CLIO/BeAGLE++

Comprehensive Lepton-Ion event Output generator

A new modern BeAGLE is born

Arjun Kumar in collaboration with Zhoudunming Tu, Abhay Deshpande

Brookhaven
National Laboratory

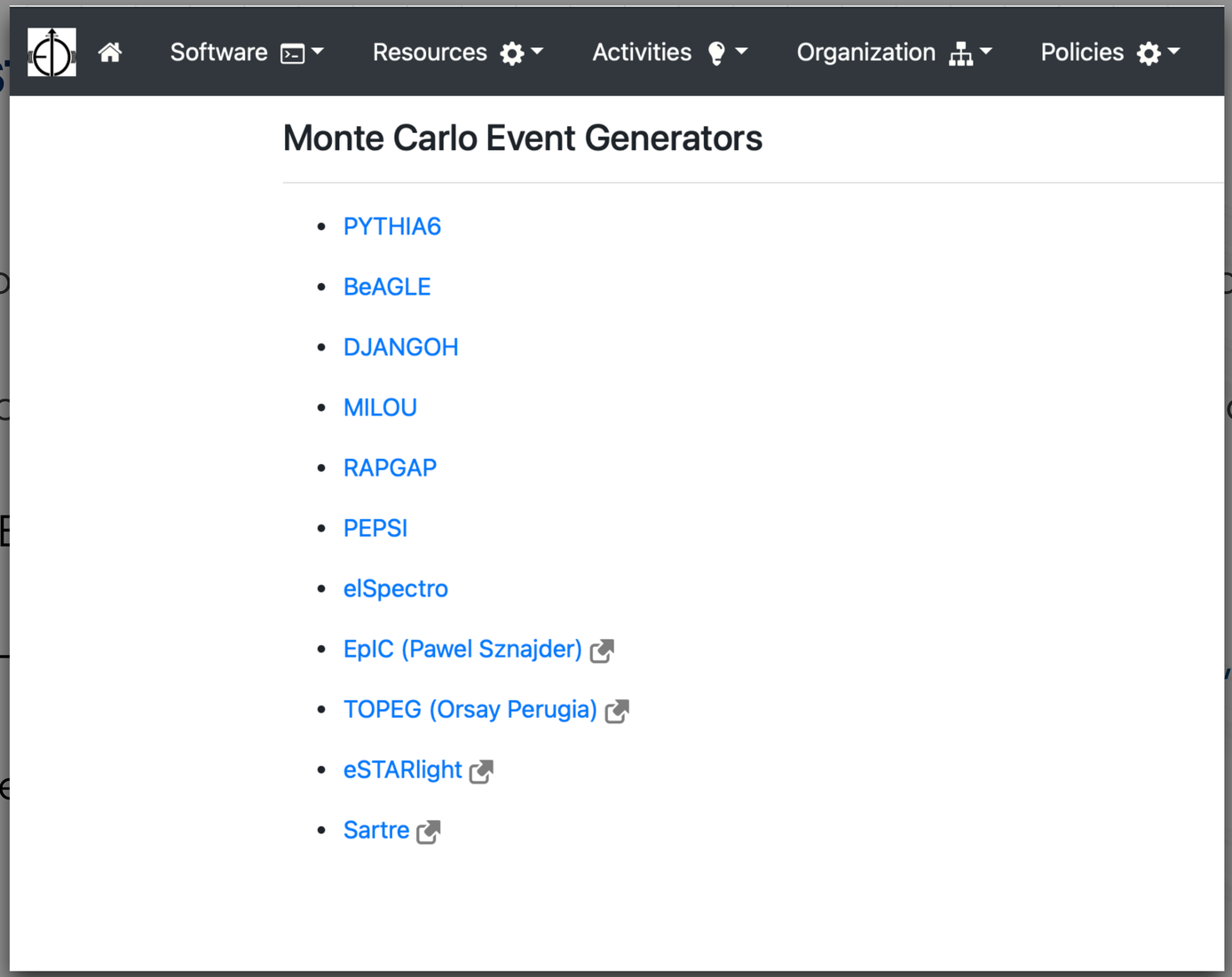
History of Event Generators and Successful Experimental Programs

- Looking at past, we clearly know any successful experimental program relies on good MC tools
- Both general purpose and specialized event generators are needed
- HERA ~ ARIADNE, LEPTO, DJANGOH, RAPGAP, PYTHIA6 etc
- LHC ~ PYTHIA, HERWIG, SHERPA, EPOS, WHIZARD, STARLight, DPMJET etc
- Detectors ~ GEANT, FLUKA

EIC is a ~ $ 2.8 billion machine, Do we have the same MC tools support?

His Experimental Programs

- Lo ogram relies on good MC tools
- Bo ded
- HE
- LH , DPMJET etc
- De



EIC is a ~ $ 2.8 billion machine, Do we have the same MC tools support?

Event Generators for EIC

- Mostly specialized event generators (GPDs, TMDs, diffraction etc)
- EIC has a wide coverage and will also measure particles in target fragmentation region
- General purpose event generator for studying particle production

this talk !!

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this talk !!

One stop for All Physics for *e*A collisions

- Cover the full physics landscape from inclusive to exclusive final states
- Aid in understanding fundamental questions such as hadronization in nuclear medium and advanced problems like centrality in eA collisions, Nuclear Breakup in DIS etc.
- Data Analysis: evaluating systematic uncertainties, backgrounds, acceptances etc…

Event Generators for EIC

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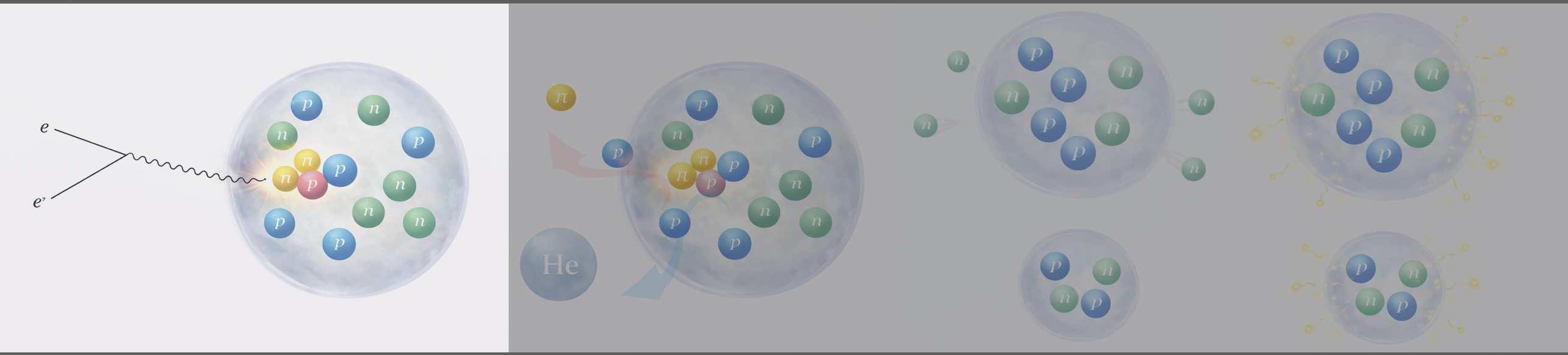
this talk !!

BeAGLE

the only generator in the market for studying particle production in eA collisions

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

Nuclear Breakup in BeAGLE



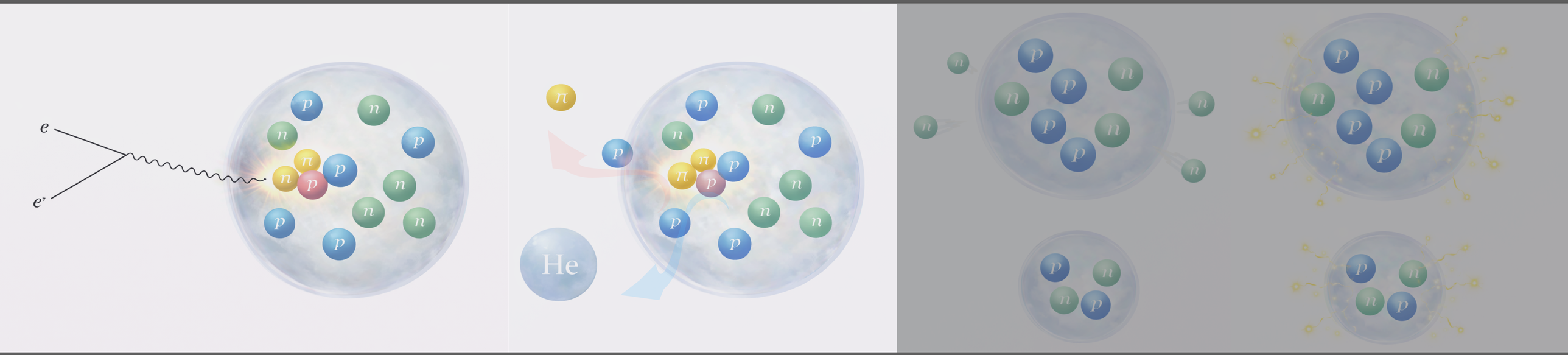
t = 0

DIS on a nucleon

Intranuclear cascade

De-excitation

Nuclear Breakup in BeAGLE



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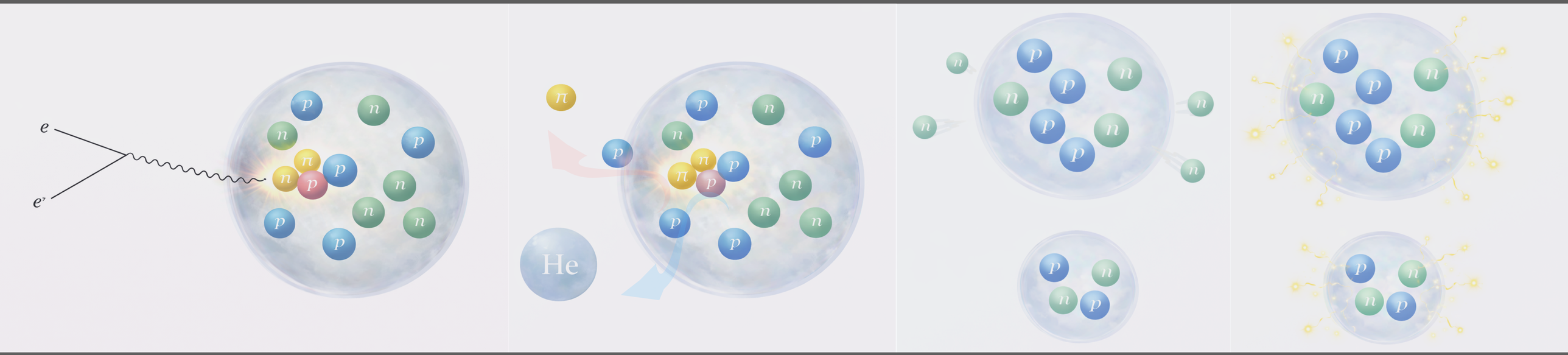

t = 0	$t = 10^{-22}$ s	$t = 10^{-20} - 10^{-17}$ s	$t = 10^{-14}$ s
DIS on a nucleon	Intranuclear cascade	De-excitation	

BeAGLE

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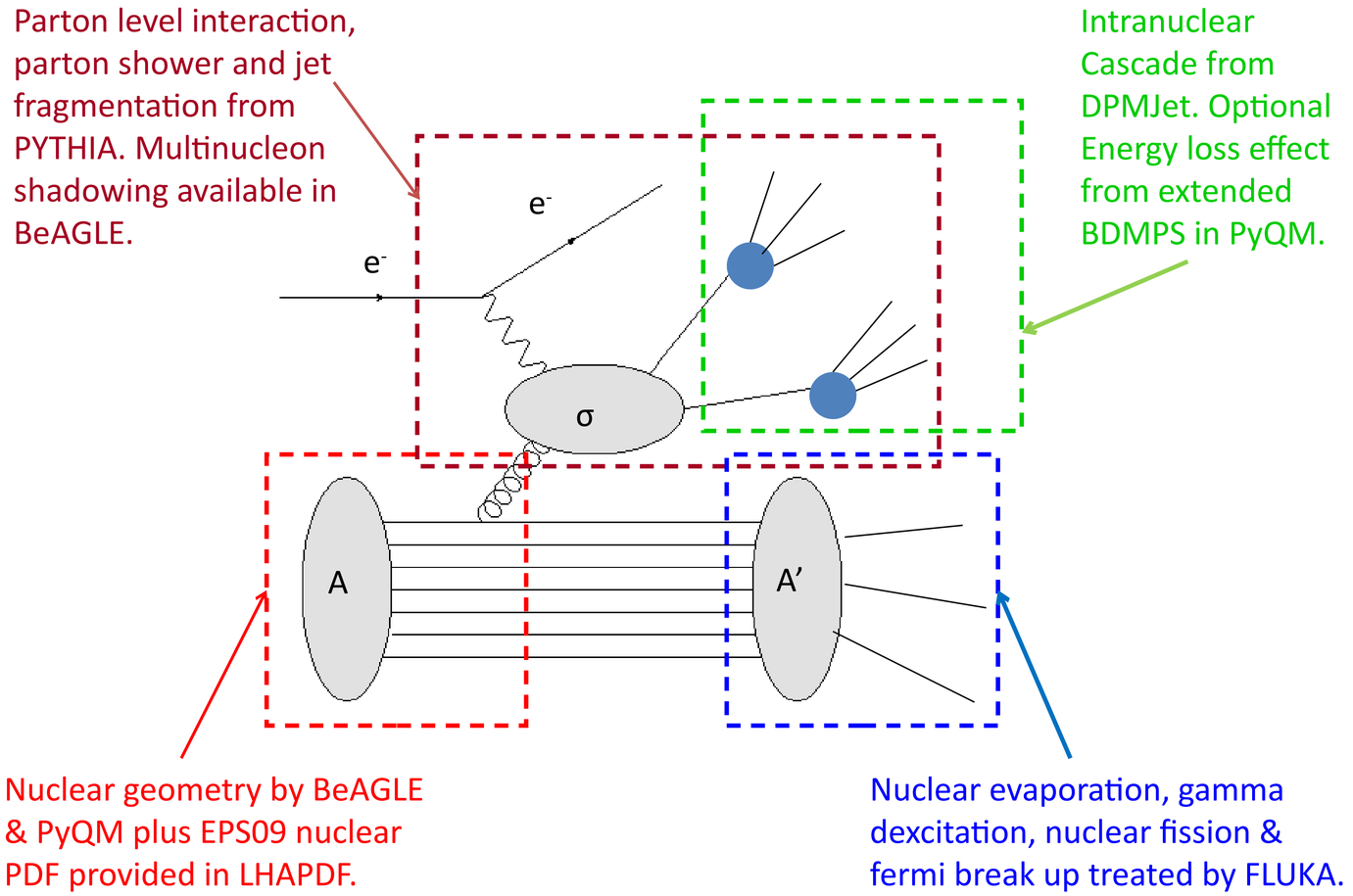


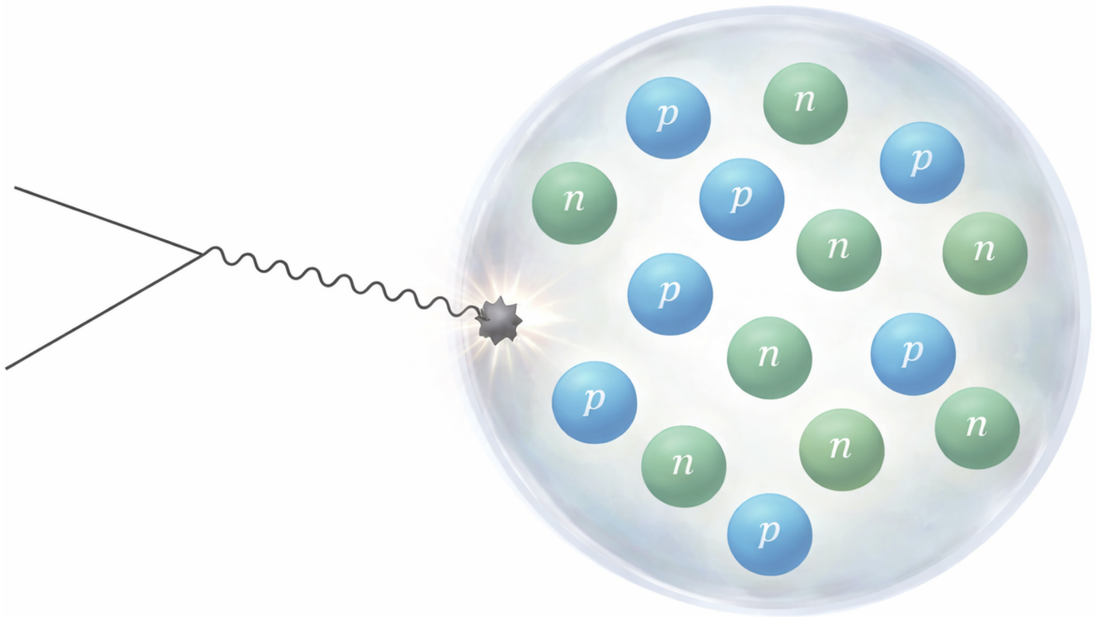
- A very successful project initiated at BNL
- Used extensively for EIC Simulations and STAR data analysis
- Particle production in target fragmentation region, Tagged-DIS, Incoherent vector meson production

Lepton Ion Interaction in BeAGLE

Impulse approximation

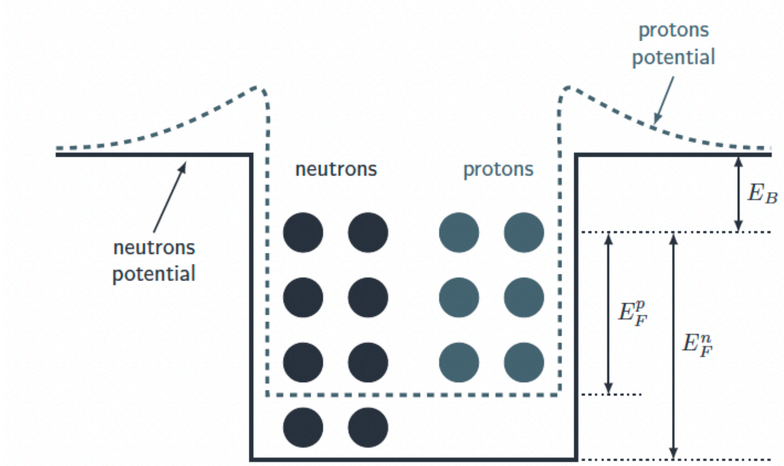
- In Impulse approximation the incoming photon interacts with a single nucleon
- For high lql, IA is justified

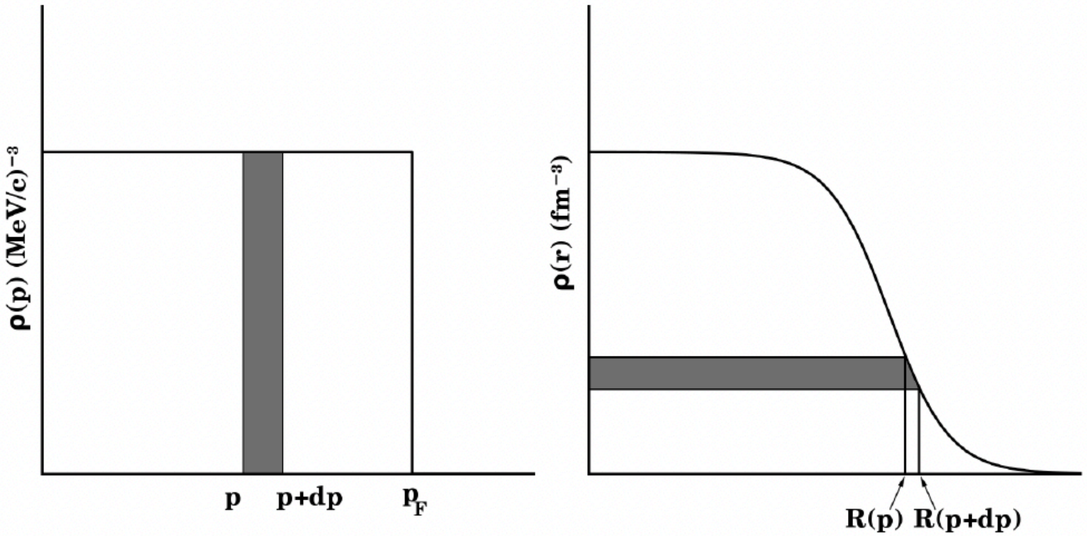
$$\sigma^A = \sum_{i=1}^{Z} \sigma_p + \sum_{i=1}^{A-Z} \sigma_n$$



- $\gamma * p$ 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 postion sampled from Woods Saxon, Modified harmonic oscillator and gaussian distributions

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

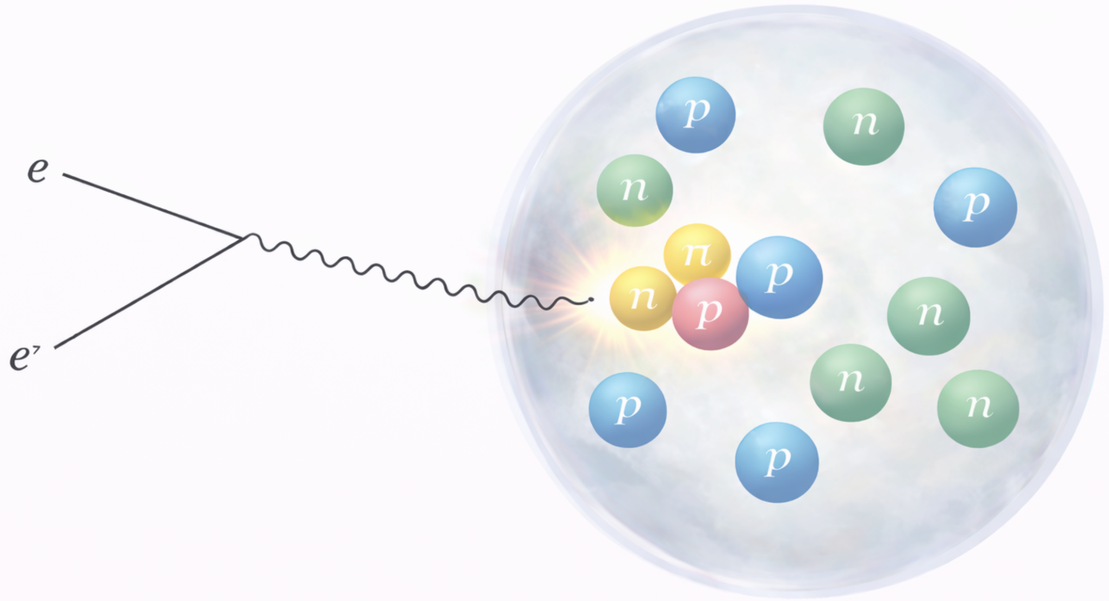
$$\rho = \begin{cases} \dfrac{\rho_0}{1+\exp\left(\frac{r-R_0}{a}\right)}, & A > 19 \\ \rho_0 \dfrac{1+\alpha\left(\frac{r^2}{a^2}\right)}{\exp\left(\frac{r^2}{a^2}\right)}, & 6 < A \leq 19 \\ \dfrac{\rho_0}{\exp\left(\frac{r^2}{a^2}\right)}, & A \leq 6 \end{cases}$$

Fig from Tomasz Golan talk at NuSTEC 2017

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

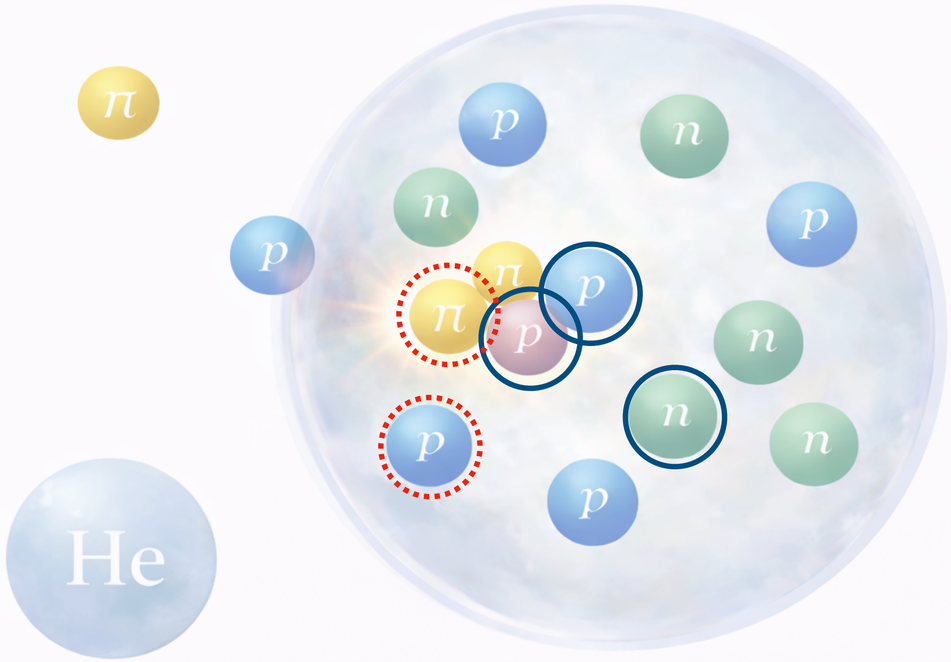


Most of Monte Carlo generators (also other communities like neutrino, spallation, pA/AA at low energies) use ***Intranuclear cascade model***

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)



elastic channel cluster emission

charge exchange, pion absorption and many more..

Intranuclear cascade (INC)

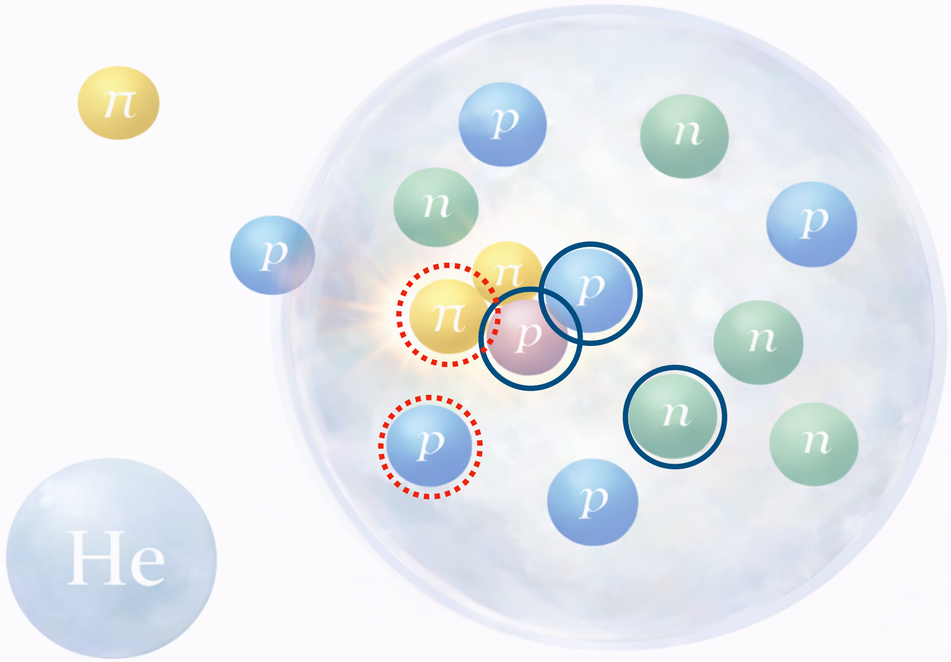
- *The main input to INC model is particle-nucleon cross section*

- *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*



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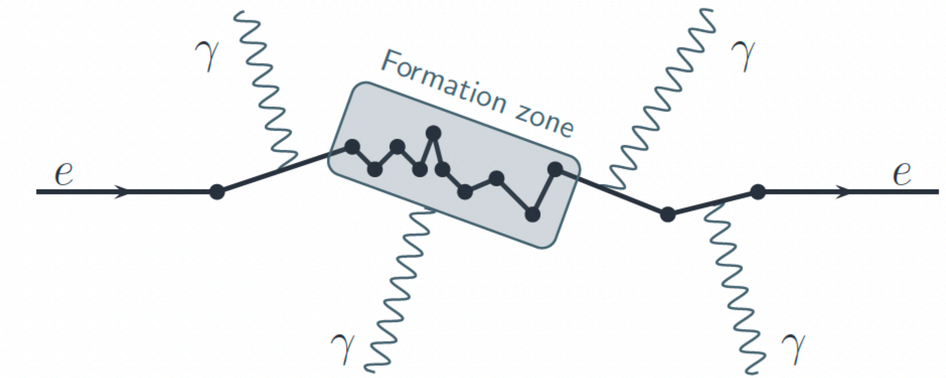
Formation time

L. D. Landau and I. Pomeranchuk, Dokl. Akad. Nauk Ser. Fiz. 92 (1953) 735

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



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

Fig from Tomasz Golan talk at NuSTEC 2017

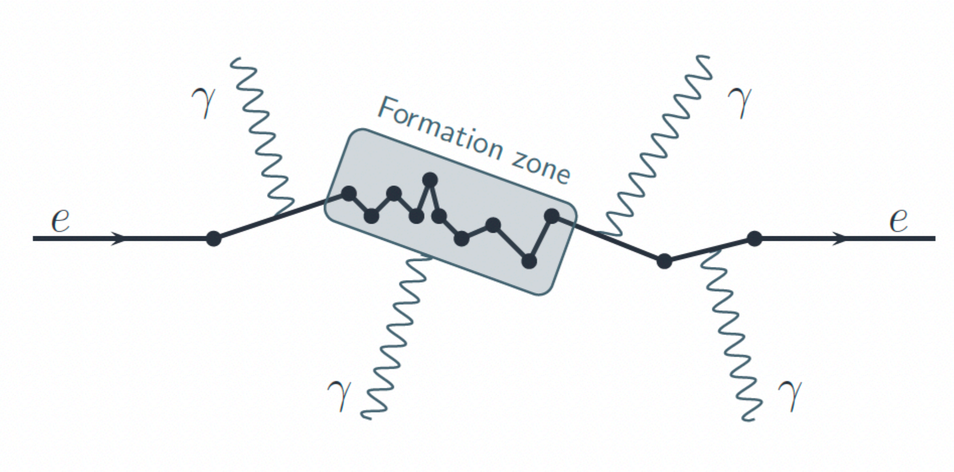
Formation Time

- Formation time is defined as

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

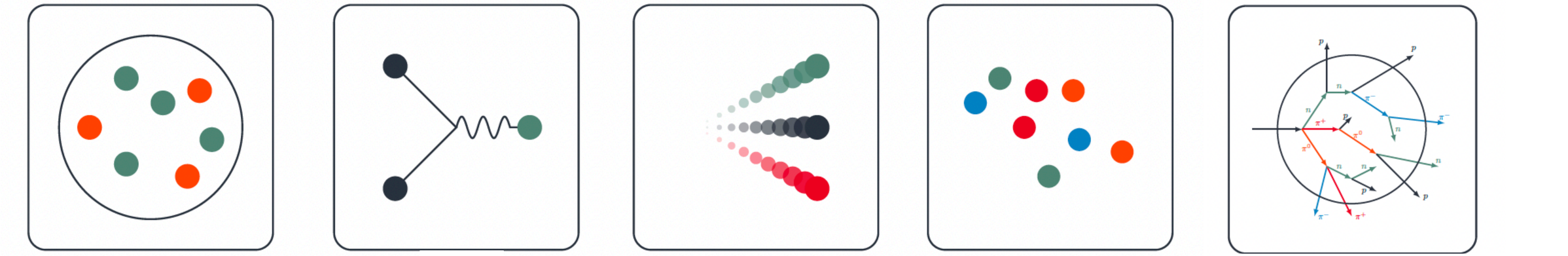
k, p - photon, electron four-momenta

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



- If time t between collision $t >> t_f$, independent emitters and total energy radiated is just average emitted in one collision multiplied by no of collisions
- If$t << t_f$, 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



- Ranft parameterization J. Ranft: Z. Phys. C43 (1989) 439

$$\tau_{\mathrm{Lab}} \approx \gamma_s \tau_s, \qquad \gamma_s = \frac{E_s}{m_s} \qquad \tau_s = \tau_0 \frac{m_s^2}{m_s^2 + p_{s\perp}^2}$$

τ_0 fitted to data

Fig from Tomasz Golan talk at NuSTEC 2017

BeAGLE

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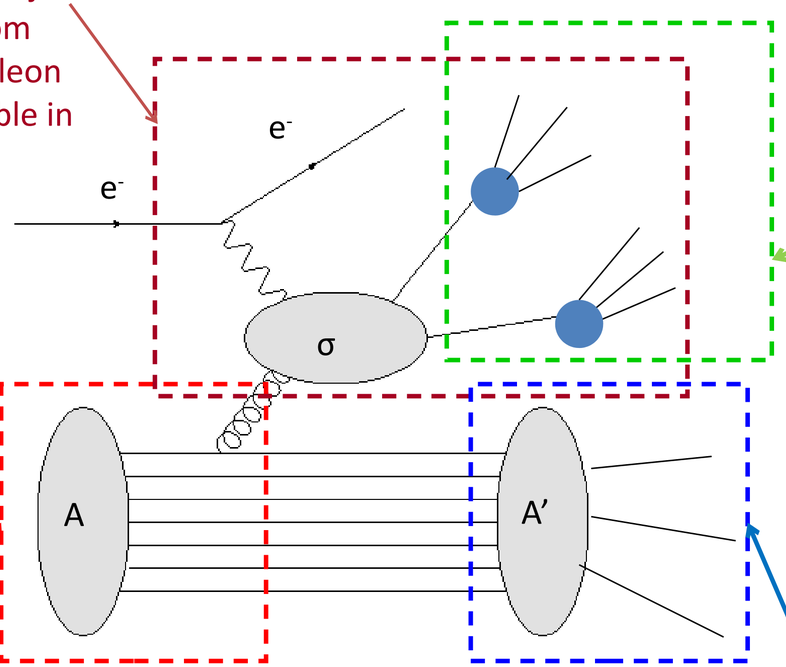
Parton level interaction, parton shower and jet fragmentation from PYTHIA. Multinucleon shadowing available in BeAGLE.

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



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

Nuclear evaporation, gamma dexcitation, nuclear fission & fermi break up treated by FLUKA.

Some Nuclear Effects

	In BeAGLE
• 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*	☑

..from M.Diefenthaler slides at HSF Generators Meeting 2022

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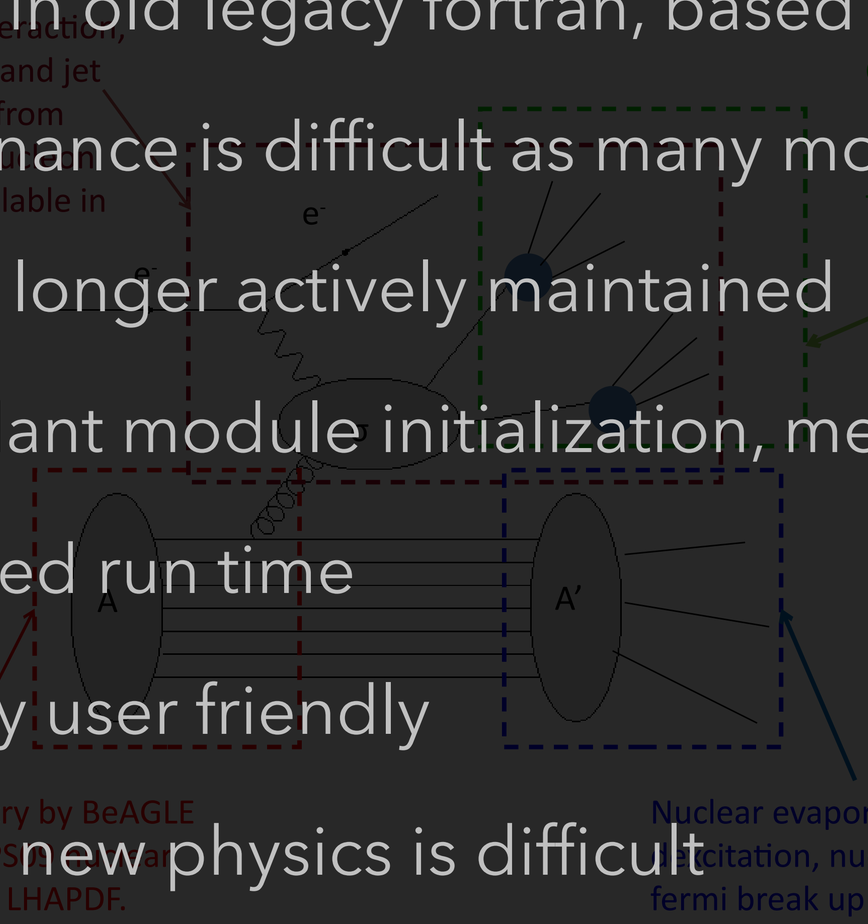
however there are several limitations

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)
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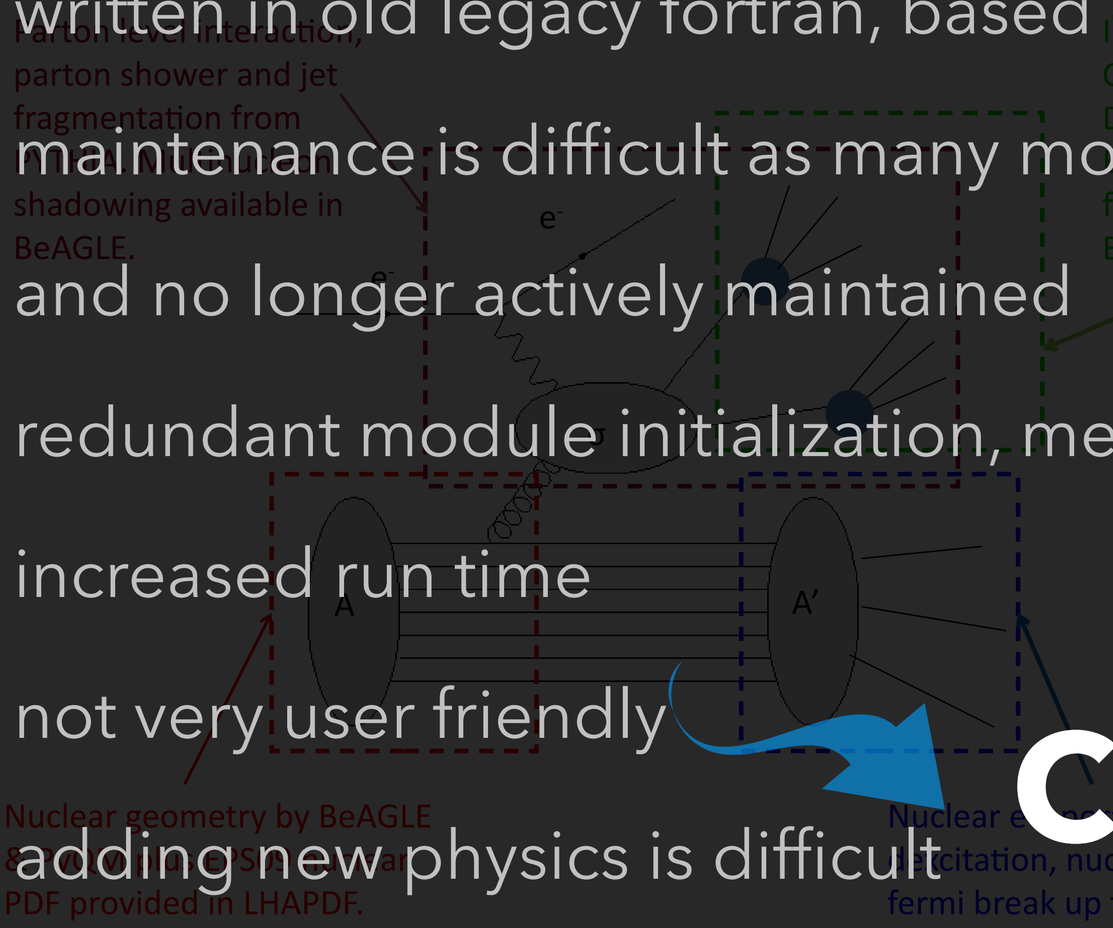

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• Nuclear evaporation, breakup	✓
• Photoni[illegible]e-e[illegible]cay of A*	✓

CLIO/BeAGLE++

From legacy code to CLIO/BeAGLE++

BeAGLE vs CLIO/BeAGLE++ : components

- Pythia6 replaced by Pythia8
- DPMJET (IntraNuclear Cascade) replaced by modified version of INCL++
- Initial Geometry from CLIO/INCL++
- FLUKA replaced by ABLA++

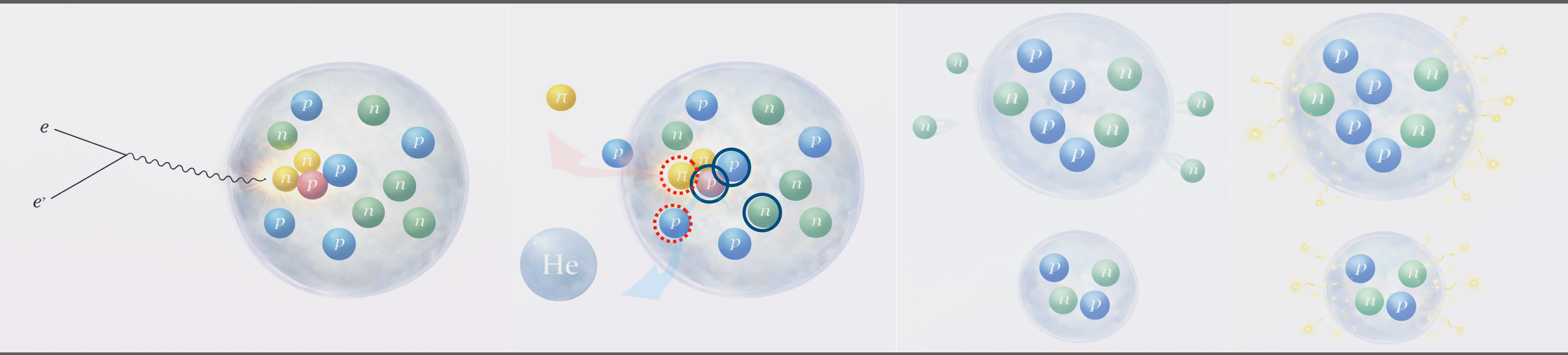
- Other dependencies: CMake, ROOT, Boost

- A complete new version of BeAGLE with new components but same core philosophy

BeAGLE

CLIO/BeAGLE++

Nuclear Breakup in CLIO/BeAGLE++



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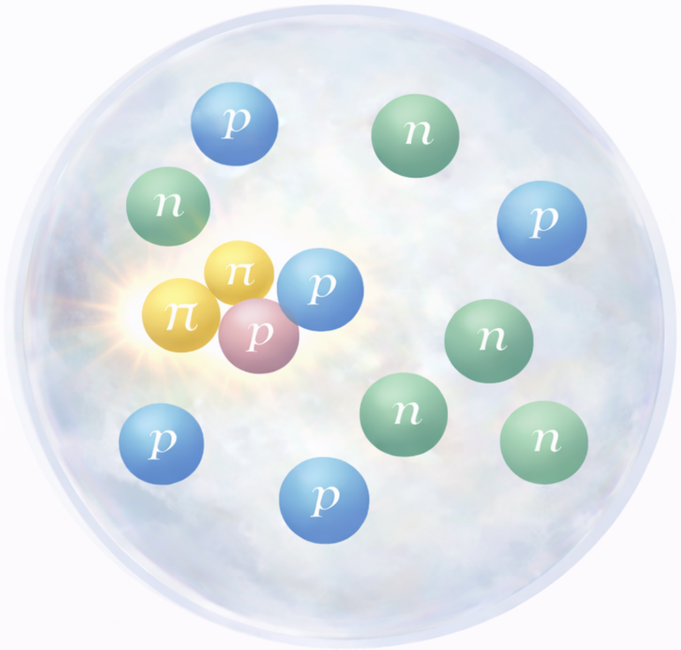
DIS on a nucleon	Intranuclear cascade	De-excitation	
Pythia8	INCL++	ABLA	

INCL++ the Liege Intranuclear cascade model



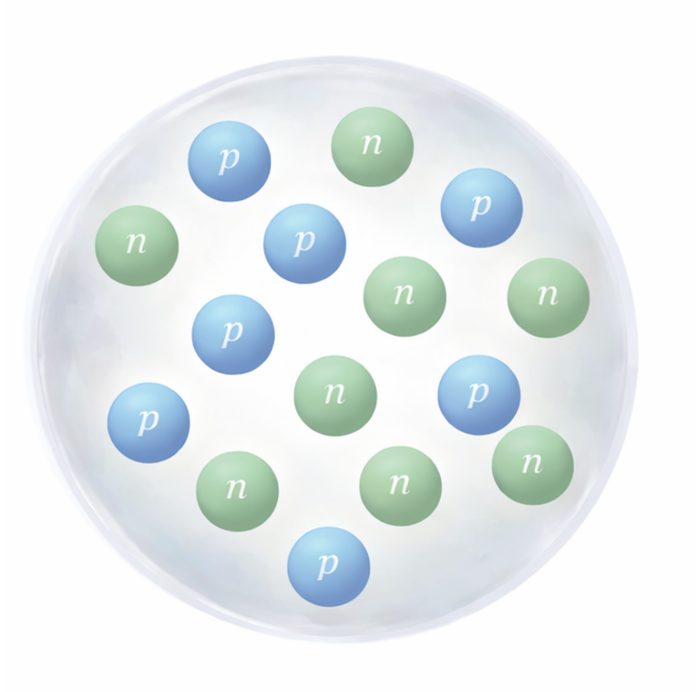
- Standalone event generator for nuclear reactions induced by baryons (n, p, Λ, Σ), anti baryons $(\bar{p})$, mesons (pions, kaons) or light ions
- Support for incident energies ranging from a few tens of MeV to 10-20 GeV.
- Sophisticated Cascade algorithm in time steps by generating a chronological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

INCL Cascade Algorithm

INCL Cascade Algorithm

Initialize target



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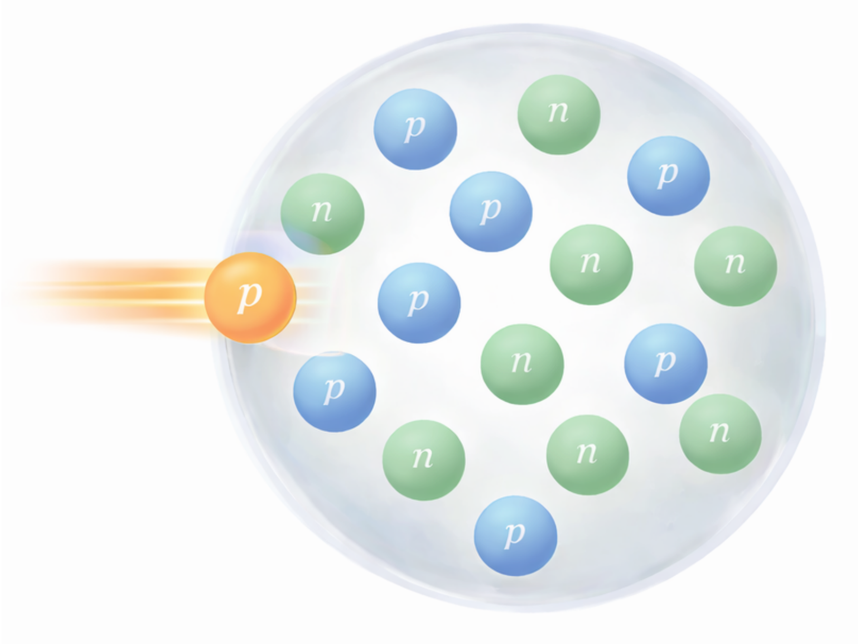

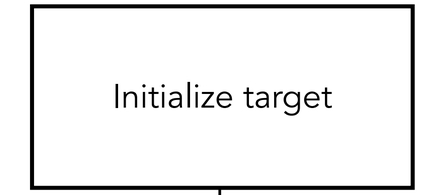

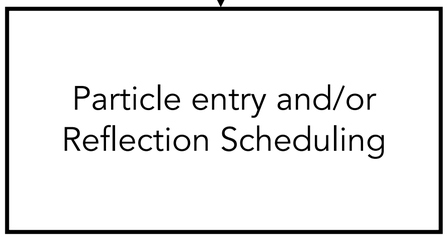

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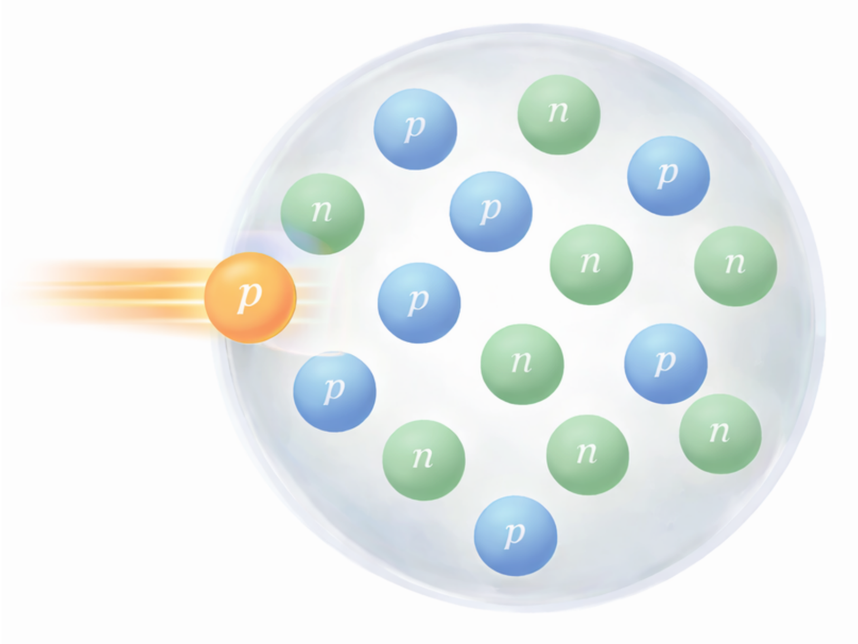

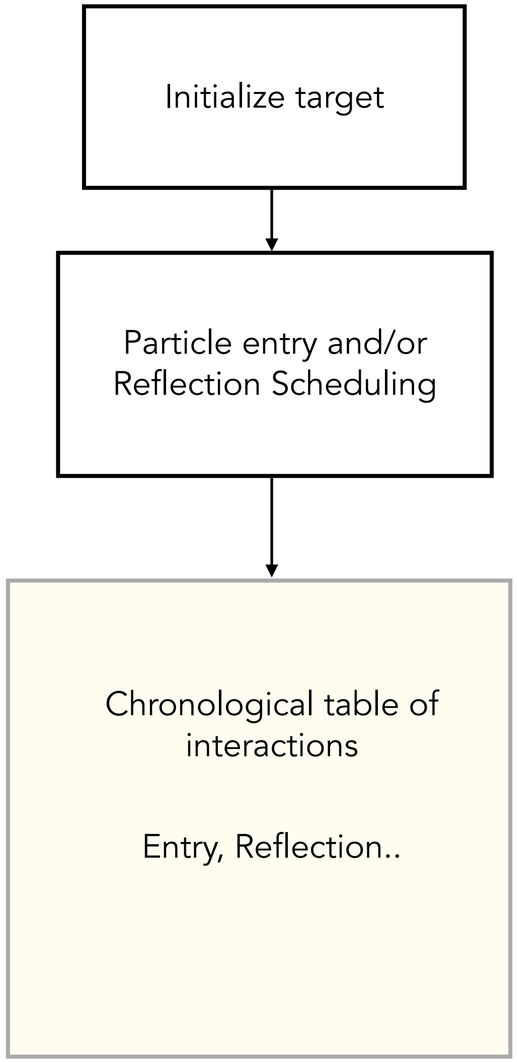

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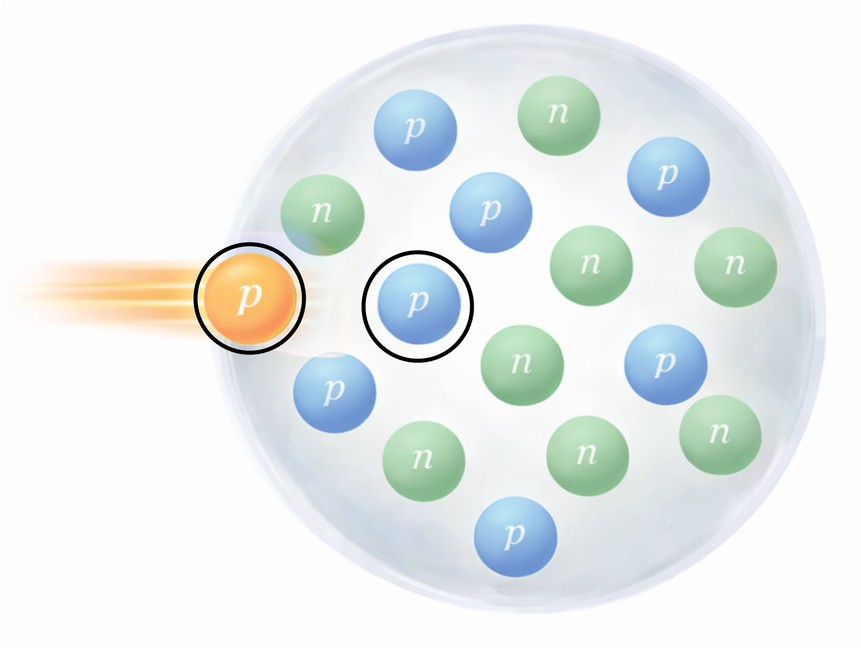

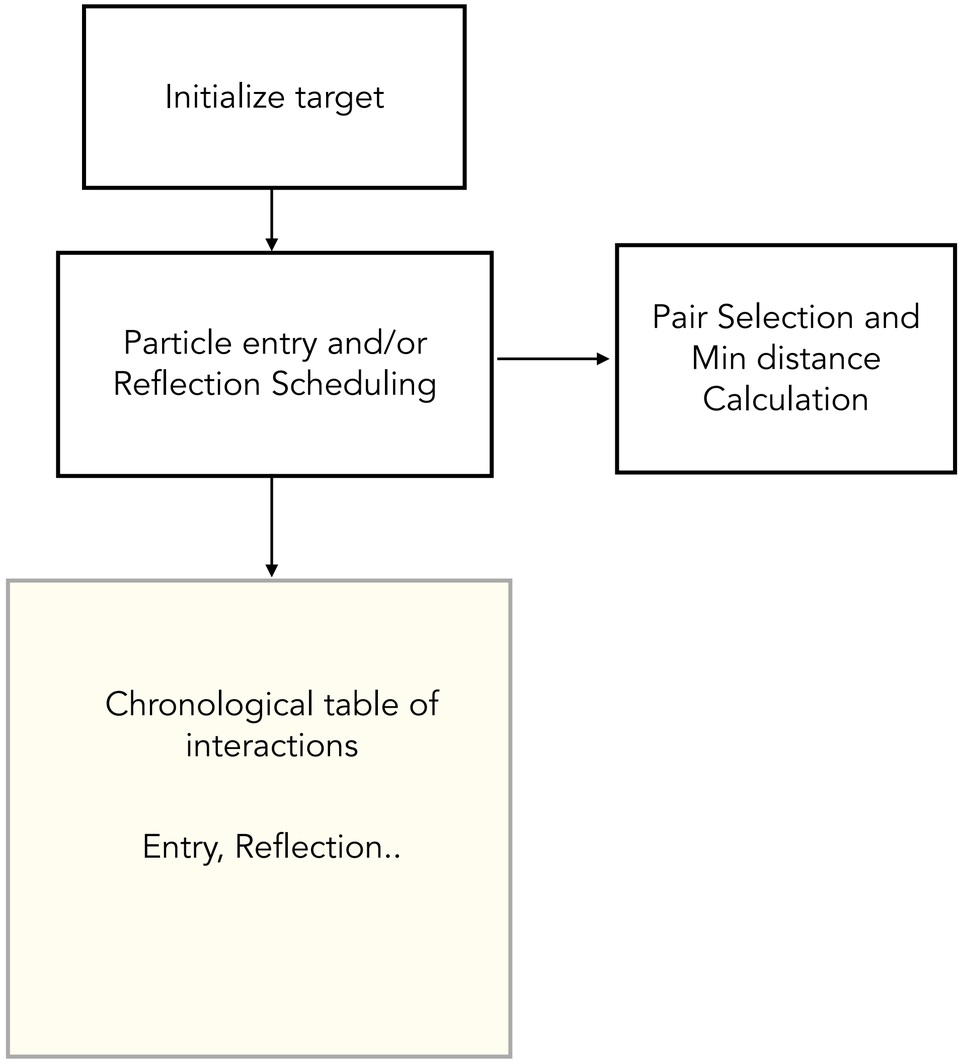

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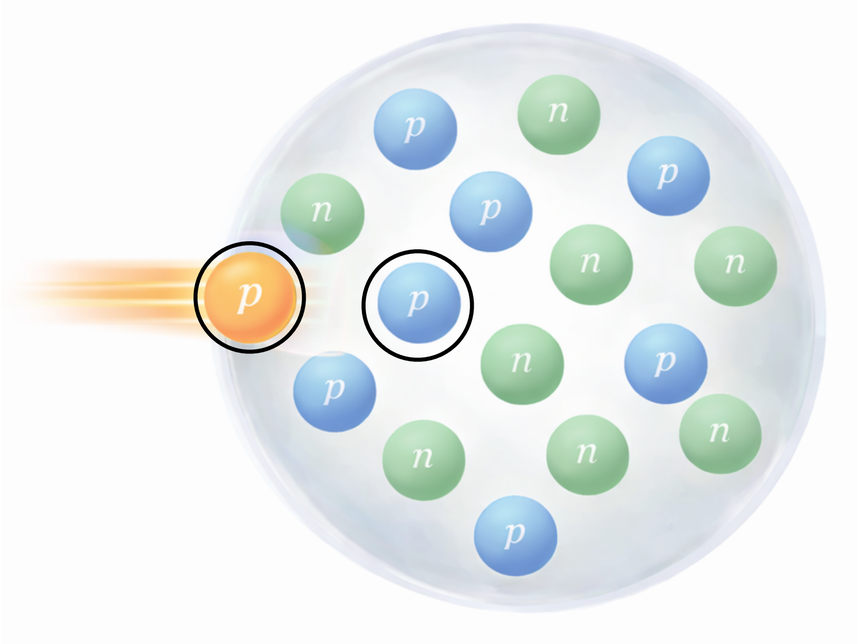

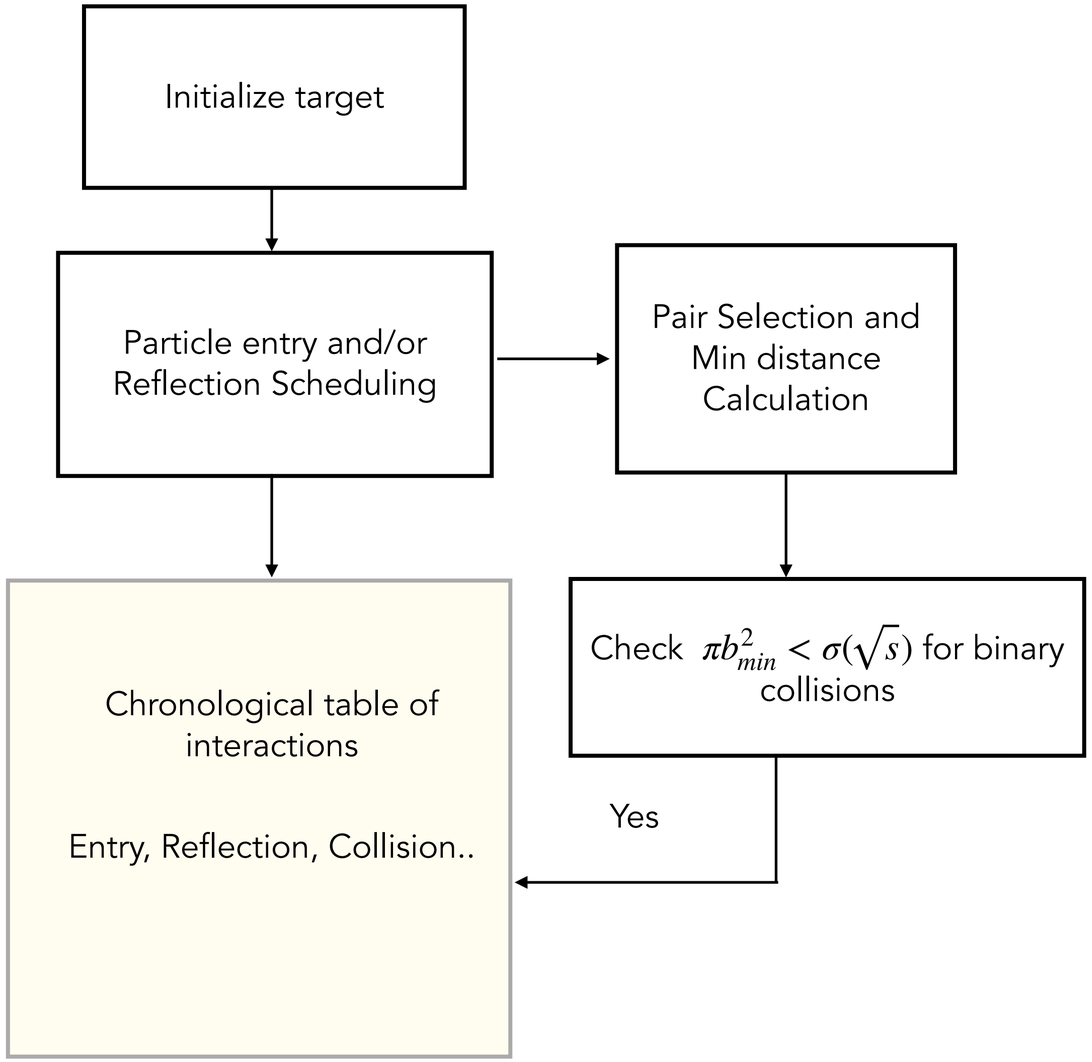

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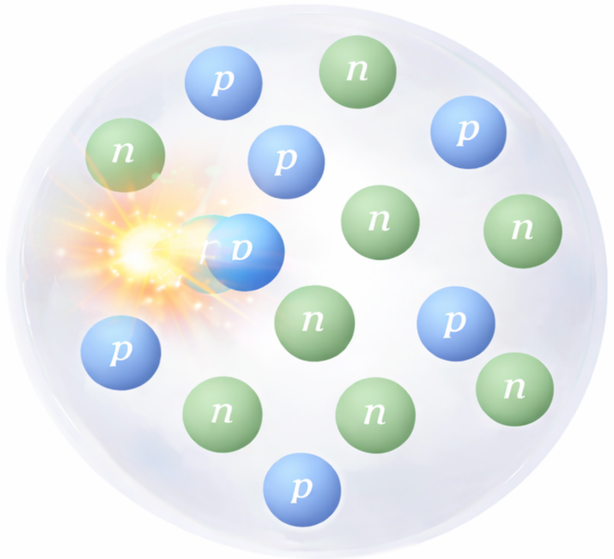

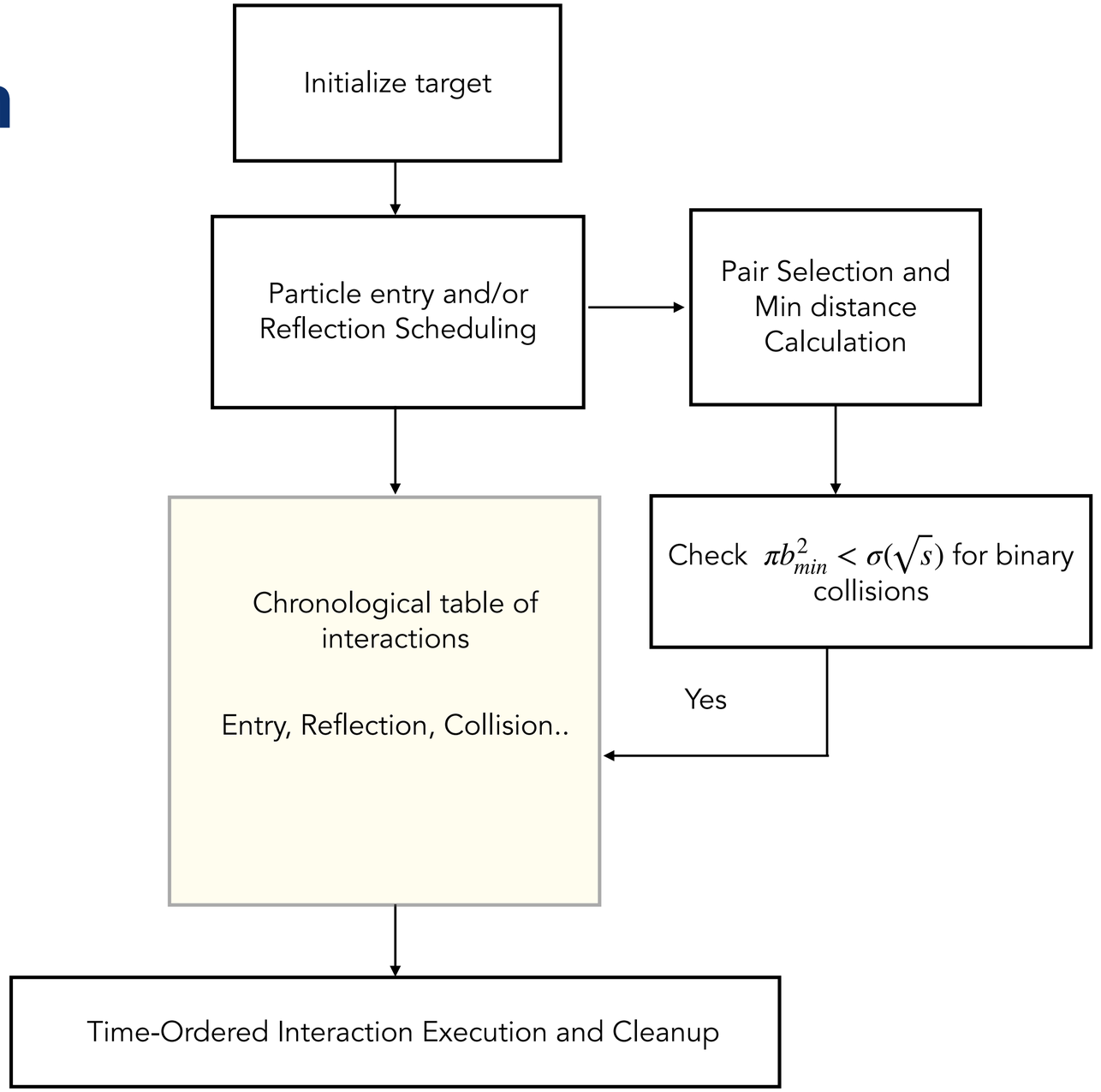

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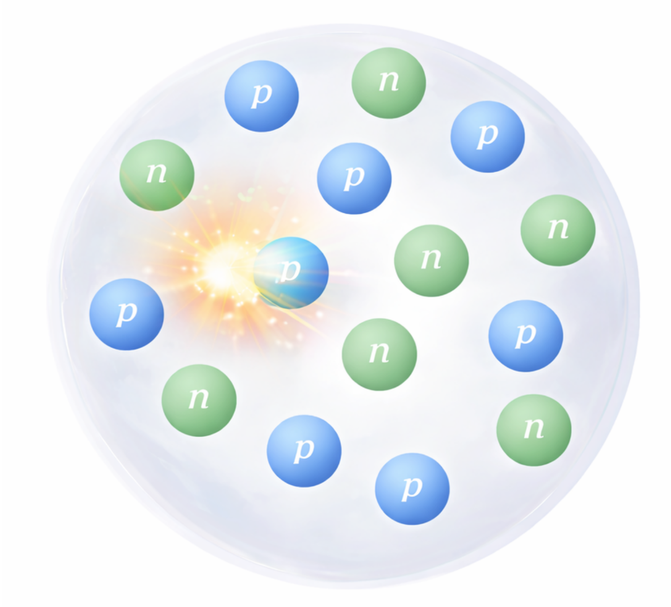

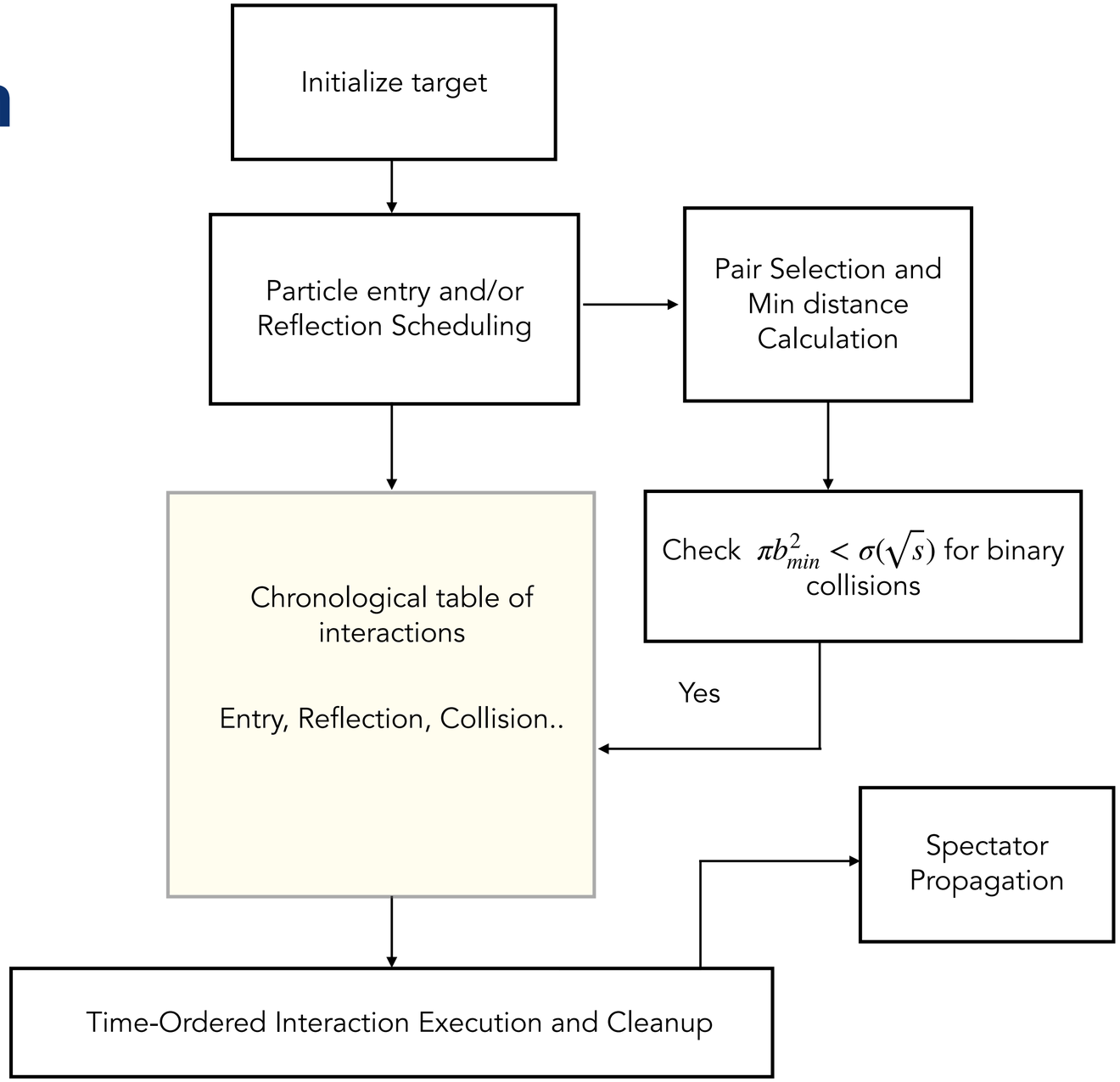

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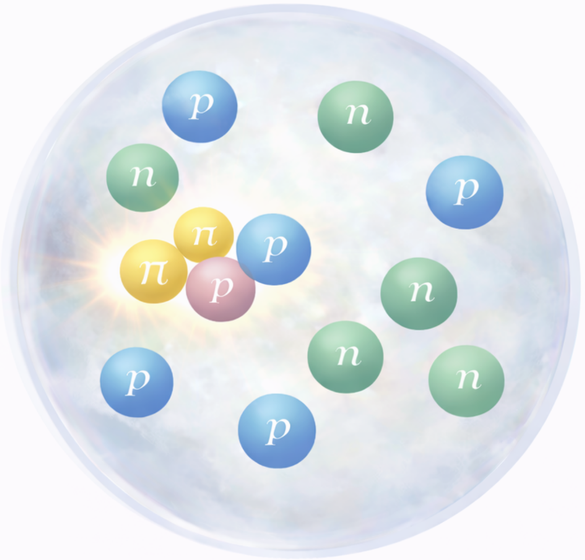

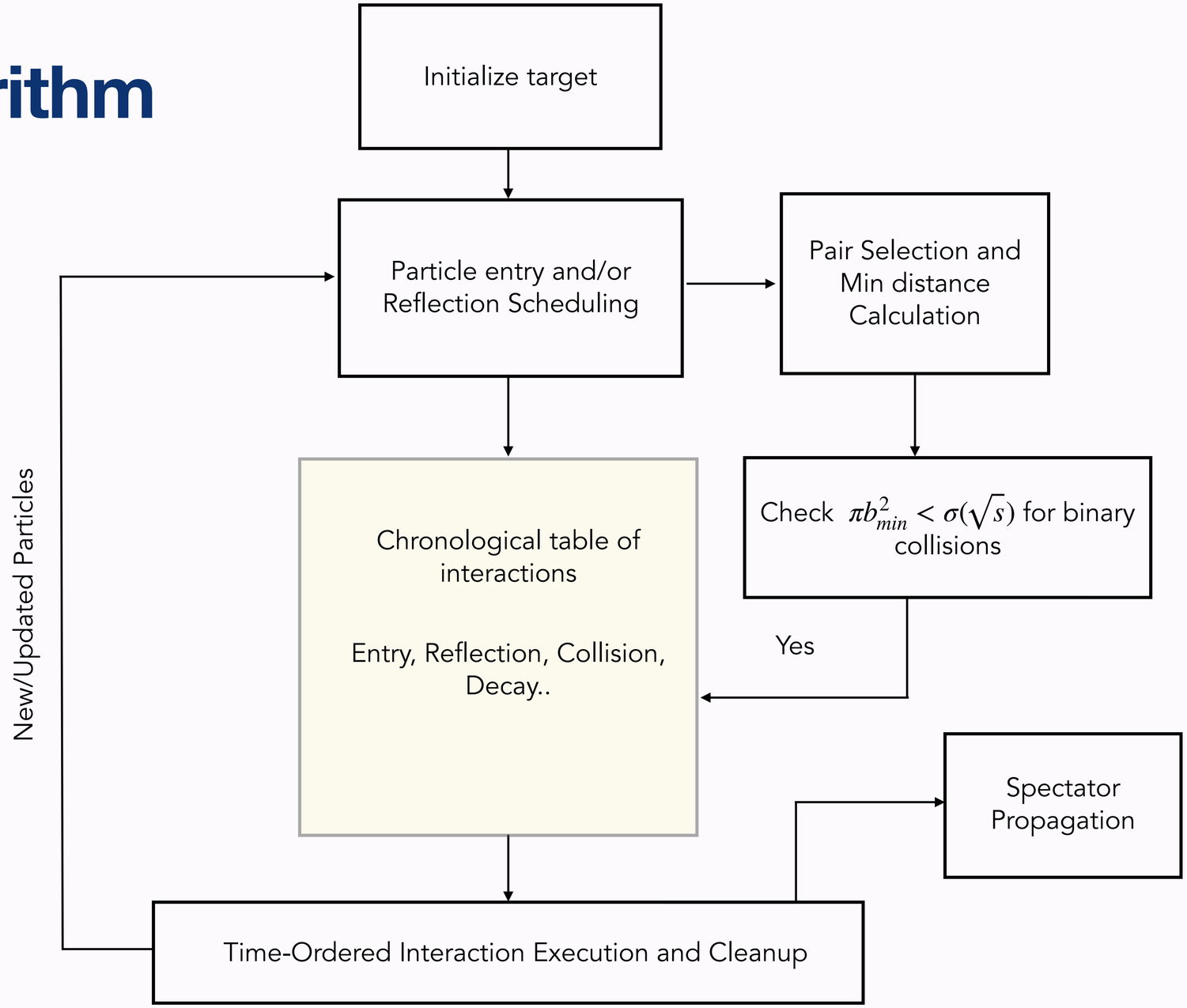

CLIO/BeAGLE++ Cascade Algorithm

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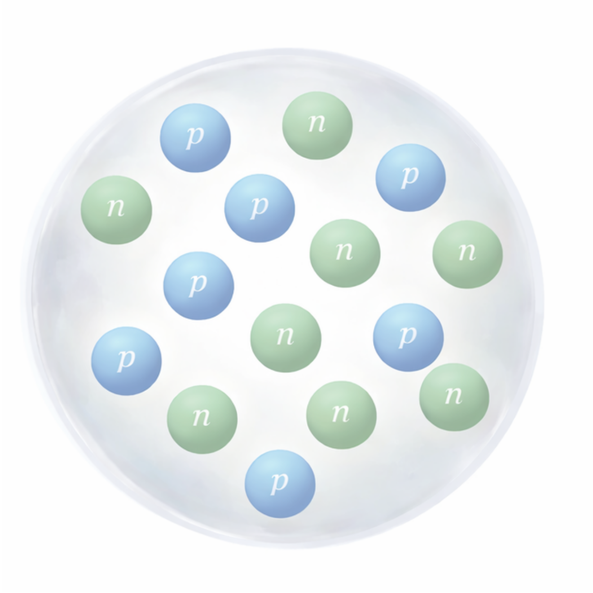
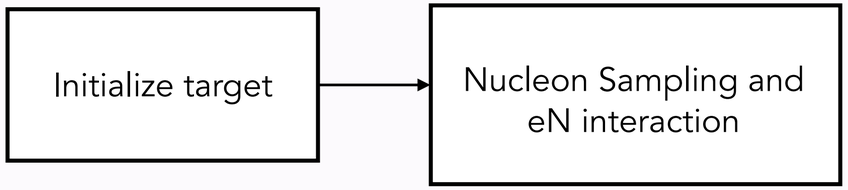
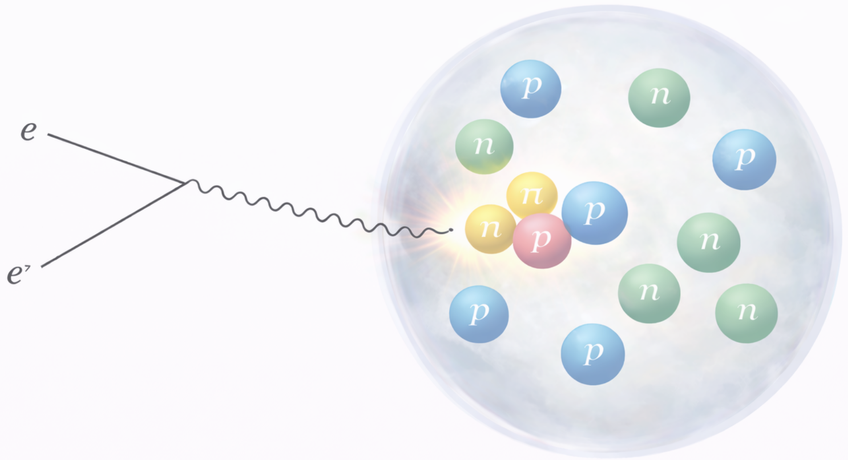
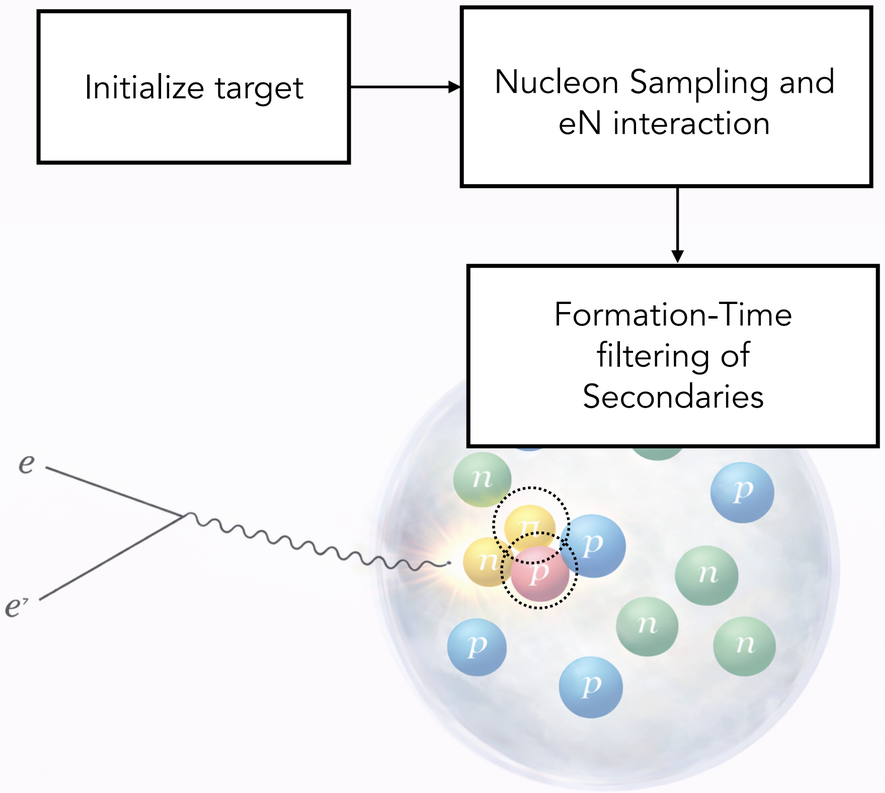


CLIO/BeAGLE++ Cascade Algorithm

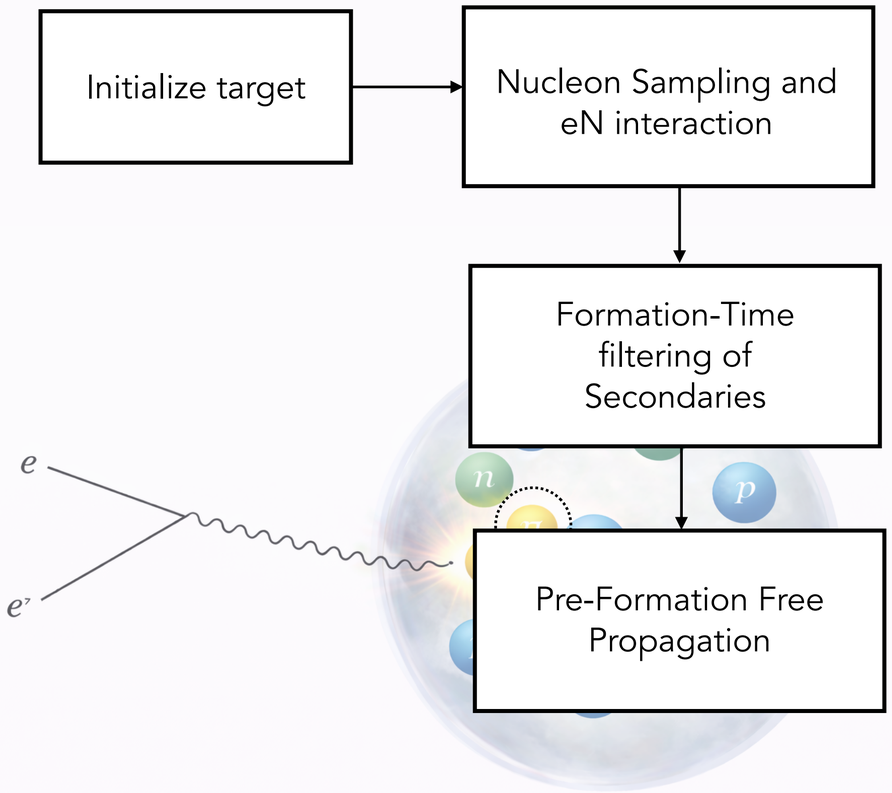




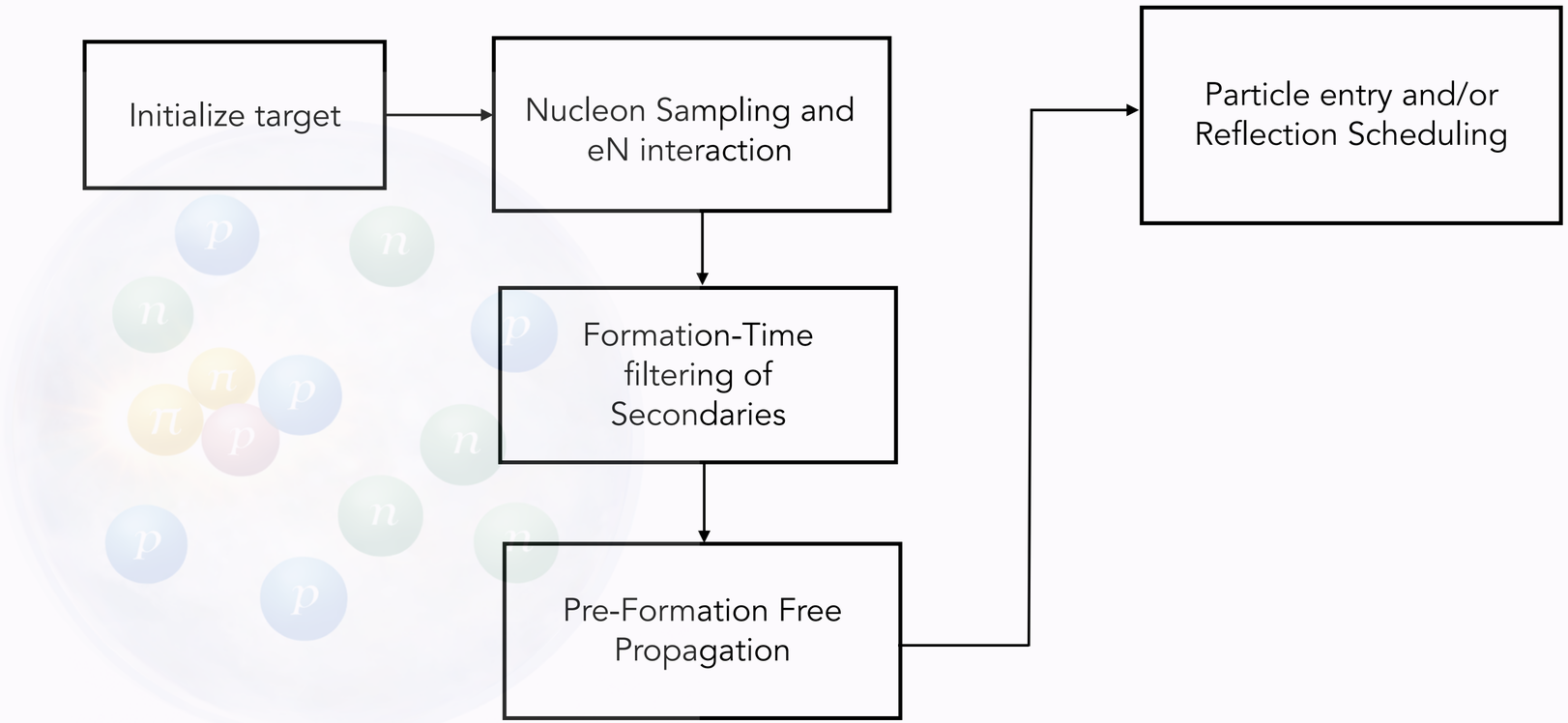
CLIO/BeAGLE++ Cascade Algorithm



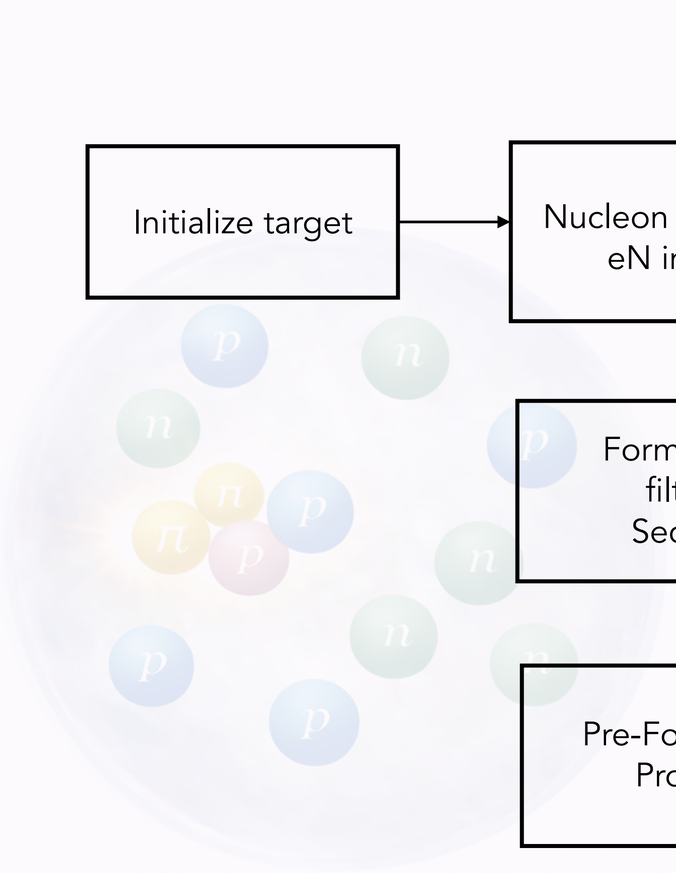
CLIO/BeAGLE++ Cascade Algorithm



CLIO/BeAGLE++ Cascade Algorithm



CLIO/BeAGLE++ Cascade Algorithm



Initialize target

Nucleon Sampling and eN interaction

Formation-Time filtering of Secondaries

Pre-Formation Free Propagation

Particle entry and/or Reflection Scheduling

Pair Selection and Min distance Calculation

Chronological table of interactions

Entry, Collision, Decay, Reflection etc

Check $\pi b_{min}^2 < \sigma(\sqrt{s})$ for binary collisions

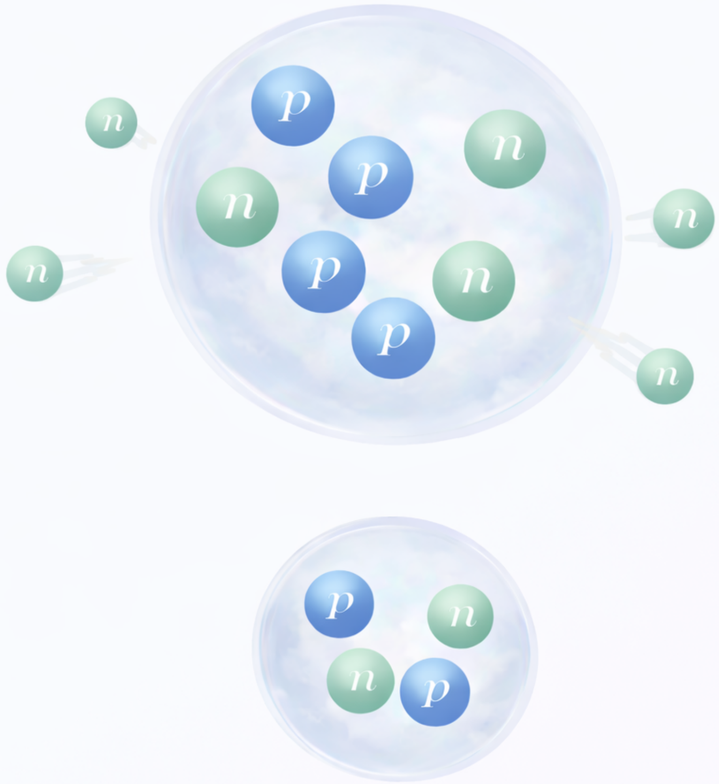
Yes

Spectator Propagation

Time-Ordered Interaction Execution and Cleanup

New/Updated Particles

ABLA: De-excitation model

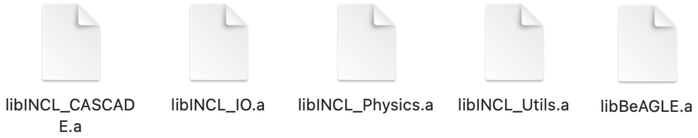


- Dynamical code that describes the de-excitation of the thermalized system
- **Open source code and easy coupling to INCL++**
- De-excitation happens through:
  - *Evaporation (particle emission)*: dominant at moderate excitation energies
  - *Fission*: critical for heavy nuclei
  - *Breakup/Multi-fragmentation*: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

A.Kelic, M.V. Ricciardi, K.H Schmidt arXiv:0906.4193

CLIO/BeAGLE++ - Structure and Layout

- *INCL++ code modified with new classes and member functions, will be shipped with CLIO/ BeAGLE++*

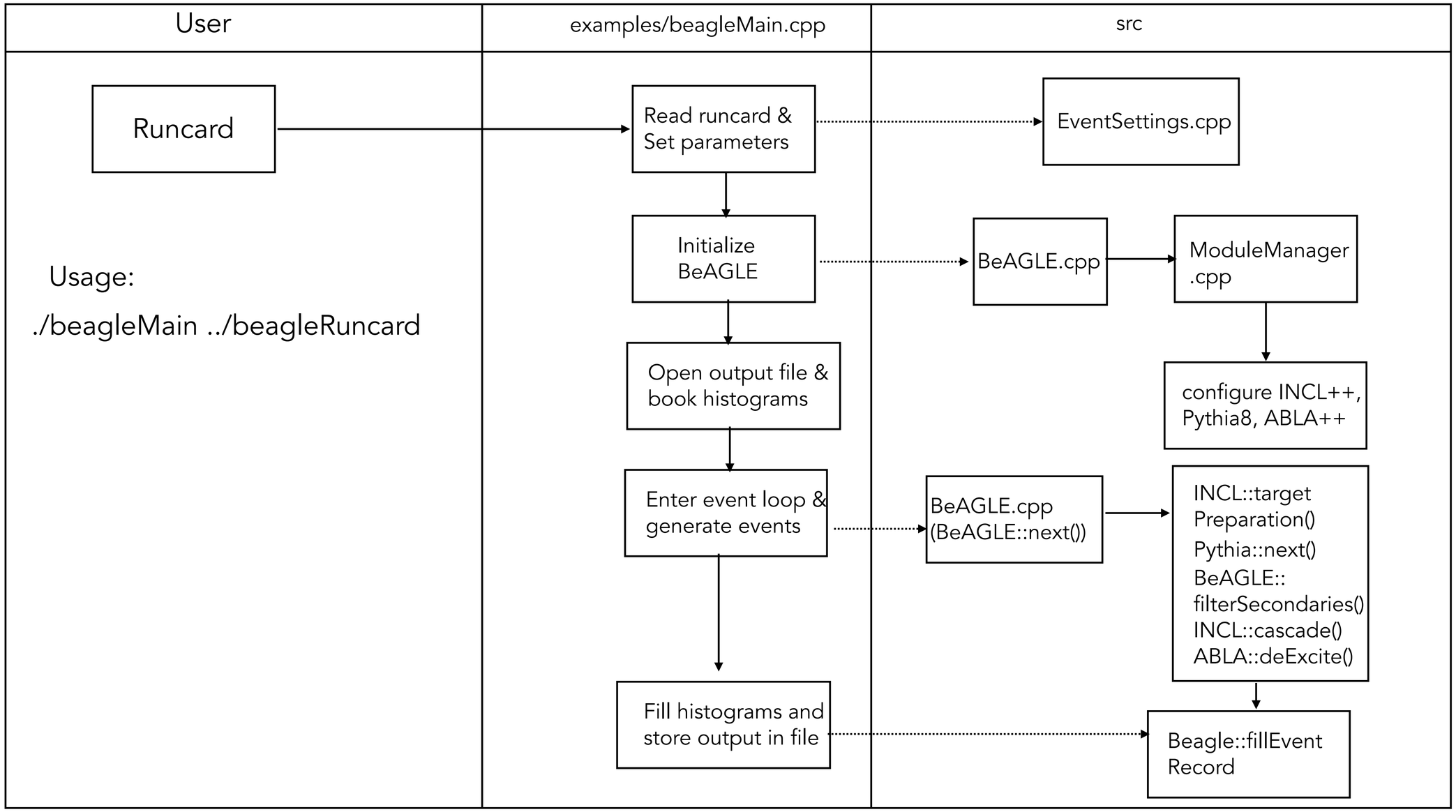


- *De-excitiaton codes also available and compiled with our code*

- *Pythia8 treated as external package and referenced via environment variables*

```
BeAGLE++/
|-- CMakeLists.txt          # Top-level CMake config
|-- src/                    #  Source code directory
|   |-- CMakeLists.txt      #CMake config for src
|   |-- BeAGLE.cpp
|   |-- EventRecord.cpp
|   |-- EventRecordINCL.cpp
|   |-- EventSettings.cpp
|   |-- Module Manager.cpp
|   |-- ParticleConverter.cpp
|   |-- ...
|-- examples/               #  steering programs folder
|   |-- CMakeLists.txt      #CMake config for examples
|   |-- beagleMain.cpp
|   |-- beagleRuncard.txt
|   |-- sampleNucleon.cpp
|   |-- build/              # contains execulatbles
|   |-- ...
|-- inclxx/               #  modified version of incl++
|-- nuclear_breakup/        #  de excitation codes
!-- pythia8
|-- cmake/                  # External modules
|-- build/                  # installation folder
|-- README.md
```

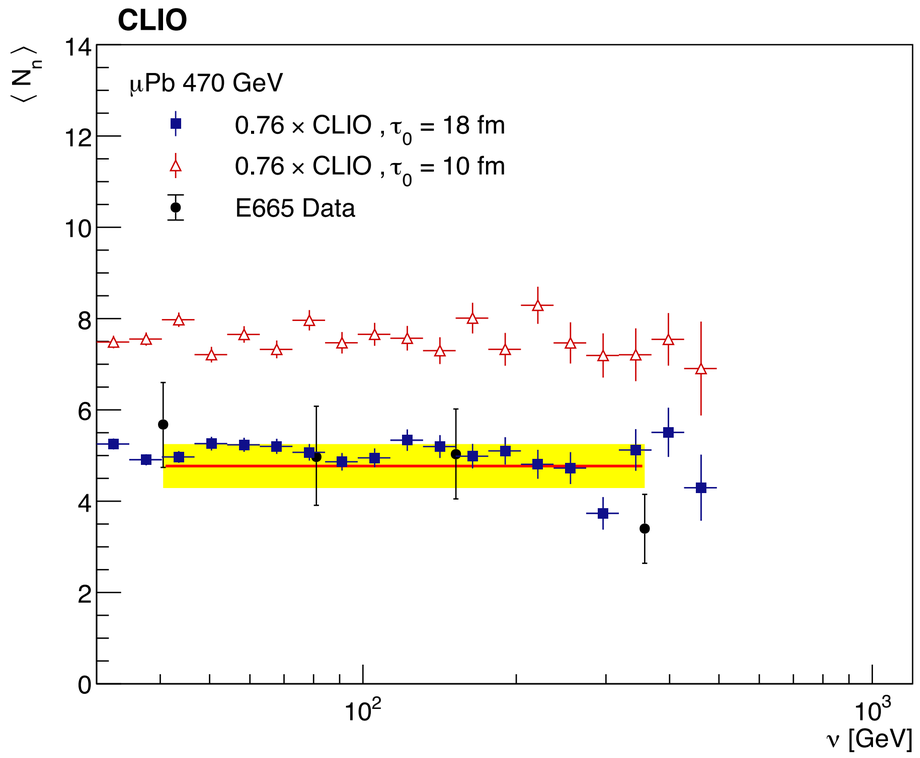
CLIO/BeAGLE++ - Activity diagram

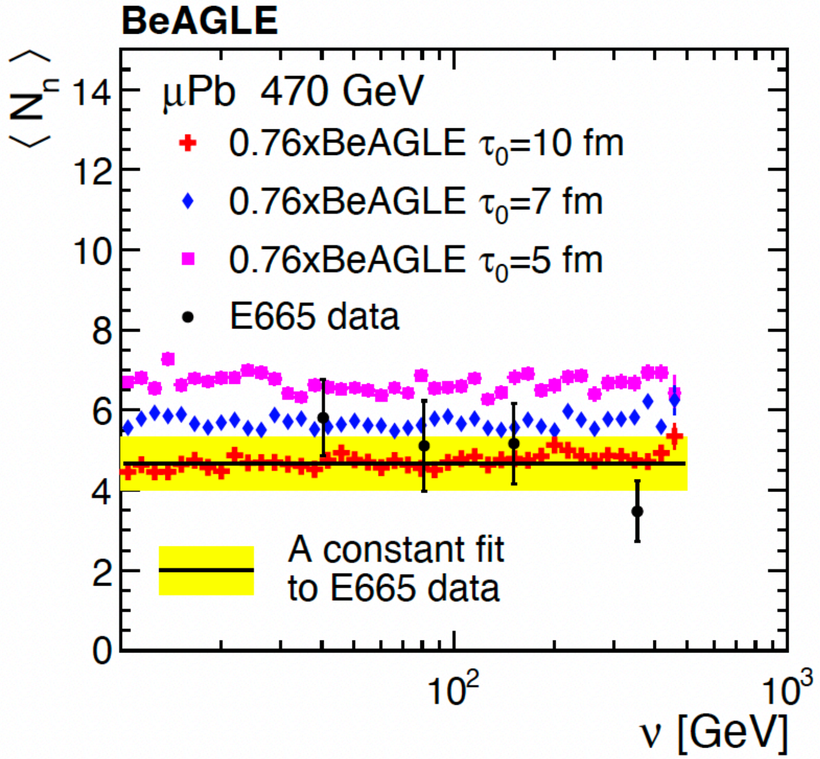


CLIO/BeAGLE++ output

```
-------- CLIO/BeAGLE++ Event Listing ----------------------

evt = 0 Q2 = 3.242 x = 0.074 W = 6.448 y = 0.050 z = 0.050 MY = 0.050

Particles (N=32)
  #          id   status               A               Z               S              px              py              pz               E               m          origin
  0          13        1               0              -1               0           0.000           0.000        -470.000         470.000           0.106               0
  1        2112        1               1               0               0           0.000           0.000           0.000           0.940           0.940               0
  2          13        1               0               0               0           1.112           1.357        -446.597         446.601           0.106               0
  3          22        1               0               0               0          -0.336          -0.211          -2.560           2.591          -0.000               0
  4          22        1               0               0               0          -0.210          -0.247          -2.610           2.630          -0.000               0
  5          22        1               0               0               0          -0.018           0.009          -0.054           0.058           0.000               0
  6          22        1               0               0               0          -0.349           0.023          -4.007           4.022          -0.000               0
  7          22        1               0               0               0          -0.030          -0.012          -0.027           0.042           0.000               0
  8          22        1               0               0               0           0.120           0.076          -0.115           0.182           0.000               0
  9         211        1               0               1               0           0.282          -0.012          -1.036           1.083           0.140               0
 10        -211        1               0              -1               0          -0.469          -0.612          -9.371           9.403           0.140               0
 11        -211        1               0              -1               0          -0.092           0.299          -0.830           0.898           0.140               0
 12         211        1               0               1               0          -0.138          -0.822          -0.376           0.924           0.140               1
 13        2212        1               1               1               0          -0.338           0.456          -1.789           2.099           0.938               1
 14        2212        1               1               1               0           0.166          -0.357          -0.296           1.060           0.938               1
 15        1002        1               2               1               0           0.201           0.299          -0.310           1.935           1.876               1
 16        2112        1               1               0               0           0.017          -0.038          -0.129           0.949           0.940               2
 17        2112        1               1               0               0           0.004           0.021           0.086           0.944           0.940               2
 18        2112        1               1               0               0          -0.032          -0.050           0.044           0.942           0.940               2
 19        2112        1               1               0               0          -0.078          -0.039          -0.116           0.951           0.940               2
 20        2112        1               1               0               0           0.052          -0.098           0.045           0.947           0.940               2
 21        2112        1               1               0               0           0.105           0.055          -0.007           0.947           0.940               2
 22        2212        1               1               1               0           0.059           0.067           0.194           0.962           0.938               2
 23        2112        1               1               0               0           0.037           0.020           0.009           0.941           0.940               2
 24        2112        1               1               0               0          -0.056          -0.099          -0.039           0.947           0.940               2
 25        2112        1               1               0               0          -0.125          -0.100           0.025           0.953           0.940               2
 26        2112        1               1               0               0           0.023          -0.004          -0.028           0.940           0.940               2
 27        2112        1               1               0               0           0.000          -0.019          -0.008           0.940           0.940               2
 28        2112        1               1               0               0          -0.085           0.038          -0.013           0.944           0.940               2
 29        2112        1               1               0               0           0.005          -0.020           0.004           0.940           0.940               2
 30        2112        1               1               0               0           0.015           0.017          -0.006           0.940           0.940               2
 31       50112        1             112              50               0           0.158           0.002          -0.099         104.213         104.213               2
Selected=0 Aborted=0 Tried=0

-------- End Event Listing ----------------------
```

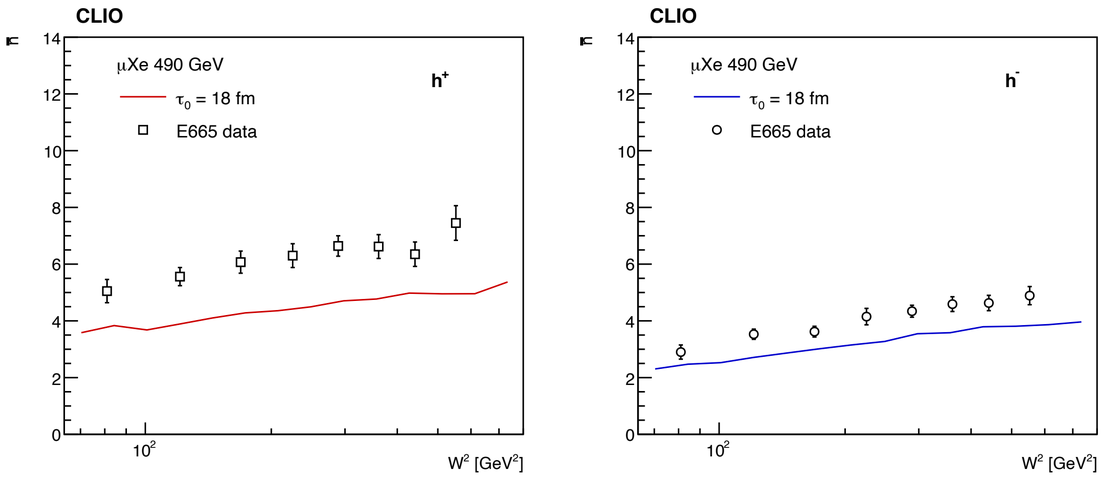
Neutron Multiplicity

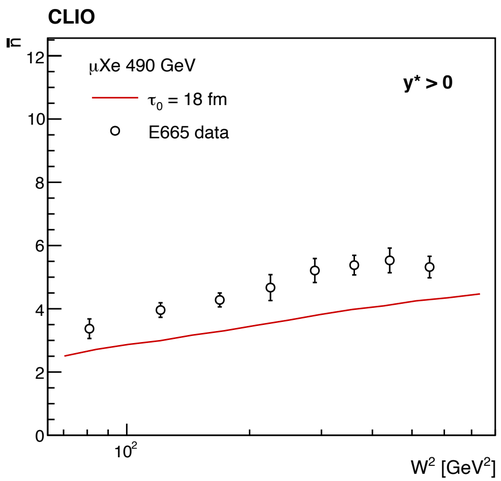


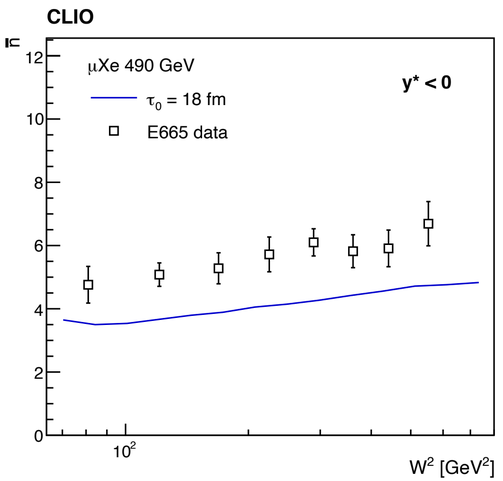


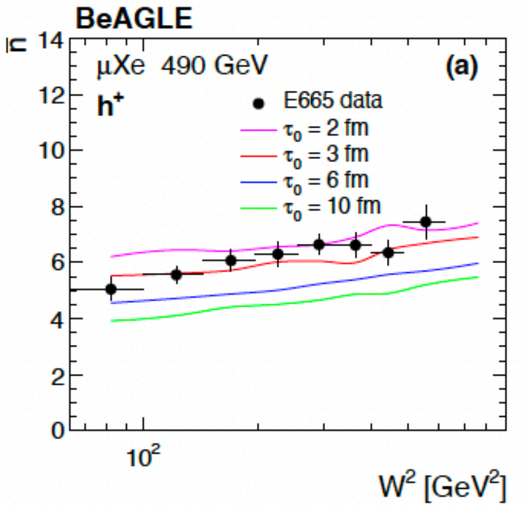
- Large value of parameter $\tau_0 = 18$ fm as compared to old code with $\tau_0 = 10$ fm (Two reasons: No formation time for successive generations in cascade, More channels upto <20 GeV induce more activity)

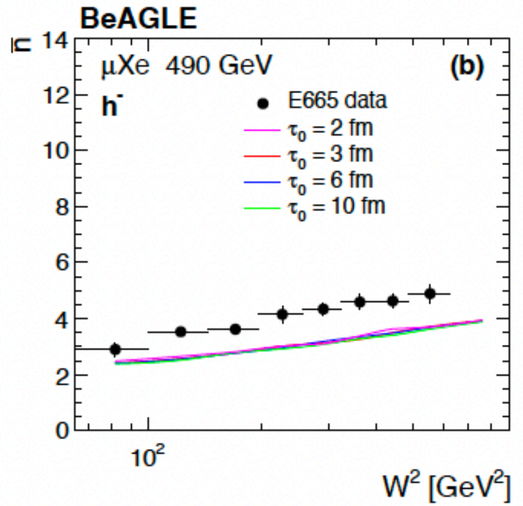
Multiplicity Distributions

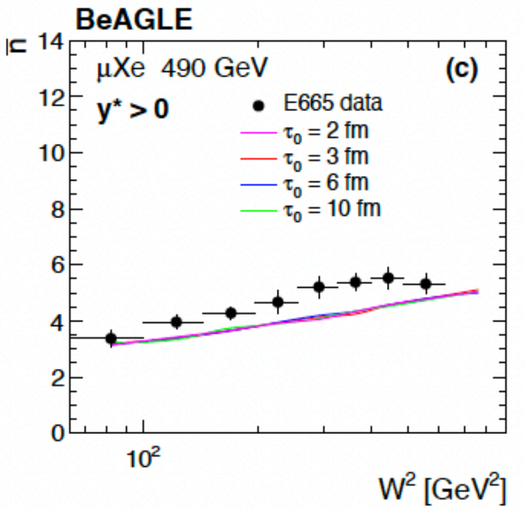


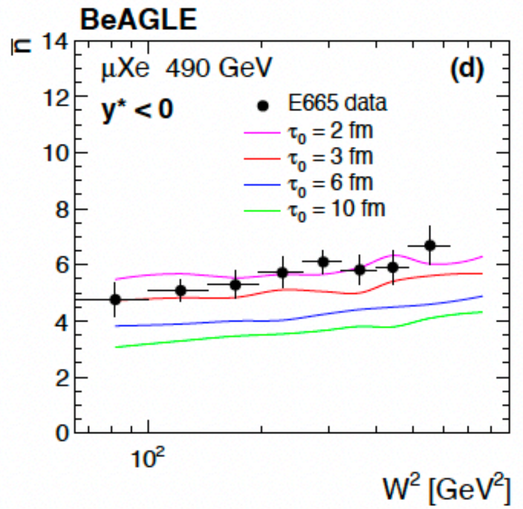




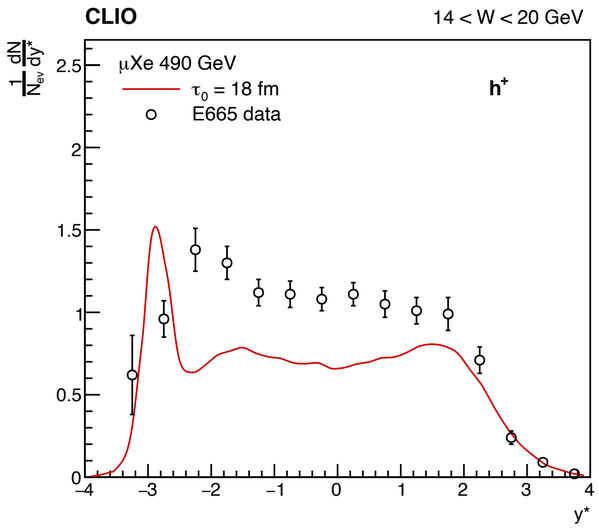


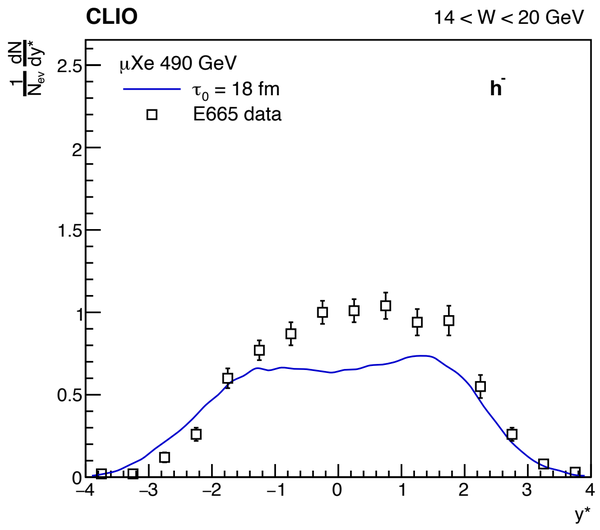


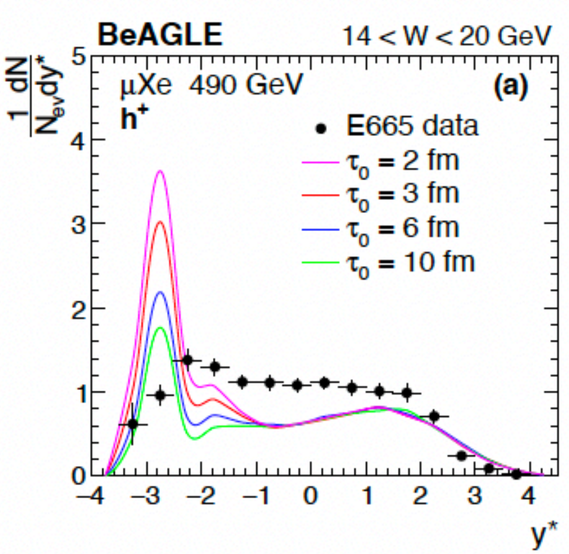


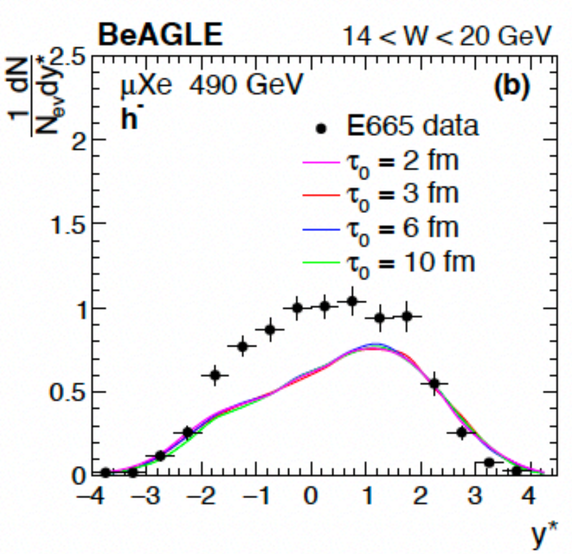


Rapidity Distributions



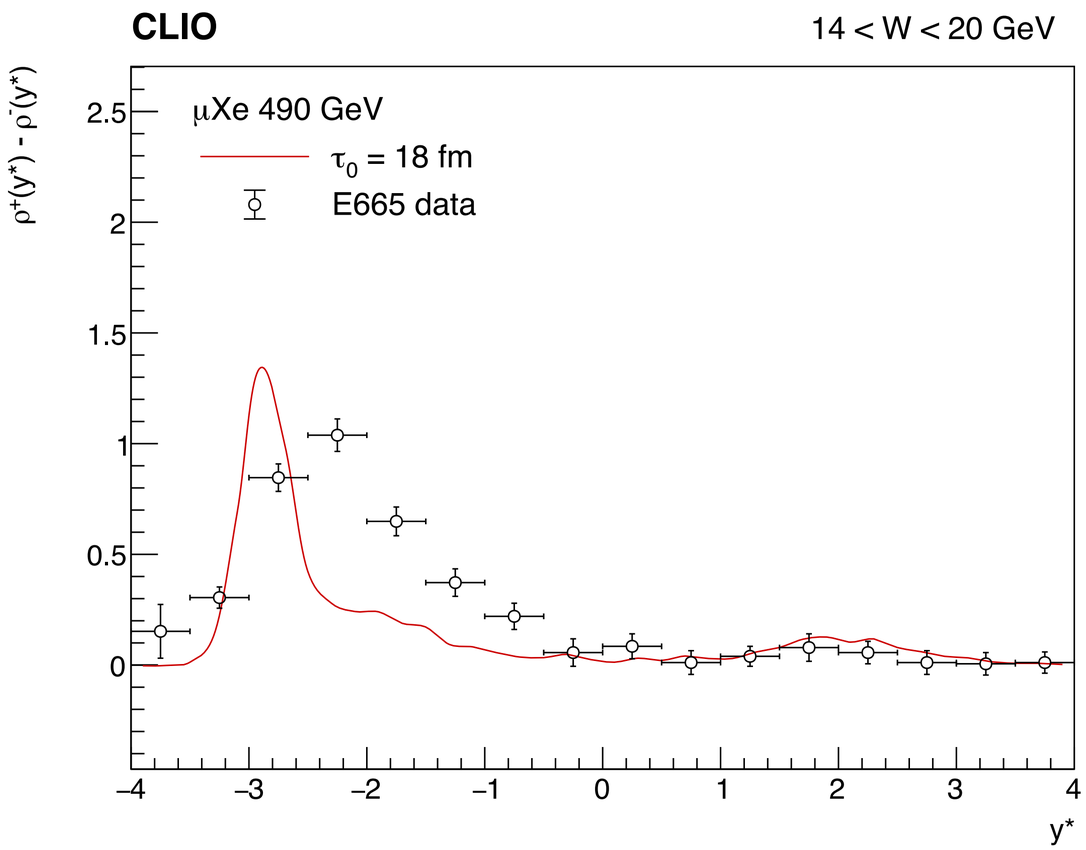


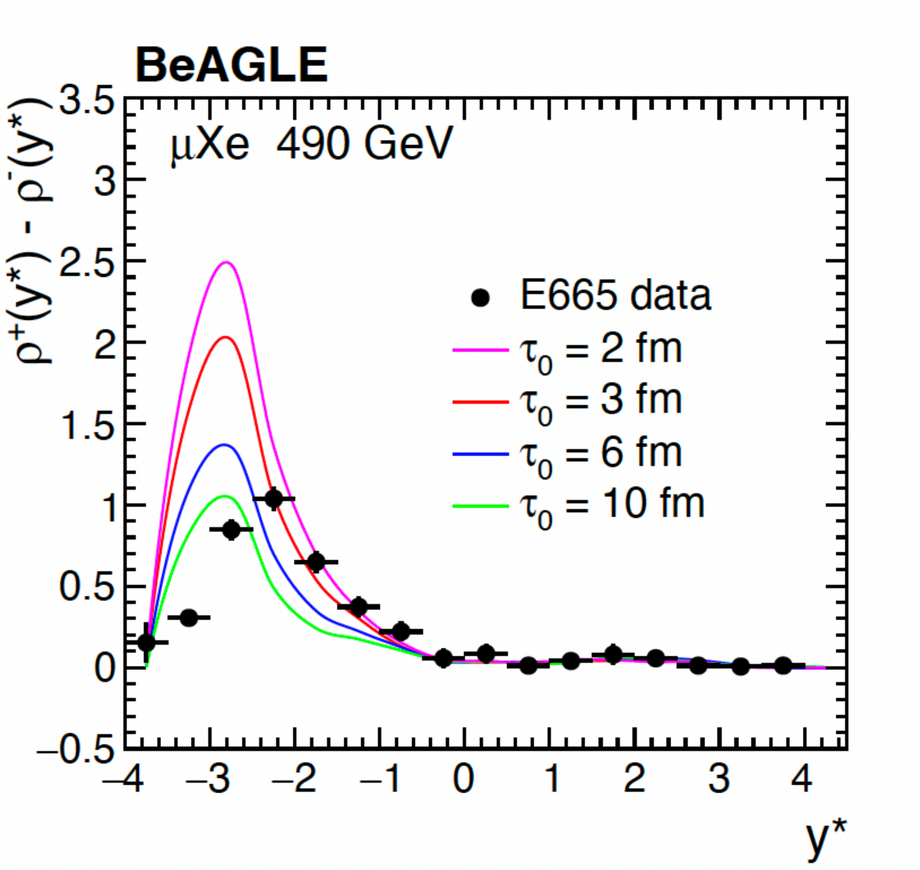




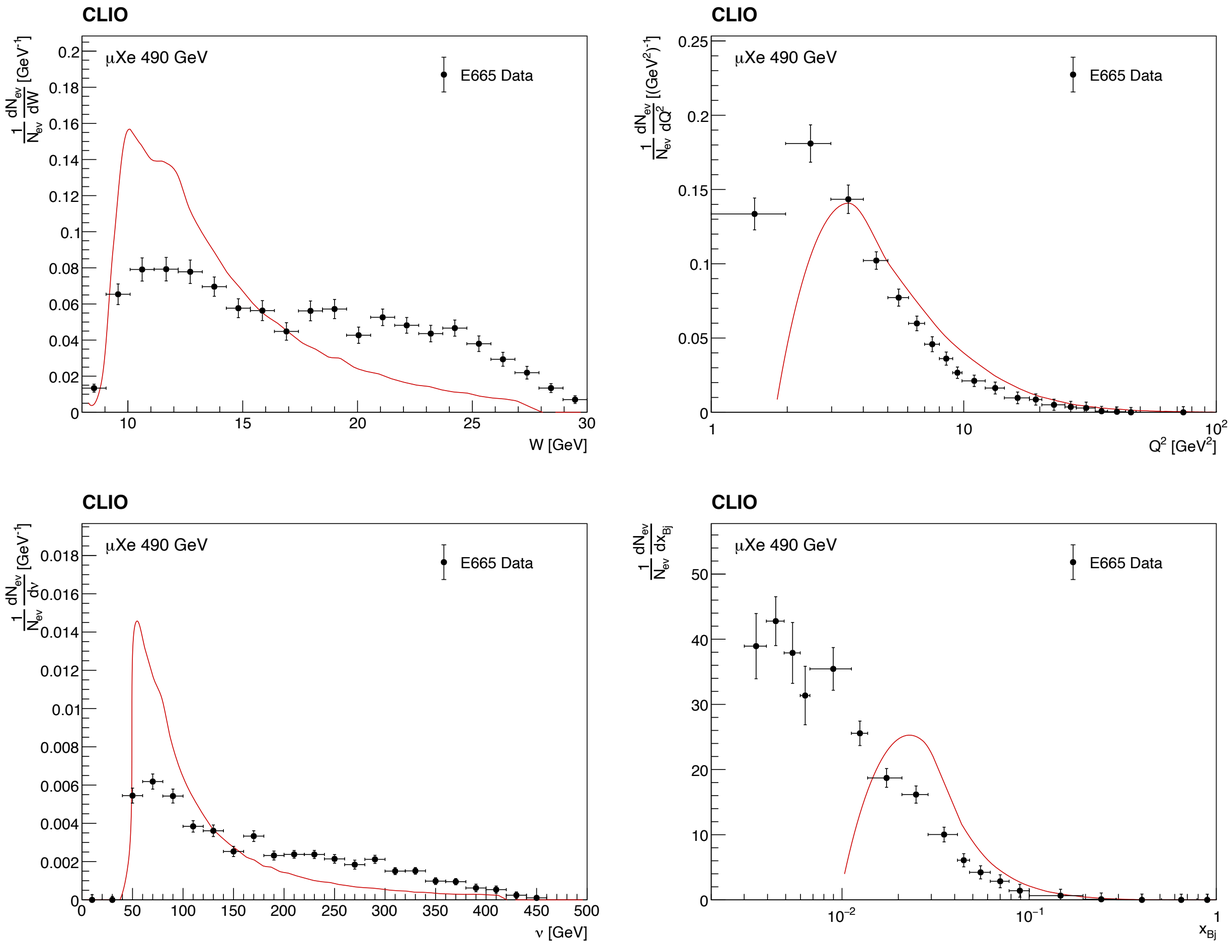
- Rapidity distribution in cms frame y* for positively and negatively charged hadrons in μXe interactions at 490 GeV

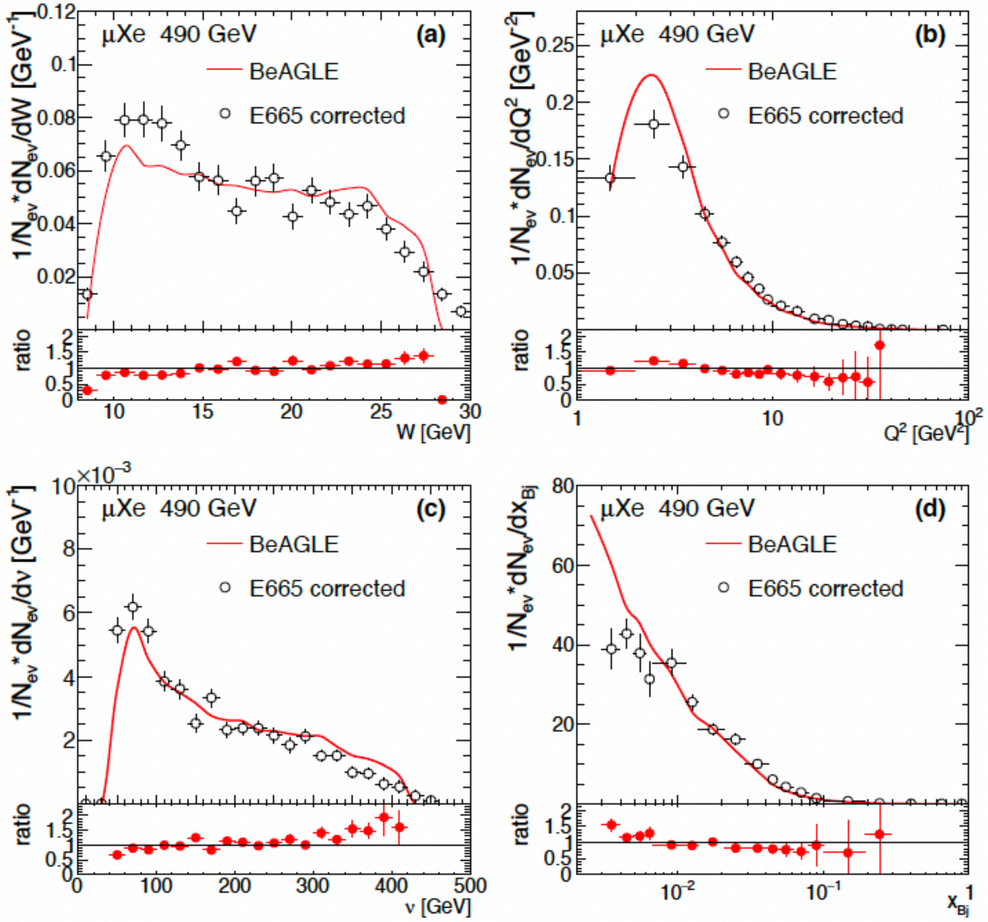
Net Charge rapidity distribution



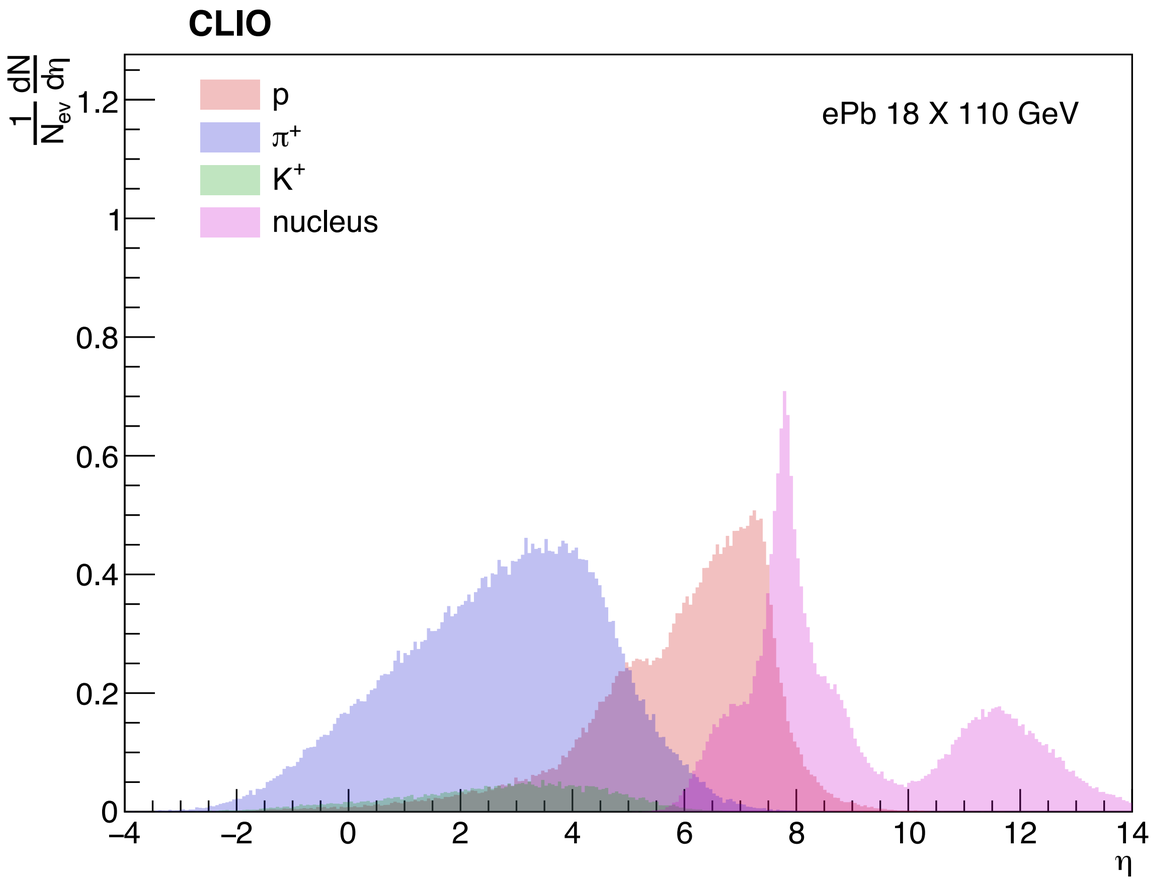


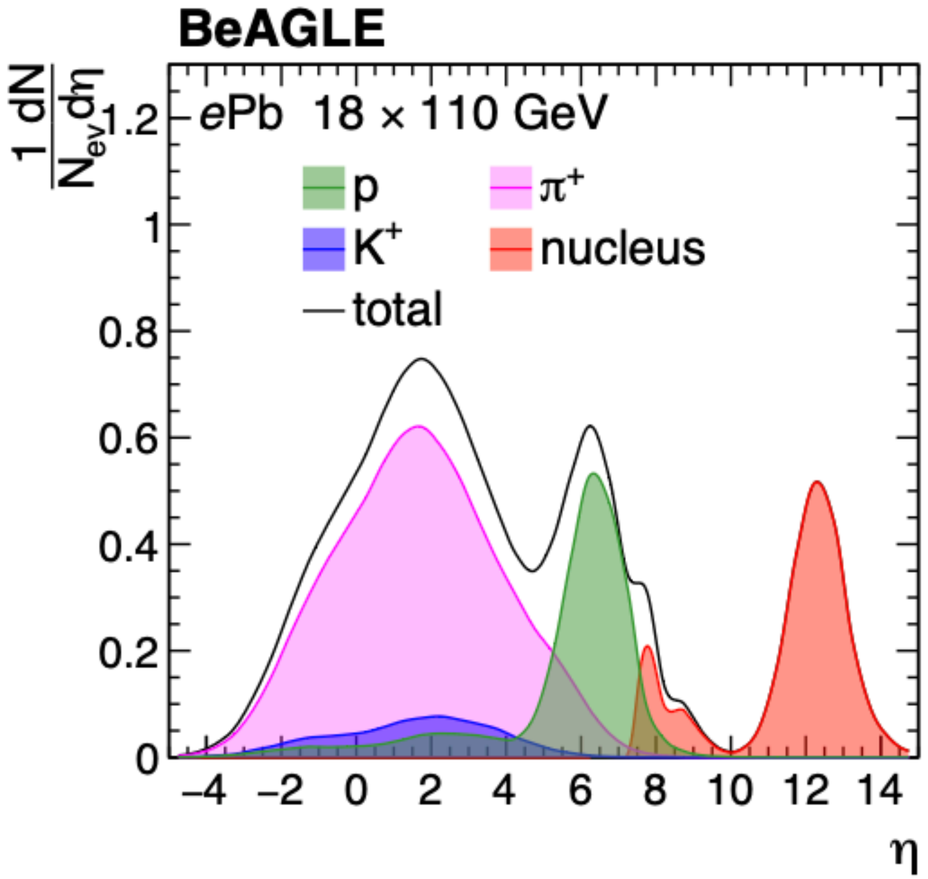
Kinematic Distributions



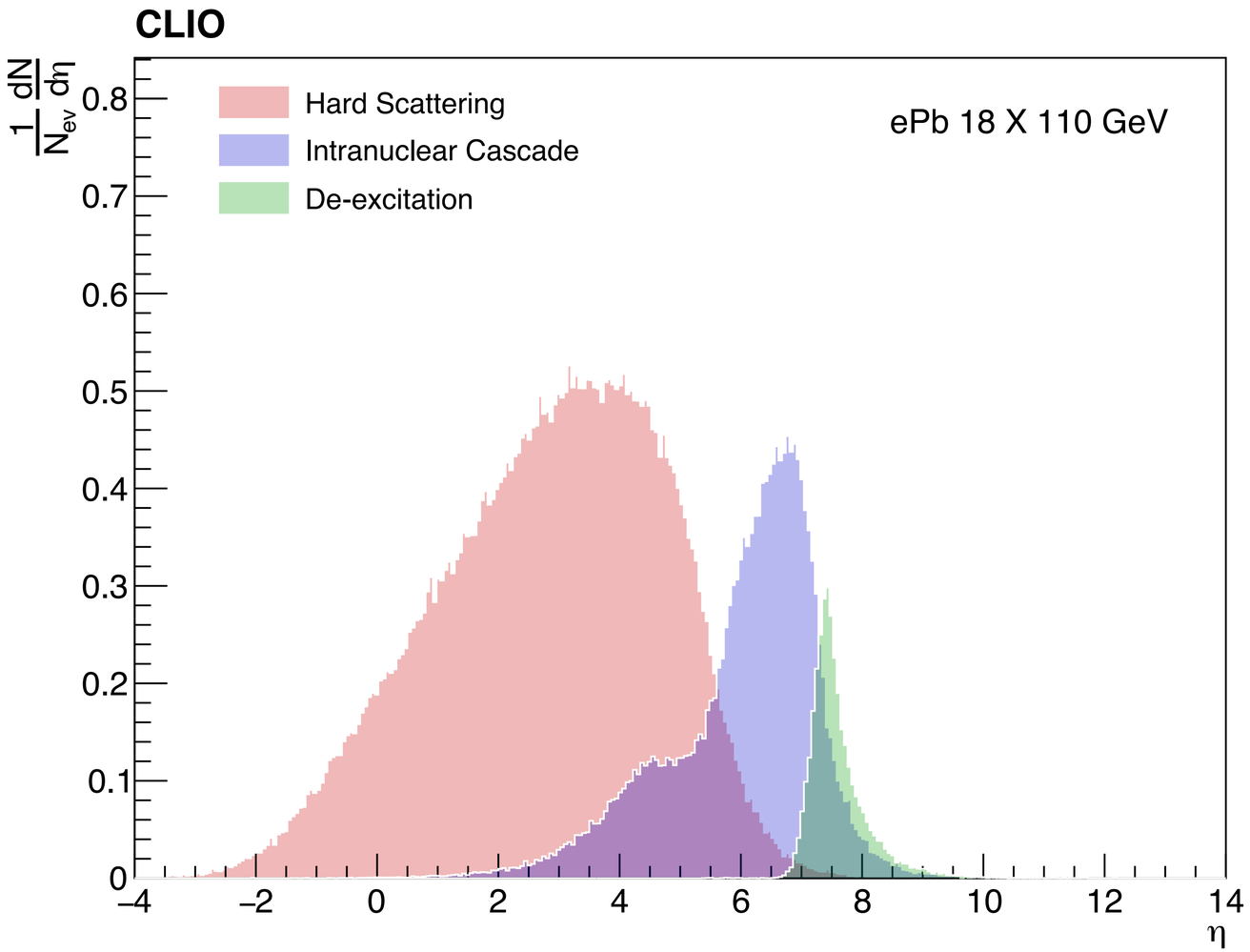


Charged Particles at EIC





Charged Particles at EIC



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

	Legacy BeAGLE	CLIO/BeAGLE++	Remarks CLIO
Hard Interaction	Pythia6	Pythia8	In future: HERWIG,SHERPA
MC technique for Cascade	Spacelike	Timelike	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~ 12-15 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

CLIO/BeAGLE++ Next Steps

- **Near Future** :
  - Add Diffractive events where the nucleus stays intact (Integrate Sartre: Exclusive and Inclusive diffraction events)
  - Implement Formation time for successive generations of particles in cascade and thorough testing of the code with different species of ions and more comparisons with the legacy code
  - Interact with user community for feedback (Different output styles etc)
  - Publish the code and physics paper: ~July
  - **Integrate with ePIC Collaboration**

CLIO/BeAGLE++ Next Steps

- **Long Term** :
  - **Adding New Physics**
    - Energy Loss (Interest from SBU, TSU groups)
    - Jets, Nuclear Structure, Impact parameter dependence on Nuclear shadowing (Interest from SBU group)
    - Thickness Function and Saturation Studies (Interest from USC, Duke groups)
    - DVCS, GPDs etc with light nuclei
  - **Investigate Model dependence** for hard interaction and de-excitation stage by coupling to other modules

Looking forward to many collaborations and contributors to join hands in this effort

MC generators are irreplaceable tools in HEP and Nuclear Experiments

- People use them before experiment exists (design, feasibility studies, requirements …)
- And during the data analysis (systematics, backgrounds …)
- **Proof of principle for a modern modular version of BeAGLE with a sophisticated FSI and De-excitation model**
- User friendly and 100x faster even generation than legacy code and very good agreement with older version

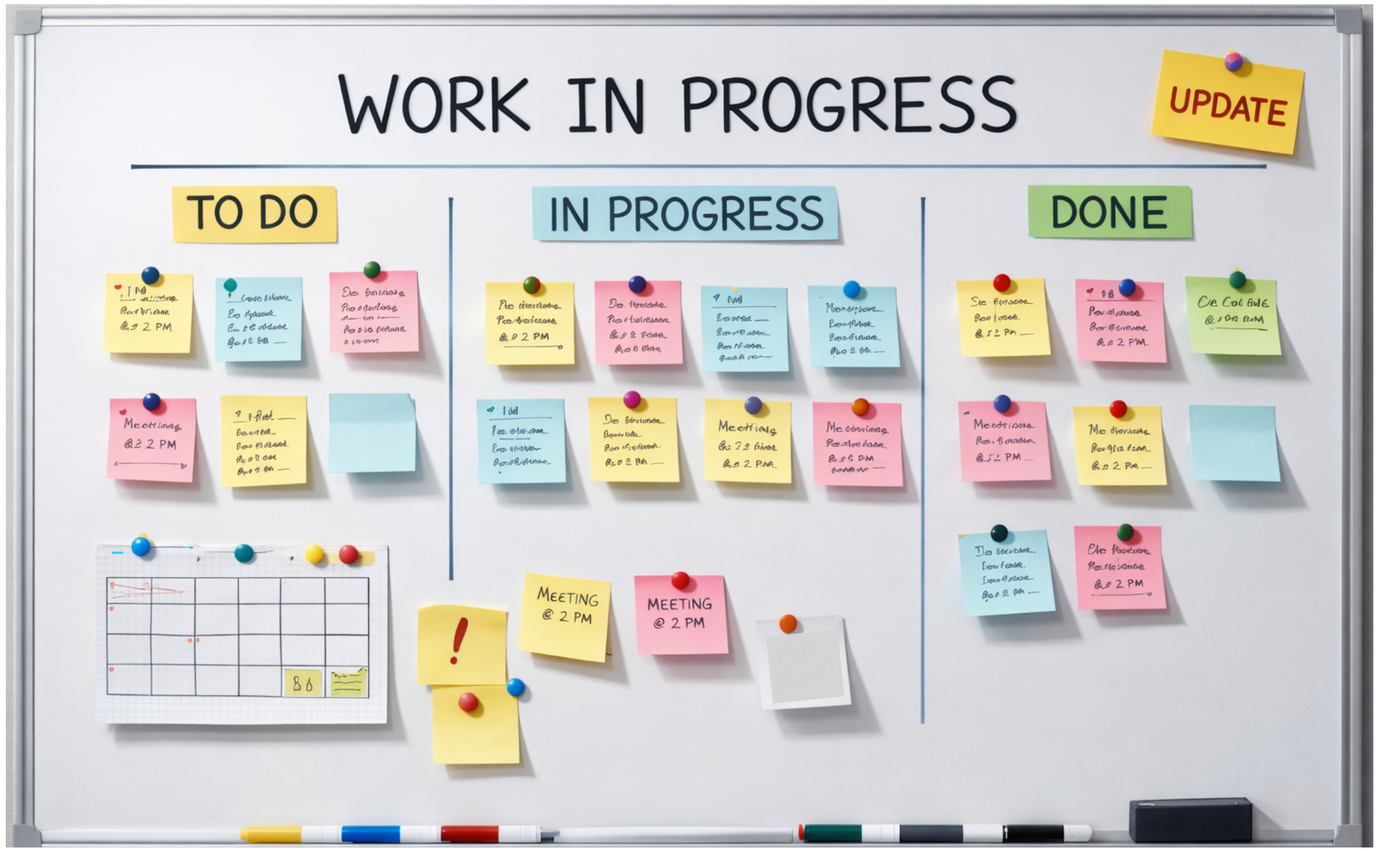
Looking forward to many collaborations and contributors to join hands in this effort

Silde inspired from Tomasz Golan talk at NuSTEC 2017

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

A MC generator development is always a work in progress



BACKUP

BeAGLE vs CLIO/BeAGLE++

dpmjet3.0-5F-new.f — Edited

dpmjet3.0-5F-new

dpmjet3.0-5F-new 〉 No Selection

```
8276 ************************************************************************
8277 * Kinematical treatment of low-mass excitations.                       *
8278 * This version dated 12.02.95 is written by S. Roesler                *
8279 ************************************************************************
8280
8281       IMPLICIT DOUBLE PRECISION (A-H,O-Z)
8282       SAVE
8283
8284       PARAMETER ( LINP = 5 ,
8285      &            LOUT = 6 ,
8286      &            LDAT = 9 )
8287
8288       PARAMETER (ZERO=0.0D0,OHALF=0.5D0,ONE=1.0D0)
8289
8290       INCLUDE 'beagle.inc'
8291
8292 * kinematics of diffractive interactions (DTUNUC 1.x)
8293       COMMON /DTDIKI/ XPH(2),XPPO(2),XTH(2),XTPO(2),PPOM(4),PSC(4),
8294      &                PPF(4),PTF(4),
8295      &                PPLM1(4),PPLM2(4),PTLM1(4),PTLM2(4),
8296      &                IDPR,IDXPR,IDTR,IDXTR,IFPPO(2),IFTPO(2)
8297
8298       DIMENSION P1(4),P2(4)
8299
8300       IREJ = 0
8301
8302       IF (KP.EQ.1) THEN
8303          PABS = SQRT(PPF(1)**2+PPF(2)**2+PPF(3)**2)
8304          POE  = PPF(4)/PABS
8305          FAC1 = OHALF*(POE+ONE)
8306          FAC2 = -OHALF*(POE-ONE)
8307          DO 1 K=1,3
8308             PPLM1(K) = FAC1*PPF(K)
8309             PPLM2(K) = FAC2*PPF(K)
8310     1    CONTINUE
8311          PPLM1(4) = FAC1*PABS
8312          PPLM2(4) = -FAC2*PABS
8313          IF (IMSHL.EQ.1) THEN
```

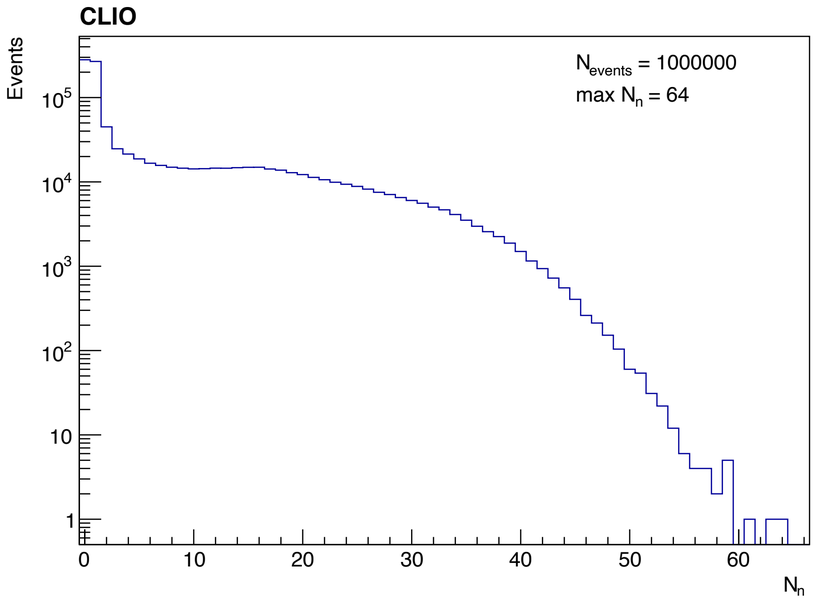
BeAGLE.h

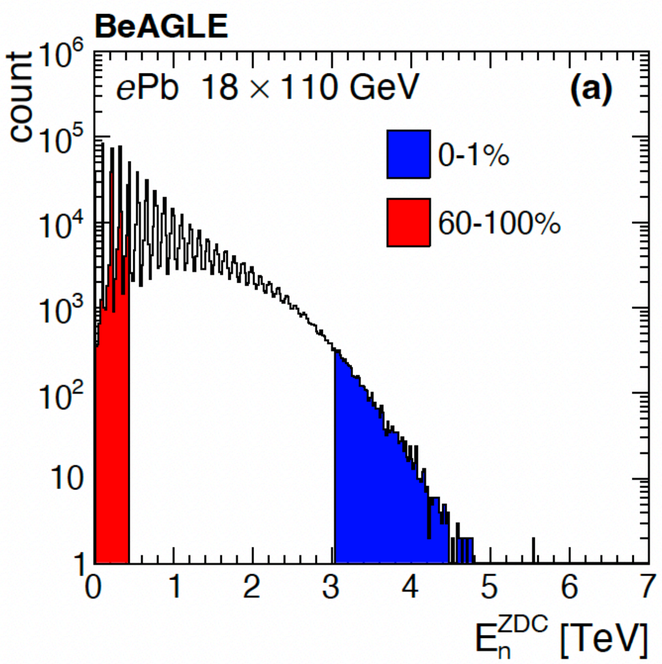
h BeAGLE

h BeAGLE 〉 No Selection

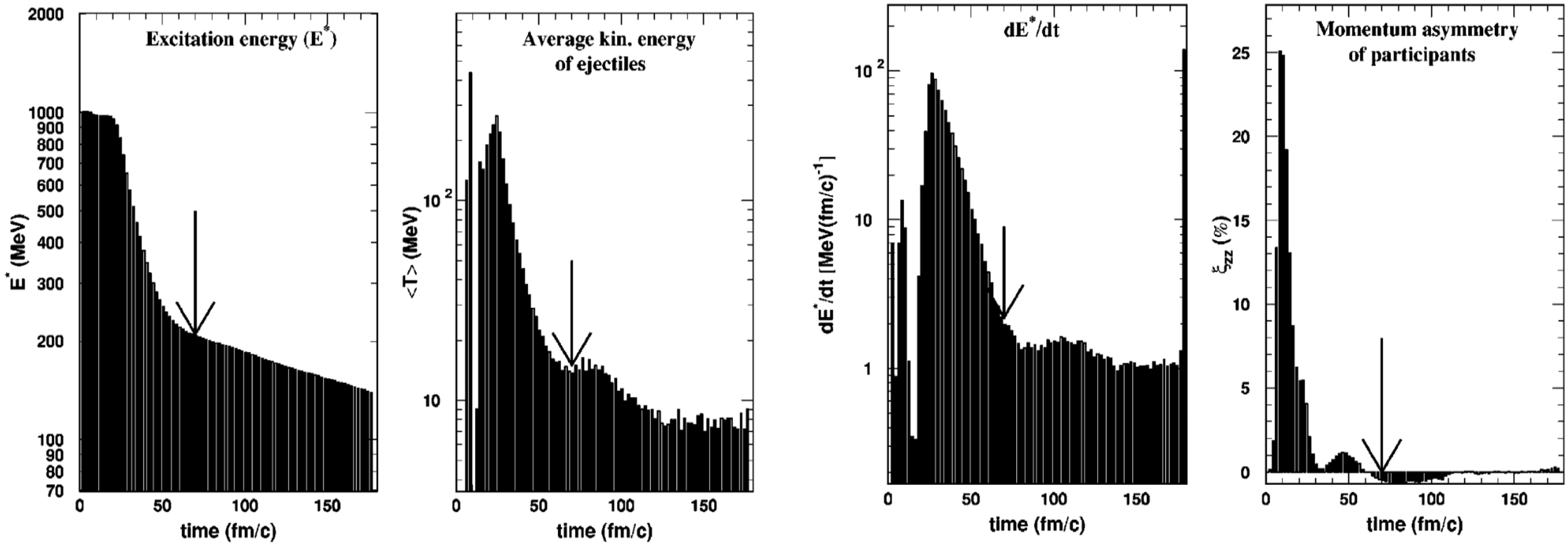
```
44
45 using namespace std;
46 using namespace CLIO;
47
48
49
50
51 class ConfigParser;
52
53 class  BeAGLE : public ModuleManager {
54 public:
55     BeAGLE();
56
57      bool init(const char* = 0);
58     virtual EventRecord* next();
59
60     chrono::duration<double> runTime() const;
61
62     void finaliseINCLevents();
63     const G4INCL::Random::SeedVector &getINCLInitialSeeds() const;
64     void filterSecondaries(const Pythia8::Event &event, double tau0, const
           G4INCL::ThreeVector vertex, bool onlyHadrons);
65
66    // void setInjectionVertex(G4INCL::ParticleList pL);
67     void propagate(G4INCL::Particle *p);
68     const G4INCL::ParticleList &getFormedInside()  const { return formedInside;  }
69     const G4INCL::ParticleList &getFormedOutside() const { return formedOutside; }
70
71     void addNuclearBreakupParticles(const G4INCL::EventInfo &afterCascade);
72     double getEnergyConservationBalance(const G4INCL::EventInfo &afterCascade);
73
74
75 private:
76
```

EIC Predictions





Stoping time INCL



INCL Basic Hypotheses

$$\lambda\!\!\!^{-} \ll d < \Lambda < R$$

with $\lambda\!\!\!^{-}$ the reduced de Broglie wavelength, d the distance between two nucleons inside the target nucleus, Λ the mean free path of the particle in the nucleus, and R the radius of the nucleus. The physical meanings of the sub-inequalities are:

- $\lambda\!\!\!^{-} \ll d$ - The size of the wave packet describing the particle is much lower than the internucleonic distance. Consequently, all nucleons appear distinct and well defined in momenta and positions for the incoming projectile. This allows a classical treatment of the particles propagation.
- $\lambda\!\!\!^{-} \ll \Lambda$ - The scattered wave reaches its asymptotic state before the next interaction and interactions can be treated in a classical approach.
- $d < \Lambda$ - Interactions are independent from each other (assuming that the time between two collisions is larger than the interaction time scale). Interactions and transport can be treated independently.
- $\Lambda < R$ - The possible interferences between the scattered waves cancel out due to the large number of interactions.