Color transparency and hadron formation effects in high-energy reactions on nuclei

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Plan:

- Introduction: the phenomenon of color transparency (CT), experimental searches for CT.
- Pionic Drell-Yan process $A(\pi^-, l^+l^-)$ at large $M_{l^+l^-}$.
- Large-angle photoproduction $A(\gamma, \pi^- p)$.
- Slow neutron production in high-energy virtual-photon-nucleus reactions.
- Hadron formation effects in pA and AA collisions.
- Reactions on deuteron
- Conclusions

Hard processes (e.g. exclusive meson electroproduction): $Q^2 \gg 1 \text{ GeV}^2$

- Quark-gluon d.o.f.
- Point-like $q\bar{q}$ and qqq configurations (PLCs): $r_\perp \sim 1/Q$

Color dipole – proton cross section in the pQCD limit $(r_\perp \to 0)$ $\sigma_{q\bar{q}} \propto r_\perp^2 \sim 1/Q^2$

Color transparency (CT): the quark configuration produced in high momentum transfer exclusive process interacts with nucleons with reduced cross section.

CT is a necessary condition for the factorization in exclusive hard processes.

Factorization is only possible when the multiple soft gluon exchanges before and after hard scattering are suppressed. This suppression may only take place if PLCs are formed in the hard scattering (similar to the EM interactions of a dipole).
In the case of nuclear target this leads to CT.

For most recent review of CT see
D. Dutta, K. Hafidi, M. Strikman, Prog. Part. Nucl. Phys. 69, 1 (2013)

CT at high energies:

500 GeV pion coherent diffractive dissociation on C and Pt targets into di-jets with high transverse momenta $(k_t \gtrsim 1 \text{ GeV})$ at Fermilab
E.M. Aitala et al., PRL 86, 4773 (2001)

CT concluded from $\sigma = \sigma_0 A^\alpha$, $\alpha = 1.6$ at high k_t. Far away from $\alpha = 2/3$ expected for incoherent diffraction in Glauber approximation.

Predicted theoretically: L. Frankfurt, G. Miller, M. Strikman, PLB 304, 1 (1993).

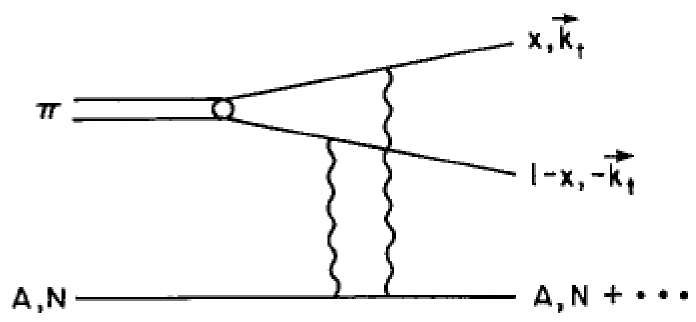


Fig. 1. Illustrative diagram for hard diffractive production of jets; other indicated only by +.... The longitudinal momentum of the quark is xP_π.

Figure taken from L. Frankfurt, G. Miller, M. Strikman, PLB 304, 1 (1993)

CT at intermediate energies (~ 10 GeV):

Coherence length

- transversely squeezed qqq or $q\bar{q}$ PLC can be decomposed into hadronic basis:

$$|\Psi_{PLC}(t)>=\sum_{i=1}^{+\infty} a_i e^{-iE_i t}|\Psi_i>= e^{-iE_1 t}\sum_{i=1}^{+\infty} a_i e^{i(E_1-E_i)t}|\Psi_i>, \quad E_i=\sqrt{p^2+m_i^2}$$

- the configuration expands to the normal hadronic size on the space (or time) scale of the coherence loss between the lowest and first radially-excited state:

$$l_h \sim t_{\rm coh} = \frac{1}{\sqrt{m_2^2+p^2}-\sqrt{m_1^2+p^2}} \simeq \frac{2p}{m_2^2-m_1^2} \equiv \frac{2p}{\Delta M^2}\ , \quad p \gg m_1, m_2$$

Estimates:

Nucleon: $\Delta M^2 \simeq m^2_{N^*(1440)} - m^2_N \simeq 1.2\ {\rm GeV}^2$

Pion: $\Delta M^2 \simeq m^2_{\pi(1300)} - m^2_\pi \simeq 1.7\ {\rm GeV}^2$

Empirical values from nuclear transparency studies at TJNAF :

$$\Delta M^2 \simeq 0.7 - 1.1\ {\rm GeV}^2$$

$$l_h = 0.4 - 0.6\ {\rm fm}\frac{p}{\rm GeV}\ .$$

Pion electroproduction at JLab: $A(e,e'\pi^+)$

Data: **B. Clasie et al., PRL 99, 242502 (2007)**

Theoretical analyses: ***A. Larson, G. Miller, M. Strikman, PRC 74, 018201 (2006);***
W. Cosyn, M.C. Martinez, J. Ryckebusch, PRC 77, 034602 (2008);
M. Kaskulov, K. Gallmeister, U.Mosel, PRC 79, 015207 (2009)

- Clear indications of the enhanced nuclear transparency due to CT at Q^2 = 1-5 GeV^2.

ρ^0 electroproduction at JLab: $A(e,e'\rho^0)$

Data: **L. El Fassi et al., PLB 712, 326 (2012)**

- Q^2 dependence of nuclear transparency for Q^2=0.8-2.4 GeV^2 indicates CT.

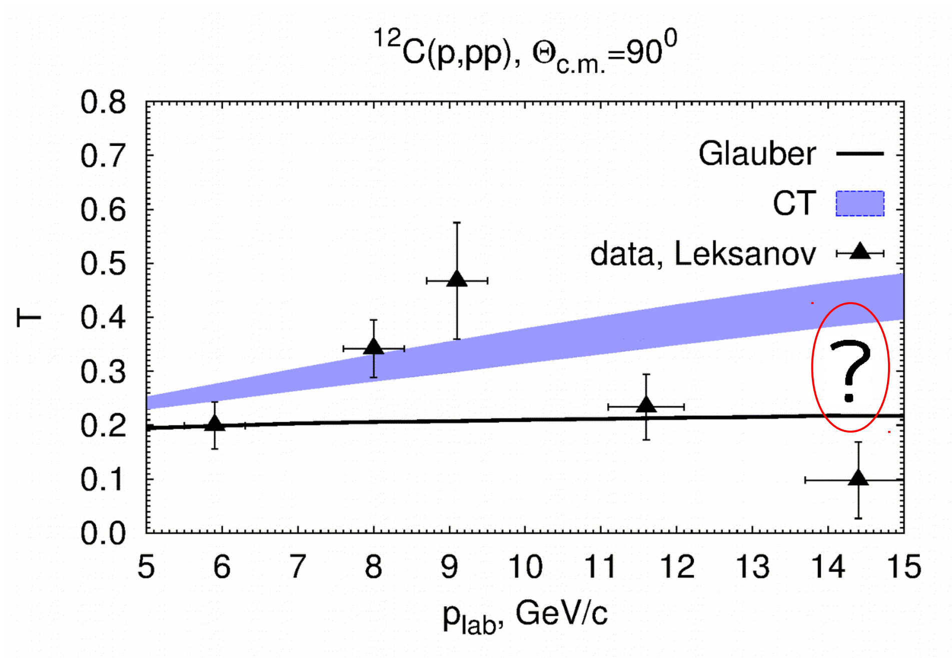
However, CT has not been observed so far for the $A(e,e'p)$ process at SLAC and JLab.
(Squeezing proton probably needs larger Q^2 values than for pion.)

CT has been predicted for the binary semi-exclusive processes with large momentum transfer

$$h + A \to h + p + (A-1)^*$$

S.J. Brodsky, 1982; A.H. Mueller, 1982

Nuclear transparency: $T = \frac{d\sigma/dt}{Z d\sigma_{pp}/dt}$



Data: EVA@AGS,
A. Leksanov et al.,
PRL 87, 212301 (2001).

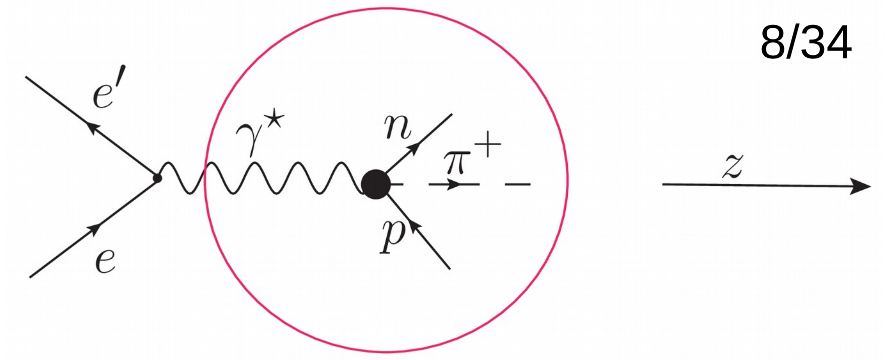
Decrease of T at high p_{lab} is not understood:

- could be due to stronger absorption of the large-size quark configurations produced by Landshoff mechanism, J.P. Ralston, B. Pire, PRL 61, 1823 (1988);
- or due to intermediate (very broad, Γ~ 1 GeV) 6q$c\bar{c}$ resonance formation with mass ~ 5 GeV, S.J. Brodsky, G.F. de Teramond, PRL 60, 1924 (1988).

Pion electroproduction at JLab:

$$A(e,e'\pi^+)$$

- collinear kinematics: $\mathbf{p}_\pi \parallel \mathbf{q} = \mathbf{p}_e - \mathbf{p}_{e'}$



Transparency:

$$T = \frac{d\sigma_{eA\to e'\pi^+}/d^3p_{e'}d\Omega_{\pi^+}}{Zd\sigma_{ep\to e'\pi^+n}/d^3p_{e'}d\Omega_{\pi^+}} = \frac{1}{Z}\int d^3r\rho_p(\mathbf{r})\,\mathrm{e}^{-\int\limits_z^\infty dz'\sigma^{\mathrm{eff}}_{\pi N}(p_\pi,z'-z)\rho(\mathbf{b},z')}$$

CT effects in a quantum diffusion model
G.R. Farrar, H. Liu, L.L. Frankfurt, M.I. Strikman, PRL 1988:

$$\sigma^{\mathrm{eff}}_{\pi N}(p_\pi,z) = \sigma_{\pi N}(p_\pi)\left(\left[\frac{z}{l_\pi} + \frac{<n^2k_t^2>}{Q^2}\left(1-\frac{z}{l_\pi}\right)\right]\Theta(l_\pi - z) + \Theta(z-l_\pi)\right)\;,\quad Q^2 = -(p_e - p'_e)^2$$

Scale of shrinkage of pion (transverse size)²

$n = 2$ **- number of valence quarks and antiquarks,**

$<k_t^2>^{1/2} \simeq 0.35\ \mathrm{GeV/c}$ **- average transverse momentum of a quark in a hadron.**

JLab data: **B. Clasie et al., PRL 99, 242502 (2007)**

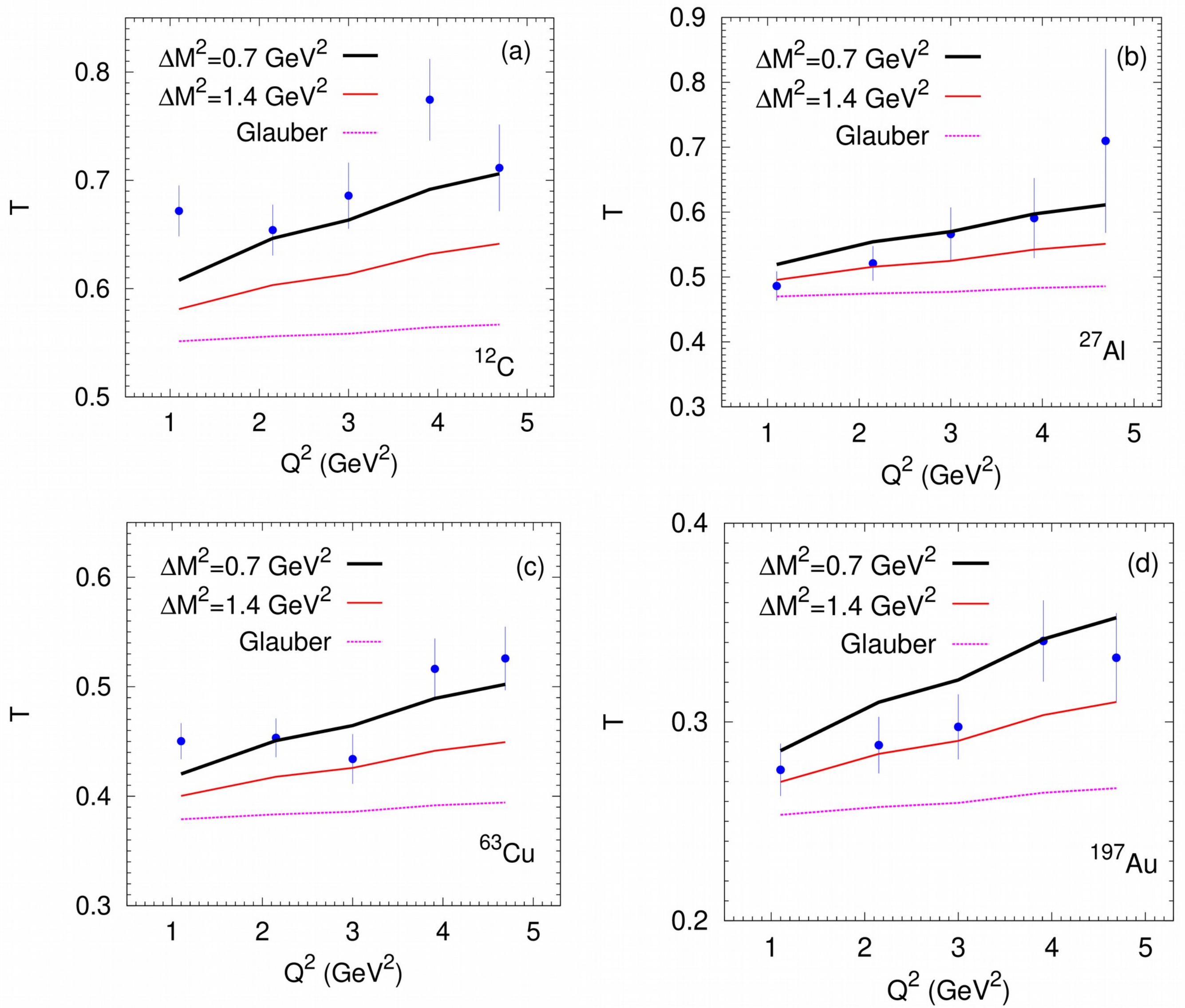
$$p_\pi = 2.8 \div 4.4 \text{ GeV/c}$$

Large coherence length:

$$l_\pi = 1.6 \div 2.5 \text{ fm}$$

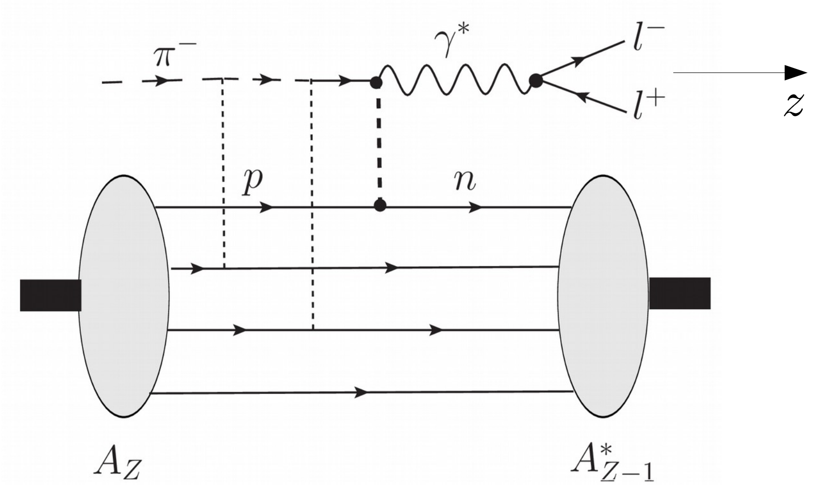
$$l_\pi \sim < r^2 >^{1/2}_{^{12}\mathrm{C}} = 2.46 \text{ fm}$$

- Significant CT effect;
- Relative effect of CT is stronger for heavy nuclei.



Glauber and quantum diffusion model calculations:
AL, M. Strikman, M. Bleicher, PRC 93, 034618 (2016)

Pionic Drell-Yan process on the nuclear target



$$T = \frac{d^4\sigma_{\pi^- A \to l^- l^+}/d^4q}{Z d^4\sigma_{\pi^- p \to l^- l^+ n}/d^4q} = \frac{1}{Z}\int d^3r e^{-\int\limits_{-\infty}^{z} dz' \sigma^{\rm eff}_{\pi N}(p_\pi, z-z')\rho(\mathbf{b},z')} \rho_p(\mathbf{r}) \ ,$$

$$q = p_{l^-} + p_{l^+} - p_\pi ,$$

$$\sigma^{\rm eff}_{\pi N}(p_\pi, z) = \sigma_{\pi N}(p_\pi)\left(\left[\frac{z}{l_\pi} + \frac{< n^2 k_t^2 >}{M^2_{l^+l^-}}\left(1 - \frac{z}{l_\pi}\right)\right]\Theta(l_\pi - z) + \Theta(z - l_\pi)\right) \ .$$

Scale of shrinkage of pion (transverse size)^2

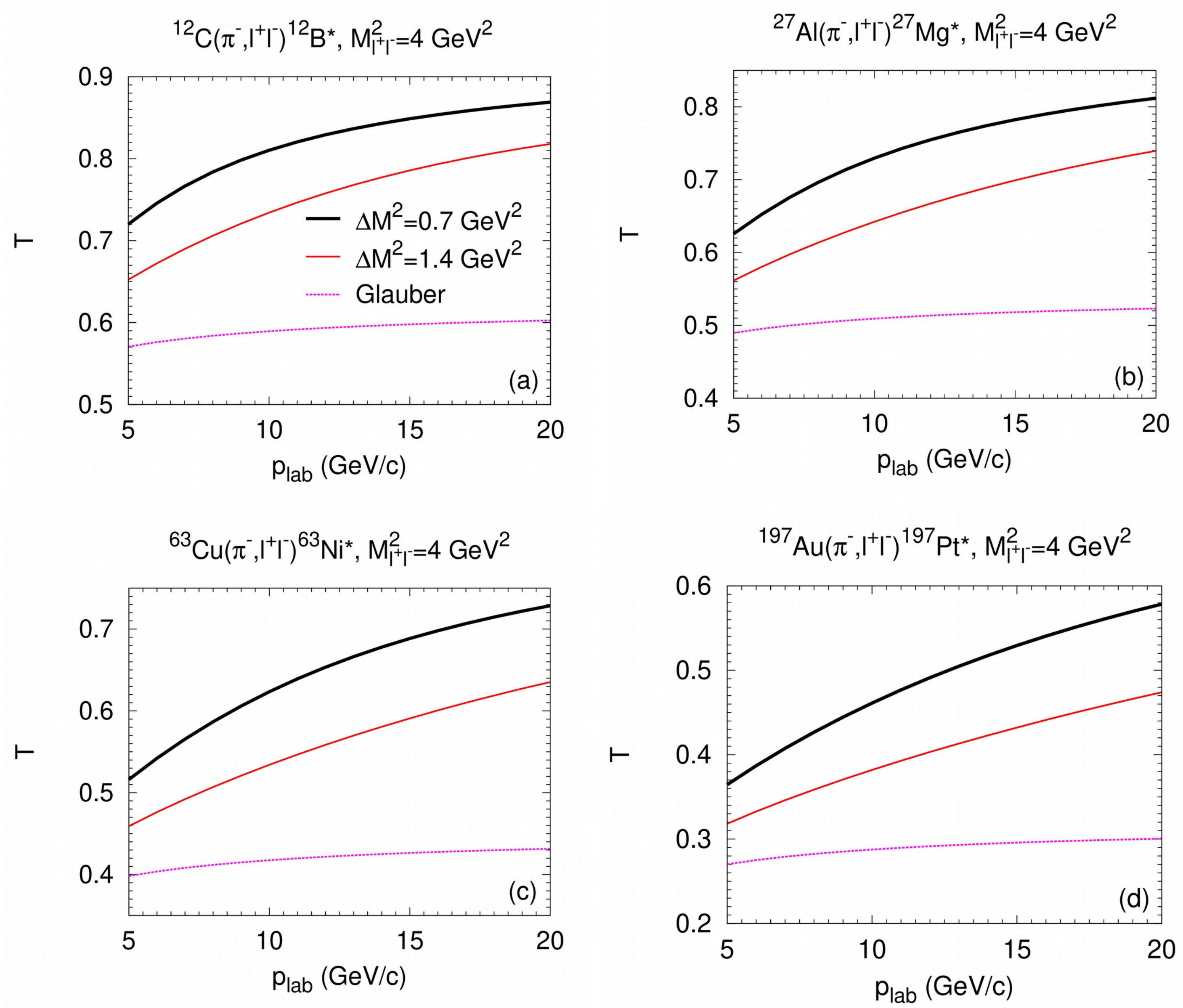
- ***T is saturated at smaller p_{lab} for light nuclei.***

- ***Possible to estimate pion coherence length,***

$$l_\pi = \frac{2p_{\rm lab}}{\Delta M^2} \ ,$$

since at saturation

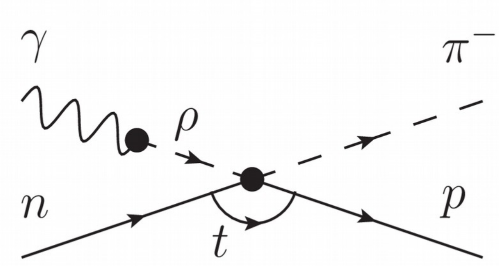
$$l_\pi \sim 2R.$$

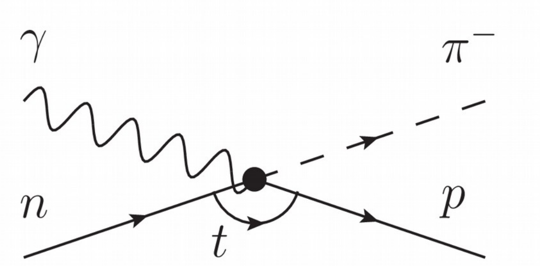


- ***Stronger relative effect of CT for heavy nuclei.***

AL, M. Strikman, M. Bleicher, PRC 93, 034618 (2016).

Photon and color transparency in large-angle A(γ,π^-p) reaction





Small |t| - resolved photon (RP), more absorption.

Large |t| - unresolved photon (UP), less absorption.

At which |t| the transition occurs ? Will this interfere with CT ?

$s \to \infty,\ t/s = \mathrm{const}$ asymptotic scaling law

S.J. Brodsky, G.R. Farrar, PRL (1973)

$$\frac{d\sigma}{dt} = \frac{f(t/s)}{s^n}\ , \quad n = \sum n_i - 2\ ,$$

n_i – the number of the constituents
$(n_B = 3, n_M = 2, n_\gamma = 1)$

$n = 7$ - UP regime

$-t \sim s/2 \sim 2\ \mathrm{GeV}^2$

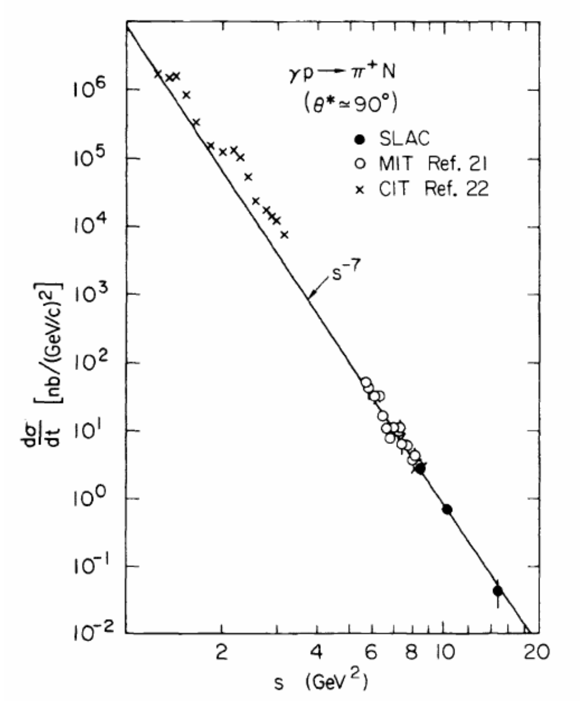


Figure from ***R.L. Anderson et al. (SLAC), PRD 14, 679 (1976)***

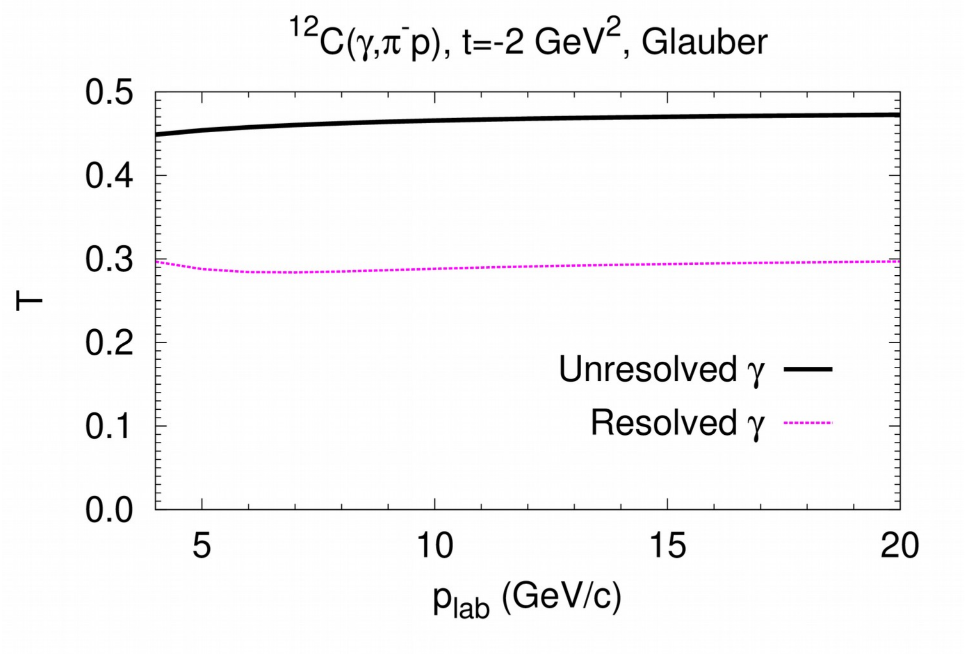
Nuclear transparency:

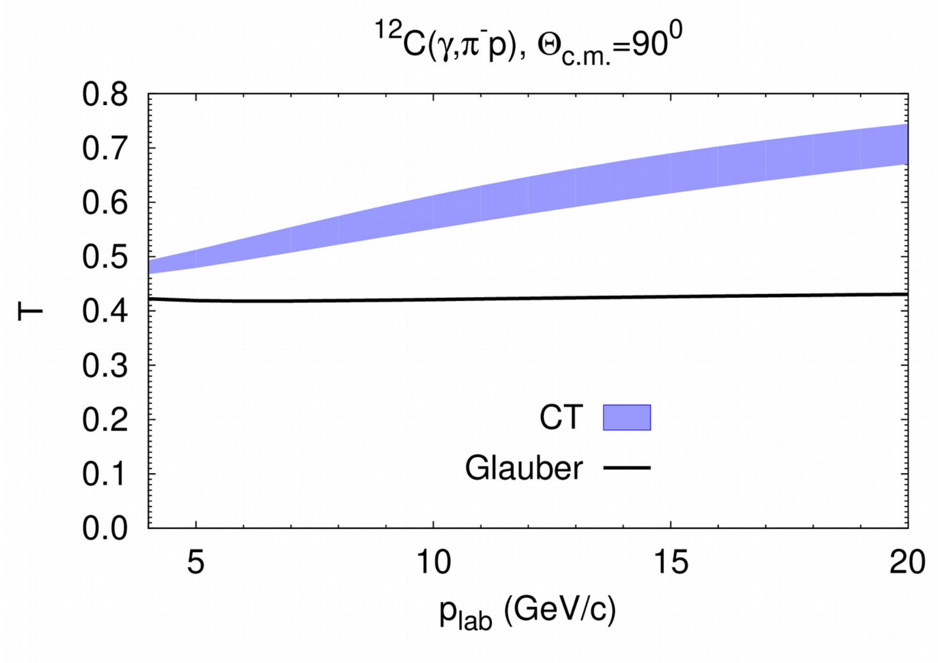
$$T = N^{-1}\int \mathrm{d}^2b\,\mathrm{d}z\;\rho_n(b,z)\exp\Big(-\sigma^{\mathrm{eff}}_{\gamma\mathrm{N}}\int\limits_{z-l_\gamma}^{z}\mathrm{d}z'\;\rho(b,z') - \int\limits_{l_r}^{\infty}\mathrm{d}l\;\rho(b_r,l)\sigma^{\mathrm{eff}}_{\pi\mathrm{N}}(p_\pi,l-l_r) - \int\limits_{l'_r}^{\infty}\mathrm{d}l'\;\rho(b_{r'},l')\sigma^{\mathrm{eff}}_{p\mathrm{N}}(p_p,l'-l'_r)\Big)\;,$$

$$l_r = \mathbf{r}\mathbf{p}_\pi/p_\pi,\; b_r = \sqrt{r^2-l_r^2},\; l'_r = \mathbf{r}\mathbf{p}_p/p_p,\; b_{r'} = \sqrt{r^2-(l'_r)^2},\; \mathbf{r}\equiv(\mathbf{b},z)\;,$$

$$\sigma^{\mathrm{eff}}_{\gamma\mathrm{N}} = \begin{cases}\sigma_{\mathrm{in}}(\rho N)\simeq\sigma_{\mathrm{in}}(\pi N) & -\ \mathrm{RP},\\ 0 & -\ \mathrm{UP},\end{cases}$$

$$l_\gamma = \frac{2p_{\mathrm{lab}}}{m_\rho^2}$$ - photon coherence length.



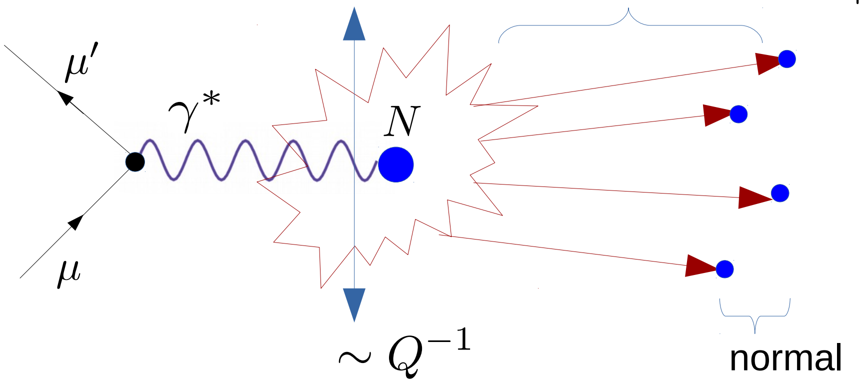


AL, M. Strikman, PLB 760, 753 (2016)

Proposed to study in Hall D @ TJNAF

High-energy virtual-photon-nucleus reactions

The space-time scale of hadronization in DIS:



$$l_h \simeq \frac{2p_h}{|M_h^2 - M_{h'}^2|} \sim 0.4 - 0.6(\mathrm{fm/GeV}) \cdot p[\mathrm{GeV}]$$

Due to CT during formation stage the "prehadrons" interact with nucleons with reduced strength.

E665 at Fermilab:

(M.R. Adams et al., 1995)

$E_{\mu^-} = 470$ GeV, H, D, C, Ca, Pb targets
$Q^2 > 0.8$ GeV^2, $\nu > 20$ GeV
low-energy neutrons ($E < 10$ MeV)

- Nucleus may serve as a "microcalorimeter" for high-energy hadrons : the excitation energy of the residual nucleus grows with the number of holes (wunded nucleons) and can be measured by the number of emitted low-energy neutrons

Theoretical analyses: M. Strikman, M.G. Tverskoy, M.B. Zhalov, PLB 459, 37 (1999); A.L., M. Strikman, arXiv:1812.08231

GiBUU model

- solves the coupled system of kinetic equations for the baryons (N,N*,Δ,Λ,Σ,…), corresponding antibaryons ($\overline{N}$,$\overline{N}$*,$\overline{\Delta}$,$\overline{\Lambda}$,$\overline{\Sigma}$,…), and mesons (π,K,...)

- initializations for the lepton-, photon-, hadron-, and heavy-ion-induced reactions on nuclei

- high-energy elementary binary collisions simulated by PYTHIA

- resonance/phenomenological cross sections for low-energy collisions

- selfconsitent mean fields: non-relativistic Skyrme-like and, optionally, relativistic (non-linear Walecka model)

Open source code in Fortran 2003 downloadable from:

https://gibuu.hepforge.org/trac/wiki

Details of GiBUU: ***O. Buss et al., Phys. Rep. 512, 1 (2012).***

Models (prescriptions) for prehadron-nucleon interaction cross section:

(I) Based on JETSET-production-formation points (GiBUU default) favoured by analysis of hadron attenuation at HERMES and EMC : K. Gallmeister, T. Falter, PLB 630, 40 (2005); K. Gallmeister, U. Mosel, NPA 801, 68 (2008)

$$\sigma_{\rm eff}(t)/\sigma_0 = X_0 + (1 - X_0)\frac{t - t_{\rm prod}}{t_{\rm form} - t_{\rm prod}} \ ,$$

$$X_0 = r_{\rm lead} a/Q^2, \ a = 1 \ {\rm GeV}^2,$$

$r_{\rm lead}$ - the ratio (#of leading quarks)/(total # of quarks) in the prehadron,

(II) Quantum diffusion model (QDM):

G.R. Farrar, H. Liu, L.L. Frankfurt, M.I. Strikman, PRL 61, 686 (1988)

$$\sigma_{\rm eff}(t)/\sigma_0 = X_0 + (1 - X_0)\frac{c(t - t_{\rm hard})}{l_h} \ ,$$

No direct way to derive X_0 for DIS (this is not exclusive process).
Thus we set X_0=0 for simplicity.

(III) Cutoff:

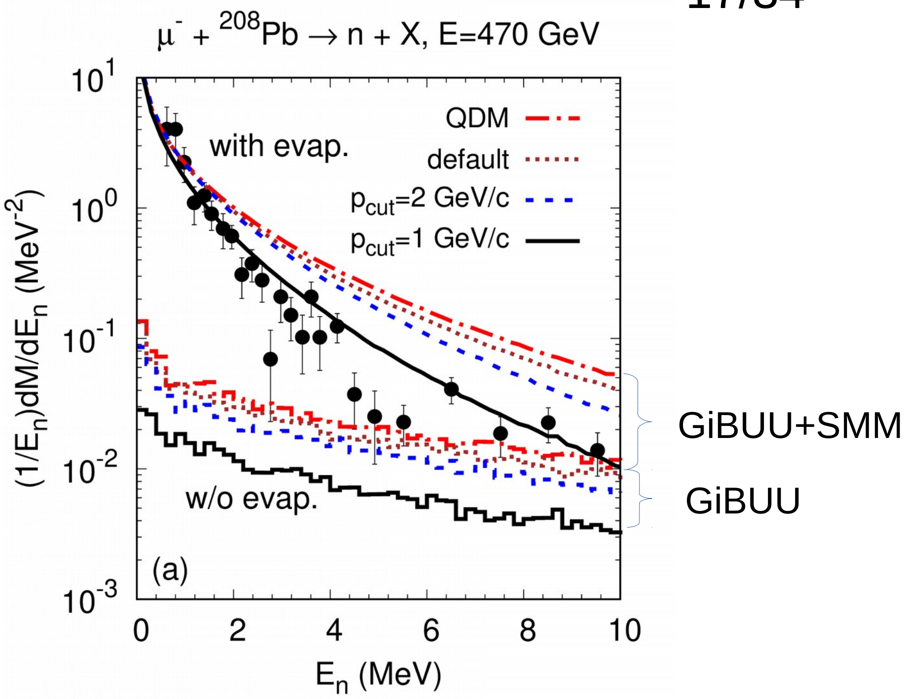
$$\sigma_{\rm eff}/\sigma_0 = \Theta(p_{\rm cut} - p) \ , \quad p_{\rm cut} \sim 1 - 2 \ {\rm GeV/c}.$$

A.L., M. Strikman, arXiv:1812.08231

Source parameters $A_{\rm res},\ Z_{\rm res},\ E^*_{\rm res},\ \mathbf{p}_{\rm res}$
were determined from GiBUU at t_{max}=100 fm/c
and used as input for statistical multifragmentation model (SMM) in evaporation mode (multifragmentation turned-off).

SMM: J.P. Bondorf, A.S. Botvina, A.S. Iljinov, I.N. Mishustin, K. Sneppen, Phys. Rept. 257, 133 (1995)

SMM code provided by Dr. Alexander S. Botvina



E665 data from M.R. Adams et al., PRL 74, 5198 (1995)

- almost all neutrons below 1 MeV are statistically evaporated;

- sensitivity to the model of hadron formation for E_n > 5 MeV;

- E665 data for lead target can be only described with very strong restriction on the FSI of hadrons (p_{cut}=1 GeV/c) in agreement with earlier calculations

M. Strikman, M.G. Tverskoy, M.B. Zhalov, PLB 459, 37 (1999)

Cuts:
$\nu > 20$ GeV,
$Q^2 > 0.8$ GeV^2.

A.L., M. Strikman, arXiv:1812.08231

Various scenaria for hadron formation can be tested in Ultraperipheral Collisions (UPCs) of heavy ions.

Quasireal photons are emitted coherently by the entire nuclei.

Minimal wavelength should match the radius of the Lorentz-contracted emitting nucleus.

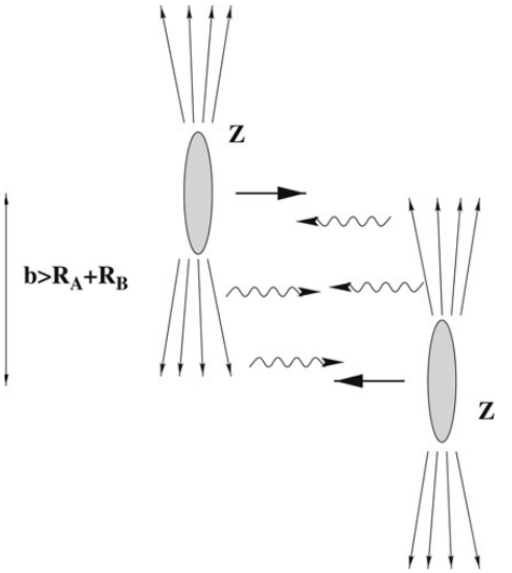


Figure from A.J. Baltz et al., Phys. Rept. 458, 1 (2008)

Maximal longitudinal momentum of the photon in the c.m. frame of colliding nuclei (collider lab. frame):

$$k_L^{\max} \simeq \frac{\gamma_L}{R_A}$$

For symmetric colliding system in the rest frame of the target nucleus:

$$k^{\max} = \gamma_L 2 k_L^{\max} \simeq \frac{2\gamma_L^2}{R_A}$$

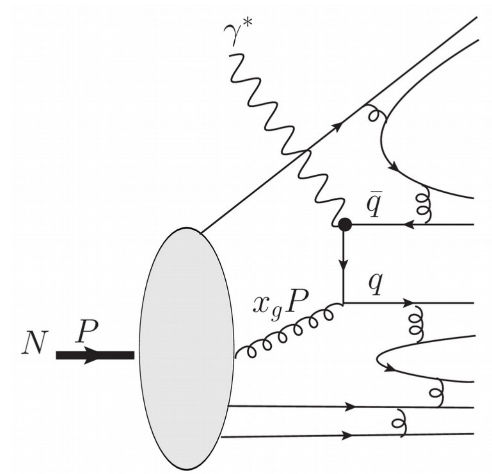
Table 1: Parameters of UPCs Au+Au at RHIC and Pb+Pb at LHC.

	$\sqrt{s_{NN}}$ (TeV)	γ_L	$k^{\max}$ (TeV/c)	W (GeV)
RHIC	0.2	106	0.642	34.7
LHC	5.5	2931	477	946

In PYTHIA model only virtual photons can be initialized via e→e'γ*.

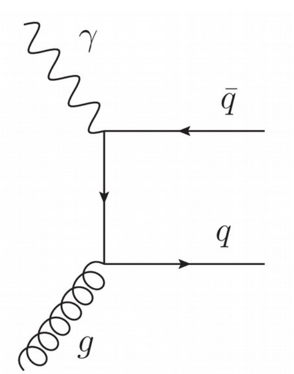
For inclusive set of PYTHIA events:

$$x_g \geq x$$



$$x_g = \frac{Q^2 + M_{q\bar{q}}^2}{2Pq} \simeq x + \frac{M_{q\bar{q}}^2}{W^2}$$

The Bjorken x in inclusive PYTHIA simulation
is set equal to minimal x_g for real photon+gluon →2 jets transition:

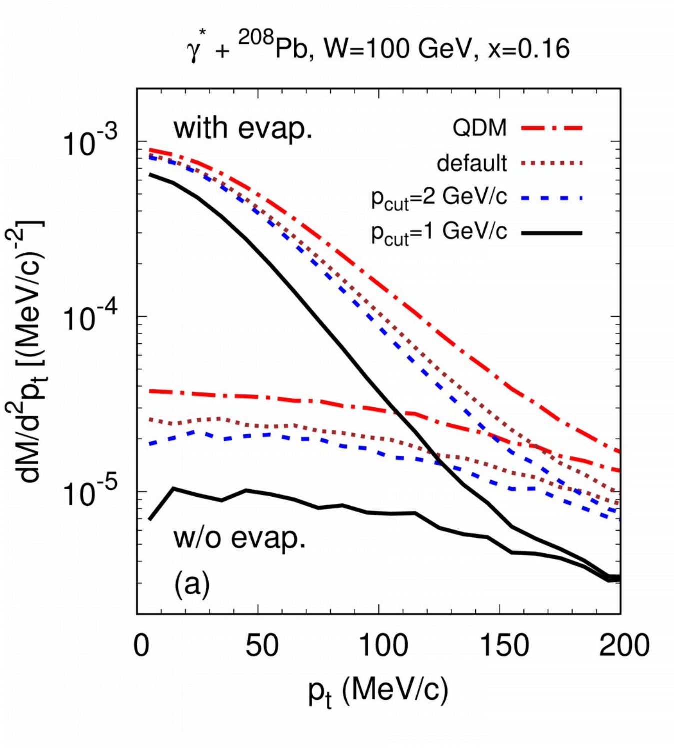


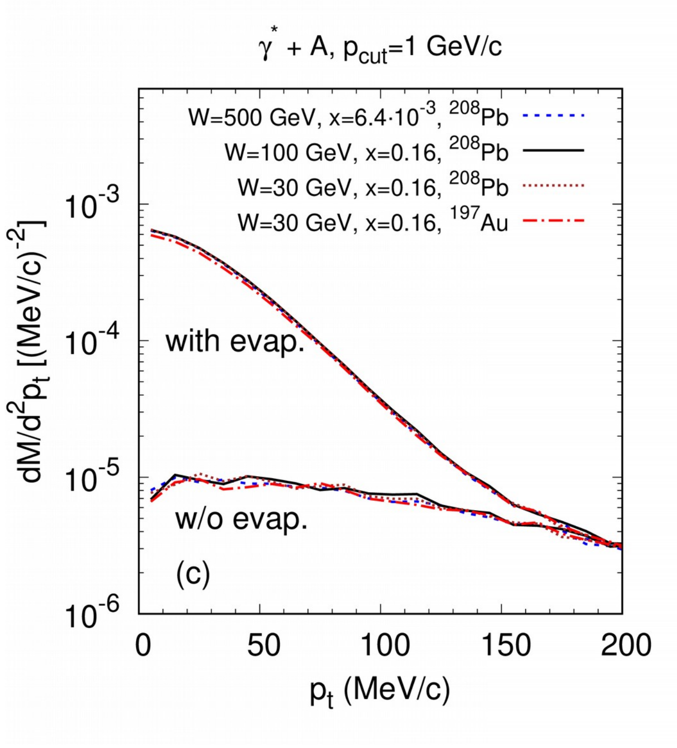
$$x_g = \frac{M_{\bar{q}q}^2}{W^2}\ , \quad M_{\bar{q}q} \simeq |p_t(\mathrm{jet}_1)| + |p_t(\mathrm{jet}_2)| \geq 40\ \mathrm{GeV}$$

typical setting at LHC for dijets

– guaranties the smallness of the photon shadowing effect
that is neglected in calculations.

Transverse momentum spectra of neutrons in quasireal-photon-nucleus collisions





- **strong sensitivity to the hadron formation model at moderate p_t**

- **no influence of photon kinematics (thus folding with photon flux not important)**

A.L., M. Strikman, arXiv:1812.08231

UPCs at NICA:

	$\sqrt{s_{NN}}$ (GeV)	γ_L	$k^{\max}$ (GeV/c)	W (GeV)
Au+Au	11.0	5.9	1.9	2.1
p+Au , γp	17.2	9.2	4.7	3.1
p+Au , γAu	17.2	9.2	55.2	10.2

Baryon resonance excitation

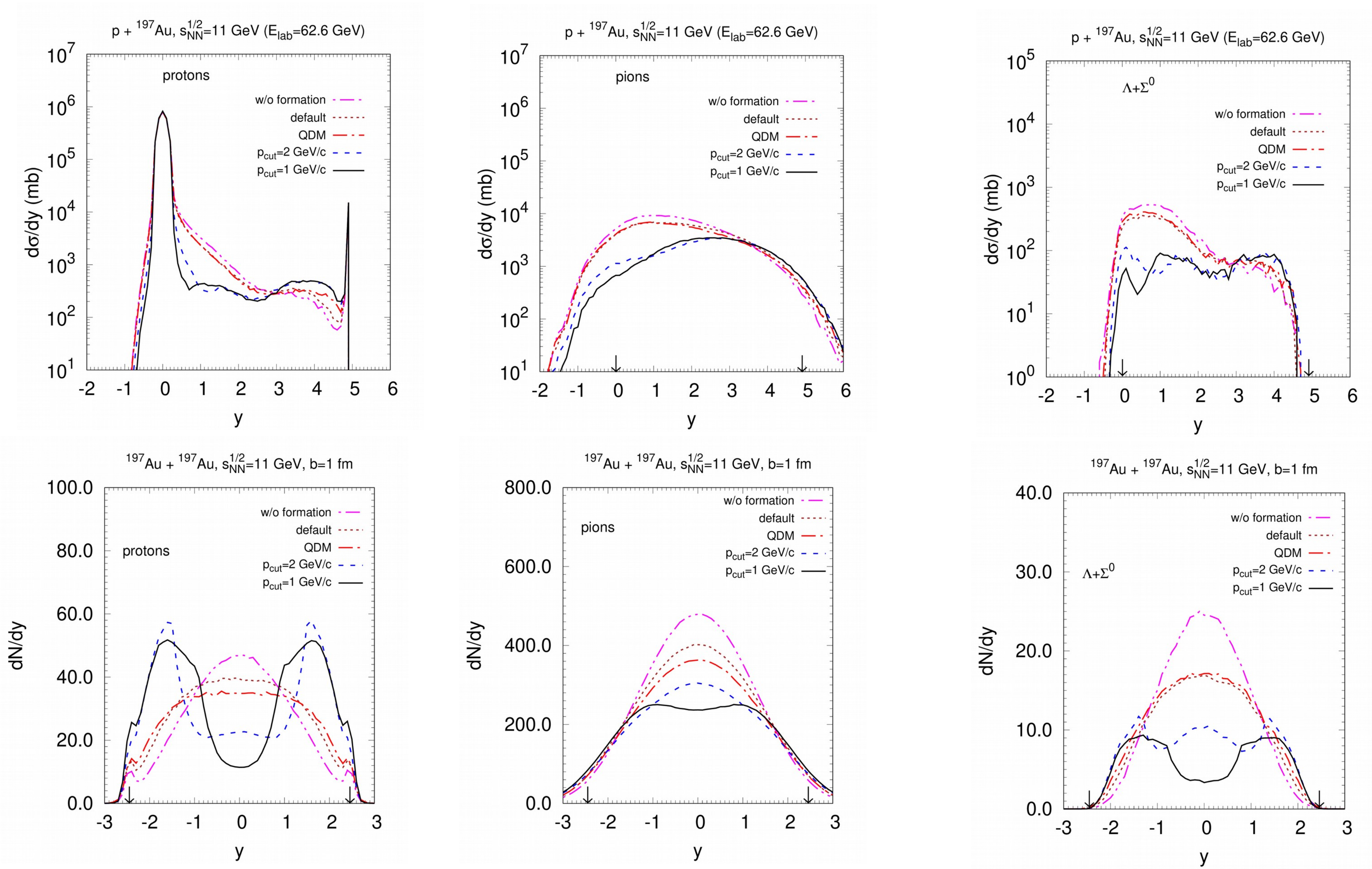
Non-perturbative QCD (string regime),
J/ψ production

In the case if photon is emitted by proton: R_p=0.6 fm.

pA and AA collisions

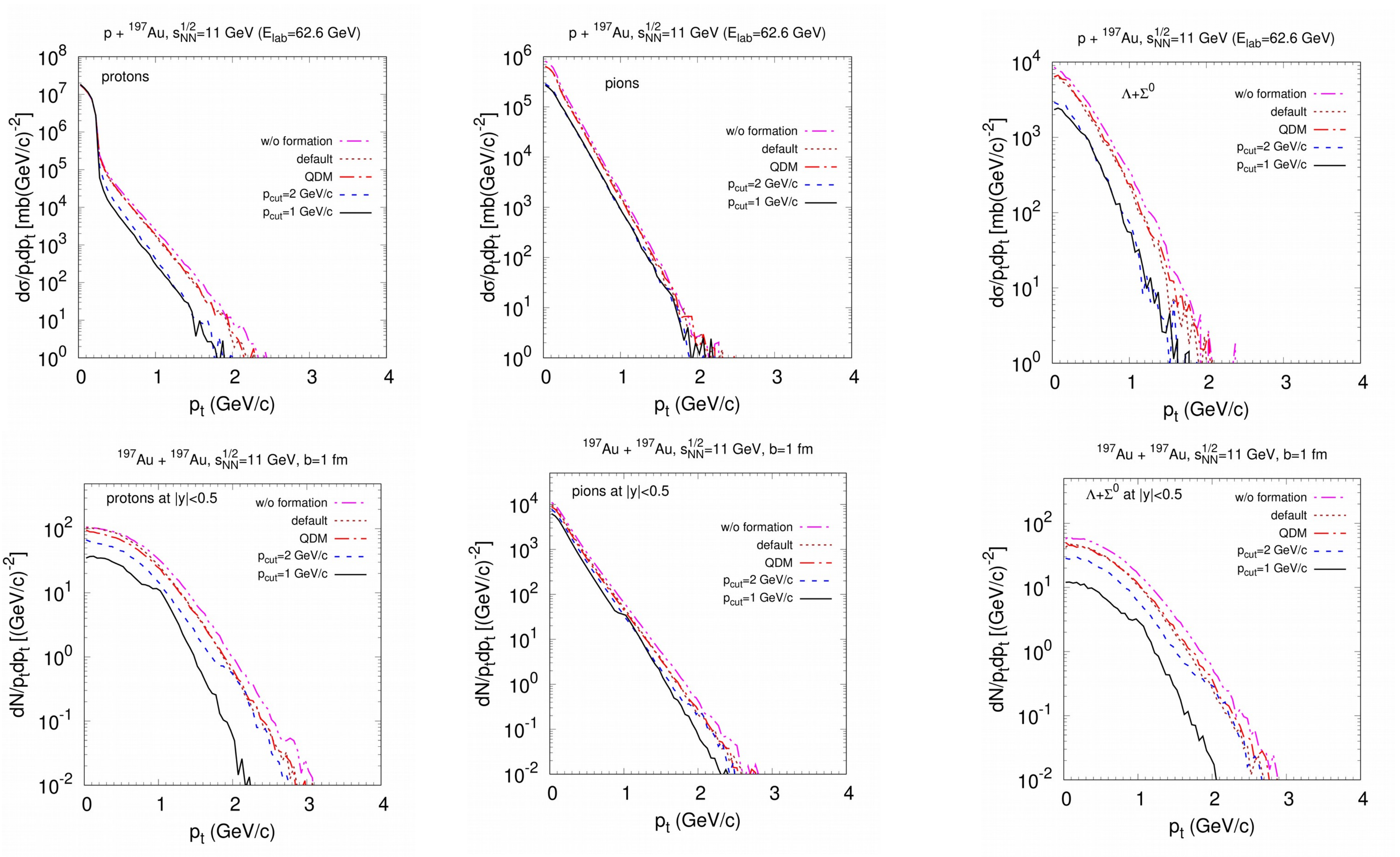
GiBUU in cascade mode
(w/o mean field)

Rapidity spectra:



- reduced stopping power and less production in midrapidity region due to hadron formation effects

Transverse momentum spectra:



- steeper spectra at large p_t due to hadron formation effects (closer to direct production in first-chance pN collisions)

Reactions on deuteron

p+ d → p + p + n_s with hard pp→ pp ($\theta_{c.m.} \approx 90^o$)

$$T = \frac{\sigma^{DWIA}}{\sigma^{IA}}$$ - transparency

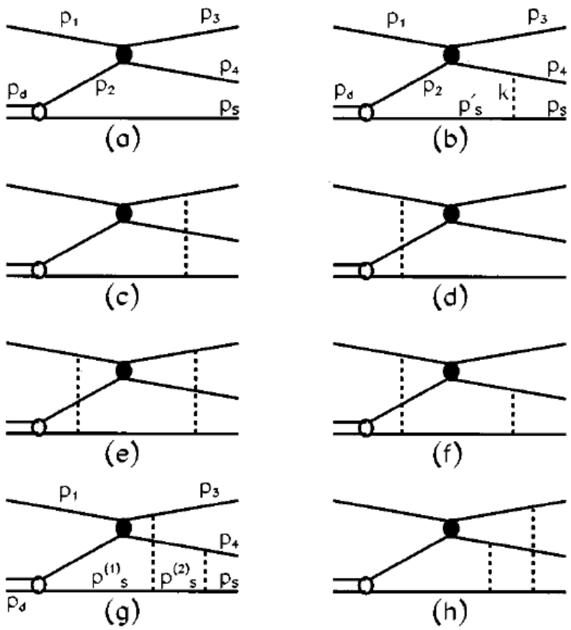
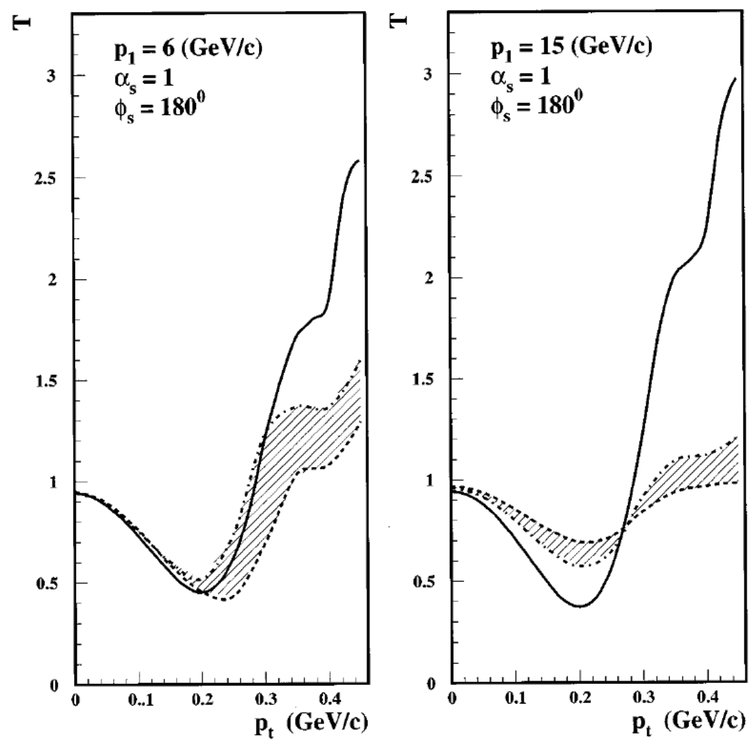


FIG. 1. Feynman diagrams of the eikonal approximation for $d(p,pp)n$ scattering. The dashed lines describe the amplitude of NN scattering, and the solid circles represent the hard pp scattering amplitude.



transverse momentum of spectator

$$\alpha_s = 2(E_s - p_s^z)/m_d$$

$$\phi_s = \angle(\boldsymbol{p}_t, \boldsymbol{p}_{3t})$$

FIG. 6. The p_t dependence of T at $\alpha_s = 1$. The solid line is for the elastic eikonal approximation which neglects color transparency effects. The shaded area corresponds to T calculated within the quantum diffusion model of CT. Dashed and dash-dotted curves correspond to QDM calculations with $\Delta M^2 = 0.7$ and $\Delta M^2 = 1.1$ GeV^2, respectively.

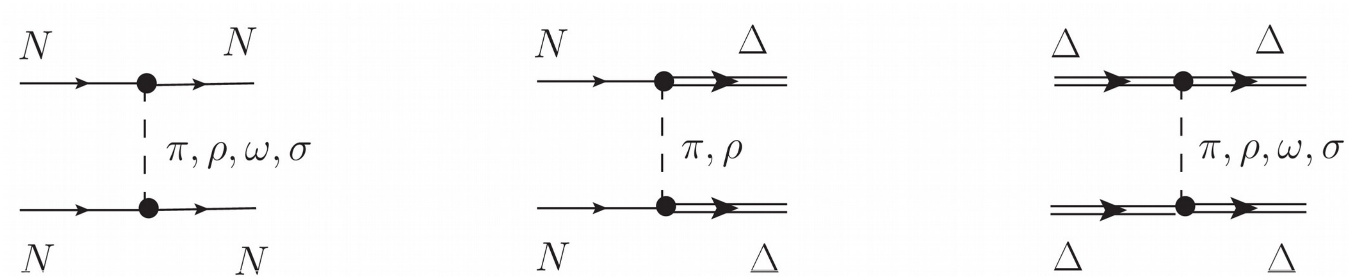
Figures from
L.L. Frankfurt, E. Piasetzky, M.M. Sargsian, M.I. Strikman, PRC 56, 2752 (1997)

- absorption at low p_t , enhancement at large p_t due to soft rescattering amplitudes
- CT moves T closer to the impulse approximation (T=1)

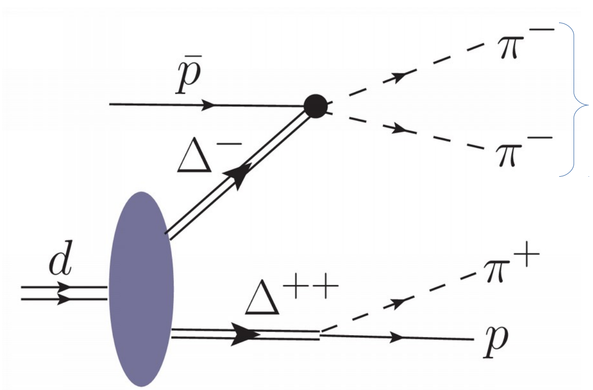
See also similar study for $\bar{p}$ + d → π^- + π^0 + p_s
AL and M. Strikman, arXiv:1909.00379

Deuteron quantum numbers I=0, J=1 allow for admixture of strongly bound Δ^{++}-Δ^{-} and Δ^{+}-Δ^{0} configurations. Good testing ground for theoretical models of non-nucleonic d.o.f. in heavier nuclei.

Coupled channel NN-ΔΔ calculations using OBEM:



R. Dymarz, F.C. Khanna, NPA 516 (1990) 549: π+ρ+ω+σ exchange model, Δ-Δ probability ~0.4-0.5%, $^3S_1^{\Delta\Delta}$ and $^7D_1^{\Delta\Delta}$ states dominate.



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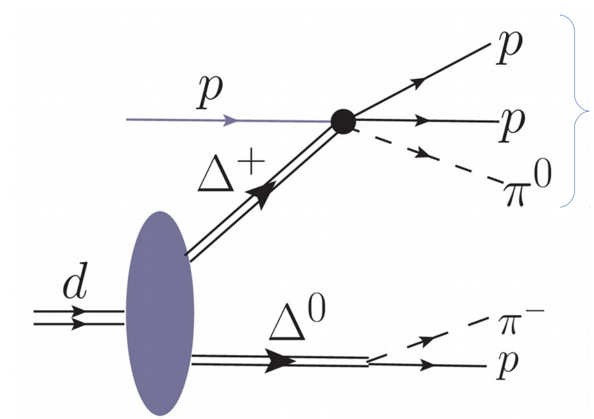


forward

AL, A. Gillitzer, J. Haidenbauer, M. Strikman, PRC 98, 054611 (2018)
proposed to study at PANDA at p_{lab}=10-15 GeV/c

can be studied at NICA SPD

Conclusions

- CT is expected to present in binary reactions ab –> cd with large scale >> 1 GeV^2 given by either min(|t|,|u|) or the $(\text{invariant mass})^2$ of one of participating particles.

- Channels with light mesons are most promising for CT. Mesons ($q\bar{q}$) are easier "squeezable" to PLC than baryons (qqq).

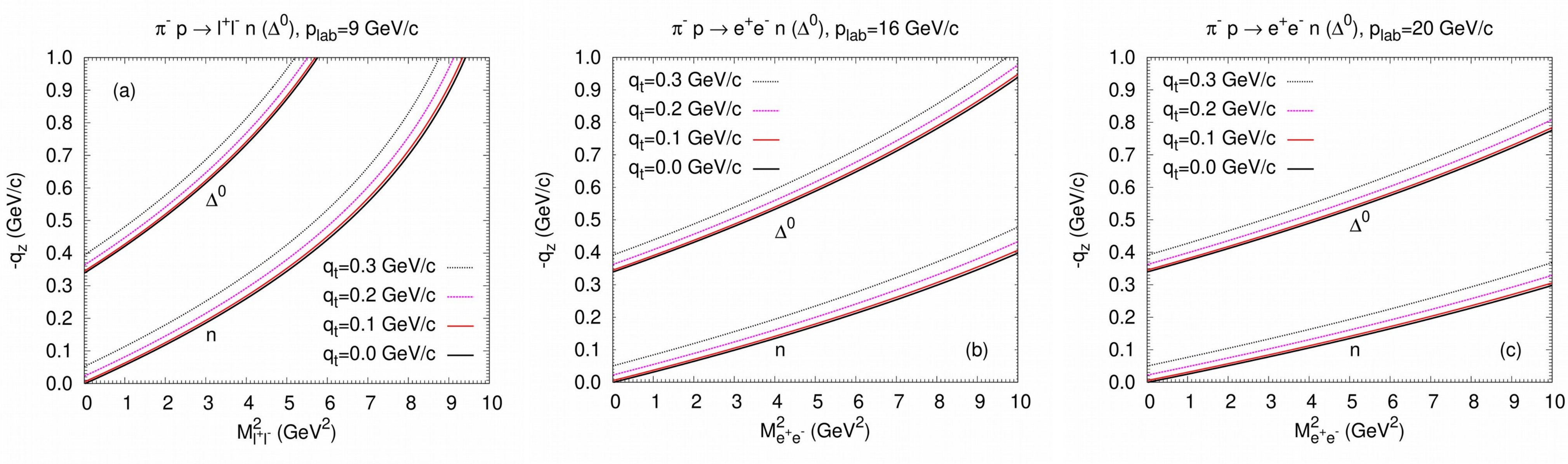
  Examples discussed were $A(e,e'\pi^+)$, pionic Drell-Yan process $A(\pi^-,l^-l^+)$ with M_{l-l+} > 4 GeV, charmonium production $A(\pi^-,J/\psi)$, and large-angle pion photoproduction $A(\gamma,\pi^- p)$.
  Open problem: at which |t| the transition from resolved to unresolved (direct) photon occur ? This may interfere with CT.

- CT-like behaviour should also persist in inclusive reactions on nuclei at high energies, such as DIS, pA and AA since they are governed by channels with large momentum transfer (large particle multiplicities). In these channels the FSI is reduced due to hadron formation length resulting in less secondary particles production and less deceleration of hadrons produced in primary hard collision.

  Examples were slow neutron production in γ^*A interactions, and p,π and hyperon production in pA and AA collisions.

Backup

Exclusive transition $\pi^- p \to l^+ l^- n$ can be selected by restricting longitudinal momentum transfer to the nucleus for a fixed $M_{e^+e^-}$:

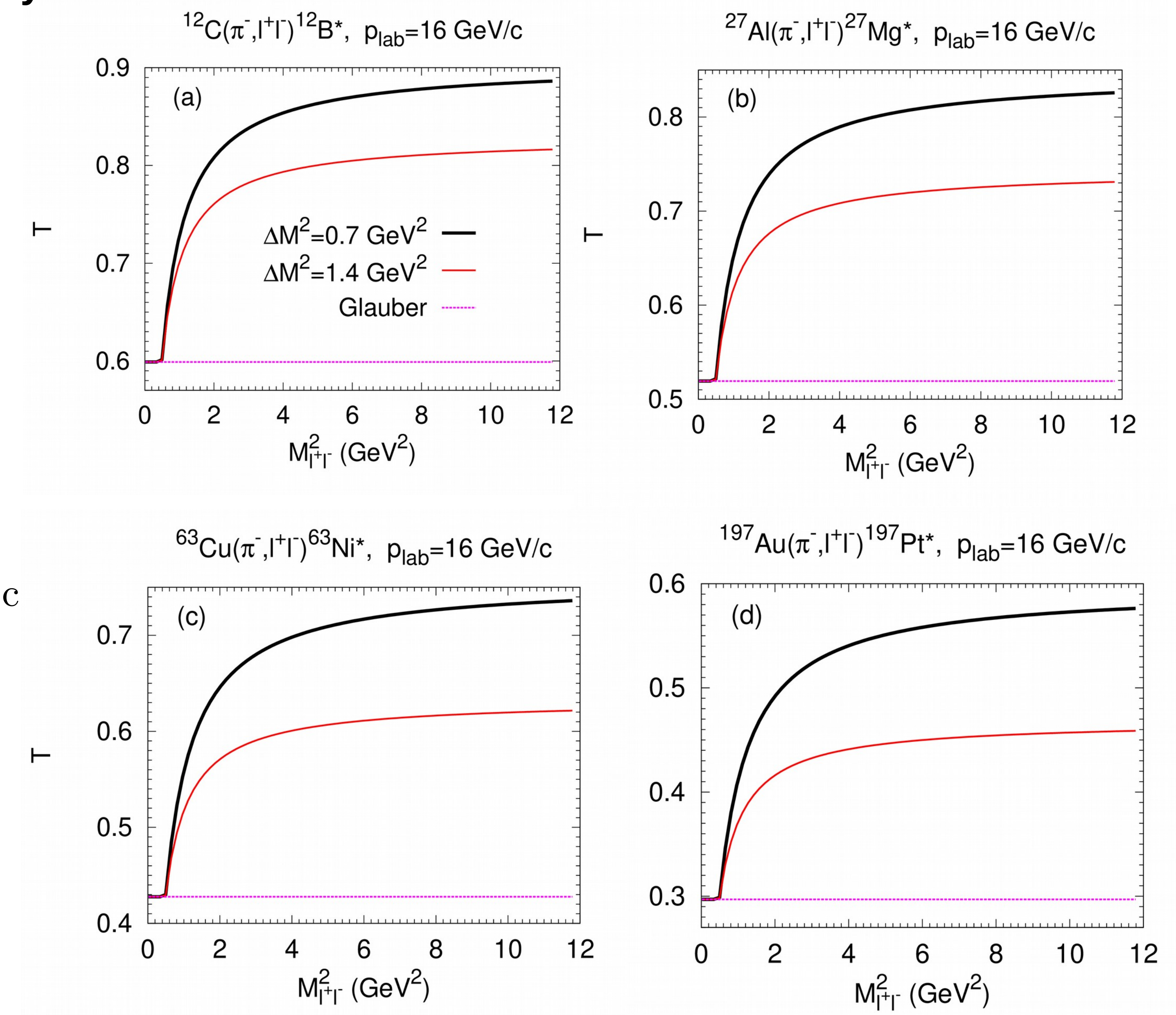


- modest momentum resolution (~100 MeV/c) is enough to select p →n transition.

Dilepton mass dependence of the Drell-Yan transparency:

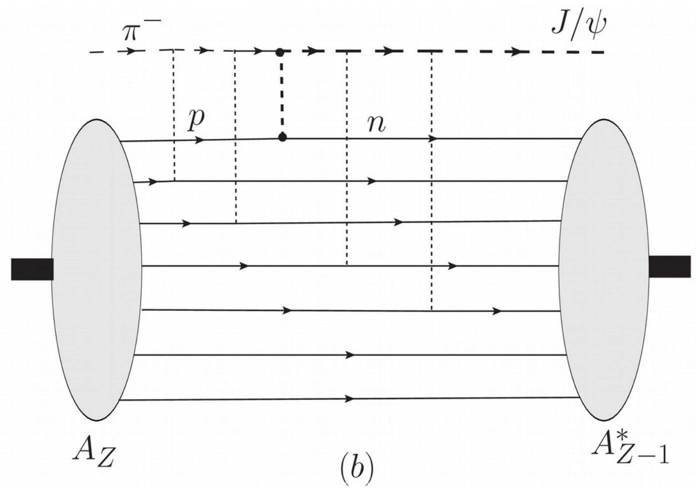
- ***transparency saturates at*** $M^2_{l^+l^-} \simeq 4\ \mathrm{GeV}^2$
- ***stronger sensitivity to pion coherence length for heavy nuclei:***

for $\Delta M^2 = 0.7\ \mathrm{GeV}^2$
$l_\pi = 9\ \mathrm{fm}$ at $p_{\mathrm{lab}} = 16\ \mathrm{GeV/c}$
$2R_{^{12}\mathrm{C}} < l_\pi \sim 2R_{^{197}\mathrm{Au}}$



J/Ψ production in pion-nucleus interactions

$A_Z(\pi^-, J/\psi)A^*_{Z-1}$



Hard process:

$m^2_{J/\psi} \gg 1 \text{ GeV}^2$

$$T = \frac{1}{Z}\int d^3r\, e^{-\int\limits_{-\infty}^{z} dz' \sigma^{\text{eff}}_{\pi N}(p_\pi, z-z')} \rho_p(\mathbf{r}) e^{-\int\limits_{z}^{+\infty} dz' \sigma^{\text{eff}}_{J/\psi N}(p_{J/\psi}, z'-z)\rho(\mathbf{b}, z')} ,$$

$$\sigma^{\text{eff}}_{J/\psi N}(p_{J/\psi}, z) = \sigma_{J/\psi N}\left(\left[\frac{z}{l_{J/\psi}} + \frac{< n^2 k_t^2 >}{M^2_{J/\psi}}\left(1 - \frac{z}{l_{J/\psi}}\right)\right]\Theta(l_{J/\psi} - z) + \Theta(z - l_{J/\psi})\right) ,$$

$$\sigma_{J/\psi N} \simeq 4 - 6 \text{ mb} , \quad < k_t^2 >^{1/2} \simeq 1 \text{ GeV/c} , \quad l_{J/\psi} \simeq \frac{2p_{J/\psi}}{m^2_{\psi'} - m^2_{J/\psi}} .$$

Transparency in

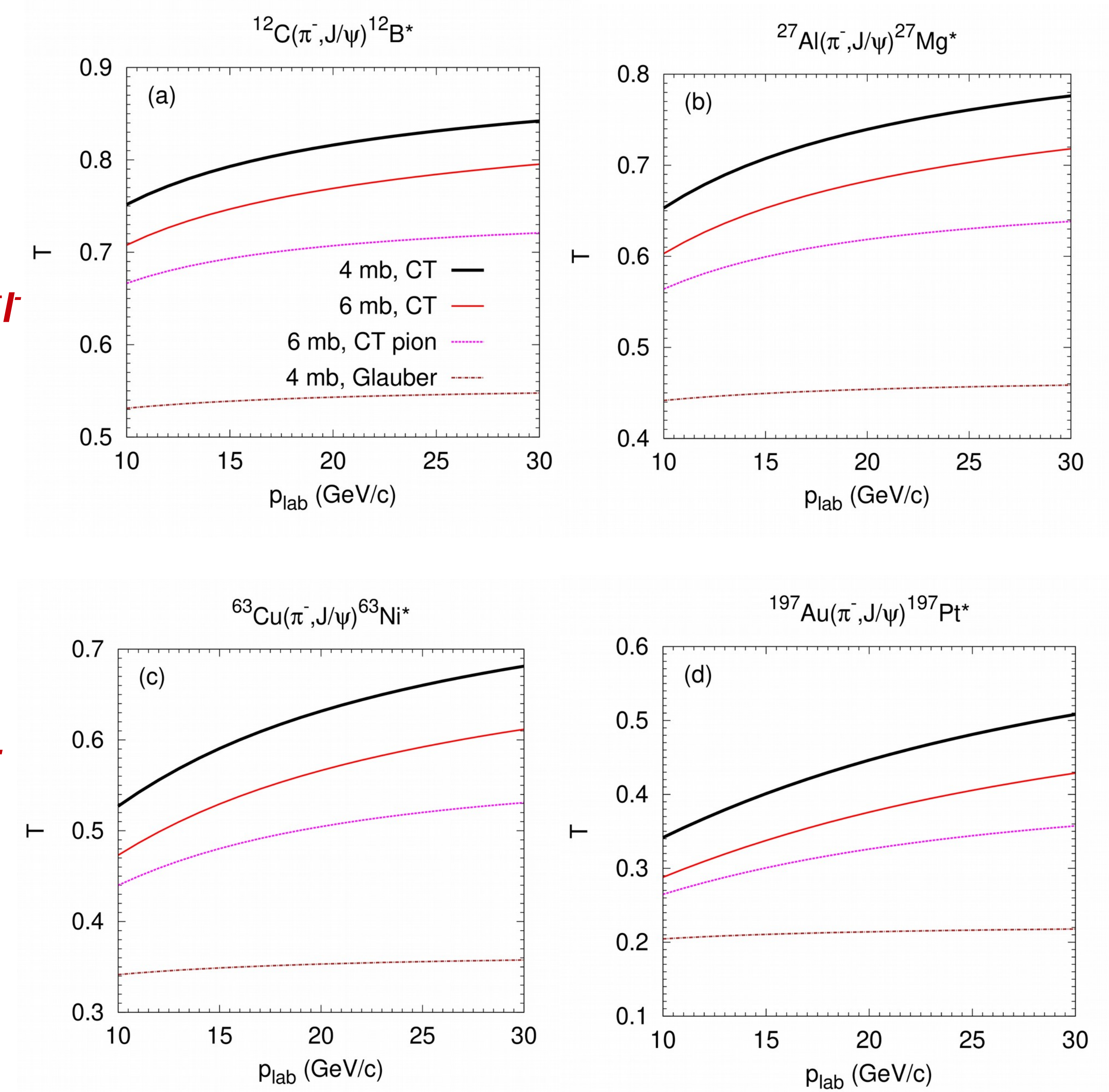
$$A_Z(\pi^-, J/\psi)A^*_{Z-1}$$

for $\sigma_{J/\psi N}$ = 4 and 6 mb.

- similar behavior to the case of l^+l^- ($\sigma_{J/\psi N}$ is small);

$$l_{J/\psi} \sim 1 \text{ fm} \ll 2R_{^{197}Au}$$
$$\text{at } p_{J/\psi} = 10 \text{ GeV/c}$$

- the influence of charmonium CT is smaller for heavy targets: better for determination of $\sigma_{J/\psi N}$



Kinetic equation with relativistic mean fields:

Distribution function in phase space (***r***,***p****)

Number of sort "j" particles = $\int \frac{g_s^j d^3r d^3p^*}{(2\pi)^3} f_j^*(x,\mathbf{p}^*)$

$$(p_0^*)^{-1}\left[p_\mu^*\partial^\mu + (p_\mu^*\mathcal{F}_j^{\alpha\mu} + m_j^*\partial^\alpha m_j^*)\frac{\partial}{\partial p^{*\alpha}}\right] f_j^*(x,\mathbf{p}^*) = I_j[\{f^*\}] \ , \qquad (*)$$

Collision term

$\mu = 0,1,2,3, \quad \alpha = 1,2,3, \quad j = N,\bar{N},\Delta,\bar{\Delta},\Lambda,\bar{\Lambda},\pi,K,\ldots \qquad x \equiv (t,\mathbf{r})$

$m_j^* = m_j + S_j$ - effective mass, $S_j = g_{\sigma j}\sigma$ - scalar field,

$p^{*\mu} = p^\mu - V_j^\mu$ - kinetic four-momentum with effective mass shell constraint $p^{*\mu}p_\mu^* = m_j^{*2}$,

$V_j^\mu = g_{\omega j}\omega^\mu + g_{\rho j}\tau_j^3\rho^{3\mu} + q_j A^\mu$ - vector field, $\qquad \tau_j^3 = +(-)1 \text{ for } j = p,\bar{n}\ (\bar{p},n)$,

$\mathcal{F}_j^{\mu\nu} = \partial^\mu V_j^\nu - \partial^\nu V_j^\mu$ - field tensor.

- For momentum-independent fields Eq.(*) is equavalent to the BUU equation

$$(\partial_t + \nabla_{\mathbf{p}}\varepsilon_j\nabla_{\mathbf{r}} - \nabla_{\mathbf{r}}\varepsilon_j\nabla_{\mathbf{p}})f_j(x,\mathbf{p}) = I_j[\{f\}]$$

$$\varepsilon_j(x,\mathbf{p}) = V_j^0 + \sqrt{m_j^{*2} + \mathbf{p}_j^{*2}} \ , \quad f_j(x,\mathbf{p}) = f_j^*(x,\mathbf{p}^*) \ .$$

Direct derivations of relativistic kinetic equation:

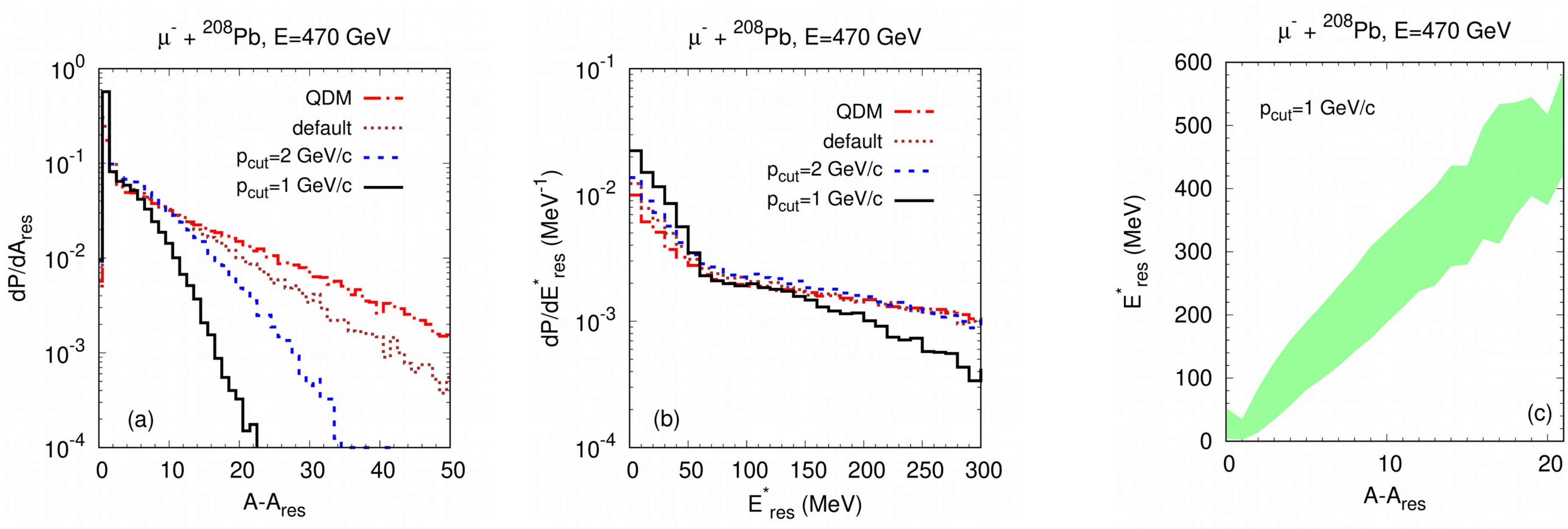
Yu.B. Ivanov, NPA 474, 669 (1987);
B. Blättel, V. Koch, U. Mosel, Rept. Prog. Phys. 56, 1 (1993).

The neutron spectrum contains both the preequlibrium part (cascade particles) and the equilibrium part from the decay of the excited residual nucleus.

Characteristics of the residual nucleus obtained by counting hole excitations in GiBUU time-evolution (corresponds to wounded nucleons in Glauber model):

$$\begin{cases} A_{\rm res} &= A - n_{\rm h} \ , \\ Z_{\rm res} &= Z - \sum_{i=1}^{n_{\rm h}} Q_i \ , \\ E^*_{\rm res} &= \sum_{i=1}^{n_{\rm h}} (E_{F,i} - E_i) \ , \\ \boldsymbol{p}_{\rm res} &= -\sum_{i=1}^{n_{\rm h}} \boldsymbol{p}_i \ . \end{cases}$$

A_{res}, Z_{res} and $\boldsymbol{p}_{res}$ are redefined by counting bound particles



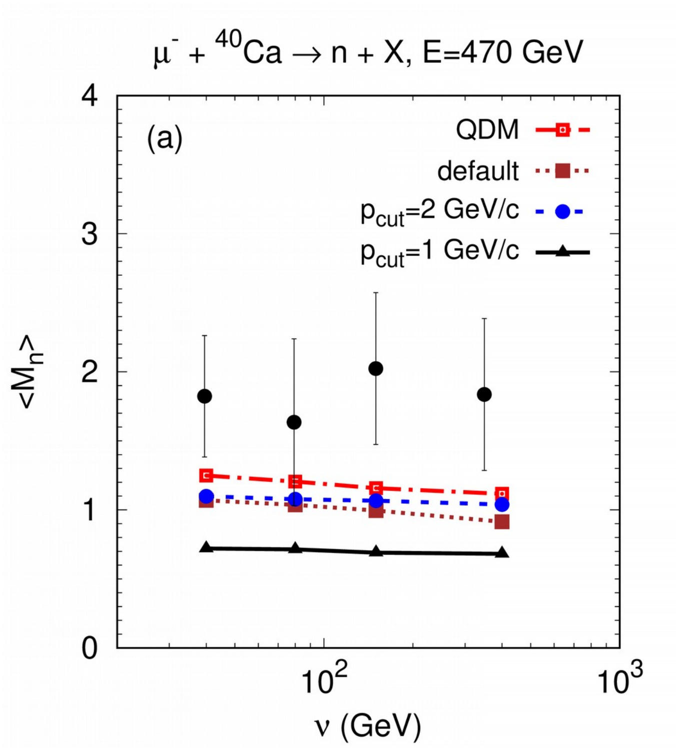
Stronger restriction on FSI of the hadrons results in smaller mass loss and smaller excitation energy.

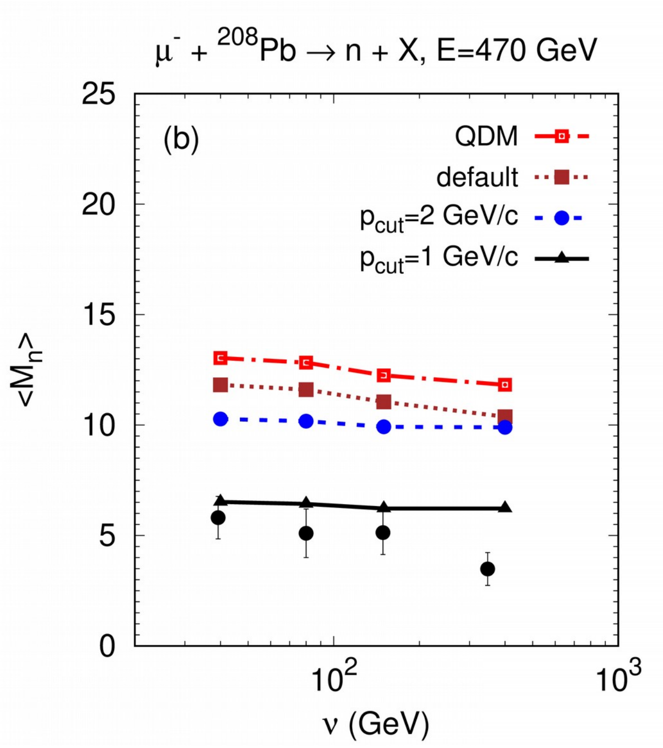
$$\langle E^*_{\rm res} \rangle \simeq 25 \ {\rm MeV} (A - A_{\rm res}),$$

the spread is due to Fermi motion.

A.L., M. Strikman, arXiv:1812.08231

Average multiplicity of neutrons with energy below 10 MeV
as a function of virtual photon energy





E665 data from
M.R. Adams et al.,
PRL 74, 5198 (1995)

- no way to describe the E665 data for calcium target with any reasonable model parameters

A.L., M. Strikman, arXiv:1812.08231