Limiting Fragmentation at RHIC and LHC Energies

Multiparticle Dynamics Group Semimar

Summer Semester 2019

Outline

Important variables in heavy-ion coll.

Rapidity:

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

Pseudorapidity:

$$\eta = \frac{1}{2} \ln \frac{|\vec{p}| + p_z}{|\vec{p}| - p_z} = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

Beam rapidity:

$$\mathrm{y}_{\mathrm{beam}} = \mp \ln\left(\frac{\sqrt{s_{\mathrm{NN}}}}{m_{\mathrm{p}}}\right)$$

From y- to eta-space

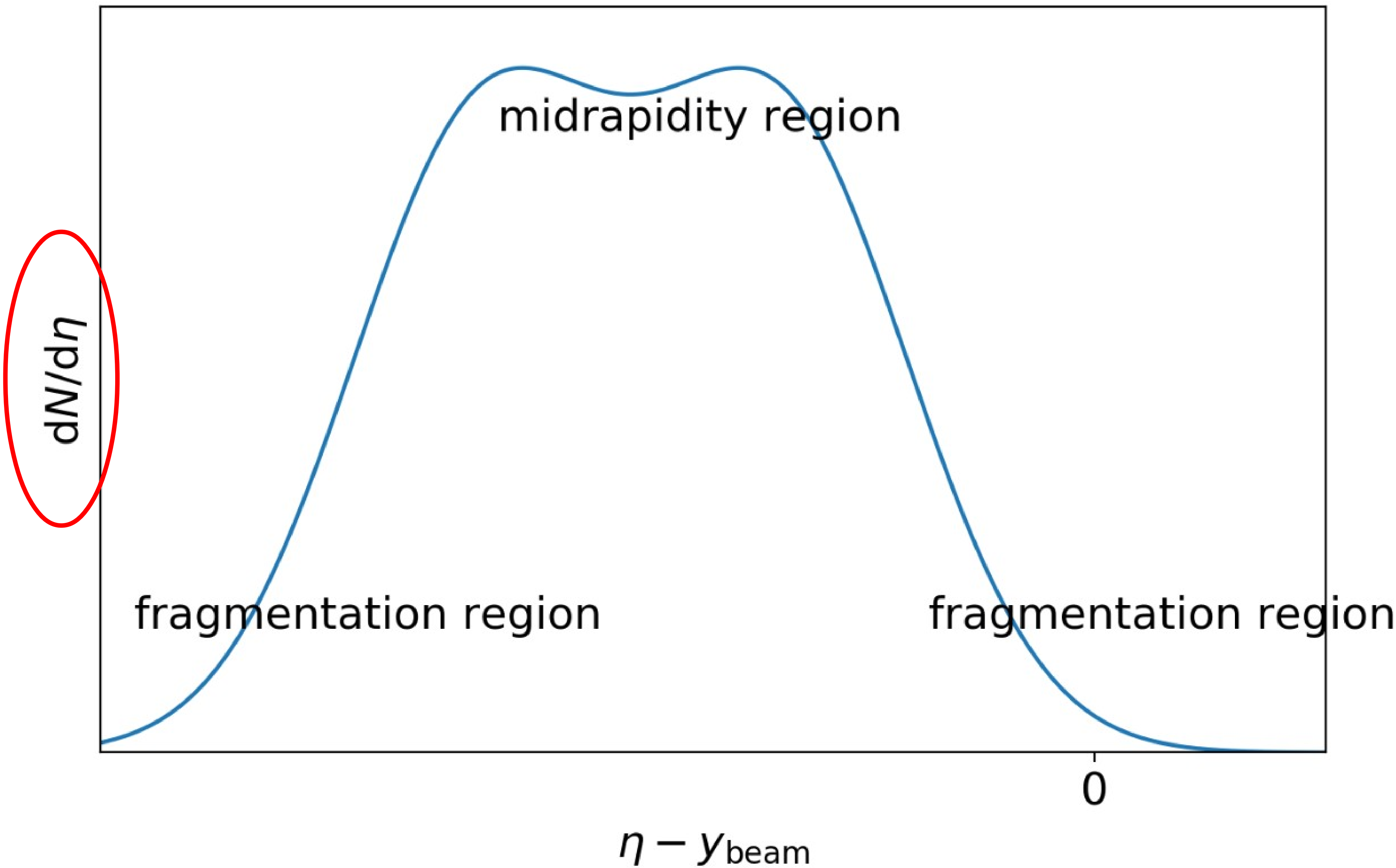
$$\frac{\mathrm{d}N}{\mathrm{d}\eta} = \frac{\mathrm{d}y}{\mathrm{d}\eta}\frac{\mathrm{d}N}{\mathrm{d}y} = \mathrm{J}\left(\eta, \frac{m}{p_\perp}\right)\frac{\mathrm{d}N}{\mathrm{d}y}$$

$$\mathrm{J}\left(\eta, \frac{m}{p_\perp}\right) = \frac{\cosh(\eta)}{\sqrt{1 + \left(\frac{m}{p_\perp}\right)^2 + \sinh^2(\eta)}}$$

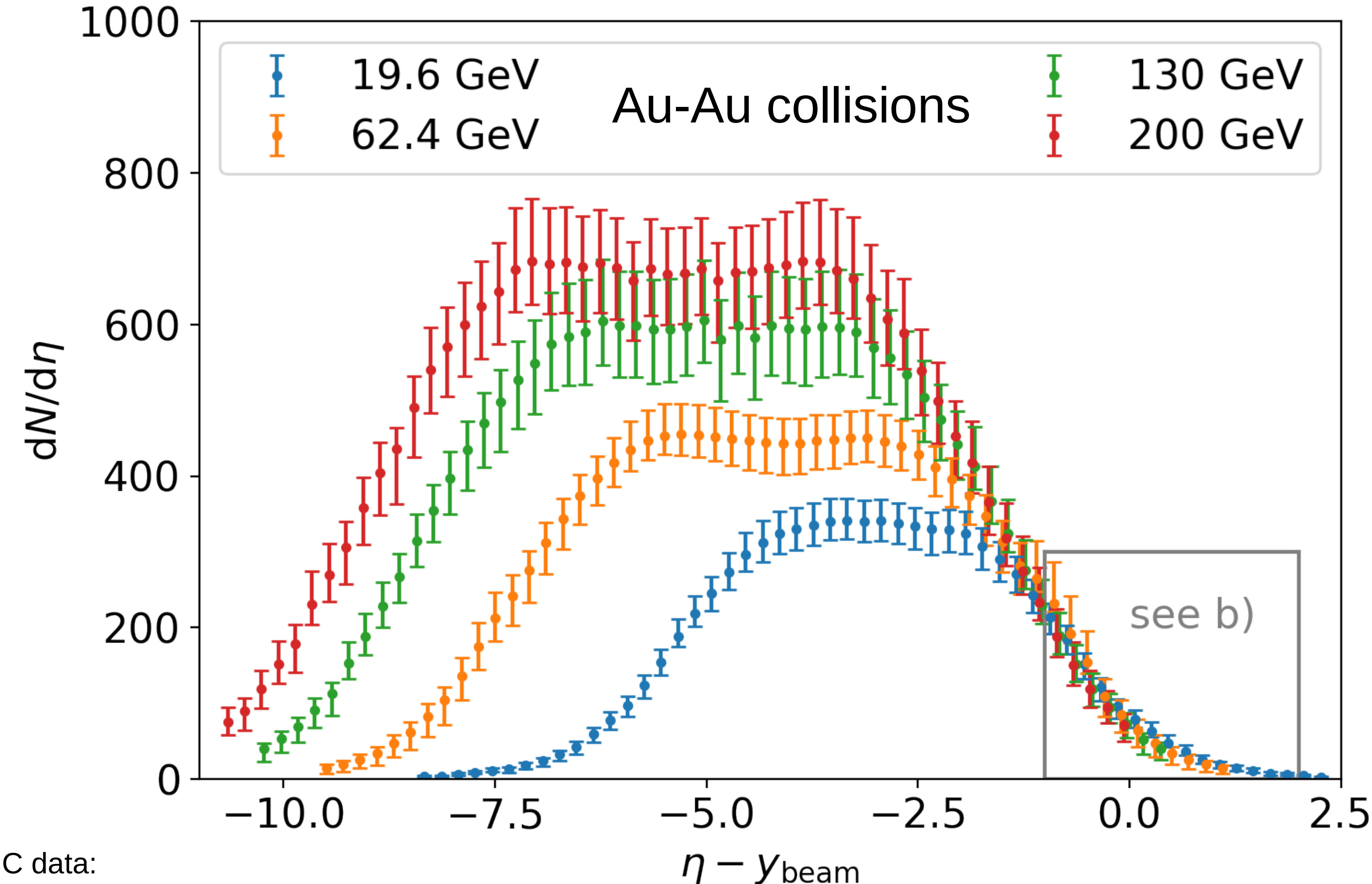
$$\langle p_\perp^{\mathrm{eff}} \rangle = \frac{\langle m \rangle \mathrm{J}_0}{\sqrt{1 - \mathrm{J}_0^2}}$$

$$\mathrm{J}\left(\eta, \mathrm{J}_0\right) = \frac{\cosh(\eta)}{\sqrt{1 + \frac{1-\mathrm{J}_0^2}{\mathrm{J}_0^2} + \sinh^2(\eta)}}$$

Main focus: the fragmentation region

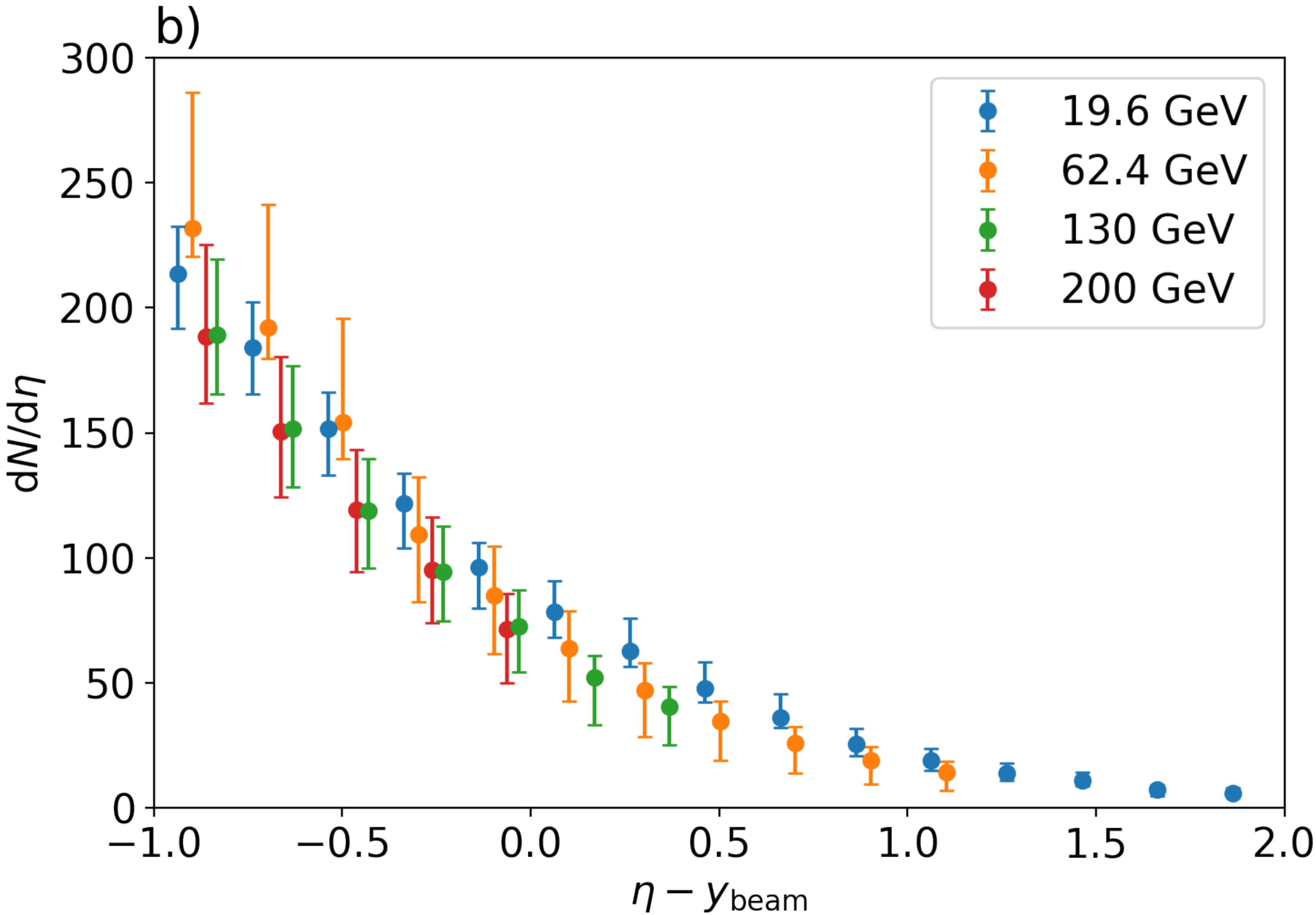


Limiting fragmentation at RHIC



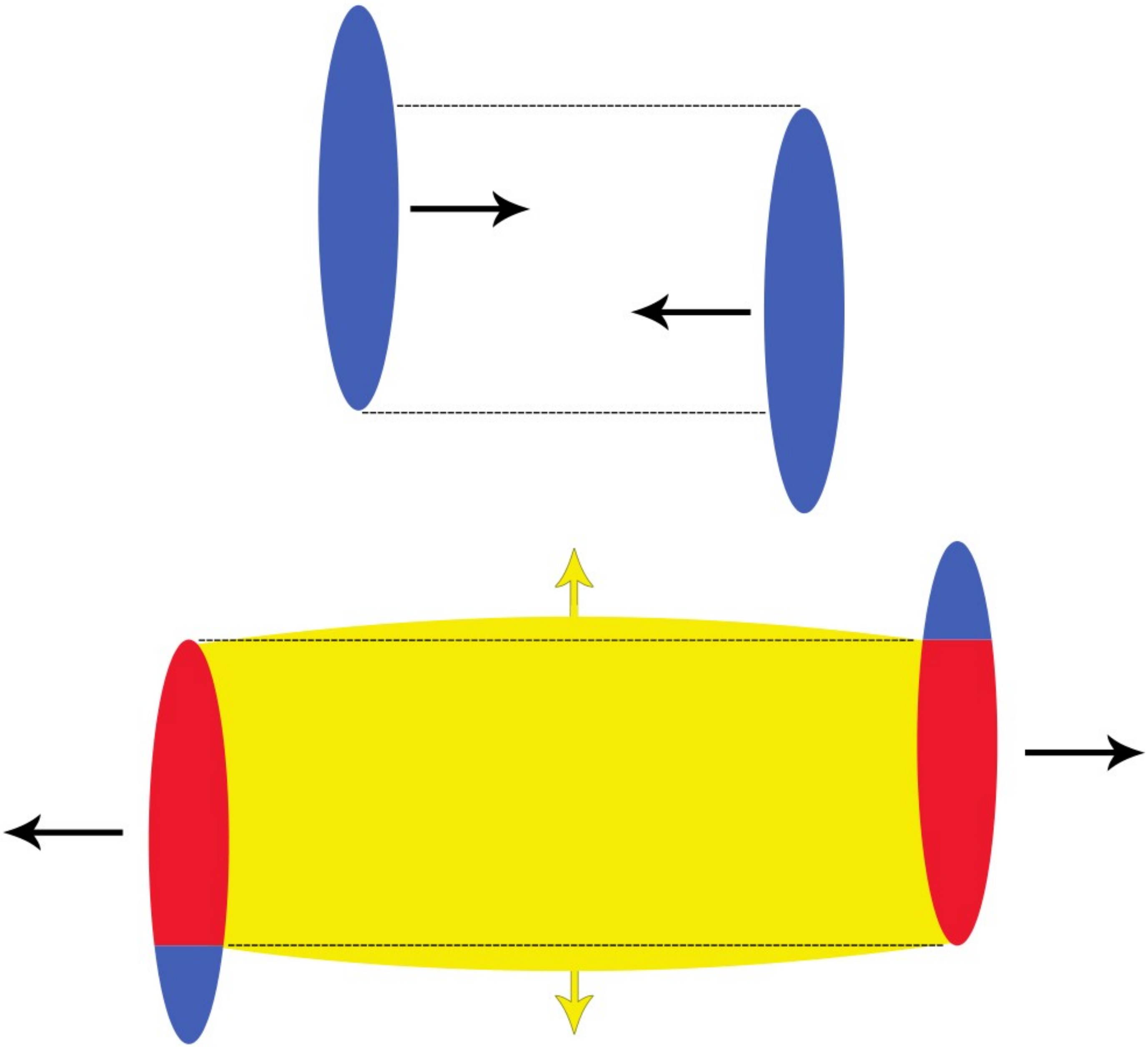
RHIC data:
B. Alver et al., Phys. Rev. C, 83, 024913 (2011)

Limiting fragmentation at RHIC



Outline

Three sources of particle production



Resulting rapidity distributions

Lorentz-invariant cross-section (exp. observable):

$$E\frac{\mathrm{d}^3 N}{\mathrm{d}p^3} = \frac{\mathrm{d}^2 N}{2\pi p_\perp \,\mathrm{d}p_\perp \,\mathrm{d}y} = \frac{\mathrm{d}^2 N}{2\pi m_\perp \,\mathrm{d}m_\perp \,\mathrm{d}y}$$

Rapidity distributions for each source:

$$\frac{\mathrm{d}N_k}{\mathrm{d}y}(y,t) = c_k \int m_\perp E\frac{\mathrm{d}^3 N_k}{\mathrm{d}p^3}\,\mathrm{d}m_\perp$$

Total rapidity distribution:

$$\frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}y}(y,t=\tau_{\mathrm{f}}) = N_{\mathrm{ch}}^{1} R_1(y,\tau_{\mathrm{f}}) + N_{\mathrm{ch}}^{2} R_2(y,\tau_{\mathrm{f}}) + N_{\mathrm{ch}}^{\mathrm{gg}} R_{\mathrm{gg}}(y,\tau_{\mathrm{f}})$$

Underlying PDE

Boltzmann-Gibbs statistics:

$\Rightarrow$ Maxwell-Jüttner for $t \longrightarrow \infty$

$$E\frac{\mathrm{d}^3N}{\mathrm{d}p^3}\bigg|_{\mathrm{eq}} \propto E\exp\left(-E/T\right) = \mathrm{m}_\perp\cosh\left(y\right)\exp\left(-m_\perp\cosh(y)/T\right)$$

Time evolution via Fokker-Planck equation:

$$\frac{\partial}{\partial t}R_k(y,t) = -\frac{\partial}{\partial y}\left[J_k(y,t)R_k(y,t)\right] + \frac{\partial^2}{\partial y^2}\left[D_k(y,t)R_k(y,t)\right]$$

drift diffusion

const. diffusion + drift linear in y = Uhlenbeck-Ornstein process
(equilibrium distr. are Gaussians at midrapidity)

Need for sinh-drift

Problem:
Linear drift does not reproduce Maxwell-Jüttner

Solution: $$J_k(y,t) = -A_k \sinh(y)$$

From FDT: $$A_k = m_\perp D_k / T$$

Drift force of the **fragmentation sources** depends on position in y-space (initial conditions).

Need for sinh-drift

Testing:
Determine A_k from peak positions
and compute D_k .

Result:
The value will be too small for actual data.
The formula for A_k only accounts for
the diffusive processes and takes not into
account the **collective expansion** of the sources.

Therefore we fit the drift coefficient to the data.

Equilibrium

Equilibrium distribution:

$$\frac{\mathrm{d}N_{\mathrm{eq}}}{\mathrm{d}y} = C\left(m_\perp^2 T + \frac{2m_\perp T^2}{\cosh y} + \frac{2T^3}{\cosh^2 y}\right)\exp\left(-\frac{m_\perp \cosh y}{T}\right)$$

with $C \propto N_{\mathrm{ch}}^{\mathrm{total}}$ (net baryons for stopping).

All this can now be compared to data!

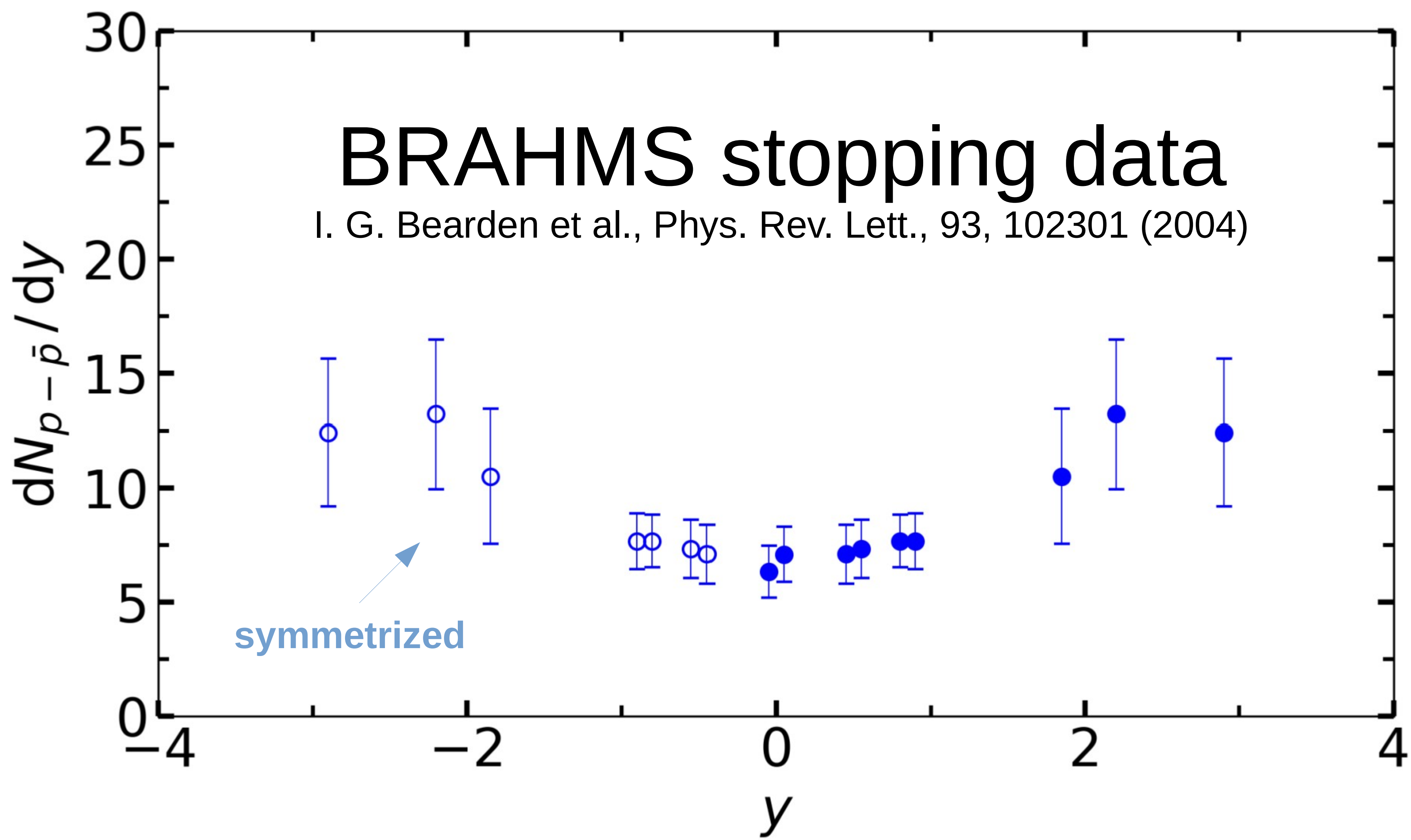
Outline

Stopping

- Net-proton distributions are measured
- No midrapidity source in stopping, since protons and antiprotons are produced in equal amounts there
- We use dimensionless FPE:

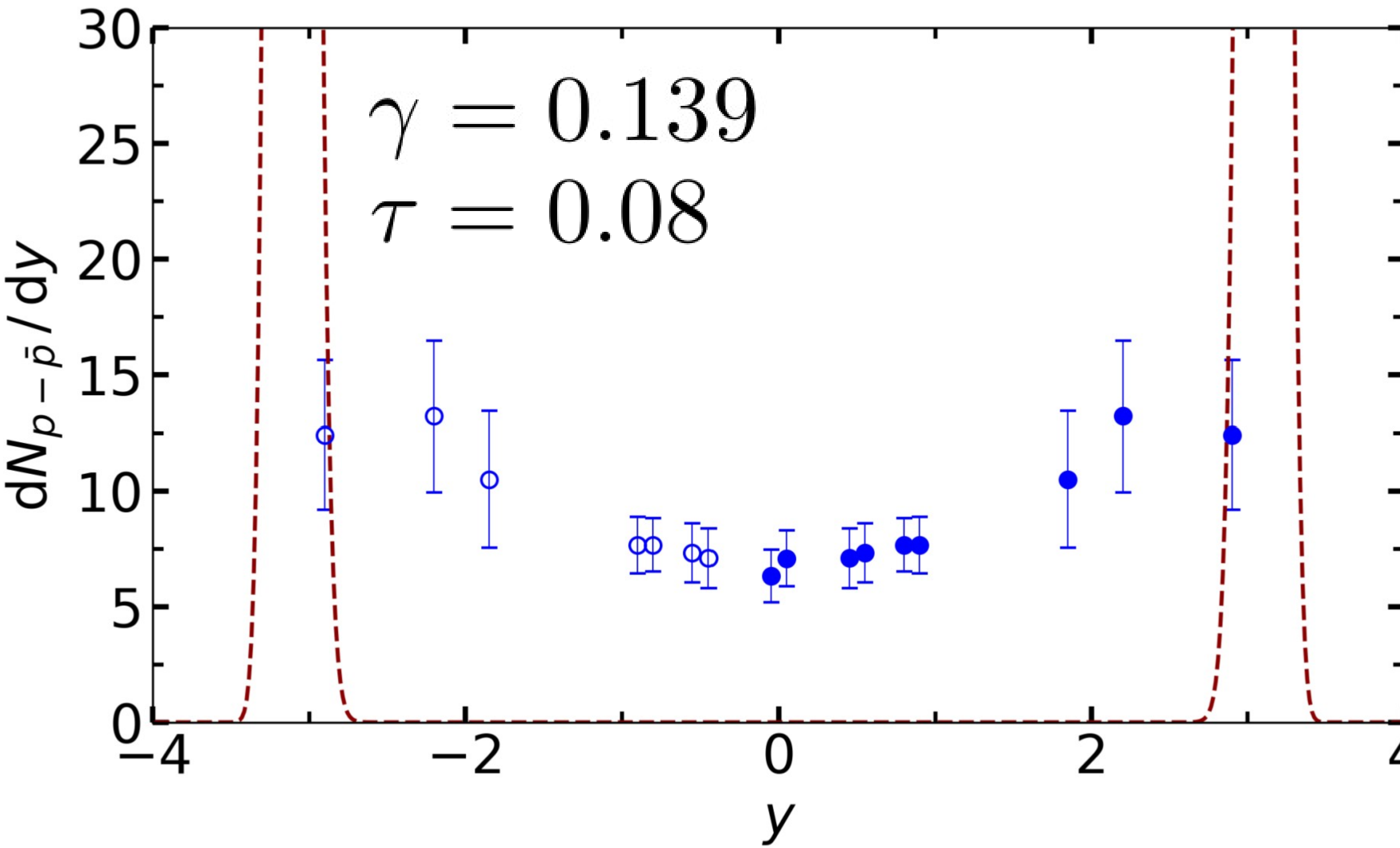
$$\frac{\partial f}{\partial \tau}(y,\tau) = \frac{\partial}{\partial y}\left[\sinh(y)\ f(y,\tau)\right] + \gamma\ \frac{\partial^2}{\partial y^2} f(y,\tau)$$

How well do the different models work?



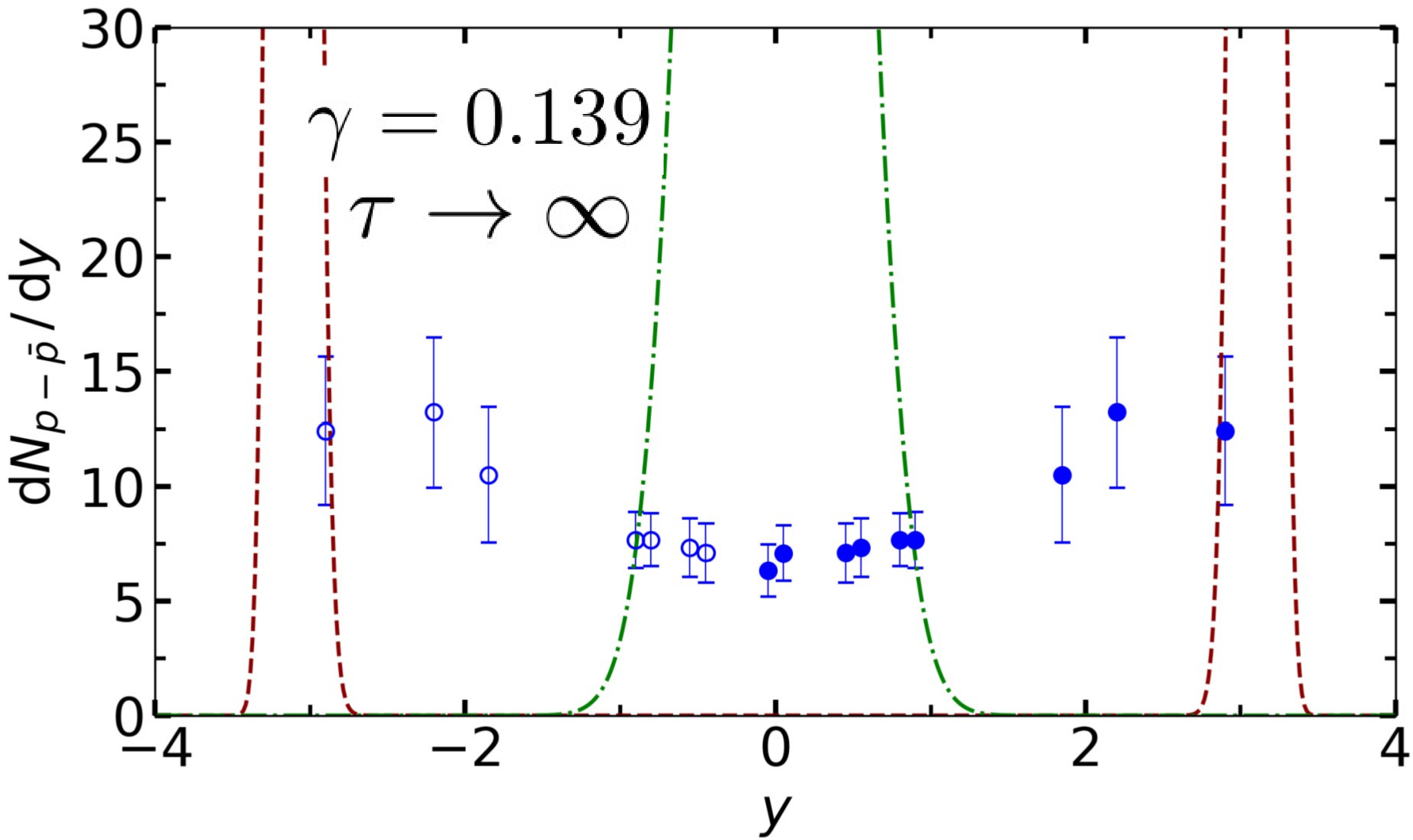
AuAu collission at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$

How well do the different models work?



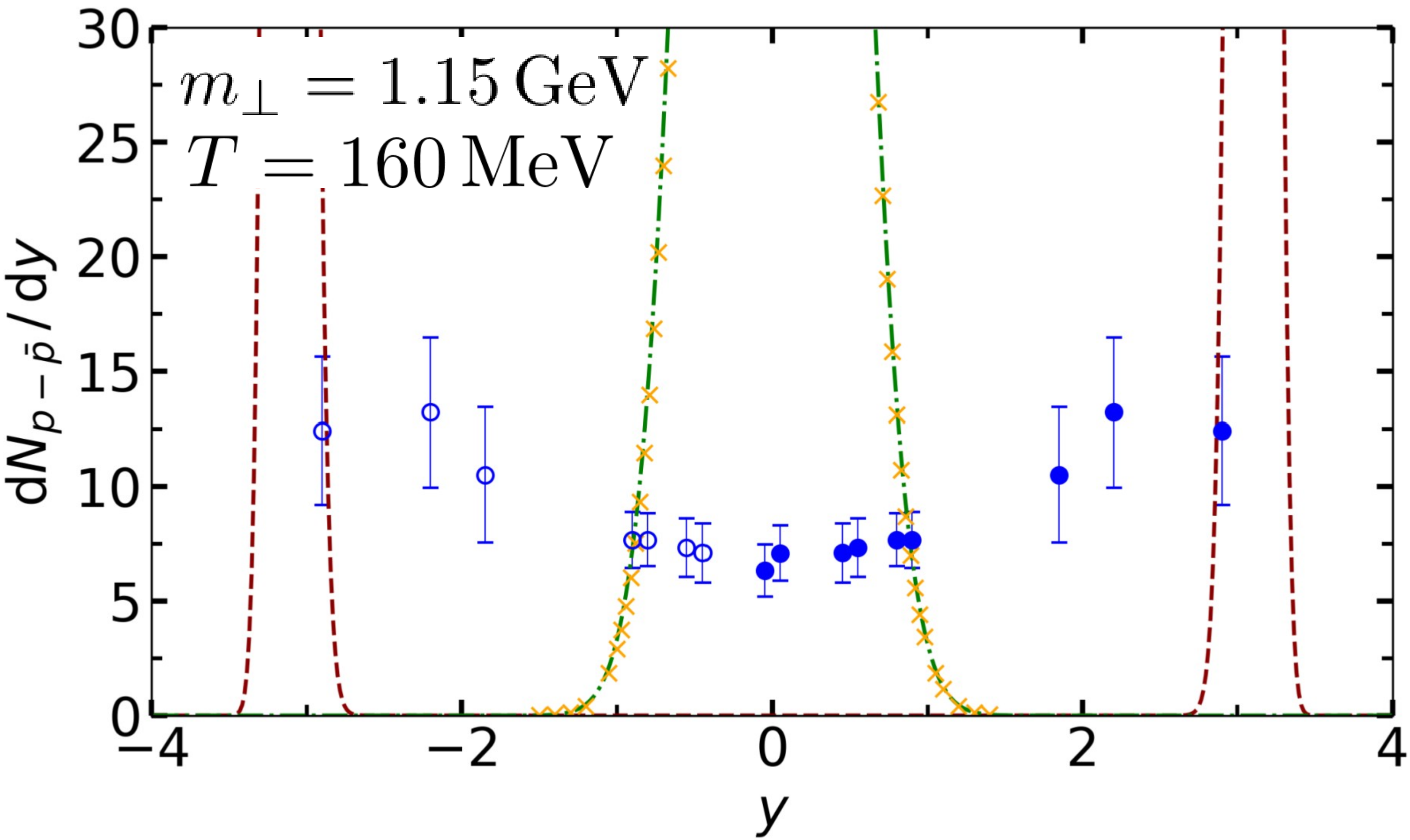
Theoretical value for drift parameter, time like fit

How well do the different models work?



Theoretical value for drift parameter, time $\to \infty$

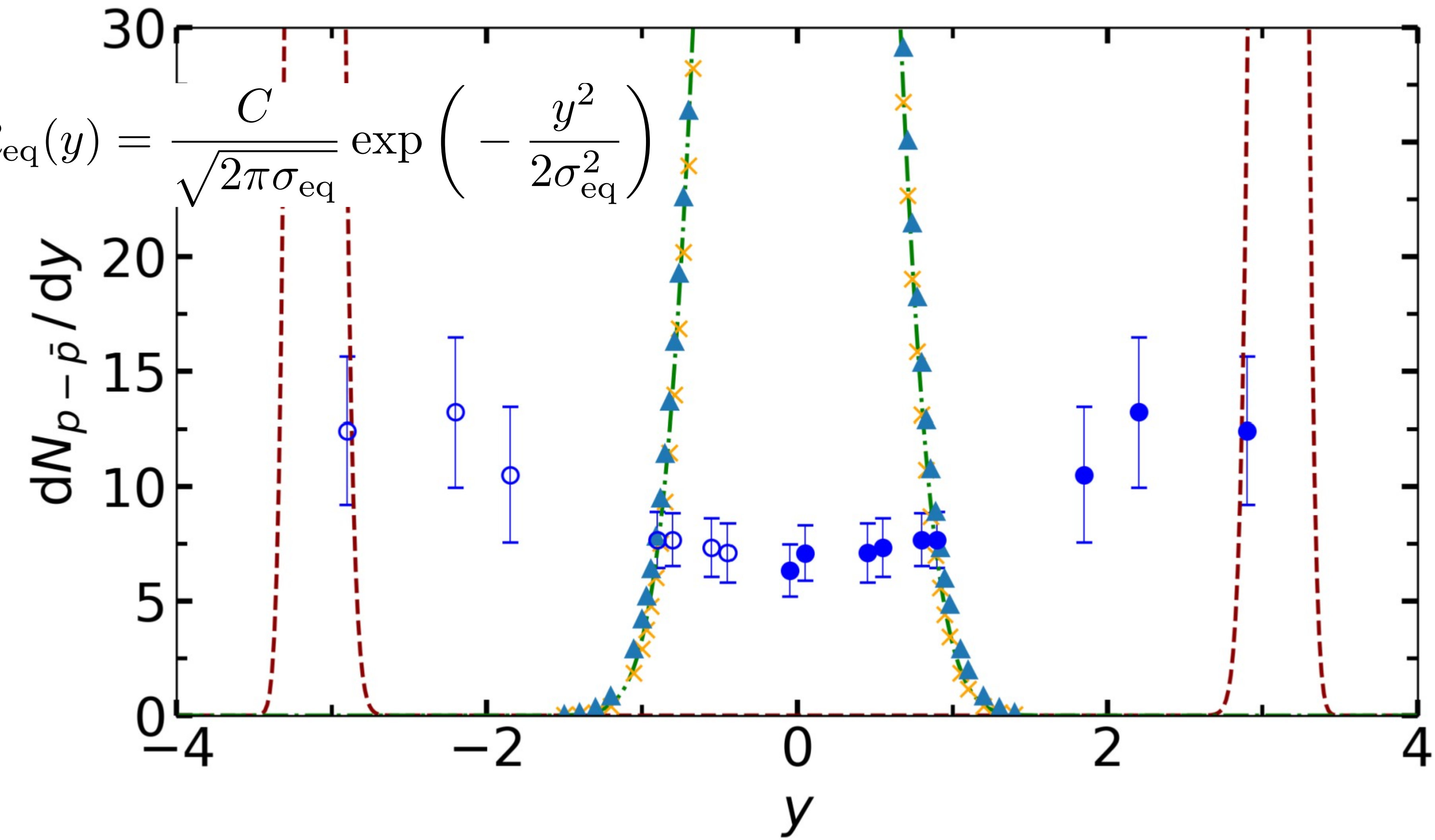
How well do the different models work?



Maxwell-Jüttner distribution

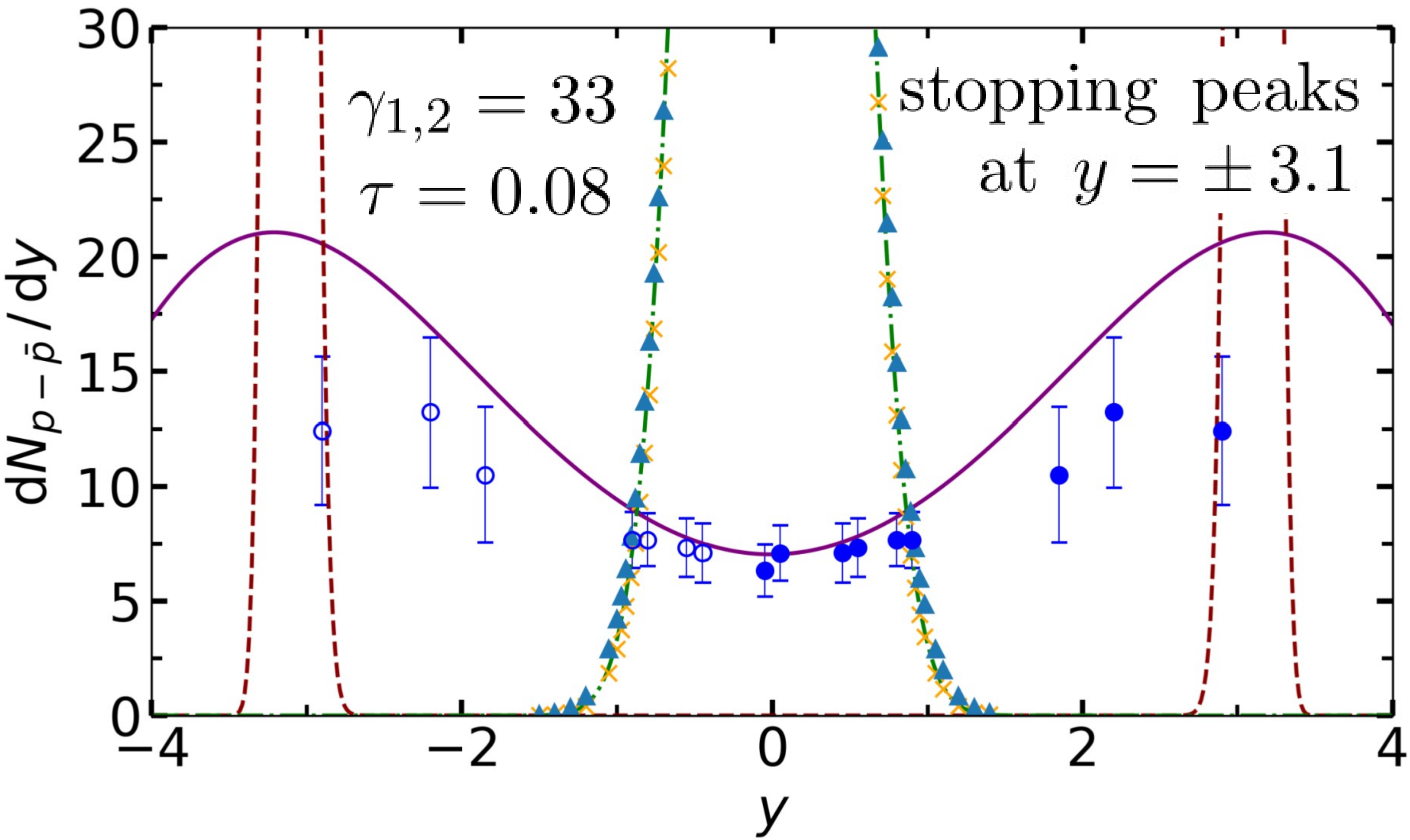
How well do the different models work?

$$R_{\mathrm{eq}}(y) = \frac{C}{\sqrt{2\pi\sigma_{\mathrm{eq}}}} \exp\left(- \frac{y^2}{2\sigma_{\mathrm{eq}}^2} \right)$$



Equilibrium solution of linear-drift model (analytical)

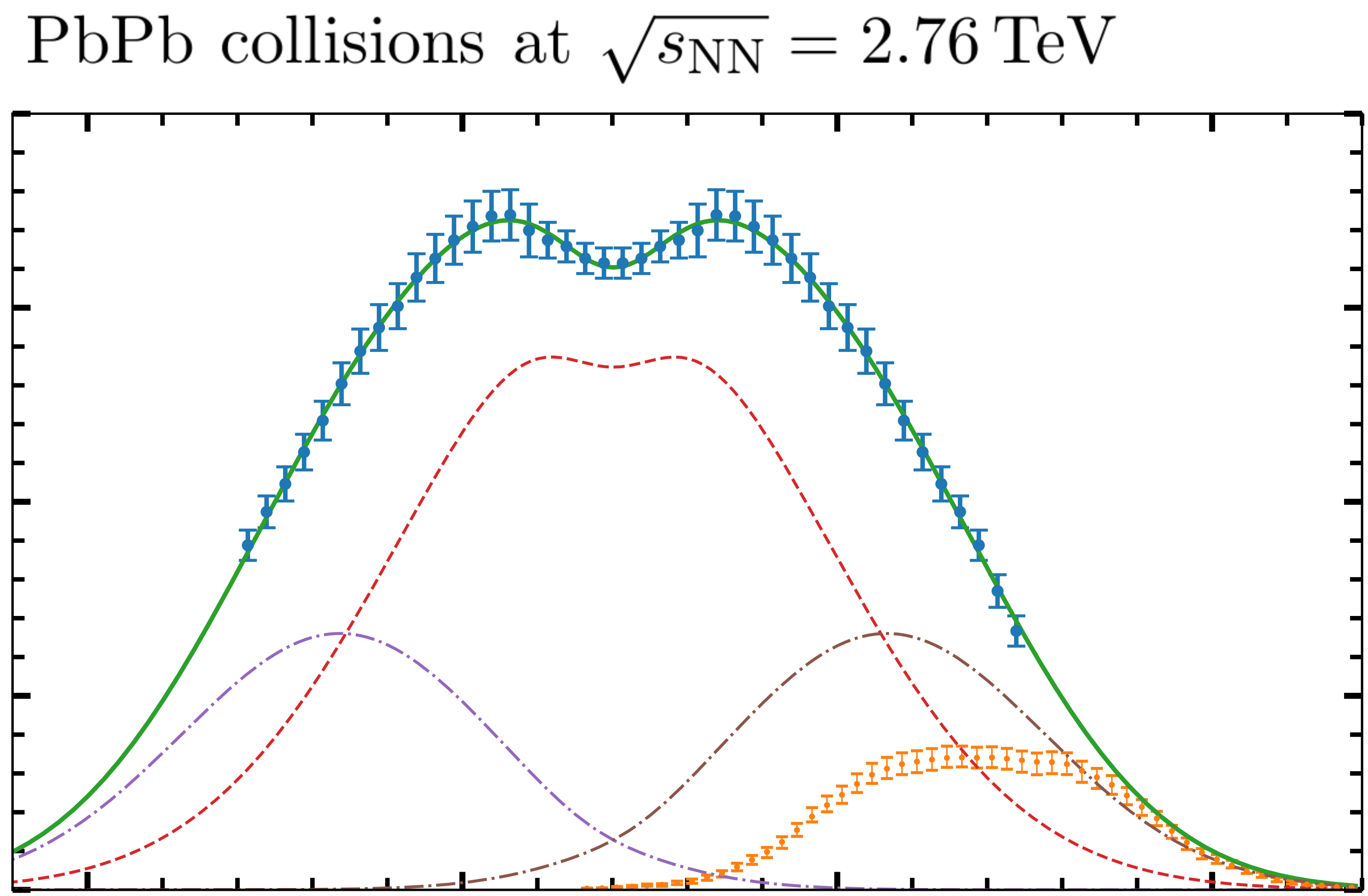
How well do the different models work?



Relativistic diffusion model, parameter fitted to data

Outline

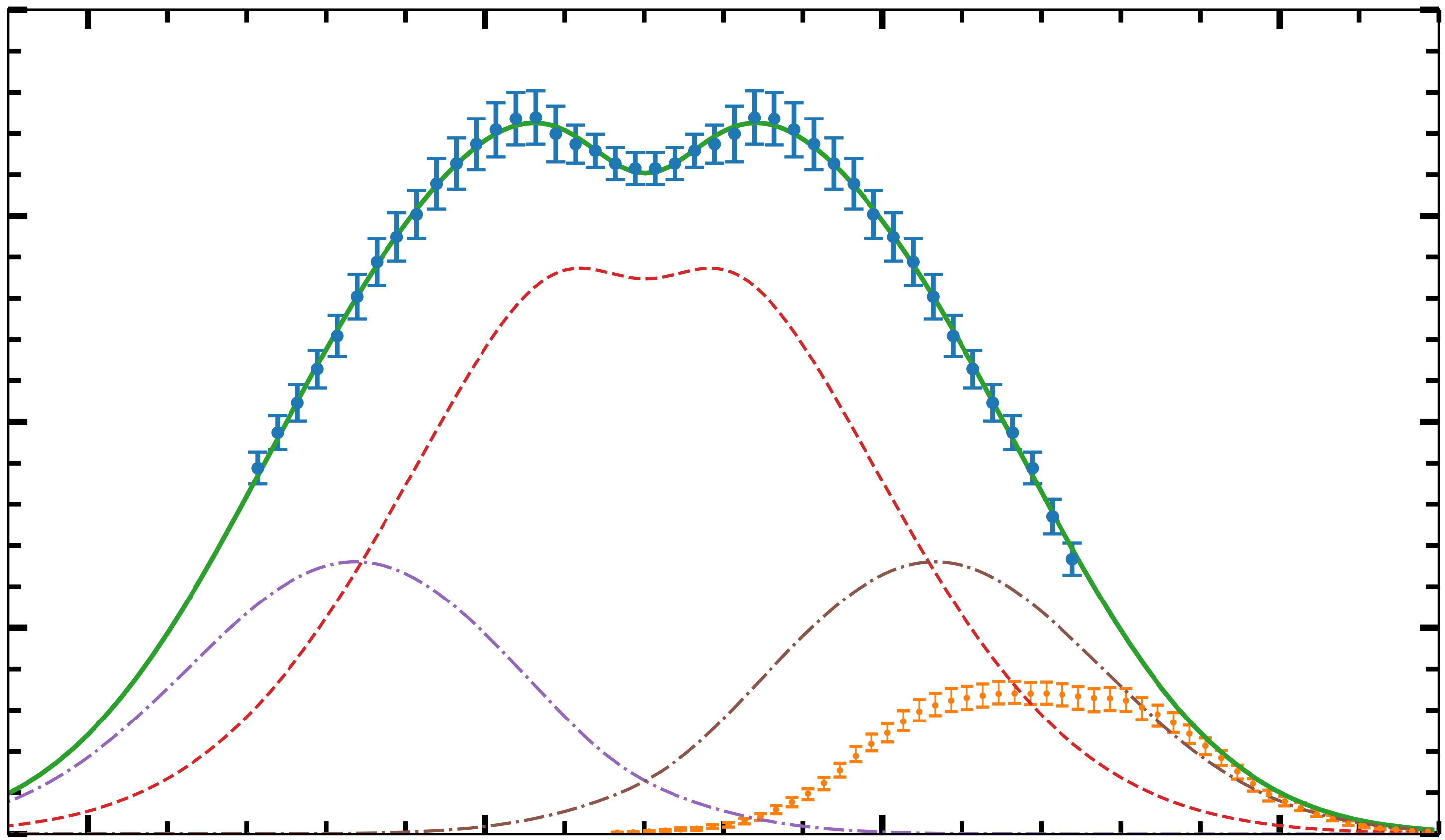
Analytical model, linear drift-term



ALICE data: E. Abbas et al., Phys. Lett. B, 726, 610 (2013)

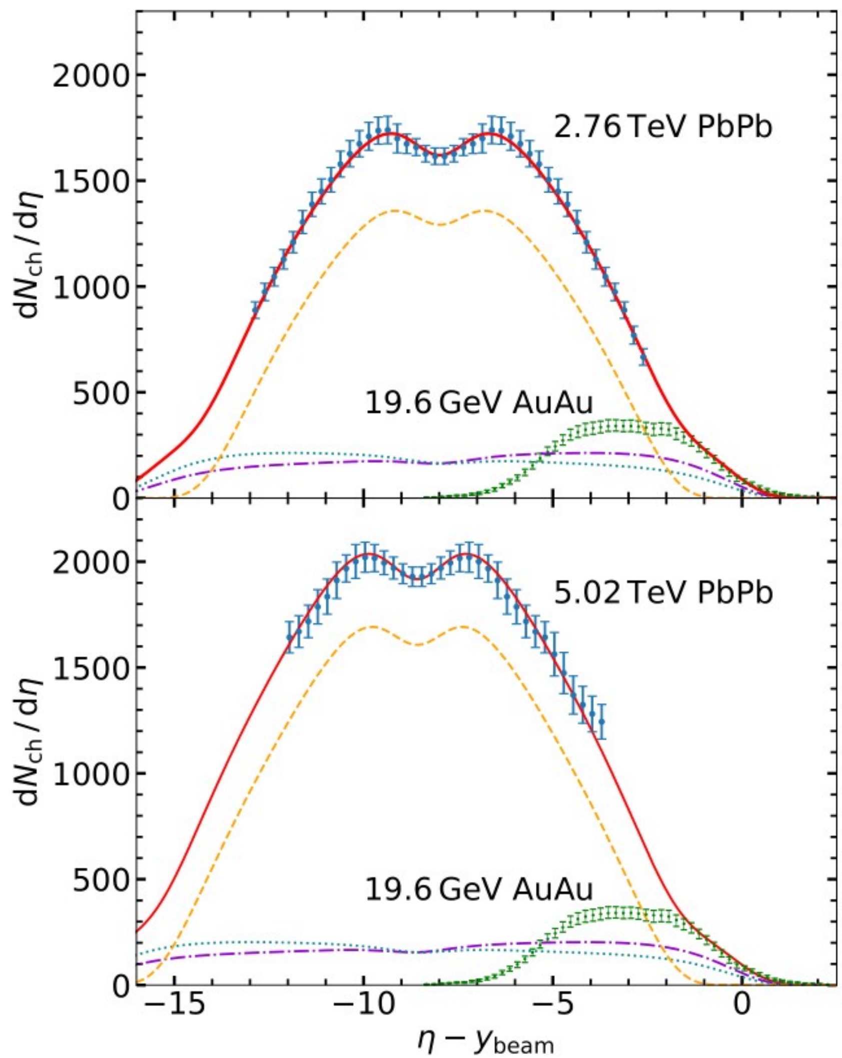
RHIC data: B. Alver et al., Phys. Rev. C, 83, 024913 (2011)

Analytical model, linear drift-term



$\sqrt{s_{NN}}$ (TeV)	y_{beam}	$N_{1,2}$	N_{gg}	$\langle y_{1,2} \rangle$	$\Gamma_{1,2}$	Γ_{gg}	χ^2	χ^2/ndf
2.76	± 7.987	3505	10681	± 3.64	4.98	6.38	2.44	0.07
5.02	± 8.586	4113	14326	± 4.67	4.99	6.38	1.17	0.04

Can the sinh-model reproduce data?



ALICE data:
E. Abbas et al., Phys. Lett. B, 726, 610 (2013)

RHIC data:
B. Alver et al., Phys. Rev. C, 83, 024913 (2011)

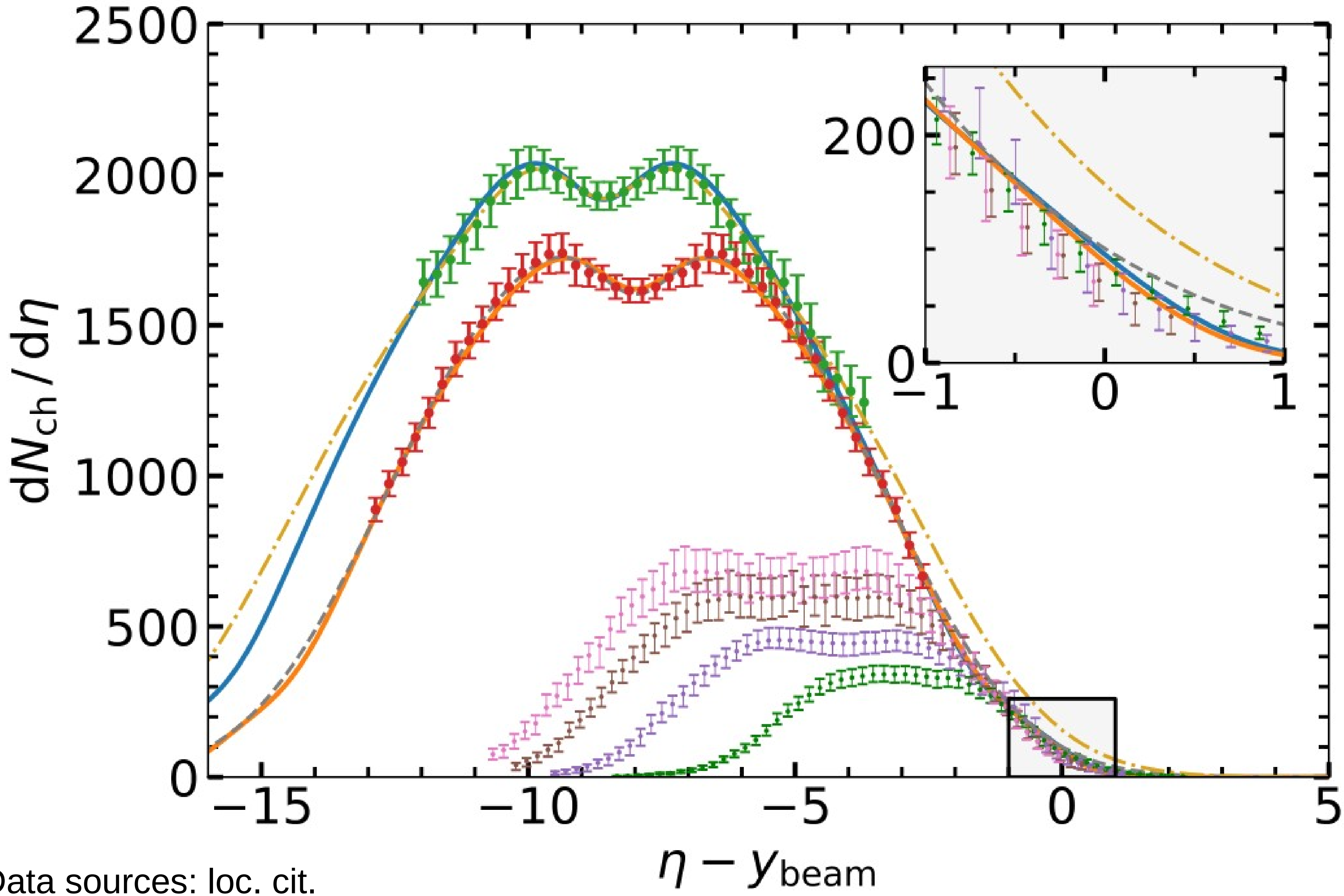
ALICE data:
J. Adam et al., Phys. Lett. B, 772, 567 (2017)

RHIC data:
loc. cit.

Same data on the next slide.

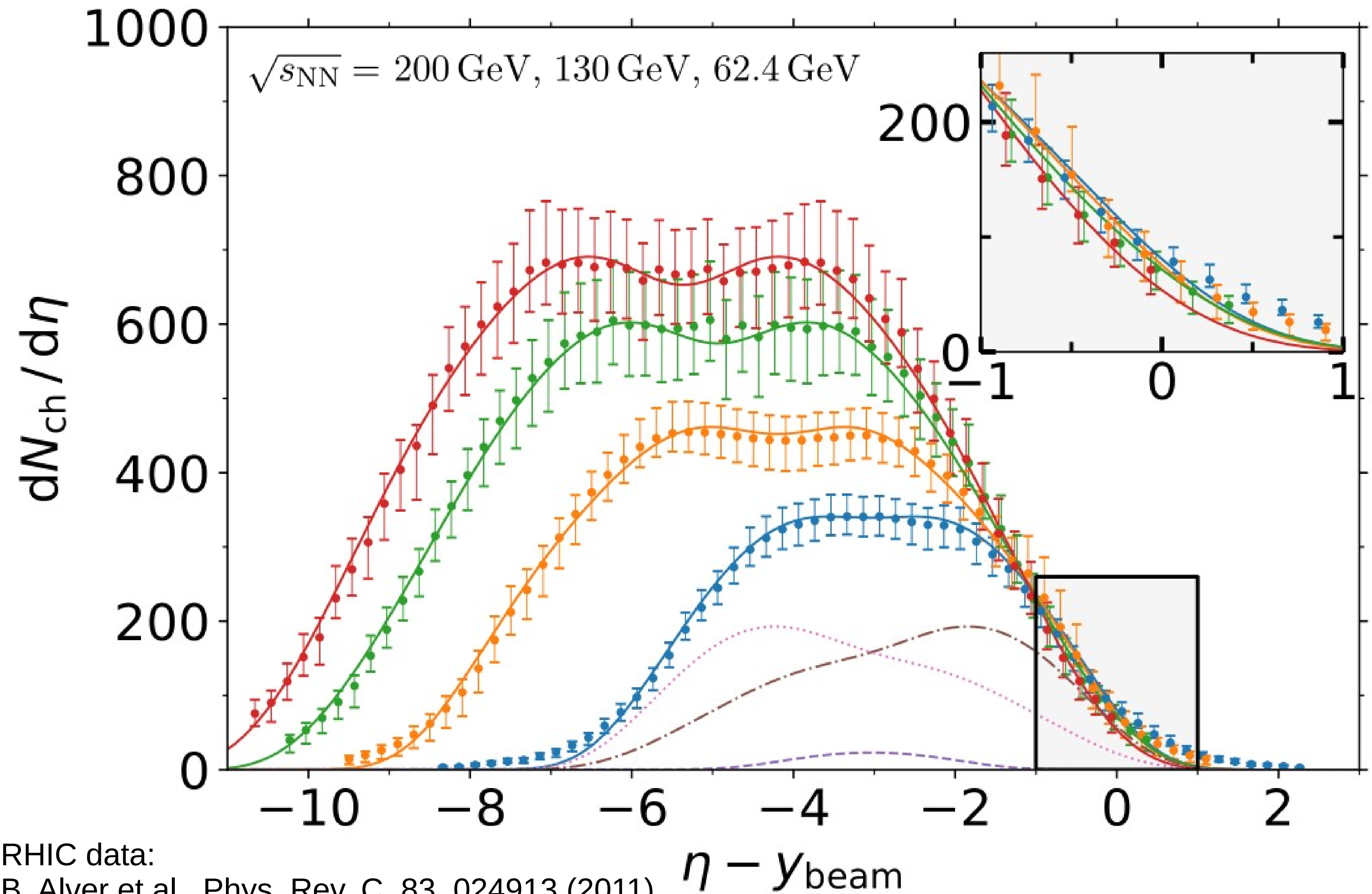
$\sqrt{s_{NN}}$ (TeV)	y_{beam}	$N_{1,2}$	N_{gg}	y_{peak}	$\langle y_{1,2} \rangle$	$\gamma_{1,2}$	γ_{gg}	χ^2	χ^2/ndf
2.76	± 7.987	2700	12000	± 3.88	± 0.56	1000	115	5.89	0.16
5.02	± 8.586	2800	15800	± 4.43	± 0.61	2000	205	7.50	0.26

Comparison to linear model



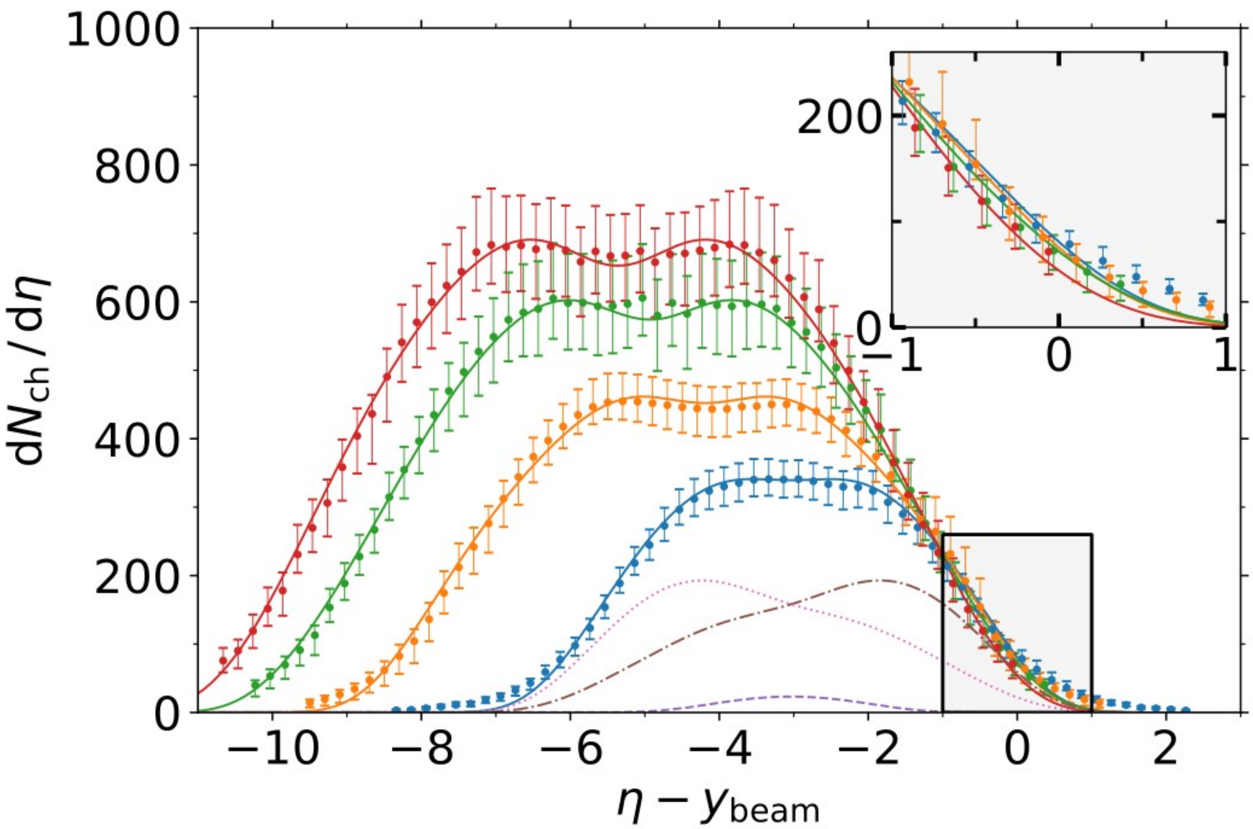
Data sources: loc. cit.

Sinh-model with RHIC-data



RHIC data:
B. Alver et al., Phys. Rev. C, 83, 024913 (2011)

Sinh-model with RHIC-data



$\sqrt{s_{\mathrm{NN}}}$ (GeV)	y_{beam}	$N_{1,2}$	N_{gg}	y_{peak}	$\langle y_{1,2}\rangle$	$\gamma_{1,2}$	γ_{gg}	χ^2	χ^2/ndf
19.6	± 3.037	870	60	± 0.86	± 0.42	6	1	157.07	3.02
62.4	± 4.197	1280	540	± 1.94	± 1.11	18	4	18.11	0.37
130	± 4.931	1350	1800	± 2.30	± 1.08	42	13	4.07	0.08
200	± 5.362	1400	2650	± 2.78	± 1.64	52	24	3.39	0.07

Outline

Conclusion

- The RDM is compatible with LF from RHIC- to LHC-energies (spanning a factor of ~260 in energy)
- Linear-drift model works well up until 2.76 TeV, after that the modification to sinh-drift becomes necessary to arrive at suitable fits
- The fragmentation sources play an essential role in heavy-ion collisions, especially for LF
- Thermal model is not suitable to describe LF
- Question is probably only solvable through experiment, but that would require a detector upgrade

References of the presented paper

This presentation is based on: B. Kellers and G. Wolschin, *Limiting Fragmentation at LHC energies*, PTEP, **5** (2019), 053D03, https://doi.org/10.1093/ptep/ptz044

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