

# **Advanced initial energy densities in $\sqrt{s} = 7$ and 8 TeV p+p collisions**

**M. Csanad<sup>1</sup>, T. Csorgo<sup>2,3</sup>, Ze-Fang Jiang<sup>4</sup> and C.-B. Yang<sup>4</sup>**

**<sup>1</sup>Etvos University, Budapest, Hungary**

**<sup>2</sup> Wigner RCP, Budapest, Hungary**

**<sup>3</sup> EKU KRC, Gyongyos, Hungary**

**<sup>4</sup> CCNU, Wuhan, China**

**Intro to initial energy density estimate**

**Improving Bjorken's estimate**

**First analysis of TOTEM/LHC p+p dn/d data @ 7 TeV**

**arXiv:1307.2082, Proc. EDS Blois (Saariselka, Finland, 2013) 53**

**Final analysis of CMS and TOTEM dn/d data @ 7 and 8 TeV**

**arXiv:1609.07176, submitted for publication**

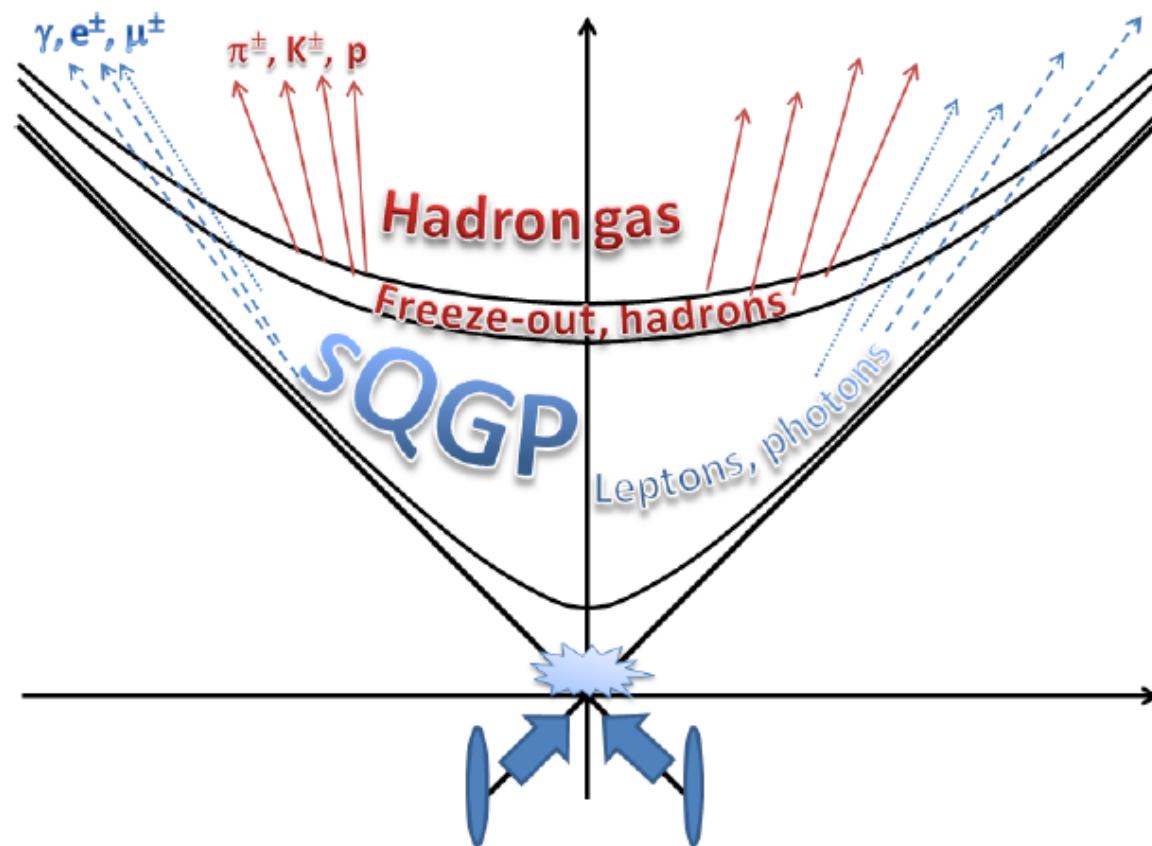
**Implications**

**Summary**

**Predictions**

# Standard Hydro Model for A+A

- Strongly interacting QGP discovered at RHIC & created at LHC
- A hot, expanding, strongly interacting, perfect QG fluid
- Hadrons created at the freeze-out
- Leptons, photons “shine through”



# Björken-estimate – hydro for p+p

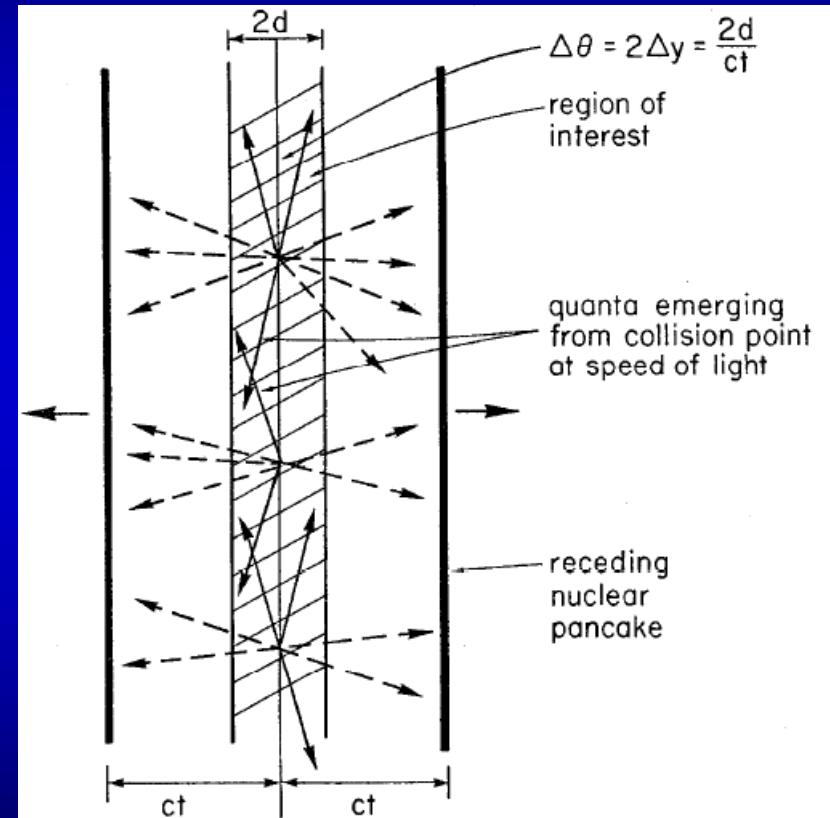
Idea: energy density measurable from  $dE/dy$   
QGP critical  $\varepsilon$ :  $\sim 1 \text{ GeV/fm}^3$

$$dE/dy = \langle m_t \cosh(y) \rangle dn/dy$$

Area from nuclear geometry  
(elastic e+A collisions)  
Famous result

J.D. Bjorken, Phys. Rev. D27 (1983)  
(2600+ citations)

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



Finite  $dn/dy$  even at LHC: Needs correction!

# Advanced estimate of initial conditions

Need for correction:

**dn/dy not flat, no rapidity plateaux even in pp @ LHC  
Finite, accelerating!**

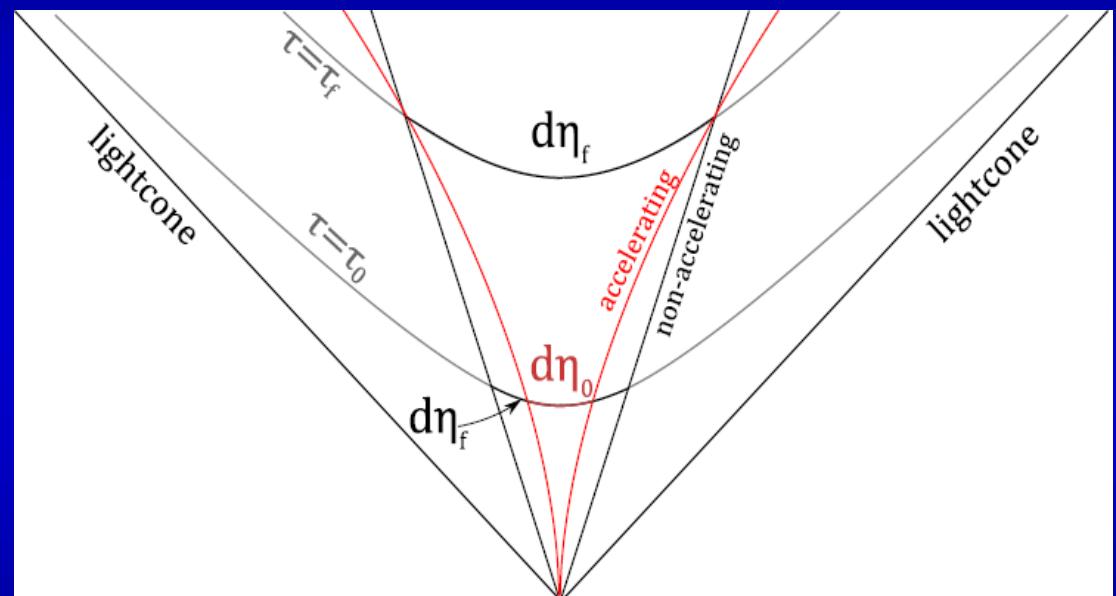
Need:

**accelerating solution  
of relativistic hydro**

Two modifications:

$y \neq \eta$

$\eta_{\text{final}} \neq \eta_{\text{initial}}$



Result:

**Advanced estimate  
of initial energy density:**

$$\varepsilon = \varepsilon_{Bj} \frac{dy}{d\eta_f} \frac{d\eta_f}{d\eta_i}$$

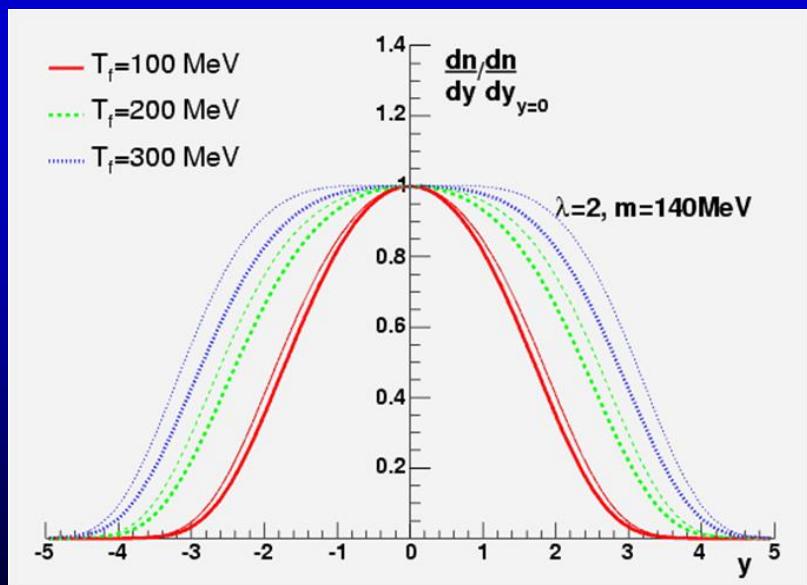
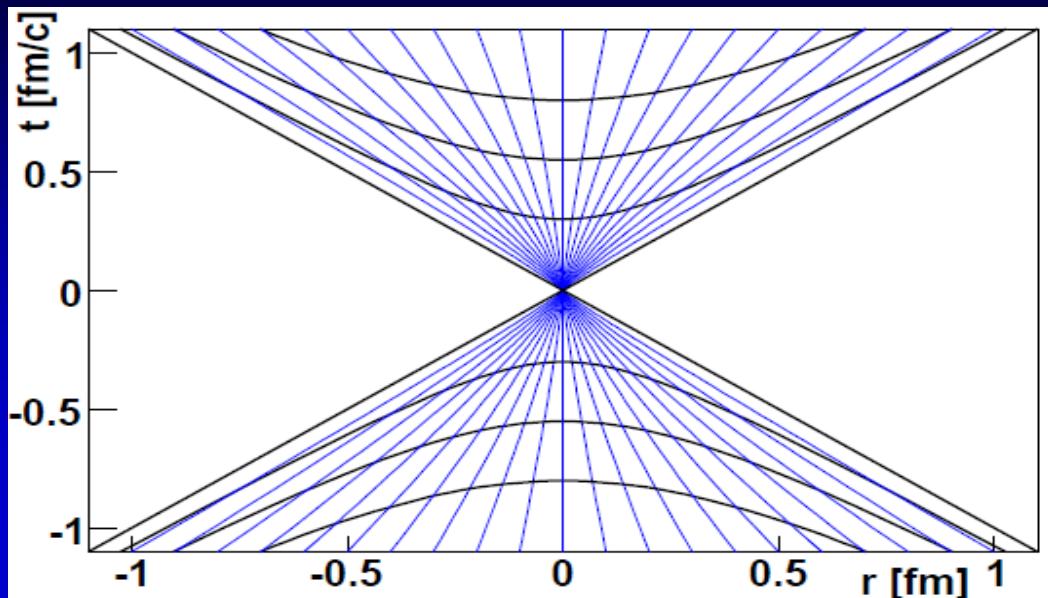
# A new solution of relativistic hydro

Velocity:  $v = \tanh(\lambda\eta)$   
Acceleration if:  $\lambda \neq 1$   
Density:  $n = n_0 (\tau/\tau_0)^\lambda$

$$\frac{dN}{dy} \approx N_0 \cosh^{\frac{\alpha}{2}-1} \left( \frac{y}{\alpha} \right) e^{-\frac{m}{T_f} \cosh^\alpha \left( \frac{y}{\alpha} \right)},$$

$$\alpha = \frac{2\lambda-1}{\lambda-1}$$

M.I. Nagy et al, PRC 77:024908, 2008  
arXiv:0709.3677  
(15 pages, 126 eqs)



Compare to RHIC data!  
**BRAHMS**  $dn/dy$  measurement:  
advanced initial & estimate

Significant correction@RHIC!

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

# Initial energy density at RHIC

Bjorken estimate from BRAHMS:  $5 \text{ GeV/fm}^3$

Advanced estimate gives:  $15 \text{ GeV/fm}^3$

Correction: 2-3x, agreement with QCD EoS !

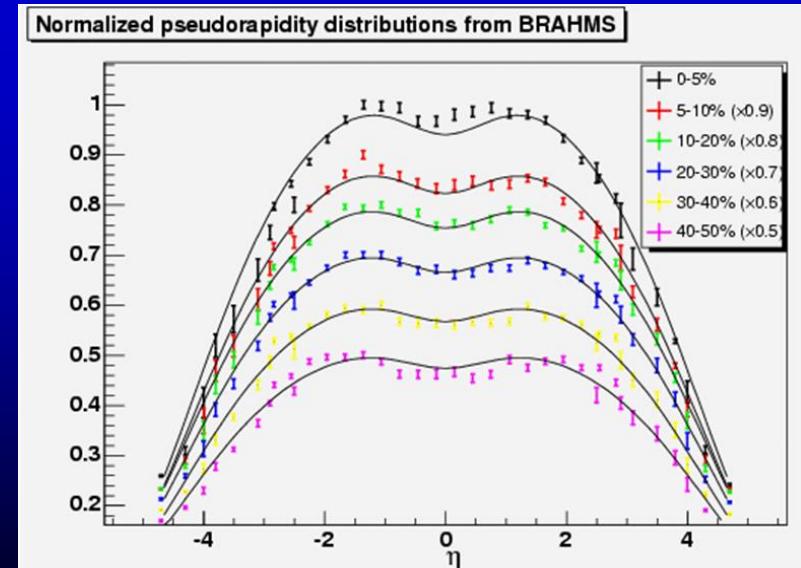
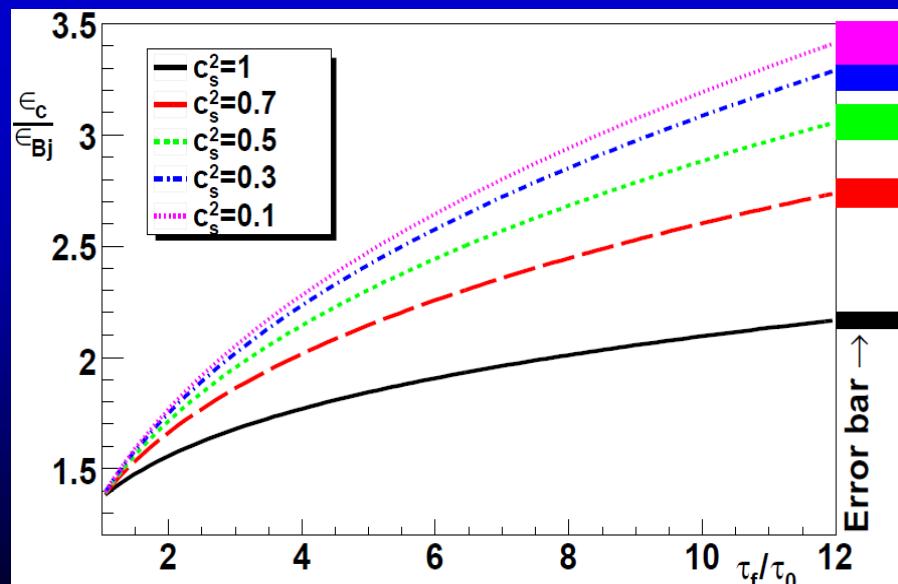
J.Phys.G35 (2008) 104128 (arXiv:0805.1562)

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

Corresponds to  $T_{\text{ini}} \simeq 2T_c \simeq 340 \text{ MeV}$

Consistent with PHENIX direct photon spectra

arXiv:0804.4168, PRL 104:132301, 2010



# Initial energy density for pp@7 TeV

Bjorken estimate:

Number of particles at midrapidity:  $\sim 7$  (measured)

Average energy:  $\langle m_t \rangle \sim 0.5$  GeV (measured)

Initial radius of the system R:  $\sim 1$  fm

(from  $R^2\pi = \sigma_{inel}/2$ , but similar final radii from HBT)

Formation time  $\tau_0$ : 1 fm/c

Energy density from this:

$$\varepsilon_{Bj} = \frac{1}{R^2 \pi \tau_0} \frac{dE}{d\eta} = \frac{\langle E \rangle}{R^2 \pi \tau_0} \frac{dn}{d\eta} = \frac{0.5 \times 7 \text{ GeV}/c}{3.67 \text{ fm}^3/c} \approx 0.95 \text{ GeV/fm}^3$$

Just below critical?? Corrections may be important ...

Missed opportunity?

arXiv:1307.2082, Proc. EDS Blois (Saariselka, Finland, 2013) 53

New analysis:

improved estimate of R, corrections for  $\pi^0$  ...

# Improving Initial Energy Density Estimate

## Initial radius:

In A+A: eA and pA elastic collisions (Hofstadter, Glauber)

Initial radius under-estimated by R:  $\sim 1$  fm

Gray disc (greyness g), or grey Gaussian proton:

$$\sigma_{\text{el}} = g^2 R^2 \pi \quad \sigma_{\text{tot}} = 2 g R^2 \pi$$

$$R^2 \pi = \sigma_{\text{tot}}^2 / (4 \sigma_{\text{el}})$$

$$R = 1.76 \pm 0.02 \text{ fm}$$

$$\text{Cross-check: } B = 4 R^2$$

$$R = 1.76 \pm 0.02 \text{ fm}$$

Decrease by a factor of  $\sim 3$

Energy also in neutrals, enhancement factor of 3/2

New analysis: arXiv:1609.07176

improved estimate of R, corrections for  $\pi^0$ , cca 1/2 decrease

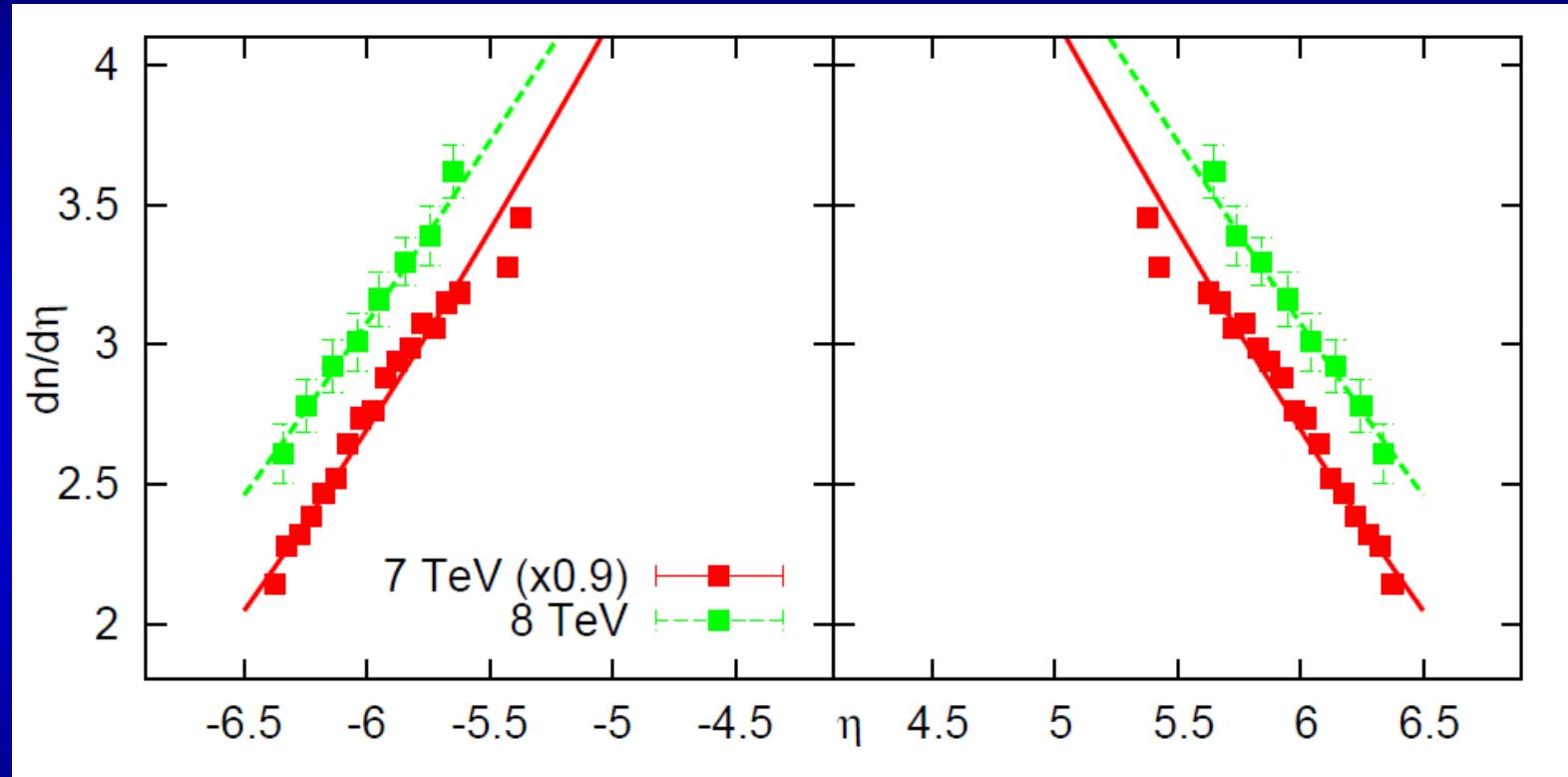
$$\epsilon_{Bj}(7 \text{ TeV}) = \frac{0.562 \times 1.5 \times 5.89}{1.76^2 \pi} \text{ GeV/fm}^3 = 0.507 \text{ GeV/fm}^3$$

$$\epsilon_{Bj}(8 \text{ TeV}) = \frac{0.571 \times 1.5 \times 6.165}{1.799^2 \pi} \text{ GeV/fm}^3 = 0.519 \text{ GeV/fm}^3,$$

# Advanced Initial Energy Density Estimate

New analysis: arXiv:1609.07176

cca 1/2 decrease but enhancement due to finite  $dn/d\eta$  fits

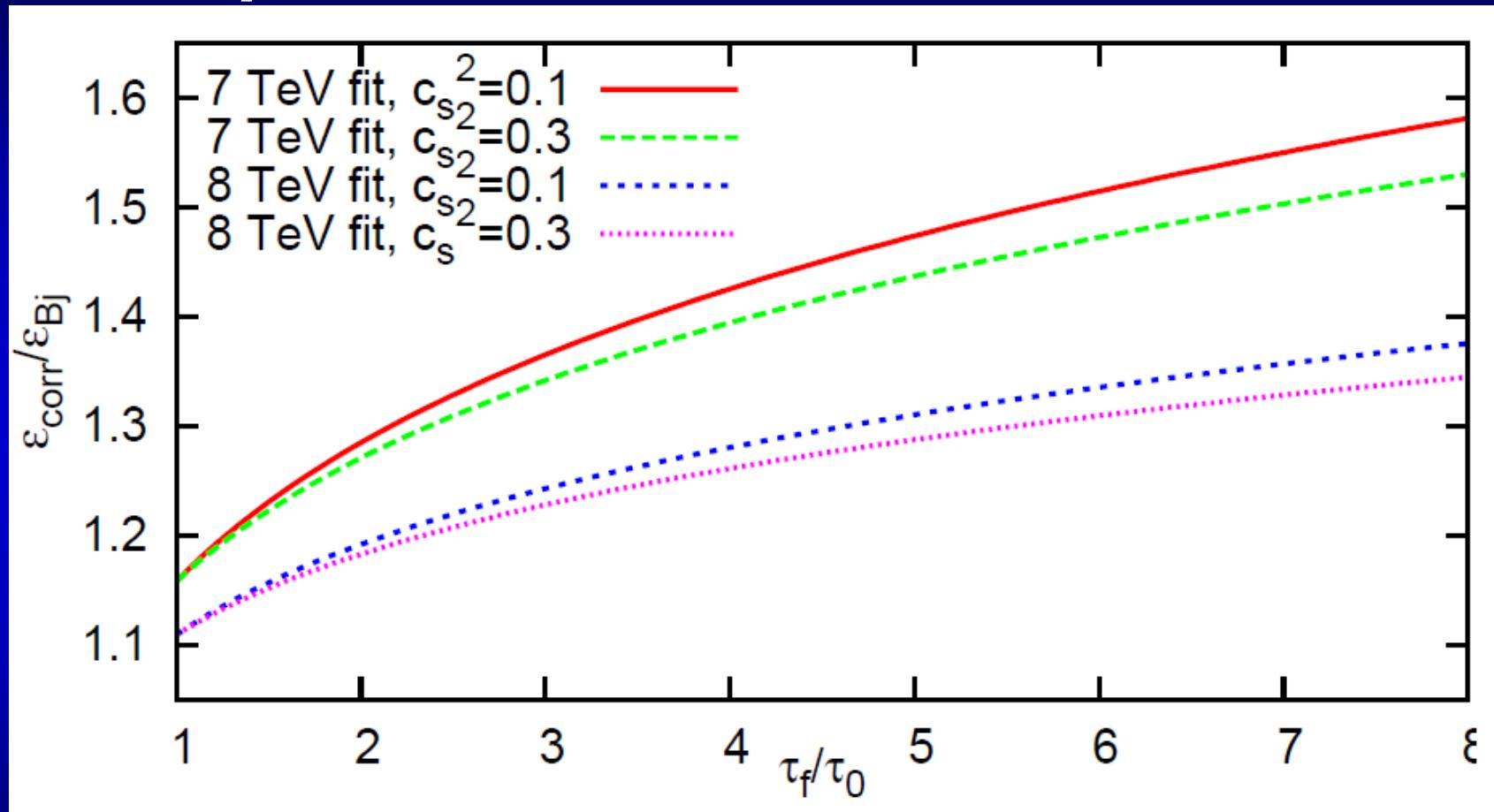


$$\epsilon_{\text{corr}}(7 \text{ TeV}) = 1.262 \epsilon_{\text{Bj}}(7 \text{ TeV}) = 0.640 \text{ GeV/fm}^3$$

$$\epsilon_{\text{corr}}(8 \text{ TeV}) = 1.240 \times \epsilon_{\text{Bj}}^{8 \text{ TeV}} = 0.644 \text{ GeV/fm}^3$$

# EoS, initial/final time dependence

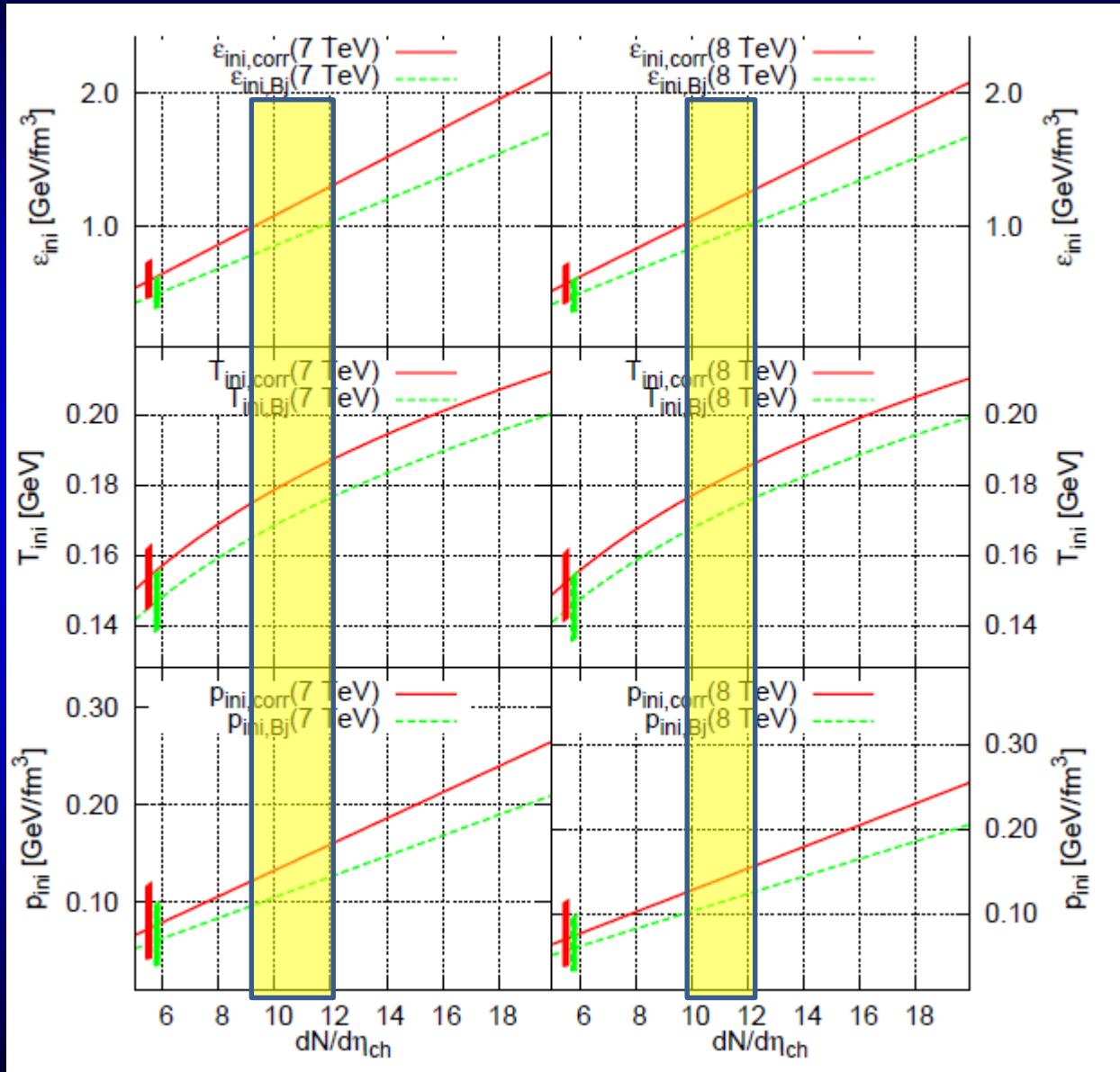
New analysis: arXiv:1609.07176



$$\epsilon_{\text{corr}}(7 \text{ TeV}) = 1.262 \epsilon_{\text{Bj}}(7 \text{ TeV}) = 0.640 \text{ GeV/fm}^3$$

$$\epsilon_{\text{corr}}(8 \text{ TeV}) = 1.240 \times \epsilon_{\text{Bj}}^{8 \text{ TeV}} = 0.644 \text{ GeV/fm}^3$$

# Multiplicity dependence



arXiv:1609.07176

$\langle n \rangle_{crit} \sim 10 - 12$   
at 7 and 8 TeV

Critical 1 GeV/fm $^3$   
Initial energy  
Density

in high  $\langle n \rangle > 10$   
pp collisions!

# Systematic uncertainties

**Bjorken-estimate:**

**Main uncertainty source: multiplicity at midrapidity**

**Area (from cross-section): very precise Formation time**

**Correction factors in  $\varepsilon/\varepsilon_{Bj}$ :**

**Statistical error (from the data): 1%**

**Fit parameter  $\lambda$ : 0.5% systematic error**

**Speed of sound  $c_s^2$ : 3%**

**(if  $c_s^2 < 0.5$ , it is 0.3 at RHIC)**

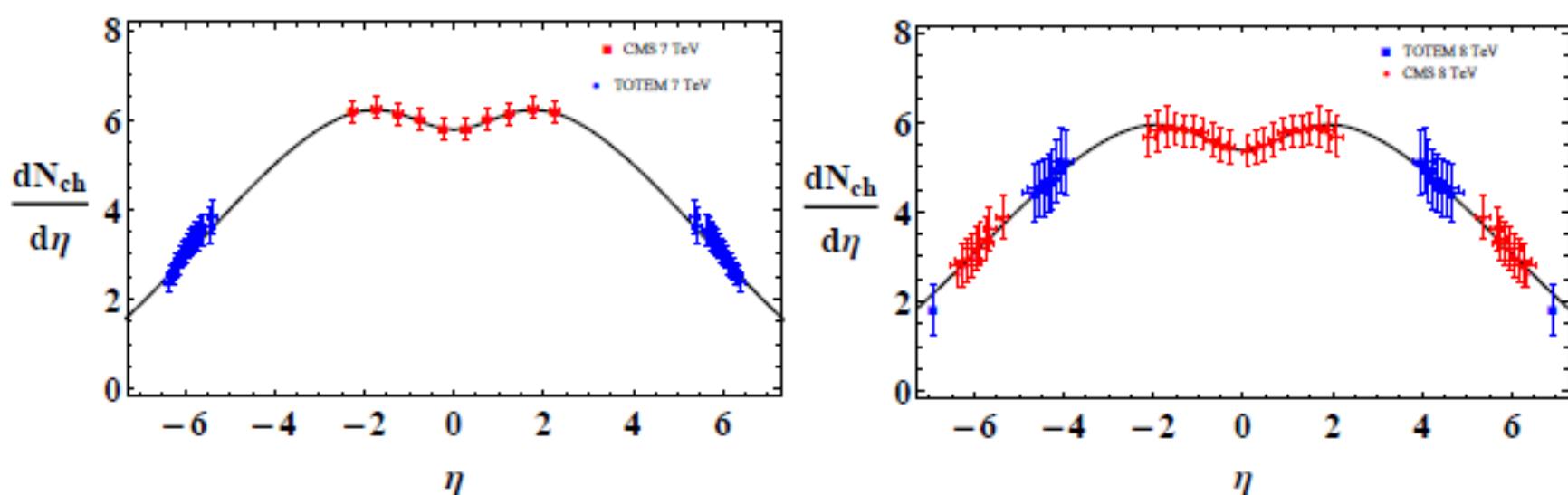
**Duration  $\tau_f/\tau_i$ : 8% (if ratio maximally 6)**

**Dissipative effects: further increase the initial  $\varepsilon$  ...**

# Systematics, cross-checks with CMS

parameter	value	stat.	syst. eff. on $\epsilon$
$\lambda$	1.073	0.1%	0.4% (from data)
$c_s^2$	0.1	-	-2%+0.2% (if $0.05 < c_s^2 < 0.5$ )
$\tau_f/\tau_0$	2	-	-4%+10% (for $\tau_f/\tau_0$ in 1.5–4)
$\tau_0$ [fm/c]	1	-	underestimates $\epsilon$
$R$ [fm]	1.766	-	1.3% (from $\sigma_{\text{tot}}$ )
$\langle E \rangle$ [GeV/c <sup>2</sup> ]	0.562	0.5%	3%
$dN/d\eta$ (7 TeV)	5.895	0.2%	3%

Table 1: Sources of statistical and systematic errors for the 7 TeV estimate.



Combined CMS+TOTEM  $d\eta/d\eta$  fits: within 0.5 % syst, the same results

# Summary

**Experimentally widely used Bjorken est. (2600+)  
& QGP critical energy density: 1 GeV/fm<sup>3</sup>**

**Advanced estimate from forward dn/dη**

**Results on the initial ε for  $c_s^2=0.1$ , at  $\tau_f/\tau_{ini}=2$**

**Both at 7 and 8 TeV,  $\varepsilon > 1 \text{ GeV/fm}^3$**

**but only in high  $n > 10$  multiplicity pp collisions!**

**[arXiv:1609.07176](https://arxiv.org/abs/1609.07176)**

**Small correction but important implications**

- pp is not as good a reference for AA as eA
- $R_{AA}$  not such a good concept, need:  
 $R_{AA}$  per unit lenght  $\equiv$  optical opacity,

**[arXiv:0911.5015](https://arxiv.org/abs/0911.5015)**

# Implications

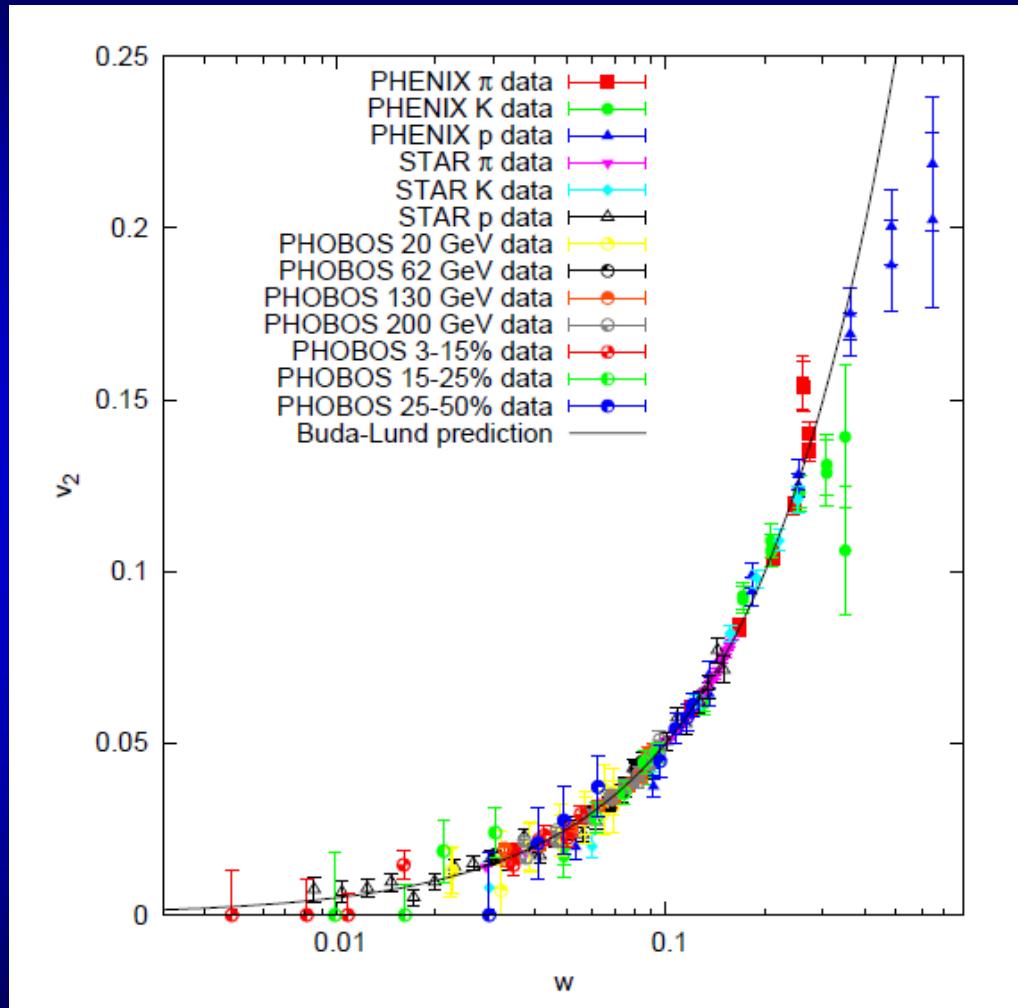
pp, pA, dA, AA are similar  
But differ in sizes (multiplicity)

Need for an electron-proton and eA collider  
to determine a clear reference

Prediction:  
Scaling laws for spectra,  
elliptic flows  
and HBT radii in pp@ LHC

Open question:  
How important is the correction in  
pp@RHIC?

# Prediction: UNIVERSAL hydro scaling of $v_2$ will hold for pp@LHC



[nucl-th/0512078](https://arxiv.org/abs/nucl-th/0512078) but new:  $v_2/n_q$  vs  $K_{ET}/n_q$  will be violated in p+p@LHC