Backward Angle Omega Meson Electroproduction

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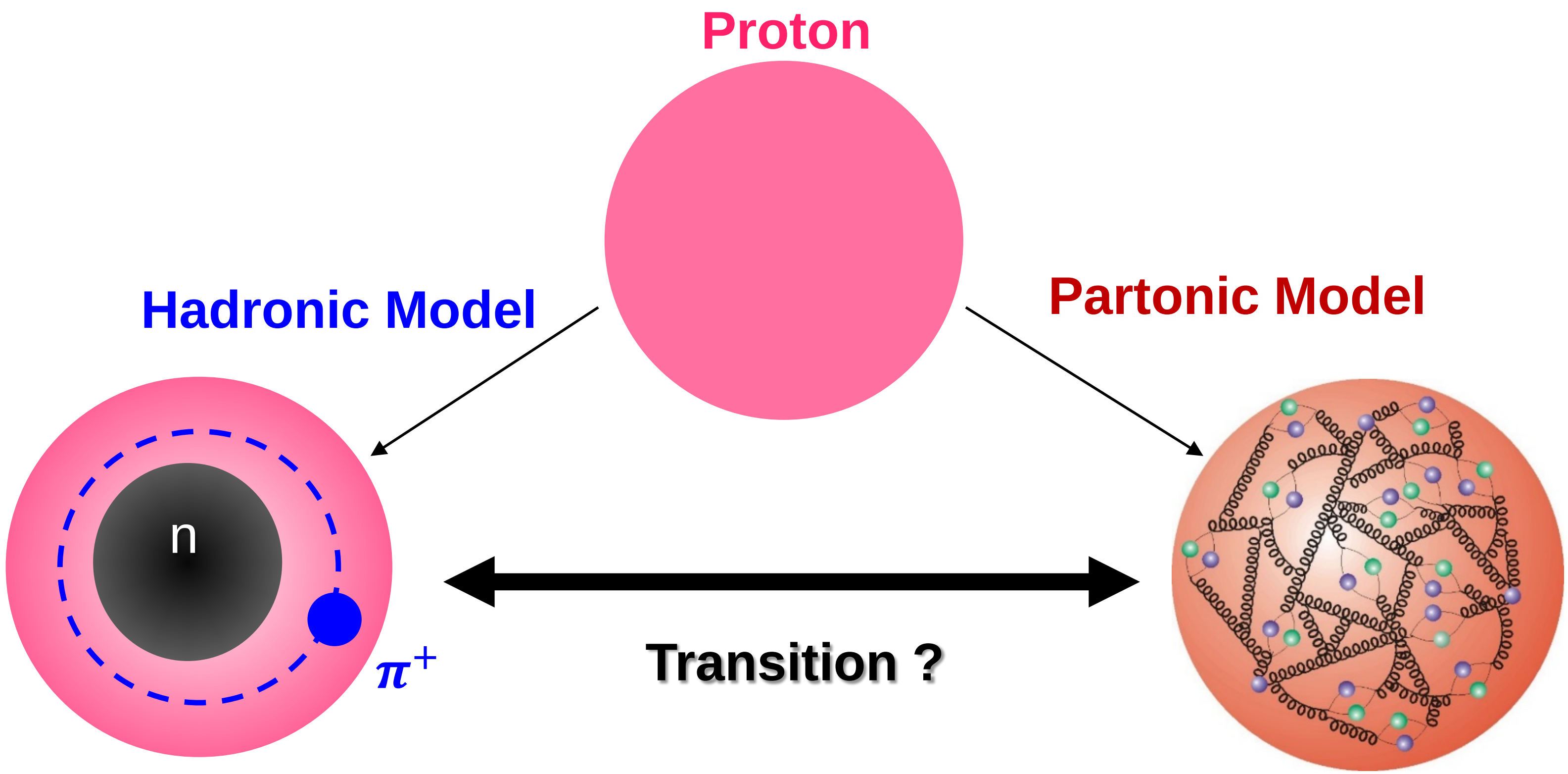
Outline

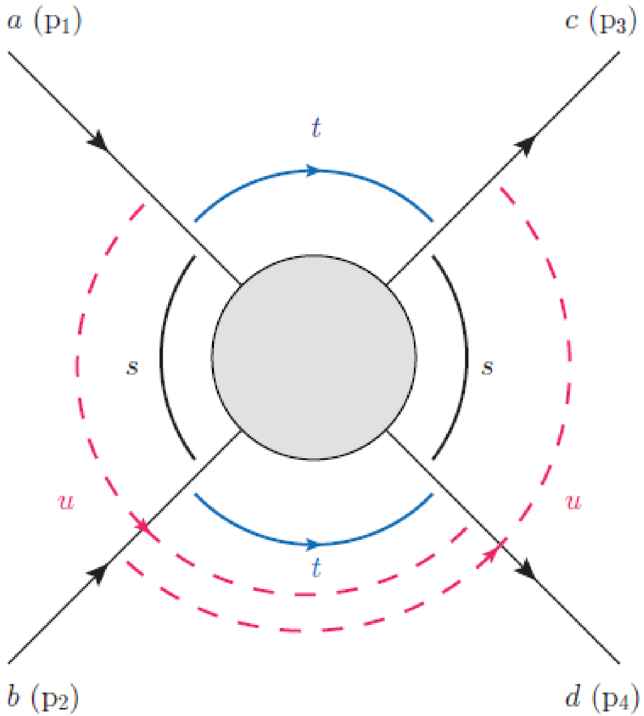
- Motivation, purpose and technique
- Theory
- Experiment
- Analysis
- Results and Outlook

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



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



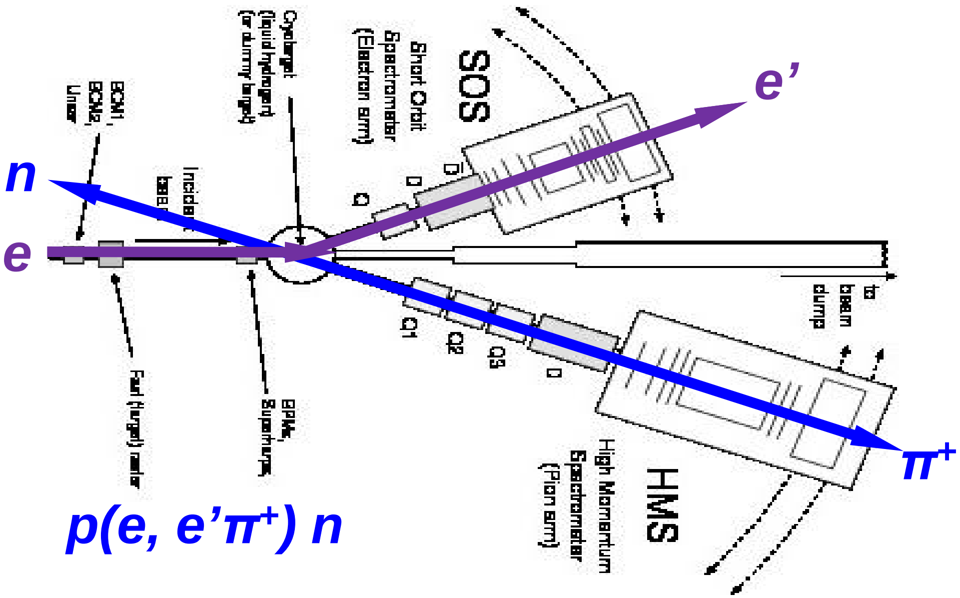
$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$

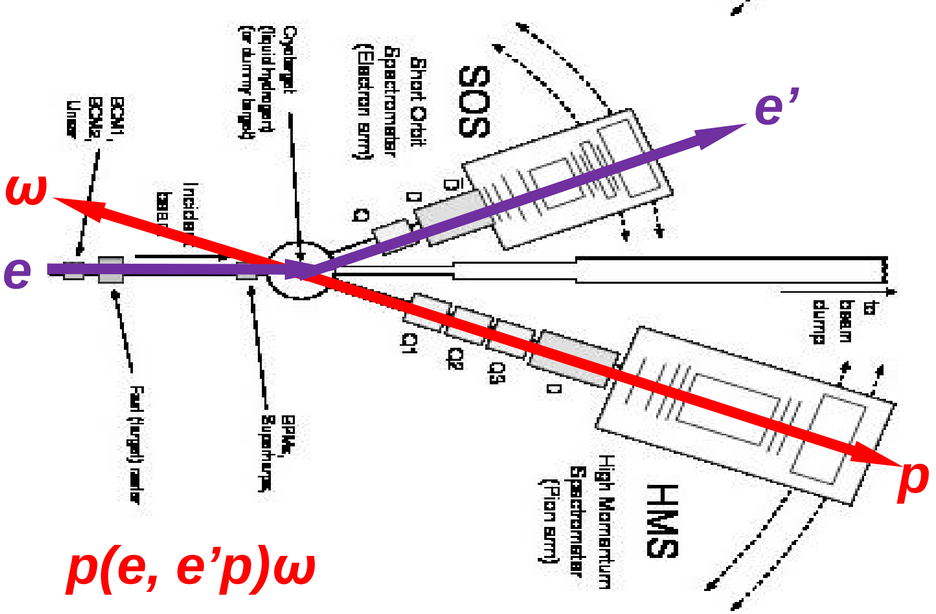
$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$

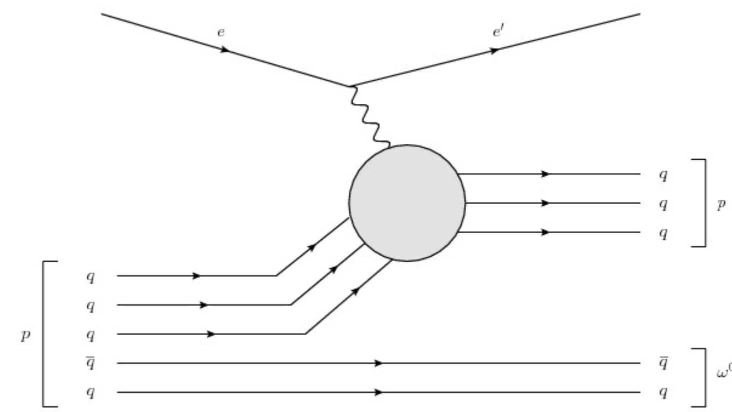
$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$

- ***s***: invariant mass of the system
- ***t***: Four-momentum-transfer squared between **target before and after interaction.**
- ***u***: Four-momentum-transfer squared between **virtual photon before interaction and target after interaction**
- ***t*-channel*: -t ~ 0*, after interaction**
  - **Target: stationary,**
  - **Meson: forward**
  - **Measure of how forward could the meson go.**
- ***u*-channel: *-u~0,* after interaction**
  - **Target: forward**
  - **Meson: stationary**
  - **Measure of how backward could the meson go**

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



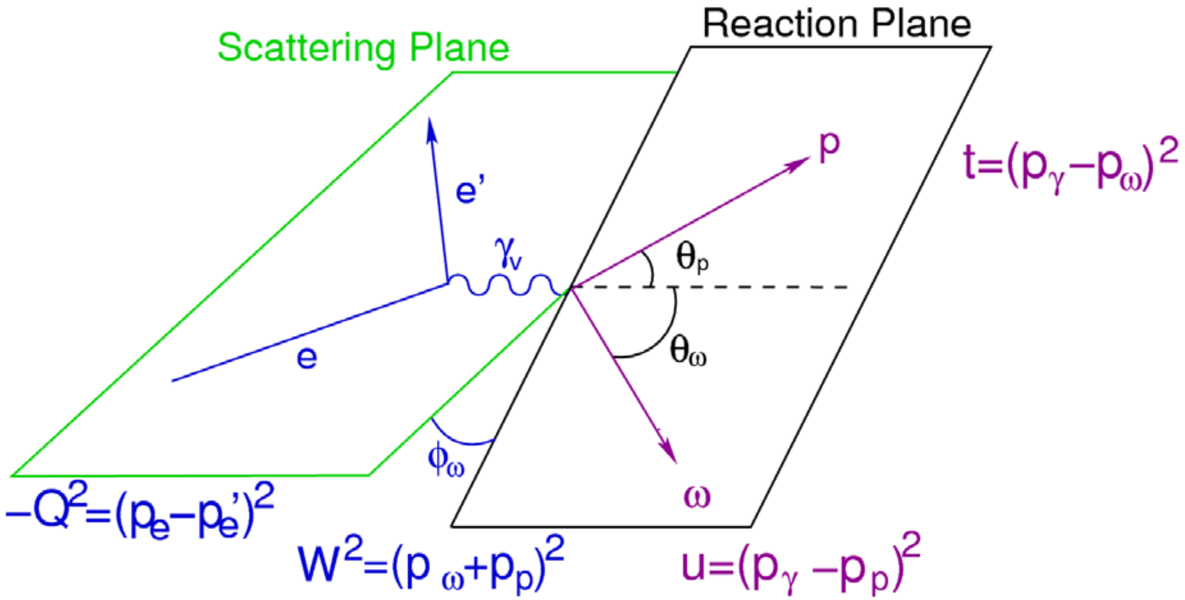




Mark Strikman: A proton being knocked out of a proton process

- **HMS along the *q*-vector (p_{γ^*})**
  - $p_{\pi+}$ is parallel to p_{γ^*} (Forward)
  - p_{ω} is anti-parallel to p_{γ^*}(Backward)
- **Exclusive channel!**
  - *p(e,e' p)ω*
  - 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**

Rosenbluth Separation



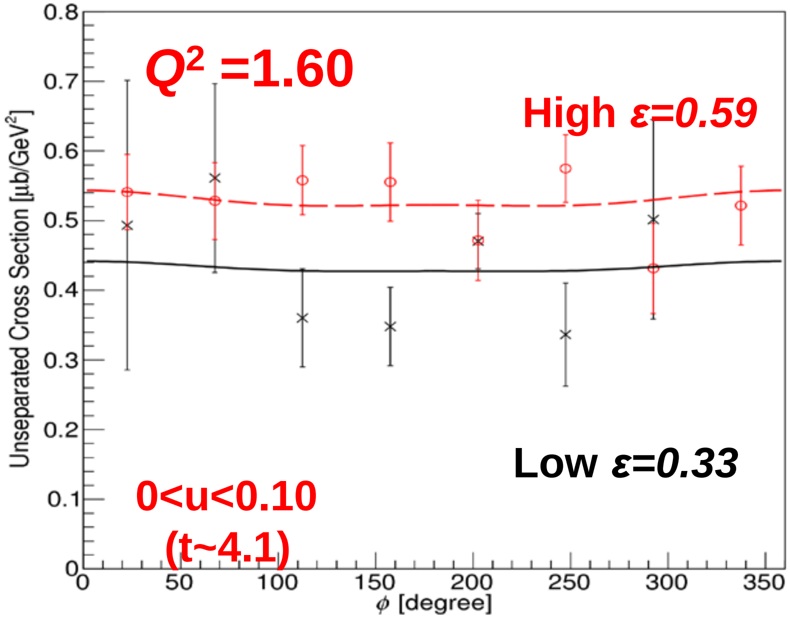
Virtual-photon polarization:

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

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

- Rosenbluth Separation 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

Separation Method

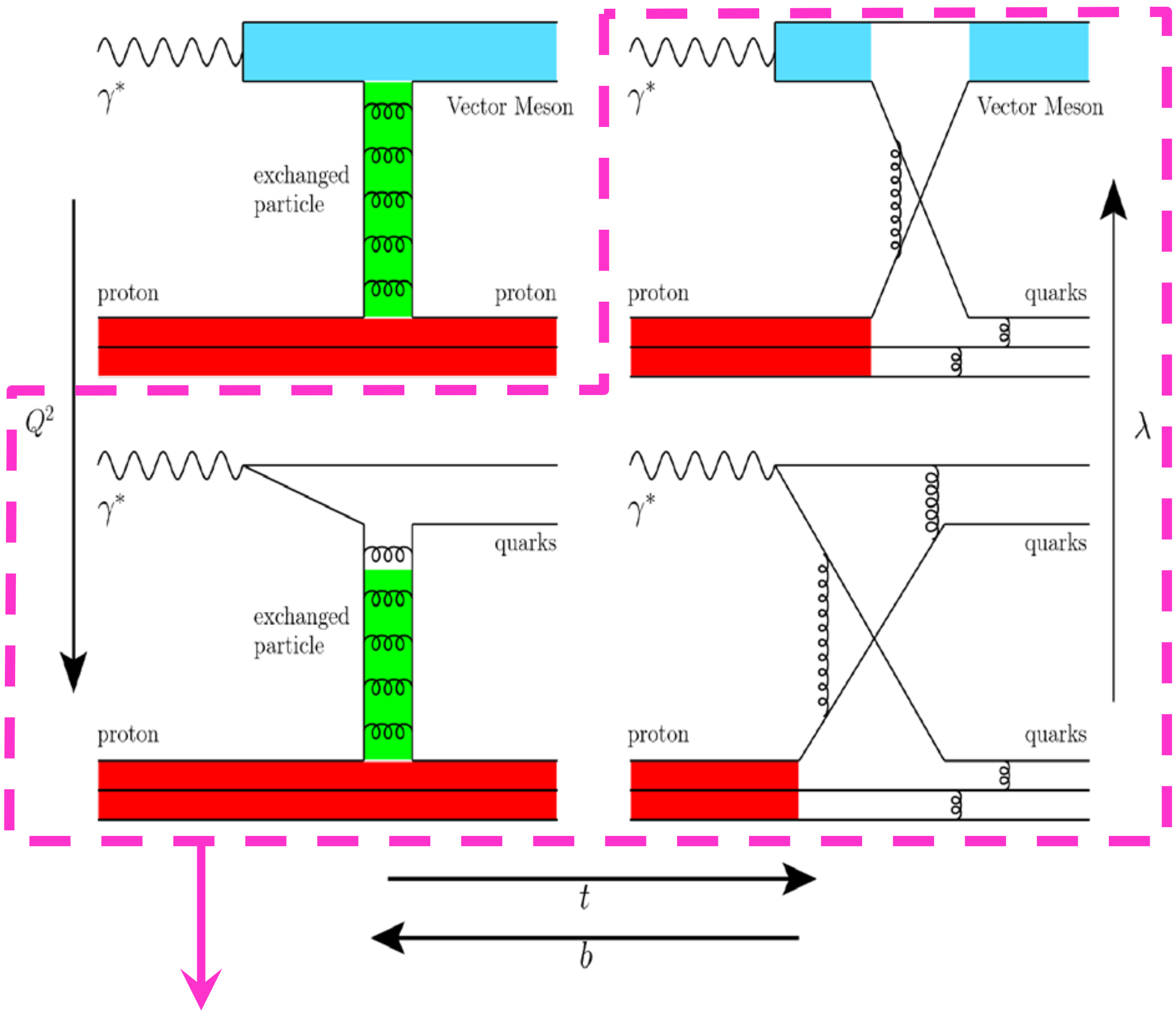


T_{inc} MeV	P_{SOS} MeV	θ_e^* deg	ϵ	θ_q deg	θ_{pq} deg	θ_{HMS} deg	P_p MeV/c	P_{HMS} MeV/c	x	$-u$ GeV²	$-t$ GeV²
			$Q^2_{nominal}$ = 1.60 GeV²	$W_{nominal}$ = 2.21 GeV							
3772	785.79	43.09	0.328	9.53	+1.0	10.53	2936.79	2927.2	0.2855	0.087	4.025
					+3.0	12.53	2913.20			0.129	3.983
4702	1715.79	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 GeV²	$W_{nominal}$ = 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

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

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

Hadronic Model: Transition (Evolution) of Proton Structure



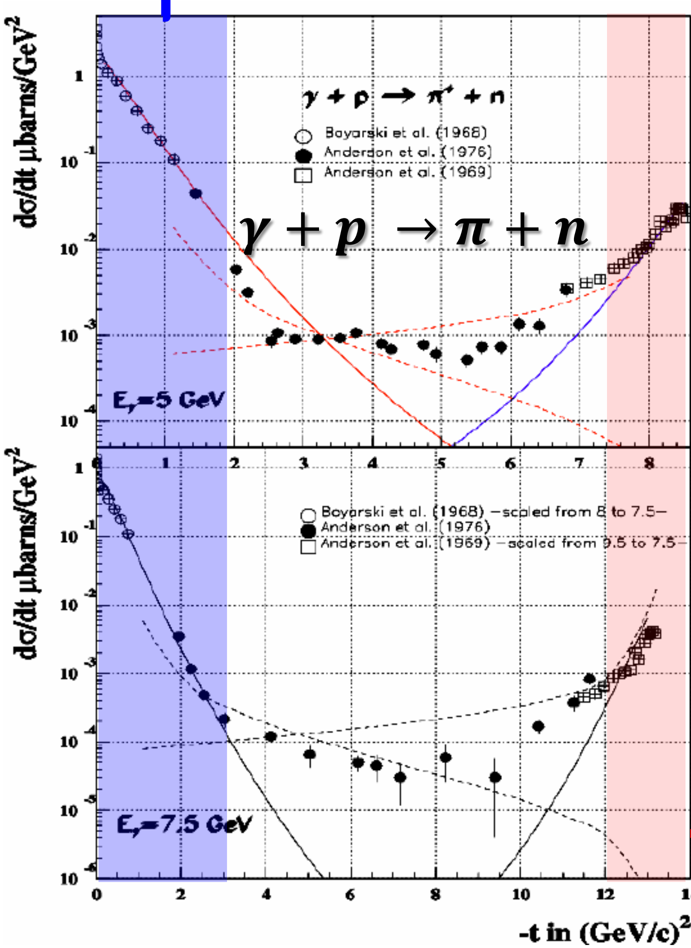
Evolution of the Proton Structure

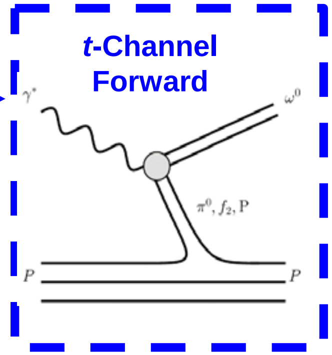
- Physics observables
  - In ***t*, *W* (*s*), *Q*^{2}, *x***
- *x* Evolution:
  - 0.2-0.3 valence quark distribution is pronounced
- *W* Evolution:
  - Above the resonance region
- ***Q*^{2} Evolution**
  - **Wavelength of the probe**
- ***t* Evolution**
  - **Impact parameter**
- What about ***u***?

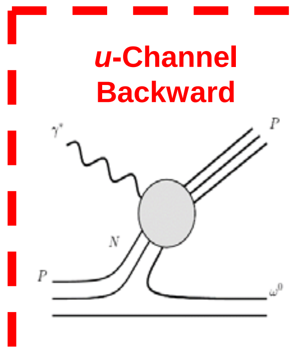
Hadronic Model: Regge Trajectory Model by JM Laget

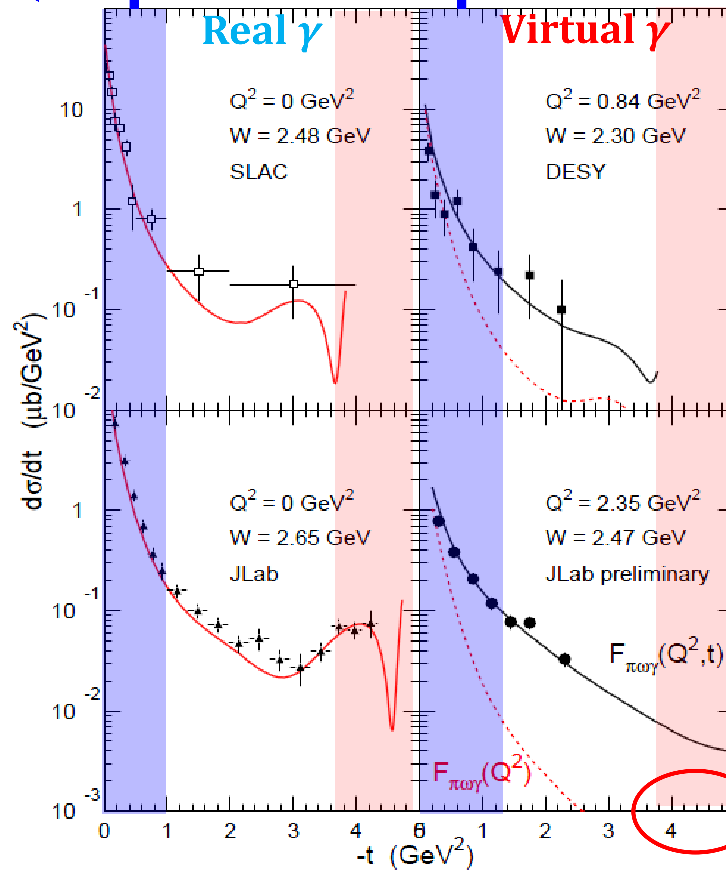
$\gamma + p \rightarrow \omega + n$ $\gamma^{*} + p \rightarrow \omega + n$

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









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

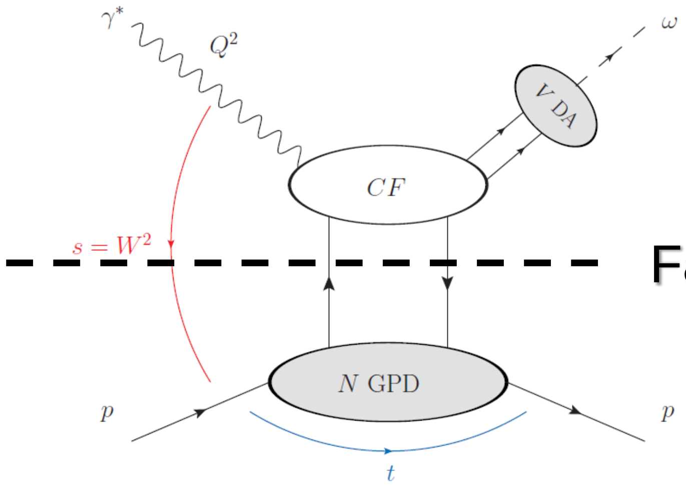
Fpi2 kinematics

Soft structure -> Hard -> Soft transition !

Partonic Model: GPD and Factorization

Hard structure

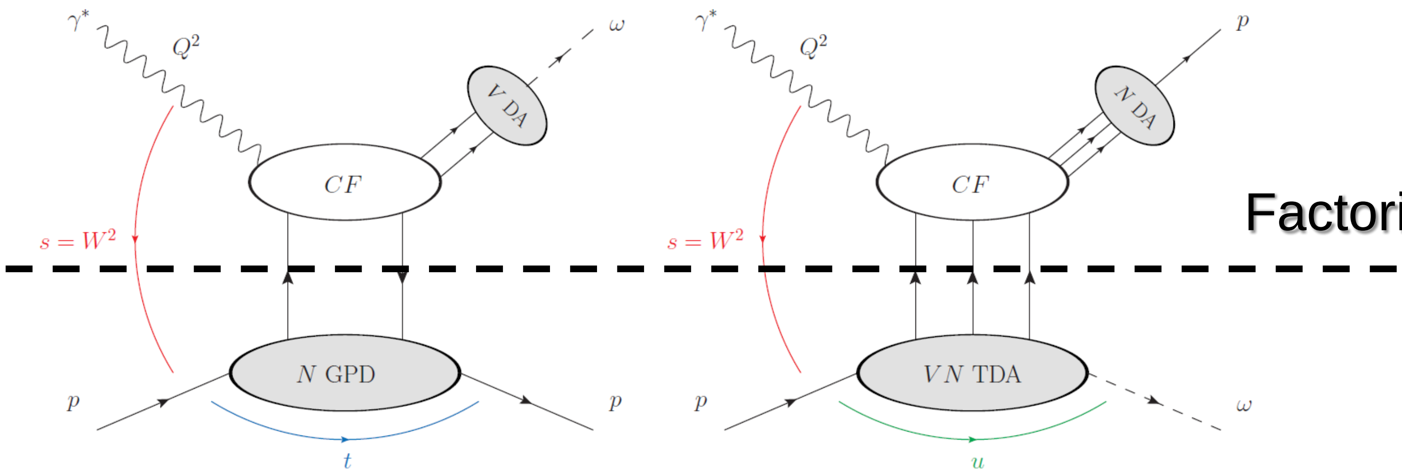
Soft structure



Factorization

- Generalized parton distribution (GPD)
  - Full spatial distribution of partons (quarks and gluons)
  - No known experimental access
    - Can be studied through factorization scheme at **sufficiently high Q^2**
    - Deep Virtual Compton Scattering (**DVCS**)
    - Deep Virtual Meson Production (**DVMP**)

Parton Based Model: TDA



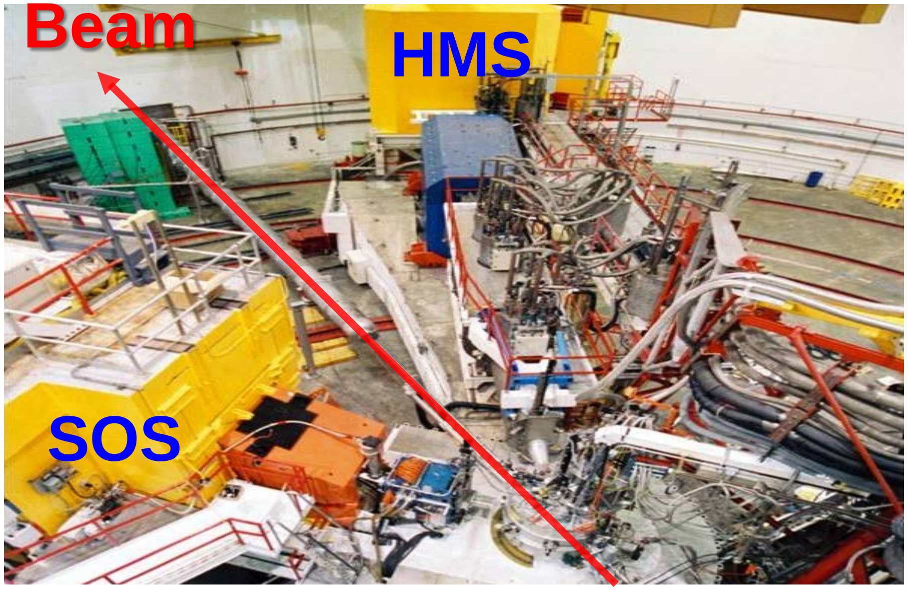
Factorization?

- **Nucleon to Meson Transition Distribution Amplitude (TDA)**
  - **Backward angle analog of GPD. Translate from -*t* space to -*u*. Translate V DA to N DA**
  - **No consensus on the TDA factorization regime**
  - If *t* is impact parameter, **physical meaning of *u* is unclear.**

- **Interaction of Interest: *u*-channel pseudocalar meson and vector meson productions**

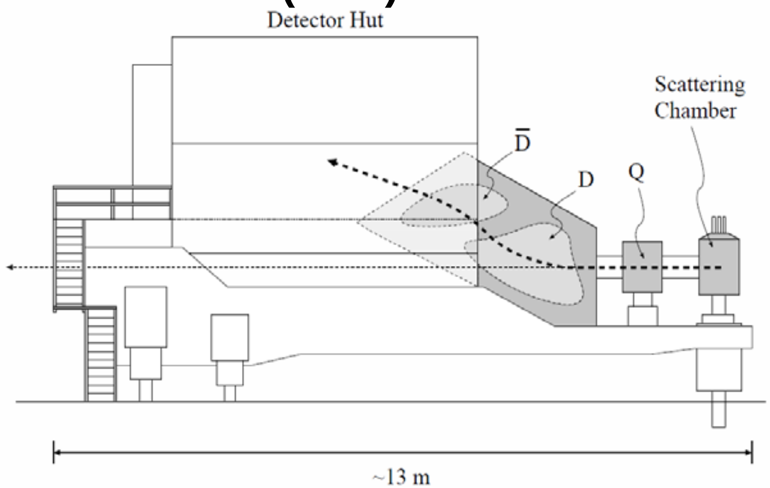
- **Two Predictions of TDA:** (B. Pire, K. Semenov, L. Szymanowski, Phys. Rev. D, **91**, 094006 (2015))
  - The **dominance of the transverse polarization** of the virtual photon resulting in the suppression of the longitudinal cross section by at least $1/Q^2$: $\sigma_T > \sigma_L$.
  - The Characteristic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

Experimental Details

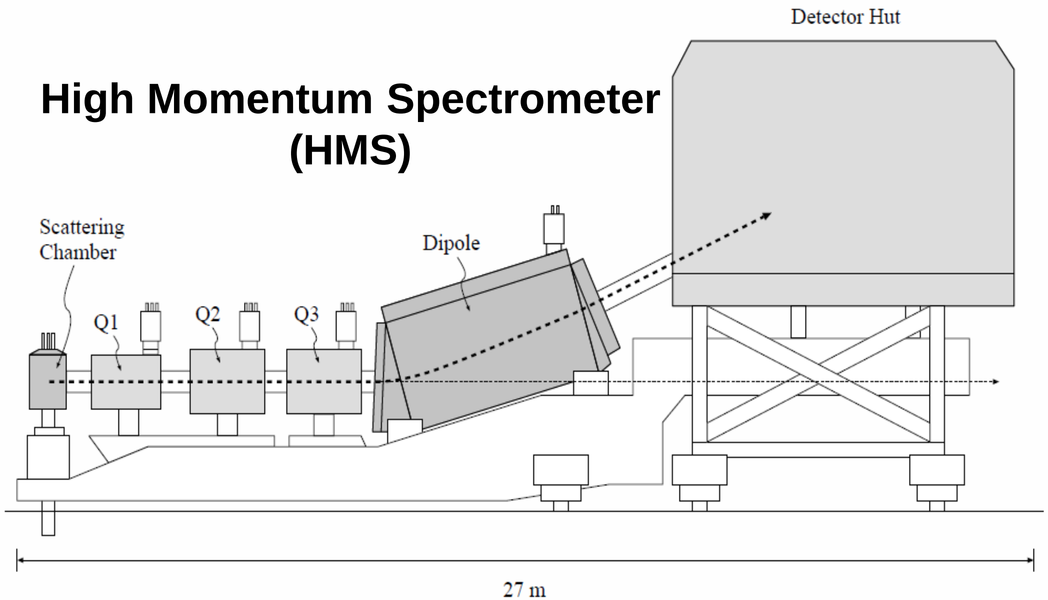


- **HMS (QQQD)**
  - **Angle Acceptance:** 6msr
  - **Momentum:** 0.5-7.5 GeV/c
  - **Momentum Acceptance:** +-9%
  - **Angular, Position Resolution:** 1mr and 1mm
- **SOS (QDDbar)**
  - **Angle Acceptance:** 9msr
  - **Momentum:** 0.1-1.8 GeV/c
  - **Momentum Acceptance:** +-20%

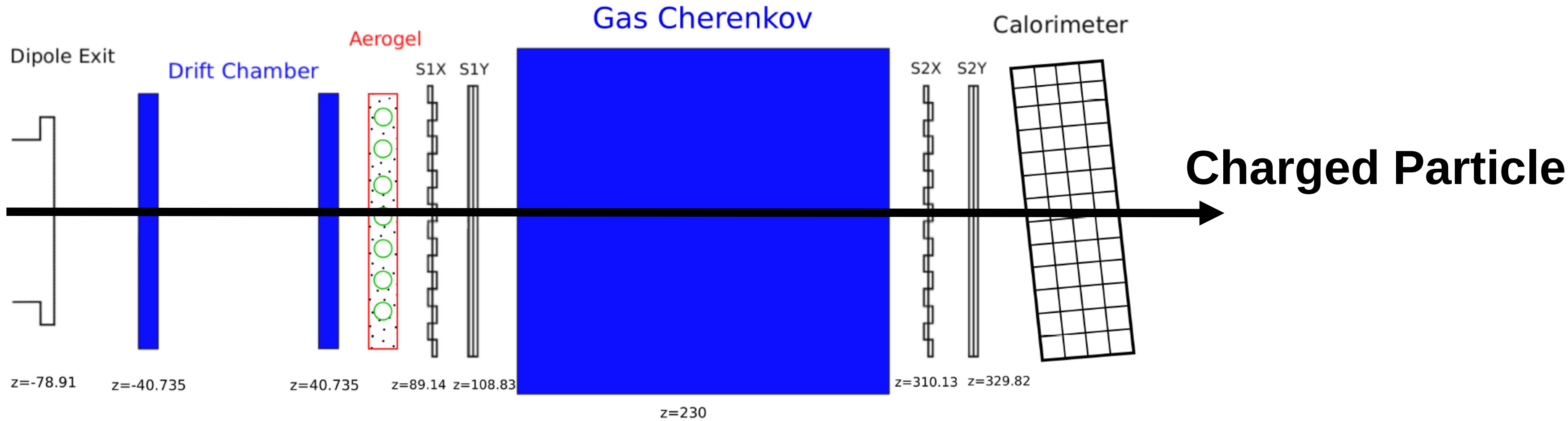
High Momentum Spectrometer (SOS)



High Momentum Spectrometer (HMS)

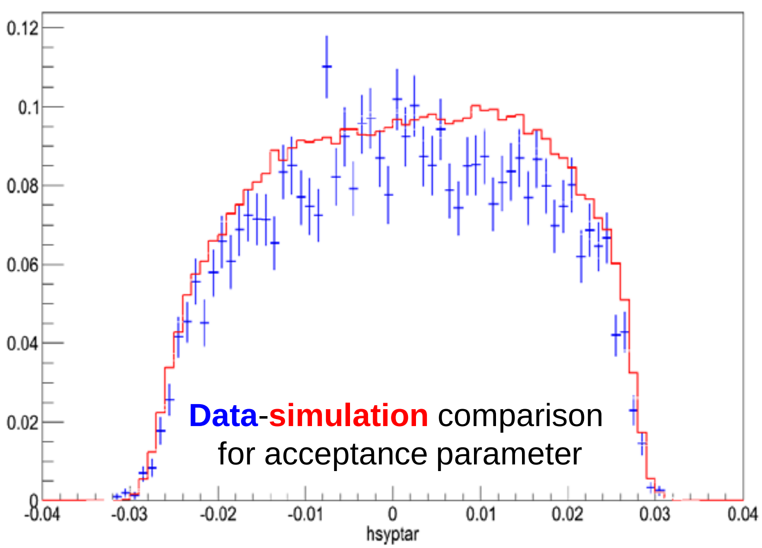


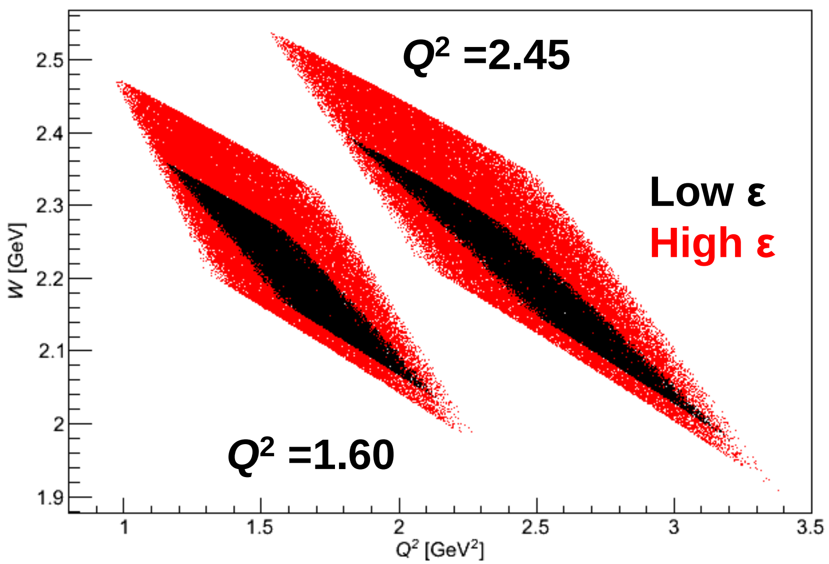
Experimental Setup and Acceptance



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

Trigger: 3/4 planes of Hodoscopes

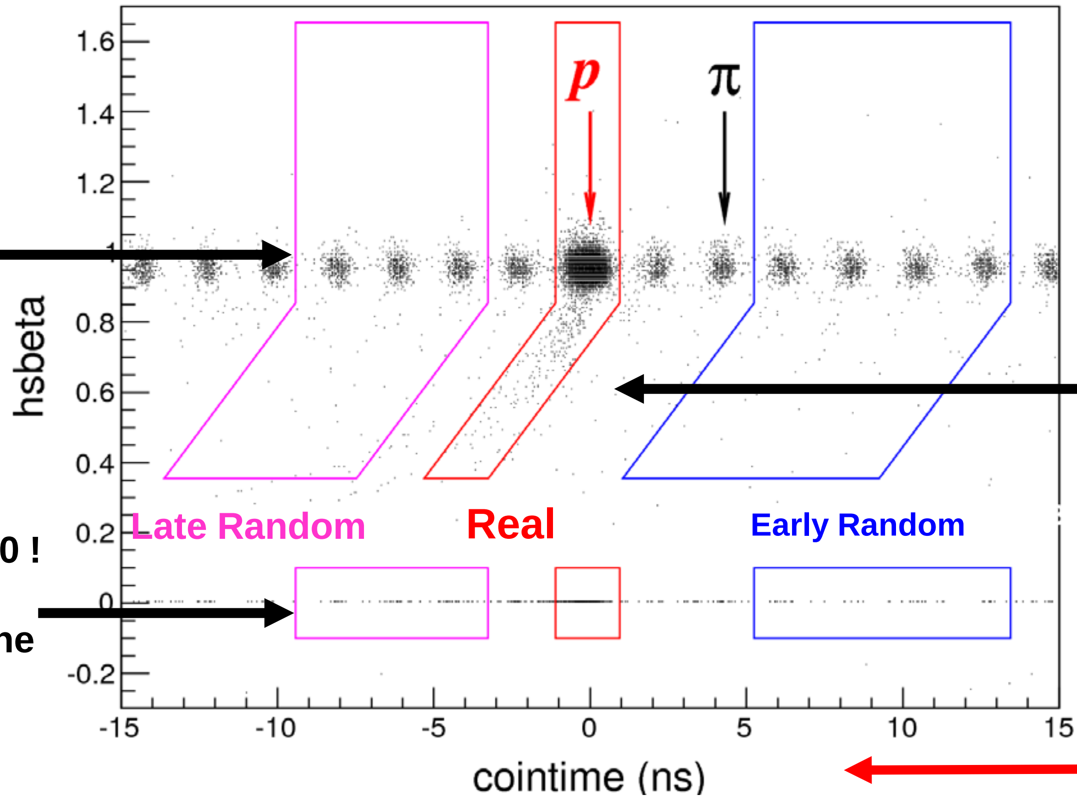




Coincidence Subtraction

Blob events: good events

Zero event: hsbeta=0 ! Cause: Missed the fiducial cut during the reconstruction



Tail event: losing momentum due to multiple scattering

Multiple scattering: dipole exit window to the last layer of hodoscope

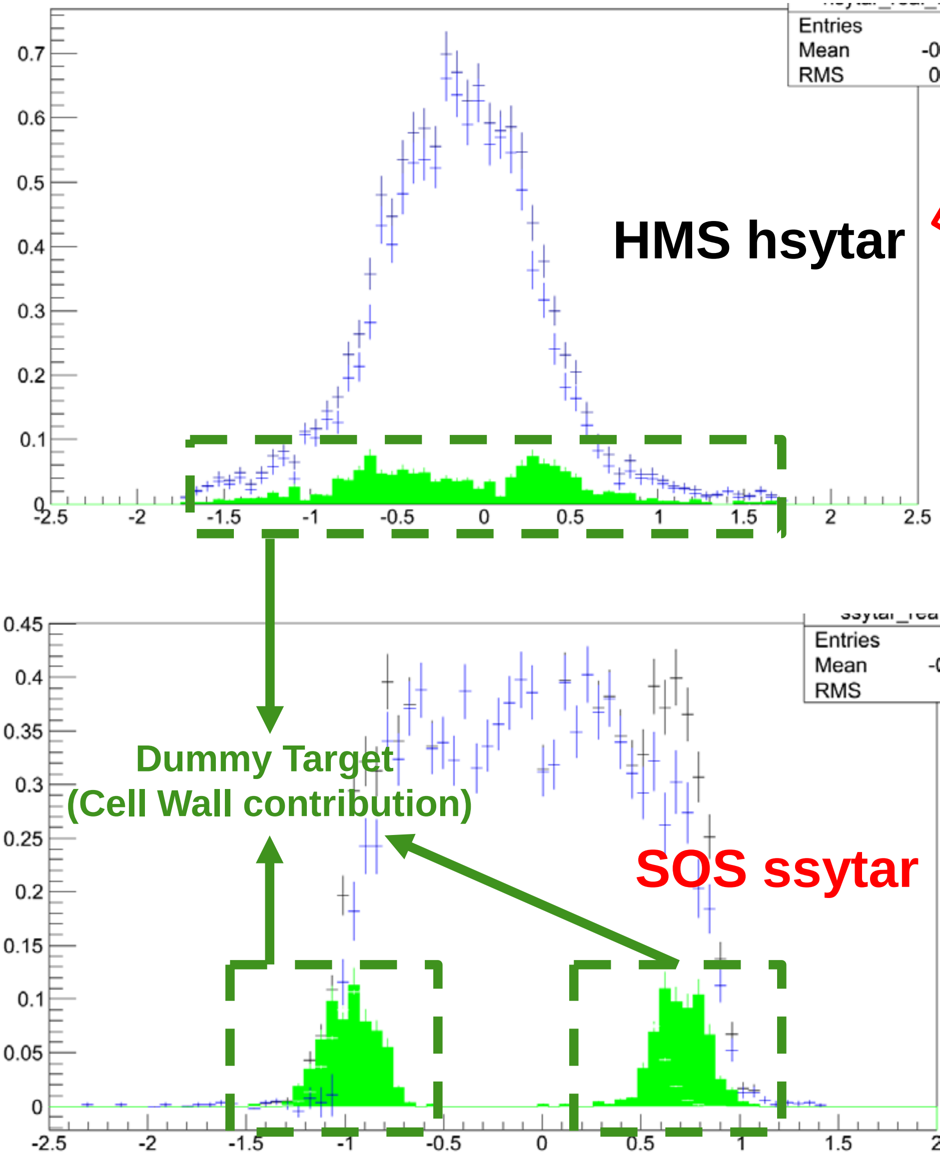
Time flow

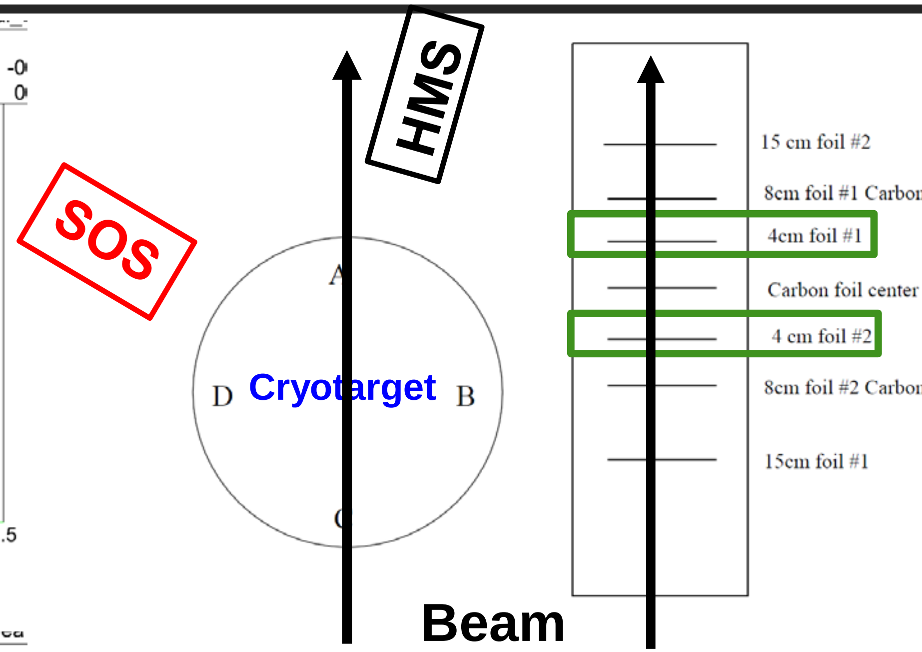
- **Random subtraction:**

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

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

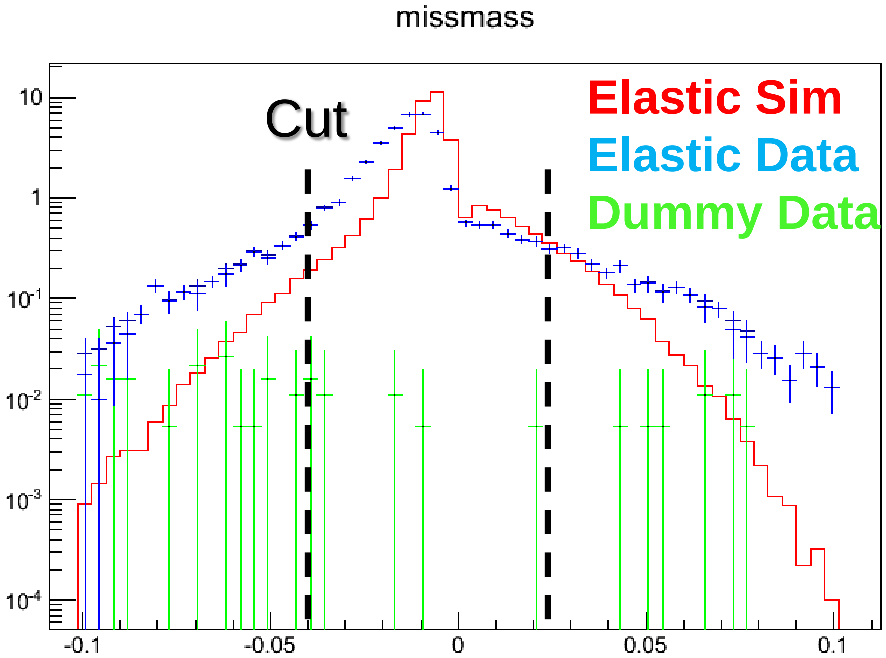
Dummy Subtraction

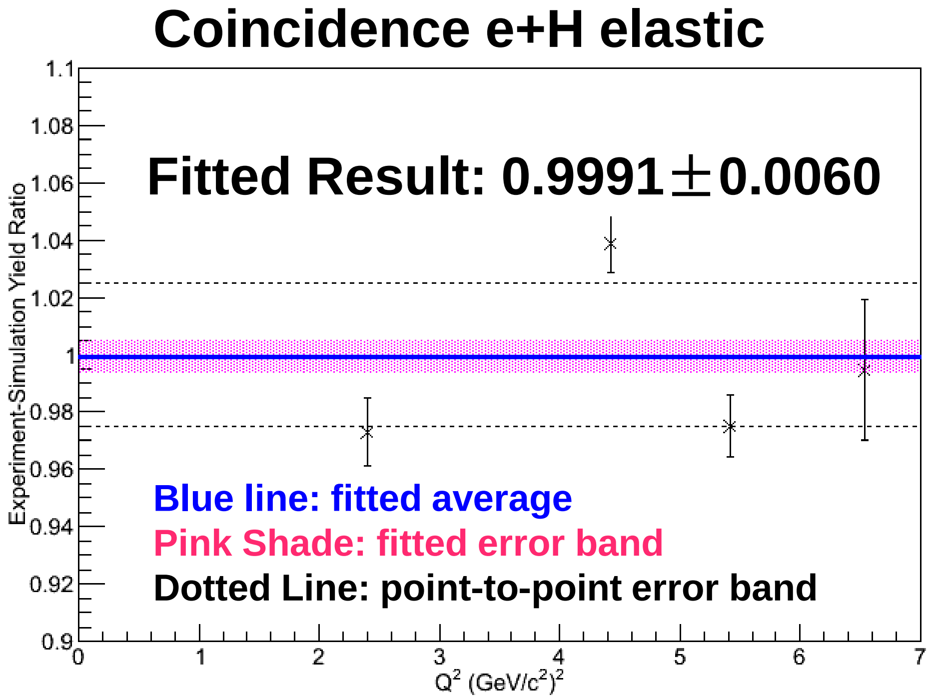




- **Cryotarget**
  - Tuna can shaped
  - With thin Al cell wall
- **Dummy Target**
  - 4cm apart Al sheets
  - Dummy target distribution is corrected for the real/dummy target thickness difference before subtracted from the real proton events

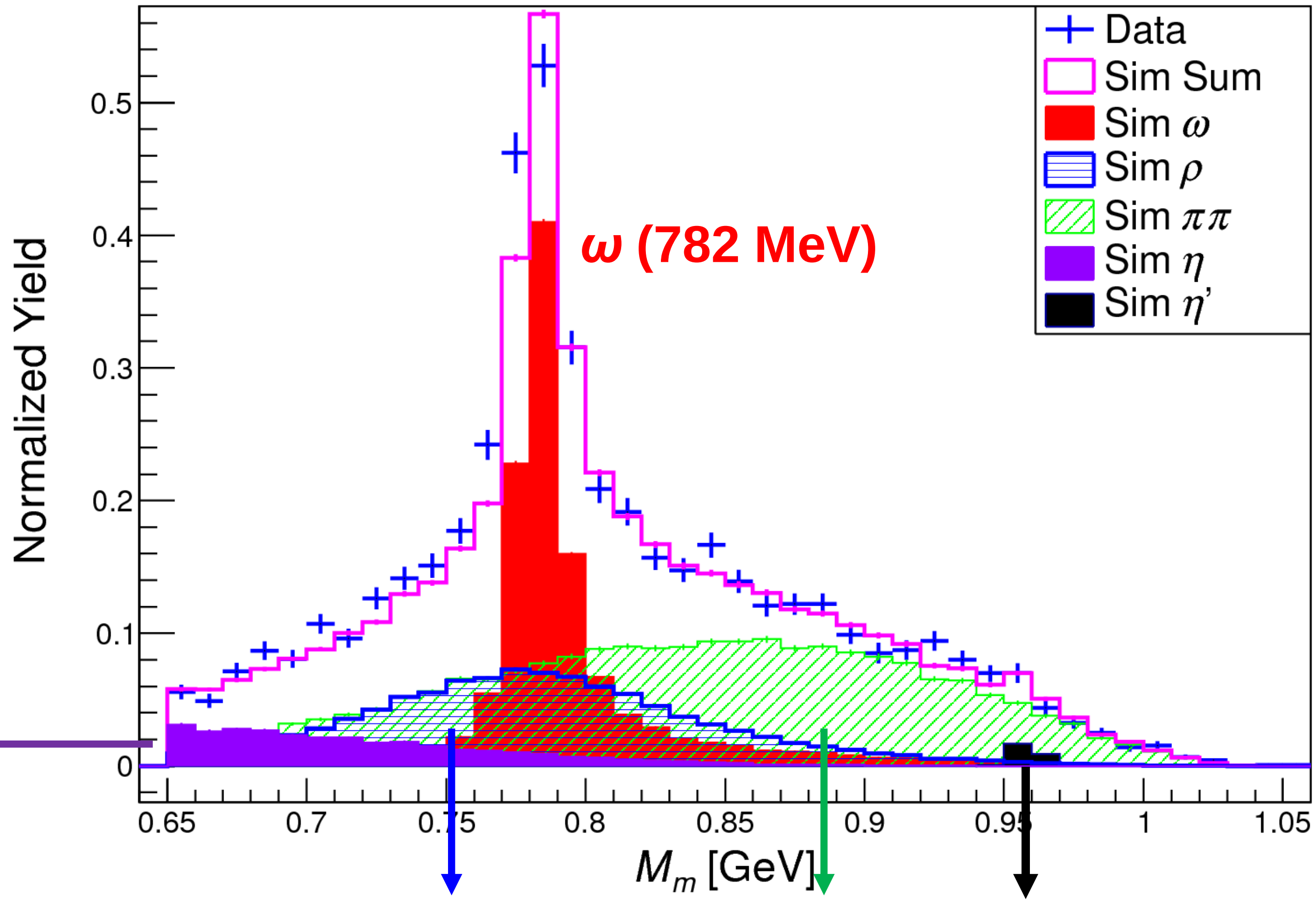
Analysis: e+H Elastic Cross-Section





- 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

Physics Background Subtraction



***η* (547)**

***ρ* (770)**

HERMES Empirical parameterization with Soding factor

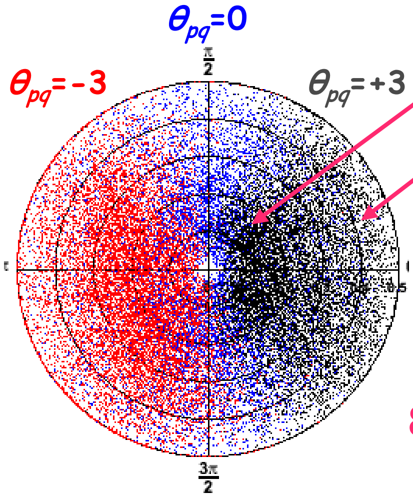
2π

***η'* (947)**

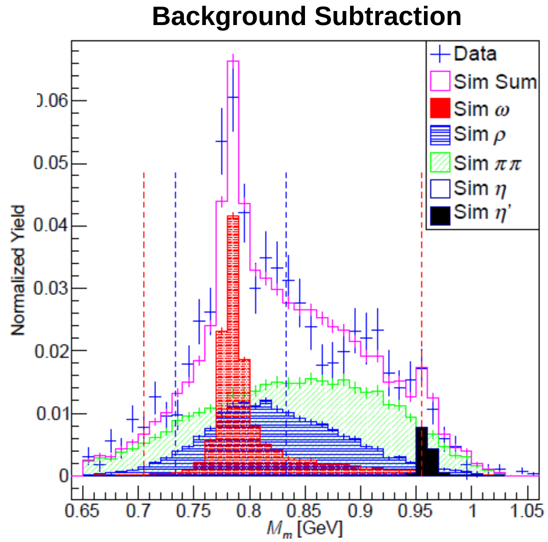
Width from PDG with Ae^{-Bu} dependence

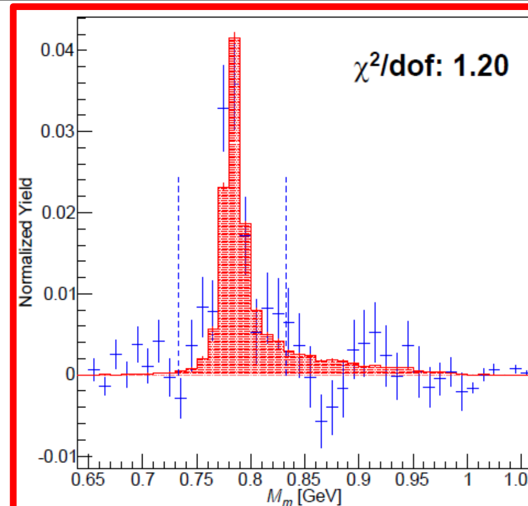
Iterative Procedure (Recipe) to A Full LT Separation

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



3 u bins
8 phi bins



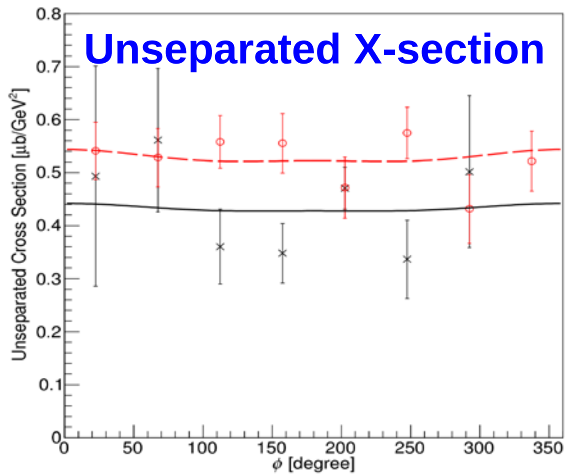


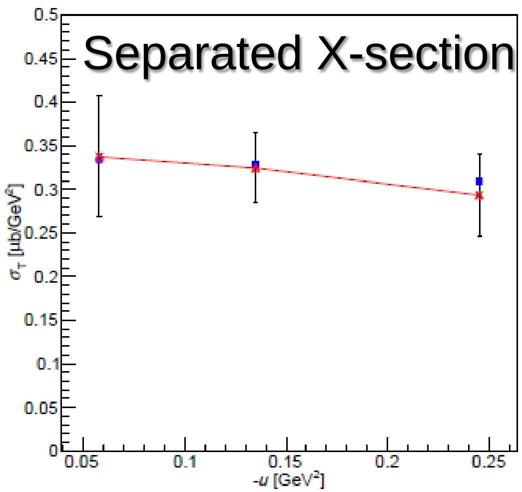
$$R=\frac{Y_{Exp}-Y_{\rho\ \mathrm{sim}}-Y_{Xspace\ \mathrm{sim}}-Y_{\eta\ \mathrm{sim}}}{Y_{\omega\ \mathrm{sim}}}$$

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



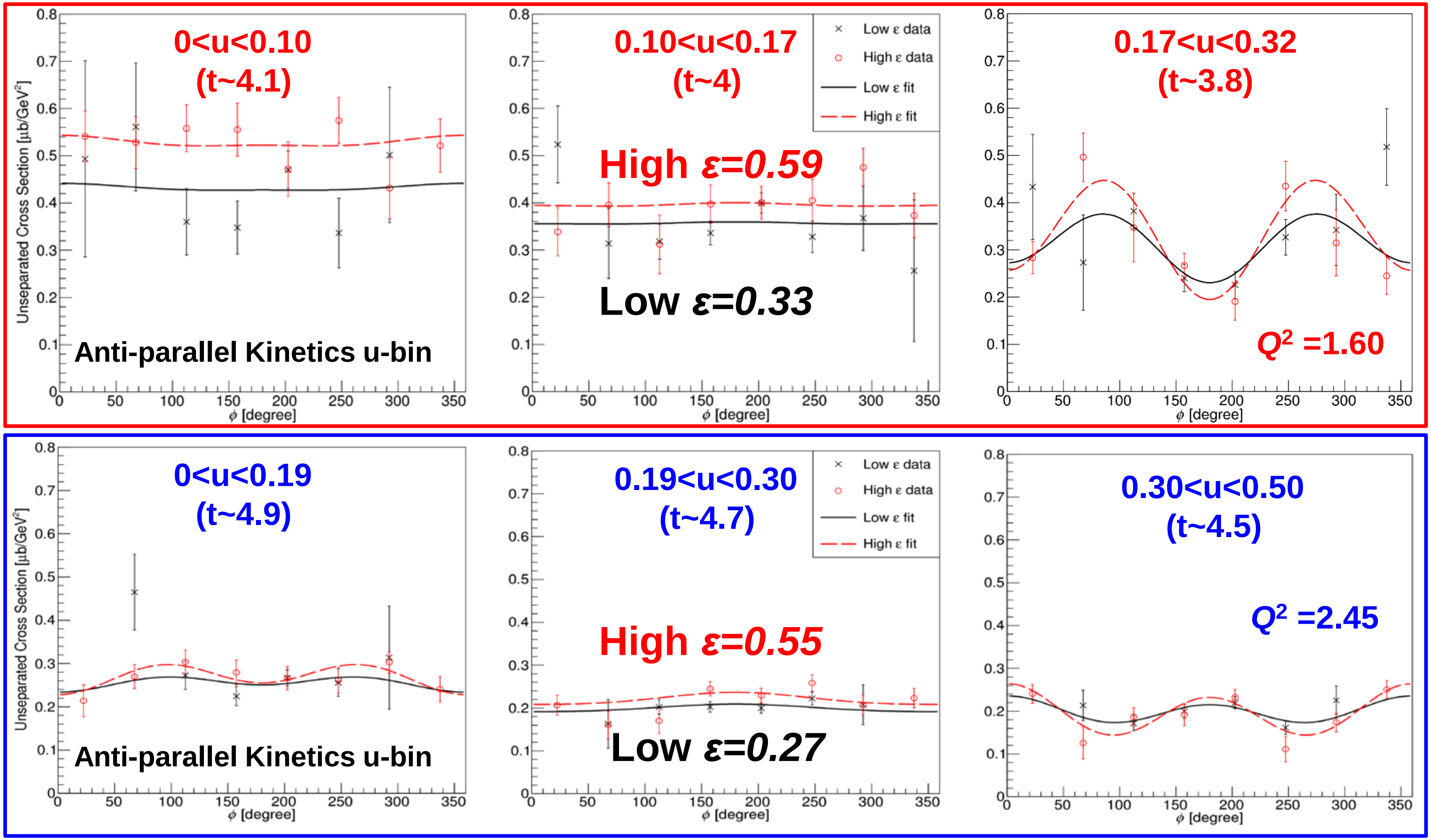


Extract T, L, LT, TT via simultaneous fit

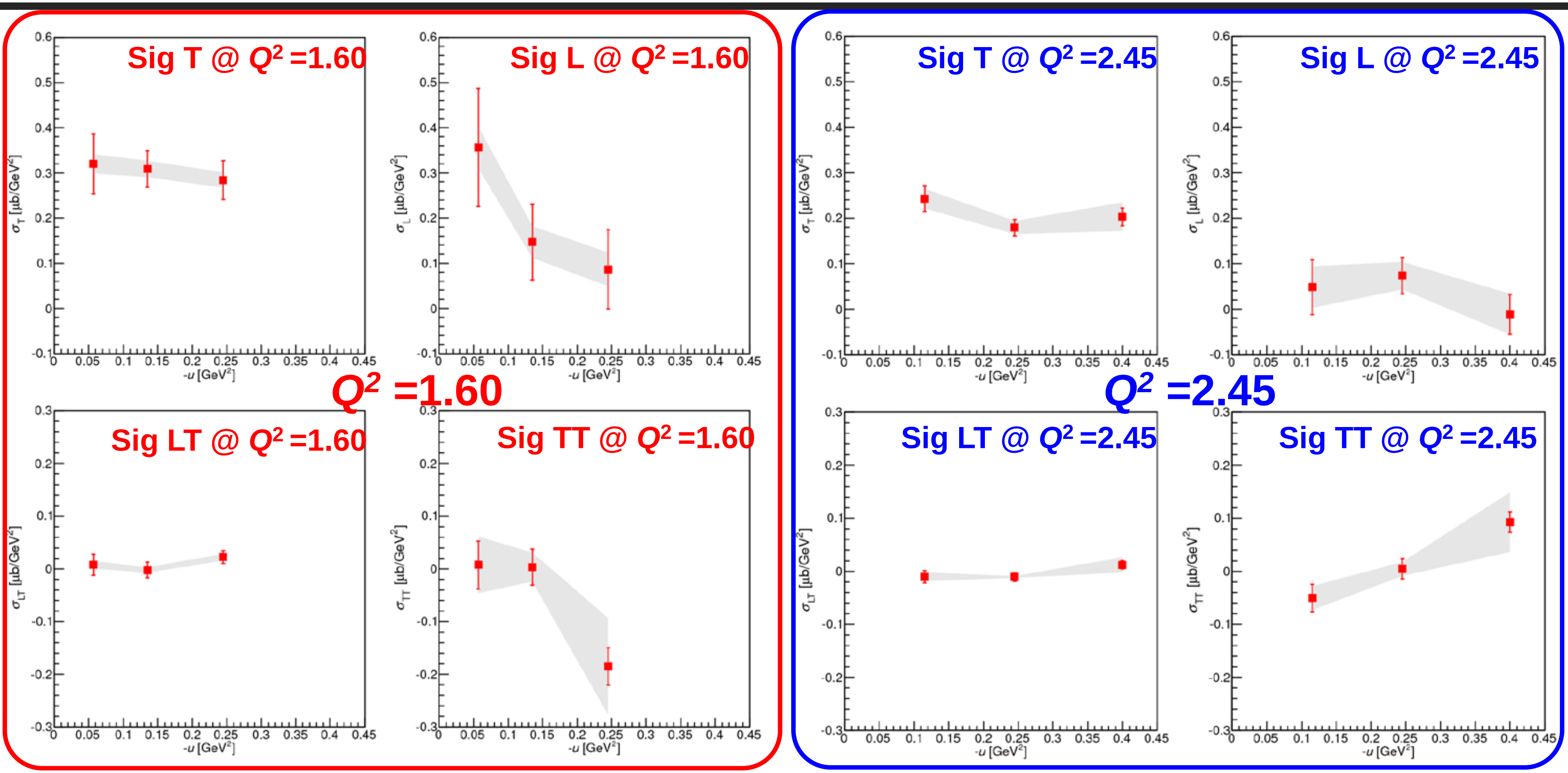
$$2\pi\frac{d\sigma}{dtd\phi}=\frac{d\sigma_T}{dt}+\varepsilon\frac{d\sigma_L}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos2\phi$$

Unseparated Cross Section (Money Plot)

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



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



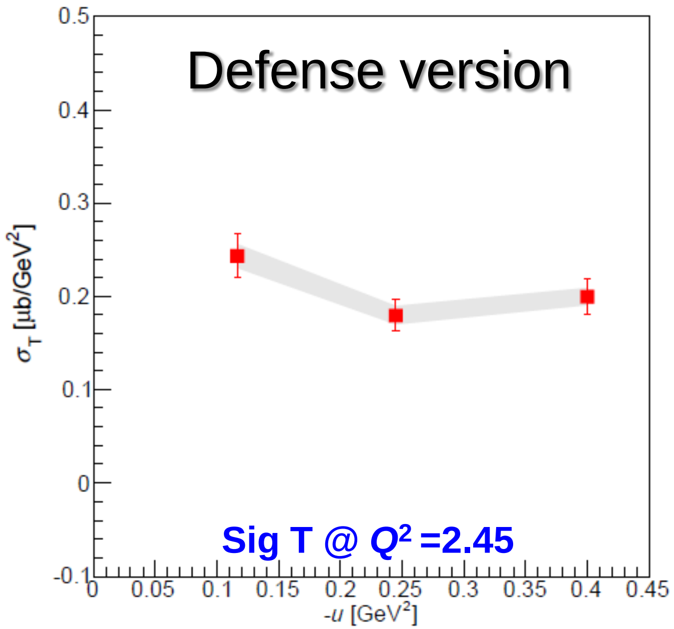
- **Observations:**
  - **SigT fall slow, SigL fall faster**
  - **SigLT is small, Sig TT has sign flip for different Q^2 values**

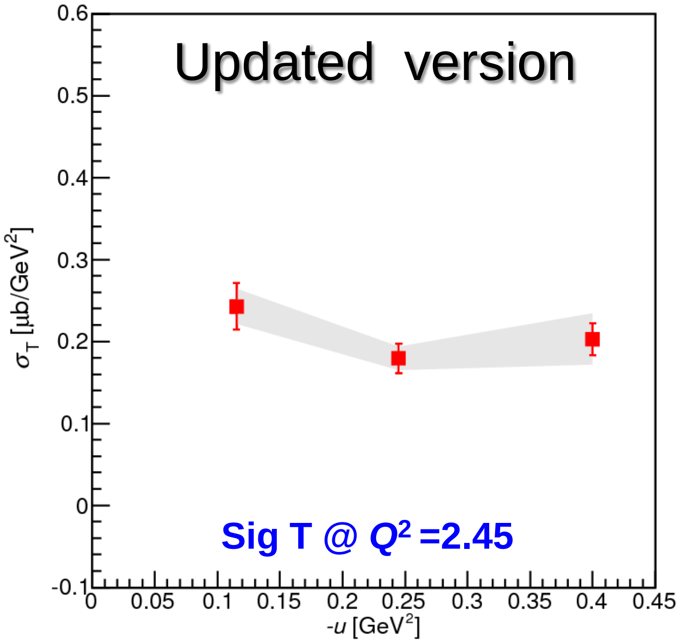
Uncertainties

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)**

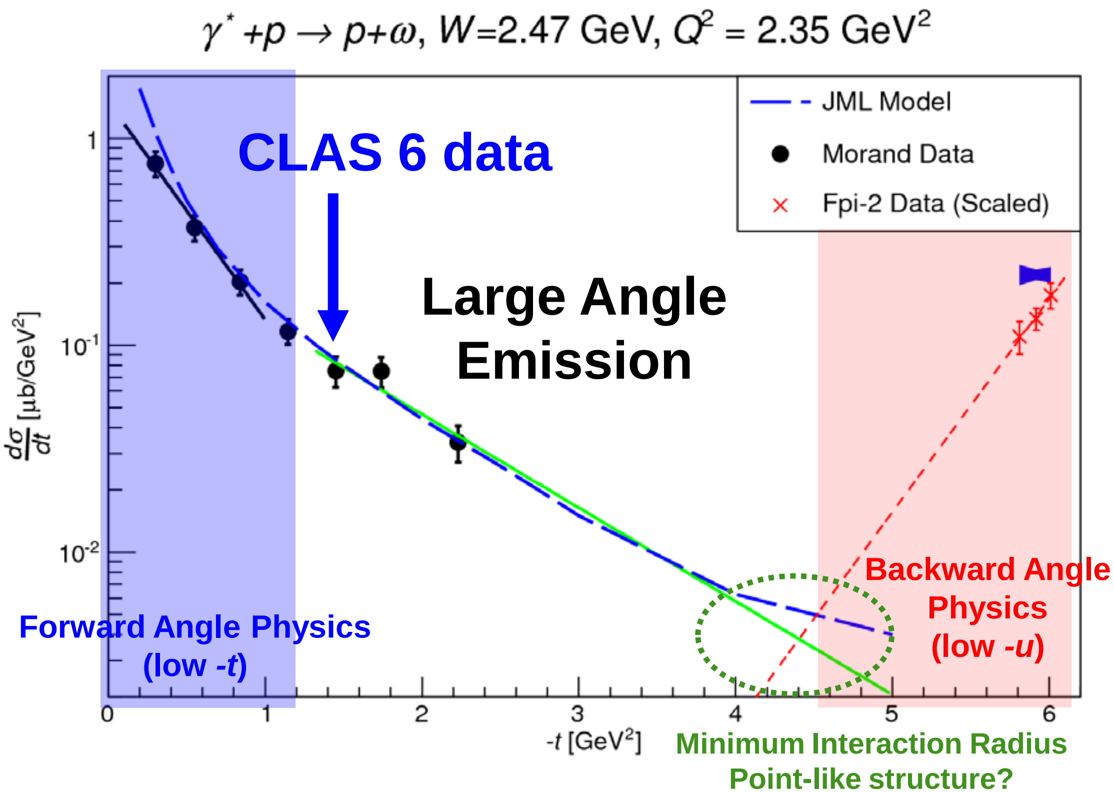
Updated Uncertainties since the Thesis



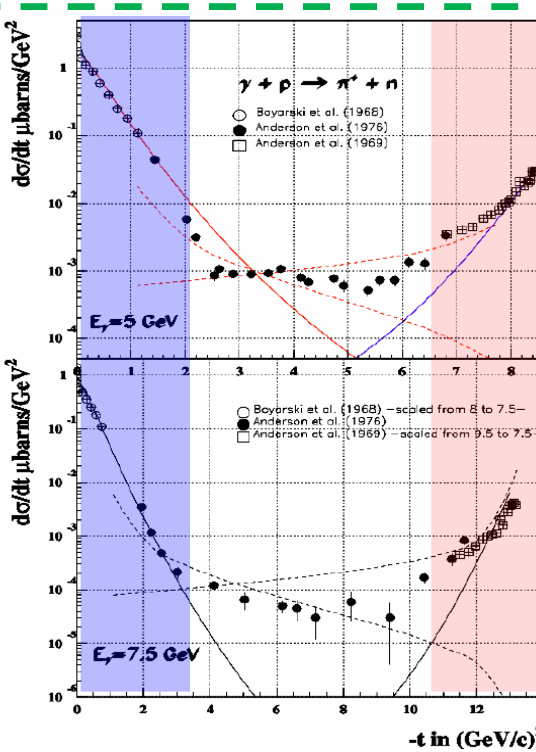


- Fitting Error is now used as the Statistical Error
- New method used for computation the scale error
- Sig_LT and Sig_TT now have scale error band

Hadronic Model: Backward Angle Omega Electroproduction Peak !



Soft structure -> Hard -> Soft transition !
First time in electroproduction

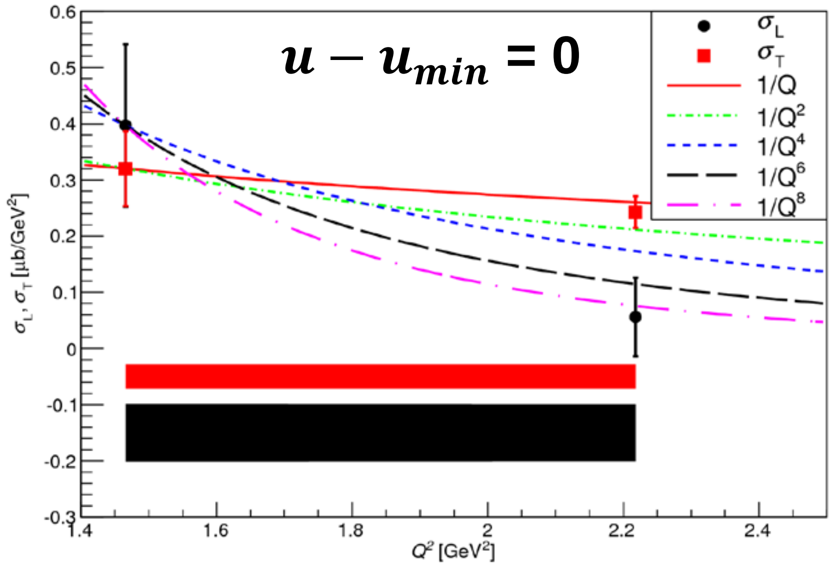


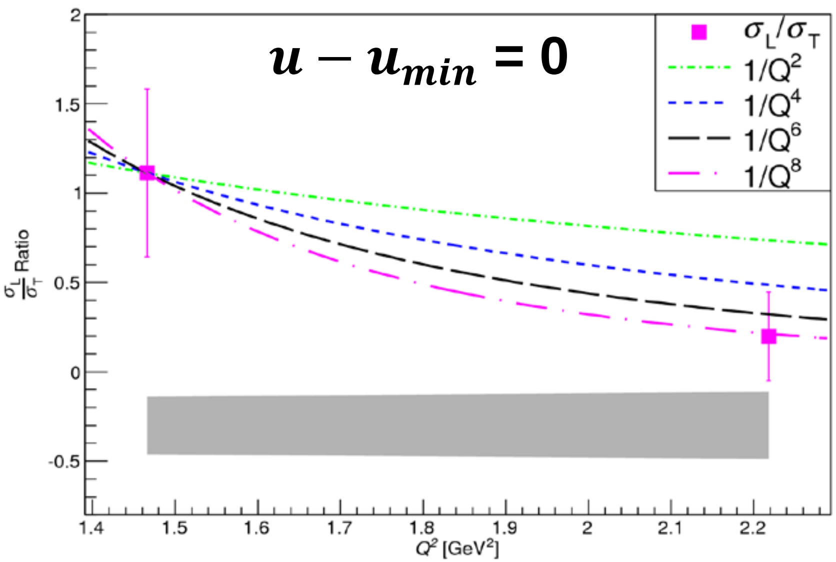
Soft structure -> Hard -> Soft transition !
In photoproduction

M. Guidal, J.-M. Laget, and M. Vanderhaeghen. *Physics Letters* B400(1):6 – 11, 1997.

- **First observation for the backward ω electroproduction peak!**
- **Calls for the resurrection of the backward angle study through Regge based model (JML, etc.)**

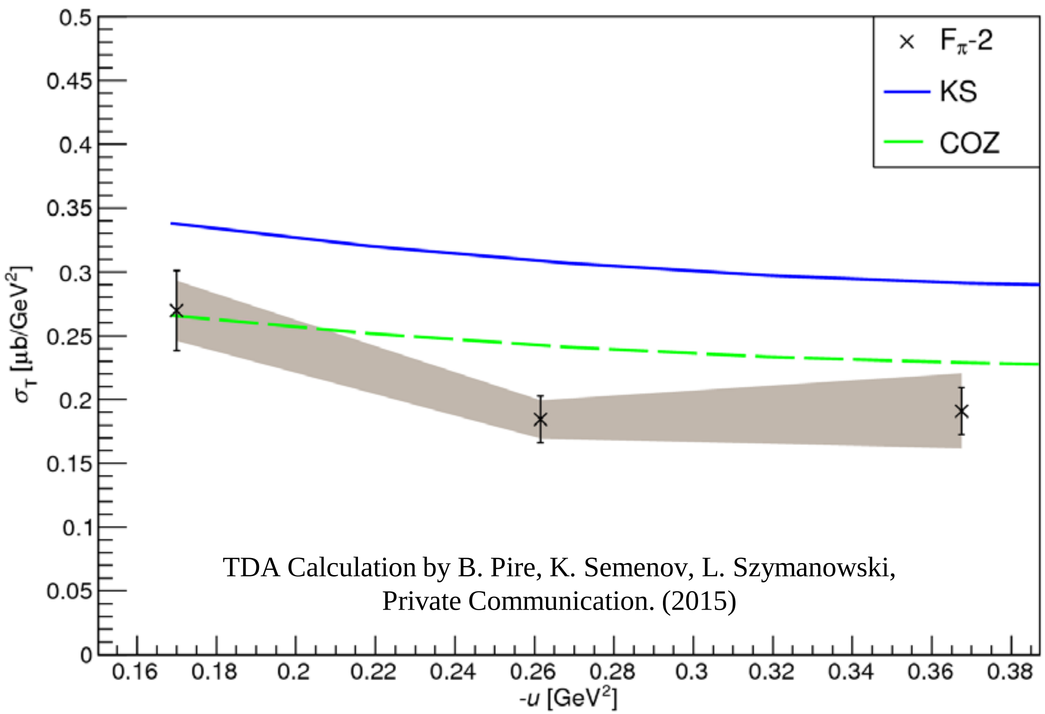
Scaling of σ_L, σ_T and σ_L / σ_T Ratio





- σ_L drops expected ~$1/Q^8$
  - Close to expectation
- σ_T **is almost constant !**
- Dominance of σ_T observed at higher Q^2 =2.45, confirms the TDA prediction

Partonic Model: TDA Prediction (Private Communication)



- **Optimal Q^2 range for TDA: >10 GeV^2**
- **TDA prediction has impressive agreement with data at Q^2 =2.45 GeV^2**
- **Studying the effectiveness of JML model and TDA model is equivalent to studying the evolution of the proton structure**

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 !

Message to the world and thank you

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

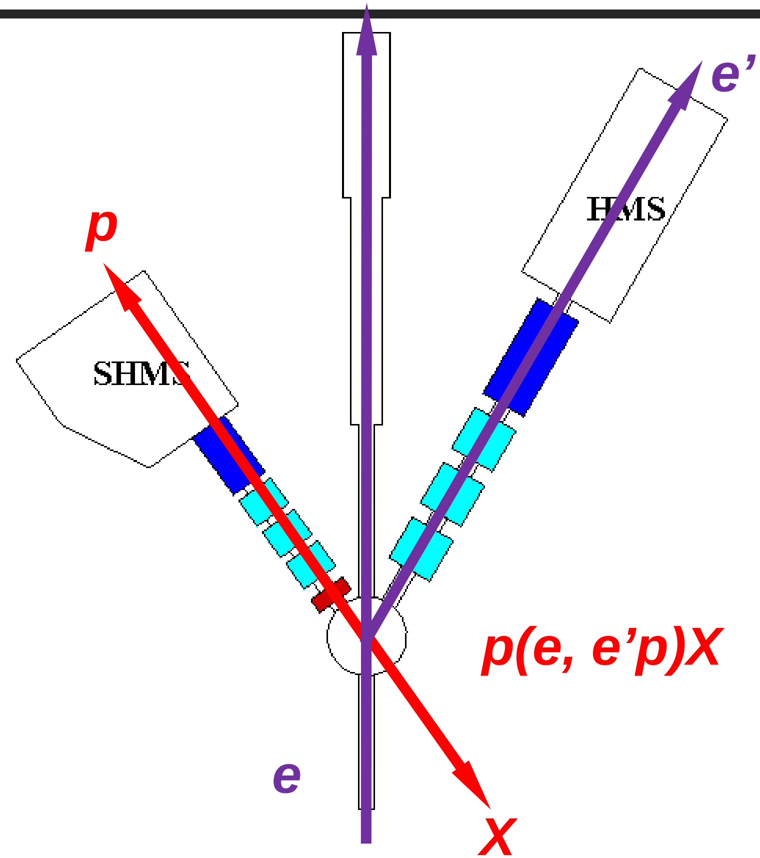
- Established a new experimental access to the previously accessible kinematics

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

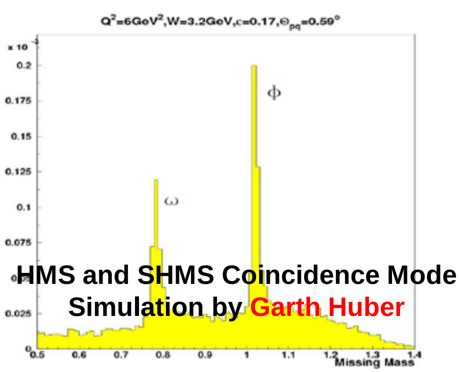
- Final release of the result calls for more studies on backward angle physics, particularly among the junior physicist.

Backup

Future Backward Meson Production Opportunities

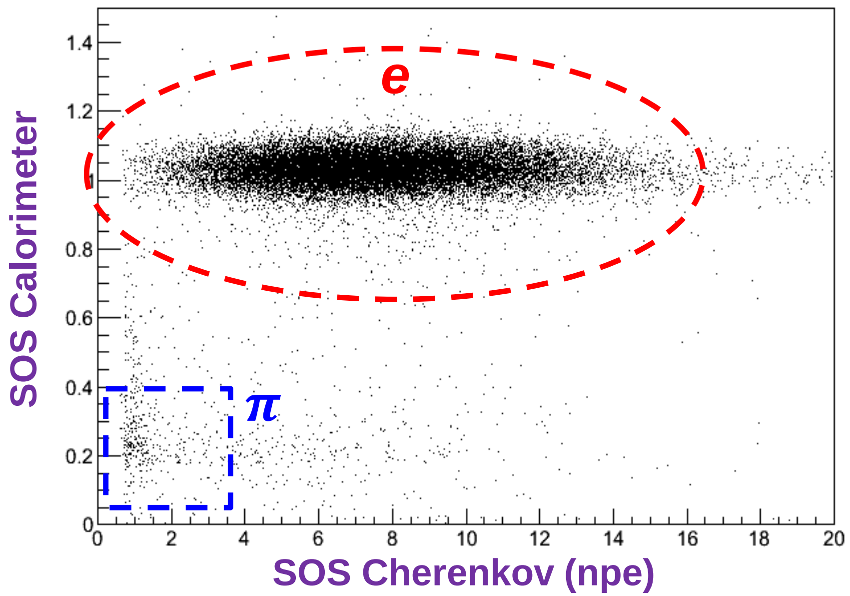


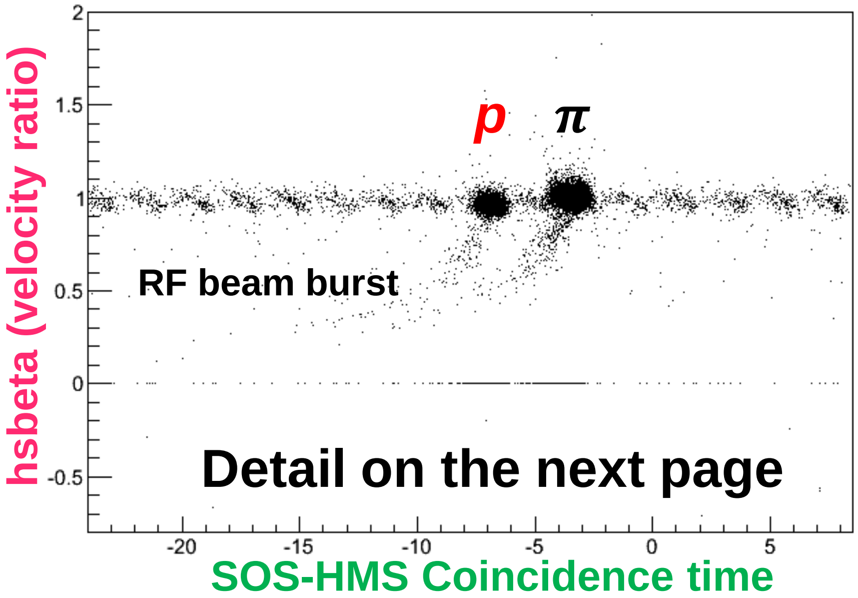
Hall A pi0 production



- **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

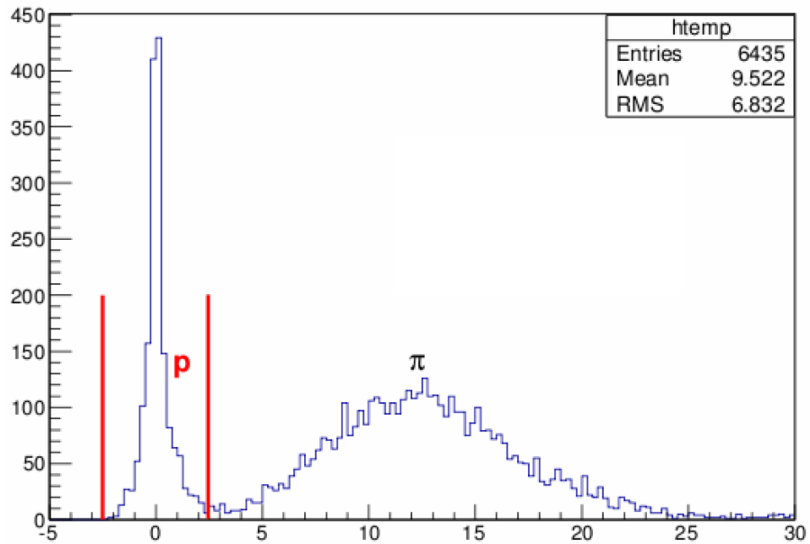
PID Cuts



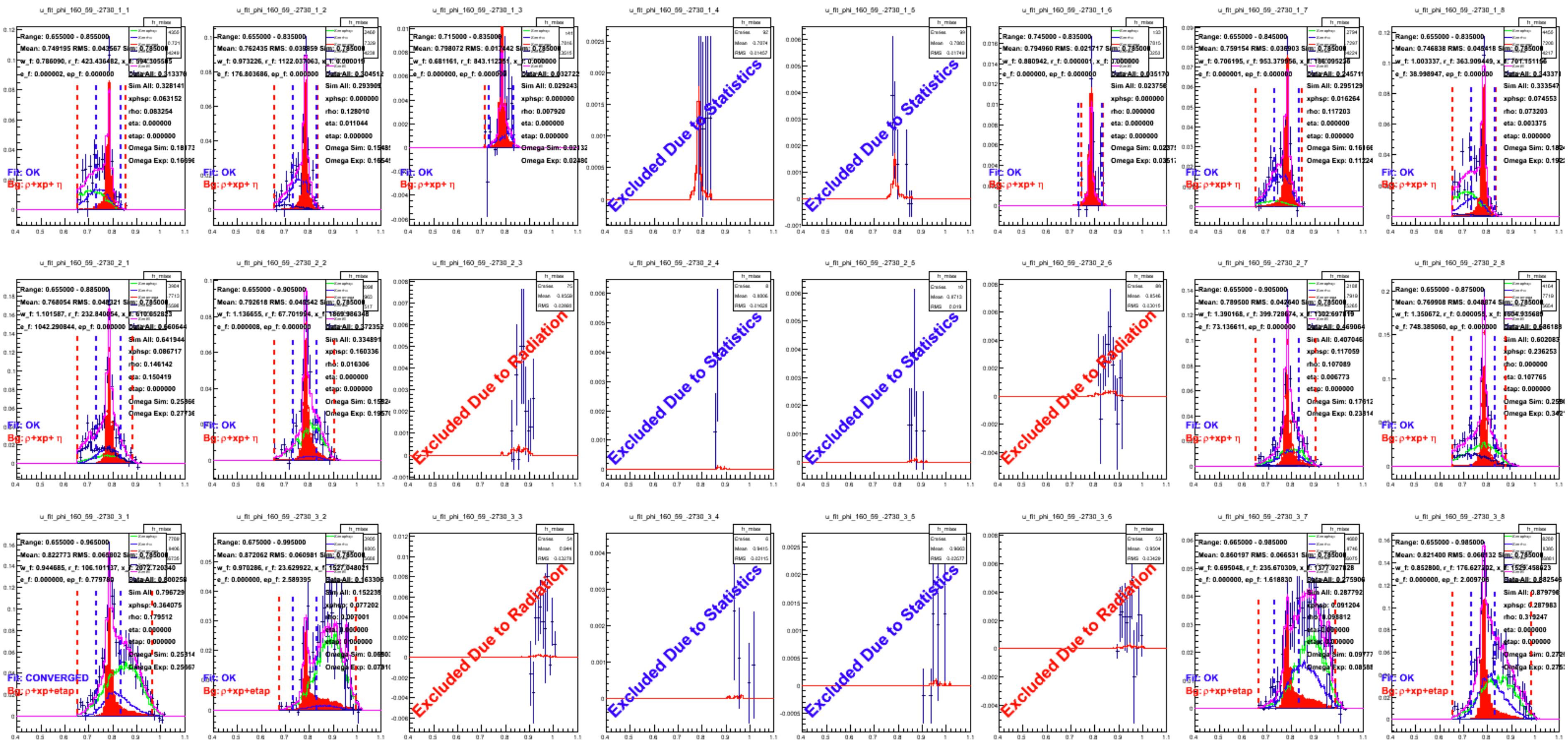


- SOS: select electron
  - Calorimeter cut
  - Cherenkov cut
- HMS: select proton
  - Coincidence timing cut
  - Hebeta (particle velocity)
  - Aerogel Cut
  - Cherenkov Cut: veto e^+

99% efficiency



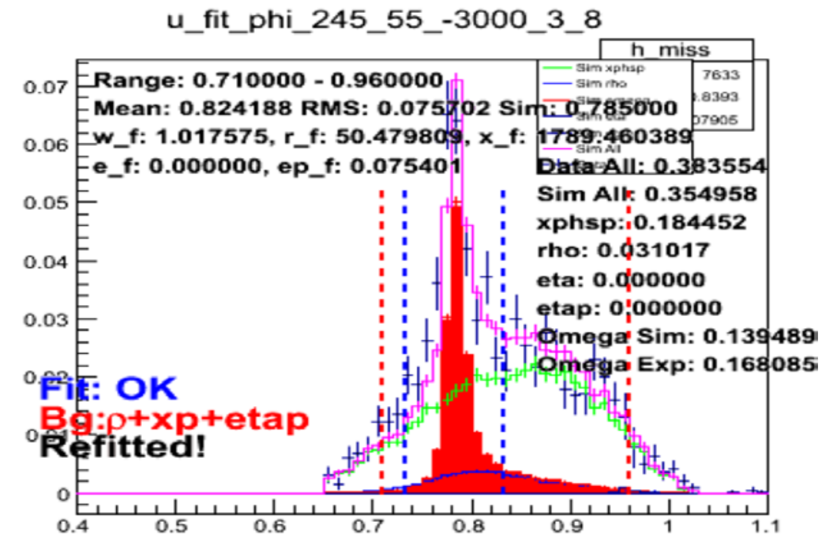
Missing Mass Distribution Background Extraction

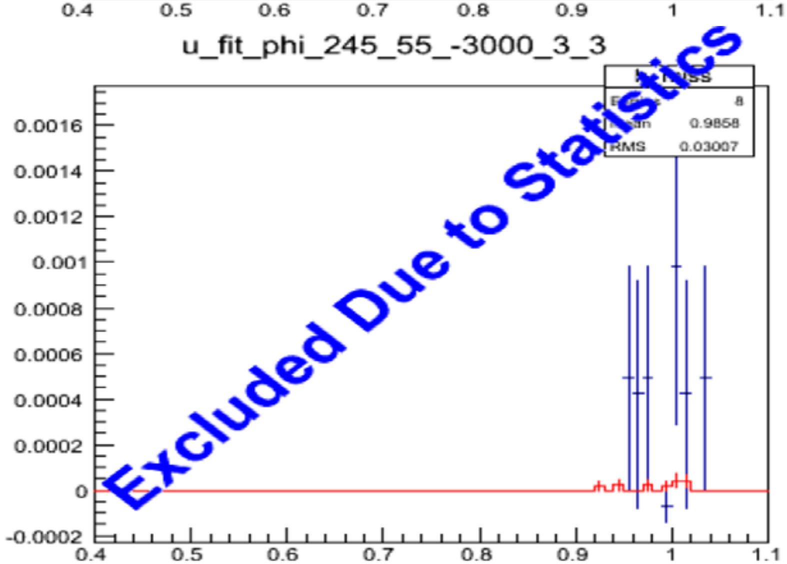


- Integration limits and fitting limits
- Exclusion criteria
  - Exclude the radiative only omega bins
  - Exclude the low statistics bins

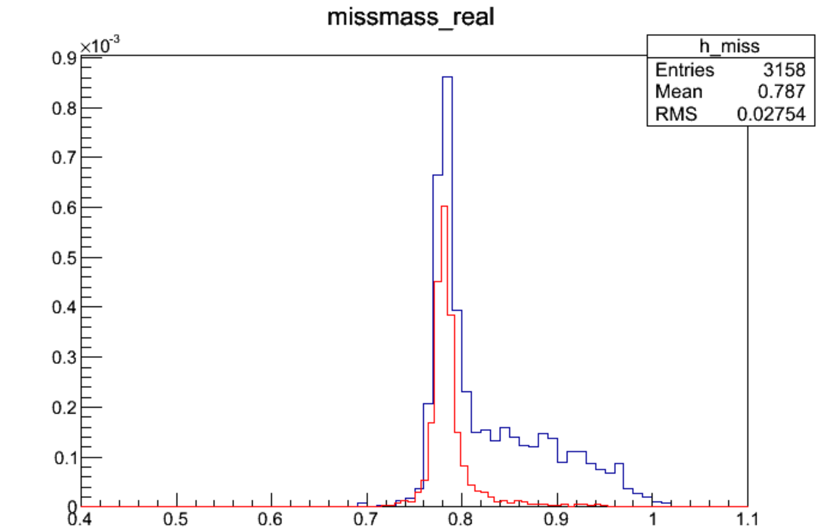
Bin Exclusion criteria

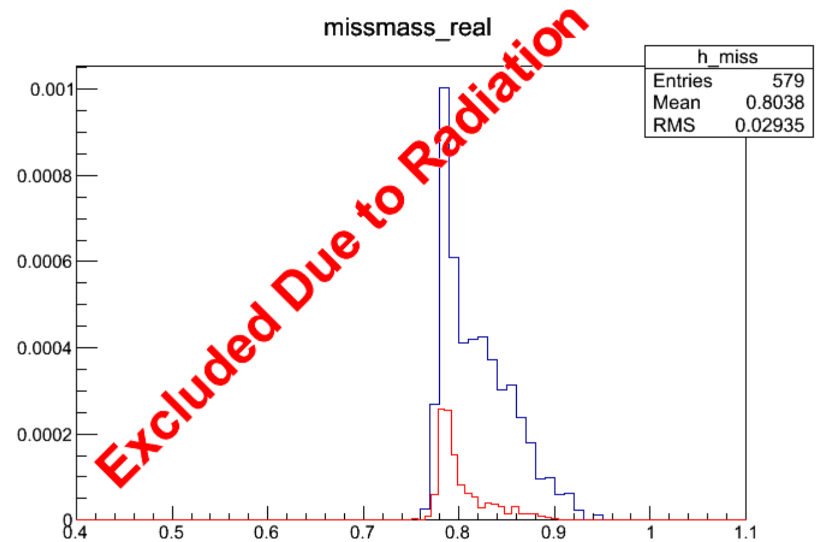
- Low Statistics



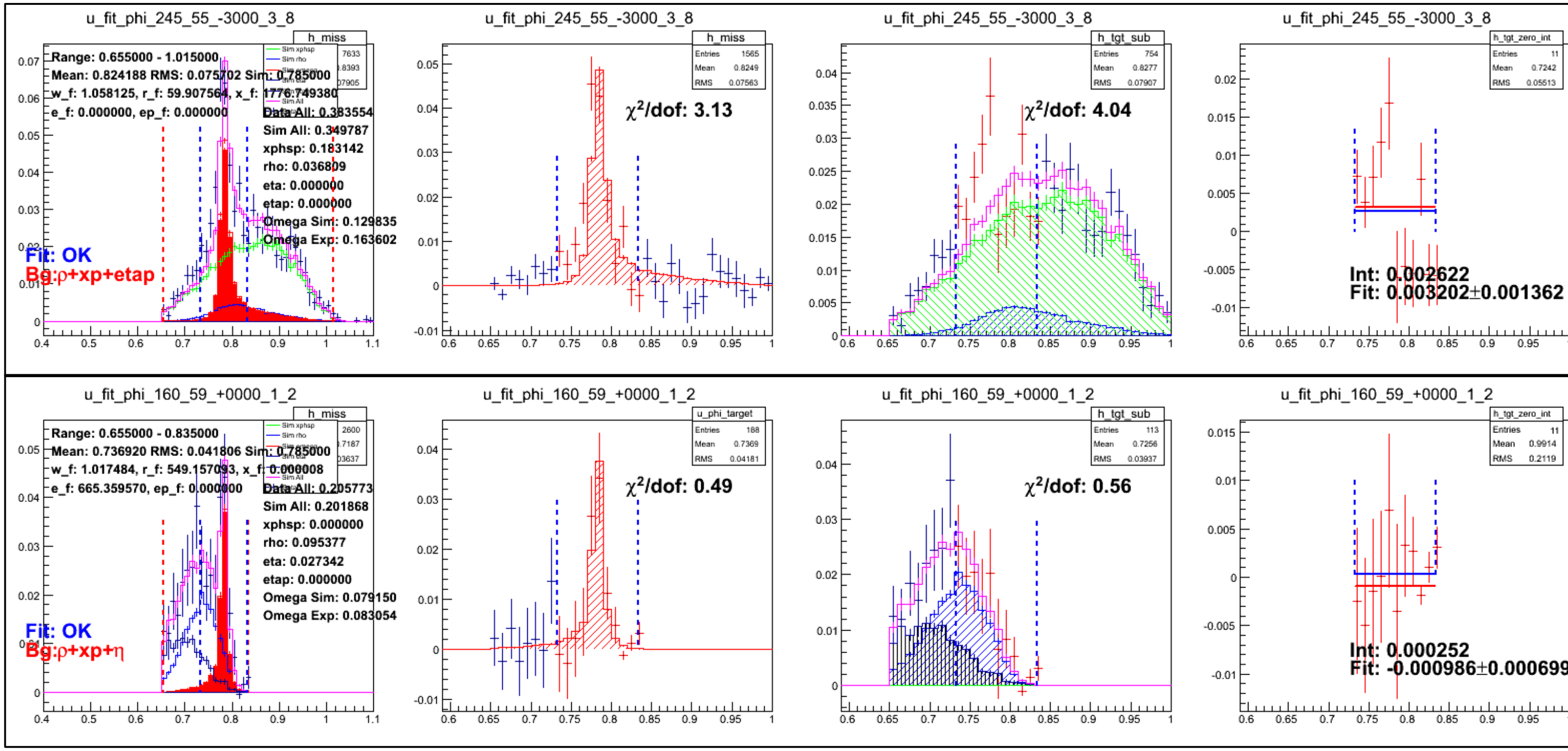


- Radiative Tail



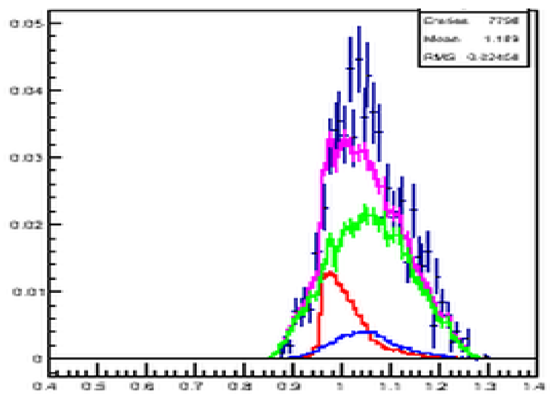


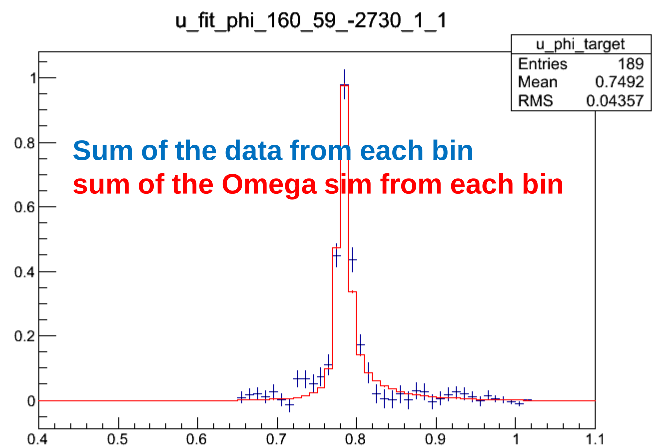
Background Extraction and Check



Worse example

Missmass edge example

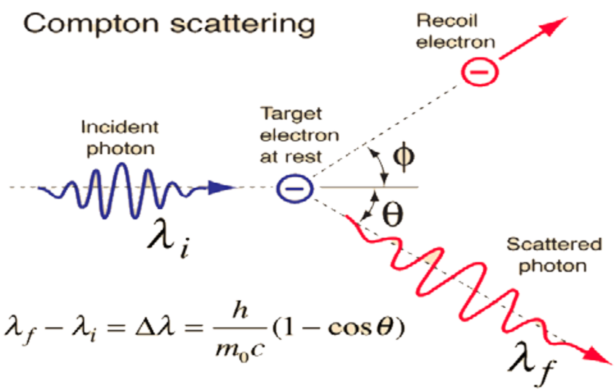


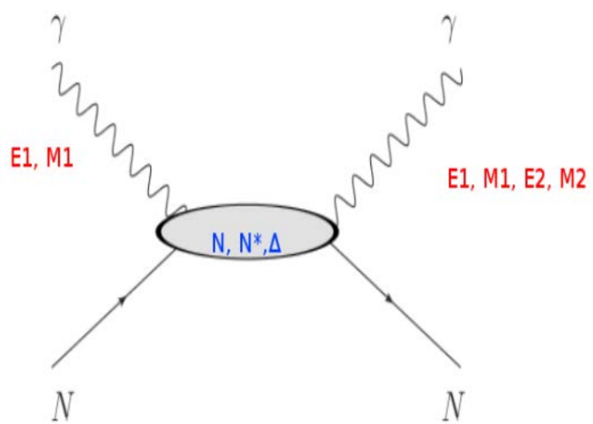


Reconstructed Missing Energy For the worse example

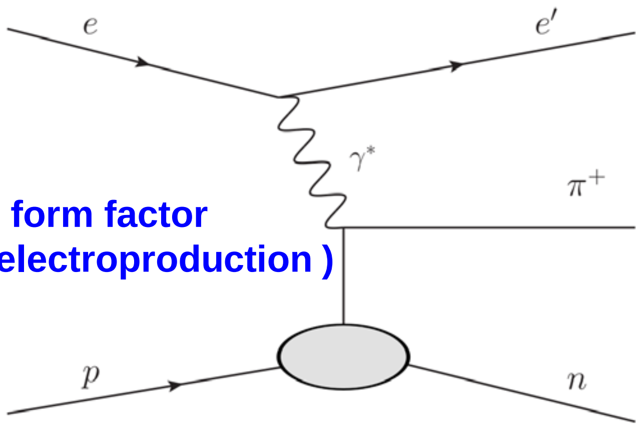
Standard Physics at Hall C (Jefferson Lab)

■ *s*-Channel Physics

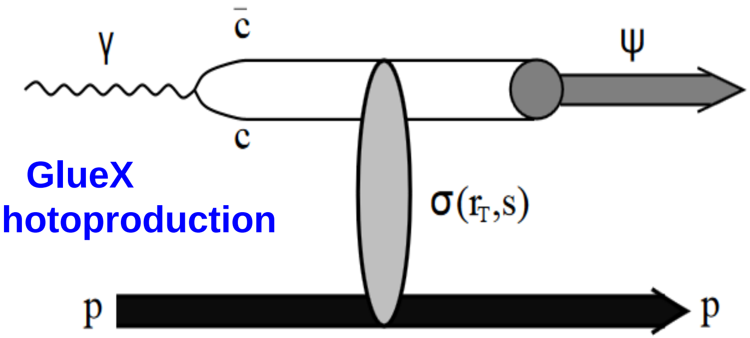




■ *t*-Channel Physics



Pion form factor
(charged π electroproduction)



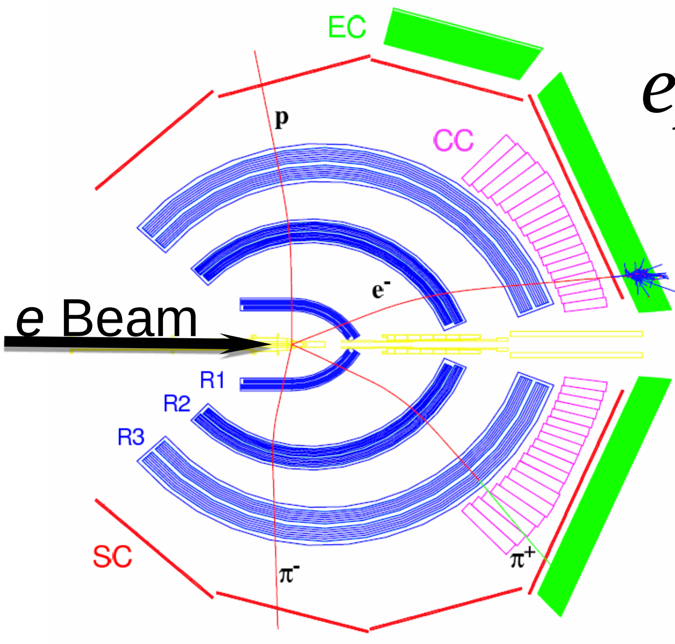
GlueX
J/psi photoproduction

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)

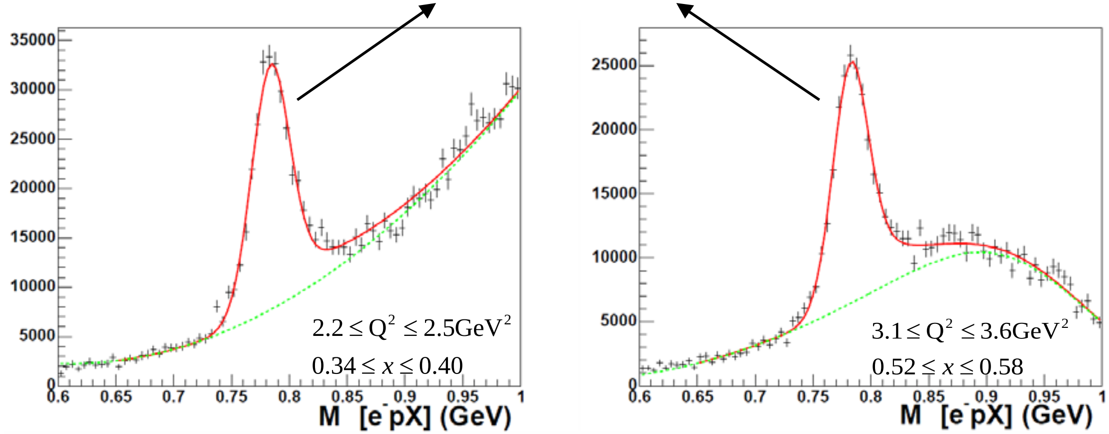
Morand et al., Eur. Phys. J. A 24, 445 (2005).



$$ep \to ep\omega$$

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

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



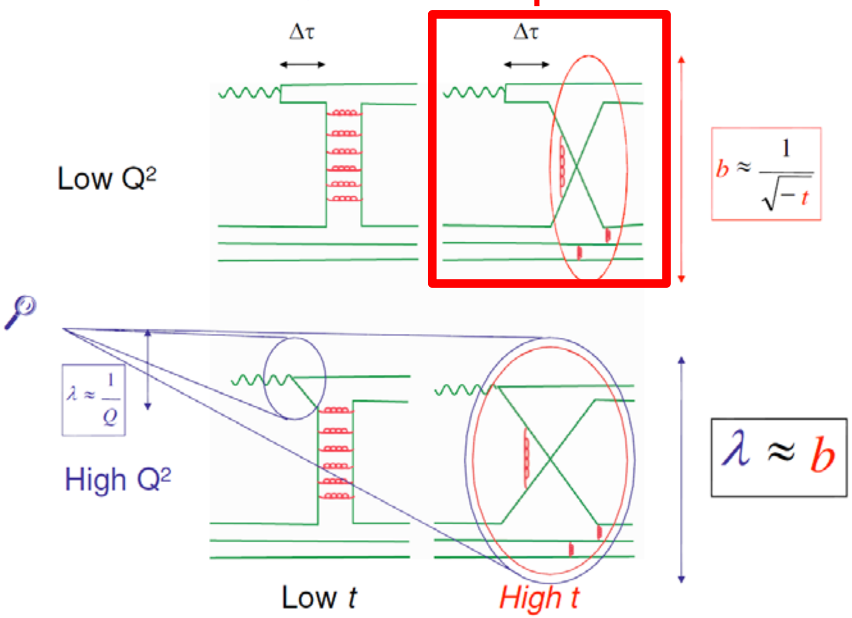
Missing mass reconstruction e^-pX

- 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:

$$ep \to ep\pi^+X$$

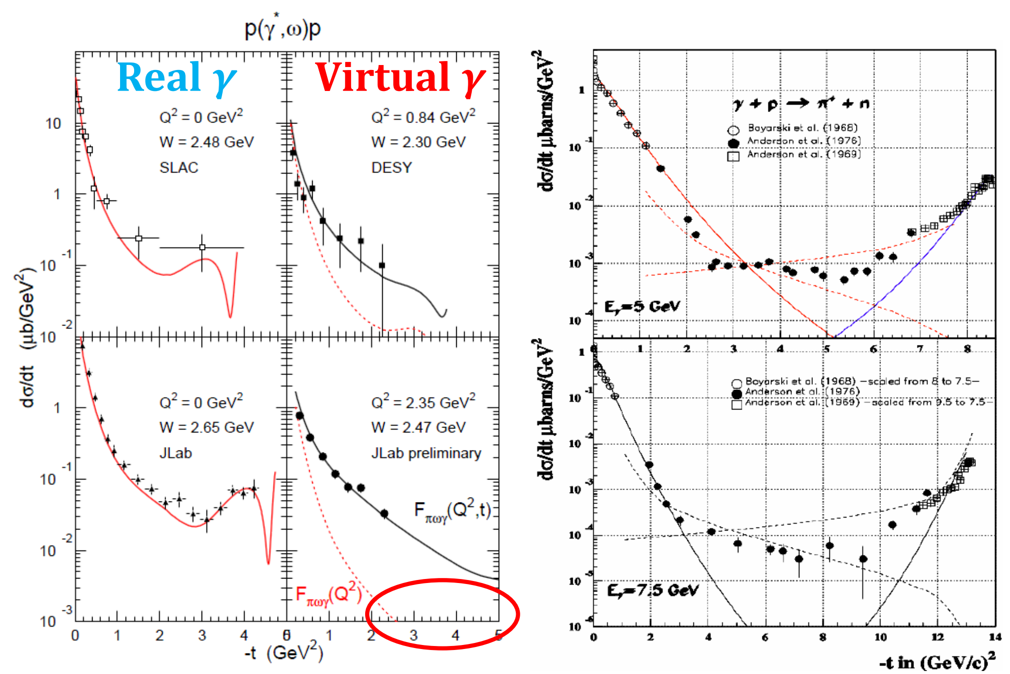
- Reconstructed e^-pX missing mass consistent with the ω mass
- Data published in 2005:
  - Morand et al., Eur. Phys. J. A 24, 445 (2005).

Regge Trajectory Model by JM Laget



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

t-Channel
Forward

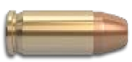
u-Channel
Backward

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

Nucleon Fragmentation Process

Before interaction

e + *H*



Standard nucleon Fragmentation gives a weird picture

Allows for kinematic settings which was previously not available

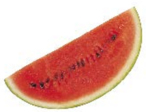
After interaction

***t*-channel**

***n* (938 MeV)**

SOS

Remains at target position

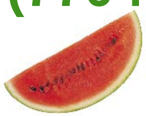


HMS

- H(*e*, *e'* π^+)*n*

***u*-channel**

ω (770 MeV)



SOS

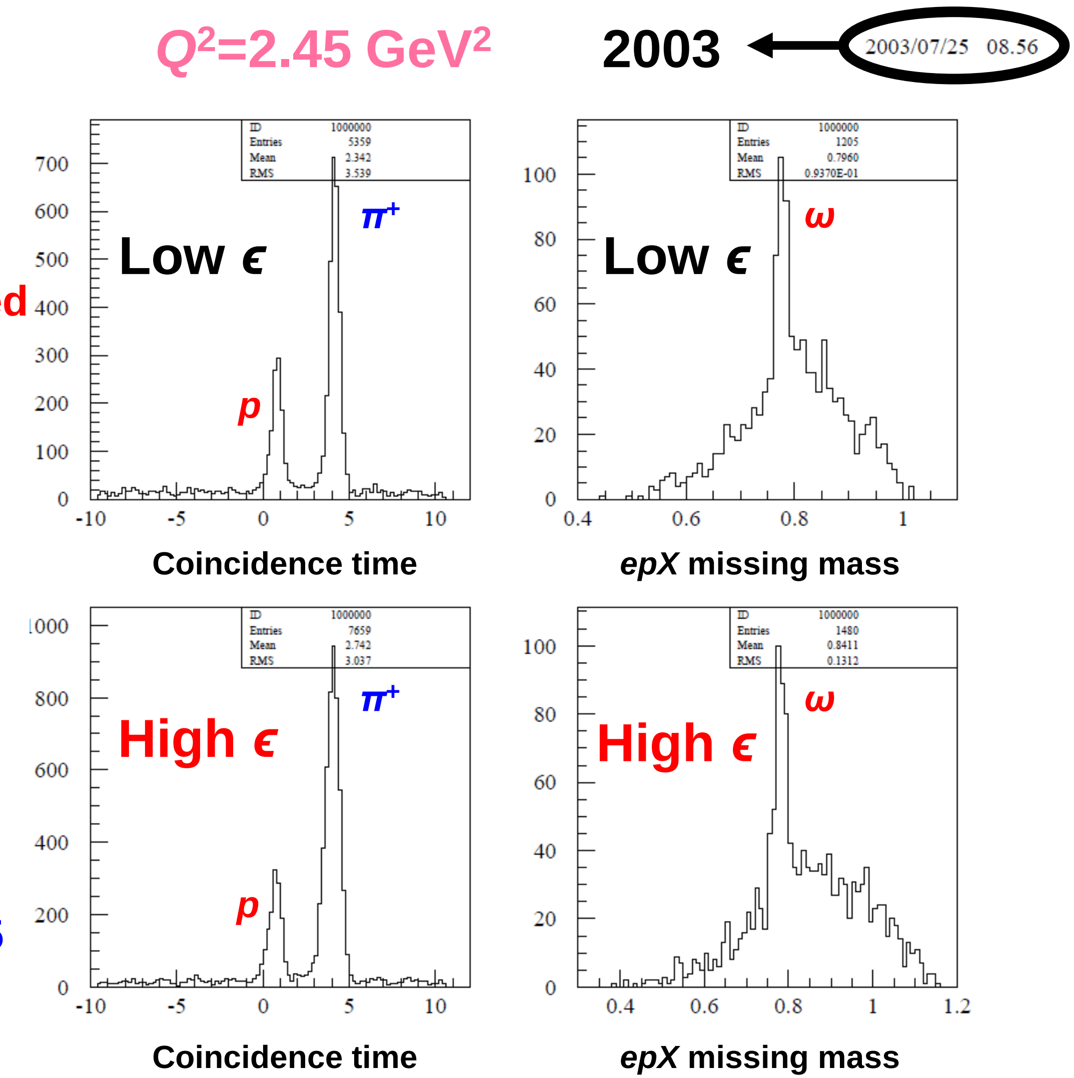
Remains at target position

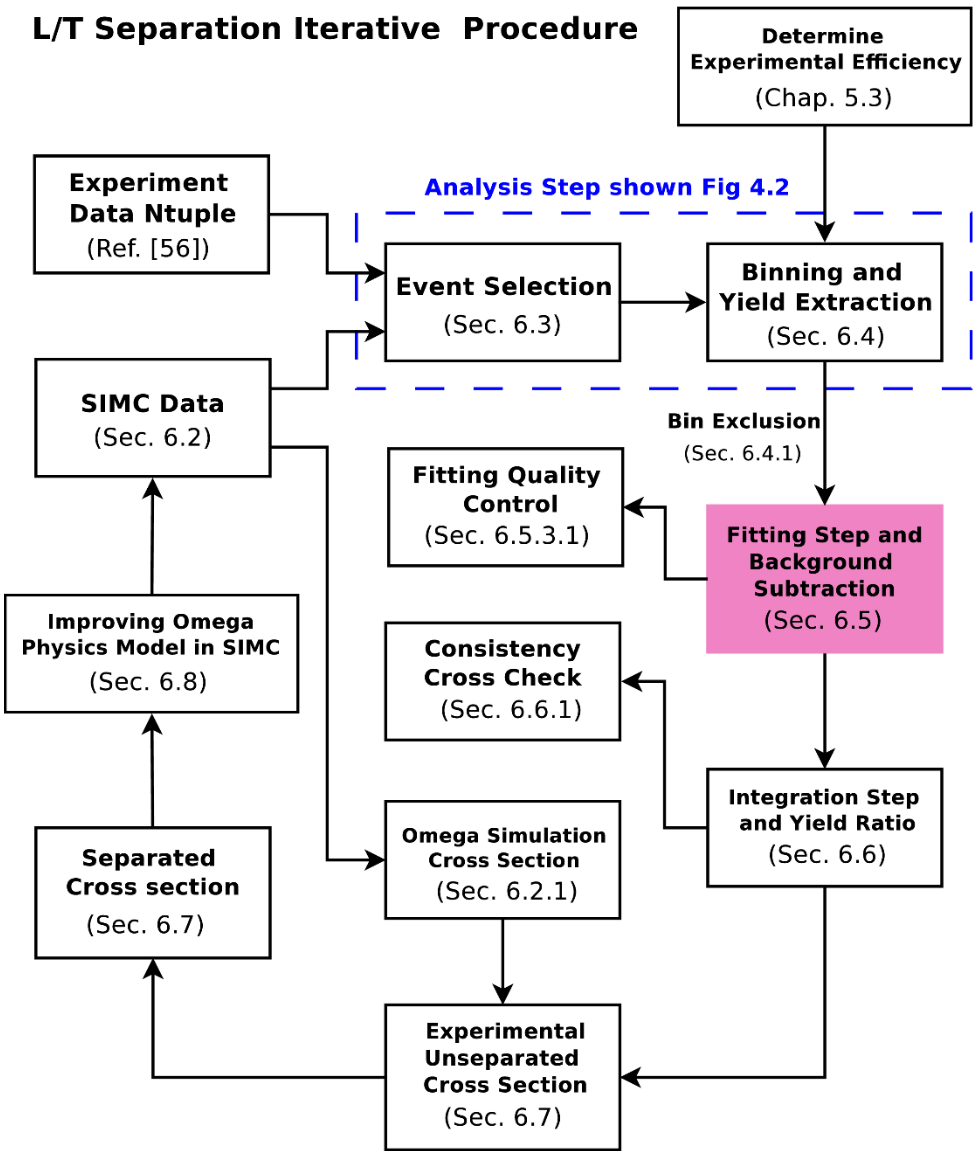
HMS

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

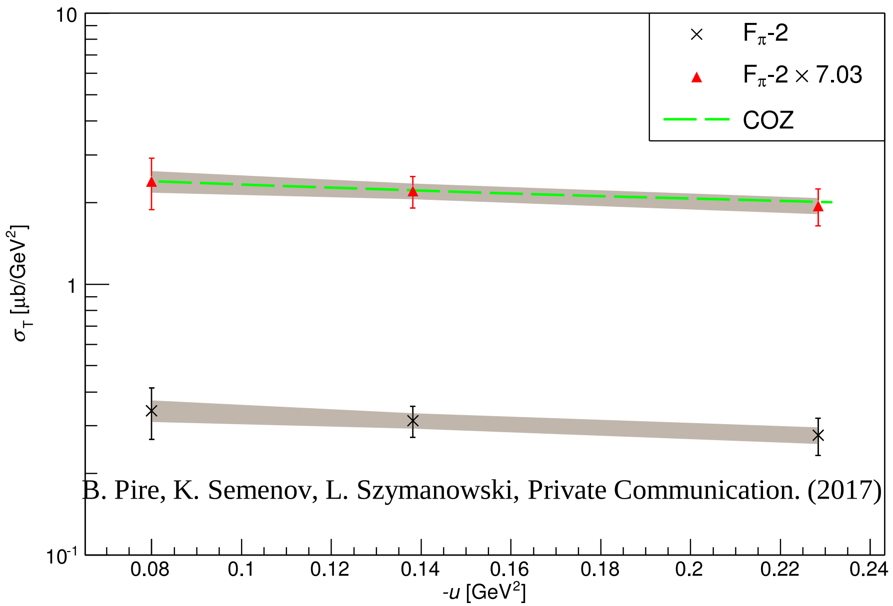
Omega Data Analysis

- 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

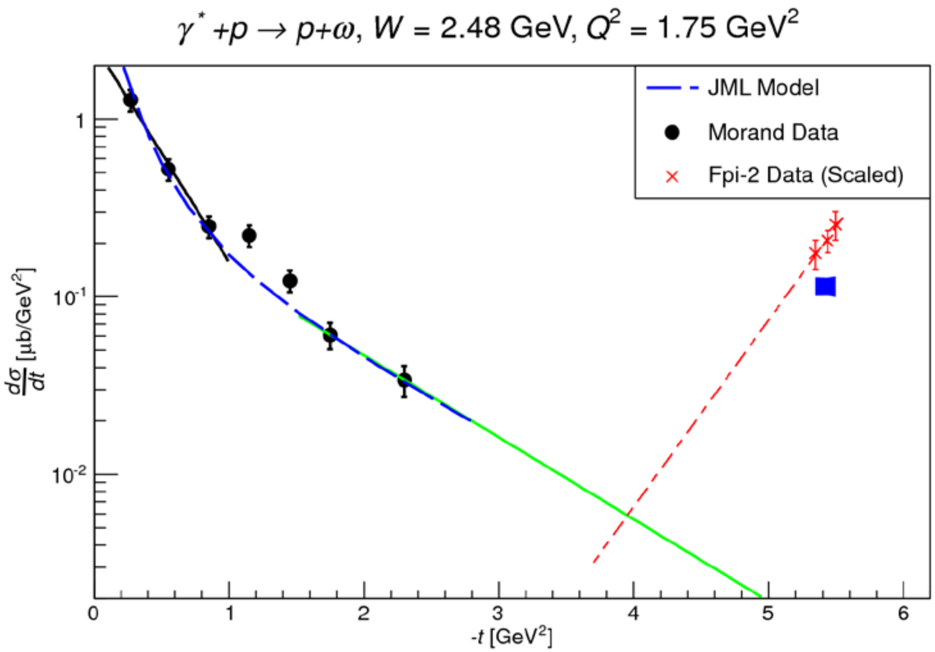



L/T Separation Iterative Procedure
Determine Experimental Efficiency
(Chap. 5.3)
Analysis Step shown Fig 4.2
Experiment Data Ntuple
(Ref. [56])
Event Selection
(Sec. 6.3)
Binning and Yield Extraction
(Sec. 6.4)
SIMC Data
(Sec. 6.2)
Bin Exclusion
(Sec. 6.4.1)
Fitting Quality Control
(Sec. 6.5.3.1)
Fitting 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)
Omega Simulation Cross Section
(Sec. 6.2.1)
Separated Cross section
(Sec. 6.7)
Experimental Unseparated Cross Section
(Sec. 6.7)

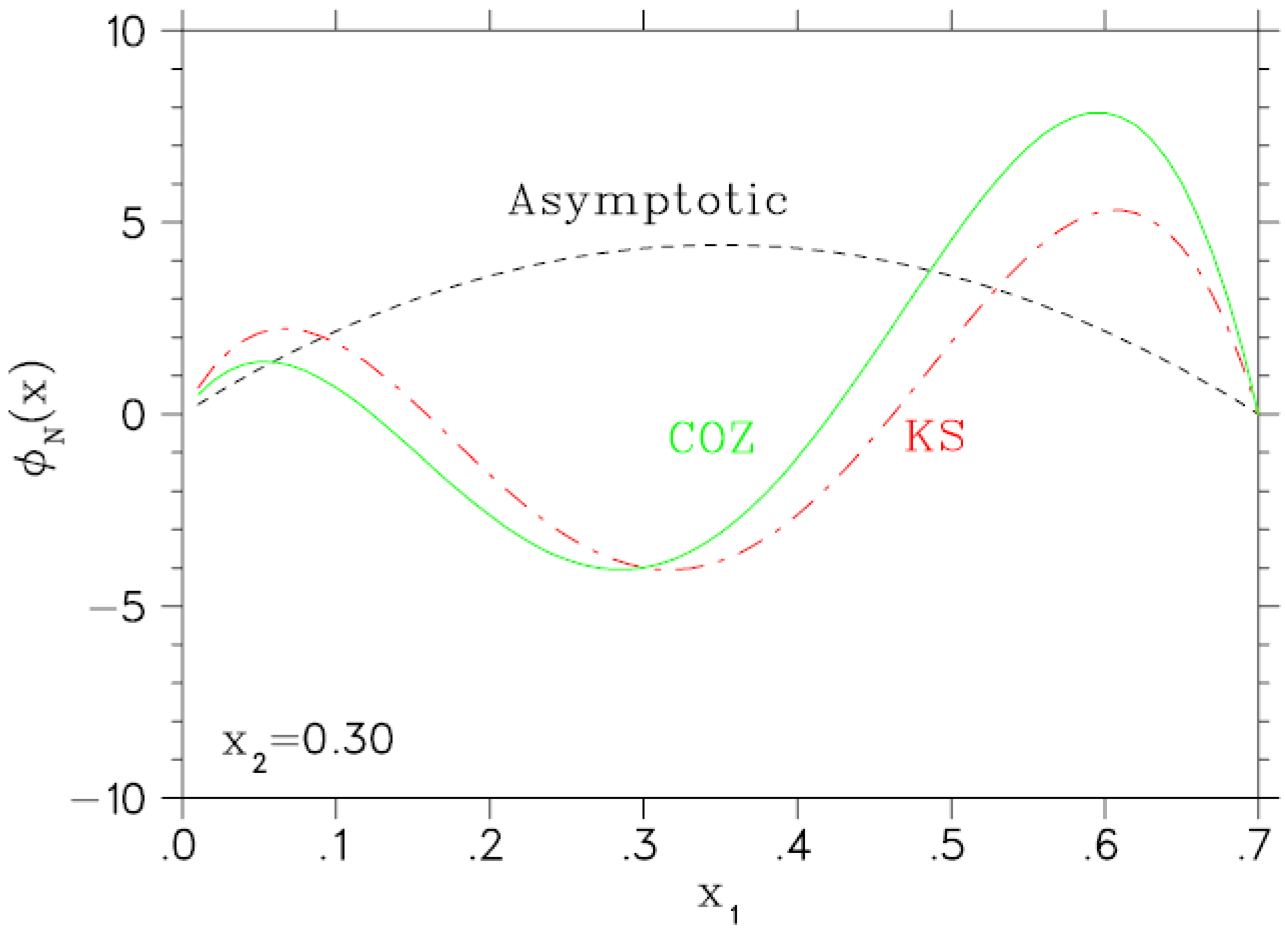
TDA @ Q^2 =1.60 GeV^2



B. Pire, K. Semenov, L. Szymanowski, Private Communication. (2017)



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

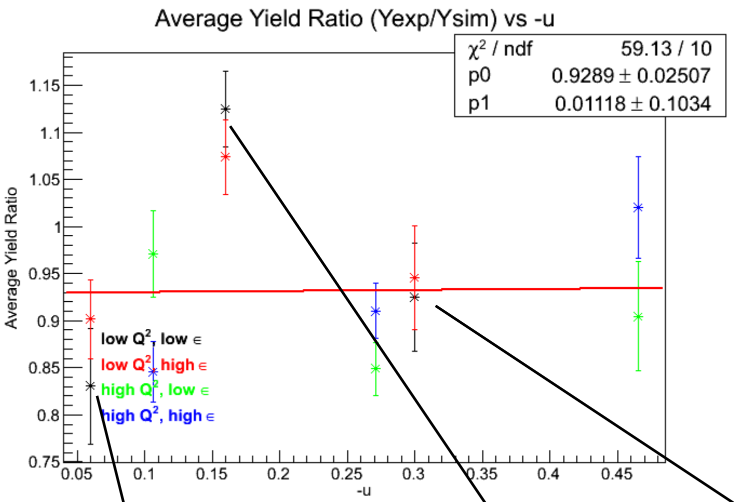
Background Sum

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**

Yield Ratio and Simulated Cross-Section



$$\sigma_T = \frac{t_0 + t_1 \cdot (-u)}{Q},$$

$$\sigma_L = \frac{l_0 + l_1 \cdot (-u)}{Q^4},$$

$$\sigma_{LT} = \left[\frac{lt_0 + lt_1 \cdot (-u)}{Q^2}\right] \cdot \sin\theta^*,$$

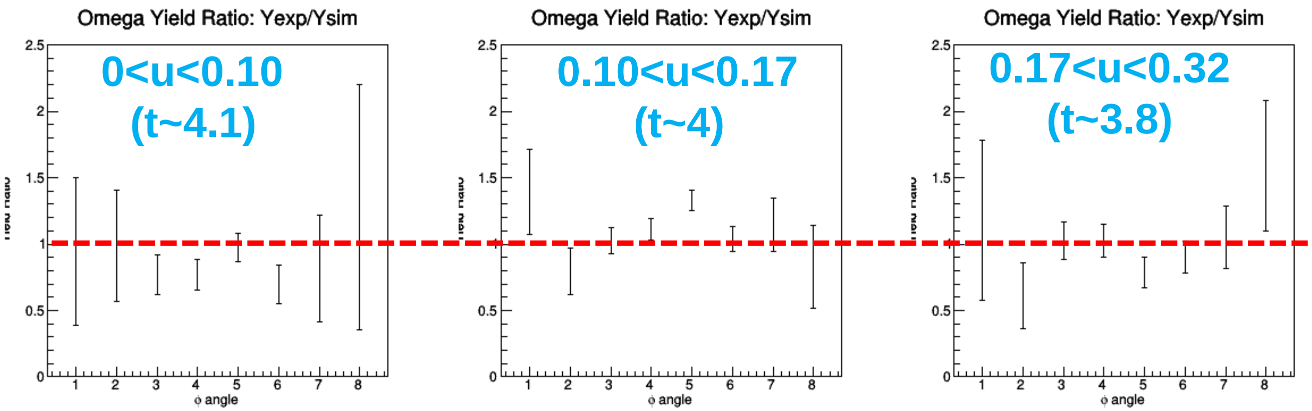
$$\sigma_{TT} = \left[\frac{tt_0 + tt_1 \cdot (-u)}{Q^2}\right] \cdot \sin^2\theta^*,$$

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

Model Cross Section

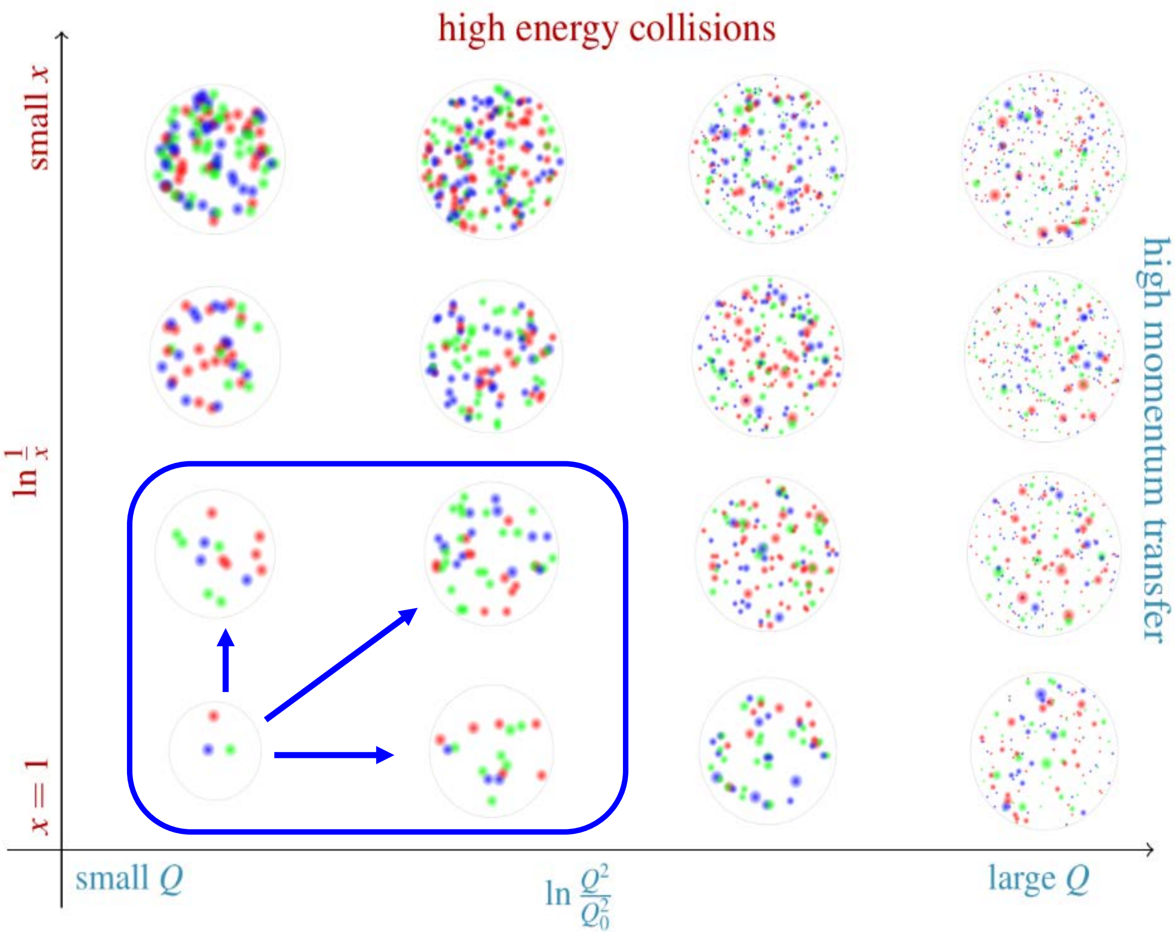
$$\left.\frac{d^2\sigma}{dt\,d\varphi}\right._{EXP} = R \left.\frac{d^2\sigma}{dt\,d\varphi}\right._{SIMC}$$

Exp/Sim Yield Ratio



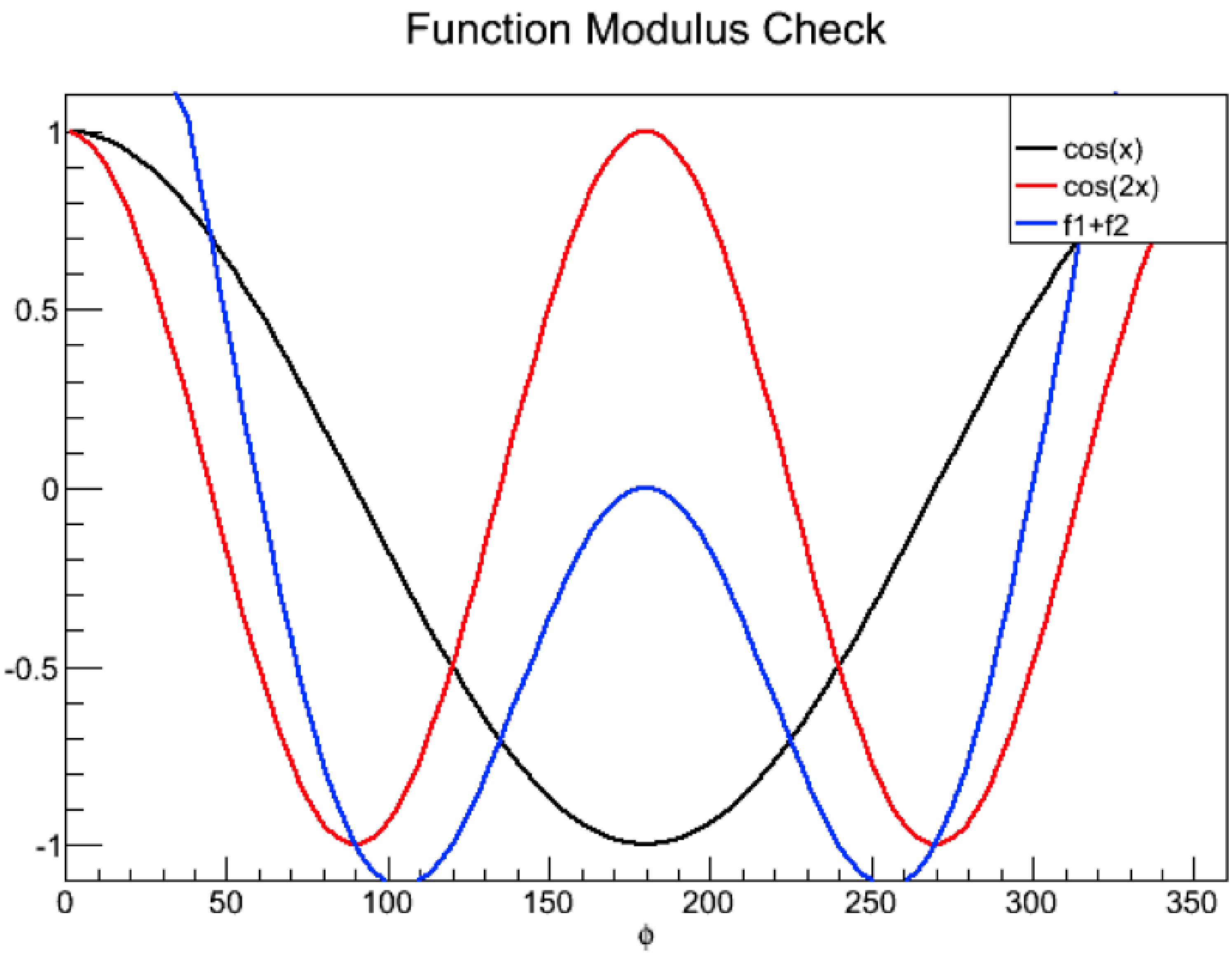
Q^2=1.6, Low *ε=0.33*

Proton Structure: Known and Unknown

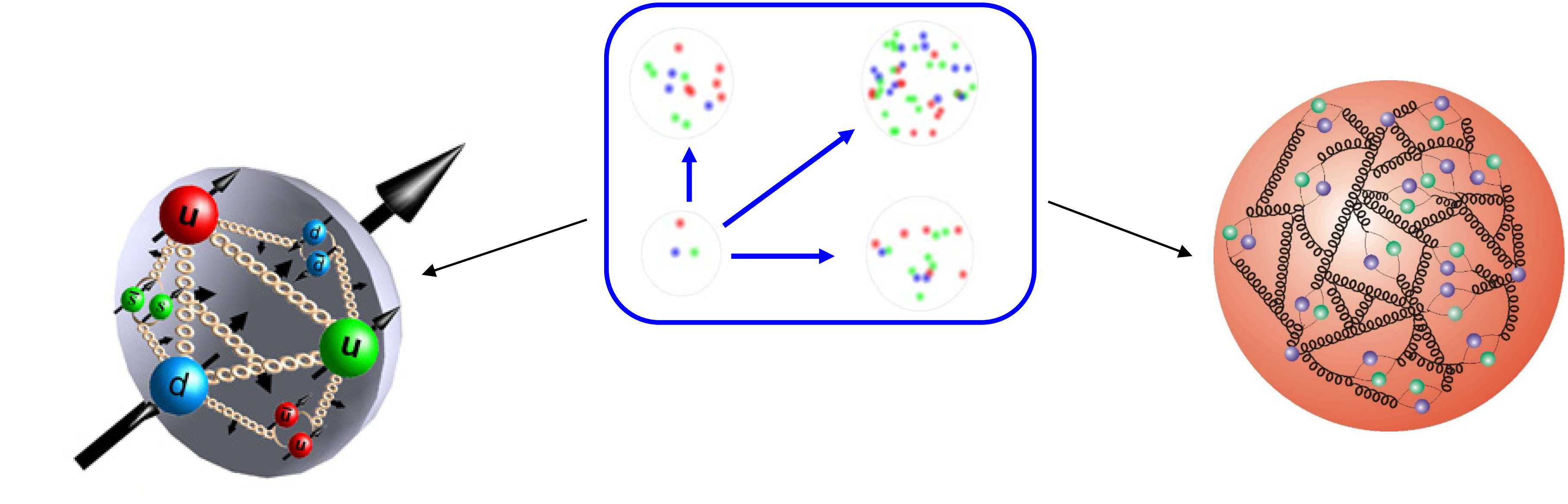


- Proton
  - Dynamic Structure
    - Parton Distribution
    - Interaction
- Static proton structural map is known
- Unknown
  - **Transition (evolution)** of the proton structure
  - General description of the proton structure
- **Goal: Study the transition of the proton structure**

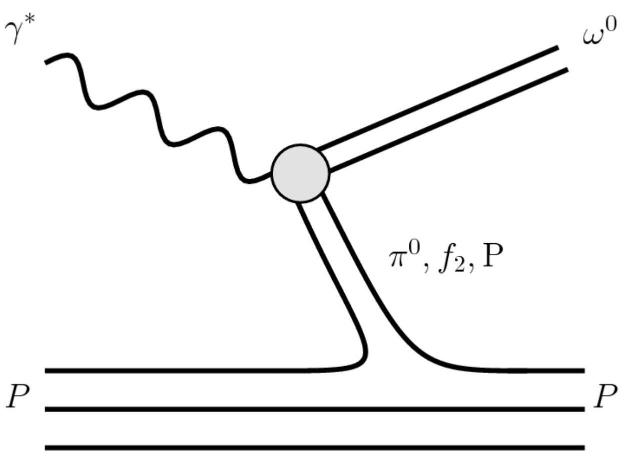
Modulus Check for SigLT and SigTT



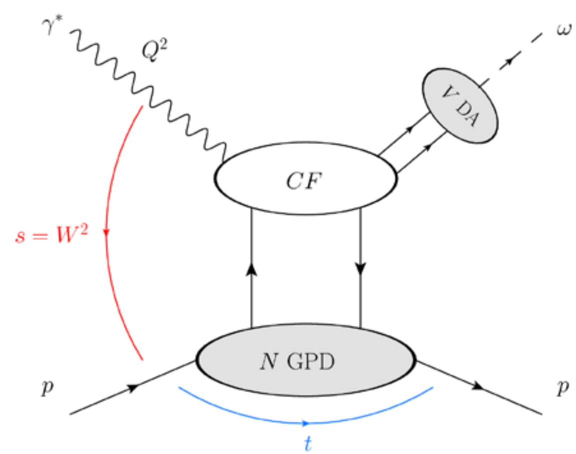
Proton Structure Description



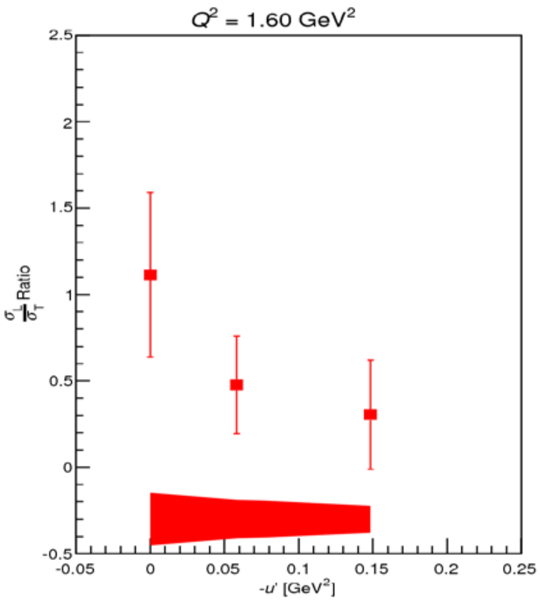
- Hadronic Model

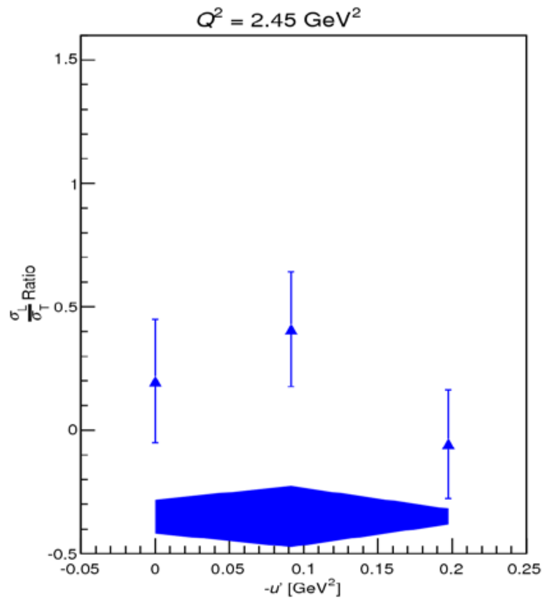


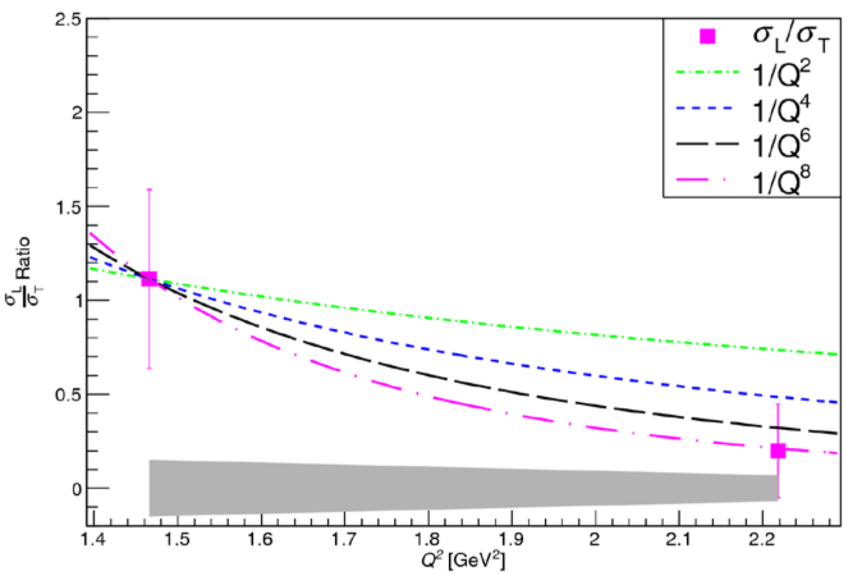
- Partonic Model



Scaling of σ_L, σ_T and σ_L / σ_T Ratio

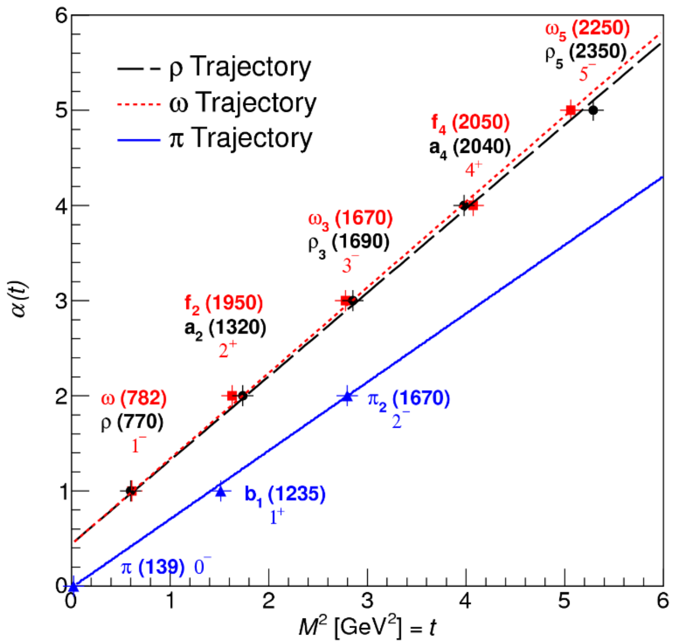




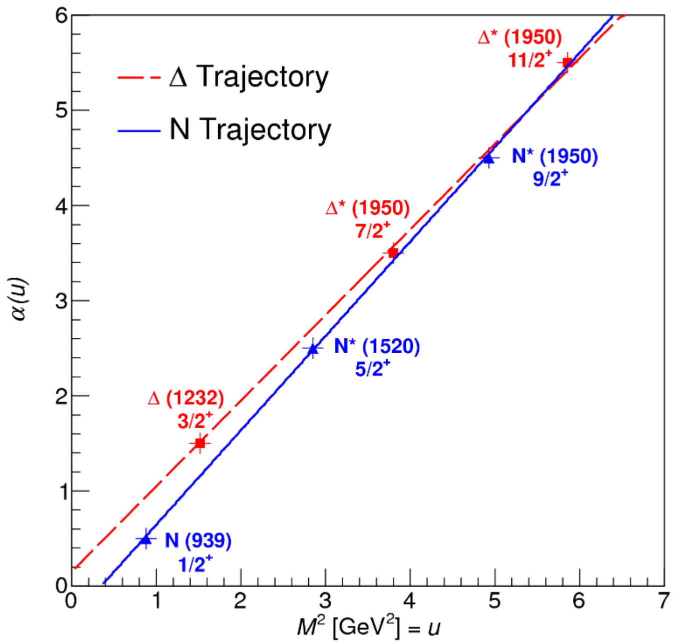


- Dominance of σ_T observed at higher Q2 =2.45, confirms the TDA prediction
- σ_L drops expected ~$1/Q^8$
- σ_T is almost constant

Trajectory

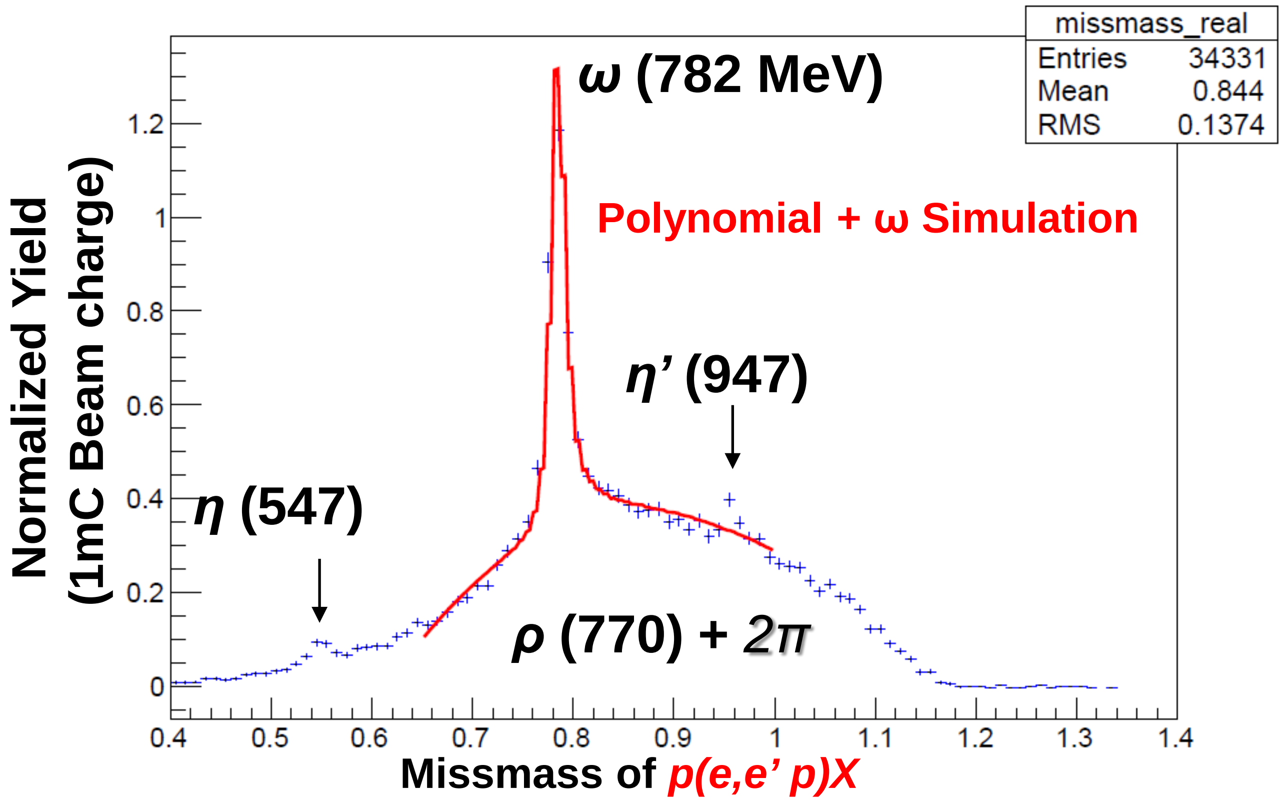


ρ Trajectory
ω Trajectory
π Trajectory
ω5 (2250)
ρ5 (2350)
5⁻
f4 (2050)
a4 (2040)
4⁺
ω3 (1670)
ρ3 (1690)
3⁻
f2 (1950)
a2 (1320)
2⁺
ω (782)
ρ (770)
1⁻
π2 (1670)
2⁻
b1 (1235)
1⁺
π (139) 0⁻
α(t)
M² [GeV²] = t



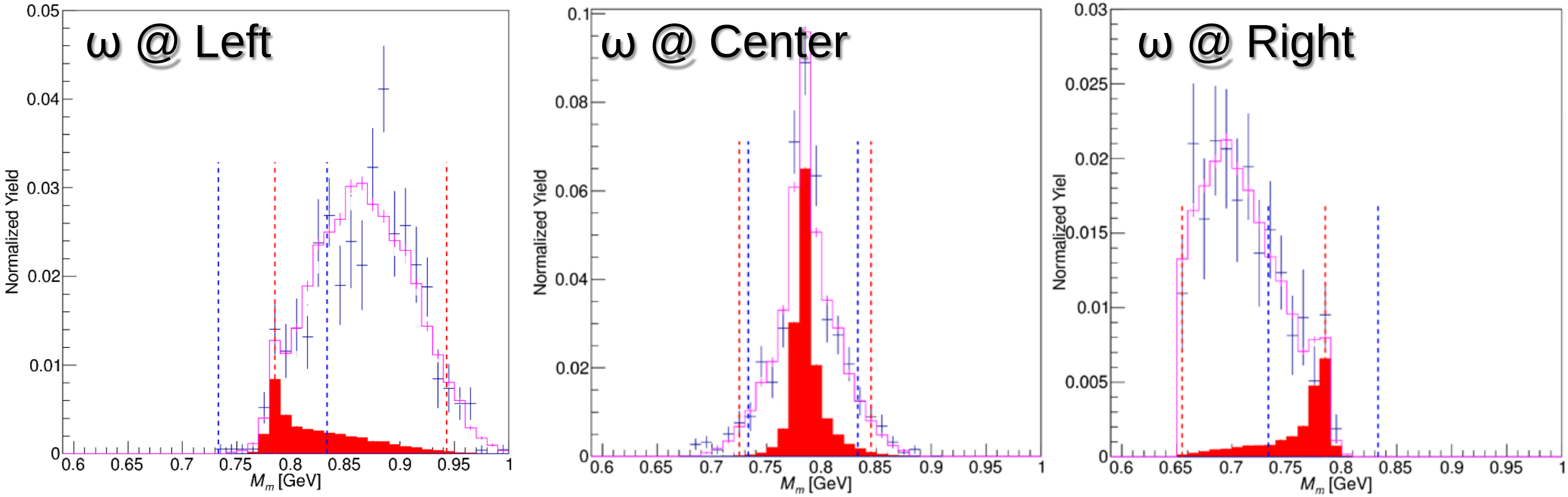
Δ Trajectory
N Trajectory
Δ* (1950)
11/2⁺
N* (1950)
9/2⁺
Δ* (1950)
7/2⁺
N* (1520)
5/2⁺
Δ (1232)
3/2⁺
N (939)
1/2⁺
α(u)
M² [GeV²] = u

Proof: These are not Elastic Events!



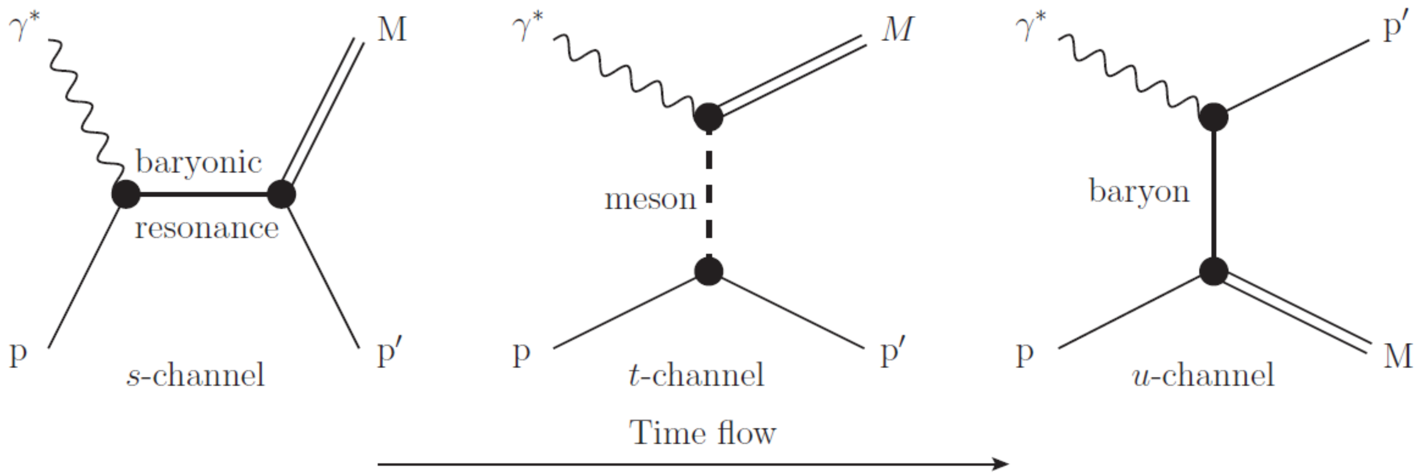
- **Good News!**
  - We see **other Scalar and Vector Mesons:** ***ρ, η, η' , two-π phasespace***
- **Bad News!**
  - Channel is **not clean**!
- **Worse News!**
  - **We can't use Polynomial fit !!**

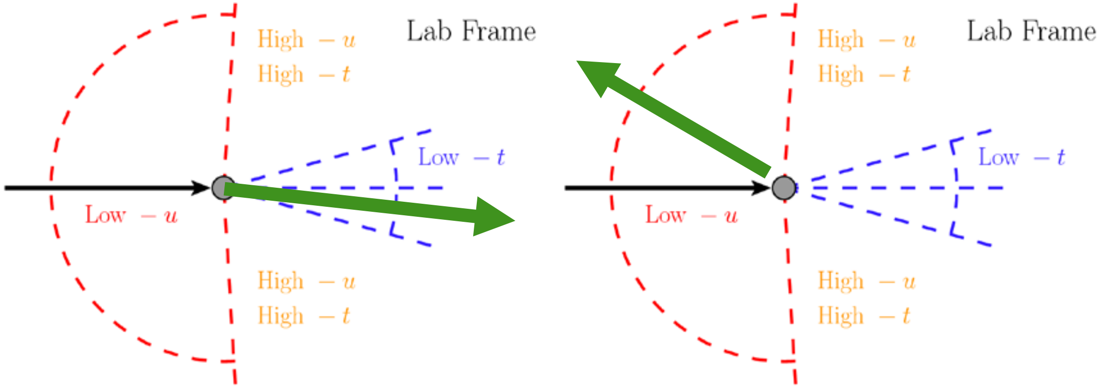
Missing Mass Distribution



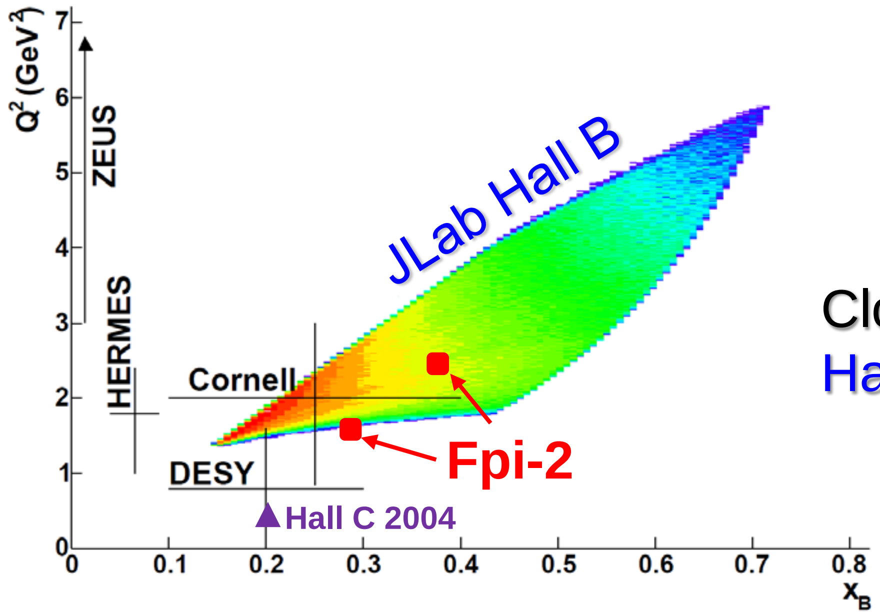
- **Most Challenging Issue: Background Subtraction!**
- **Omega is not always in the center**
- **Four sets of Monte-Carlo is used fit the data**
  - ***ω*** **+** ***ρ*** **+ Phase-space +** ***η or η'***

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





Exclusive ω Electro-Production Data



Closest data set to ours is the Hall B Morand data

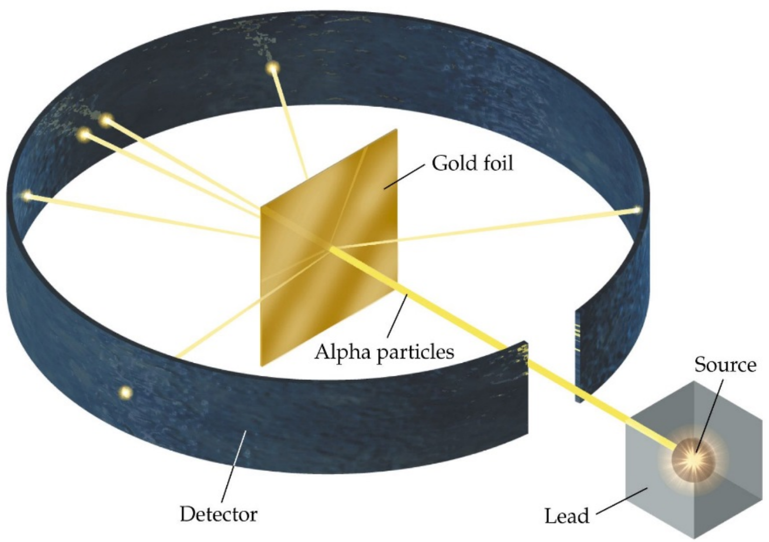
	Q^2 GeV^2	W GeV	x	$-t$ GeV^2
HERMES (Airapetian et al., 2014)	> 1	3-6.3	0.06-0.14	< 0.2
DESY (Joos et al., 1977)	0.3-1.4	1.7-2.8	0.1-0.3	< 0.5
Zeus (Breitweg et al., 2000)	3-20	40-120	~0.01	< 0.6
Cornell (Cassel et al., 1981)	0.7-3	2.2-3.7	0.1-0.4	<1
JLab Hall C (Ambrozewicz et al., 2004)	~0.5	~1.75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

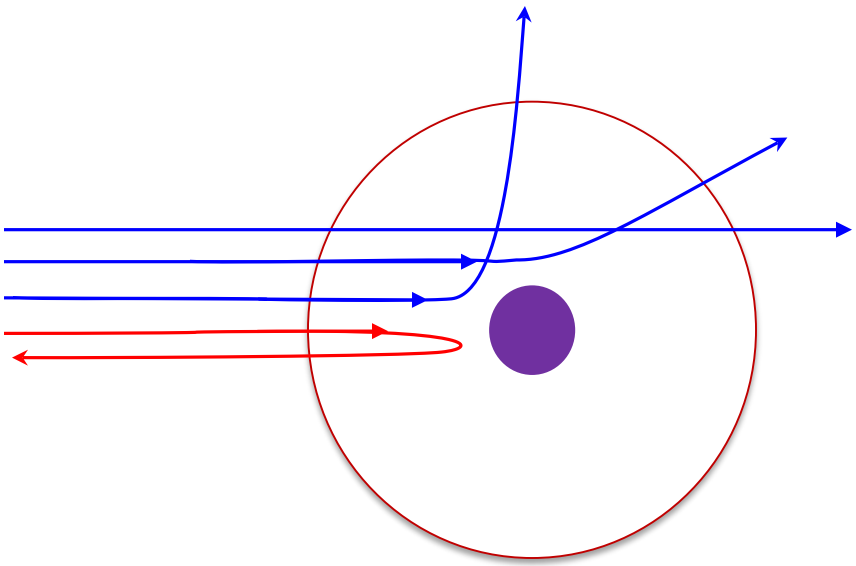
$\sigma_{\rm T}$ and $\sigma_{\rm L}$ Uncertainty Propagation

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

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

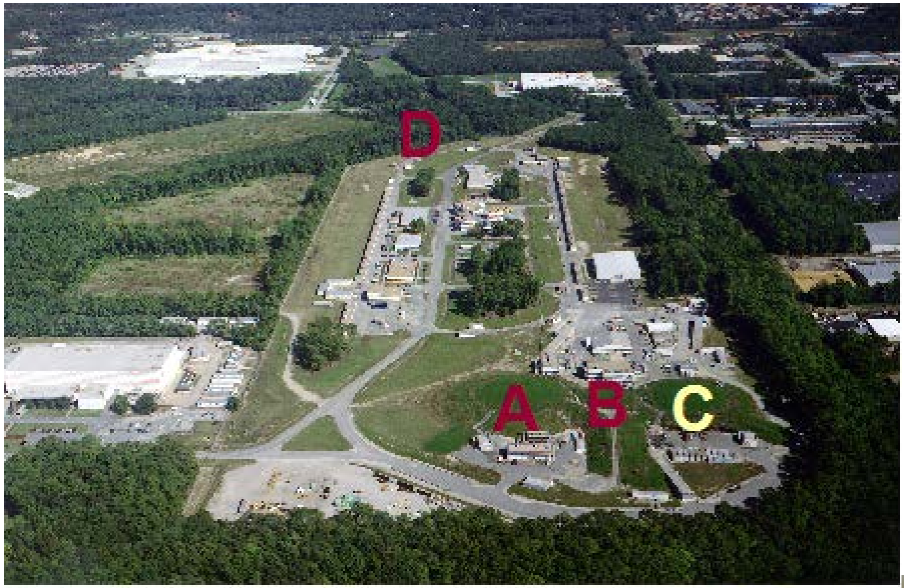
Rutherford Experiment Atomic Structure





- **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?

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**