INITIAL ENERGY DENSITY IN P+P AND A+A COLLISIONS

UNIVERSE 3 (2017) 1, 9 ARXIV:1609.07176
+ ARXIV:1711.10740 + MANUSCRIPT IN PREP.
M. CS., T. CSÖRGŐ, Z-F. JIANG, G. KASZA. M. NAGY

2 INTRODUCTION

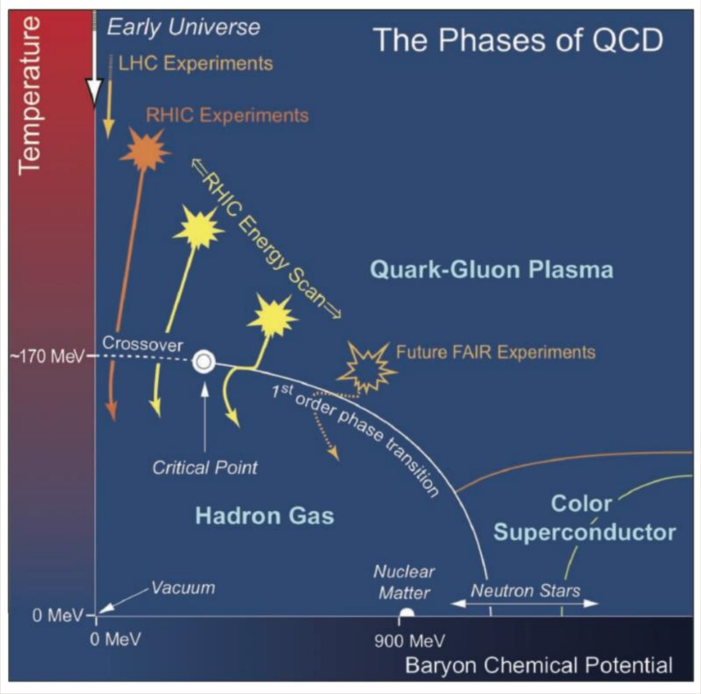
Goals of high energy heavy ion physics

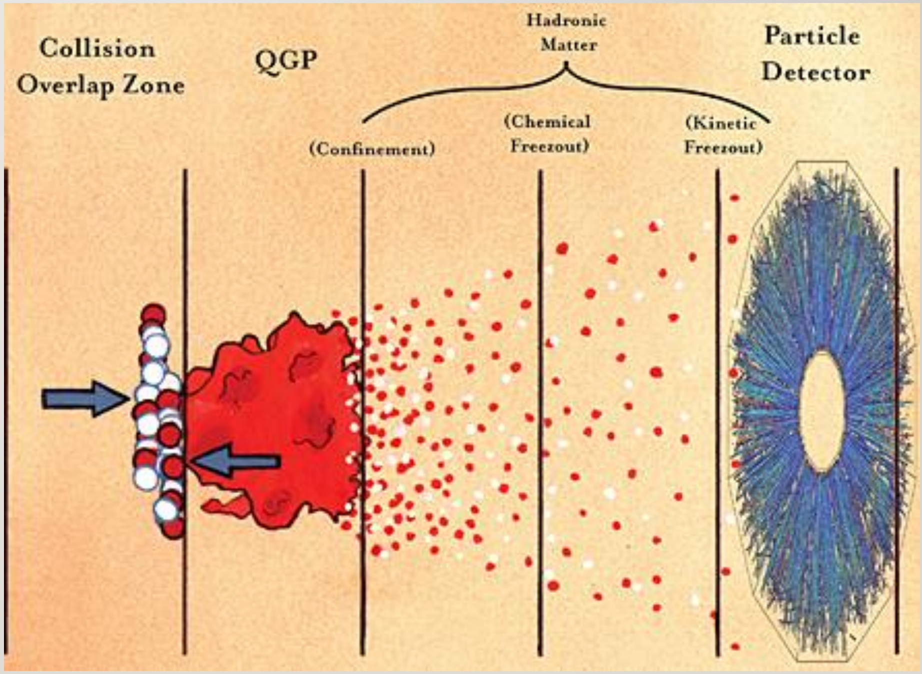
The Bjorken estimate of initial energy density

3

PHASE DIAGRAM OF QUARK MATTER

- Hadron gas, quark medium, many other phases
- Necessary and sufficient conditions fpr quark medium?



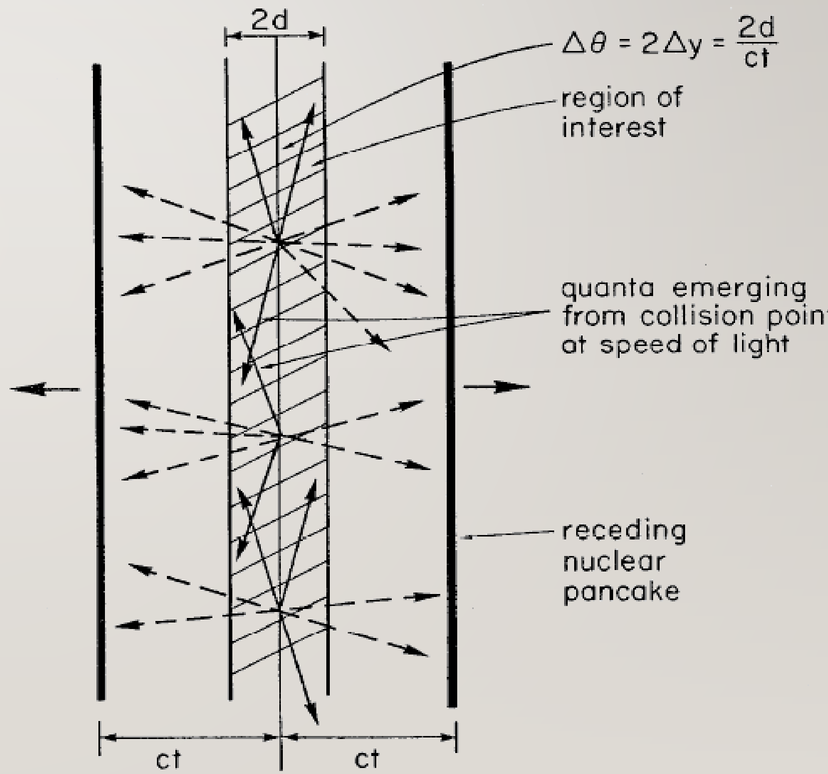


4 THE BJORKEN-ESTIMATE

- The original idea: energy density based on dE/dy
- QGP critical $\epsilon_c \sim 1$ GeV/fm³ (from $\epsilon_c = (6-8)\times T_c^4$)
- Result (~2000x cited)

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

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

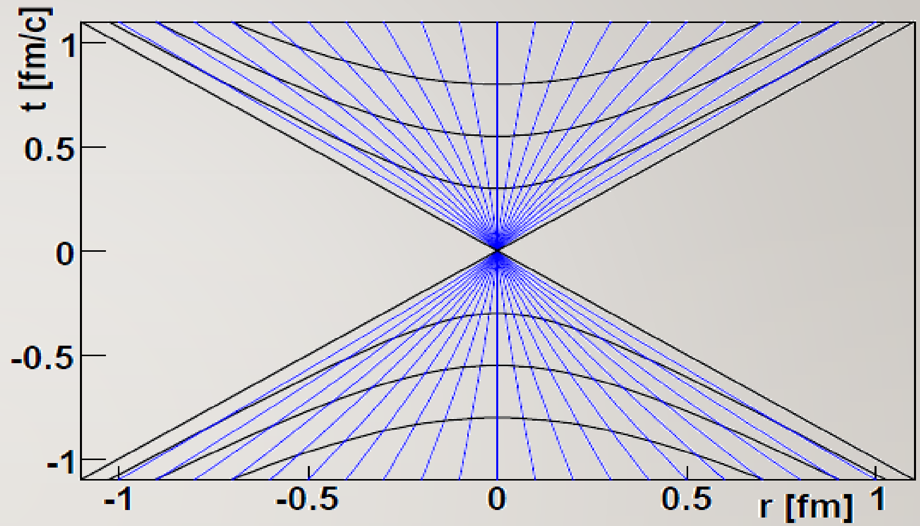


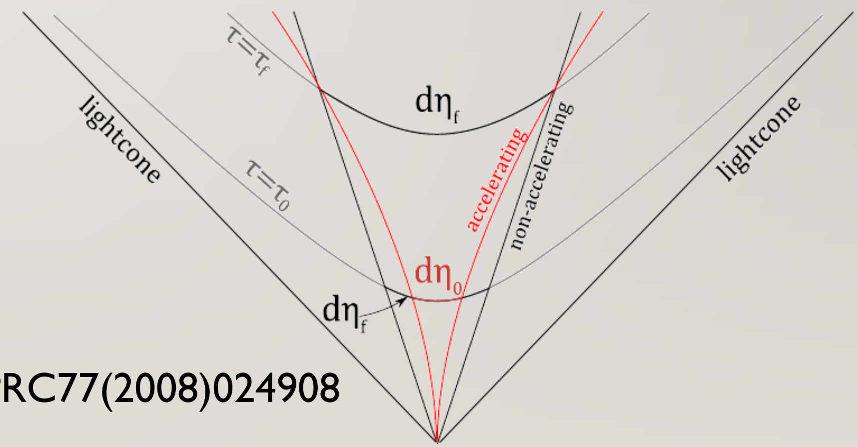
- Boost invarinat flow
  Phys.Rev. D27 (1983)
- Needs correction!

5 AN ACCELERATING SOLUTION OF HYDRO

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

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

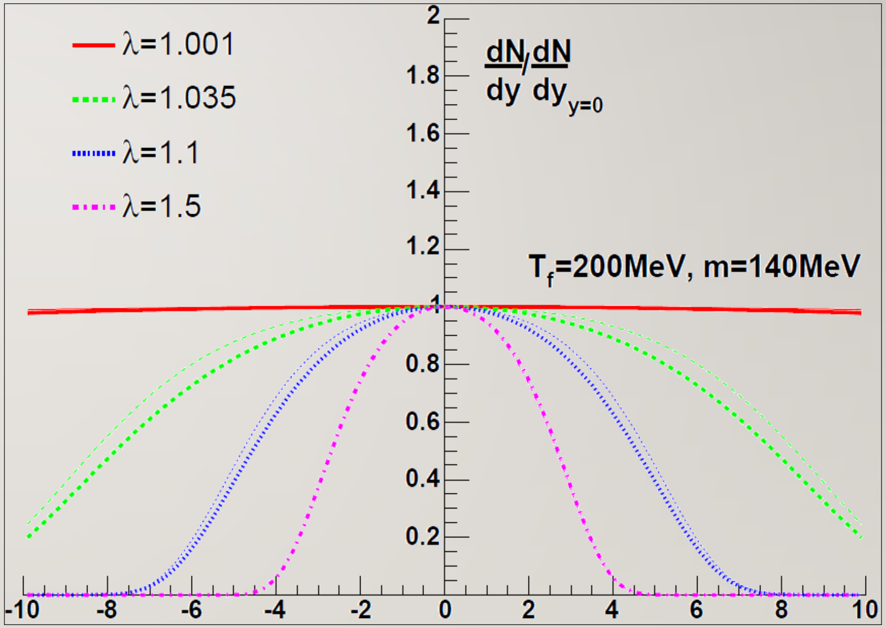




M. Nagy, T. Csörgő, M.Cs. et al, PLB663(2008)306, PRC77(2008)024908

6 THE PSEUDORAPIDITY DENSITY

- $\frac{dN}{dy} \cong N_0 \cosh^{-\frac{\alpha}{2}-1}\left(\frac{y}{\alpha}\right) \exp\left[-\frac{m}{T_f}\cosh^{\alpha}\frac{y}{\alpha}\right]$
- Main parameter: $\alpha = \frac{2\lambda-1}{\lambda-1}$
- Particle mass m,
- Freeze-out temp. T_f
- Measure acceleration!
- Extension to more complex flows: G. Kasza et al.



- Extension to viscous flows: Z. Jiang et al.

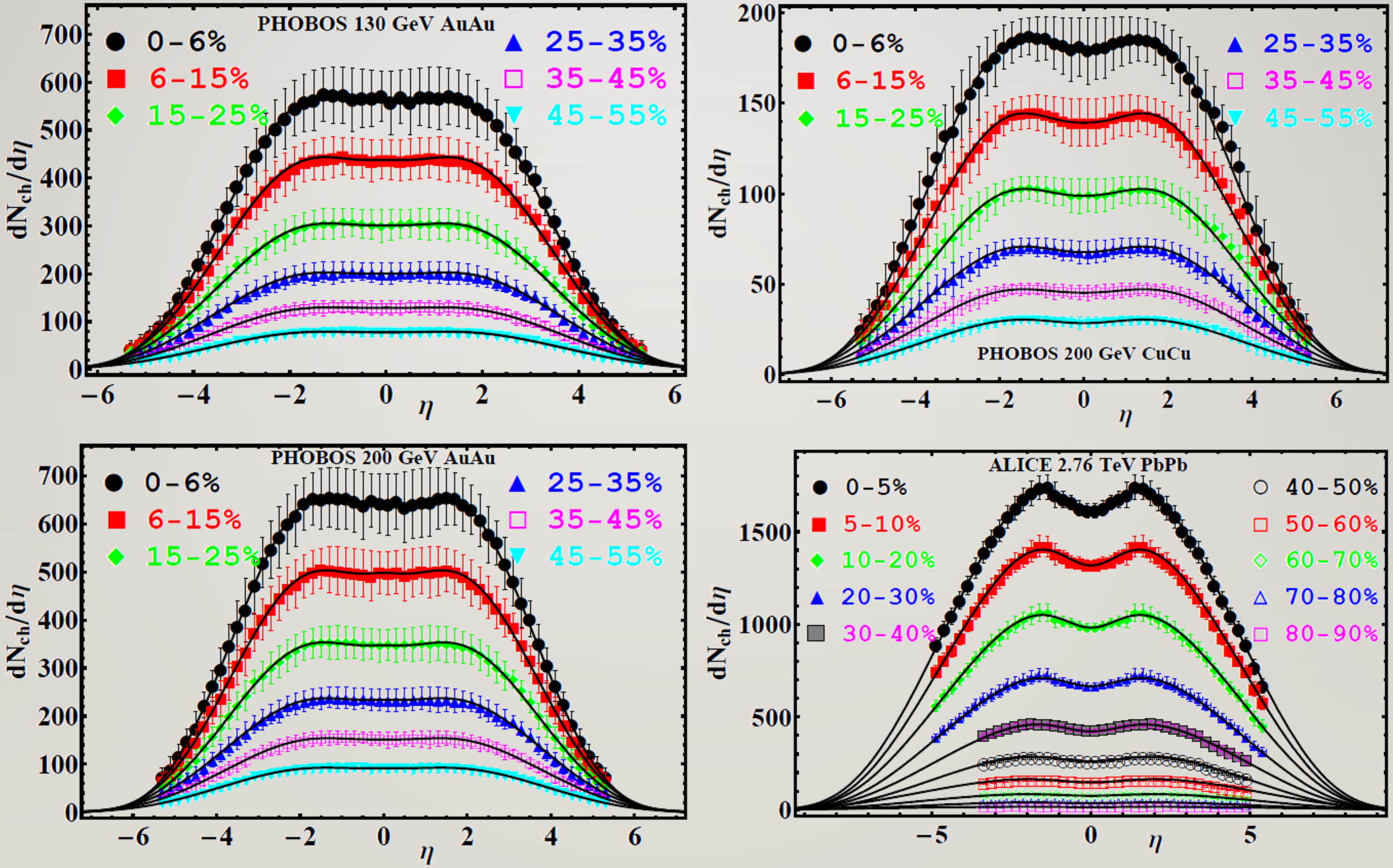
7

HOW DOES THIS WORK?

In A+A collisions: very well!

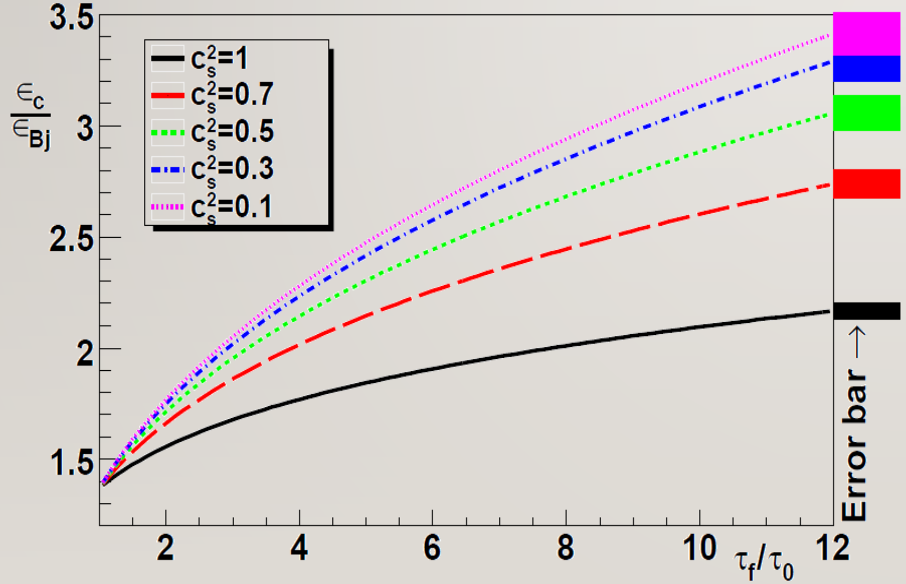
PSEUDORAPITY DENSITIES IN A+A

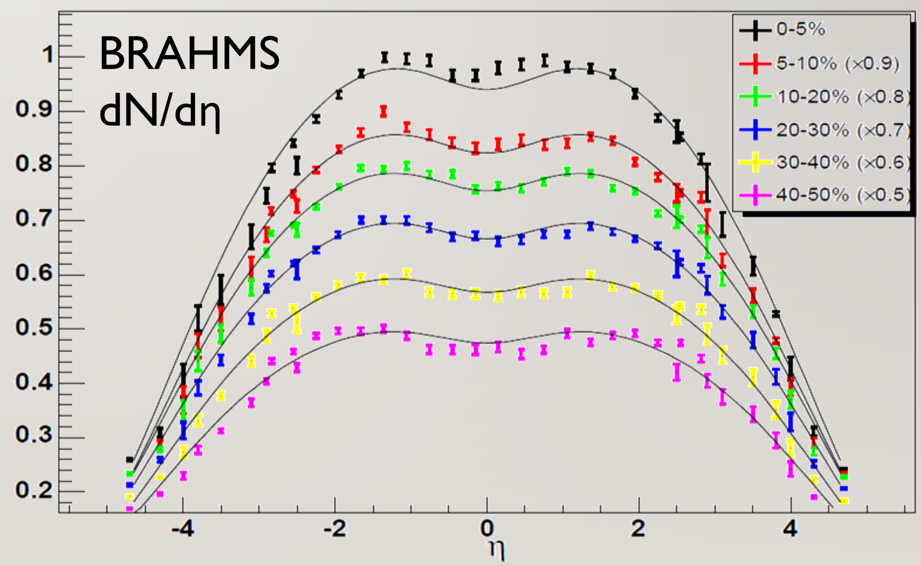
- Described well from RHIC to LHC



9 INITIAL ENERGY DENSITY AT RHIC

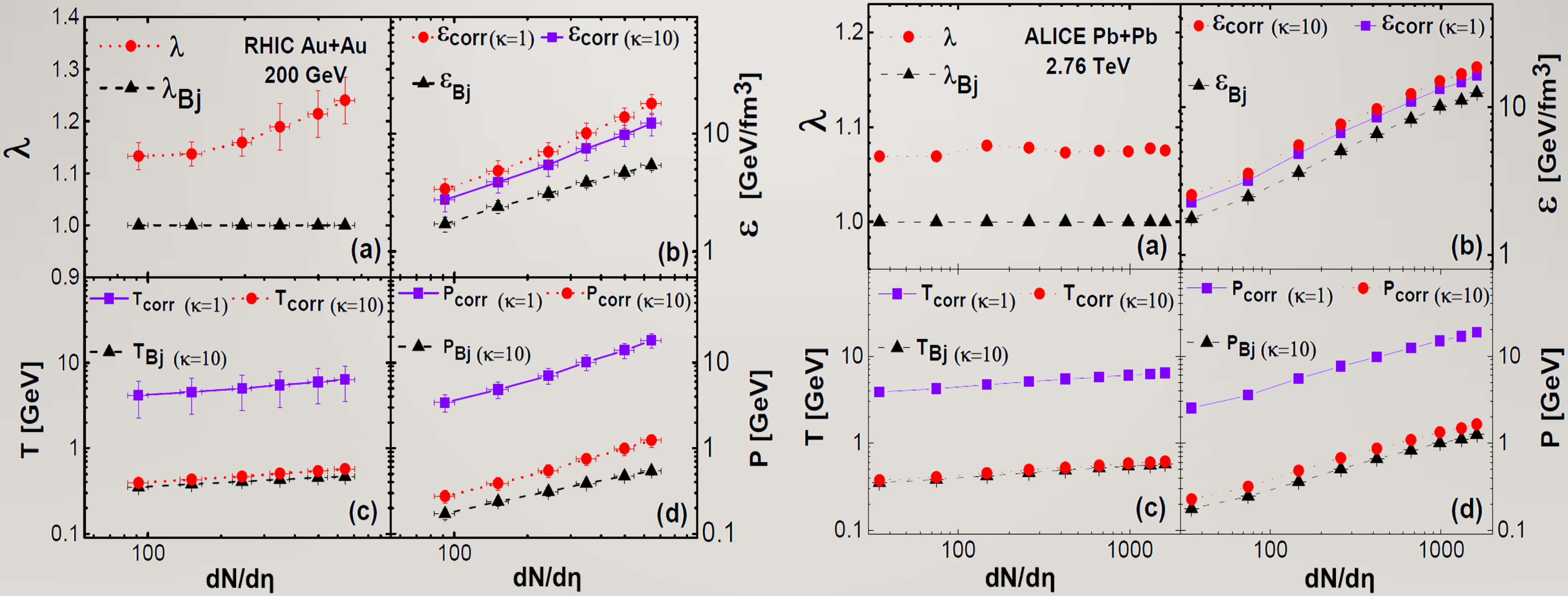
- Bjorken estimate from BRAHMS: $\epsilon_{\mathrm{Bj}} = \frac{\langle E \rangle}{R^2 \pi \tau_0} \frac{dN}{d\eta} \cong 5\ \mathrm{GeV/fm^3}$
- Advanced estimate: $\epsilon = \epsilon_{\mathrm{Bj}} (2\lambda - 1) \left(\tau_f / \tau_i\right)^{(\lambda-1)(2-c_{\mathrm{sound}}^2)}$
- Correction: 2-3x, result ~15 GeV/fm^3, QCD agreement!
- Corresponds to $T_{\mathrm{ini}} \cong 2T_c \cong 340$ MeV, confirmed by γ spectra





10 ENERGY DENSITIES IN AA, RHIC TO LHC

- Effect of acceleration and equation of state
- How about the effects of viscosity?
  - Work in prep.: G. Kasza, J. Ze-Fang, M. Nagy, T. Csörgő



WHAT ABOUT PP COLLISIONS?

Can an sQGP created there as well?

Yes, depending on multiplicity

12 BJORKEN ENERGY DENSITY ESTIMATE IN PP

- Rough estimate via the Bjorken formula: $\epsilon_{\mathrm{Bj}} = \frac{\langle E \rangle}{R^2 \pi \tau_0} \frac{dN}{d\eta}$
  - 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:

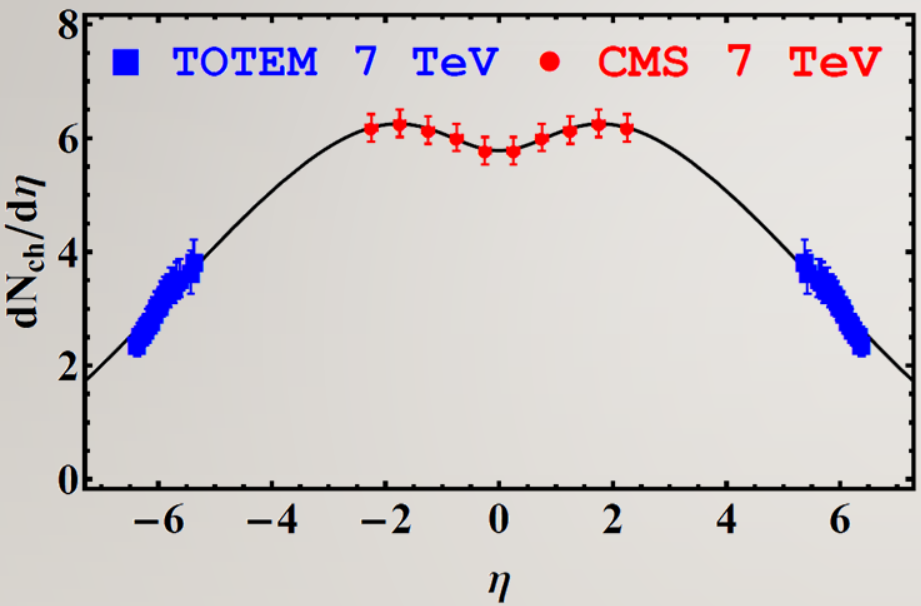
$$\epsilon_{\mathrm{Bj}}(7\ \mathrm{TeV}) = \frac{1}{R^2 \pi \tau_0} \frac{dE}{d\eta} = \frac{\langle E \rangle}{R^2 \pi \tau_0} \frac{dn}{d\eta} = \frac{0.562 \times 1.5 \times 5.89}{1.76^2 \pi} \frac{\mathrm{GeV}}{\mathrm{fm}^3} = 0.507 \frac{\mathrm{GeV}}{\mathrm{fm}^3}$$

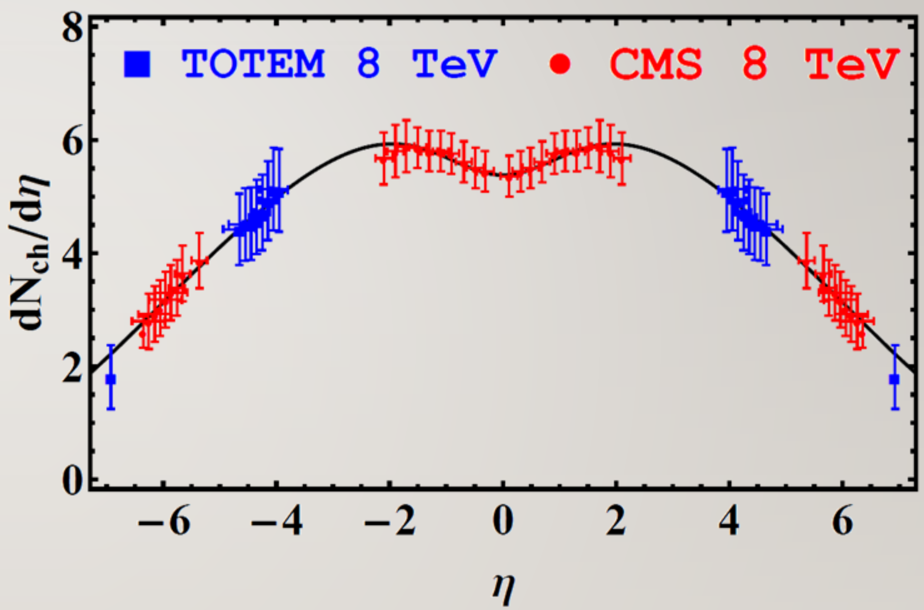
$$\epsilon_{\mathrm{Bj}}(8\ \mathrm{TeV}) = \frac{1}{R^2 \pi \tau_0} \frac{dE}{d\eta} = \frac{\langle E \rangle}{R^2 \pi \tau_0} \frac{dn}{d\eta} = \frac{0.571 \times 1.5 \times 6.17}{1.80^2 \pi} \frac{\mathrm{GeV}}{\mathrm{fm}^3} = 0.519 \frac{\mathrm{GeV}}{\mathrm{fm}^3}$$

- This is at average multiplicity; compare to $\epsilon_{\mathrm{crit}} \approx 1 \frac{\mathrm{GeV}}{\mathrm{fm}^3}$

13 CORRECTED ENERGY DENSITY ESTIMATE

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



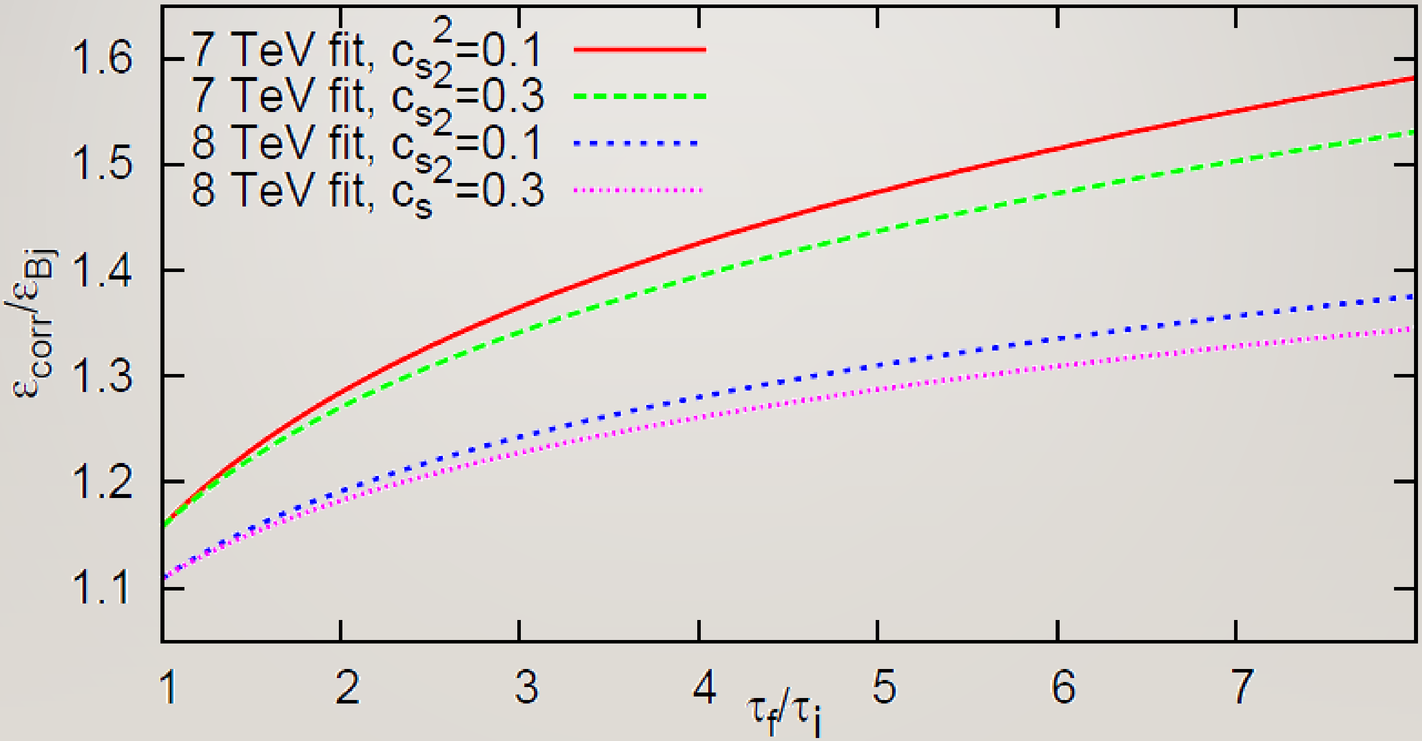


- 7 TeV: $\epsilon_{\mathrm{corr}} = 0.645\,\frac{\mathrm{GeV}}{\mathrm{fm}^3}$, 8 TeV: $\epsilon_{\mathrm{corr}} = 0.641\,\frac{\mathrm{GeV}}{\mathrm{fm}^3}$
- This is at average multiplicity; compare to $\epsilon_{\mathrm{crit}} \approx 1\,\frac{\mathrm{GeV}}{\mathrm{fm}^3}$

14 DEPENDENCE ON INITIAL TIME AND C_{SOUND}

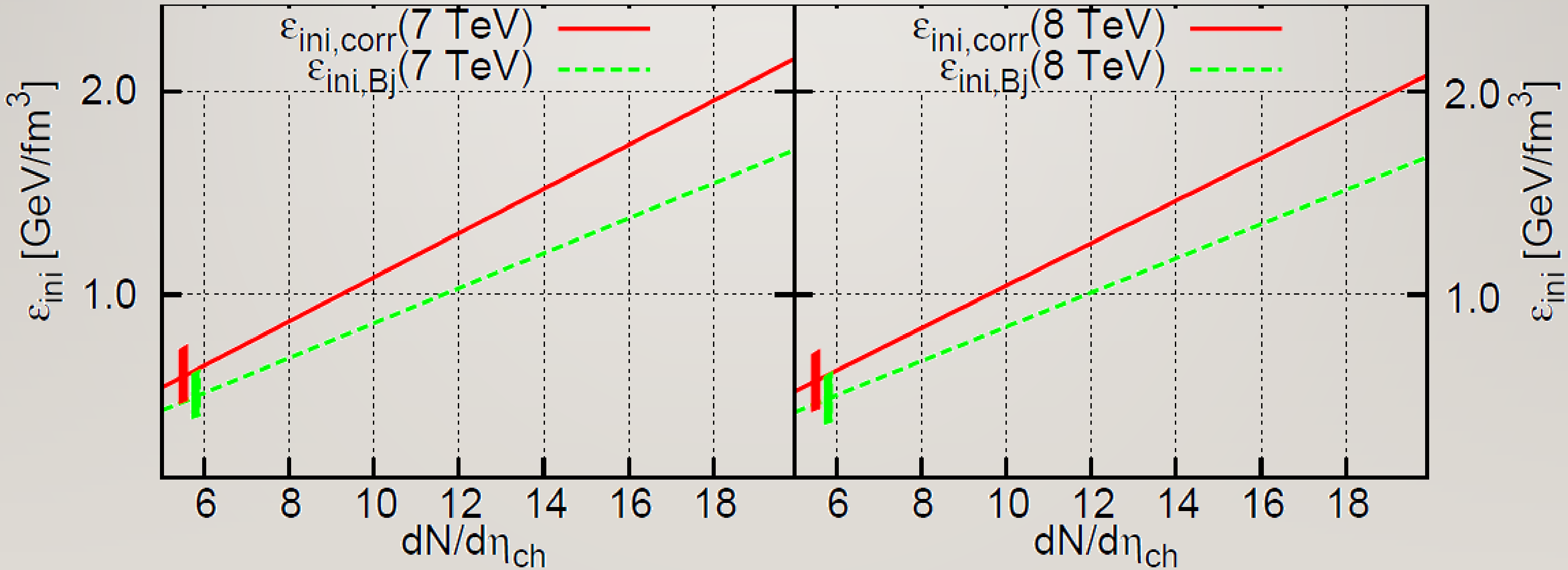
- Recall the correction factor:

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



15 DEPENDENCE ON MULTIPLICITY

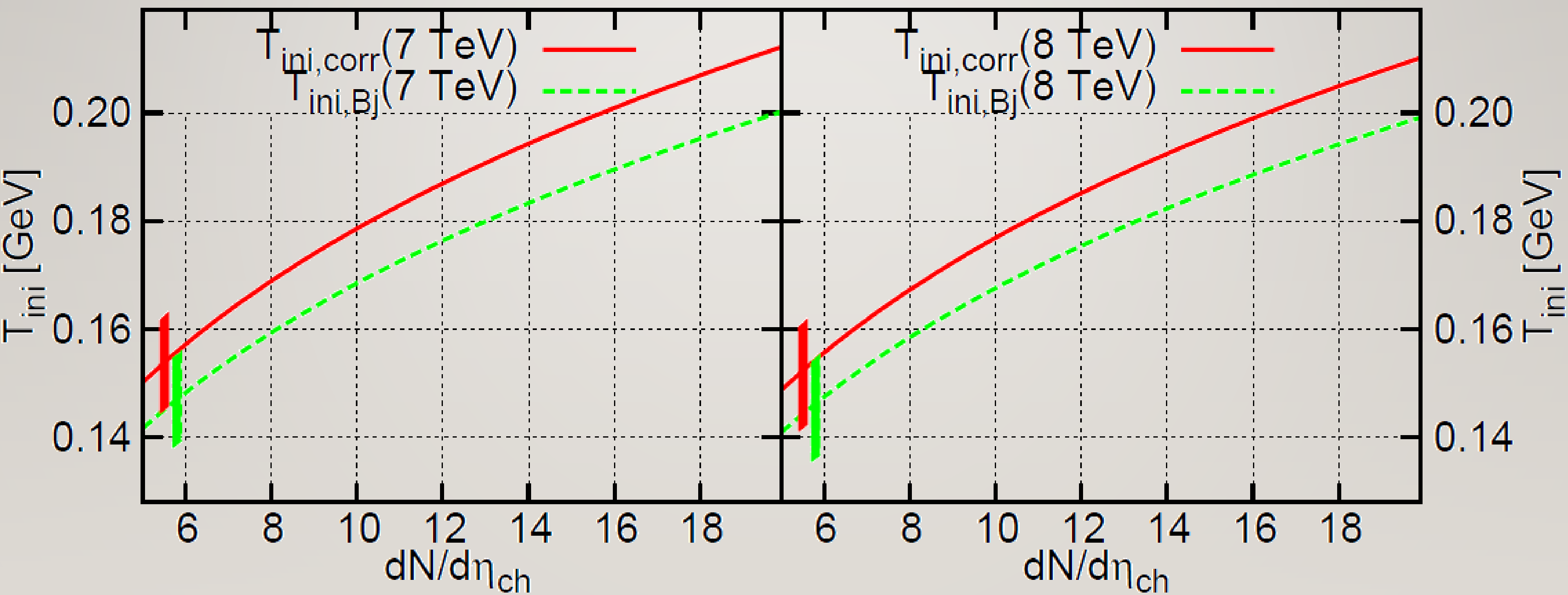
- Several multiplicity classes, 6-20, even 40-50 seen!
- Initial energy density estimate above 1 GeV/fm³, if:
  - Bjorken estimate: $dN_{\mathrm{ch}}/d\eta > 12$
  - Corrected estimate: $dN_{\mathrm{ch}}/d\eta > 9$



16

INITIAL TEMPERATURE ESTIMATE

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



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?

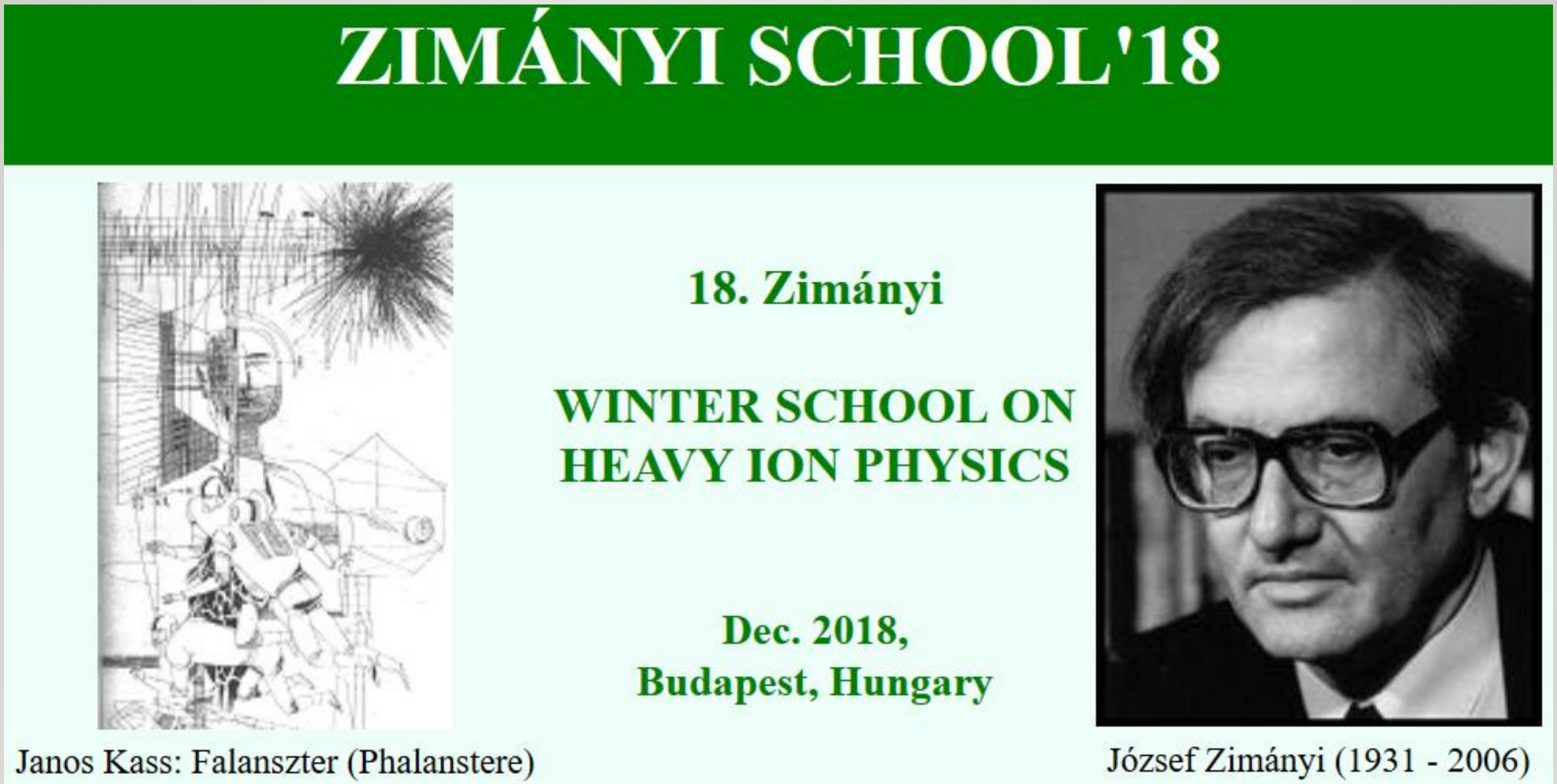
18 WHAT DID WE LEARN?

- Experimentally widely used Bjorken estimate
- Advanced estimate: acceleration work, from $dN/d\eta$
- Hydro $dN/d\eta$ works well in A+A from 130 to 2760 GeV
- It also works in p+p
- From TOTEM and CMS p+p data at 7 & 8 TeV:
  - $\epsilon_{\mathrm{corr}} \approx 0.64\ \mathrm{GeV/fm^3}$
  - 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 <u>high multiplicity</u> p+p

19

THANK YOU FOR YOUR ATTENTION

… and let me invite you to the Zimányi School 2018!



20 SYSTEMATIC UNCERTAINTIES

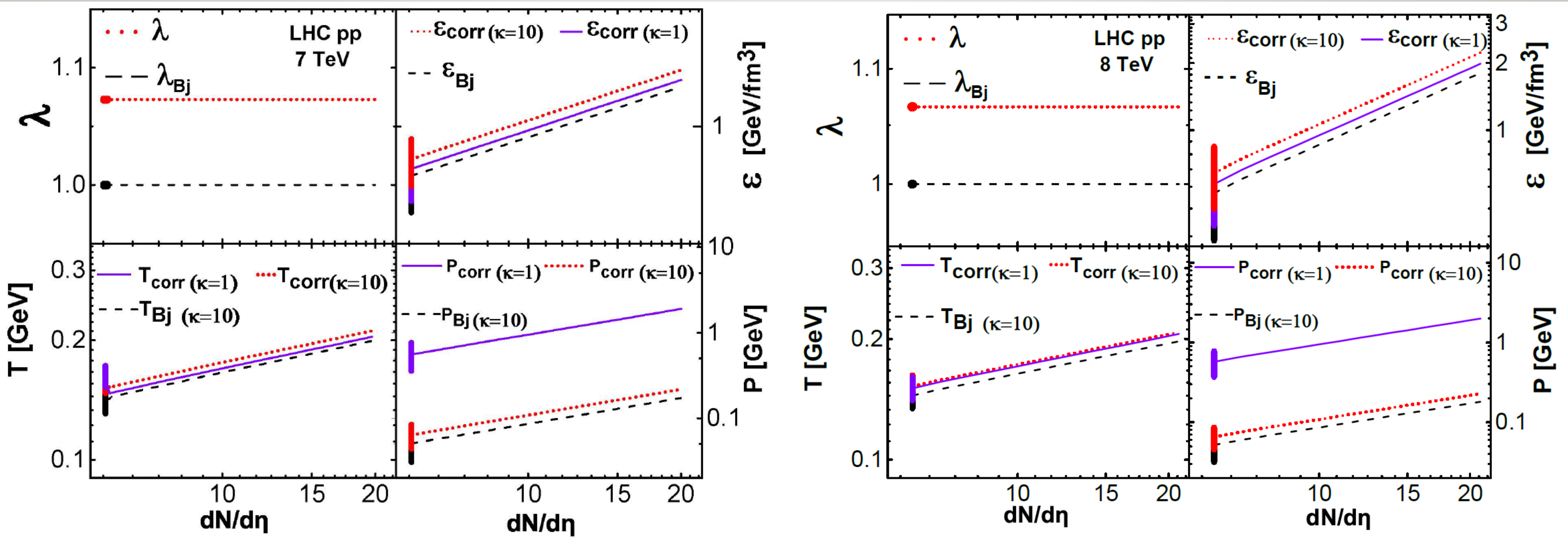
- All sources of uncertainties at 7 TeV:

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%
$dN/d\eta\|_{\eta=0}$	5.895	0.2%	3% (equivalently from N_0)

21 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

22 MULTIPLICITY DEPENDENCE



COMMENT: DN/DH @ LHC IS NOT TRIVIAL

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