Baryon Stopping & Entropy Production, BNL, June 1, 2009

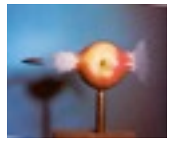
09:00 - 09:45	Overview and issues	Peter Steinberg (BNL)
09:45 - 10:30	Review of Proton Stopping Data	Peter Christiansen (Lund)
10:30 - 11:00	Coffee Break	
11:00 - 11:45	Colliding Shock Waves in AdS_5	Yuri Kovchegov (OSU)
11:45 - 12:30	Comparing p+p vs. A+A	Mike Lisa (OSU)
12:30 - 2:00	Lunch & Discussion	
2:00 - 2:45	Entropy Production in QCD	Berndt Mueller (Duke)
2:45 - 3:30	Entropy Production from the CGC	Adrian Dumitru (Baruch)
3:30 - 4:00	Coffee Break	
4:00 - 4:45	Entropy Production from AdS/CFT	Amos Yarom (Princeton)
4:45 - 5:30	Measuring Bremstrahhlung at the LHC	Brian Cole (Columbia)

Thoughts on Baryon Stopping & Entropy Production

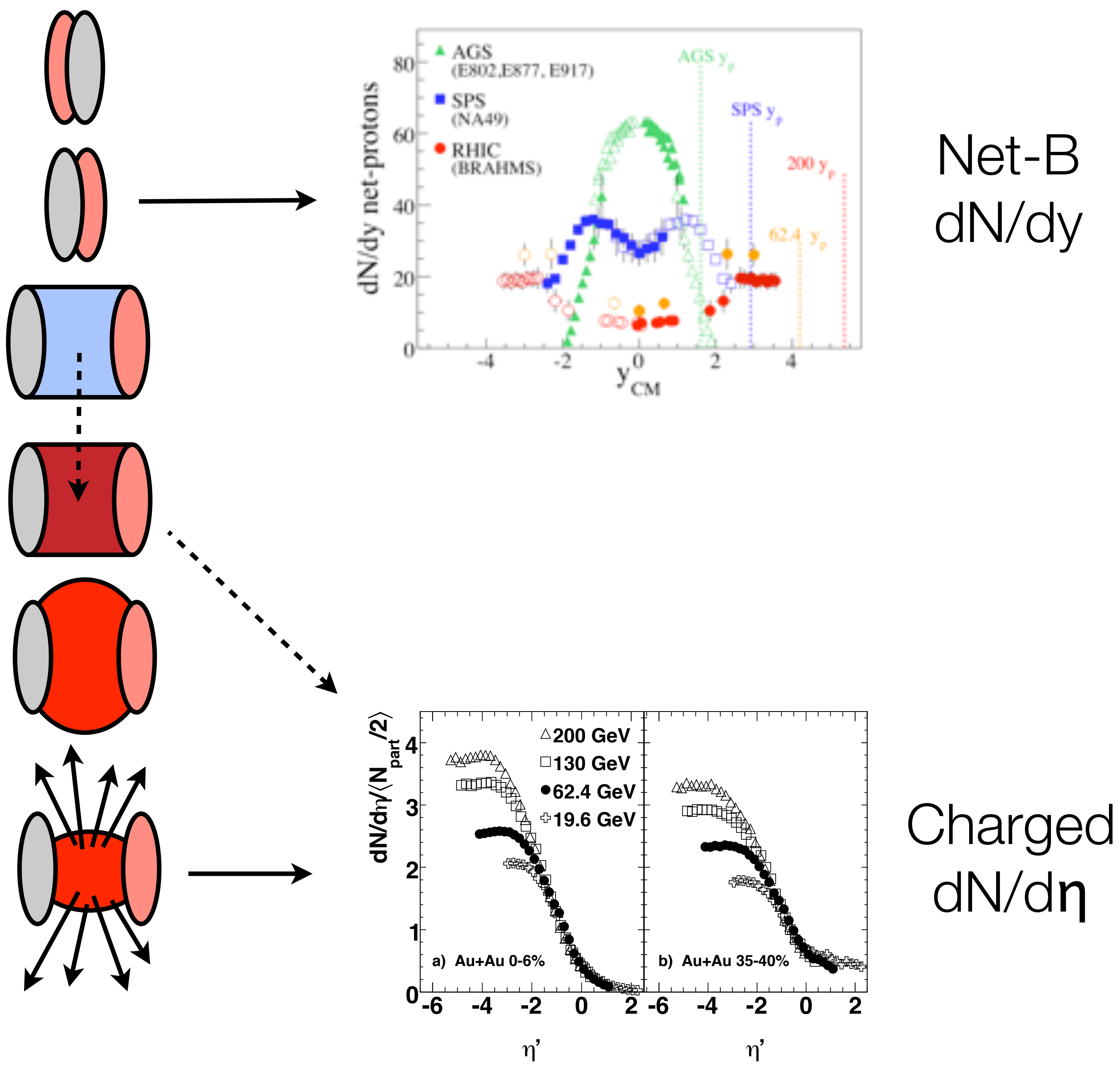
Peter Steinberg
Brookhaven National Laboratory

RHIC-AGS Users Meeting Workshop: "Baryon Stopping & Entropy Production"
Brookhaven National Laboratory
June 1, 2009

The “Standard Model” of Stopping



- **Nuclei collide**
- **Nucleons “stop”** → BRAHMS
- **Energy is deposited**
- **Entropy is produced**
- **Hydrodynamic evolution**
- **Particles in final state** → PHOBOS
  (& BRAHMS)



Do the two data sets (energy & entropy) tell the <u>same</u> story?

Baryon Stopping

- **A topic of lots of interest in the 1980's and 1990's (Busza, Videbaek et al)**
  - Particularly in the p+A programs, who were studying "proton energy loss" in "cold nuclear matter"
  - Need PID and forward coverage

- **Limited recent data led to recent limited discussion of the subject**
  - BRAHMS data on dN/dy very important
  - Relatively little theoretical work!

ETTERS 17 May 1984

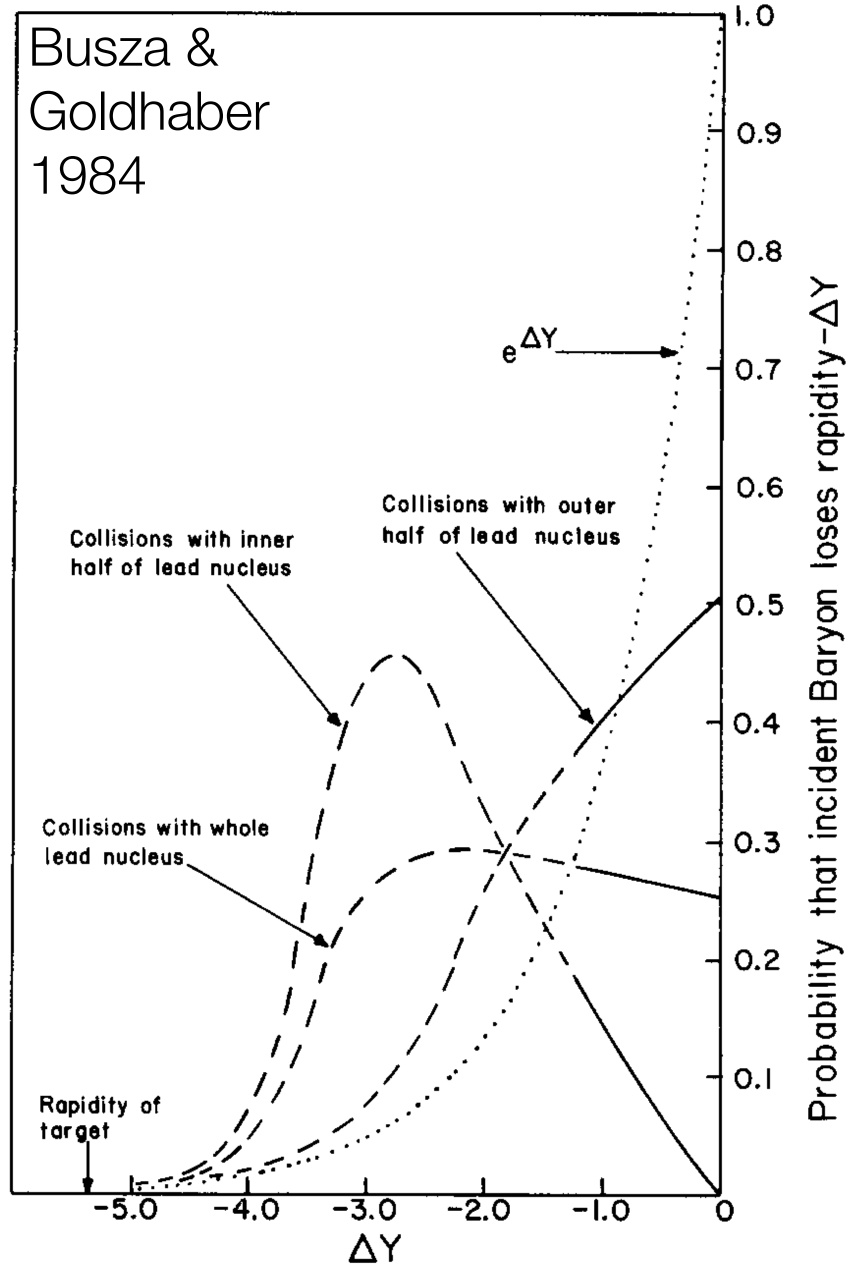
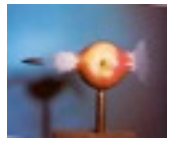


Fig. 3. Extrapolated probability distributions for rapidity loss of protons striking lead nuclei. The dashed lines are the

BRAHMS dN_B/dy

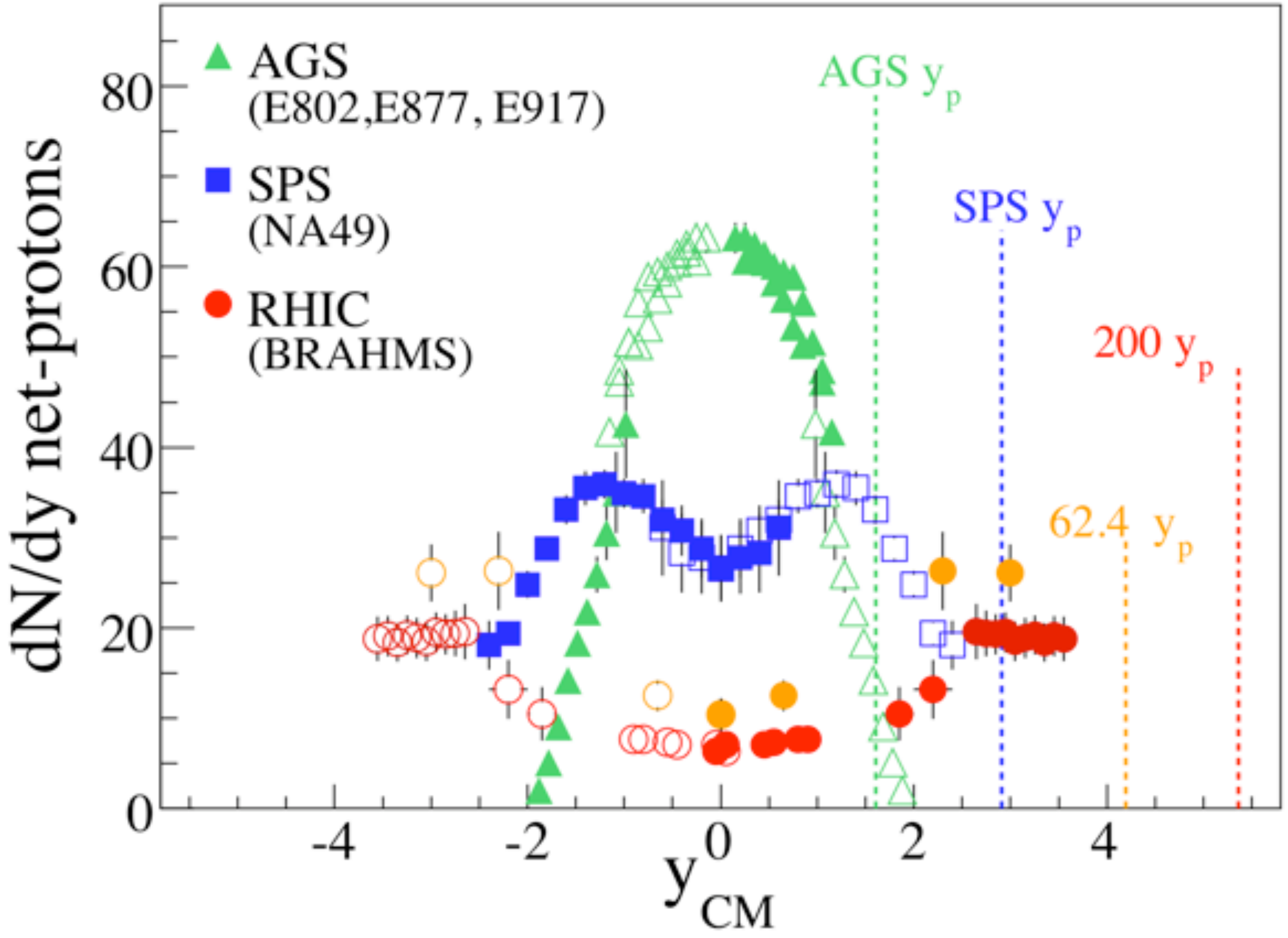


- **Will be shown by P. Christiansen**
  - This discussion is about general issues, not experimental details!

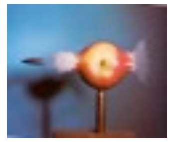
- **General empirical interpretation: “pile-up” at low energies gives way to “transparency” at high energy**

- **At high energy, baryon density is clearly <u>not</u> piling up at midrapidity**

arxiv:0901.0872



Quantifying stopping (200 GeV)



- **Average rapidity loss ~ 2 units**

$$\delta y = y_b - \frac{2}{N_{part}} \int_0^{y_b} y \cdot dN/dy \cdot dy$$

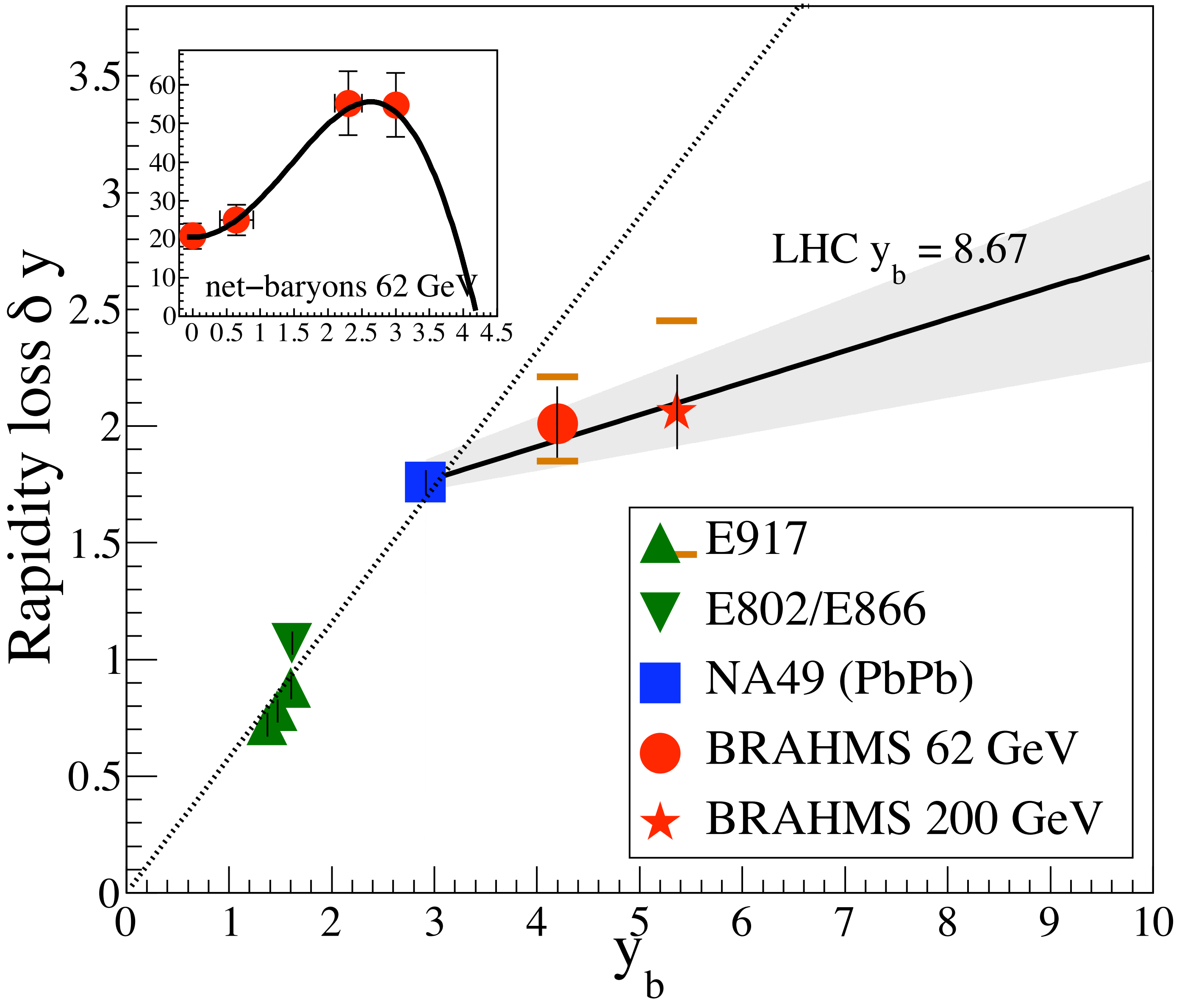
  - “The rapidity distribution of the net-protons after the collision then not only determines the energy available for particle production, but also yields information on the stopping of the ions due to their mutual interactions”

- **Energy loss of ΔE~73±6 GeV**

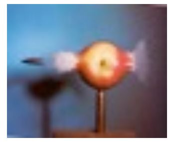
$$E = m_T \cosh(y)$$

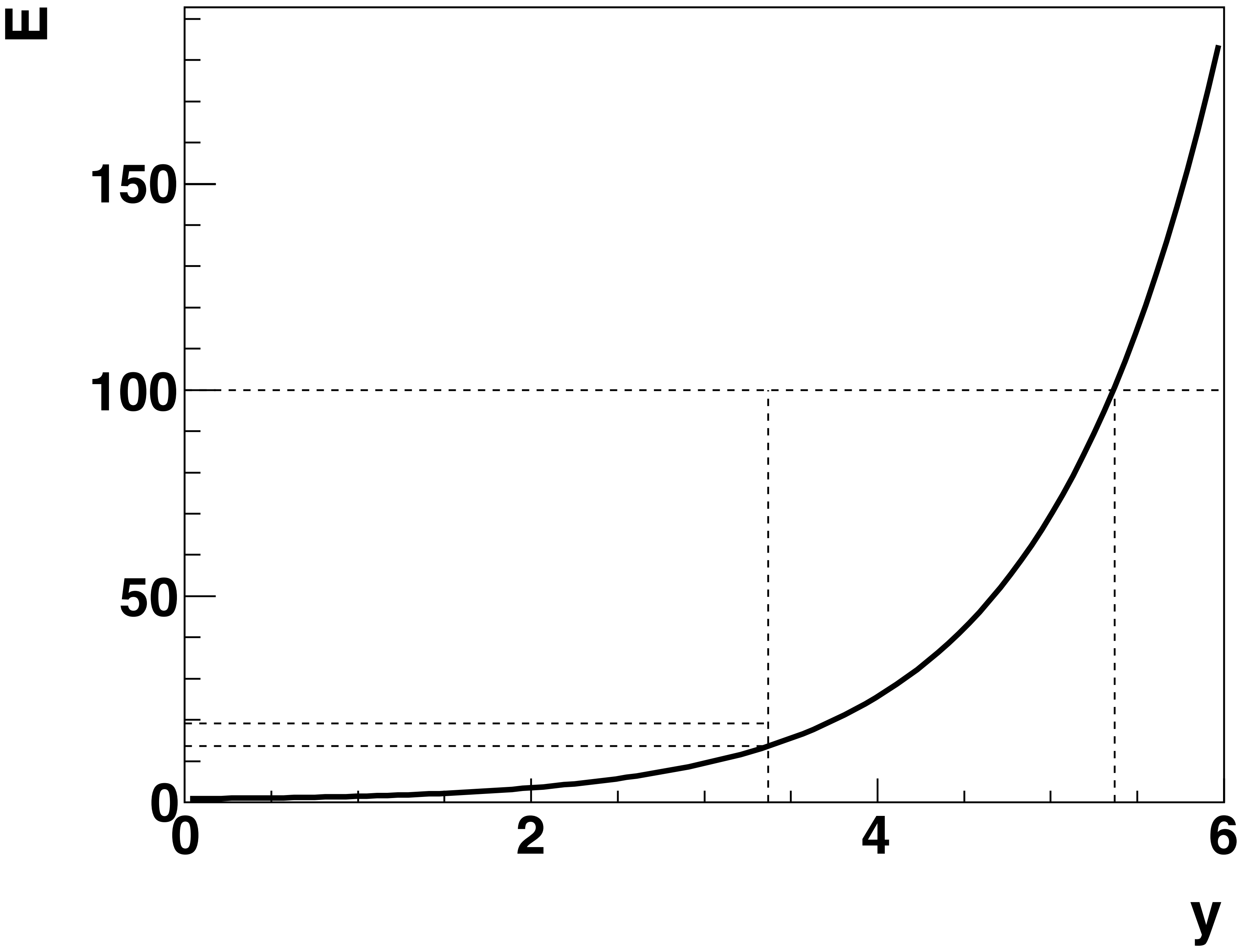
  - A combination of proton rapidity <u>loss</u> and transverse momentum <u>gain</u> ($\langle p_T \rangle \sim m_p$), i.e. $m_T \rightarrow 1.4 m_0$

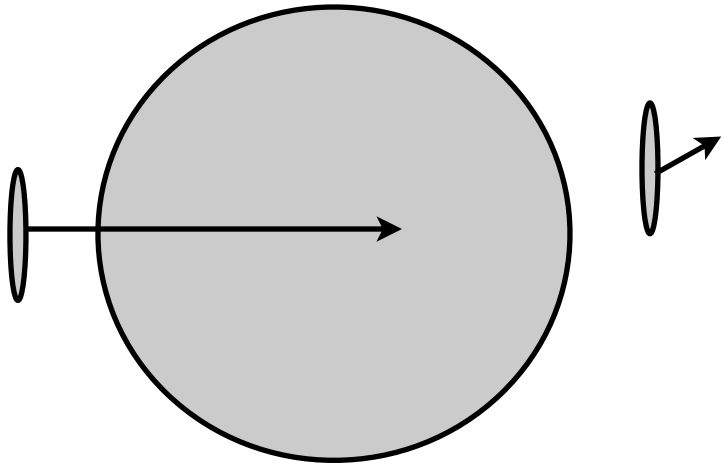
arxiv:0901.0872



Illustrating energy loss







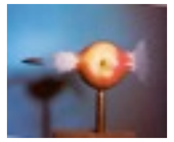
$\langle \delta y \rangle = -2$

87% loss → $\langle m_T \rangle \sim 1.4$ GeV

75% loss

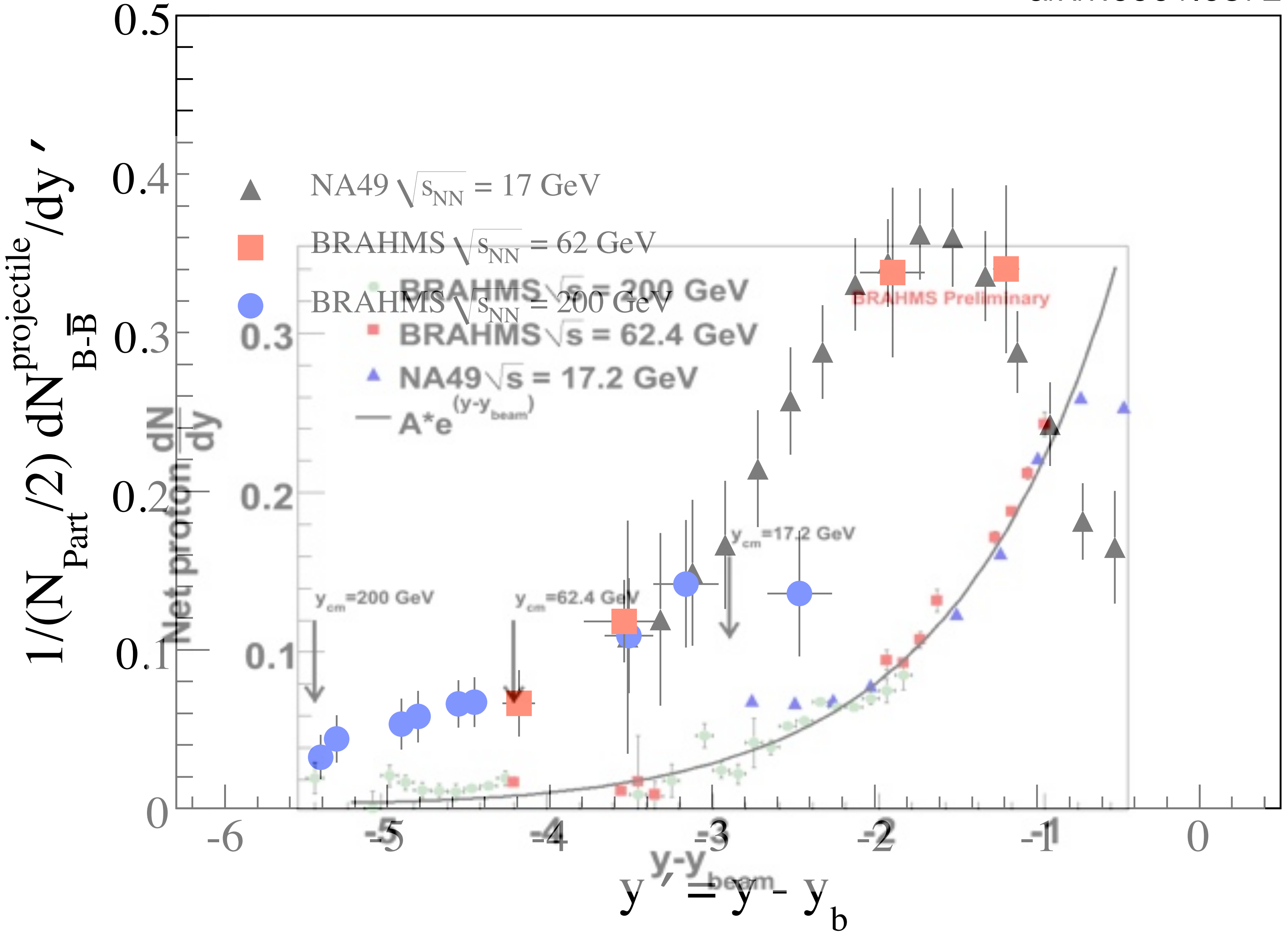
Protons are slowed longitudinally and dispersed tranversely

Stopping is “energy independent”



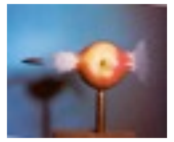
- **Decomposing net baryons into “target” and “projectile”, BRAHMS extracted a “per proton” dN/dy**
  - Good for three energies, except one point at 200 GeV
- **No real dependence on √s**
  - Not even NN cross section!
- **A+A is <u>very</u> different than p+p**
  - dN/dy ~ exp(y’) (dN/dx ~ const)

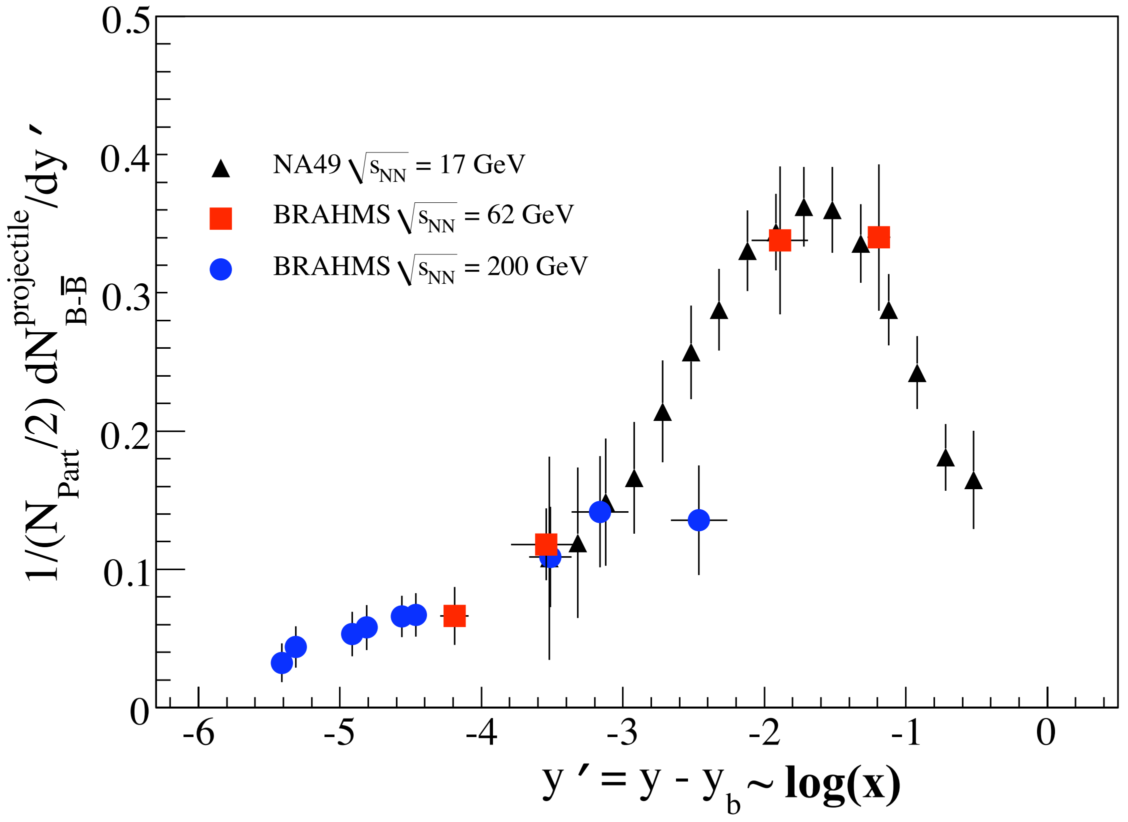
arxiv:0901.0872



p+p from talk by F. Videbaek

“BMS” stopping





Decoherence of partons in incoming nuclei, adding some p_T

Bass, Muller, Srivastava: nucl-th/0212103

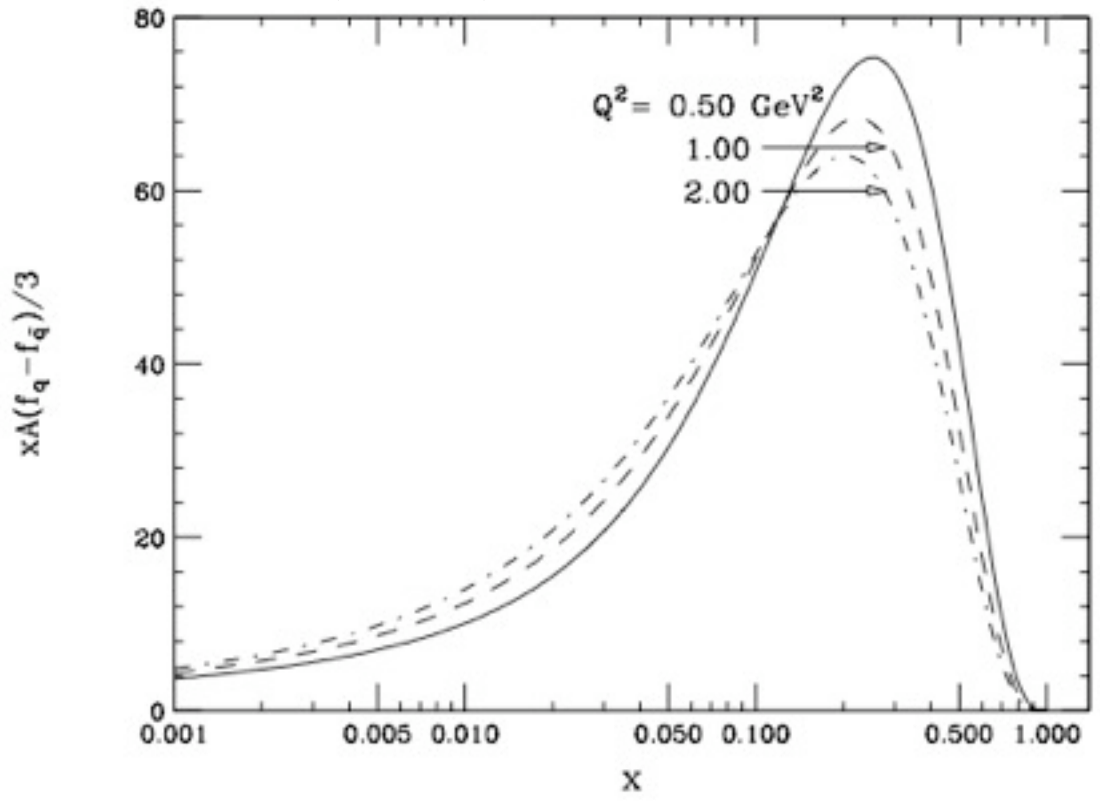
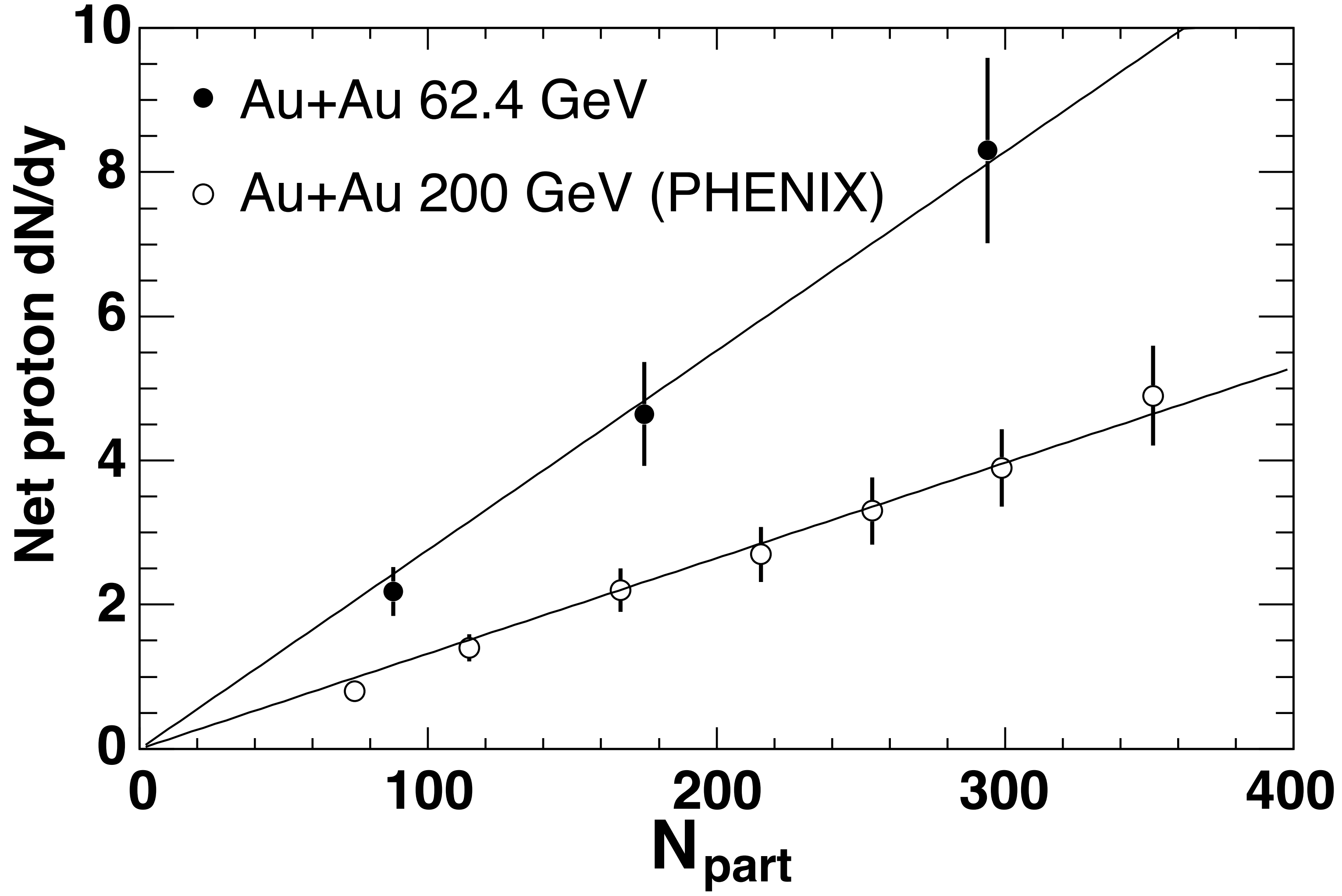


FIG. 1: Net baryon content of the partonic distribution function of gold-nucleus at the factorization scales (Q_0^2) of 0.50 GeV^2 (solid curve), 1.00 GeV^2 (dashed curve) and 2.00 GeV^2 (dot-dashed curve), for the GRV-HO [13] parametrization. Parton shadowing is not included.

In this view, stopping is “built-in” to the nucleon/nuclear PDFs: good for explaining “limiting fragmentation”, bad for standard stopping

Interlude - centrality dependence

- **BRAHMS only presents the net dN/dy for 0-10% centrality**
- **PHOBOS measured net dN/dy vs. N_{part} for 62.4 GeV Au+Au**
- **Linear with N_{part} down to most peripheral collisions considered**
- **Why would each participant contribute equally if nuclei are transparent?**

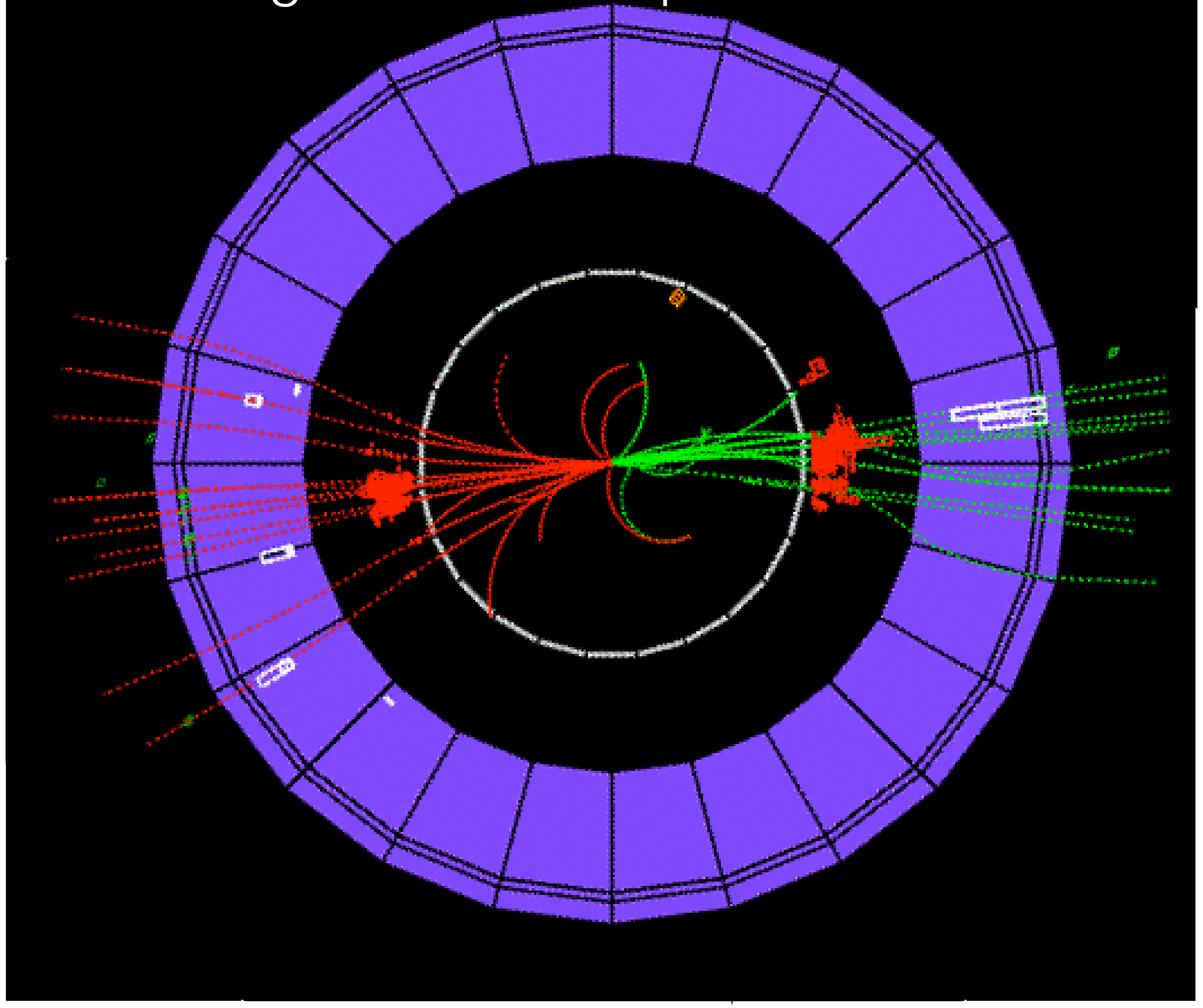


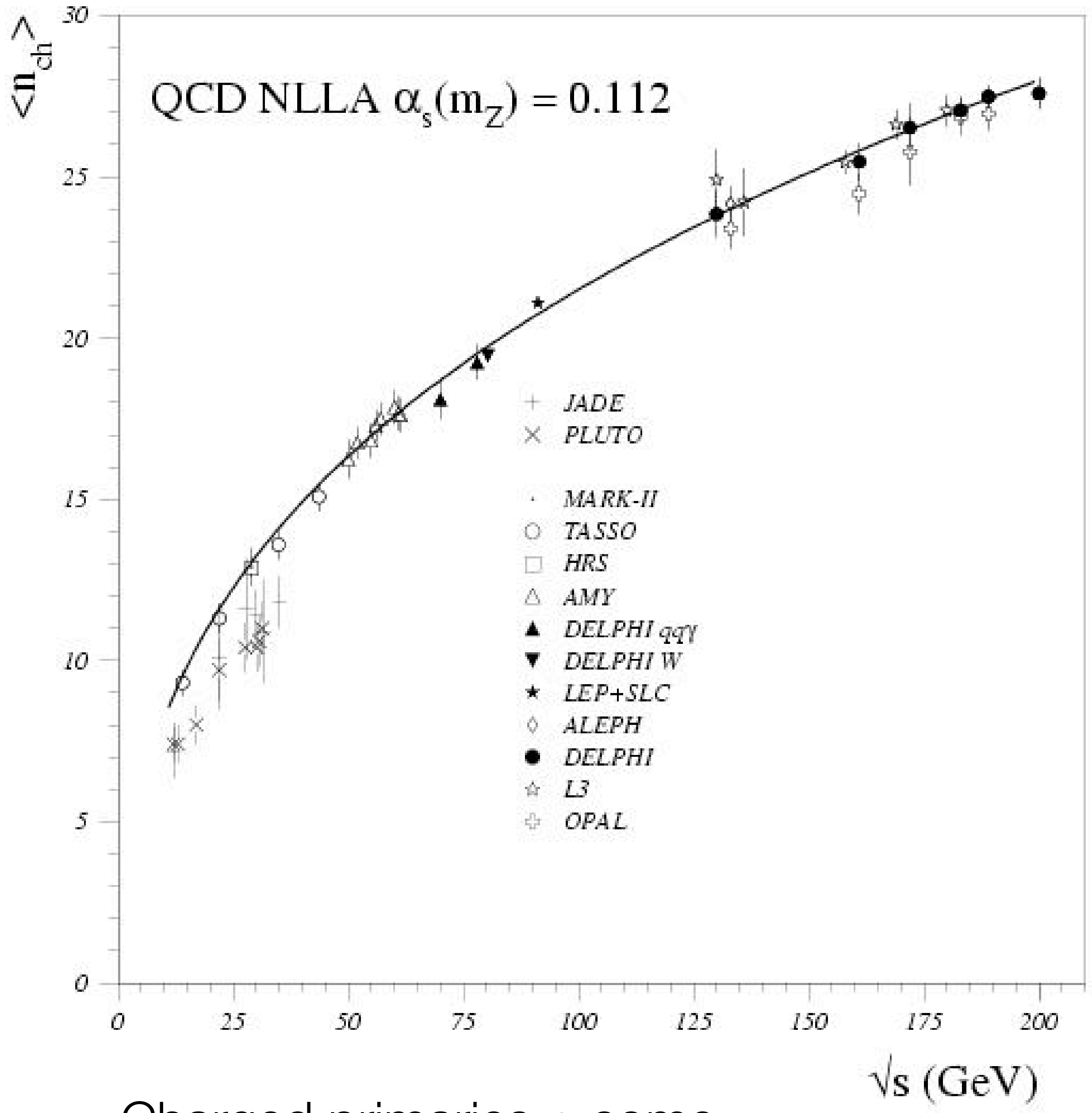
Entropy production

- **Entropy reflects the degrees of freedom available to the QGP on thermalization**
  - wQGP vs. sQGP
- **Several ways to estimate it (experimentally)**
  - Phase space density (e.g. Pratt & Pal, at midrapidity)
  - Multiplicity density, assuming thermal freezeout, and isentropic evolution
- **Current estimates are consistent (see e.g. Muller & Rajagopal), so I will stick with multiplicity estimates**
  - Thermal models give $S \sim 7.2\ N_{ch}$
- **PHOBOS has discussed comparisons of multiplicities with elementary systems: useful to have an empirical context**
  - Only 4π multiplicities discussed here

Multiplicity Systematics - e^+e^-

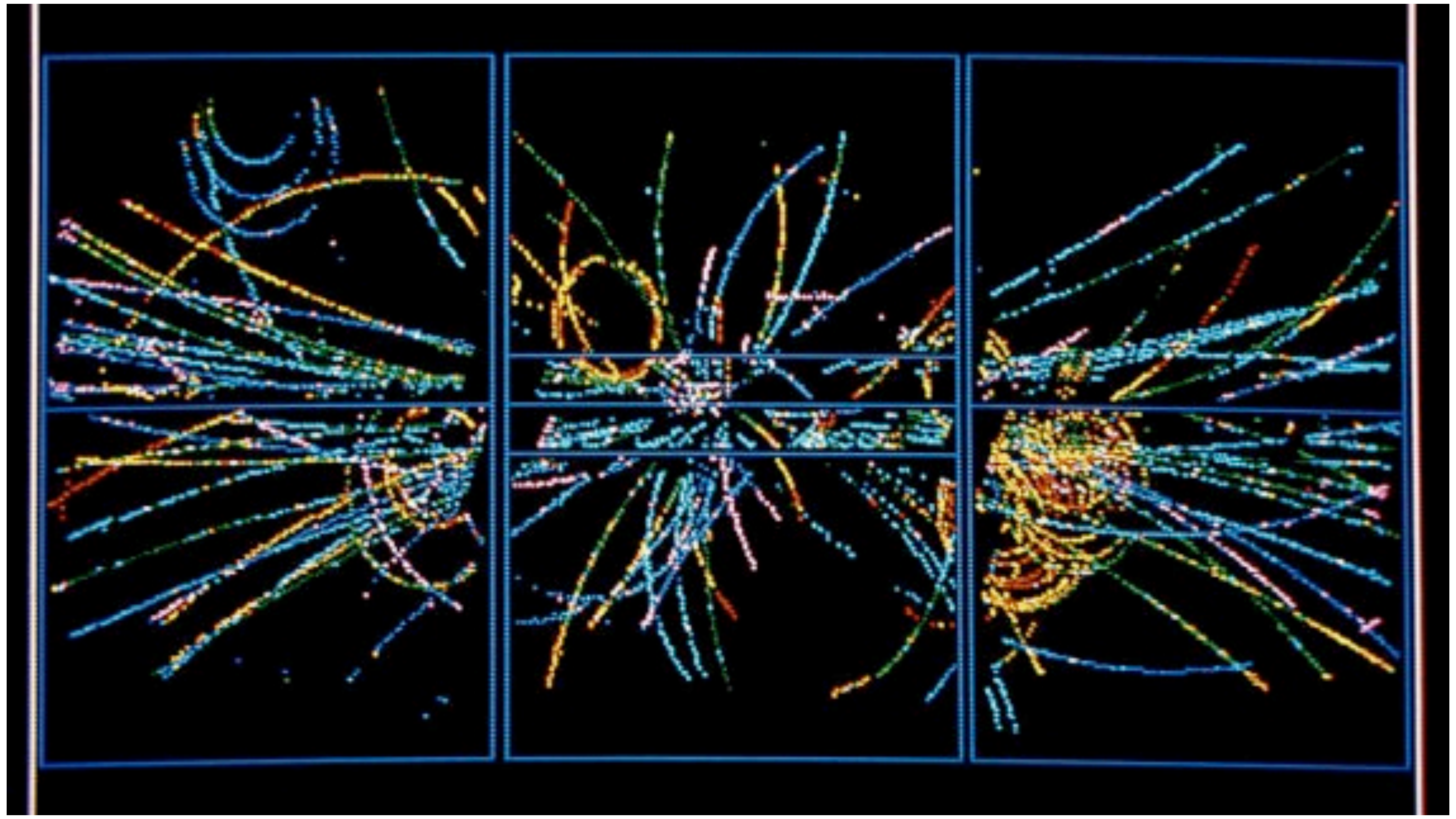
“free” fragmentation of quarks into hadrons

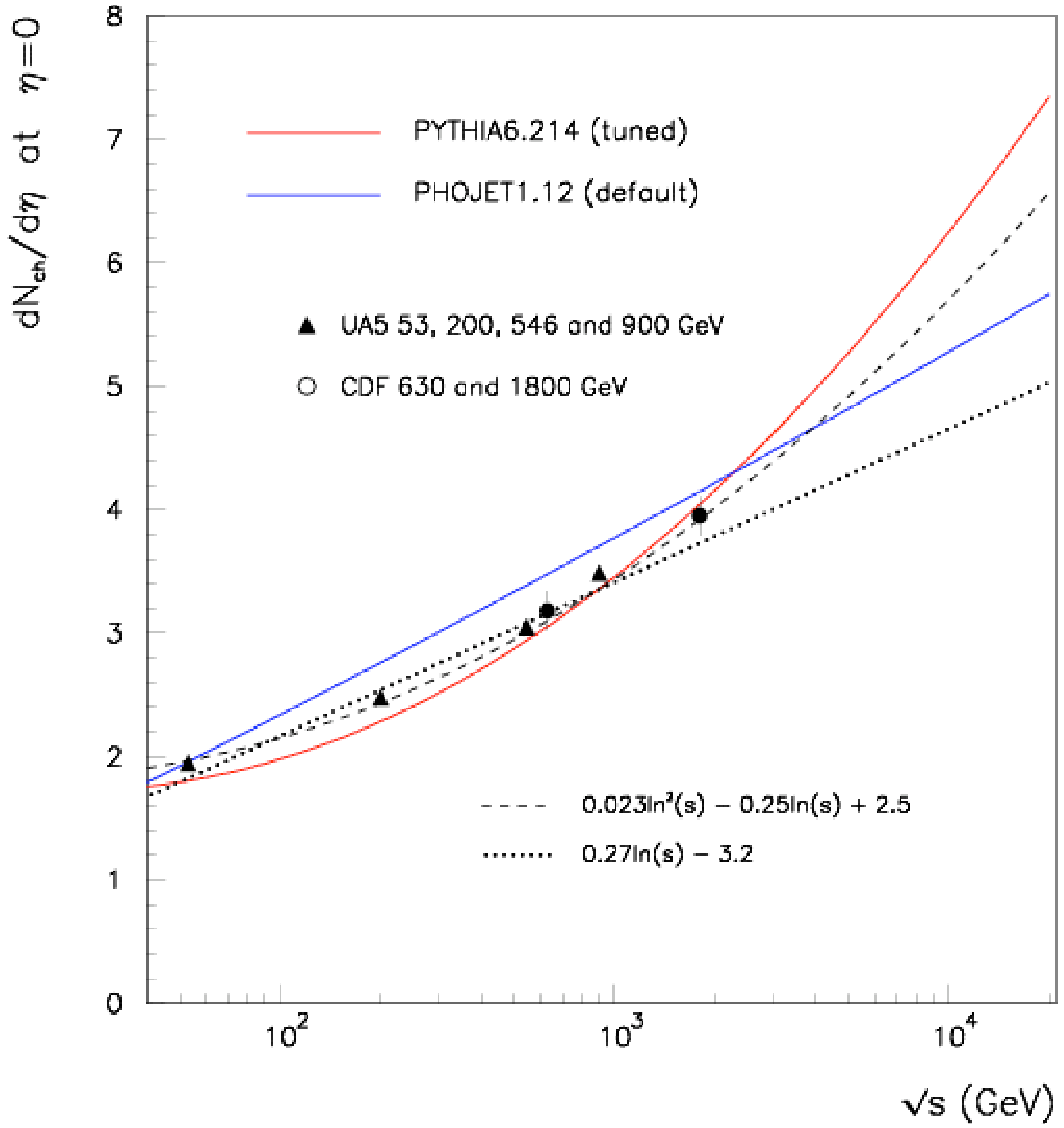




Charged primaries + some secondaries (up to 8% correction)

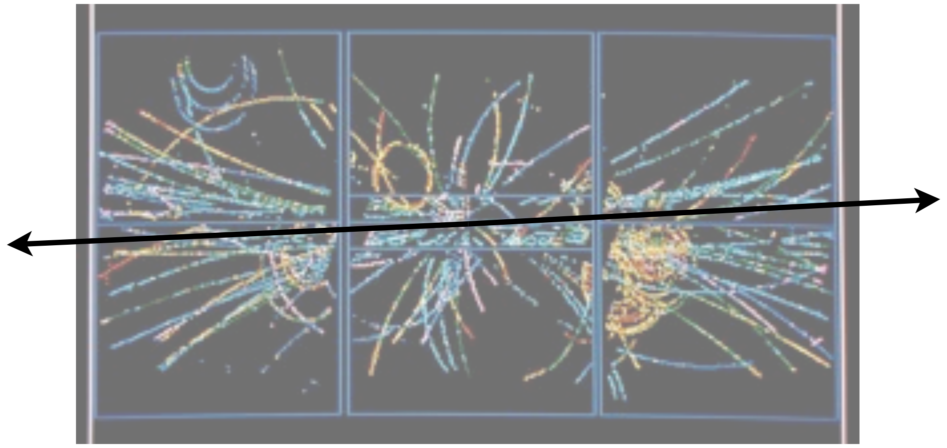
Multiplicity Systematics - p+p





Leading Particle Effect

“leading” particles keep arbitrary fraction of √s

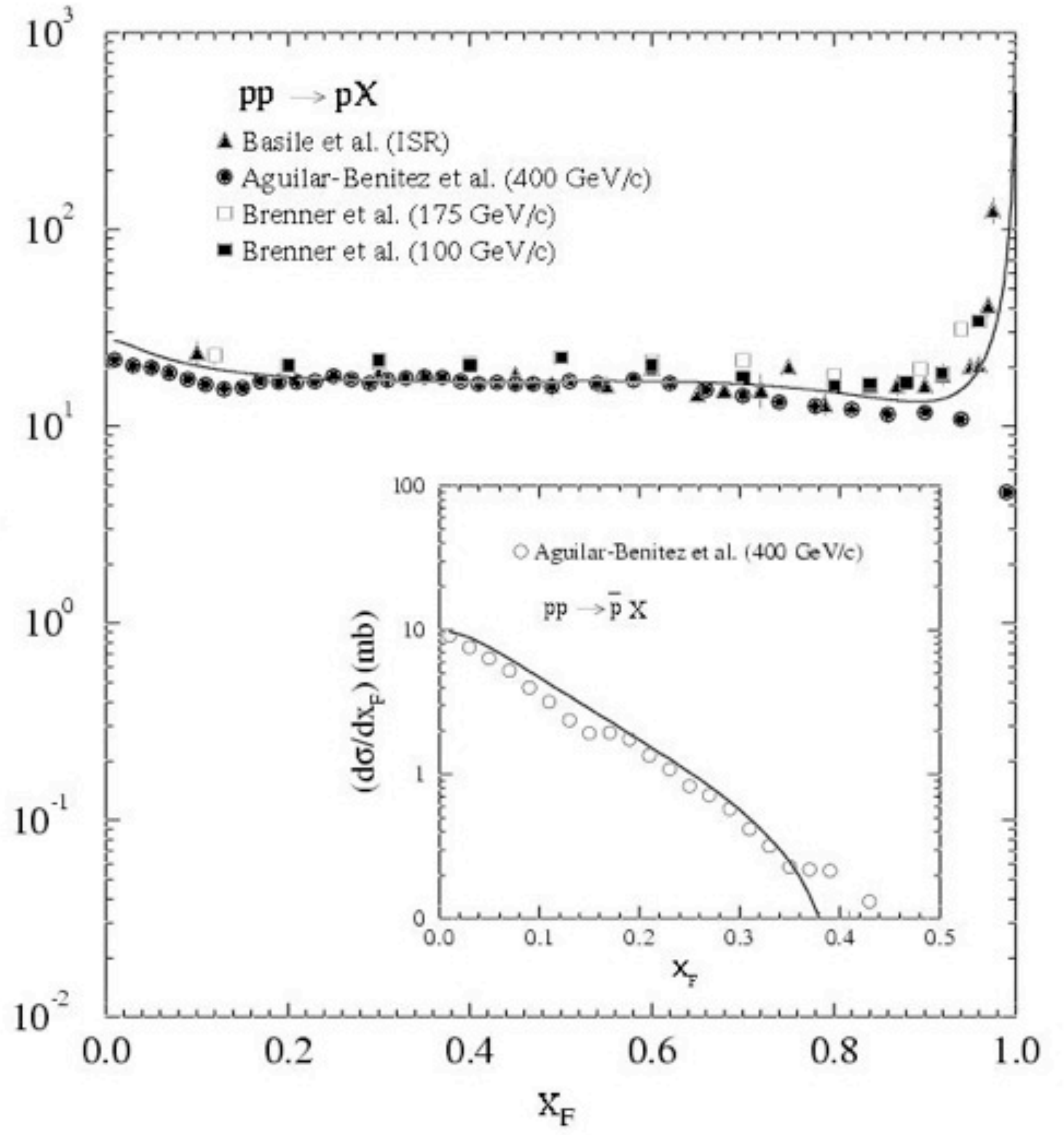


flat probability distribution→

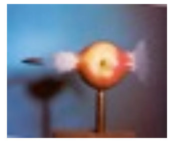
$$x_F = \frac{2p_z}{\sqrt{s}} \qquad \langle x_F \rangle \sim 1/2$$

$$\sqrt{s_{eff}} = \langle x_F \rangle \sqrt{s} = \frac{\sqrt{s}}{2}$$

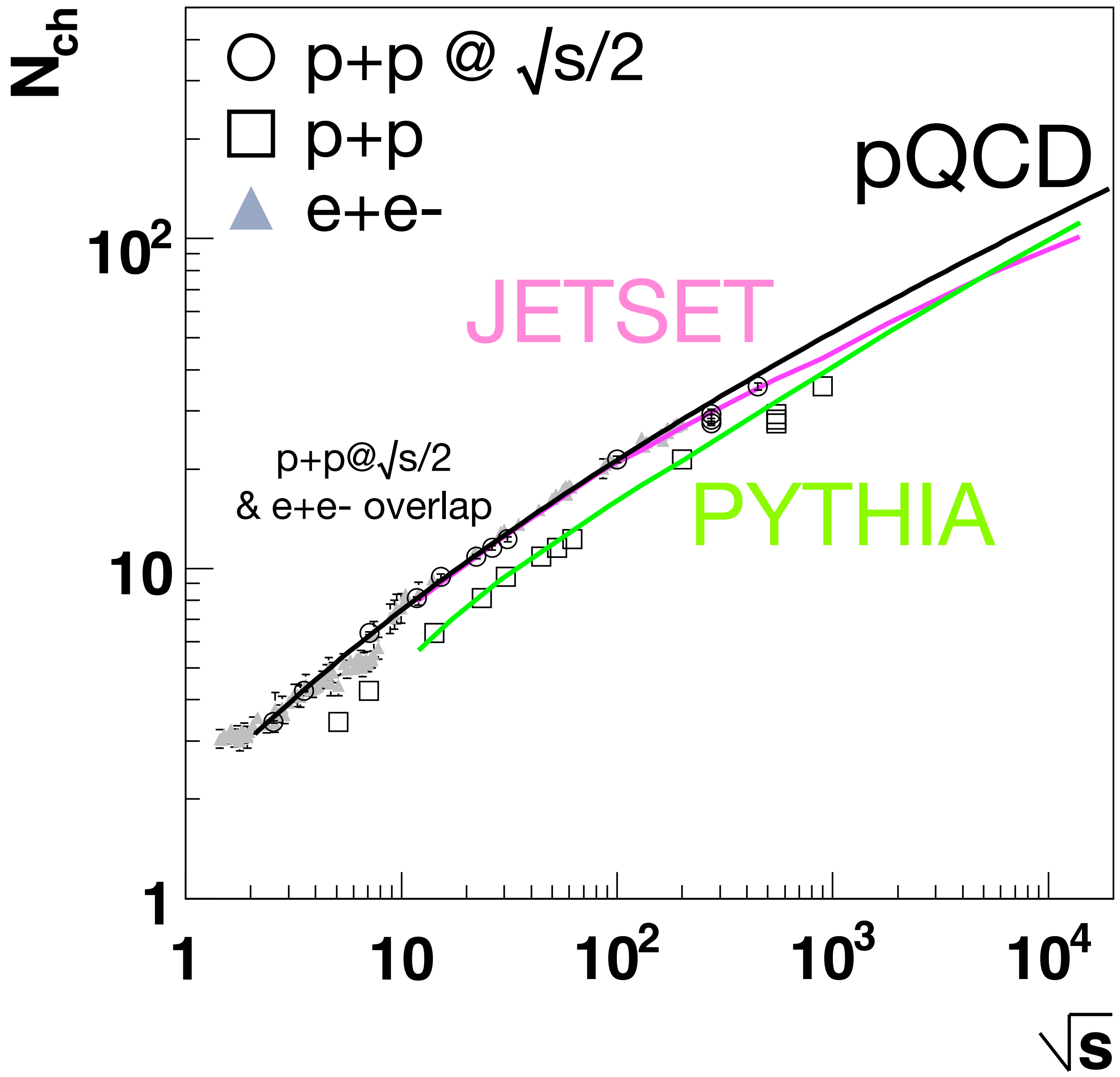
“effective energy” (a la Basile et al)



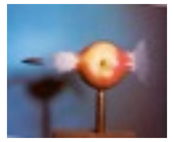
Effective energy in action

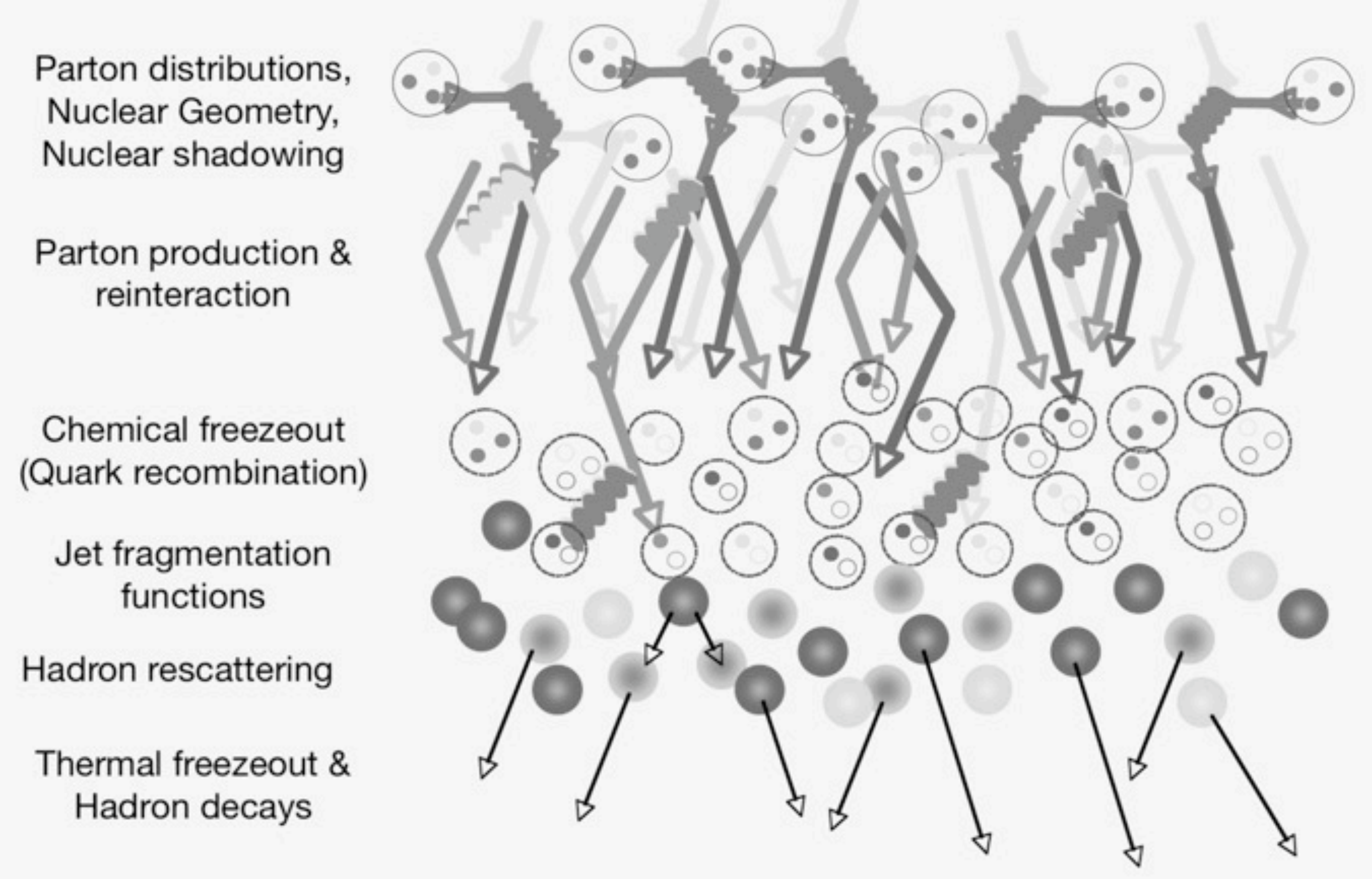


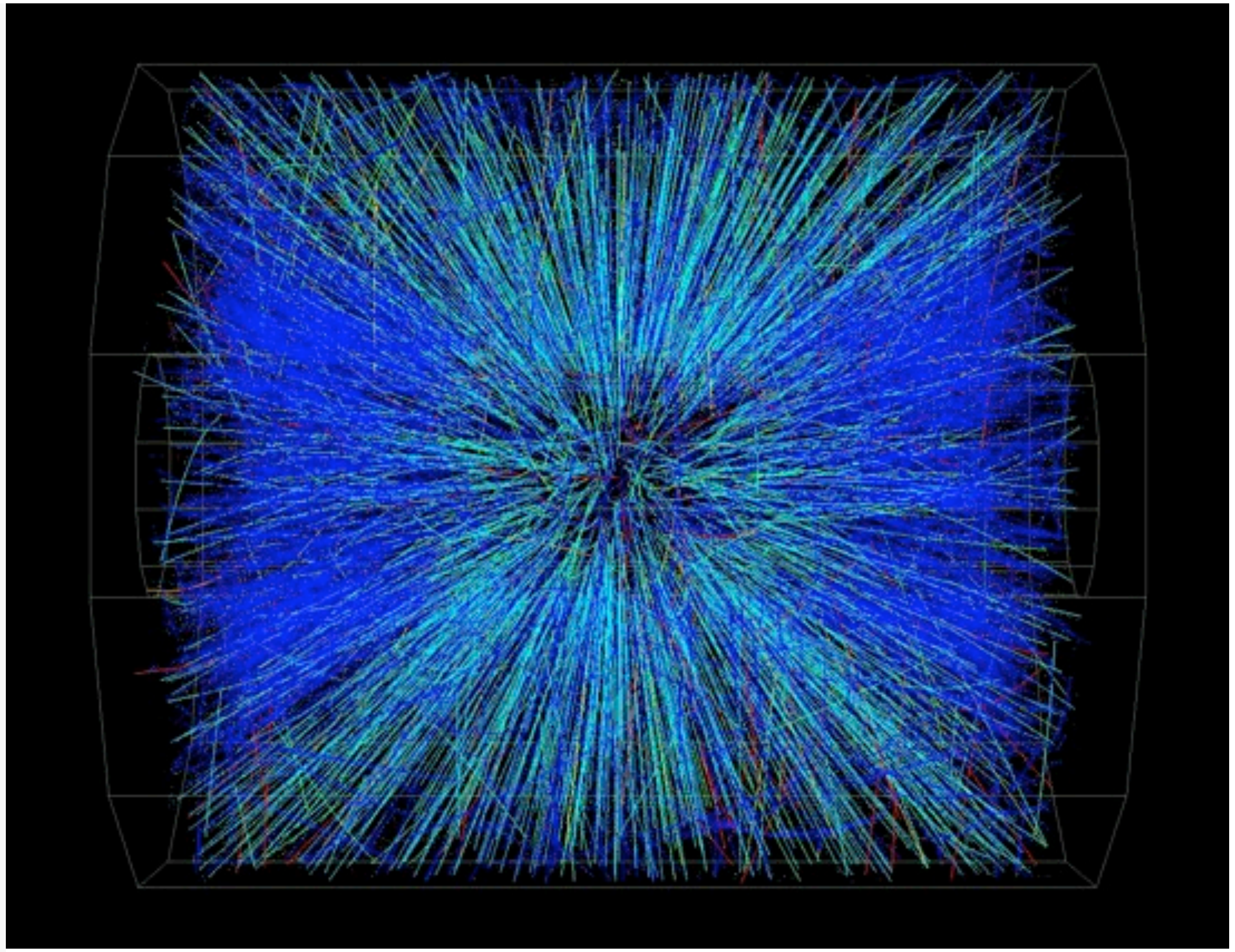
- **You don't really believe it until you try it yourself!**
  - Simple 1/2 prescription does a surprisingly good job of making e+e- and p+p overlap
- **Of course dN/dy cannot be the same due to larger rapidity range**
- **Models tuned on existing data**
  - No obvious scaling built in



Entropy Production in A+A



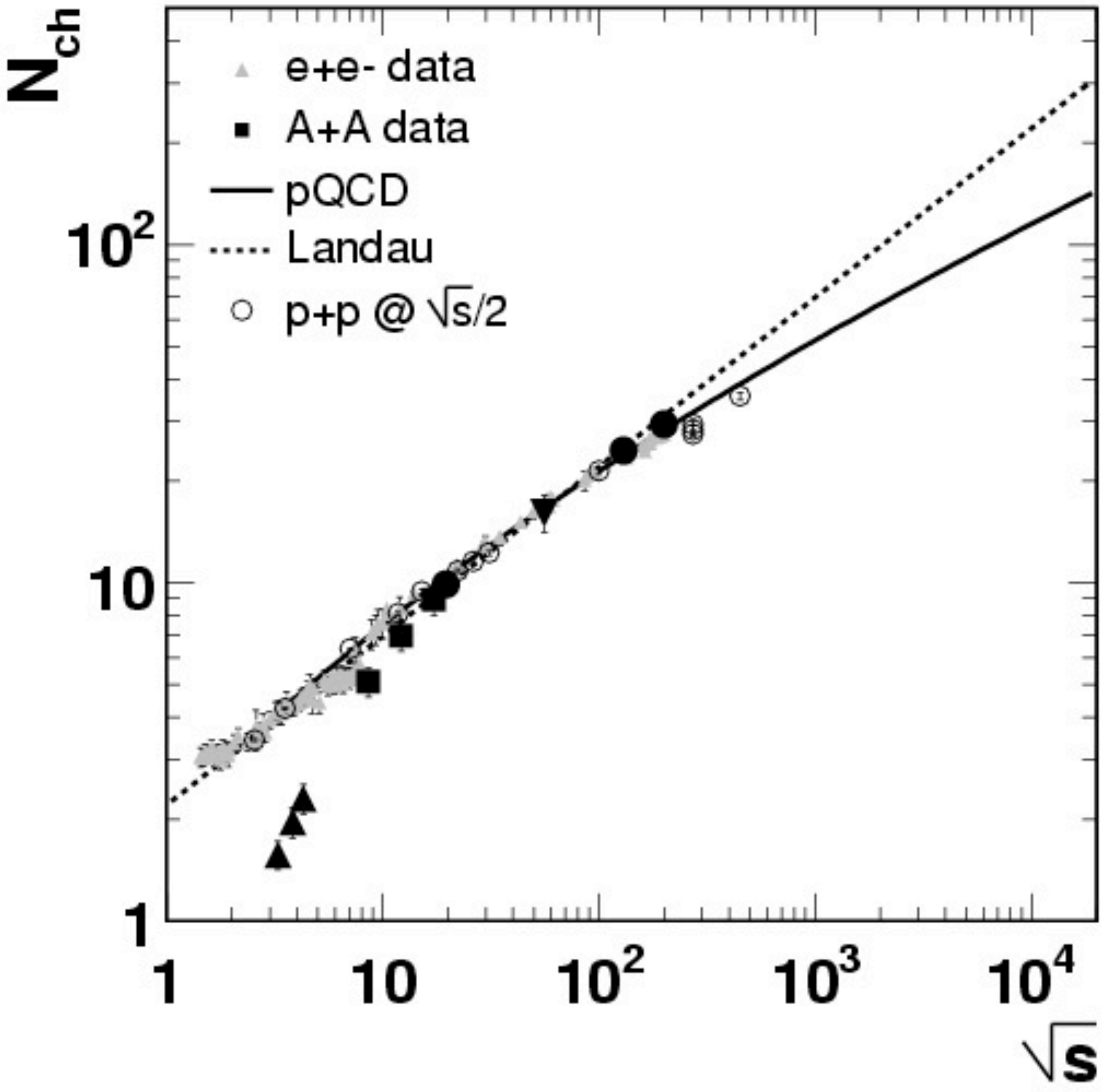




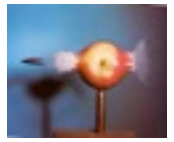
Nominally, all of these stages have different degrees of freedom

A+A in the context of elementary systems - how much energy?

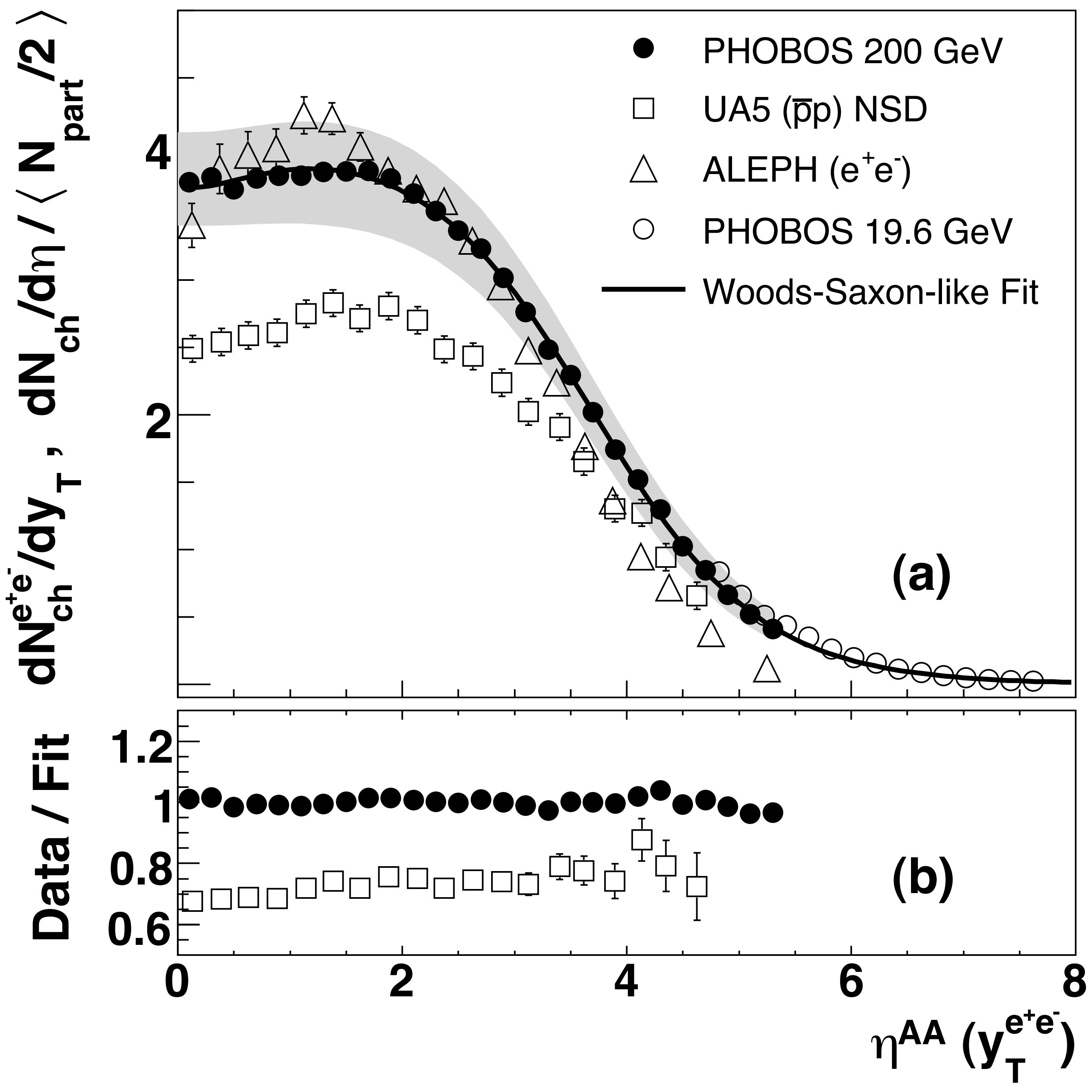
- **Heavy ion data is only scaled once:**
  - Divided by overall volume $N_{part}/2$
- **Overlaps e+e- and p+p(@√s/2) over a decade in beam energy**
- **Old observation (2002) but germane**
  - How much energy is available in A+A?
  - If e+e- has "all", and p+p has "half" → then **A+A has "all"**
- **At low energy, scaling broken systematically with increasing muB**
  - Is this less energy, or less *entropy*?
  - More on this later!



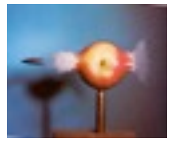
Longitudinal distributions in context

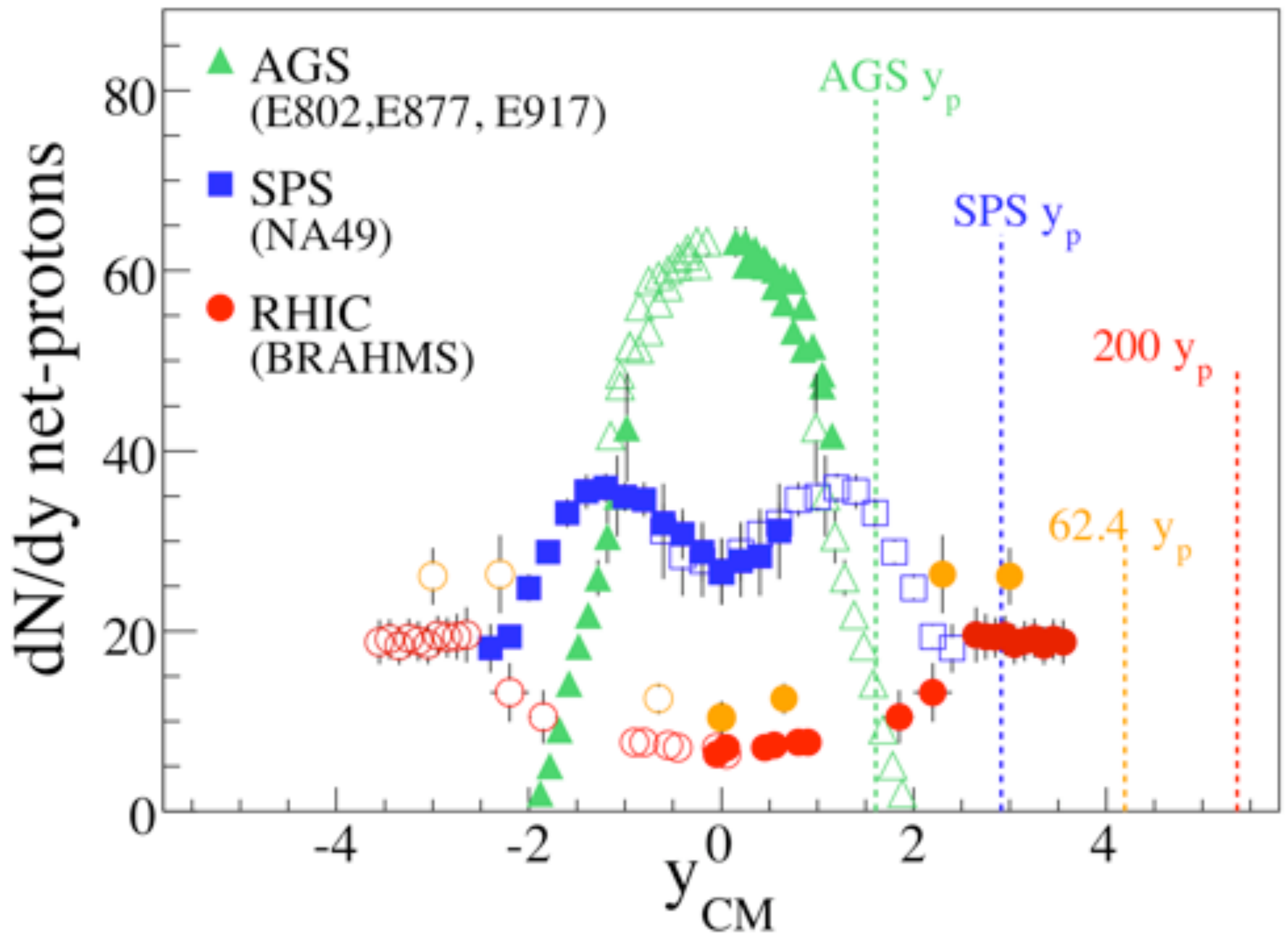


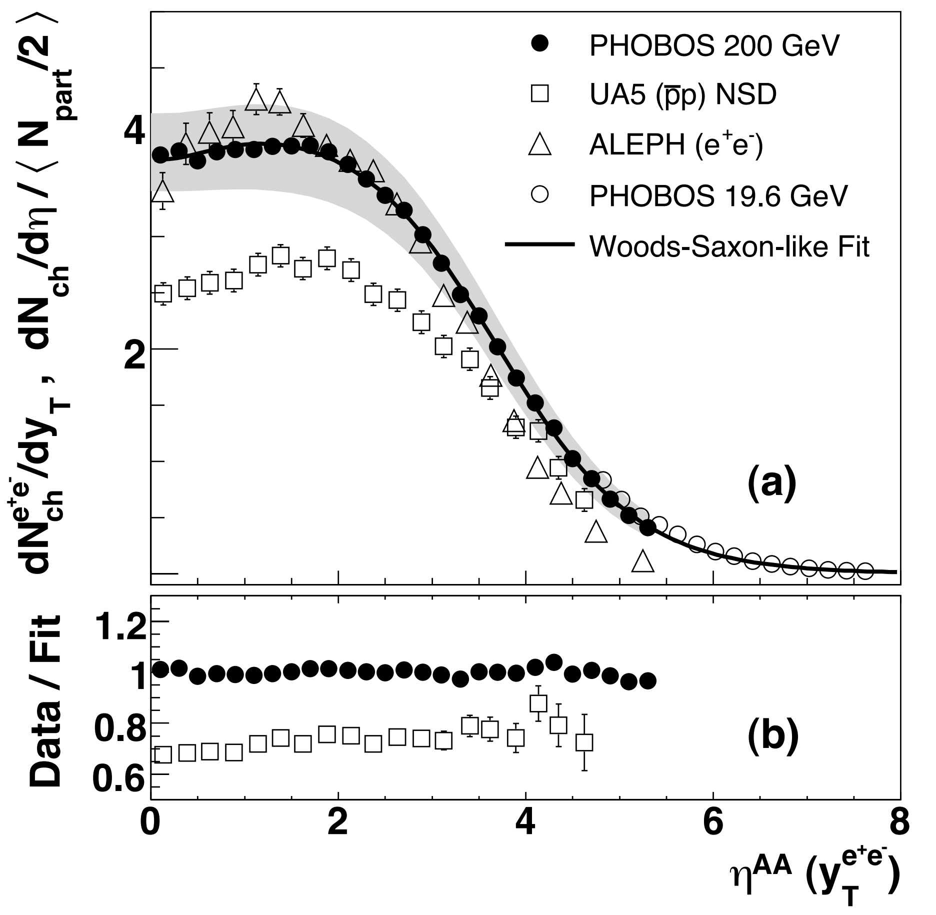
- **It's not just the multiplicity that agrees, but the longitudinal distributions over 4π**
- **If an accident, a very detailed one**
  - If you argue that dN/dy has "no information", then you have to generalize that assessment!
- **If not an accident, tells us that longitudinal phase space (i.e. stopping?) is essentially similar**



Do these tell the same story?







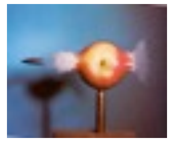
ΔE(200 GeV) ~ 150 GeV

“transparency”

ΔE(200 GeV) ~ 200 GeV

“full stopping”

Do these tell the same story?



they seem to be telling two *very different* stories:

Bjorken

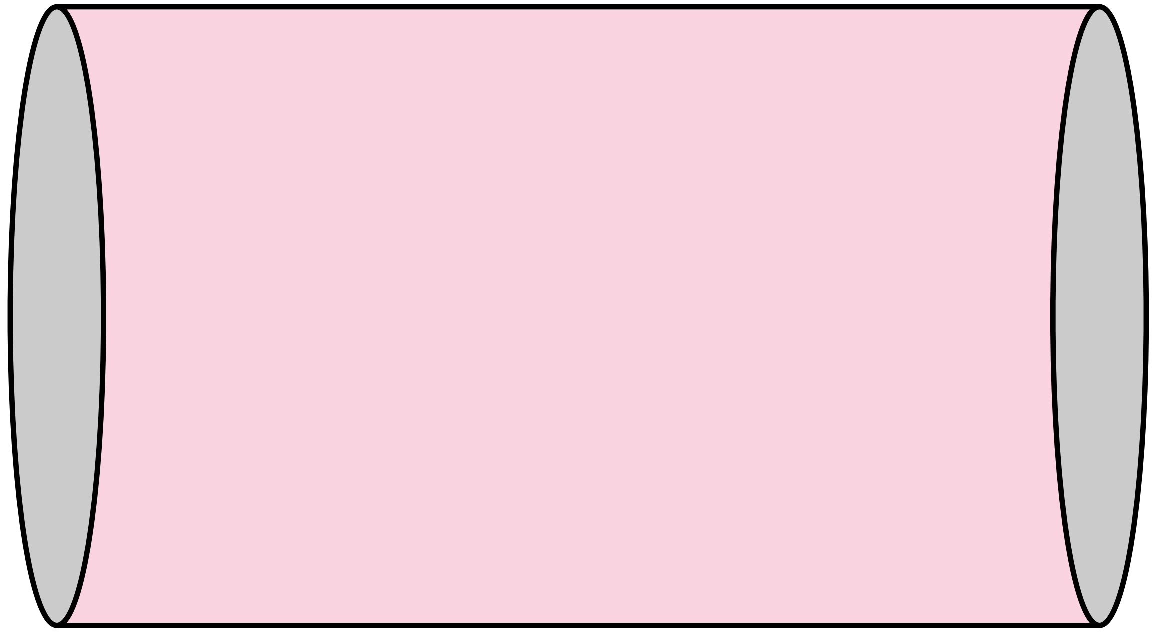
Landau

“transparency”

“full stopping”

Bjorken's story

Bjorken

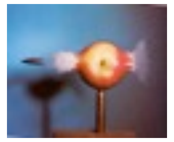


"transparency"

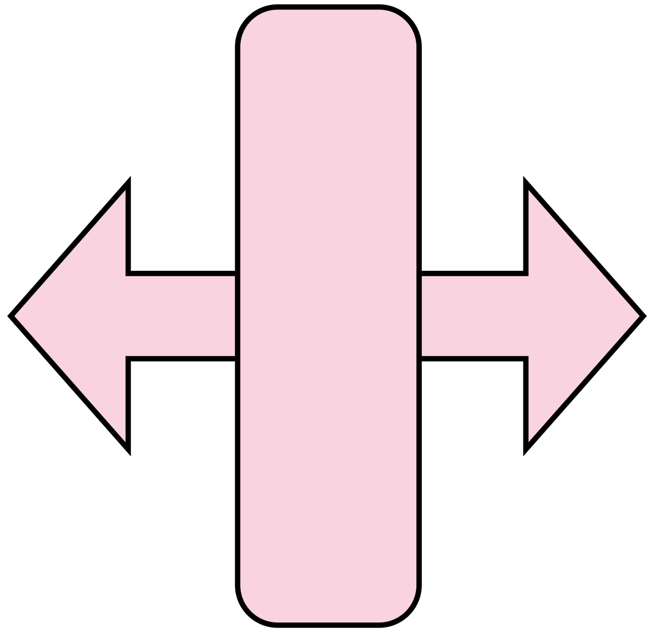
the pancakes pass through each other and the baryons leave energy in the central region. the evolution obeys the laws of hydrodynamics

Baryons assumed to be on the "outside", escaping at the speed of light

Landau's story



Landau

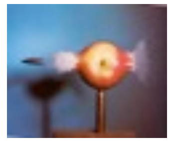


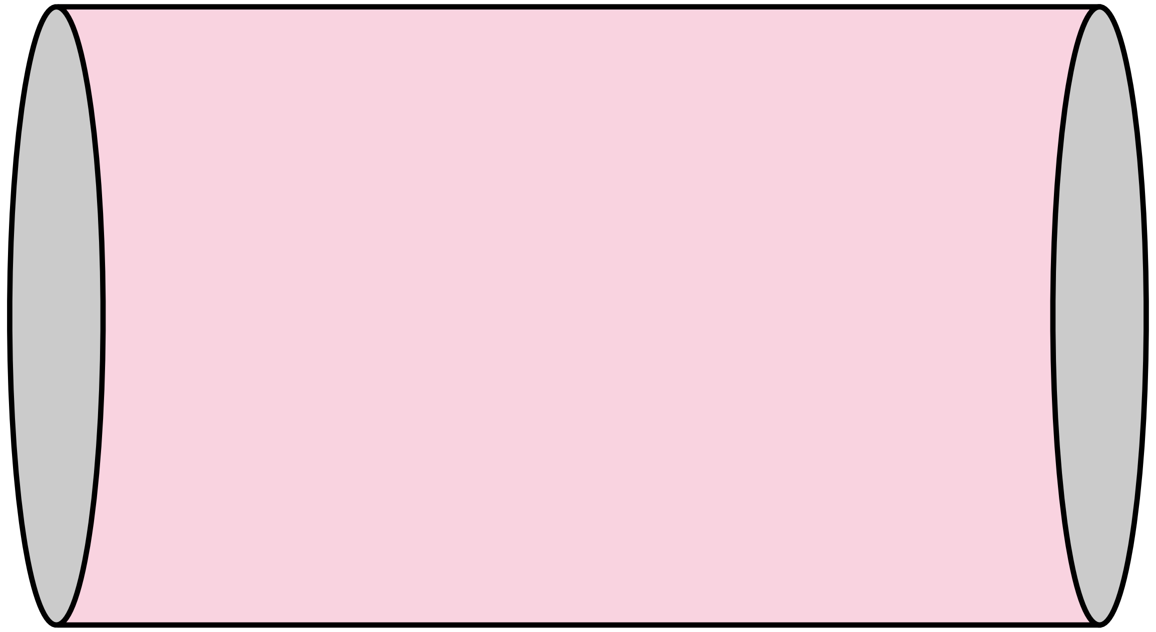
"stopping"

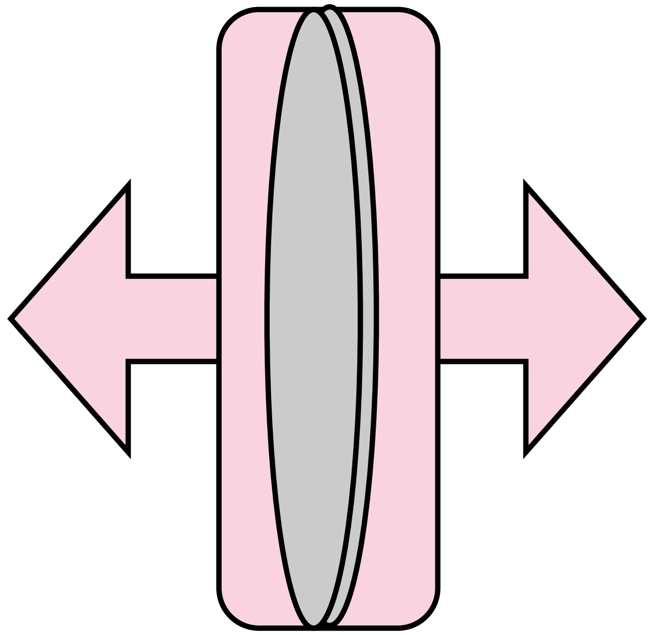
the pancakes stop each other as they collide, and the energy then explodes longitudinally via hydrodynamics

Baryons assumed to be...
nowhere (i.e. ignored)

Bjorken v. Landau (1953-1983)



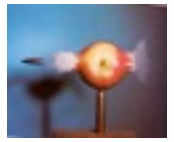


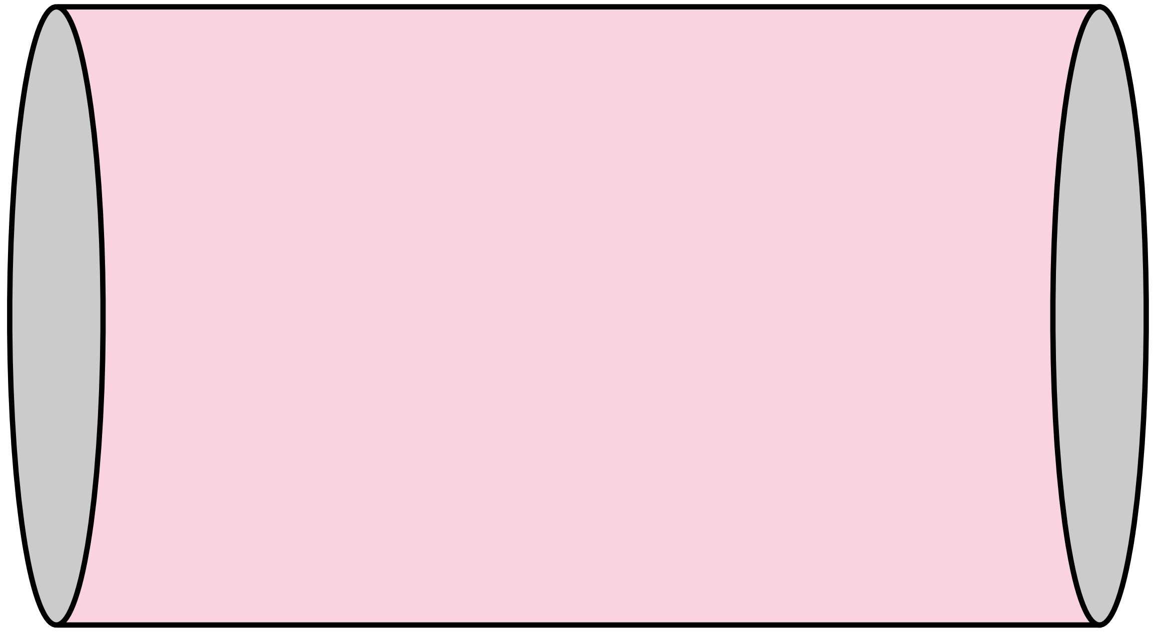


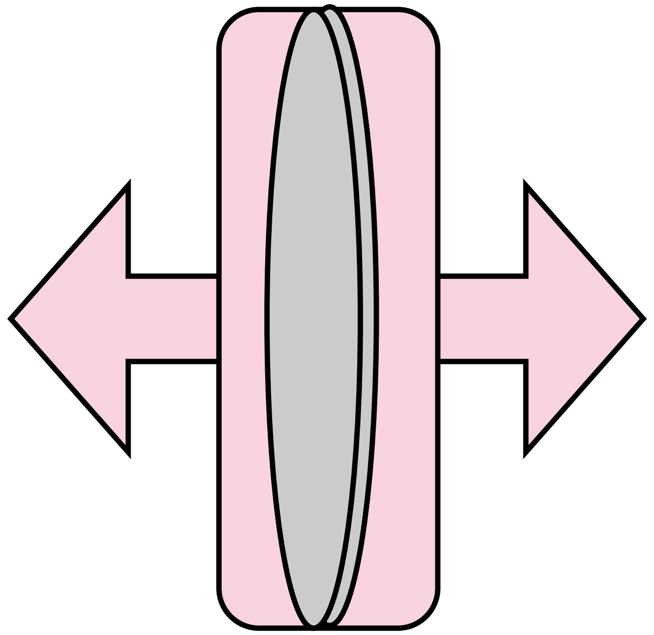
Landau and Bjorken are telling a story with the same middle (hydrodynamics), and same end (v_z=z/t, hadronization at T_{ch}), but with a different beginning

So it's not just the amount of energy, but how it is deposited that matters (e.g. is it born expanding, or standing still -- or somewhere in between?)

Thermalization time





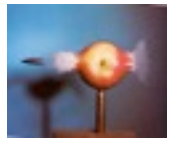


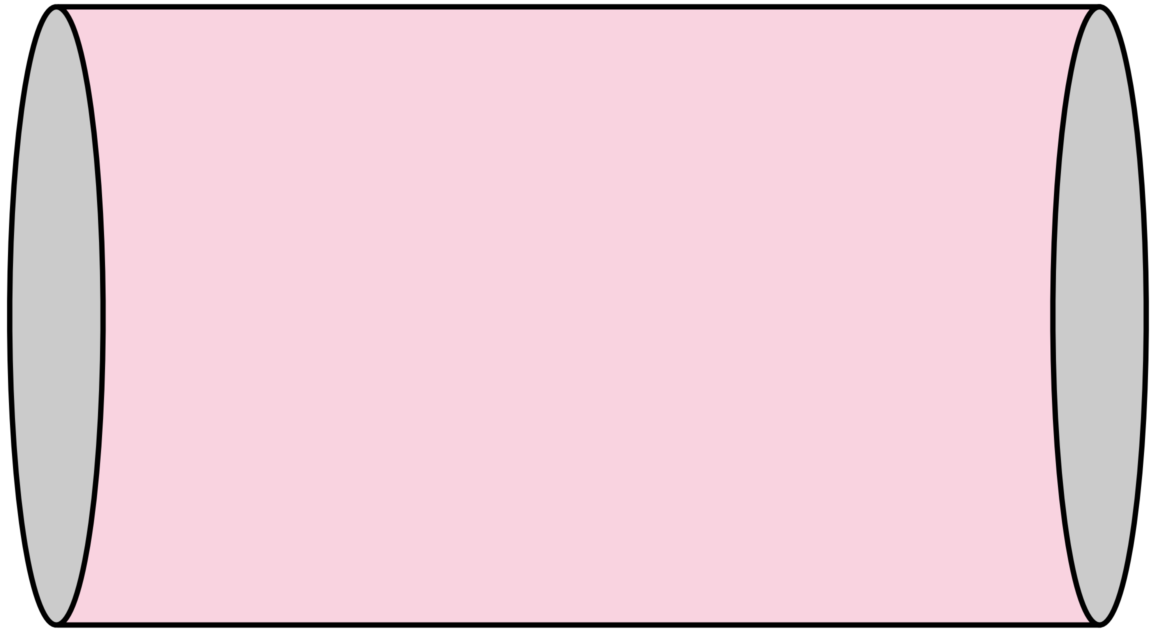
$\tau_0 >> 2R_0/\gamma$

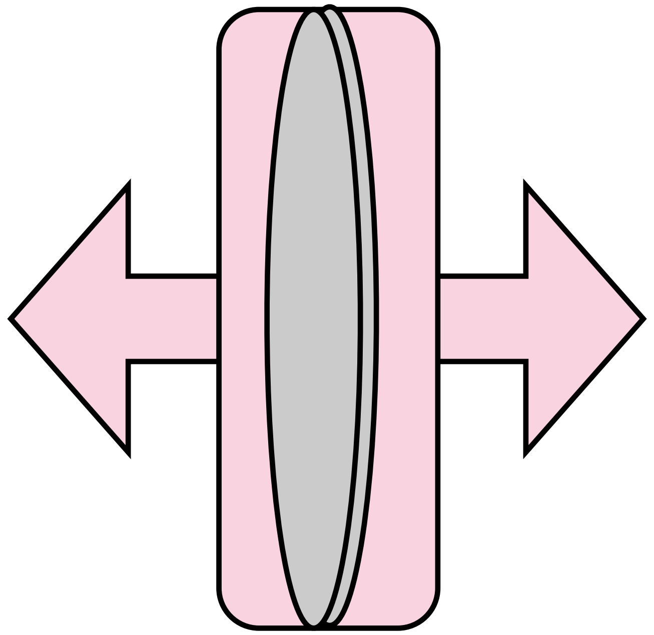
$\tau_0 = 2R_0/\gamma$

Discussions of thermalization time are not simply deciding a “property”, but the nature (and dimensionality: 2+1 vs 3+1) of the initial state!

Experimental access to stopping?

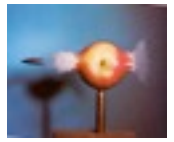


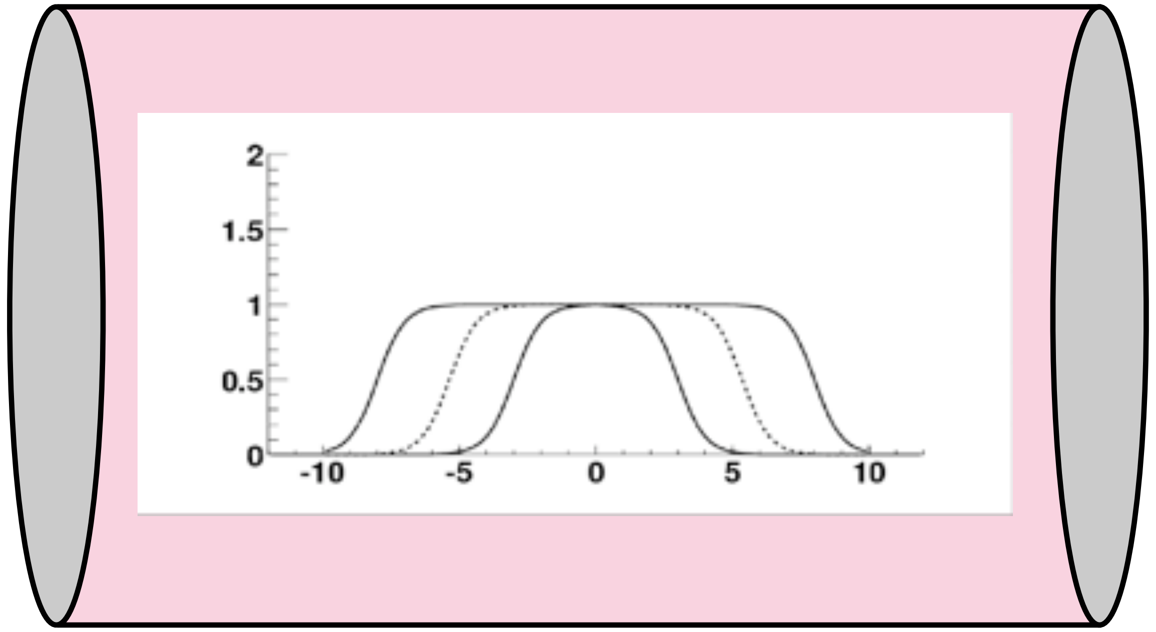




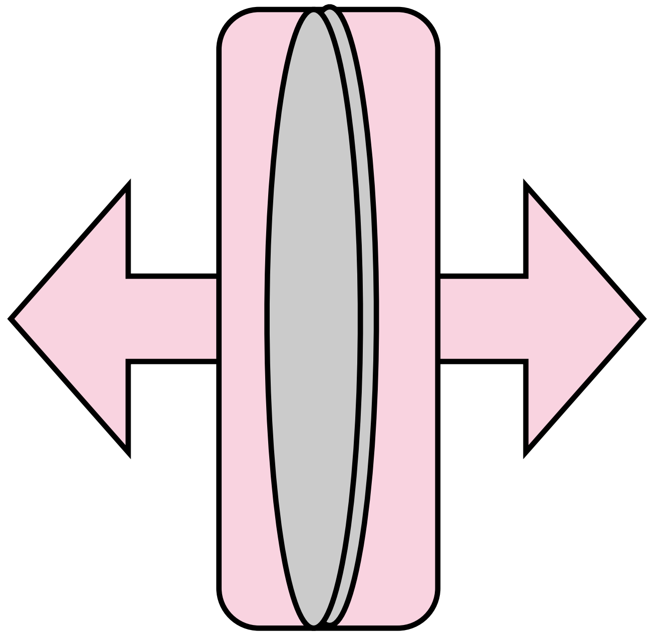
Can the final (pseudo) rapidity distribution
(mesons or baryons)
tell us how the energy was stopped?

Using final rapidity distributions to probe the initial state



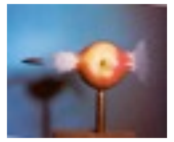


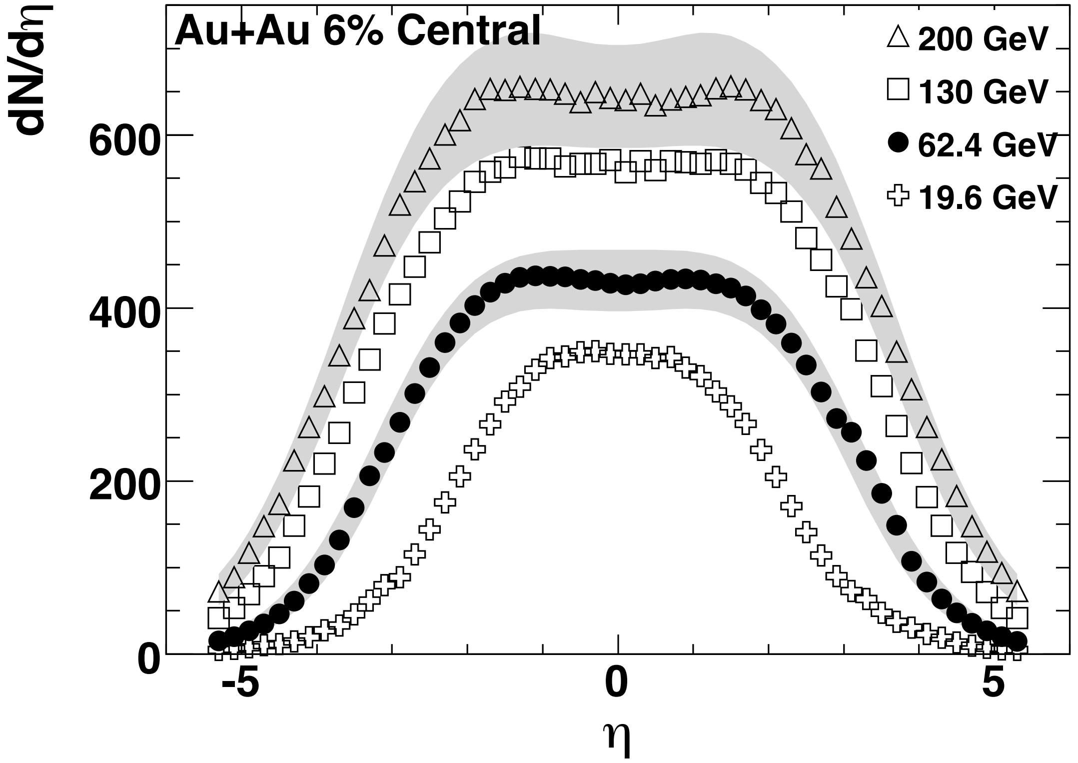
Bjorken initial conditions suggests a widening plateau in dN/dy

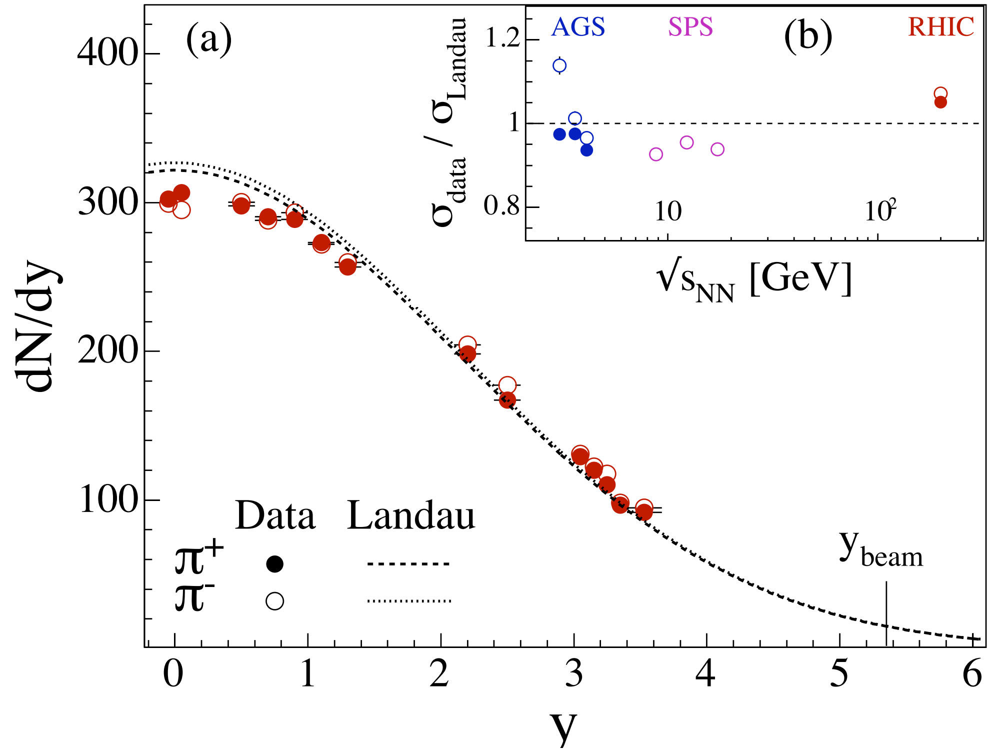


Landau implies dN/dy is Gaussian with $\sigma^2 = \frac{1}{2}\ln(s/m^2)$

Using final rapidity distributions to probe the initial state





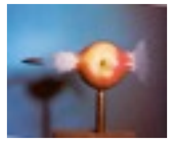


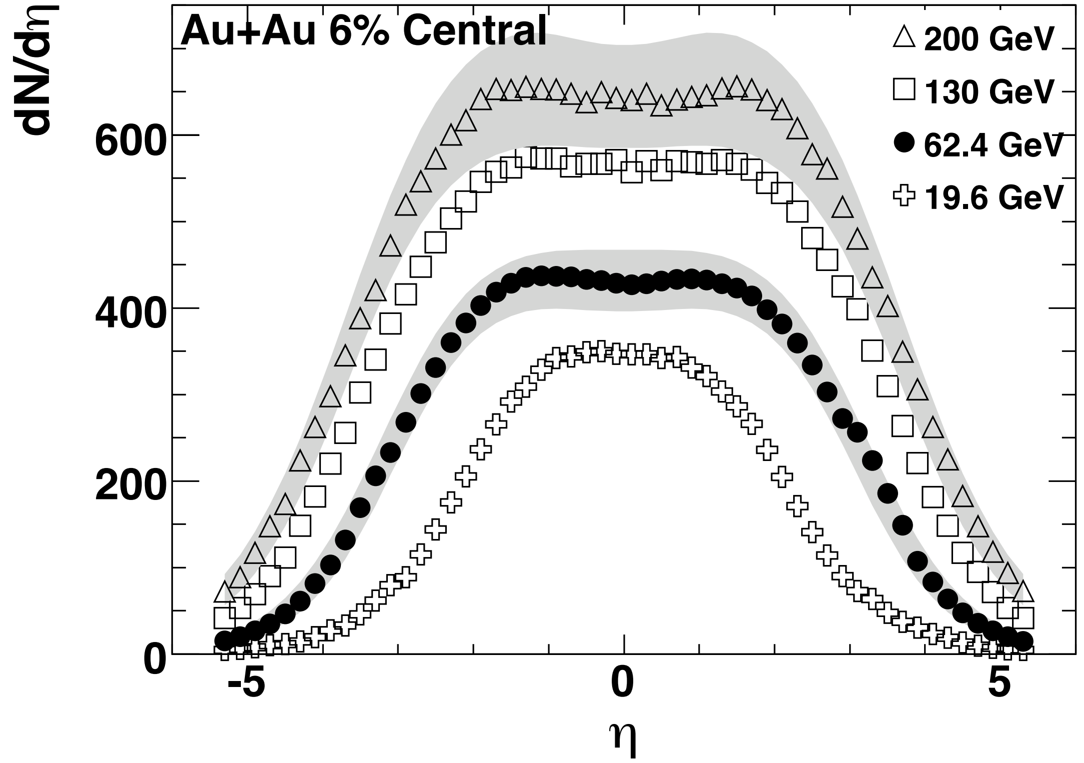
dN/dη shows a "plateau" that gets wider with increasing beam energy

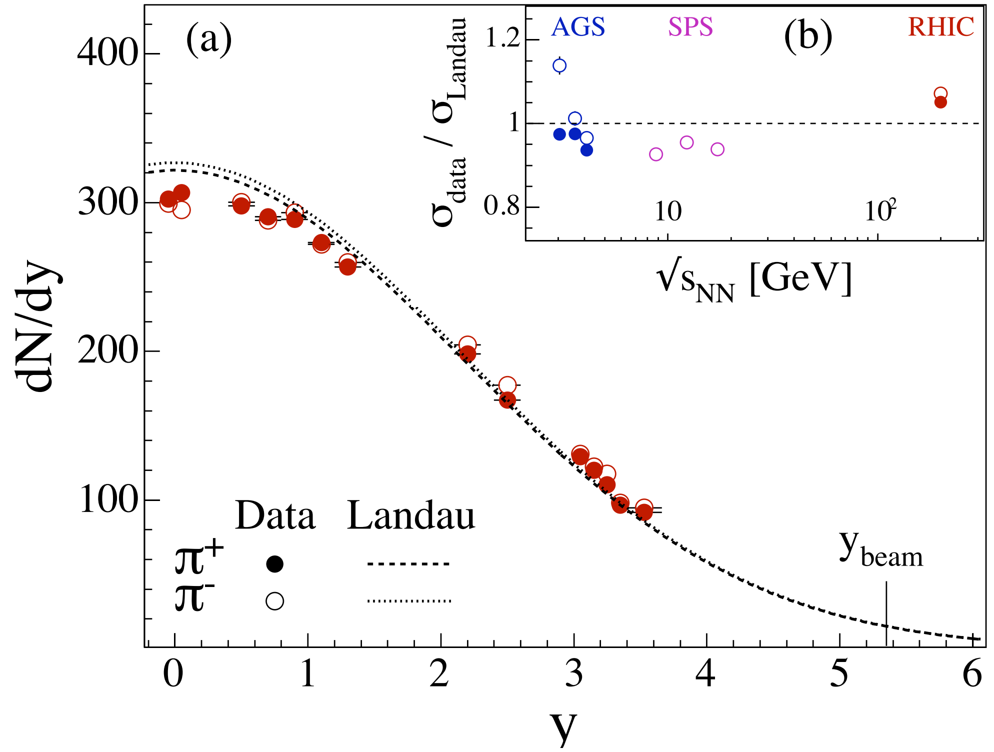
dN/dy has no plateau, width follows prediction from Landau (1955)

$\sigma^2 = \frac{1}{2}\ln(s/m^2)$

Which side are you on?

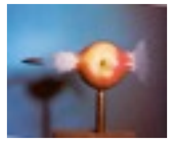


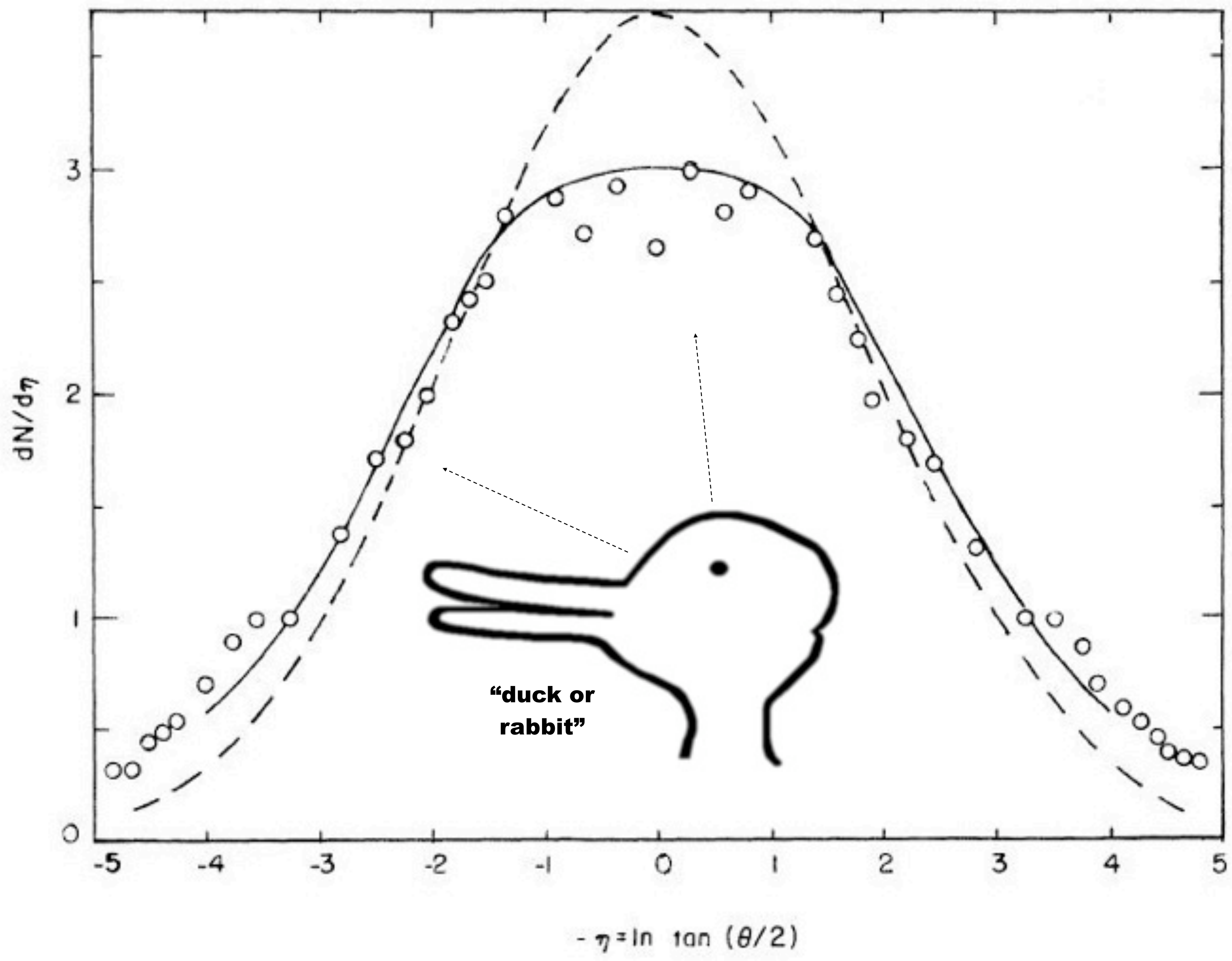




The “same” data (dN/dy or dN/d**η**) is used to defend both stories!
and BRAHMS and PHOBOS are used to defend the opposite
of what their respective experiments promote in papers...

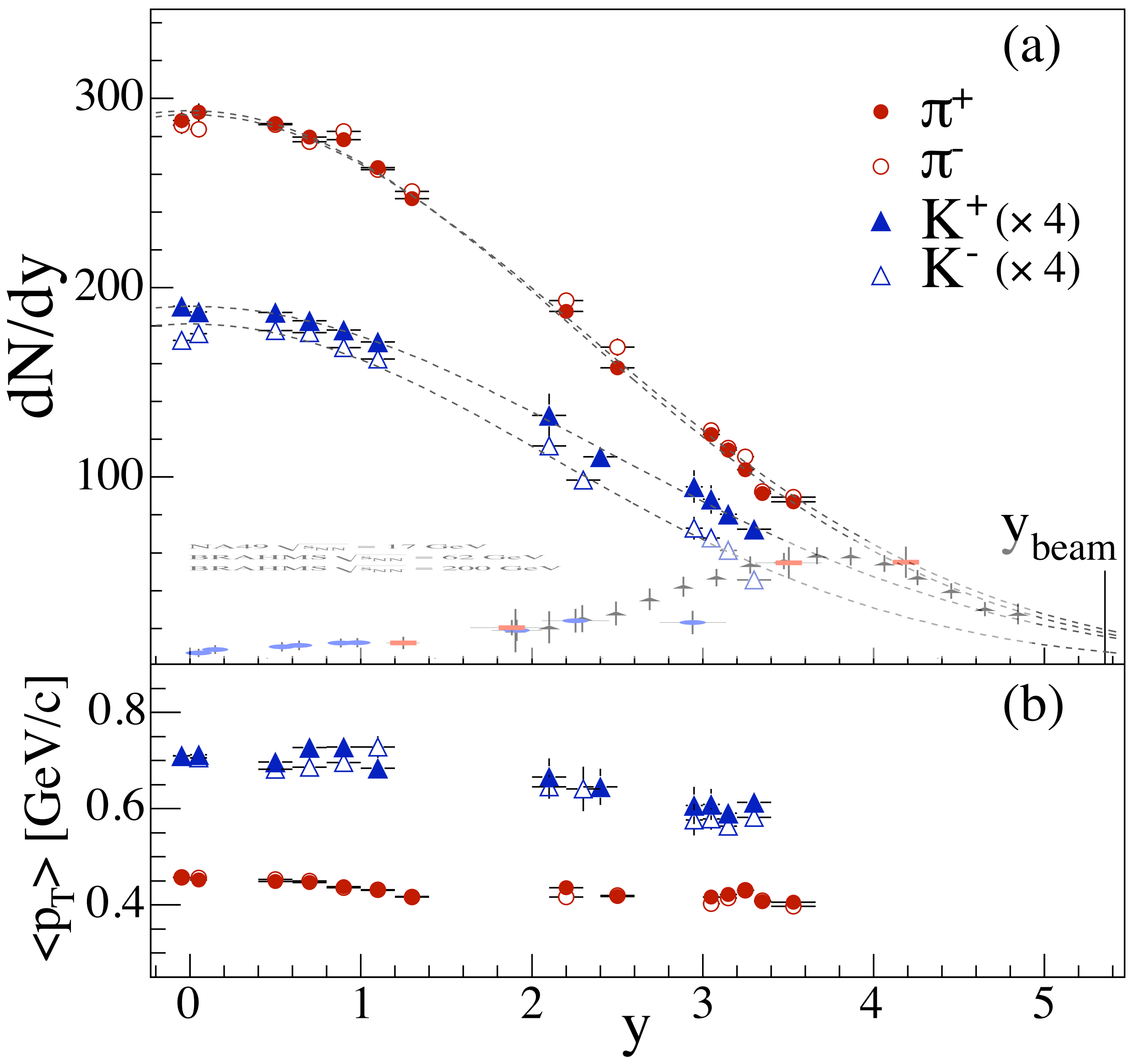
A recurring situation (Carruthers 1975)





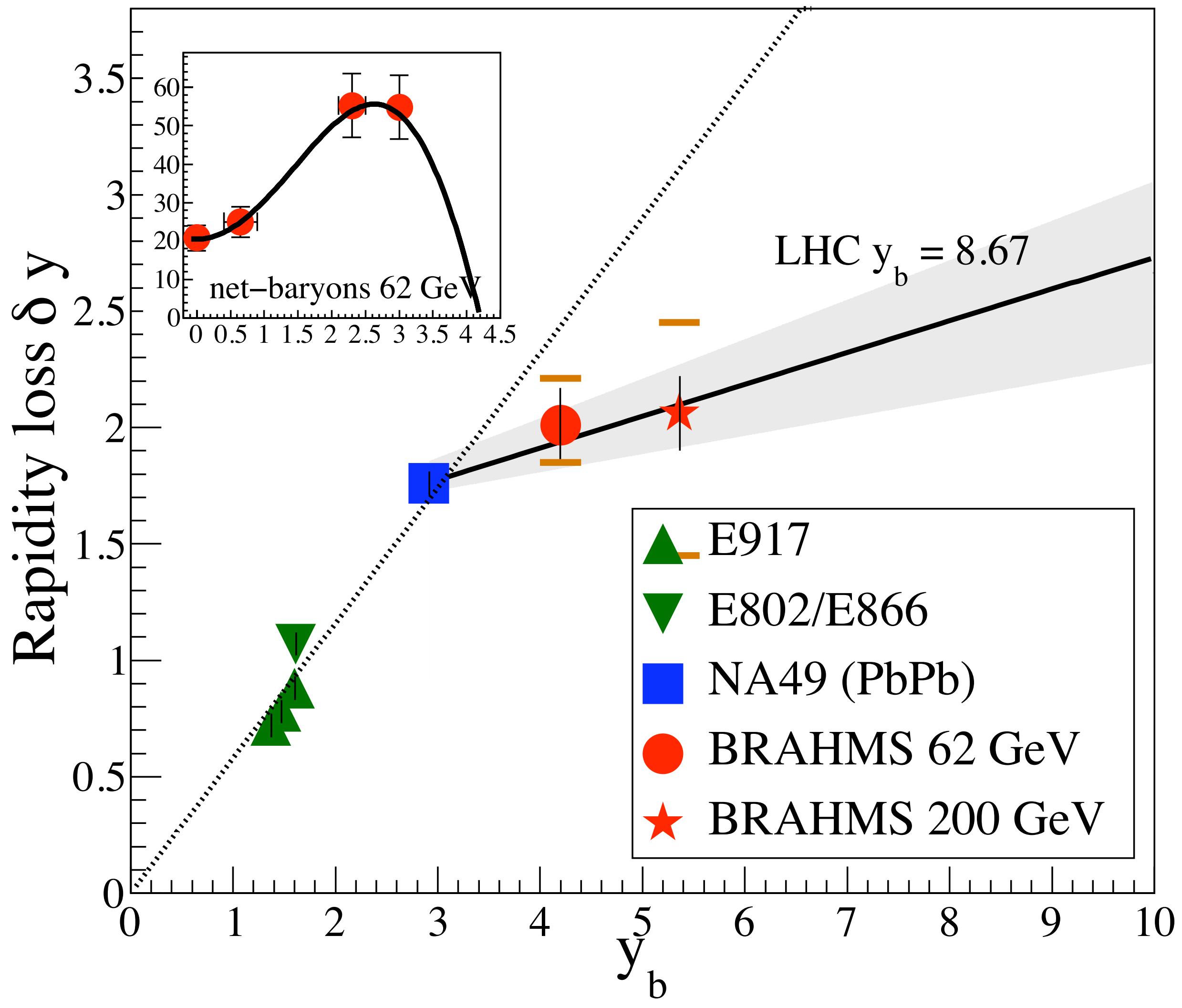
Putting the baryons back

- **Neither Bjorken nor Landau tell us <u>how</u> baryons stop**
  - “Something happens” and energy is deposited in the collision zone
- **Bjorken better fit to “standard” stopping scenario**
  - Partially-stopped nuclei end up in the fragmentation region and can be ignored
- **Complete stopping <u>seems</u> at odds with BRAHMS data**
  - Why would pions/kaons and protons be so different if all come from “stopped” energy

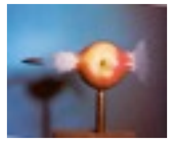


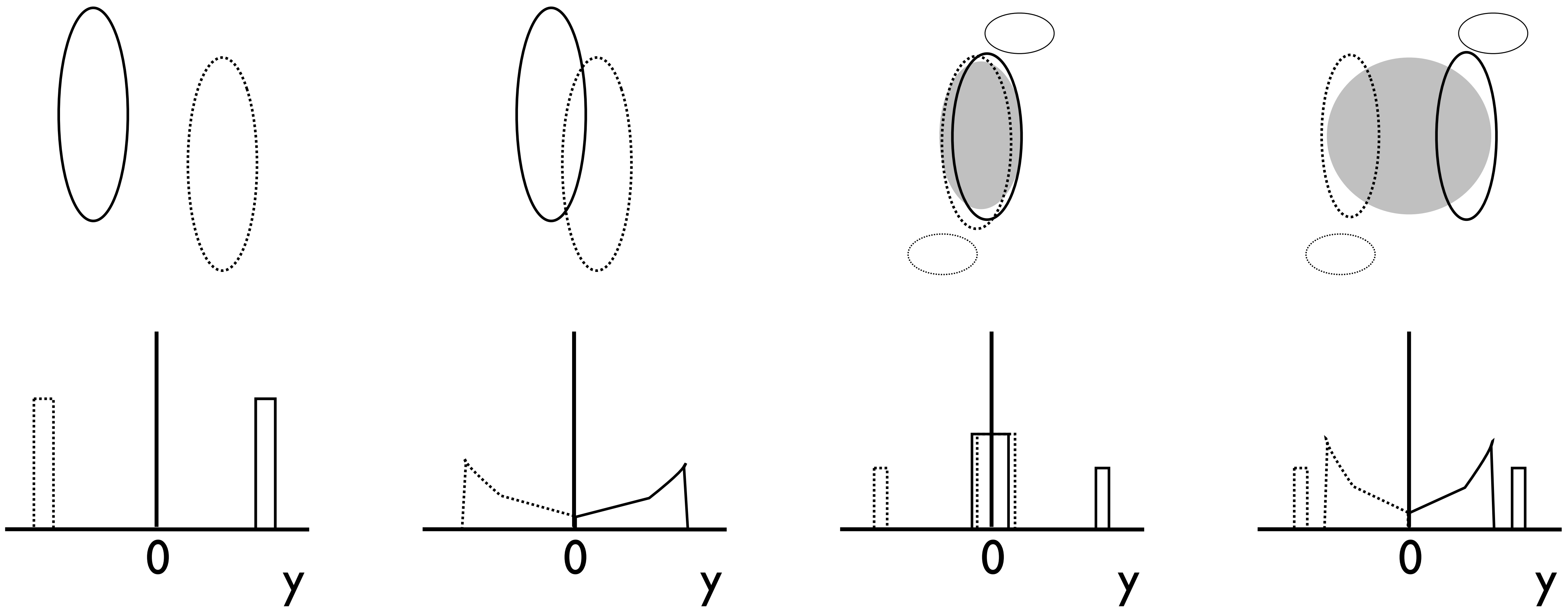
Where do the baryons go?

- **The “standard” stopping scenario takes a reasonable approach**
  - (1) Each baryon loses energy in the oncoming nucleus
  - (2) Baryons then <u>decouples</u> from the subsequent longitudinal evolution
- **However a baryon strongly-coupled to expanding fluid can *reaccelerate***
  - If this is the case, then the standard scenario is not measuring energy loss at all
- **The net baryon dN/dy is then measuring <u>net</u> rapidity loss**
  - If so, then baryons <u>decoupled</u> from entropy!



“Fireball Sandwich” scenario





1. Incoming nuclei (beam rapidities)

2. First collision: partial stopping of baryons

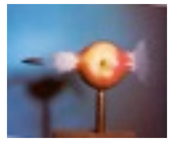
3. Second collisions: full baryon stopping, displaced centroids, thermalization (spectators decouple)

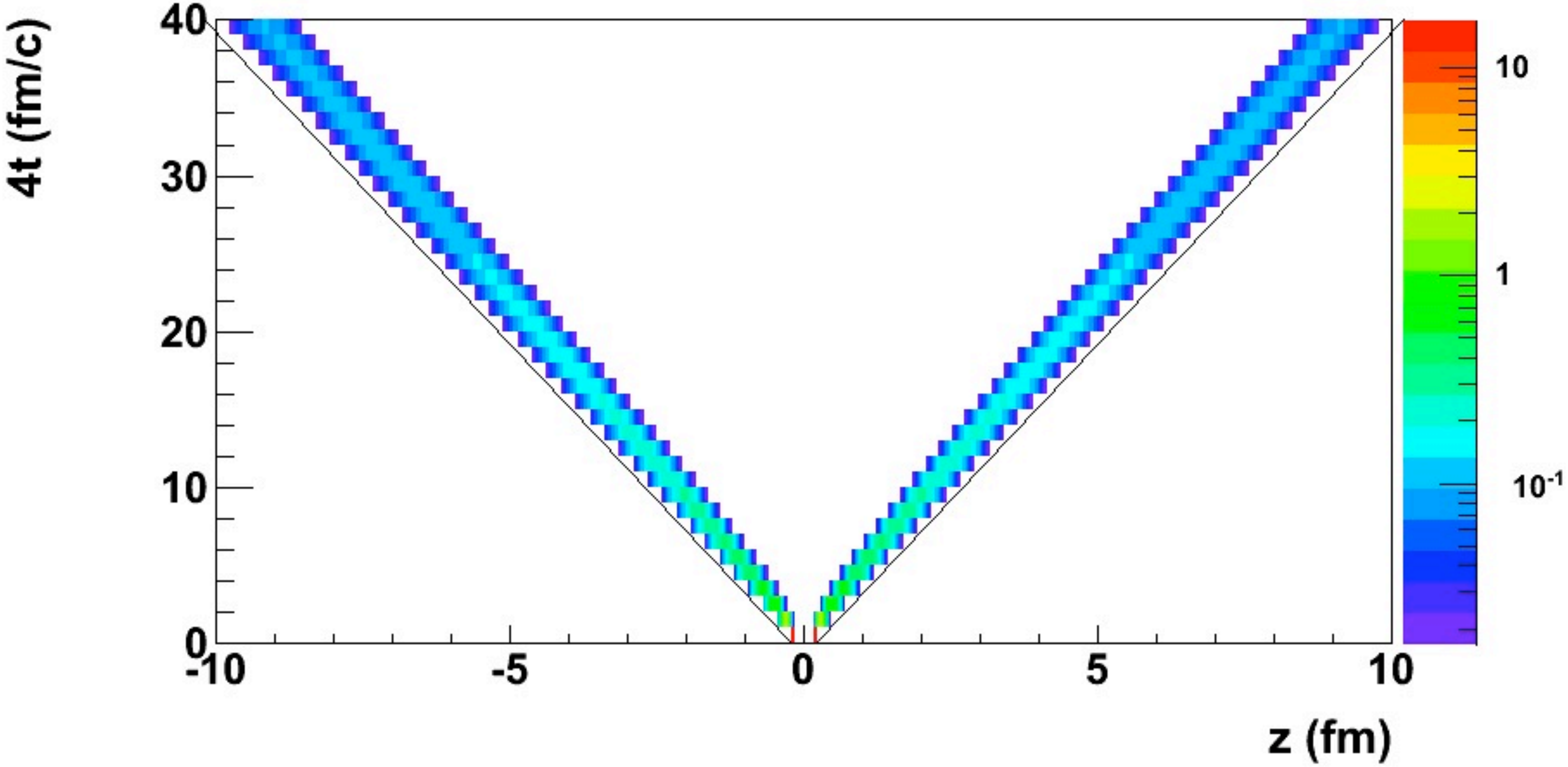
4. Longitudinal expansion of matter, baryons reaccelerated

baryons outside, fireball inside

entropy produced <u>by now</u>!

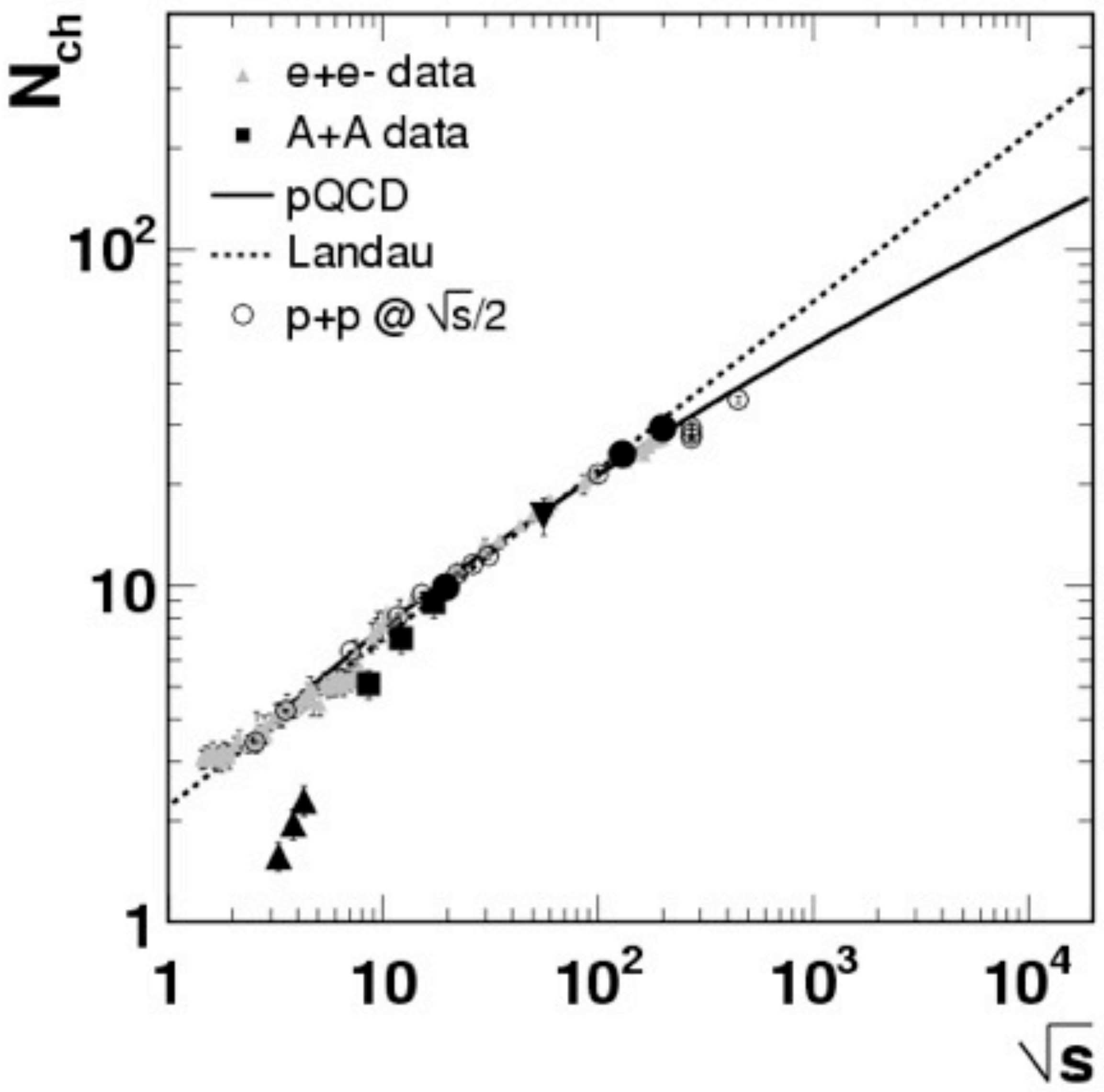
Try this in 1D hydro

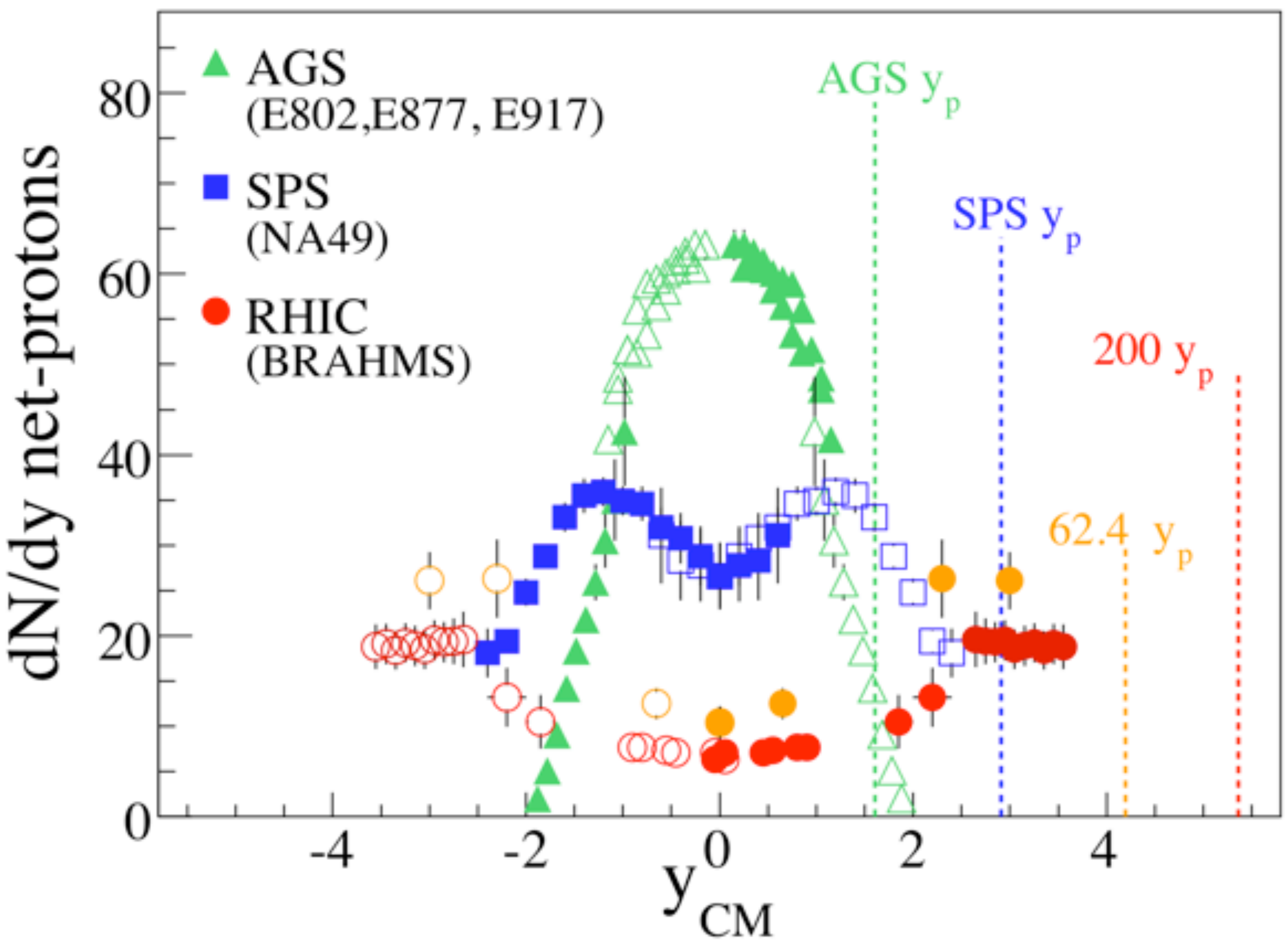




1+1D hydro from A. Dumitru, baryons from rest are accelerated!

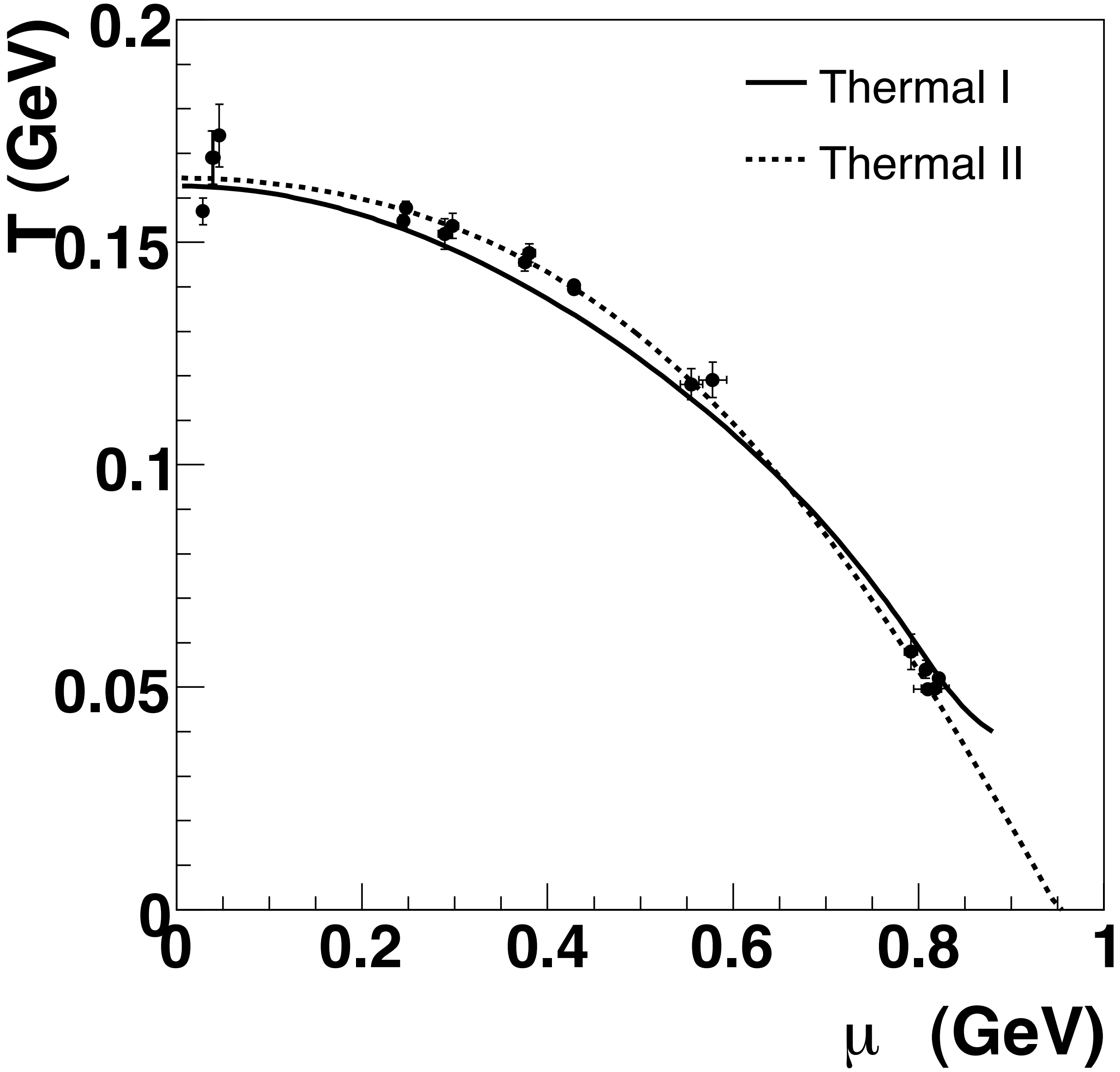
One last thing: How do net-baryons affect entropy?



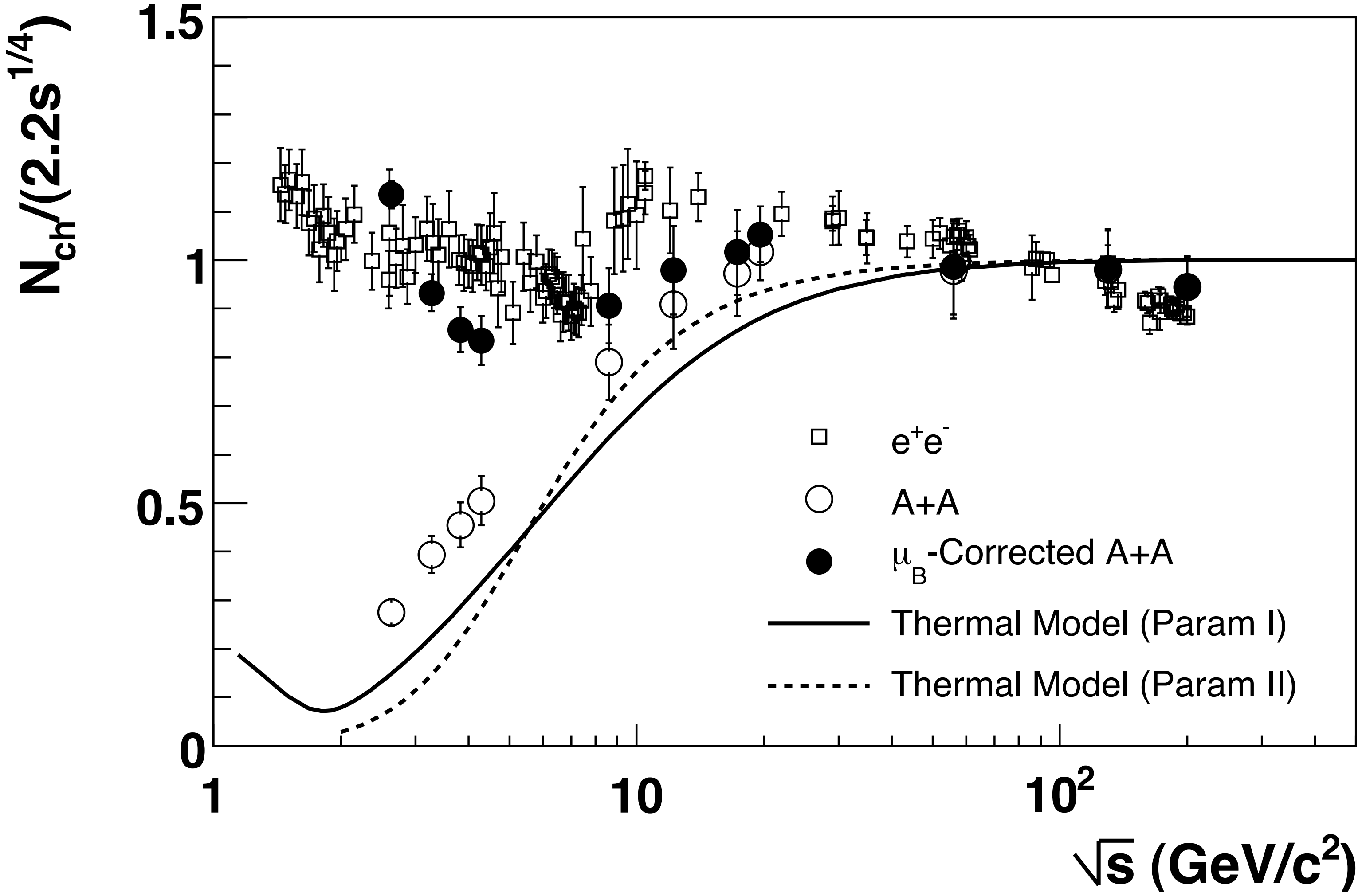


“Deviation” of multiplicity at low energy correlates with “pileup” of baryons

Thermal models at high μ_B



Cleymans, Wheaton, Stankiewicz, PAS, et al, nucl-th/0506027



Fits give:

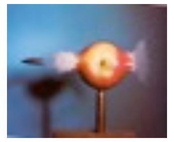
μ_B & T vs. $\sqrt{s}$

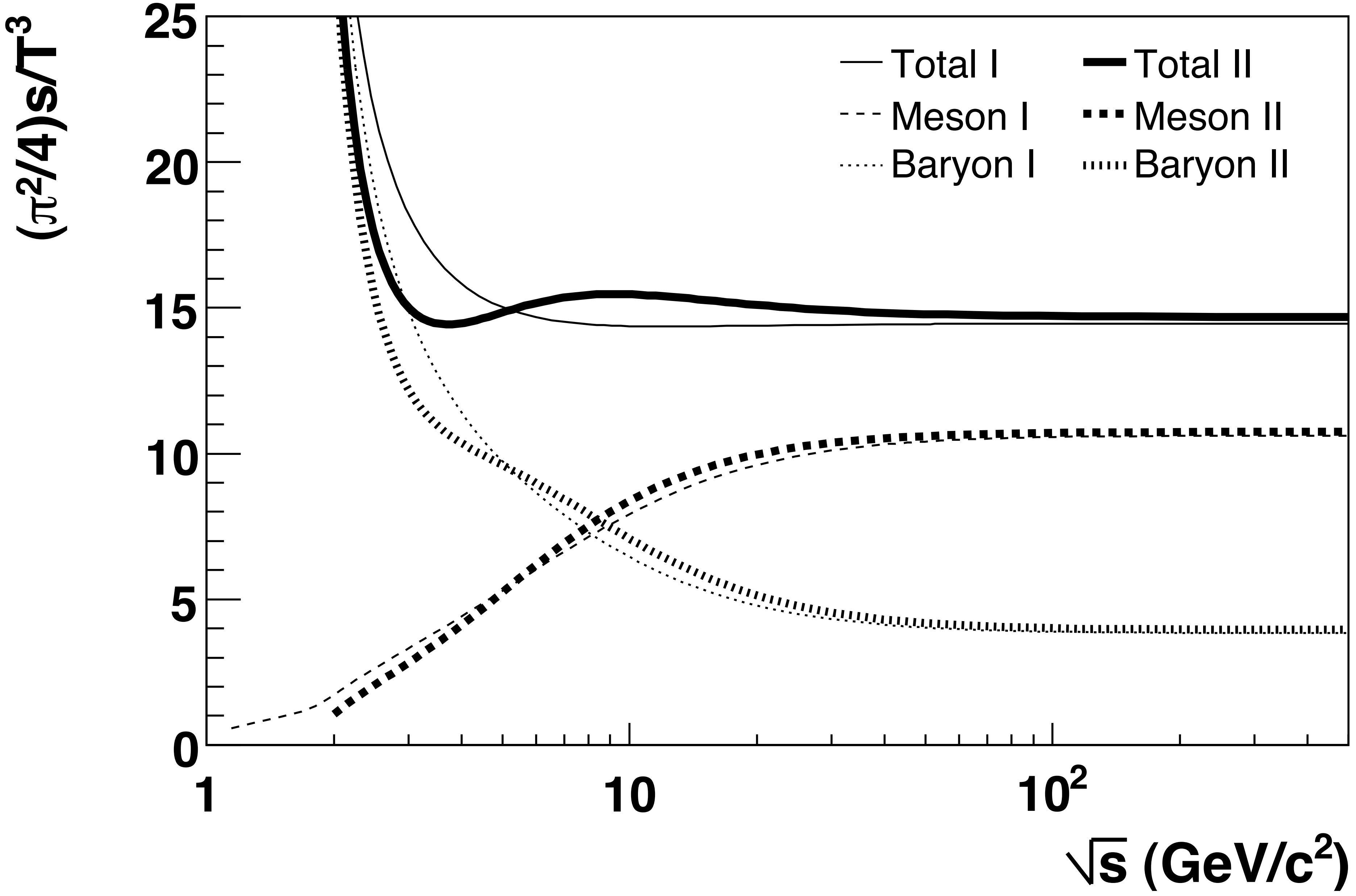
$$\mu_B(\sqrt{s}) = \frac{1.2735}{(1 + 0.2576\sqrt{s})}$$

$$\frac{s(T, \mu_B)}{s(T = T_c, \mu_B = 0)}$$

Entropy is suppressed at high μ_B!

Same thermal model: nDOF is *constant*...





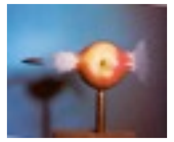
Despite all of the changes in the composition:

"baryon/meson"
"fermion/boson"
"matter/radiation"

the system decouples at same "nDOF" (s/T^3)!

what is this magic number?

Discussion points



- **Baryon stopping**
  - How is the energy released (not even discussed so far!)?
  - How much of it is released in the initial stages
  - do baryons decouple immediately from system, or can they be reaccelerated?
  - p+p vs. A+A: how does the leading particle effect work?
- **Entropy production**
  - How does the available energy turn into entropy (how do baryons affect this?)
  - What are the degrees of freedom in the early stages which determine entropy?
  - How good of an assumption is isentropic evolution (e.g. viscous effects?)
- **Bjorken vs. Landau is a good way of setting issues into relief**
  - Thermalization time is not just a number!

Rapidity Distributions in pQCD (QCD prefers Landau?)

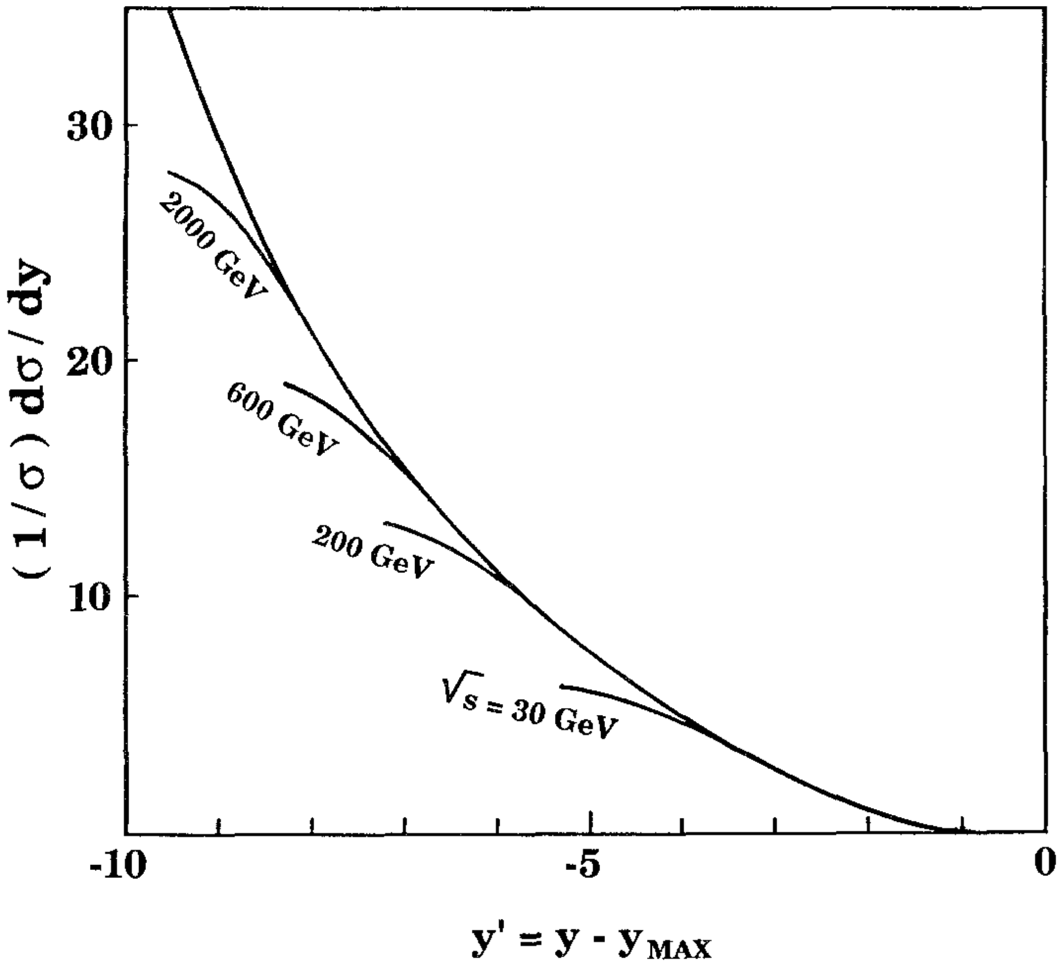


Fig. 1. The translational invariance. Except for the small rapidity region, the rapidity distribution is on the same universal curve (measured from y_{max})

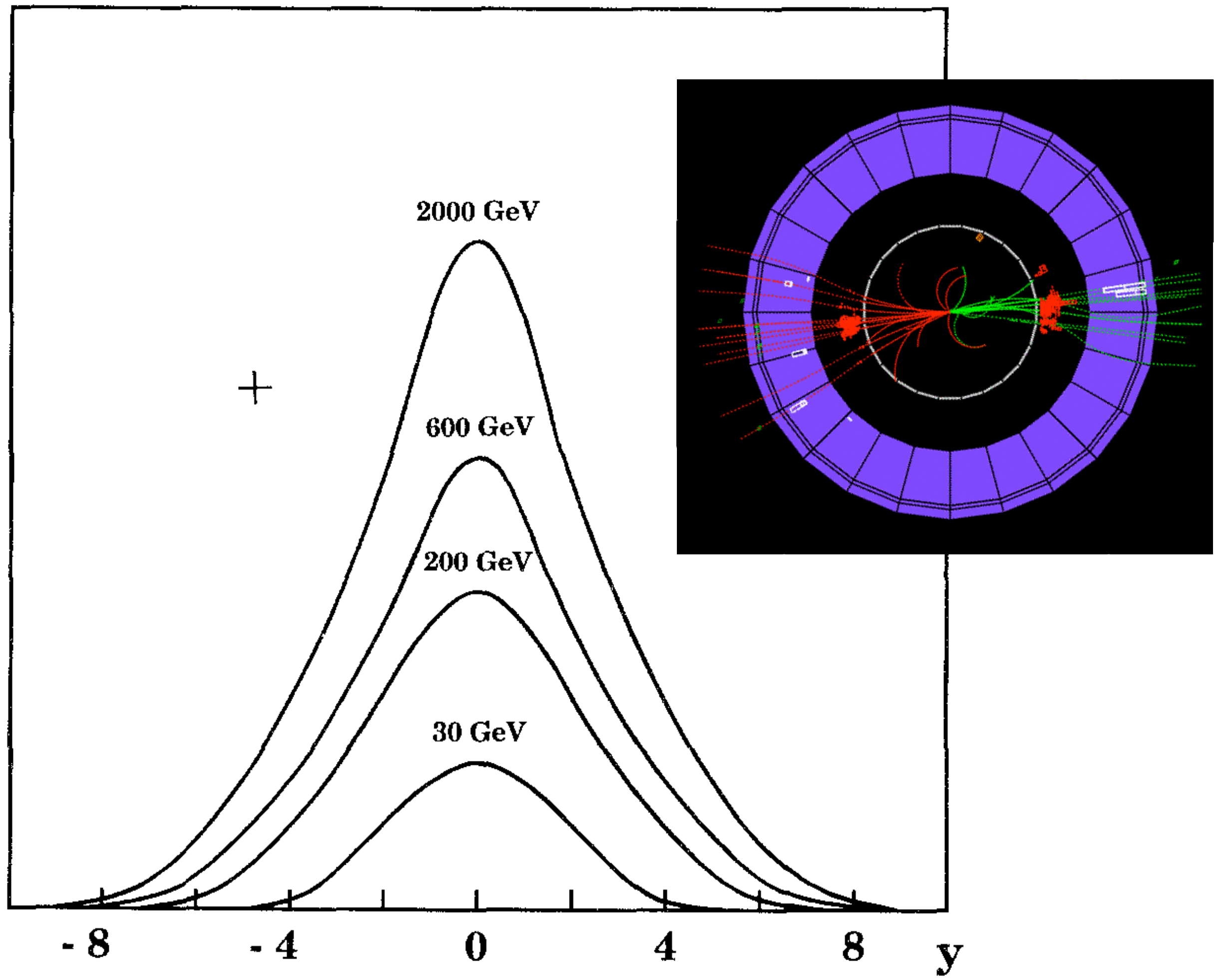


Fig. 2. The rapidity distribution at high energies. The height grows faster than the width, and there is no widening central plateau

pQCD: Limiting fragmentation and $\boldsymbol{\sigma}^2=½\ln(s/m^2)$...what gives?