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

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UNIVERSITY OF REGINA

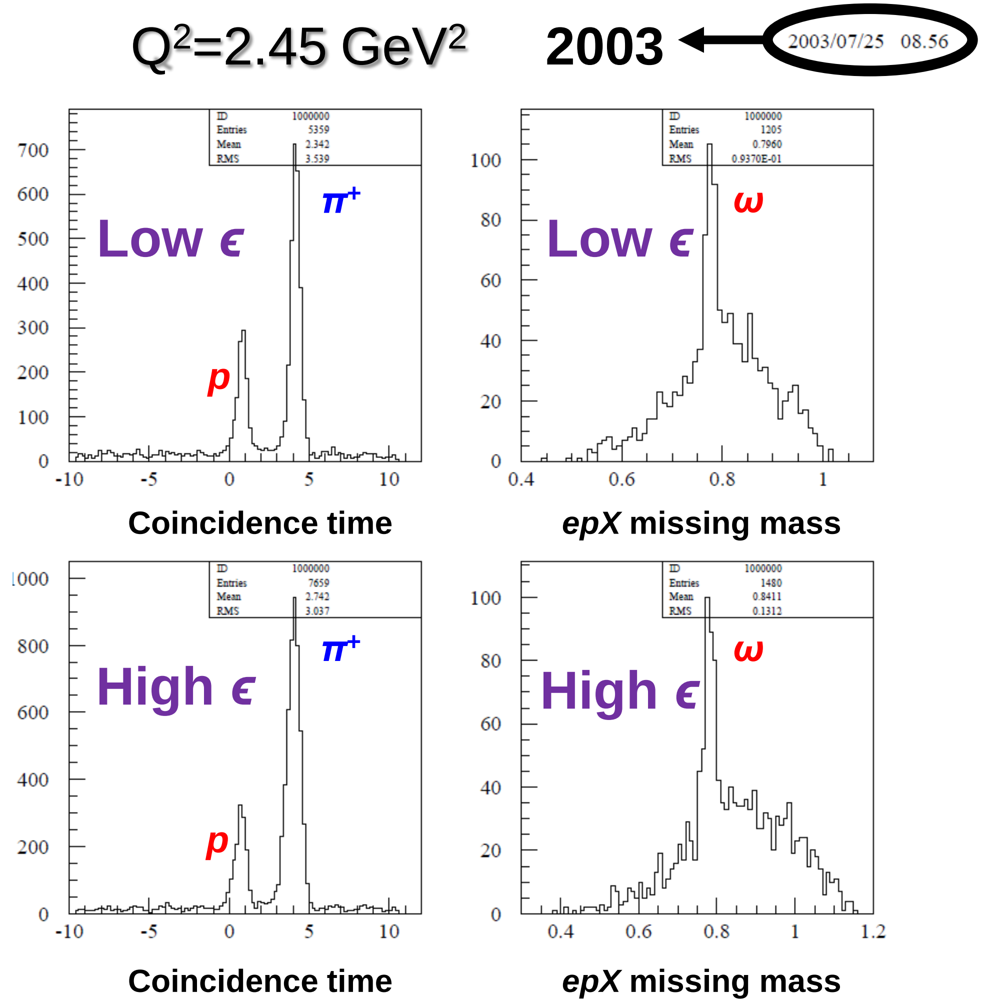
Hall C Workshop. January, 2015.

Outline

- Where the data come from
- Theoretical justification
- Plan for data analysis

Fpi-2 E01-004 Experiment

- Fpi-2 (E01-004) 2003
  - Spokesperson: **Garth Huber, Henk Blok, Dave Mack**
  - 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 GeV²**
  - Two ϵ settings for each Q²



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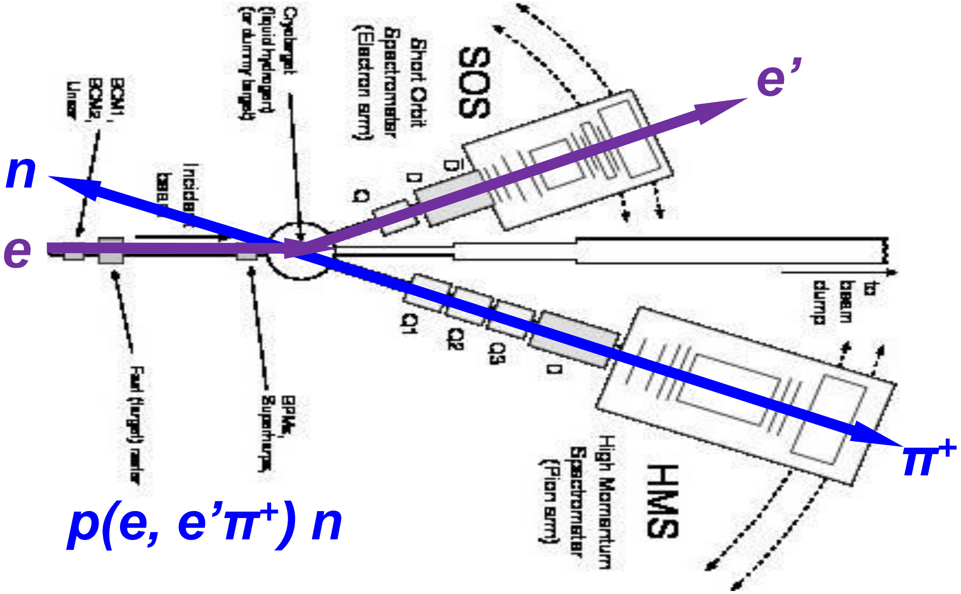
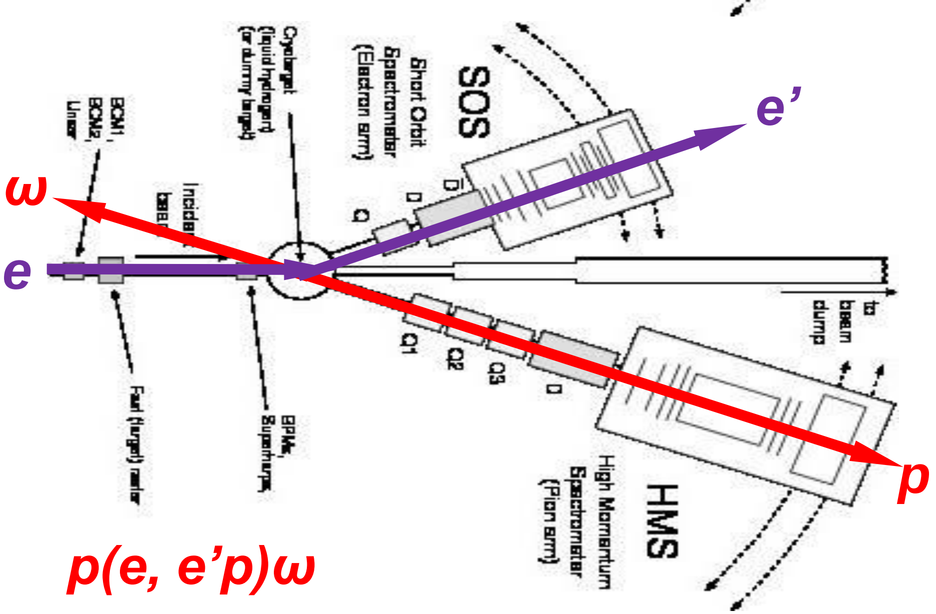
t-Channel π vs *u*-Channel ω^0 Production





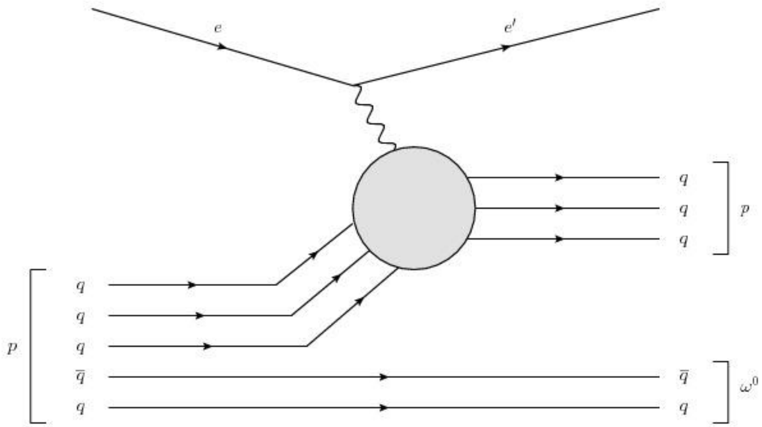
- HMS along the *q*-vector (p_{γ^*})
  - $p_{\pi+}$ is parallel to p_{γ^*}
  - p_{ω} is anti-parallel to p_{γ^*}

- Shared kinematics:

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

u-Channel ω^0 Production

Christian Weiss: “A proton being knocked out of a proton”



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

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

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

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

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

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

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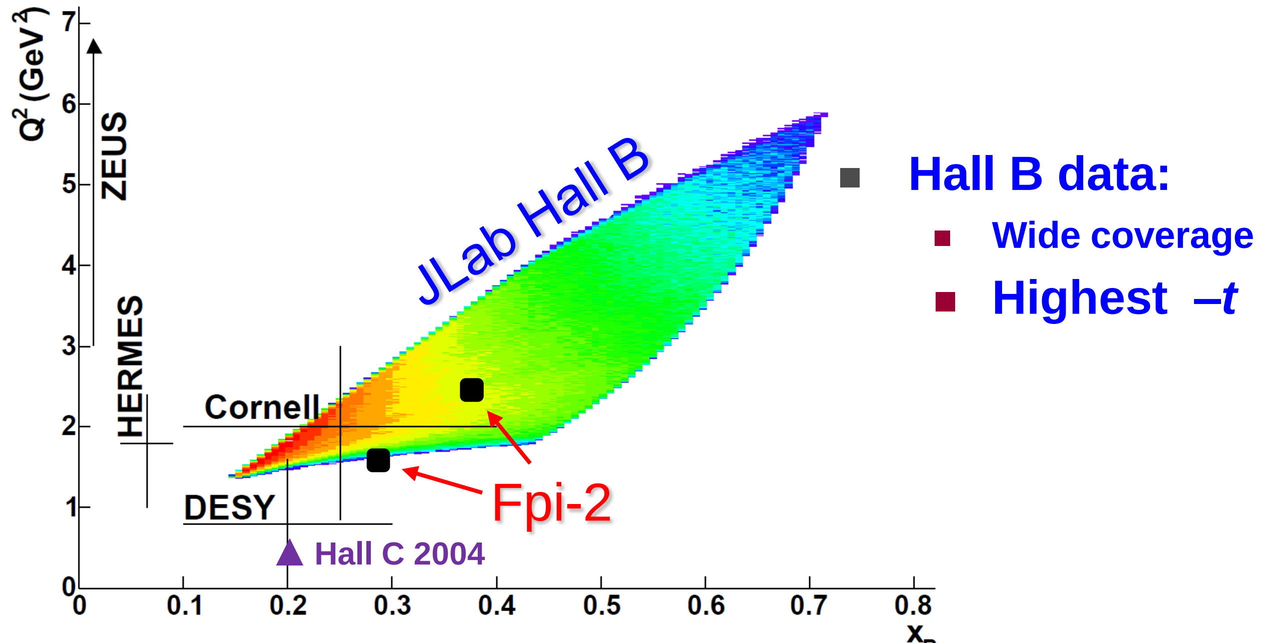
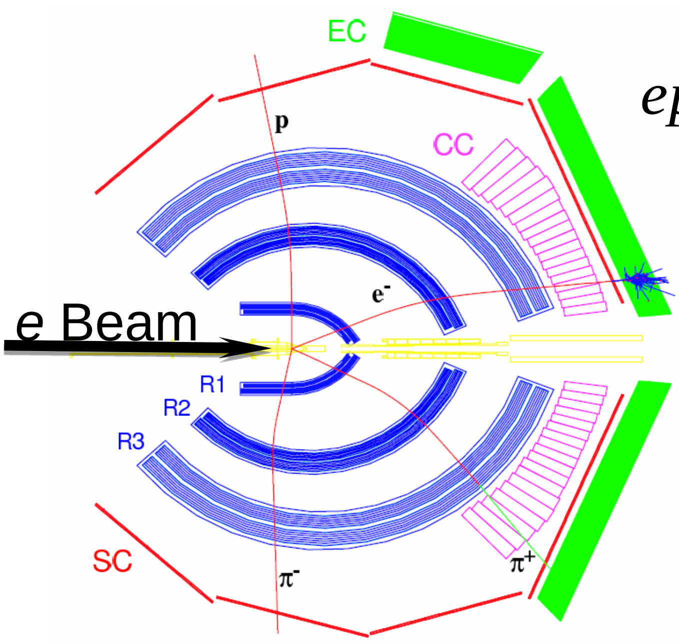
Exclusive ω electro-production data



	Q^2 GeV²	W GeV	x	$-t$ GeV²
HERMES (Airapetian et al., 2014)	> 1	3-6.3	0.06-0.14	< 0.2
DESY (Joos et al., 1977)	0.3-1.4	1.7-2.8	0.1-0.3	< 0.5
Zeus (Breitweg et al., 2000)	3-20	40-120	~0.01	< 0.6
Cornell (Cassel et al., 1981)	0.7-3	2.2-3.7	0.1-0.4	<1
JLab Hall C (Ambrozewicz et al., 2004)	~0.5	~1.75	0.2	0.7-1.2
JLab Hall B (Morand et al., 2005)	1.6-5.1	1.8-2.8	0.16-0.64	<2.7
JLab Fpi-2 (2017?)	1.6, 2.45	2.21	0.29, 0.38	4.0, 4.74

High t Data from CLAS Hall B (2005)

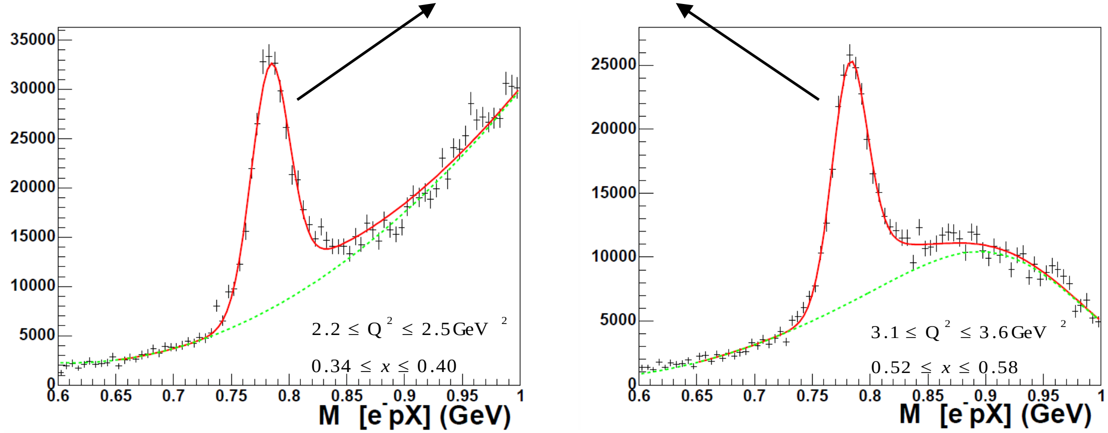
Morand et al., Eur. Phys. J. A 24, 445 (2005).



$$ep \rightarrow ep\,\omega$$

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

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



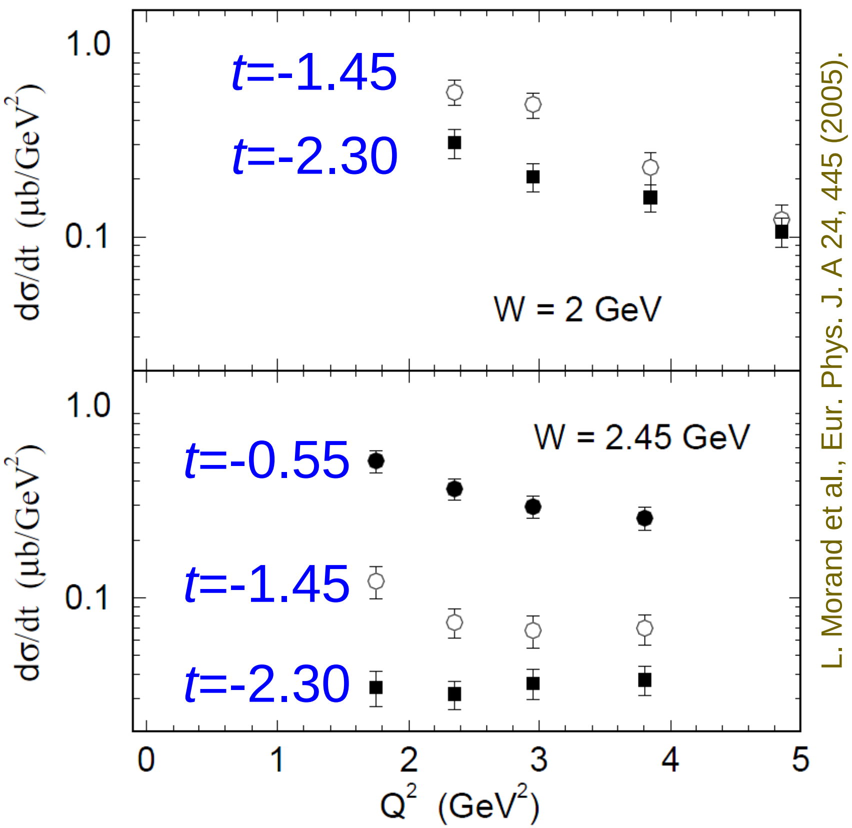
Missing mass reconstruction e^-pX

- 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).

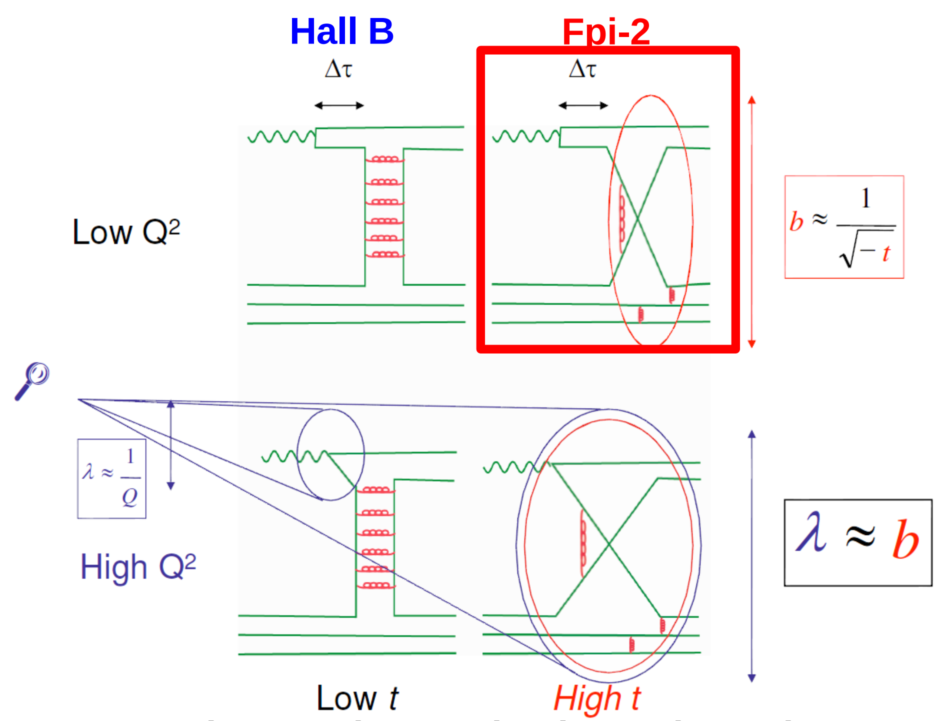
High -*t* Data from CLAS Hall B (2005)



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

Hall B & Fpi-2 kinematics comparison

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

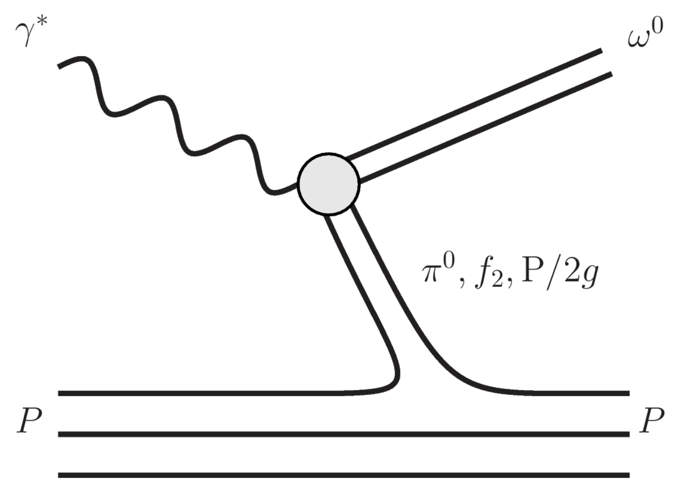


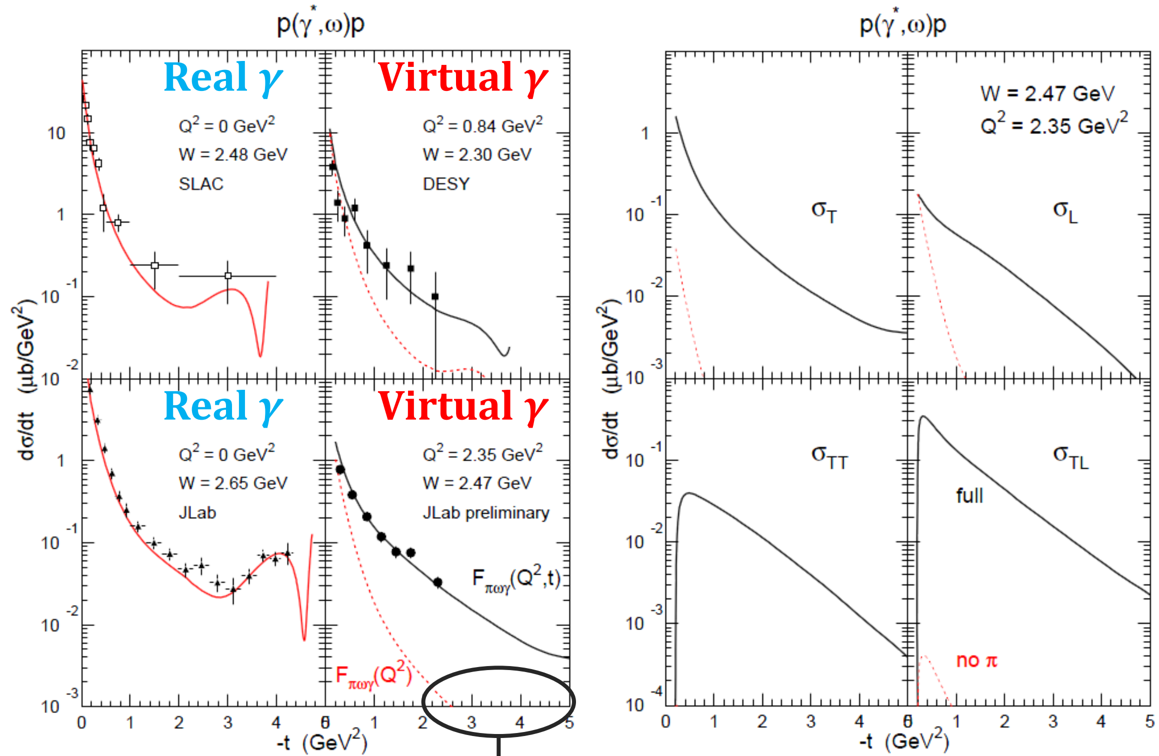
Hard Scattering Mechanism schematics

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

Regge Trajectory Model by JM Laget

Produced vector meson	Exchanged Regge trajectories
ρ	$\sigma,\ f_2,\ P/2g$
ω	$\pi^0,\ f_2,\ P/2g$
ϕ	$P/2g$





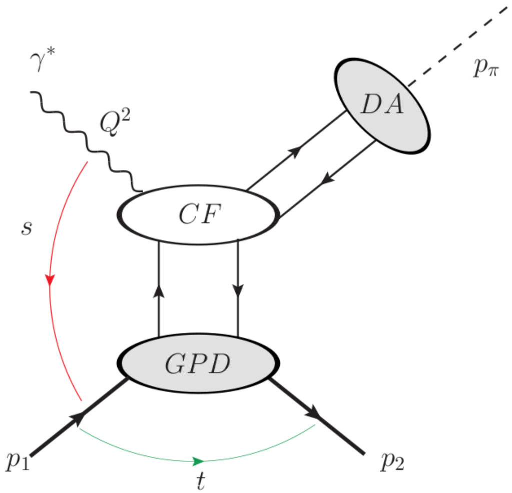
No data yet,

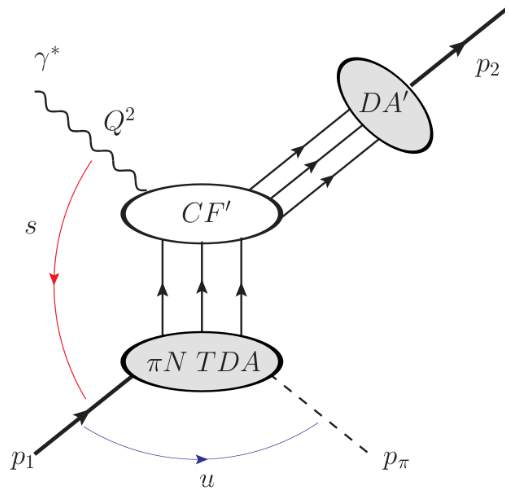
Fpi2 kinematics Q^2=2.54, *W=2.21, -t=4.7*

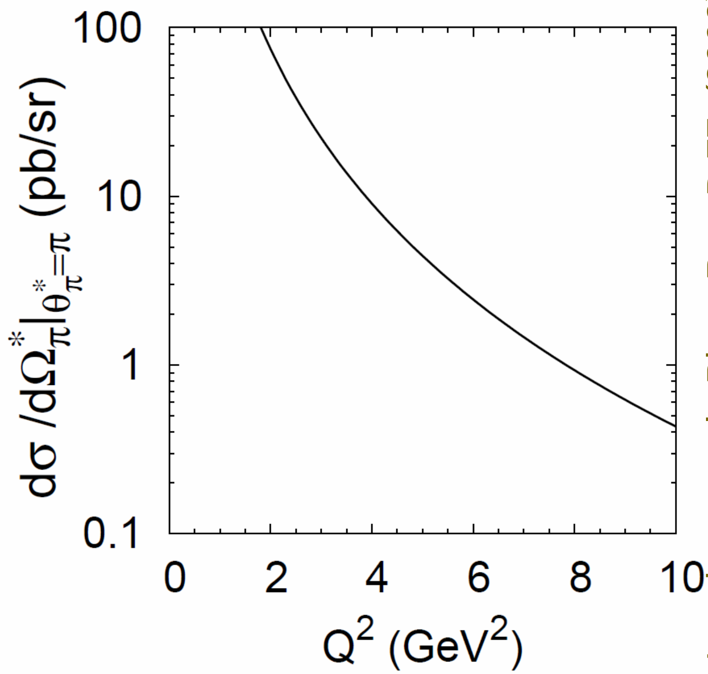
J. M. Laget, Phys. Rev. D 70, 2004

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

Further motivation: Transition Distribution Amplitude (TDA)



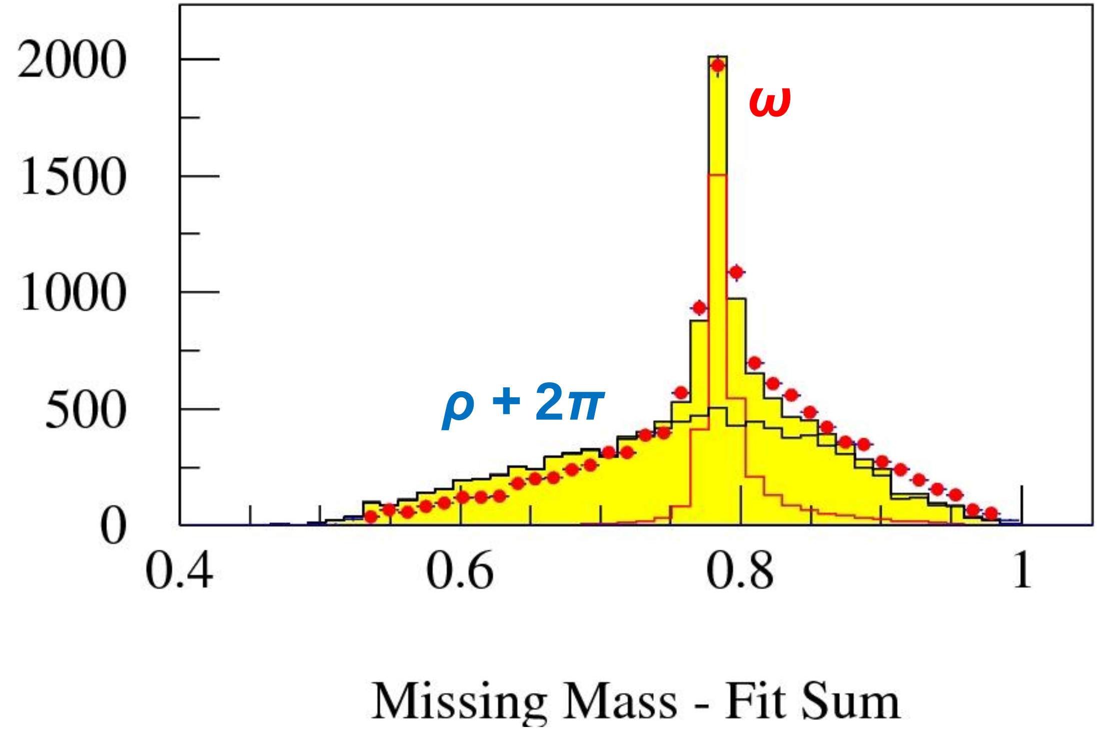




Lansberg, et al., Phys. Rev. D **77**, (2008)

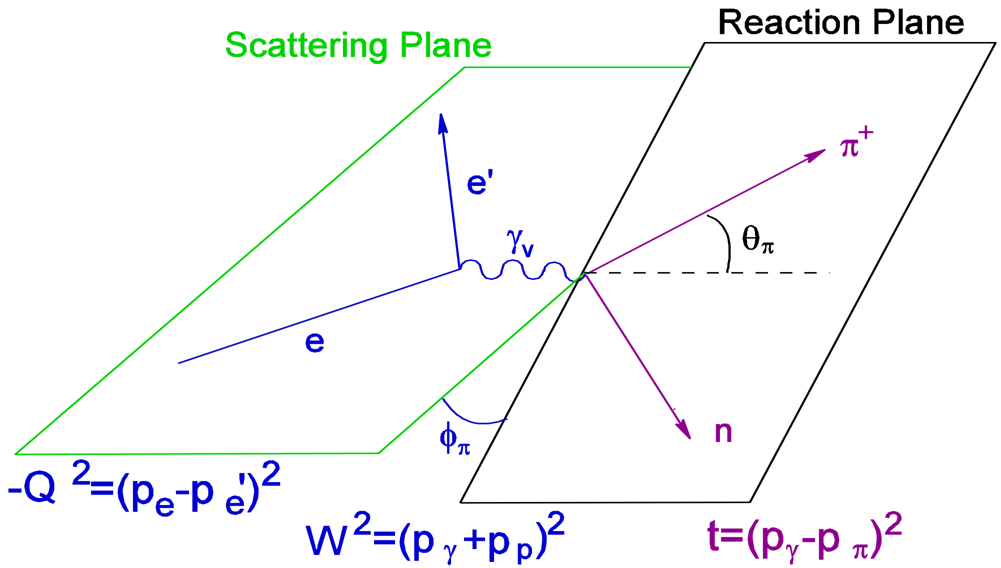
- TDA backward angle analog of GPD
- Interaction of Interest: ***u*-channel *π* production**
- Extension of the TDA model to describe the backwards vector meson production
- Publication:
  - Lansberg, et al., Phys. Rev. D **77**, (2008)
  - Pasquini, B. *et al.* Phys.Rev. D80 (2009)
  - Lansberg, J.P. *et al.* arXiv:0709.2567 [hep-ph] CPHT-PC141.0907

Data Analysis Plan



- Data analysis is similar to that used for the Fpi-2
- Physics Background Removal
  - ***ρ***
  - **Phase space of 2*π* production**
  - **Method: BG simulation or fitting a polynomial?**

Rosenbluth Separation Method



Virtual-photon polarization:

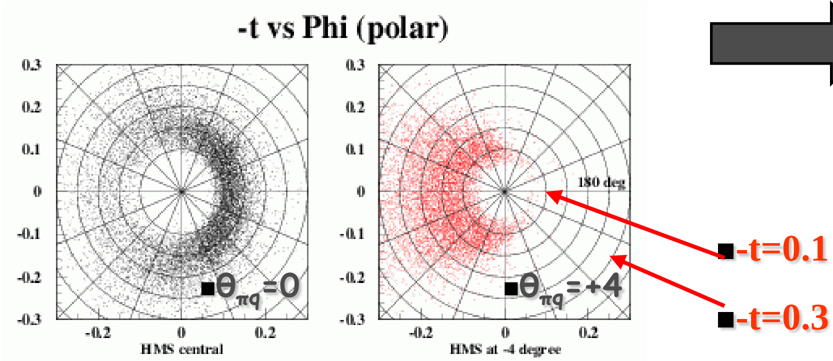
$$\varepsilon = \left(1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$

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

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

Extract Response Functions through Iterative Procedure

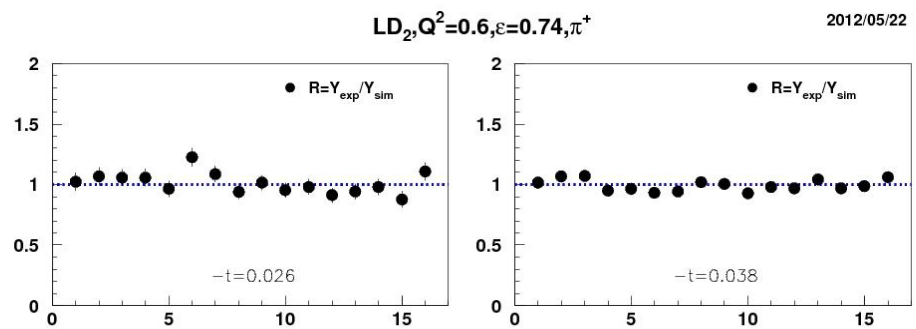
Improve φ coverage by taking data at multiple π (HMS) angles, $-4^o<\theta_{\pi q}<4^o$.

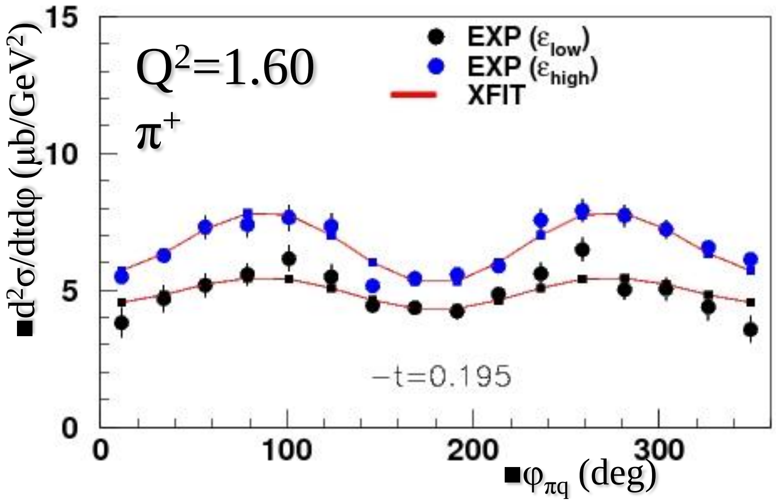


For each π HMS setting, form ratio:

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

Combine ratios for π settings together, propagating errors accordingly.





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

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

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

Project Objective and Future Prospective

- Objective
  - Obtain the complete L/T separated cross section for the u-channel ω meson production
  - To initiate more *u*-channel production studies

- Prospective (Fpi-12 experiment: E06-12-101)
  - Extended *u*-channel ω production
  - *u*-channel ϕ ($s\bar{s}$) production is possible! Garth Huber has more to say on this during the Exclusive Meson Workshop

Backup

Fpi-2 E01-004 Experiment

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

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

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

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

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

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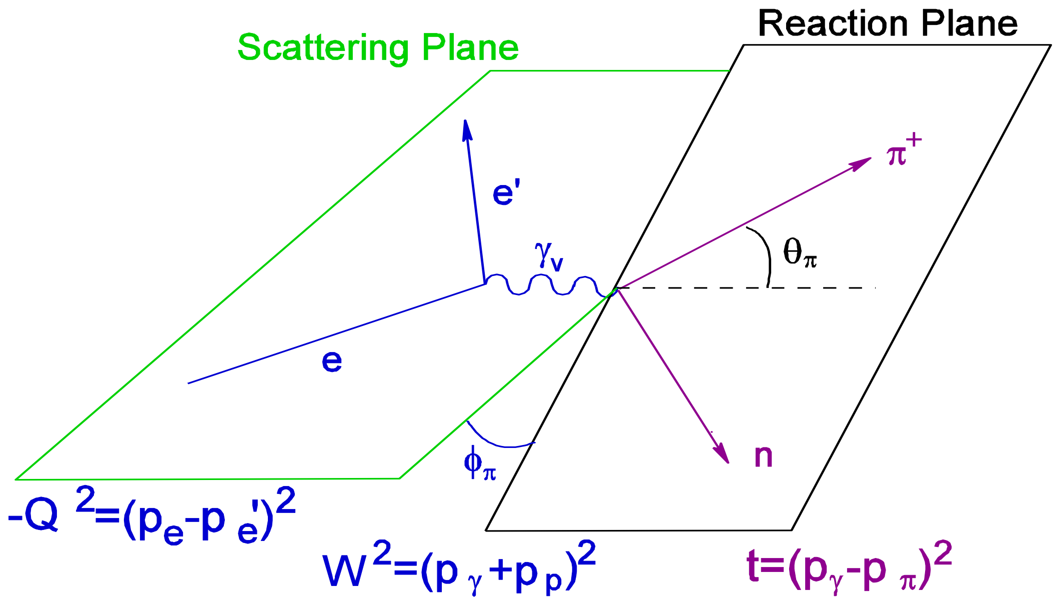
						-3.0		0.491	20.79		0.241
						3.0		0.490	20.75		0.240

π^+coverage ***ω coverage***

ω (782): $J^P = 1^-$, $I^G = 0^-$, M_ω =782 MeV.

$$\omega : \frac{u\bar{u} + d\bar{d}}{\sqrt{2}}$$

L/T 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

- Experimental differential cross section depend on the Longitudinal and Transverse part of the virtual photon:

$$2\pi \frac{d^2\sigma}{dt\, d\phi_p} = \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt}$$

ϵ: virtual photon polarization

$$\epsilon = \left(1 + \frac{2|\mathbf{q}|^2}{Q^2} \tan^2 \frac{\theta_e}{2}\right)^{-1}$$

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

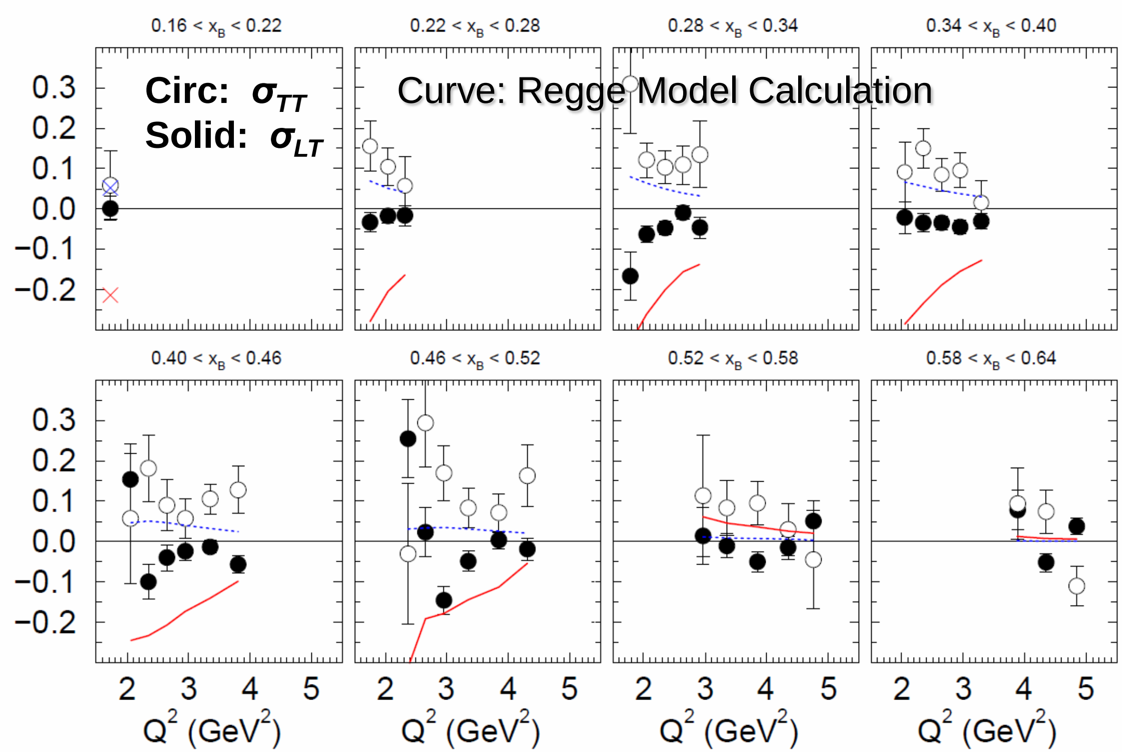
Slide on combine HMS setting to get the azimuthal

- Slide on combine HMS settings to get the azimuthally coverage

- MC/experiment ratio

- Exacted separated dsigma/dt

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

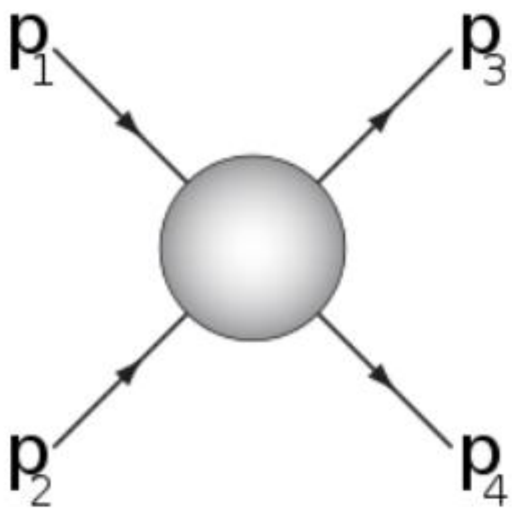


- Specialty: Highest -*t* (low *u*) ω meson production data
- Excitement:
  - **Observation:** Q^2 independent cross section at high -*t*
  - **Possible interoperation:** Virtual photon is more likely to couple to a point-like object as −*t* increases.

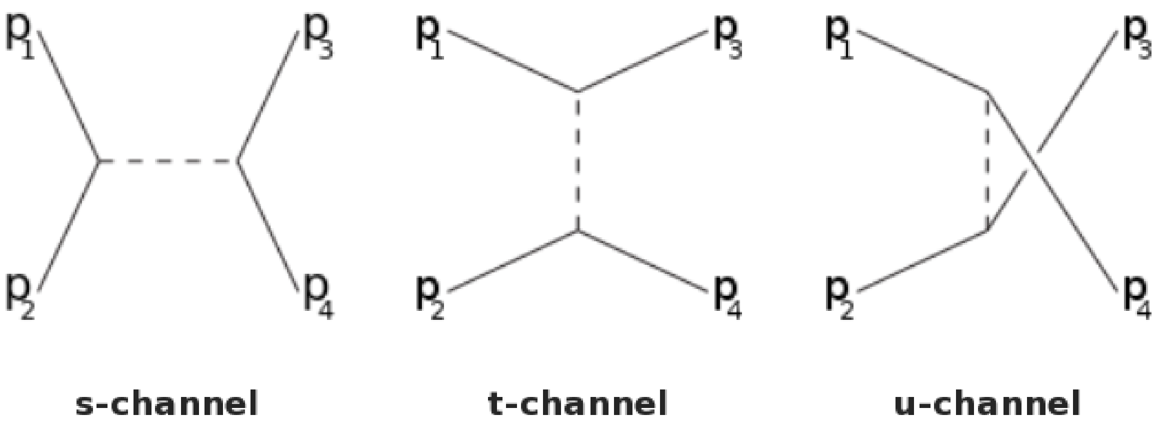
Integrated over -2.7 GeV^2 < t < t_0 where t_0 ranges -0.09 to -1.61 GeV, as *x* ranges between 0.203 to 0.61

Mandelstam variables (s,t,u-Channels)

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



$$\gamma^*(q) + N(p_1) \longrightarrow \pi(p_\pi) + N(p_2)$$



$$s = (p_1 + q)^2; \quad u = (p_\pi - p_1)^2; \quad t = (p_2 - p_1)^2.$$

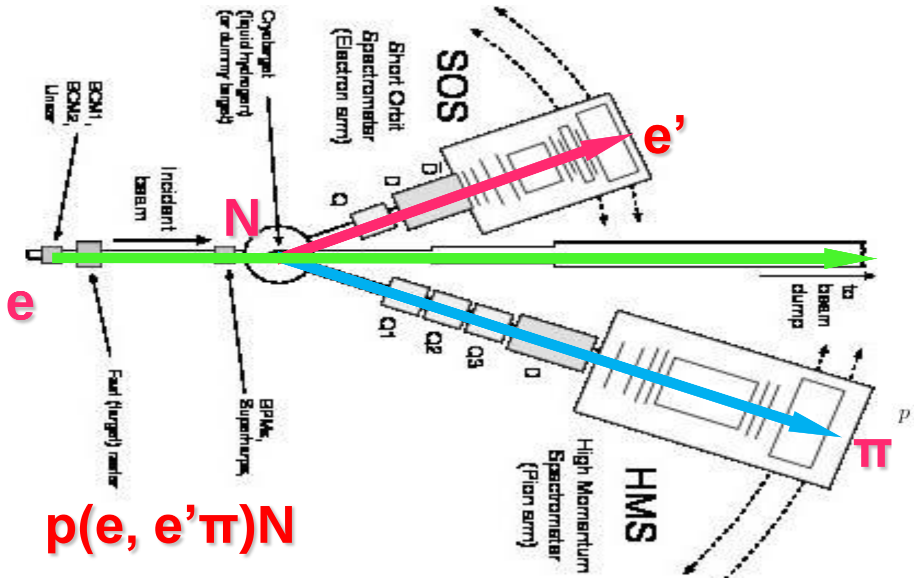
Pseudoscalar meson ($J^P = 0^-$)

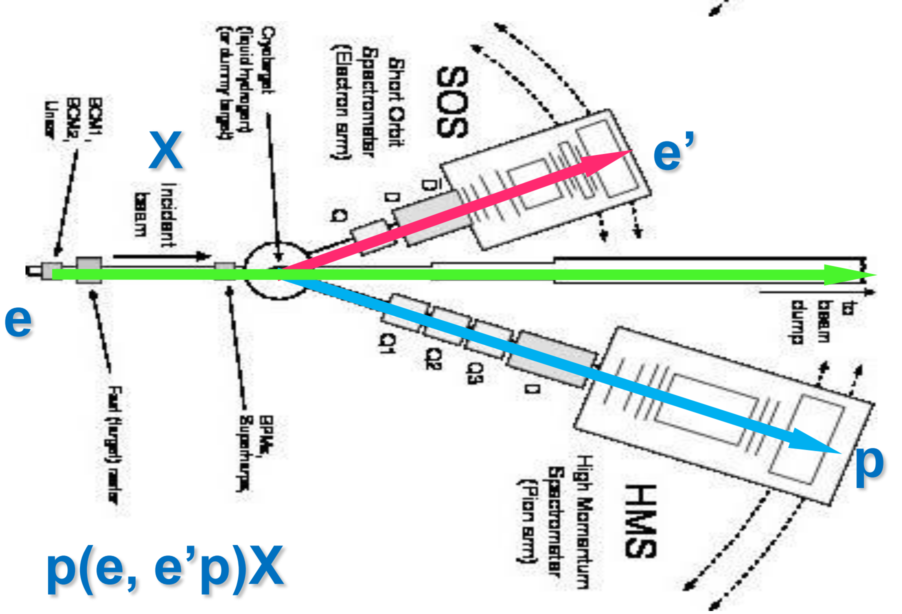
Particle name	Particle symbol	Antiparticle symbol	Quark content	Rest mass (MeV/c^2)	I^G	J^{PC}	S	C	B'	Mean lifetime (s)	Commonly decays to (>5% of decays)
Pion[6]	π^+	π^-	$u\bar{d}$	139.570 18 ± 0.000 35	1^-	0^-	0	0	0	$(2.6033 \pm 0.0005) \times 10^{-8}$	$\mu^+ + \nu_\mu$
Pion[7]	π^0	Self	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$[a]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

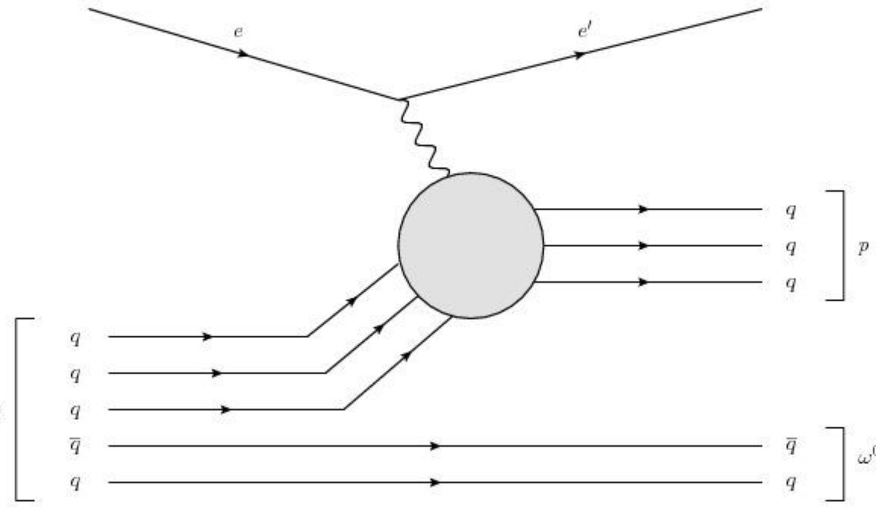
Vector meson ($J^P = 1^-$)

Particle name	Particle symbol	Antiparticle symbol	Quark content	Rest mass (MeV/c²)	I^G	J^{PC}	S	C	B'	Mean lifetime (s)	Commonly decays to (>5% of decays)
Charged rho meson[23]	$\rho^+(770)$	$\rho^-(770)$	$u\bar{d}$	775.11 ±0.34	1^+	1^-	0	0	0	$(4.41 \pm 0.02) \times 10^{-24}$[f][g]	$\pi^\pm + \pi^0$
Neutral rho meson[23]	$\rho^0(770)$	Self	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$	775.26 ±0.25	1^+	1^{--}	0	0	0	$(4.45 \pm 0.03) \times 10^{-24}$[f][g]	$\pi^+ + \pi^-$
Omega meson[24]	$\omega(782)$	Self	$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	782.65 ±0.12	0^-	1^{--}	0	0	0	$(7.75 \pm 0.07) \times 10^{-23}$[f]	$\pi^+ + \pi^0 + \pi^-$ or $\pi^0 + \gamma$
Phi meson[25]	$\phi(1020)$	Self	$s\bar{s}$	1 019.461 ±0.019	0^-	1^{--}	0	0	0	$(1.54 \pm 0.01) \times 10^{-22}$[f]	$K^+ + K^-$ or $K^0_S + K^0_L$ or $(\rho + \pi) / (\pi^+ + \pi^0 + \pi^-)$
J/Psi[26]	J/ψ	Self	$c\bar{c}$	3 096.916 ±0.011	0^-	1^{--}	0	0	0	$(7.09 \pm 0.21) \times 10^{-21}$[f]	See J/ψ(1S) decay modes

u-Channel ω^0 Production (May 2014 - Present)







- Discovered during E01-004 experiment
- Missing mass peak is consistent with the mass of the omega meson (783 MeV).
- Not studied by any other experiment or theory

Equations

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

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

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

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

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

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

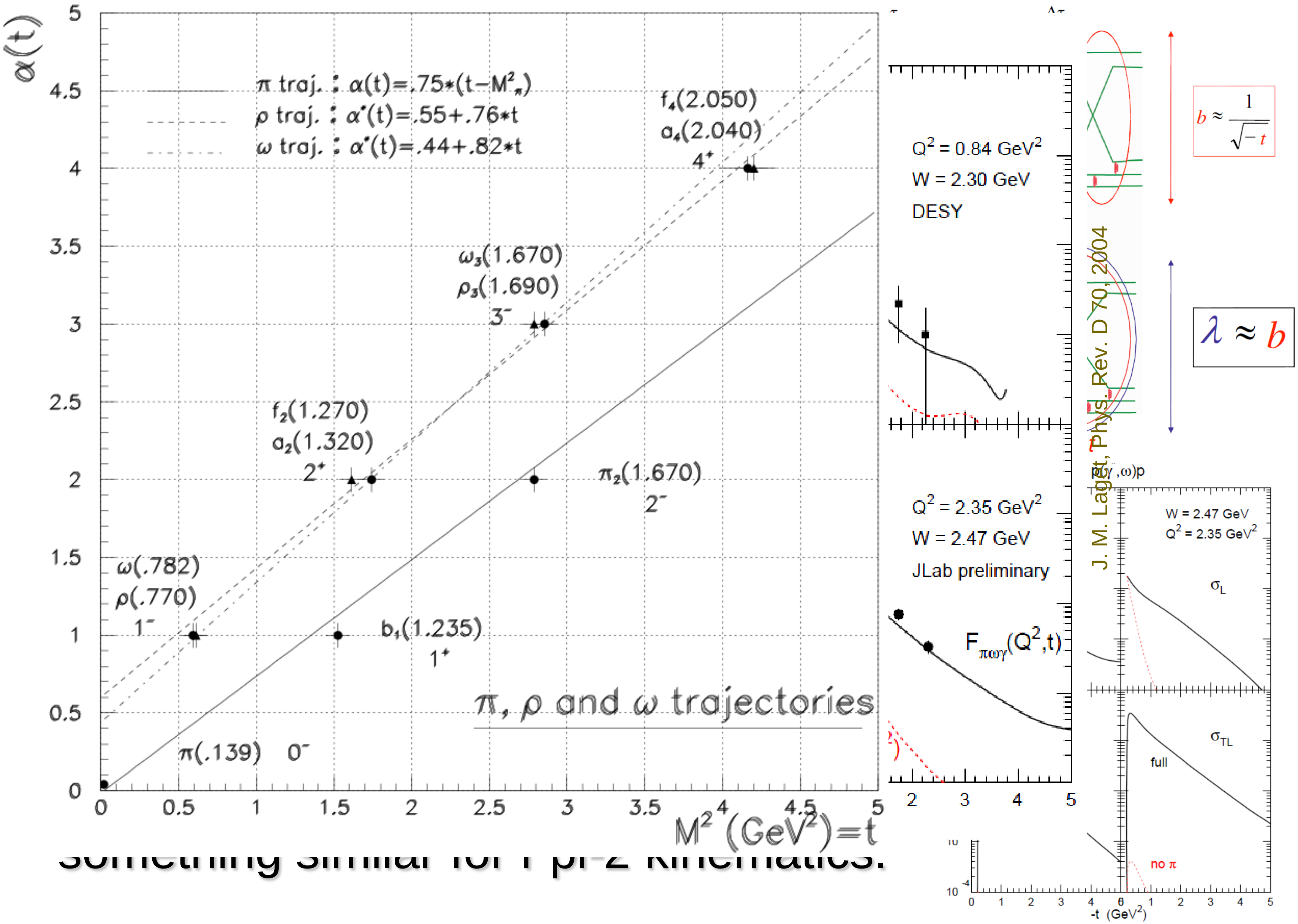
$$= W^2 + Q^2 - p^2$$

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

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

Regge Trajectory Based Model by JML

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



something similar for t pi-2 kinematics.

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

Hall B public page

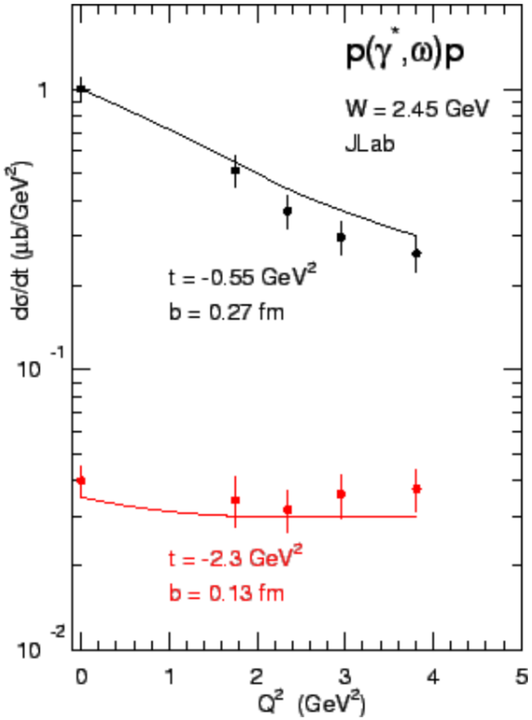


Figure 2: When the impact parameter is large (top), the cross section for ω meson production falls quickly as a function of Q^2. But when the experiment selects the kinematics corresponding to small impact parameter (bottom), the cross section becomes constant with Q^2 indicating that the interaction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

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

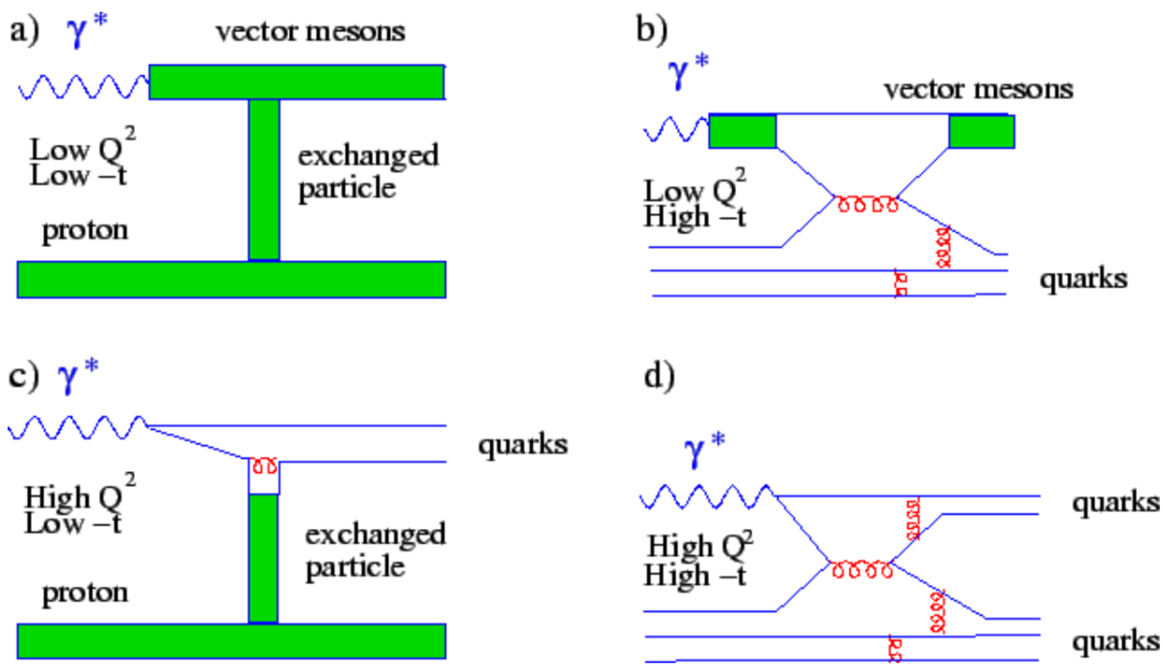


Figure 3: These diagrams depict the effective interaction at low energies of composite particles (green bars) and how the substructure is revealed by selected kinematics. The substructure of the incoming photon beam is revealed at high Q^2, and the constituents of the target are uncovered using large-angle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