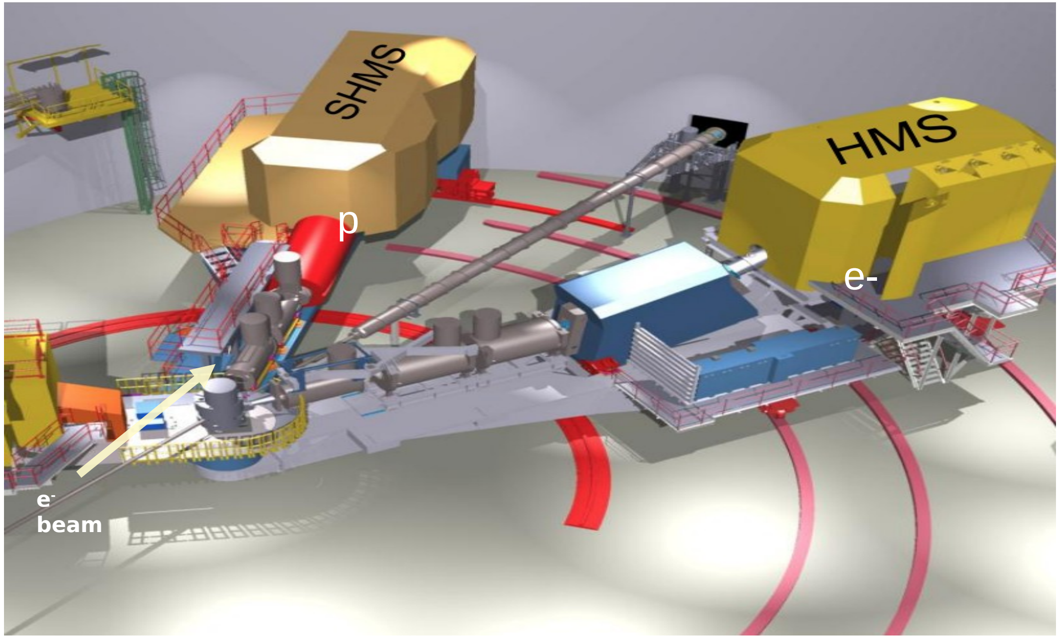
UPDATES ON

COLOR TRANSPARENCY EXPERIMENT

IN HALL C, JEFFERSON LAB



Deepak Bhetuwal

Mississippi State University

Jan 28, 2020

Hall C Users Meeting, Jan 28-29, 2020

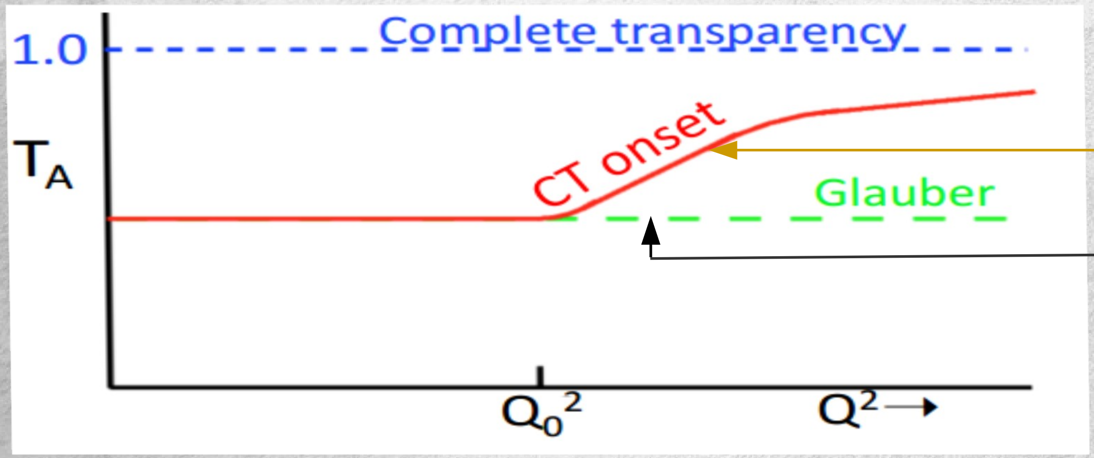
OUTLINE

- Color Transparency Introduction and History
- CT Past Experiments
- Jefferson Lab Experiment E12-06-107
- Data VS Simulation (SIMC)
- Detector Calibration
- Detector Efficiency
- Preliminary Result
- Summary

COLOR TRANSPARENCY

Color transparency (CT) is a a unique prediction of Quantum Chromo Dynamics (QCD) where the final (and/or initial) state interactions of hadrons with the nuclear medium are suppressed for **exclusive processes** at high momentum transfers squared(Q^2).

A clear signal for the onset of CT for baryons would show the transition from the nucleon-meson picture to quark-gluon degrees of freedom → **Onset is signature for QCD degrees of freedom in nuclei.**



QCD prediction

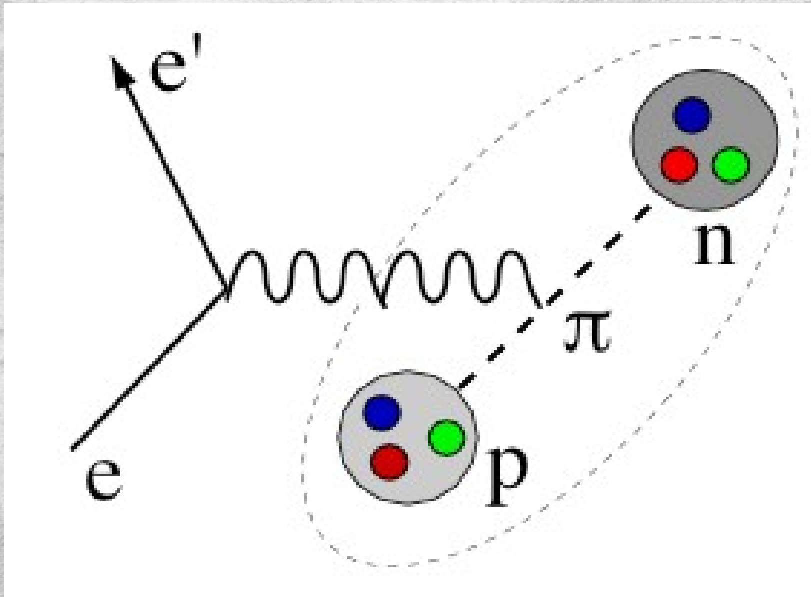
Traditional nuclear physics prediction

OR

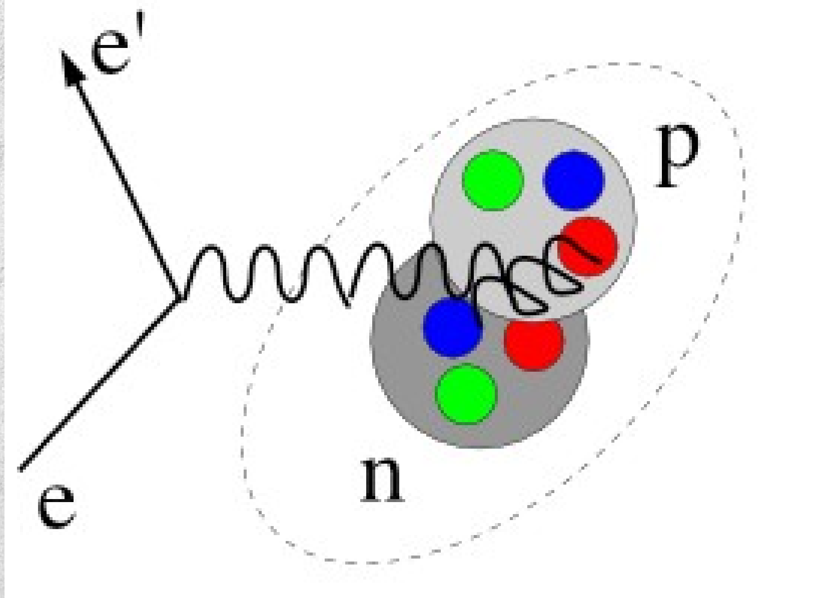
Conventional Glauber calculations predict constant T with increasing Q^2 (Energy independent).

TRANSITION

Mapping the transition from the nucleon-meson degrees of freedom to the quark-gluon degrees of freedom of QCD.



Nucleon-meson degrees of freedom effective at low energies



Quark-gluon degrees of freedom at high energies

Exclusive processes (processes with completely determined initial and final states), are used to study the transition region.

HOW TRANSPARENT IS YOUR NUCLEUS?

Exclusive Processes

Nucleons

$A + B \rightarrow C + D$

$\Downarrow$

N

Nuclei

$A + B \rightarrow C + D + X$

$\Downarrow$

$^{A}N_{Z}$

Exclusive processes on nucleons and nuclei is used to measure transparency of nuclei

NUCLEAR TRANSPARENCY

$$T_A = \frac{\sigma_A}{A\,\sigma_N}$$

(nuclear cross section)

(free nucleon cross section)

$\sigma_A/A \rightarrow$ bound nucleon cross section

Ratio of cross-sections for exclusive processes from nuclei to nucleons is termed as Transparency

σ_A is parameterized as $= \sigma_N A^{\alpha}$

Experimentally α = 0.72 – 0.78, for π, κ, p

GLAUBER NUCLEAR TRANSPARENCY

Traditional nuclear physics calculations (Glauber calculations) predict transparency to be energy independent .

Ingredients

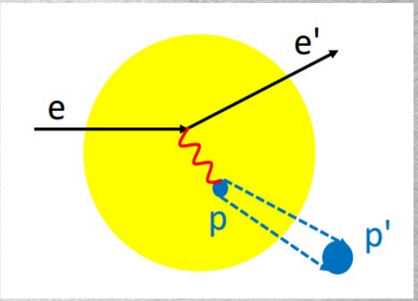
- σ_{hN} (h-N cross-section)
- Glauber multiple scattering approximation
- Correlations & FSI effects.

CT PHENOMENA

Introduced by Mueller and Brodsky, 1982. It arises in picture of quark-gluon interactions only.

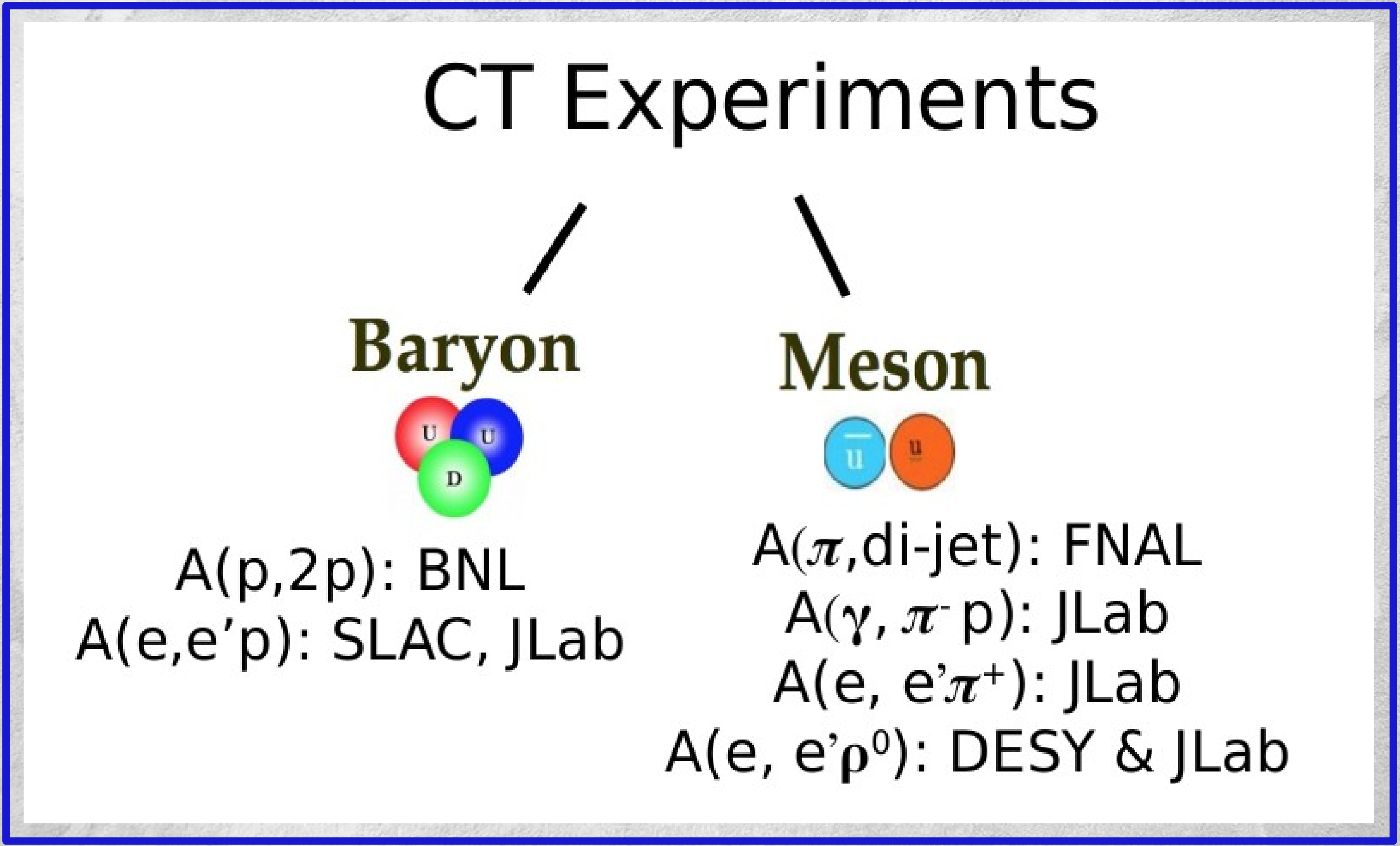
Basically, CT takes place in the following 3 steps:

(1) The formation of a small-sized wave packet in a high momentum transfer reaction (PLC Creation).
(2) The interaction between such an object and nucleons is suppressed (color neutrality or screening).
(3) If the wave packet escapes the nucleus while still small, no or reduced FSI occur.



A(e, e’p)

CT PAST EXPERIMENTS



CT PAST RESULTS – FERMI LAB

CT is well established at high energies.

500 GeV π^+ + Pt ⟶ 2 Jets

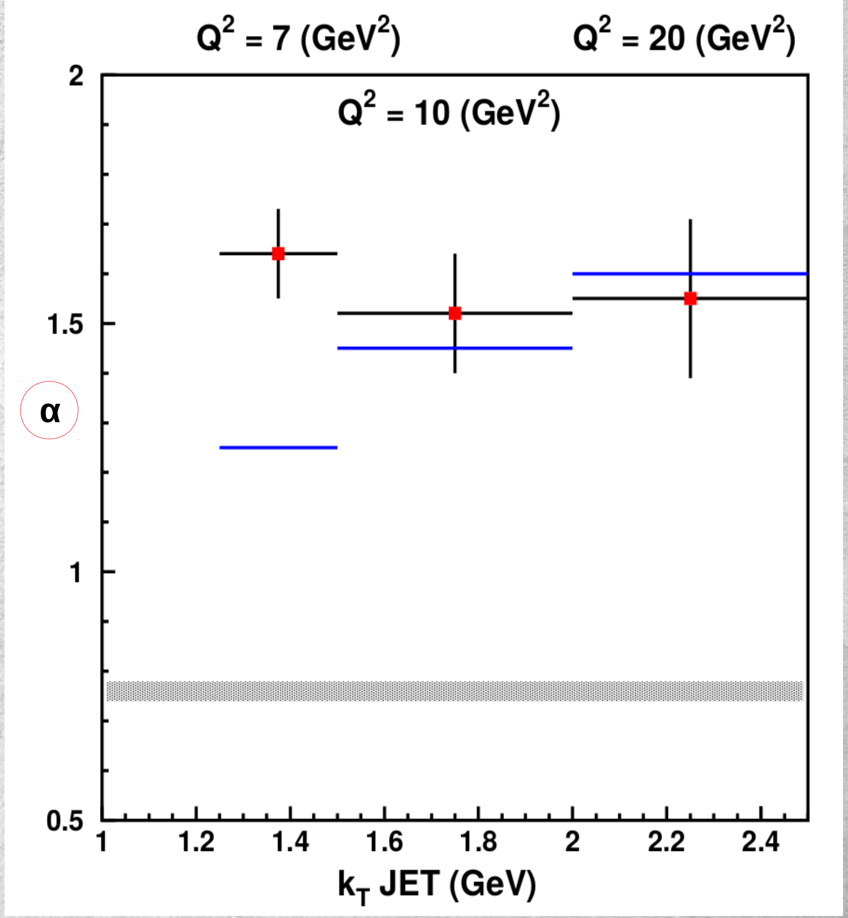
$$\sigma_A = \sigma_N A^{\alpha}$$

Experimentally α = 0.72 - 0.78 for π, κ, p

σ_A is Nuclear cross section

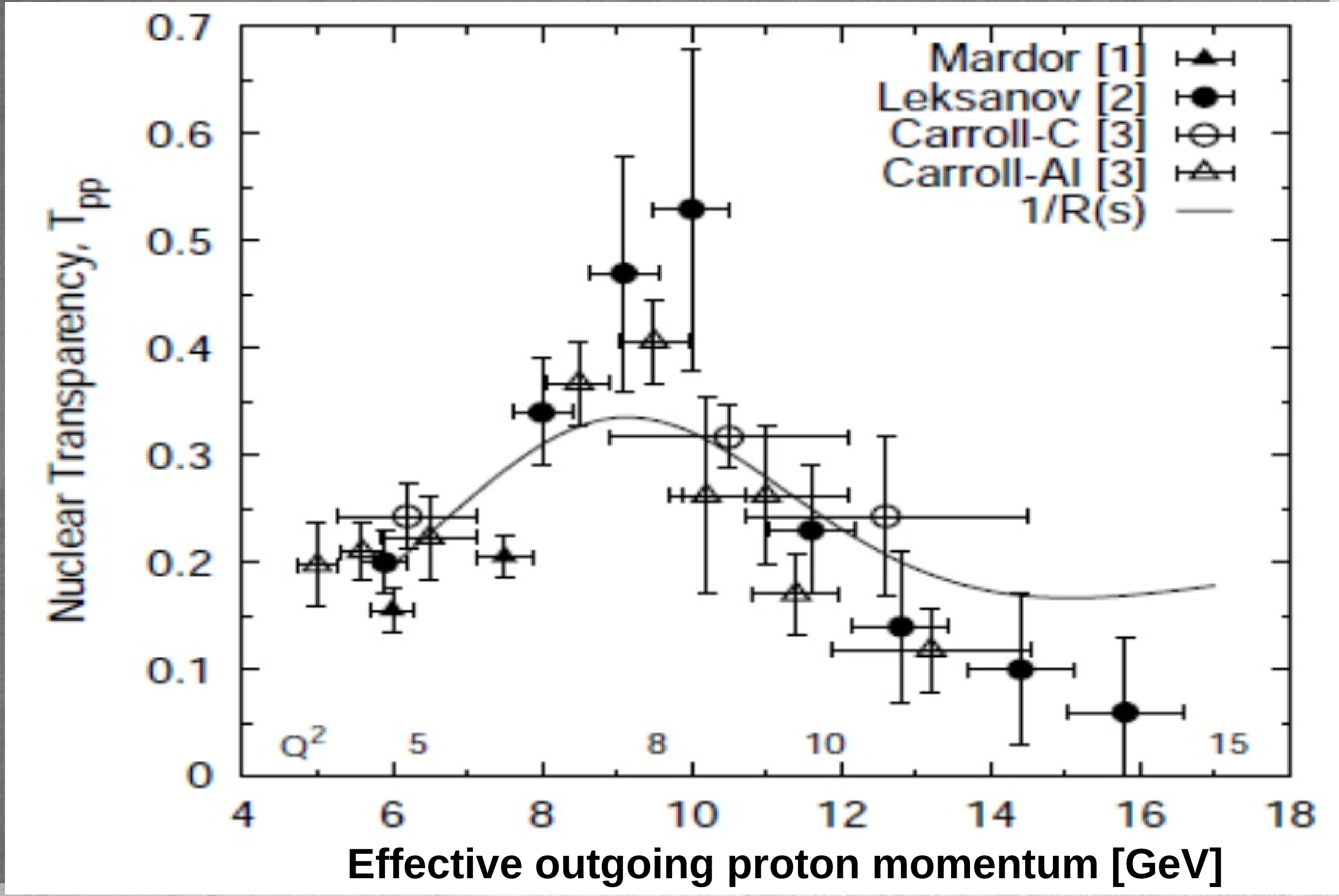
σ_N is free nucleon cross section

Coherent diffractive dissociation of pions at Fermi Lab



Source: Color Transparency: past, present and future
D. Dutta, K. Hafidi, M. Strikman

CT PAST RESULTS [BNL A(P,2P)]



A. Leksanov et al. PRL 87 (2001)
J. L. S. Aclander et al., PRC 70 (2004)

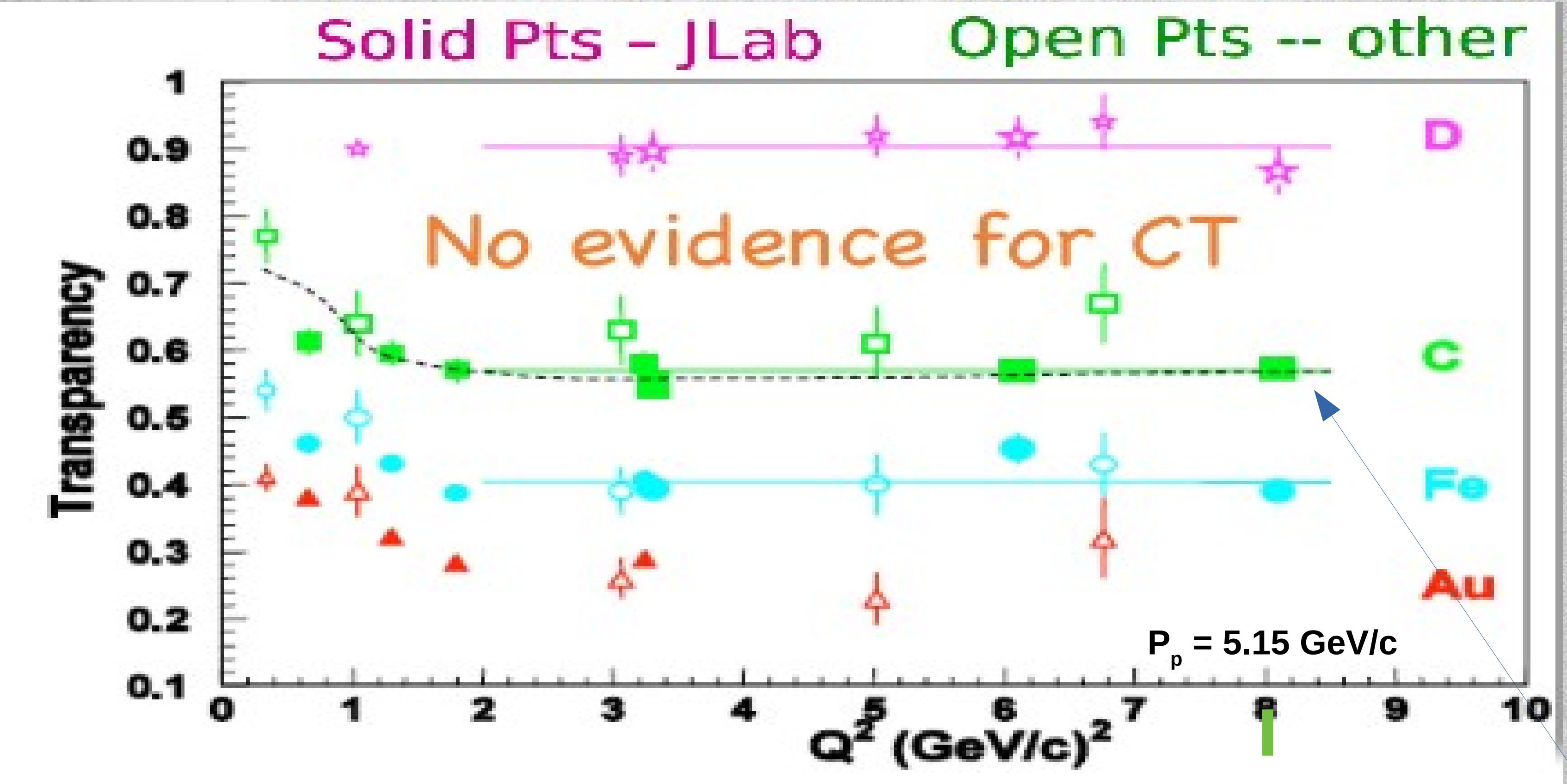
(p, 2p) experiment at BNL found an enhancement in the transparency.

Decreases at higher momentum.

Result inconsistent with CT only.

Can be explained by including additional mechanisms such as nuclear filtering or charm resonance.

CT PAST RESULTS [A(e,e'P)]



N. C. R. Makins et al. PRL 72, 1986 (1994)
G. Garino et al. PRC 45, 780 (1992)
D. Abbott et al. PRL 80, 5072 (1998)
K. Garrow et al. PRC 66, 044613 (2002)

Plateau consistent with conventional calculations ...

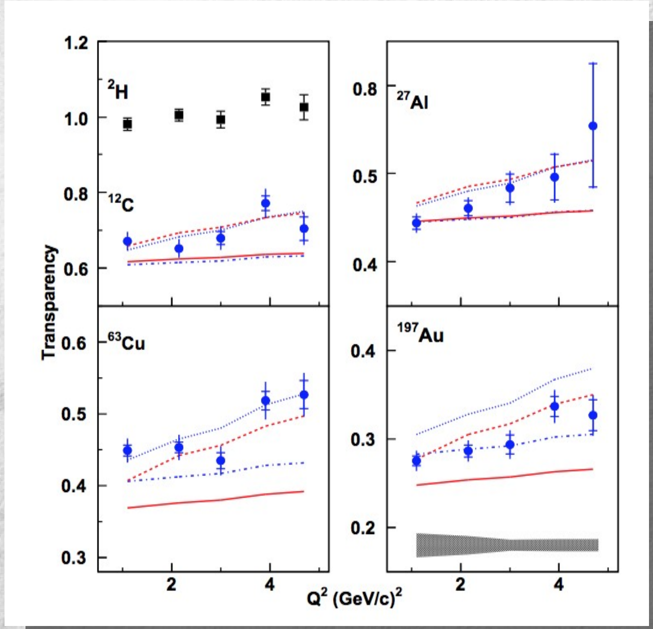
CT PAST RESULTS - MESONS

CT is well established at high energies. Onset of CT has been measured in Mesons but not in Baryons.

PION - A(e, e'π)

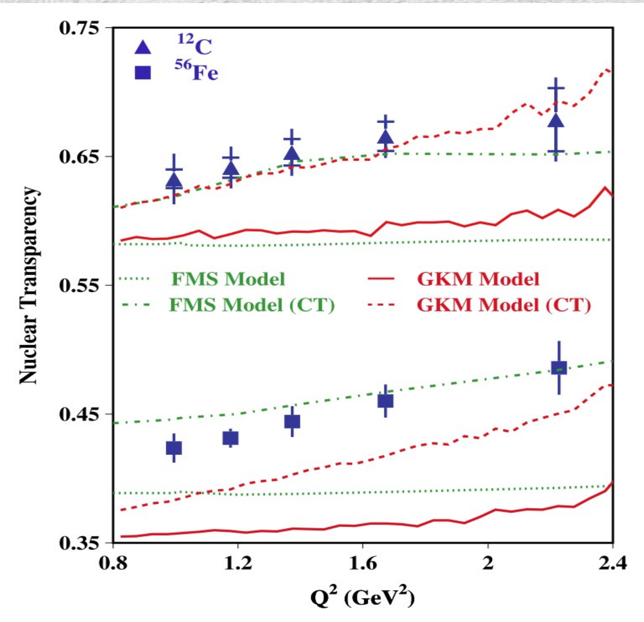
RHO - A(e, e'ρ)

Hall C E01-107 pion electroproduction



B.Clasie *et al.* PRL 99:242502 (2007)

X. Qian *et al.* PRC81:055209 (2010)



L. El Fassi *et al.* PLB 712,326 (2012)

CLAS E02-110 rho electroproduction

CT EXPERIMENT: E12-06-107

First experiment to run in Hall C in the 12 GeV era to take data using the new magnetic spectrometer SHMS (Super High Momentum Spectrometer) along with HMS (High Momentum Spectrometer)!

The experiment E12-06-107, to search for color transparency (CT) in protons, ran in Hall C at JLab in Spring 2018.

Coincidence trigger: SHMS measures Protons, HMS measures electrons.

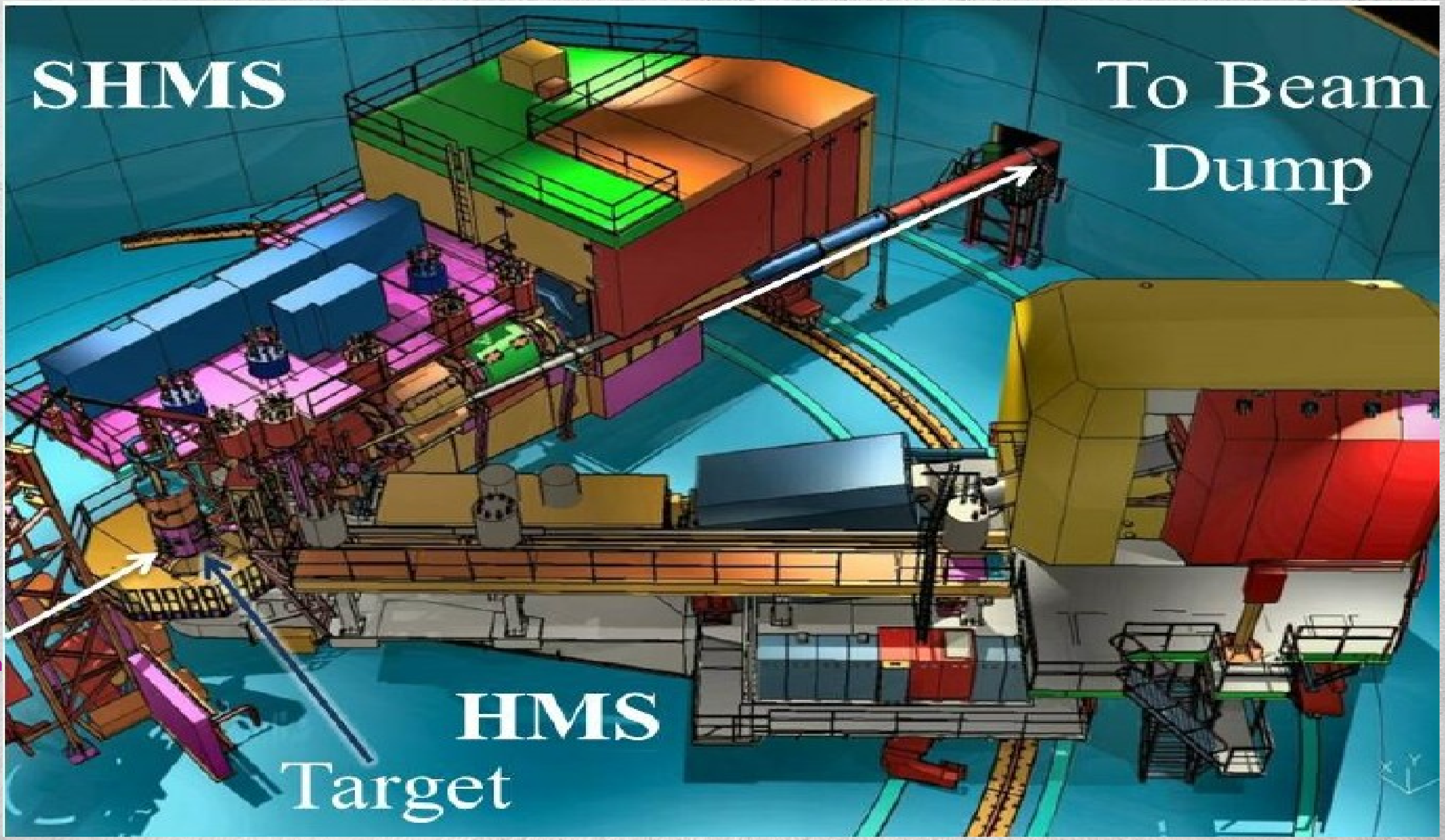
Targets: 10 cm LH_2 (Elementary process, Hee'p check), 6% radiation length (r.l.) ^{12}C (production), Al dummy (background).

~20 days of data taking with E_{beam} of 6.4 GeV and 10.6 GeV and up to 60 uA of beam current.

Data collected over a wide range of 4 Q^2 points covering the region where a previous A(p,2p) experiment at BNL had observed an enhancement.

	Q^2 [GeV^2]	SHMS angle [deg]	SHMS central P [GeV/c]	HMS angle [deg]	HMS central P [GeV/c]
6.4 GeV beam	8.0	17.1	5.122	45.1	2.131
10.6 GeV beam	9.5	21.6	5.925	23.2	5.539
	11.5	17.8	7.001	28.5	4.478
	14.3	12.8	8.505	39.3	2.982

EXPERIMENTAL HALL C

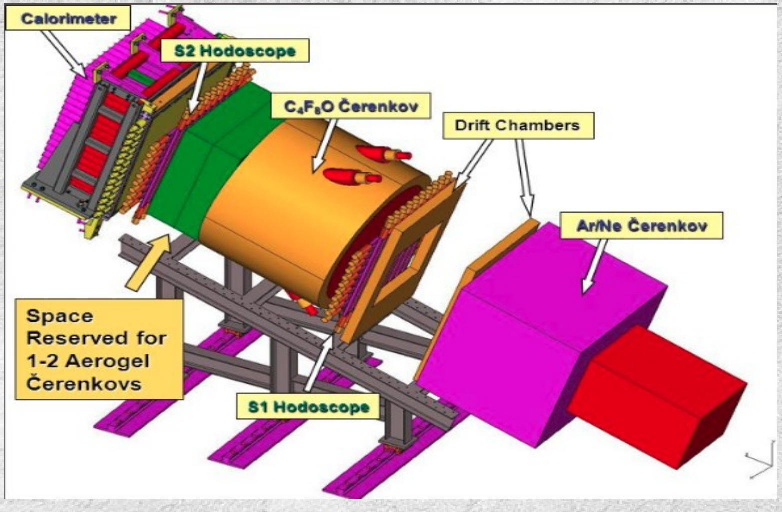


e-
beam

DETECTOR HUT

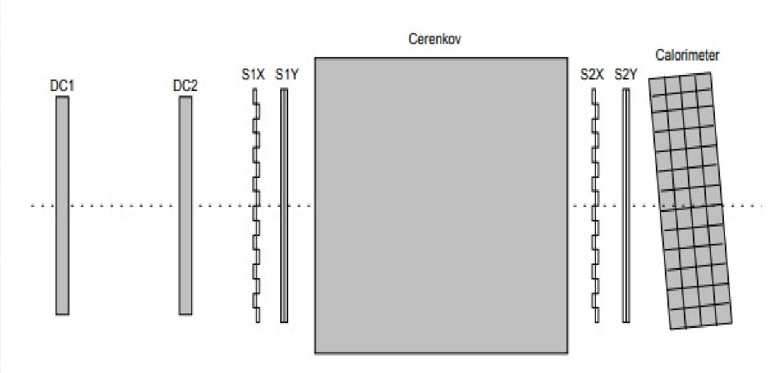
SHMS HUT

Drift Chambers (DC)
Hodoscopes (HODO)
Cerenkovs (HGC,NGC & Aerogel)
Calorimeter (CAL)



HMS HUT

Drift Chambers (DC)
Hodoscopes (HODO)
Cerenkovs (Gas, Aerogel)
Calorimeter (CAL)

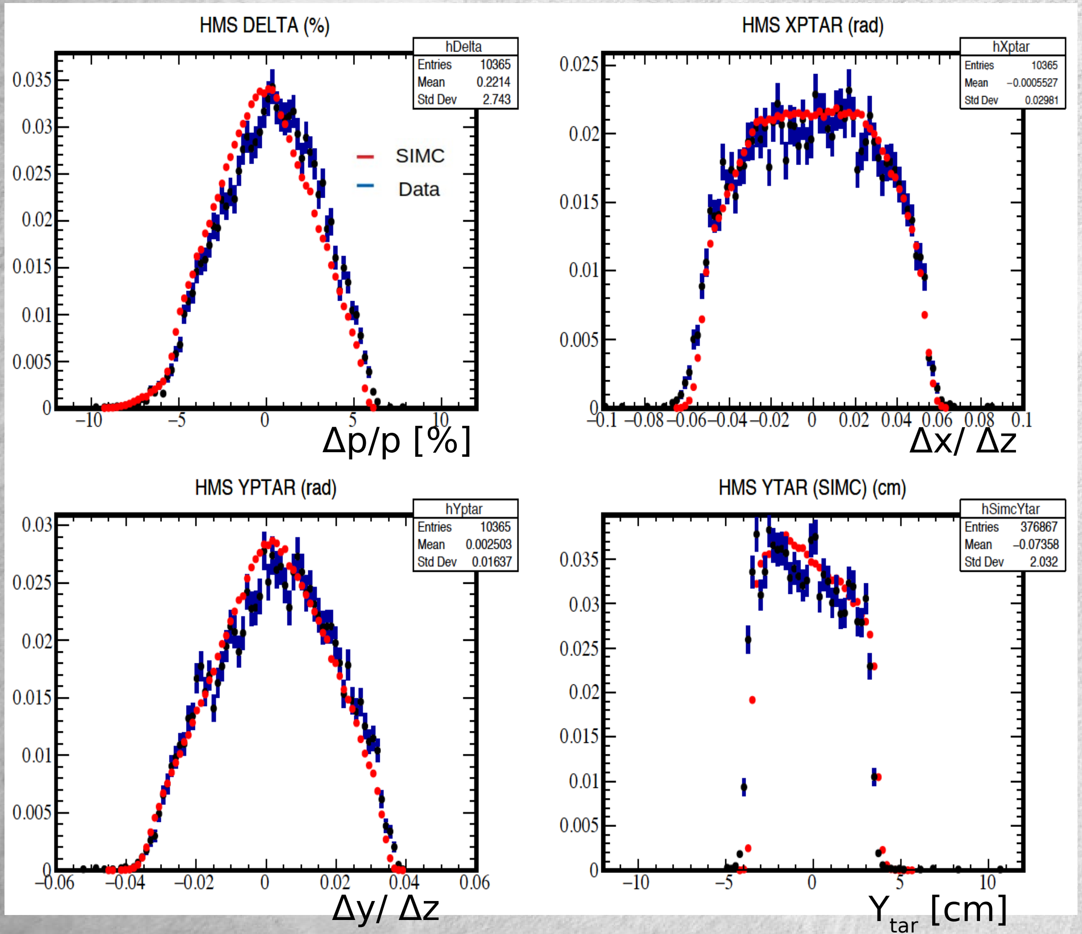


SIMULATION AND DATA

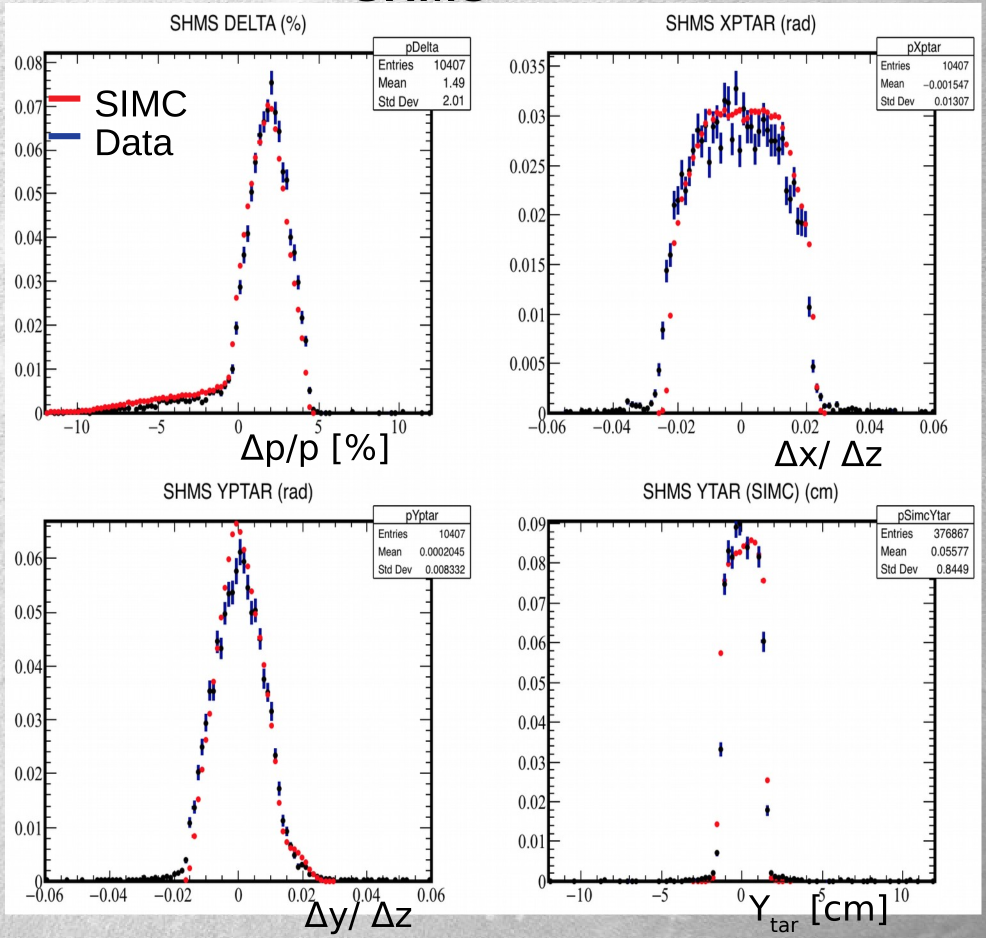
SPECTROMETER QUANTITIES

Hydrogen: $Q^2 = 8\ GeV^2$

HMS



SHMS

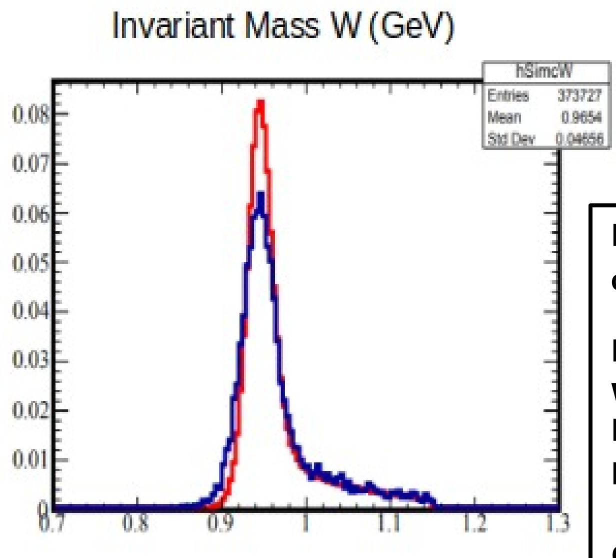


SIMULATION AND DATA

PHYSICS QUANTITIES

$Q^2 = 8\ GeV^2$

Hydrogen

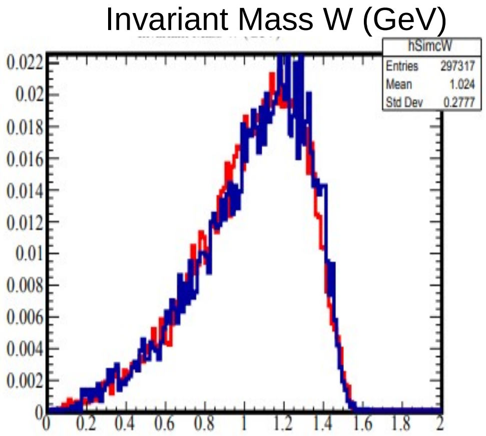


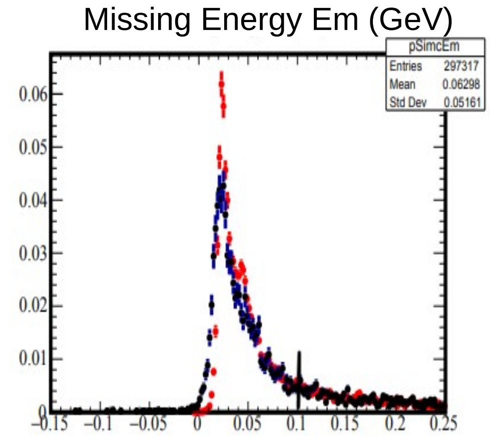
SIMC

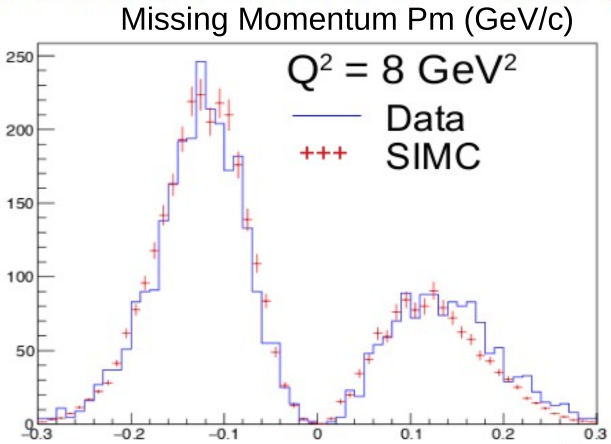
Data

- E_m - missing energy
- ω - energy transfer in lab frame
- P_m - missing momentum
- W - invariant mass
- E_b - beam energy
- E_f - final energy of scattered electron
- q - 3-momentum transfer
- P' - momentum of the struck proton
- Q^2 - 4-momentum transfer squared
- T_p - kinetic energy of struck proton
- T_{A-1} - kinetic energy of the residual A-1 nucleus

$$E_m = \omega - T_p - T_{A-1}$$
$$\omega = E_b - E_f$$
$$W = \mathrm{sqrt}\,(q^2 - Q^2)$$
$$\vec{p}_m = \vec{p}\,' - \vec{q}.$$

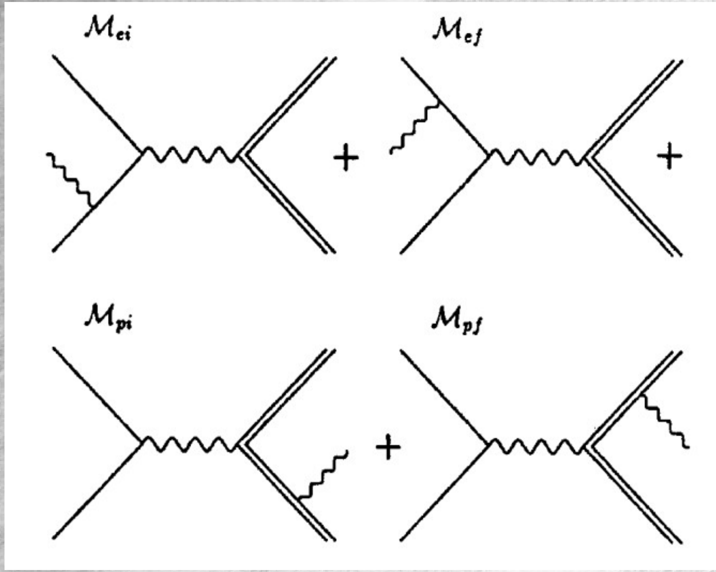


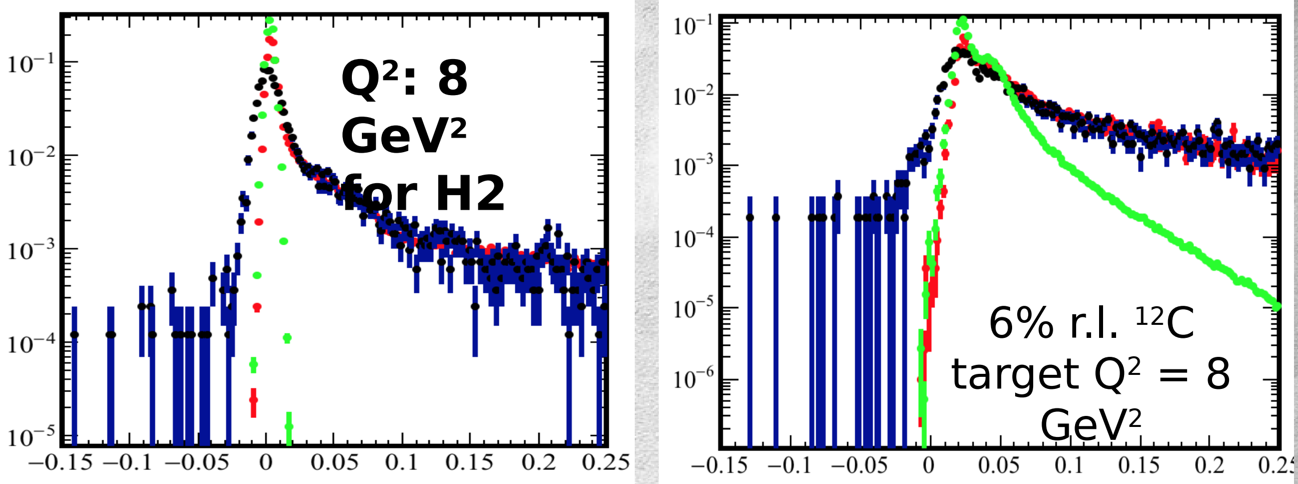




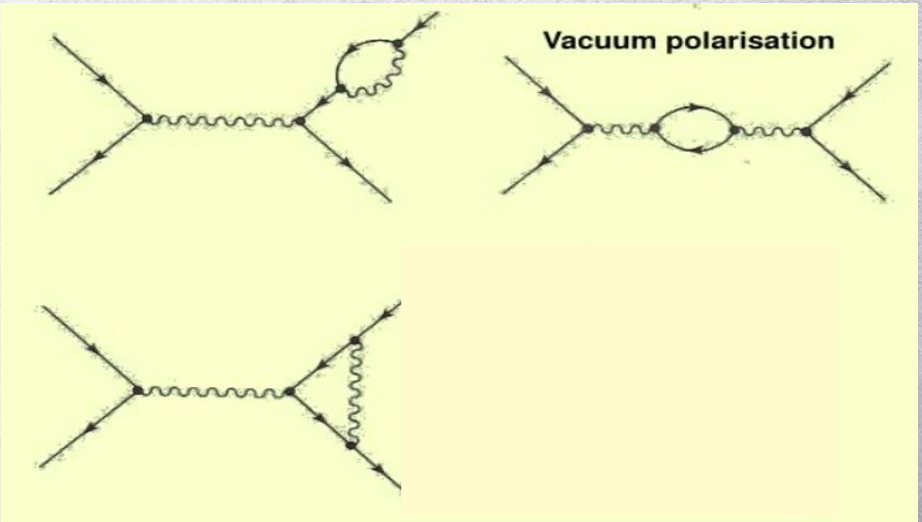
Carbon

SIMC AND DATA





Hydrogen and Carbon radiative tails: Emiss spectra

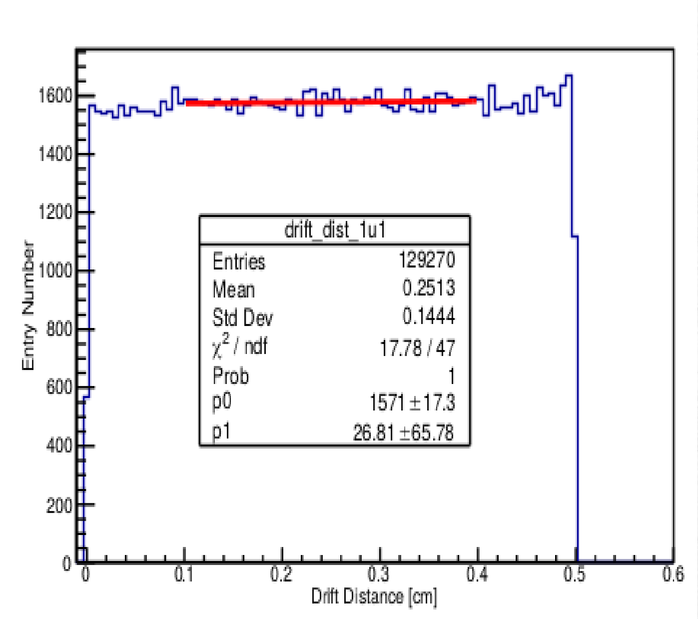


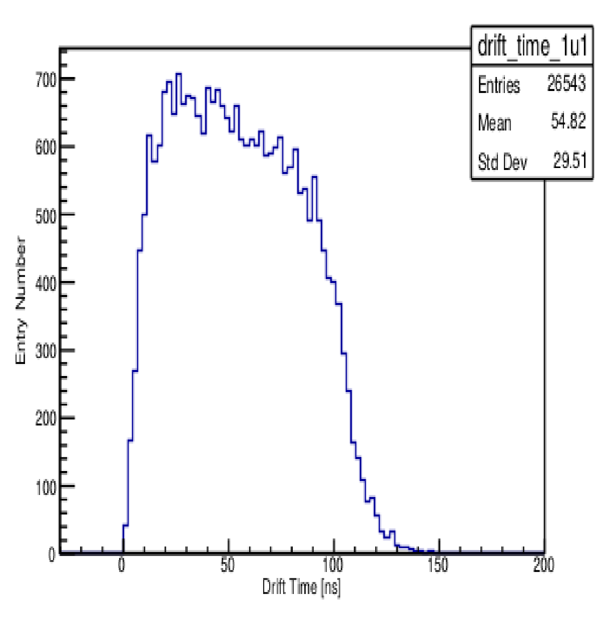
- Data
- MC with radiative effects
- MC without radiative effects

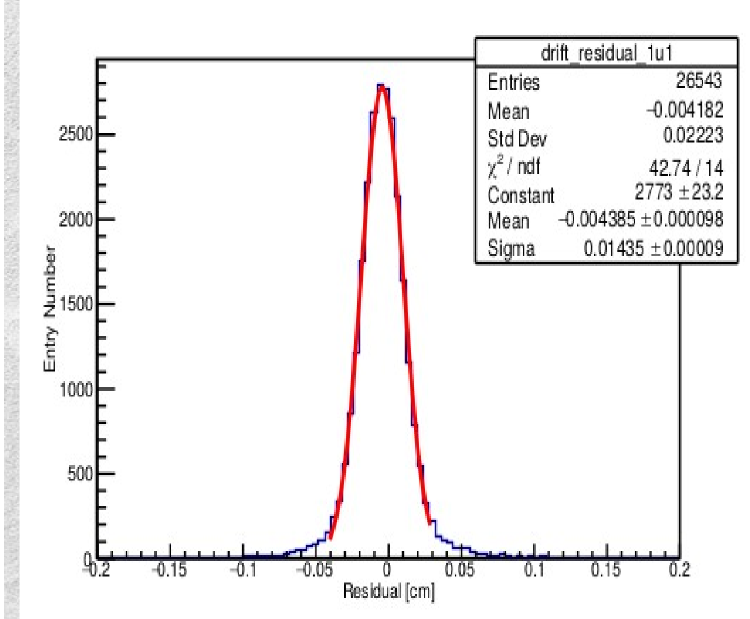
Radiative effect is in agreement with PWIA model in Monte Carlo (SIMC). Radiative effects agree with simulation in the tails.

CALIBRATION PLOTS

DRIFT CHAMBER CALIBRATION [Super High Momentum Spectrometer (SHMS)]





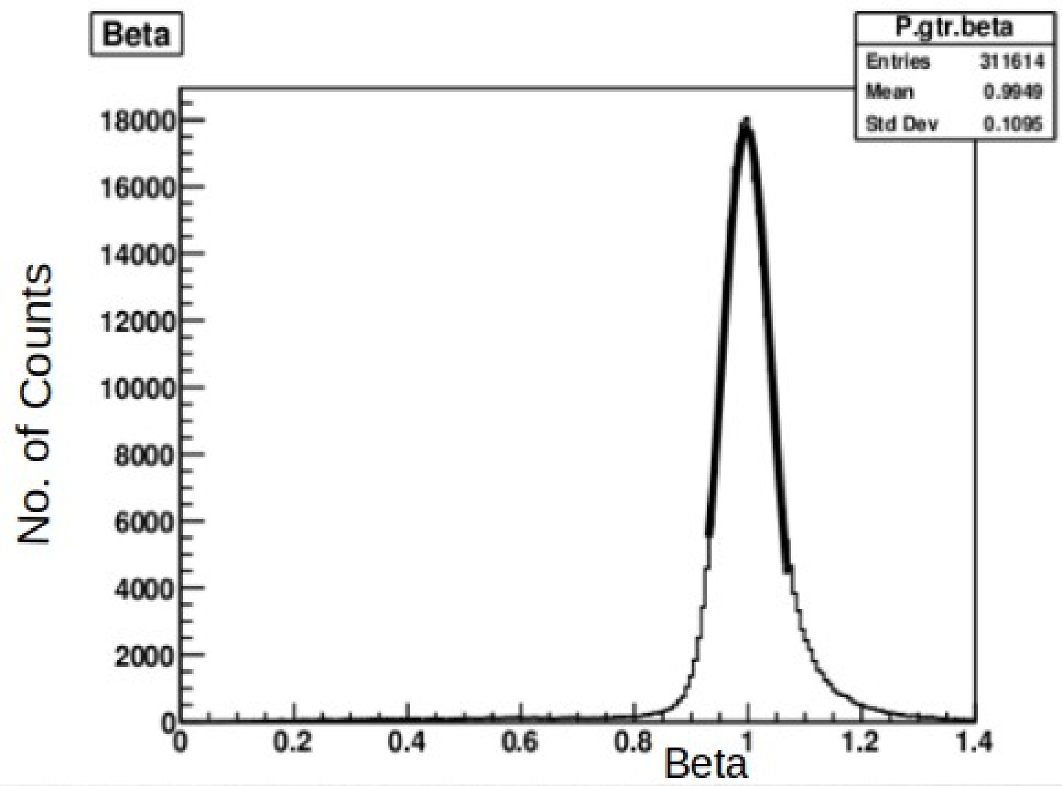


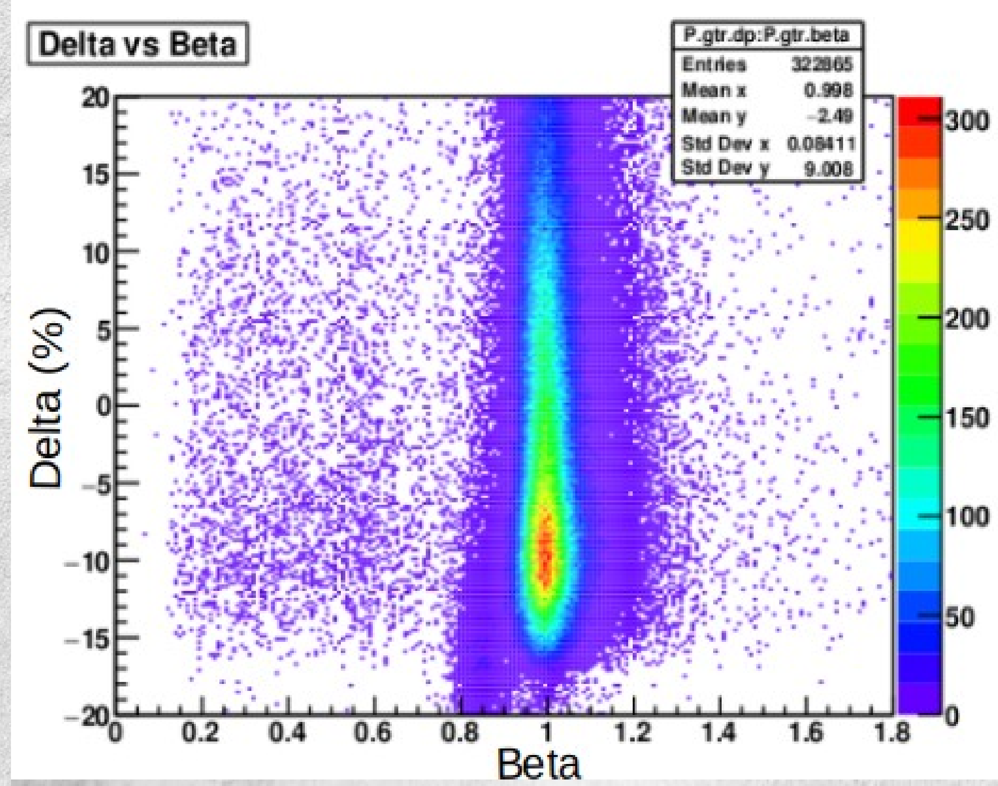
Drift distance: The distance a ionized particle has to traverse across a cell i.e. from the edge of a cell into the sense wire. The distribution should look flat with the fitted slope ~0.

Residual: Difference between the final track position and the hit location from an individual plane. The tracking resolution of the plane is given by the width of the distribution, sigma.

CALIBRATION PLOTS

HODOSCOPE CALIBRATION (SHMS)

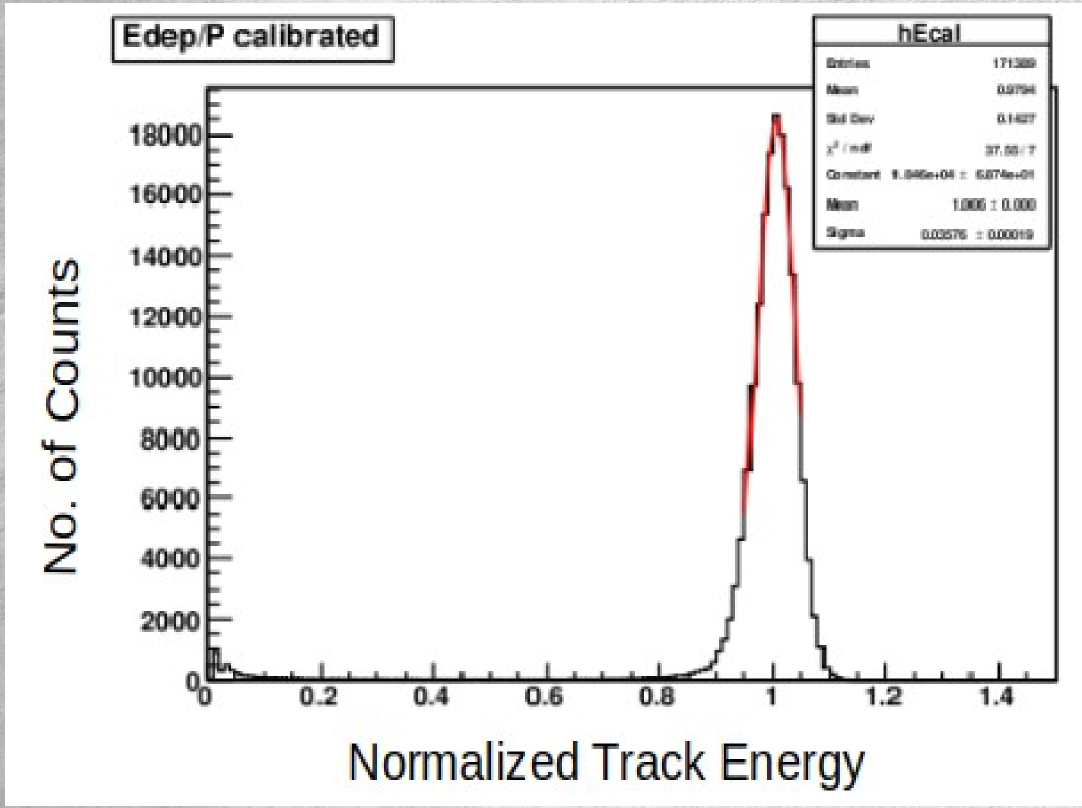


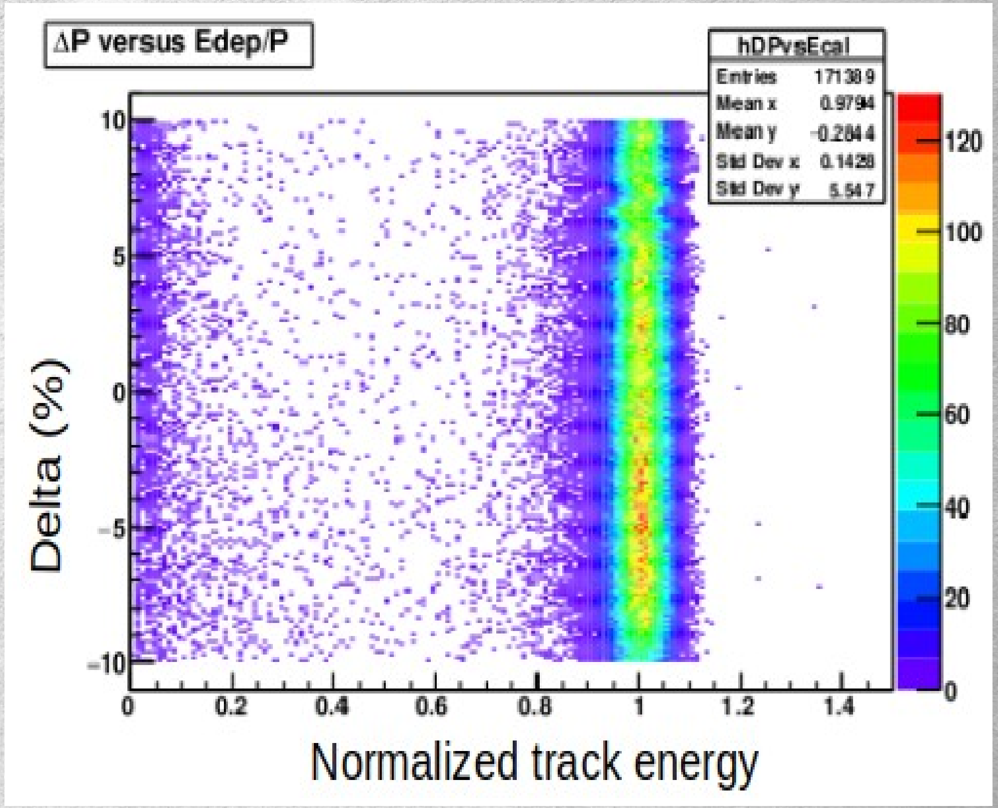


Beta: Beta (p/E) calculated from TOF should be peaked at 1 with the minimum width possible and should be independent to delta (dp/p) and position of the hit.

CALIBRATION PLOTS

CALORIMETER CALIBRATION (SHMS)





Normalized Track Energy (E_tottracknorm = E_{dep}/p): NTE should be peaked at 1 with the minimum width possible and should be independent to delta and position of the hit.

COINCIDENCE TIME

relative time difference between e- and p at the target

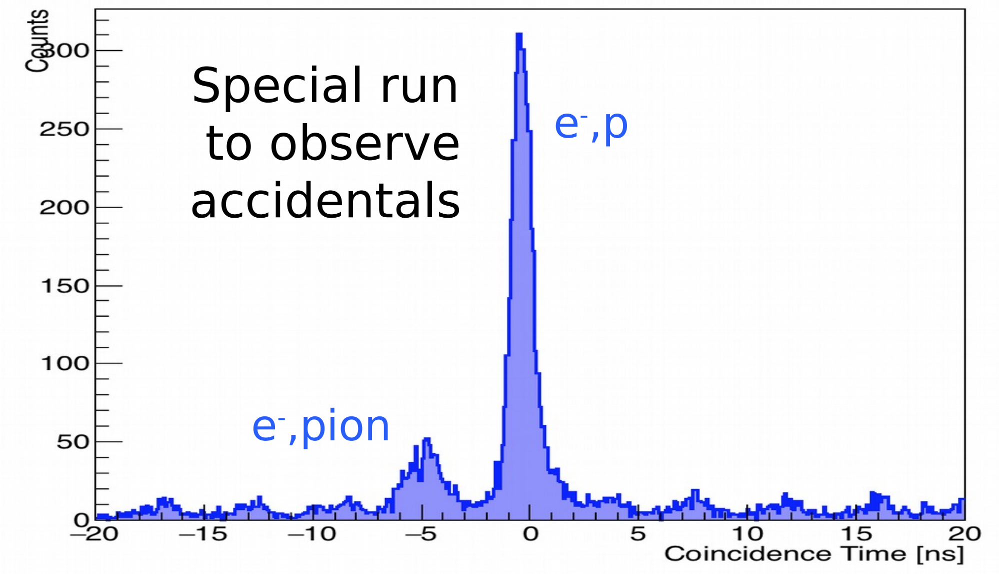
General coincidence time: $t_{coin} = t_e^{tar} - t_p^{tar}$

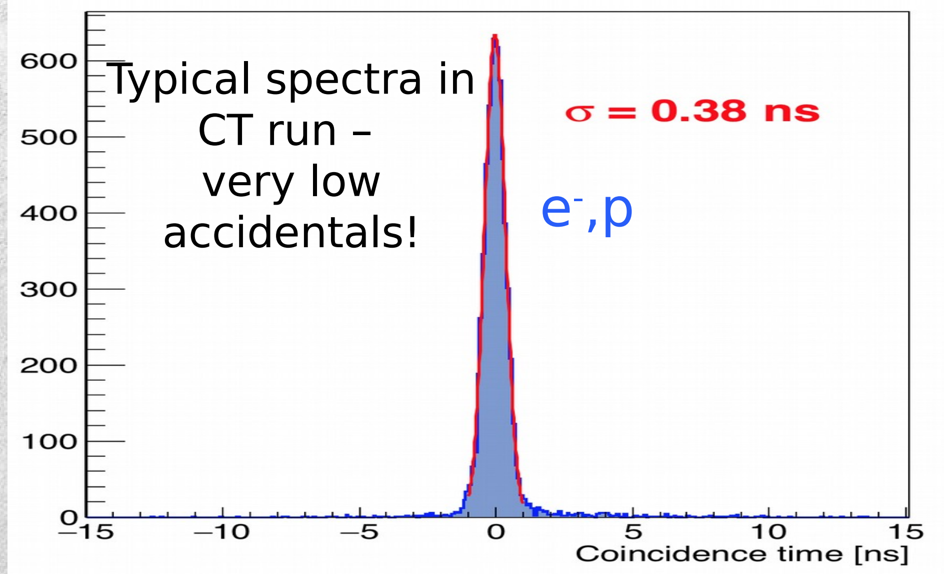
The time of each particle: $t_{e,p}^{tar} = (t_{e,p}^{trigger} - \Delta t_{e,p}^{corr})$

Each particle time corrected for:

- Particle traveling along central ray to focal plane
- Path length variations
- Difference in time between hodoscope start and focal plane time

Coincidence time spectra:





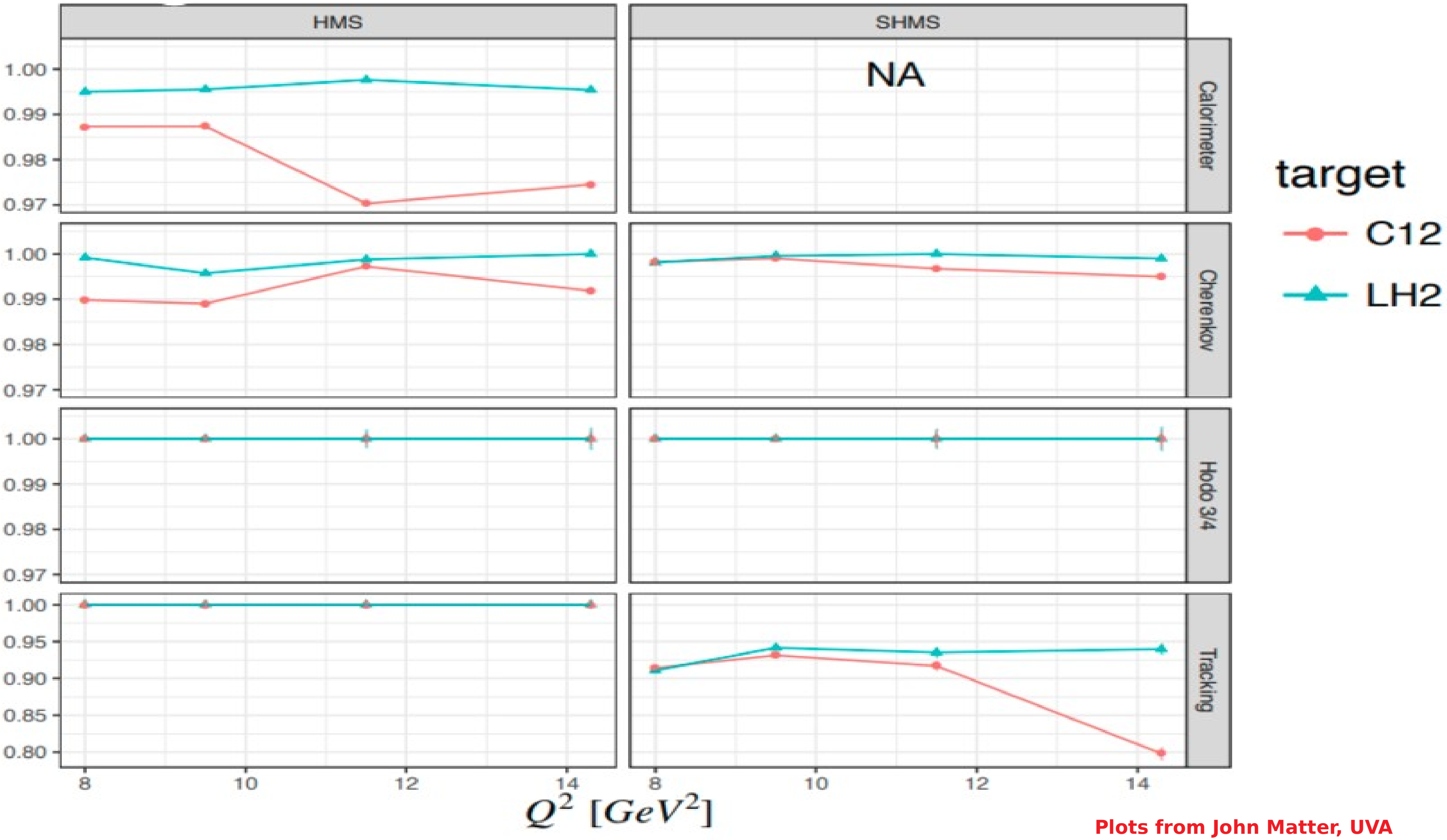
CUTS

Cut	Value
HMS delta	-8%<delta<8%
SHMS delta	-10%<delta<20%
SHMS cerenkov	<0.1 photoelectrons
SHMS beta	0.6<beta<1.4
HMS beta	0.8<beta<1.2
HMS cerenkov	>0 photoelectrons
HMS calorimeter	0.80<E/P<1.15
W	0.85<W<1.03 (upper limit different for Q^2)
E_{miss}	<0.1 GeV (For H2); <0.08 GeV (For C12);
abs(P_{miss})	<0.1 GeV (For H2); <0.3 GeV (For C12);

DETECTOR EFFICIENCIES

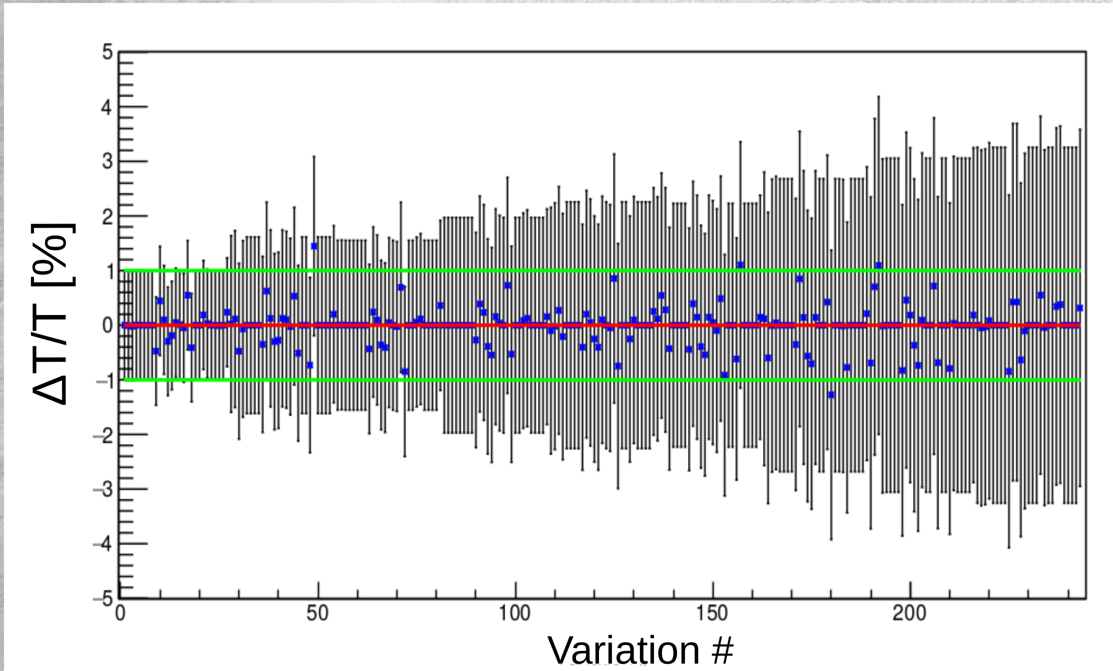
Calorimeter, Cherenkov, hodo 3/4 mostly ~99%

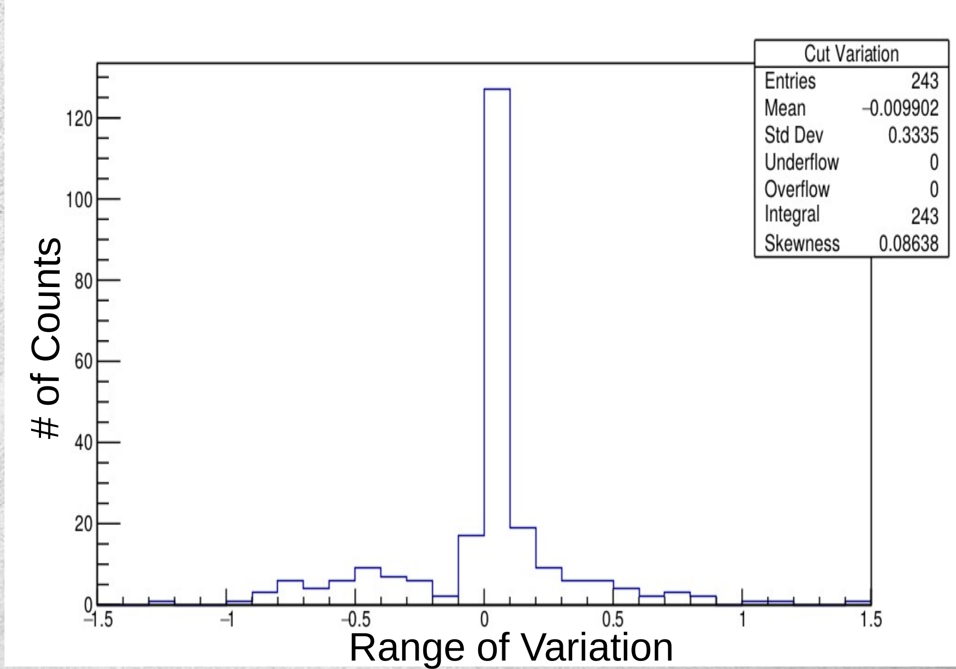
SHMS tracking efficiency is 80—95%



Plots from John Matter, UVA

CUT VARIATION EFFECT

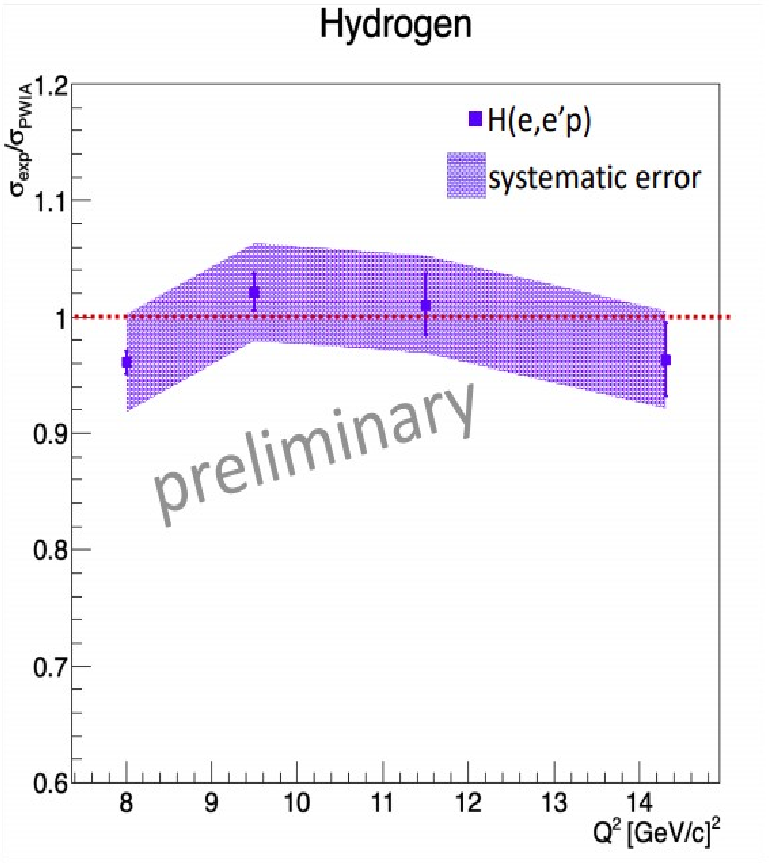




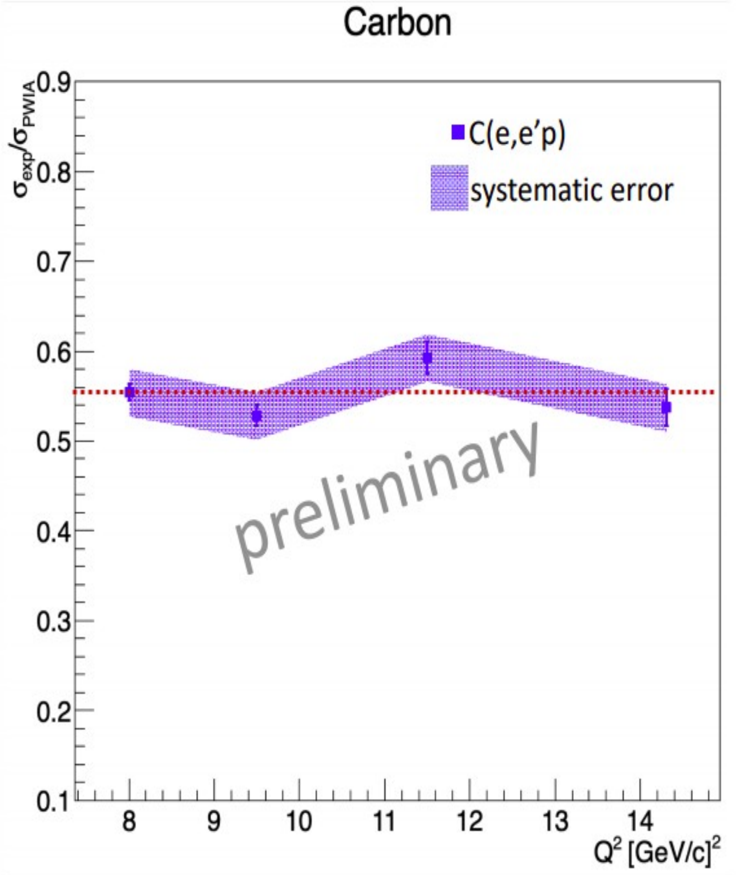
Mean of the % difference in Transparency
Range of the the % difference in Transparency

PRELIMINARY HYDROGEN AND NUCLEAR TRANSPARENCIES

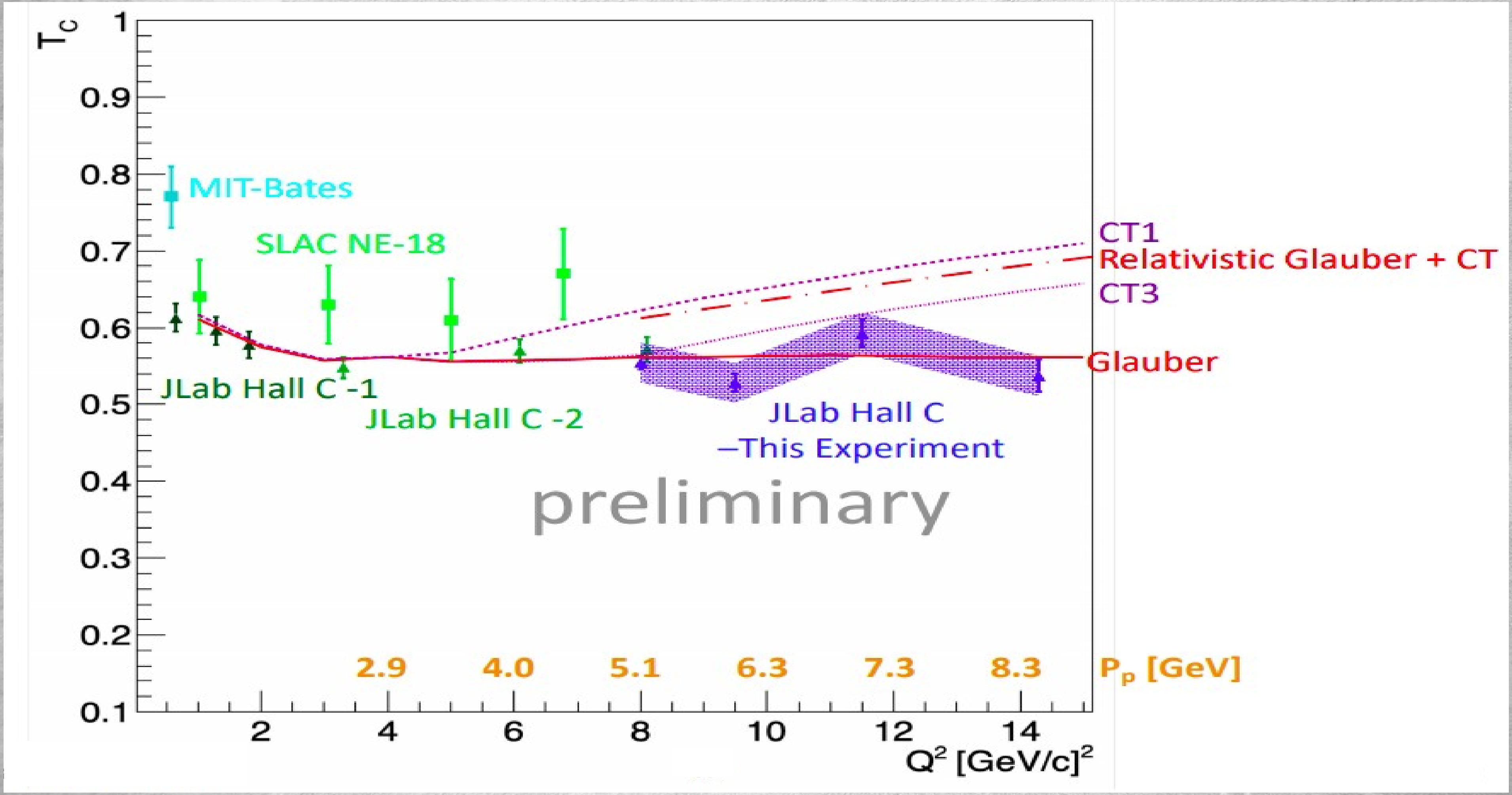
Emiss < 100 MeV
Pmiss < 100 MeV



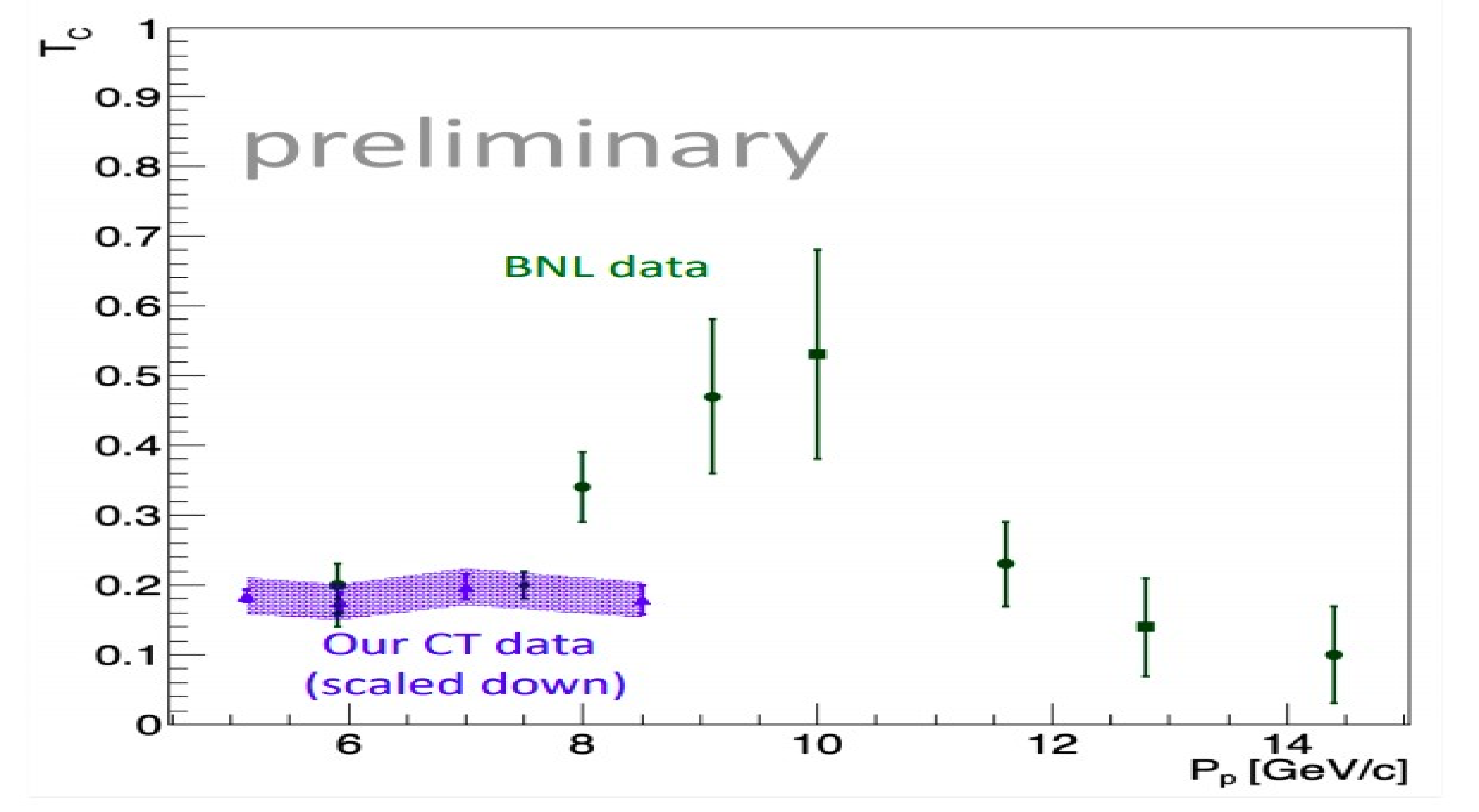
Emiss < 80 MeV
Pmiss < 300 MeV



TRANSPARENCY – PRELIMINARY



CT RESULT VS BNL RESULT [SCALED]



STATUS OF THE WORK

Done with calibration of the detectors.

Improved HMS and SHMS efficiencies calculation, improved HMS and SHMS optics now.

Analysis to understand systematics is ongoing → full results expected by the next few months!

The CT draft article will be ready soon.

SUMMARY

Measuring the onset of CT is a signature for the onset of QCD degrees of freedom in nuclei.

First experiment to run in the 12 GeV era in Hall C and to take data using both the SHMS and HMS.

Experiment took 4 data points in Q^2 regime 8-14.3 $(GeV/c)^2$, region overlaps with Brookhaven data.

Preliminary results do not show the onset of Color transparency in protons.

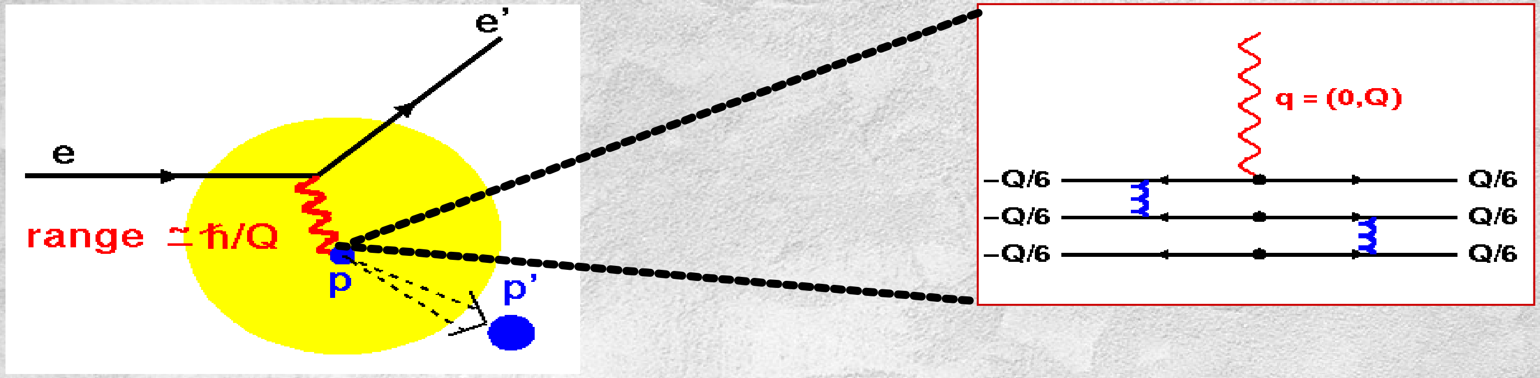
U.S. DEPARTMENT OF ENERGY | Office of Science

Work supported by DOE office of science
(US DOE Grant Number: DE-FG02-07ER41528)

Thanks to the Hall C Collaborators!

BACKUPS

WHY IS THE PLC SELECTED OUT?



Using e-p scattering as an example

- **The momentum is distributed roughly equally among the quarks, (for it to be elastic scattering)** ➡ **lifetime** $\cong \hbar/cQ$

  ➡ **range** $\cong \hbar/Q$

- **At high Q, an elastic interaction can occur only if the transverse size of the hadron involved is smaller than the equilibrium size.**

COLOR SCREENING / LIFE TIME OF PLC

The lifetime of the PLC is dilated in the frame of the nucleus

$$\gamma t_f = \frac{E}{m} t_f$$

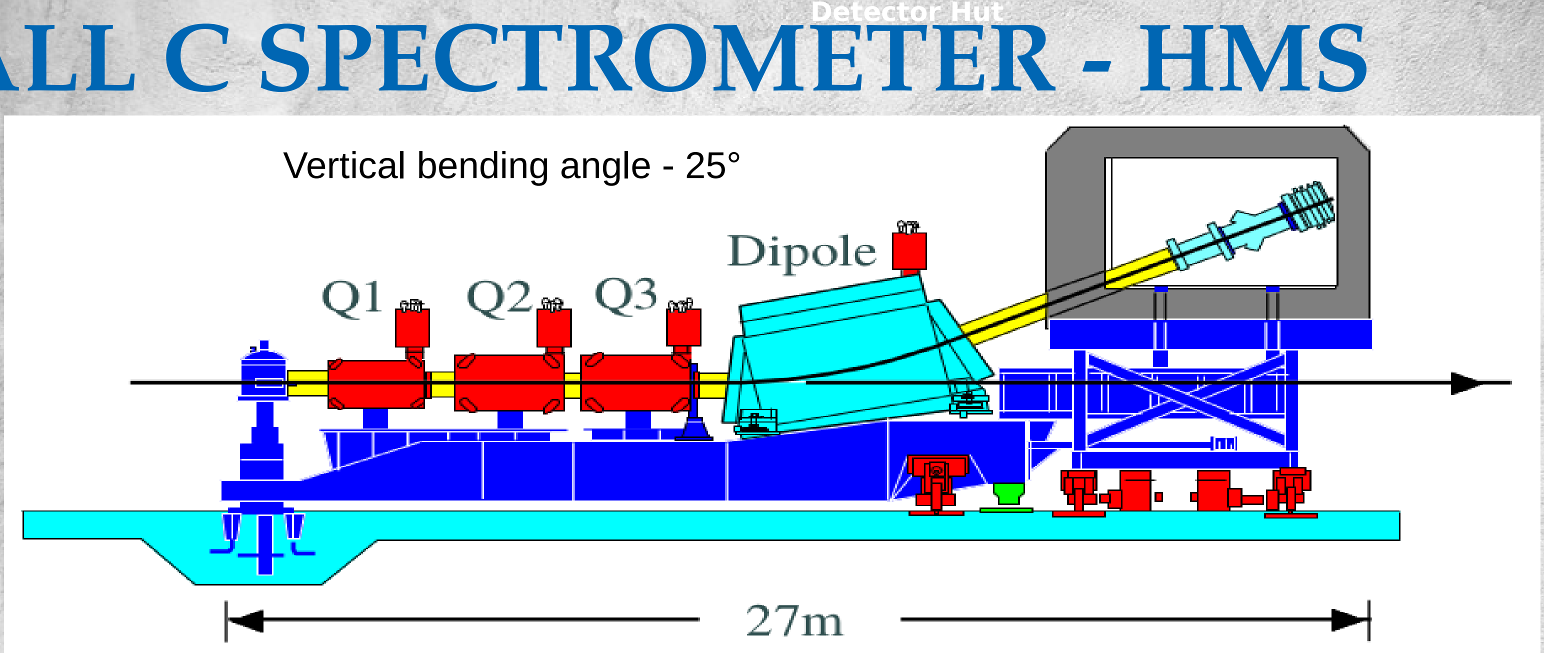
The PLC can propagate out of the nucleus before returning to its equilibrium size.

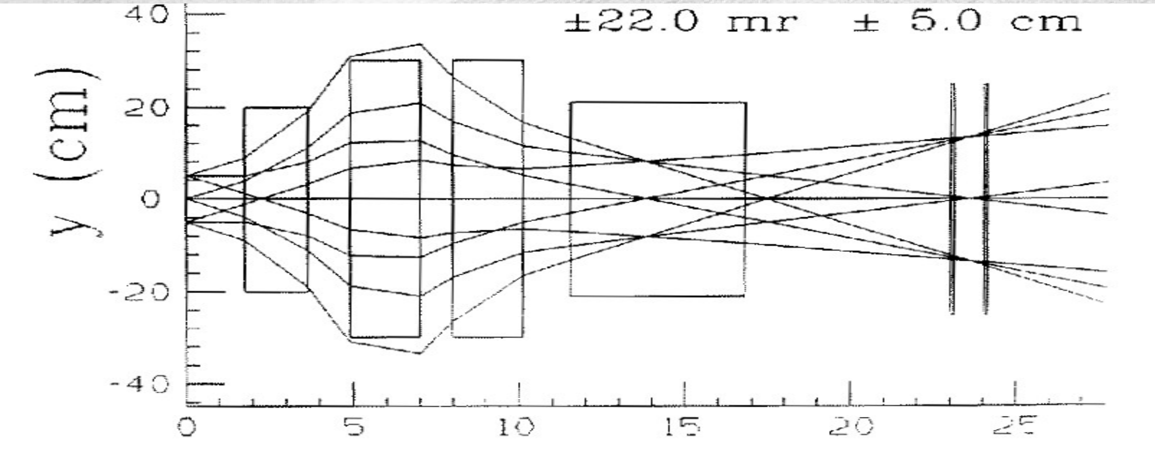
The color field of a color neutral object vanishes with decreasing size of the object .

$$\sigma_{PLC} \approx \sigma_{hN} \frac{b^2}{R^2_h}$$

(Analogues to electric dipole in QED)

HALL C SPECTROMETER - HMS

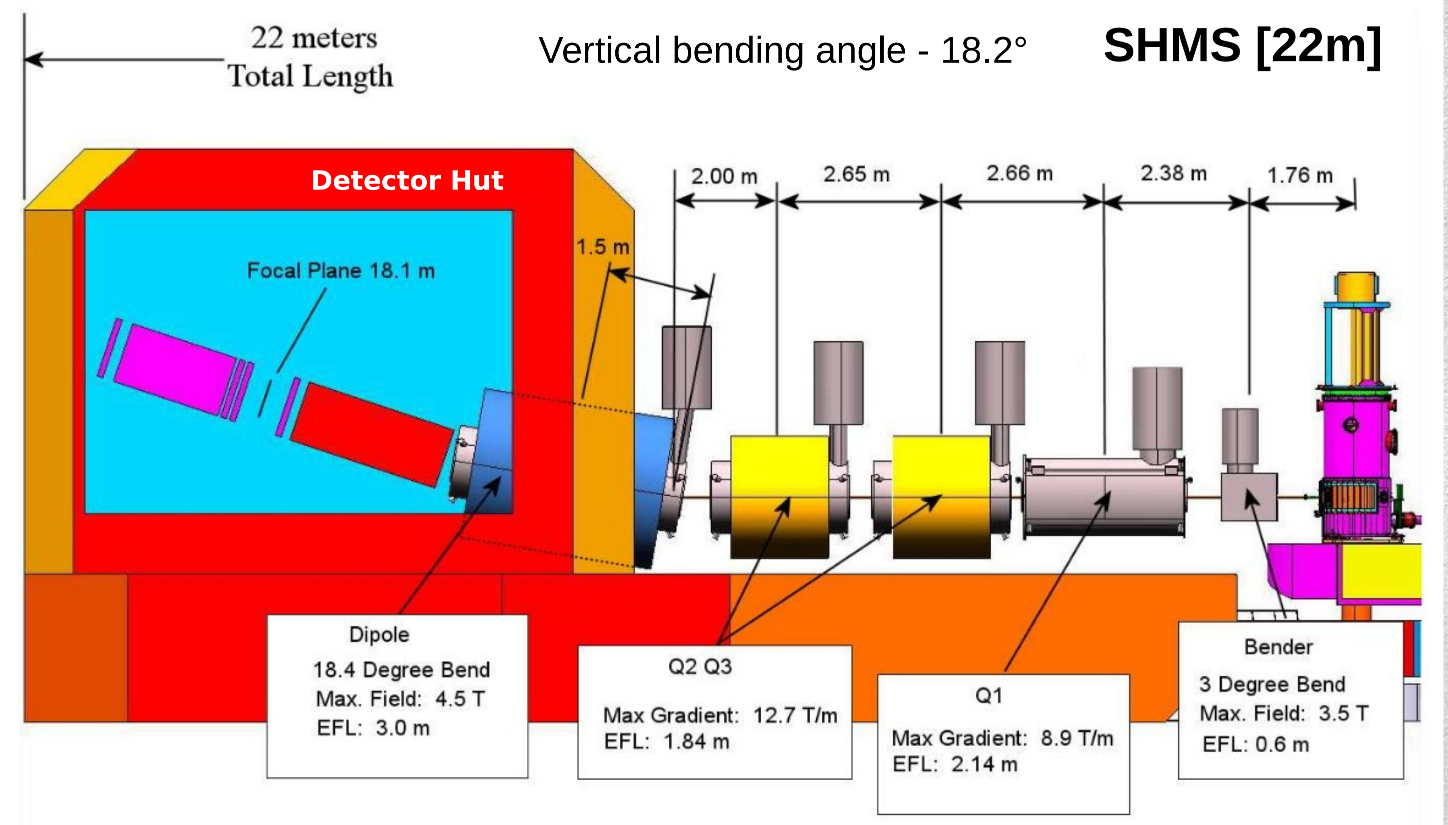




HMS Characteristics:

- <0.1% dP/P resolution
- >6 mSr Acceptance
- P_0 = 0.5 to 7.5 GeV/c
- Scattering angle = 12.5 deg to 90 deg
- Momentum acceptance = -10% to +10%

HALL C SPECTROMETER - SHMS



SHMS Characteristics:

- 5×10^{-4} dP/P resolution
- 4 mSr Acceptance
- P_0 = 1 to 11 GeV/c
- Scattering Angle = 5.5 deg to 40 deg
- Momentum acceptance = -15% to +25%

Minimum opening angle between HMS and SHMS is 17^0 & each spectrometer has well shielded detector HUTS

SIMC – MONTE CARLO SIMULATION

SPECTROMETER QUANTITIES: δ (dp/p), x'_{tar} (dx/dz), y'_{tar} (dy/dz), y_{tar} **FOCAL PLANE QUANTITIES:** x_{fp}, y_{fp}, x'_{fp}, y'_{fp}

Physics Monte Carlo developed for Hall C, Jlab and built to simulate most exclusive and semi-inclusive processes.

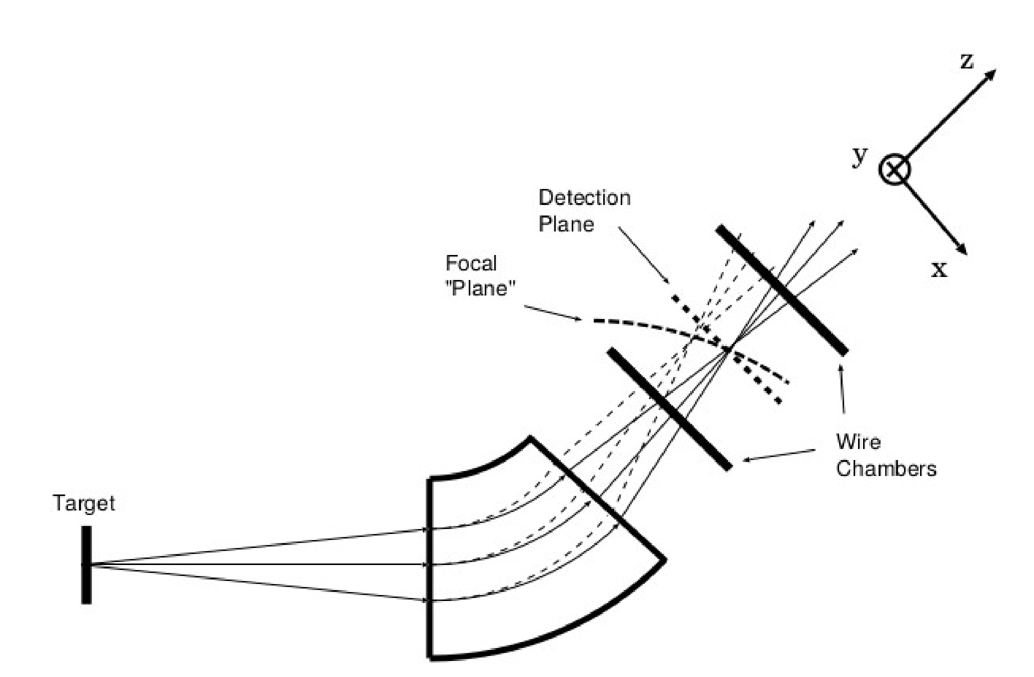
Features:
1) Optics (COSY) and “aperture checking” Monte Carlos of spectrometers [HMS, SOS, SHMS, HRS’s, BigCal,…]
2) Includes radiative effects, multiple scattering, ionization energy loss, particle decay
3) Simple prescriptions available for FSIs, Coulomb Corrections, etc.

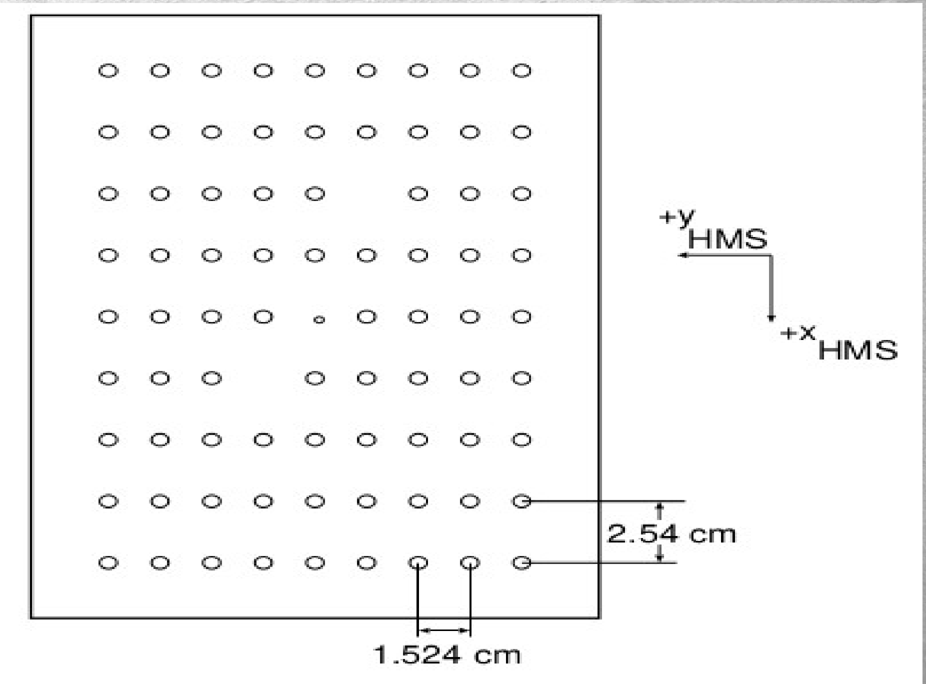
Overview:
1) Initialization – Choose reaction, final state (if appropriate) – Disable/enable implementation of (or correction for) raster, eloss …
2) Event generation – Select vertex based on target size, position, raster size, beam spot size – Determine energy, angle generation that will populate 100% of the acceptance (accounting for radiation, energy loss, …)
3) Physics Processes – Event-by-event multiple scattering, reactions [elastic and quasielastic reactions such as H(e,e’p), A(e,e’p) , exclusive pion production, kaon electroproduction, semi-inclusive reactions etc.], radiative corrections, particle decay, coulomb corrections
4) Acceptance – Can apply geometric cuts or spectrometer model. Default spec. models include target/spec. offsets, model of magnetic elements, apertures at front, back, middle of magnets, collimators, detector active area
5) Event Reconstruction – Tracks are fitted in the focal plane and reconstructed to the target. Apply (average) energy loss, fast raster corrections. Calculate physics quantities for Ntuple.

OPTICS

Optics study is done to reconstruct events from the detectors back to the target. The sieve slit is used in fitting reverse optics matrix elements.

$$\left(x'_{\mathrm{tar}}, y'_{\mathrm{tar}}, y_{\mathrm{tar}}, \delta\right) = \sum_{j,k,l,m=0}^{N} \mathcal{M}^{(i)}_{jklm} \, (x_{\mathrm{fp}})^j \, (y_{\mathrm{fp}})^k \, (x'_{\mathrm{fp}})^l \, (y'_{\mathrm{fp}})^m$$





OPTICS CONTD.

Using the best optimized matrix to match the reconstructed target quantities at the target. We see the x'_{tar} (dx/dz) vs y'_{tar} (dy/dz) plot to see if our matrix is optimized.