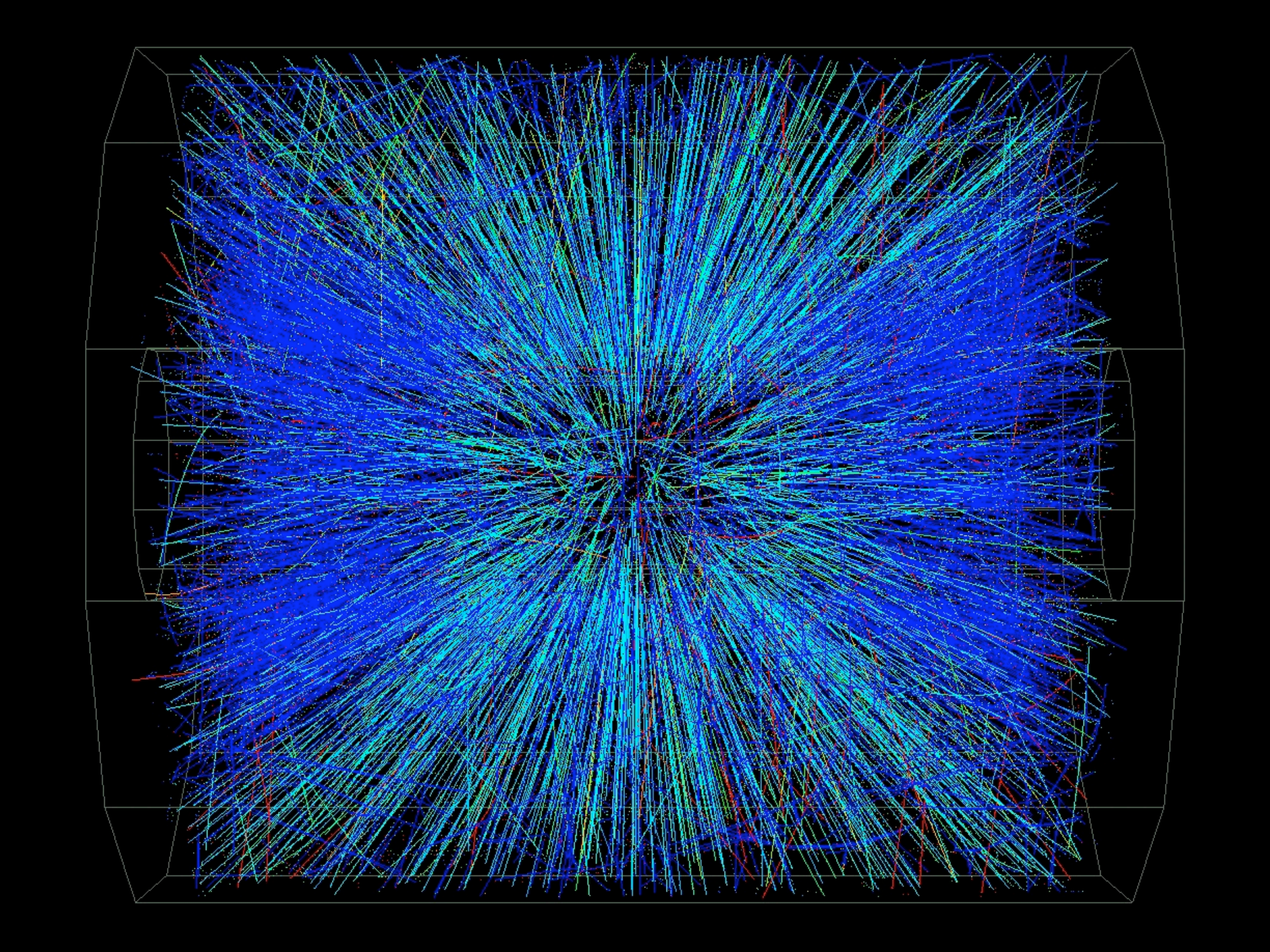
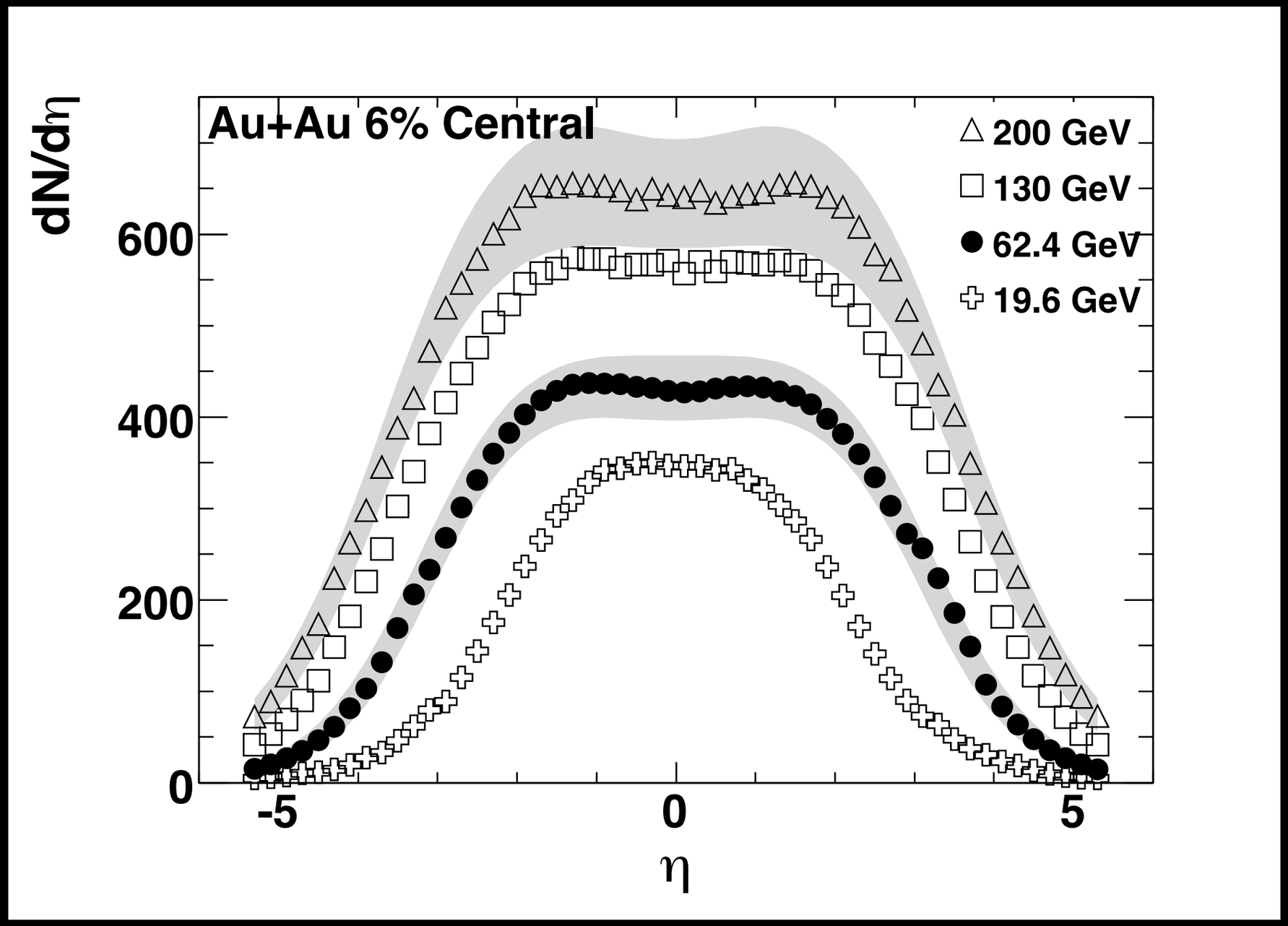
Multiplicity Systematics at high E and μ_B

Peter Steinberg
Brookhaven National Laboratory
“From High Energy to High μB” Workshop
RHIC/AGS Users’ Meeting
June 5, 2006



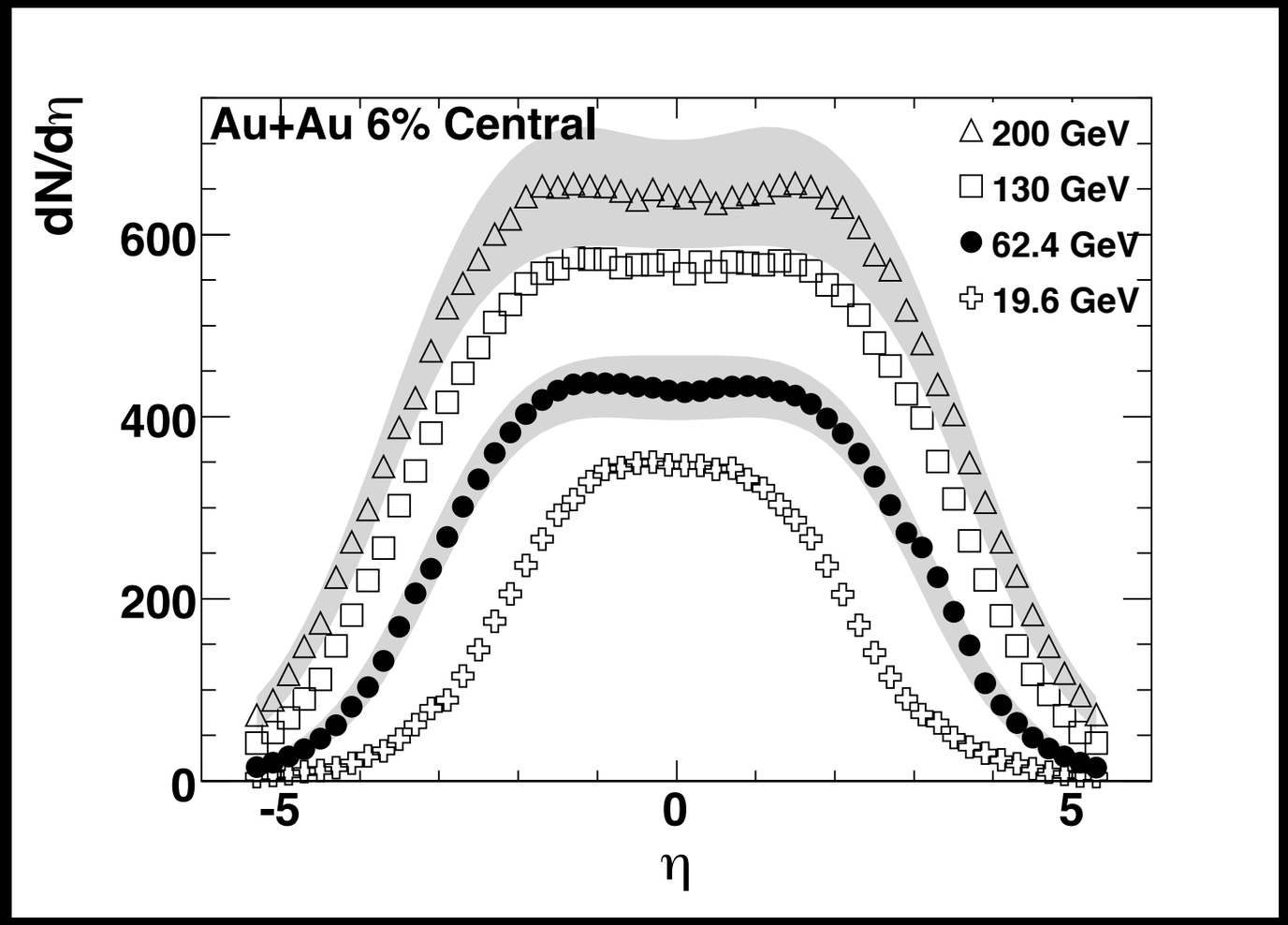
dN/dη vs. Beam Energy



RHIC has covered a lot of ground in 5 years of A+A

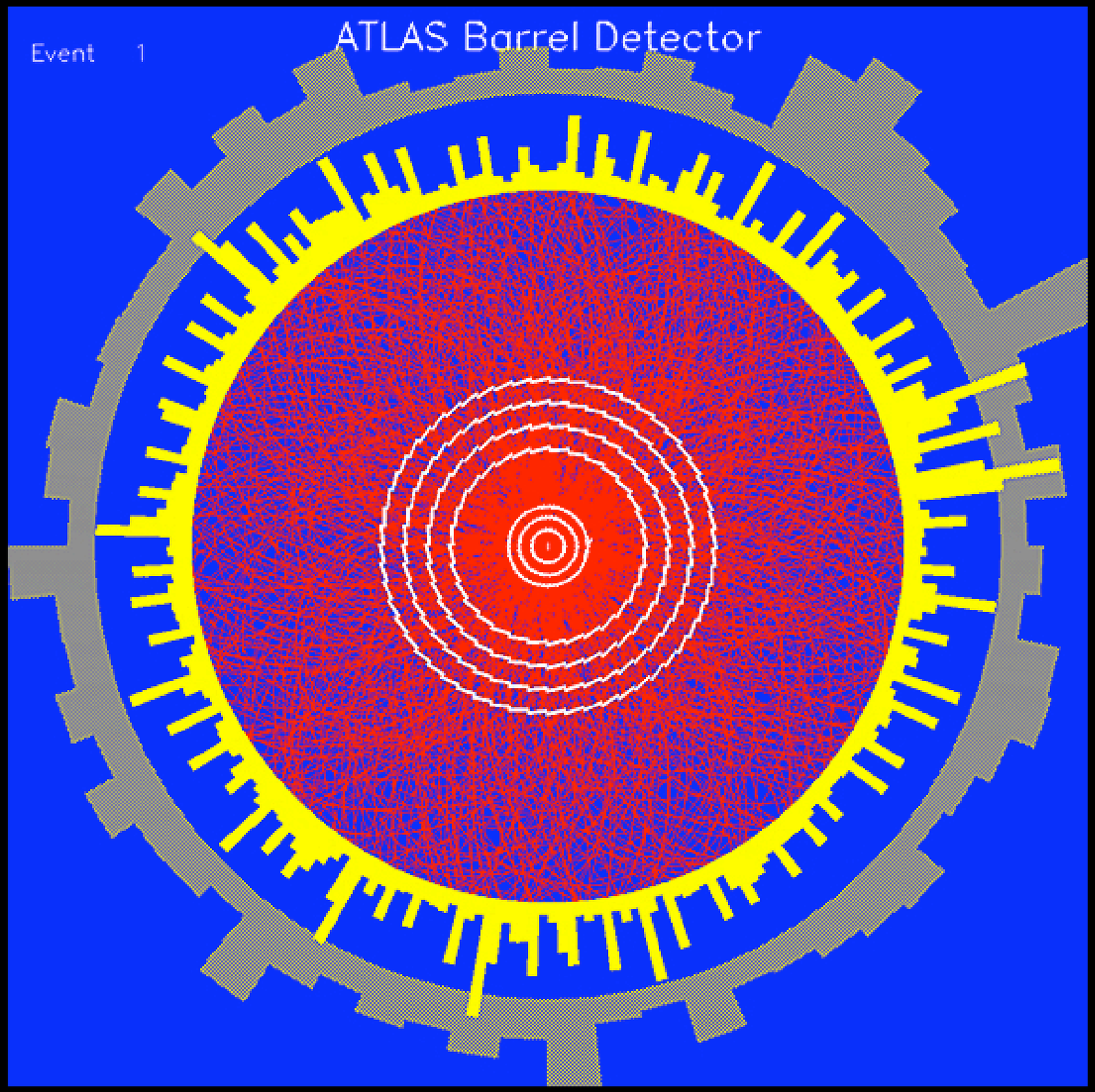
Scope of this talk

- N_{ch}
- $dN/d\eta|_{\eta=0}$
- $dN/d\eta$

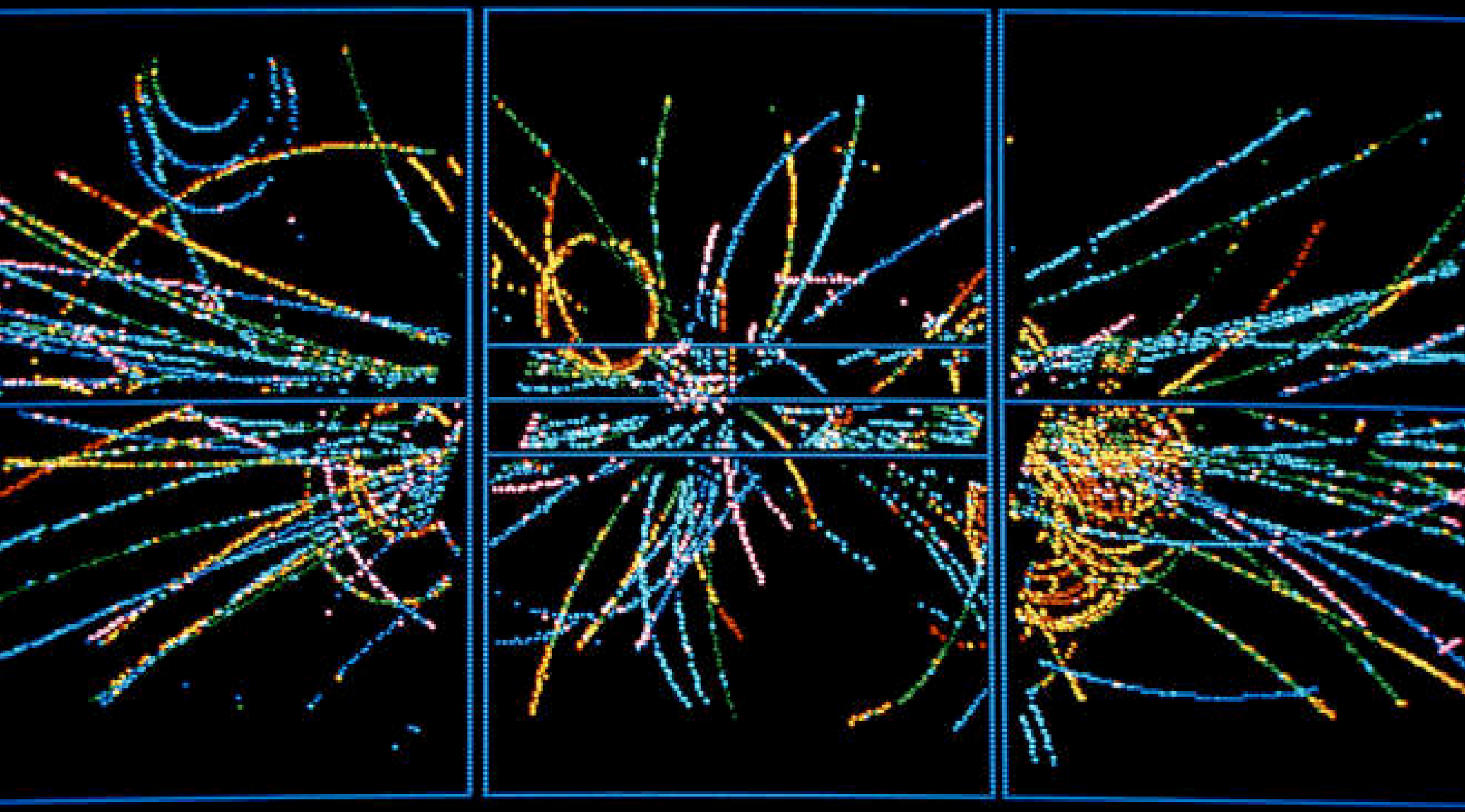


- **Some discussion of p_T distributions**

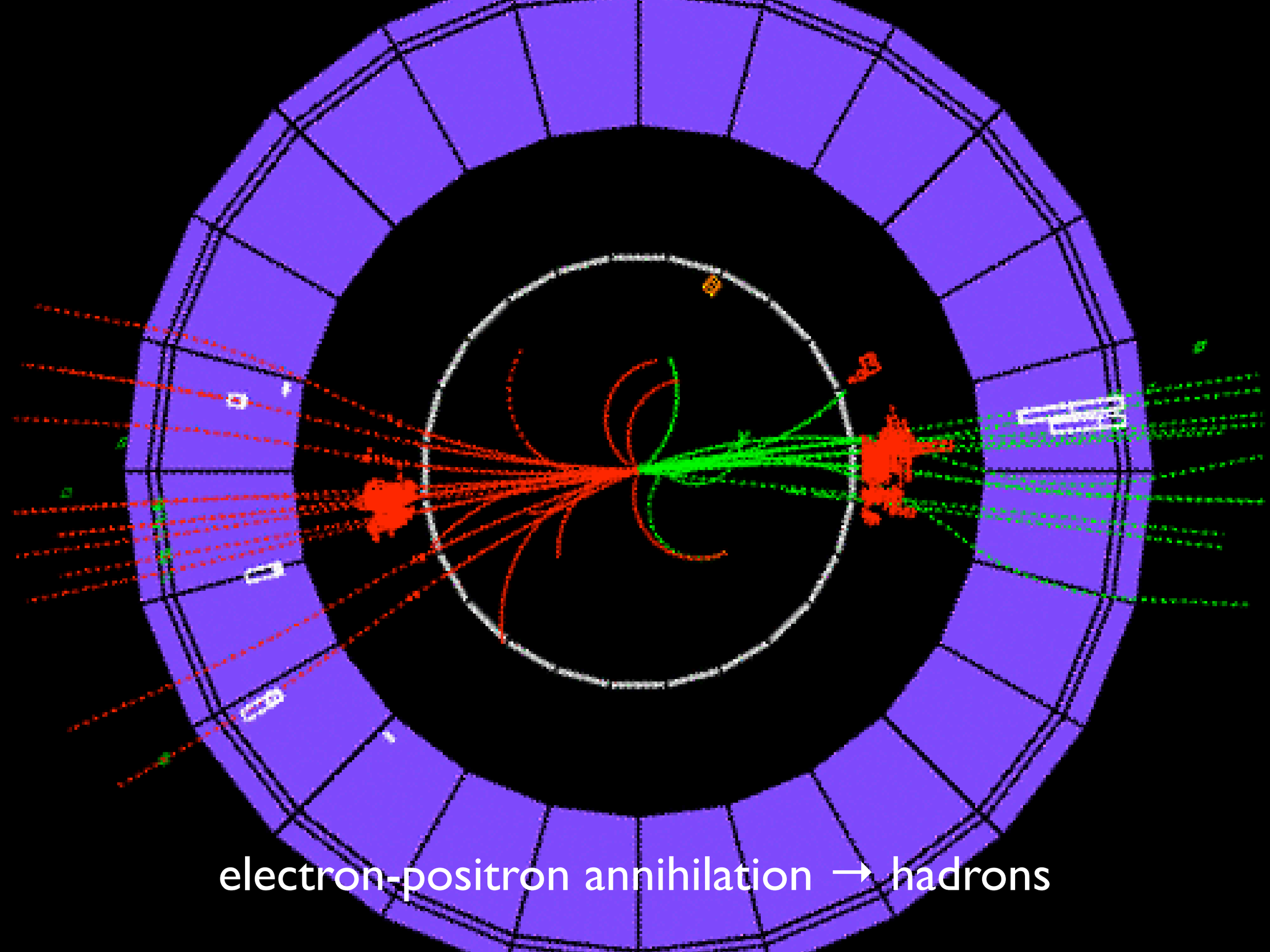
Hope to hear more in rest of this workshop!



What will the LHC look like? Only 2 years to go...



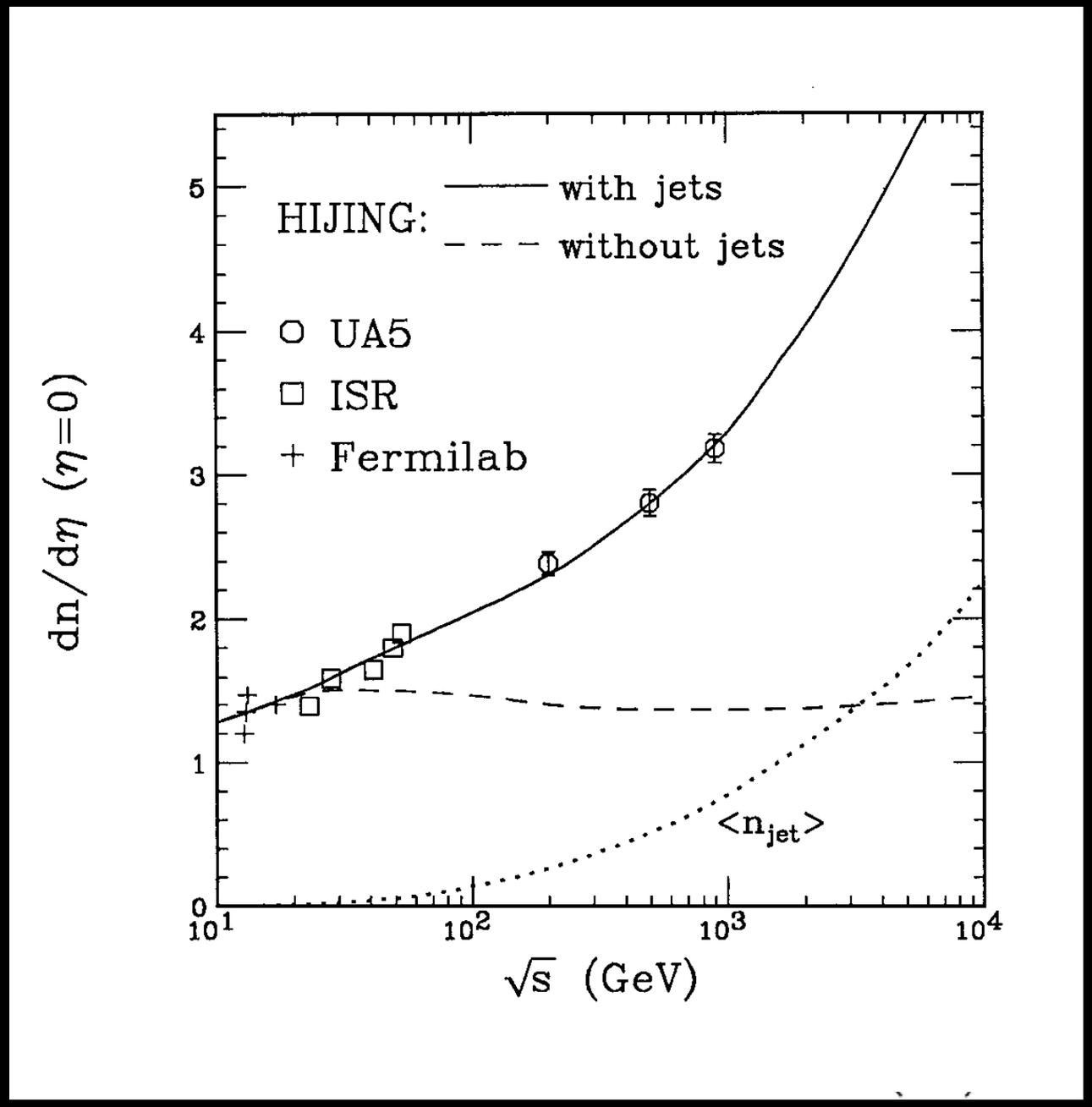
proton + (anti)proton collisions



electron-positron annihilation → hadrons

Modelling p+p

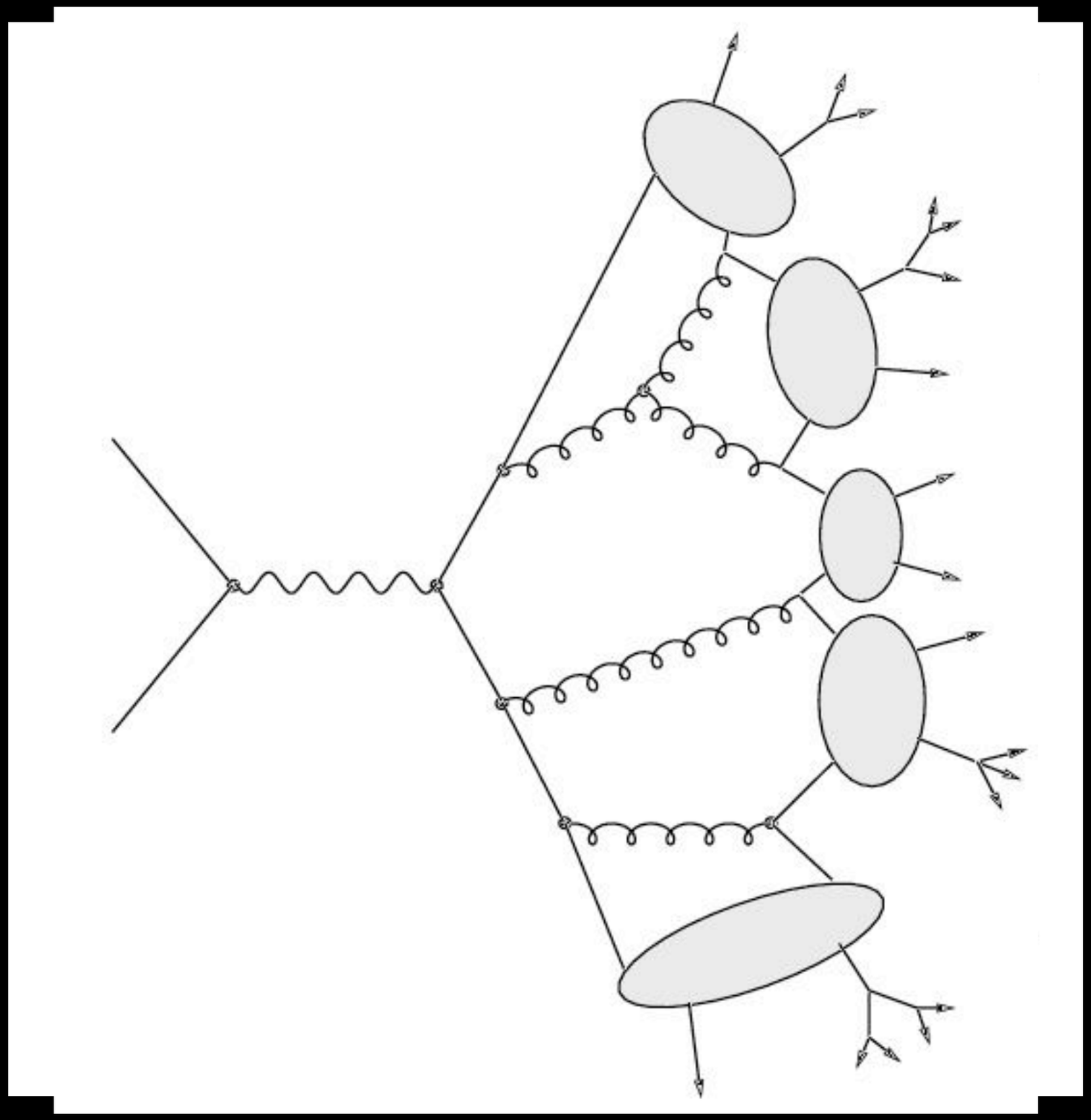
- **Obviously a huge subject**
- **Two component picture**
  - Parametrize soft component
  - PDFs & pQCD model hard component
  - pQCD evolution controls hard part
- **Various implementations**
  - PYTHIA, HERWIG, PHOJET, HIJING
  - Very different evolution



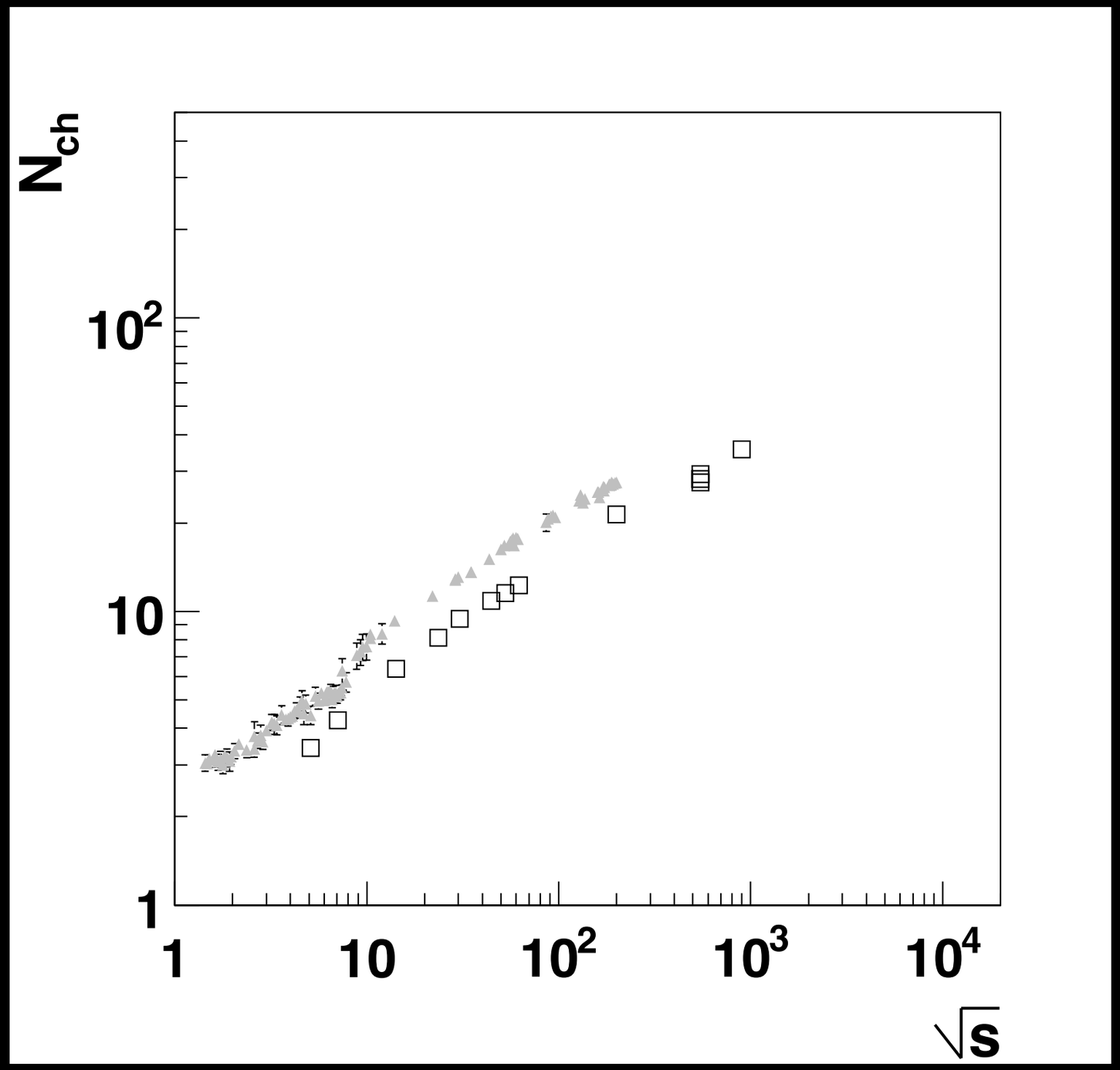
I. Dawson, ATLAS

Modelling e+e-

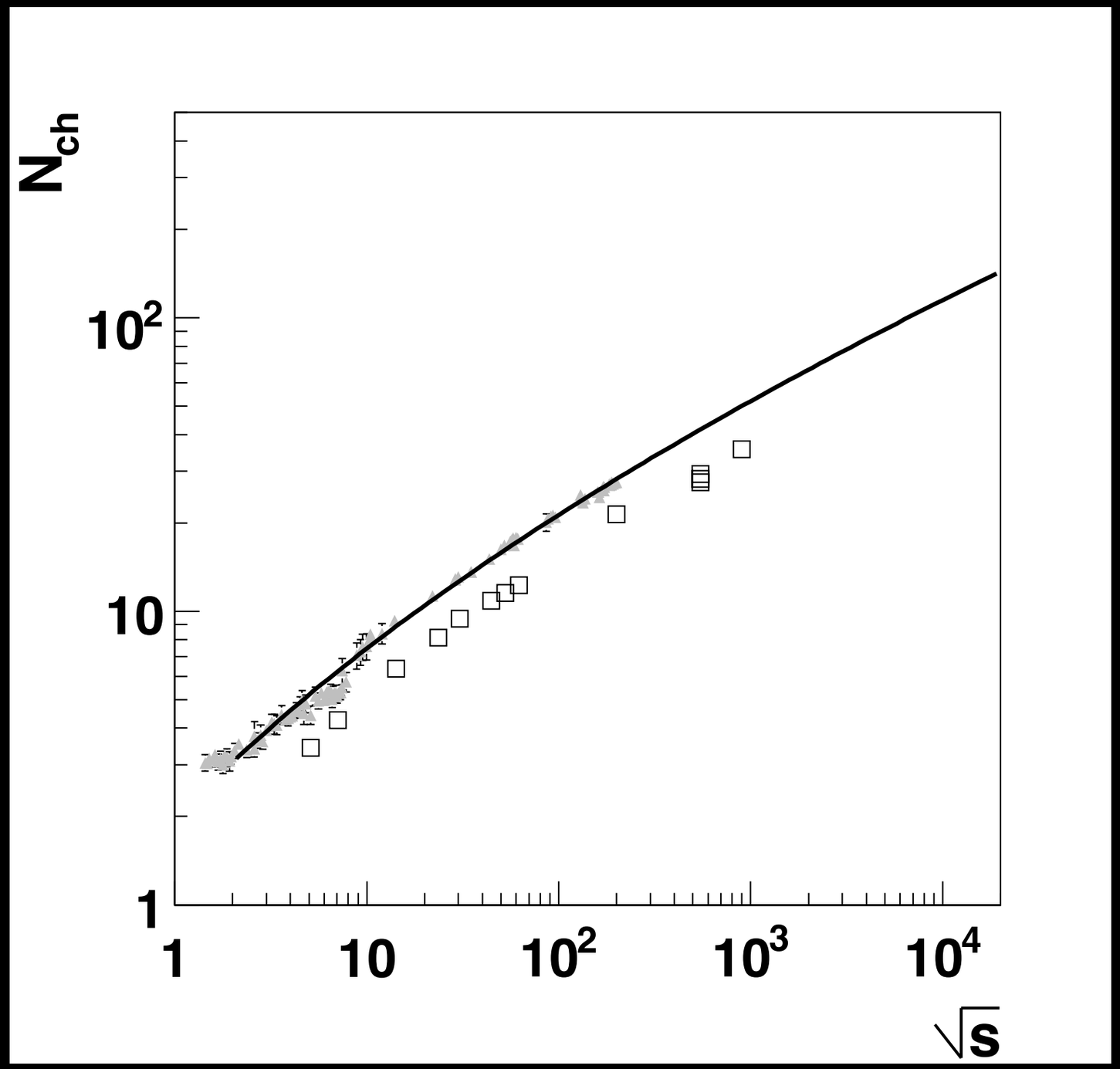
- **An equally huge subject**
- **Two common approaches**
  - String model → Parton showers
  - Resummed pQCD calculations (MLLA)
- **Effectively one-component**
  - Entire system is hadronized
  - pQCD evolution is <u>primary</u> dynamical component of the total multiplicity



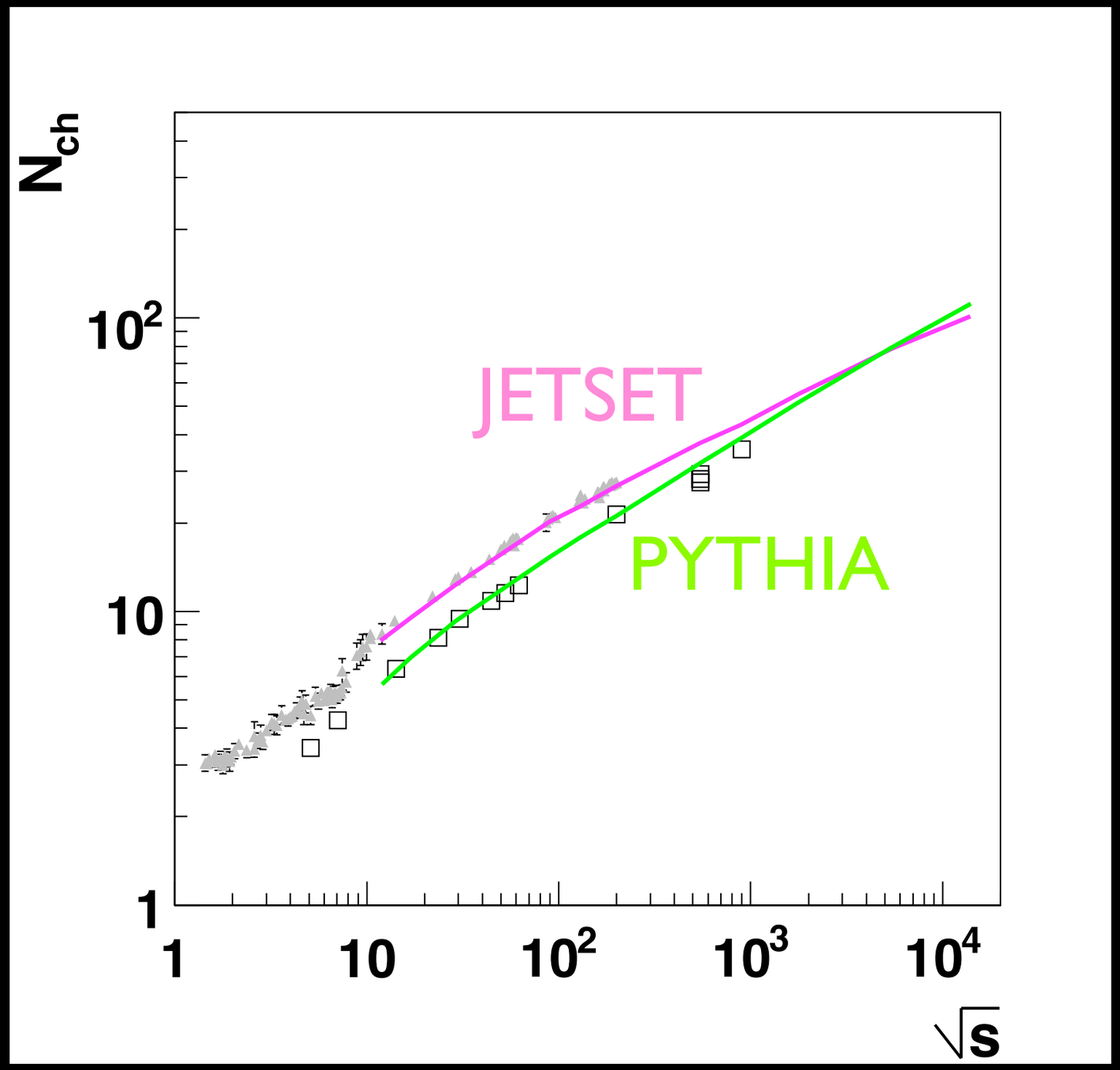
Raw Data on N_{ch}



pQCD

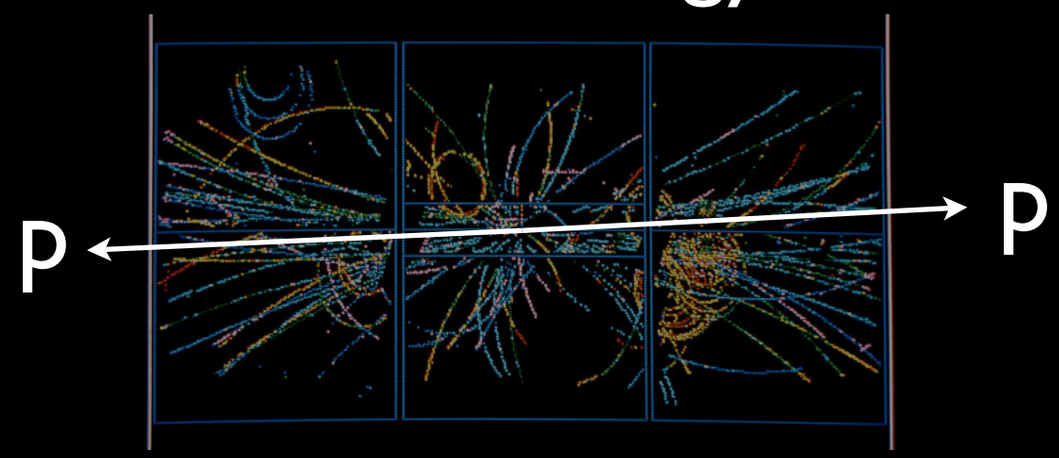


JETSET & PYTHIA



The Leading Effect

"leading" particles "keep" an arbitrary fraction of the initial energy

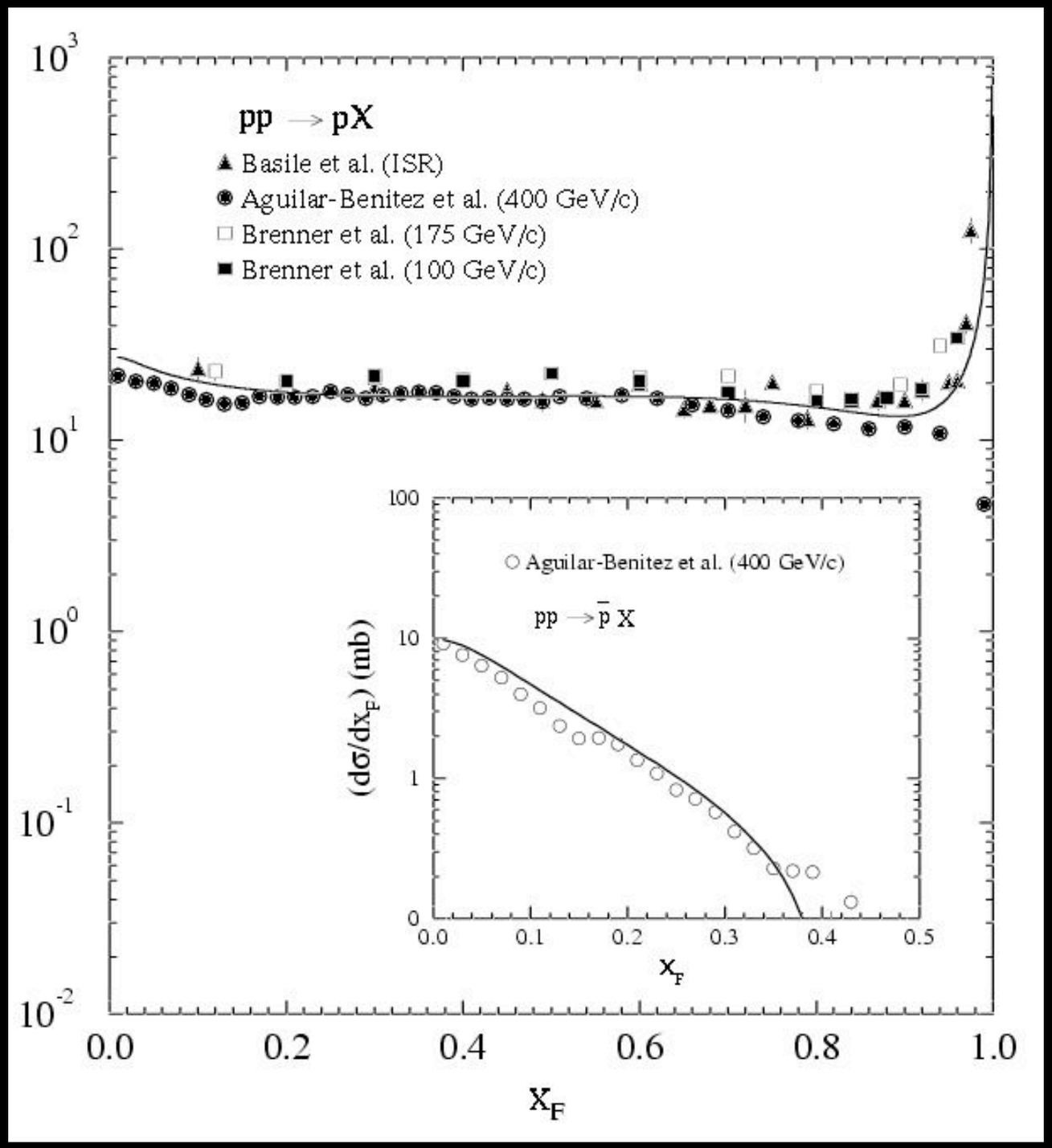


Flat probability distribution:

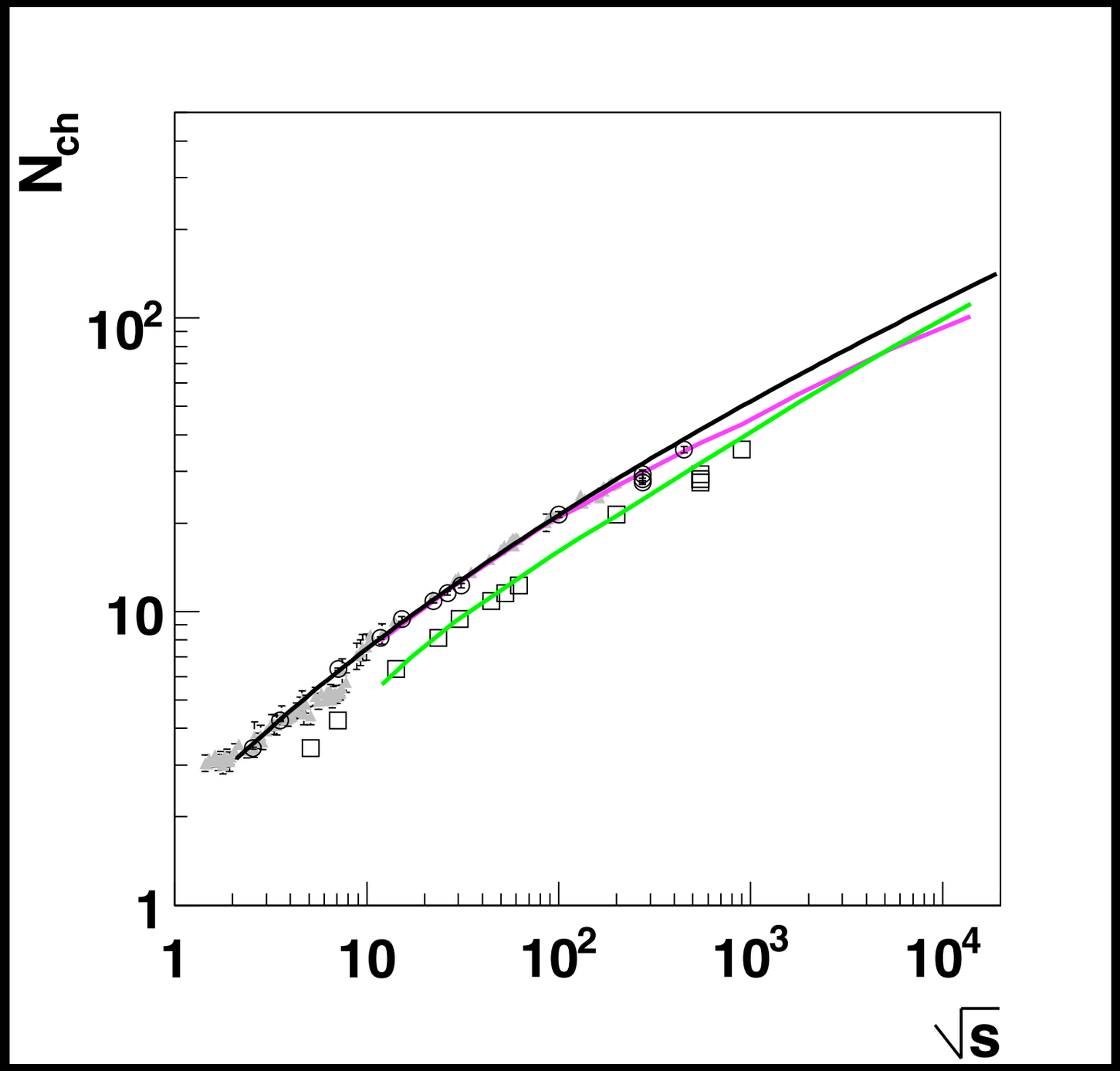
$$x_F = \frac{2p_z}{\sqrt{s}} \qquad \langle x_F \rangle \sim 1/2$$

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

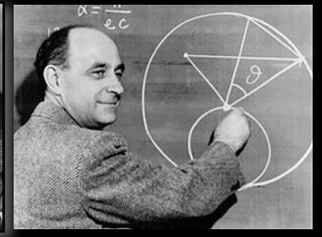
"effective energy"
(a la Basile et al)



Correct Leading Effect



One more thing...



Fermi-Landau Model

$$E = \sqrt{s_{NN}}$$

Total Energy

$$V = \frac{V_0}{\sqrt{s_{NN}}/2m_N}$$

Total Volume

$$\epsilon = \frac{s}{2m_N V_0}$$

Energy Density E/V
(>3 TeV/fm^3 @ RHIC!)

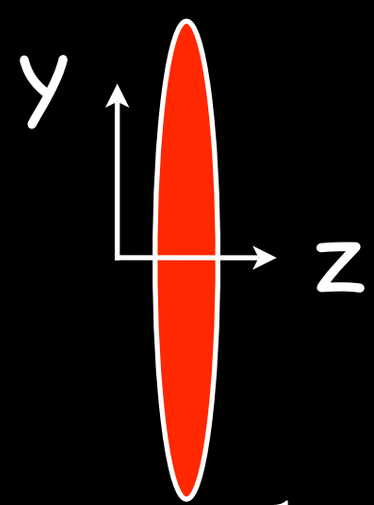
$$p = \frac{1}{3}\epsilon \Rightarrow \sigma \propto \epsilon^{3/4}$$

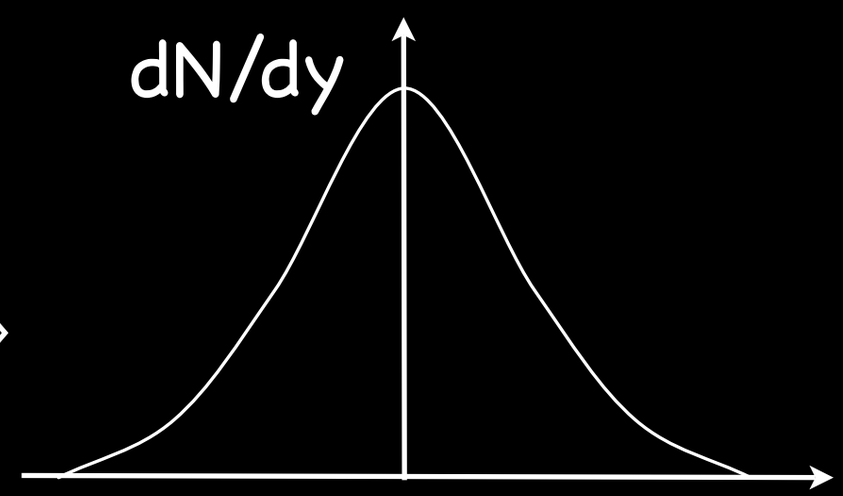
Cooper, Frye, Schonberg (1975)

$$N_\pi \propto E_{\text{c.m.}}{}^a, \quad \frac{1 - c_0{}^2}{1 + c_0{}^2} = a\,.$$

Energy + Volume + Blackbody thermodynamics

Longitudinal Flow

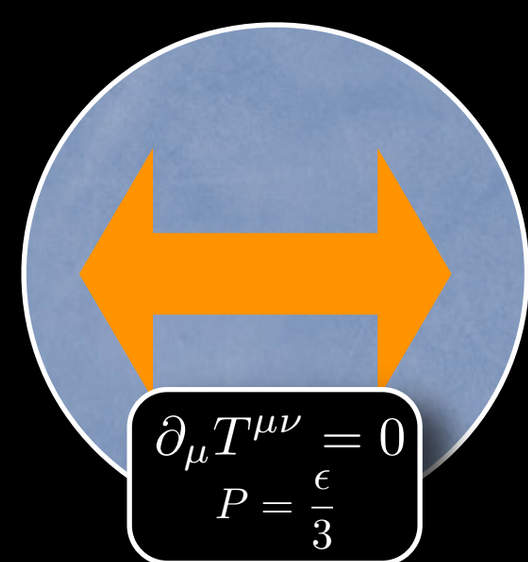


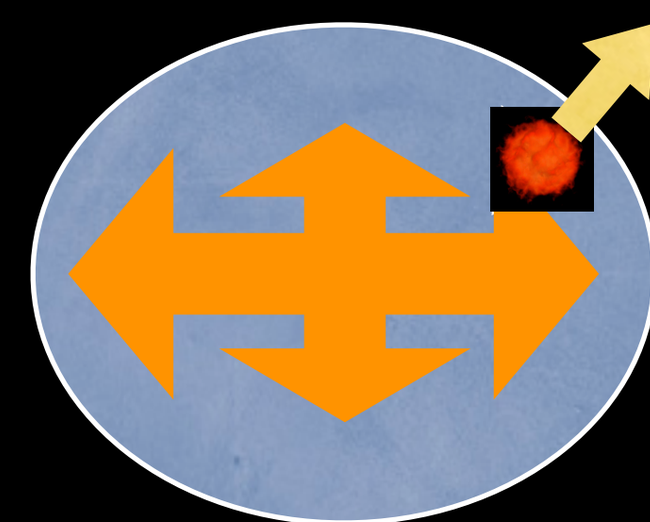


$$\Delta z \sim \frac{1}{\sqrt{s}}$$

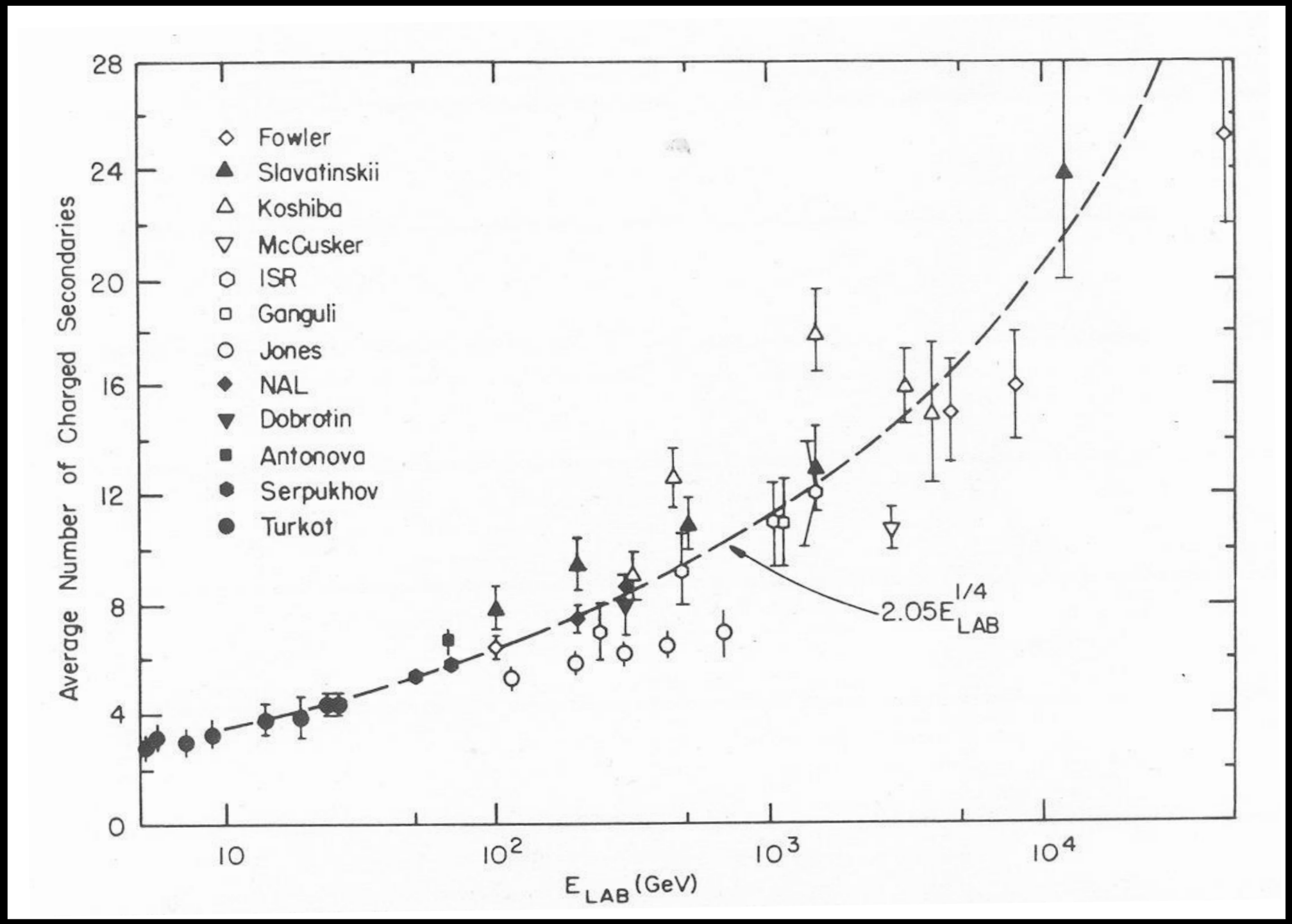
$$\sigma_y = \sqrt{\frac{1}{2}\ln\left(\frac{s}{4M_P^2}\right)}$$

1955: Landau solves "Relativistic Hydrodynamics" in <u>full 3D</u>

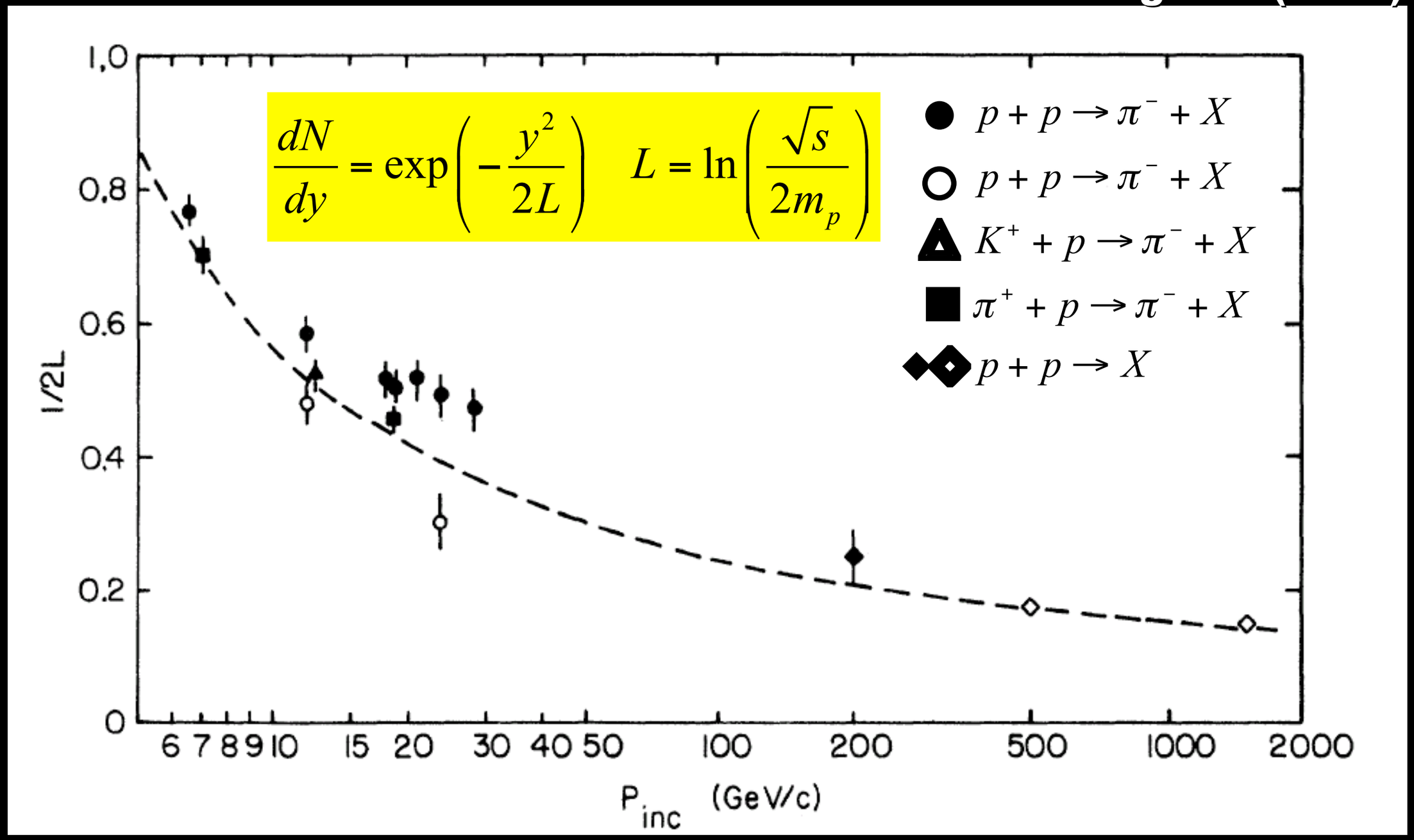


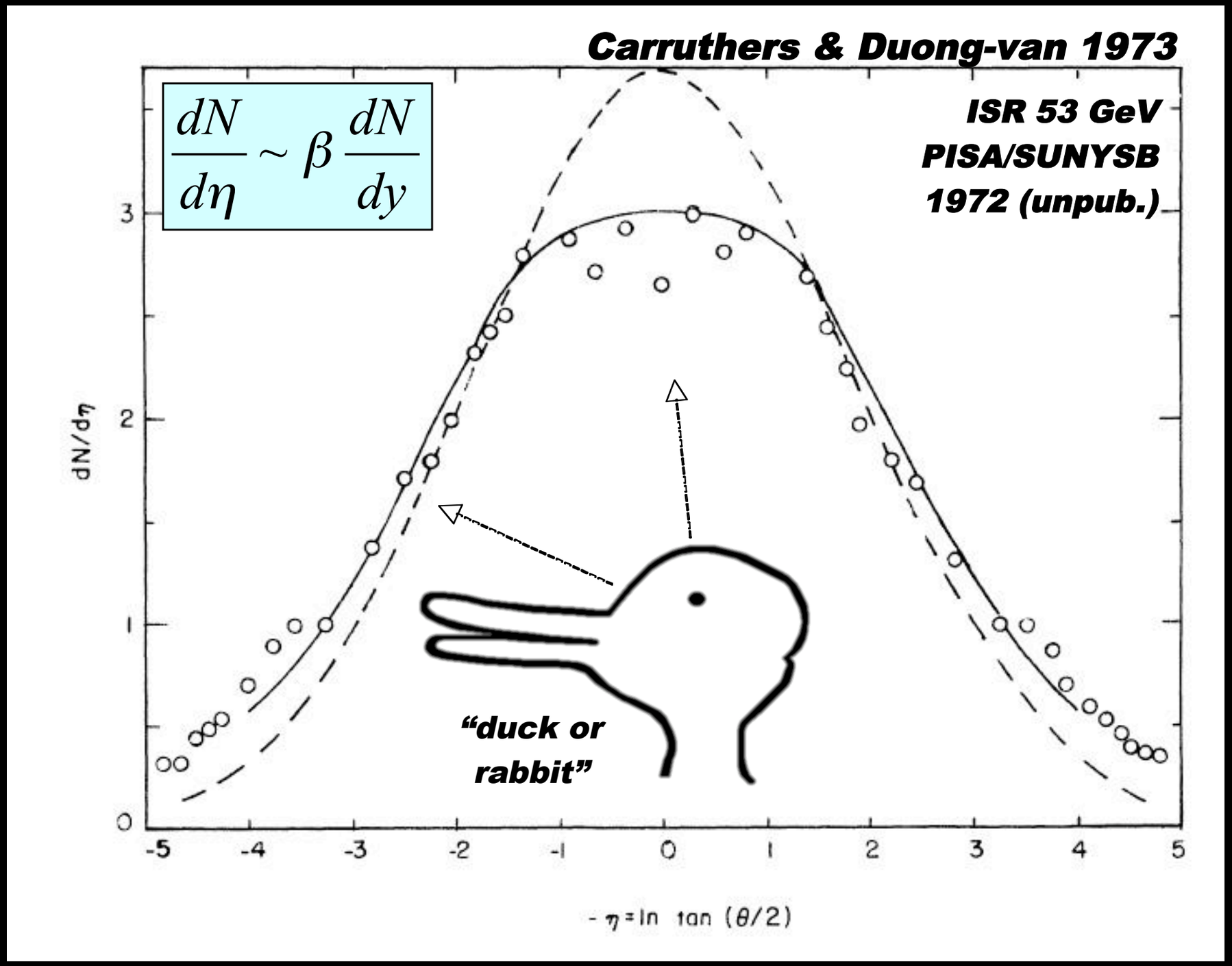


Carruthers 1973



Carruthers & Duong-Van (1973)

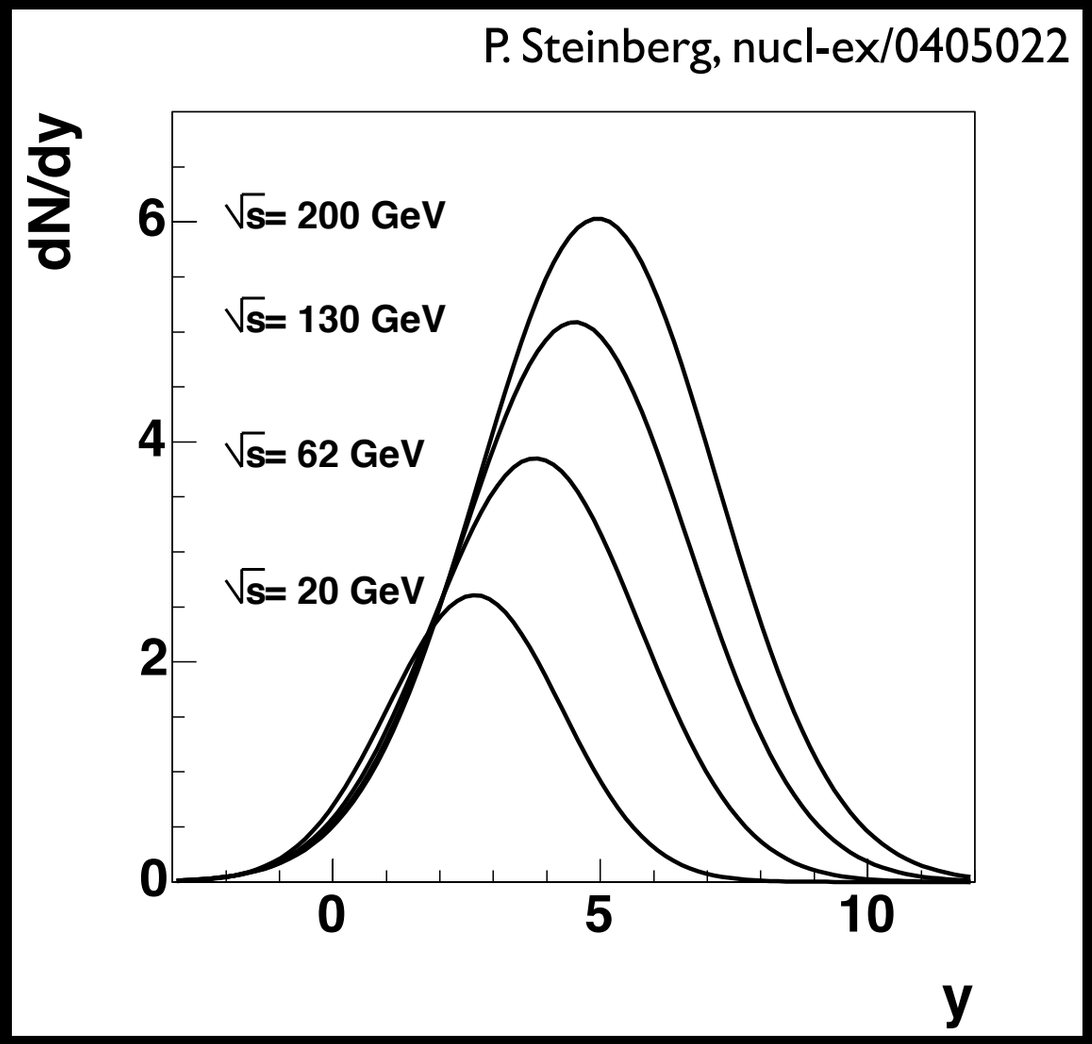



Carruthers & Duong-van 1973
$\frac{dN}{d\eta} \sim \beta \frac{dN}{dy}$
ISR 53 GeV
PISA/SUNYSB
1972 (unpub.)
dN/dη
"duck or rabbit"
- η = ln tan (θ/2)

$$\frac{dN}{dy} = K s^{1/4} \frac{1}{\sqrt{2\pi L}} \exp\left(-\frac{y^2}{2L}\right)$$

$$y' = y + y_{beam} = y + e^L$$

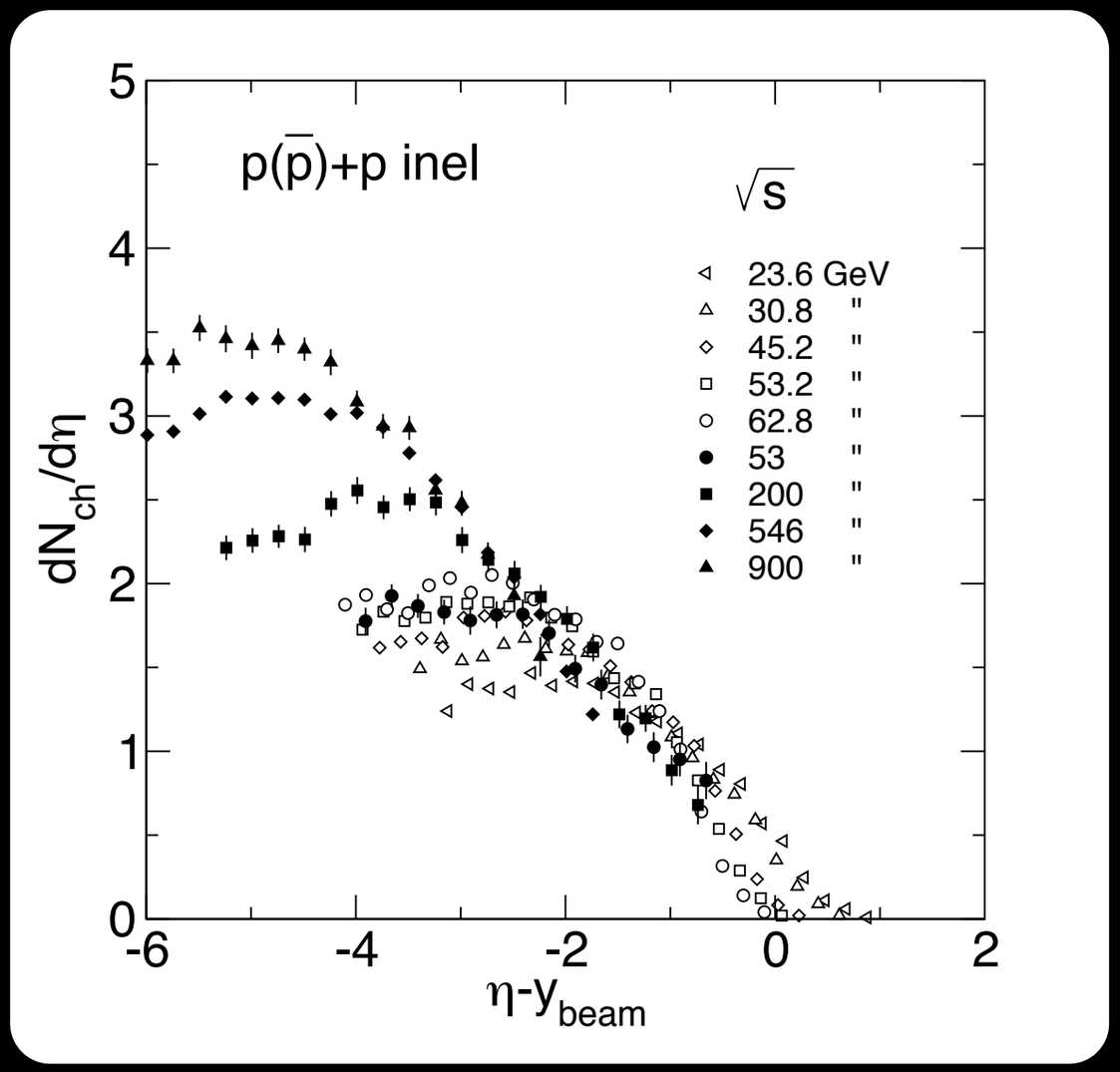
$$\frac{dN}{dy'} \sim \frac{1}{\sqrt{L}} \exp\left(-\frac{y'^2}{2L} - y'\right)$$

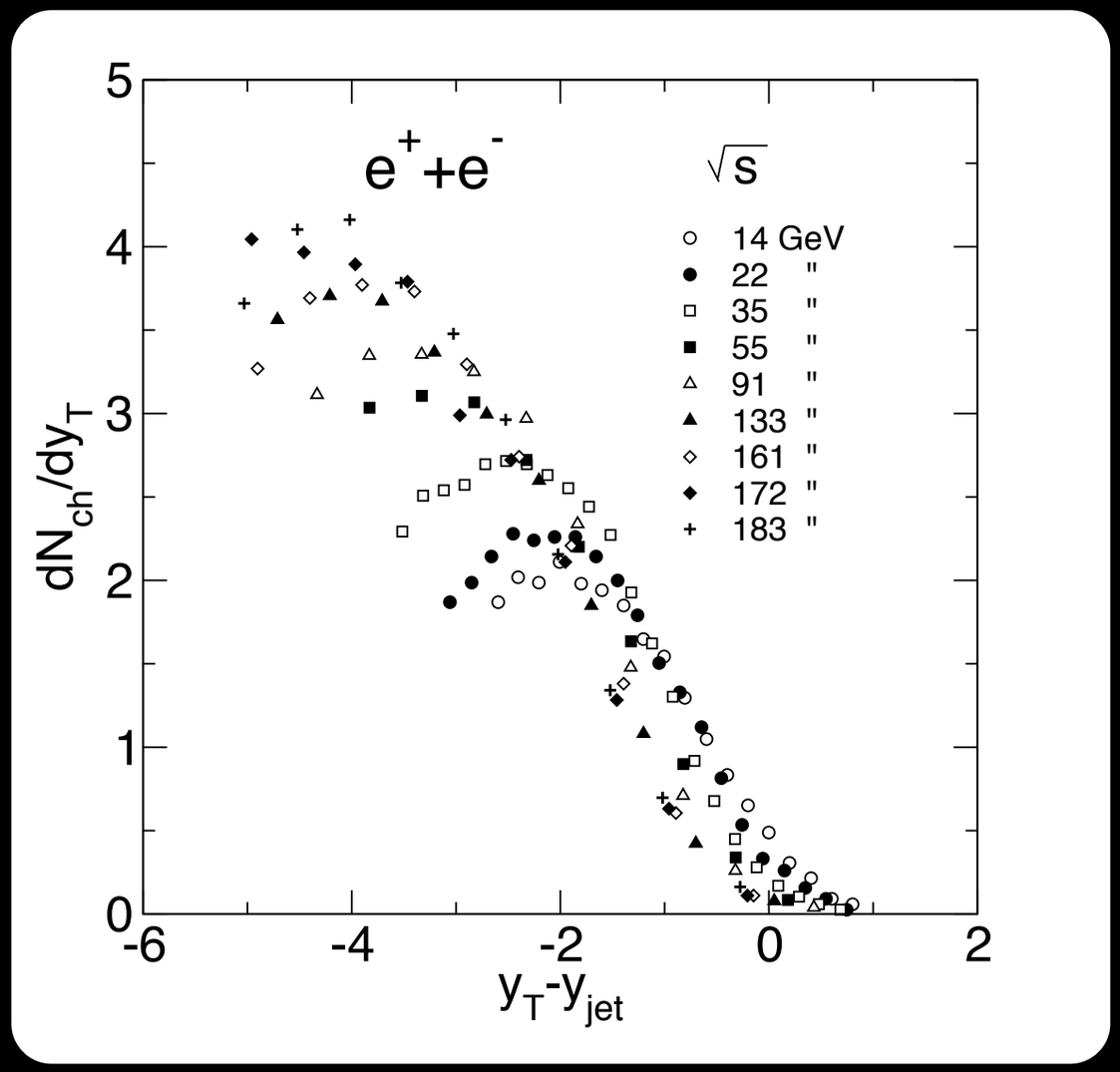


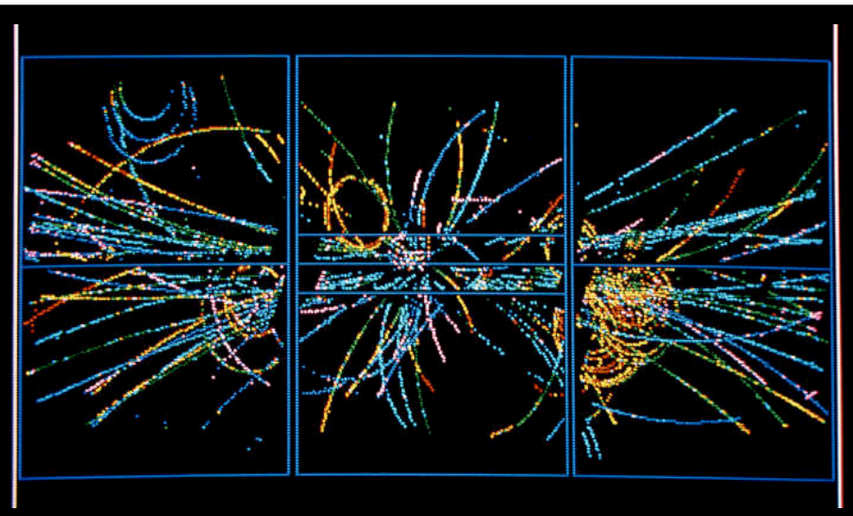
Landau/Fermi multiplicity formula
&
Landau's hydro dN/dy

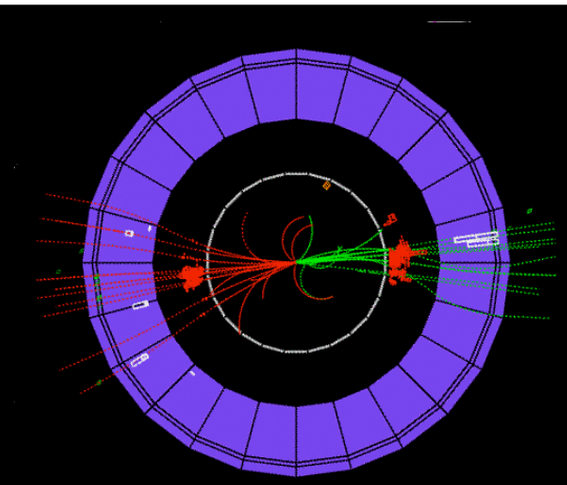
→ "Limiting Fragmentation"

Compiled in PHOBOS White Paper (2004)



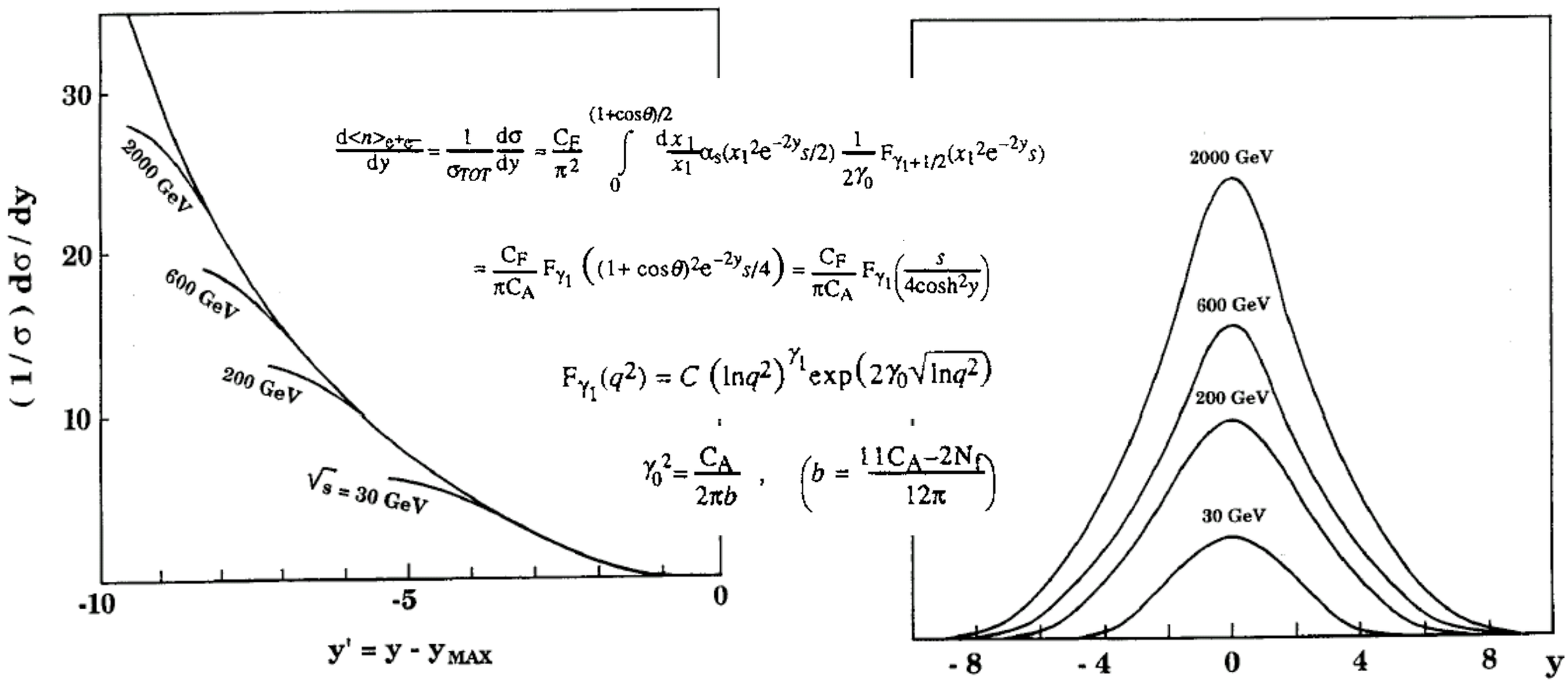






pQCD “vs.” Landau

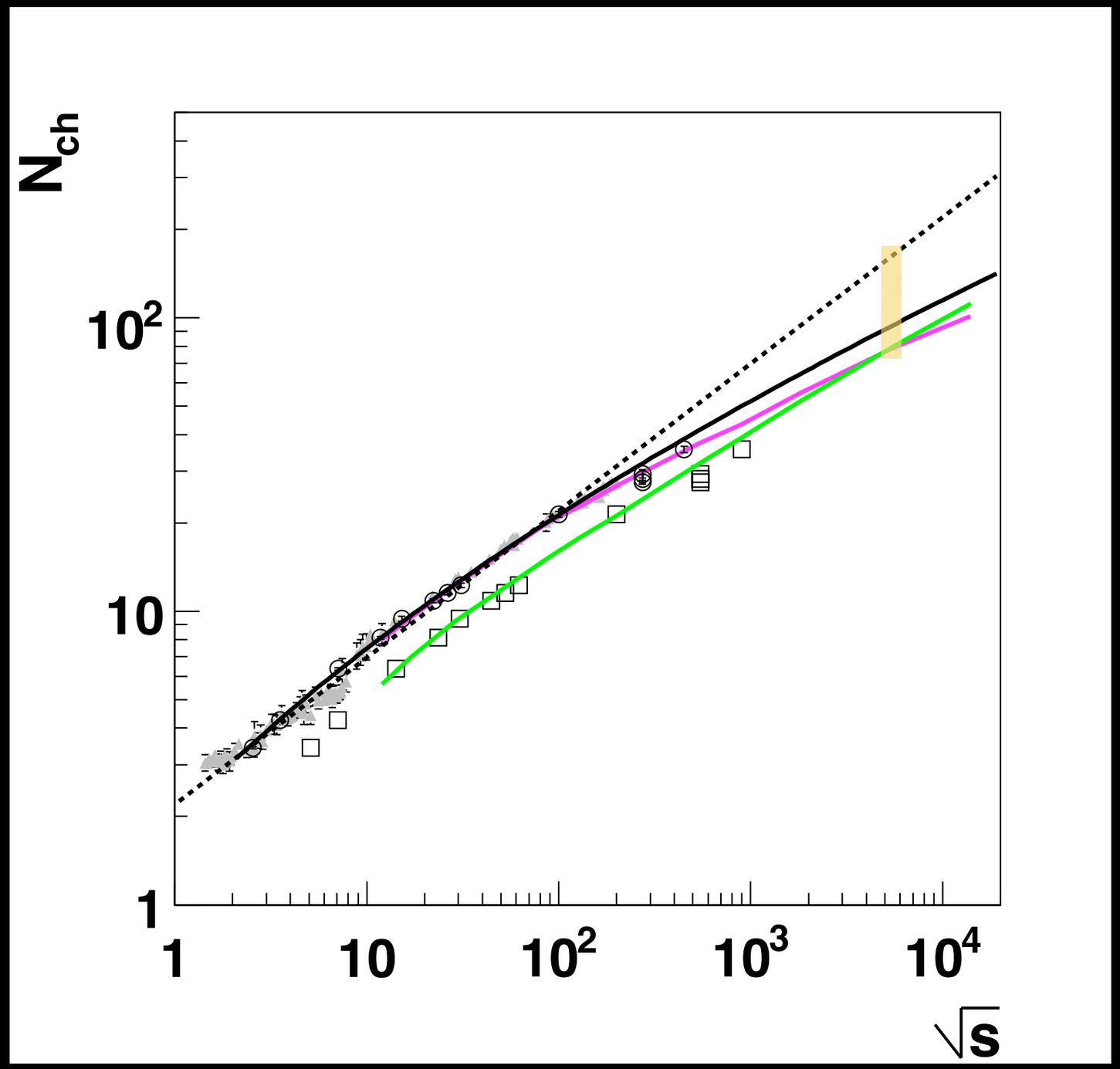
. Tesima, Z. Phys. C (1989)



MLLA pQCD shows “limiting fragmentation” & $\sigma_y \propto \sqrt{log(s)}$

pQCD ↔ Landau Hydro [?!]

Extrapolating p+p/e^+e^-



Landau evolution

pQCD evolution

are quite close for available data...

From p+p/e^+e^- → A+A

- **Variety of models and physical assumptions for p+p and e+e-**
  - Extrapolating even elementary collisions is not 100% straightforward
- **In principle, A+A has more dynamical content...**

Parton distributions,
Nuclear Geometry,
Nuclear shadowing

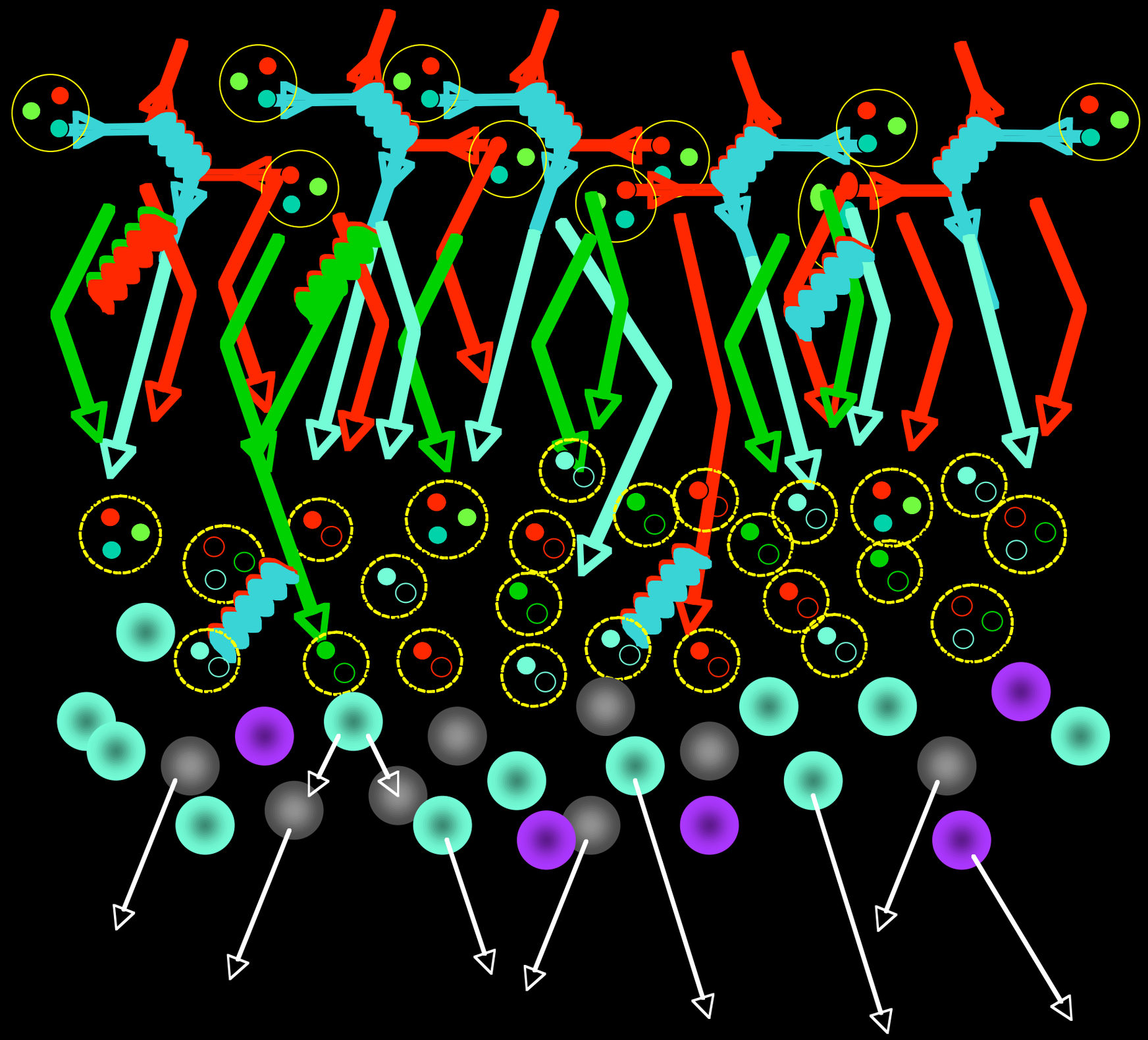
Parton production &
reinteraction

Chemical freezeout
(Quark recombination)

Jet fragmentation
functions

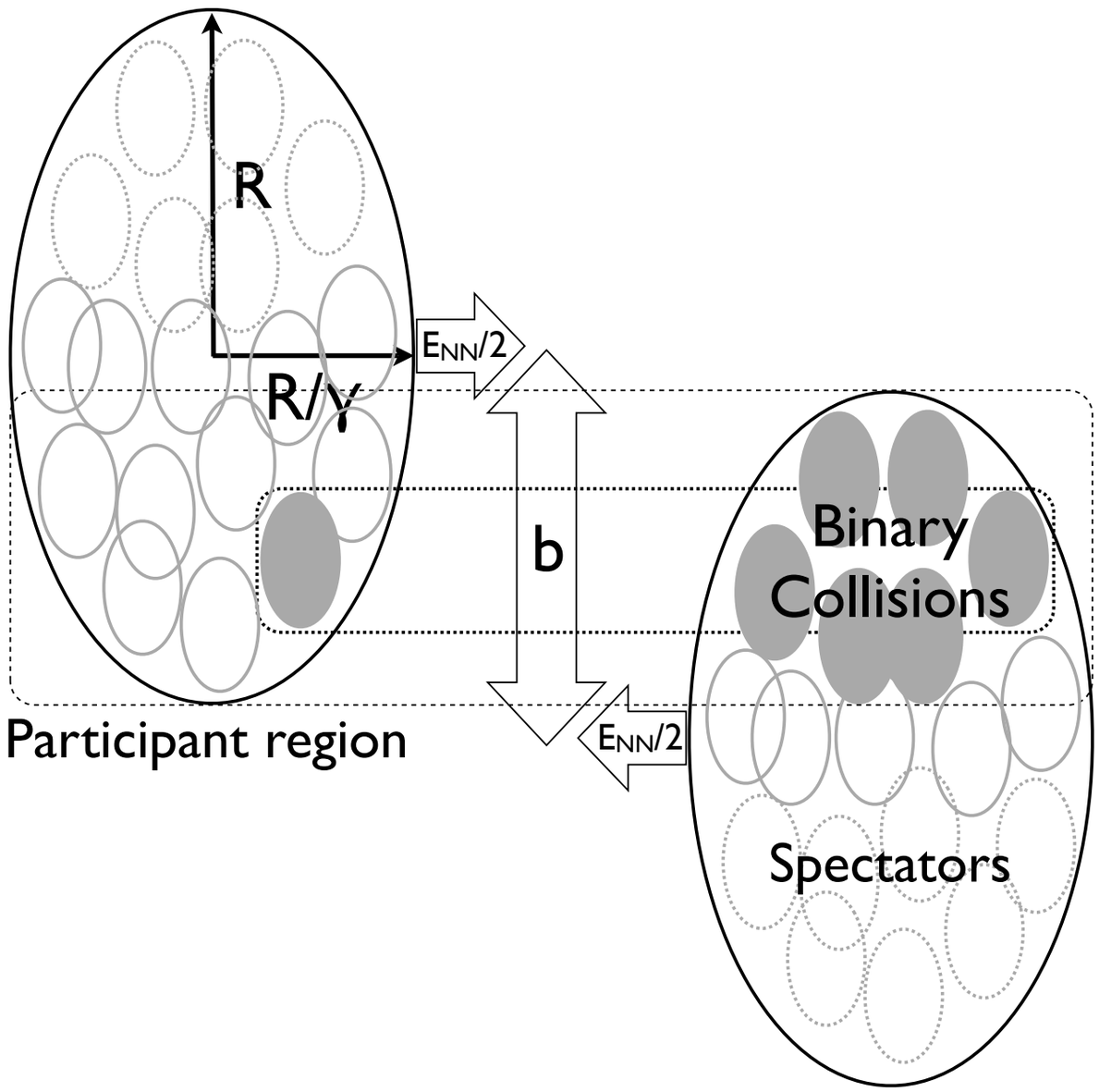
Hadron rescattering

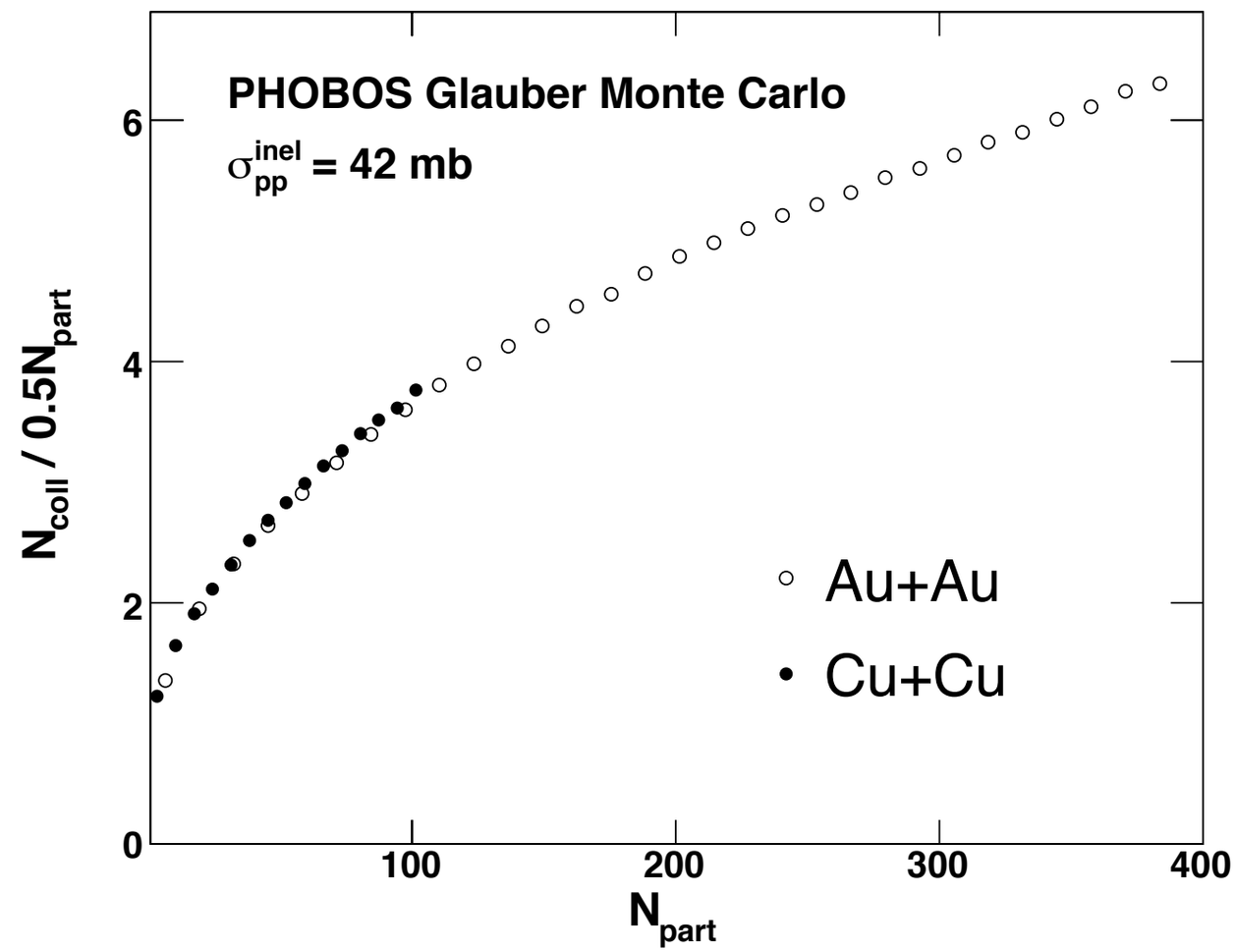
Thermal freezeout &
Hadron decays



Many dynamical stages, all in principle independent...

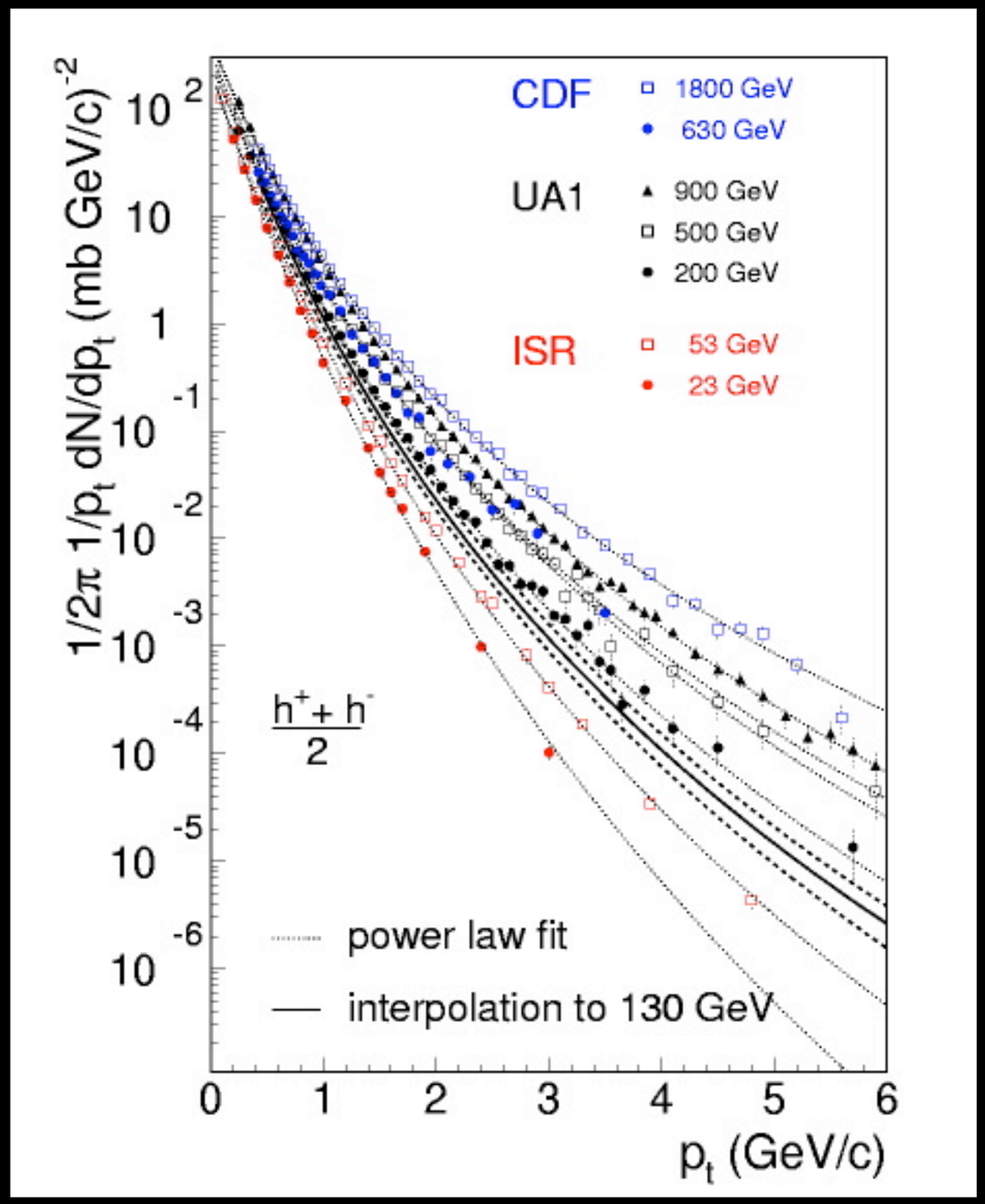
Nuclear Geometry

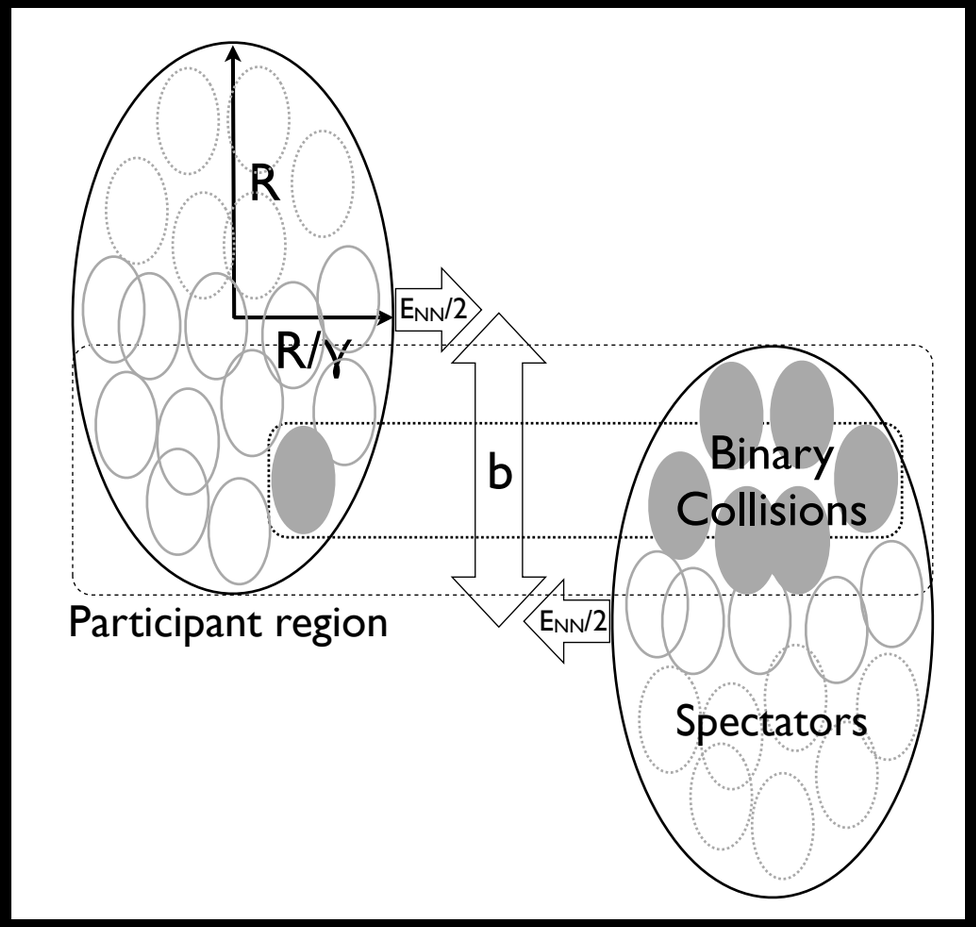




For most heavy ion events, $\nu \equiv \frac{\langle N_{coll} \rangle}{\langle N_{part} \rangle} > 1$

Two-Component Model





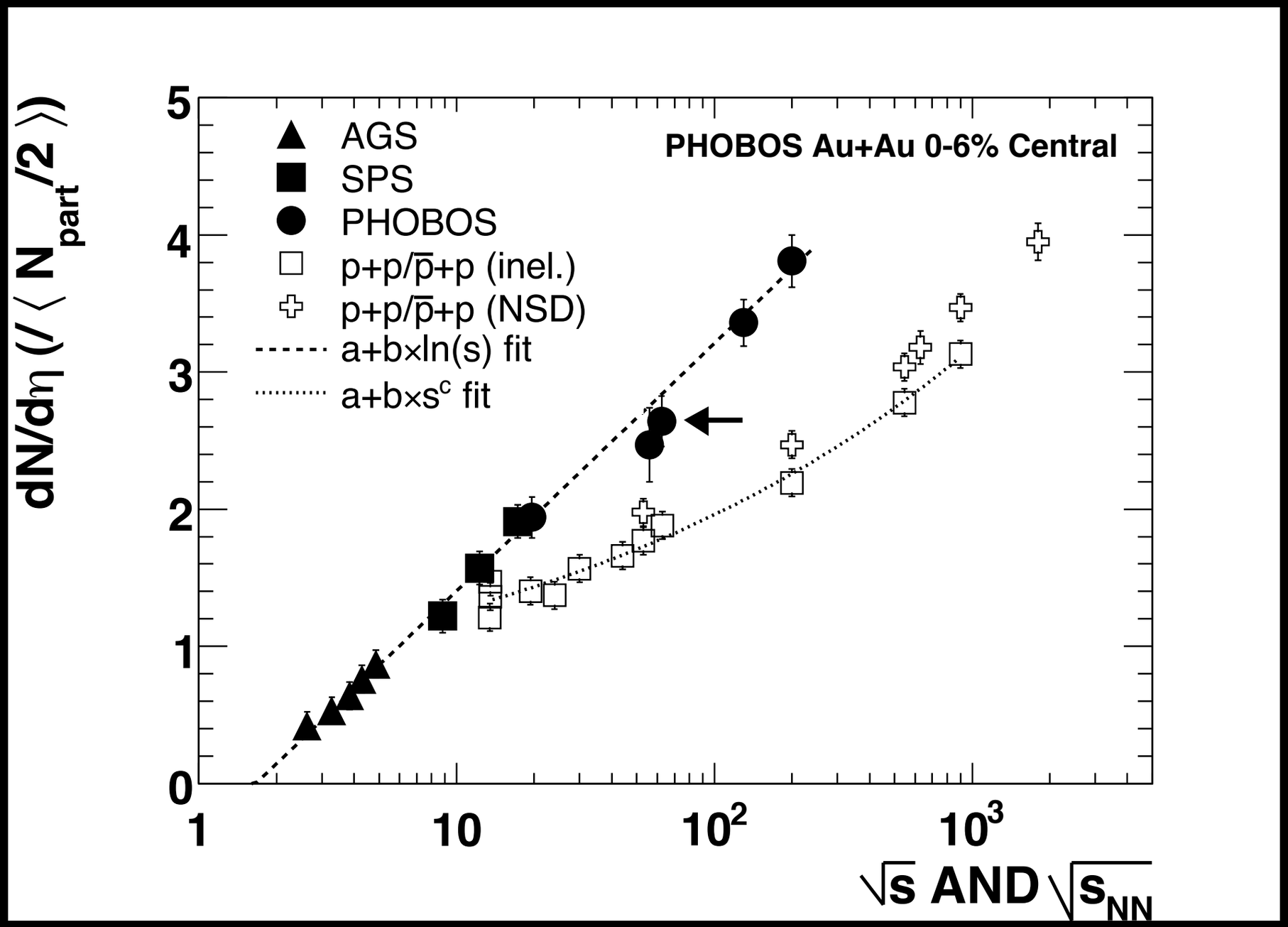
p+p seems to have a "soft" E-indep. component & "hard" E-dep. component

Changing ν should increase fraction of hard production

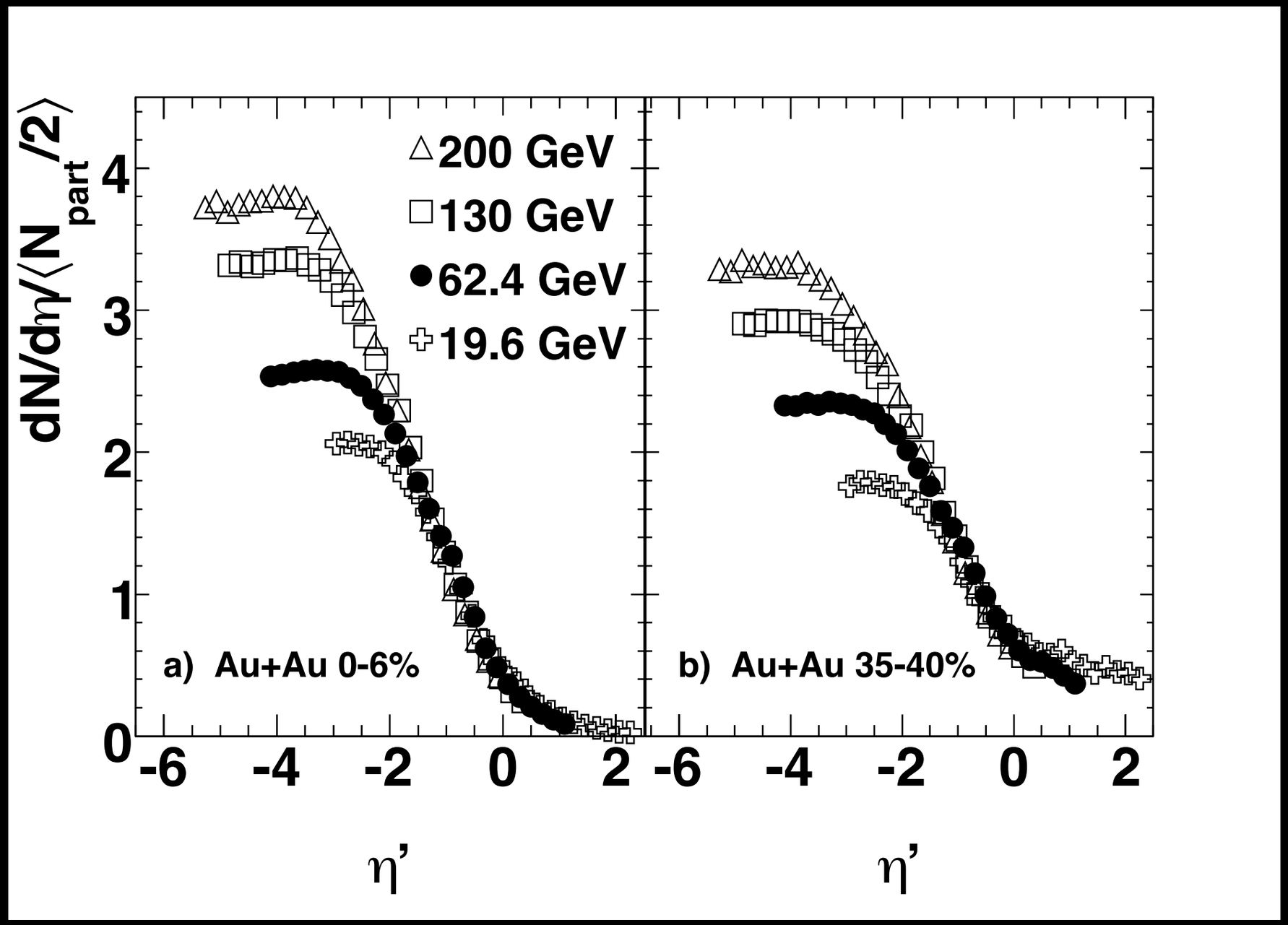
Rules of Thumb

- **“log rise” of dN/dη**
- **“limiting fragmentation”**
- **“N_{part} scaling”**
- **Energy/Centrality “factorization”**

Mid-rapidity Yields

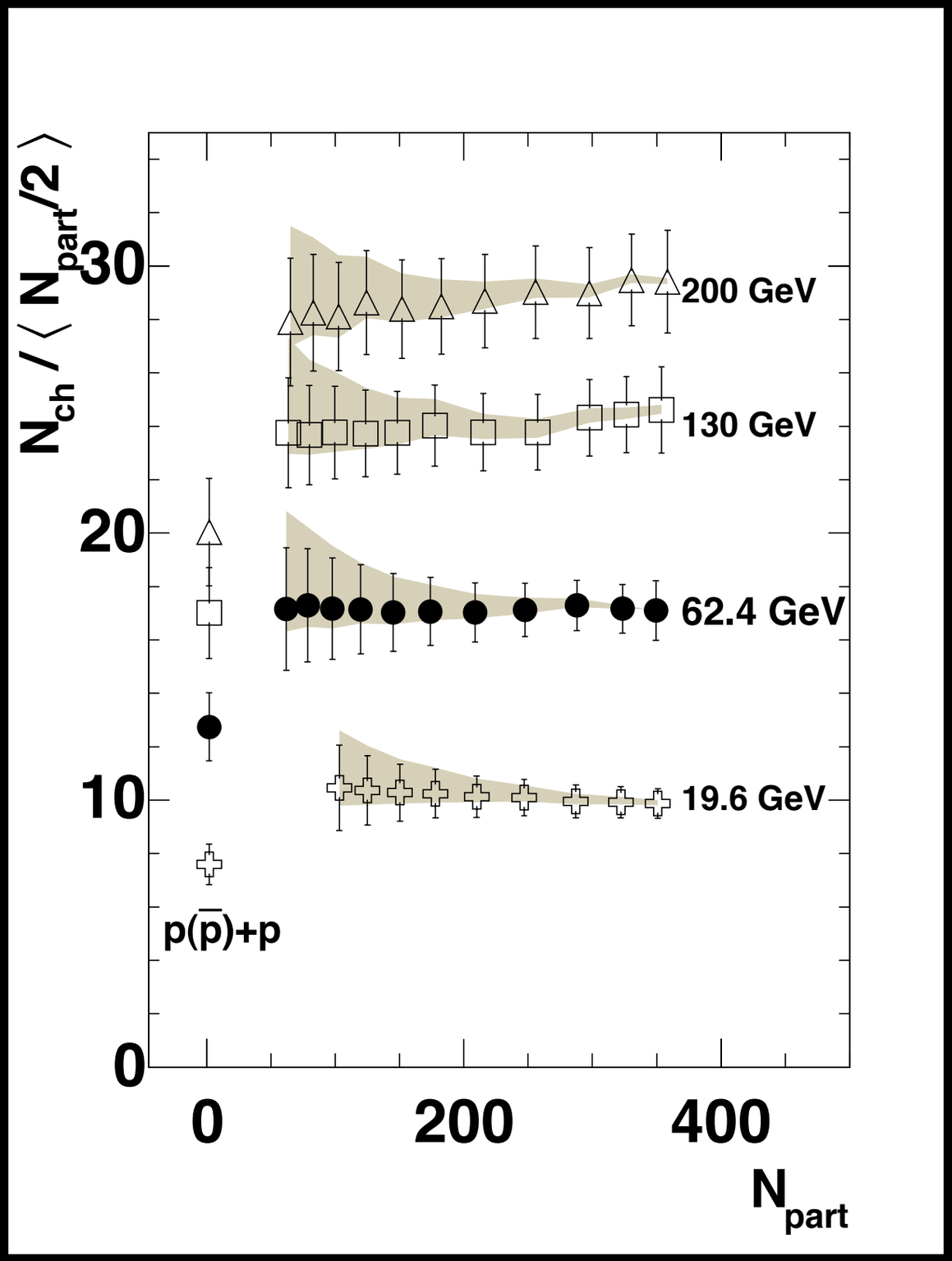


Limiting Fragmentation



~Invariance of yields at a fixed distance from beam rapidity (see Anna's talk)

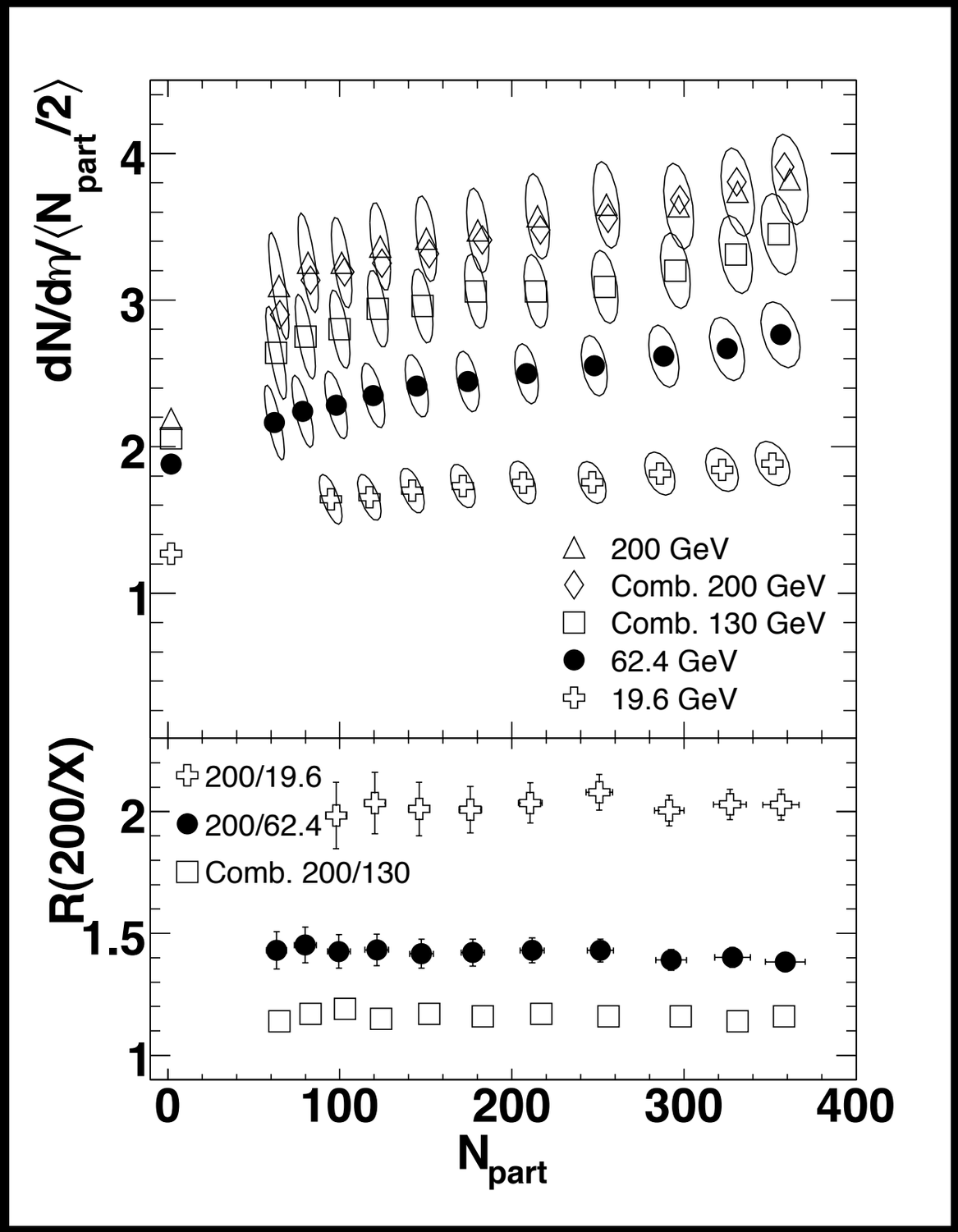
N_{part} Scaling



With increasing centrality, rise at mid-rapidity is balanced by decrease at forward rapidity

Integral is surprisingly constant per participant. No obvious trend down to p+p multiplicity

Energy & Centrality



All yields per N_{part} rise with increasing N_{part}

Contribution of "hard" component?

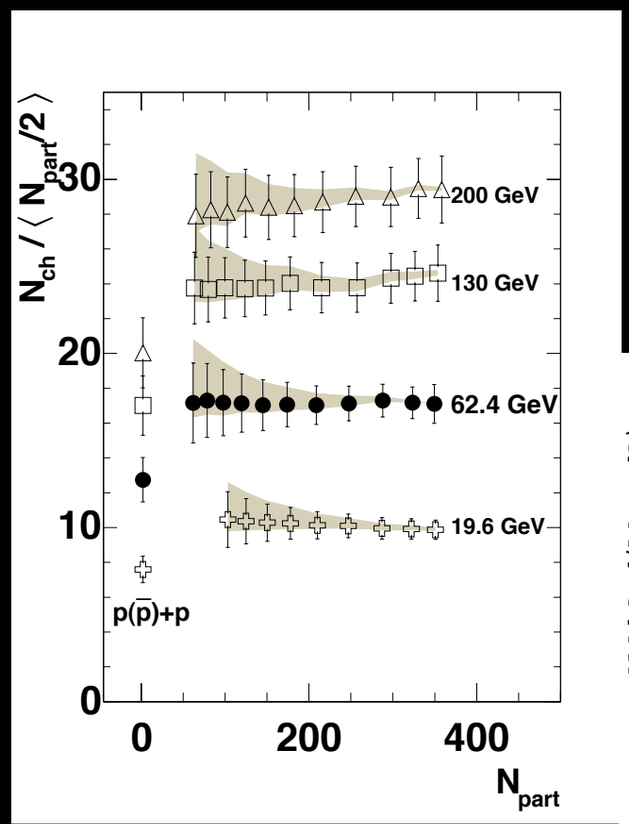
$$\frac{dN_{AA}}{d\eta} = \frac{dN_{pp}}{d\eta}\left((1-x)\frac{N_{part}}{2} + xN_{coll}\right)$$

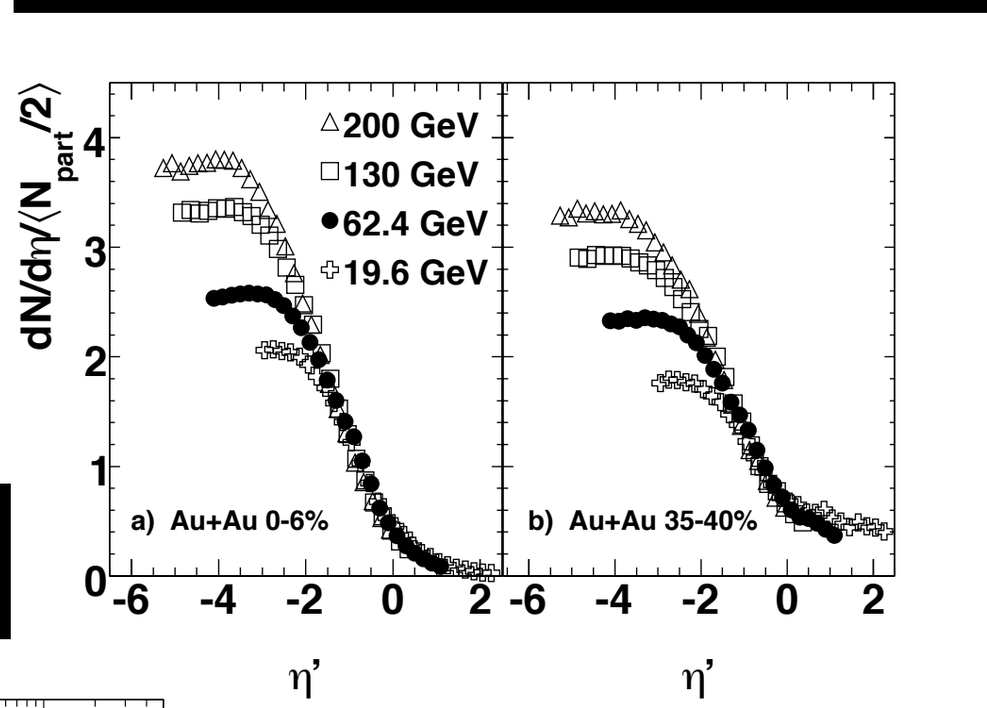
But they all rise at the <u>same</u> rate: where is the increasing hard component at higher energies?

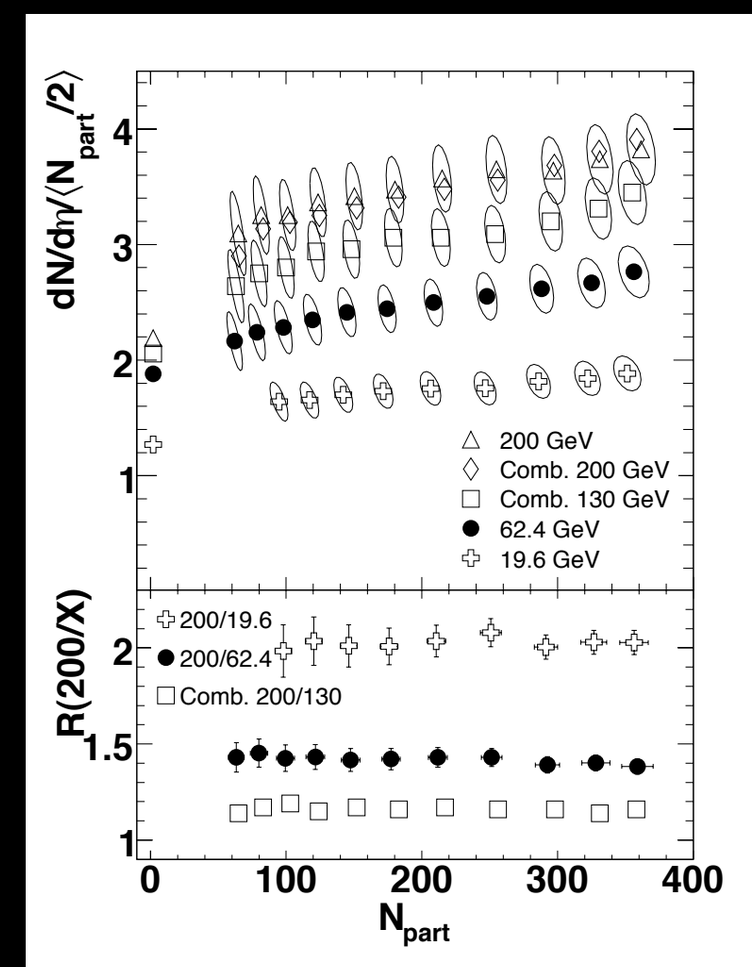
“One Component” Picture

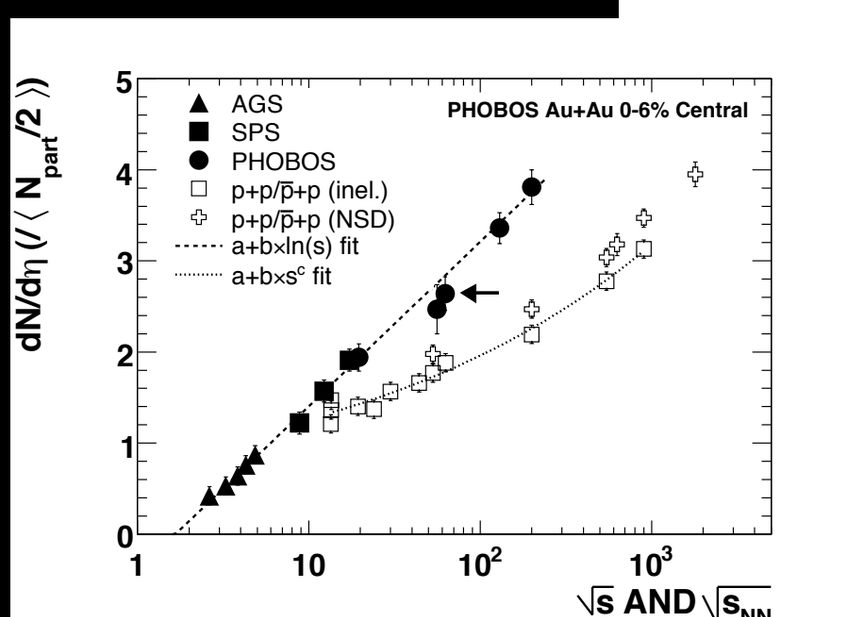
What if N_{part} scaling of N_{tot} is fundamental?

Centrality dependence of limiting curve is E-independent



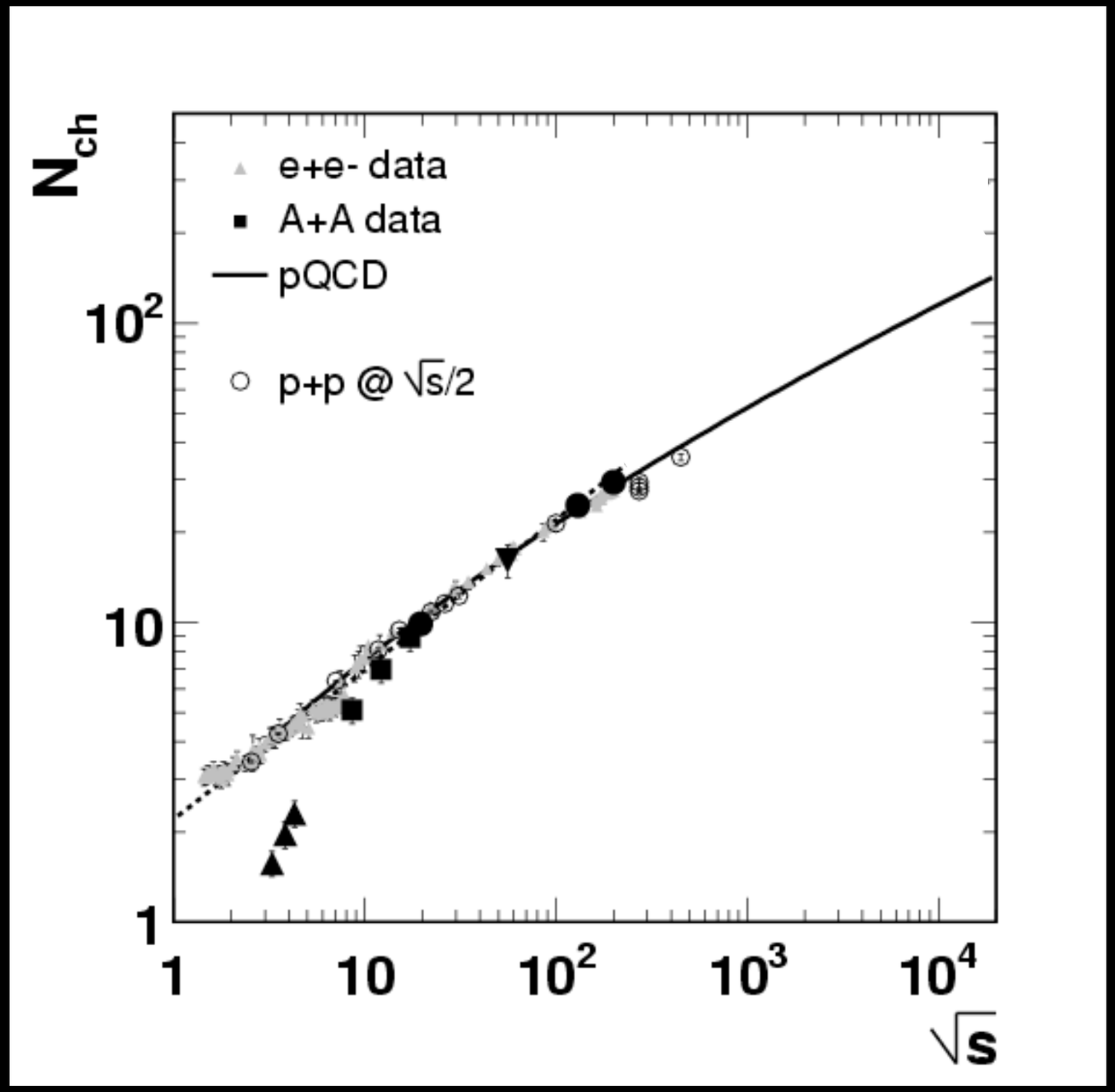






If “peel off” is energy-independent, dN/dη is just crawling up limiting curve

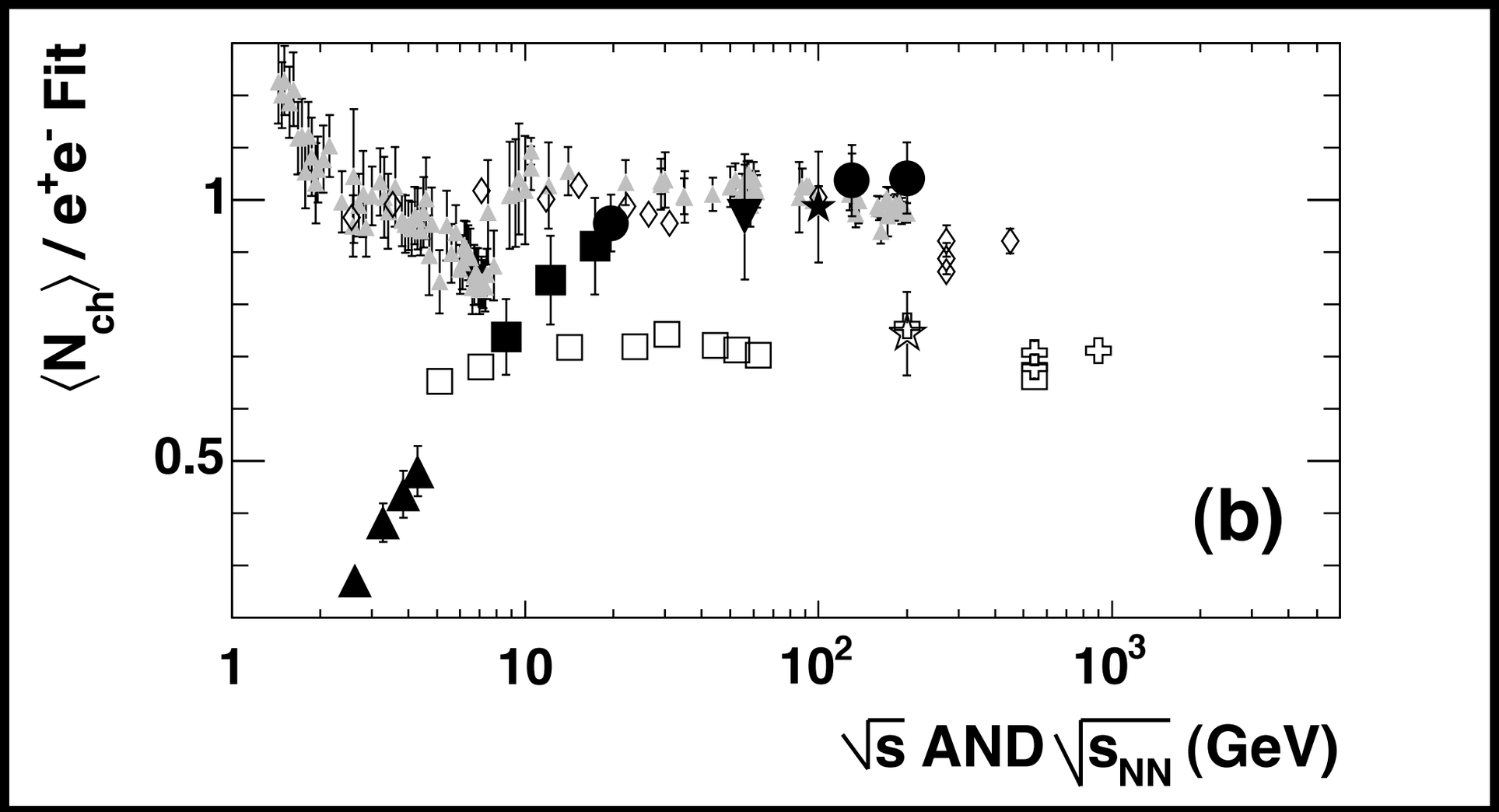
Comparison with e^+e^-/p+p



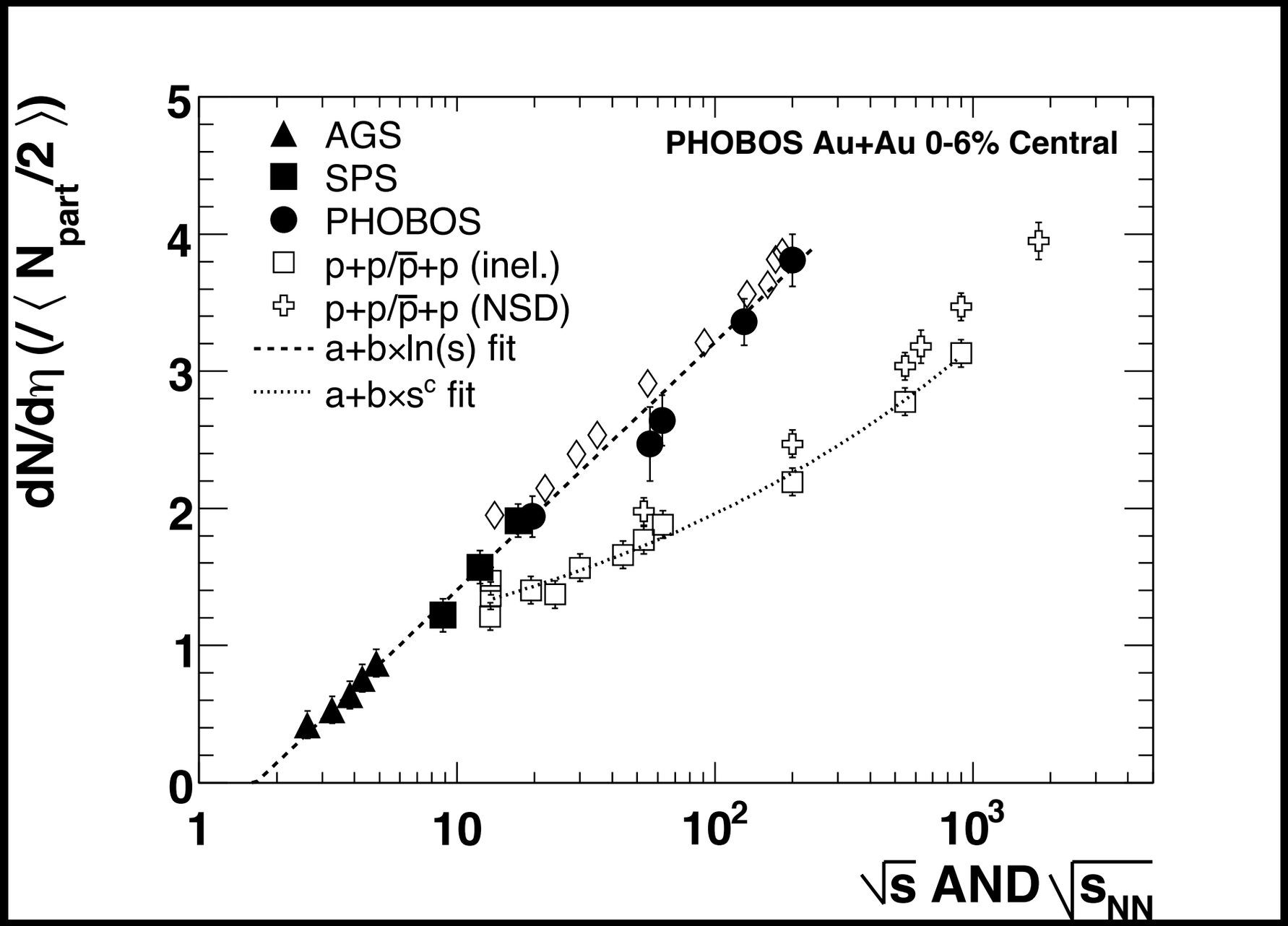
A+A same as e+e- and p+p above SPS

A+A appears "Suppressed" at low energy

Comparison with e^+e^-/p+p



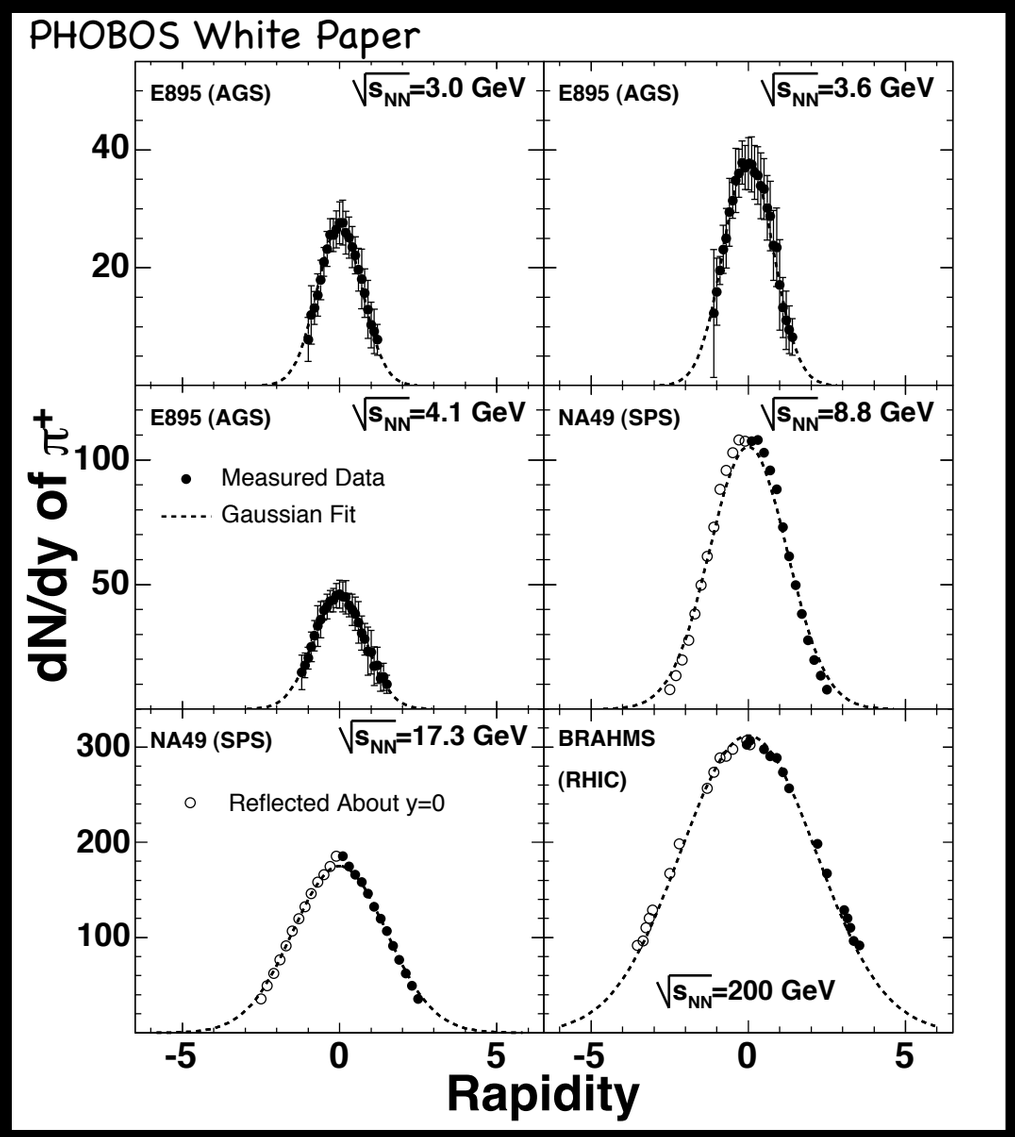
Comparison with e^+e^-/p+p

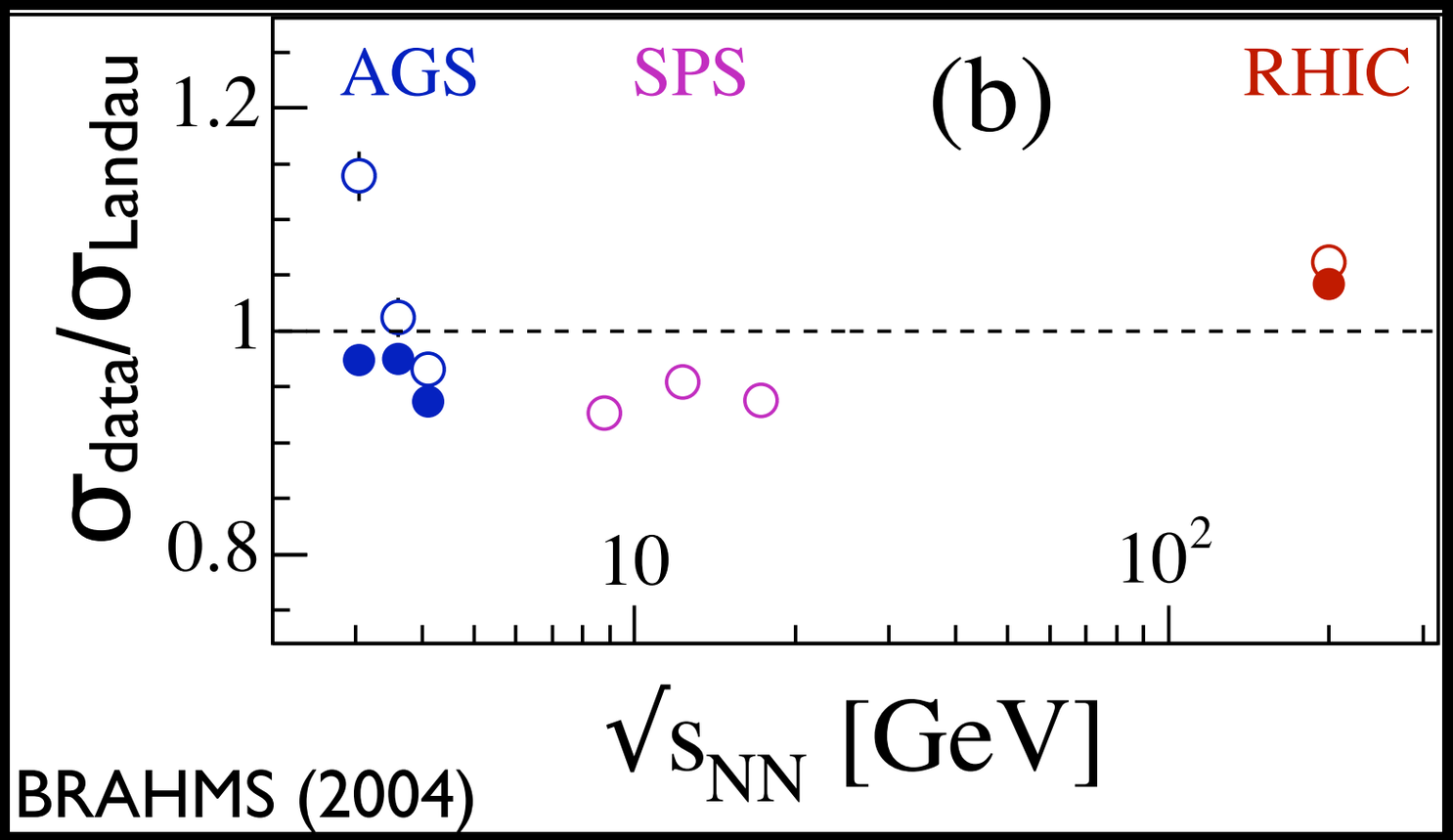


Effective Energy in A+A

- **Without scaling, A+A from 20-200 GeV has same trend as e+e- and p+p at same "effective" energy**
  - Implies ~"complete stopping" in A+A
- **Not inconsistent w/ Landau initial state**
  - Issue of thermalization in any system on such short time scales is controversial
  - Does not seem contradicted by data

Landau Model vs. A+A



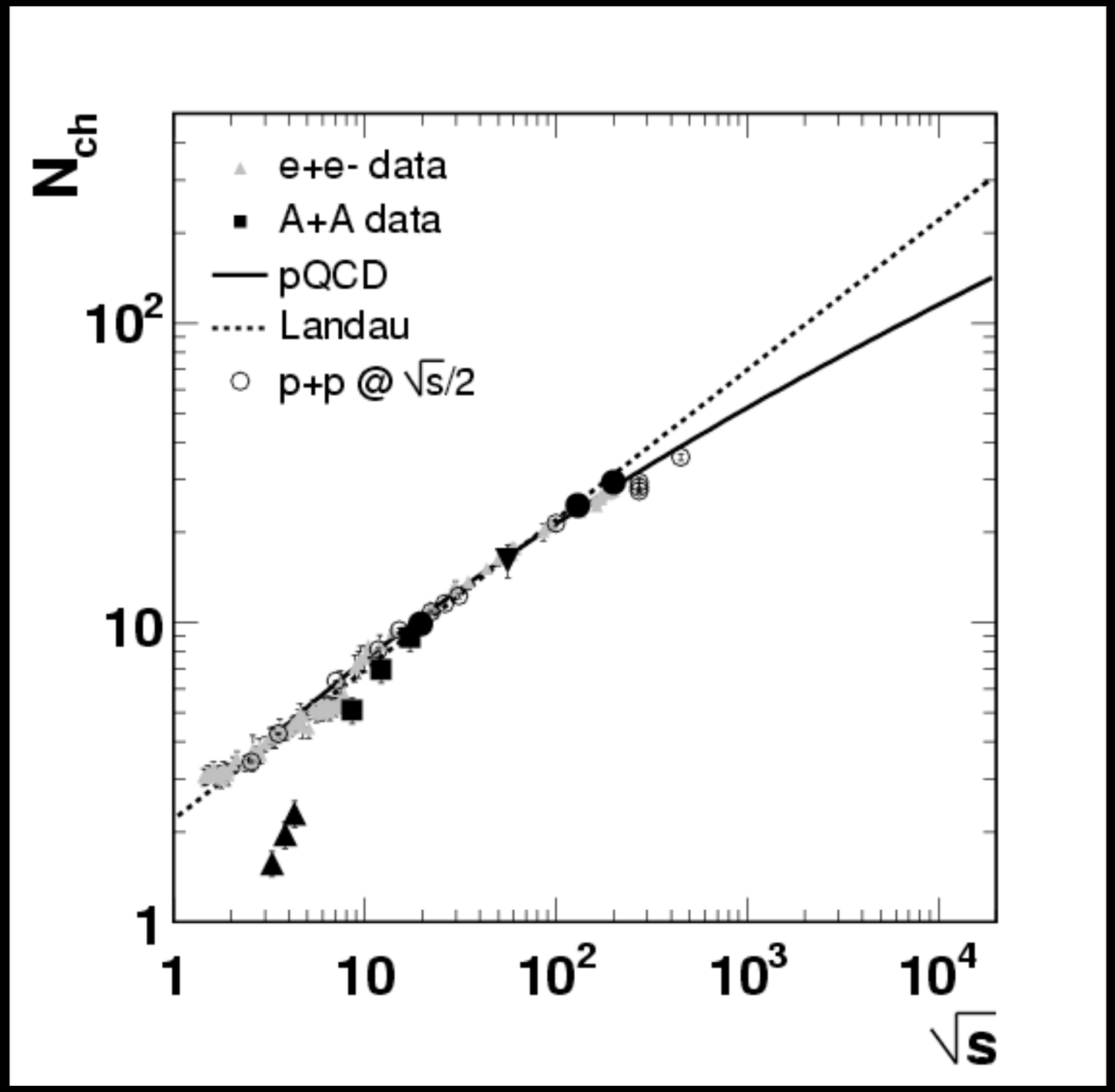


Landau's predictions from 1955 remain valid in 2005

$$\sigma_y = \sqrt{\frac{1}{2}\ln\left(\frac{s}{4M_P^2}\right)}$$

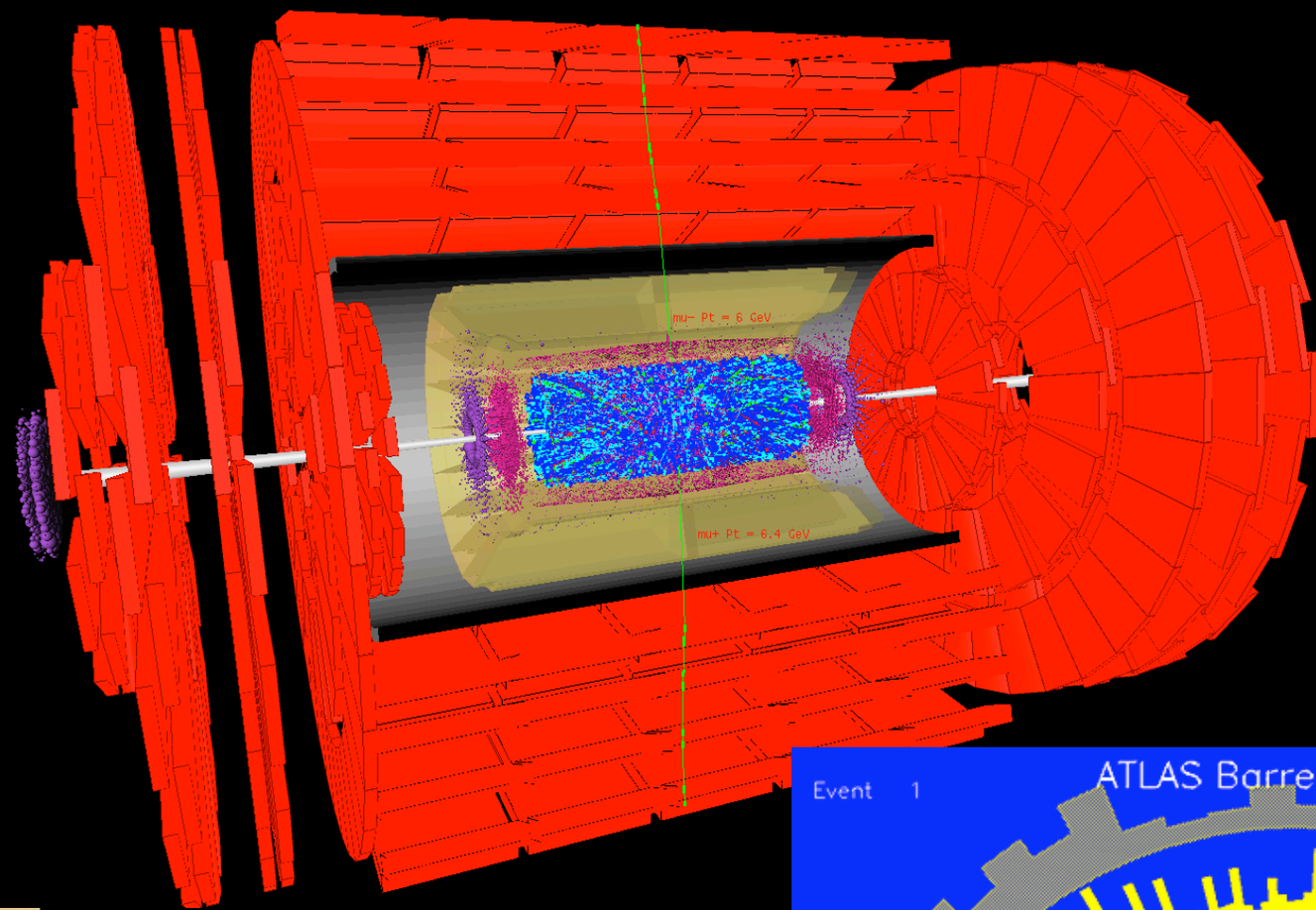
Comparison with e^+e^-/p+p

osculation?

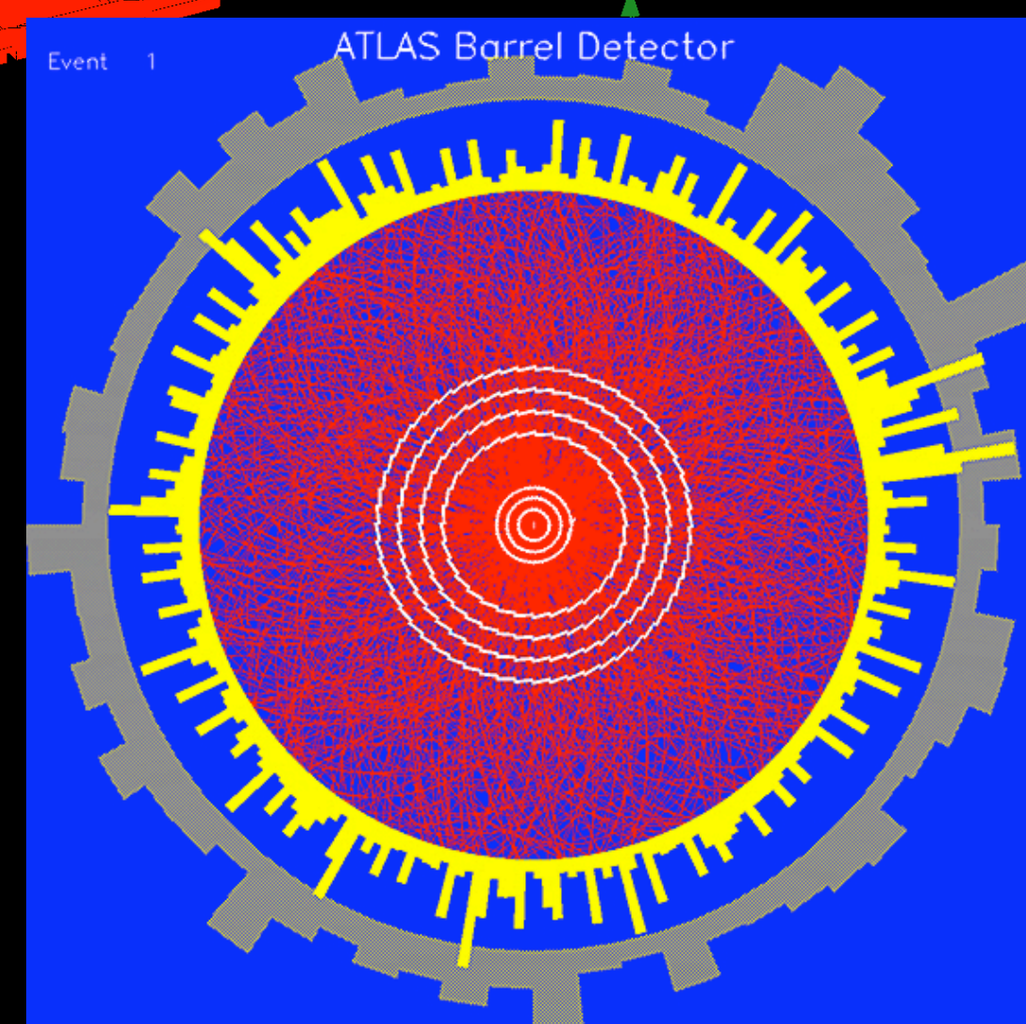


Where will things go @ LHC? (ILC? CLIC?)

CMS



ATLAS



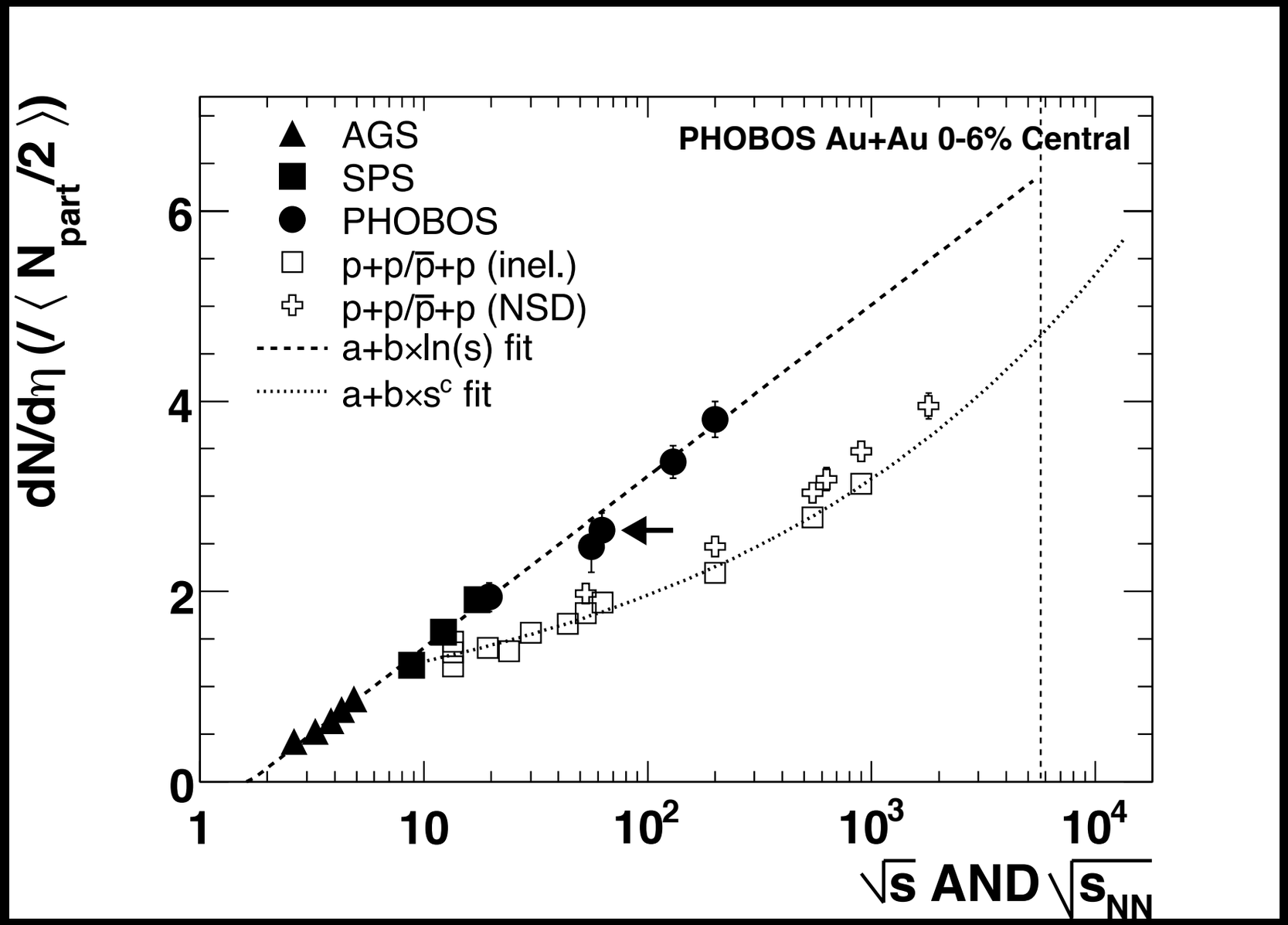
ALICE

Towards the LHC?

Can what we know about current data (200 GeV A+A) be strong guidance for the LHC (5500 GeV A+A)?

Big jump (x27) in energy!
Even LHC will only be x7 Tevatron.
e+e- machines were often x2 at a time

Extrapolating Data

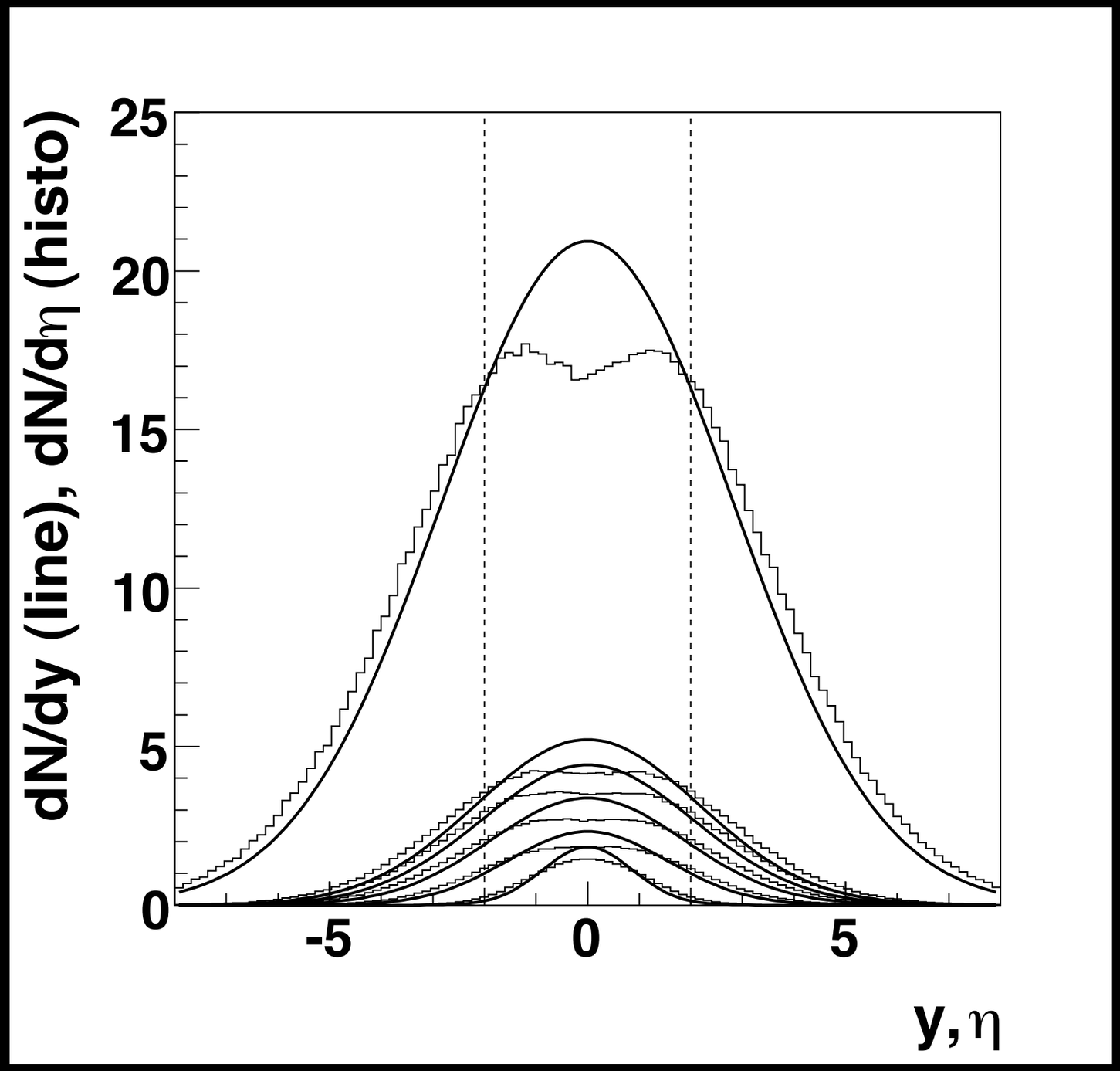


Simple extension of log-rise gives dN/dη ~ 1200

Ignores observed non-linear rise of p+p data

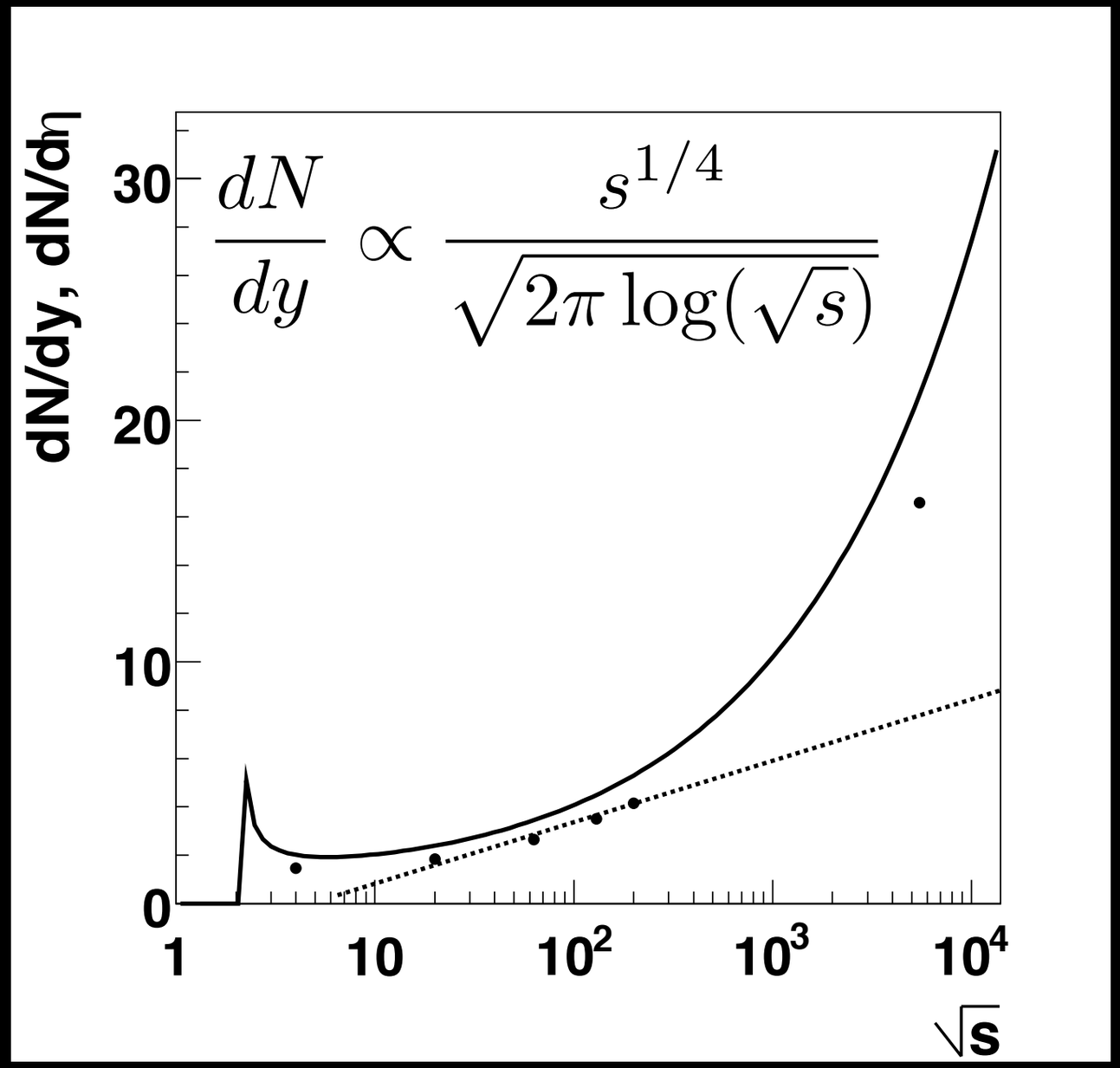
Kinematic Effects

Landau calc. of T=140 MeV pions



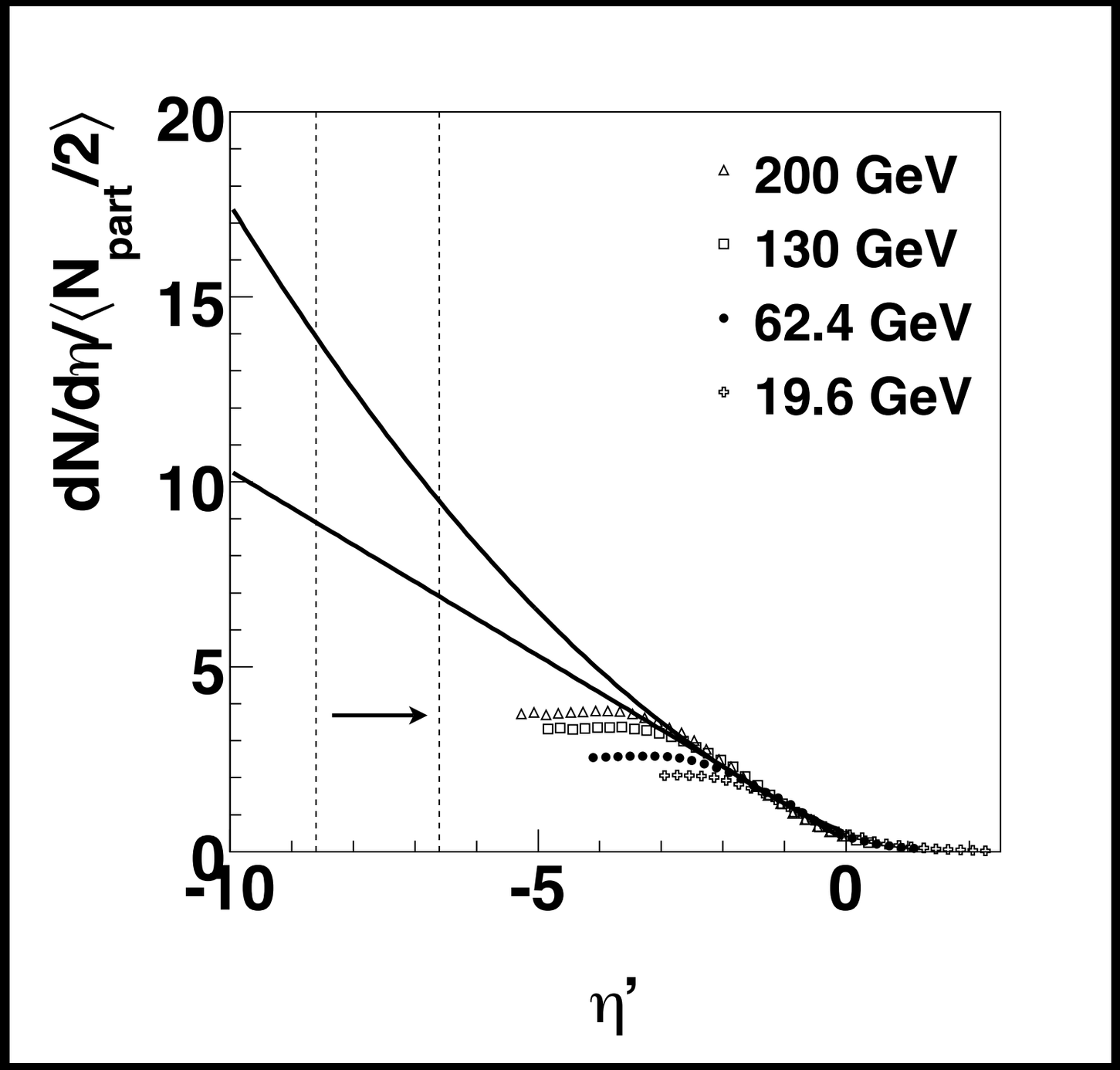
Relationship between y and η depends on energy and p_T spectrum

Landau dN/dy, dN/dη



Careful extrapolating a piecewise linear function...
Physics might "jump" at higher energies

Limiting Fragmentation to the LHC



Same as with dN/dη -- extrapolation not constrained
(functions are for illustration only!)

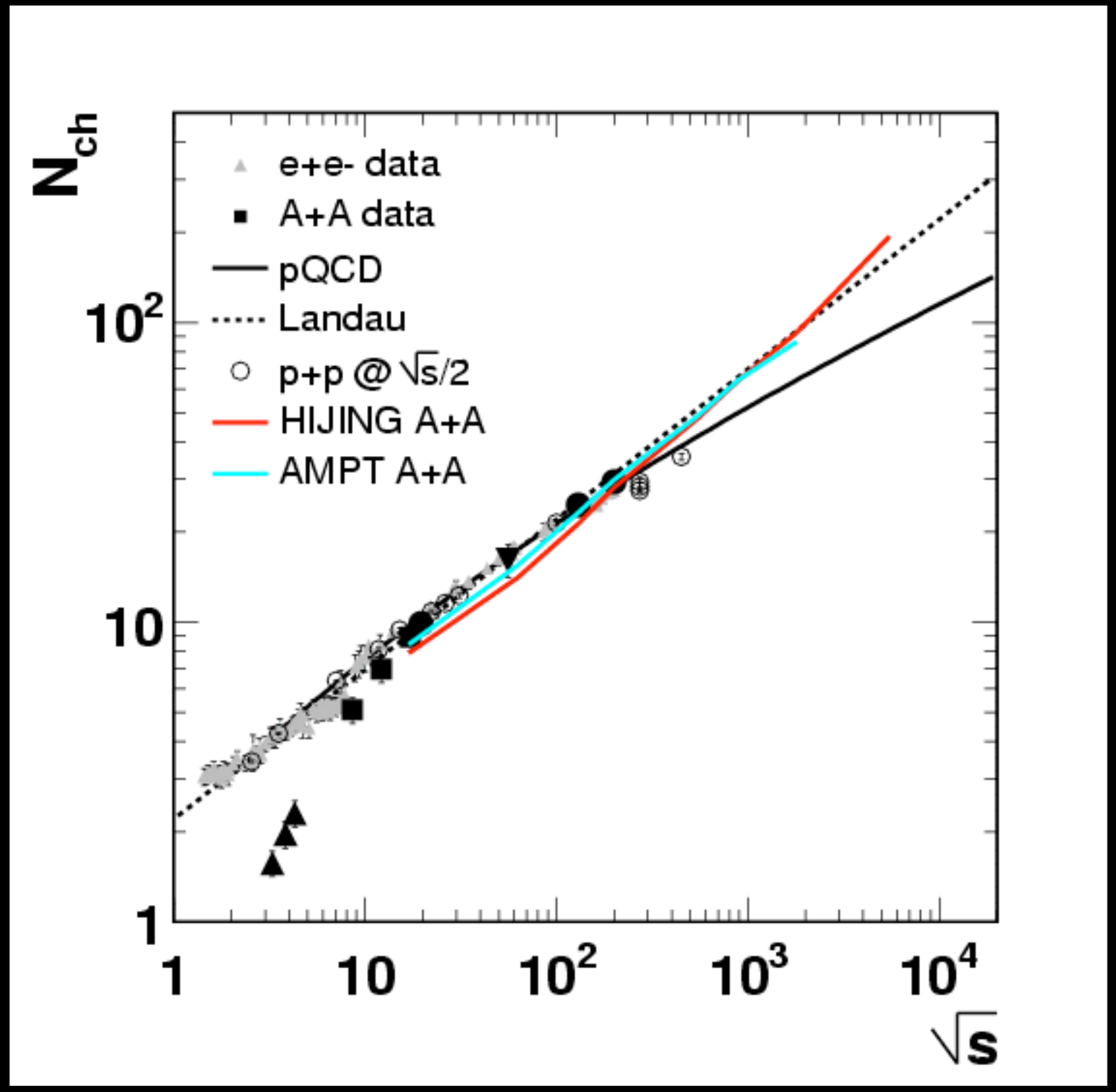
Extrapolating Data

- **Data does not speak for itself**
  - Interpolation is straightforward
  - Extrapolation is tricky

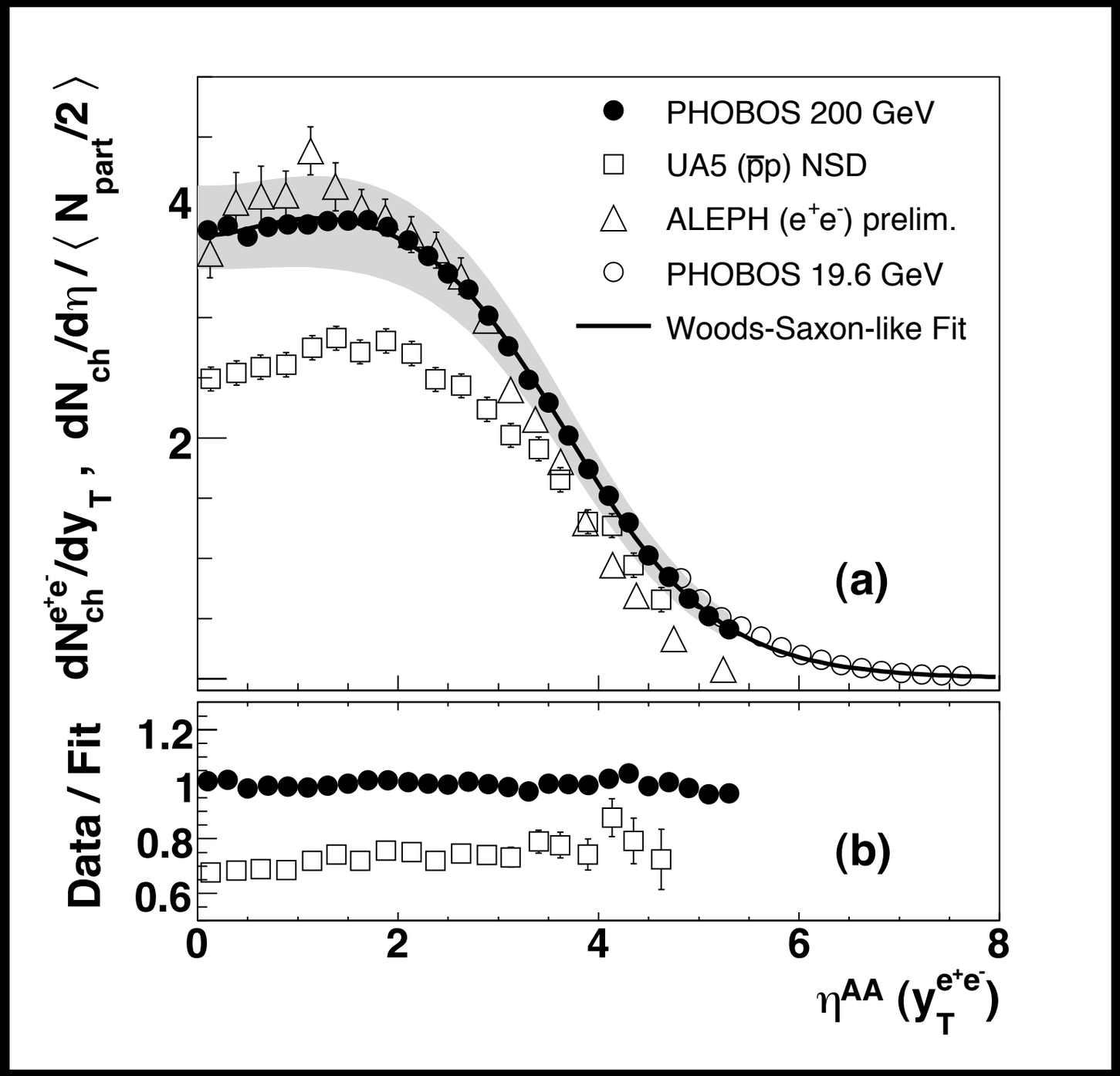
"Past performance is no guarantee of future results..."

- **Prediction requires some physical input (i.e. concrete model)**

Heavy Ion Models



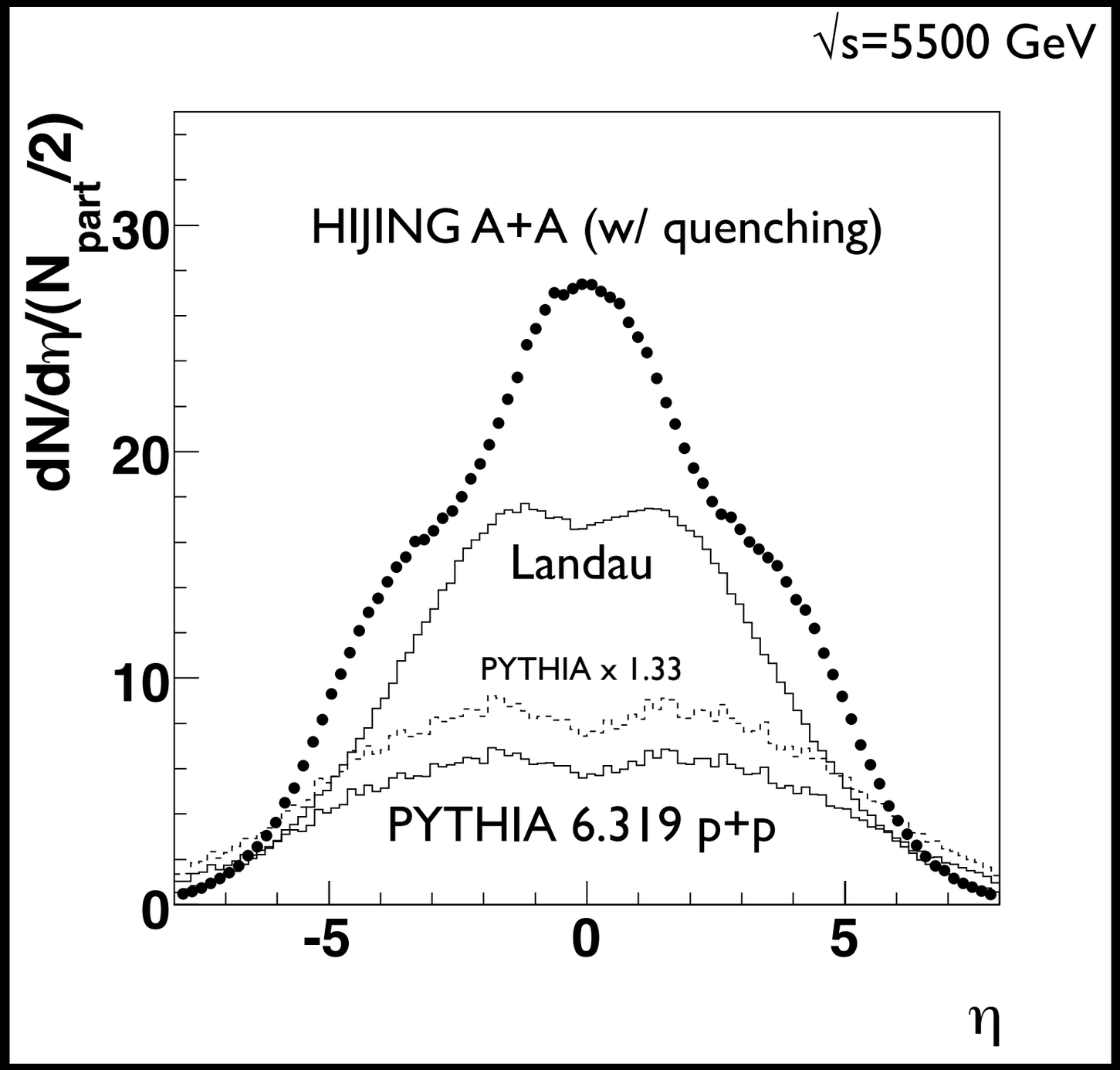
dN/dη: A+A vs. p+p/e+e-



A+A/p+p
~ 4/3

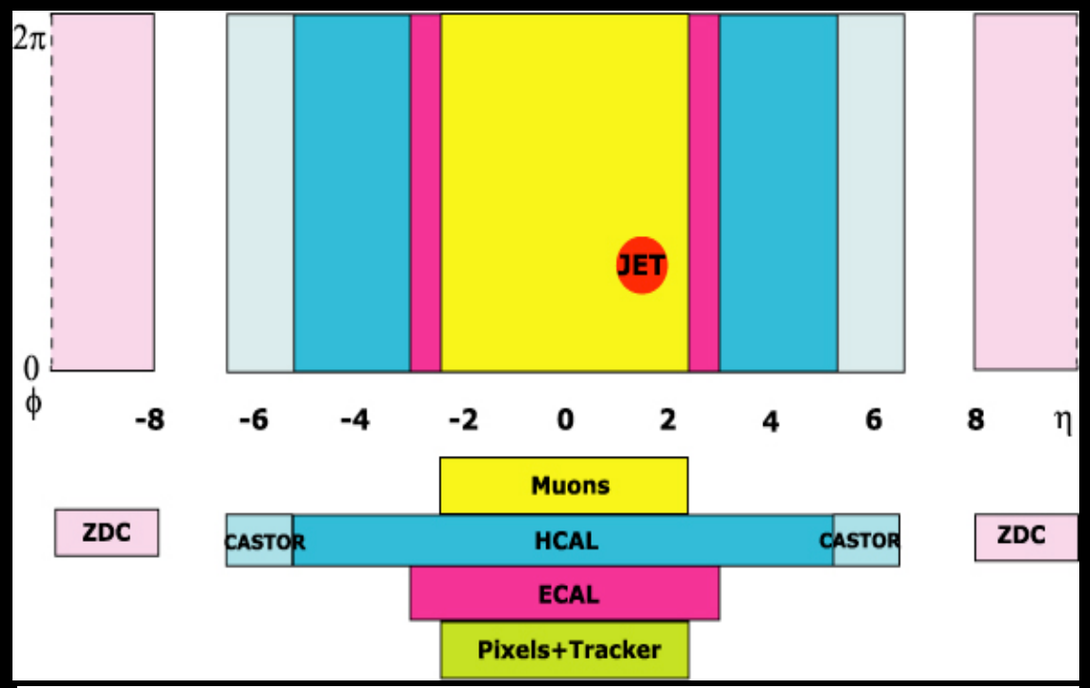
At same energy, angular distributions always similar

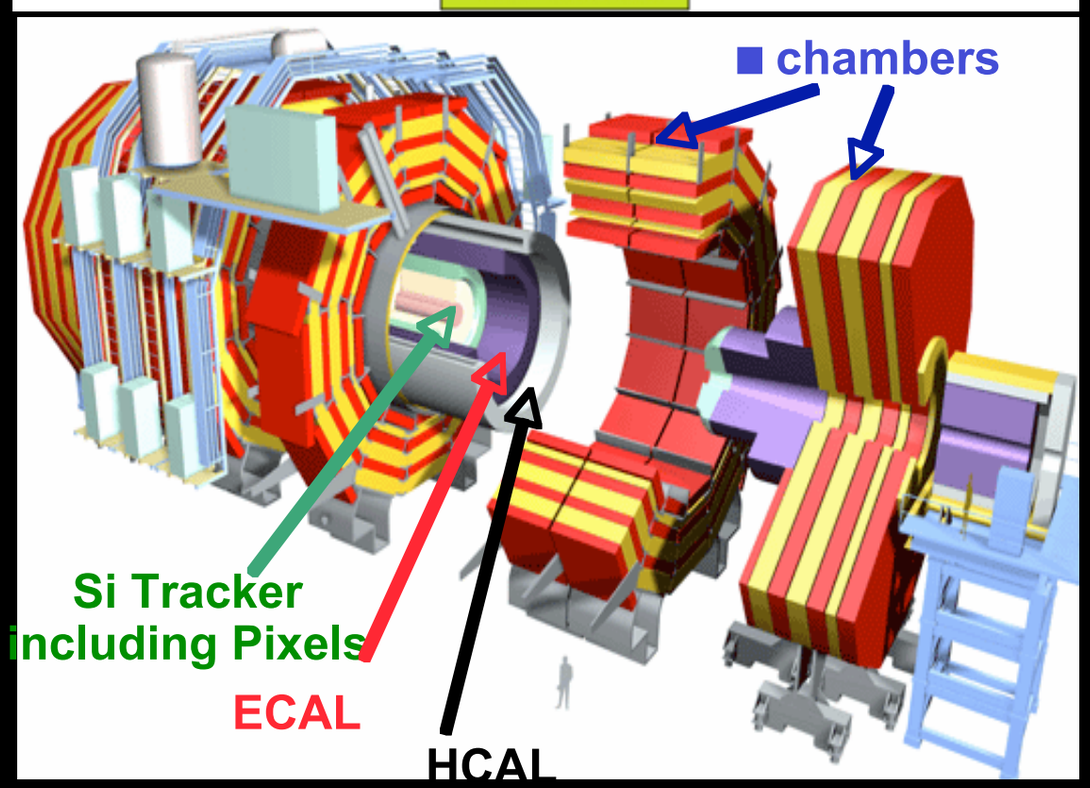
“Predicting LHC”

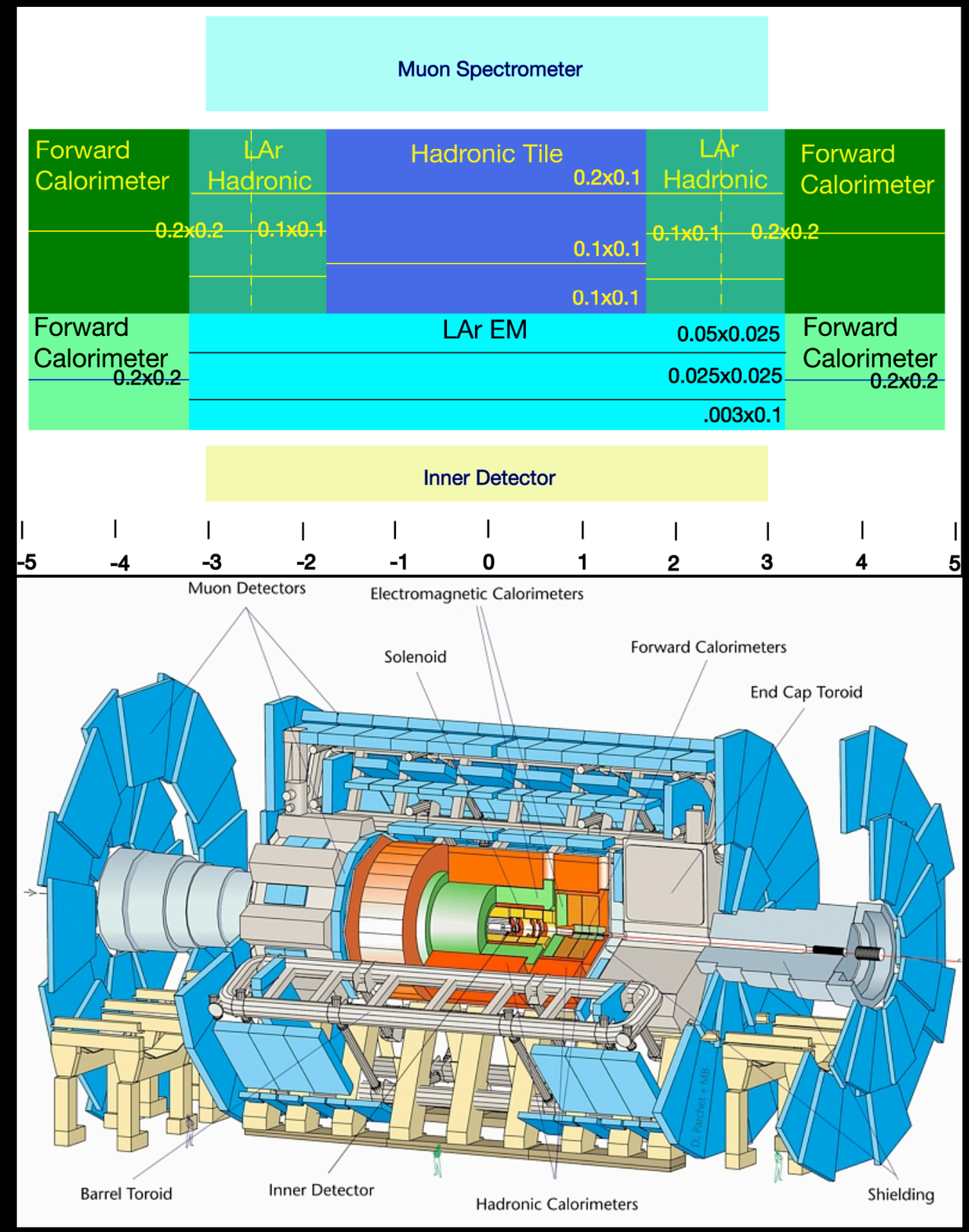


Clear that we will need not just dN/dη at η=0!

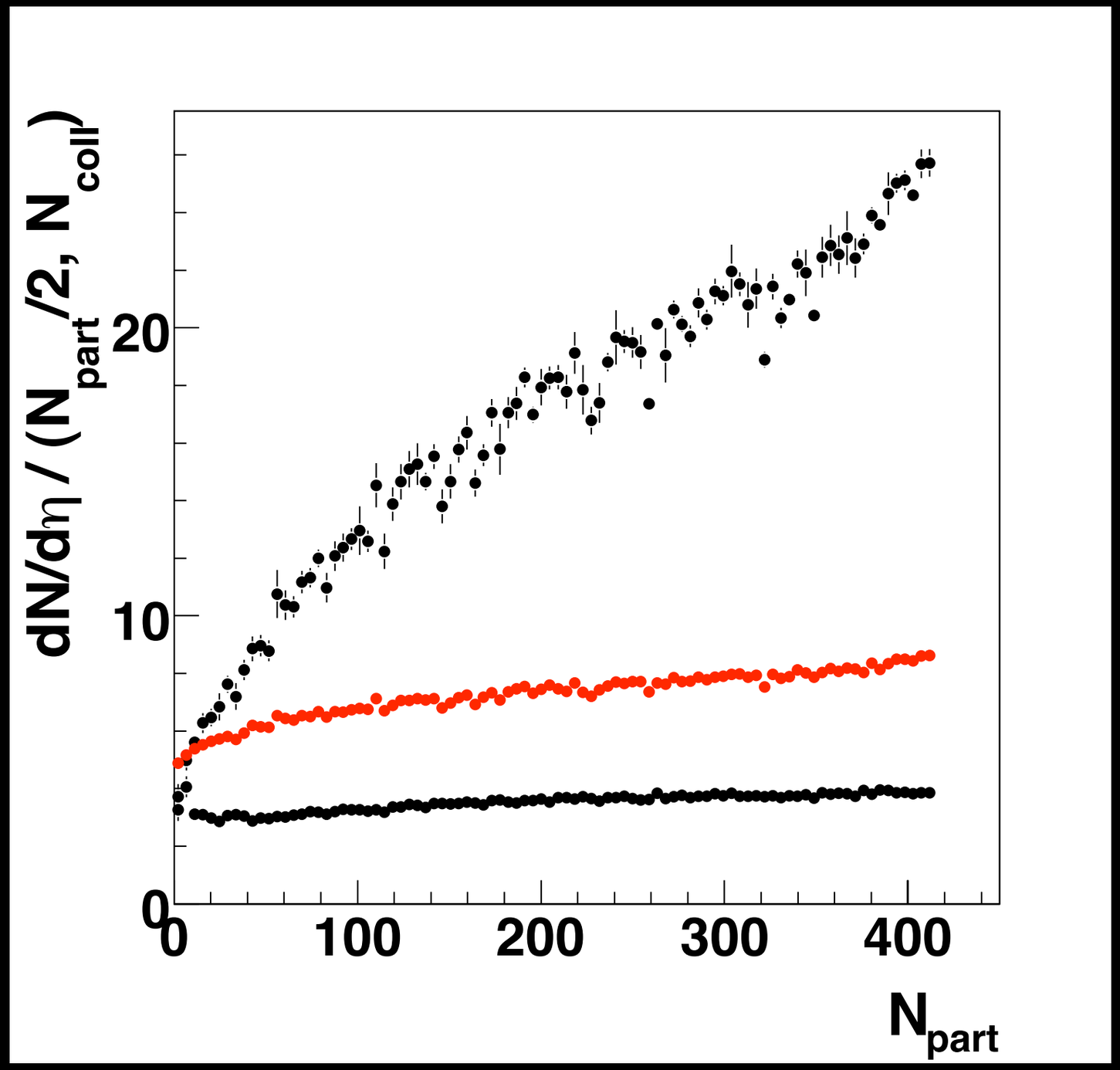
LHC Detectors







Need for Centrality



/N_{part}/2

"PHOBOS prediction"

/N_{coll}

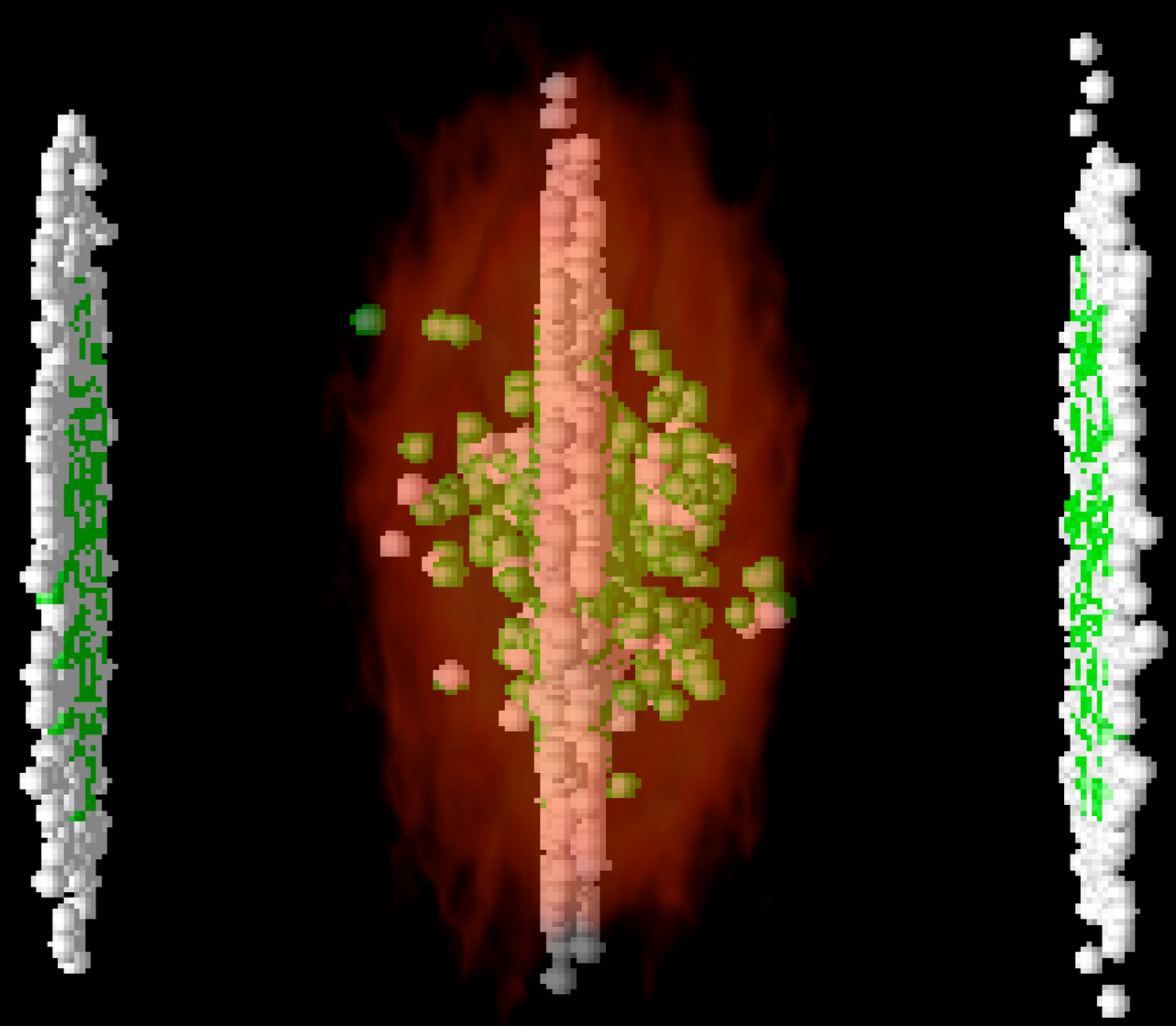
(dominance of semi- hard physics!)

HIJING <u>w/ quenching</u>

Multiplicity at Finite μ_B

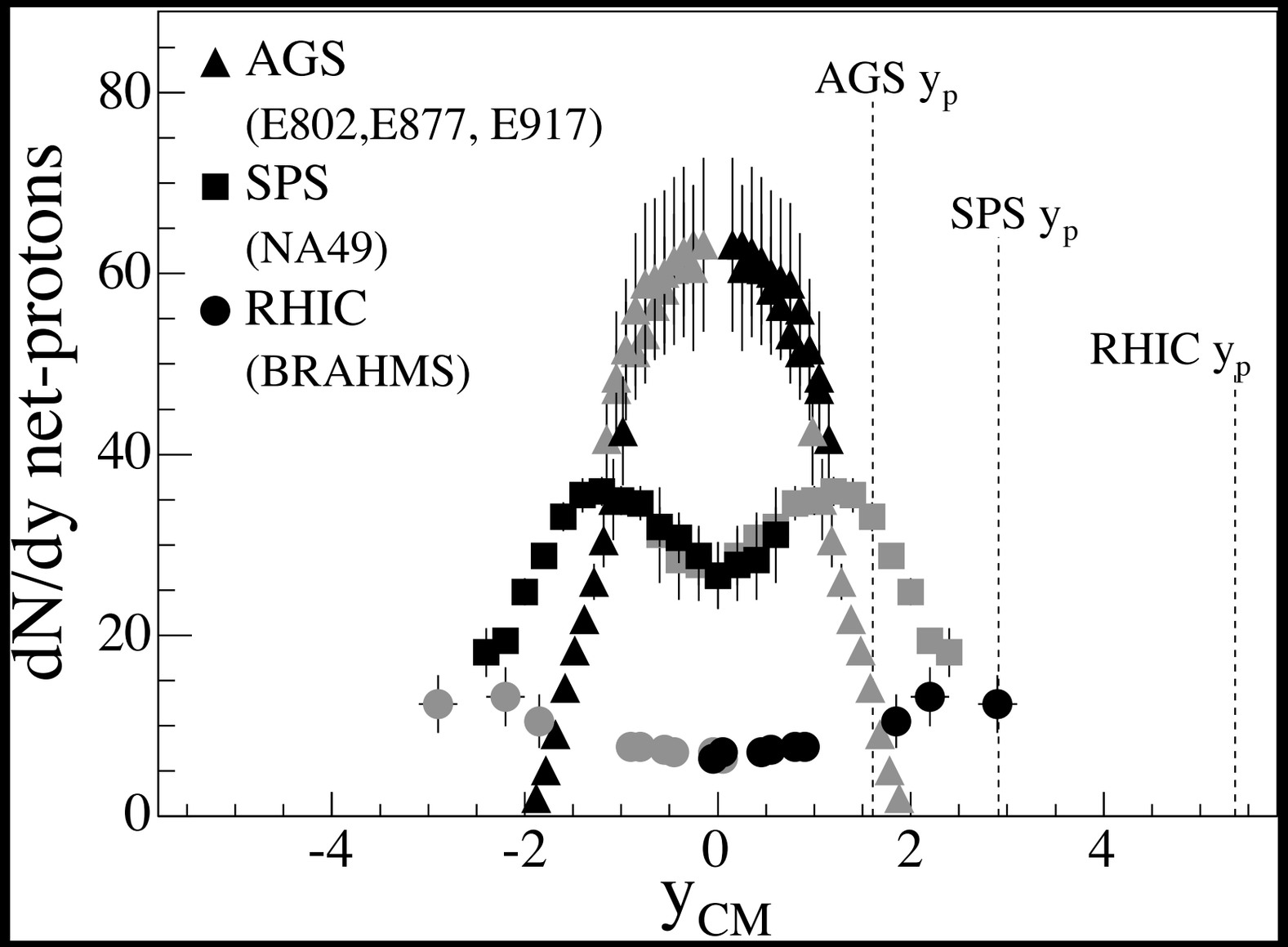
(work with Cleymans, Wheaton, Stankiewicz, UCT)

What about the Baryons?



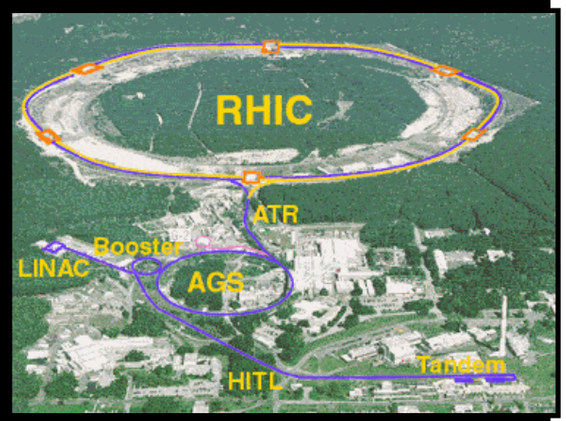
Nucleons are “baryons”, which are conserved and much heavier than pions - an uneven trade!

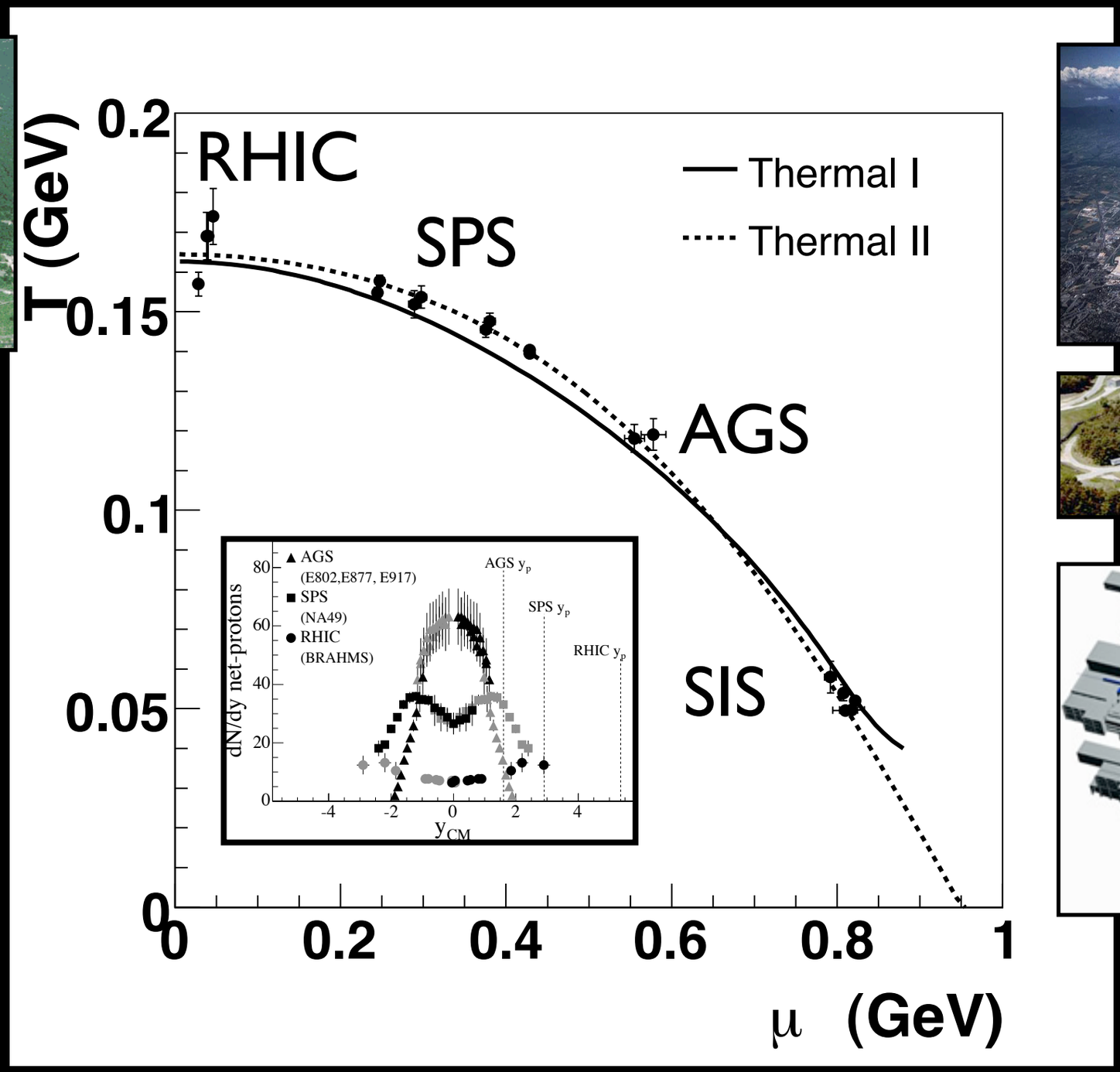
“Baryochemistry”

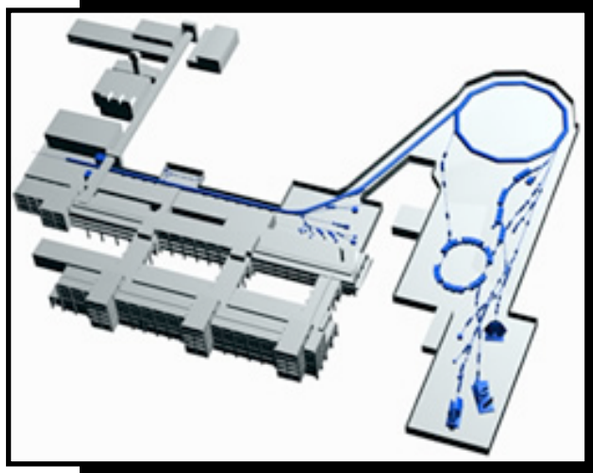


At low energies, the participating baryons are found to “pile up”, with most of them nearly at rest.
At higher energies, relatively little at mid-rapidity

“Phase Diagram”







As beam energy decreases, increases chemical potential

Baryochemistry

In equilibrium:

$$G = E + PV - TS = \mu_B N_B$$

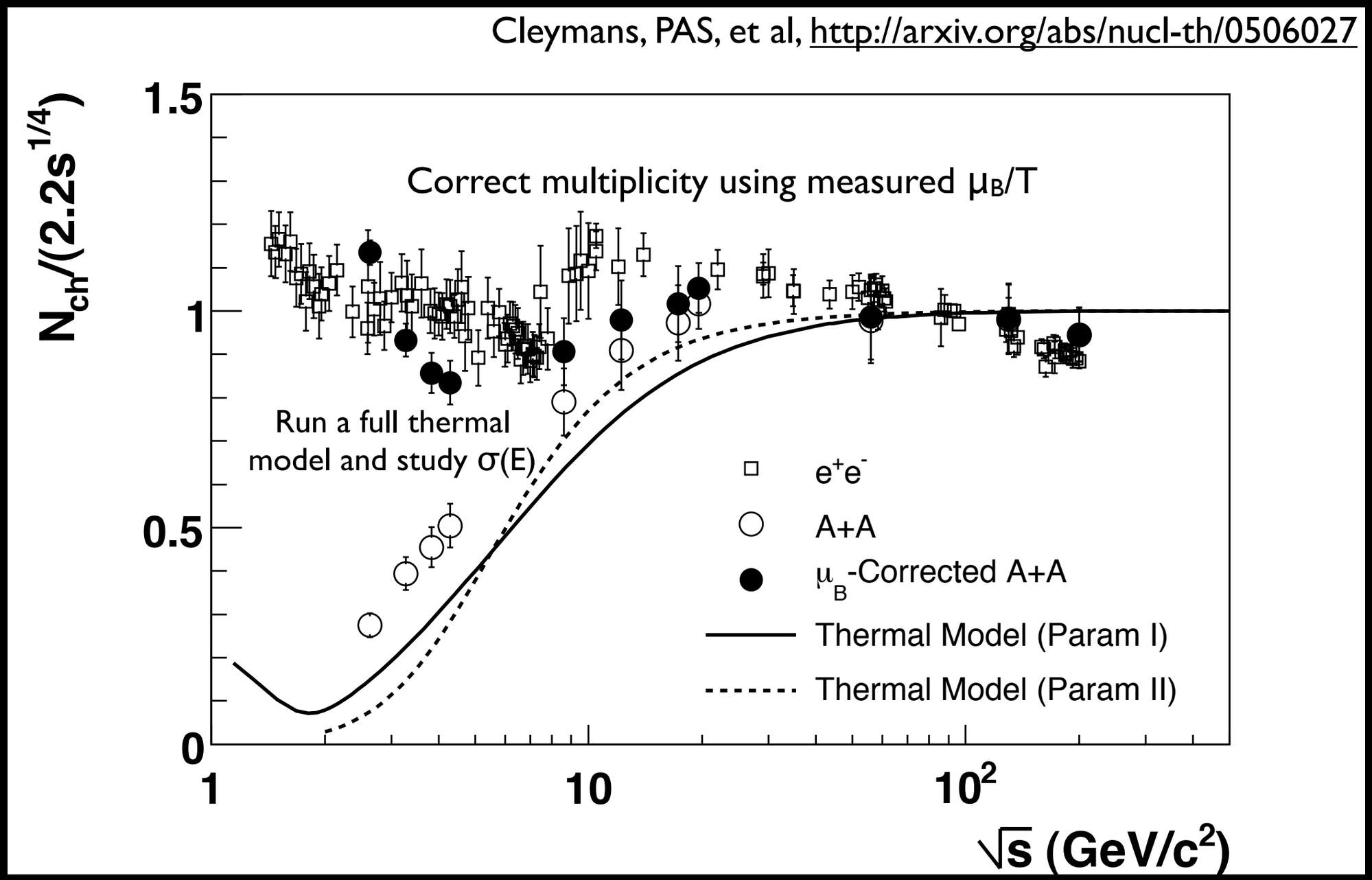
Rearranges to:

$$S = \frac{E + PV}{T} - \frac{\mu_B N_B}{T}$$

So chemical potential reduces entropy, and thus total multiplicity:

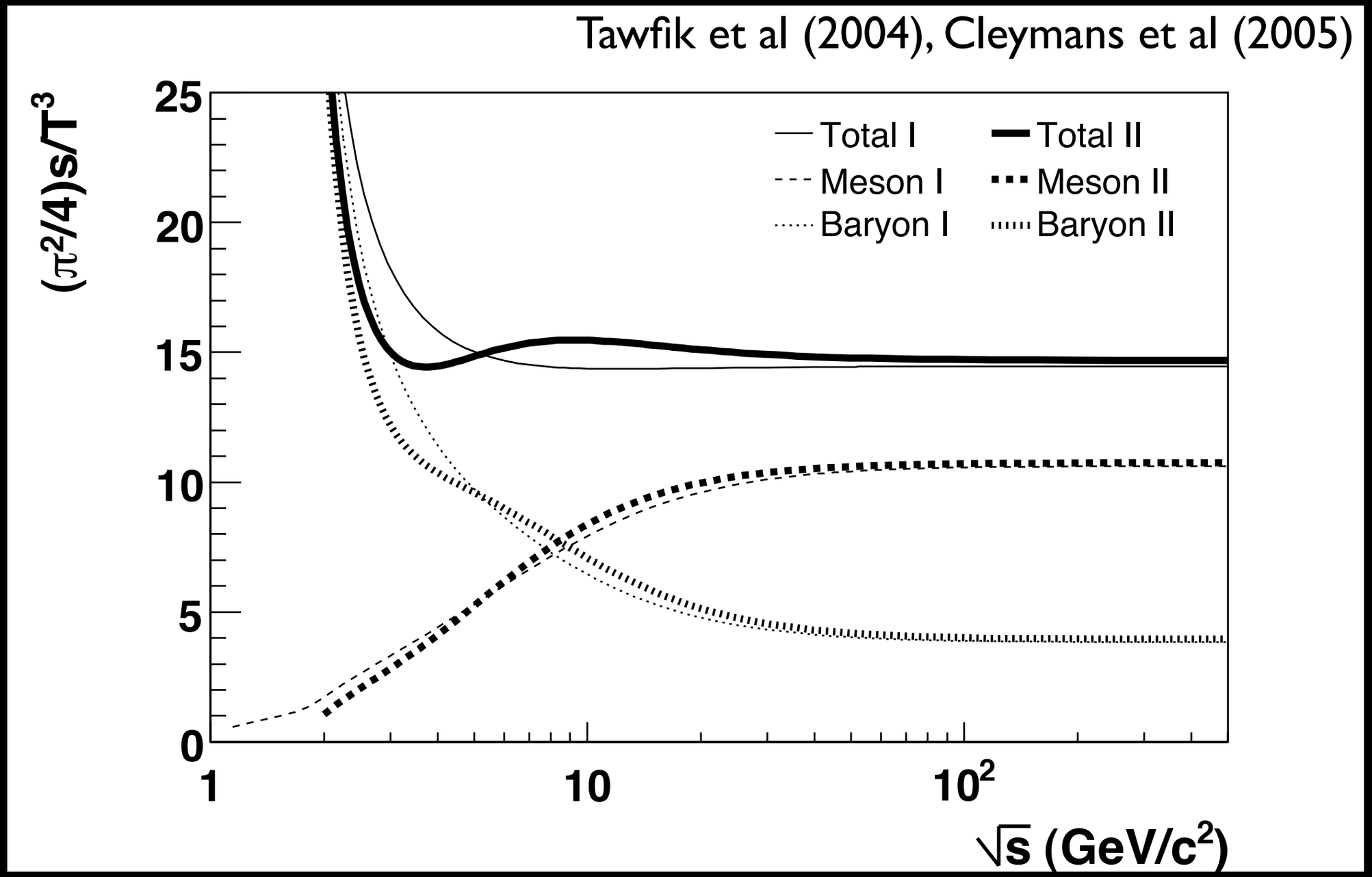
$$\Delta \frac{N_{ch}}{N_{part}/2} \propto \frac{\mu_B}{T}$$

Application to Data



Qualitative model of relationship between baryon density and entropy

Baryons vs. Mesons

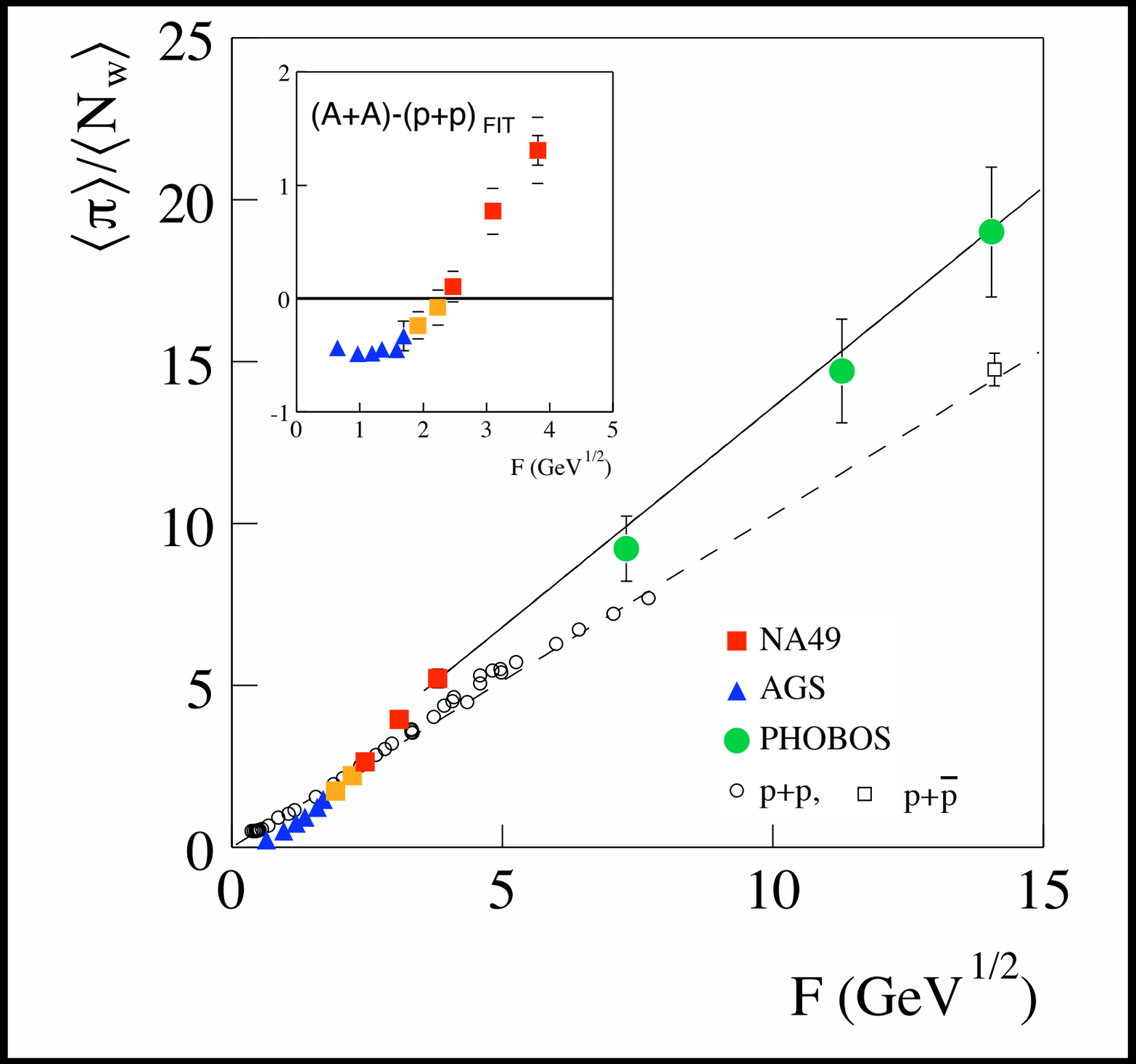


As energy changes, s/T^3 (~degrees of freedom) remain constant if mesons AND baryons are included

NA49 “kink”

“Entropy?”

where are the baryons?



~Landau variable...

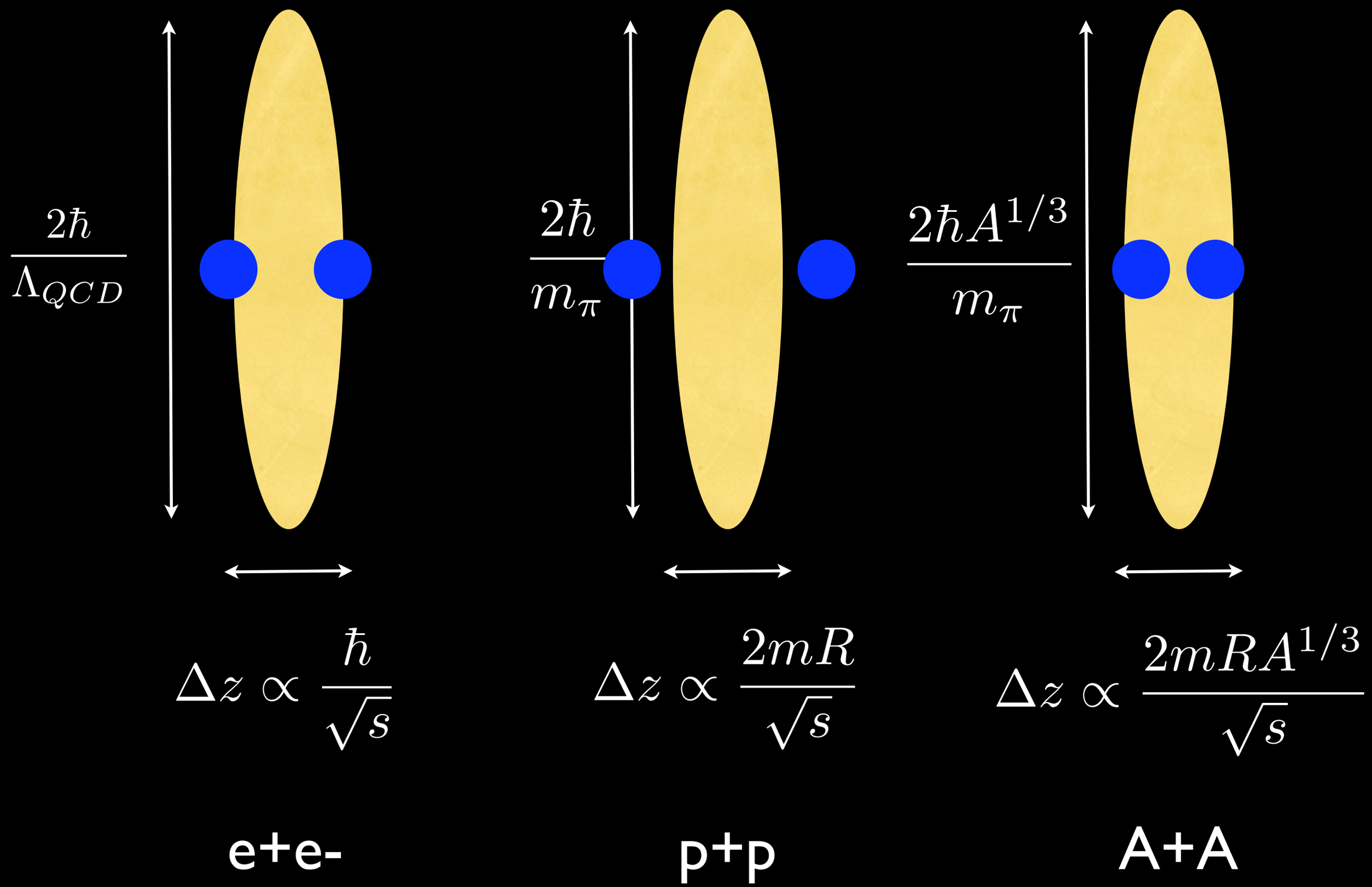
Conclusions

- **LHC will be an exciting place**
  - Lots of ideas how things will turn out
  - Only one way to really know...
  - Concrete predictions should be made *now*, before p+p turn-on in 2007!

- **Low energy RHIC will be an exciting place**
  - Baryon number and entropy will become entangled - dynamical consequences?

One can risk sketching the energy evolution of the b-spectrum without appealing to Monte Carlo. Asymptotically the main contribution to the rapidity plateau density $\rho(y_{\parallel}) \sim N'(W/\mathrm{ch}\,y_{\parallel}) \sim \sqrt{\alpha_s}N(W)$ comes from non-jet flow of <u>soft</u> hadrons which do not influence the jet axis. It is the parametrically smaller contribution of <u>hard</u> radiation $\sim\alpha_s N(W)$ that is pushed out from the region $y_{\parallel} \approx 0$ due to the bias. Therefore the dip should grow shallower (at least in relative scale) when W increases.

Azimov, Dokshitzer, Khoze, Troian (1985)



Similar geometries <u>and</u> energy densities (& net baryons?)