What is BeAGLE?:
Benchmark eA Generator for LEptoproduction

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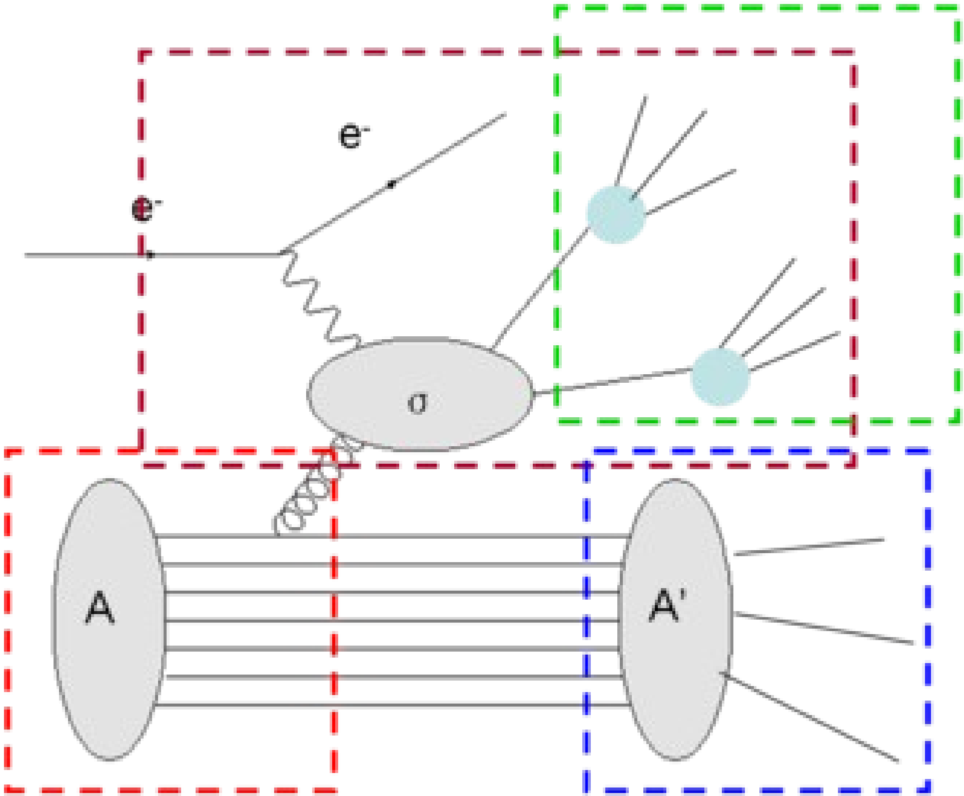
BeAGLE Structure

Elke Aschenauer + Wan Chang + MDB + J.H.Lee +Zhoudunming Tu + Liang Zheng

From: https://wiki.bnl.gov/eic/index.php/BeAGLE



A hybrid model consisting of DPMJet and PYTHIA with nPDF EPS09.

Nuclear geometry by DPMJet and nPDF provided by EPS09.

Parton level interaction and jet fragmentation completed **in Pythia**

Intra Nuclear Cascade & **N. Armesto**
Nuclear evaporation (gamma dexcitation/nuclear fission/fermi break up) treated by DPMJet **(Fluka)**

Energy loss effect from routine by **Accardi, Dupré** Salgado&Wiedemann to simulate the nuclear fragmentation effect in cold nuclear matter **is available.**

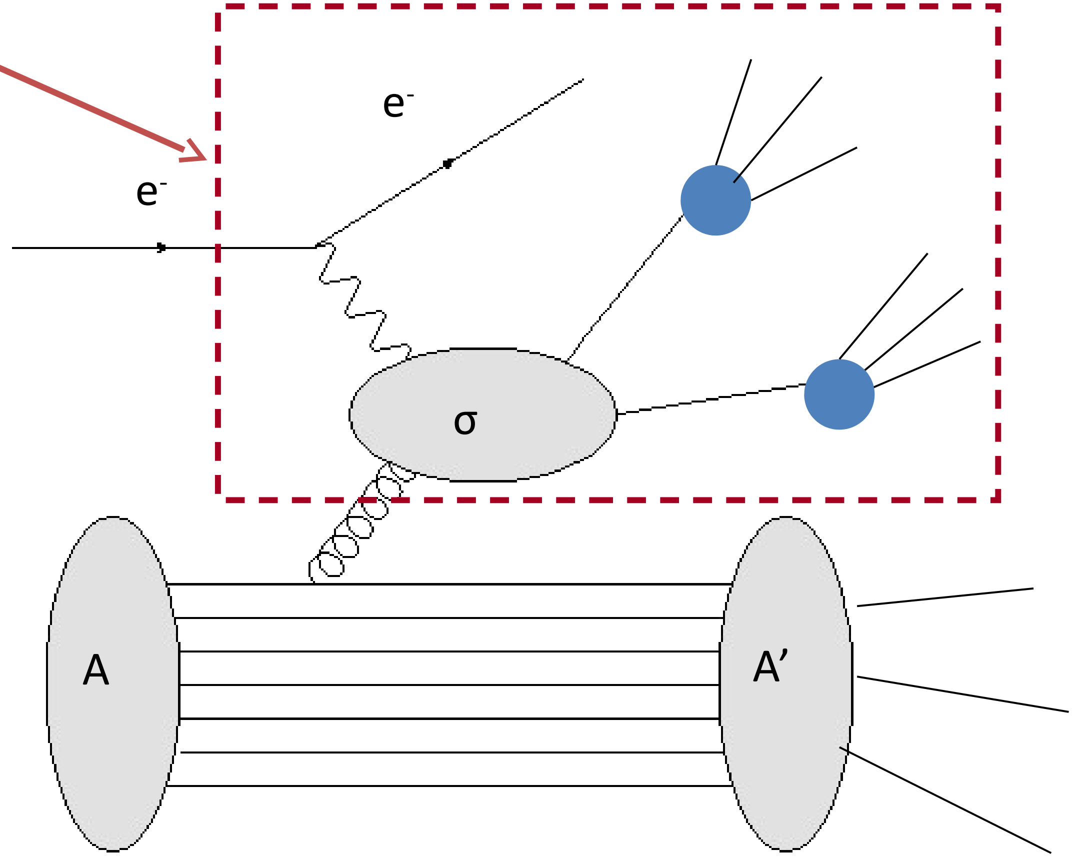
Additional Collaborators/Support

- JLAB (mostly LDRDs) + MIT LNS:
  - A. Accardi, MDB, R. Dupré, M. Erhart, C. Fogler, F. Hauenstein, O. Hen,D. Higinbotham, C. Hyde, V. Morozov, P. Nadel-Turonski, K. Park, B. Schmookler, A. Sy, T. Toll, G. Wei
- Advice from:
  - R.Ent, M. Strickman, T. Ullrich, R. Venugopalan, C. Weiss

BeAGLE: A hybrid model

Hard interaction and jet fragmentation completed in PYTHIA 6.

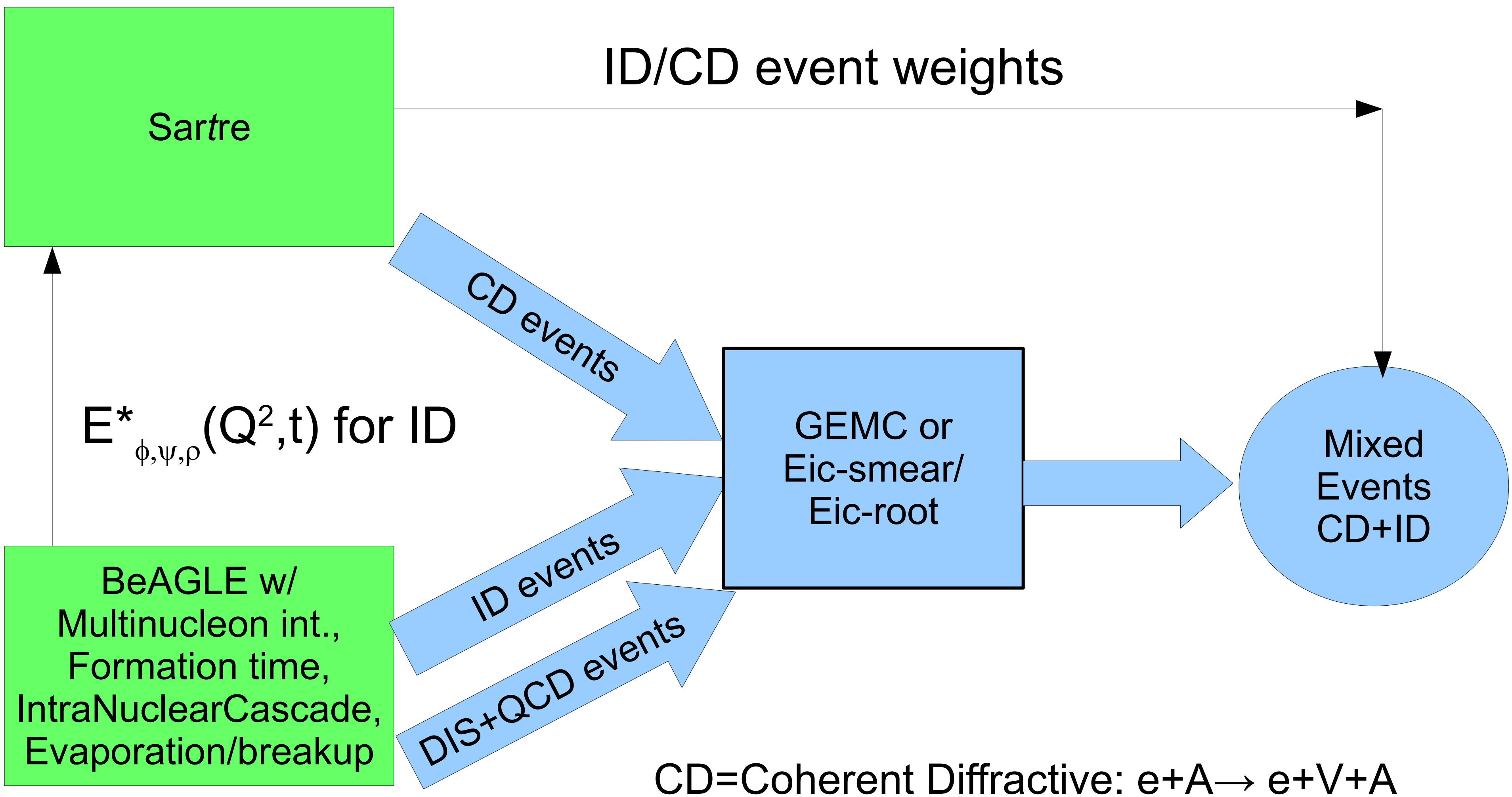
We can substitute a different model for the hard interaction. E.g. GCF!



What can Pythia do?

- Inelastic γ^*p or γ^*n scattering inside of an eA
  - DIS (LO + QCDC + PGF)
  - Resolved photon: $\gamma^* \rightarrow q\bar{q}$
  - GVMD: $\gamma^* \rightarrow V$ followed by elastic/diffractive scatter
    - POTENTIALLY VERY POWERFUL using $V=J/\psi$
- NOT quasielastic eN (w/ SRC)
  - Read in GCF events instead (also GCF-DIS)
- NOT coherent e+A

Event mixing: BeAGLE+Sar*t*re



CD=Coherent Diffractive: e+A→ e+V+A
ID = Incoherent Diffractive e+A→ e+V+X
DIS+QCD = Pythia (LO + QCDC + PGF)

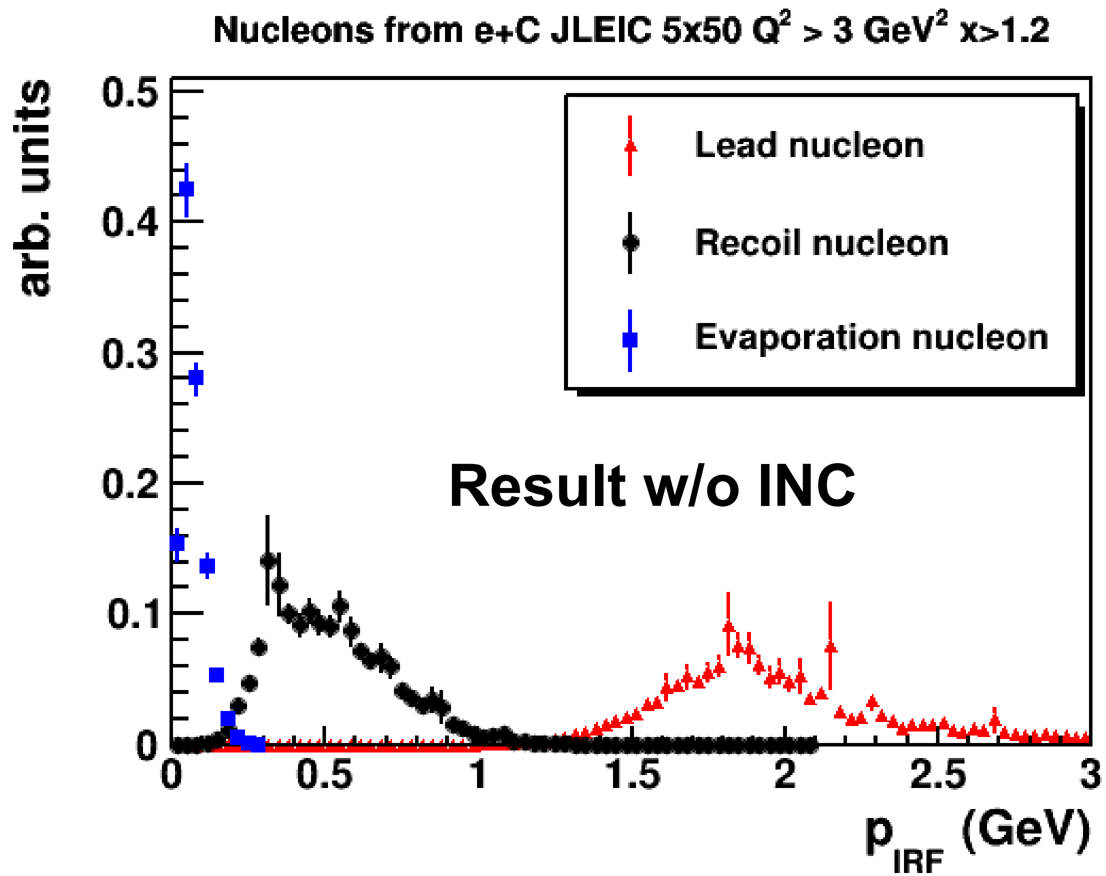
Quasi-elastic with SRCs

e + C 5x50A

$3<Q^2<10 GeV^2$
$x_{Bj}>1.2$

Result is GCF + BeAGLE

Total momentum Ion Rest Frame



Nice result! Evaporation nucleons are easily separated from pair nucleons.

"e"A is not pA!

(FNAL) E665, Z. Phys. C 65, 225 244 (1995)

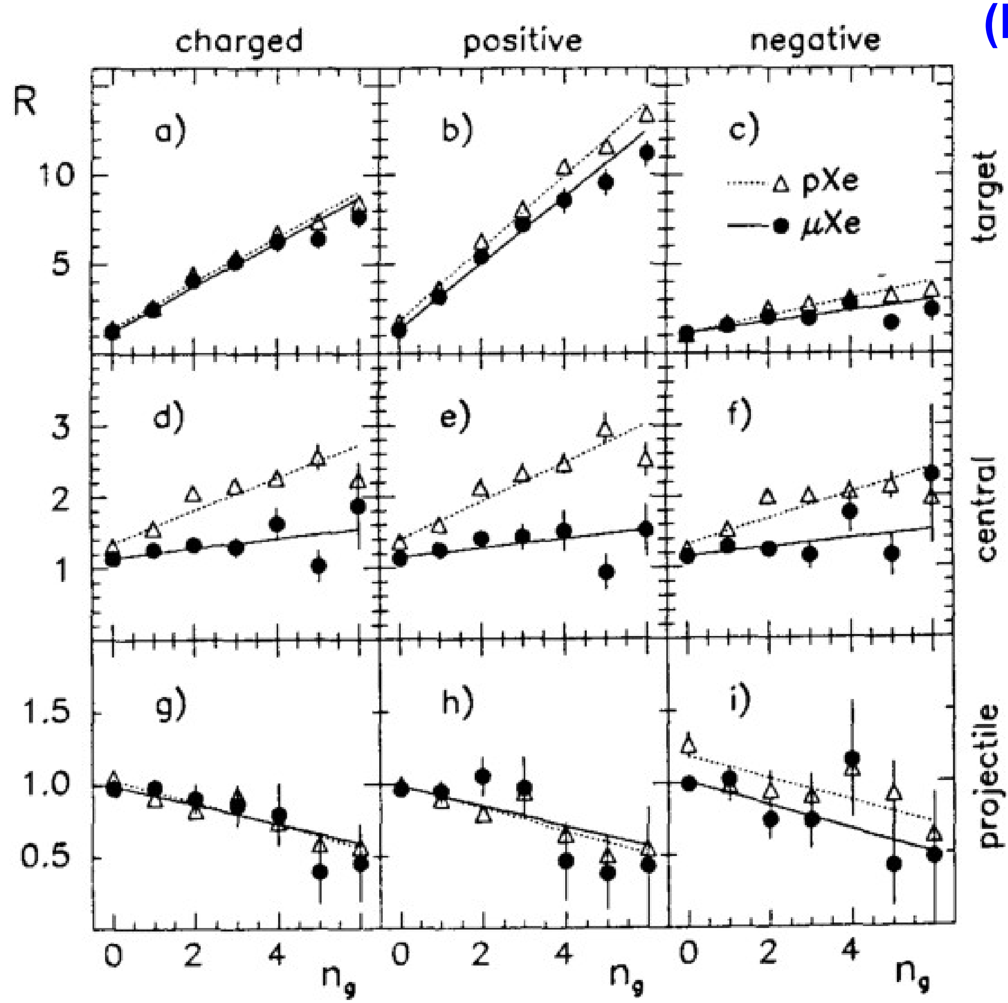


Fig. 10. Multiplicity ratio $R(n_g)_{\mu Xe}$ (full circles) and $R(n_g)_{pXe}$ (open triangles) as a function of the number n_g of grey tracks. The plots are for all charged, for positive and negative hadrons, and for three rapidity intervals (target, central, projectile). The lines are the results of straight-line fits to the data points

Grey tracks in FT are like forward protons @ EIC.

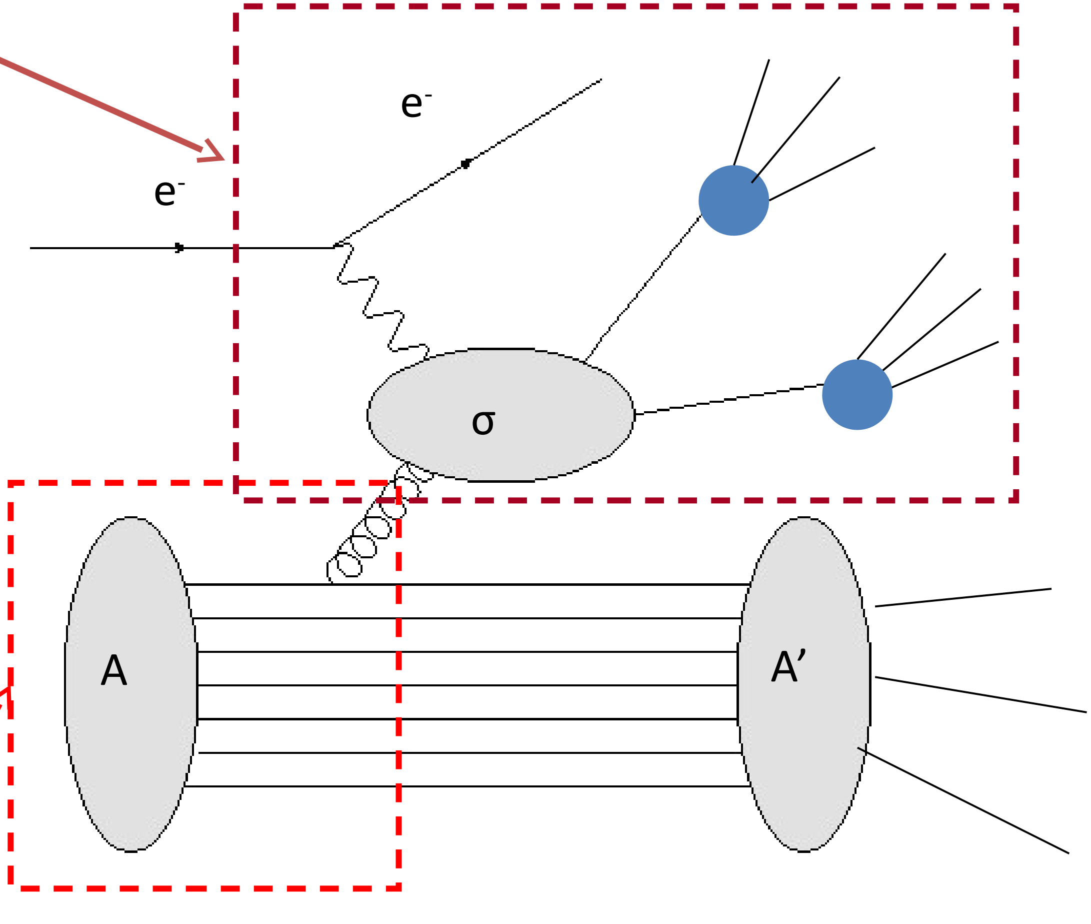
pA collisions (NA5) are much more violent than μA (E665).

To first approximation we can treat μA as hard μN+ nuclear response

BeAGLE: A hybrid model

Hard interaction and jet fragmentation completed in PYTHIA 6.

NOTE: See various talks by Kong concerning improved handling of Deuterons and Fermi momentum in general.



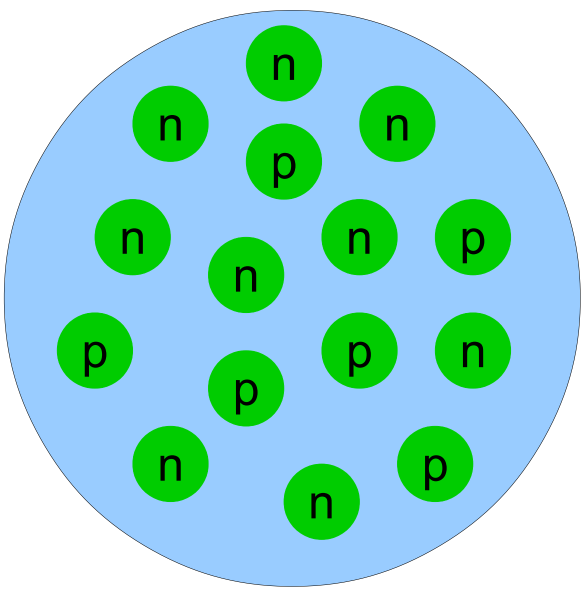
Nuclear geometry by DPMJET.
Nuclear PDF: EPS09LO x CTEQ6L1.
Multi-nucleon shadowing in BeAGLE .

New issue for an eA collider!

What is the momentum of the nucleon in a nucleus in the lab frame?
What is the mass of the proton inside the nucleus? Model dependent.
DPMJET & Pythia assume nucleons on-mass-shell.

Target Rest Frame

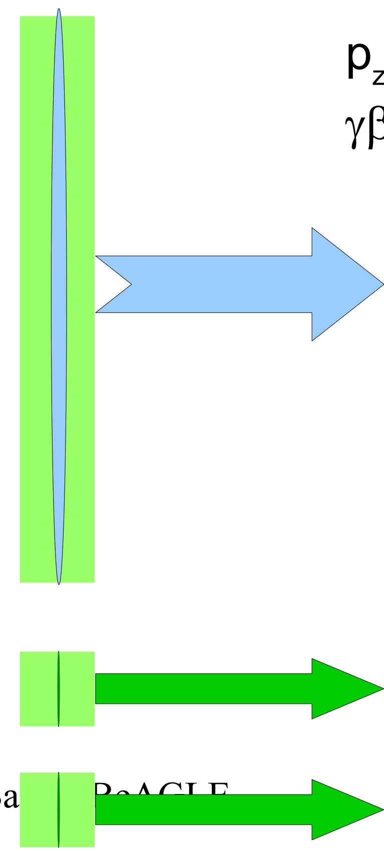
M_{Au}=197 x 0.99961 amu,   1amu=0.931494GeV



M_p=1.0073 amu p

M_n=1.0087 amu n

Collider Laboratory Frame



p_{zAu}=197 x **100 GeV/c**

$\gamma\beta = p_z/M = 107.396$

NOT 100 GeV!

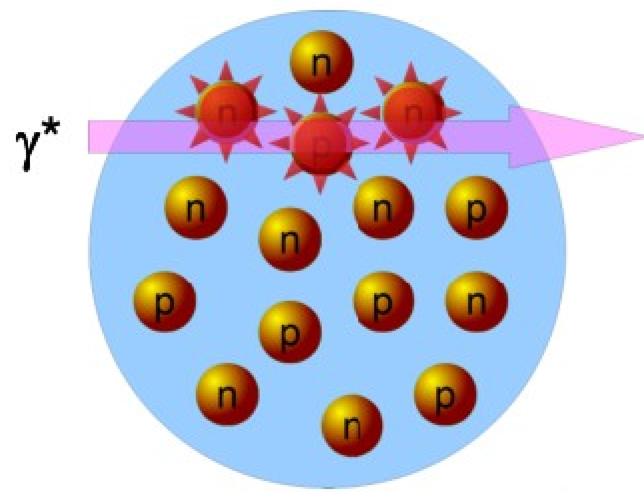
$p_z(p)=\gamma\beta M_p$ = **100.77 GeV/c**

$p_z(n)=\gamma\beta M_p$ = **100.91 GeV/c**

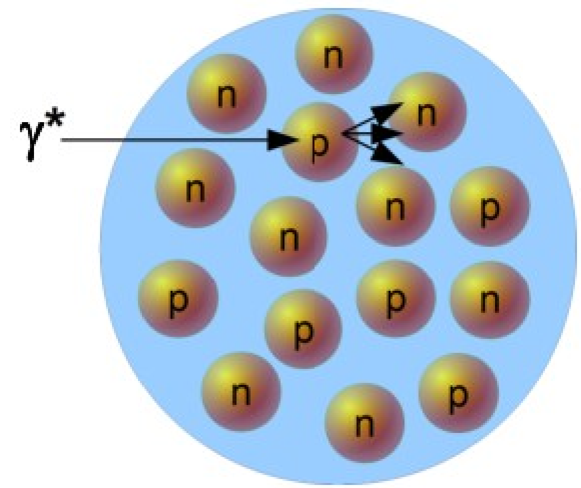
What is "Shadowing"

Shadowing can be defined as:

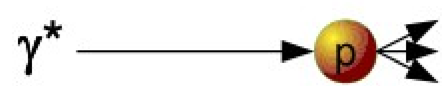
$\sigma(eA) < A\,\sigma(ep)$



It can, in principle be caused by literal shadowing, where the effect is dynamical and involves multiple nucleons...

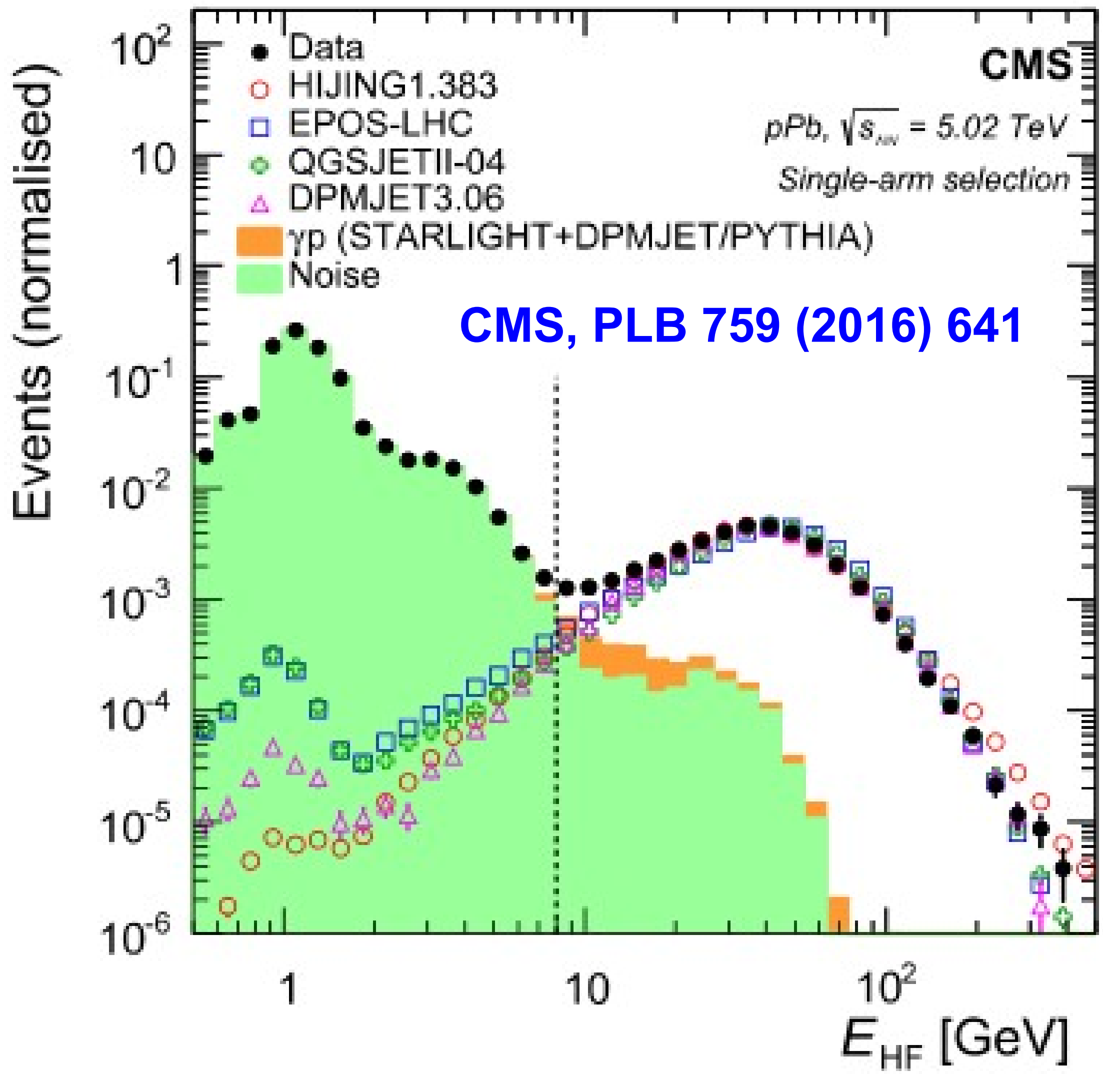


Or by modification of the individual nucleons on a slow timescale, followed by point-like interaction of the probe.



BeAGLE allows both approaches.

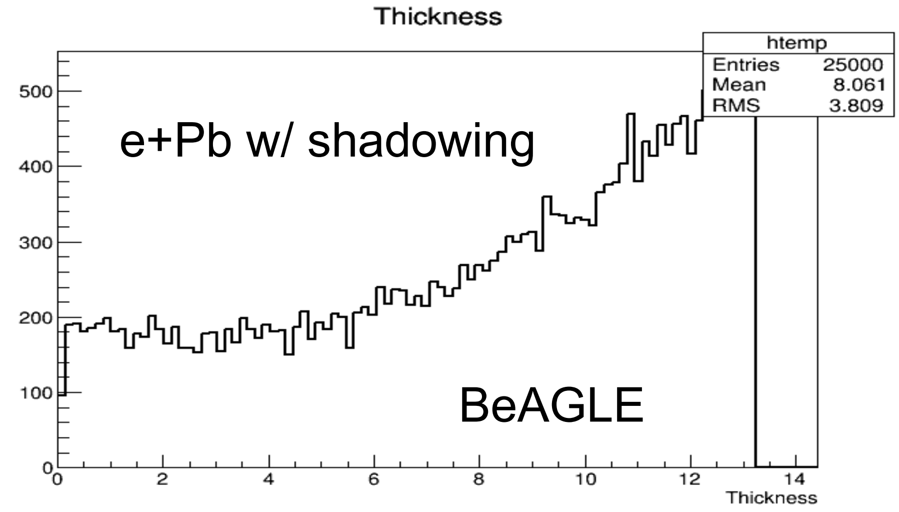
DPMJET still in use!

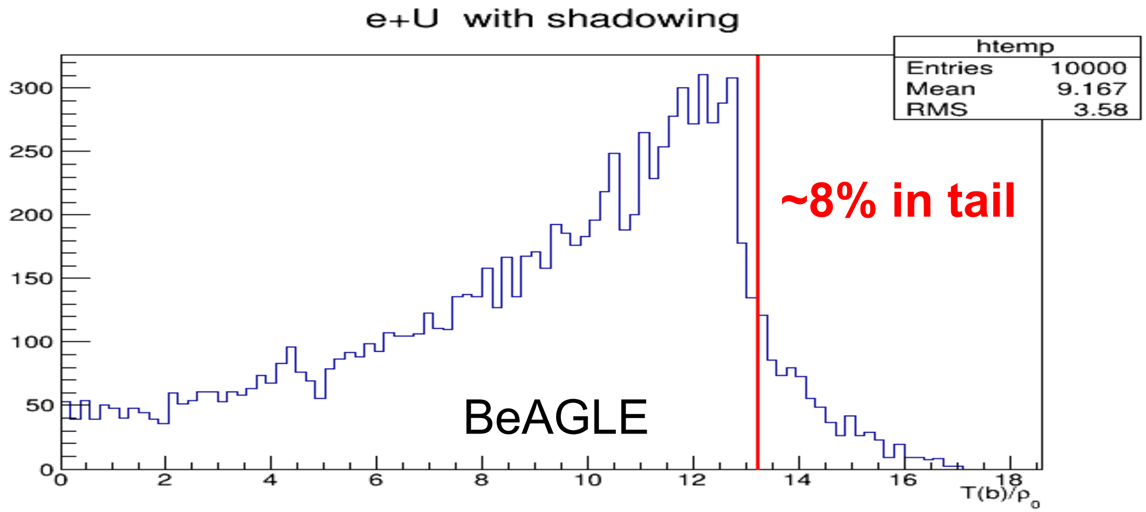


CMS p+Pb forward hadronic calorimeter, $3<\eta<5$

Works better than HIJING!

Effective thickness U vs Pb

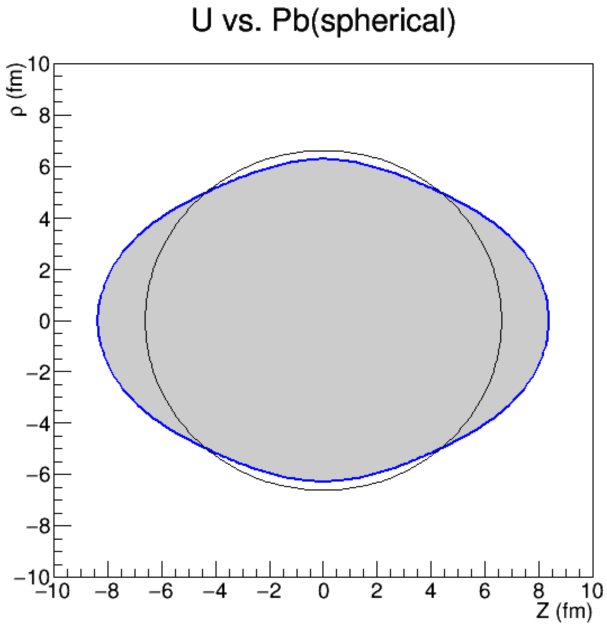




T(b) = thickness in nucleons/fm^2

ρ_0 = Pb density 0.17 nucleons/fm^3

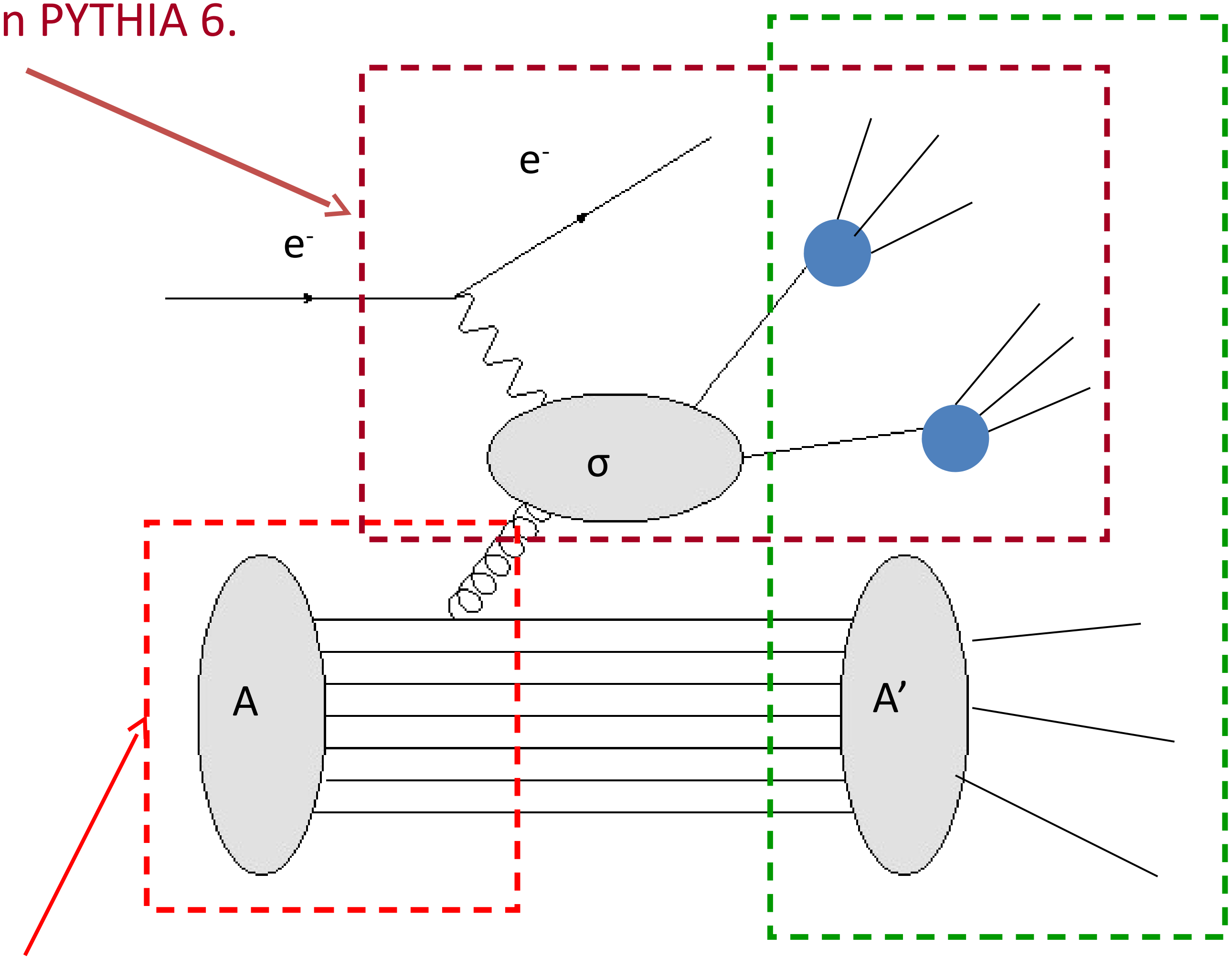
T/ρ_0 is effective-Pb thickness in fm



BeAGLE: A hybrid model

Hard interaction and jet fragmentation completed in PYTHIA 6.

Formation zone
Intranuclear cascade handled in DPMJet.



Key parameter: τ_0

Nuclear geometry by DPMJET.
Nuclear PDF: EPS09.
Multi-nucleon shadowing in BeAGLE .

Fast hadrons ignore the nucleus

E665, PRD 50 (1994) 1836 **All are ν >100 GeV, y<0.75**

$x<0.005$, $Q^2<1.0$ GeV^2 **$x>0.03$, $Q^2>2.0$ GeV^2**

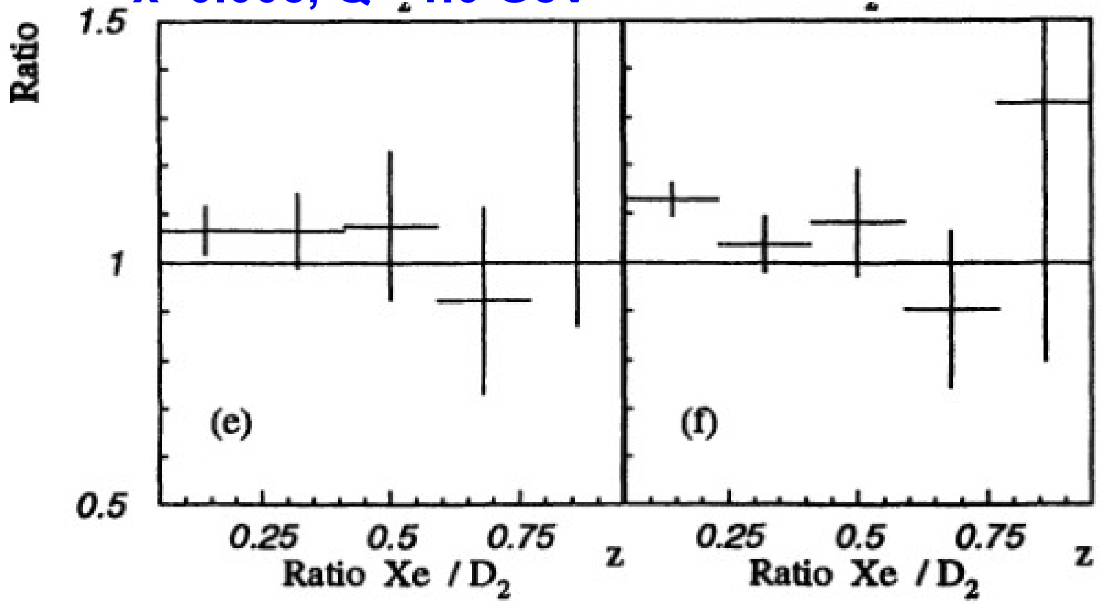


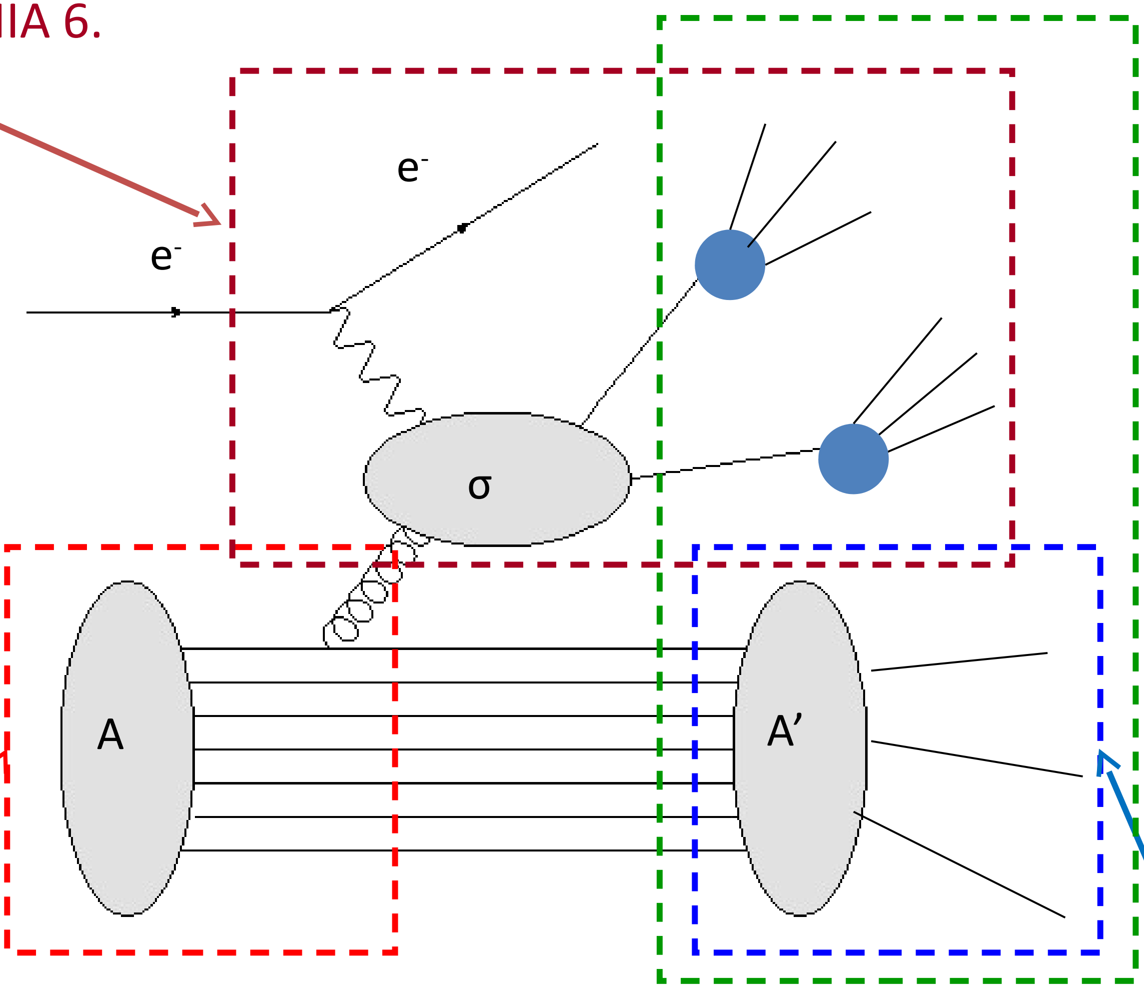
FIG. 7. z distributions: Xe and D_2. These plots show the z distributions from xenon and deuterium and the ratios of the distributions. The distributions on the left are from events in the low kinematic region: Kin_1, while those on the right are from events in the high kinematic region: Kin_2. The data have been corrected for acceptance but not for target length effects; they are tabulated in Tables XIX and XXX.

$z=E_h/\nu$ in TRF

BeAGLE: A hybrid model

Hard interaction and jet fragmentation completed in PYTHIA 6.

Formation zone
Intranuclear cascade
handled in DPMJet.

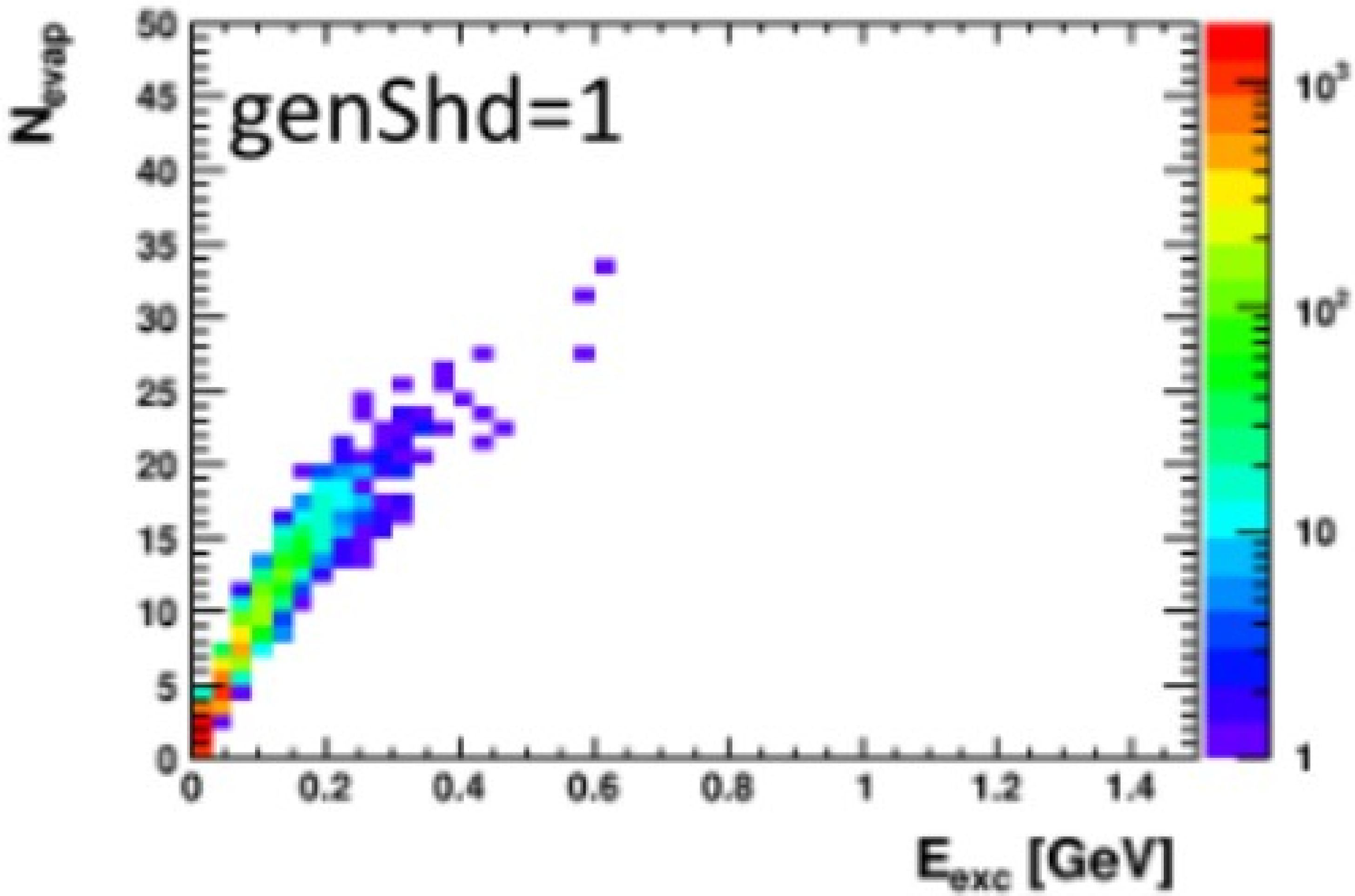


Nuclear geometry by DPMJET.
Nuclear PDF: EPS09.
Multi-nucleon shadowing in BeAGLE .

Nuclear response (evaporation, γ de-excitation, fission, breakup) treated by DPMJet/Fluka

Evaporation is driven by E_{exc}

BeAGLE (DPMJET)

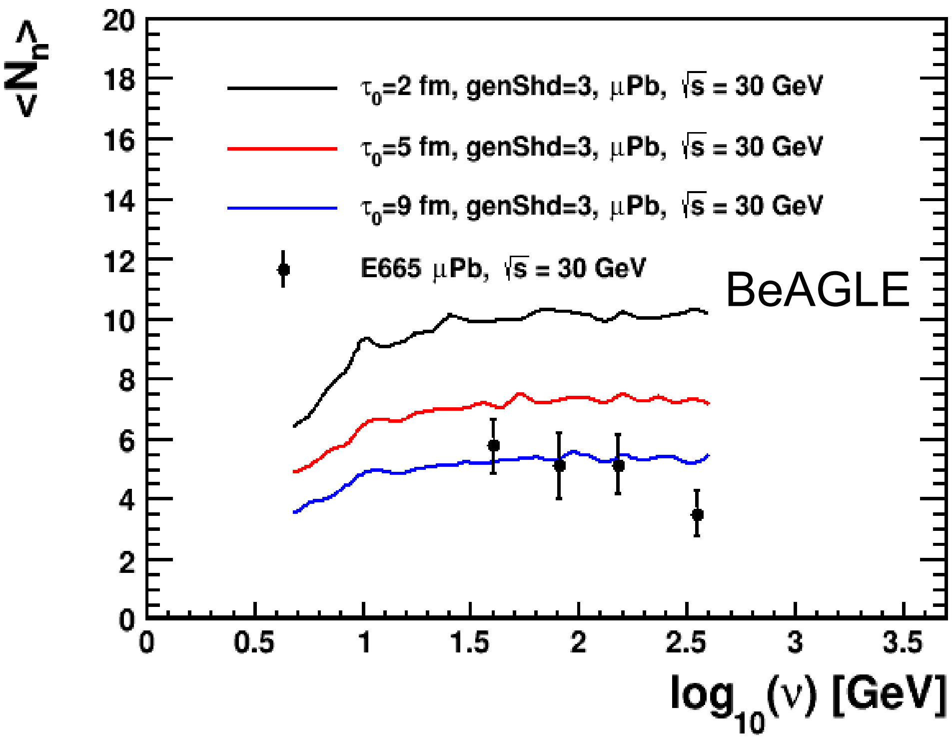


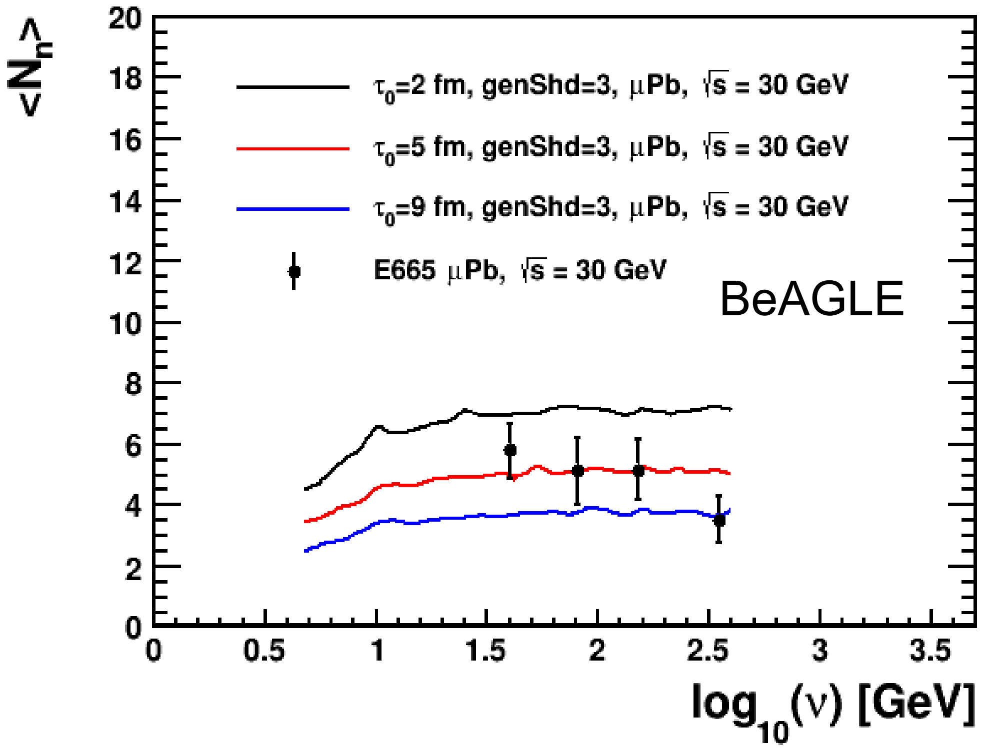
Tune to E665 neutron data

μ+Pb→n+X **DIS + diffractive** data: E665, PRL 74 (1995) 5198

E665 estimates coherent diffraction/total of 13% in μXe: ZPC 65 (1995) 225

μPb should be 15-30% CD/total.





0% CD/total
ePb prefers τ_0= 9fm.

30% CD/total
ePb prefers τ_0= 5 fm

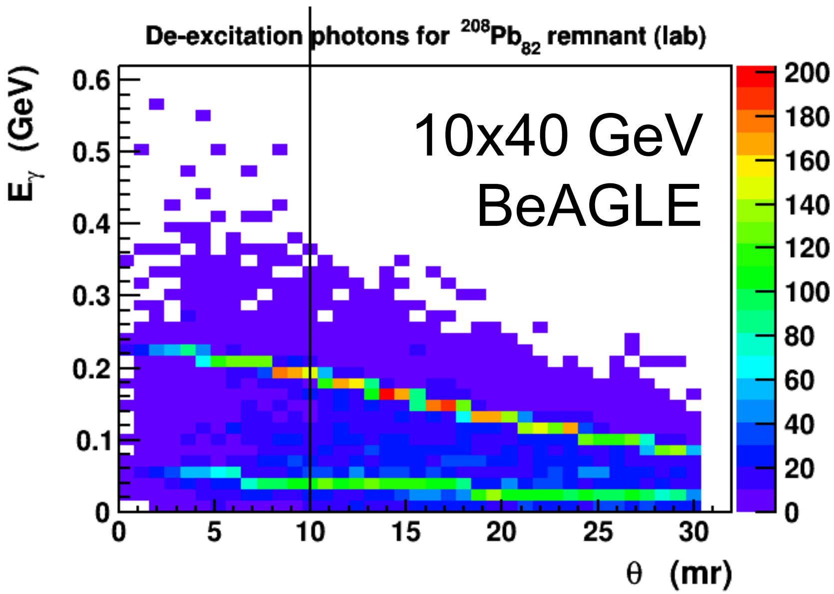
Final State Effects

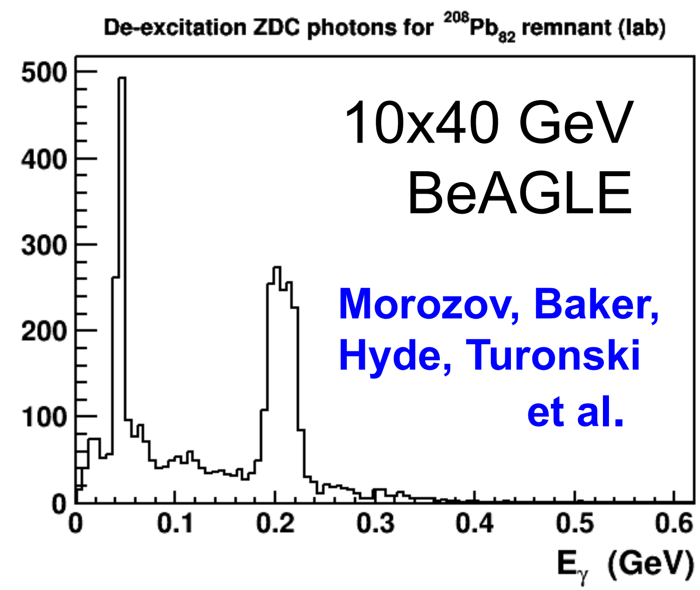
- These are semi-classical – not quantum interference.
- The nuclear remnant is on mass-shell nucleons sitting in a mean field. Not a shell-model etc.
- Formation time followed by possible low energy hadronic scattering (DPMJET)
- Excited nucleus decaying (FLUKA in DPMJET)

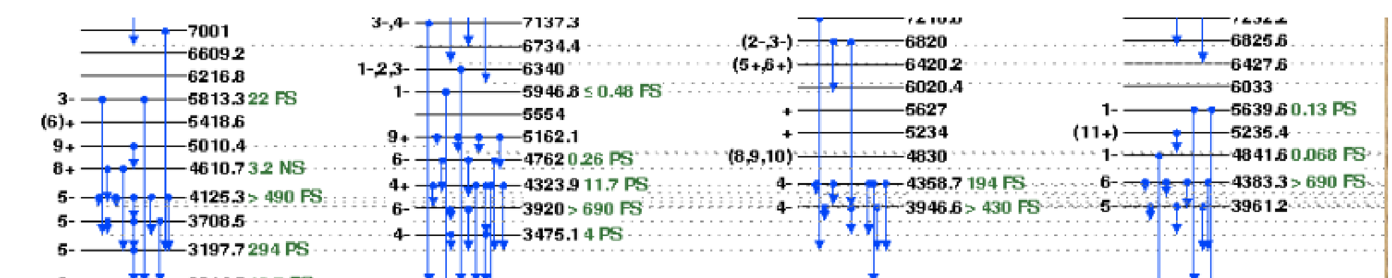
Simulation challenge in e+A: nuclear detail

One example: de-excitation photons from $^{208}Pb_{82}$ following

$e+Pb \rightarrow e'+Pb^{*}+J/\psi \rightarrow e'+Pb+\gamma+\gamma+\gamma+J/\psi$ in (collider) lab frame

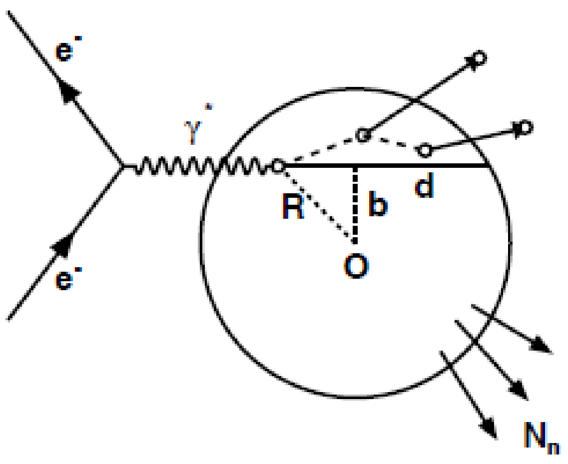






BeAGLE (FLUKA) does not know all of these, but it uses the important ones!

Key Features of BeAGLE



Multistep process.

Hard interaction (DIS or diffractive) involving one or more nucleons.

Intra Nuclear Cascade w/ Formation Zone

Excited nuclear remnant will decay:
Fission &/or evaporation of nucleons
De-excitation by gamma emission.

Good model of both hard process AND nuclear interaction.

Improvements from white paper diffraction studies:

More correct (lower) value of $\langle E_{exc} \rangle$

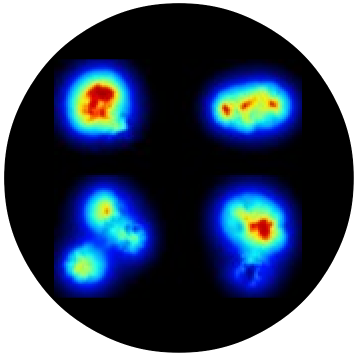
Added b-dependence of E_{exc}, increasing fluctuations.

Larger $P(N_{n\text{-}evap}=0)$.

REPEAT OF 6 SLIDES FROM MDB 07-DEC-2017

- Spatial imaging of gluons in the nucleus:
  - Exclusive Coherent Vector Meson Production
    - $e+A \rightarrow e+V+A$ where $V=J/\psi$ or ϕ (or ρ or ω)
  - Exclusive Incoherent VM Production
    - $e+A \rightarrow e+V+X$
- The "Lore" is Backwards!
  - Evaporation neutrons (ZDC) are NOT enough to tag coherent vs. incoherent diffraction.
  - Evaporation neutrons CAN tag collision geometry for incoherent diffraction.

Incoherent diffraction as physics

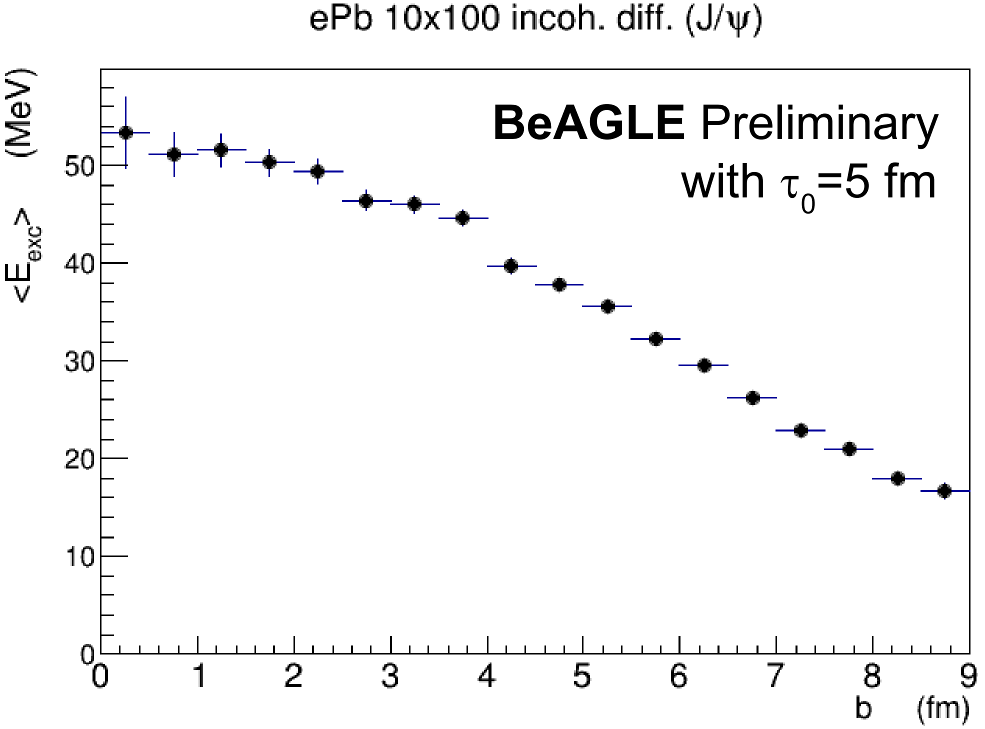


- Sensitive to shape fluctuations
  - We already see "hot spots" in the proton
  - Are these the same inside a nucleus?
- Geometry tagging of incoherent events?
  - Are nucleon shapes in the middle of the nucleus different than those at the edges?
  - Concern: Maybe it can't be done with evaporation neutrons becuase the excited nucleus "forgets" its history by the time it evaporates.

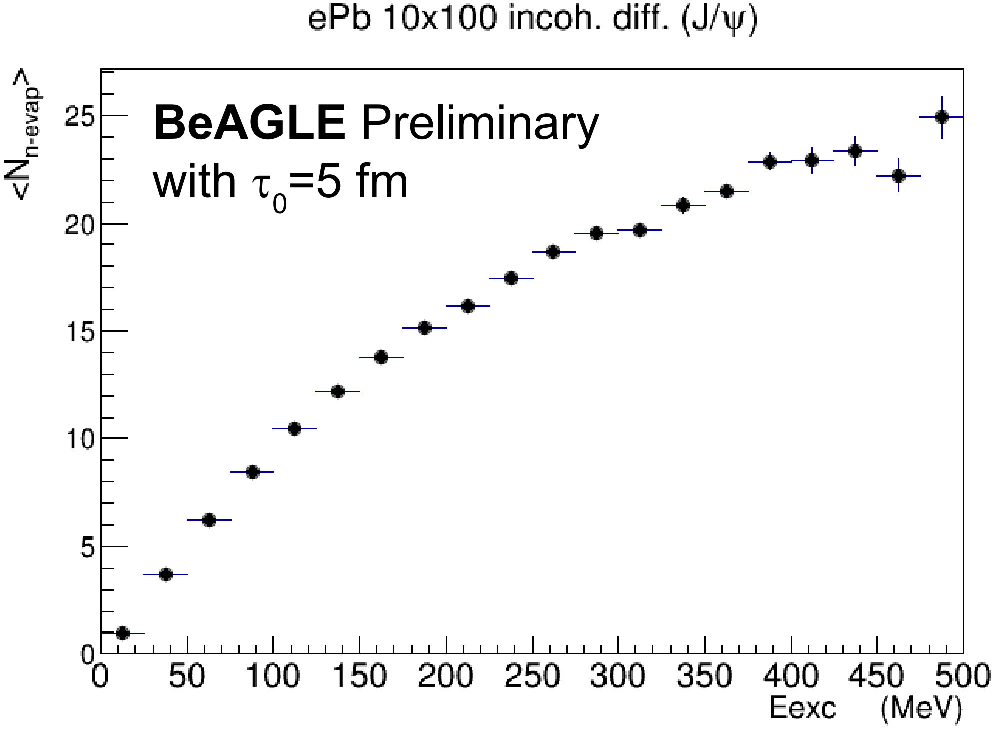
* - Example theoretical proton fluctuation configuration tuned to match ep incoherent diffractive data - from B. Schenke

The nucleus remembers!

Energy conservation!

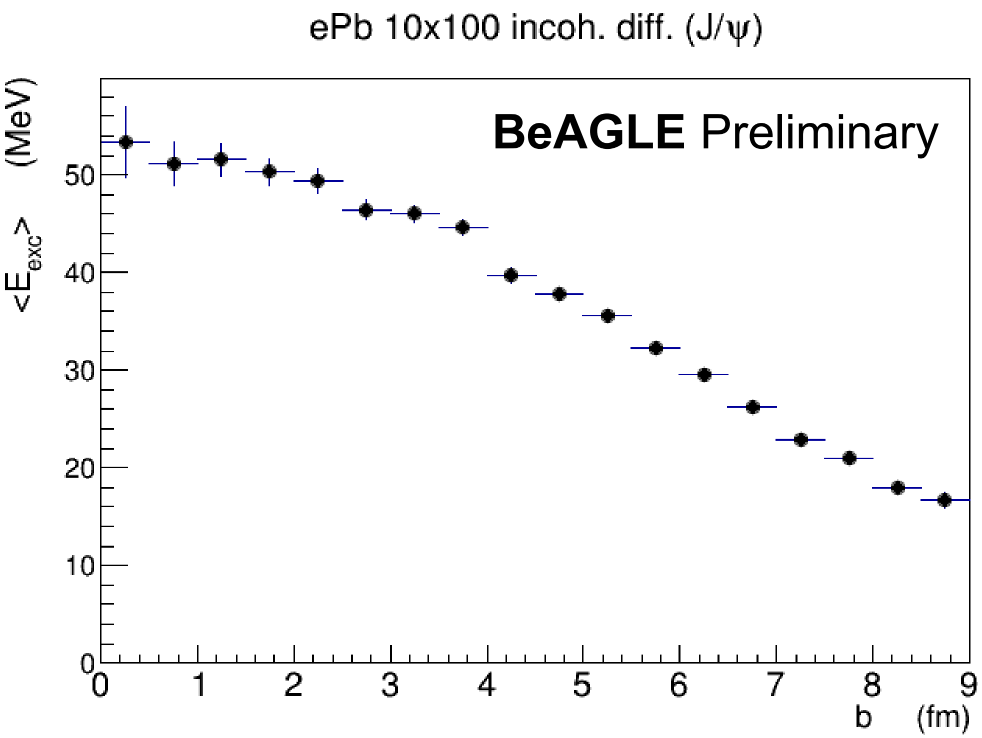


Central diffractive events excite the nucleus more than peripheral.

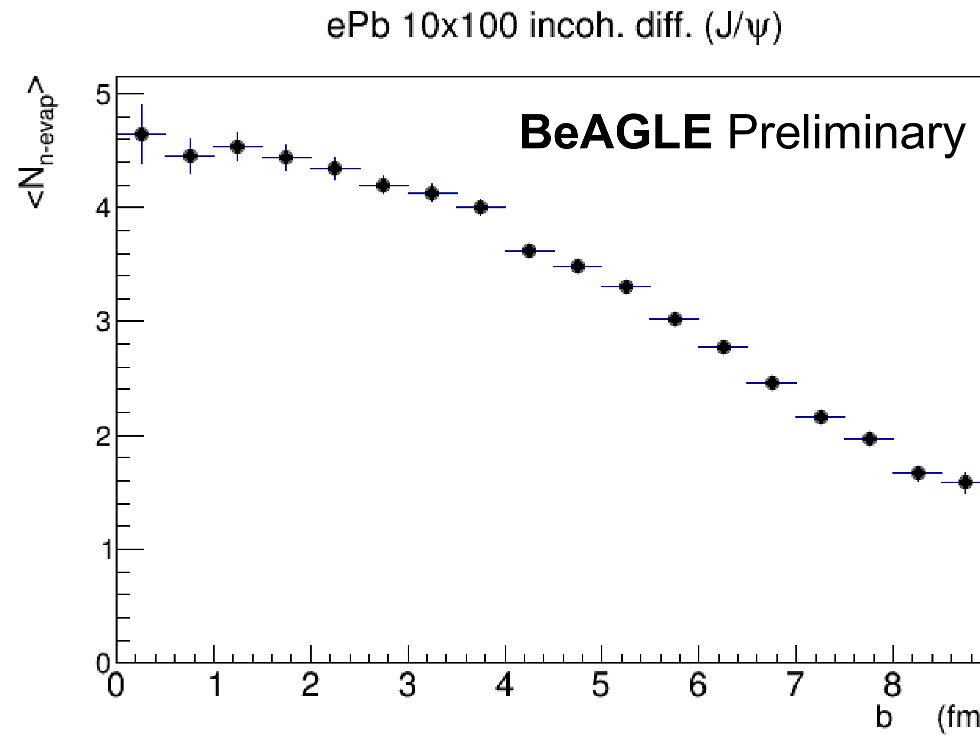


The hotter (more excited) remnant nuclei emit more evaporation neutrons – which we can detect!

ZDC & impact parameter correlated

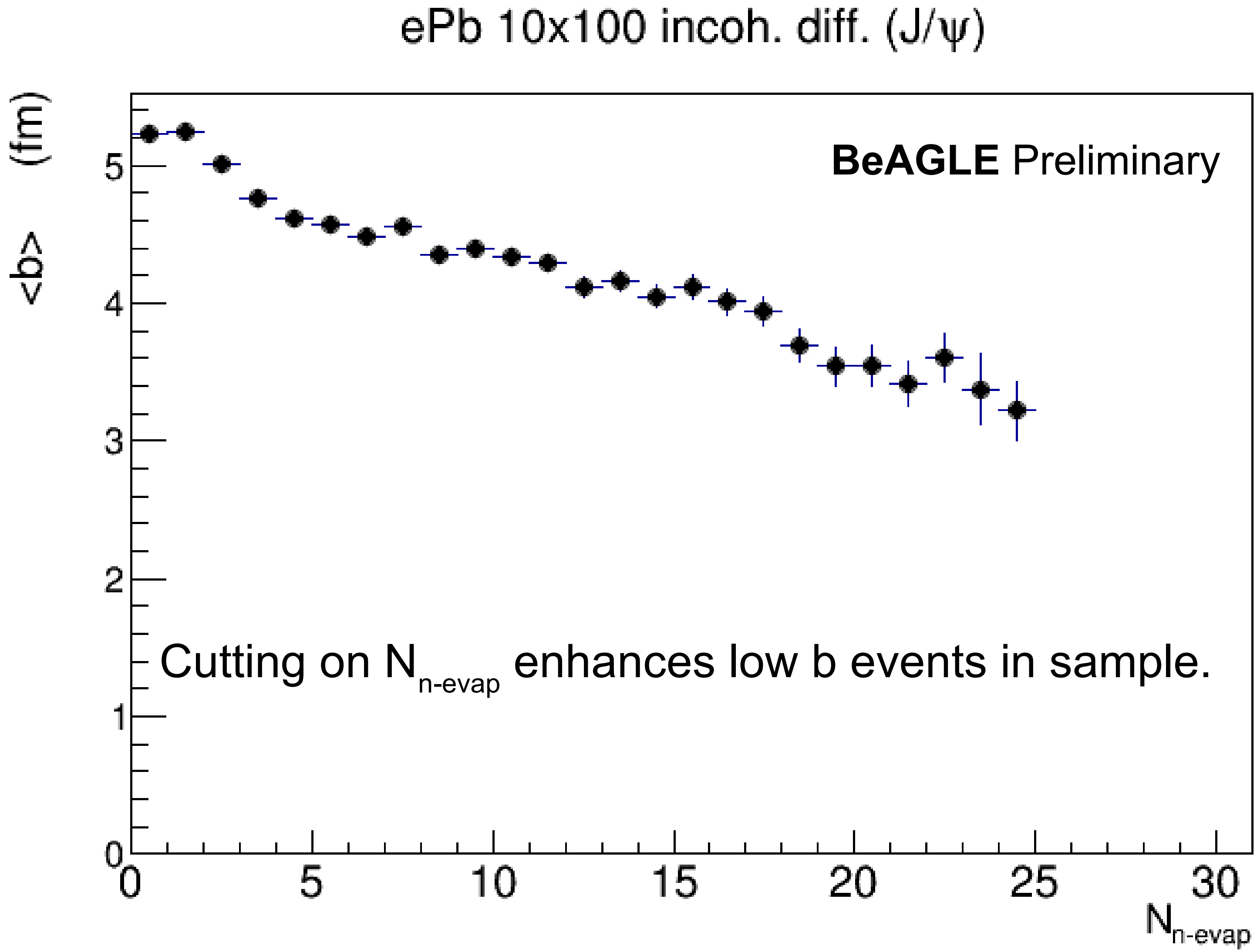


Central diffractive events excite the nucleus more than peripheral.

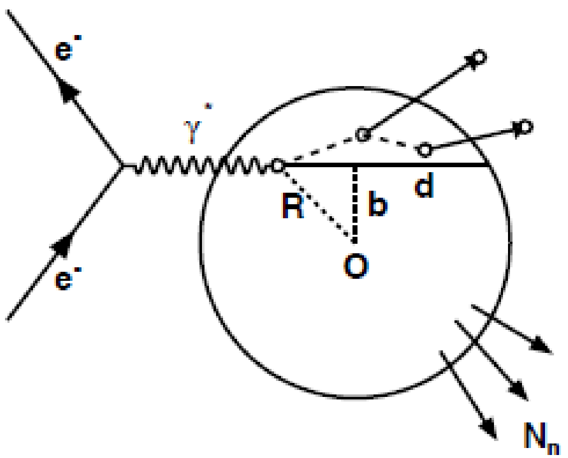


The hotter (more excited) remnant nuclei emit more evaporation neutrons – which we can detect!

ZDC can tag impact parameter!



A paradox ?



Incoherent diffraction:

How can the ZDC do:

a GOOD job at geometry tagging

but a BAD job at vetoing?

The # of evaporation neutrons is much smaller (on average) for peripheral than central events.

So we can tell them apart.

But some peripheral events slip by w/ $N_{nevap}=0$!

Outlook

- BeAGLE is a reasonable starting place for our simulations.
- Lots of work ongoing
  - Fixing known bugs (p^{μ} conservation, ^{3}He issue)
  - Major effort underway (Aschenauer et al.) to further tune BeAGLE to E665 Streamer Chamber data.
  - GCF(QE) + BeAGLE nearly ready (including INC)
  - GCF (DIS) + BeAGLE is on the horizon
  - BeAGLE/RAPGAP (instead of Pythia) partly implemented.

eA: Basic Quantum Mechanics

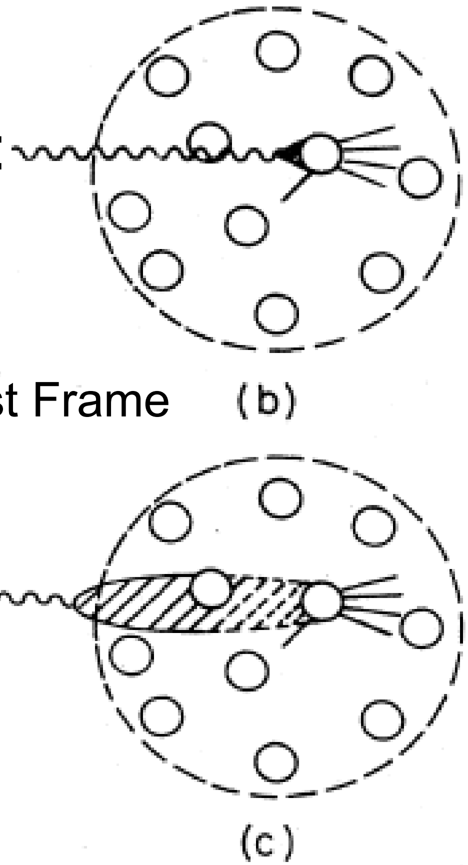
$\hbar = c = 1$ $r = 0.88$ fm $1/(2Mr) = 0.12$ $\Delta p_z \Delta z = 1/2$

Bauer, Spital, Yennie, Pipkin
Rev. Mod. Phys. 50 (1978) 261

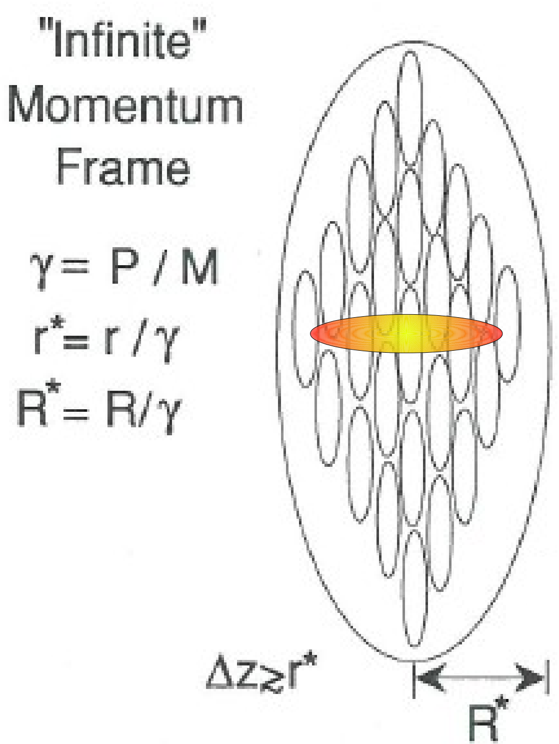
High x_{Bj}:

Nucleus Rest Frame

Low x_{Bj}:



$\lambda_h/r \approx 1/(2Mxr) = 0.12/x_{Bj}$



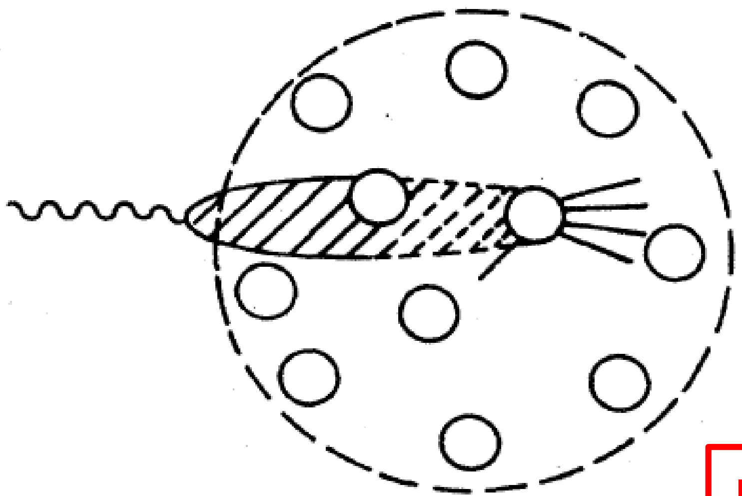
$p_z^{quark} = Mx\gamma$

$\Delta z = 1/(2Mx\gamma)$

$\Delta z/r^* = 1/(2Mxr)$
$= 0.12/x_{Bj}$

For $x_{Bj} << 0.12$, parton wavefunctions and/or interaction cannot be localized.

What's new about BeAGLE? Multinucleon shadowing


(c)

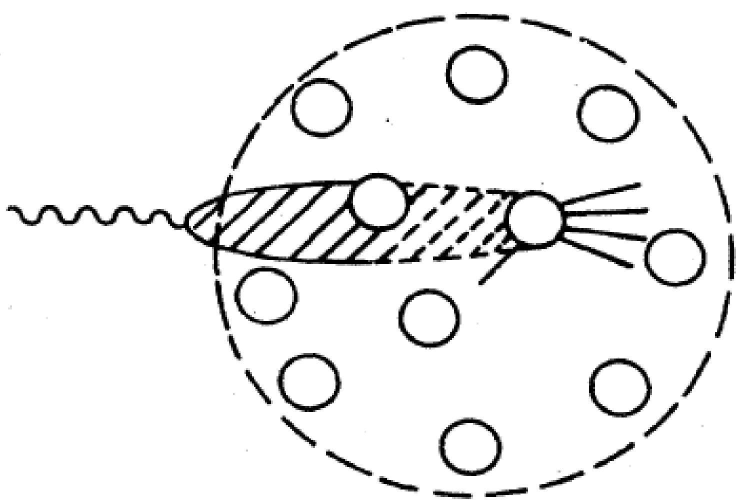
Targ. RF picture of the γ^*:

- Sometimes point-like with $\sigma\sim0$
- Sometimes hadronic ("dipole") $\sigma\sim$few mb
- Time fraction such that total σ_{ep} correct
- Coherence length of "dipole" is $\lambda\sim1/(2Mx)$

Not just DPMJet + Pythia

Do NOT model shadowing / saturation in detail to find $\sigma_{dipole}(x,Q^2)$! Rather, use an input value of nuclear shadowing $R^{Au}(x,Q^2)$ to find $\sigma_{dipole}(x,Q^2)$. Then model probability of multiple nucleon DIS.

Quantum collisions still shadow



(c)

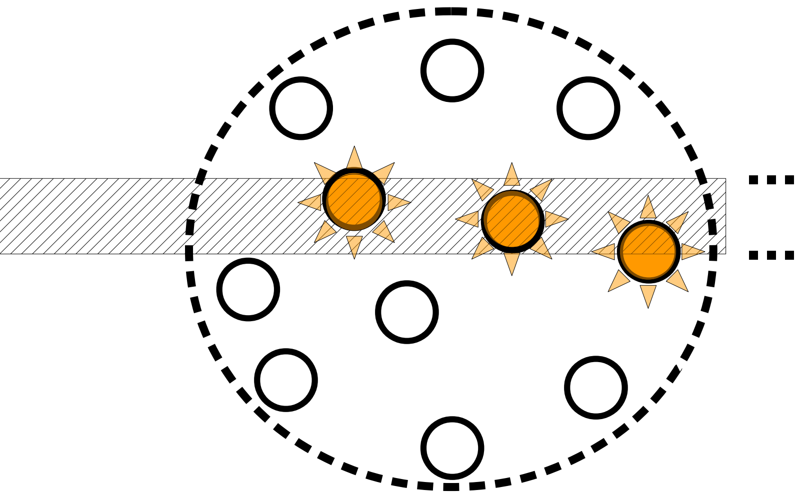
The virtual photon spends part of it's time as a hadronic state ("dipole") with a coherence length of $\lambda \sim 1/(2Mx)$.

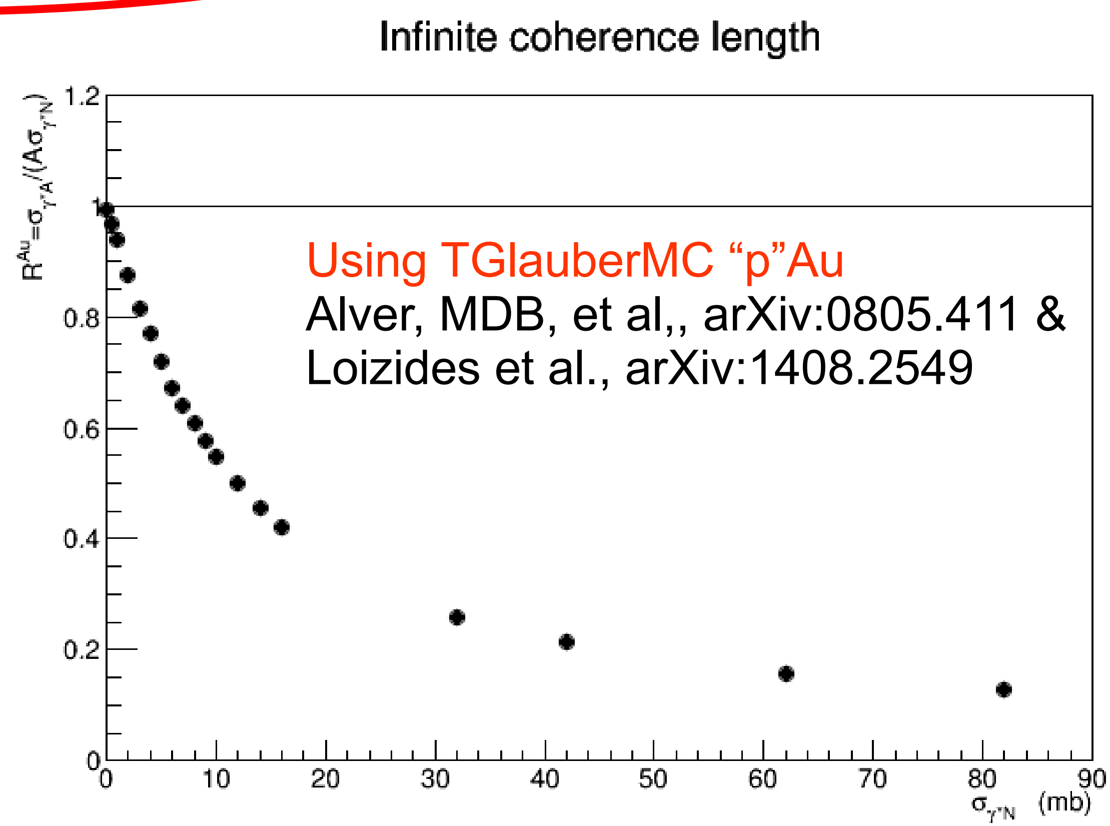
So at low x it can hit BOTH the front and the back ("shadowed") nucleon. But the number of events is still reduced compared to the case of A nucleons "side-by-side"!

Making the map for λ>>R

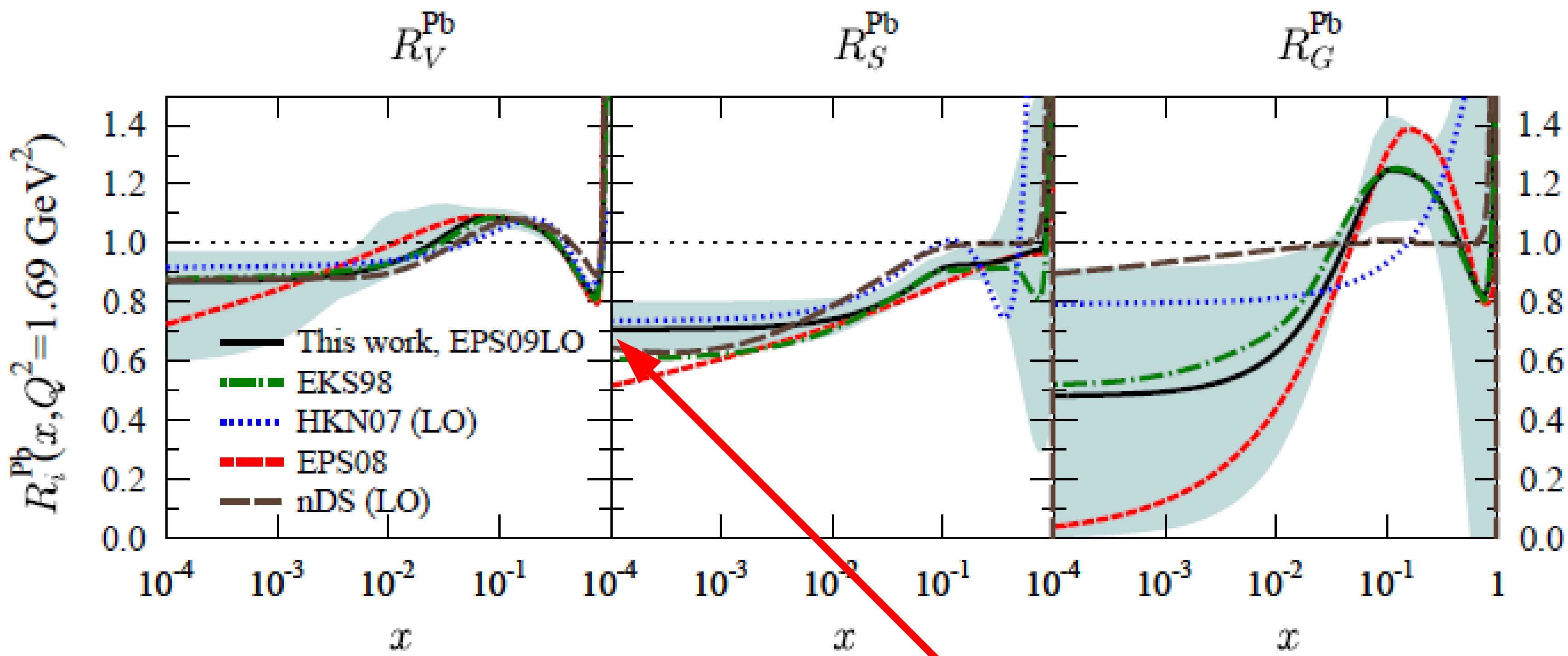
Most of the complications in saturation theory are in predicting the dependence on x, Q^2. With Glauber, we can make a simple map:

$$\sigma^A/\sigma^N(x,Q^2) \longleftrightarrow \sigma_{\text{“dipole”}}(x,Q^2) \longleftrightarrow P(N_{coll},b)$$





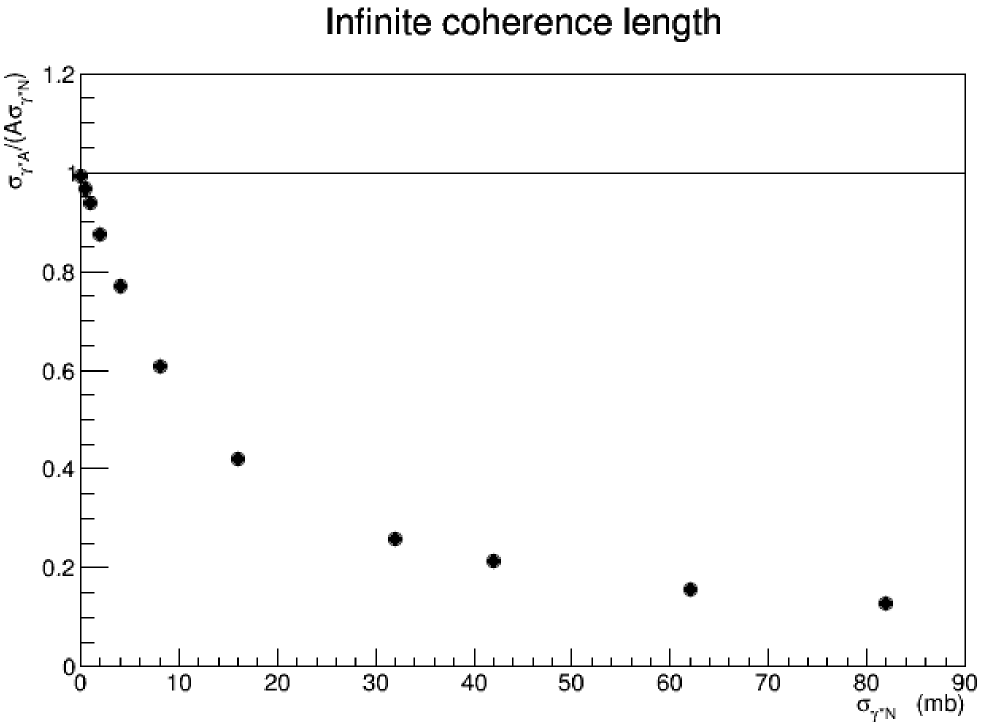
Simplified R using $F_2^{EPS09LO}(x,Q^2)$



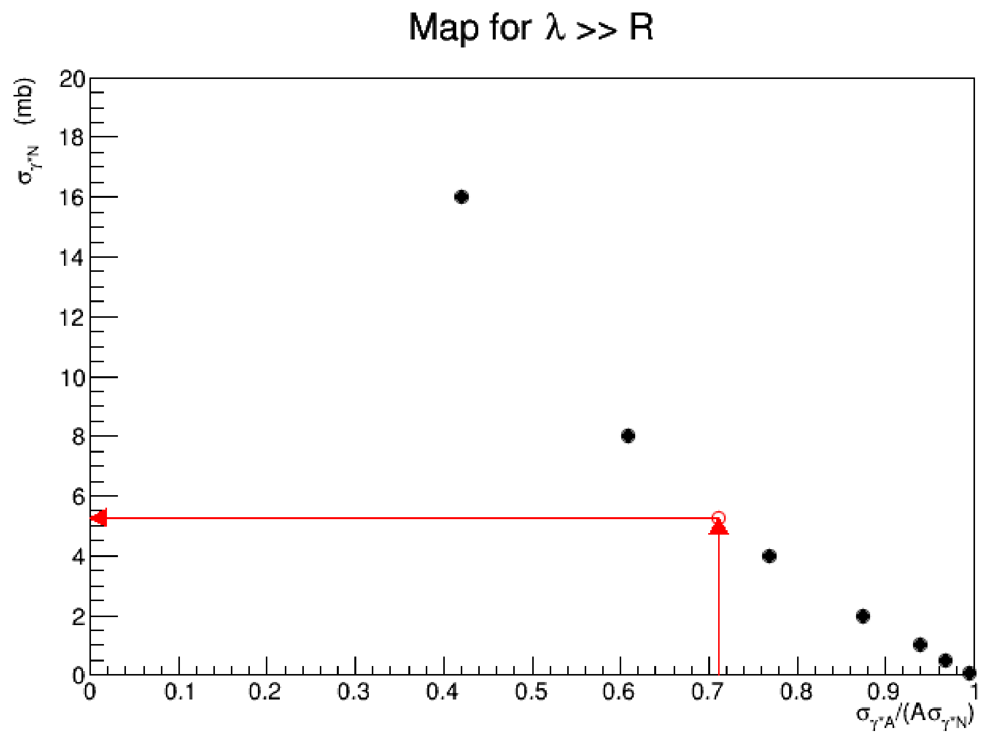
$R(x \to 0, Q^2=1.69\mathrm{GeV}^2) \equiv y_0(A) = 0.890\ (A/12)^{-0.0803} = 0.711$ for Au

0.708 for Pb

Looking up the appropriate $\sigma_{\gamma^*N}(x,Q^2)$



Flip axes to make map.



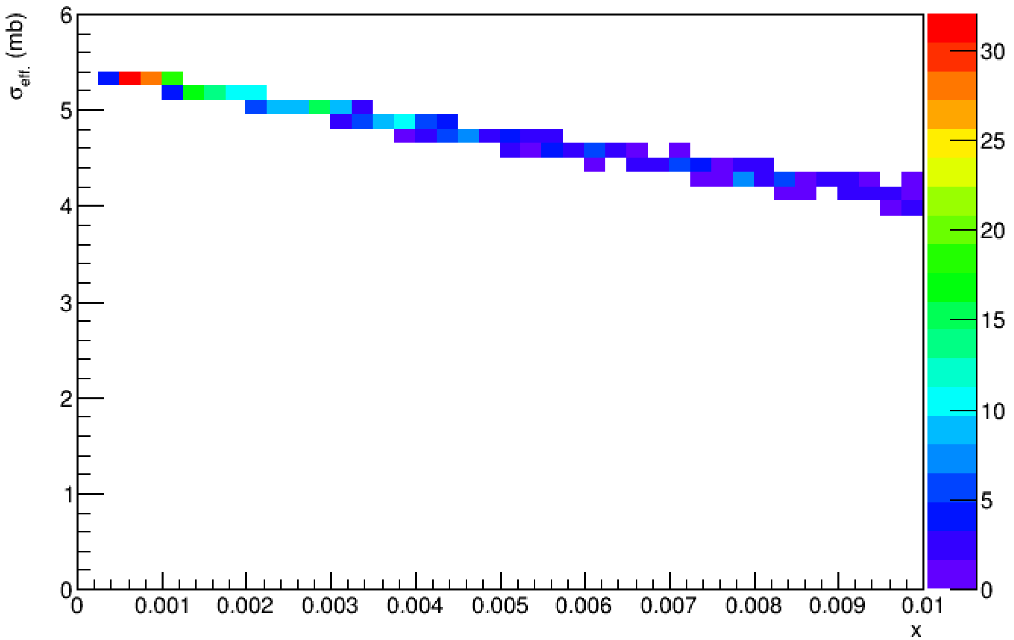
Event-by-event, given, x,Q^2:

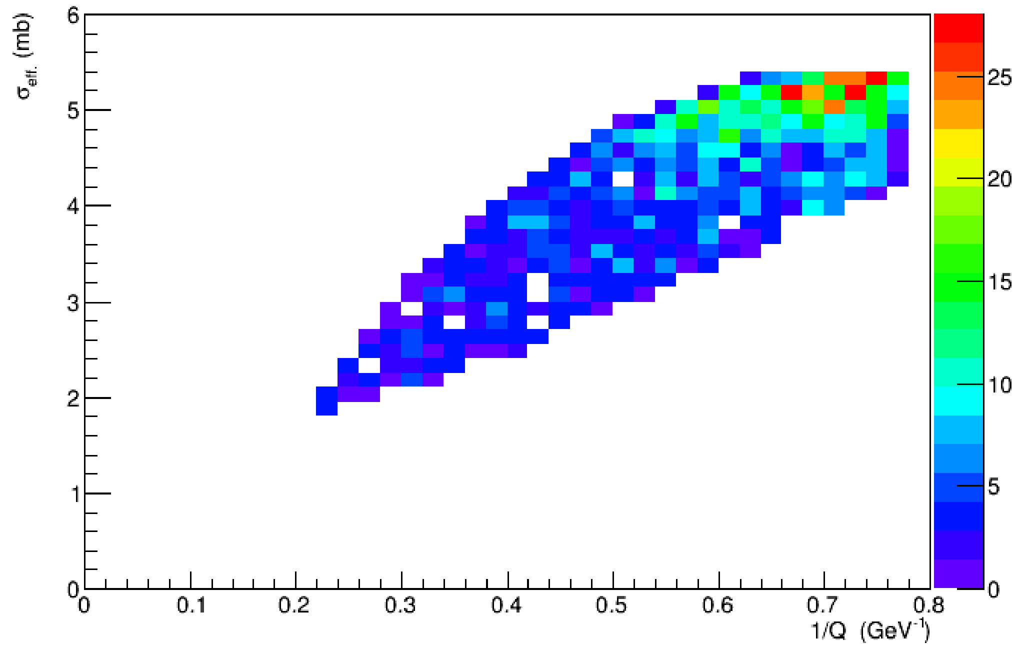
E.g. for $x=0.001$, $Q^2=1.69$ GeV^2

$R^{(Au/N)}(x\rightarrow 0, Q^2=1.69\text{GeV}^2) = 0.711$

$\sigma_{dipole} = 5.26$ mb

Effective σ_{dip} from $R_{(A)}^{(EPS09LO)}(x,Q^2)$





Effective σ:

Includes possible effects of λ/R<∞

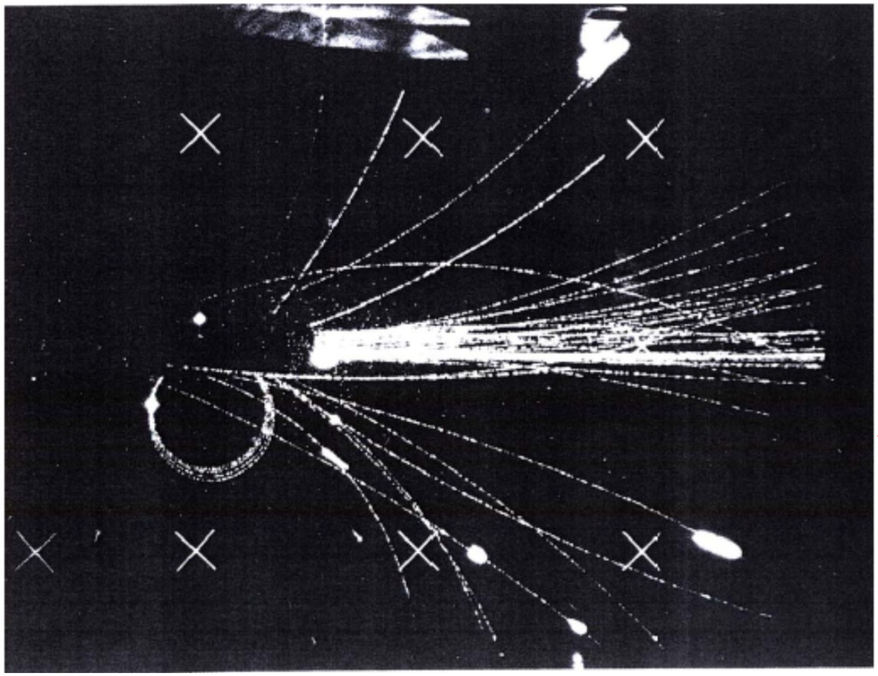
Weak function of x for x<0.01

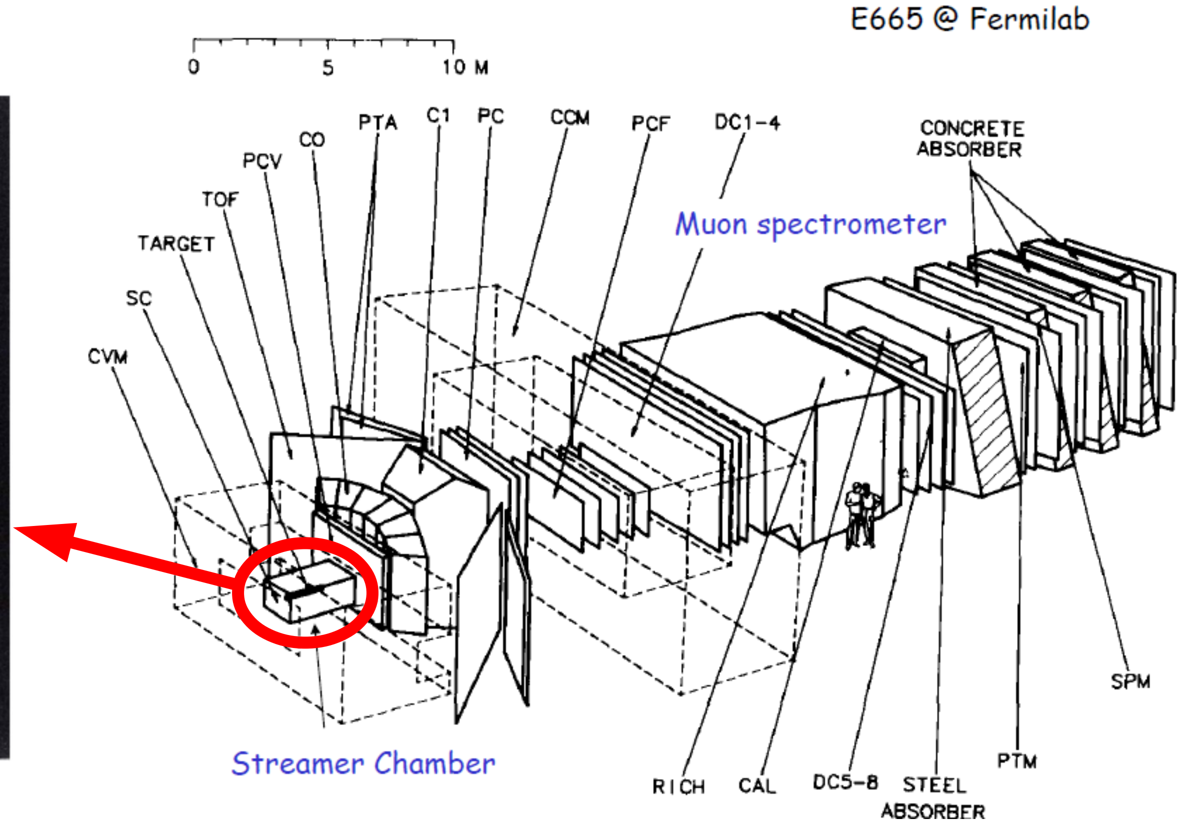
Effective $\sigma \sim 1/Q$ rather than $1/Q^2$

Note: EPS09LO only valid for Q>1.3 GeV

FNAL E665: 490GeV μ+A FixedTgt

Streamer chamber in FT ideal for this.





- Streamer chamber
  - Blind to large slow remnants (absorbed in target)
  - Sees charged produced particles, evaporated particles, Intranuclear Cascade
  - Slow tracks $0.3<\beta<0.7$ are grey (evaporation, INC)
  - Data taking rate 1.5 Hz

NA5@CERN: p+Xe 200GeV FixTgt

C. DeMarzo et al. PRD 26 (1982) 1019

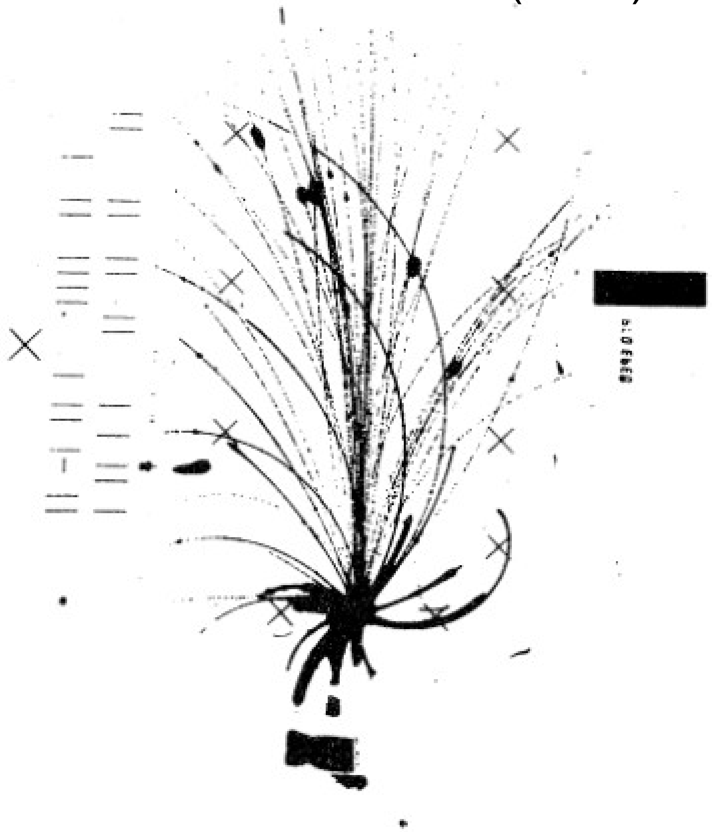
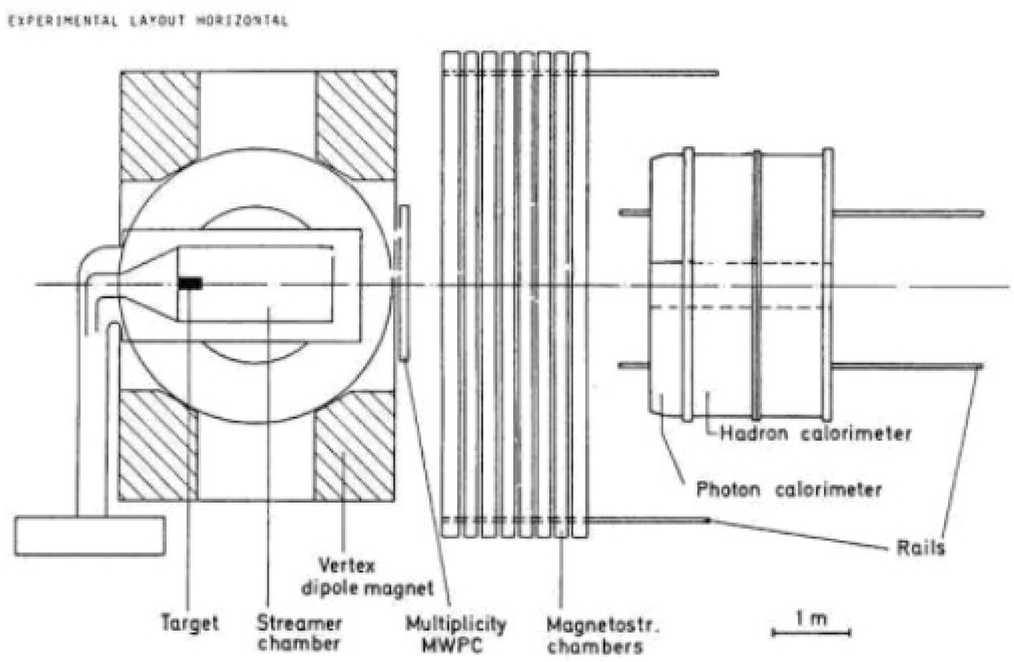


FIG. 2. Photograph of a pXe interaction at 200 GeV/c incident momentum.

Very similar Streamer Chamber as E665,
Made by the SAME group at MPI,Munich

NA5 s ≈ E665 <W^2>



E665 & Neutron Detection

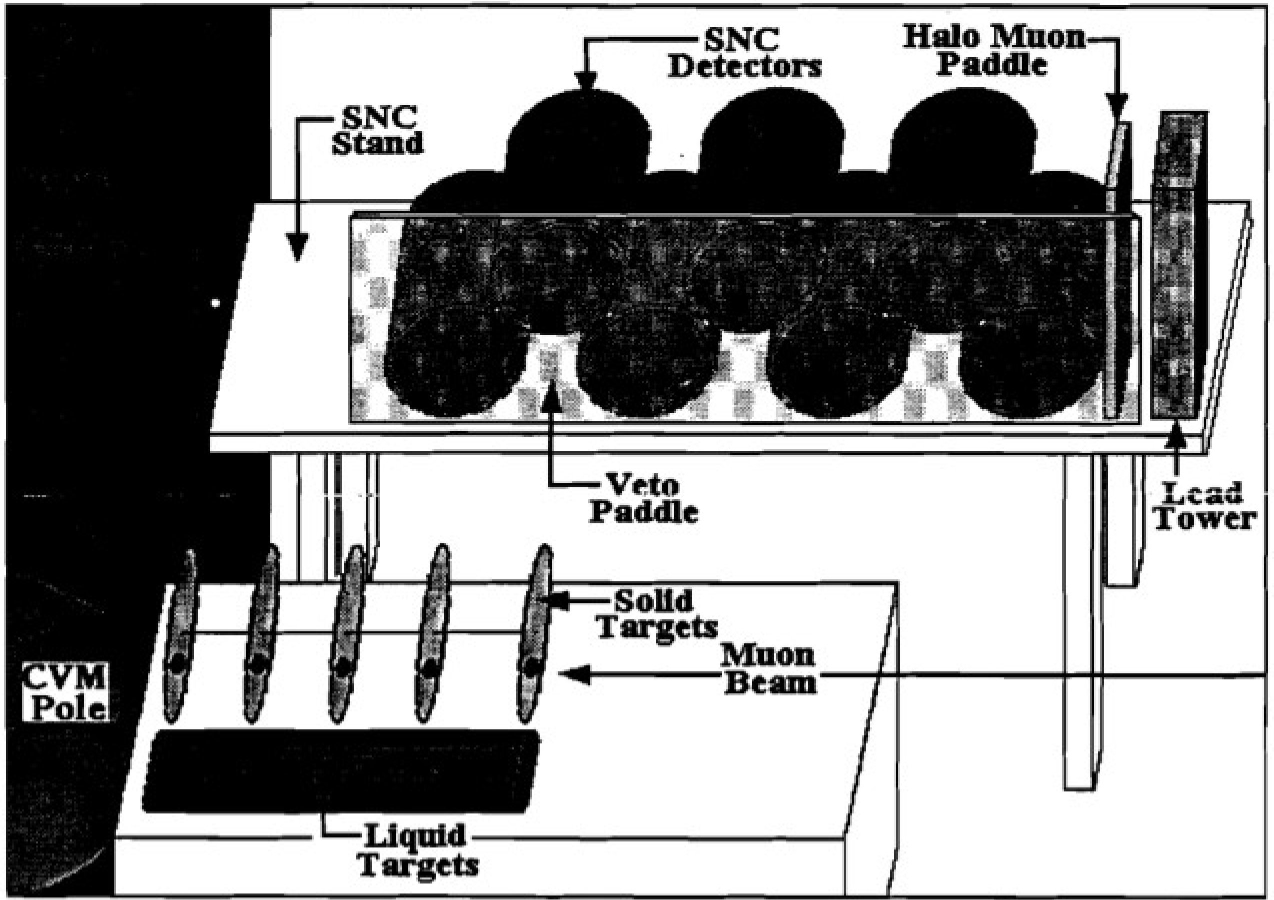


Figure 5.1: Location of the SNC experimental setup with respect to the target-vertex area.

Unlike at an EIC, E665 neutron detector had small relative coverage.

Not event-by-event

Warning: E665 data is usually a mix of DIS & diffractive...

PhD Thesis, Henry Clark, Ohio University (1993)