GPD Workshop at Stony Brook University: Backward Angle Meson Production

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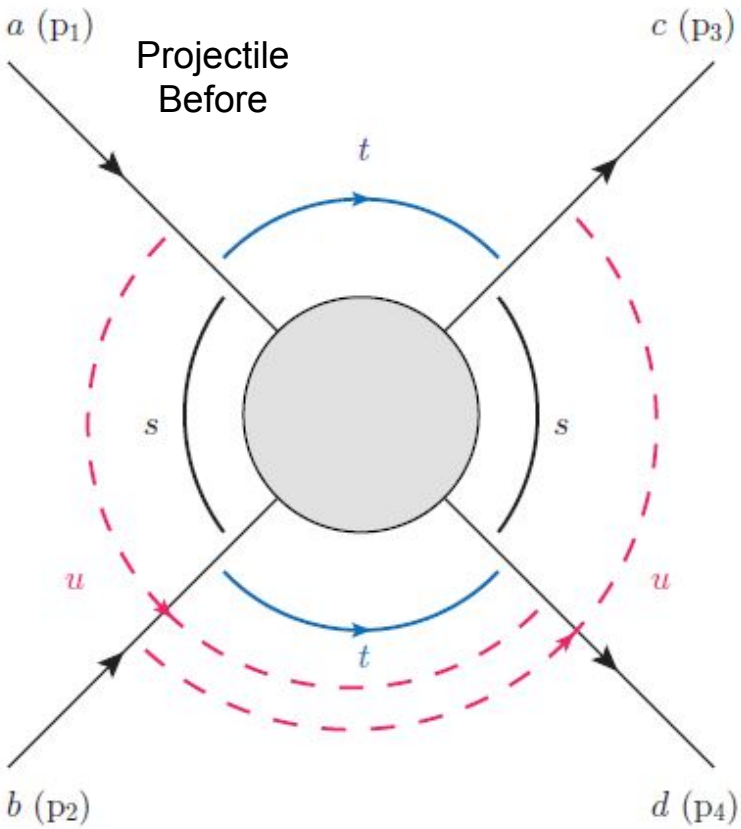
Outline

- Introduction to the backward angle physics
- An example analysis for the backward production
- Theory framework
  - Regge
  - Transition Distribution Amplitude
- Lead-out for the backward meson production at EIC (from JLab 12 GeV)
- Backward meson production at EIC and PANDA

Mandelstam variables (*s*,*t*,*u*-Channels)



Target Before

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

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

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

- ***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

$$t \approx t_{min}, \; u \approx u_{max}, \; t < Q^2$$

- ***u*-channel: *-u~0*, after interaction**
  - Target: forward
  - Meson: stationary

$$u \approx u_{min}, \; t \approx t_{max}, \; t > Q^2$$

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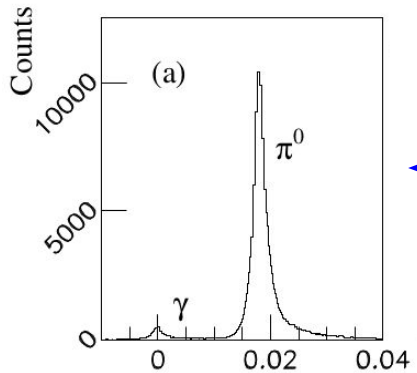
6 GeV Backward Angle Physics at W < 2 GeV

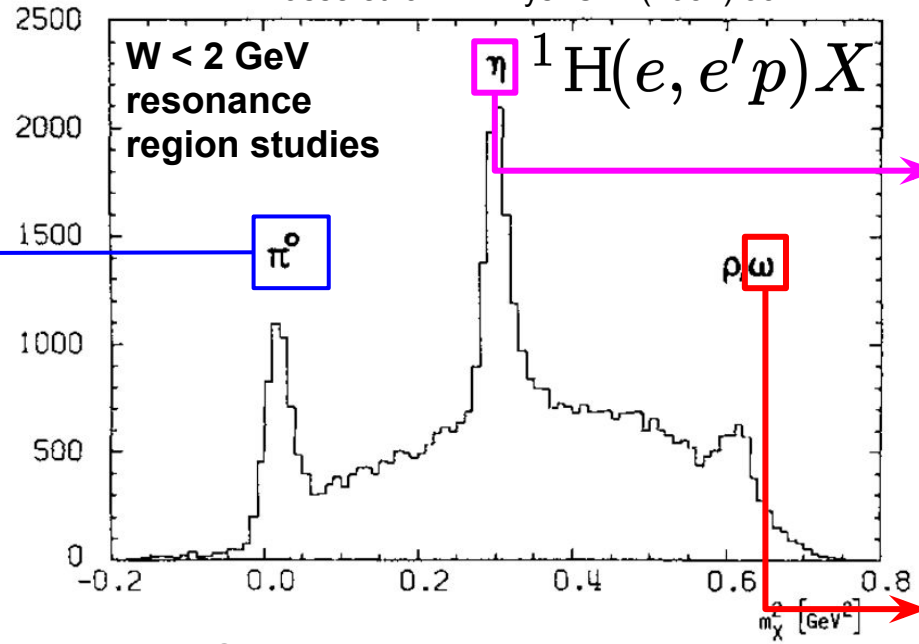
G. Laveissière et al. Phys. Rev. C 79, 015201 (2004)



Hall A VCS experiments:
E93-050
E00-110

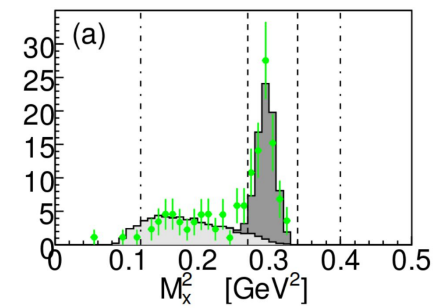
Hall C: E01-002

F. W. Brasse et. al. Z. Phys. C22 (1984) 33



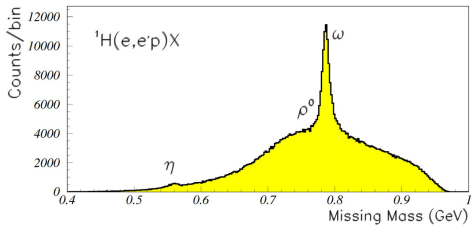
DESY spectrometer experiment

M. Dalton et al. Phys. Rev. C 80, 015205 (2008)



Hall C E01-002

P. AmbrozwiczPhys. Rev. C 70, 035203 (2004)

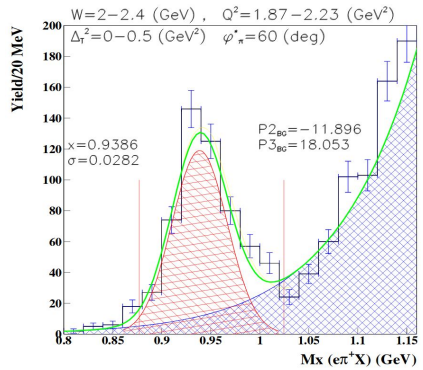


Hall C E91-016

- **Backward Angle physics is not a new concept**
- **Common features: resonance region studies.**

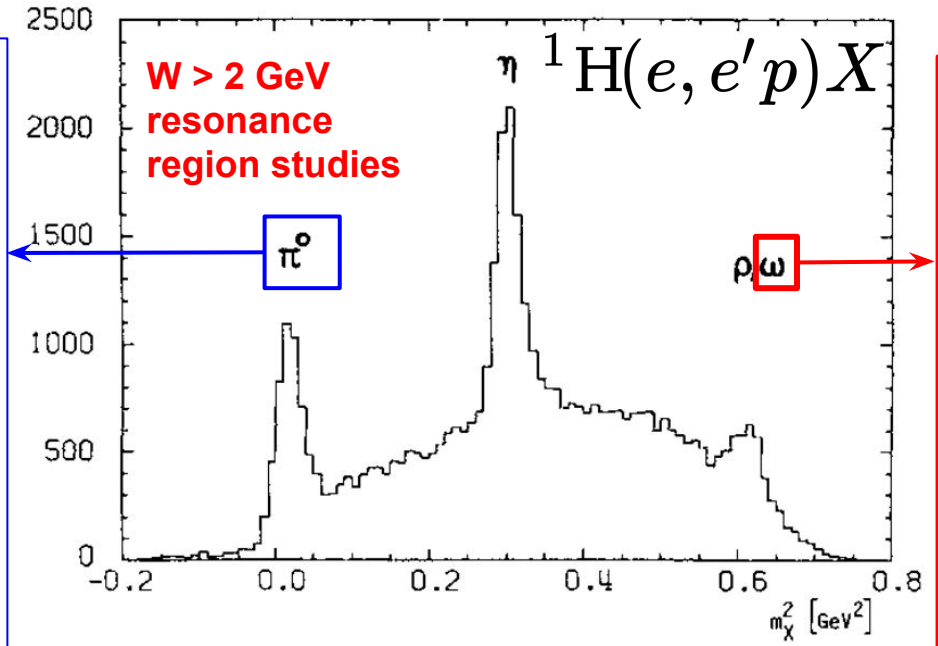
6 GeV Backward Angle Physics at W > 2 GeV

Charged Pion Production from CLAS 6

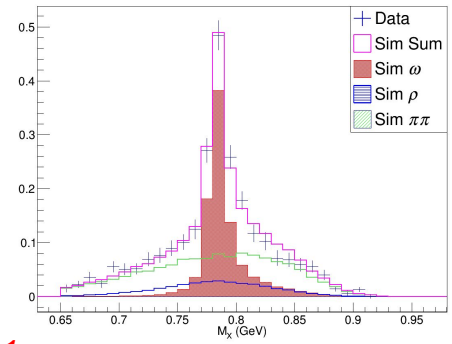


^{1}H*(e, e'π$^+$)X*

- Q^2 Scaling



Hall C experiment E001-004



^{1}H*(e, e'p)X*

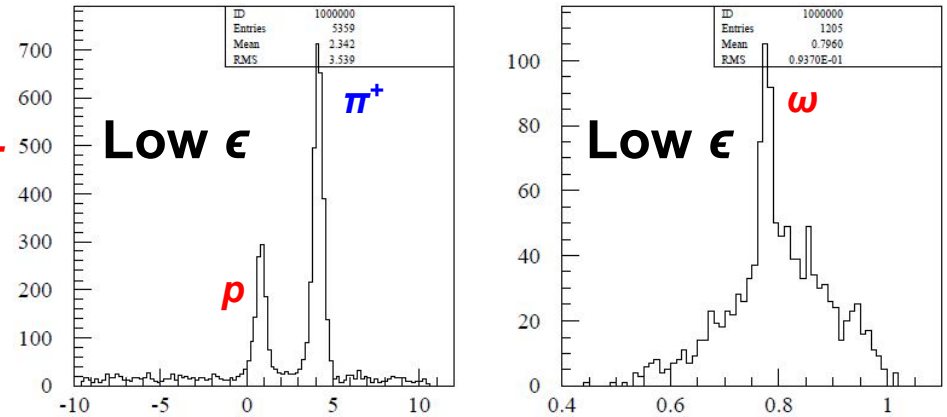
- Parasitic data
- Full L/T separation

- **Backward angle physics in this talk: backward angle physics above the resonance region (W>2 GeV^2)**
- ***u'* -> u_{min}, *t* > Q^2**
- **A systematic backward angle physics program:**
  - **JLab 6 -> JLab 12 -> EIC**

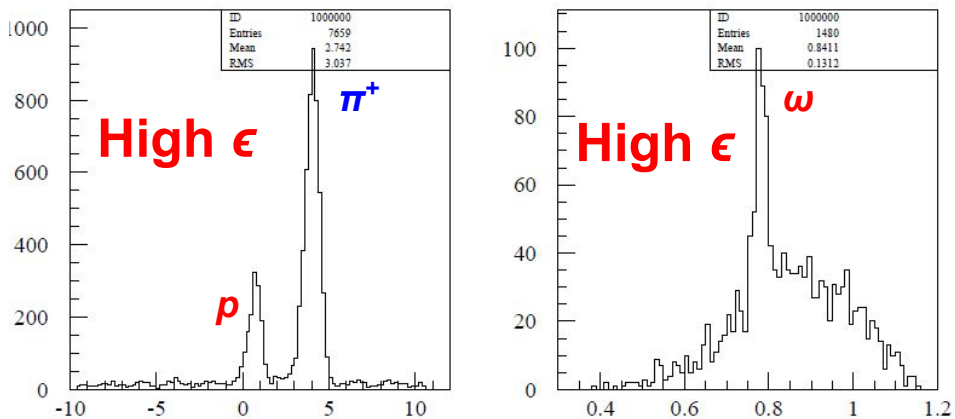
Backward Angle Example from 6 GeV Era

- **Fpi-2 (E01-004) 2003**
  - Spokesperson: **Garth Huber, Henk Blok**
  - Standard HMS and SOS (e) configuration
  - **Electric form factor of charged π** 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
- **LT Separation!**

Q^2=2.45 GeV^2 **2003** 2003/07/25 08.56

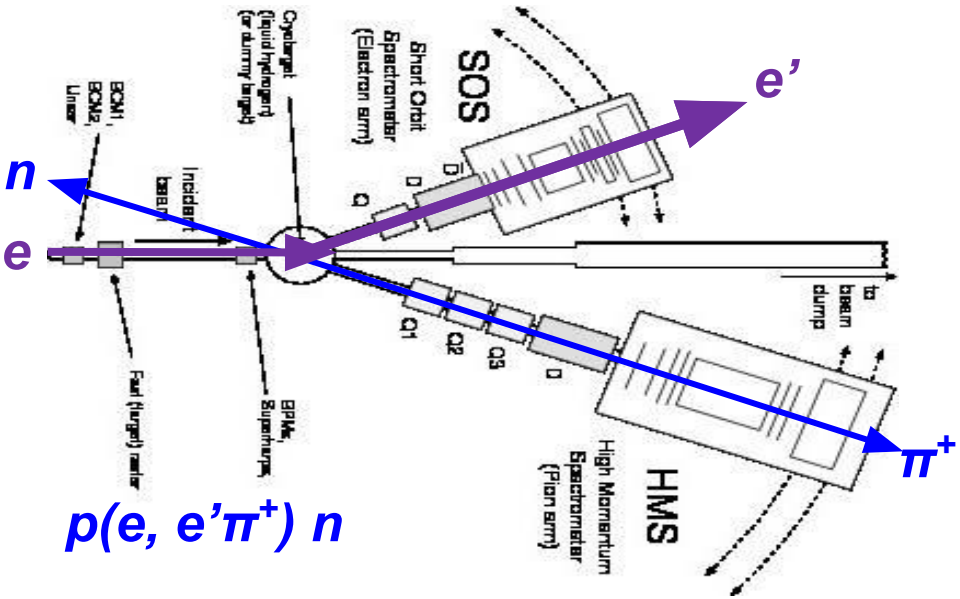


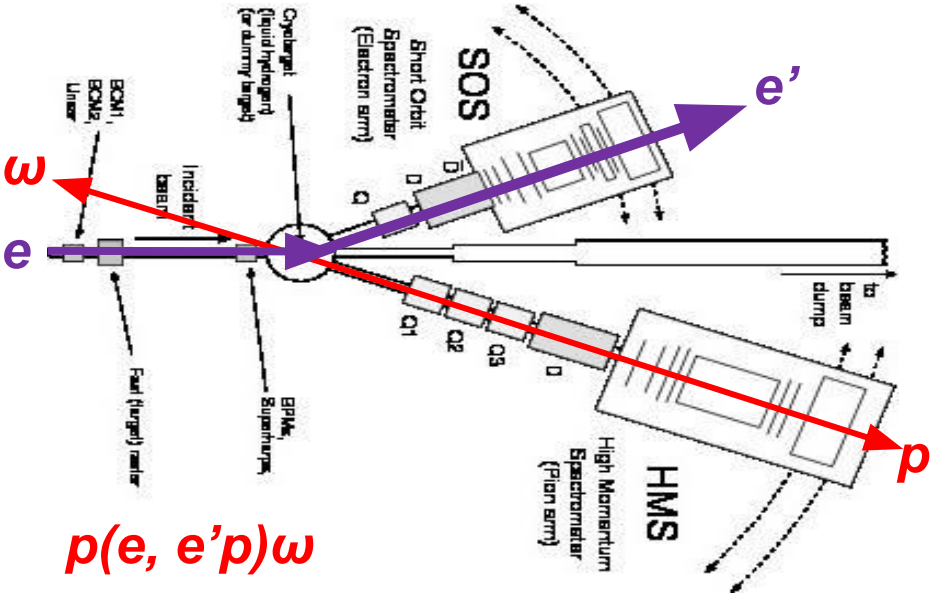
Coincidence time ***epX* missing mass**



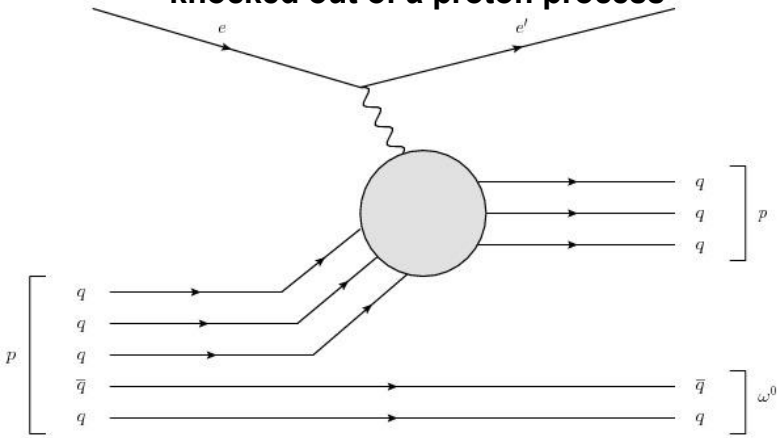
Coincidence time ***epX* missing mass**

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



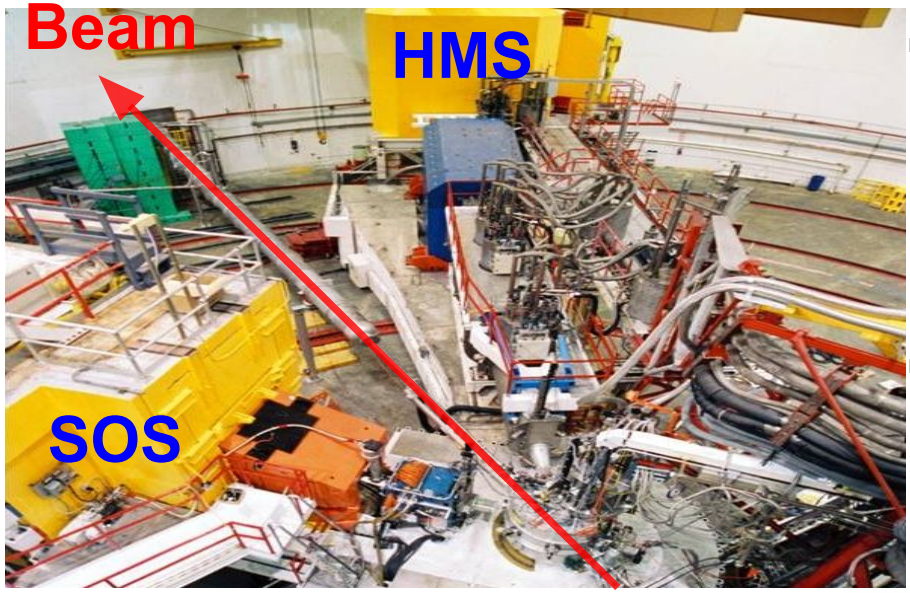


Mark Strikman and Christian Weiss: A proton being knocked out of a proton process



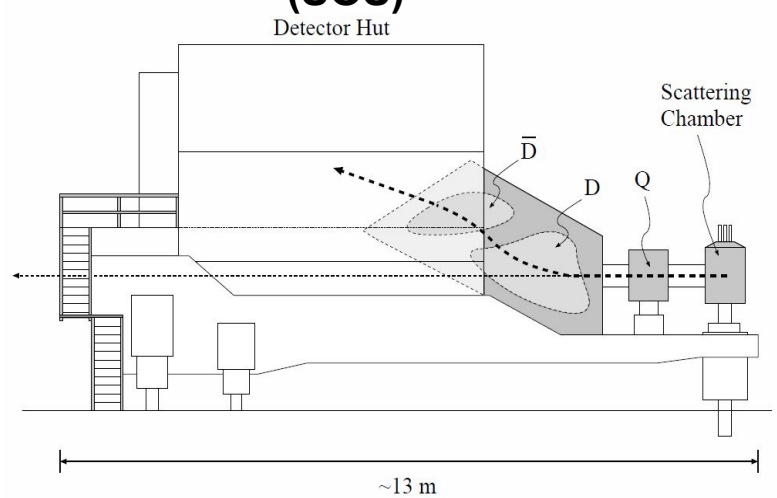
- **HMS along the *q*-vector (p_{γ^*})**
  - p_{π^+} is parallel to p_{γ^*} (Forward)
  - p_{ω} is anti-parallel to p_{γ^*} (Backward)
- **Exclusive channel!**
  - $p(e,e'\,p)\omega$
  - We donot detect any part of decayed ω
  - Contain physics background
- **Full L/T separation on this *u*-channel process**
- **One of the last Hall C 6 GeV analysis**

Experimental Setup

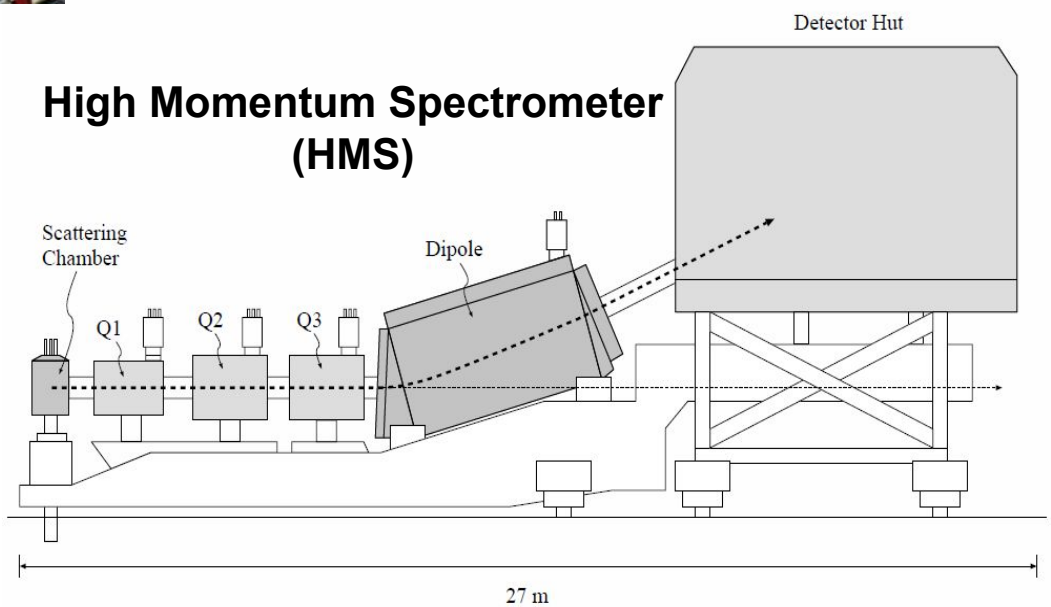


- **HMS (QQQD)**
  - **Angle Acceptance:** 6msr
  - **Momentum:** 0.5-7.5 GeV/c
  - **Momentum Acceptance:** +-9%
  - **Angular, Position Resolution:** 1mr and 1mm
- **SOS (QDDbar)**
  - **Angle Acceptance:** 9msr
  - **Momentum:** 0.1-1.8 GeV/c
  - **Momentum Acceptance:** +-20%

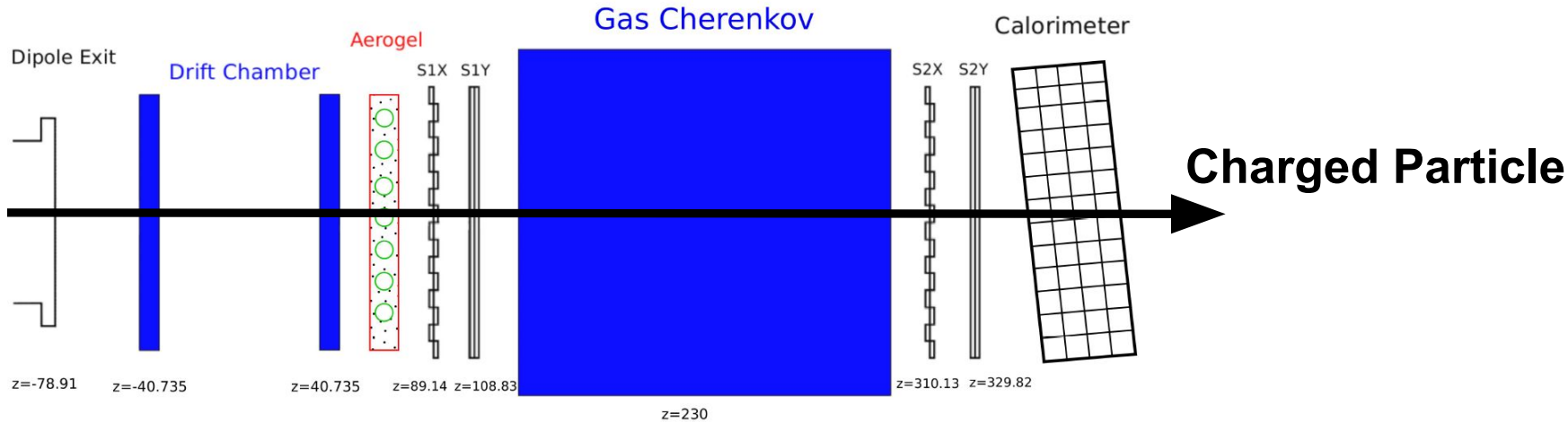
High Momentum Spectrometer (SOS)



High Momentum Spectrometer (HMS)

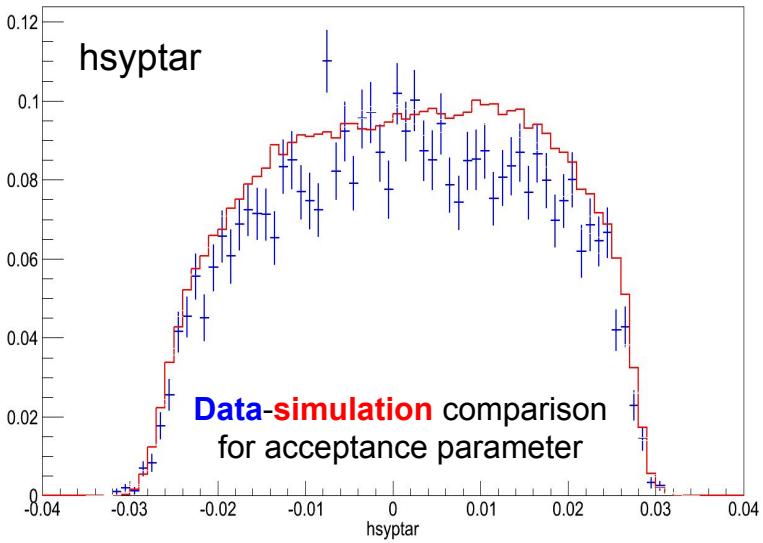


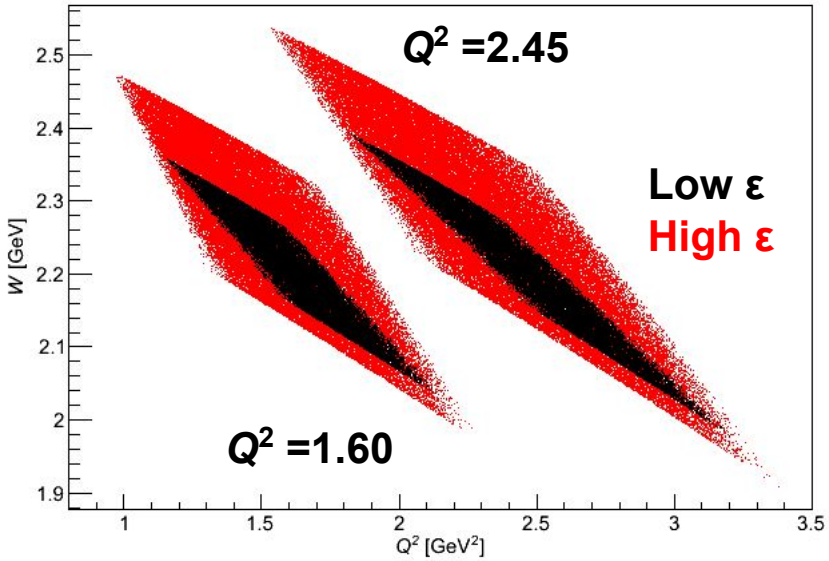
Experimental Setup and Acceptance



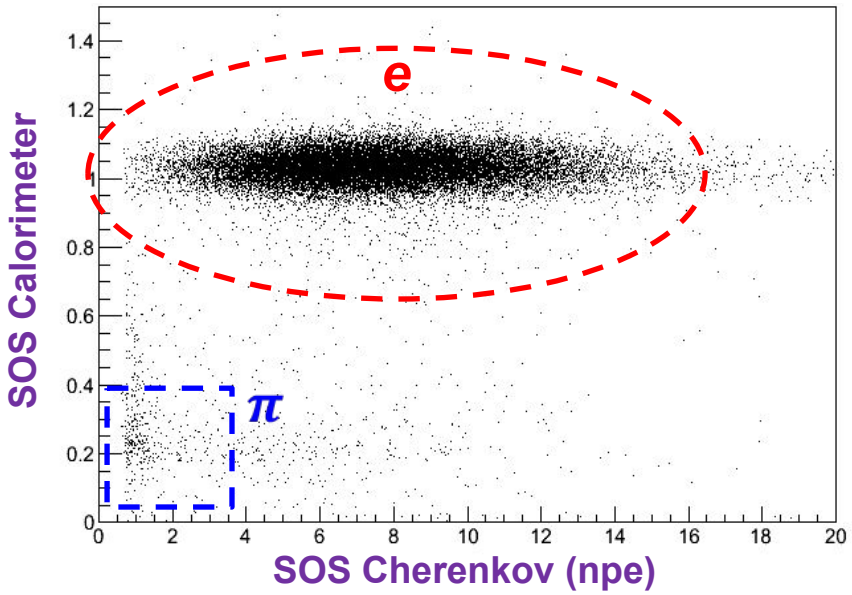
HMS detector (focal plane) layout, SOS is very similar

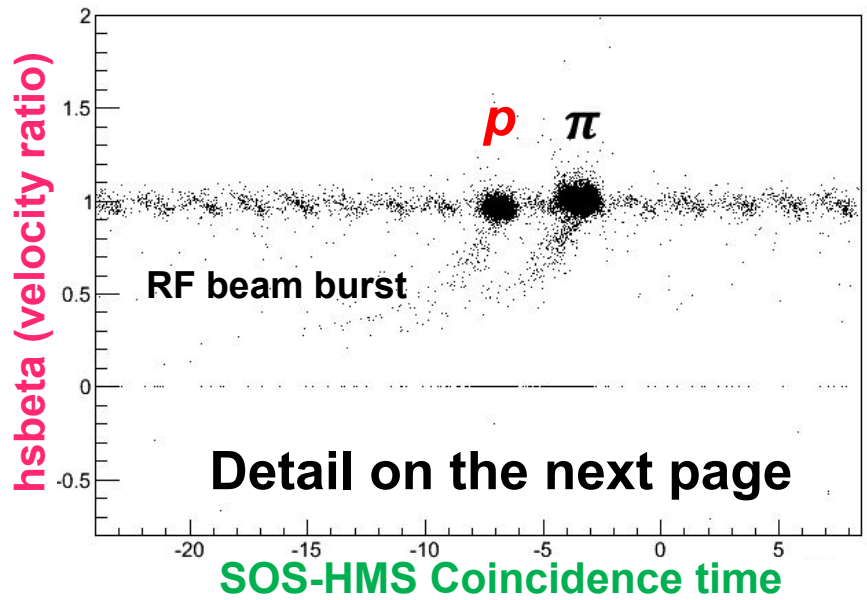
Trigger: 3/4 planes of Hodoscopes





PID Cuts

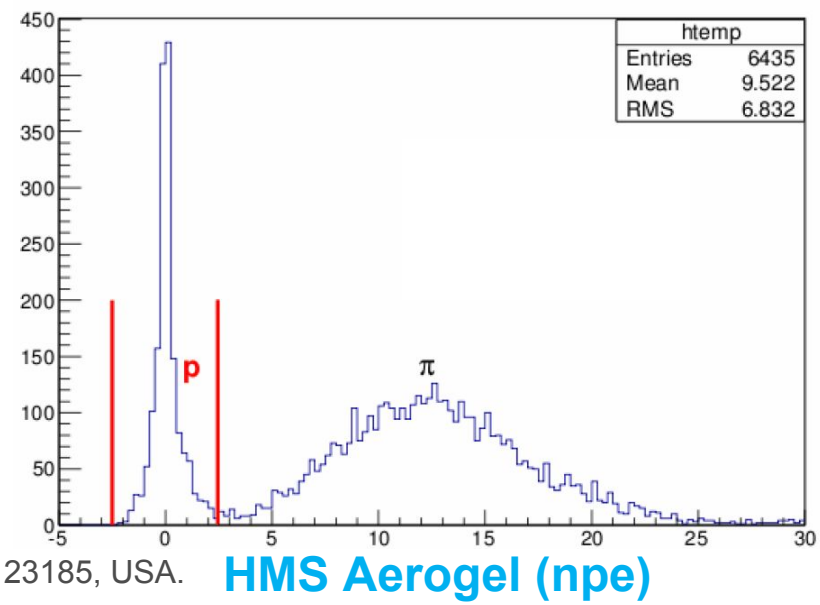




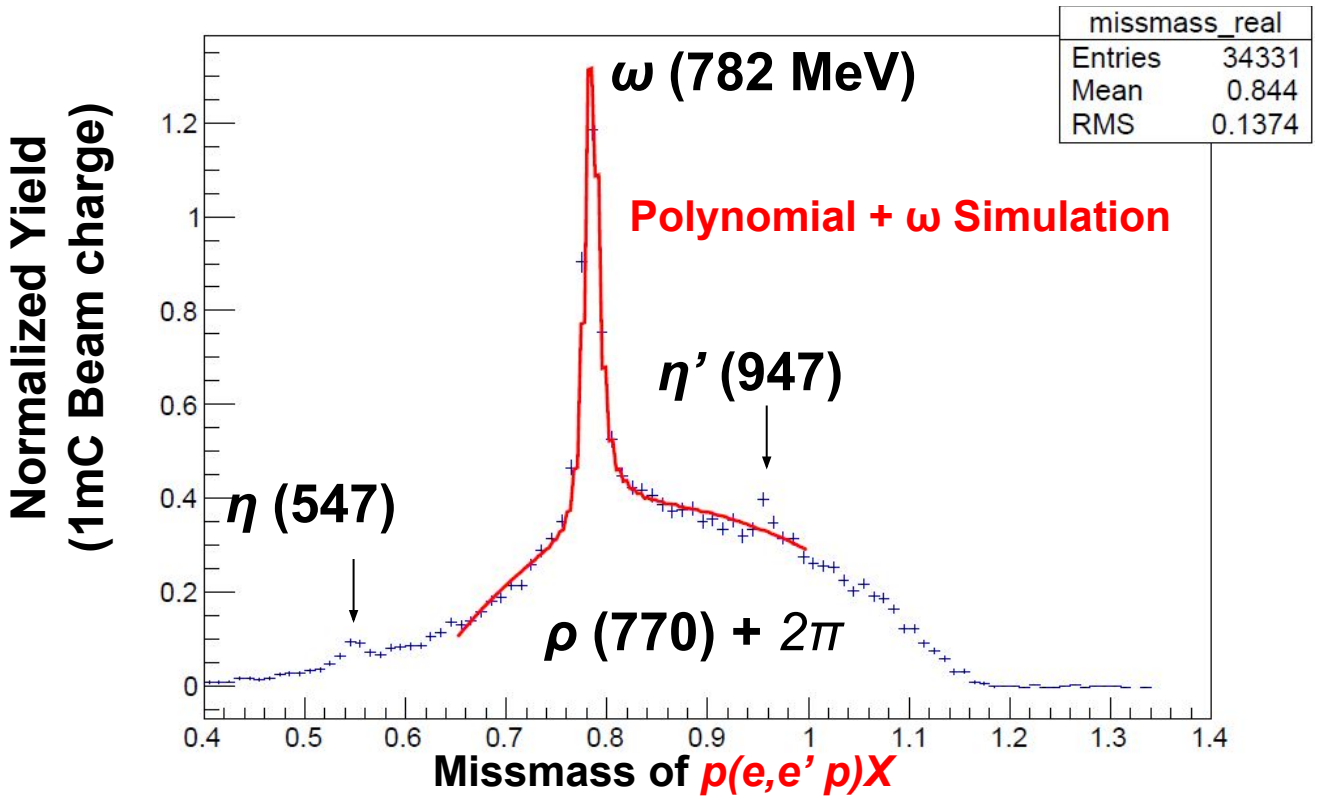
- SOS: select electron
  - Calorimeter cut
  - Cherenkov cut

99% efficiency

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

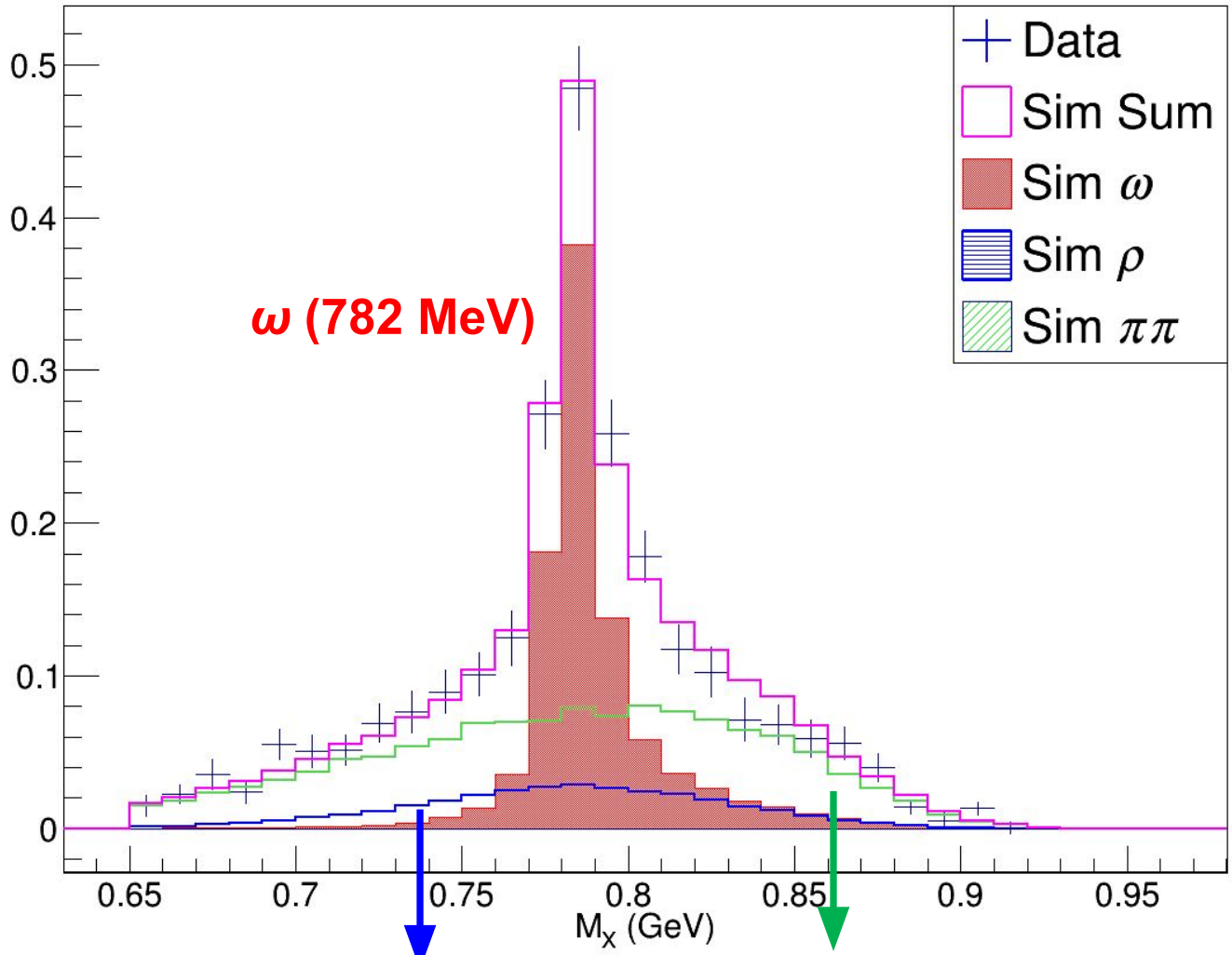


Proof: These are not Elastic Events!



- **Good News!**
  - We see **other Scalar and Vector Mesons:** ***ρ, η, η' , two-π phasespace***
- **Bad News!**
  - Channel is **not clean**!
- **Worse News!**
  - **We can't use Polynomial fit !!**

Physics Background Subtraction

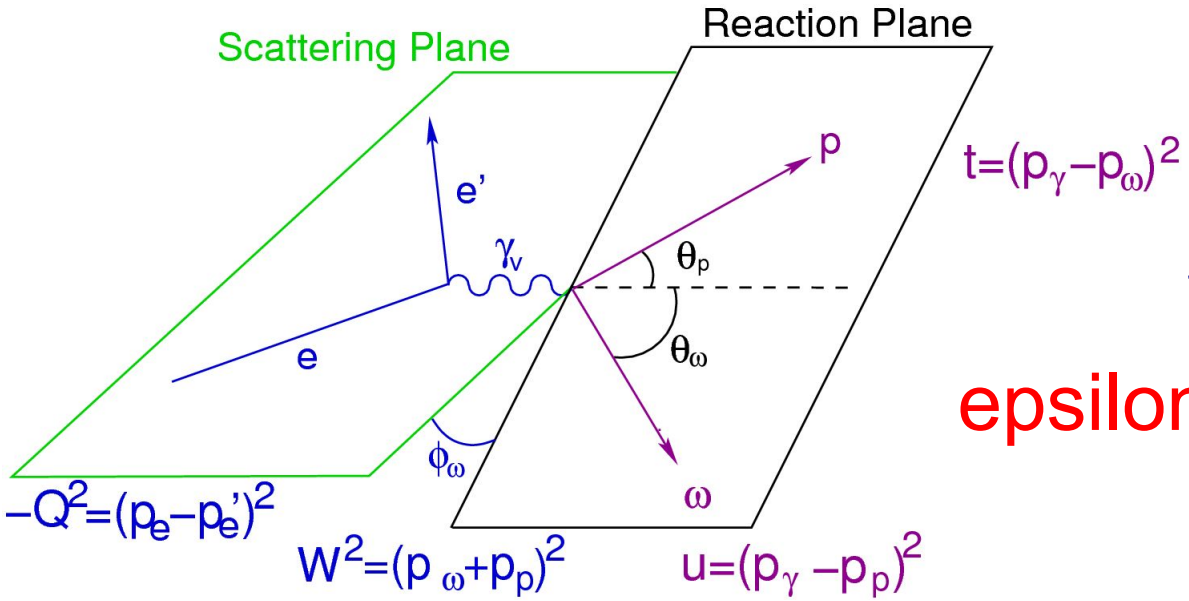


ρ (770)

HERMES Empirical parameterization with Soding factor

2π phase-space

Rosenbluth Separation



Virtual-photon polarization:

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

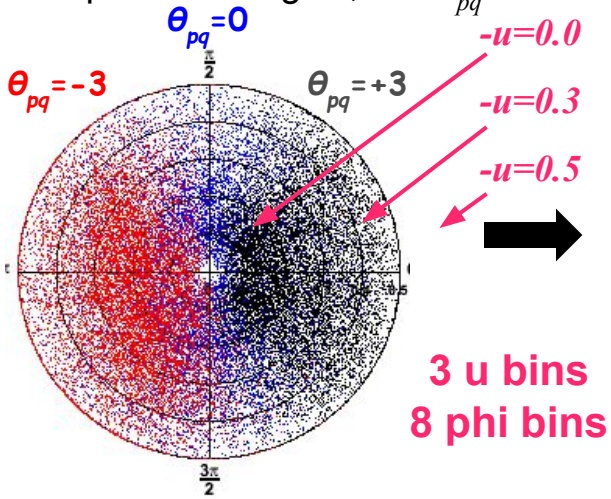
epsilon leverage ~ 0.30

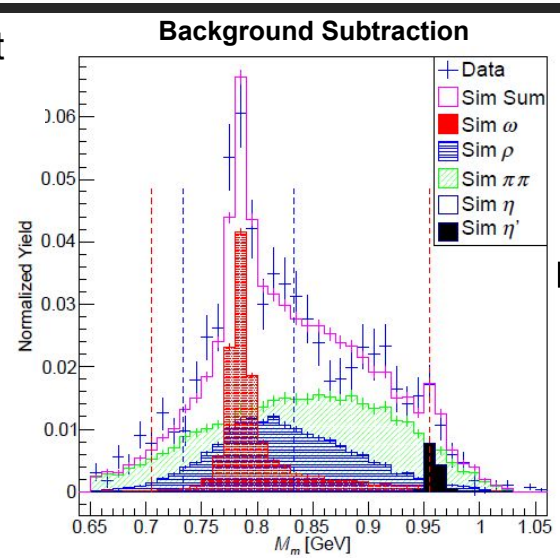
$$2\pi\frac{d\sigma}{dtd\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

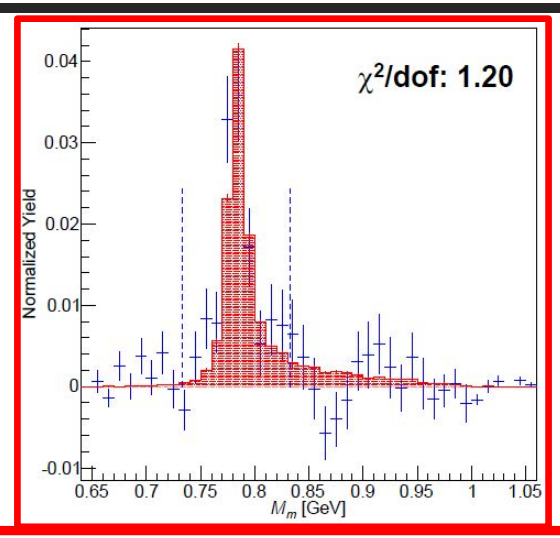
- Rosenbluth Separation requires
  - Separate measurements at different ε (virtual photon polarization)
  - All Lorentz invariant physics quantities: Q^2, W, t, u, remain constant
  - Beam energy, scattered e angle and virtual photon angle will change as the result, thus event rates are dramatically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

Iterative Procedure (Recipe) to A Full LT Separation

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





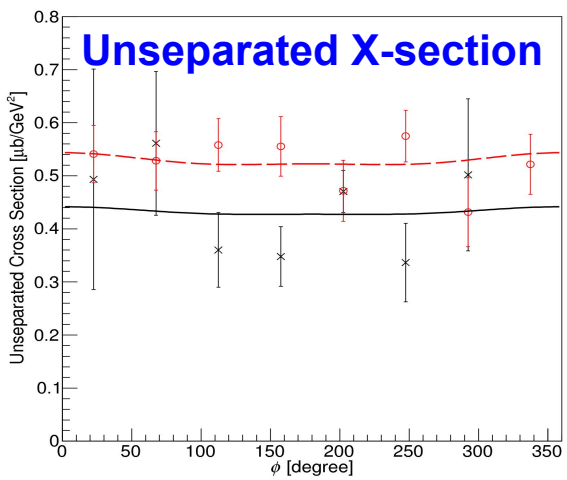


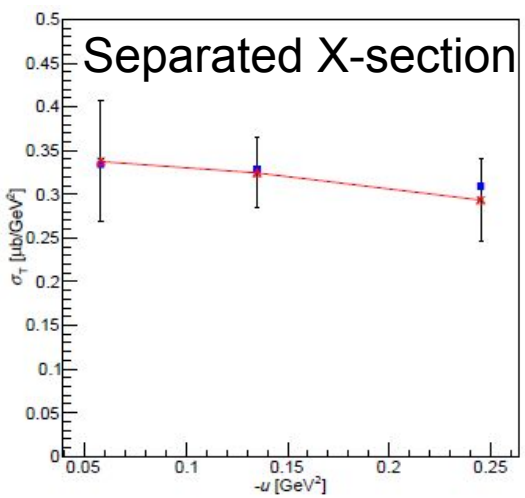
$$R = \frac{Y_{Exp} - Y_{\rho\ \mathrm{sim}} - Y_{Xspace\ \mathrm{sim}} - Y_{\eta\ \mathrm{sim}}}{Y_{\omega\ \mathrm{sim}}}$$

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



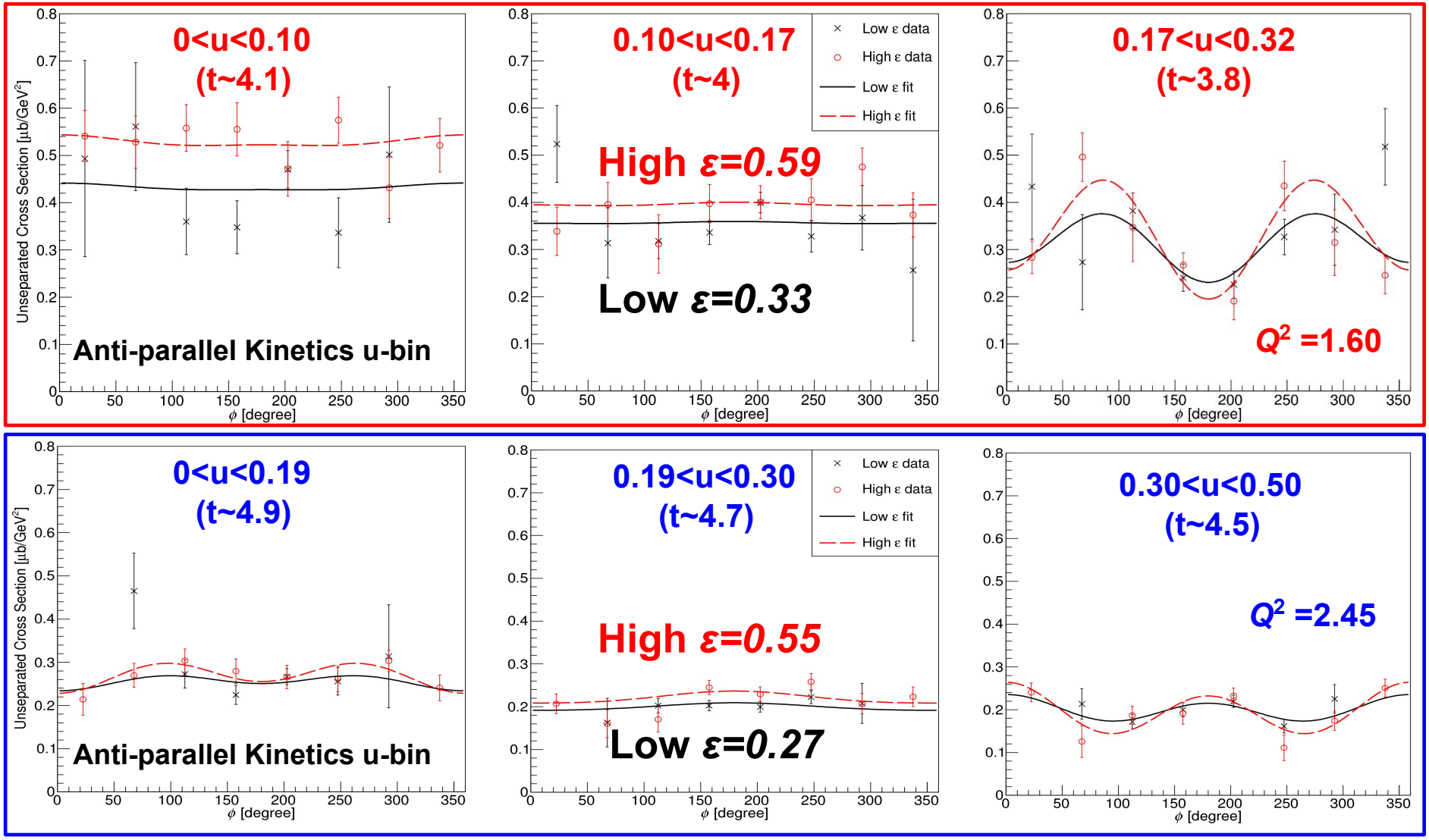


Extract T, L, LT, TT via simultaneous fit

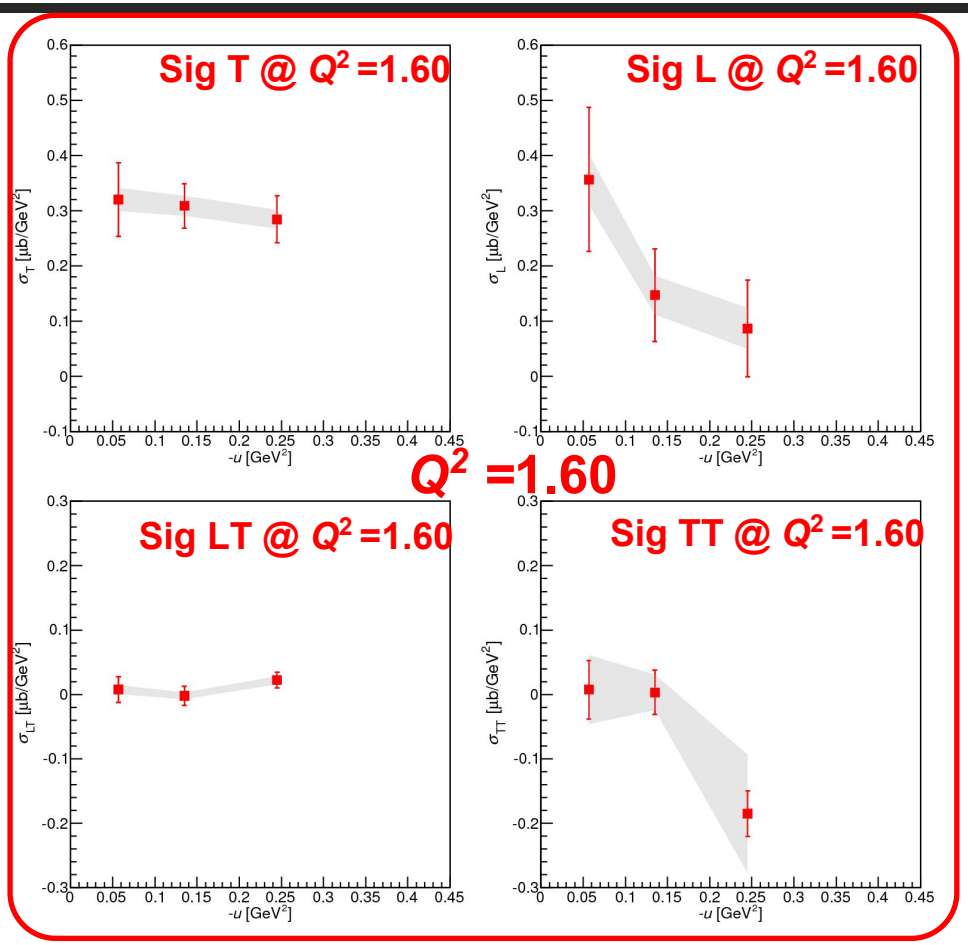
$$2\pi\frac{d\sigma}{dtd\phi} = \frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

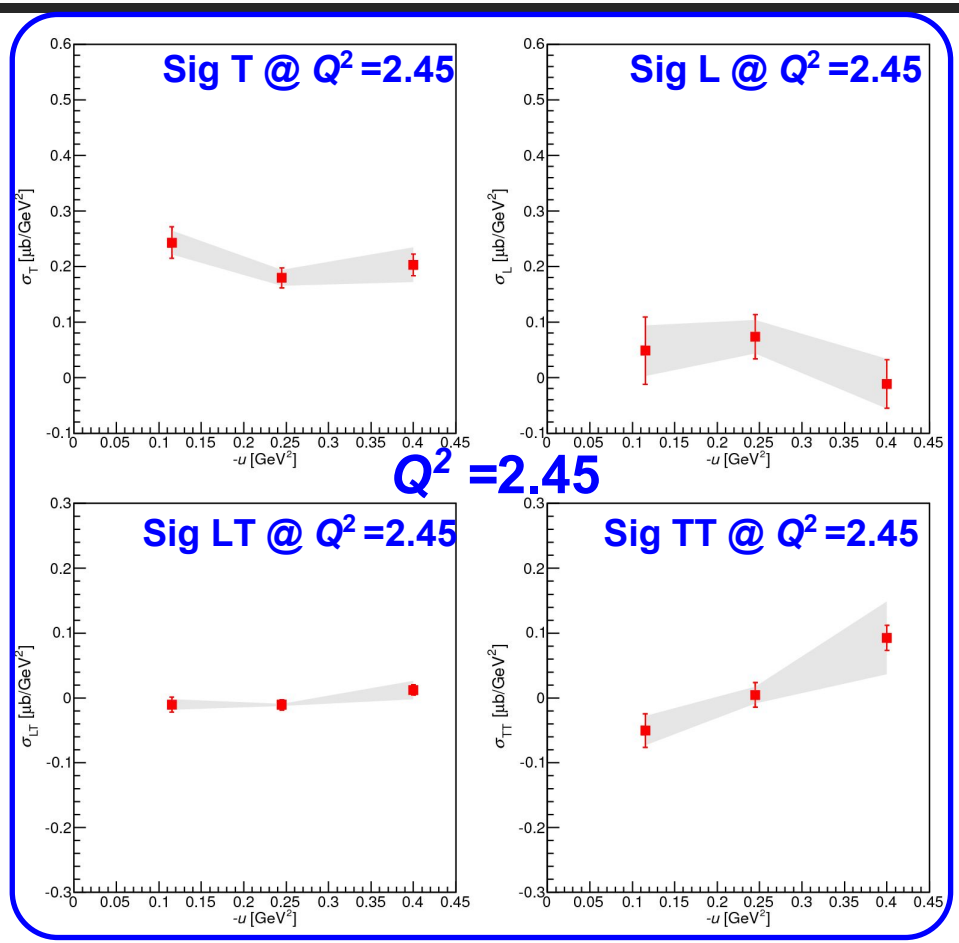
Unseparated Cross Section (Money Plot)

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



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





- **Observations:**
  - **SigT fall slow, SigL fall faster**
  - **SigLT is small, Sig TT has sign flip for different Q^2 values**

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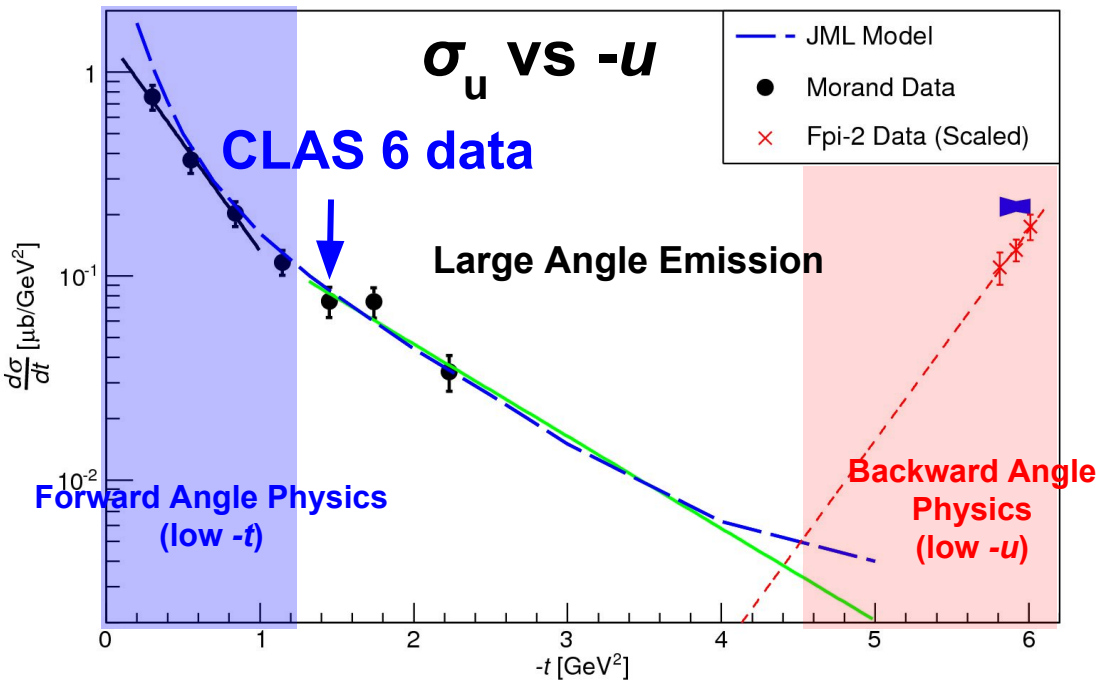
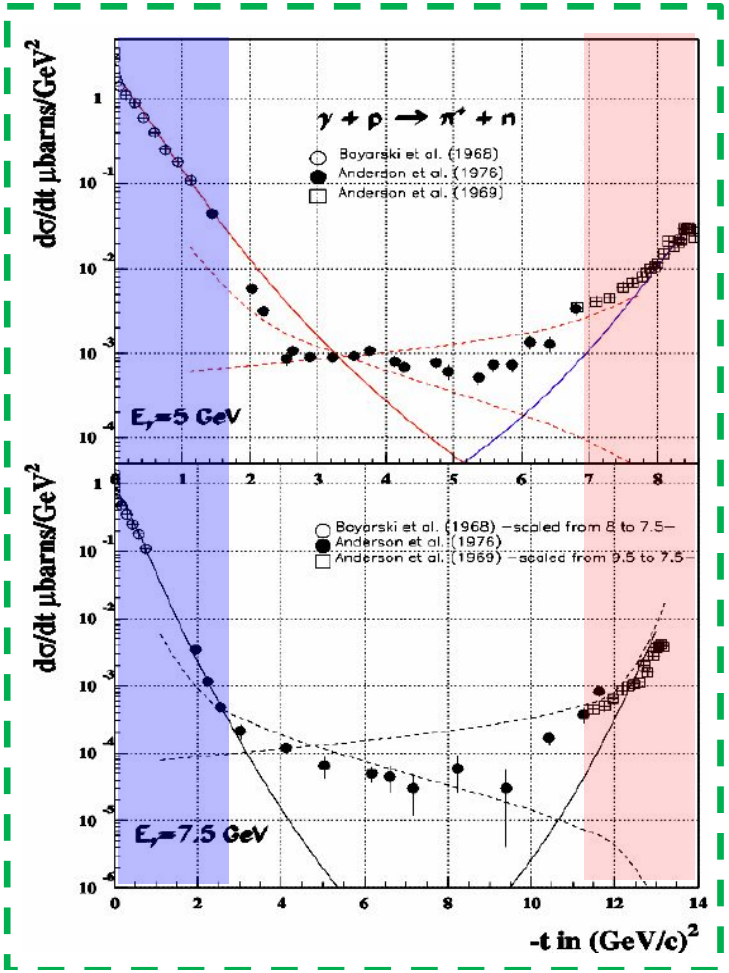
Backward Angle Omega Electroproduction Peak

$\gamma^* + p \rightarrow p + \omega$, W=2.47 GeV, Q^2 = 2.35 GeV^2



Soft structure -> Hard -> Soft transition

First time in electroproduction



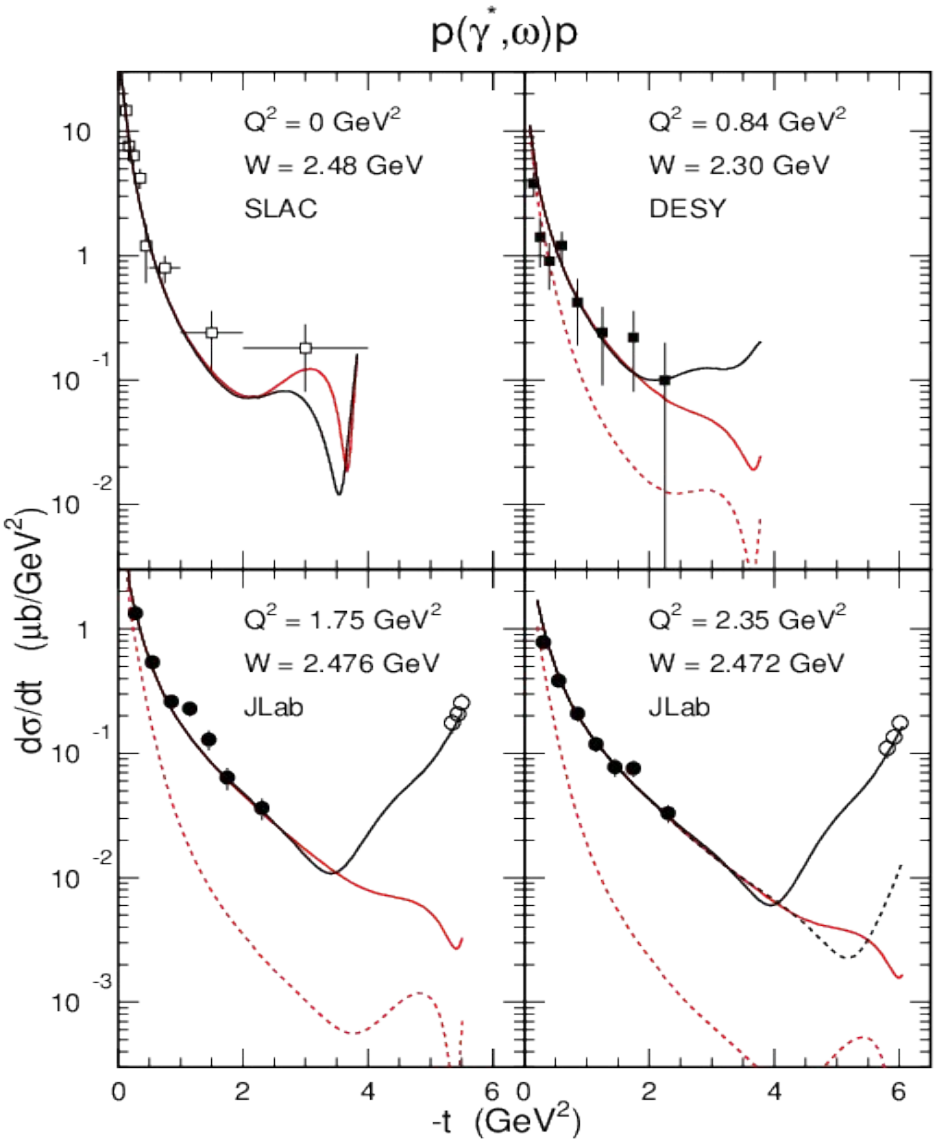
Soft structure -> Hard -> Soft transition

In photoproduction

M. Guidal, J.-M. Laget, and M. Vanderhaeghen. *Physics Letters B*400(1):6 – 11, 1997.

- **Observation for the backward *ω* electroproduction peak!**

Regge Trajectory Model by JM Laget

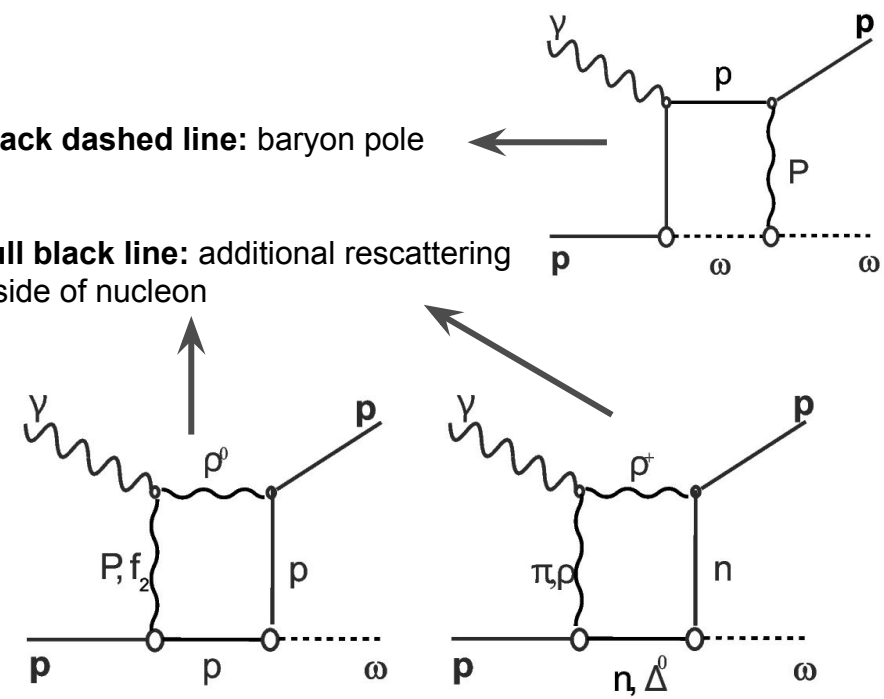


J. M. Laget, private communication, May, 2018

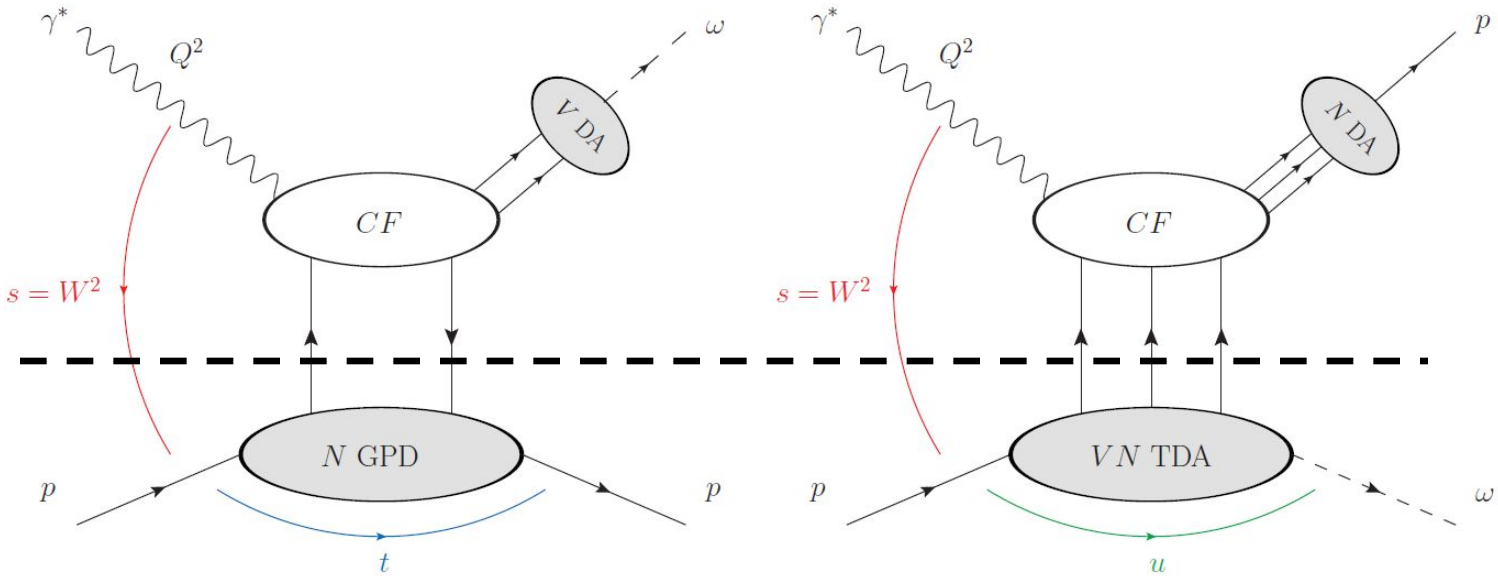
	W (GeV)	*x*	Q^2 (GeV^2)	*-t* (GeV^2)	*-u* (GeV^2)
Hall B	1.8-2.8	0.16-0.64	1.6-5.1	< 2.7	> 1.68
Fpi-2	2.21	0.29	1.6	4.014	0.08-0.13
		0.38	2.45	4.724	0.17-0.24

Black dashed line: baryon pole

Full black line: additional rescattering inside of nucleon



QCD GPD-like Model: TDA



- **Nucleon to Meson Transition Distribution Amplitude (TDA)**
  - **Backward angle analog of GPD. Translate from -*t* space to -*u*.**

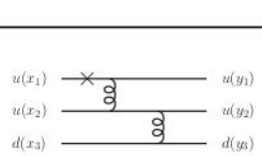
- **Two Predictions of TDA:** (B. Pire, K. Semenov, L. Szymanowski, Phys. Rev. D, **91**, 094006 (2015))
  - The **dominance of the transverse polarization** of the virtual photon resulting in the suppression of the longitudinal cross section by at least $1/Q^2$: $\sigma_T > \sigma_L$.
  - The Characteristic $1/Q^8$-scaling behaviour of the σ_T for a fixed Bjorken x.

TDA Meson Prodution Cross Section

- Unpolarized exclusive meson production cross section for π^0:

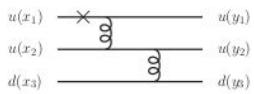
$$\frac{d^2\sigma_T}{d\Omega_\pi} = |\mathcal{C}^2| \frac{1}{Q^6} \frac{\Lambda(s, m^2, M^2)}{128\,\pi^2 s(s-M^2)} \frac{1+\xi}{\xi} \left(|\mathcal{I}|^2 - \frac{\Delta_T^2}{M^2}|\mathcal{I}'|^2\right)$$

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

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, 054021, 2011

TDAs Formulism (1 min version)

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

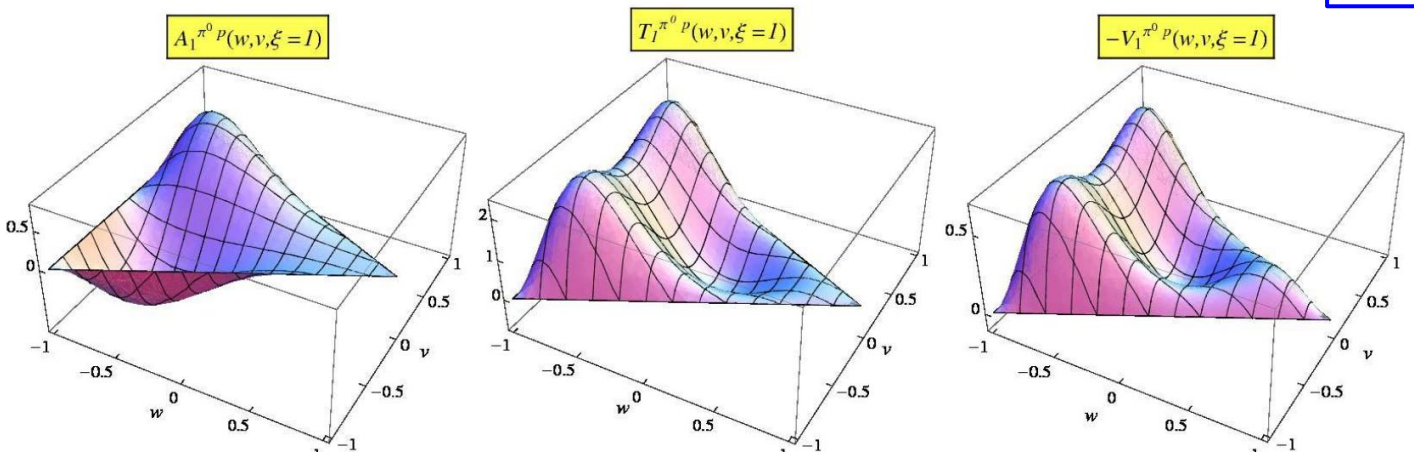
$$V_1^{\pi^0 p}(x_1,x_2,x_3,\xi_u=1) = -\frac{1}{2}\times\frac{1}{4}V^P\left(\frac{x_1}{2},\frac{x_2}{2},\frac{x_3}{2}\right)$$

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

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

Input parameter by the Nucleon DA model

- COZ (Chernyak, Ogloblin and Zhitnitsky, 1989)
- KS (King and Sachrajda, 1987)



CZ *N* DA used

computed as functions of quark-diquark coordinates

TDAs Formalism (1 min version)

- Fourier transform of the πN transition matrix element

$$4\mathcal{F}\langle\pi_\alpha(p_\pi)|\widehat{O}_{\rho\tau\chi}(\lambda_1 n,\lambda_2 n,\lambda_3 n)|N_\iota(p_1)\rangle$$

$$=\delta(x_1+x_2+x_3-2\xi_u)\sum_{s.f.}(f_a)_\iota^{\alpha\beta\gamma}\,s_{\rho\tau,\chi}\boxed{H^{\pi N}_{s.f.}(x_1,x_2,x_3,\phi,\Delta^2;\mu_F^2)}$$

- πN TDA invariant amplitudes (**eight TDAs in total**)

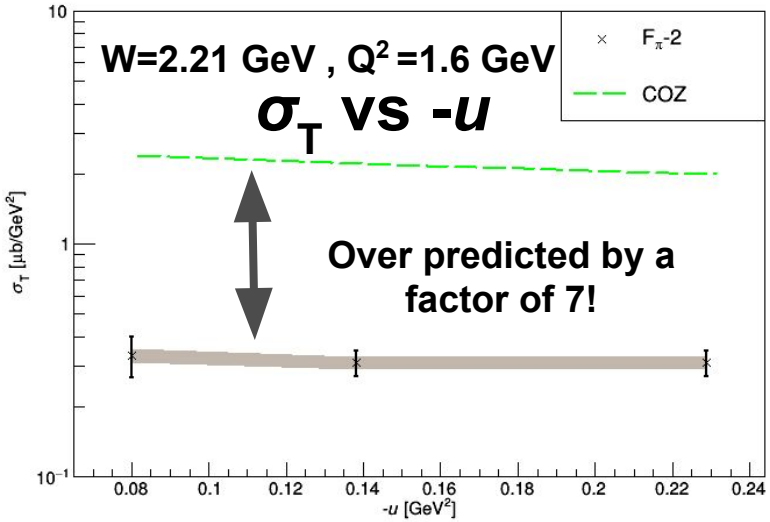
$$H^{\pi N}_{s.f.}=\{V^{\pi N}_{1,2},A^{\pi N}_{1,2},T^{\pi N}_{1,2,3,4}\}$$

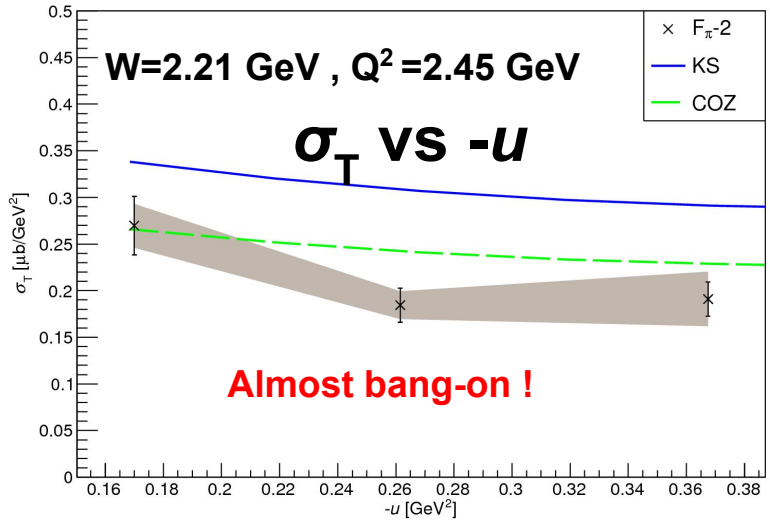
meson to nucleon transition form factor.

- Factorizing out the *u* dependence:

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

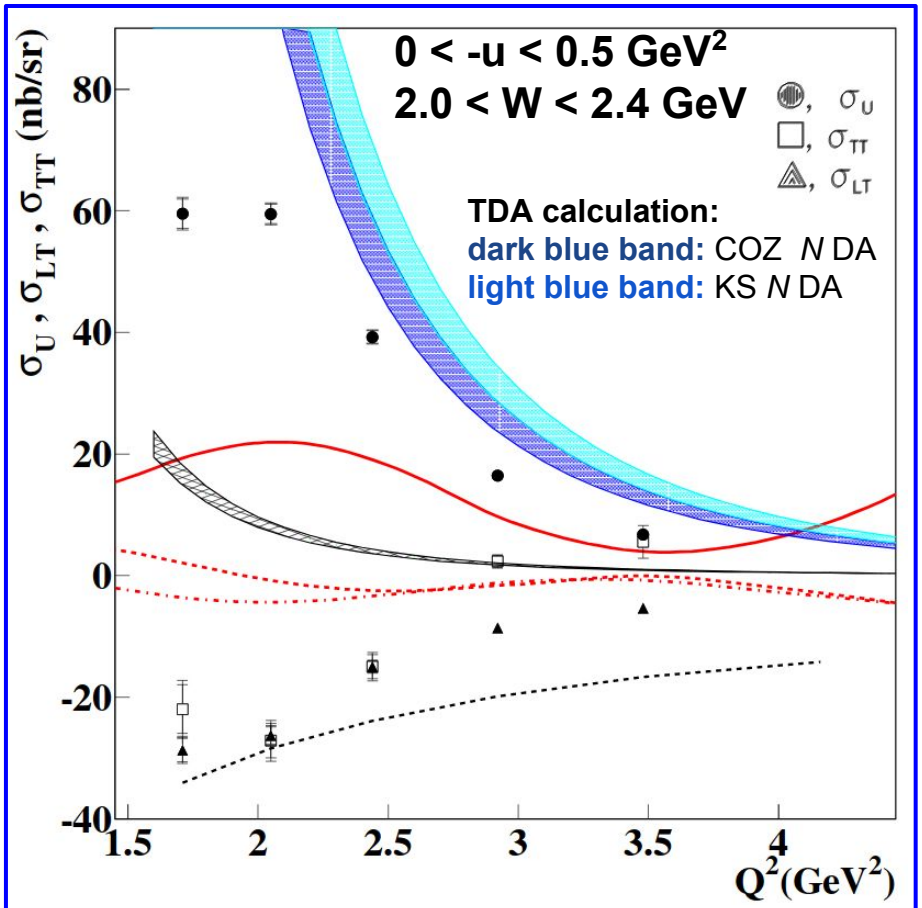
Comprison to TDA calculation





TDA Calculation by B. Pire, K. Semenov, L. Szymanowski, Private Communication. (2015)

Hall C Omega Production

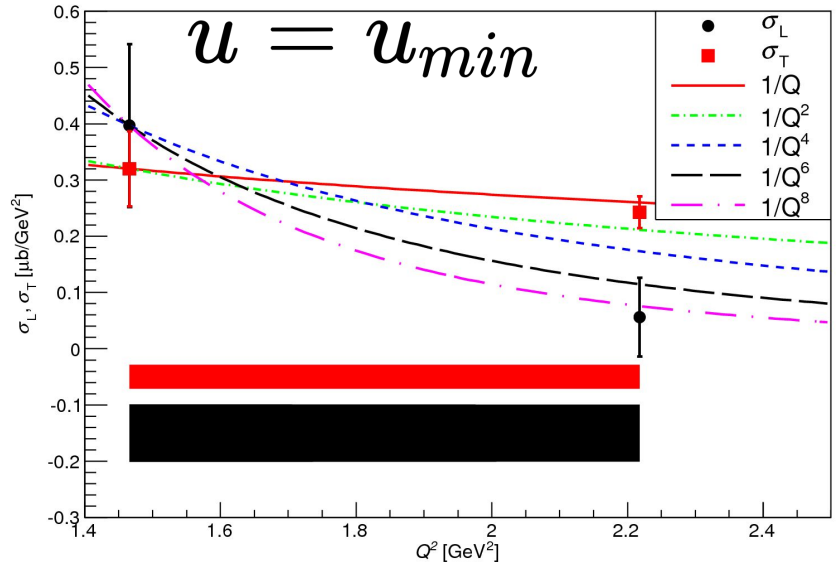


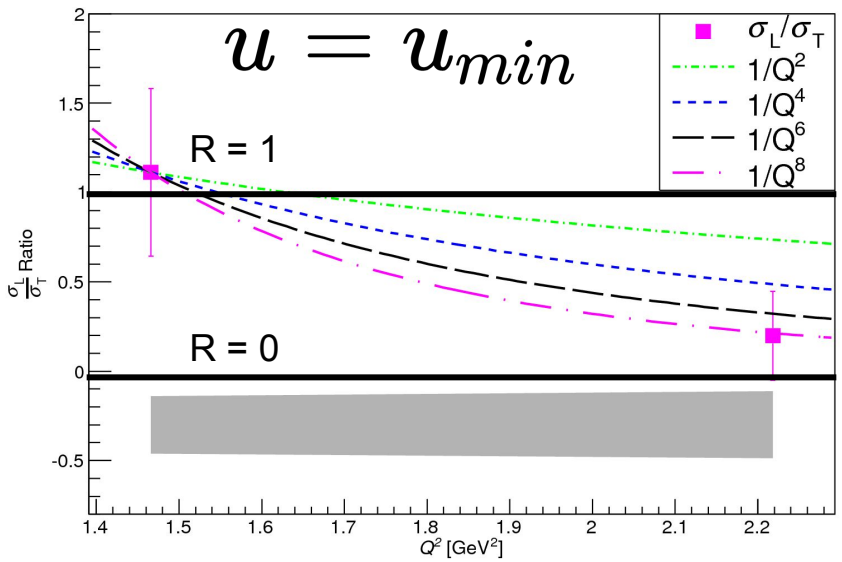
Hall B charged π production

K. Park et. al,Physics Letters B
Volume 780, 10 May 2018, Pages 340-345, (2017)

Indication of early TDA scaling !?

Scaling of σ_L, σ_T and σ_L/σ_T Ratio





- σ_L dropped fast
- σ_T most stay constant
- σ_L/σ_T ratio shows σ_T dominates at Q^2 = 2.45 GeV as the TDA prediction.
- TDA need to be further tested

Three Stages of Studying the TDA

- **Stage 1: Study and validation of the TDA framework, by measuring the general scaling trend of the separated L/T cross sections.**
  - CLAS 6 and Hall C data from 6 GeV data (Done)
  - 12 GeV validation (We are here)

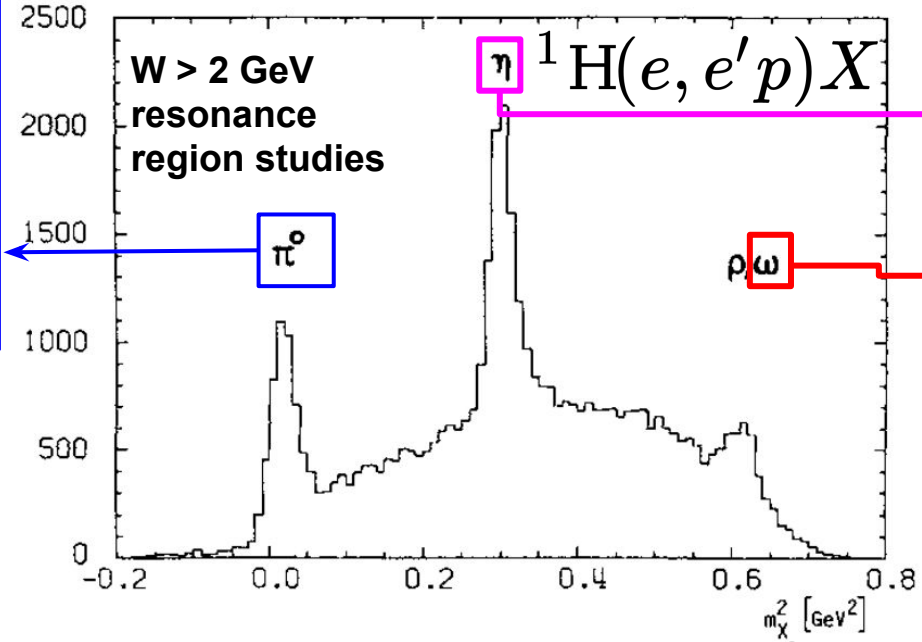
- **Stage 2: Determination of the u dependence and extract the πN transition form factor** G(u)**, with 12 GeV.**

- **Stage 3: Extraction the TDAs by probing the single and double spin asymmetries for backward meson production and universality check**
  - EIC and PANDA

Backward Angle Physics 12 GeV

PAC 46 LOI: backward angle π^0 electroproduction at Hall C

- **L/T separation at 2, 3 and 4 GeV.**
- **Q^2 scaling test at 5.5 GeV**

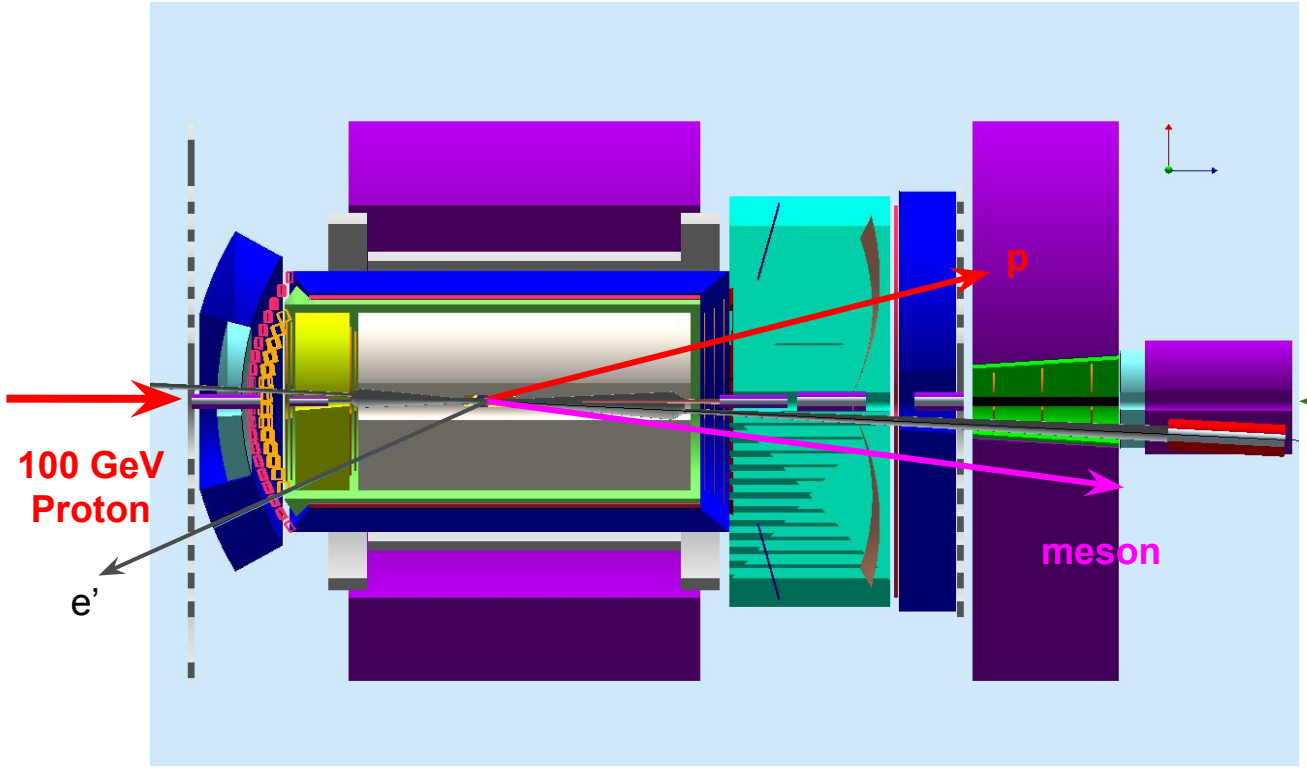


Parasitic data:
K and π form factor experiments and others approved 12 GeV programs

JLab 12 GeV Backward Meson Production Objective

- *-u* dependence for various meson electroproduction and L/T sparation
- Further validate the TDA formulism and predictions the other mesons
  - $\sigma_T > \sigma_L$
- Perfect lead-out for the EIC

SSA and DSA with TDA



If the TDA factorization is valid:

σ_L -> 0,

σ_{LT} -> small

σ_T -> dominates

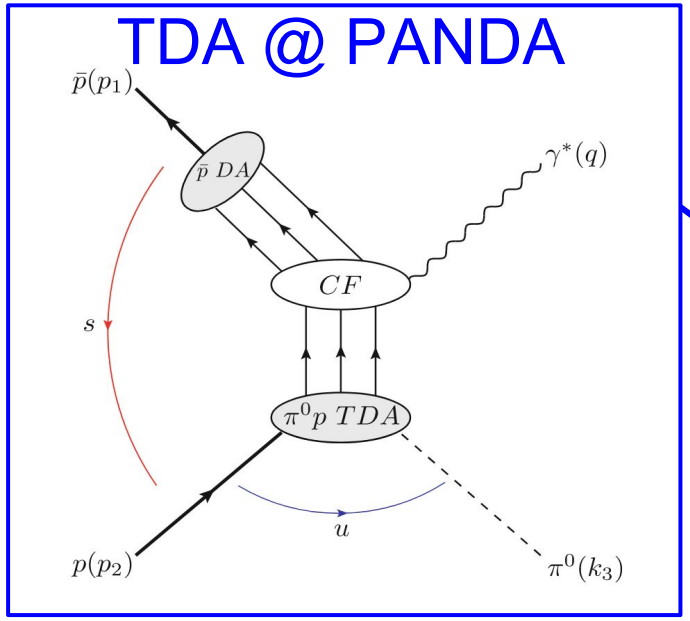
σ_{TT} -> ϕ dependence

- **Extract TDAs through Signle Spin Asymmetry and Double Spin Asymmetry:**

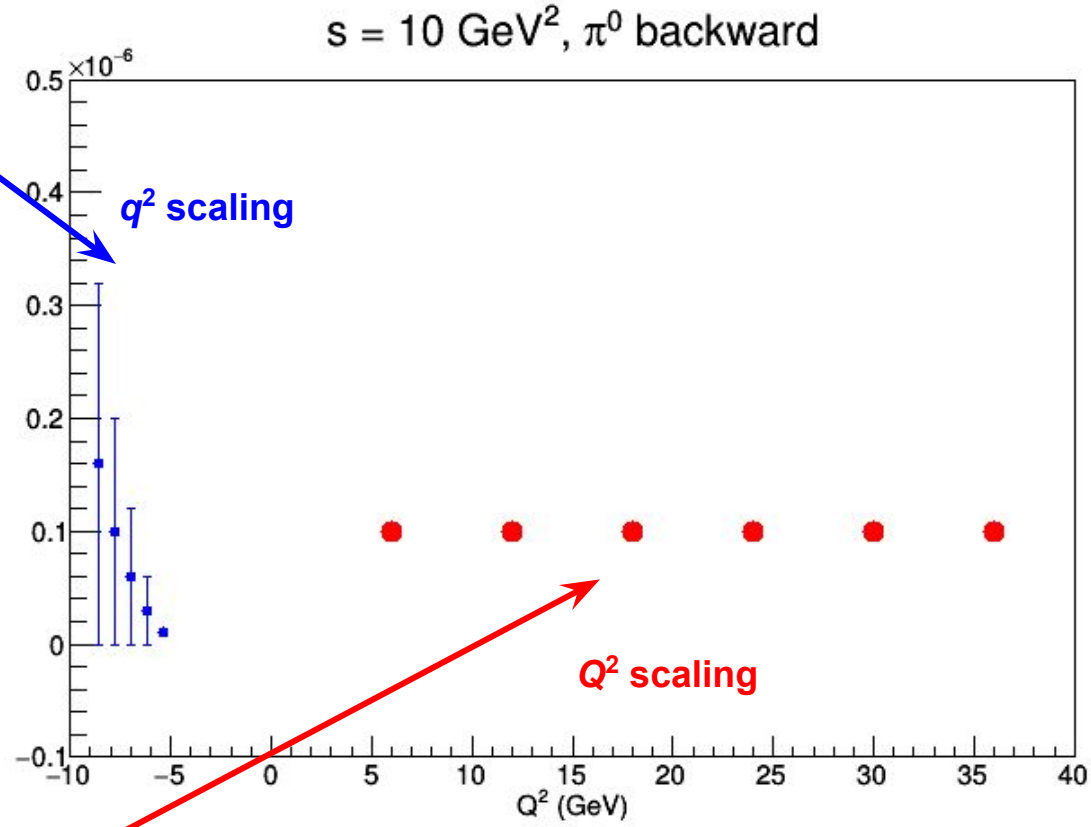
$$\mathcal{A} = \frac{1}{|\vec{s}_1|}\left(\int_0^{\pi} d\tilde{\varphi}|\mathcal{M}_T^{s_1}|^2 - \int_{\pi}^{2\pi} d\tilde{\varphi}|\mathcal{M}_T^{s_1}|^2\right)\left(\int_0^{2\pi} d\tilde{\varphi}|\mathcal{M}_T^{s_1}|^2\right)^{-} = -\frac{4}{\pi}\frac{\frac{|\Delta_T|}{M}\,\mathrm{Im}(\mathcal{I}'(\mathcal{I})^*)}{|\mathcal{I}|^2 - \frac{\Delta_T^2}{M^2}|\mathcal{I}'|^2}. \quad \textbf{(SSA)}$$

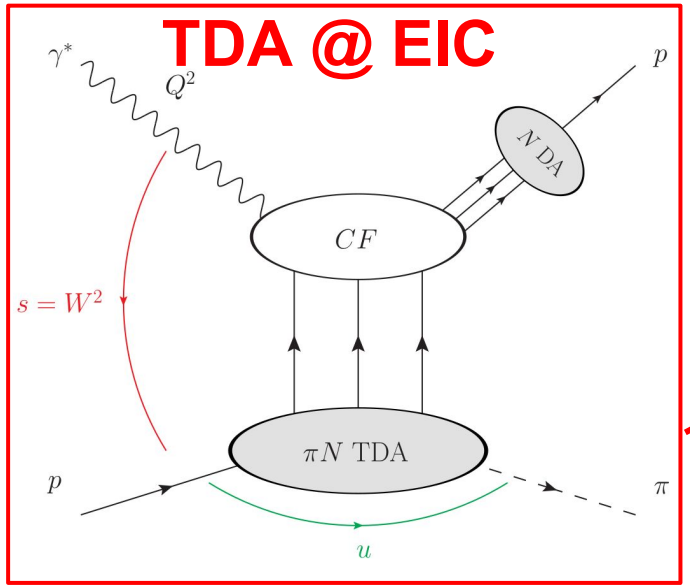
- **Space-like Q^2 scaling (EIC) vs Time-like q^2 scaling (PANDA)**
  - **Universality test**

Q^2 (space-like) and q^2 (time-like) Scaling



The PANDA Collabration,, Eur. Phys. J. A (2015) 51: 107





Same TDAs for PANDA and EIC, the ultimate universality check

Summary and Thanks you

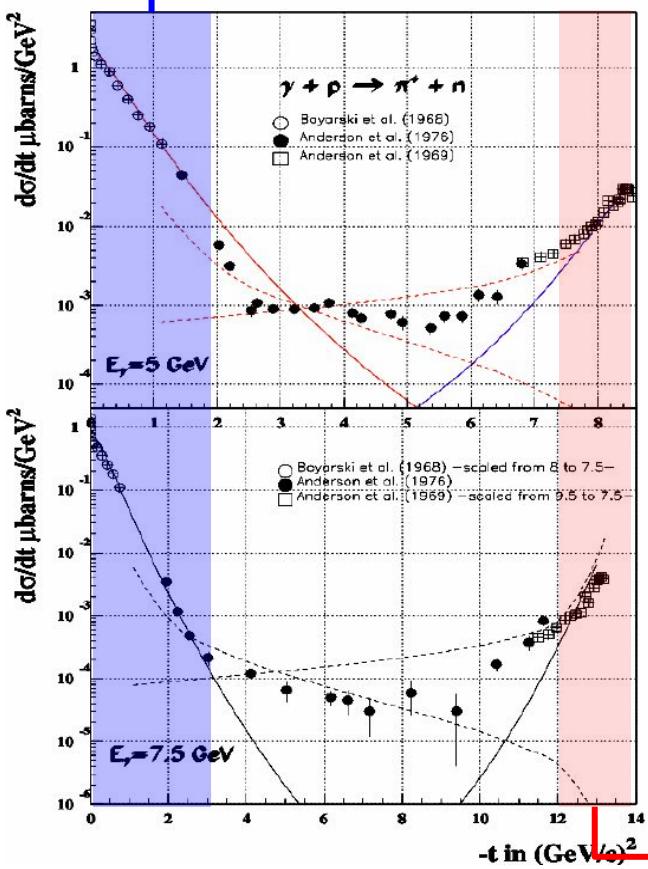
- 6 GeV-> 12 GeV-> EIC backward meson program with QCD GPD-like TDA model.
  - 6 GeV and 12 GeV validation
  - EIC extraction and universality check.

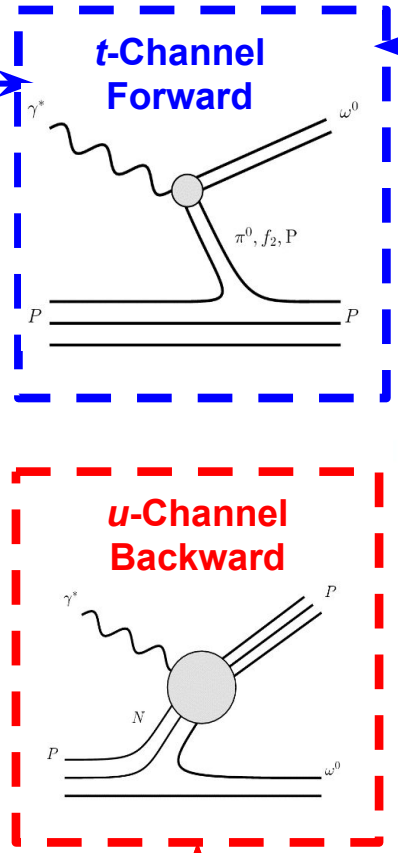
- Highest gratitudes to
  - **B. Pire, K. Semenov, L. Szymanowski for the TDA calculation**
  - **J. M. Laget for the Regge calculation**
  - **Garth Huber and Justin Stevens funding support**
  - Hall C collabration
  - College of William and Mary

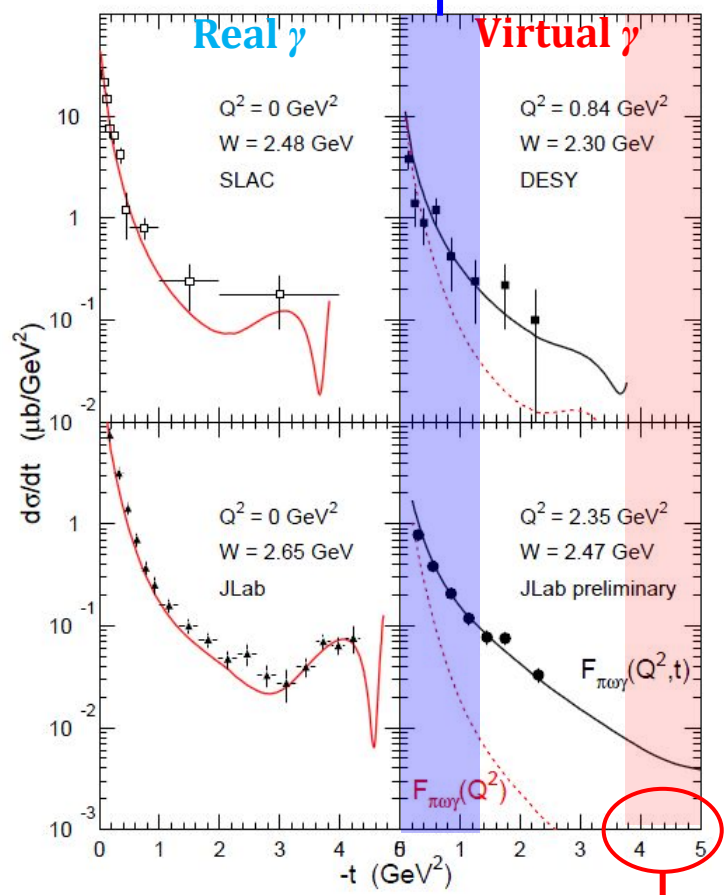
Regge Trajectory: Real photon vs virtual photon

$\gamma + p \rightarrow \pi + n$

$\gamma^* + p \rightarrow \omega + n$







M. Guidal, J.-M. Laget, and M. Vanderhaeghen. *Physics Letters B*400(1):6 – 11, 1997.111

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

Soft structure -> Hard -> Soft transition !

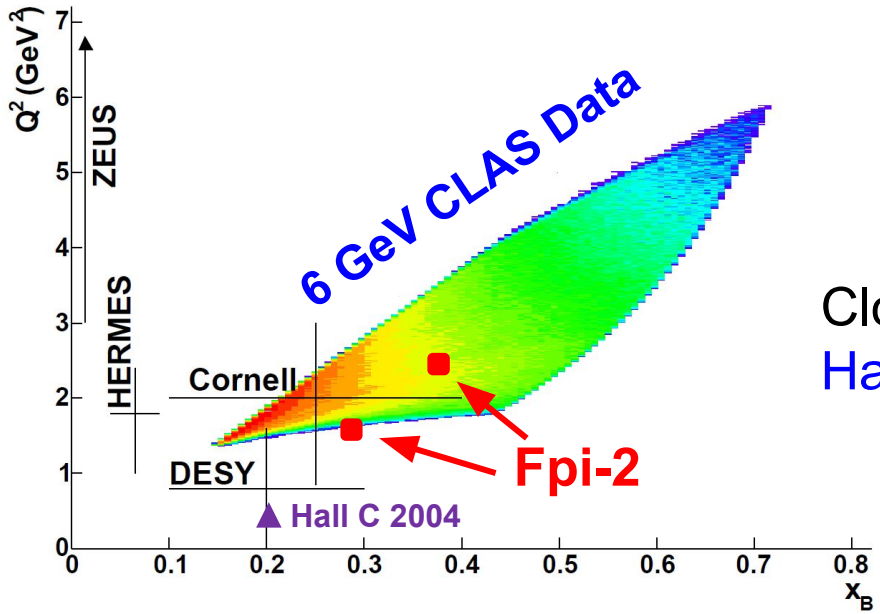
Fpi2 kinematics

Transverse Target Single Spin Asymmetry

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

$$= -\frac{4}{\pi}\frac{\frac{|\Delta_T|}{M}\,\mathrm{Im}(\mathcal{I}'(\mathcal{I})^*)}{|\mathcal{I}|^2 - \frac{\Delta_T^2}{M^2}|\mathcal{I}'|^2}.$$

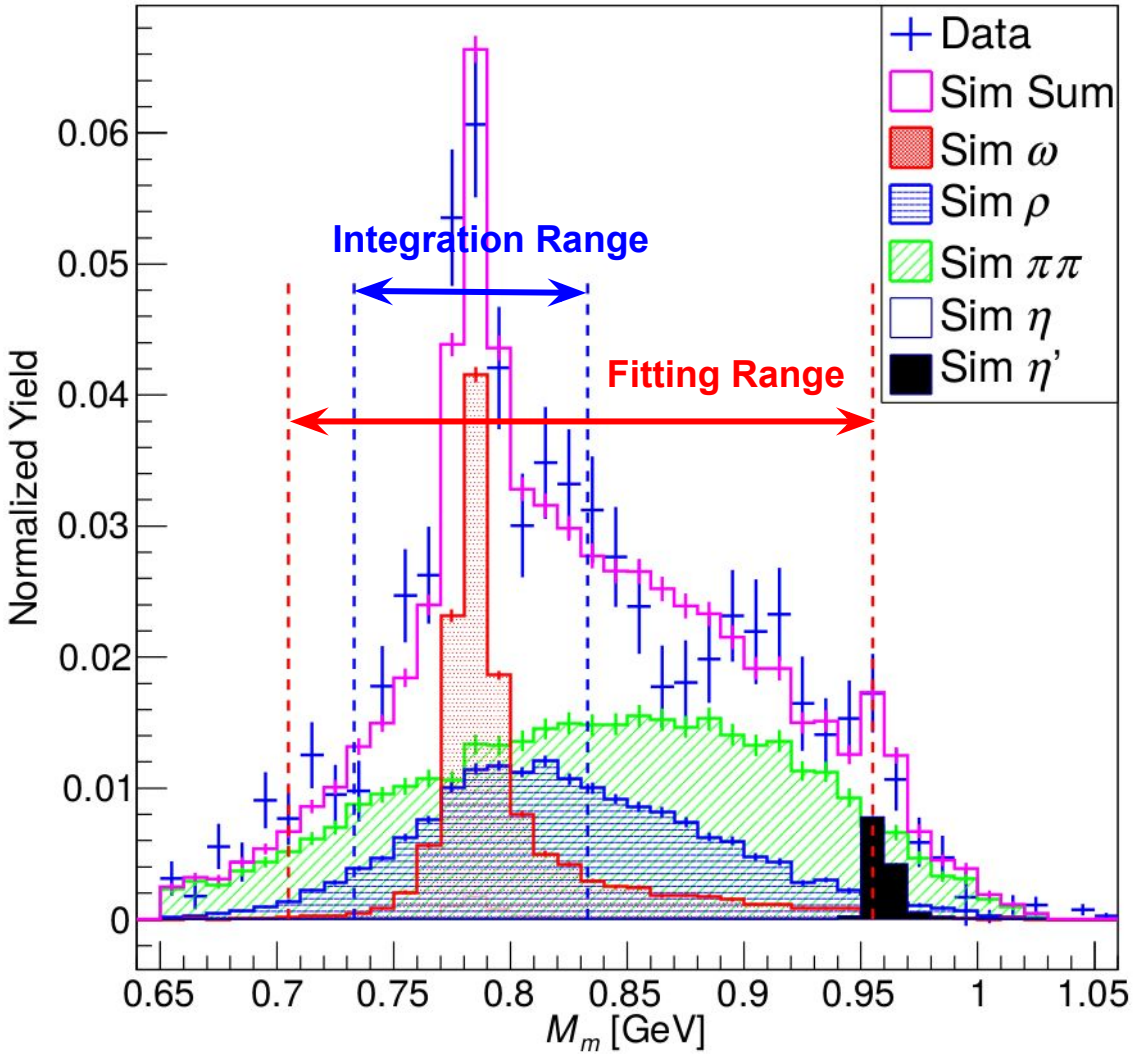
Exclusive ω Electro-Production Data



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 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

Fitting step (Background Subtraction)



- **Fitting data within the with four simulations**
  - Fitting
  - Subtracting background distributions
  - Obtain omega experimental yield: $Y_{\omega\ \mathrm{Exp}}$
  - Each simulation distribution has scale factor

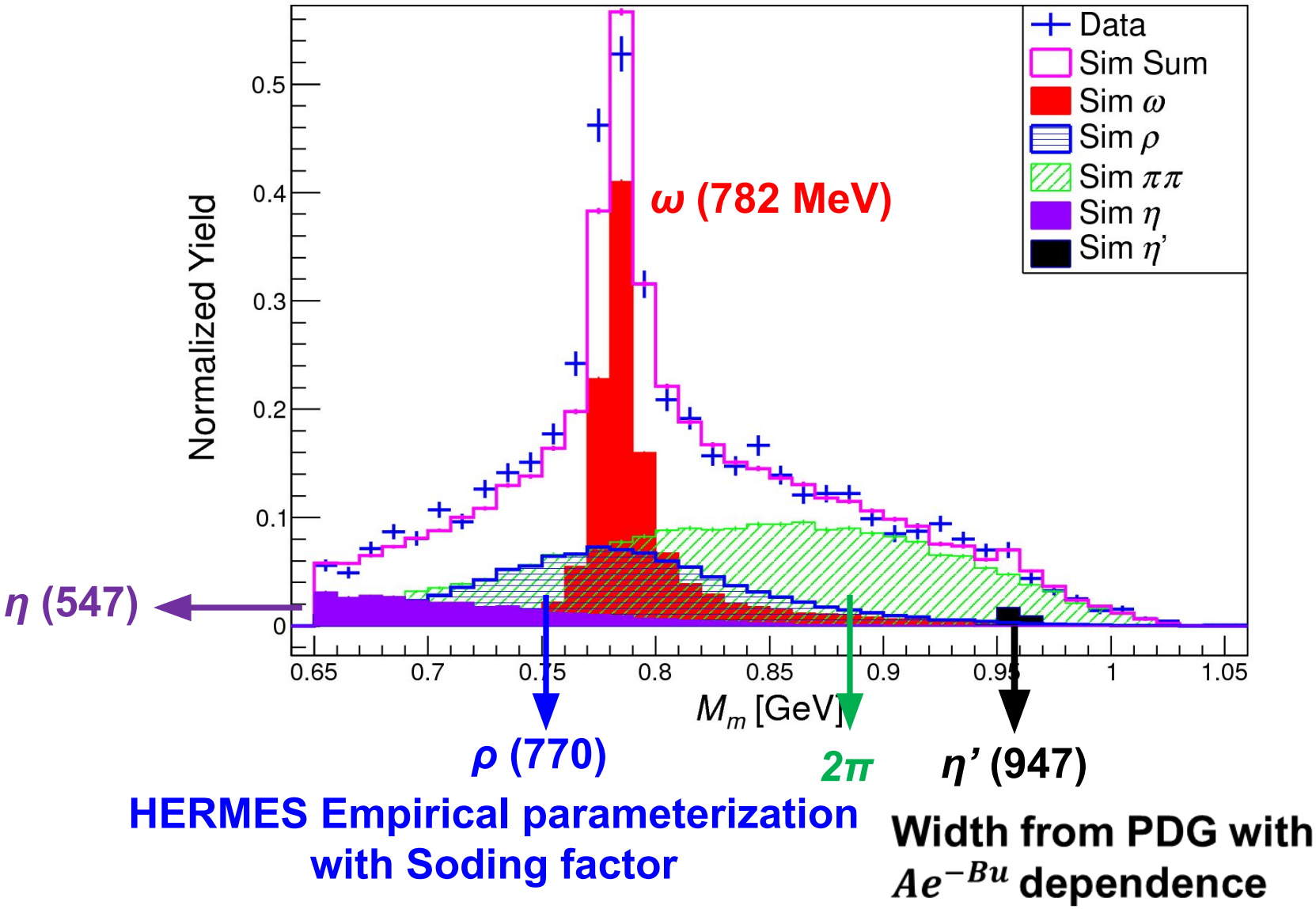
$$R = \frac{Y_{Exp} - Y_{\rho\ \mathrm{sim}} - Y_{Xspace\ \mathrm{sim}} - Y_{\eta\ \mathrm{sim}}}{Y_{\omega\ \mathrm{sim}}}$$

Data (blue point)
Xspace Sim (green)
***ρ* Sim (light blue)**
***ω* Sim (red)**
η or η' (black)
Simulation Sum (pink)

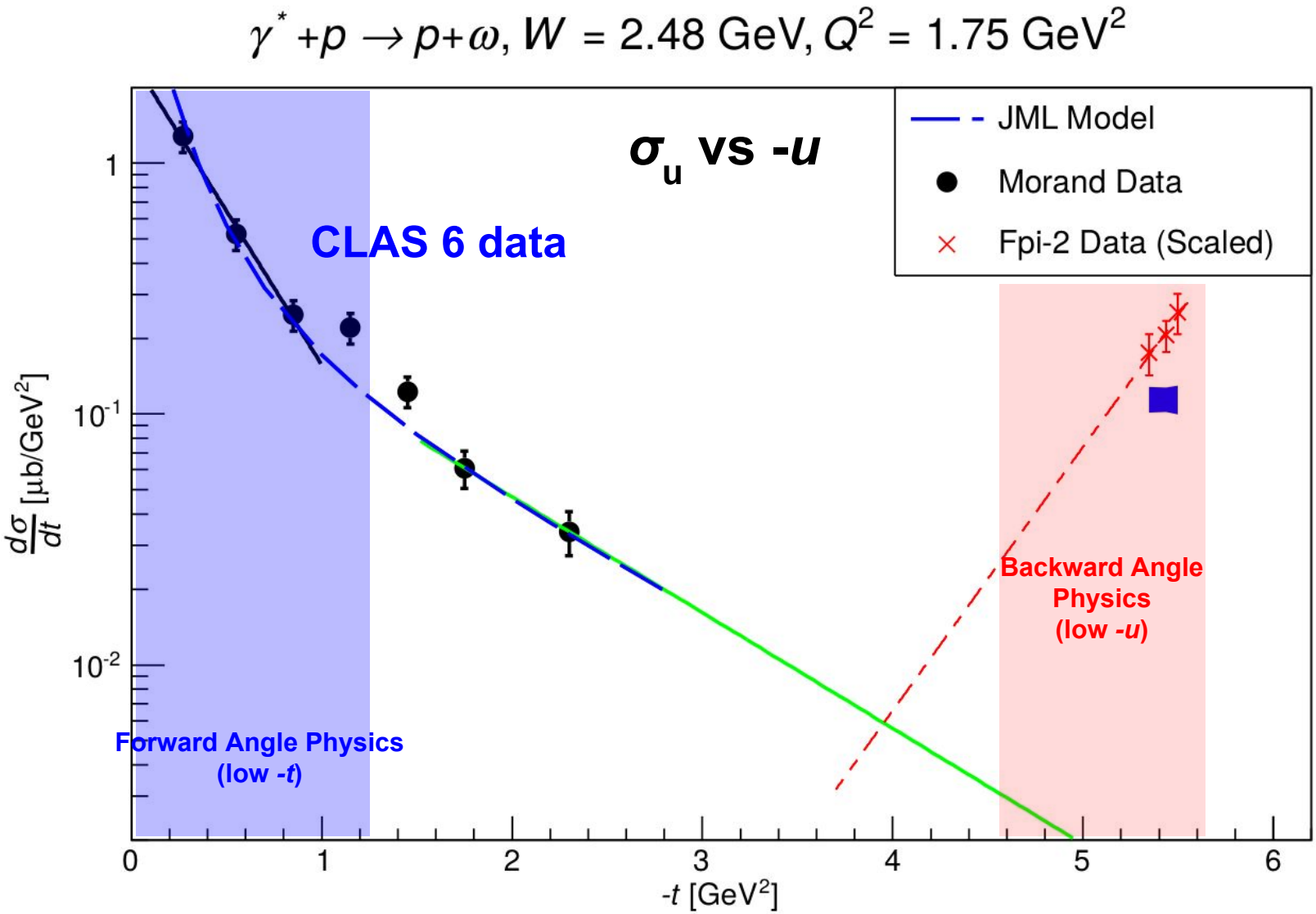
TDA Stratagy at EIC

- Single and Double spin assymetries

Physics Background Subtraction



Backward Angle Omega Electroproduction Peak !



Wenliang Li, Dept. of Physics, William and Mary, Williamsburg, VA 23185, USA.

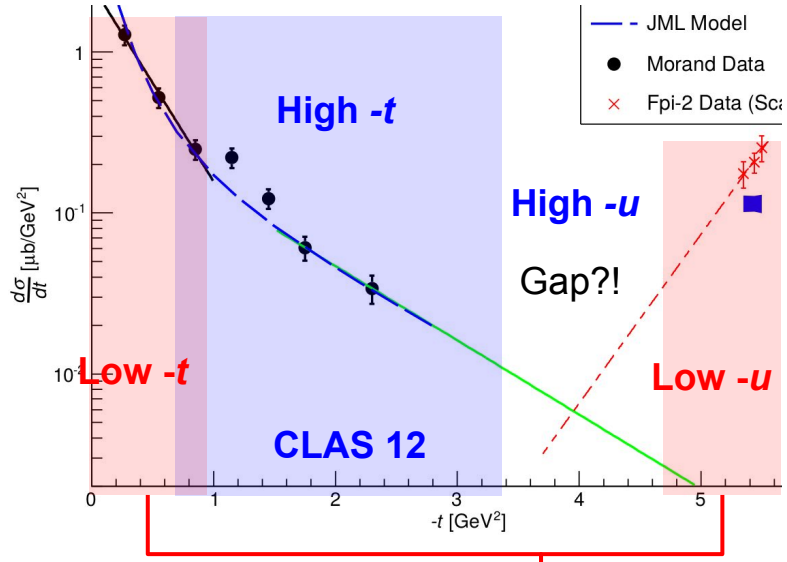
Analysis Status and what have we learned

- **Analysis Status:**
  - Final round of uncertainty review is under way
  - Expected publication data: summer 2018
  - Contacted theory group ……

- **Achieved Objectives**
  - Studying the model effectiveness in both Regge Based Model and TDA is the studying the QCD transition
  - Established a new experimental access to the previously accessible kinematics
  - Abstracted the theory framework that can be used to study the previously ignored backward angle process
  - Final release of the result calls for more studies on backward angle physics, particularly among the junior physicist.
  - Software avaliable: ***https://github.com/billlee77/omega_analysis***

Backward Angle Physics Stratagy

- **We are ready for the *-u* channel physics studies.**
  - Variary of existing and proposed backward angle physics, i.e recent CLAS paper by K. Park

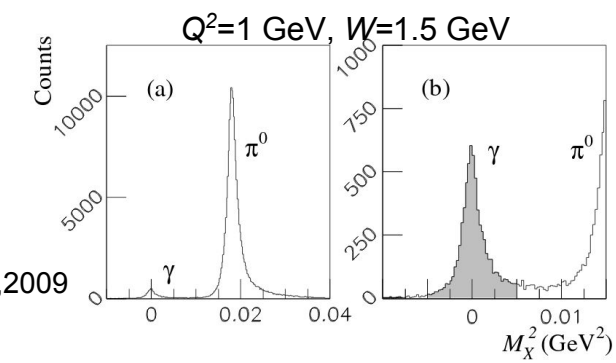


- **What can we learn?**
  - Regge Model
  - GPD/TDA factorization

- **Stratagy moving forward with backward physics**
  - Large angle region (large -t and -u) scan by CLAS
  - L/T separation near the meson (-t) and baryon (-u)
    - Hall A and C
  - Q2 evolution for L/T cross section
  - Real photon data from GlueX

Hall A/C LT separation near meson and baryon pole (extreme forward/backward angle)

- **LOI: Backward DVCS and DVMP**
  - Previous studies done by Charles, Carlos in 2007.
  - Hall A
    - 2 HRS capable of resolving DVCS peak, with limited kinematics
  - Hall C
    - Possible L/T separation with full kinematics!
    - HMS + SHMS may not have enough resolution
    - HMS + SHMS + NPS? (Currently under study)



Hall A VCS, G. Laveissière, et. al, phys.Rev.C79:015201,2009

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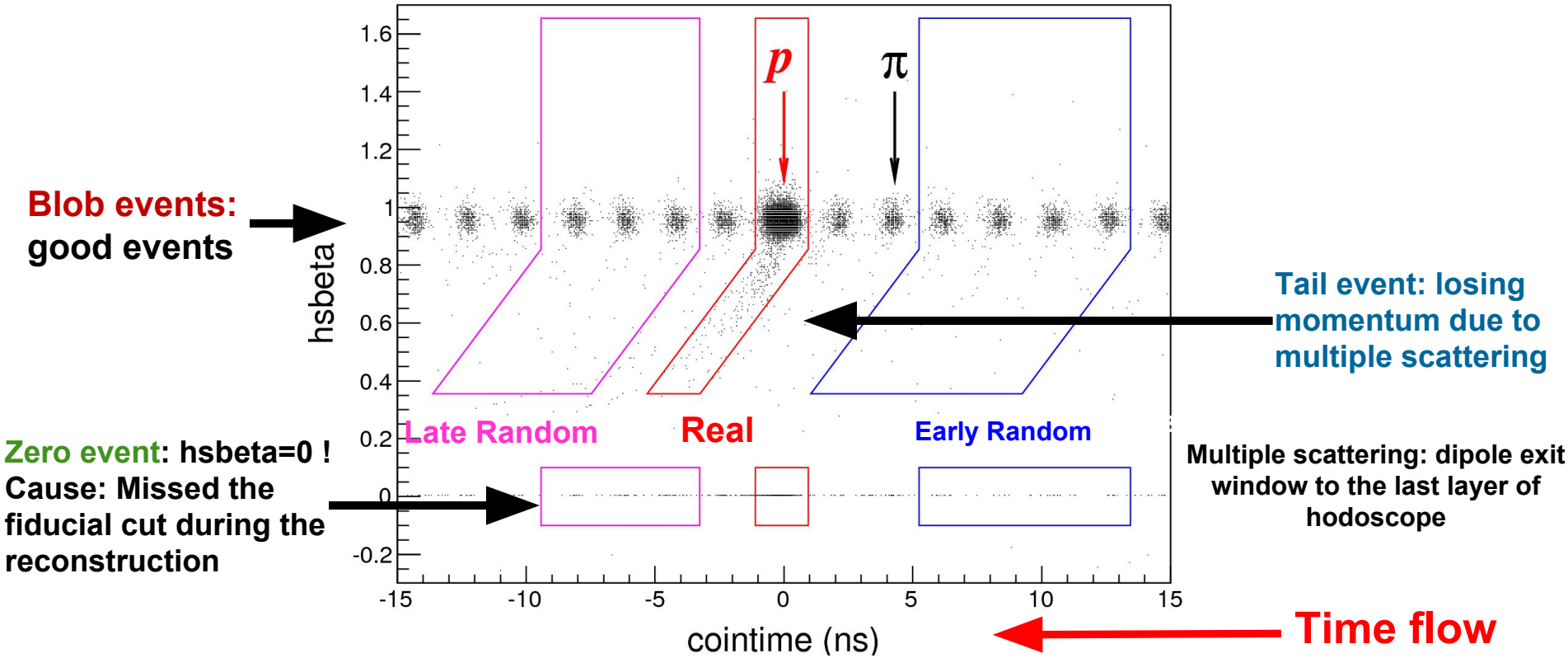
Coincidence Subtraction

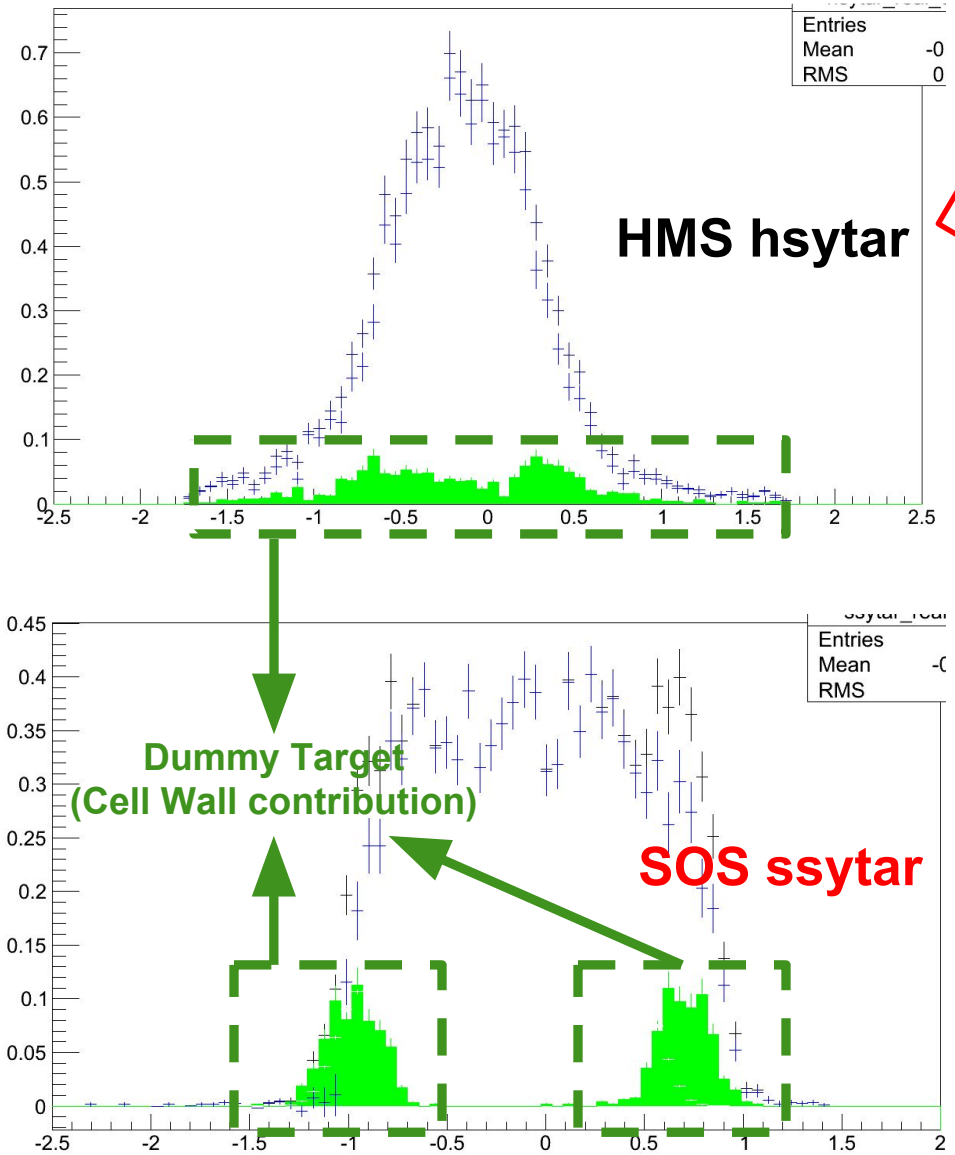


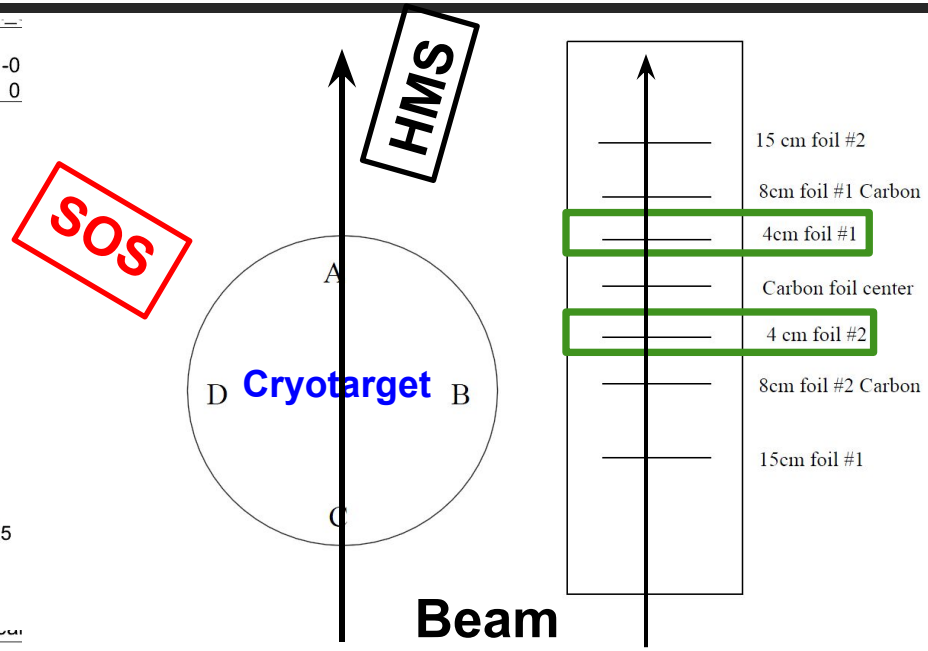
- **Random subtraction:**

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

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

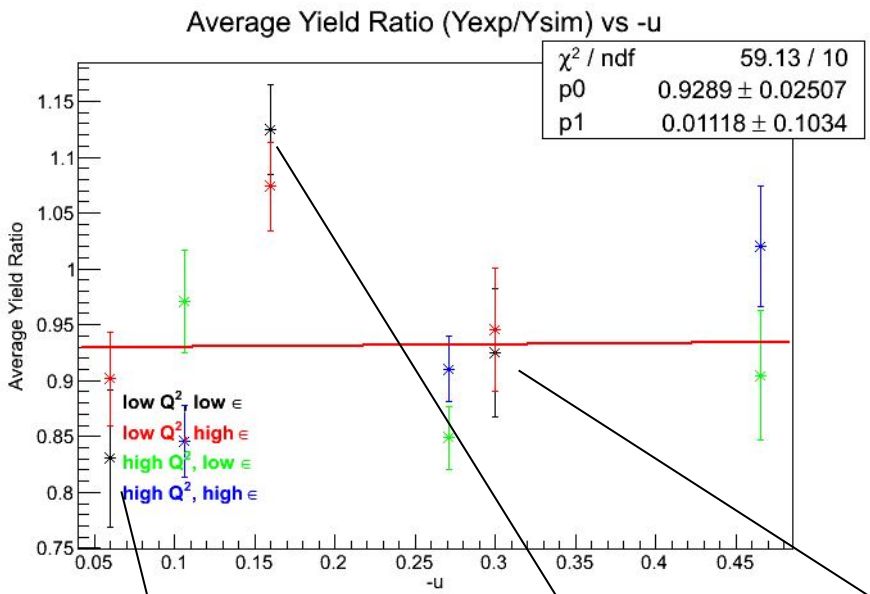
Dummy Subtraction





- **Cryotarget**
  - Tuna can shaped
  - With thin Al cell wall
- **Dummy Target**
  - 4cm apart Al sheets
  - Dummy target distribution is corrected for the real/dummy target thickness difference before subtracted from the real proton events

Yield Ratio and Simulated Cross-Section

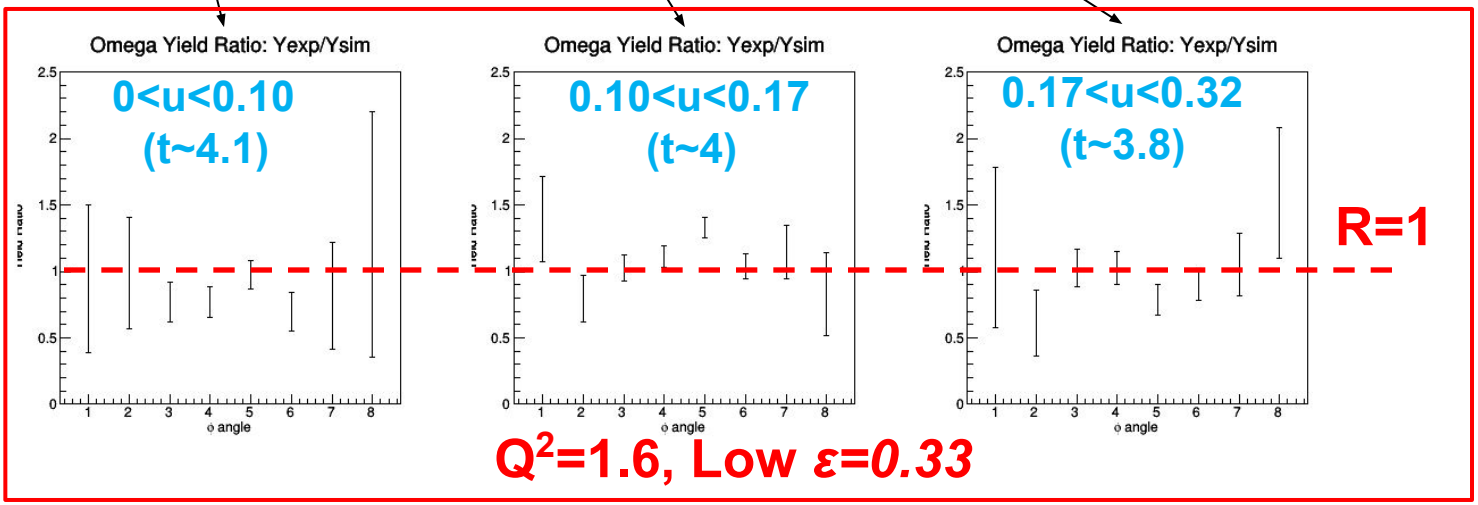


$$\sigma_T = \frac{t_0 + t_1 \cdot (-u)}{Q},$$
$$\sigma_L = \frac{l_0 + l_1 \cdot (-u)}{Q^4},$$
$$\sigma_{LT} = \left[\frac{lt_0 + lt_1 \cdot (-u)}{Q^2}\right] \cdot \sin\theta^*,$$
$$\sigma_{TT} = \left[\frac{tt_0 + tt_1 \cdot (-u)}{Q^2}\right] \cdot \sin^2\theta^*,$$

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

Model Cross Section

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



Exp/Sim Yield Ratio

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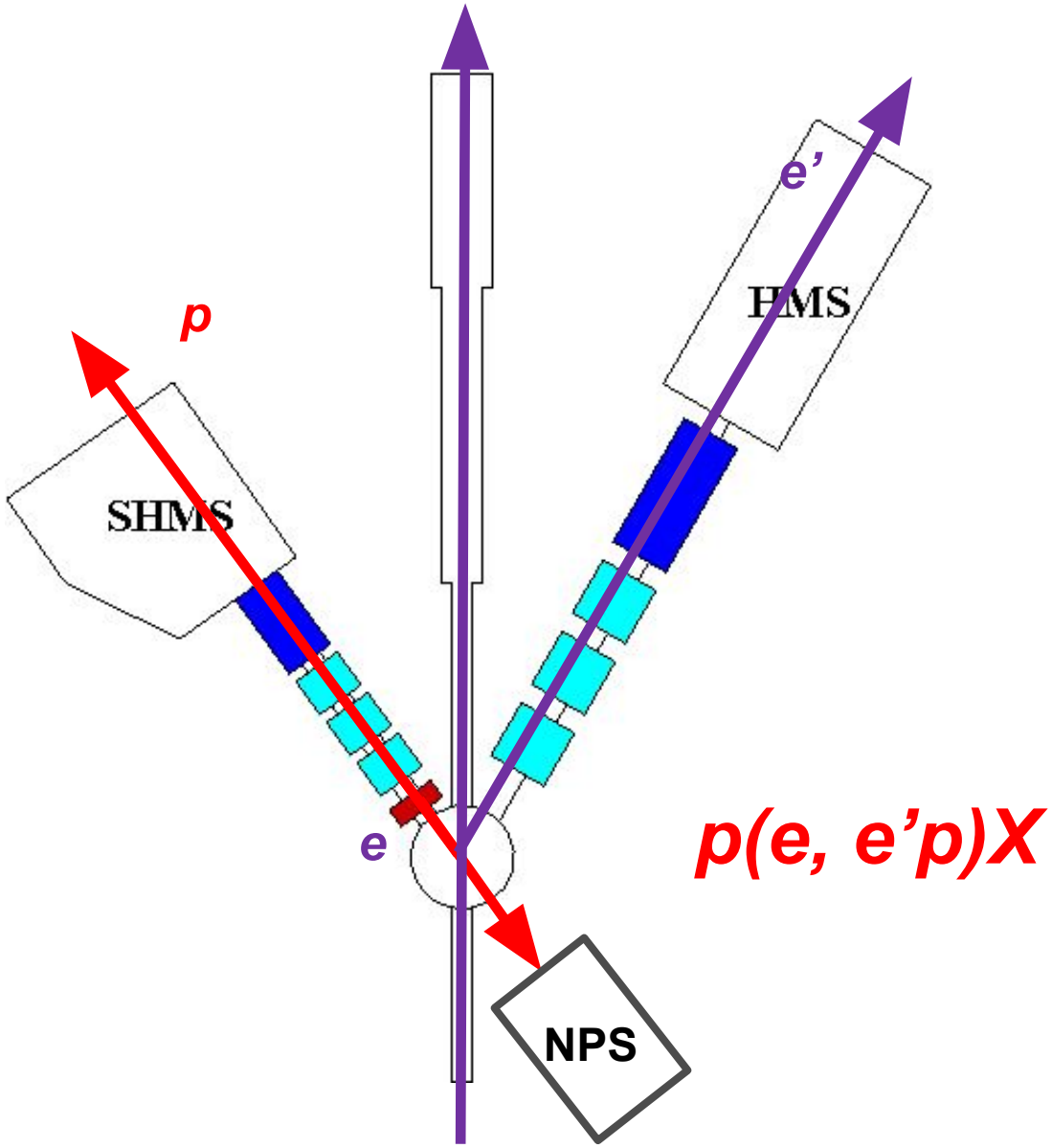
Uncertainties budget

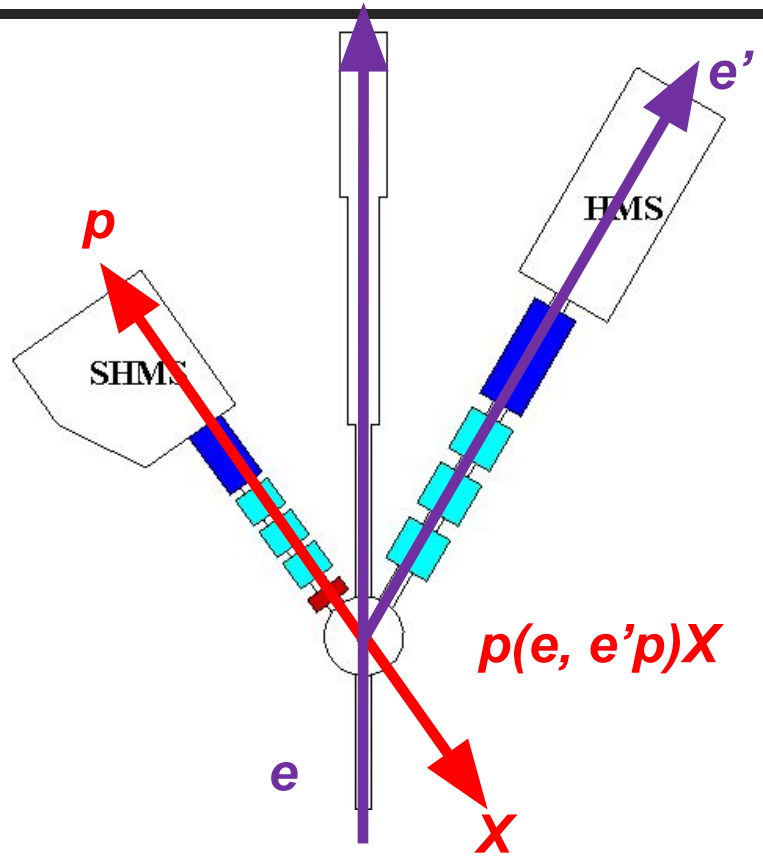
Correction	Uncorrelated (Pt-to-Pt) (%)	ϵ uncorr. u corr. (%)	Correlated (scale) (%)	Section
HMS Cherenkov			0.02	Sec. 3.6.3
HMS Aerogel			0.04	Sec. 5.3.7
SOS Calorimeter			0.17	Sec. 3.6.4
SOS Cherenkov			0.02	Sec. 3.6.3
HMS beta	0.4			Sec. 5.1.2
HMS Tracking		0.4	1.0	Sec. 5.3.3
SOS Tracking		0.2	0.5	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_{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)**

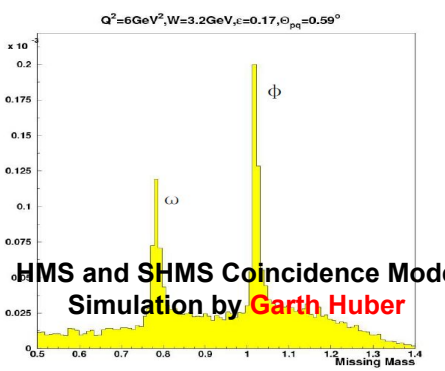
Thank you



Future Backward Meson Production Opportunities



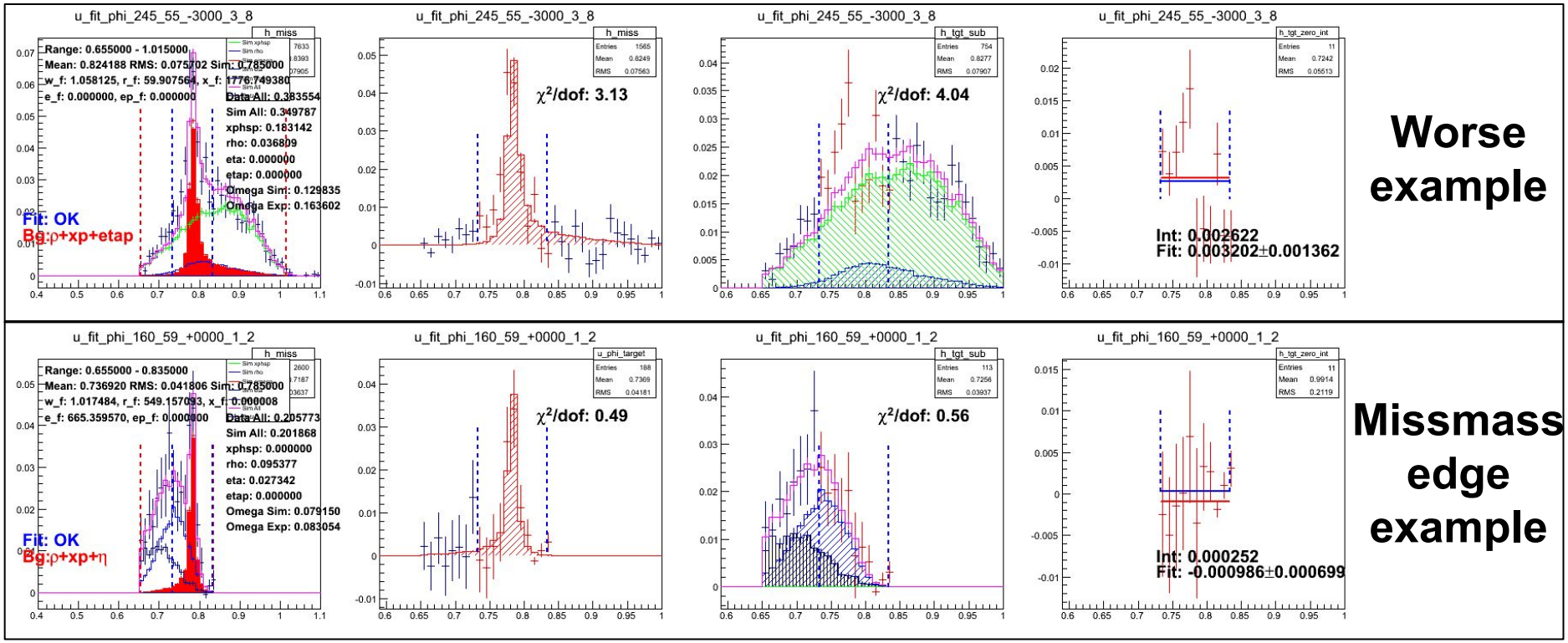
Hall C pi0 production

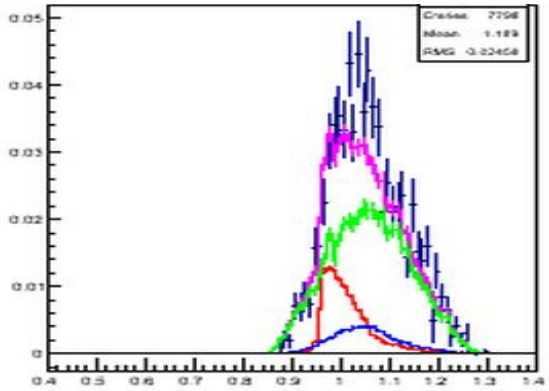


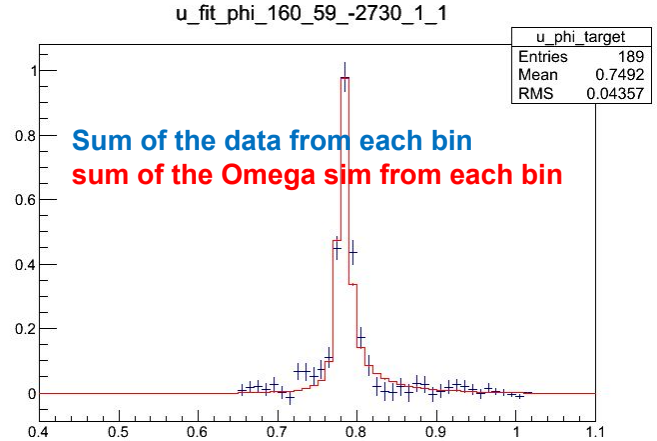
HMS and SHMS Coincidence Mode Simulation by Garth Huber

- **6 GeV data mining**
  - Pion transparency experiment (E92-110)
    - 2 GeV and 4.7 GeV (poor statistics)
- **Upcoming 12 GeV experiment**
  - Fpi-12 experiment (E12-06-101):
    - ***η, η', ω, $\phi(s\bar{s})$, ρ***
    - ***ω, $\phi(s\bar{s})$*** production ratio would yield valuable information.
  - Large Emission Experiment at CLAS: E12-12-007
    - $\phi(s\bar{s})$
  - Potential LOI (2018): **Backward π^0** production at Hall C.
- Backward-angle program with Panda @ GSI

Background Extraction and Check

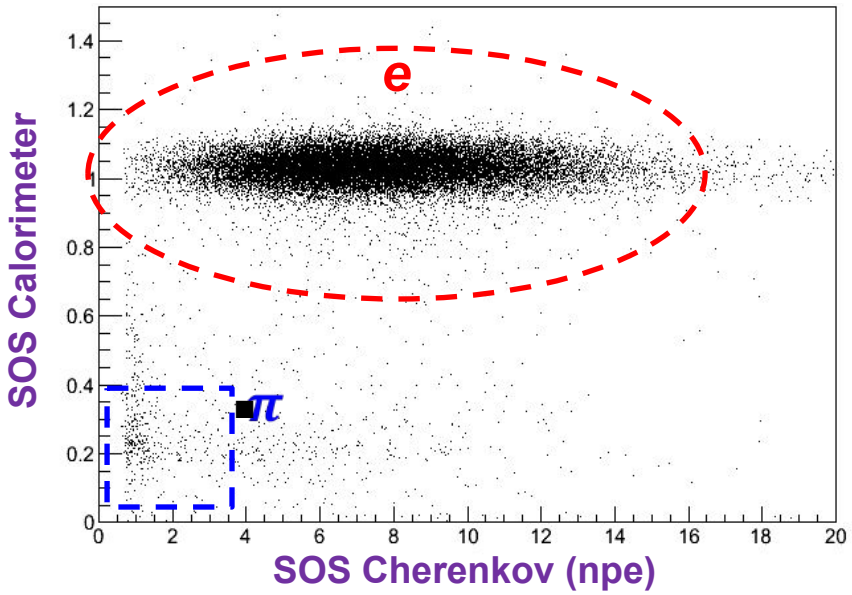


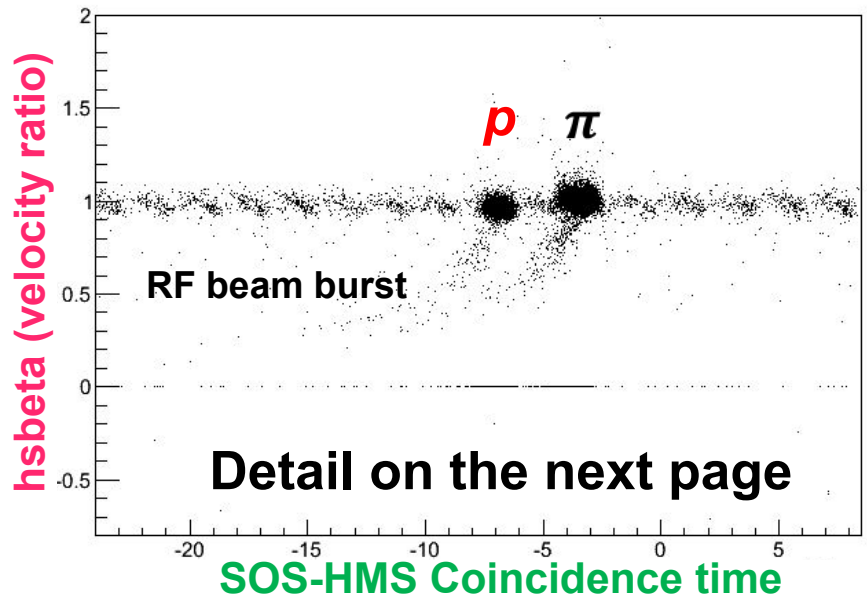




Reconstructed Missing Energy For the worse example

PID Cuts

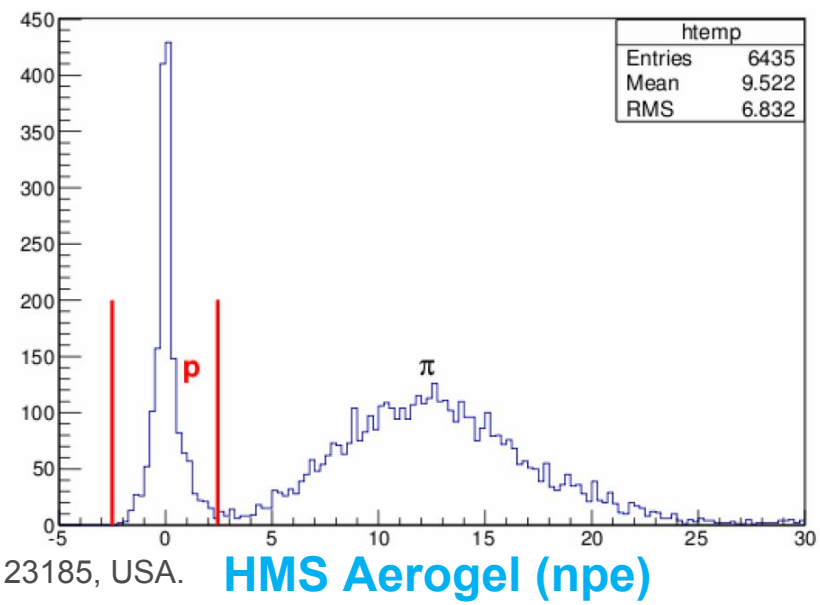




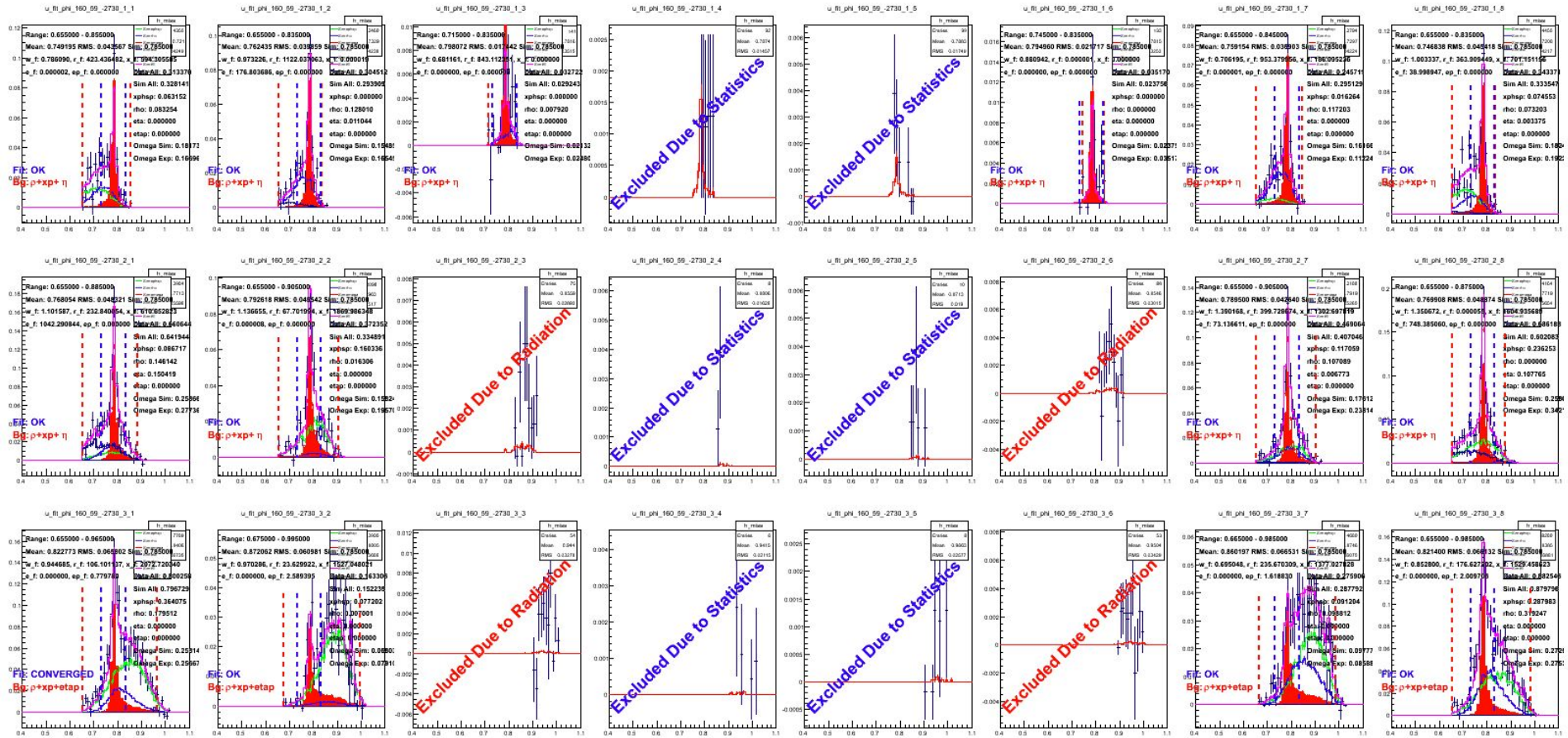
- SOS: select electron
  - Calorimeter cut
  - Cherenkov cut

99% efficiency

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



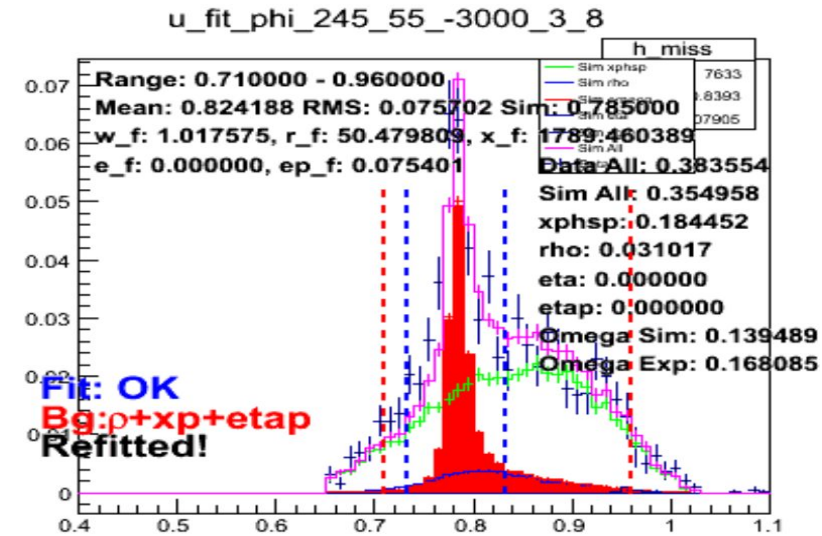
Missing Mass Distribution Background Extraction

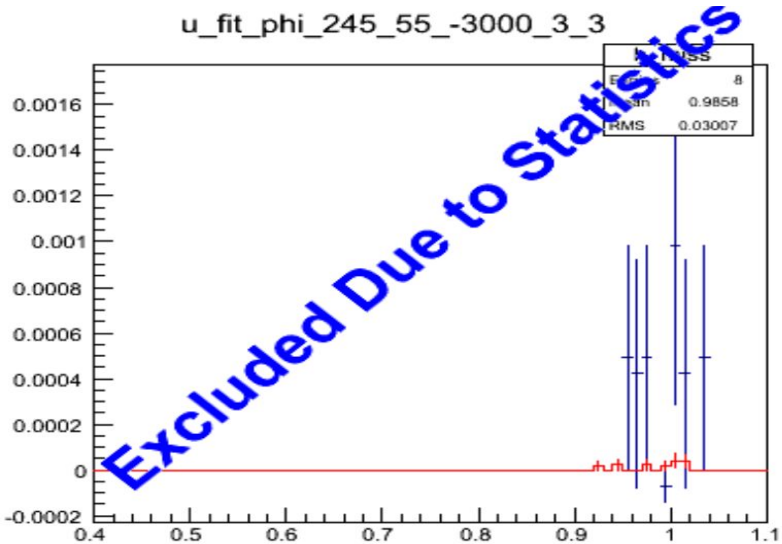


- Integration limits and fitting limits
- Exclusion criteria
  - Exclude the radiative only omega bins
  - Exclude the low statistics bins

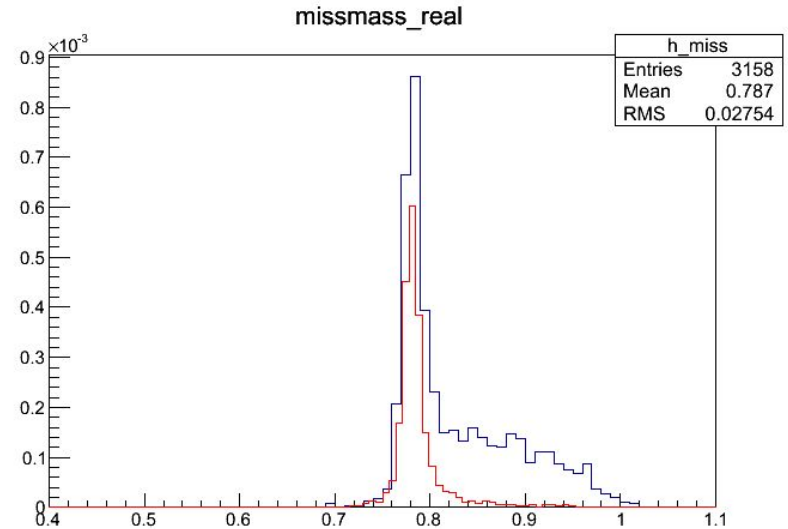
Bin Exclusion criteria

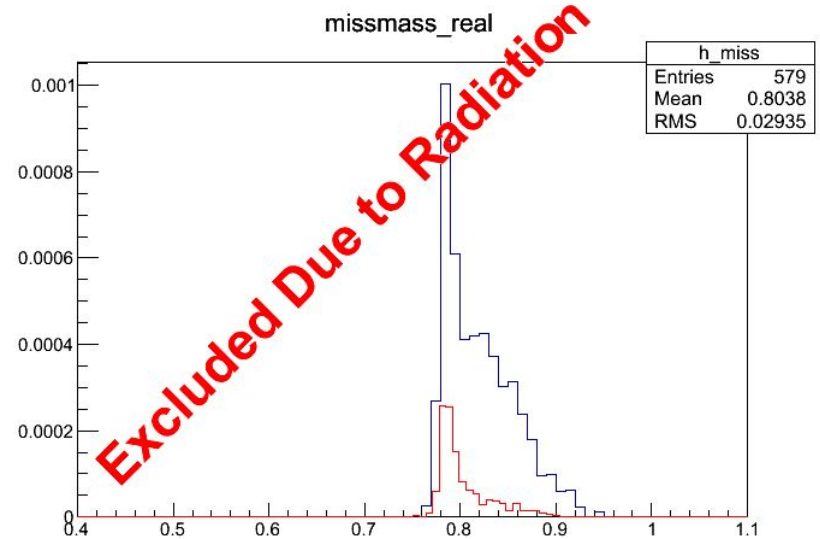
- Low Statistics



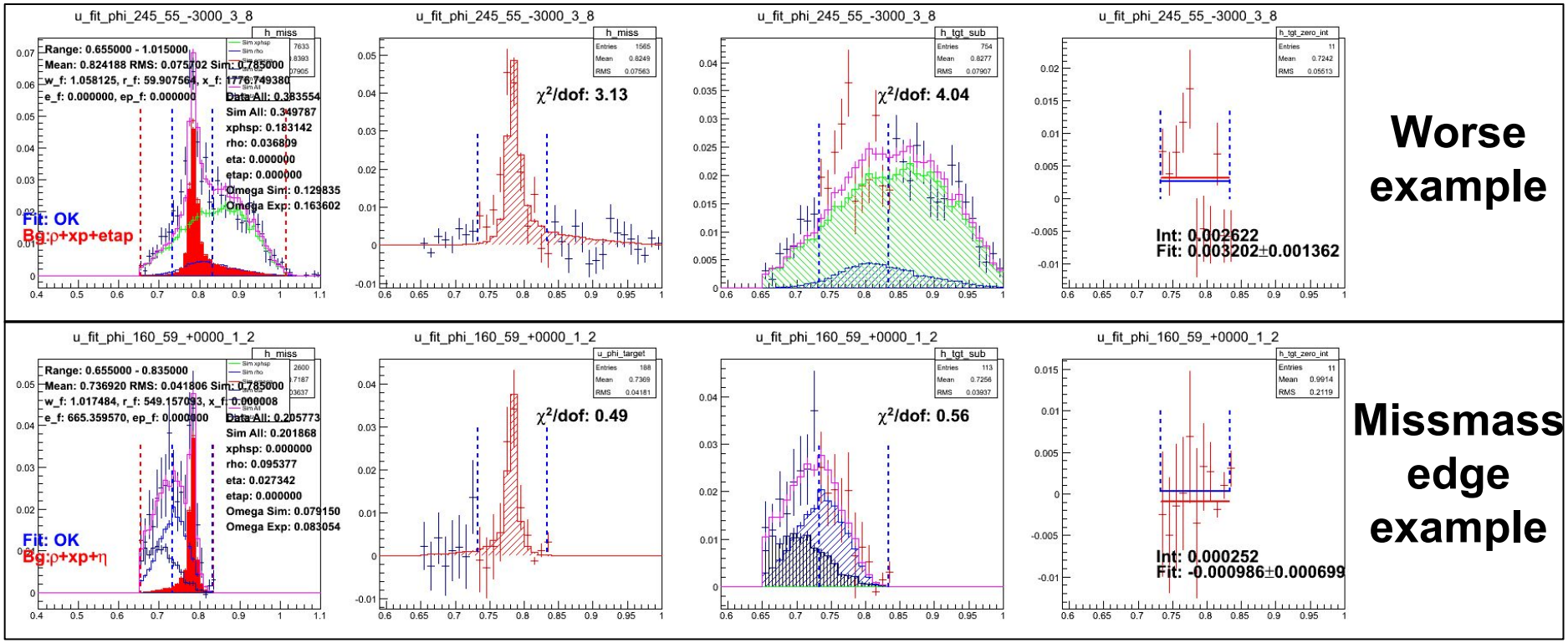


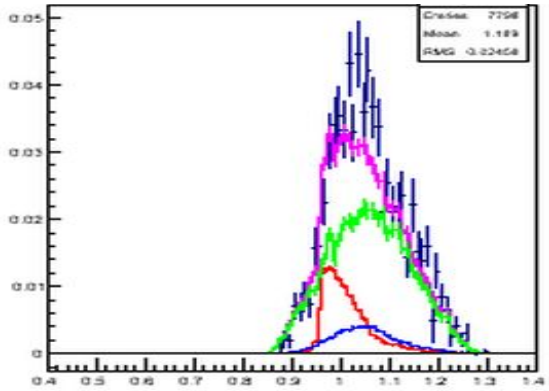
- Radiative Tail



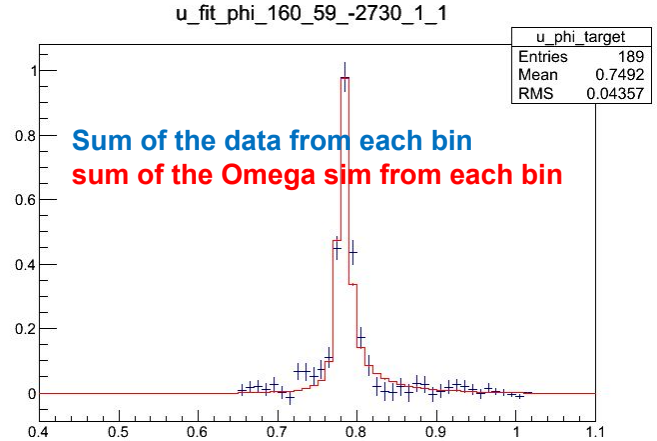


Background Extraction and Check



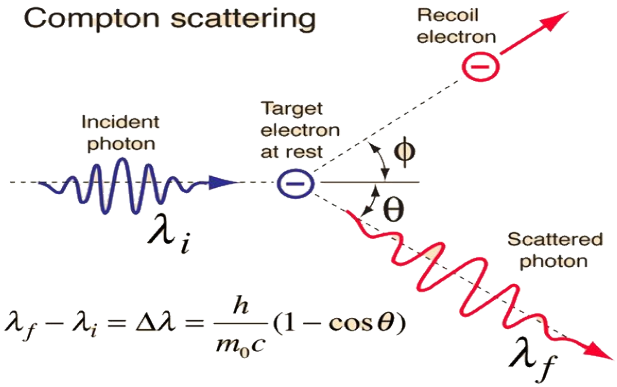


Reconstructed Missing Energy For the worse example

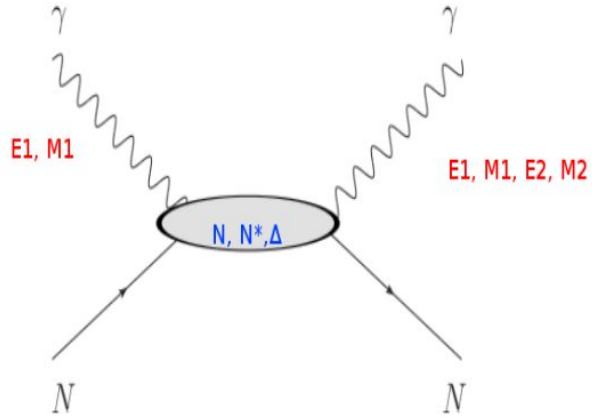


Standard Physics at Hall C (Jefferson Lab)

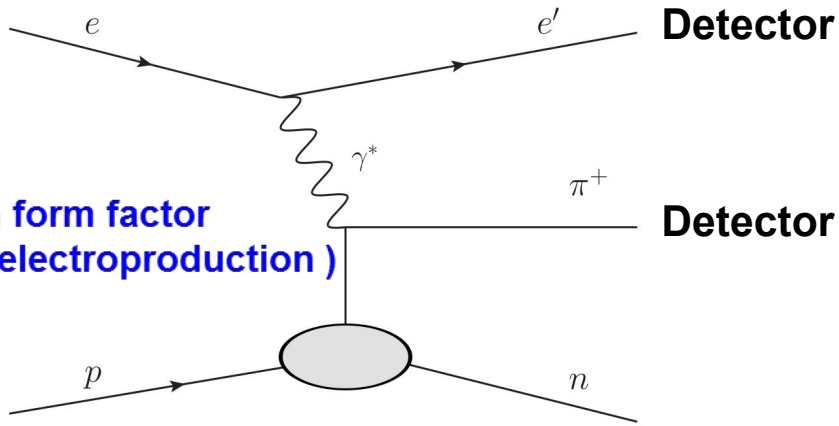
- ***s*-Channel Physics**



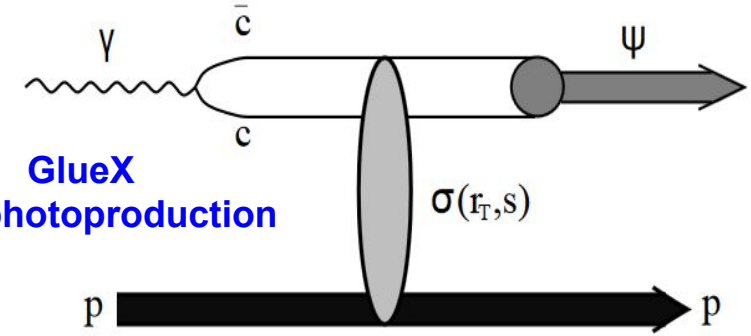
$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1-\cos\theta)$$



- ***t*-Channel Physics**



Pion form factor
(charged π electroproduction)



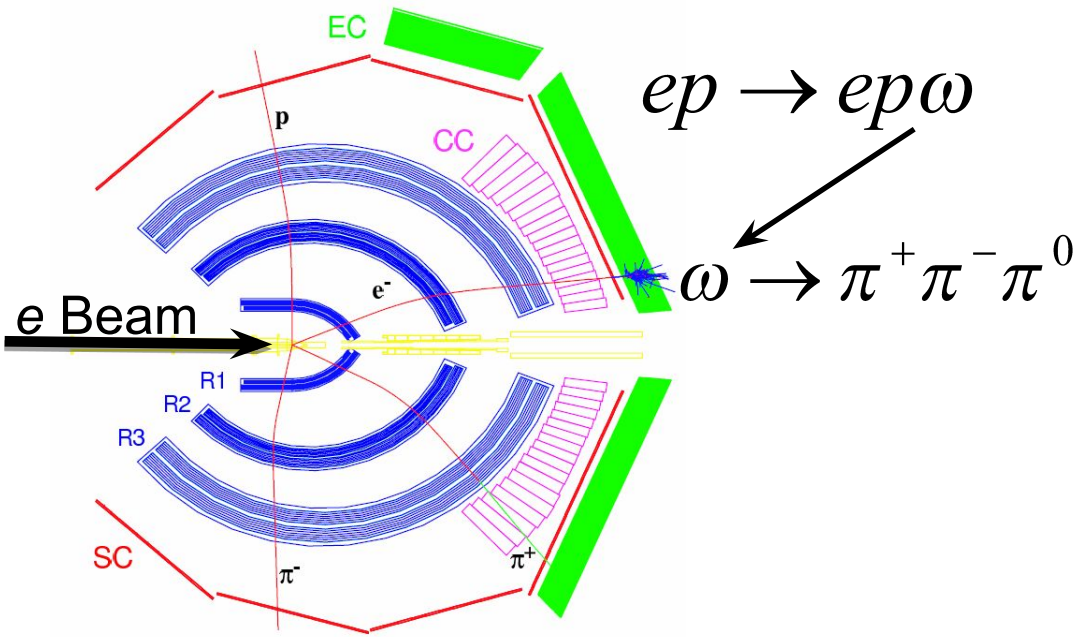
GlueX
J/psi photoproduction

- **All could be parameterized in four Lorentz invariant Quantities: *x*, *W* ($\sqrt{s}$), Q^2 and *t***

What about *u*? Should we include *u*?

High t Data from CLAS Hall B (2005)

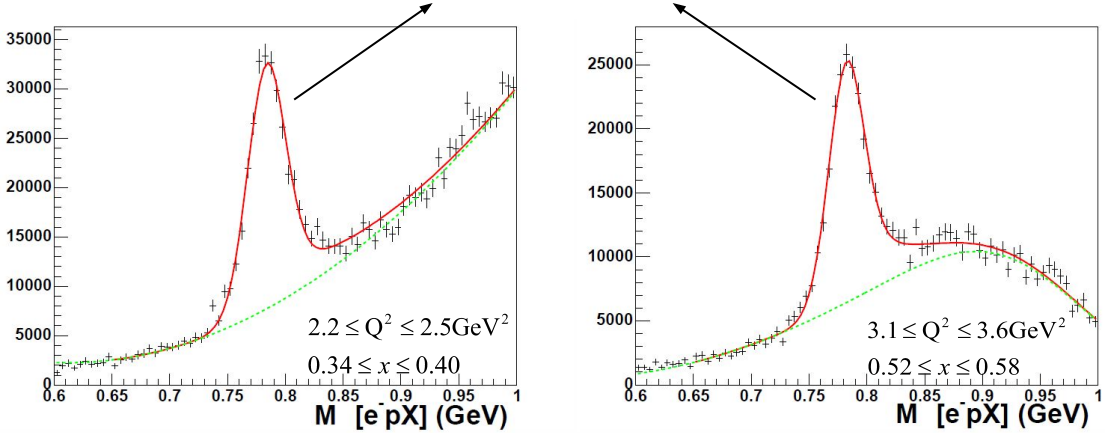
Morand et al., Eur. Phys. J. A 24, 445 (2005).



$$ep \rightarrow ep\omega$$

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

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



Missing mass reconstruction e^-pX

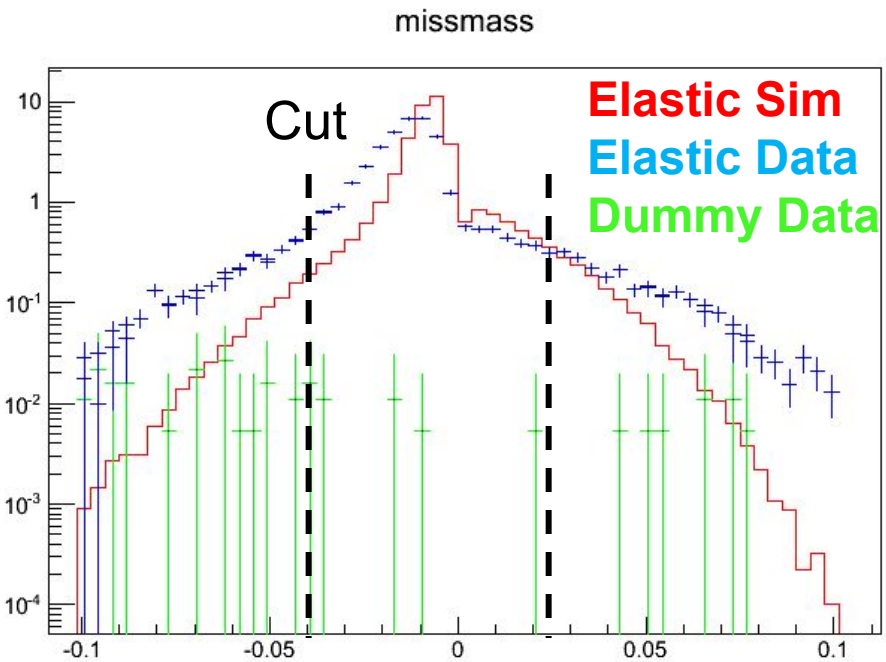
- Hall B Experiment **e1-6**
  - Oct 2001 – Jan 2002
  - Beam energy: 5.754 GeV
- Kinematic coverage:
  - W : 1.8-2.8 GeV
  - Q2: 1.6-5.1 GeV^2
  - **$-t$: < 2.7 GeV^2**
  - x: 0.16-0.64
- Event selection:

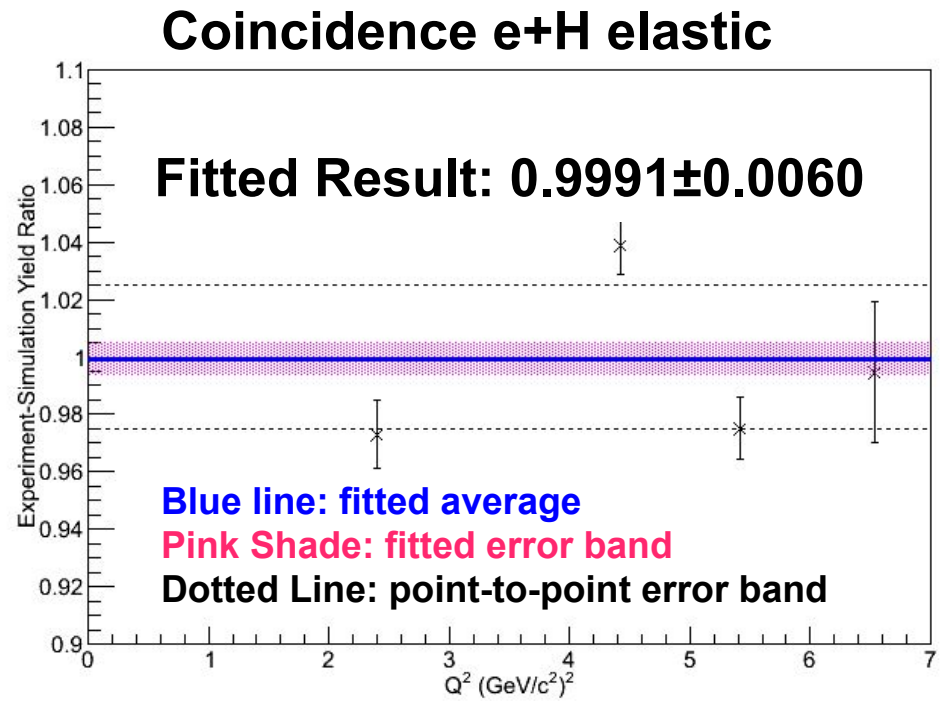
$$ep \rightarrow ep\pi^+X$$

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

Wenliang Li, Dept. of Physics, William and Mary, Williamsburg, VA 23185, USA.

Analysis: e+H Elastic Cross-Section

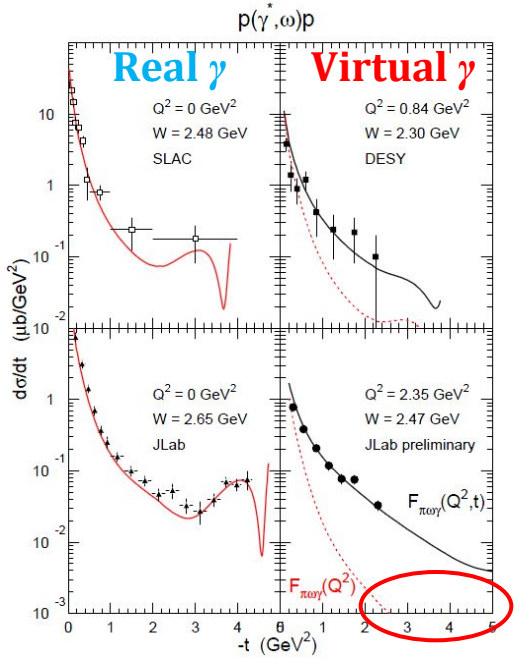




- Extracted cross section is consistent with Bosted, AMT (Arrington, Melnitchouk, Tjon Phys. Rev. C 76, 035205 (2007)) and Brash empirical e-p elastic cross section parameters.
- ±2.0% (point to point) error from Heep will be included to the final Omega analysis systematics

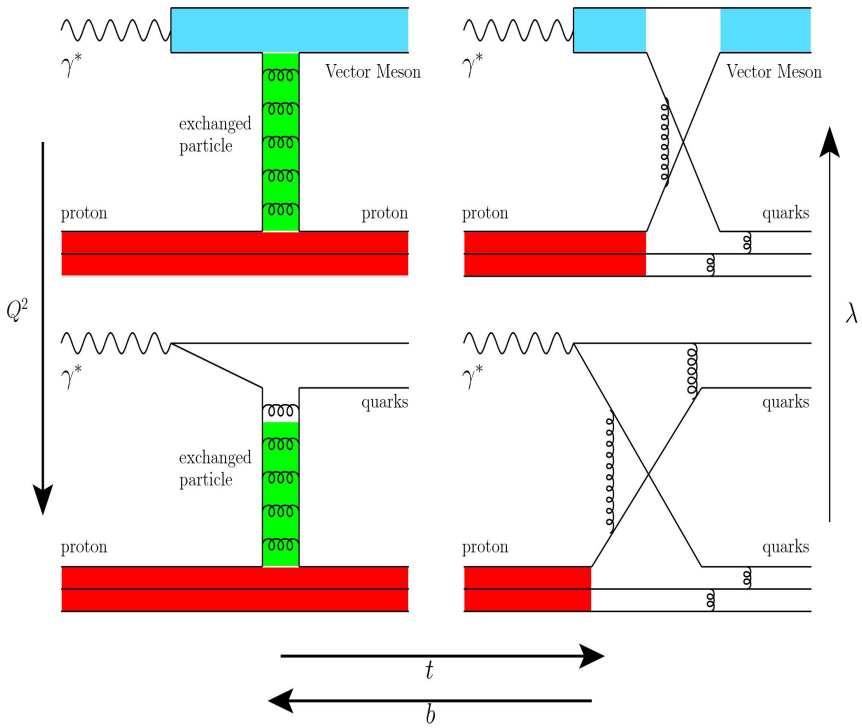
Regge Trajectory Model by JM Laget

	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	2.45	4.724	0.17-0.24



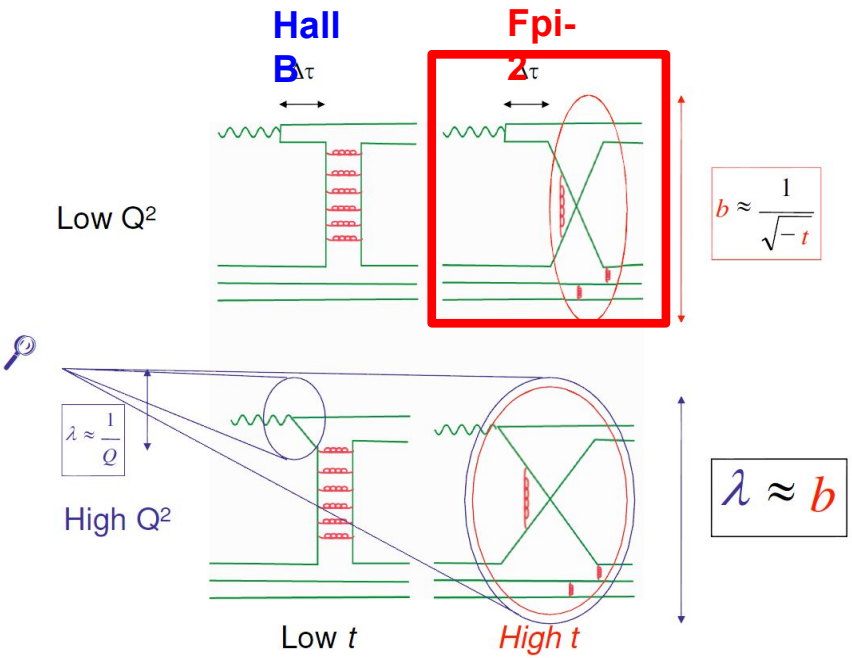
Fpi2 kinematics

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



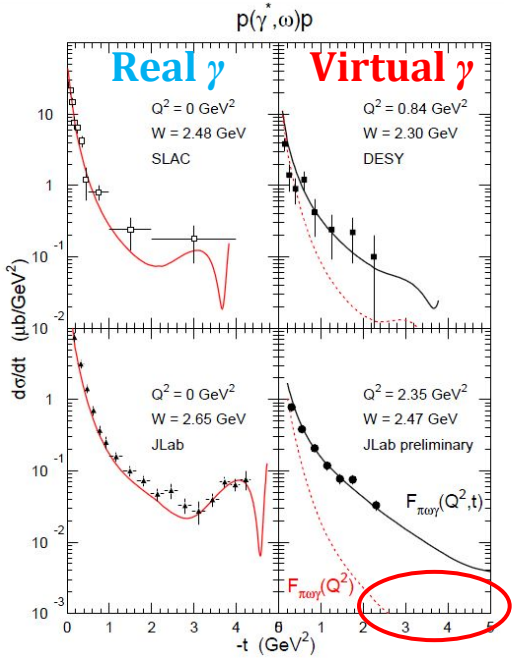
- Physics observables parameterized In ***t, W (s), Q^2, x***
  - *x* and *W* are fixed
- ***Q^2* Evolution**
  - **Wavelength of the probe**
- ***t* Evolution**
  - **Impact parameter**
- What about ***u***?

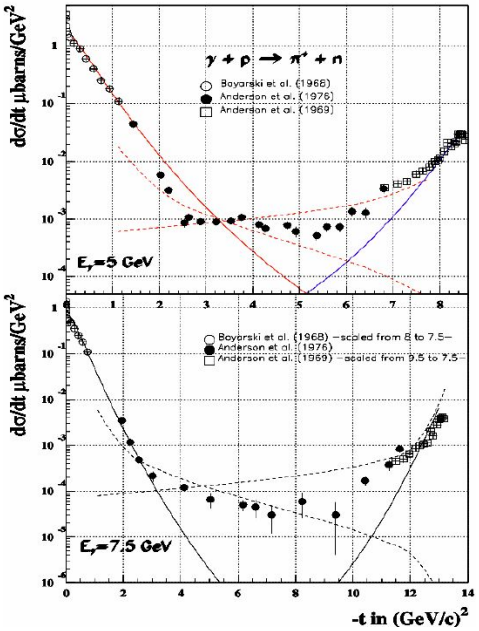
Regge Trajectory Model by JM Laget



Hard Scattering Mechanism schematics

	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	2.45	4.724	0.17-0.24





Fpi2 kinematics

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

***t*-Channel Forward**

***u*-Channel Backward**

Nucleon Fragmentation Process

Before interaction

e **+** ***H***

Standard nucleon Fragmentation gives a weird picture

Allows for kinematic settings which was previously not available

After interaction ***t*-channel**

***n* (938 MeV)**

SOS

Remains at target position

HMS

- **H(*e*, *e'* π^+)*n***

***u*-channel**

***ω* (770 MeV)**

SOS

Remains at target position

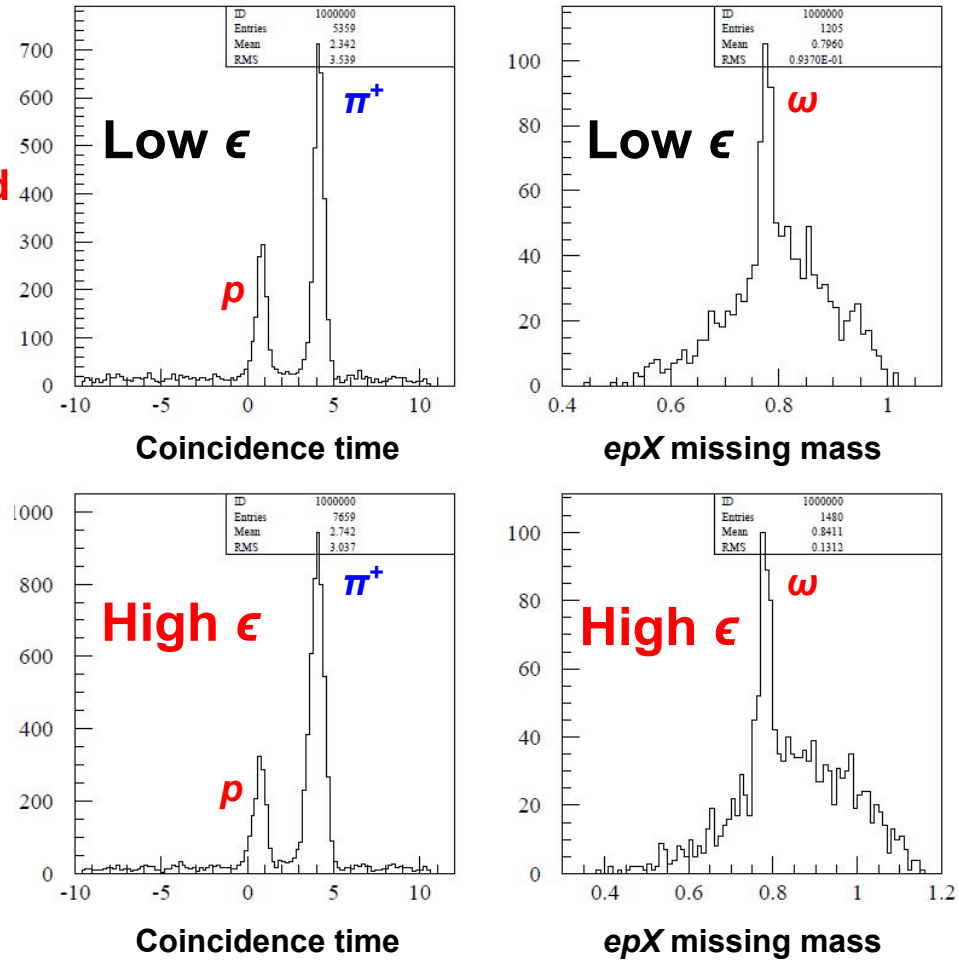
HMS

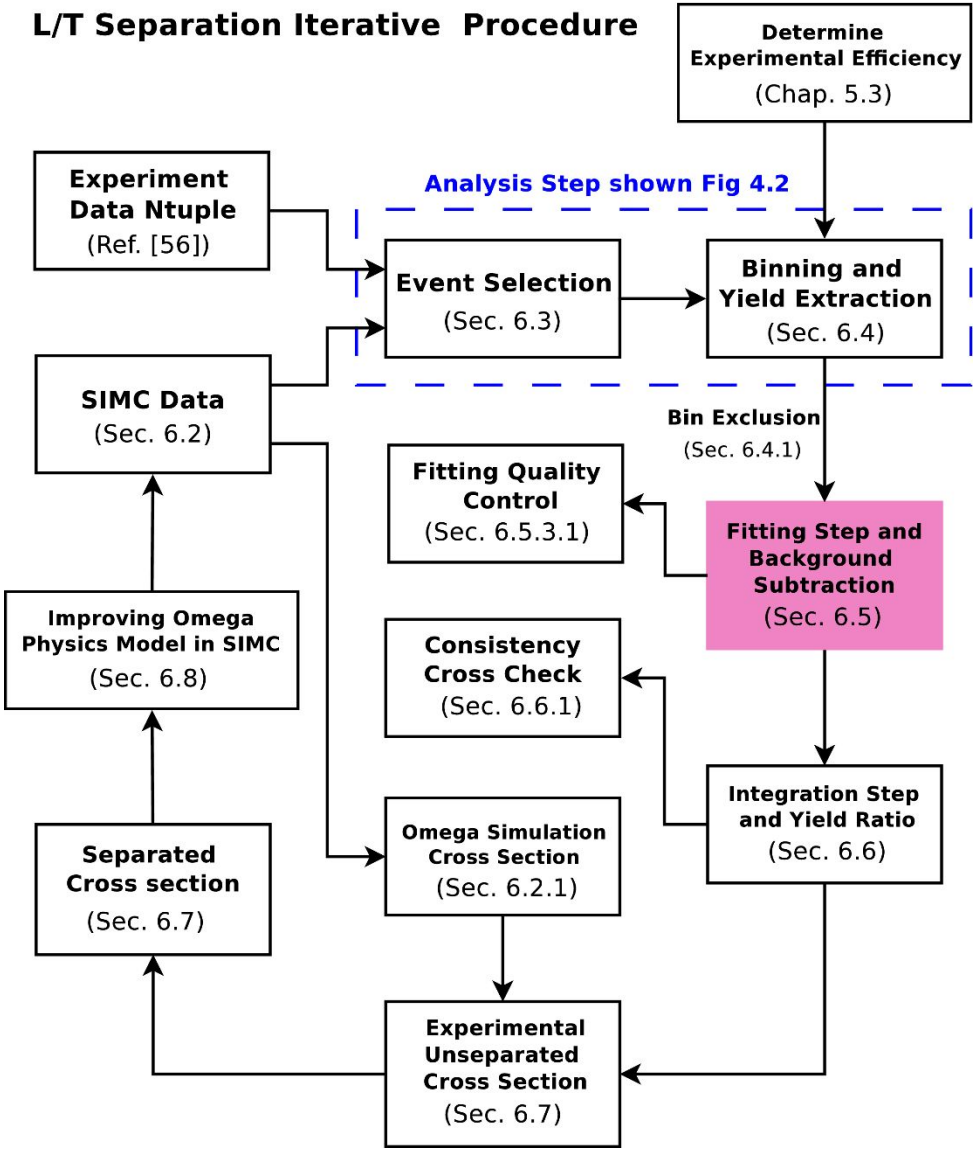
- **H(*e*,*e'* *p*)*ω***
- **Exclusive Chanel: *ω* is not tagged Allows for kinematic settings which was previously not available**

Omega Data Analysis

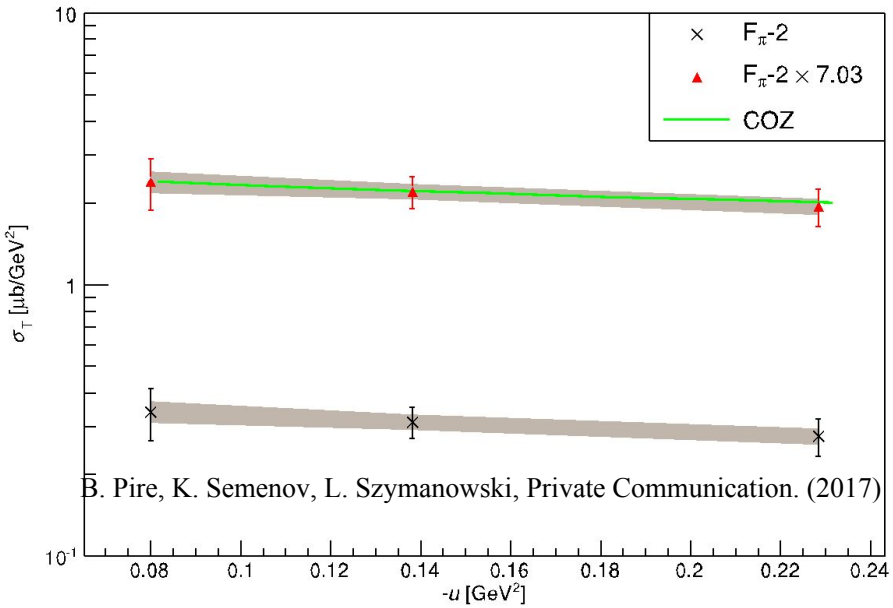
- Fpi-2 (E01-004) 2003
  - Spokesperson: **Garth Huber, Henk Blok**
  - Standard HMS and SOS (e) configuration
  - **Electric form factor of charged** through exclusive π production
- Primary reaction for Fpi-2
  - ***p(e, e' π^+)n***
- In addition, we have for free
  - ***p(e,e' p)ω***
- Kinematics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

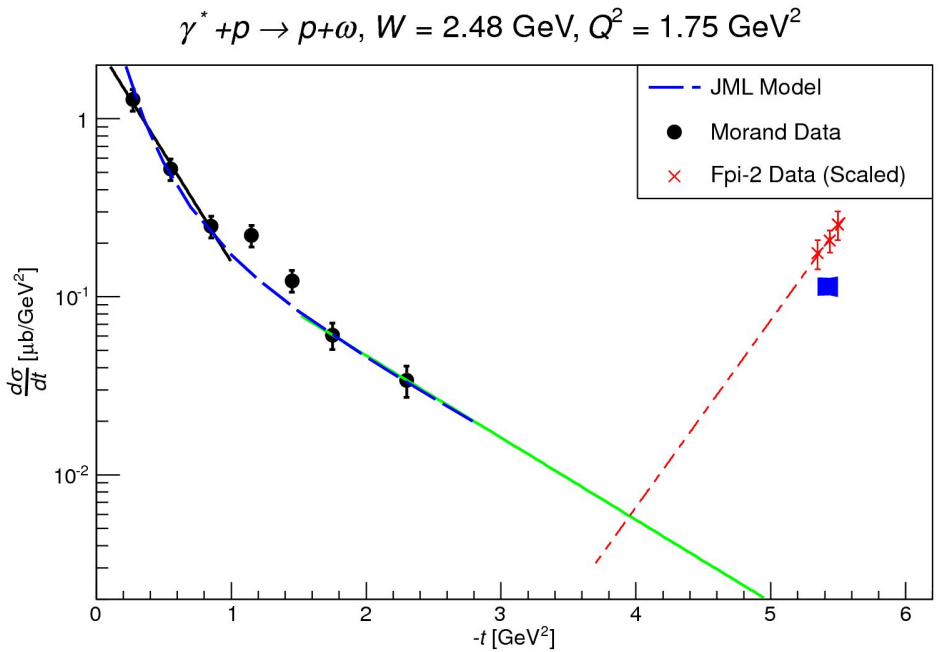
Q^2=2.45 GeV^2 **2003** 2003/07/25 08.56



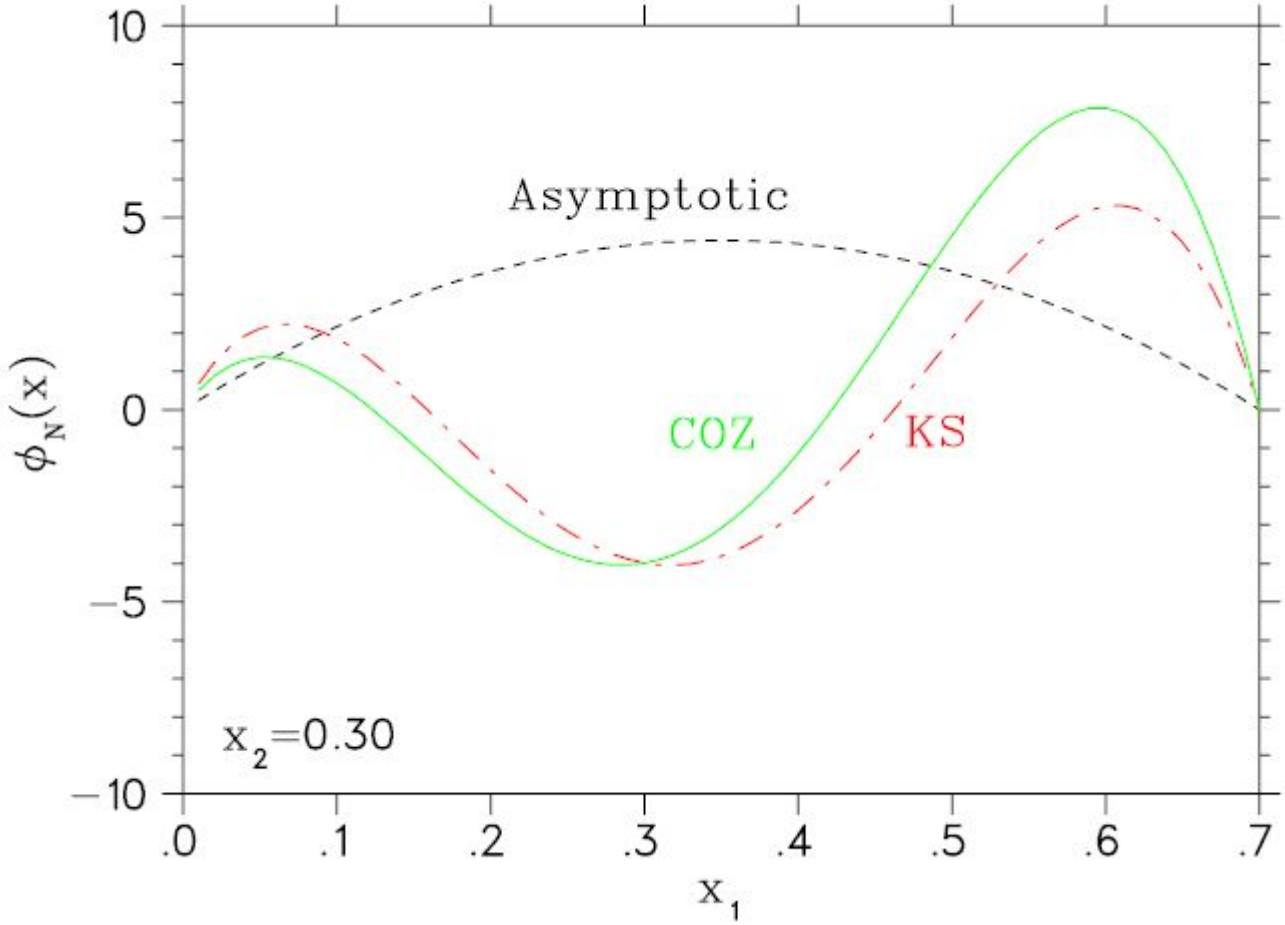

L/T Separation Iterative Procedure
Determine Experimental Efficiency (Chap. 5.3)
Experiment Data Ntuple (Ref. [56])
Analysis Step shown Fig 4.2
Event Selection (Sec. 6.3)
Binning and Yield Extraction (Sec. 6.4)
SIMC Data (Sec. 6.2)
Bin Exclusion (Sec. 6.4.1)
Fitting Quality Control (Sec. 6.5.3.1)
Fitting Step and Background Subtraction (Sec. 6.5)
Improving Omega Physics Model in SIMC (Sec. 6.8)
Consistency Cross Check (Sec. 6.6.1)
Integration Step and Yield Ratio (Sec. 6.6)
Separated Cross section (Sec. 6.7)
Omega Simulation Cross Section (Sec. 6.2.1)
Experimental Unseparated Cross Section (Sec. 6.7)

TDA @ Q^2 =1.60 GeV^2





Nucleon DA Model



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

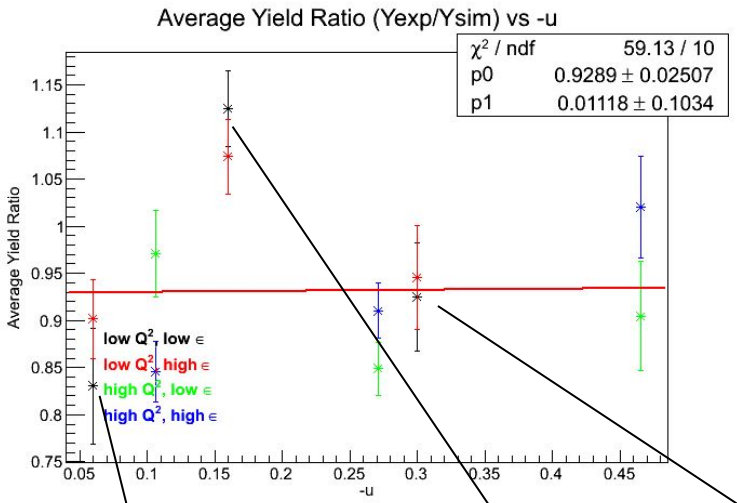
- $$R = \frac{Y_{Exp} - Y_{\rho\ \mathrm{sim}} - Y_{Xspace\ \mathrm{sim}} - Y_{\eta\ \mathrm{sim}}}{Y_{\omega\ \mathrm{sim}}}$$

Background Sum

Zero= Data – Omega- Bg

- **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**

Yield Ratio and Simulated Cross-Section



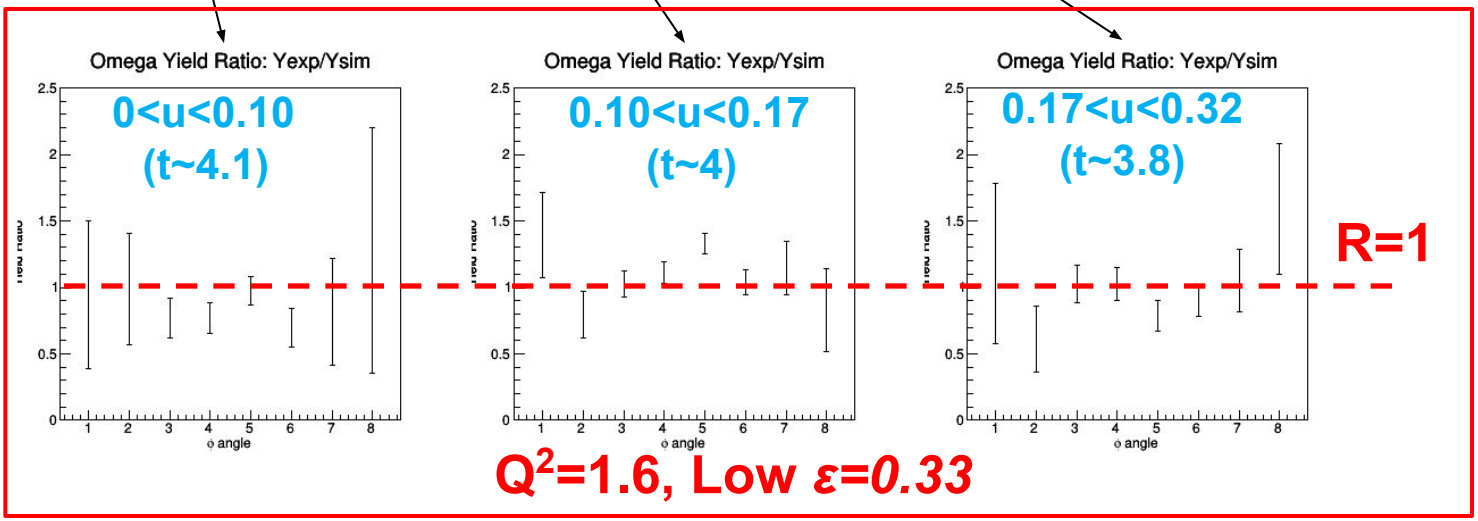
$$\sigma_T = \frac{t_0 + t_1 \cdot (-u)}{Q},$$
$$\sigma_L = \frac{l_0 + l_1 \cdot (-u)}{Q^4},$$
$$\sigma_{LT} = \left[\frac{lt_0 + lt_1 \cdot (-u)}{Q^2}\right] \cdot \sin\theta^*,$$
$$\sigma_{TT} = \left[\frac{tt_0 + tt_1 \cdot (-u)}{Q^2}\right] \cdot \sin^2\theta^*,$$

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

Model Cross Section

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

Exp/Sim Yield Ratio



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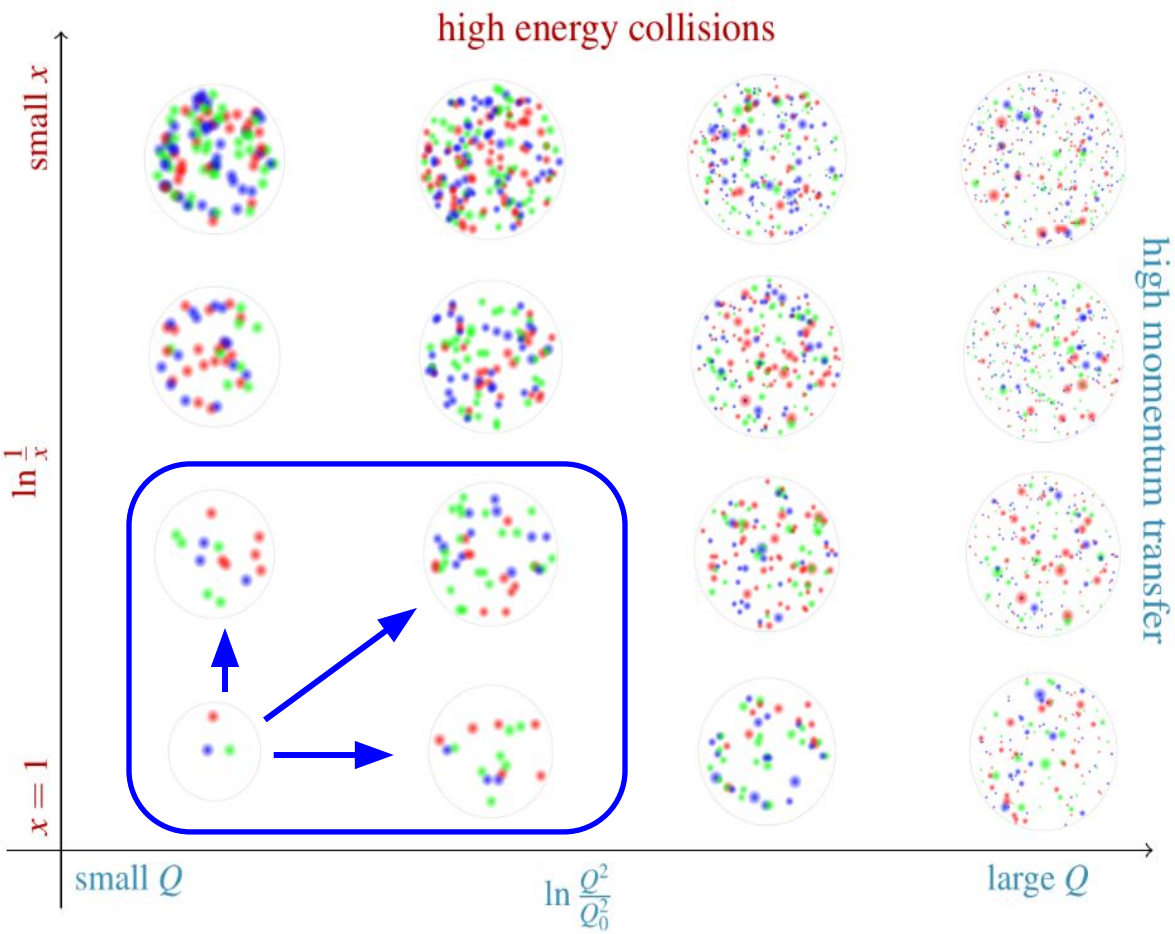
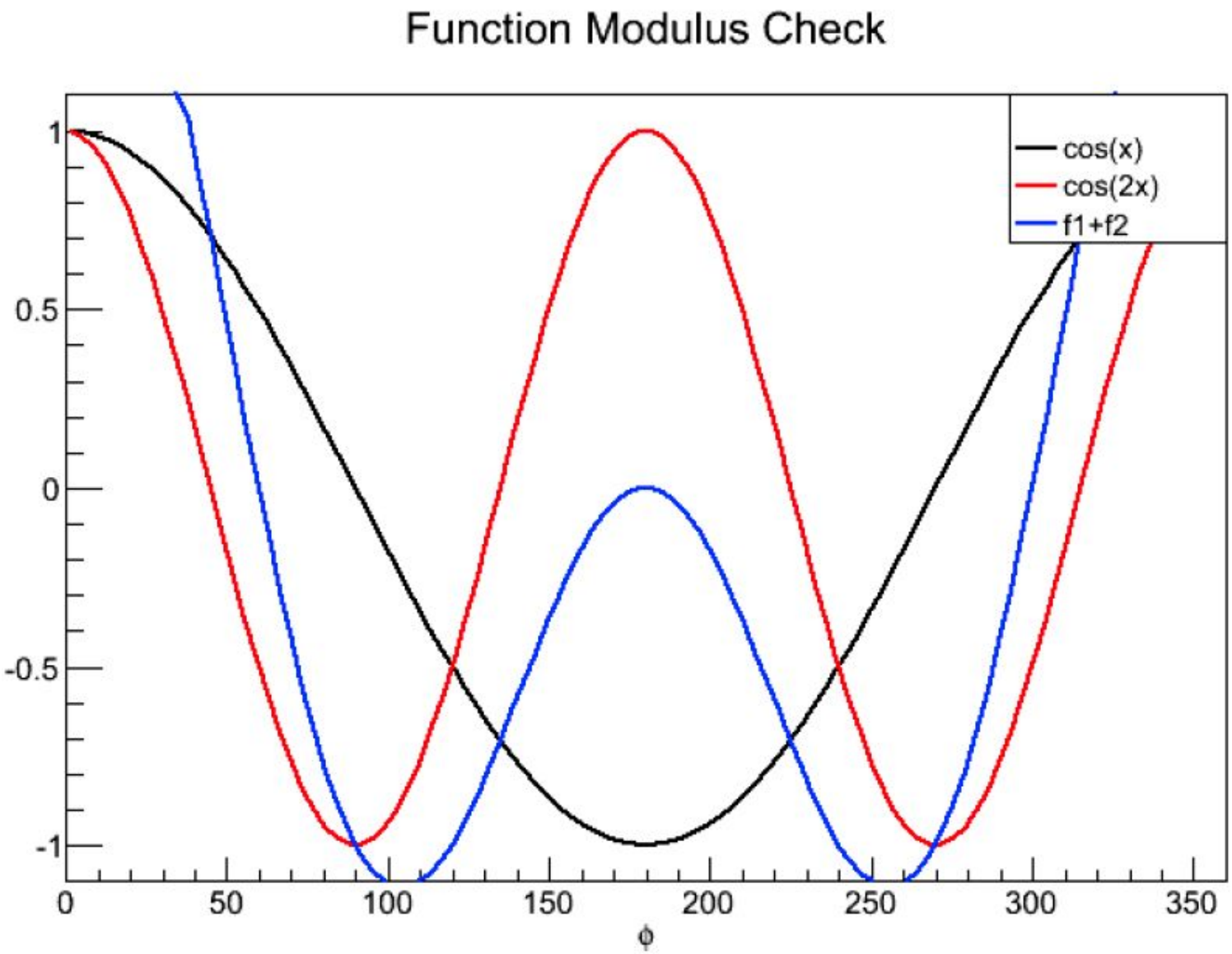
Proton Structure: Known and Unknown



- Proton
  - Dynamic Structure
    - Parton Distribution
    - Interaction
- Static proton structural map is known
- Unknown
  - **Transition (evolution)** of the proton structure
  - General description of the proton structure
- **Goal: Study the transition of the proton structure**

Modulus Check for SigLT and SigTT



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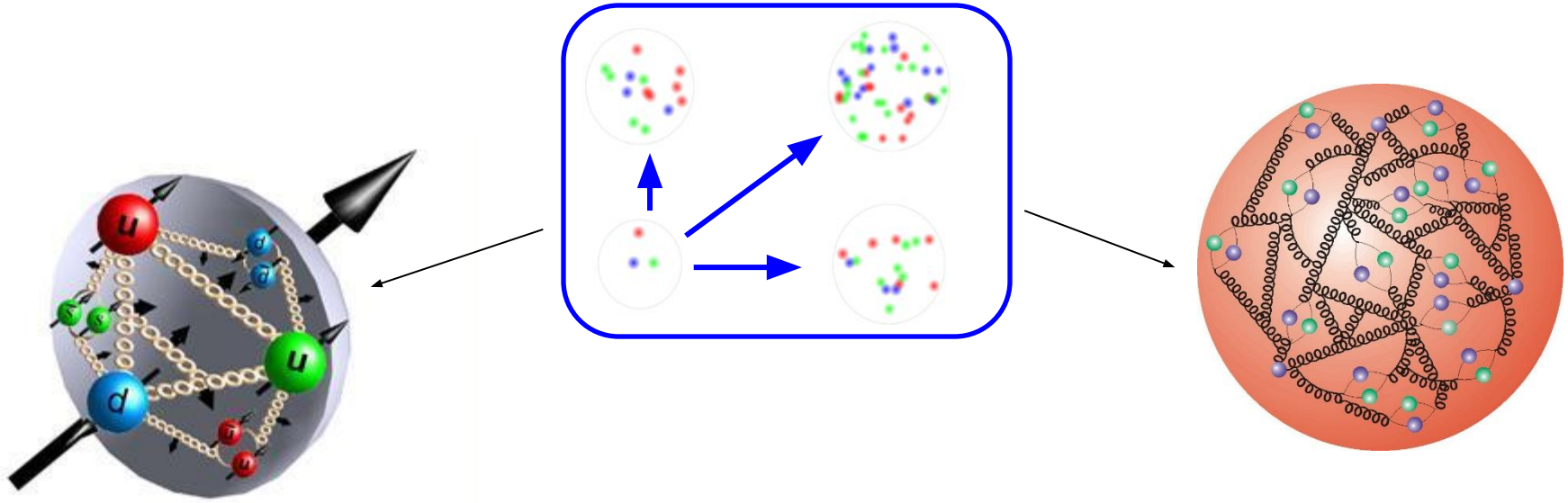
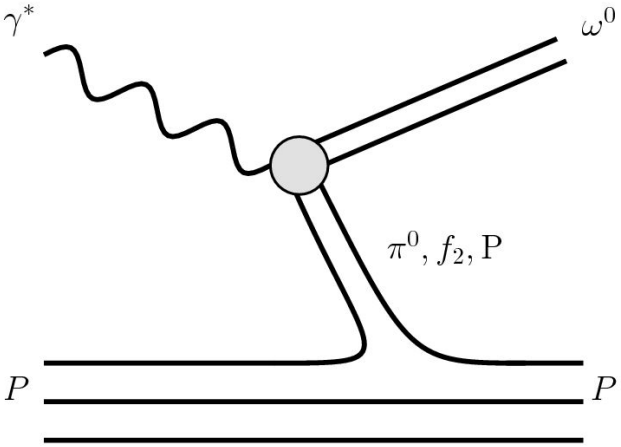
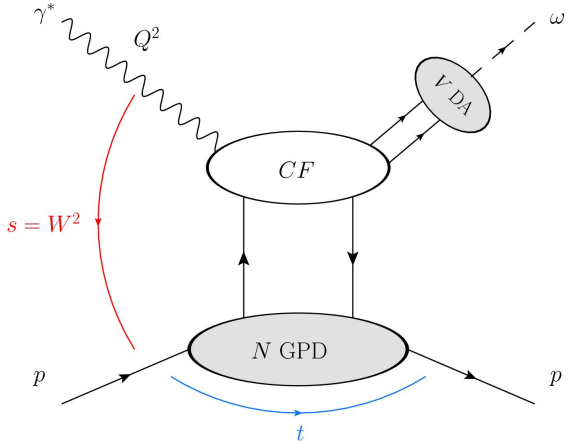
Proton Structure Description



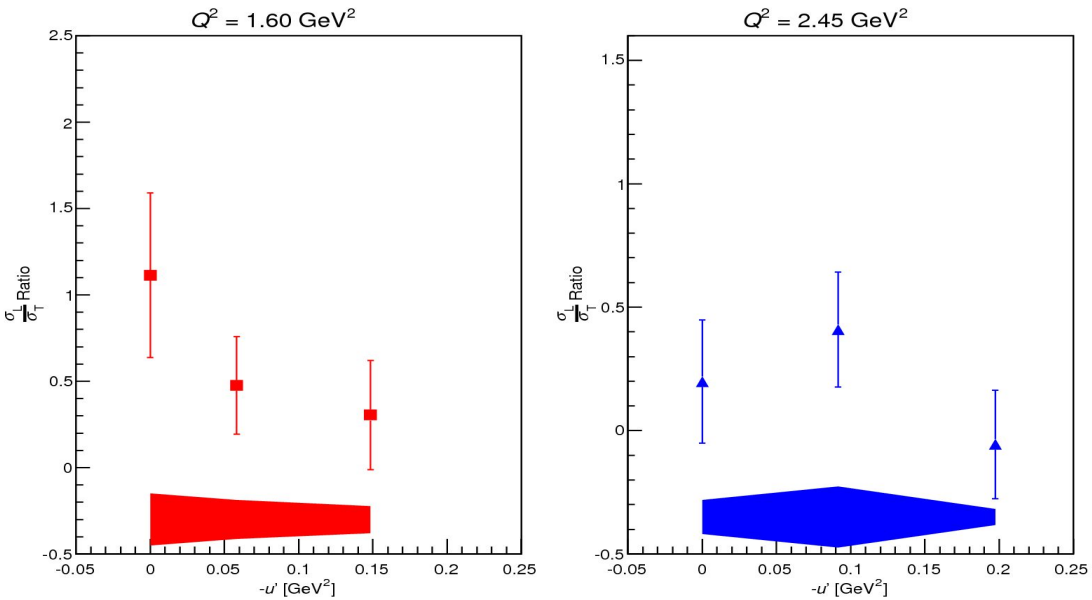
- Hadronic Model

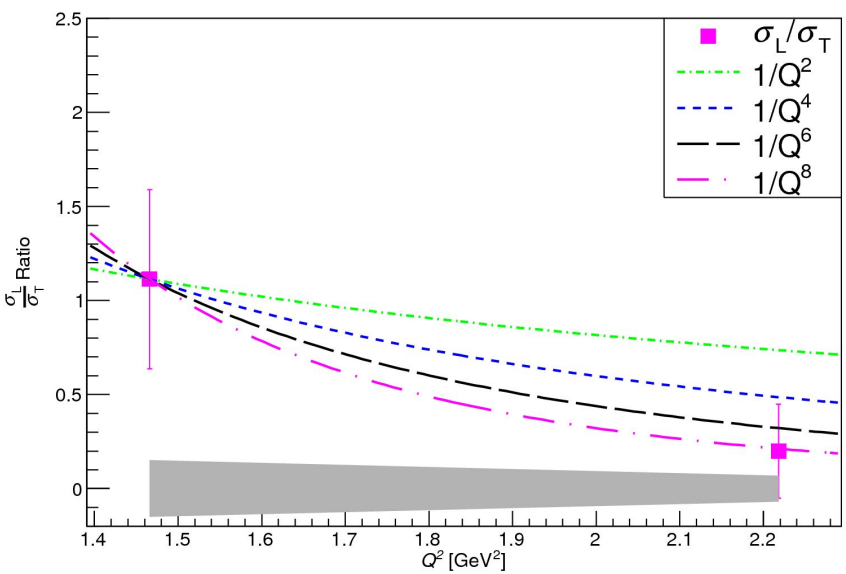


- Partonic Model



Scaling of σ_L, σ_T and σ_L / σ_T Ratio





-
- Dominance of σ_T observed at higher Q2 =2.45, confirms the TDA prediction
- σ_L drops expected ~$1/Q^8$
- σ_T is almost constant

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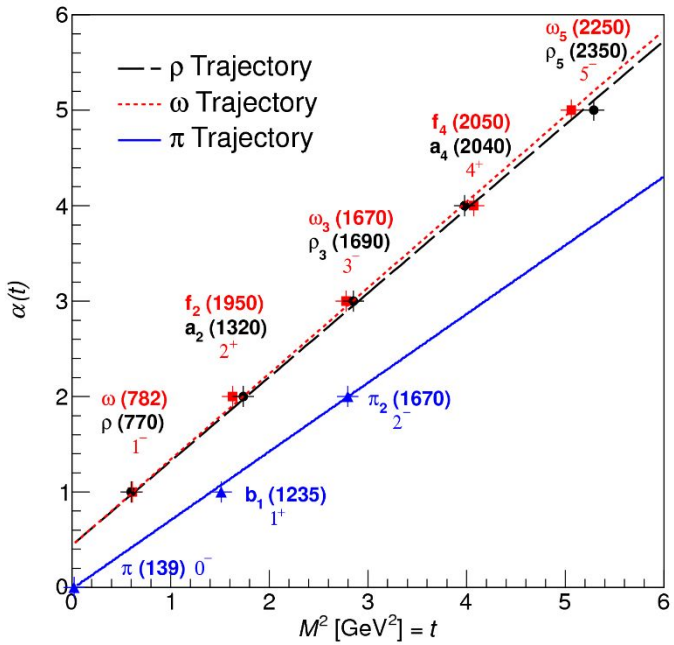
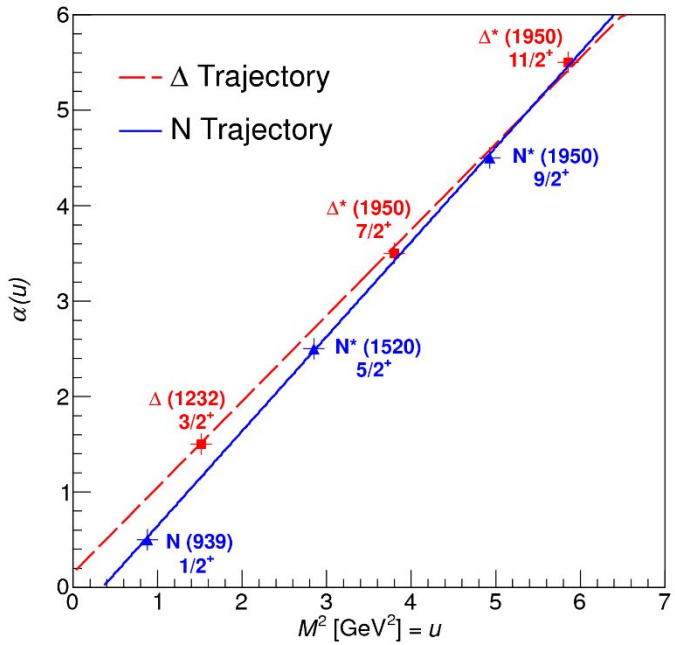
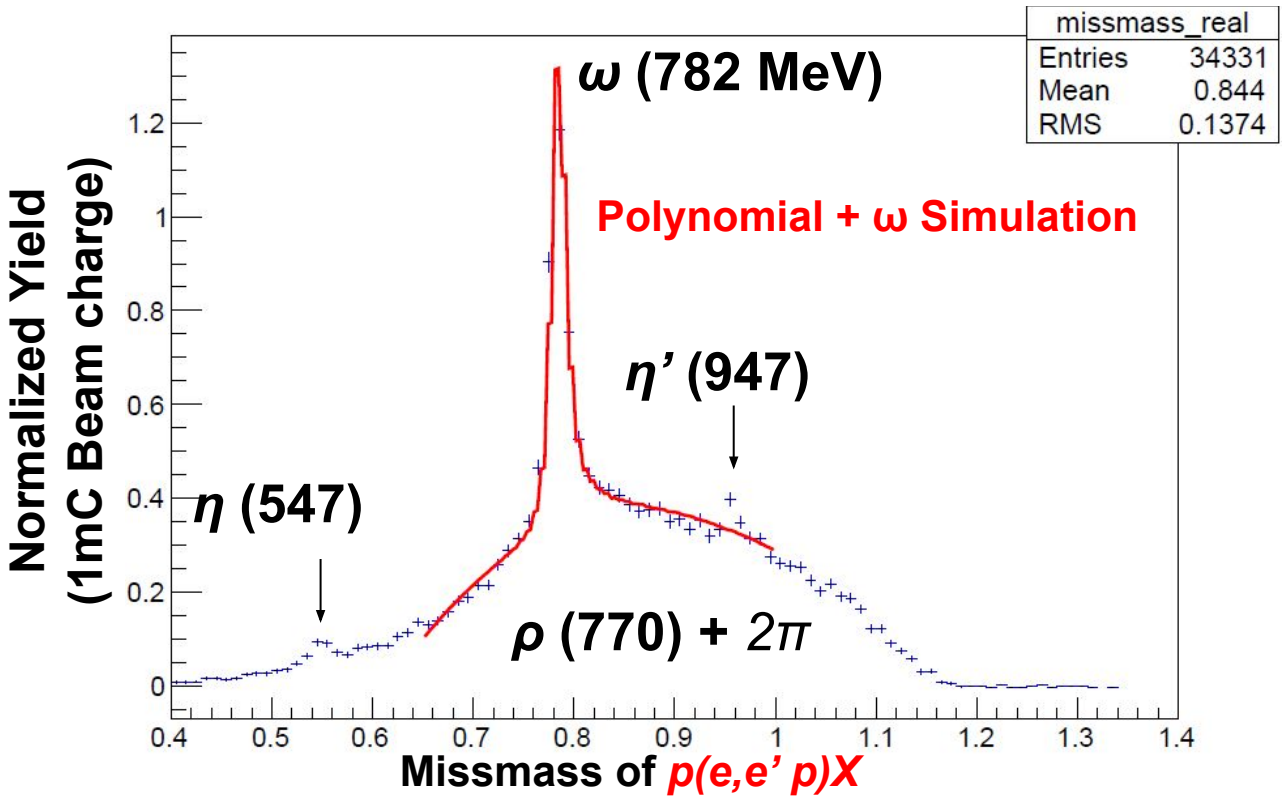
Trajectory


ρ Trajectory
ω Trajectory
π Trajectory
ω5 (2250)
ρ5 (2350)
5−
f4 (2050)
a4 (2040)
4+
ω3 (1670)
ρ3 (1690)
3−
f2 (1950)
a2 (1320)
2+
ω (782)
ρ (770)
1−
π2 (1670)
2−
b1 (1235)
1+
π (139) 0−
α(t)
M2 [GeV2] = t

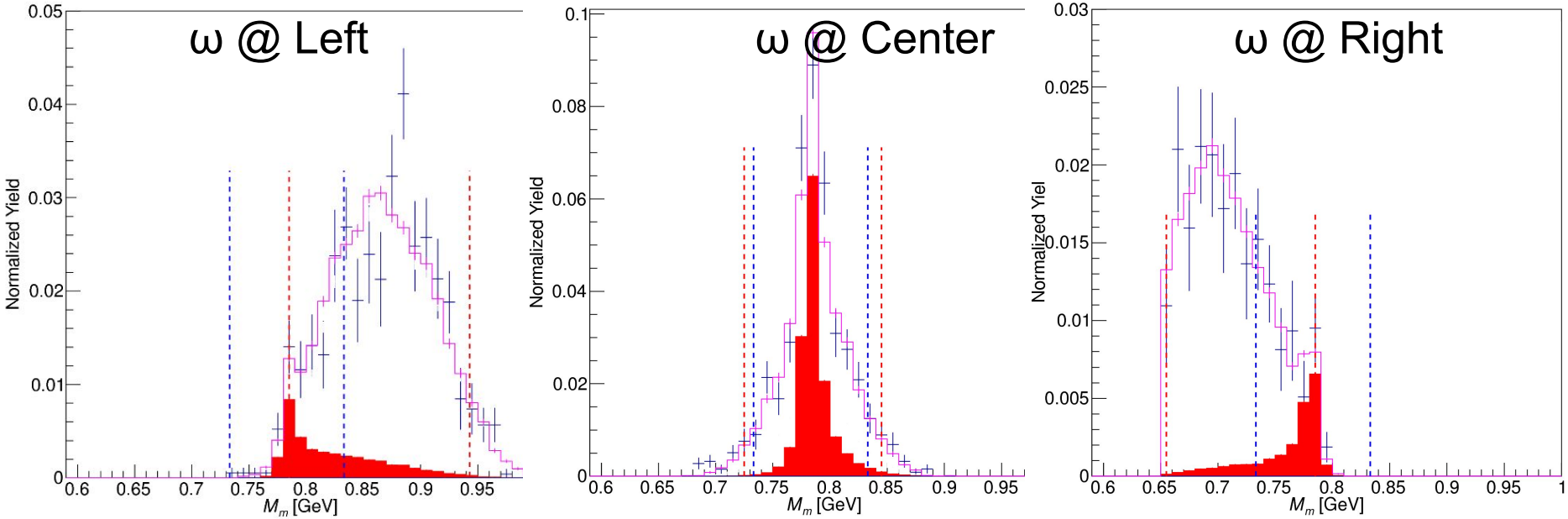

Δ Trajectory
N Trajectory
Δ* (1950)
11/2+
N* (1950)
9/2+
Δ* (1950)
7/2+
N* (1520)
5/2+
Δ (1232)
3/2+
N (939)
1/2+
α(u)
M2 [GeV2] = u

Proof: These are not Elastic Events!



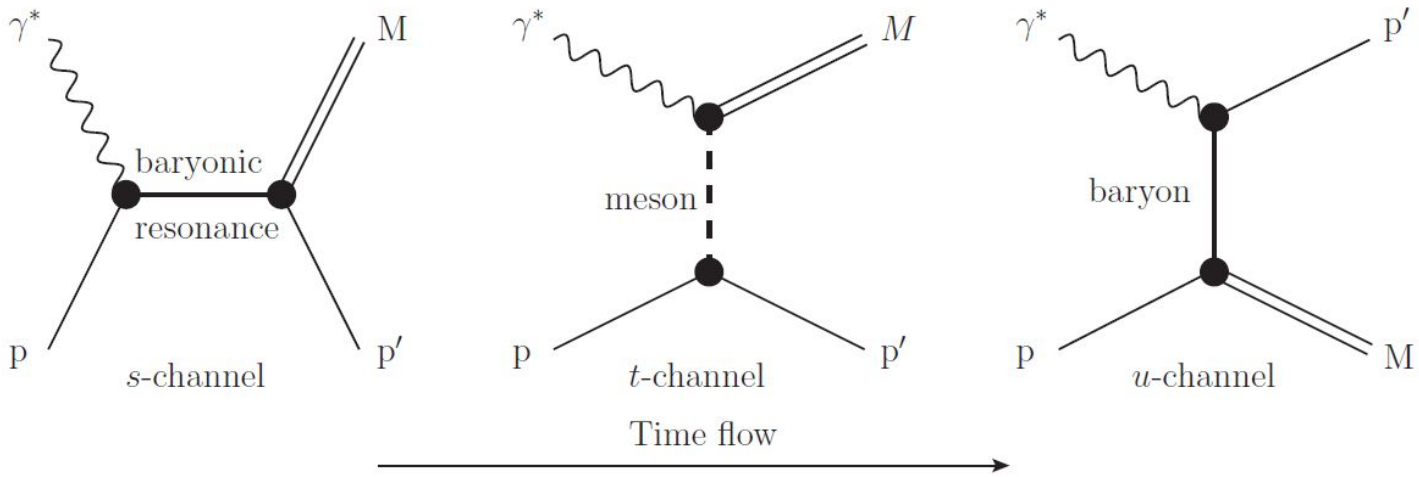
- **Good News!**
  - We see **other Scalar and Vector Mesons:** ***ρ, η, η' , two-π phasespace***
- **Bad News!**
  - Channel is **not clean**!
- **Worse News!**
  - **We can't use Polynomial fit !!**

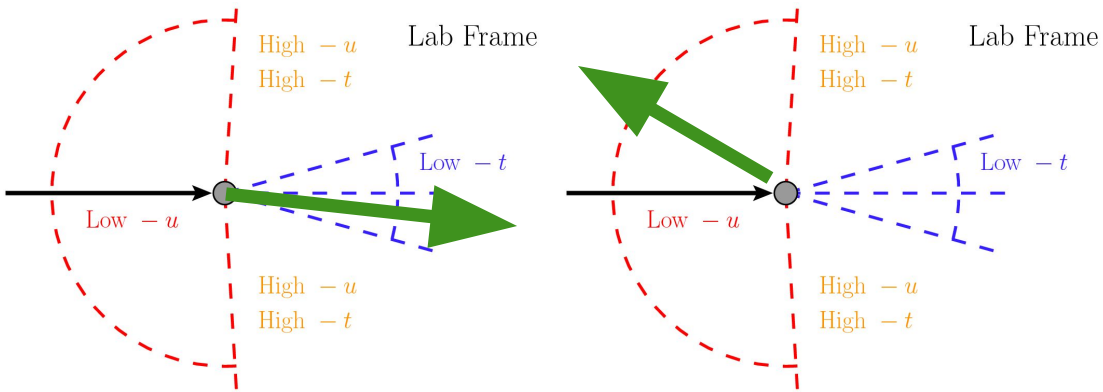
Missing Mass Distribution



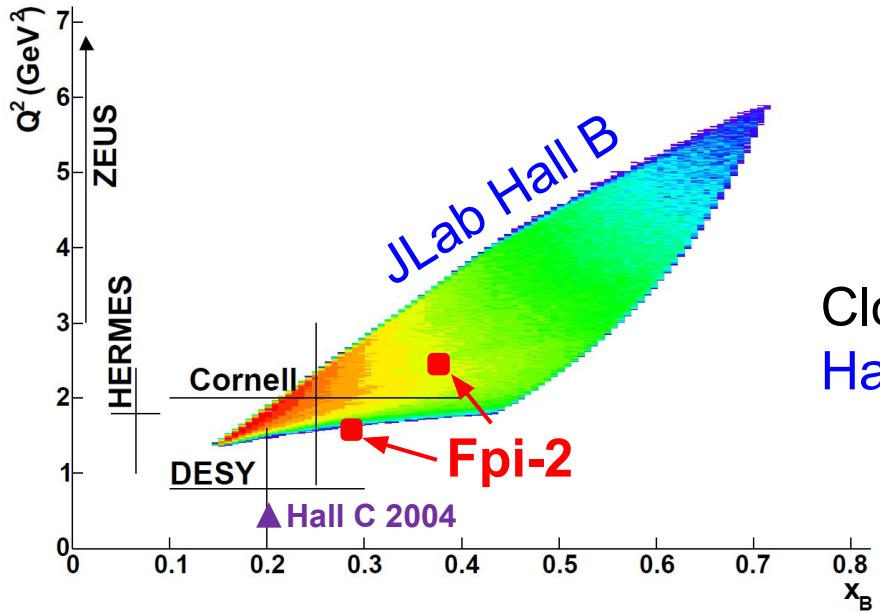
- **Most Challenging Issue: Background Subtraction!**
- **Omega is not always in the center**
- **Four sets of Monte-Carlo is used fit the data**
  - ***ω* + *ρ* + Phase-space + *η or η'***

Mandelstam variables (*s*,*t*,*u*-Channels)





Exclusive ω Electro-Production Data



Closest data set to ours is the Hall B Morand data

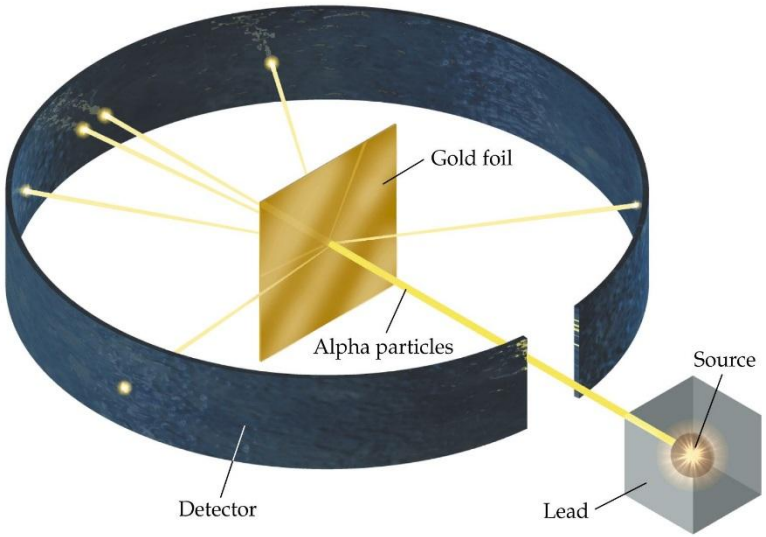
	Q^2 GeV^2	W GeV	x	$-t$ GeV^2
HERMES (Airapetian et al., 2014)	> 1	3-6.3	0.06-0.14	< 0.2
DESY (Joos et al., 1977)	0.3-1.4	1.7-2.8	0.1-0.3	< 0.5
Zeus (Breitweg et al., 2000)	3-20	40-120	~0.01	< 0.6
Cornell (Cassel et al., 1981)	0.7-3	2.2-3.7	0.1-0.4	<1
JLab Hall C (Ambrozewicz et al., 2004)	~0.5	~1.75	0.2	0.7-1.2
JLab Hall 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

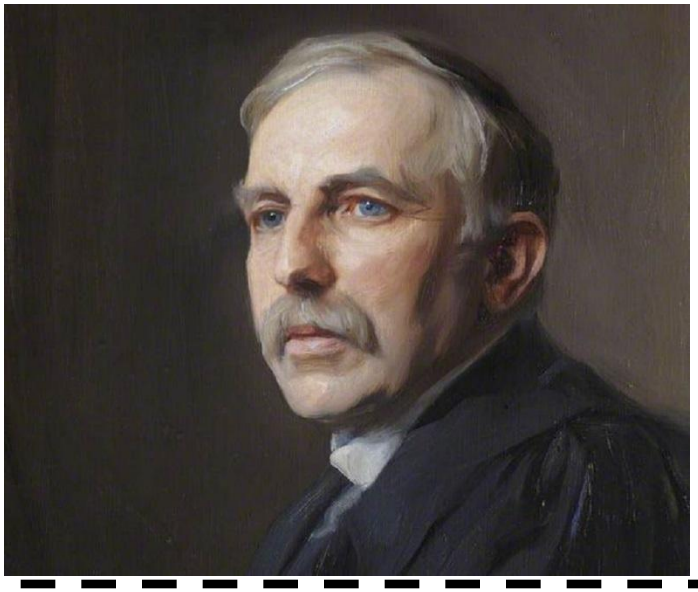
σ_T and σ_L Uncertainty Propagation

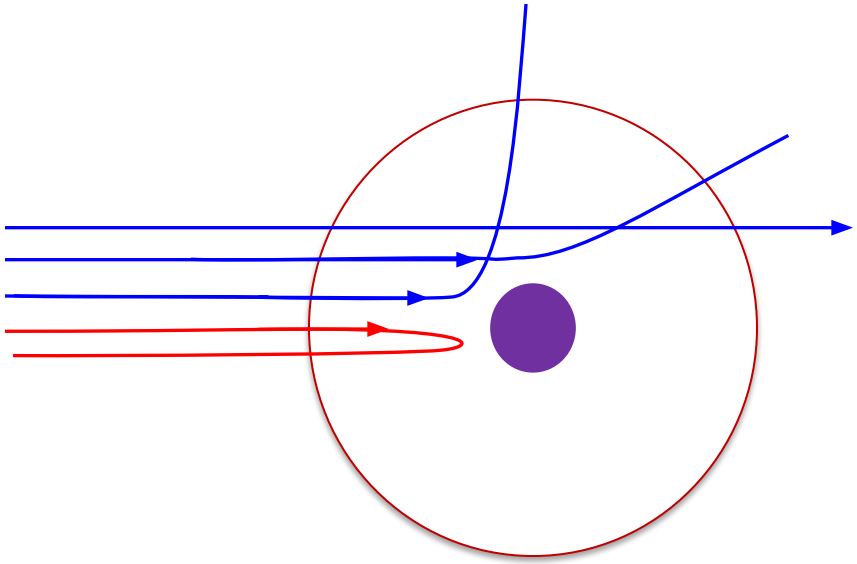
$$\frac{\delta\sigma_T}{\sigma_T}(\%) = \frac{1}{(\epsilon_1 - \epsilon_2)}\sqrt{\epsilon_1^2\left(\frac{\delta\sigma_1}{\sigma_1}\right)^2\left(1+\frac{\epsilon_2}{R}\right)^2 + \epsilon_2^2\left(\frac{\delta\sigma_2}{\sigma_2}\right)^2\left(1+\frac{\epsilon_1}{R}\right)^2}, \tag{6.35}$$

$$\frac{\delta\sigma_L}{\sigma_L}(\%) = \frac{1}{(\epsilon_1 - \epsilon_2)}\sqrt{\left(\frac{\delta\sigma_1}{\sigma_1}\right)^2(R+\epsilon_1)^2 + \left(\frac{\delta\sigma_2}{\sigma_2}\right)^2(R+\epsilon_2)^2}, \tag{6.36}$$

Rutherford Experiment Atomic Structure

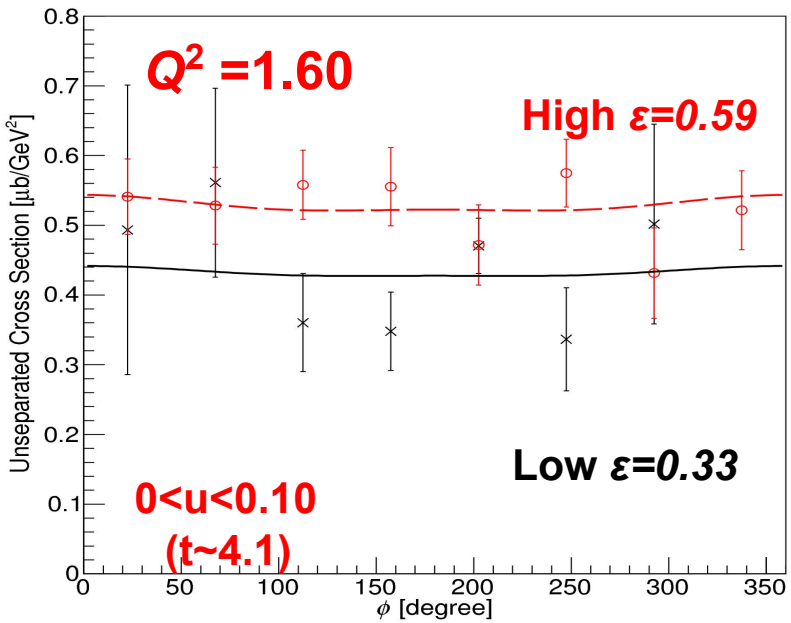






- **Rutherford Experiment:**
  - **Need both forward and backward scattered alpha particles to yield complete atomic structure!**
- **What about nucleons?**
  - Does ***t*-channel** physics contain all the nucleon structure information?
  - ***u*-channel** physics contain **unique information** whose meaning is unclear (B. Pire et. al)
- How do we **access u-channel** physics?

Separation Method



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

- **L/T separation**
  - Requires detailed comparison at high and low epsilon value
  - High and low epsilon runs involved
- **Simple L/T separation**
  - $\sigma_{total} = \sigma_T + \epsilon\, \sigma_L$
    - σ_T: difference
    - σ_L: offset
    - σ_{LT} and σ_{TT}: modulation
- **Experimental Kinematics**
  - W is fixed
  - Two Q^2 settings
  - High and low epsilon runs for each Q^2 setting

T_{inc} MeV	P_{SOS} MeV	θ_e^* deg	ϵ	θ_q deg	θ_{pq} deg	θ_{HMS} deg	P_p MeV/c	P_{HMS} MeV/c	x	$-u$ GeV^2	$-t$ GeV^2
			$Q^2_{nominal}$ = 1.60 GeV^2			$W_{nominal}$ = 2.21 GeV					
3772	785.79	43.09	0.328	9.53	+1.0	10.53	2936.79	2927.2	0.2855	0.087	4.025
					+3.0	12.53	2913.20			0.129	3.983
4702	1715.79	25.73	0.593	13.28	0.0	13.28	2939.53	2927.2	0.2855	0.082	4.030
					−2.7	10.58	2917.79			0.121	3.991
					+3.0	16.28	2913.15			0.129	3.982
			$Q^2_{nominal}$ = 2.45 GeV^2			$W_{nominal}$ = 2.21 GeV					
4210	770.83	51.48	0.270	9.19	1.4	10.59	3355.82	3331.7	0.3796	0.184	4.778
					3.0	12.14	3324.12			0.241	4.721
5248	1808.83	29.43	0.554	13.61	0.0	13.61	3363.86	3331.7	0.3796	0.169	4.793
					3.0	16.61	3324.28			0.241	4.721
					−3.0	10.61	3324.49			0.240	4.722

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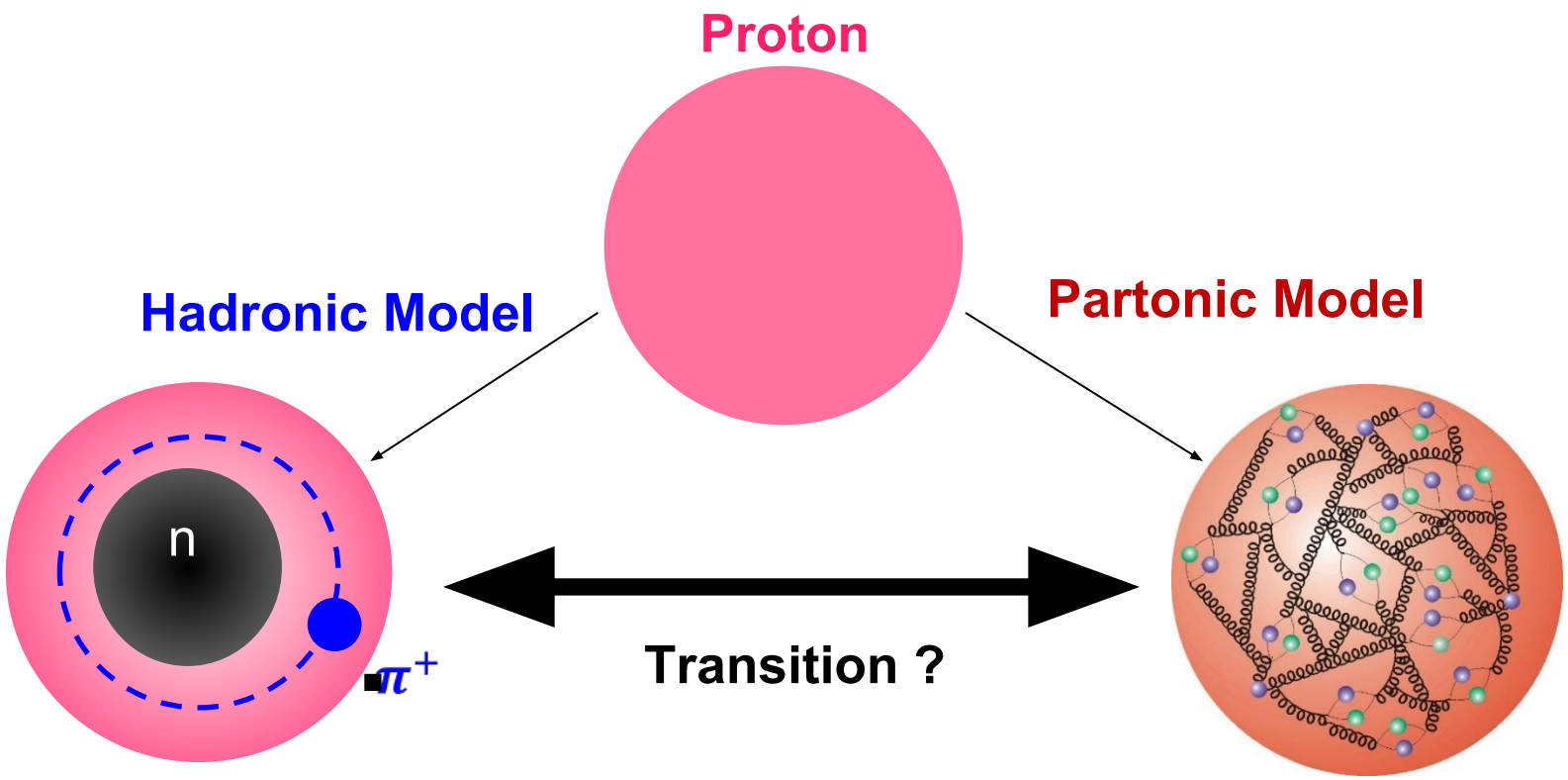
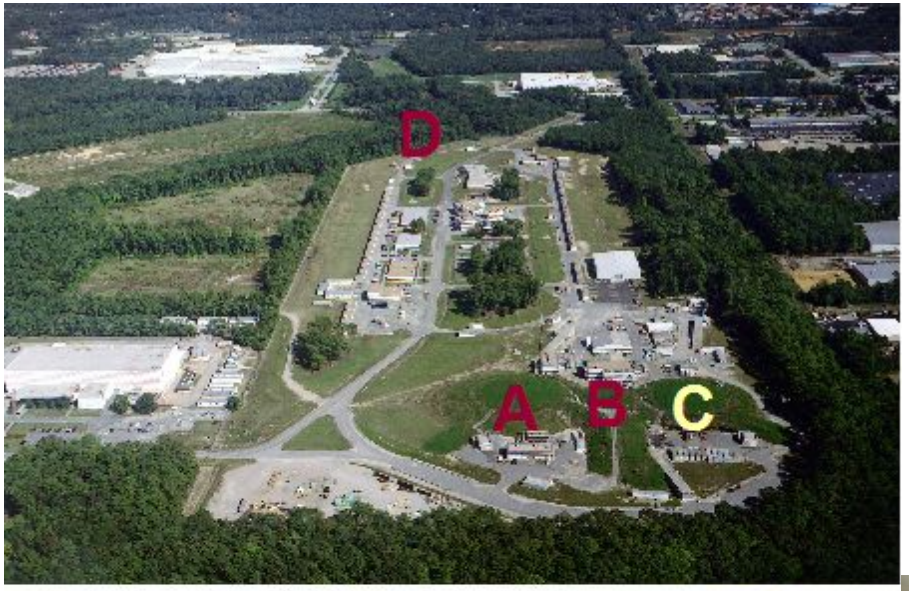
Motivation

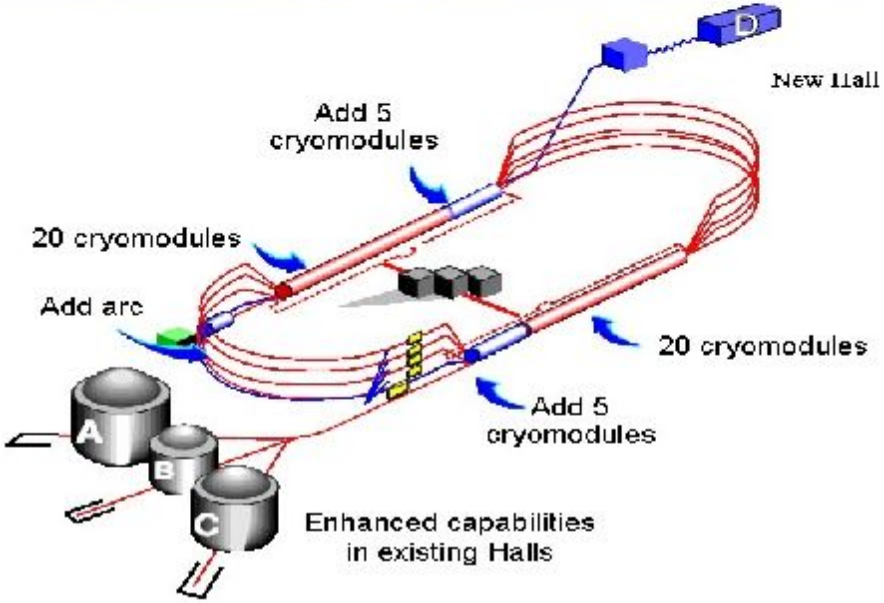
- Motivation
  - Probing dynamic property of the proton structure
    - **Dependent on the properties of the probe**
  - Studying the **transition** of QCD
- Objective
  - Establishing a new approach
    - Backward-angle (*u*-channel) observables
    - LT separation



Jefferson Lab Hall C



- **Main Structure**
  - **Two Super-Conducting Linear Accelerators**
  - **Experimental Hall: A ,B, C, D**
- **Hall C**
  - **High precision high beam current**
  - **LT separation**
- **April 2017: 12 GeV upgrade completed**
  - **New spectrometer is on line**



Message to the world and thank you

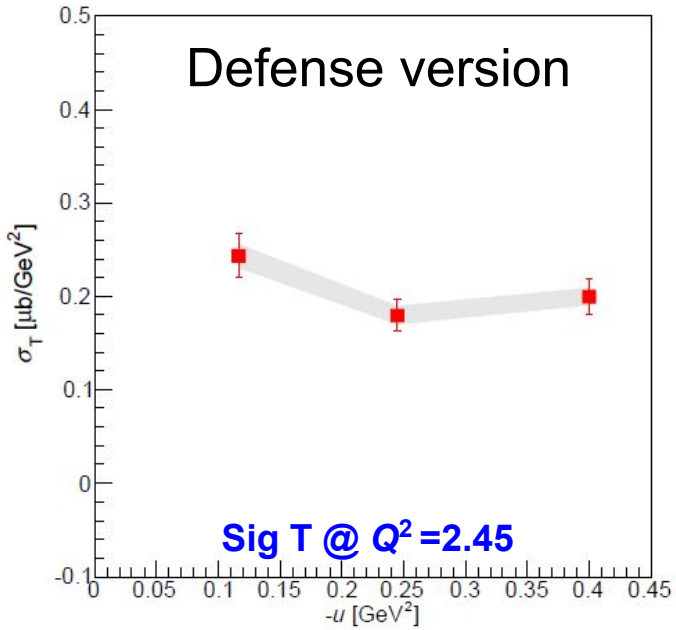
- **Studying the model effectiveness in both Regge Based Model and TDA is the studying the QCD transition**

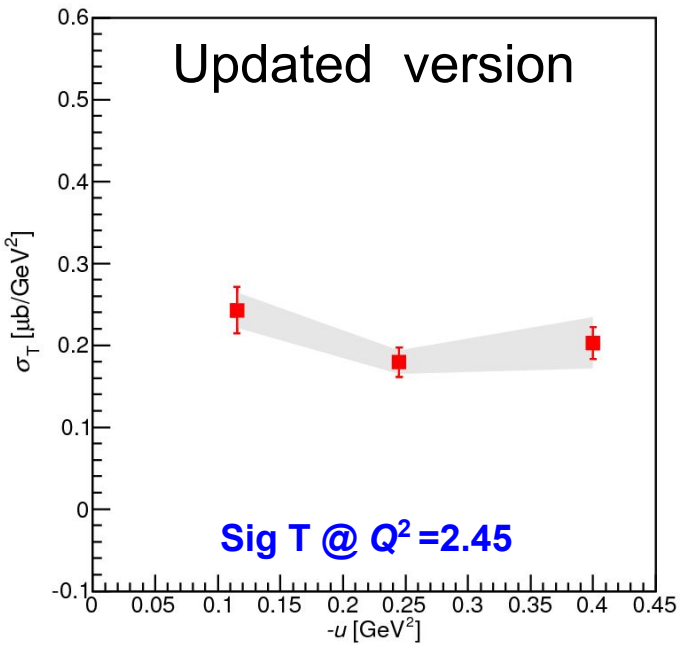
- **Established a new experimental access to the previously accessible kinematics**

- **Abstracted the theory framework that can be used to study the previously ignored backward angle process**

- **Final release of the result calls for more studies on backward angle physics, particularly among the junior physicist.**

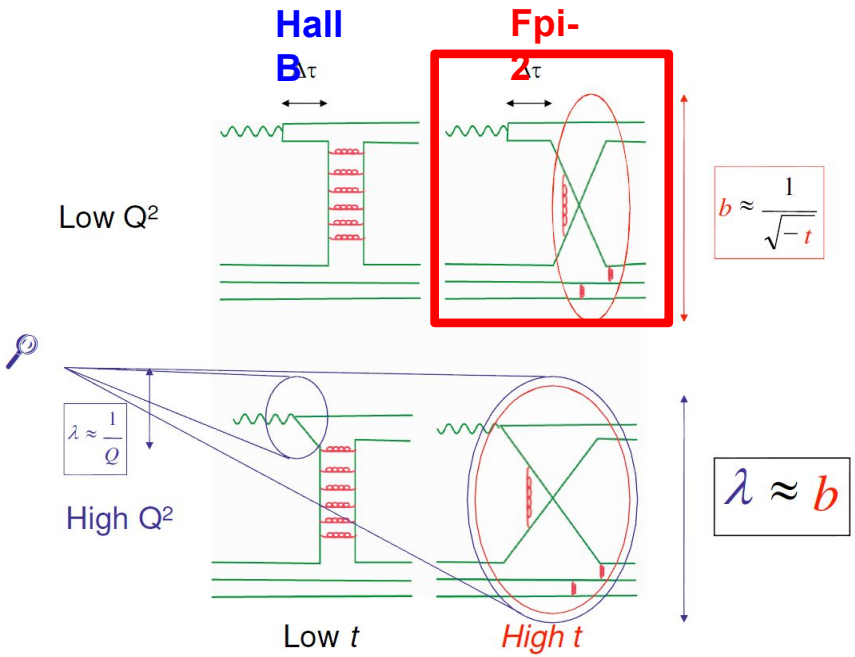
Updated Uncertainties since the Thesis





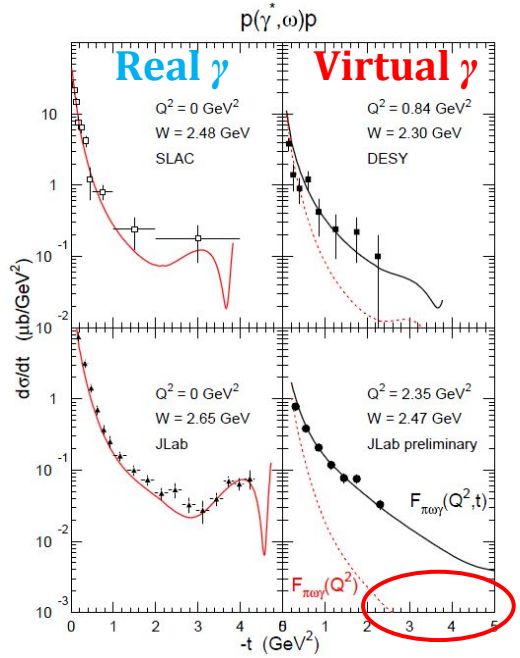
- Fitting Error is now used as the Statistical Error
- New method used for computation the scale error
- Sig_LT and Sig_TT now have scale error band

Theory Motivation: Regge Trajectory Model by JM Laget



Hard Scattering Mechanism schematics

	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	2.45	4.724	0.17-0.24



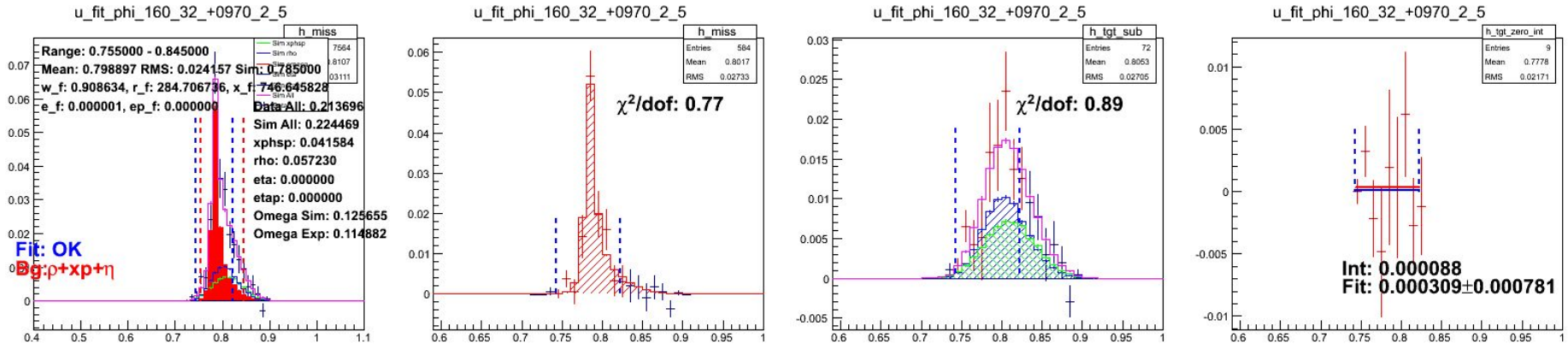
Fpi2 kinematics

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

***t*-Channel Forward**

***u*-Channel Backward**

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 raw counts**

Conclusion

-

- *u*-channel omega electroproduction peak observed for the first time

- σ_T has ~1/Q dependence, where σ_L has ~1/Q^8 dependence. Dominance of σ_T over σ_L observed at Q^2 =2.45 GeV^2

- At **Q^2 =2.45 GeV^2** , TDA prediction agrees with data !