Measurement of Semi-Inclusive π^0 Production as Validation of Factorization

PAC-40 Proposal PR12-13-007

Spokespersons Rolf Ent, Tanja Horn, Hamlet Mkrtchyan & Vardan Tadevosyan

- Essential ingredient of basic (e,e'π) cross section measurements to lay a solid foundation for the SIDIS program at a 12-GeV JLab.

JLab Theory Group Report (Prokudin & Radyushkin):

> The physical goal of the experiment is to check so called factorization of SIDIS cross section into quark distribution $f(x)$ for the initial nucleon and final pion fragmentation function $D(z)$. The precision of such a factorization is crucial for experimental determination of fragmentation functions and applications of QCD theory to meson production experiments. The accuracy of factorization is expected to increase with energy, and an important question is to which extent it is settled at JLab energies. The use of neutral pions for this purpose has several advantages, in particular, absence of contamination from pion generated from diffractively produced ρ mesons, and reduced nucleon resonance contribution.

Beam Time Request: 25 days* at 11.0 GeV

(not including setup and checkout time as this depends on scheduling)

*fully overlapping the PR12-13-010 beam time request

Measurement of Semi-Inclusive π^0 Production as Validation of Factorization

PR12-13-007

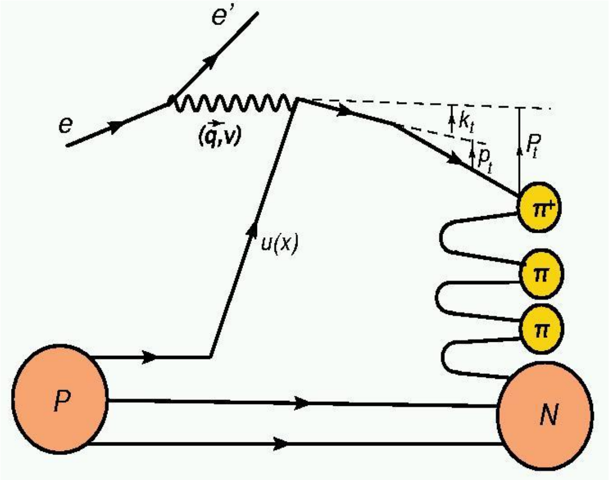
Presentation outline:

- Basic SIDIS Cross Sections: why need for (e,e'π^0)?
- PR12-13-007 Kinematics
- The Neutral-Particle Spectrometer (NPS)
- PAC, Theory, and TAC Comments
  - Will address most NPS-related comments, for PR12-13-007, PR12-13-010 and PR12-13-009
- Conclusion

Hall C SIDIS Program – basic (e,e'π) cross sections

Why need for (e,e'π) cross sections?

PAC37 Report: "the **cross sections** are **such basic tests of the understanding of SIDIS** at 11 GeV kinematics that they will play a **critical role** in establishing the entire SIDIS program of studying the partonic structure of the nucleon. In particular they complement the CLAS12 measurements in areas where the precision of spectrometer experiments is essential, being able to separate P_T and ϕ-dependence for small P_T."



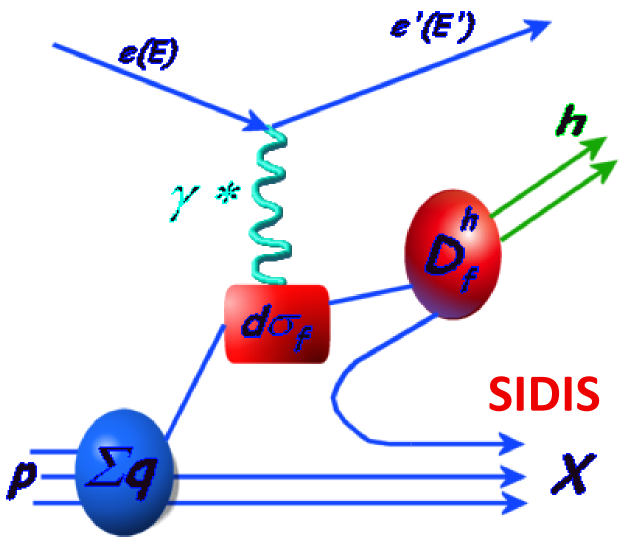
Final transverse momentum of the detected pion $\mathbf{P_T}$ arises from convolution of the struck quark transverse momentum $\mathbf{k_t}$ with the transverse momentum generated during the fragmentation $\mathbf{p_t}$.

$$P_T = p_t + z\,k_t + O(k_t^2/Q^2)$$

Goal: Map the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV) of π^+, π^- **and π^0** production off proton ~~and deuteron~~ targets to study(*) the k_T dependence of (unpolarized) up and down quarks

(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

SIDIS – Flavor Decomposition



DIS probes only the sum of quarks and anti-quarks → requires assumptions on the role of sea quarks $\sum e_q^2(q+\bar{q})$

Solution: Detect a final state hadron in addition to scattered electron

→ Can 'tag' the flavor of the struck quark by measuring the hadrons produced:
'flavor tagging'

$Z = E_h/\nu$

$M_x^2 = W'^2 \sim M^2 + Q^2\,(1/x - 1)(1 - z)$

$$\frac{1}{\sigma_{(e,e')}}\frac{d\sigma}{dz}(ep \rightarrow hX) = \frac{\sum_q e_q^2 f_q(x) D_q^h(z)}{\sum_q e_q^2(x) f_q(x)}$$

$f_q(x)$: parton distribution function

$D_q^h(z)$ fragmentation function

Measure inclusive (e,e') at same time as (e,e'h)

- Leading-Order (LO) QCD
- after integration over p_T and ϕ
- NLO: gluon radiation mixes x and z dependences
- Target-Mass corrections at large z
- ln(1-z) corrections at large z

SIDIS Formalism

General formalism for (e,e'h) coincidence reaction w. polarized beam:

[A. Bacchetta et al., JHEP 0702 (2007) 093]

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h,t}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} +$$

$$\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)F_{UU}^{\cos(2\phi_h)} + \lambda_e\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}\Big\}$$

(Ψ = azimuthal angle of e' around the electron beam axis w.r.t. an arbitrary fixed direction)

Use of polarized beams will provide useful azimuthal beam asymmetry measurements (**F_{LU}**) at low p_T complementing CLAS12 data

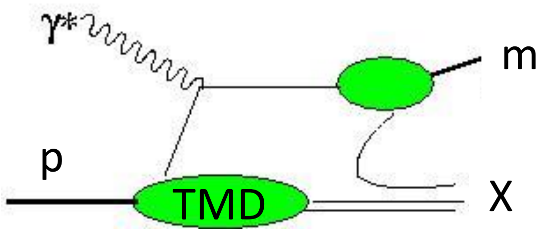
If beam is unpolarized, and the (e,e'h) measurements are fully integrated over ϕ, only the **$F_{UU,T}$** and **$F_{UU,L}$** responses, or the usual transverse (σ_T) and longitudinal (σ_L) cross section pieces, survive.

Unpolarized k_T-dependent SIDIS: $F_{UU}^{\cos(\phi)}$ and $F_{UU}^{\cos(2\phi)}$, in framework of Anselmino et al. described in terms of *convolution of quark distributions f and (one or more) fragmentation functions D*, each with own characteristic (Gaussian) width.

(Approved experiment E12-09-017 addresses extensive charged-pion data set)

Transverse momentum dependence of SIDIS

Linked to framework of Transverse Momentum Dependent Parton Distributions



$TMD^q(x,k_T)$

N \ q	U	L	T	
U	f_1		$h_1^{\perp}$	Unpolarized target
L		g_1	$h_{1L}^{\perp}$	Longitudinally pol. target
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$	Transversely pol. target

Unpolarized k_T-dependent SIDIS: in framework of Anselmino et al. described in terms of convolution of quark distributions q and (one or more) fragmentation functions D, each with own characteristic (Gaussian) width

→ **Emerging new area of study**

$$\sigma = \sum_q e_q^2 q(x) \otimes D(z)$$

Basic precision cross section measurements:

- Crucial information to validate theoretical understanding
- Validation of factorization theorem needed for most future SIDIS experiments and their interpretation
- Can constrain TMD evolution
- Questions on target-mass corrections and ln(1-z) resummations require precision large-z data

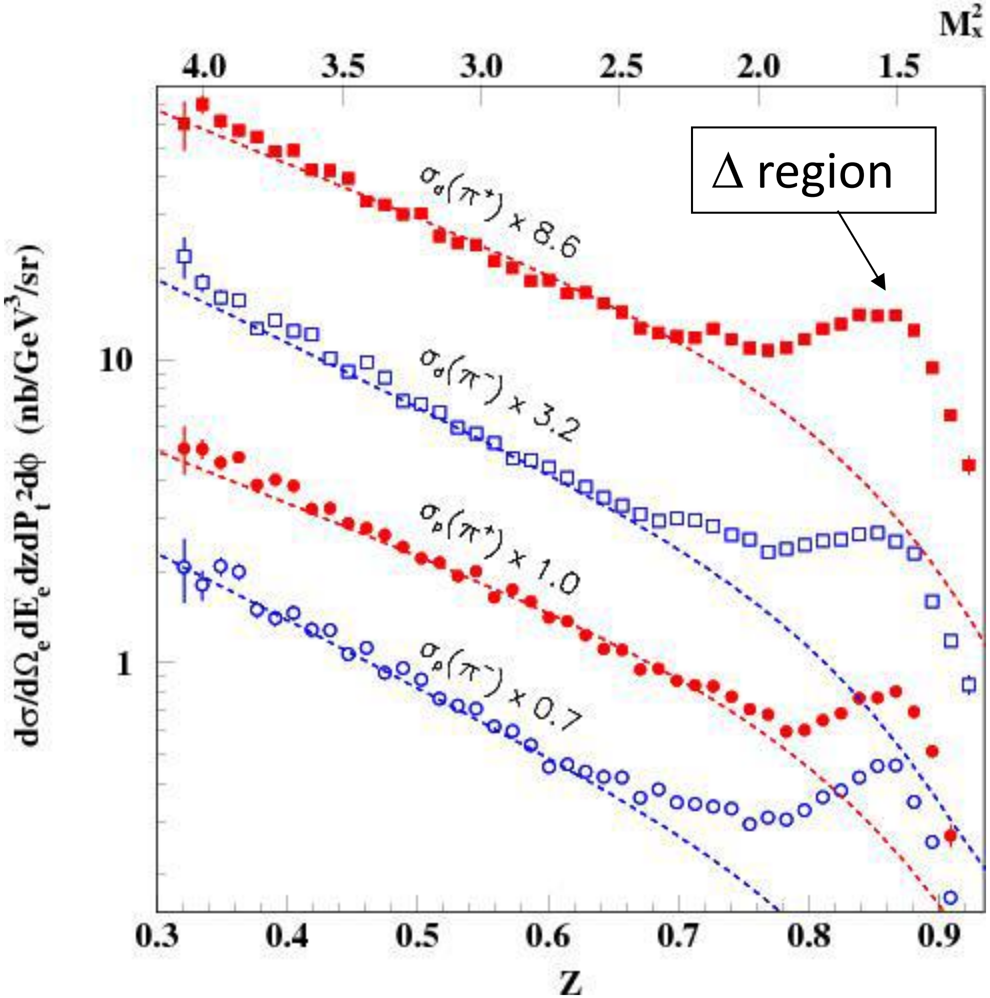
Hall C SIDIS Program – basic (e,e'π) cross sections

Low-energy (x,z) factorization, or possible *convolution in terms of quark distribution and fragmentation functions*, at JLab-12 GeV must be well validated to substantiate the SIDIS science output. Many questions at intermediate-large z (~0.2-1) and low-intermediate Q^2 (~2-10 GeV^2) remain.

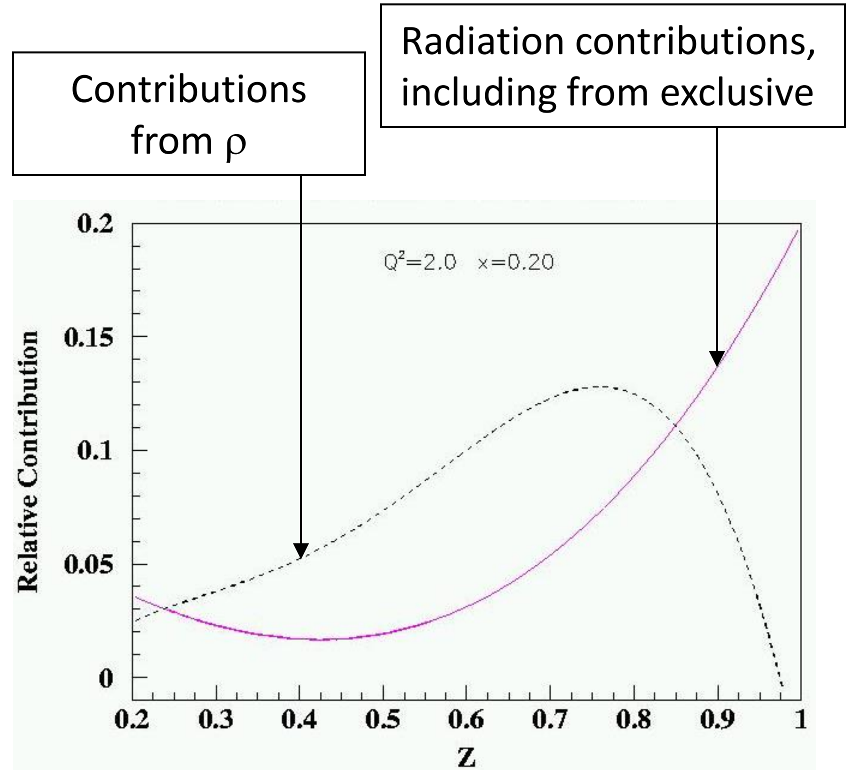
Why need for (e,e'π^0) beyond (e,e'$\pi^{+/-}$)?

- No diffractive ρ contributions
- Smaller radiative tail
  - no pole contributions
- Less resonance region contributions
  - for example, compare with ep → $e\pi^-\Delta^{++}$
- Proportional to average fragmentation function
  - easier to disentangle quark and fragmentation functions

Why need for $(e,e'\pi^0)$ beyond $(e,e'\pi^{+/-})$?



Further non-trivial contributions to $(e,e'\pi^+)$ Cross Sections:



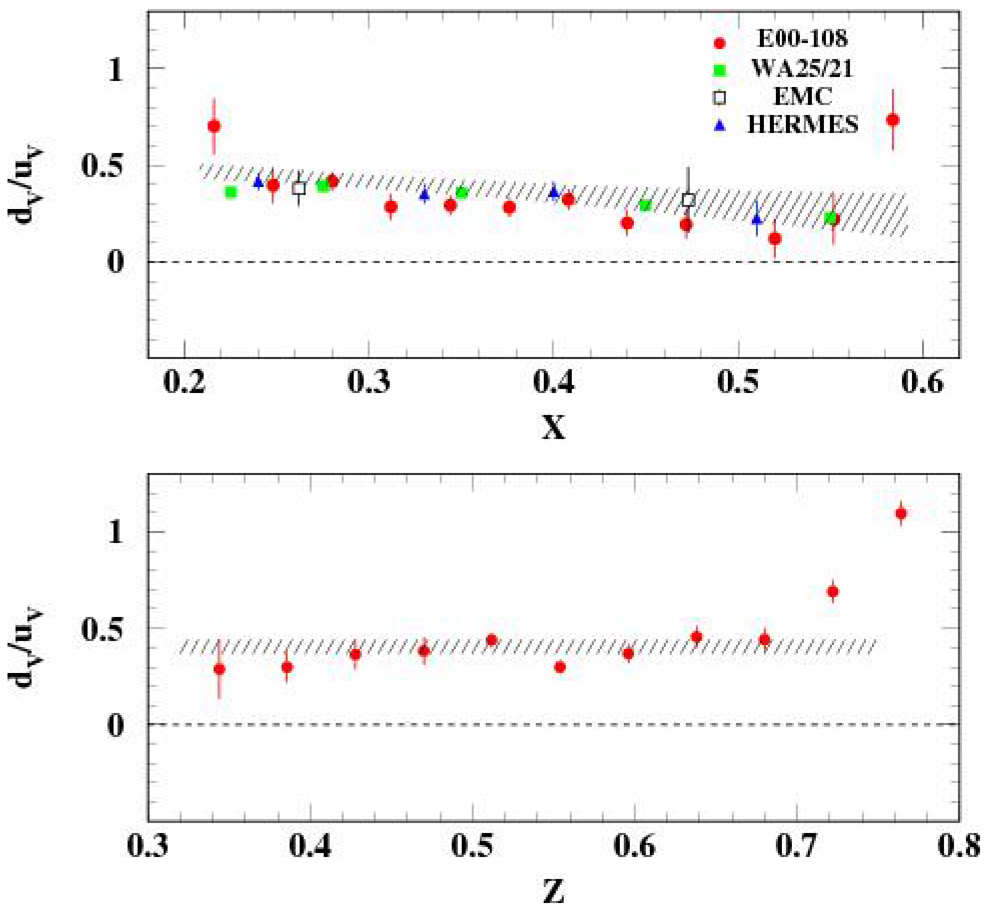
$$M_x^2 = W'^2 \sim M^2 + Q^2\,(1/x - 1)(1 - z)$$

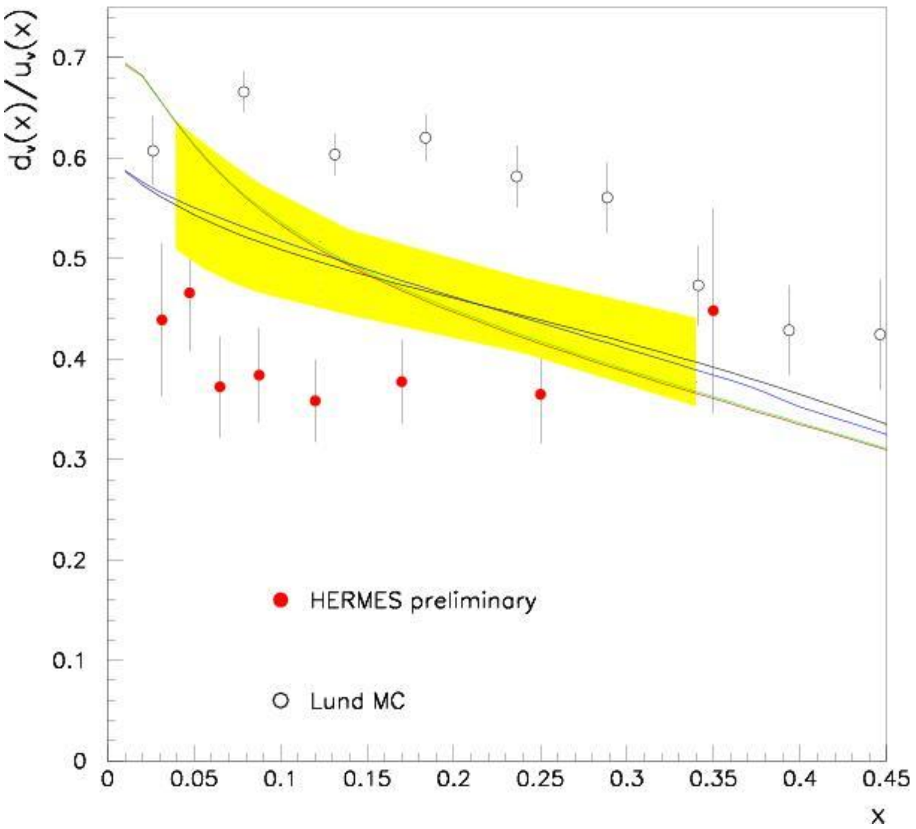
M_x^2 ⟷ $z = E_h/\nu$

$(e,e'\pi^0)$:

- ☺ no diffractive ρ contributions
- ☺ no exclusive pole contributions
- ☺ reduced resonance contributions
- ☺ proportional to average D

The Problem Child: d_v/u_v





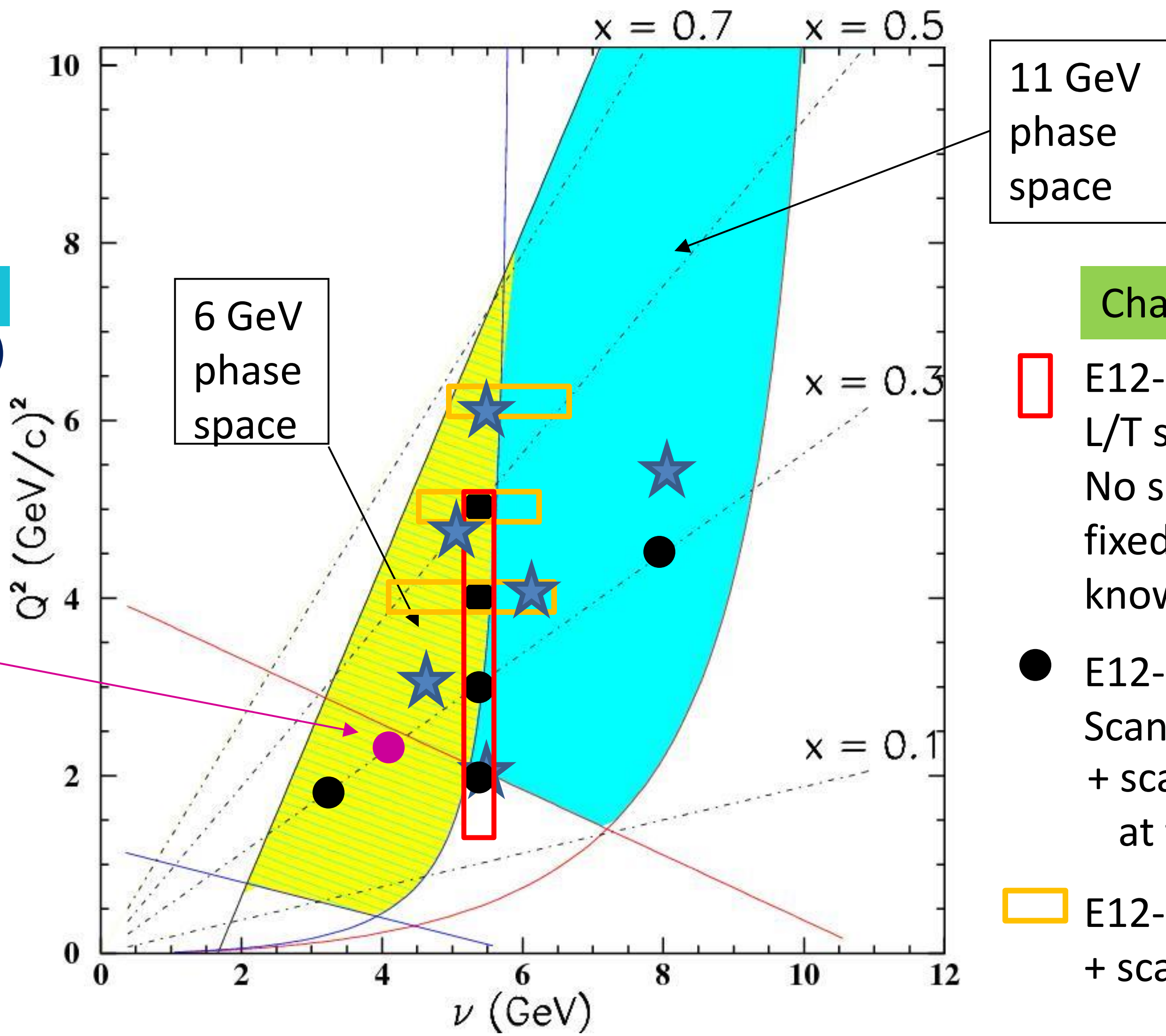
As long as we do not quantitatively understand the extraction of a basic and known quantity like d_v/u_v (at intermediate x) from SIDIS data, we should question the SIDIS analysis, and leave no stone unturned to reach final quantitative understanding.

Hall C SIDIS Program Kinematics (typ. $x/Q^2 \sim$ constant)

HMS + SHMS Accessible Phase Space for Deep Exclusive Scattering

PR12-13-007
π^0 kinematics
Scan in (x,z,p_T)
Overlap with
E12-09-017 &
E12-09-002

E00-108



Charged pions:

E12-06-104
L/T scan in (z,p_T)
No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

E12-09-017
Scan in (x,z,p_T)
+ scan in Q^2 at fixed x

E12-09-002
+ scans in z

For semi-inclusive, less Q^2 phase space at fixed x due to:
i) $M_X^2 > 2.5$ GeV^2; and ii) need to measure at both sides of Θ_γ

E12-09-017 Kinematics & PR12-13-007 Kinematics

Map of P_T dependence in x and z, and in Q^2 to check (p_T/Q) and (p_T^2/Q^2) behavior

Charged pions

Kin	x	Q^2 (GeV^2)	z	Days
I	0.2	2.0	0.3 -0.6	4.5
II	0.3	3.0	0.3 -0.6	5.8
III	0.4	4.0	0.3 -0.6	5.3
IV	0.5	5.0	0.3 -0.6	5.3
V	0.3	1.8	0.3 -0.6	6.9
VI	0.3	4.5	0.3 -0.6	4.0

Neutral pions

Kin	x	Q^2 (GeV^2)	z	Days
A	0.2	2.0	0.4 -0.8	1
C	0.36	4.0	0.3 -0.8	3
E	0.5	4.8	0.4 -0.8	5
B	0.36	3.0	0.5 -0.8	1
D	0.36	5.5	0.3 -0.8	5
F	0.6	6.0	0.4-0.8	10

Overlaps with E12-09-002 Kinematics → F

Each kinematics requires an angle (P_T) scan to cover up to P_T ~ 0.4 (0.5) GeV well (o.k.)

Each kinematics/days identical to DVCS, to cover up to P_T ~ 0.4 (0.5) GeV well (o.k.)

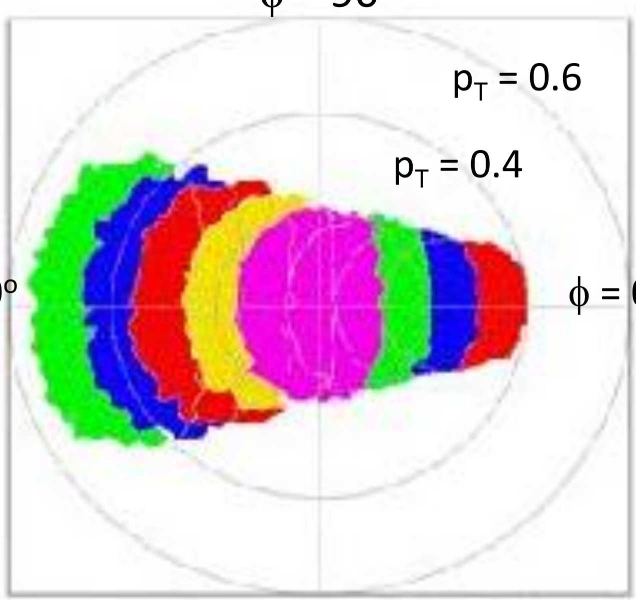
Spin-offs:
- Radiative correction modeling for (e,e'π)
- Single-spin asymmetries at low p_T (< 0.4 GeV)

E12-09-017: P_T coverage

Can do meaningful $\pi^{+/-}$ measurements at low p_T (down to 0.05 GeV) due to excellent momentum and angle resolutions!

- Excellent ϕ coverage
  up to p_T = 0.2 GeV
- Sufficient up to p_T = 0.4 GeV
  → coverage at ϕ = 0, π
- Limited up to p_T = 0.5 GeV
  → use f(ϕ) from CLAS12

ϕ = 90°



ϕ = 180° ϕ = 0°

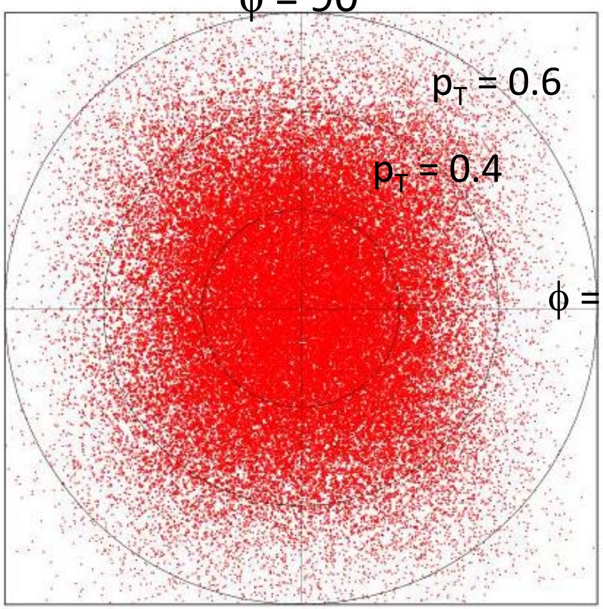
ϕ = 270°

PR12-13-007: P_T coverage

Basic π^0 SIDIS cross sections with excellent precision, and very good momentum and angle resolutions!

- Excellent ϕ coverage
  up to p_T = 0.3 GeV
- Sufficient up to p_T = 0.4 GeV
- Limited up to p_T = 0.5 GeV
  → use f(ϕ) from CLAS12

ϕ = 90°

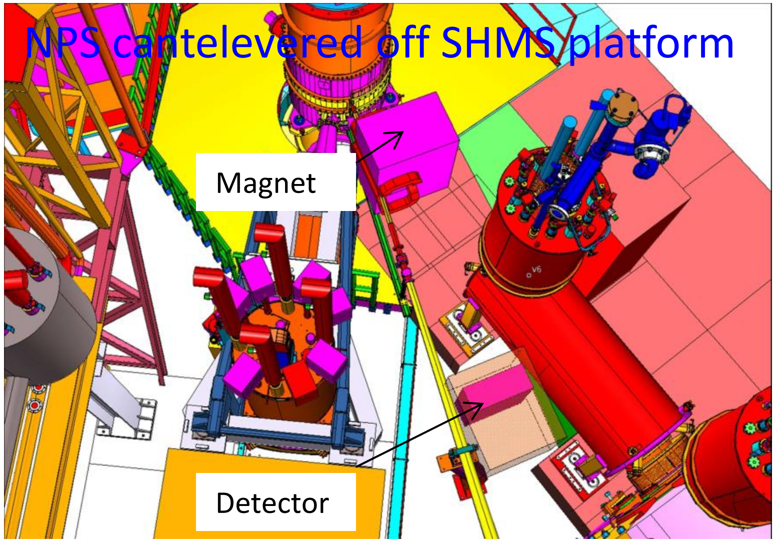


ϕ = 180° ϕ = 0°

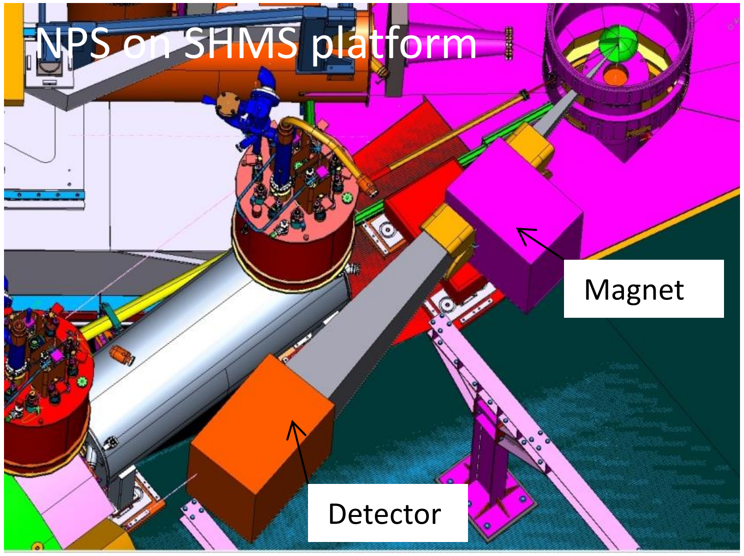
ϕ = 270°

The Neutral-Particle Spectrometer (NPS)

The NPS is envisioned as a facility in Hall C, utilizing the well-understood HMS and the SHMS infrastructure, to allow for precision (coincidence) cross section measurements of neutral particles (γ,π^0).



NPS angle range: 5.5 – 30 degrees



NPS angle range: 25 – 60 degrees

The need for such a device can be exemplified by the submitted program to PAC40:

PR12-13-007 – Measurement of Semi-inclusive π^0 production as Validation of Factorization

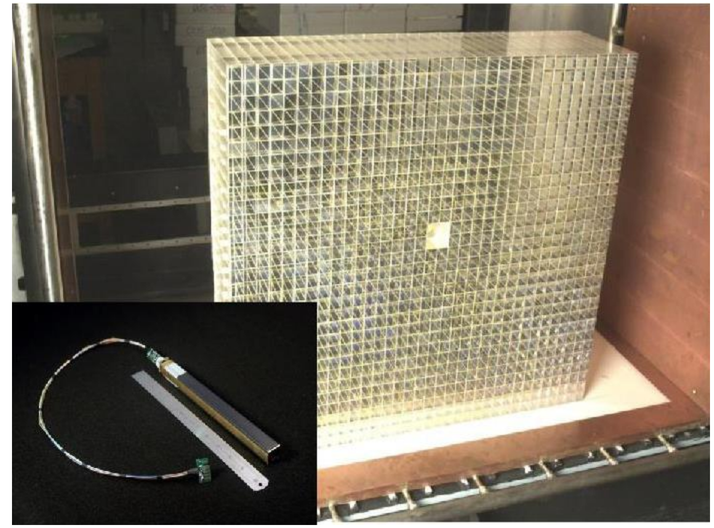
PR12-13-010 – Exclusive Deeply Virtual Compton and Neutral Pion Cross Section Measurements in Hall C

(PR12-13-007 & PR12-13-010 can run as one run group – unique in Hall C)

PR12-13-009 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies

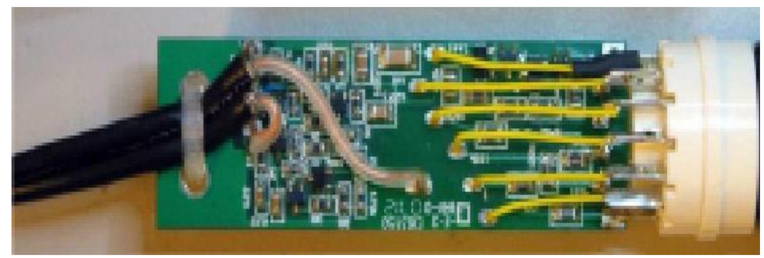
LOI12-13-003 – Large Center-of-Mass Angle, Exclusive Photoproduction of π^0 Mesons at Photon Energies of 5-11 GeV

The Neutral-Particle Spectrometer (NPS)



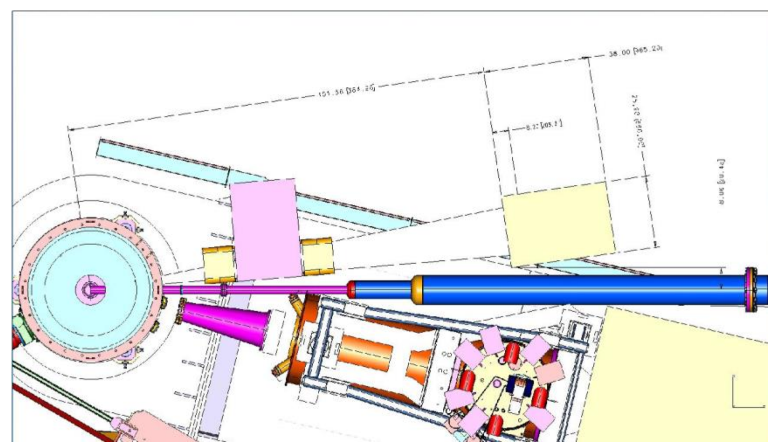
• a ~25 msr neutral particle detector consisting of 1116 $PbWO_4$ crystals in a temperature-controlled frame – use PRIMEx crystals or more likely new.

• HV distribution bases with built-in amplifiers for operation in a high-rate environment – new



• essentially deadtime-less digitizing electronics to independently sample the entire pulse form for each crystal – JLab-developed Flash ADCs

• Two sweeping magnets, one horizontal bending with ~0.3 Tm field strength, and one vertical bending with ~0.6 Tm field strength for larger angles/WACS. Both designed to use an existing power supply – new



• Cantelevered platforms off the SHMS carriage to allow for remote rotation (in the small angle range), and platforms to be on the SHMS carriage (in the large angle range) – new

• A dedicated beam pipe with as large critical angle as possible to reduced beamline-associated backgrounds – further study has shown only a small section needs modification (JLab/Hall C)

HV and cabling is assumed from JLab, and similar as for BigCal

PR/C12-11-102 @ PAC38 & PAC39 – PAC Comments

PAC38 conditionally approved PR12-11-102

Measurement of the Ratio R = σ_L/σ_T in Exclusive and Semi-Inclusive π^0 Production

• The PAC recognizes a higher priority to the exclusive case than the semi-inclusive one and proposes … focused on the first case, which is an important step for the GPD interpretation of exclusive pion production.

PAC39 deferred C12-11-102 (emphasizing exclusive π^0 production)

• … PAC is not convinced … in the top half of the priority list of experiments … for the first 5 years

• … new and ambitious facility for photon detection in Hall C could envisage a larger scope to the experimental program

Nonetheless, the time scale to build any new facility to augment the precision role of Hall C for coincidence experiments to include photon detection is typically a few years

We have followed up on the spirit of these (and other) PAC comments, and submit to PAC40 a program with larger scope, consisting of 3 proposals with similar setup (and 1 LOI):

PR12-13-007 – Measurement of Semi-inclusive π^0 production as Validation of Factorization

PR12-13-010 – Exclusive Deeply Virtual Compton and Neutral Pion Cross Section Measurements in Hall C

(PR12-13-007 & PR12-13-010 can run as one run group – unique in Hall C)

PR12-13-009 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies

LOI12-13-003 – Large Center-of-Mass Angle, Exclusive Photoproduction of π^0 Mesons at Photon Energies of 5-11 GeV

Theory Report (Prokudin, Radyushkin)

We stress that the measurement of basic SIDIS process is a fundamental testing ground of our understanding of the mere reaction mechanism. Thus the experiments must be performed at JLab 12.

This is nice of course, but also some (3) valuable issues were raised:

1. As it is noted in the proposal, there are various sources of pion production that lead to additional contributions to the cross section in the $z \to 1$ limit. In particular, exclusive limit of π^+ and π^- production is affected by a large contribution from resonance region, thus complicating a simple parton model interpretation. As evident from Fig. 2 in the proposal, the maximum of this contribution comes from the region $z \in [0.8, 1]$. Yet only the $z \in [0.4, 0.8]$ region for π^0 production is considered in the proposal. It is not clear how large is the difference between charged and neutral pion production in that region.

Since $M_x^2 = M^2 + Q^2 (1/x - 1)(1 - z)$ one by necessity ends up for z → 1 in the nucleon resonance region. We have used a M_x^2 cut of 2.5 GeV^2 based on the earlier 6-GeV JLab data, even if this may be somewhat relaxed for the (e,e'π^0) reaction. This corresponds to z ~ 0.8.

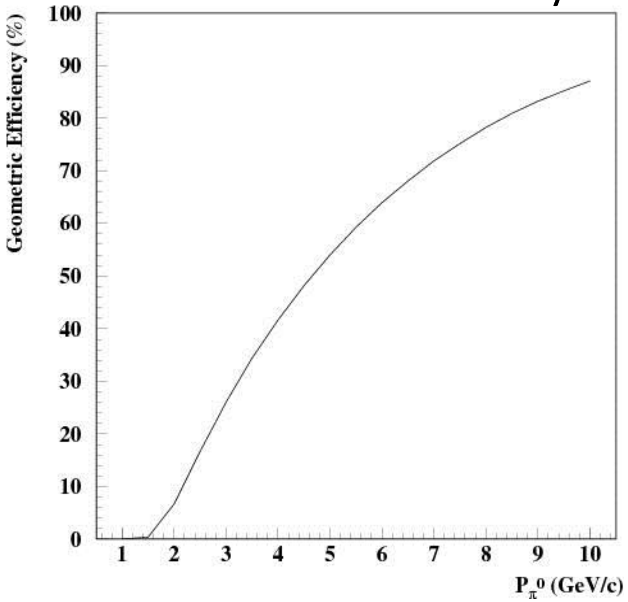
Nonetheless, basic cross section data in the z = [0.8;1] region are certainly valuable, so we added a projection in the following Table.

π^0 SIDIS count rate estimate – example

q = 5.865 GeV/c

x	Q^2	z	Counts/ hr/μA	days	Counts /μA
0.6	6.0	0.3	8	10	2K
		0.4	80		20K
		0.5	174		43K
		0.6	228		57K
		0.7	224		56K
		0.8	168		42K
		0.9	~100		25K

π^0 detection efficiency



$M_x^2 = M^2 + Q^2 (1/x – 1)(1 - z)$

This is a worst-case example assuming 1 μA beam current.
The final choice of beam current is determined by PR12-13-010

Theory Report (Prokudin, Radyushkin) – cont.

2. An important part of the proposed experiment is to check the following relation:

$$\sigma^{\pi^0}(x,z) = (\sigma^{\pi^+}(x,z) + \sigma^{\pi^-}(x,z))/2 \,. \quad (1)$$

In order to demonstrate experimental feasibility of this check, one should compare uncertainties for π^+ and π^- measurements and demonstrate that a similar precision is possible in case of π^0.

This is a good point. In fact a strength as systematic uncertainties are nicely matched:

$\sigma^{\pi^0}(x,z)$

Source	pt-to-pt (%)	scale (%)
Acceptance	0.4	1.0
Electron PID	<0.1	<0.1
π° efficiency [a]	1.0	1.0
Electron tracking efficiency	0.1	0.5
Charge	0.5	2.0
Target thickness	0.2	0.5
Kinematics	0.3	<0.1
Total (including rad, mod)	1.6	3.4
Total	1.2	2.5

[a] includes combinatoric background

3% precision

$\sigma^{\pi^+}(x,z) + \sigma^{\pi^-}(x,z)$

See E12-06-104:

	pt-to-pt (%)	scale (%)
Total (incl. rad. mod.)	1.8	3.3
Total	1.4	2.6

Note: for charged pions the uncertainties related to pion absorption, decay, tracking and radiative corrections are larger, on the other hand the model uncertainty is as of yet smaller.

2-3% precision each

Theory Report (Prokudin, Radyushkin) – cont.

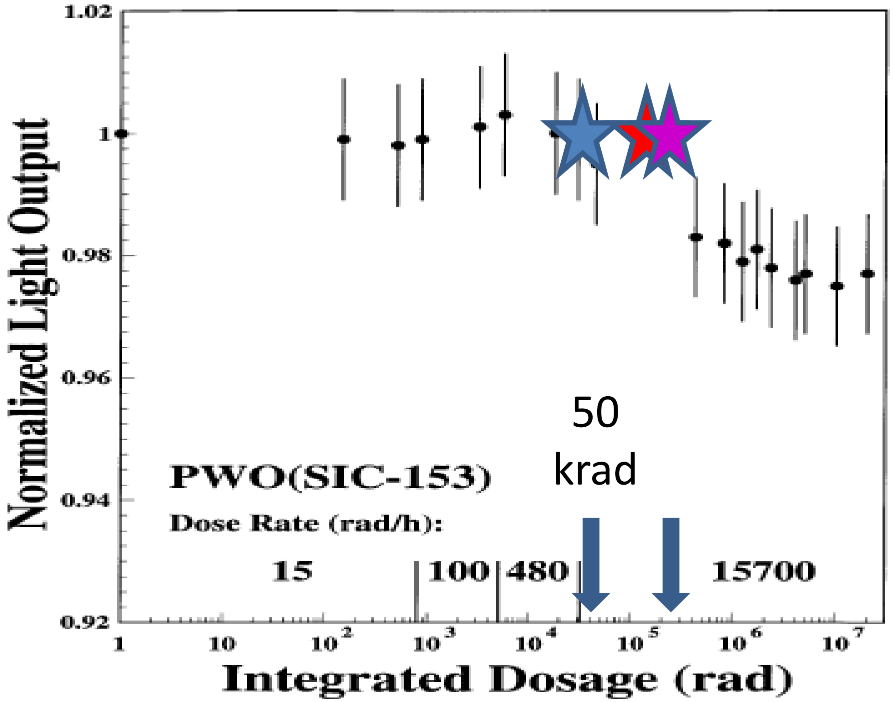
3. Another observation is that the region $z \to 1$ receives a non-negligible QCD correction due to resummation of threshold logs $\ln(1-z)$ that can be large when $z \to 1$. This phenomenon affects the predictions for production of pions of all pion types, π^+, π^-, and π^0. As pointed out in Refs.[1, 2], the lowest orders estimates for the production cross sections are not valid anymore in the $z \to 1$ region even for the QCD improved parton model calculations.

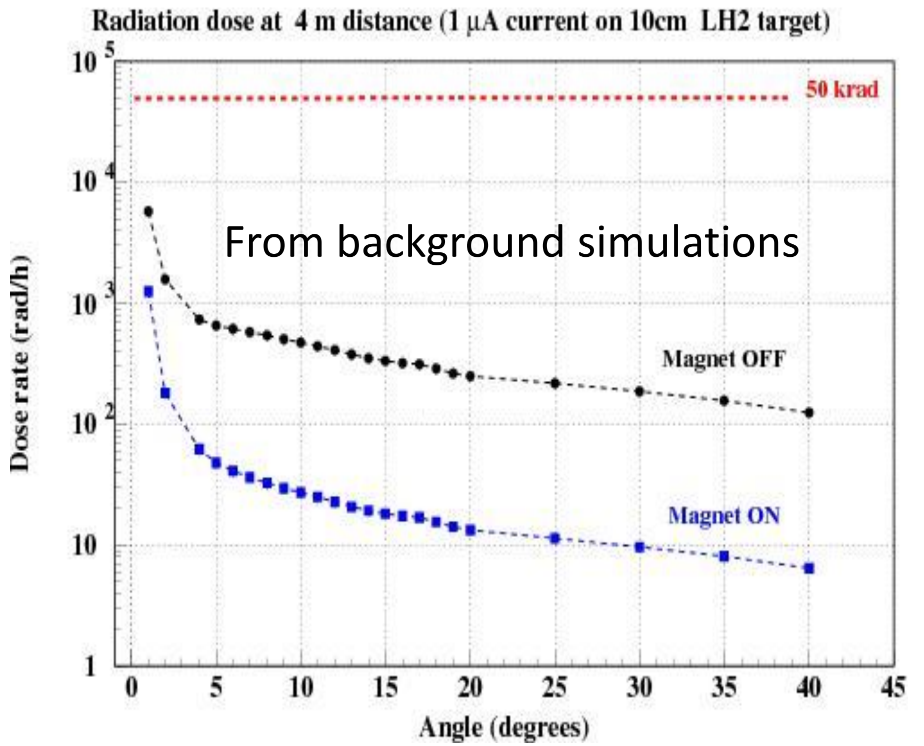
This is of course correct, and reinforces both the authors' earlier point on the inclusion of the region z = [0.8;1] and the need for basic cross section measurements. There are still many outstanding and basic questions related to the SIDIS foundation at a 12-GeV JLab and elsewhere.

We stress that the measurement of basic SIDIS process is a fundamental testing ground of our understanding of the mere reaction mechanism. Thus the experiments must be performed at JLab 12.

We conclude that the proposed measurement is very valuable and important, certainly of high scientific interest. The authors of the proposal should address the issues raised above.

TAC Report – levels of radiation damage





LHC radiation dose studies: Conservative dose limit = 50-few 100 krad

Background simulations: Dose dominated by small-angle operation

★ PR12-13-007: integrated dose = 50 krad

★ PR12-13-009: integrated dose = 150 krad

(corresponds nicely with scaling from Hall A/RCS experiment)

★ PR12-13-010: integrated dose ~ 200 krad

TAC Report – Radiation Damage and Curing

PbWO4 spontaneously recovers from ~ 1 Mrad damage in ~30 days at ambient conditions. A fast and effective way of in-situ curing is optical bleaching.

A) Standard curing at 500-700 nm wavelengths

- Requires hall access, removing front panel and installing the curing system
- **2 shifts needed** (recovery time ~10-15 hours)
- **Once per 2-3 weeks** (50 krad dose accumulation at rates <100 -150 rad/h with Sweeping Magnet ON)

B) Stimulated recovery with visible and IR light

- In development stage: **J. of Phys.: Conf. Ser. 404 (2012) 012063**.
- Proven to work for shallow doses (~30 Gy)
- **Can be operated remotely, no hall access needed**
- Light intensity ~10^{16} photon/s per block, can be supplied by a set of LEDs
- Fast curing with blue light, with PMTs off
- Continuous curing with IR, with PMTs on
- Further feasibility studies needed

TAC Report – readout requirements and data

- In consultation with JLab's Fast Electronics Group, we do plan to use F250 Flash ADCs for the PbWO4 readout
- Given the Hall C/SHMS F250 ADCs and existing/planned spares, already close to sufficient Flash ADC readout channels
- Further discussion with the Fast Electronics Group (Cuevas, Raydo) has been ongoing on readout and triggering
- One option is to read out most channels above a threshold, and only sample the wave form of select high-rate channels
- Assuming 20 blocks/event, the event size is 1.12 kB
- For 100 PAC days and 20 MB/s (Hall A/DVCS2 rate), one would require ~15K$ tapes to record the data

Measurement of Semi-Inclusive π^0 Production as Validation of Factorization

PAC-40 Proposal PR12-13-007

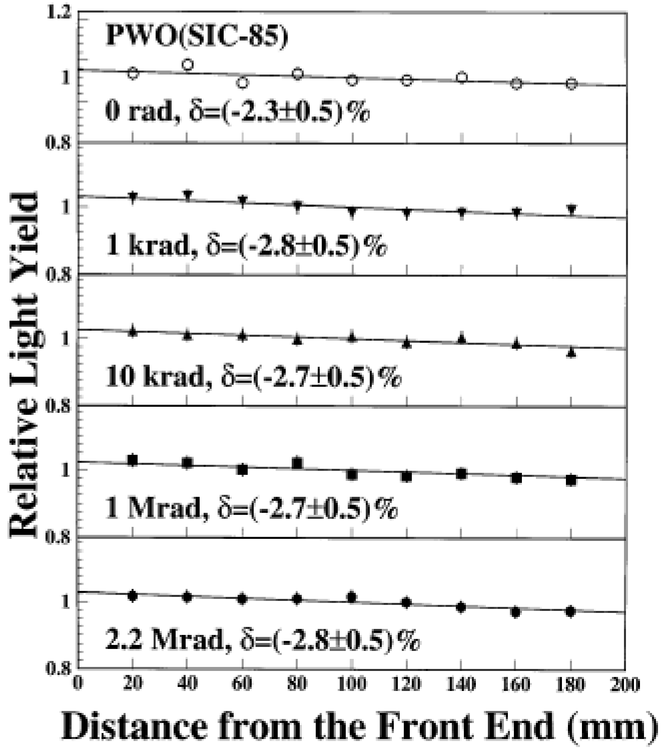
• Essential ingredient of basic $(e,e'\pi)$ cross section measurements to lay a solid foundation for the SIDIS program at a 12-GeV JLab.

- Chosen kinematics overlap much of the (x,Q^2,z) phase space of 12-GeV approved SIDIS program.
- Precision (~3%) neutral-pion SIDIS unpolarized cross section data comes with specific advantages to validate theoretical understanding.
- Can determine $\cos(\phi)$ and $\cos(2\phi)$ moments up to p_T = 0.4-0.5 GeV
- Much recent interest in unpolarized azimuthal moments - HERMES, COMPASS, Jlab
- Much recent interest in TMD evolution, target-mass corrections and ln(1-z) resummation

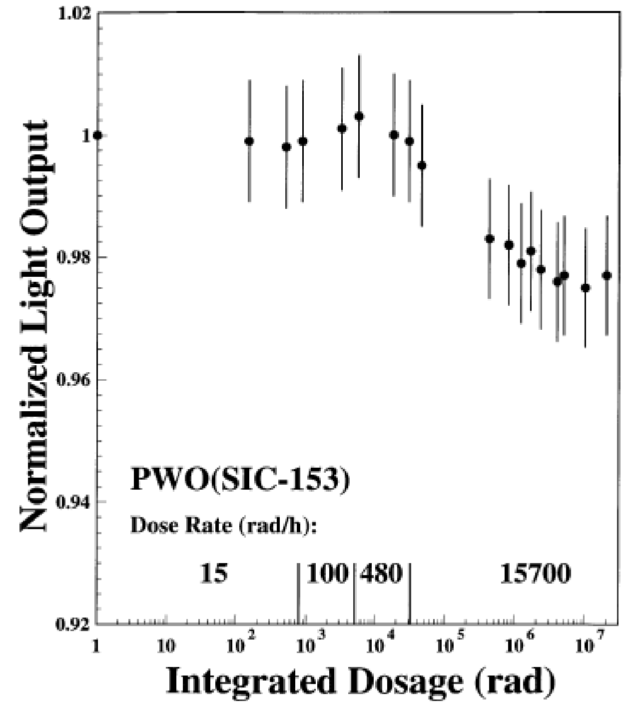
Beam Time Request: 25 days* at 11.0 GeV
(not including setup and checkout time as this depends on scheduling)
*fully overlapping the PR12-13-010 beam time request

NPS collaboration eager to develop neutral-particle spectrometer facility to augment Hall C's role of precision measurements with γ and π^0 channels

Effect of accumulated radiation dose for PbWO4 per LHC studies



The light response uniformity as a function of the integrated dose for PbWO4 (From R.-Y. Zhu, NIM, A413, p297, 1998)



The normalized light output of PbWO4 crystals as function of the integrated dose (From R.-Y. Zhu, NIM, A413, p297, 1998)

Conclusion: light output and slope do not change up to an accumulated dose of 50 krad, with only small effects up to an accumulated does of ~2.2 Mrad.

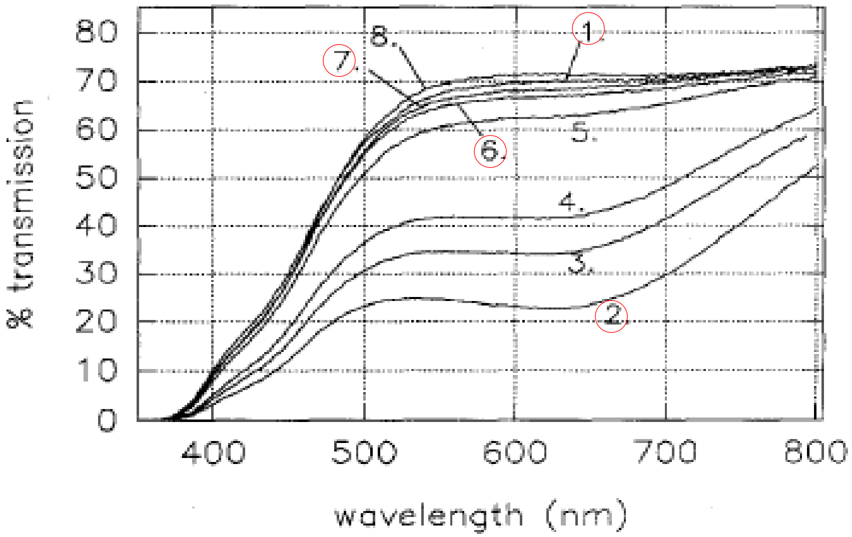
This result confirms that the mechanism for scintillation is not damaged, with only the front few cm subjected to the radiation dose. (Note: expected dose rates at LHC are ~15-500 rad/h).

NPS Calorimeter's Radiation Damage Recovery

$PbWO_4$ spontaneously recovers from ~ 1 Mrad damage in ~30 days at ambient conditions. A fast and effective way of *in-situ* curing is <u>optical bleaching.</u> Two approaches are considered:

A) Standard curing at 500-700 nm wavelengths

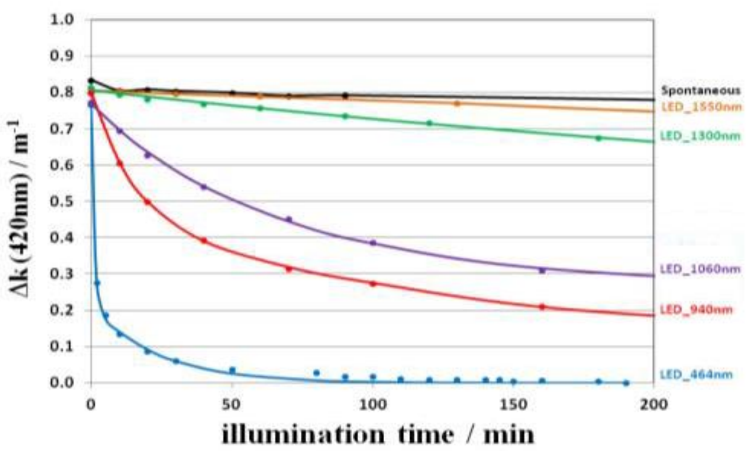
- **Requires hall access, removing front panel and installing the curing system**
- **2 shifts needed (recovery time ~10-15 hours)**
- **Once per 2-3 weeks (50 krad dose accumulation at rates <100 -150 rad/h with Sweep Magnet ON)**



Transmission of 21cm PbWO4 crystal before radiation (1), after a dose of 834 krad.(2), and 5 hours of bleaching at 700 nm (3), 12 hours at 700 nm (4), 5 hours at 600 nm (5), 10 hours at 600 nm (6), 7 hours at 640 nm (7). (8) corresponds to 2 hours of thermal annealing at 200º C. (From C. L. Woody et al., IEEE Trans. Nucl. Science 43, 1996, p.1585).

B) Stimulated recovery with visible and IR light (not fully established, in the development stage)

- **Proven to work for shallow doses (~30 Gy)**
- **Can be operated remotely, no hall access**
- **Light intensity in 10^{16} photon/s range per block, can be supplied by a set of LEDs**
- **Fast curing with blue light, with PMTs off**
- **Continuous curing with IR, with PMTs on**
- **Extensive feasibility studies needed**



Stimulated recovery of 30 Gy radiation induced absorption coefficient Δk at 420 nm in a PbWO-II crystal, by illumination with different lights at room temperature. (R.W. Novotny, J. of Phys.: Conf. Ser. 404 (2012) 012063).