Measurement of Double Pion Electroproduction Cross-sections

Reaction: $ep \rightarrow e'p'\pi^+\pi^-$

$Q^2 = [2.0, 5.0] GeV^2$

$W = [1.400, 2.125] GeV$

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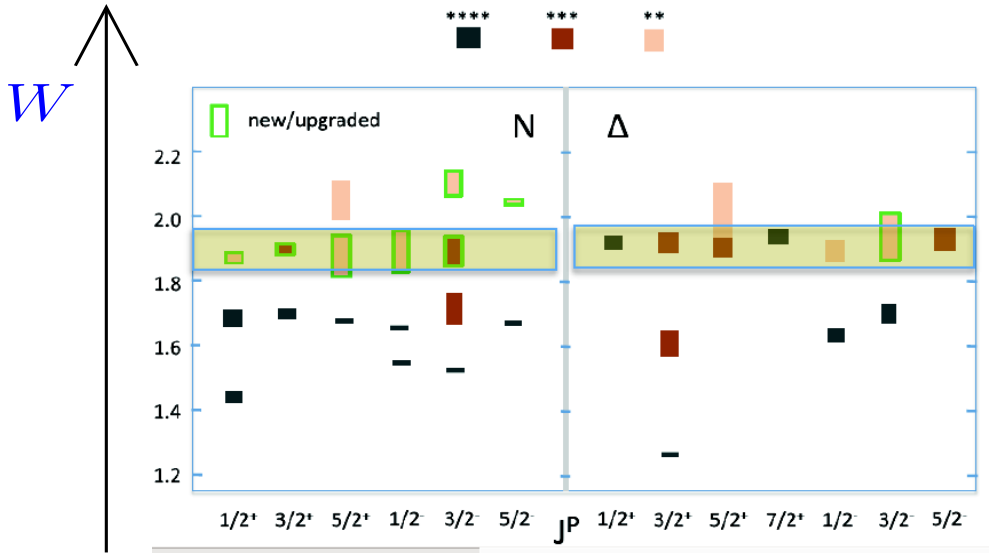
Partially supported by US National Science Foundation under grant PHY-1205782

CLAS Hadron Spectroscopy Group Meeting
November 3, 2016

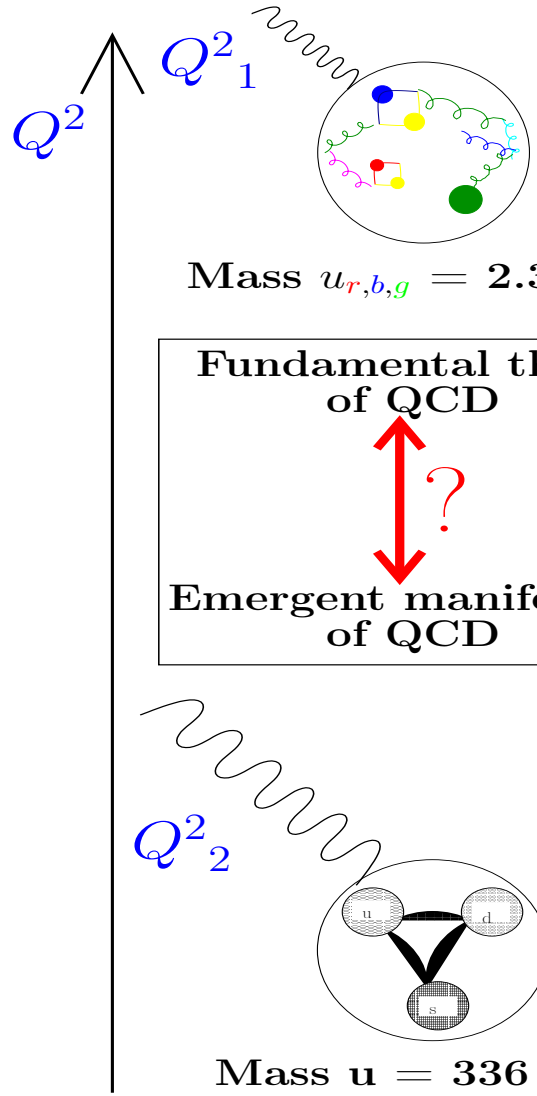
Outline

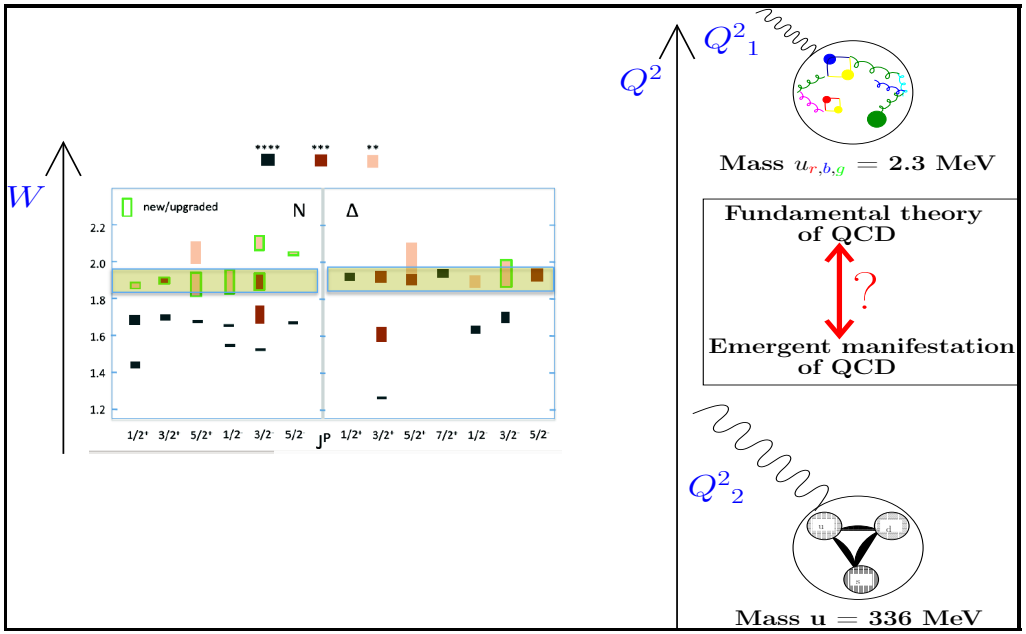
1. My analysis
   - In the physics perspective
   - In the N* program perspective
   - Measurements
   - Core tasks
   - Preliminary results
2. Summary and Outlook

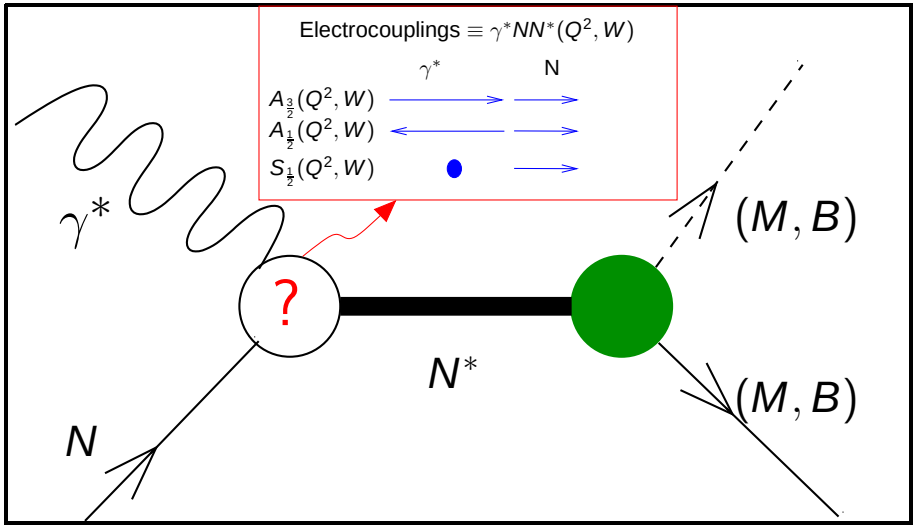
Photoproduction → Spectroscopy



Electroproduction → Transition Form Factors (TFF)

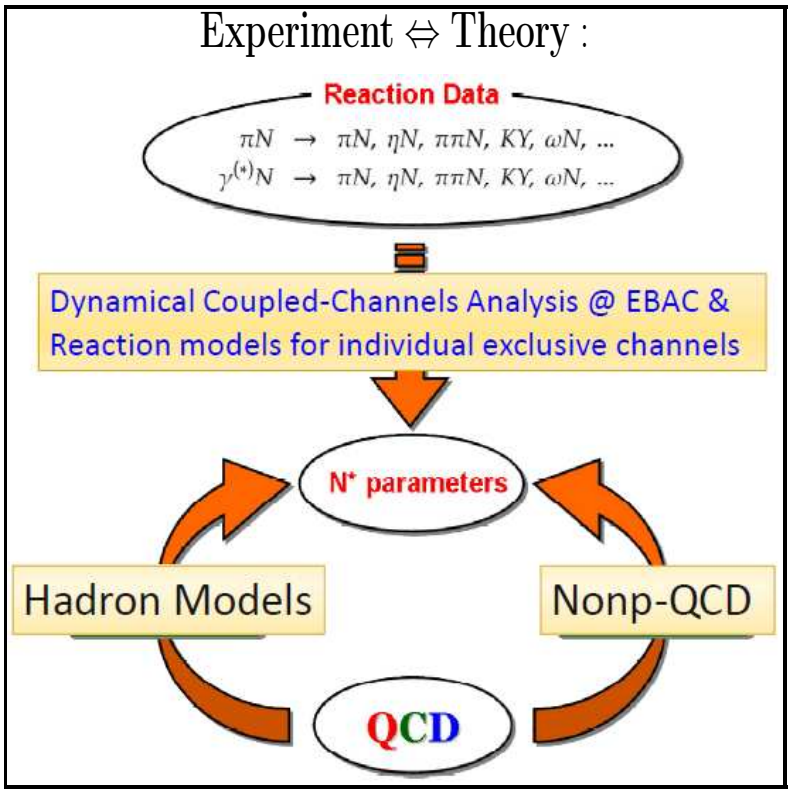


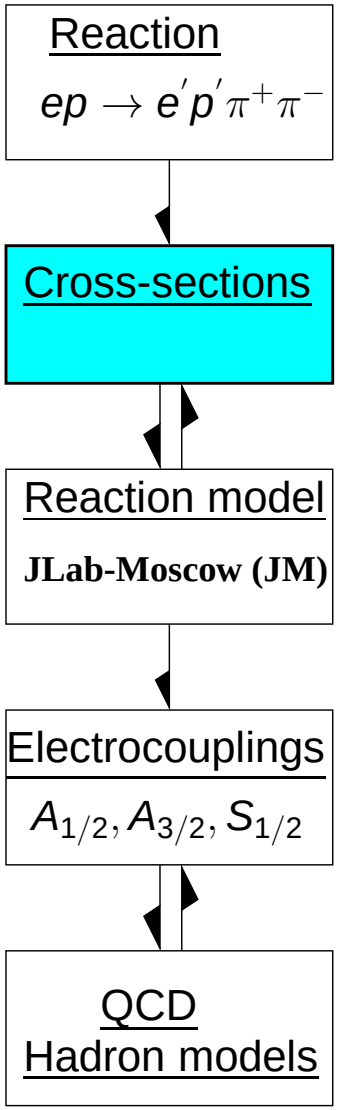




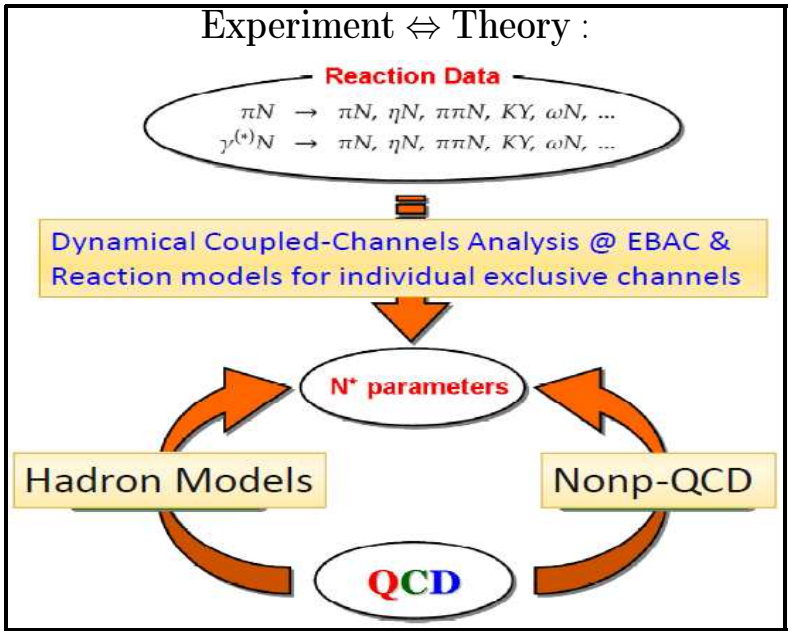
- $A_{\frac{1}{2}}(W), A_{\frac{3}{2}}(W) \rightarrow A_{\frac{1}{2}}(Q^2, W), A_{\frac{3}{2}}(Q^2, W), S_{\frac{1}{2}}(Q^2, W) := \text{TFF}$

Epistemological structure of the N* program



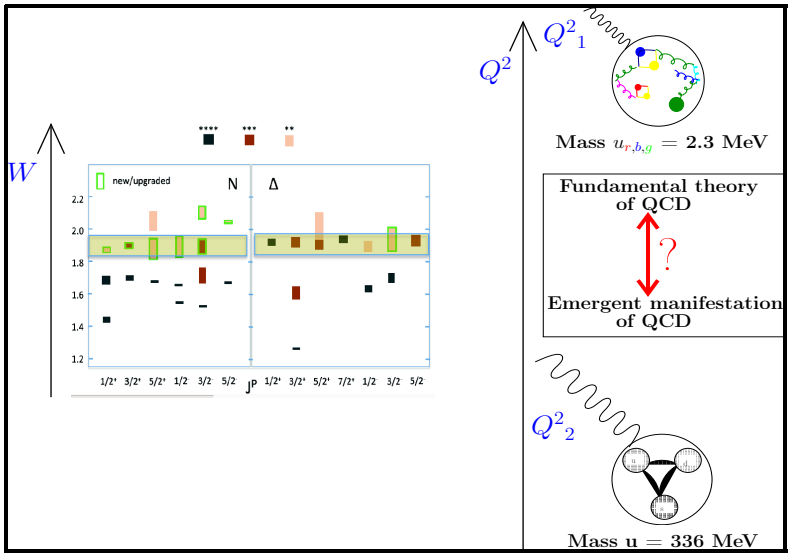


Reaction and its kinematic coverage



Results from the N* Program at Jefferson Lab.
(Journal of Physics: Conference Series 299 (2011) 012008)

$p(\gamma, K)X$	[3]	$p(e, e'K^+K^-)p, p(e, e'K^+\pi^-)X$	[17]
$p(\gamma, \eta, \eta')p$	[4]	$p(e, e'\pi)N$	[18]
$D(\gamma, \eta),\ D(\gamma, \eta')$	[5]	$\vec{p}(\vec{e}, e'p)\pi^0$	[19]
$p(\gamma, \pi)N$	[6]	$p(e, e'\omega)p$	[20]
$p(\vec{\gamma}, \omega)p$	[7]	$p(e, e'\pi^+\pi^-)p$	[21]
$\vec{\gamma}\vec{p} \rightarrow K^+\Lambda, K^+\Sigma, K^0\Sigma^+$	[8]	$\vec{p}(\vec{e}, e'\pi)n$	[22]
$\vec{p}(\vec{\gamma}, \pi^+)n, \vec{p}(\vec{\gamma}, p)\pi^0$	[9]	$p(\vec{e}, e'p)\pi^0,\ p(\vec{e}, e'\pi^+)n$	[23]
$\vec{p}(\vec{\gamma}, \eta)p$	[10]	$p(e, e'p)\pi^0$	[24]
$\vec{p}(\vec{\gamma}, \pi^+\pi^-p)$	[11]	$p(e, e'K^+)\Lambda, \Sigma$	[25]
$n(\vec{\gamma}, K\Lambda)$	[12]	$p(e, e'\pi^0)p, p(e, e'\pi^+)n$	[26]
$p(e, e'\pi)N$	[13]	$p(e, e'\pi^+\pi^-p)$	[27]
$p(e, e'\pi^+)n,\ p(e, e'p)\pi^0,\ n(e, e'\pi^-)p$	[14]	$p(\vec{e}, e'K, \vec{\Lambda}, \vec{\Sigma})$	[28]
$p(e, e'p)\eta$	[15]	$p(e, e'p)\pi^0, \eta$	[29]
$p(\vec{e}, e'p)\pi^0,\ p(\vec{e}, e'\pi^+)n$	[16]		

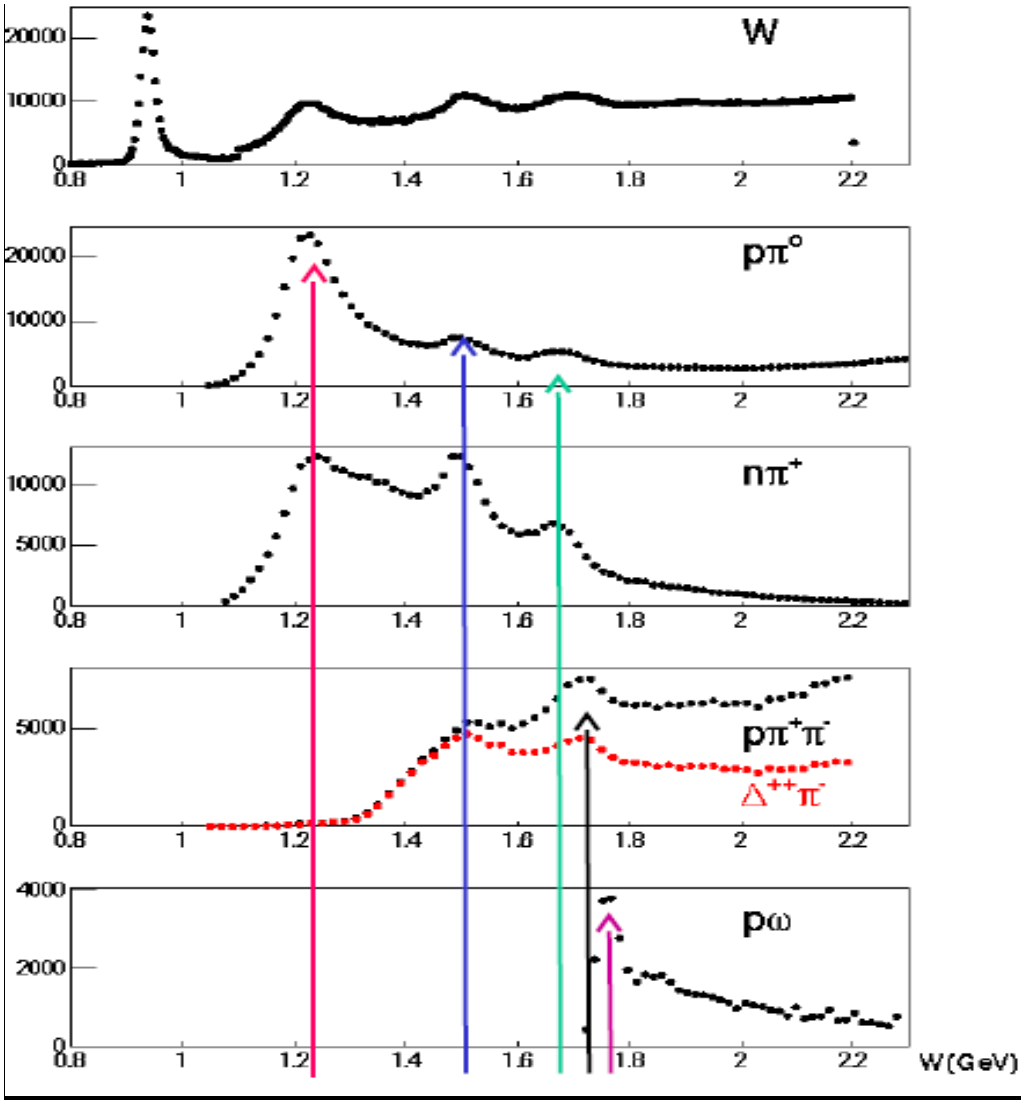


Q^2 coverage , GeV^2	W coverage, GeV	Bin size over W/Q^2 , GeV/GeV^2	Data status
0.20-0.60	1.30-1.57	0.025/0.050	Completed [69]
0.50-1.50	1.40-2.10	0.025/0.3-0.4	Completed [70]
2.0-5.0	1.40-2.00	0.025/0.5	In progress
0.	1.60-2.80	0.025	In progress

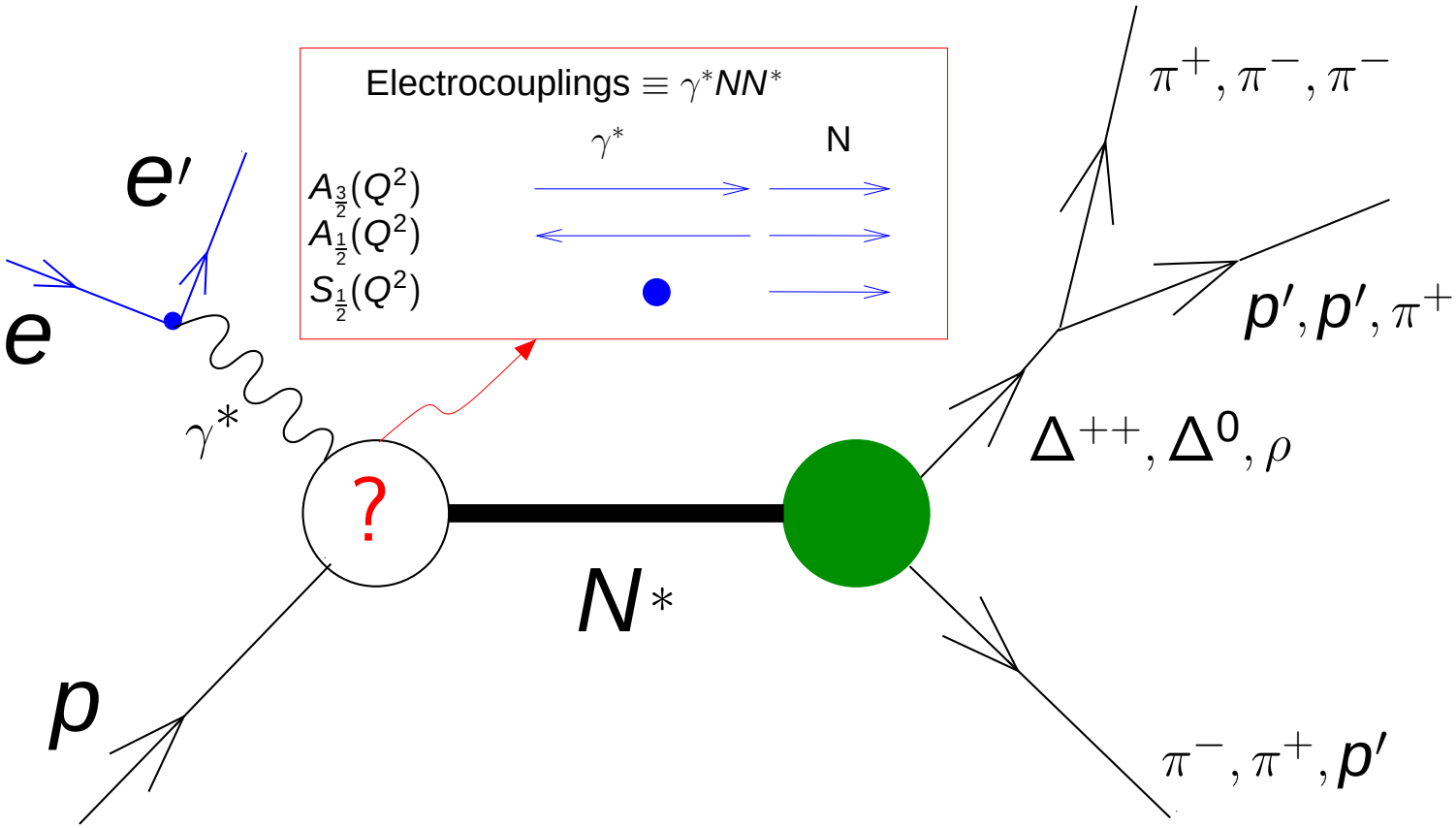
Significance of $p\pi^+\pi^-$ channel

In relation to π channel

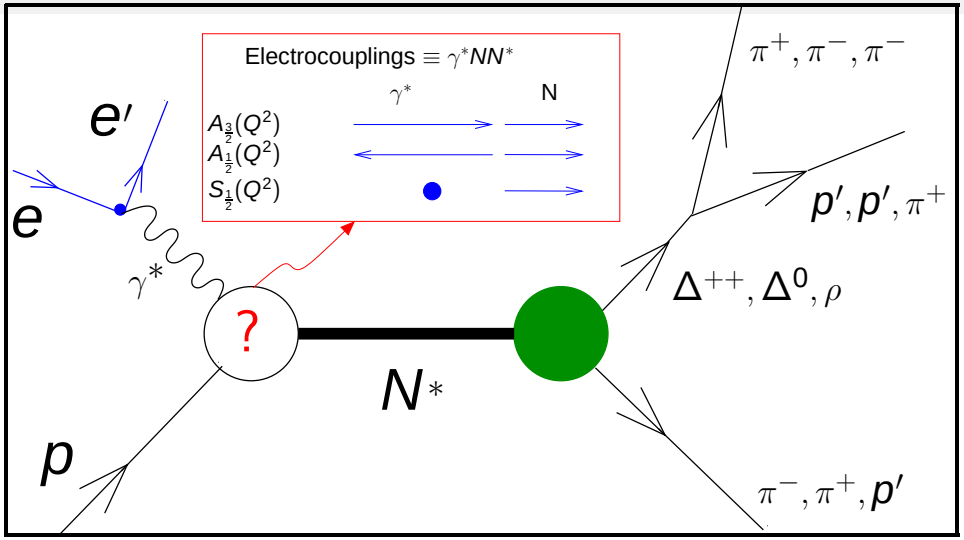
- Access to higher W
- Cross-check for extracted TFFs
  - Has different background contributions



Cross-sections from $ep \rightarrow e'p'\pi^+\pi^-$



Cross-sections from $ep \rightarrow e'p'\pi^+\pi^-$



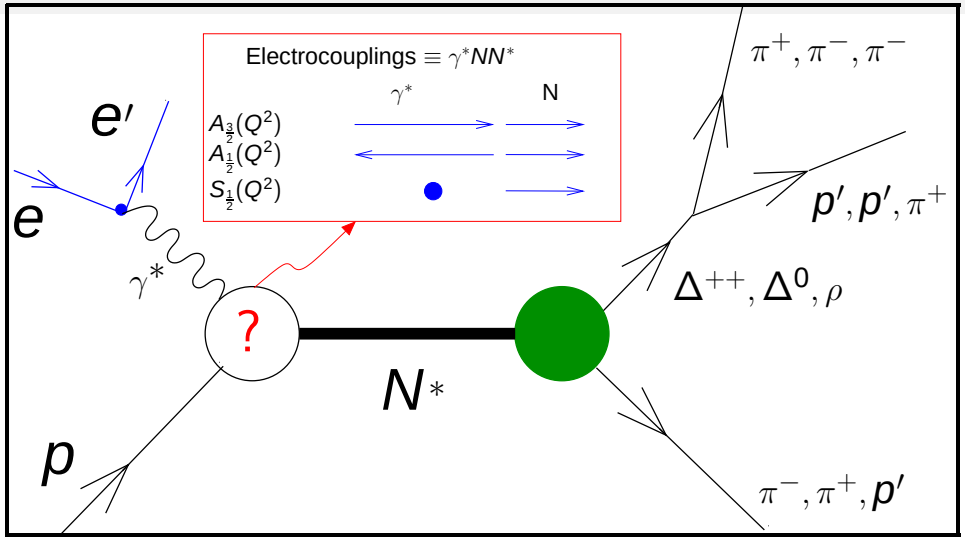
Variable sets

Δ^{++} : $M_{p\pi^+}, \theta^*_{\pi^-}, \phi^*_{\pi^-}, \alpha^*_{[p'\pi^+][p\pi^-]}, M_{\pi^+\pi^-}$

Δ^0 : $M_{p\pi^-}, \theta^*_{\pi^+}, \phi^*_{\pi^+}, \alpha^*_{[p'\pi^-][p\pi^+]}, M_{p\pi^+}$

ρ : $M_{\pi^+\pi^-}, \theta^*_p, \phi^*_p, \alpha^*_{[\pi^+\pi^-][p'p]}, M_{p\pi^+}$

Cross-sections from $ep \rightarrow e'p'\pi^+\pi^-$



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Δ^0 : $M_{p\pi^-}, \theta^*_{\pi^+}, \phi^*_{\pi^+}, \alpha^*_{[p'\pi^-][p\pi^+]}, M_{p\pi^+}$

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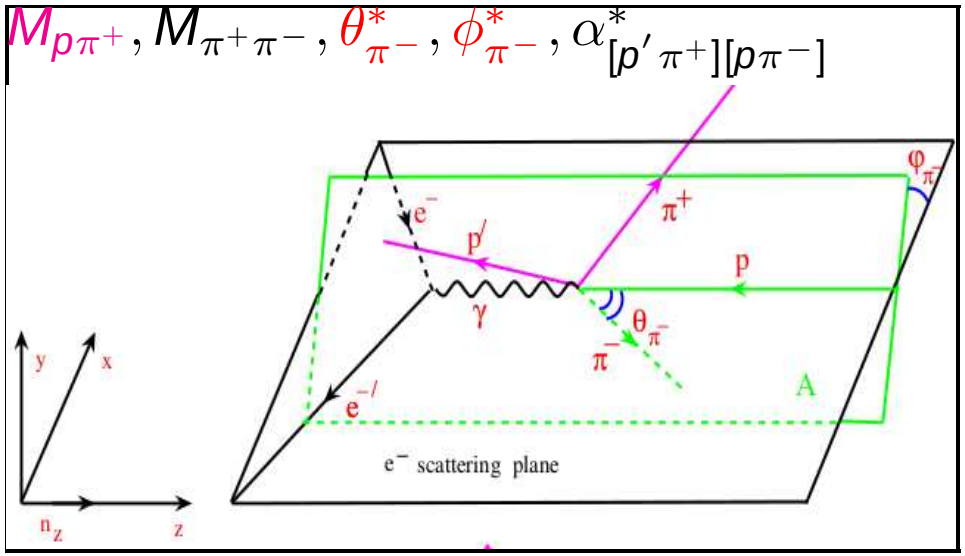
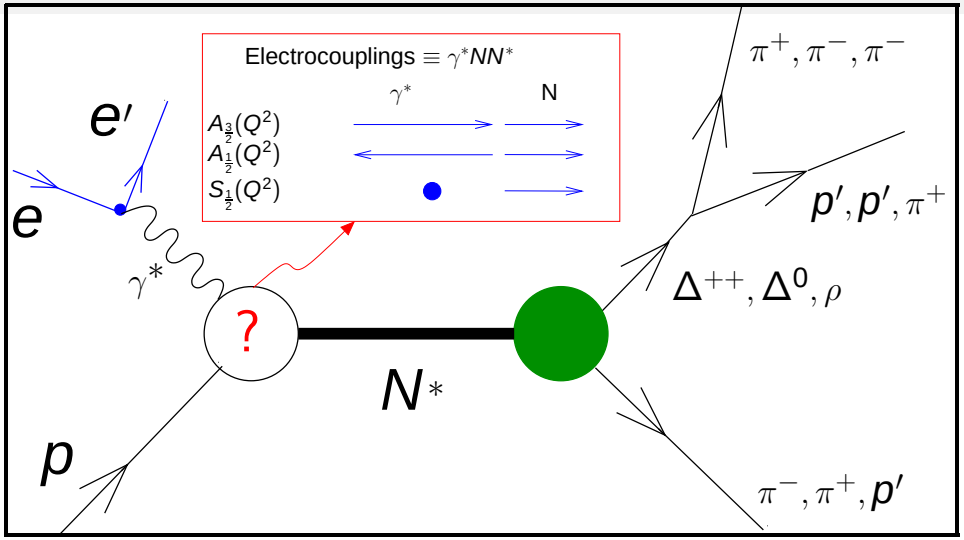


Cross-sections from $ep \rightarrow e'p'\pi^+\pi^-$



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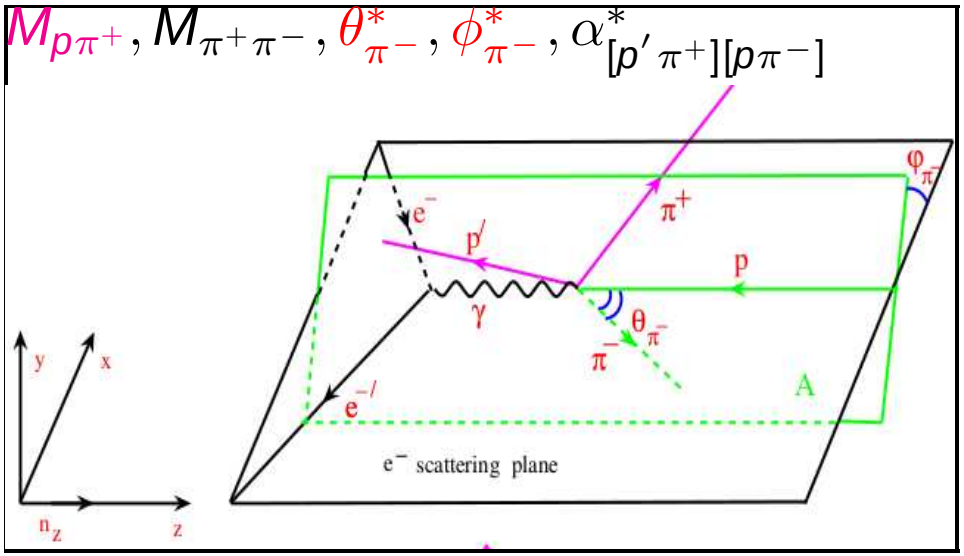
Δ^0 : $M_{p\pi^-}, \theta^*_{\pi^+}, \phi^*_{\pi^+}, \alpha^*_{[p'\pi^-][p\pi^+]}, M_{p\pi^+}$

ρ : $M_{\pi^+\pi^-}, \theta^*_{p}, \phi^*_{p}, \alpha^*_{[\pi^+\pi^-][p'p]}, M_{p\pi^+}$

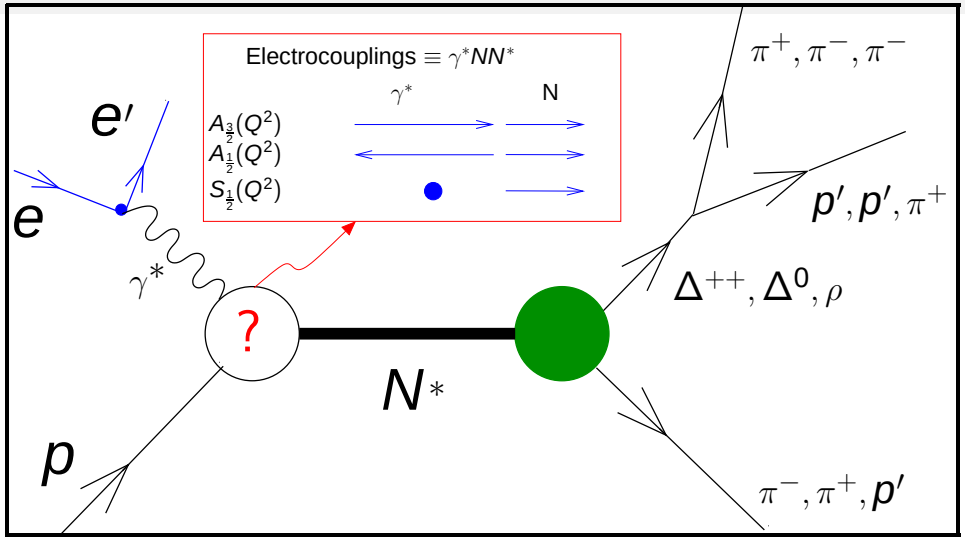


Cross-sections

Independent of γ^* polarization:

1 $\frac{d^5\sigma}{d\tau^5} \rightarrow \frac{d\sigma}{dX_{ij}}$

Cross-sections from $ep \to e'p'\pi^+\pi^-$



Variable sets

Δ^{++} : $M_{p\pi^+}, \theta^*_{\pi^-}, \phi^*_{\pi^-}, \alpha^*_{[p'\pi^+][p\pi^-]}, M_{\pi^+\pi^-}$

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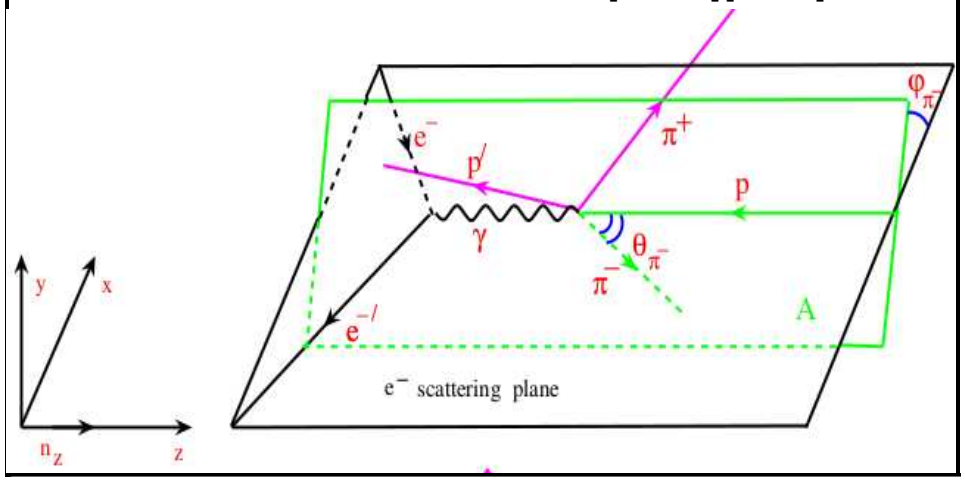
$M_{p\pi^+}, M_{\pi^+\pi^-}, \theta^*_{\pi^-}, \phi^*_{\pi^-}, \alpha^*_{[p'\pi^+][p\pi^-]}$



Cross-sections

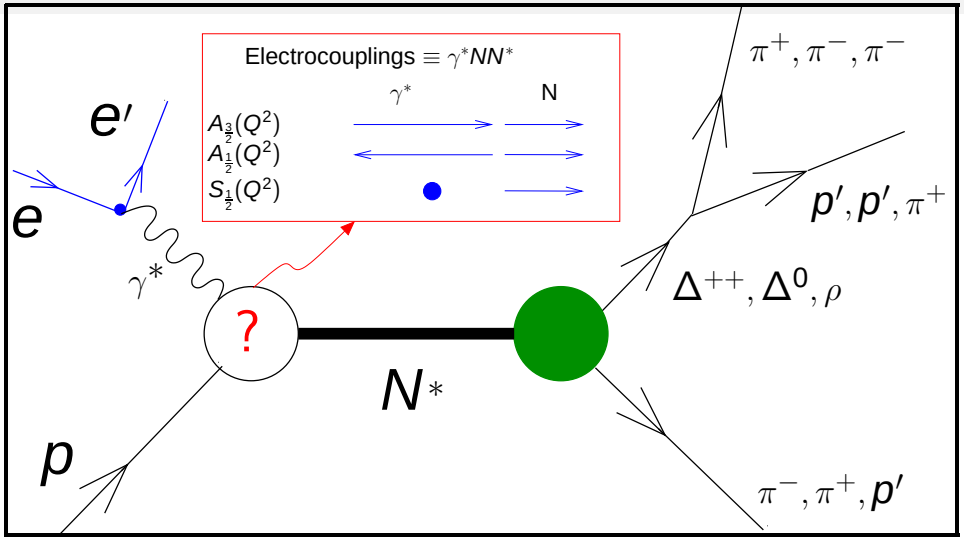
1. Independent of γ^* polarization:

$$\frac{d^5\sigma}{d\tau^5} \to \frac{d\sigma}{dX_{ij}}$$

2. Sensitive to γ^* polarization:

$$\left(\frac{d^2\sigma}{dX_{ij}d\phi_i}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + R2_{LT}{}^{c,X_{ij}}\cos\phi_i + R2_{TT}{}^{c,X_{ij}}\cos 2\phi_i + \delta_{X_{ij}\alpha_i}\left(R2_{LT}{}^{s,\alpha_i}\sin\phi_i + R2_{TT}{}^{s,\alpha_i}\sin 2\phi_i\right)$$

Cross-sections from $ep \to e'p'\pi^+\pi^-$



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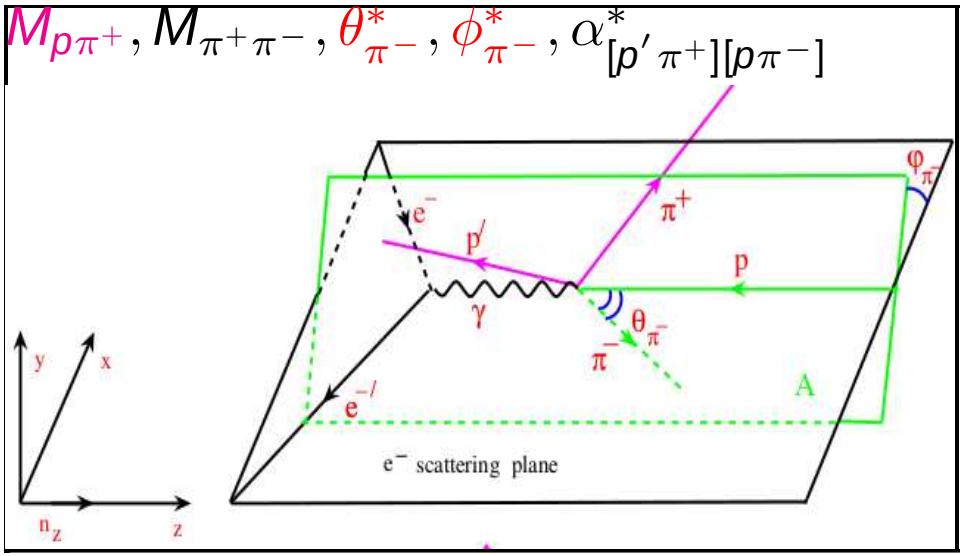
ρ : $M_{\pi^+\pi^-}, \theta^*_{p}, \phi^*_{p}, \alpha^*_{[\pi^+\pi^-][p'p]}, M_{p\pi^+}$



Cross-sections

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All possible observables: A glimpse

Polarization Observables for Electroproduction

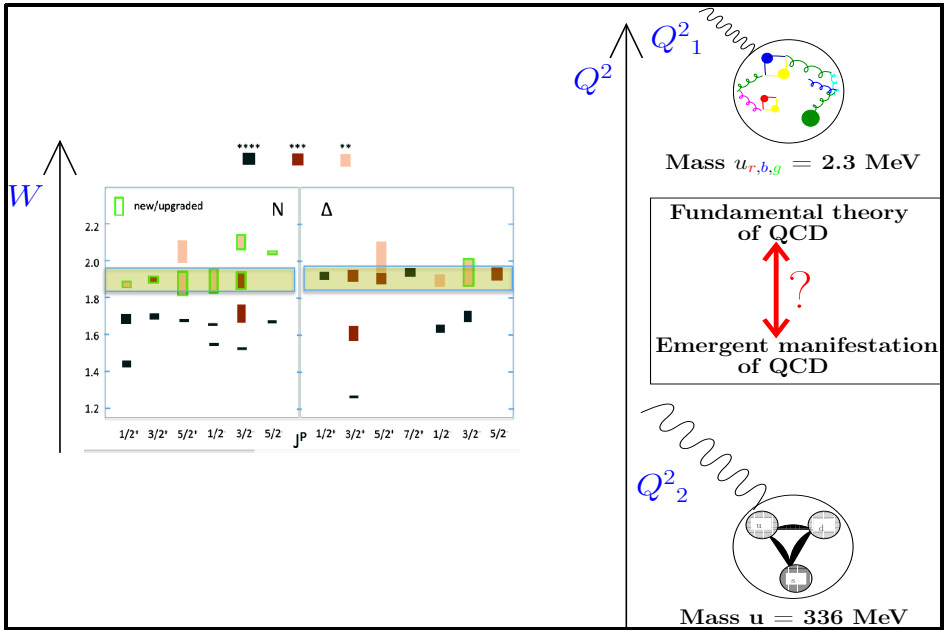
(arXiv:nucl-th/9506029v1)

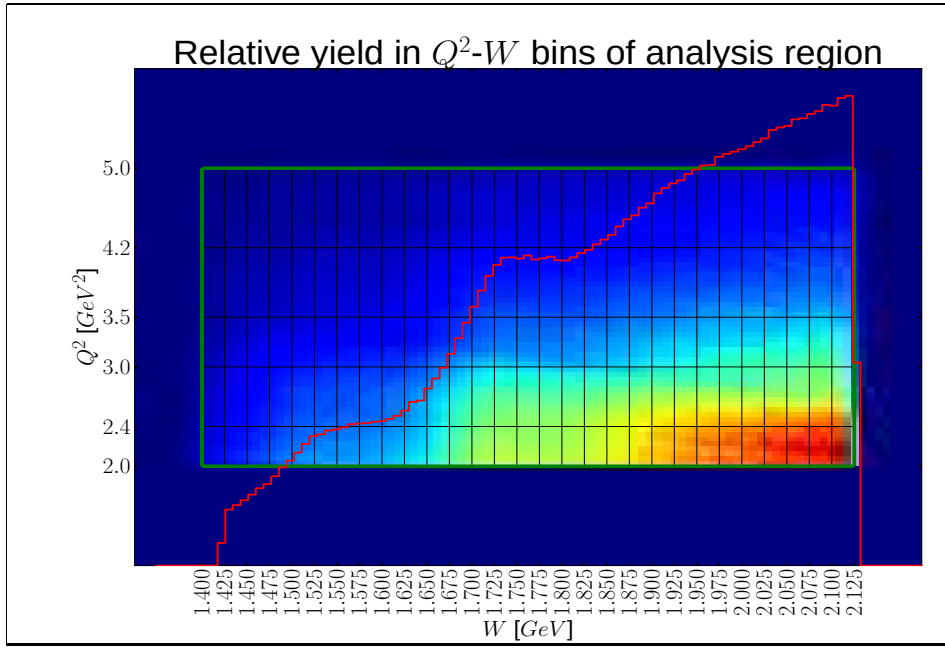
	Target				Recoil			Target + Recoil								
β	–	–	–	–	x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
α	–	x	y	z	–	–	–	x	y	z	x	y	z	x	y	z
T	R_T^{00}	0	R_T^{0y}	0	0	$R_T^{y'0}$	0	$R_T^{x'x}$	0	$R_T^{x'z}$	0	$*$	0	$R_T^{z'x}$	0	$R_T^{z'z}$
L	R_L	0	R_L^{0y}	0	0	$*$	0	$R_L^{x'x}$	0	$R_L^{x'z}$	0	$*$	0	$*$	0	$*$
^cTL	$^cR_{TL}^{00}$	0	$^cR_{TL}^{0y}$	0	0	$*$	0	$^cR_{TL}^{x'x}$	0	$*$	0	$*$	0	$^cR_{TL}^{z'x}$	0	$*$
^sTL	0	$^sR_{TL}^{0x}$	0	$^sR_{TL}^{0z}$	$^sR_{TL}^{x'0}$	0	$^sR_{TL}^{z'0}$	0	$*$	0	$*$	0	$*$	0	$*$	0
^cTT	$^cR_{TT}^{00}$	0	$*$	0	0	$*$	0	$*$	0	$*$	0	$*$	0	$*$	0	$*$
^sTT	0	$^sR_{TT}^{0x}$	0	$^sR_{TT}^{0z}$	$^sR_{TT}^{x'0}$	0	$^sR_{TT}^{z'0}$	0	$*$	0	$*$	0	$*$	0	$*$	0
$^cTL'$	0	$^cR_{TL'}^{0x}$	0	$^cR_{TL'}^{0z}$	$^cR_{TL'}^{x'0}$	0	$^cR_{TL'}^{z'0}$	0	$*$	0	$*$	0	$*$	0	$*$	0
$^sTL'$	$^sR_{TL'}^{00}$	0	$^sR_{TL'}^{0y}$	0	0	$*$	0	$^sR_{TL'}^{x'x}$	0	$*$	0	$*$	0	$^sR_{TL'}^{z'x}$	0	$*$
TT'	0	$R_{TT'}^{0x}$	0	$R_{TT'}^{0z}$	$R_{TT'}^{x'0}$	0	$R_{TT'}^{z'0}$	0	$*$	0	$*$	0	$*$	0	$*$	0

- Note that this table is applicable for single pseudoscalar electroproduction
- In case of double (charged) pseudoscalar electroproduction, in addition to ${}^cR2_{LT}^{00}$ and ${}^cR2_{TT}^{00}$, ${}^sR2_{LT}^{00}$ and ${}^sR2_{TT}^{00}$ can be also be measured:

$$\left(\frac{d^2\sigma}{dX_{ij}\,d\phi_i}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + R2_{LT}{}^{c,X_{ij}}\cos\phi_i + R2_{TT}{}^{c,X_{ij}}\cos 2\phi_i + \delta_{X_{ij}\alpha_i}\left(R2_{LT}{}^{s,\alpha_i}\sin\phi_i + R2_{TT}{}^{s,\alpha_i}\sin 2\phi_i\right)$$

Summary





51 (30 new)1D Cross-sections per Q^2, W bin

1. $\frac{d\sigma}{dX_{ij}}$ (3x3=9)
2. γ^* polarization dependent
   - i $R2_T^{X_{ij}} + R2_L^{X_{ij}}$ (3x4=12)
   - ii $R2_{LT}^{c,X_{ij}}$ (3x4=12)
   - iii $R2_{TT}^{c,X_{ij}}$ (3x4=12)
   - iv $R2_{LT}^{s,\alpha_i}$ (3x1=3)
   - v $R2_{LT}^{s,\alpha_i}$ (3x1=3)

X_{ij} := Variable sets

1. $M_{p\pi^+}, \theta^*_{\pi^-}, \phi^*_{\pi^-}, \alpha^*_{[p'\pi^+][p\pi^-]}, M_{\pi^+\pi^-}$
2. $M_{p\pi^-}, \theta^*_{\pi^+}, \phi^*_{\pi^+}, \alpha^*_{[p'\pi^-][p\pi^+]}, M_{p\pi^+}$
3. $M_{\pi^+\pi^-}, \theta^*_{p}, \phi^*_{p}, \alpha^*_{[\pi^+\pi^-][p'p]}, M_{p\pi^+}$

Experiment: $ep \rightarrow e'X$

1. Reconstruct $ep \rightarrow e'p'\pi^+\pi^-$
   - I Particle identification
   - II Fiducial cuts
   - III Momentum corrections
   - IV Energy loss corrections
   - V Event selection
   - VI Bin events $\Rightarrow N_R^i$
2. A^i from Simulation
3. $N_T^i = N_R^i / A^i$
4. Radiative effects correction
5. $\sigma(Q^2, W) = \frac{\sum N_T^i}{L\Gamma(Q^2, W)}$

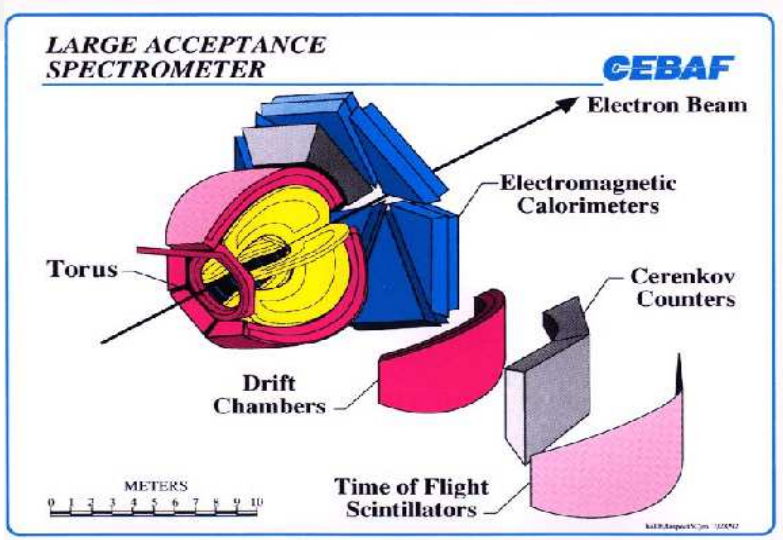
Experiment: $ep \rightarrow e'X$ Natural process

1. Reconstruct $ep \rightarrow e'p'\pi^+\pi^-$
   - I Particle identification
   - II Fiducial cuts
   - III Momentum corrections
   - IV Energy loss corrections
   - V Event selection
   - VI Bin events $\Rightarrow N_R^i$
2. A^i from Simulation
3. $N_T^i = N_R^i / A^i$
4. Radiative effects correction
5. $\sigma(Q^2, W) = \frac{\sum N_T^i}{\mathrm{L}\Gamma(Q^2, W)}$

Simulation: $ep \rightarrow e'p'\pi^+\pi^-$ Model(JM) based process

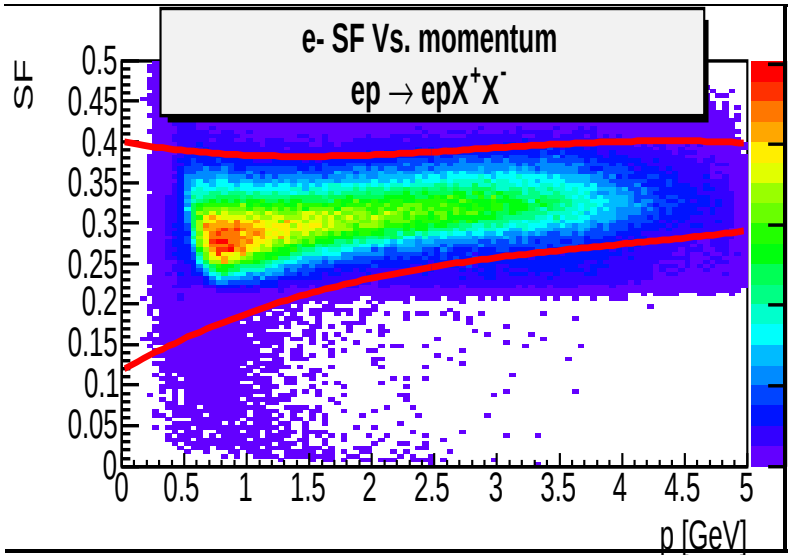
1. Reconstruct $ep \rightarrow e'p'\pi^+\pi^-$
   - I similar
   - II similar
   - III N.A.
   - IV similar
   - V similar
   - VI similar
2. $A^i = N_R^i / N_T^i$
3. $N_T^i = N_R^i / A^i$
4. N.A.
5. N.A.

Particle identification



Electrons

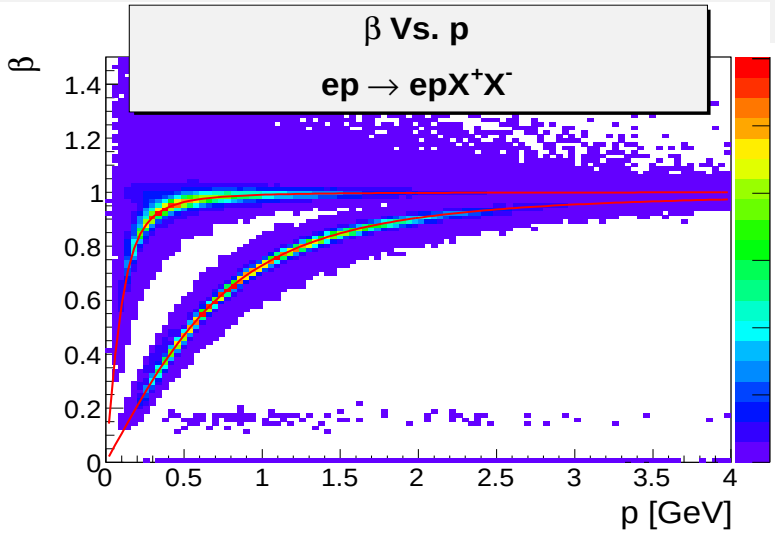
- Coincident “hit” in DC,CC,SC,EC
  - Only electrons trigger CC
- Additionally, use the EC
  - SF = $\frac{E_{EC}}{p}$ = constant

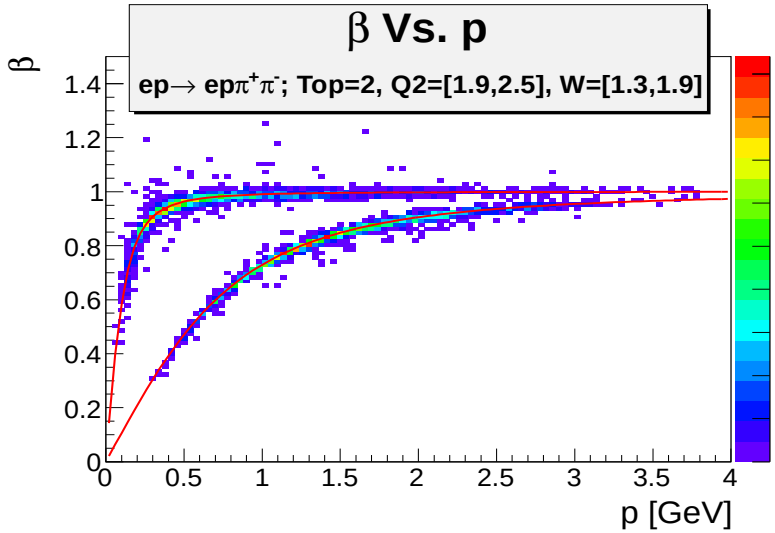


Particle identification

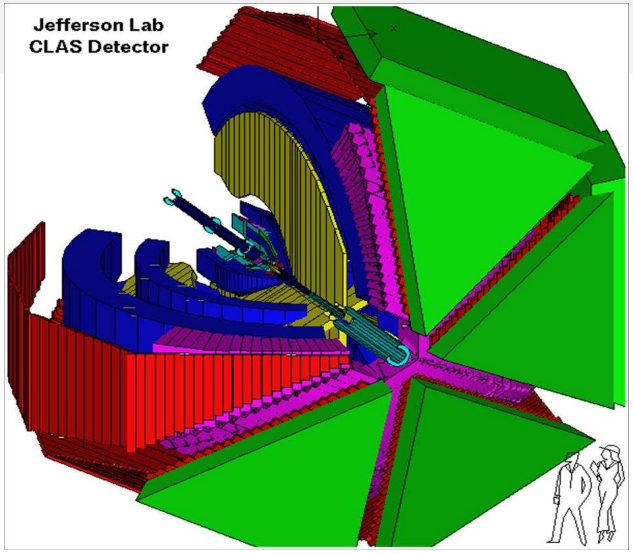
Protons & pions

- Coincident “hit” in DC & SC
- Use $\beta(=\frac{L}{t})$ vs. p correlation
  - t from SC
  - L & p from DC



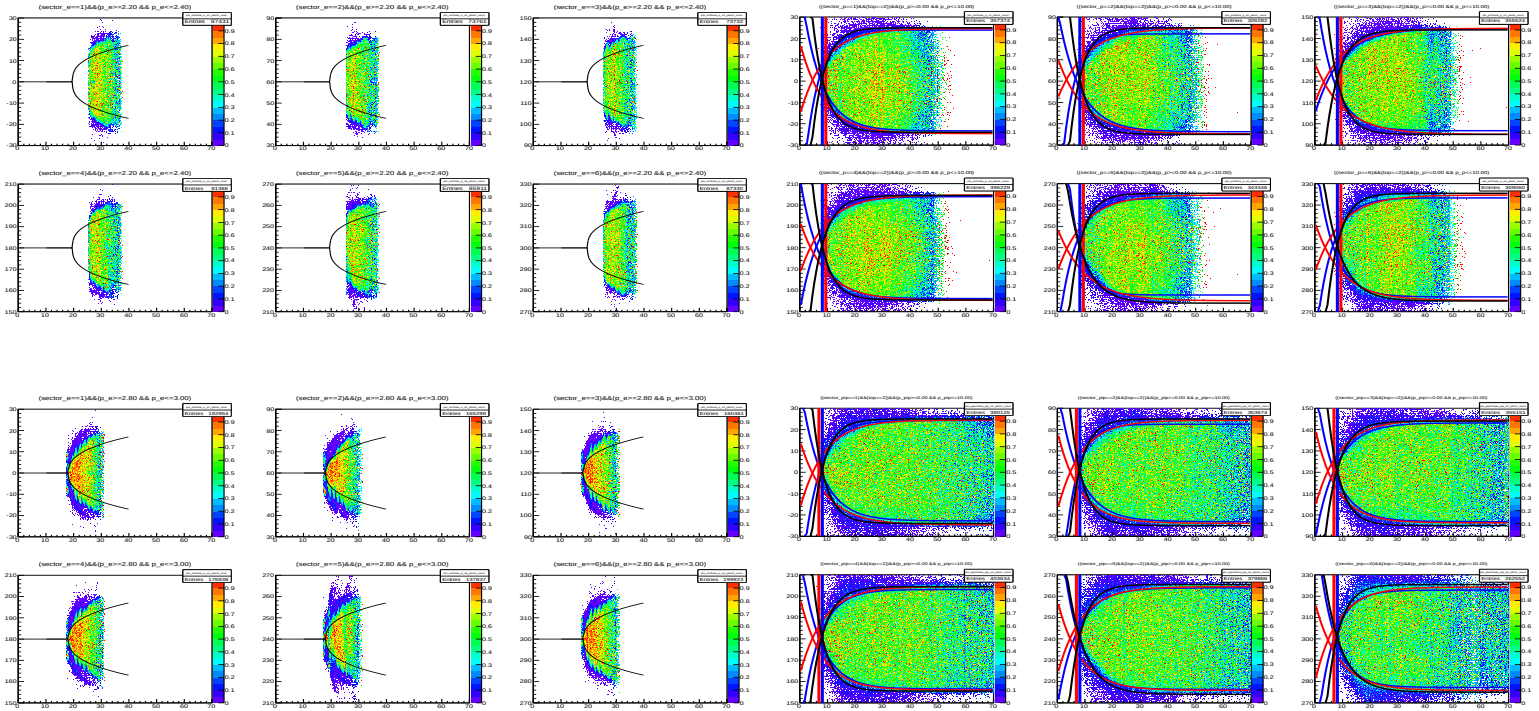


Fiducial cuts



Electron, protons and pions

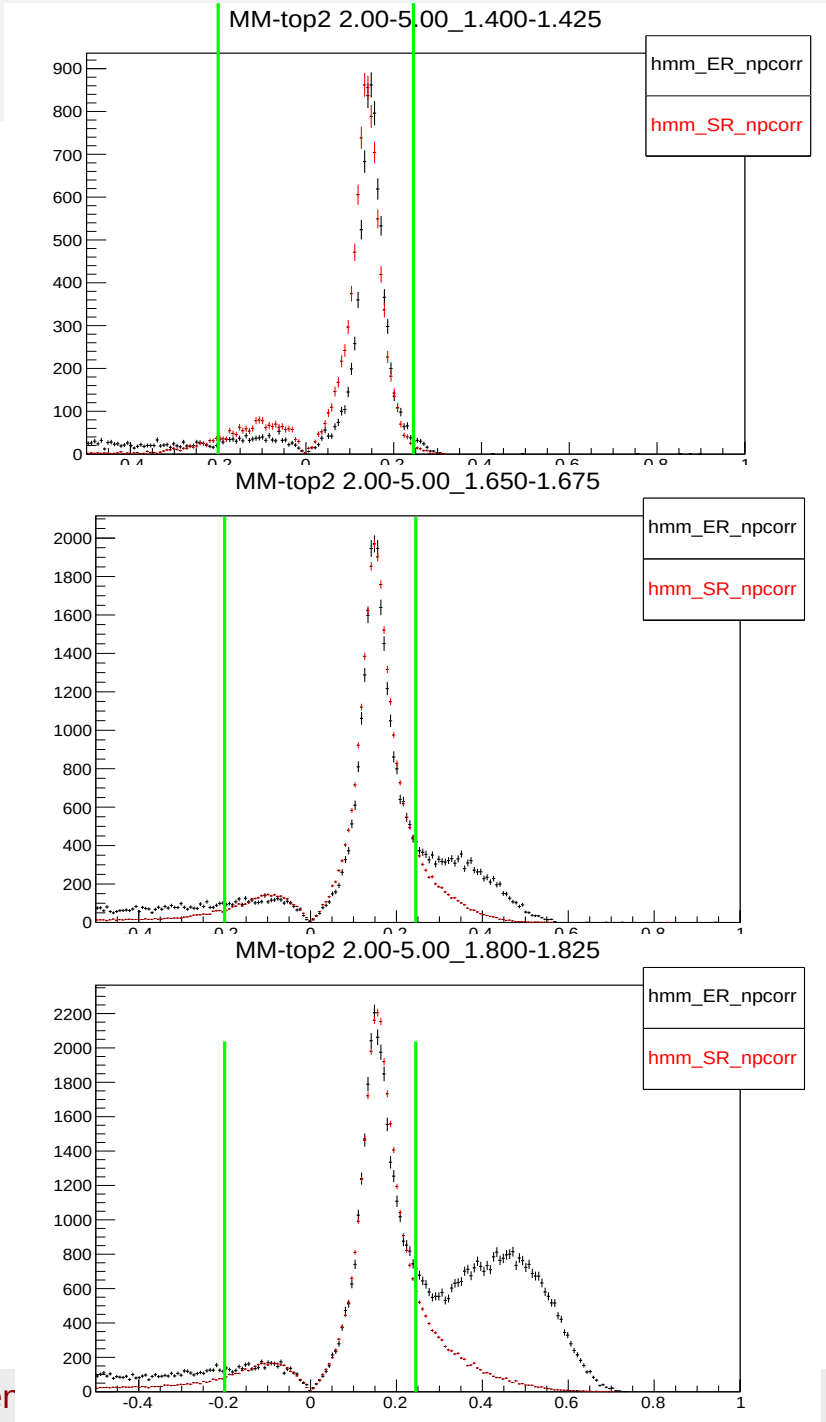
- Remove if detected at and beyond edges of fiducial volume



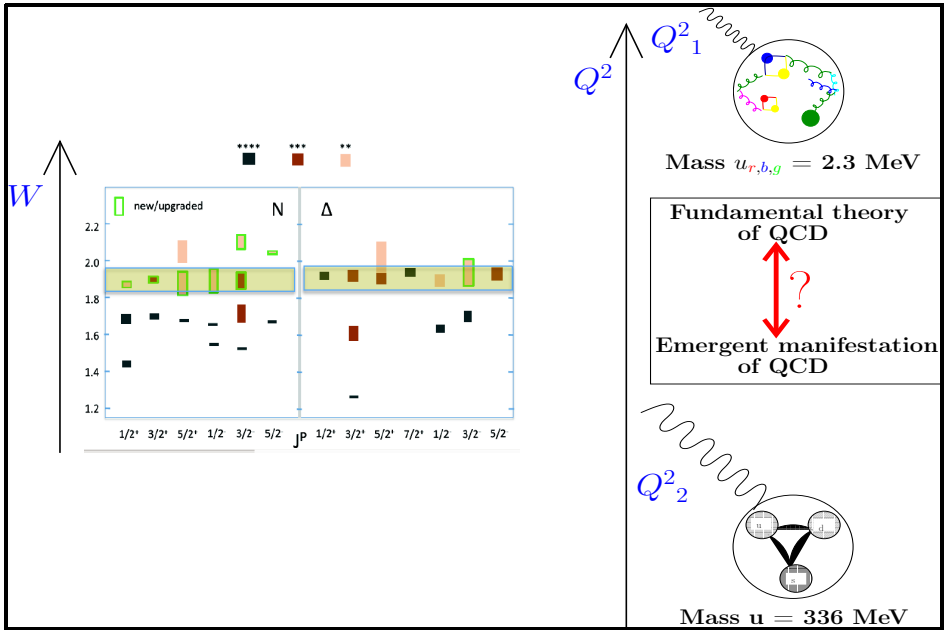
Event selection

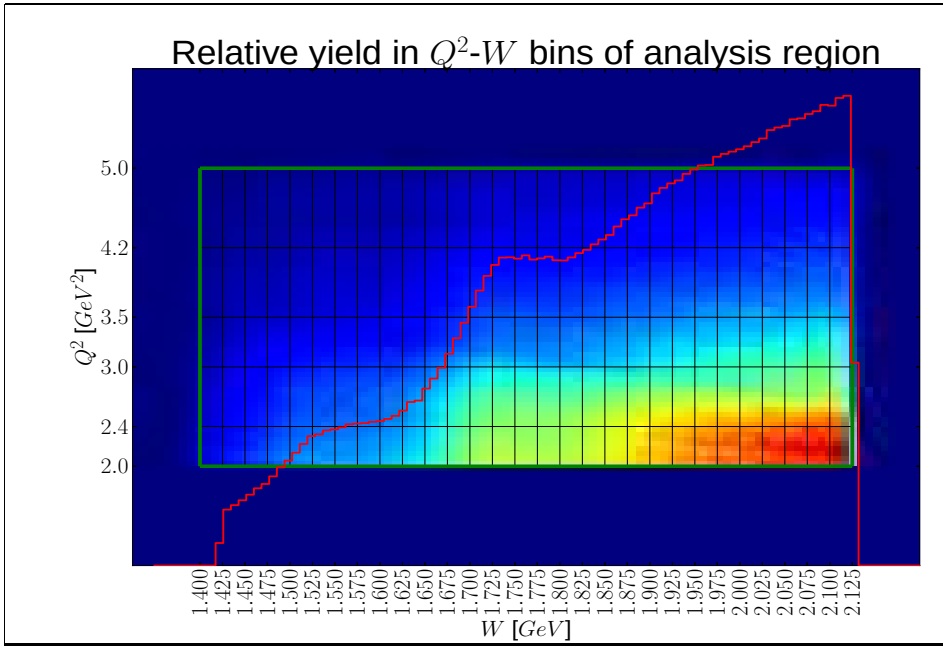
Based on Missing Mass technique

- $ep \rightarrow e'p'\pi^+X$



E16 experiment conducted in Hall B





51 (30 new)1D Cross-sections per Q^2, W bin

1. $\frac{d\sigma}{dX_{ij}}$ (3x3=9)
2. γ^* polarization dependent
   - i $R2_T^{X_{ij}} + R2_L^{X_{ij}}$ (3x4=12)
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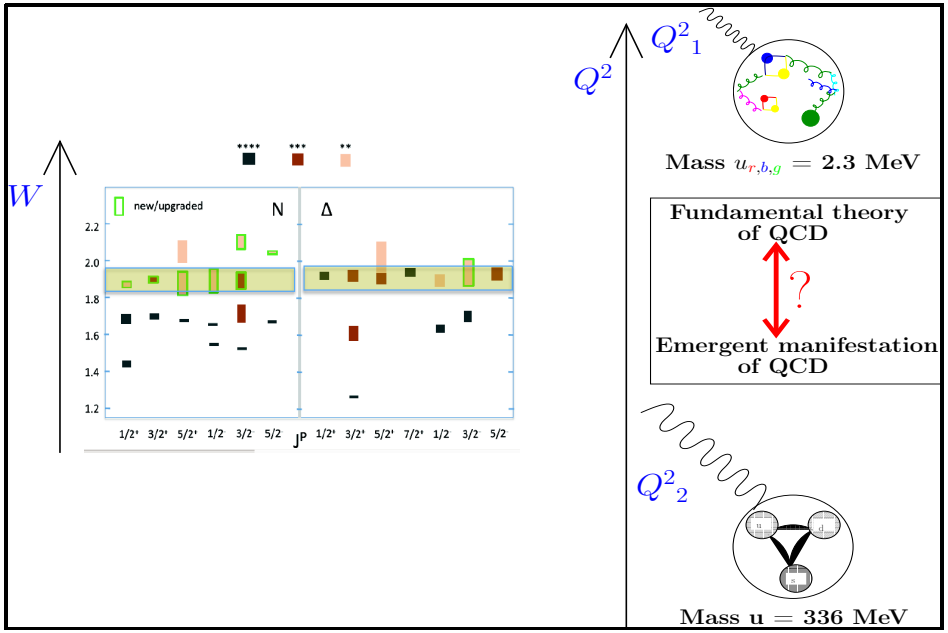
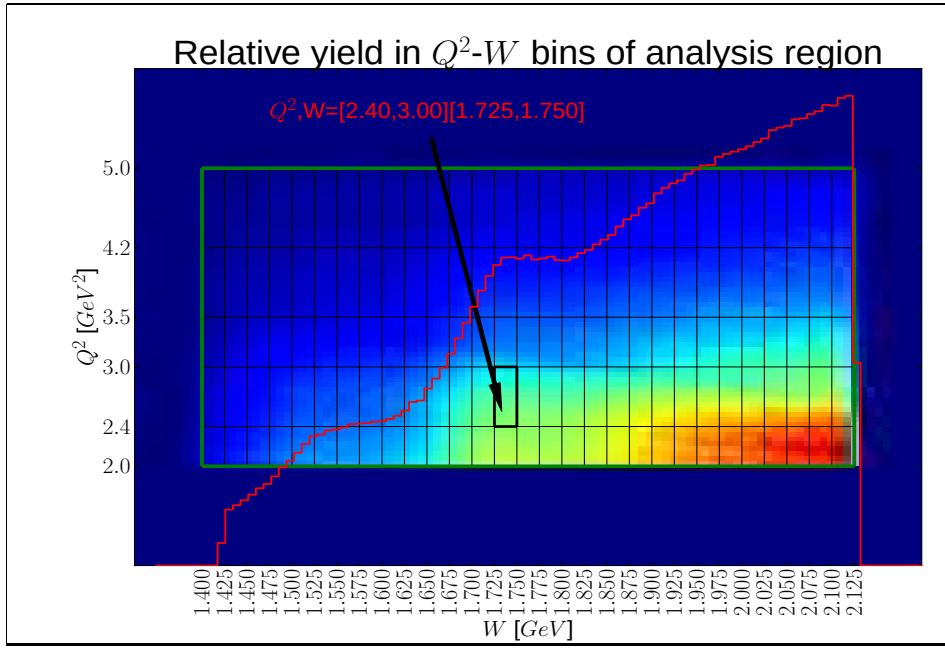
   - iv $R2_{LT}^{s,\alpha_i}$ (3x1=3)
   - v $R2_{LT}^{s,\alpha_i}$ (3x1=3)

X_{ij} := Variable sets

1. $M_{p\pi^+}, \theta^*_{\pi^-}, \phi^*_{\pi^-}, \alpha^*_{[p'\pi^+][p\pi^-]}, M_{\pi^+\pi^-}$
2. $M_{p\pi^-}, \theta^*_{\pi^+}, \phi^*_{\pi^+}, \alpha^*_{[p'\pi^-][p\pi^+]}, M_{p\pi^+}$
3. $M_{\pi^+\pi^-}, \theta^*_{p}, \phi^*_{p}, \alpha^*_{[\pi^+\pi^-][p'p]}, M_{p\pi^+}$

E16 experiment conducted in Hall B





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Single-differential cross-sections

Q^2, W bin $= [2.4, 3.0) GeV^2, [1.725, 1.750) GeV$

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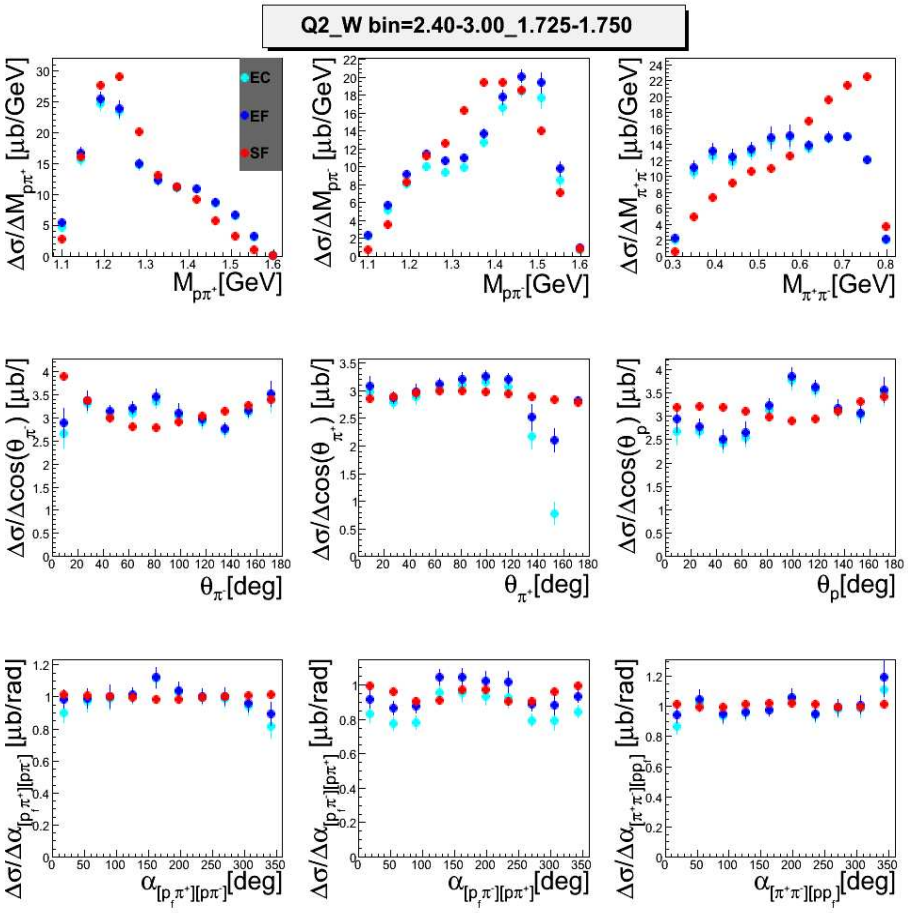

γ^* polarization dependent cross-sections

Q^2, W bin $= [2.4, 3.0) GeV^2, [1.725, 1.750) GeV$

$$\left(\frac{d^2\sigma}{dX_{ij}\,d\phi_i}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + \underline{R2_{LT}{}^{c,X_{ij}} \cos\phi_i} + \underline{R2_{TT}{}^{c,X_{ij}} \cos 2\phi_i} + \delta_{X_{ij}\alpha_i} \left(\underline{R2_{LT}{}^{s,\alpha_i} \sin\phi_i} + \underline{R2_{TT}{}^{s,\alpha_i} \sin 2\phi_i}\right)$$

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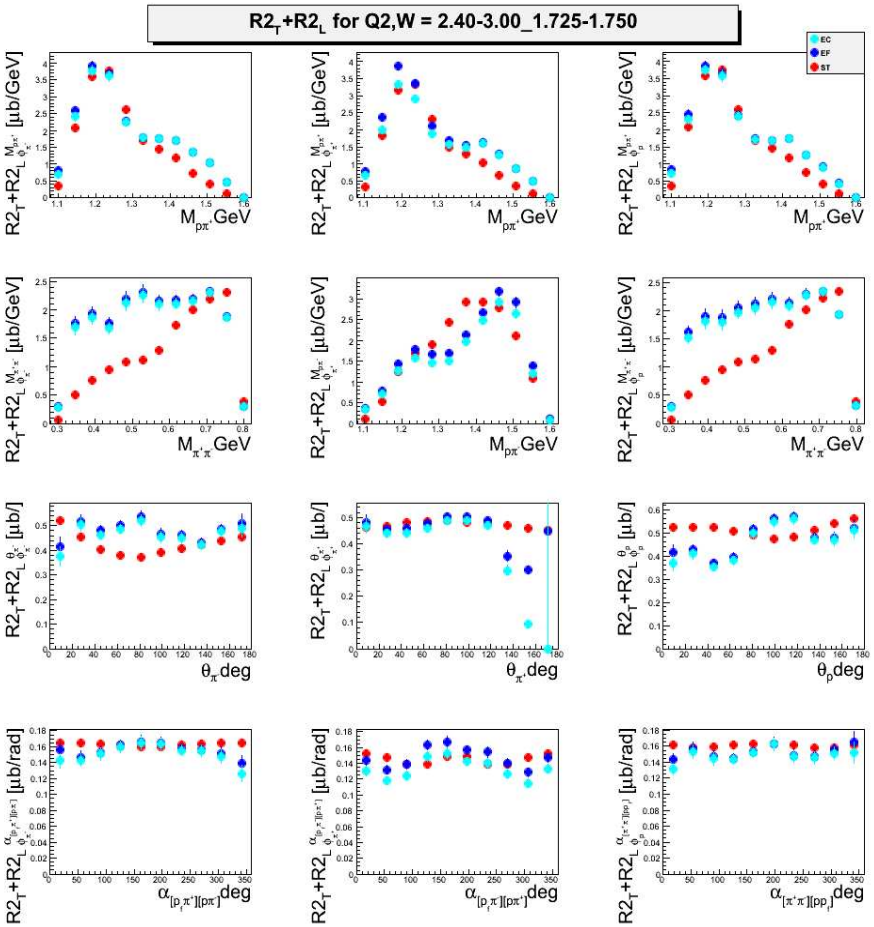

$$\left(\frac{d^2\sigma}{dX_{ij}\,d\phi_i}\right) = \underline{R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}}} + R2_{LT}{}^{c,X_{ij}} \cos\phi_i + R2_{TT}{}^{c,X_{ij}} \cos 2\phi_i + \delta_{X_{ij}\alpha_i}\left(R2_{LT}{}^{s,\alpha_i} \sin\phi_i + R2_{TT}{}^{s,\alpha_i} \sin 2\phi_i\right)$$

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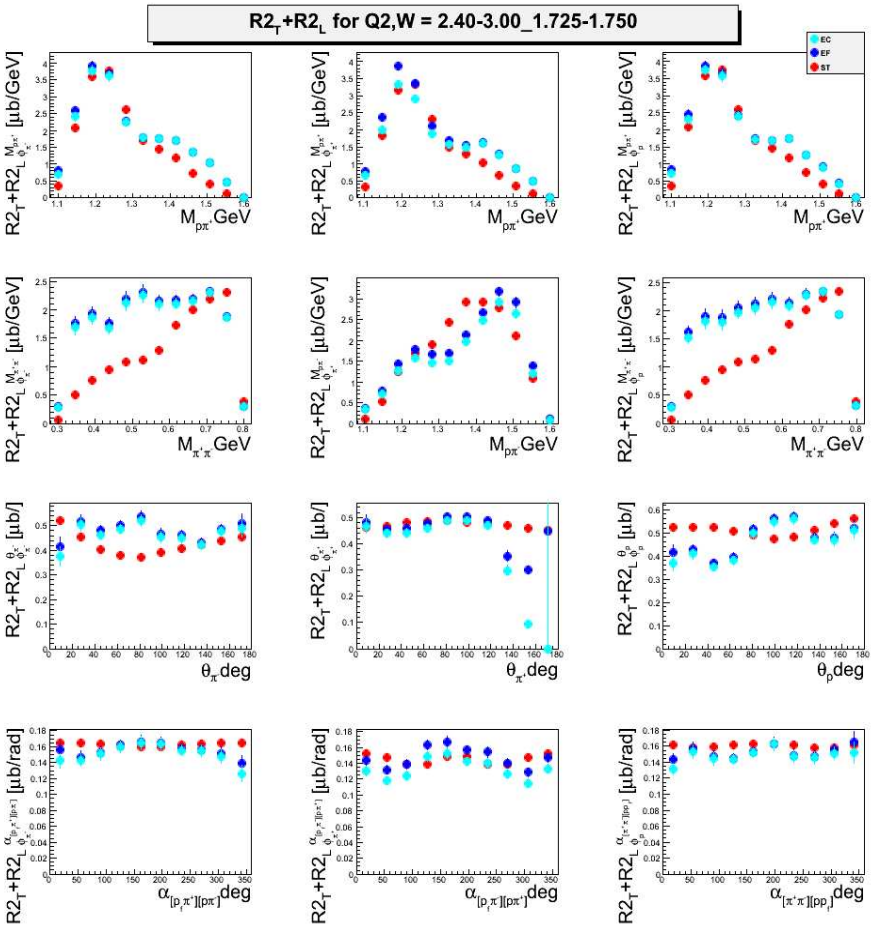

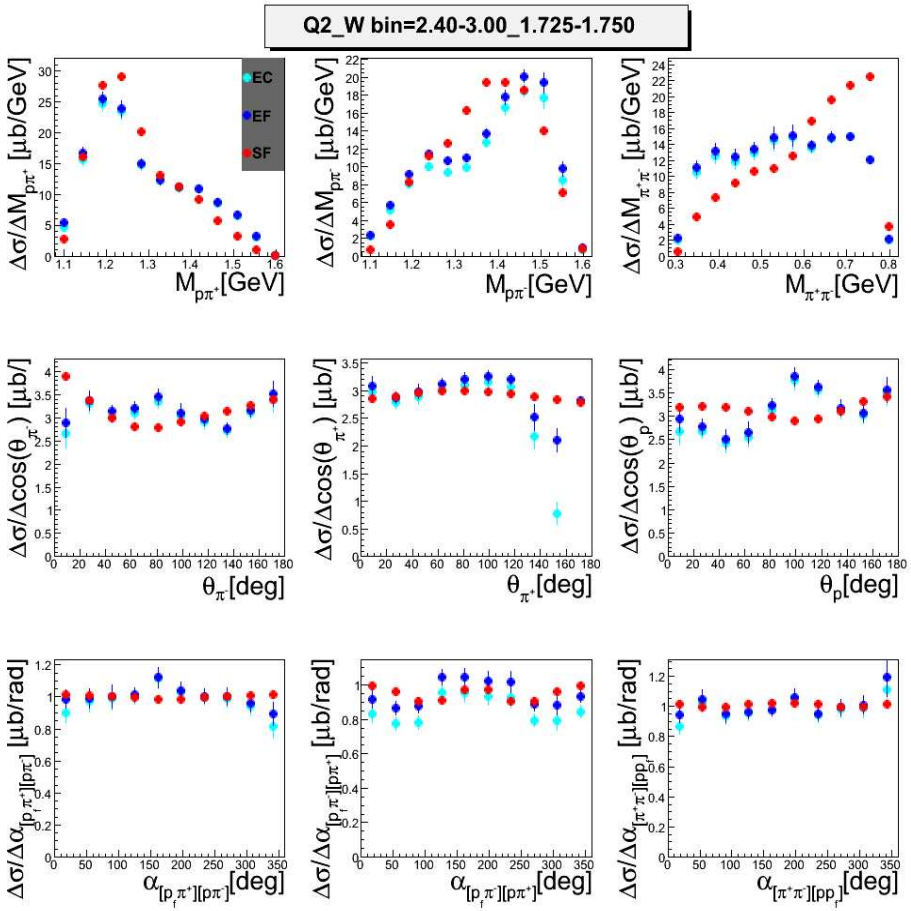

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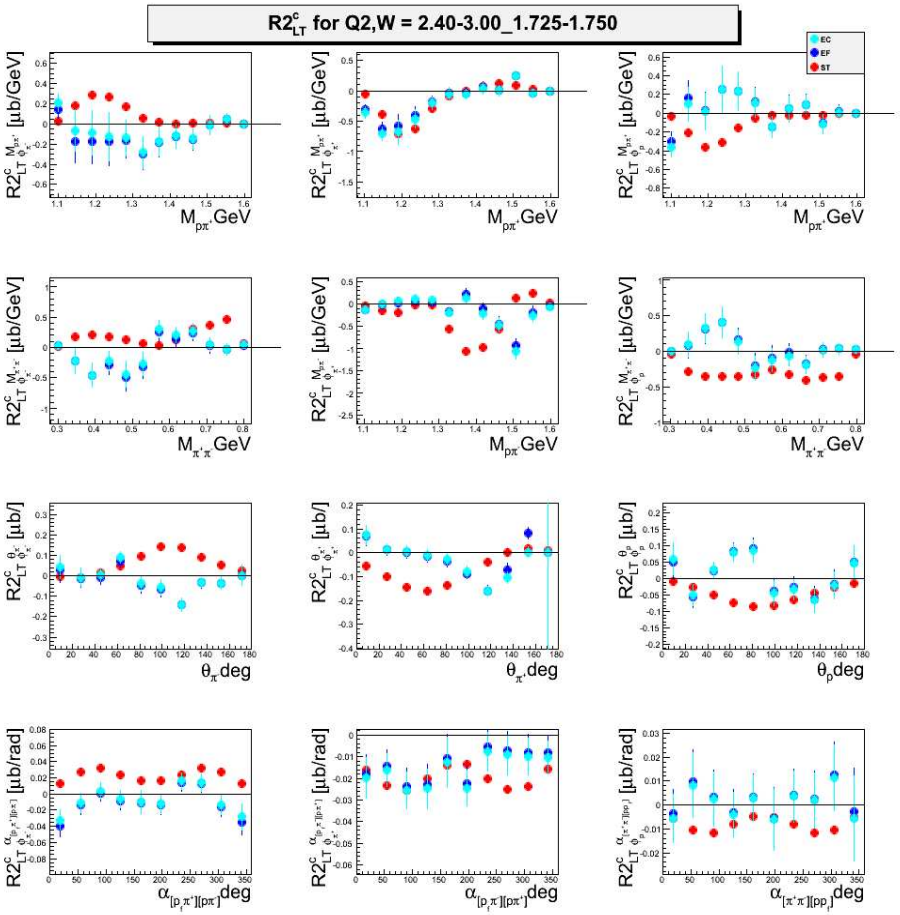

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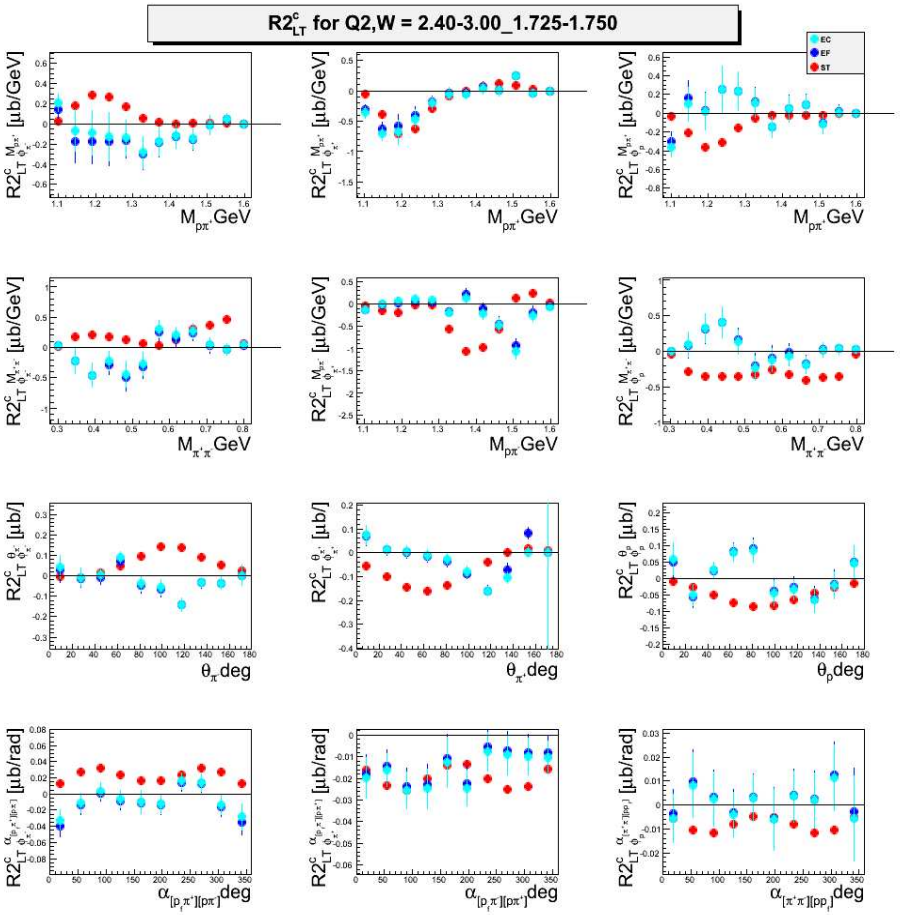

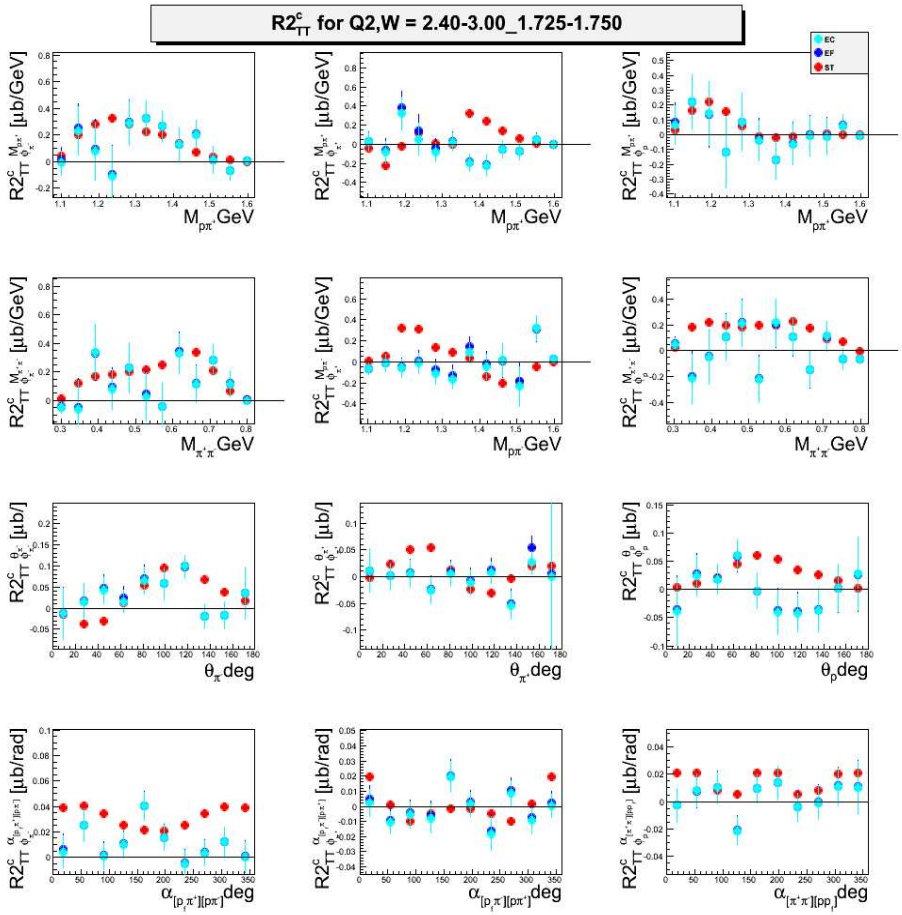

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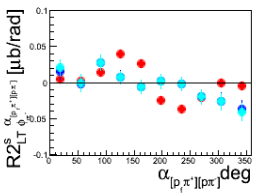
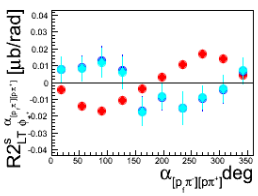
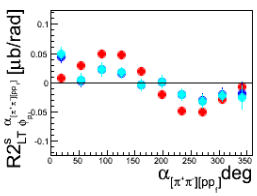
$R2^s_{LT}$ for Q2,W = 2.40-3.00_1.725-1.750







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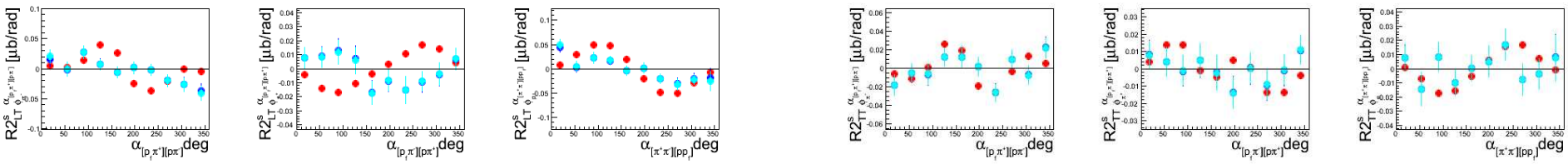

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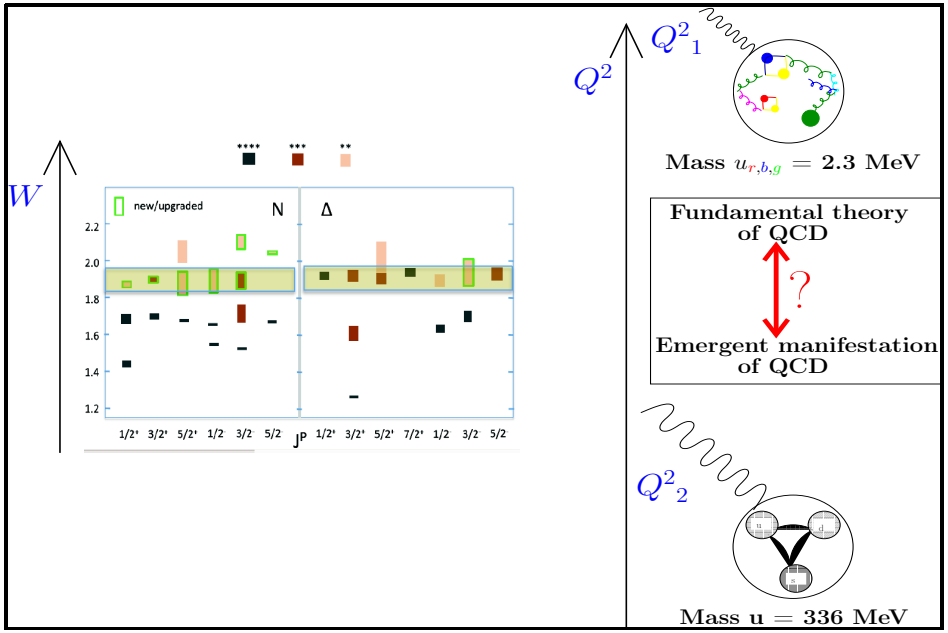
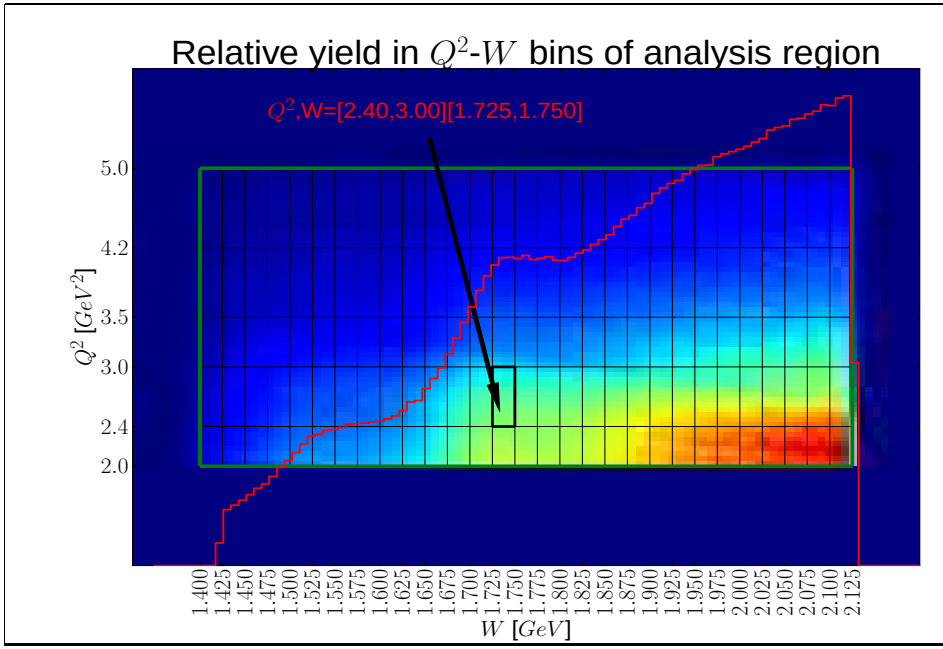
Overview of measurements





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51 sets of cross-sections measured in every Q^2-W bin, of which 30 are new

- Summary
  - 51 sets of cross-sections measured in each bin of, hitherto uncharted, Q^2-W region.
  - Of these 51, 30 are measured for the first time and are related to the photon polarization.
- Outlook
  - Working on analysis note and finalizing data studies.