u-Channel Omega Meson Production from the Fpi-2 Experiment

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Hall C Workshop. January, 2017.

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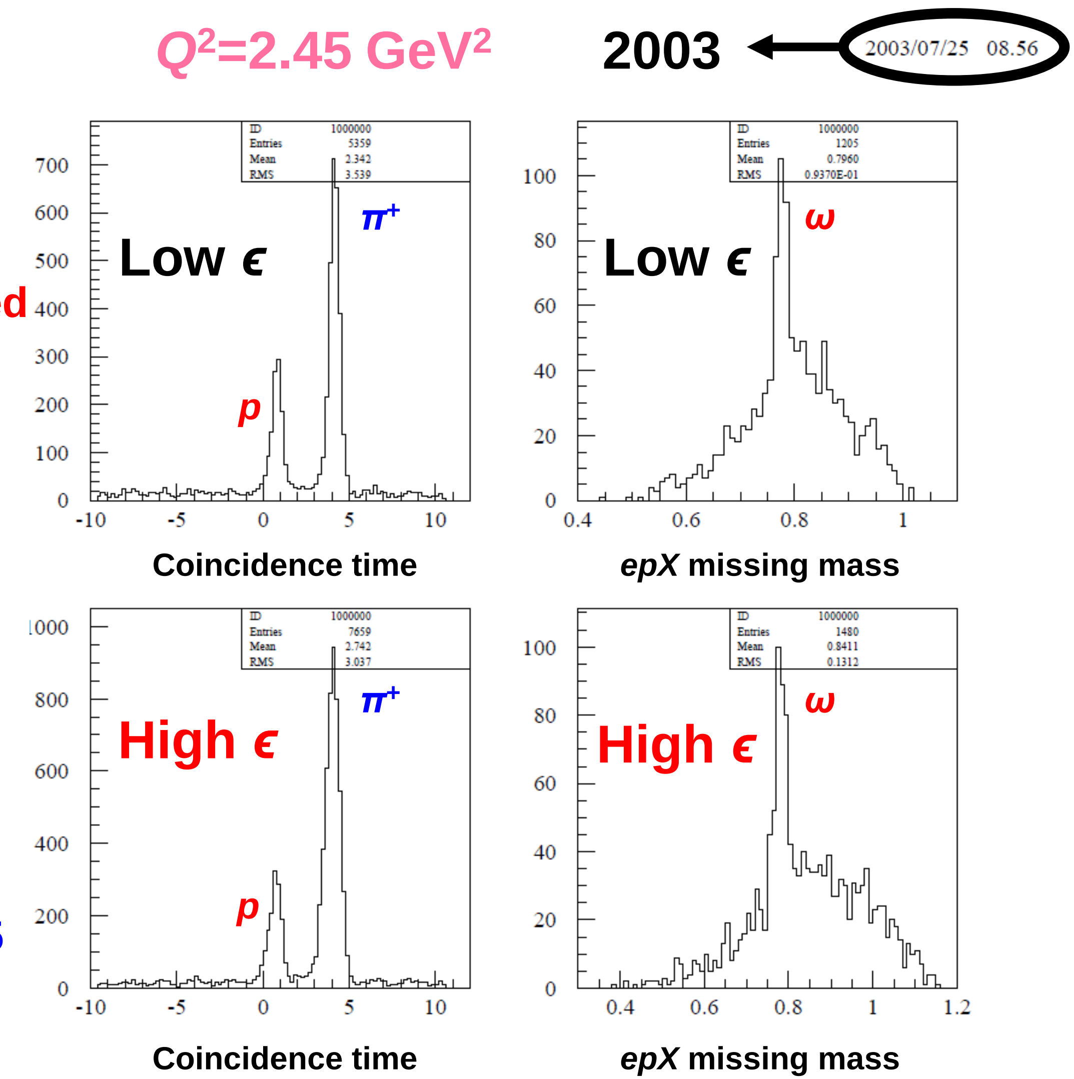
Outlook from last year and Outline

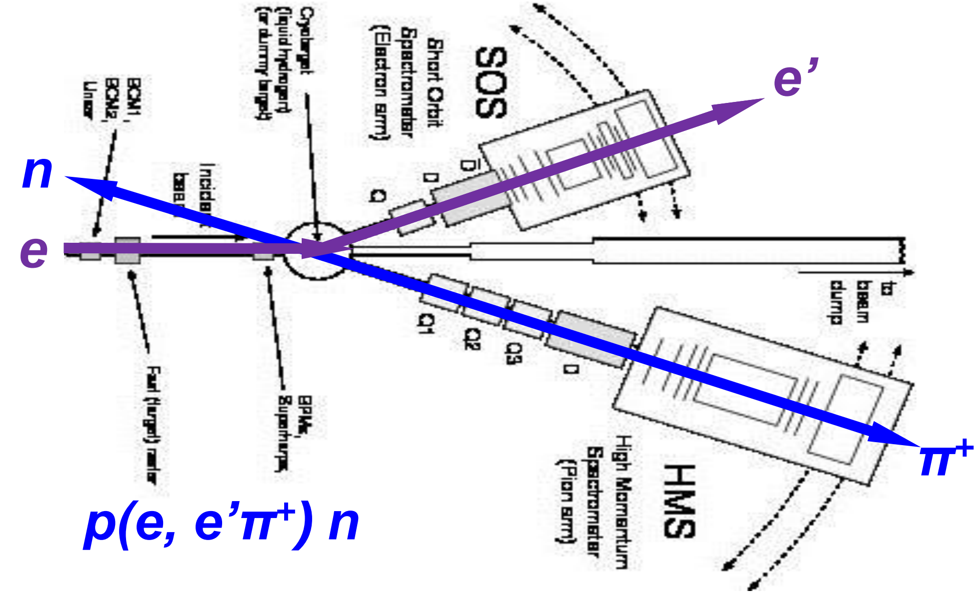
- Outline
  - Brief introduction to the experiment
  - Theoretical Justification
  - **Preliminary Experimental Results**

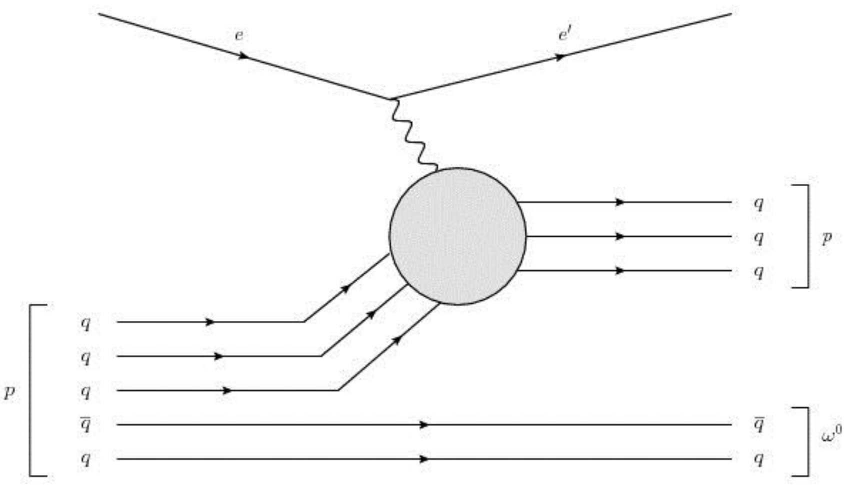
Fpi-2 E01-004 Experiment

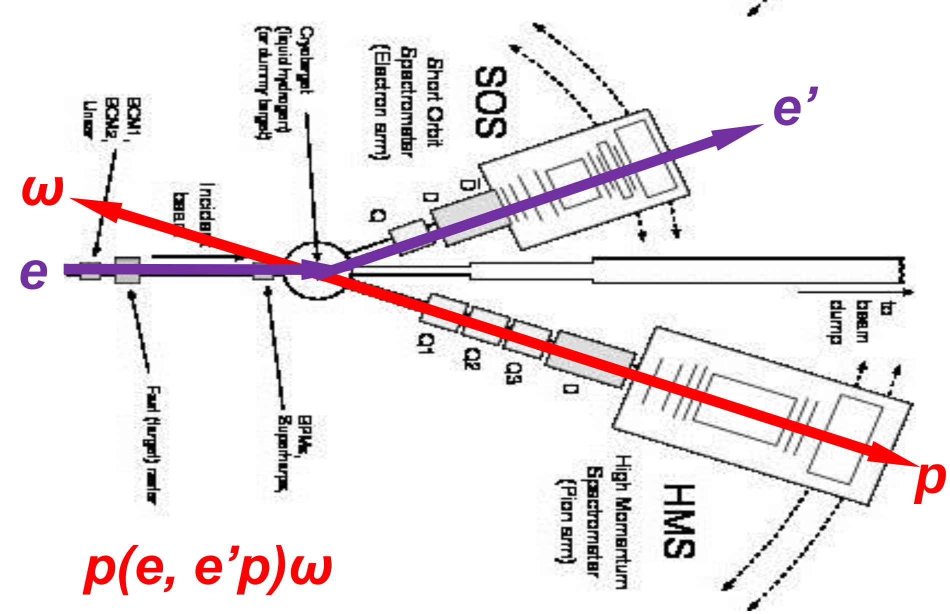
- Fpi-2 (E01-004) 2003
  - Spokesperson: **Garth Huber, Henk Blok**
  - Standard HMS and SOS (e) configuration
  - **Electric form factor of charged** through exclusive π production
- Primary reaction for Fpi-2
  - ***p*(*e*, *e'* π^+)*n***
- In addition, we have for free
  - ***p*(*e*,*e'* *p*)ω**
- Kinematics coverage
  - **W= 2.21 GeV, Q^2=1.6 and 2.45 GeV^2**
  - Two ϵ settings for each Q^2



t-Channel π vs u-Channel ω^0 Production

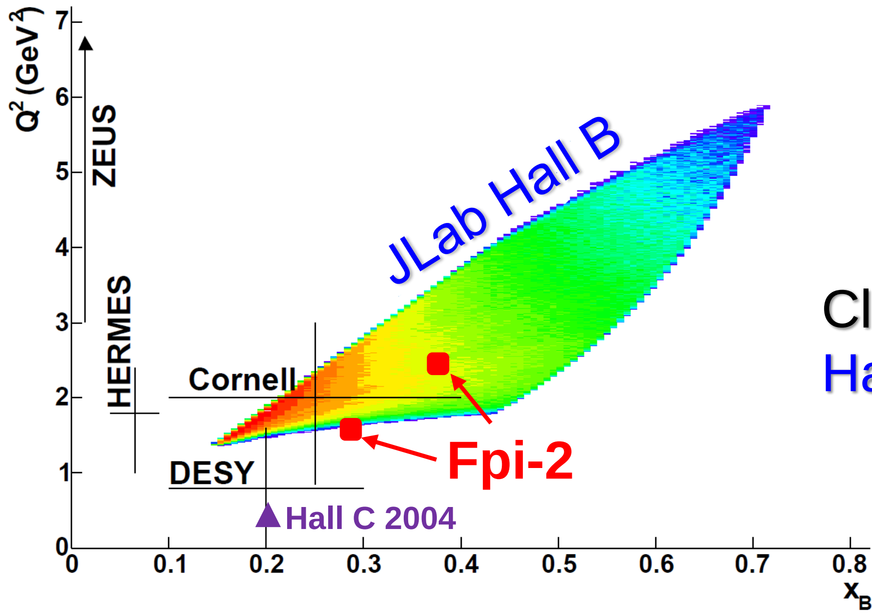






- HMS along the q-vector ($p_{\gamma*}$)
  - $p_{\pi+}$ is parallel to $p_{\gamma*}$ (Forward)
  - p_{ω} is anti-parallel to $p_{\gamma*}$(Backward)

Exclusive ω Electro-Production Data

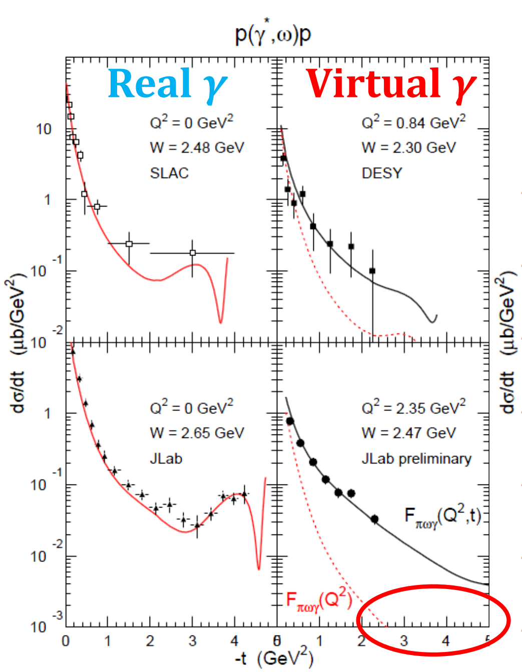


Closest data set to ours is the Hall B Morand data

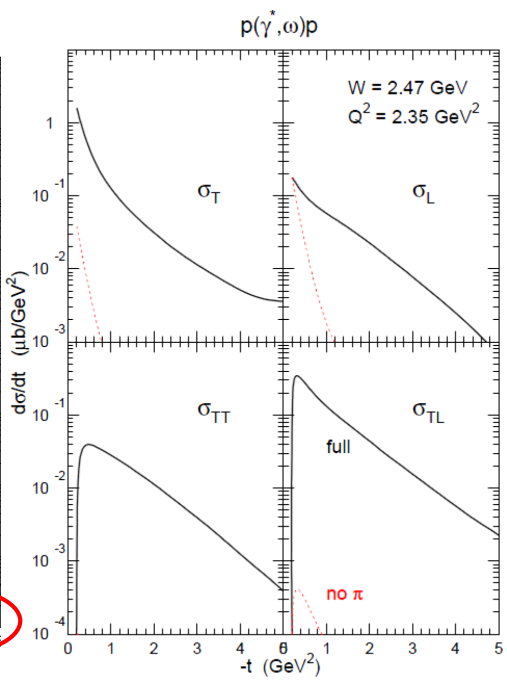
	Q^2 GeV^2	*W* GeV	*x*	*-t* GeV^2
HERMES (Airapetian et al., 2014)	> 1	3-6.3	0.06-0.14	< 0.2
DESY (Joos et al., 1977)	0.3-1.4	1.7-2.8	0.1-0.3	< 0.5
Zeus (Breitweg et al., 2000)	3-20	40-120	~0.01	< 0.6
Cornell (Cassel et al., 1981)	0.7-3	2.2-3.7	0.1-0.4	<1
JLab Hall C (Ambrozewicz et al., 2004)	~0.5	~1.75	0.2	0.7-1.2
JLab Hall C (Dalton et al., 2005)	5-7	1.5		>4.0
JLab Hall B (Morand et al., 2005)	1.6-5.1	1.8-2.8	0.16-0.64	<2.7
JLab Fpi-2 (2017)	1.6, 2.45	2.21	0.29, 0.38	4.0, 4.74

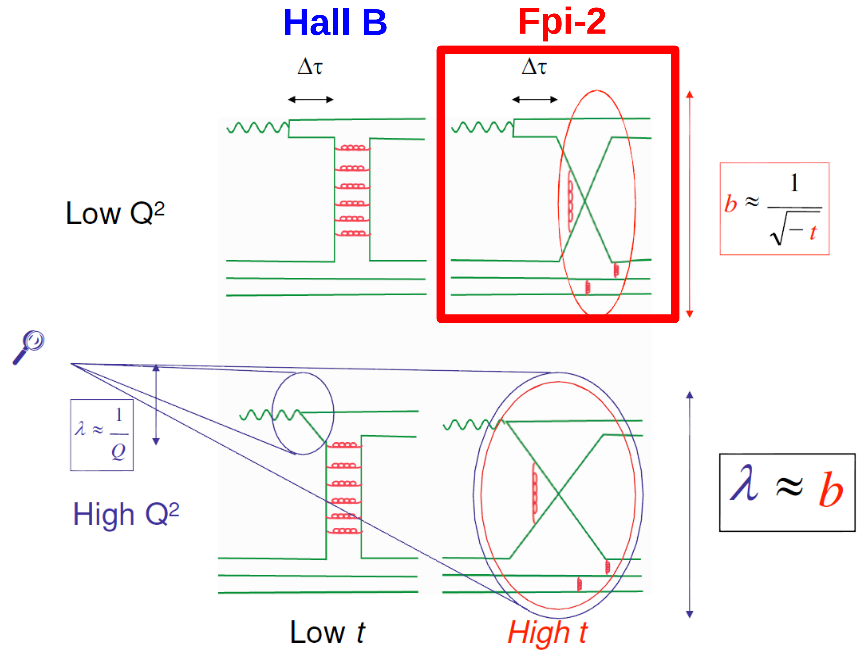
Regge Trajectory Model by JM Laget

	W (GeV)	x	Q^2 (GeV^2)	-t (GeV^2)	-u (GeV^2)
Hall B	1.8-2.8	0.16-0.64	1.6-5.1	< 2.7	> 1.68
Fpi-2	2.21	0.29	1.6	4.014	0.08-0.13
		0.38	2.54	4.724	0.17-0.24

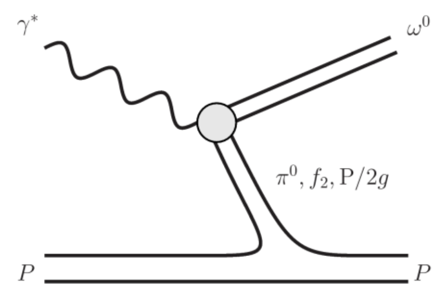


Fpi2 kinematics

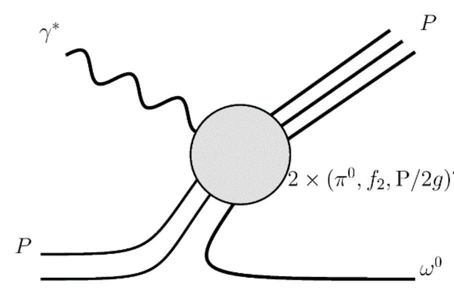




Hard Scattering Mechanism schematics



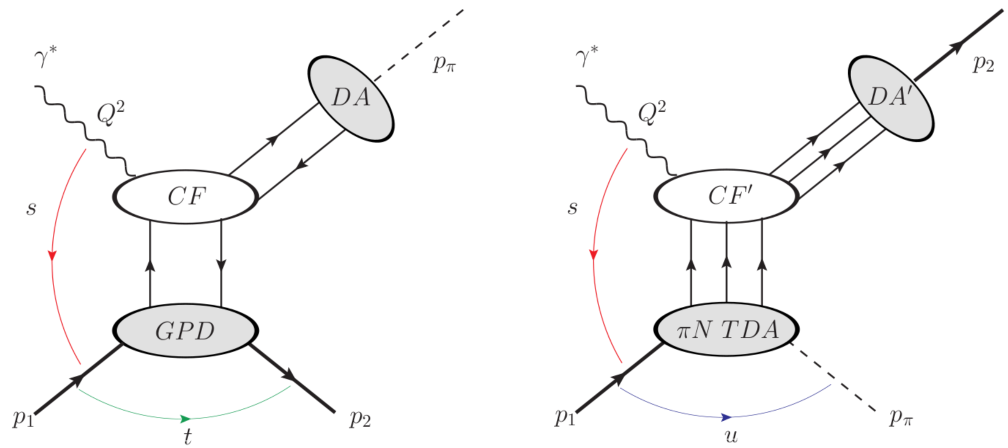
t-Channel
Forward



u-Channel
Backward

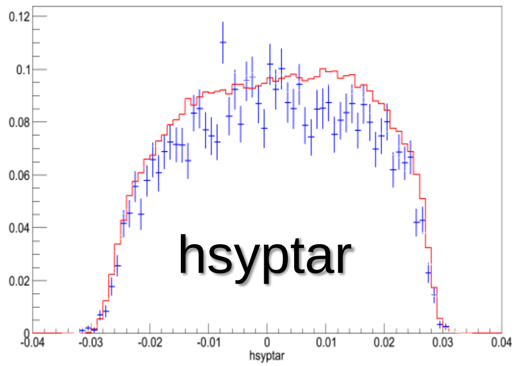
J. M. Laget, Phys. Rev. D 70, 2004

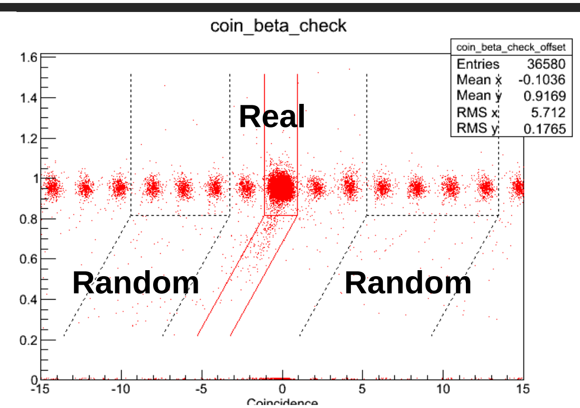
Further motivation: Transition Distribution Amplitude (TDA)

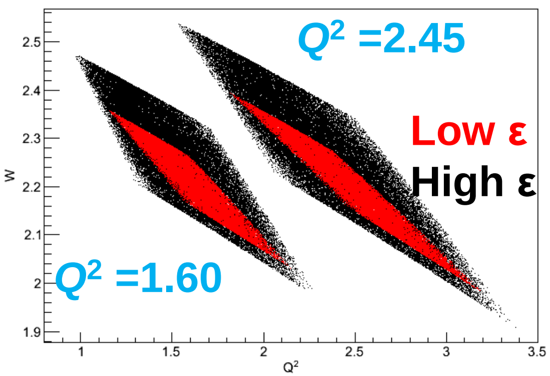


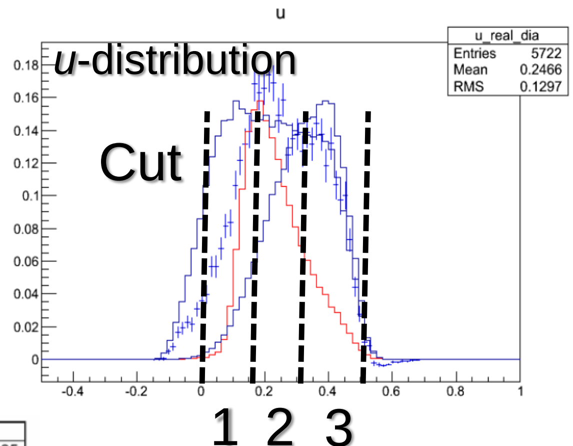
- TDA backward angle analog of GPD
- Interaction of Interest: ***u*-channel pseudocalar** and **vector *π* and production**
- Extension of the TDA model to describe the backwards vector meson production
- TDA Factorization Made two Predictions (B. Pire, K. Semenov, L. Szymanowski, Phys. Rev. D, **91**, 094006 (2015)).
  - The dominance of the transverse polarization of the virtual photon resulting in the suppression of the longitudinal cross section by at least $1/Q^2$: $\sigma_T > \sigma_L$. (**We can validate this !)**
  - The Characteristic **$1/Q^8$**-scaling behaviour of the σ_T for a fixed Bjorken x (**We can't test this.)**

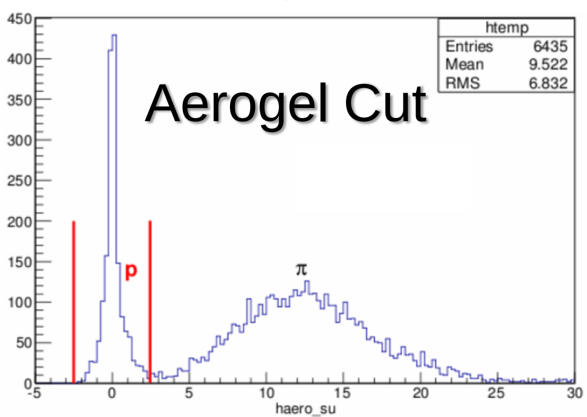
Analysis: Cuts Applied and Efficiency Study





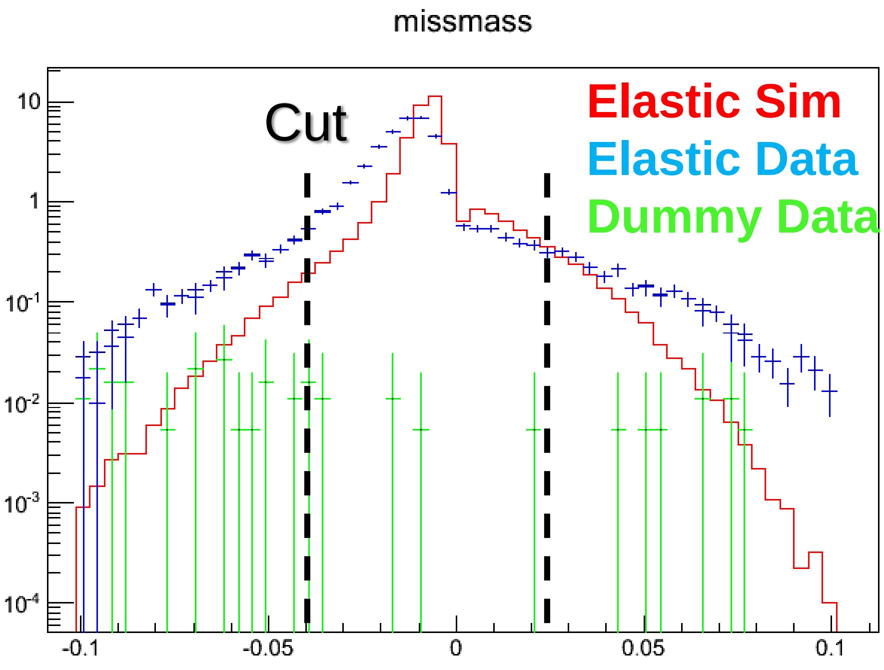


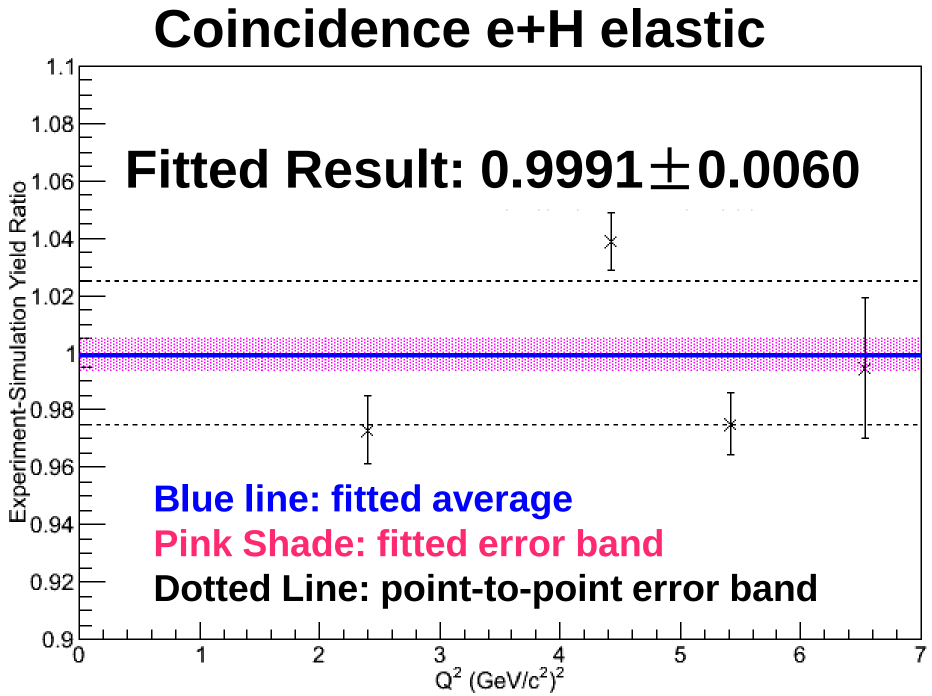




- **Cuts Applied**
  - Detector acceptance cuts
  - Cointime-hsbeta cuts (Hsbeta=0 events included)
  - PID Cuts
  - Diamond cuts
  - *u* cut
- Efficiency Results
  - Tracking Efficiency Correction (<3%)
  - Proton Scattering Efficiency (4.7%)
  - Aerogel Cut Efficiency (7.3%)
  - Other standard efficiencies

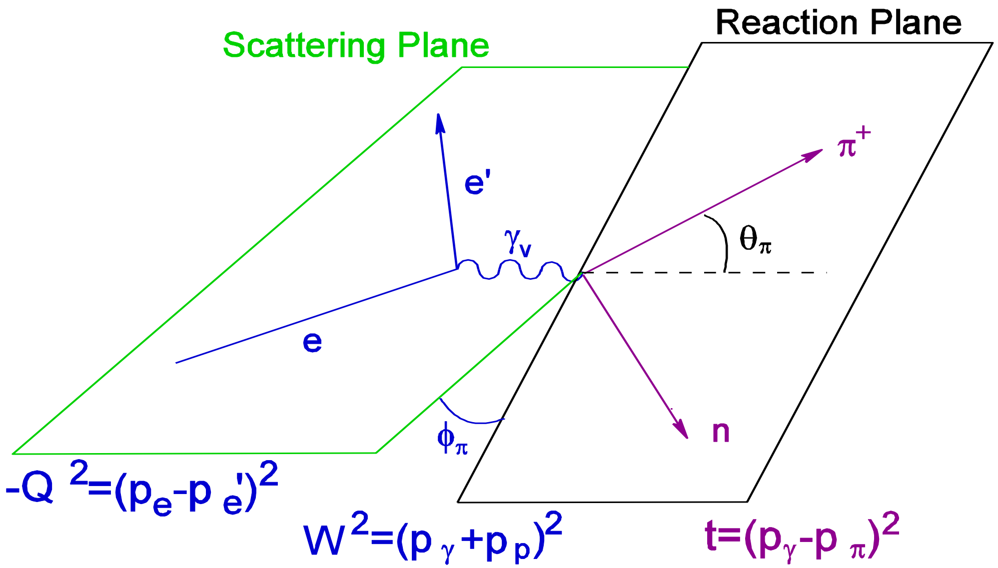
Analysis: e+H Elastic Cross-Section





- Extracted cross section is consistent with Bosted, AMT (Arrington, Melnitchouk, Tjon Phys. Rev. C 76, 035205 (2007)) and Brash empirical e-p elastic cross section parameters.
- ±2.0% (point to point) error from Heep will be the included to the final Omega analysis systematics

Rosenbluth Separation Method



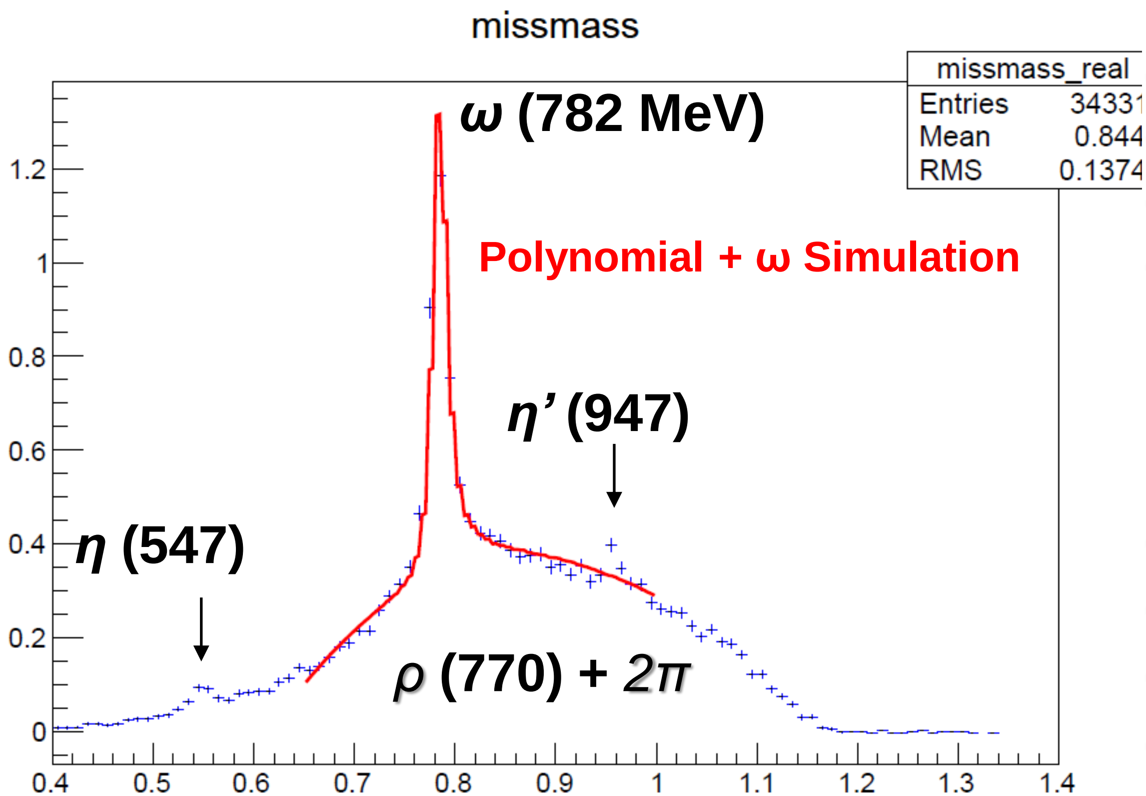
Virtual-photon polarization:

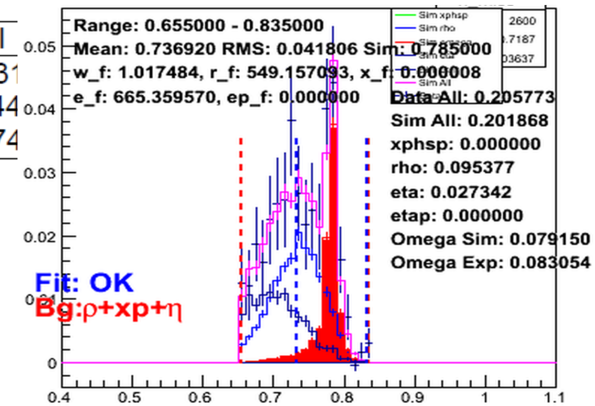
$$\varepsilon=\left(1+2\frac{(E_e-E_{e'})^2+Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$

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

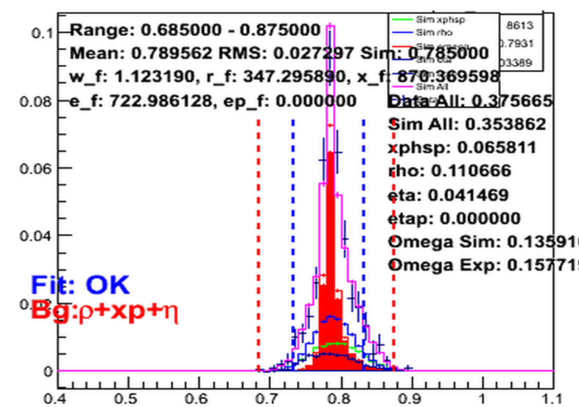
- Rosenbluth Separation method requires
  - Separate measurements are taken at different ϵ (virtual photon polarization)
  - All Lorentz invariant physics quantities such as Q^2, W, t, u, remain constant
  - Beam energy, scattered e angle and virtual photon angle will change as the result, thus event rates are dramatically different

Missing Mass Distribution

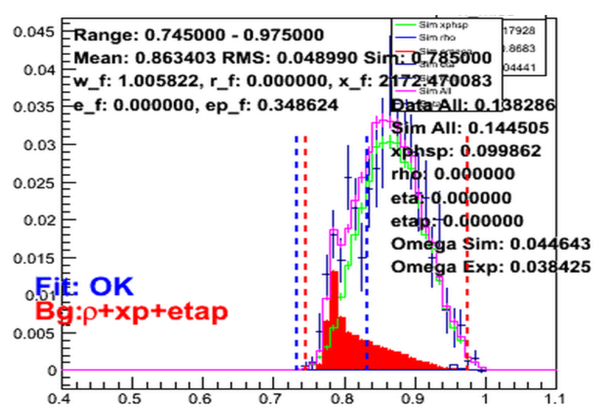




ω @ Right



ω @ Center

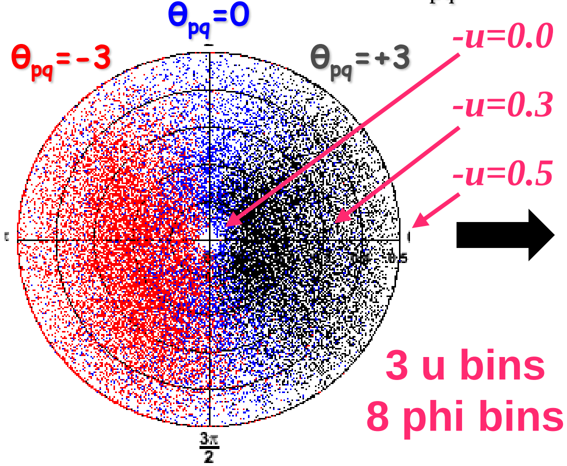


ω @ Left

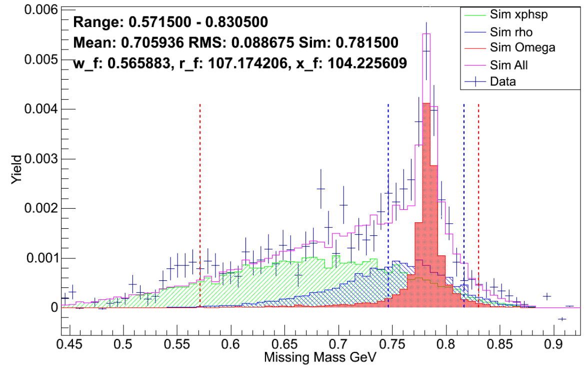
- **Most Challenging Issue: Background Subtraction!**
- **Omega is not always in the center**
- **Four sets of Monte-Carlo is used fit the data**
  - ***ω* + *ρ* + Phase-space + *η or η'***

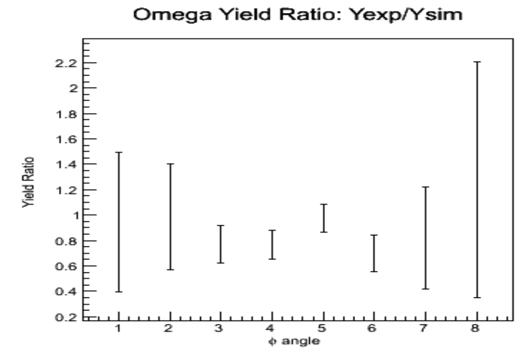
Iterative Procedure (Recipe) to A Full LT Separation

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



Background Subtraction





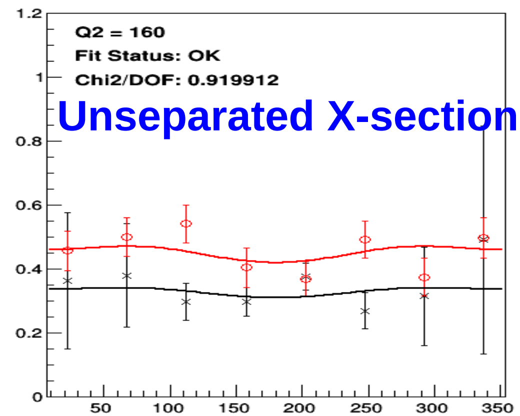
For each HMS setting, form ratio:

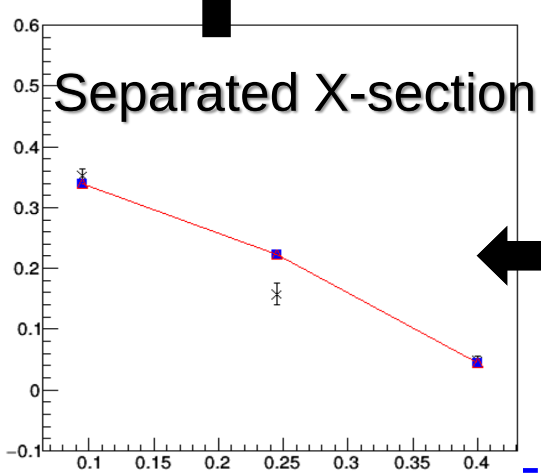
$$R=\frac{Y_{Exp}-Y_{\rho\ \mathrm{sim}}-Y_{Xspace\ \mathrm{sim}}-Y_{\eta\ \mathrm{sim}}}{Y_{\omega\ \mathrm{sim}}}$$

Combine ratios for settings together, propagating errors accordingly.

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

Empirical Model

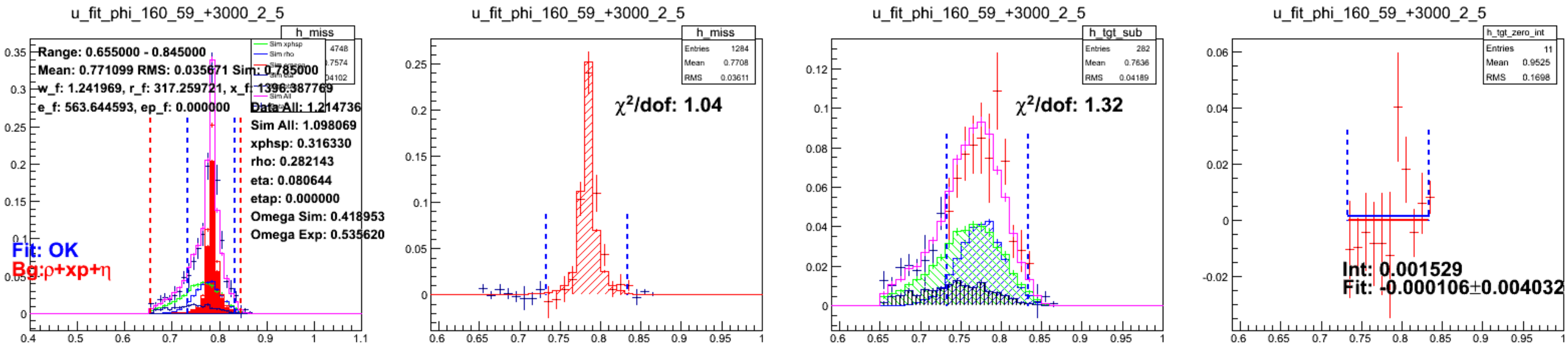




Extract T, L, LT, TT via simultaneous fit

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

Missing Mass Distribution Background Extraction



Data (blue point)

Xspace Sim (green)

ρ Sim (light blue)

ω Sim (red)

η or η' (black)

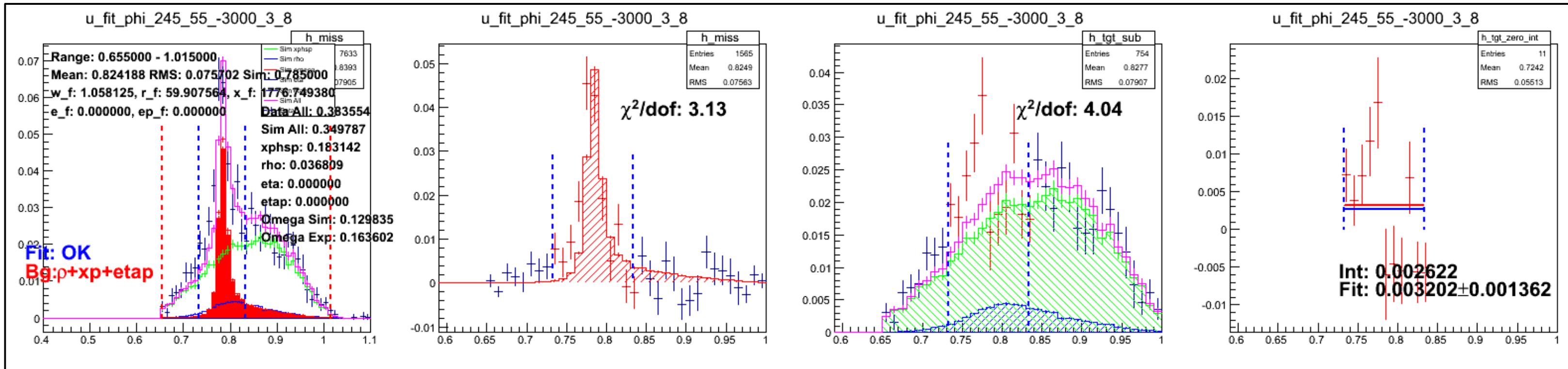
Simulation Sum (pink)

Omega | **Background Sum** | **Zero= Data – Omega- Bg**

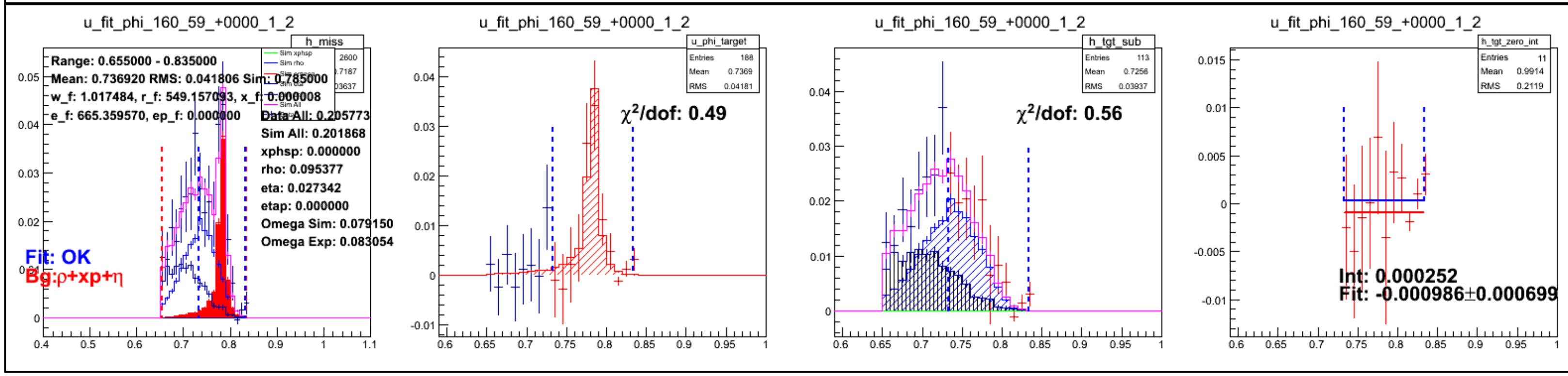
$$R = \frac{Y_{Exp} - Y_{\rho\ \mathrm{sim}} - Y_{Xspace\ \mathrm{sim}} - Y_{\eta\ \mathrm{sim}}}{Y_{\omega\ \mathrm{sim}}}$$

- **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 counts**

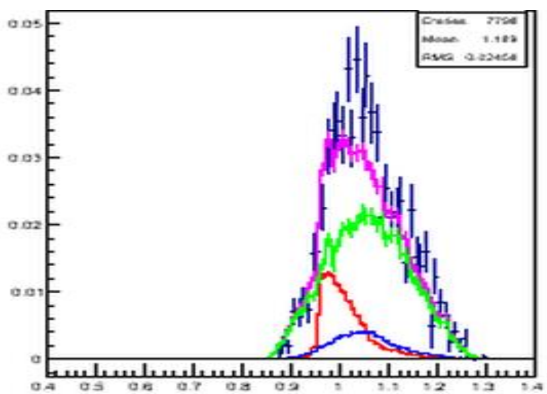
Background Extraction and Check



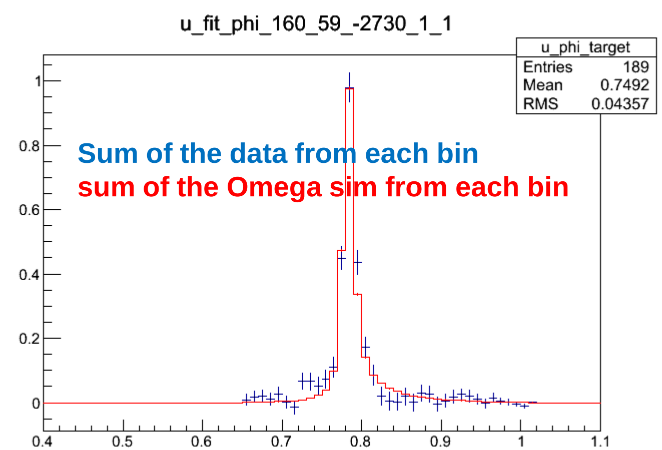
Worse example



Missmass edge example



Reconstructed Missing Energy For the **worse example**



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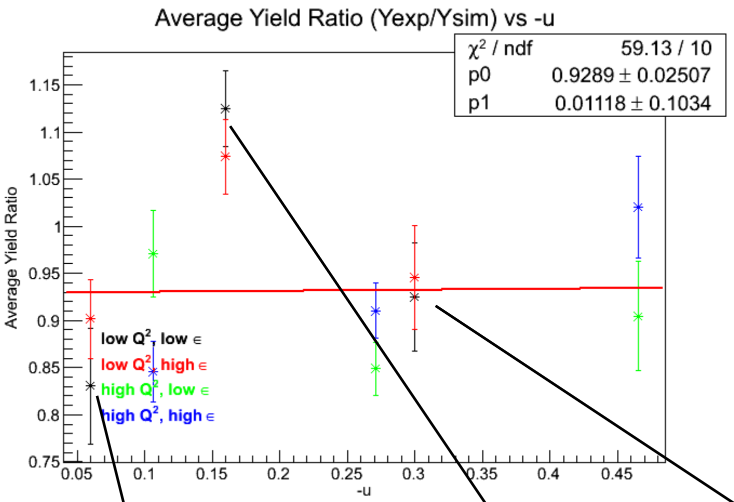
Yield Ratio and Simulated Cross-Section



$$\sigma_T = A + B\cdot(-u) + C\cdot\ln(Q^2) + D\cdot(-u)\cdot\ln(Q^2)\,,$$

$$\sigma_L = A + B\cdot(-u) + C\cdot\ln(Q^2) + D\cdot(-u)\cdot\ln(Q^2)\,,$$

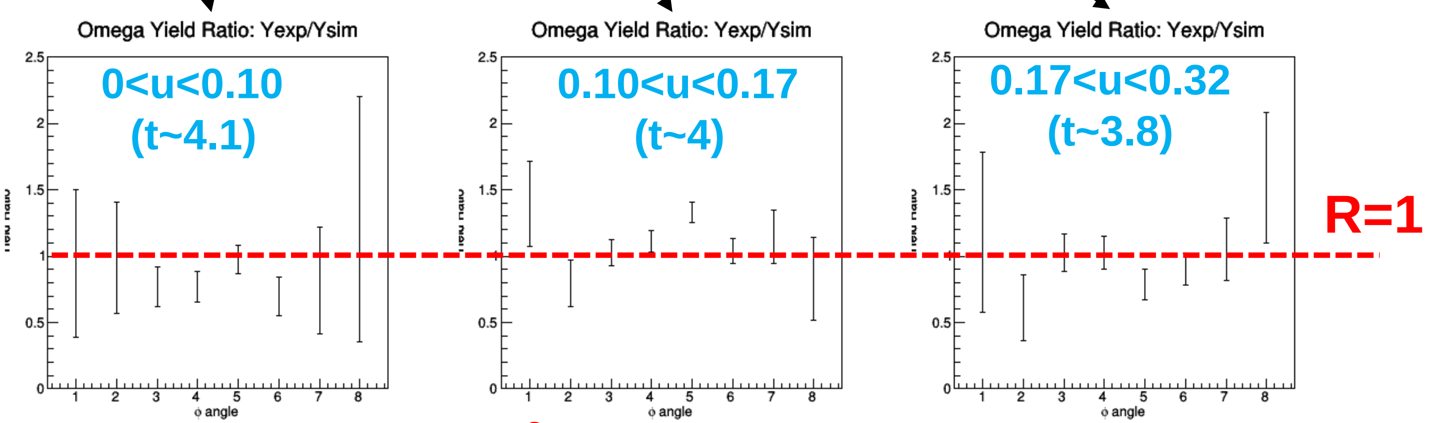
$$\sigma_{LT} = (A + B\cdot(-u))\sin\theta^*\,,$$

$$\sigma_{TT} = (A + B\cdot(-u))\sin^2\theta^*$$

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

Model Cross Section

$$\left.\frac{d^2\sigma}{dt\,d\varphi}\right|_{EXP} = R\left.\frac{d^2\sigma}{dt\,d\varphi}\right|_{SIMC}$$



Exp/Sim Yield Ratio

Q^2=1.6, Low ε=0.33

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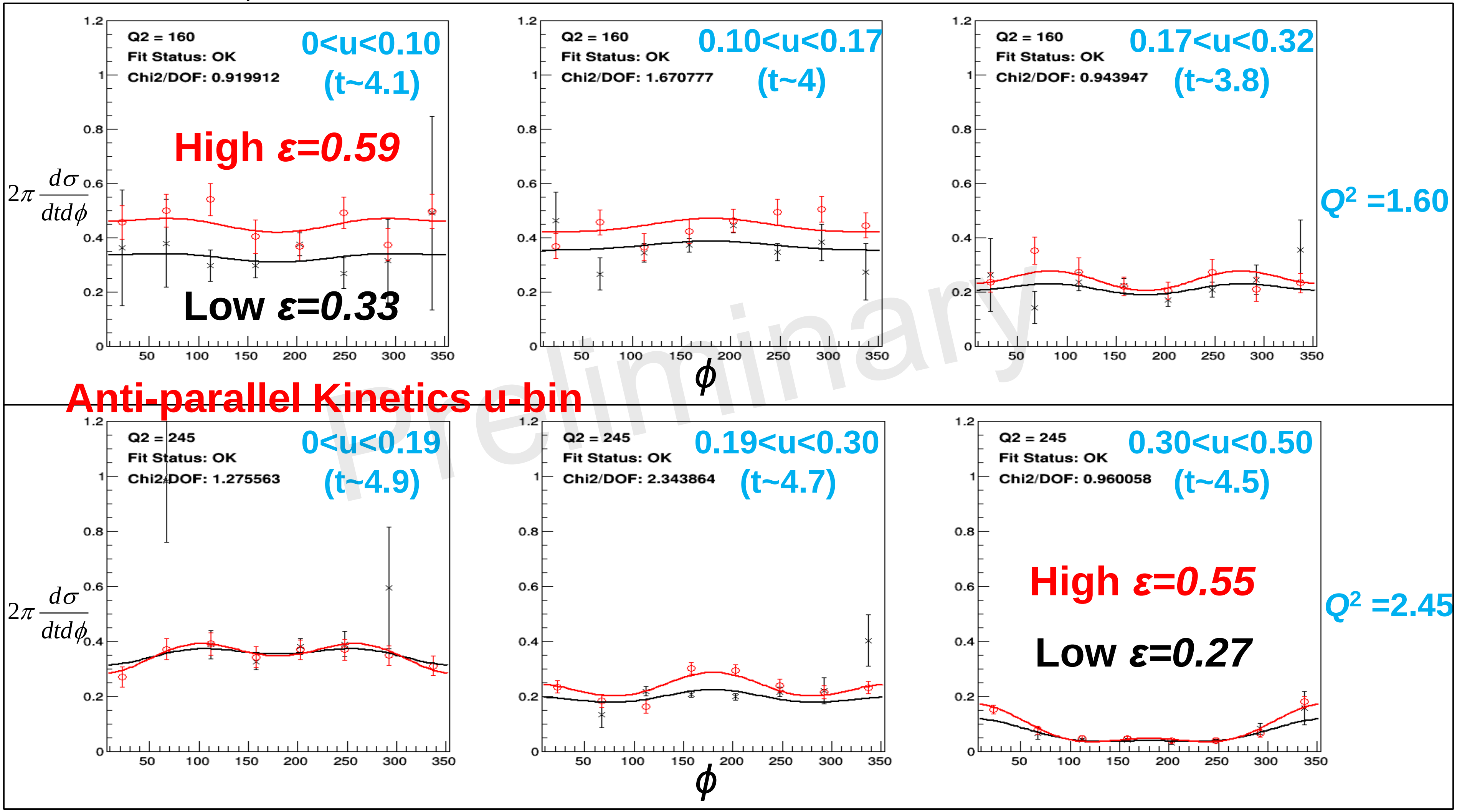
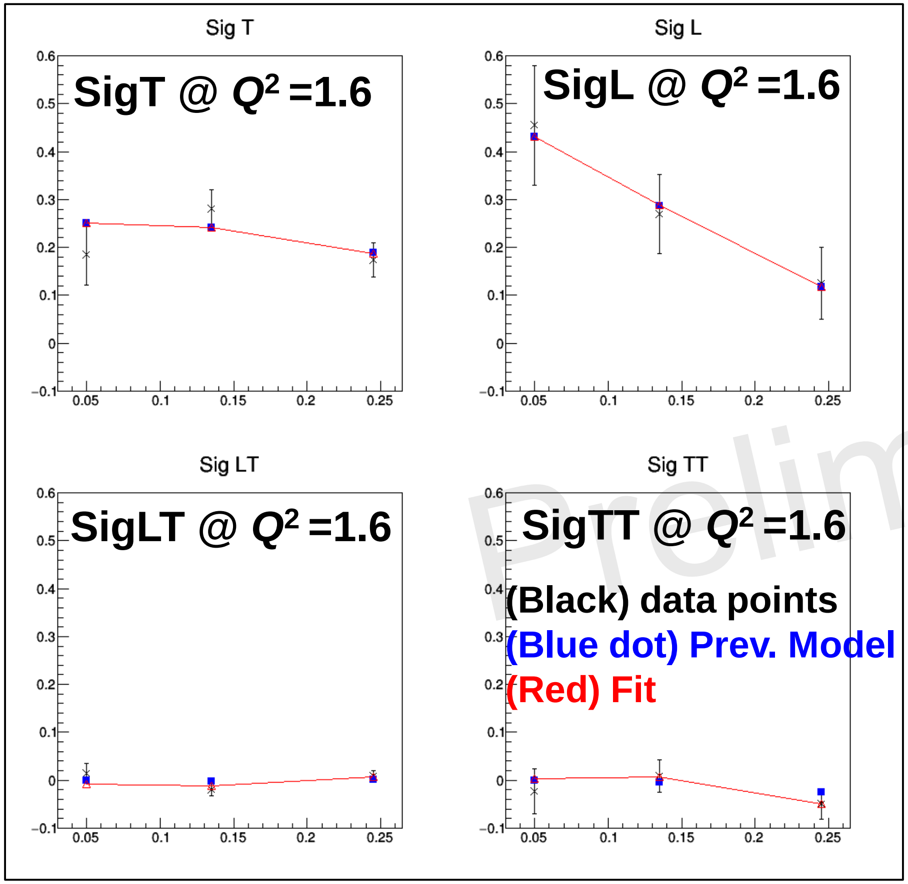
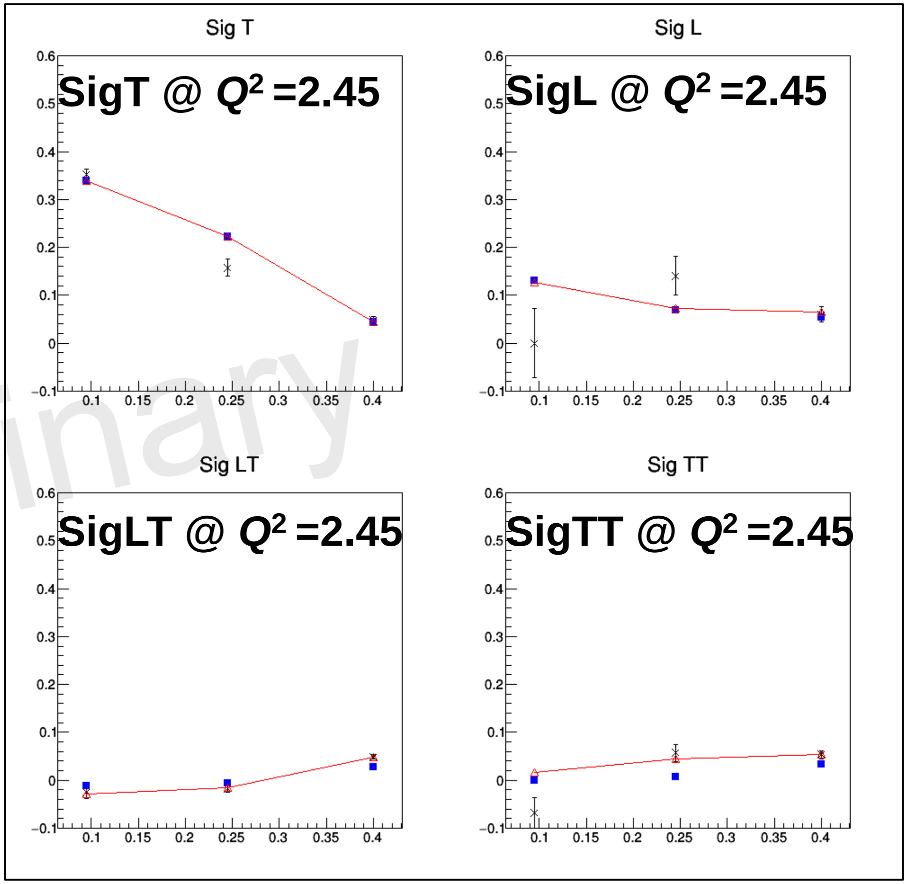
Unseparated Cross Section (Money Plot)

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



Separated Cross Section



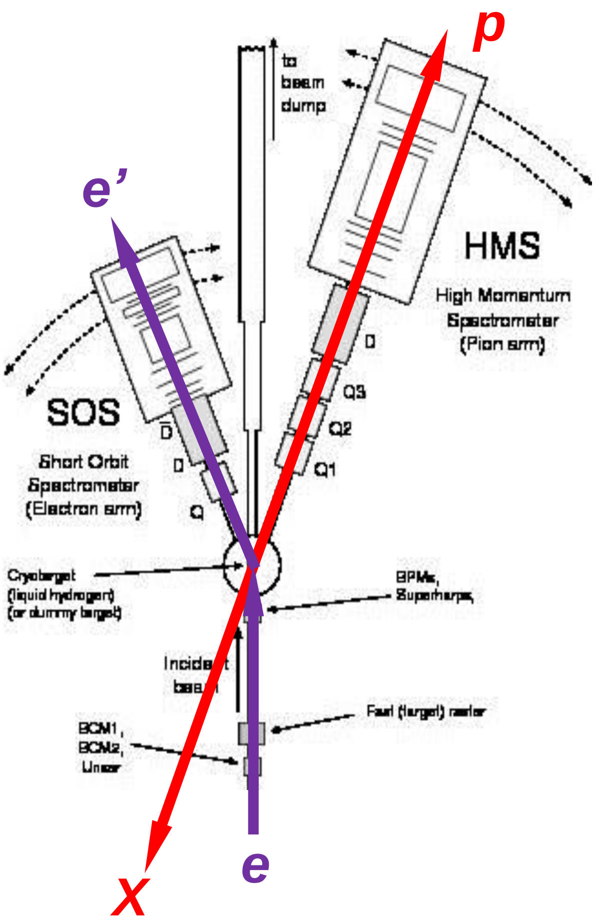


- **Observations:**
  - **SigT dominate SigL at 2.45 at u~0: validated the TDA prediction ($\sigma_T > \sigma_L$) for $Q^2 = 2.45$**
  - **SigT behave differently at different Q^2.**
  - **LT and TT are small**

Remaining Work

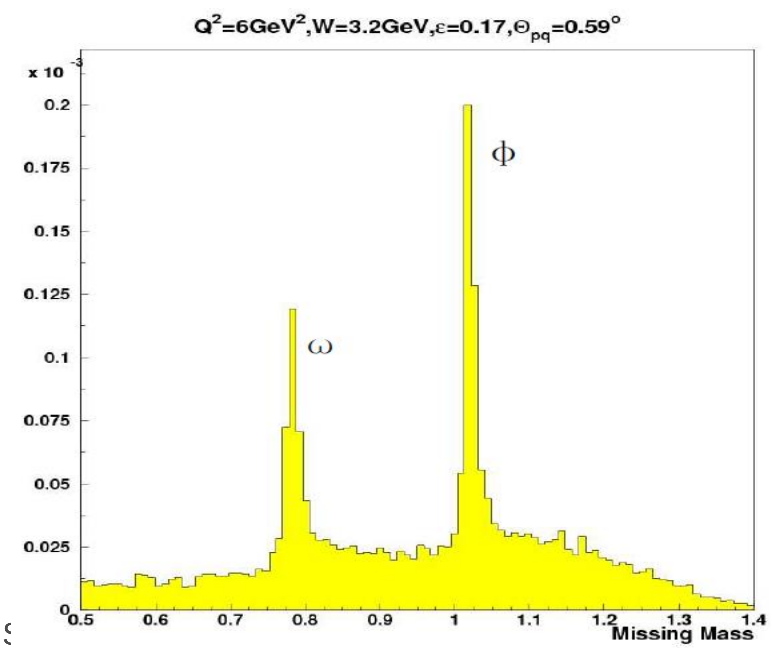
- Reconstruct the focal plane parameters
- Systematics studies:
  - Integration limit dependence
  - Fitting limit dependence
- Demonstrate stability of the separated cross section
- A rebin analysis is on the way
- Compare to the predicted result by TDA model

Future Backward Meson Production Opportunities



p(e, e'p)X

- Potential LOI (2018):
  - **Backward π^0** production at Hall C.
- Other extreme forward angle physics program
- Fpi 12 experiment (for free)
  - η, η', ω, $\phi(s\bar{s})$, ρ



Thanks You

- Special thanks to Dave Gaskell and Henk Blok.
- Fantastic quality NTuples analyzed by Tanja Horn.
- Gratitude to my graduate student colleagues and my family (specially my wife Noemi)

Fpi-2 E01-004 Experiment

- Fpi-2 (E01-004) experiment: 2nd pion form factor experiment 2001
  - Spokesperson: Garth Huber, Henk Blok, Dave Mack
  - Standard HMS and SOS (e) configuration.

- Using exclusive charged π production to determine the electric form factor from the L/T separated differential cross section

E_{beam} GeV	$P_{\rm SOS}$ GeV/c	$\theta_{\rm SOS}$ deg	ϵ	$P_{\rm HMS}$ MeV/c	θ_q deg	$\theta_{\rm HMS}-\theta_q$ deg	x GeV/c	P_m deg	θ_{mq}	$-t$ GeV^2/c^2	$-u$ GeV^2/c^2
$Q^2_{nominal}$ = 1.6 GeV^2 $W_{nominal}$ = 2.21 GeV											
3.778	-0.79	43.09	0.328	-9.534	2931	−1.0	0.2855	0.311	9.17	4.014	0.087
						−3.0		0.367	24.59		0.129
4.702	-1.65	25.73	0.5933	-13.281	2931	0.0	0.2855	0.304	0.09	4.014	0.082
						2.7		0.357	22.93		0.121
						−3.0		0.367	24.61		0.129
$Q^2_{nominal}$ = 2.45 GeV^2 $W_{nominal}$ = 2.21 GeV											
4.210	-0.77	51.48	0.270	-9.190	3336	−1.4	0.3796	0.431	10.57	4.742	0.184
						−3.0		0.491	20.82		0.241
5.248	-1.74	29.43	0.554	-13.606	3336	0.0	0.3796	0.415	0.00	4.742	0.169
						−3.0		0.491	20.79		0.241
						3.0		0.490	20.75		0.240

- Primary reaction for Fpi-2
  - ***p(e, e' π^+)n*** and ***n(e, e' π^-)p***
  - Through standard ***t***-channel

- In addition, we have (for free)
  - ***p(e,e' p)ω***
  - Through ***u*-channel**

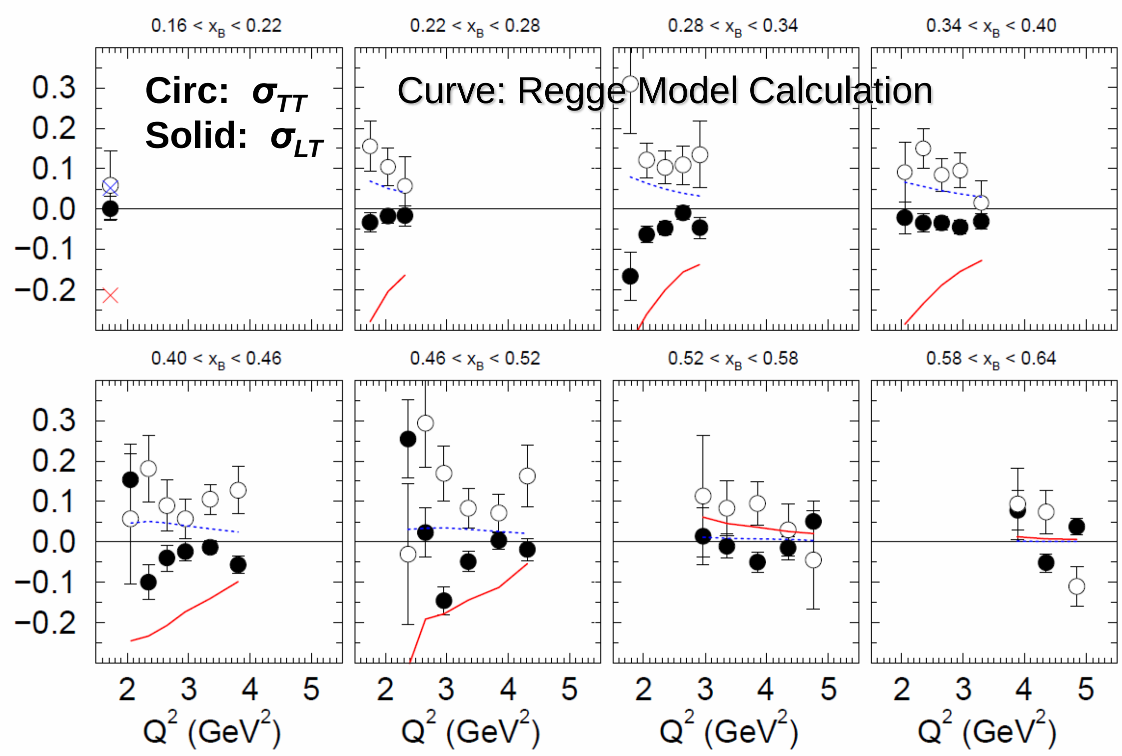
- Kinematics coverage
  - Same of Fpi-2 π^+ data
  - Same data set:
    - **W= 2.21 GeV, Q^2=1.6 and 2.45 GeV^2**
    - Two ϵ settings for each Q^2

π^+coverage ***ω coverage***

ω (782): $J^P = 1^-$, $I^G = 0^-$, $\omega : \dfrac{u\bar{u} + d\bar{d}}{\sqrt{2}}$

M_ω =782 MeV.

High -*t* Data from CLAS Hall B (2005)



Integrated over -2.7 GeV^2 < $t < t_0$
where t_0 ranges -0.09 to -1.61 GeV,
as *x* ranges between 0.203 to 0.61

- Specialty: Highest -*t* (low *u*) ω meson production data
- Excitement:
  - **Observation:** Q^2 independent cross section at high -*t*
  - **Possible interoperation:** Virtual photon is more likely to couple to a point-like object as −*t* increases.

Pseudoscalar meson ($J^P = 0^-$)

Particle name	Particle symbol	Antiparticle symbol	Quark content	Rest mass (MeV/c²)	I^G	J^{PC}	S	C	B'	Mean lifetime (s)	Commonly decays to (>5% of decays)
Pion[6]	π^+	π^-	$u\bar{d}$	139.570 18 ± 0.000 35	1^-	0^-	0	0	0	$(2.6033 \pm 0.0005) \times 10^{-8}$	$\mu^+ + \nu_\mu$
Pion[7]	π^0	Self	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$[a]	134.9766 ± 0.0006	1^-	0^{-+}	0	0	0	$(8.52 \pm 0.18) \times 10^{-17}$	$\gamma + \gamma$
Eta meson[8]	η	Self	$\frac{u\bar{u}+d\bar{d}-2s\bar{s}}{\sqrt{6}}$[a]	547.862 ± 0.018	0^+	0^{-+}	0	0	0	$(5.02 \pm 0.19) \times 10^{-19}$[b]	$\gamma + \gamma$ or $\pi^0 + \pi^0 + \pi^0$ or $\pi^+ + \pi^0 + \pi^-$
Eta prime meson[9]	$\eta'(958)$	Self	$\frac{u\bar{u}+d\bar{d}+s\bar{s}}{\sqrt{3}}$[a]	957.78 ± 0.06	0^+	0^{-+}	0	0	0	$(3.32 \pm 0.15) \times 10^{-21}$[b]	$\pi^+ + \pi^- + \eta$ or $(\rho^0 + \gamma)$ / $(\pi^+ + \pi^- + \gamma)$ or $\pi^0 + \pi^0 + \eta$
Charmed eta meson[10]	$\eta_c(1S)$	Self	$c\bar{c}$	2 983.6 ± 0.7	0^+	0^{-+}	0	0	0	$(2.04 \pm 0.05) \times 10^{-23}$[b]	See η_c decay modes
Bottom eta meson[11]	$\eta_b(1S)$	Self	$b\bar{b}$	9 398.0 ± 3.2	0^+	0^{-+}	0	0	0	Unknown	See η_b decay modes
Kaon[12]	K^+	K^-	$u\bar{s}$	493.677 ± 0.016	½	0^-	1	0	0	$(1.2380 \pm 0.0021) \times 10^{-8}$	$\mu^+ + \nu_\mu$ or $\pi^+ + \pi^0$ or $\pi^0 + e^+ + \nu_e$ or $\pi^+ + \pi^+ + \pi^-$
Kaon[13]	K^0	$\bar{K}^0$	$d\bar{s}$	497.614 ± 0.024	½	0^-	1	0	0	[c]	[c]

Vector meson ($J^P = 1^-$)

Particle name	Particle symbol	Antiparticle symbol	Quark content	Rest mass (MeV/c^2)	I^G	J^{PC}	S	C	B'	Mean lifetime (s)	Commonly decays to (>5% of decays)
Charged rho meson[23]	$\rho^+(770)$	$\rho^-(770)$	$u\bar{d}$	775.11 ±0.34	1^+	1^-	0	0	0	$(4.41 \pm 0.02) \times 10^{-24}$[f][g]	$\pi^\pm + \pi^0$
Neutral rho meson[23]	$\rho^0(770)$	Self	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$	775.26 ±0.25	1^+	1^{--}	0	0	0	$(4.45 \pm 0.03) \times 10^{-24}$[f][g]	$\pi^+ + \pi^-$
Omega meson[24]	$\omega(782)$	Self	$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	782.65 ±0.12	0^-	1^{--}	0	0	0	$(7.75 \pm 0.07) \times 10^{-23}$[f]	$\pi^+ + \pi^0 + \pi^-$ or $\pi^0 + \gamma$
Phi meson[25]	$\phi(1020)$	Self	$s\bar{s}$	1 019.461 ±0.019	0^-	1^{--}	0	0	0	$(1.54 \pm 0.01) \times 10^{-22}$[f]	$K^+ + K^-$ or $K^0_S + K^0_L$ or $(\rho + \pi) / (\pi^+ + \pi^0 + \pi^-)$
J/Psi[26]	J/ψ	Self	$c\bar{c}$	3 096.916 ±0.011	0^-	1^{--}	0	0	0	$(7.09 \pm 0.21) \times 10^{-21}$[f]	See J/ψ(1S) decay modes

Equations

$$s+u+t=m_1^2+m_2^2+m_3^2+m_4^2$$

$$s+u+t=Q^2+2m_p^2+m_\omega^2$$

$$x_B=\frac{Q^2}{2pq}$$

$$Q^2=-q^2$$

$$s=W^2=(p+q)^2$$

$$2pq=W^2-p^2-q^2$$

$$=W^2+Q^2-p^2$$

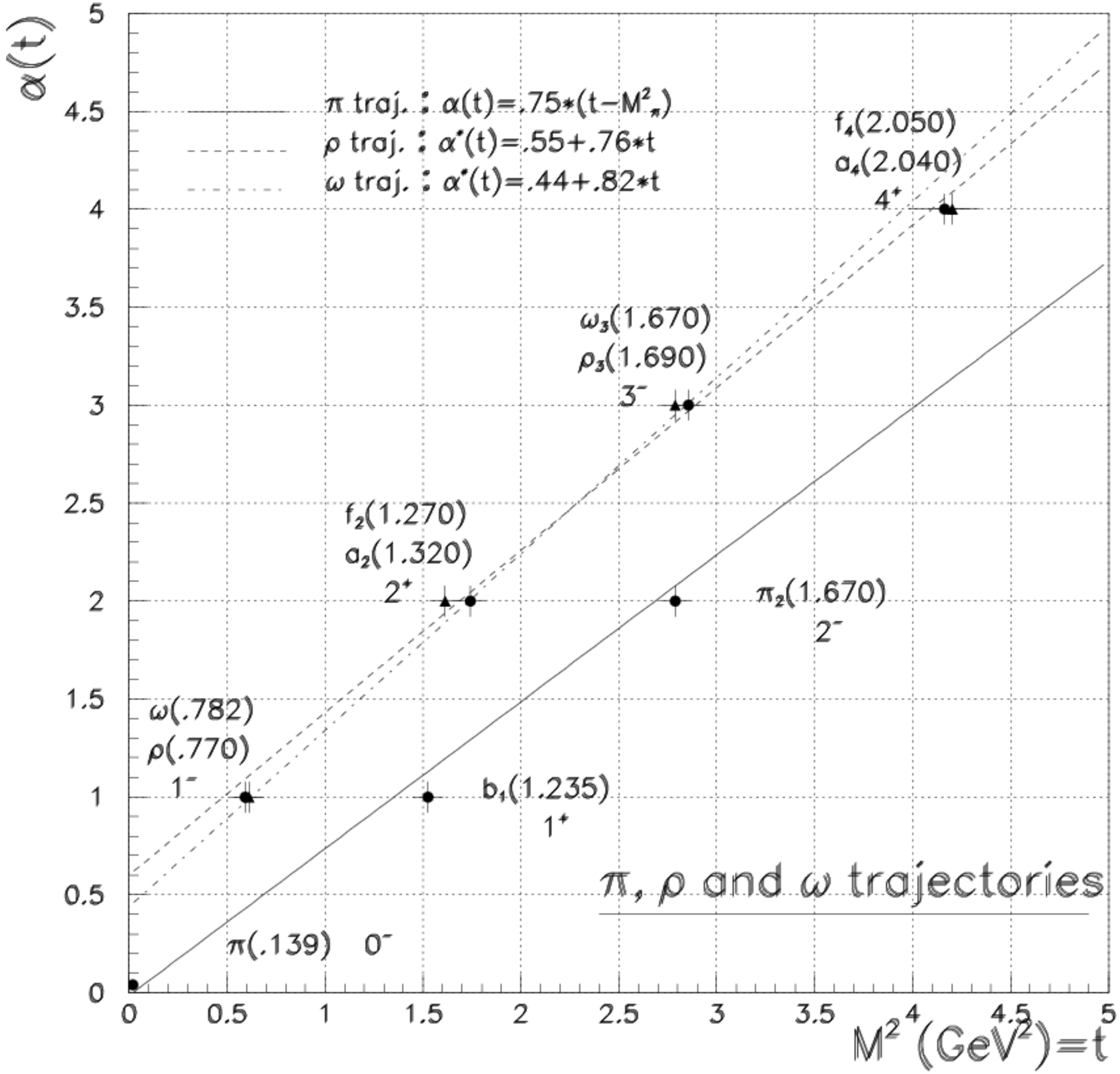
$$x=\frac{Q^2}{W^2+Q^2-p^2}$$

$$=\frac{Q^2}{W^2+Q^2-m_p{}^2}\text{(Fixed target)}$$

Wenliang Li, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.

Regge Trajectory Based Model by JML

L. Morand, Ph.D. Thesis, University of Paris 2003



J. M. Laget, Phys. Rev. D 70, 054023 – Published 28 September 2004

Produced vector meson	Exchanged Regge trajectories
ρ	σ, f_2, P/2g
ω	π^0, f_2, P/2g
ϕ	P/2g

Hall B public page

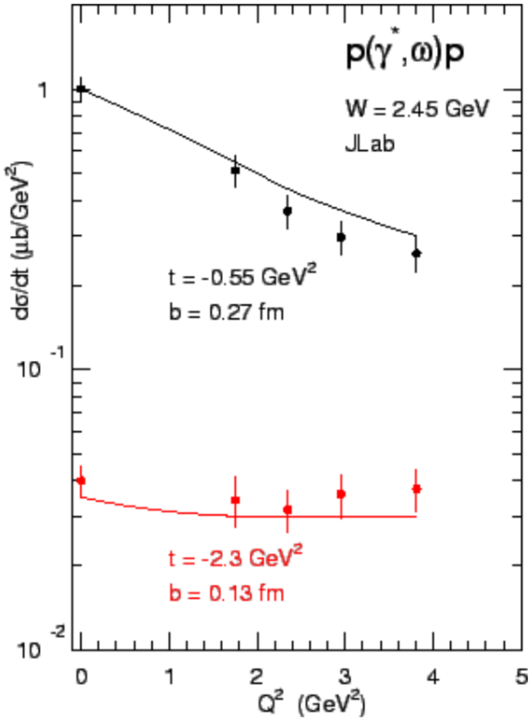


Figure 2: When the impact parameter is large (top), the cross section for ω meson production falls quickly as a function of Q^2. But when the experiment selects the kinematics corresponding to small impact parameter (bottom), the cross section becomes constant with Q^2 indicating that the interaction takes place between quarks.

Hall B public page:
https://www.jlab.org/Hall-B/public/hight_vmweb.html#fig2

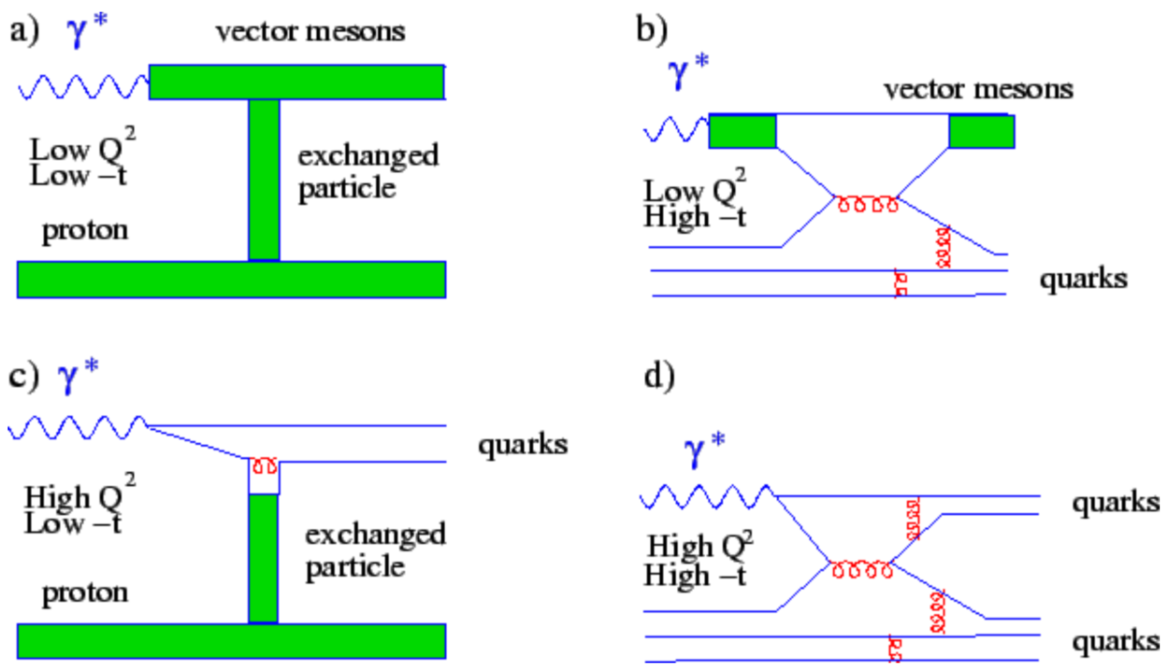
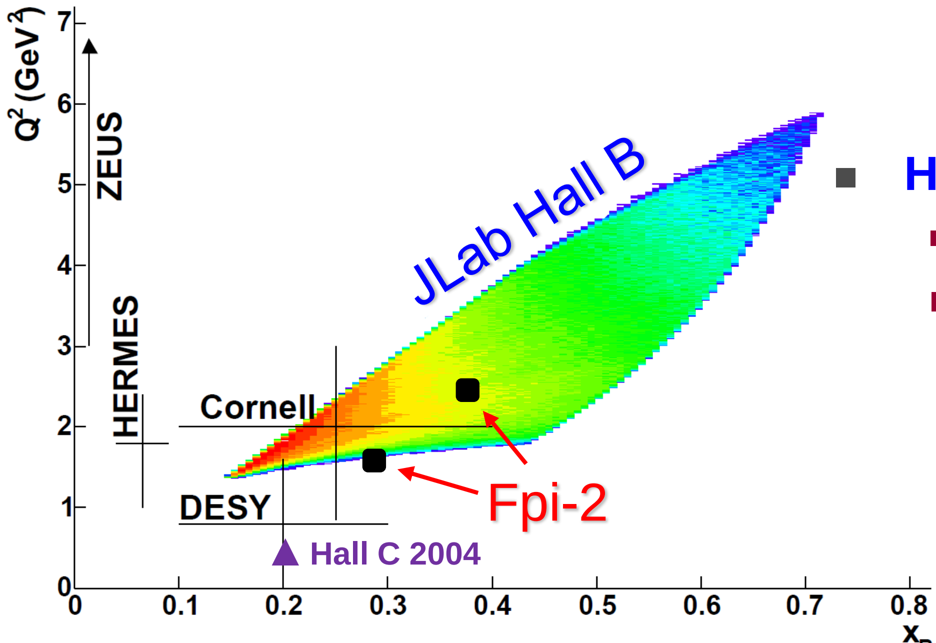


Figure 3: These diagrams depict the effective interaction at low energies of composite particles (green bars) and how the substructure is revealed by selected kinematics. The substructure of the incoming photon beam is revealed at high Q^2, and the constituents of the target are uncovered using large-angle scattering, or high *-t* reactions.

Exclusive ω electro-production data

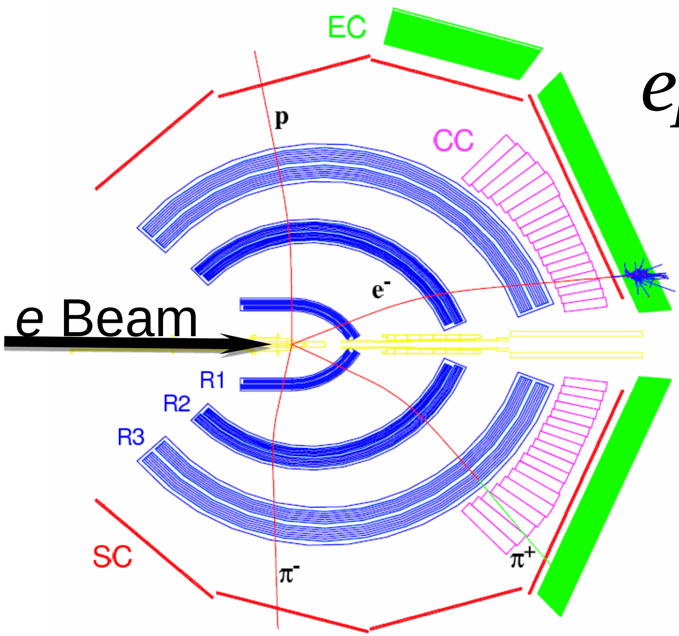


- **Hall B data:**
  - Wide coverage
  - Highest –*t*

	Q^2 GeV^2	*W* GeV	*x*	-*t* GeV^2
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 (2017?)	1.6, 2.45	2.21	0.29, 0.38	4.0, 4.74

High t Data from CLAS Hall B (2005)

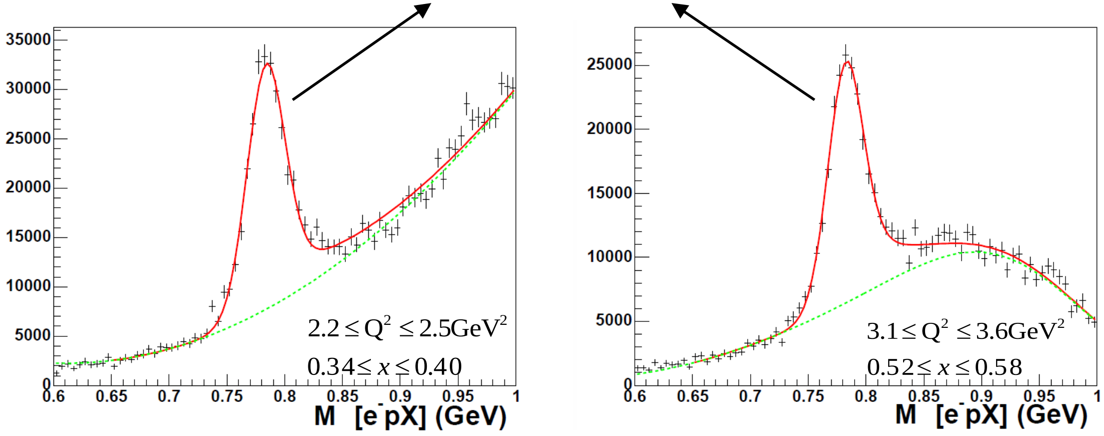
Morand et al., Eur. Phys. J. A 24, 445 (2005).



$ep \rightarrow ep\omega$

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

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



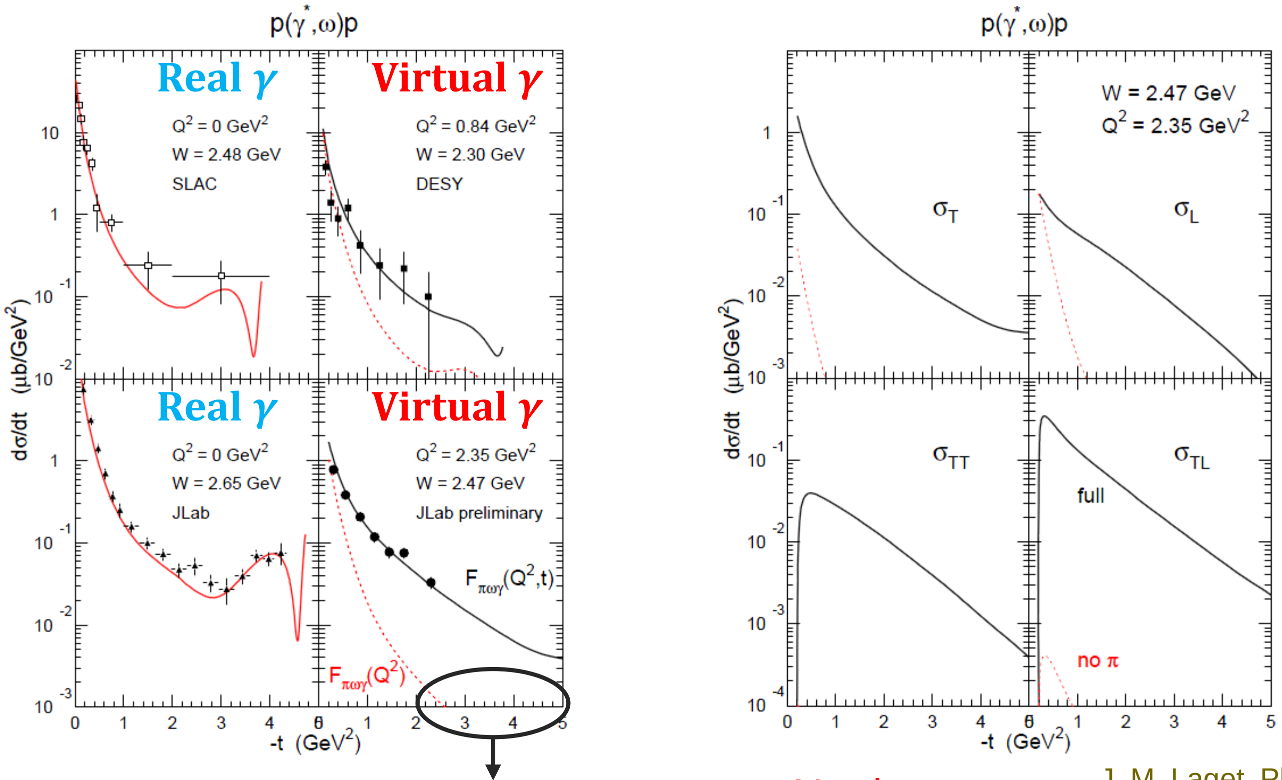
Missing mass reconstruction e^-pX

- Hall B Experiment **e1-6**
  - Oct 2001 – Jan 2002
  - Beam energy: 5.754 GeV
- Kinematic coverage:
  - *W* : 1.8-2.8 GeV
  - Q2: 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 2005:
  - Morand et al., Eur. Phys. J. A 24, 445 (2005).

Regge Trajectory Model by JM Laget



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

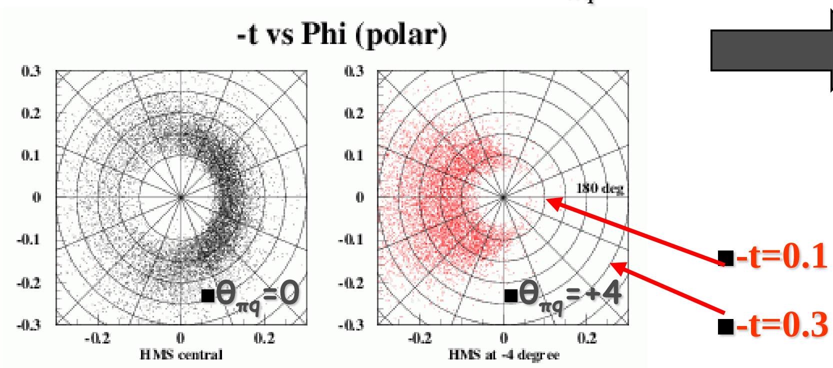
No data yet,

Fpi2 kinematics Q^2=2.54, W=2.21, $-t$=4.7

- “The determination of the dependency against the momentum transfer *t* of the longitudinal and the transverse parts of the **various meson electro-production channels must be actively pursued at JLab energy range**”
- It would be great if JML could make a calculation similar for Fpi-2 kinematics

Extract Response Functions through Iterative Procedure

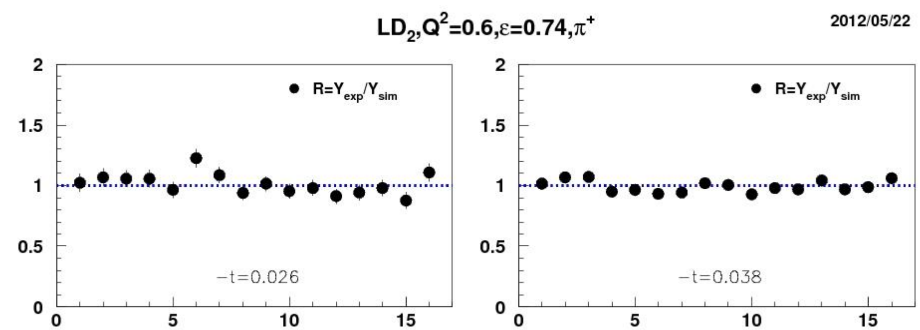
Improve φ coverage by taking data at multiple π (HMS) angles, $-4^{o}<\theta_{\pi q}<4^{o}$.



For each π HMS setting, form ratio:

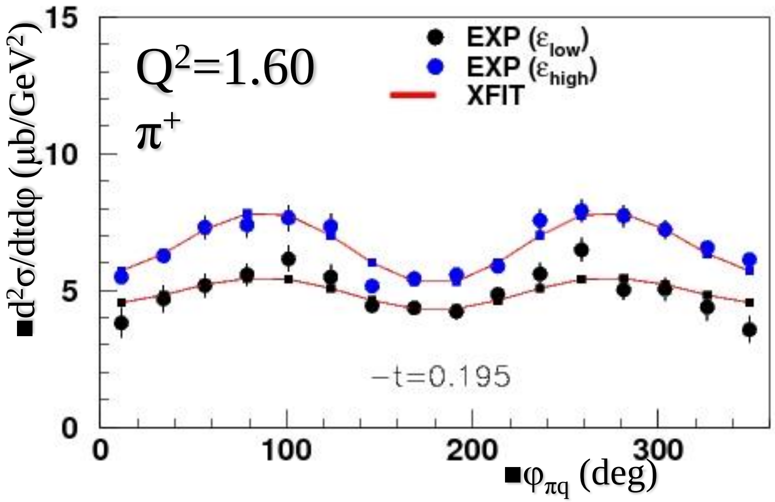
$$R=\frac{Y_{EXP}}{Y_{SIMC}}$$

Combine ratios for π settings together, propagating errors accordingly.



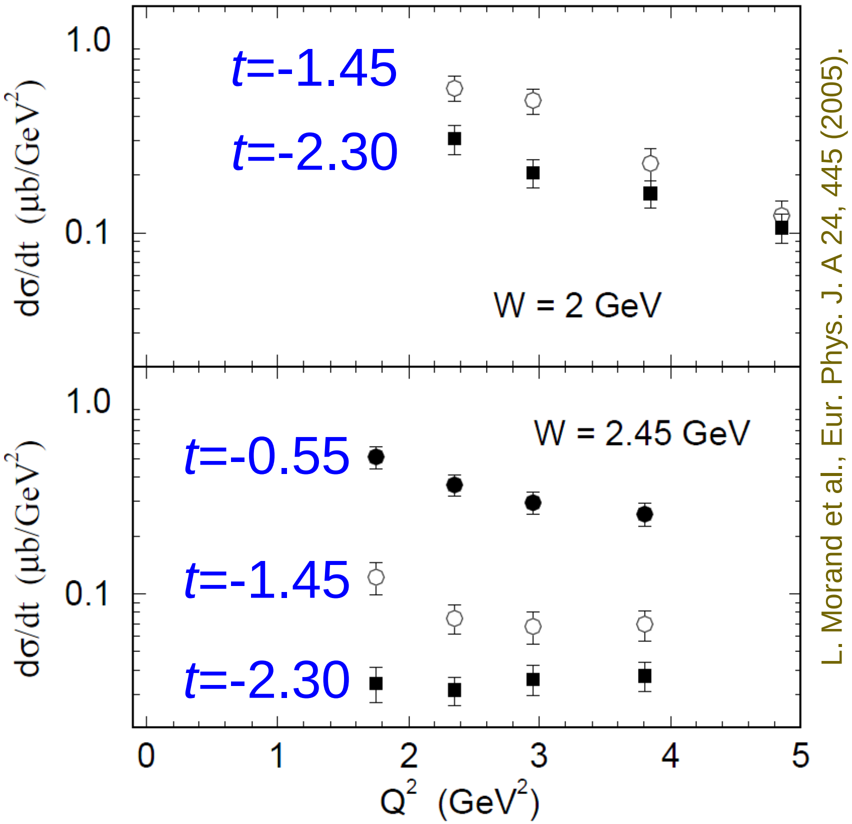
Extract via simultaneous fit of L,T,LT,TT

$$\frac{d^2\sigma}{dt d\varphi}_{EXP}=\left(\frac{Y_{EXP}}{Y_{SIMC}}\right)\frac{d^2\sigma}{dt d\varphi}_{SIMC}$$



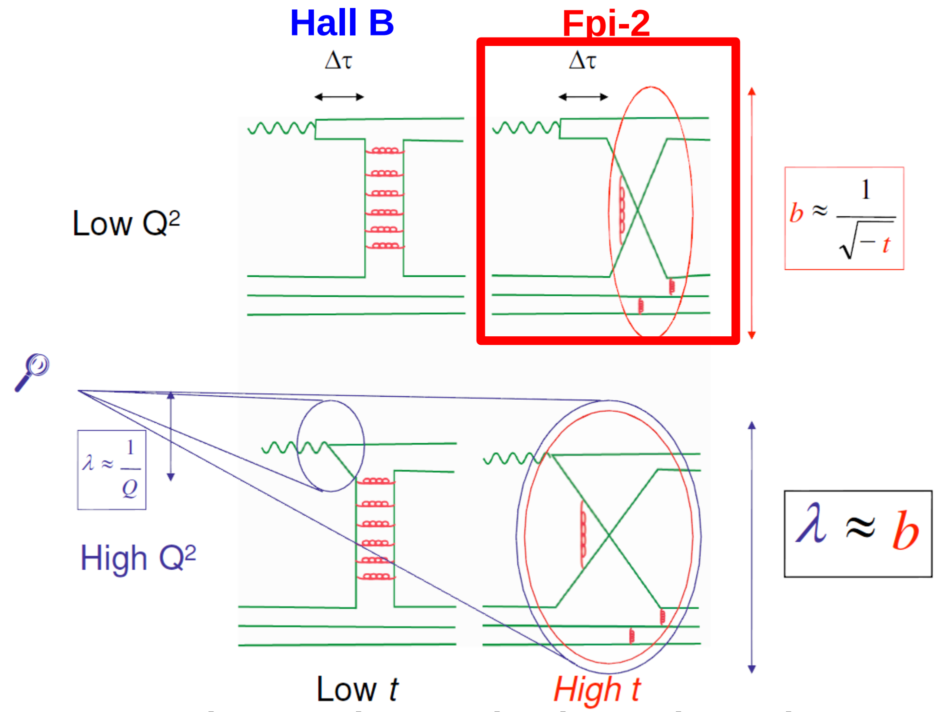
$$2\pi\frac{d\sigma}{dt\,d\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

High -*t* Data from CLAS Hall B (2005)



Hall B & Fpi-2 kinematics comparison

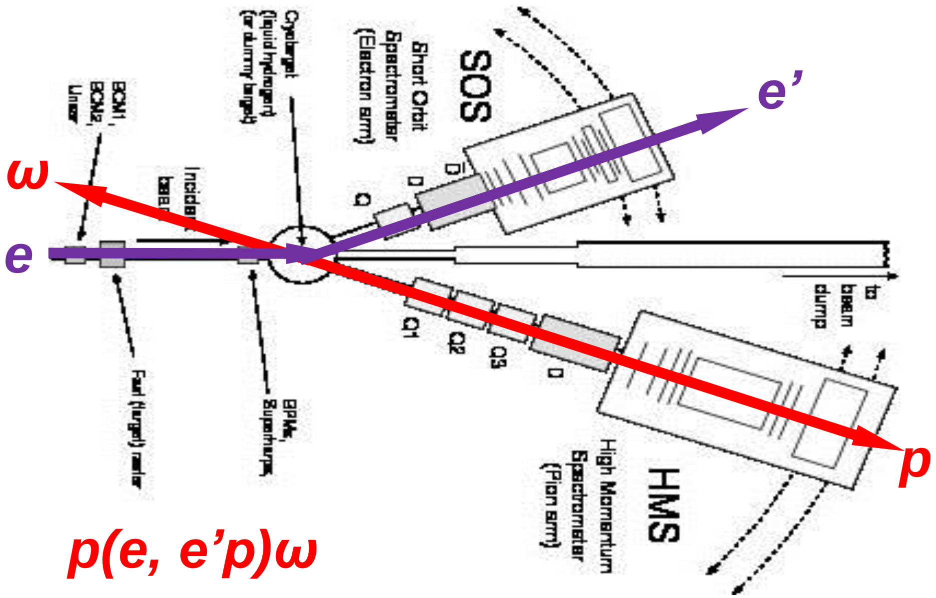
	W (GeV)	x	Q^2 (GeV²)	**-*t* (GeV²)**	**-*u* (GeV²)**
Hall B	1.8-2.8	0.16-0.64	1.6-5.1	**< 2.7**	**> 1.68**
Fpi-2	2.21	0.29	1.6	**4.014**	**0.08-0.13**
		0.38	2.54	**4.724**	**0.17-0.24**



Hard Scattering Mechanism schematics

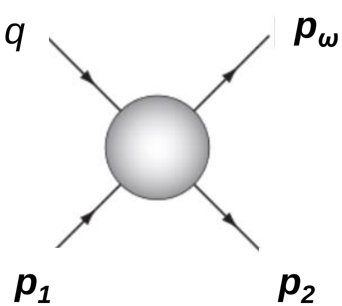
- **Excitement:**
  - **Observation: Q² independent cross section at high -*t***
  - **Possible interoperation: Virtual photon is more likely to couple to a point-like object as -*t* increases.**

Backward Angle (u-Channel) ω Production



E_{beam} GeV	ϵ	$P_{\rm SOS}$ GeV/c	$\theta_{\rm SOS}$ deg	$P_{\rm HMS}$ GeV/c	θ_q deg	$\theta_{\rm HMS}$ deg
$Q^2_{nominal}$ = 1.6 GeV^2 $W_{nominal}$ = 2.21 GeV						
3.778	0.328	-0.79	43.09	2.931	-9.53	−10.53 −12.53
4.702	0.593	-1.65	25.73	2.931	-13.28	−13.28 −10.58 −16.28
$Q^2_{nominal}$ = 2.45 GeV^2 $W_{nominal}$ = 2.21 GeV						
4.210	0.270	-0.77	51.48	3.336	-9.19	−10.59 −12.19
5.248	0.554	-1.74	29.43	3.336	-13.61	−13.61 −10.61 −16.61

$$\gamma^*(q) + p(p_1) \rightarrow \omega(p_\omega) + p(p_2)$$



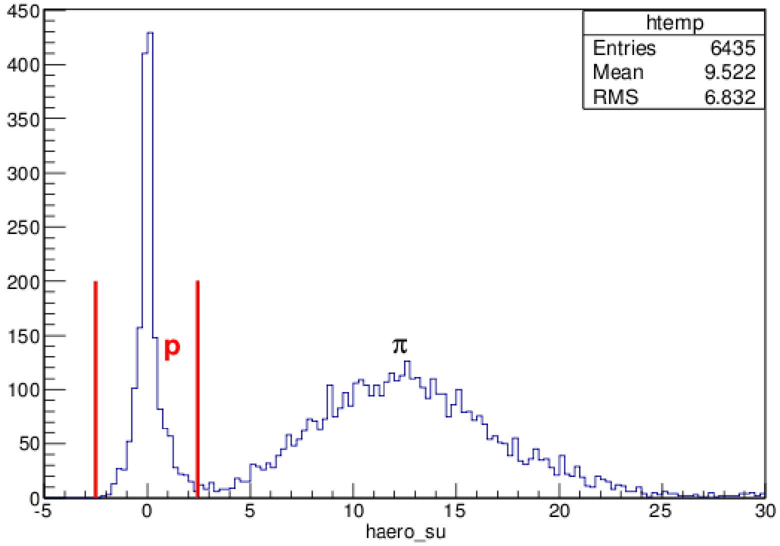
$$s = (p_1 + q)^2 = (p_\omega + p_2)^2$$

$$t = (p_2 - p_1)^2 = (p_\omega - q)^2$$

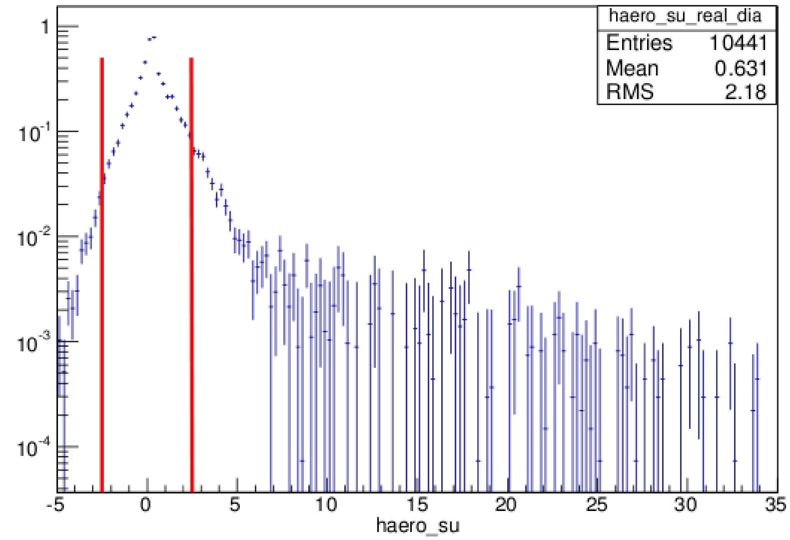
$$u = (p_\omega - p_1)^2 = (p_2 - q)^2$$

- Experiment was carried out at Hall C, Jefferson Lab 2004
- HMS (recoiled proton) along the *q*-vector (p_{γ^*})
  - p_ω is anti-parallel to p_{γ^*}
- *t:* Comparing *p* before and after interaction
- *u:* Comparing *p* before interaction with *ω* after interaction
- *u*-channel interaction when *u*~0

Analysis: Efficiency Study

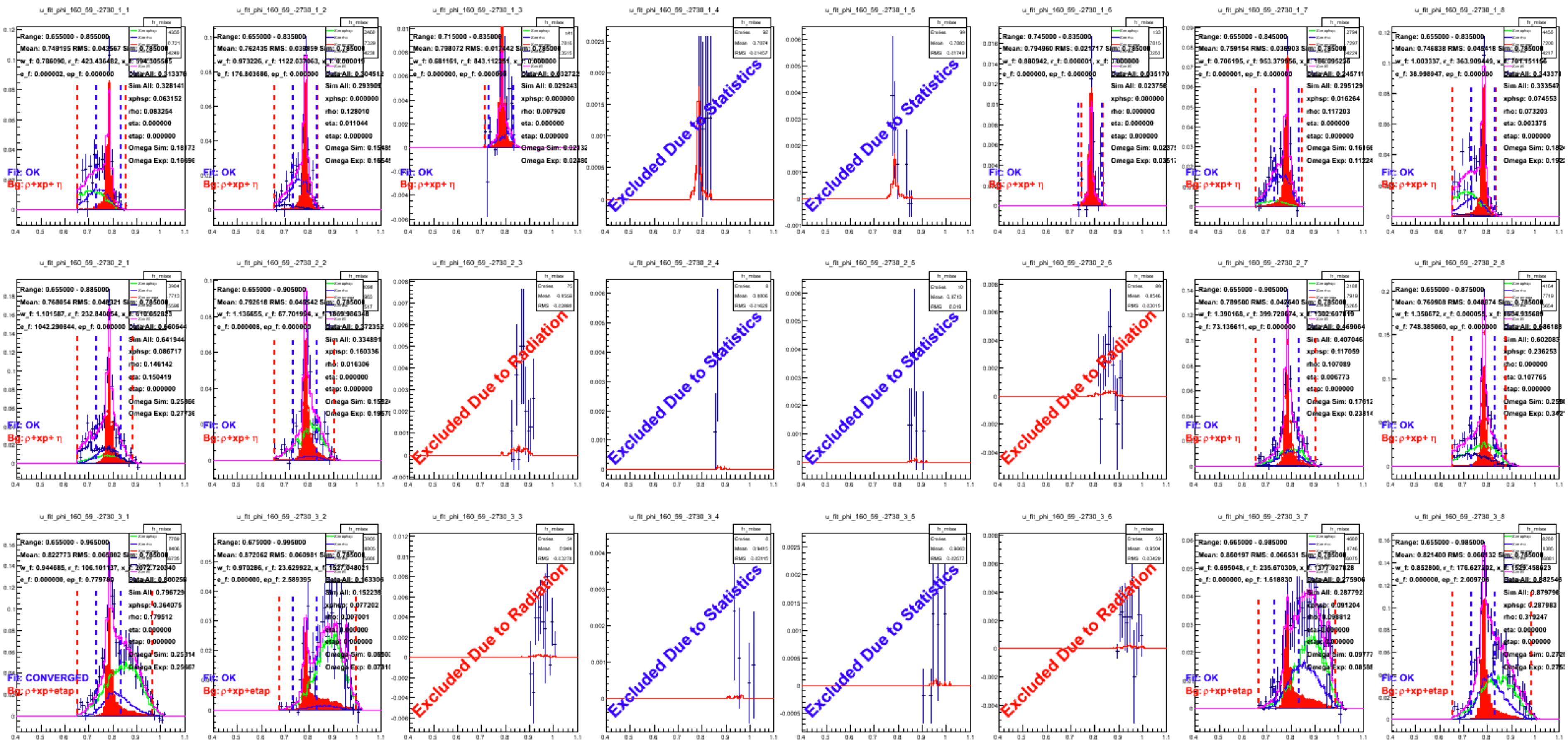


(a) Without hsbeta-cointime cut



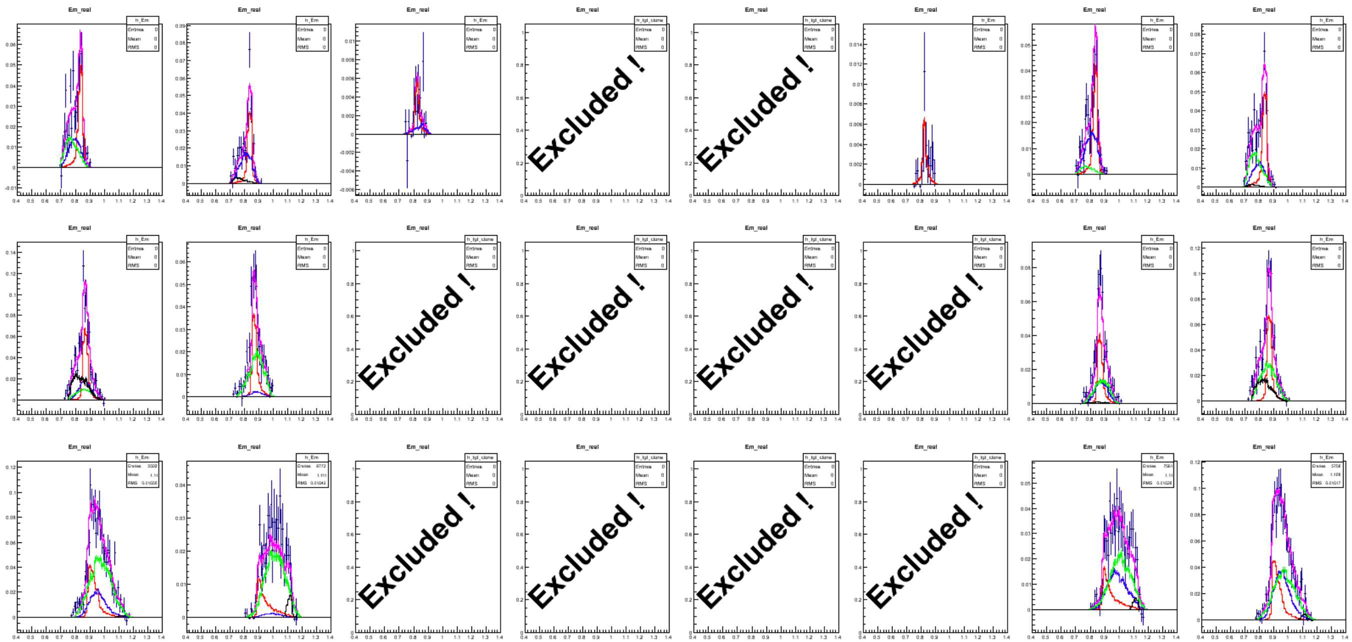
(b) With hsbeta-cointime cut

Missing Mass Distribution Background Extraction

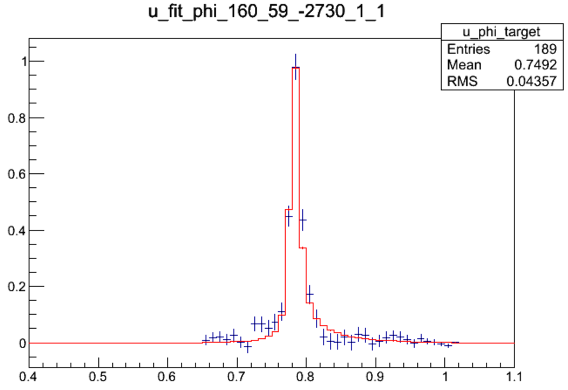


- Integration limits and fitting limits
- Exclusion criteria
  - Exclude the radiative only omega bins
  - Exclude the low statistics bins

Background Subtraction Checking



Reconstructed the E_m distribution, with missing mass scale factor

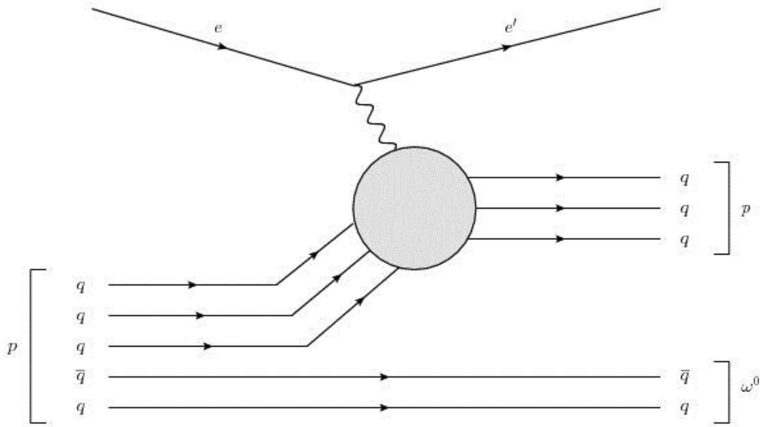


Sum of the data from each bin

sum of the Omega sim from each bin

u-Channel ω^0 Production

Christian Weiss: "A proton being knocked out of a proton"



$$\gamma^*(q) + p(p_1) \rightarrow \omega(p_\omega) + p(p_2)$$

$$s = (p_1 + q)^2 = (p_\omega + p_2)^2$$

$$t = (p_2 - p_1)^2 = (p_\omega - q)^2$$

$$u = (p_\omega - p_1)^2 = (p_2 - q)^2$$

E_{beam} GeV	ϵ	$\theta_{\mathrm{HMS}} - \theta_q$ deg	x	P_ω GeV^2/c^2	$\theta_{\omega q}$ GeV^2/c^2	$-t$	$-u$
		$Q^2_{nominal}$ = 1.6 GeV^2		$W_{nominal}$ = 2.21 GeV			
3.778	0.328	−1.0	0.2855	0.311	9.17	4.014	0.087
		−3.0		0.367	24.59		0.129
4.702	0.593	0.0	0.2855	0.304	0.09	4.014	0.082
		2.7		0.357	22.93		0.121
		−3.0		0.367	24.61		0.129
		$Q^2_{nominal}$ = 2.45 GeV^2		$W_{nominal}$ = 2.21 GeV			
4.210	0.270	−1.4	0.3796	0.431	10.57	4.742	0.184
		−3.0		0.491	20.82		0.241
5.248	0.554	0.0	0.3796	0.415	0.00	4.742	0.169
		3.0		0.490	20.75		0.240
		−3.0		0.491	20.79		0.241

- In fixed target experiment
  - *t:* Comparing *p* before and after interaction
  - *u:* Comparing *p* before interaction with *ω* after interaction
  - *u*-channel interaction when *u*~0
- High *t* corresponds to low *u*
  - $|u|_{min} = 0$

Kinematics Table

E_{beam} GeV	ϵ	$P_{\rm SOS}$ GeV/c	$\theta_{\rm SOS}$ deg	$P_{\rm HMS}$ GeV/c	θ_q deg	$\theta_{\rm HMS}$ deg
$Q^2_{nominal}$ = 1.6 GeV^2 $W_{nominal}$ = 2.21 GeV						
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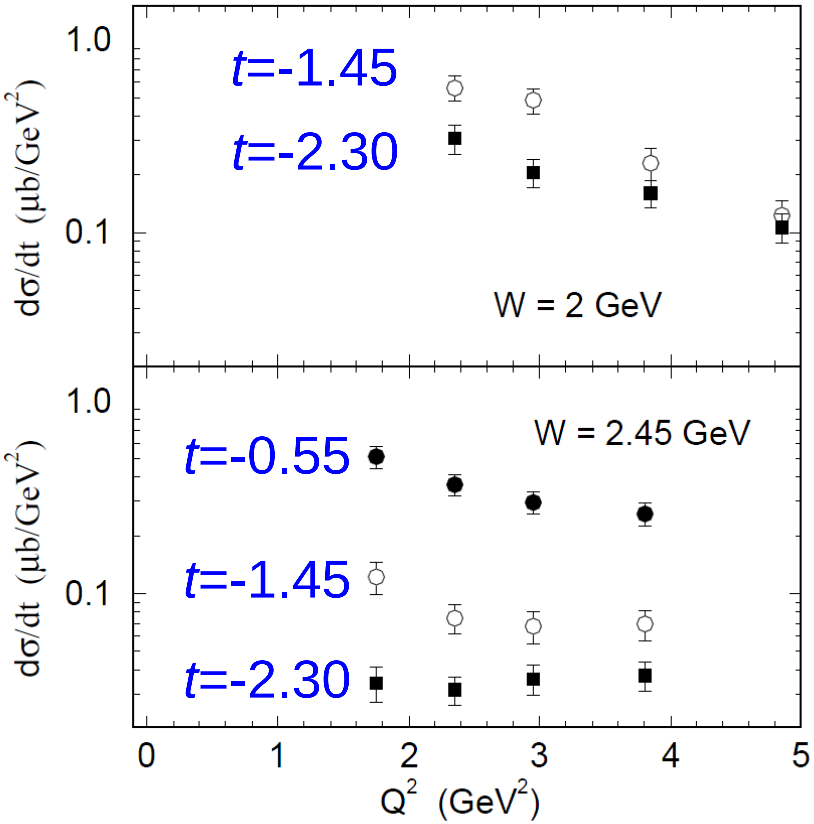
$Q^2_{nominal}$ = 2.45 GeV^2 $W_{nominal}$ = 2.21 GeV						
4.210	0.270	-0.77	51.48	3.336	-9.19	-10.59 -12.19
5.248	0.554	-1.74	29.43	3.336	-13.61	-13.61 -10.61 -16.61

E_{beam} GeV	ϵ	$\theta_{\rm HMS}-\theta_q$ deg	x	P_ω GeV/c	$\theta_{\omega q}$ deg	$-t$ GeV^2/c^2	$-u$ GeV^2/c^2	θ^*_ω	θ^*_p
$Q^2_{nominal}$ = 1.6 GeV^2 $W_{nominal}$ = 2.21 GeV									
3.778	0.330	-0.9 -3.0	0.2855	0.311 0.367	8.8 24.3	4.014	0.088 0.129	176.0 167.4	-3.8 -12.7
4.702	0.593	0.0 2.7 -3.0	0.2855	0.304 0.357 0.367	0.1 -22.9 24.6	4.014	0.082 0.121 0.129	180.0 -168.4 167.2	0.0 11.4 -12.6
$Q^2_{nominal}$ = 2.45 GeV^2 $W_{nominal}$ = 2.21 GeV									
4.210	0.270	-1.4 -3.0	0.3796	0.431 0.491	10.5 20.8	4.742	0.184 0.242	173.4 165.4	-6.8 -14.5
5.248	0.554	0.0 3.0 -3.0	0.3796	0.415 0.490 0.491	0.0 20.7 -20.7	4.742	0.170 0.241 0.241	180.0 -165.2 165.3	0.0 14.3 -14.3

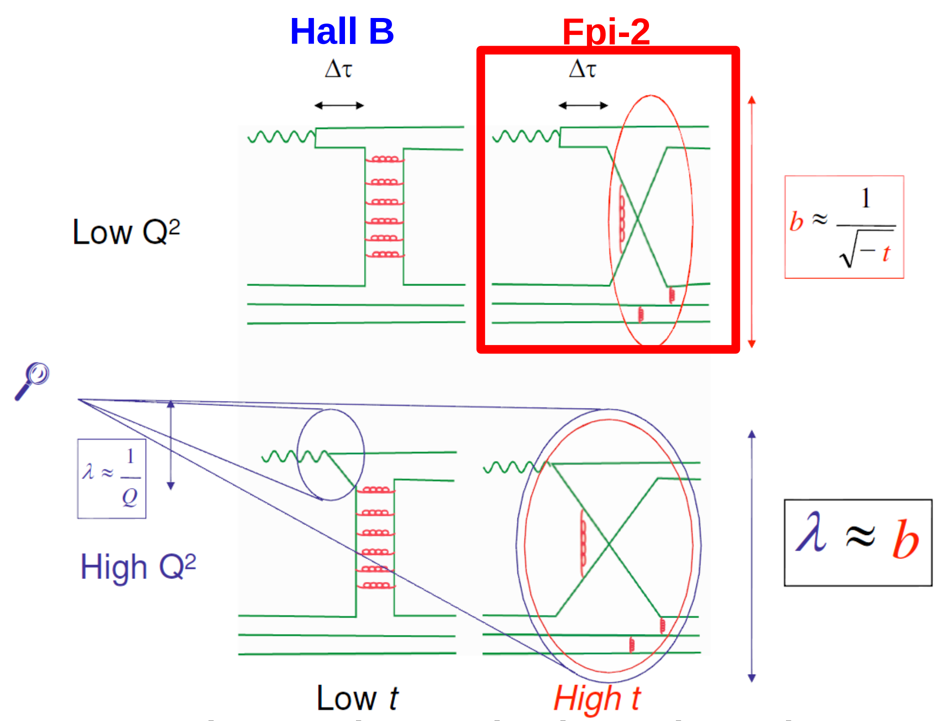
High -*t* Data from CLAS Hall B (2005)



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

Hall B & Fpi-2 kinematics comparison

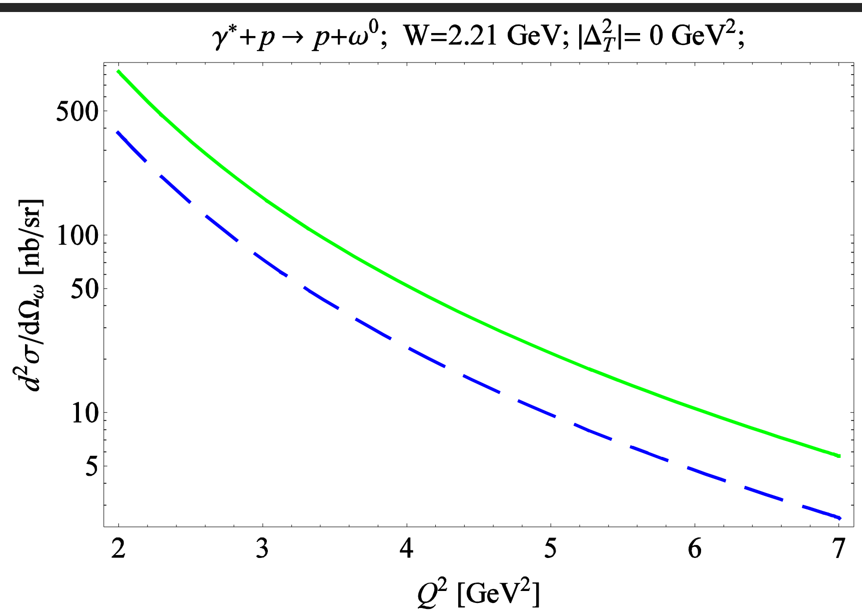
	W (GeV)	x	Q^2 (GeV²)	**$-t$ (GeV²)**	**$-u$ (GeV²)**
Hall B	1.8-2.8	0.16-0.64	1.6-5.1	**< 2.7**	**> 1.68**
Fpi-2	2.21	0.29	1.6	**4.014**	**0.08-0.13**
		0.38	2.54	**4.724**	**0.17-0.24**

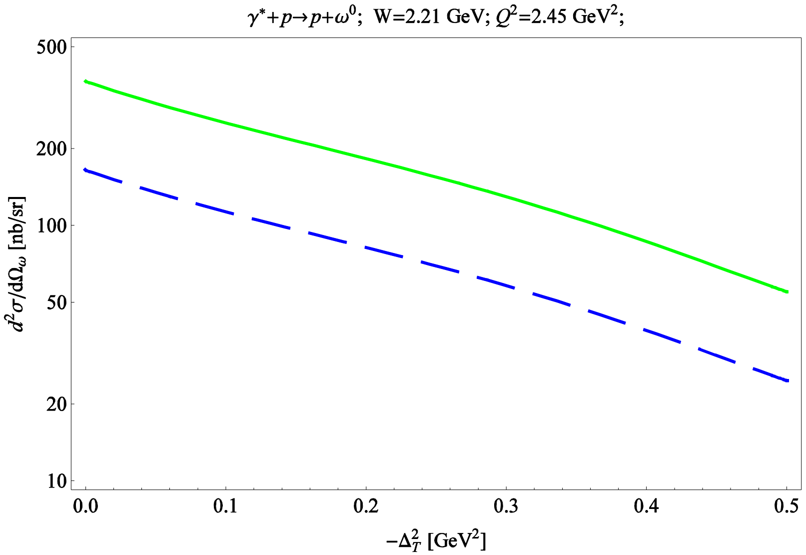


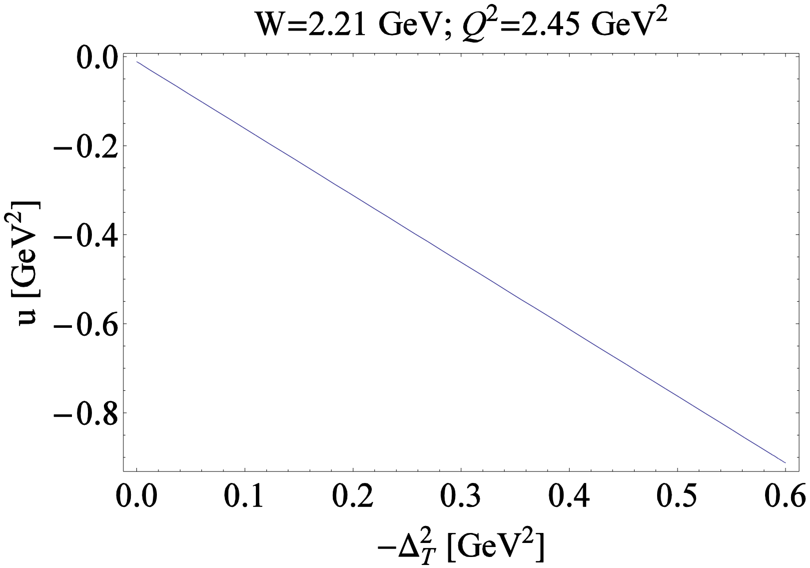
Hard Scattering Mechanism schematics

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

TDA Prediction (Private Communication)







$Q^2 = 2.45$ GeV^2, $W = 2.21$ GeV

KS model

$u = -0.184$ GeV^2 $d^2\sigma/d\Omega_\omega = 326.22$ [nb/sr]

$u = -0.242$ GeV^2 $d^2\sigma/d\Omega_\omega = 331.877$ [nb/sr]

$u = -0.17$ GeV^2 $d^2\sigma/d\Omega_\omega = 326.234$ [nb/sr]

$u = -0.241$ GeV^2 $d^2\sigma/d\Omega_\omega = 331.703$ [nb/sr]

$Q^2 = 2.45$ GeV^2, $W = 2.21$ GeV

COS model

$u = -0.184$ GeV^2 $d^2\sigma/d\Omega_\omega = 146.455$ [nb/sr]

$u = -0.242$ GeV^2 $d^2\sigma/d\Omega_\omega = 148.995$ [nb/sr]

$u = -0.17$ GeV^2 $d^2\sigma/d\Omega_\omega = 146.461$ [nb/sr]

$u = -0.241$ GeV^2 $d^2\sigma/d\Omega_\omega = 148.916$ [nb/sr]