Particle Production and Physics at Zero Degrees in eA

Mark D. Baker*

Sept. 24, 2019

Geometry tagging @ 0^o is different in eA than AA

Mix of primary, secondary & spectator particles @ 0^o

*- mdbaker@bnl.gov, mdbaker@jlab.org, mdbaker@mdbpads.com

Zero Degrees in the Olden Days

AGS Fixed Target Au+Au

E-866-MEM-19

ZCAL Performance for Run '93 from PASS12

James C. Dunlop, Mark D. Baker
Massachusetts Institute of Technology

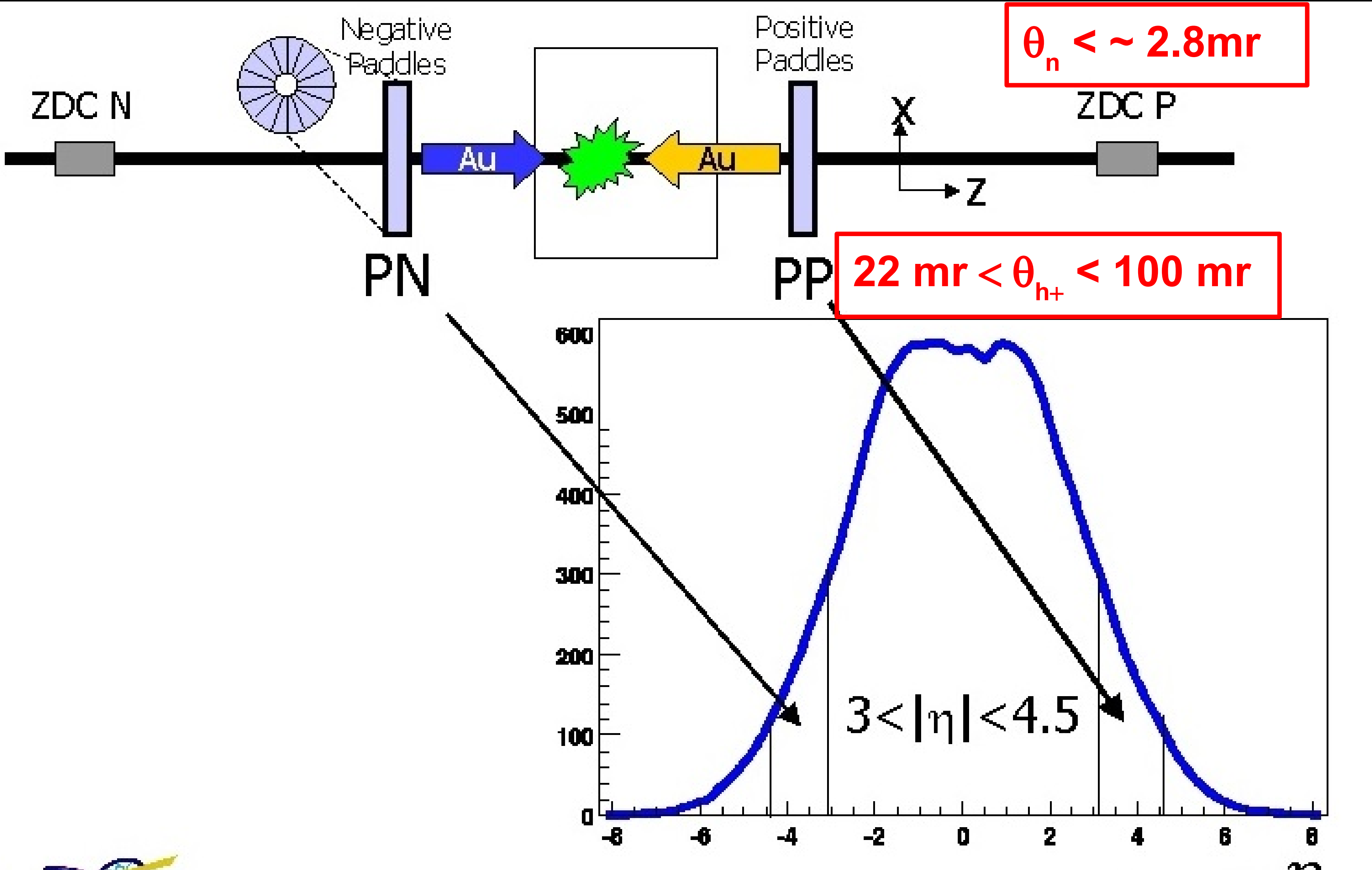
July 10, 1995

The purpose in writing this memo was to understand the performance of the ZCAL for central $Au-Au$ events and to communicate that understanding. We will examine the resolution of the ZCAL and the correction factors needed to find the number of projectile participants (N_{pp}). To this end, we have collected some of the existing information on the E866 Zero-degree Calorimeter (ZCAL) and added some new information available from the output of the 1993 PASS12.

At AGS & early RHIC: Zero degrees was for event characterization
The rest of the detector for physics.

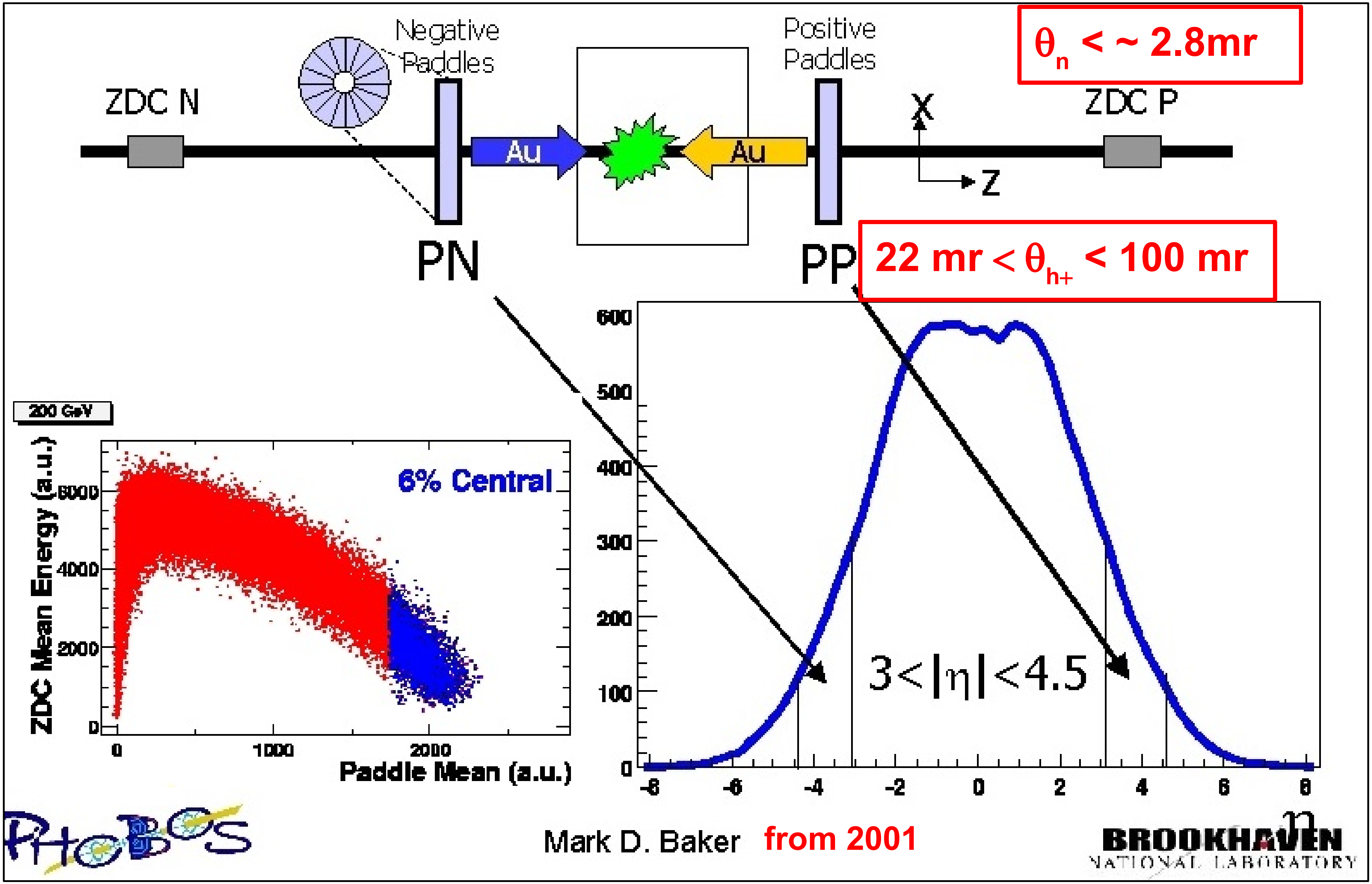
In this memo, we estimated 5% "contamination" of ZDC with produced particles...

Event Characterization for AA – an example

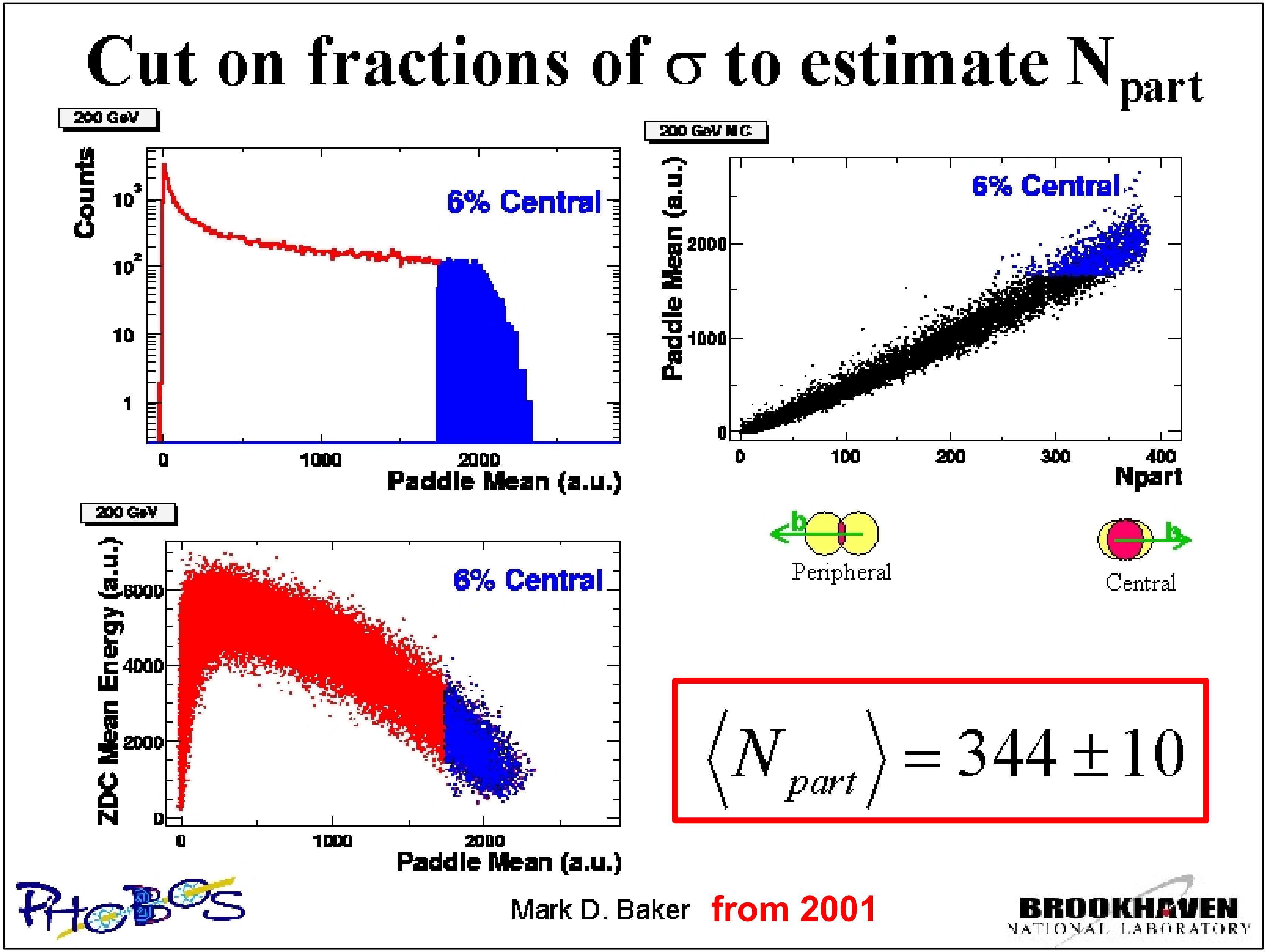


Mark D. Baker **from 2001**

Event Characterization for AA – an example

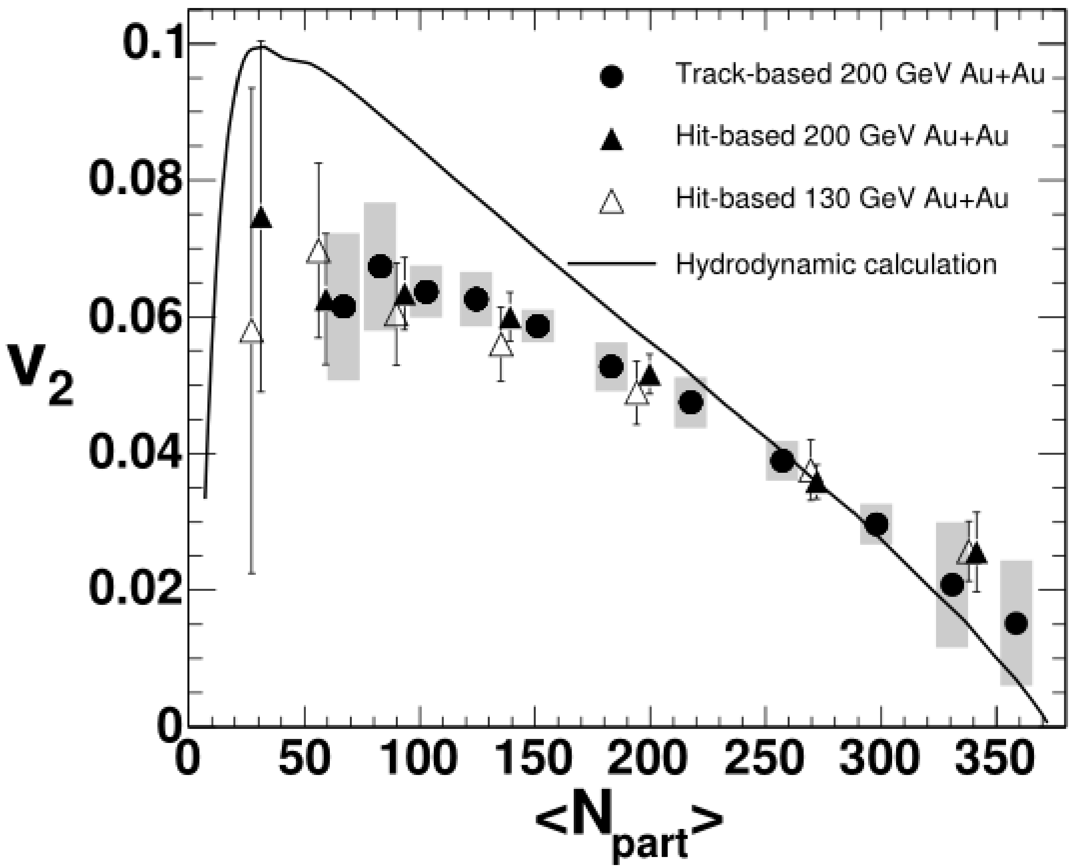


Event characterization rather precise in AA!



Precise centrality bins were crucial at RHIC

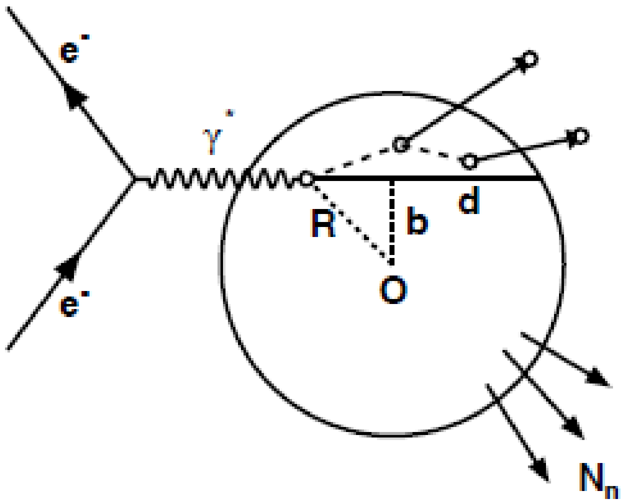
B.B. Back et al., PHOBOS Collaboration, "The Phobos Perspective on Discoveries at RHIC", Nucl. Phys. A757 (2005) 28

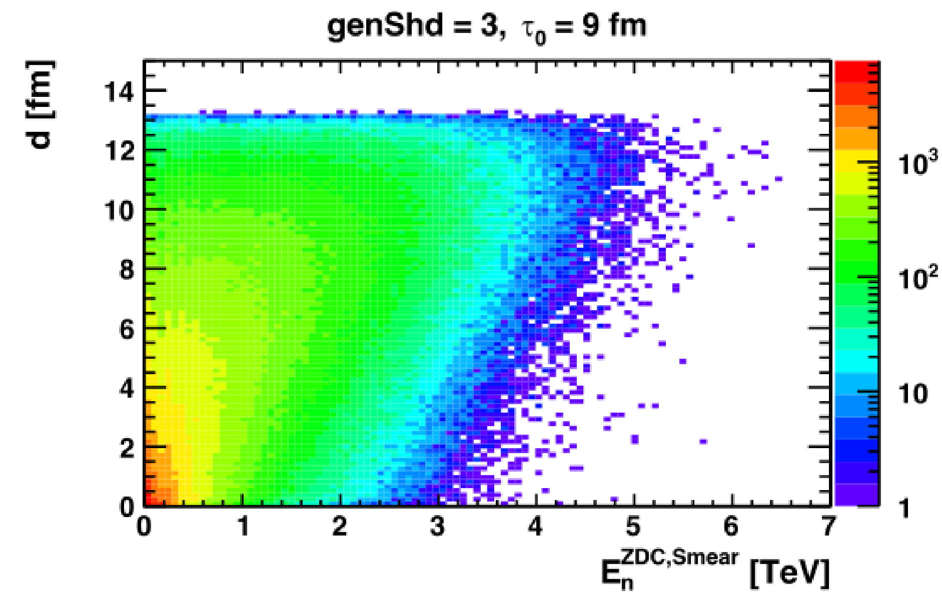


Precise event characterization was used by all 4 experiments @ RHIC to make the "near-perfect liquid QGP" discovery.

Zero Degrees in e+Pb

BeAGLE Plots from Wan Chang

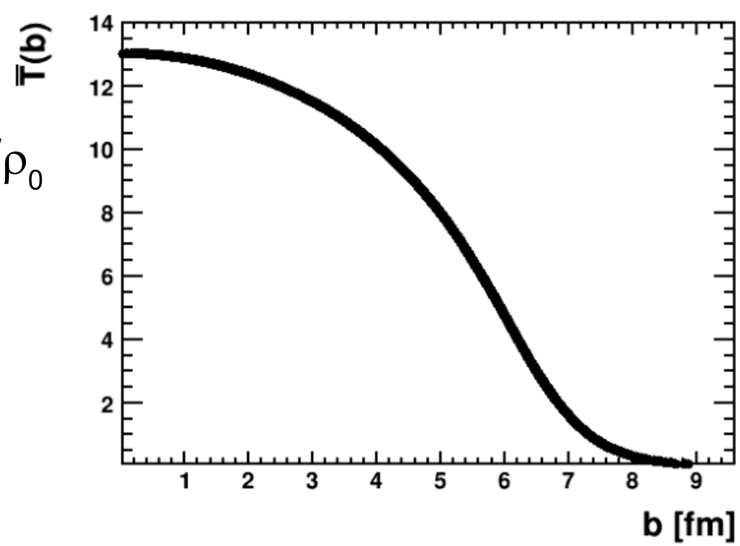


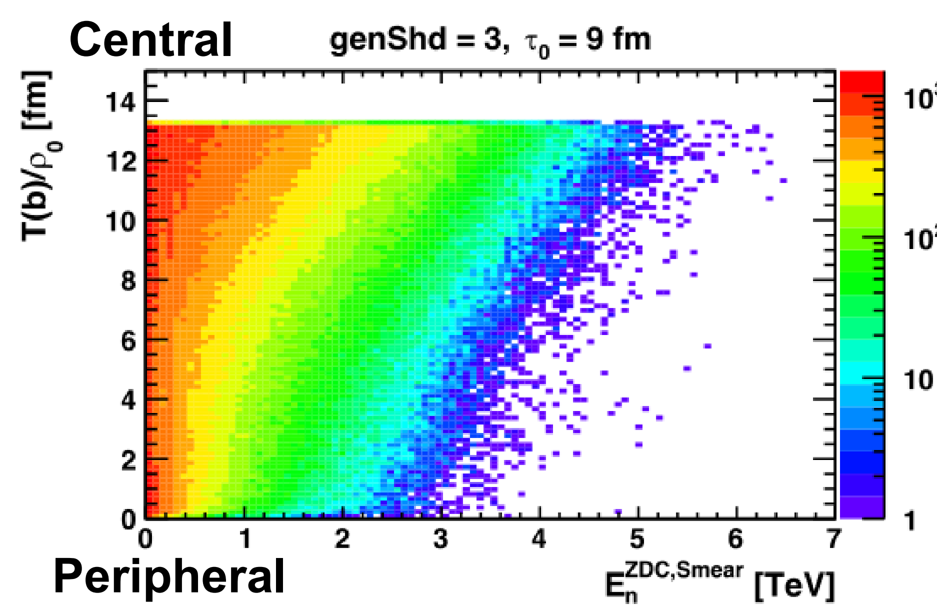


$d \equiv \int dz\, \rho(x,y,z)/\rho_0$ from $Z_{collision} \to \infty$

$T(b) \equiv \int dz\, \rho$ from $-\infty \to \infty$

$T(b)/\rho_0$ [fm]





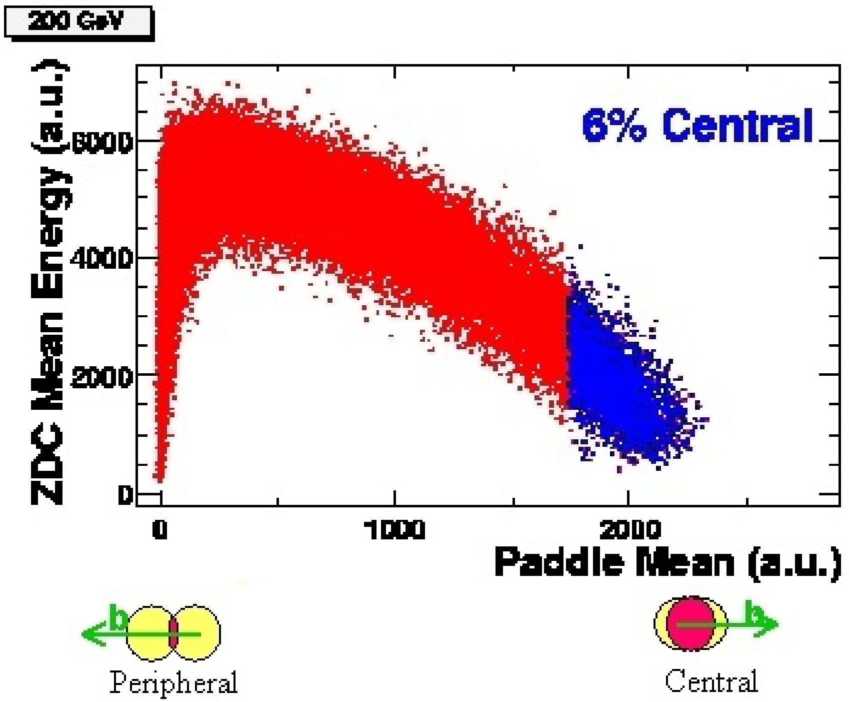
Central e+A is HIGH ZDC activity

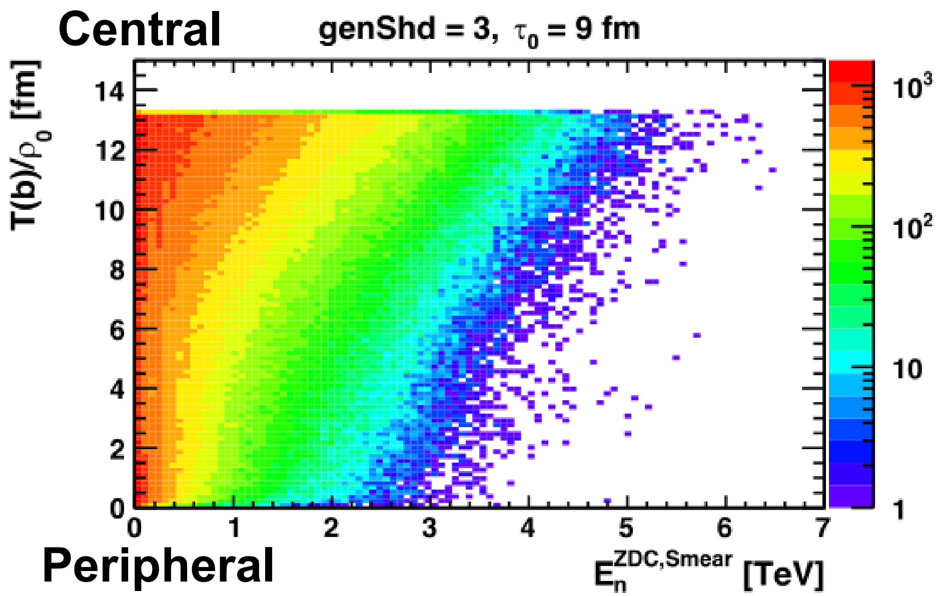
A+A

Spectator neutrons decrease with centrality – low E_{ZDC} @ b=0

e+A

Evaporation neutrons increase with centrality – high E_{ZDC} @ b=0

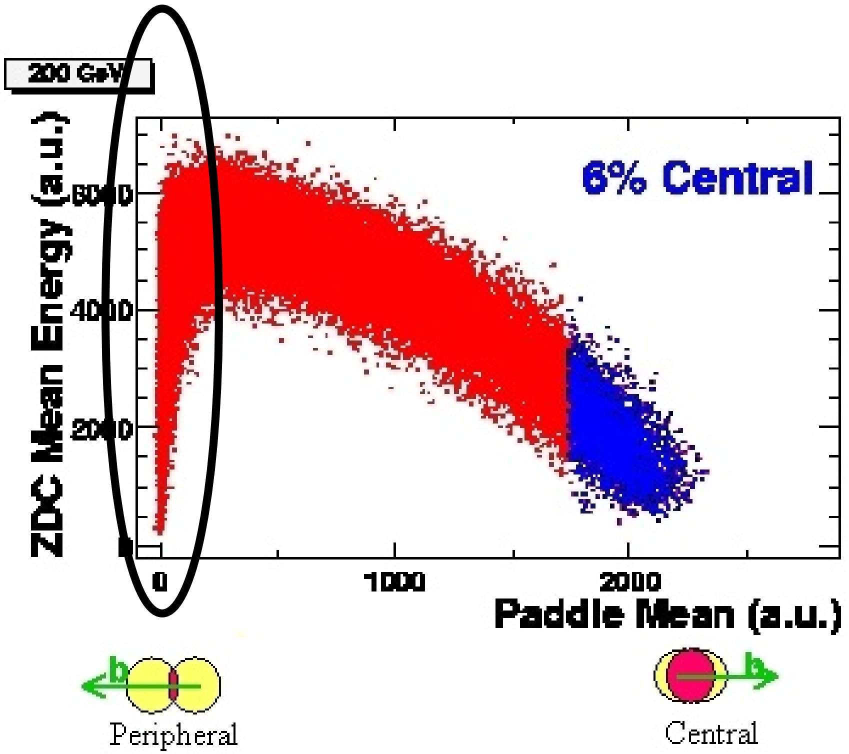


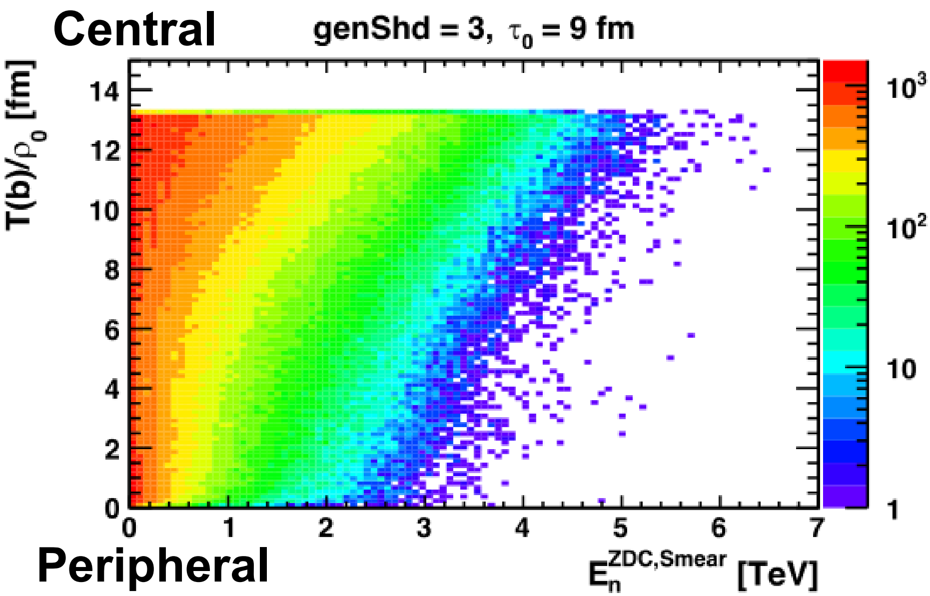


Very Peripheral A+A is more like e+A

A+A
Very peripheral region:
Excitation & breakup like in e+A

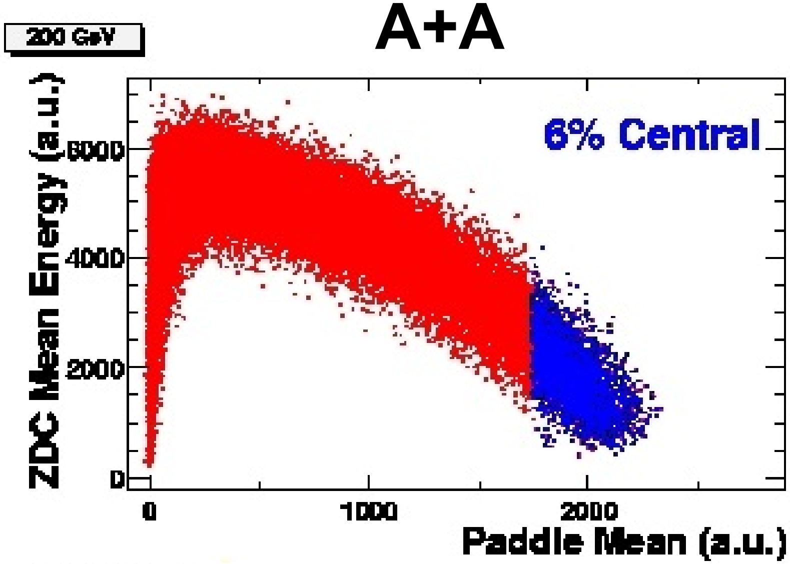
e+A
Evaporation neutrons increase with centrality – high E_{ZDC} @ b=0

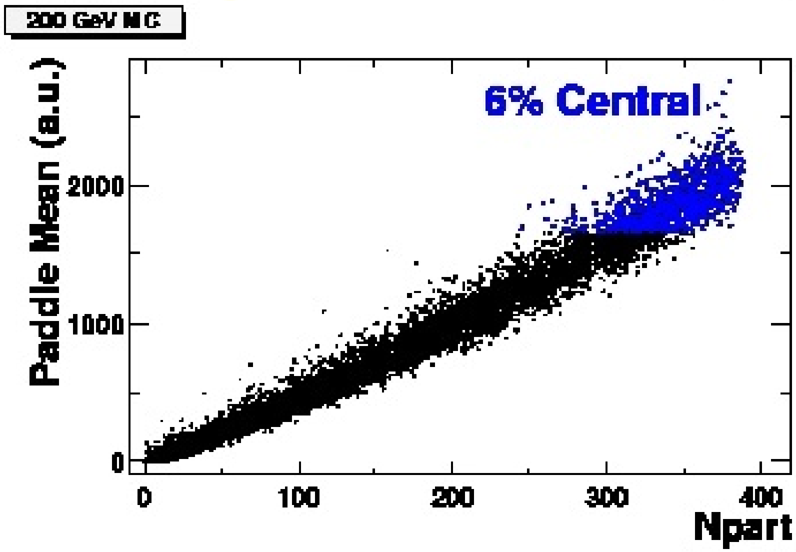


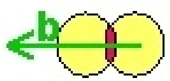


Correlation in A+A much stronger than e+A!

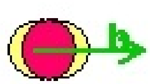
A+A





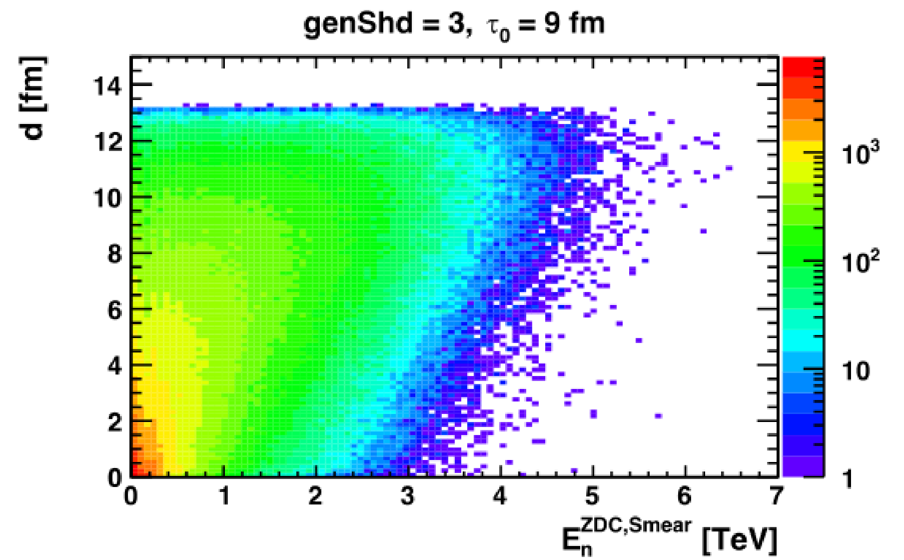


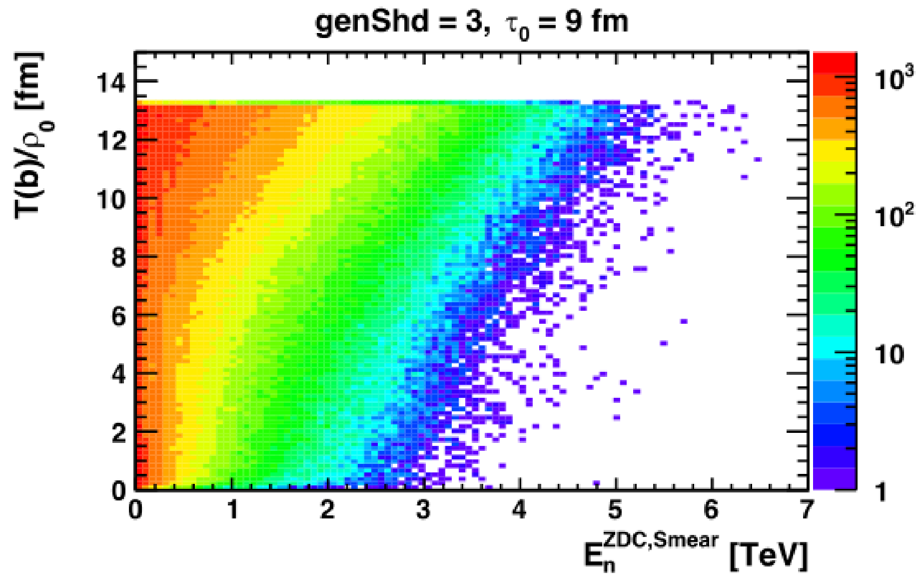
Peripheral



Central

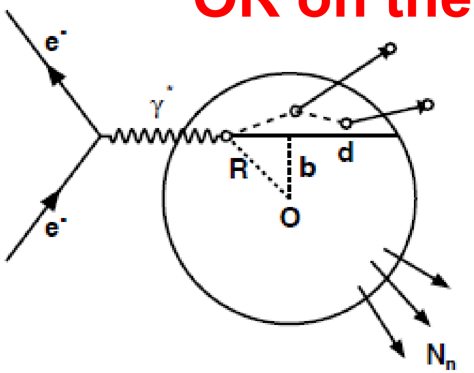
e+A



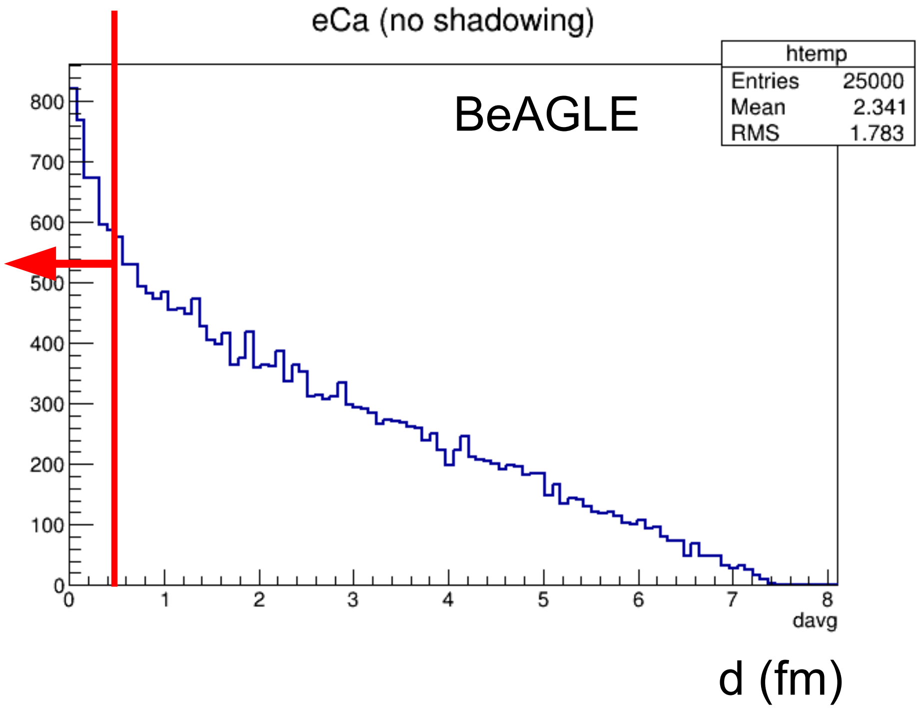


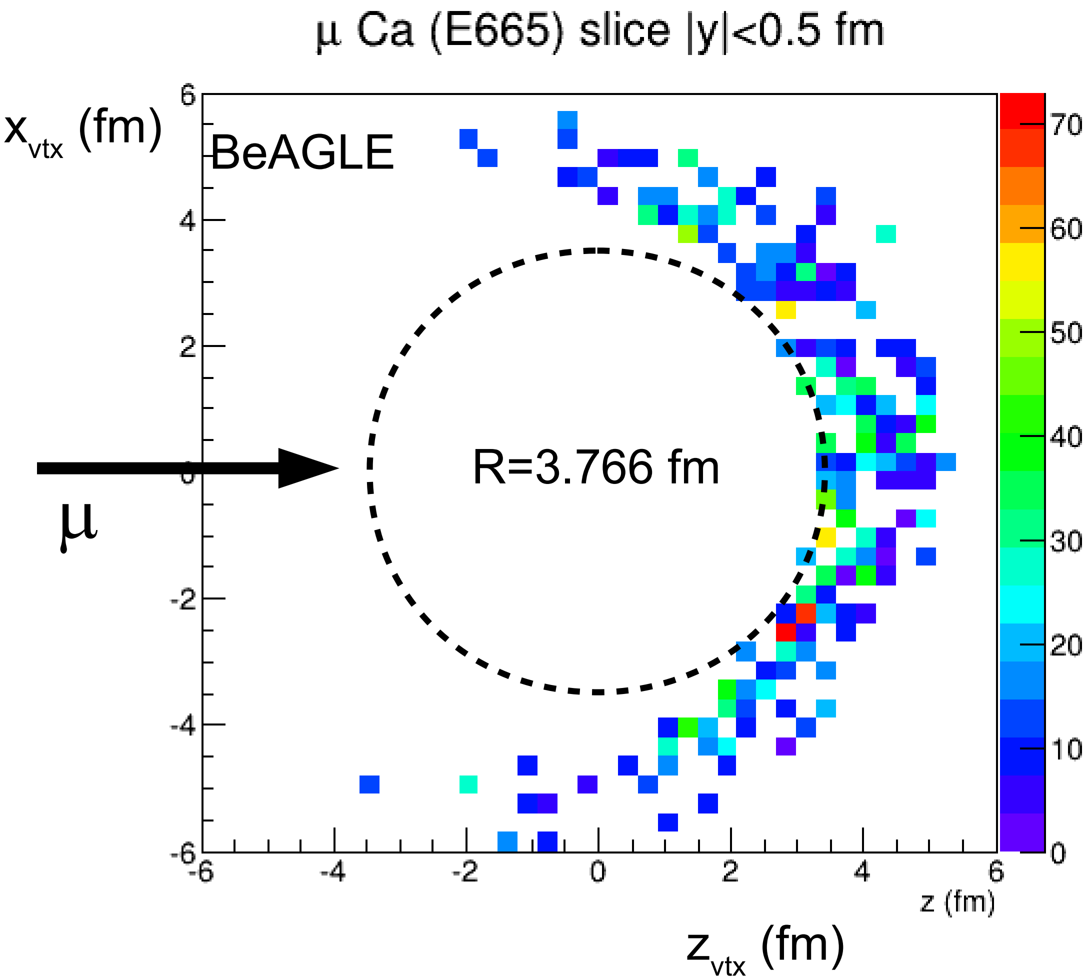
Intranuclear cascading driven by "d"

Low activity is due to collisions that are peripheral (high b)
OR on the BACK of the nucleus

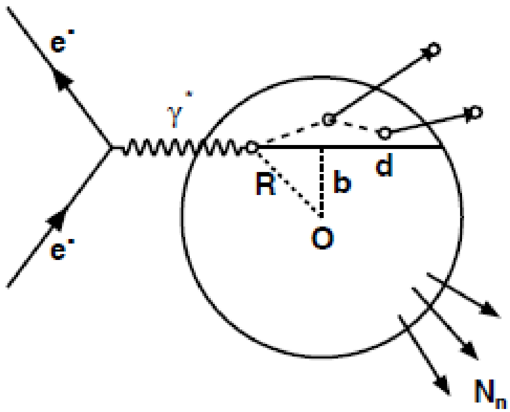


$d \equiv \int dz\, \rho/\rho_0$ from $Z_{first\text{-}collision} \rightarrow \infty$





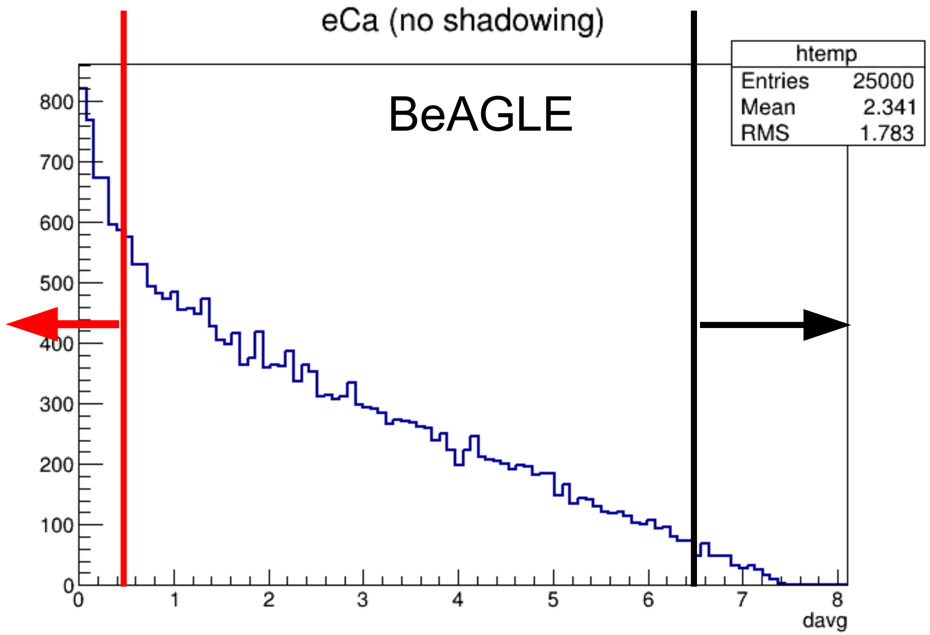
Central (high E_{ZDC}) cut is more meaningful

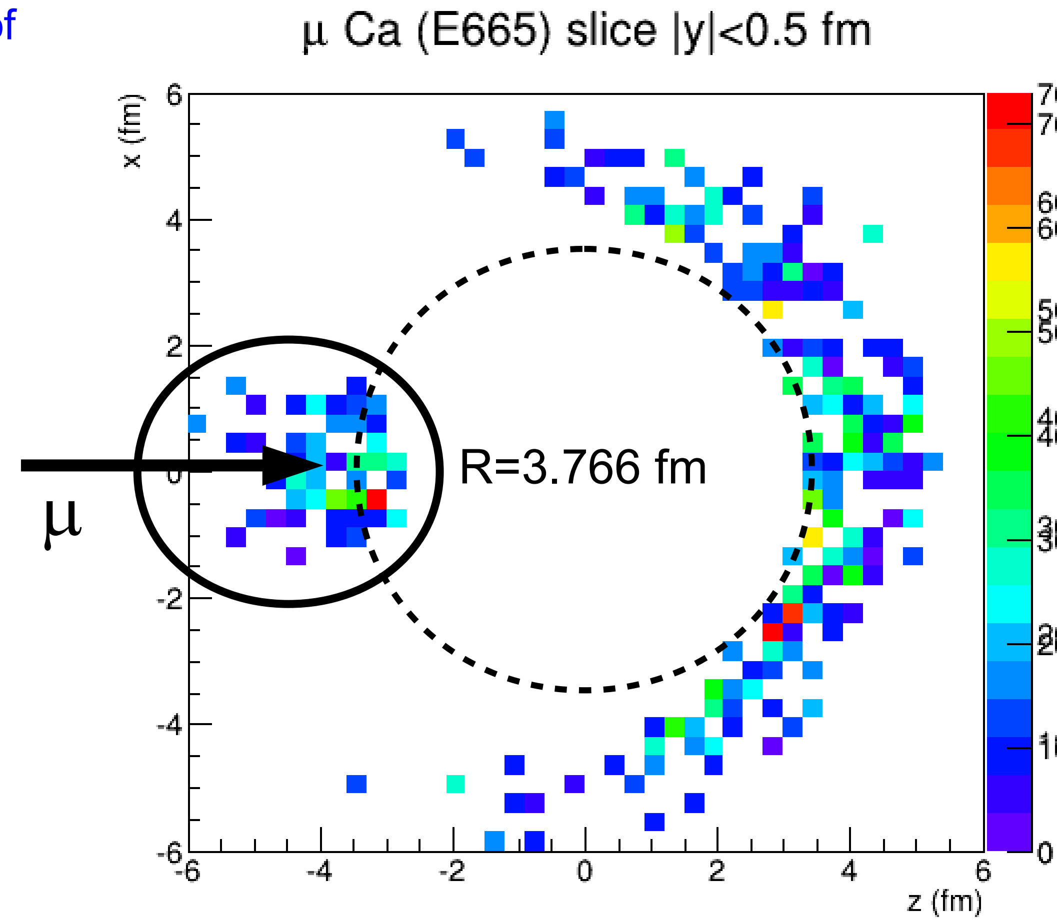


Intra-nuclear cascading increases with d (forward particle production)

Leads to evaporation of nucleons from excited nucleus (very forward)

$$d \equiv \int dz\, \rho/\rho_0 \quad \text{from } Z_{\text{first-collision}} \rightarrow \infty$$

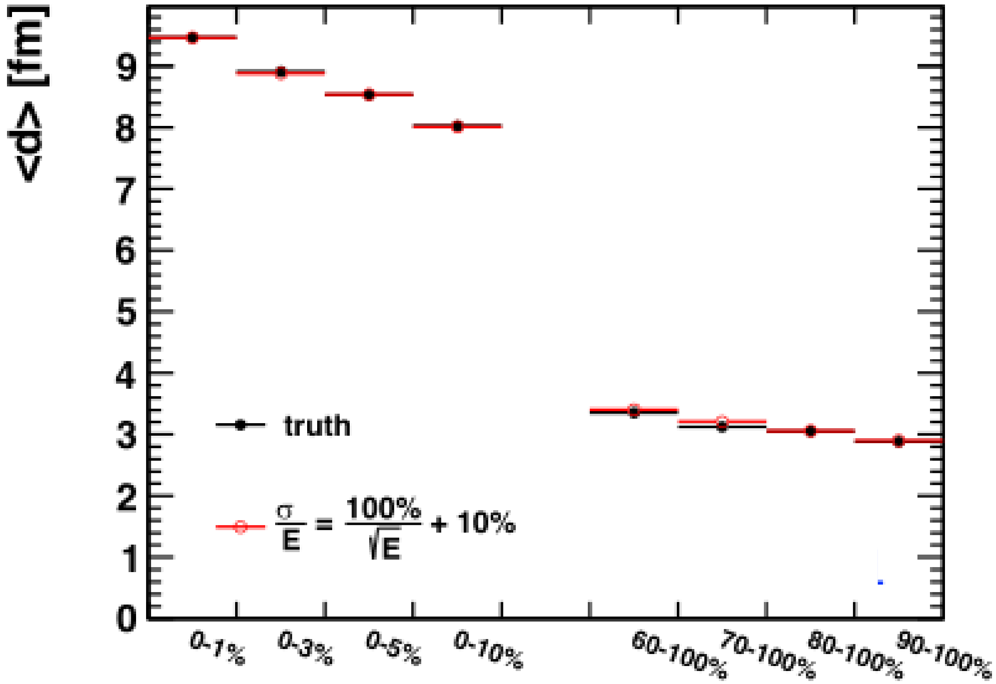




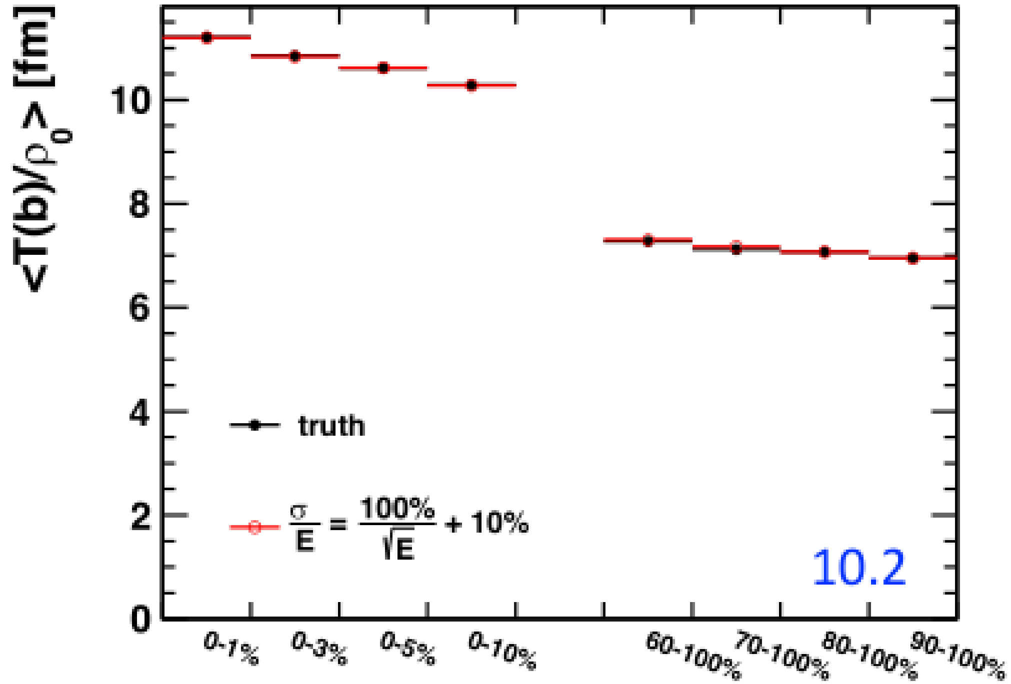
Aschenauer, MDB, Chang, Lee, Tu, Zheng

Tight "central" cuts are meaningful in e+A

The average value of traveling length d in different centrality bins:



The average value of nuclear thickness $T(b)/\rho_0$ in different centrality bins :



From Wan Chang

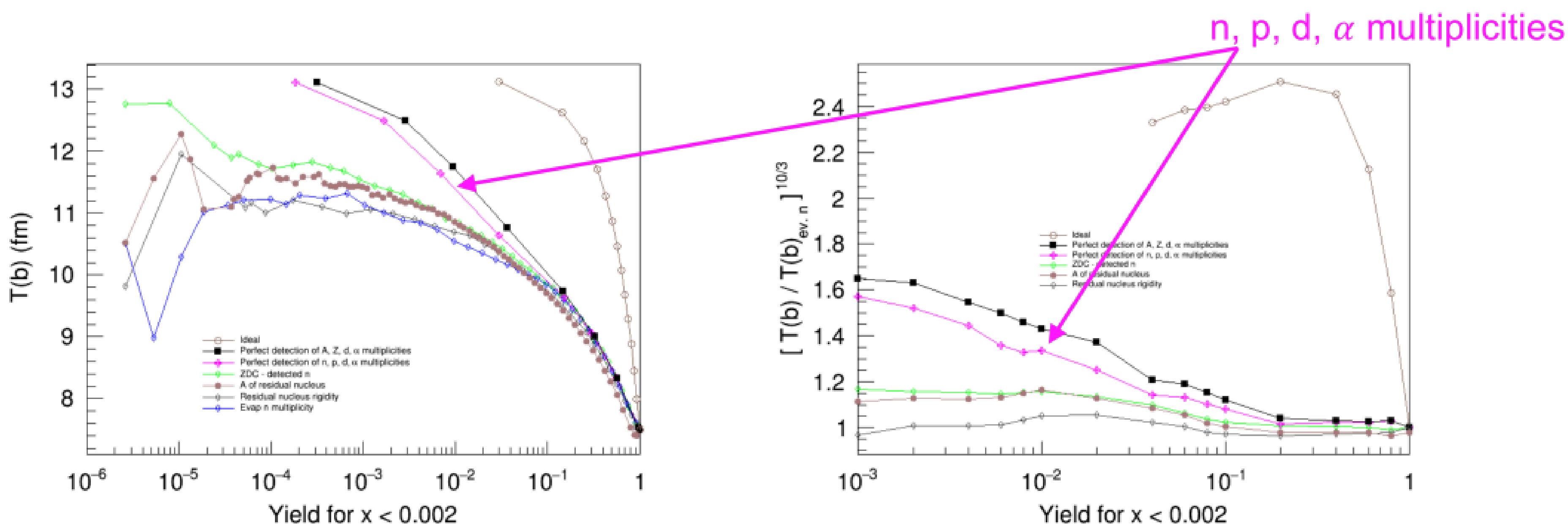
Tight geometry cuts are also easy, even a crude calorimeter suffices.

See Wan Chang's talk for more details.

Geometry tagging improved using p,d,α

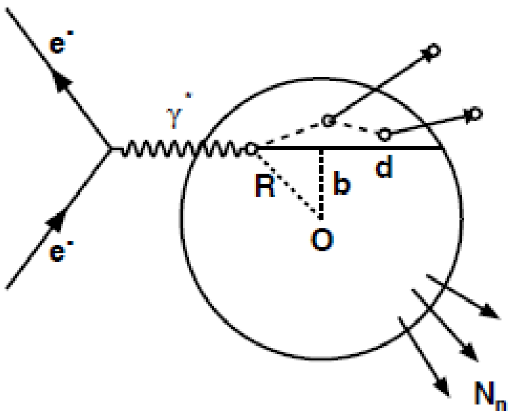
What if we also detect the charged particles? **From Vasiliy Morozov (et al.)**

- Detecting protons and light ions (*d* and ^4He) in addition to neutrons increases the selectivity in *b* and the effective nuclear thickness *T(b)*
- For a 1% yield cut, the increase in equivalent collision energy is about 40% (magenta curve on right) compared with using evaporation neutrons only



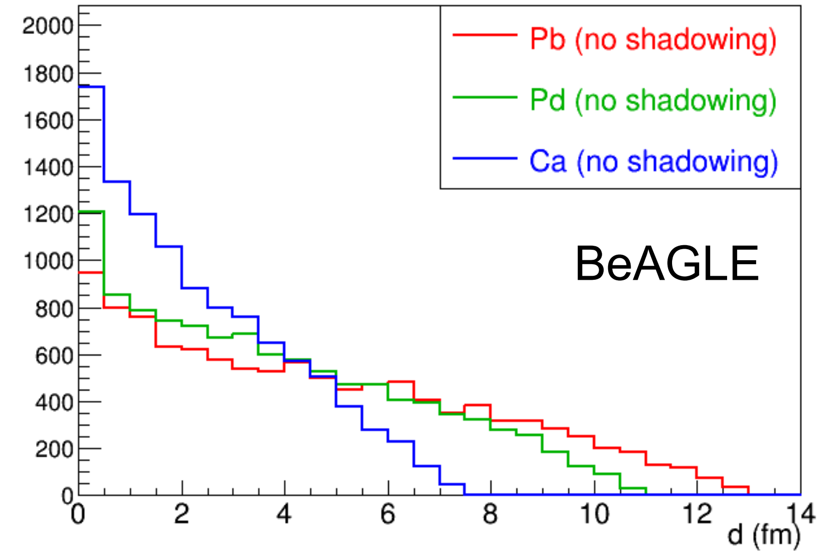
CFNS Summer School 2019 52 August 3, 2019 Jefferson Lab

Geometry tagging vs. A-scan

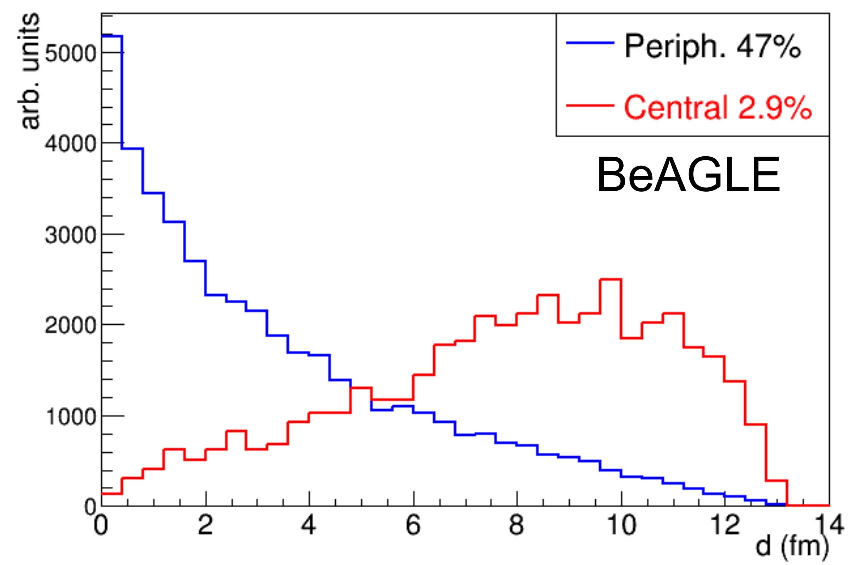


Intra-nuclear cascading increases with d (forward particle production)

Leads to evaporation of nucleons from excited nucleus (very forward)



Tagged ePb (samples scaled to same area)



<d> increases w/ A, but all nuclei have a lot of “skin” (low d events).

ZDC tagging allows more distinctive low d and a high d samples

Also high T(b) samples.

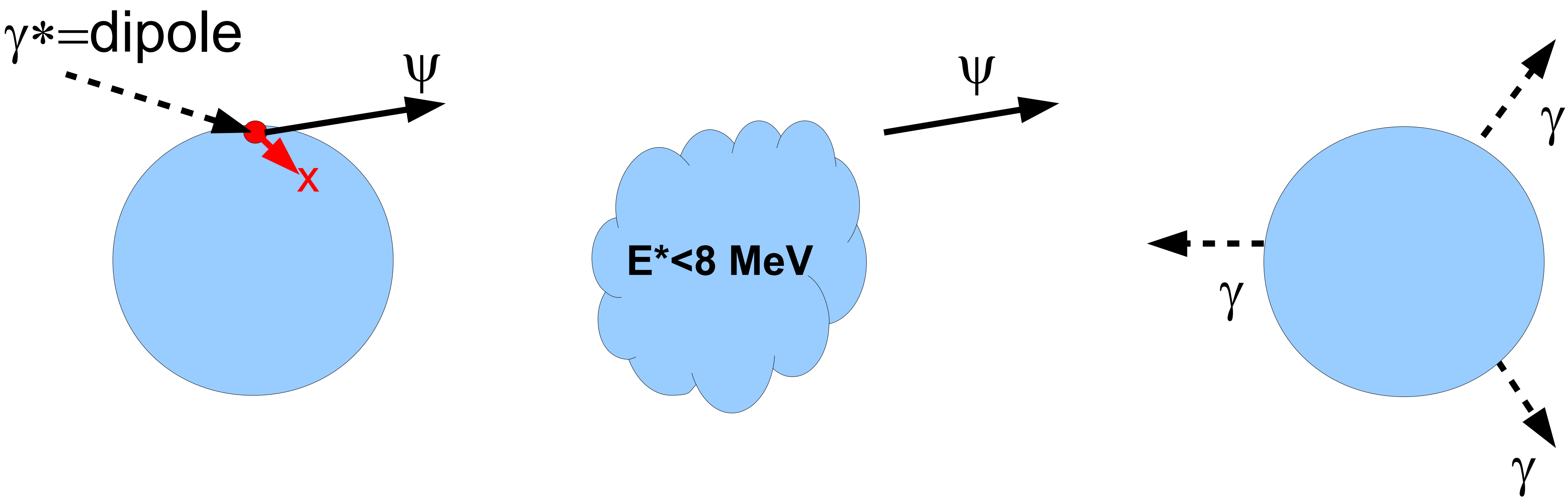
e+A geometry tagging summary

- e+A is different than A+A
- We will NOT have detailed plots vs. "centrality" with 10 meaningful bins like in A+A.
- We CAN remove the e+"skin" collisions and enhance nuclear effects substantially.
- We CAN make meaningful, rather tight, cuts on the high Thickness (central) events.
- A fancy ZCAL is not needed for this.
- Forward charged particles add value.

Don't forget forward photons

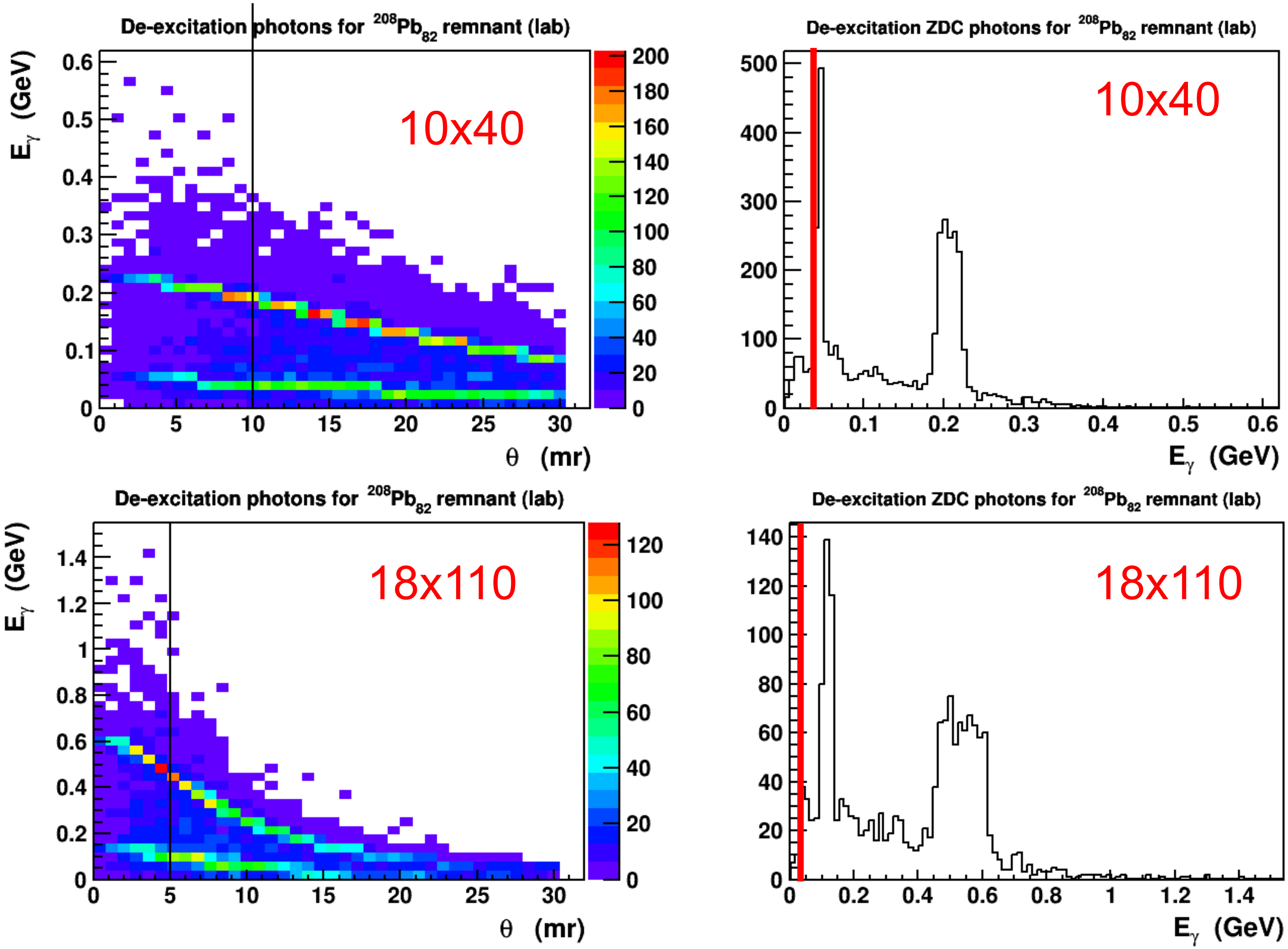
- Problems vetoing incoherent diffractive events at low |t| due to events where the struck nucleon is reabsorbed:

$$e + {}^{208}Pb_{82} \rightarrow e' + {}^{208}Pb_{82} + J/\psi + \gamma + \gamma + \gamma ...$$



Cartoons in Ion Rest Frame

Photons from $^{208}Pb_{82}$ in lab frame



Detailed studies ongoing.

It is clear that γ's will be needed for low |t|!

w/ Morozov, Hyde, Turonski et al.

Many primary particles go forward in e+A

- Reconstructing, not just counting or tagging, forward particles is important for a lot of physics in e+A (see all the talks in this meeting!).
- Three quick examples
  - $e+D \rightarrow e'+J/\psi+n+p$
  - Quasi-elastic e+N collisions with SRCs in e+A
  - Target remnant jet in regular DIS

ZDC neutrons as physics

Slide adapted from Yulia Furletova

Exclusive J/PSI production : (5 GeV x 100 GeV/nucleon)

e + D-> e' + J/Psi + (n') +(p')

$$t = (D-D')^2 \approx A \frac{P_T^{\,2}}{xL} - t_0$$

Need good E and θ resolution!

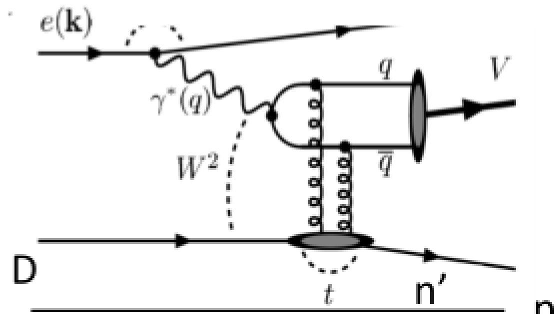
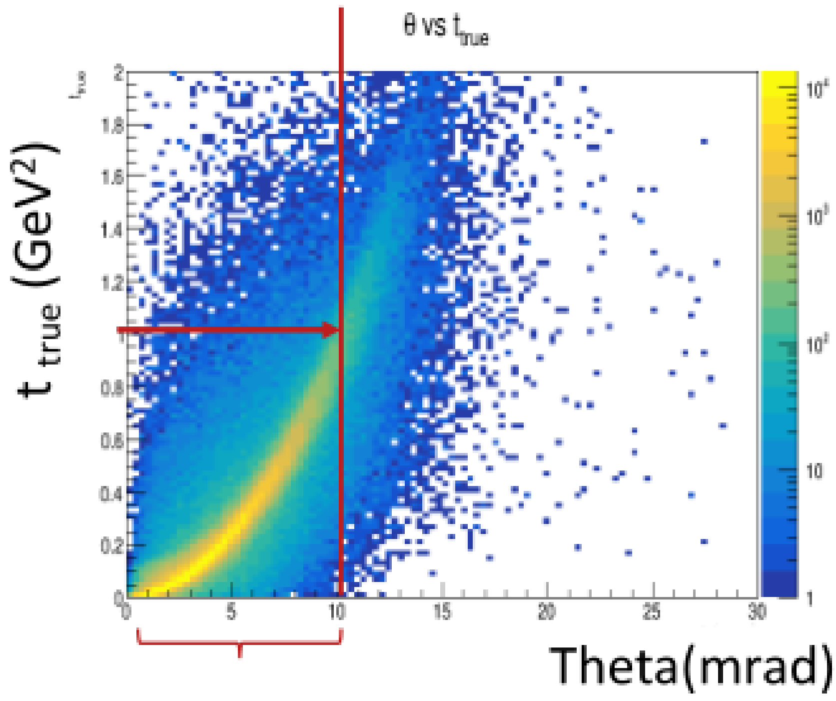


Figure 2. Exclusive vector meson production described by perturbative quantum chromodynamics.

For **Zero Degree calorimeter**, as one of proposals: to use a high granularity (fast silicon) calorimeter concept (developed at Argonne)

Advantages : particle flow calorimeter, charge/neutral rejection



t from neutron = t from J/ψ needed to rule out e.g.:

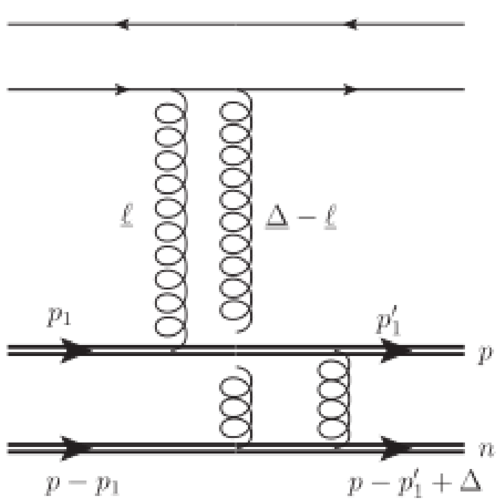
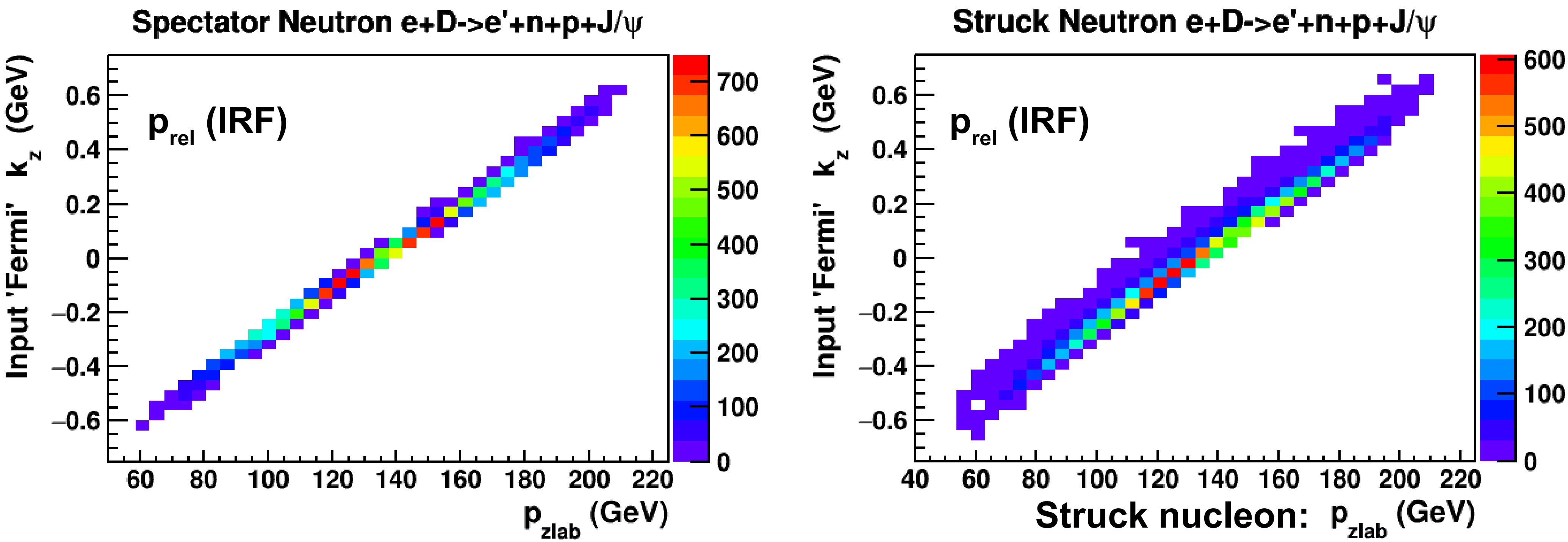


Diagram from:

Miller, Sievert, Venugopalan, PRC 93(2016) 045202

18x135 e+D momentum boost effect



IRF = ion rest frame z along γ^* Lab frame z along outgoing D direction

$\sigma_n(k_z) \sim (M_N/E_{beam})\sigma(E_{ZDC})$ so for $E_{ZDC} \sim E_{beam}$: $M_N\ \sigma(E)/E$

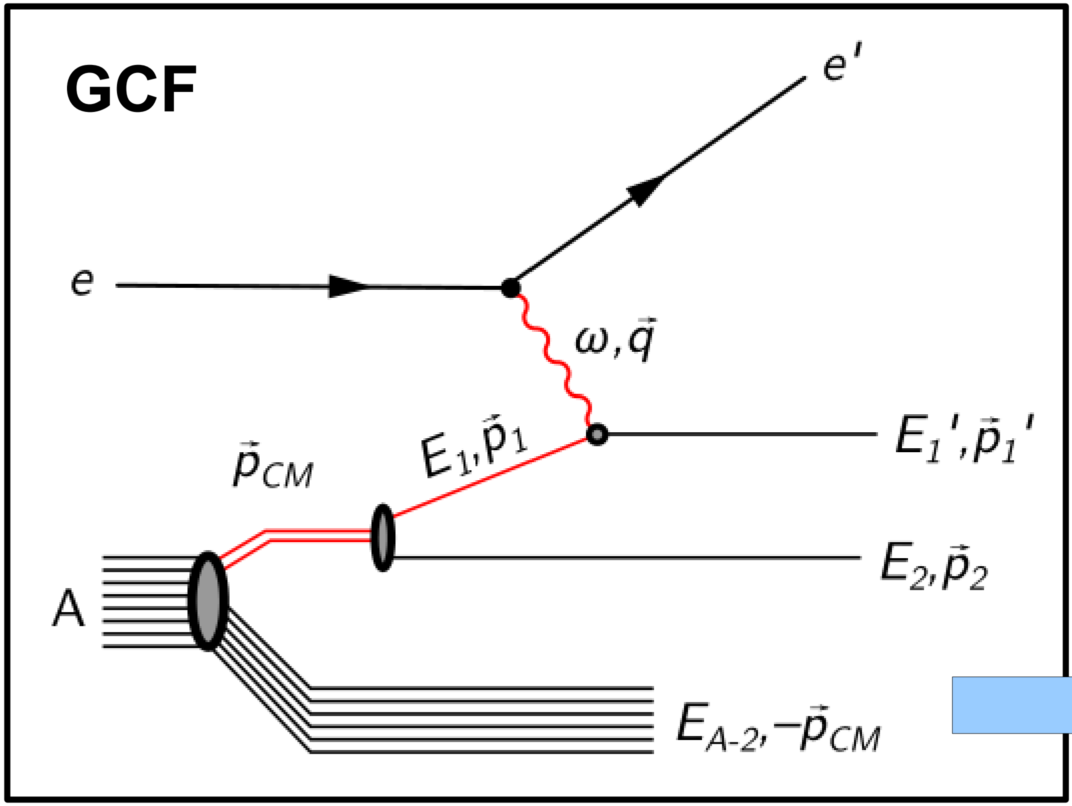
~ 47 MeV for a 5% calorimeter or 175 MeV for a 10%+100%/sqrt(E) calorimeter

Full reconstruction needed to confirm that spectator model (PWIA) applies.

See talk by Zhoudunming Tu tomorrow for much more...

Quasi-elastic with Short Range Correlations

MDB, Hauenstein, Hen, Schmidt, Schmookler *



Note: We have not yet included all available nuclear effects such as INC (IntraNuclear Cascading) from BeAGLE.

Coming soon...

BeAGLE (FLUKA) for nuclear breakup & evaporation

GCF: https://www.mit.edu/~src_emc/fri/schmidt_20190322.pdf
BeAGLE: https://wiki.bnl.gov/eic/index.php/BeAGLE

*** - Supported by Higinbotham et al. JLAB LDRD**

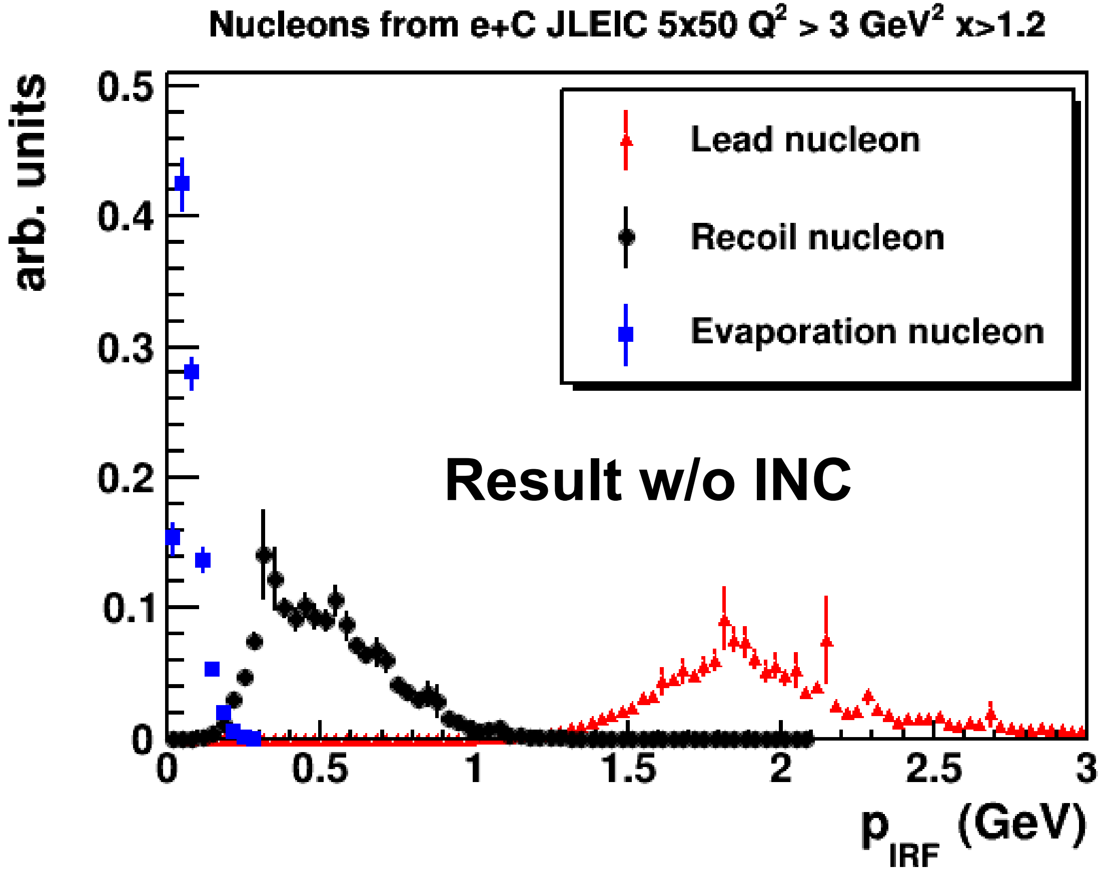
Quasi-elastic with Short Range Correlations

e + C 5x50A

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

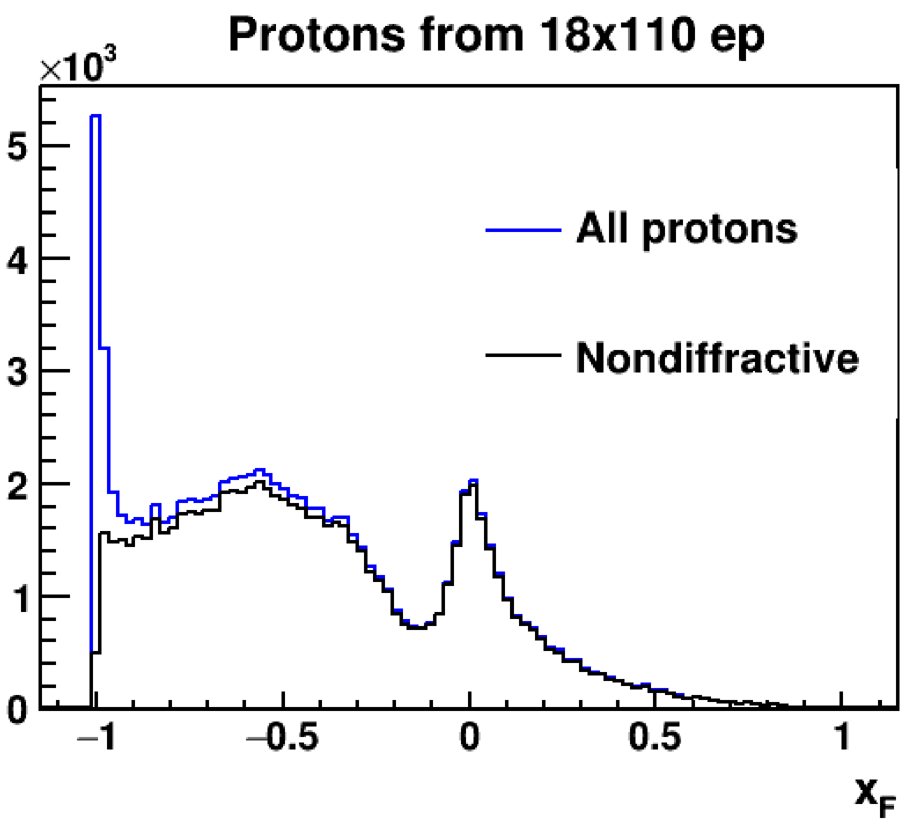
Result is GCF + BeAGLE

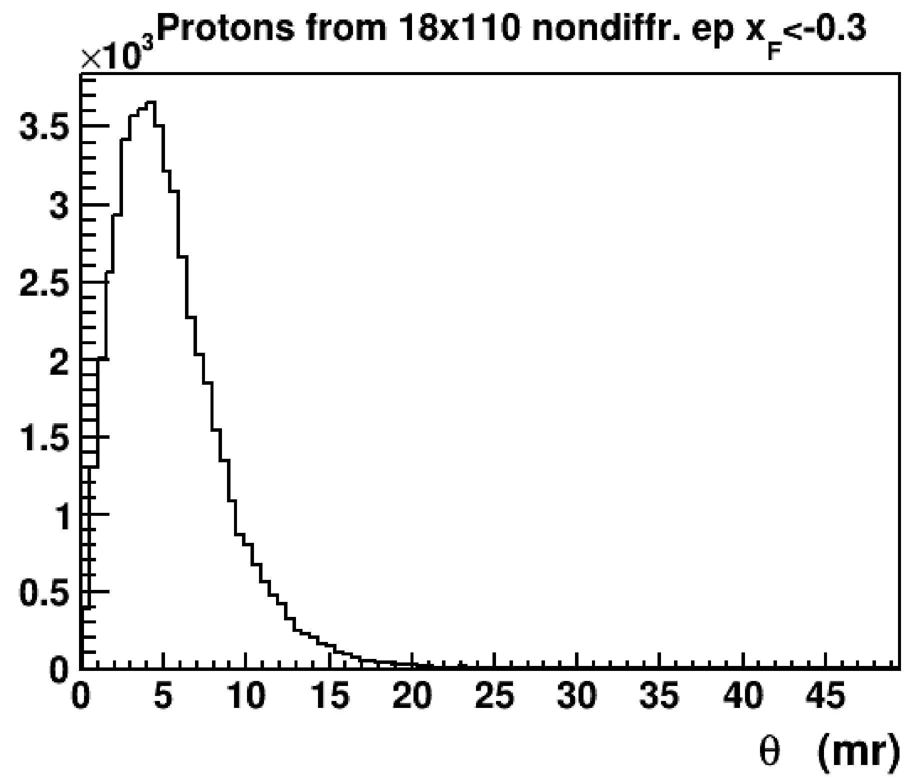
Total momentum Ion Rest Frame



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

Leading target remnant jet proton is forward!

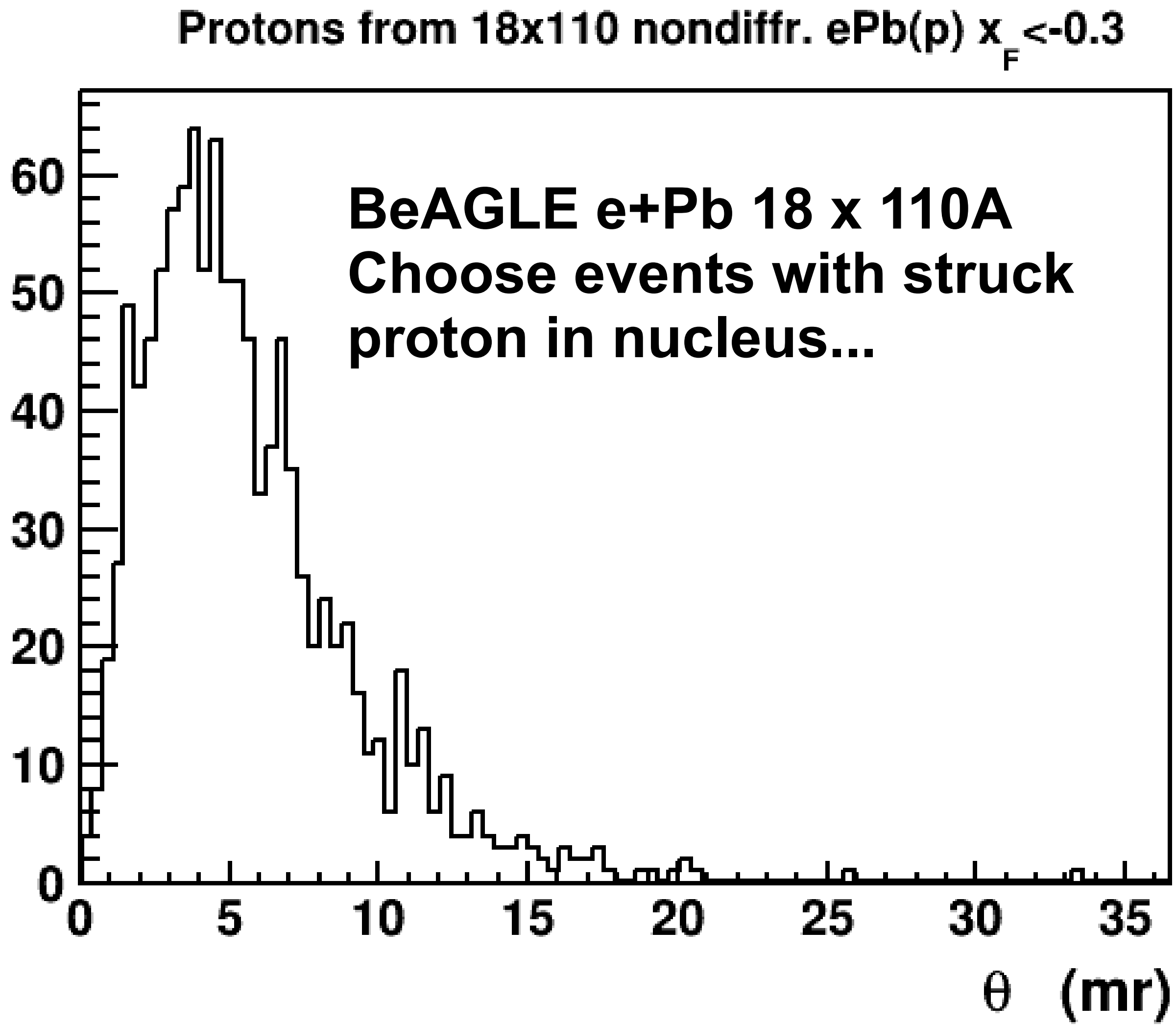




$x_F \equiv 2\, p_L/W$ in nominal HCMS of γ^*+N system, θ in lab wrt Pb beam

Mostly DIS - from BeAGLE ep –
which is Pythia tuned to ZEUS forward protons & neutrons
BeAGLE crew: Aschenauer, MDB, Chang, Lee, Tu, Zheng

Similar result for e+Pb (with struck proton)



Sanity check:

x_F**=-0.3,** p_T**=300 MeV**

P_{zlab}**=0.3*110=33 GeV**

θ = 0.3/33 = 9 mr

$x_F \sim -x_L \equiv p_{zlab}/p_{zbeam}$ **in (collider) lab frame**

Conclusions

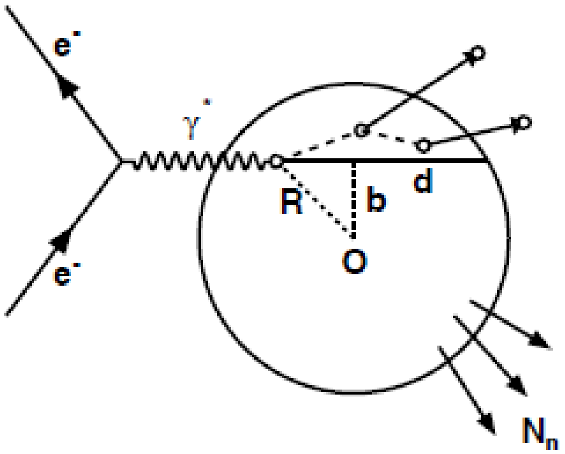
- Lots of important physics in forward e+A
  - Need reconstruction, not just tagging
  - See all the other talks!
- Must be simulated and studied in its own right
  - A+A experience is not quite relevant...
    - (p+A and ultraperipheral A+A may be helpful)
  - e+p collider studies irrelevant for forward protons
- This workshop is a great step!

Extras

BeAGLE – Benchmark eA Generator for LEptoproduction

- Aschenauer, Chang, MDB, Lee, Tu, Zheng & Accardi, Dupré, Ehrhart
- Merger of
  - Pythia6: hard interaction (adding RAPGAP option)
  - Glauber + multinucleon shadowing
  - PyQM: Optional radiative jet quenching
  - DPMJET3-F (DPMJET3+Fluka) – nuclear response
- Tuned to ZEUS forward nucleons, FNAL E665 (FixTarg) slow neutrons, + HERMES

Key features of BeAGLE



<u>Multistep process.</u>

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

Intra Nuclear Cascade w/ Formation Zone

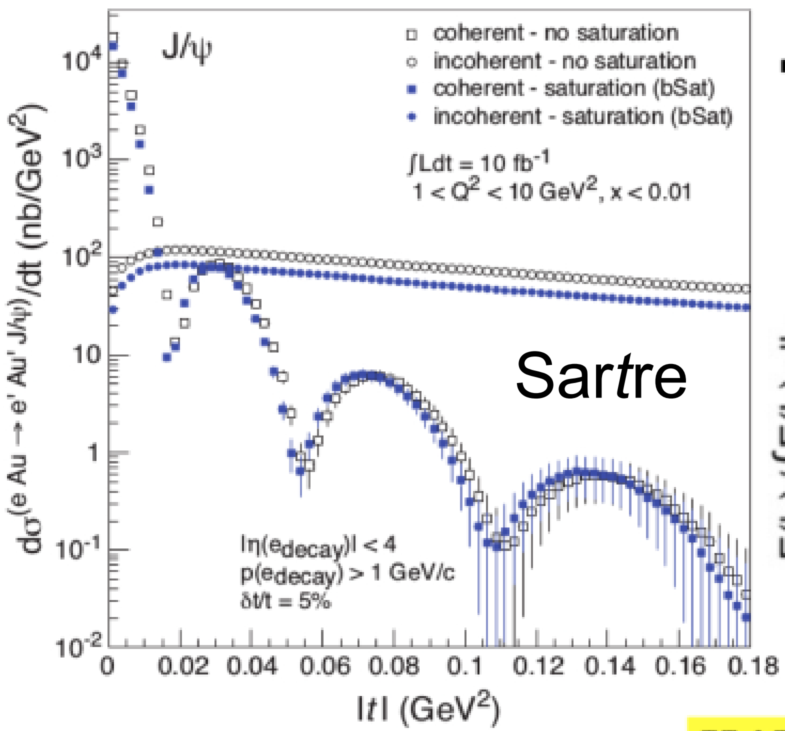
Excited nuclear remnant decays by:
- Fission &/or evaporation of nucleons
- De-excitation by gamma emission.

Try to model both hard process AND nuclear interaction.

It helps if A is big enough (12?) to leave a substantial remnant which can be modeled in the ion rest frame as a collection of on-mass-shell nucleons with Fermi motion sitting in a mean field.

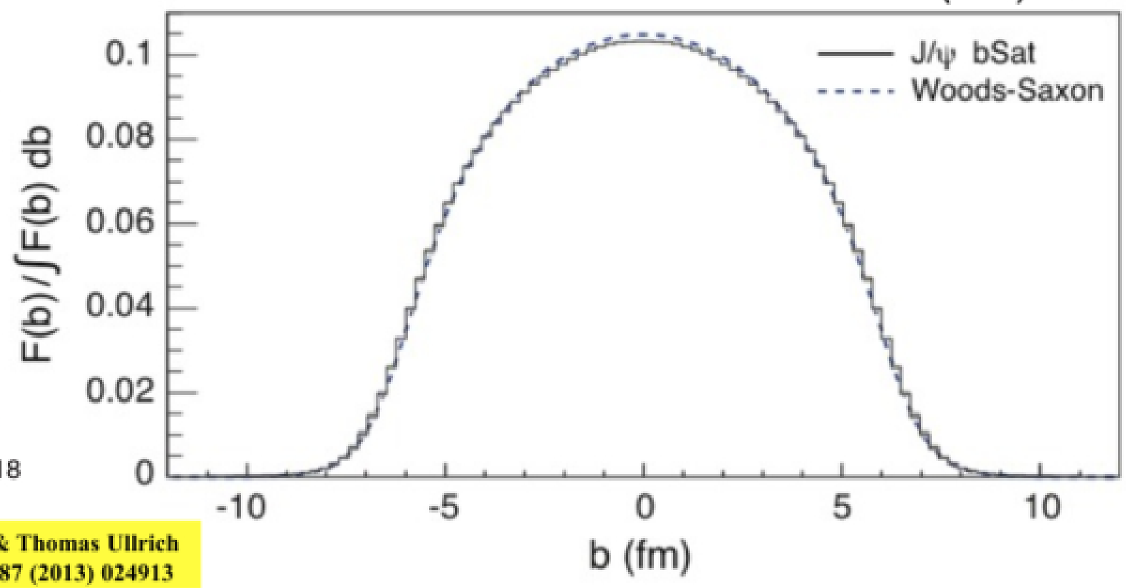
Probing the spatial gluon distribution at EIC

Momentum transfer t conjugate to transverse coordinate b



$$F(b) \propto \int \mathrm{d}\Delta \Delta J_0(\Delta b) \sqrt{\frac{\mathrm{d}\sigma}{\mathrm{d}t}}$$

$t = \Delta^2/(1-x) \approx \Delta^2$

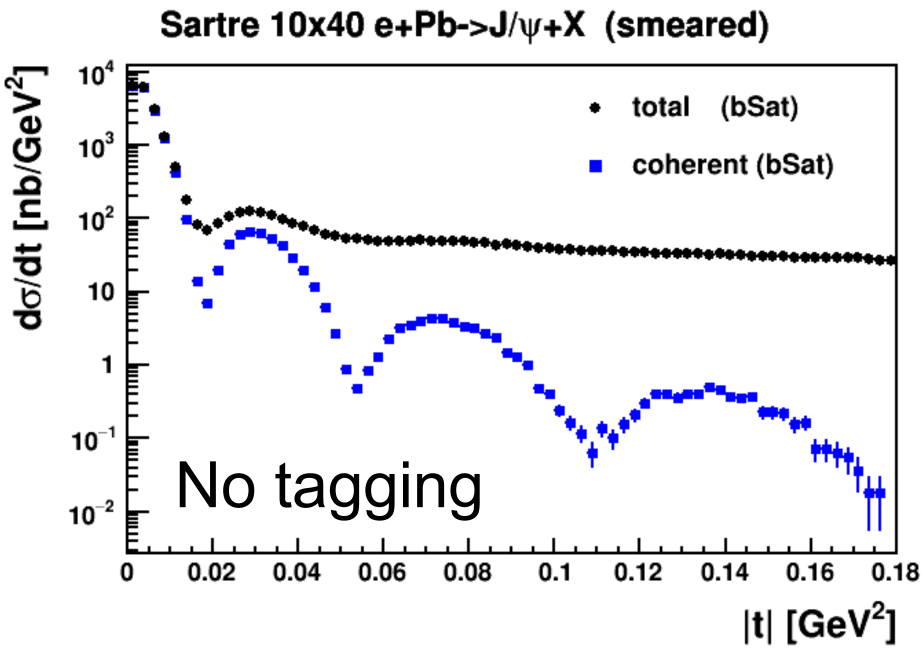


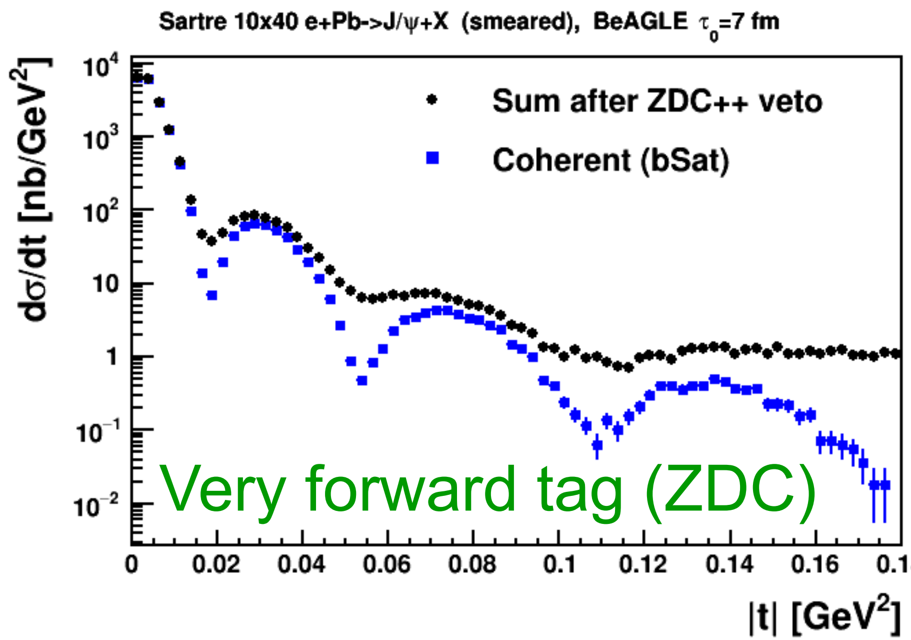
T.T. & Thomas Ullrich
PRC 87 (2013) 024913

EIC will be able to retrieve the spatial gluon distribution with high precision.

IF we can extract the coherent diffraction pattern

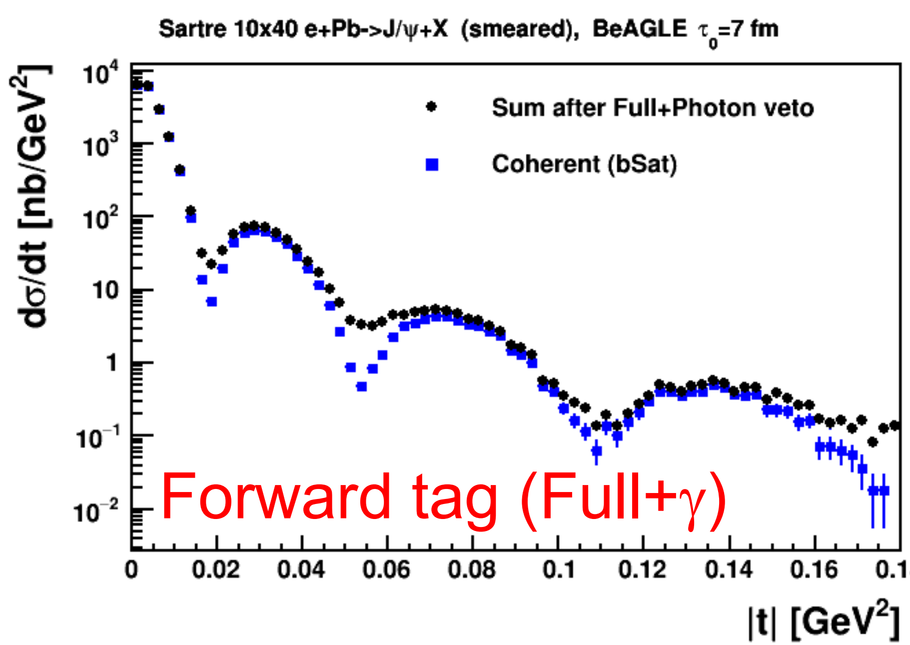
JLEIC veto tagging results (e+Pb)



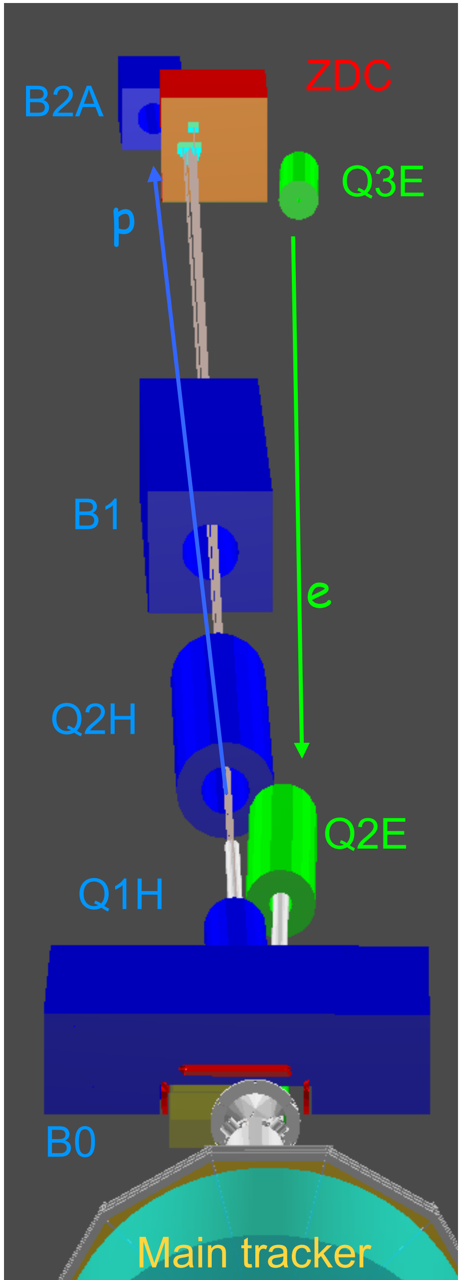


- Veto tagging helps.
- Very forward tag alone is questionable (need 3 dips).

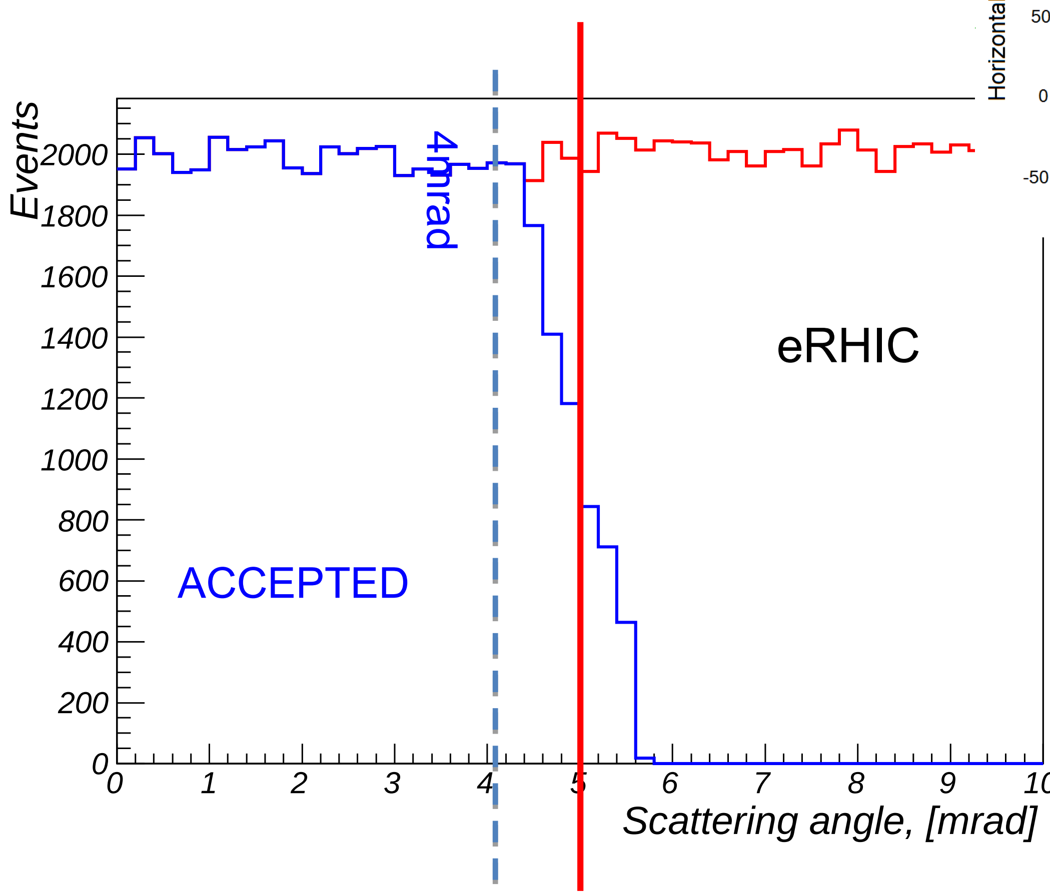
- Forward tag better. Not ideal…
- Still studying impact on G(b) reconstruction.

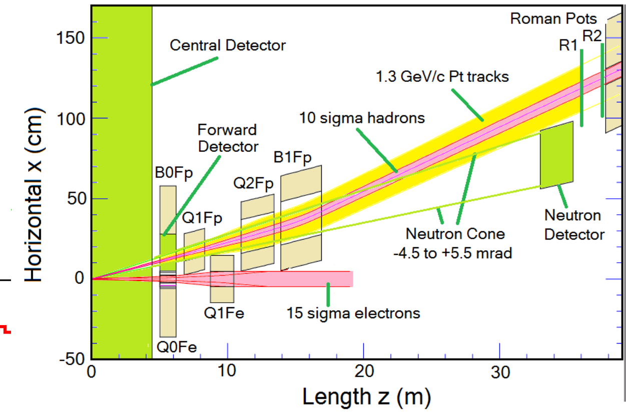


Angular acceptance for neutrons



→ NB: here particles generated flat in θ
→ ZDC is handled as a "black hole" volume



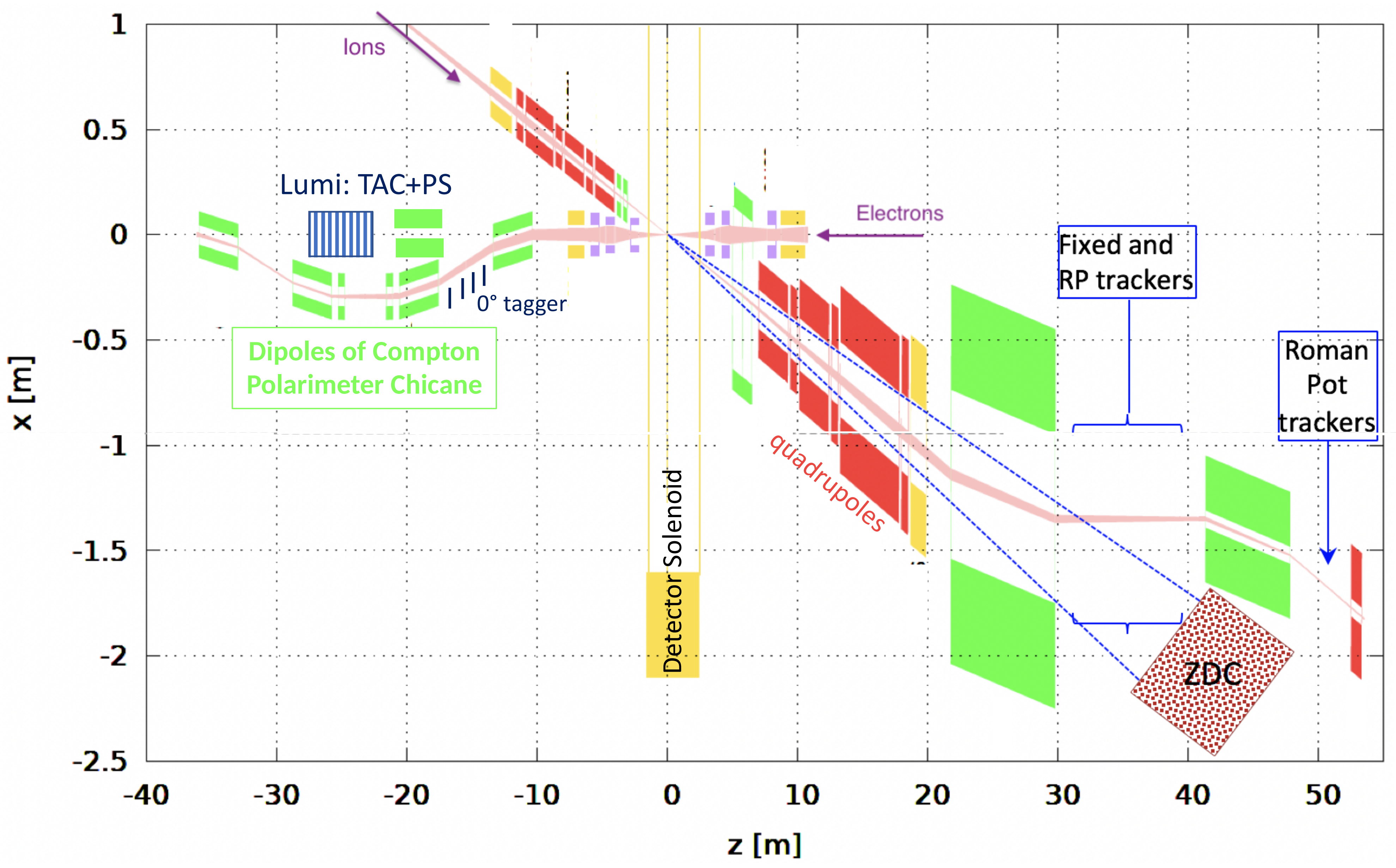


→ NB: space for ZDC needs to be increased for better hadronic shower containment

Achieve the 4 mrad acceptance requirement

From A. Kiselev

JLEIC approach: Large "dispersion"



Fermi momentum at a collider

Longitudinal momentum in the ion rest frame gets magnified by γ

In ion rest frame:

$P^{\mu} = \{M; 0, 0, 0\}$ OR $\{M + E_{kinF}; k_{xF}, k_{yF}, k_{zF}\}$

In lab collider frame:

$P^{\mu} = \{\gamma M; 0, 0, \gamma\beta M\}$ OR $\{\gamma M + \gamma\beta k_{zF} + \gamma E_{kinF}; k_{xF}, k_{yF}, \gamma\beta M + \gamma k_{zF}\}$

Since $\beta \sim 1$ and $E_{kinF} << k_{zF}$:

$E \sim p_z \sim E_{beam}(1 + k_{zF}/M)$

Conceptual problem for e+D w/ large k

Main problem – Everything lives on mass shell.
No remnant to absorb energy-momentum imbalance.

$W^{\mu} = \{\nu + M_d;\ 0,\ 0,\ \mathrm{sqrt}(\nu^2 + Q^2)\}$

$W^{\mu} = \{\nu + E_n + E_p;\ 0,\ 0,\ \mathrm{sqrt}(\nu^2 + Q^2)\}$

Energy not conserved in the ion rest frame (E & p_z fail in other frames)

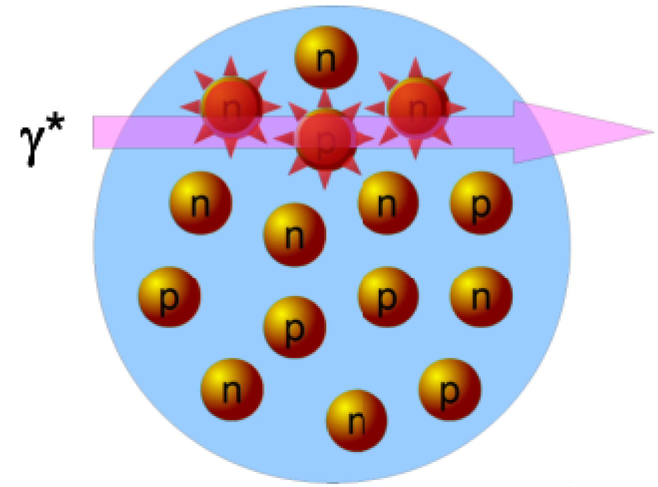
Note: DPMJET3-F has the same problem. Minimized due to minimal p_F.

Must adjust 4-momenta of final state.

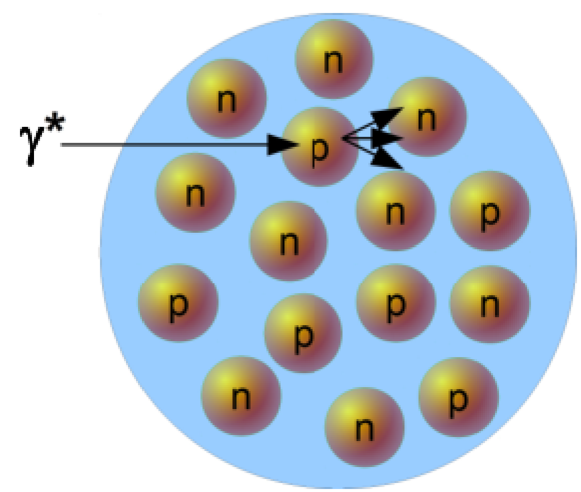
What is "Shadowing" ?

Shadowing can be defined as:

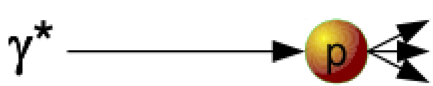
$\sigma(eA) < A\,\sigma(ep)$



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

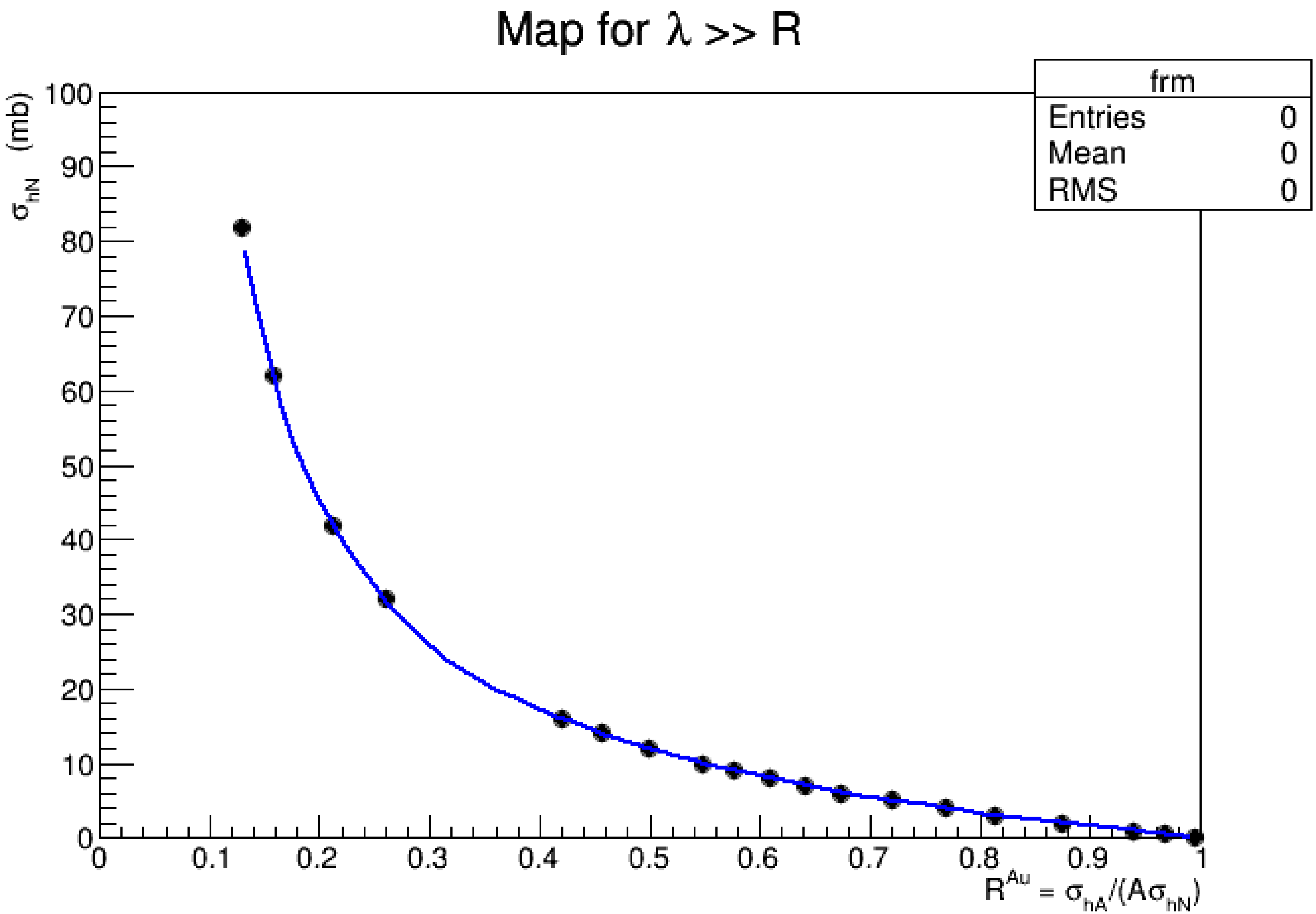


Or by modification of the individual nucleons on a slow timescale, followed by point-like interaction of the probe.



BeAGLE allows both approaches.

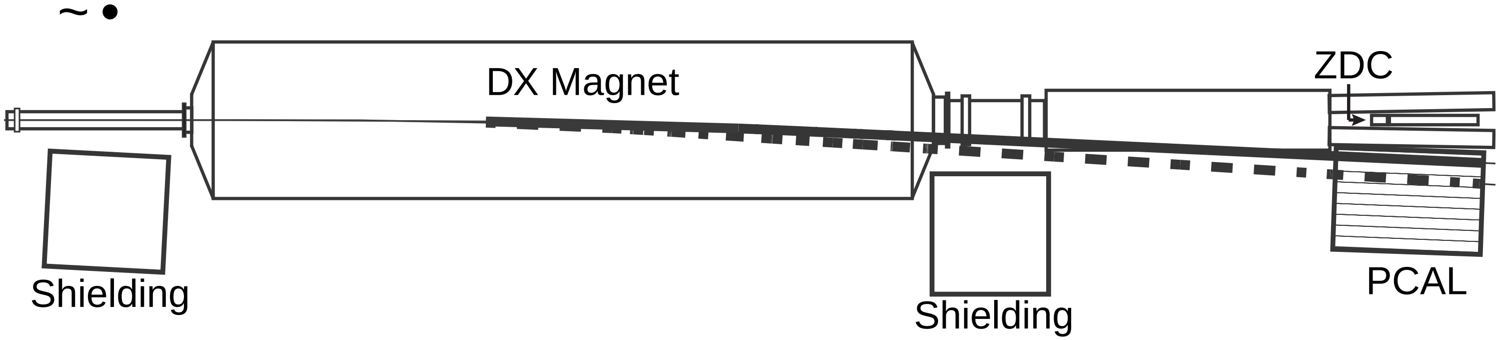
Glauber Map

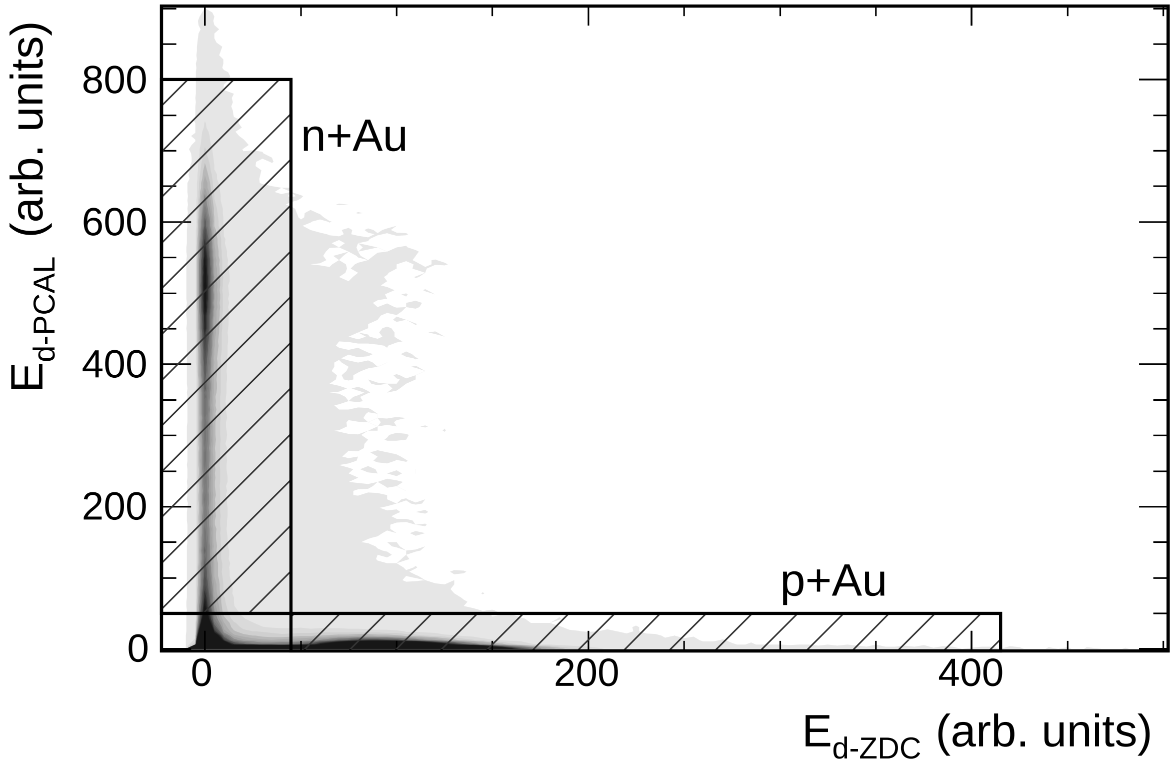


Map for λ >> R
frm
Entries 0
Mean 0
RMS 0
σ_{hN} (mb)
100
90
80
70
60
50
40
30
20
10
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
$R^{Au} = \sigma_{hA}/(A\sigma_{hN})$

Spectator tagging in d+Au

B.B. Back et al., PHOBOS Collaboration, **"Nucleon-Gold Collisions at 200 A·GeV Using Tagged d+Au Interactions in PHOBOS", PRC 92 (2015) 034915**

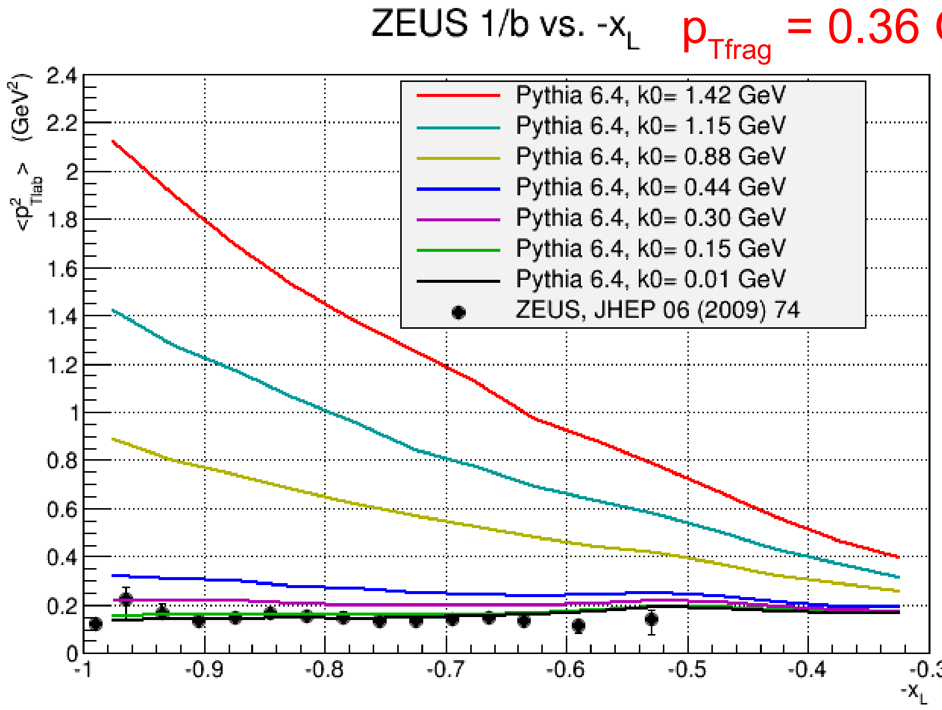


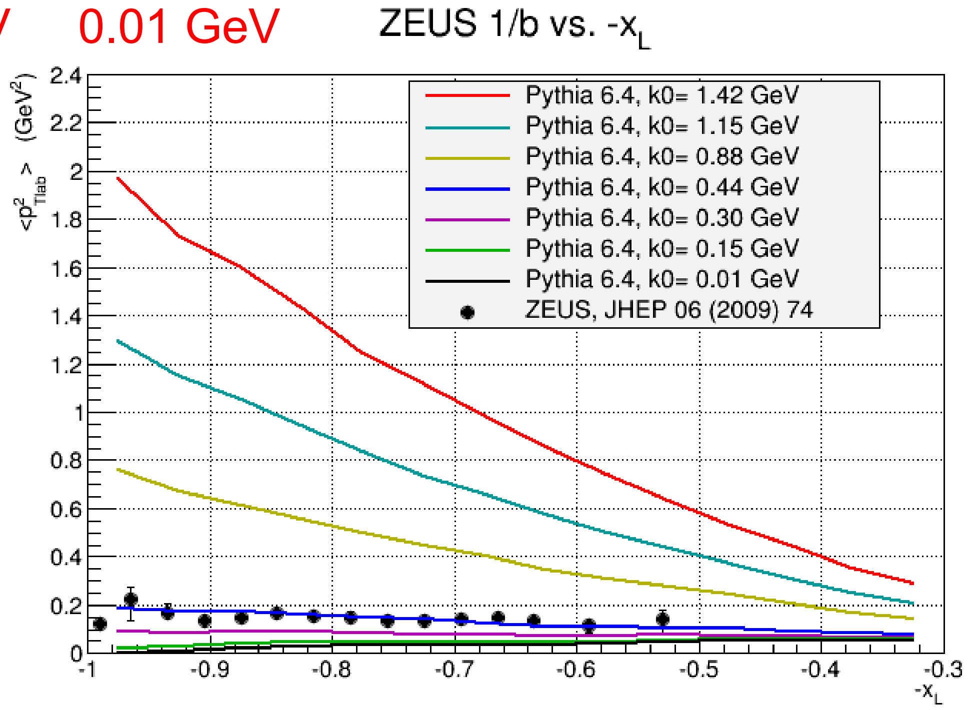


Tune to ZEUS forward proton p_T

PARJ(21) is fragmentation p_T AND beam remnant cluster breakup p_T
PARP(91) is rms intrinsic k_T of partons in the nucleon

p_{Tfrag} = 0.36 GeV 0.01 GeV





p_{Tfrag} = PARJ(21) = 0.36 GeV
k_0=k_T= PARP(91)= 0.01 GeV

p_{Tfrag} = PARJ(21)= 0.01 GeV
k_0=k_T= PARP(91)=0.44 GeV

Tradeoff: In the end we used PARJ(21)=PARP(91)=0.32 GeV

Tune to ZEUS forward proton p_L

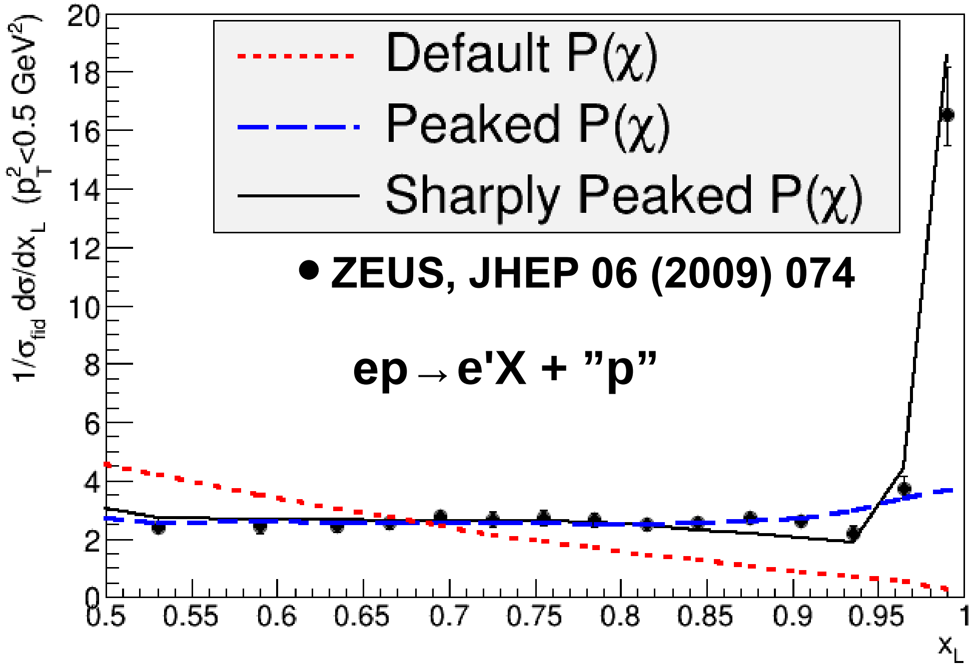
Non-trivial beam remnant clusters fragment into diquark+meson or baryon+quark. The p_L fraction carried by baryon/diquark is called χ.

Tuned P(χ) to better match ZEUS.

	MSTP(94)	PARP(97)	P(χ)
Default	3	-	Frag. function
Peaked	2	9	$10(1-\chi)^9$
Sharply	2	75	$76(1-\chi)^{75}$

In the end we used:
MSTP(94)=2, PARP(97)=6
Matches both forward p & n

σ_{fid} = σ for h+ $0.5<x_L<0.89$, $p_T^2<0.5$ GeV^2



NOTE: <p_T> is NOT affected by P(χ).