A_{LL} Experiment

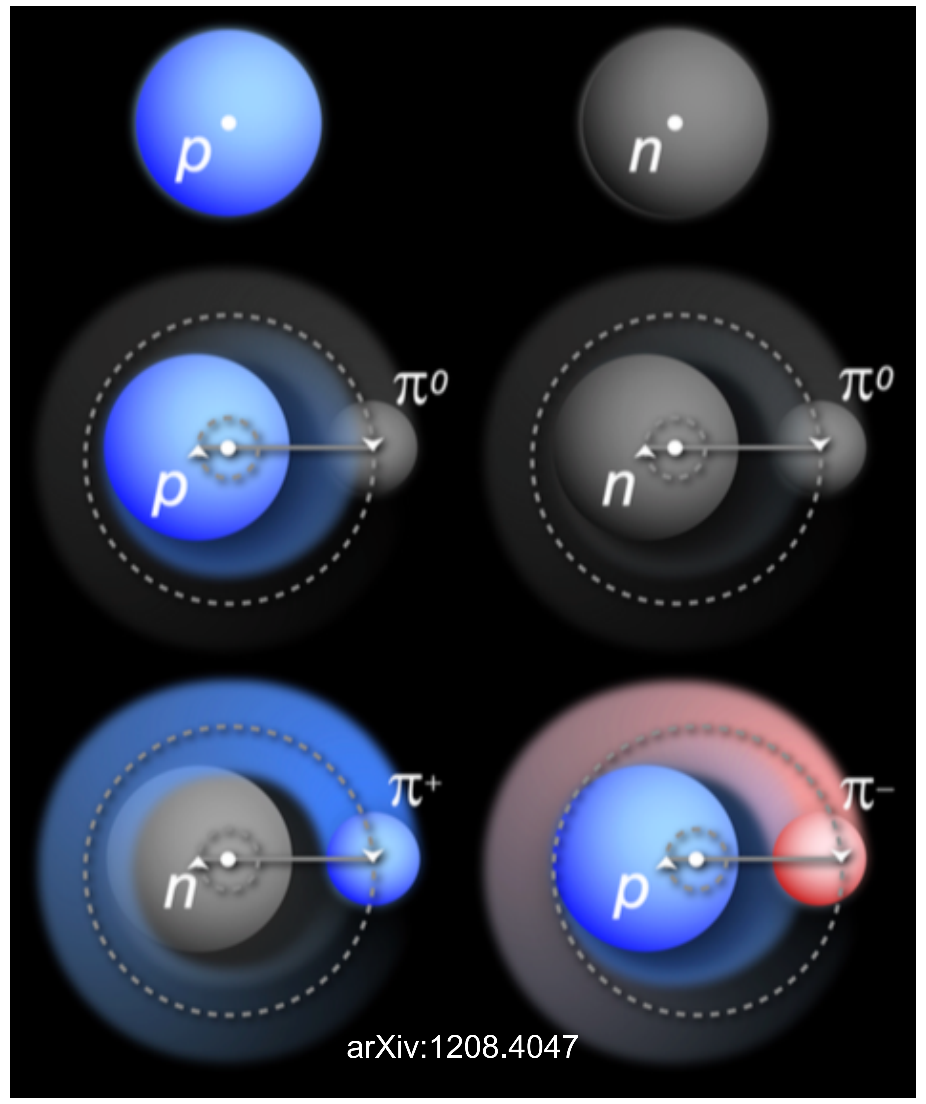
E12-21-005 : Double Spin Asymmetry in Wide Angle Charged Pion Photoproduction

SBS Collaboration Meeting
17th July 2023

R. Montgomery (UoG) for:
G. Cates (UVa);
A. Tadepalli (JLab);
B. Wojtsekhowski (JLab)

And all other WAPP and SBS Collaborators

Pion Photoproduction $\gamma N \to \pi N$

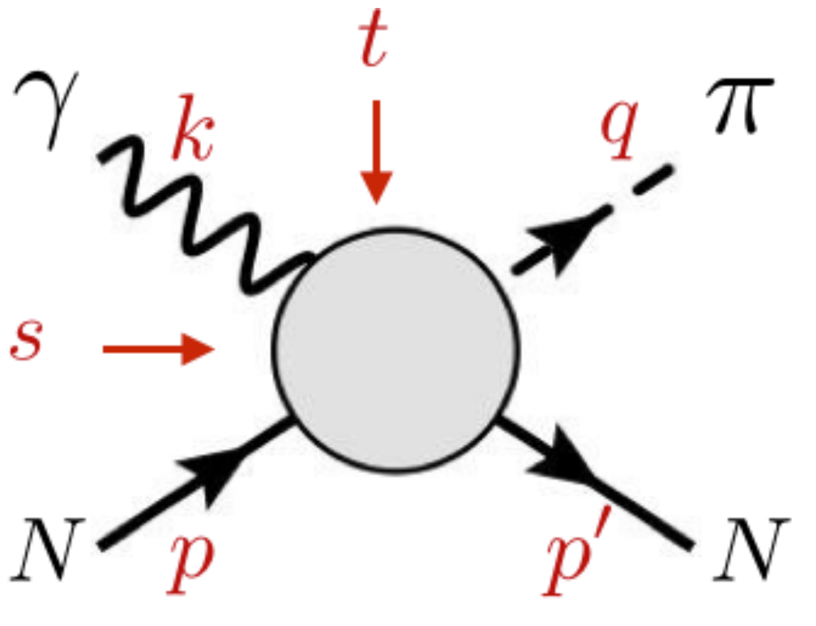


Mandelstam Variables

$$s = (k+p)^2 = (q+p')^2$$

$$t = (k-q)^2 = (p'-p)^2$$

$$u = (k-p')^2 = (q-p)^2$$



PHYSICAL REVIEW VOLUME 102, NUMBER 5 JUNE 1, 1956

Pion Production by Inelastic Scattering of Electrons in Hydrogen*

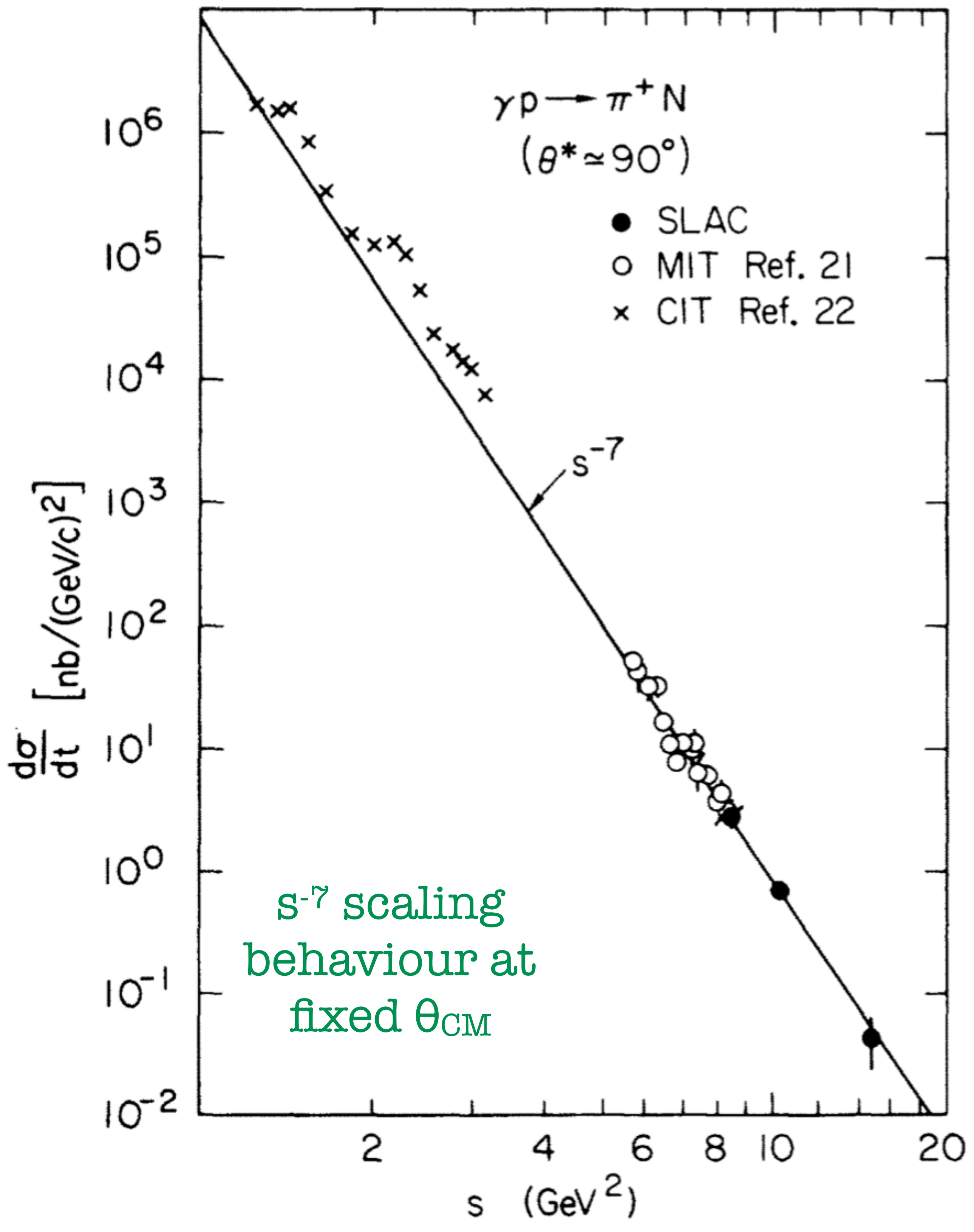
W. K. H. Panofsky, W. M. Woodward,† and G. B. Yodh
High-Energy Physics Laboratory and Department of Physics, Stanford University, Stanford, California
(Received February 27, 1956)

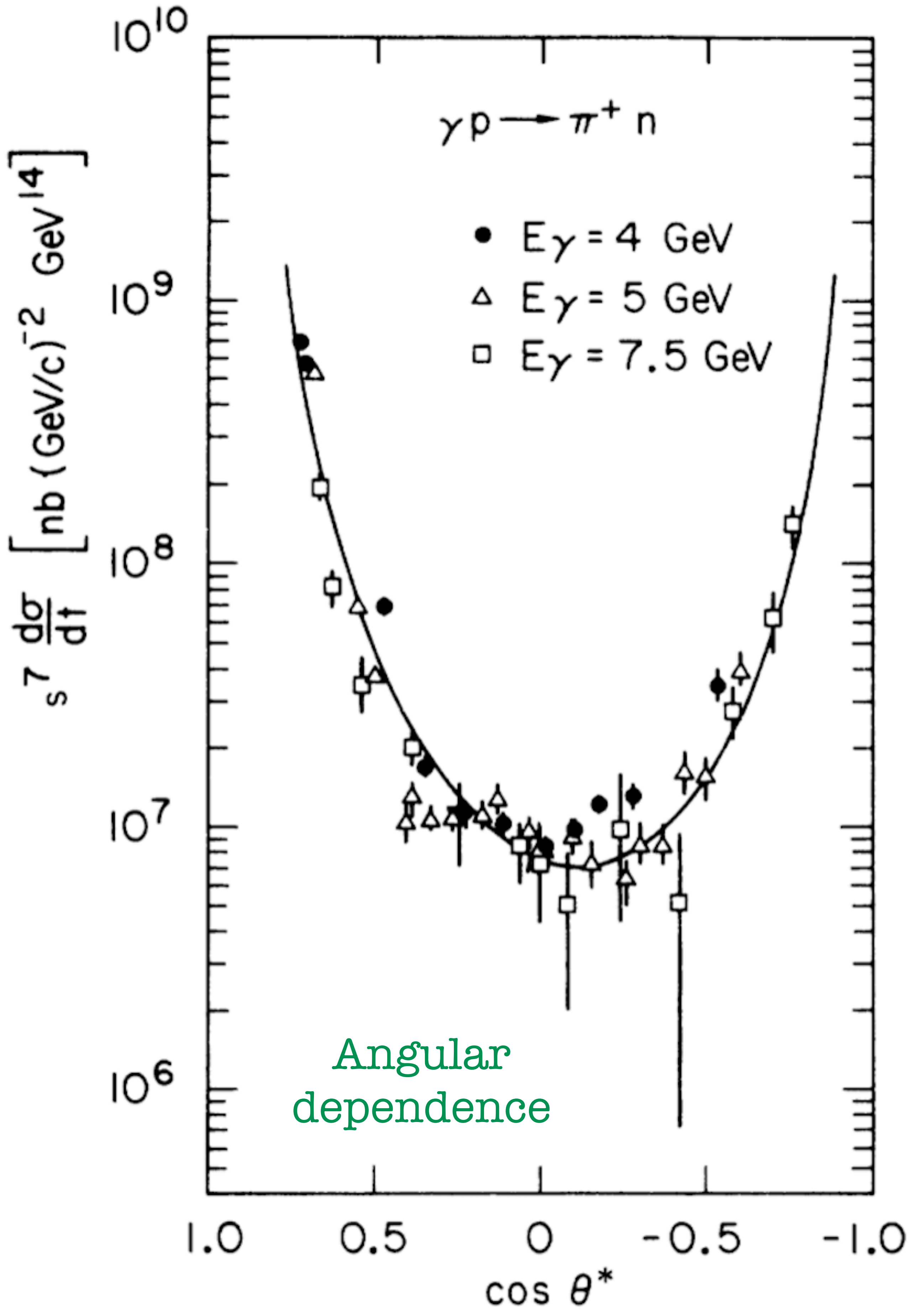
1956

- Pion crucial in nuclear physics
  - meson cloud
  - nucleon-nucleon interaction
  - simplest QCD state
  - Goldstone boson
  - nucleon/nuclear PDFs
  - up/down sea-antiquark asymmetry
  - …

- $\gamma N \to \pi N$
  - Simplest inelastic hadronic process
  - Important testing ground for our understanding
  - Key probe in transition from meson-nucleon to quark-gluon degrees of freedom in exclusive processes
  - Been around for decades!
    - Initial studies SLAC 1950's
    - Since then: more SLAC, JLab, Bonn, Mainz, Spring-8
  - Still strong interest in this topic…

Pion Photoproduction $\gamma N \rightarrow \pi N$





SLAC cross section data for $\gamma p \rightarrow \pi^+ n$ versus s and $\cos\theta_{CM}$

Phys. Rev. D 14, 679 (1976)

- Several kinematic regions w/ different physics
  - Near threshold (EFT/chiral perturbation theory)
  - Nucleon resonance (PWA)
  - Above resonances, SIDIS (pQCD, GPDs…)
- Lots of data in near threshold to resonance
- Limited data above resonances (SLAC, CLAS, Hall A…)

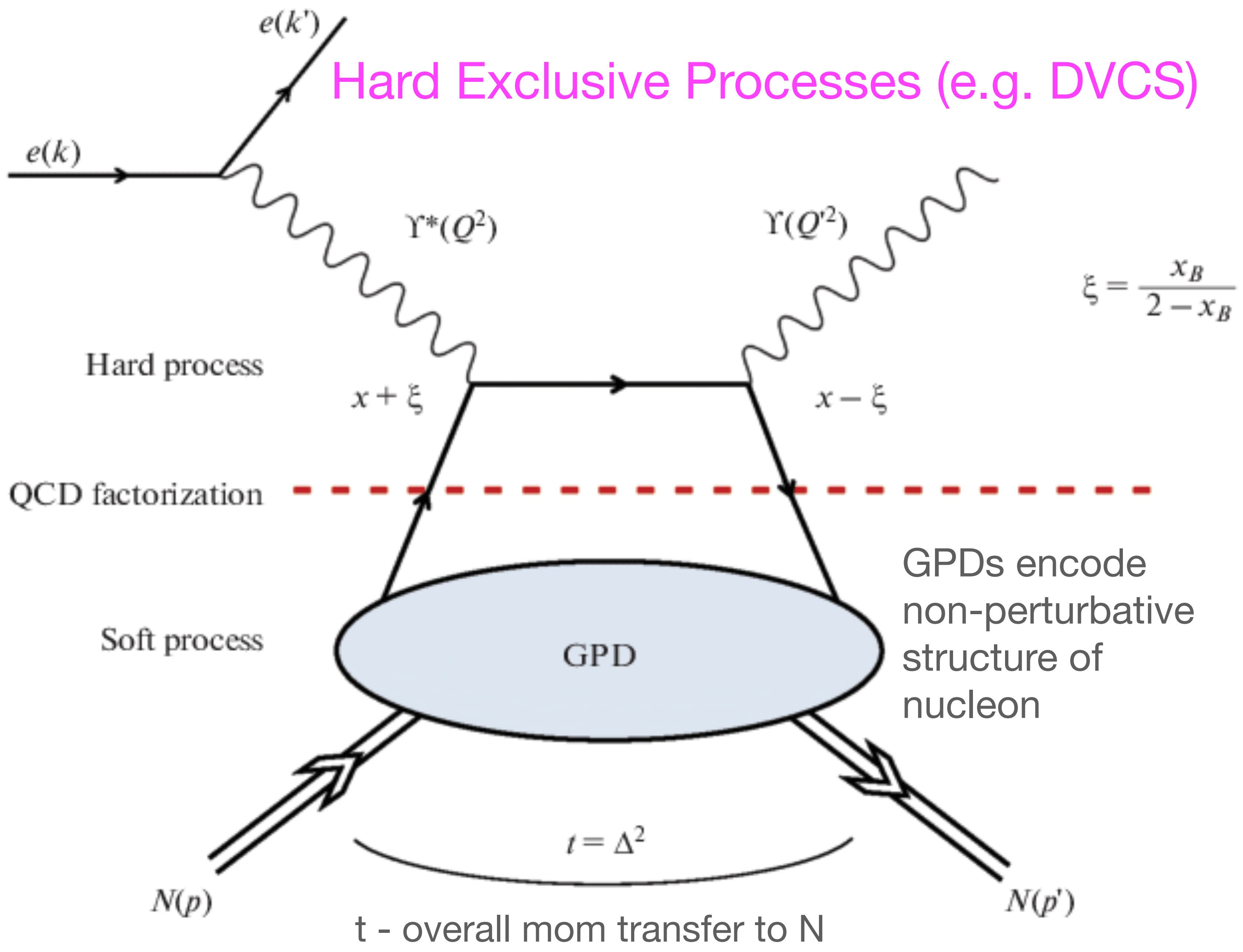
- Observables in wide angle regime very sensitive to underlying reaction mechanism
- Wide angle = large s, t, u >> Λ_{QCD}^2

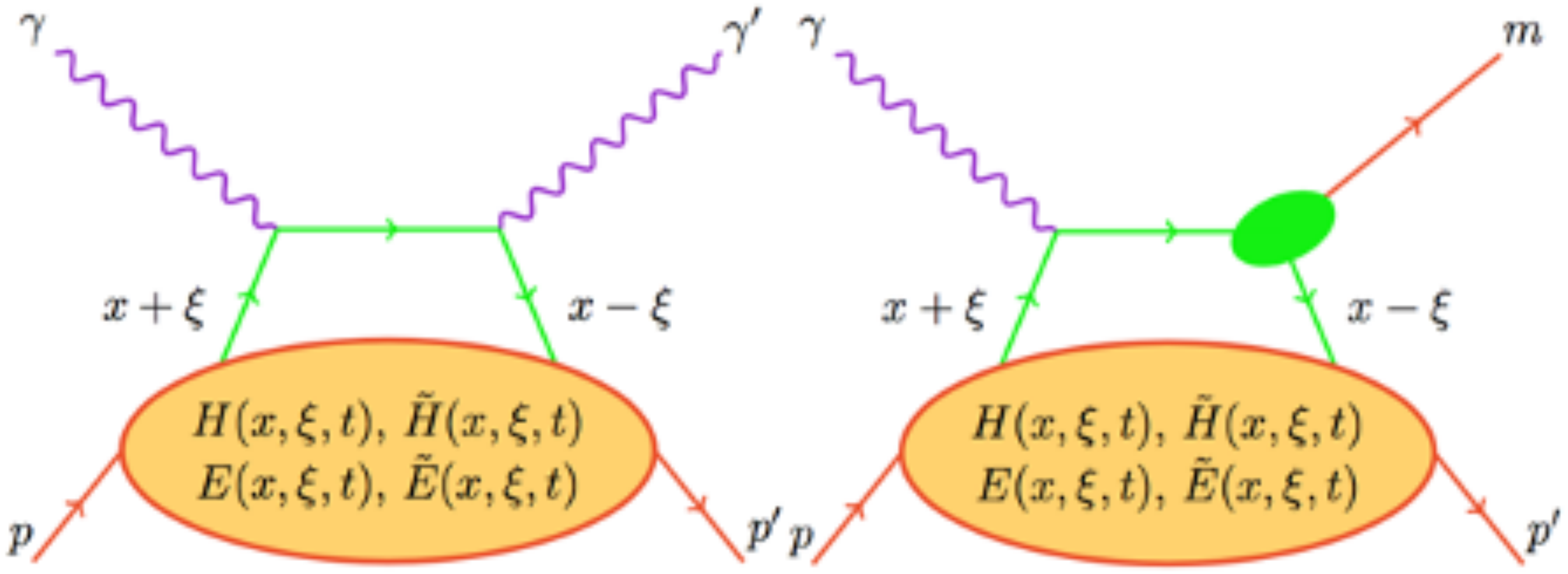
- Many intriguing features
- e.g. SLAC, E_γ~4-7.5 GeV, large -t and -u
  - s^{-7} scaling of cross-section
  - Scaling behaviour explained by constituent counting rule

- Theories can't explain absolute values of $\pi^\pm$ cross sections from experiments (SLAC, Hall A…)

- Underlying reaction mechanism at high energies still not understood after >60 years of study…

Generalised Parton Distributions (GPD) Based Theory





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

Kroll and Passek-Kumerički: Phs Rev D 97, 074023 (2018)

- Essential to understand mechanism responsible for observed cross sections in wide angle regime

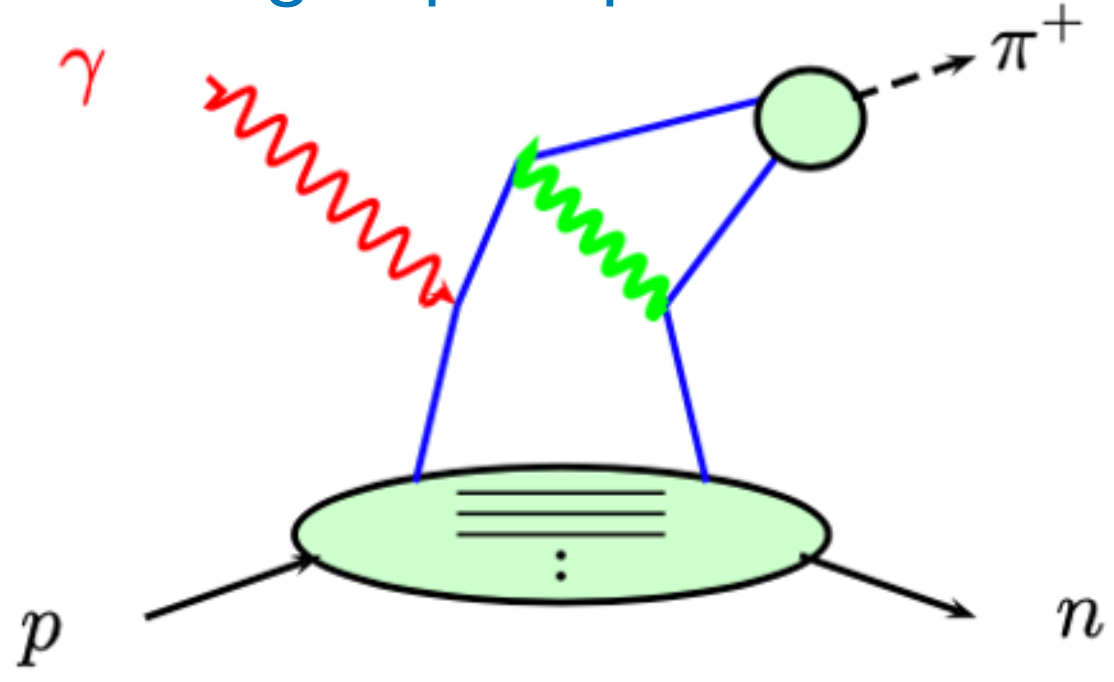
- Above resonance, at large s, -t, -u >> Λ^2_{QCD} (Λ~1GeV):
  - GPD treatment should work

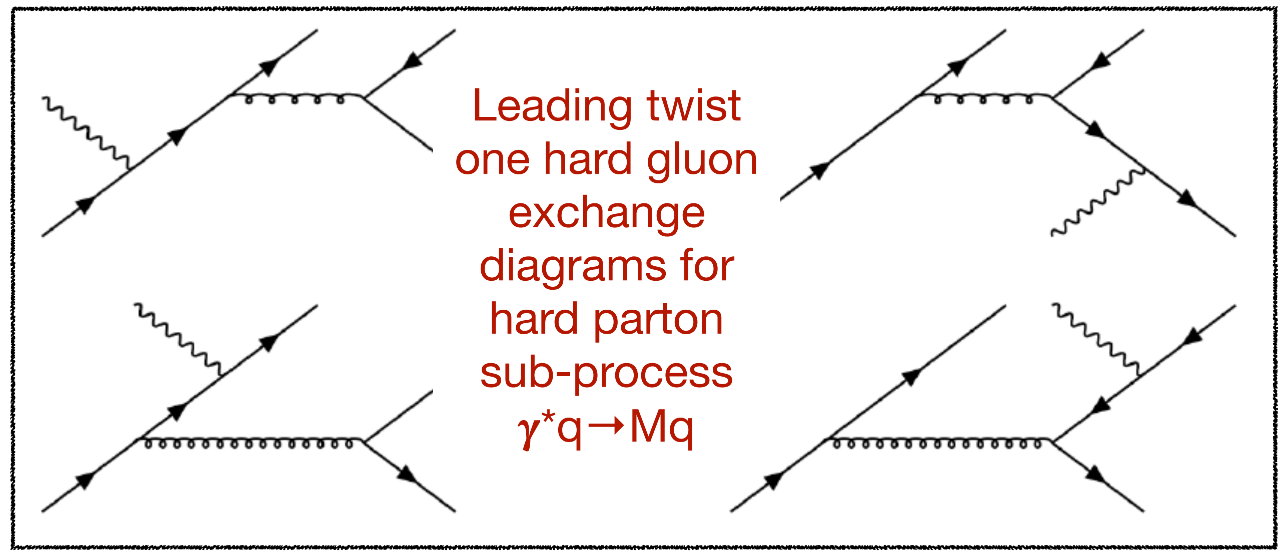
- GPDs:
  - 3D nucleon tomography by correlating transverse position and longitudinal momentum of partons
  - Soft part of amplitude: universal non-perturbative GPDs
  - Not measured directly, experiments measure differential cross sections and beam/target polarisation asymmetries

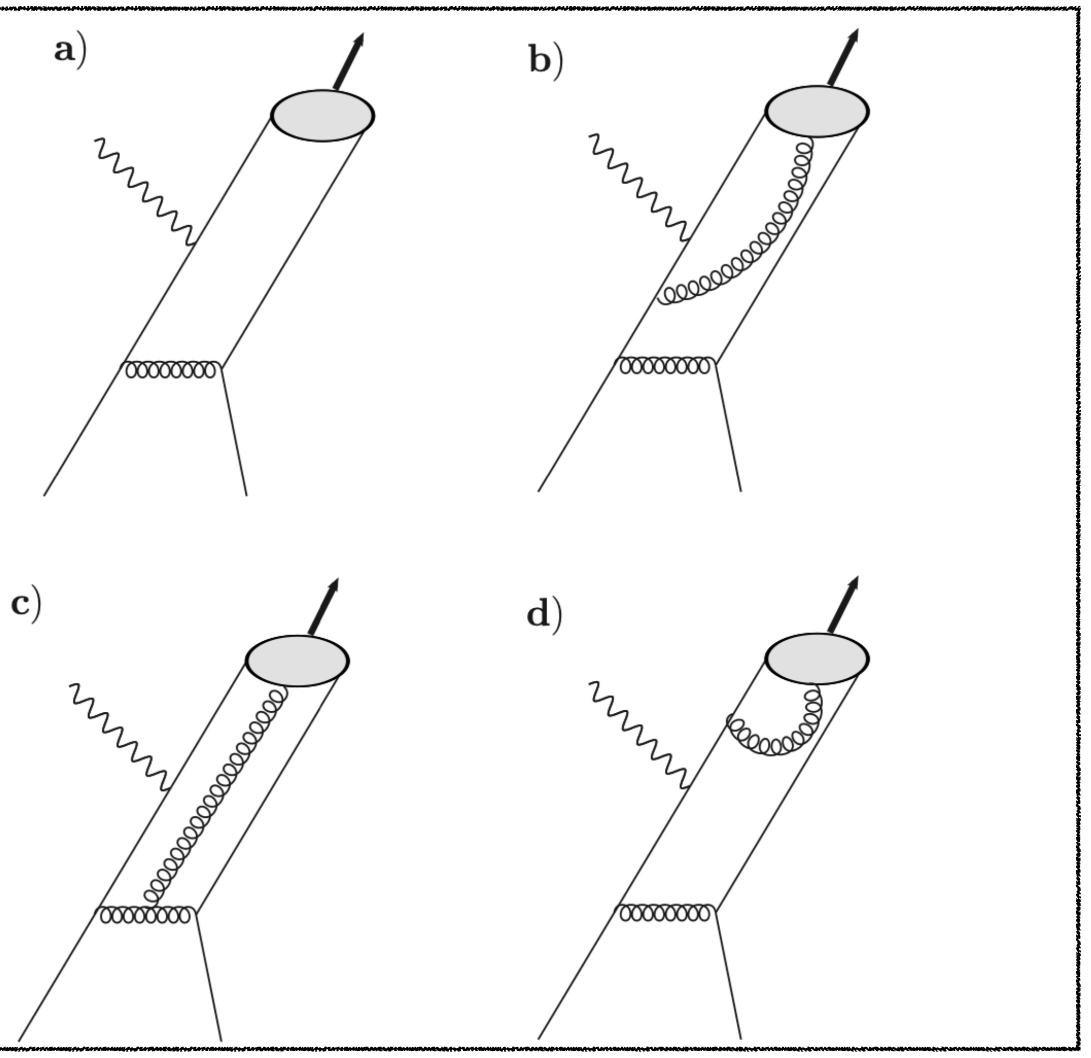
- GPD formalism should work for Compton scattering AND exclusive meson production (at high Q^2)
- DVCS and Wide Angle Compton Scattering at JLab:
  - Leading order treatment works well
- Wide angle meson photoproduction:
  - Leading twist 2 analysis fails (helicity non-flip GPDs)

GPD Based Theory Predictions

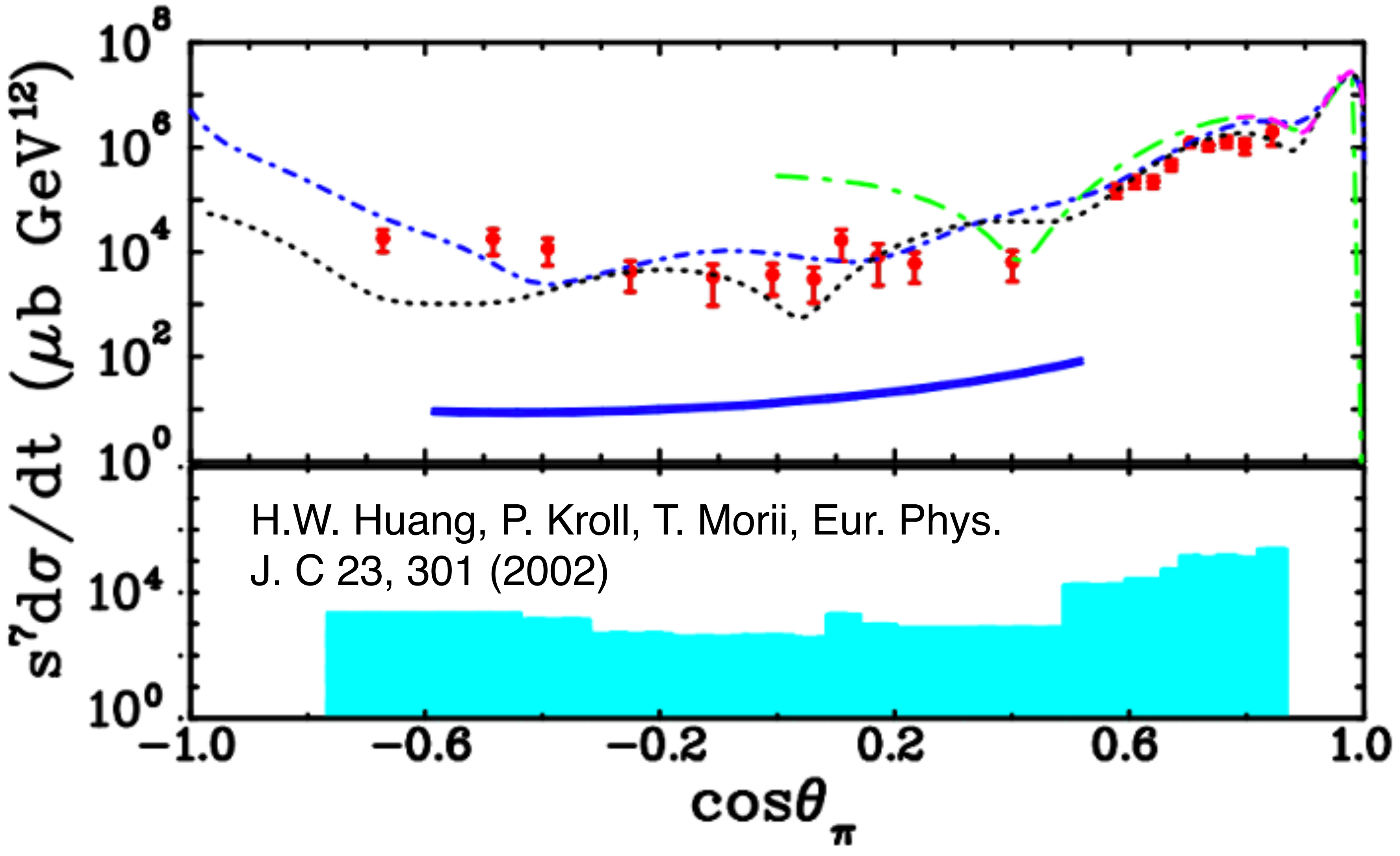
Handbag mechanism for charged pion production





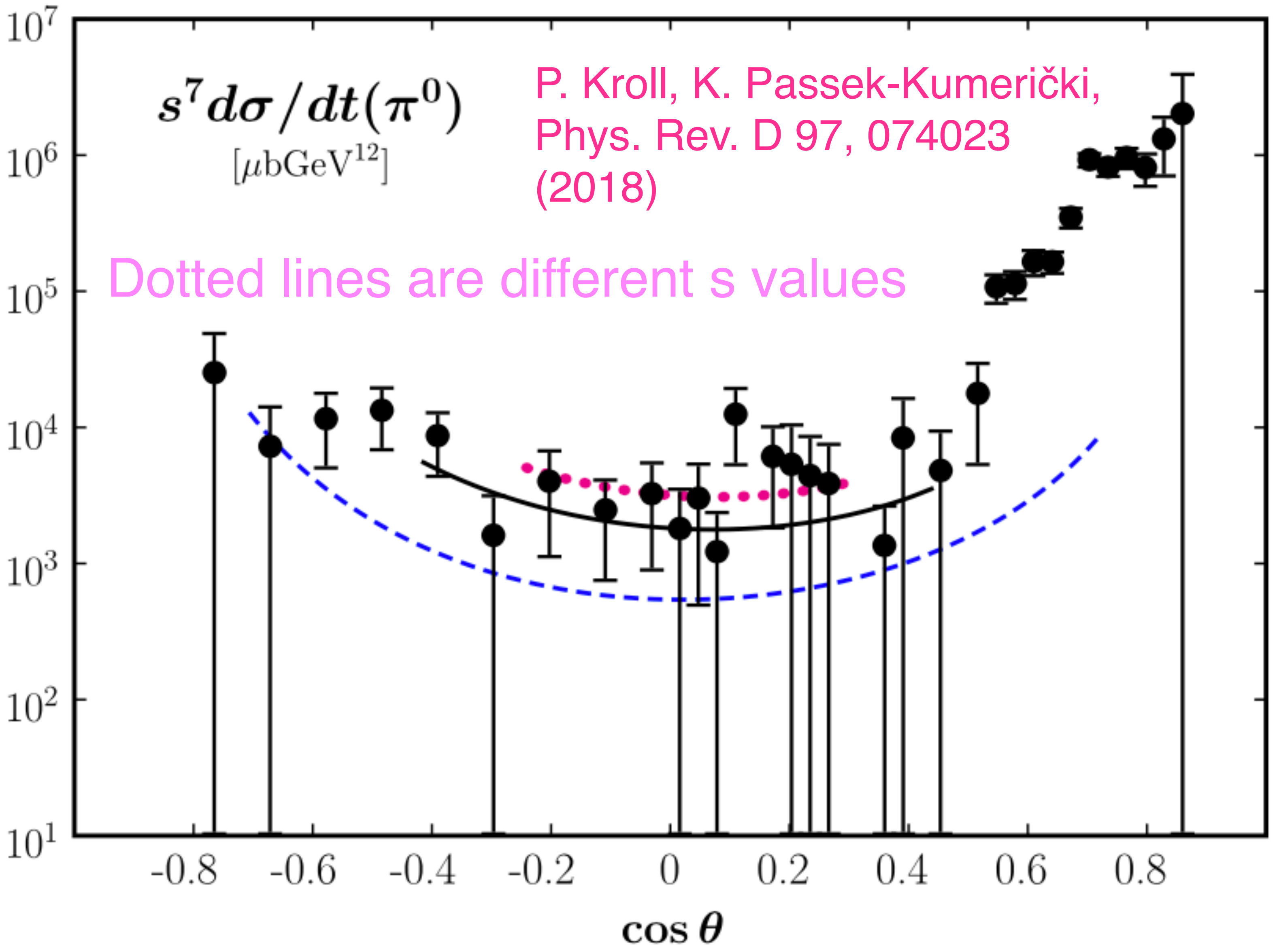


b, c, d are twist-3 Fock components of the meson distribution amplitude



Extra hadron in final state adds non-perturbative "soft" distribution amplitude, complicating analysis

s, -t, u >= 2.5 GeV^2



- Calculations using handbag model including only leading twist underestimate CLAS π^0 cross-sections by >2 orders of magnitude!

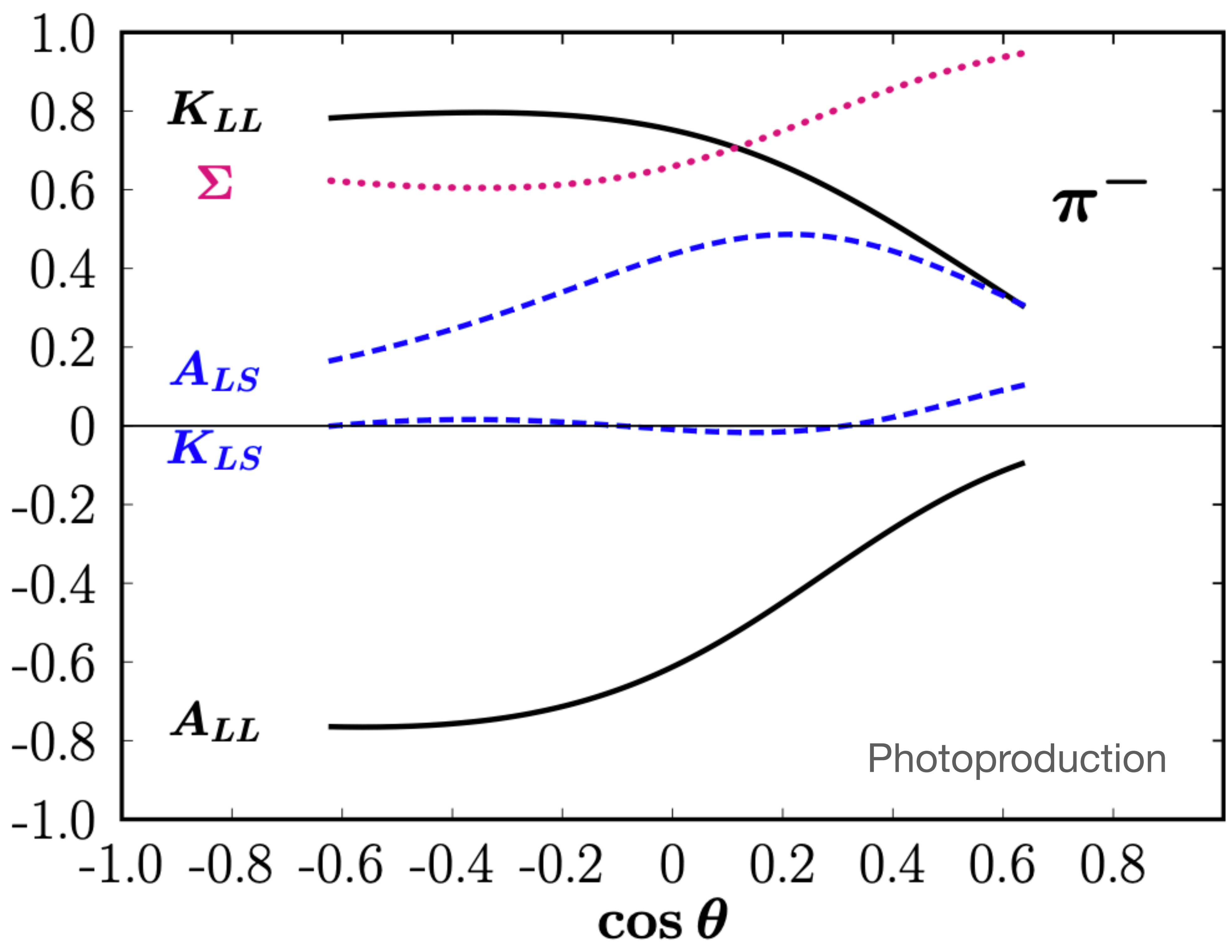
- Leading twist treatment within GPD framework not sufficient
- Figuring out why will reveal nature of interaction mechanism responsible for cross-sections

- Calculations including higher twist (twist-3, 2 and 3 body) contributions do agree

Twist-3 Dominance: Smoking Gun for Experimentalists

- GPD theory including twist-2 and twist-3 amplitudes solve issue in wide angle regime
  - P. Kroll and K. Passek-Kumerički (Phys Rev D 97, 074023 (2018))
- Predictions suggest dominance of twist-3
  - Should test this experimentally - need more data in wide angle regime!

- Signatures of twist-3: cross-sections and spin dependent double polarisation observables
- Measuring polarisation observables in wide angle regime → extremely valuable to test validity of handbag mechanism in GPD framework



- A_{LL}, K_{LL}: helicities of incoming photon and longitudinal polarisation for initial (A_{LL}) or final nucleon (K_{LL})

- A_{LS} and K_{LS}: helicities of incoming photon and sideway polarisation of initial (A_{LS}) or final nucleon (K_{LS})

$$A_{LL}^{twist-2} = K_{LL}^{twist-2}$$

$$A_{LL}^{twist-3} = -K_{LL}^{twist-3}$$

If twist-3 dominant:
K_{LL} opposite to A_{LL}

Never before measured for charged pions in wide angle regime
SBS can do this…

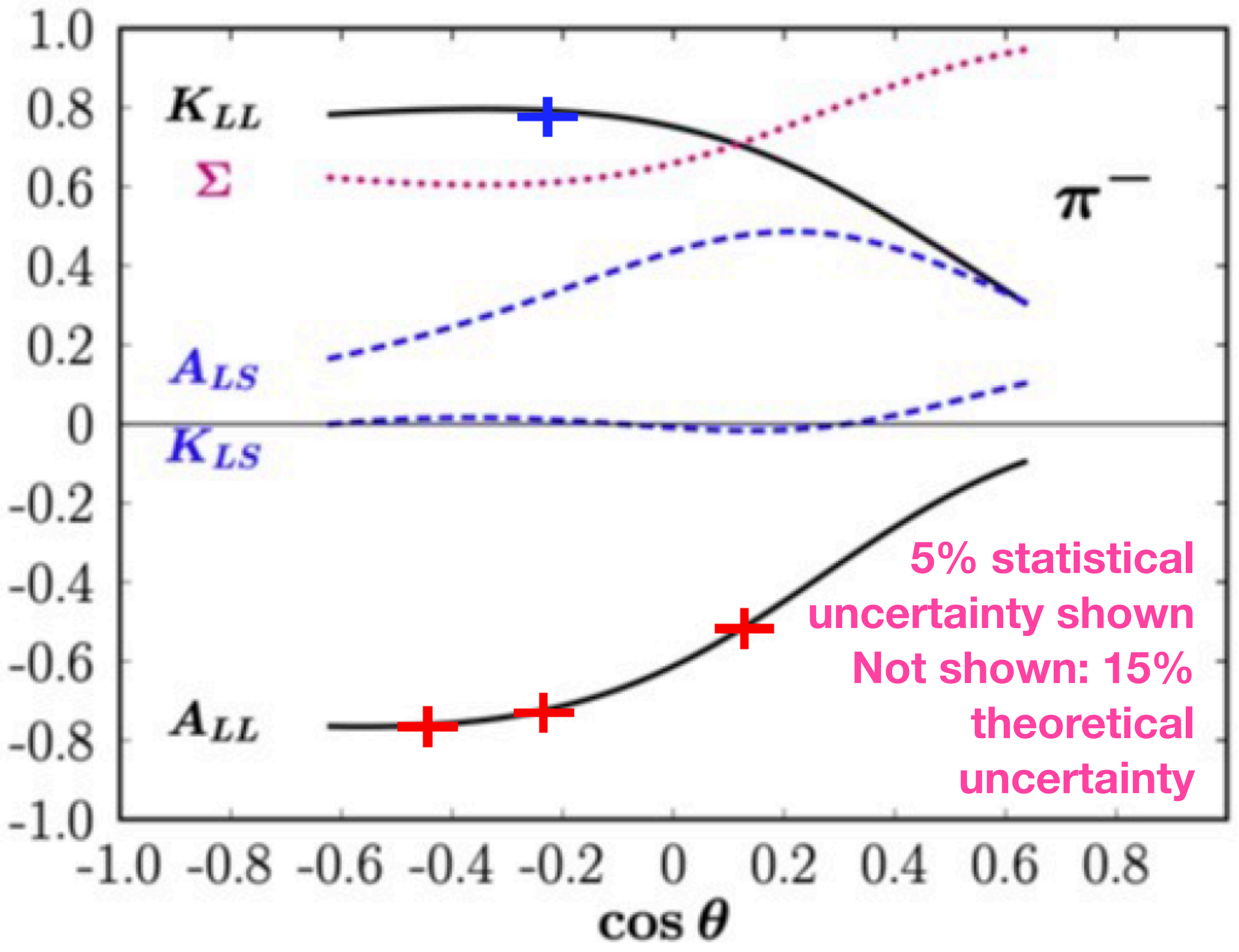
SBS WAPP Plans

- Two WAPP measurements
- WAPP Collaboration ~60 collaborators from ~20 institutions

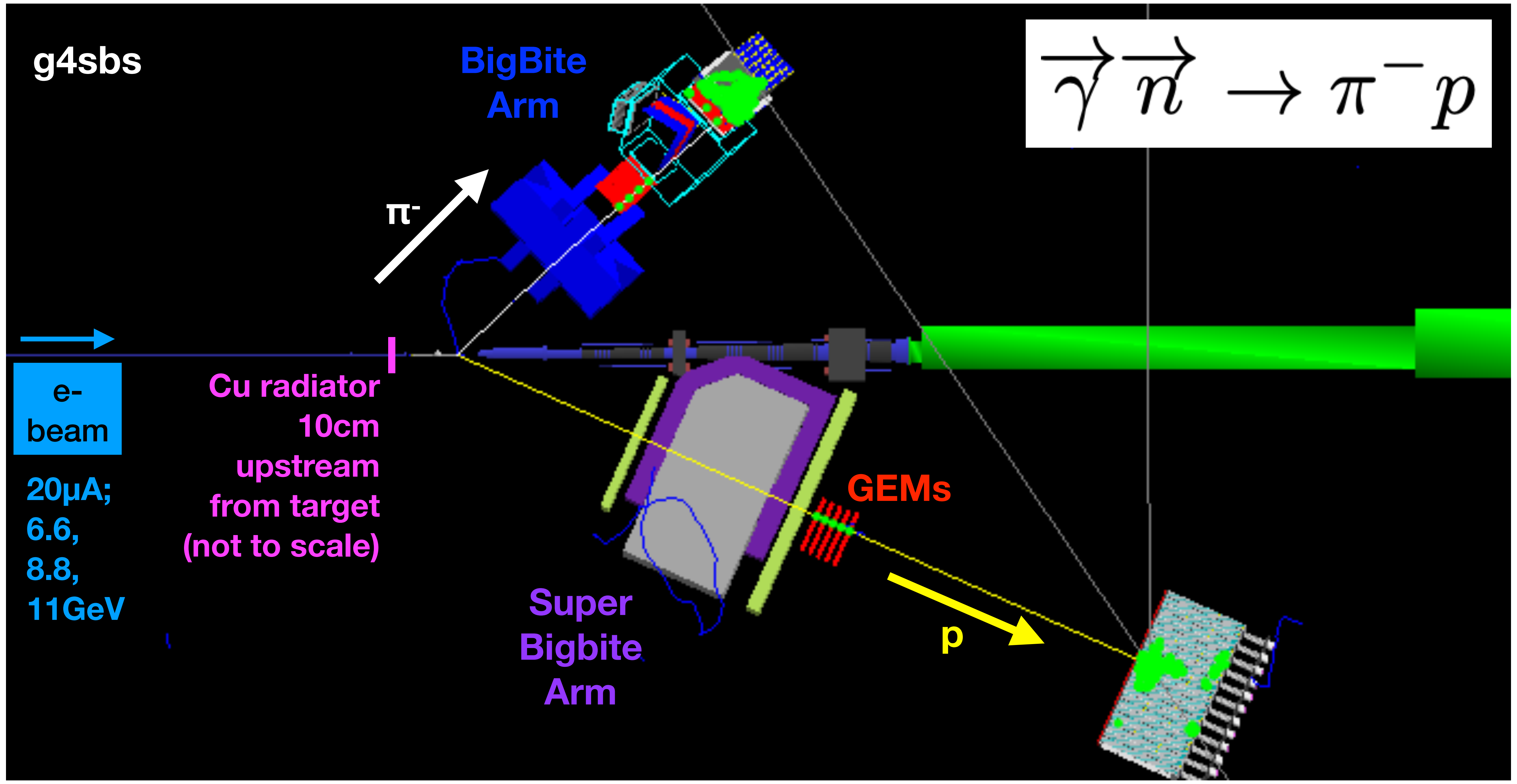
- E12-20-008 … K_{LL}
- (spokespeople: J. Arrington, A. Puckett, A. Tadepalli, B. Wojtsekhowski)
- See Arun's talk

- E12-21-005 … A_{LL}
- (spokespeople: G. Cates, R. Montgomery; A. Tadepalli, B. Wojtsekhowski)
- This talk…

E12-21-005 A_{LL} Original Plan

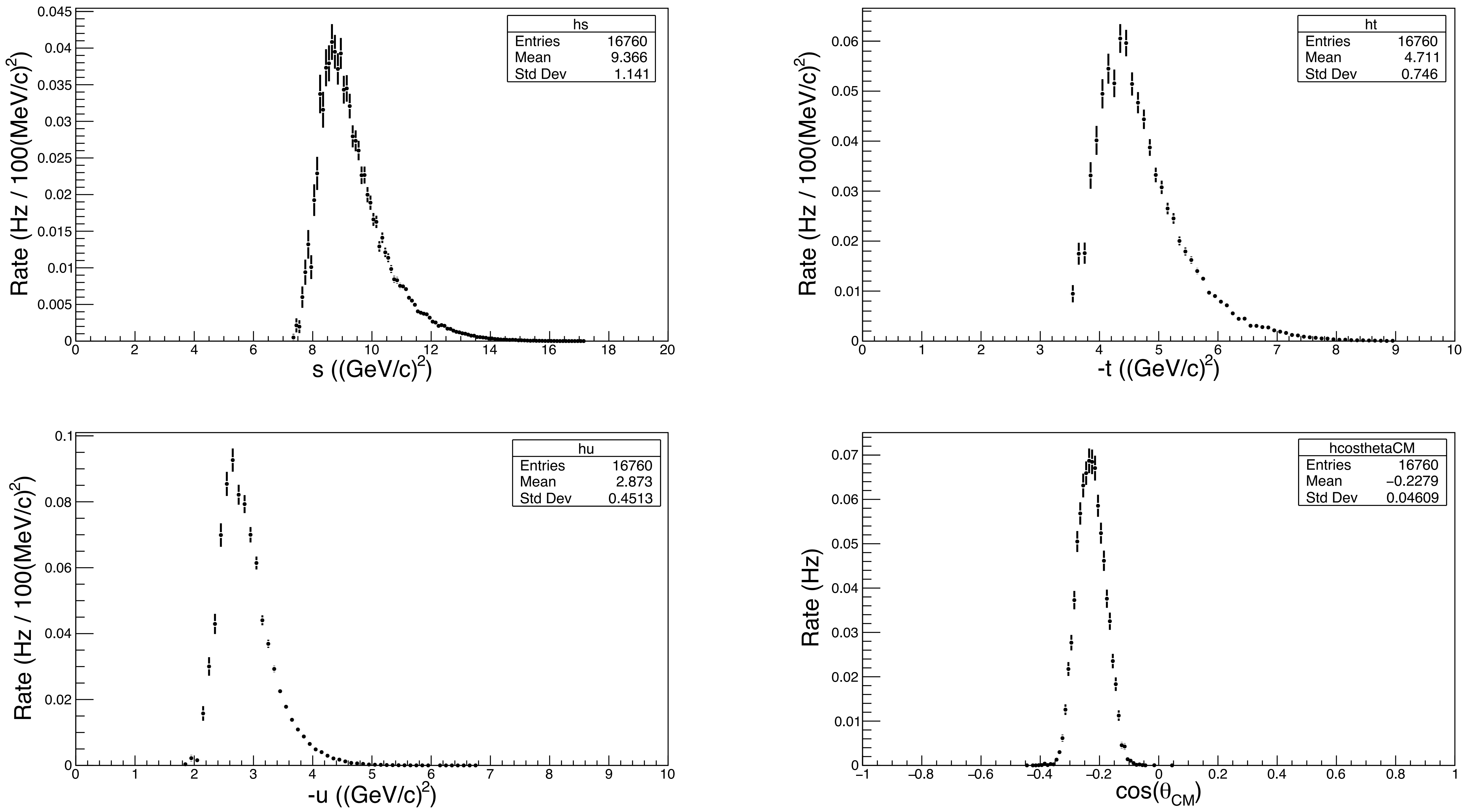


- Measure A_{LL} for $\gamma n \rightarrow \pi^- p$ in wide angle regime (s, -t, -u >> Λ^2_{QCD})
- Shed light on:
  - Nature of interaction mechanism of meson photoproduction
  - Twist-3 dominance in handbag mechanism cross-section calculations
- Test if:
  - A_{LL} equals $-K_{LL}$?
  - A_{LL} depends on θ_{CM} at s = 9 GeV^2 and large -u, -t?
  - A_{LL} has s-dependence at s > 9 GeV^2 ?
- 10 PAC days awarded (PAC49 2021) for 5 Kinematic points to test above



- Set up similar to GEn:
  - BB for π-
  - SBS for p
  - Same polarised 60cm ^{3}He target
  - Add GEMs in SBS arm (veto to help proton ID)
  - Add 6% Cu radiator 10cm upstream of target (0.9mm thick)
  - 20µA, 6.6, 8.8, 11GeV beam
  - 5 angle settings of BB/SBS

E12-21-005 A_{LL} Simulations



- Simulated in g4sbs

- Pion photoproduction generator from A. Puckett for K_{LL}
  - many thanks to Andrew for help with g4sbs/analysis

- e.g. shown: cross-section weighted Mandelstam variables
- s, -t, -u >> Λ_{QCD}^2, wide angle regime
- Large enough for handbag mechanism to play dominant role

- g4sbs used to estimate kinematics, event rates, acceptances, efficiencies, $f_{\pi\text{-}p}$

- Expected statistical uncertainty on A_{LL} with proposed beam time: 5%

Kin	Beam E_e (GeV)	$<E_\gamma>$ (GeV)	θ_{π^-} (°) (i.e. BB)	p_{π^-} (GeV/c)	θ_p (°) (i.e. SBS)	p_p (GeV/c)	θ_{CM}	< s > (GeV/c)^2	< -t > (GeV/c)^2	< u > (GeV/c)^2
A	6.6	4.5	41.9	2.02	24.3	3.29	103	9.3	4.7	2.9
B	6.6	4.5	30.0	2.74	32.8	2.53	82	9.3	3.3	4.3
C	6.6	4.5	52.0	1.58	19.5	3.74	116	9.3	5.5	2.1
D	8.8	6.0	37.2	2.61	21.9	4.23	103	12.1	6.4	4.0
E	11.0	7.5	33.7	3.20	20.2	5.15	103	15.0	8.1	5.2

$$N_{\pi^-p} = \frac{d\sigma}{dt}_{\pi^-p} \frac{p_{\pi^-}^2}{\pi} \Delta\Omega_{\pi^-} f_{\pi^-p} \left[\frac{\Delta E_\gamma}{E_\gamma} \frac{t_{rad}}{X_0} \mathcal{L}_{e-n} \right]$$

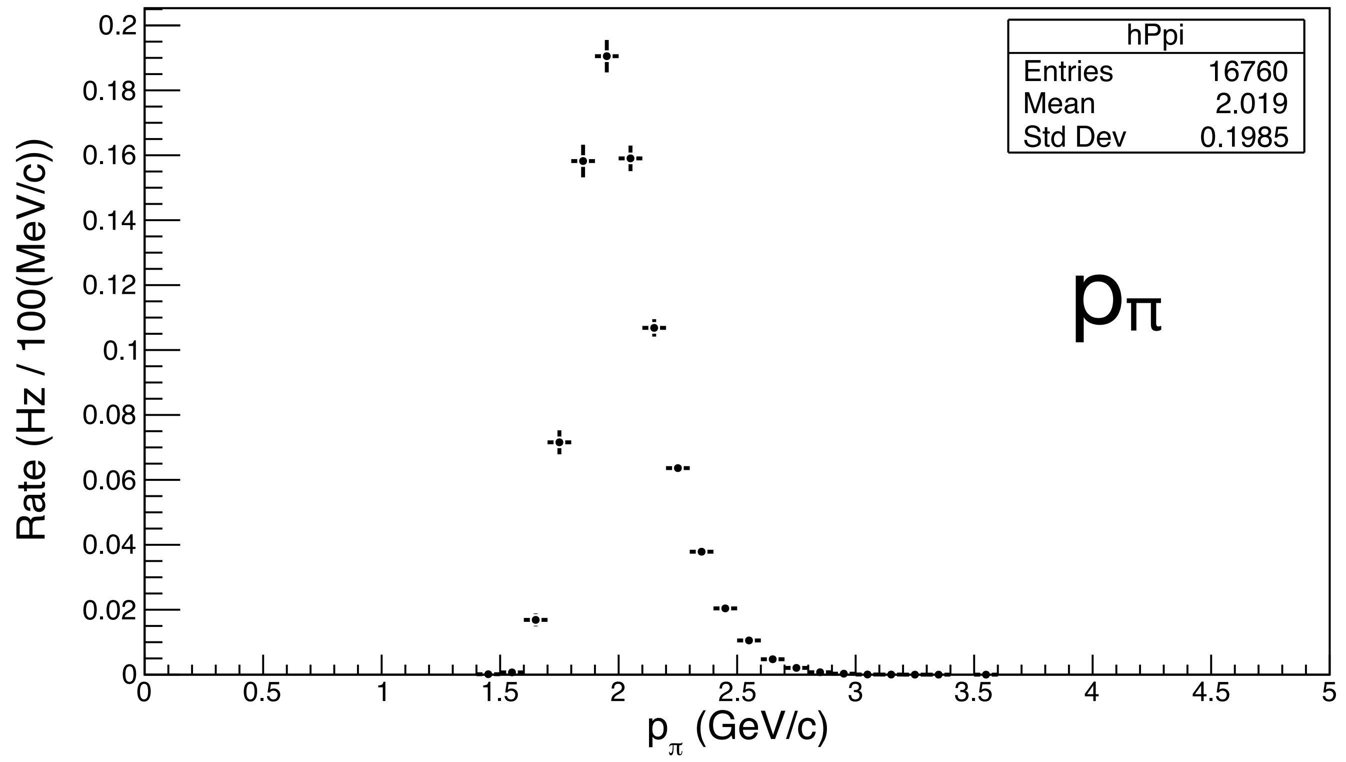
cross-section

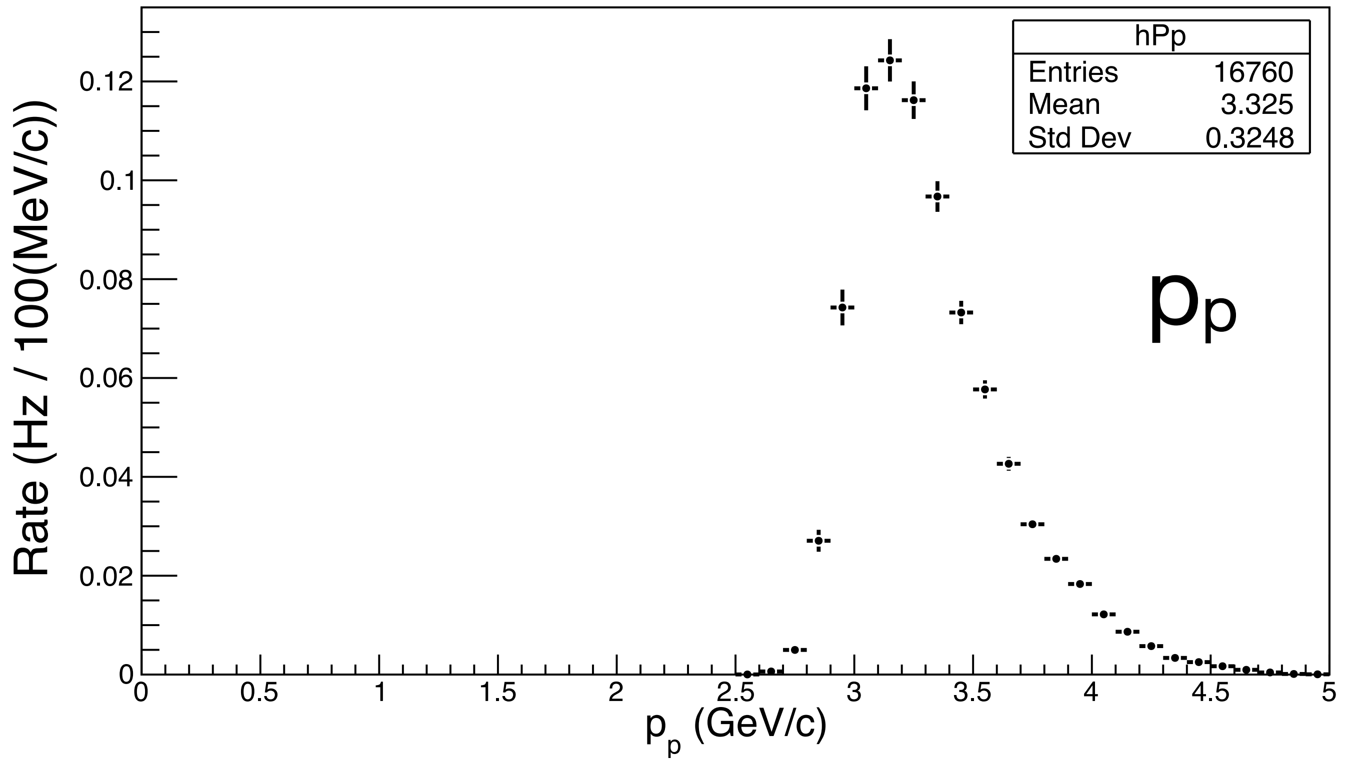
Range of Δt, expressed in p_π and BB solid angle (50msr)

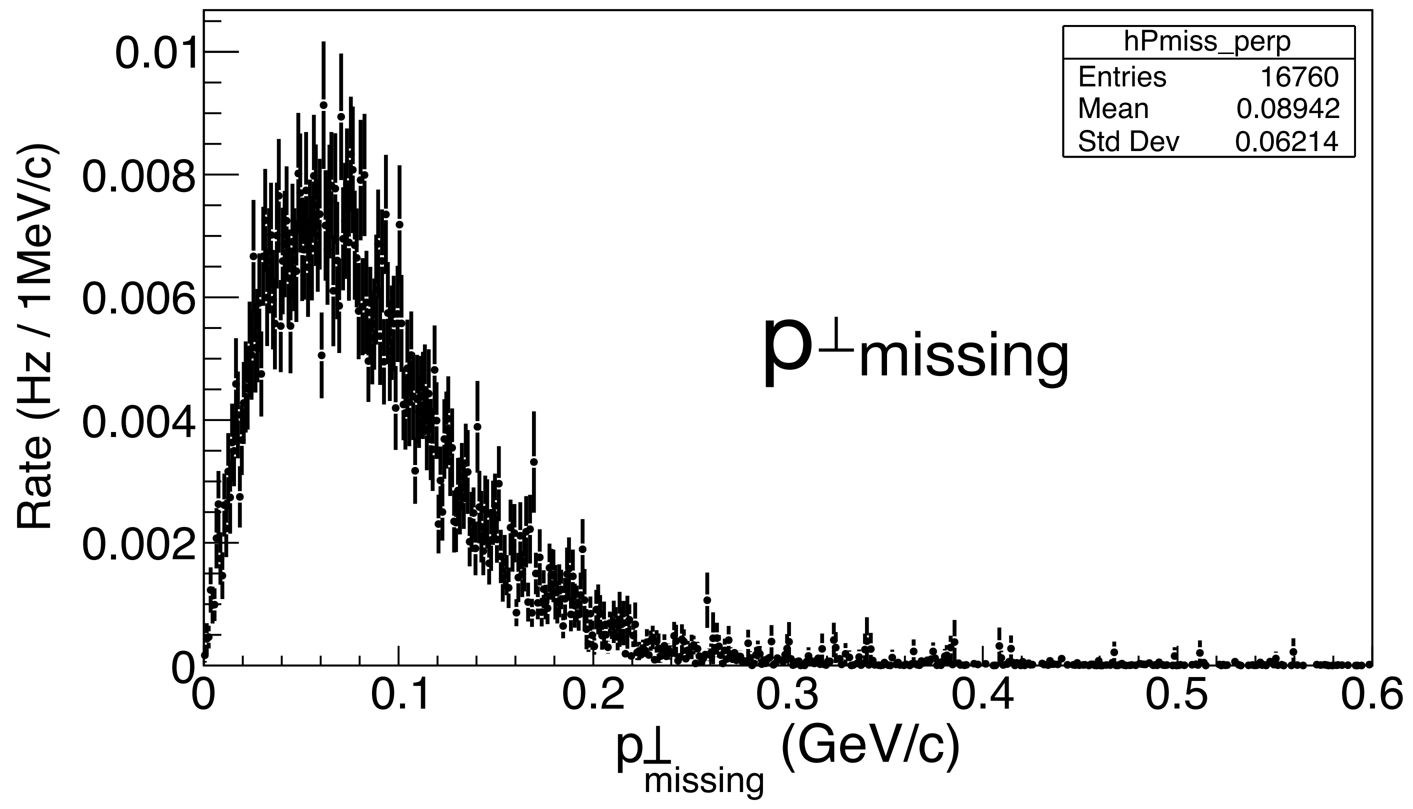
fraction of events detected in SBS obtained from g4sbs

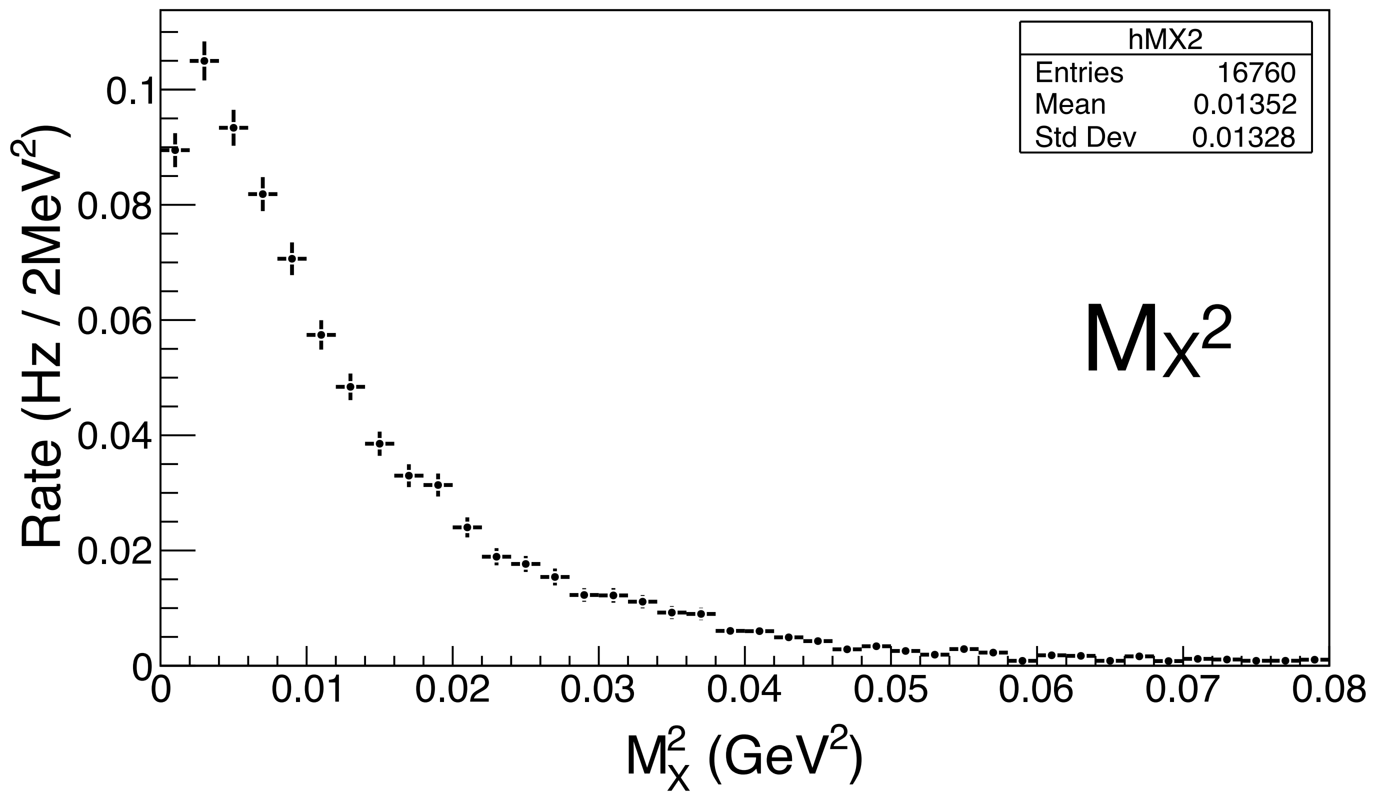
No of photons per incident electron and for photon energy range.
t_{rad}/X_0 ~ 0.082
$\mathcal{L}$ ~ 1.8x10^{36}Hzcm^{-2}

E12-21-005 A_{LL} Exclusivity Checks Examples



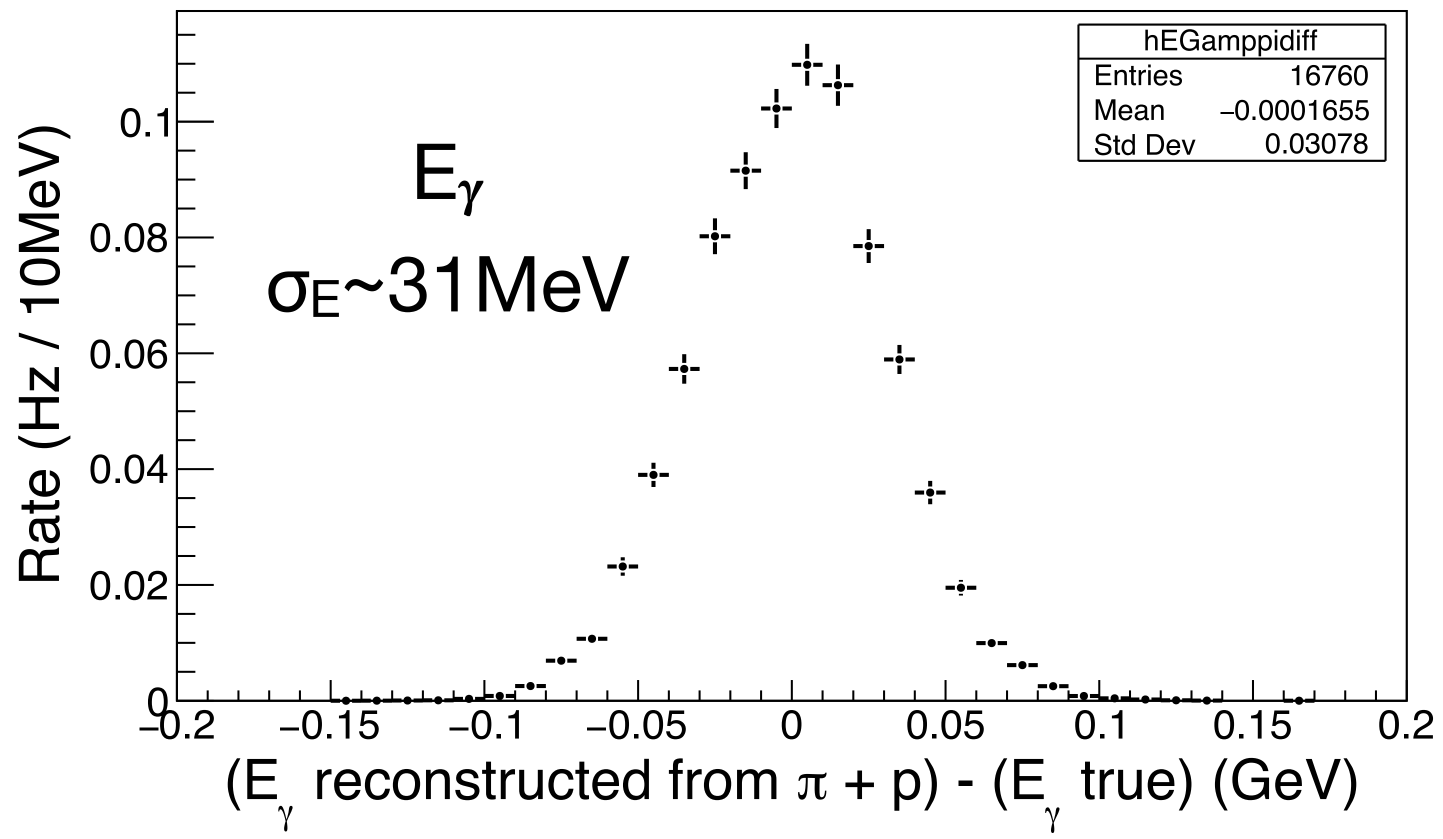






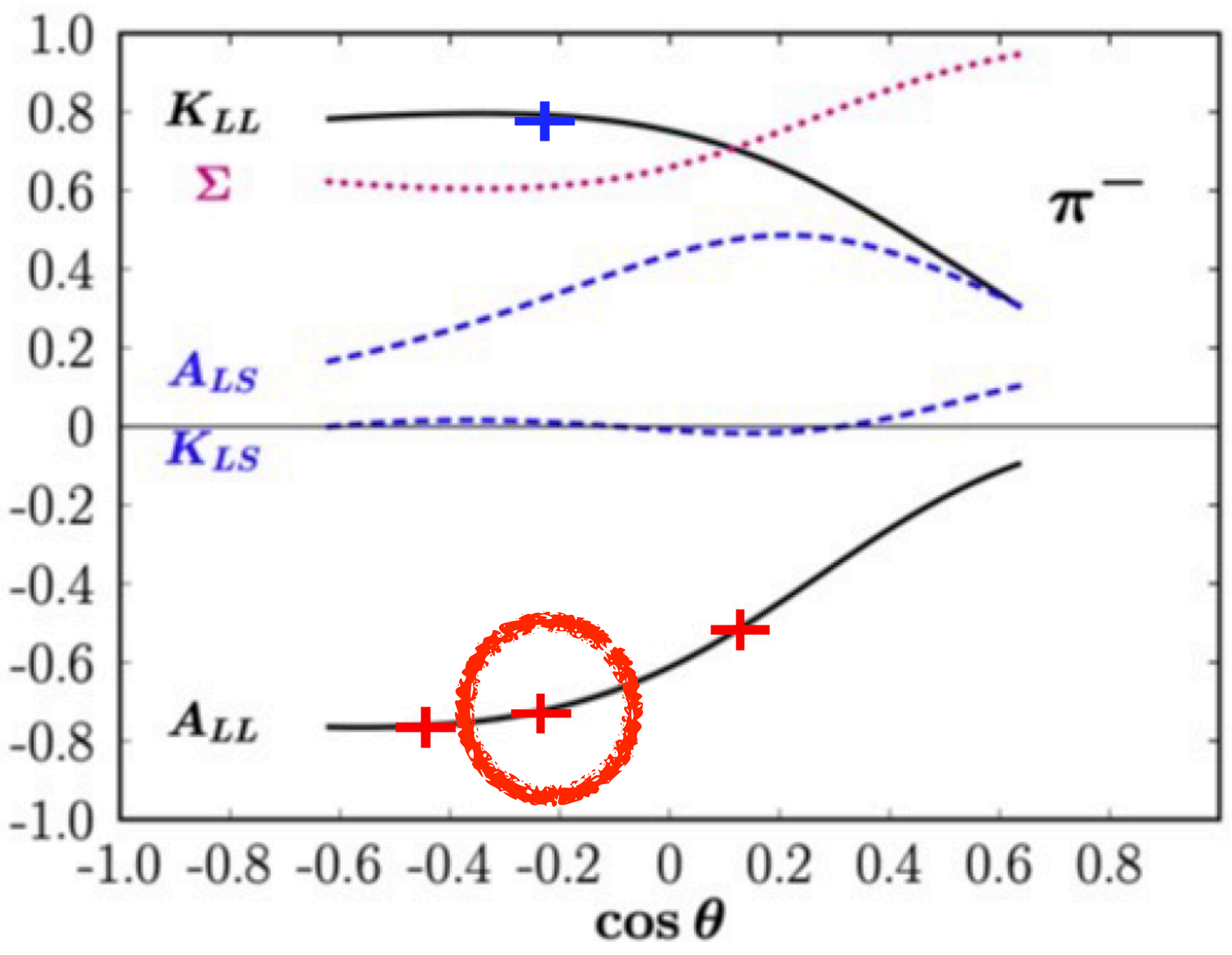
$$E_\gamma = \frac{s_{p\pi} - m_n^2}{1(E_\pi + E_p - p_\pi cos\theta_\pi - p_p cos\theta_p)}$$

$$s_{p\pi} = (E_p + E_\pi)^2 - (p_p + p_\pi)^2$$



- Distributions cross-section weighted, acceptance averaged, smeared for estimated momentum/angular resolutions
- $p_{missing}^{\perp}$= total mom of pion and proton projected to plane perpendicular to beam direction
- Event "acoplanarity"
  - angle between pion and proton production planes
- Cut at <=0.1GeV/c to remove inelastic and non-exclusive events
- Resolution of photon energy reconstruction allows background removal e.g. multi-pion final states
- $E\gamma$ formula originally developed for K_{LL}
- Cutting on missing mass parameter will also be used for this (M_x<=0.05GeV^2)

After ERR - Propose to Remove Radiator



	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
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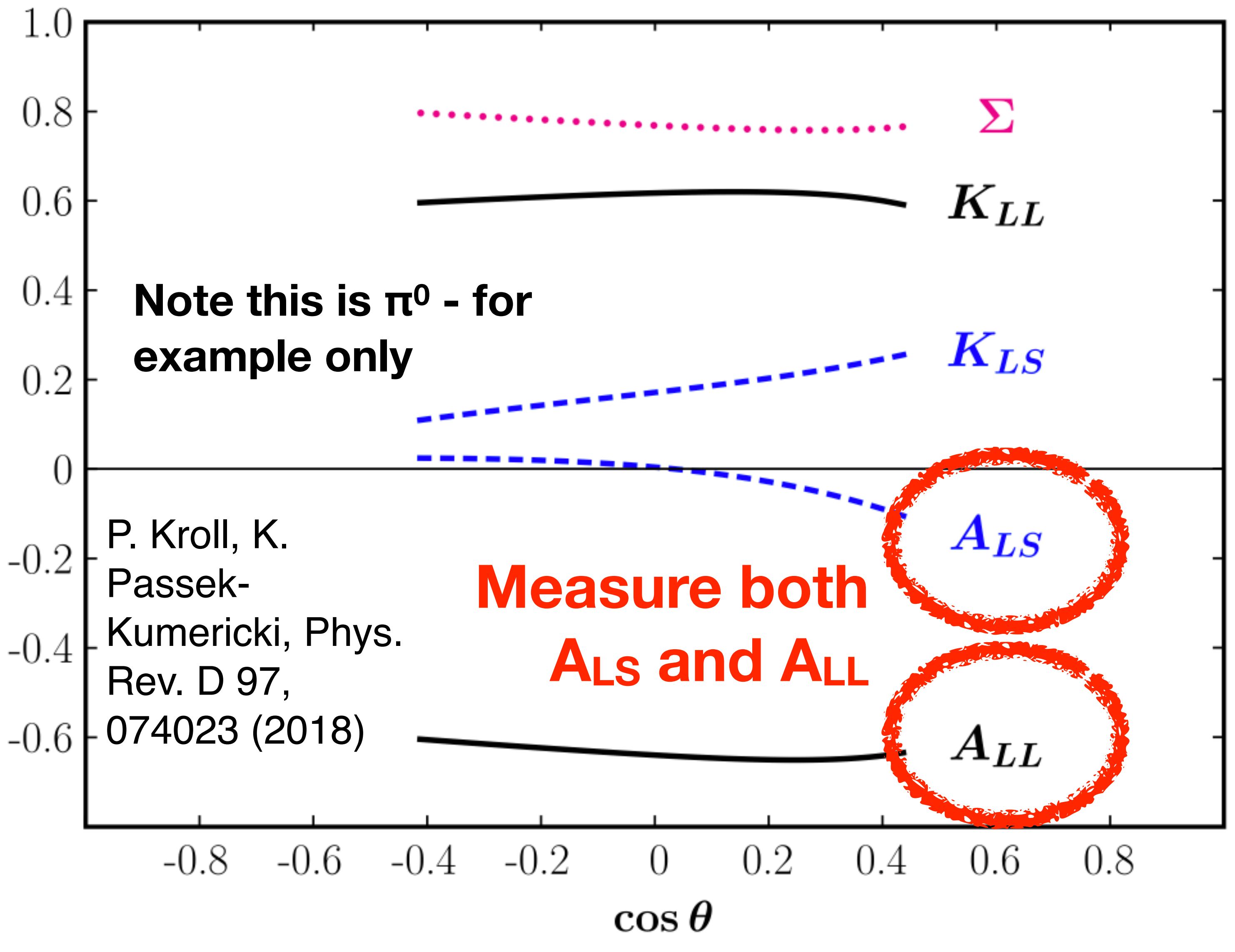
E	11	33.7	7.5	3.20	20.2	5.15	103	15.0	8.1	5.2

New plan: Only Kin B (almost 90˚ CM angle)

- ERR May 2022 … major issue was radiator…
- (https://hallaweb.jlab.org/wiki/index.php/SBS_2022_ALL_Experimental_Readiness_Review)

- **New plan:**
  - Radiator removed
  - Projected event rate loss factor 0.55 (smaller number of photons per incident electron)
    - (Estimated via effective photon approximation V.M. Budnev, et al., Physics Reporta (Section C of Physics Letters) 15, no. 4 (1975) 181–282)
  - Beam current increased 20μA → 45μA
  - Request 3.5 PAC days at end of GEn II run
  - *One kinematic setting only* ~ Kin B (6.6GeV), SBS and BB **both** at ~31.5˚ (θ_{CM} almost 90˚)
  - Matches K_{LL} to check twist-3 dominance
  - A_{LL} statistical uncertainty increases 5% → 10%
  - Uncertainties enough for ~10σ comparison

Plan To Now Measure A_{LL} and A_{LS}



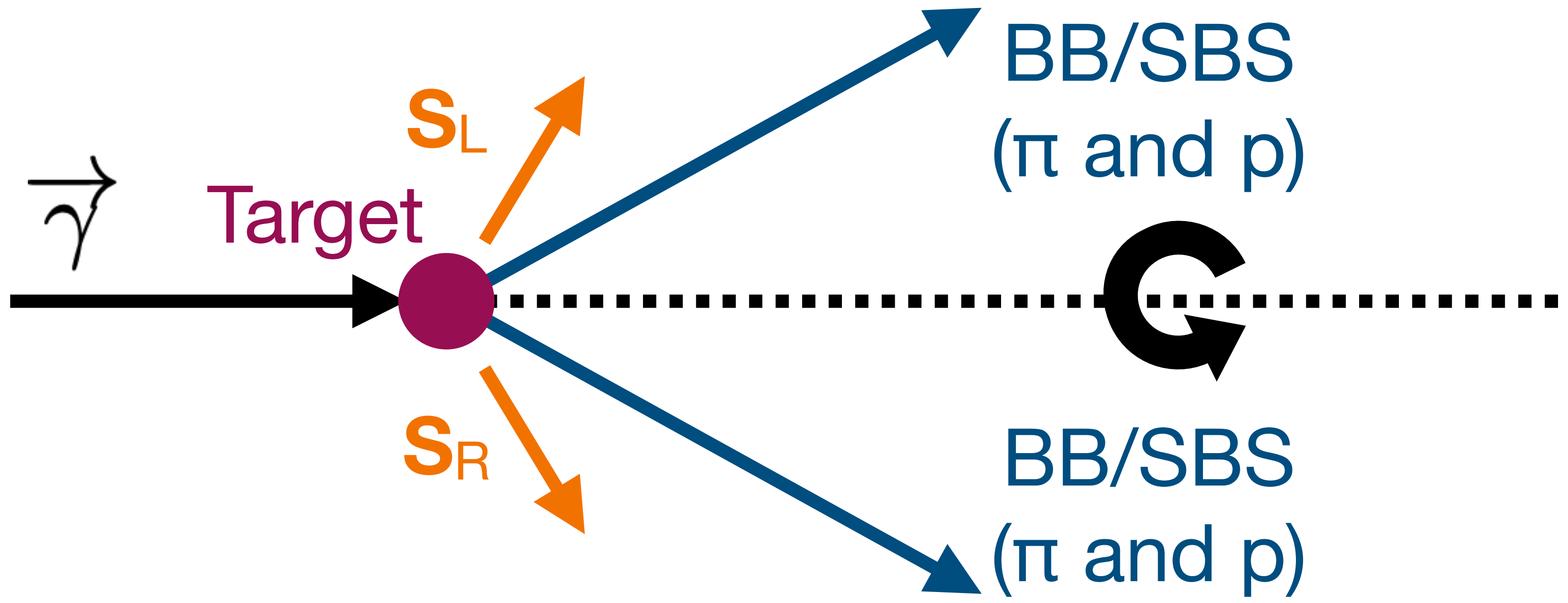
Spin dependent observables for test of twist-3 dominance

$$A_{LL}^{\text{twist}-3} = -K_{LL}^{\text{twist}-3} = -4\,\frac{S_T^{\pi^0}\left[S_T^{\pi^0} - \frac{t}{2m^2}S_S^{\pi^0} + \kappa\frac{\sqrt{-t}}{2m}\bar{S}_T^{\pi^0}\right]}{F^{\pi^0}}$$

$$A_{LS}^{\text{twist}-3} = -K_{LS}^{\text{twist}-3} = 2\,\frac{S_T^{\pi^0}}{F^{\pi^0}}\left[\frac{\sqrt{-t}}{m}\bar{S}_T^{\pi^0} - 2\kappa\left(S_T^{\pi^0} - \frac{t}{2m^2}S_S^{\pi^0}\right)\right]$$

A_{LL} = helicity of incoming photon and longitudinal polarisation of initial nucleon
A_{LS} = helicity of incoming photon and sideway polarisation of initial nucleon

- Measure A_{LS} AND A_{LL} (concept from Bogdan)
- Compensate for loss in photons by doing 2 simultaneous measurements
- Double productivity by accessing A_{LS} simultaneously without tricky target change



- Cannot easily change target to flip transverse polarisation
- Target polarised at 60˚ to beam
- BB and SBS symmetric around beam line, ~31.5˚ each

- Measure both p and π- in both BB and SBS
- Flip of transverse polarisation (**S**) around beam line equivalent to measuring in either BB or SBS
- Longitudinal component stays same

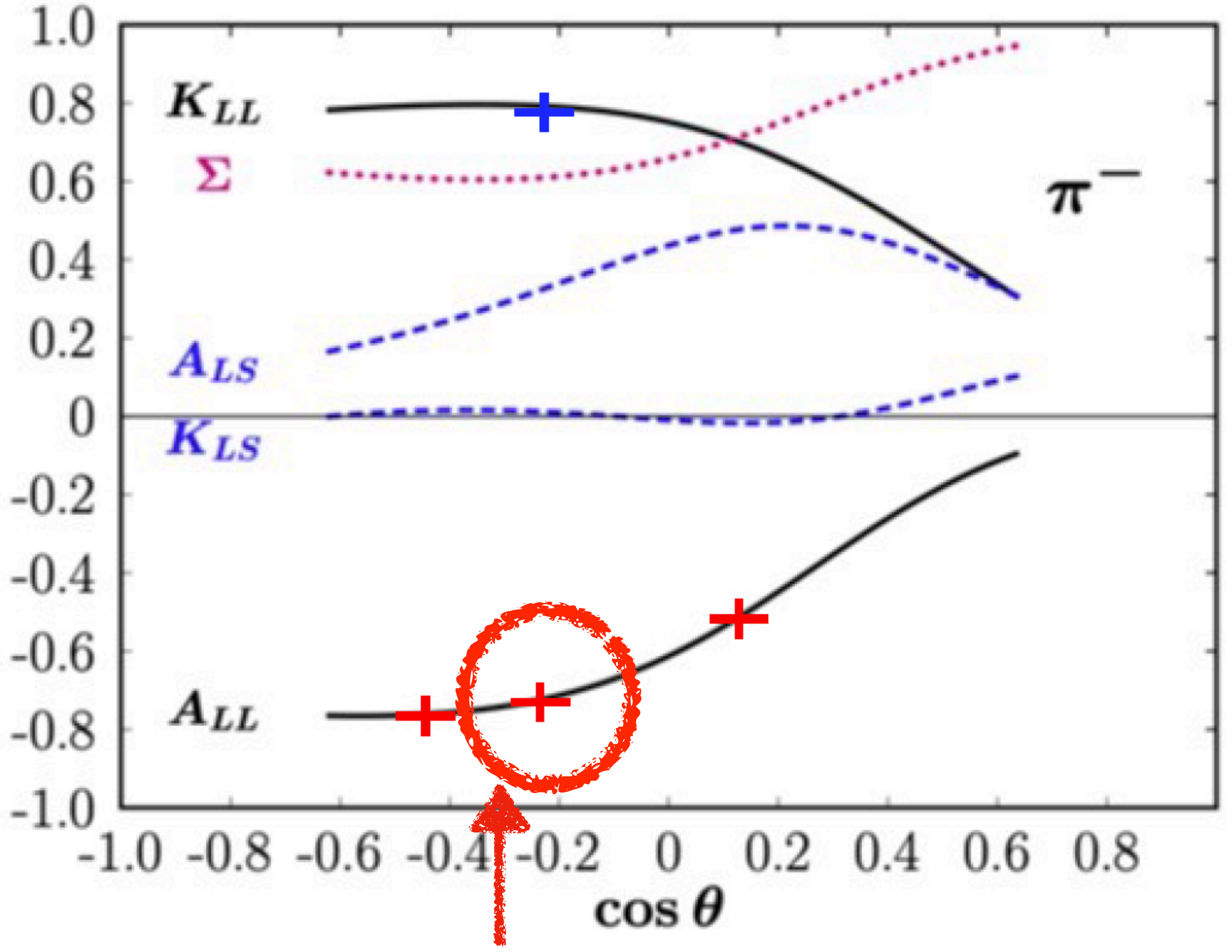
Transverse part cancels due to opposite signs

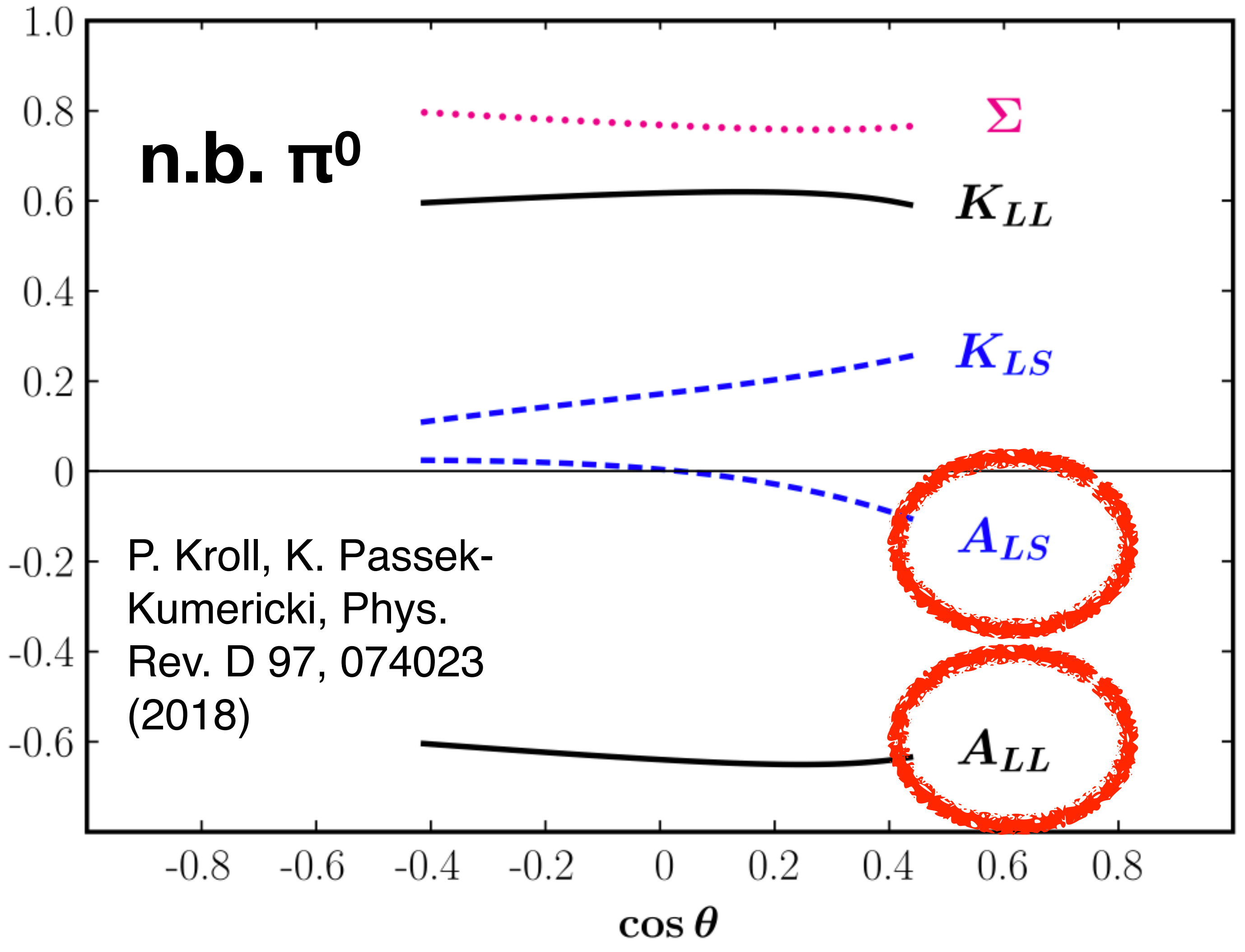
$$A_{LL} = \frac{A_{BB} + A_{SBS}}{2}$$

$$A_{LS} = \frac{A_{BB} - A_{SBS}}{2}$$

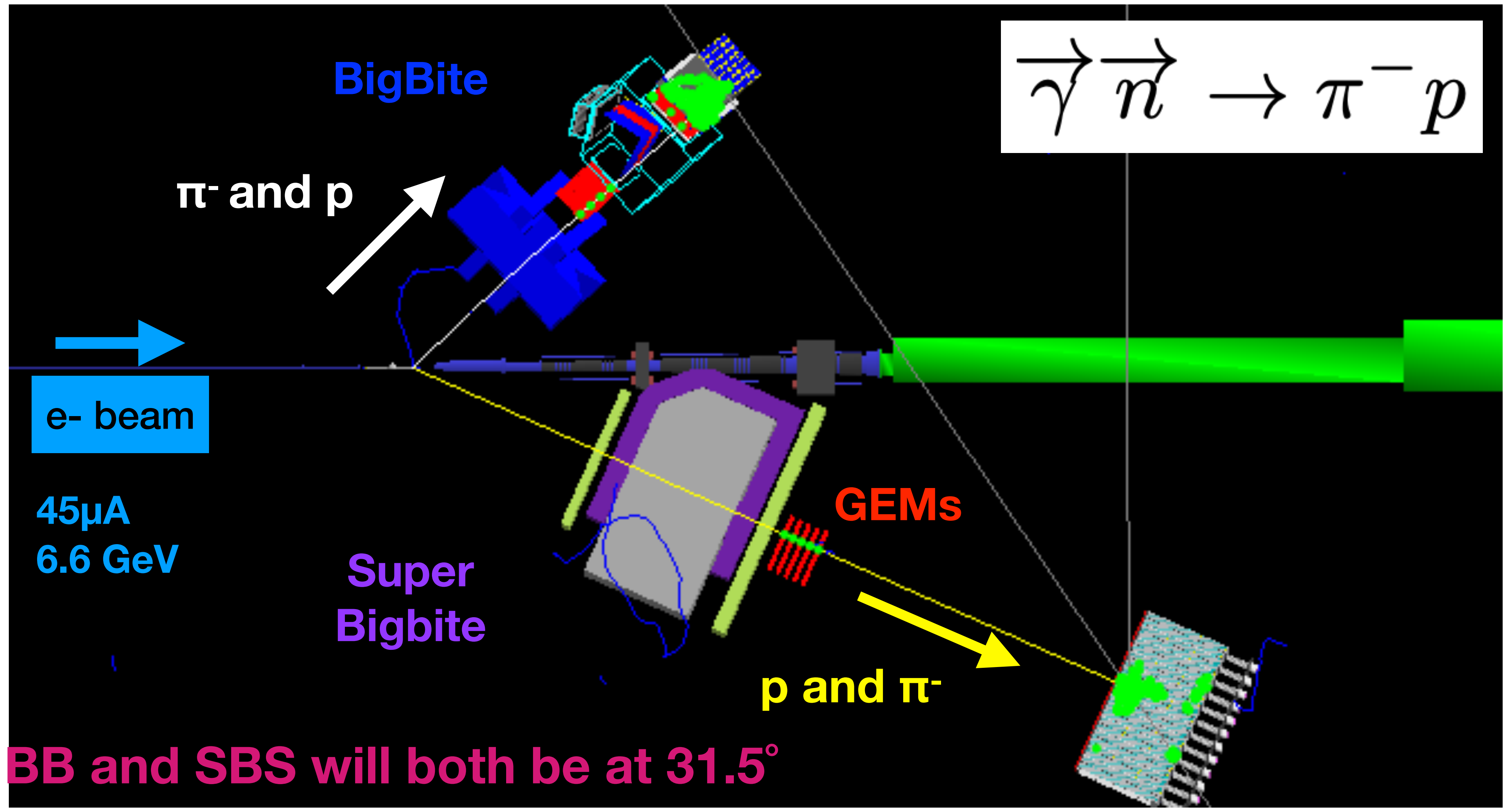
- Raw asymmetry has contributions from A_{LL} and A_{LS}
- Asymmetry observed by BB compared to SBS differs by opposite signs of A_{LS} only
- A_{LL} is average and A_{LS} is difference in BB/SBS asymmetries

Summary





Old 5% statistical uncertainty shown, but now will be 10%
15% theory uncertainty not shown
Still enough to test theory on level of 10σ (including accuracy of K_{LL})



- E12-21-005:
  - 3.5 PAC days to *opportunistically* measure **A_{LL} and A_{LS}** at θ_{CM} ~ 90˚at end of GEn
  - (initially granted 10 PAC days)
- Set-up same as GEn, with:
  - 45μA 6.6GeV, BB and SBS at 31.5˚; target polarised 60˚ to beam
  - Include SBS GEMs in DAQ
  - Trigger checkout needs to be checked for p and π^- in both arms simultaneously
- A_{LL} complimentary to SBS K_{LL}
- SBS measurements will:
  - Test twist-3 dominance in pion photoproduction cross-sections in wide angle regime
  - Test validity of handbag mechanism within GPD-based framework
  - Help study interaction mechanism for wide angle pion photoproduction
  - ~70years old problem

Thank You

Parameterised Cross Section and Original Projected Rates

- Cross-section parameterisation*:

$$\frac{d\sigma}{dt}_{\gamma n\rightarrow\pi^- p} = 1.7 \times 0.83 \times (10/s)^7 (1 - cos(\theta_{CM}))^{-5} (1 + cos(\theta_{CM}))^{-4}$$

- Event rate $N_{\pi^- p}$:

$$N_{\pi^- p} = \frac{d\sigma}{dt}_{\pi^- p} \frac{p^2_{\pi^-}}{\pi} \Delta\Omega_{\pi^-} f_{\pi^- p} \left[\frac{\Delta E_\gamma}{E_\gamma} \frac{t_{rad}}{X_0} \mathcal{L}_{e-n} \right]$$

process cross-section

Range of Δt, expressed in p_π and BB solid angle (50msr)

fraction of events detected in SBS obtained from g4sbs

Number of photons per incident electron and for photon energy range.
$t_{rad}/X_0 \sim 0.082$
$\mathcal{L} \sim 1.8\text{x}10^{36}\text{Hzcm}^{-2}$

Kin	A	B	C	D	E
$f_{\pi\text{-}p}$	0.31	0.18	0.51	0.35	0.37
Pion detection	0.41	0.38	0.37	0.42	0.37
Proton detection	0.86	0.81	0.88	0.92	0.93
$p_{miss\perp}$ cut	0.85	0.86	0.82	0.82	0.84
Estimated counts per hour	1420	980	1150	530	120

- To get final estimated rate, $N_{\pi\text{-}p}$ corrected for
  - expected DAQ dead time
  - from g4sbs studies: losses due to pion/proton detection/trigger efficiencies and event selection cut on missing momentum for reaction

* π^+ cross-section from: R.L. Anderson et al., Phys. Rev. D 14, 679 (1976)
Correction for π^- from π^+/π^+ yields from deuteron from: L.Y. Zhu et al., Phys. Rev. Lett. 91 (2003) 022003; Phys.Rev. C71 (2005) 044603

Original Proposed Measurements

- Below table accepted originally by PAC (who awarded 10 PAC days)
- Accounts for:
    - Production at kinematics (photon/neutron polarisations; dilution from $\pi^-\Delta^{++}$ background)
    - Spectrometer angle changes
    - Target polarisation measurement (every 4 hours)
    - BB optics runs and trigger checkout for π^- (as opposed to e')
    - Beam pass changes and associated beam positioning

Kin	Beam E_e (GeV)	$<E_\gamma>$ (GeV)	cos (θ_{CM})	< s > $(GeV/c)^2$	< -t > $(GeV/c)^2$	< u > $(GeV/c)^2$	Beam on target (hours)	Time (hours)	ΔA_{LL} accuracy
A	6.6	4.5	-0.23	9.3	4.7	2.9	6	37	±0.05
B	6.6	4.5	0.14	9.3	3.3	4.3	6	27	±0.05
C	6.6	4.5	-0.44	9.3	5.5	2.1	8	27	±0.05
D	8.8	6.0	-0.23	12.1	6.4	4.0	16	47	±0.05
E	11.0	7.5	-0.23	15.0	8.1	5.2	60	98	±0.05