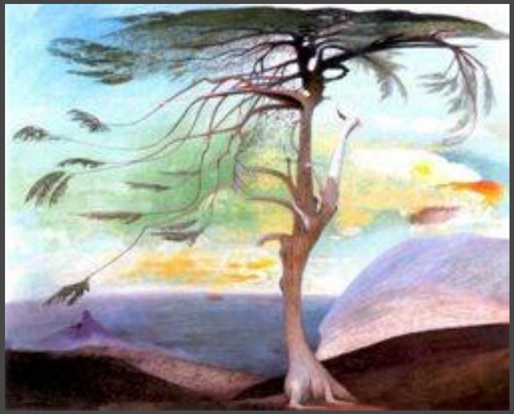

ZIMÁNYI SCHOOL 2012

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Budapest, Hungary

INITIAL ENERGY DENSITY IN LHC P+P COLLISIONS

04 Dec 2012

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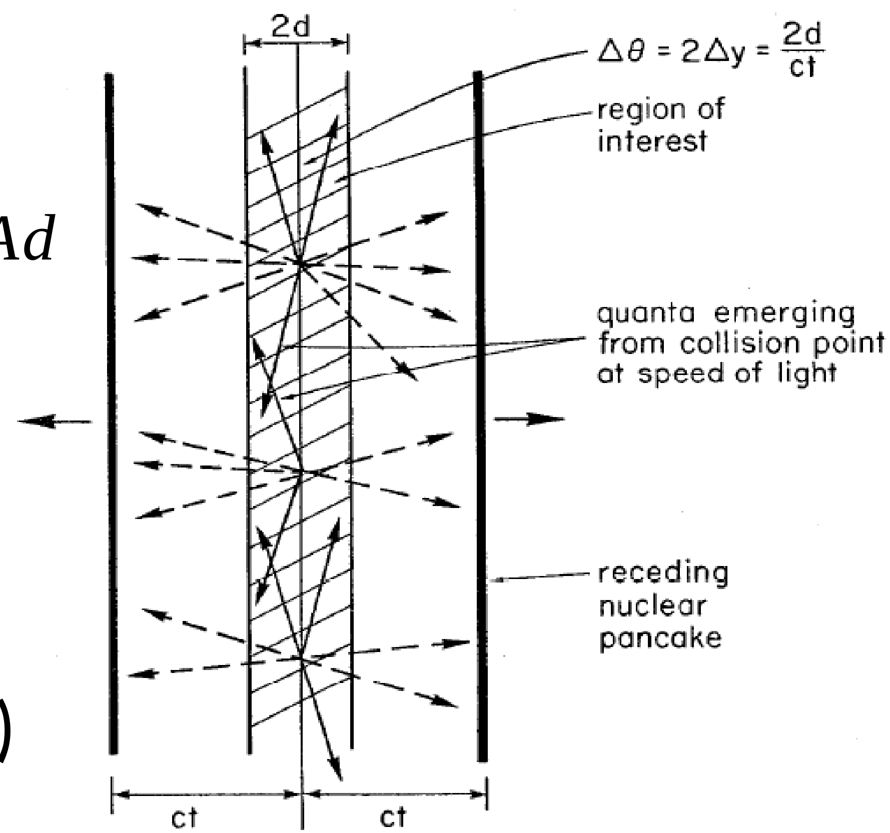
The Bjorken-estimate

- The original idea: energy density based on dE/dy
- QGP critical ε: ≤1 GeV/fm^3 (from ε_c=6-8×T_c^4)
- Result (1900x cited)

$$E = N\frac{dE}{dy}\Delta y = N\frac{dE}{dy}\frac{1}{2}\frac{2d}{t} = \varepsilon \cdot Ad$$

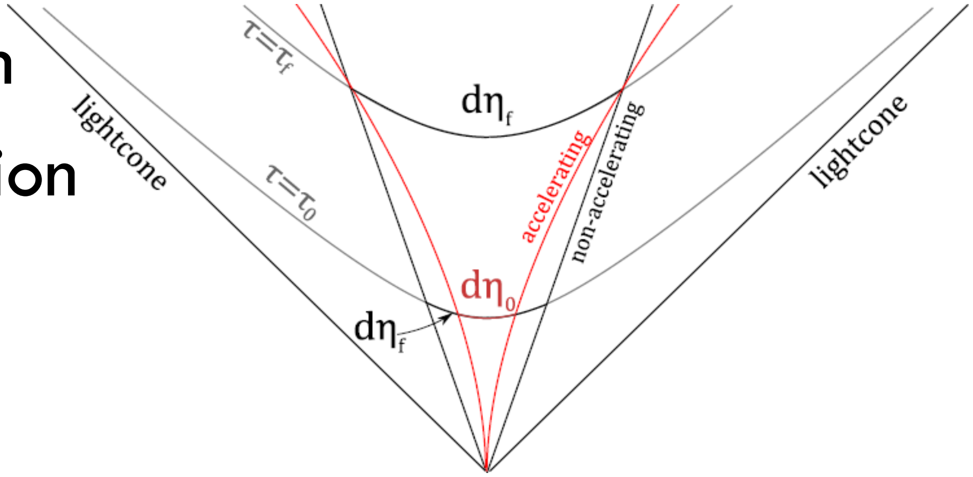
$$\varepsilon_{Bj} = \frac{1}{R^2\pi\tau_0}\frac{dE}{d\eta} = \frac{\langle E\rangle}{R^2\pi\tau_0}\frac{dn}{d\eta}$$



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

An advanced estimate

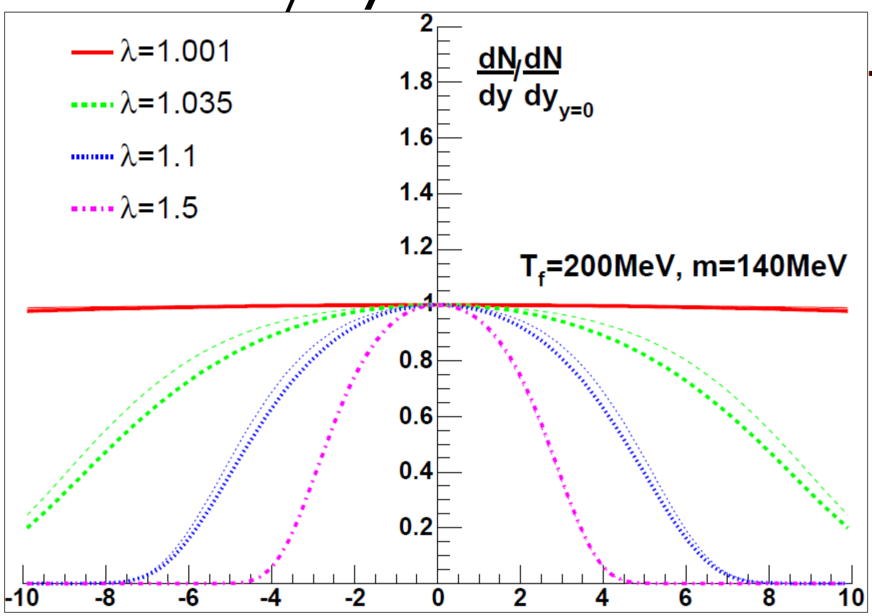
- Fact: dn/dy not flat
- Finiteness & acceleration
- Need accelerating solution of relativistic hydro
- Two modifications:
  - $y \neq \eta$ & $\eta_{final} \neq \eta_{initial}$

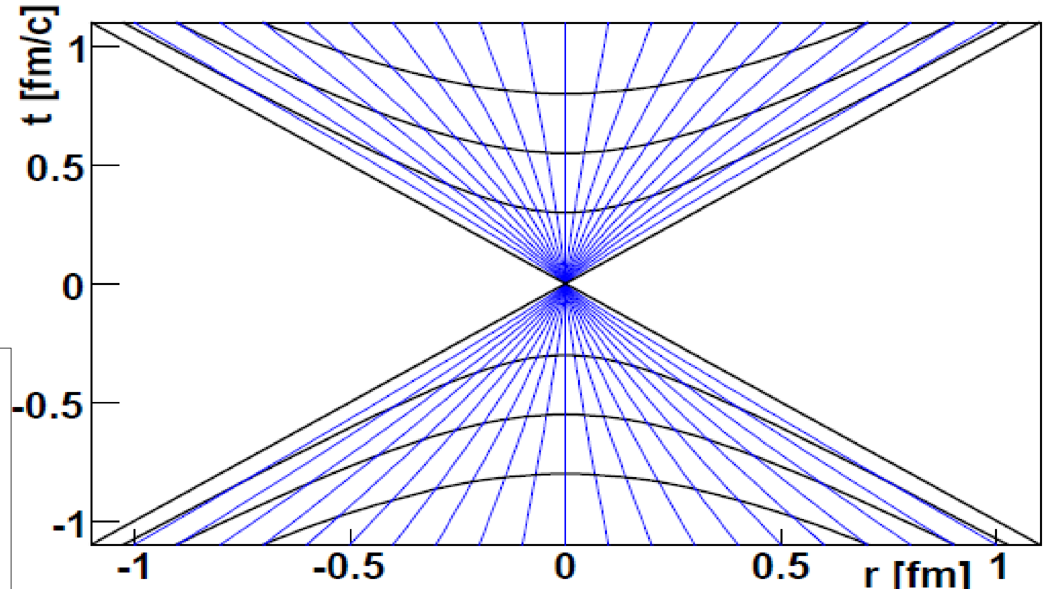


- Corrected initial energy density: $$\varepsilon = \varepsilon_{Bj} \frac{dy}{d\eta_f} \frac{d\eta_f}{d\eta_i}$$
- Work needed to accelerate!
- Correction w.r.t. EoS: $$\varepsilon = \varepsilon_{Bj} (2\lambda - 1) \left(\frac{\tau_f}{\tau_i} \right)^{(\lambda-1)(2-c^2_{\text{sound}})}$$

A solution of relativistic hydro

- Velocity: $\tanh(\lambda\eta)$
- Acceleration: $\lambda\neq 1$
- Density: $(\tau/\tau_0)^{\lambda}$
- dn/dy calculable!



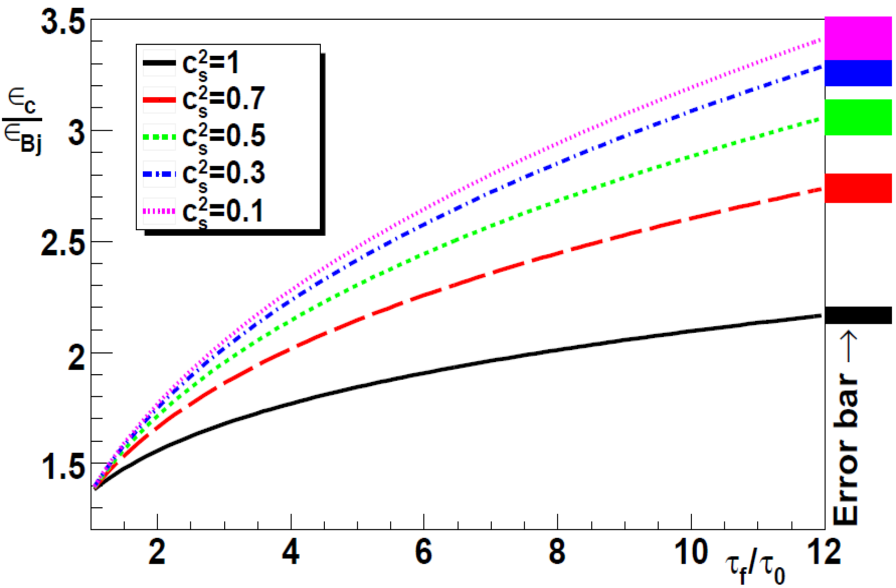


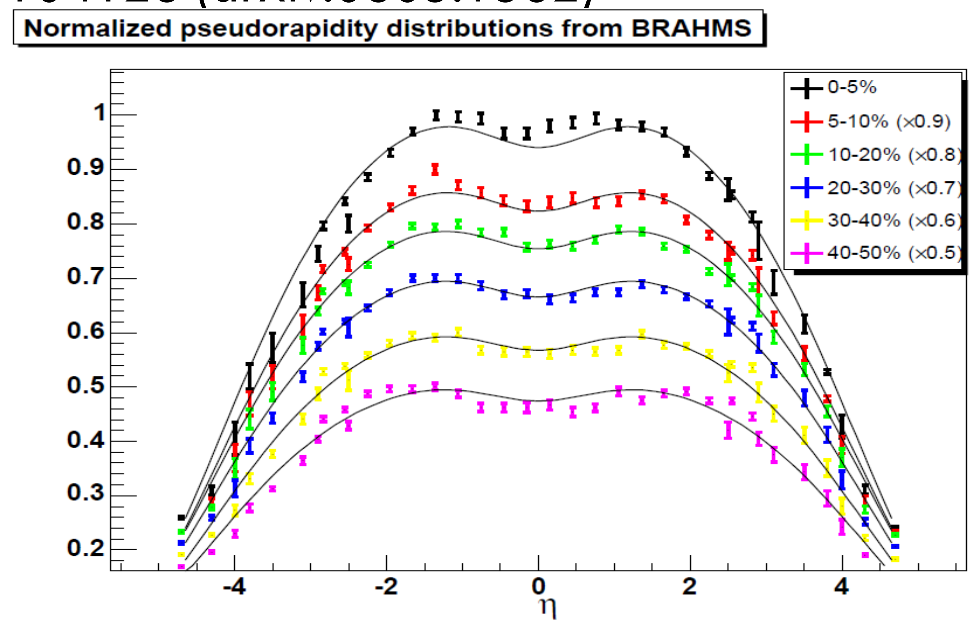
- Compare this to RHIC data!
- dn/dy measurement yields advanced initial ε estimate
- Significant correction at RHIC!

- Reference: Phys.Lett. B663 (2008) 306-311 (nucl-th/0605070)

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)





Initial energy density at LHC

- Rough estimate possible via the Bjorken formula
  - Number of particles at midrapidity: 5.89 (CMS, ALICE)
  - Average energy: $\langle m_t \rangle$=0.562 GeV (CMS)
  - Initial radius of the system R: ~1.081 fm (TOTEM, σ_{inel})
  - Formation time τ_0: 1 fm/c (conservative estimate)
- Energy density from this:

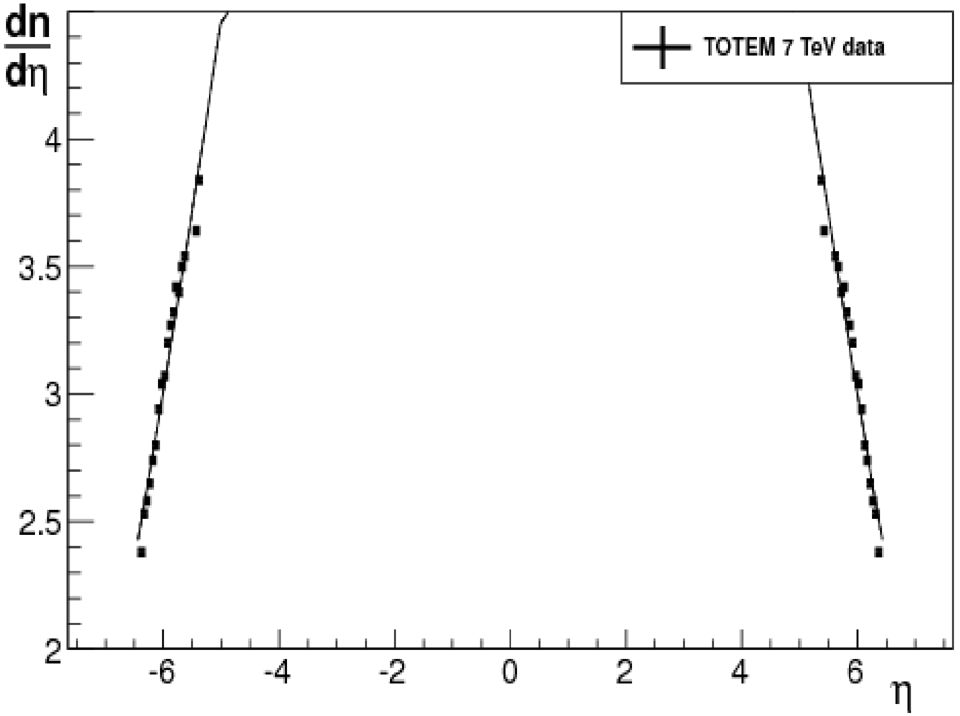
$$\varepsilon_{Bj} = \frac{1}{R^2 \pi \tau_0} \frac{dE}{d\eta} = \frac{\langle E \rangle}{R^2 \pi \tau_0} \frac{dn}{d\eta} = \frac{0.562 \times 5.89\,\mathrm{GeV}/c}{3.67\,\mathrm{fm}^3/c} \approx 0.90\,\mathrm{GeV}/\mathrm{fm}^3$$

- Just below critical? Important question!

Correction from initial acceleration

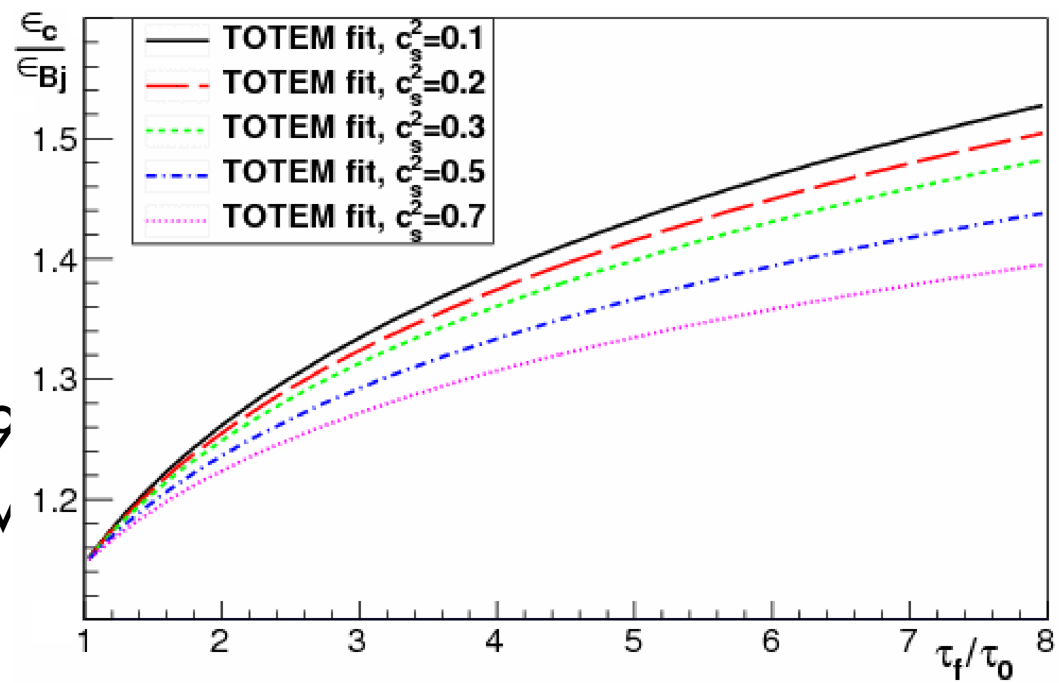
- Initial acceleration pushes outer volume elements
- This modifies the dn/dη distribution
- Estimate acceleration from it!
- $\lambda = 1$: no acceleration
- TOTEM fit: $\lambda = 1.073 \pm 0.001 \pm 0.004$
- Without EoS: 20%

$$\varepsilon = \varepsilon_{Bj}(2\lambda - 1)\left(\frac{\tau_f}{\tau_i}\right)^{(\lambda-1)(1-c_s^2)}$$



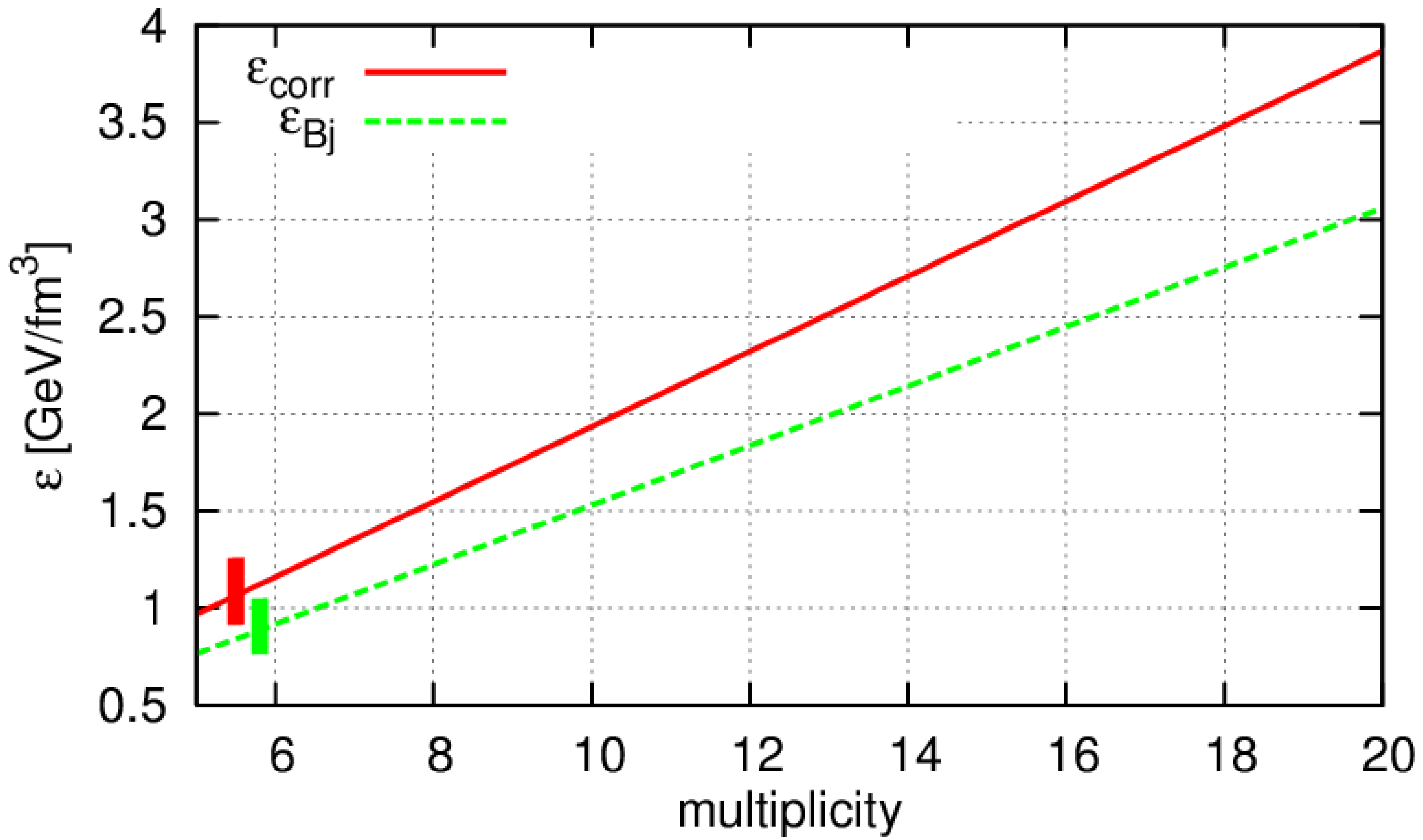
Advanced estimate

- Fit result: λ=1.073
- Conservatively: c_s^2=0.1
- ~25% correction
- Input parameters:
  - dN/dy at midrap.: 5.89
  - Average m_t: 0.562 GeV
  - Area: 3.67 fm^2
    - From cross sections
  - Freeze-out time / form. time: at least 2
- Bjorken result: 0.90 Gev/fm^3
- Corrected result: 1.14 GeV/fm^3



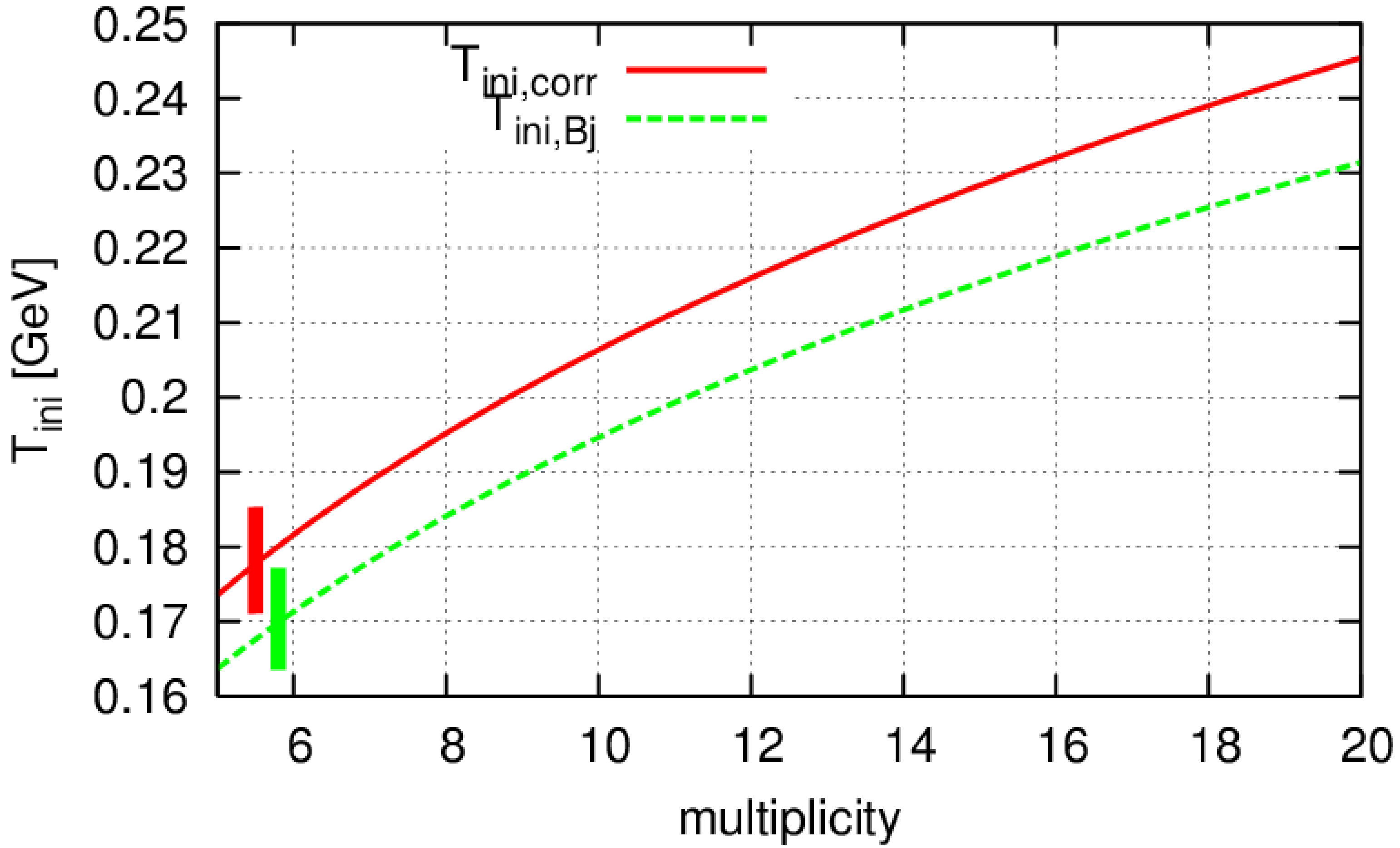
Dependence on particle number

- Several multiplicity classes, 6-20, even 30 seen!



Initial temperature estimate

- Temperature from $\varepsilon \sim T^4$



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

Systematic uncertainties

- All sources of uncertainties:

parameter	value	statistical uncertainty	systematic uncertainty
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% (if ratio 1.5…4)
τ_0	1 fm/c	-	understimation on ε
R (from σ_{inel})	1.081 fm	0.5%	1.5% (from data)
$\langle m_t \rangle$	0.562 GeV/c^2	0.5%	3% (from data)
$dN/d\eta$	5.985	0.2%	3% (from data)

- Conclusion:
  - $\varepsilon_{ini} = (1.14 \pm 0.01(\text{syst})\ ^{+0.21}_{-0.16}(\text{syst}))\ \text{GeV/fm}^3$

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:
  - Radial flow
  - V2 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.
- Advanced estimate: acceleration work, from $dn/d\eta$
- Results on the initial ε for $c_s^2=0.1$, at $\tau_f/\tau_{ini}=2$
- From TOTEM data: $\varepsilon_{ini}= (1.14 \pm 0.01 \pm 0.2)$ GeV/fm^3
  - This at $dN/dy=6$ & linearly rises with multiplicity!
- Critical energy density: 1 GeV/fm^3
- Results not incompatible with supercrit. sQGP phase