Double Spin Asymmetry in Wide-Angle Charged Pion Photoproduction

PR12-21-005

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The pion-nucleon processes

Since prediction as a carrier of nuclear force pion was the subject of an enormous number of papers and is related to every aspect of the nucleon structure, the meson cloud, ... , pdfs.

In the low energy domain the photo-pion process is a foundation represented by Kroll & Ruderman (PR 1954), experiments at Stanford by Panofsky & Woodward (PR 1956), Gell-Mann & Watson review (Annual Review Nucl. Sci 1954) and many results obtained later.

Production cross section, a bit modulated in the resonance region, shows scaling in amazing agreement with the pQCD mechanism.

There is a large interest in finding the dominant mechanism of this process and having QCD-based calculation. In the GPD era the calculation from the first principles is the main goal, which for the pion photoproduction was likely achieved by Kroll & Passek-Kumericki (PRD 2018). This development, important to all aspects of pion physics especially in the JLab physics program, will be tested in the proposed experiment (if approved).

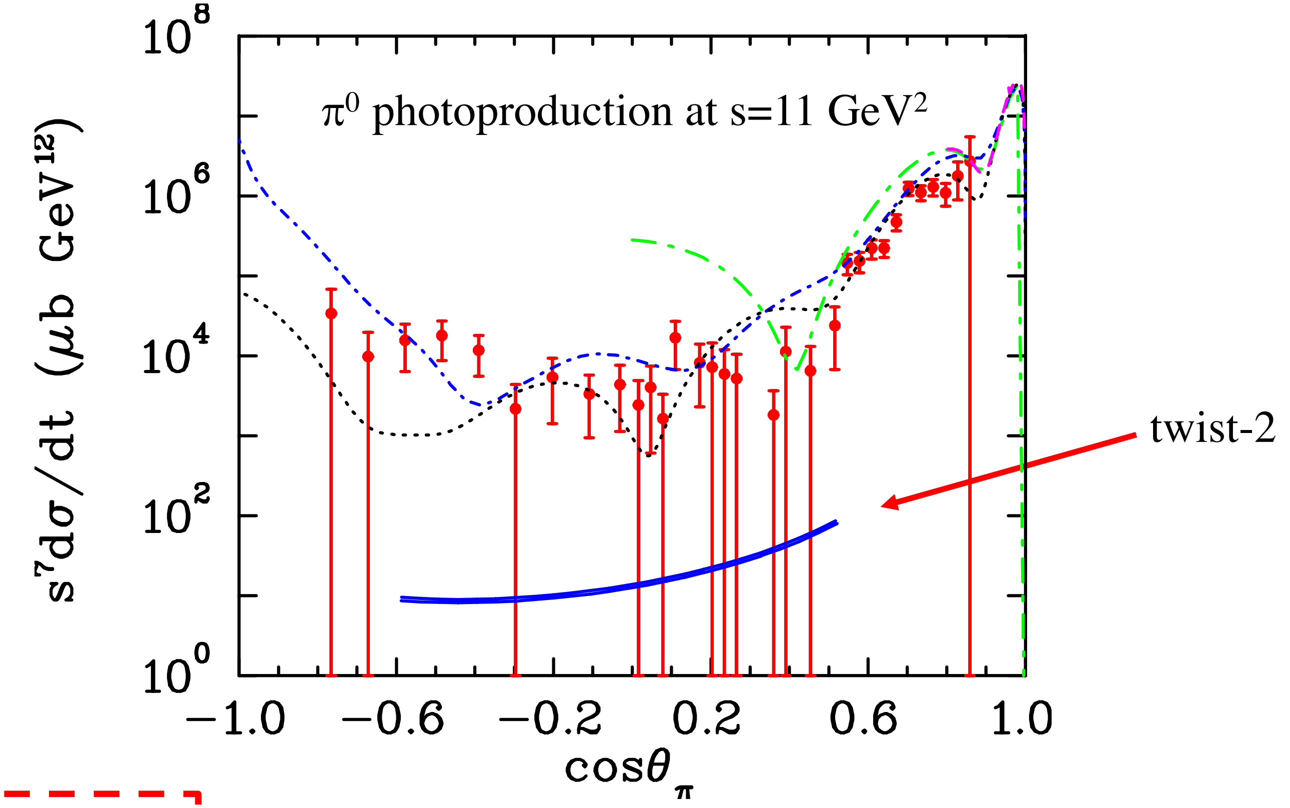
The proposed experiment has the kinematical parameters (s, $-t$, $-u$) where the GPD twist-3 calculations are supposed to work and the design is supposed to provide precision results.

Pion photo-production physics

There are several regions in *s, t, u* with very different physics, for example:

1) Near threshold – effective field theory
2) Resonance region – partial wave analysis
3) Above resonances, semi-inclusive deep inelastic scattering – pQCD, GPDs

At sufficiently large *s, -t, -u* (calculable!) in the wide angle regime, the GPD-based calculations should work. However, the twist-2 treatment is not sufficient.



Introduction

The observable to measure in the experiment

For start, let us look the case of Compton scattering

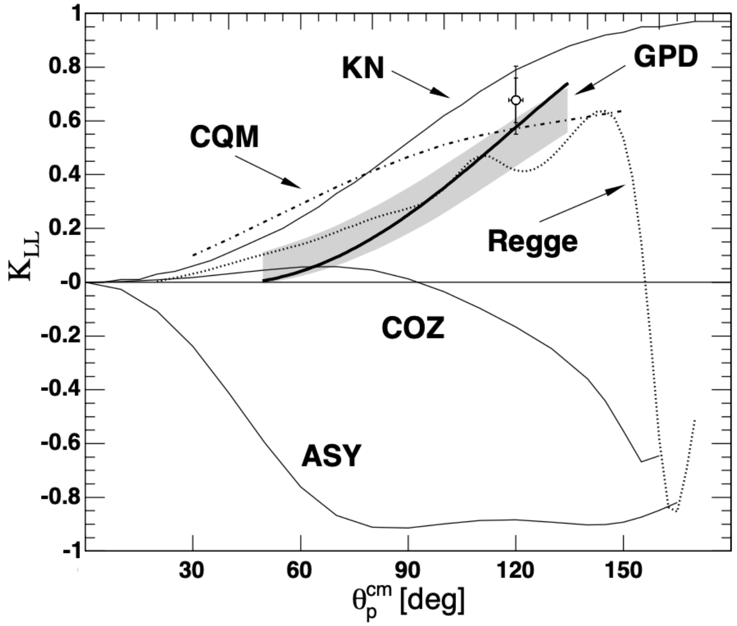
$$\gamma p \to \gamma' p$$

$$R_V(t) = \sum_q e_q^2 \int_0^1 \frac{\mathrm{d}x}{x} H_v^q(x,0,t)$$

poorly constrained even at moderate $-t$

$$R_A(t) = \sum_q e_q^2 \int_0^1 \frac{\mathrm{d}x}{x} \tilde{H}_v^q(x,0,t)$$

$$R_T(t) = \sum_q e_q^2 \int_0^1 \frac{\mathrm{d}x}{x} E_v^q(x,0,t)$$



$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_{\mathrm{KN}} \left\{ \frac{1}{2} \frac{(s-u)^2}{s^2+u^2} \left[R_V^2(t) + \frac{-t}{4m^2} R_T^2(t) \right] + \frac{1}{2} \frac{t^2}{s^2+u^2} R_A^2(t) \right\}$$

$$A_{LL} = K_{LL} = \frac{R_A(t)}{R_V(t)} A_{LL}^{\mathrm{KN}}$$

$$A_{LS} = -K_{LS} = A_{LL} \left[\frac{\sqrt{-t}}{2m} \frac{R_T(t)}{R_V(t)} - \beta \right]$$

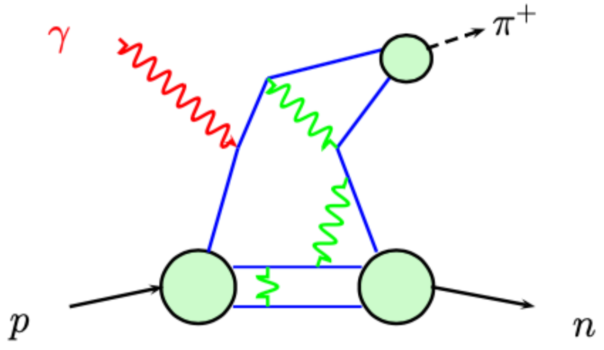
Diehl & Kroll, EPJ C73 (2013)

Pion photo-production with GPD

Peter Kroll, report at SBS meeting, 2/2021

Brodsky-Lepage(80)

Efremov-Radyushkin(80)



form factors, WACS, WAMP, ...

all partons participate in hard process by exchange of gluons

lowest Fock state dominates

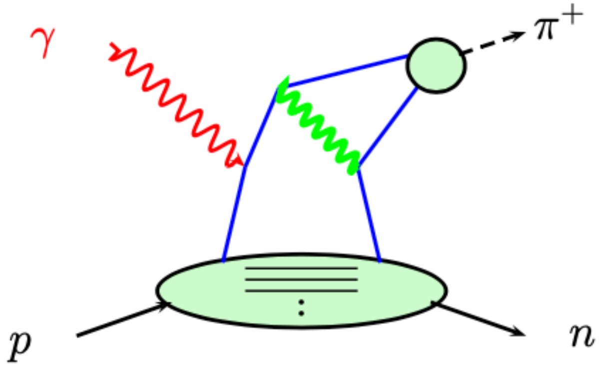
higher ones suppressed by $1/s^n$

soft matrix elements: distr. ampl.

underestimates data, larger $-t, -u$ required?

handbag mechanism

Radyushkin(98), DFJK(98)



only one active parton

all Fock components of nucleon contribute

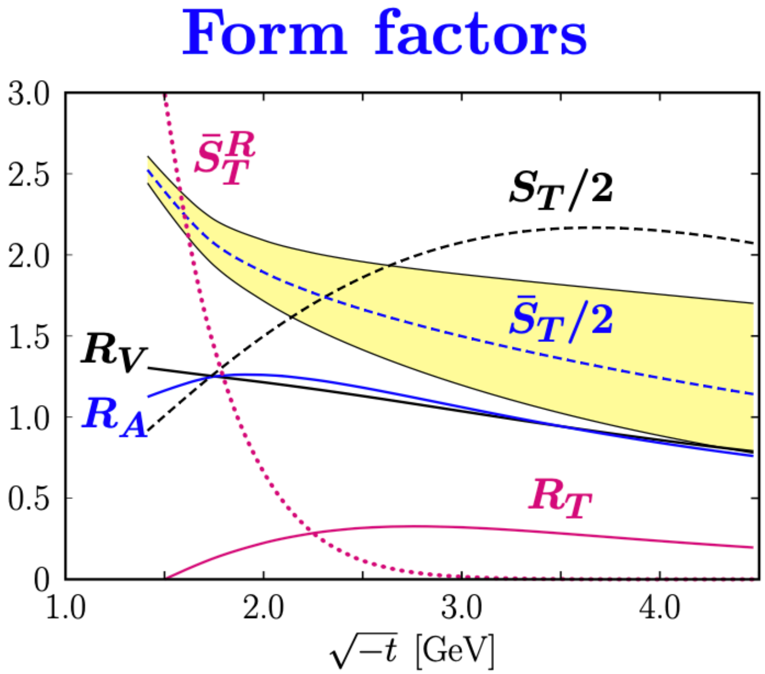
soft matrix elements: proton GPDs, pion DA

Feynman end-point mechanism -

possible that BL-ER dominates asymptotically

The observable to measure in experiment

Peter Kroll, report at SBS meeting, 2/2021

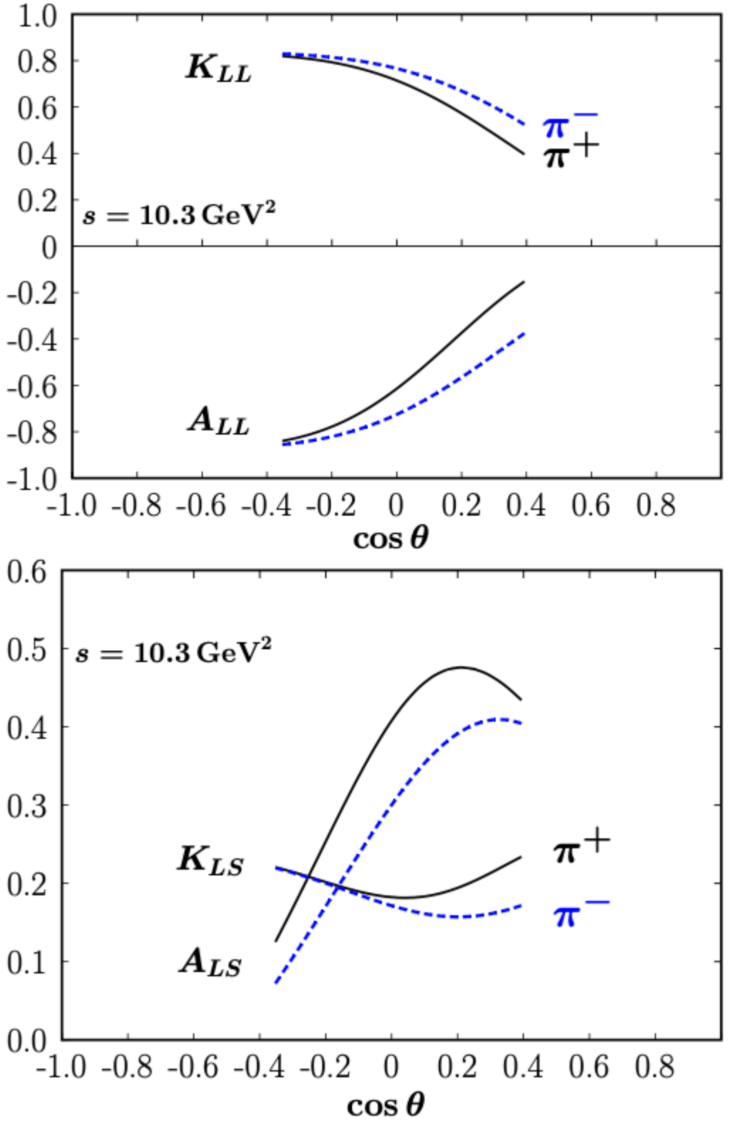


from KPK18 $\qquad$ π^0 FFs scaled by t^2

$R_V(H), R_T(E)$ from nucleon FF analysis (Diehl-K(13))
$R_A(\widetilde{H})$ FF analysis plus WACS K_{LL}
$S_T(H_T), \bar{S}_T(\bar{E}_T)$ low $-t$ from DVMP analysis (Goloskokov-K(11))
$S_S(\widetilde{H}_T) = \bar{S}_T/2$ (since $\bar{E}_T = 2\widetilde{H}_T + E_T$) large $-t$ behavior see next slide

Pion photo-production with GPD

Peter Kroll, report at SBS meeting, 2/2021



photoproduction of charged pions

$A_{LL}^{twist-2} = K_{LL}^{twist-2}$ as for WACS

$$A_{LL}^{twist-3} = -K_{LL}^{twist-3}$$
$$\simeq -\frac{4}{F}\,S_T\left[S_T - \frac{t}{2m^2}S_S\right]$$

$$A_{LS}^{twist-3} = -K_{LS}^{twist-3} \simeq -\frac{2}{F}\,\frac{\sqrt{-t}}{m}\,\bar{S}_T S_T$$

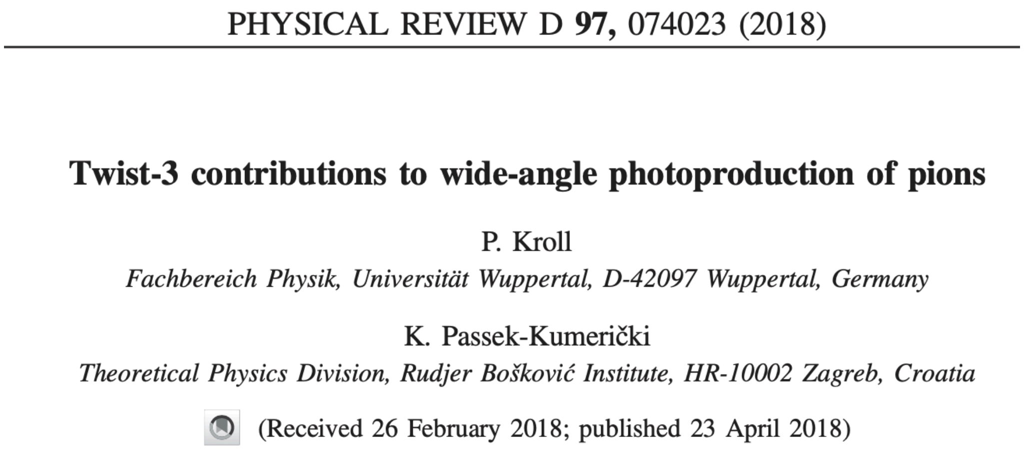
characteristic signature

for dominance of twist-3

like $\sigma_T \gg \sigma_L$ in DVMP

WAMP twist-3

Pion photo-production from nucleon



PHYSICAL REVIEW D **97,** 074023 (2018)

Twist-3 contributions to wide-angle photoproduction of pions

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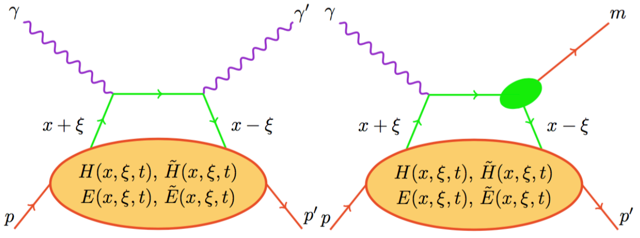
(Received 26 February 2018; published 23 April 2018)



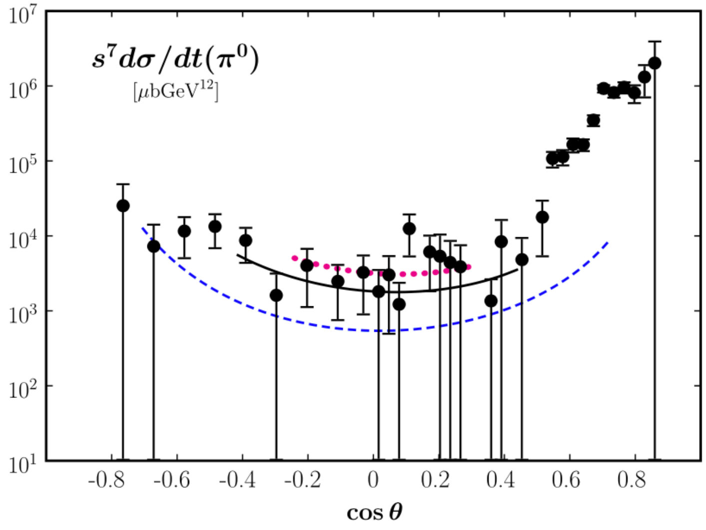
(a) Compton scattering on the proton (b) Meson photoproduction

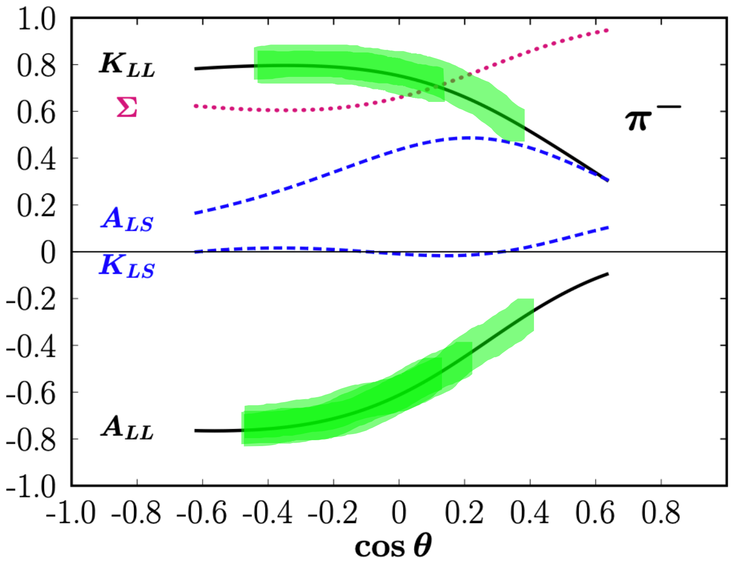
Figure 1.6: Compton scattering and meson photoproduction in the handbag model.

$$A_{\rm LL}^{\rm twist-3} = -K_{\rm LL}^{\rm twist-3}, \qquad (51)$$

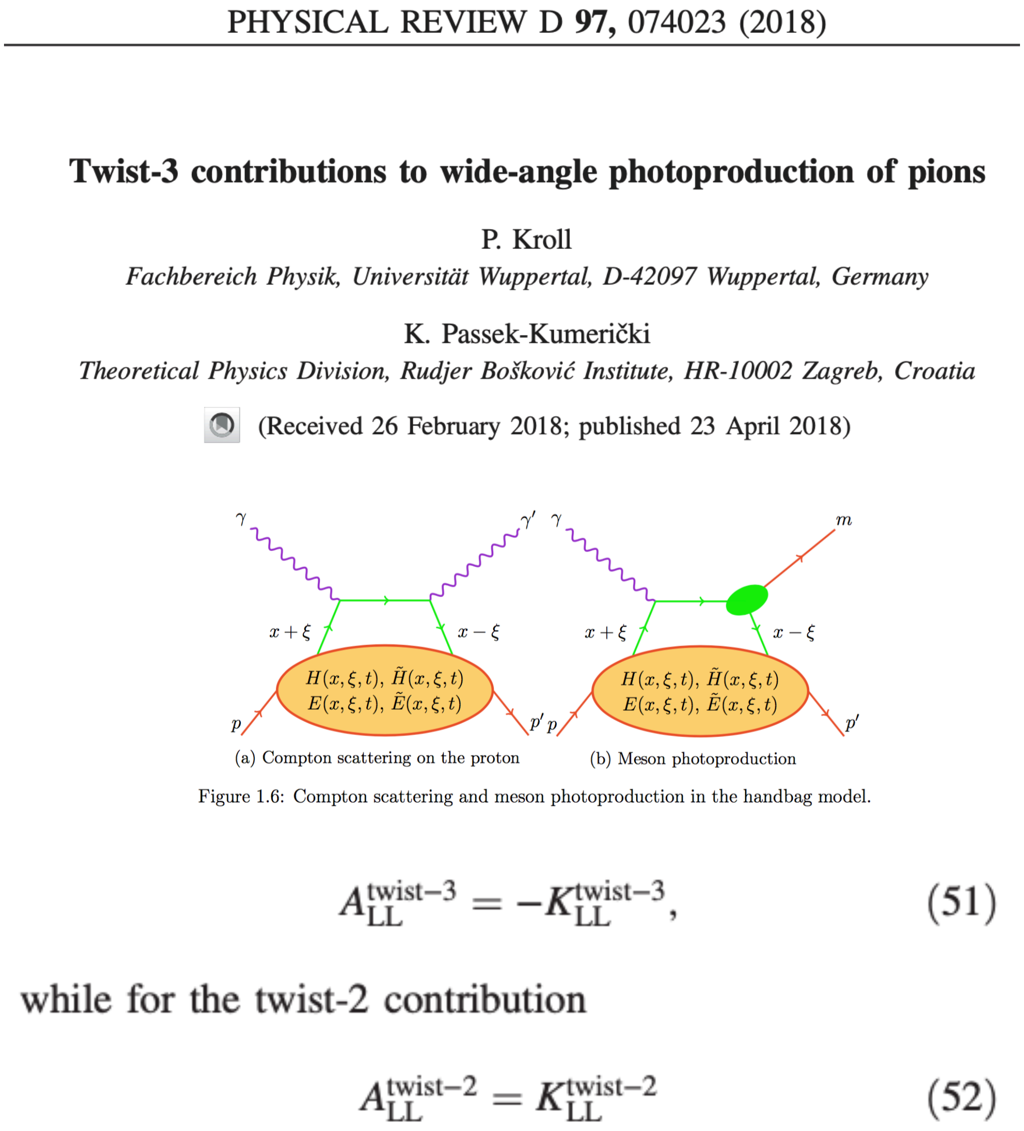
while for the twist-2 contribution

$$A_{\rm LL}^{\rm twist-2} = K_{\rm LL}^{\rm twist-2} \qquad (52)$$





The observable to measure in the experiment



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while for the twist-2 contribution

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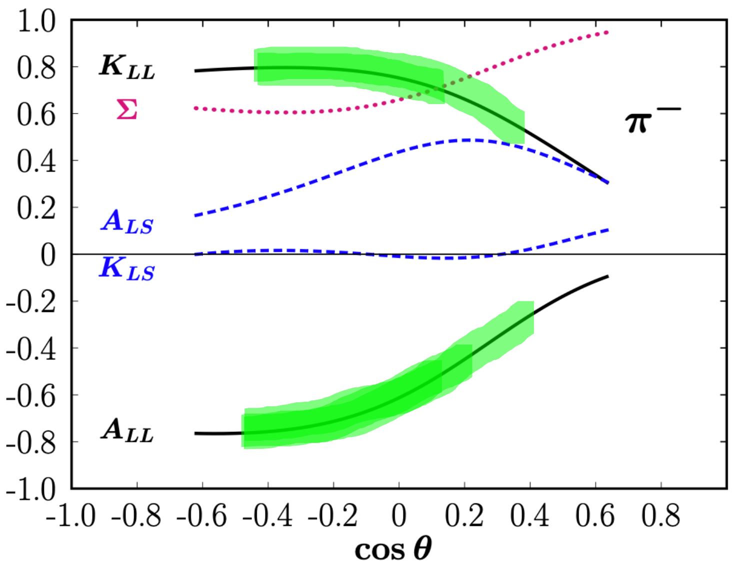
photon helicity

target polarization

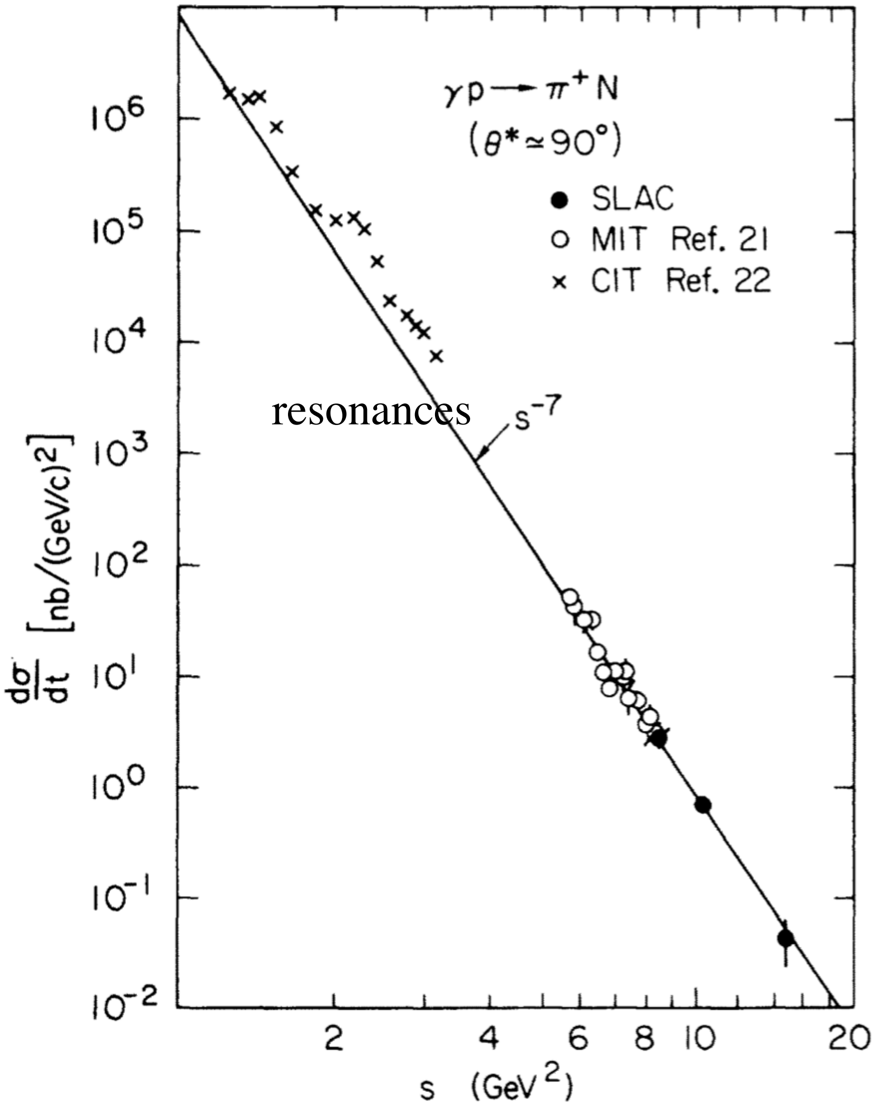
$$K_{LL} = \frac{d\sigma(+,\rightarrow) - d\sigma(-,\rightarrow)}{d\sigma(+,\rightarrow) + d\sigma(-,\rightarrow)}$$

$$A_{LL} = \frac{d\sigma(+\rightarrow) - d\sigma(-\rightarrow)}{d\sigma(+\rightarrow) + d\sigma(-\rightarrow)}$$

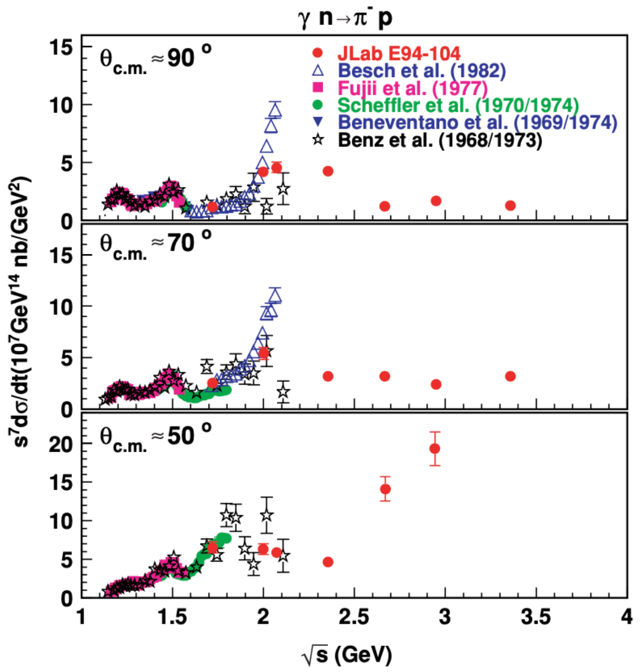


Importance of the large s, -t, -u

Phys. Rev. D **14**, 679 (1976)

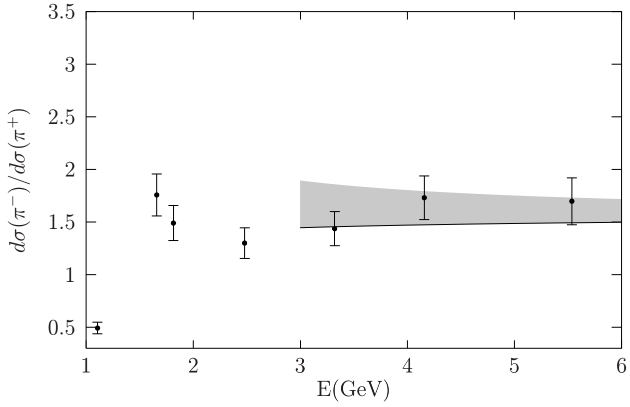


PHYSICAL REVIEW C **71**, 044603 (2005)



high t/s

low t/s

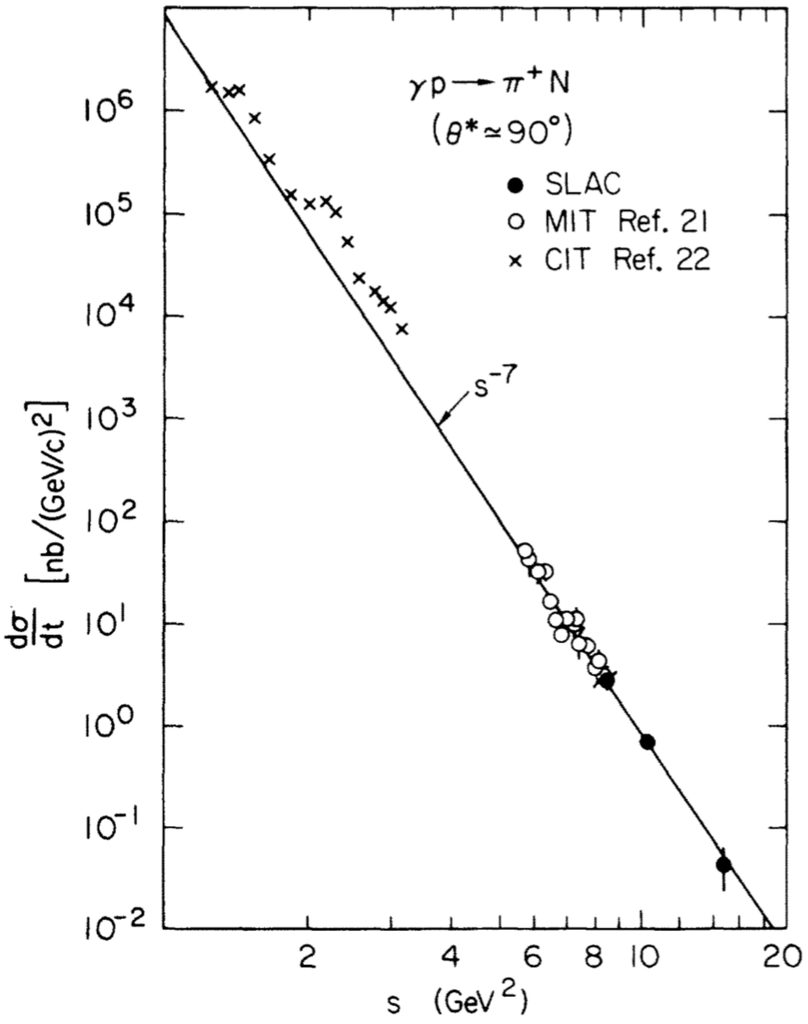


ratio at
90° COM

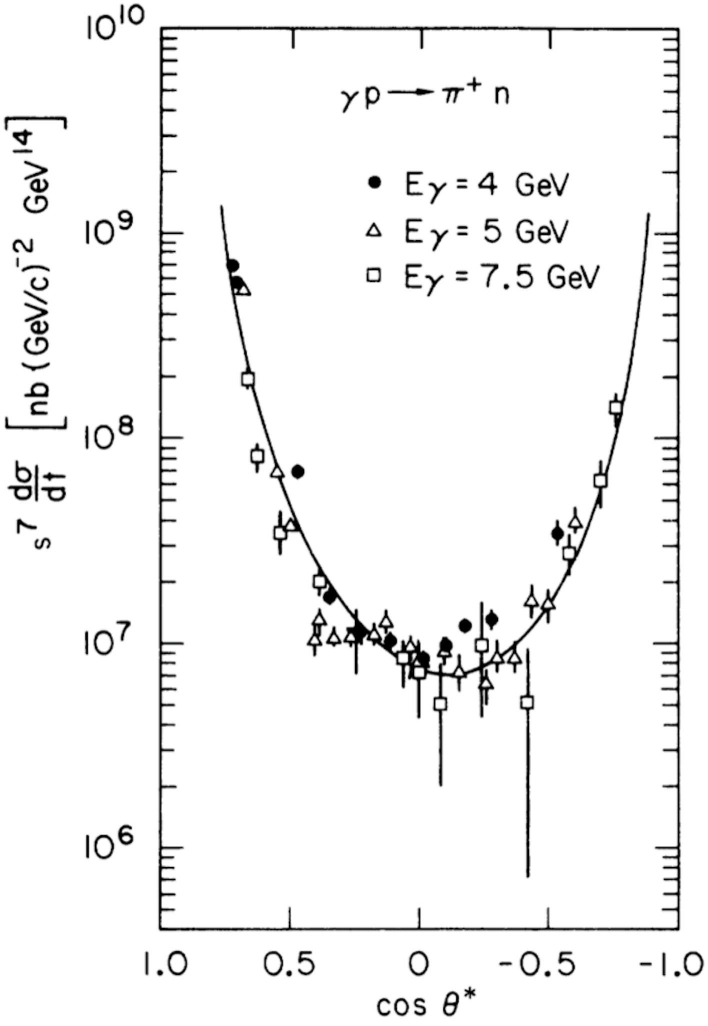
Eur. Phys. J. C 33, 91–103 (2004)

The pion photo-production cross section

Phys. Rev. D **14**, 679 (1976)



Scaling

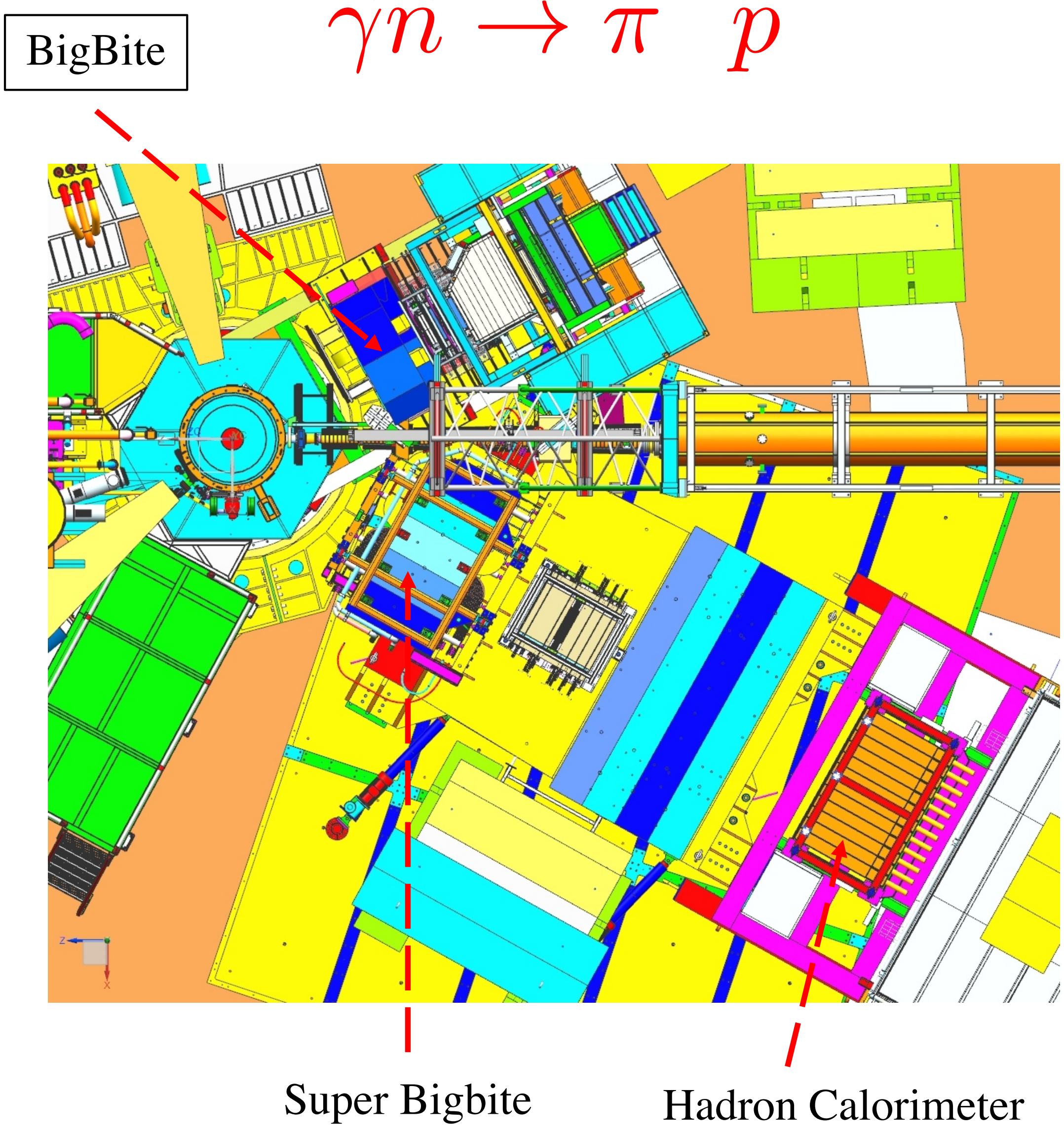


Angular dependence

SLAC data

Experiment: Layout and Parameters

$\vec{\gamma}\vec{n} \rightarrow \pi^- p$



Beam: 20 μA, 85% polarization
Target: 60 cm polarized He-3

Pion arm at 30-42^o
Proton arm at 20-33^o

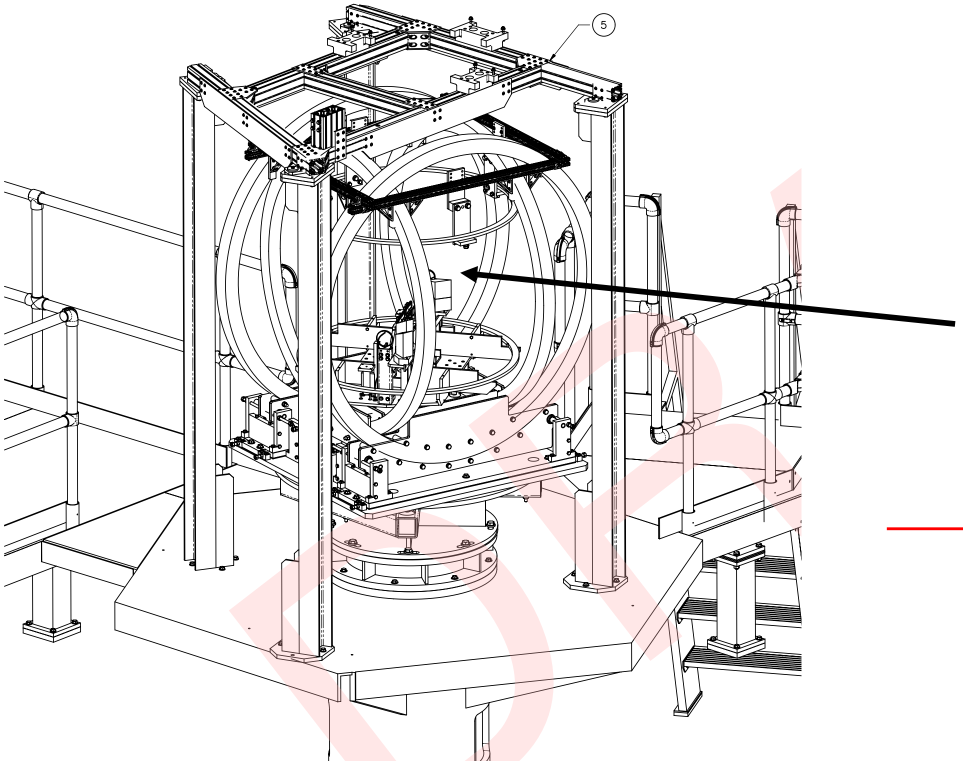
With 10 days total of beam time the resulting accuracy for each of FIVE kinematical points will be

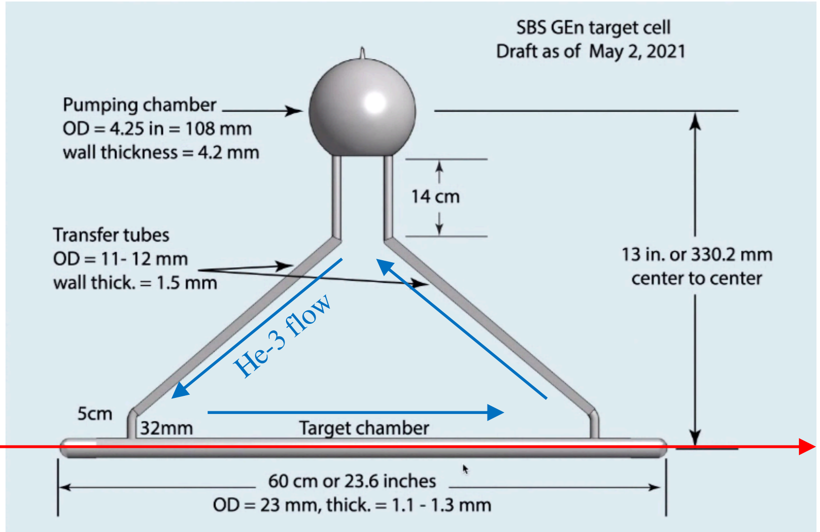
$$\Delta A_{LL} = 0.05$$

Systematics is 0.05, mainly from the uncertainties in the target and beam polarizations.

Experiment layout

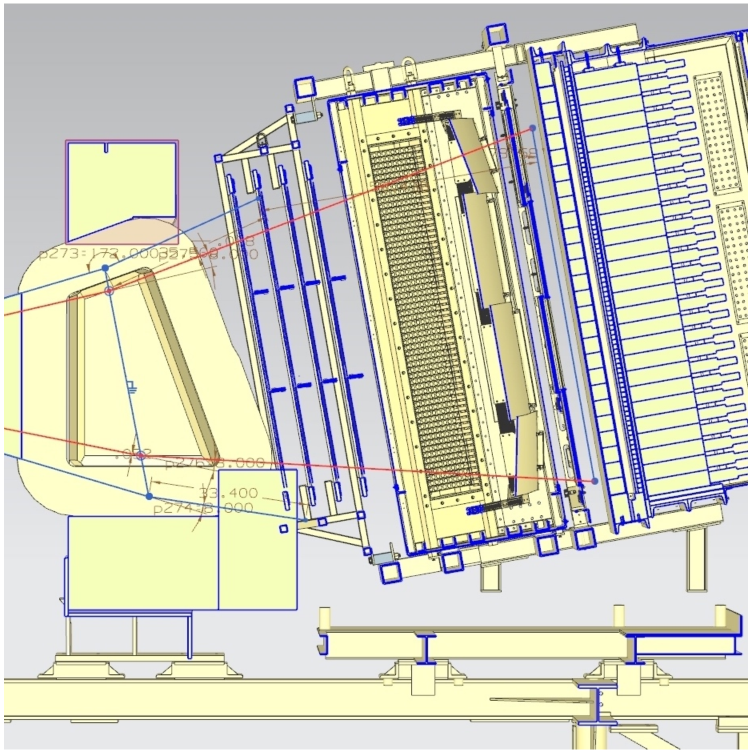
Equipment: Polarized Target

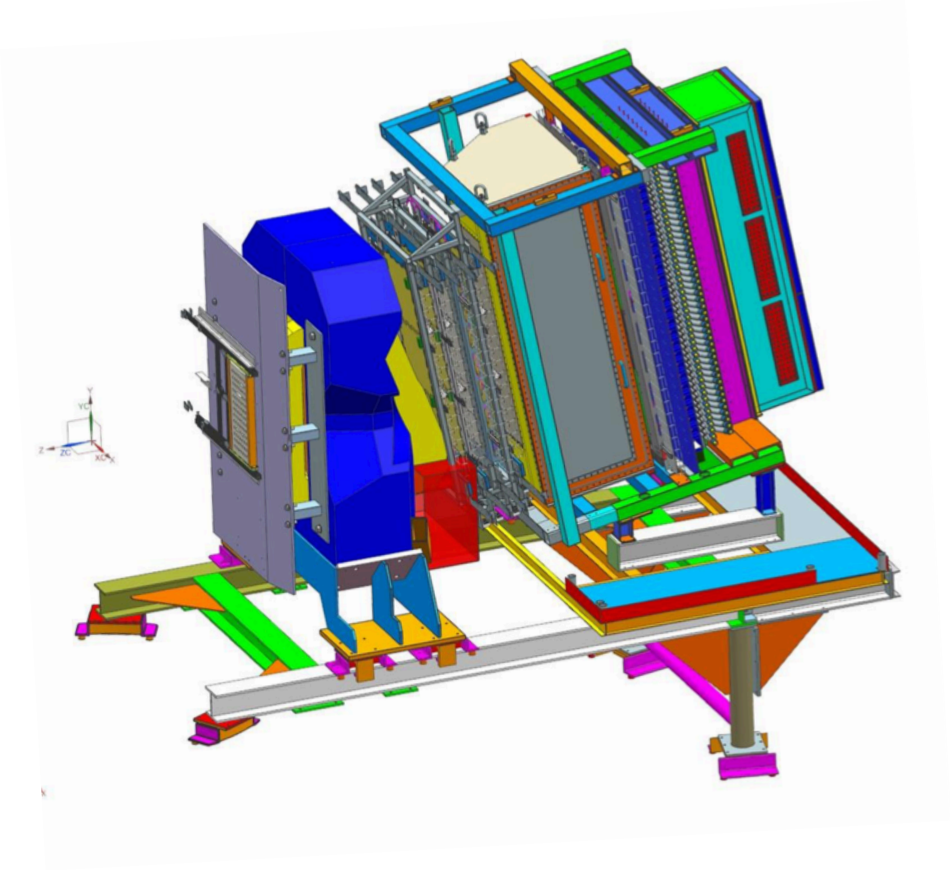




Target cell is 60 cm long with 10 atm He-3
Nuclei polarization is 60%
Beam current (in this experiment) is 20 μA

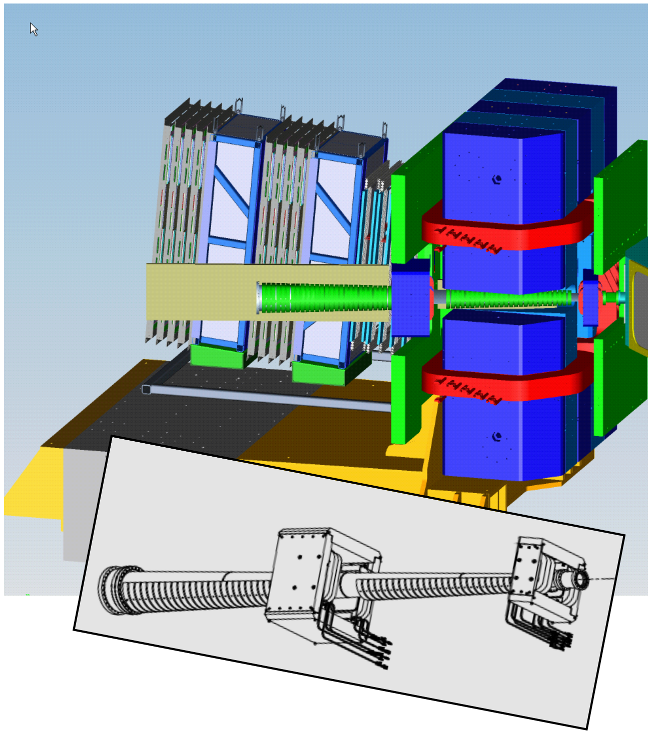
Experiment: BigBite spectrometer

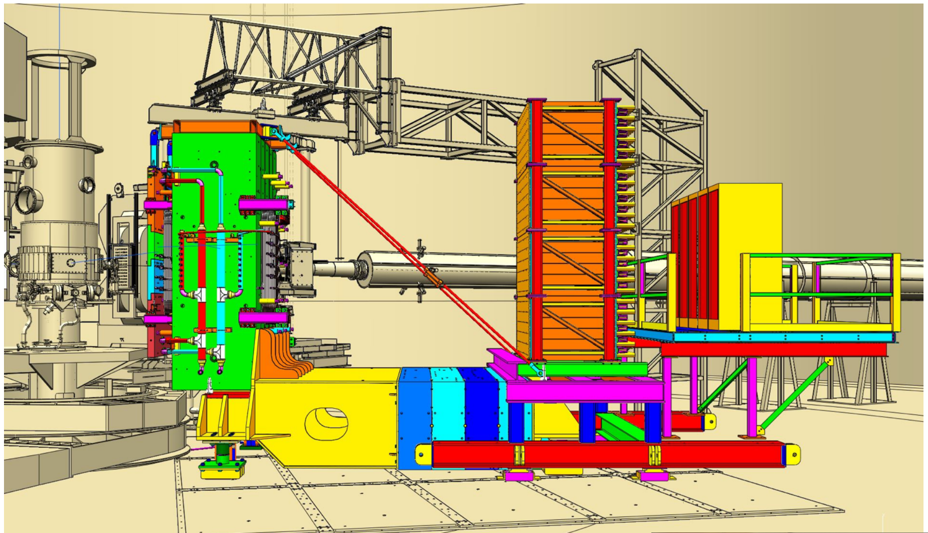




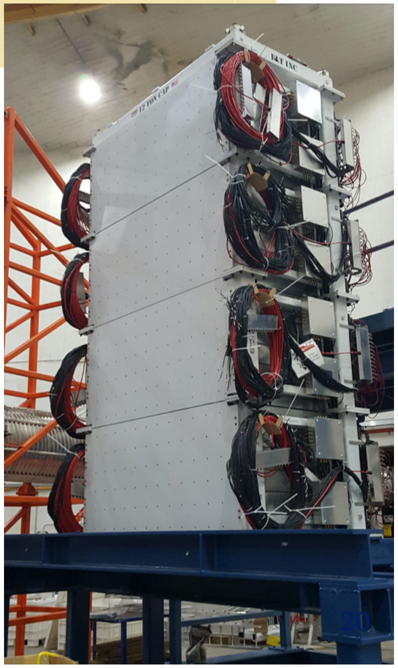
Solid angle ~ 50 msr
Momentum / angular resolutions ~ 1% / 1 mrad
PID with two-layer shower and Gas Cherenkov
Time resolution ~ 0.5 ns

Experiment: Super Bigbite spectrometer





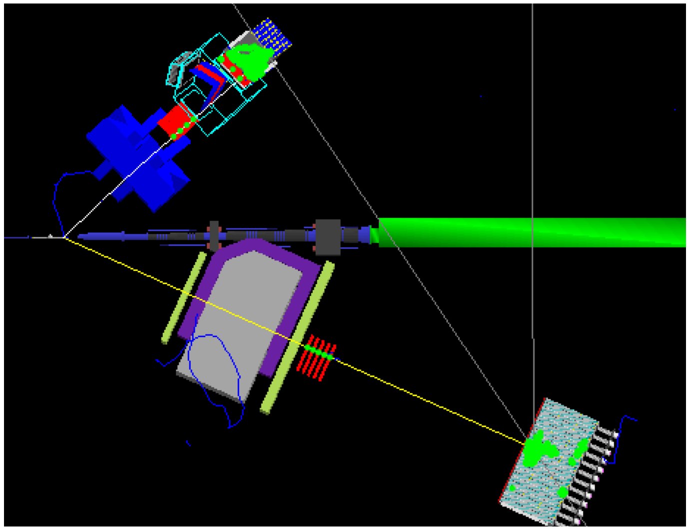
Solid angle for this setup ~ 35 msr
Momentum / angular
resolutions are ~ 1% / 1 mrad
Time resolution (HCAL) ~ 0.5 ns

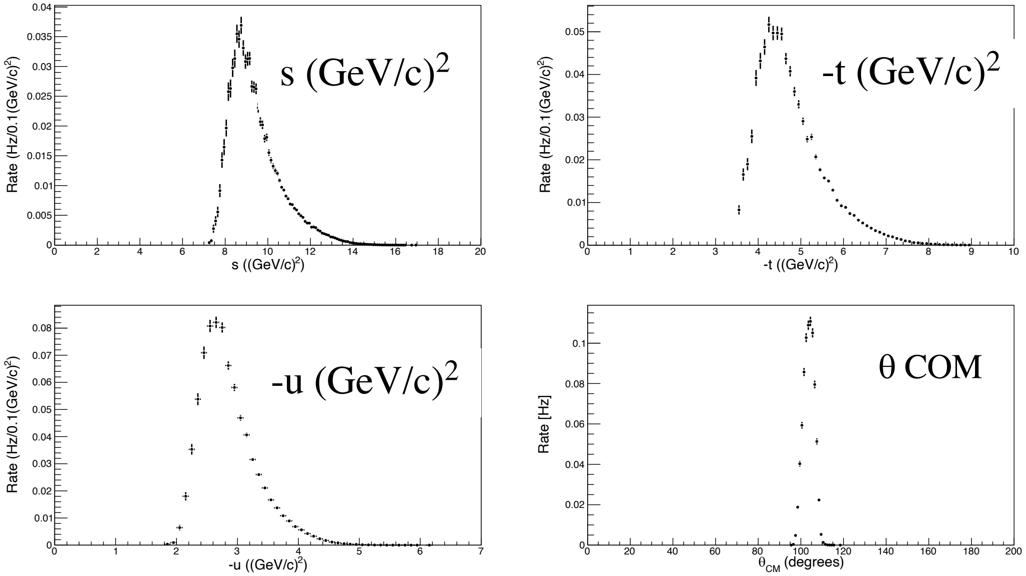


Hadron Calorimeter

Detectors

MC simulation





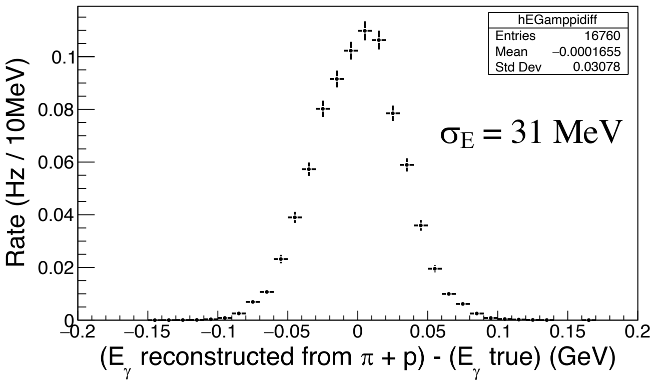
	E_e GeV	θ_{π^-} deg.	E_γ GeV	p_{π^-} GeV/c	θ_p deg.	p_p GeV/c	θ_{CM} deg.	$< s >$ $(GeV/c)^2$	$< -t >$ $(GeV/c)^2$	$< -u >$ $(GeV/c)^2$
A	6.6	41.9	4.5	2.02	24.3	3.29	103	9.3	4.7	2.9
B	6.6	30.0	4.5	2.74	32.8	2.53	82	9.3	3.3	4.3
C	6.6	52.0	4.5	1.58	19.5	3.74	116	9.3	5.5	2.1
D	8.8	37.2	6.0	2.61	21.9	4.23	103	12.1	6.4	4.0
E	11	33.7	7.5	3.20	20.2	5.15	103	15.0	8.1	5.2

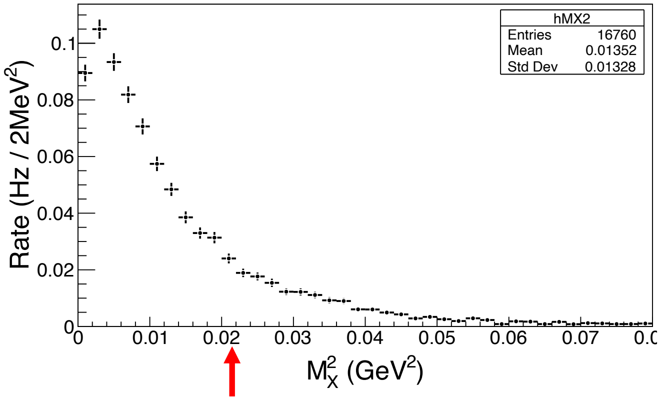
Wide-angle regime: s, $-t$, $-u$ >> Λ^2

Geant4 simulation

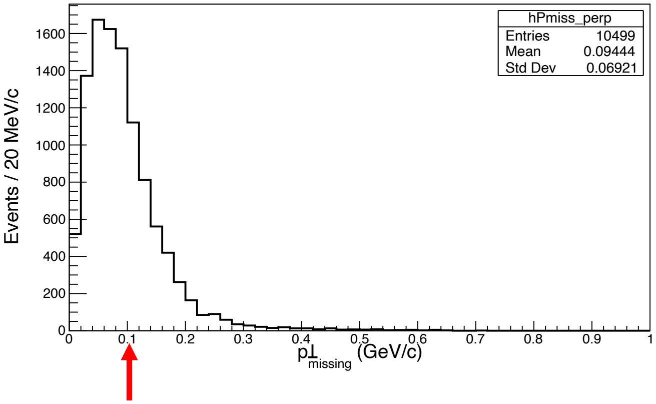
Experiment: Event reconstruction

$$\vec{\gamma}\vec{n} \to \pi^- p$$





two-pion threshold

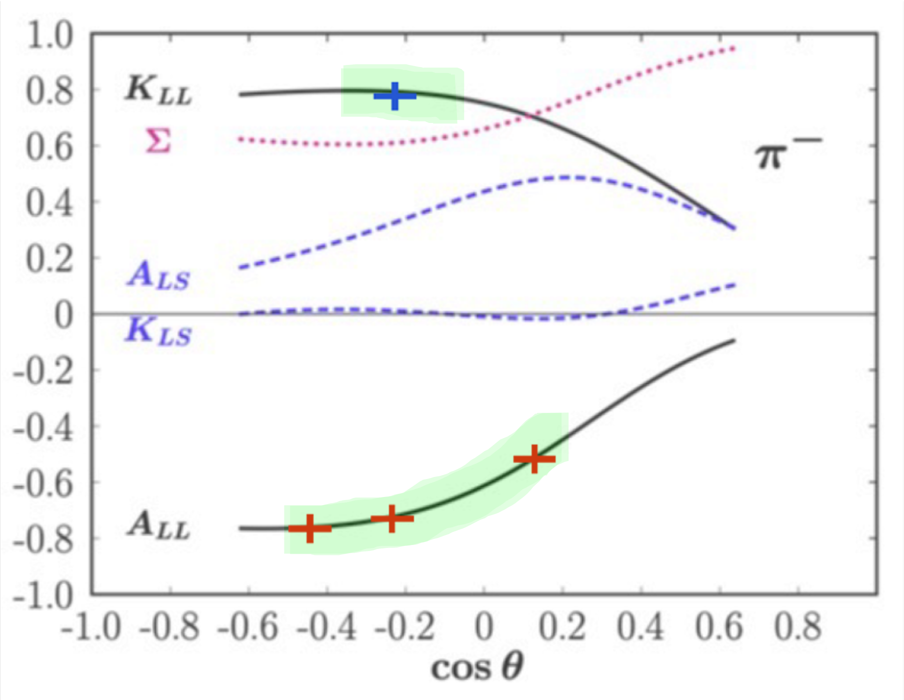


cut

Kinematics	A	B	C	D	E
Pion detection efficiency	0.41	0.43	0.38	0.41	0.40
Proton detection efficiency	0.88	0.81	0.90	0.92	0.94
Efficiency after cut on $p_{miss,\perp}$	0.67	0.66	0.67	0.65	0.64
Rate of good events per hour	1365	1094	1048	522	141

Geant4 simulation

Projected results and beam time request



🟩 15% theoretical uncertainty

E_γ [GeV]	$< s >$ $[(\mathrm{GeV}/c)^2]$	$< -t >$ $[(\mathrm{GeV}/c)^2]$	$< -u >$ $[(\mathrm{GeV}/c)^2]$	$\cos\theta_{CM}$	Beam on target [hour]	Time [hour]	stat ΔA_{LL} accuracy
4.0-5.5	9.3	4.7	2.9	-0.23	6	37	±0.05
4.0-5.5	9.3	3.3	4.3	+0.14	8	27	±0.05
4.0-5.5	9.3	5.5	2.1	-0.44	8	27	±0.05
5.0-7.5	12.1	6.4	4.0	-0.23	16	47	±0.05
6.5-9.0	15.0	8.1	5.2	-0.23	60	98	±0.05

10 days total with overhead

Summary

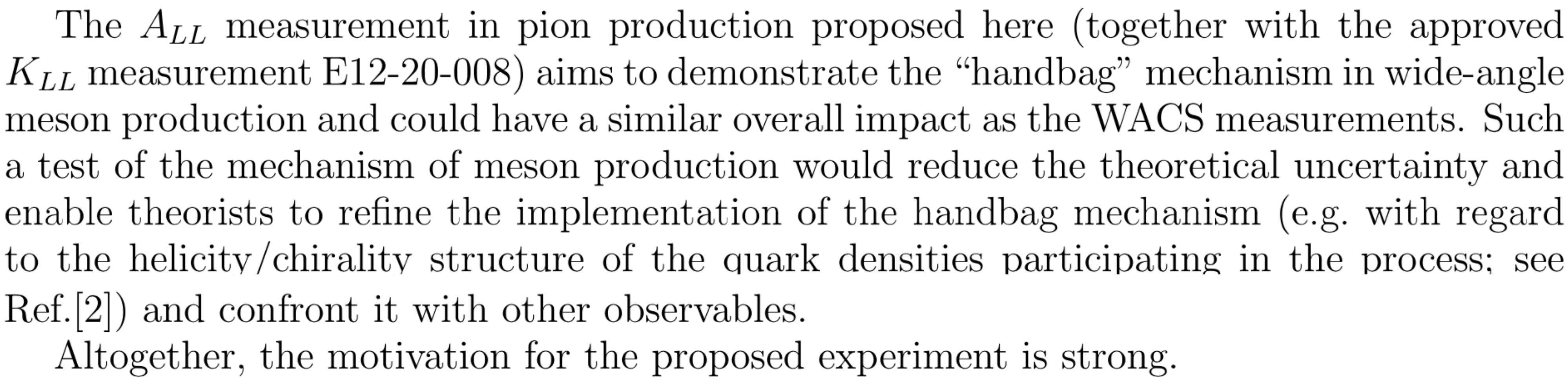
- Measurement of ALL asymmetry in single pion photo-production together with approved PionKLL experiment will test the novel GPD-based calculation.

- The proposed test of ALL at several *s* and -*t* values will provide confidence in the overall result.

- Pion photo-production physics originated about 70 years ago could reach next stage of understanding.

Backup slides

Theory review on PR12-21-005



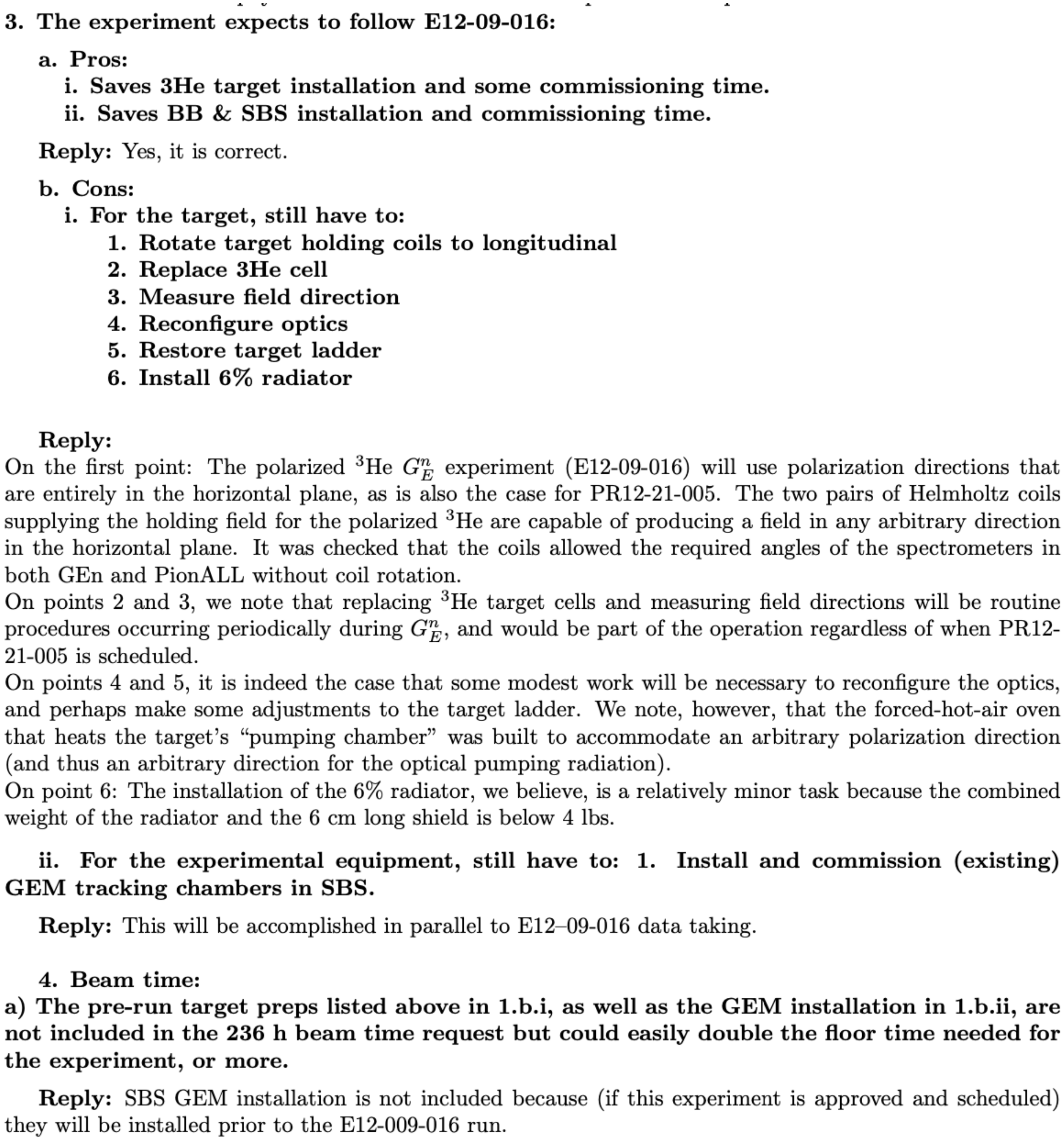
The A_{LL} measurement in pion production proposed here (together with the approved K_{LL} measurement E12-20-008) aims to demonstrate the "handbag" mechanism in wide-angle meson production and could have a similar overall impact as the WACS measurements. Such a test of the mechanism of meson production would reduce the theoretical uncertainty and enable theorists to refine the implementation of the handbag mechanism (e.g. with regard to the helicity/chirality structure of the quark densities participating in the process; see Ref.[2]) and confront it with other observables.

Altogether, the motivation for the proposed experiment is strong.

… nuclear final-state interactions that change its momentum or possibly the observed particle type. Those interactions could be estimated in an eikonal-type formulation appropriate to high-energy scattering, including spin dependence in the initial configuration and the re-scattering process.

Reply: We agree with this suggestion. From our experience with the first GEN experiment on He-3 the FSI correction is likely to be below 5% at the momentum of the particles produced in this experiment due to helicity conservation at high momenta. As in nTPE and GEn experiments, we are collaborating with Misak Sargsian who developed the state-of-the-art eikonal-type codes for exclusive reactions.

Technical review on PR12-21-005



3. The experiment expects to follow E12-09-016:

a. Pros:

- **i. Saves 3He target installation and some commissioning time.**
- **ii. Saves BB & SBS installation and commissioning time.**

Reply: Yes, it is correct.

b. Cons:

i. For the target, still have to:

1. **Rotate target holding coils to longitudinal**
2. **Replace 3He cell**
3. **Measure field direction**
4. **Reconfigure optics**
5. **Restore target ladder**
6. **Install 6% radiator**

Reply:

On the first point: The polarized ^{3}He G_E^n experiment (E12-09-016) will use polarization directions that are entirely in the horizontal plane, as is also the case for PR12-21-005. The two pairs of Helmholtz coils supplying the holding field for the polarized ^{3}He are capable of producing a field in any arbitrary direction in the horizontal plane. It was checked that the coils allowed the required angles of the spectrometers in both GEn and PionALL without coil rotation.

On points 2 and 3, we note that replacing ^{3}He target cells and measuring field directions will be routine procedures occurring periodically during G_E^n, and would be part of the operation regardless of when PR12-21-005 is scheduled.

On points 4 and 5, it is indeed the case that some modest work will be necessary to reconfigure the optics, and perhaps make some adjustments to the target ladder. We note, however, that the forced-hot-air oven that heats the target's "pumping chamber" was built to accommodate an arbitrary polarization direction (and thus an arbitrary direction for the optical pumping radiation).

On point 6: The installation of the 6% radiator, we believe, is a relatively minor task because the combined weight of the radiator and the 6 cm long shield is below 4 lbs.

ii. For the experimental equipment, still have to: 1. Install and commission (existing) GEM tracking chambers in SBS.

Reply: This will be accomplished in parallel to E12–09-016 data taking.

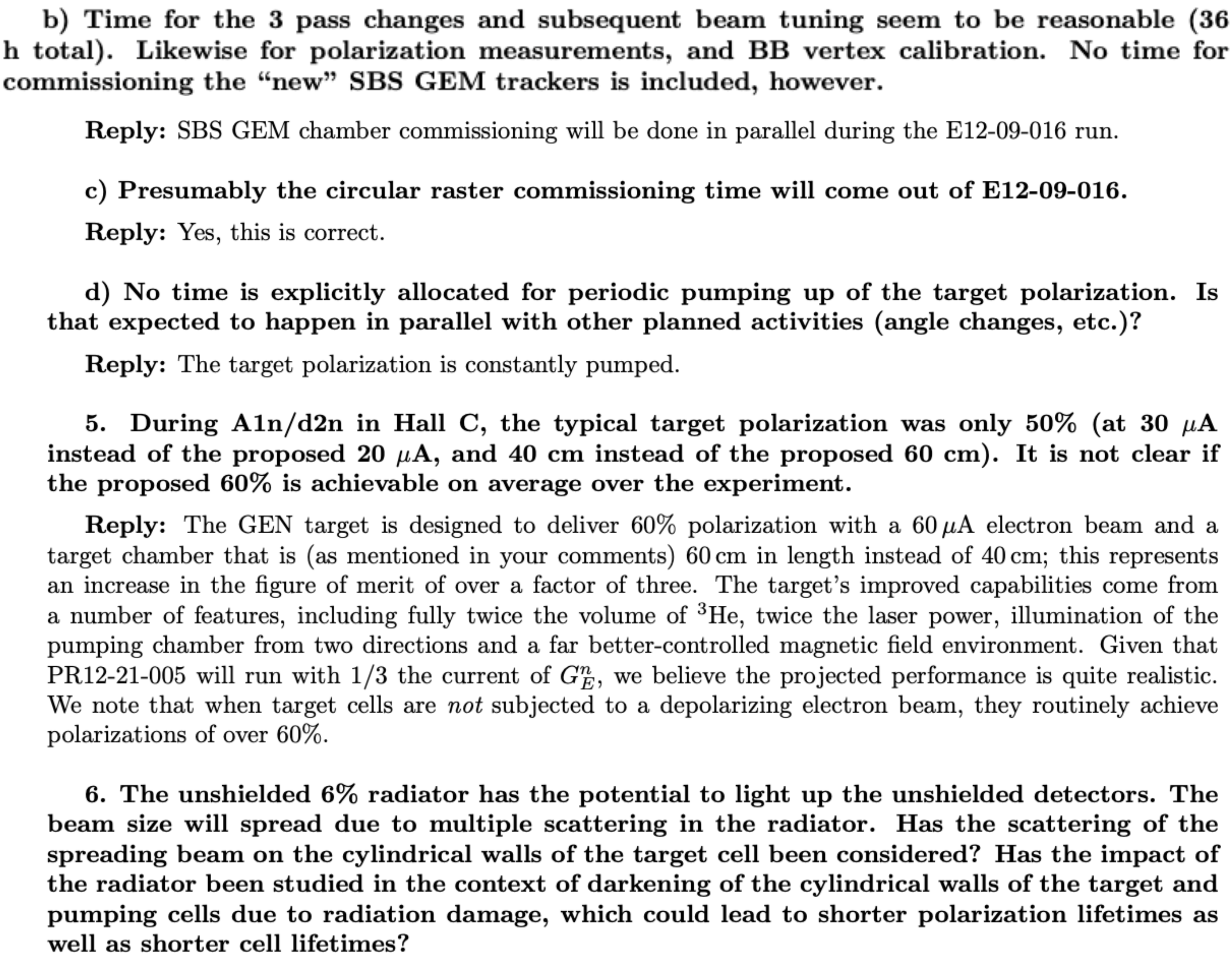
4. Beam time:

a) The pre-run target preps listed above in 1.b.i, as well as the GEM installation in 1.b.ii, are not included in the 236 h beam time request but could easily double the floor time needed for the experiment, or more.

Reply: SBS GEM installation is not included because (if this experiment is approved and scheduled) they will be installed prior to the E12-009-016 run.

Technical

Technical review on PR12-21-005



b) Time for the 3 pass changes and subsequent beam tuning seem to be reasonable (36 h total). Likewise for polarization measurements, and BB vertex calibration. No time for commissioning the "new" SBS GEM trackers is included, however.

Reply: SBS GEM chamber commissioning will be done in parallel during the E12-09-016 run.

c) Presumably the circular raster commissioning time will come out of E12-09-016.

Reply: Yes, this is correct.

d) No time is explicitly allocated for periodic pumping up of the target polarization. Is that expected to happen in parallel with other planned activities (angle changes, etc.)?

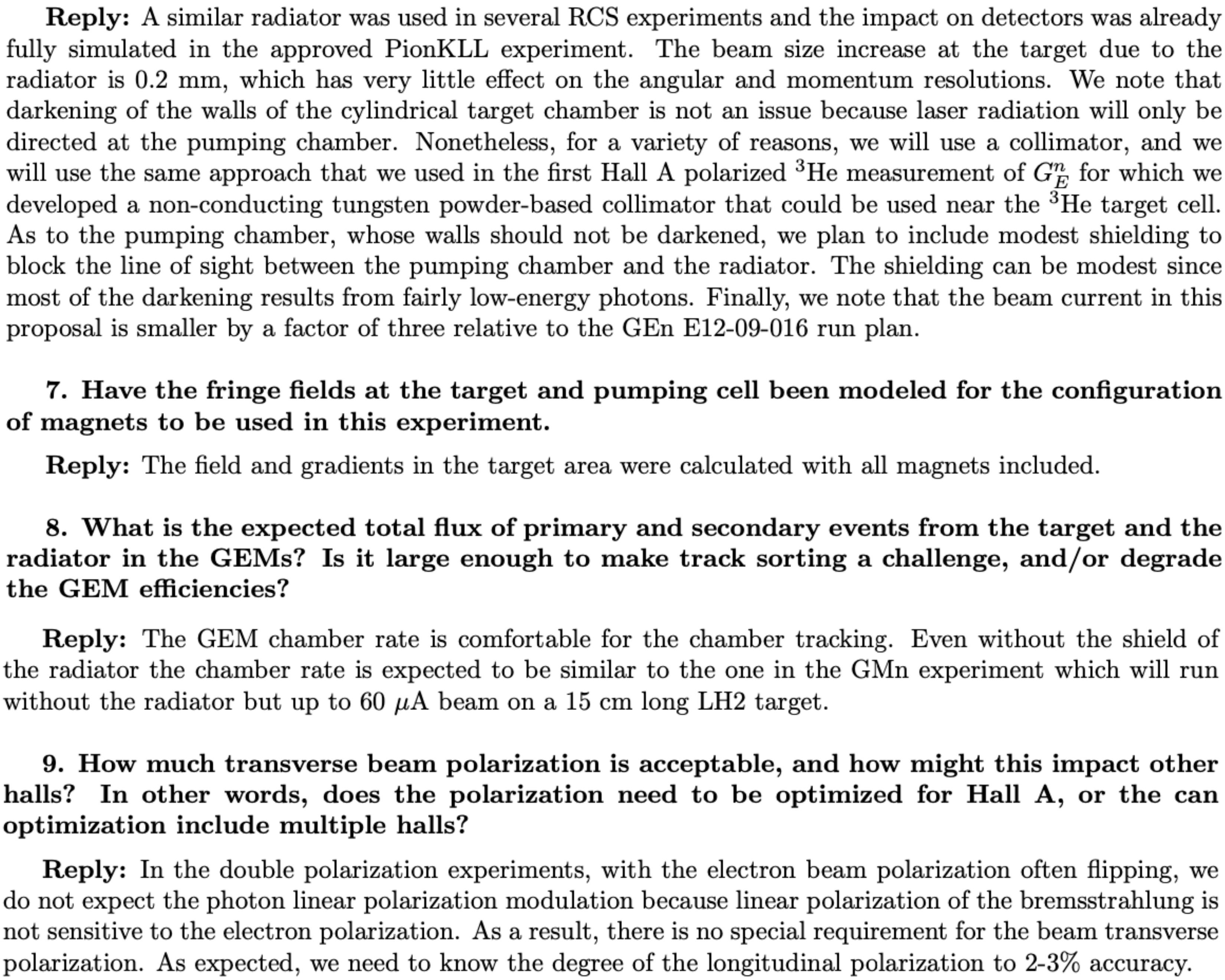
Reply: The target polarization is constantly pumped.

5. During A1n/d2n in Hall C, the typical target polarization was only 50% (at 30 μA instead of the proposed 20 μA, and 40 cm instead of the proposed 60 cm). It is not clear if the proposed 60% is achievable on average over the experiment.

Reply: The GEN target is designed to deliver 60% polarization with a 60 μA electron beam and a target chamber that is (as mentioned in your comments) 60 cm in length instead of 40 cm; this represents an increase in the figure of merit of over a factor of three. The target's improved capabilities come from a number of features, including fully twice the volume of ^{3}He, twice the laser power, illumination of the pumping chamber from two directions and a far better-controlled magnetic field environment. Given that PR12-21-005 will run with 1/3 the current of G_E^n, we believe the projected performance is quite realistic. We note that when target cells are *not* subjected to a depolarizing electron beam, they routinely achieve polarizations of over 60%.

6. The unshielded 6% radiator has the potential to light up the unshielded detectors. The beam size will spread due to multiple scattering in the radiator. Has the scattering of the spreading beam on the cylindrical walls of the target cell been considered? Has the impact of the radiator been studied in the context of darkening of the cylindrical walls of the target and pumping cells due to radiation damage, which could lead to shorter polarization lifetimes as well as shorter cell lifetimes?

Technical review on PR12-21-005



Reply: A similar radiator was used in several RCS experiments and the impact on detectors was already fully simulated in the approved PionKLL experiment. The beam size increase at the target due to the radiator is 0.2 mm, which has very little effect on the angular and momentum resolutions. We note that darkening of the walls of the cylindrical target chamber is not an issue because laser radiation will only be directed at the pumping chamber. Nonetheless, for a variety of reasons, we will use a collimator, and we will use the same approach that we used in the first Hall A polarized ^{3}He measurement of G_E^n for which we developed a non-conducting tungsten powder-based collimator that could be used near the ^{3}He target cell. As to the pumping chamber, whose walls should not be darkened, we plan to include modest shielding to block the line of sight between the pumping chamber and the radiator. The shielding can be modest since most of the darkening results from fairly low-energy photons. Finally, we note that the beam current in this proposal is smaller by a factor of three relative to the GEn E12-09-016 run plan.

7. Have the fringe fields at the target and pumping cell been modeled for the configuration of magnets to be used in this experiment.

Reply: The field and gradients in the target area were calculated with all magnets included.

8. What is the expected total flux of primary and secondary events from the target and the radiator in the GEMs? Is it large enough to make track sorting a challenge, and/or degrade the GEM efficiencies?

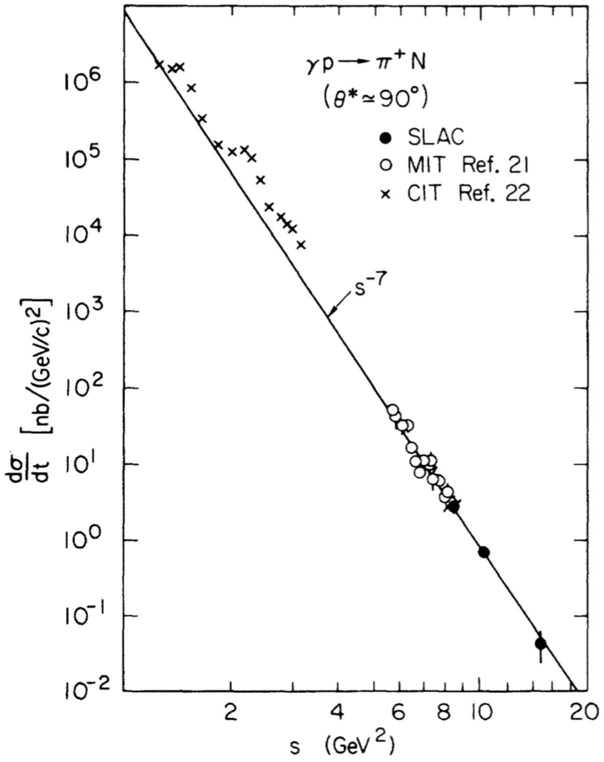
Reply: The GEM chamber rate is comfortable for the chamber tracking. Even without the shield of the radiator the chamber rate is expected to be similar to the one in the GMn experiment which will run without the radiator but up to 60 μA beam on a 15 cm long LH2 target.

9. How much transverse beam polarization is acceptable, and how might this impact other halls? In other words, does the polarization need to be optimized for Hall A, or the can optimization include multiple halls?

Reply: In the double polarization experiments, with the electron beam polarization often flipping, we do not expect the photon linear polarization modulation because linear polarization of the bremsstrahlung is not sensitive to the electron polarization. As a result, there is no special requirement for the beam transverse polarization. As expected, we need to know the degree of the longitudinal polarization to 2-3% accuracy.

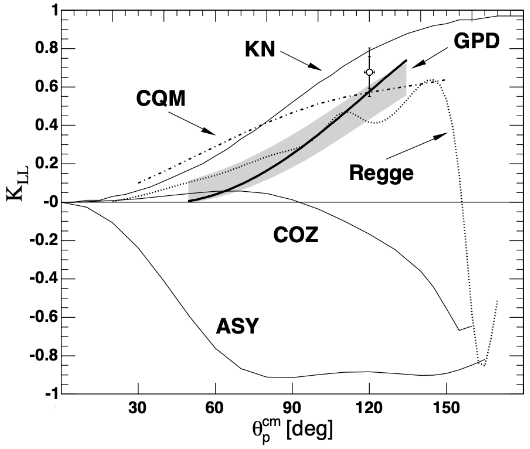
Scaling: Pion production and real Compton scattering

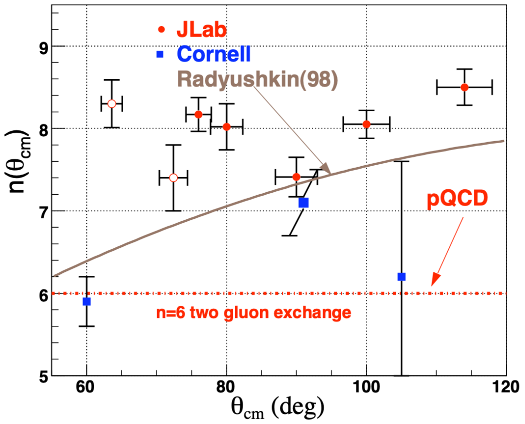
Phys. Rev. D **14**, 679 (1976)



$$\frac{d\sigma}{dt}(s,t) \sim \frac{1}{s^{n-2}} F\left(\frac{t}{s}\right)$$

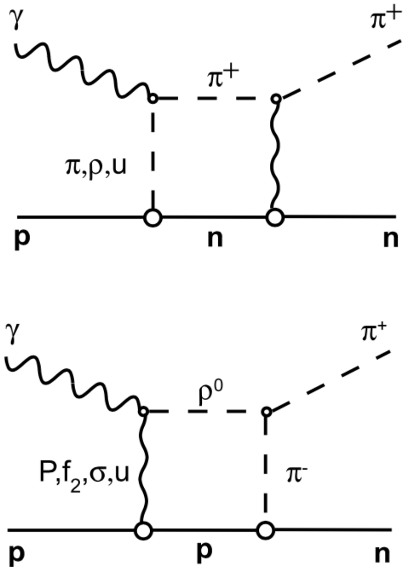
E99-114, PRL 98, 152001 (2007)

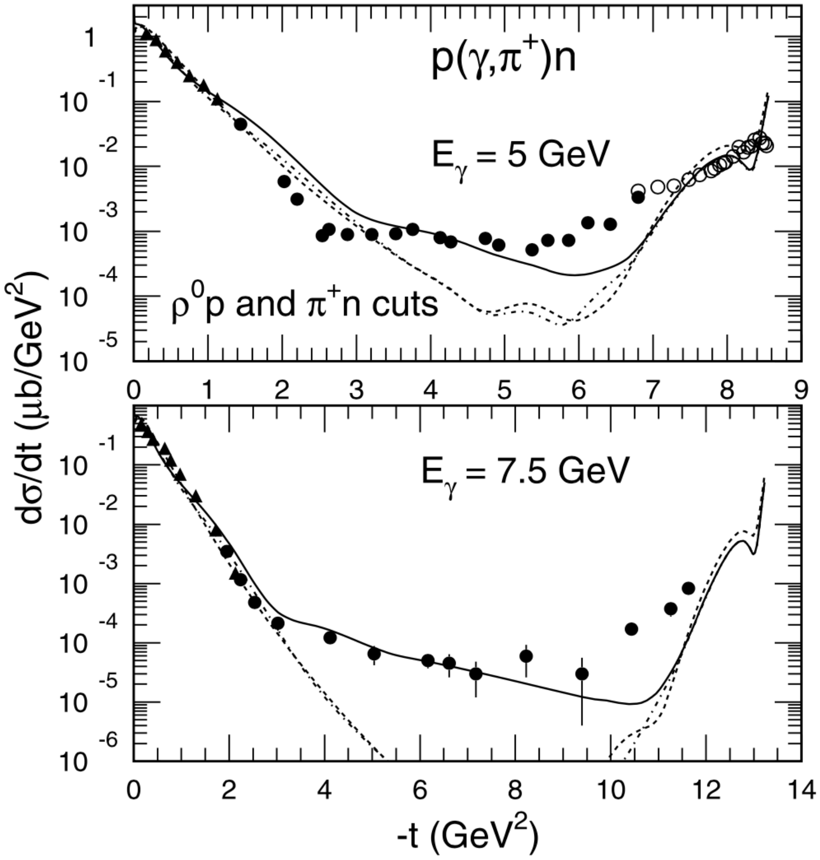




Pion photo-production in Regge model

J-M. Laget, Physics Letters B 685 (2010) 146–150

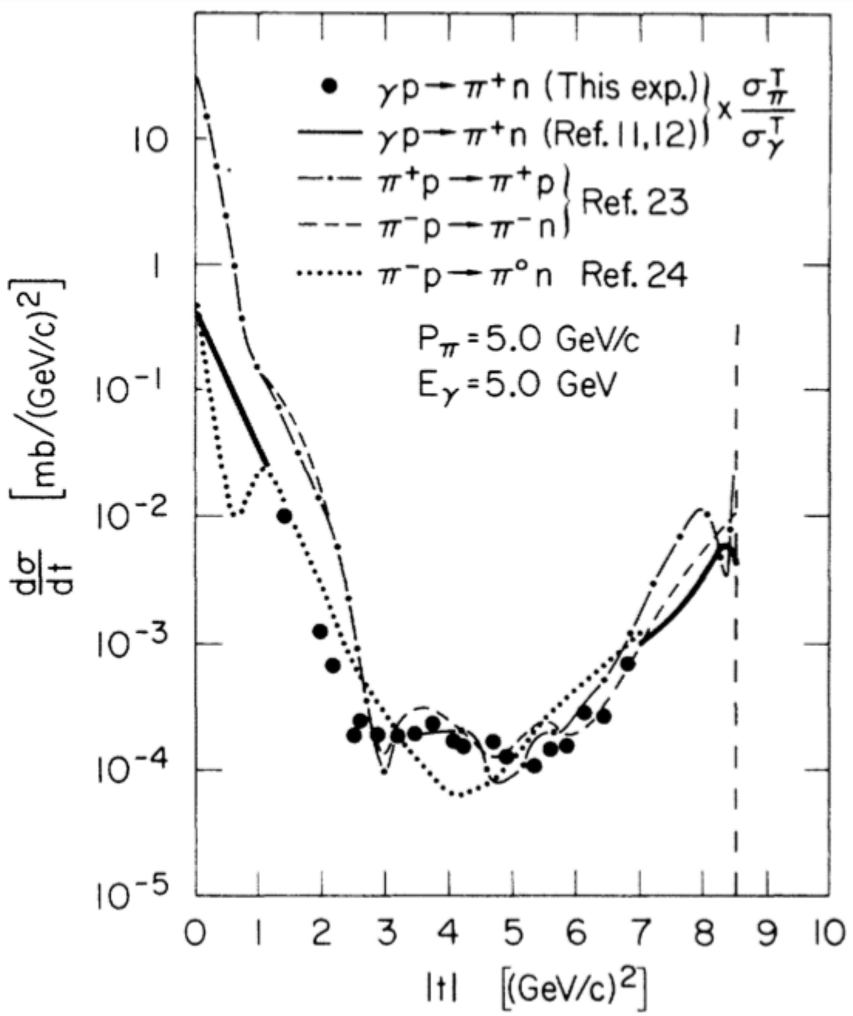




Pion scattering and production processes

$$\frac{d\sigma}{dt}(\gamma p \to \pi^0 p) = \frac{\alpha}{4}\left(\frac{\gamma_\rho^2}{4\pi}\right)\frac{1}{2}\left[\frac{d\sigma}{dt}(\pi^+ p \to \pi^+ p) + \frac{d\sigma}{dt}(\pi^- p \to \pi^- p)\right]$$

Phys. Rev. D **14**, 679 (1976)



The two-pion photo-production background

Eur Phys J A (2004) 19, s01, 257–260

Phys. Rev. D **14**, 679 (1976)

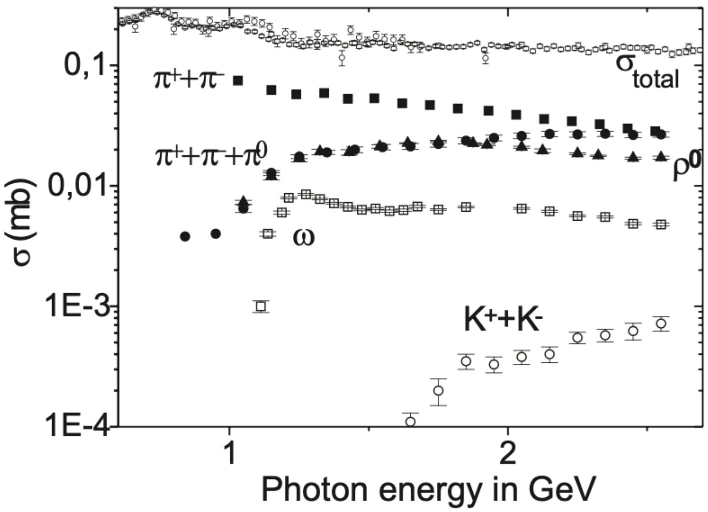
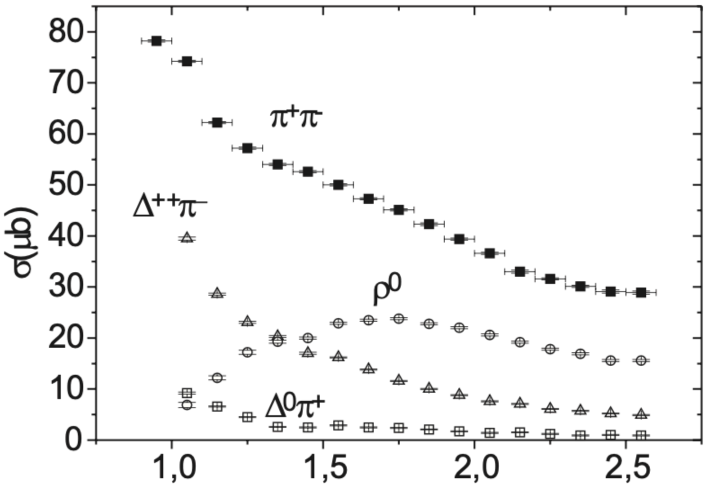
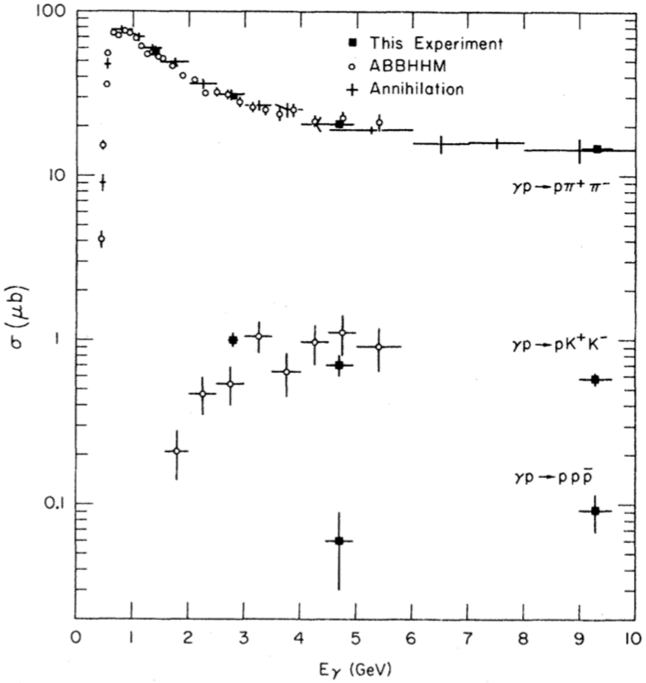
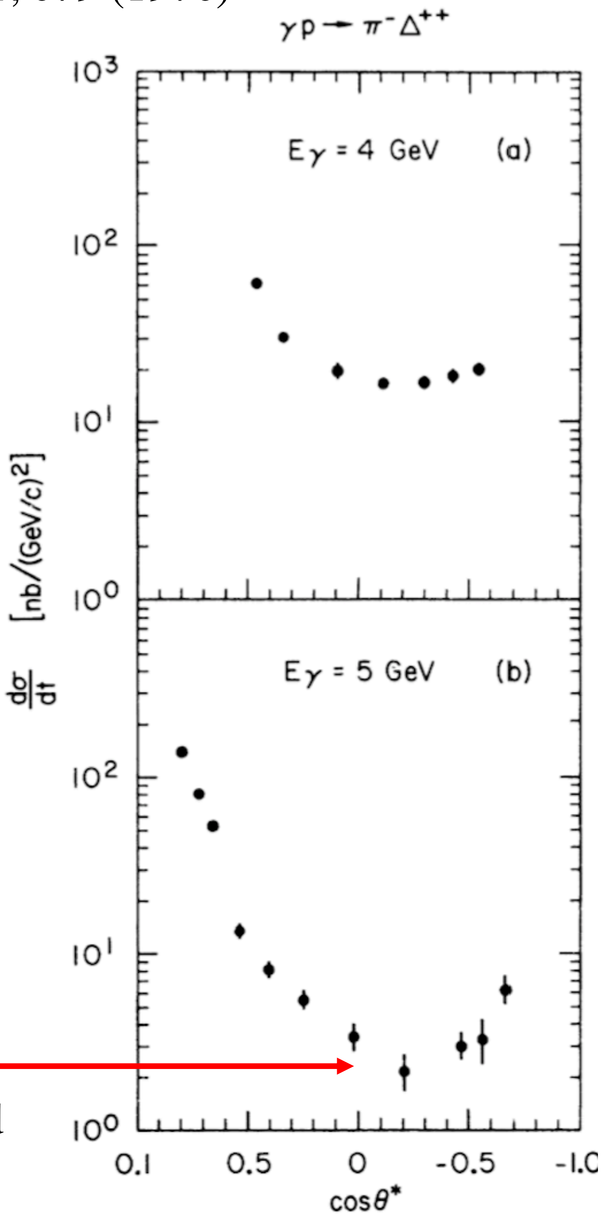


Fig. 2. Total meson production cross sections



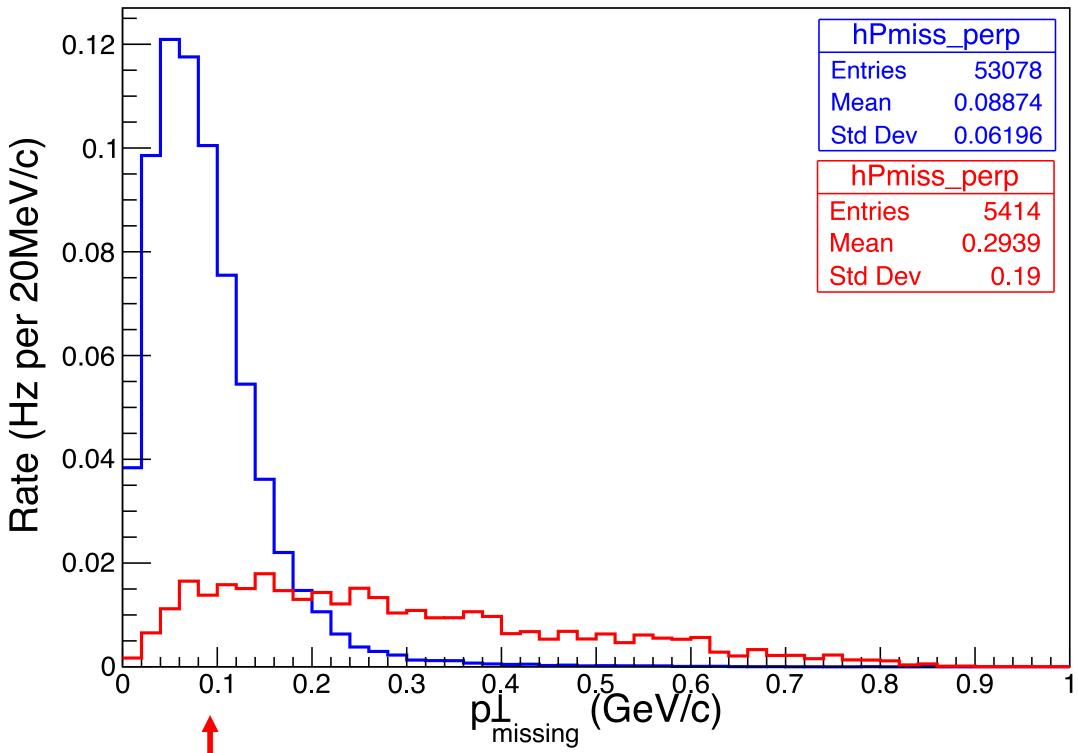




full dσ/dt
for background

Two-pion cross section

The two-pion photo-production background



cut

$\pi^{-}p$ events: 0.64 fraction below the cut

$\pi^{-}\Delta^{++}$ events: 0.13 fraction below the cut

Background rejection by using a cut on the missing p_{perp}