Effect of in-medium cross-section on particle production in low energy nuclear collisions

Chi-Kin Tam, Western Michigan University
On behalf of HiRA collaboration

Content

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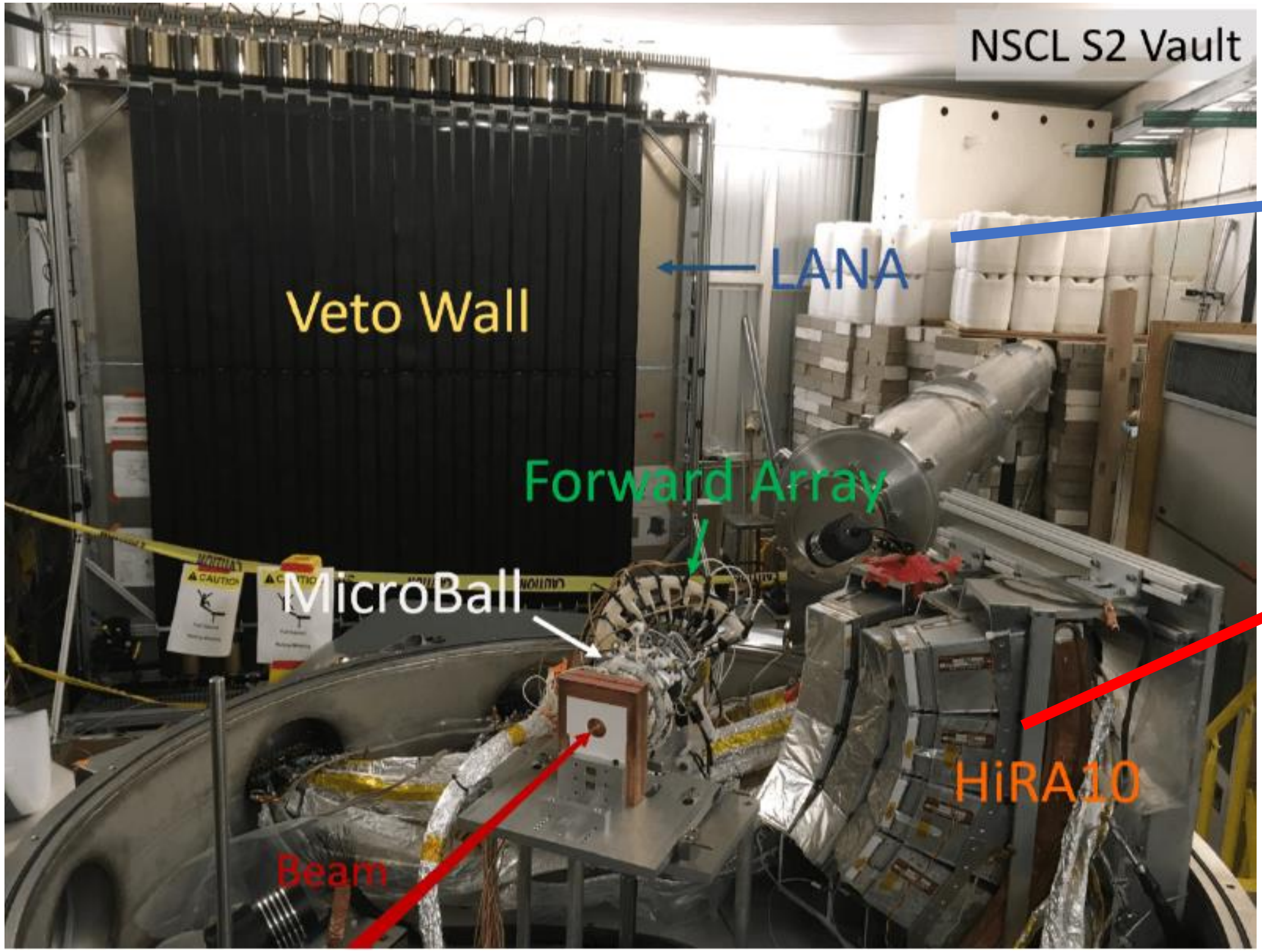
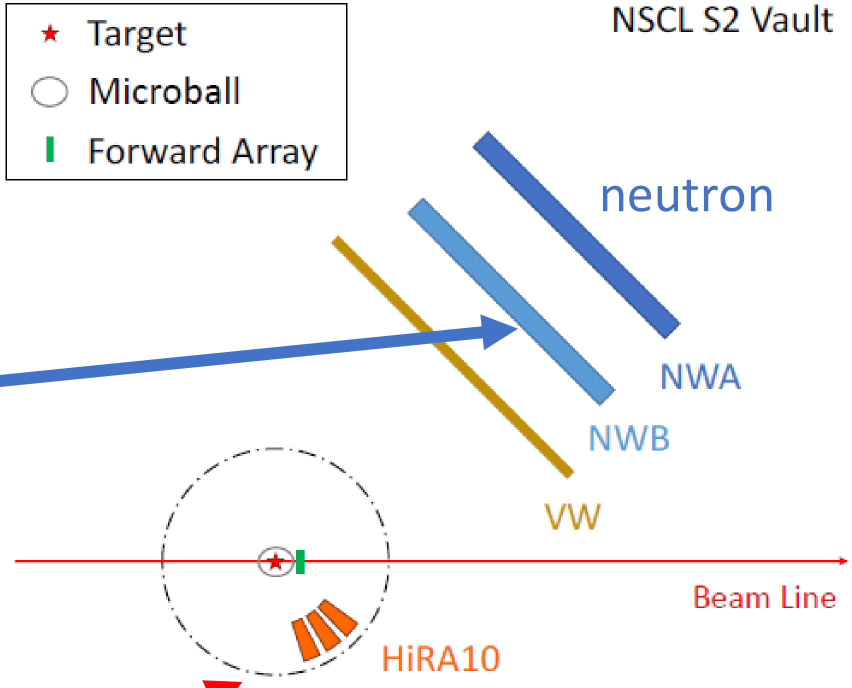
  - $^{40,48}Ca + ^{58,64}Ni$ @ 56, 140 MeV/A
  - Transverse Momenta spectra
  - $R_{21}(N,Z)$ and Iso-scaling
- Transport model
  - AMD with secondary decay
  - Effect of event selection
- Filtered AMD model : constraints on σ_{NN}
  - Comparison with data
  - Iso-scaling

Experiment





p, d, t, ^{3}He, ^{4}He

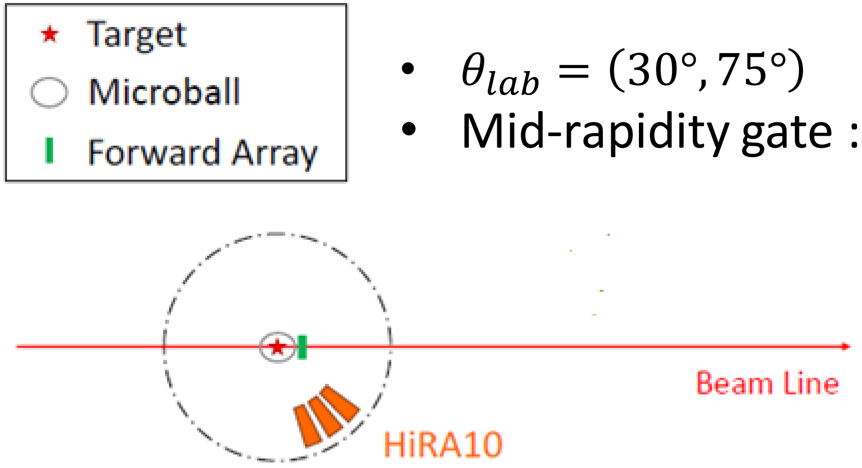
Beam	Target
Ca40 @ 56 MeV/A	Ni58
Ca48 @ 56 MeV/A	Ni64
Ca40 @ 140 MeV/A	Sn112
Ca48 @ 140 MeV/A	Sn124

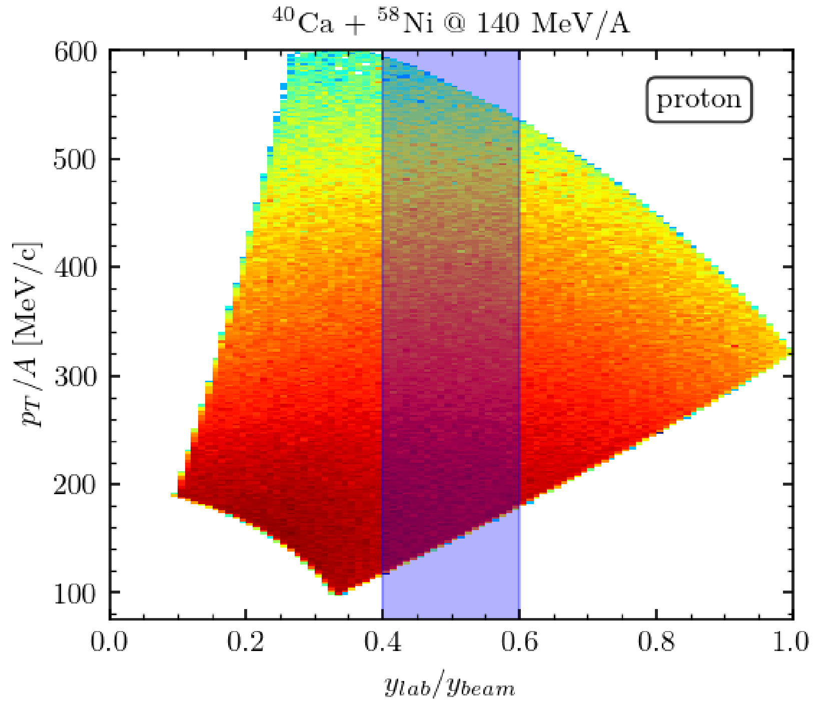
Kuan Z., Measuring neutrons in heavy ion collision, Ph.D. thesis, MSU (2020).

Experimental spectra

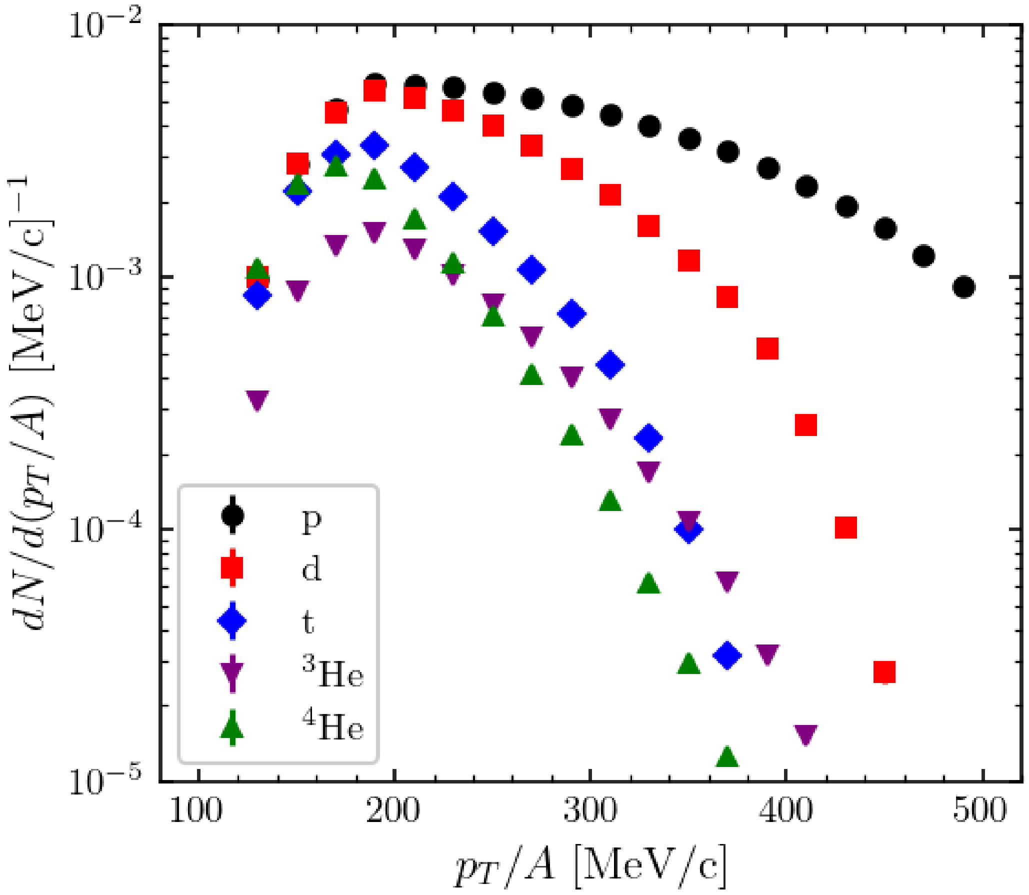
- $\theta_{lab} = (30°, 75°)$
- Mid-rapidity gate : $y_{lab}/y_{beam} = (0.4, 0.6)$

- Selected central events
- PID of p, d, t, ^{3}He, ^{4}He
- Efficiencies corrected





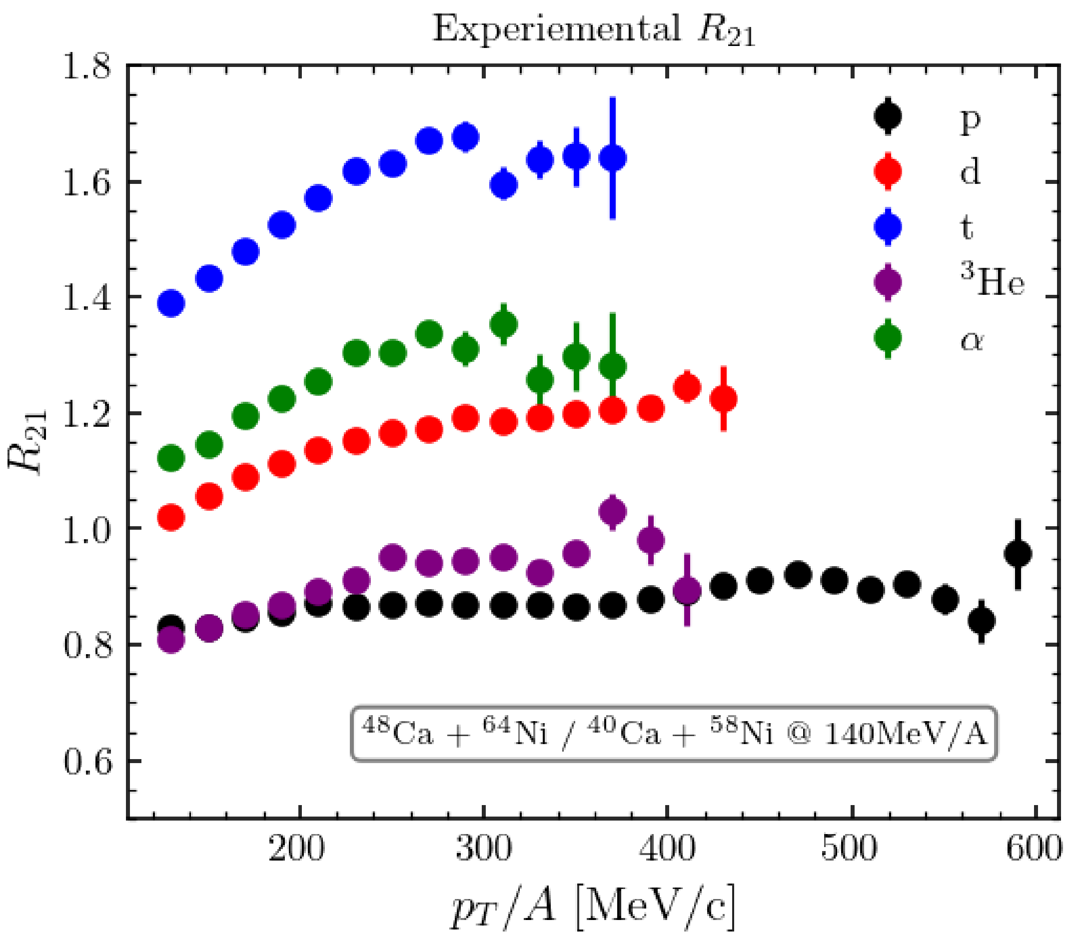
$^{48}Ca + ^{64}Ni$ @ $140\ MeV/A$



Isoscaling Ratio R_{21}

$$R_{21}(N,Z) = \frac{Y_2(N,Z)}{Y_1(N,Z)}$$

Reaction 2 : ^{48}Ca + ^{64}Ni @ 140 MeV/A
Reaction 1 : ^{40}Ca + ^{58}Ni @ 140 MeV/A



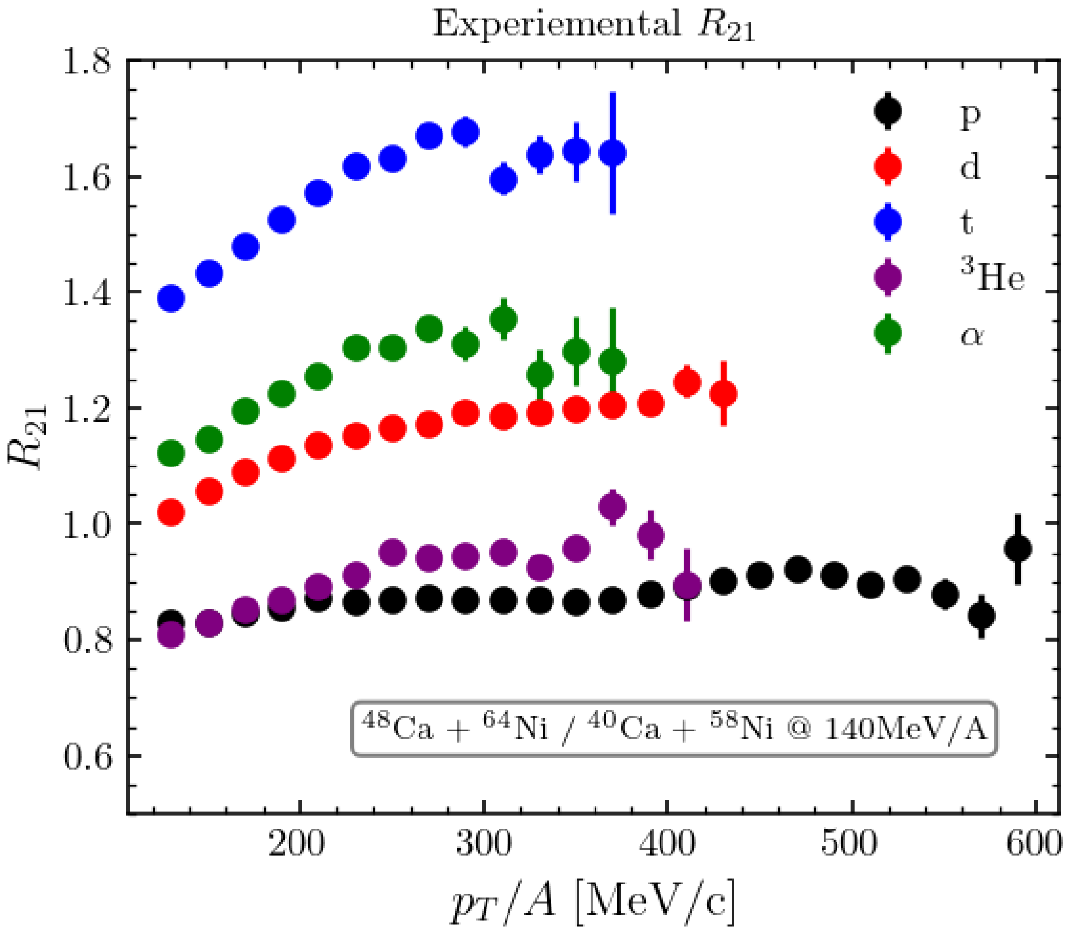
- $R_{21}(p), R_{21}(^3He) < 1$ implies more protons are produced in the proton-rich reaction
- $R_{21}(t) > 1$ implies more tritons produced in n-rich reaction

M.B. Tsang. at al PHYSICAL REVIEW C, VOLUME 64, 054615

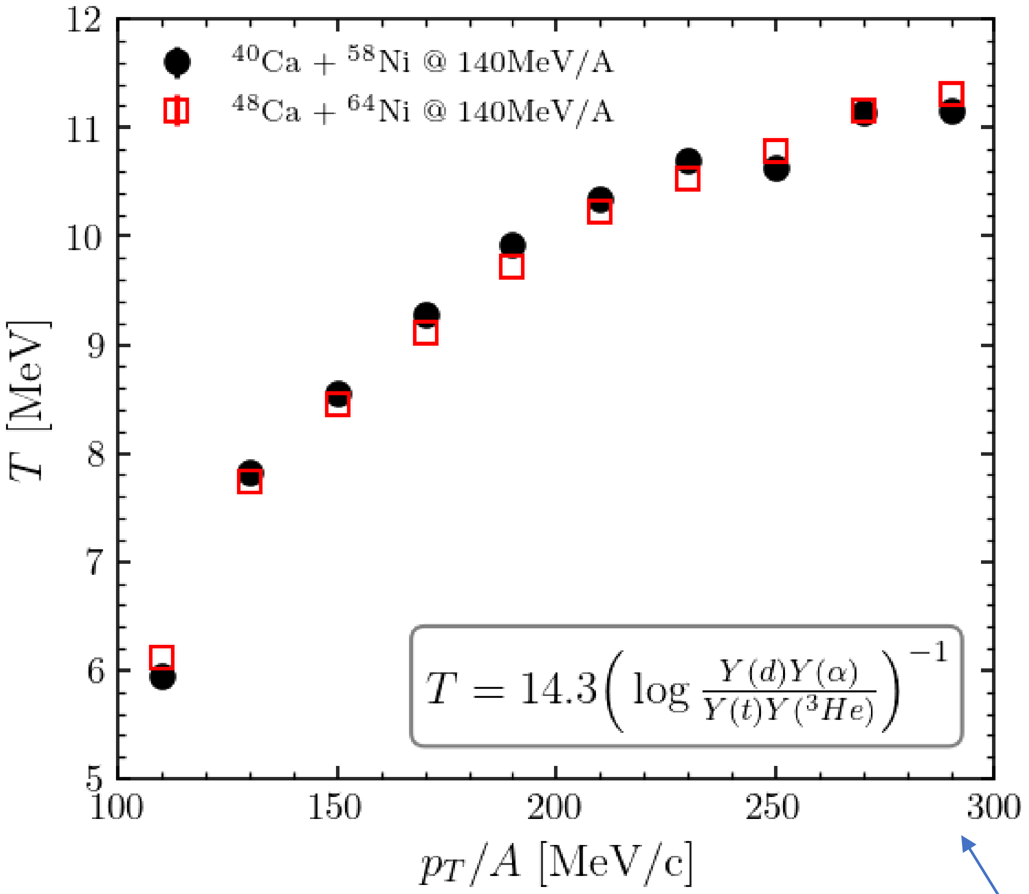
Isoscaling Ratio R_{21}

$$R_{21}(N,Z) = \frac{Y_2(N,Z)}{Y_1(N,Z)} = C\exp(\alpha N + \beta Z)$$

M.B. Tsang. at al PHYSICAL REVIEW C, VOLUME 64, 054615



- Grand-canonical ensemble
- Chemical potential $\alpha = \Delta\mu_n/T$, $\beta = \frac{\Delta\mu_p}{T}$
- Chemical Temperature similar in both reactions



limits comes from triton acceptance

Isoscaling Ratio R_{21}

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- Grand-canonical ensemble
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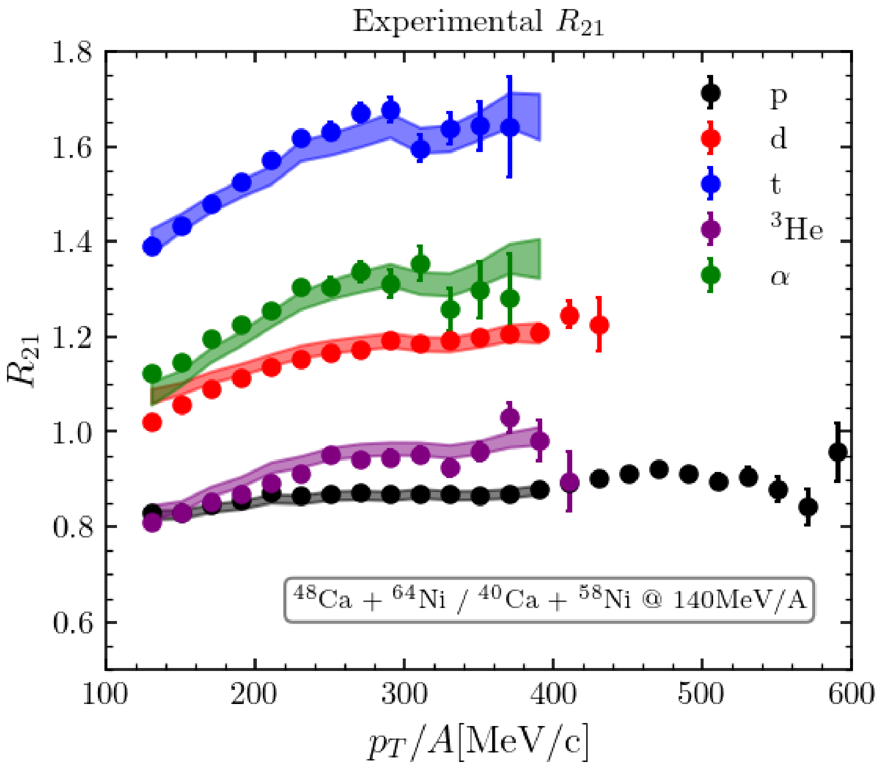
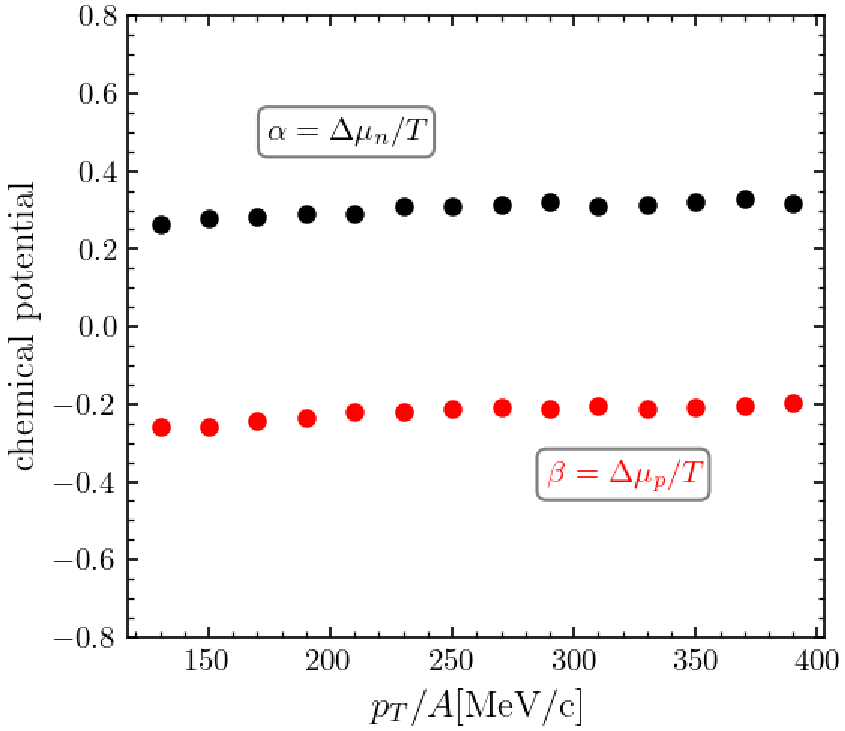
- Chemical Temperature similar in both reactions

Points are data
Shades are fit





- $R_{21}(p) \approx R_{21}(^3He), R_{21}(d) \approx R_{21}(^4He)$ suggests $|\alpha| \approx |\beta|$.
- Can be used to construct pseudo-neutron spectrum $Y(n^*) = Y(p) \cdot Y(t)\ /Y(3He)$
- Sensitive to the in-medium cross section σ_{NN} in transport model

AMD : Model Detail

Version : amdbx-20220819-Bs

- Reaction systems
  - ^{40}Ca + ^{58}Ni @ 140 MeV/A
  - ^{48}Ca + ^{64}Ni @ 140 MeV/A
- Default AMD sec. decay
  - Dynamic part ends at 300 fm/c
  - 10 decays / prim. event
- Cluster correlation included
- Sensitivity
  - Effective mass : SkM*, SLy4
  - Symmetry energy : SLy4 modified SLy4 (L=108MeV)
  - In-medium cross-section σ_{NN}: screened and free

Akira. JPS Conf. Proc. , 010076 (2020)
Natsumi at al PHYSICAL REVIEW C 93, 044612 (2016)
Yoshiko, et al Prog. Theor. Exp. Phys. 2012, 01A202

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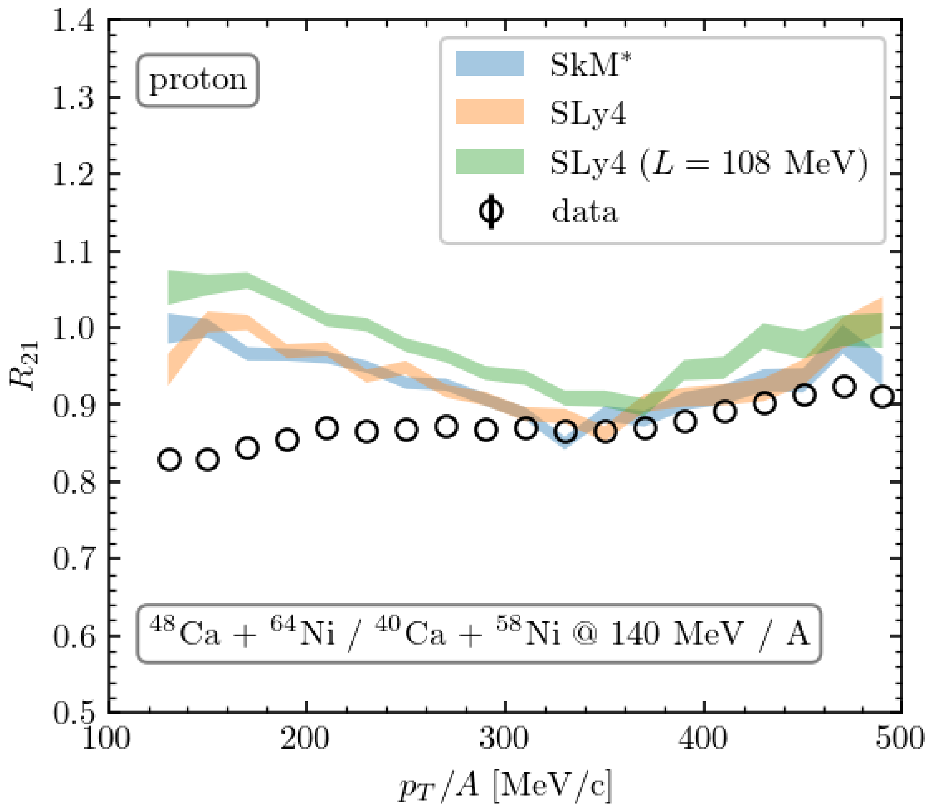

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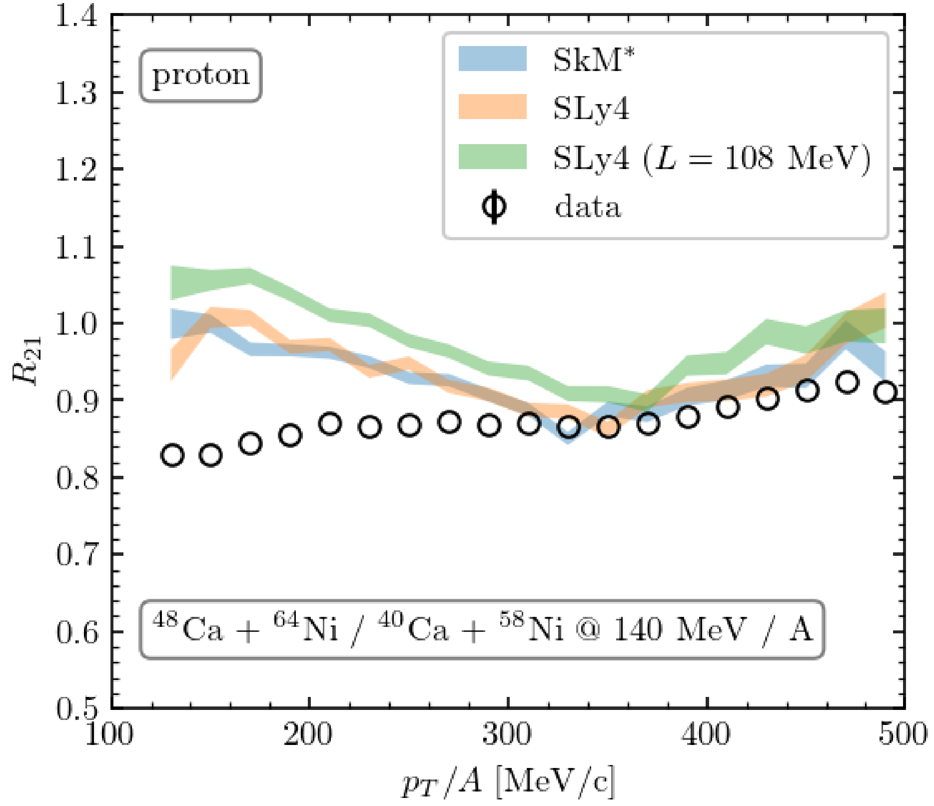

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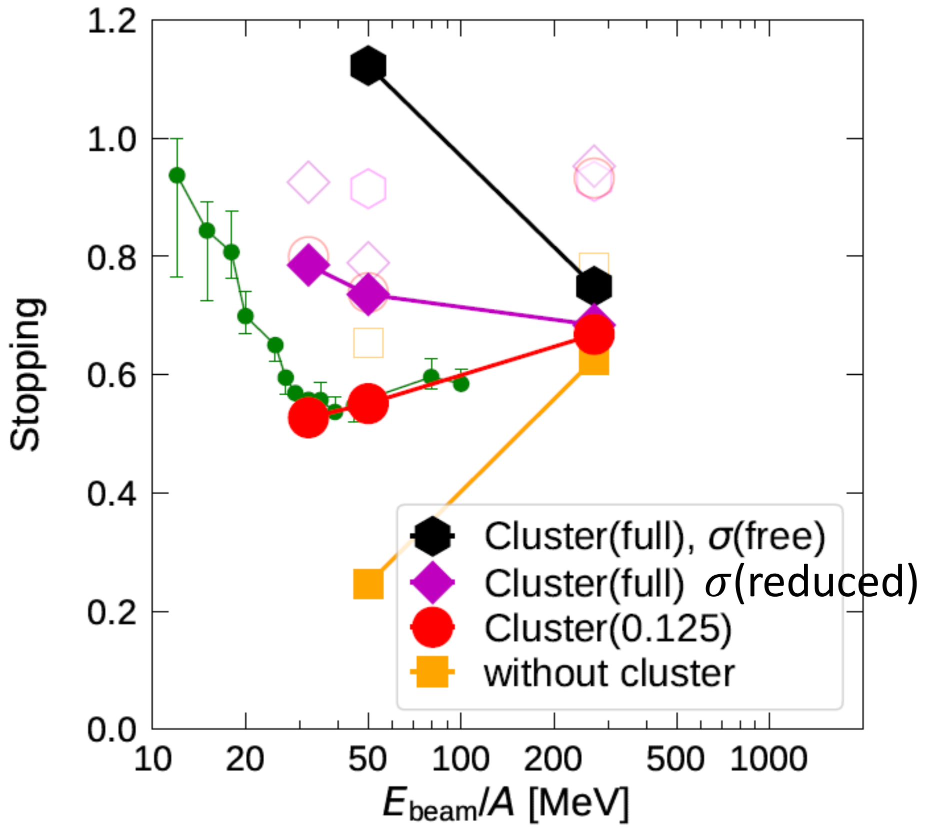
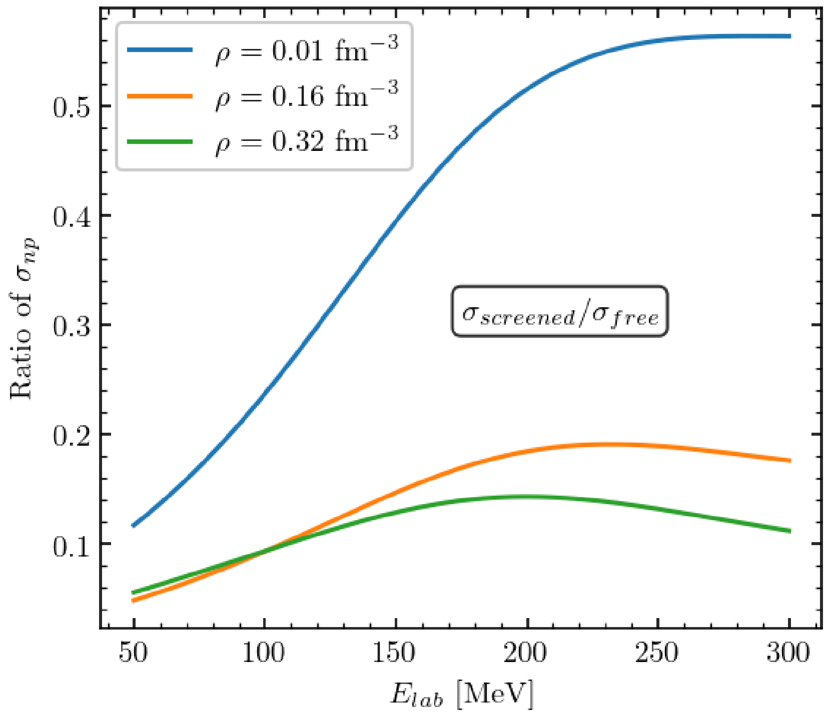
In-medium NN cross section σ_{NN}

- Probability of NN interaction
- reduced σ_{NN} in HIC (collective flow, stopping)
- reduction factor not well-constrained
- essential to reducing EoS uncertainties



A. Ono. JPS Conf. Proc. , 010076 (2020)

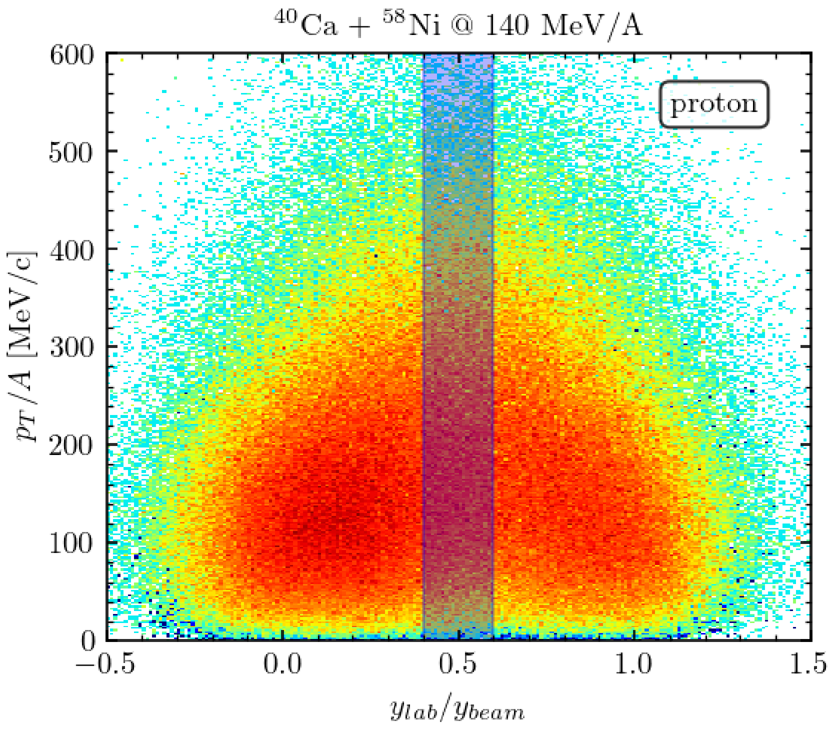


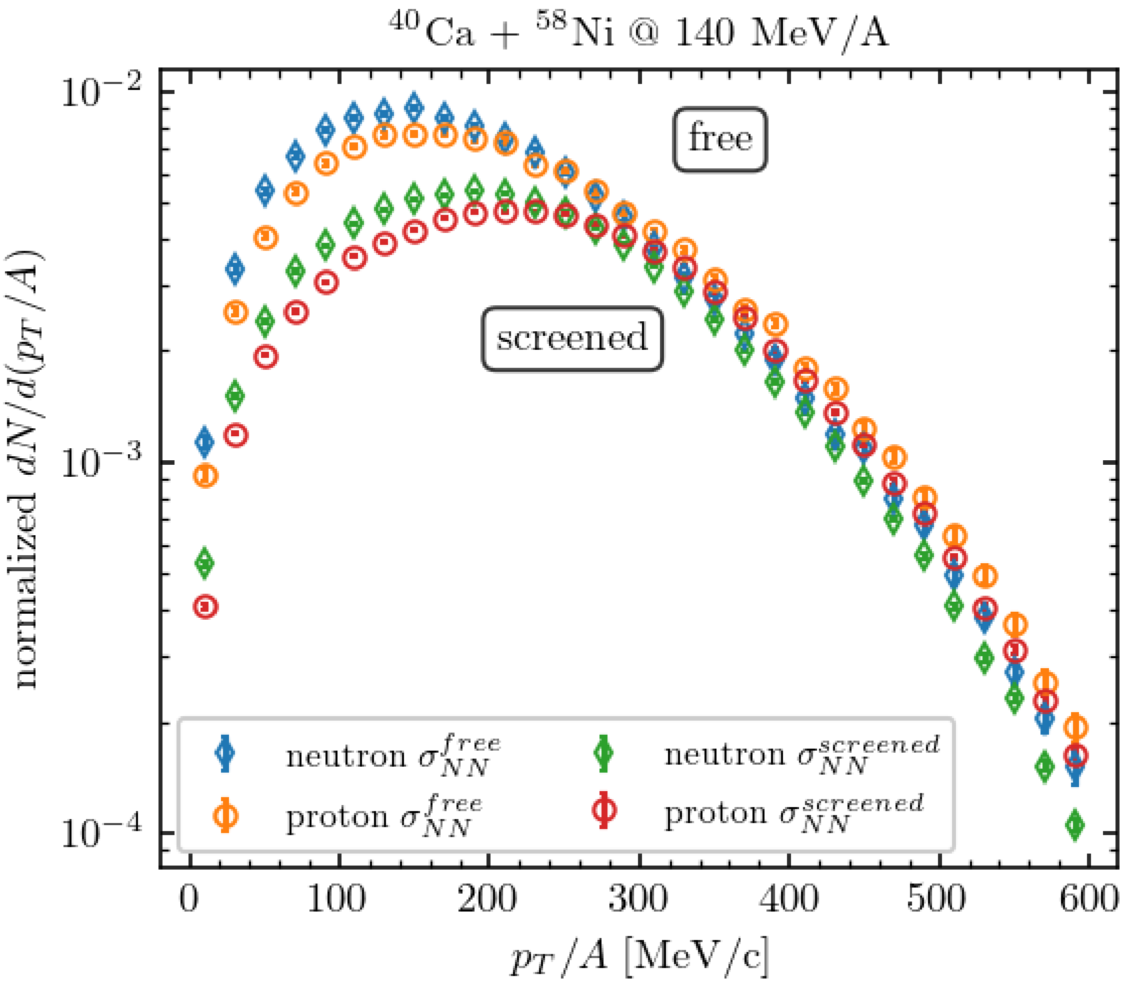
$$\sigma_{NN}^{screened} = \tanh(\sigma_{NN}^{free} \,/\, \sigma_0)\,, \sigma_0 = y\rho^{-2/3}$$

- More reduction at large densities
- Isospin-dependence ignored
- Screened AMD we use $y = 0.85$

P. Danielewicz. Acta Phys.Polon. B33 (2002) 45-64
Barker PHYSICAL REVIEW C 99, 034607 (2019)

A quick look at the effect of σ_{NN} on n, p production in pure AMD





- Central events with mid-rapidity cut
- Neutron, proton yield reduced due to screened
- More yield in mid-rapidity region (interaction zone)
- More yield in low – Pt

Next, we need to have a fair comparison with data, i.e. select AMD events with the same centrality as in data.

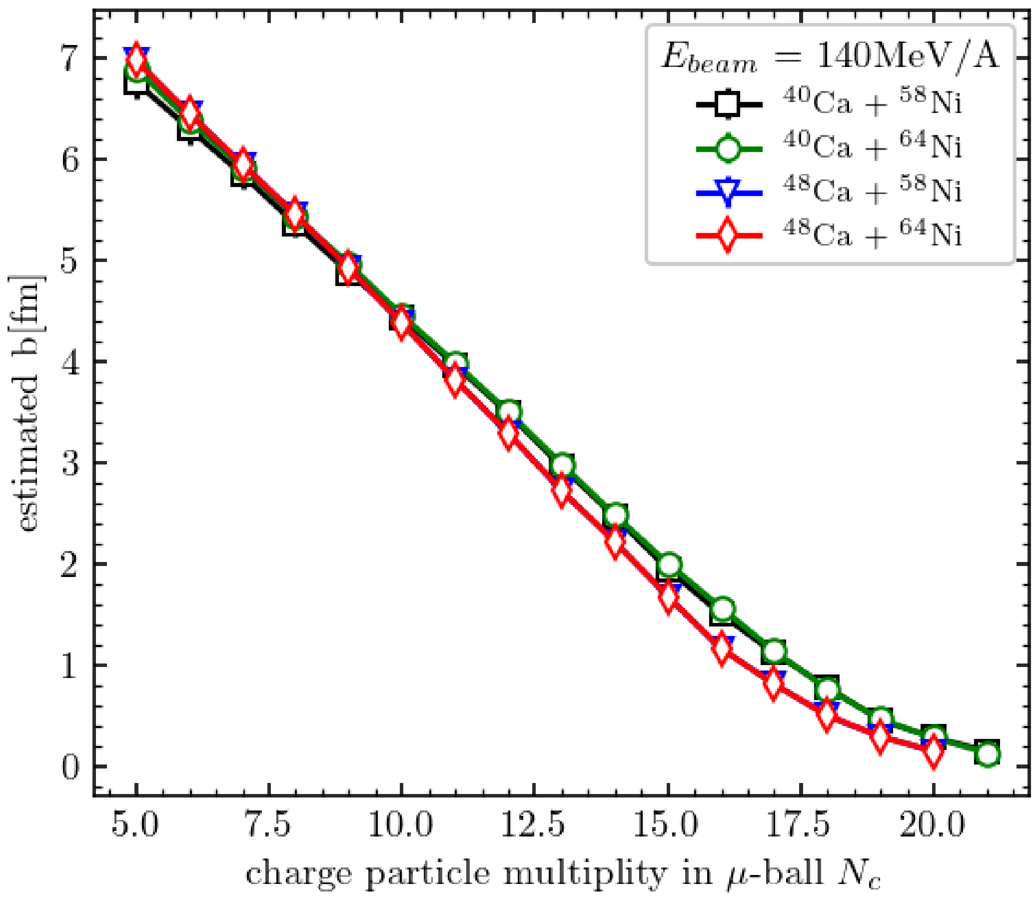
Fair comparison with Data

- Ideally, select AMD events with the same method as in data.

- Event selection in experiment
  - charge-particle multiplicity N_C measured by $\sim 4\pi$ detector
  - Assume b decreases with N_C montonically
  - Ignore fluctuation in N_C for each b

$$\hat{b}(x) = \frac{b(x)}{b_{max}} = \frac{\sqrt{P(N_C \geq x)}}{\sqrt{P(N_C \geq N_{C,min})}}$$

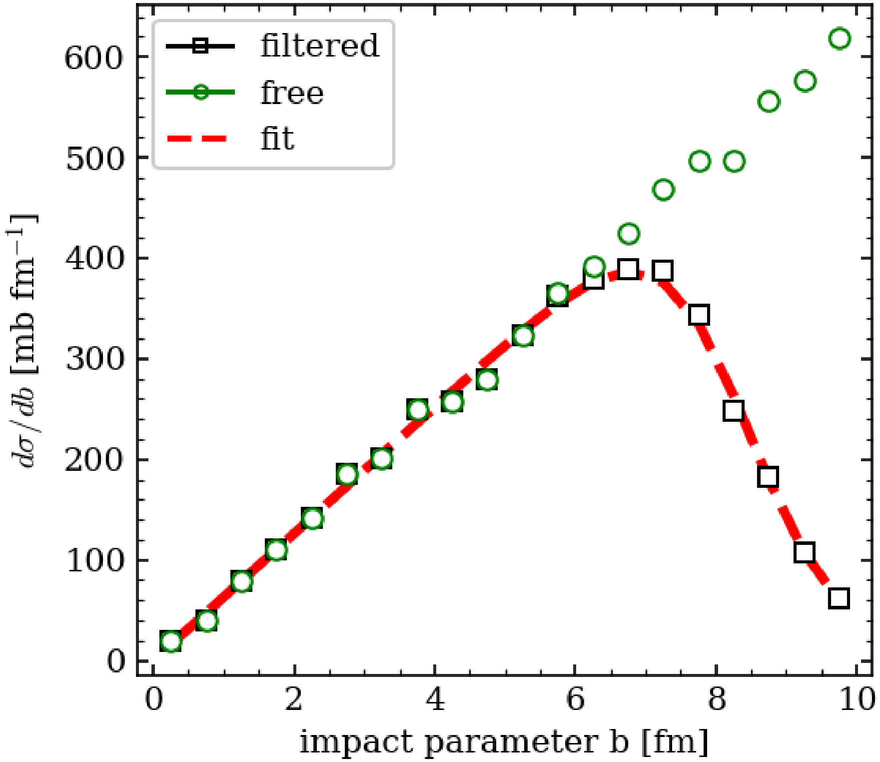
- b_{max} : Estimated from beam intensity
- $P(N_C)$: measured multiplicity distribution

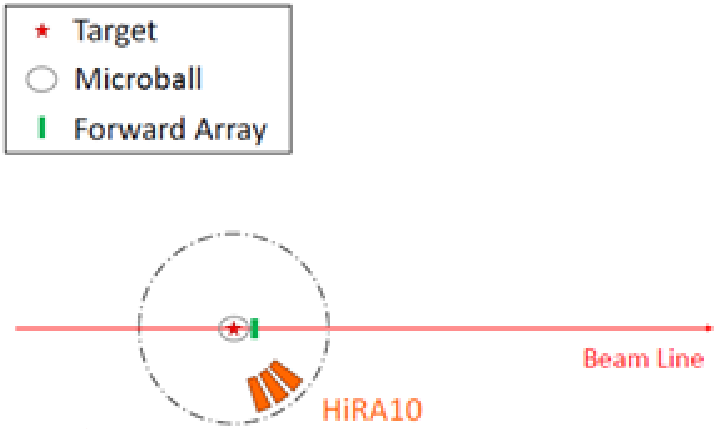


S.,Sweany. Constraining the proton/neutron effective mass splitting through heavy ion collision, Ph.D. thesis, MSU (2020).

Event selection in AMD

- Count charge-particle multiplicity with experimental filter
    - angular coverage
    - E_{lab} threshold (Sn, Pb foil)
    - single hit per crystal per event

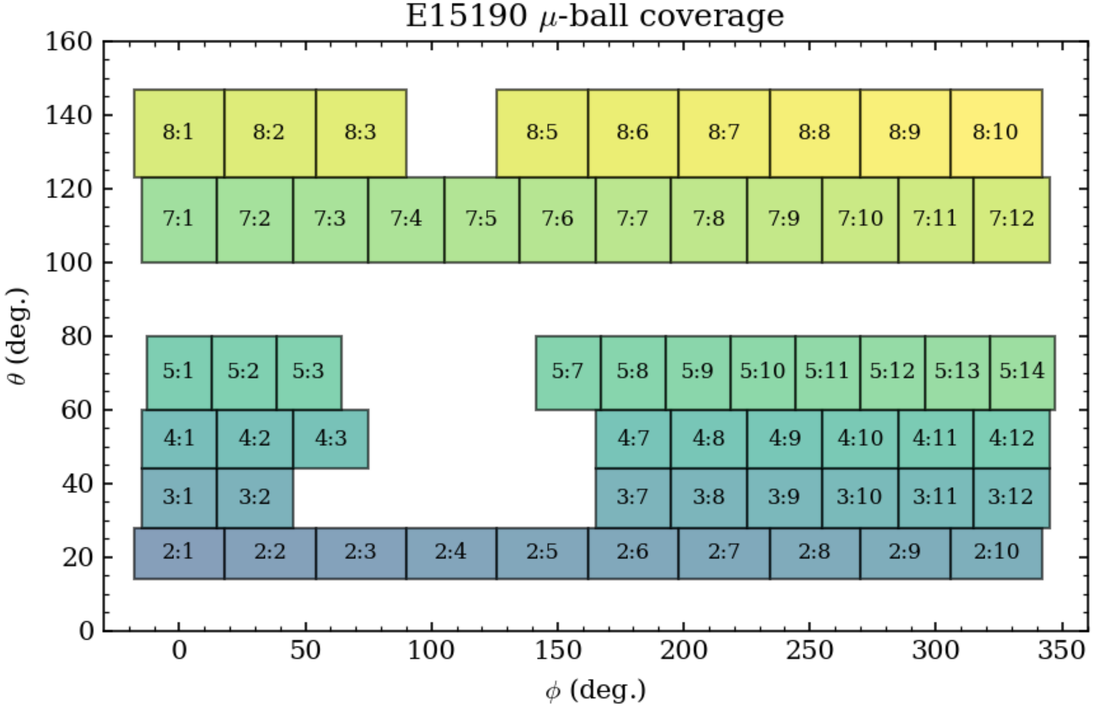




Beam Direction = z-direction

θ = angle btw particle and z

ϕ = azimuthal angle



- Remove events which are invisible in experiment

Event selection in AMD

- Count charge-particle multiplicity with experimental filter
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  - E_{lab} threshold (Sn, Pb foil)
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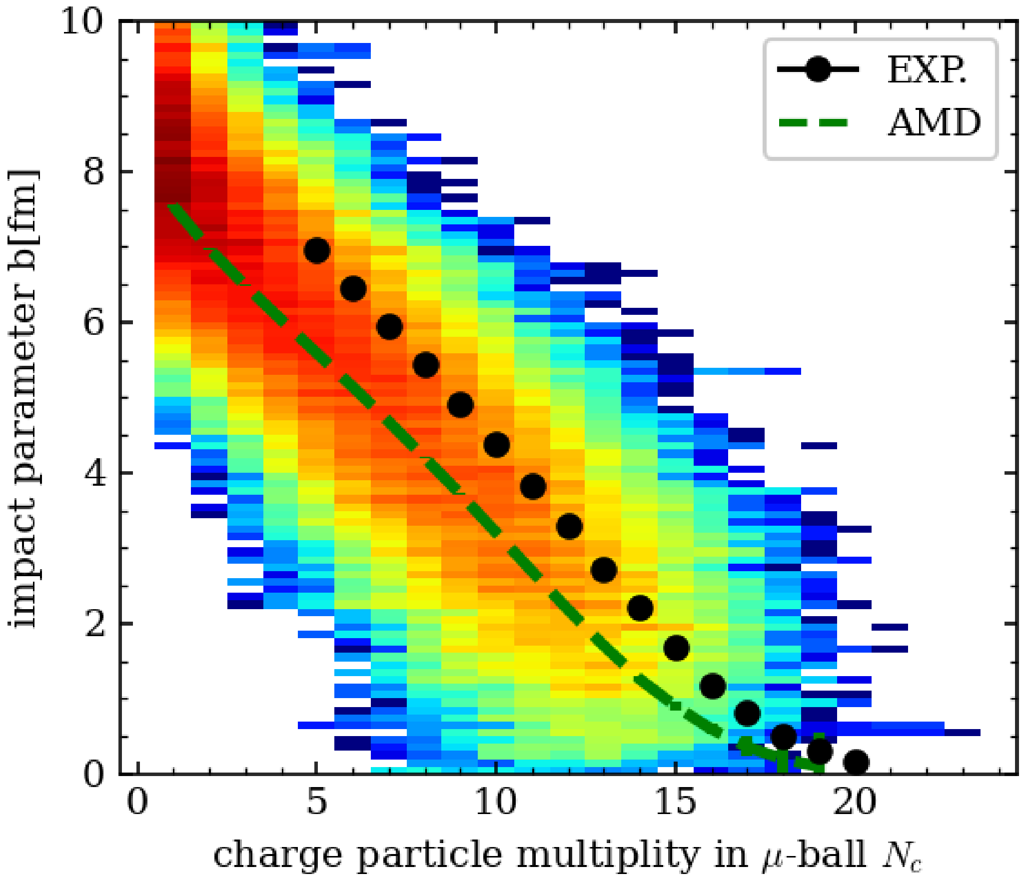

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- In model, fluctuation of b for each N_C
- Use N_C^{AMD} to determine b, comparable to data

2D histogram : true distribution of b against N_C^{AMD}
Black pts : estimated b from N_C^{EXP}
Green line : estimated b from N_C^{AMD}

Event selection in AMD

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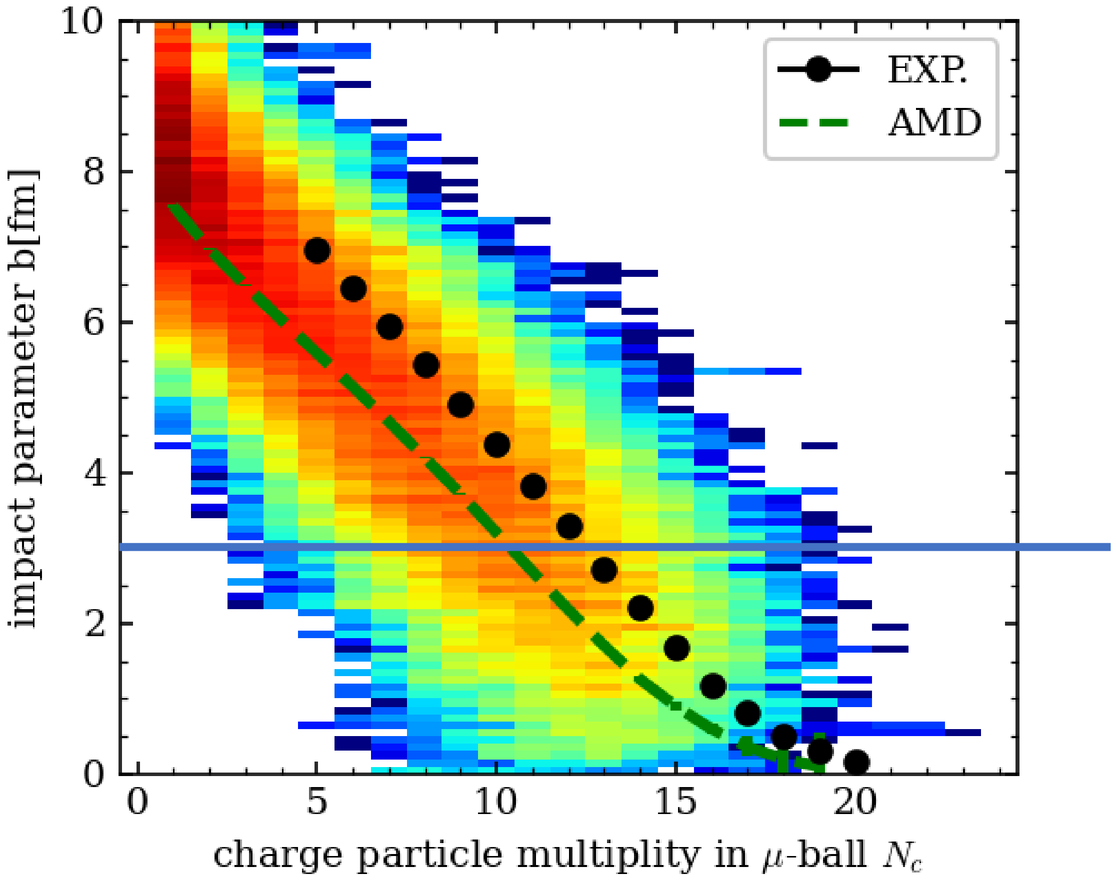


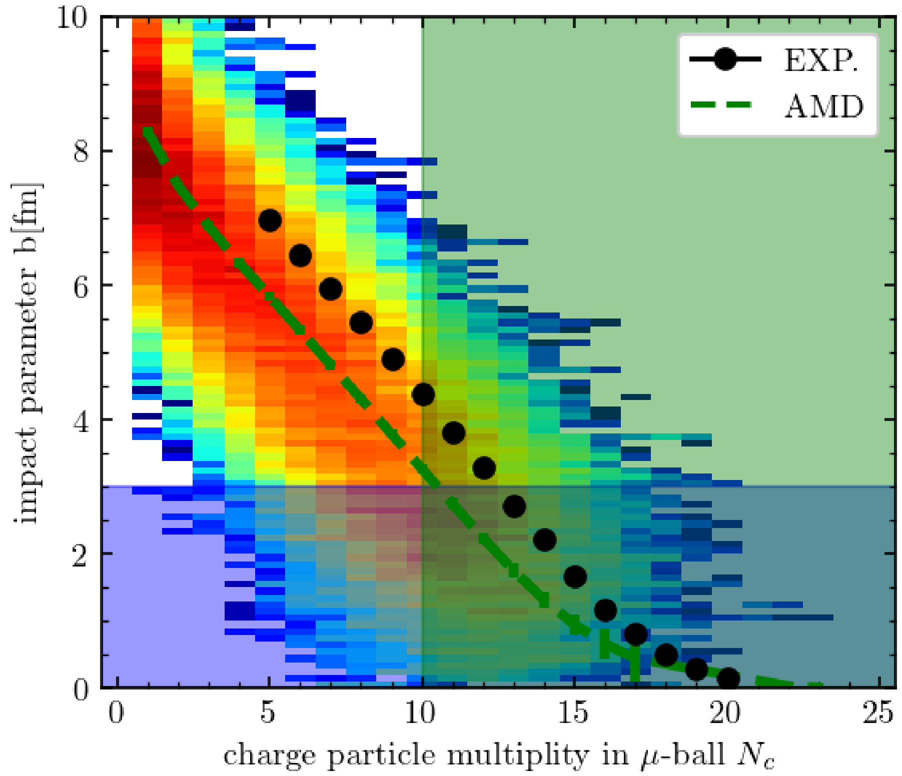
- In model, fluctuation of b for each N_C
- Use N_C^{AMD} to determine b, comparable to data
- Experimental cut equivalent to $N_C^{AMD} \geq 10$ in model

2D histogram : true distribution of b against N_C^{AMD}
Black pts : estimated b from N_C^{EXP}
Green line : estimated b from N_C^{AMD}

Effect of centrality cut in AMD : p_T spectra

- A. Select events with $b < 3$ fm
- B. Select events with $N_C \geq 10$

$^{48}Ca + 64Ni$ @$140 MeV/A$



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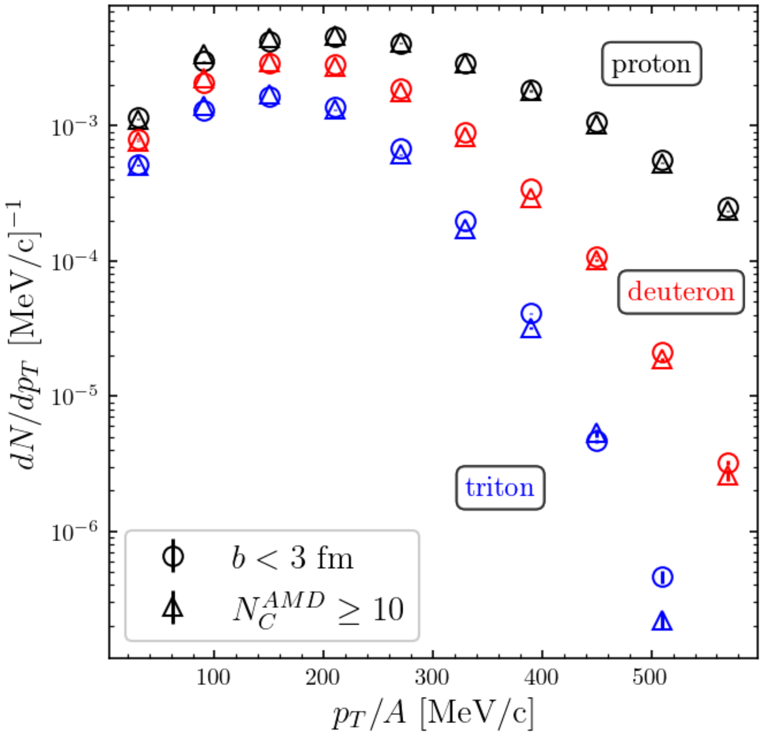

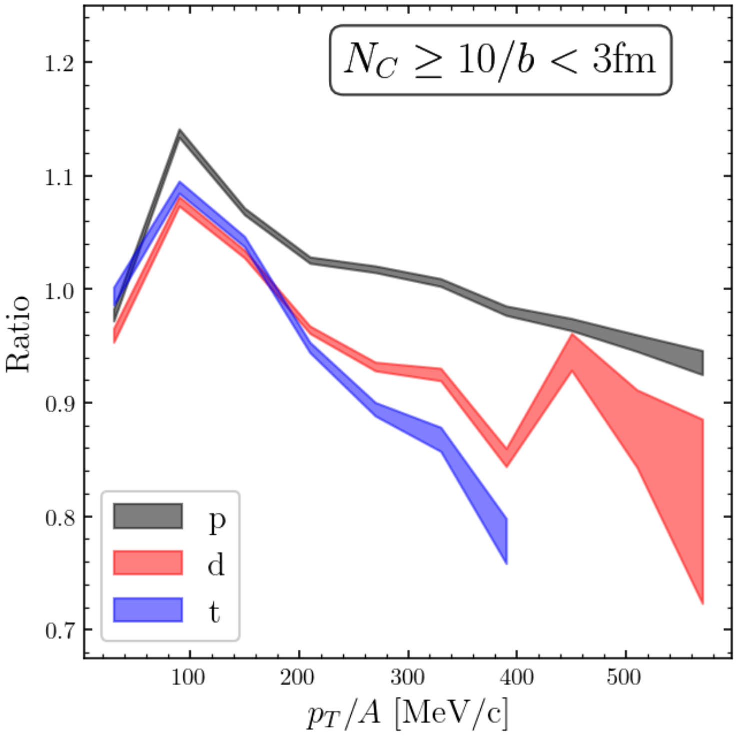

- Similar in proton p_T spectra
- Spectrum with $N_C \geq 10$ is smaller at high p_T
- Smaller available energy from collision in $N_C \geq 10$
- More at low p_T, could be phase-space effect.

Effect of centrality cut in AMD : p_T spectra

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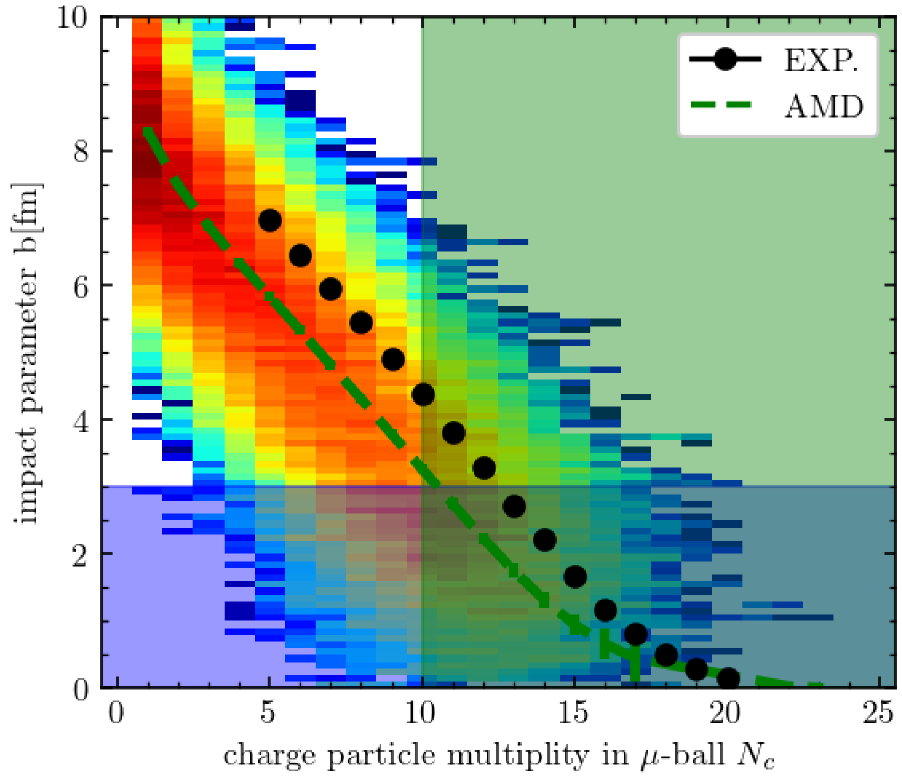
- B. Select events with $N_C \geq 10$



2D histogram : true distribution of b against N_C^{AMD}
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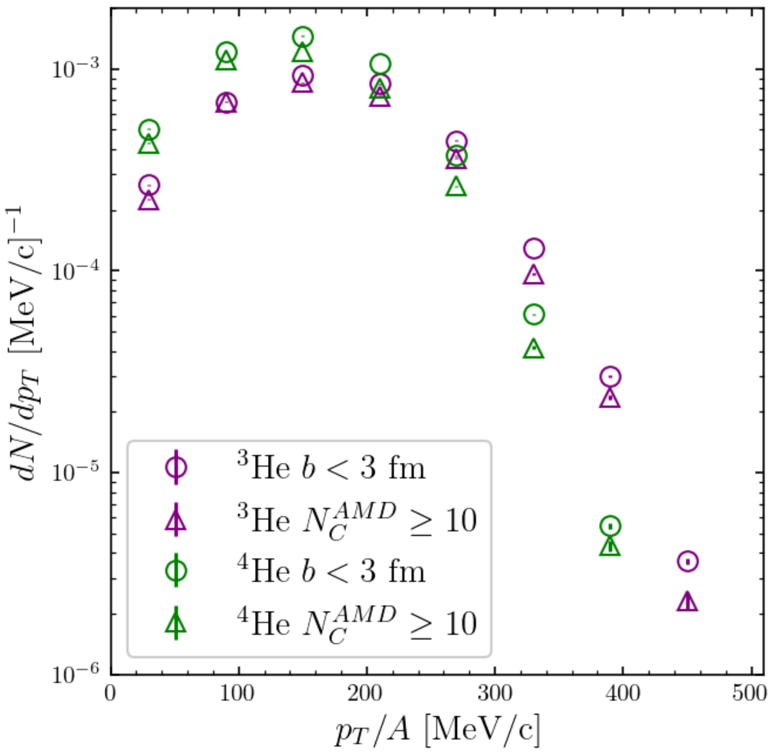
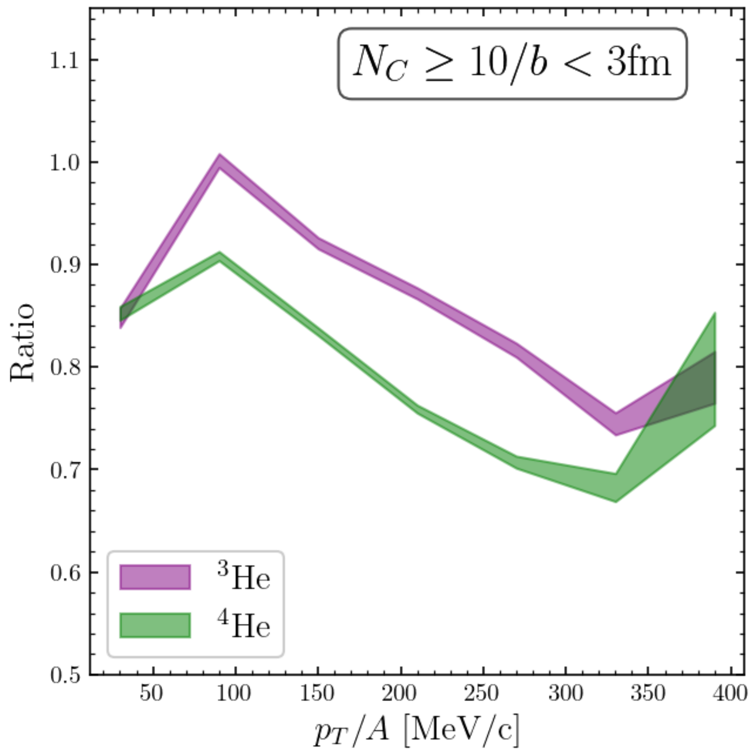
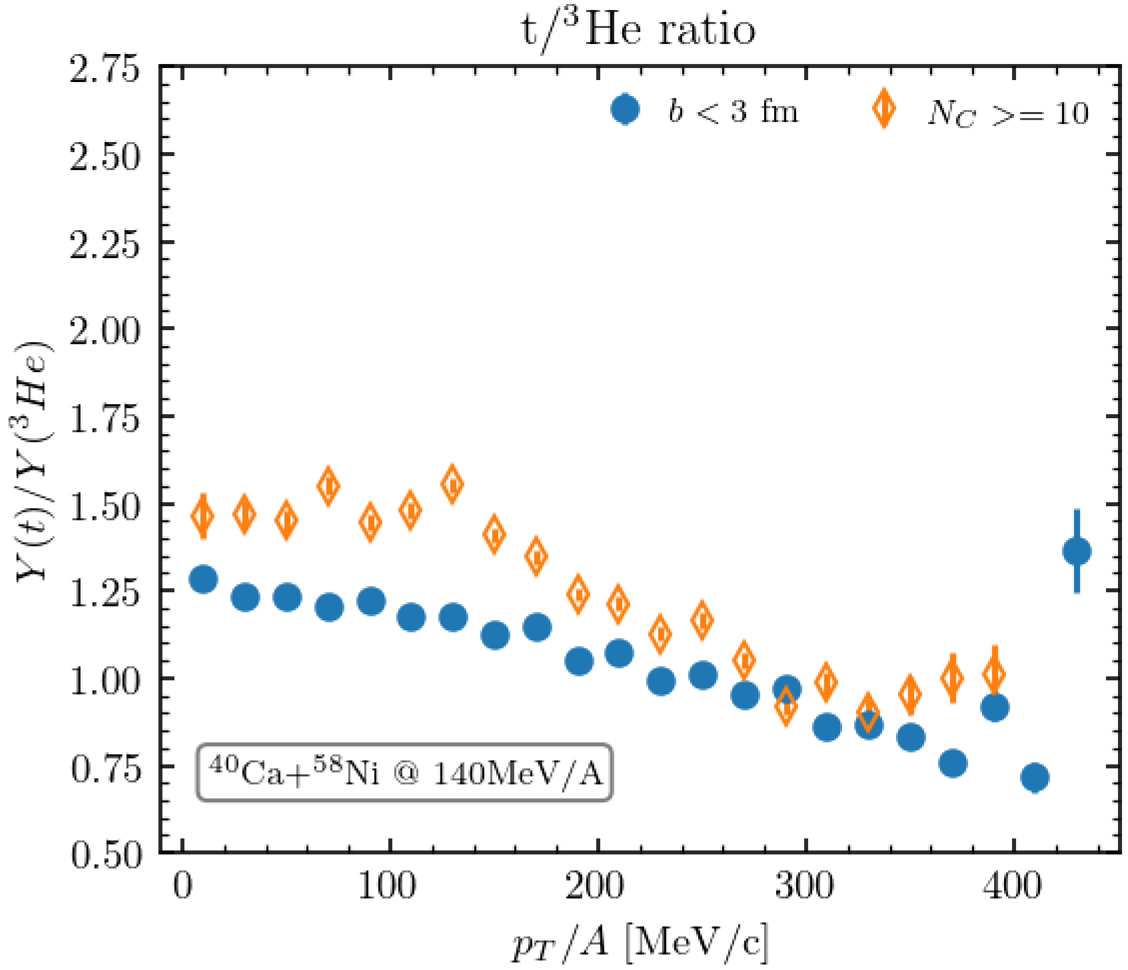
$^{48}Ca + 64Ni$ @$140MeV/A$

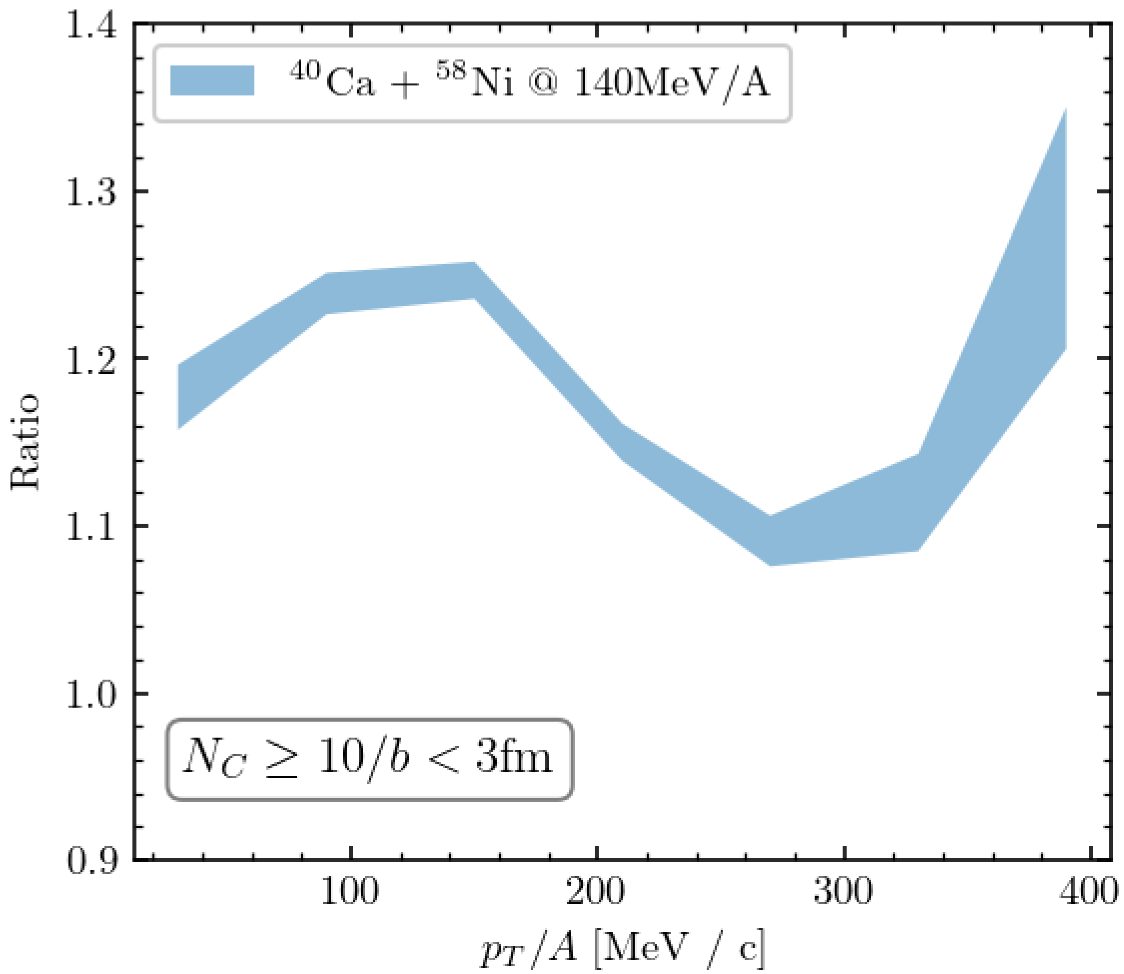




- Opposite trend in Helium spectra
- Spectra with $N_C \geq 10$ is larger at high p_T

Effect of centrality cut in AMD : $t\ /\ 3He$ ratio

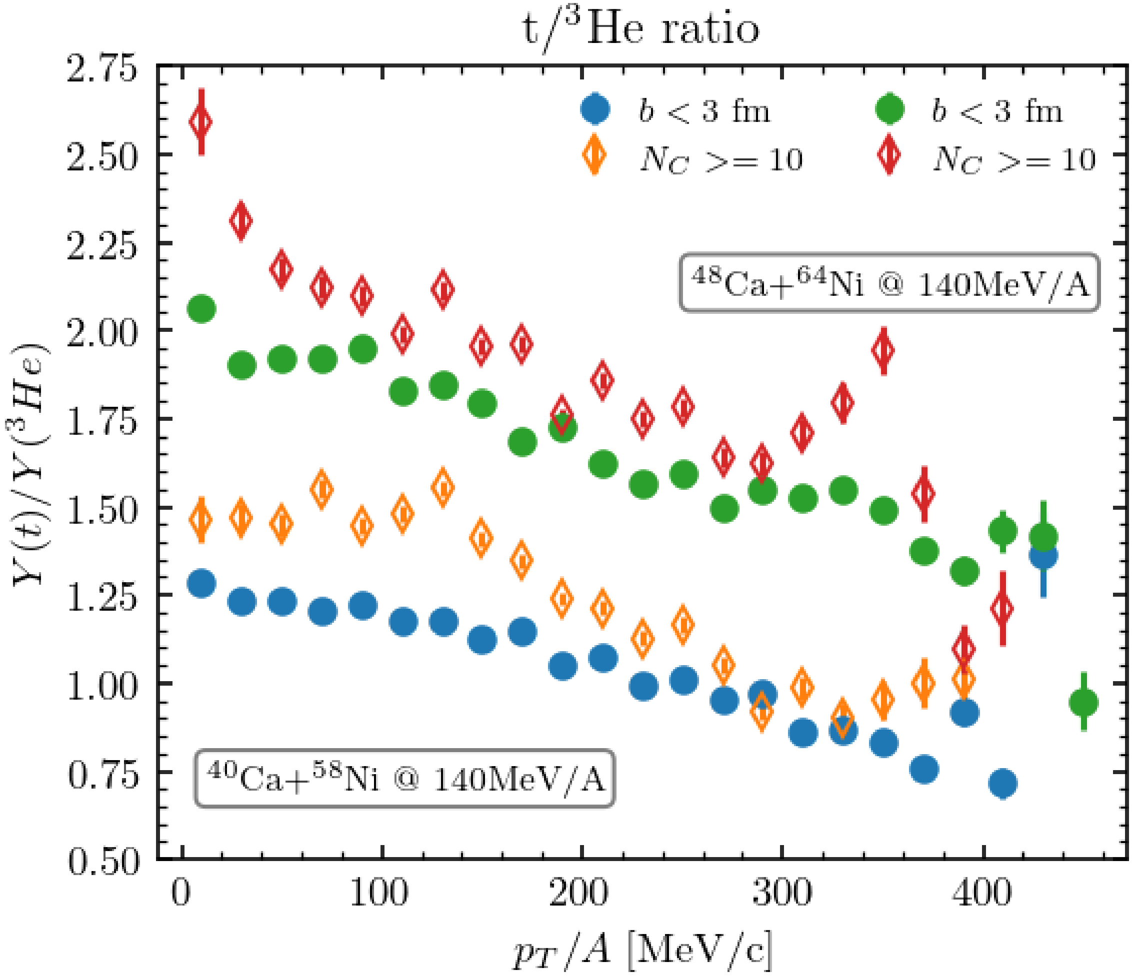


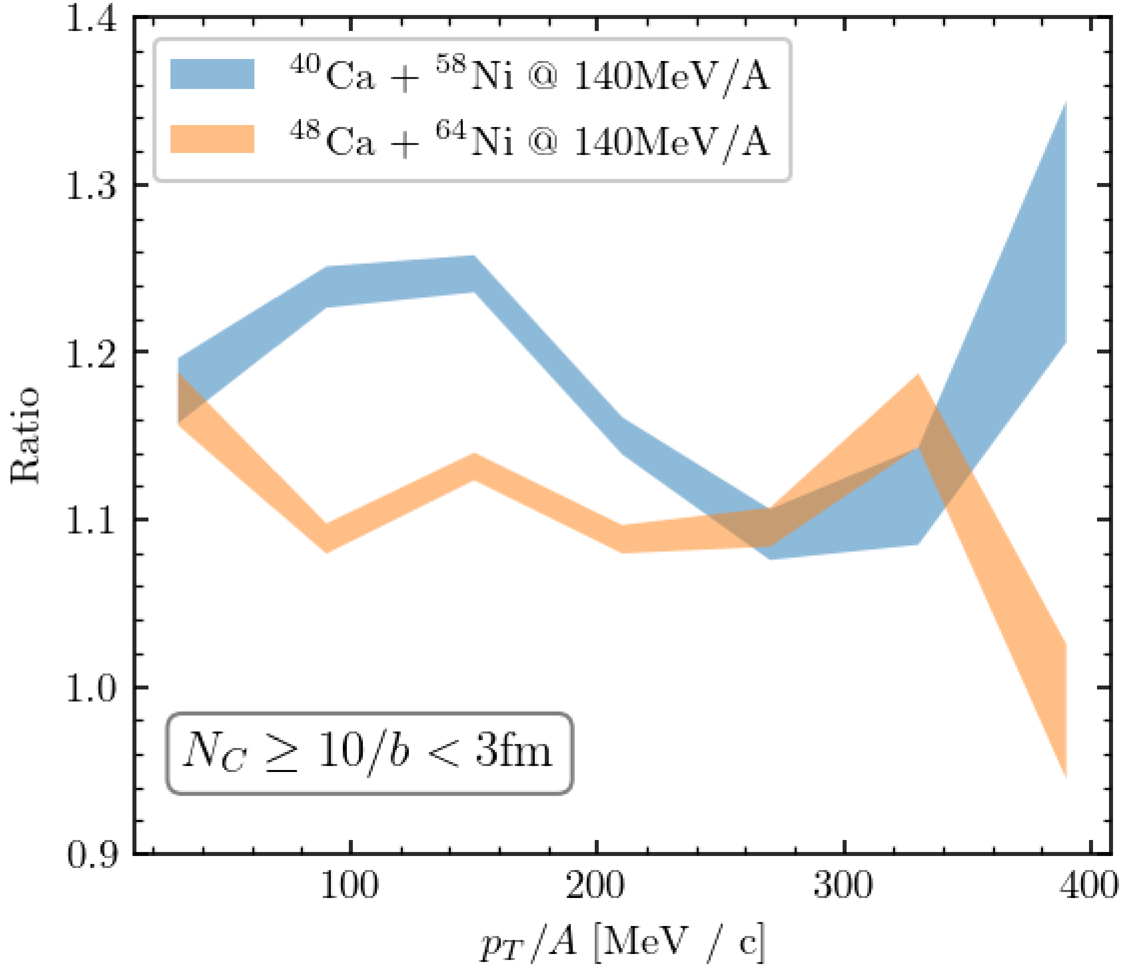


Diamonds : $b < 3$fm
Circles : $N_C \geq 10$

- About 20 % difference in proton-rich reaction

Effect of centrality cut in AMD $t\ /\ 3He$ ratio

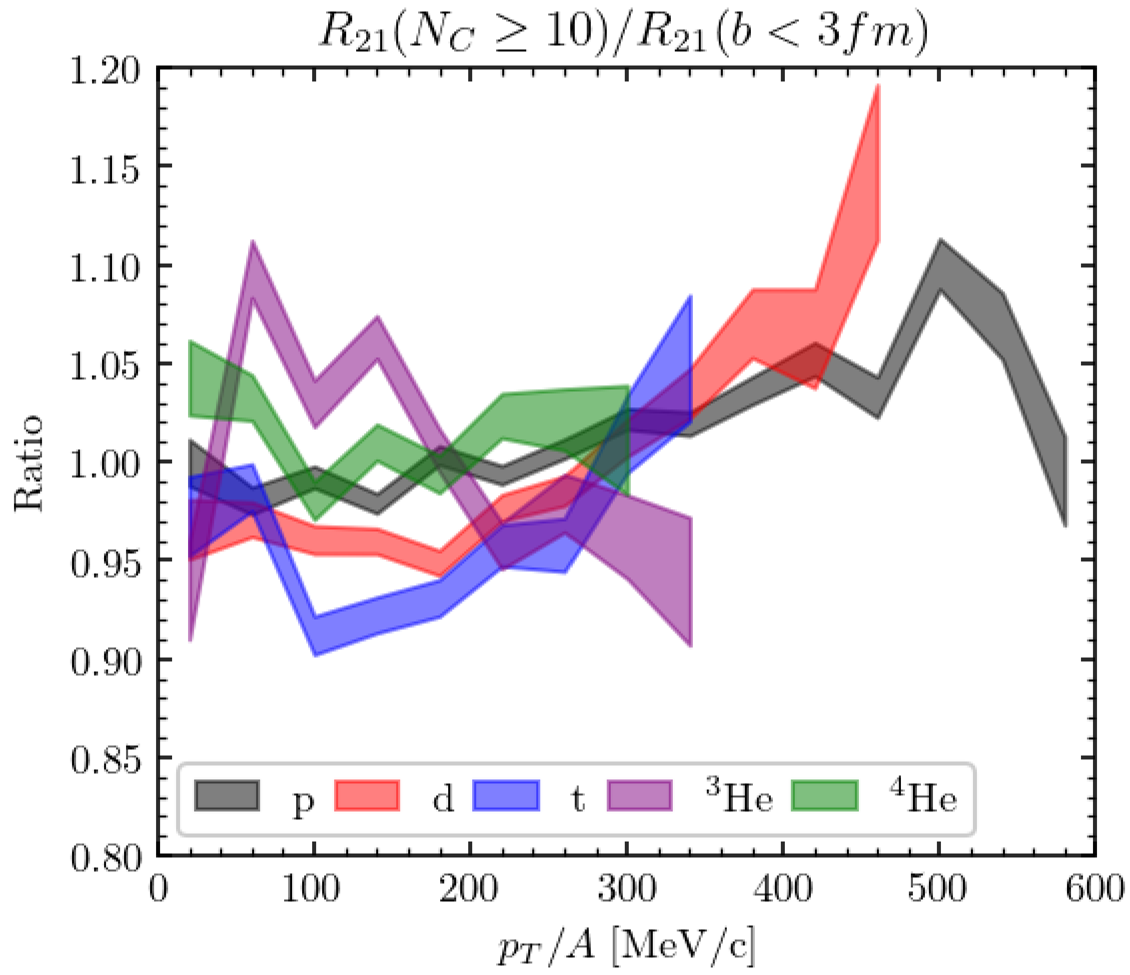




Diamonds : $b < 3\text{fm}$
Circles : $N_C \geq 10$

- About 20 % difference in proton-rich reaction
- About 12 % difference in proton-rich reaction

Effect of centrality cut in AMD : R_{21}

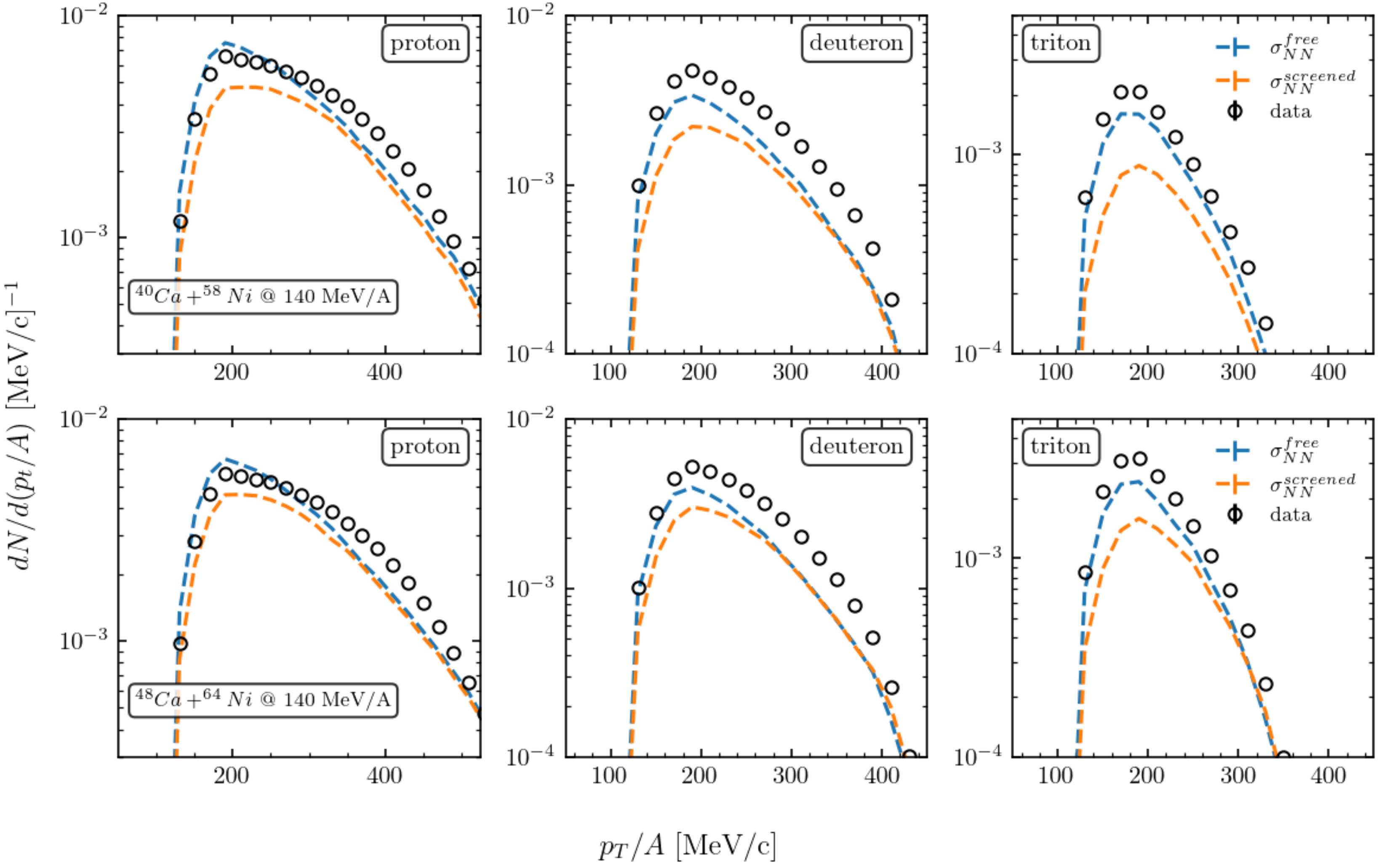


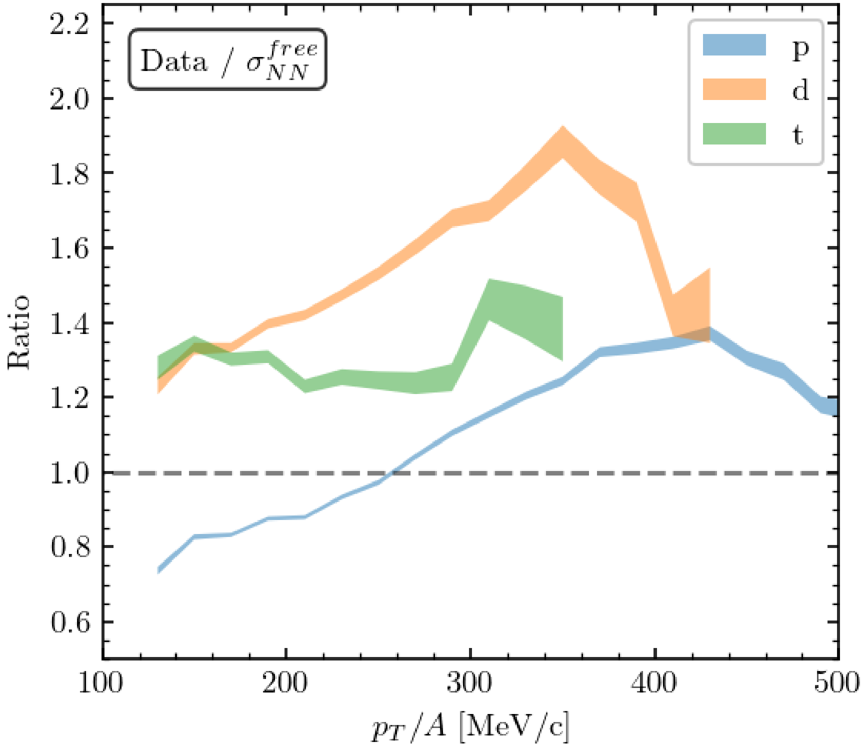
Diamonds : $b < 3$fm
Circles : $N_C \geq 10$

- Effect of different centrality cuts roughly cancels out in R_{21}
- The effect is also roughly cancels out in double ratio (not shown)
- Ready to compare AMD to experimental data

Compare to experimental data

E_{thres} , punch-thr, $\theta_{lab} = (30°, 75°)$
y_{lab} / y_{beam}= (0.4,0.6)



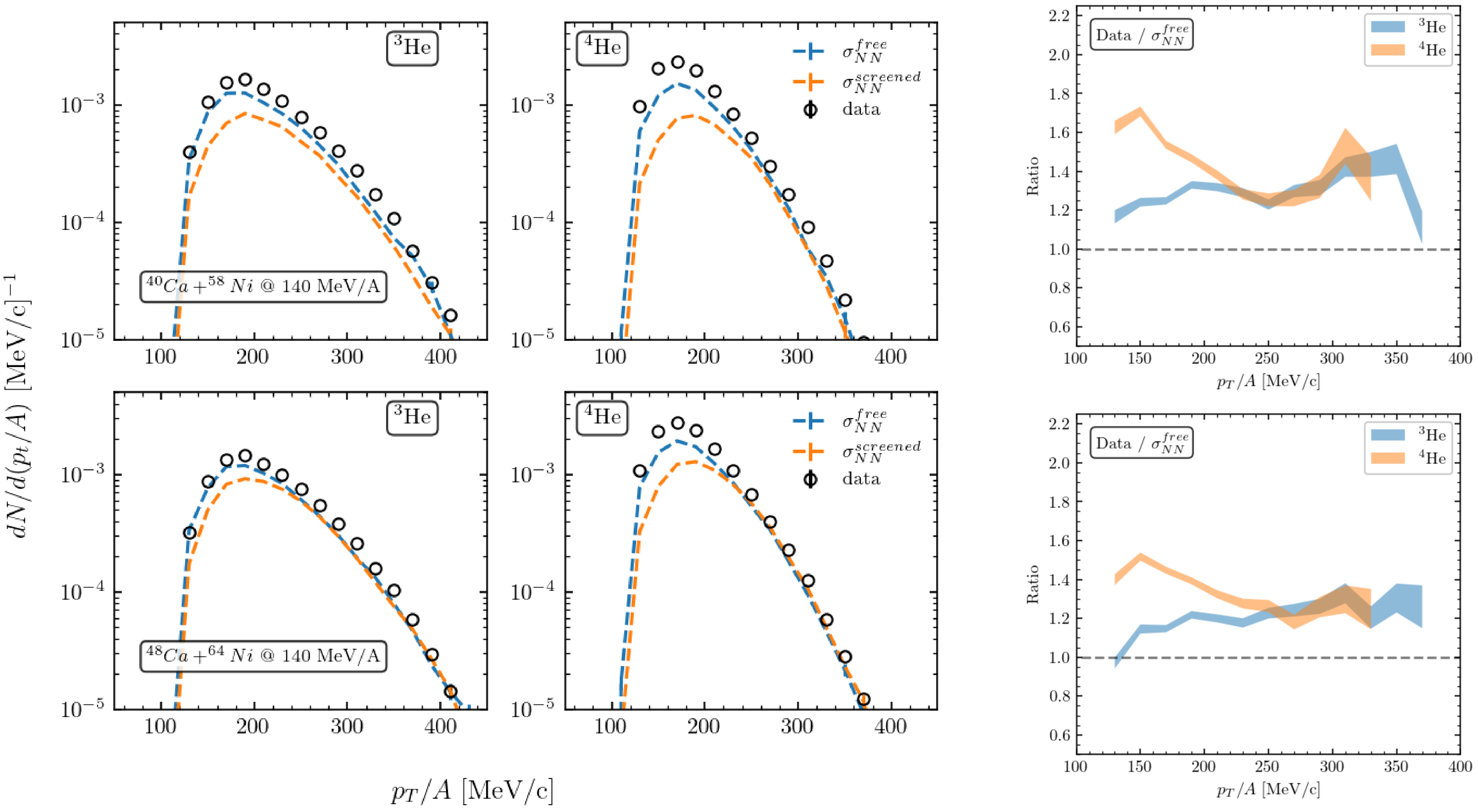


Integrated counts in y_{lab} / y_{beam} > 0 is closer to data using σ_{NN}^{free}

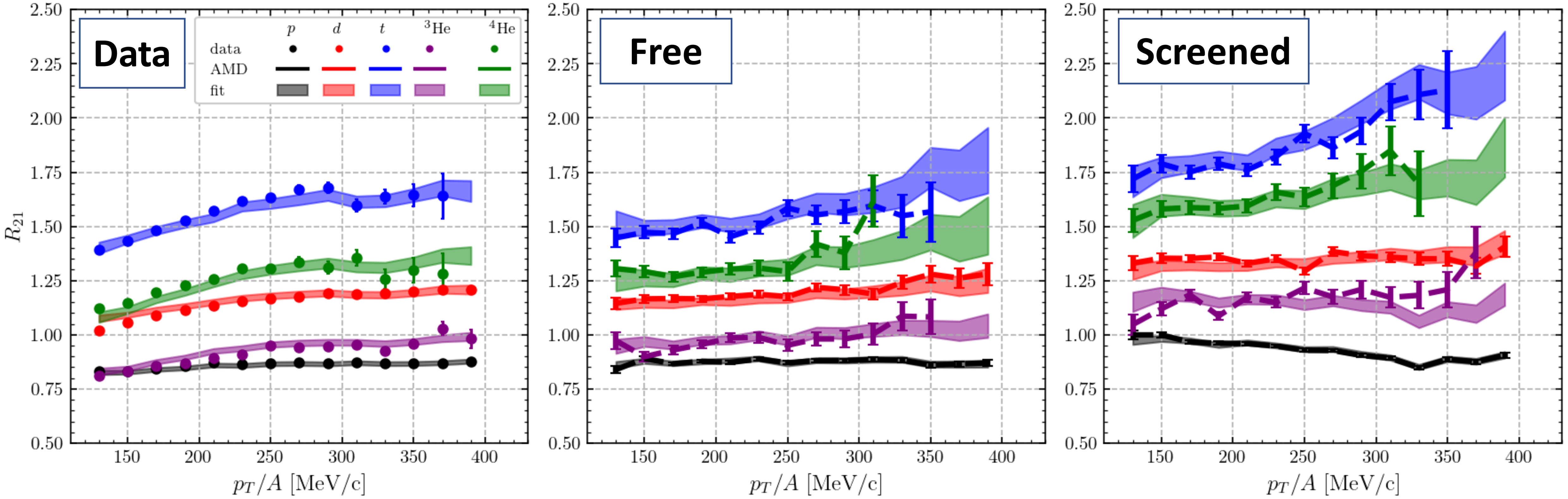
- Calculation with σ_{NN}^{free} agrees better with experimental p_T spectra
- Use of increased σ_{NN} in recent experiment Sn + Sn @ 270MeV/A

Physics Letters B 822 (2021) 136681
J.W. Lee Eur. Phys. J. A 58 201 (2022)

Similar trend in Helium p_T spectra



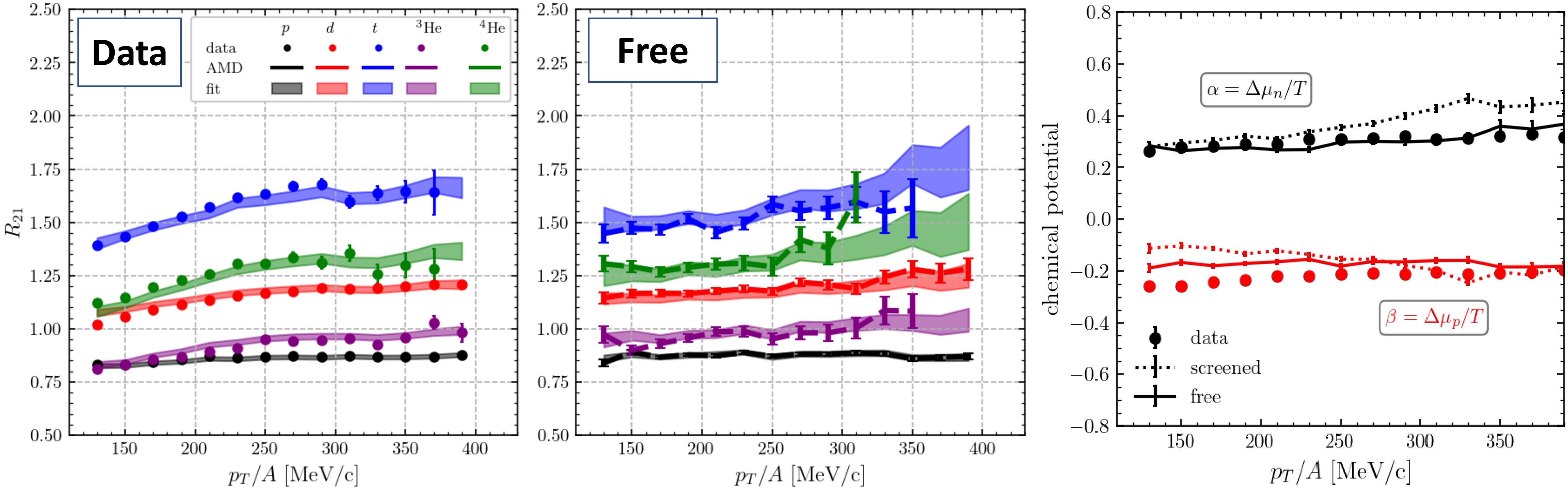
Effect of σ_{NN} on isoscaling $R_{21} = C \cdot \exp(\alpha N + \beta Z)$



- Iso-scaling is observed in AMD with both σ_{NN}^{free} and $\sigma_{NN}^{screened}$

Points : Data
Dotted Lines : AMD
Shades : fit to isoscaling law

Effect of σ_{NN} on isoscaling $R_{21} = C \cdot \exp(\alpha N + \beta Z)$



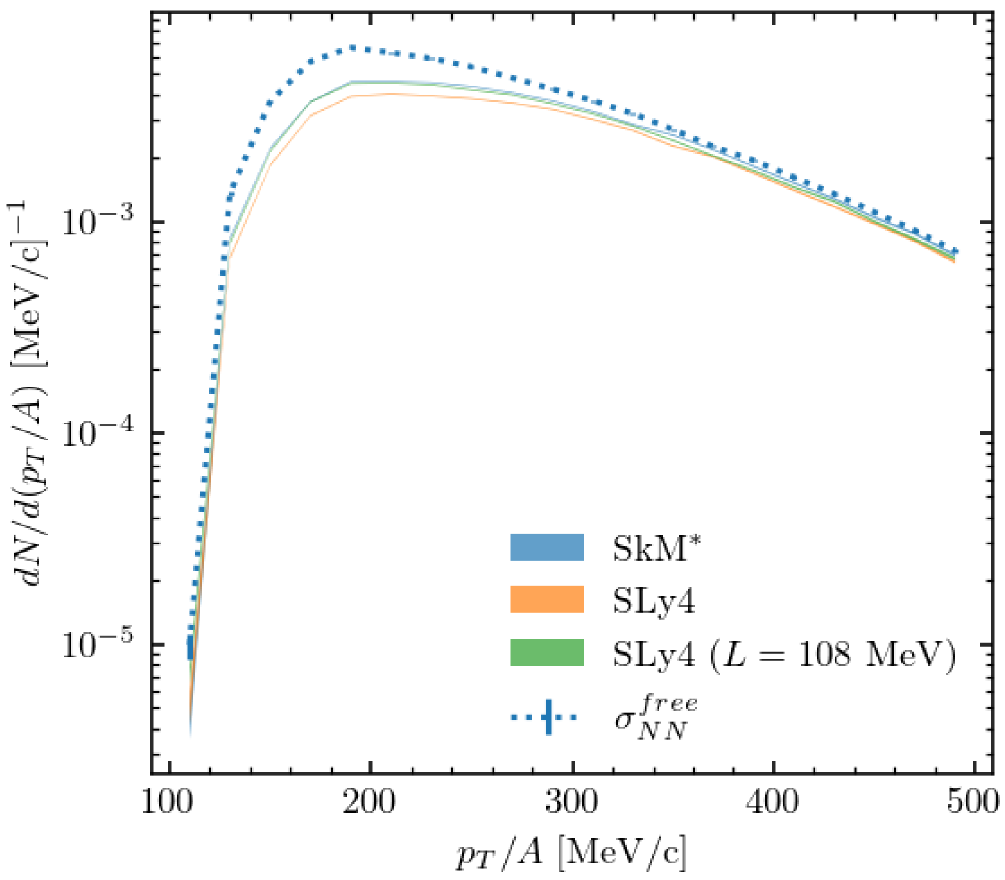
Points : Data
Dotted Lines : AMD
Shades : fit to isoscaling law

- Iso-scaling is observed in AMD with both σ_{NN}^{free} and $\sigma_{NN}^{screened}$
- reduced σ_{NN}: R_{21}(^{3}He) is significantly larger than 1.
- free σ_{NN}: R_{21}(p, ^{3}He) are below 1 which implies p-rich reaction produces more protons, ^{3}He, as it should be.
- extracted chemical potential are in better agreement

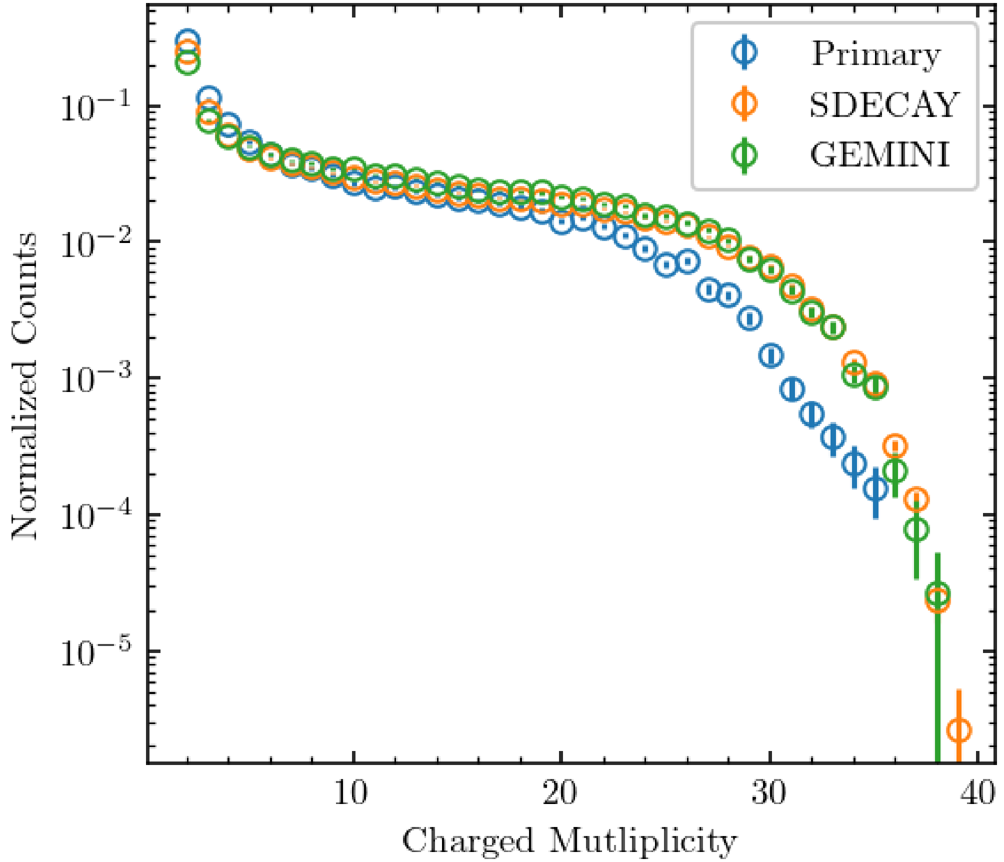
Summary and outlook

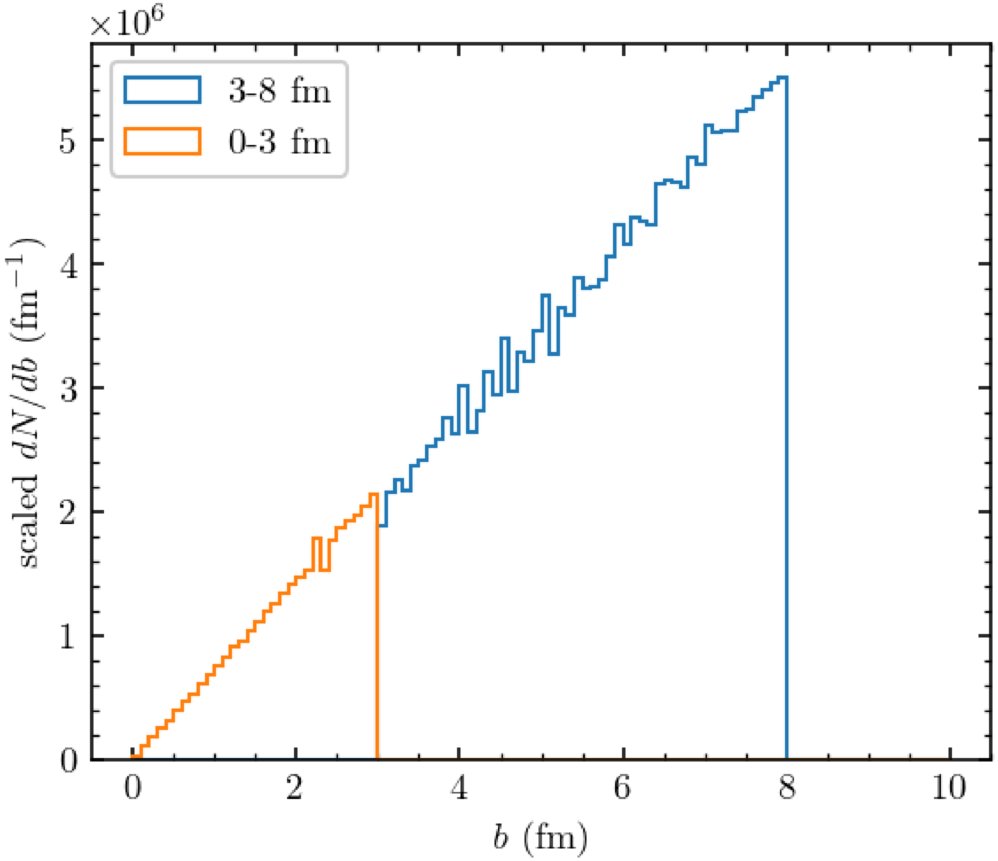
- To correctly compare model to data, events should be selected in the same way as in experiment.
- Simple cut on b affects single ratios in the same reaction but not much in R_{21} or double ratio.
- Isoscaling observed in AMD with both σ_{NN}^{free} and $\sigma_{NN}^{screened}$
- p_T spectra and R_{21} calculated in AMD with free σ_{NN} are in a better agreement with experimental data at E_{beam}= 140 MeV/A compared to using reduced σ_{NN}.

Backup : effect of σ_{NN} over skyrme : proton spectra

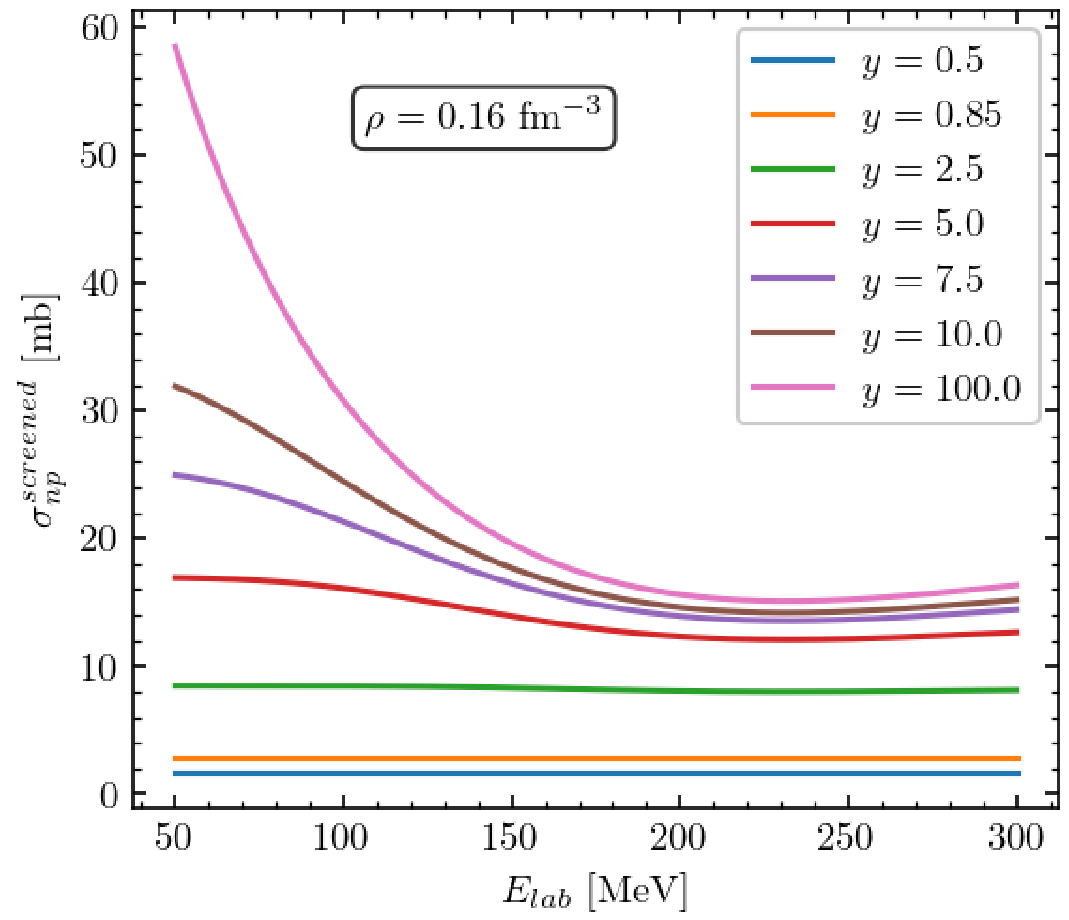


Backup : AMD Detail

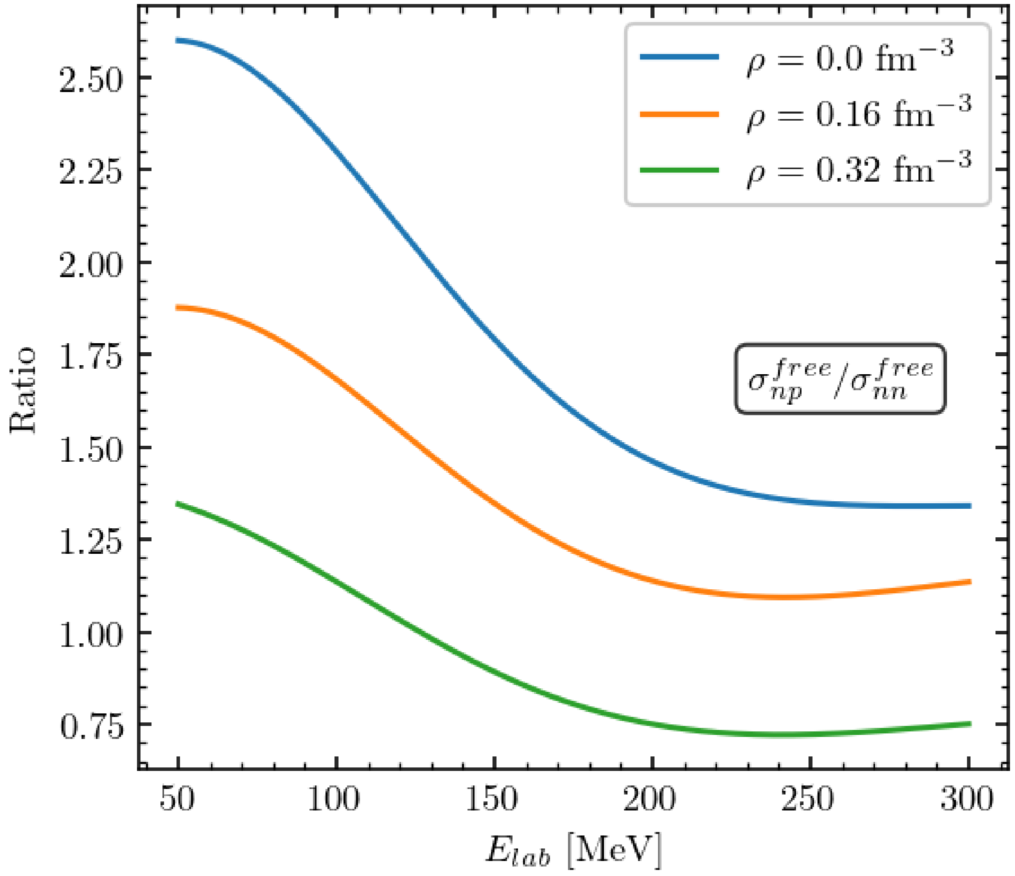




Backup : screening effect with different y

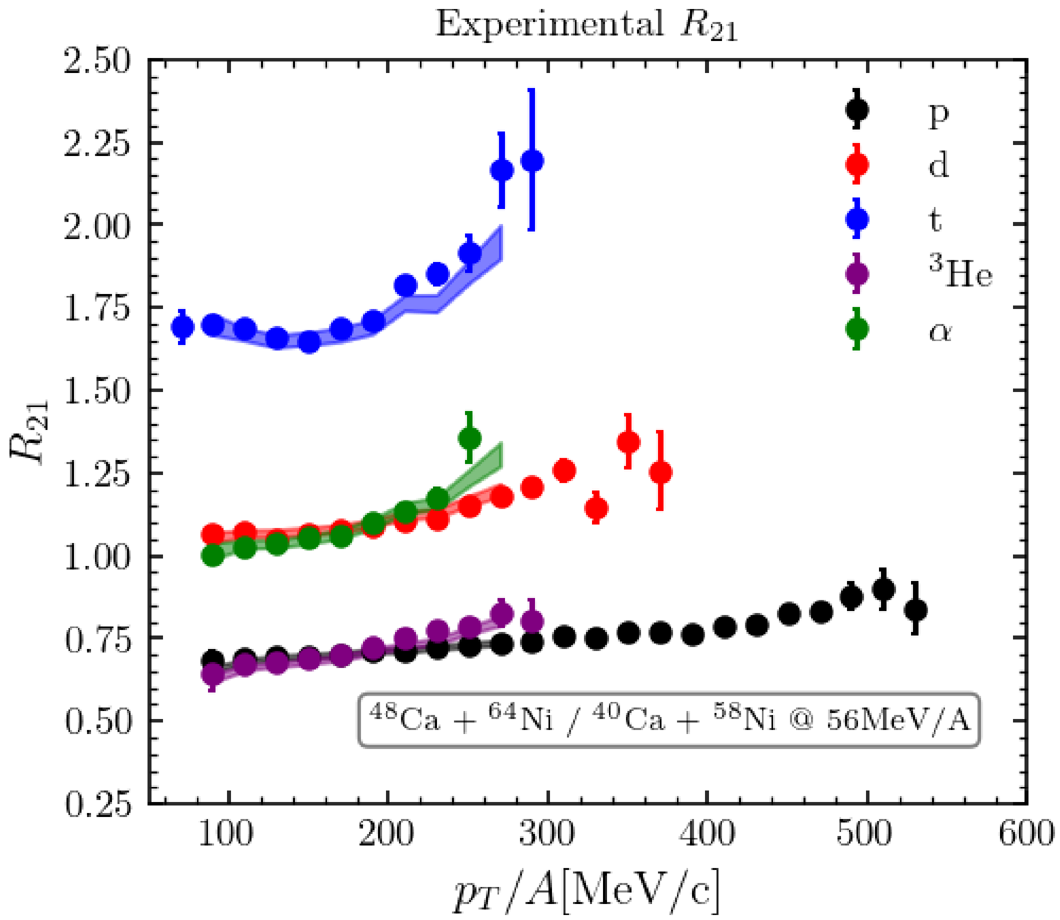


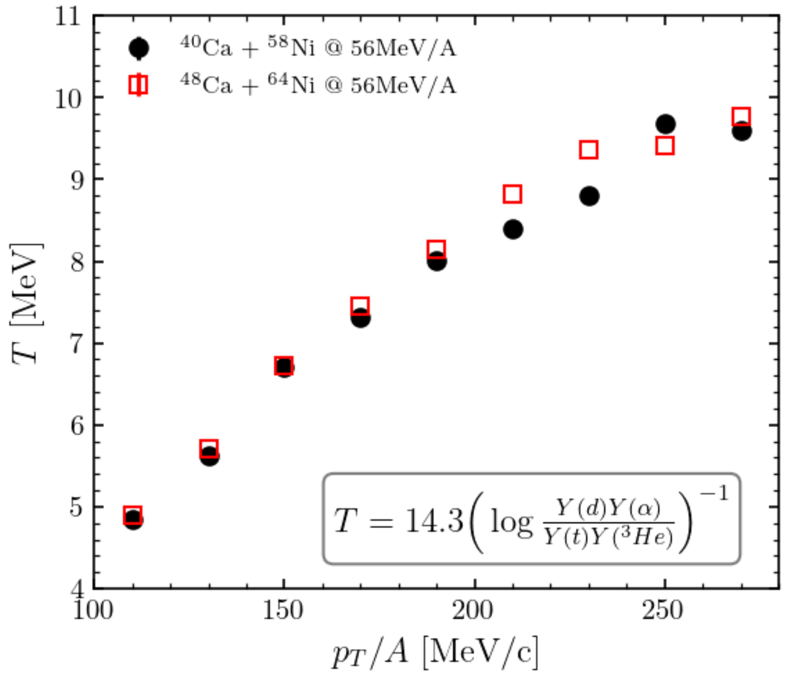
Backup : free $\sigma_{np} > \sigma_{nn}, \sigma_{pp}$ at all densities

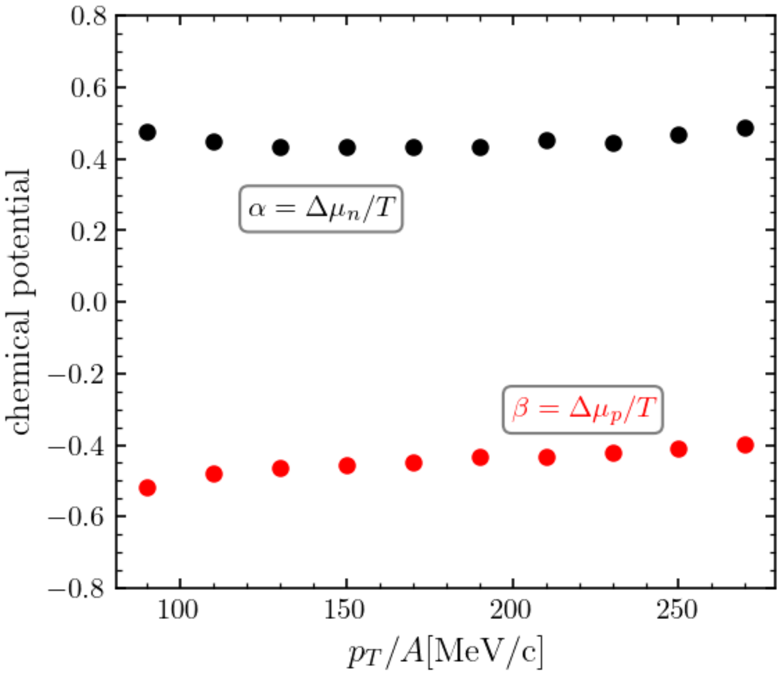


Phys. Rev. C 48, 1702 1993
Phys. Rev. C 49, 1994

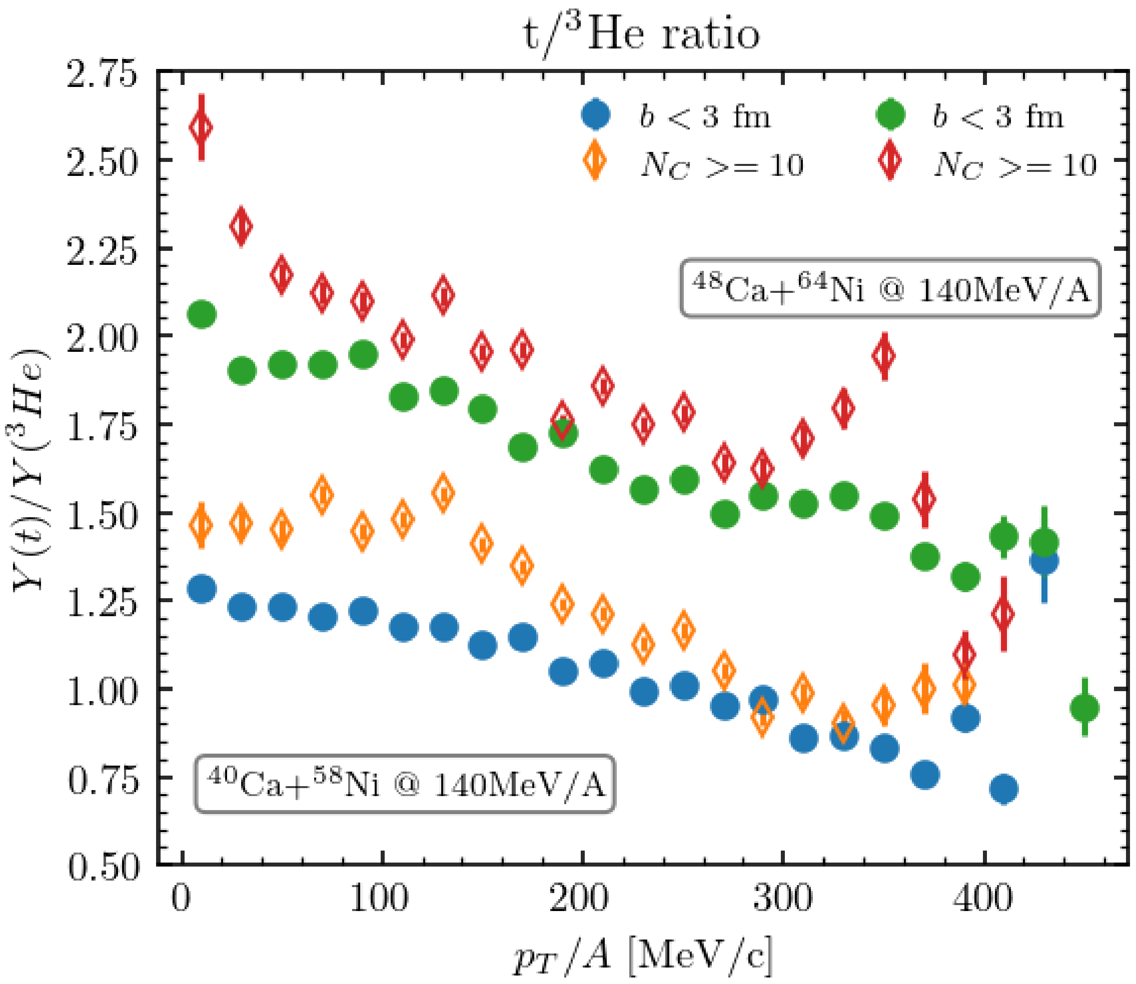
Back up : experimental result for 56 MeV/A

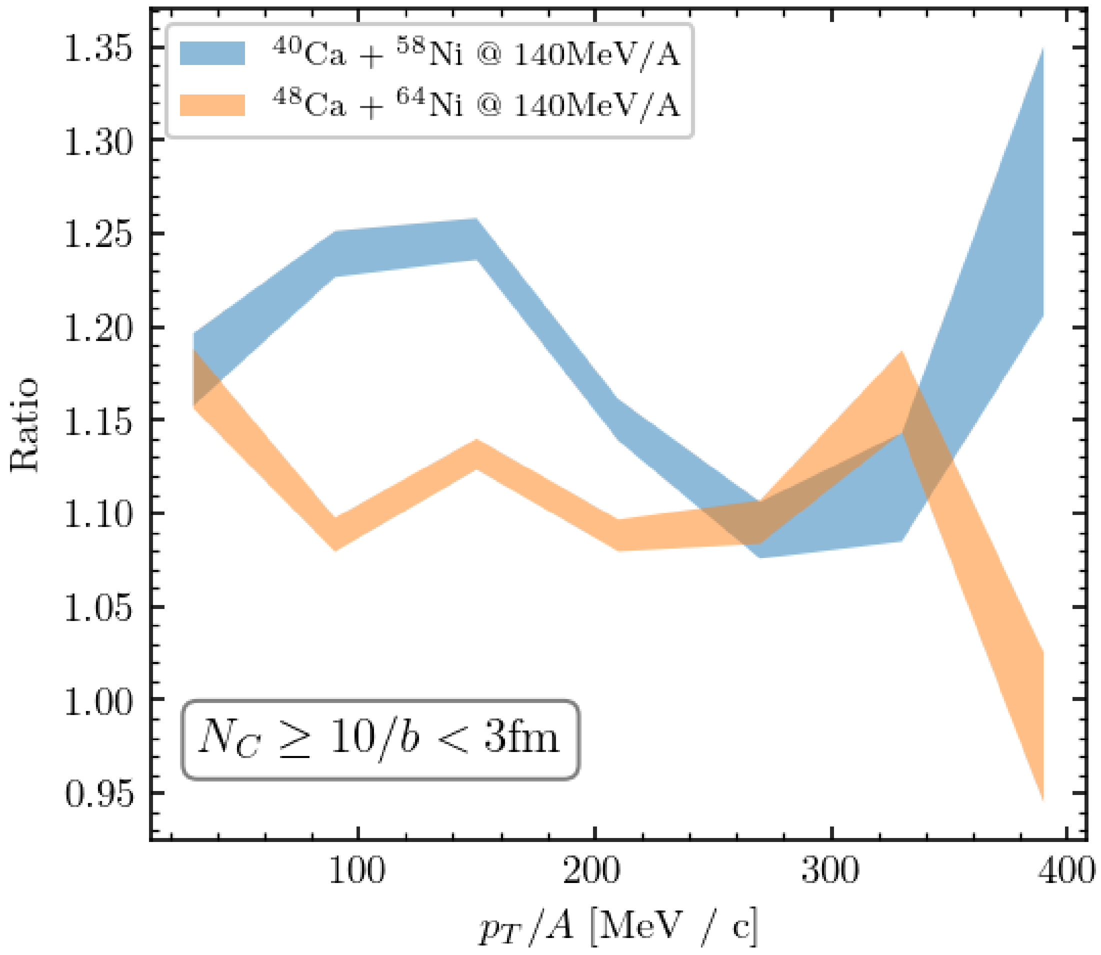




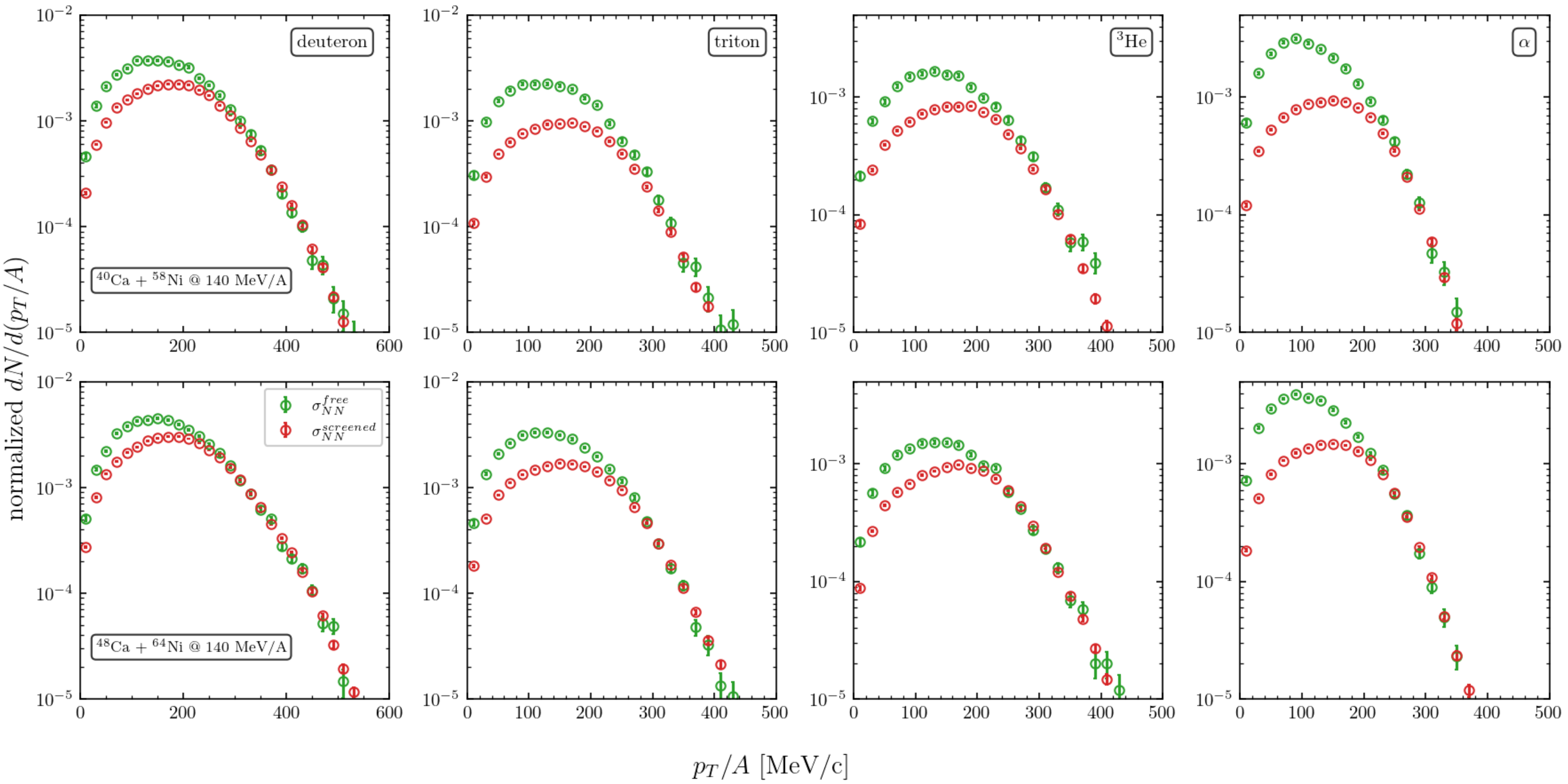


Backup :Effect of centrality cut on $Y(t)\ /\ Y(3He)$

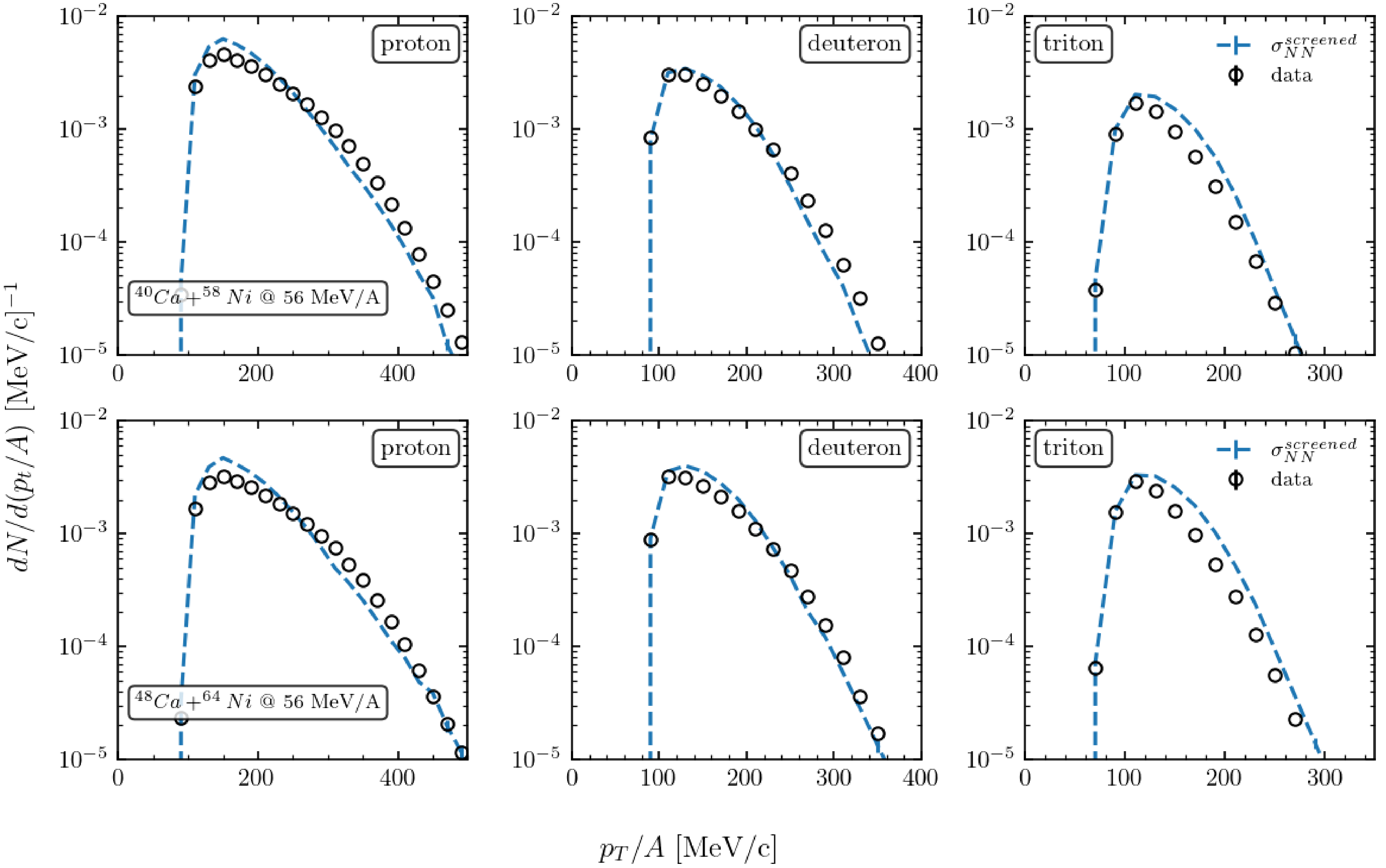




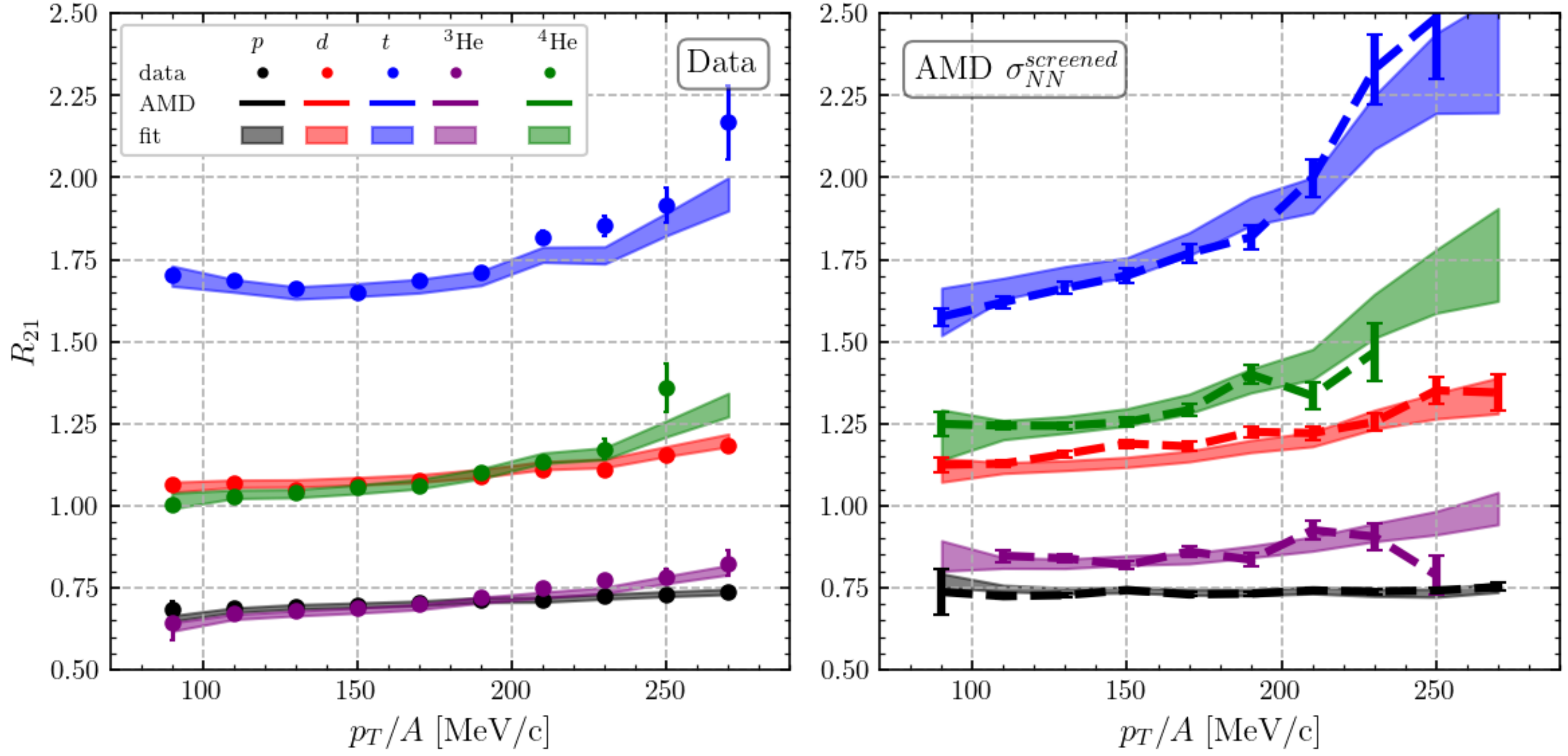
Backup : effect of σ_{NN} on spectra of d in d, t, ^{3}He and ^{4}He

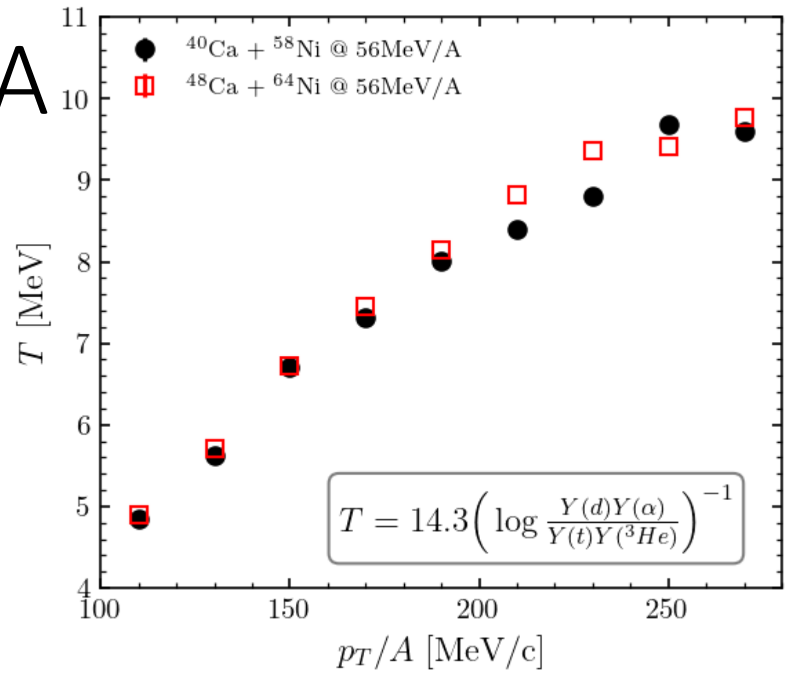


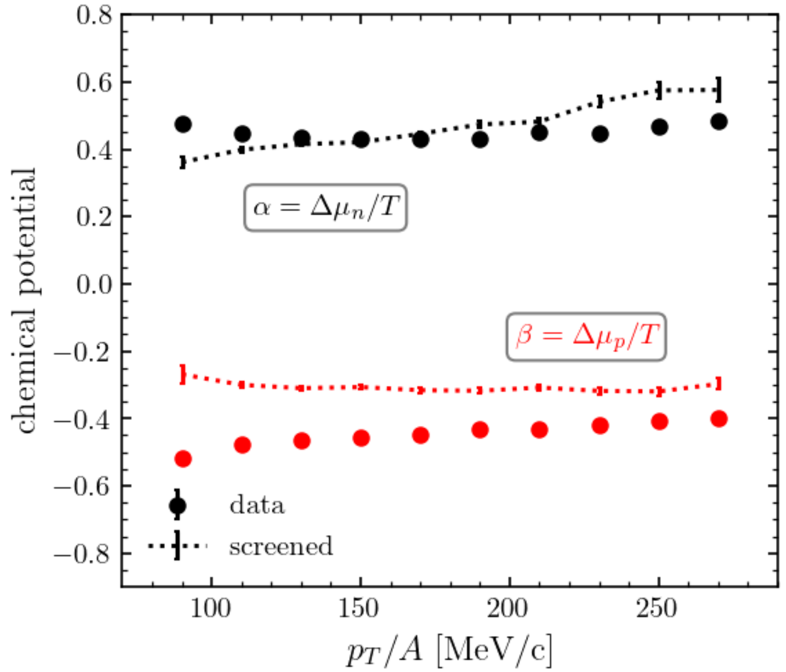
Backup : Result at E_{beam} =56 MeV/A



Backup : Isoscaling at E_{beam} =56 MeV/A







- In AMD, $R_{21}(p)$ and $R_{21}(^3He)$ are more separated, suggesting larger difference in magnitude between α and β
- As opposed to 140MeV/A systems, Reduced σ_{NN} reproduces R_{21} better than that at 56 MeV/A.