3, QCD agreement!
- Corresponds to $T_{ini} \cong 2T_c \cong 340$ MeV
- Confirmed by photon spectra at PHENIX, published 2010
- Reference e.g.: J.Phys.G35 (2008) 104128 (arXiv:0805.1562)





Sources of uncertainties

- For the correction factor $\varepsilon/\varepsilon_{Bj}$:
  - Fit parameter λ
  - Statistical error (from the data)
  - Speed of sound c_s^2
  - Duration τ_f/τ_i
- For the original Bjorken-estimate:
  - Main uncertainty source: multiplicity at midrapidity dN/dy
  - Area (if taken from cross-section): very precise
  - Formation time
  - Average transverse mass