# Proton-proton correlation functions measured using position-sensitive FAUST

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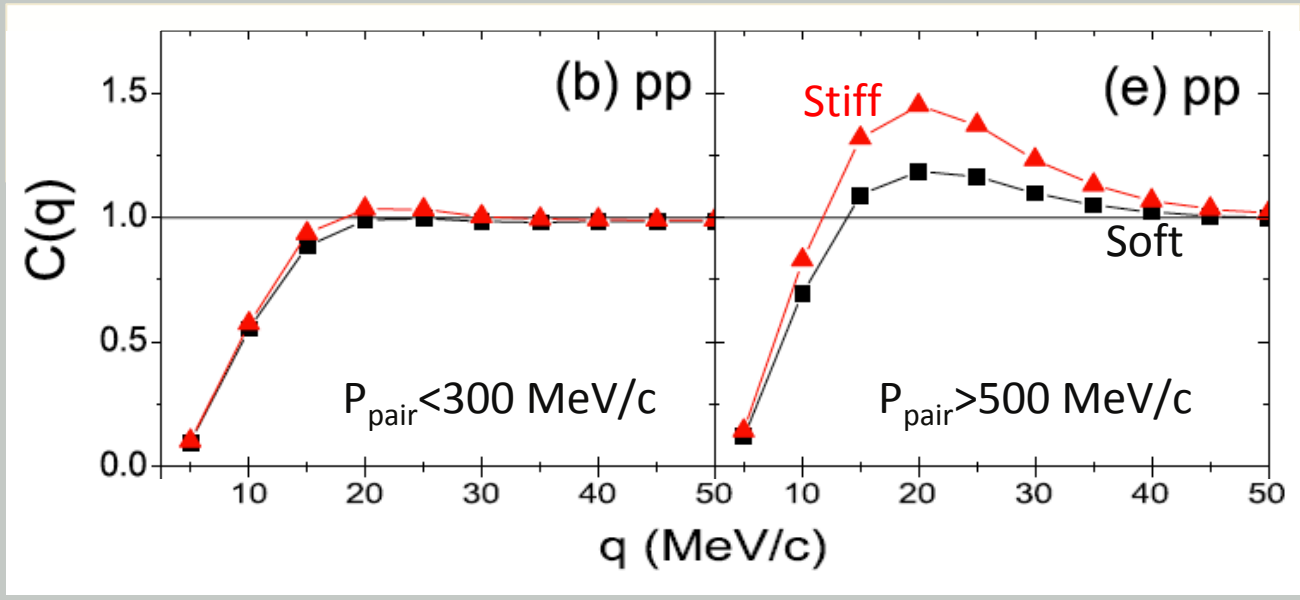
# Correlation Function Predictions

$$q_{\mathrm{Re}l} = \left|q_{\mathrm{Re}l}\right| = \frac{1}{2}\left|p_1 - p_2\right|$$

$$C(q) = 1 + R(q) = N\frac{Y_c(q_{\mathrm{Re}l})}{Y_{uc}(q_{\mathrm{Re}l})}$$

Isospin-dependent Boltzmann-Uehling-Uhlenbeck (iBUU04)

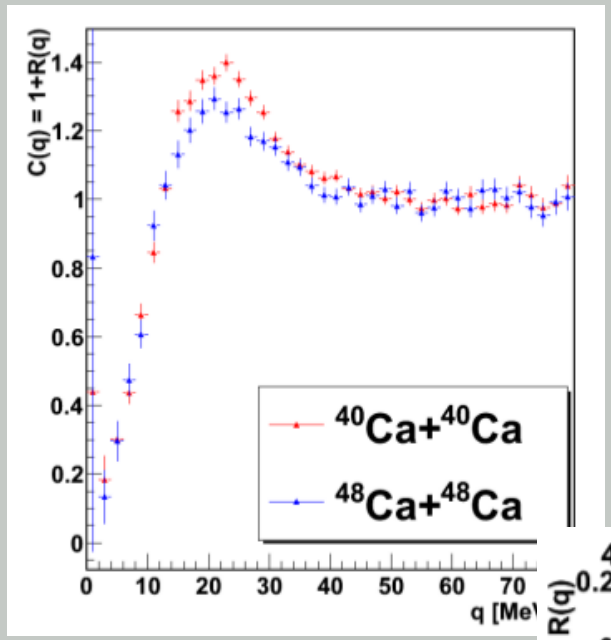
$^{52}$Ca+$^{48}$Ca 80A MeV b=0 fm

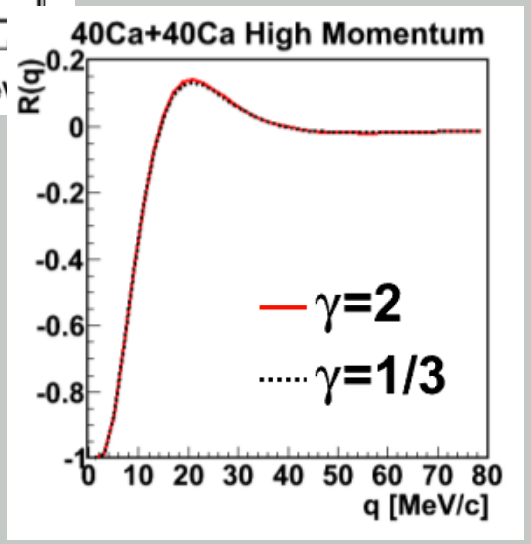





L. Chen, V. Greco, C. Ko, and B. Li, *Phys. Rev. C* 68 (2003).

# Previous Experimental Work



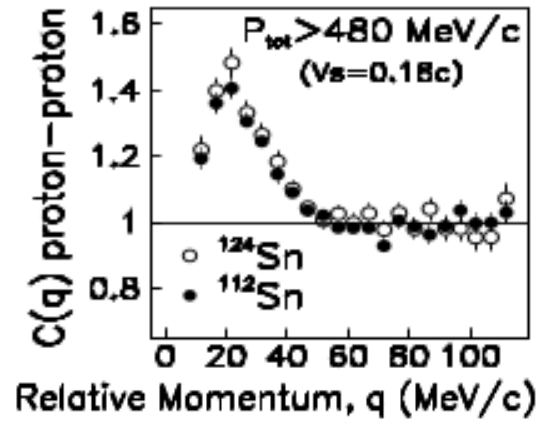

- $P_{pair}$>500 MeV/c
- early emitted protons
- pBUU, 80 MeV/ nucleon
- Central collisions
- Very little difference between γ

V. Henzl et al., *Phys. Rev. C* 85, 014606 (2012).



M. Kilburn, Proton-proton correlation functions as a probe to reaction dynamics, PhD thesis, Michigan State University (2011).

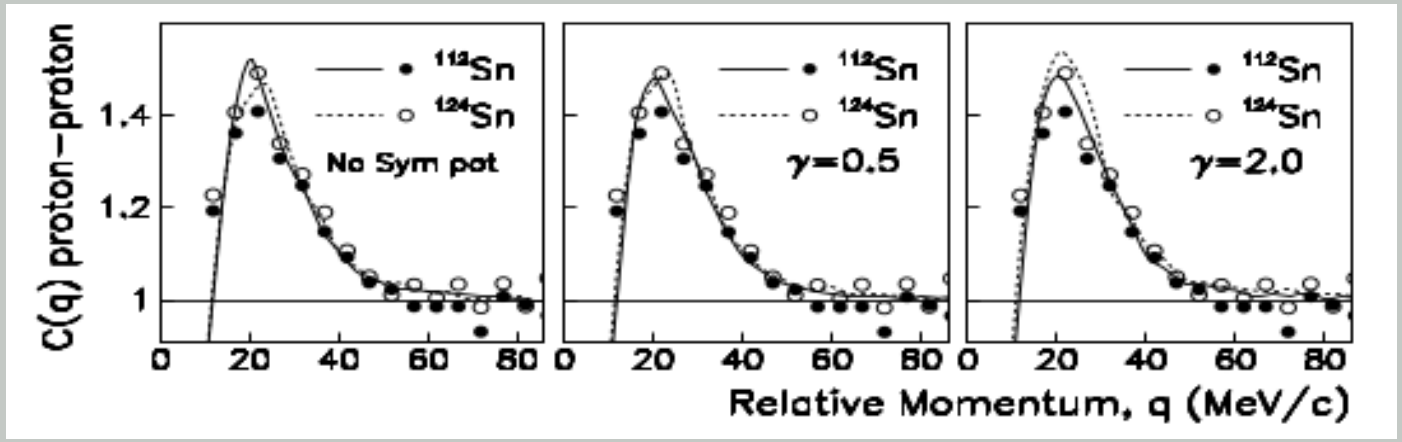
# $^{36}Ar + ^{112,124}Sn$ at 61 MeV/u




- Comparing system-to-system
- Less n-rich (smaller) target has lower-peaked correlation function
- Consistent with 'stiff' γ

points: early emitted data

lines: iBUU04






R. Ghetti, et al., *Nucl. Phys. A*, 752 (2005).

# Reaction Systems

| Beam | Energy (MeV/u) | Target | System Z | System A | System Δ |
|---|---|---|---|---|---|
| $^{40}$Ca | 40 | $^{58}$Ni | 48 | 98 | 0.020 |
| $^{40}$Ar | 40 | $^{58}$Fe | 44 | 98 | 0.102 |
| $^{40}$Ar | 30 | $^{58}$Fe | 44 | 98 | 0.102 |
| $^{40}$Ar | 30 | $^{70}$Zn | 48 | 110 | 0.127 |

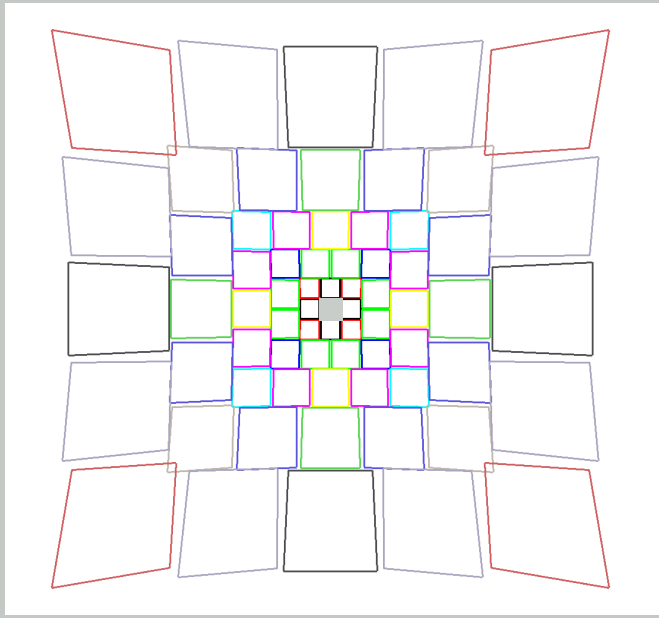
Previous: varied asymmetry (Δ) & mass (A). Constant charge (Z).

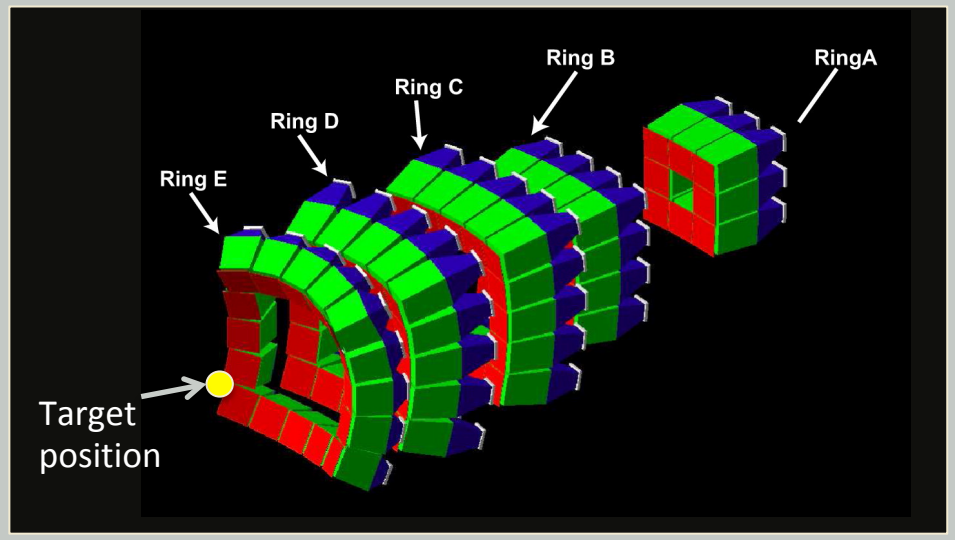
**Vary:**

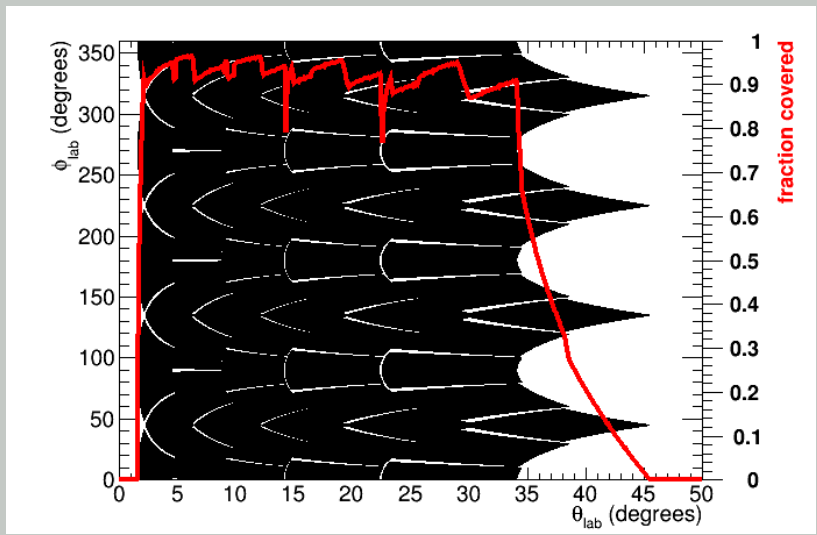
- System delta, changing target & projectile, same overall A
- Beam energy, same system
- System delta, changing target, same projectile

# Forward Array Using Silicon Technology (FAUST)

- 68: 300 um Si(ΔE)- 3 cm CsI(E) telescopes
- 5 ring configuration
- Position-sensitive Si



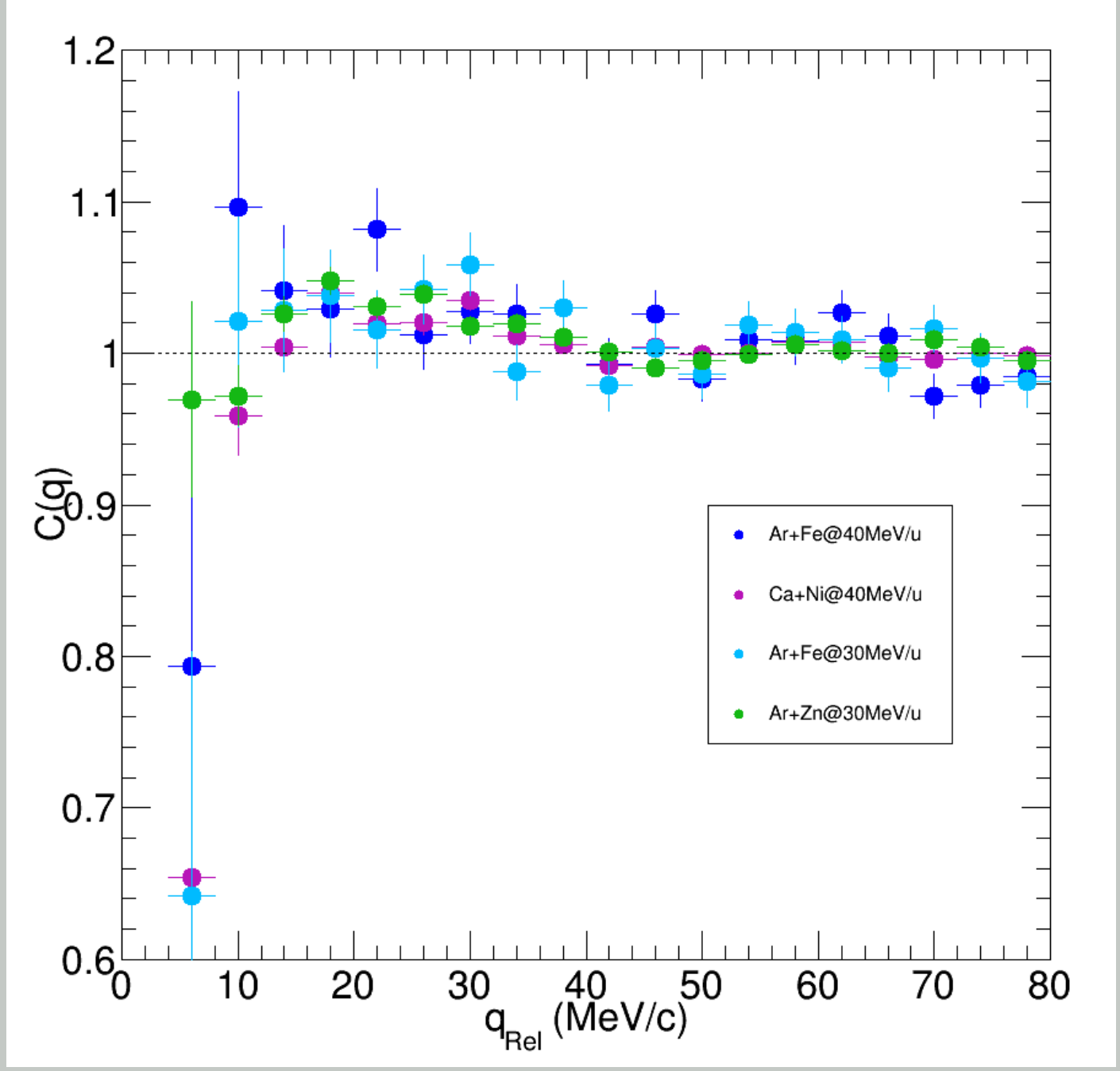


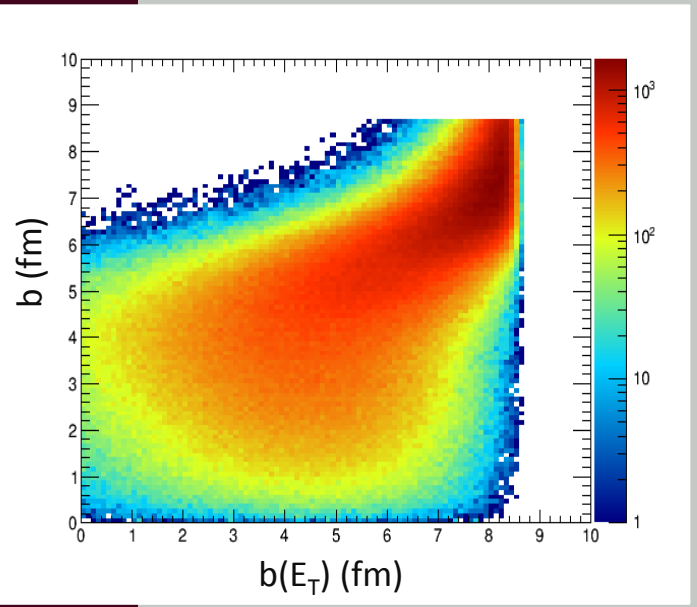

S. Soisson et al., *Nucl. Instr. Meth. A* 613, 240 (2010).

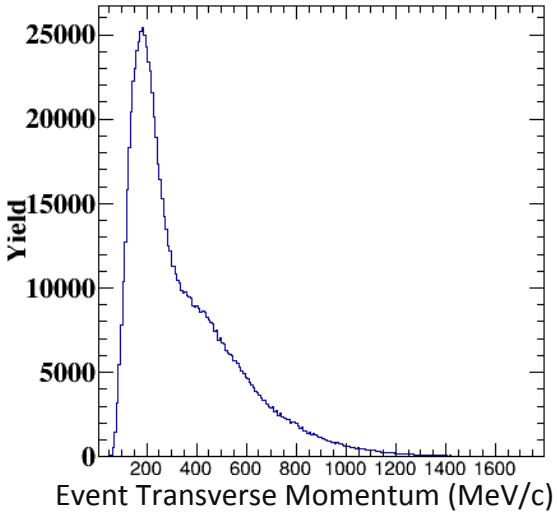
F. Gimeno-Nogues et al., *Nucl. Instr. Meth. A* 399 (1997).

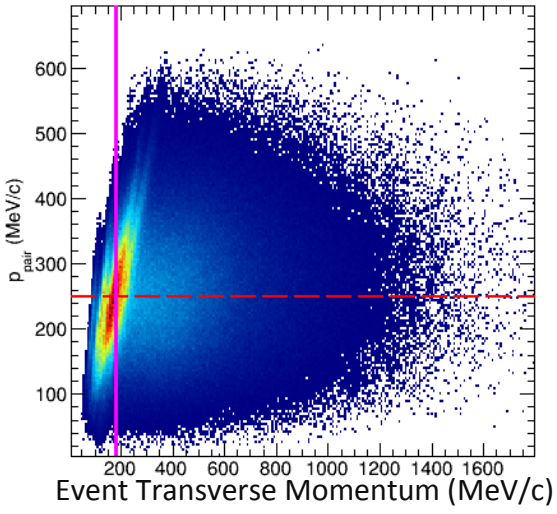
L.A. Heilborn, et al. *In Prep*.


1.2
1.1
1
0.9
0.8
0.7
0.6
C(q)
0
10
20
30
40
50
60
70
80
$q_{Rel}$ (MeV/c)
Ar+Fe@40MeV/u
Ca+Ni@40MeV/u
Ar+Fe@30MeV/u
Ar+Zn@30MeV/u

# Proton Pair Selection




HIPSE

Measurement

- Violence of collision
- Early emitted protons

$$\sum_{Event} p_{\perp}$$



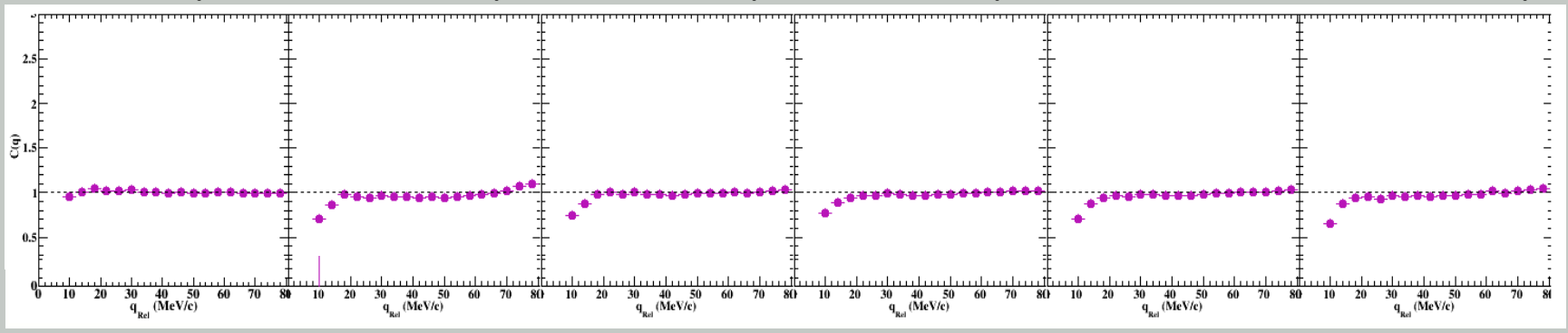
J. Gauthier et al., *Phys. Rev. C* 90 (2014).

Violence

$^{40}Ca+^{58}Ni$ @ 40 MeV/u

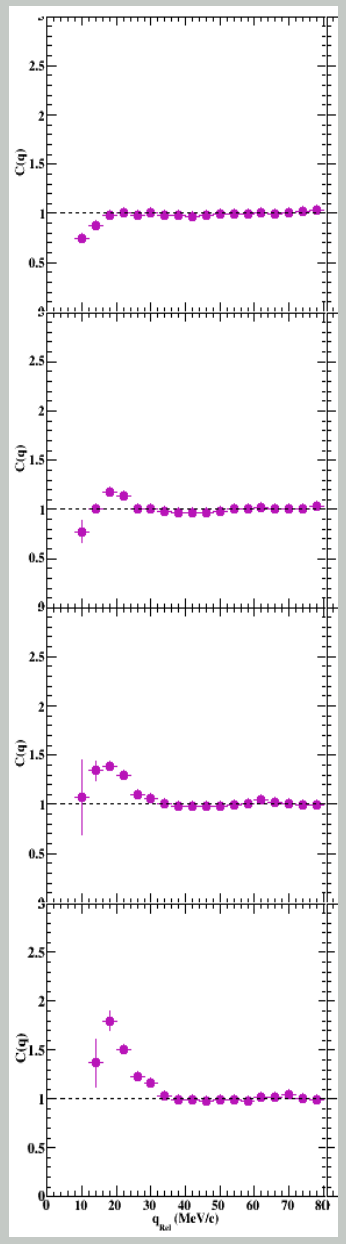
$p_T$(Event) minimum

0 MeV/c >140 MeV/c >180 MeV/c >220 MeV/c >260 MeV/c >300 MeV/c



$^{40}Ca+^{58}Ni$ @ 40 MeV/u

Earliness
$p_{Pair}$ minimum
>350 MeV/c >300 MeV/c >250 MeV/c 0 MeV/c

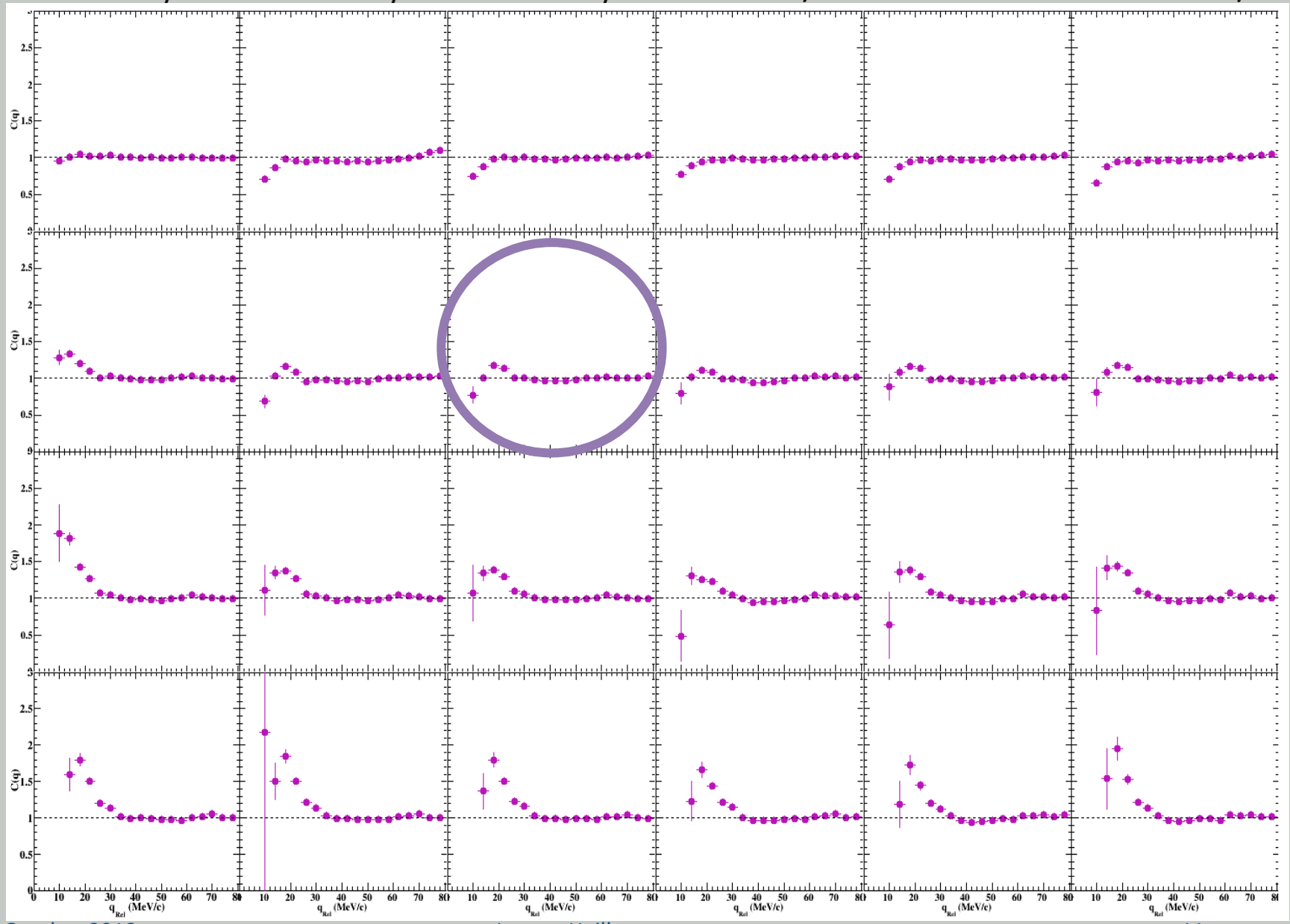


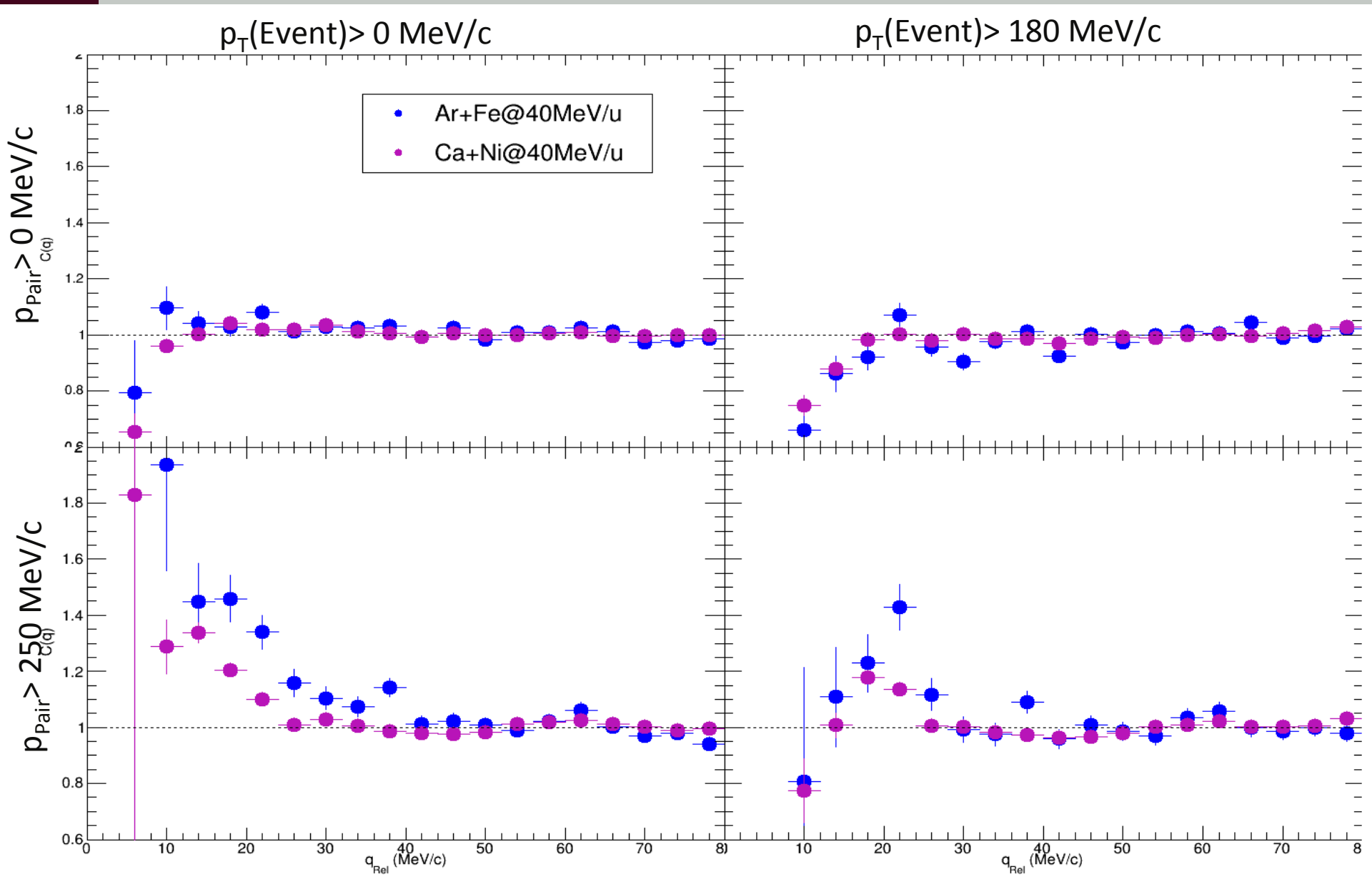
Violence
$p_T$(Event) minimum

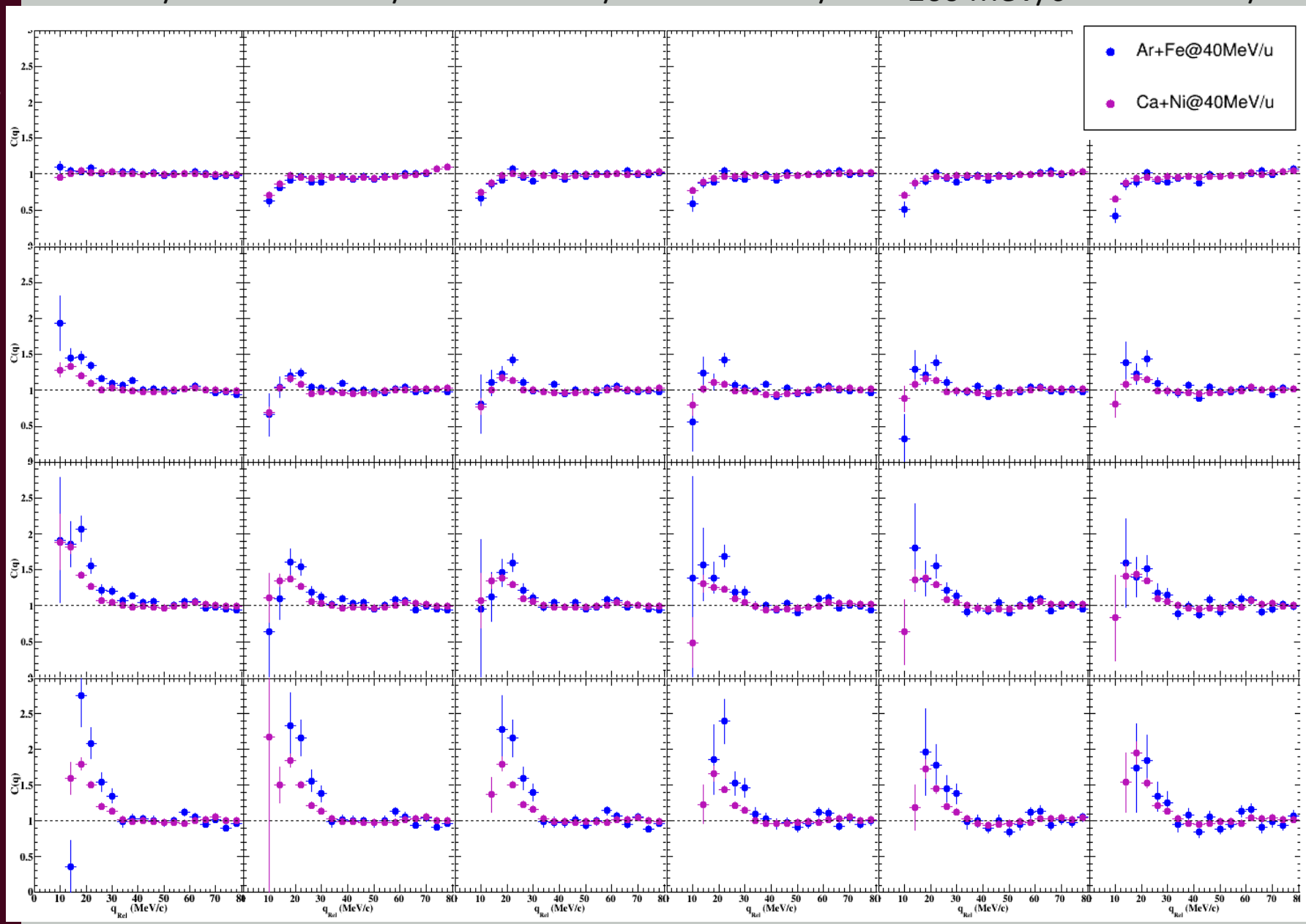
0 MeV/c | 140 MeV/c | 180 MeV/c | 220 MeV/c | 260 MeV/c | 300 MeV/c

Earliness
$p_{Pair}$ minimum

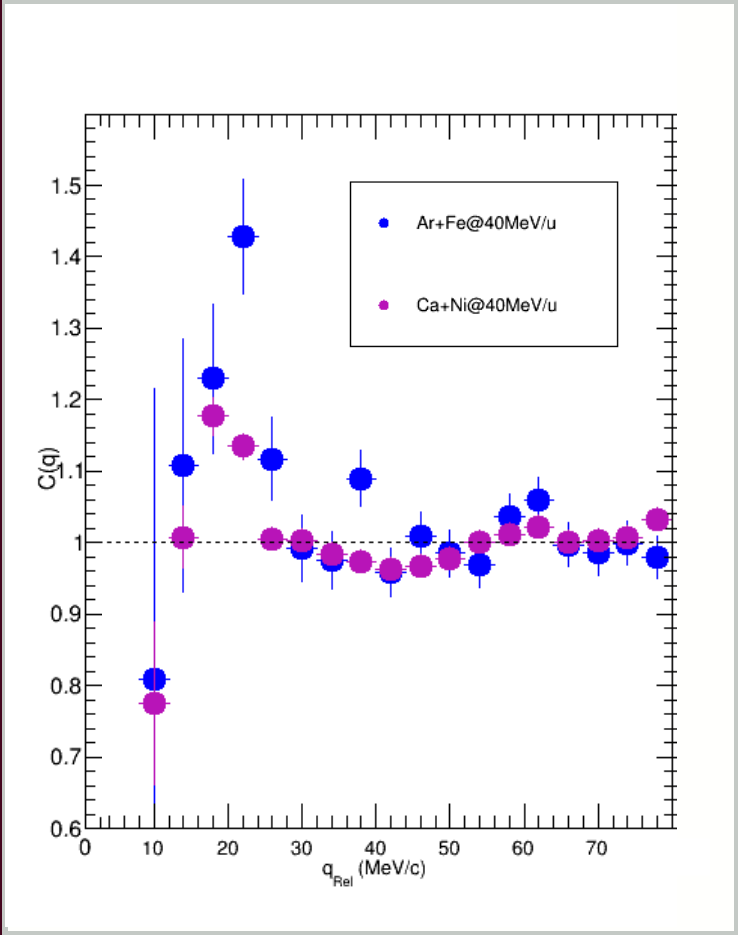
0 MeV/c | 250 MeV/c | 300 MeV/c | 350 MeV/c




$p_T$(Event)> 0 MeV/c
$p_T$(Event)> 180 MeV/c
Ar+Fe@40MeV/u
Ca+Ni@40MeV/u
$p_{Pair}$> 0 MeV/c
$p_{Pair}$> 250 MeV/c
C(q)
$q_{Rel}$ (MeV/c)

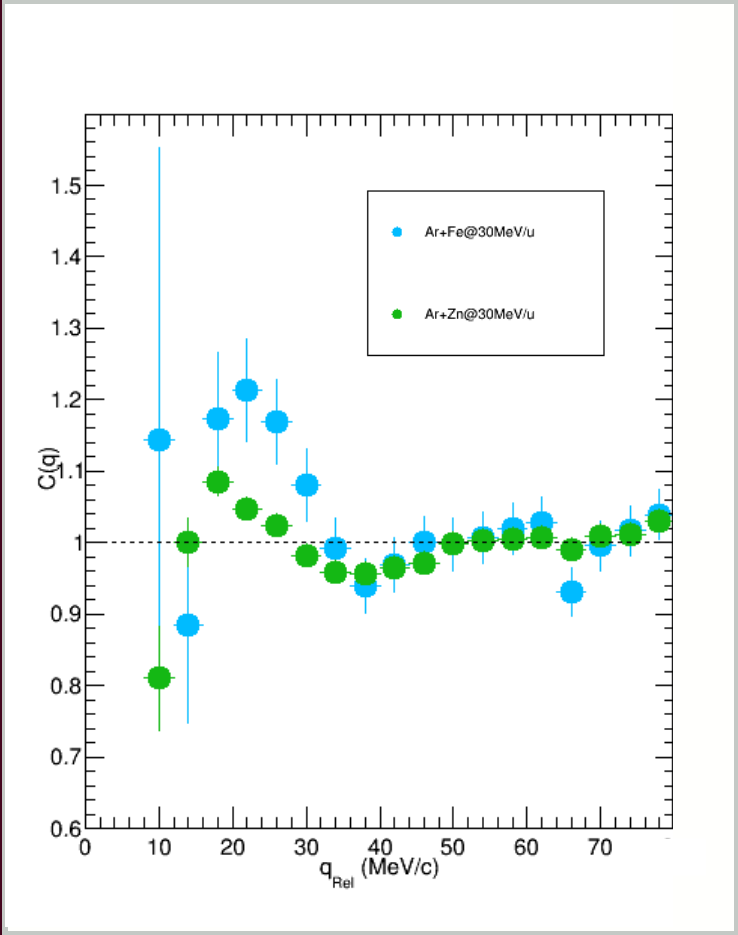

$p_T$(Event) minimum
0 MeV/c
140 MeV/c
180 MeV/c
220 MeV/c
260 MeV/c
300 MeV/c
$p_{Pair}$ minimum
0 MeV/c
250 MeV/c
300 MeV/c
350 MeV/c
Ar+Fe@40MeV/u
Ca+Ni@40MeV/u
C(q)
$q_{Rel}$ (MeV/c)

# 40 MeV/nucleon Systems



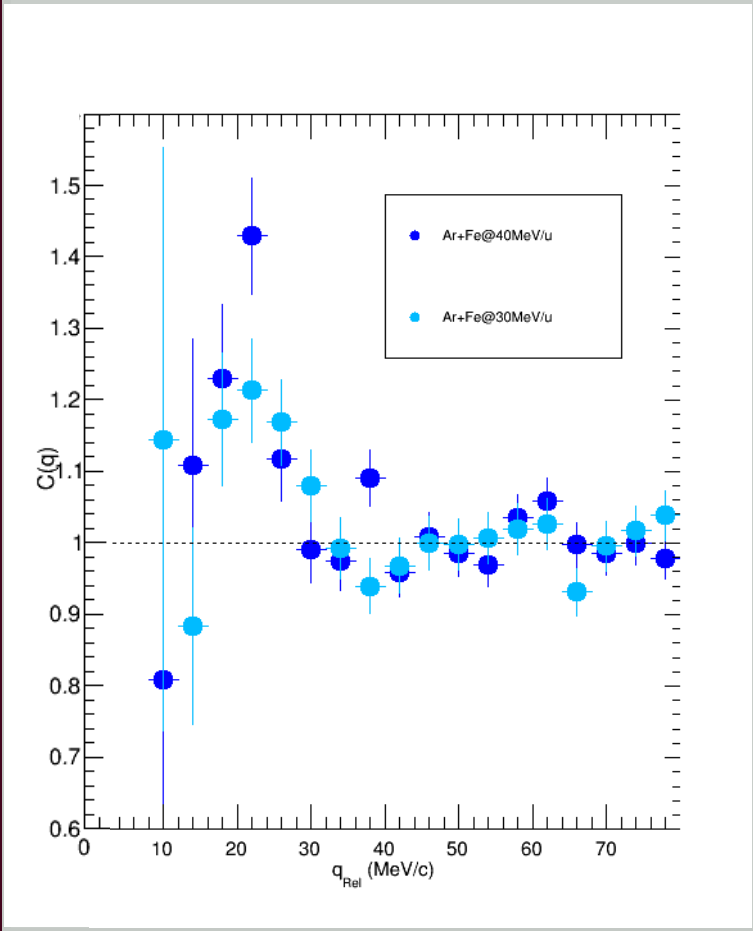

- Constant A
- Different Δ, Z
- ➢ Lower Δ, Higher Z: lower correlation function

# 30 MeV/nucleon Systems




- Constant Projectile
- Similar Δ
- Different target Z & A
- ➢ Higher Z & A target: lower correlation function
- ➢ Larger source—more total nucleons

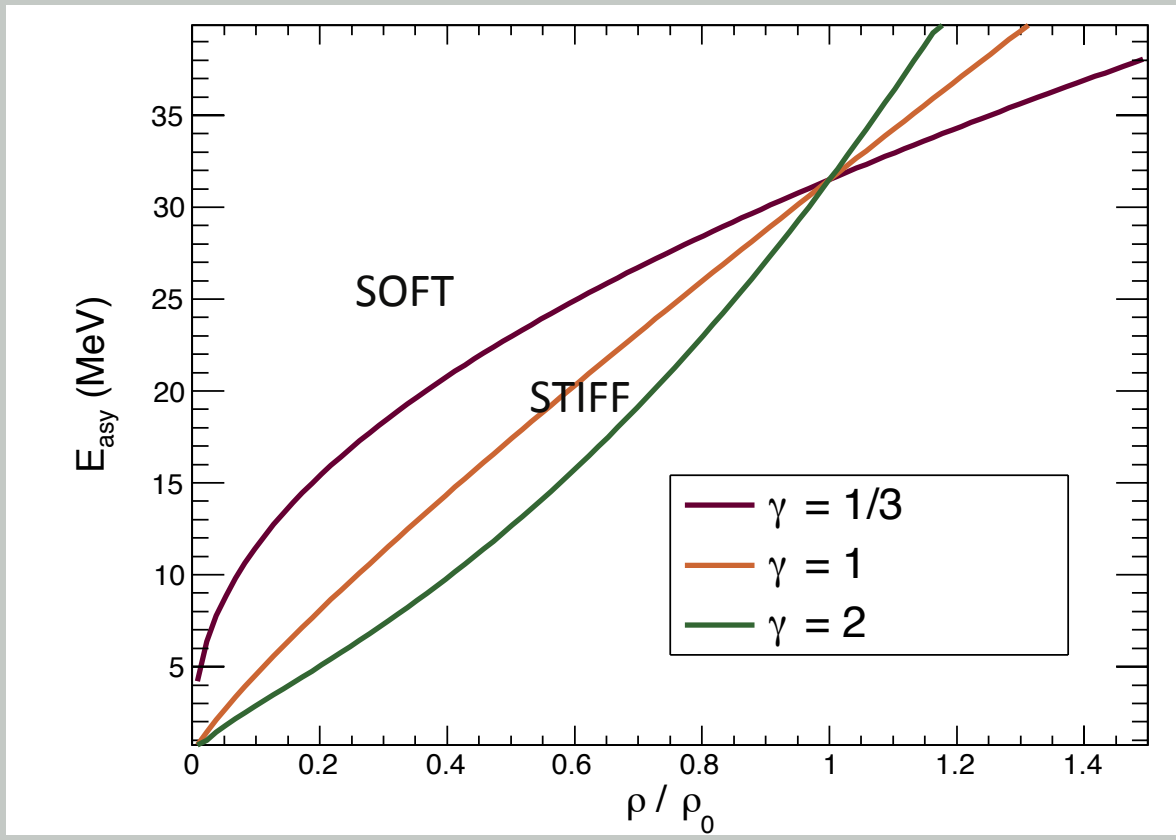
# $^{40}Ar+^{58}Fe$ at two Beam Energies




- Constant system
- Different energy
  - ➢ Lower energy: lower correlation function
  - ➢ Protons have less energy, emitted over longer timescale

# Transport Model: pBUU

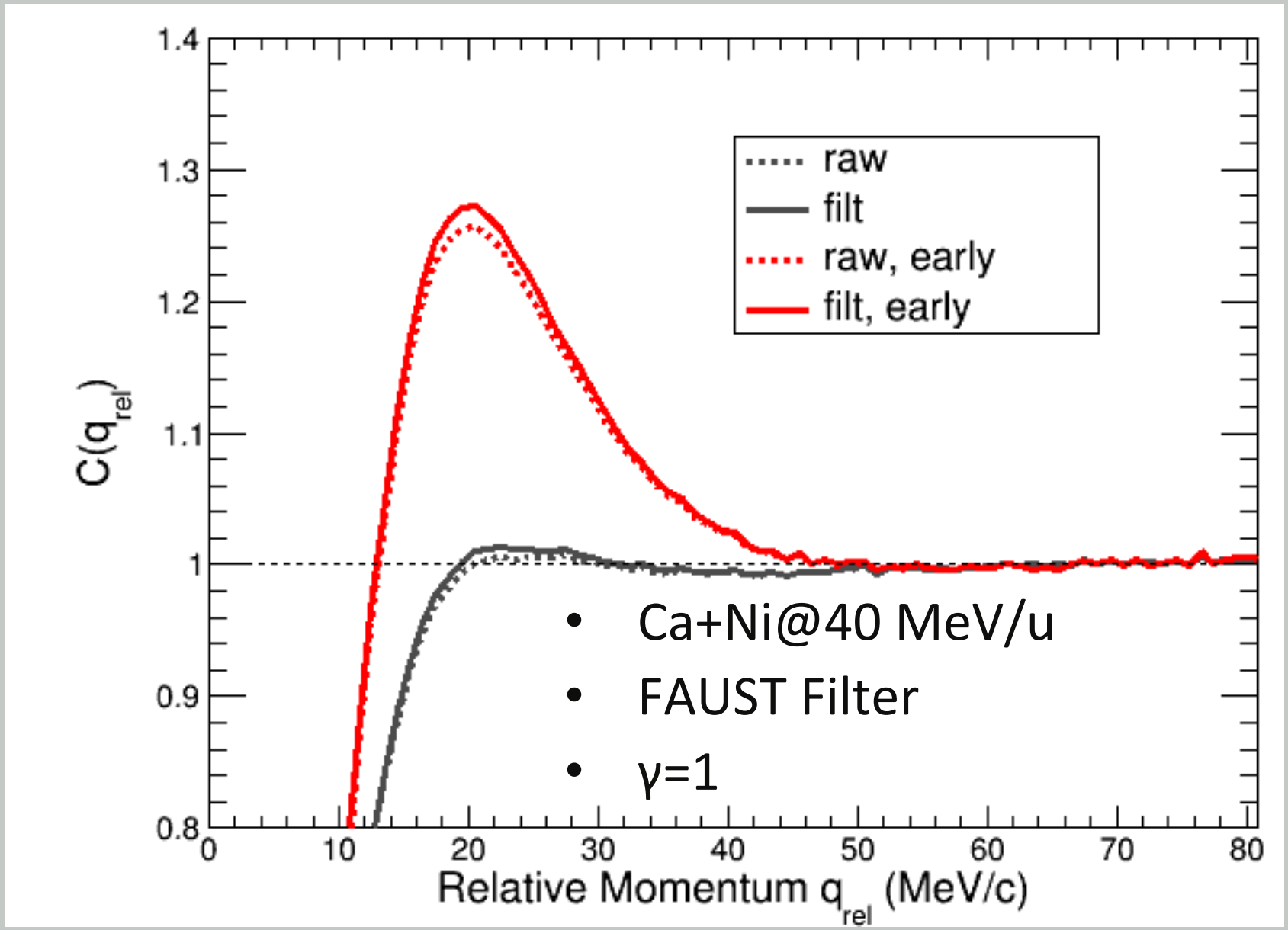
- Soft vs stiff $E_{asy}(\rho)$
- Below saturation density
- Run to 300 fm/c

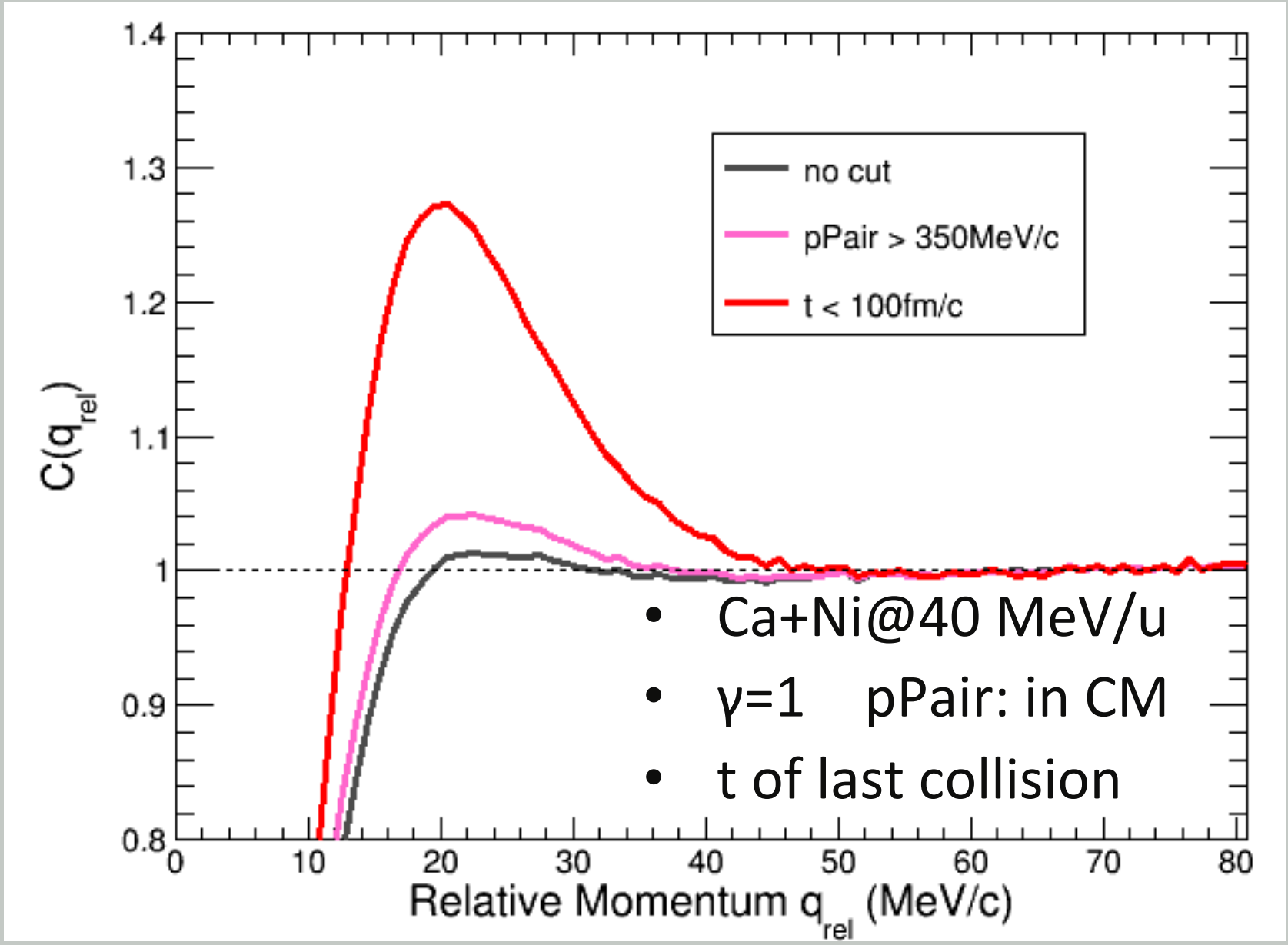


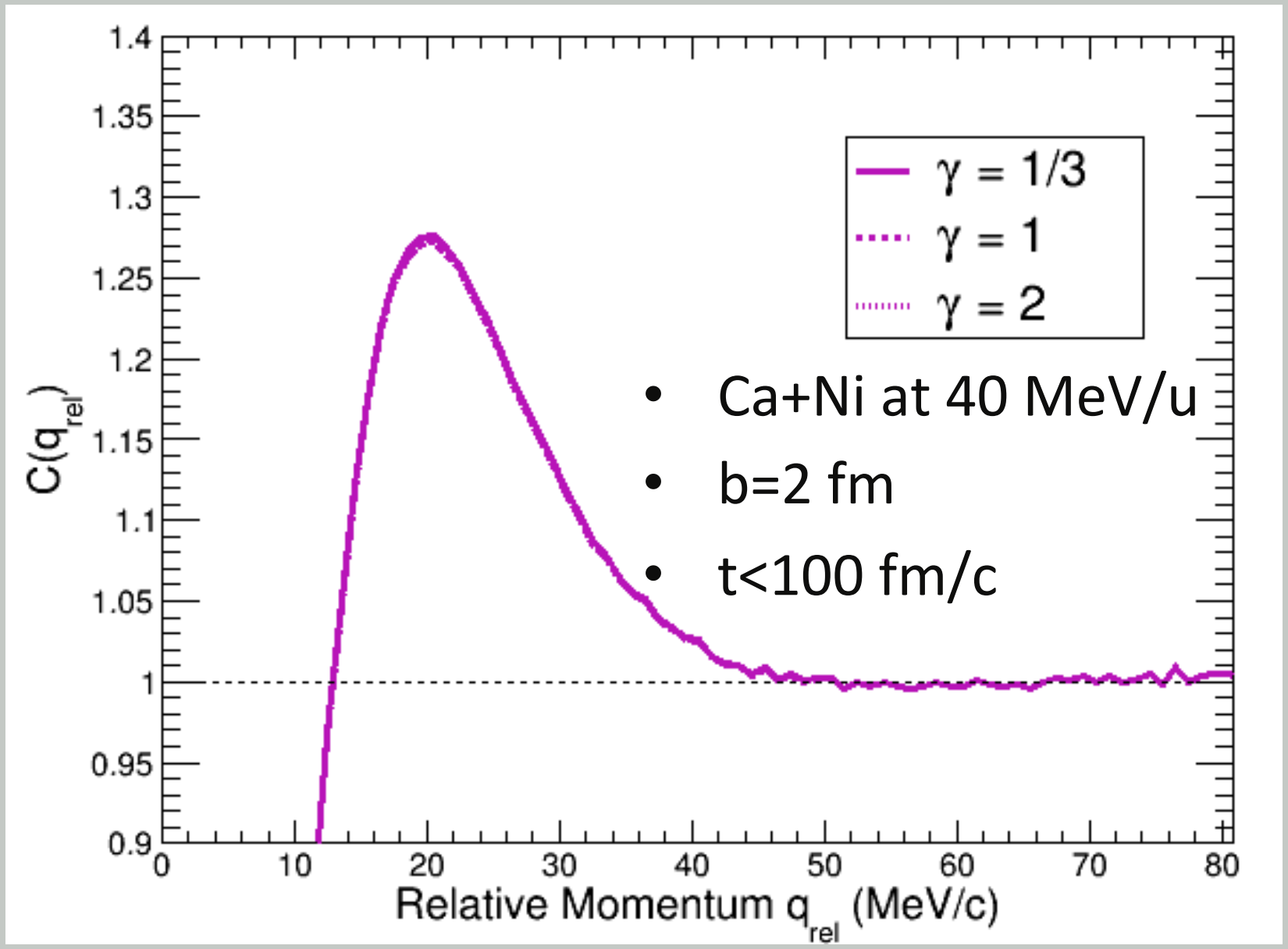

$$E_{asy} = S_{kin}\left(\frac{\rho}{\rho_0}\right)^{(2/3)} + S_{int}\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

B. Barker, *private comm.*, 2015-2018.

P. Danielewicz and G. Bertsch, Nucl. Phys. A 533, 712 (1991).

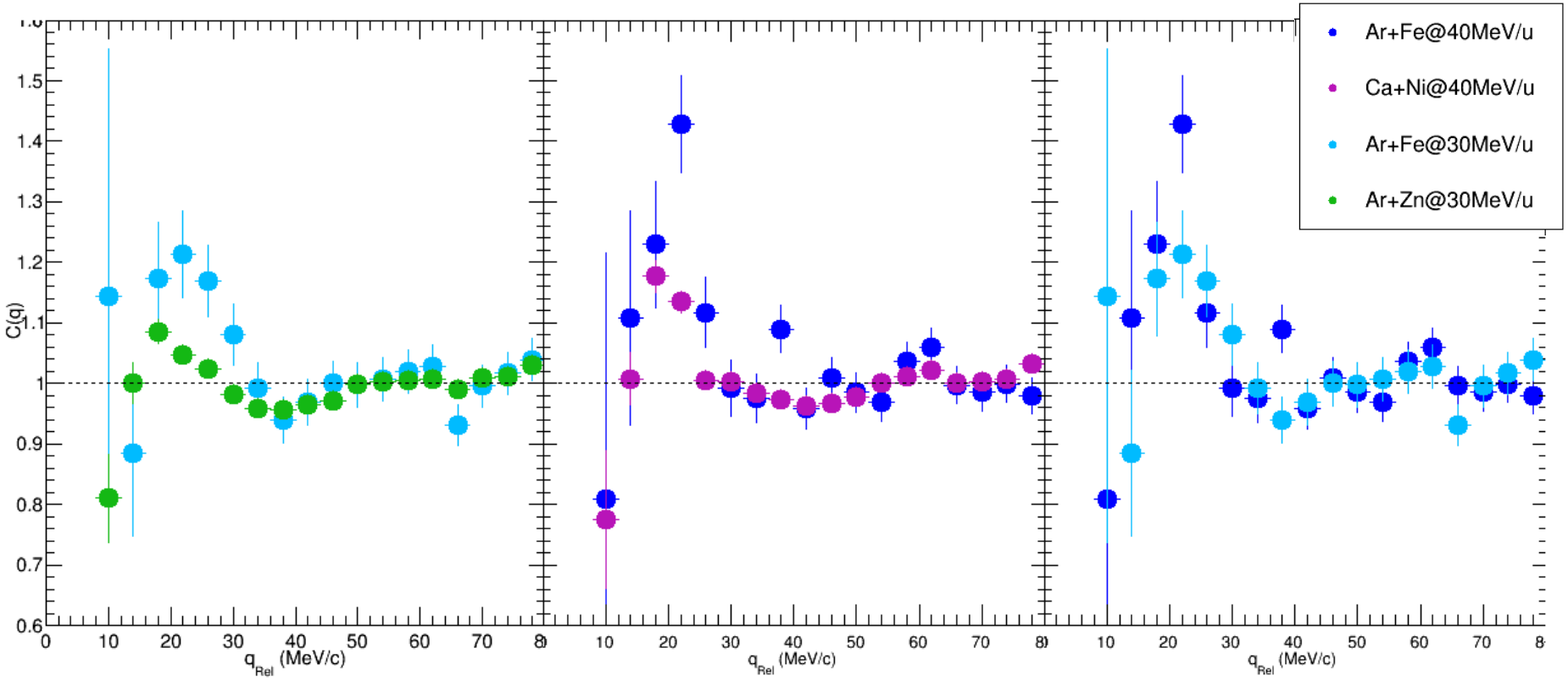

raw
filt
raw, early
filt, early
C(q_rel)
Relative Momentum q_rel (MeV/c)
1.4
1.3
1.2
1.1
1
0.9
0.8
0
10
20
30
40
50
60
70
80
• Ca+Ni@40 MeV/u
• FAUST Filter
• γ=1


1.4
1.3
1.2
1.1
1
0.9
0.8
C(q_rel)
0
10
20
30
40
50
60
70
80
Relative Momentum q_rel (MeV/c)
no cut
pPair > 350MeV/c
t < 100fm/c
• Ca+Ni@40 MeV/u
• γ=1 pPair: in CM
• t of last collision




- Ca+Ni at 40 MeV/u
- b=2 fm
- t<100 fm/c

# Experimentally extracted pp correlation functions



# Summary

- Complete position-sensitive FAUST upgrade
- pBUU pp correlation functions
  - Asymmetry energy effect smaller than system or impact parameter → no parameterizations excluded
- Experimental pp correlation functions
  - Higher correlation functions extracted for:
    - Smaller system (less neutron-rich)
    - Higher beam energy
    - More neutron-rich system (less total charge)

# Acknowledgments

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