Neutron production in nucleus fragmentation region in UPC

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Why do we need to study neutron production in coincidence with fast particles (jet pair, J/ψ, ...) in UPC ?

- Number of emitted neutrons measures the excitation energy of the nucleus: each neutron takes ≈ 10 MeV of excitation energy.

- Sensitivity to the space-time picture of hadron formation

E665 (μ^-A at 470 GeV) ***M.R. Adams et al., PRL 74, 5198 (1995);***
M. Strikman, M.G. Tverskoy, M.B. Zhalov, PLB 459, 37 (1999);
AL, M. Strikman, PRC 101, 014617 (2020)

- In case of incoherent J/ψ production, the target nucleus emits neutrons with probability close to 1 (neutron tagging). This allows to determine from which nucleus the photon was emitted and, hence, to study the photon energy dependence of J/ψ production at higher energies.

M. Strikman, M. Tverskoy, M. Zhalov, PLB 626, 72 (2005);
V. Guzey, M. Strikman, M. Zhalov, EPJC 74, 2942 (2014)

- Sensitivity to the space distribution of the energy deposition in the nucleus (ph excitation due to $\gamma^* N \rightarrow J/\psi N'$ transition) allows to access nuclear shadowing.

Outline:

- Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) model

- Statistical multifragmentation model (SMM)

- Neutron production in pA, μ^- A DIS - comparison with data

- Predictions for UPC at RHIC and LHC for associated neutron production in 2-jet events

- Decay of a ph configuration excited in a nucleus by interaction with high-energy photon

- Summary

Boltzmann-Uehling-Uhlenbeck (BUU) equation for one-component system of fermions or bosons:

$$(\partial_t + \nabla_{\mathbf{p}_1}\varepsilon_1 \nabla_{\mathbf{r}} - \nabla_{\mathbf{r}}\varepsilon_1 \nabla_{\mathbf{p}_1}) f_1 = \int \frac{g_s d^3 p_2}{(2\pi)^3}\, v_{12} \int d\Omega\, \frac{d\sigma_{12\to 34}}{d\Omega}\, (f_3 f_4 \bar{f}_1 \bar{f}_2 - f_1 f_2 \bar{f}_3 \bar{f}_4)\ ,$$

$f_i \equiv f(\mathbf{r}, \mathbf{p}_i, t)$ - single-particle distribution function (Wigner density),

$\varepsilon_i \equiv \varepsilon(\mathbf{r}, \mathbf{p}_i, t)$ - single-particle energy,

$v_{12} = \sqrt{(p_1 p_2)^2 - (m_1 m_2)^2}/\varepsilon_1 \varepsilon_2$ - relative velocity of colliding particles,

$d\sigma_{12\to 34}/d\Omega$ - angular differential cross-section of elastic scattering,

$\bar{f}_i \equiv 1 \mp f_i$ (upper sign: fermions; lower sign: bosons)

Number of particles:

$$N = \int \underbrace{\frac{g_s d^3 r d^3 p}{(2\pi)^3}}_{\text{Lorentz-invariant}} \underbrace{f(\mathbf{r}, \mathbf{p}, t)}_{\text{Lorentz-invariant}}$$

g_s - spin degeneracy (=2 for nucleon)

Usual non-relativistic Boltzmann equation if $\bar{f}_i = 1,\ \varepsilon = p^2/2m.$

However, with properly defined single-particle energies BUU equation is Lorentz-invariant.

Most numerical models apply the test particle method to solve BUU equation:

G.F. Bertsch, S. Das Gupta, Phys. Rep. 160, 189 (1988)

$$f(\boldsymbol{r},\boldsymbol{p},t) = \frac{(2\pi)^3}{g_s N_{\rm test}} \sum_{n=1}^{N\cdot N_{\rm test}} \delta(\boldsymbol{r}-\boldsymbol{r_n}(t))\delta(\boldsymbol{p}-\boldsymbol{p_n}(t)) \ ,$$

$N_{\rm test}$ - number of test particles per nucleon
(typically ~200-1000 for uniform coverage of phase space)

Hamiltonian equations of motion for centroids:

Formally solving Vlasov equation

$$(\partial_t + \nabla_{\mathbf{p}}\varepsilon\nabla_{\mathbf{r}} - \nabla_{\mathbf{r}}\varepsilon\nabla_{\mathbf{p}}) f(\mathbf{r},\mathbf{p},t) = 0$$

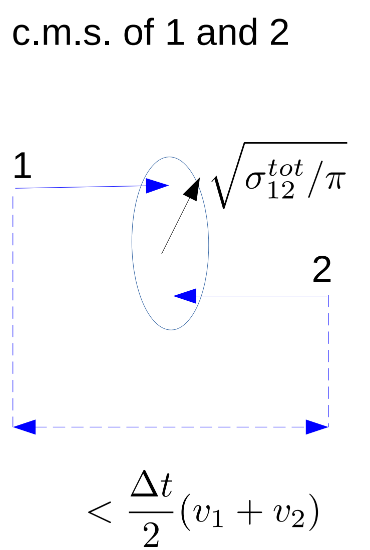
$$\begin{cases} \dfrac{d\boldsymbol{r_n}}{dt} = \dfrac{\partial\varepsilon(\boldsymbol{r_n},\boldsymbol{p_n},t)}{\partial\boldsymbol{p_n}} \ , \\ \dfrac{d\boldsymbol{p_n}}{dt} = -\dfrac{\partial\varepsilon(\boldsymbol{r_n},\boldsymbol{p_n},t)}{\partial\boldsymbol{r_n}} \ . \end{cases}$$

Collision term is modeled within the geometrical minimum distance criterion:

Drawback: collision ordering depends on the frame.

In modern transport codes (incl. GiBUU) done better with Kodama recipe restoring Lorentz invariance (approximately)

T. Kodama et al., PRC 29, 2146 (1984)



- If particles 1 and 2 collide, the final state “f” is sampled by Monte-Carlo:

$$P_f = \frac{\sigma_f}{\sigma_{12}^{\rm tot}} \ , \quad \sum_f \sigma_f = \sigma_{12}^{\rm tot}$$

- Empirical or theoretical c.m. angular distributions for elastic and inelastic scattering $NN \to NN$, $NN \leftrightarrow N\Delta$ etc.

- Resonance production and decay, e.g. $\pi N \to \Delta,\ \Delta \to \pi N$

isospin dependent partial decay width; total width

$$\sigma_{\pi N \to \Delta}(\sqrt{s}) = \frac{4\pi}{q^2(\sqrt{s})} \frac{2s\Gamma_{\Delta\to\pi N}(\sqrt{s})\Gamma_\Delta(\sqrt{s})}{(s-m_\Delta^2)^2 + s\Gamma_\Delta^2(\sqrt{s})} \ , \quad q(\sqrt{s}) = \sqrt{(s+m_\pi^2-m_N^2)^2/4s - m_\pi^2}$$

c.m. momentum of pion and nucleon

$$P_{\rm decay} = 1 - {\rm e}^{-\Gamma_\Delta \Delta t/\gamma}$$

- Collision or decay is accepted with probability

$$P = \prod_{i=1}^{n_{\rm nucl}} [1 - f_i(\boldsymbol{r}, \boldsymbol{p}_i, t)]$$

$n_{\rm nucl}$ - number of outgoing nucleons

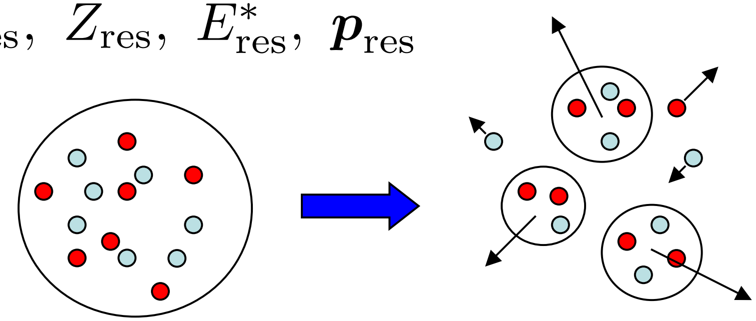
…. and more ..., see details of GiBUU: ***O. Buss et al., Phys. Rep. 512, 1 (2012)***

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:

$A_{\rm res},\ Z_{\rm res},\ E^*_{\rm res},\ \boldsymbol{p}_{\rm res}$



● -p

○ -n

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

probability (→ $W_{\text{partition}}$)

entropy (→ $S_{\text{partition}}$)

Hybrid GiBUU+SMM

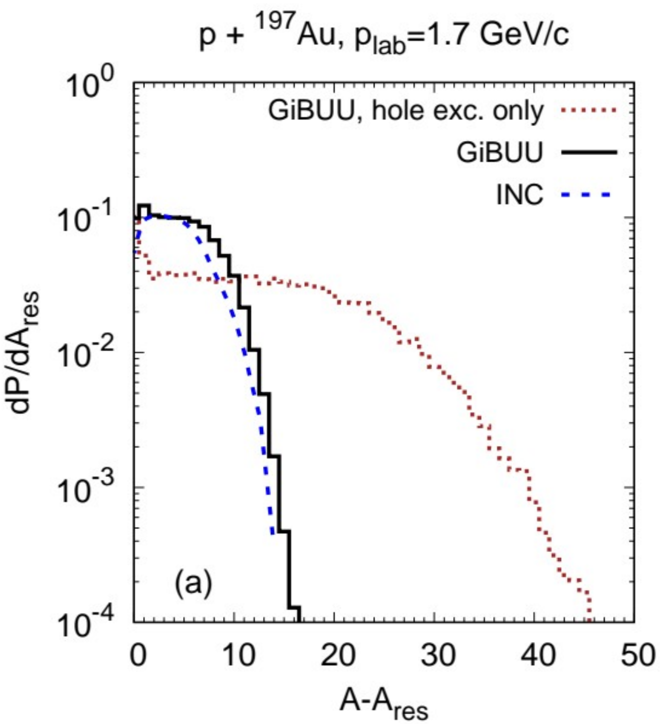
- **Non-Equilibrium dynamics within BUU until residue approaches stable configuration and local equilibration.**
- **Determination of parameters of the residue** $A_{\rm res},\ Z_{\rm res},\ E^*_{\rm res},\ \boldsymbol{p}_{\rm res}$
- **Apply SMM**

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

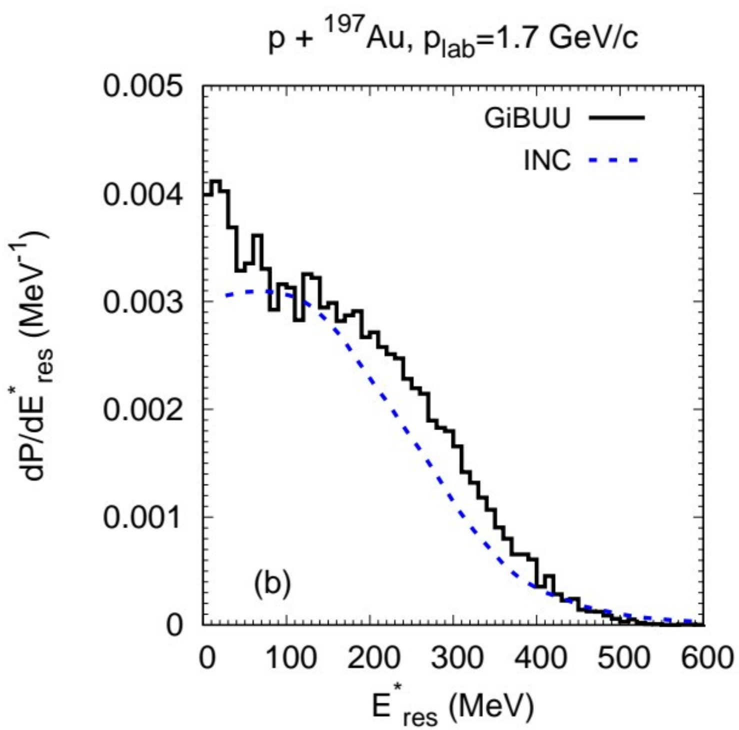
Excited nuclear residue in pA collisions

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

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



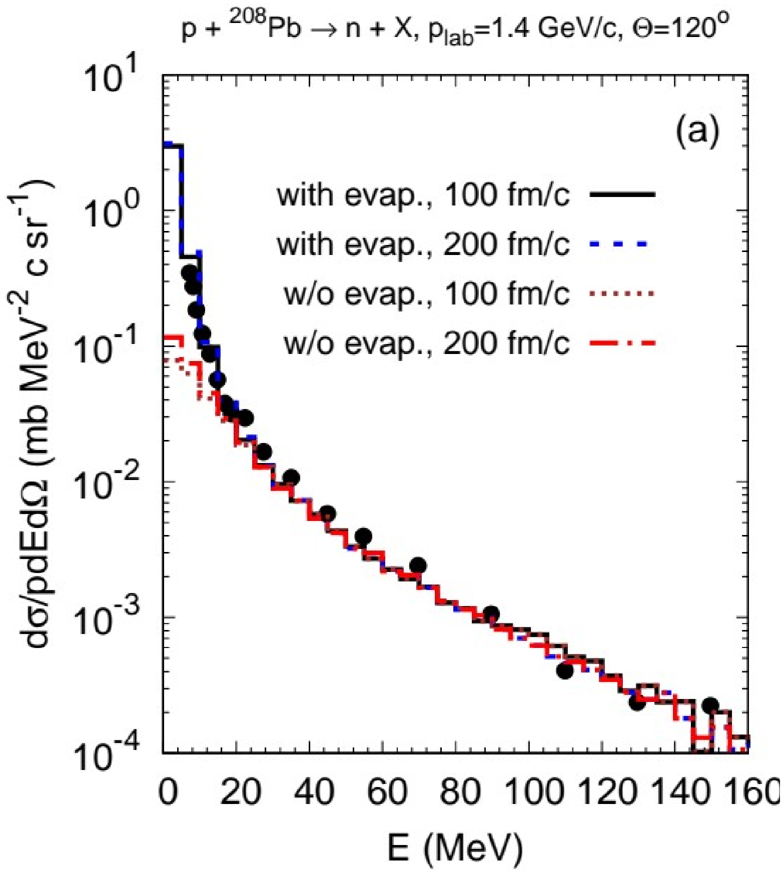
A_{res}, Z_{res} and $\boldsymbol{p}_{res}$ redefined by counting bound particles

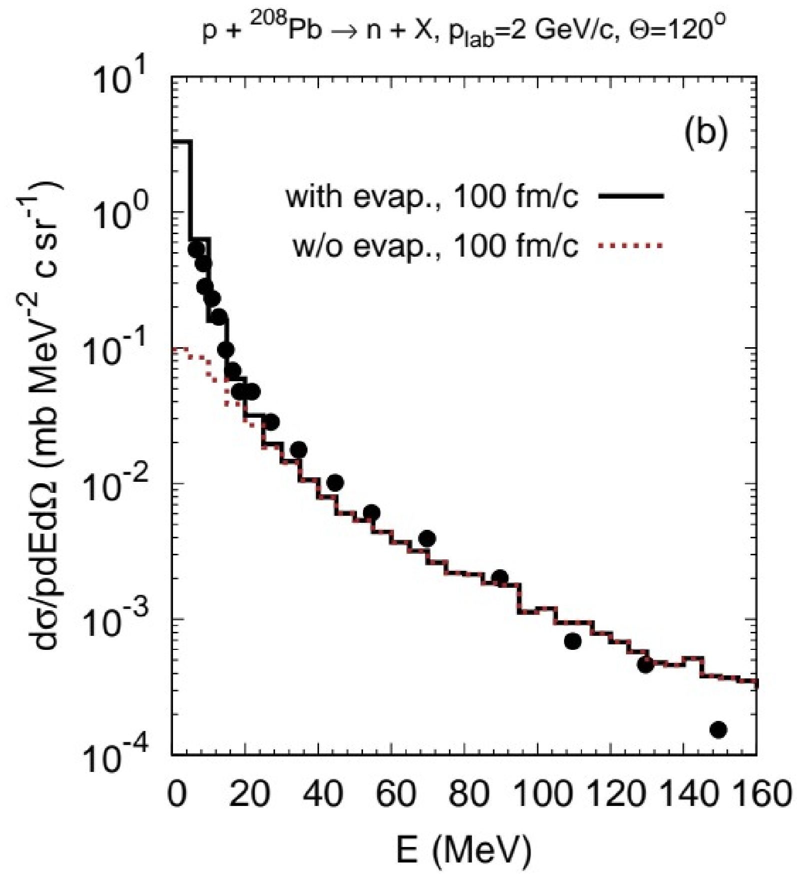


AL, M. Strikman, PRC 101, 014617 (2020), arXiv:1812.08231

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

Neutron energy spectra from pA collisions





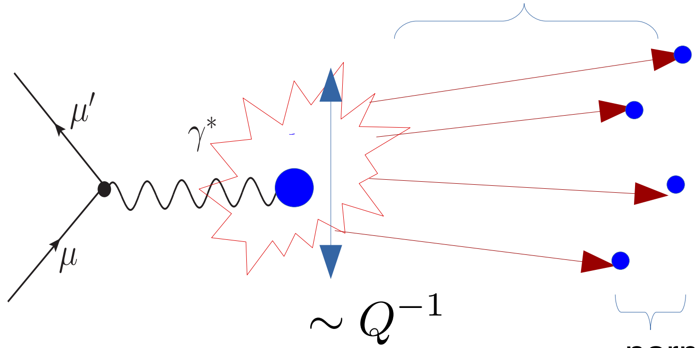
- high-energy part well described by GiBUU alone,
  low-energy part needs statistical evaporation from SMM

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

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

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)

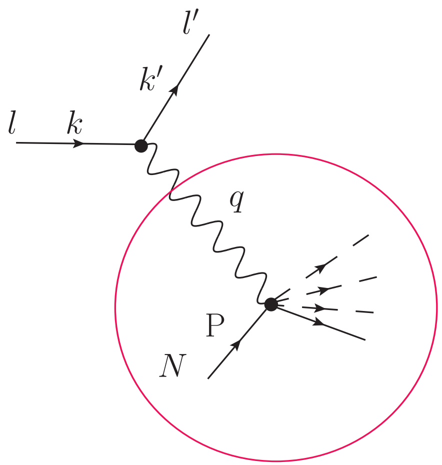
$E_{\mu^-} = 470$ GeV, H, D, C, Ca, Pb targets
$Q^2 > 0.8$ GeV^2, $\nu > 20$ GeV
low-energy neutrons ($E < 10$ MeV)

- Nucleus may serve as a "microcalorimeter" for high-energy hadrons : the excitation energy of the residual nucleus grows with the number of holes (wounded 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).

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 $dP_i = \frac{\rho_i(\boldsymbol{r}) d^3r}{A} \ , \quad i = p, n \ .$

- outgoing lepton is sampled by using differential cross section

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

taken from PYTHIA

$\Omega \ , \ E'$ - 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

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

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

(I) Based on JETSET-production-formation points (GiBUU default) favored 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)***

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

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

r_{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)

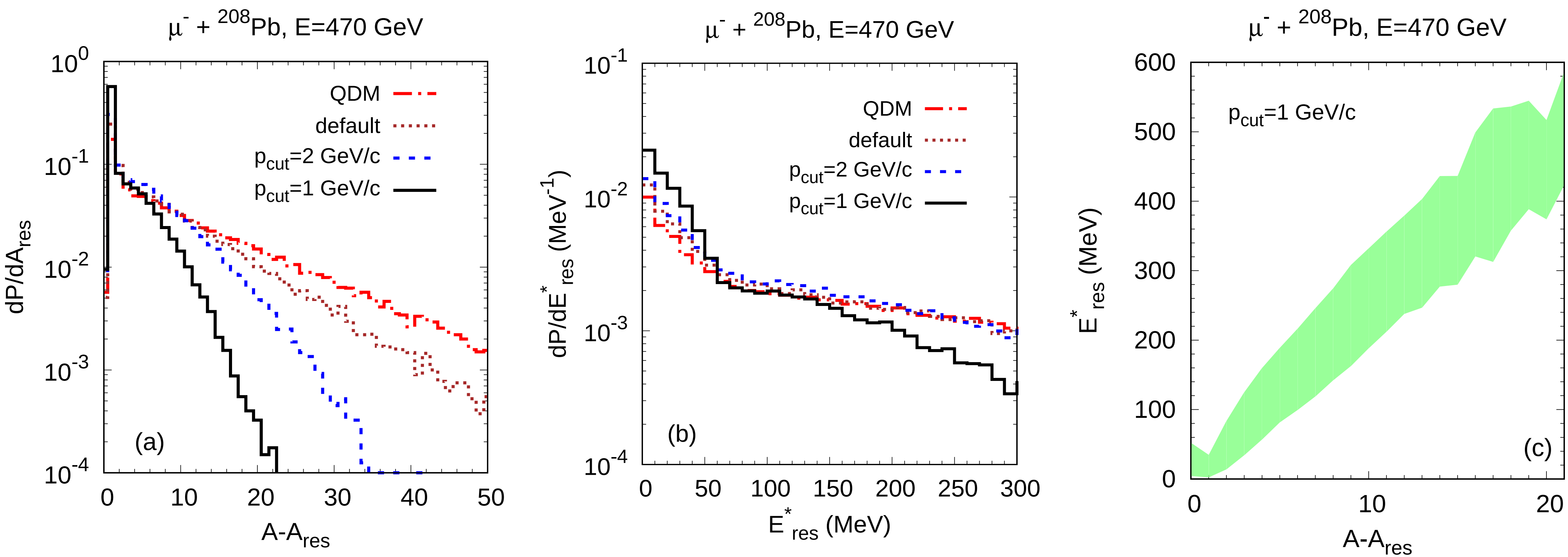
$$\sigma_{\text{eff}}(t)/\sigma_0 = X_0 + (1 - X_0)\frac{c(t - t_{\text{hard}})}{l_h} \ ,$$

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

(III) Cutoff:

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

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



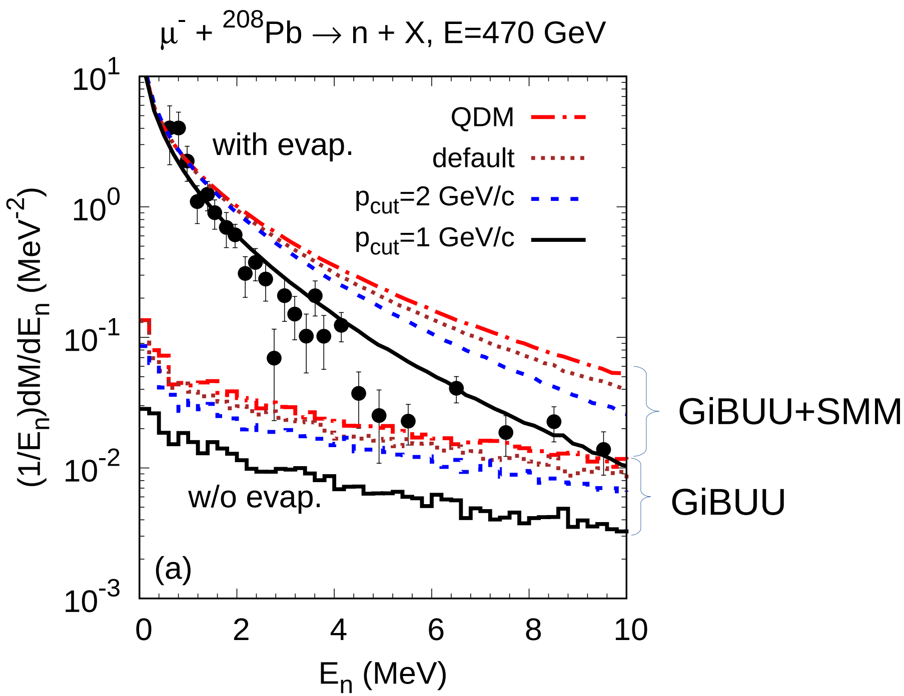
Stronger restriction on FSI of the hadrons results in smaller mass loss and smaller excitation energy.

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

the spread is due to Fermi motion.

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

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



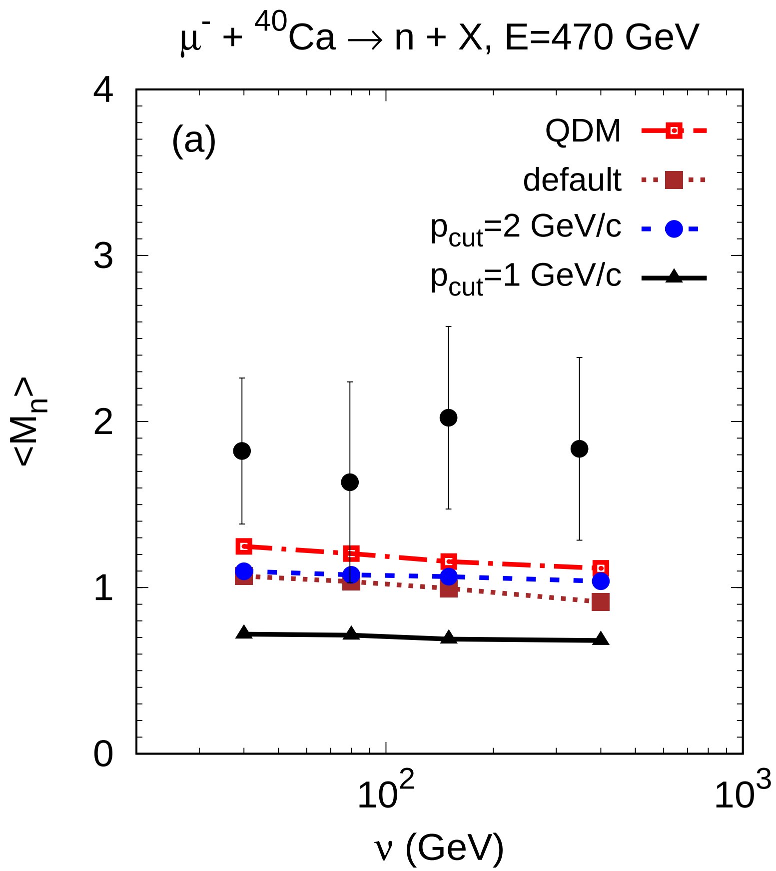
E665 data from
M.R. Adams et al., PRL 74, 5198 (1995)

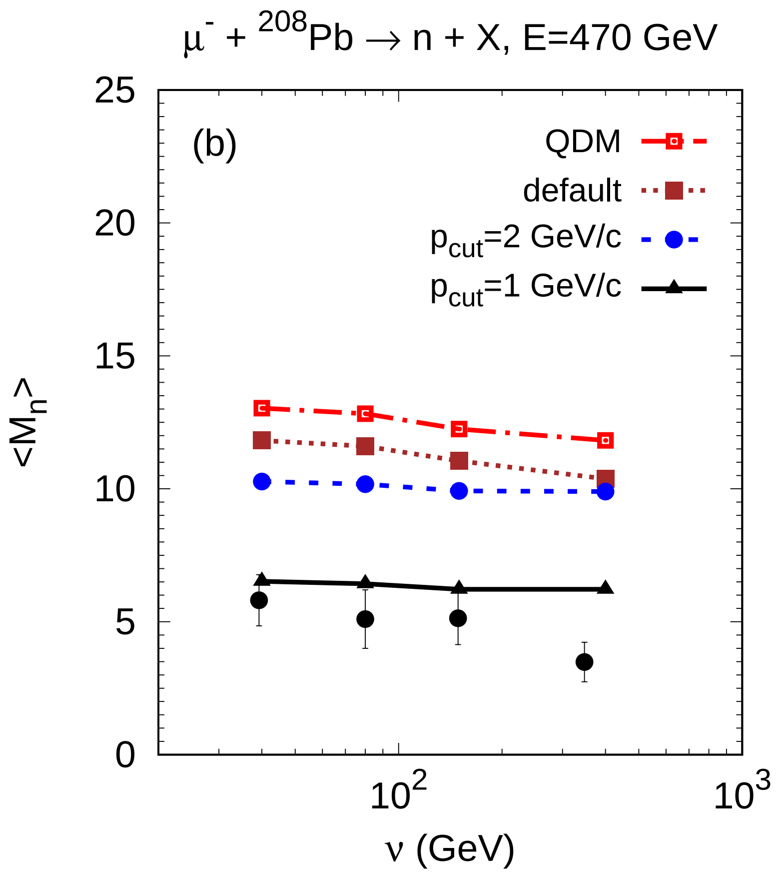
Cuts:
$\nu > 20\ \mathrm{GeV},$
$Q^2 > 0.8\ \mathrm{GeV}^2.$

- 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.

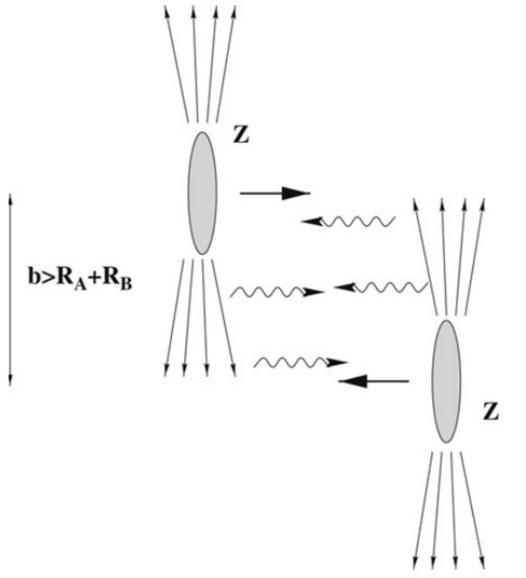


Figure from A.J. Baltz et al., Phys. Rept. 458, 1 (2008)

→ 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:

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

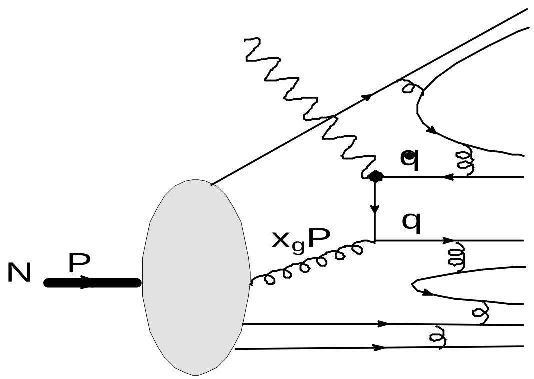
Table 1: Parameters of UPCs Au+Au at RHIC and Pb+Pb at LHC.

	$\sqrt{s_{NN}}$ (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*.

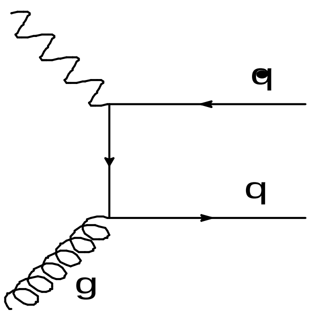
For inclusive set of PYTHIA events:

$$x_g \geq x$$



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

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



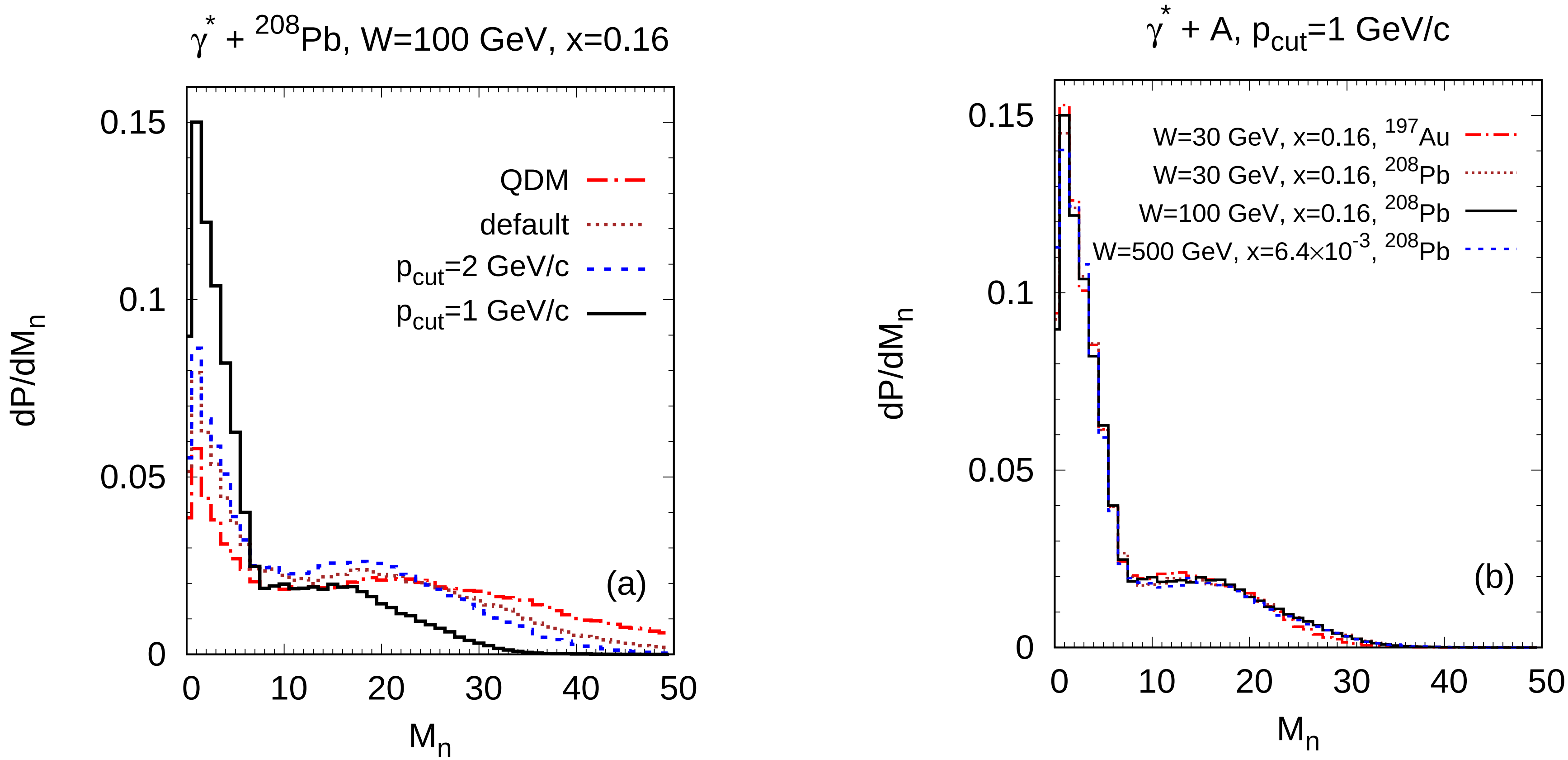
$$x_g = \frac{M_{\bar{q}q}^2}{W^2}\ , \quad M_{\bar{q}q} \simeq |p_t(\mathrm{jet}_1)| + |p_t(\mathrm{jet}_2)| \geq 40\ \mathrm{GeV}$$

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

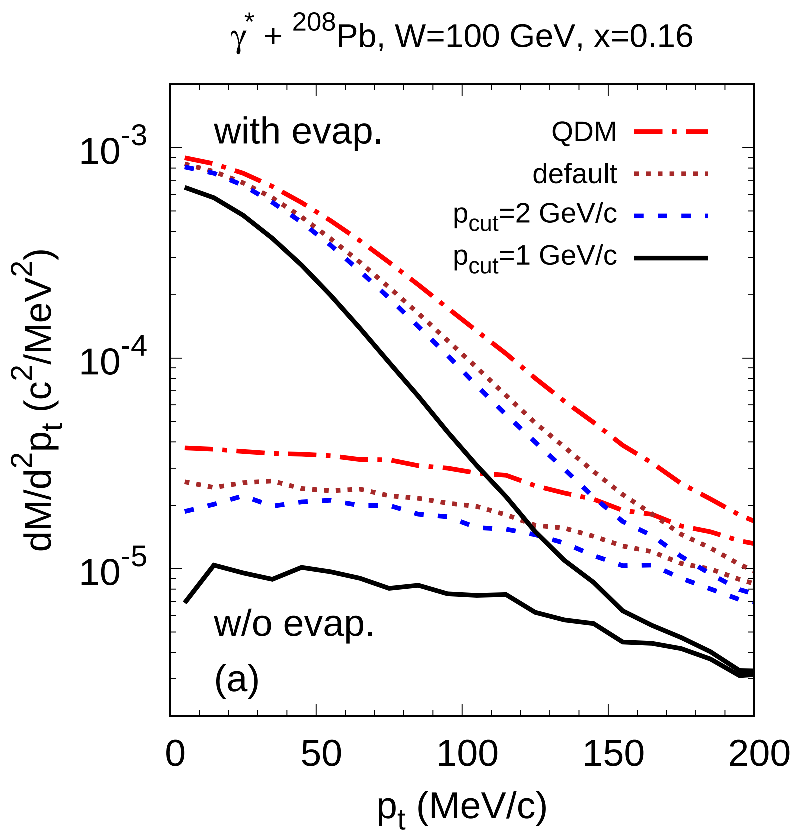


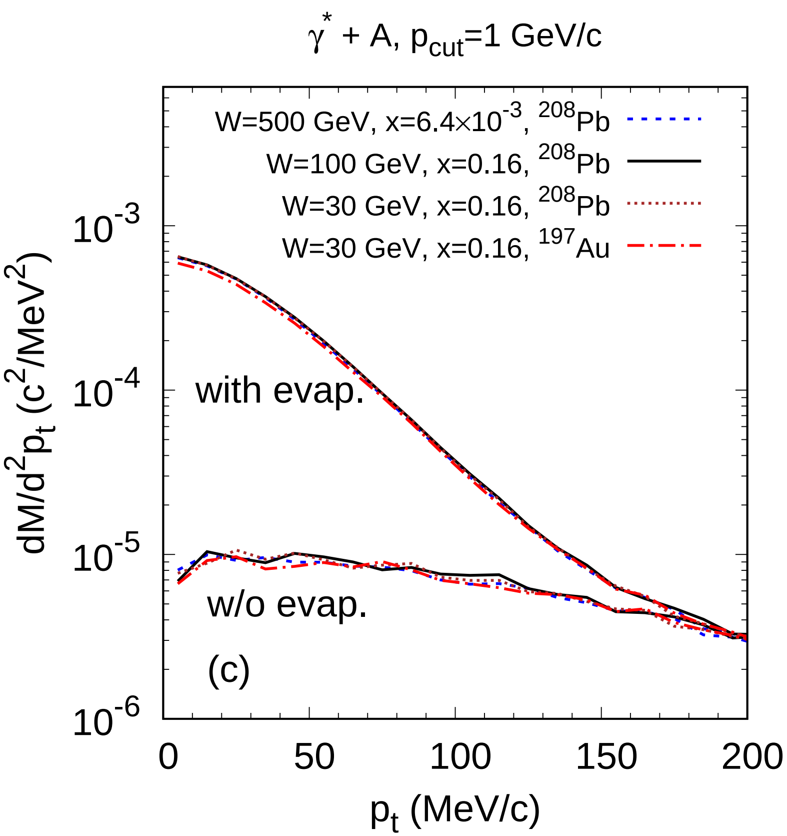
Neutrons in the direction of the target ZDC are selected by the ATLAS detector cut $x_F > 0.1$,
S.N. White, arXiv:1101.2889

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



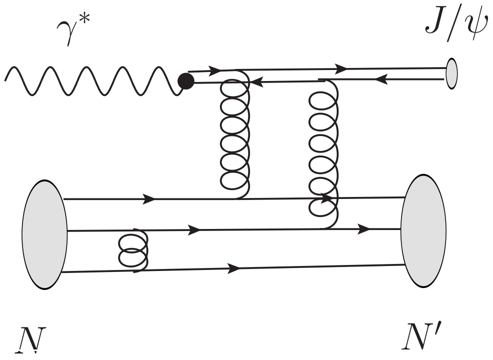


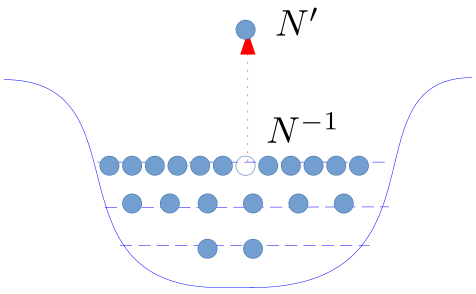
- **strong sensitivity to the hadron formation model at moderate p_t**

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

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

Decay of a ph configuration





- Struck nucleon N is chosen (equal probability for every particle):

$$dP_i = \frac{2d^3r d^3p}{A(2\pi)^3} f_i(\boldsymbol{r}, \boldsymbol{p}) \ , \quad i = n, p$$

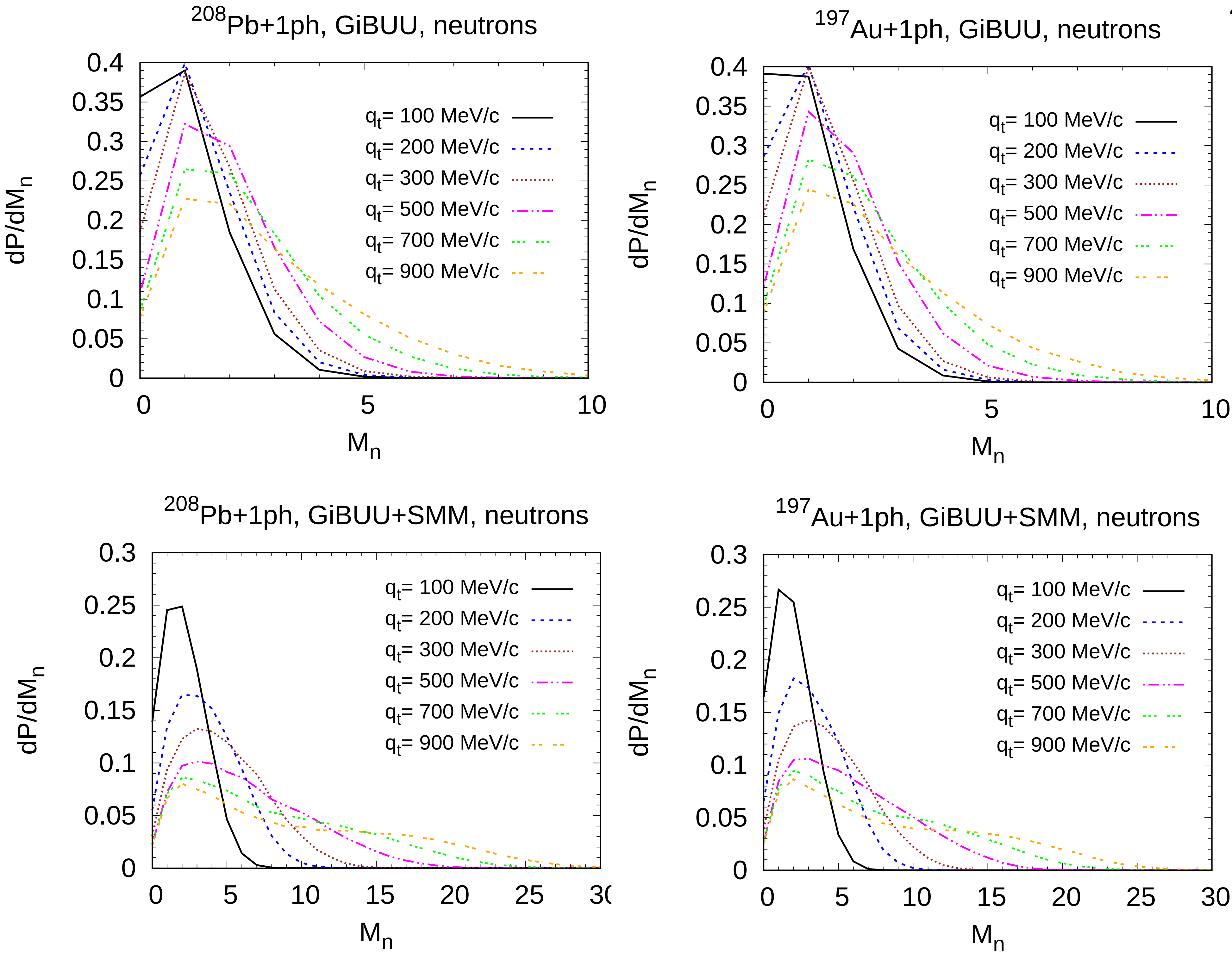
- Assumed transverse momentum transfer and “-” momentum conservation, i.e.

$$\boldsymbol{p}_{N't} = \boldsymbol{p}_{Nt} + \boldsymbol{q}_t \ ,$$
$$E_{N'} - p^z_{N'} = E_N - p^z_N \ . \qquad \text{(z along photon momentum)}$$

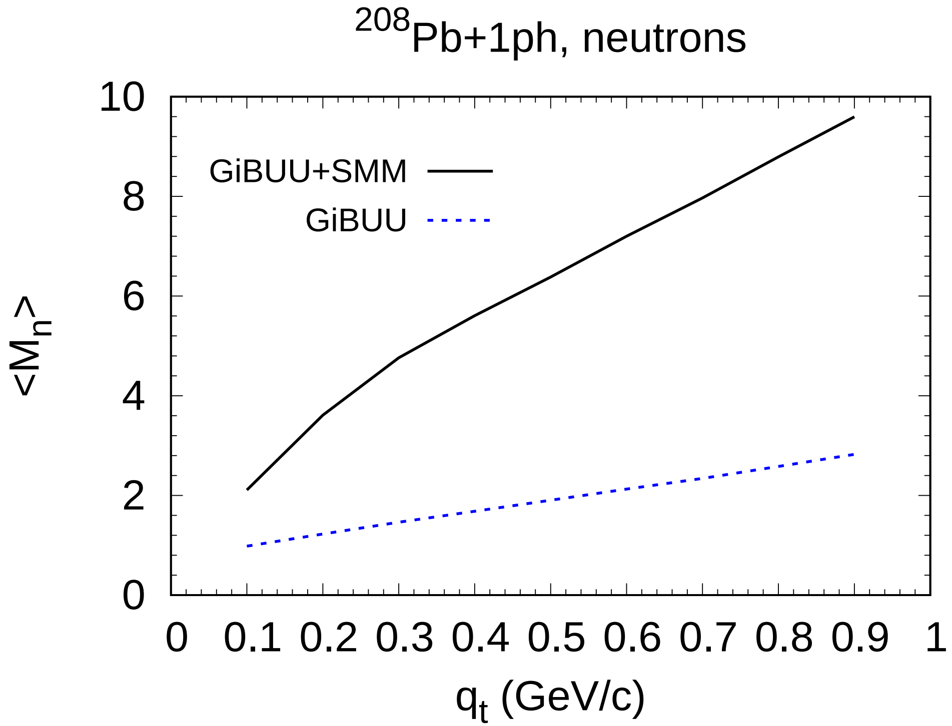
- Pauli blocking for N’ is respected

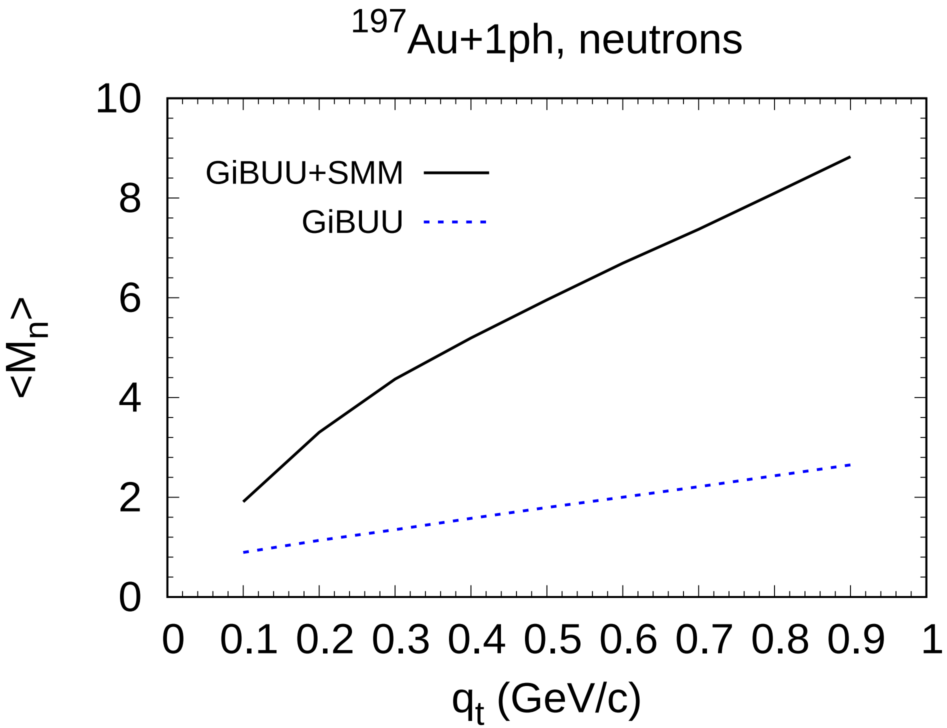
- Excited ph configuration will decay to more and more complex nuclear states until the nucleus finally emits several particles (mostly neutrons and photons)

AL, M. Strikman, work in progress



^{208}Pb+1ph, GiBUU, neutrons
^{197}Au+1ph, GiBUU, neutrons
^{208}Pb+1ph, GiBUU+SMM, neutrons
^{197}Au+1ph, GiBUU+SMM, neutrons
dP/dM$_n$
M$_n$
q$_t$= 100 MeV/c
q$_t$= 200 MeV/c
q$_t$= 300 MeV/c
q$_t$= 500 MeV/c
q$_t$= 700 MeV/c
q$_t$= 900 MeV/c





- About 50-60% of neutrons are statistically evaporated

Shadowing effects

- At high energies the inelastic J/ψN cross section dominates, elastic cross section is small

- Large coherence length of a photon:

$$l_c = \frac{2\omega}{Q^2 + m^2_{J/\psi}}$$

- Photon interacts with a nucleus via its hadronic (J/ψ) component

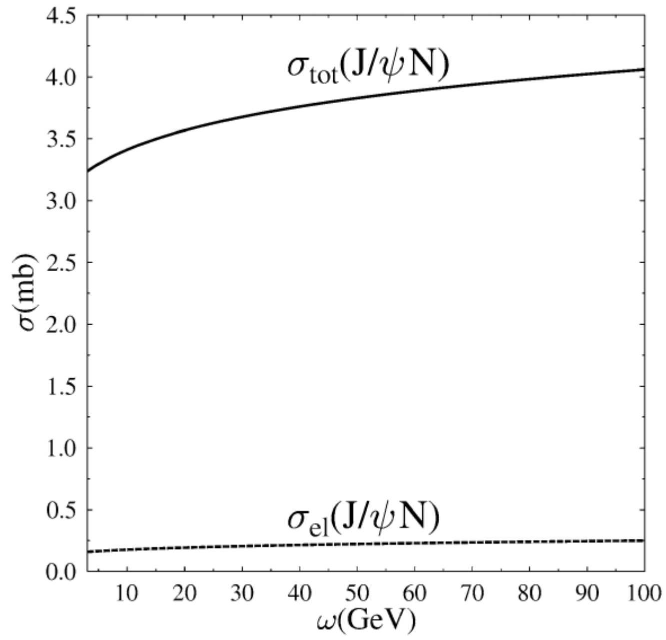


Fig. 4. The elastic and the total J/ψ-nucleon cross section in dependence of the energy of the J/ψ in the rest frame of the nucleon.

Taken from L. Gerland et al., PLB 619, 95 (2005)

- The struck nucleon should be chosen with a “shadowed” probability distribution

$$dP_i^{\rm shad} \propto d^3r d^3p f_i(\boldsymbol{r},\boldsymbol{p}) \exp[-\sigma^{\rm inel}_{J/\psi N} \int_{-\infty}^{+\infty} dz' \rho(\boldsymbol{b},z')] \ , \quad i=n,p$$

Summary

- Hybrid GiBUU+SMM model is constructed and tested by comparison with neutron production data in pA collisions and μ^-A DIS.

- Sensitivity of slow neutron production in high-energy γ^*A collisions (two-jet events) to the hadron formation length.

- $\gamma^* N \rightarrow J/\psi N'$ reaction on the bound nucleon leads to the ph excitation in the nucleus that should decay by emitting neutrons. Expected sensitivity of the neutron multiplicity distributions to the photon shadowing pattern.