Threshold Pion Electro-Production at High Q^2

$$\gamma^* + p = \pi^0 + p'$$

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- Motivation: See recent talk by Braun at Jlab 12 GeV upgrade Workshop. Study PQCD

- Feasibility study for new measurements from Q^2 = 0.50 - 10 GeV^2 at 12 GeV. Investigate kinematics and W resolution and missing mass resolution
  - Beam Energy 4 GeV - 12 GeV
  - Use HRS for Electron- Need good W resolution 1 MeV
  - Use MPS for Proton - large acceptance

- Several people and groups have shown interest In such a proposal recoil Including polarization measurements.

basic idea: decouple "hard" and "soft" momenta

$$M(Q_1^2, Q_2^2, \ldots; k_1^2, k_2^2, \ldots) \quad = \quad H(Q_1^2, Q_2^2, \ldots; \mu^2) \otimes S(\mu^2; k_1^2, k_2^2, \ldots)$$

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factorization scale

- **H: hard function can be calculated in pQCD (if we are lucky)** — High Q^2
- **S: soft function can be simplified using LET (if we are lucky)** — Low t

$$\gamma^* + p = \pi^0 + p'$$

Differential Cross Section

For unpolarized protons, the virtual photon cross section is

$$d\sigma_{\gamma^*} = \frac{\alpha_{em}}{8\pi}\frac{k_f}{W}\frac{d\Omega_\pi}{W^2 - m_N^2}|\mathcal{M}_{\gamma^*}|^2$$

with

$$|\mathcal{M}_{\gamma^*}|^2 = M_T + \epsilon\, M_L + \sqrt{2\epsilon(1+\epsilon)}\, M_{LT}\cos(\phi_\pi) + \epsilon M_{TT}\cos(2\phi_\pi) + \lambda\sqrt{2\epsilon(1-\epsilon)}\, M'_{LT}\sin(\phi$$

$$f_\pi^2 M_T = \frac{4\vec{k}_i^2 Q^2}{m_N^2}|G_1^{\pi N}|^2 + \frac{c_\pi^2 g_A^2 \vec{k}_f^2}{(W^2 - m_N^2)^2} Q^2 m_N^2 G_M^2 + \cos\theta\frac{c_\pi g_A |k_i||k_f|}{W^2 - m_N^2} 4Q^2 G_M \mathrm{Re}\, G_1^{\pi N}$$

$$f_\pi^2 M_L = \vec{k}_i^2 |G_2^{\pi N}|^2 + \frac{4c_\pi^2 g_A^2 \vec{k}_f^2}{(W^2 - m_N^2)^2} m_N^4 G_E^2 - \cos\theta\frac{c_\pi g_A |k_i||k_f|}{W^2 - m_N^2} 4m_N^2 G_E \mathrm{Re}\, G_2^{\pi N}$$

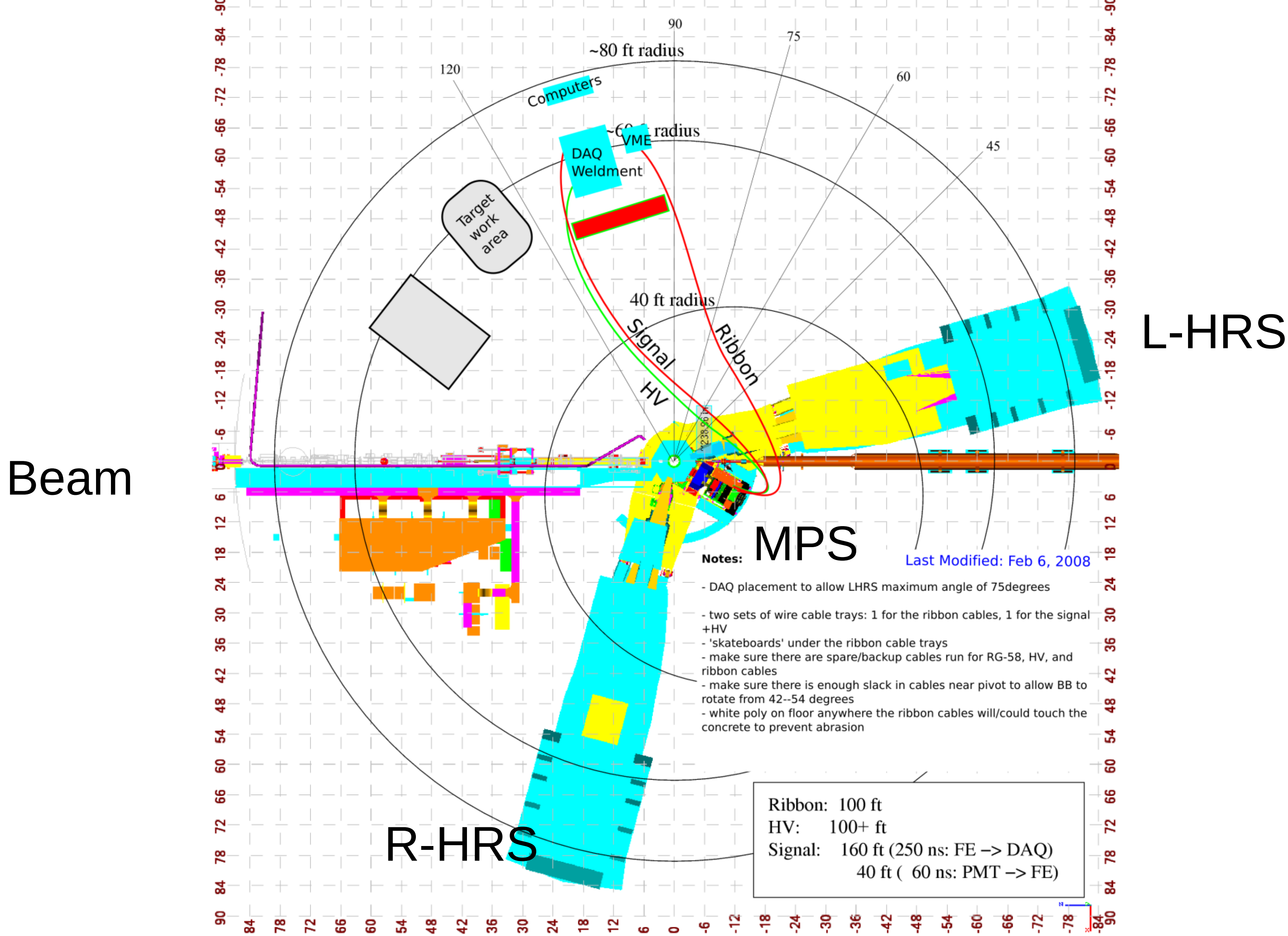
$$f_\pi^2 M_{LT} = -\sin\theta\frac{c_\pi g_A |k_i||k_f|}{W^2 - m_N^2} Q m_N \left[G_M \mathrm{Re}\, G_2^{\pi N} + 4G_E \mathrm{Re}\, G_1^{\pi N}\right]$$

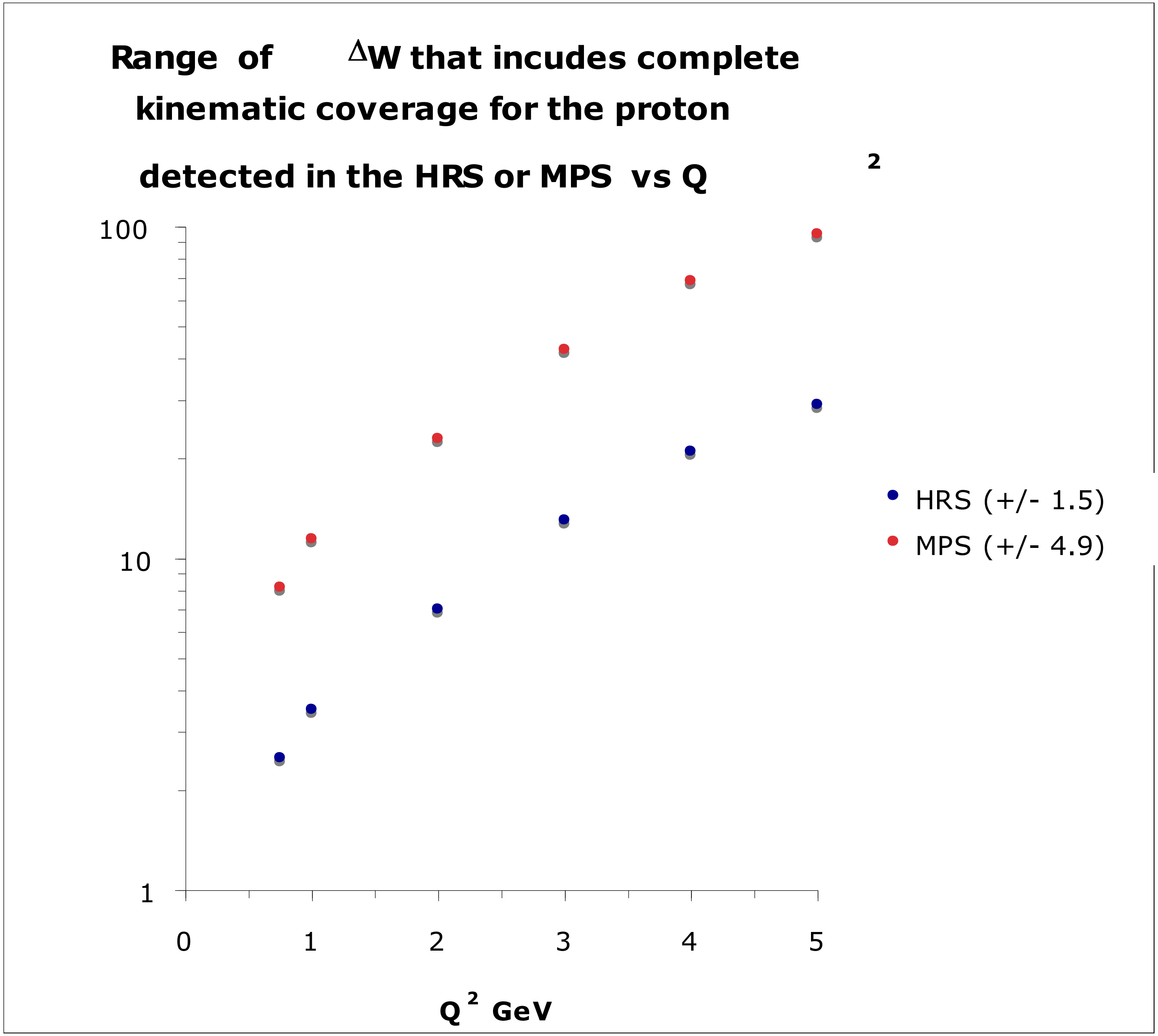
$$f_\pi^2 M_{TT} = 0\,,$$

$$f_\pi^2 M'_{LT} = -\sin\theta\frac{c_\pi g_A |k_i||k_f|}{W^2 - m_N^2} Q m_N \left[G_M \mathrm{Im}\, G_2^{\pi N} - 4G_E \mathrm{Im}\, G_1^{\pi N}\right]$$

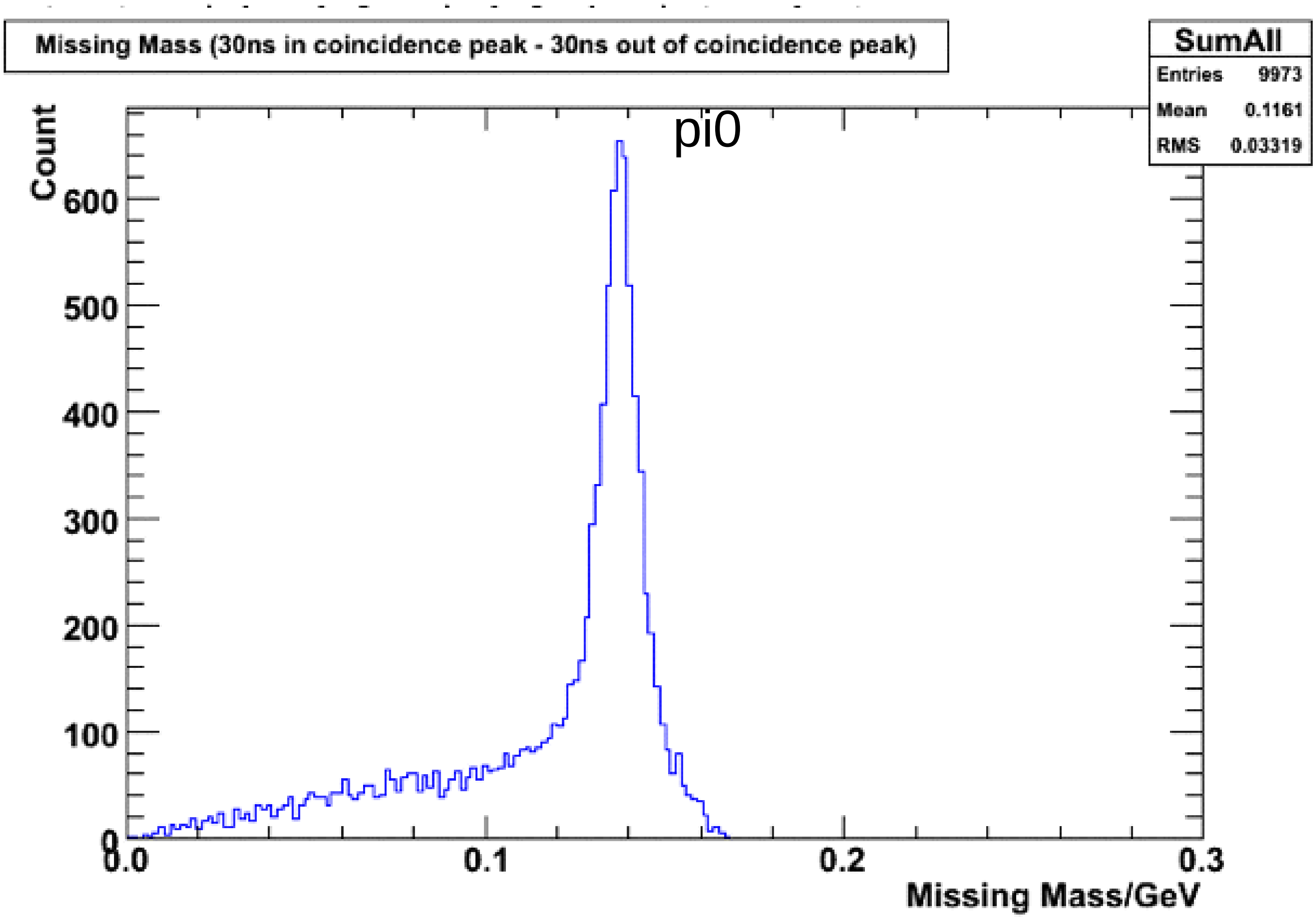
$p(e,e'p)\pi^0$				
Facility	$Q^2(GeV^2)$	W(GeV)	Ref	Comment
SLAC	7.1,9.4	1.10 -1.40	P.E. Bosted et al. PR D 49,3091(1994)	Poor W Resolution
Jlab Hall C	2.8,4.0	1.1 - 1.7	V.V Frolov et al. PRL 82,45(1999)	Delta & S11 No threshold data
Jlab Hall A	1.0	1.1 - 2.0	G. Laveissiere et al. PRC69,45203(2004)	Delta No Threshold Data
Jlab Hall A	1.0	1.23	J. Kelly et al. PRL 95,10200(2005)	Recoil Polarization No Threshold data
Jlab Hall C	6.4,7.7	1.1 - 1.7	E01-002	Delta & S11 No Threshold data
Jlab Hall B	1 - 4	Threshold	E01-113	DVCS Poor W Resolution
$p(e,e'\pi^+)n$				
Jlab Hall C	1 - 10	Above Resonances	T. Horn Proposal PAC 32	Test PQCD Concepts, Scaling
$p(p,p'p)\pi^0$				
IUCF E=400,325	Low	Threshold	H.O. Meyer et al. PRC 63,64002(2001)	Spin Observables

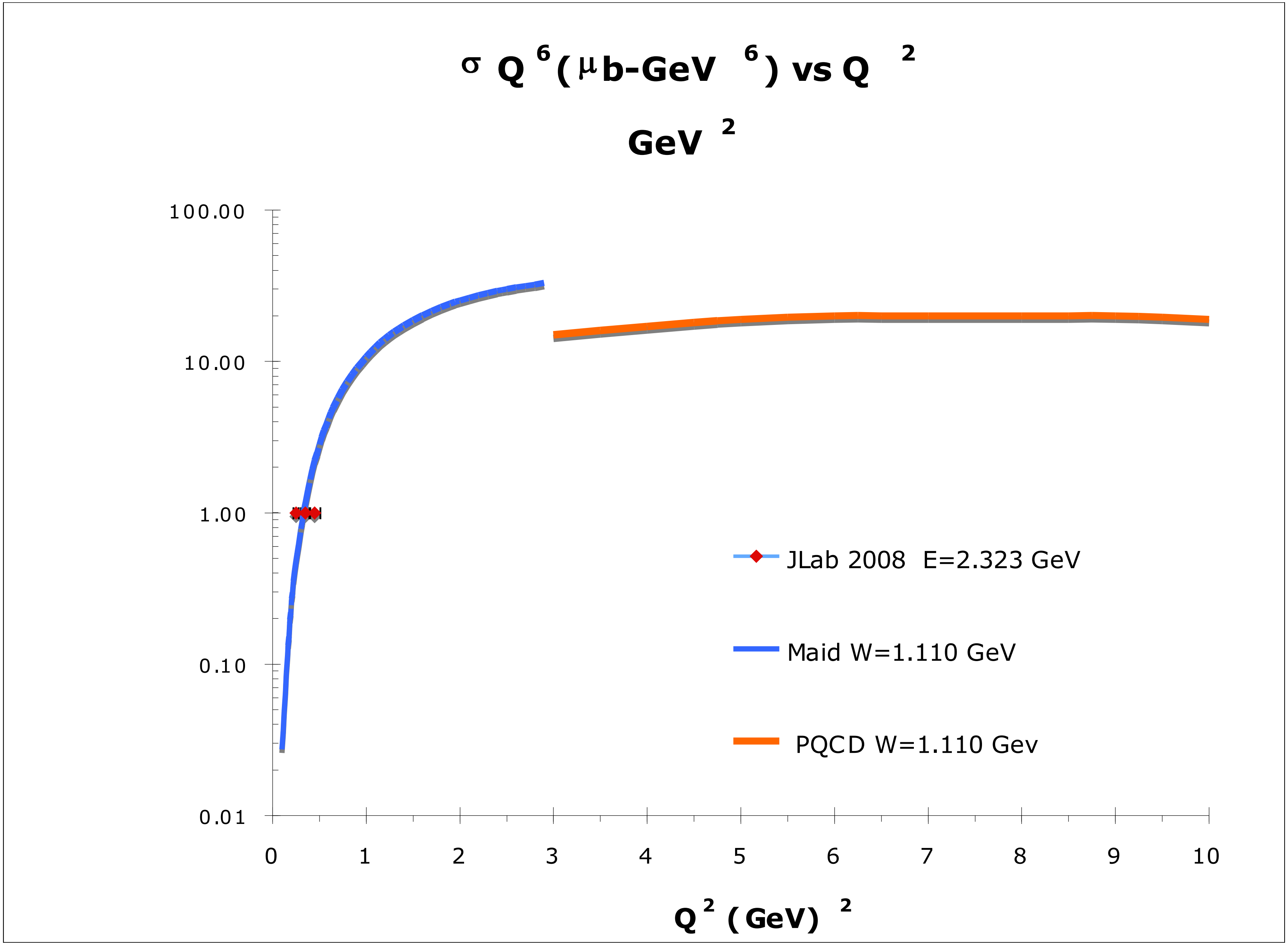
Threshold pion production at High Q^2




Range of ΔW that incudes complete
kinematic coverage for the proton
detected in the HRS or MPS vs Q
2
100
10
1
0
1
2
3
4
5
Q 2 GeV
HRS (+/- 1.5)
MPS (+/- 4.9)

Data from E04-007
Q^2=-0.45 GeV^2

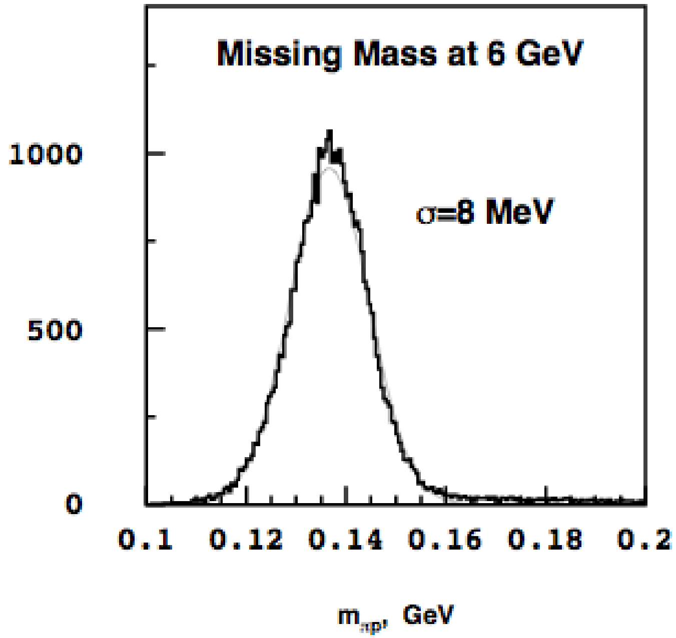


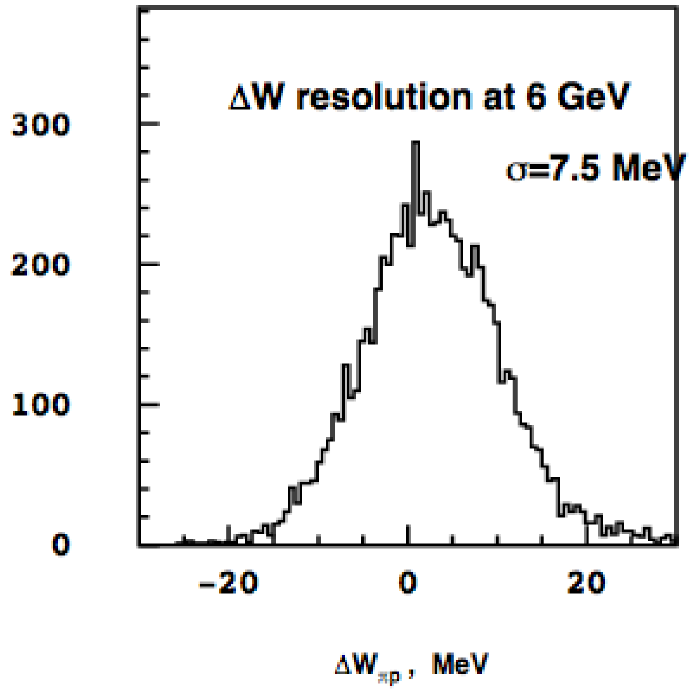


σ Q 6 (μ b-GeV 6) vs Q 2
GeV 2
100.00
10.00
1.00
0.10
0.01
0 1 2 3 4 5 6 7 8 9 10
Q 2 (GeV) 2
JLab 2008 E=2.323 GeV
Maid W=1.110 GeV
PQCD W=1.110 Gev

E Beam GeV	HRS Angle	Q^2 GeV^2	Electron P (MeV)	Proton P(MeV)	Counts/day
			HRS	MPS	L= 10^{38} Hz/cm^2
4	15.8	- 1	3320	1055	432,000
5	18.7	- 2	3788	1626	24,500
6	19.7	- 3	4254	2146	2390
8	17.0	- 4	5271	2646	849
10	15.2	- 5	7175	3136	386
11	19.0	- 10	8230	5520	12

E=6 GeV, LHRS(e), RHRS(p)

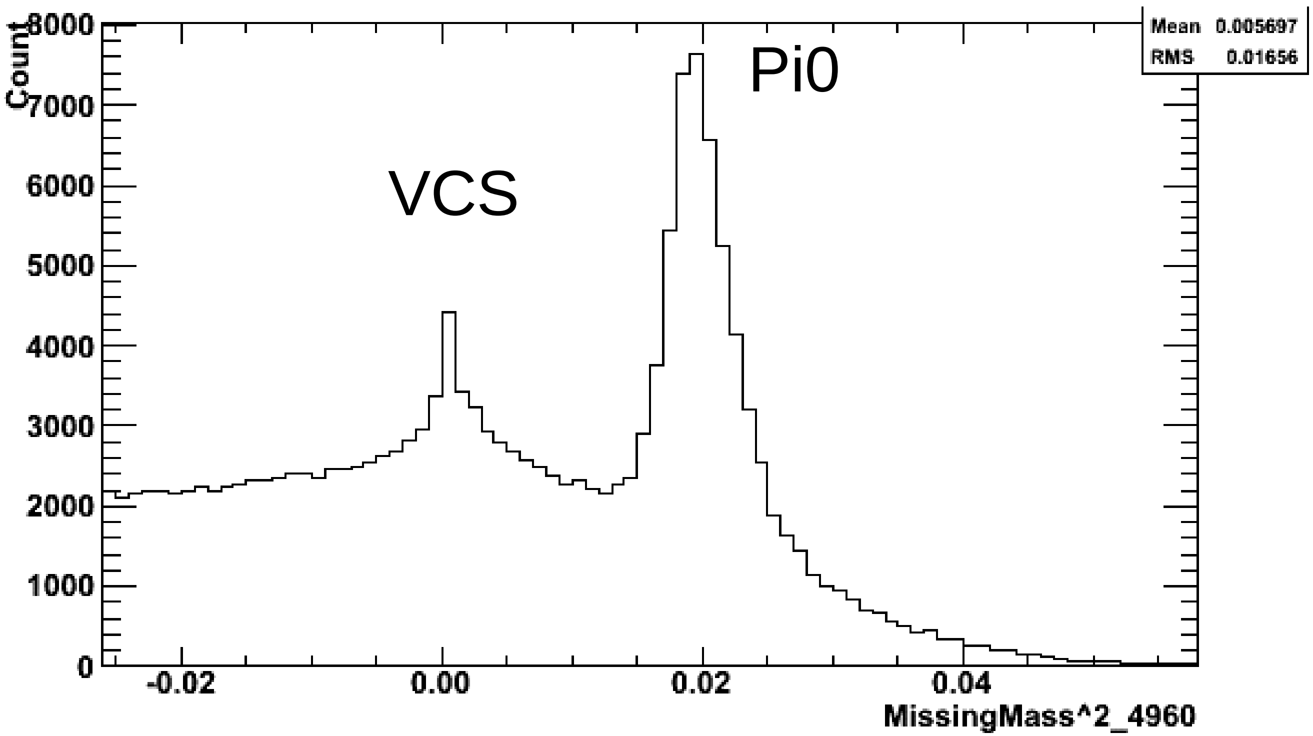


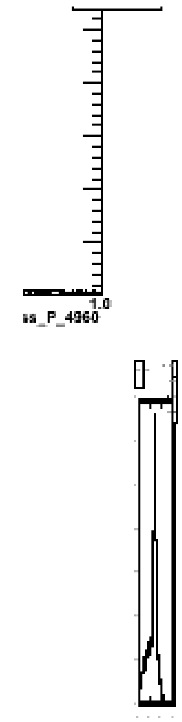


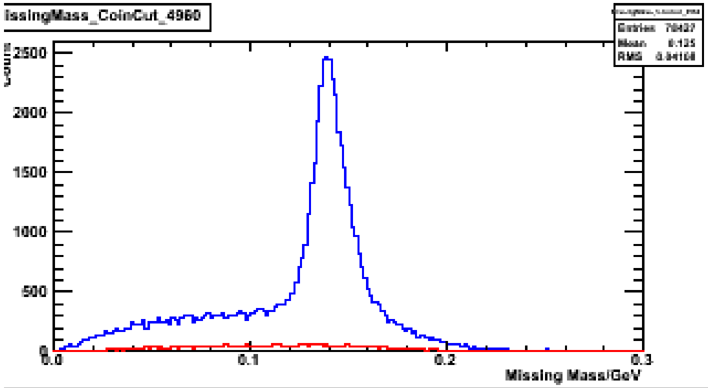
Questions

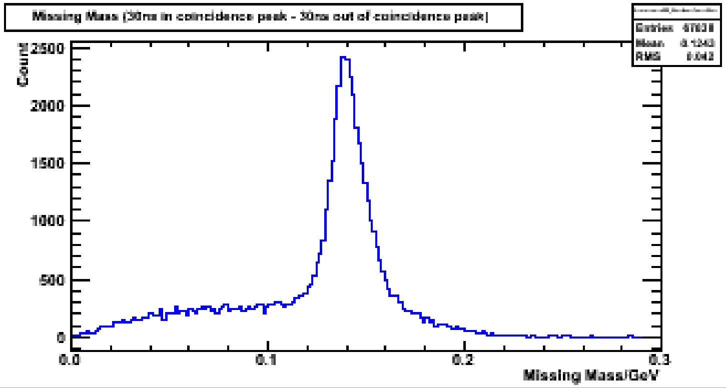
- What are the limits in resolution in W and how close to threshold do you have to be to expect these PQCD and ChPT predictions to be valid? How coarse or fine do you bin the data?
- How low in in Q^2 can you go for PQCD to work?
- How do you get higher than $Q^2 = -3\ GeV^2$?
  - Electron energy too high
  - MPS resolution not good enough
  - For large angles rates are too low.

Data from E04-007
Q^2=-0.45 GeV^2









Outlook

theory:

- detailed predictions possible near to threshold
- present LCSR accuracy probably 50%; can be improved to 20%(?)
- elastic πN rescattering can be taken into account
- can be incorporated in full PWA

- There exist two form factors related to multipoles
- S_{0+}, and L_{0+} and I expect that clean separation
- between them is much easier if you have polarization
- observables, similar to the situation with the proton
- electric vs. magneruc form factors. Also, you will have
- less problems with two-photon exchange contributions.
- So, polarization is obviously a great plus.

- 3) I think you can say that the intersting issue is
- how chiral symmetry works in hard reactions.

- For small $q^2 \sim m_\pi^2$ we have chiral perturbation
- theory and it works nicely (as it must). Question is
- what happens when m_π is still treated as small parameter,
- but q^2 is large, of order or larger than hadronic scale.
- In this situation chiral perturbation theory is not applicable,
- but people expect that the approach based on chiral algebra
- (soft pion theorems) still has to work up to a scale of
- order $Q^2 \sim m_N^3/m_\pi$ whereafter QCD based approaches
- are expected to become applicable. The task is to check
- this scenario.

- As a bonus, if you find that soft-pion theorems
- "work" for Q^2 of order 1 GeV or so, it will allow to extract
- proton axial form factor from the data on pi^+ production.

- Just a technical detail: chiral perturbation theory is good because
- it allows to calculate correction proportional to powers of the
- pion mass. When I say it is not applicable for $Q^2 >> m_\pi^2$, this
- will imply that terms of order m_π^2 will remain out of control.
- This is what one loses. Chiral algebra, on the other hand,
- does need small q^2, but remain selfconsistent to order m_π^1.
- This means that for large q^2 you cannot expect theoretical accuracy
- better than smth like 5%, but this is not bad at all.

Hall C Data

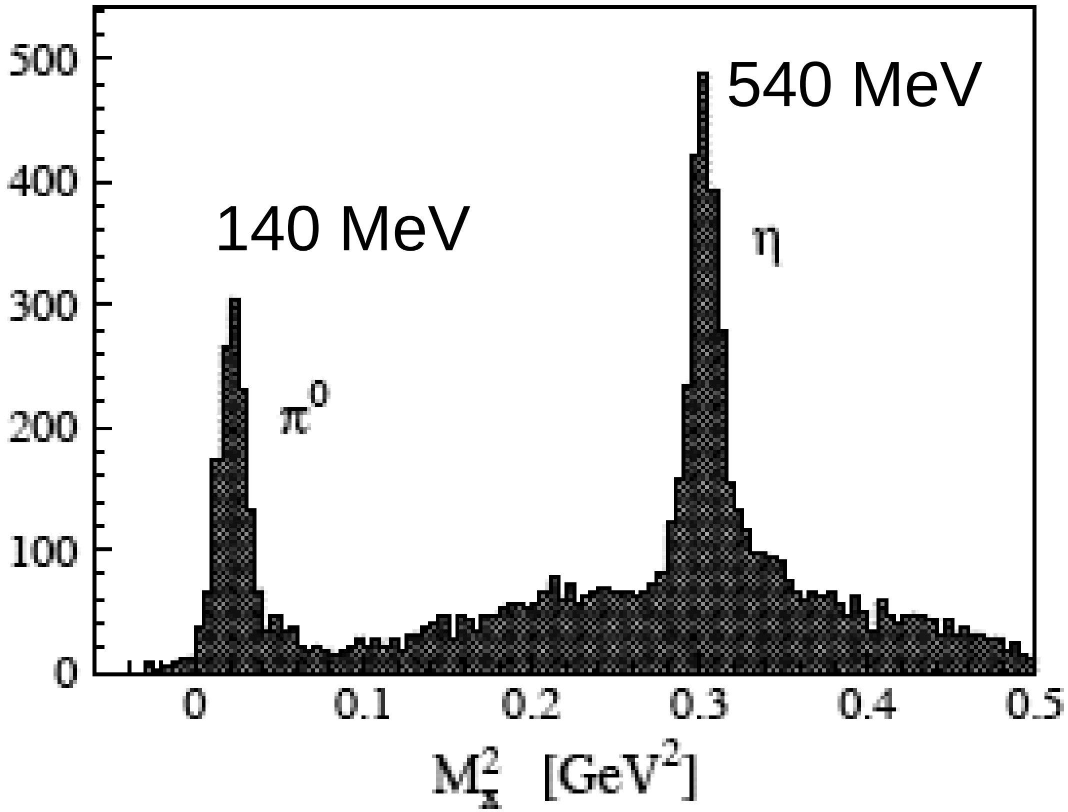


FIG. 1. Example of a missing mass distribution for the reaction $p(e,e'p)X$. The data are from one experimental setting at $Q^2 = 2.8$ GeV^2 ($1.1 < W < 1.7$ GeV).

V.V Frolov et al. PRL 82,45(1999)

$\theta_{central}$, degree	Ω, msr	D, meter	Hor. range, degree	Vert. range, degree
3.5	5	9.5	$\pm$ 1.3	$\pm$3.3
5.0	12	5.8	$\pm$ 1.9	$\pm$4.9
7.5	30	3.2	$\pm$ 3	$\pm$8
15	72	1.6	$\pm$ 4.8	$\pm$12.2
30	76	1.5	$\pm$ 4.9	$\pm$12.5

Table 1: The solid angle of MPS vs. central scattering angle.

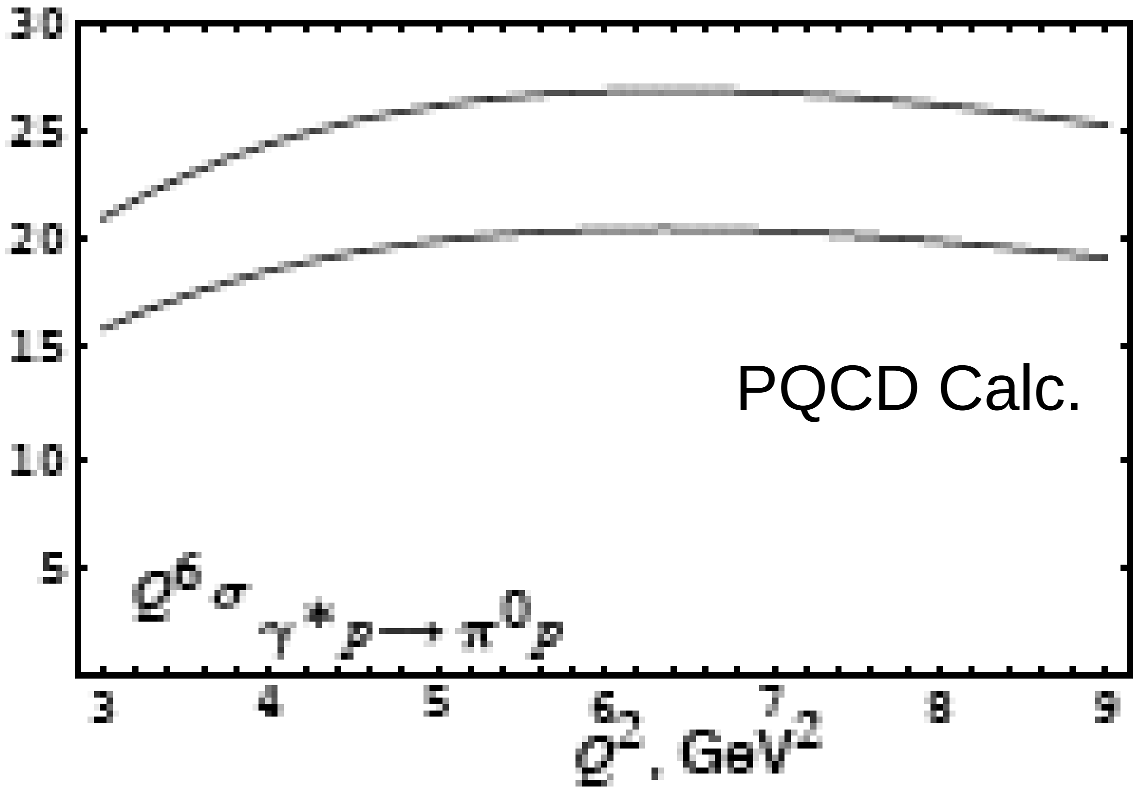


Figure: Integrated cross section $Q^6\sigma_{\gamma^* p \to \pi^0 p}$ for $W = 1.11$ GeV (lower curve) and $W = 1.15$ GeV (upper curve)

$W_{threshold} = 1.07326$ GeV

Threshold Pion Production in QCD

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based on

V.M. Braun, D. Ivanov, A. Lenz and A. Peters, Phys.Rev.D75:014021,2007

V.M. Braun, D. Ivanov and A. Peters, arXiv:0710.3265, PRD, to appear

JLAB, 02/19/08

E=4 GeV, LHRS(e), RHRS(p)