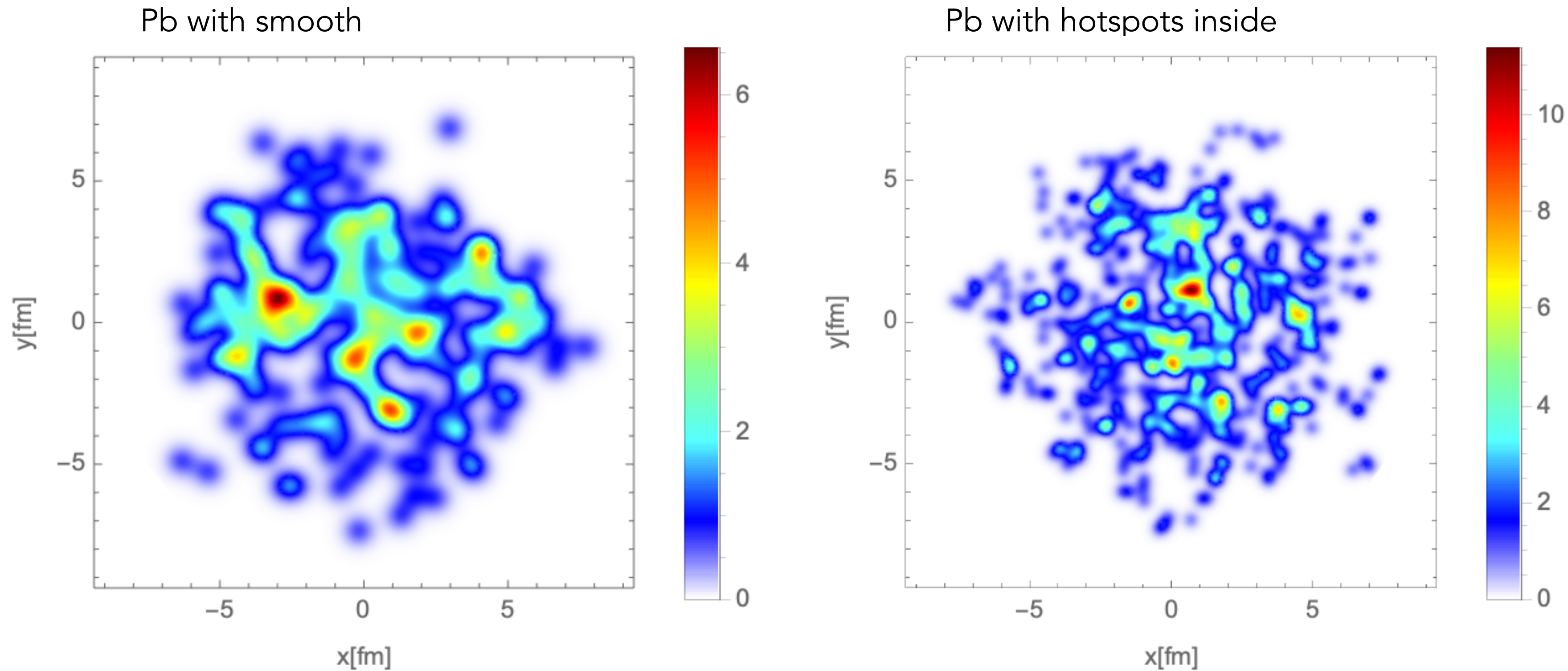


Centrality determination in eA collisions using BeAGLE++

Gluon Saturation, Diffraction and Multihadron Production at the EIC, July 2026

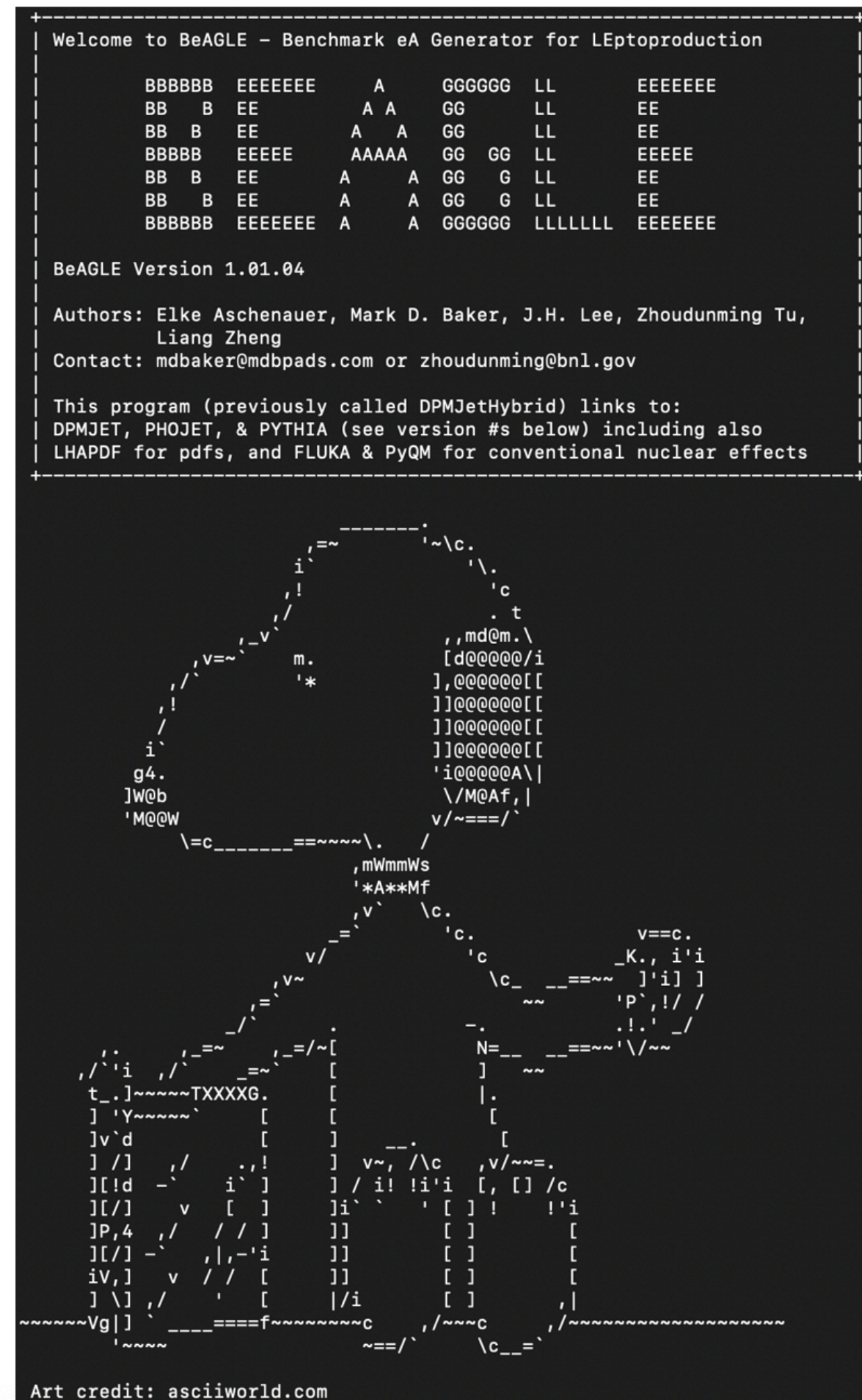
Arjun Kumar in collaboration with Zhoudunming Tu

Connecting Centrality Determination to Saturation Observables



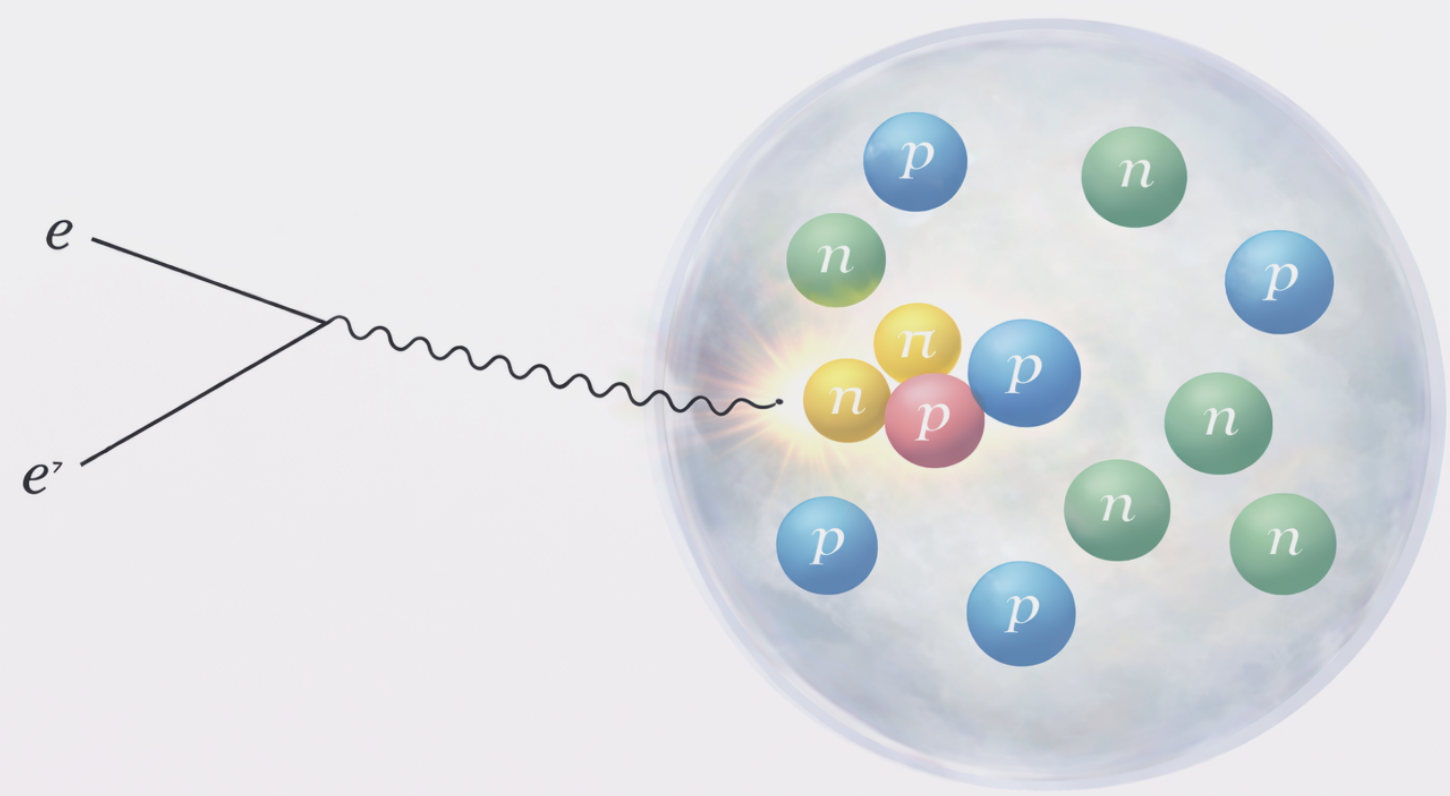
$Q_S \sim T(b)$, Centrality based measurement could enhance : Nuclear modification of hadron production, Transverse momentum broadening, Dihadron azimuthal decorrelation, Diffractive observables at small-x etc.

BeAGLE: A General Purpose Event Generator



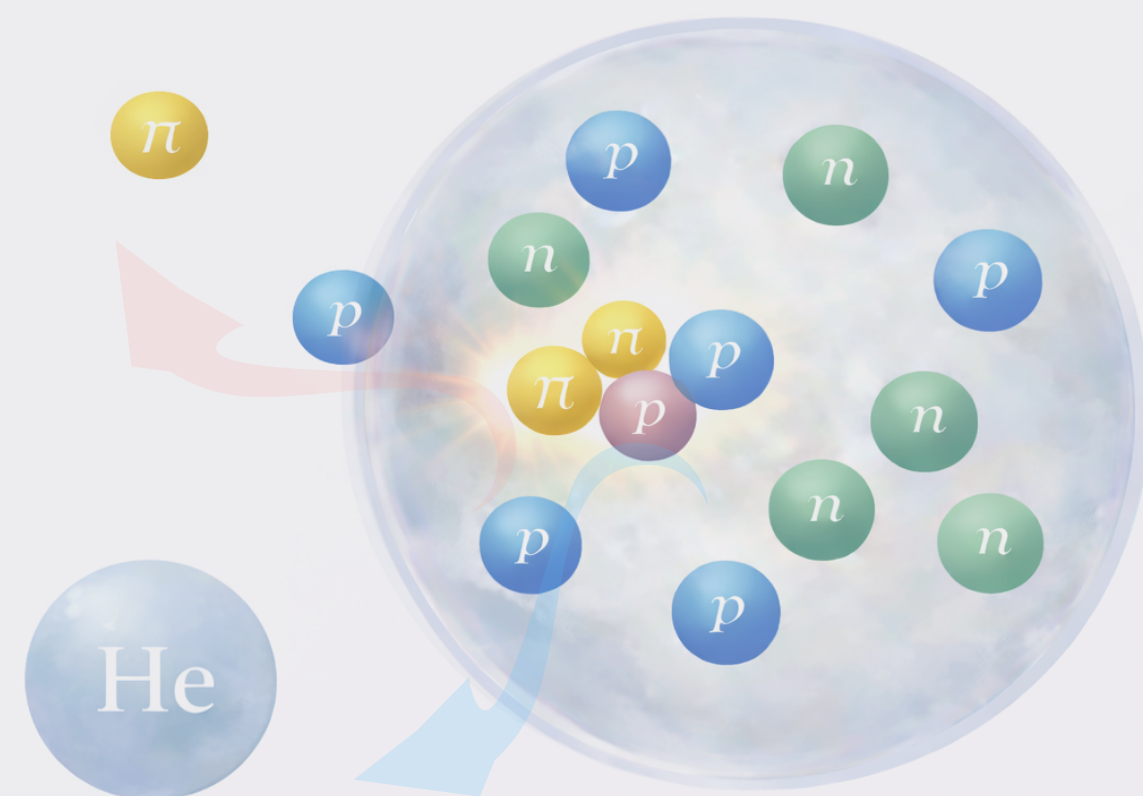
- **Benchmark eA Generator for LEptoproduction** is a Monte Carlo event generator developed for simulating **eA** collisions
- Developed to provide a realistic description of both the *hard scattering process* and the *nuclear final state*, making it a key tool for EIC physics studies
- Particle production in target fragmentation region, Tagged-DIS, Incoherent vector meson production
- Provides a realistic framework for studying the geometry dependence of QCD observables, including potential saturation signatures

Nuclear Breakup in BeAGLE



$t = 0$

DIS on a nucleon

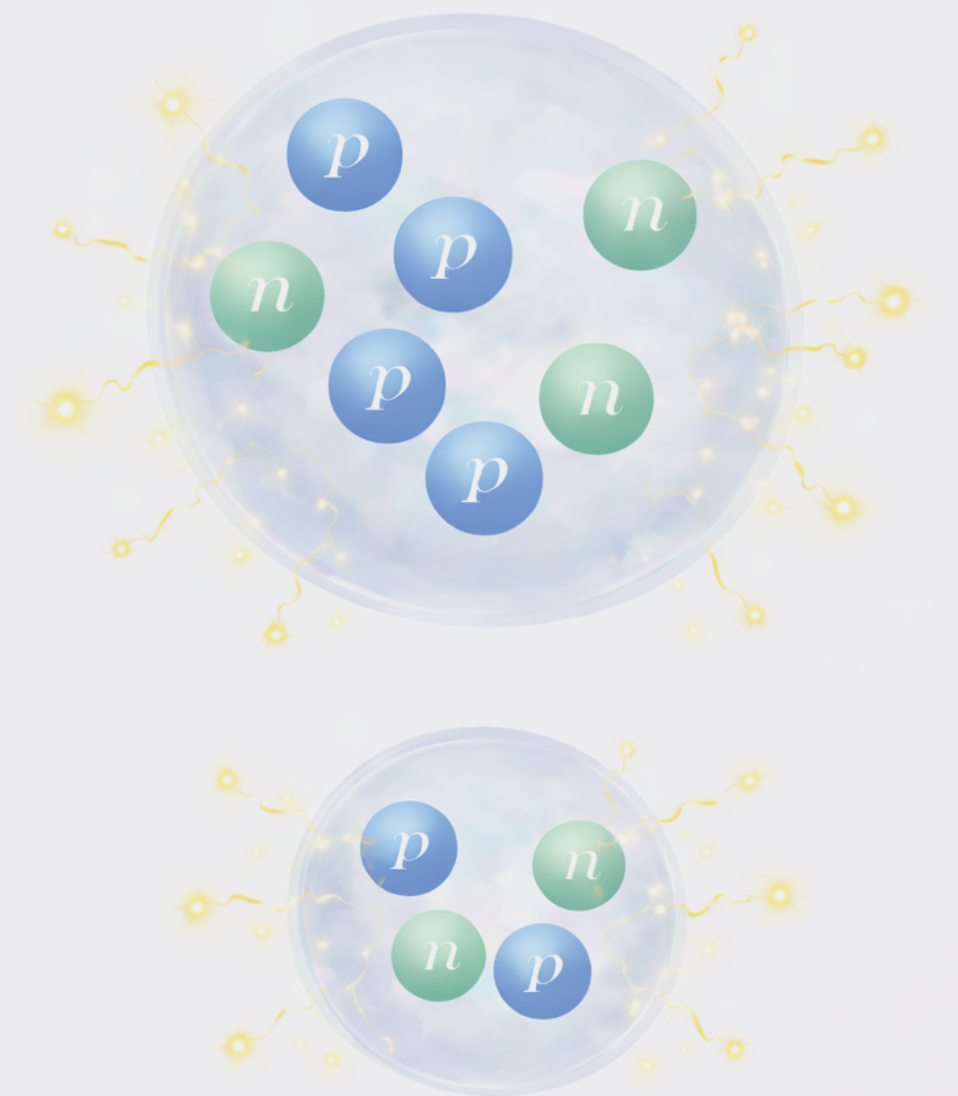


$t = 10^{-22}$ s

Final State Interactions



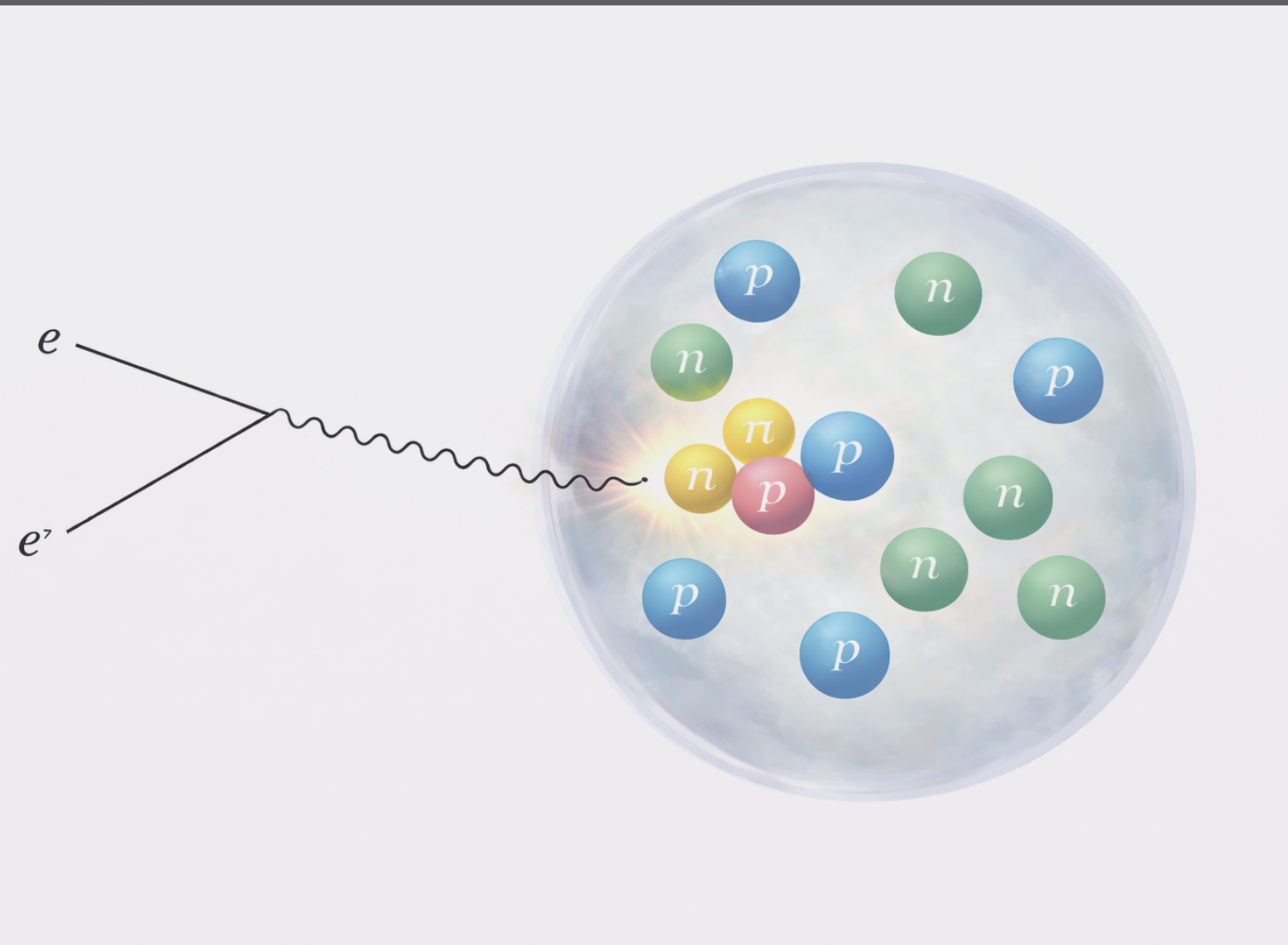
$t = 10^{-20} - 10^{-17}$ s



$t = 10^{-14}$ s

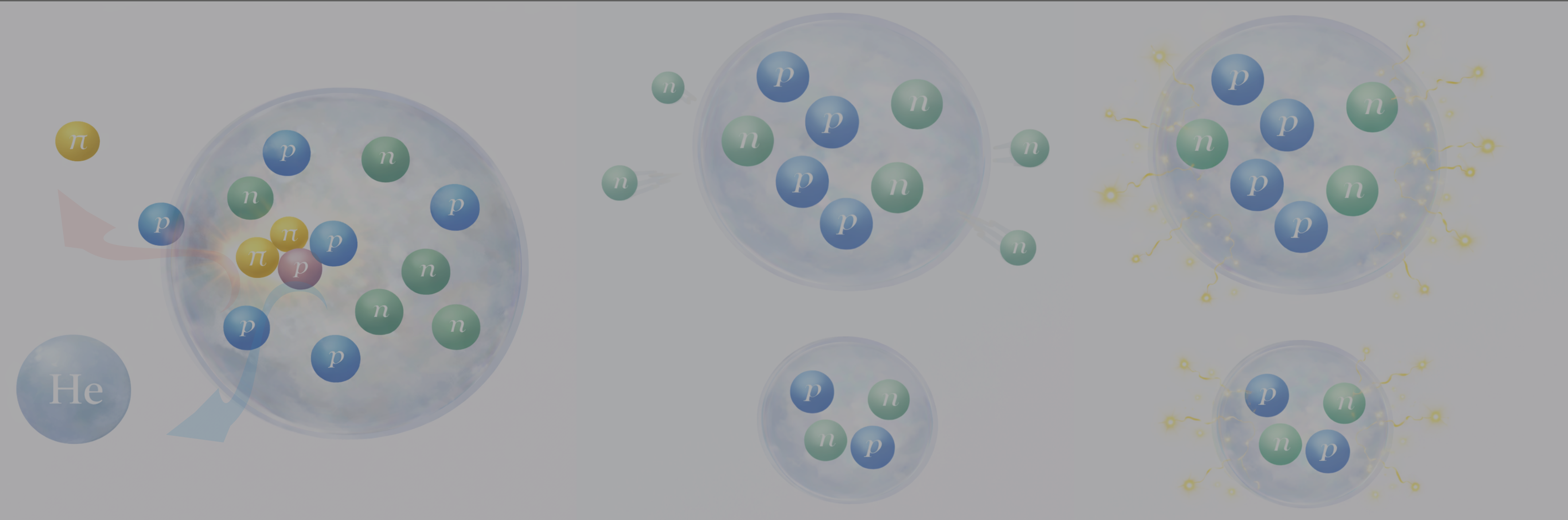
De-excitation

BeAGLE Model



$t = 0$

DIS on a nucleon



Final State Interactions

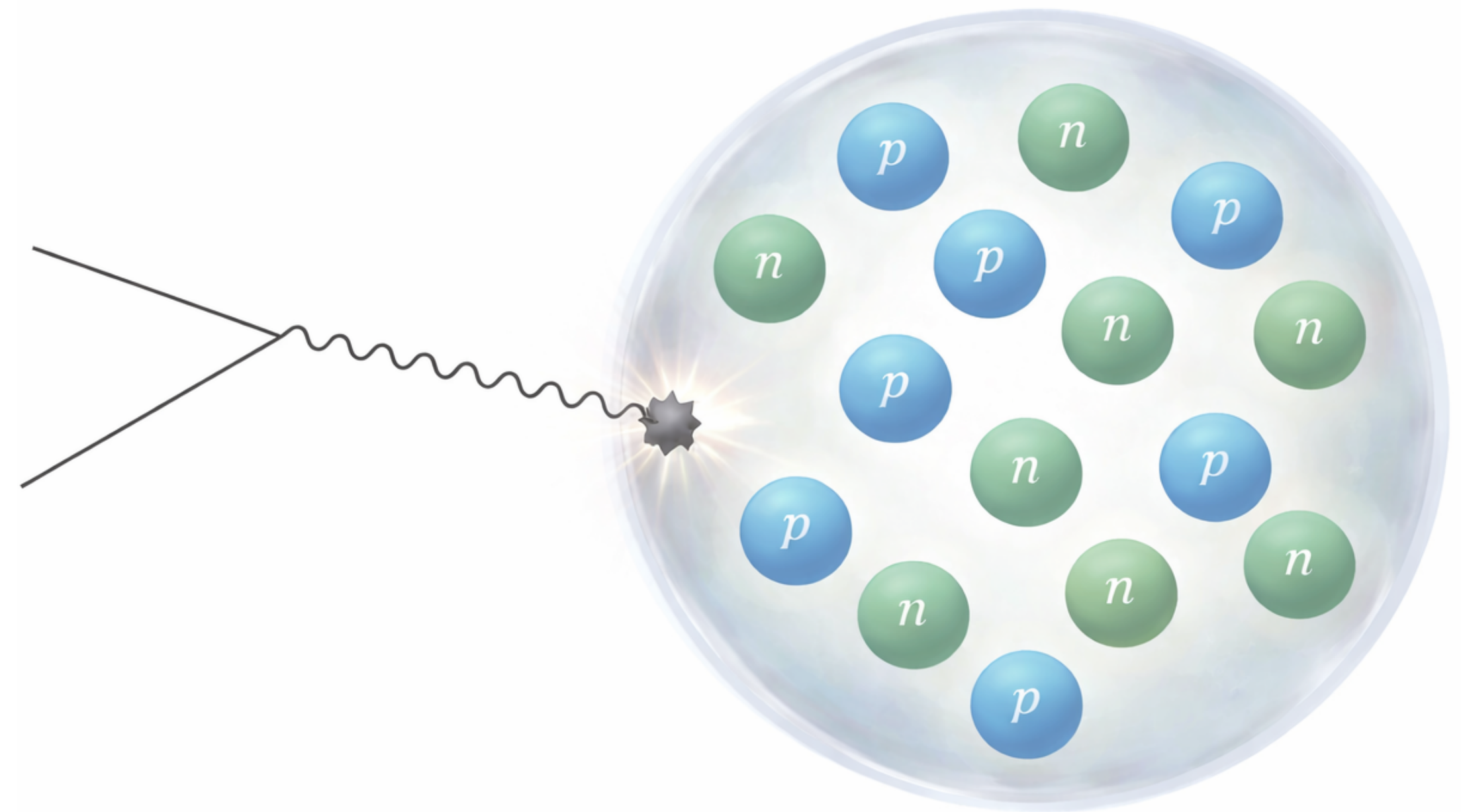
De-excitation

Impulse approximation

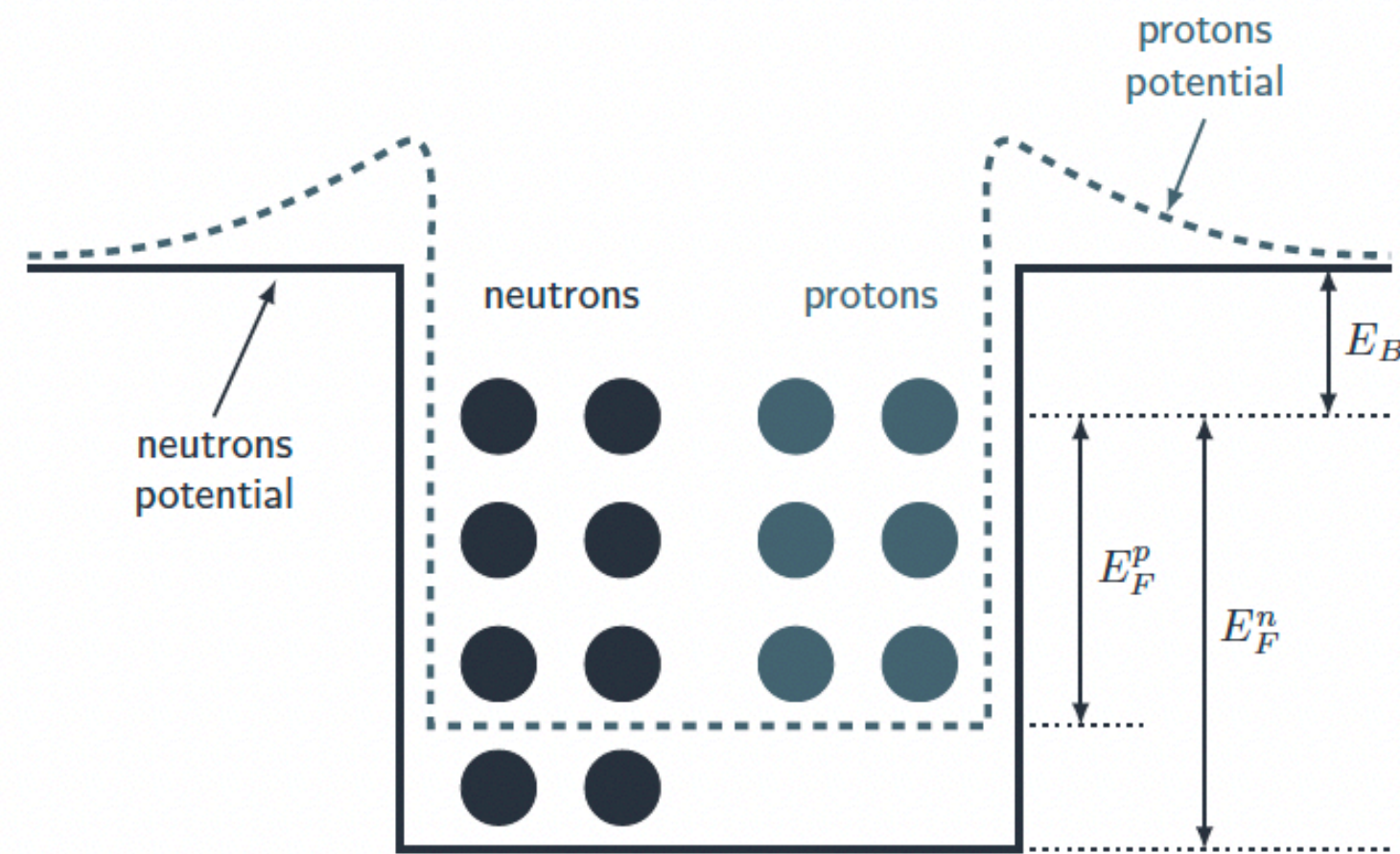
- In Impulse approximation the incoming photon interacts with a single nucleon
- For high $|q|$, IA is justified

$$\sigma^A = \sum_{i=1}^Z \sigma_p + \sum_{i=1}^{A-Z} \sigma_n$$

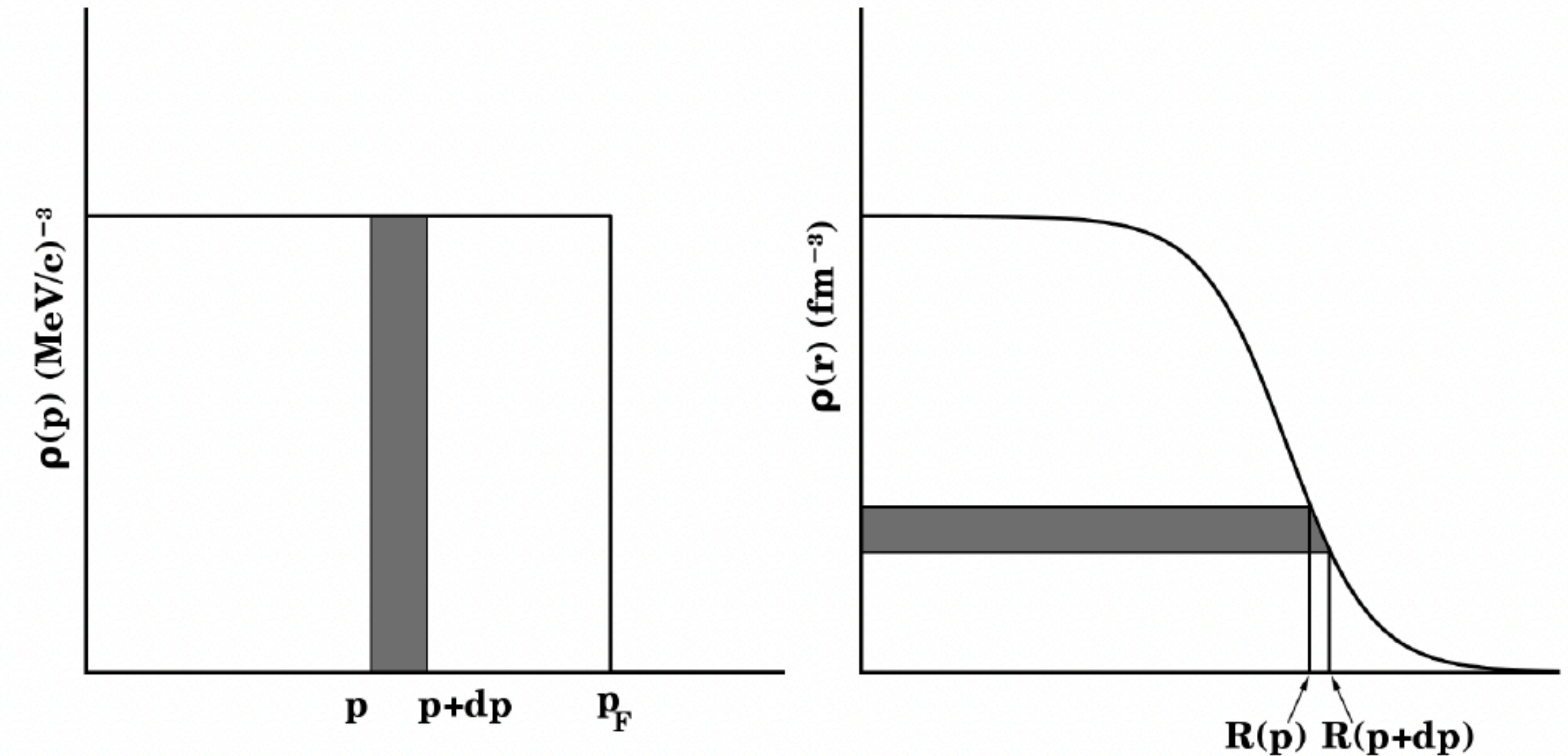
- $\gamma^* p$ for a free nucleon at high energies is described using quark-parton model
- Then add several nuclear effects such as a nuclear pdfs, semi-classical nuclear model etc



Nucleus: Fermi gas model



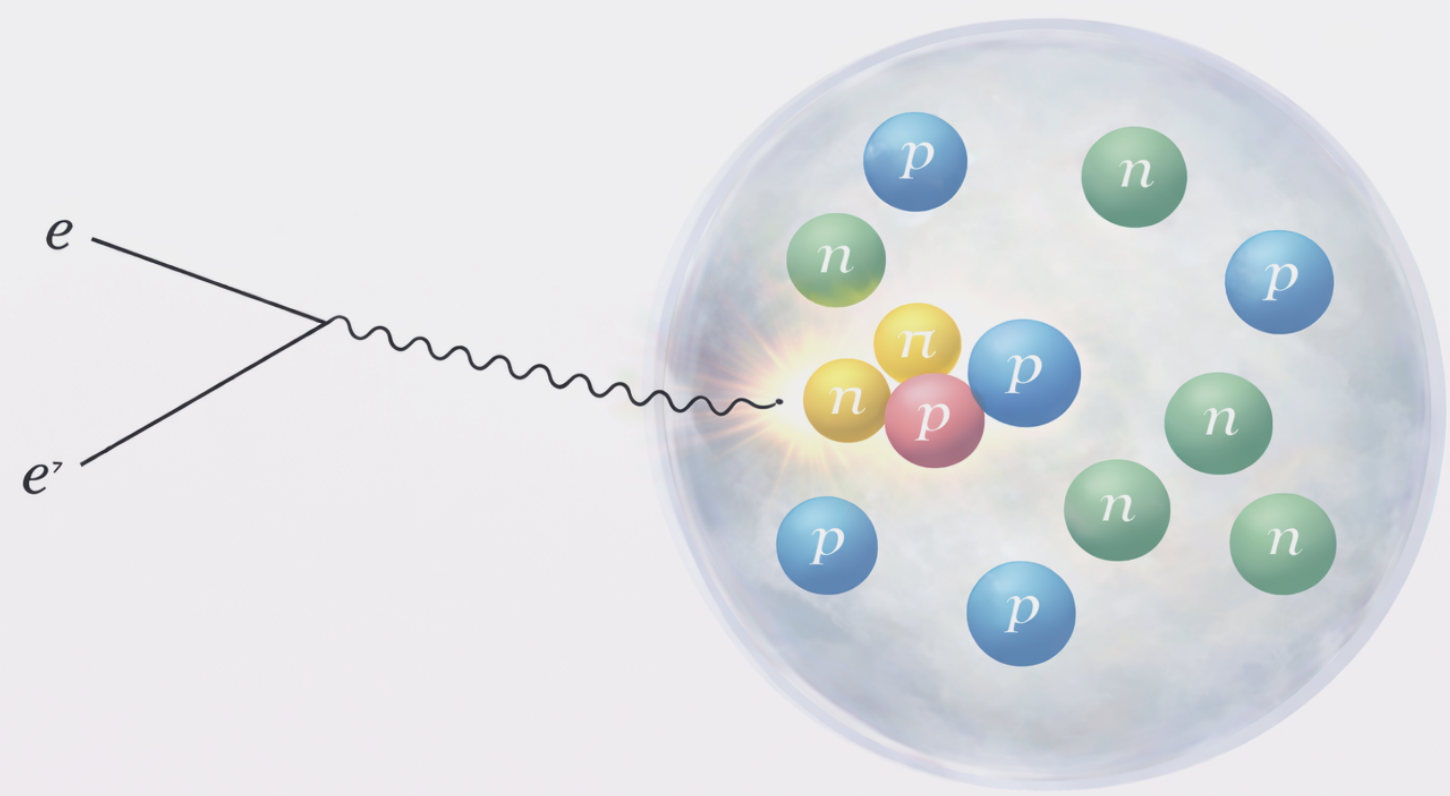
- Nucleons move freely within the nuclear volume in constant binding potential
- Initial nucleon momenta sampled uniformly inside a sphere of radius p_f and position sampled from Woods Saxon, Modified harmonic oscillator and gaussian distributions



$$p_F = \left(\frac{9\pi}{8} \right)^{1/3} \frac{\hbar}{r_0}$$

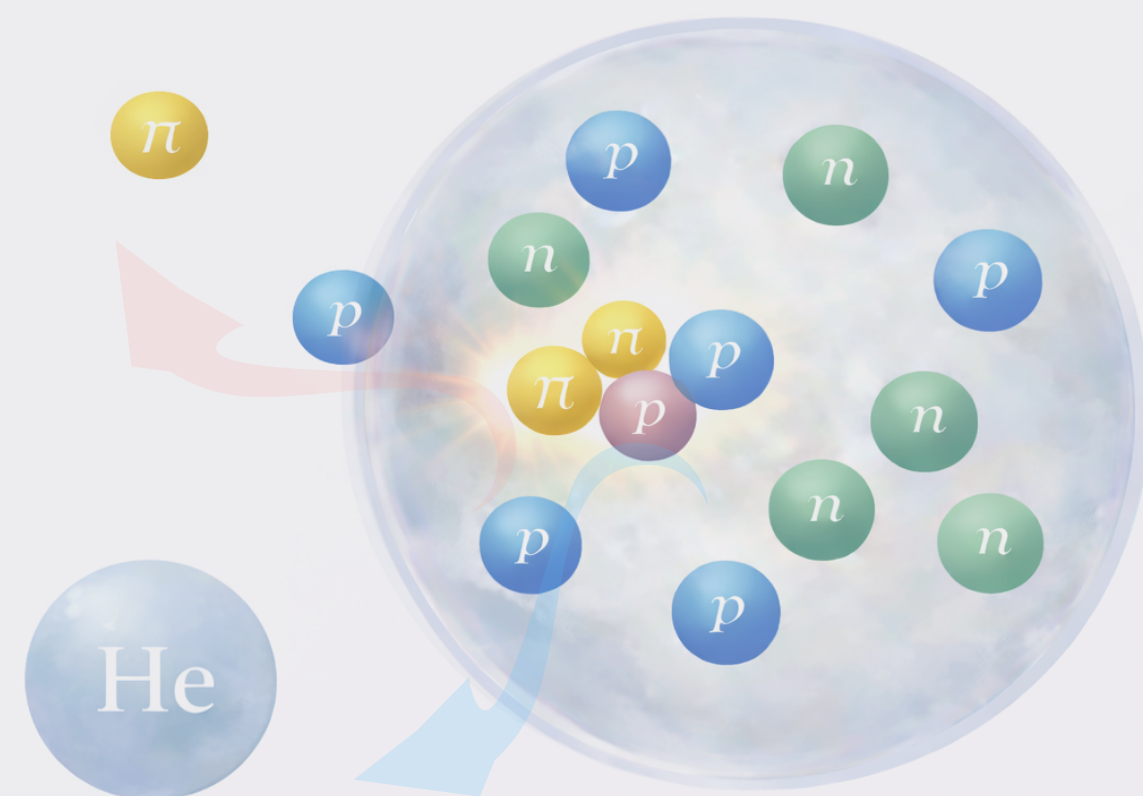
$$\rho = \begin{cases} \frac{\rho_0}{1 + \exp\left(\frac{r-R_0}{a}\right)}, & A > 19 \\ \rho_0 \frac{1 + \alpha\left(\frac{r^2}{a^2}\right)}{\exp\left(\frac{r^2}{a^2}\right)}, & 6 < A \leq 19 \\ \frac{\rho_0}{\exp\left(\frac{r^2}{a^2}\right)}, & A \leq 6 \end{cases}$$

Nuclear Breakup in BeAGLE



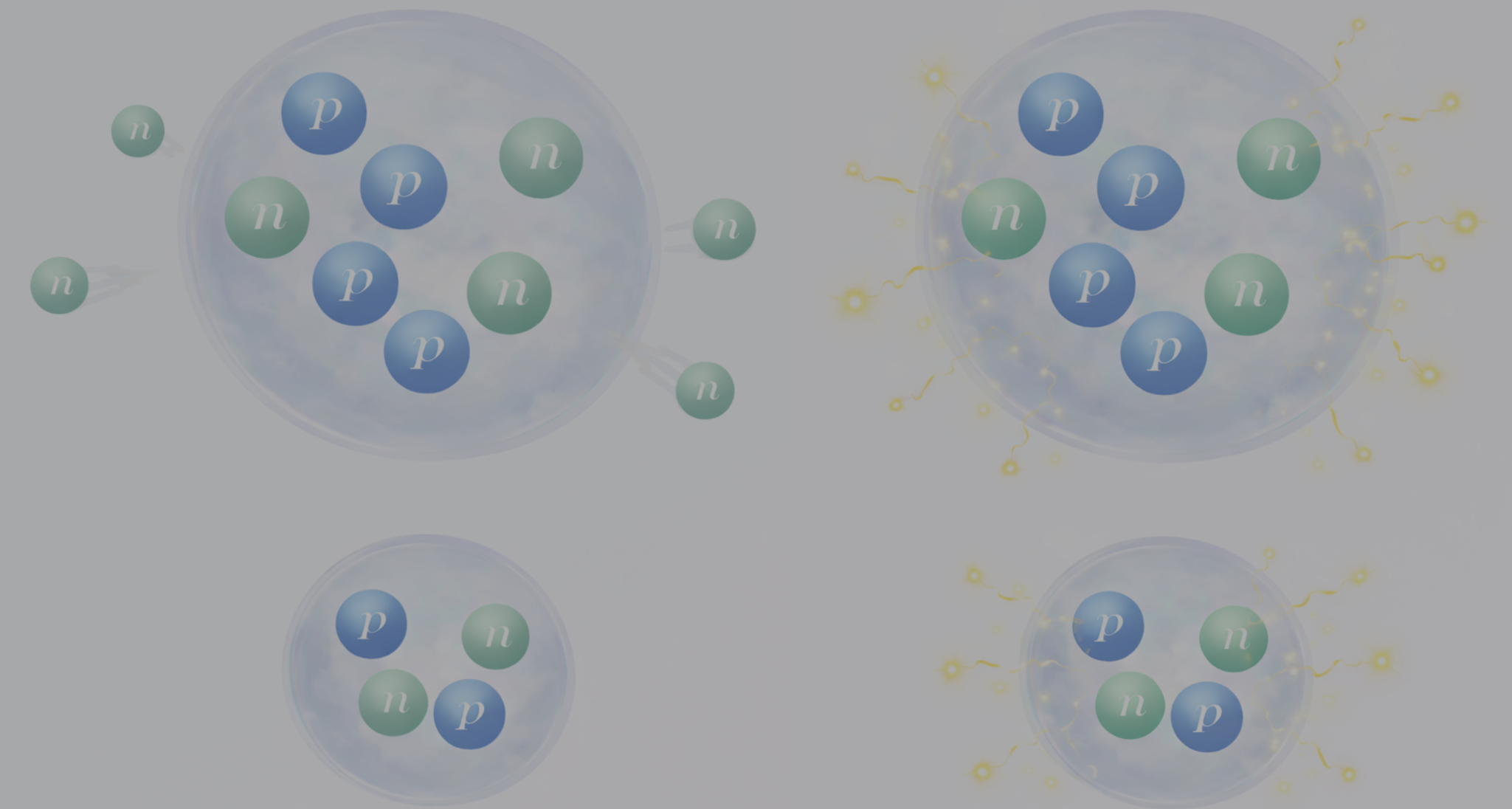
$t = 0$

DIS on a nucleon



$t = 10^{-22}$ s

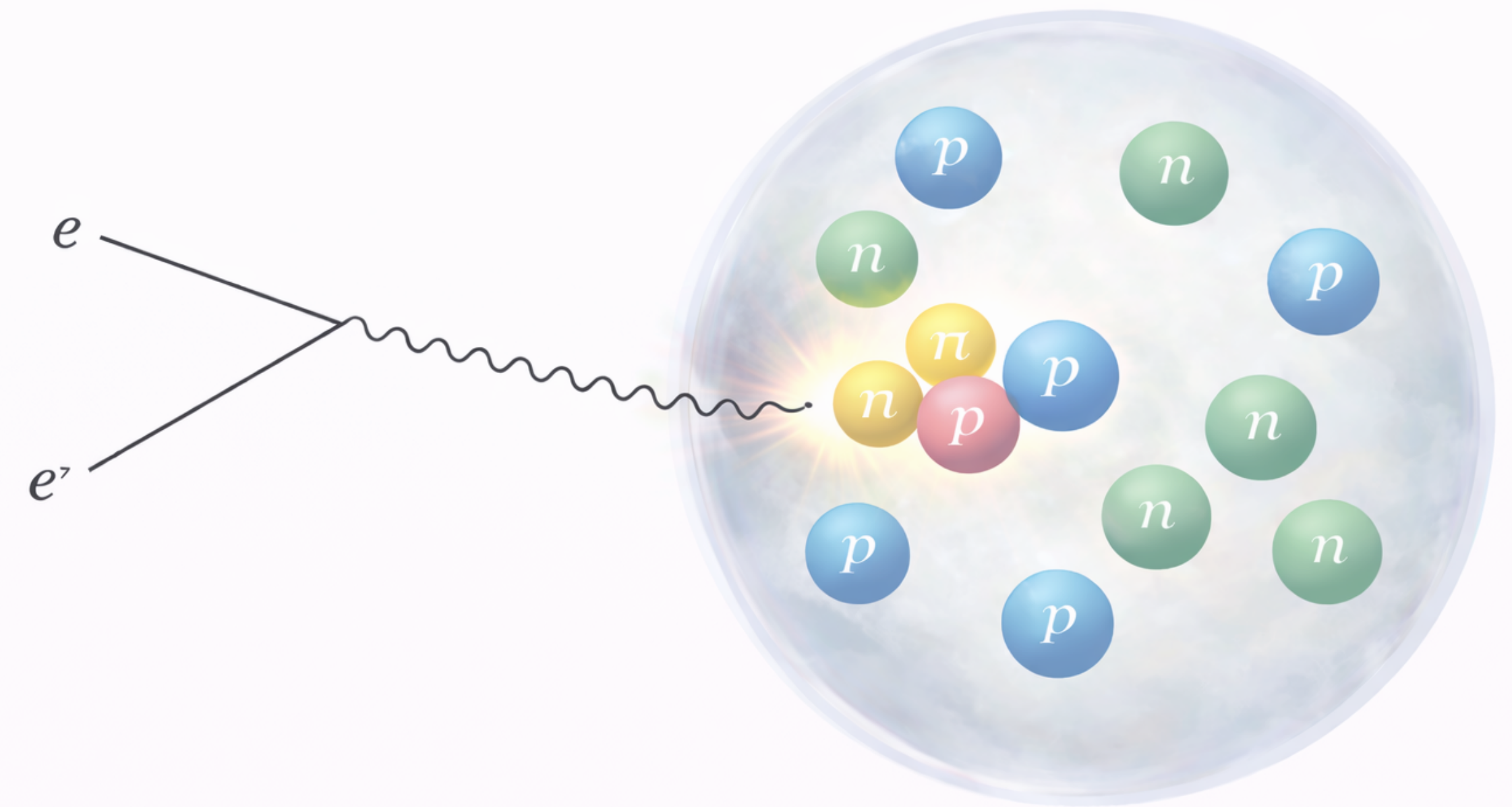
Final State Interactions



De-excitation

Final State Interactions

- After the hard interactions, the secondaries will interact with the other nucleons inside the nucleus
- FSI describe the propagation of particles through nucleus → Phenomenological Model

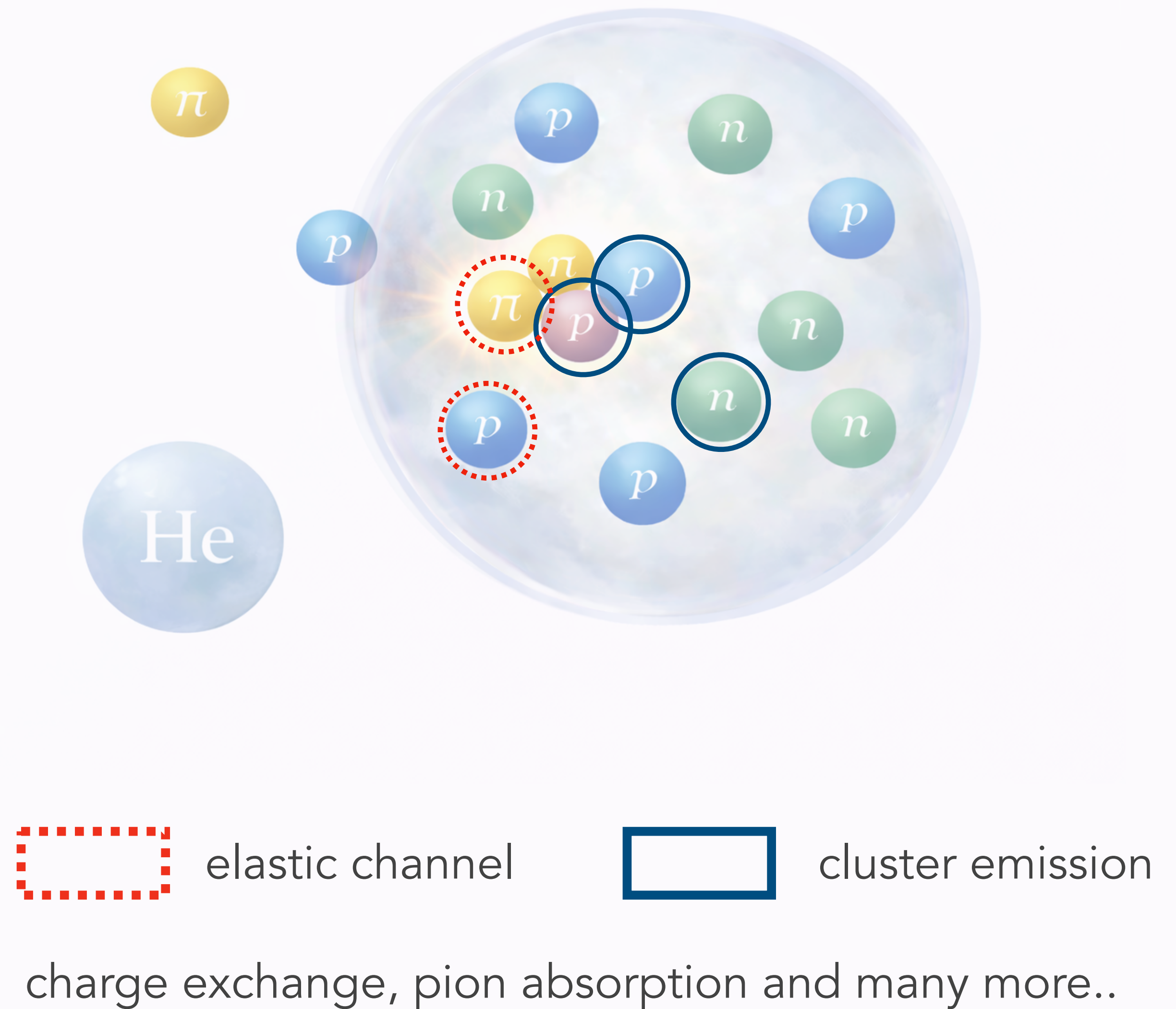


*Most of Monte Carlo generators (also other communities like neutrino, spallation, pA/AA at low energies) use **Intranuclear cascade model***

Intranuclear cascade (INC)

An INC model is a semi-classical transport model and treats the nuclear reaction as a avalanche of independent binary collisions

- *Fast Cascade Phase*: Incoming hadrons enters the nucleus and produce cascade of binary interactions
- *Pre-equilibrium/Excited Residual Nucleus*: After several collisions, some particles escape and the remaining nucleus is left excited
- *De-excitation*: via evaporation(neutrons, protons, light fragments), fission, gamma emission (generally an independent statistical de-excitation model)



Intranuclear cascade (INC)

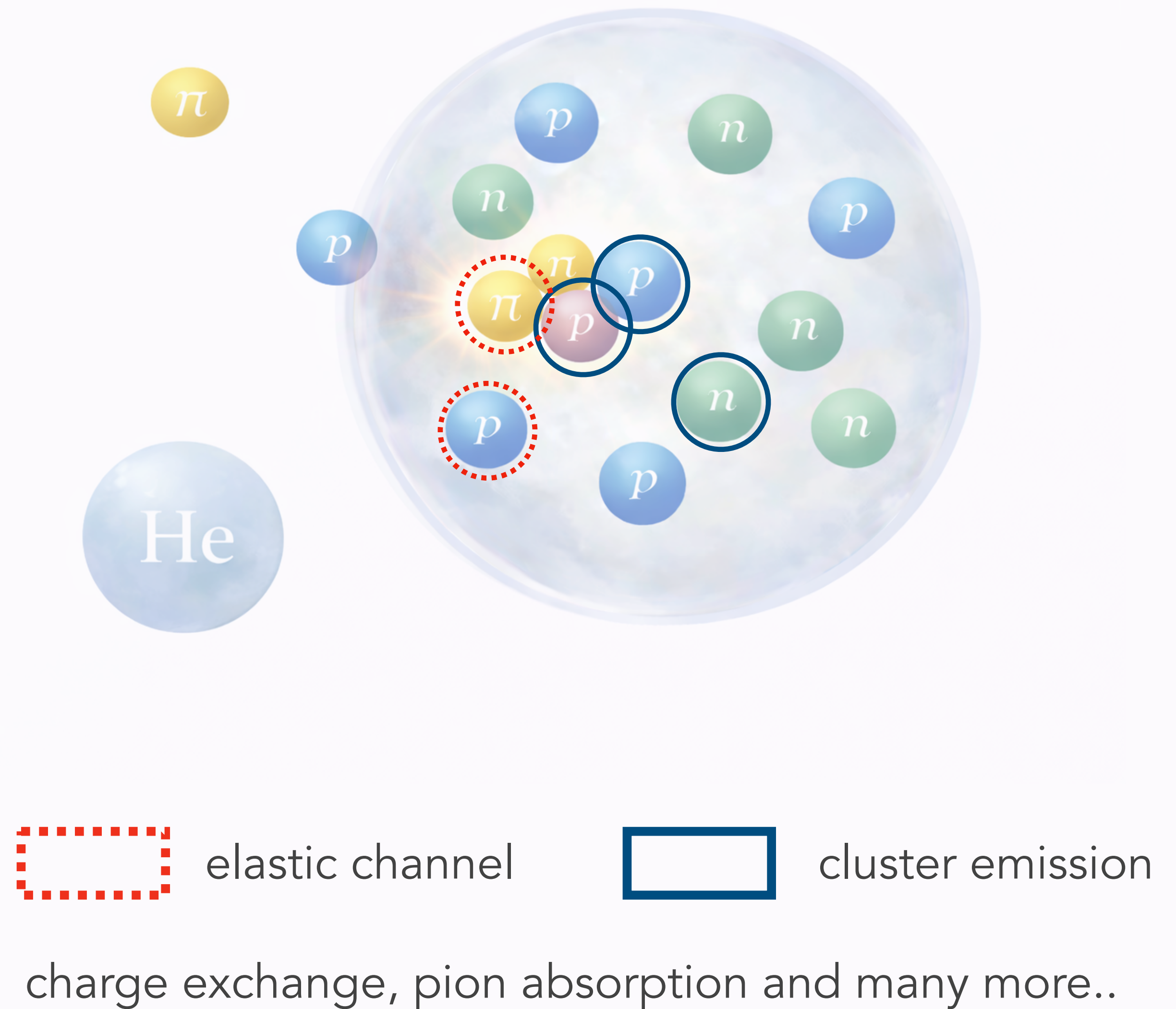
- The main input to INC model is particle-nucleon cross section

- Ratio of cross sections such as

$$\frac{\sigma_{el}}{\sigma_{tot}}, \frac{\sigma_{cex}}{\sigma_{tot}}, \frac{\sigma_{abs}}{\sigma_{tot}}$$

etc. used to evaluate what kind of interaction happens

- In INC model particles are assumed to be classical and move along the straight line



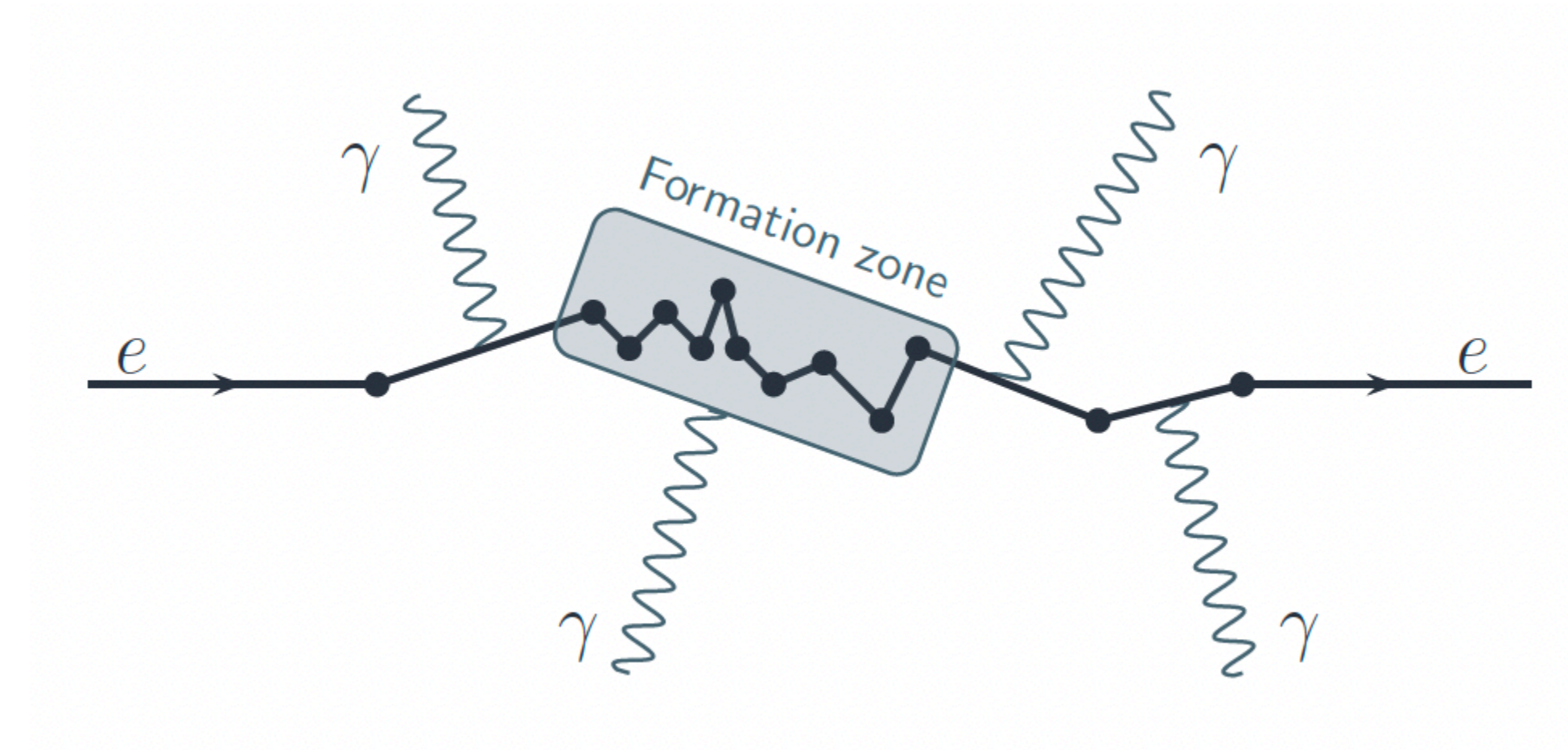
The background is a complex, abstract visualization. It features a dense network of thin, glowing lines in various colors (blue, orange, yellow, green) that radiate from a central point, resembling particle tracks or a complex network. On the left side, there are several semi-transparent, light blue rectangular panels containing data plots. One panel shows a histogram with the label $d\mathcal{E}/dp_T$ and $q(Q)$. Another panel shows a similar histogram. The overall color palette is dominated by light blues and greys, with the central burst of tracks adding vibrant orange and yellow highlights.

Formation time

Formation Time

- The concept of formation time was introduced by Landau and Pomeranchuk in the context of electrons passing through a layer of material
- For high energy electrons they observed less radiated energy than expected
- The energy radiated in such a process is

$$\frac{dI}{d^3k} \sim \left| \int_{-\infty}^{\infty} \vec{j}(\vec{x}, t) e^{i(\omega t - \vec{k} \cdot \vec{x}(t))} d^3x dt \right|^2$$



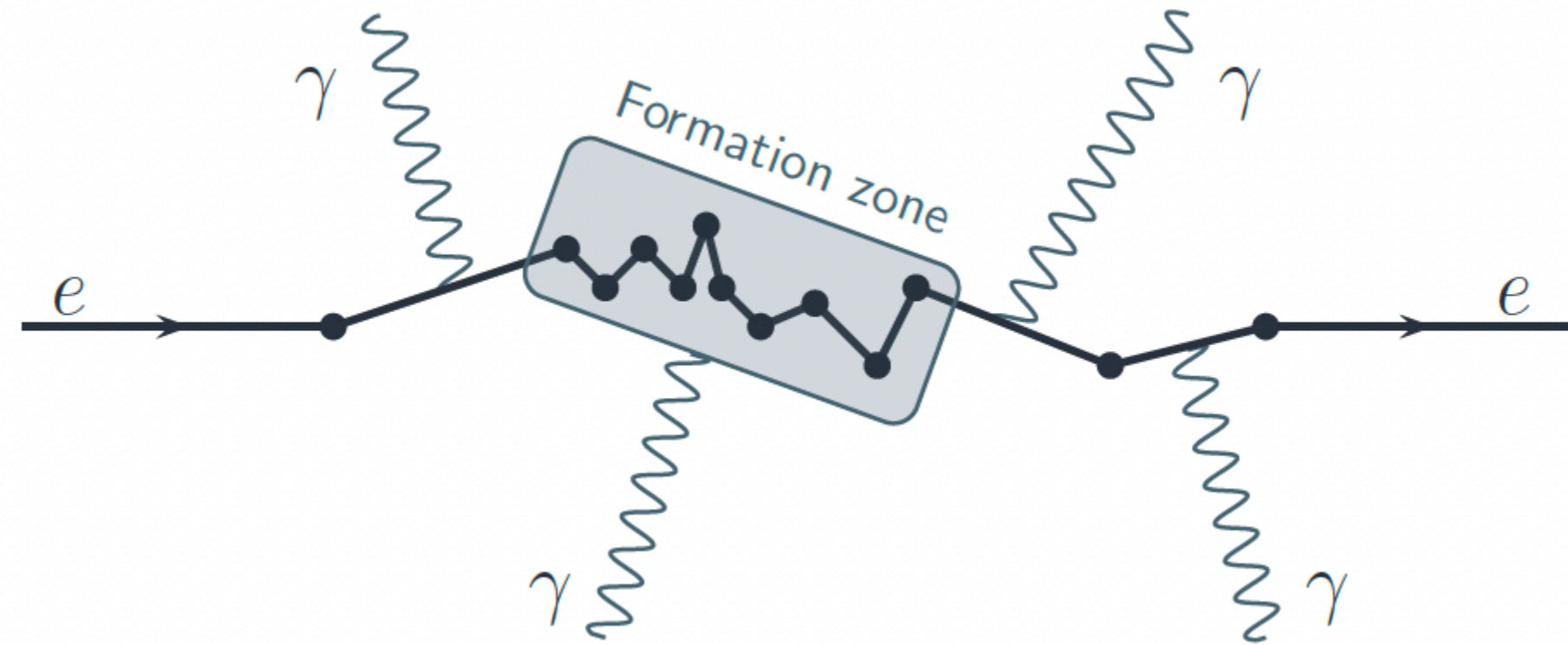
Formation Time

- Formation time is defined as

$$t_f \equiv \frac{1}{\omega - \vec{k}\vec{v}} = \frac{E}{kp} = \frac{E}{m_e} \frac{1}{\omega_{r.f.}} = \gamma T_{r.f.}$$

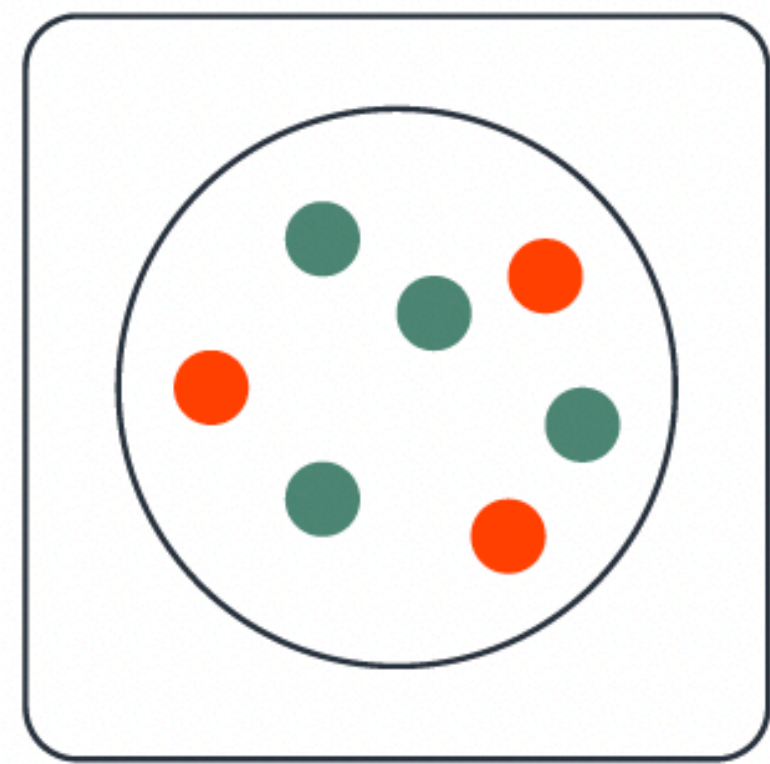
k, p - photon, electron four-momenta

$\omega_{r.f.}$ - photon frequency in the rest frame of the electron

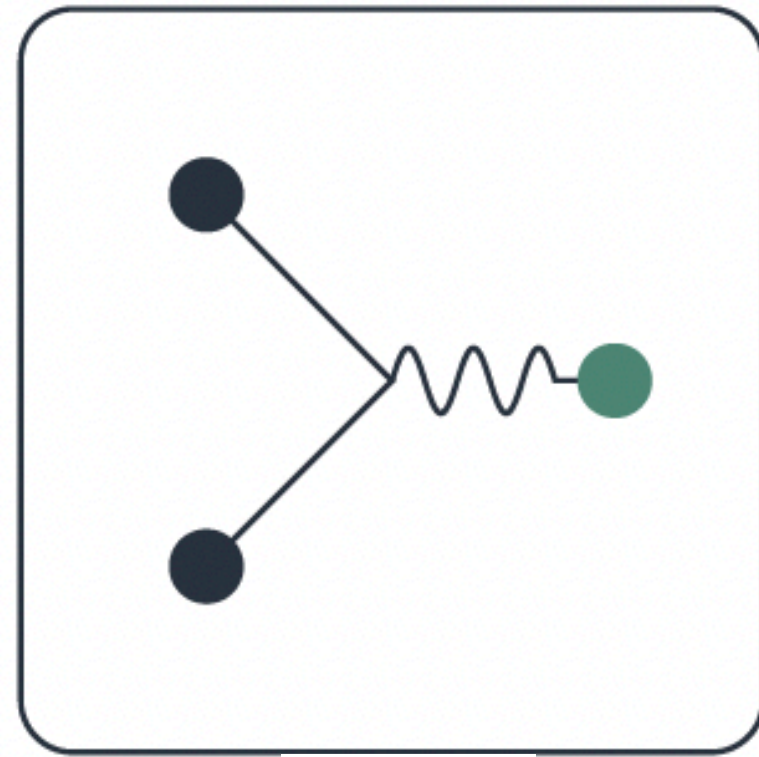


- If time t between collision $t \gg t_f$, independent emitters and total energy radiated is just average emitted in one collision multiplied by no of collisions
- If $t \ll t_f$, destructive interference and photon is produced coherently over length of formation zone reducing bremsstrahlung
- L. Stodolsky extended this idea to hadrons (1975) and further introduced to MC generators by J. Ranft (late 1980s)

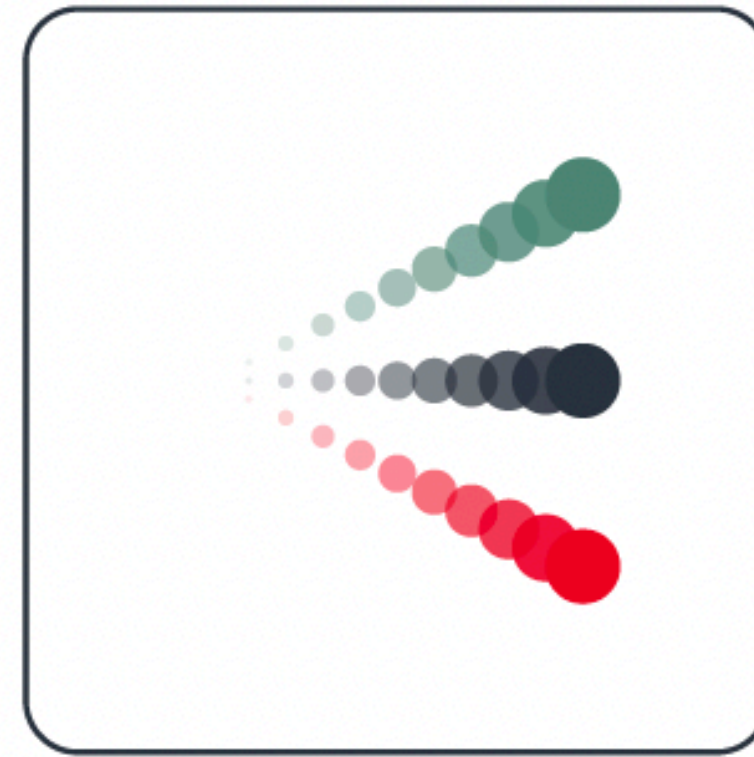
Formation Zone Intranuclear Cascade model



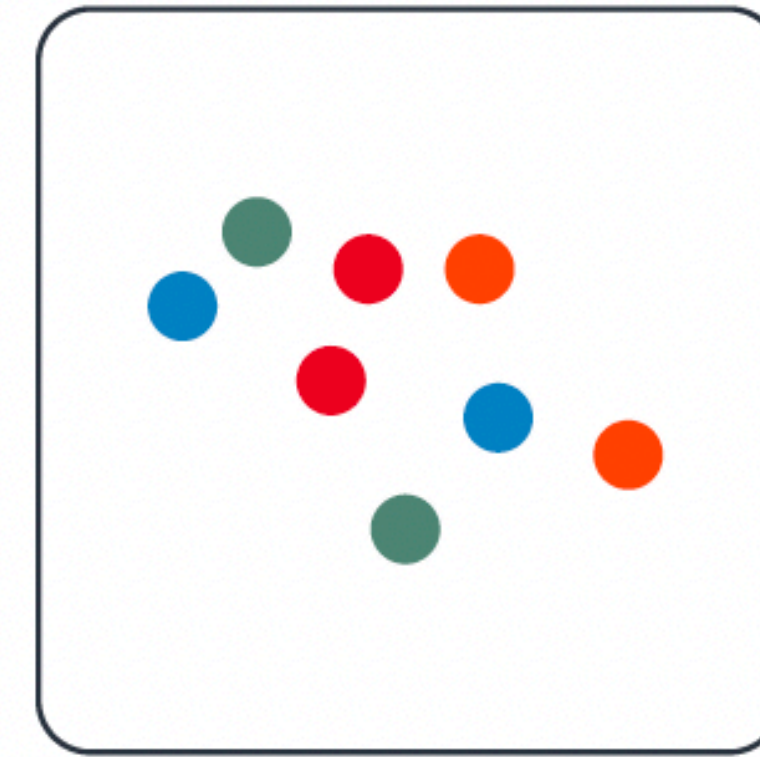
IA



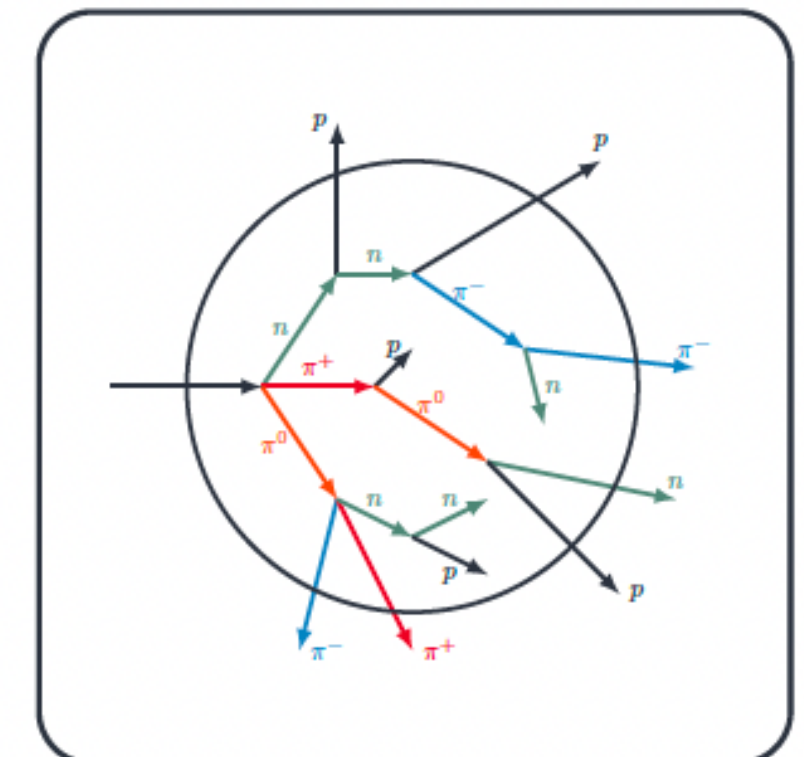
eN



formation time



hadronization

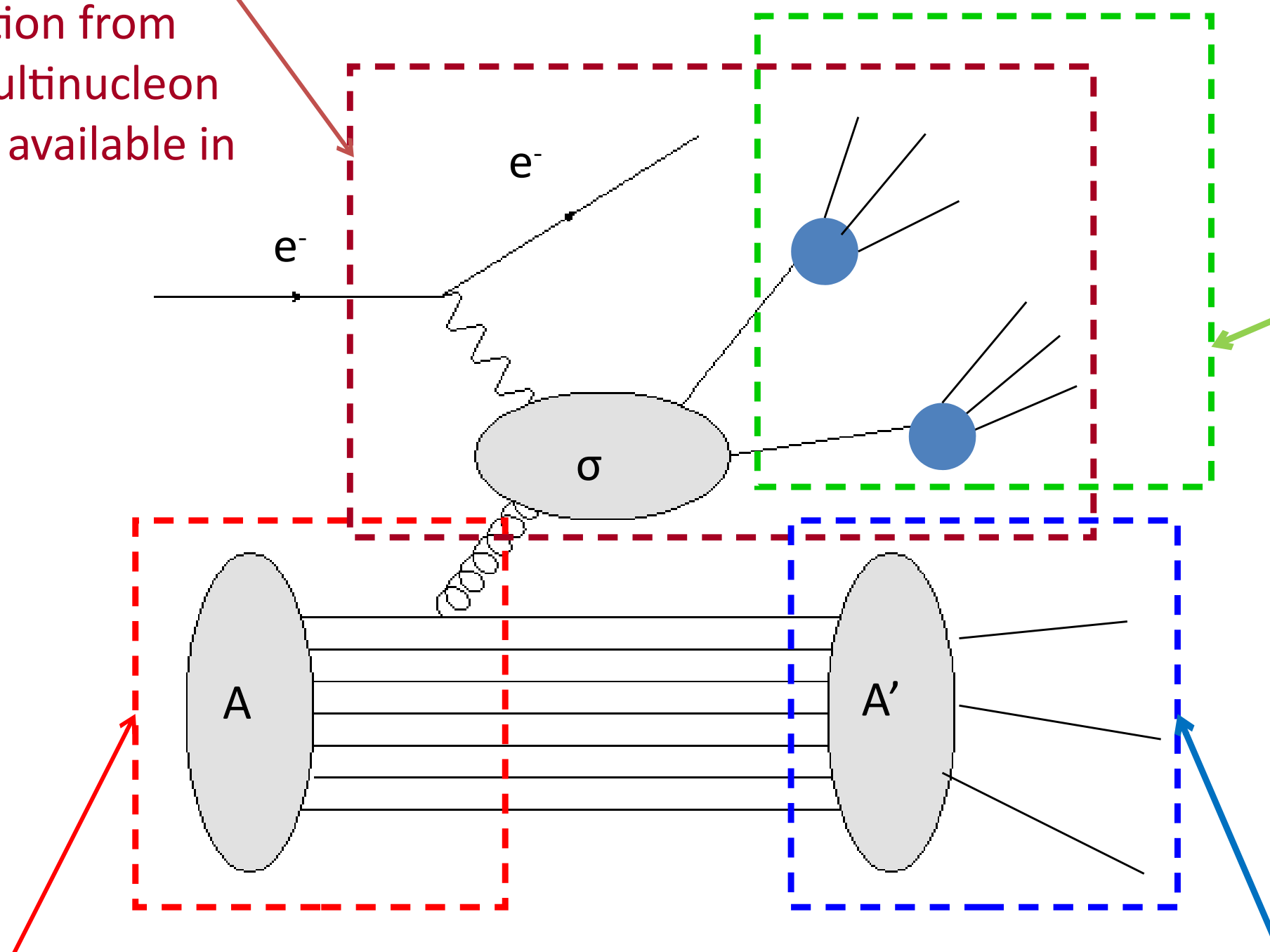


Intranuclear cascade

- Ranft parameterization [J. Ranft: Z. Phys. C43 \(1989\) 439](#)

$$\tau_{\text{Lab}} \approx \gamma_s \tau_s, \quad \gamma_s = \frac{E_s}{m_s}, \quad \tau_s = \tau_0 \frac{m_s^2}{m_s^2 + p_{s\perp}^2} \quad \tau_0 \text{ fitted to data}$$

Parton level interaction, parton shower and jet fragmentation from PYTHIA. Multinucleon shadowing available in BeAGLE.



Intranuclear Cascade from DPMJet. Optional Energy loss effect from extended BDMPS in PyQM.

Some Nuclear Effects

- Parton distribution functions
- Parton saturation (CGC etc.)
- Short-range correlations
- "Fermi motion"
- Partonic (or "dipole") MS
- Partonic gluon radiation
- Medium-modified hadronization
- Formation times
- Hadronic Cascade
- Nuclear evaporation, breakup
- Photonic de-excitation of A^*

In BeAGLE



Nuclear geometry by BeAGLE & PyQM plus EPS09 nuclear PDF provided in LHAPDF.

Nuclear evaporation, gamma de-excitation, nuclear fission & fermi break up treated by FLUKA.

BEAGLE

W.Chang, E.C.Aschenauer, M.D.Baker, A.Jentsch, J.H Lee, Z. Tu, Z.Yin, L.Zheng PRD 106 (2022) 012007

however there are several limitations

1. written in old legacy fortran, based on pythia6

2. maintenance is difficult as many modules are outdated

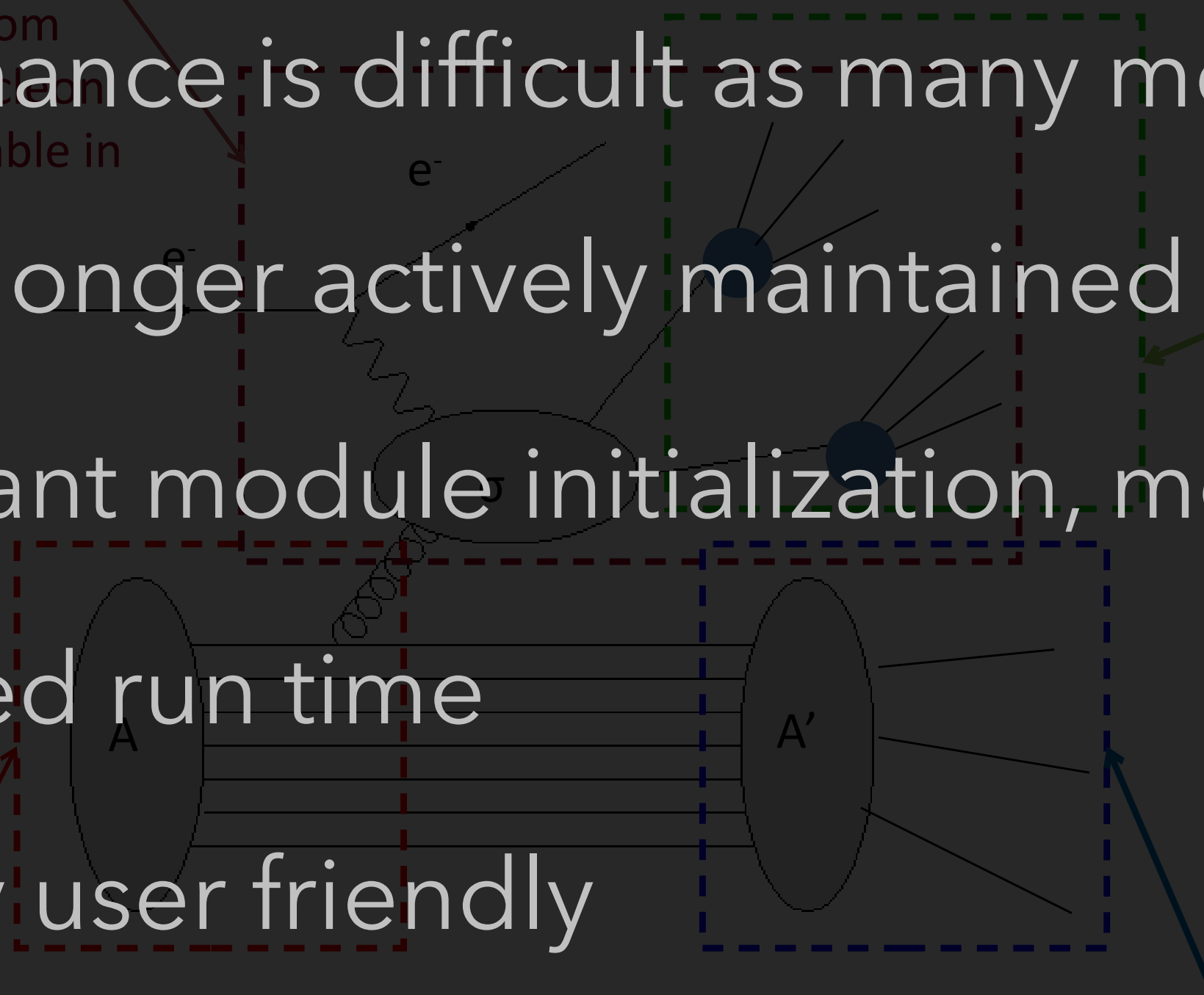
and no longer actively maintained

3. redundant module initialization, memory leaks,

increased run time

4. not very user friendly

5. adding new physics is difficult



Some Nuclear Effects

	In BeAGLE
• Parton distribution functions	☒
• Parton saturation (CGC etc.)	☒
• Short-range correlations	☒ (GCF)
• "Fermi motion"	☒
• Partonic (or "dipole") MS	☒
• Partonic gluon radiation	☒
• Medium-modified hadronization	☒
• Formation times	☒
• Hadronic Cascade	☒
• Nuclear evaporation, breakup	☒
• Photonic de-excitation of A*	☒

BEAGLE

W.Chang, E.C.Aschenauer, M.D.Baker, A.Jentsch, J.H Lee, Z. Tu, Z.Yin, L.Zheng PRD 106 (2022) 012007

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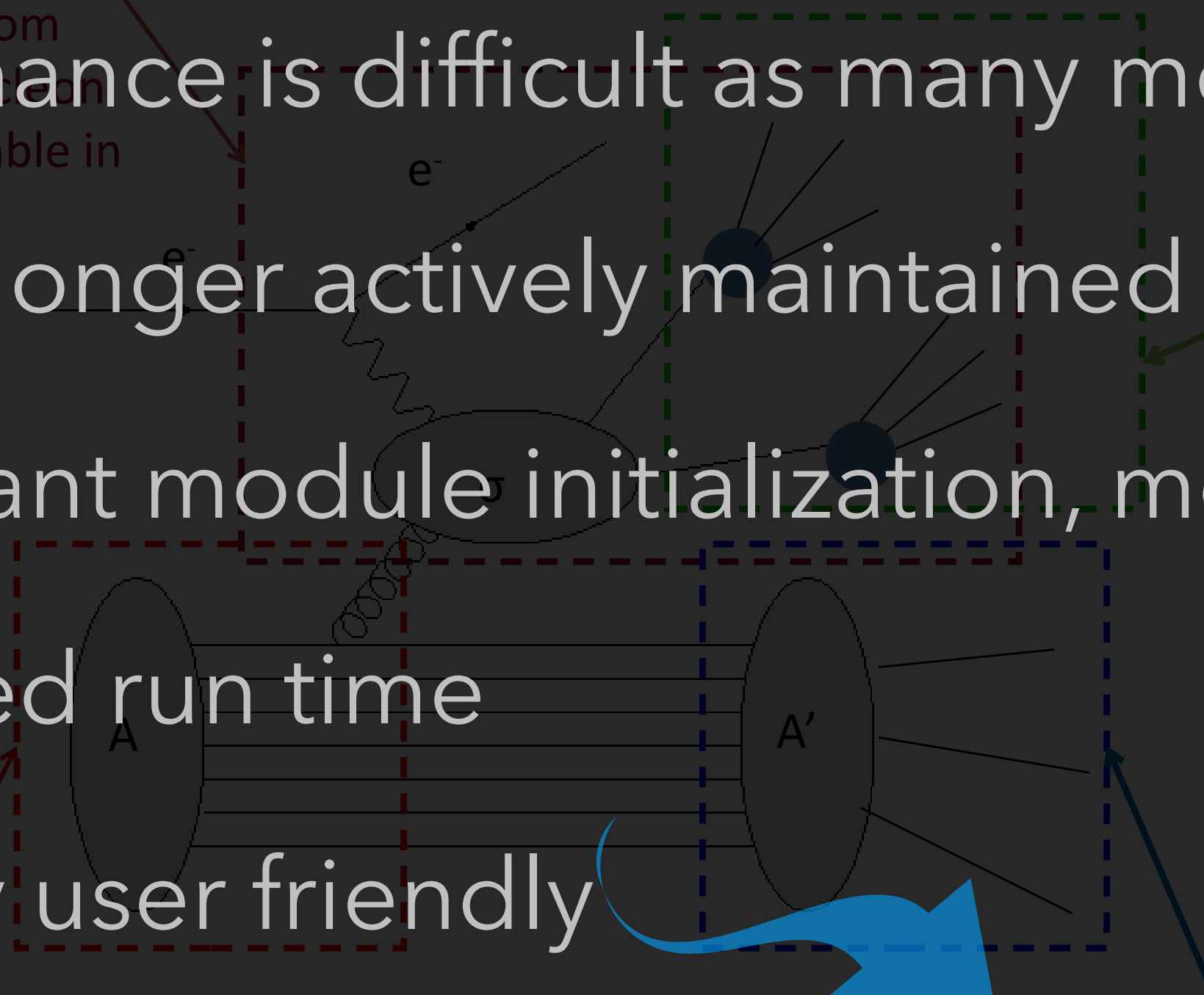
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Some Nuclear Effects

	In BeAGLE
• Parton distribution functions	☒
• Parton saturation (CGC etc.)	☒
• Short-range correlations	☒ (GCF)
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• Partonic (or "dipole") MS	☒
• Partonic gluon radiation	☒
• Medium-modified hadronization	☒
• Formation times	☒
• Hadronic Cascade	☒
• Nuclear evaporation, breakup	☒
• Photo-excitation of A*	☒

BeAGLE++



Nuclear geometry by BeAGLE
& PyQMD. EPS nuclear
PDF provided in LHAPDF.

Nuclear evaporation, breakup
& photo-excitation, nuclear fission &
fermi break up treated by FLUKA.

The background is a complex, abstract visualization. It features a dense network of thin, glowing lines in various colors (blue, orange, yellow, green) that radiate from a central point, resembling particle tracks or data connections. On the left side, there are faint, semi-transparent overlays of scientific plots. One plot shows a histogram with the label $d\mathcal{Z}/dp_T$ and $q(Q)$. Another plot below it shows a series of vertical bars. The overall color palette is dominated by light blues and greys, with the glowing lines providing a vibrant contrast.

From legacy code to BeAGLE++

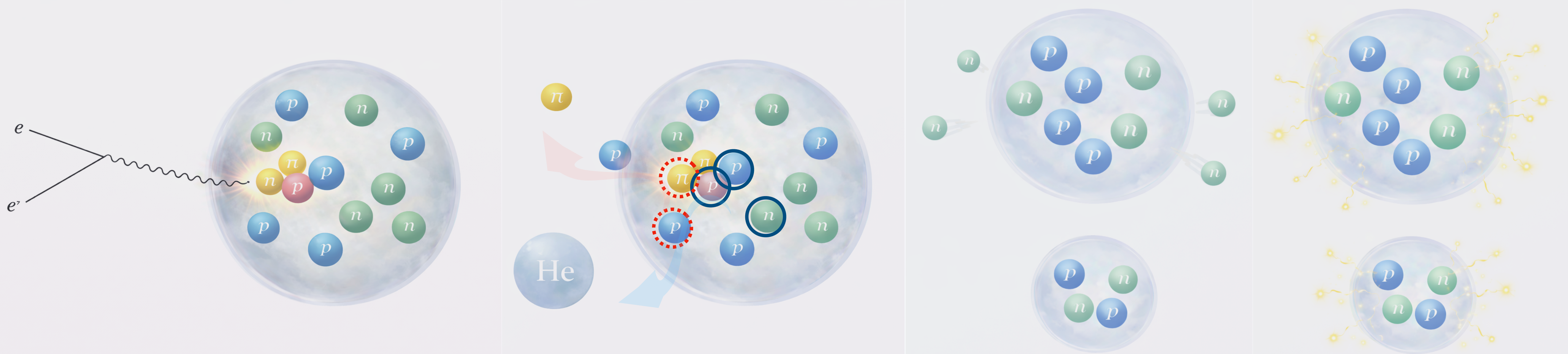
BeAGLE vs BeAGLE++ : components

- **Pythia6** replaced by **Pythia8**
- **DPMJET** (IntraNuclear Cascade) replaced by **modified version of INCL++**
- Initial Geometry from **BeAGLE++/INCL++**
- **FLUKA** replaced by **ABLA++**
- Other dependencies: CMake, ROOT, Boost
- A complete new version of BeAGLE with new components but same core philosophy

BeAGLE

BeAGLE++

Nuclear Breakup in BeAGLE++



t = 0

t = 10^{-22} s

t = 10^{-20} – 10^{-17} s

t = 10^{-14} s

DIS on a nucleon

Pythia8

Final State Interactions

Modified INCL++

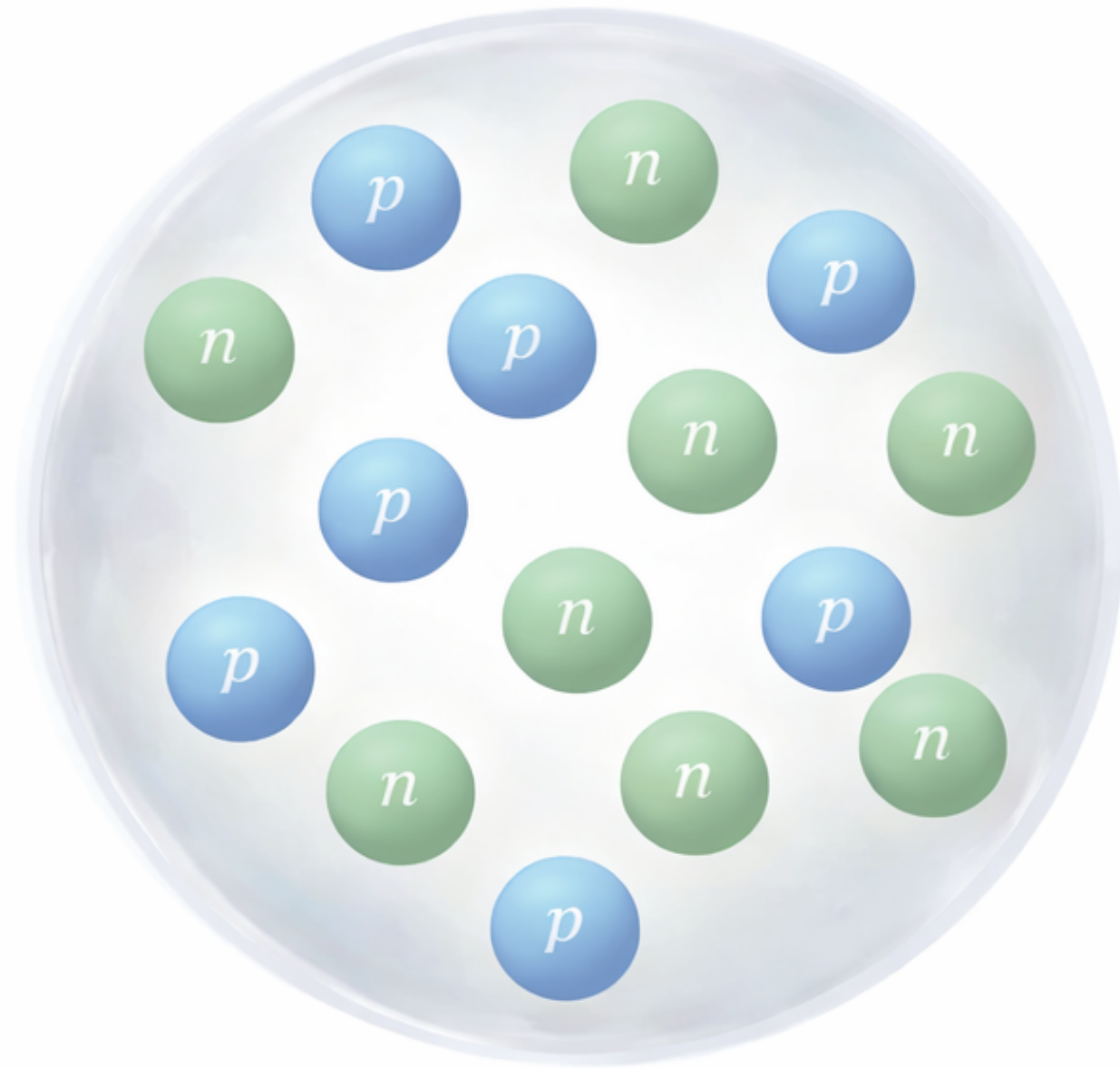
De-excitation

ABLA

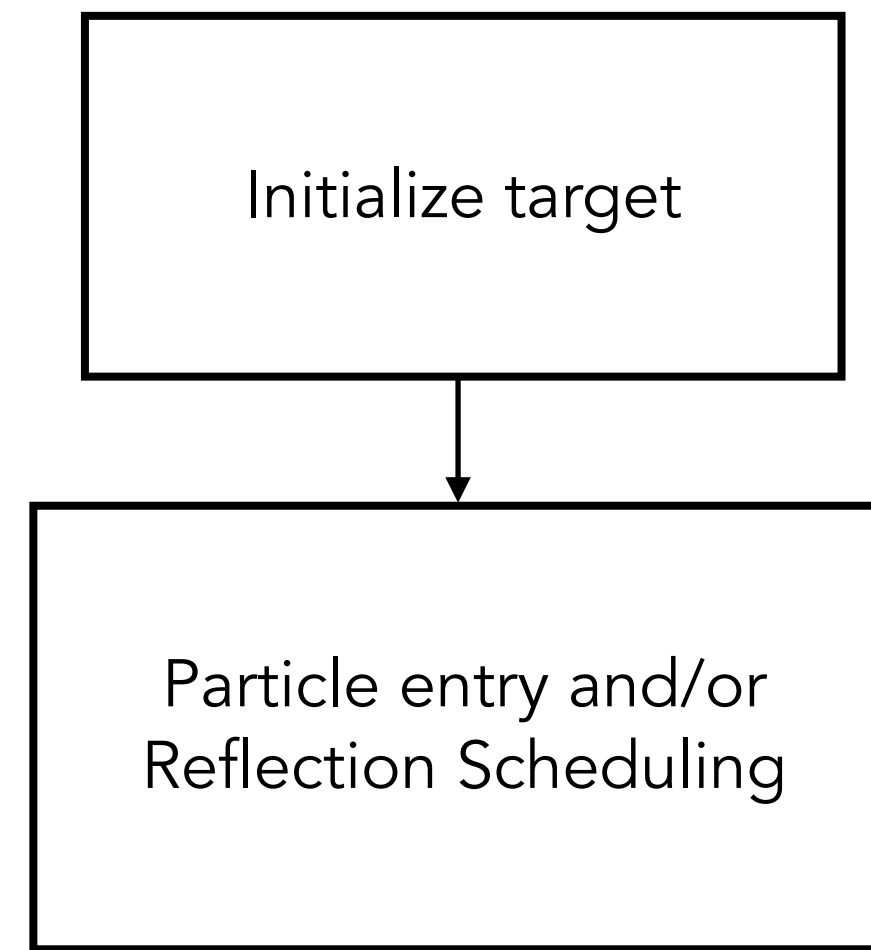
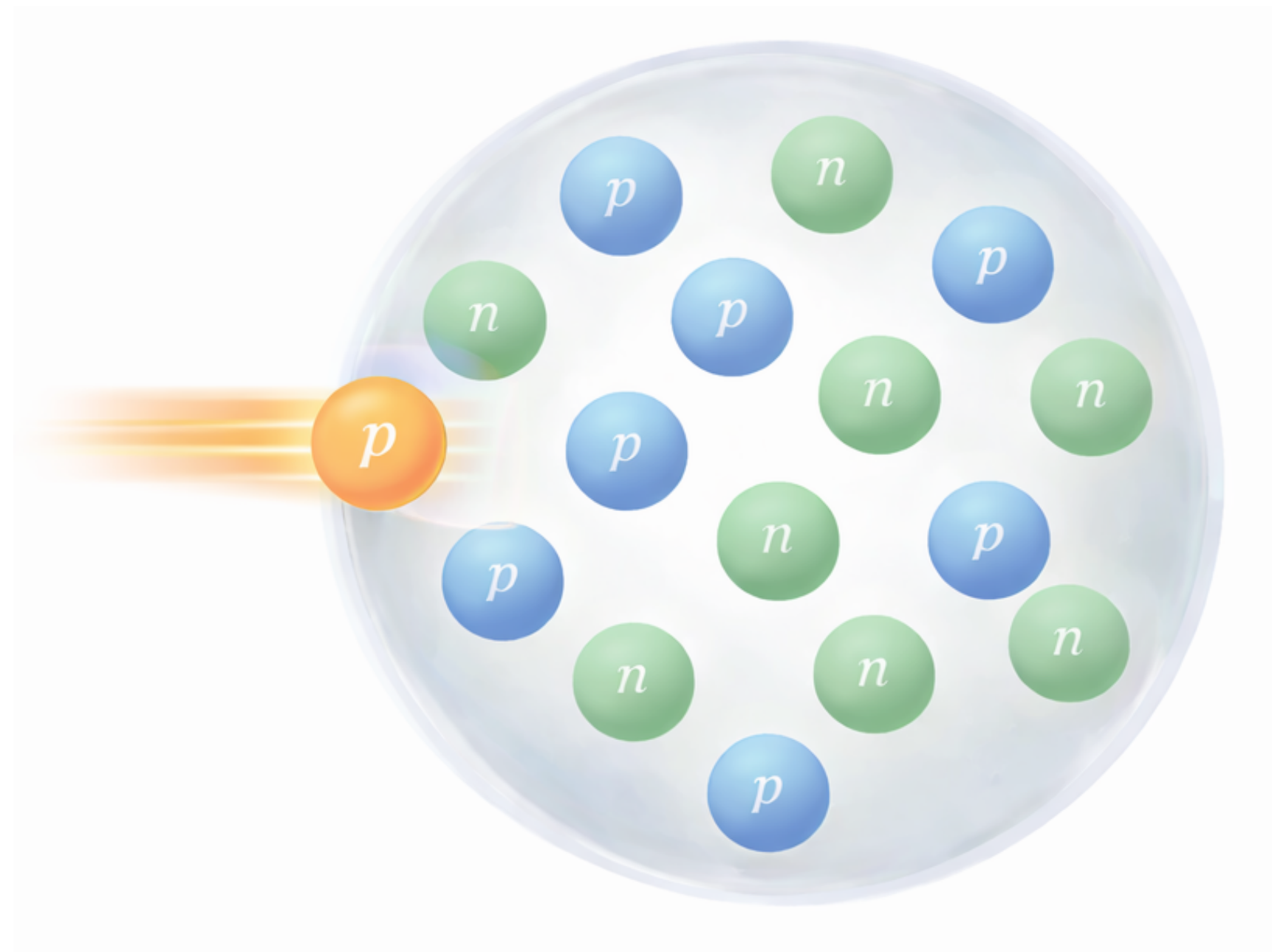
INCL Cascade Algorithm : A Toy Model

INCL Cascade Algorithm

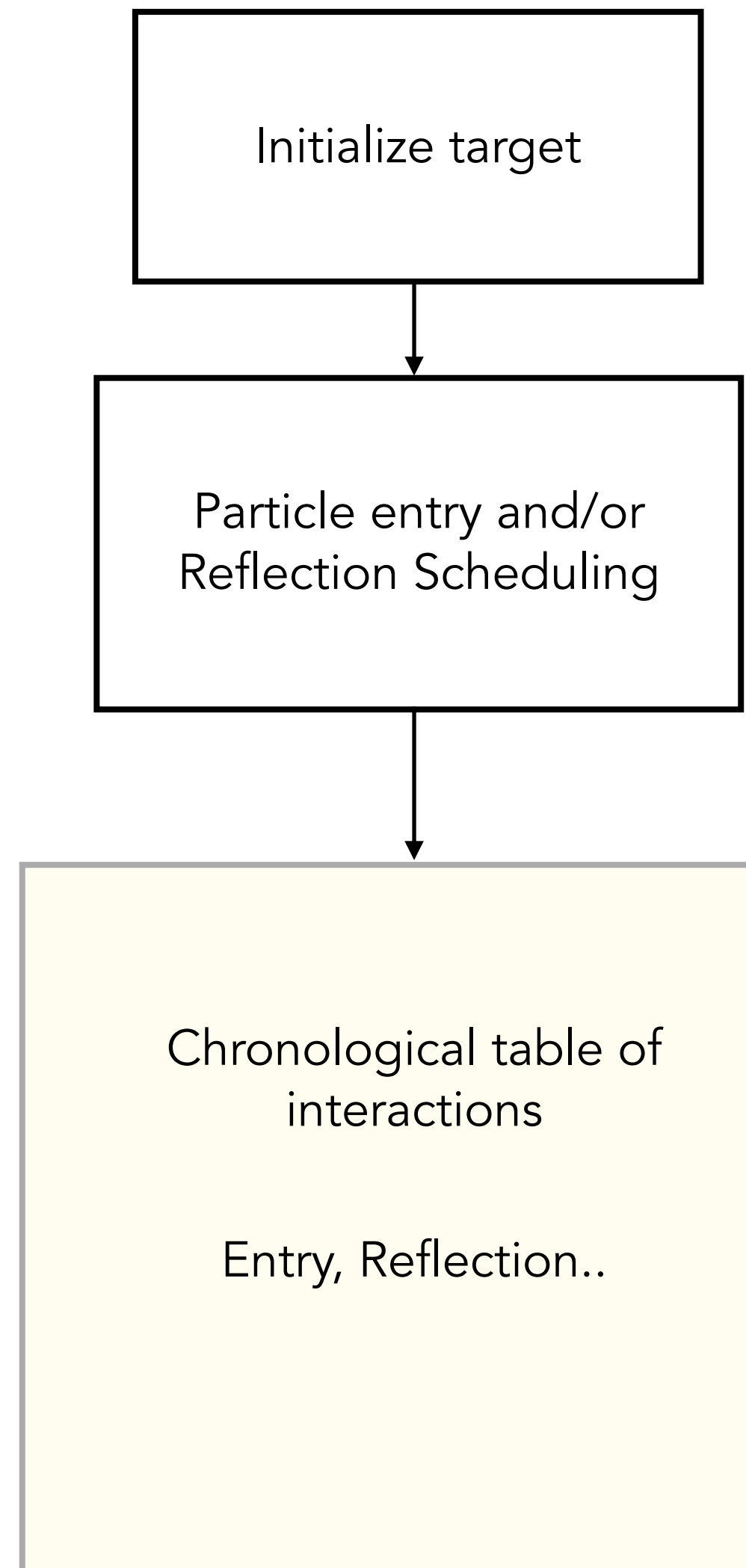
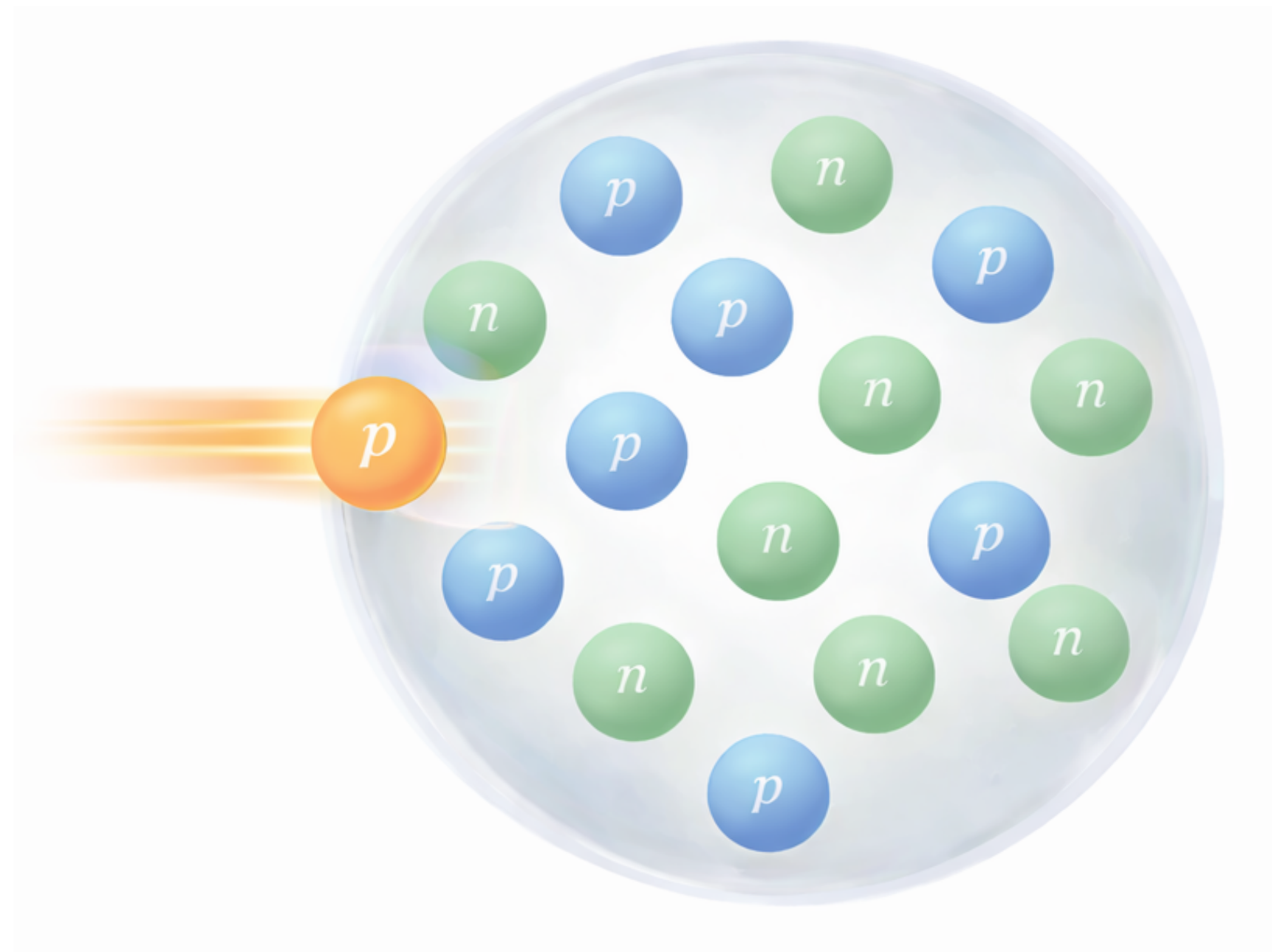
Initialize target



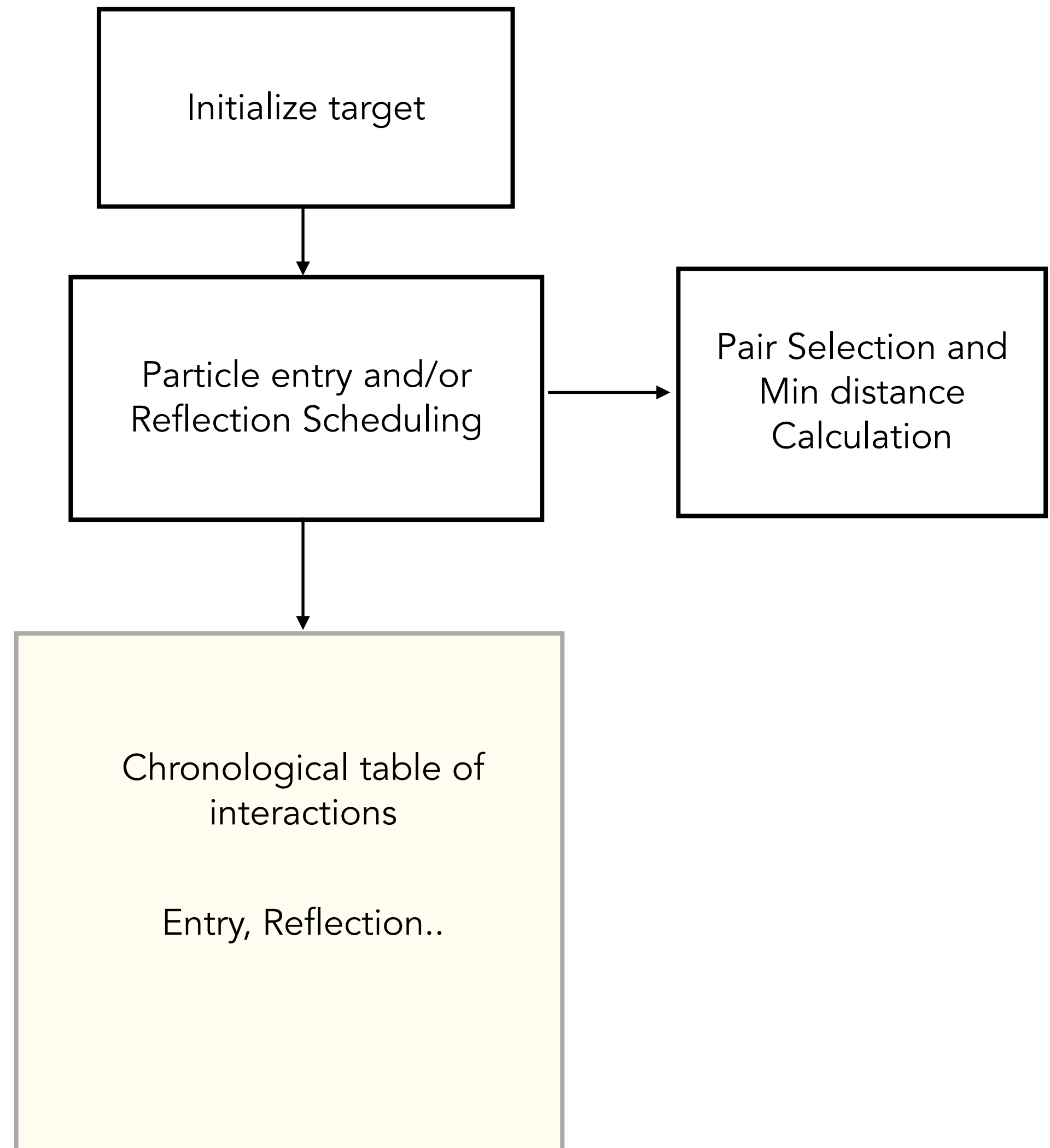
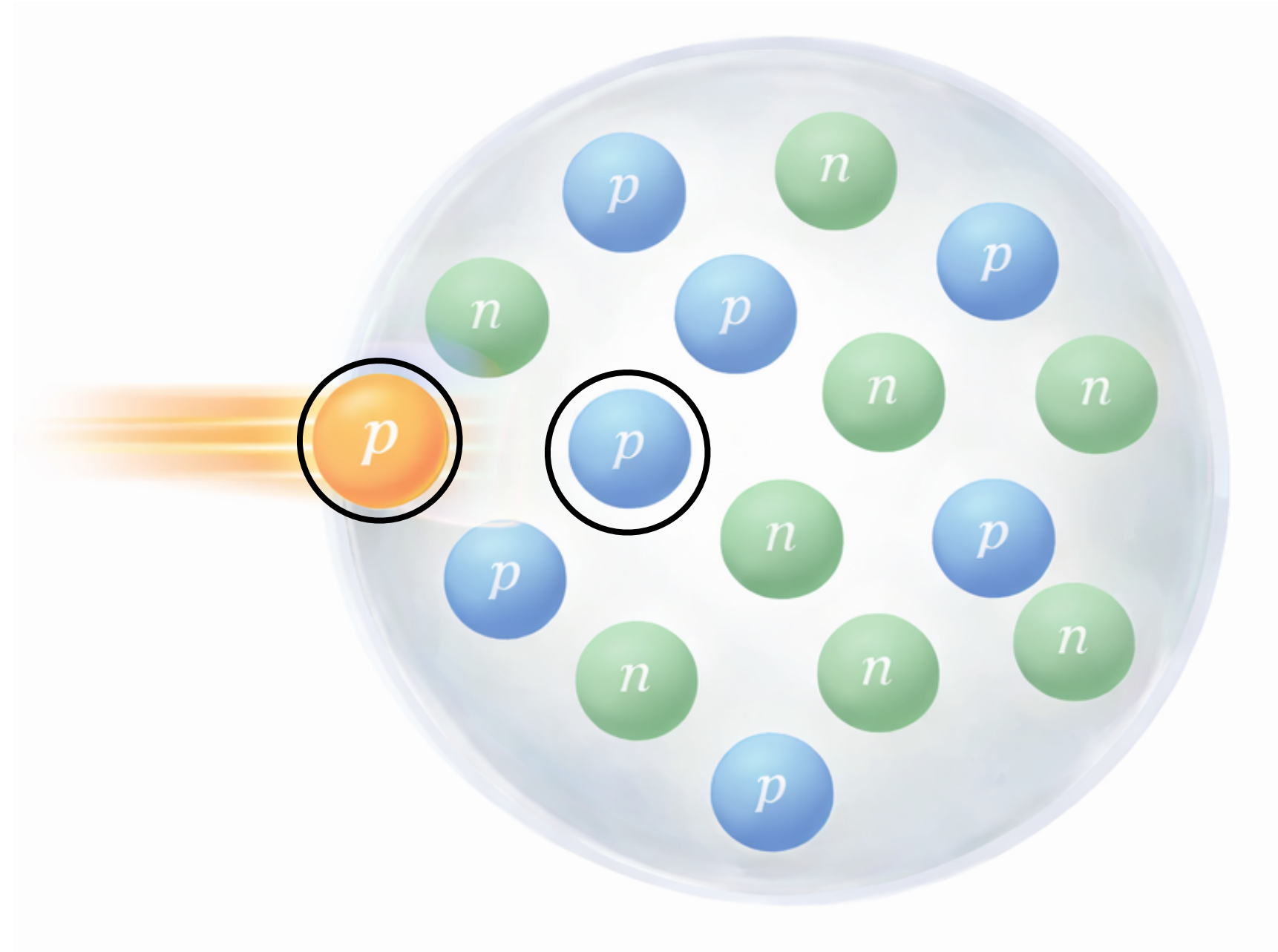
INCL Cascade Algorithm



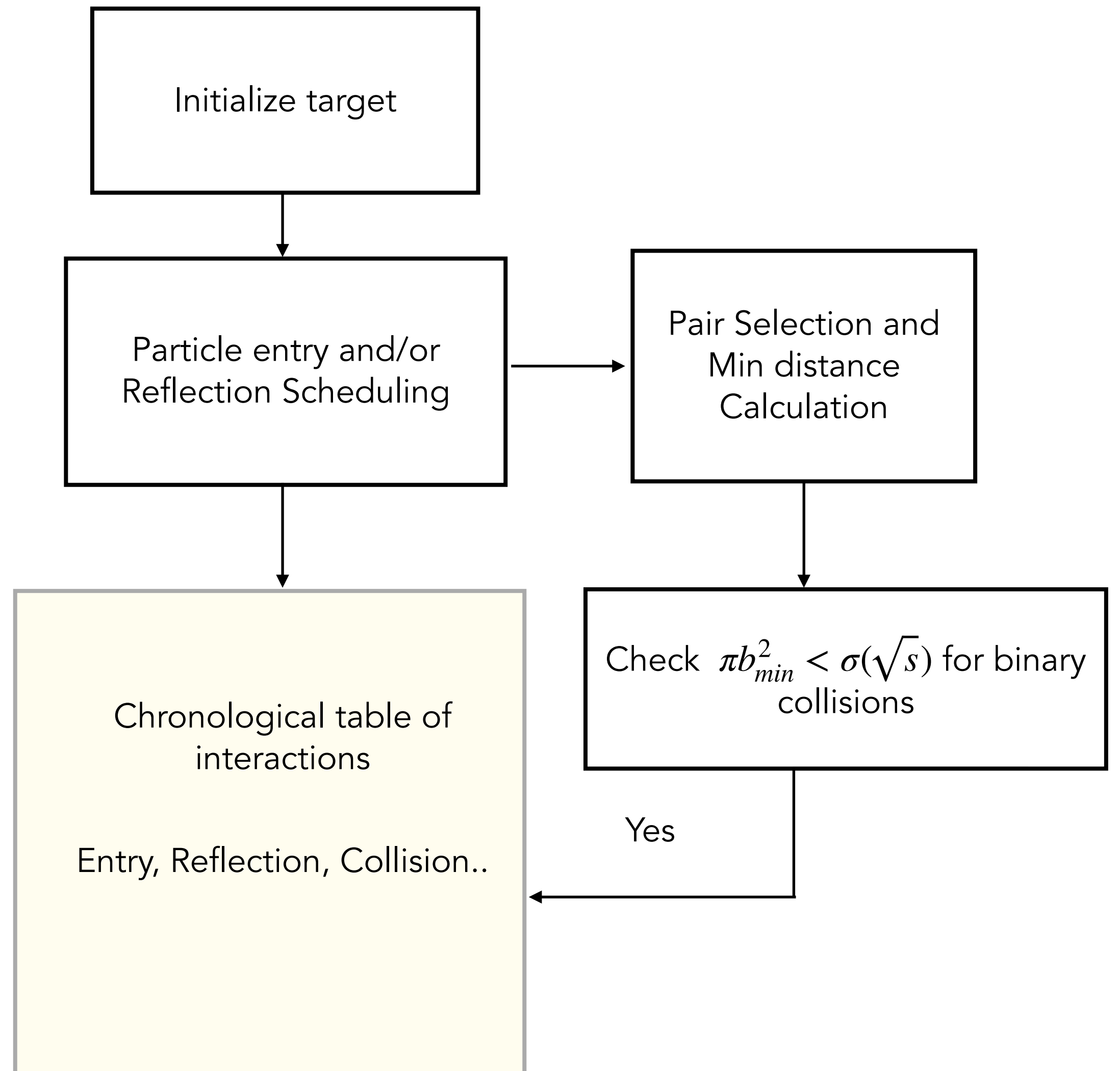
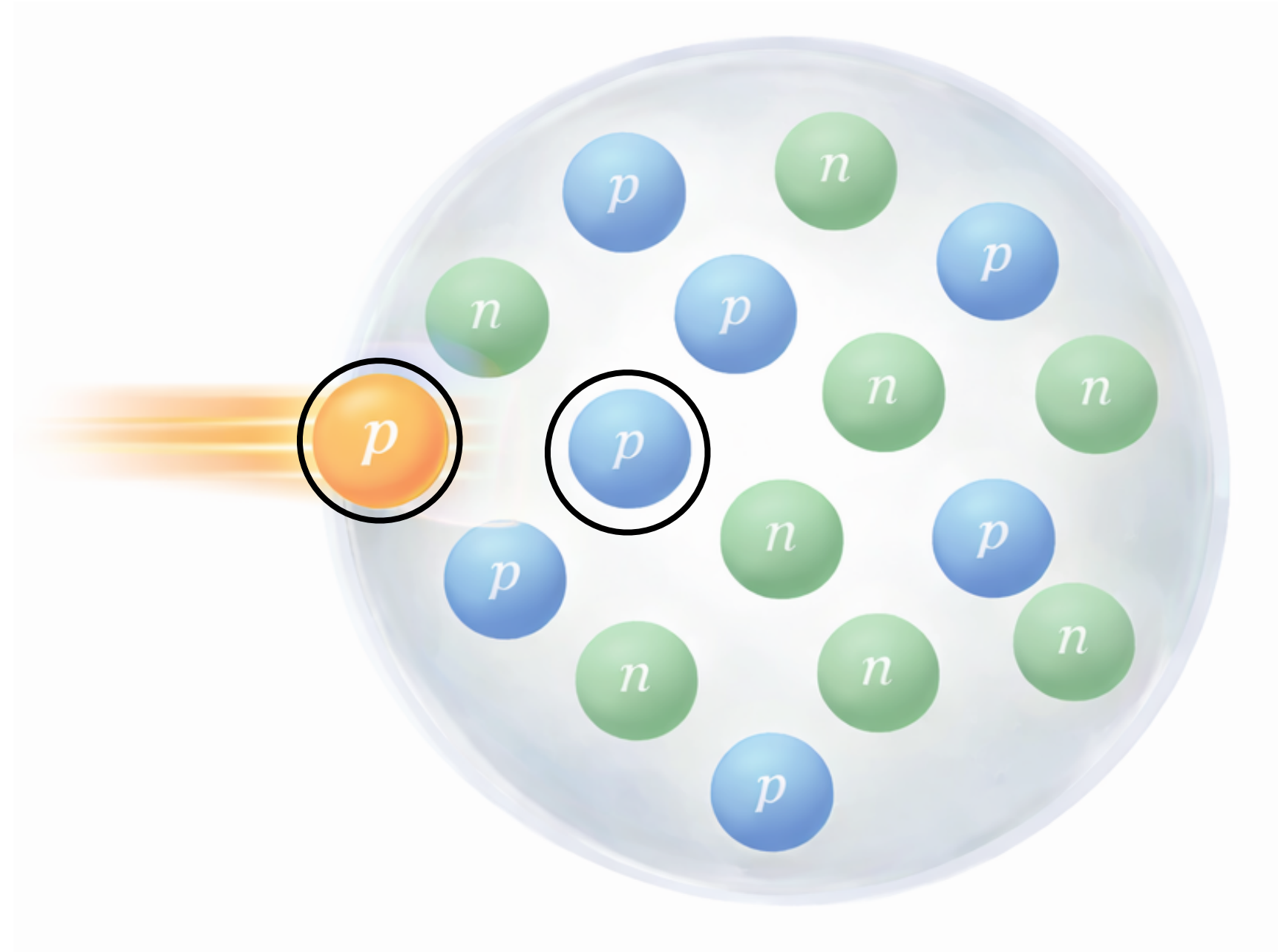
INCL Cascade Algorithm



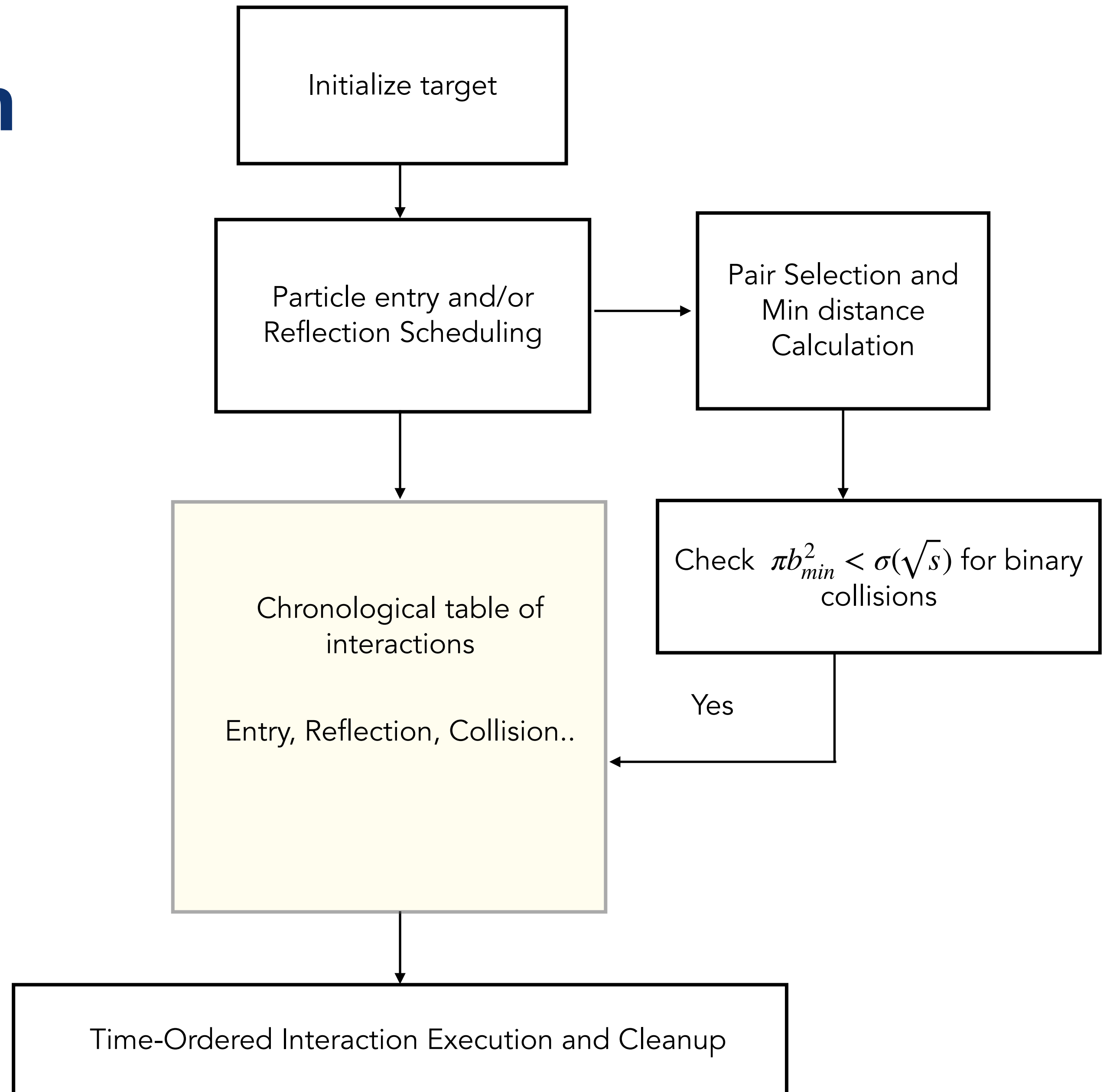
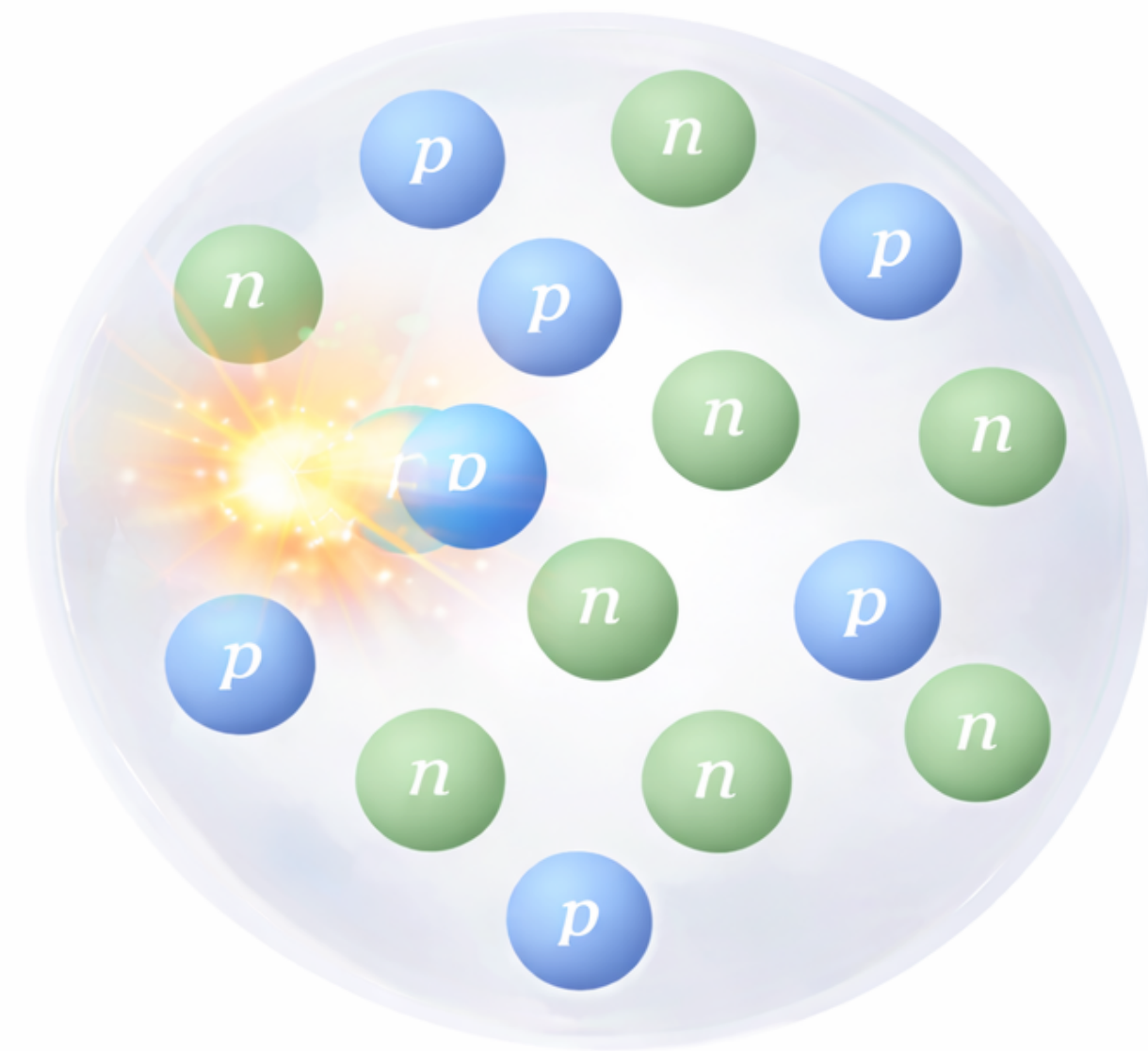
INCL Cascade Algorithm



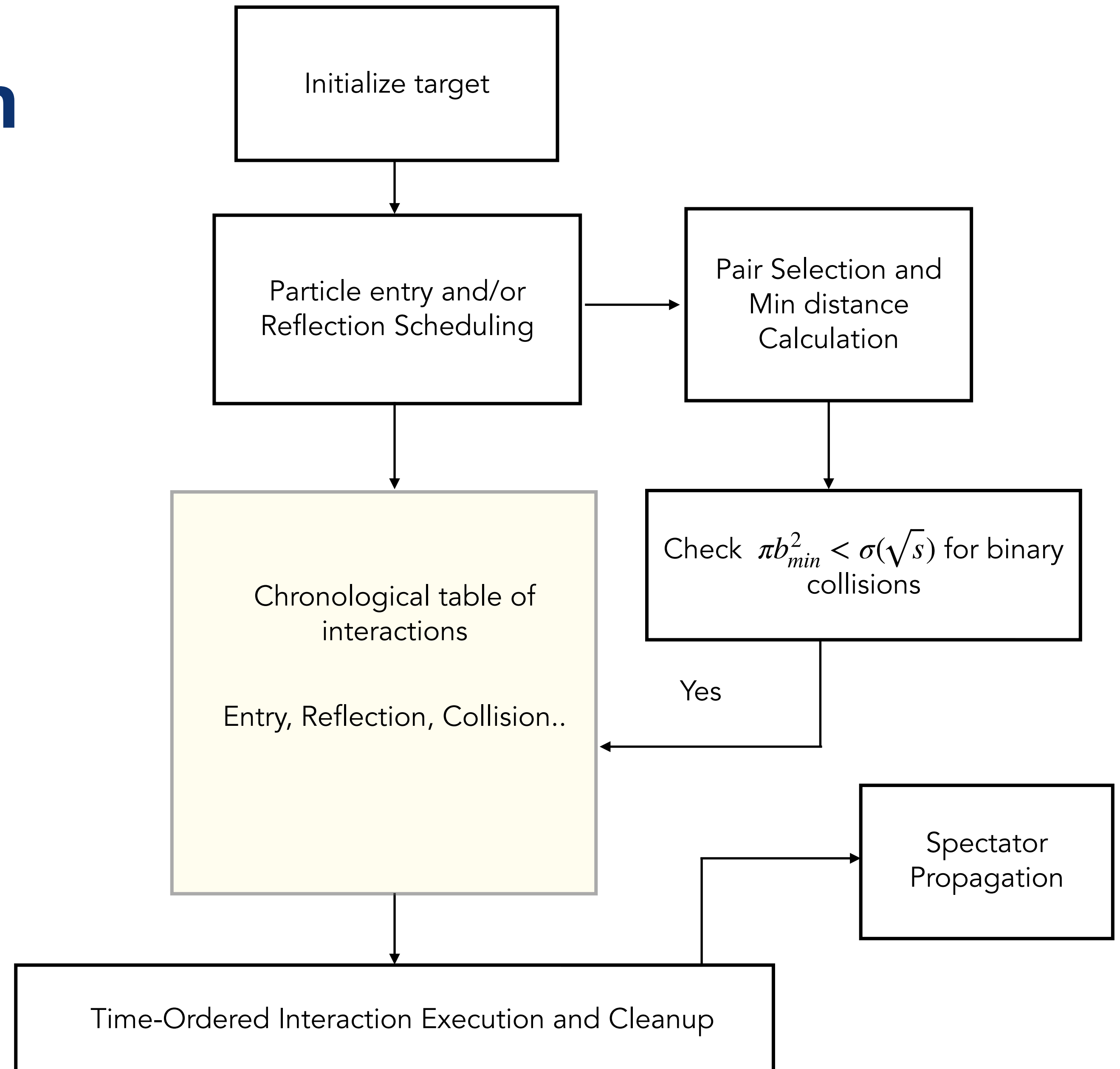
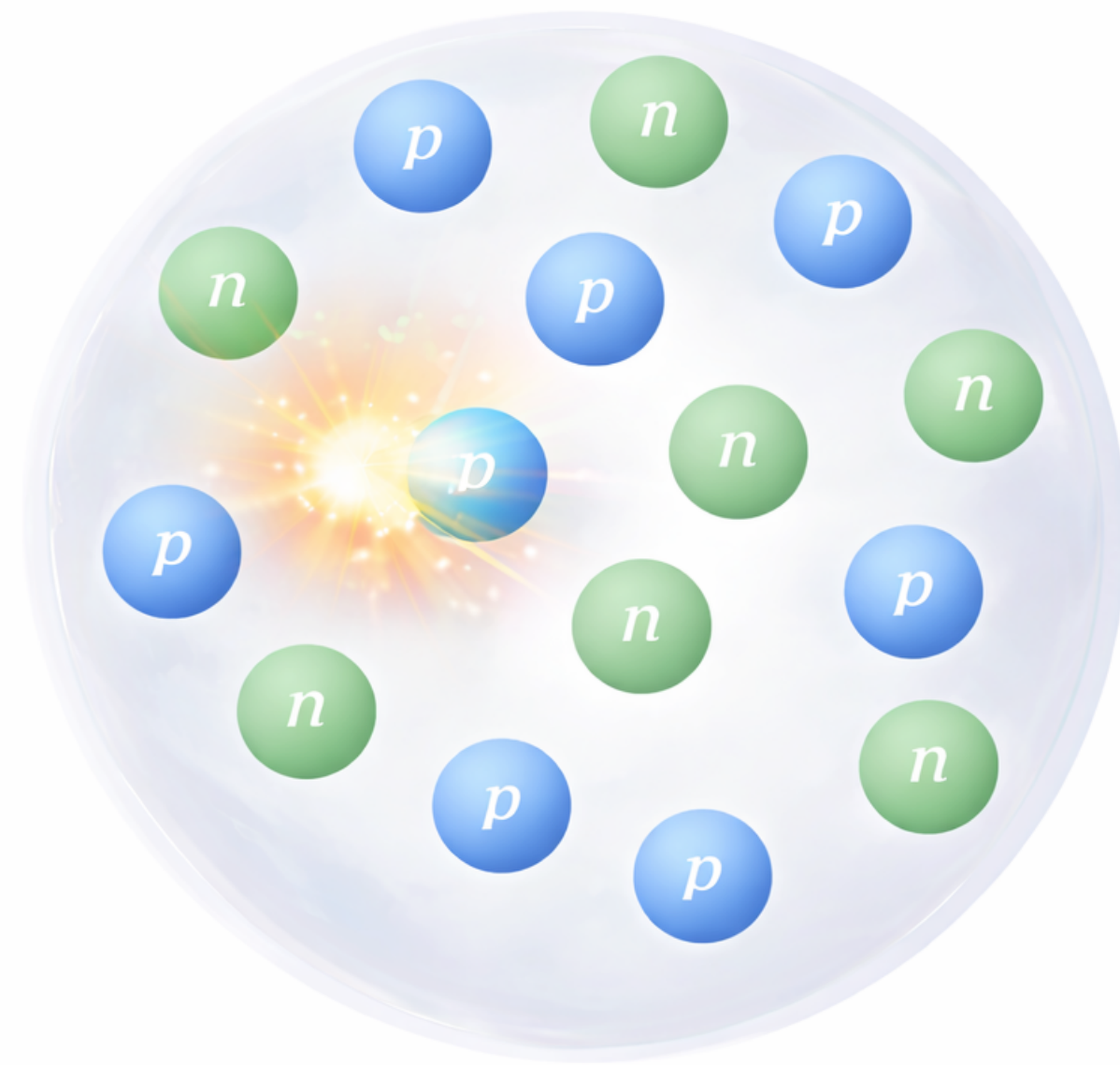
INCL Cascade Algorithm



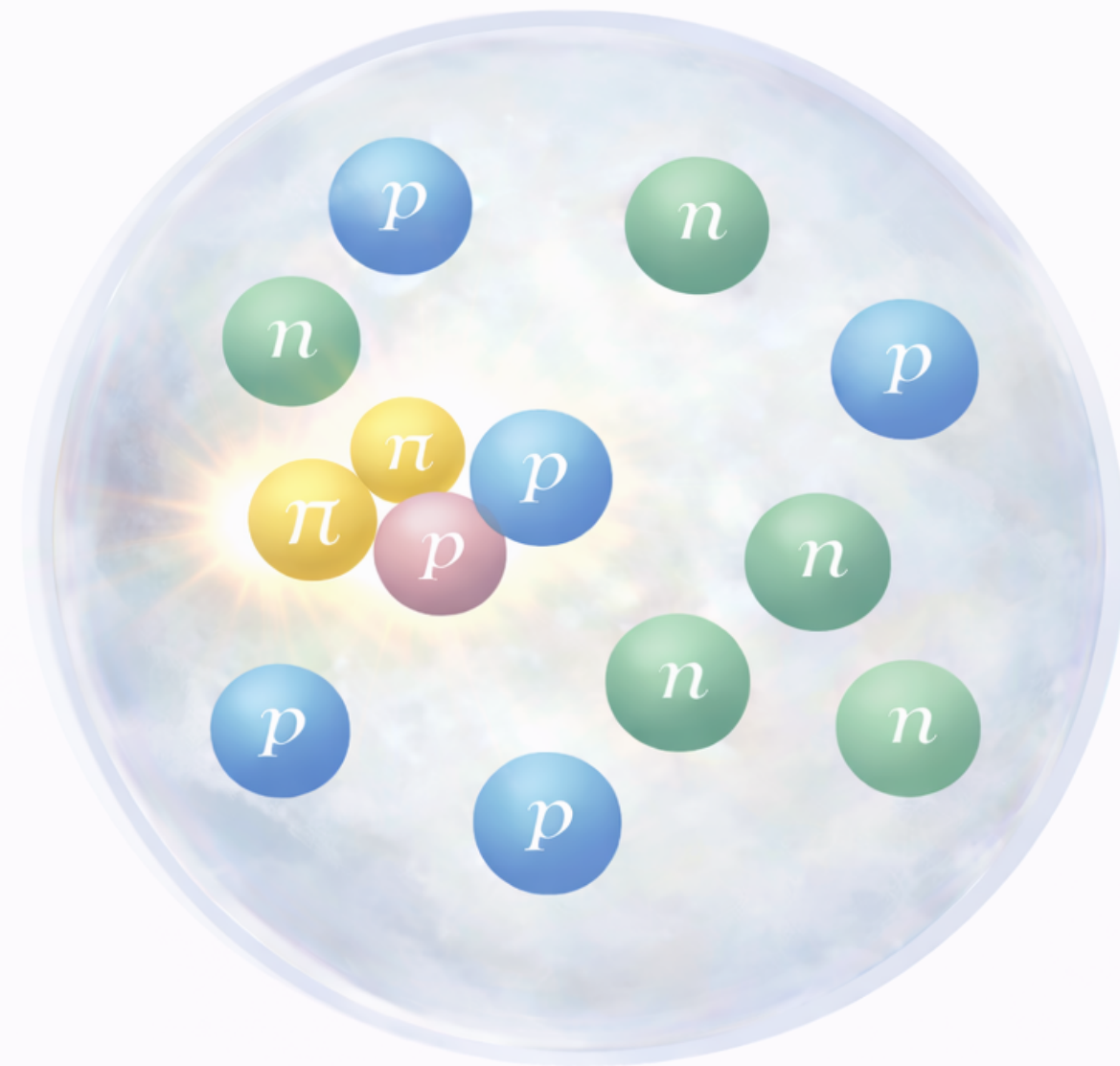
INCL Cascade Algorithm



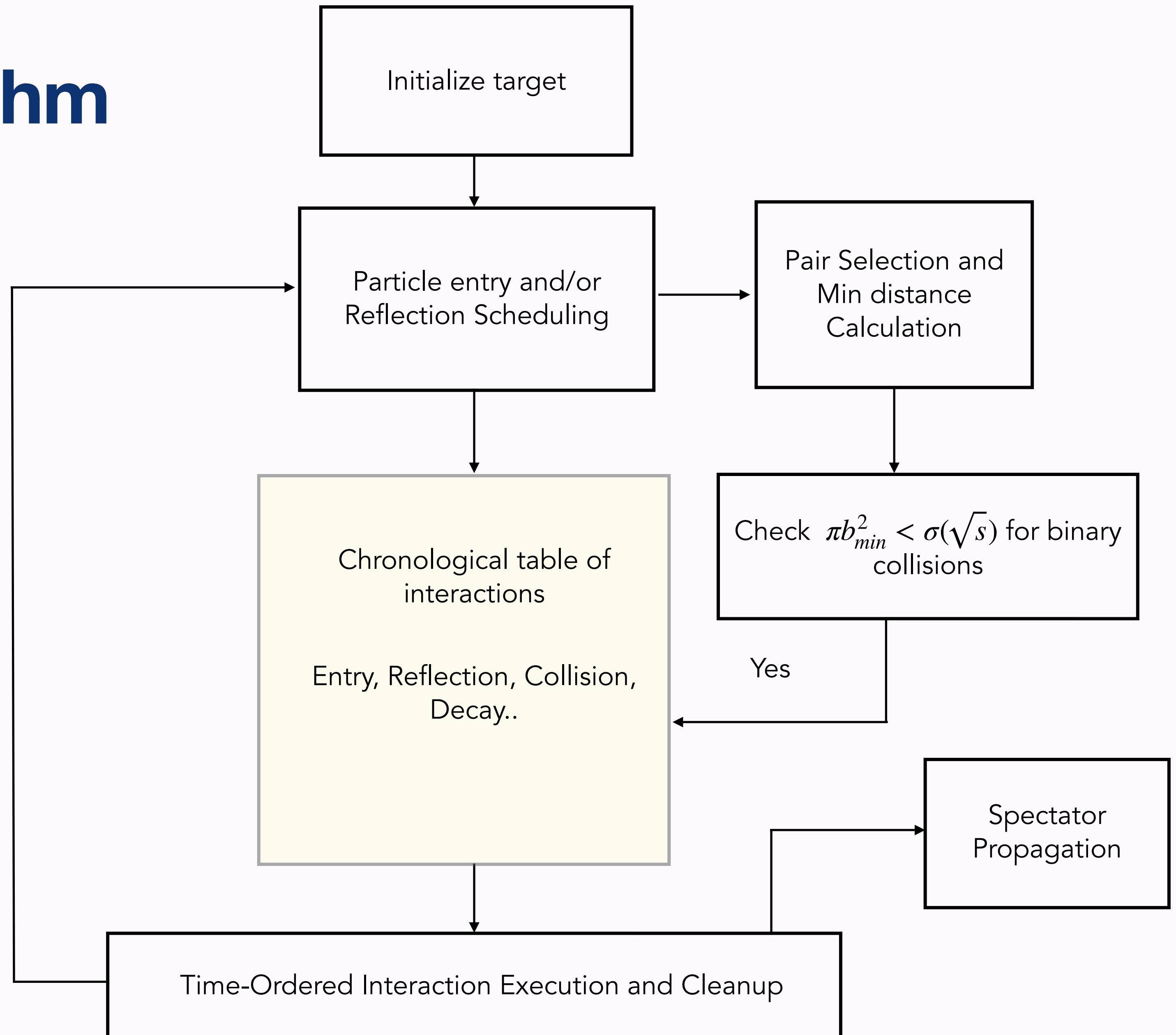
INCL Cascade Algorithm



INCL Cascade Algorithm



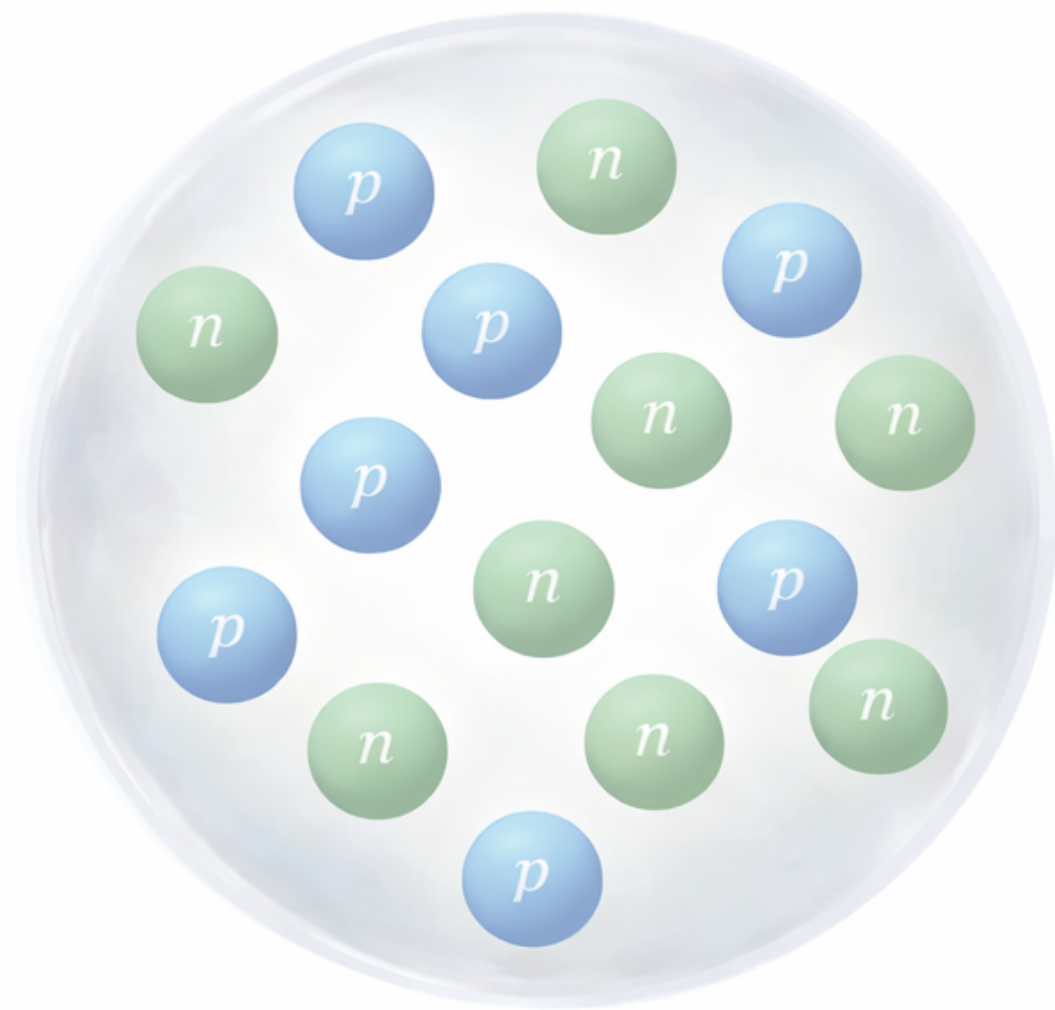
New/Updated Particles



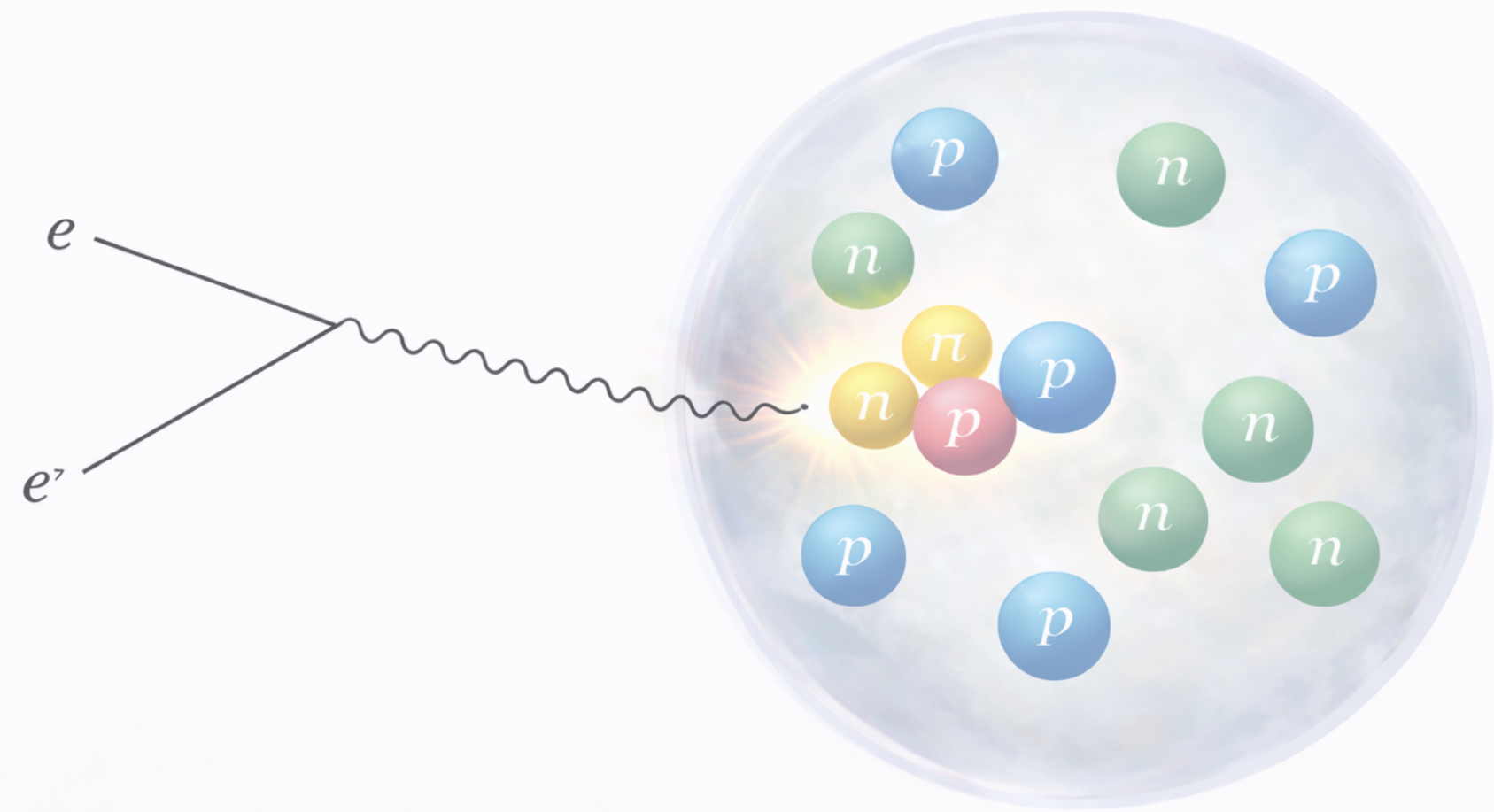
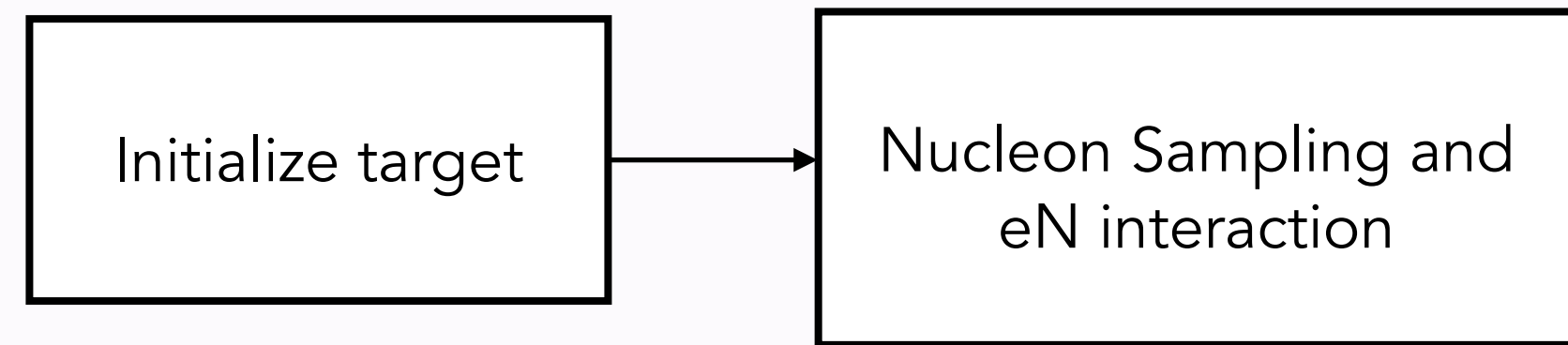
BeAGLE++ Cascade Algorithm

BeAGLE++ Cascade Algorithm

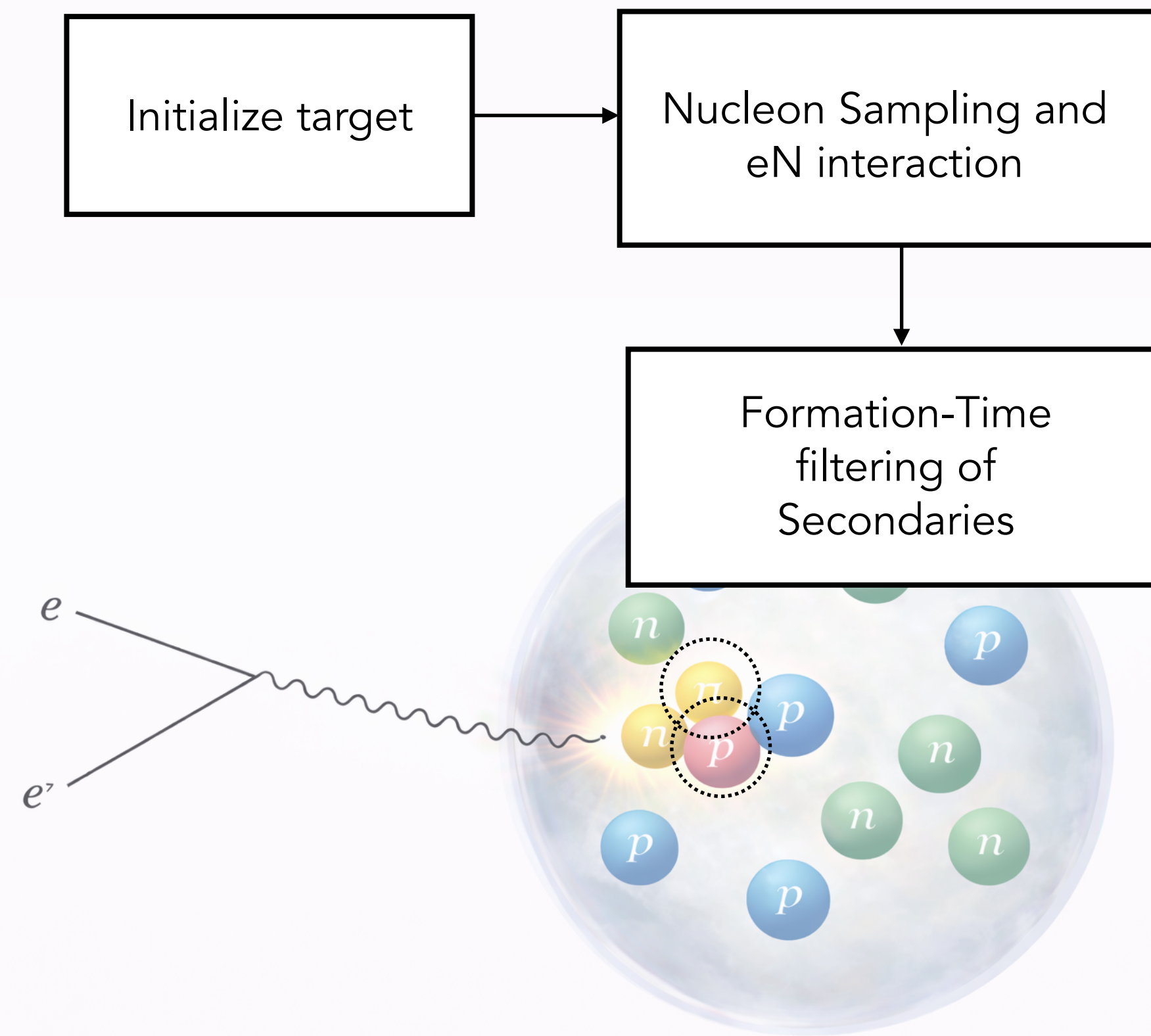
Initialize target



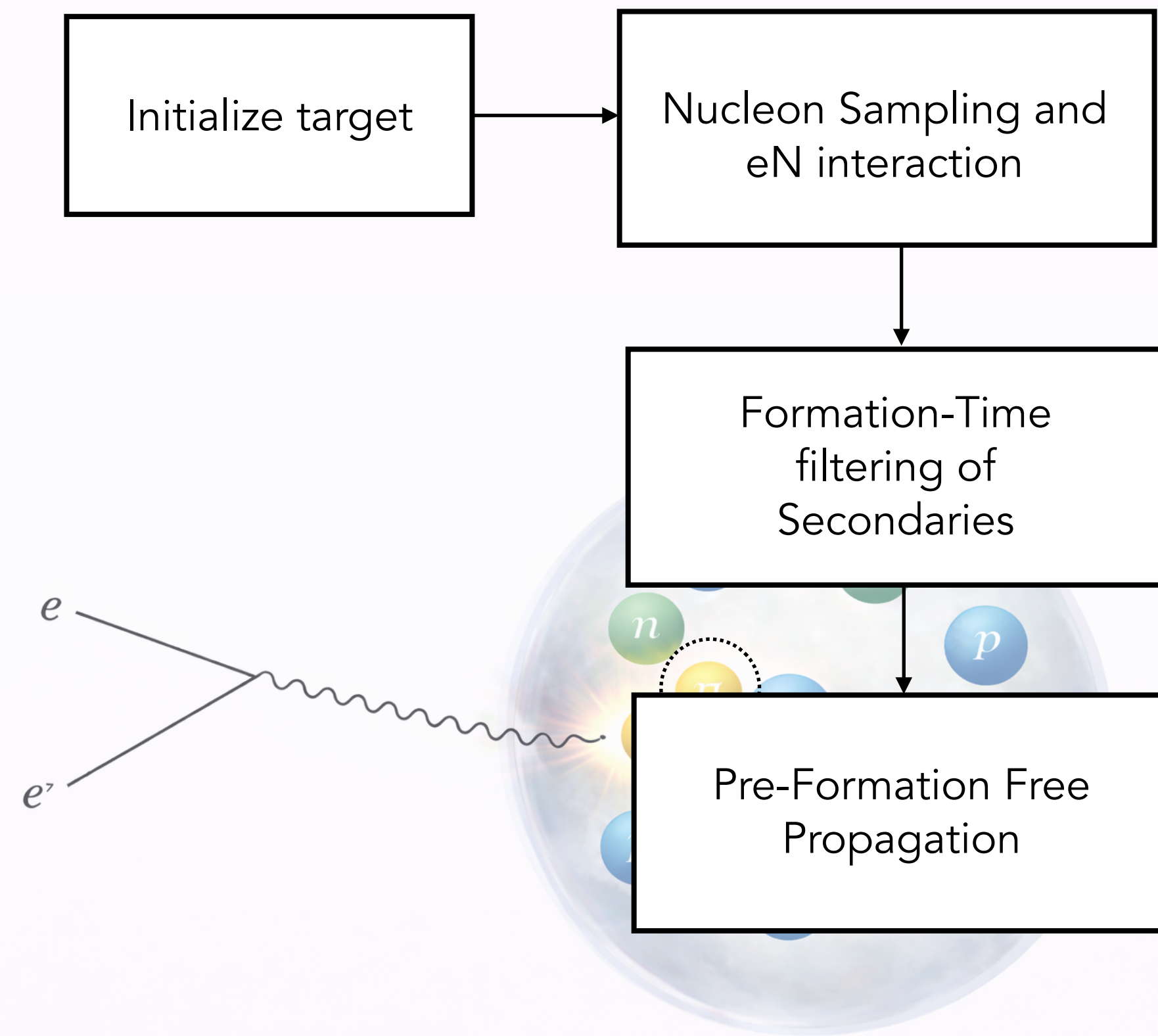
BeAGLE++ Cascade Algorithm



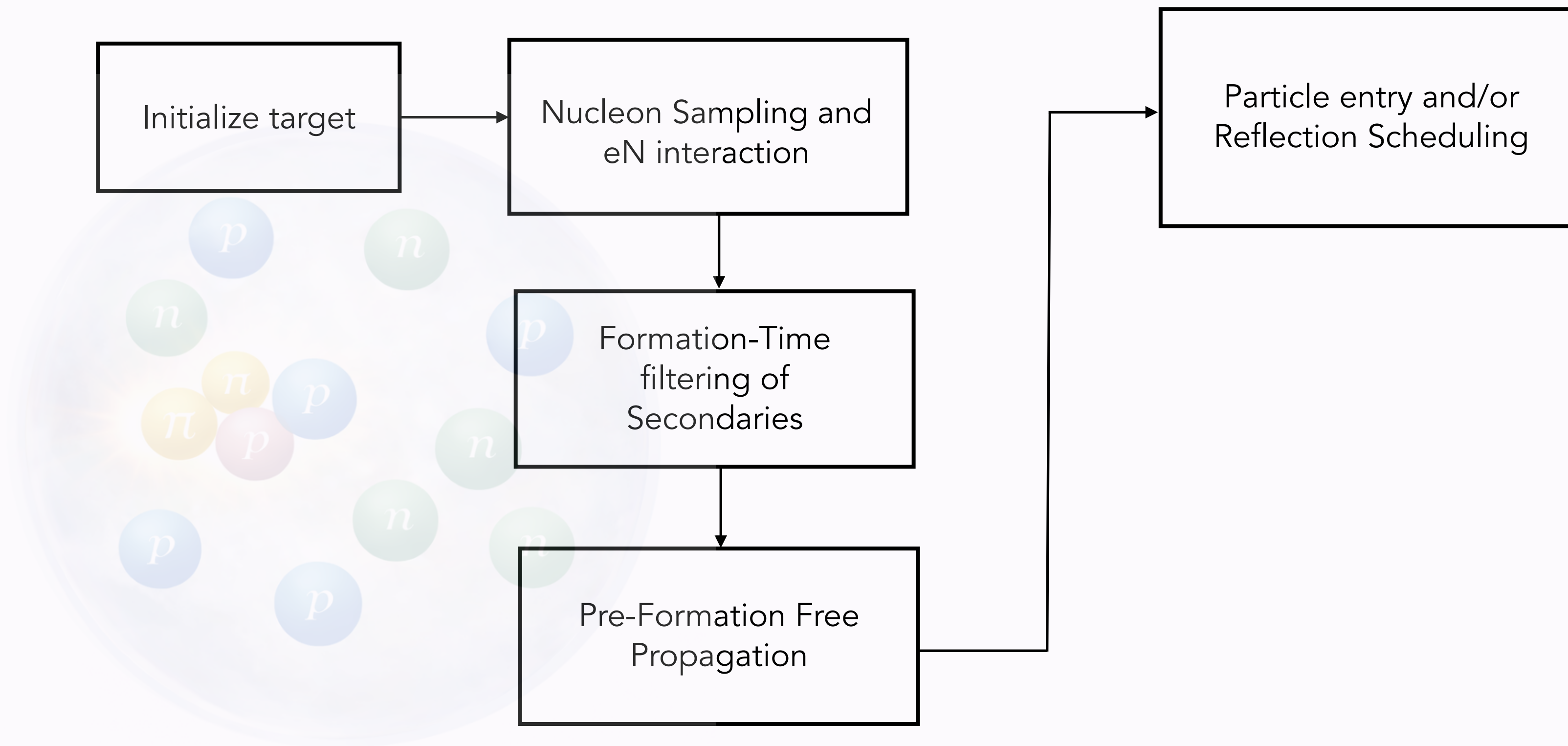
BeAGLE++ Cascade Algorithm



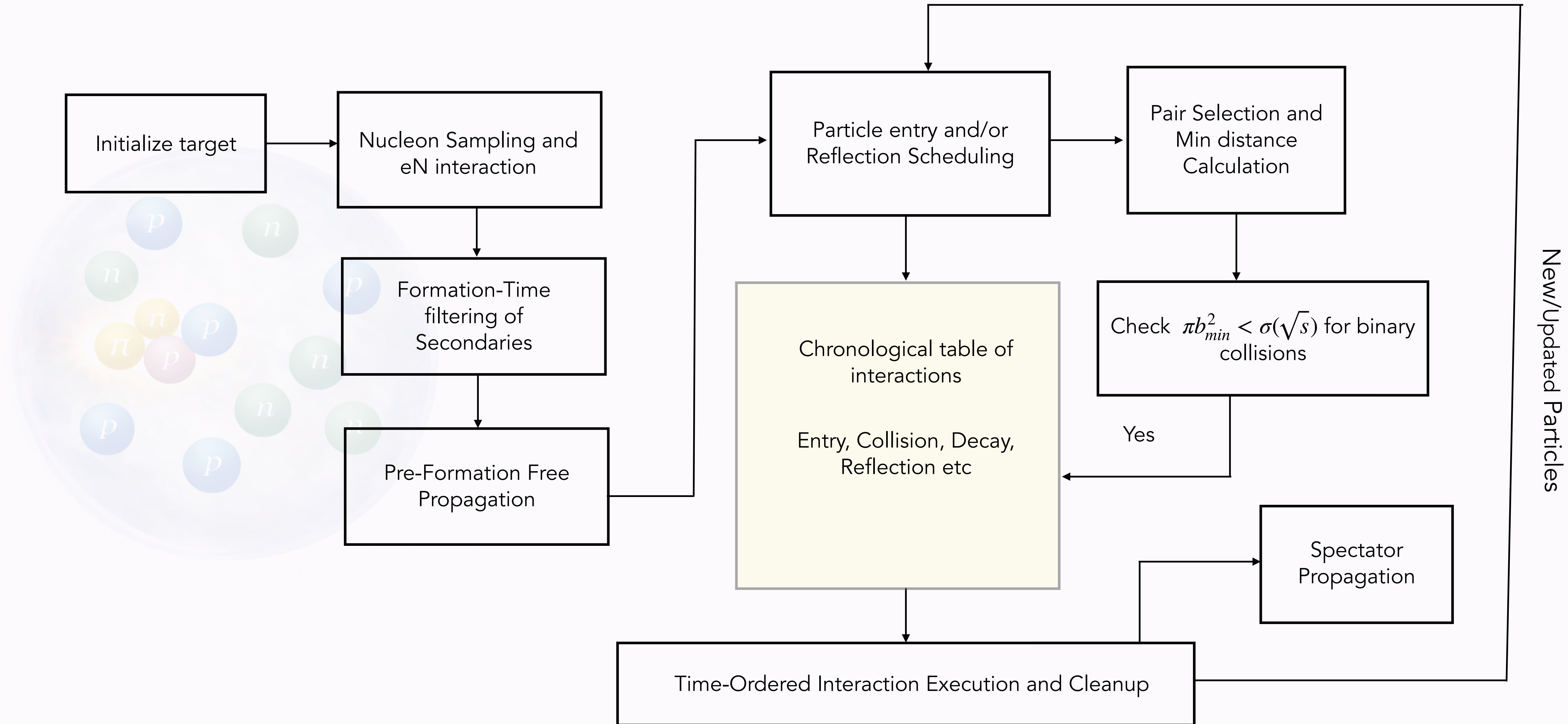
BeAGLE++ Cascade Algorithm



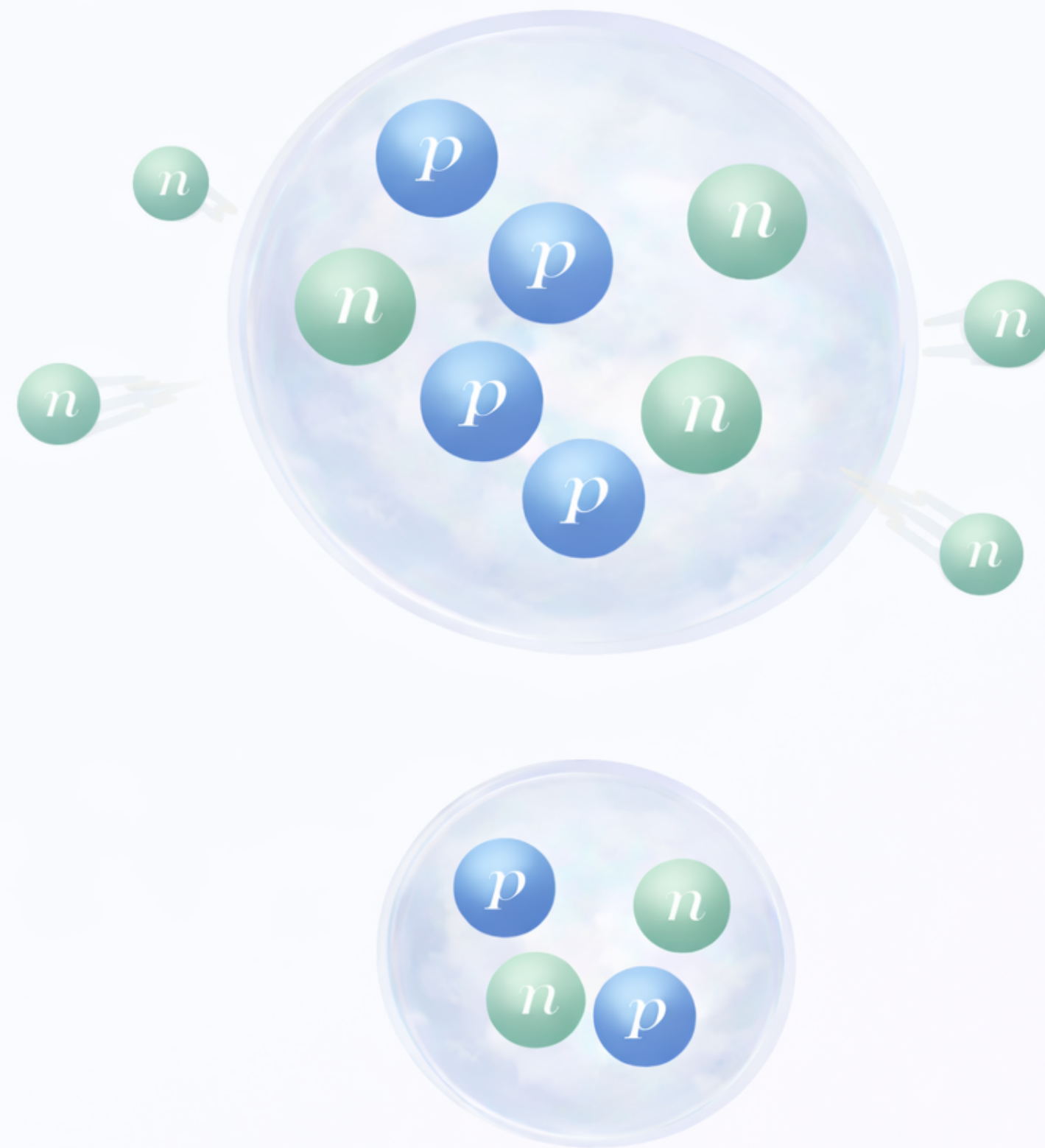
BeAGLE++ Cascade Algorithm



BeAGLE++ Cascade Algorithm



ABLA: De-excitation model

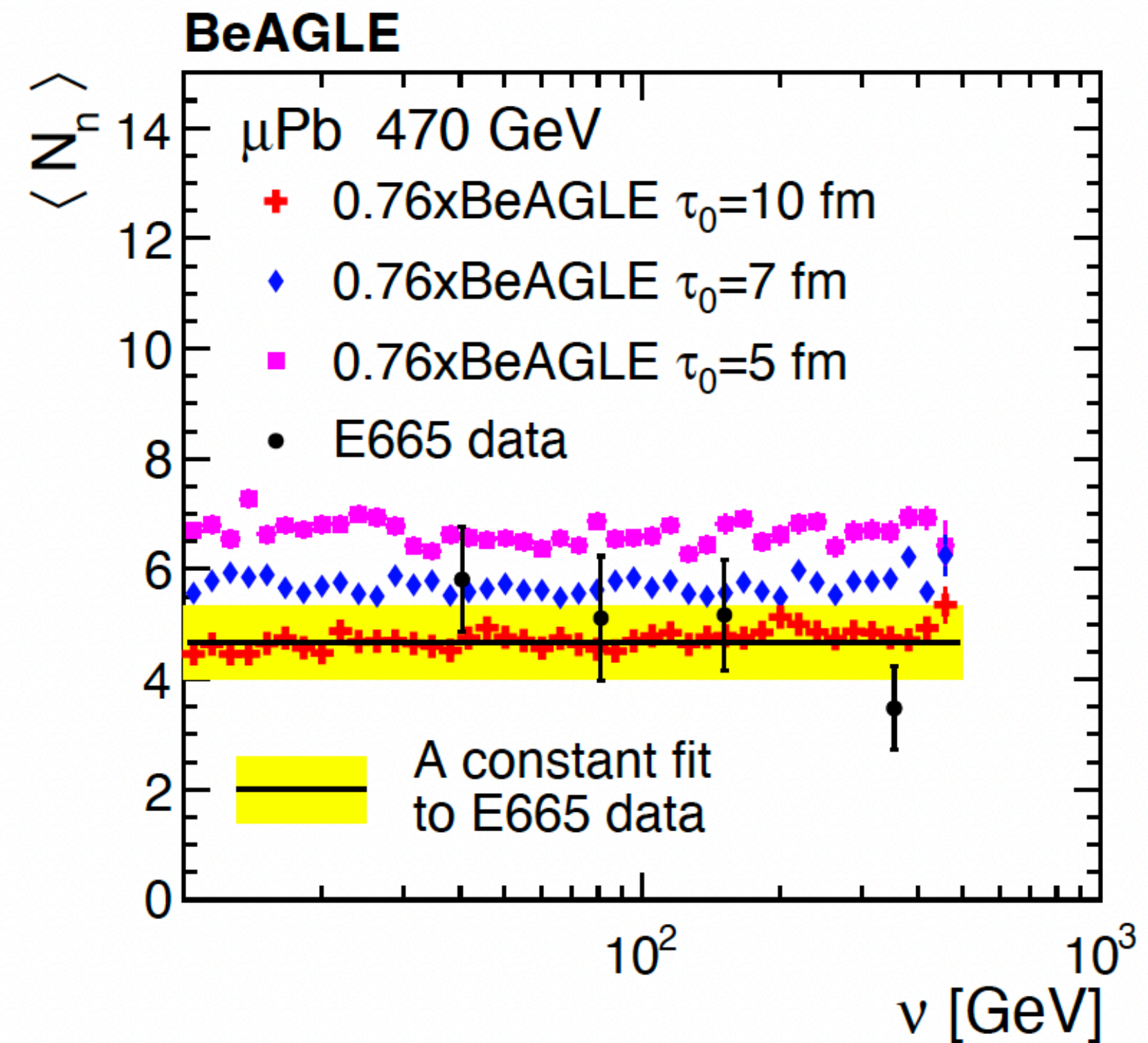
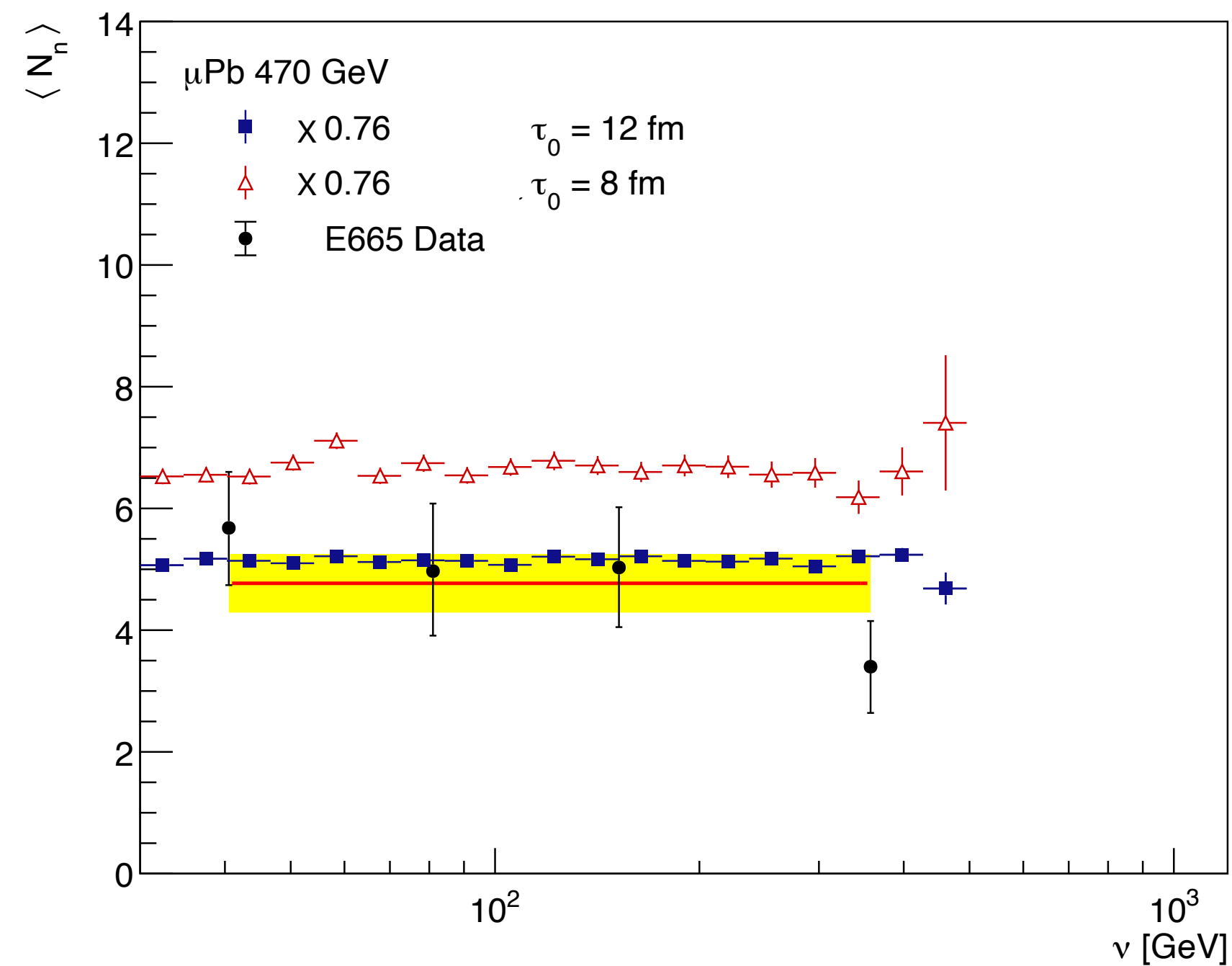


- Dynamical code that describes the de-excitation of the thermalized system
- **Open source code and easy coupling to INCL++**
- De-excitation happens through:
 - *Evaporation (particle emission)*: dominant at moderate excitation energies
 - *Fission*: critical for heavy nuclei
 - *Breakup/Multi-fragmentation*: activates at high excitation energies
 - *Gamma de-excitation*: excitation energies below particle thresholds

Project at matured state with version 0.0 ready and at par with legacy code

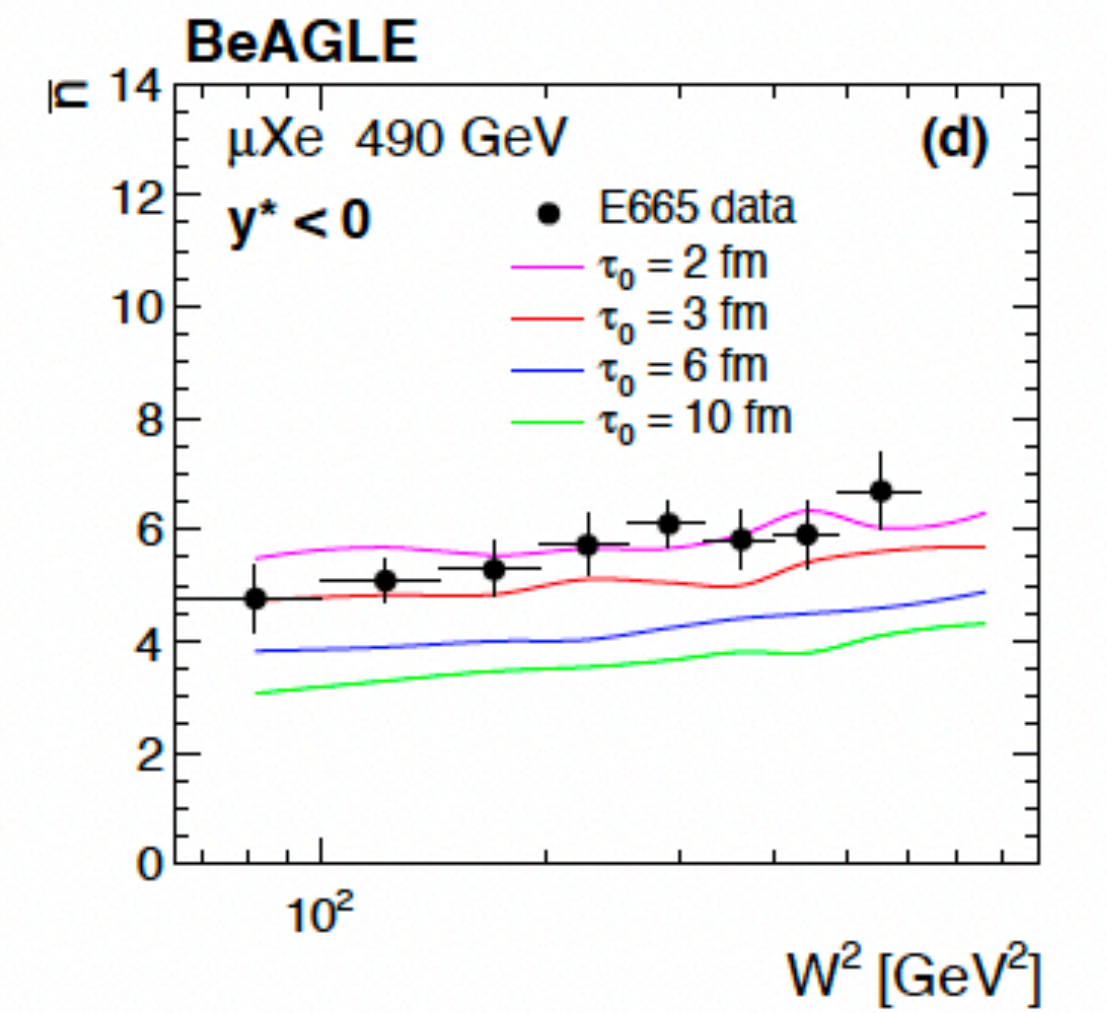
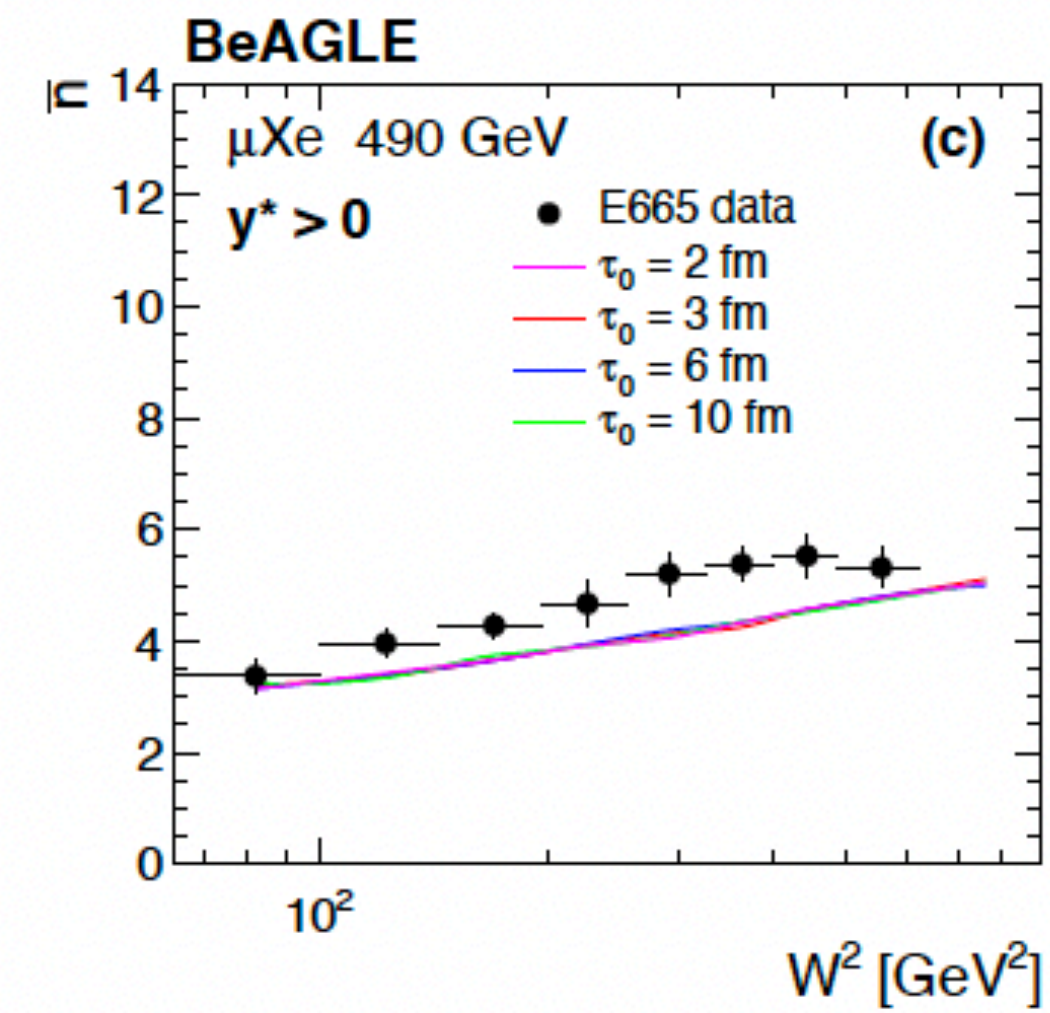
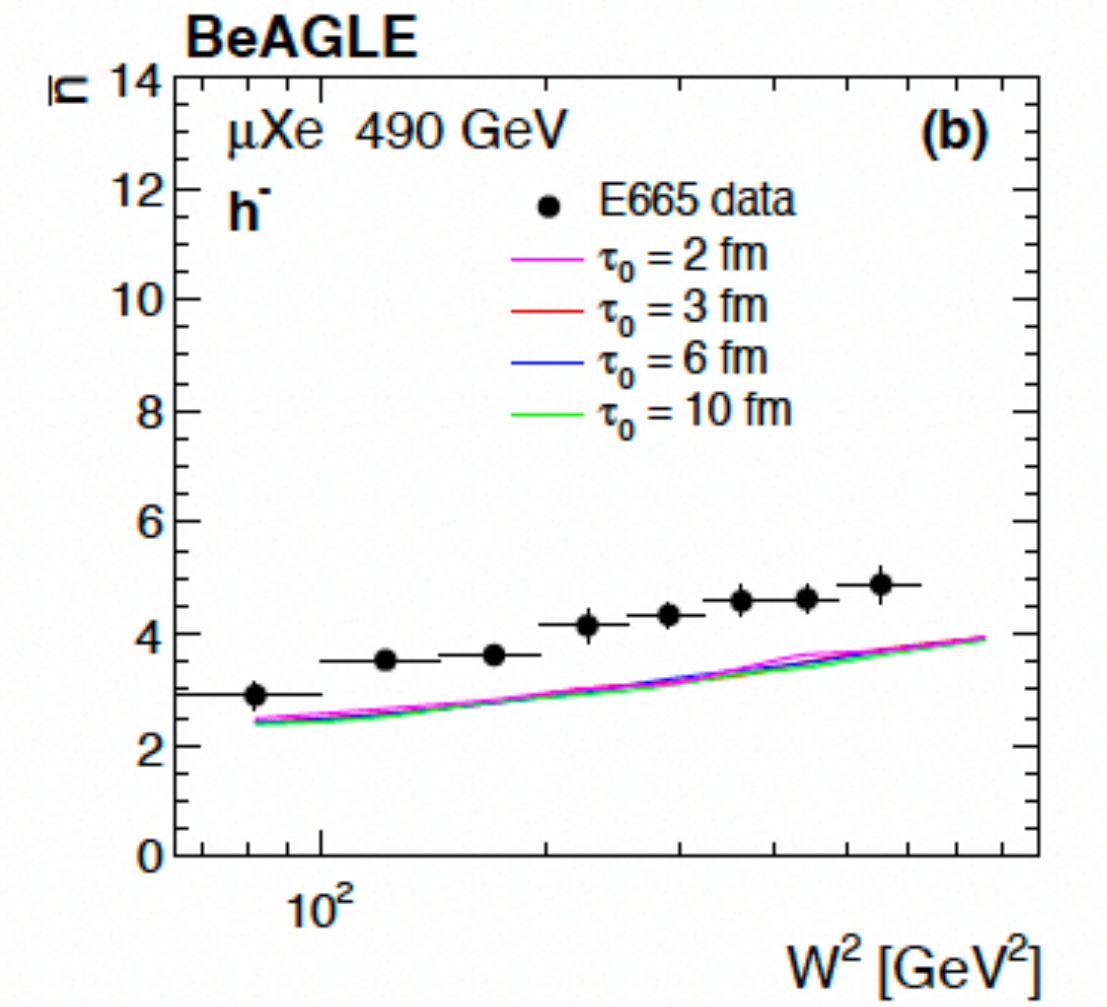
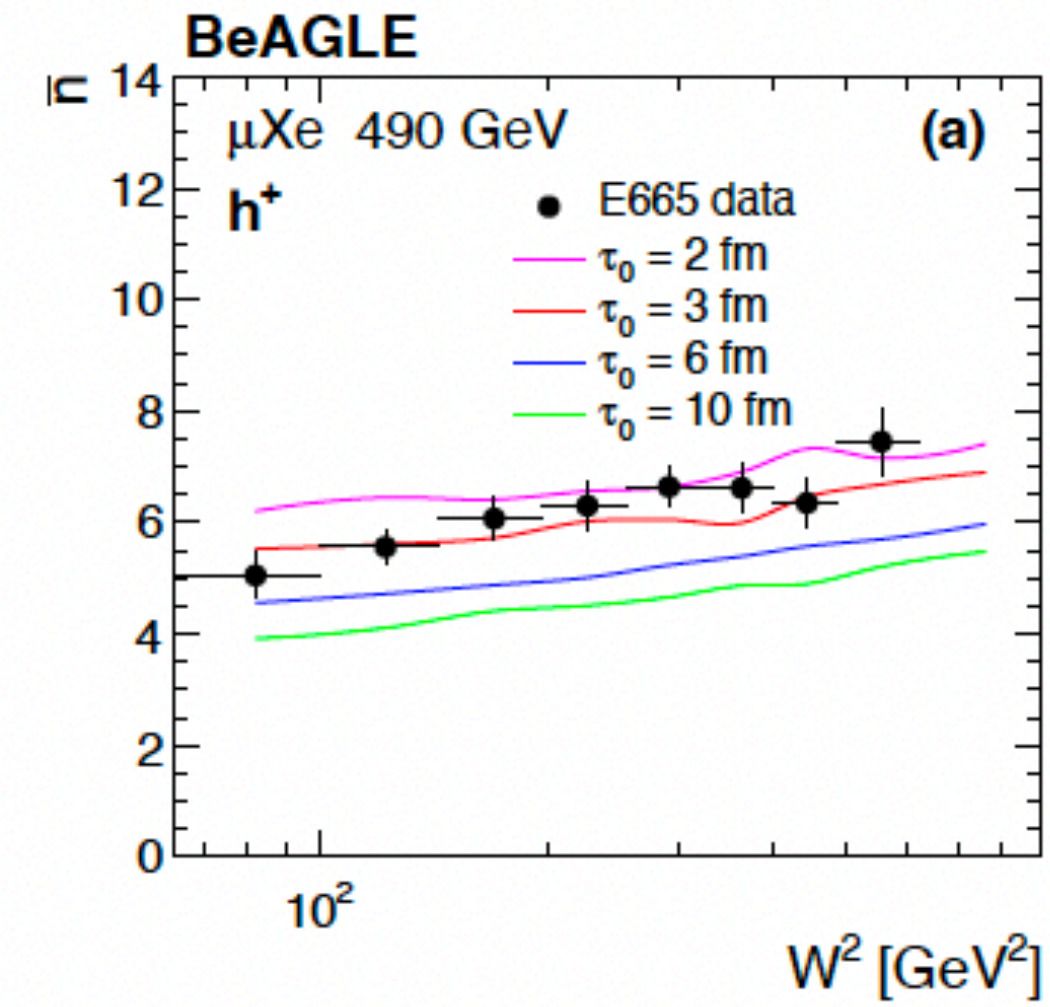
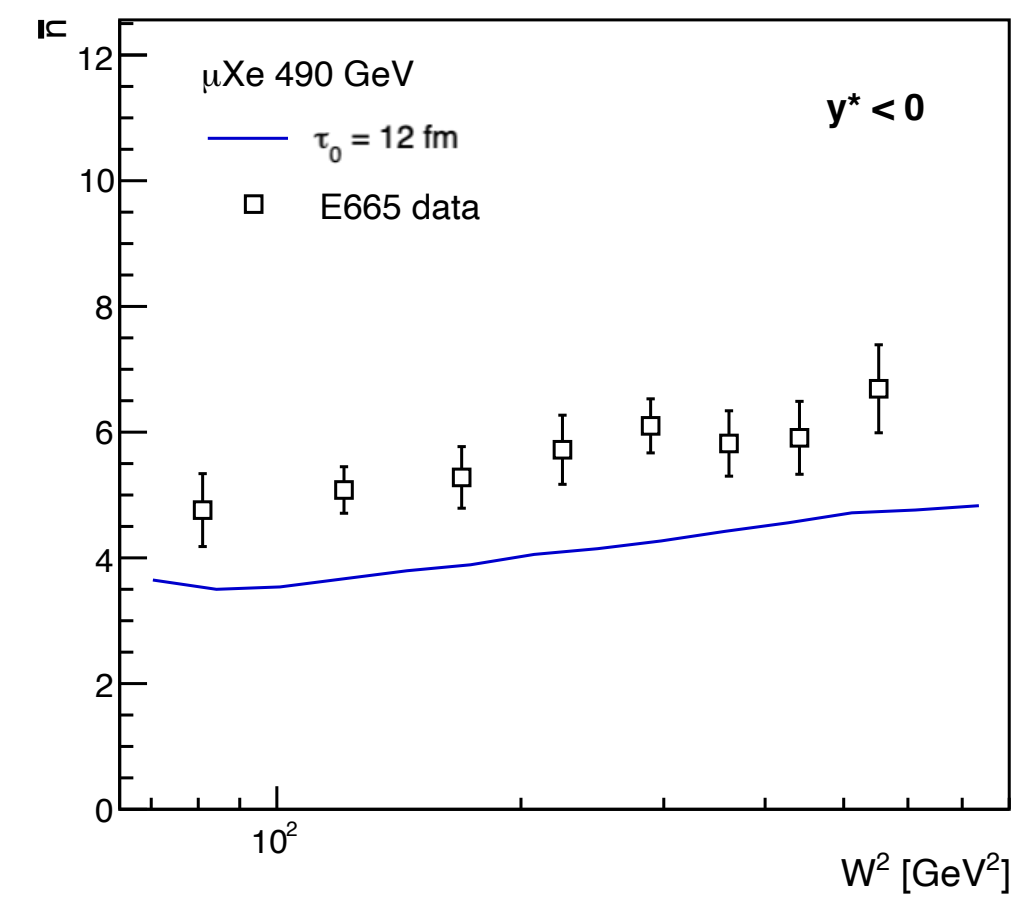
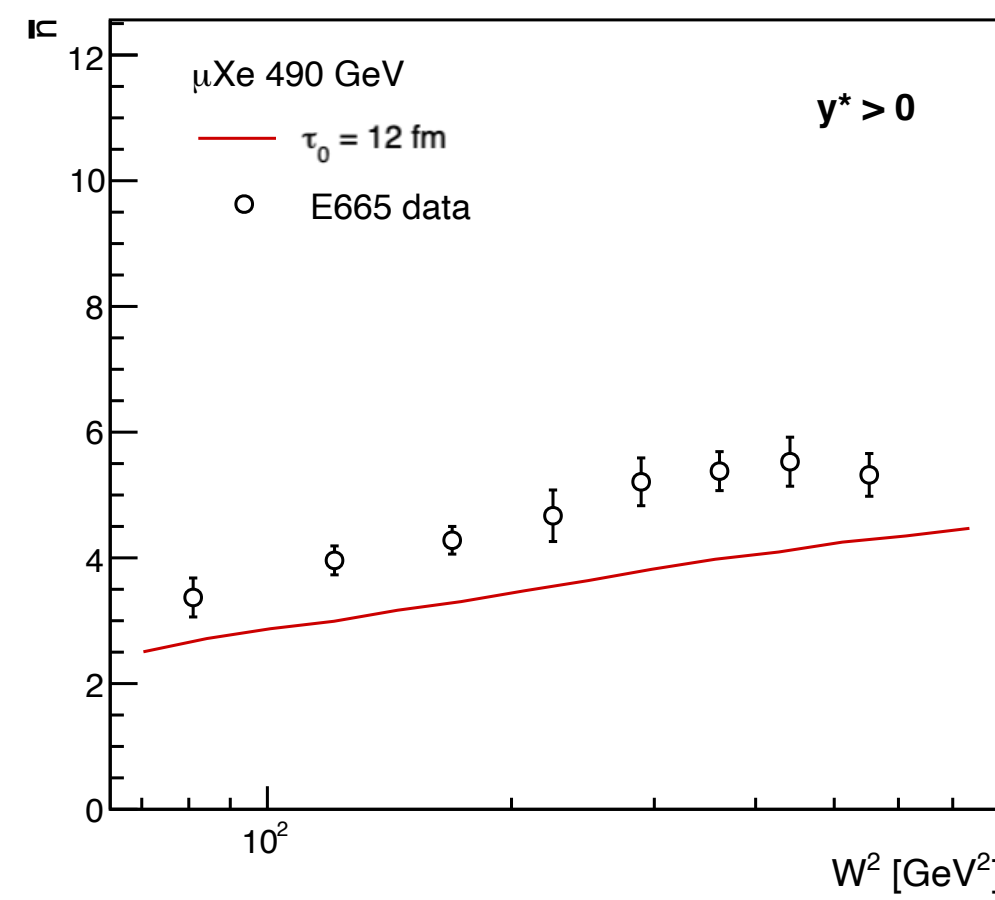
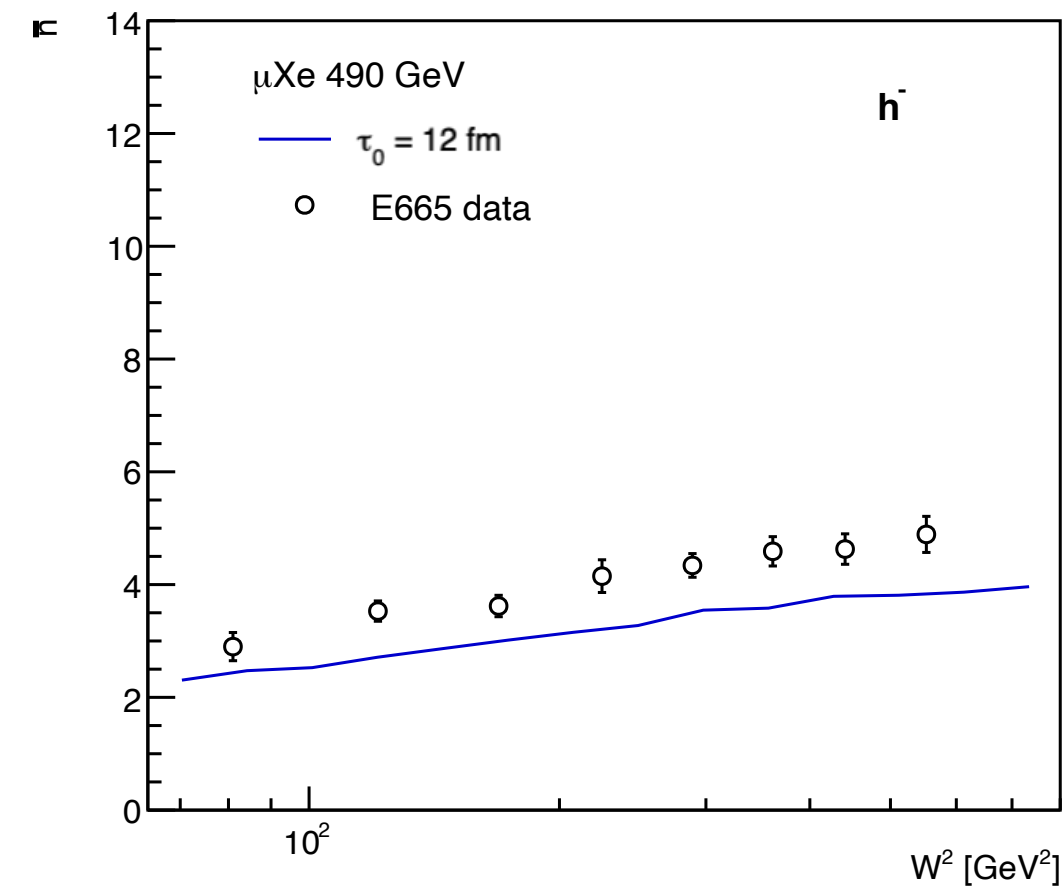
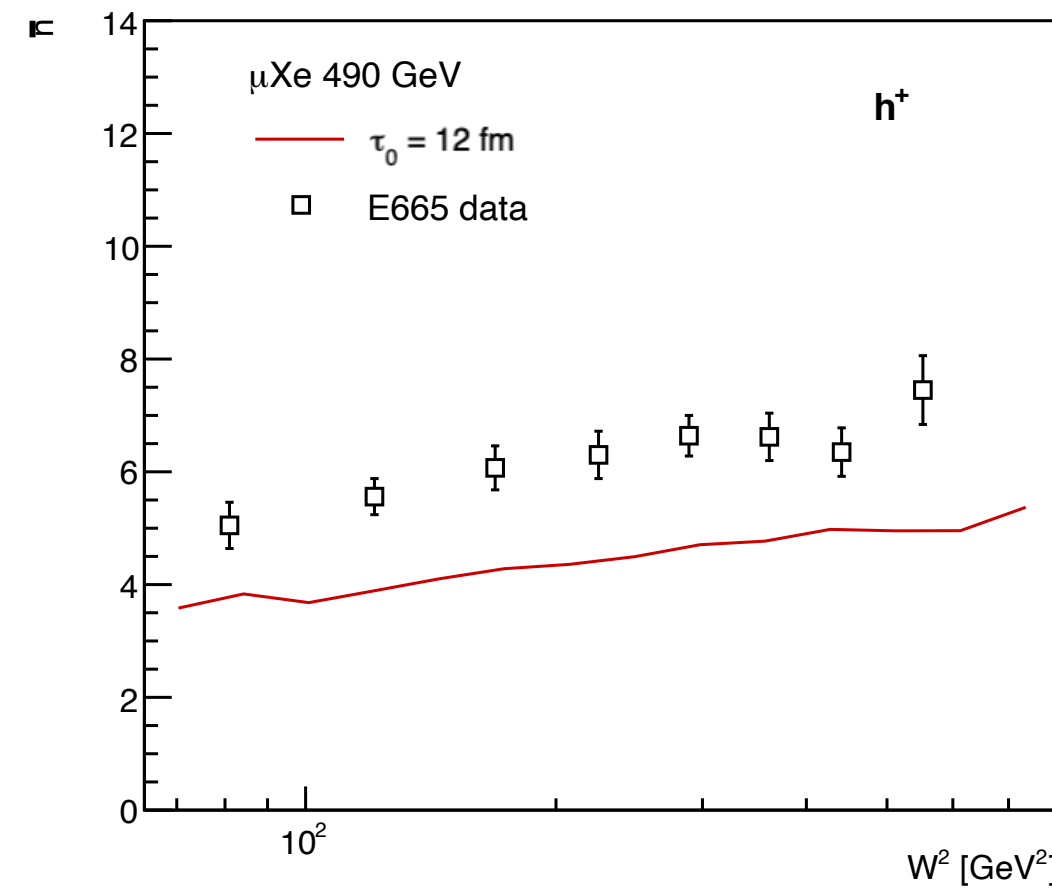
	Legacy BeAGLE	BeAGLE++	Remarks
Hard Interaction	Pythia6	Pythia8	In future: HERWIG,SHERPA
MC technique for Cascade	Spatial	Temporal	No dependence on step size
Cluster emission during cascade	No	Yes	Coalescence algorithm in INCL++
De-excitation	Fluka	ABLA07	In future: FLUKA, Gemini++
Event Generation	Very Slow	Very Fast	1M events~ 15-20 mins for Pb on laptop
Initial Geometry	Fixed	Different models	Neutron thickness and level structure
Modular	No	Yes	Easy coupling, OOPS, Polymorphism
User friendly	No	Yes	Easy installation, run from own laptop
Maintenance	Hard	Easy	Easily understandable, Modern architecture

Neutron Multiplicity

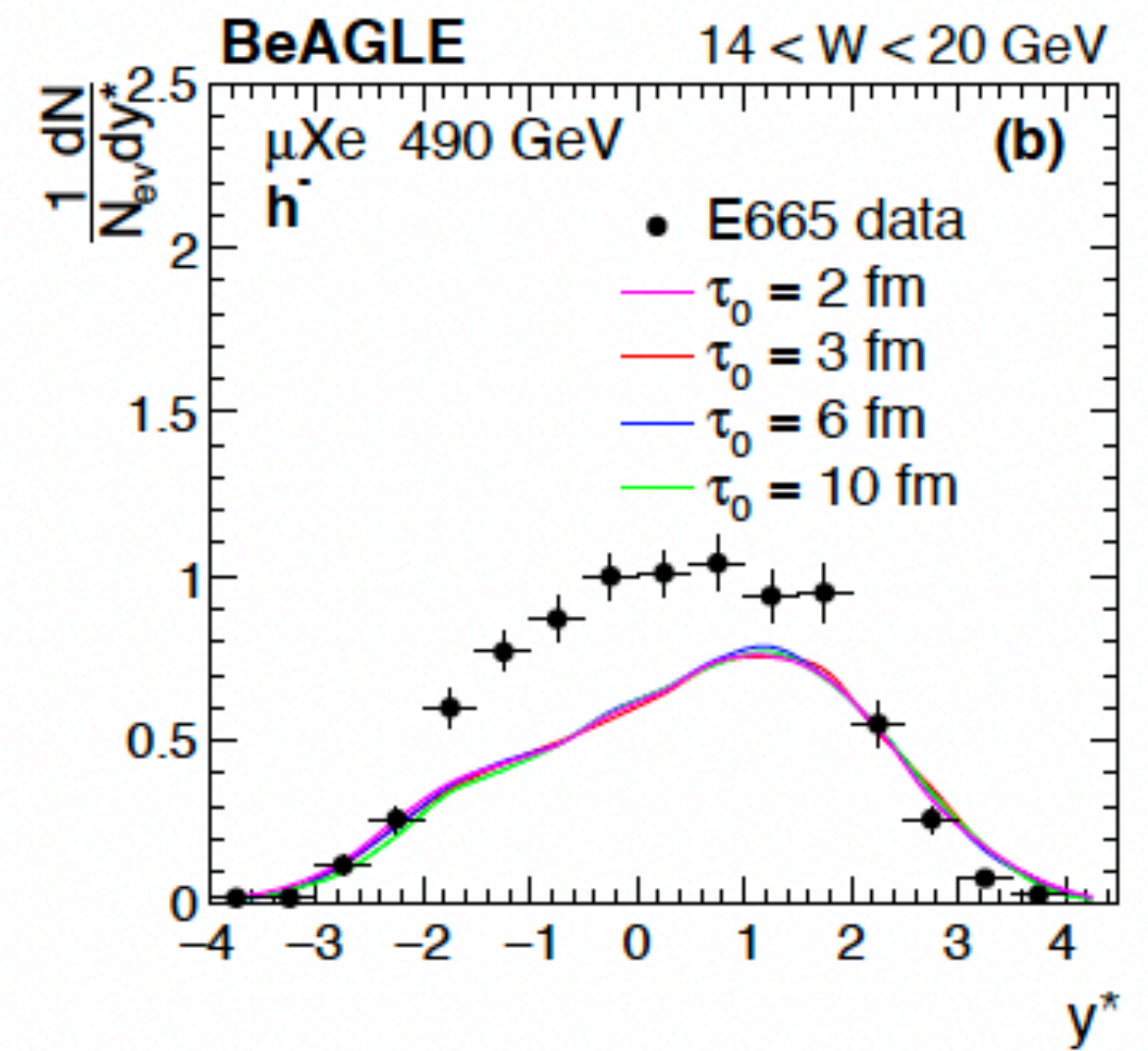
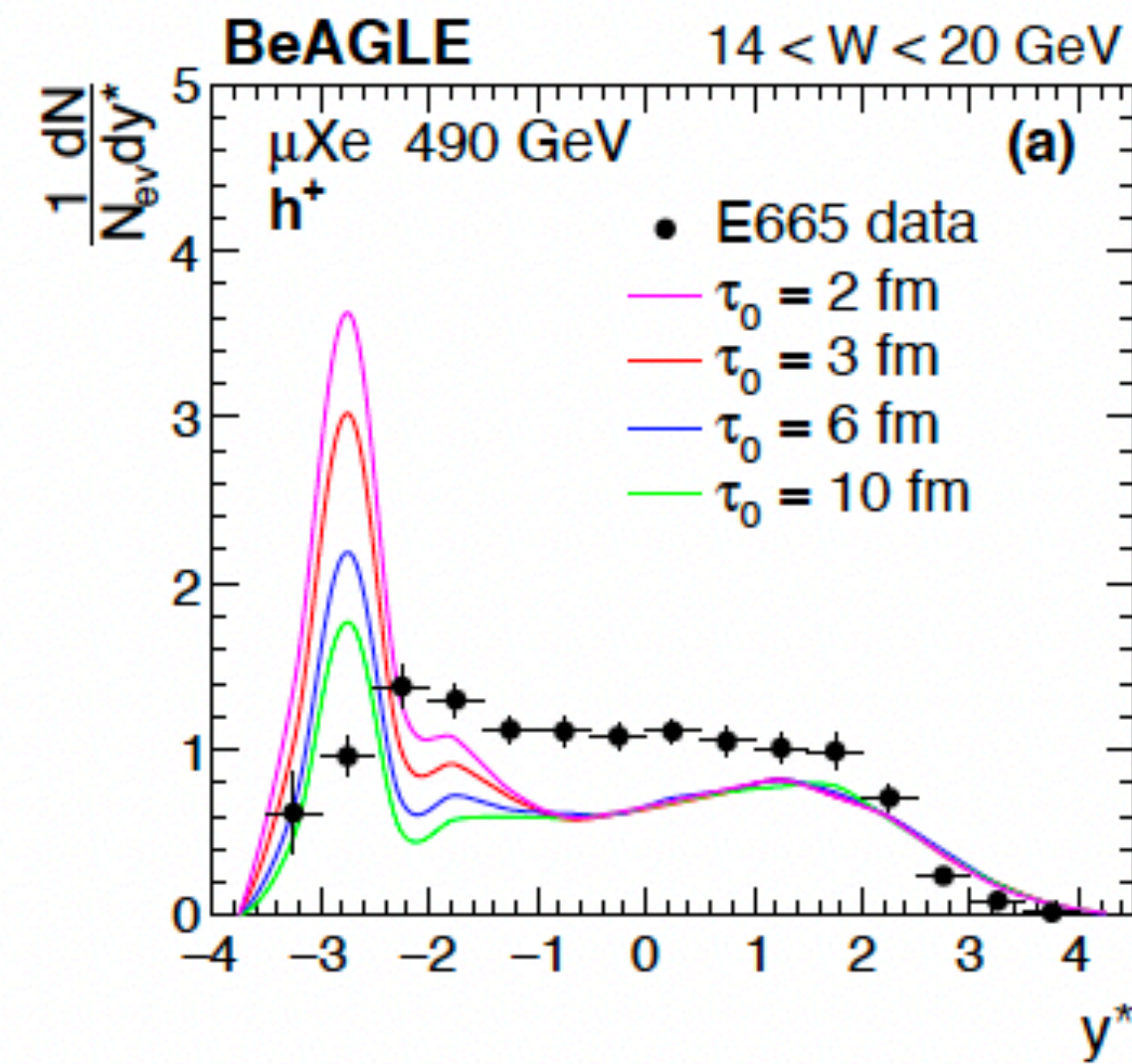
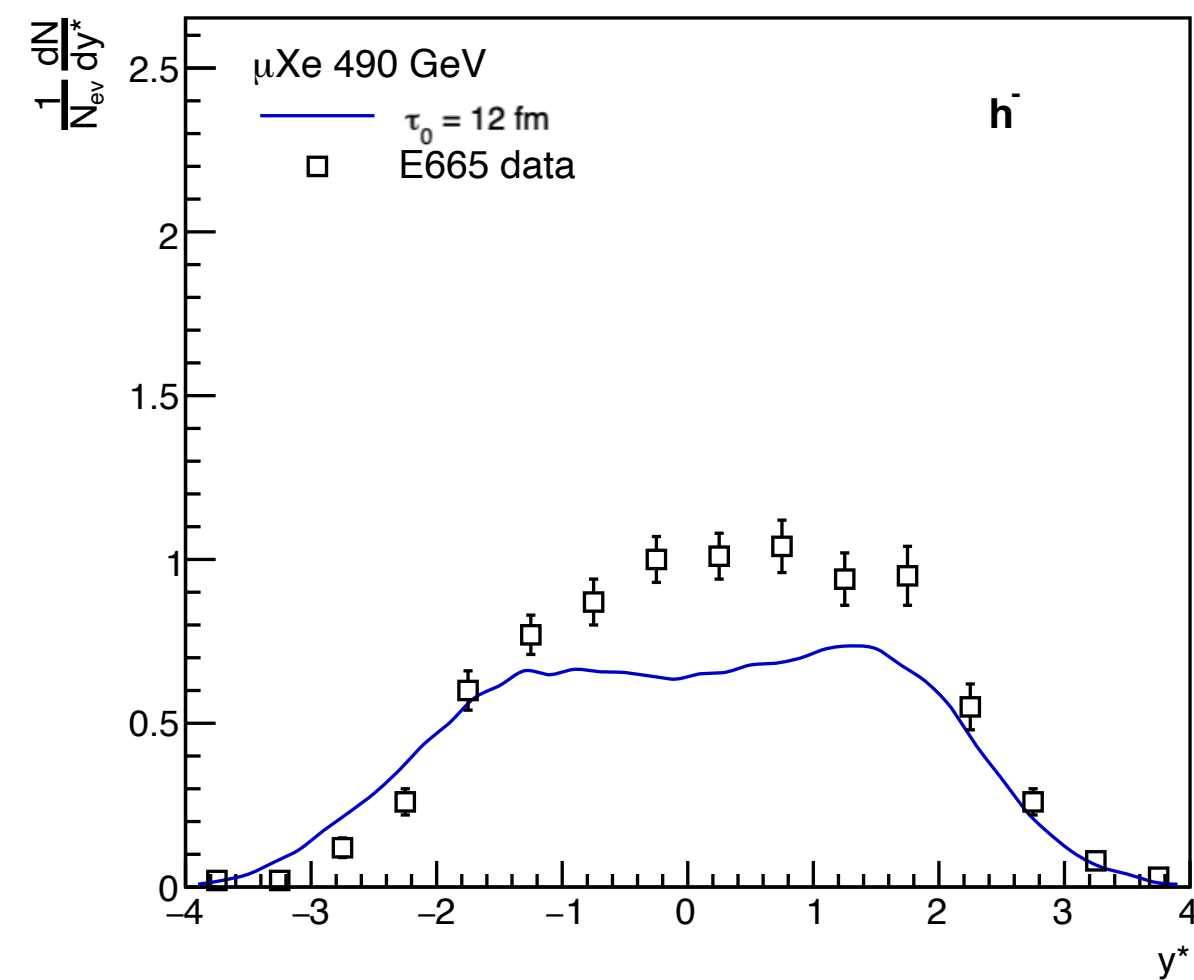
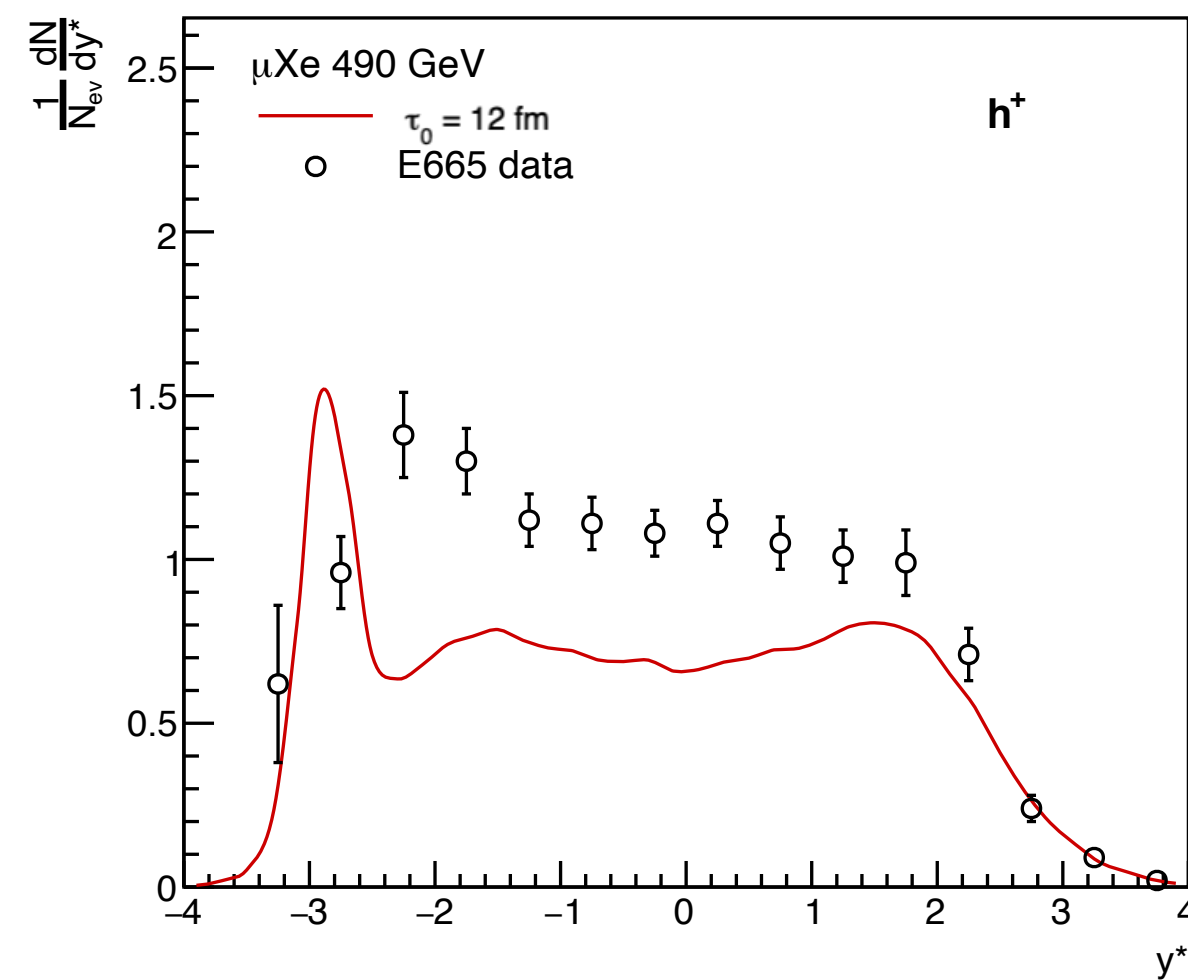


- Large value of parameter $\tau_0 = 12$ fm as compared to old code with $\tau_0 = 10$ fm (Final state interaction are different: more channels upto <20 GeV induce more activity,)

Multiplicity Distributions

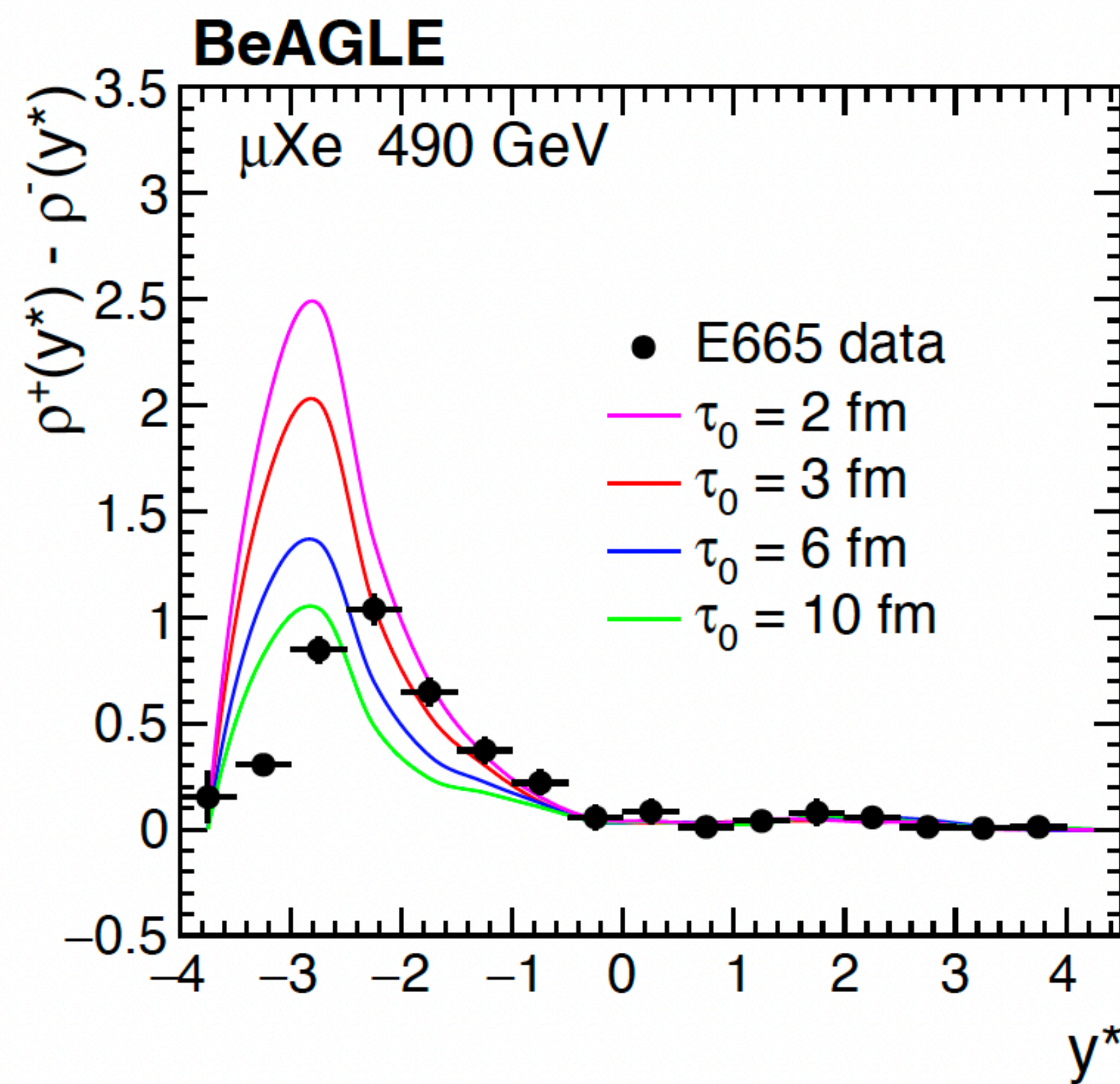
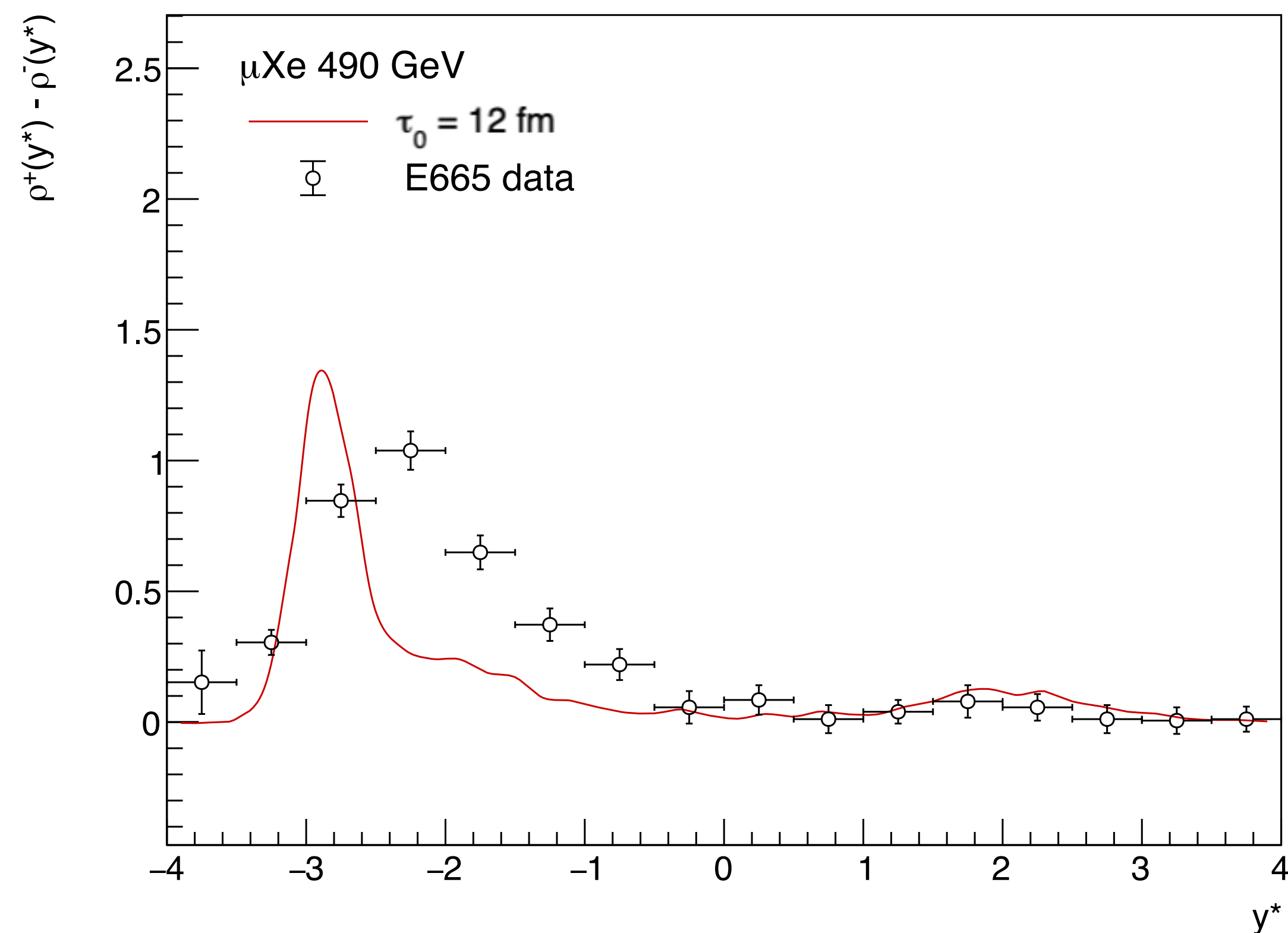


Rapidity Distributions

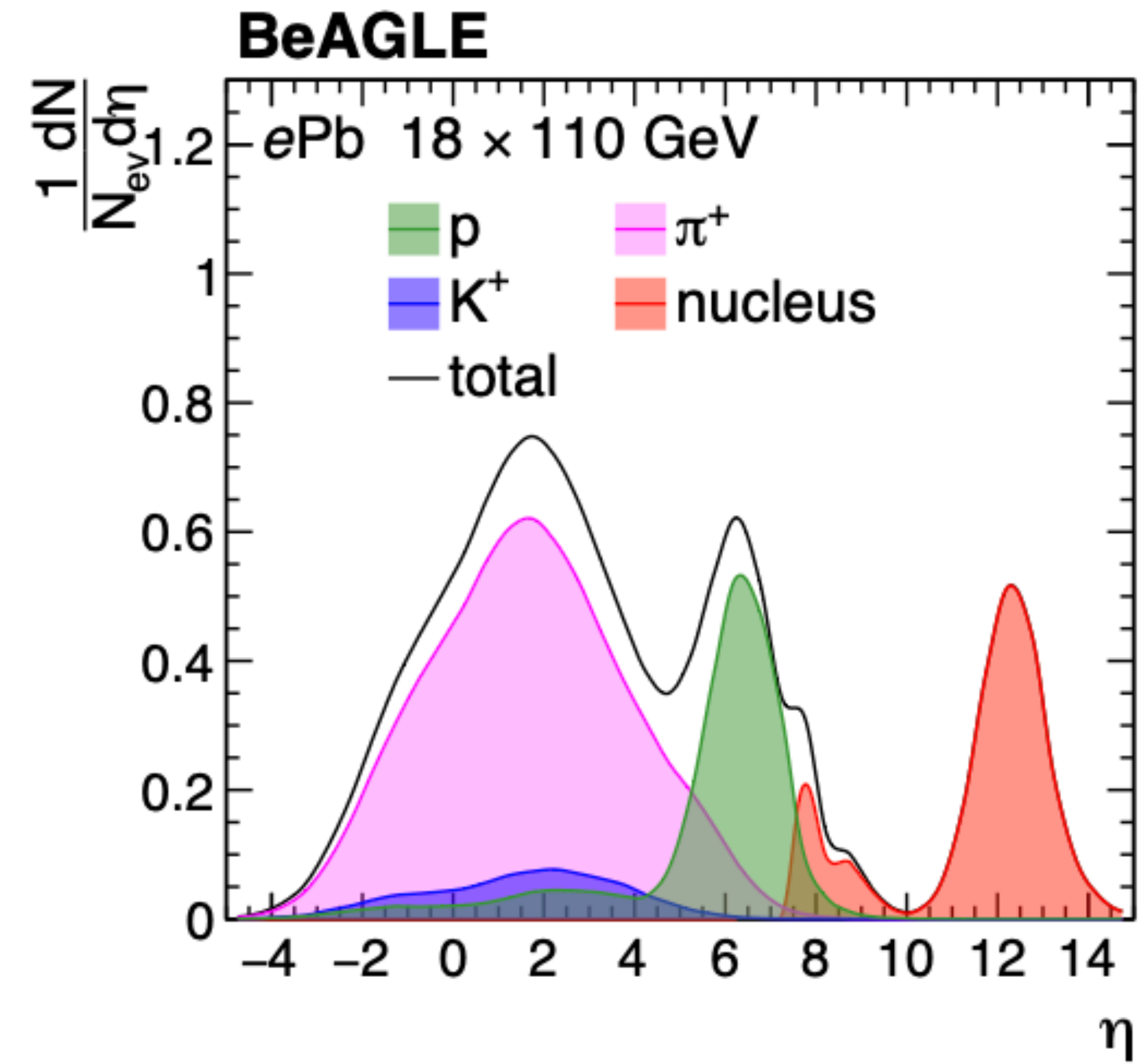
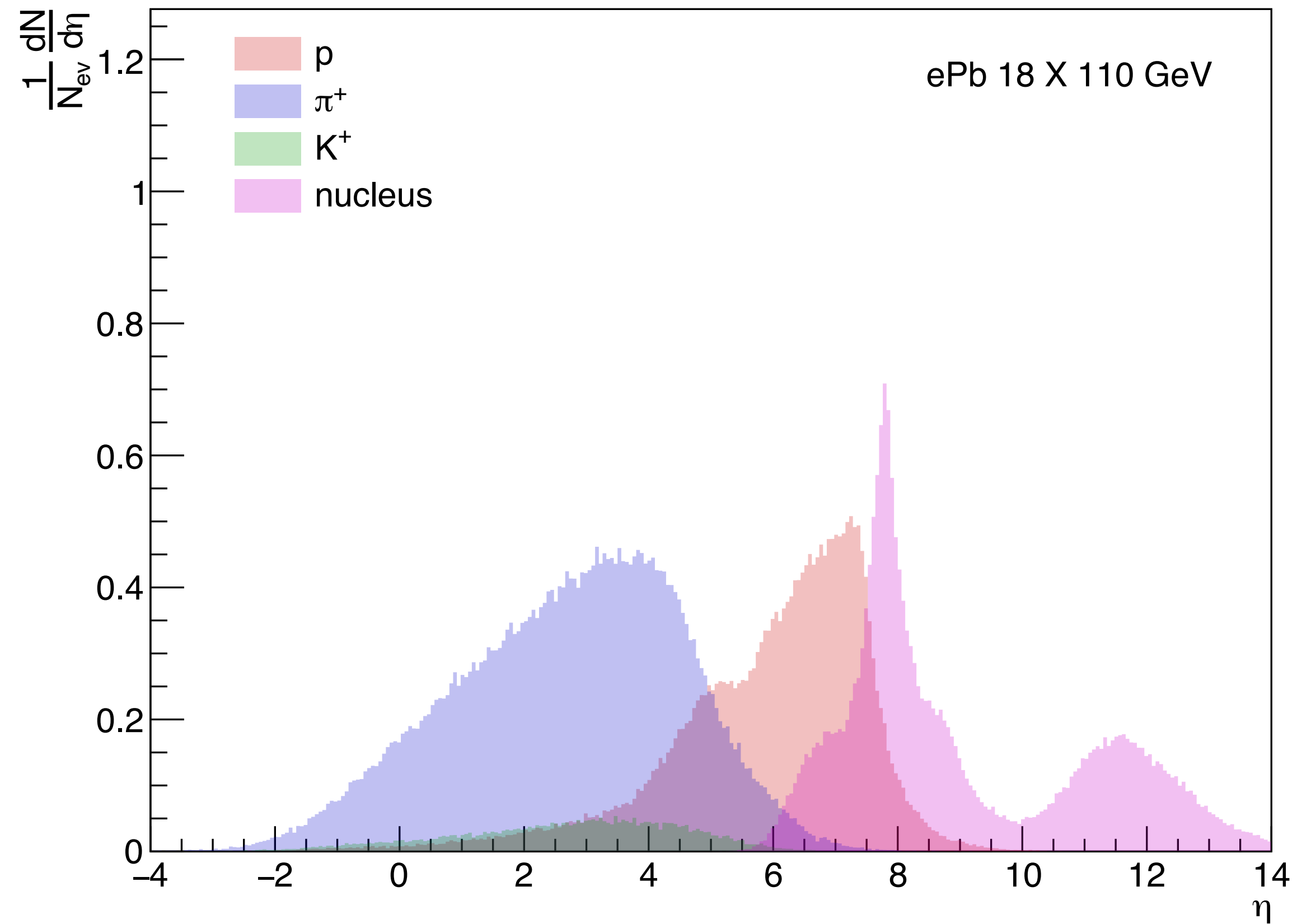


- Rapidity distribution in cms frame y^* for positively and negatively charged hadrons in μXe interactions at 490 GeV

Net Charge rapidity distribution



Charged Particles at EIC



Thickness function and effective path length

- To have a better handle of collision geometry we compute

- $T(b)/\rho_0 = \int_{-\infty}^{+\infty} \rho(b, z)/\rho_0 \, dz$ thickness function on event by event basis

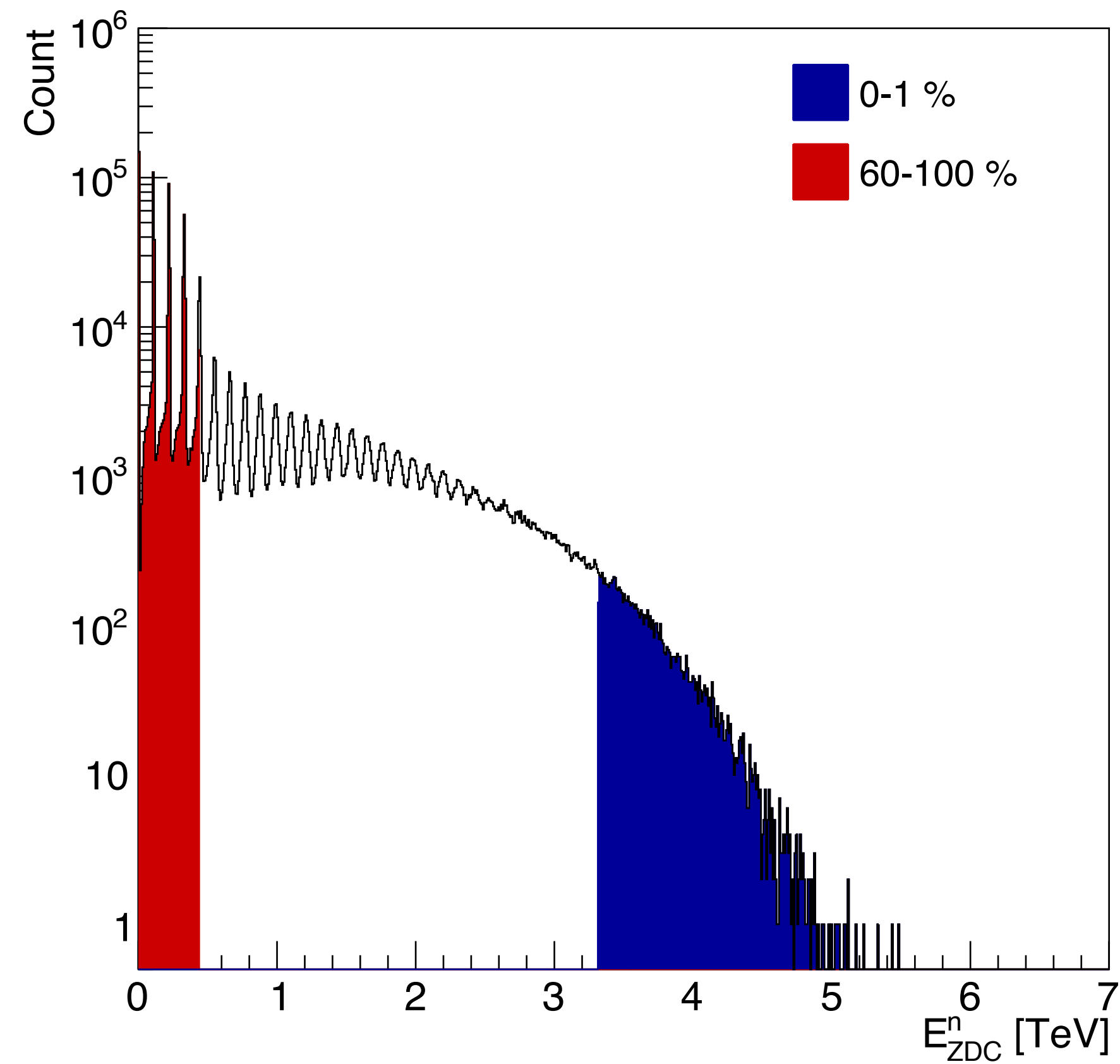
- Currently we compute this beforehand and save this information in a table and interpolate for corresponding impact parameter 'b'.

$$d(b, z_0)/\rho_0 = \int_{z_0}^{+\infty} \rho(b, z)/\rho_0 \, dz \text{ where } z_0 \text{ is position of struck nucleon along the photon direction}$$

Currently this is computed for every event at time of generating the event which leads to slow event generation, add roughly ~10 mins for 1million events.

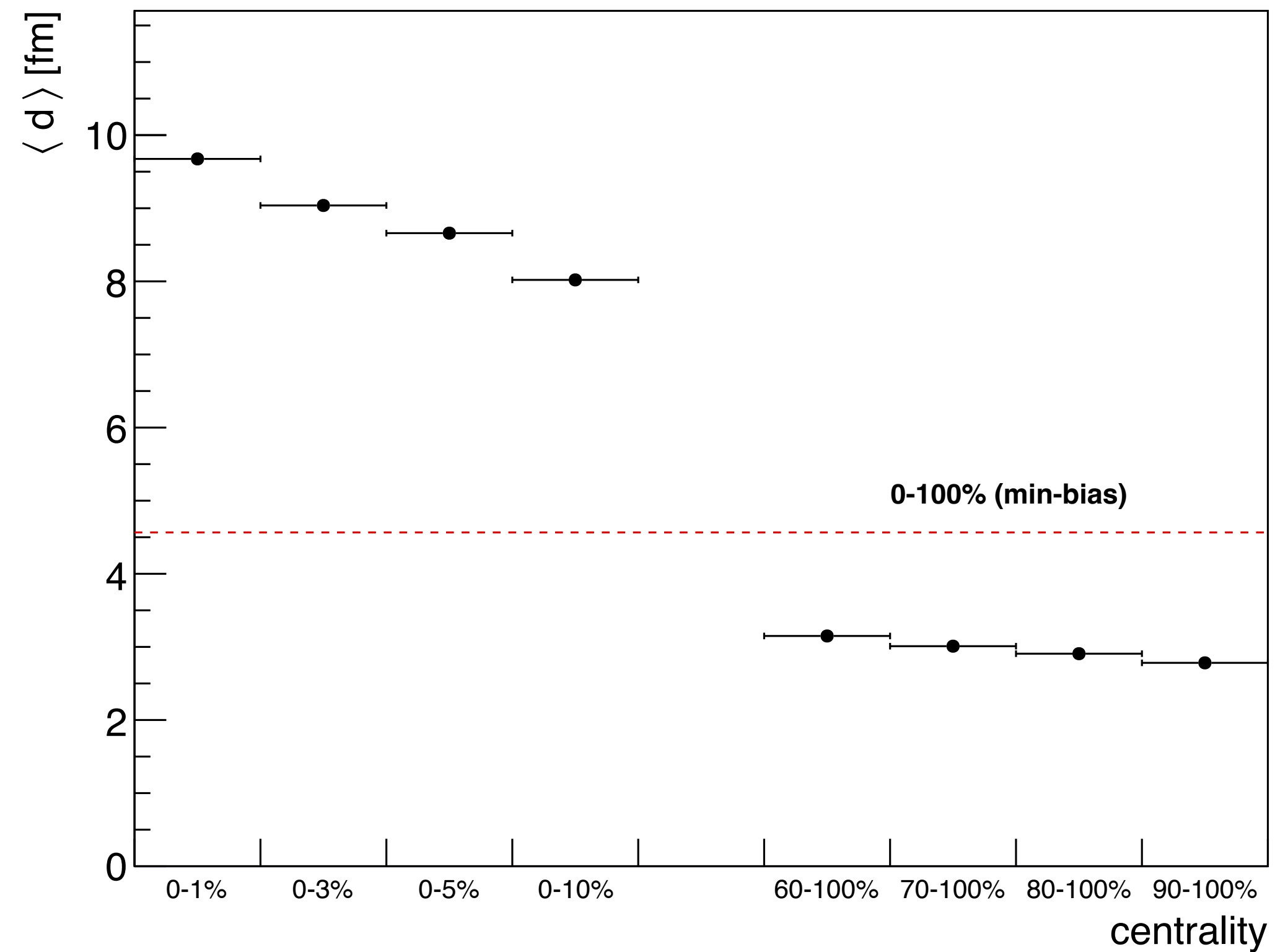
A 2-d table and interpolate from it?

Centrality selection



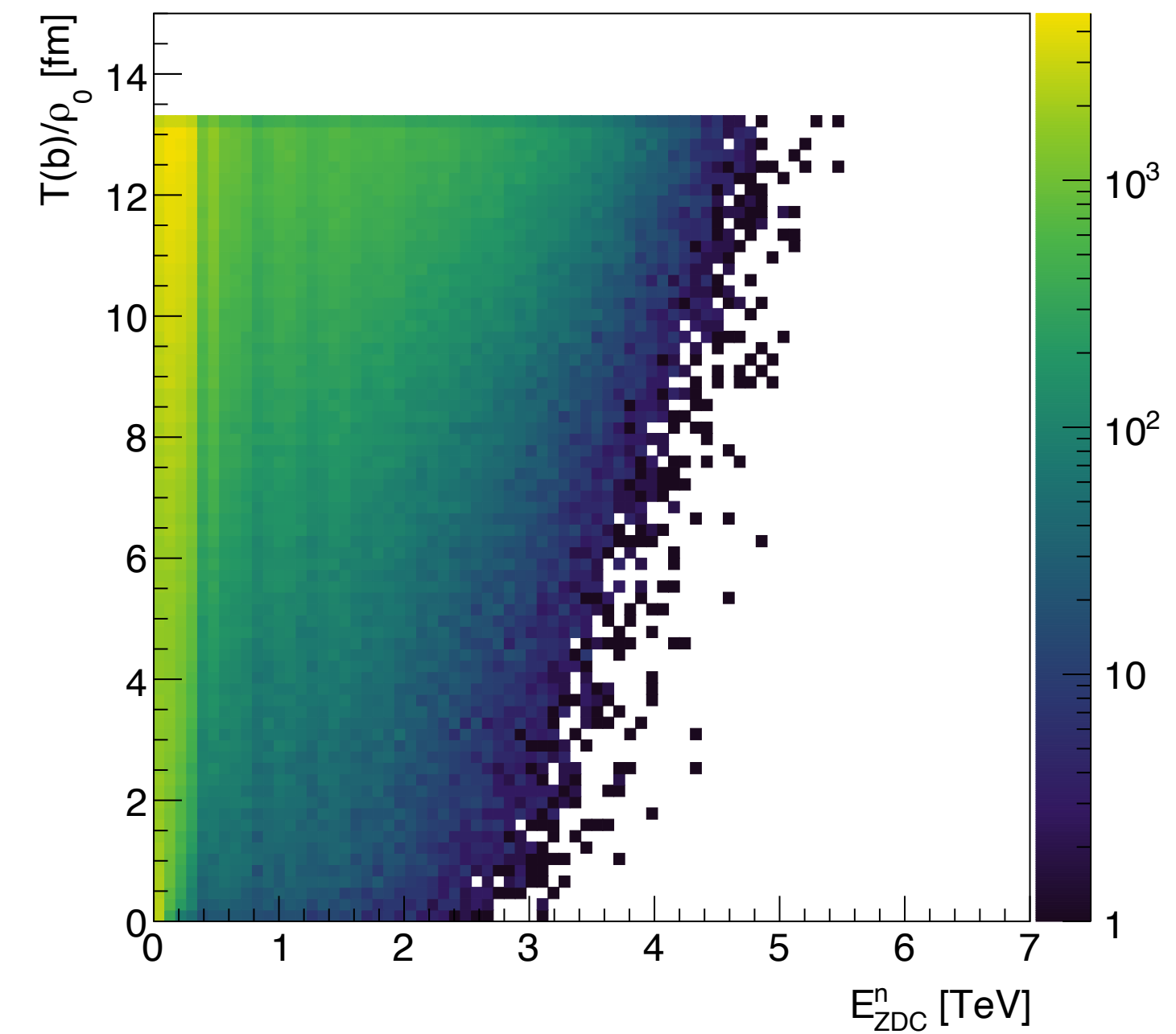
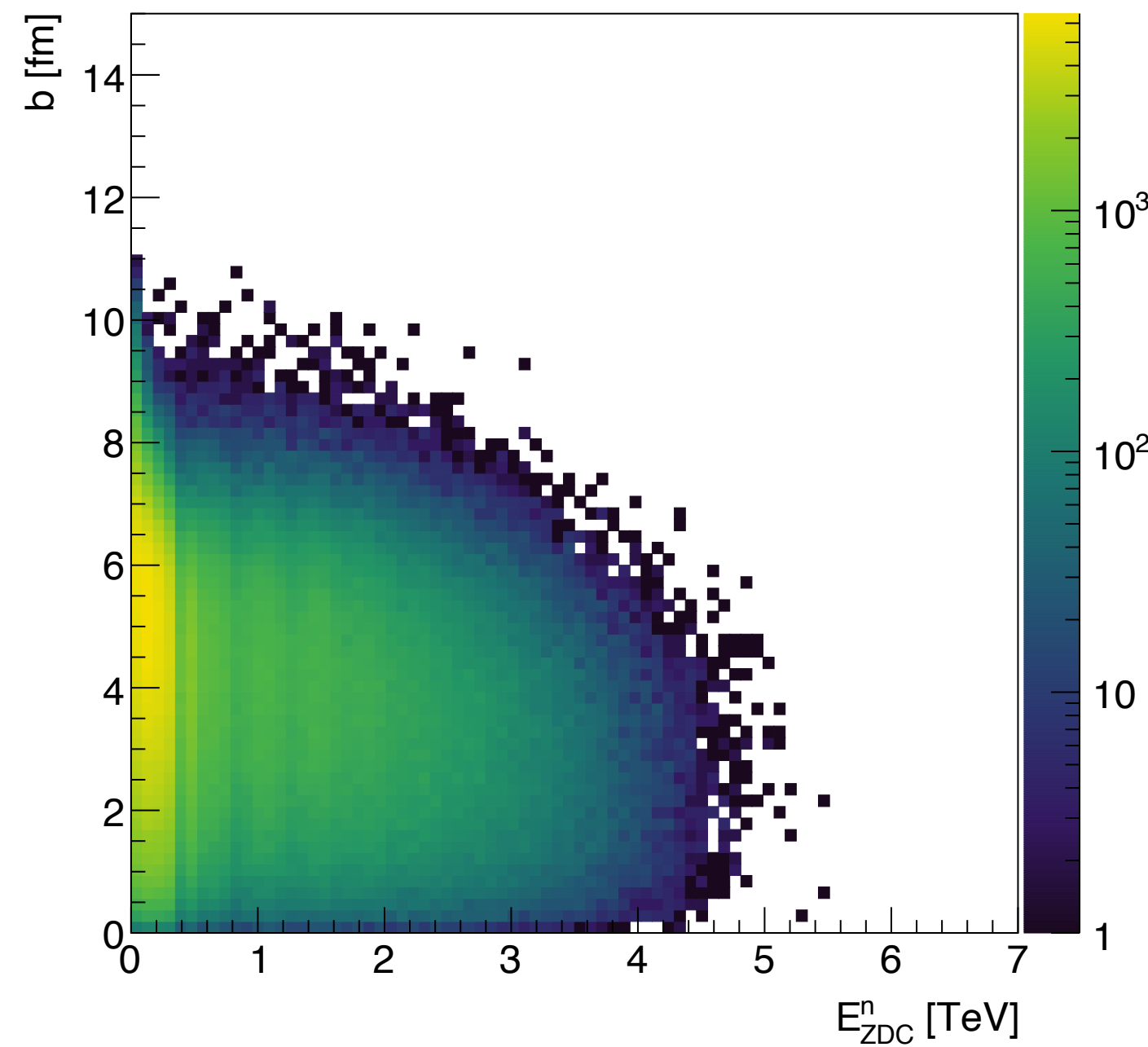
- Centrality selection by the energy deposition in the ZDC
- Higher energy deposited in the ZDC (large multiplicity of evaporation neutrons) is expected to correspond to more-central events.

Centrality selection



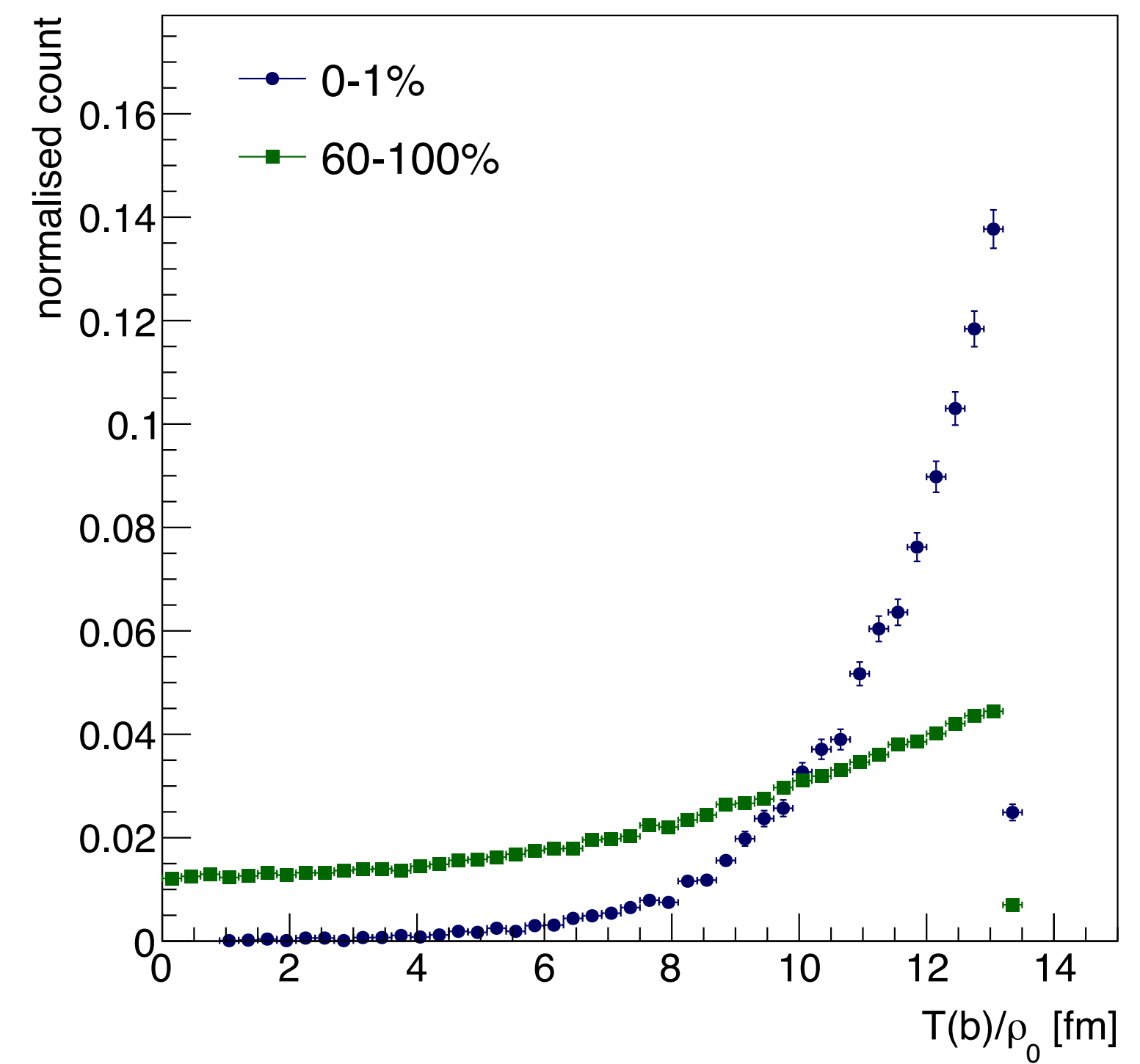
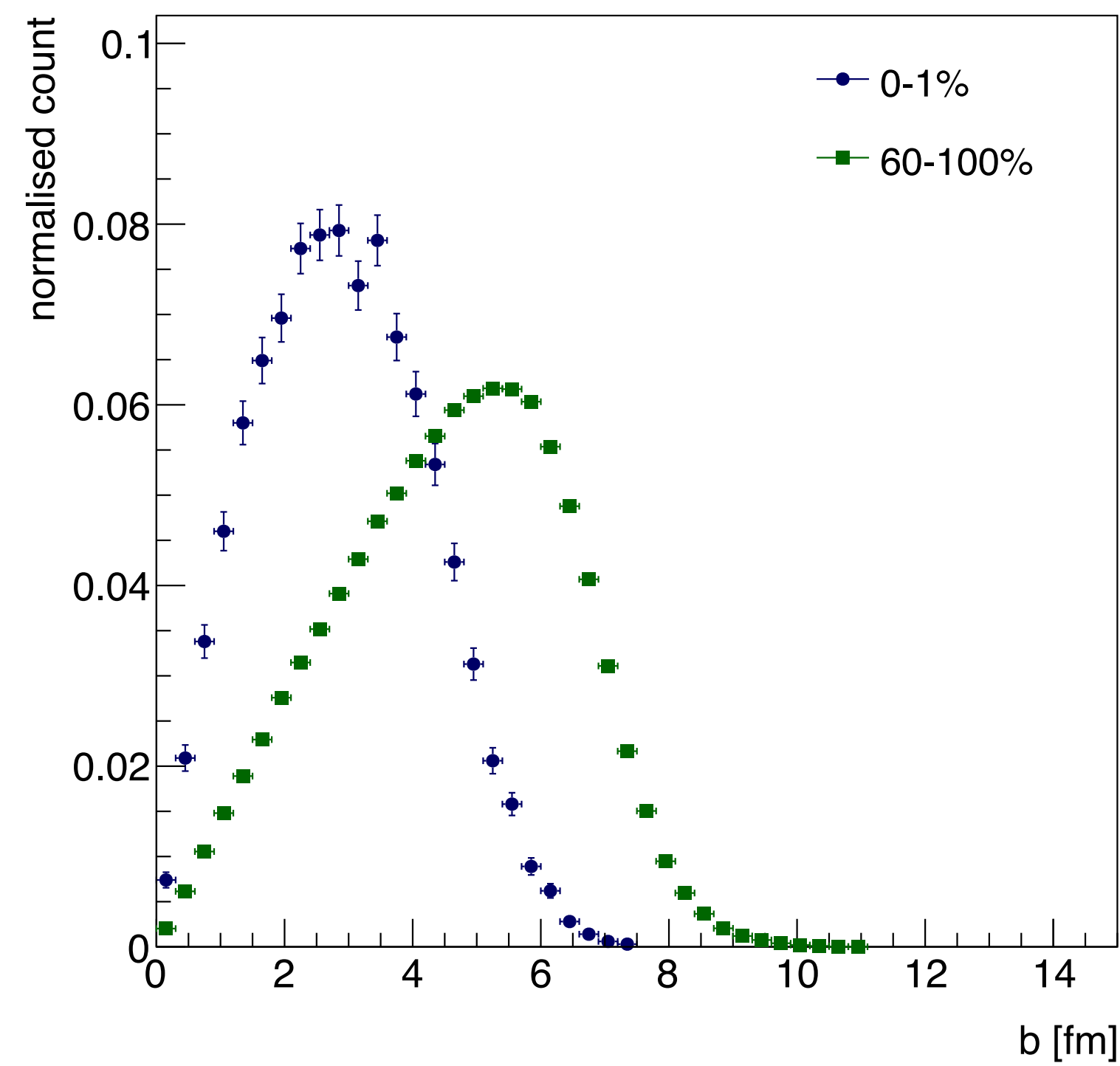
- Effective path length $\langle d \rangle$ as a function of the ZDC energy percentage class
- Higher energy deposited in the ZDC (large multiplicity of evaporation neutrons) have higher path length.

Correlations with Neutron Energy



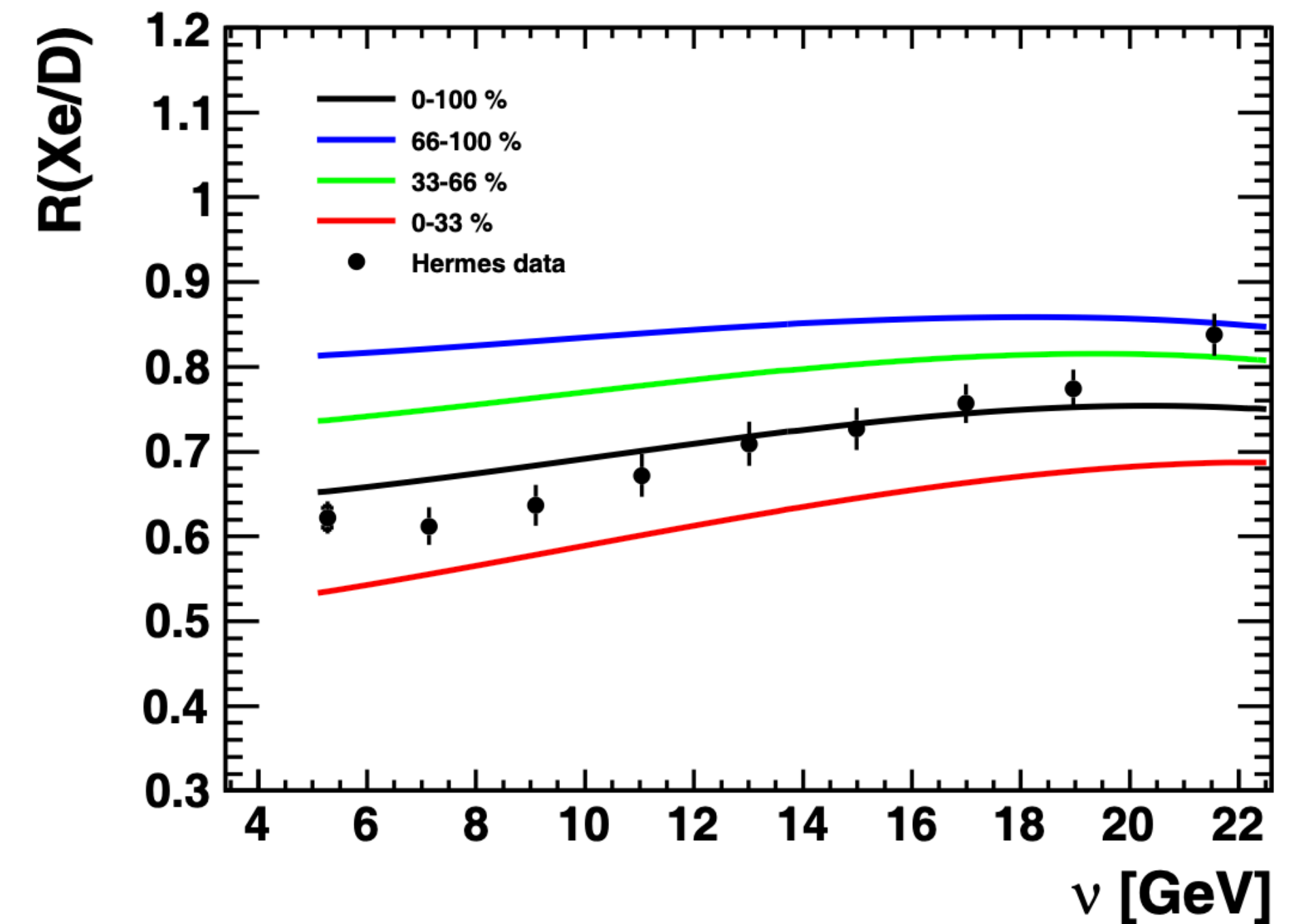
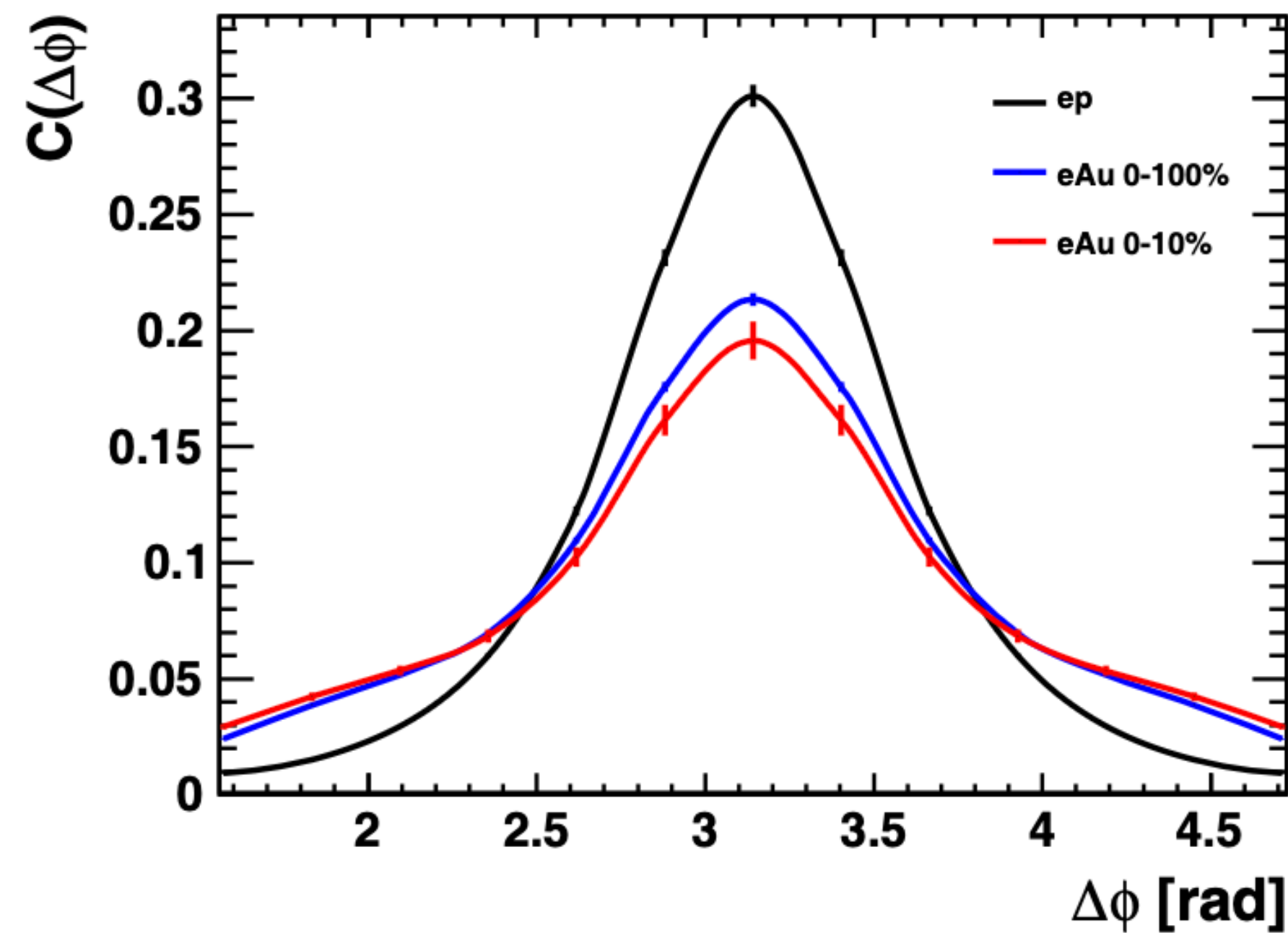
- With increasing energy, b decreases while $T(b)/\rho_0$ becomes larger i.e Central events have larger thickness

Impact parameter and Thickness function distributions



Impact on various observables (legacy BeAGLE)

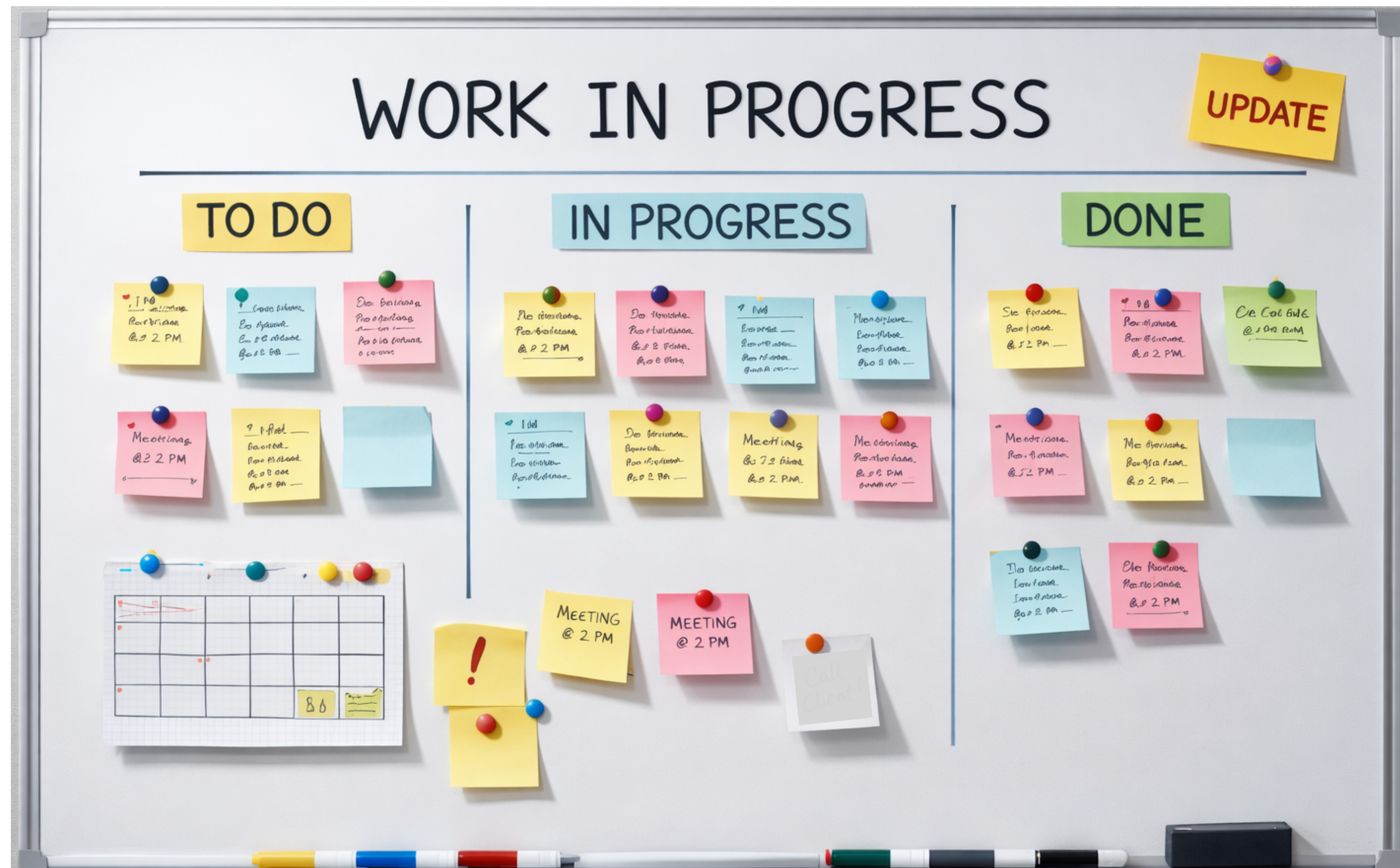
$$R_A^h(\nu, Q^2, z, p_t^2) = \frac{\left(\frac{N^h(\nu, Q^2, z, p_t^2)}{N^e(\nu, Q^2)} \right)_A}{\left(\frac{N^h(\nu, Q^2, z, p_t^2)}{N^e(\nu, Q^2)} \right)_D},$$



BeAGLE++: A Tool for Physics Exploration

- ✓ **Particle Production in the target fragmentation region**
 - ✓ Estimation of collision geometry and event characterization
 - Impact of centrality on saturation and cold nuclear matter observables
- **Semi-inclusive DIS off nuclei**
 - Investigating energy loss in nuclear matter
 - Mapping the space-time evolution of hadronization
- **Tagged-DIS events**
 - Neutron Structure (Unpolarized, Polarized structure functions)
 - Proton Structure
 - Probing the Strong Coupling constant
- **Diffraction Events**
 - Nuclear breakup in incoherent diffractive events
- **Exploring rare Isotope production at EIC**

A MC generator development is always a work in progress

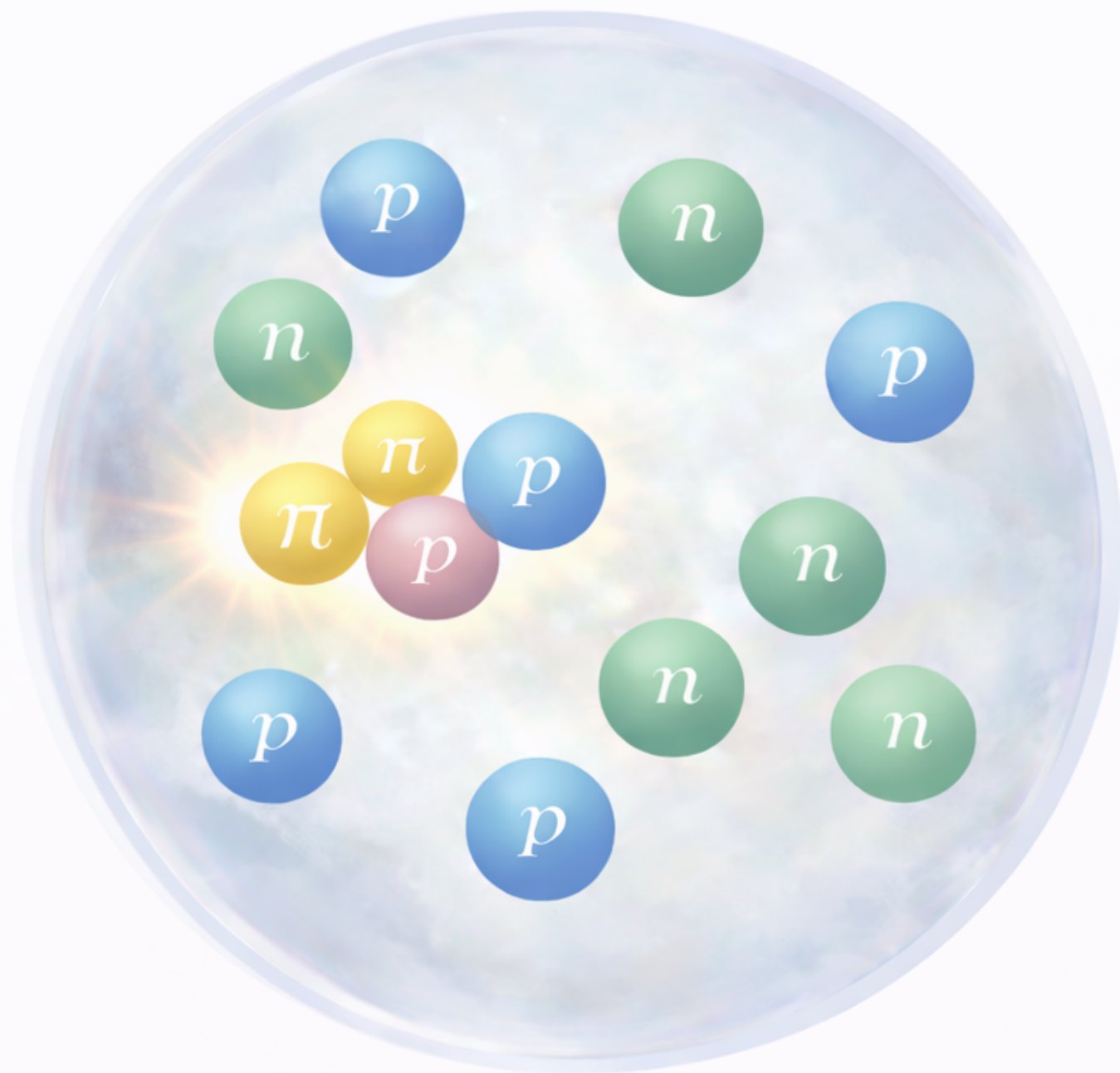


Acknowledgments

- Pythia8 team
- INCL team : for providing the INCL++ code (communication with José Luis, Davide Mancusi)
- BeAGLE authors: Core philosophy of model
- Sartre authors: Architecture inspiration
- CFNS, EIC groups for discussions
- ChatGPT Enterprise from BNL

BACKUP

INCL++ the Liege Intranuclear cascade model



- Standalone event generator for nuclear reactions induced by baryons (n, p, Λ, Σ), anti baryons ($\bar{p}$), mesons (pions, kaons) or light ions
- Support for incident energies ranging from a few tens of MeV to 10-20 GeV.
- Sophisticated Cascade algorithm in time steps by generating a chronological table of interactions in advance
- Emission of hadrons and light clusters
- Highly tested and validated against spallation reactions data

D. Mancusi, A. Boudard, J. Cugnon, J.-C. David, P. Kaitaniemi and S. Leray, PRC 90 (2014) 054602

Stopping time INCL

