Exclusive π^- Electroproduction off the Neutron in Deuterium in the Resonance Region

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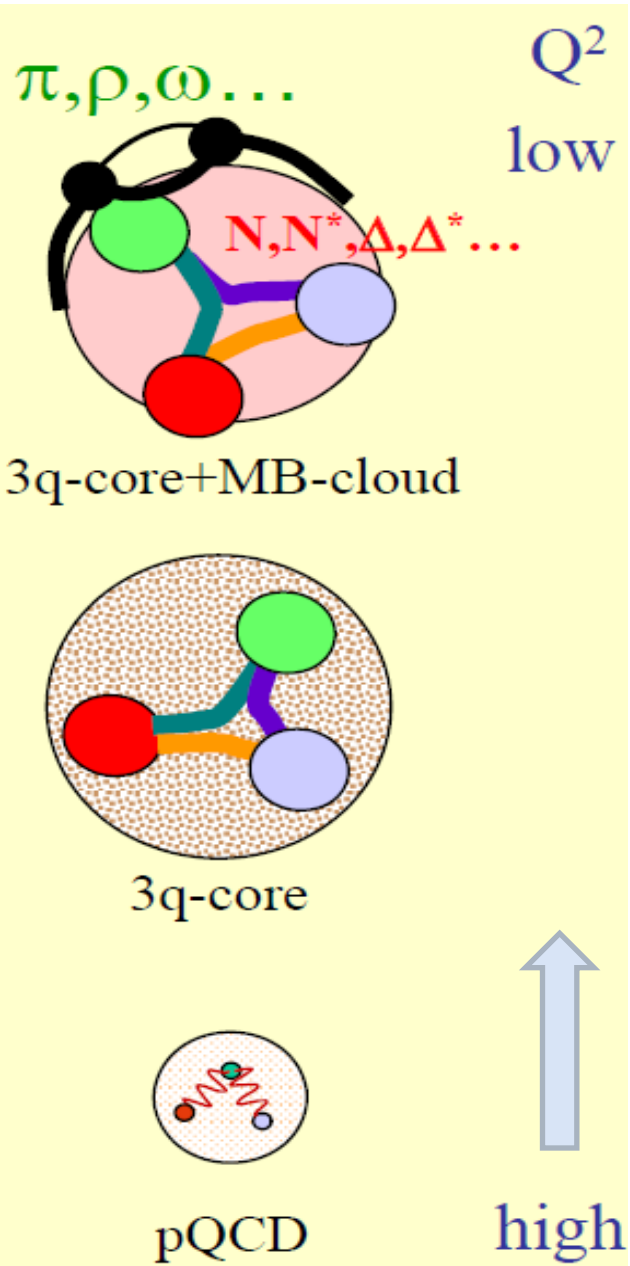
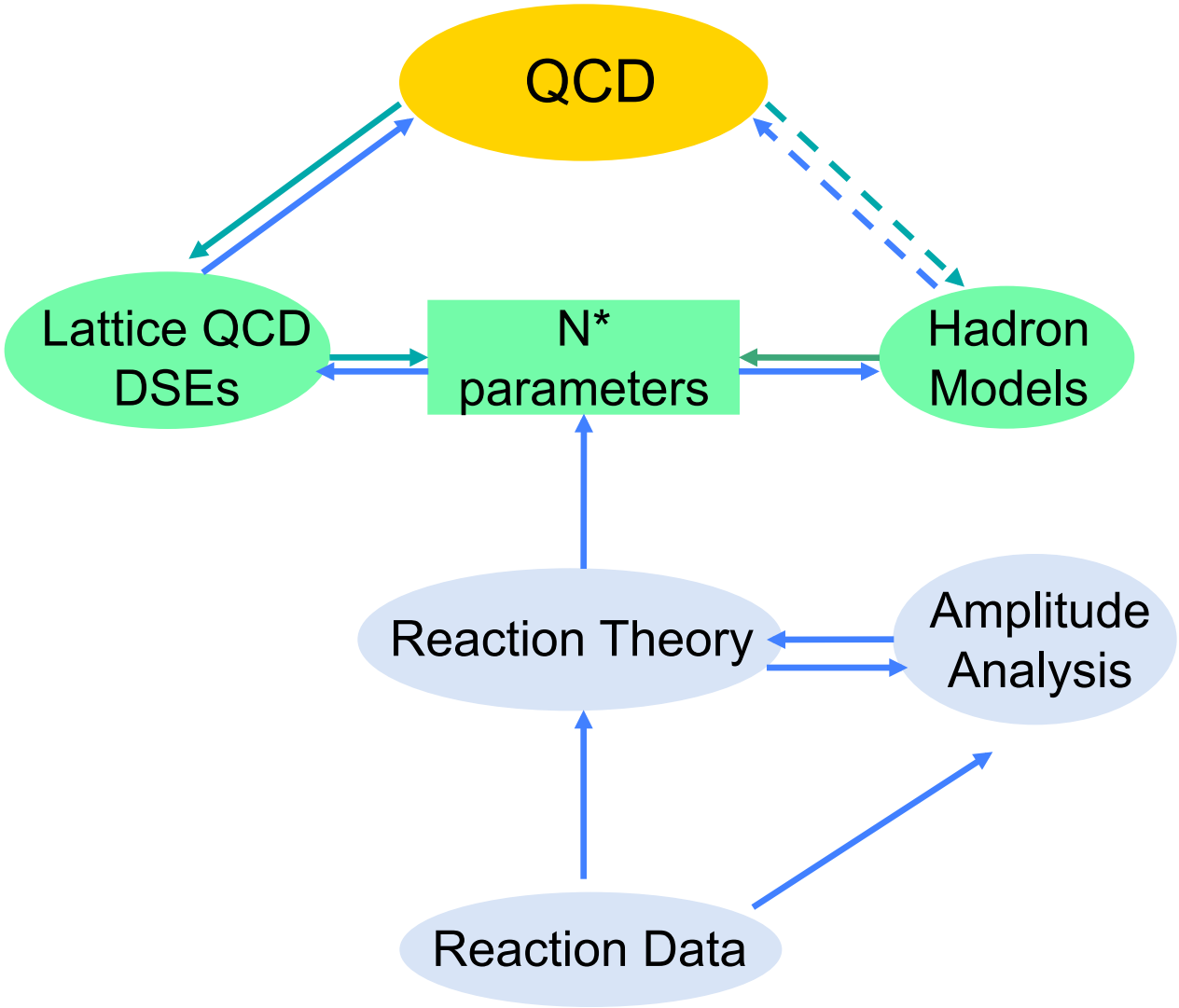
Outline

- Introduction
- Data Analysis
- Preliminary Results
- Summary and Outlook

Motivation





Electroproduction, Photoproduction

Pion Electroproduction Reactions

$$\gamma^* + p \longrightarrow \pi^0 + p$$

$$\gamma^* + p \longrightarrow \pi^+ + n$$

H_2 target

$$\gamma^* + d(p) \longrightarrow \pi^+ + n + n_s$$

$$\gamma^* + d(n) \longrightarrow \pi^- + p + p_s$$

D_2 target

CLAS e1e run

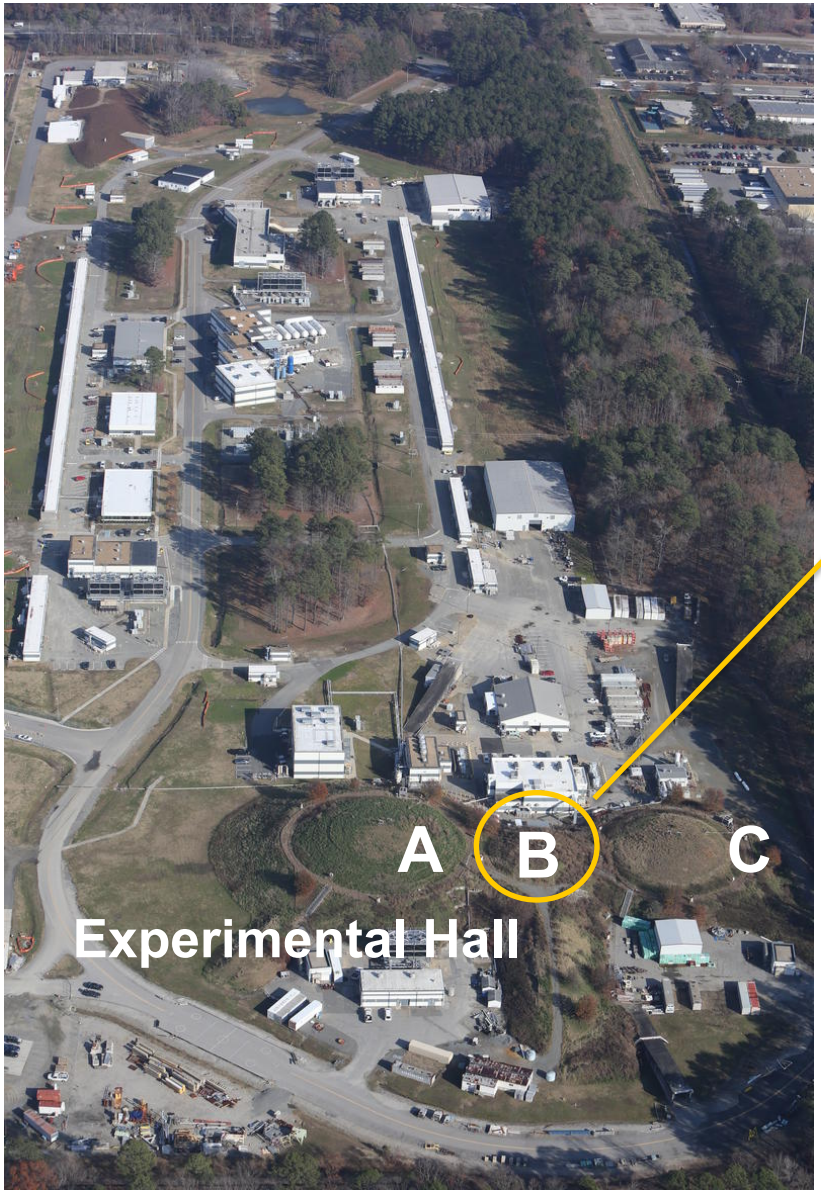
$$\gamma^* + d(p) \longrightarrow \pi^+ + \pi^- + p + n_s$$

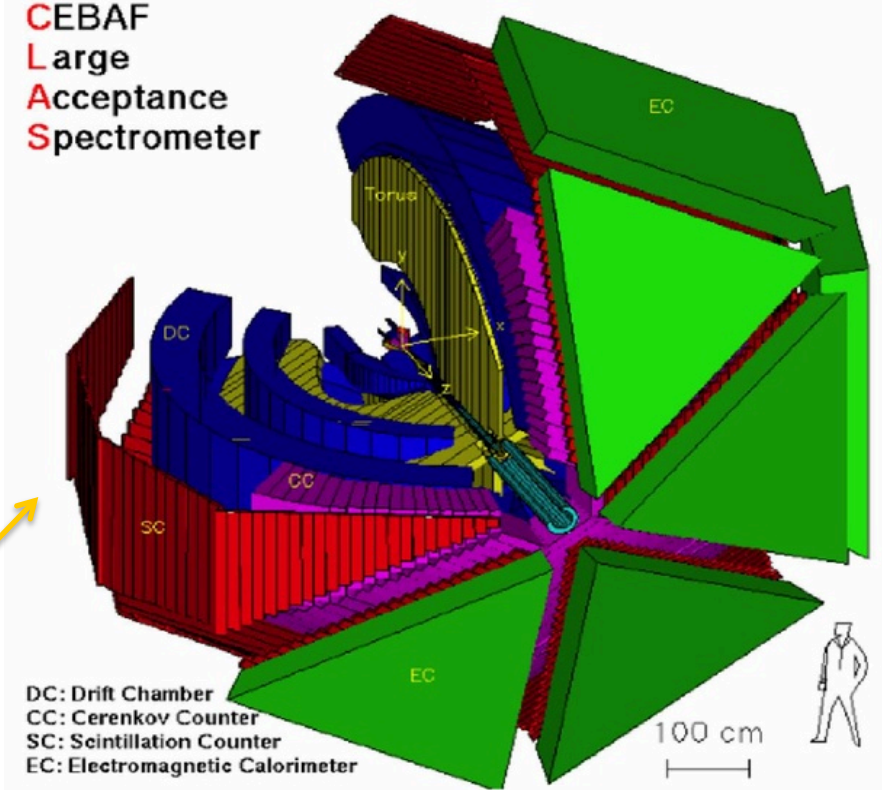
$$\gamma^* + d(n) \longrightarrow \pi^- + p + p_s$$

D_2 target

CLAS BoNuS

JLab Continuous Electron Beam Electron Beam Accelerator



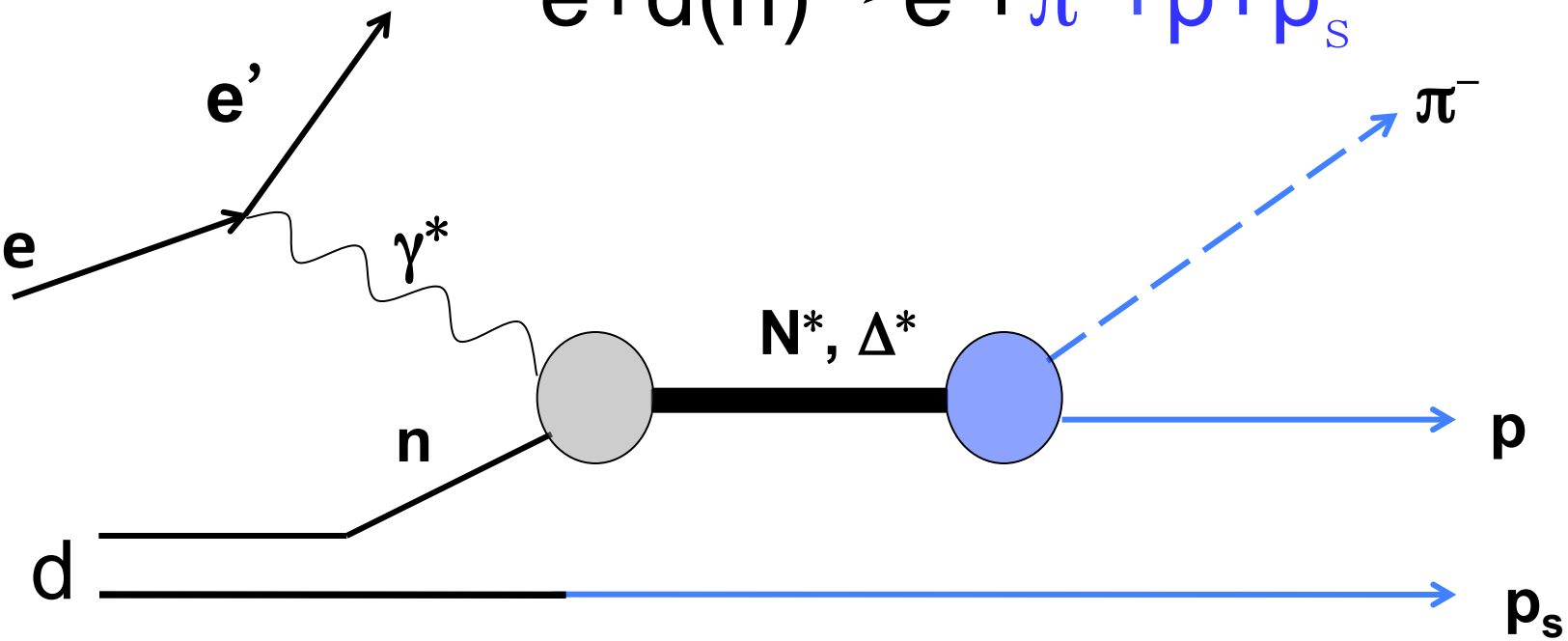


e1e run

- Electron beam: $E_0 = 2.039$ GeV
- Target: liquid deuterium
- Integrated luminosity: 2.6788×10^{39} cm^{-2}
- Target length: 2 cm

Exclusive Quasi-free π^- Electroproduction

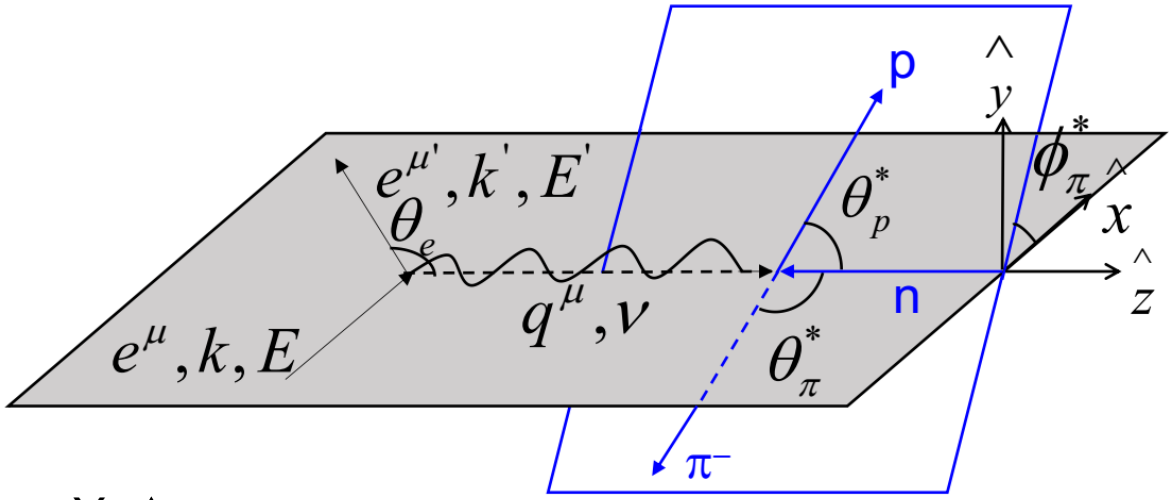
$$e+d(n) \rightarrow e' + \pi^- + p + p_s$$

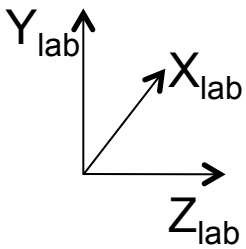


Energy and momentum conservation → Initial state of neutron (Off-shell)

$$p_s^{\mu} + n^{\mu} = d^{\mu} \ , \quad \vec{P}_{ps} + \vec{P}_n = 0$$

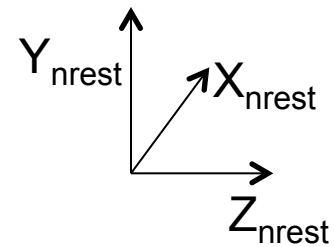
Exclusive π^- Production Kinematic



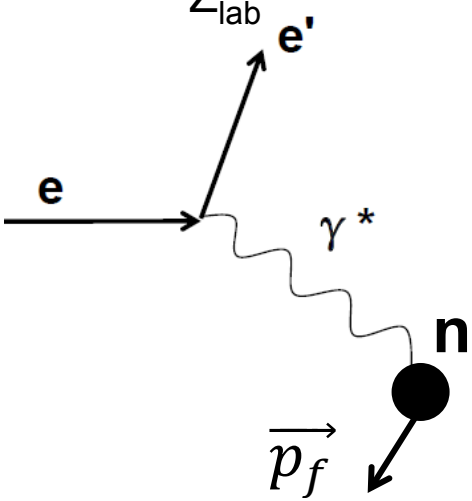


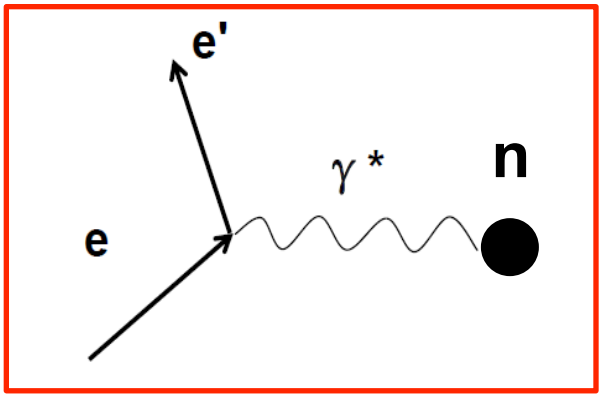
Lab → n at rest

boost



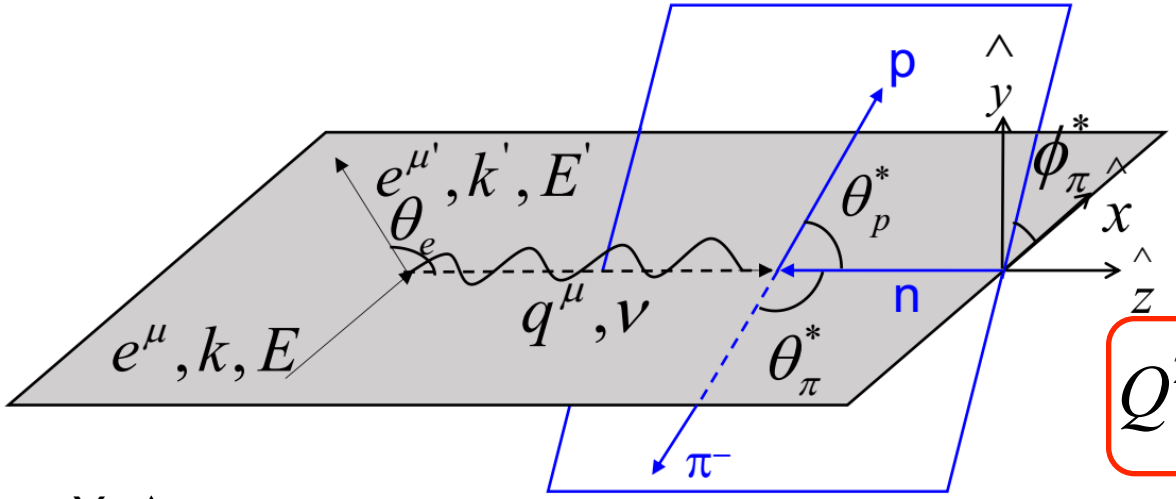
$$\vec{\beta}_1 = -\frac{\vec{n}}{E_n}$$





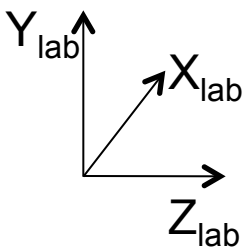
$$q^\mu + n^\mu + p_i^\mu = \pi^\mu + p^\mu + p_s^\mu$$

Exclusive π^- Production Kinematic



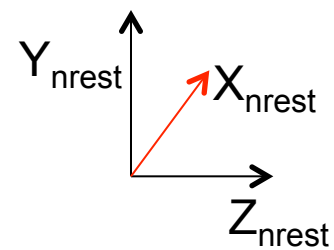
$$W_f = \sqrt{\left(p^u + \pi^{-u}\right)^2}$$

$$Q^2 = -\left(q^u\right)^2 = -\left(e^u - e'^u\right)^2$$

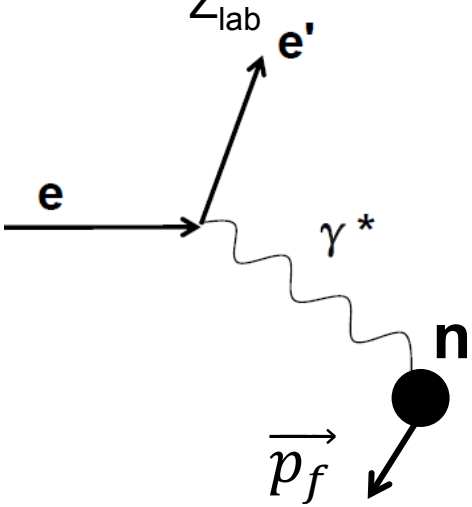


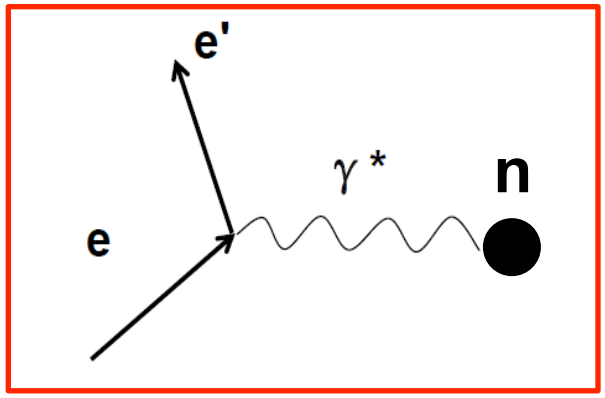
Lab → n at rest

boost



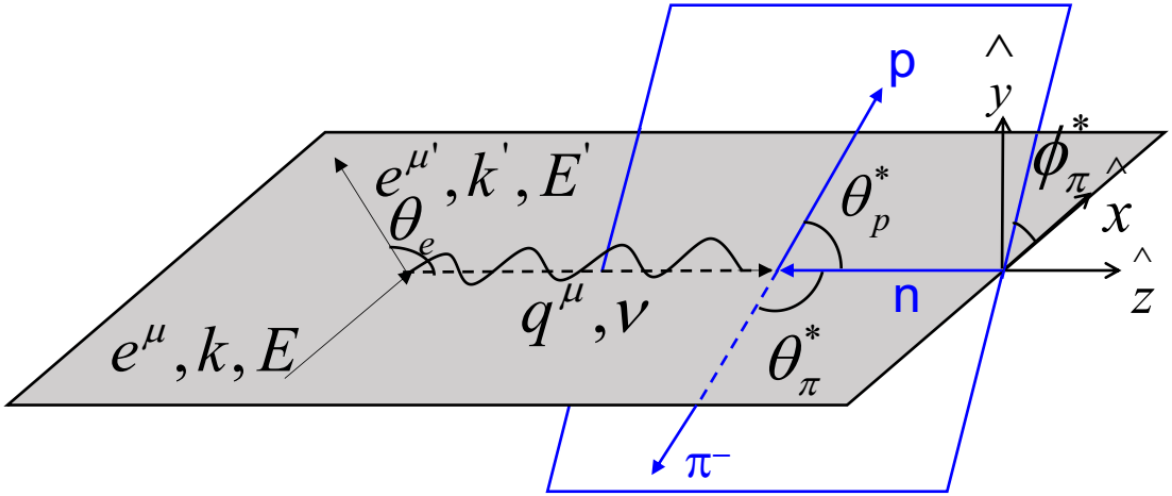
$$\vec{\beta}_1 = -\frac{\vec{n}}{E_n}$$





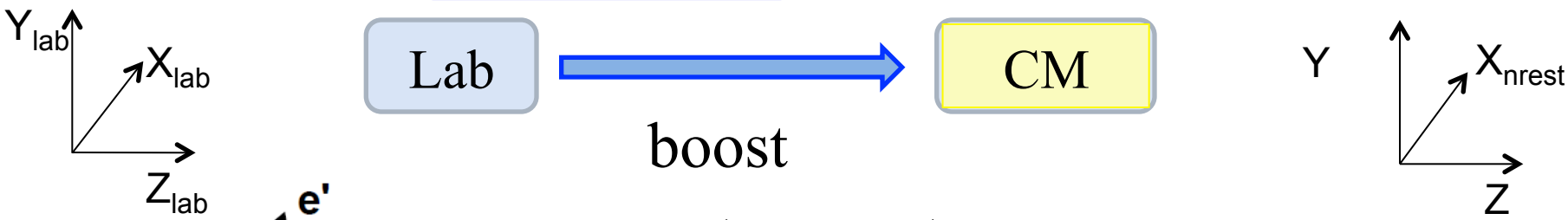
$$q^\mu + n^\mu + p_i^\mu = \pi^\mu + p^\mu + p_s^\mu$$

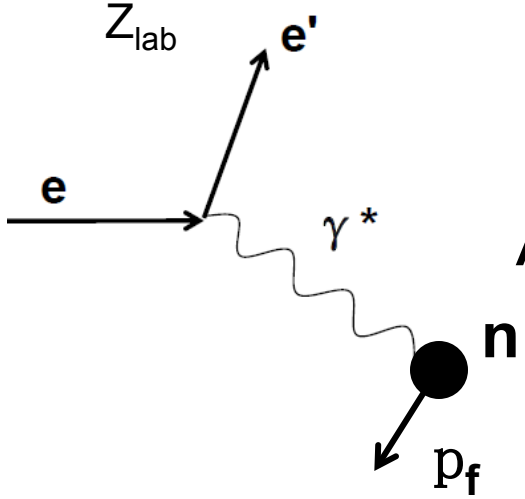
Exclusive π^- Production Kinematic



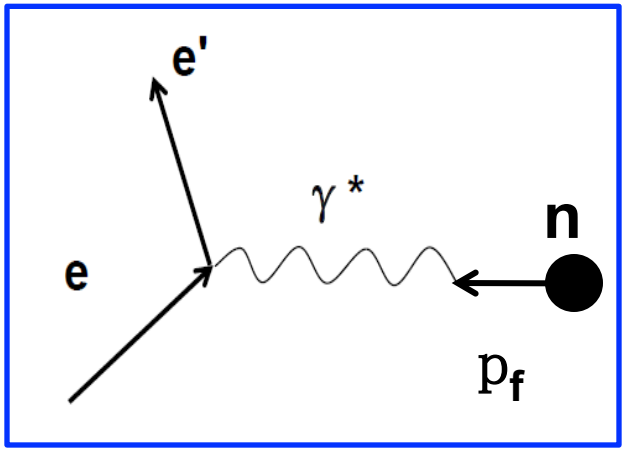
$$\cos\theta^*$$

$$\phi^*$$

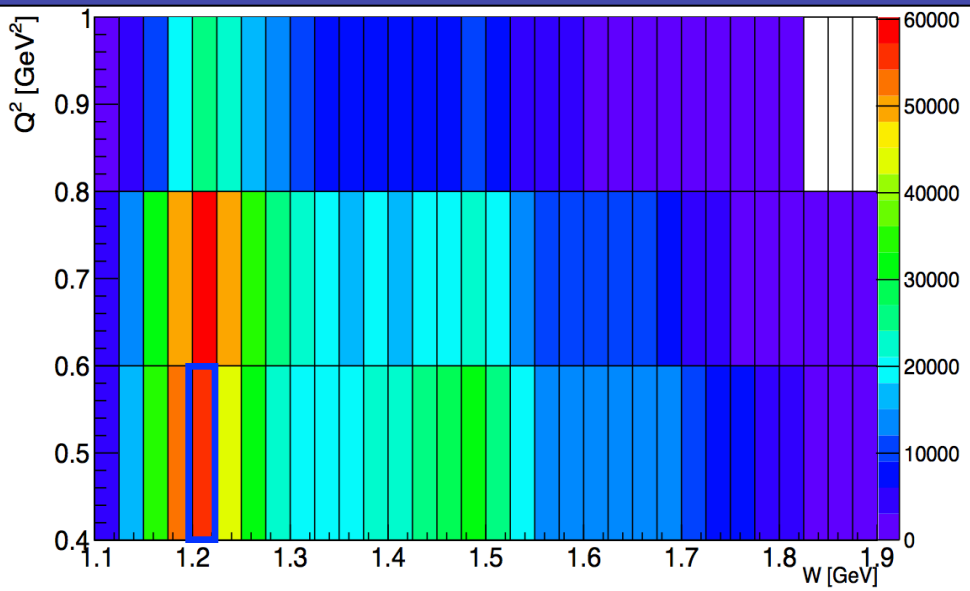


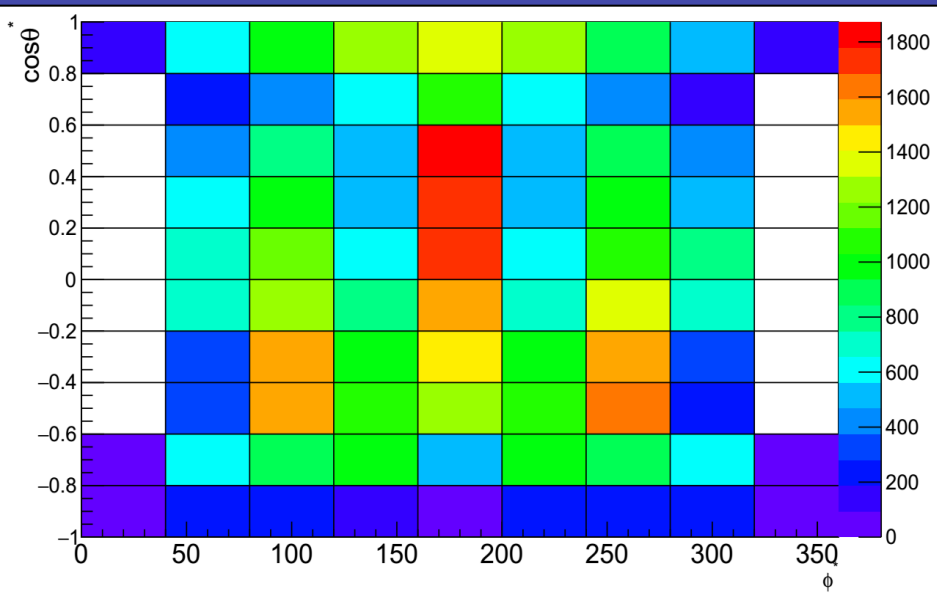


$$\vec{\beta}_2 = -\frac{\left(\vec{p} + \vec{\pi}^-\right)}{E_p + E_{\pi^-}}$$



Exclusive π^- Production Kinematic



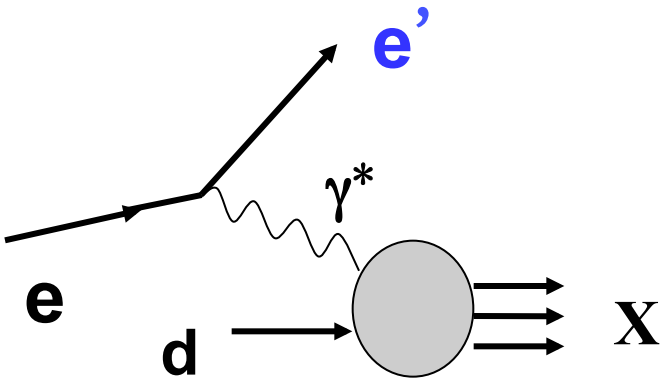


E_0=2.039 GeV

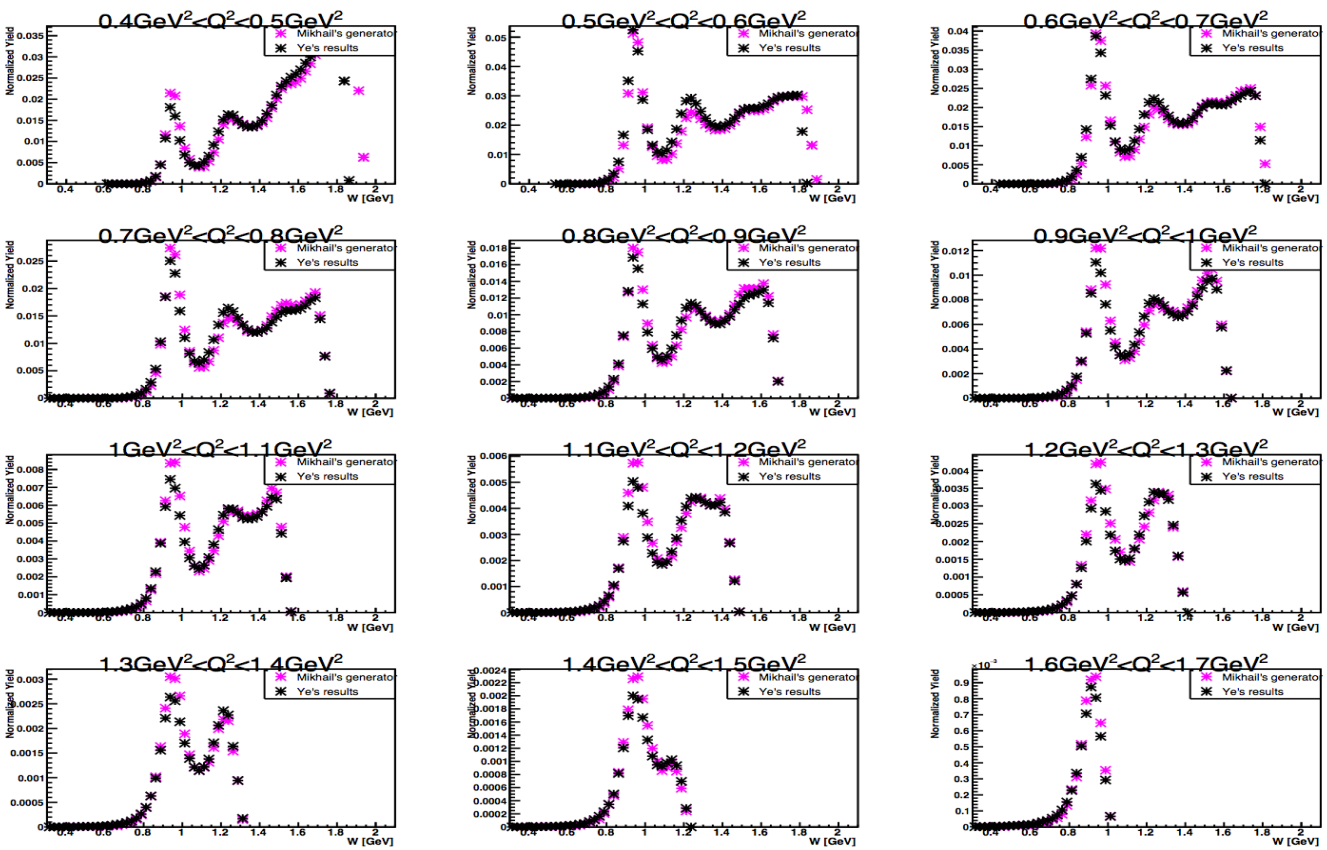
Variable	Lower limit	Upper limit	Number of bins	Bin size
W GeV	1.1	1.825	29	0.025
Q^2 GeV^2	0.4	1.0	3	0.2
cos θ*	-1	1	10	0.2
ϕ*	0 °	360°	9, 8, 6	40°, 45°, 60°

Inclusive Cross Section

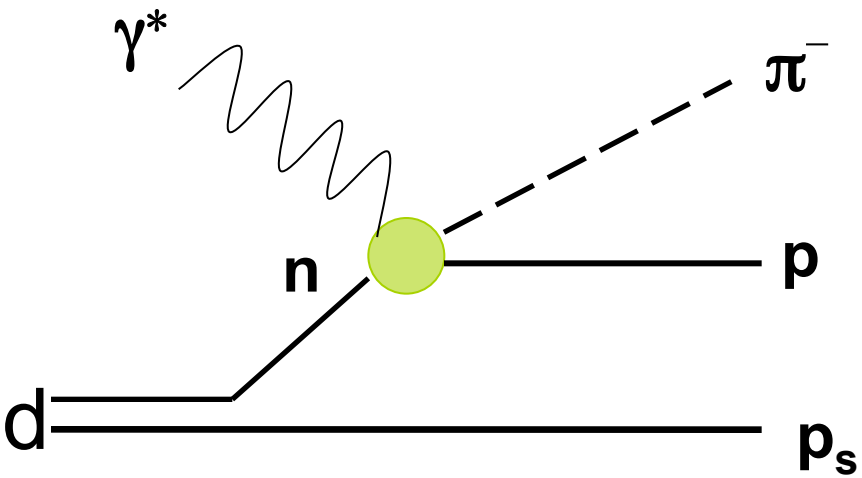
$$\frac{d^2\sigma}{dWdQ^2} = \frac{N_{reaction}\left(W, Q^2\right)}{\Delta W \Delta Q^2 L}$$



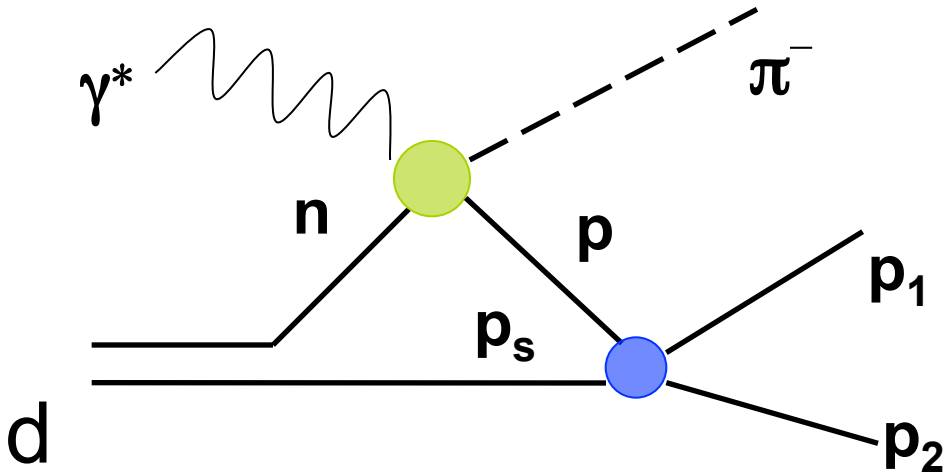
* Osipenko parameterization
* Experimental data



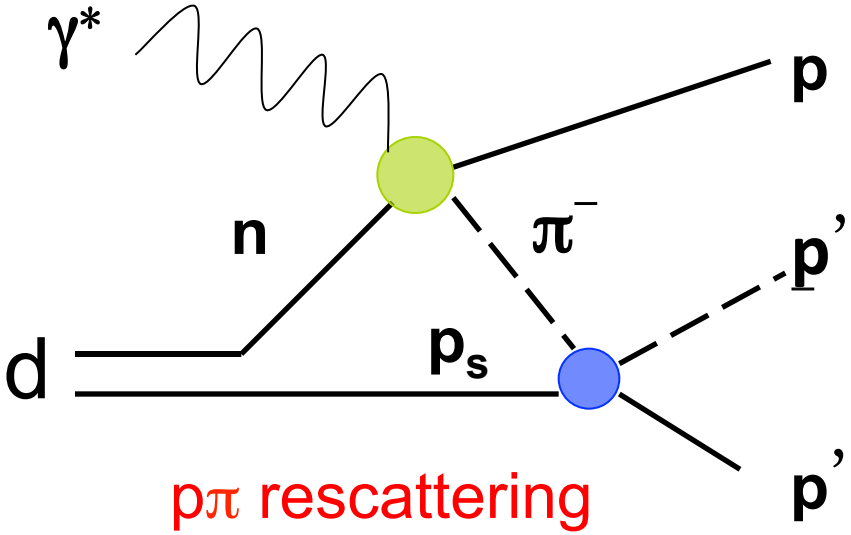
Final State Interaction Sketch



Quasi-free

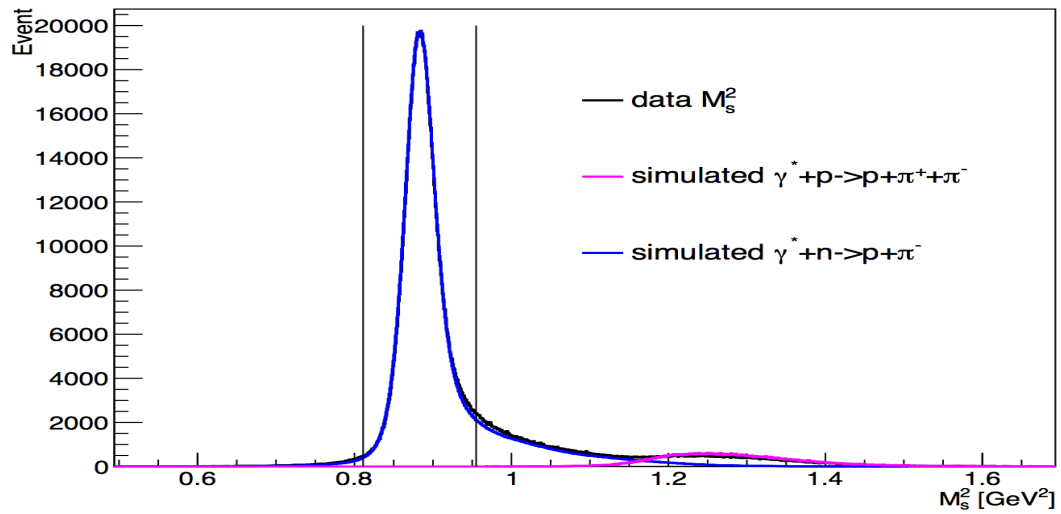


pp rescattering



pπ rescattering

Exclusive Event Selection

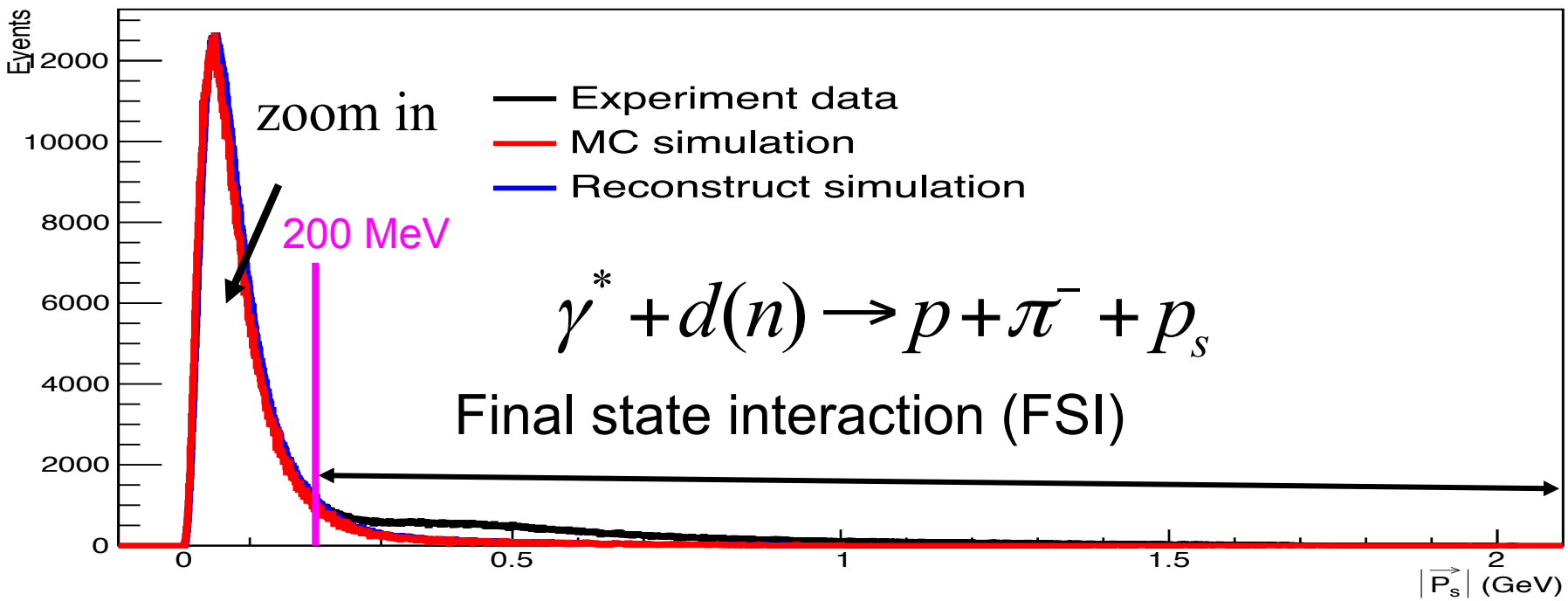


Missing mass square

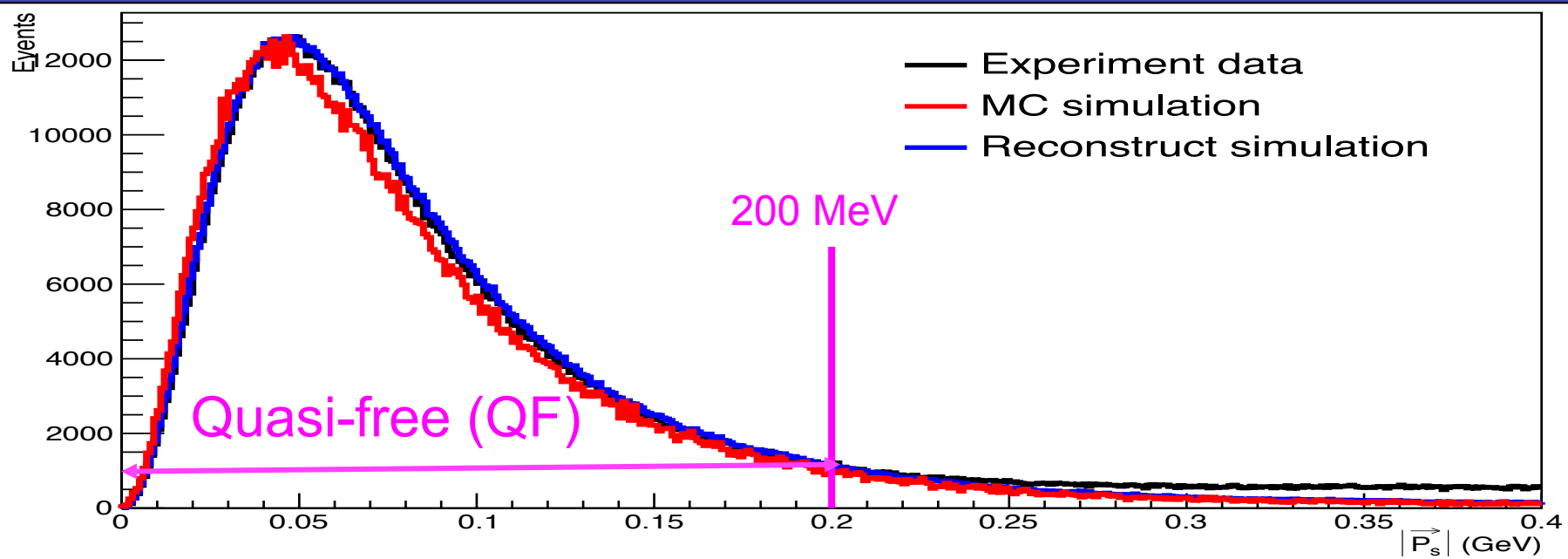
$$\left(q^{\mu}+d^{\mu}-p^{\mu}-\pi^{\mu}\right)^2$$

Missing momentum

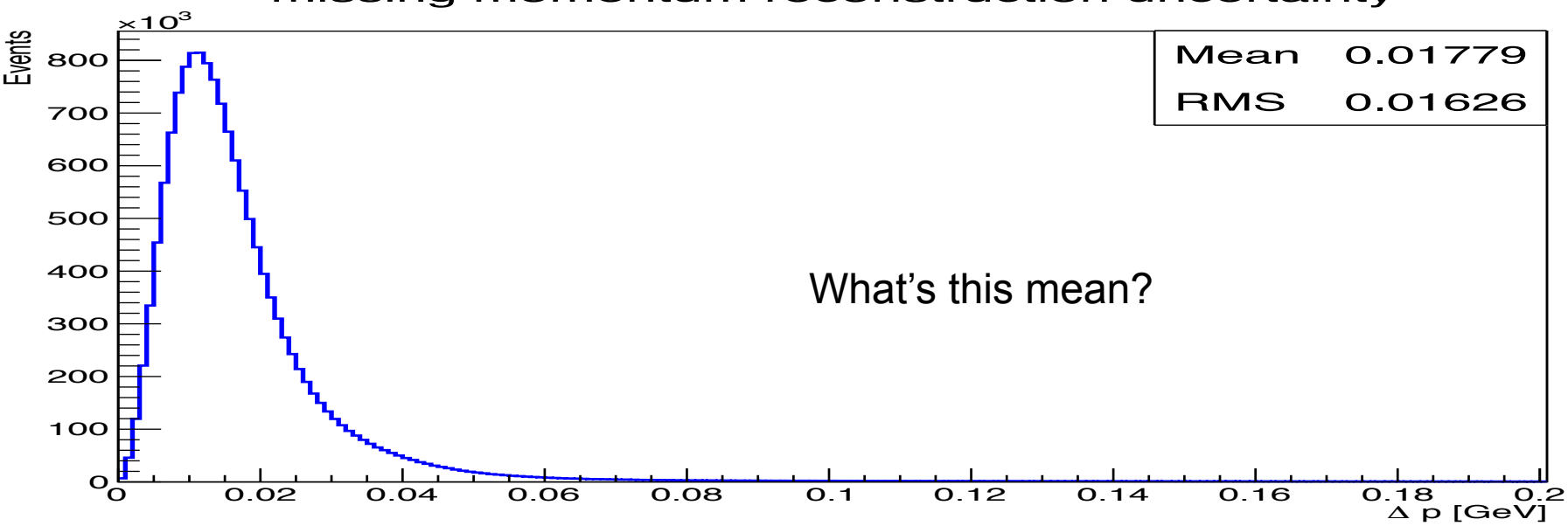
$$\left|\vec{q}-\vec{\pi^-}-\vec{p}\right|$$



Exclusive Quasi-free Event Selection



missing momentum reconstruction uncertainty



Simulation

MAID2000 generated data

$$\gamma^* + n \rightarrow p + \pi^-$$

Simulation

MAID2000 generated data

$$\gamma^* + n \rightarrow p + \pi^-$$

experimental data

$$\gamma^* + d(n) \rightarrow p + \pi^- + p_s$$

Simulation

MAID2000 generated data $\gamma^* + n \rightarrow p + \pi^-$

simulation $\gamma^* + n + p_s \rightarrow p + \pi^- + p_s$

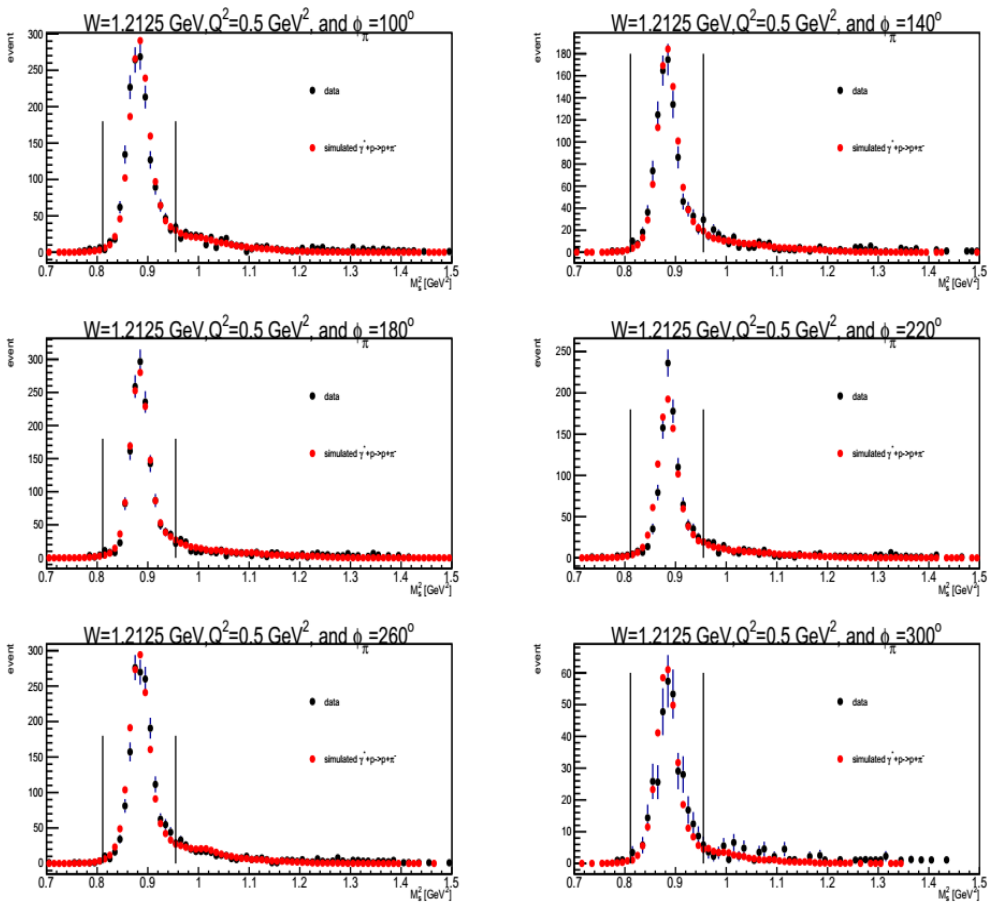
experimental data $\gamma^* + d(n) \rightarrow p + \pi^- + p_s$

Background Study

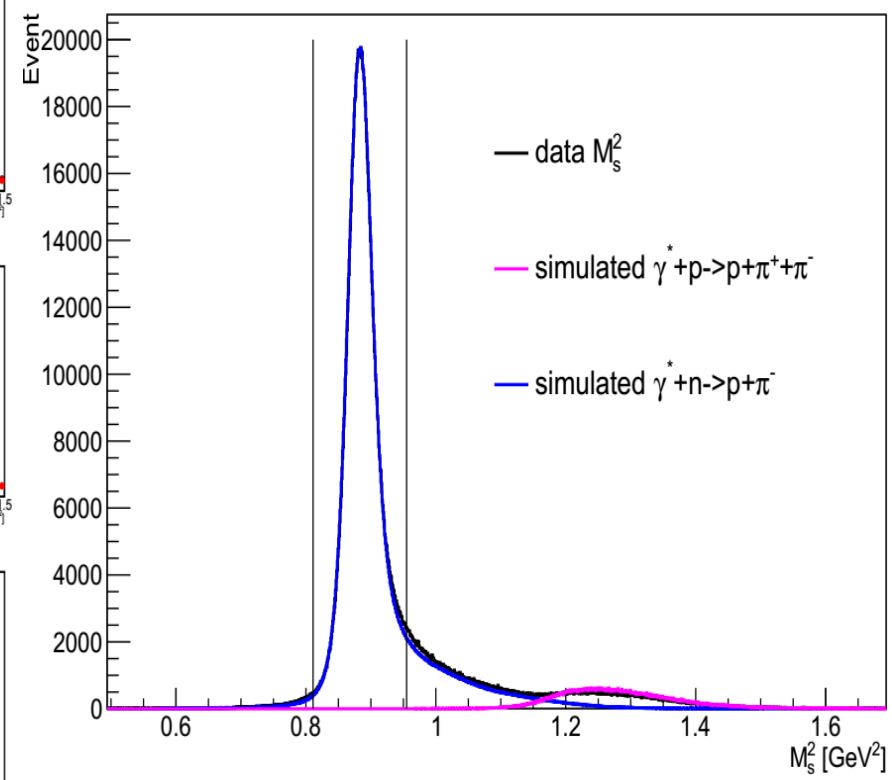
$$\gamma^* + n + p_s \rightarrow p + \pi^- + p_s$$

$$\gamma^* + d(n) \rightarrow p + \pi^- + p_s$$

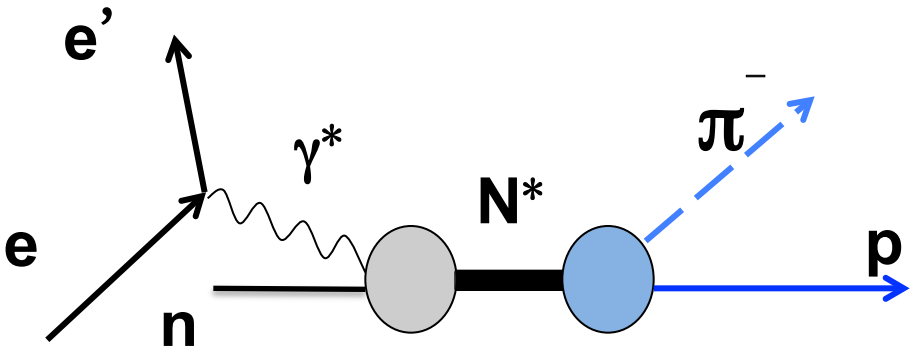
$$\gamma^* + p \rightarrow p + \pi^- + \pi^+$$



Isobar Model for Nππ final state (JM)



Differential Cross Section



$$\frac{d\sigma}{dW dQ^2 d\Omega^*_{\pi^-}} = \Gamma_v \boxed{\frac{d^2\sigma}{d\Omega^*_\pi}}$$

virtual photon flux $\Gamma_v \equiv \frac{\alpha}{4\pi}\frac{1}{E^2}\frac{W\left(W^2 - m_n^2\right)}{m_n^2 Q^2 (1-\varepsilon)}$

$$\varepsilon \equiv \left(1 + 2\frac{|q|^2}{Q^2}\tan^2\frac{\theta_e}{2}\right)^{-1}$$

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

The Legendre polynomial expansion

$$\sigma_T + \varepsilon\sigma_L = \sum_{i=0}^{2l} A_i P_i(\cos\theta^*_\pi)$$

$$\sigma_{TT} = \sum_{i=0}^{2l-2} B_i P_i(\cos\theta^*_\pi)$$

$$\sigma_{LT} = \sum_{i=0}^{2l-1} C_i P_i(\cos\theta^*_\pi)$$

electromagnectic multipoles

$E_{l\pm}, M_{l\pm}, S_{l\pm}$

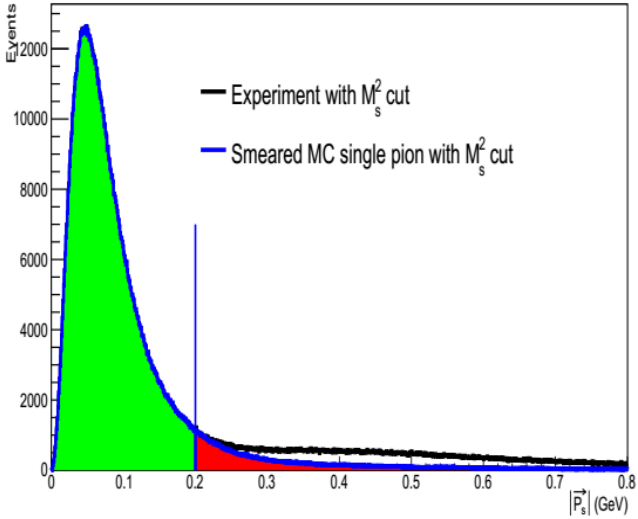
Differential Cross Section

$$\boxed{\frac{d^2\sigma^{excl}}{d\Omega_\pi^*}} = \frac{(\Delta N_{full}(W,Q^2,\cos\theta^*,\phi^*) - S_{ratio}\Delta N_{full}(W,Q^2,\cos\theta^*,\phi^*))R_{BC}}{\Gamma_v A(W,Q^2,\cos\theta^*,\phi^*)\Delta W\Delta Q^2\Delta\cos\theta^*\Delta\phi^* L_{\text{int}}}$$

Differential Cross Section

$$\boxed{\frac{d^2\sigma^{excl}}{d\Omega_\pi^*}} = \frac{(\Delta N_{full}(W,Q^2,\cos\theta^*,\phi^*) - S_{ratio}\Delta N_{full}(W,Q^2,\cos\theta^*,\phi^*))R_{BC}}{\Gamma_v A(W,Q^2,\cos\theta^*,\phi^*)\Delta W\Delta Q^2\Delta\cos\theta^*\Delta\phi^* L_{\text{int}}}$$

$$\frac{d^2\sigma^{cut}}{d\Omega_\pi^*} = \frac{(\Delta N_{full}^{cut}(W,Q^2,\cos\theta^*,\phi^*) - S_{ratio}N_{full}^{cut}(W,Q^2,\cos\theta^*,\phi^*))R_{BC}}{\Gamma_v A^{cut}(W,Q^2,\cos\theta^*,\phi^*)\Delta W\Delta Q^2\Delta\cos\theta^*\Delta\phi^* L_{\text{int}}}$$

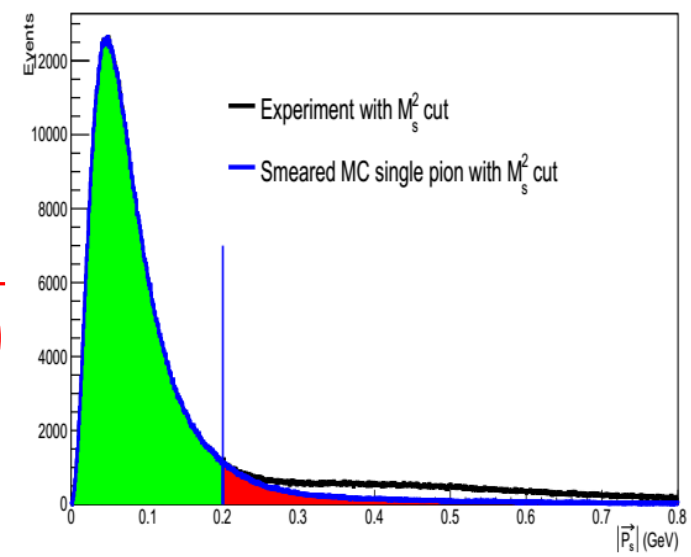


Differential Cross Section

$$\frac{d^2\sigma^{excl}}{d\Omega_\pi^*} = \frac{(\Delta N_{full}(W,Q^2,\cos\theta^*,\phi^*) - S_{ratio}\Delta N_{full}(W,Q^2,\cos\theta^*,\phi^*))R_{BC}}{\Gamma_v A(W,Q^2,\cos\theta^*,\phi^*)\Delta W\Delta Q^2\Delta\cos\theta^*\Delta\phi^* L_{\text{int}}}$$

$$\frac{d^2\sigma^{cut}}{d\Omega_\pi^*} = \frac{(\Delta N_{full}^{cut}(W,Q^2,\cos\theta^*,\phi^*) - S_{ratio}N_{full}^{cut}(W,Q^2,\cos\theta^*,\phi^*))R_{BC}}{\Gamma_v A^{cut}(W,Q^2,\cos\theta^*,\phi^*)\Delta W\Delta Q^2\Delta\cos\theta^*\Delta\phi^* L_{\text{int}}}$$

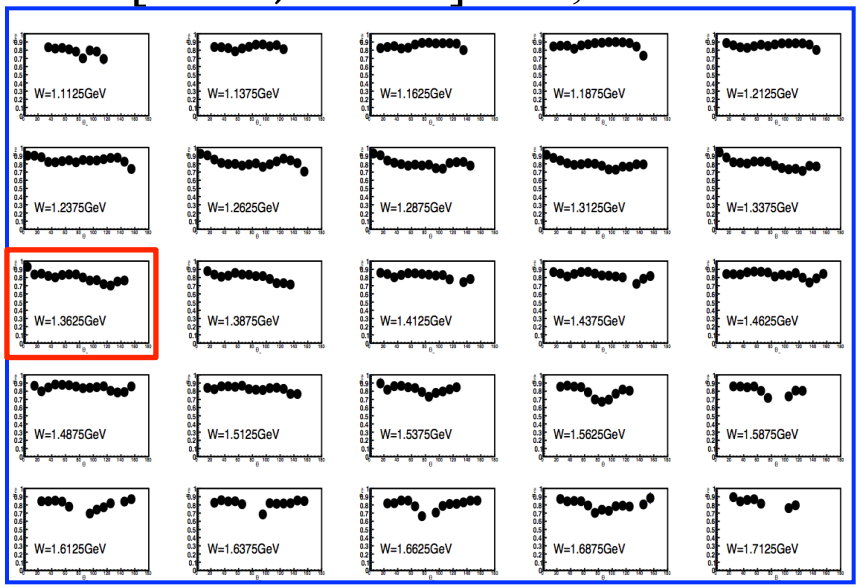
$$\frac{d^2\sigma^{quasi-free}}{d\Omega_\pi^*} = \frac{d^2\sigma^{cut}}{d\Omega_\pi^*}\frac{1}{r\left(W,Q^2,\cos\theta^*,\phi^*\right)}$$

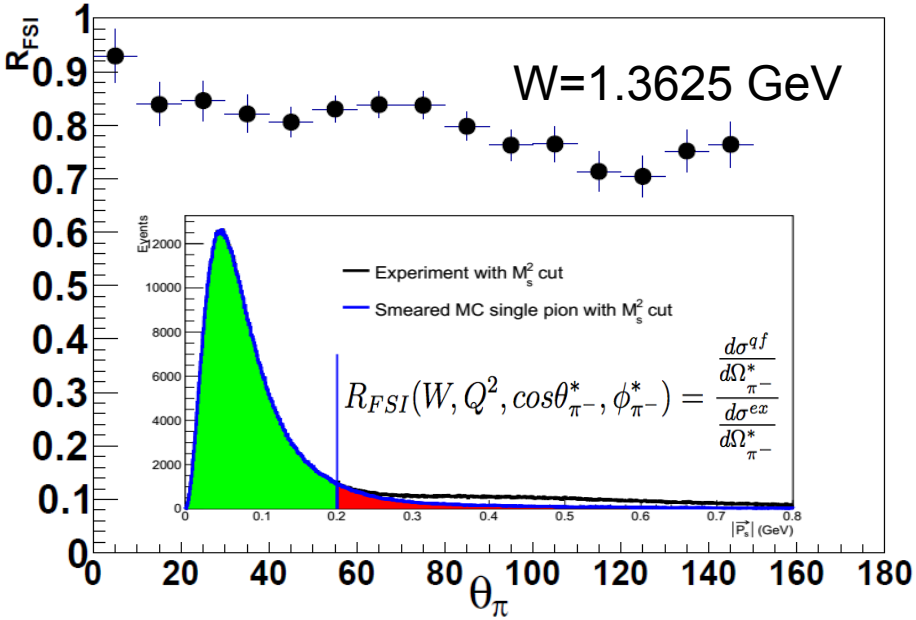


Final State Interaction Contribution Factor

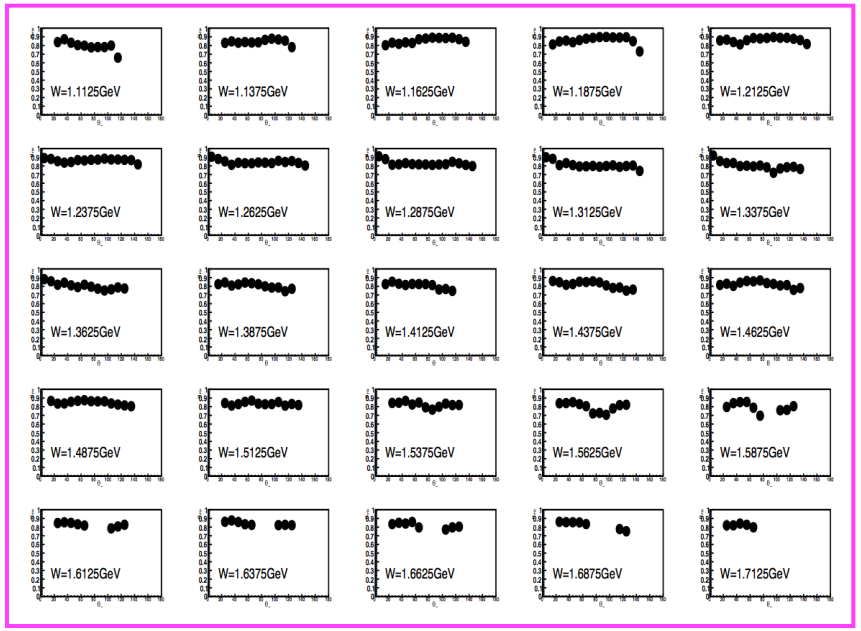
$W \in [1.125, 1.7125]\ GeV$, ΔW=25MeV

Q^2=0.5GeV^2

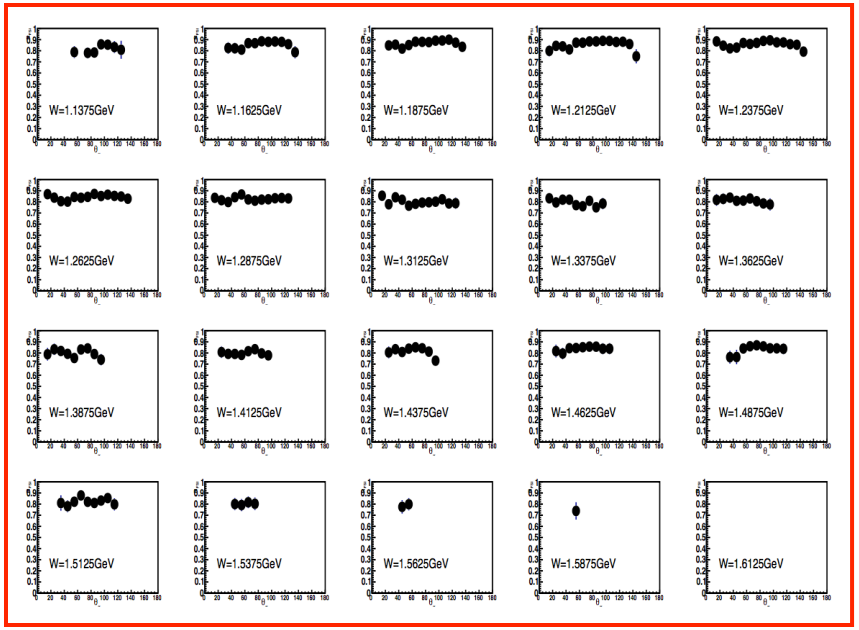




Q^2=0.7GeV^2



Q^2=0.9GeV^2



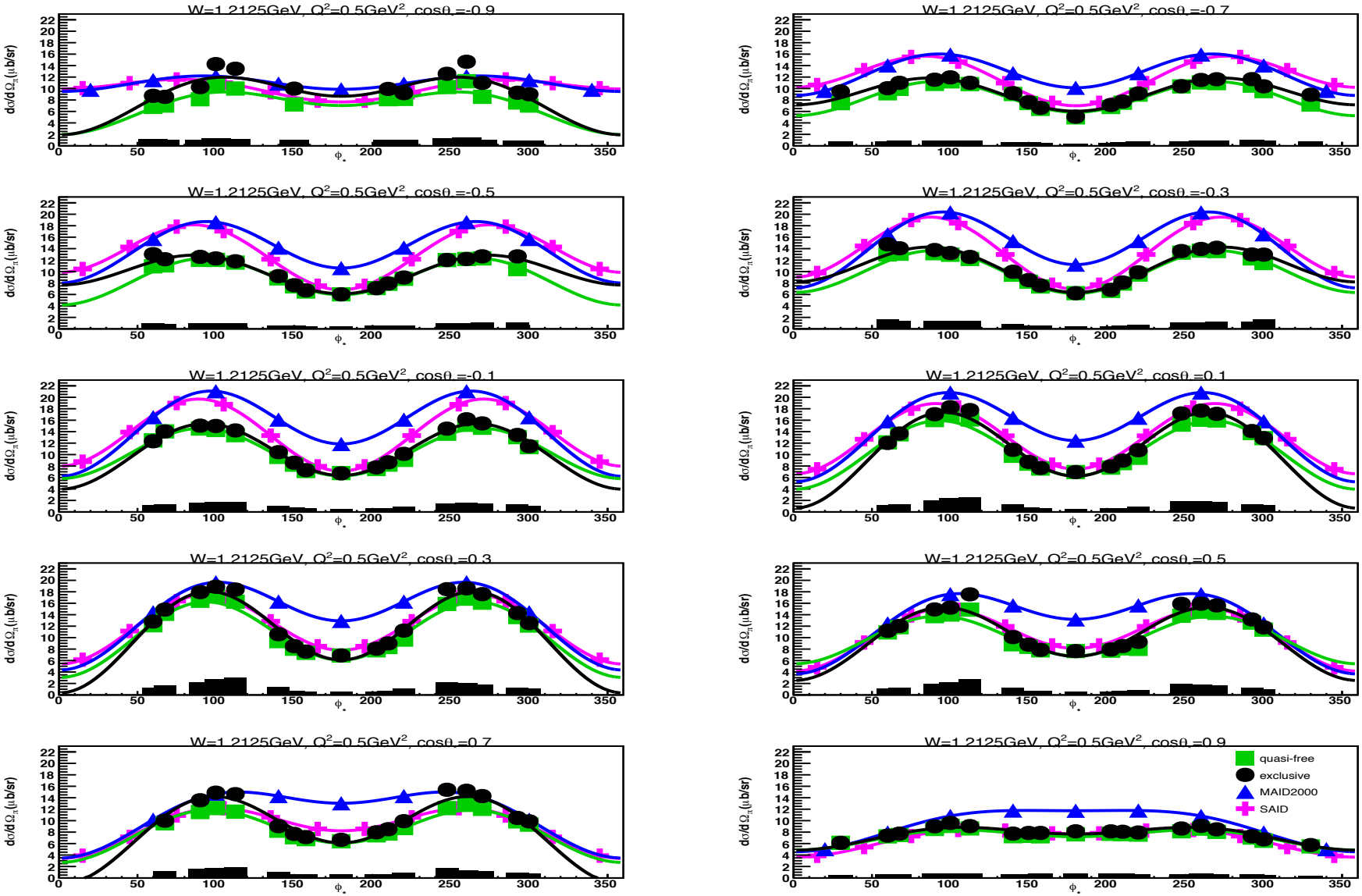
Preliminary Results

● $\frac{d^2\sigma^{exclusive}}{d\Omega_\pi^*}$ ● $\frac{d^2\sigma^{quasi-free}}{d\Omega_\pi^*}$ ✚ SAID model ▲ MAID model

Q^2=0.5GeV^2

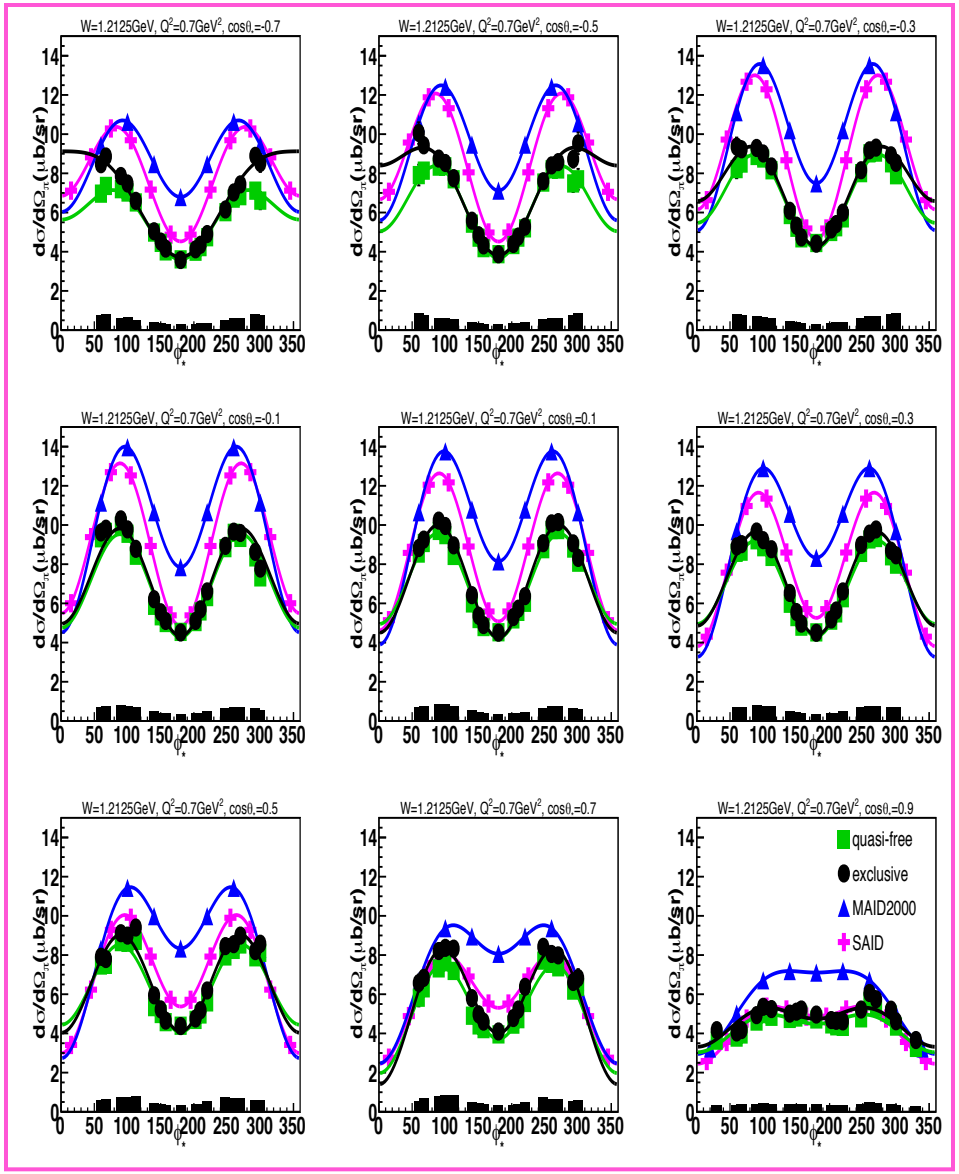
$\cos\theta^* \in (-1,1)$

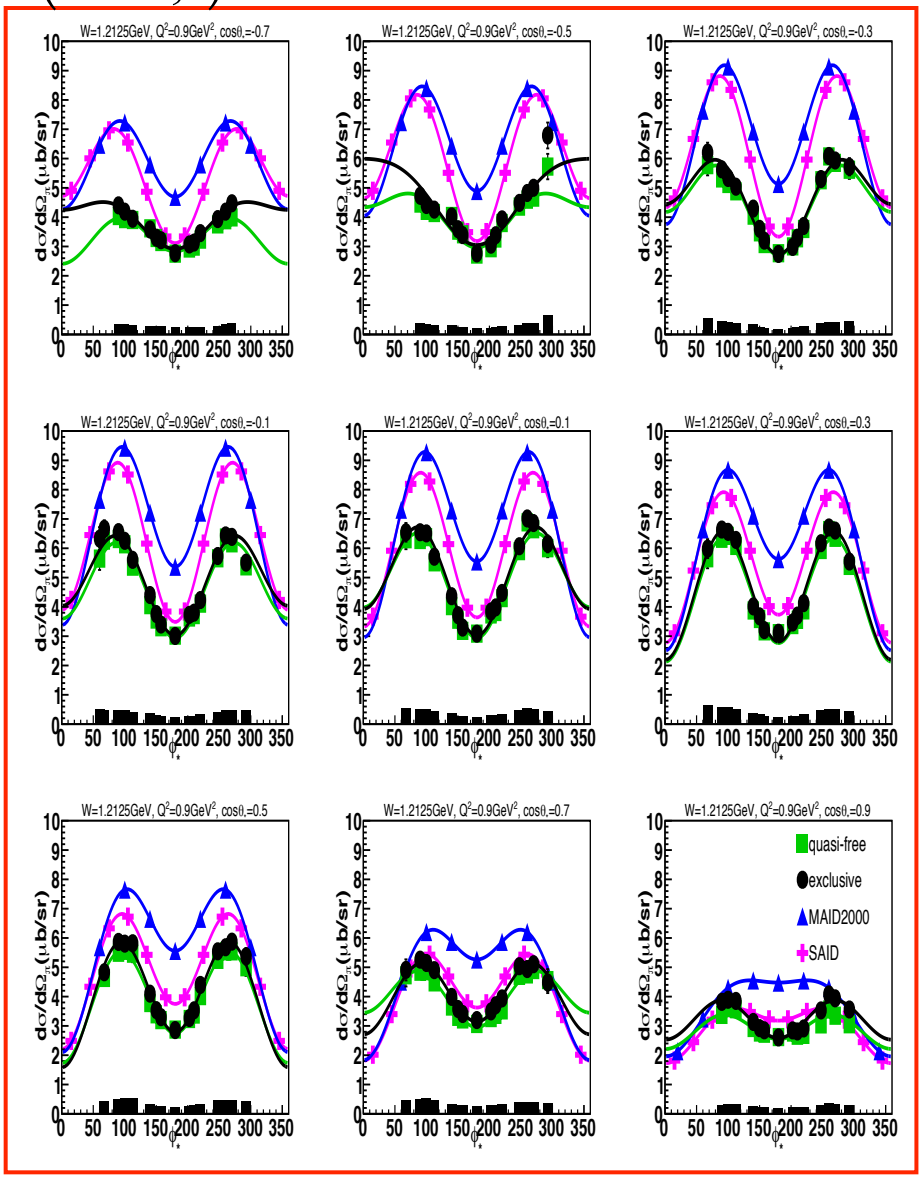
$\Delta\cos\theta^* = 0.2$



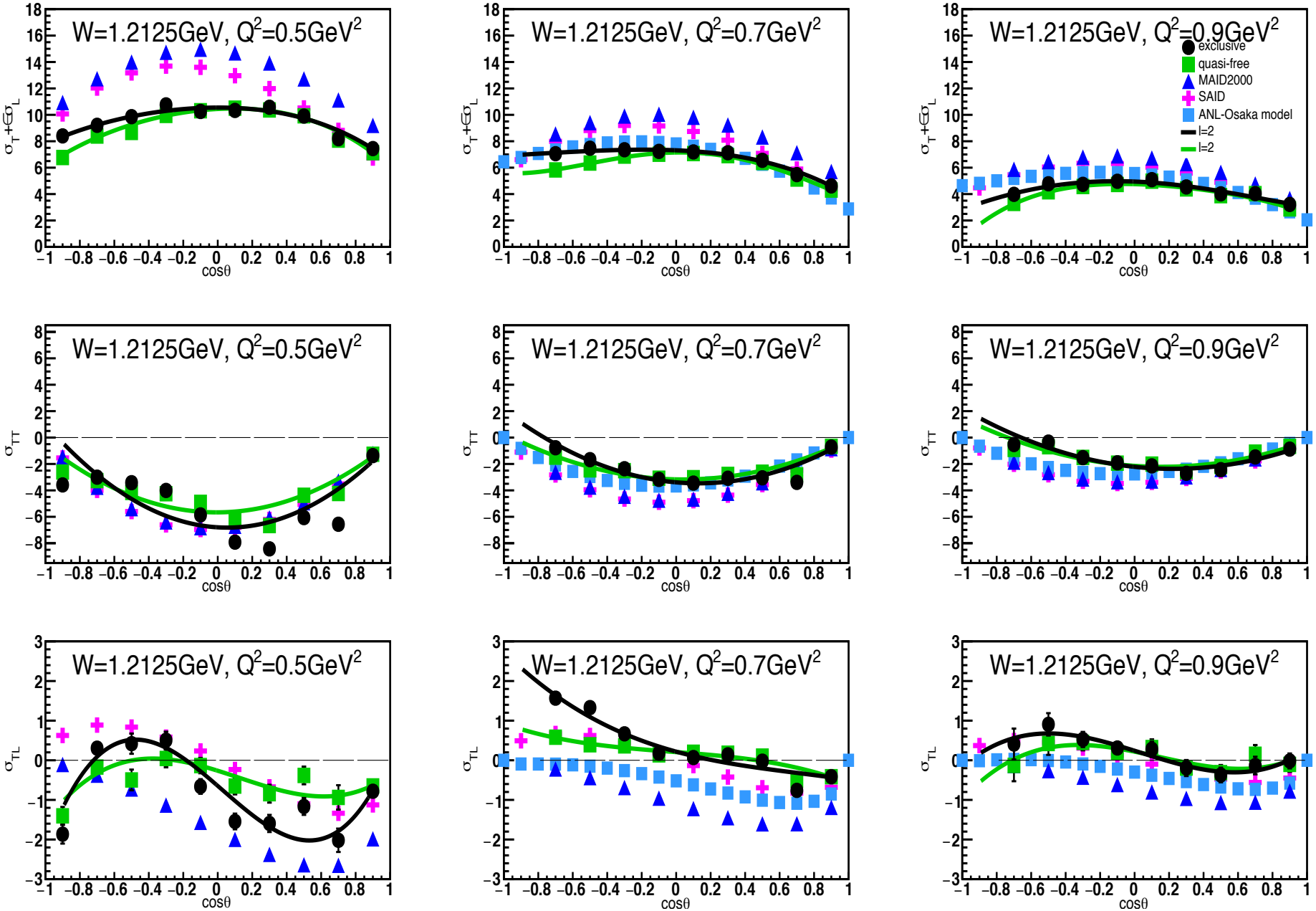
Preliminary Results

Q^2=0.7 GeV^2 ΔQ^2=0.2GeV^2 $\cos\theta^* \in (-0.8,1)$ $\Delta\cos\theta^* = 0.2$ **Q^2=0.9 GeV^2**





Preliminary Results



Systematic Uncertainties

Sources	Uncertainty (%)
Electron θ_{CC} cut	0.78
Electron SF cut	1.26
Electron fiducial cut	2.10
Proton ΔT cut	1.39
Proton fiducial cut	2.39
Pion ΔT cut	1.78
Pion fiducial cut	1.73
M_s^2 cut	2.29
p_s cut	2.21
Boosts	2.12
Potential	3.2
Bin center correction	0.55
Radiative correction	1.0
Normalization	5.0
Total	8.39

Summary and Outlook

- The exclusive full, quasi-free $\gamma^* n\ (p) \rightarrow \pi^- p\ (p)$ reaction cross sections in the corresponding kinematic coverage $W = 1.1 - 1.825$ GeV and $Q^2 = 0.4 - 1.0\ \mathrm{GeV}^2$ is first time achieved, from which the $n-N^*$ transition form factors will be extracted by phenomenological models.

- We will need more data statistics for $\gamma^* n\ (p) \rightarrow \pi^- p\ (p)$ channel to get better fit results in both very forward and backward polar and azimuthal angles of π^-.

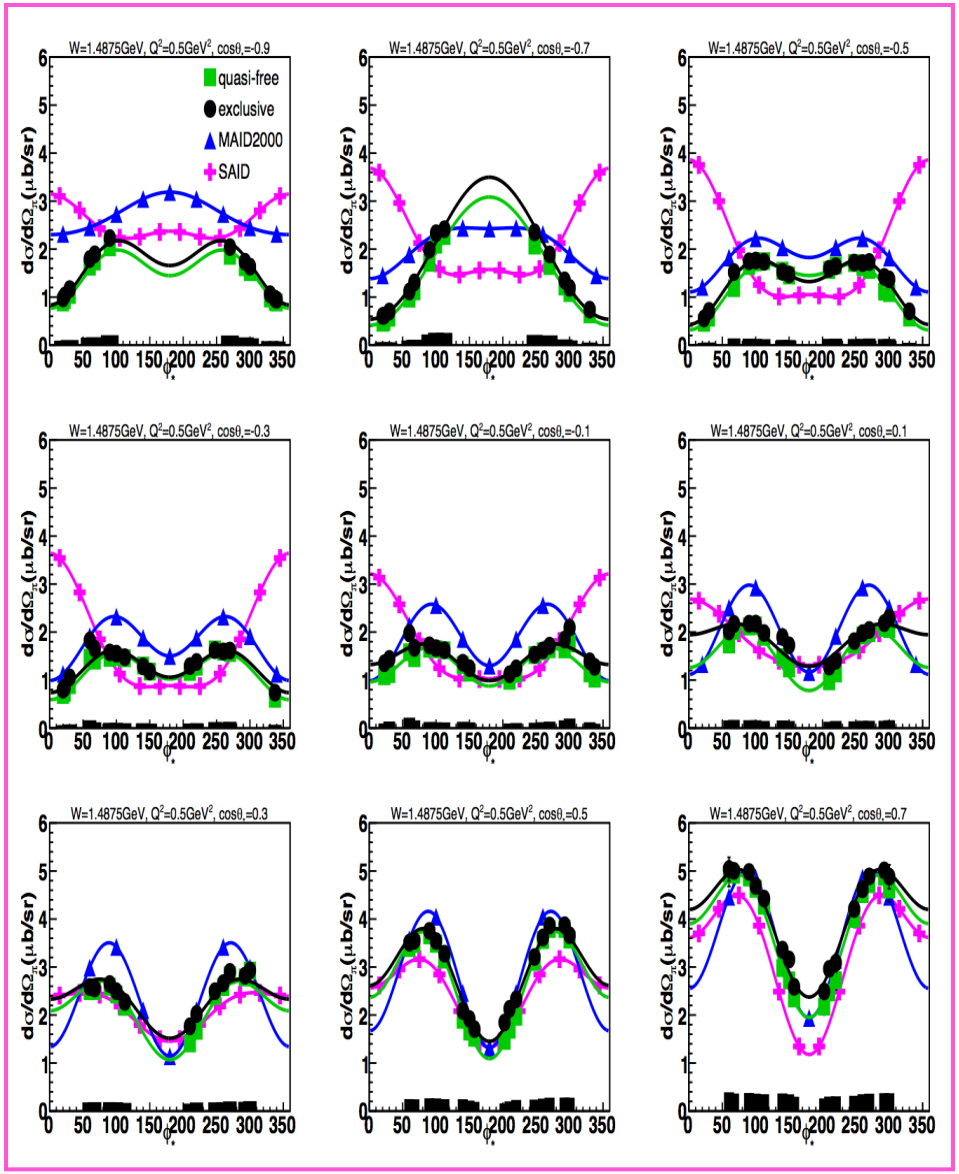
- The 1st round review feedback of my analysis note has been received, and a revised version will be available soon.

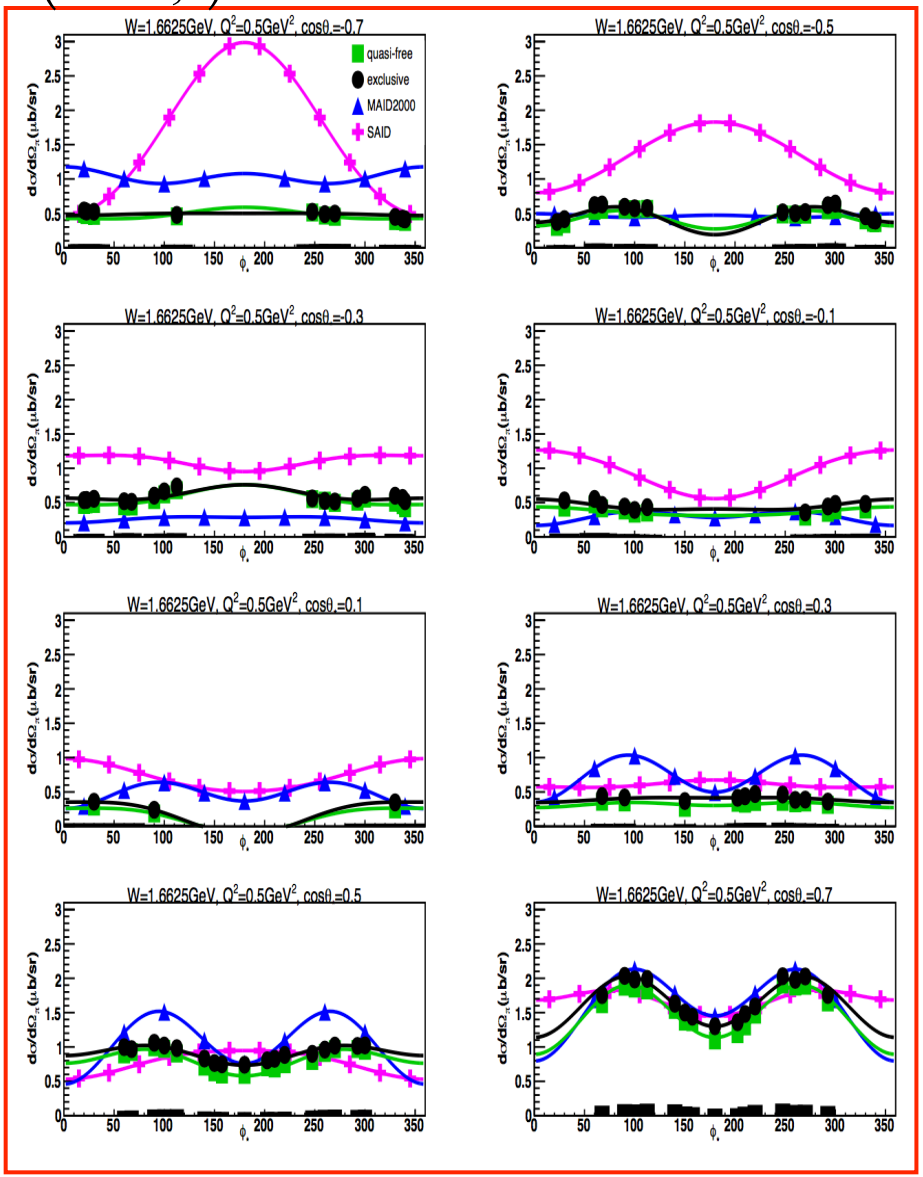

Thank you !

Backup

Preliminary Results

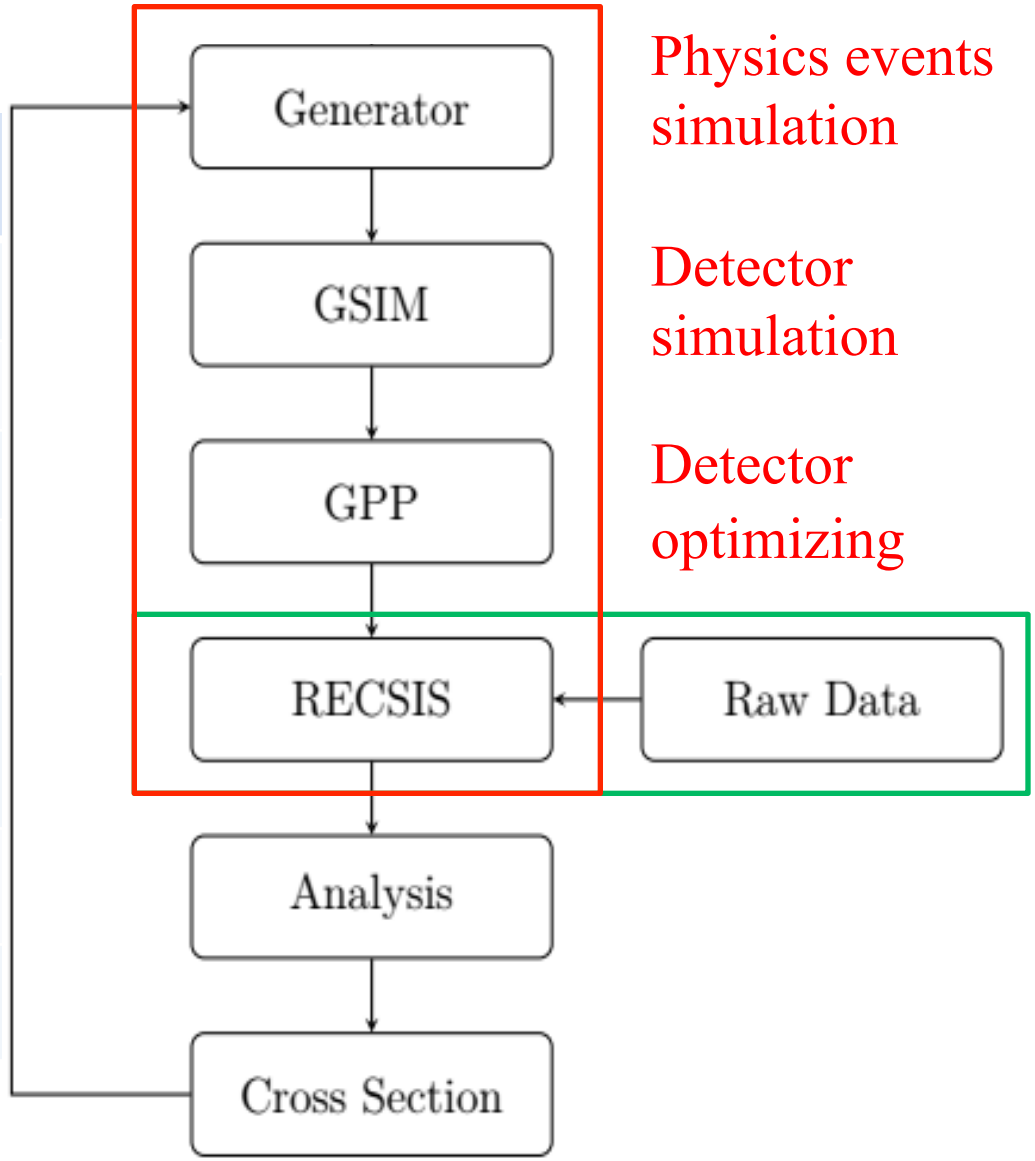
W=1.4875 GeV² Q^2=0.5GeV² $\cos\theta^* \in (-0.8,1)$ $\Delta\cos\theta^* = 0.2$ **W=1.6625 GeV²**



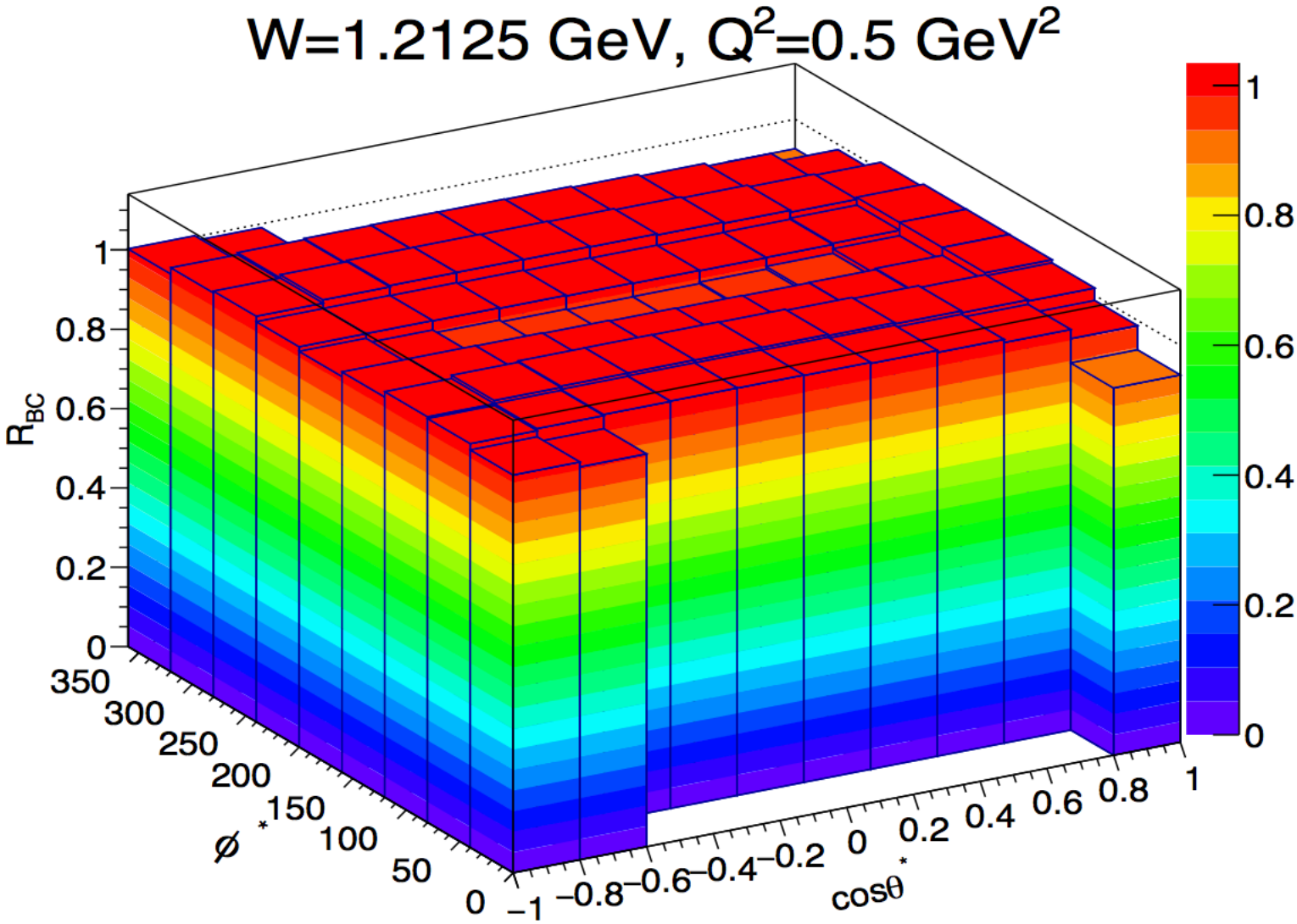


Data Analysis Flowchart

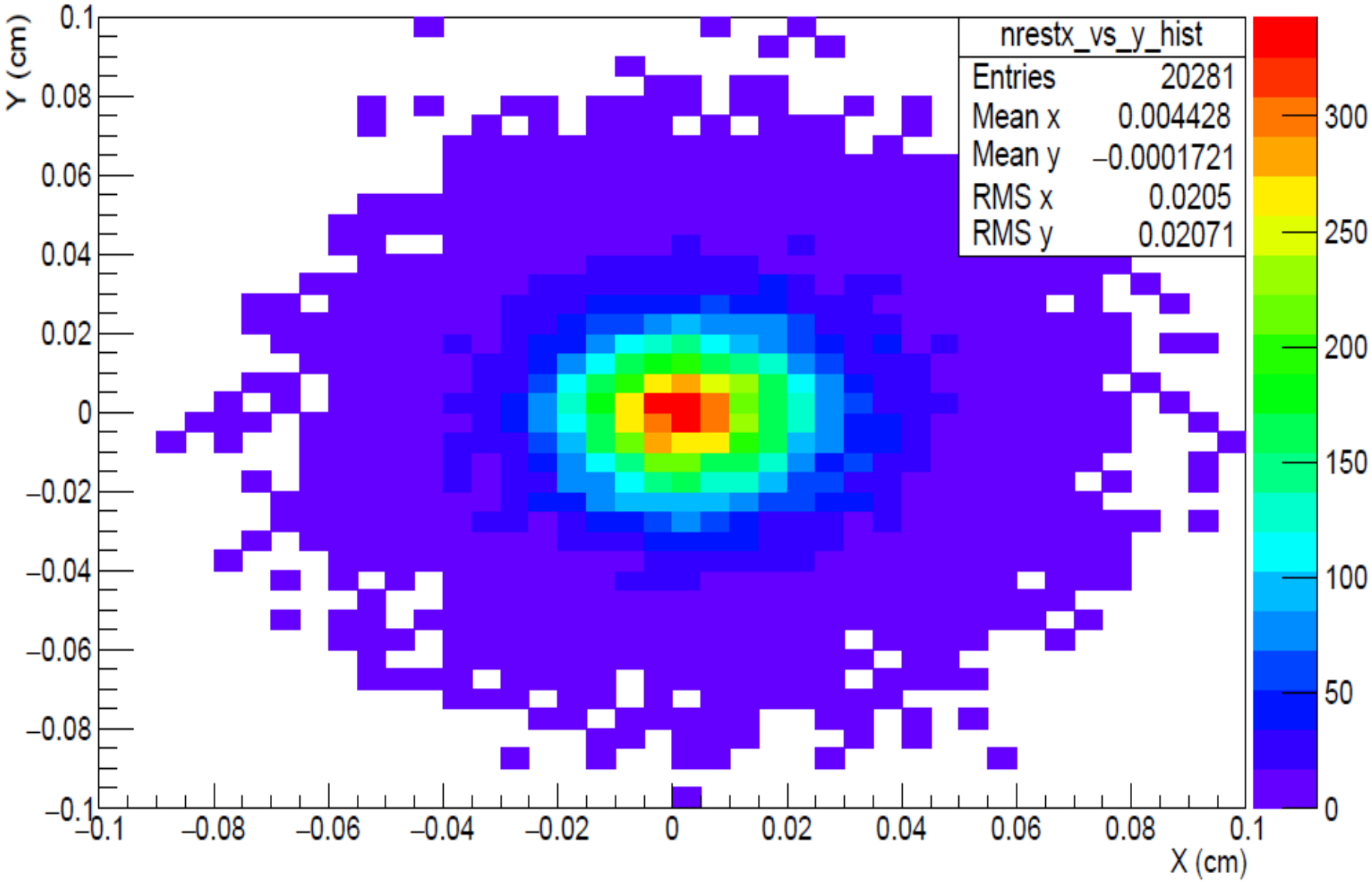
Analysis	Data	Simulation
e' ID	Yes	Yes
p' ID	Yes	Yes
π^- ID	Yes	Yes
e' momentum correction	Yes	No
p' energy loss correction	Yes	Yes
Exclusive cut	Yes	Yes
Quasi-free cut	Yes	Yes



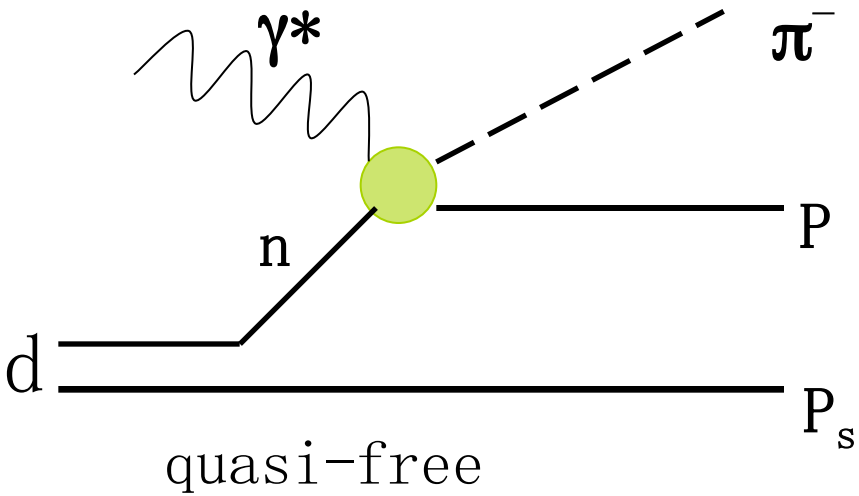
Radiative Correction

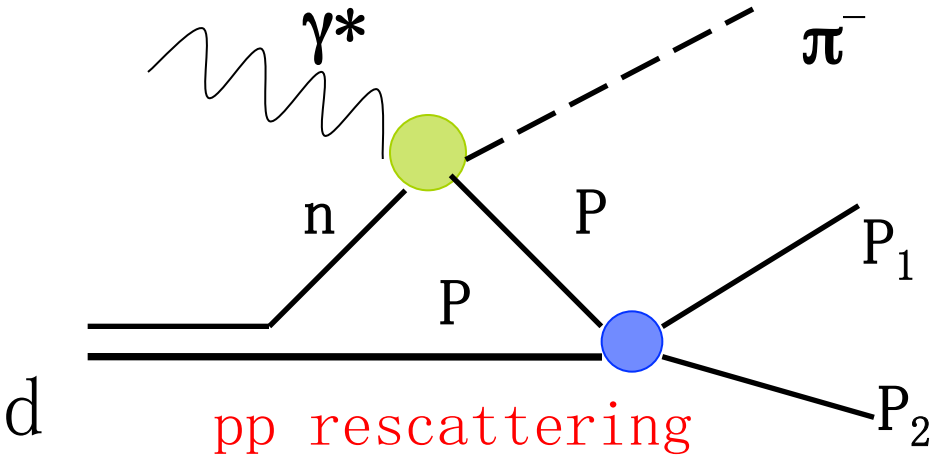


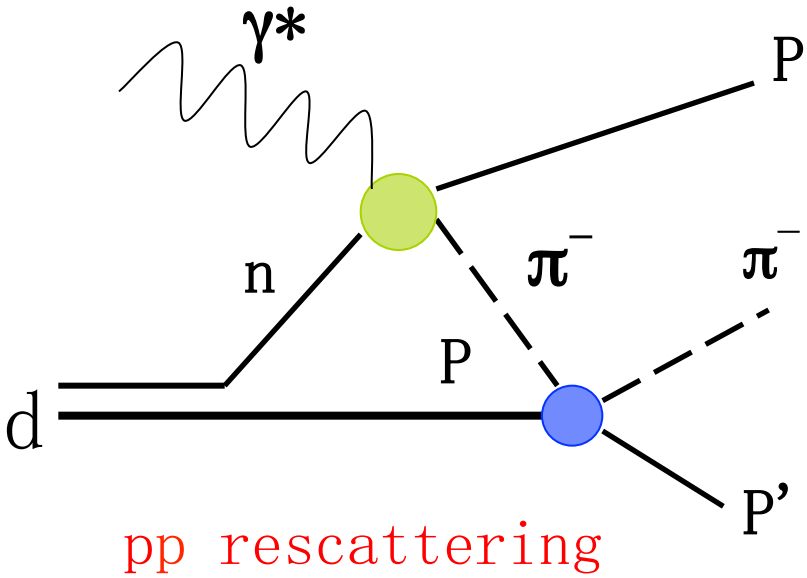
The X and Y projection of Z_{nrest} in the CM frame

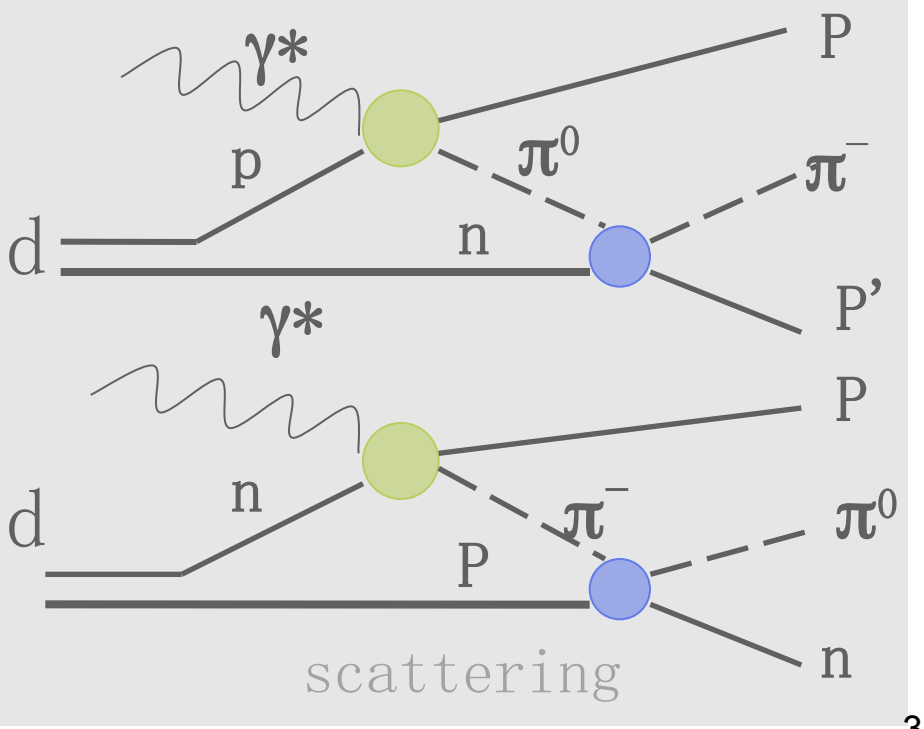


Final state interactions









Other Channels

$\gamma^* p(n) \rightarrow p\ \pi^+\pi^-(n)$ main background channel

$\gamma^* p(n) \rightarrow p\ \pi^0(n) \rightarrow \pi^- p$ final state goes in channel

$\gamma^* n(p) \rightarrow p\ \pi^-(p) \rightarrow \pi^0 n$ final state goes out channel

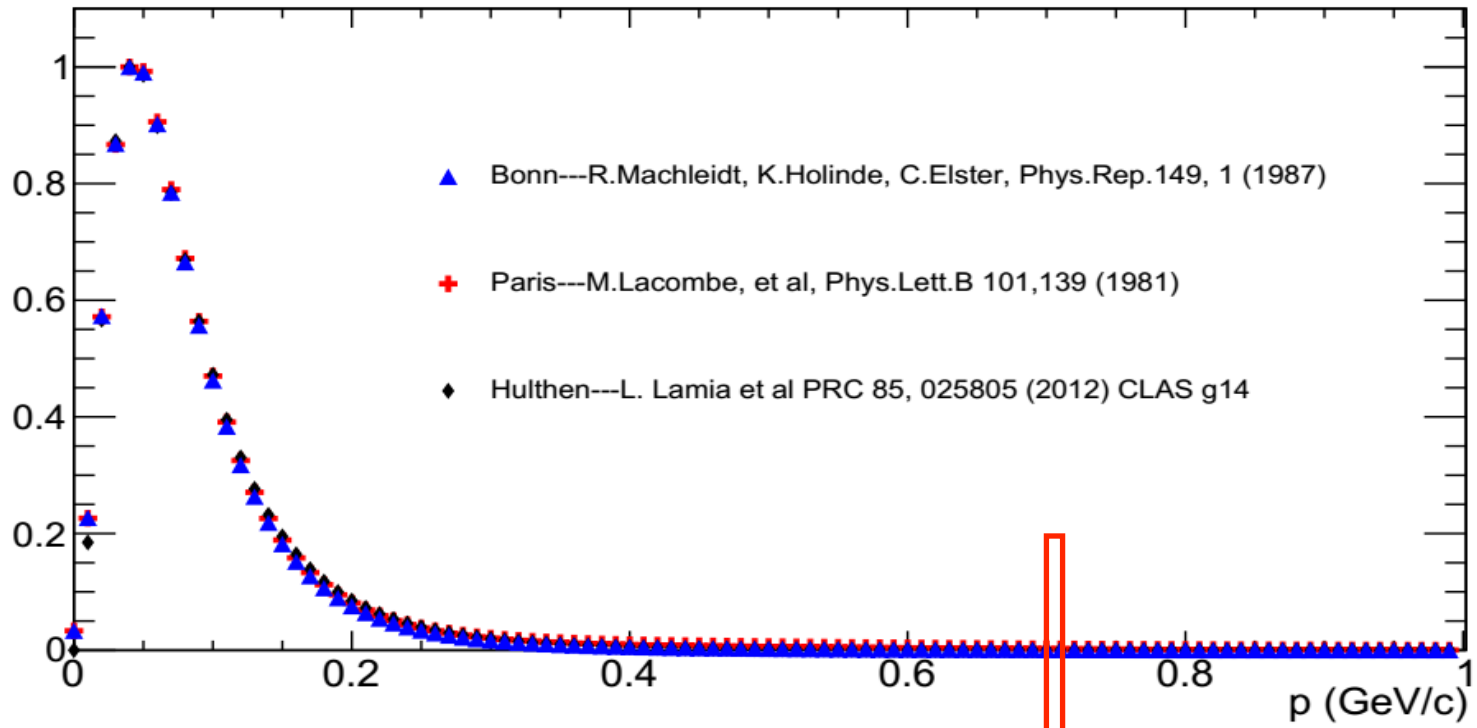
Need combined analysis channels

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

$$\gamma^* + d(p) \rightarrow \pi^+ + n + n_s$$

$$\gamma^* + d(n) \rightarrow \pi^- + p + p_s$$

Simulation



comparison data courtesy of Reinhard Schumacher

$$\gamma^* + n \rightarrow p + \pi^-$$

MAID2000 generated data

$$\gamma^* + n + p_s \rightarrow p + \pi^- + p_s$$

experimental data

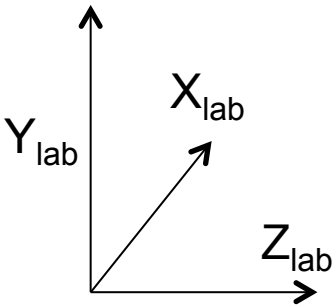
$$\gamma^* + d(n) \rightarrow p + \pi^- + p_s$$

Data Status

Reaction	Observable	W value GeV	Q^2 value GeV^2	Lab/experiment
$en(p) \to e'\pi^- p(p)$ $ep(n) \to e'\pi^+ n(n)$	$R_{\pi^-\backslash\pi^+}$	2.15, 3.11	1.2, 4.0	Cornell/WSL [13]
$en(p) \to e'\pi^- p(p)$ $ep(n) \to e'\pi^+ n(n)$	$d\sigma\backslash d\Omega_\pi$	2.15, 2.65	1.2, 2.0	Cornell/WSL [14]
$en(p) \to e'\pi^- p(p)$ $ep(n) \to e'\pi^+ n(n)$	$R_{\pi^-\backslash\pi^+}$	1.28-1.71	0.5	Daresbury/NINA [58]
$en(p) \to e'\pi^- p(p)$ $ep(n) \to e'\pi^+ n(n)$	$R_{\pi^-\backslash\pi^+}$	1.3-1.7	1.0	Daresbury/NINA [42]
$ep(n) \to e'\pi^+ n(n)$ $en(p) \to e'\pi^- p(p)$	$R_{\pi^+\backslash\pi^-}$	1.16, 1.232	0.0856, 0.0656	ALS [29]
$en(p) \to e'p\pi^-(p)$	σ_L, σ_T	1.15, 1.6	0.4	JLab-HallA [28]
$en(p) \to e'p\pi^-(p)$	σ_L, σ_T	1.95, 2.45	0.6, 1.0, 1.6, 2.45	JLab-HallC [34]

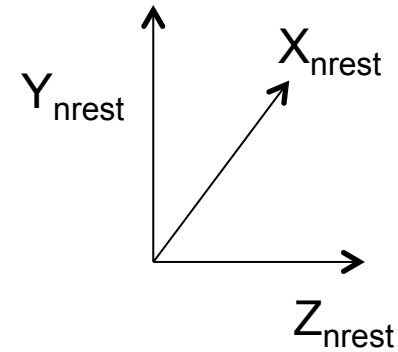
$$R_{\pi^-\backslash\pi^+} = \frac{d\sigma(\gamma_\nu + n \to \pi^- + p)}{d\sigma(\gamma_\nu + p \to \pi^+ + n)} = \frac{Rate(e+d \to e+\pi^- + p(p))}{Rate(e+d \to e+\pi^+ + n(n))}$$

Exclusive π^- Production Kinematic

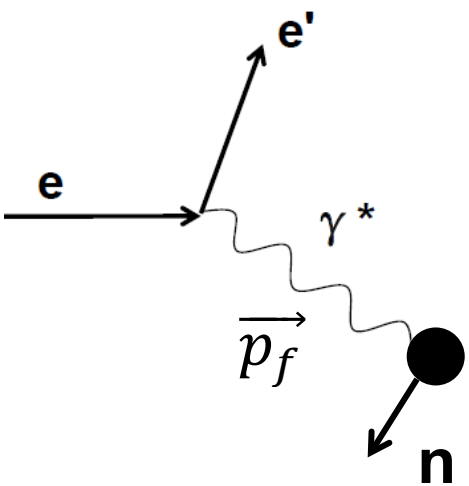


Lab → n at rest

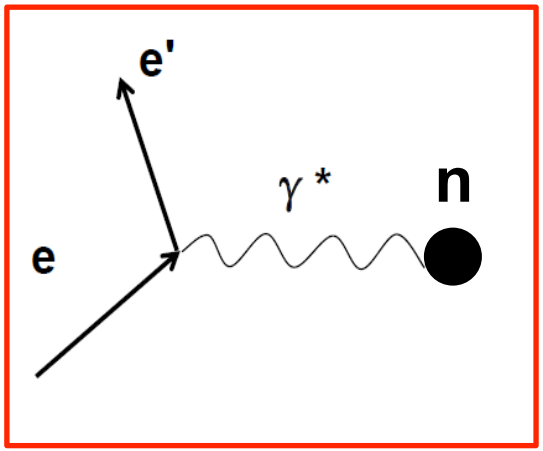
boost



$$\vec{\beta}_1 = -\frac{\vec{n}}{E_n}$$



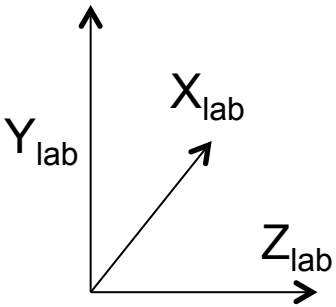
$$W_f = \sqrt{\left(p^u + \pi^{-u}\right)^2}$$



$$Q^2 = -\left(q^u\right)^2 = -\left(e^u - e'^u\right)^2$$

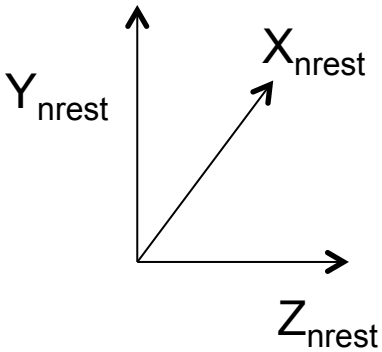
$$q^\mu + n^\mu + p_i^\mu = \pi^\mu + p^\mu + p_s^\mu$$

Exclusive π^- Production Kinematic

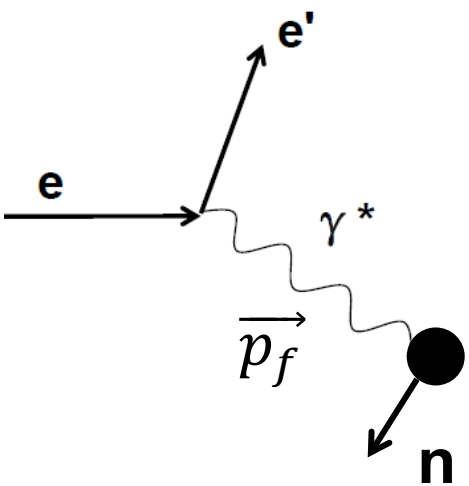


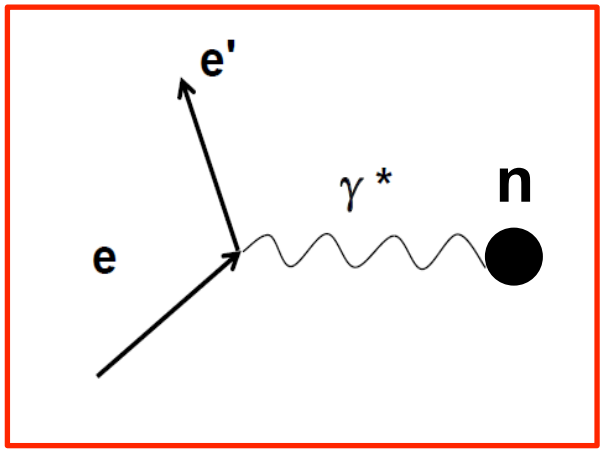
Lab → n at rest

boost



$$\vec{\beta}_1 = -\frac{\vec{n}}{E_n}$$





$$q^\mu + n^\mu + p_i^\mu = \pi^\mu + p^\mu + p_s^\mu$$