

# Initial energy density in 7 TeV pp @ LHC



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Intro to initial energy density estimate  
Improving Bjorken's estimate

Analysis of Au+Au@RHIC

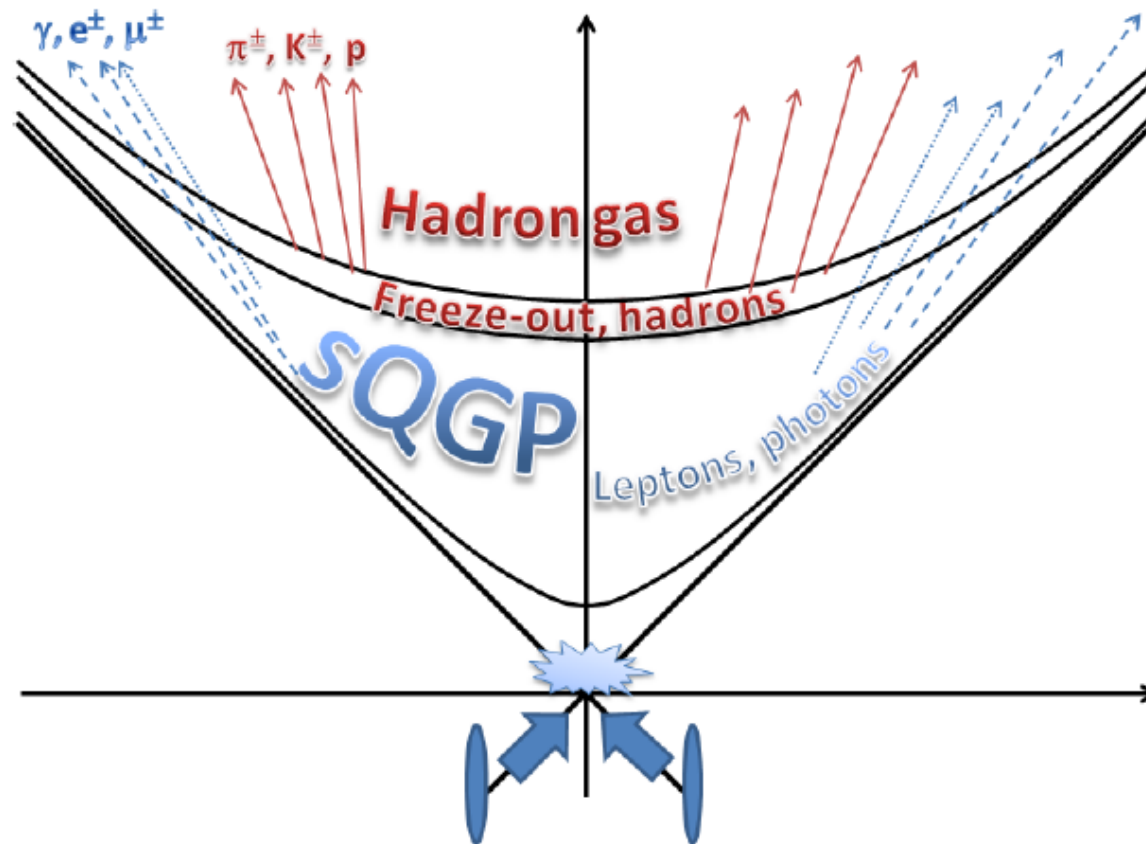
Analysis of TOTEM/LHC p+p  $dn/d\eta$  data @ 7 TeV

Implications  
Summary  
Predictions

[arXiv:1307.2082](https://arxiv.org/abs/1307.2082)

# 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”



# Bjorken-estimate – hydro for p+p

Idea: energy density measurable from  $dE/dy$

QGP critical  $\varepsilon$ :  $\sim 1 \text{ GeV}/\text{fm}^3$

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

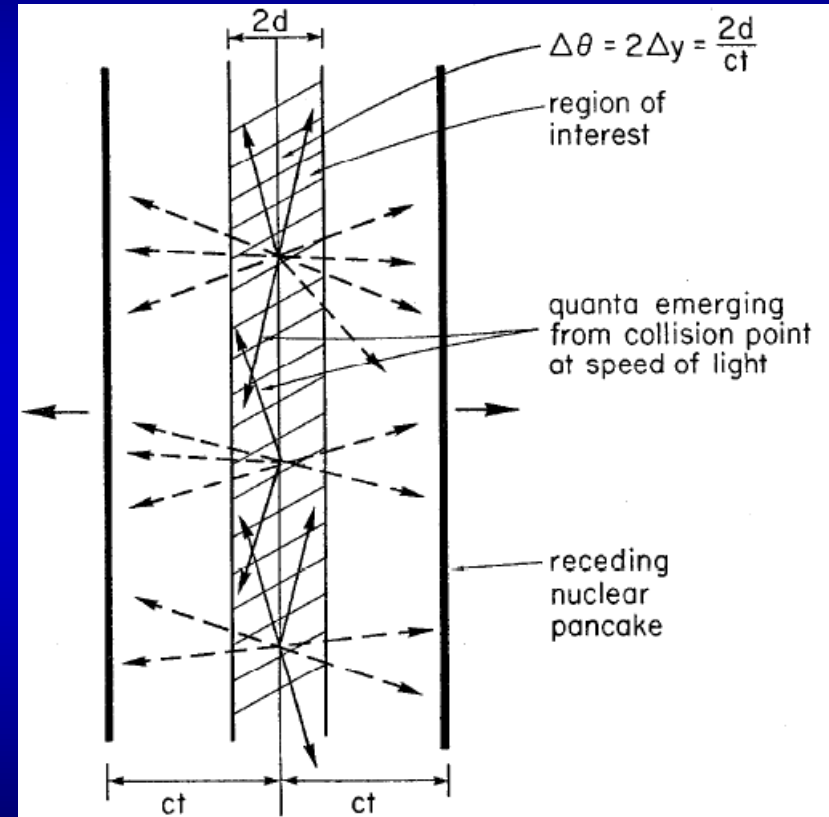
Area from HBT

Result

J.D. Bjorken, Phys.Rev. D27 (1983)  
(1800+ cited)

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

Needs correction!



# Advanced estimate

**Need for correction:  
dn/dy not flat, no rapidity plateau even @ LHC  
Finite, accelerating!**

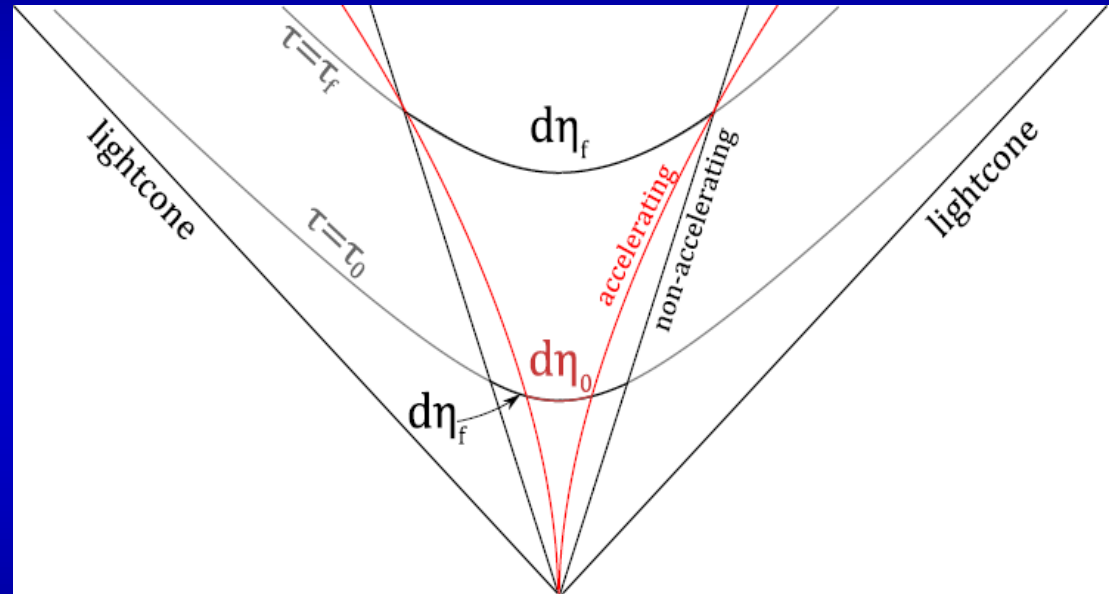
**Need:  
accelerating solution  
of relativistic hydro**

**Two modifications:**

$$\mathbf{y} \neq \eta$$

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

**Advanced estimate  
of initial energy density:**



$$\mathcal{E} = \mathcal{E}_{Bj} \frac{dy}{d\eta_f} \frac{d\eta_f}{d\eta_i}$$

# A new solution of relativistic hydro

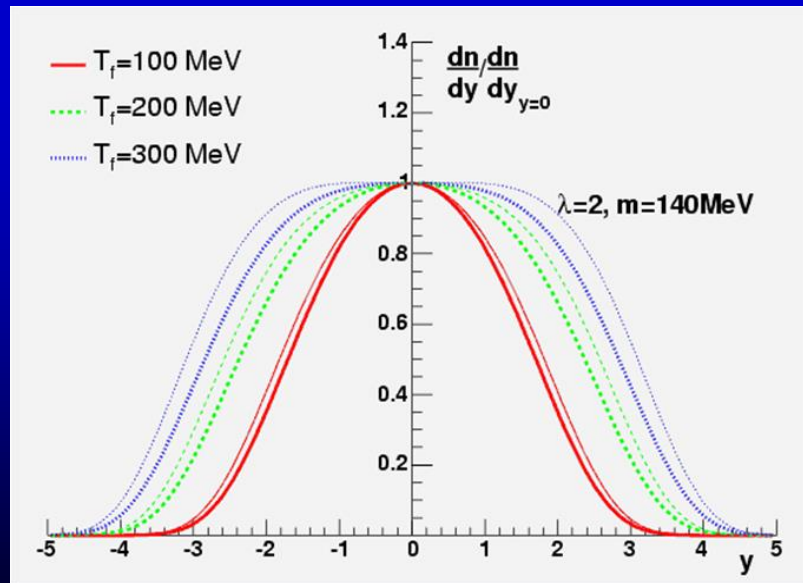
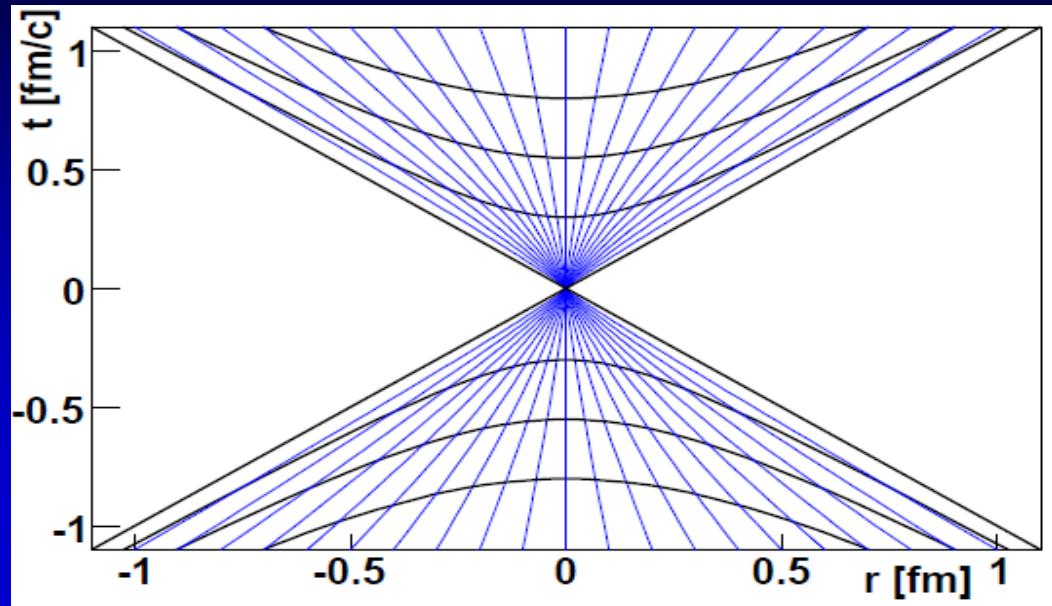
Velocity:  $\tanh(\lambda\eta)$

Acceleration:  $\lambda \neq 1$

Density:  $(\tau/\tau_0)^\lambda$

$dn/dy$  calculated, simple  
but **NOT**  
on a back-of-the-envelope,

Full details: 15 pages, 126 eqs  
[arXiv:0709.3677](https://arxiv.org/abs/0709.3677) N.I. Nagy et al,  
**Phys. Rev. C.77:024908,2008**



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

**Significant correction@RHIC!**

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

# Initial energy density at RHIC

Bjorken estimate from BRAHMS: 5 GeV/fm<sup>3</sup>

Advanced estimate gives:

Correction:

2-3x, result: 15 GeV/fm<sup>3</sup>, QCD EoS agreement!

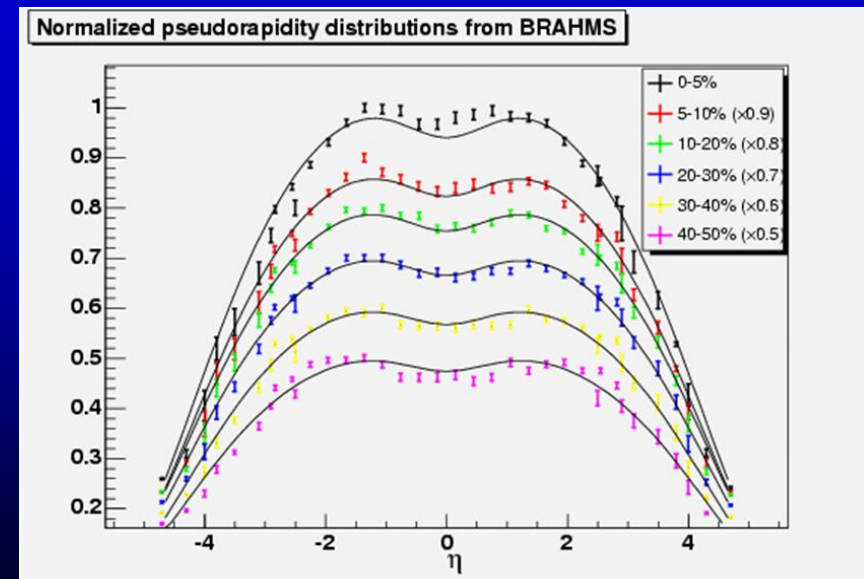
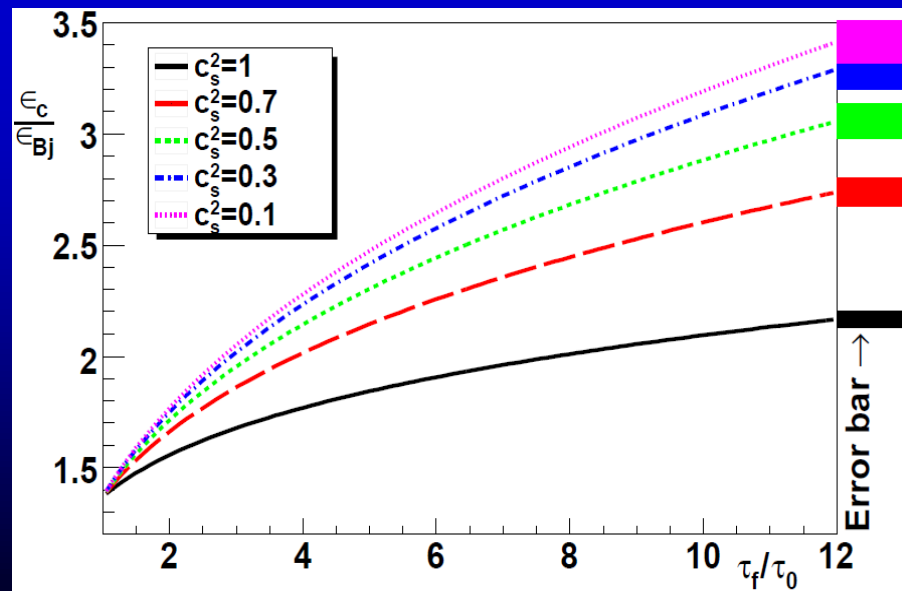
J.Phys.G35 (2008) 104128 (arXiv:0805.1562)

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

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

Consistent with PHENIX direct photon spectra

<http://arxiv.org/abs/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 ( $R^2\pi = \sigma_{inel}/2$ , or HBT)

Formation time  $\tau_0$ :  $1$  fm/c

## Energy density from this:

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

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

Missed opportunity?

# Energy density from TOTEM $dn/d\eta$

	TOTEM data		CMS data		Joint data	
Norm	10,51	$\pm 0,04$	7,39	$\pm 0,03$	7,48	$\pm 0,01$
$T_f$	0,12	fixed	0,122	$\pm 0,002$	0,117	$\pm 0,001$
$\Lambda$	1,073	$\pm 0,003$	1,061	$\pm 0,002$	1,0535	$\pm 0,0002$
$\chi^2/N_{DF}$	2068/32		82,7/6		8502/42	

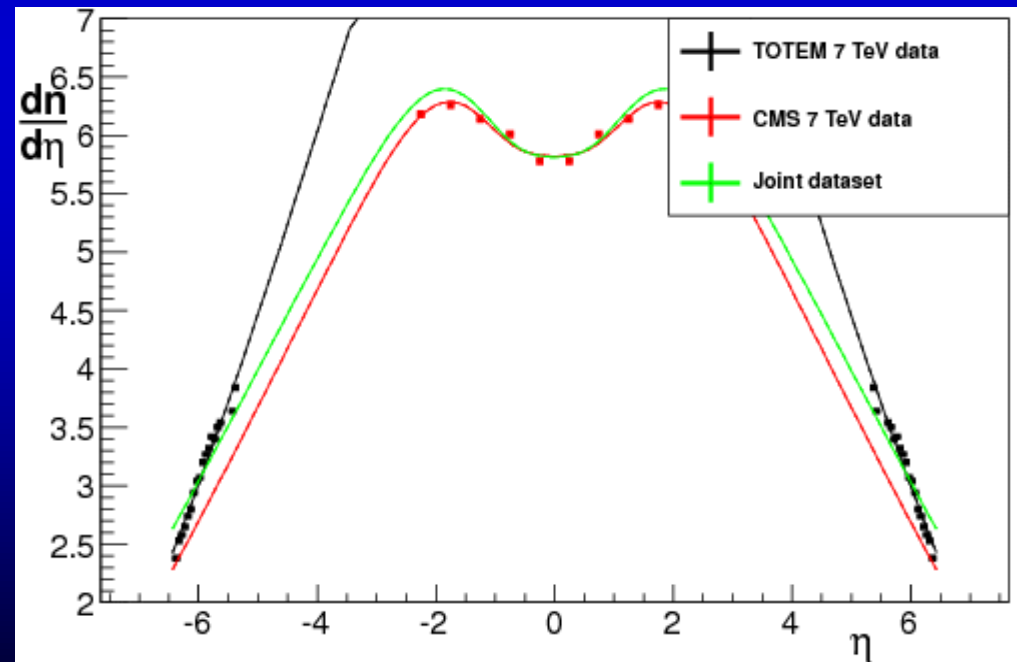
Errors of 0.1% (?)

Normalization (?)

NSD events in CMS

$\lambda \sim 1.05-1.1$

$\chi^2$  too big (joint fit...)





# Initial energy density in 7 TeV p+p?

Rough result:  $\lambda \simeq 1.05-1.07$

$\sim 25\%$  correction

Input parameters:

$dn/dy: \sim 7$

Mean E:  $\sim 0.5$  GeV

Radius:  $\sim 1$  fm

Form. time:  $\sim 1$  fm/c

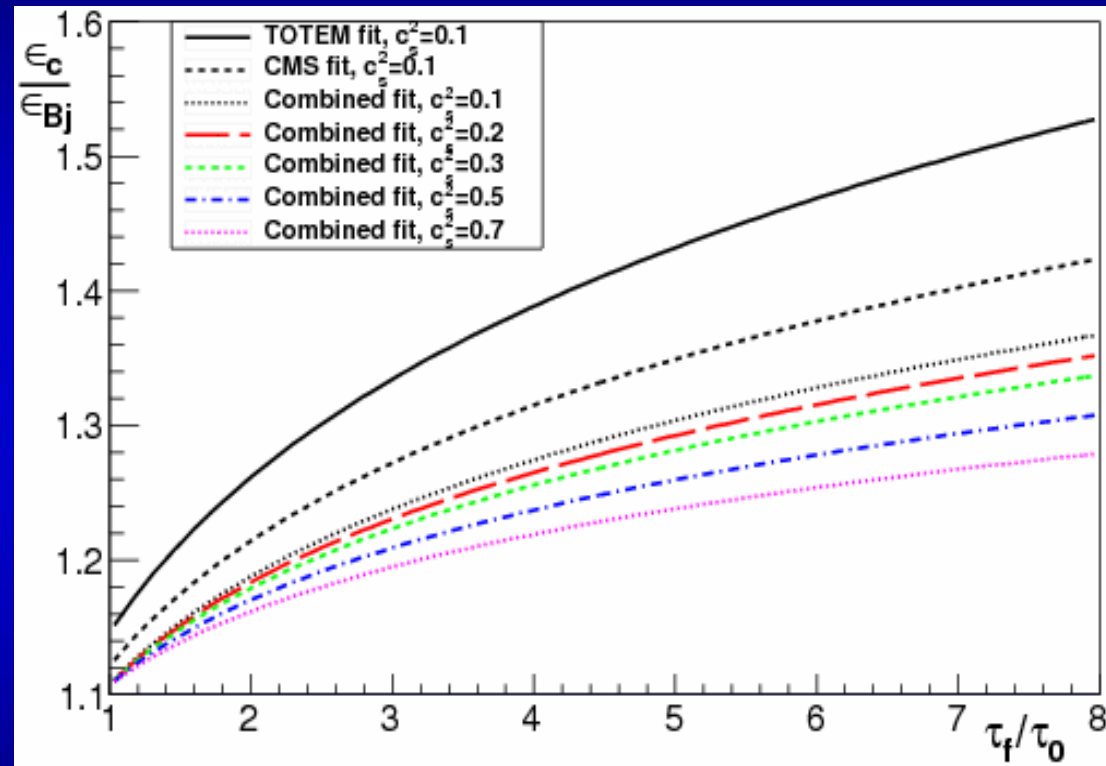
Corrected result:

$\sim 1.2$  GeV/fm<sup>3</sup>

→

Initial  $\varepsilon$  just above the critical value of 1 GeV!

Small correction, but big difference in physics ...



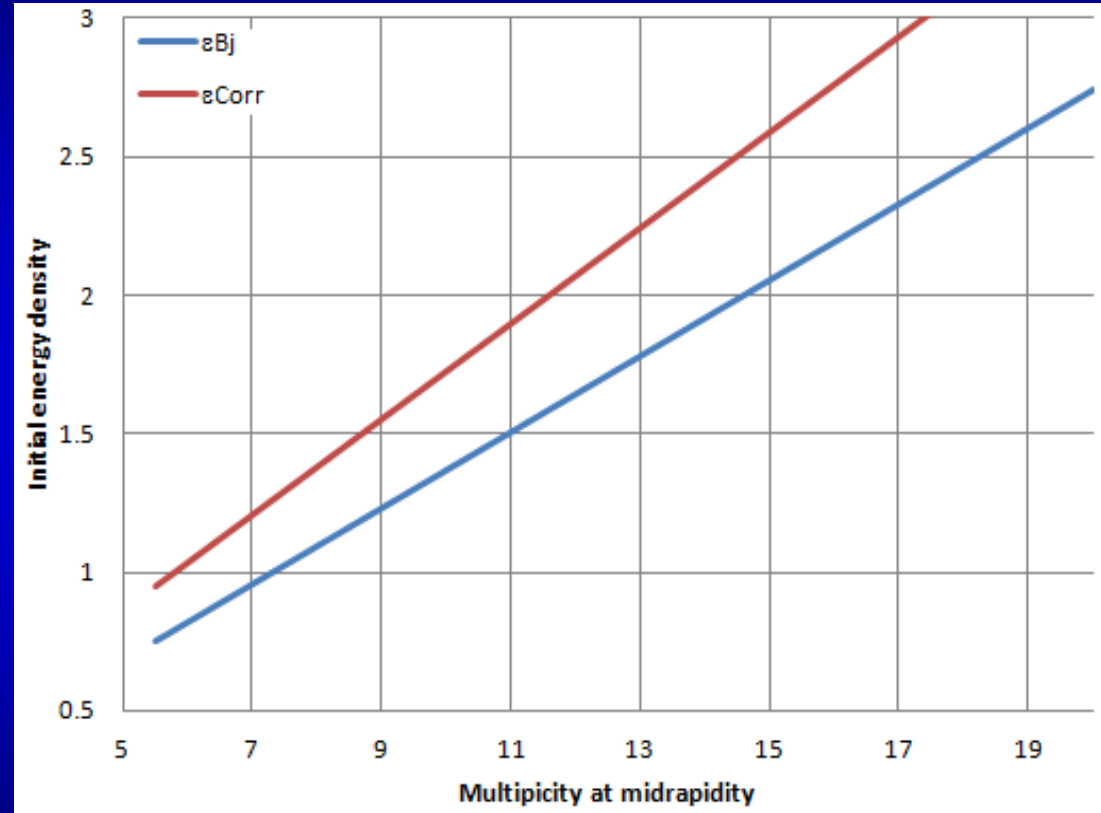
# Dependence on particle number

Several multiplicity classes can be defined

CMS:  $\langle n \rangle \sim 6-20$

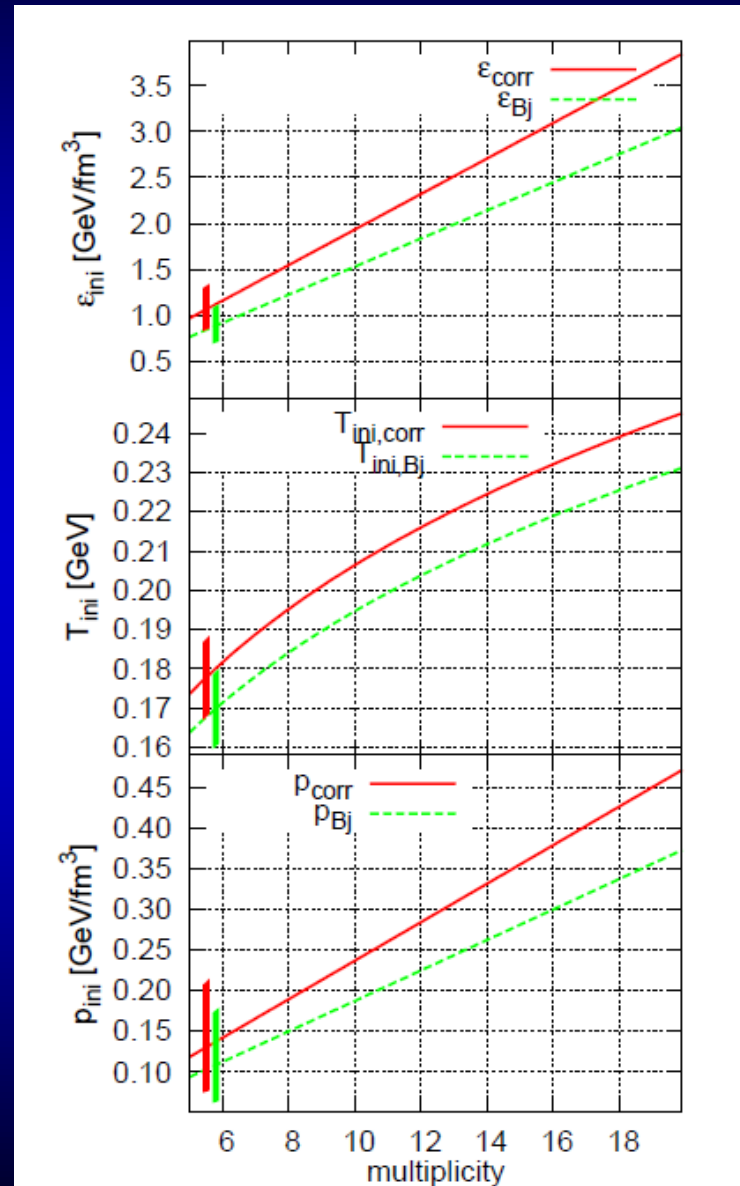
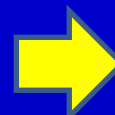
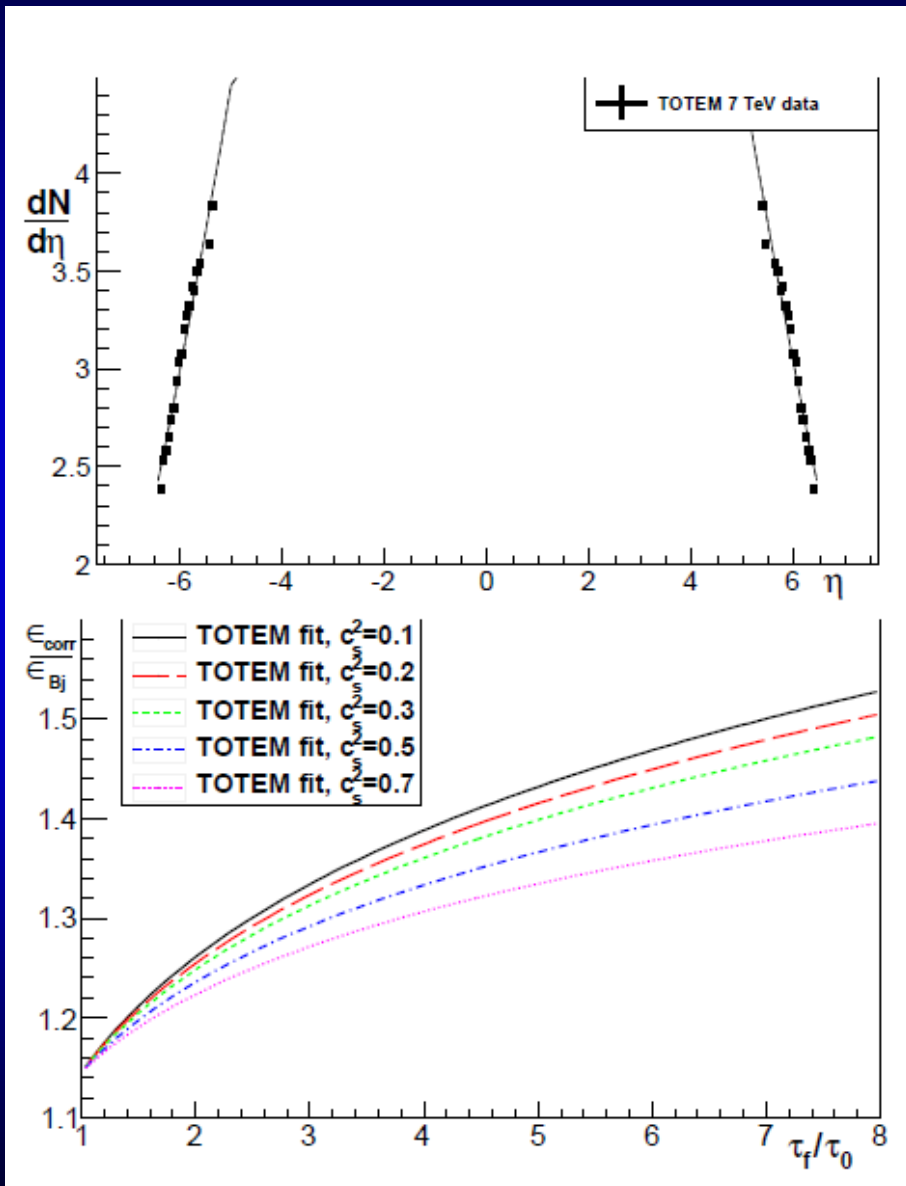
**Bjorken result:**  
above critical  
IF  $\langle n \rangle \geq 7.5$

**Corrected estimate:**  
above critical  
for ANY  $\langle n \rangle$



**QGP is formed in  $\sim$ ALL  
p+p collisions at LHC @ 7 TeV**

# Results for TOTEM $dn/d\eta$ data@7 TeV



# 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)**

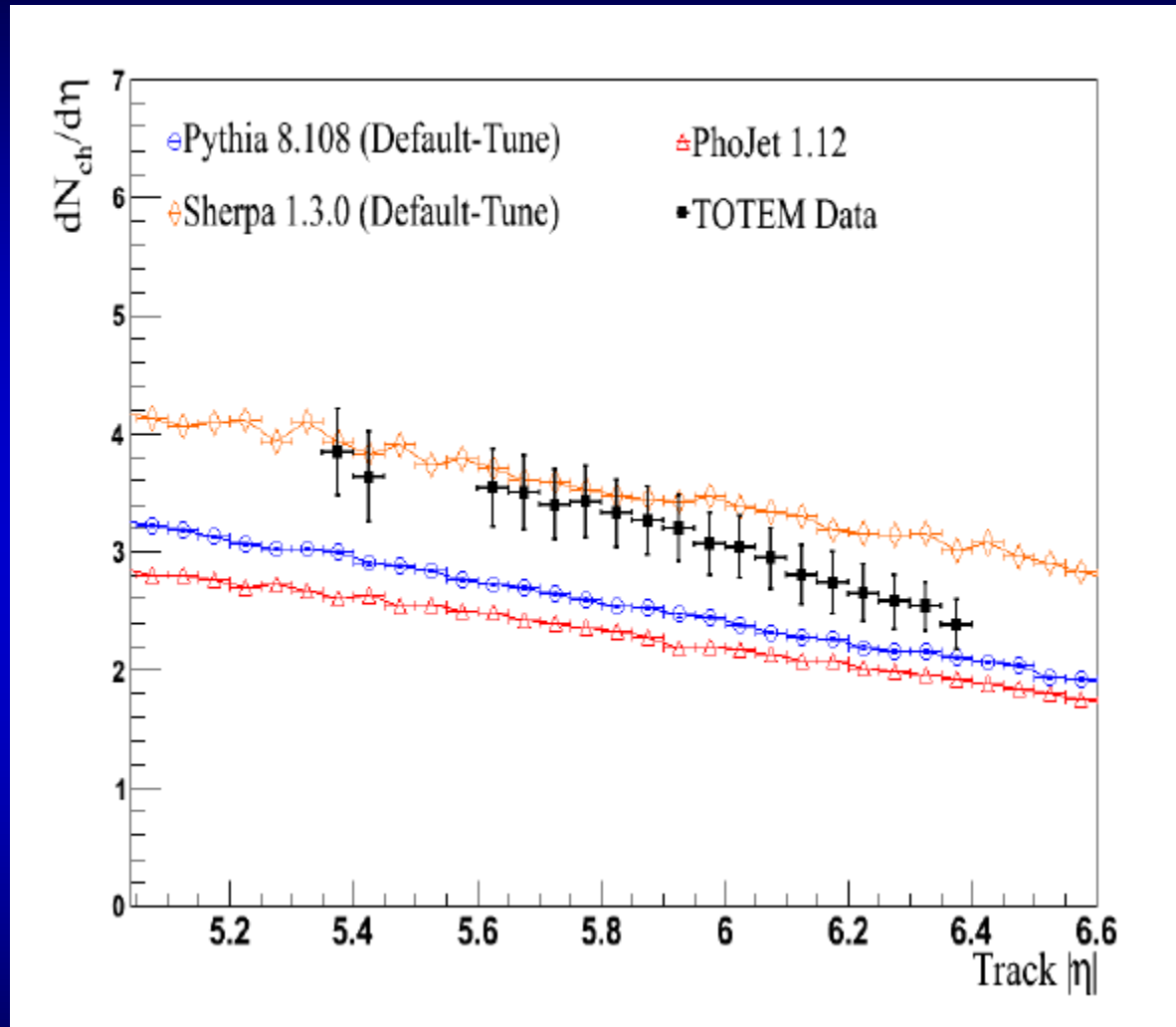
# Results 2.

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]	1.081	0.5%	1.5% (from $\sigma_{inel}$ )
$\langle E \rangle$ [GeV/c <sup>2</sup> ]	0.562	0.5%	3%
$dN/d\eta$	5.895	0.2%	3%

Table I: Sources of statistical and systematic errors.

[arXiv:1307.2082](https://arxiv.org/abs/1307.2082)

# Comment: $dn/d\eta$ @ 7 TeV is not trivial



[arXiv:1307.2082](https://arxiv.org/abs/1307.2082) and MC vs TOTEM data, [arXiv:1205.4105](https://arxiv.org/abs/1205.4105)

# 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?

# Summary

**Experimentally widely used Bjorken est. (1800+)  
QGP critical energy density: 1 GeV/fm<sup>3</sup>**

**Advanced estimate from forward dn/dη  
Results on the initial ε for c<sub>s</sub><sup>2</sup>=0.1, at τ<sub>f</sub>/τ<sub>ini</sub>=2**

	Bjorken	TOTEM fit	CMS fit	Combined fit
ε <sub>ini</sub>	0.95 GeV/fm <sup>3</sup>	1.20 GeV/fm <sup>3</sup>	1.15 GeV/fm <sup>3</sup>	1.13 GeV/fm <sup>3</sup>

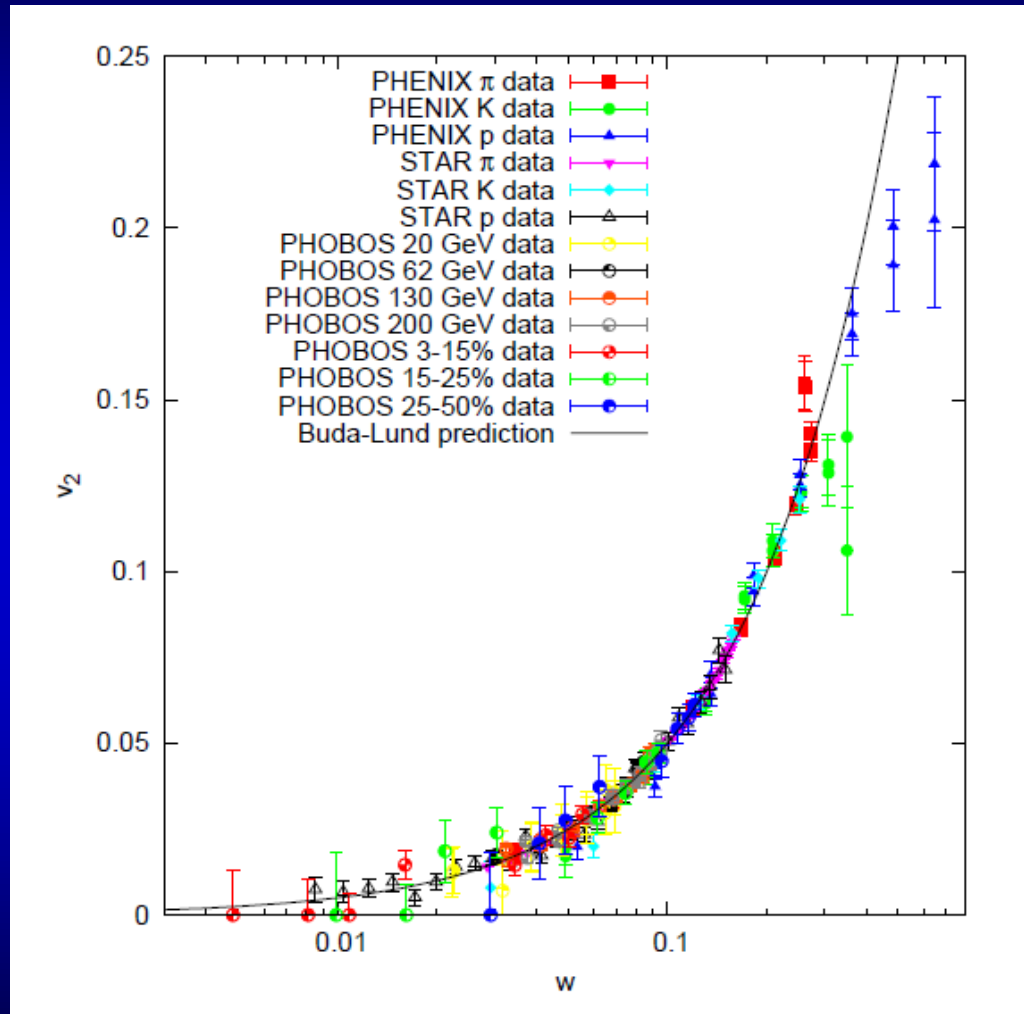
**Small correction but important implications**

- pp is not a good reference
- R<sub>AA</sub> not such a good concept, need:  
R<sub>AA</sub> per unit length ≡ optical opacity,

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



# 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