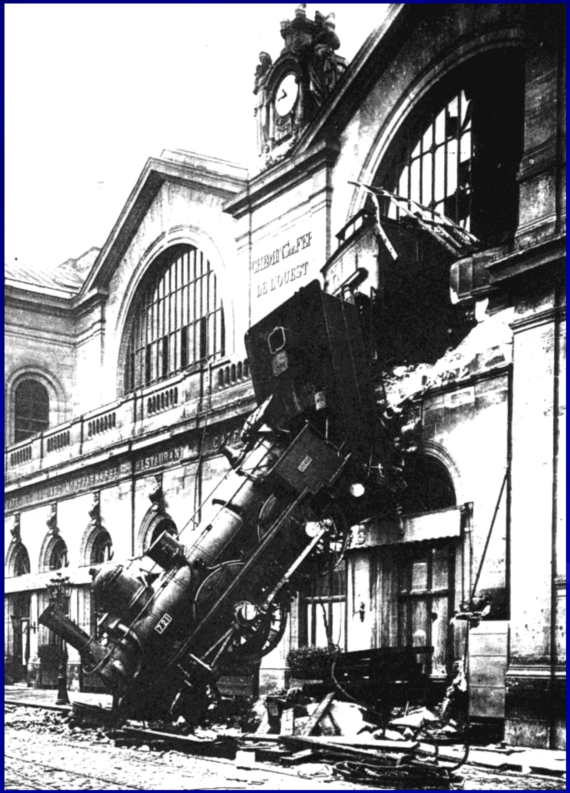
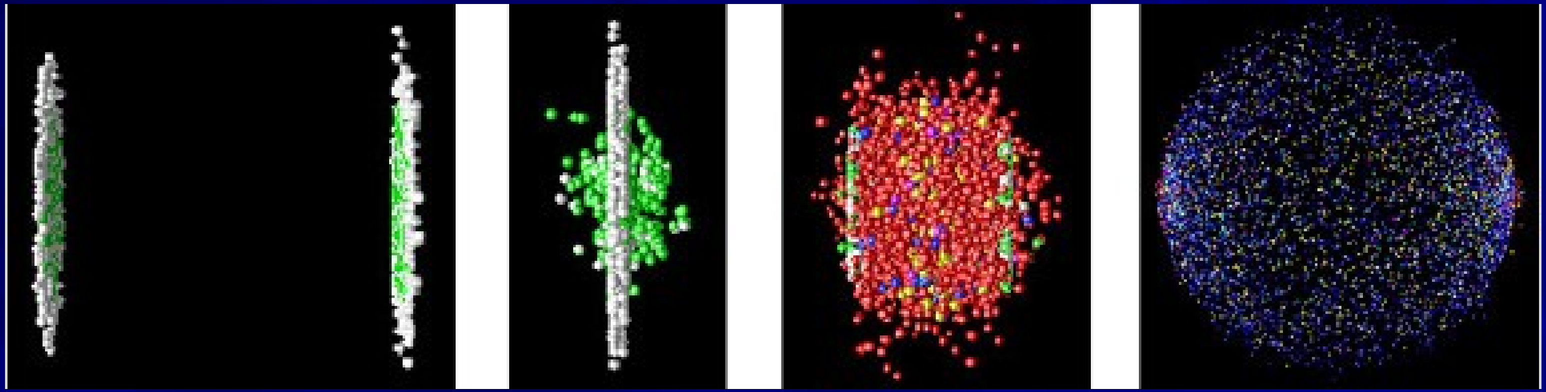
An overview of stopping at RHIC

- An introduction to stopping
- How to experimentally measure stopping:
  - $d^2N/dydp_T \rightarrow dN/dy$
  - dN/dy net-p → dN/dy net-B / weak decay corrections
    - Important for comparing to theory!
  - Observations about the rapidity loss in A+A
- New results from BRAHMS
- Models of stopping
- How does stopping fit in the big picture of particle production

An Introduction to Stopping

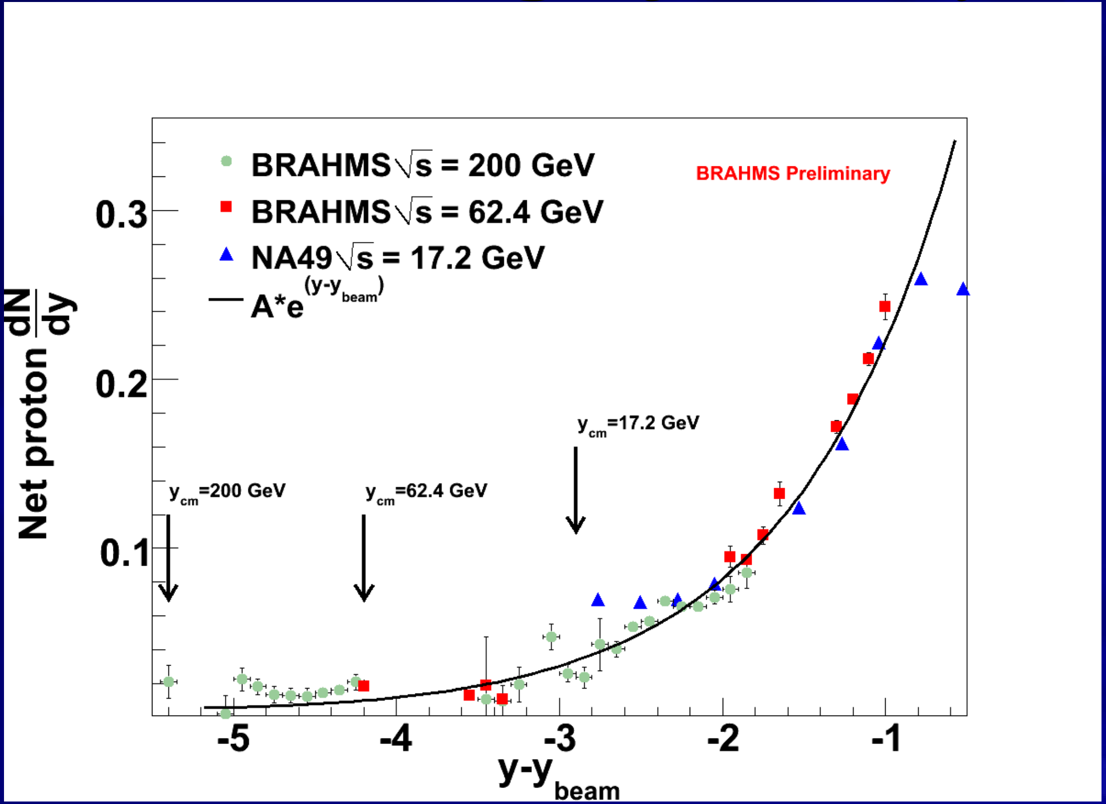


What is stopping ?



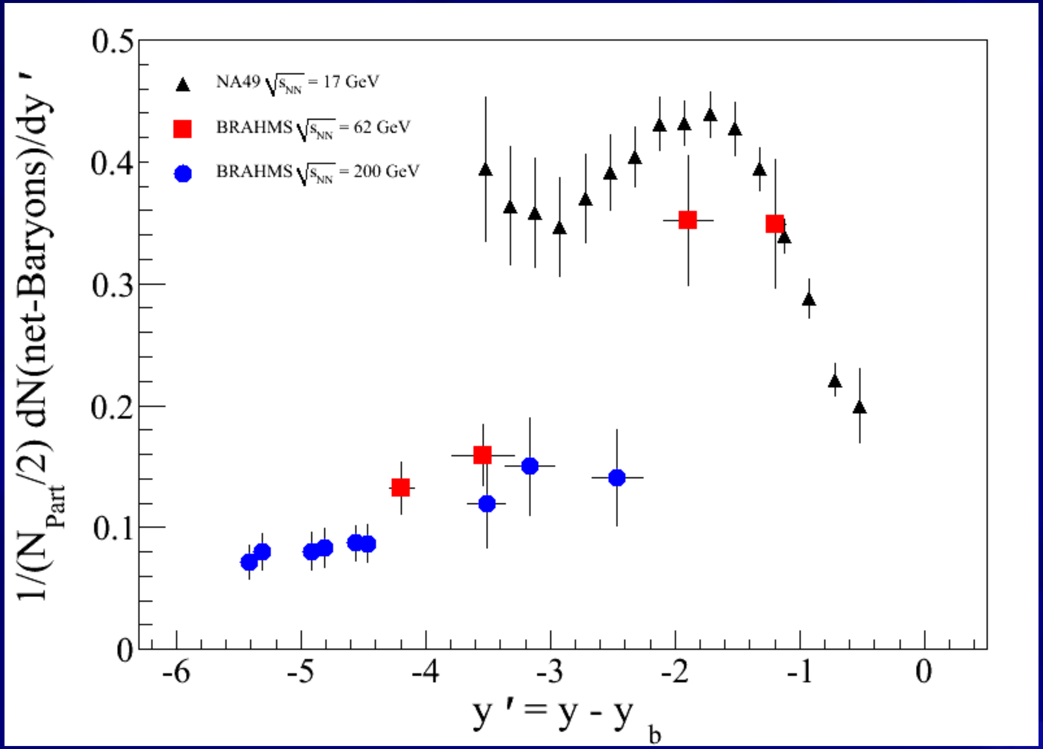
- Energy conservation
  - Kinetic energy of initial baryons is used to create a hot and dense zone.
- Baryon (qqq) number conservation
  - Before: 2*197 baryons → After: 2*197 net-baryons (B-Bbar)
- Stopping is the study of baryon transport in the collisions
  - Initial interactions → understand the formation of the initial state!
  - Rescattering/flow of partons and hadrons
  - Decays

Stopping in p+p collisions: Scaling of dN/dy



- Universal behavior of dN/dy for net-protons when observed in the “projectile” frame

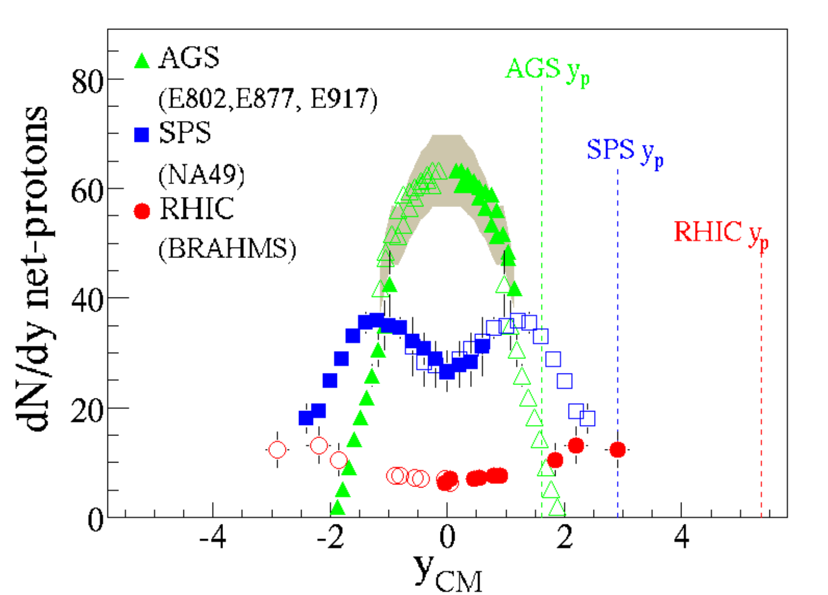
Stopping in A+A collisions: No obvious scaling of dN/dy

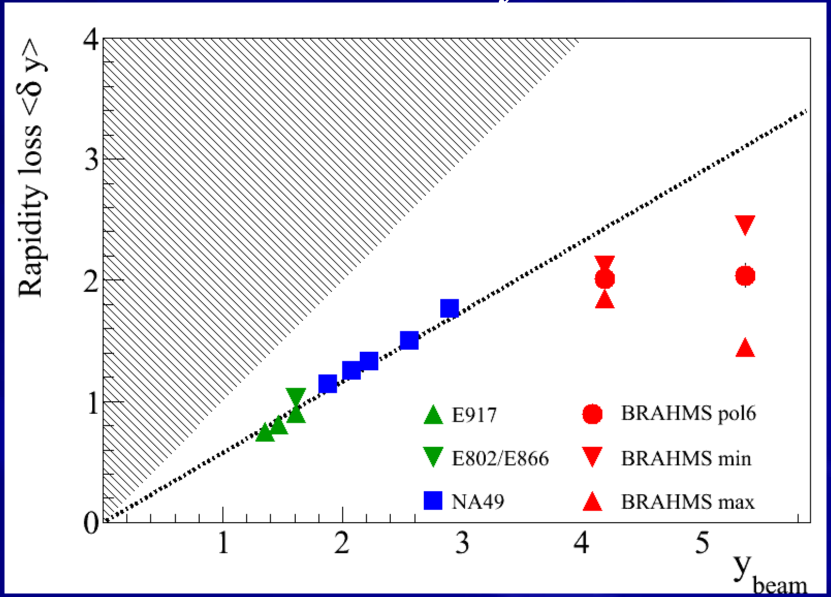


- No obvious scaling in projectile frame
  - But when the target contribution is subtracted there is scaling!

Rapidity loss: A way to quantify stopping

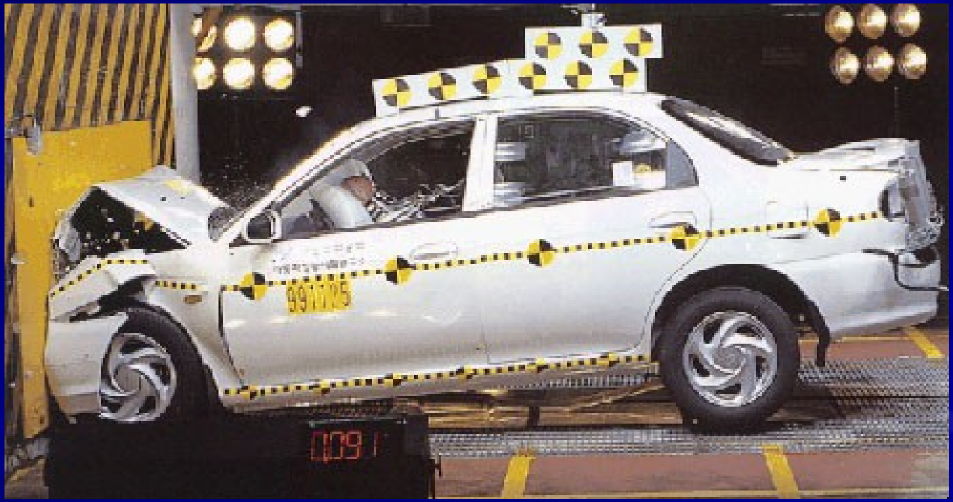
Rapidity loss (in CM): $\langle \delta y \rangle = y_{beam} - \int_0^{y_{beam}} y \frac{dN_{net-b}(y)}{dy} dy$





- At lower energy (until SPS) rapidity loss scales with y_{beam} [Phys.Rev.C52, 2684, (1995)]
- Above SPS energies it seems to saturate

How to Experimentally Measure Stopping

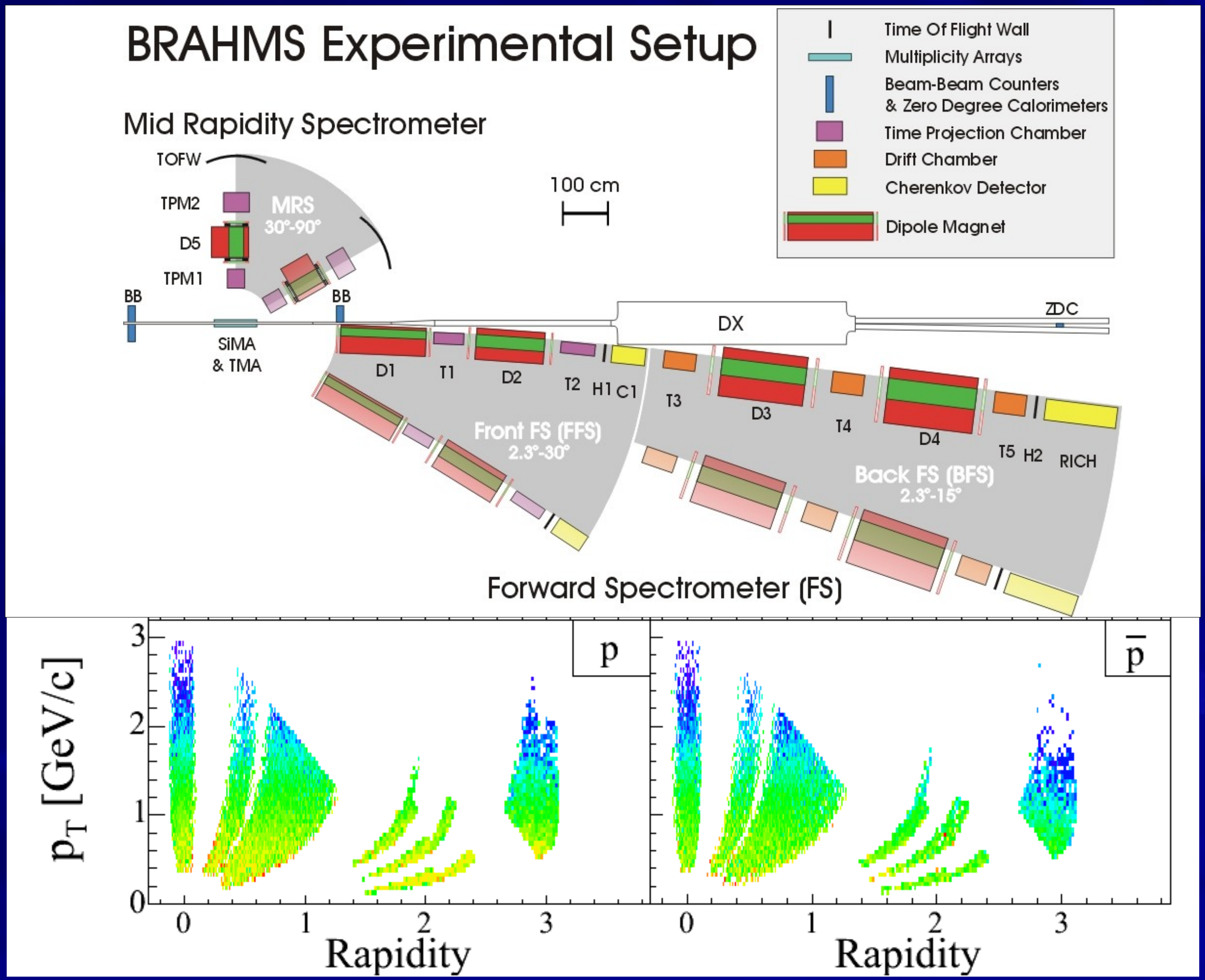


How to measure the net-baryon dN/dy after the collision

- Need good rapidity coverage
  - BRAHMS, (STAR FTPC), NA49
- Need good p_T coverage
  - 1st problem: extrapolate spectra to obtain dN/dy
- Need good particle identification for protons, Λs and neutrons
  - 2nd problem: Neutrons are hard to measure
  - 3rd problem: BRAHMS can measure protons, but not Λs. STAR can measure forward Λs only.

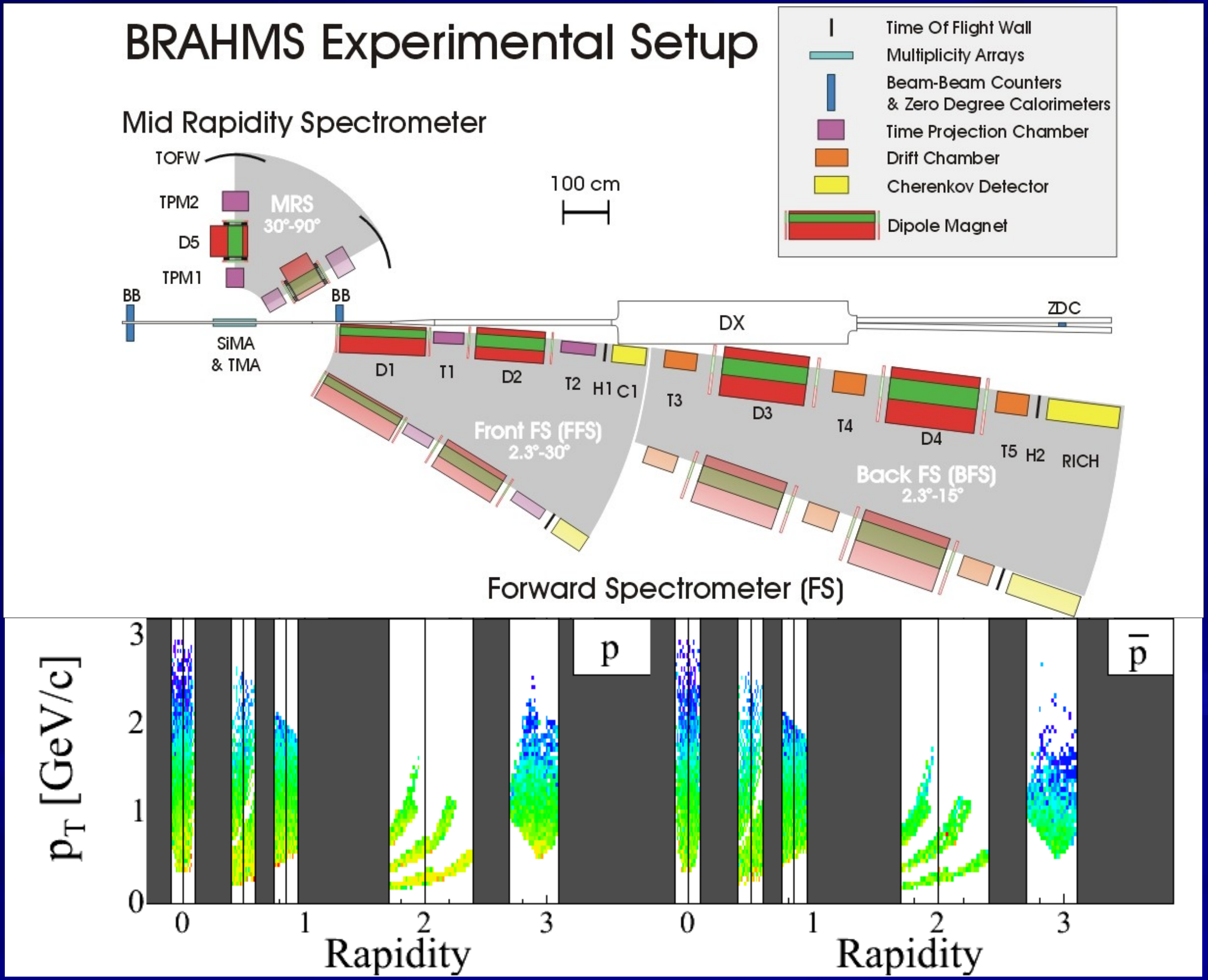
In the following I will use BRAHMS as an example

Starting point: $1/(2\pi p_T)\, d^2N/dydp_T$



A single spectrometer setting covers a small fraction of phase space, but by combining different settings p_T-spectra can be obtained at many different rapidities.
MRS(0<y<1),
FFS(1<y<2),
FS(2.0<y<3.5)

Apply cuts in rapidity and project → p_T spectra



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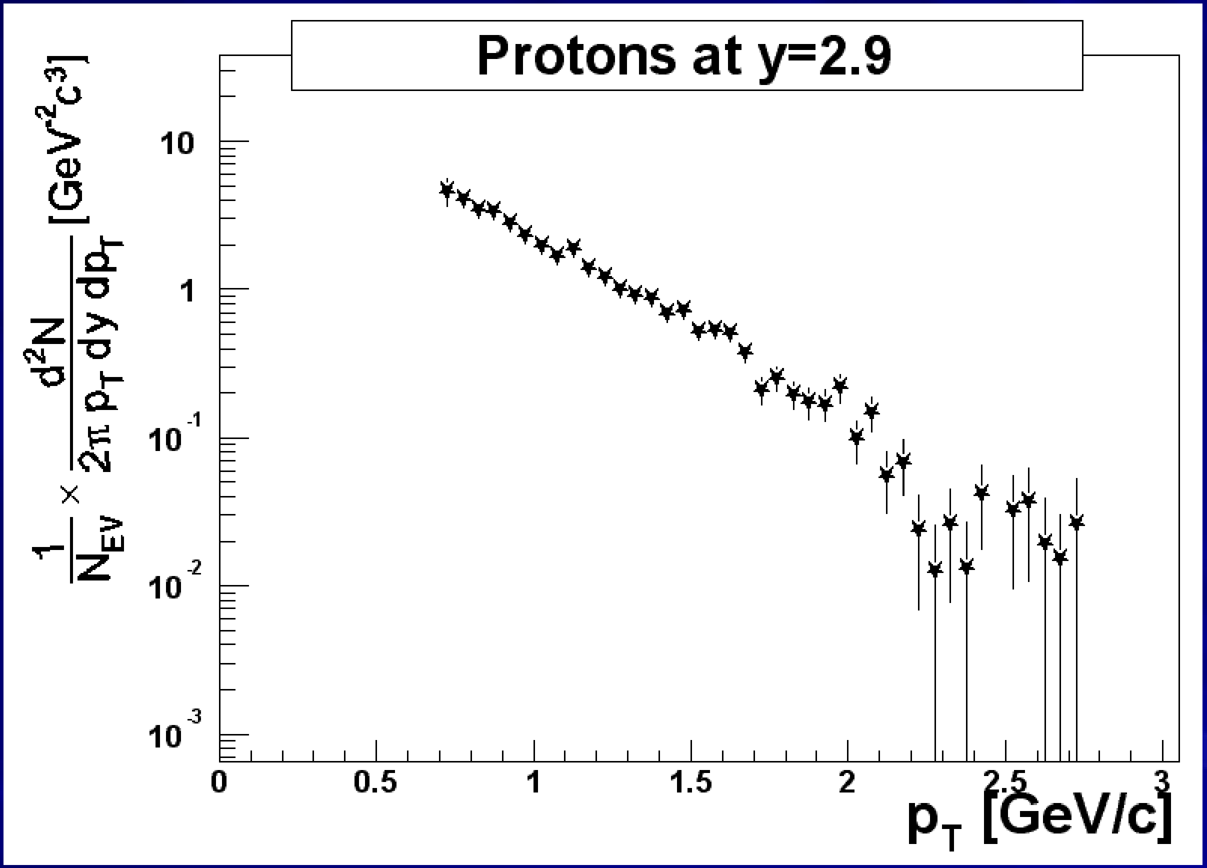
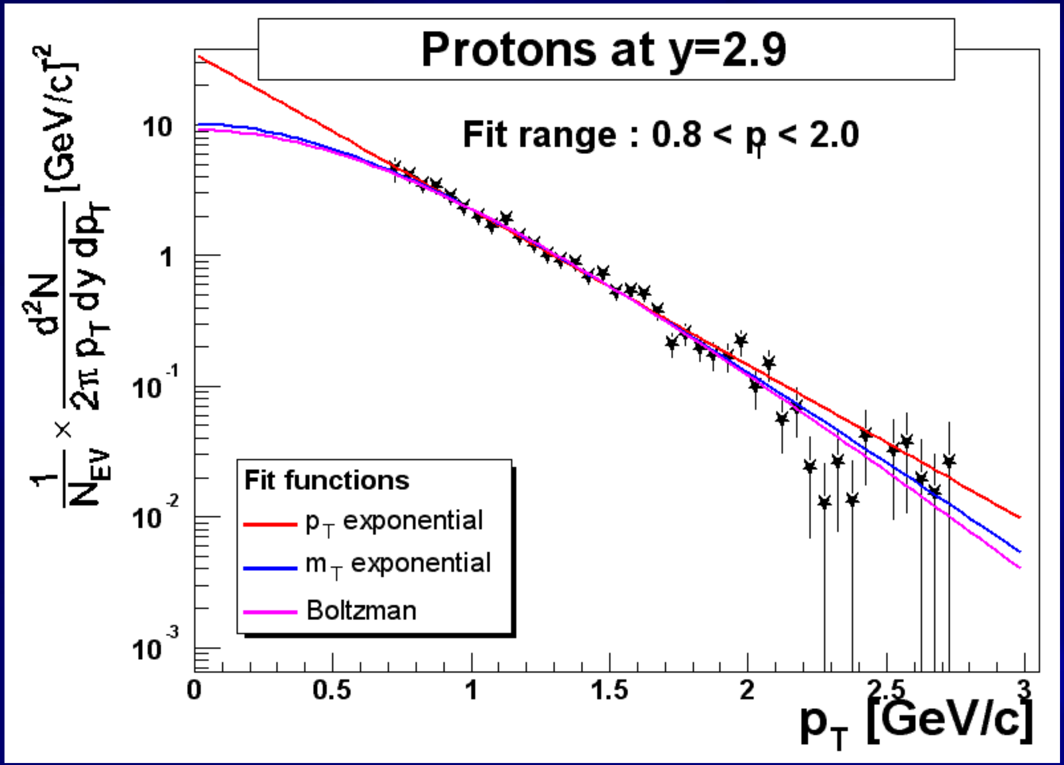
Example of p_T-spectrum



- To obtain dN/dy we need to extrapolate the yield to the regions where there is no experimental coverage

Extracting dN/dy



Fit p_T spectra and use the fit to extrapolate into regions where we don't measure to get dN/dy.

$$m_T = \sqrt{m^2 + p_T^2}$$

$$f(p_T) = N \cdot e^{-p_T/T}$$

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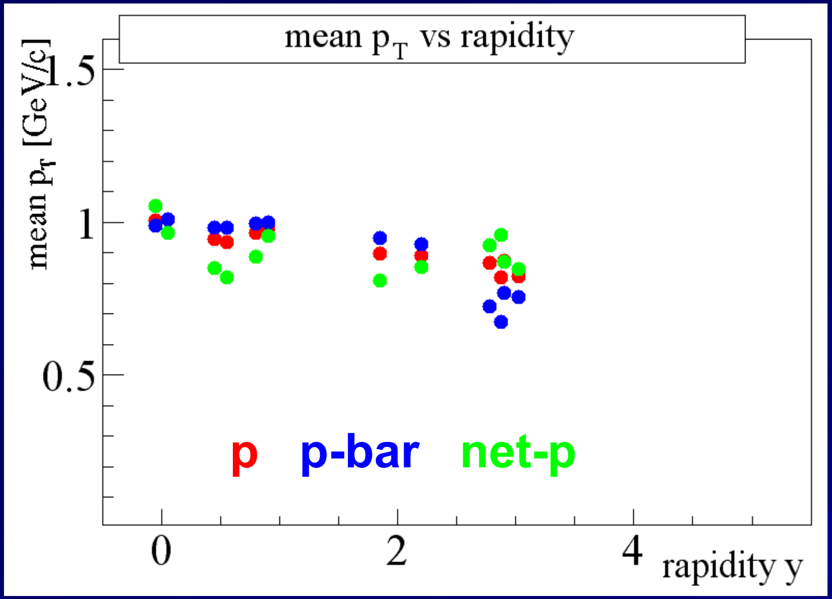
$$f(p_T) = N \cdot m_T \cdot e^{-m_T/T}$$

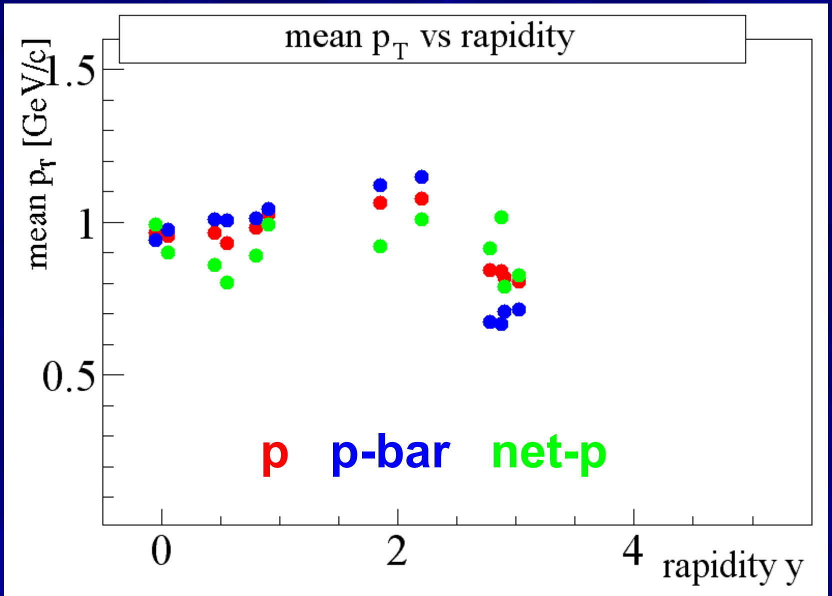
The fit function used was required to be able to fit at all rapidities.

This rules out pt-exponential and Boltzman.

$<p_T>$ vs y: A consistency check for fits

pT-gauss fit | **mT-exponential fit**





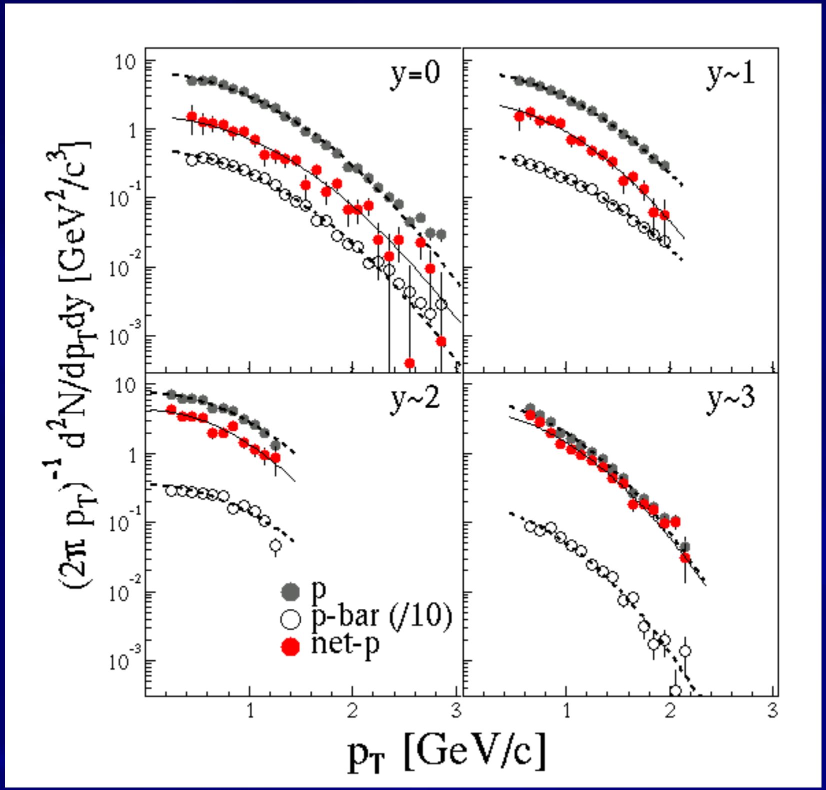
- However, the final fit function used was a Gaussian in p_T:

$$f(p_T) = N \cdot e^{-p_T^2/T}$$

- Gave better χ^2, but also a more consistent behavior of the $<p_T>$ as a function of rapidity

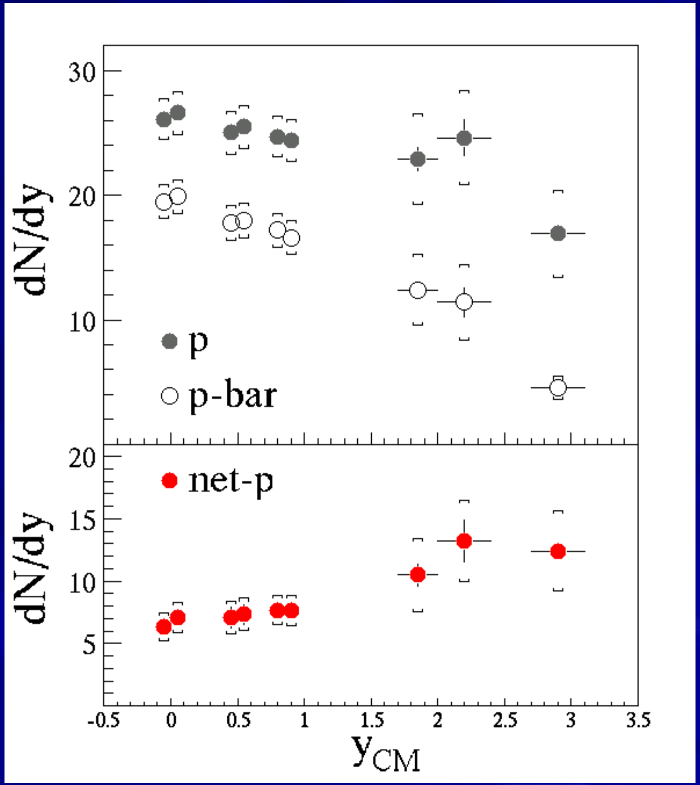
BRAHMS 200 GeV results (1/2)

pT-gauss fit



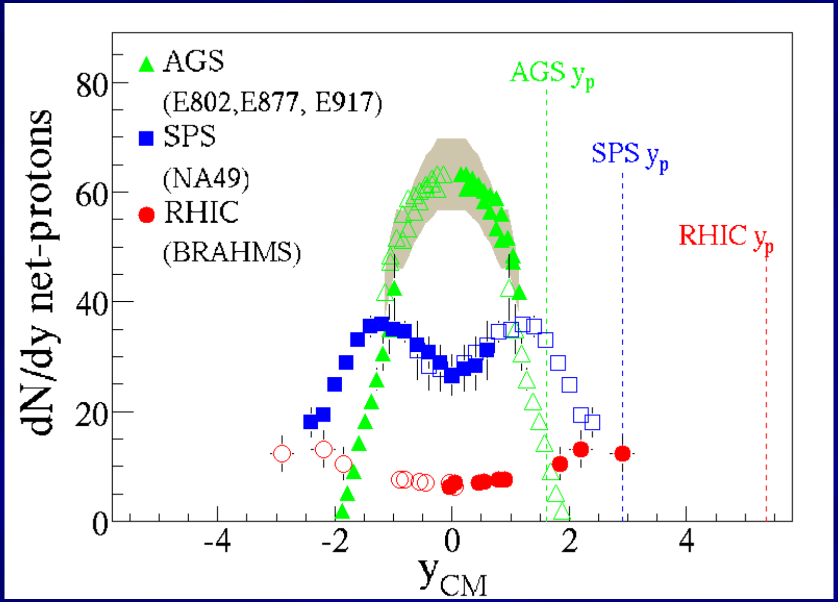
→

Extrapolated fits



- Results from PRL93, 102301 (2004)

BRAHMS 200 GeV results (2/2)



- Problems:
  - BRAHMS net-protons contains protons from weak decays, e.g:
    - $\Lambda \rightarrow p+\pi^-$
  - Bulk of net-protons are outside the acceptance
  - How to normalize the BRAHMS results to model calculations

Idea: Convert net-protons to net-B

- Net-B turns out to be less sensitive to net-Λ than net-p (Mentioned in NA49 stopping paper: PRL82, 2471 (1999))
- Net-B we know how to normalize and we can use the number of participants (=net-B) to constrain our extrapolation to |y|>3
- Conversion formula:

$$n_B = n_{p,measured} \frac{n_p + n_n + n_\Lambda + n_{\Sigma^+} + n_{\Sigma^-}}{n_p + c_1 n_\Lambda + c_2 n_{\Sigma^+}}$$

- Where the n quantities are the net-quantities.
- c1 and c2 is the number of measured protons per Λ and Σ^+ respectively

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- Conversion formula dominant terms only:

$$n_B = n_{p,measured} \frac{n_p + n_n + n_\Lambda}{n_p + c_1 n_\Lambda}$$

- Where the n quantities are the net-quantities.
- c1 is the number of measured protons per Λ

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- Net-B we know how to normalize and we can use the number of participants (=net-B) to constrain our extrapolation to |y|>3
- Conversion formula dominant terms only:

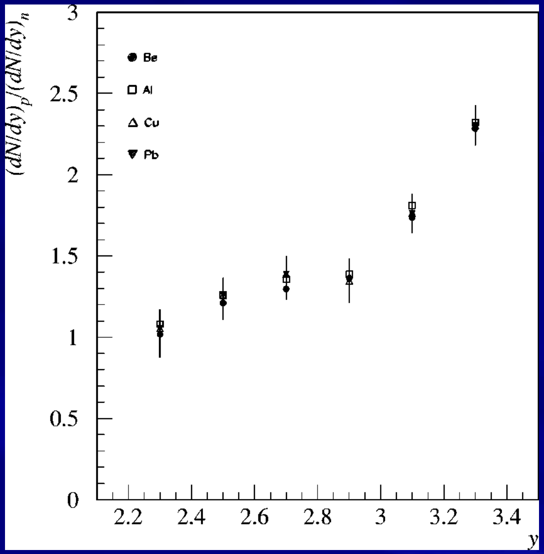
$$n_B = n_{p,measured} \frac{1 + r_n + r_\Lambda}{1 + c_1 r_\Lambda}$$

- Where the n quantities are the net-quantities.
- The r quantities are the ratios: $r_X = n_X/np$
- c1 is the number of measured protons per Λ

Equilibration of protons and neutrons

- Initially at RHIC: n/p = (197-79)/79~1.5
- E947 observes (PRC65, 014904 (2001)) equilibration after a few units of rapidity:

p/n ratios as a function of rapidity in p+Be, p+Al, p+Cu, and p+Pb collisions at 19 GeV/c. Fixed target with y_{proton}=3.7.
After ~1.5 unit of rapidity, p and n is equilibrated.

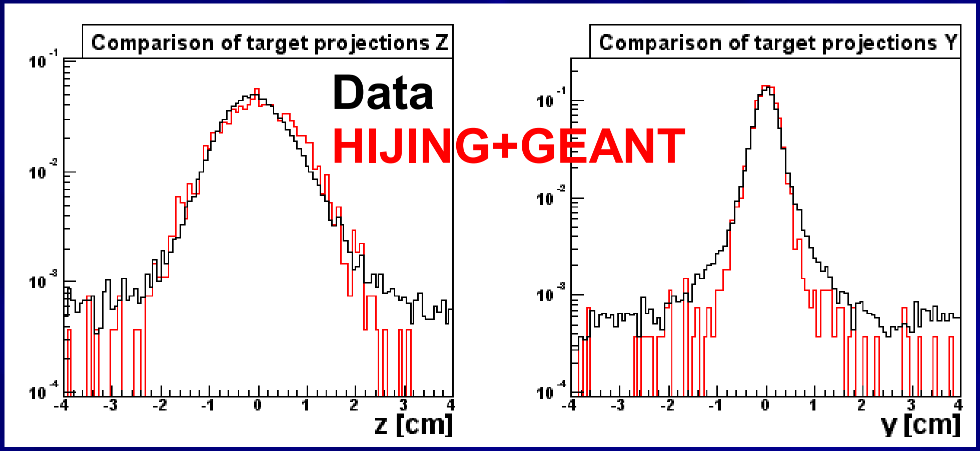


- A similar result is obtained with HIJING and AMPT simulations, i.e., isospin in final state is carried by pions.
- In the region covered by BRAHMS n/p =1
  – At 62 GeV and forward rapidity n/p slightly larger than 1

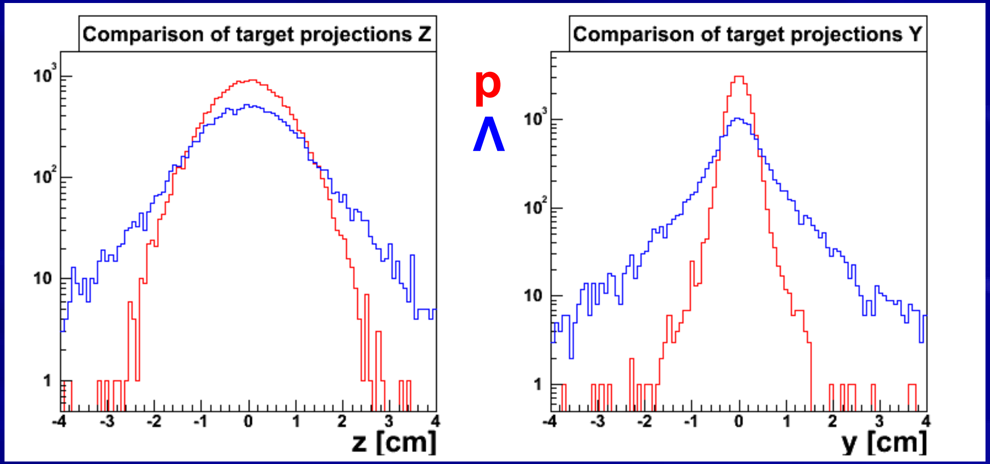
How to determine c1 (protons observed per Λ)

- Obtained from GEANT detector simulation of BRAHMS with HIJING as input
  – Plots shown are for the BRAHMS Mid Rapidity Spectrometer (y=0)
  – Z = along beam
  – Y = transverse plane
- pT dependence of c1 was ignored
  – c1 = 0.53 ± 0.05
  – Similar for all settings
  – Agrees with detailed study in PRC 72, 014908 (2005)

Tracks projected back to interaction point



Same as above, but for p and Lambda only



The correction factor

- The value of r_n and c1 turns out to make n_B insensitive to n_Λ:

$$n_B = n_{p,\,measured} \frac{2 + r_\Lambda}{1 + \text{٠.٥٣}\, r_\Lambda} \sim 2\, n_{p,\,measured}$$

- Very important point! This is why we think that net-B is better determined than net-p (weak decay corrected)

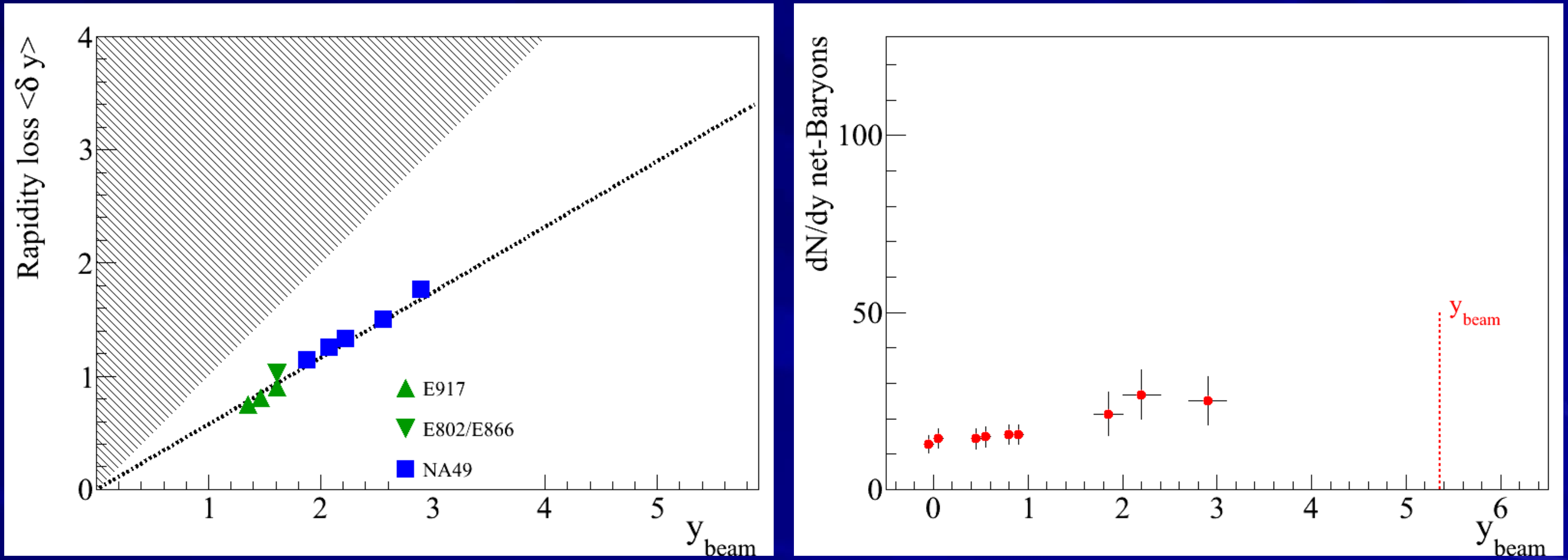
- For the full correction expression we obtain

$$n_B = 2.03 \pm 0.08\, n_{p,\,measured}$$

- And much more uncertainly for feed-down corrected protons: $\left(n_p = 0.67 \pm 0.12\, n_{p,\,measured}\right)$

Rapidity loss: 200 GeV

Rapidity loss (in CM): $$\langle \delta y \rangle = y_{beam} - \int_0^{y_{beam}} y \frac{dN_{net-b}(y)}{dy} dy$$



- NA49 data points from QM06 proceeding [J.Phys.G34, S951, (2007)]

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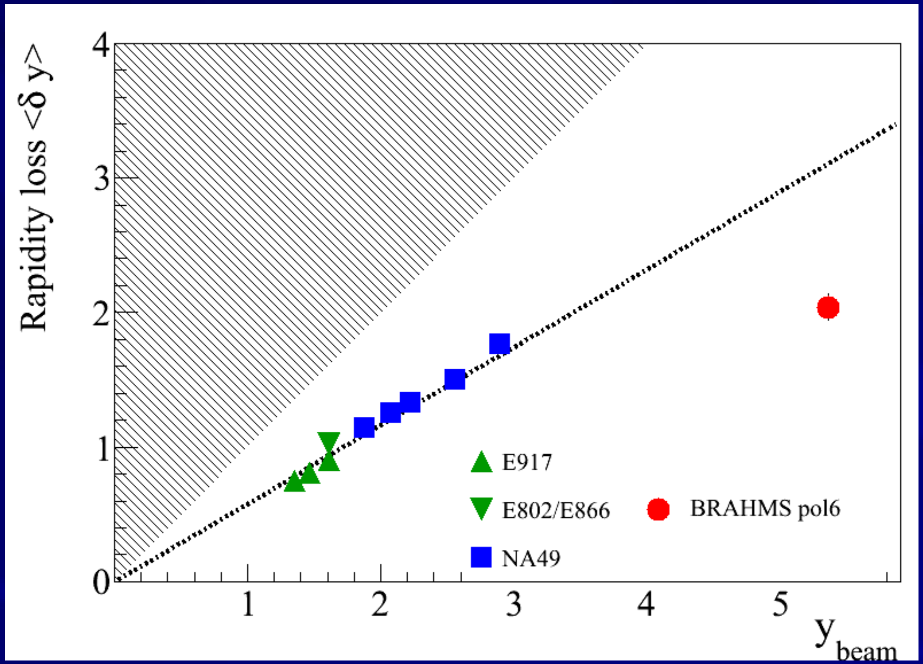

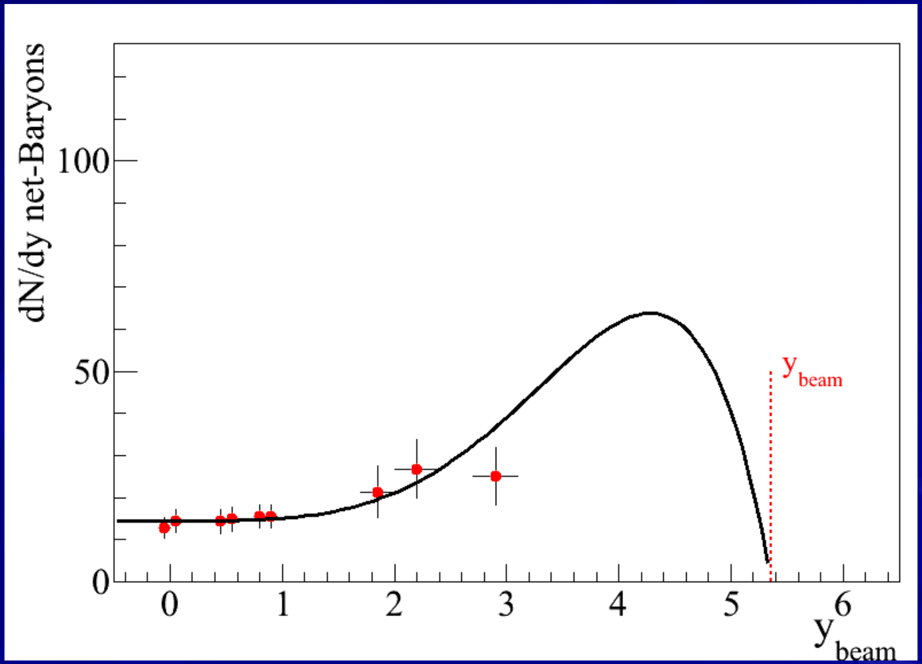

- Fit with symmetric 6th degree polynomium
  - 4 parameters, but ~3 constraints: Integral, dN/dy (y=0), dN/dy(y_{beam})=0

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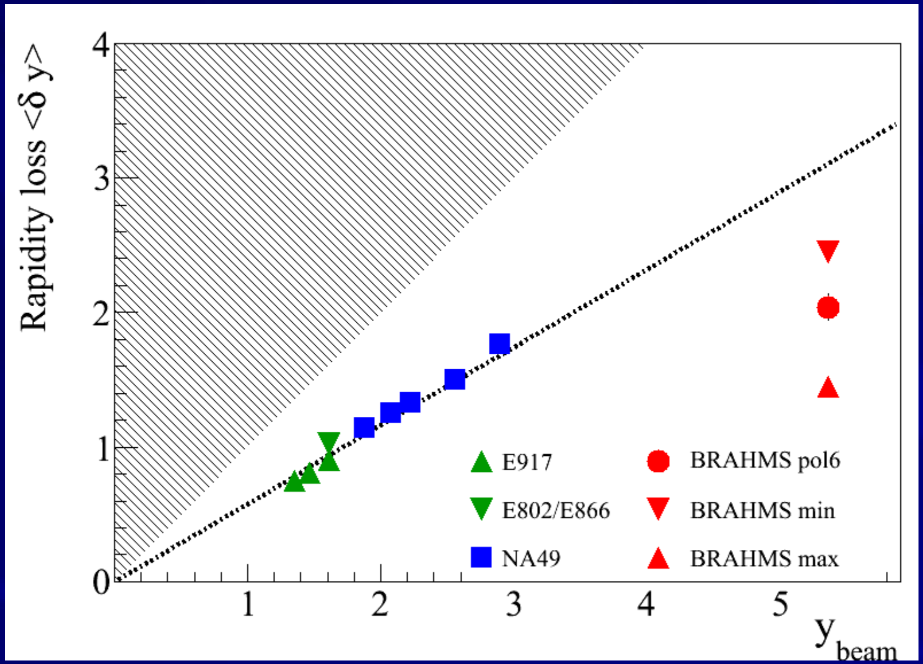
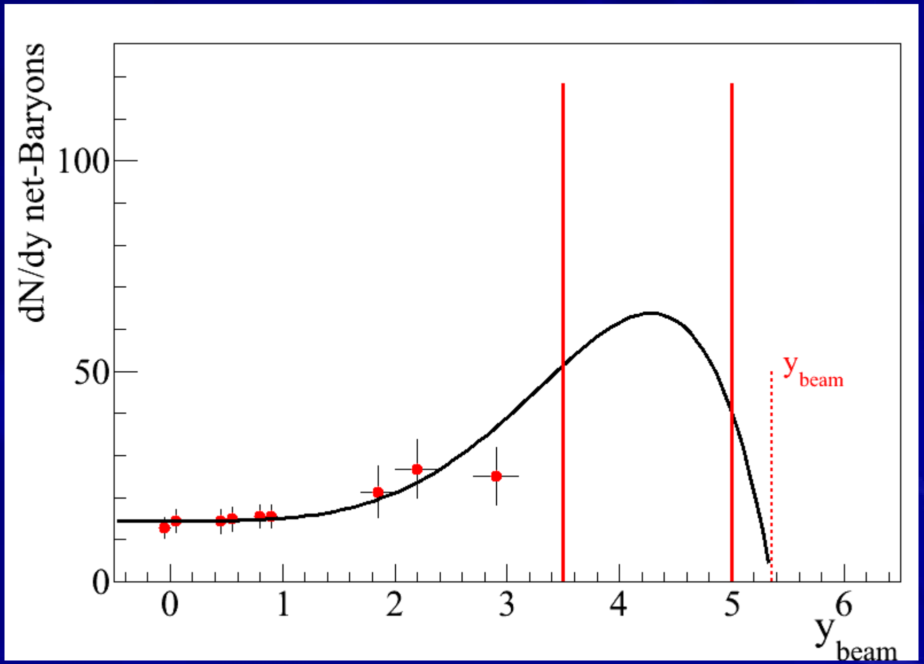
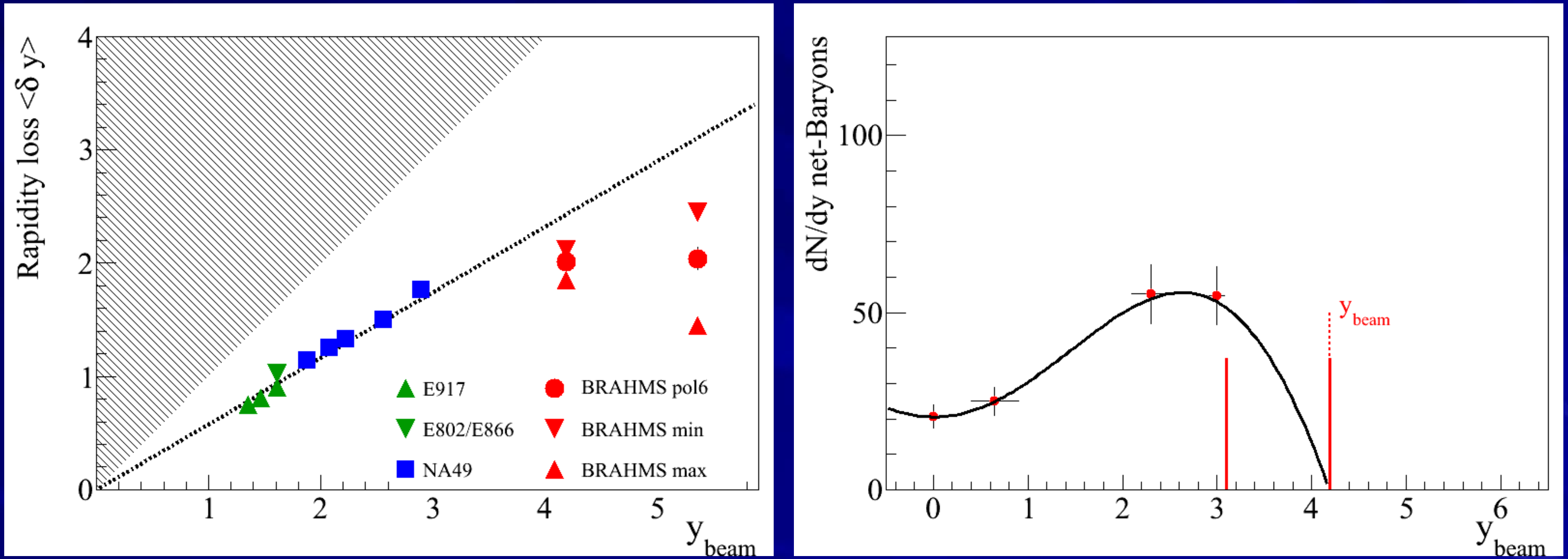




- Minimum and maximum estimates, but placing remaining net-baryons at y=3.5 (max) or y=5.0 (min)

Rapidity loss: 62 GeV

Rapidity loss (in CM): $\langle \delta y \rangle = y_{beam} - \int_0^{y_{beam}} y \frac{dN_{net-b}(y)}{dy} dy$

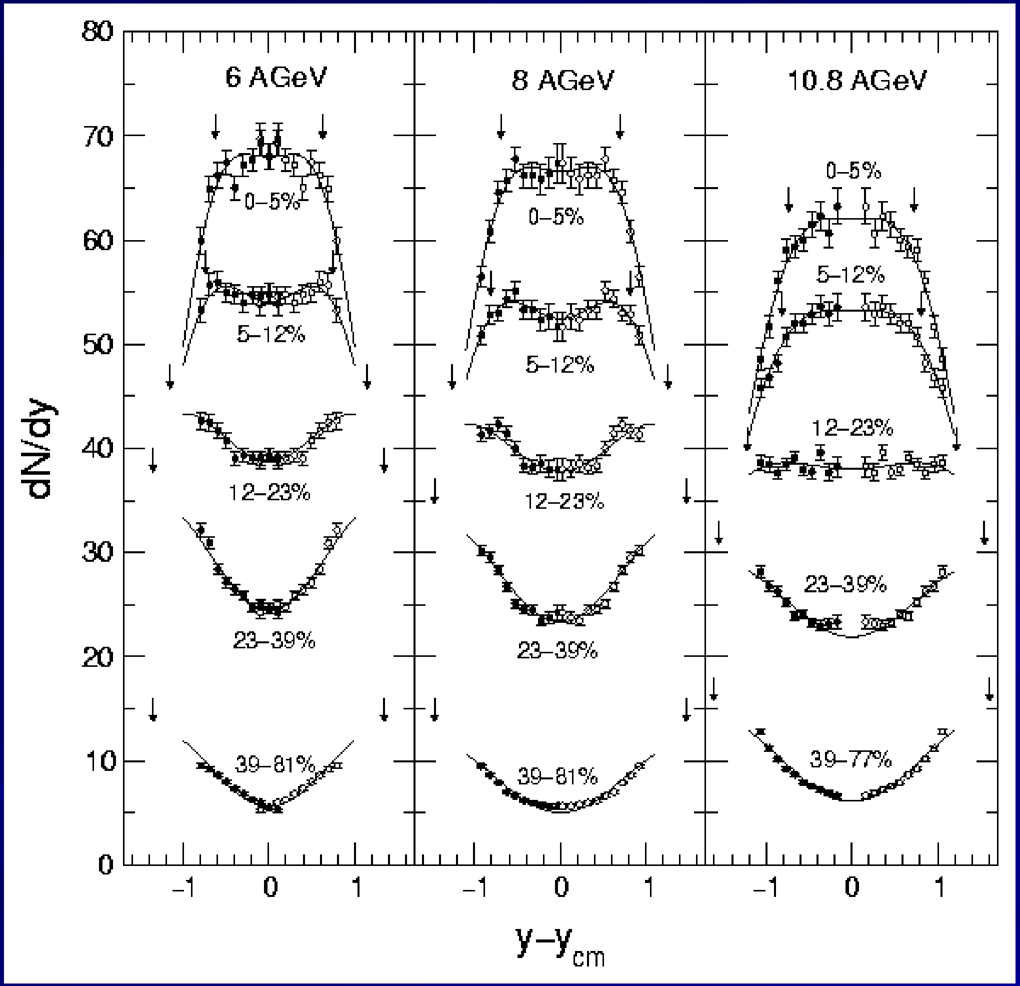


- Similar methods as for 200 GeV → Confirms trend and has much better coverage
- Accepted for publication in PLB (arXiv:0901.0872)

Is the rapidity loss a good measurement of stopping?

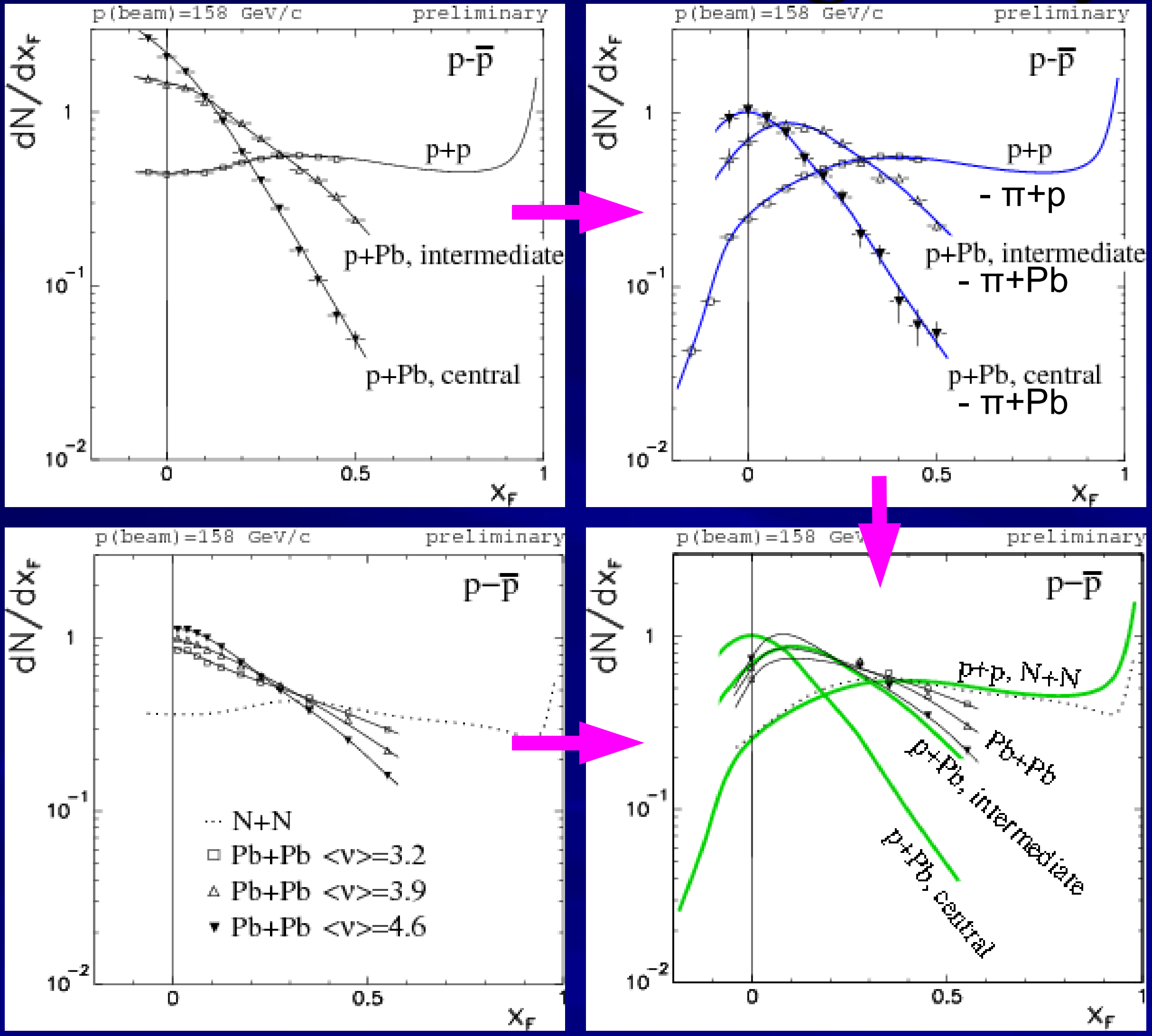
- Problem is that at low energy the contributions from the two nuclei (target and projectile) overlap significantly near mid-rapidity
  - Because of symmetry we know there (y=0) that half the nucleons actually comes from the target!
    - We **UNDERESTIMATE** the rapidity loss (worse at low beam energy) because we do not take into account rapidity losses that are greater than ybeam
- Solution: Try to separate contributions from target and projectile

E917: Separating “projectile” and “target” by fitting



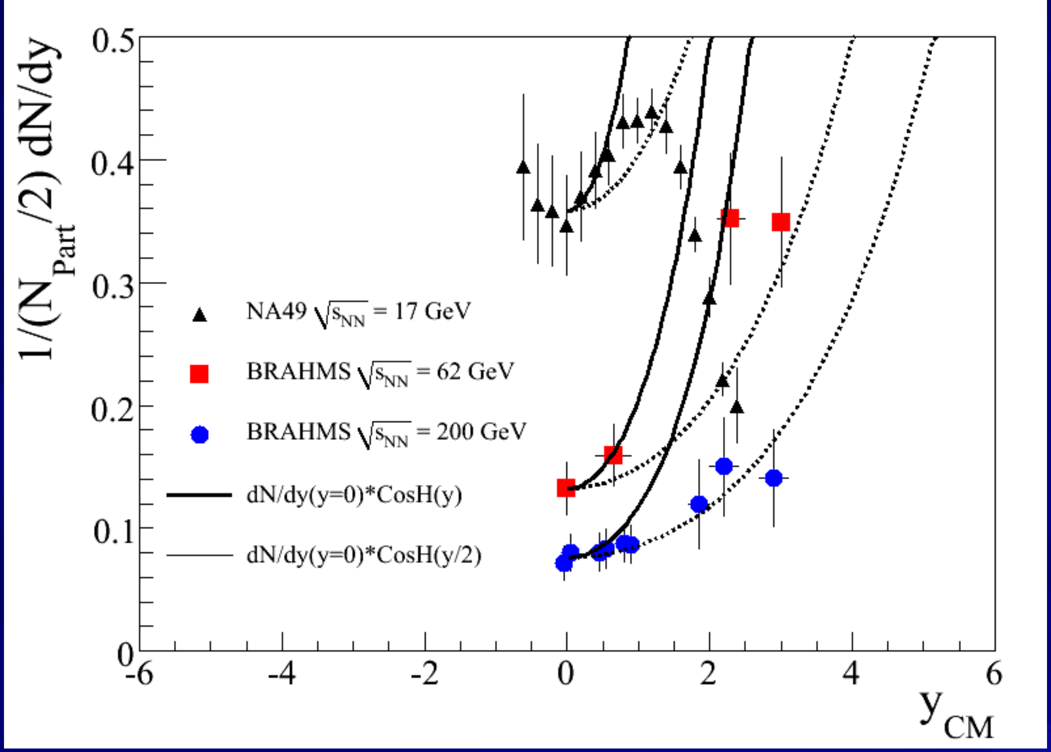
- Describe data by the som of two symmetric Gaussians
- Rapidity loss is then approximately y_{beam} minus Gaussian mean (vertical arrow)
  - NB! only meaningful for central collisions
- p+p picture is recovered in peripheral collisions
- Reference: [PRL 86, 1970 (2001)]

NA49: Separating "projectile" and "target" by π+p/A



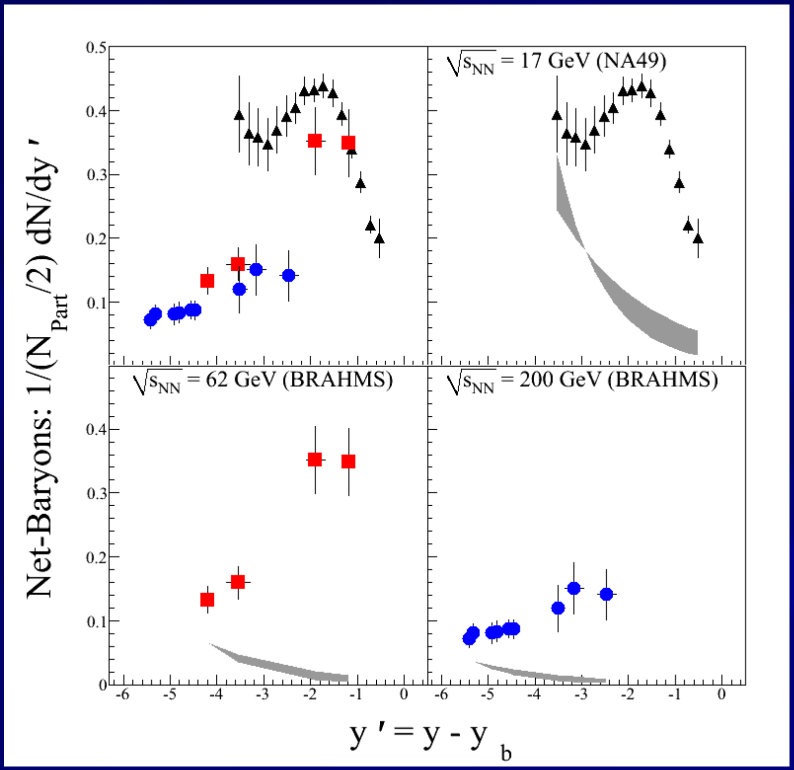
- Left: Uncorrected net-p distributions
- Right: net-p in p+p/A minus net-p in π+p/A
  - For Pb+Pb only the xF=0 (y_{CM}=0) points have been halfed
- Stopping is larger in central p+A than in central Pb+Pb
- [Acta Phys. Pol. B 33, 1483 (2002)] (unfortunately never published)

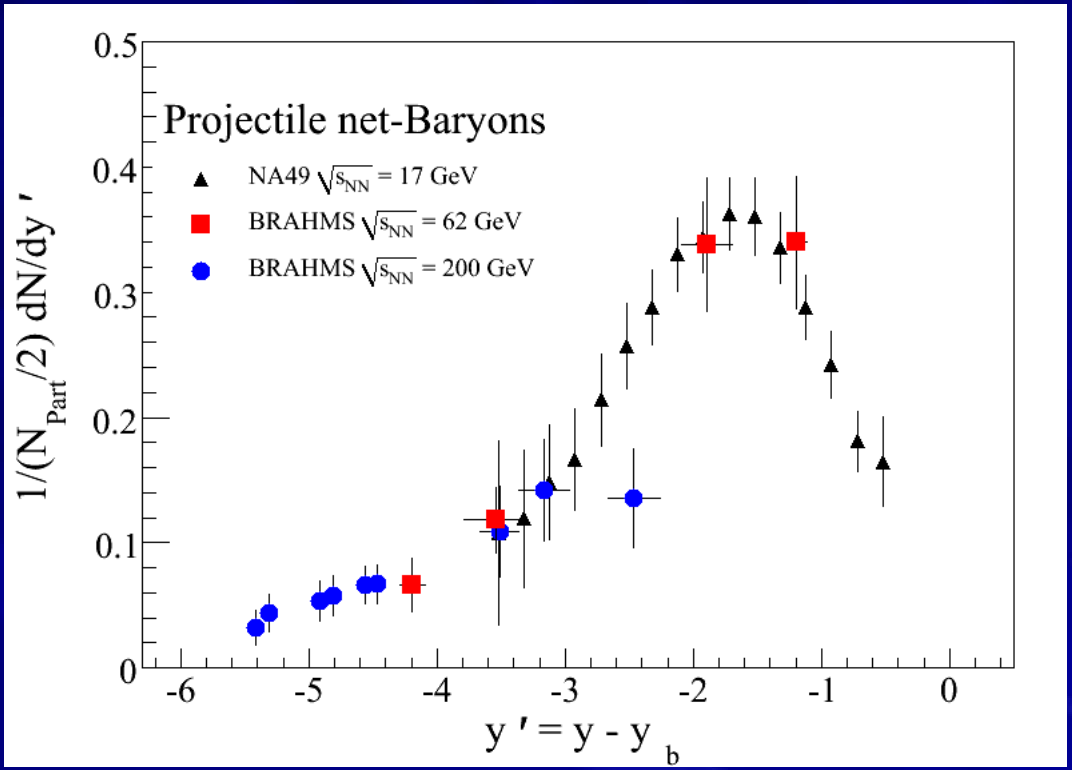
Separating "projectile" and "target" by tail approximation



- Separate "projectile" and "target" using pp expectations
  - exp(-y') tail is coming from pp data → Cosh(y)
  - exp(-y'/2) proposed for baryon junction → Cosh(y/2)
    - See reference: [Z. Phys.C 43, 241 (1989)]

"Projectile" net-baryons shows rapidity scaling

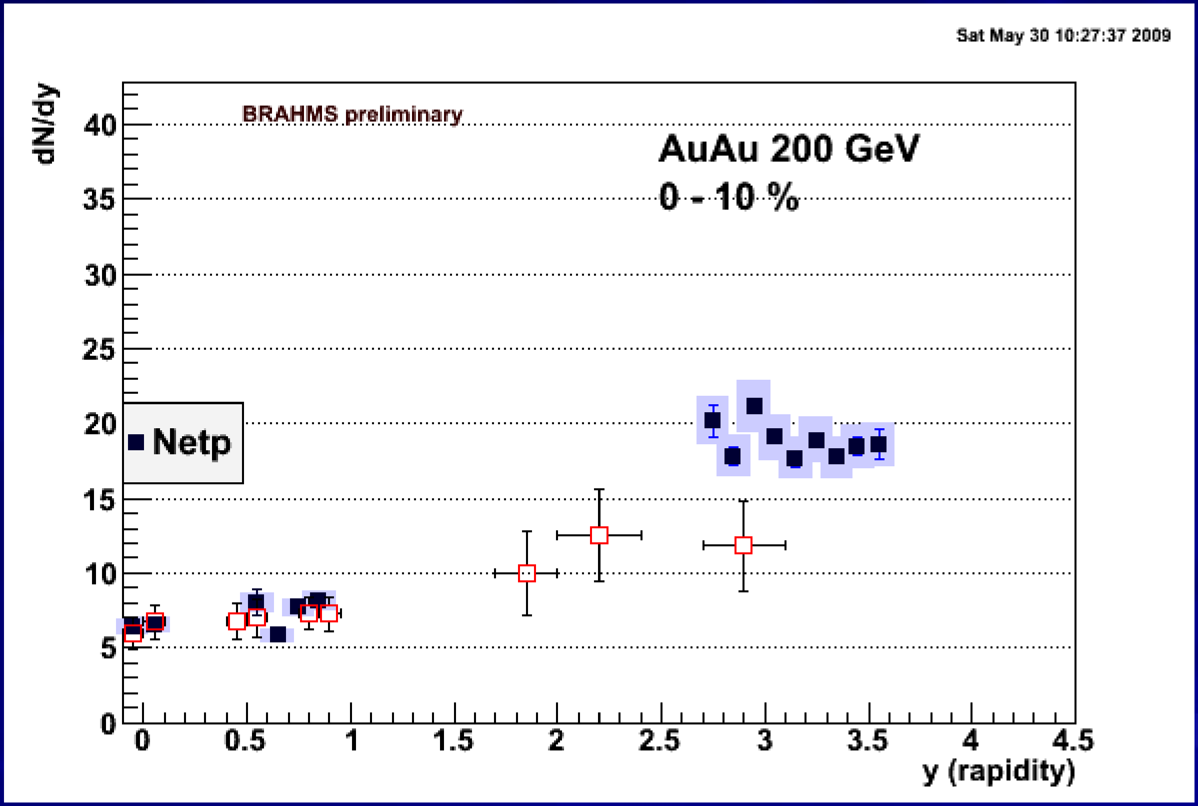




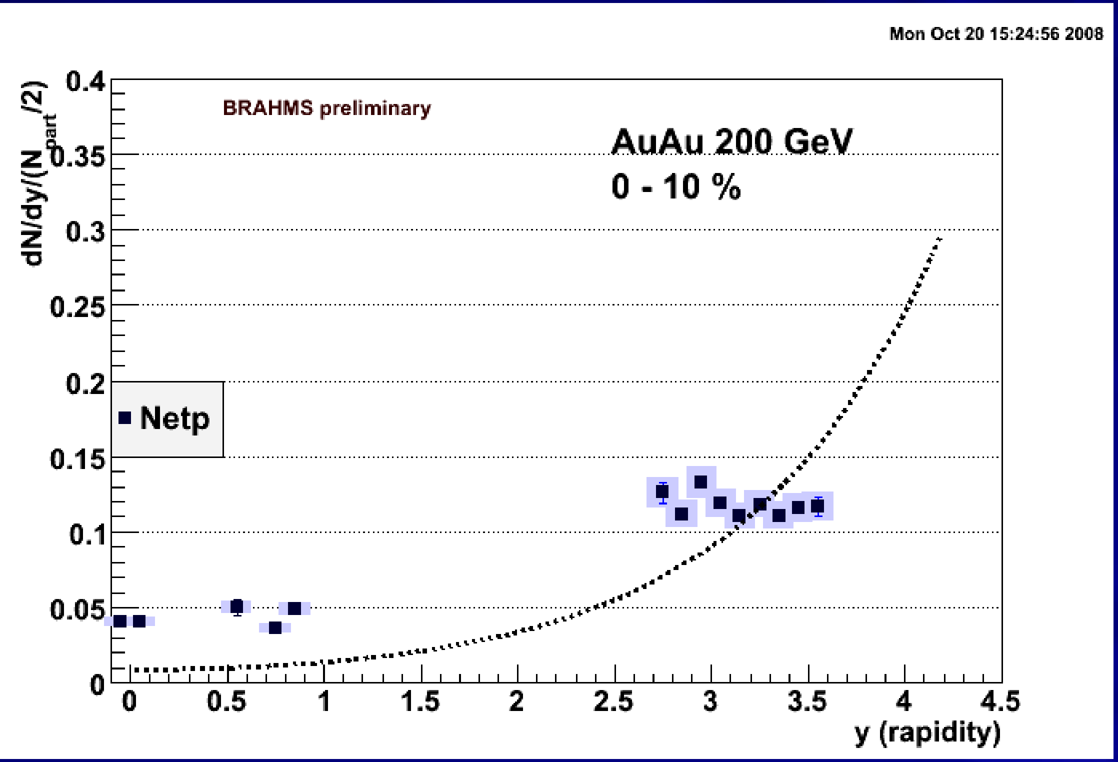
- When the net-Baryons are corrected for the "target" contribution universal scaling is also observed in A+A collisions – Particularly for the large rapidity losses!
- The stopping mechanism at SPS and RHIC is similar! (?)

New results from BRAHMS (Taken from Videbæks QM talk)

New results from BRAHMS vs published results

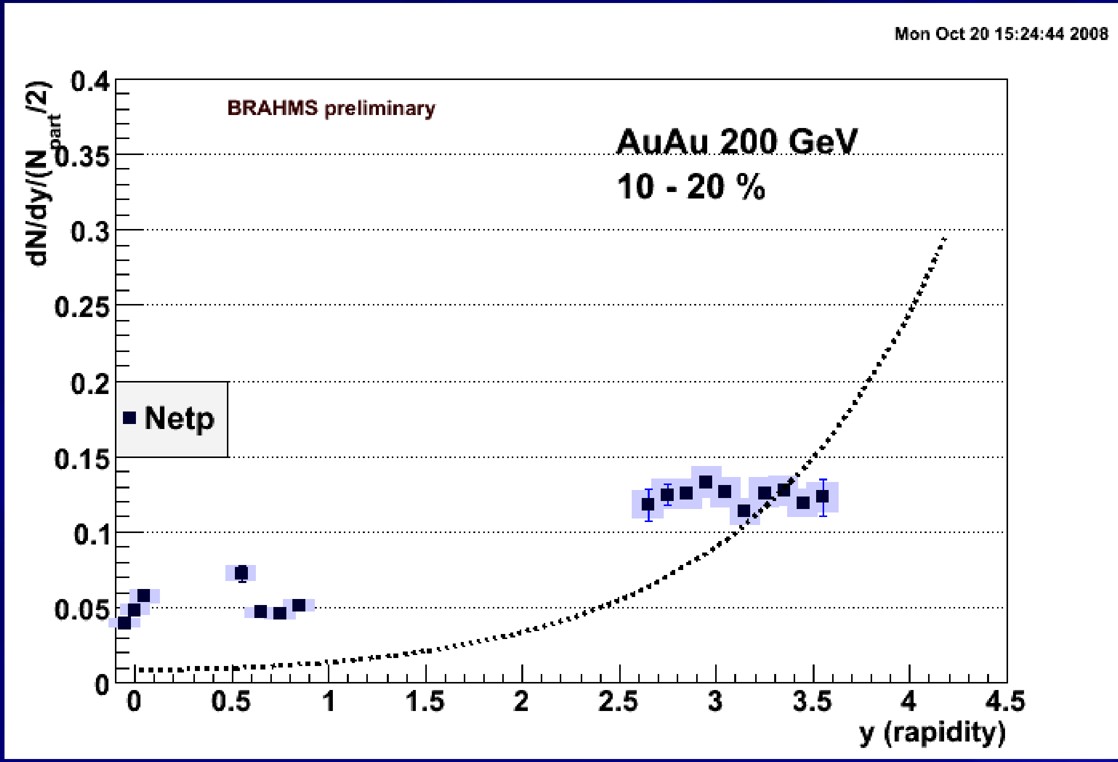


Centrality dependence of dN/dy for net-protons at 200 GeV



- Dashed line is universal pp fit

Centrality dependence of dN/dy for net-protons at 200 GeV



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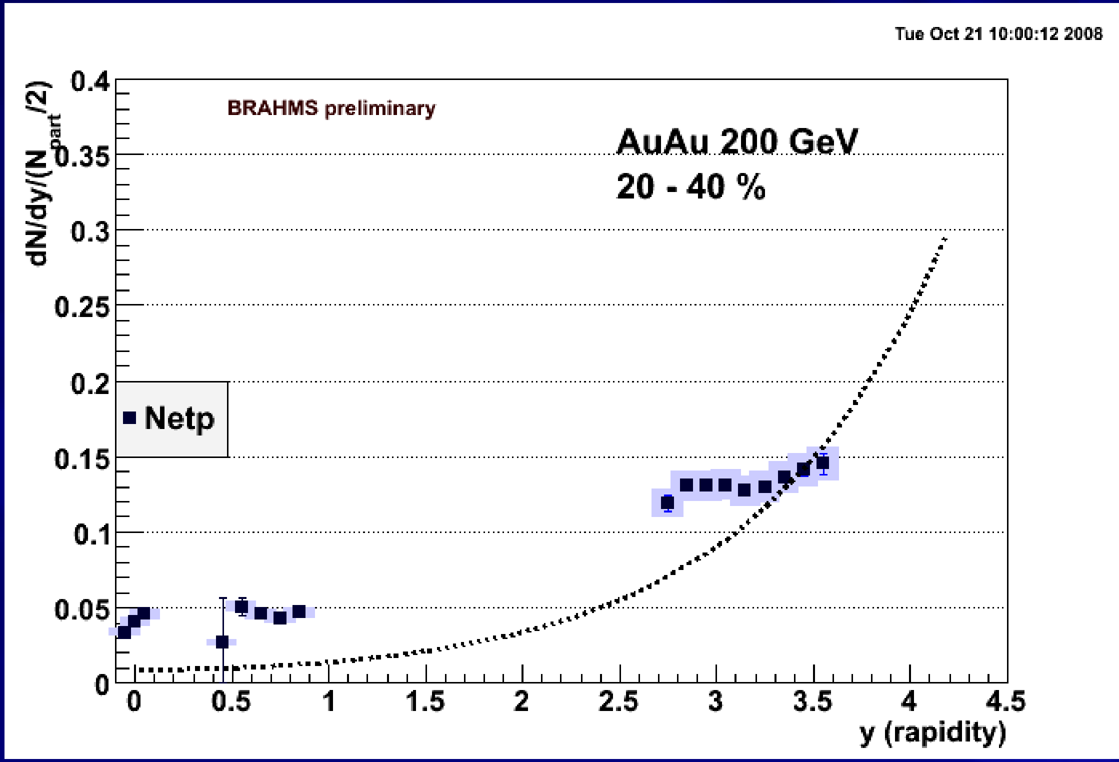

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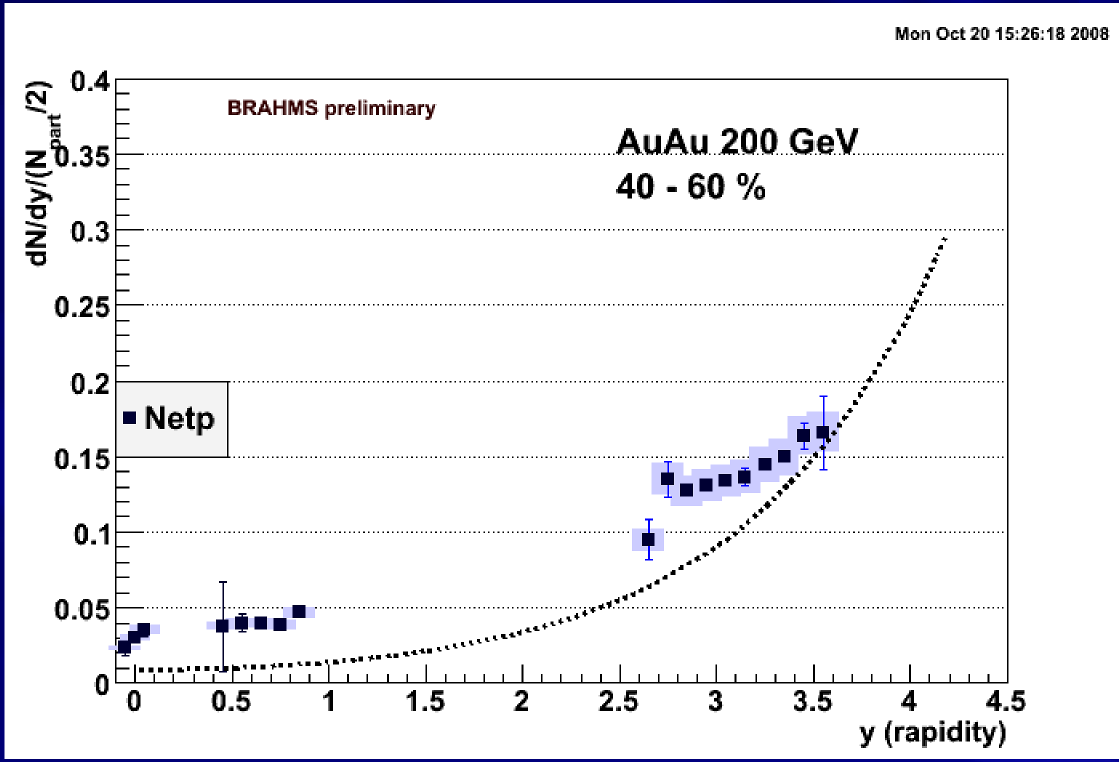

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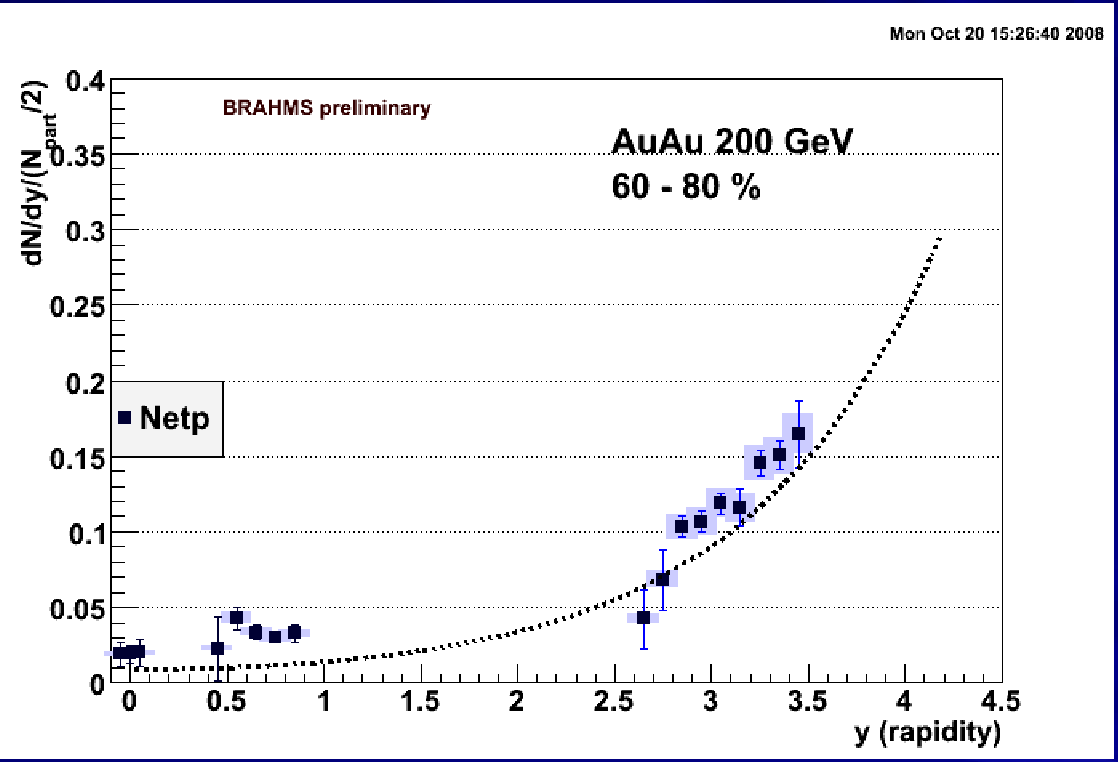
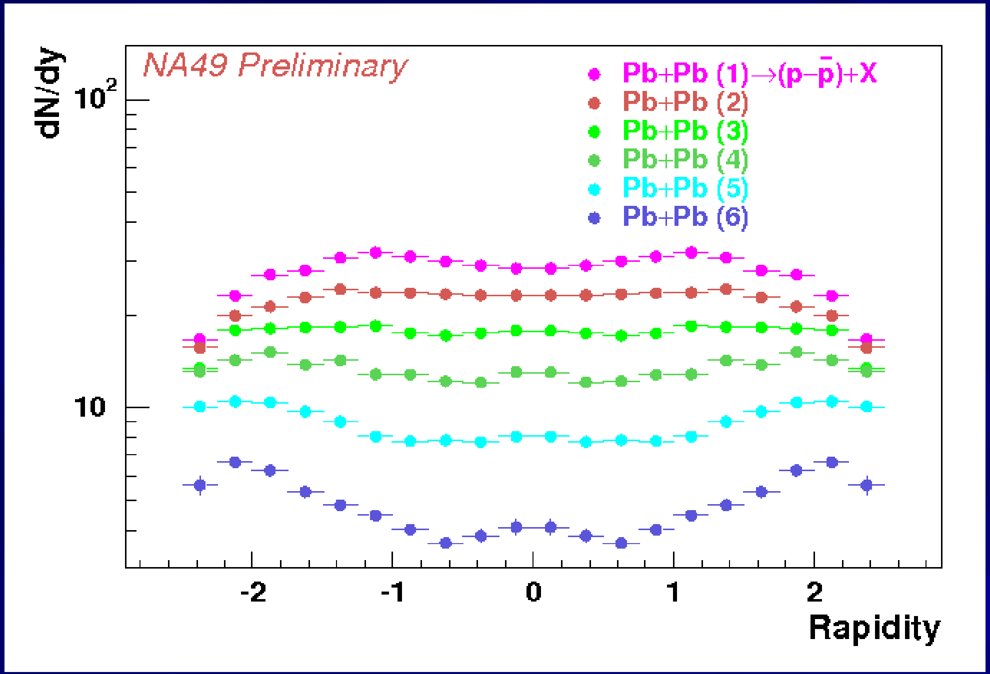
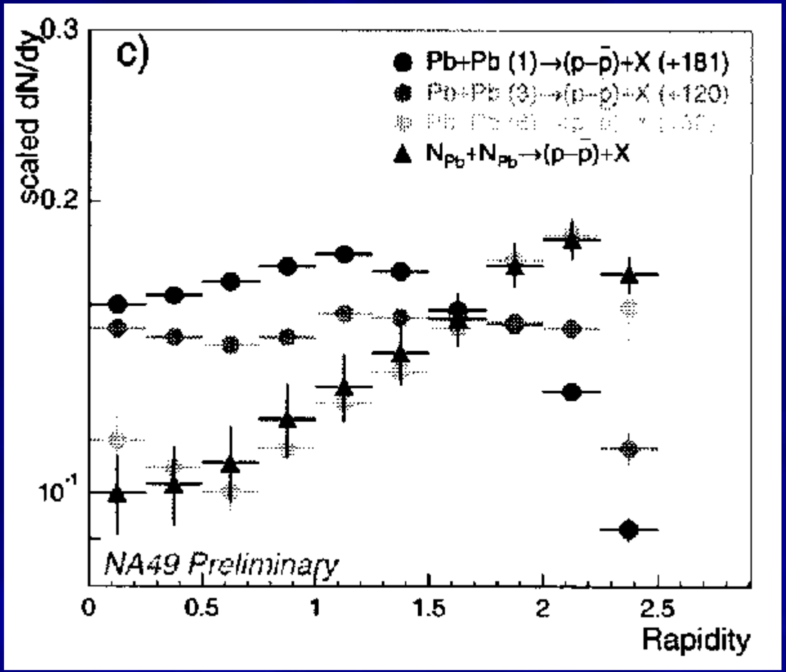


- Significant centrality dependence
  - Peripheral collisions are similar to pp

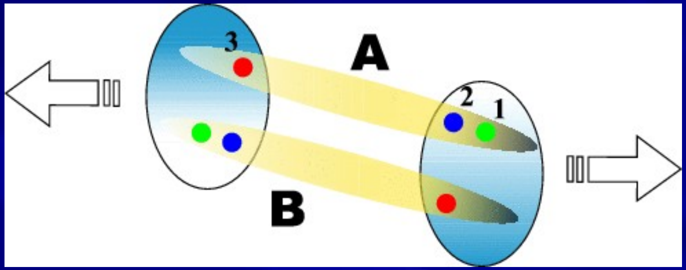
NA49 centrality dependence





- NA49 has observed similar centrality dependence, see [NPA661,362(1999)].
- Pb+Pb and p+p net-protons are similar for the centrality class 48-100% (some trigger bias)

Models



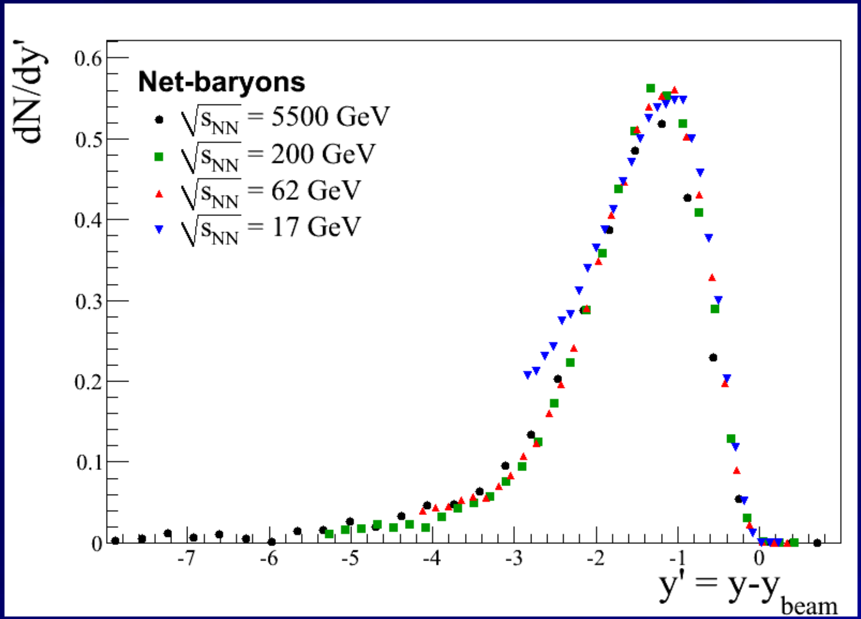
Some questions for models (and experiments)

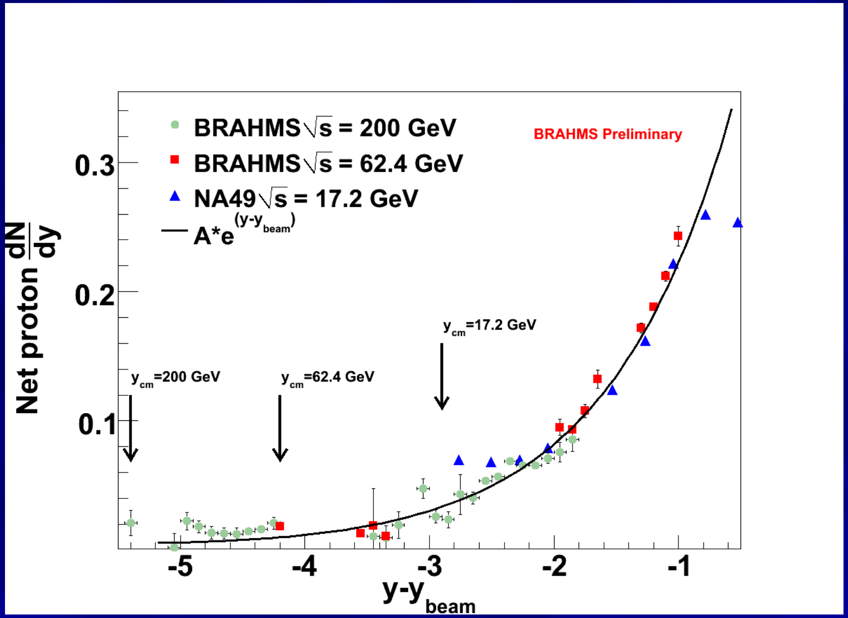
- Are the observed universal scaling relations for pp and AA accidental or fundamental?

- Stopping in pp from PYTHIA
  - is stopping a purely soft (string breaking/fragmentation) process or does hard processes contribute?
    - Important for centrality dependence

- Stopping in AA
  - New "coherent" models
    - Q^2 dependence of valence quark pdfs

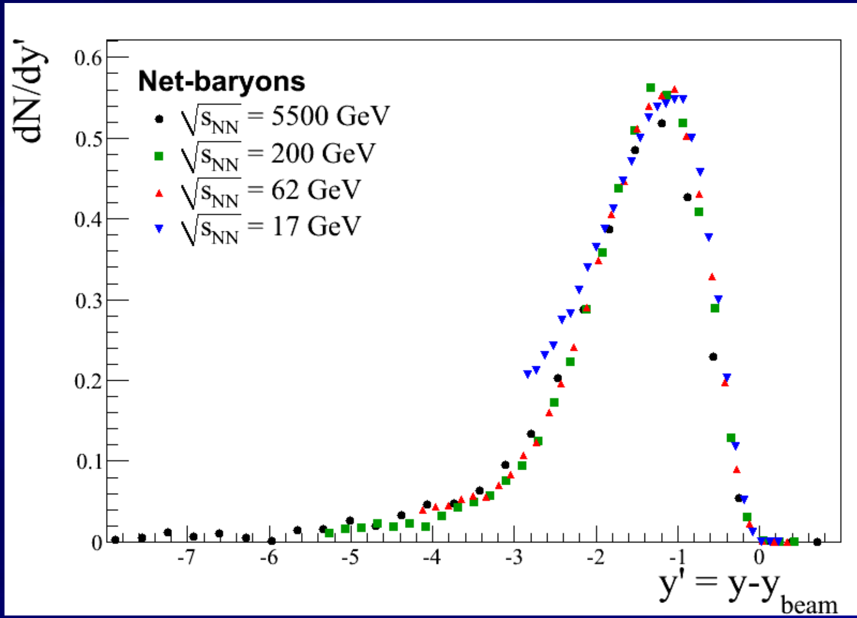
Stopping in PYTHIA

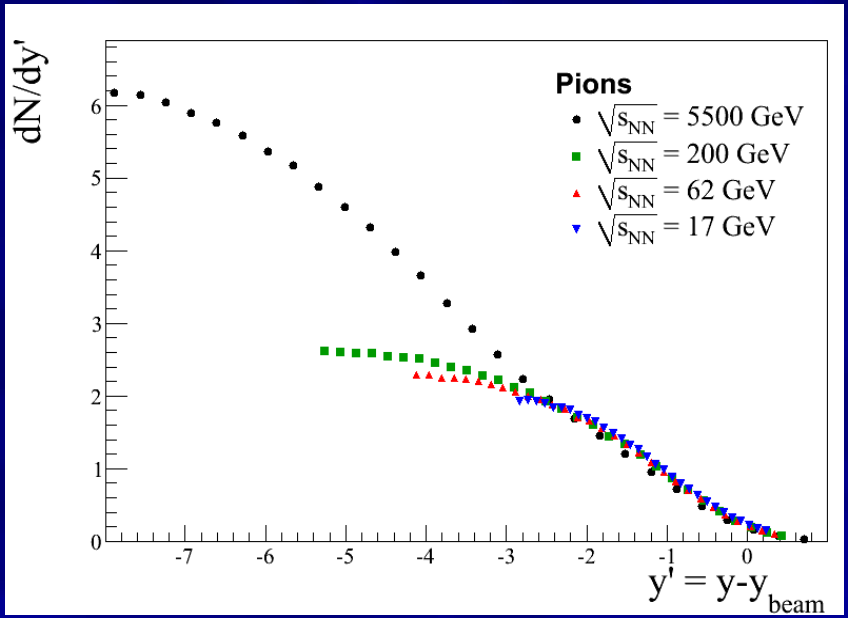




- PYTHIA (v 8.108, w.o. tuning) shows an almost universal stopping curve from SPS to LHC energies
- Stopping is dominated by string breaking (soft processes)
  - Universality is in the model

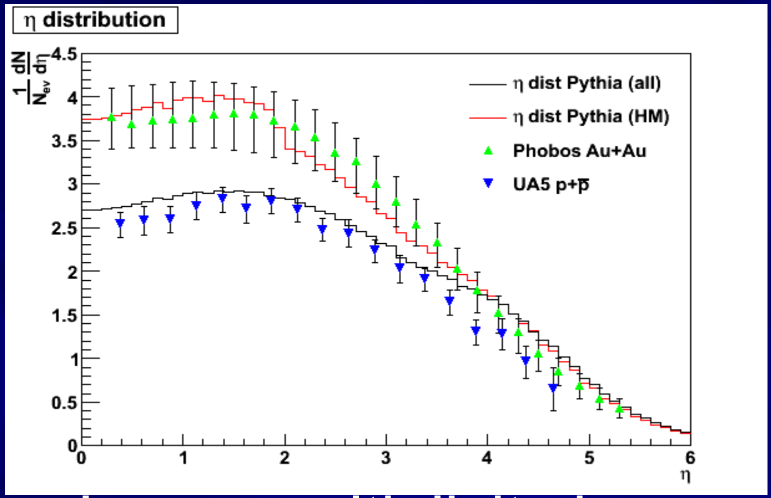
Perhaps related to limiting fragmentation

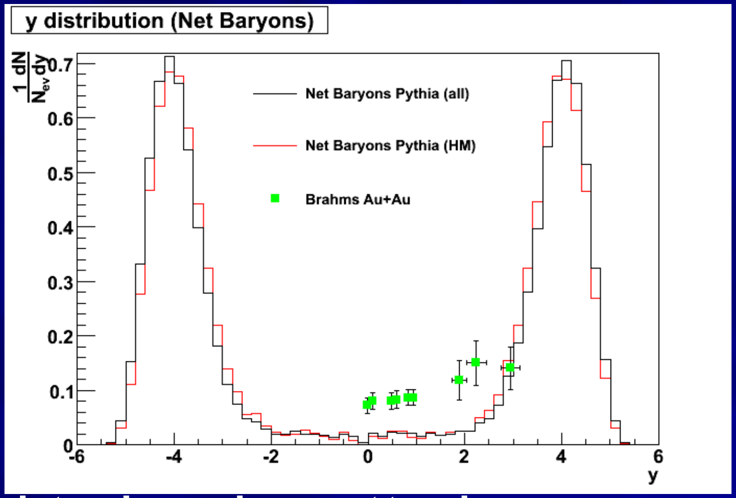




- Forward physics seems more or less universal
- Hard physics dominates around mid-rapidity because of phase space
- At large energies more multiple interactions and more activity per interaction (initial and final state radiation)

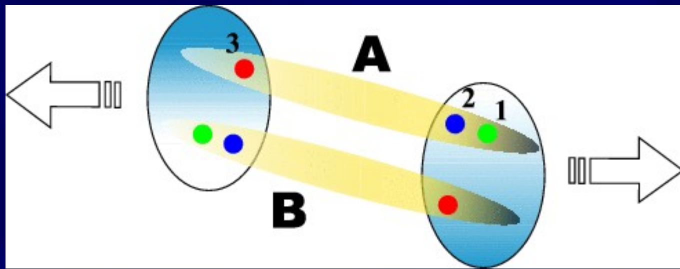
p+p is not only min bias: Could we learn more?!

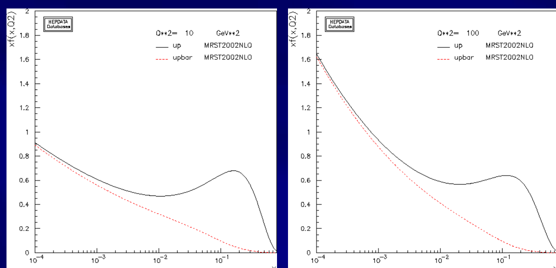


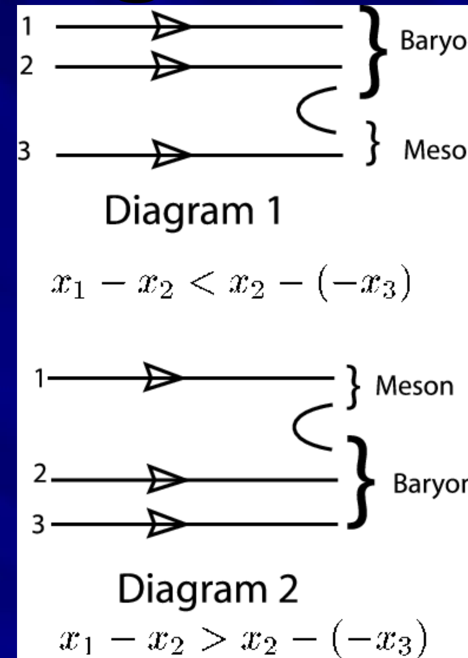


- Large multiplicity in pp coupled to hard scatterings
  - Small effect on stopping in PYTHIA
    - Large stopping at RHIC is not essential for larger particle production!
- But is PYTHIA true? problems with p/p-bar ratios and p_T dependence
- Experiment could (should?) decide if this is true!
  - BRAHMS (problem to cut on multiplicity)
  - STAR (less rapidity coverage)

A p+p and A+A stopping model based on strings







- Input are the pdf's for valence quarks: x1>x2>x3 (and x3<0) taken at:

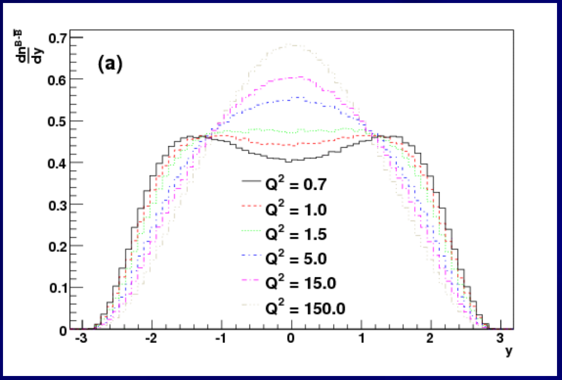
$$Q_A^2 = \left(\frac{N_{part}}{2}\right)^{\alpha} Q_0^2 \left(\frac{s}{s_0}\right)^{\lambda_v}$$

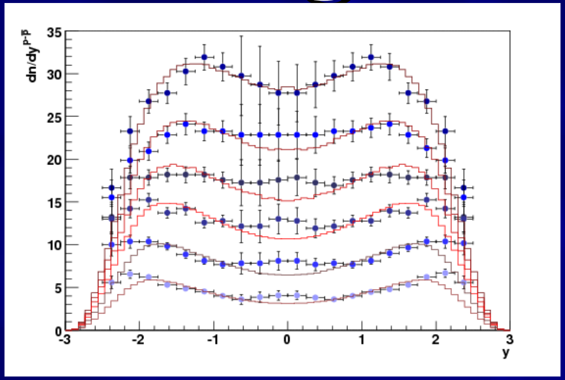
- Where α and λ_v are to be determined from fits to data

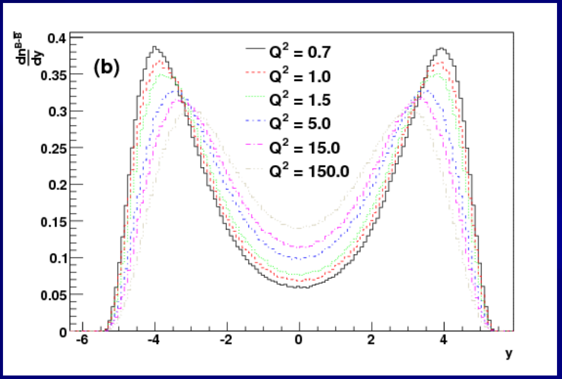
- Fragmentation by q+q-bar string breaking between "closest" valence quarks
  - Diagram 2 gives large rapidity losses

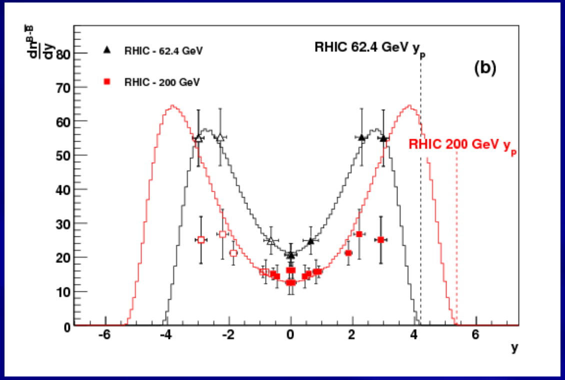
[J. Alvarez-Muniz et-al, arXiv:0903.0975]

A p+p and A+A stopping model based on strings









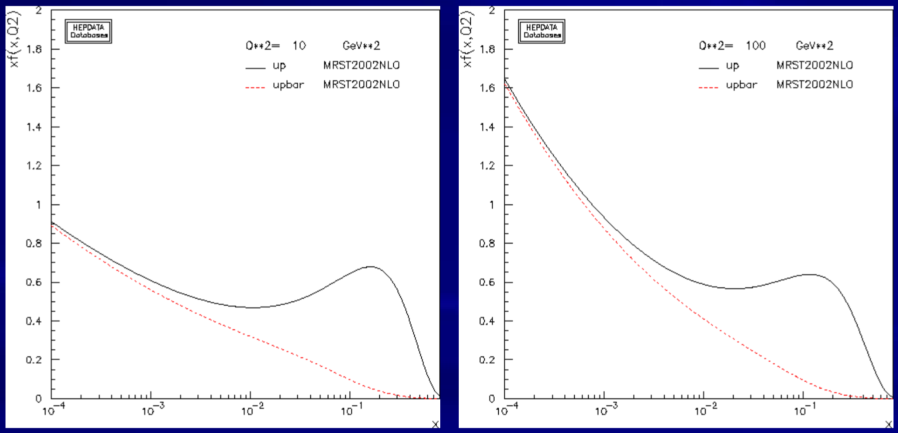
- Is it universal? Probably if energy dependence of Q^2 is weak.

A CGC model for stopping: CGC kicks out valence quarks

- CGC saturation momentum:

$$Q_s^2(x) = A^{1/3} Q_0^2 x^{-\lambda}$$

- Where λ~0.2-0.3 controls the rapidity/energy dependence



- Mehtar-Tani and Wolschin. [PRL 102, 182301 (2009)]

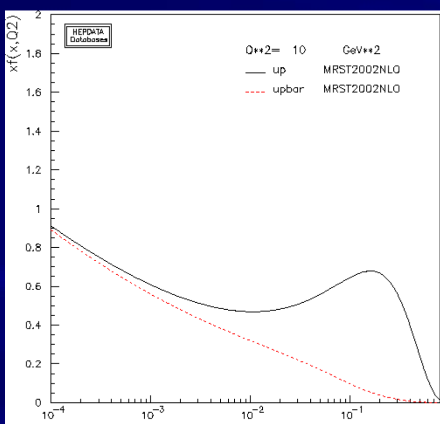
A CGC model for stopping: CGC kicks out valence quarks

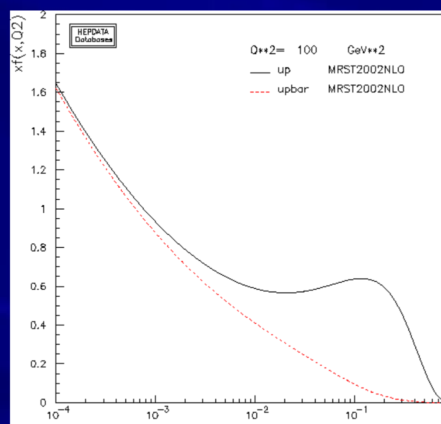
d/Au quarks → ← Au gluons

- CGC saturation momentum:

$$Q_s^2(x) = A^{1/3} Q_0^2 x^{-\lambda}$$

- Where λ~0.2-0.3 controls the rapidity/energy dependence





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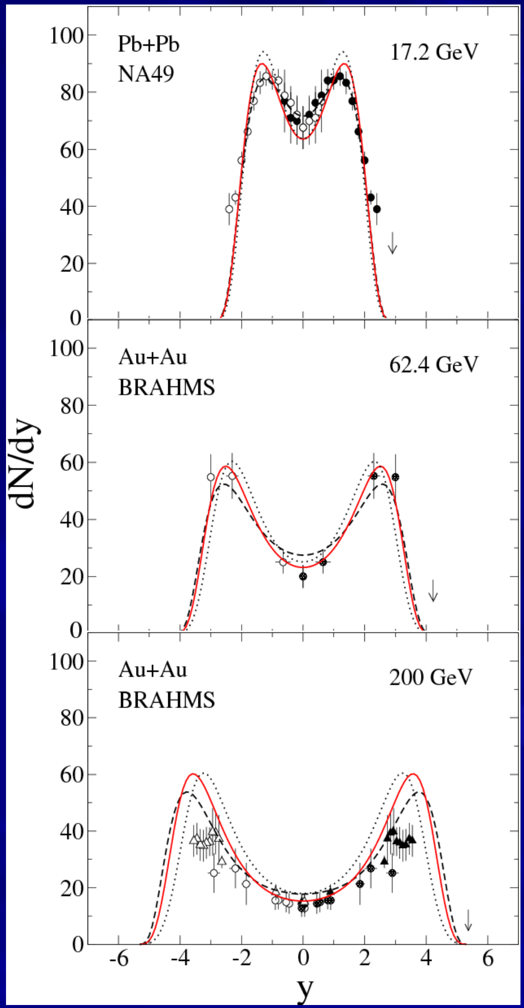


- Curves corresponds to different values for λ and Q_0

Dashed: λ=0 (universal) and Q_0^2=0.08 GeV²

λ=0.15 and Q_0^2=0.07 GeV²

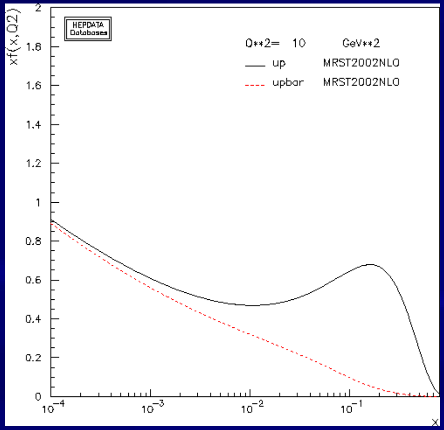
Dotted: λ=0.3 (~HERA) and Q_0^2=0.06 GeV²

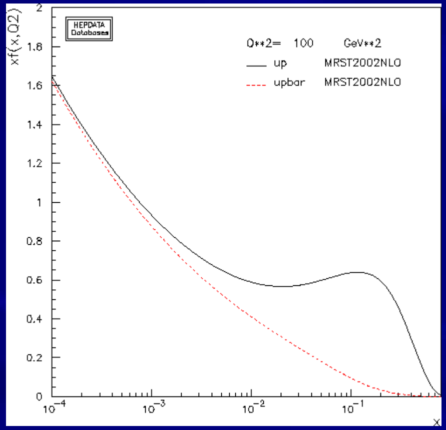
A CGC model for stopping: CGC kicks out valence quarks

- CGC saturation momentum:

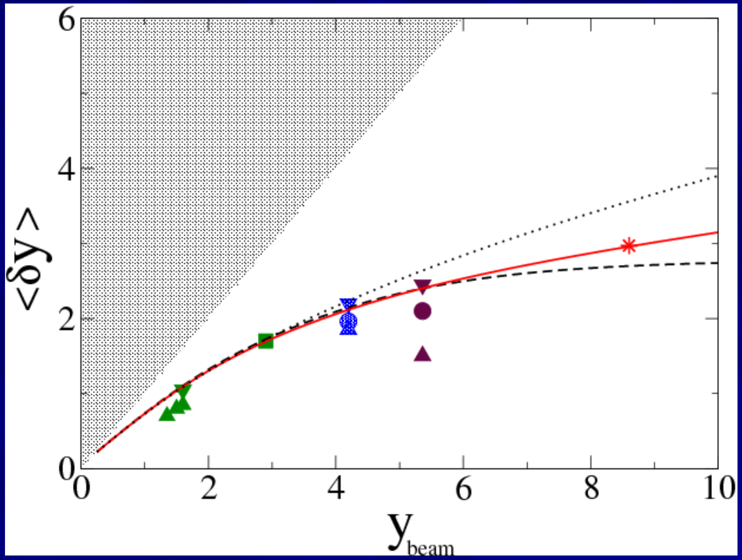
$$Q_s^2(x) = A^{1/3} Q_0^2 x^{-\lambda}$$

- Where λ~0.2-0.3 controls the rapidity/energy dependence



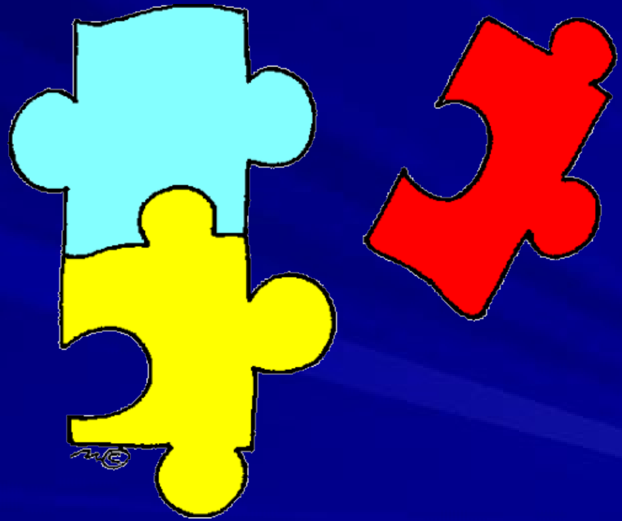


- Mehtar-Tani and Wolschin. [PRL 102, 182301 (2009)]

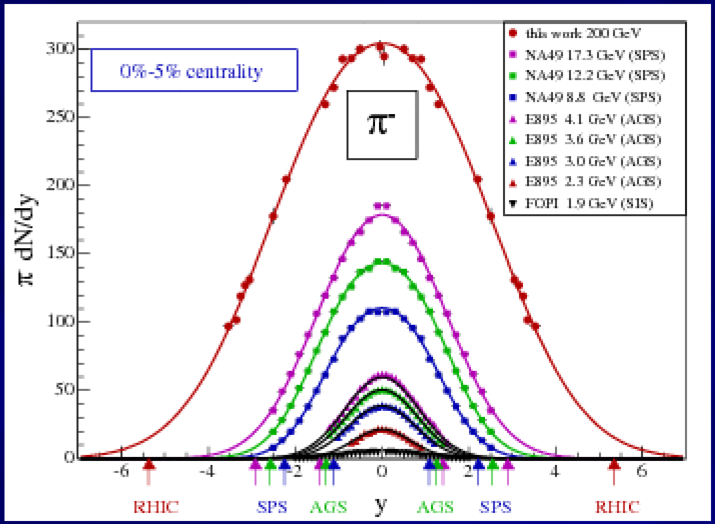


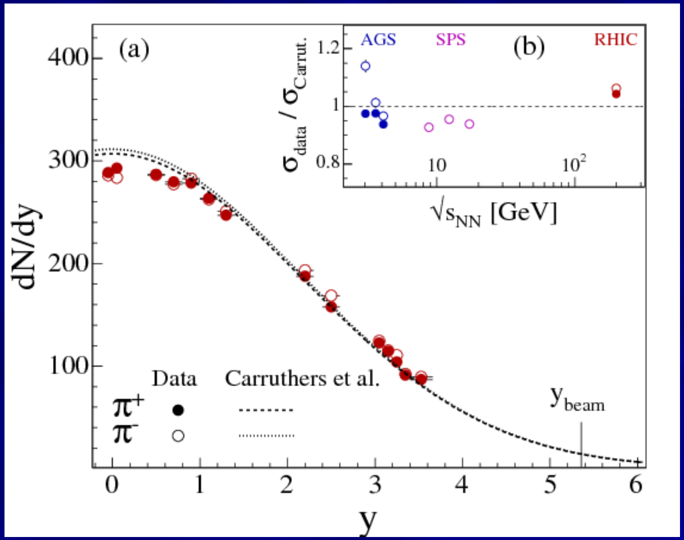
- Two universal parameters controls stopping and particle production
- Universality is broken by λ
  - Mostly at forward rapidity (very small x)
- Centrality dependence?

What is the relation to particle production in general



Landau hydrodynamics





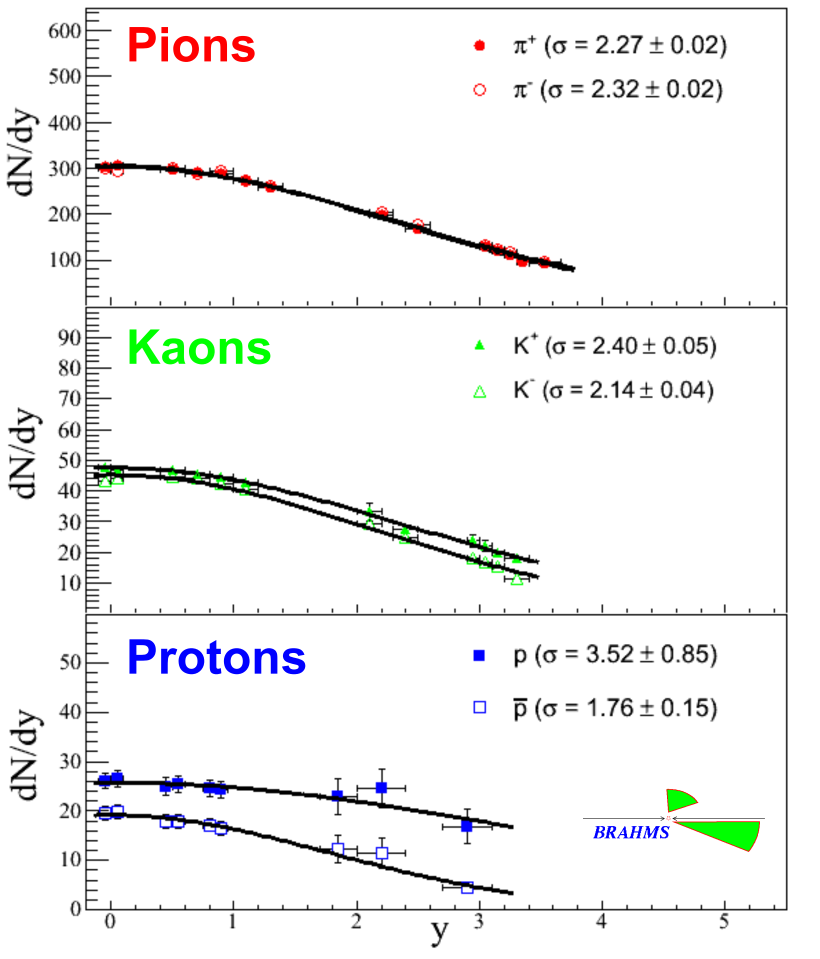
- Landau hydrodynamics predicts Gaussian rapidity distibutions with a width σ given by:

$$\sigma^2 = \ln\left(\frac{\sqrt{s}}{2m_p}\right) = \ln\gamma_{CM} \sim y_{CM} - \ln 2$$

- Recent reference with exact result [PRC 78, 054902 (2008)]

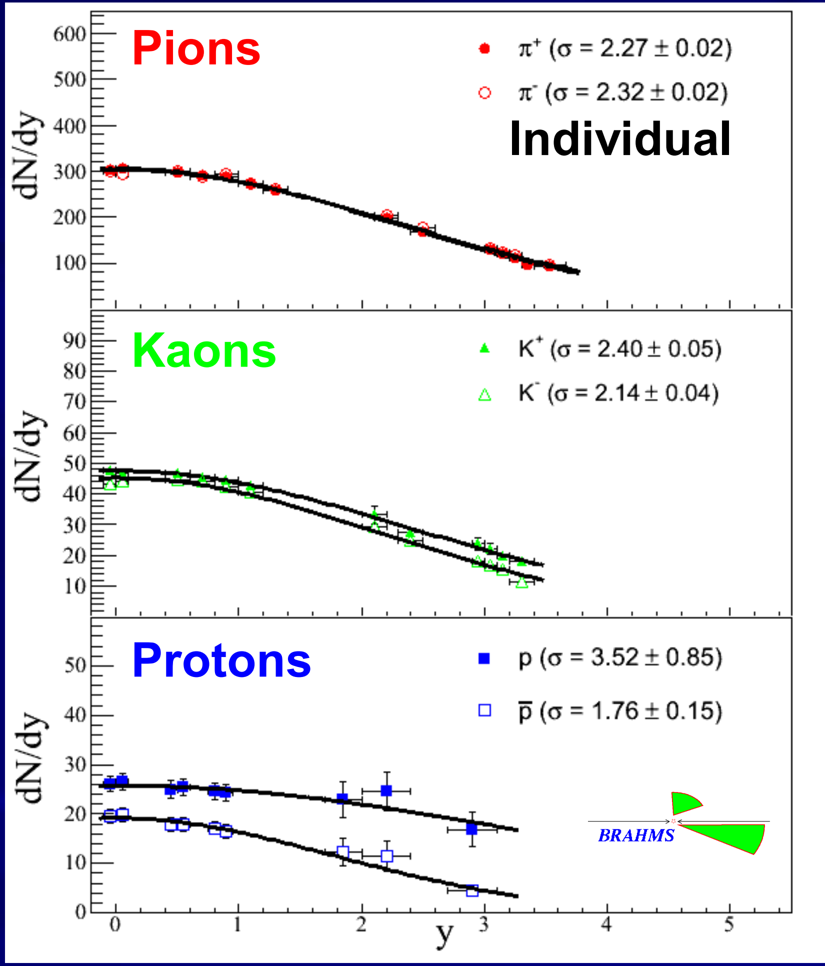
[L.D. Landau, Izv. Akad. Nauk SSSR 17 (1953) 52
P.Carruthers, M.Duong-van, PRD 8 (1973) 859]

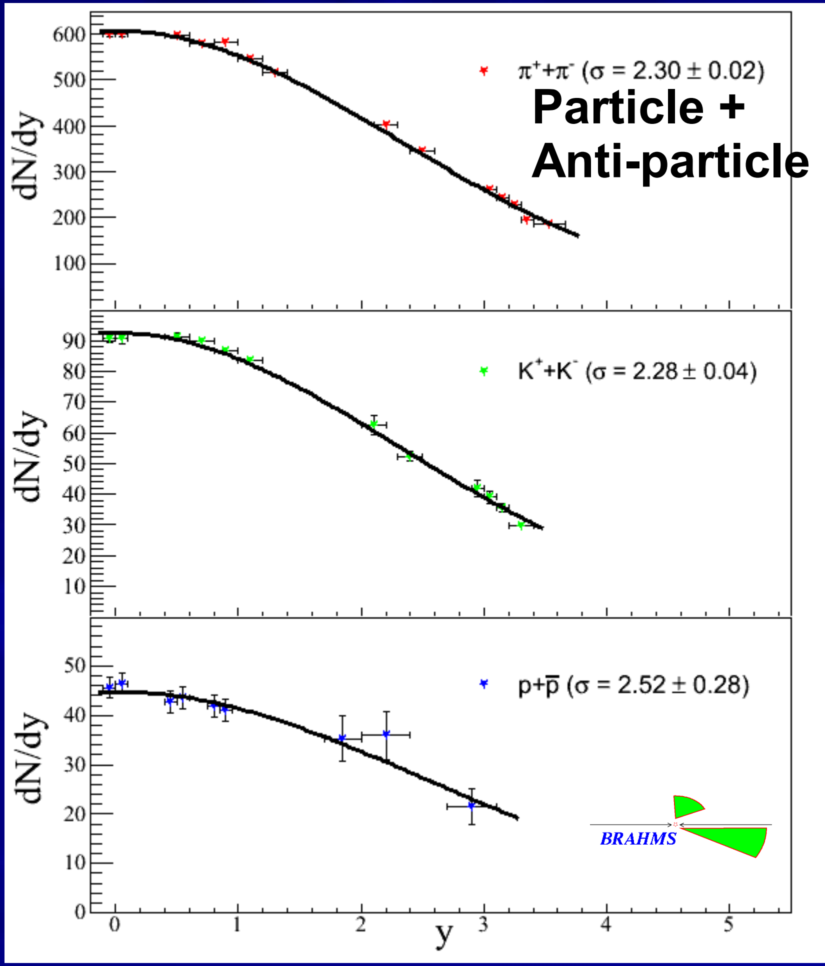
Does other dN/dy behave as Landau hydro?



Ordering of individual sigmas:
p-bar < K^- < π^+ < π^- < K^+ < p

Does other dN/dy behave as Landau hydro?

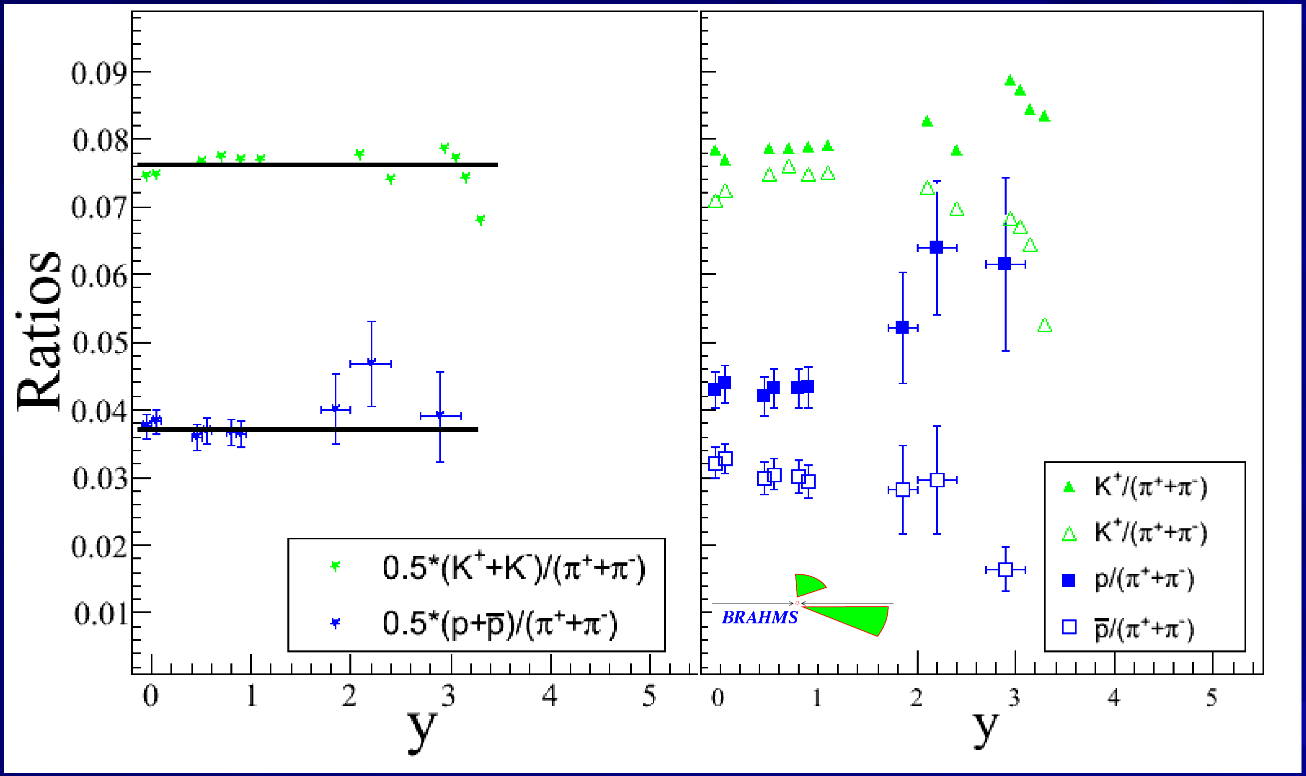




Ordering of individual sigmas: p-bar < K^- < π^+ < π^- < K^+ < p

Particle + anti-particle sigmas are similar and ~Landau

Interpretation a la statistical model via T and $\mu_B(y)$



For small chemical potentials (μ<T): exp(-μ/T)+exp(μ/T) (=2cosh(μ/T)) ~1-μ/T + 1+μ/T~2 i.e. constant

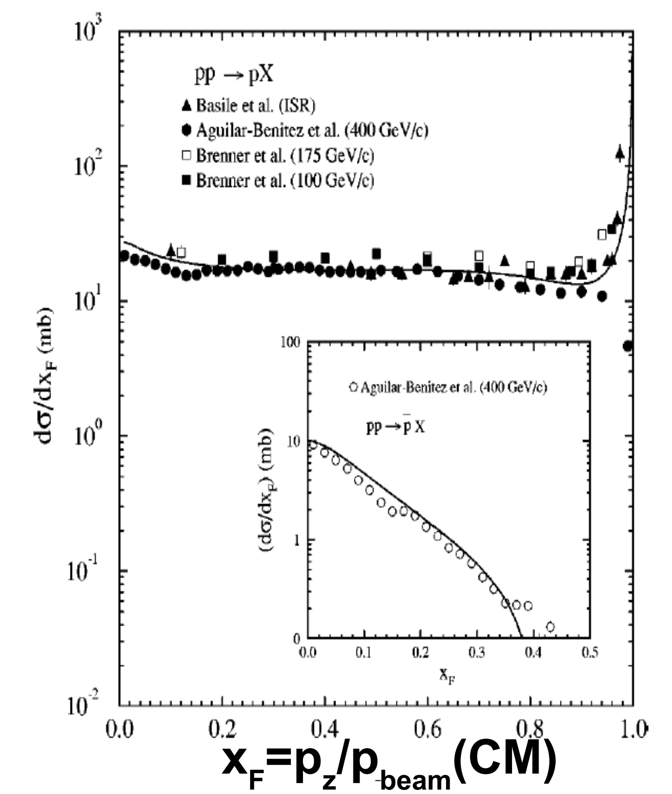
- The chemical freezeout temperature seems to be independent of rapidity so that it is only the baryon chemical potential which changes
- Might be just accidental

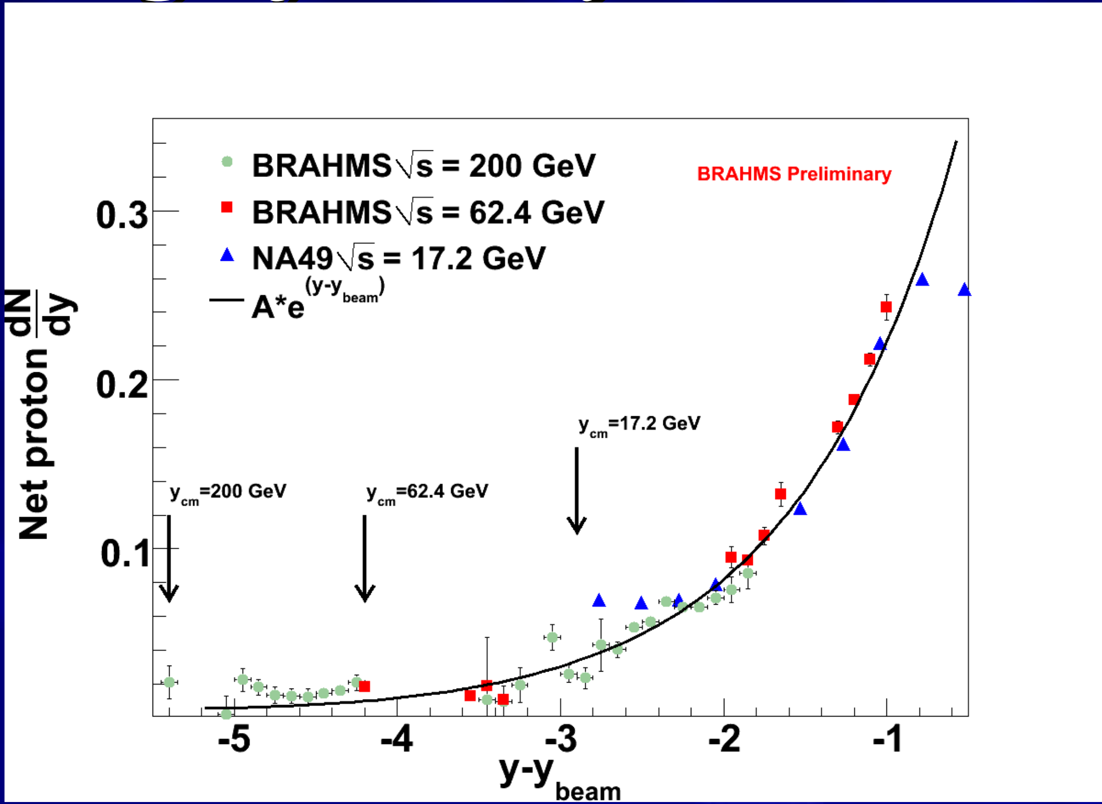
Summary

- Experimental data indicates
  - The net-baryon rapidity loss does not change significantly from AGS/SPS to RHIC for p+p and central A+A
  - Peripheral (60-80%) A+A shows same rapidity loss as p+p
  - Need more published data at SPS and RHIC (p+p, p/d+A, A+A)
- New coherent models shows reasonable agreement with data
  - Mechanism of stopping is clearer
  - Can the new models handle p+p, p+A, and A+A
- For models it would be particularly interesting to study (if possible) stopping for the projectile only
- Same mechanism of stopping from AGS/SPS to LHC?
  - PYTHIA indicates breaking of rapidity scaling at LHC due to the increase of the hard scale → more multiple interactions with higher activity

Backup slides

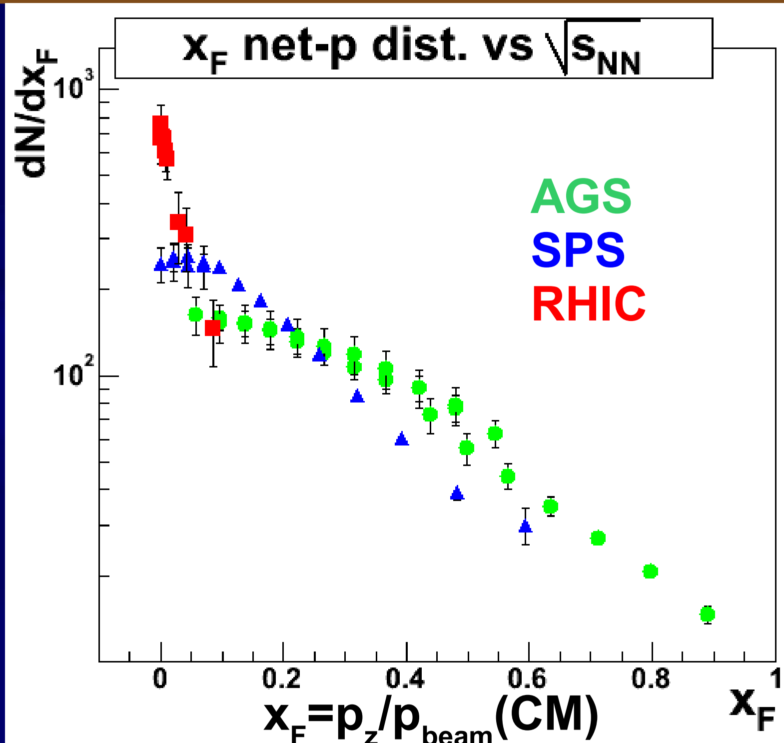
Stopping in p+p collisions: Scaling of dN/dy

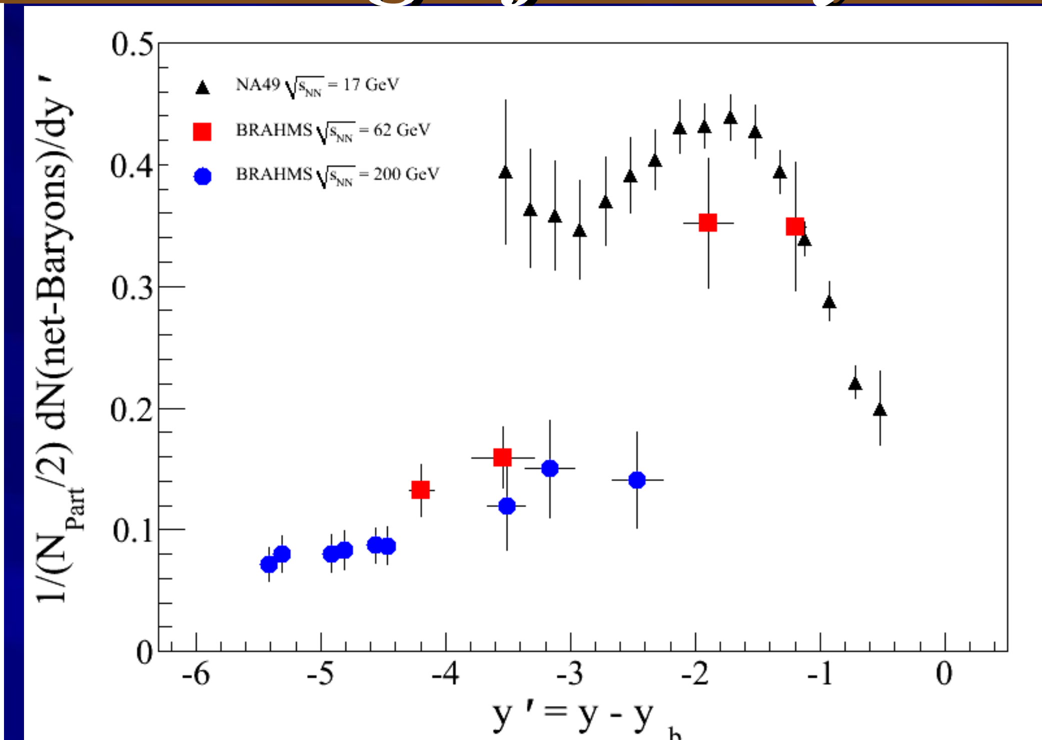




- p+p collisions (at low energy) exhibits Feynman scaling so that dN/dx_F~constant → dN/dy~$A^*\exp(-(y_{beam}-y))$
- This universal behavior is also observed at RHIC

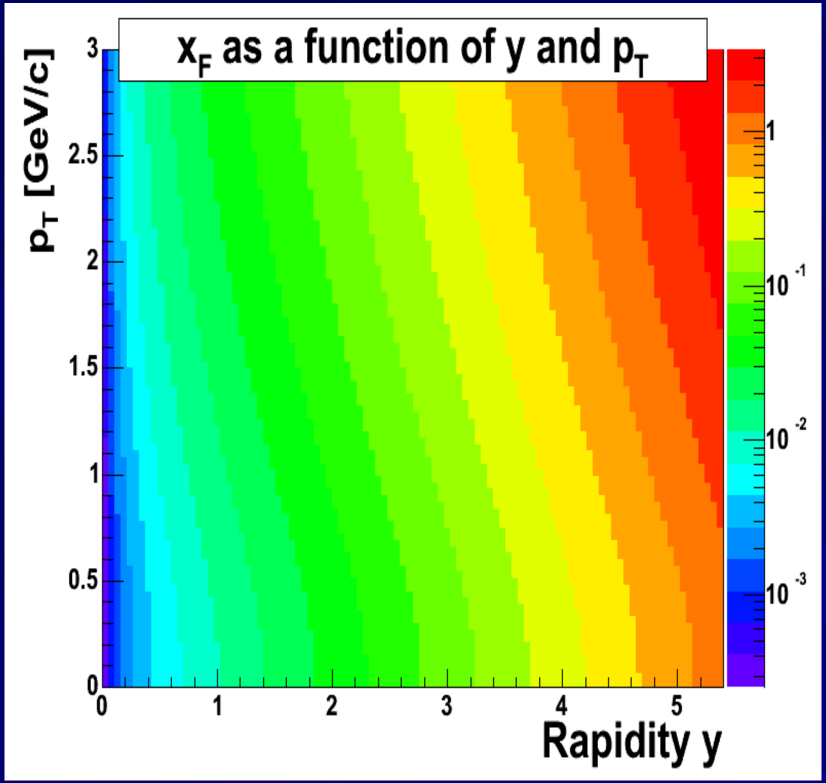
Stopping in A+A collisions: No obvious scaling of dN/dy

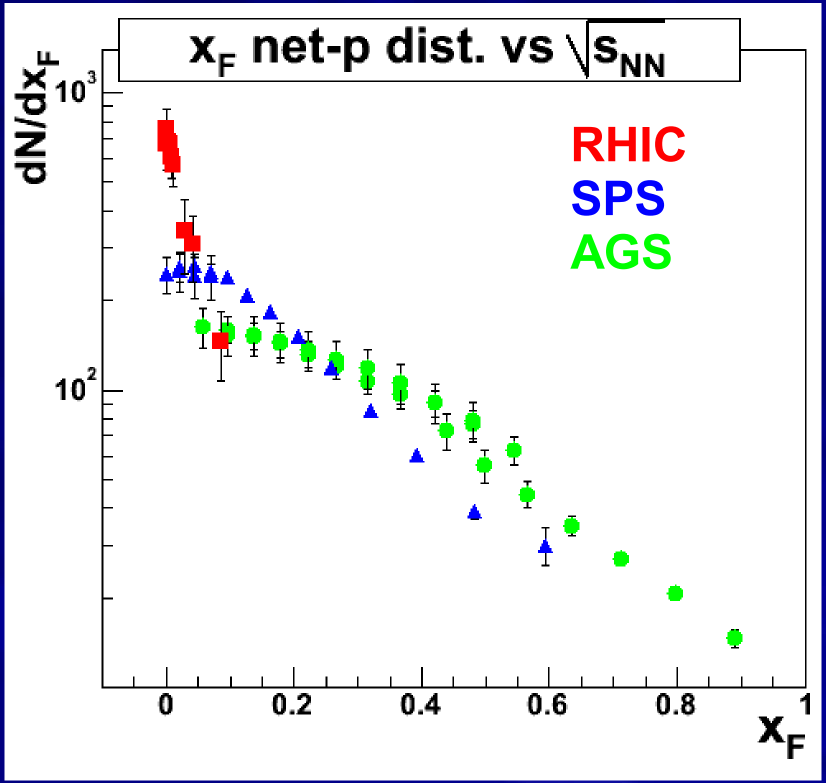




- In A+A collisions there is no Feynman scaling
- No obvious scaling in y'=ybeam-y either
  - But when the target contribution is subtracted there is scaling!
- Quantify stopping by rapidity loss

dN/dxF





- XF = p/PCM

How to measure the net-baryon dN/dy after the collision

- Need good rapidity coverage
  - BRAHMS, (STAR FTPC), NA49
- Need good p_T coverage
  - 1st problem: extrapolate spectra to regions with no coverage
    - Solution: Require good fit description and consistent $\langle p_T \rangle$
- Need good particle identification for protons, Λs and neutrons
  - 2nd problem: Neutrons are hard to measure
    - Solution: Use results from AGS: E941
  - 3rd problem: BRAHMS can measure protons, but not Λs. STAR can measure forward Λs only.
    - Solution 1: NA49 can measure both protons and Λs.
    - Solution 2: The Λs almost cancel in the conversion to net-B!

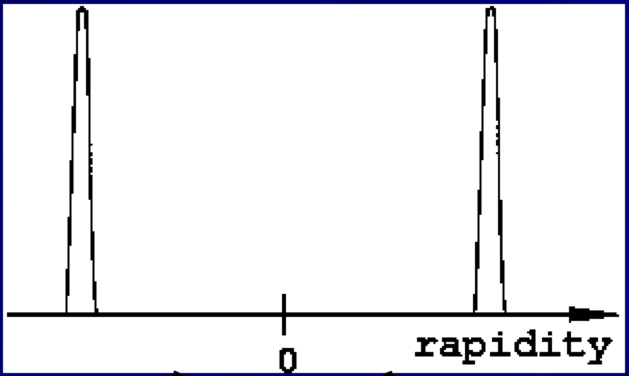
In the following I will use BRAHMS as an example

How to measure stopping

Use rapidity variable → distributions are boost invariant

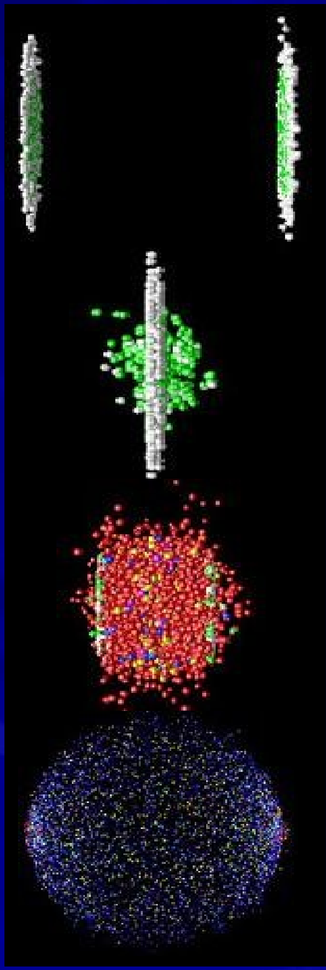
$$y = \frac{1}{2}\log\left(\frac{E+p_z}{E-p_z}\right)$$

“Velocity” space

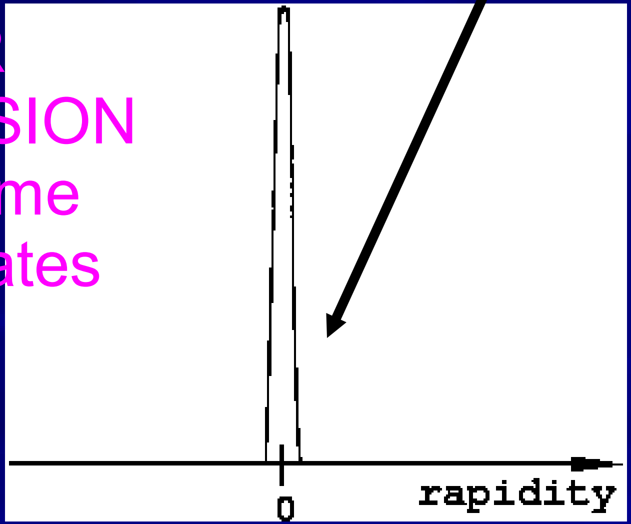


BEFORE COLLISION

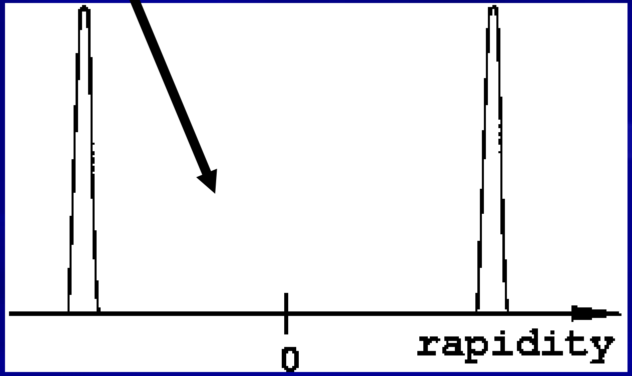
Physical space



AFTER COLLISION
2 extreme final states

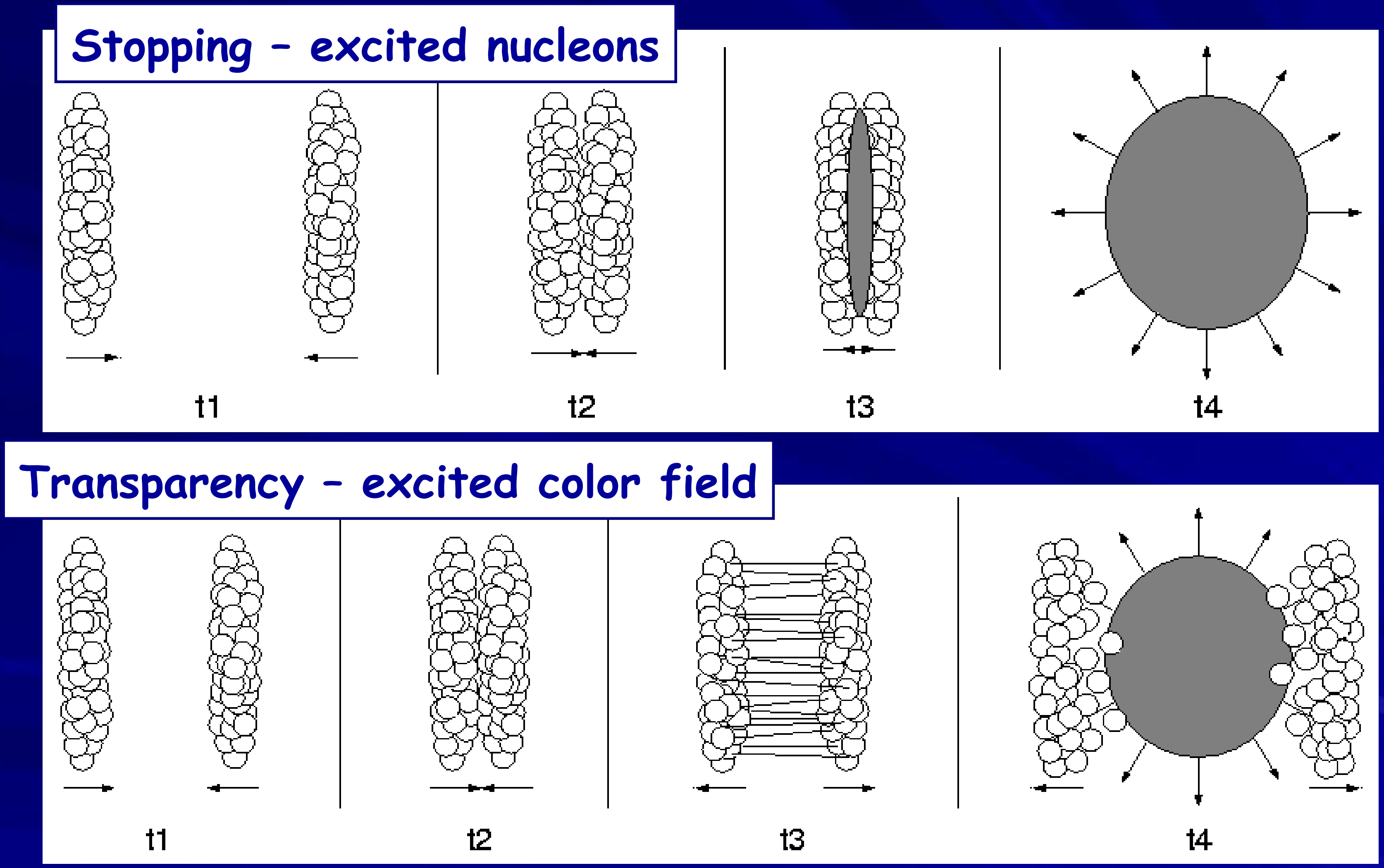


Full stopping



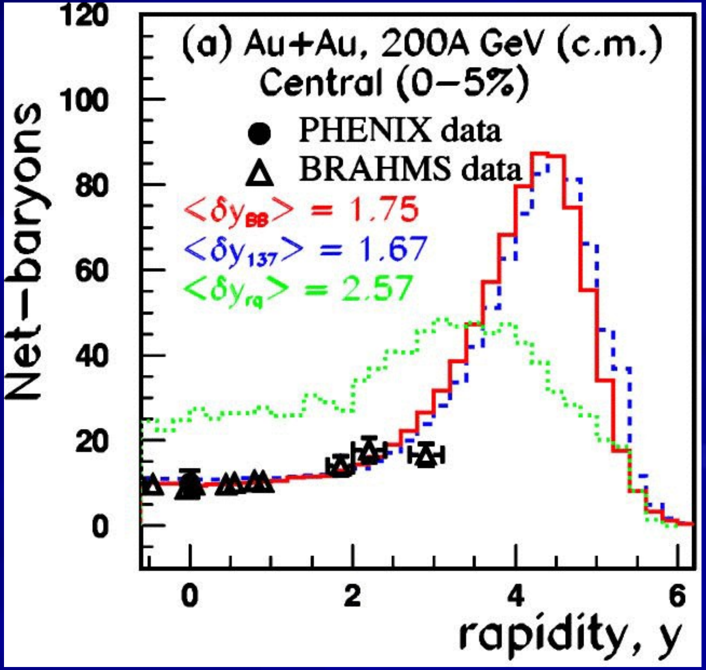
Full transparency

Two physics pictures

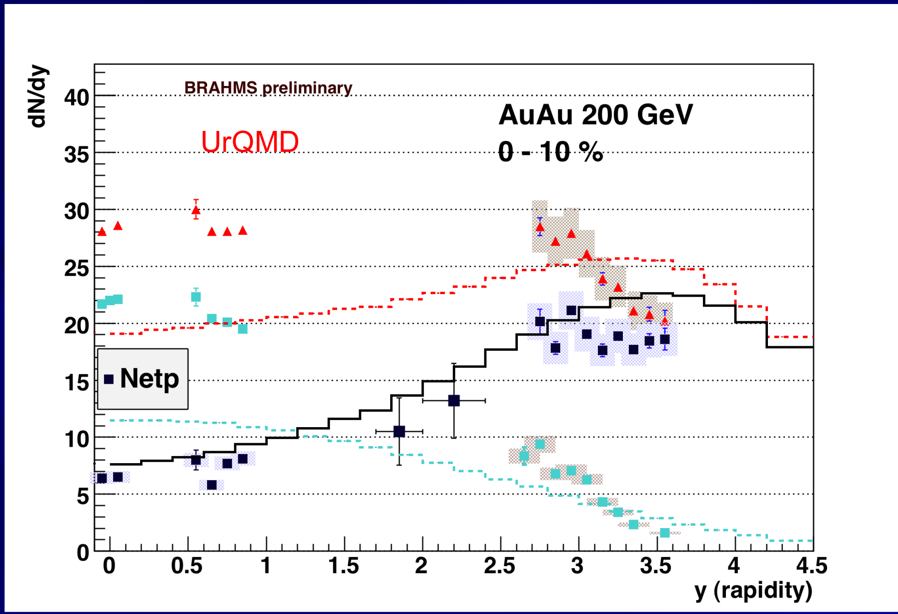


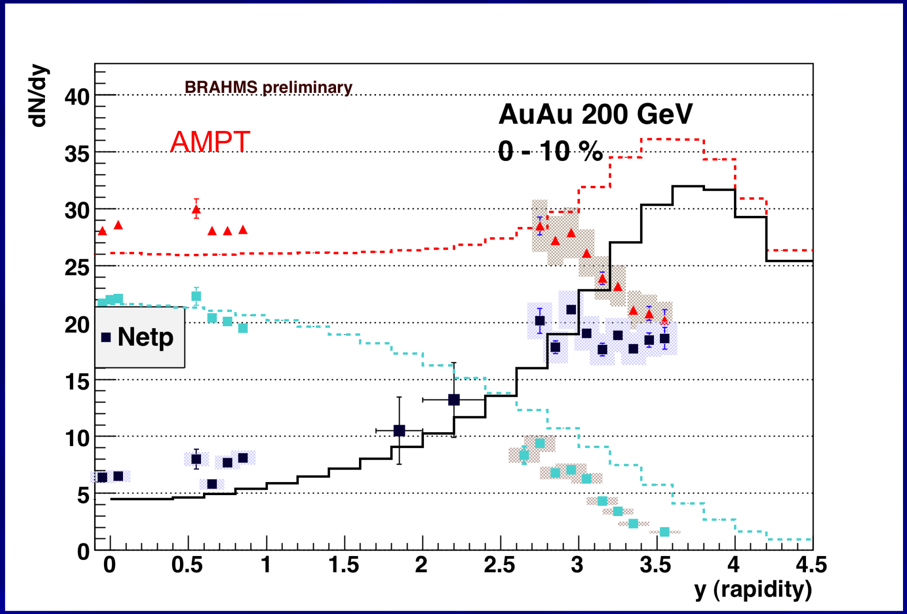
This is also important for models

- Some examples where comparison to net-p is done with the calculation normalized to the number of initial protons which is ~Npart/2.5 ≠ Npart/2
  - But I believe it is better to use net-B even there are systematic uncertainties
- Crosscheck normalization:
  - The plot on the right has wrong normalization of data:
    - dN/dy(y=0) ~14 and not 10!
  - It seems that by accident the two corrections from previous page has both been applied
  - [V. T. Pop et al, PRC 70, 064906 (2004)]



Model Comparisons shown at QM09





- Both models are "incoherent". Several binary collisions with reduced cross section after the first one.

Can energy conservation explain Landau

Assume: $$\frac{dN}{dy} = \frac{N_{total}}{\sqrt{2\pi}\,\sigma} e^{-y^2/2\sigma^2}$$

And that $\langle m_T \rangle$ does not depend on rapidity.

Integrate $\langle m_T \rangle$Cosh(y)dN/dy and set equal to total energy:

$$E_{total} = N_{total} \langle m_T \rangle e^{\sigma^2/2} = N_{part/2} \sqrt{s}$$

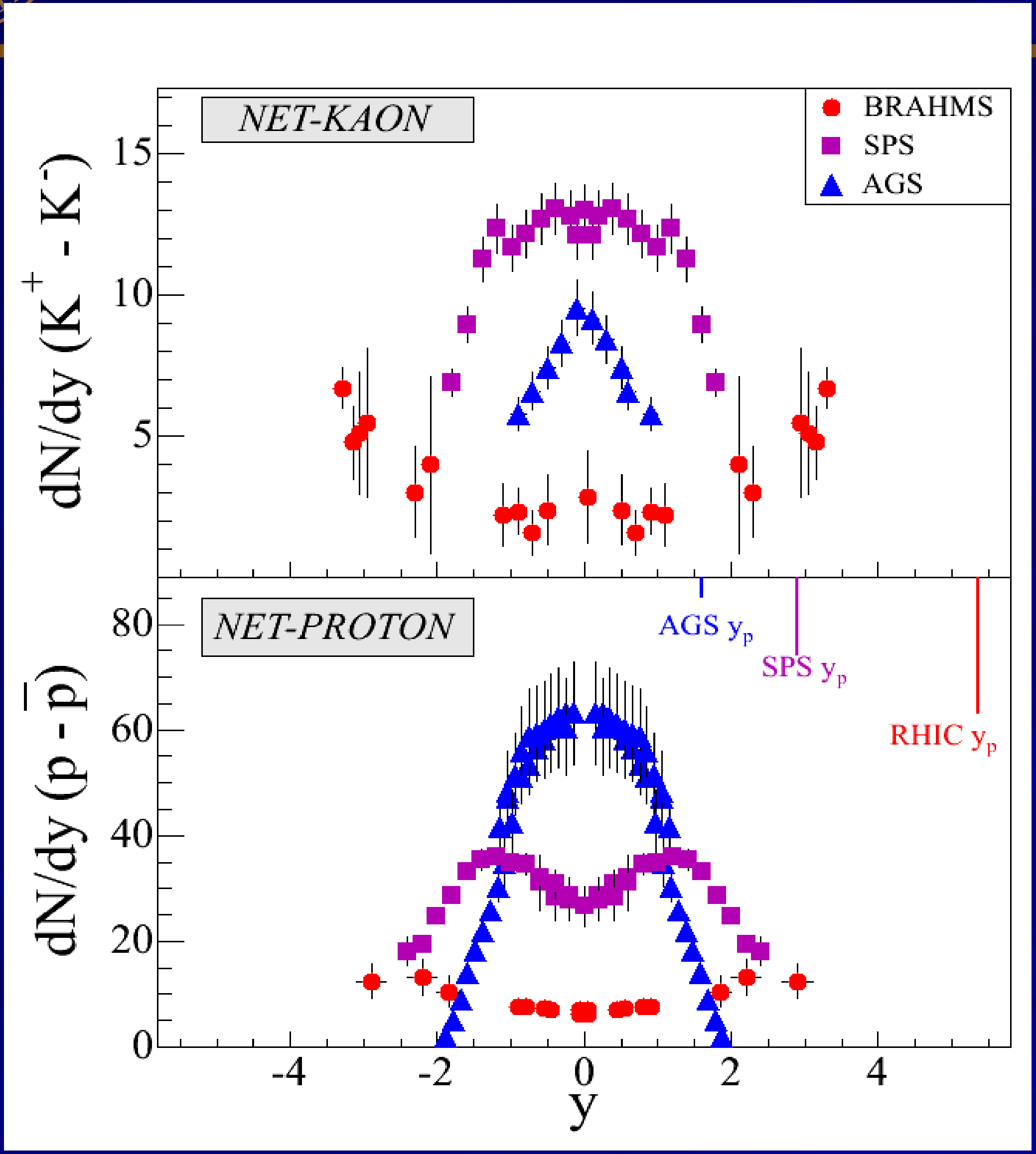
So that: $$\sigma^2 = 2 \ln \frac{N_{part/2} \sqrt{s}}{N_{total} \langle m_T \rangle}$$

Landau/experimental fits to data predicts: $$\frac{N_{total}}{N_{part/2}} = A s^{1/4}$$

So that: $$\sigma^2 = \ln \frac{\sqrt{s}}{A^2 \langle m_T \rangle^2} = \ln \frac{2 m_p}{A^2 \langle m_T \rangle^2} + \ln \frac{\sqrt{s}}{2 m_p}$$

But the first term is not small......

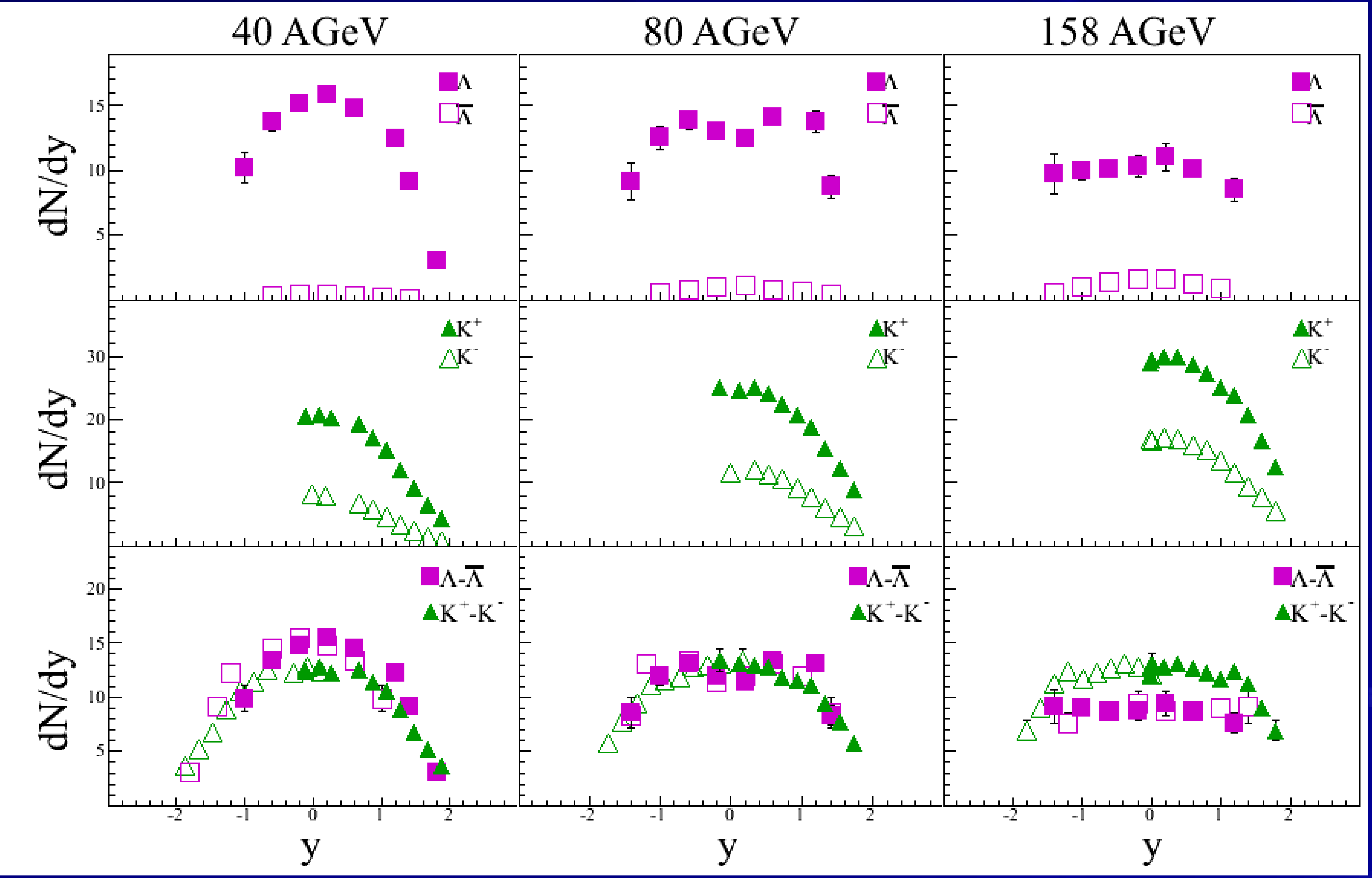
Net-kaons



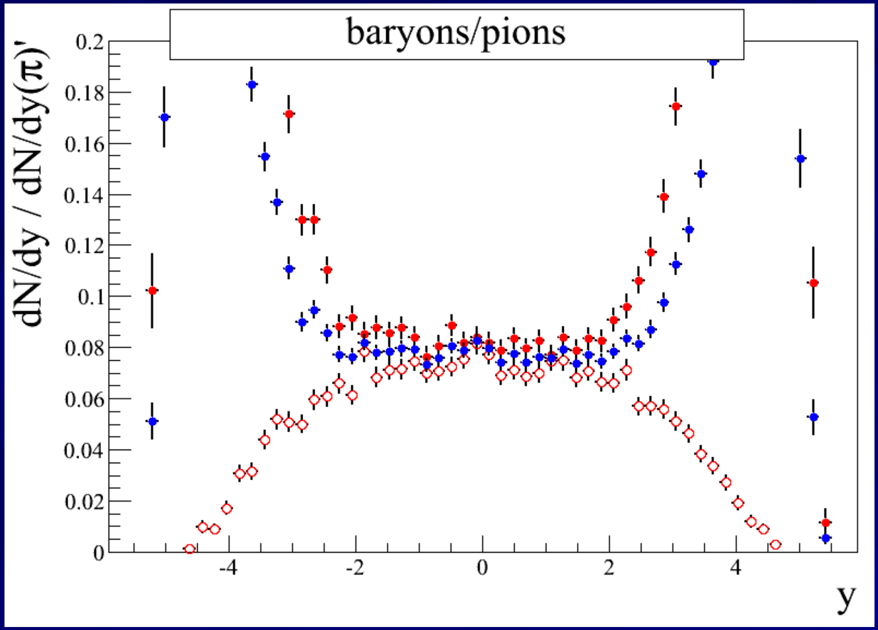
Net-Kaons follows the net-protons.

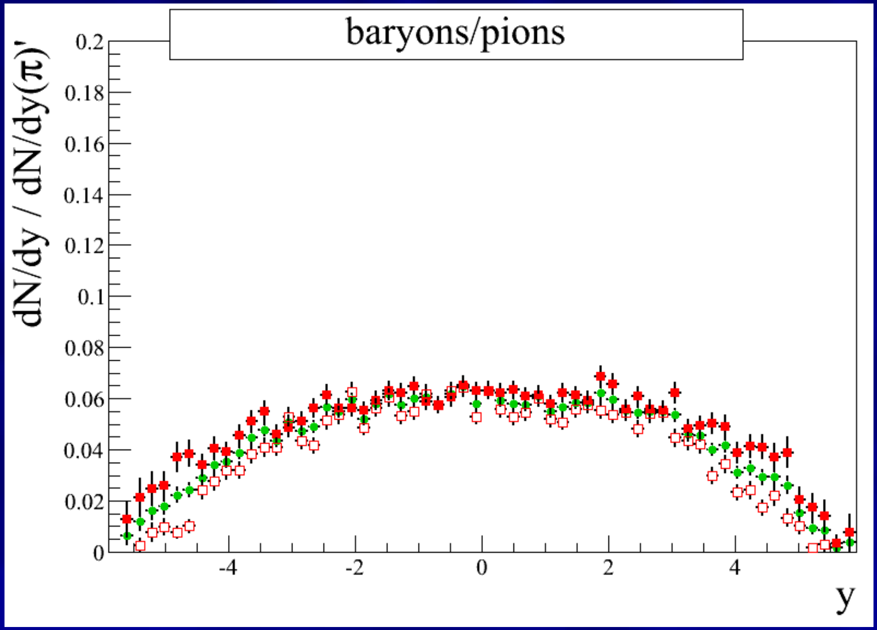
Suggest that there is (at least) a central and a fragmentation source.

Net-Lambdas vs Net-Kaons at SPS



PYTHIA ratios vs y at 200 GeV





- Similar behavior for baryons, but different for kaons