u–channel Exclusive Electroproduction at Jefferson Lab

Garth Huber

University of Regina

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CFNS Workshop on Baryon Dynamics
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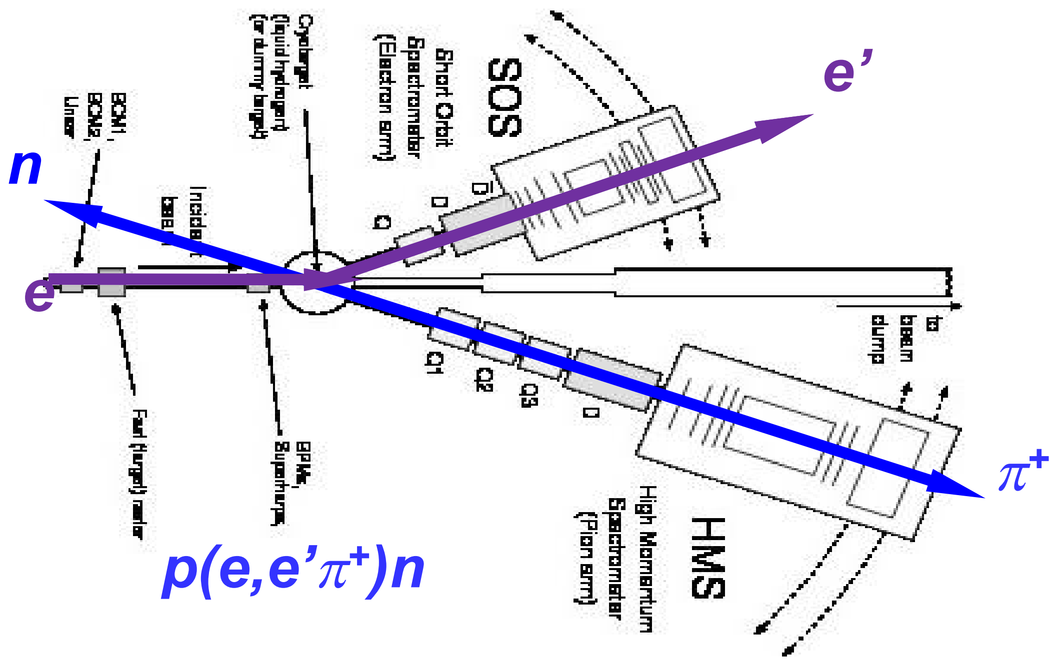
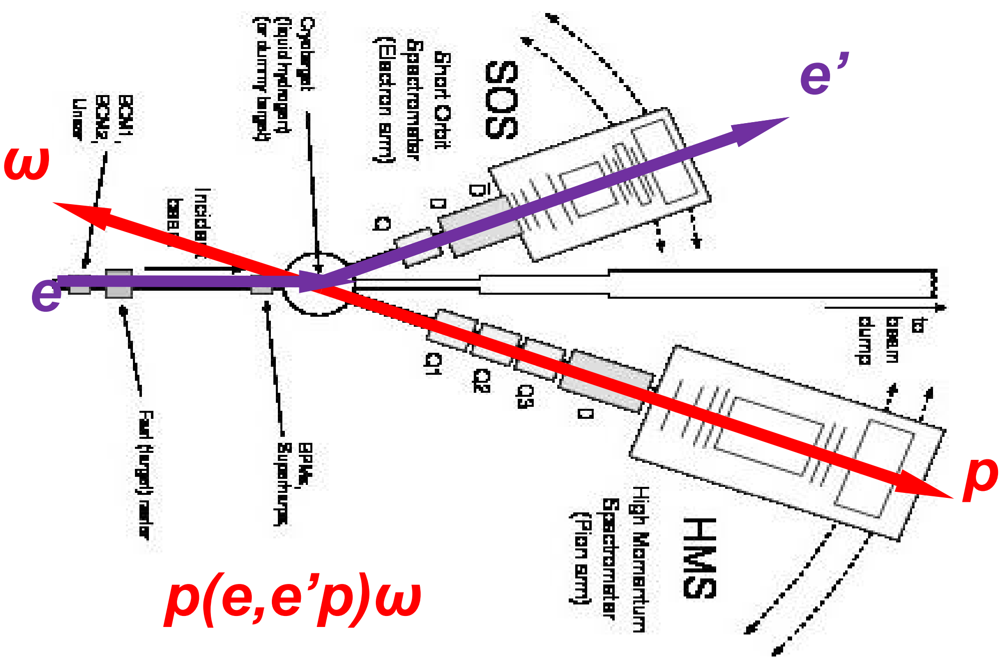
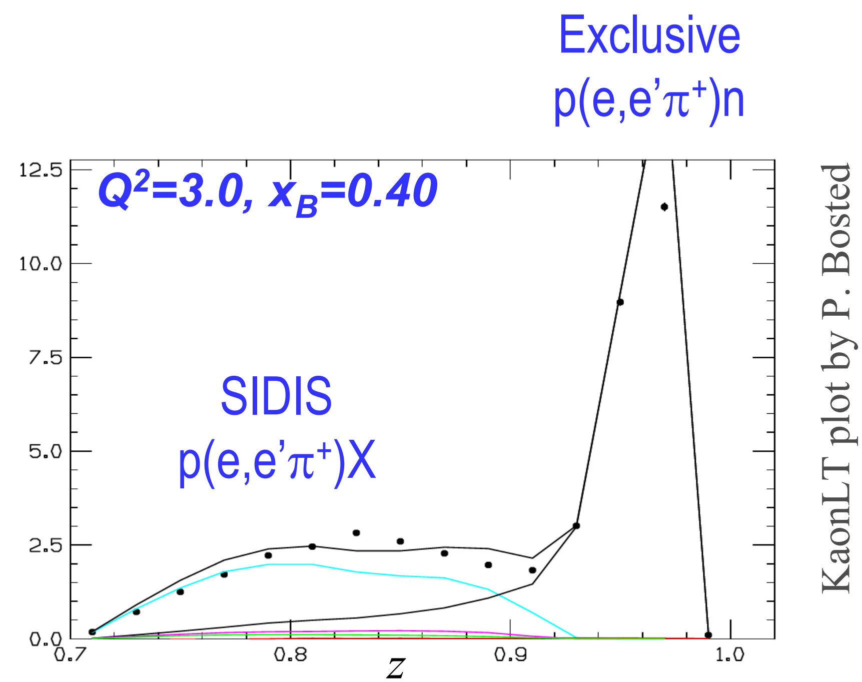
t–Channel π^+ vs u–Channel ω Production





Hadron detected along *q*–vector ($p_{\gamma*}$)

- $p_{\pi+}$ is parallel to $p_{\gamma*}$ (forward)
- p_{ω} is anti–parallel to $p_{\gamma*}$ (backward)
- Exclusive channel is kinematic endpoint at $z\rightarrow1$

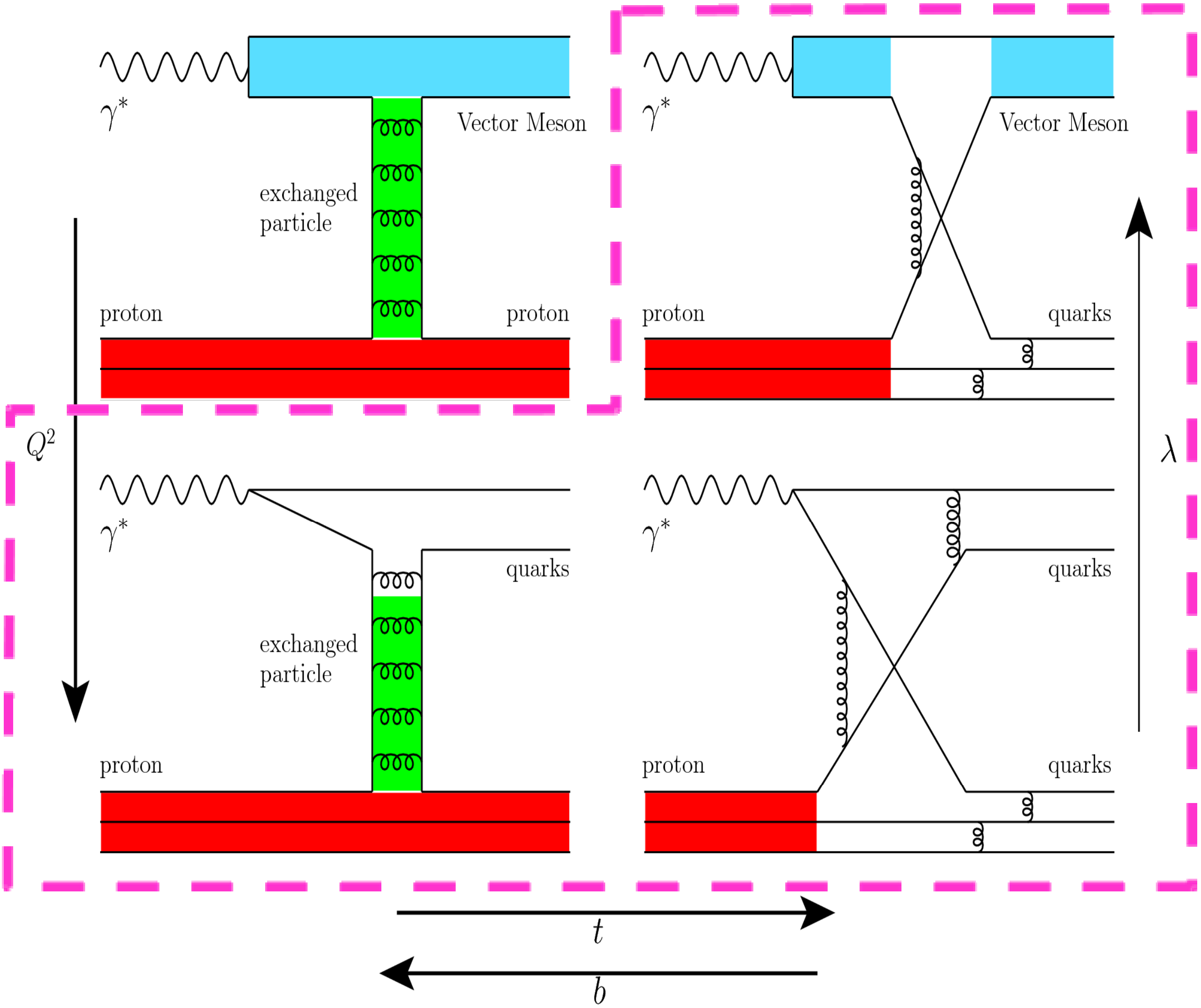


***p(e,e'p)ω* Exclusive channel**

- Full kinematic reconstruction of final state
- Do not detect any part of decayed ω

Garth Huber, huberg@uregina.ca

Hadronic Model: Evolution of Proton Structure



Evolution of the Proton Structure

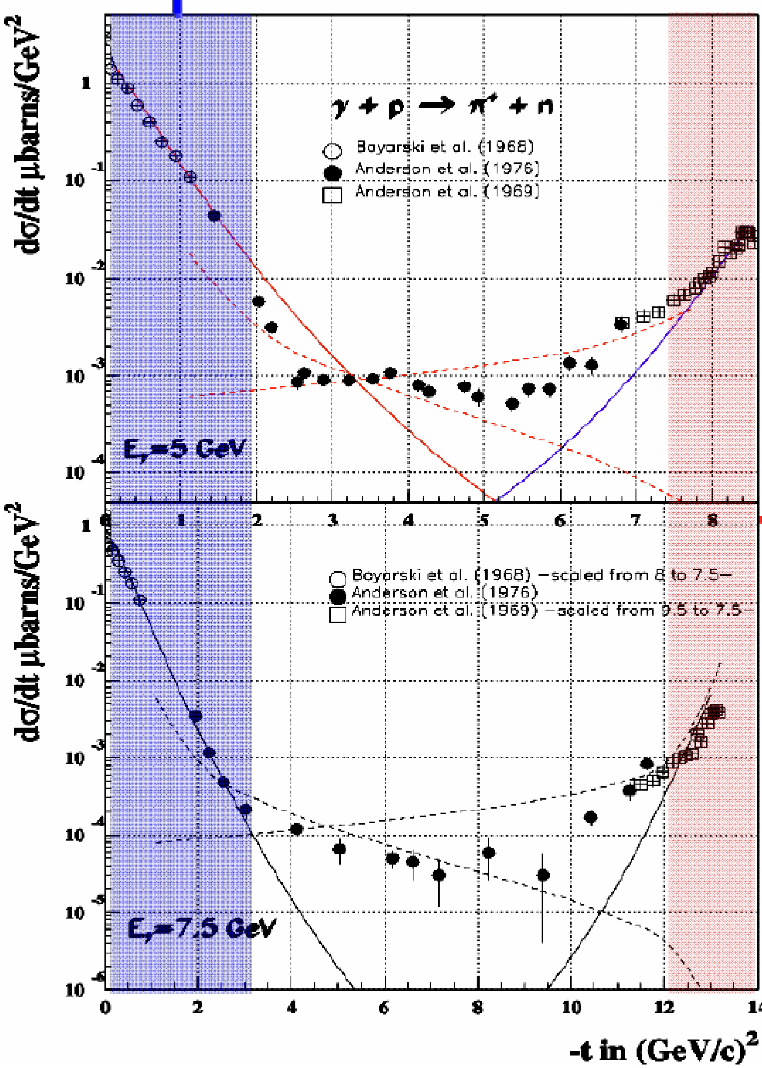
- Physics observables
  - ***t*, *W* (*s*), *Q*², *x***
- *x* Evolution:
  - 0.2–0.3 valence quark distribution pronounced
- *W* Evolution:
  - Above resonance region
- ***Q*² Evolution**
  - **Wavelength of γ^* probe**
- ***t* Evolution**
  - **Impact parameter** $\left(b \sim 1/\sqrt{-t}\right)$
- What about ***u***?
  - **Baryon exchange processes**

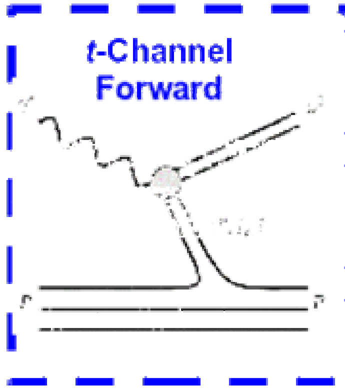
Garth Huber, huberg@uregina.ca

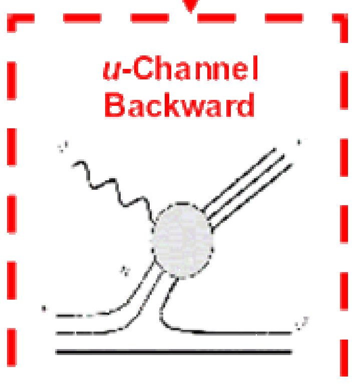
Hadronic Model: Regge Model by JM Laget

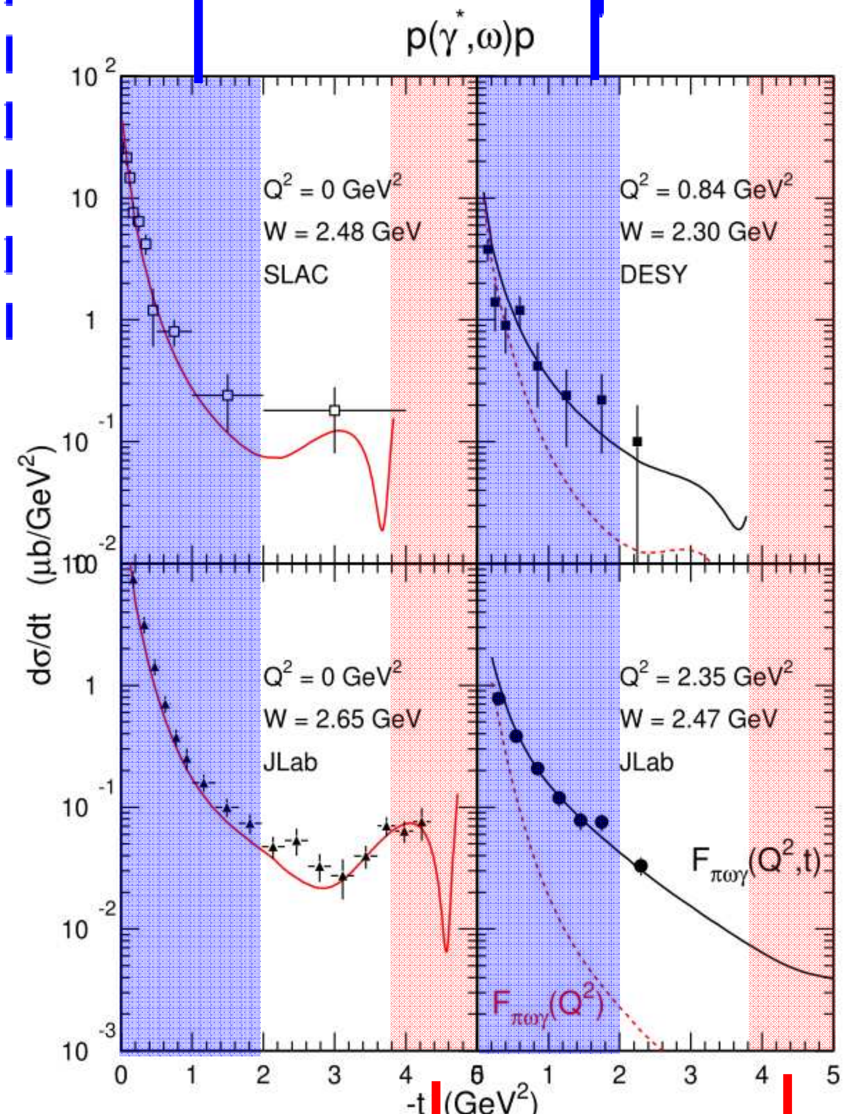
M. Guidal, J.-M. Laget, M. Vanderhaeghen, PLB **400**(1997)6

J.-M. Laget, Prog.Part.Nucl.Phys. **111**(2020)103737









Soft structure → Hard → Soft transition

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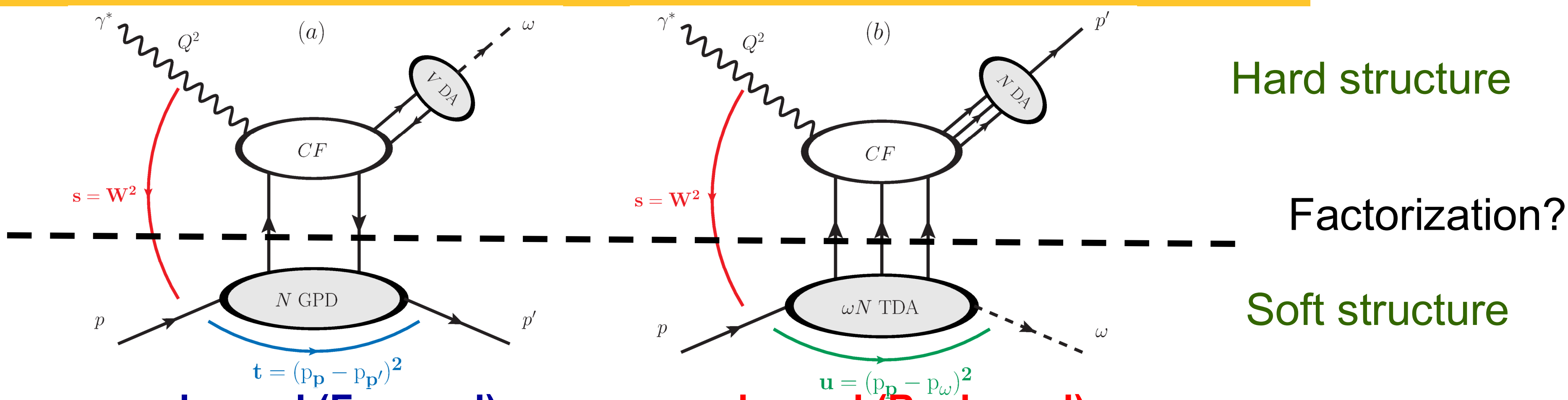
Partonic Model: TDA and Factorization



t–channel (Forward) *u*–channel (Backward)

Baryon to Meson Transition Distribution Amplitude (TDA)

- Extension of collinear factorization to backward angle regime. Further generalization of the concept of GPDs.
- Backward angle factorization first suggested by Frankfurt, Polykaov, Strikman, Zhalov, Zhalov at JLab 2002 Exclusive Reactions Workshop.
- TDAs describe the transition of nucleon to 3–quark state and final state meson. *[gray oval of plot b]*
- A fundamental difference between GPDs and TDAs is that TDAs are defined as hadronic matrix elements of 3–quark operator, while GPDs involve quark–antiquark operator.
- **Can be accessed experimentally in backward angle meson electroproduction reactions.**

Garth Huber, huberg@uregina.ca

Skewness in Backward Angle Regime

- **Forward angle kinematics,** $-t \sim -t_{min}$ and $-u \sim -u_{max}$, in the regime where handbag mechanism and GPD description may apply, Skewness is defined in usual manner:

$$\xi_t = \frac{p_1^+ - p_2^+}{p_1^+ + p_2^+} \quad \text{where } p_{1,2} \text{ refer to light cone + components}$$

$$\text{in } \gamma^*(q) + p(p_1) \rightarrow \omega(p_\omega) + p'(p_2)$$

- **Backward angle kinematics,** $-u \sim -u_{min}$ and $-t \sim -t_{max}$, Skewness is defined with respect to *u*–channel momentum transfer in TDA formalism

$$\xi_u = \frac{p_1^+ - p_\omega^+}{p_1^+ + p_\omega^+}$$

- GPDs depend on x, ξ_t and $t=(\Delta^t)^2=(p_2-p_1)^2$
  TDAs depend on x, ξ_u and $u=(\Delta^u)^2=(p_\omega-p_1)^2$

- Impact parameter space interpretation of TDAs is similar to GPDs, except one has to Fourier transform with respect to $\Delta^u_T \approx (p_\omega - p_1)_T$

Garth Huber, huberg@uregina.ca

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Impact parameter Interpretation of TDA

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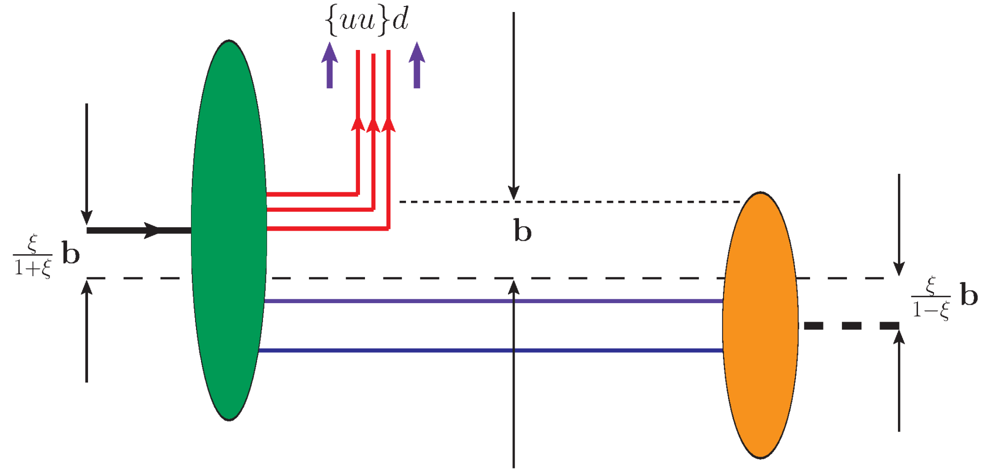
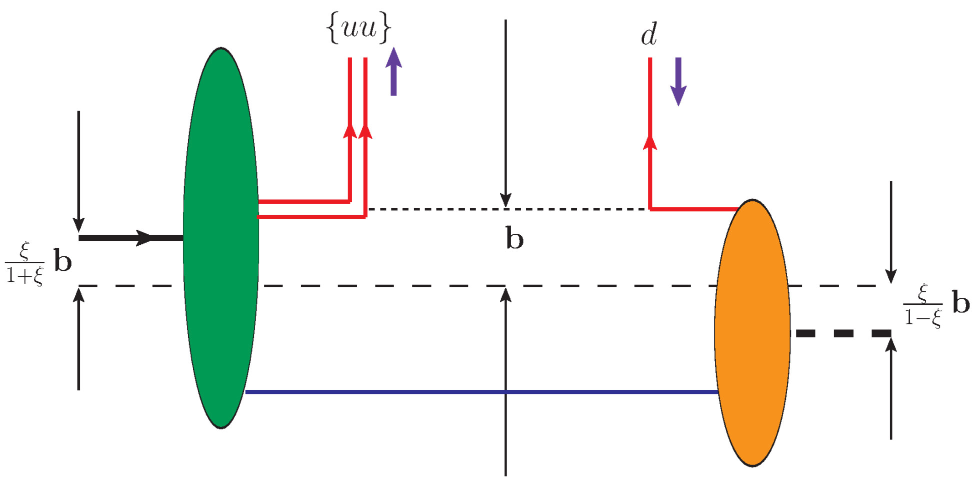
- After integrating over one momentum fraction x_i, the three exchanged quarks can be treated as an effective diquark+quark pair
- Impact picture then looks very much like that for GPDs



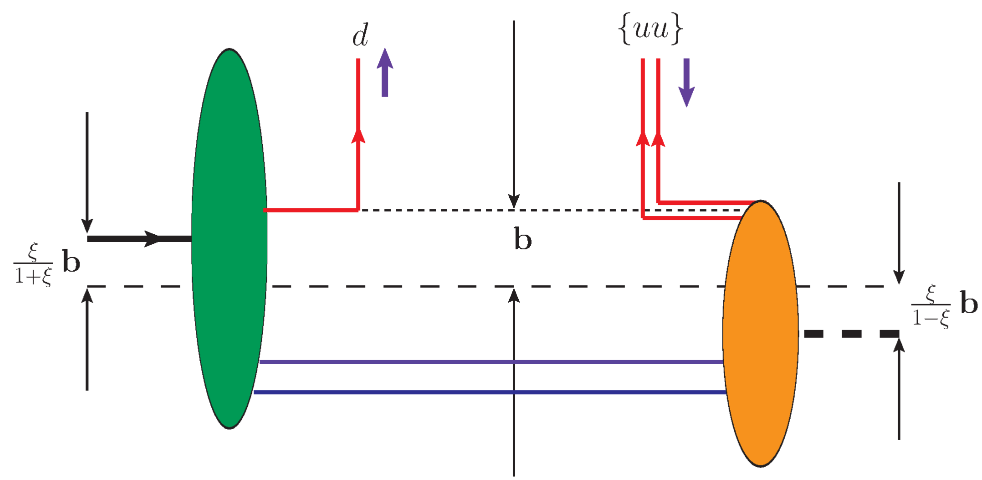
ERBL : $x_3 = w_3 + \xi \geq 0; \quad x_1 + x_2 = \xi - w_3 \geq 0;$

$\longrightarrow$ All 3 quark momentum fractions x_i positive



DGLAP I : $x_3 = w_3 + \xi \leq 0; \quad x_1 + x_2 = \xi - w_3 \geq 0;$

$\longrightarrow$ One x_i negative



DGLAP II : $x_3 = w_3 + \xi \geq 0; \quad x_1 + x_2 = \xi - w_3 \leq 0;$

$\longrightarrow$ Two x_i negative

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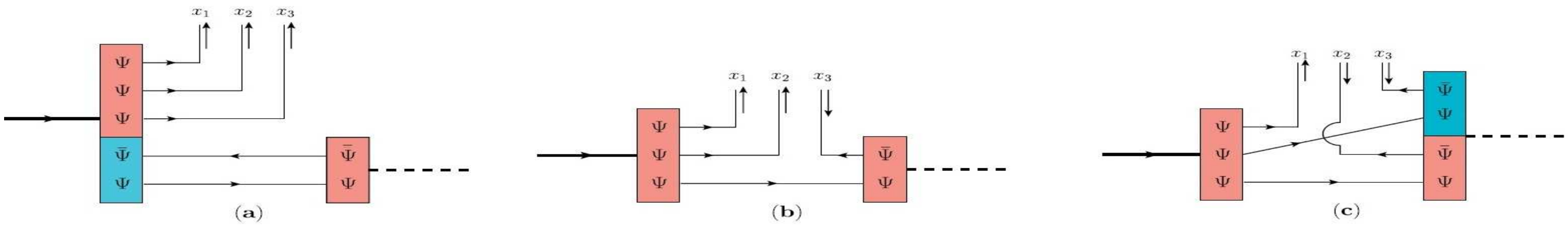
Partonic Interpretation of TDA

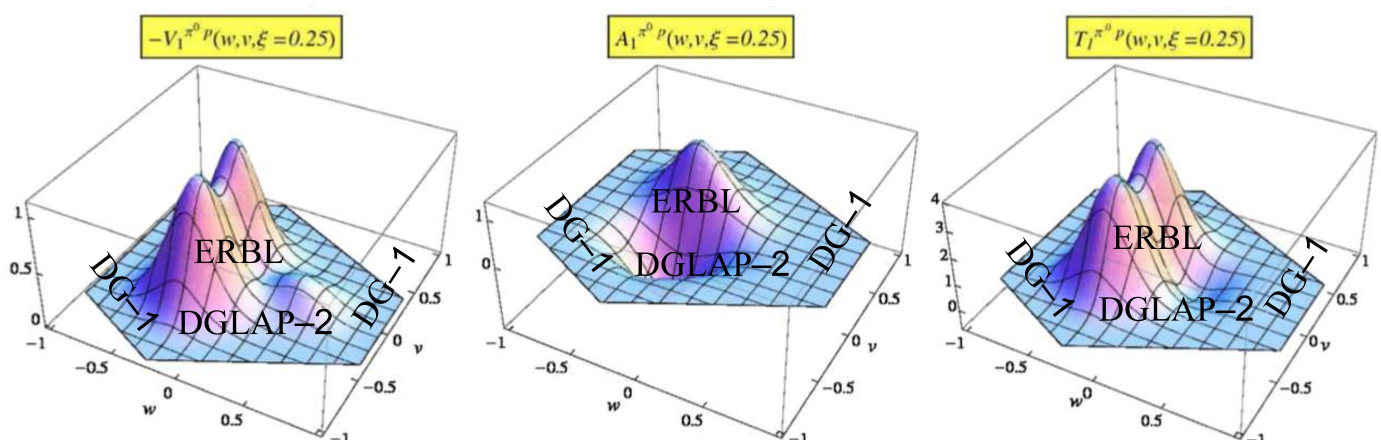
Main reactions of interest to date:

- Backward angle exclusive π^0, π^+, ρ, ω, φ production
- Backward angle DVCS



Interpretation of πN TDAs in light–cone quark model

a) Quark sea contrib to baryon wf (ERBL region)
b) Minimal Fock states of baryon & meson (DGLAP–1) region
c) Quark sea contribution to meson wf (DGLAP–2)



$v = (x_1 - x_2)/2$
$w = (x_3 - x_1 - x_2)/2$

$\pi^0 p$ TDAs (CZ): **Vector** **Axial–Vector** **Tensor**

Model based on spectral representation w/ CZ sol for DA as input (function of quark–diquark coord)

J.P. Lansberg et al., PRD **85** (2012) 054201

Garth Huber, huberg@uregina.ca

Backward Angle Collinear Factorization

- **Kinematical regime for collinear factorization involving TDAs is similar to that involving GPDs:**
  - x_B fixed
  - $|u|$–momentum transfer small compared to Q^2 and s
  - Q^2 and s sufficiently large

Two Key Predictions in Factorization Regime:

  - **Dominance of transverse polarization** of virtual photon, resulting in suppression of longitudinal cross section by at least $1/Q^2$: $\sigma_T \gg \sigma_L$
  - Characteristic $1/Q^8$–scaling behavior of σ_T for fixed x_B

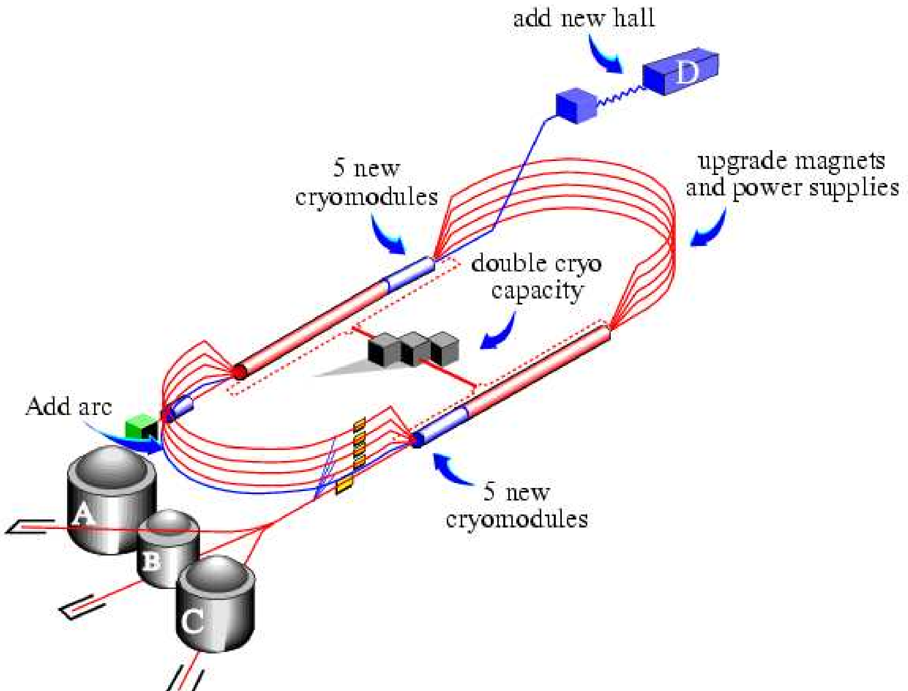
- Early scaling for GPD physics occurs $2<Q^2<5$ GeV^2
  - Maybe something similar occurs for TDA physics…

Garth Huber, huberg@uregina.ca

Limitations

Garth Huber, huberg@uregina.ca

- Exclusive ERBL and DGLAP1,2 regions are somewhat analogous to J/3q, J+2q, J+q exchange processes in SIDIS *u*–channel, could have different Junction contributions
- **Very difficult to selectively probe ERBL and DGLAP regions**. In an exclusive process, one has to exchange entire baryon in *u*–channel, and the problem is even more complicated than familiar deconvolution problem for GPDs
  - **Only exception appears to be at high ξ_u, where DGLAP regions disappear, so dominant picture (e.g. for impact parameter interpretation) is ERBL based one**
  - In general, JLab kinematics are expected to be more ERBL dominated, while EIC kinematics will be more DGLAP region
- Comparing exclusive *u*–channel processes for different final states (e.g. π^0, ρ^0, ω, φ) might help disentangle any Junction contributions from hadron form factor parts



Two 1.5 GHz Superconducting Linear Accelerators provide electron beam for Nucleon & Nuclear structure studies.

- **Beam energy E → 12 GeV.**
- **Beam current >100 μA.**
- **Duty factor 100%, 85% polarization.**
- Experiments in all 4 Halls can receive beam simultaneously.

“6 GeV” JLab Hall C Experimental Setup

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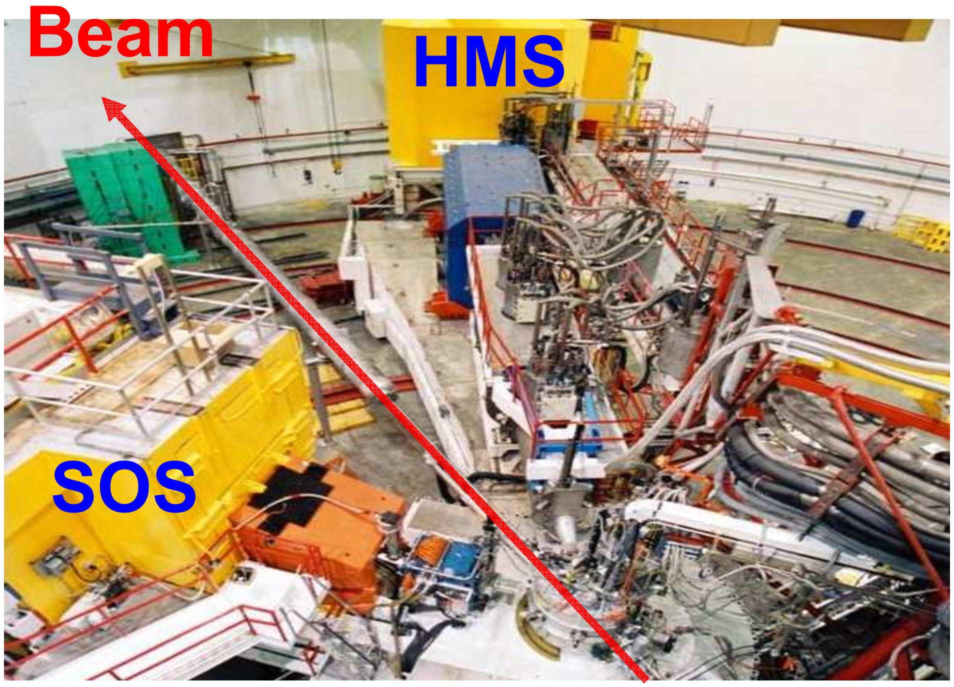
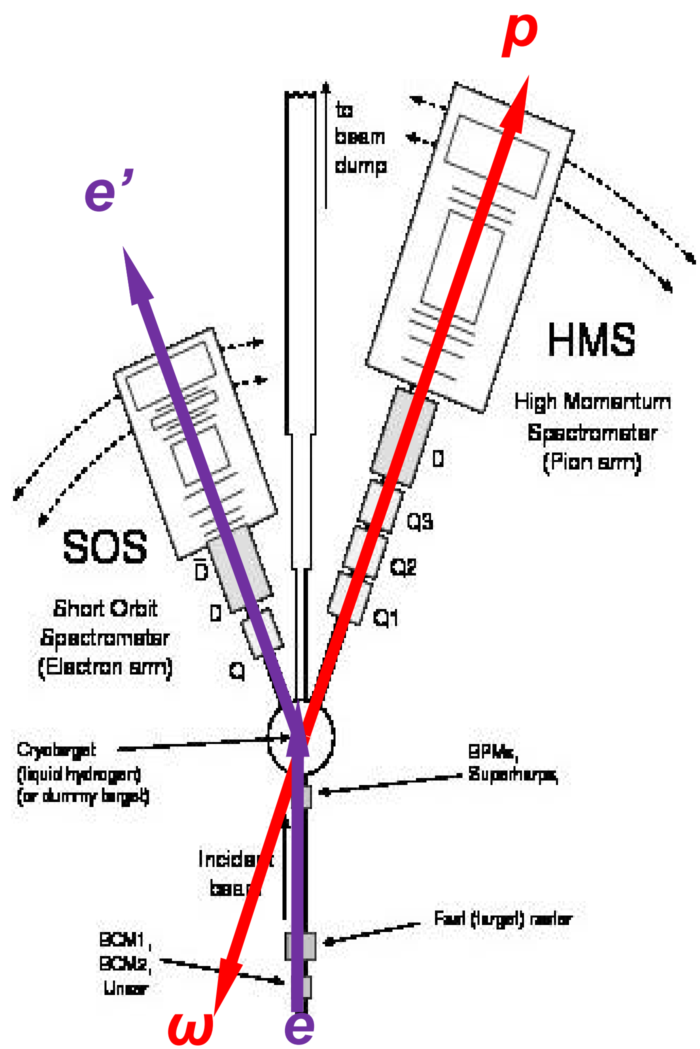


E_e (GeV)	ε	−*u* (GeV^2)	−*t* (GeV^2)	ξ_u	ξ_t
$<Q^2>$=1.60 GeV^2 $<W>$=2.21 GeV					
3.772	0.328	0.058 – 0.245	3.85 – 4.15	0.075 – 0.177	0.722 – 0.735
4.702	0.593				
$<Q^2>$=2.45 GeV^2 $<W>$=2.21 GeV					
4.210	0.270	0.117 – 0.400	4.48 – 4.94	0.126 – 0.256	0.748 – 0.764
5.248	0.554				

p(e,e’p)ω

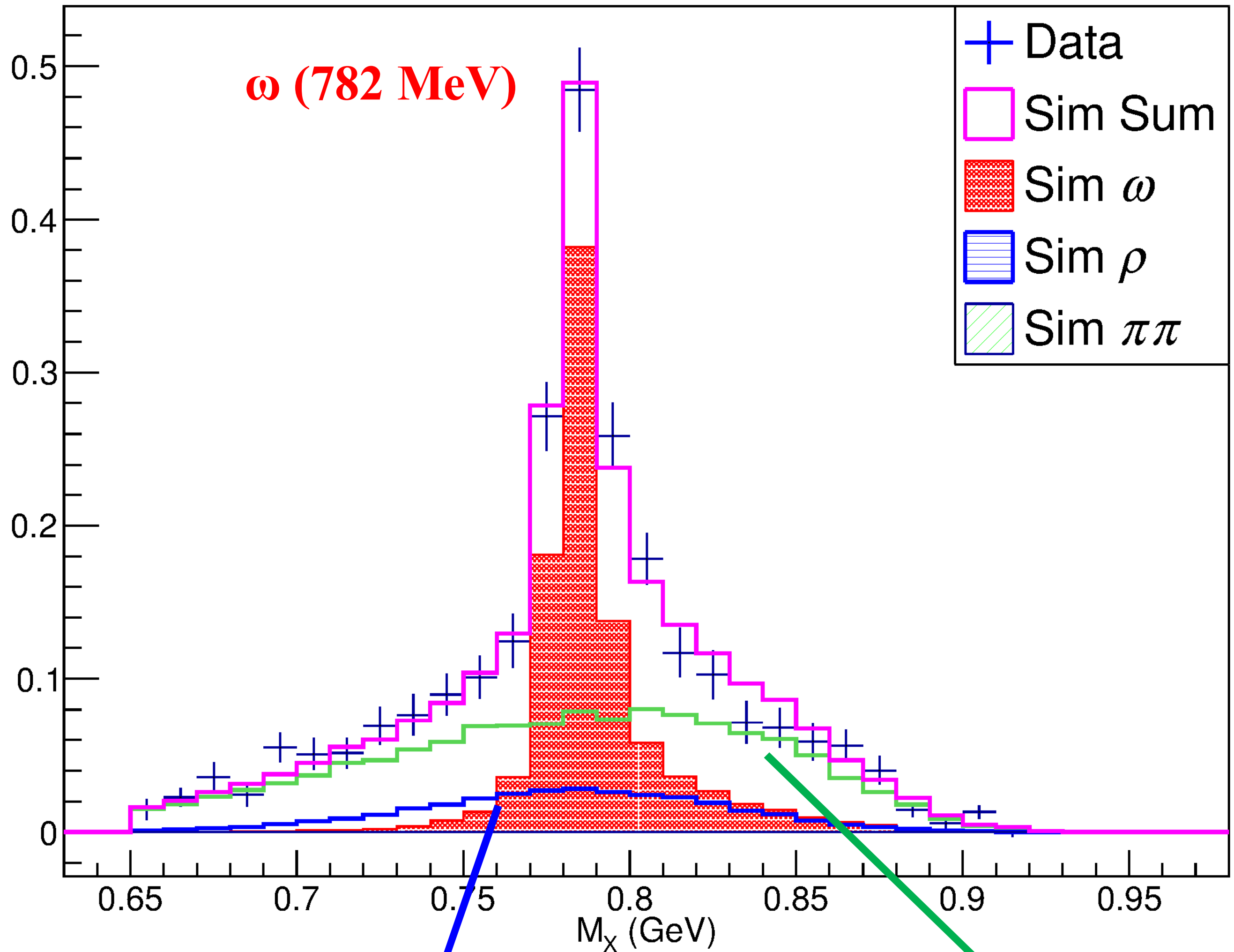


One of last analyses of Hall C 6 GeV era

Garth Huber, huberg@uregina.ca

Physics Background Subtraction

$$M_x = \sqrt{(E_e + m_p - m_{e'} - E_p)^2 - (\vec{p}_e - \vec{p}_{e'} - \vec{p}_p)^2}$$



ρ (770 MeV)

HERMES Empirical parameterization
with Soding skewness factor

2π production
phase-space

Garth Huber, huberg@uregina.ca

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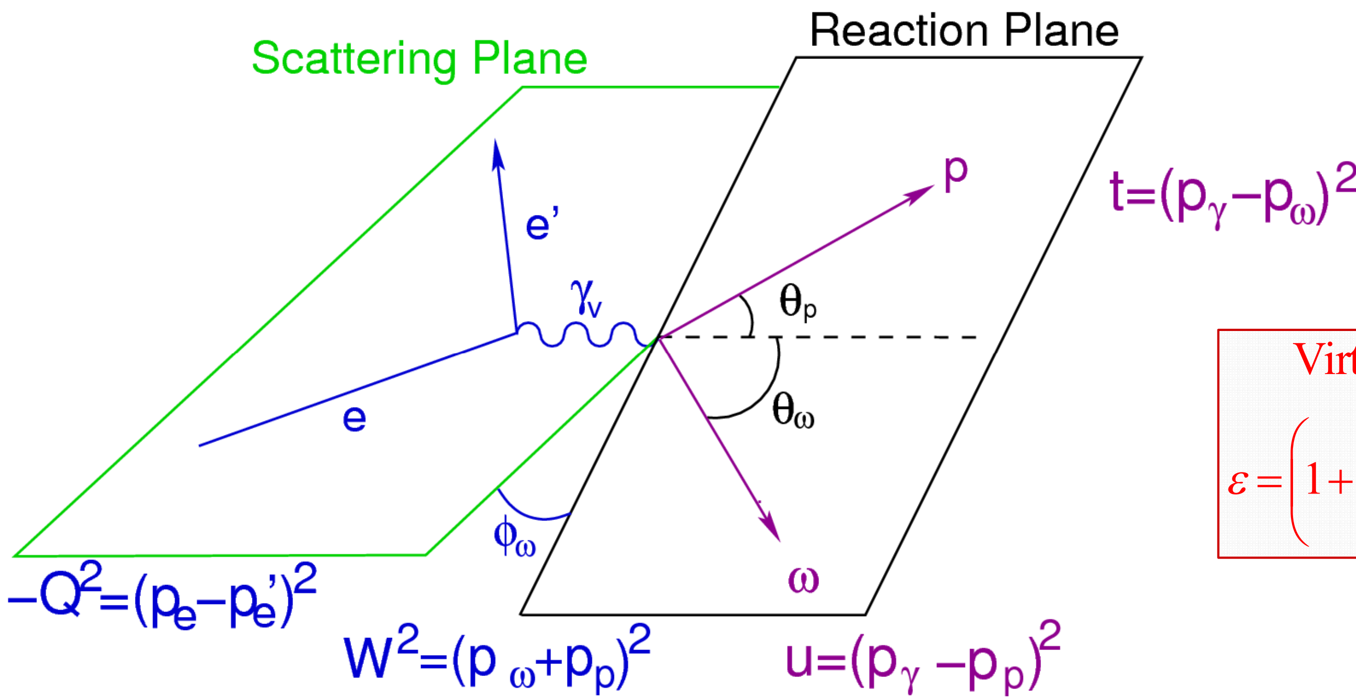
Rosenbluth (L/T/LT/TT) Separation



Virtual-photon polarization:

$$\varepsilon = \left(1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$

$$2\pi\frac{d^2\sigma}{dt\,d\phi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Rosenbluth Separation requires:

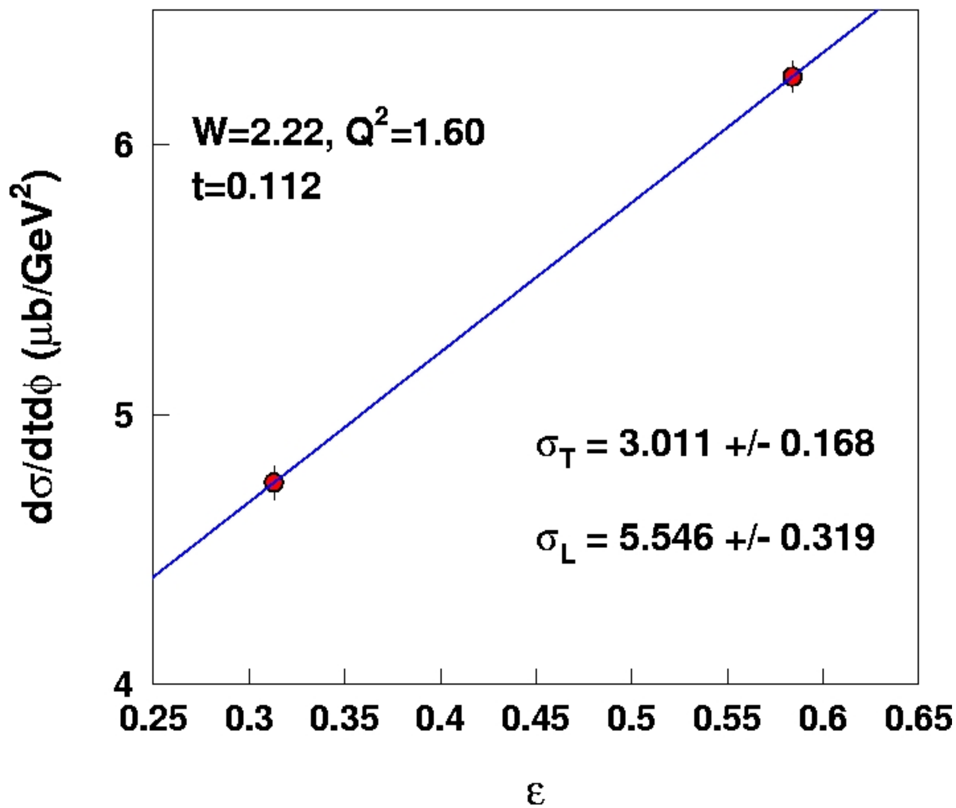
- Separate measurements at different ε (virtual photon polarization)
- All Lorentz invariant physics quantities: Q^2, *W, t, u,* remain constant
- Beam energy, scattered e' angle and virtual photon angle will change as a result, event rates are dramatically different at high, low ε

Garth Huber, huberg@uregina.ca

"Simple" Longitudinal–Transverse Separation

Garth Huber, huberg@uregina.ca

- For uniform φ–acceptance, σ_{TT}, $\sigma_{LT} \rightarrow 0$ when integrated over φ
- Determine $\sigma_T + \varepsilon\, \sigma_L$ for high and low ε in each *u*–bin for each Q^2
- Isolate σ_L, by varying photon polarization, ε

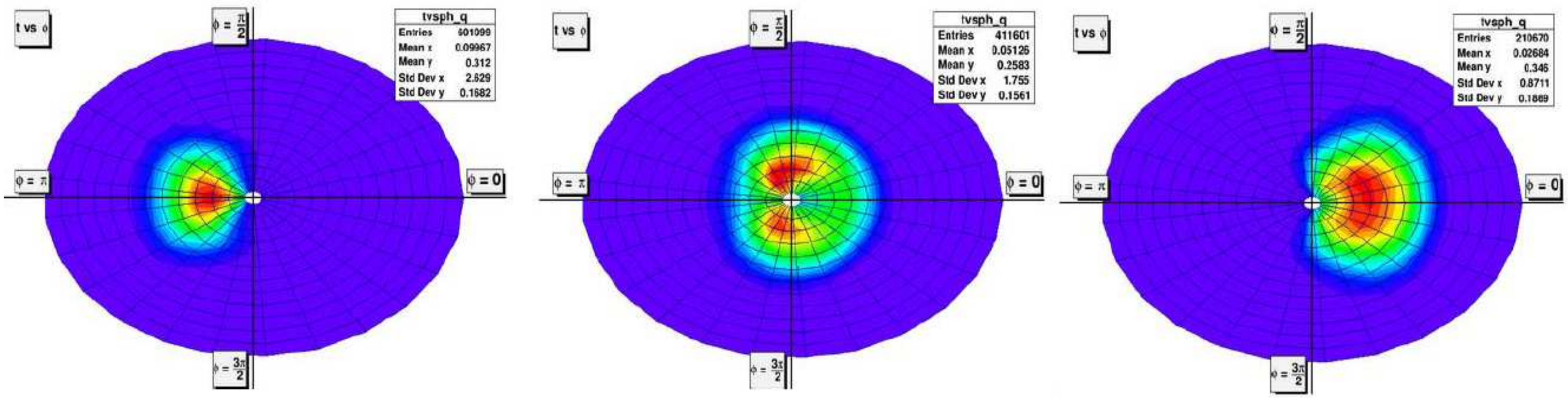


$$\varepsilon = [1+2(1+\tau)\tan^2(\theta/2)]^{-1}$$

$$2\pi \frac{d\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

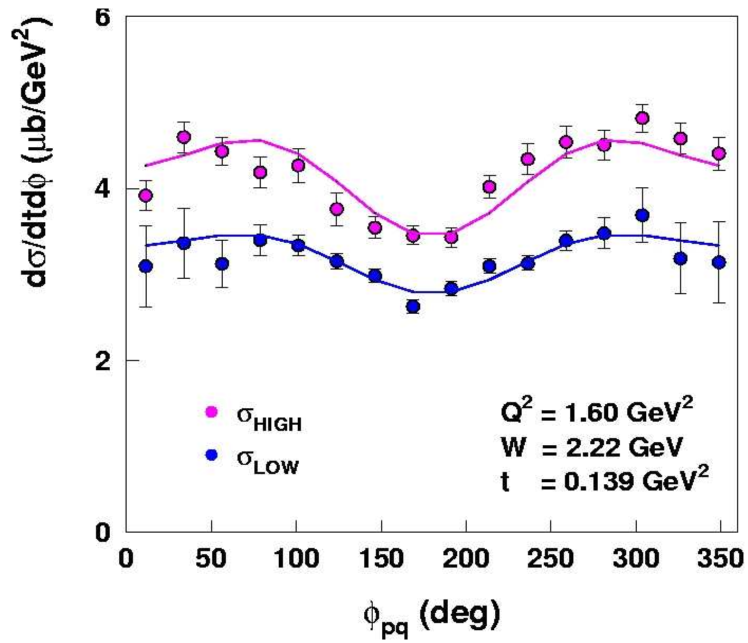
"More Realistic" L/T Separation

$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$



Cross-Section Determination:

- In reality, φ acceptance not uniform
- Must measure σ_{LT} and σ_{TT}
- Three hadron spectrometer angles needed for full azimuthal (φ_p) coverage to determine the interference terms
- Extract σ_L by simultaneous fit using measured azimuthal angle (φ_p) and knowledge of photon polarization (ε)



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Separated Cross Sections $\frac{d\sigma}{dt}$ vs $-u$

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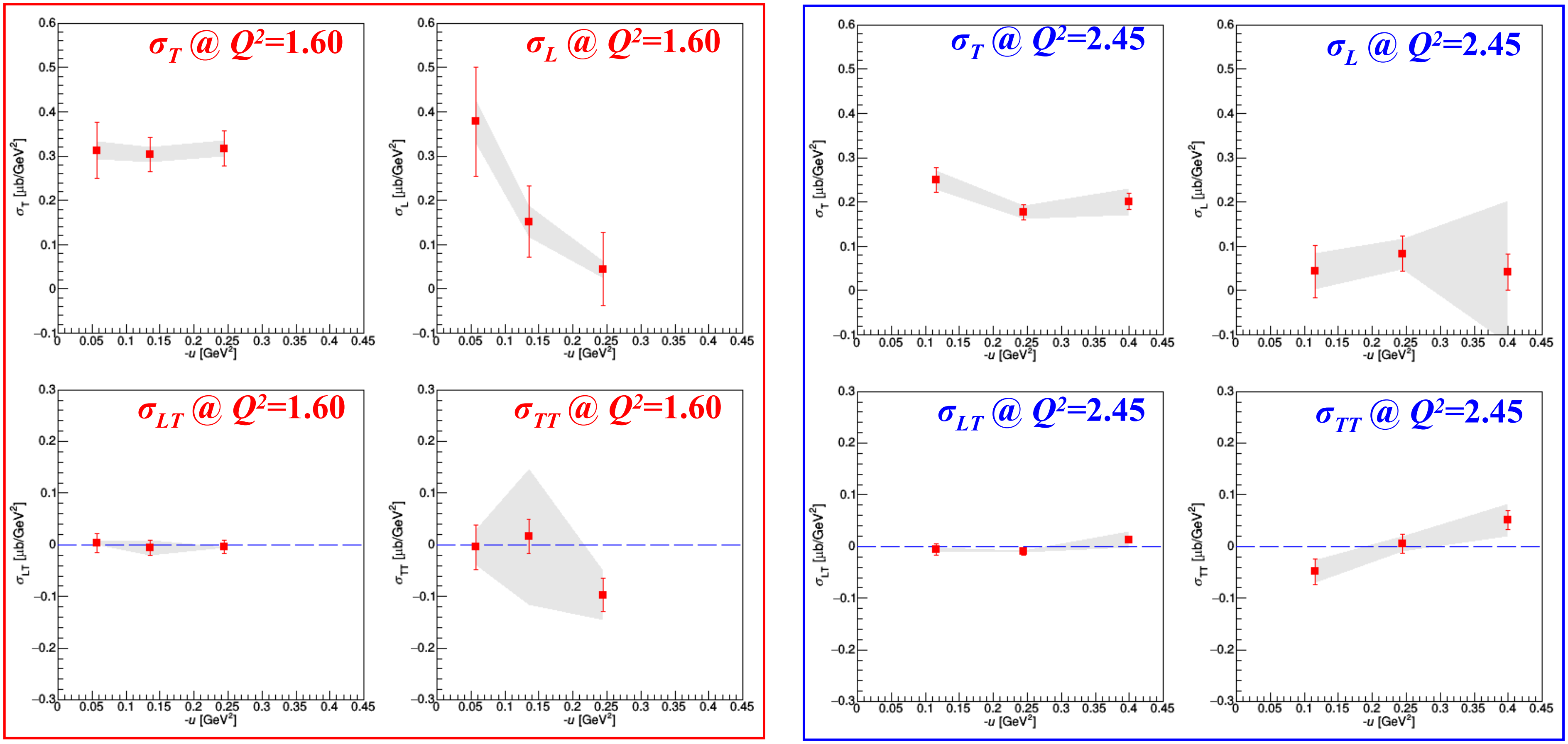
$p(e,e'p)\omega$



Observations:

- σ_T falls slowly with $-u$; σ_L falls faster.
- σ_{LT} is very small; σ_{TT} may sign flip for different Q^2 values.

Error bars = statistical and uncorrelated syst. unc; Error bands = correlated syst. unc.

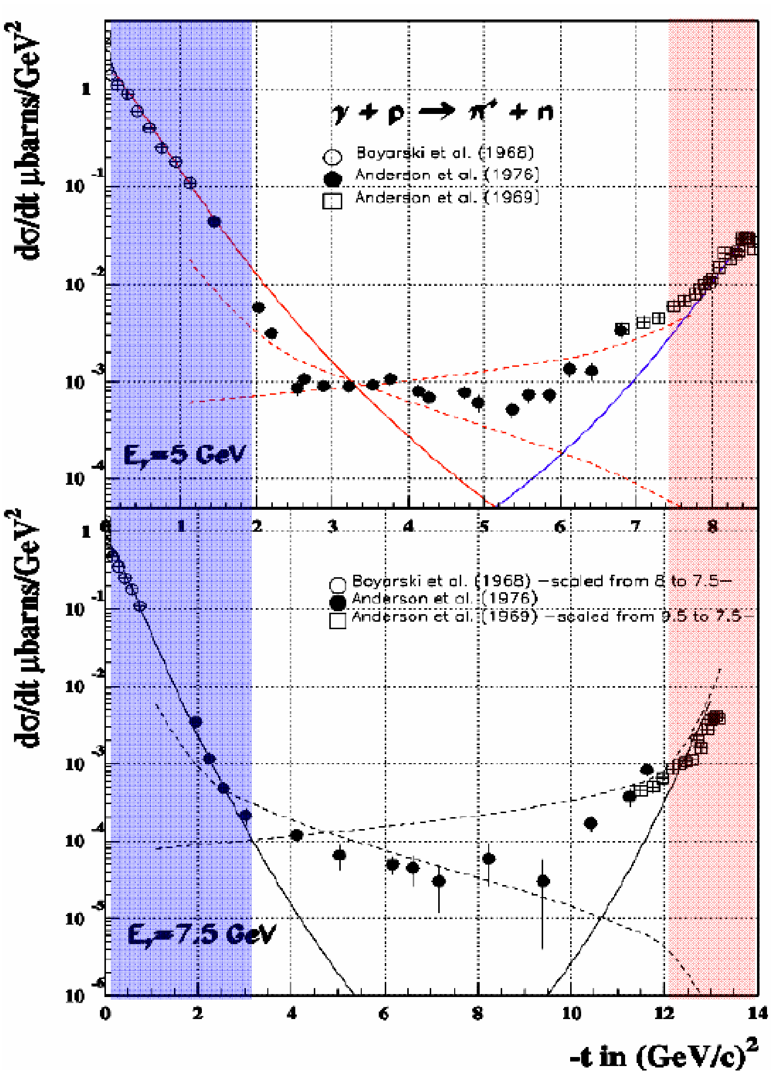
W.B. Li, arXiv: 1712.03214

Garth Huber, huberg@uregina.ca

Backward Angle Omega Electroproduction Peak

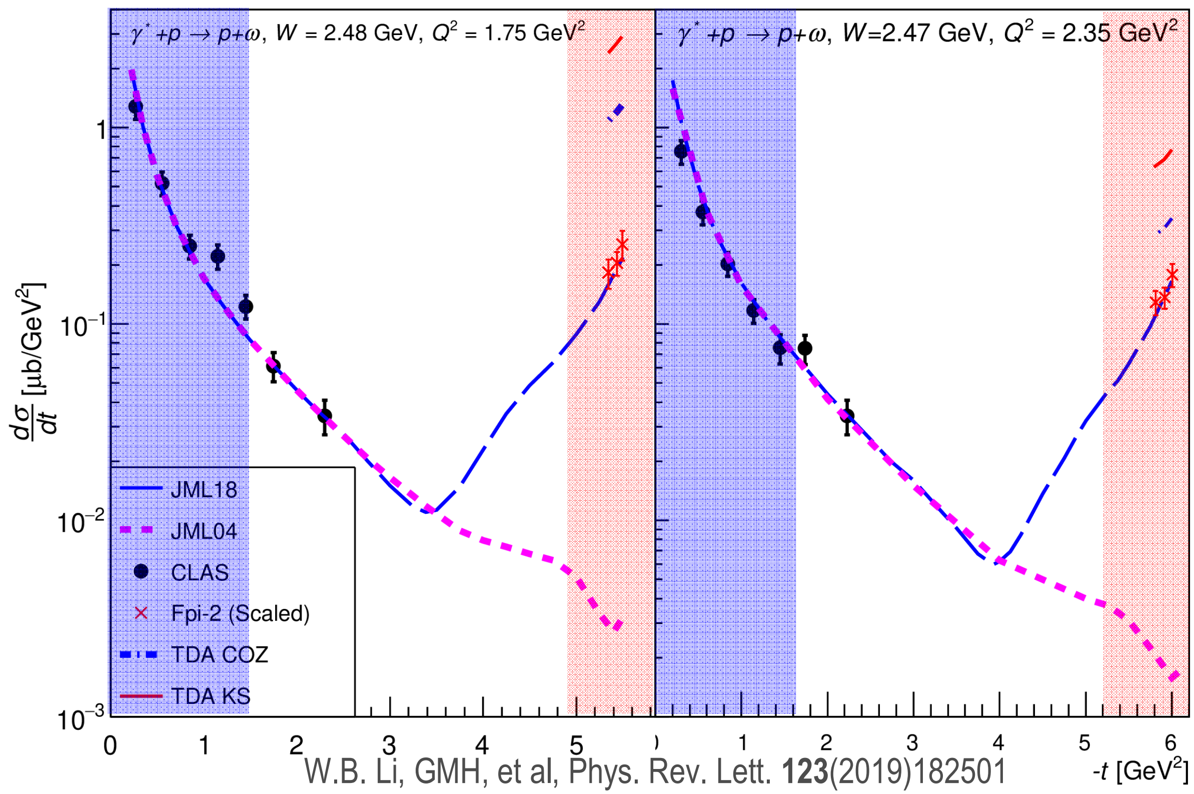
Garth Huber, huberg@uregina.ca

Photoproduction



M. Guidal, J.–M. Laget, M. Vanderhaeghen, PLB **400**(1997)6

First observation of backward angle peak in electroproduction



W.B. Li, GMH, et al, Phys. Rev. Lett. **123**(2019)182501

Hall C data are scaled to match kinematics of Hall B data

	W (GeV)	x_B	Q^2 (GeV²)	*−t (GeV²)*	*−u (GeV²)*
Hall B	**1.8 – 2.8**	**0.16 – 0.64**	**1.6 –5.1**	**< 2.7**	**> 1.68**
Hall C	**2.21**	**0.29**	**1.6**	**4.014**	**0.08 – 0.13**
		0.38	**2.45**	**4.724**	**0.17 – 0.24**

Backward Peak is Larger than Expected

- In photoproduction, the ratio of the forward (t–channel) to backward (u–channel) peaks is ~100:1
- The same was expected for electroproduction
  - It was thus a surprise when we observed the ratio of forward/backward peaks to be ~10:1
- J.M. Laget (JML) has been able to provide a natural explanation for this surprisingly large ratio within the Regge model formalism
  - The L/T ratio for the backward peak can help distinguish various theoretical explanations, but JML model is not yet able to give such predictions
- Study of other exclusive channels over a broad kinematic range is needed to confirm whether strong backward peaks are ubiquitous or not

Garth Huber, huberg@uregina.ca

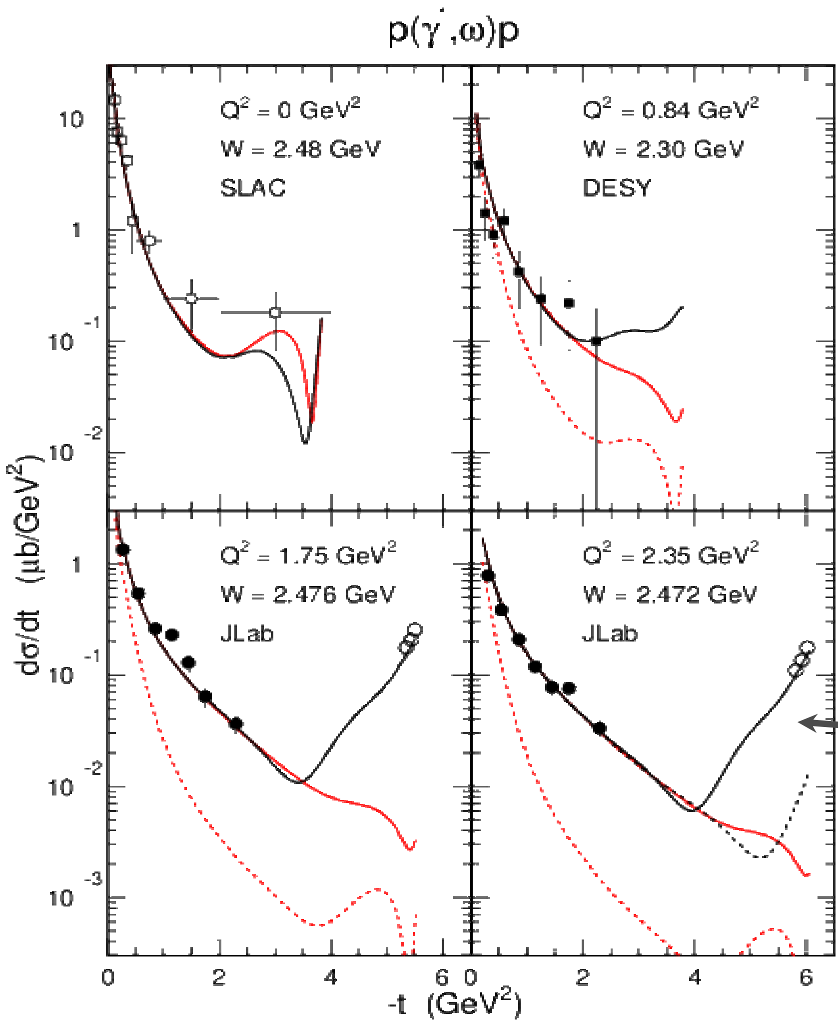
JML Regge Model description of *u*–Peak

Garth Huber, huberg@uregina.ca

- **Model provides natural description of JLab π electroproduction cross sections without destroying good agreement at Q^2=0.**

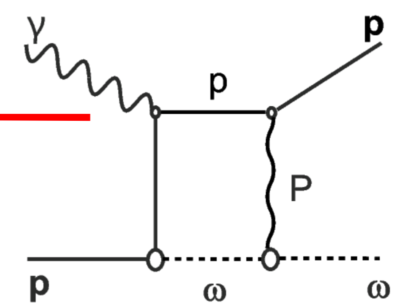
  [PLB **685**(2010)146; PLB **695**(2011)1999]

- Model also consistent with magnitude and slope of backward angle ω peak.
- Would be interesting to examine L/T ratio predicted by model when full calc available.

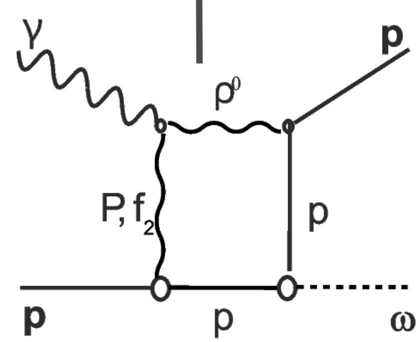


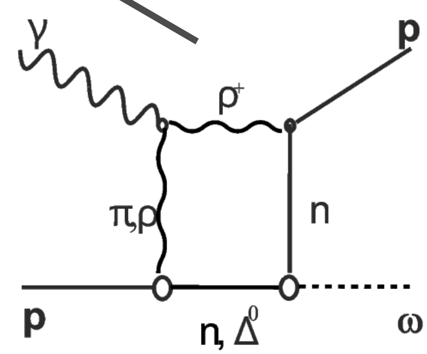
J–M Laget, Private Communication (2018) and W.B. Li, GMH, et al., PRL **123**(2019)182501

Red line: Non–degenerated Regge trajectory for *N*–exchange in *u*–channel w/ *t*–dependent cutoff mass



Black line: Include *ρN* and *ρΔ* rescattering inside nucleon (Regge cuts)

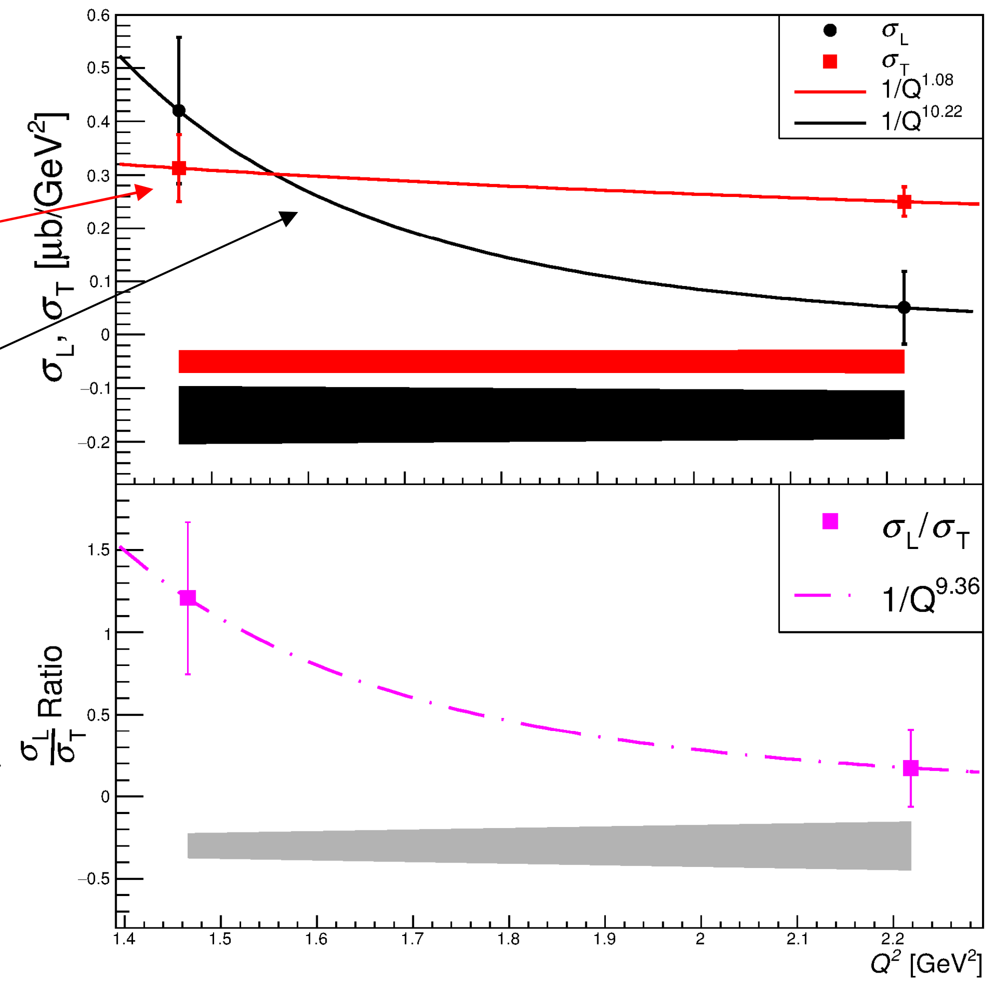




$p(e,e'p)\omega$ Q^2–Dependence

- To investigate Q^2–dependence, fit lowest $-u$ bin values of σ_T and σ_L to Q^{-n} function
  - σ_T appears to have a flat Q^2–dependence within measured range
  - σ_L shows much stronger decrease
- **Decreasing L/T ratio indicates the gradual dominance of σ_T as Q^2 increases.**
- Trend qualitatively consistent with prediction of TDA Collinear Factorization.

$-u = -u_{min}$



Q^2=1.47
W=2.26
$-u_{min}$=0.058

Q^2=2.23
W=2.28
$-u_{min}$=0.117

W.B. Li, GMH, et al., PRL **123** (2019) 182501

Garth Huber, huberg@uregina.ca

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TDA model Comparison to Data

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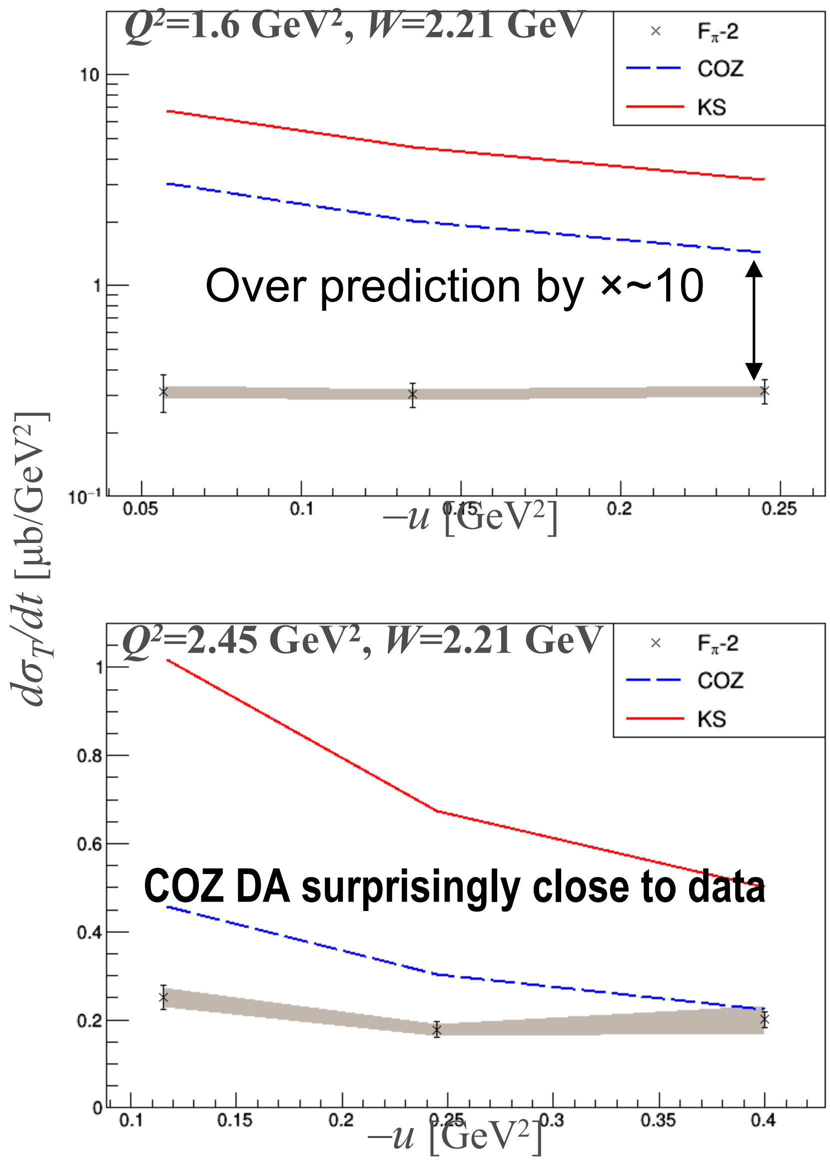
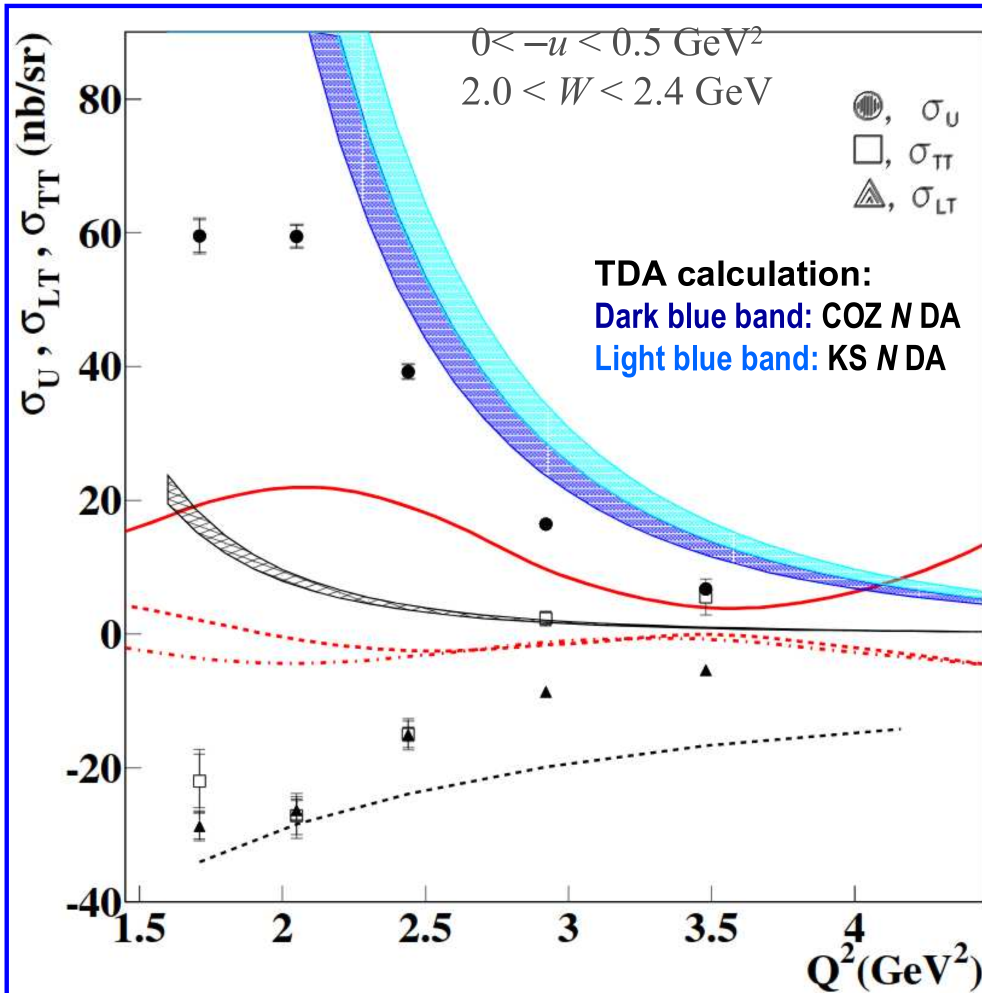
Garth Huber, huberg@uregina.ca



Hall C ω electroproduction

TDA calculation by B. Pire, K. Semenov, L. Szymanowski
W.B. Li, GMH, et al., PRL **123** (2019) 182501

Both data sets suggestive of early TDA scaling $Q^2 \approx 2.5$ GeV² !?



Hall B π^+ Electroproduction

K. Park et al., PLB **780** (2017) 340

Hall C *u*–channel Near–term Goals

1. Determine if backward angle peak observed in exclusive ω electroproduction occurs also in other channels, over a broad kinematic range.
2. Measure *u*–dependence of L/T–separated cross sections, to determine the relevance of Regge–rescattering and TDA mechanisms in JLab kinematics.
3. Assuming the backward angle peak is present, as expected, measure the σ_T/σ_L ratio over a wide Q^2 range for W>2 GeV.
   - Where does $\sigma_T \gg \sigma_L$, as predicted by TDA formalism?
4. Determine the Q^2–dependence of σ_T at fixed x_B.
   - Where does $\sigma_T \sim Q^{-8}$ as predicted by TDA formalism?

Garth Huber, huberg@uregina.ca

JLab Hall C – 12 GeV Upgrade

SHMS:
- 11 GeV/c Spectrometer
- Partner of existing 7 GeV/c **HMS**

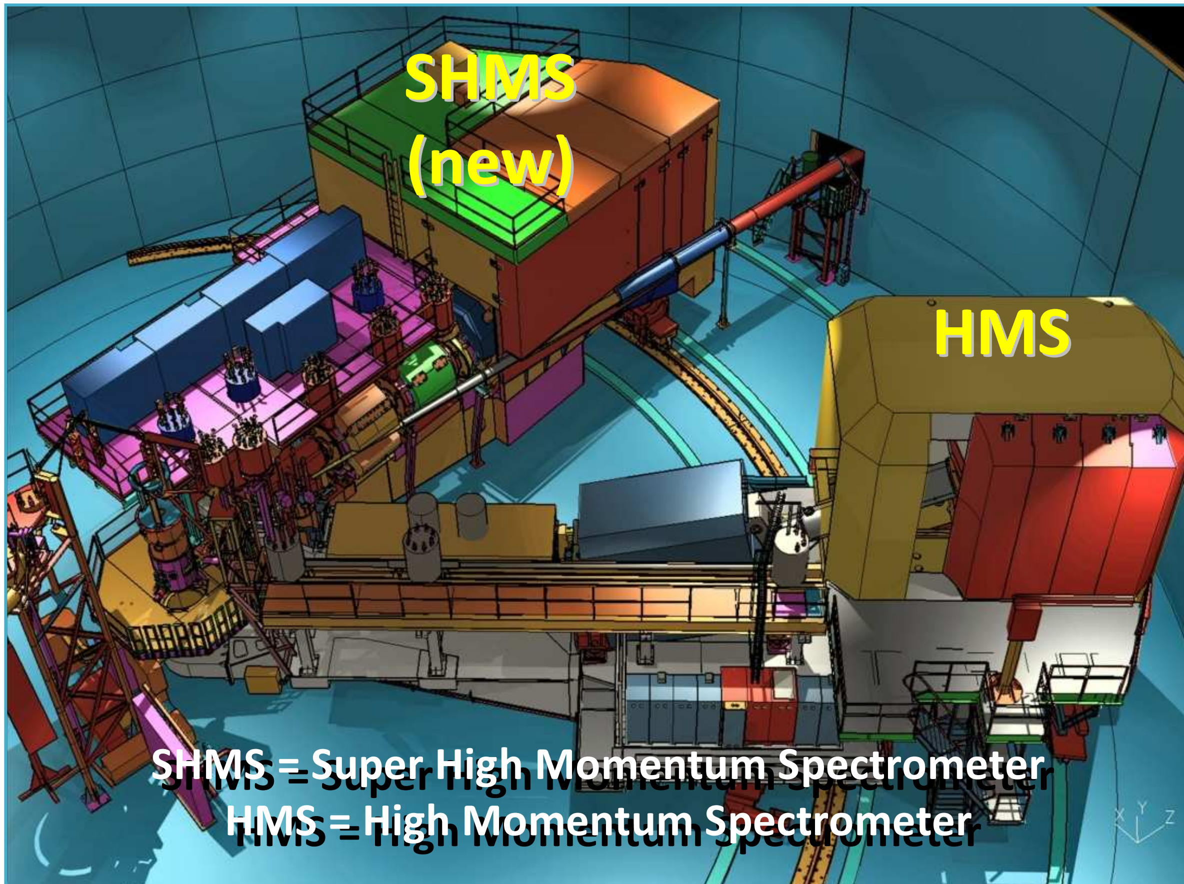
MAGNETIC OPTICS:
- Point-to Point QQQD for easy calibration and wide acceptance.
- Horizontal bend magnet allows acceptance at forward angles (5.5°)

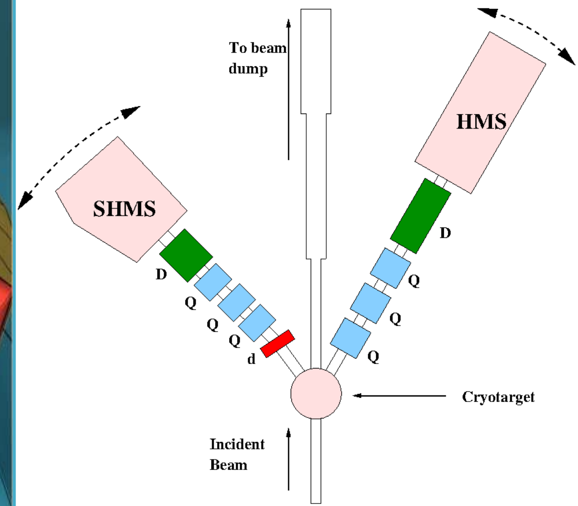
Detector Package:
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter

Well-Shielded Detector Enclosure

Rigid Support Structure
- Rapid & Remote Rotation
- Provides Pointing Accuracy & Reproducibility demonstrated in HMS

Luminosity
- ~4x10^{38} cm^{-2} s^{-1}



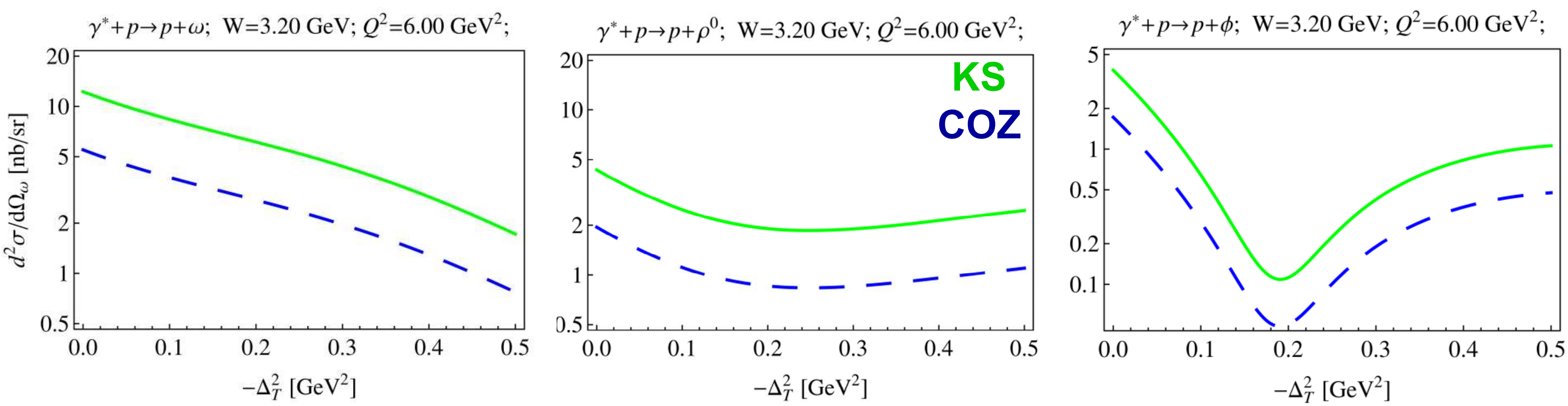


Upgraded Hall C has some similarity to SLAC End Station A, where the quark substructure of proton was discovered in 1968.

TDA Model Predictions for JLab E12–19–006

PionLT experiment (E12–19–006) L/T separations up to Q^2=8.5 GeV^2
Spokespersons: D. Gaskell, G.M. Huber, T. Horn

- **Data acquired 2021–22**
- **L/T–Separations over wide kinematic range will allow σ_T » σ_L and $1/Q^8$ scaling predictions to be checked with greater authority**
- u–channel φ–electroproduction particularly interesting
  - Sensitive to Strangeness content of nucleon
- Combined analysis of ρ, ω production allows one to disentangle isotopic structure of VN TDAs in non–strange sector



B. Pire et al., PRD **91** (2015) 094006

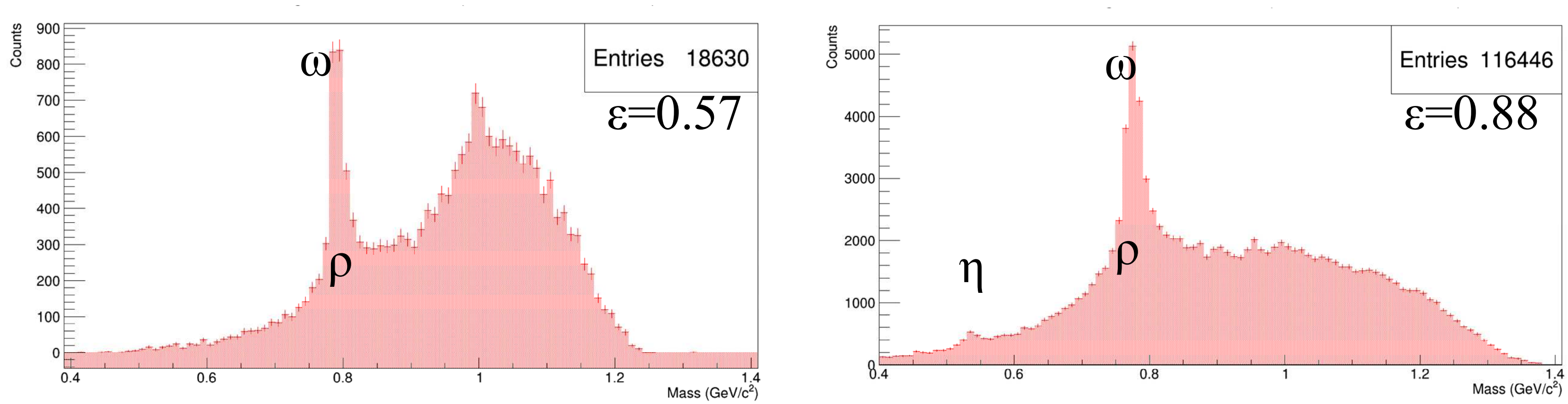
At Q^2=6.0 GeV^2, ω predicted to remain dominant (unlike *t*-channel), φ to drop rapidly with –*u*.

Garth Huber, huberg@uregina.ca

Example "12 GeV" data already acquired

p(e,e'p)X Online Data Analysis

Q^2=3.00 W=2.32 θ_{pq}=+3.0° $-u$=0.15 ξ_u=0.15



Plots by Stephen Kay

K^+ L/T–experiment (E12–09–011)

Spokespersons: T. Horn, G.M. Huber, P. Markowitz

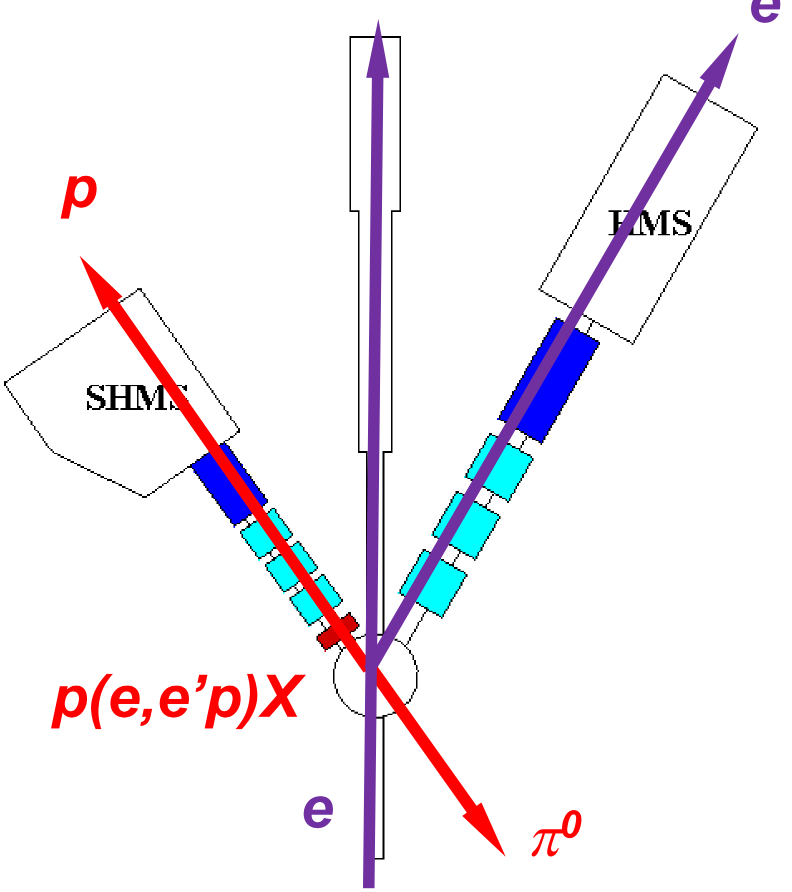
- Data acquired 2018–19
- Abundant *u*–channel *p(e,e'p)X* data acquired will allow backward angle studies over a wide kinematic range
- Planned first extraction of Beam Spin Asymmetry for *u*–channel reactions (PhD student: Alicia Postuma)

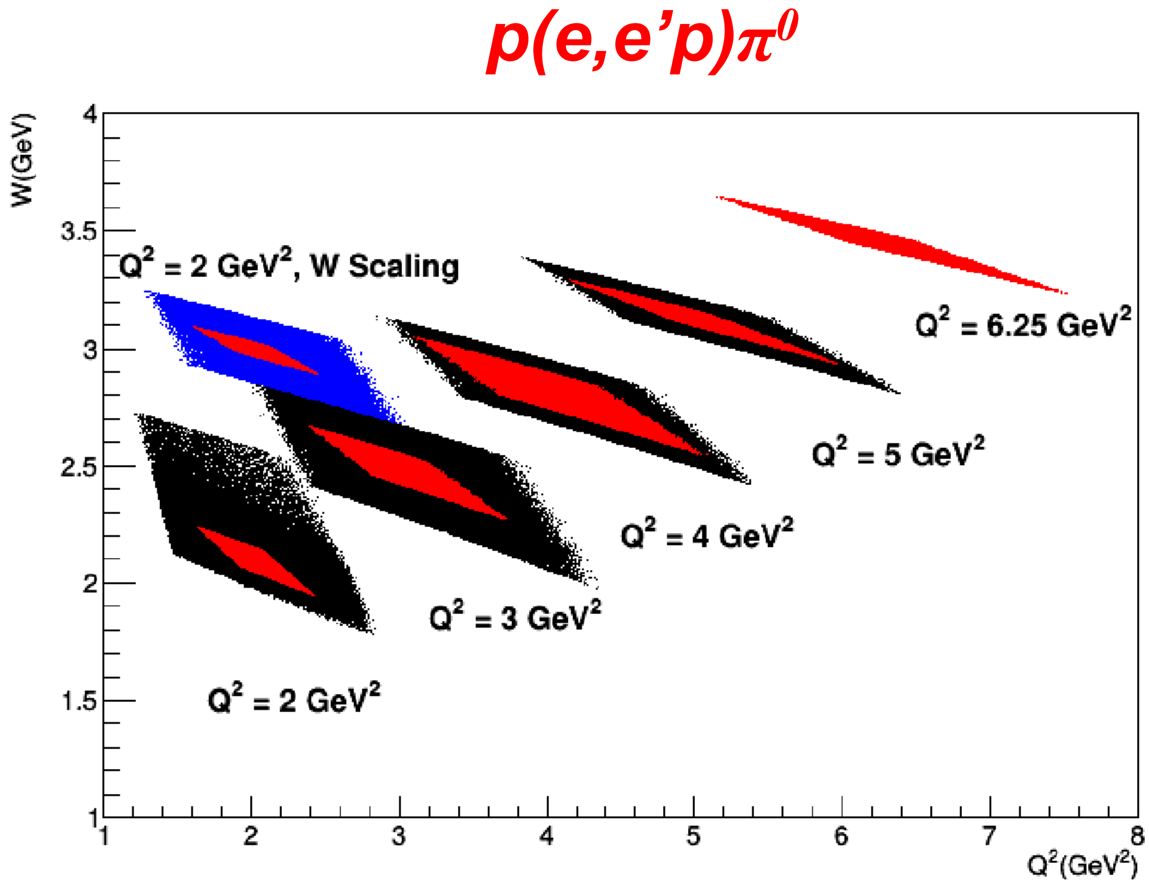
Setting	Low ε data	High ε data
Q^2=0.50 W=2.40	✔	✔
Q^2=2.1 W=2.95	✔	✔
Q^2=3.0 W=2.32	✔	✔
Q^2=3.0 W=3.14	✔	✔
Q^2=4.4 W=2.74	✔	✔
Q^2=5.5 W=3.02	✔	✔

Garth Huber, huberg@uregina.ca

Backward Exclusive π^0 Production

Garth Huber, huberg@uregina.ca





E12–20–007: $u\approx0$ π^0 production in Hall C

Spokespersons: W.B. Li, G.M. Huber, J. Stevens

Purpose: test applicability of TDA formalism for π^0 production

- Is σ_T dominant over σ_L?
- Does the σ_T cross section at constant x_B scale as $1/Q^8$?

- Kinematics overlap forward angle $p(e,e'\pi^0)p$ experiment with NPS+HMS
- Beam time possible for 2025–26

$p(e,e'p)\pi^0$ Kinematics

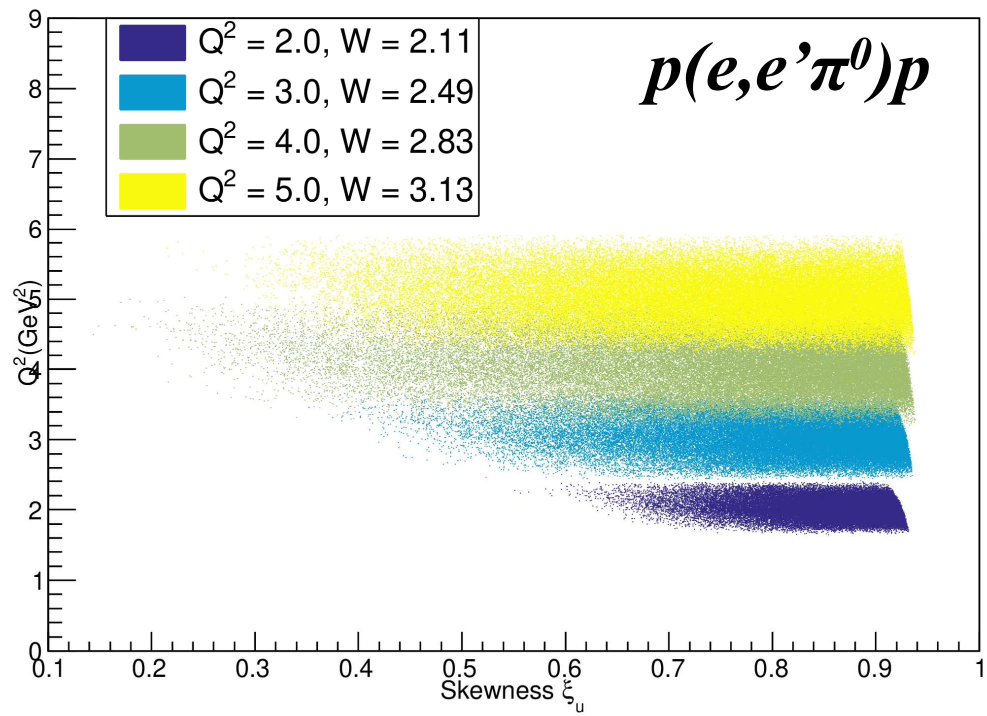
- **Backward angle kinematics match forward angle experiment using NPS currently running in Hall C**
  - **DVCS/π^0 E12-13-010** *(Spokespersons: T. Horn, C. Hyde, C. Munoz-Camacho, R. Paremuzyan, J. Roche)*
- **Combination of both experiments will allow forward/backward peak ratio to be measured for π^0 electroproduction for first time**

L/T–separations planned for fixed x_B=0.36 at:

Q^2	2.0	3.0	4.0	5.5*
W	2.11	2.49	2.83	3.26*

* Low ε only possible for θ_{pq}=+1.64°

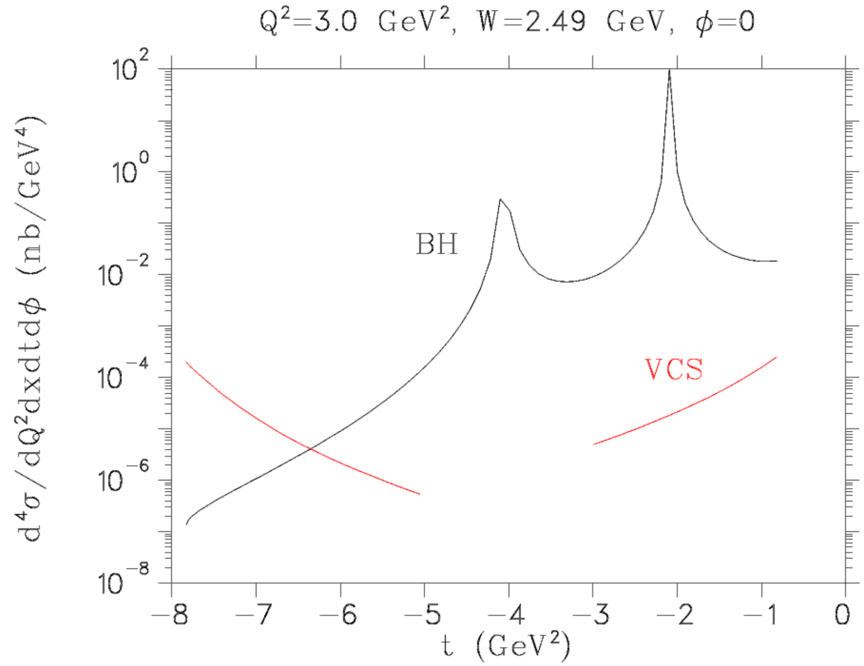
E12–20–007 covers a broad range in skewness, approaching $\xi_u \rightarrow 1$, which is ERBL dominated



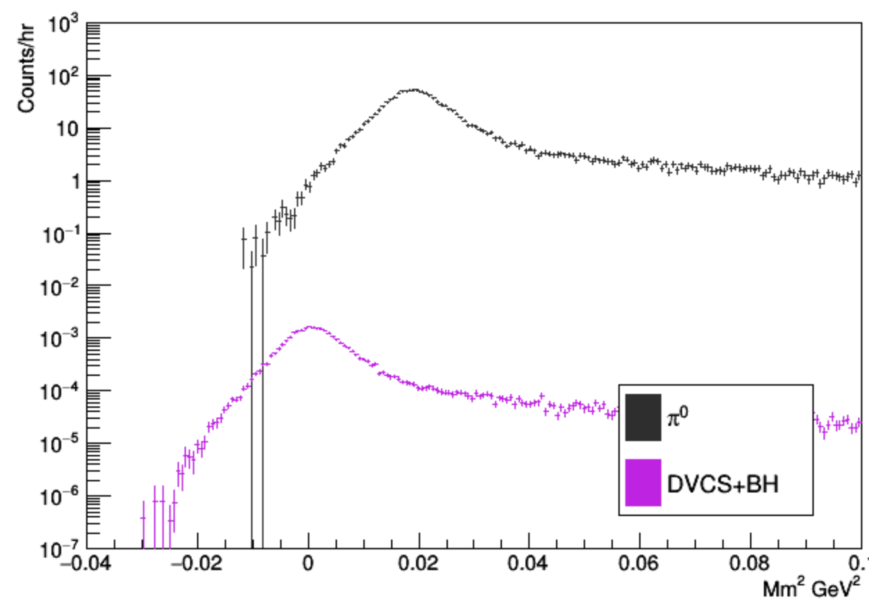
Garth Huber, huberg@uregina.ca

π^0 Channel Expected to be Clean

- In comparison to backward–angle ω electroproduction, there is little physics background in π^0 production.
- Bethe–Heitler process has no backward–angle peak, and will be negligible.
- Virtual Compton Scattering (VCS) should dominate backward–angle γ production, but is expected to be much smaller than π^0 production.



SHMS+HMS Q^2=3.0 Simulation



BH+VCS simulations based on code by P. Guichon and M. Vanderhaeghen.
- BH calculation is exact.
- VCS calculation makes use of ad–hoc ansatz based on *u*–channel ω data.

Garth Huber, huberg@uregina.ca

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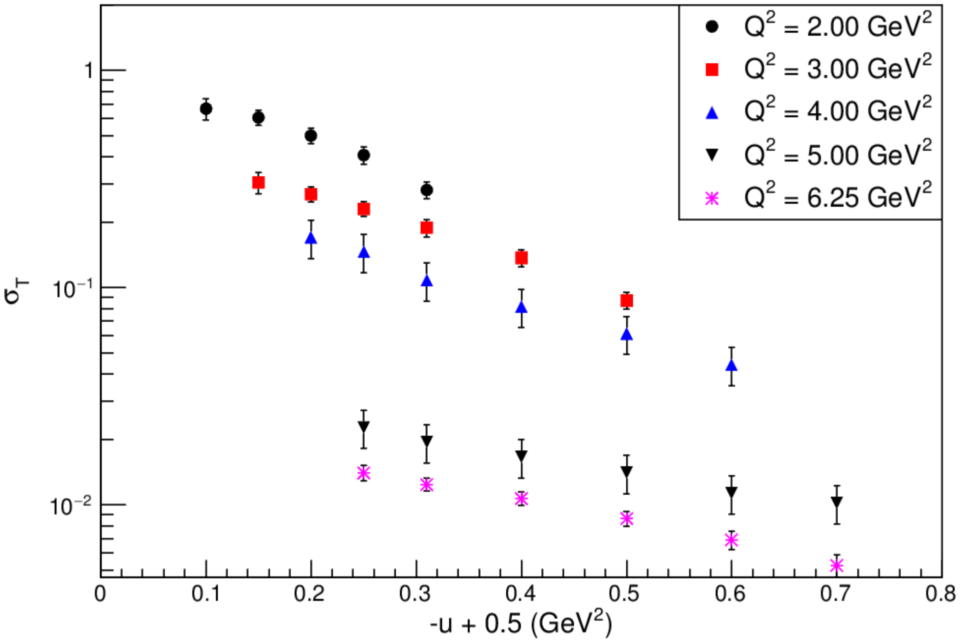
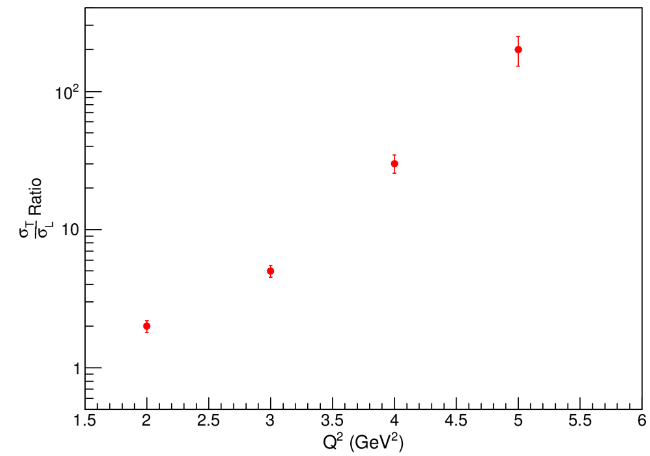
E12–20–007 Projected Data Quality

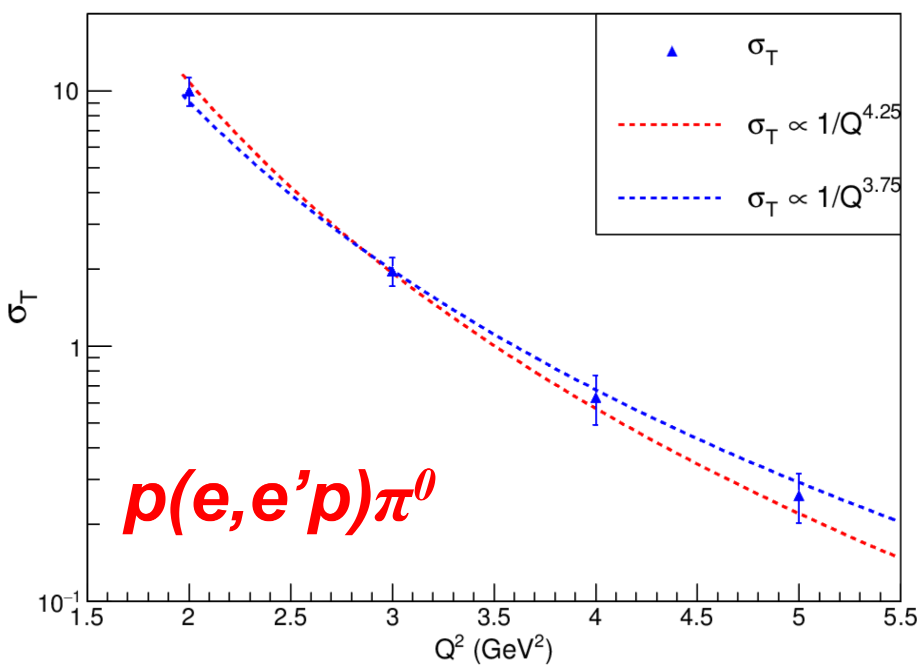


Projected SHMS+HMS *u*–coverage and uncertainties at each Q^2.

- L/T separations for comparison with Regge and TDA model calculations.
- σ_T units are arbitrary.



T/L ratio is expected to be large.



Projected uncertainty in Q^{-n}, which could be used to test TDA prediction: $\sigma_T \sim Q^{-8}$.

Garth Huber, huberg@uregina.ca

Summary

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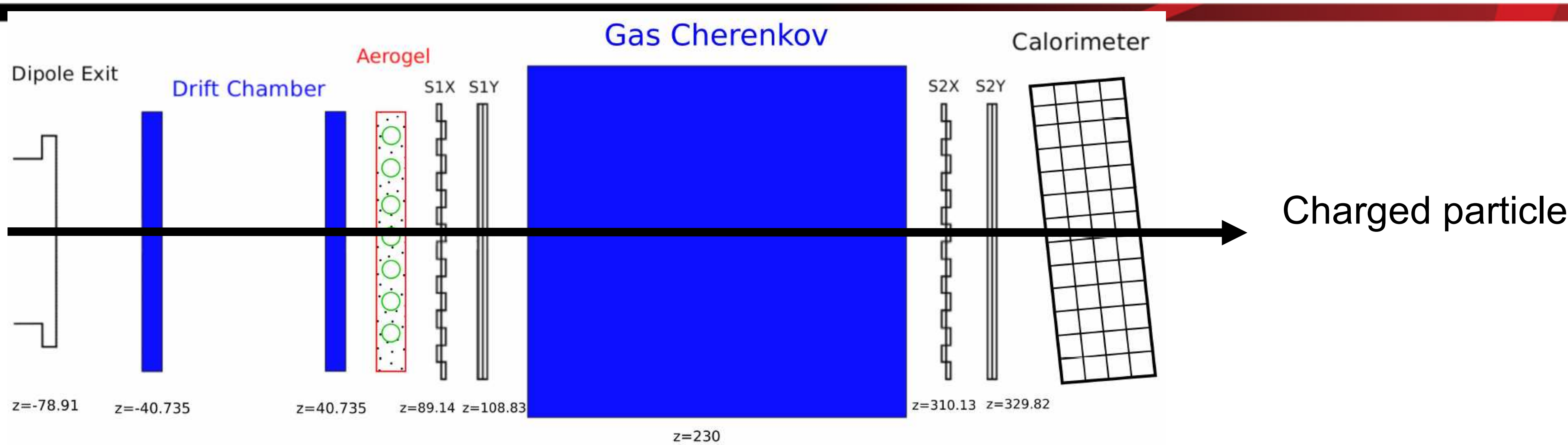
- **New experimental technique pioneered at JLab Hall C has opened up a unique kinematic regime for study:**
  - Extreme backward angle ($u \approx 0$) scattering
  - Detect forward–going proton in parallel kinematics, leaving "recoil" meson nearly–at–rest in target
- Possible access to **Transition Distribution Amplitudes**
  - Universal perturbative objects in *u*–channel, analogous to Generalized Parton Distributions (GPDs)
  - Access to 3–quark plus sea component $\psi_{(3q+q\bar{q})}$ of nucleon
- **J.–M. Laget Regge Model** provides natural explanation of magnitude and *u*–slope of observed backward angle peak
  - σ_L/σ_T separations will be essential to distinguish between alternate theoretical descriptions
- **Color Transparency (CT) also is a signal of factorization** and can be used to distinguish Regge and TDA explanations (see our LOI12-23-009)
  - Does Baryon Junction predict absence of *u*–channel CT? If so, the comparison would be interesting

Garth Huber, huberg@uregina.ca

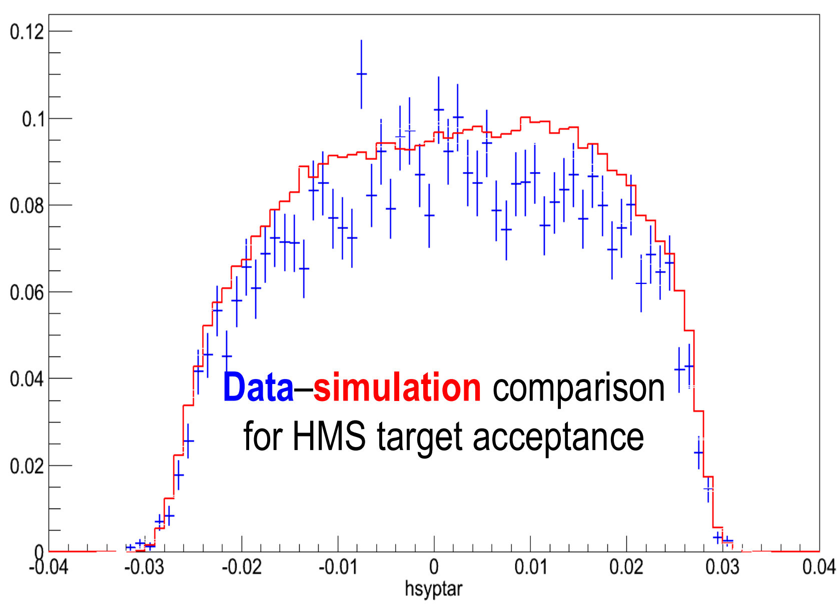
Garth Huber, huberg@uregina.ca

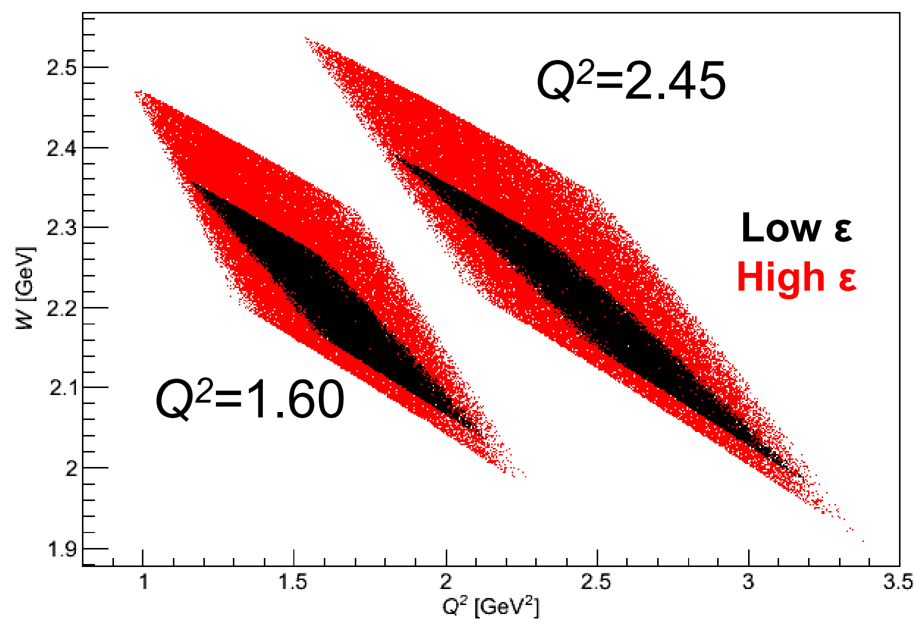
Experimental Setup and Acceptance



HMS focal plane detector layout, SOS is very similar

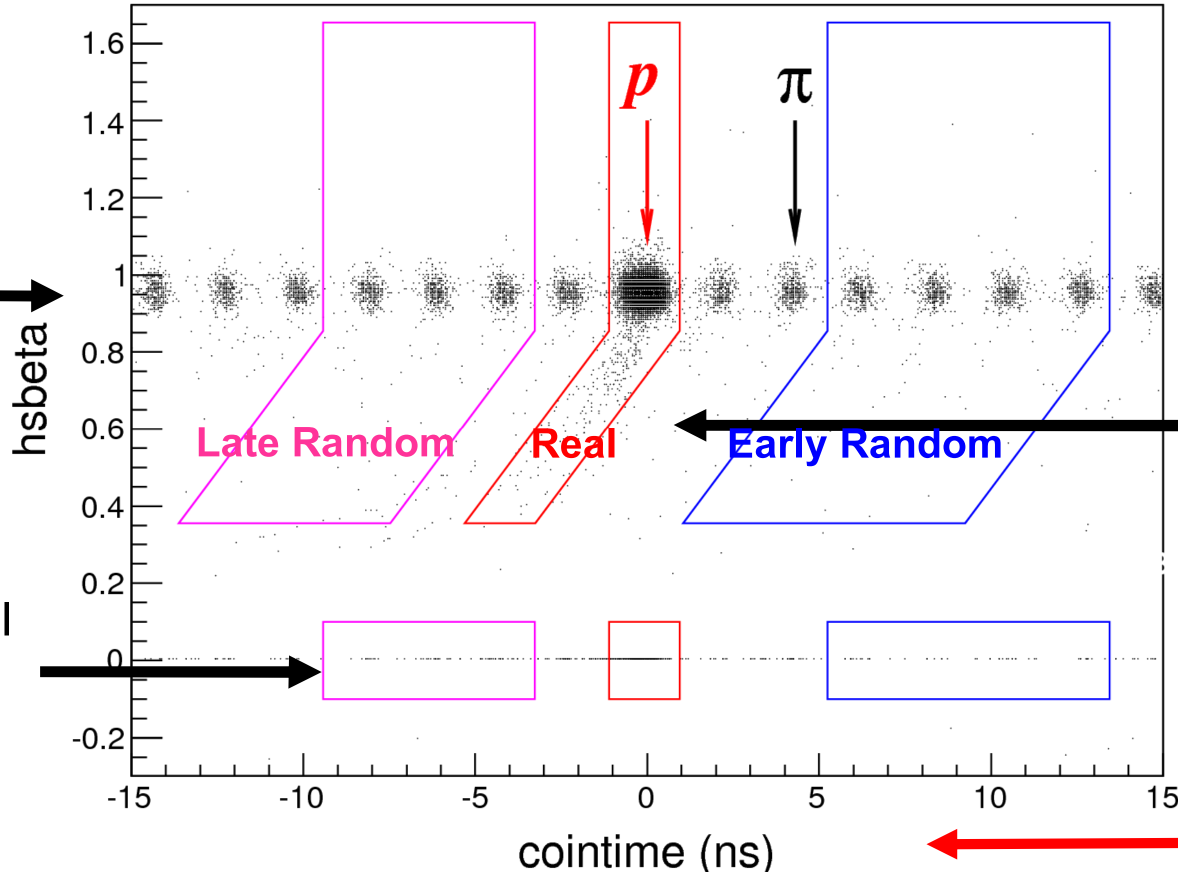
Trigger: ¾ planes of Hodoscopes





Coincidence Time Selection

Blob: Good events



Tail: Multiple scattering contribution

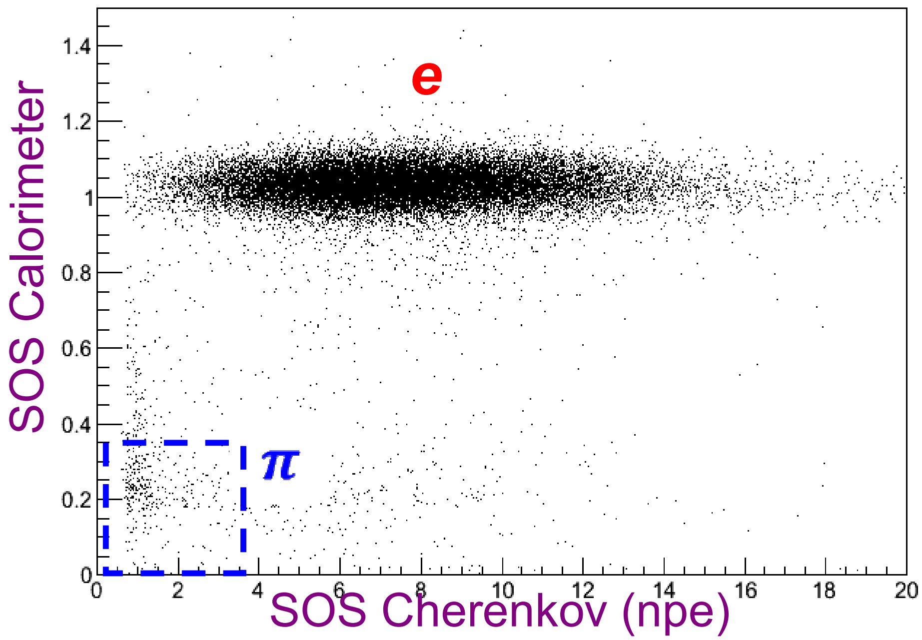
β=0: Events missing fiducial cut during reconstruction

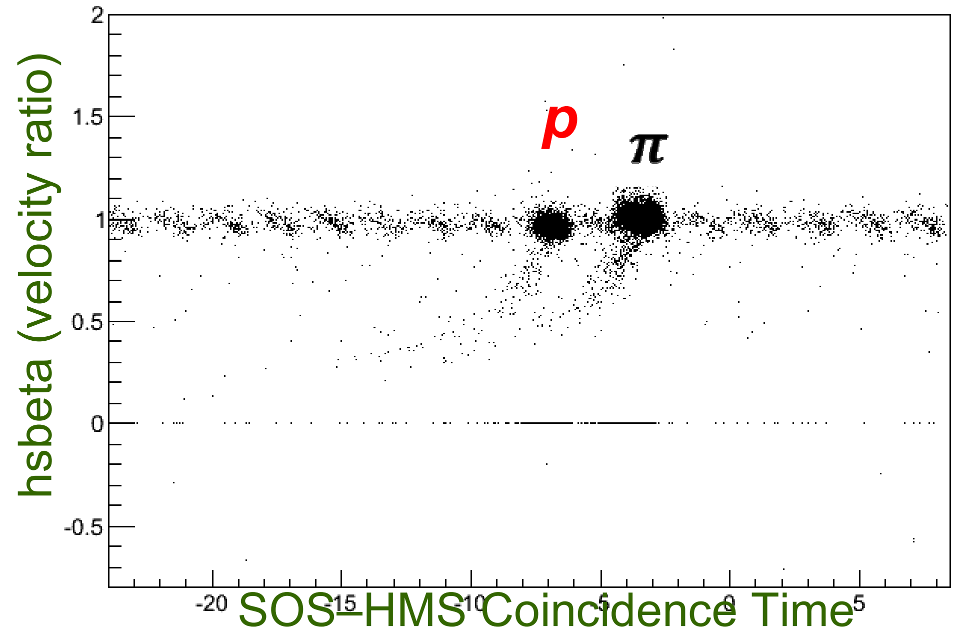
- **Random subtraction:**

$$\text{Coincidence proton} = \text{Real Events} - \left(\frac{\text{Late Random Events} + \text{Early Random Events}}{7}\right)$$

- **Missing proton due to scattering, absorption: ~7%**

Particle Identification

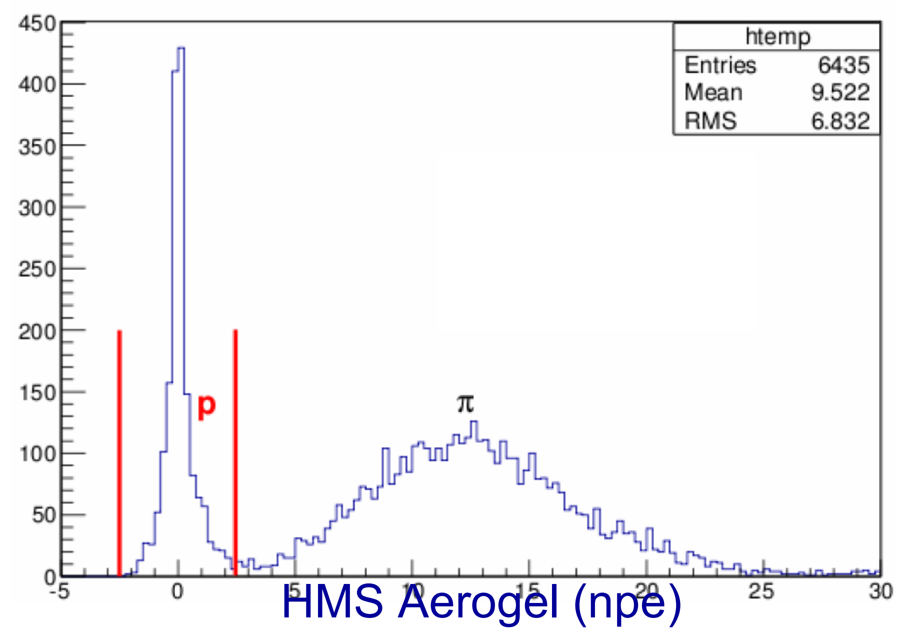




SOS: select electron
- Calorimeter cut
- Cherenkov cut

~99% efficiency

HMS: select proton
- Coincidence timing cut
- hsbeta (particle velocity)
- Aerogel Cut
- Cherenkov cut: veto e^+



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Systematic Uncertainties

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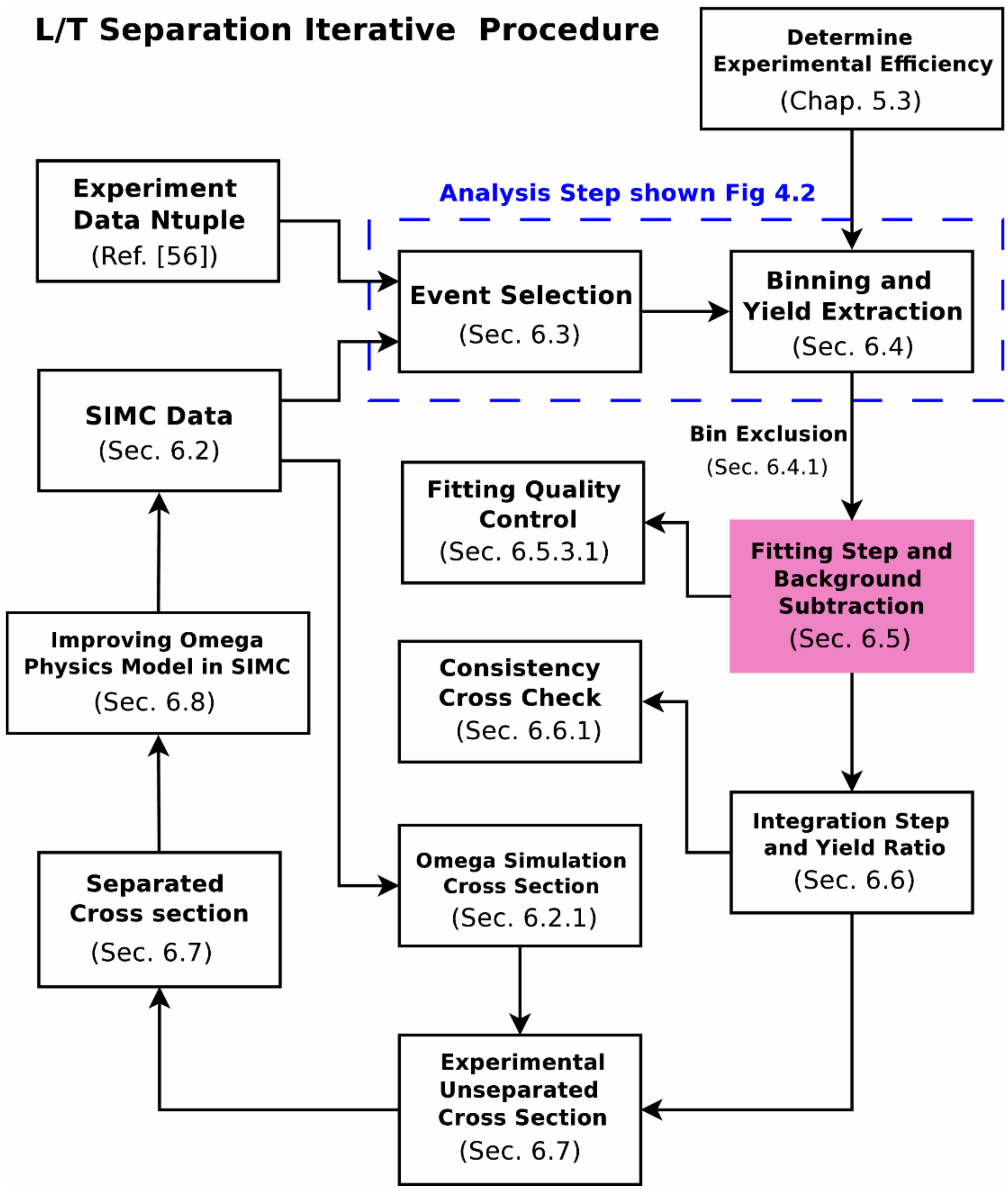
Correction	Uncorrelated (Pt-to-Pt) (%)	ϵ uncorr. u corr. (%)	Correlated (scale) (%)	Section
HMS Cherenkov			0.02	Sec. 3.6.3
HMS Aerogel			0.04	Sec. 5.3.7
SOS Calorimeter			0.17	Sec. 3.6.4
SOS Cherenkov			0.02	Sec. 3.6.3
HMS beta	0.4			Sec. 5.1.2
HMS Tracking		0.4	1.0	Sec. 5.3.3
SOS Tracking		0.2	0.5	Sec. 5.3.3
HMS Trigger		0.1		Sec. 3.7
SOS Trigger		0.1		Sec. 3.7
Target Thickness		0.3	1.0	Secs. 3.5.2, 5.3.5
CPU LT		0.2		Sec. 5.3.2.2
Electronic LT		0.1		Sec. 5.3.2.1
Coincidence Blocking			0.1	Sec. 5.3.6
$d\theta$	0.1	0.7-1.1		Ref. [3]
$dE_{\rm Beam}$	0.1	0.2-0.3		Ref. [3]
dp_e	0.1	0.1-0.3		Ref. [3]
$d\theta_p$	0.1	0.2-0.3		Ref. [3]
PID		0.2		Sec. 5.1.1
Beam Charge		0.3	0.5	Sec. 3.4
Radiative Correction		0.3	1.5	Sec. 4.1.4
Acceptance	1.0	0.6	1.0	Sec. 3.8
Proton Interaction			0.7	Sec. 5.3.9
Background Fitting Limit	2.0	0.8	0.8	Secs. 6.5.3, 6.10.2
ω Integration Limit	1.7	1.0	0.3	Secs. 6.6, 6.10.2
Model Dependence	0.7			Secs. 6.2.1, 6.10.2
Total	2.9	1.7-2.0	2.6	

- **Unseparated σ**
  - **Statistical**
  - **Systematic Error**
    - **Uncorrelated Error**
    - **ϵ uncorrelated u correlated**
    - **Scale error**
- **Model dependent Error to the separated (Scale error)**
  - **Parameterization**
  - **ϕ limits**
  - **u limits (small contribution)**

Garth Huber, huberg@uregina.ca

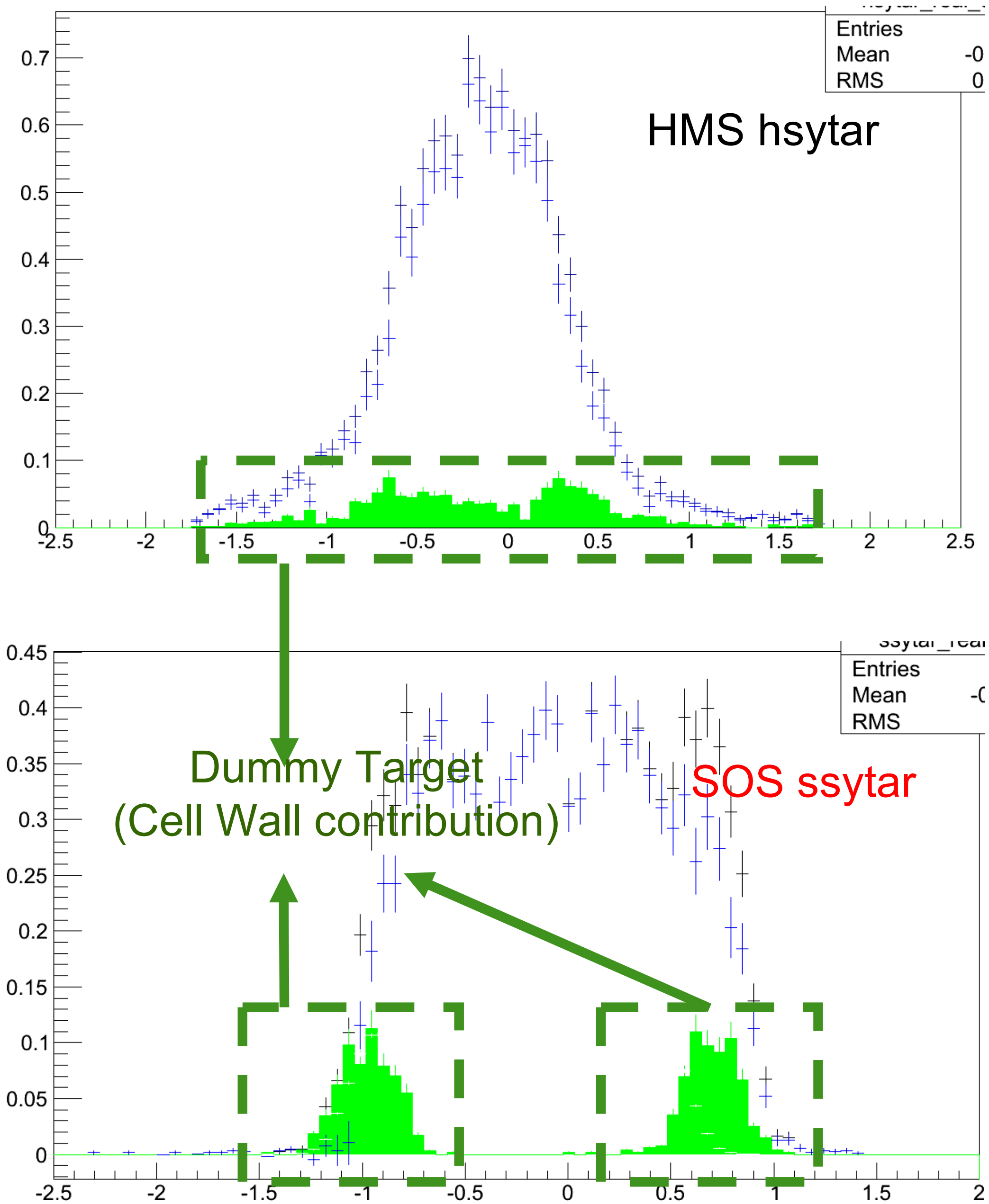
Analysis Details in arXiv:1712.02314

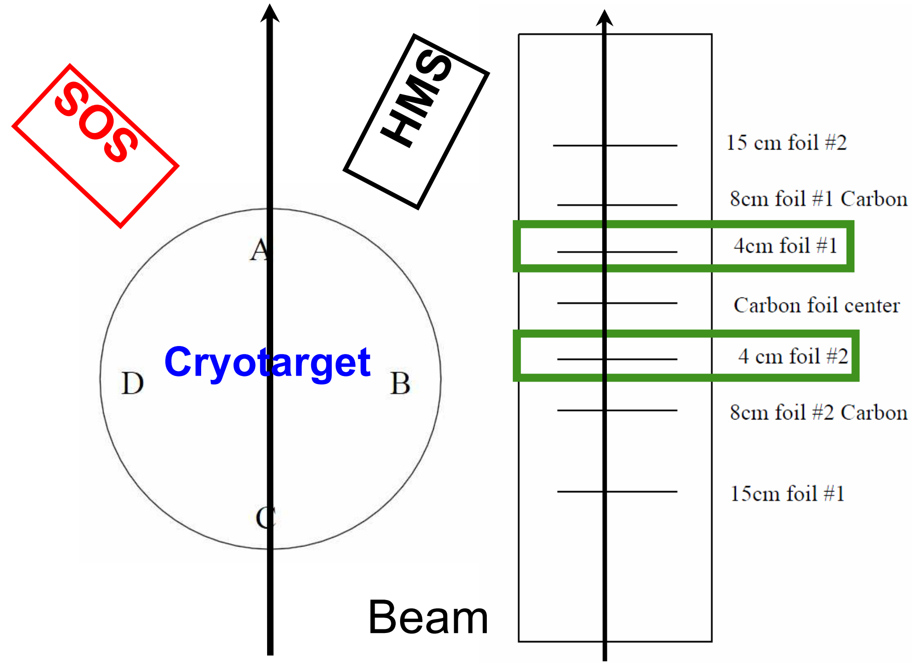


Garth Huber, huberg@uregina.ca

Target Cell Subtraction

Garth Huber, huberg@uregina.ca

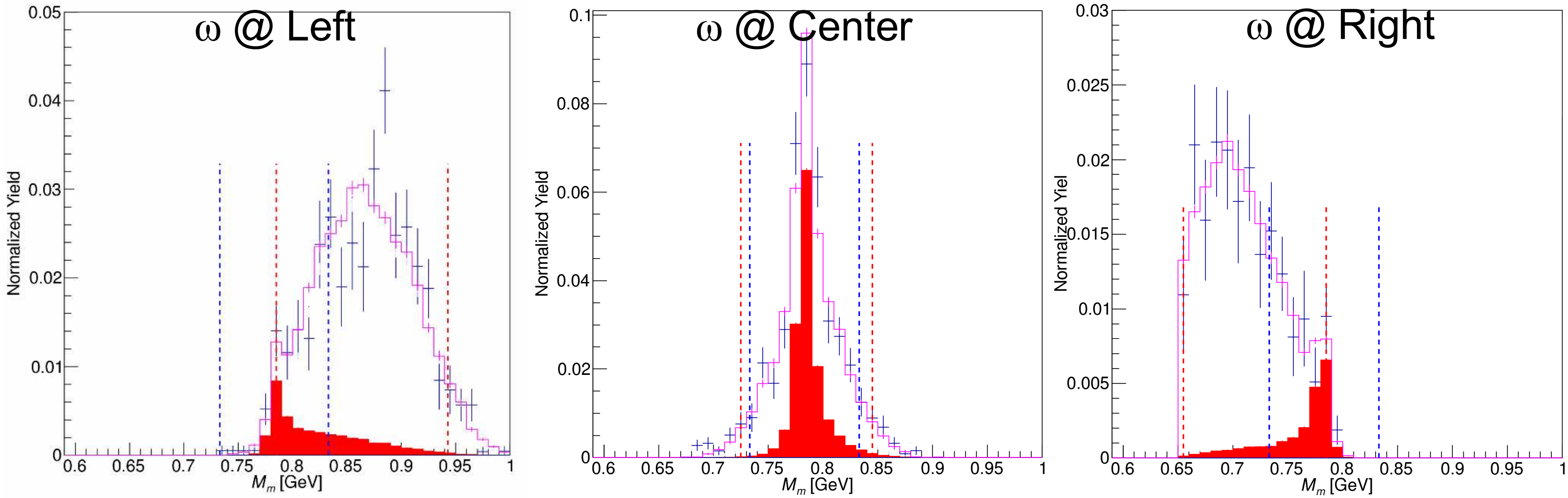




Cryotarget
- Tuna can shaped
- Thin Al cell wall

Dummy Target
- Al sheets 4cm apart
- Dummy target distribution corrected for the real/dummy thickness difference before subtraction from proton events

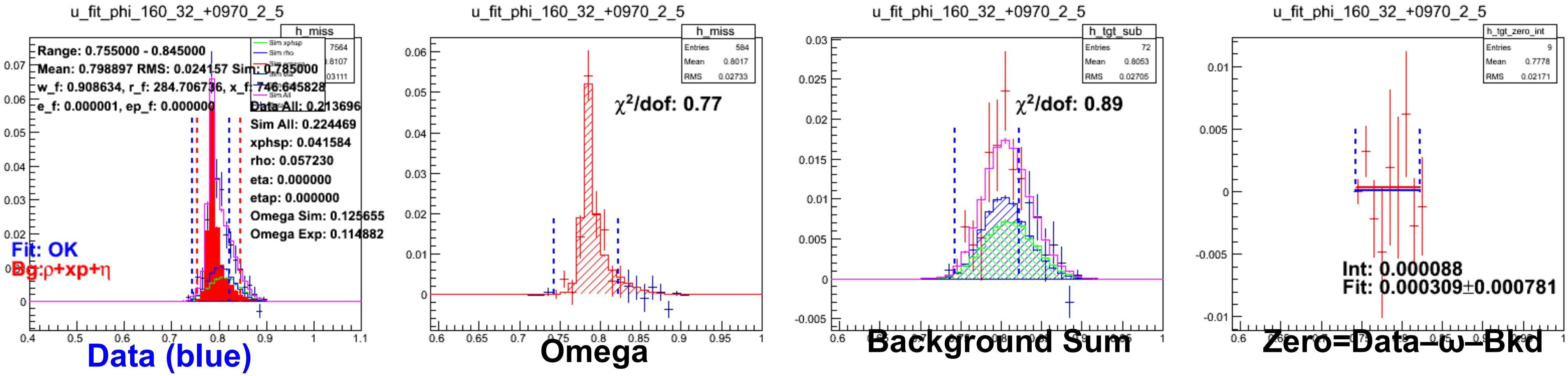
Missing Mass Distribution



- **Most Challenging Issue: Background Subtraction!**
- **Omega is not always in the center**
- **Four sets of Monte-Carlo is used fit the data**
  - ***ω + ρ* + Phase-space + *η or η'***

Garth Huber, huberg@uregina.ca

Missing Mass Background Removal



Data (blue)
Xspace Sim (green)
ρ Sim (cyan)
ω Sim (red)
η or η' (black)
Sim Sum (pink)

$$R = \frac{Y_{Exp} - Y_{\rho\ \mathrm{sim}} - Y_{Xspace\ \mathrm{sim}} - Y_{\eta\ \mathrm{sim}}}{Y_{\omega\ \mathrm{sim}}}$$

- Fitting Limits (red dashed line):
  - Not fixed, fit 95% data distribution
- Integration Limits (blue dashed line):
  - Fixed for all u-phi bins!
- Bin Exclusion criteria:
  - Radiative tail exceeds 50% total ω sim
  - Less that 100 raw counts

Garth Huber, huberg@uregina.ca

Bin Exclusion Criteria

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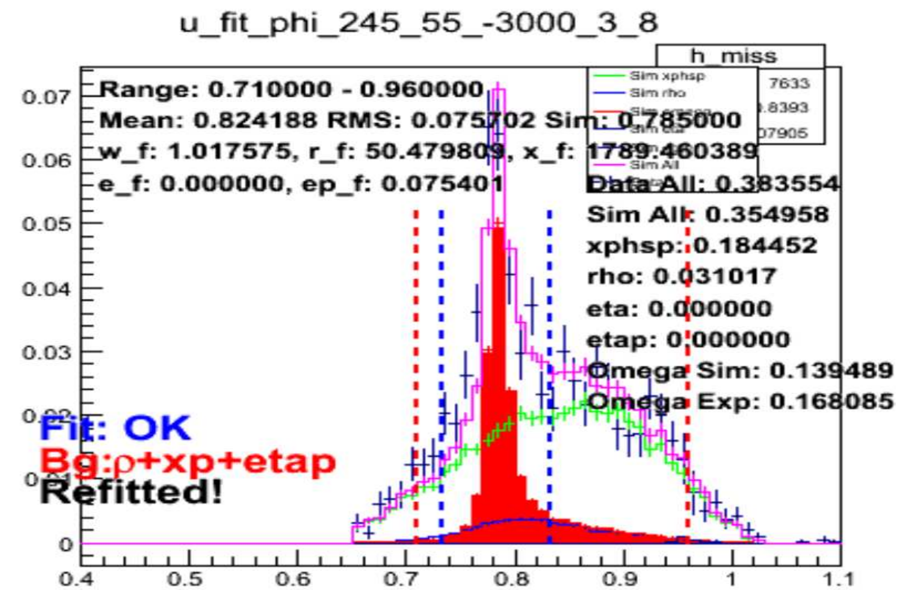
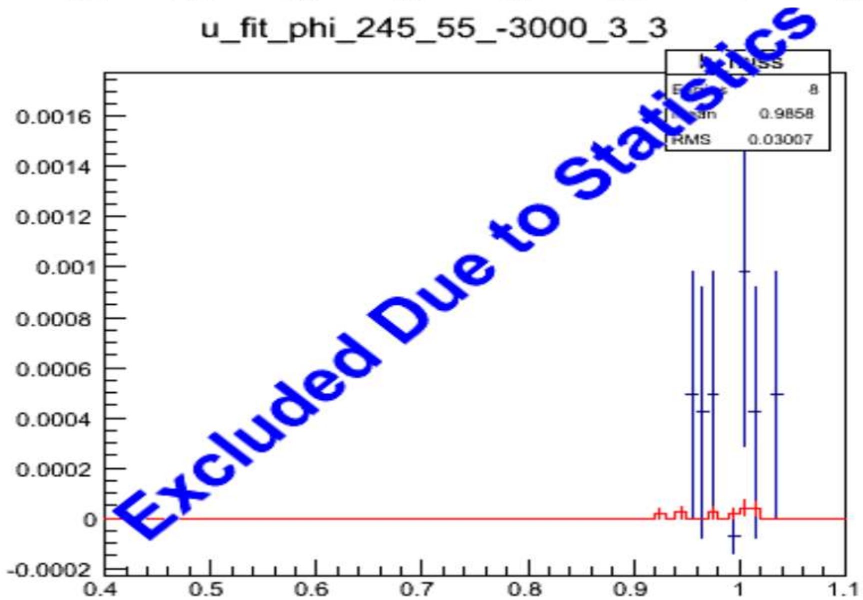
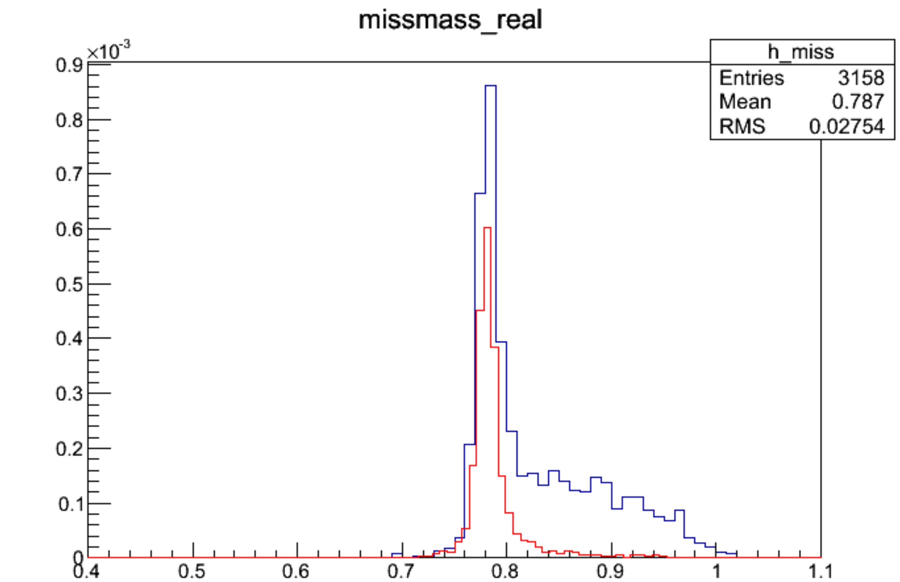
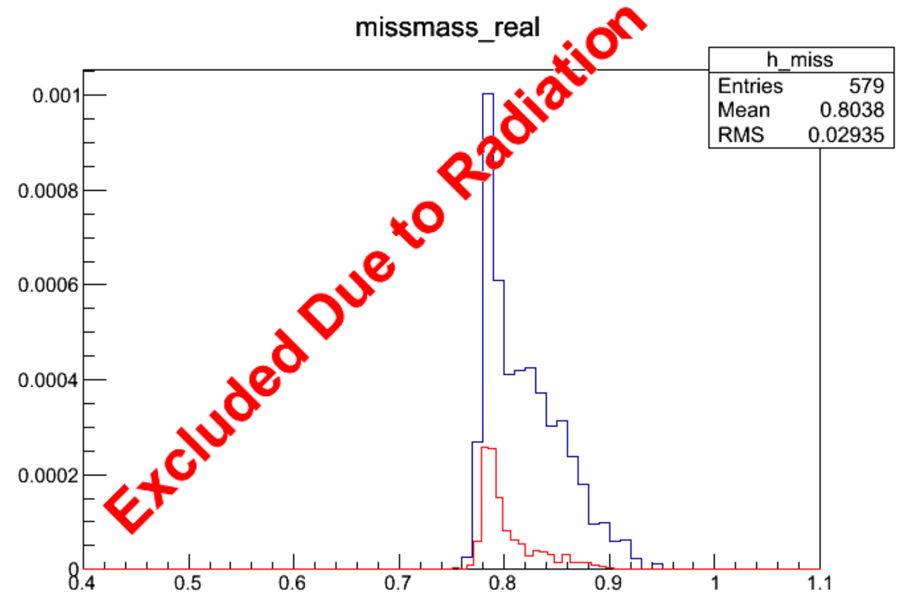
- Low Statistics





- Radiative Tail





Garth Huber, huberg@uregina.ca

Missing Mass Distribution Exclusion

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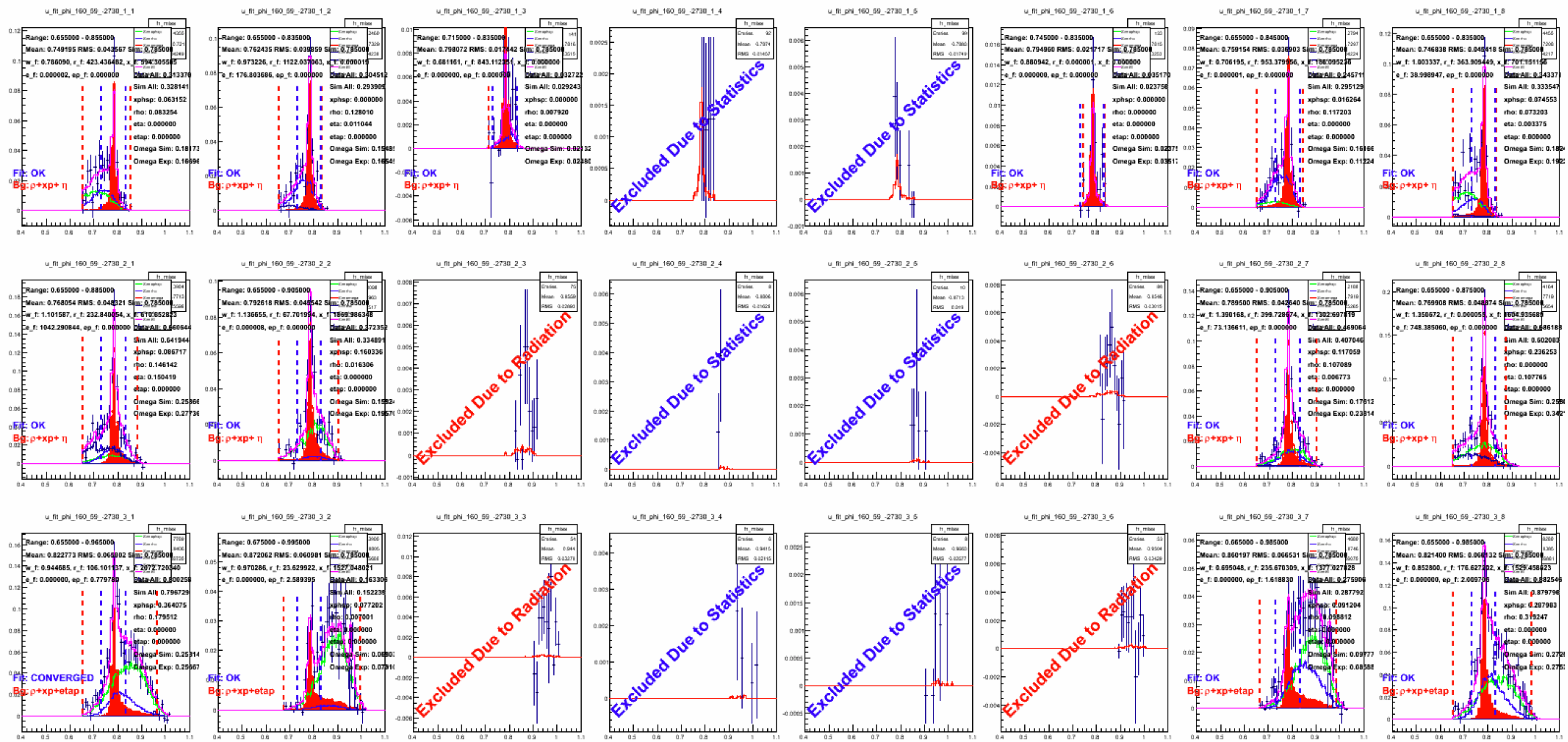
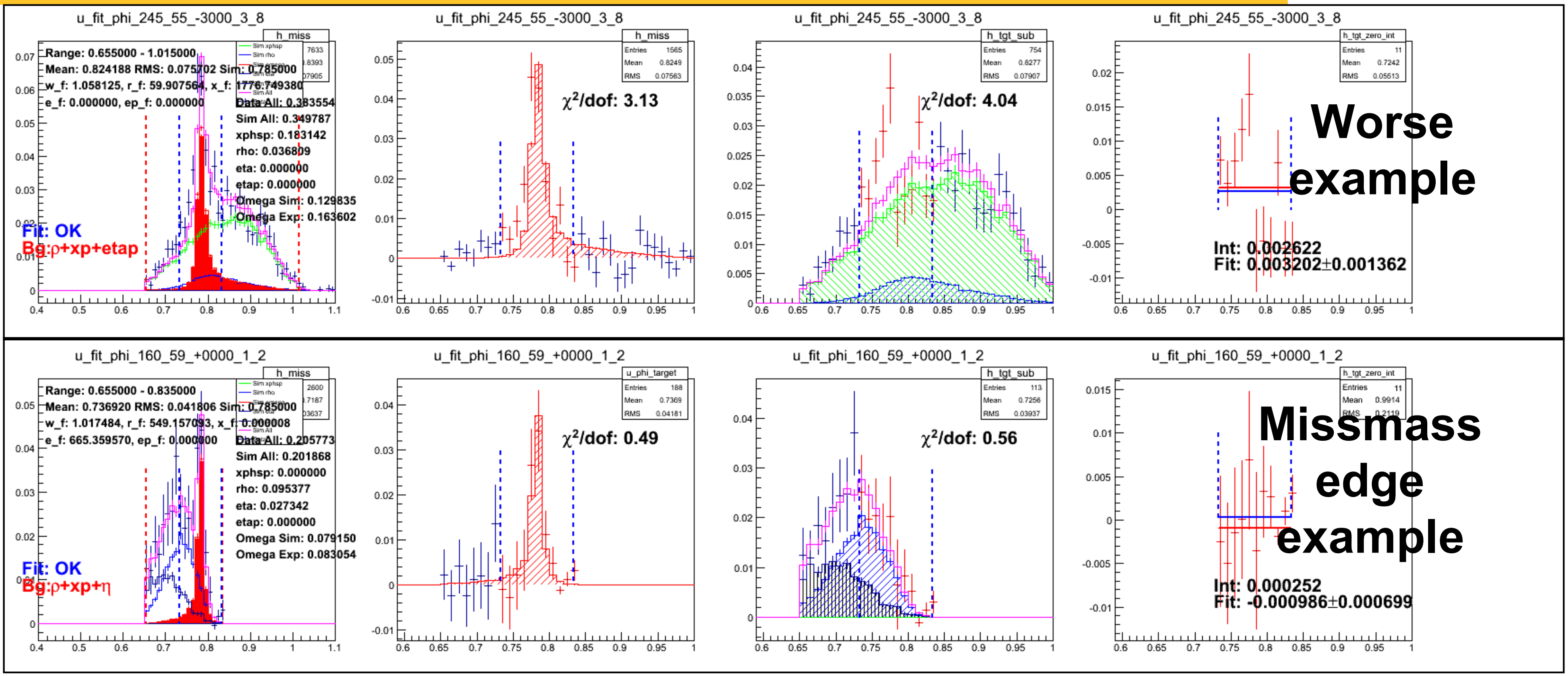
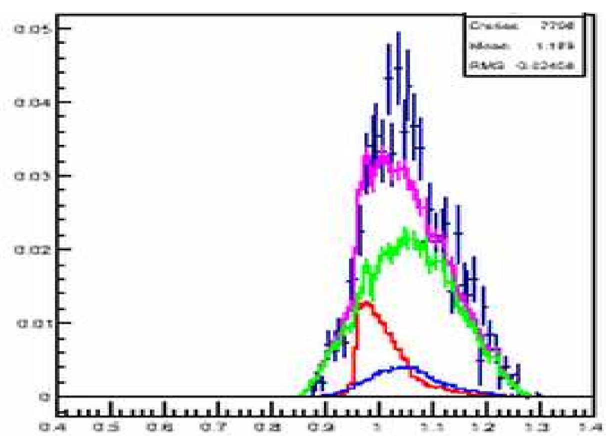


- Integration limits and fitting limits
- Exclusion criteria
  - Exclude the radiative only omega bins
  - Exclude the low statistics bins

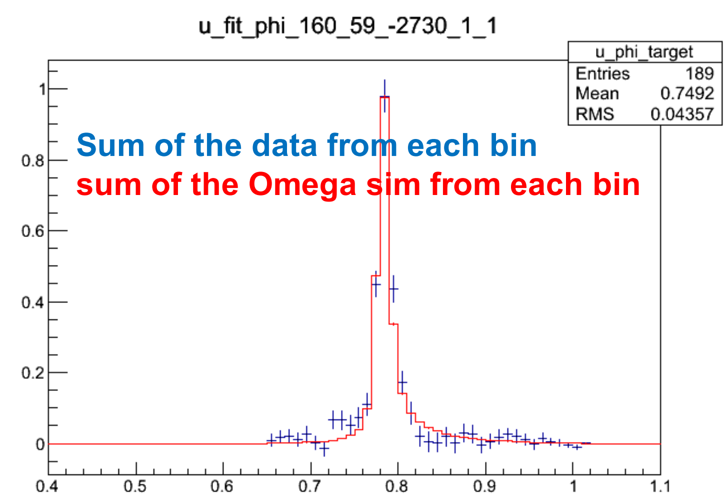
Background Extraction and Check





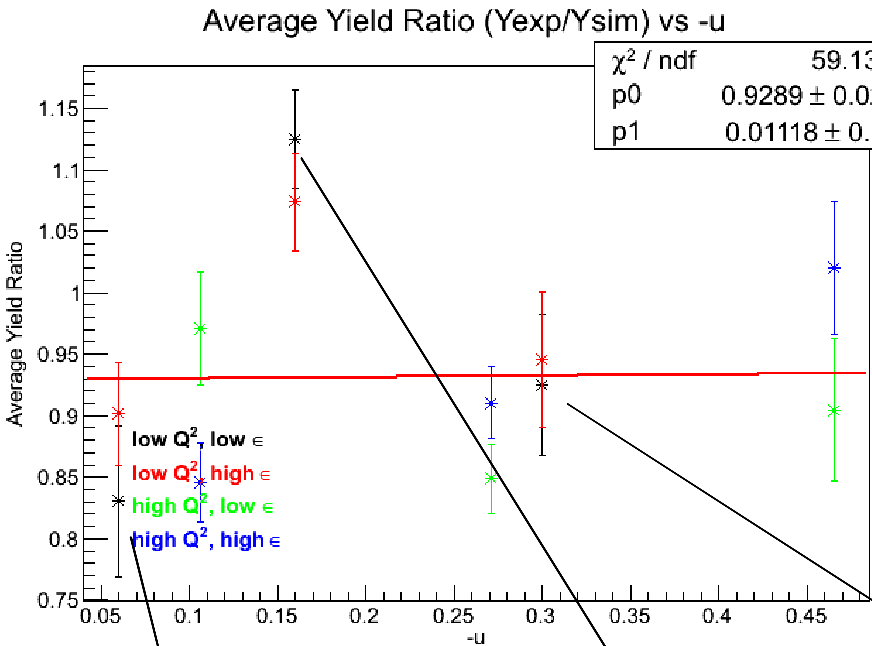
Reconstructed Missing Energy

Worse Example



Garth Huber, huberg@uregina.ca

Yield Ratio and Model Cross–Section

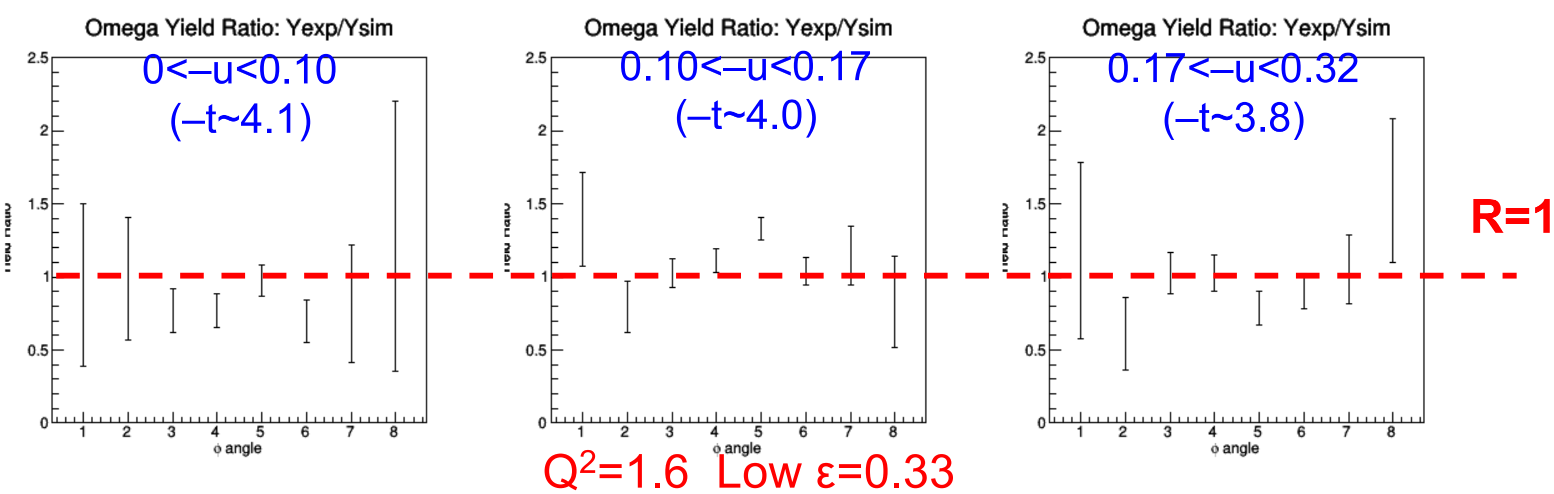


$$\sigma_T = \frac{t_0 + t_1 \cdot (-u)}{Q},$$
$$\sigma_L = \frac{l_0 + l_1 \cdot (-u)}{Q^4},$$
$$\sigma_{LT} = \left[\frac{lt_0 + lt_1 \cdot (-u)}{Q^2}\right] \cdot \sin\theta^*,$$
$$\sigma_{TT} = \left[\frac{tt_0 + tt_1 \cdot (-u)}{Q^2}\right] \cdot \sin^2\theta^*,$$

$$2\pi \frac{d\sigma}{dt d\phi} = \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} + \sqrt{2\varepsilon(\varepsilon+1)} \frac{d\sigma_{LT}}{dt} \cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$

Model Cross Section

$$\frac{d^2\sigma}{dt d\varphi}_{EXP} = R \frac{d^2\sigma}{dt d\varphi}_{SIMC}$$



Exp/Sim Yield Ratio

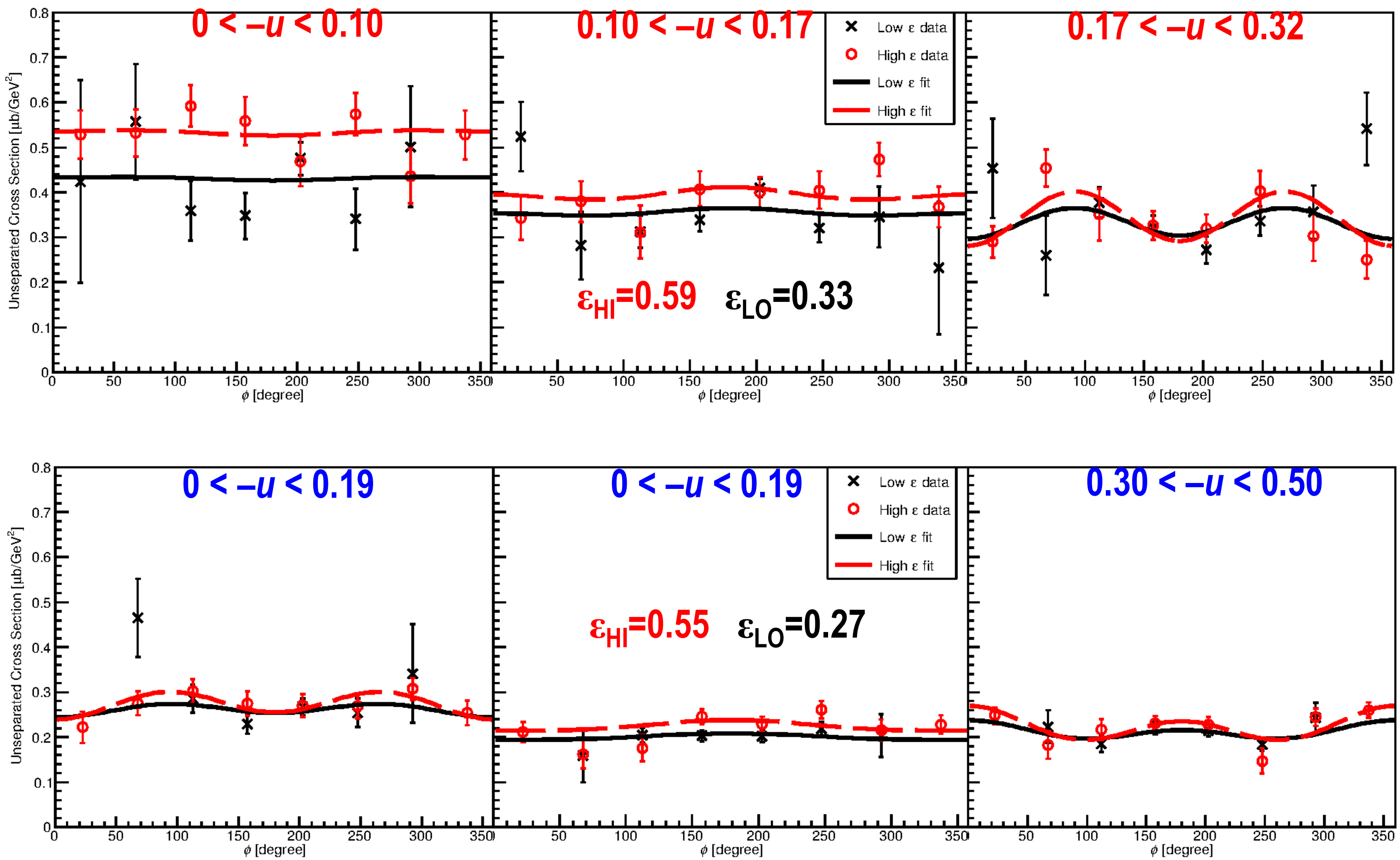
Garth Huber, huberg@uregina.ca

Unseparated Cross Sections

$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Q^2=1.60 GeV^2

Q^2=2.45 GeV^2



Garth Huber, huberg@uregina.ca

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Iterative Procedure for L/T Separation

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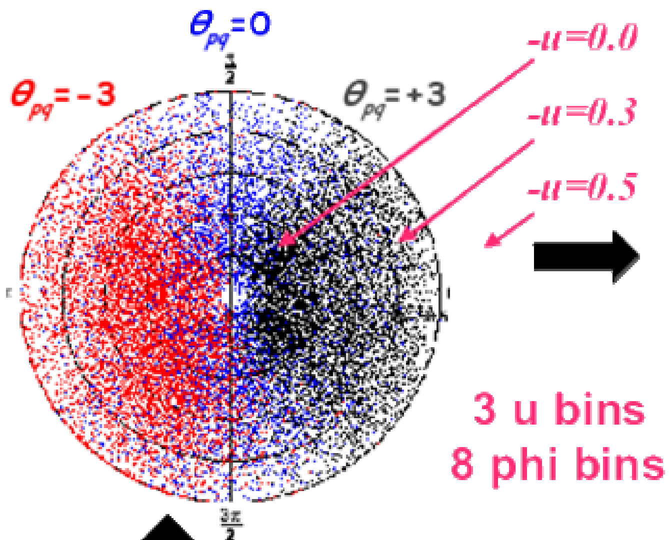
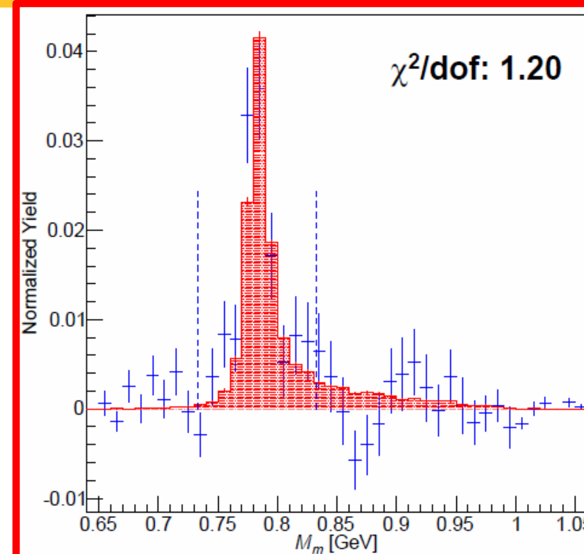
Improve φ coverage by taking data at multiple HMS angles, $-3^{\circ}<\theta_{pq}<+3^{\circ}$.



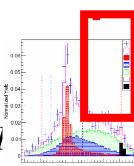
Separated X-section

Unseparated X–section



$$R=\frac{Y_{Exp}-Y_{\rho\ sim}-Y_{Xspace\ sim}}{Y_{\omega\ sim}}$$

$$\frac{d^2\sigma}{dt\,d\varphi}_{EXP}$$



$$\frac{d^2\sigma}{dt\,d\varphi}_{SIMC}$$

Empirical Model

Extract L,T,LT,TT via simultaneous fit

$$2\pi\frac{d^2\sigma}{dt\,d\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Jefferson Lab Fπ Collaboration

W.B. Li, et al., Phys. Rev. Lett. 123 (2019) 182501., arXiv: 1910.00464

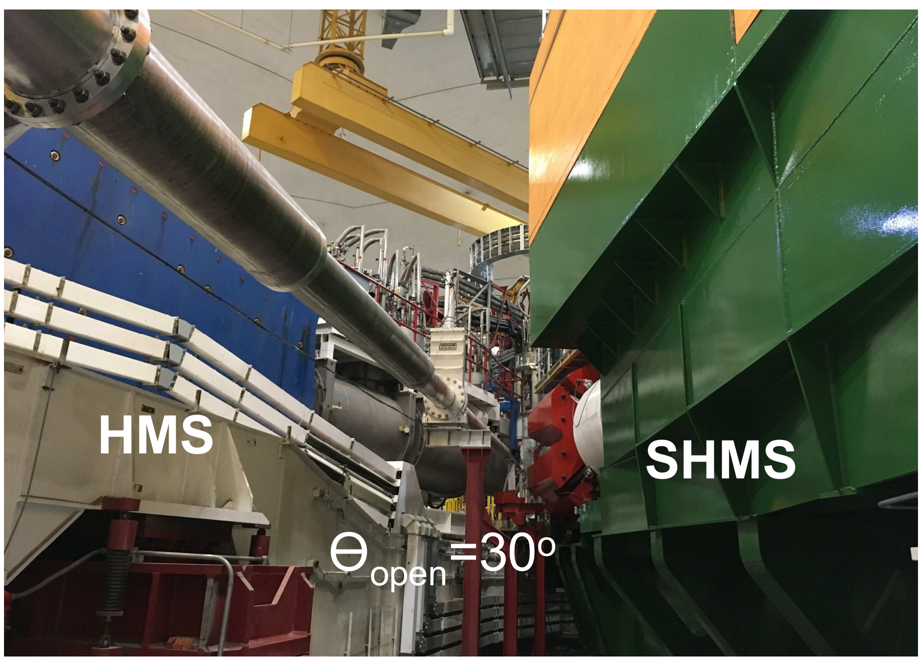
R. Ent, D. Gaskell, M.K. Jones, D.J. Mack, D. Meekins, L. Pentchev, J. Roche, G. Smith, W. Vulcan, G. Warren, S.A. Wood
Jefferson Lab, Newport News, VA , USA
G.M. Huber, W.B. Li, V. Kovaltchouk, G.J. Lolos, C. Xu
University of Regina, Regina, SK, Canada
H.P. Blok, V. Tvaskis
Vrije Universiteit, Amsterdam, Netherlands
T. Horn
Catholic University of America, Washington, DC, USA
E. Beise, H. Breuer, C.C. Chang, P. King, J. Liu
University of Maryland, College Park, MD, USA
W. Boeglin, P. Markowitz, J. Reinhold
Florida International University, FL, USA
J. Arrington, R. Holt, D. Potterveld, P. Reimer, X. Zheng
Argonne National Laboratory, Argonne, IL, USA
H. Mkrtchyan, V. Tadevosyan
Yerevan Physics Institute, Yerevan, Armenia
S. Jin, W. Kim
Kyungook National University, Taegu, Korea
M.E. Christy, C. Keppel, L.G. Tang
Hampton University, Hampton, VA, USA
J. Volmer
DESY, Hamburg, Germany
A. Matsumura, T. Miyoshi, Y. Okayasu
Tohuku University, Sendai, Japan
K. Aniol, D. Margaziotis
California State University, Los Angeles, CA, USA
E.J. Brash, E. Gibson, I. Niculescu, C. Perdrisat, V. Punjabi, A. Sarty

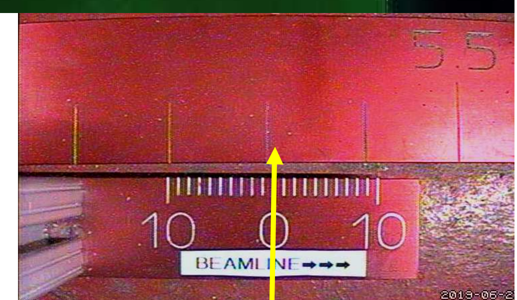
And special co-authors (for the calculations):
B. Pire, K. Semenov, L. Szymanowski
J.–M. Laget

SHMS Small Angle Operation

- L/T–separation program requires access to hadron spectrometer angles ~5.5^{o} with respect to beamline
- Made possible with the new SHMS

- Other kinematic settings challenge the minimum opening angle between the two spectrometers

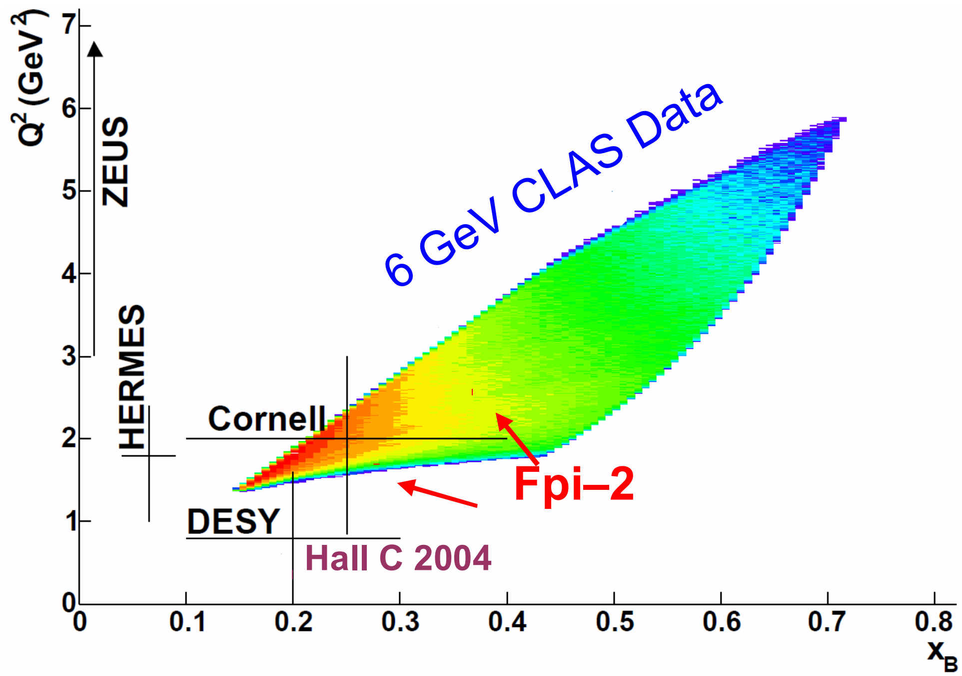




SHMS at 5.69^{o}

Garth Huber, huberg@uregina.ca

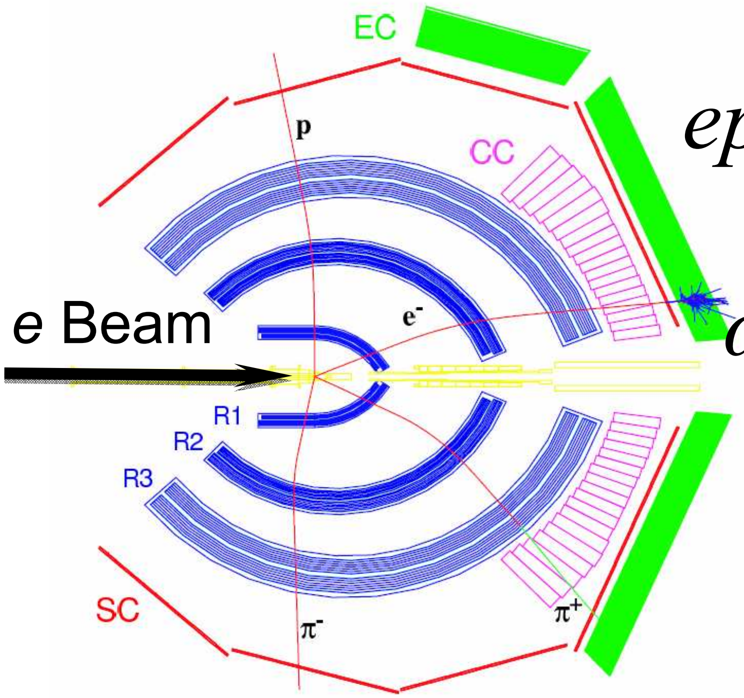
Exclusive ω Electro–Production Data



Closest data set to ours is:
L. Morand et al., [Hall B]
EPJA **24** (2005) 445

	Q^2 GeV²	W GeV	x	$-t$ GeV²
HERMES (Airapetian et al., 2014)	> 1	3–6.3	0.06–0.14	< 0.2
DESY (Joos et al., 1977)	0.3–1.4	1.7–2.8	0.1–0.3	< 0.5
Zeus (Breitweg et al., 2000)	3–20	40–120	~0.01	< 0.6
Cornell (Cassel et al., 1981)	0.7–3	2.2–3.7	0.1–0.4	<1
JLab Hall C (Ambrozewicz et al., 2004)	~0.5	~1.75	0.2	0.7–1.2
JLab Hall B (Morand et al., 2005)	1.6–5.1	1.8–2.8	0.16–0.64	<2.7
JLab Fpi-2 (W.B. Li et al., 2019)	1.6, 2.45	2.21	0.29, 0.38	4.0, 4.74

Garth Huber, huberg@uregina.ca



$$ep \rightarrow ep\omega$$

$$\omega \rightarrow \pi^+\pi^-\pi^0$$

High –t data from CLAS Hall B (

$\omega(782\text{MeV})$

$2.2 \leq Q^2 \leq 2.5\text{GeV}^2$
$0.34 \leq x \leq 0.40$

$3.1 \leq Q^2 \leq 3.6\text{GeV}^2$
$0.52 \leq x \leq 0.58$

Missing mass reconstruction *e⁻pX*

- Hall B Experiment **e1–6**
  - Oct 2001 – Jan 2002
  - Beam energy: 5.754 GeV
- Kinematic coverage:
  - *W* : 1.8–2.8 GeV
  - Q^2: 1.6–5.1 GeV^2
  - **$-t$: < 2.7 GeV^2**
  - *x*: 0.16–0.64
- Event selection:

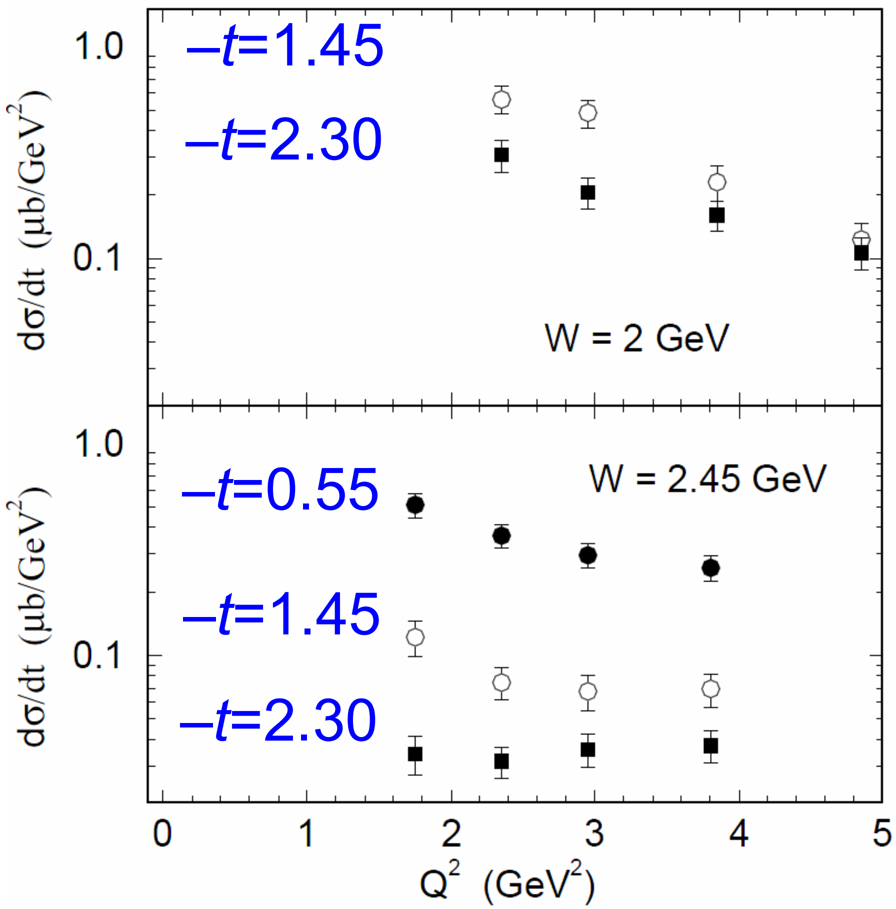
$$ep \rightarrow ep\pi^+X$$

- Reconstructed *e⁻pX* missing mass consistent with the *ω* mass
- Data published in:
  - Morand et al., Eur. Phys. J. A **24** (2005) 445.

Garth Huber, huberg@uregina.ca

University of Regina

High –*t* data from CLAS Hall B (2005)



L. Morand et al., Eur. Phys. J. A 24, 445 (2005).

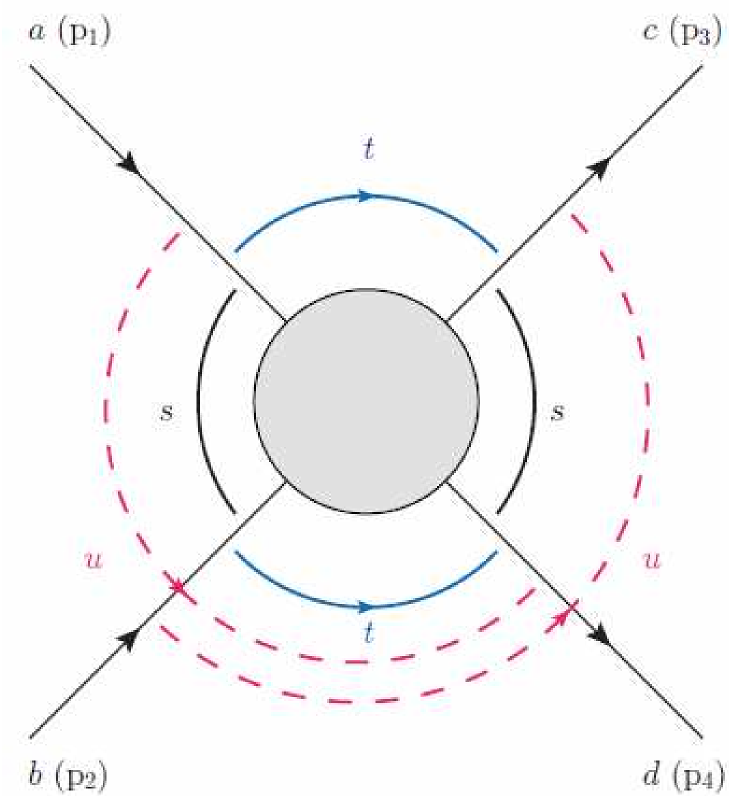
- **Excitement:**
  - **Observation: Q^2 independent cross section at high –*t***
  - **Possible interpretation: Virtual photon is more likely to couple to a point–like objects as –*t* increases.**

- Are really looking at point charge like structures within the nucleon?

Garth Huber, huberg@uregina.ca

Mandelstam variables (*s,t,u*–channels)

Garth Huber, huberg@uregina.ca



$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$

$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$

$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$

s: invariant mass of the system

t: Four–momentum–transfer squared between **target before and after interaction**

u: Four–momentum–transfer squared between **virtual photon before interaction and target after interaction**

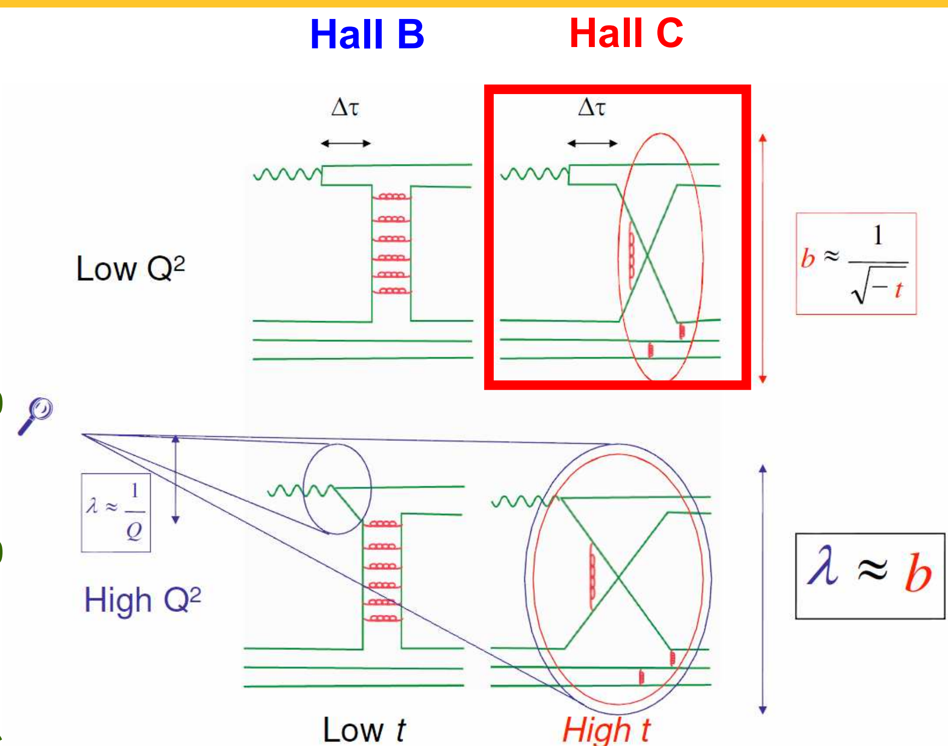
***t*-channel*: –t ~ 0*, after interaction**

- **Target: stationary**
- **Meson: forward**
- **Measure of how forward could the meson go.**

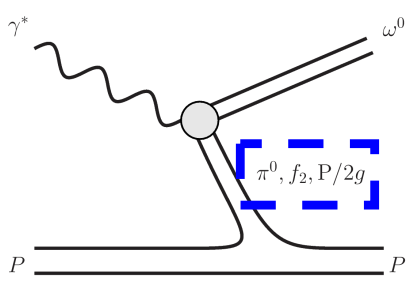
***u*-channel: *–u~0,* after interaction**

- **Target: forward**
- **Meson: stationary**
- **Measure of how backward could the meson go**

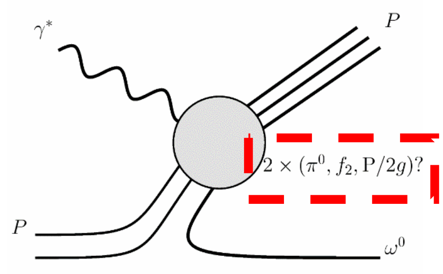
Hadronic Model: Regge Model by JM Laget



Hard Scattering Mechanism schematics

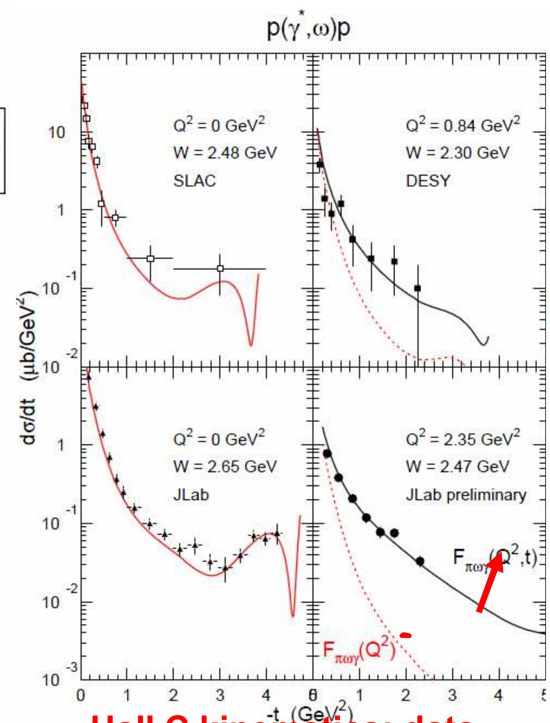


t–Channel Forward

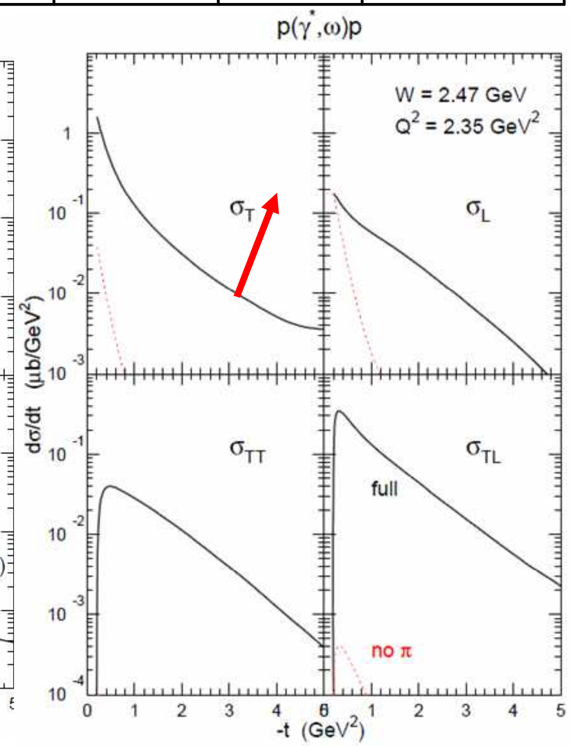


u–Channel Backward

	W (GeV)	x	Q^2 (GeV²)	$-t$ (GeV²)	$-u$ (GeV²)
Hall B	1.8–2.8	0.16–0.64	1.6–5.1	< 2.7	> 1.68
Hall C	2.21	0.29	1.6	4.014	0.08–0.13
		0.38	2.45	4.724	0.17–0.24



Hall C kinematics: data suggest a u–channel contribution



J. M. Laget, Phys. Rev. D 70, 2004

Garth Huber, huberg@uregina.ca

University of Regina

TDA Formalism (e.g. u–channel π^0)

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- Fourier transform of the πN transition matrix element

$$4\mathcal{F}\langle \pi_\alpha(p_\pi)|\widehat{O}_{\rho\tau\chi}(\lambda_1 n, \lambda_2 n, \lambda_3 n)|N_\iota(p_1)\rangle$$
$$= \delta(x_1+x_2+x_3-2\xi_u)\sum_{s.f.}(f_a)_\iota^{\alpha\beta\gamma}\, s_{\rho\tau,\chi}\, H^{\pi N}_{s.f.}(x_1,x_2,x_3,\xi_u,\Delta^2;\mu_F^2)$$

Factorization scale

- πN TDA invariant amplitudes (**eight TDAs at leading twist**)

$$H^{\pi N}_{s.f.} = \{V^{\pi N}_{1,2}, A^{\pi N}_{1,2}, T^{\pi N}_{1,2,3,4}\}$$

- Factorizing out the *u*–dependence:

meson to nucleon transition form factor

$$H^{\pi N}(x,\xi_u,\Delta^2) = H^{\pi N}(x_i,\xi_u)\times G(\Delta^2)$$

$$\Delta^2 = u$$

J.P. Lansberg, B. Pire, K. Semenov–Tian–Shansky, L. Szymanowski, Phys. Rev. D **85** (2011) 054201

Garth Huber, huberg@uregina.ca

TDAs Formalism – 1

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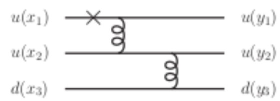
α		T_α	T'_α
1		$\frac{-Q_u(2\xi)^2[(V_1^{p\pi^0}-A_1^{p\pi^0})(V^p-A^p)+4T_1^{p\pi^0}T^p+2\frac{\Delta_T^2}{M^2}T_4^{p\pi^0}T^p]}{(2\xi-x_1-i\epsilon)^2(x_3-i\epsilon)(1-y_1)^2y_3}$	$\frac{-Q_u(2\xi)^2[(V_2^{p\pi^0}-A_2^{p\pi^0})(V^p-A^p)+2(T_2^{p\pi^0}+T_3^{p\pi^0})T^p]}{(2\xi-x_1-i\epsilon)^2(x_3-i\epsilon)(1-y_1)^2y_3}$

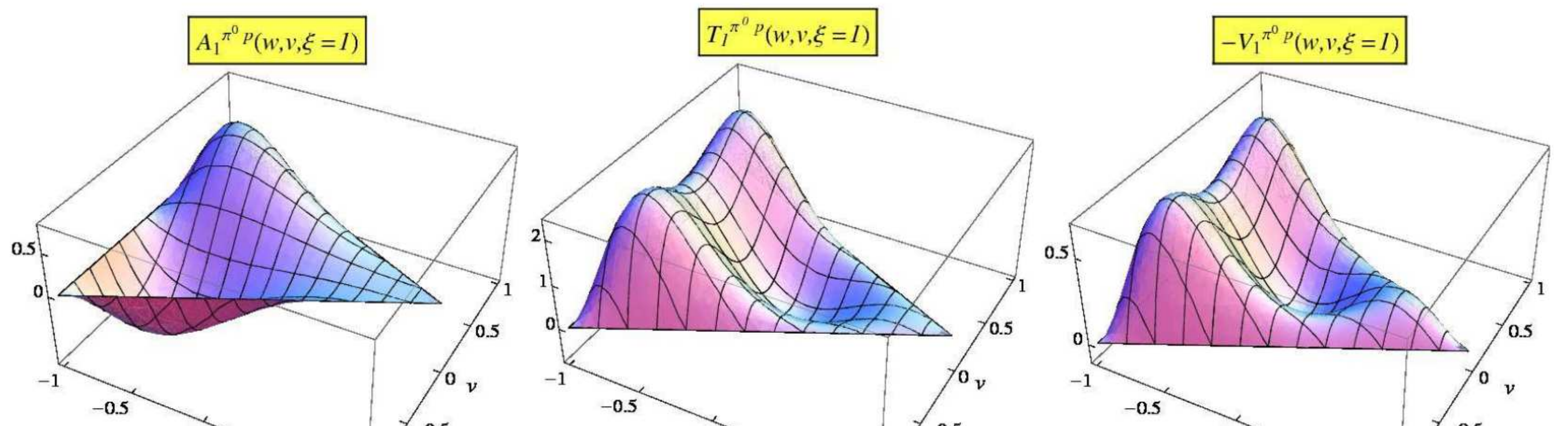
First three TDAs ←

$$V_1^{\pi^0 p}(x_1,x_2,x_3,\xi_u=1) = -\frac{1}{2}\times\frac{1}{4}V^P\left(\frac{x_1}{2},\frac{x_2}{2},\frac{x_3}{2}\right)$$

$$A_1^{\pi^0 p}(x_1,x_2,x_3,\xi_u=1) = -\frac{1}{2}\times\frac{1}{4}A^P\left(\frac{x_1}{2},\frac{x_2}{2},\frac{x_3}{2}\right)$$

$$T_1^{\pi^0 p}(x_1,x_2,x_3,\xi_u=1) = \frac{3}{2}\times\frac{1}{4}T^P\left(\frac{x_1}{2},\frac{x_2}{2},\frac{x_3}{2}\right)$$

Input PDF from Nucleon DA model:
- COZ (Chernak, Ogloblin, Zhitnitsky, 1989)
- KS (King and Schrajda, 1987)



$\pi^0 p$ TDAs (CZ): **Vector** **Axial–Vector** **Tensor**

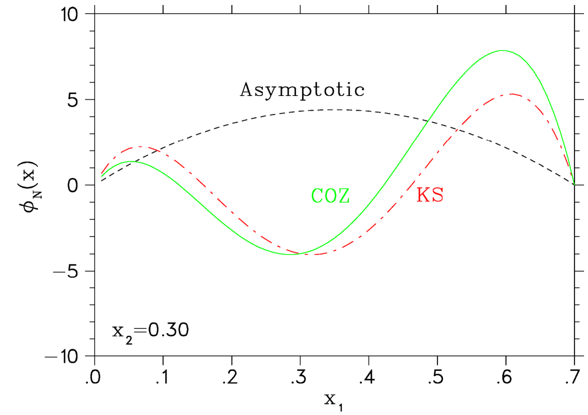
computed as functions of quark-diquark coordinates

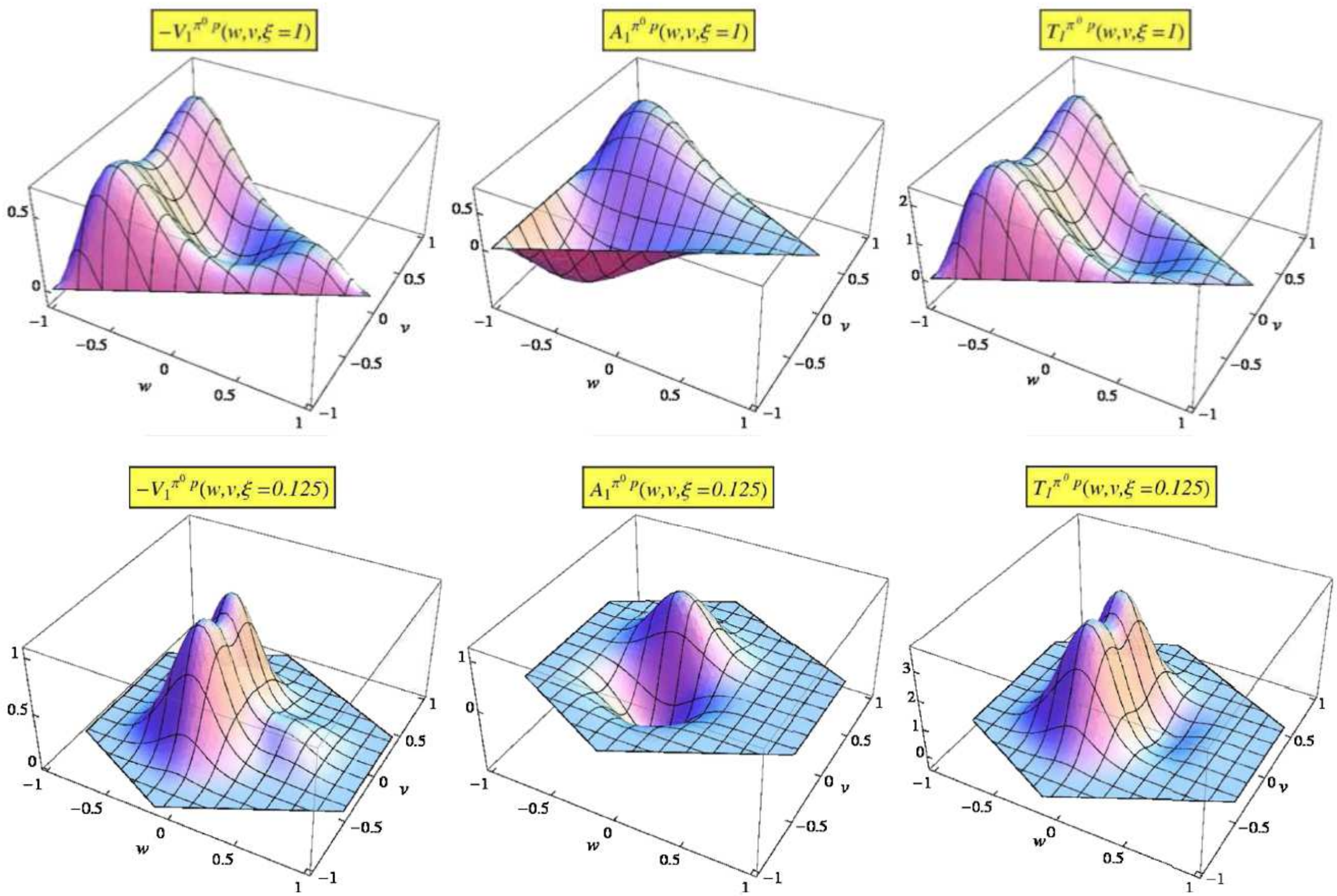
J.P. Lansberg et al., PRD **85** (2012) 054201

Garth Huber, huberg@uregina.ca

π^0p TDAs as functions of q–diquark coordinates

$$w = \xi_u - x_3;\; v = \frac{x_1 - x_2}{2}$$





Garth Huber, huberg@uregina.ca

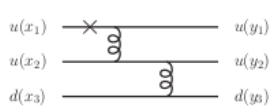
TDA Meson Production Cross Section

Garth Huber, huberg@uregina.ca

- Unpolarized exclusive π^0 production cross section:

$$\frac{d^2\sigma_T}{d\Omega_\pi} = |\mathcal{C}^2| \frac{1}{Q^6} \frac{\Lambda(s, m^2, M^2)}{128\,\pi^2 s(s-M^2)} \frac{1+\xi}{\xi} \left(|\mathcal{I}|^2 - \frac{\Delta_T^2}{M^2} |\mathcal{I}'|^2\right)$$

$$\mathcal{I} = \int \left(2\sum_{\alpha=1}^{7} T_\alpha + \sum_{\alpha=8}^{14} T_\alpha \right) \qquad \mathcal{I}' = \int \left(2\sum_{\alpha=1}^{7} T'_\alpha + \sum_{\alpha=8}^{14} T'_\alpha \right)$$

α		T_α	T'_α
1		$\frac{-Q_u(2\xi)^2[(V_1^{p\pi^0}-A_1^{p\pi^0})(V^p-A^p)+4T_1^{p\pi^0}T^p+2\frac{\Delta_T^2}{M^2}T_4^{p\pi^0}T^p]}{(2\xi-x_1-i\epsilon)^2(x_3-i\epsilon)(1-y_1)^2y_3}$	$\frac{-Q_u(2\xi)^2[(V_2^{p\pi^0}-A_2^{p\pi^0})(V^p-A^p)+2(T_2^{p\pi^0}+T_3^{p\pi^0})T^p]}{(2\xi-x_1-i\epsilon)^2(x_3-i\epsilon)(1-y_1)^2y_3}$

J. P. Lansberg, B. Pire, K. Semenov-Tian-Shansky, L. Szymananovski, Phys. Rev. D **85** (2011) 054021

Transverse Target Single Spin Asymmetry $\gamma^* N \to \pi N$

More distinguishing features with a polarized target

- TSA= $\sigma^\uparrow - \sigma^\downarrow \sim \mathrm{Im}$ part of the amplitude.
- Sensitive to the contribution of the DGLAP-like regions.
- Non vanishing and Q^2-independent TSA within TDA approach.
- $10-15\%$ TSA for $\gamma^* N \to \pi N$ with two component TDA model.

$$\mathcal{A} = \frac{1}{|\vec{s}_1|}\left(\int_0^\pi d\tilde{\phi}|\mathcal{M}_T^{s_1}|^2 - \int_\pi^{2\pi} d\tilde{\phi}|\mathcal{M}_T^{s_1}|^2\right)\left(\int_0^{2\pi} d\tilde{\phi}|\mathcal{M}_T^{s_1}|^2\right)^{-1}; \quad \tilde{\phi} \equiv \phi - \phi_s$$