Nuclear cascade in low-energy nuclear breakup

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Plan:

- Introduction:
  studies of DIS on nuclei in the current fragmentation region (***talk by U.M.***),
  slow neutron production in the target fragmentation region,
  sensitivity to the hadron formation (CT).

- Hybrid GiBUU+SMM model and its validation in pA reactions.

- Slow neutron production in high-energy virtual-photon-nucleus reactions:
  comparison with E665 data from μ^- A at 470 GeV, predictions for AA UPCs,
  influence of hadron formation effects.

- Conclusions.

Based on the work: **AL, M. Strikman, PRC 101, 014617 (2020), arXiv:1812.08231**

Deep inelastic scattering (DIS) studies of forward production with nuclear targets

HERMES at HERA:

A. Airapetian et al., PLB 577, 37 (2003)

$E_{e^+} = 27.6$ GeV, D, N, Kr targets
$Q^2 > 1$ GeV^2, $W > 2$ GeV
$\pi^\pm,\ \pi^0,\ K^\pm,\ p,\ \bar{p}$ production.

EMC at CERN SPS:

J. Ashman et al., ZPC 52, 1 (1991)

$E_{\mu^-} = 100,\ 120,\ 200,\ 280$ GeV, D, C, Cu, Sn targets
$Q^2 > 2-5$ GeV^2, $\nu > 10-50$ GeV
charge hadron production.

Analysis (GiBUU model) in: **K. Gallmeister, U. Mosel, NPA 801, 68 (2008)**

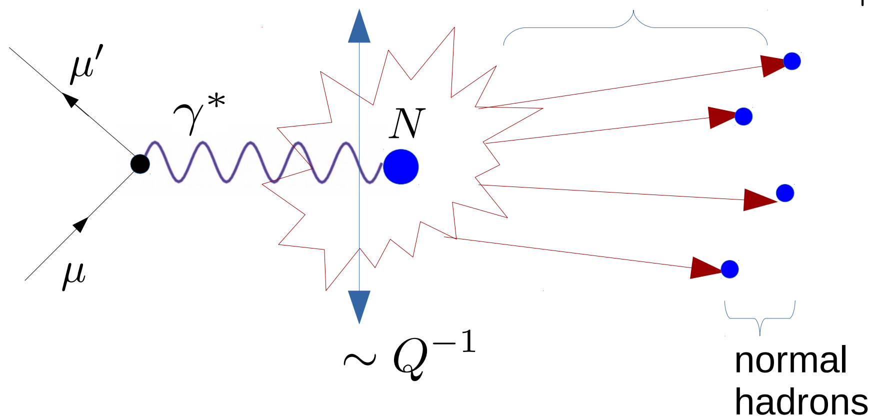
Differential multiplicity ratious

$$R_M^h(\nu, Q^2, z_h, p_T^2, \dots) = \frac{\left[N_h(\nu, Q^2, z_h, p_T^2, \dots)/N_e(\nu, Q^2)\right]_A}{\left[N_h(\nu, Q^2, z_h, p_T^2, \dots)/N_e(\nu, Q^2)\right]_{\mathrm{D}}}, \quad z_h = E_h/\nu,$$

are sensitive to the model for hadronization and favor ***linear increase of prehadron cross sectrions with time***; consistent with the quantum diffusion model (QDM) of CT **G.R. Farrar, H. Liu, L.L. Frankfurt, M.I. Strikman, PRL 61, 686 (1988).**

The space-time scale of hadronization in DIS:

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



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

E665 at Fermilab:

M.R. Adams et al., PRL 74, 5198 (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

Previous theoretical analysis: M. Strikman, M.G. Tverskoy, M.B. Zhalov, PLB 459, 37 (1999)

➡ ***Only hadrons with momenta less than about 1 GeV/c should interact with target remnant to reproduce neutron multiplicity below 10 MeV ($<M_n> \approx 5$ for Pb target).***

GiBUU model

(previous talk by U.M.)

- 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).***

Kinetic equation with relativistic mean fields:

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

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

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

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

$m_j^* = m_j + S_j$ - 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 $p^{*\mu}p_\mu^* = m_j^{*2}$,

$V_j^\mu = g_{\omega j}\omega^\mu + g_{\rho j}\tau_j^3\rho^{3\mu} + q_jA^\mu$ - 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).***

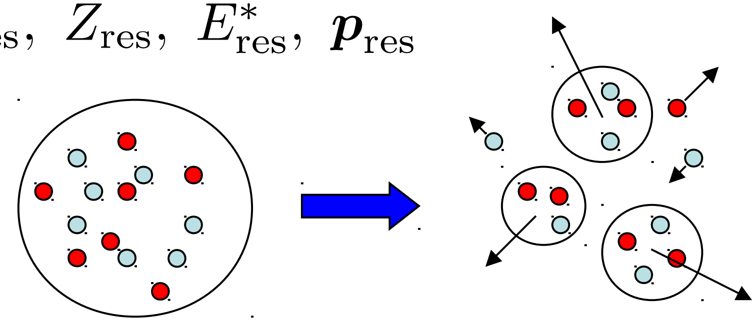
Used RMF: non-linear Walecka model parameterset NL3 from ***G.A. Lalazissis et al., PRC 55, 540 (1997)***

Statistical multifragmentation model (SMM)

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

Equilibrated nuclear residue:

$\mathrm{A}_{\mathrm{res}},\ Z_{\mathrm{res}},\ E^*_{\mathrm{res}},\ \boldsymbol{p}_{\mathrm{res}}$



● -p

○ -n

$$W_{\text{partition}} \propto \exp(S_{\text{partition}})$$

probability

entropy

Hybrid GiBUU+SMM

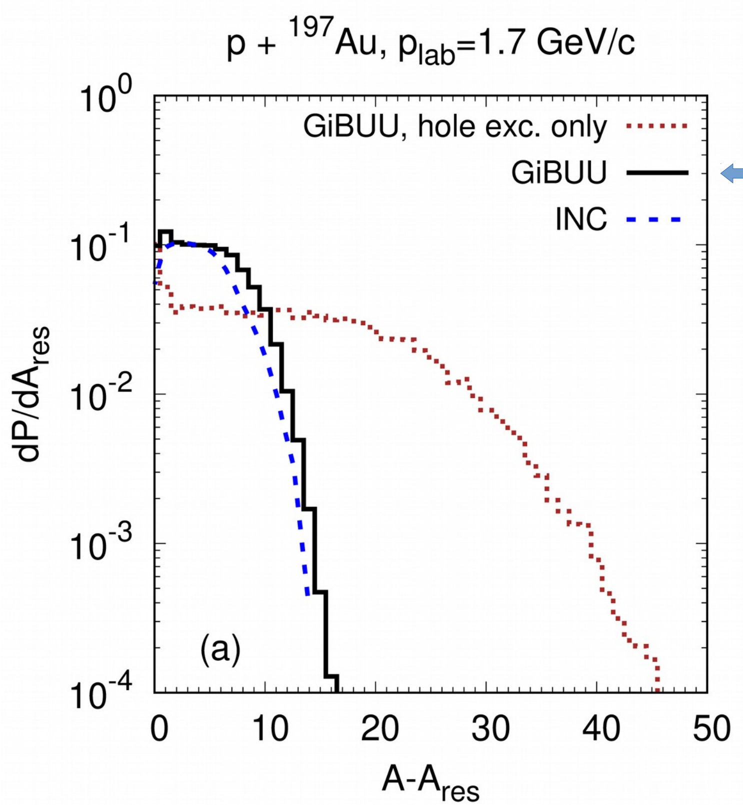
- **Non-Equilibrium dynamics within BUU until residue approaches stable configuration and local equilibration.**
- **Determination of parameters of the residue** $\mathrm{A}_{\mathrm{res}},\ Z_{\mathrm{res}},\ E^*_{\mathrm{res}},\ \boldsymbol{p}_{\mathrm{res}}$
- **Apply SMM**

SMM code provided by ***Dr. Alexander S. Botvina***

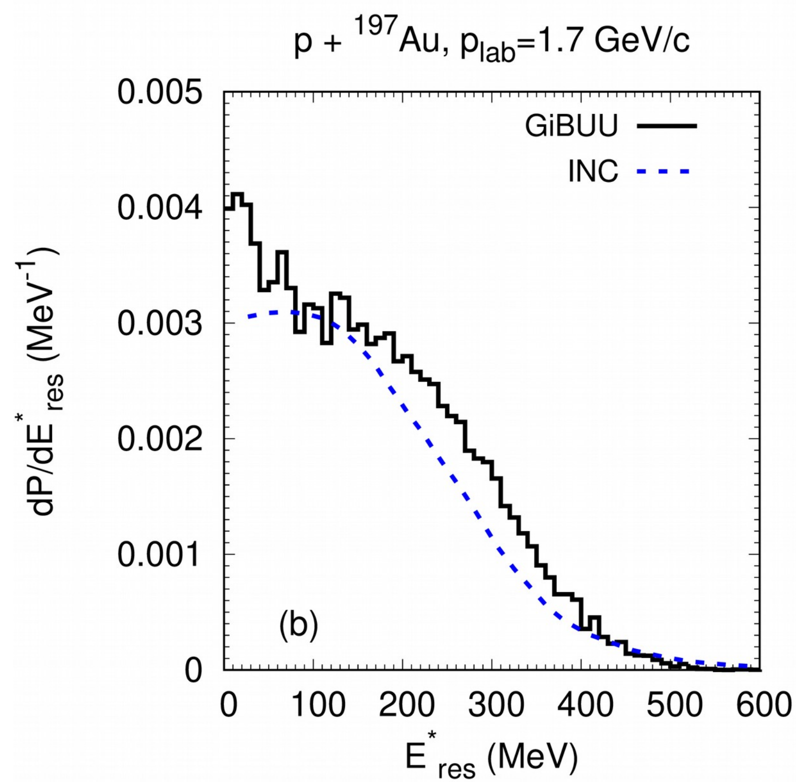
GiBUU+SMM hybrid model validation in pA collisions

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

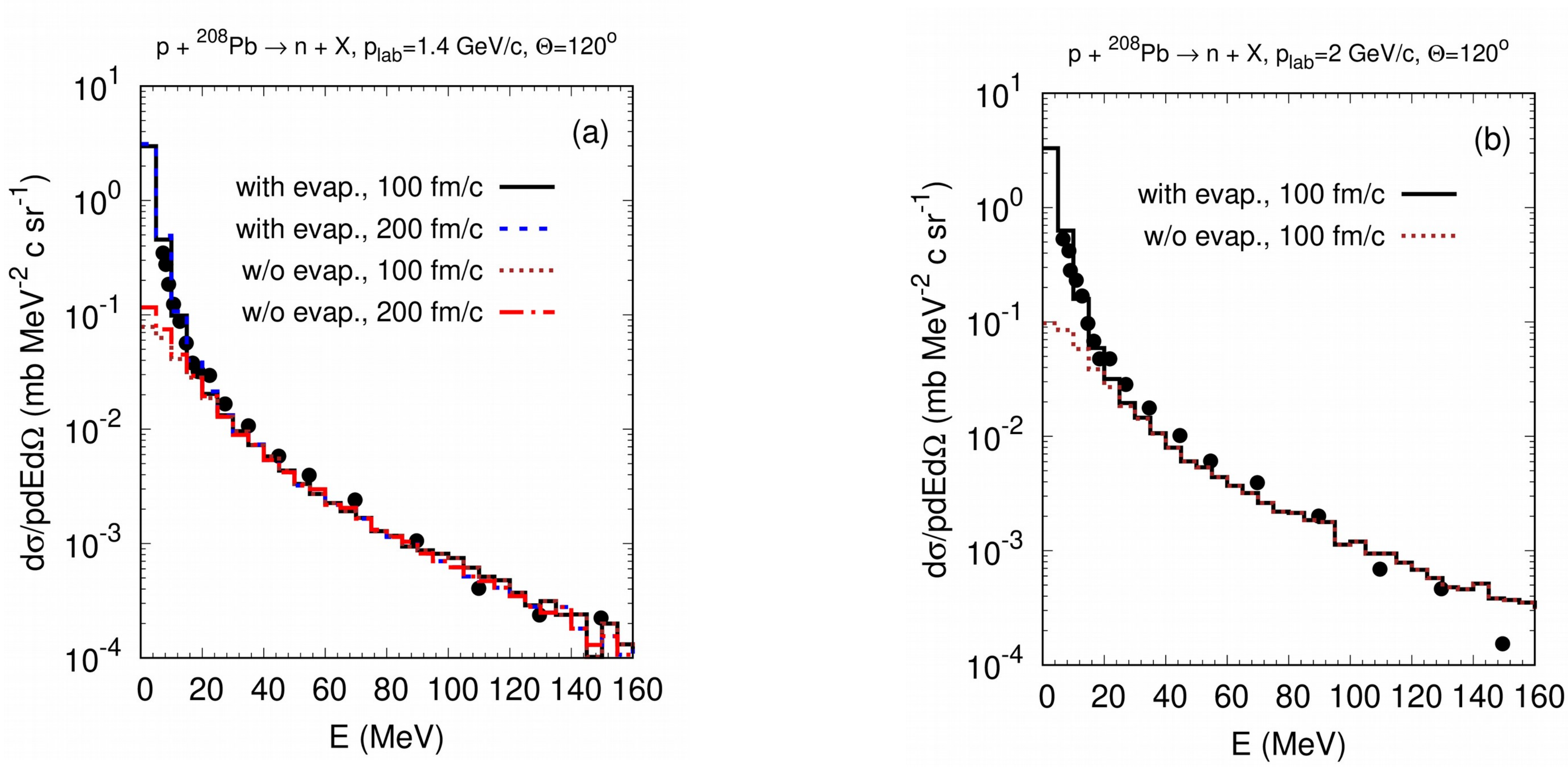
$$\begin{aligned} A_{\mathrm{res}} &= A - n_{\mathrm{h}} \,, \\ Z_{\mathrm{res}} &= Z - \sum_{i=1}^{n_{\mathrm{h}}} Q_i \,, \\ E^*_{\mathrm{res}} &= \sum_{i=1}^{n_{\mathrm{h}}} (E_{F,i} - E_i) \,, \\ \boldsymbol{p}_{\mathrm{res}} &= -\sum_{i=1}^{n_{\mathrm{h}}} \boldsymbol{p}_i \,. \end{aligned}$$



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

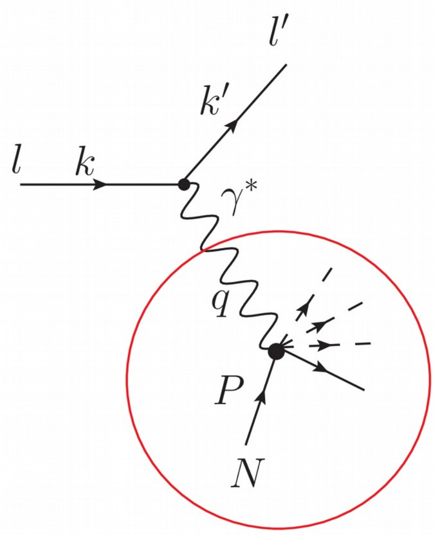


Intranuclear cascade (INC) calculations: ***V.S. Barashenkov, F.G. Gereghi, A.S. Iljinov, V.D. Toneev, NPA 222, 204 (1974)***



Data: ***Yu. D. Bayukov et al., ITEP-172-1983 (1983)***

Slow neutron production in high-energy virtual-photon-nucleus reactions



$$q = k - k' \ , \quad Q^2 = -q^2 \ , \quad y = Pq/Pk$$

$$W^2 = (P+q)^2 = m_N^2 - Q^2 + 2Pq \simeq 2Pq$$

- nucleon is randomly chosen with probability $dP_i = \dfrac{\rho_i(\boldsymbol{r})d^3r}{A} \ , \quad i = p, n \ .$

- outgoing lepton is sampled by using differential cross section

$$\frac{d\sigma}{dydQ^2} = \frac{\pi}{E'}\frac{d\sigma}{d\Omega dE'} \ , \qquad \frac{d\sigma}{d\Omega dE'} = \Gamma[\sigma_T(W^2,Q^2) + \epsilon\sigma_L(W^2,Q^2)] \equiv \Gamma\sigma^* \ ,$$

$\Omega \ , \ E'$ - solid angle and energy of the scattered lepton in the nucleon rest frame

M.E. Christy, P.E. Bosted, PRC 81, 055213 (2010)

- collision of virtual photon with the struck nucleon is simulated via PYTHIA 6.4

- Fermi motion and Pauli blocking are taken into account

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)

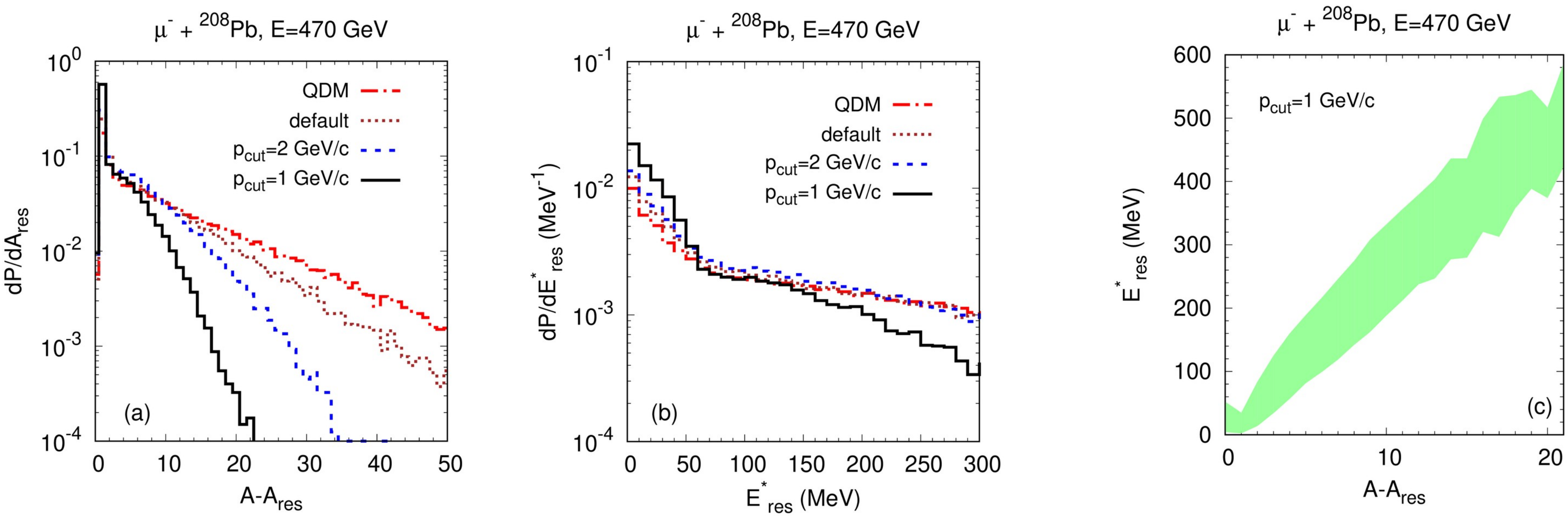
$$\sigma_{\rm eff}(t)/\sigma_0 = X_0 + (1 - X_0)\frac{c(t - t_{\rm hard})}{l_h} \ ,$$

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

(III) Cutoff:

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

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 SMM



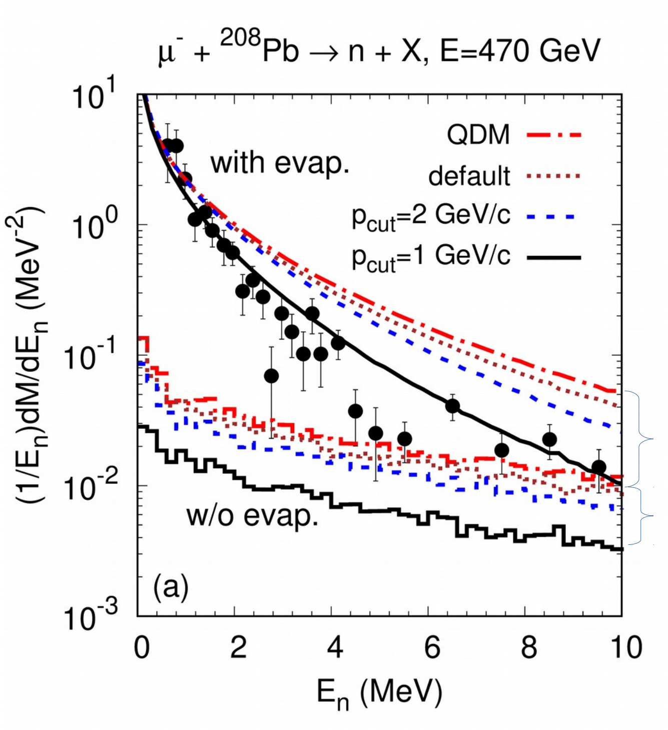
Stronger restriction on FSI of the hadrons results in smaller mass loss and smaller excitation energy.

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

the spread is due to Fermi motion.

AL, M. Strikman, PRC 101, 014617 (2020), arXiv:1812.08231

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



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

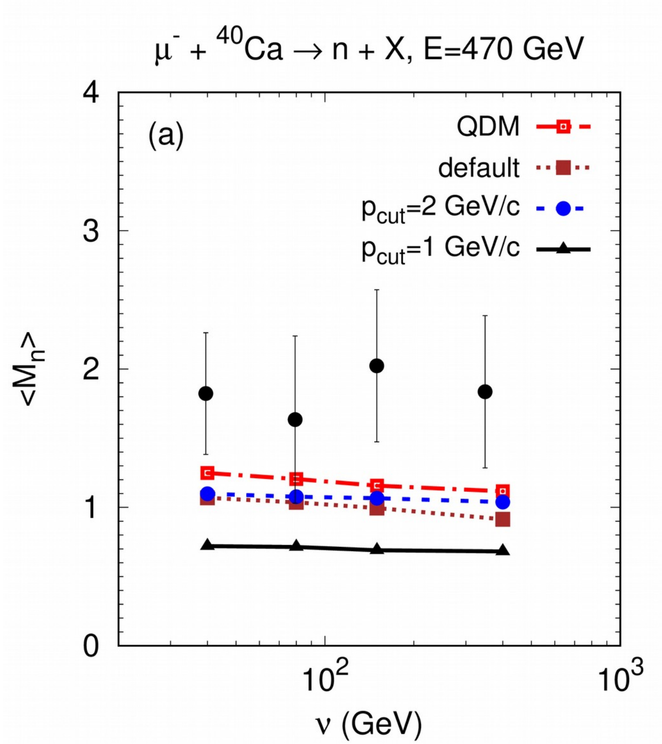
Cuts:
$\nu > 20$ GeV,
$Q^2 > 0.8$ GeV^2.

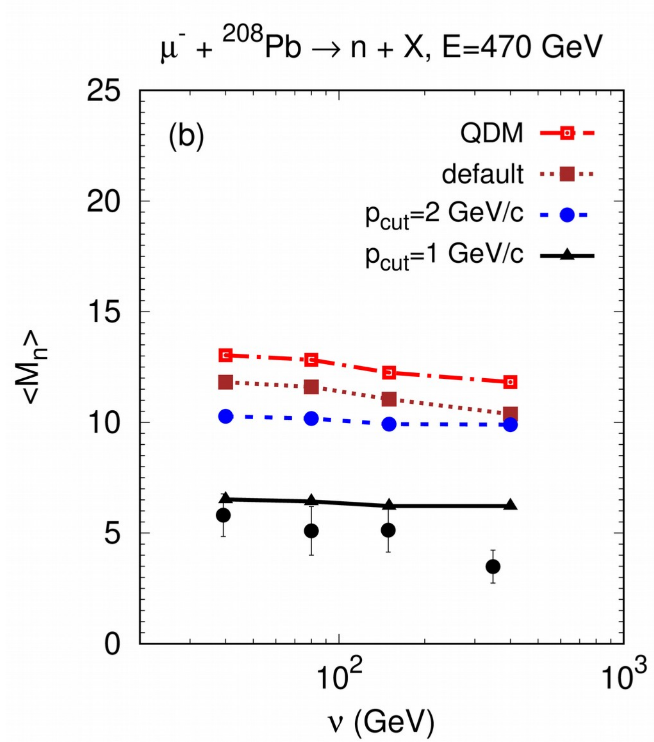
- almost all neutrons below 1 MeV are statistically evaporated;
- sensitivity to the model of hadron formation for $E_n > 5$ MeV;
- E665 data for lead target can be only described with very strong restriction on the FSI of hadrons (p_{cut}=1 GeV/c) in agreement with earlier calculations

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

AL, M. Strikman, PRC 101, 014617 (2020), 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: either problem with data or in the mechanism of interaction of DIS products with nuclear residue

AL, M. Strikman, PRC 101, 014617 (2020), 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.

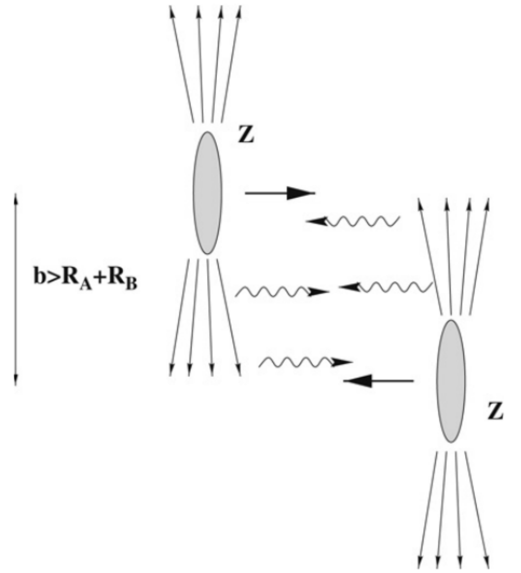


Figure from A.J. Baltz et al., Phys. Rept. 458, 1 (2008)

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:

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

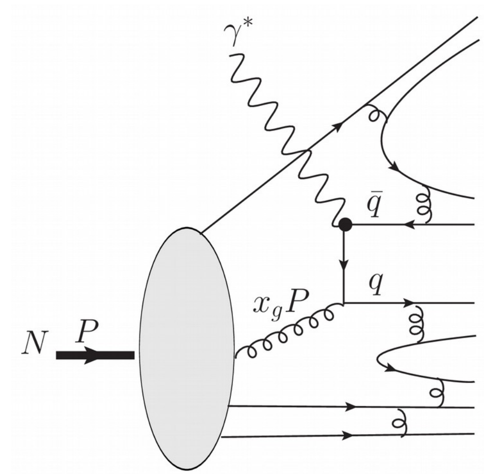
Table 1: Parameters of UPCs Au+Au at RHIC and Pb+Pb at LHC.

	$\sqrt{s_{NN}}$ (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:

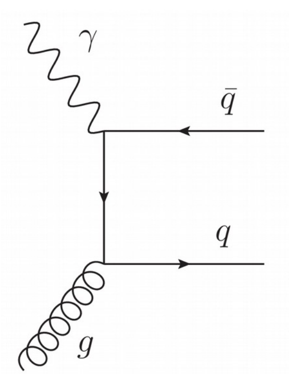
$$x_g \geq x$$



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

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

Daniel Tapia Takaki
talk on Monday



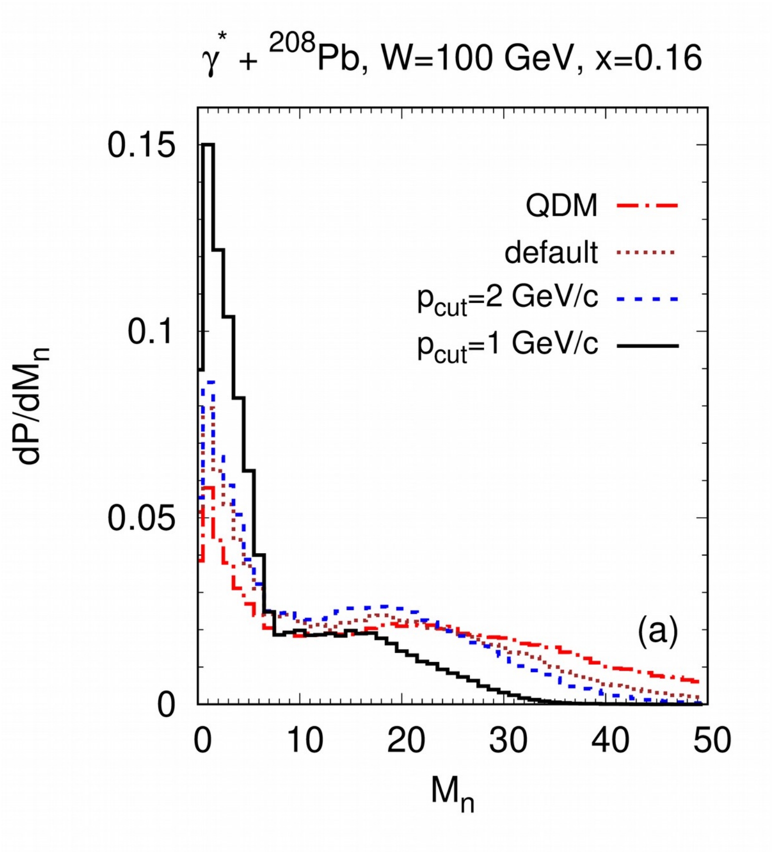
$$x_g = \frac{M_{\bar{q}q}^2}{W^2}\,, \quad M_{\bar{q}q} \simeq |p_t(\mathrm{jet}_1)| + |p_t(\mathrm{jet}_2)| \geq 40\ \mathrm{GeV}$$

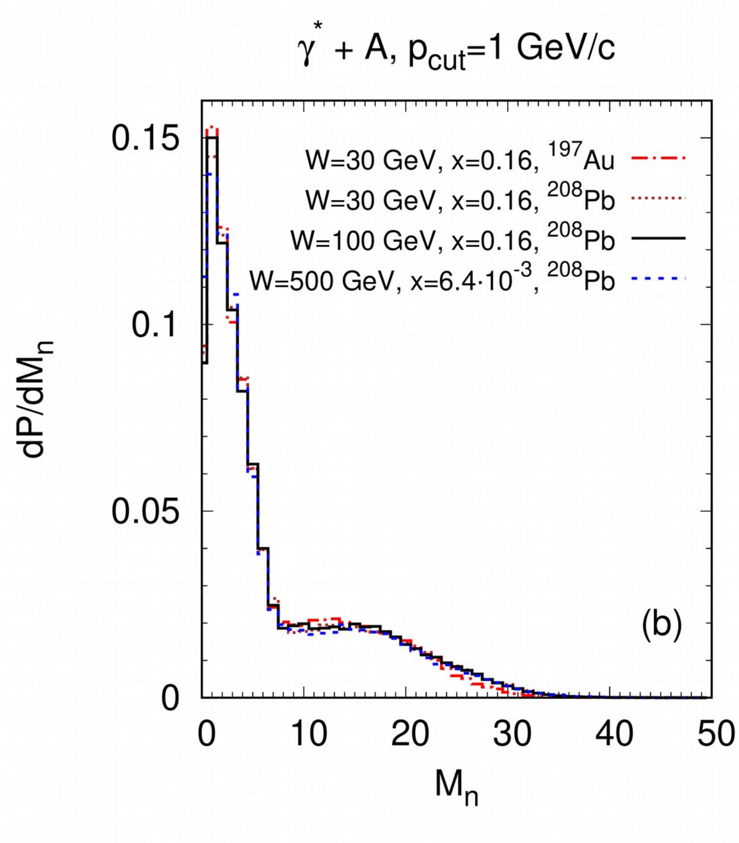
typical setting at LHC for dijets

G. Aad et al. (ATLAS), arXiv:1511.00502

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

Multiplicity distributions of neutrons in quasireal-photon-nucleus collisions



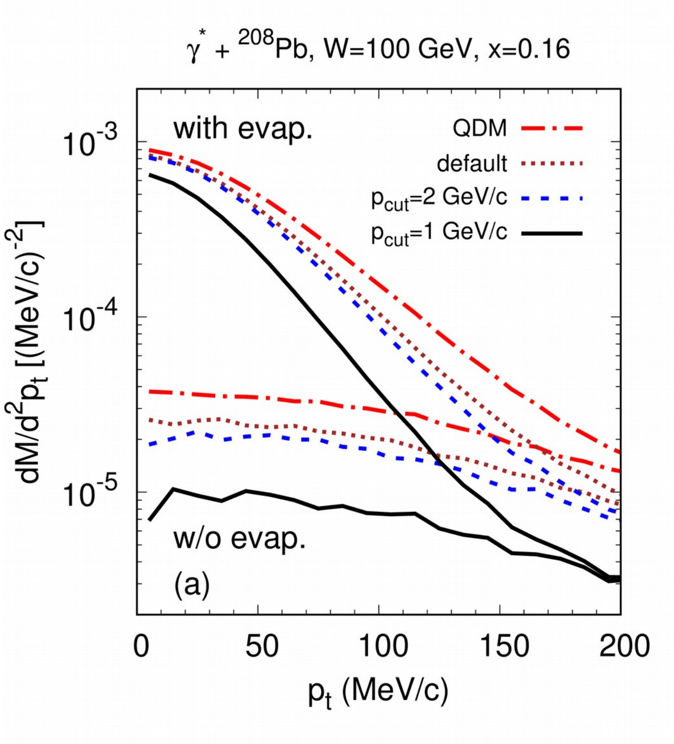


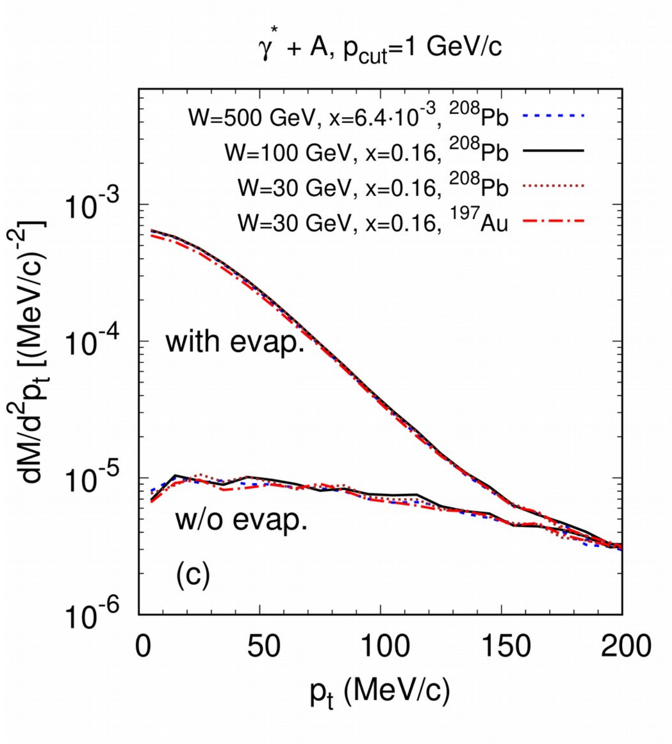
Neutrons in the direction of the target ZDC are selected by the ATLAS detector cut $x_F > 0.1$,
S.N. White, arXiv:1101.2889

Average values: $\overline{M_n} = 17.8$ (QDM), 14.7 (def.), 13.1 (p_{cut} =2 GeV/c), 7.2 (p_{cut} =1 GeV/c)

AL, M. Strikman, PRC 101, 014617 (2020), arXiv:1812.08231

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



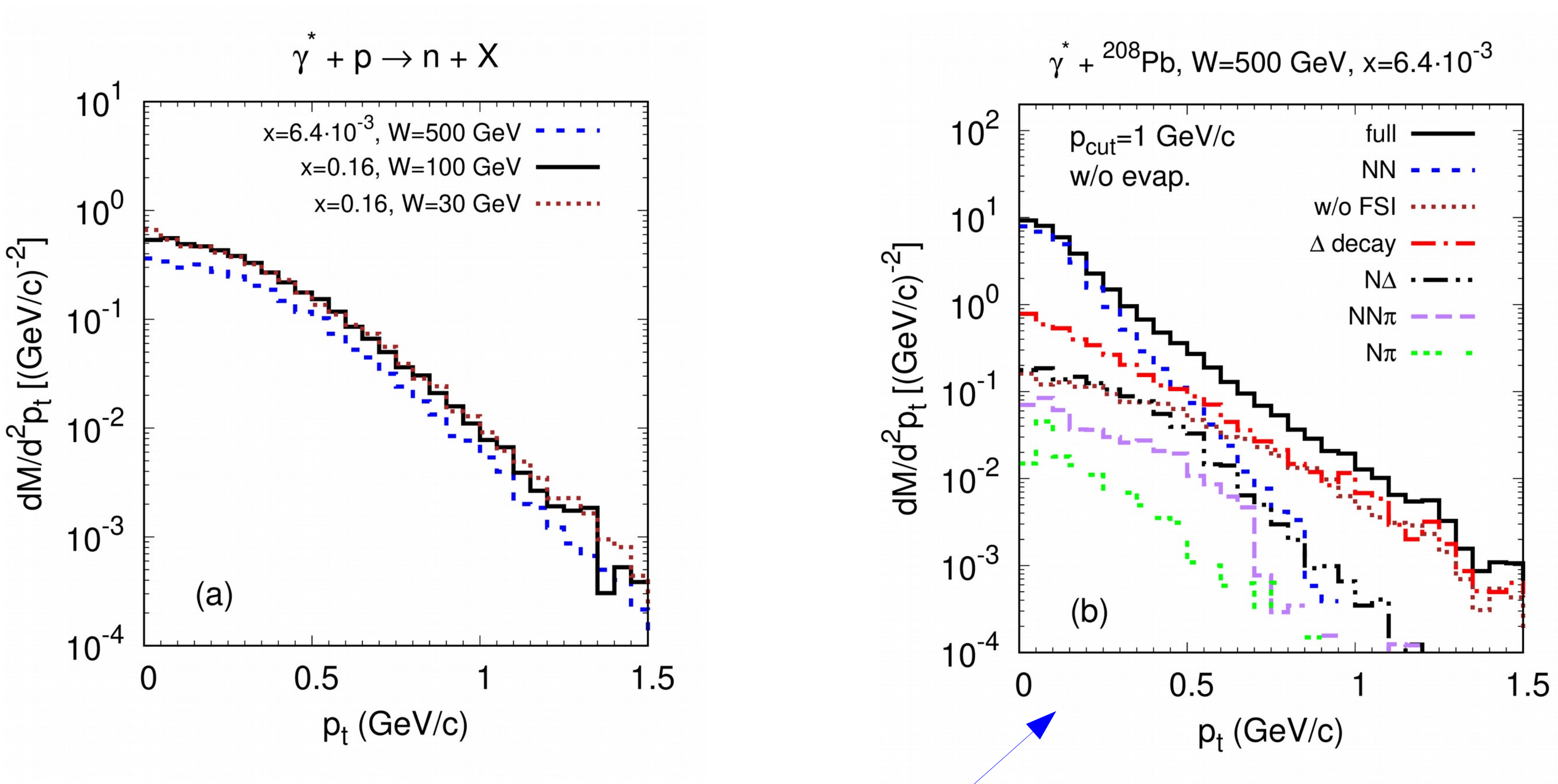


- **strong sensitivity to the hadron formation model at moderate p_t**

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

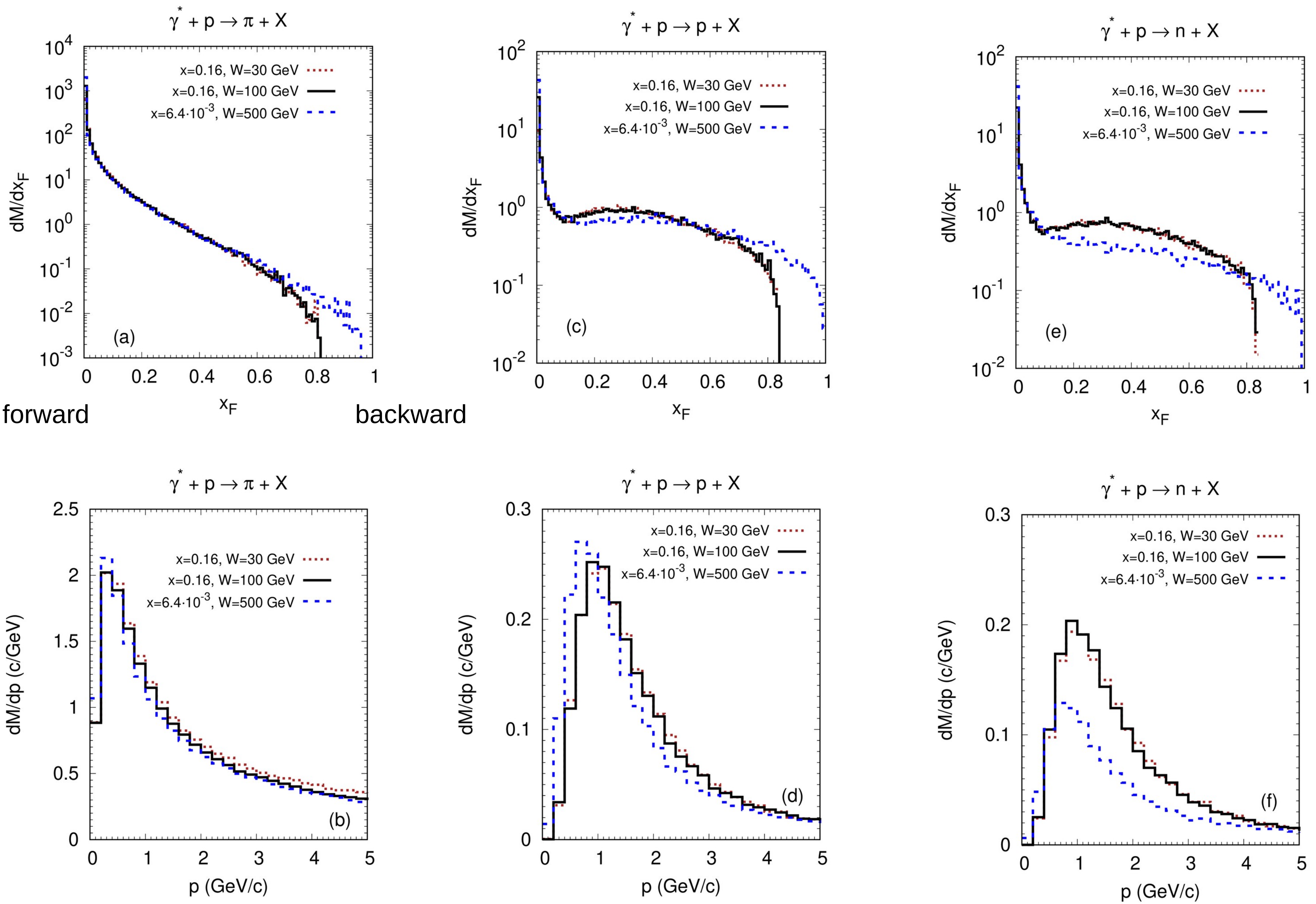
AL, M. Strikman, PRC 101, 014617 (2020), arXiv:1812.08231

How are the neutron spectra composed ?



Low-p_t part dominated by N+N → neutron + X processes induced by primordial nucleons with momenta < 1 GeV/c. Direct neutrons (w/o FSI) practically don't contribute at low p_t !

In the proton r.f., z along γ* momentum: $x_F = \dfrac{E - p^z}{m_N}\ , \quad x_F < 1 - x.$



Conclusions

- Hybrid GiBUU+SMM model is applied to γ*A collisions.

- The multiplicity of slow (E < 10 MeV) neutrons measured in $\mu^{-}+^{208}Pb$ DIS at E_{beam}=470 GeV (E665 experiment at Fermilab) is a factor of 2 smaller than expected from GiBUU+SMM calculations with default treatment of hadron formation and with QDM model of CT. It can be only reproduced if the hadrons with momenta above 1 GeV/c are not allowed to interact with the rest of the nucleus.

-This indicates the presence of a novel dynamics in the production of hadrons in the nuclear fragmentation region.

- Problem with Ca target: neutron multiplicity is underestimated with any assumption on CT.

- Different hadron formation scenaria can be tested by slow neutron production (in the target nucleus frame) in UPCs of heavy ions at the LHC and RHIC and, in long run, at the EIC.