Probing the equation of state of nuclear matter with two-particle correlations

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for the HiRA group

Outline

- Equation of state of nuclear matter at low energies
  - transport theory (BUU)
  - p-p correlations
  - NSCL 03045 Experiment
- particle emission chronology

  (neutron and proton emission times and symmetry energy)
- Summary

EOS and Symmetry Energy

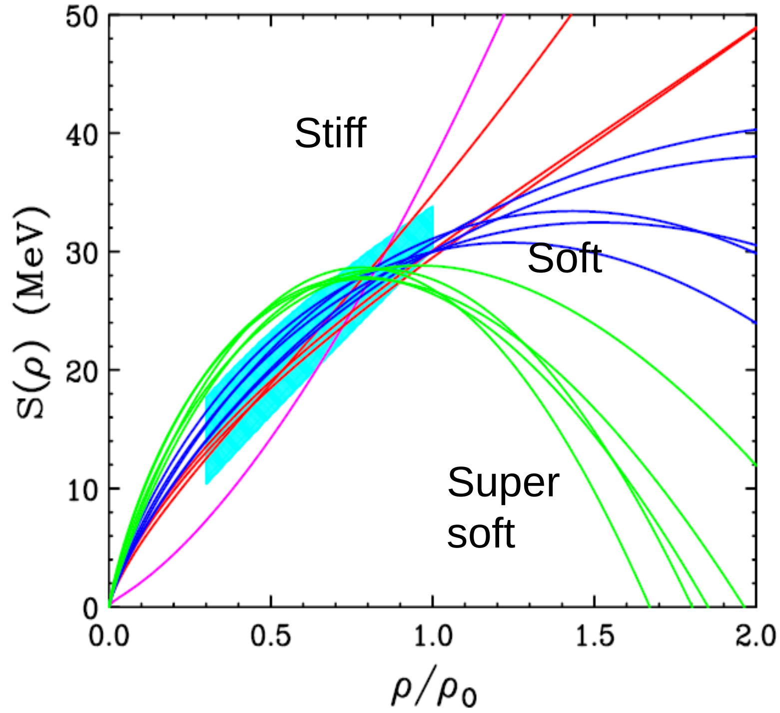
$$E/A\,(\rho,\delta) = E/A\,(\rho,0) + \delta^2 \cdot S(\rho)$$

$$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = (N-Z)/A$$

Both astrophysical and laboratory observables can constrain the EoS indirectly

- What are the observables?
- At what densities or asymmetries do these constraints apply?
- What are the accuracies or model dependencies of these constraints?

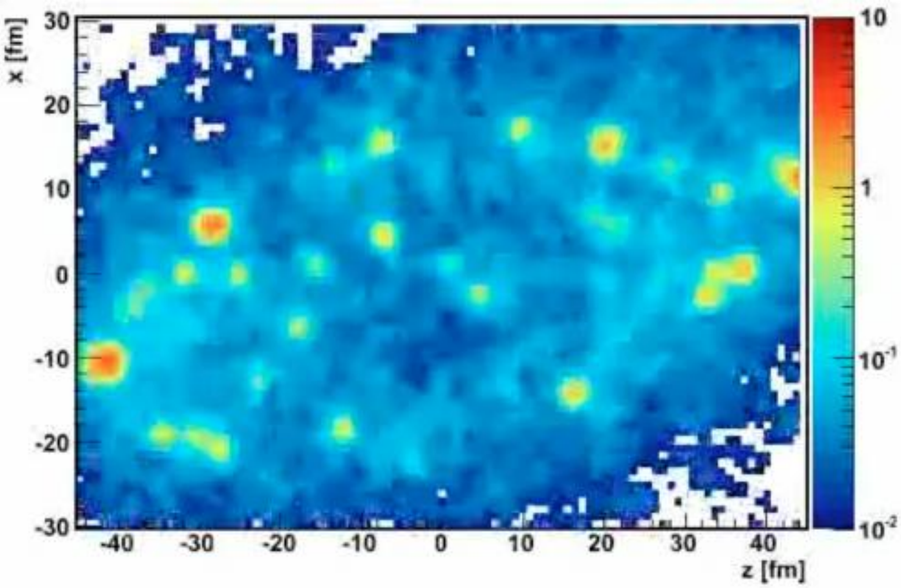
adapted from
M.B. Tsang, Prog. Part.Nucl.Phys. 66, 400 (2011)
Brown, Phys. Rev. Lett. 85, 5296 (2001)



Modeling heavy ion collisions

Our tool: Transport models

- BUU – Boltzmann-Uehling-Uhlenbeck
- QMD – Quantum Molecular Dynamics
- AMD – Antisymmetrized Molecular Dynamics
- Simulates the time-dependent evolution of the collision



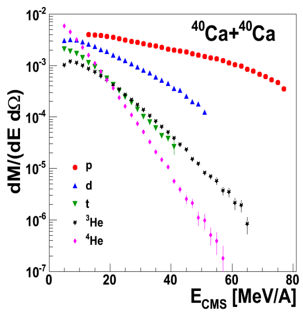
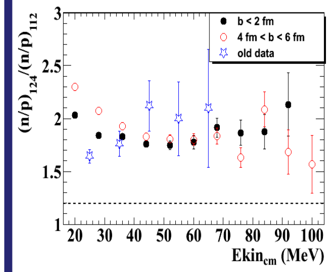
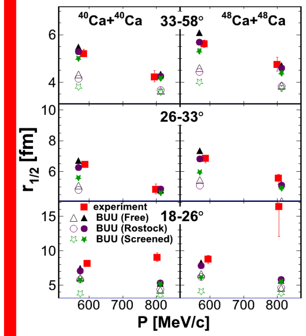
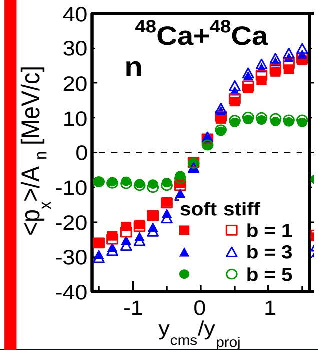
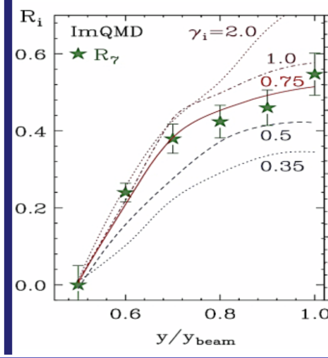
Danielewicz, Acta. Phys. Pol. B 33, 45 (2002)

Danielewicz, Bertsch, NPA533 (1991) 712

Main ingredients

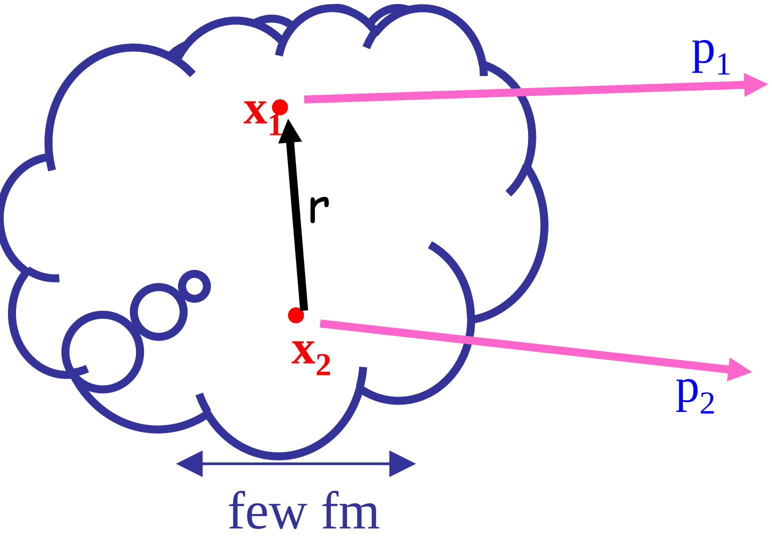
- Nucleons in mean-field
- **Symmetry energy**
- Momentum-dependent nuclear interaction
- **In-medium cross section ➔effective mass**
- **Cluster production**

What we hope to learn?

	Spectra	(Double-) ratios	Femtoscopy	Flow	Isospin diffusion
pBUU Transport model ingredients ↓					
Symmetry energy		✔	*		✔
Cross section	✔	✔	✔	✔	✔
Cluster production	✔	✔	✔	✔	✔

Our approach: Use different isotopes
(fix Z of your initial system and vary N)

Proton femtoscopy



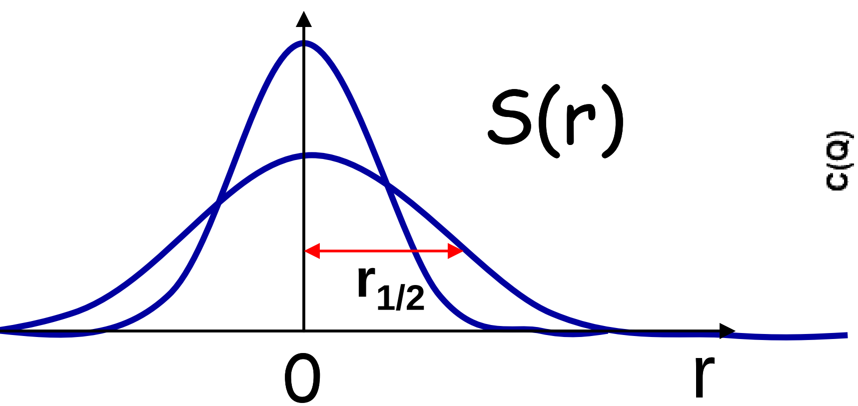
Theoretical CF: Koonin-Pratt equation

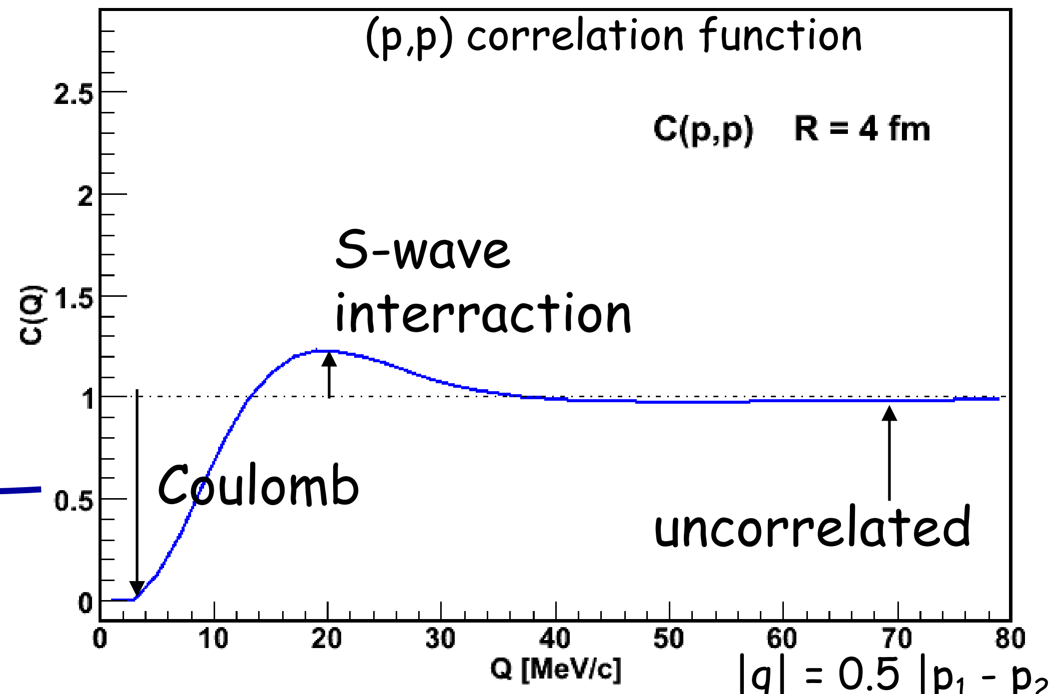
$$C(\vec{q}) = \int d^3r \left|\Phi_{\vec{q}}(\vec{r})\right|^2 S(\vec{r})$$

S.E. Koonin, PLB70 (1977) 43
S.Pratt et al., PRC42 (1990) 2646

$\Phi_{\vec{q}}(\vec{r})$ … 2-particle wave function

$S(\vec{r})$ … source function

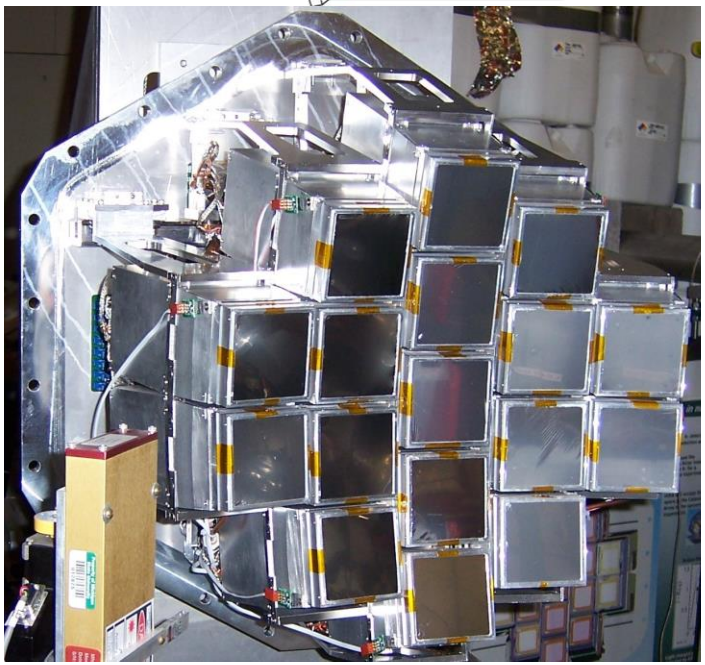




Our experiment

NSCL experiment 05045: HiRA + 4π detector

HiRA High Resolution Array = High Resolution Array



- 4π detector => impact parameter + reaction plane
- HiRA => light charge particle correlations (angular coverage 20-60° in LAB,
-63 cm from target (= ball center))

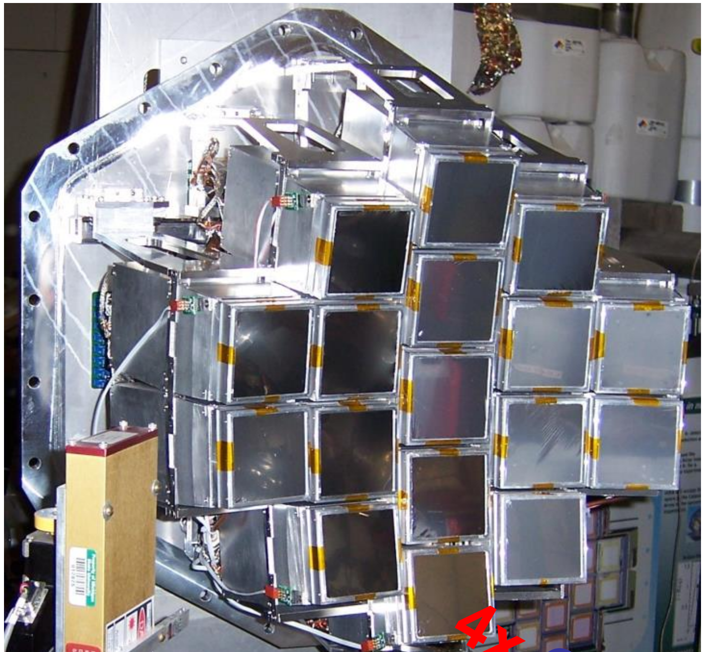
Reaction systems:

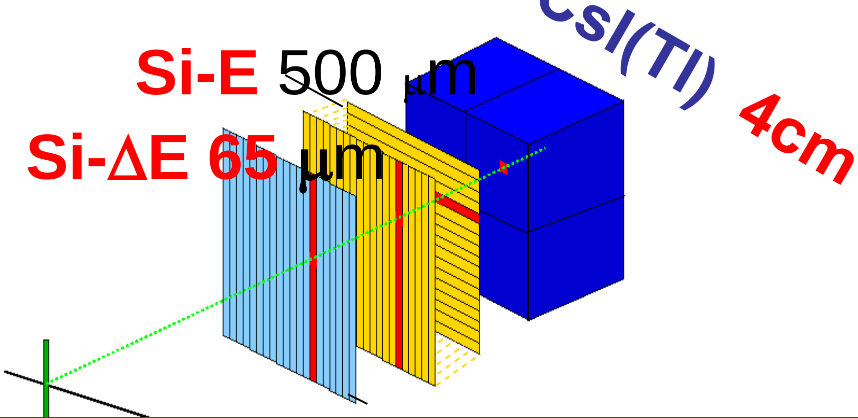
^{40}Ca + ^{40}Ca @ 80 MeV/u

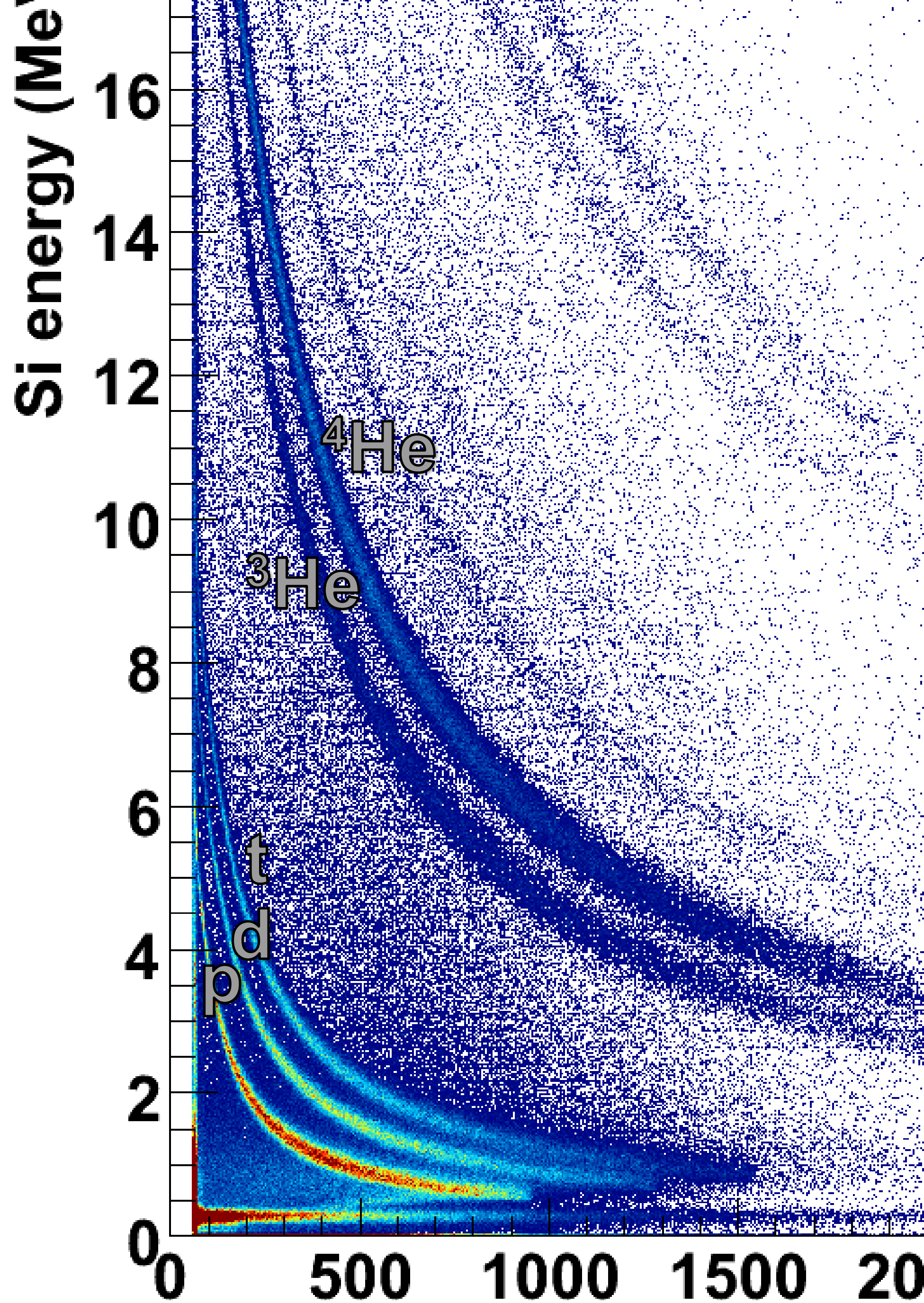
^{48}Ca + ^{48}Ca @ 80 MeV/u

NSCL experiments 050

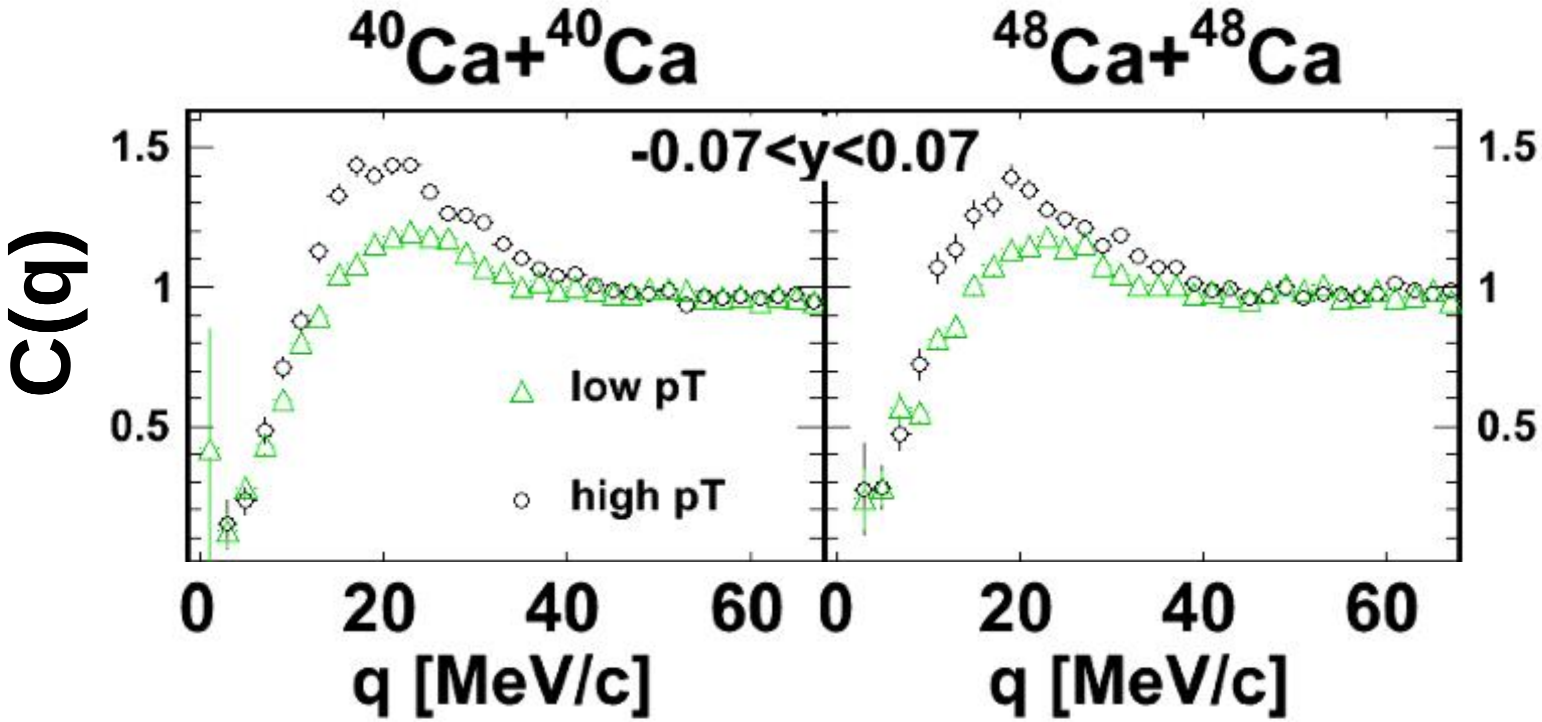
HiRA = High Resolution Array







Experimental correlation functions

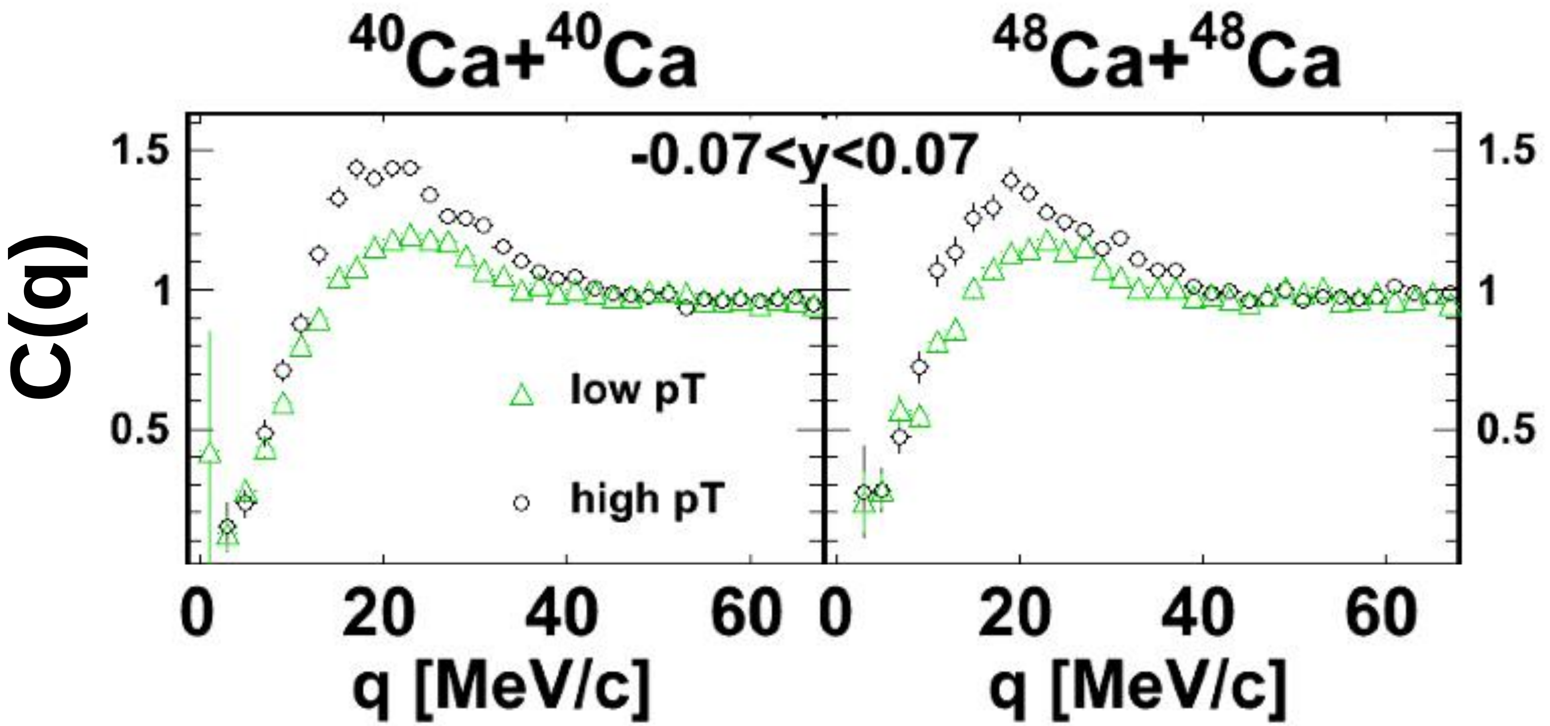


Low P_T : [150,350] MeV
High P_T : [350,700] MeV

Measured correlation functions depend on rapidity and the transverse momentum of the pair

<u>Next step:</u>
extract the sizes

Gaussian S(r)?



Koonin-Pratt Equation

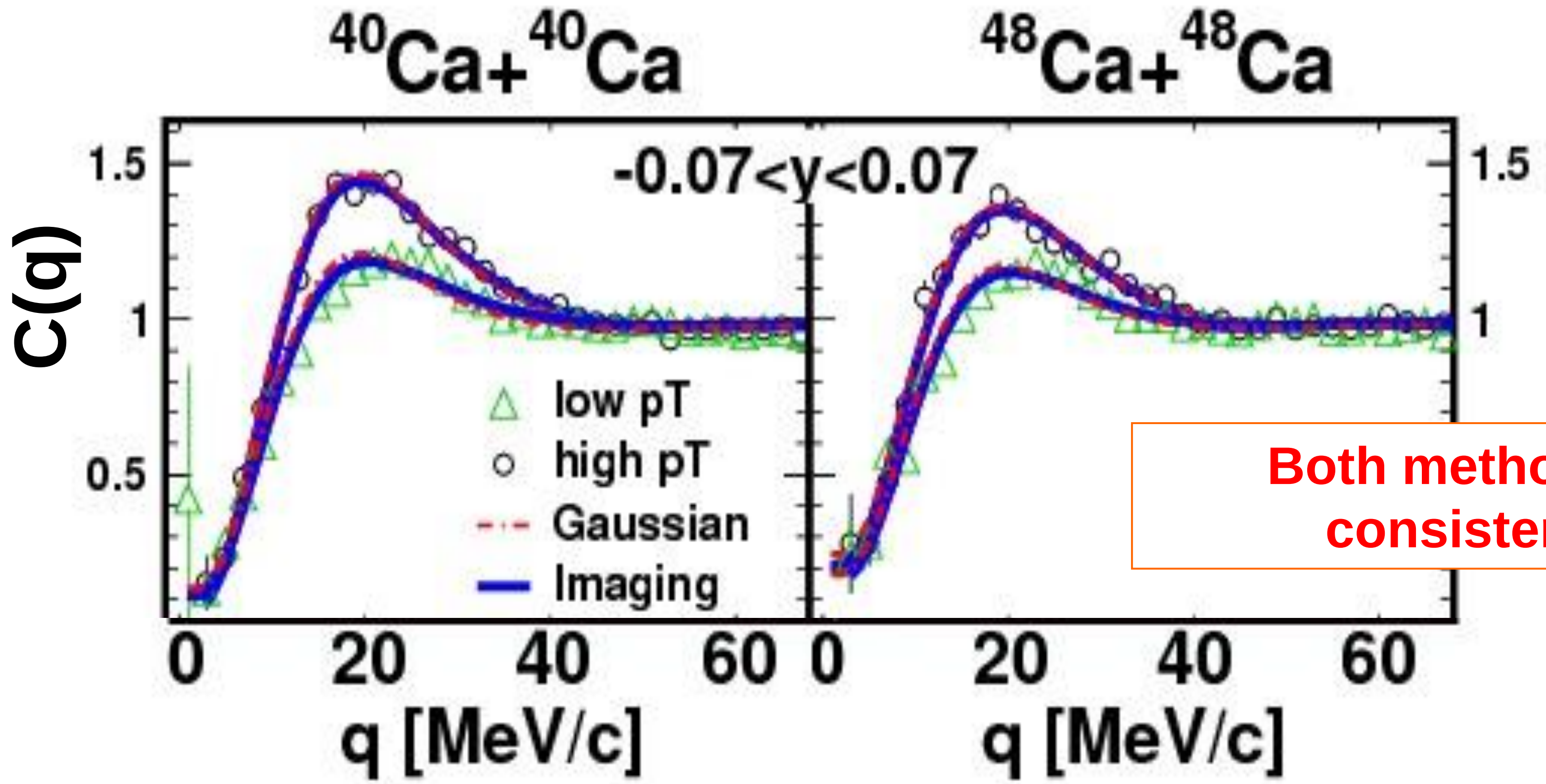
$$C(\vec{q}) = 1 + 4\pi \int K(q,r) S(r) r^2 dr$$

Brown, Danielewicz, PLB398 (1997) 252
Danielewicz, Pratt, PLB618 (2005) 60

Two ways of characterizing the size of the p-p source

1) S(r) - Gaussian shape
2) Imaged S(r) (Brown, Danielewicz)

Fits to the data



Both methods give consistent fits

Koonin-Pratt Equation

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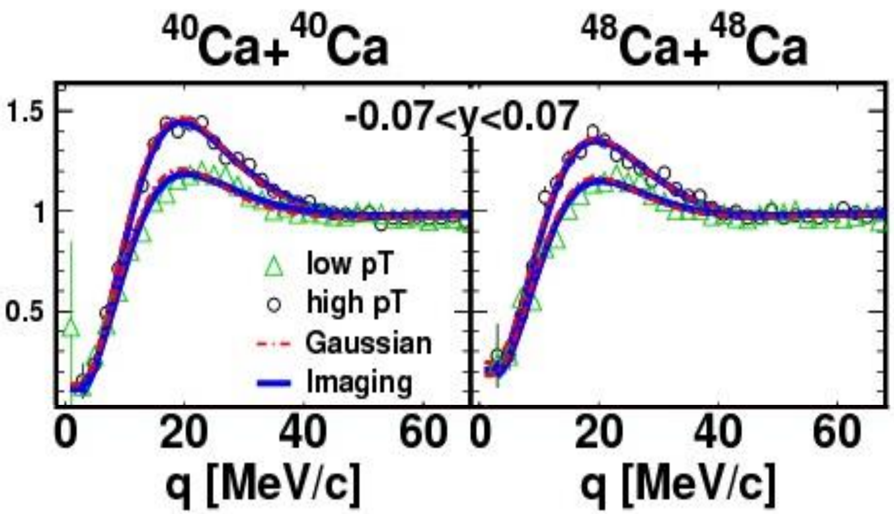
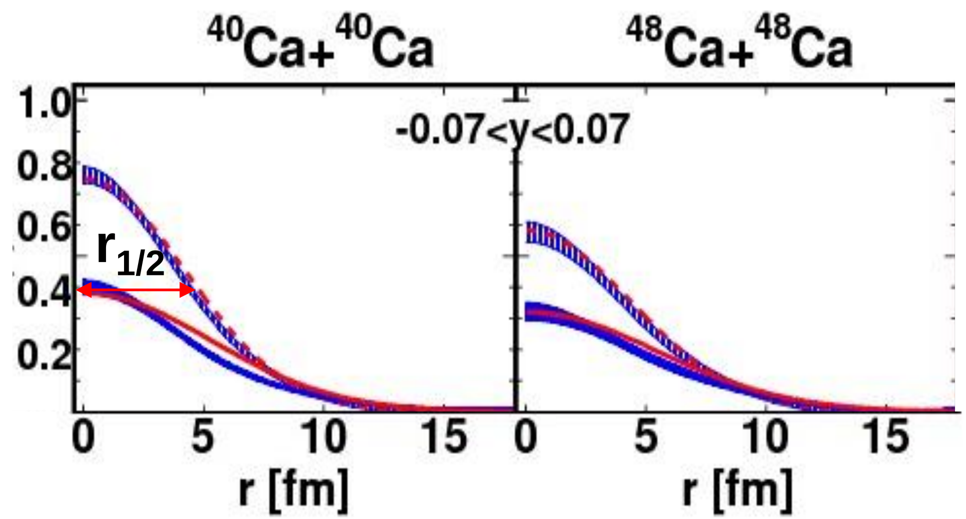
Fits to the data

Correlation function C(Q)



Source distribution : S(r) x10^3

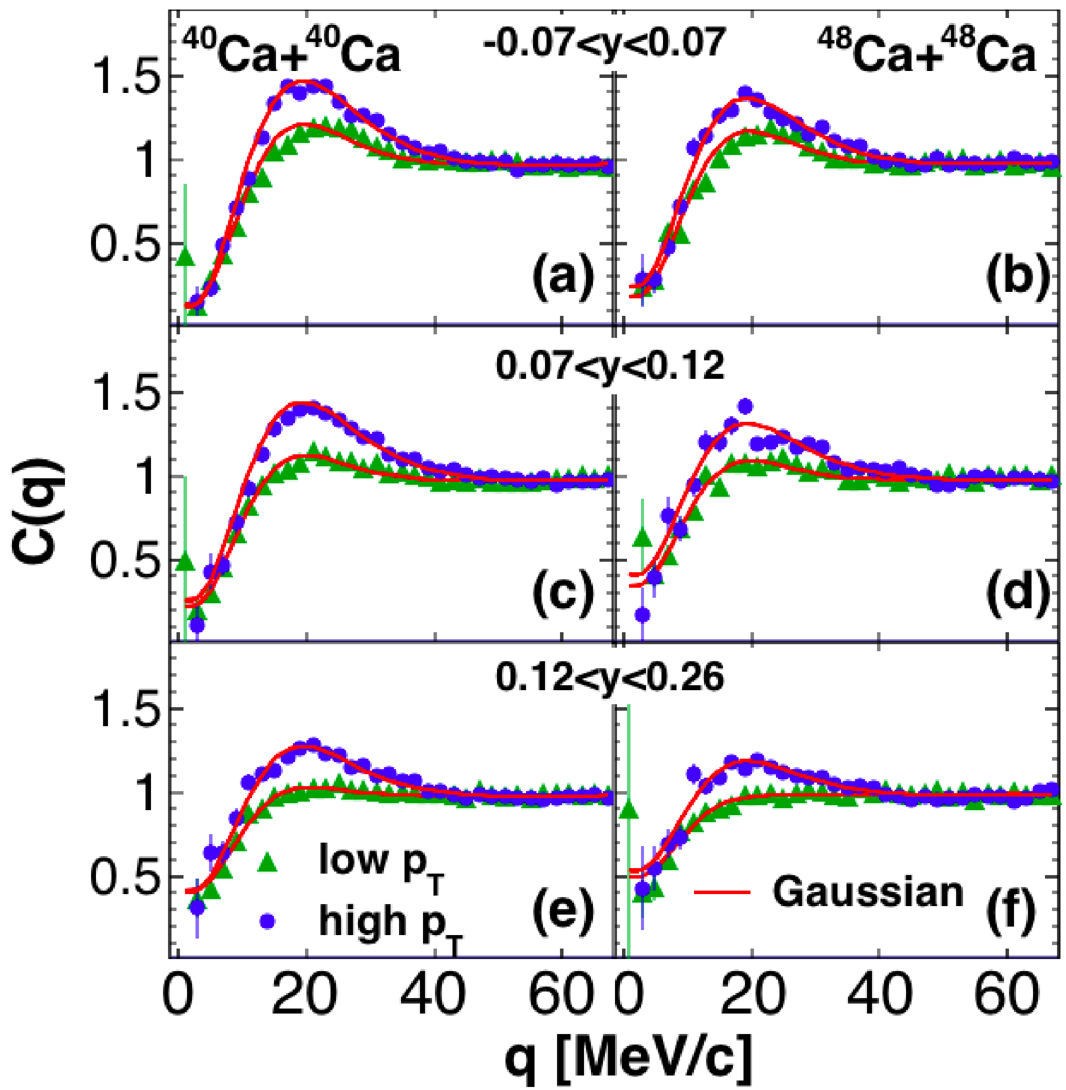


$$r_{1/2} = 2\sqrt{\ln 2}\,R_G$$

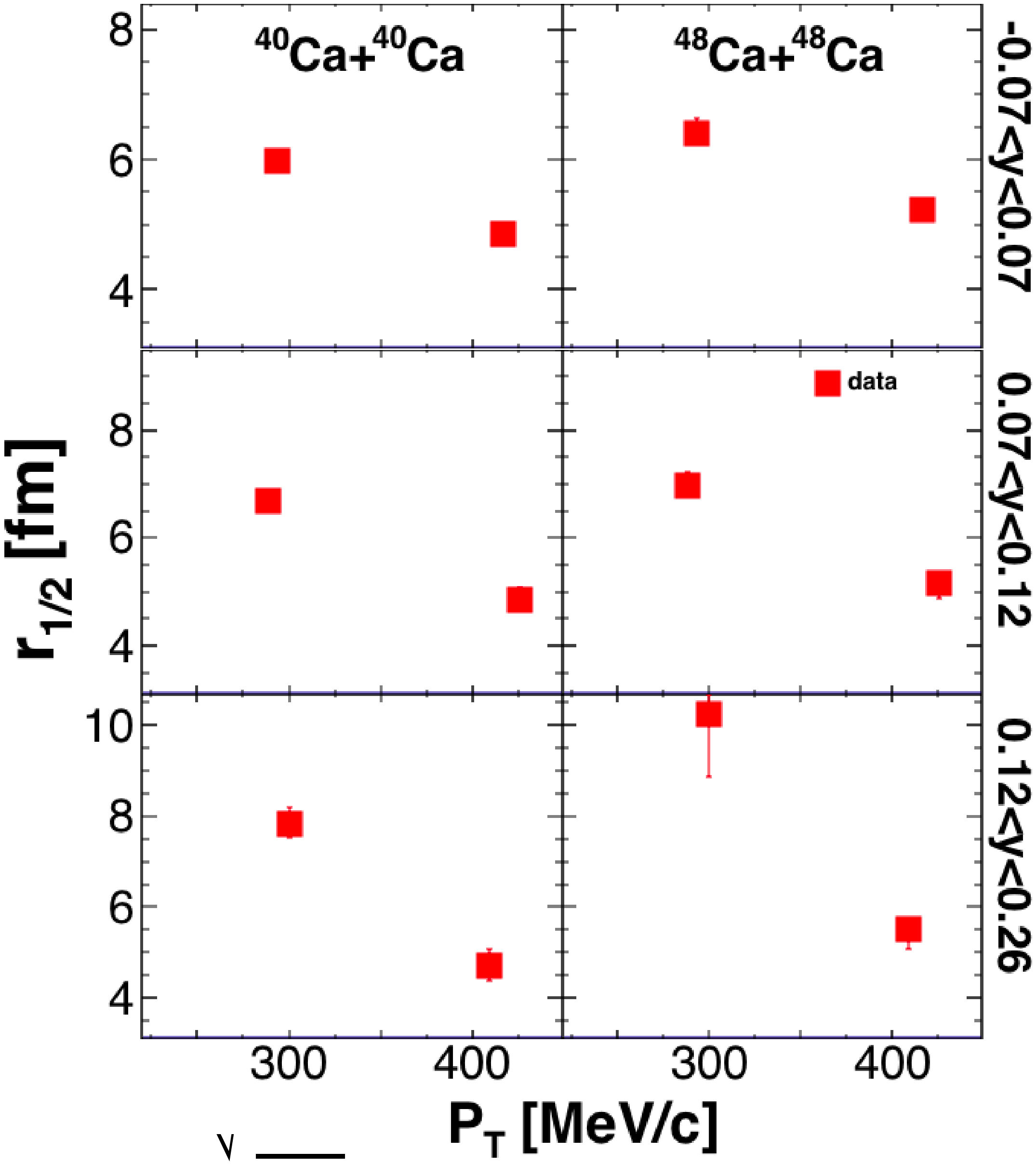
Fits to the data

Correlation function C(Q)

rapidity &
momentum
dependence



Fit results



Small rapidity:
reflect the participant zone of the reaction

Large rapidity:
reflect the expanding, fragmenting and evaporating projectile-like residues

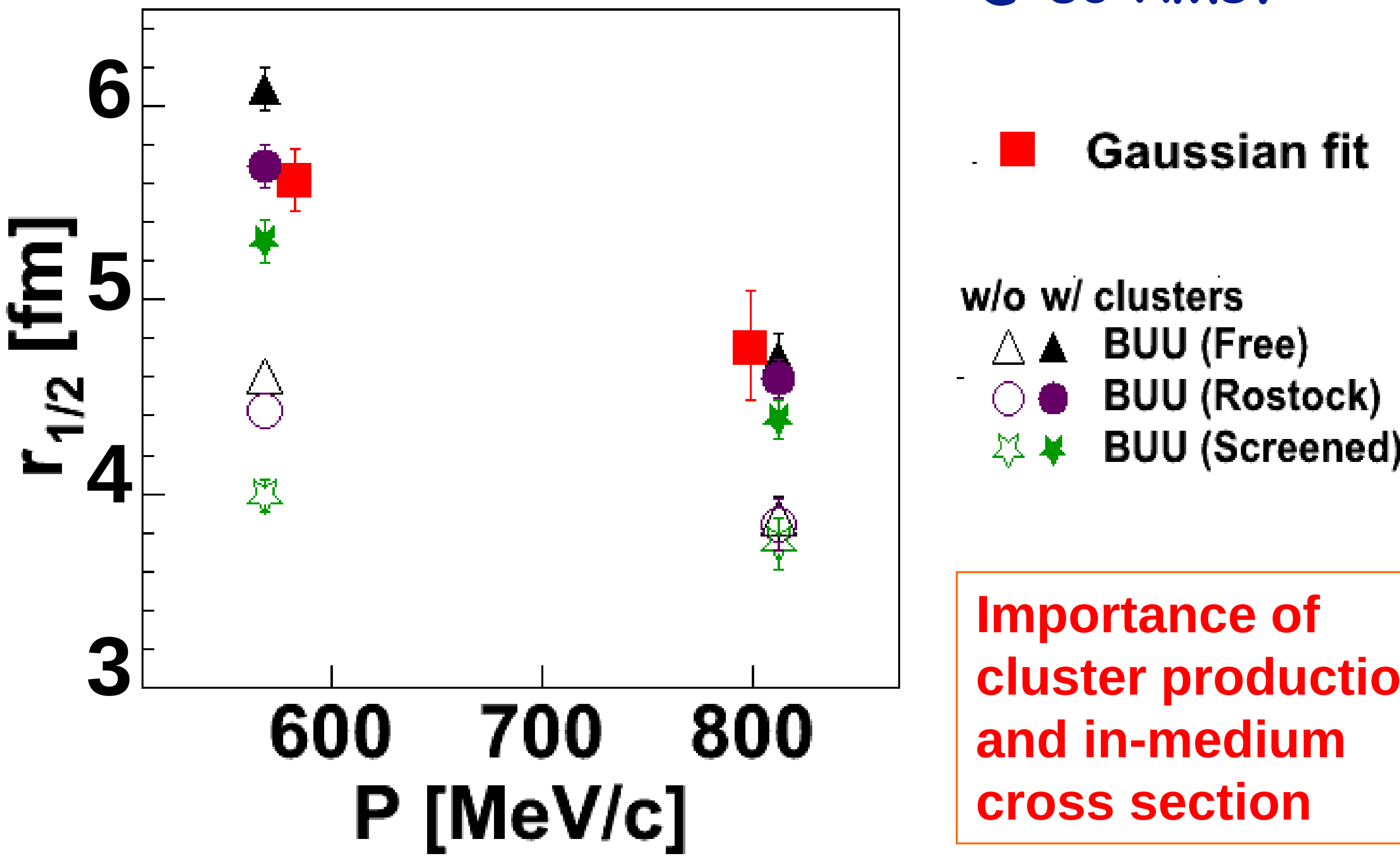
Higher velocity protons are more strongly correlated than their lower velocity counterparts, consistent with emission from expanding and cooling sources

Sensitivity to the initial size

$$r_{1/2} = 2\sqrt{\ln 2}R_G$$

Comparing data to theory (pBUU)

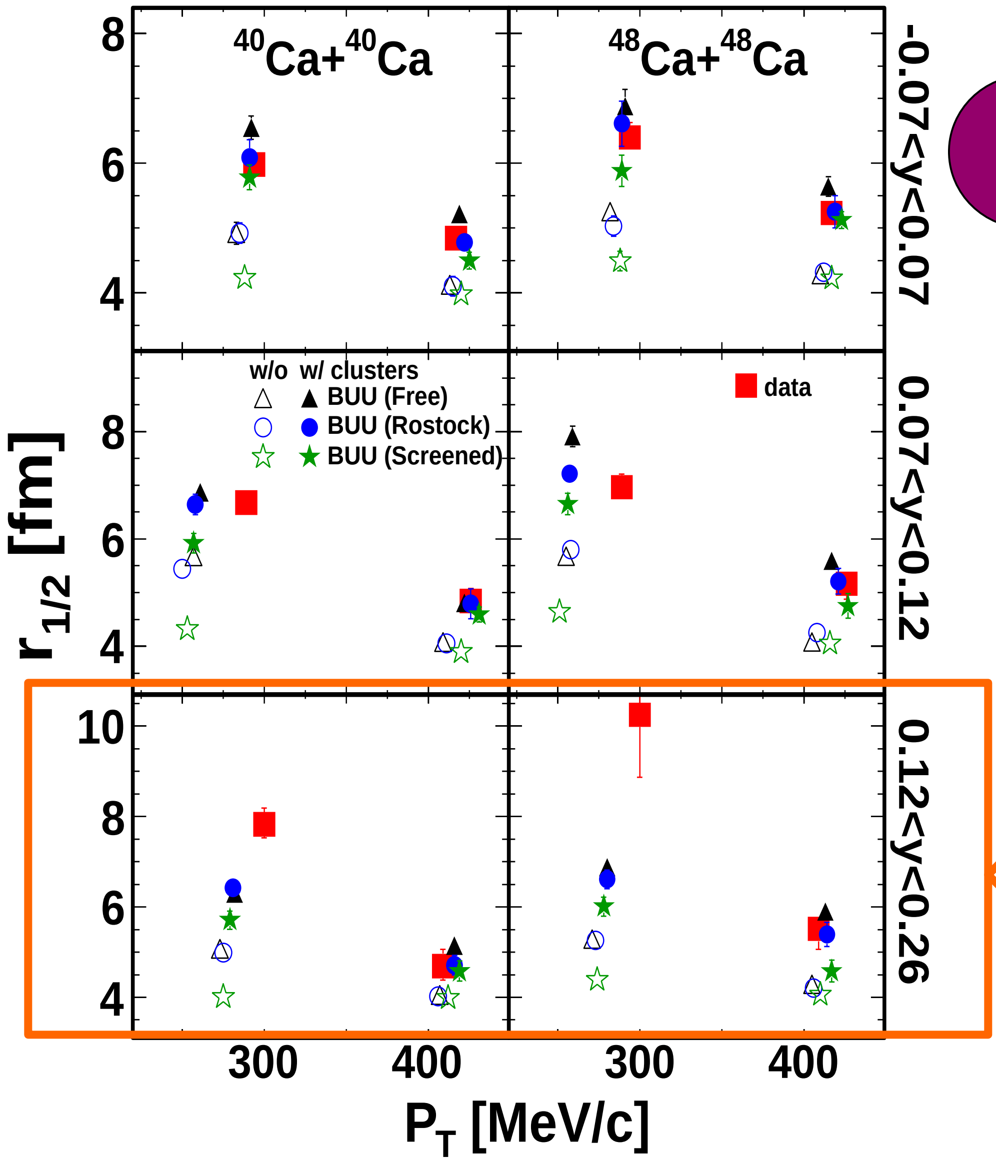
Proton femtoscopy in $^{48}Ca+^{48}Ca$ @ 80 AMeV

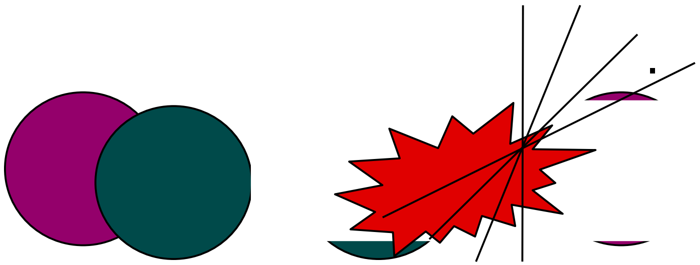


Importance of cluster production and in-medium cross section

Henzl et al., Phys.Rev. C85 (2012) 014606

Comparing data to theory (pBUU)





BUU Parameters

✓Rostock in-medium reduction

✓ Importance of the clusters

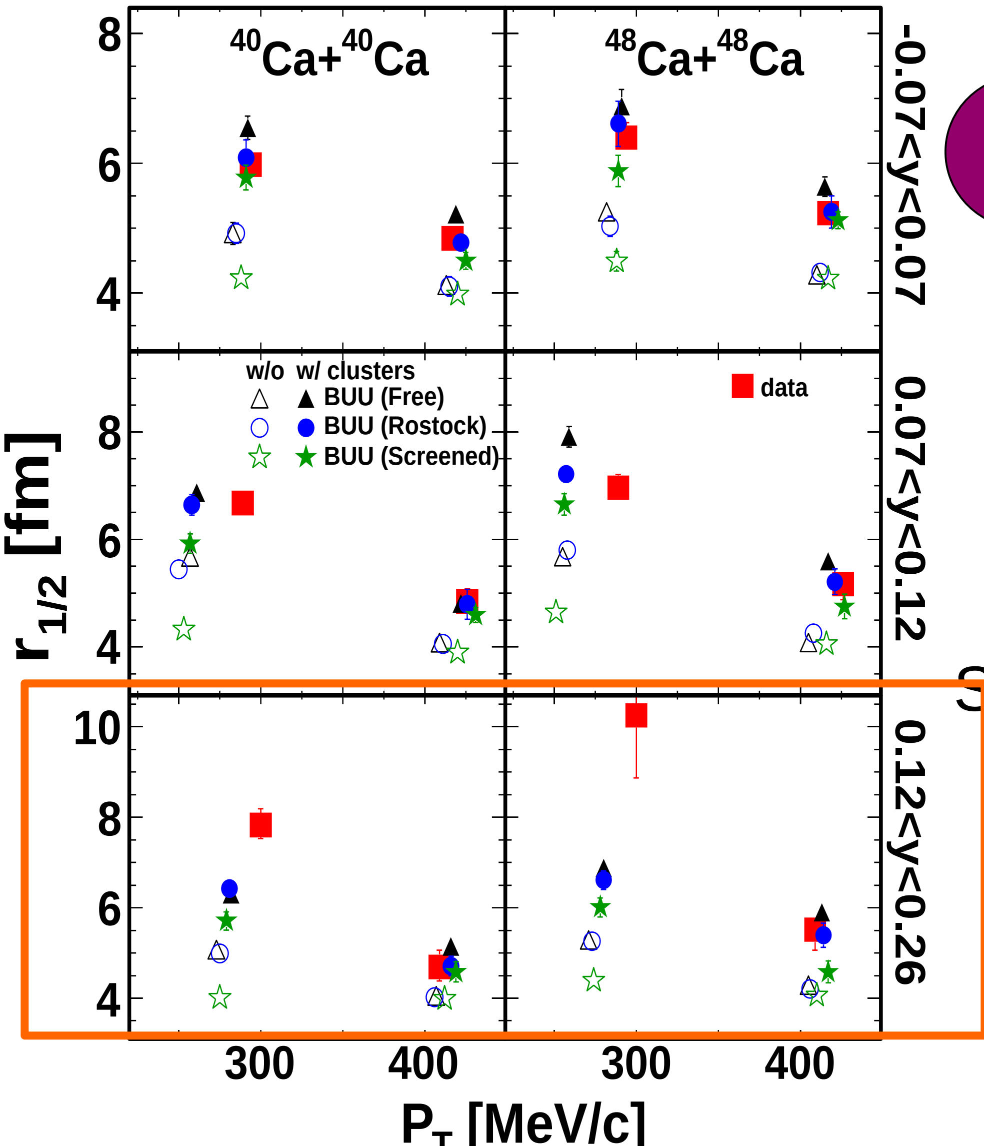
✓No dependence on symmetry energy – not shown

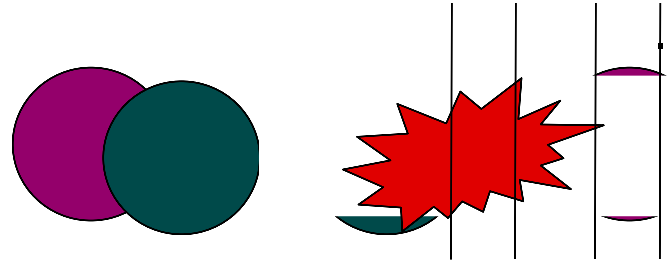
BUU does reasonably well

Except at larger rapidities - Spectator source

Where evaporation and secondary decays are important!

Comparing data to theory (pBUU)





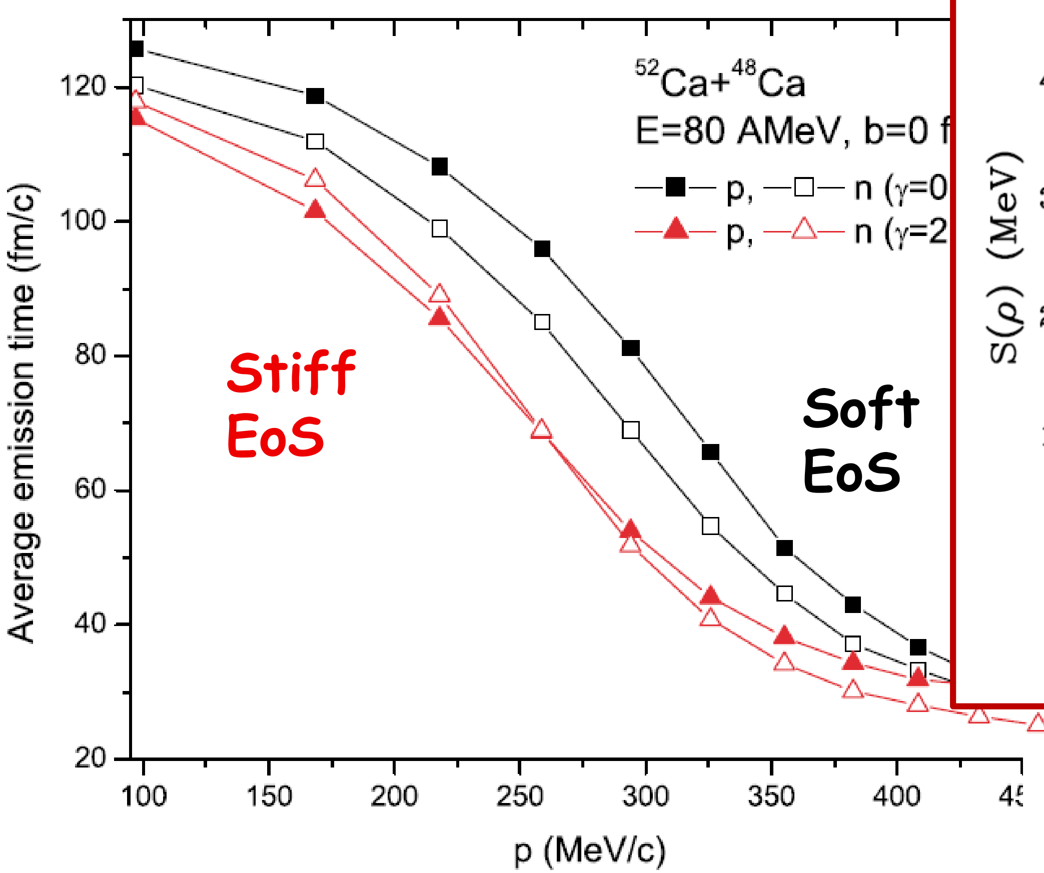
$$S(r) = \frac{\lambda_G \cdot e^{-\frac{r_\perp^2}{4R_G^2} - \frac{r_{||}^2}{4(R_G^2 + 0.5(v\tau)^2)}}}{(4\pi)^{3/2} R_G^2 \sqrt{R_G^2 + 0.5(v\tau)^2}}$$

Assuming the decay occurs from a spherical source with R_G and the timescale of the decay is τ

Averaged emission time
of particles in transport theory

Emission of p's and n's: S

L-W Chen et al., PRL90 (2003) 162701



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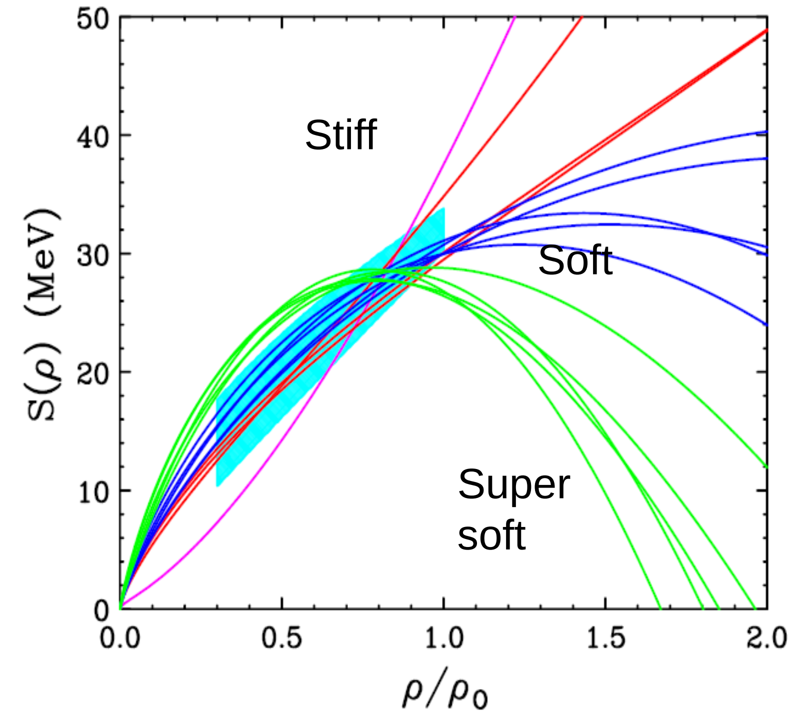
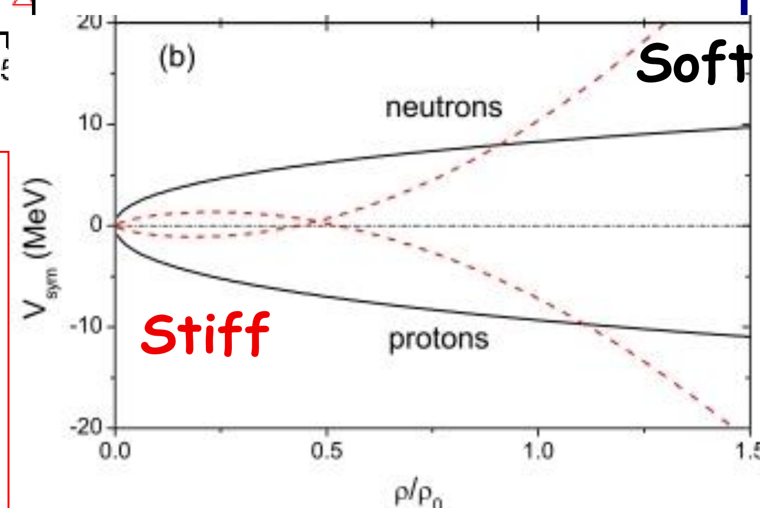
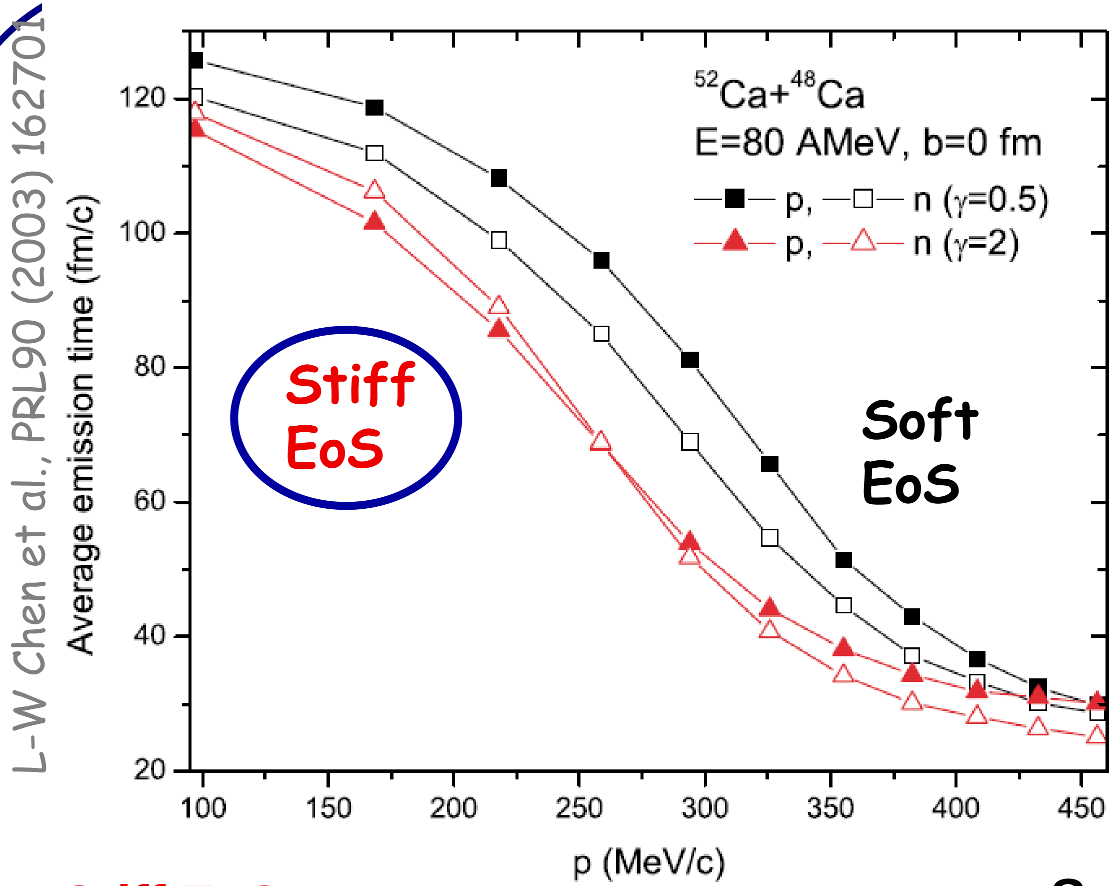
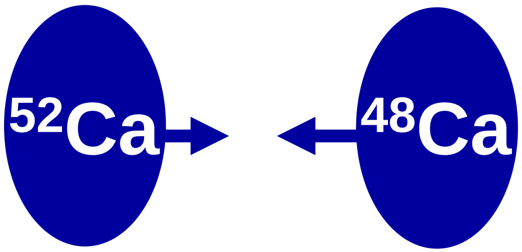


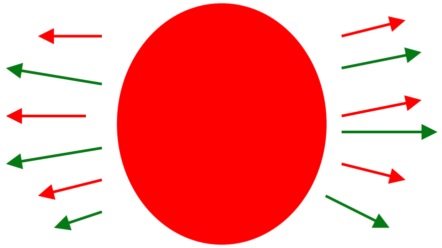


Stiff EoS **(γ=2)**	***Soft EoS*** **(γ=0.5)**
p's and n's emitted at similar time	**p's emitted after n's**
faster emission times	**later** emission times

Emission of p's and n's: Sensitivity to SymEn







<u>***Stiff EoS*** **(γ=2)**</u>

p's and n's emitted at <u>similar time</u>

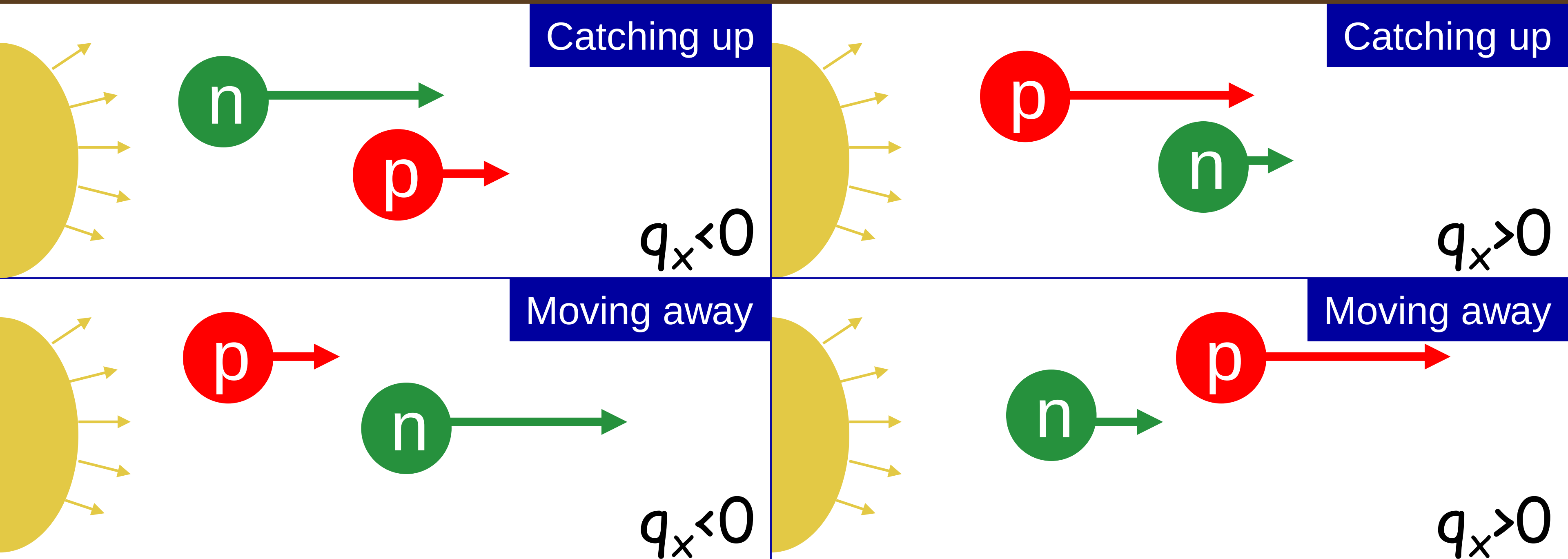
<u>faster</u> emission times

<u>***Soft EoS*** **(γ=0.5)**</u>

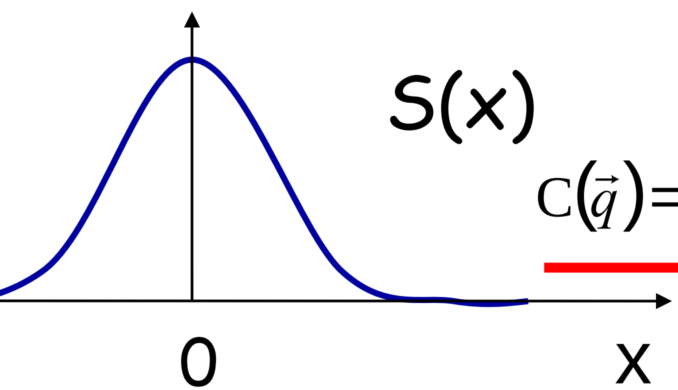
p's emitted <u>after</u> n's

<u>later</u> emission times

Possible emission configurations (stiff EOS)



$\Delta q=0.5(p_p - p_n) = (q_x, q_y=0, q_z=0)$; $r = (x, y=0, z=0)$



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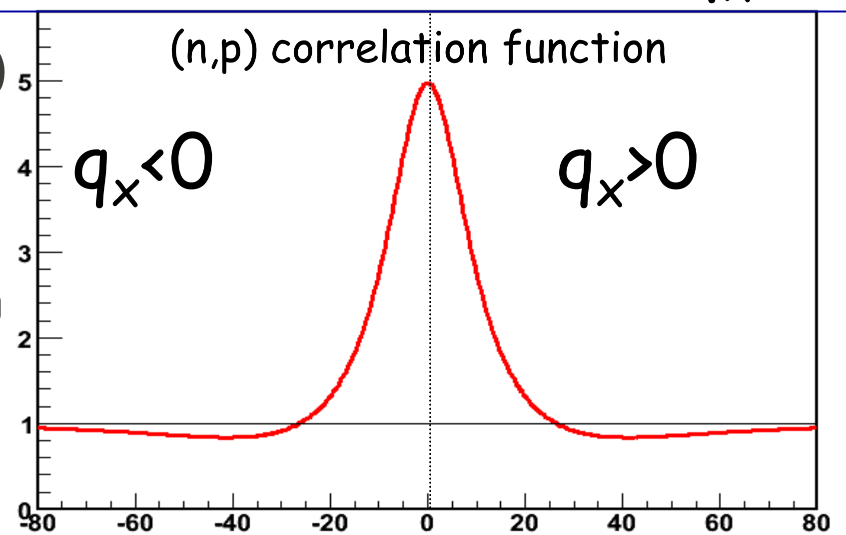
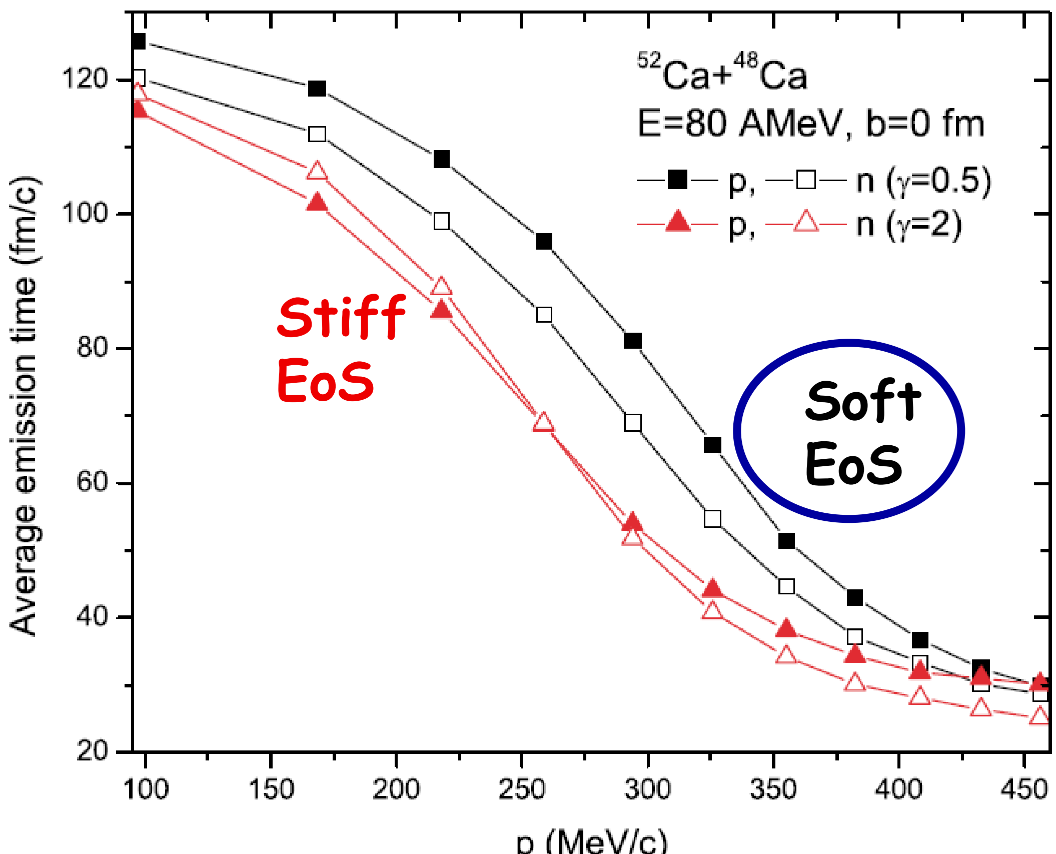
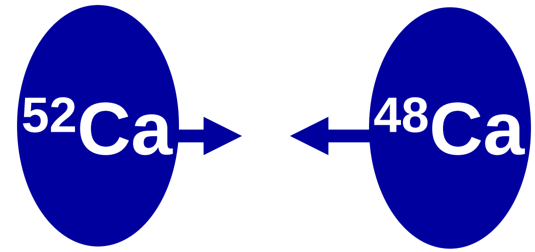
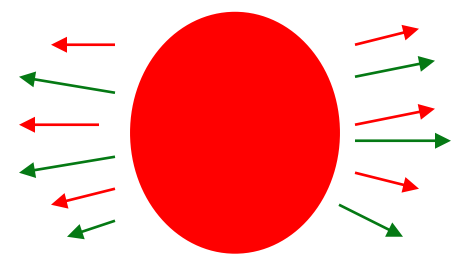


Emission of p's and n's

L-W Chen *et al.*, PRL90 (2003) 162701







Stiff EoS (γ=2)

p's and n's emitted at <u>similar time</u>

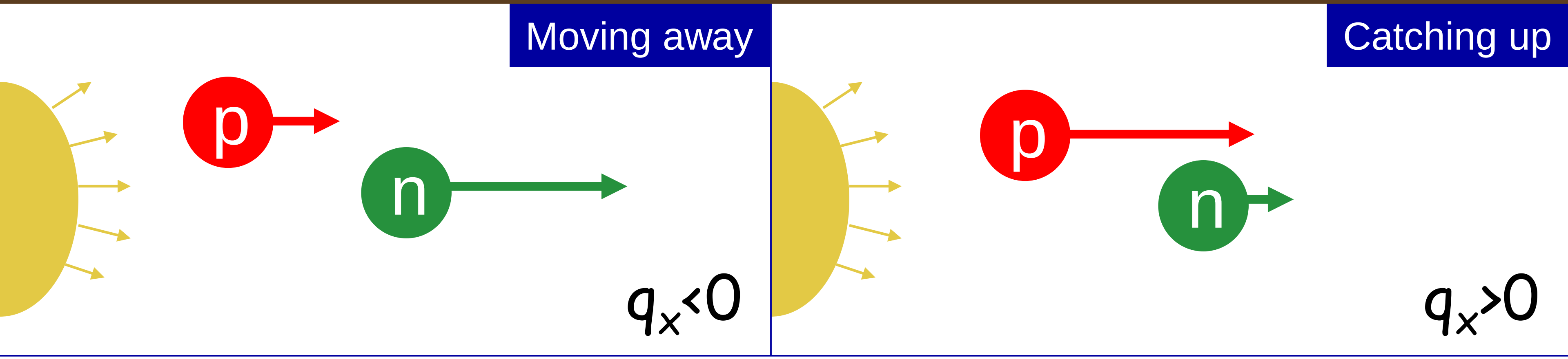
<u>faster</u> emission times

Soft EoS (γ=0.5)

p's emitted <u>after</u> n's

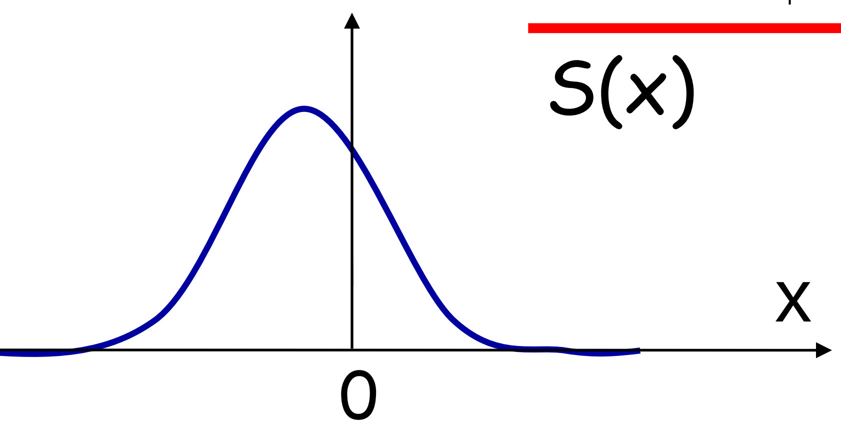
<u>later</u> emission times

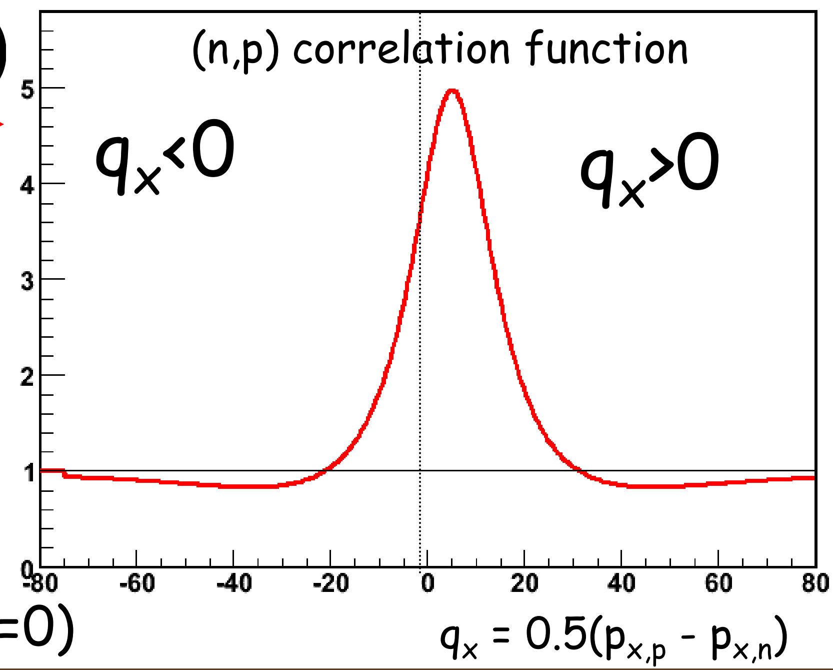
Sensitivity to particle emission (soft EOS)



$$C(\vec{q}) = \int d^3r \left|\Phi_{\vec{q}}(\vec{r})\right|^2 S(\vec{r})$$

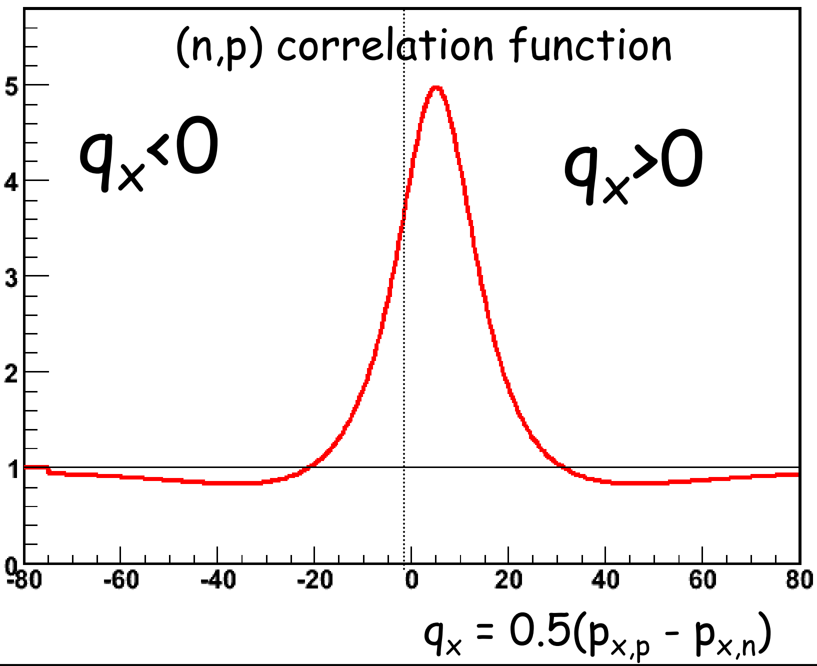
S(x)



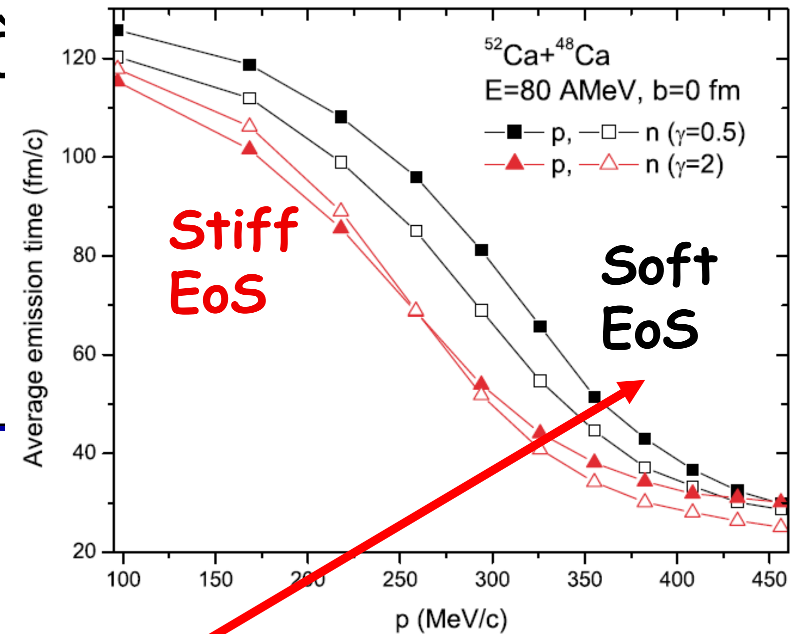


$\Delta q = 0.5(p_p - p_n) = (q_x, q_y = 0, q_z = 0)$; $r = (x, y = 0, z = 0)$

Relating asymmetry in the CF to space-time asymmetry



$C(q_x) = $ ¿



Classically, average separation b/t protons and neutrons

$$x(t) = (x_p - x_n) - V(t_p - t_n)$$

$$\langle x\rangle = \langle x_p - x_n\rangle - V\langle t_p - t_n\rangle$$

=0

$$\langle x\rangle < 0 \text{ if } \begin{cases} \langle x\rangle_p < \langle x\rangle_n \\ \langle t_p\rangle > \langle t_n\rangle \end{cases}$$

Not expected if n,p emitted from the same source (no n-p differential flow)

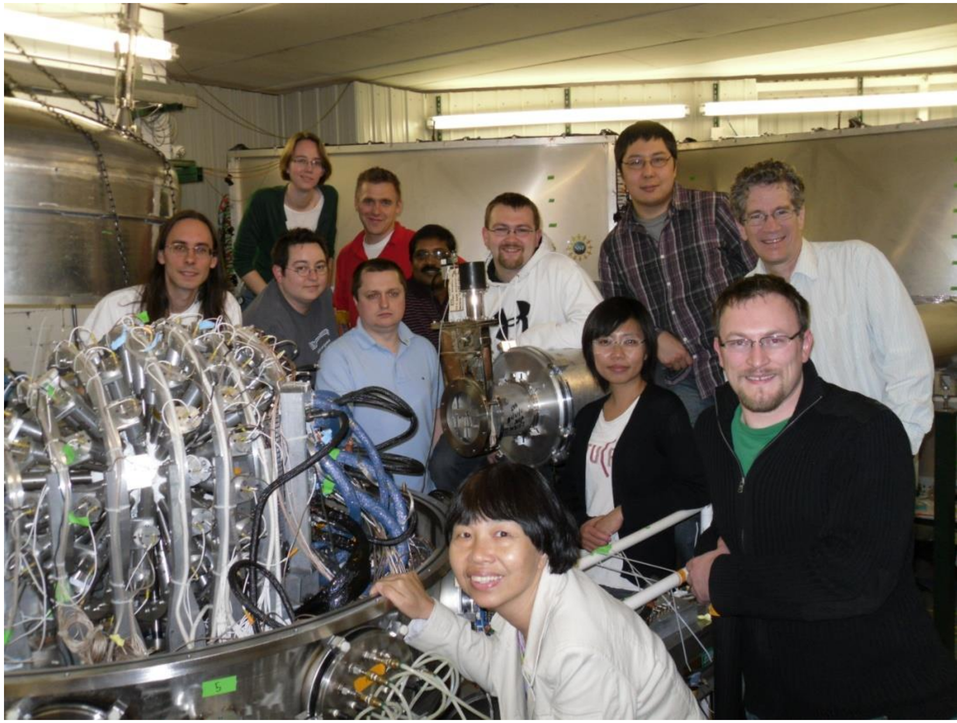
Protons emitted later

Voloshin et al., PRL 79:4766-4769,1997
Lednicky et al., PLB 373:30-34,1996

Summary

- Two particle correlations provide a unique probe to study the space-time extend of the source
  - add constrains on the in-medium cross-section
  - importance of the clusters, symmetry energy
  - validate theoretical models
- The average relative emission time of n’s and p’s *potentially* sensitive to the symmetry energy and can be “measured” with two particle correlations
- Transport models
  - Predictions are model dependent
  - Collaboration between theorists and experimentalists beneficial for both sides

Thank you HiRA collaborators



V. Henzl,[1,*] M. A. Kilburn,[1,2] Z. Chajęcki,[1] D. Henzlova,[1,*] W. G. Lynch,[1,2,†] D. Brown,[1,2] R. J. Charity,[3] A. Chibihi,[4] D. Coupland,[1,2] P. Danielewicz,[1,2] R. deSouza,[5] M. Famiano,[6] C. Herlitzius,[1,7] S. Hudan,[5] Jenny Lee,[1,2] S. Lukyanov,[8] A. M. Rogers,[1,2] A. Sanetullaev,[1,2] L. Sobotka,[3] Z. Y. Sun,[1,9] M. B. Tsang,[1] A. Vander Molen,[1] G. Verde,[10] M. Wallace,[1,2] and M. Youngs[1,2]