Impact of $\gamma_v NN^*$ Electrocuplings at High Q^2 and Preliminary Cross Sections off the Neutron

Ralf W. Gothe

UNIVERSITY OF SOUTH CAROLINA

Nucleon Resonances: From Photoproduction to High Photon
October 12 - 16, 2015, ECT*, Trento, Italy

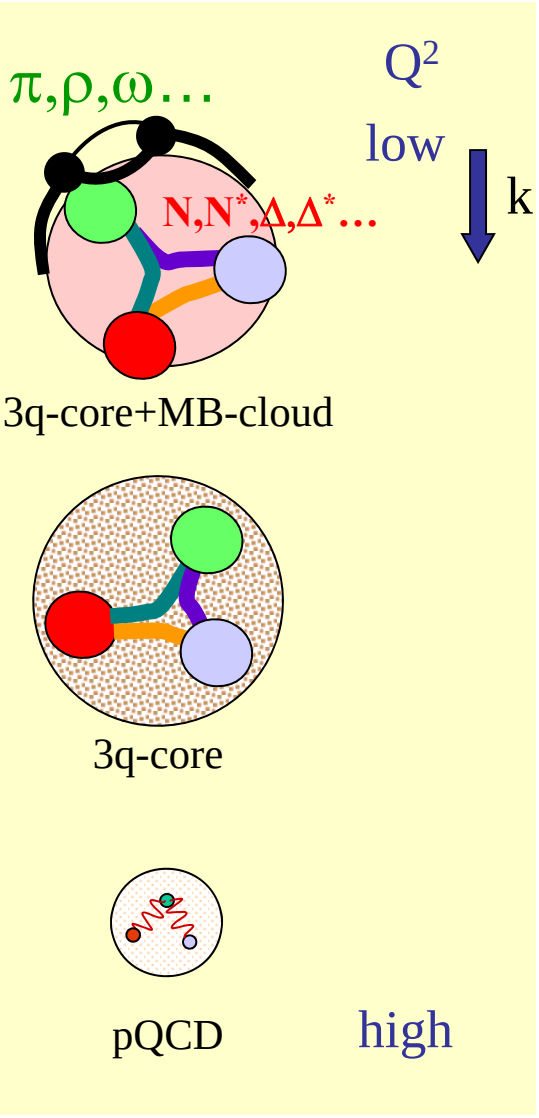
ECT*

- **$\gamma_v NN^*$ Vertexcouplings:** A unique window into baryon and quark structure?
- **Analysis and New Results:** Phenomenological but consistent.
- **Outlook:** New experiments with extended scope and kinematics.
- **QCD based Theory:** Can we solve non-perturbative QCD and confinement?

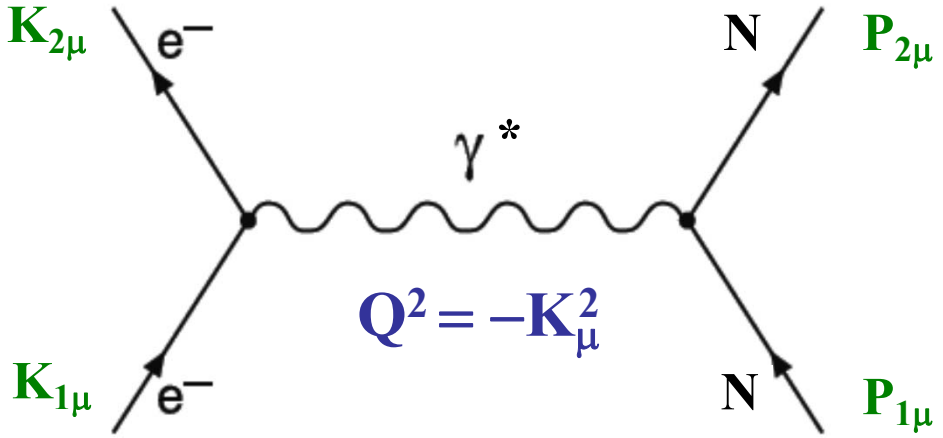
This work is in parts supported by the US National Science Foundation under the Grant PHY-1205782

Transition Form Factors

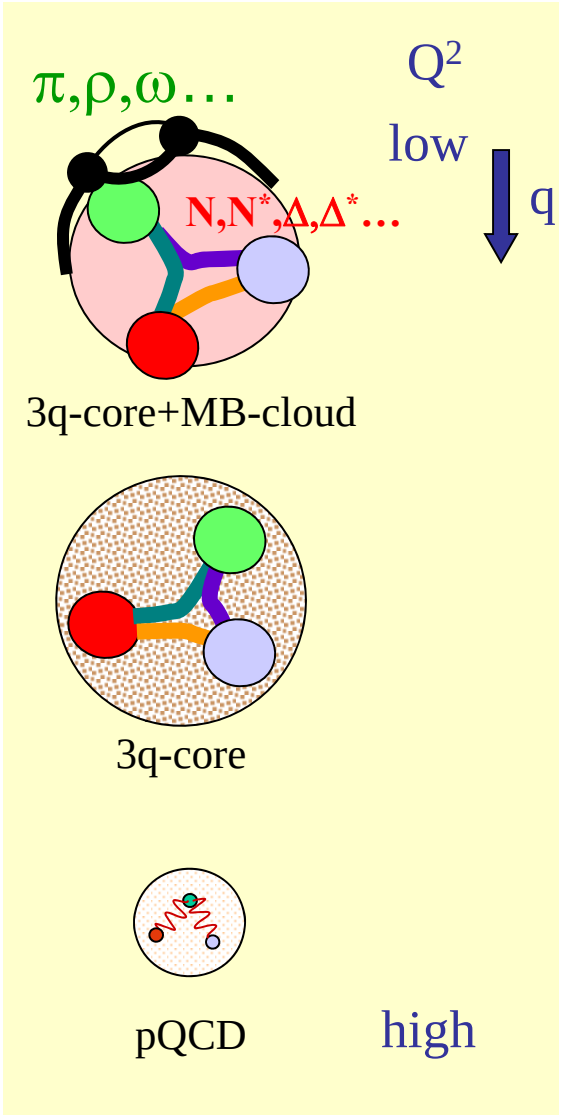
Hadron Structure with Electromagnetic Probes



- Study the structure of the nucleon spectrum in the domain where dressed quarks are the major active degree of freedom.
- Explore the formation of excited nucleon states in interactions of dressed quarks and their emergence from QCD.



Hadron Structure with Electromagnetic Probes



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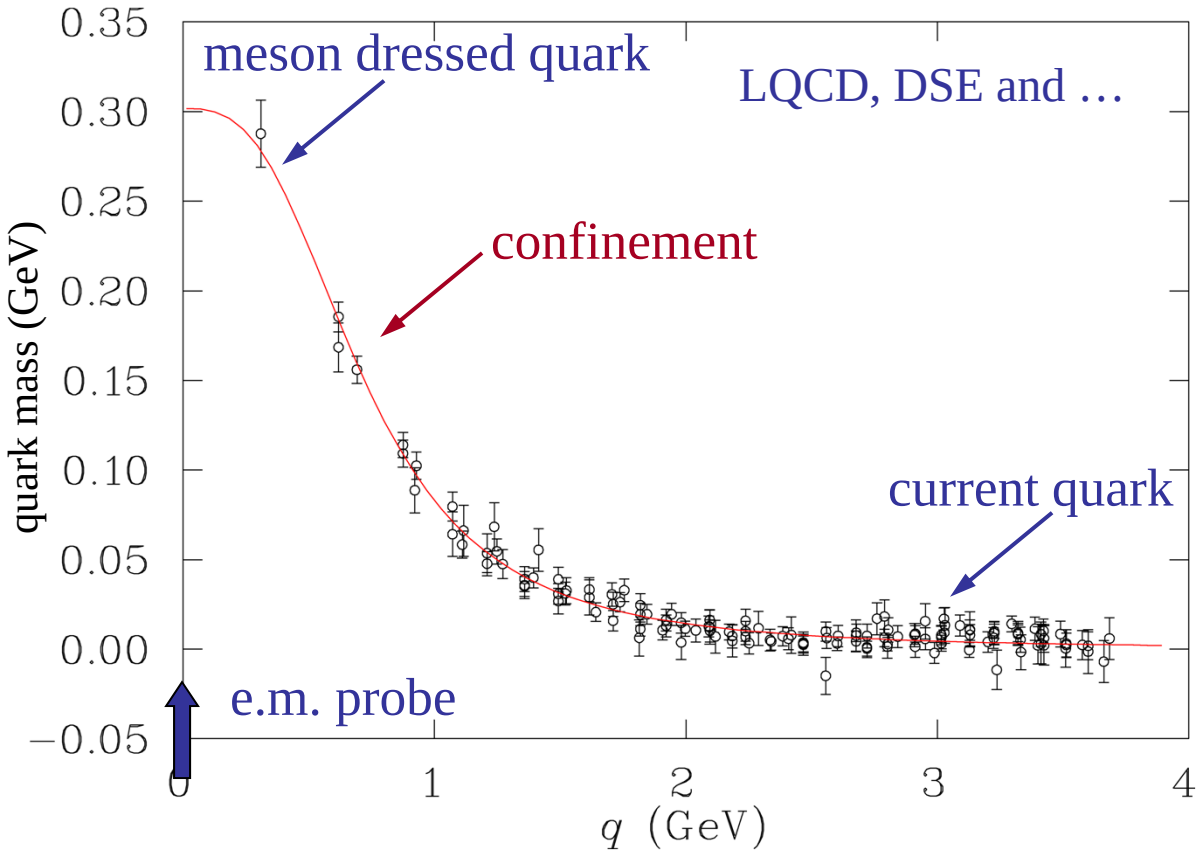
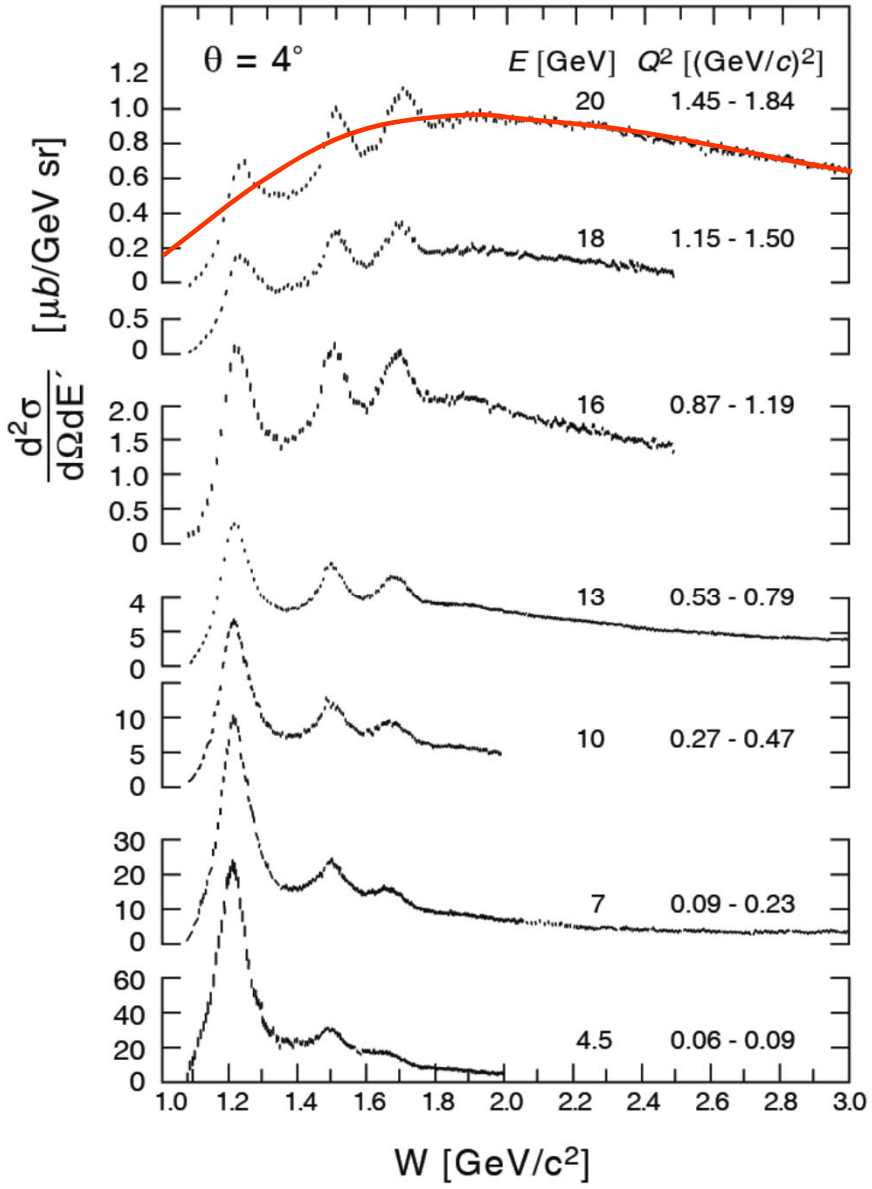
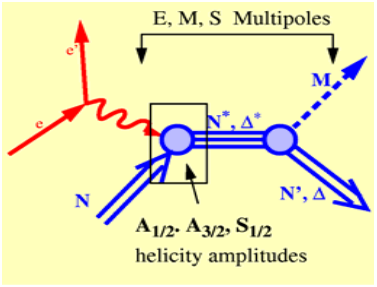
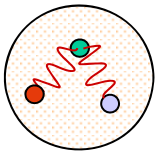


Baryon Excitations and Quasi-Elastic Scattering

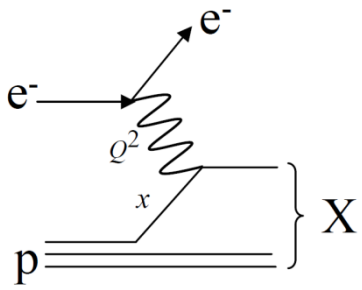


hard and confined



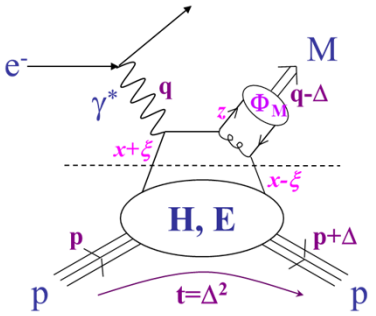


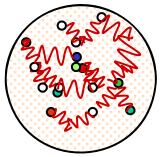
quasi-elastic



hard

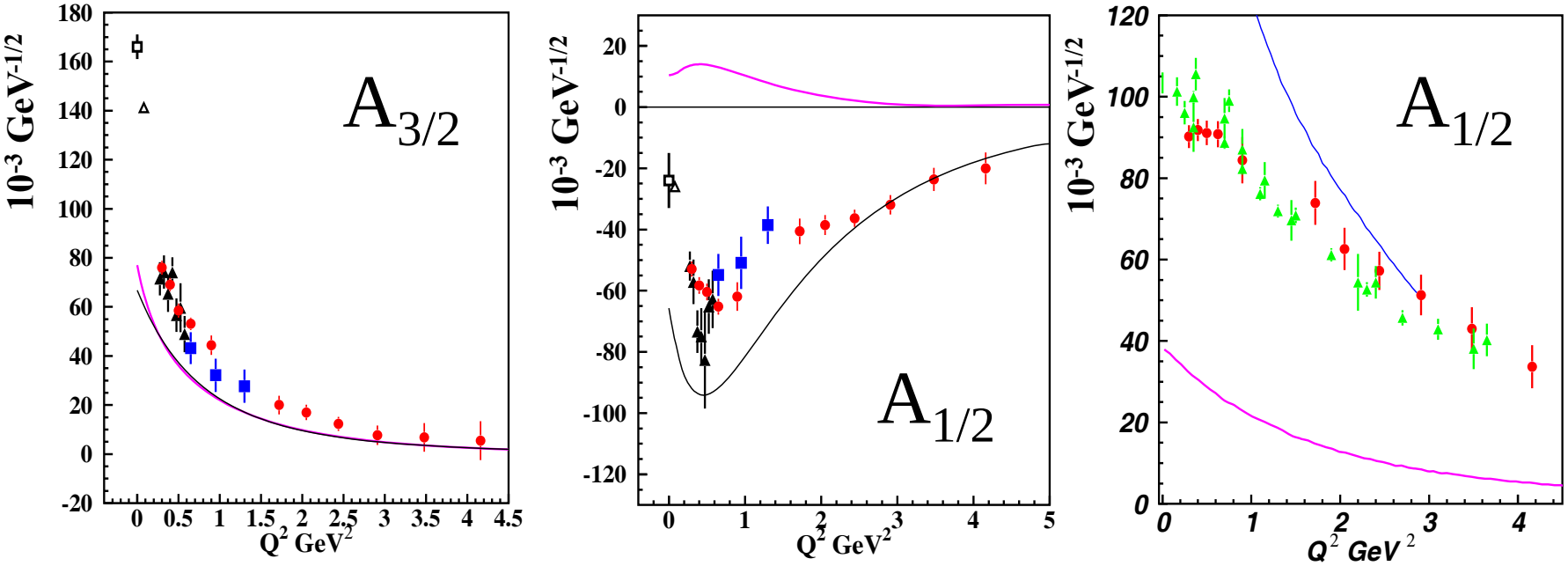
soft





Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Electrocouplings of N(1520)D_{13} and N(1535)S_{11}



Argonne Osaka / EBAC DCC MB dressing (absolute values)

E. Santopinto, M. Giannini, hCQM PRC 86, 065202 (2012)

S. Capstick, B.D. Keister (rCQM) PRD51, 3598 (1995)

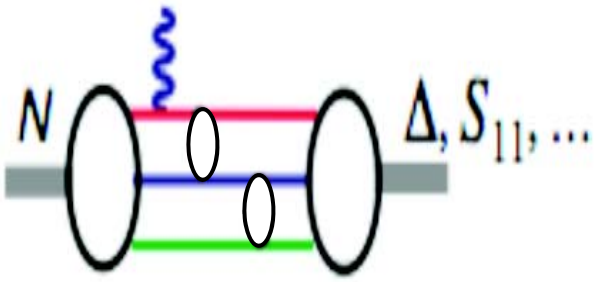
$\pi^+\pi^-p$ 2012

$\pi^+\pi^-p$ 2010

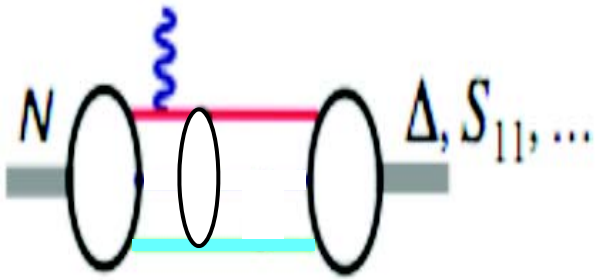
$N\pi$ 2009

ηp CLAS/Hall-C

Evidence for the Onset of Scaling?

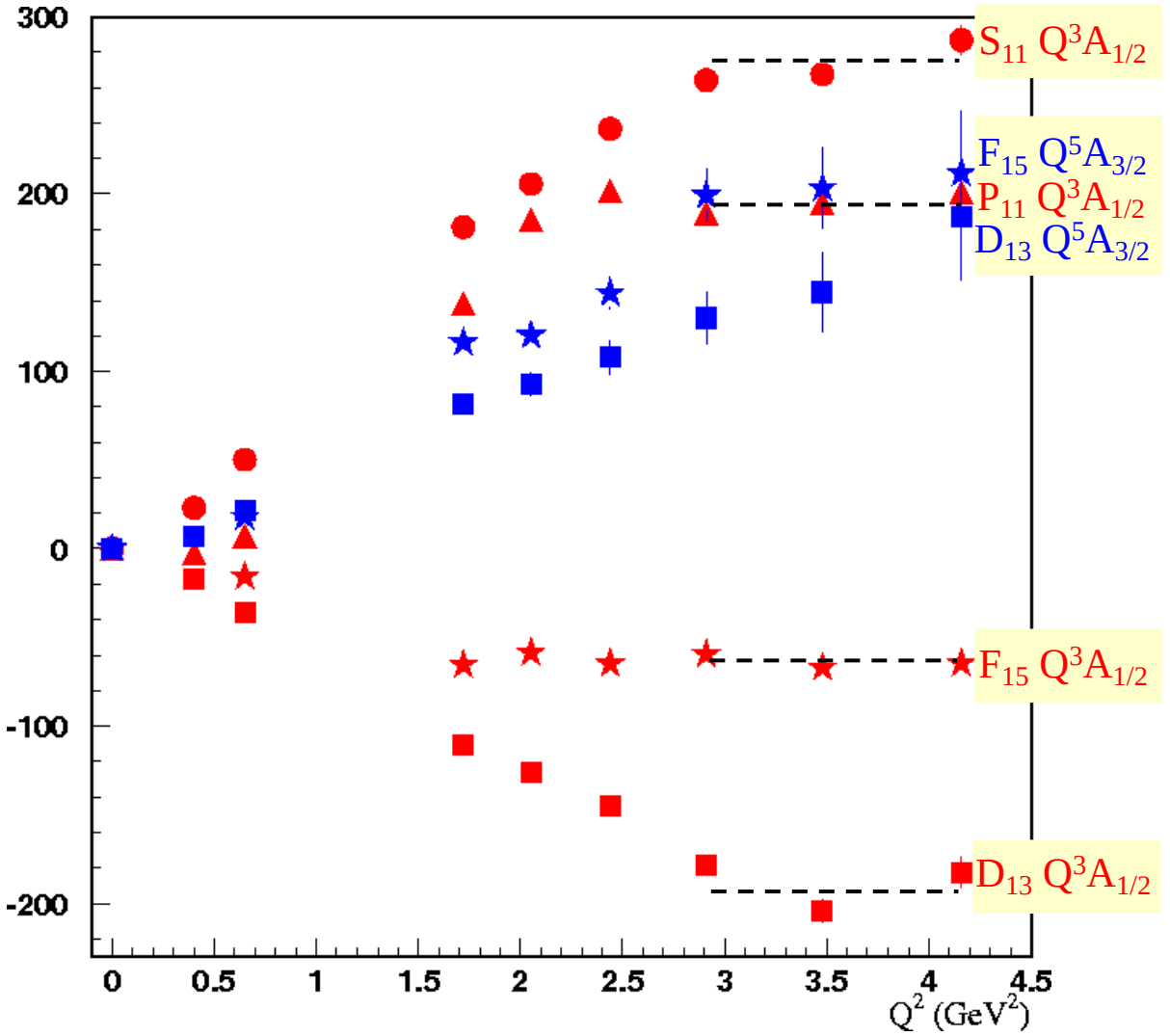


- $A_{1/2} \alpha 1/Q^3$
- $A_{3/2} \alpha 1/Q^5$
- $G_M^* \alpha 1/Q^4$

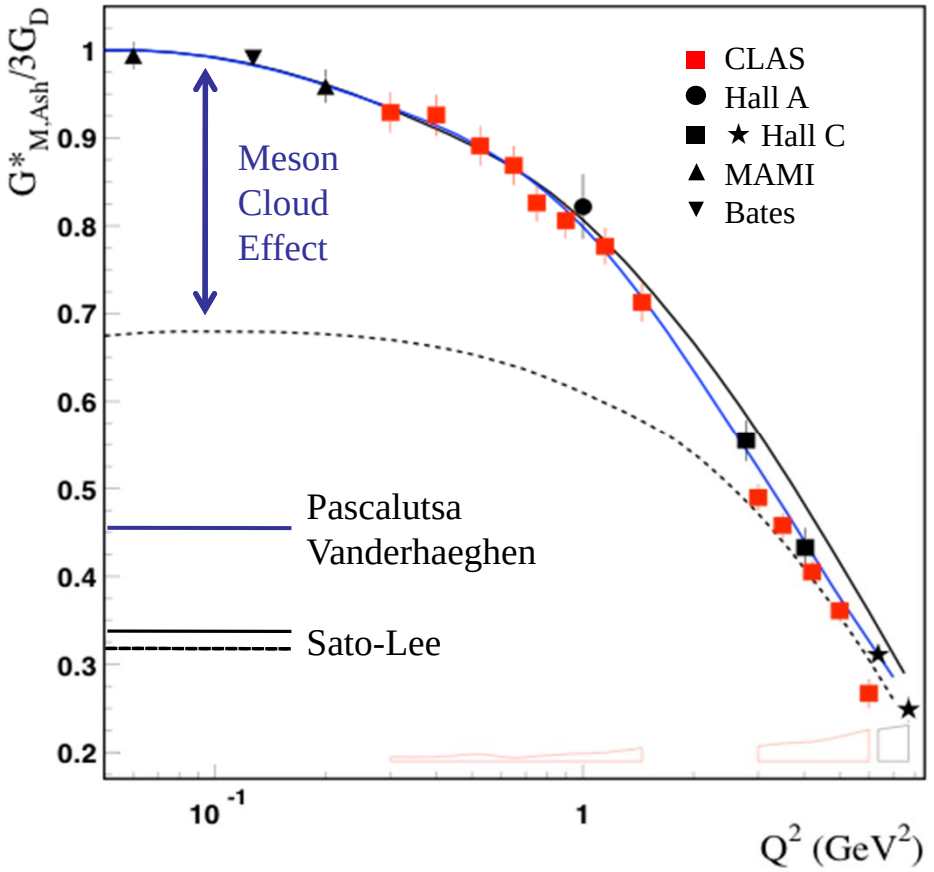


q^2q

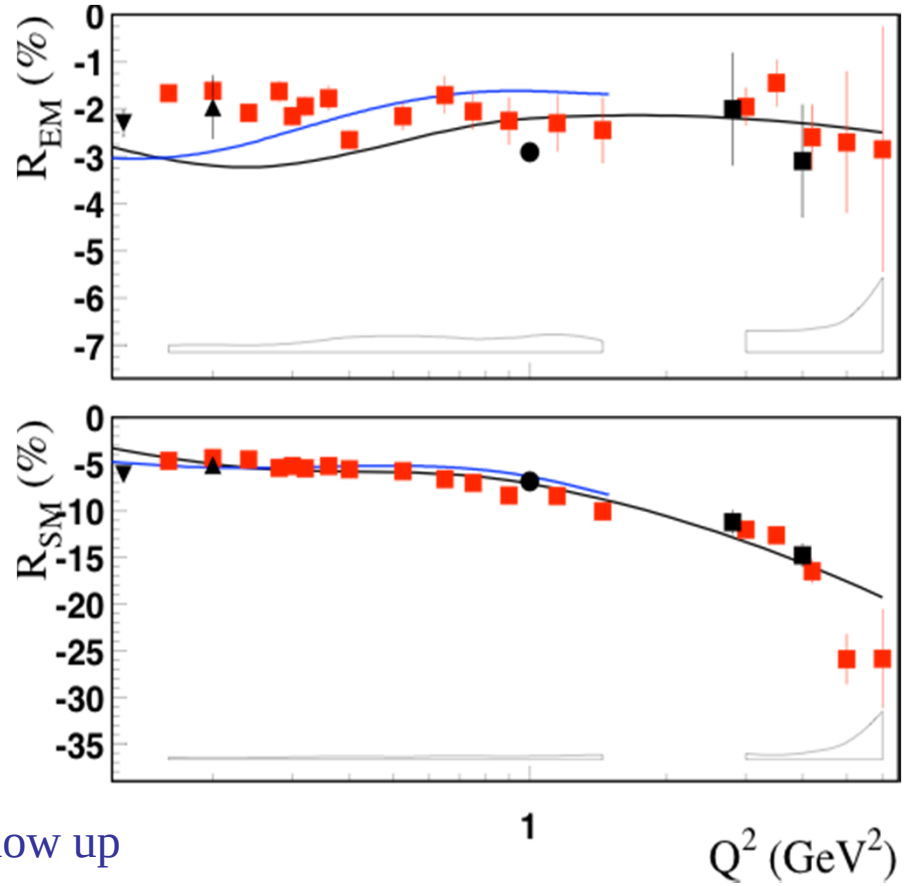
Phys. Rev. C80, 055203 (2009)



$N \rightarrow \Delta$ Multipole Ratios R_{EM} , R_{SM}

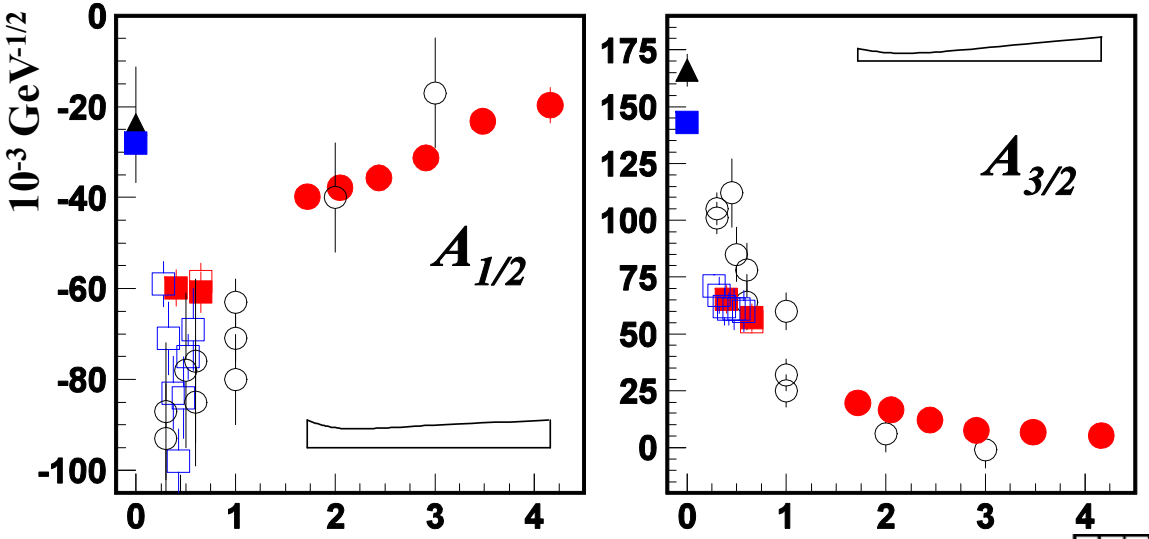


Phys. Rev. Lett. 97, 112003 (2006)



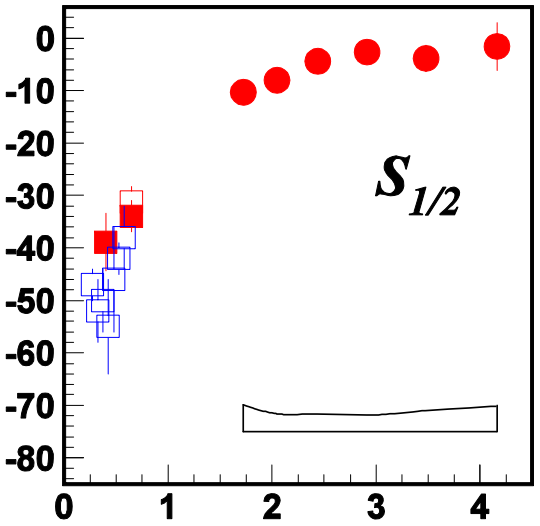
- New trend towards pQCD behavior does not show up
  - $R_{EM} \rightarrow +1$ $R_{SM} \rightarrow$ const
  - $G^*_{M,J.-S.} \rightarrow 1/Q^4$ $G^*_{M,Ash} \rightarrow 1/Q^5$
- CLAS12 can measure G^*_M, R_{EM}, and R_{SM} up to Q^2~12 GeV^2

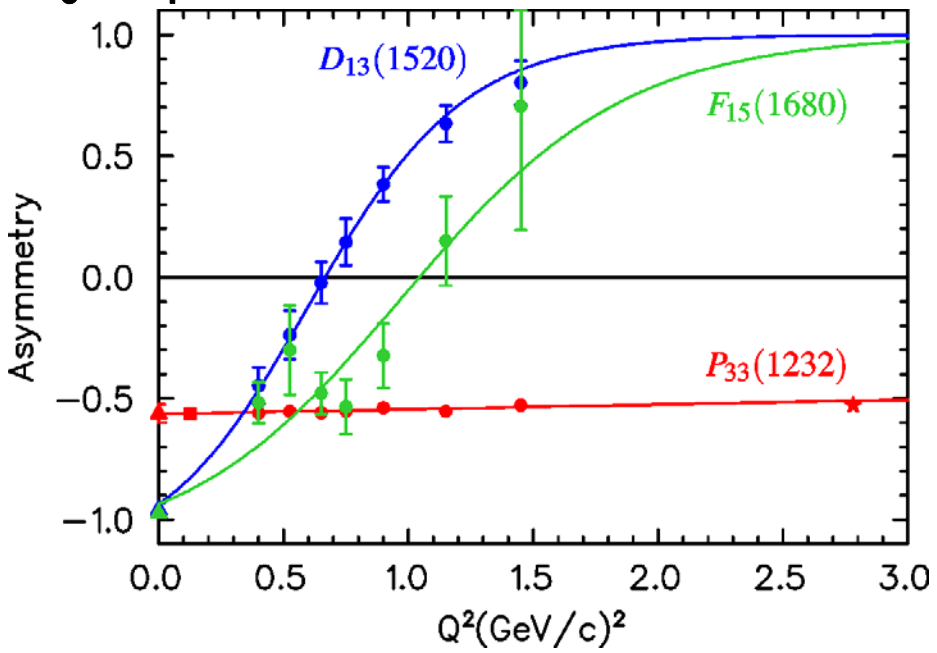
$N(1520)D_{13}$ Helicity Asymmetry



$$A_{hel} = \frac{A_{1/2}^2 - A_{3/2}^2}{A_{1/2}^2 + A_{3/2}^2}$$

L. Tiator



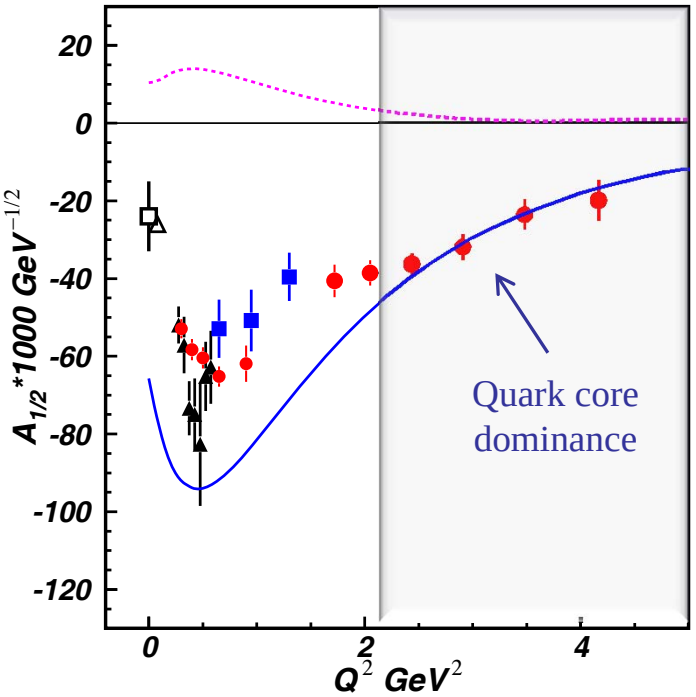


○ world data

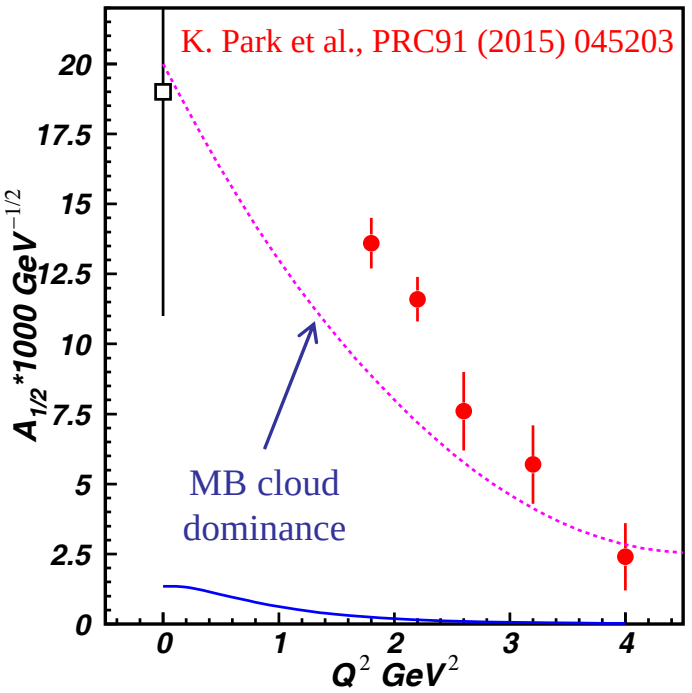
▲ PDG estimation ● ■ Nπ (UIM, DR)

Interplay between Meson-Baryon Cloud and Quark Core

$N(1520)3/2^-$



$N(1675)5/2^-$



Argonne-Osaka MB dressing (absolute values)

E. Santopinto and M. Giannini, PRC 86 (2012) 065202

The almost direct access to

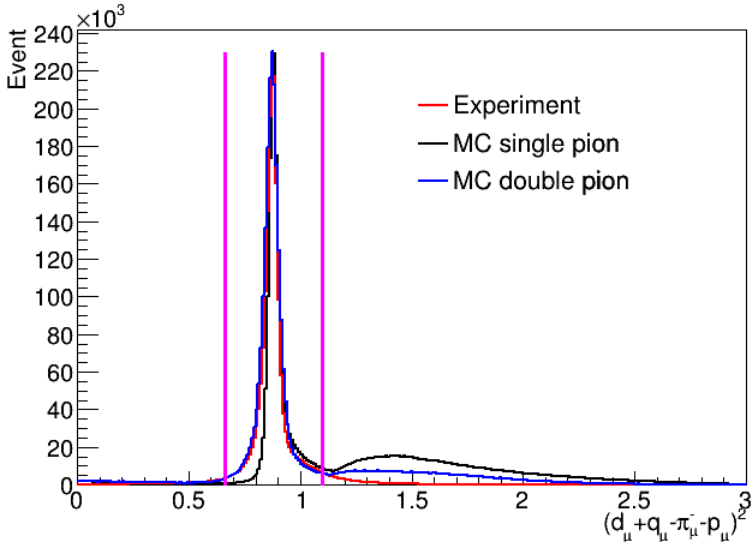
- quark core from the data on $N(1520)3/2^-$
- meson-baryon cloud from the data on $N(1675)5/2^-$

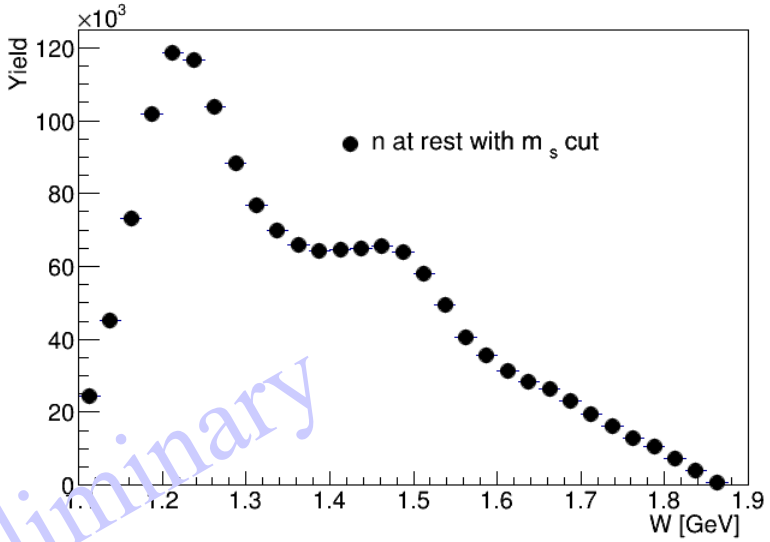
sheds light on the transition from the confined quark to the colorless meson-baryon structure and its dependents on the N* quantum numbers.

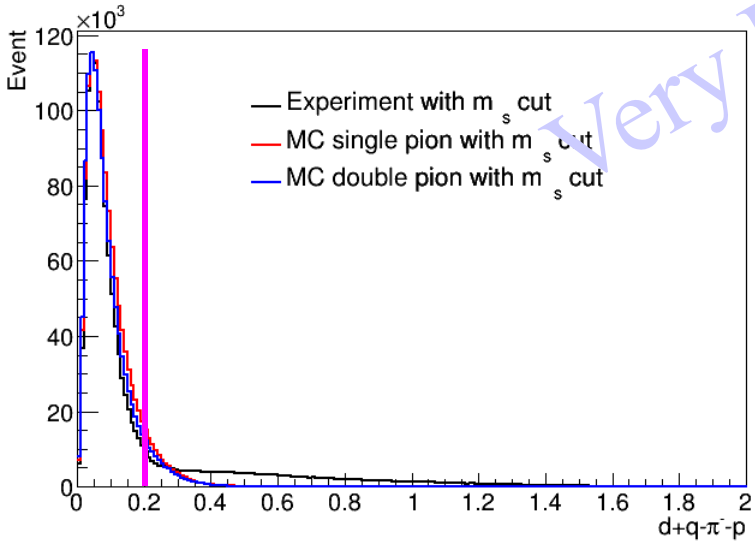
New Experimental Results & Approaches

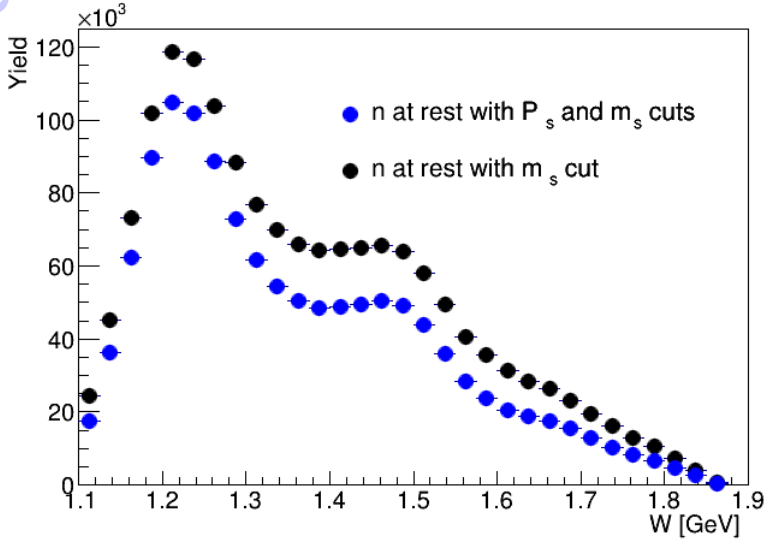
Single π Electroproduction off the Deuteron

Ye Tian



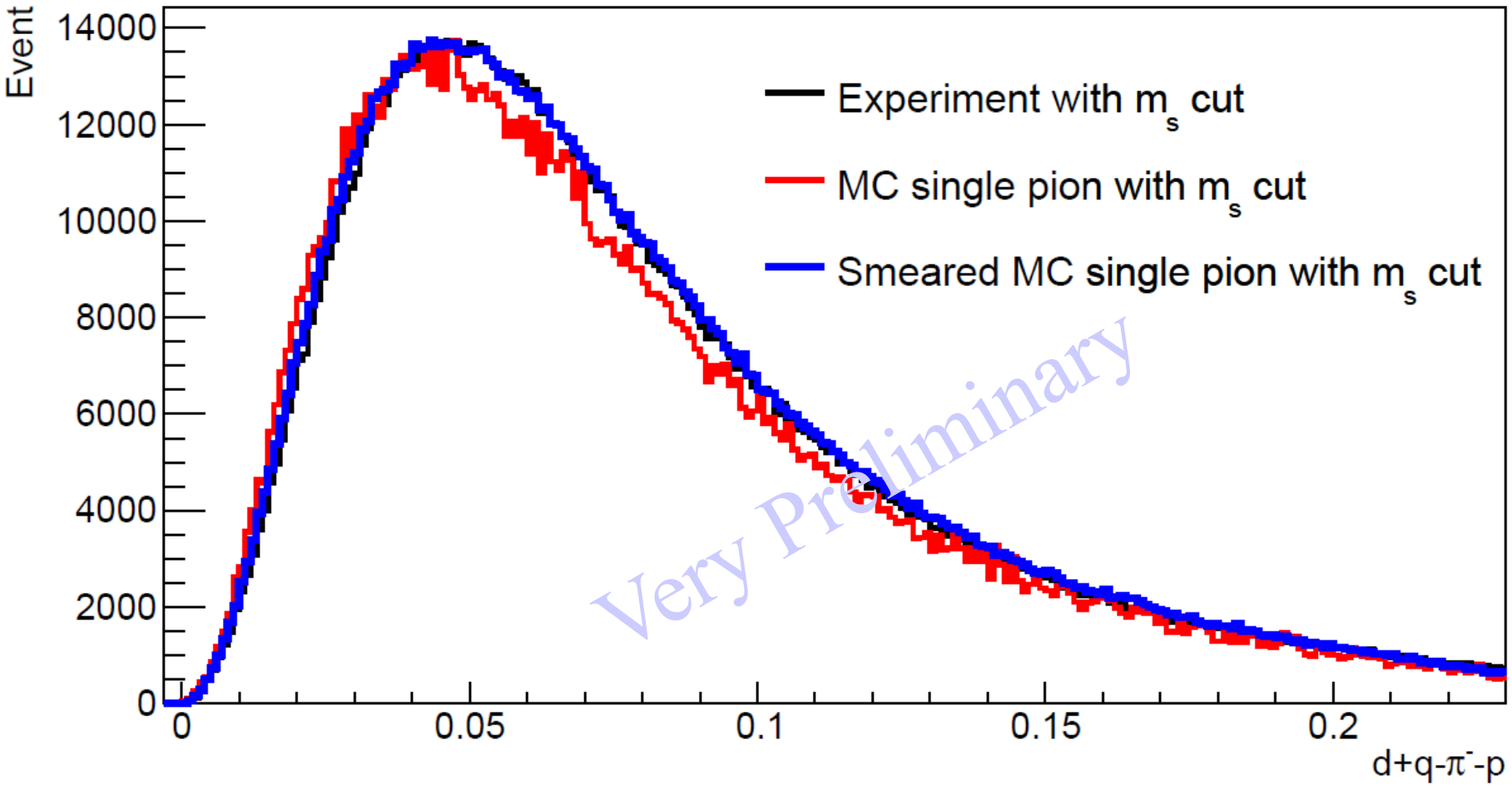






Single π Electroproduction off the Deuteron

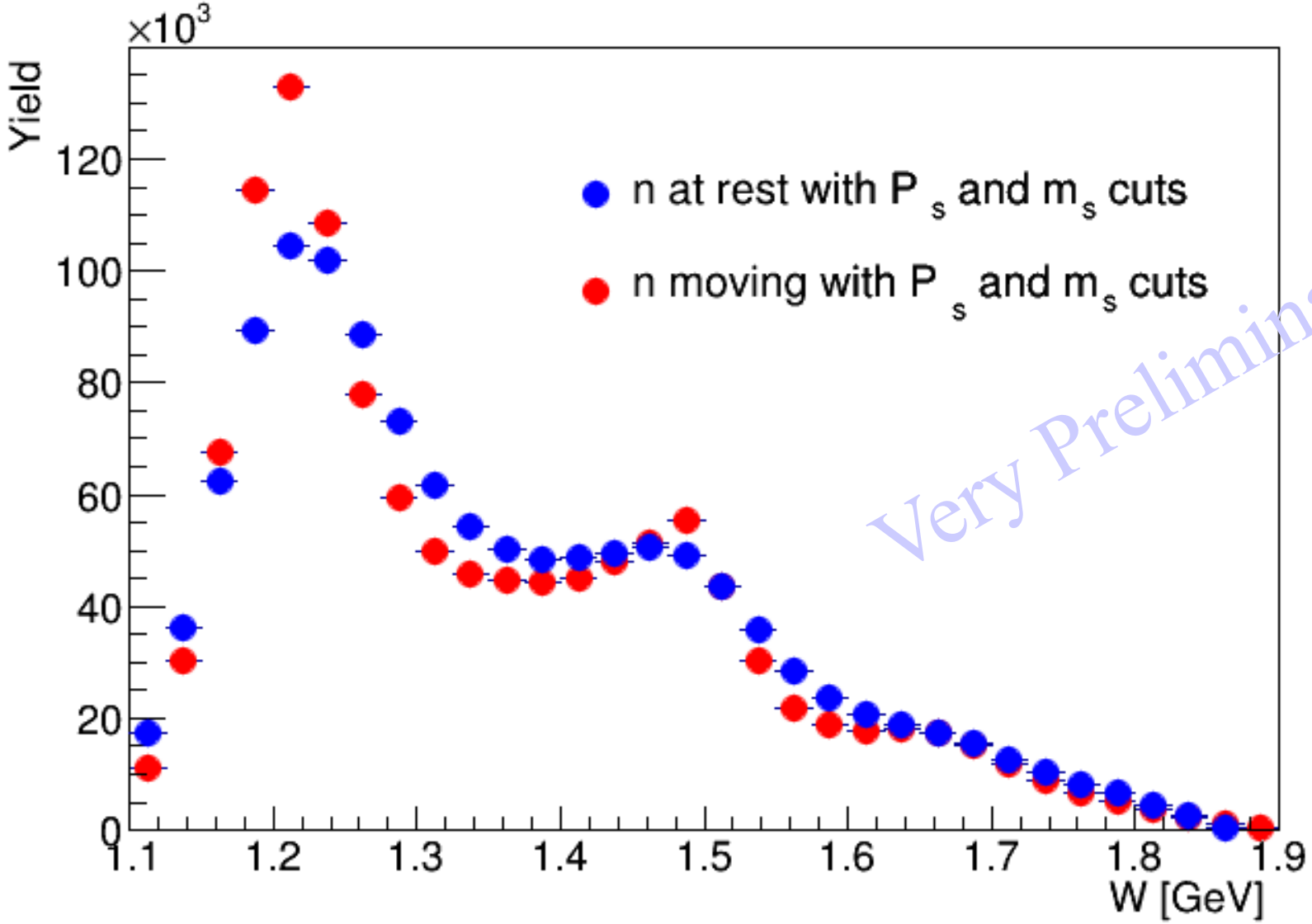
Ye Tian



Below a missing momentum of 0.2 GeV the **measured data** coincides with the **resolution smeared theoretical Fermi momentum distribution**.

Single π Electroproduction off the Deuteron

Ye Tian



Single π^- Electroproduction off the Deuteron

Ye Tian

W = 1125 MeV

ΔW = 25 MeV

W = 1685 MeV

Q^2 = 0.7 GeV^2

ΔQ^2 = 0.2 GeV^2

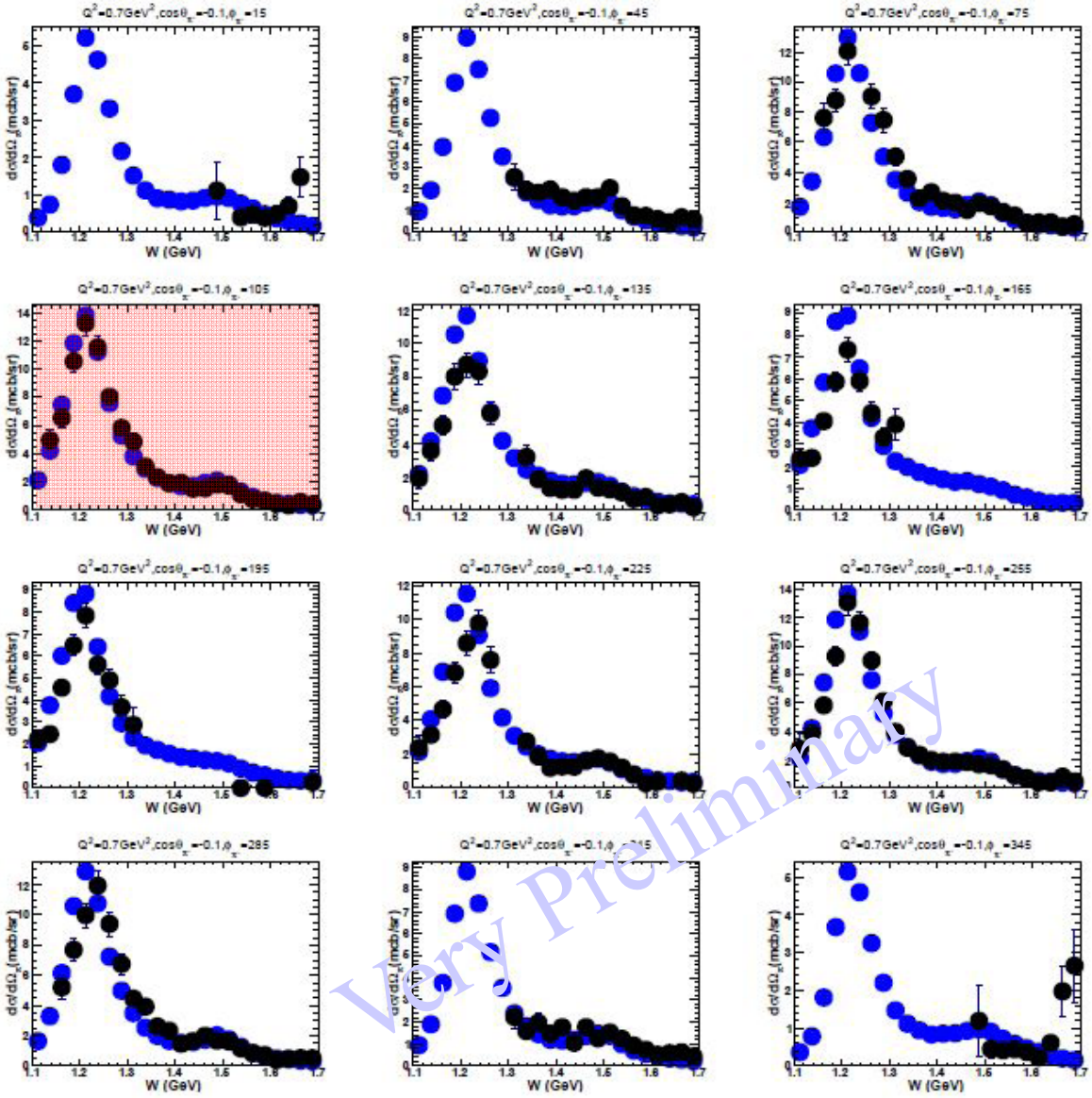
cos(θ) = -0.1

Δcos(θ) = 0.2

ϕ = 15°

Δϕ = 30°

ϕ = 345°



Single π^- Electroproduction off the Deuteron

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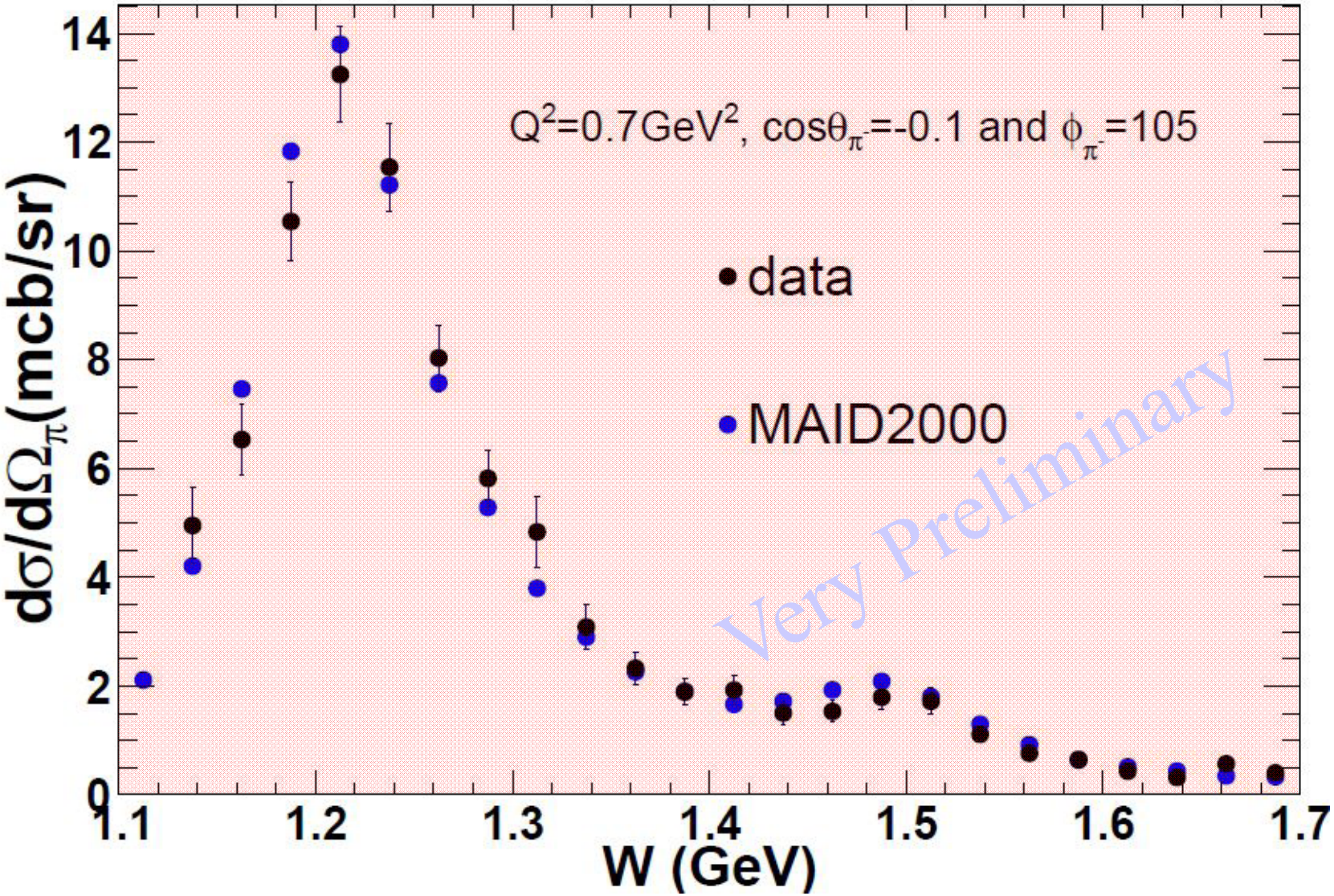


FSI for $\gamma n \to \pi^- p$

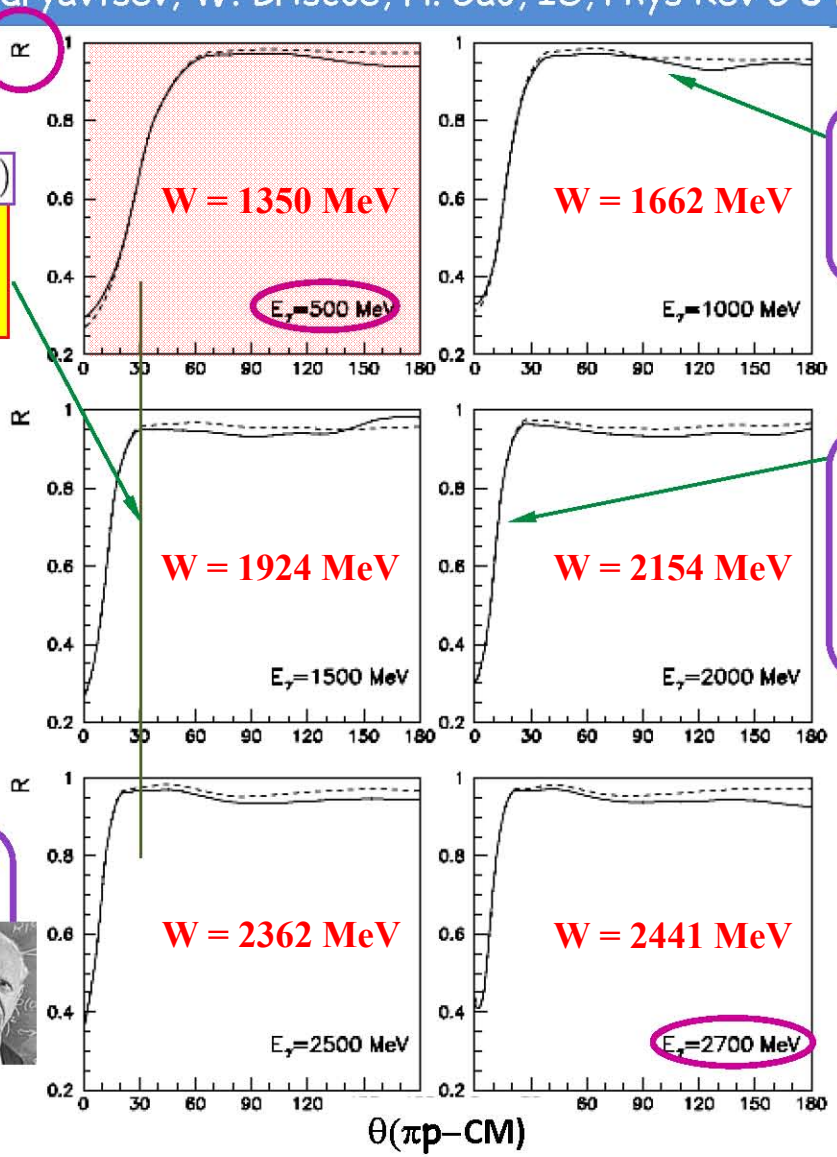
[V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, IS, Phys Rev C 84, 035203 (2011)]

$$R_{FSI} = (d\sigma/d\Omega_{\pi p})/(d\sigma^{IA}/d\Omega_{\pi p})$$

Cuts:
p_s > 200 MeV/c
p_f > 200 MeV/c

CLAS data:
E > 1 GeV
θ > 32 deg

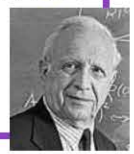
- There is no large sensitivity to cuts.



- For CLAS data
  - The FSI correction factor R < 1.
  - The behavior is smooth vs. θ.
  - The effect $\Delta\sigma/\sigma \leq 10\%$.

- There is a **sizeable** FSI effect from **S-wave** part of **pp-FSI** at small angles.
- This region **narrows** as the E_γ increases.

- Our estimation of the **Glauber FSI** corrections gives the value of 5%.
- **Previous** estimations gave the order of 15-30%.



--- [IA + NN_{fsi}] / IA
___ [IA + $(NN+\pi N)_{fsi}$] / IA

Single π Electroproduction off the Deuteron

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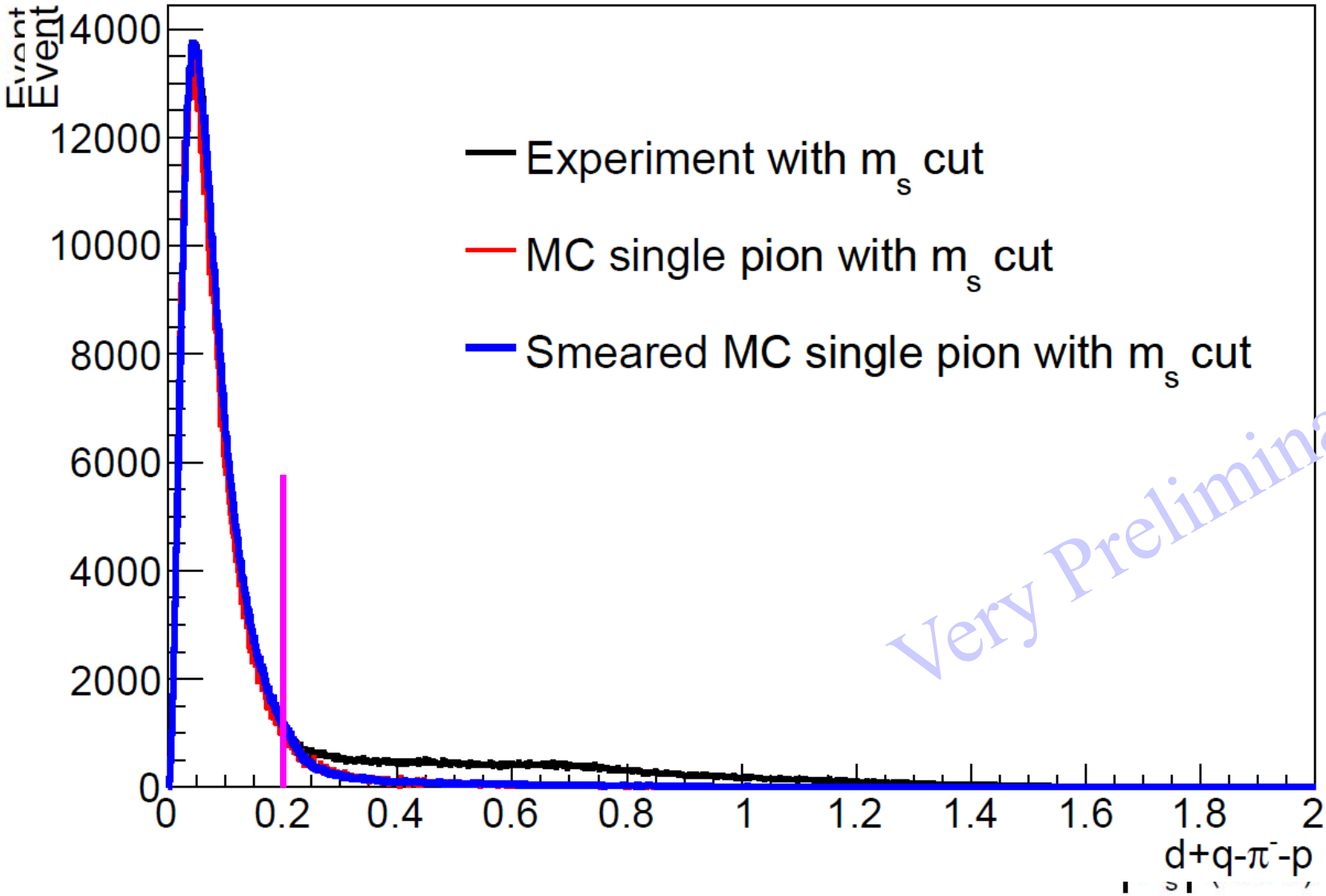

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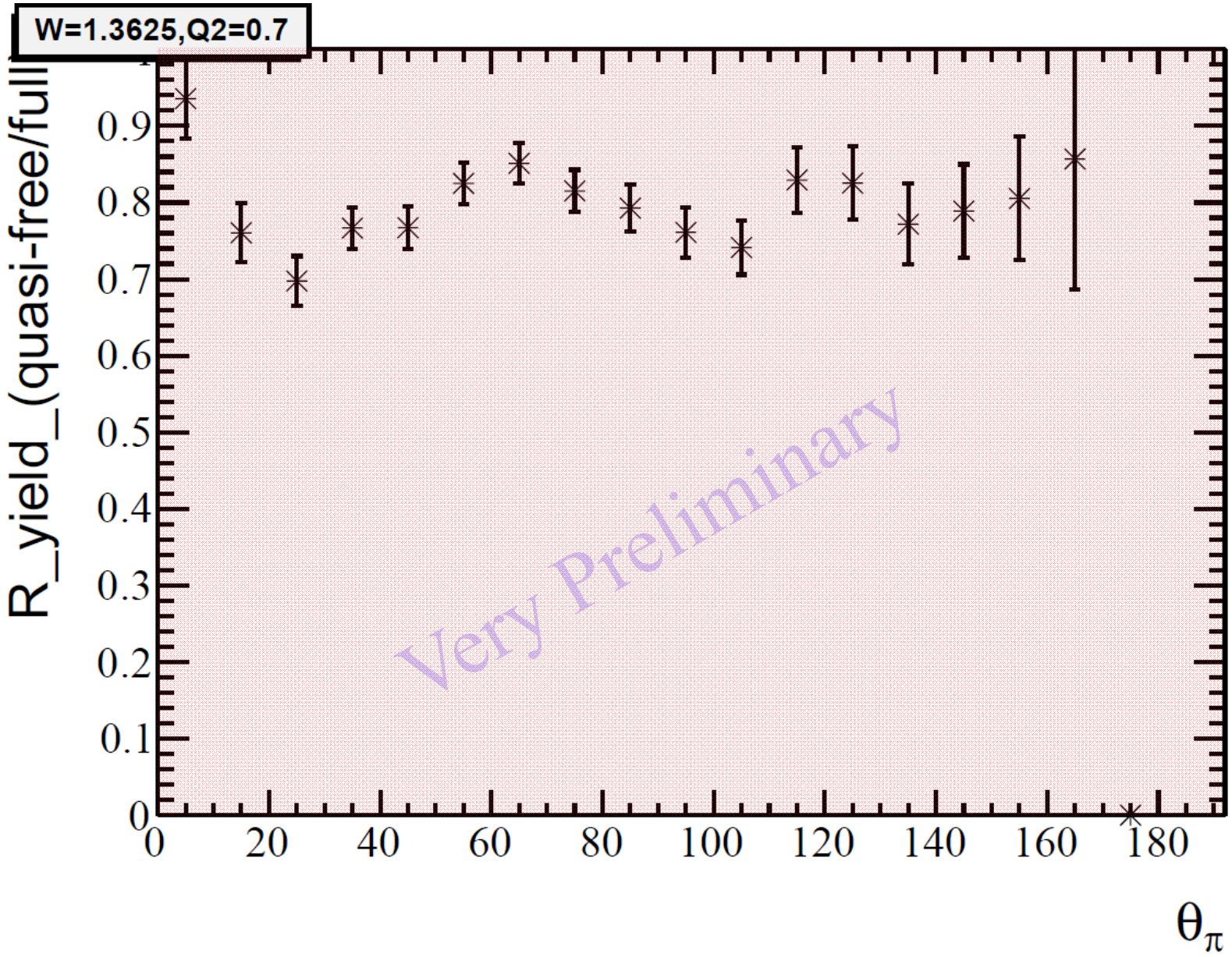
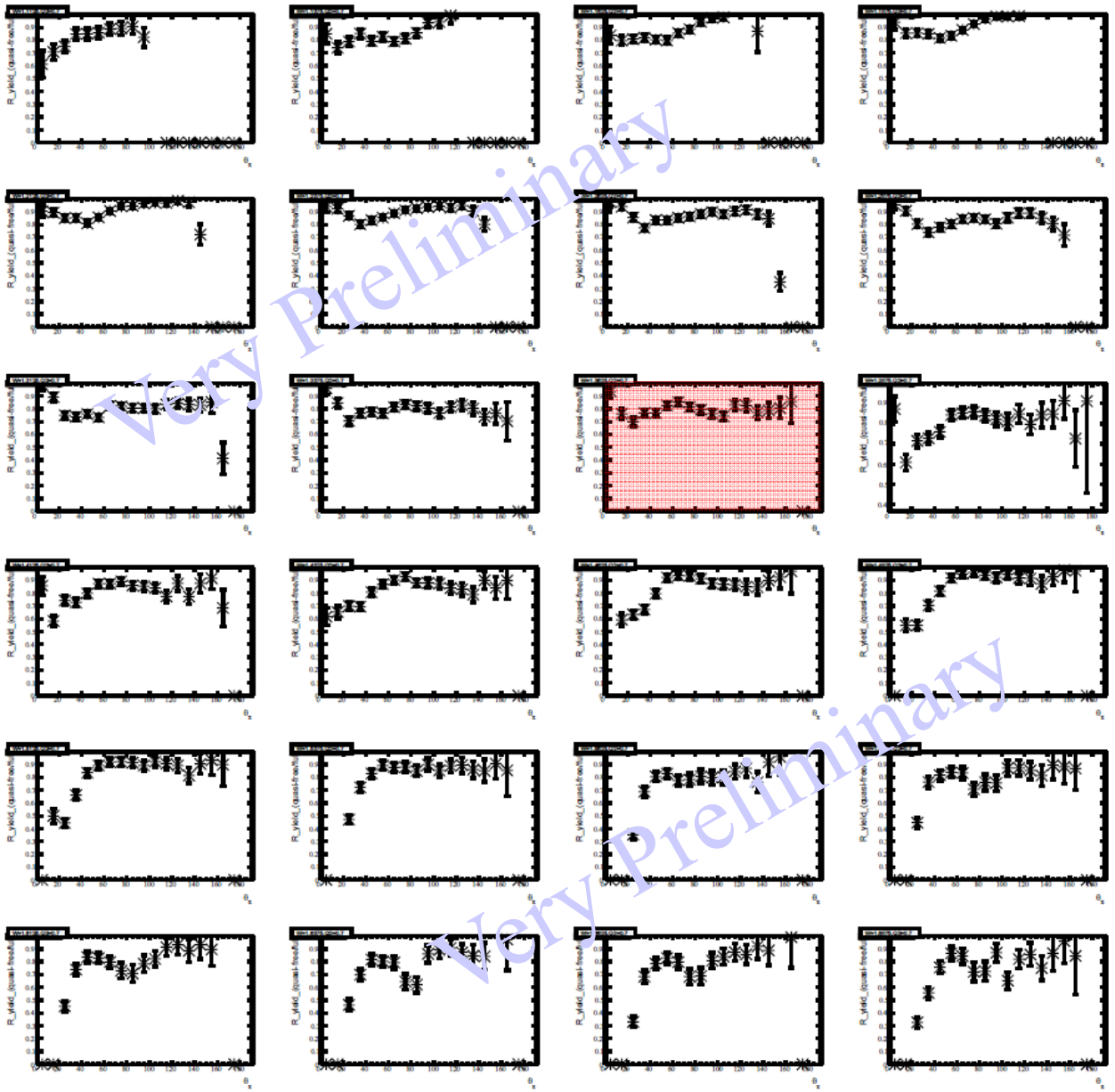


Single π Electroproduction off the Deuteron

W = 1125 MeV

ΔW = 25 MeV

Ye Tian



$Q^2 = 0.7$ GeV^2

$\Delta Q^2 = 0.2$ GeV^2

W = 1685 MeV

Single π Electroproduction off the Deuteron

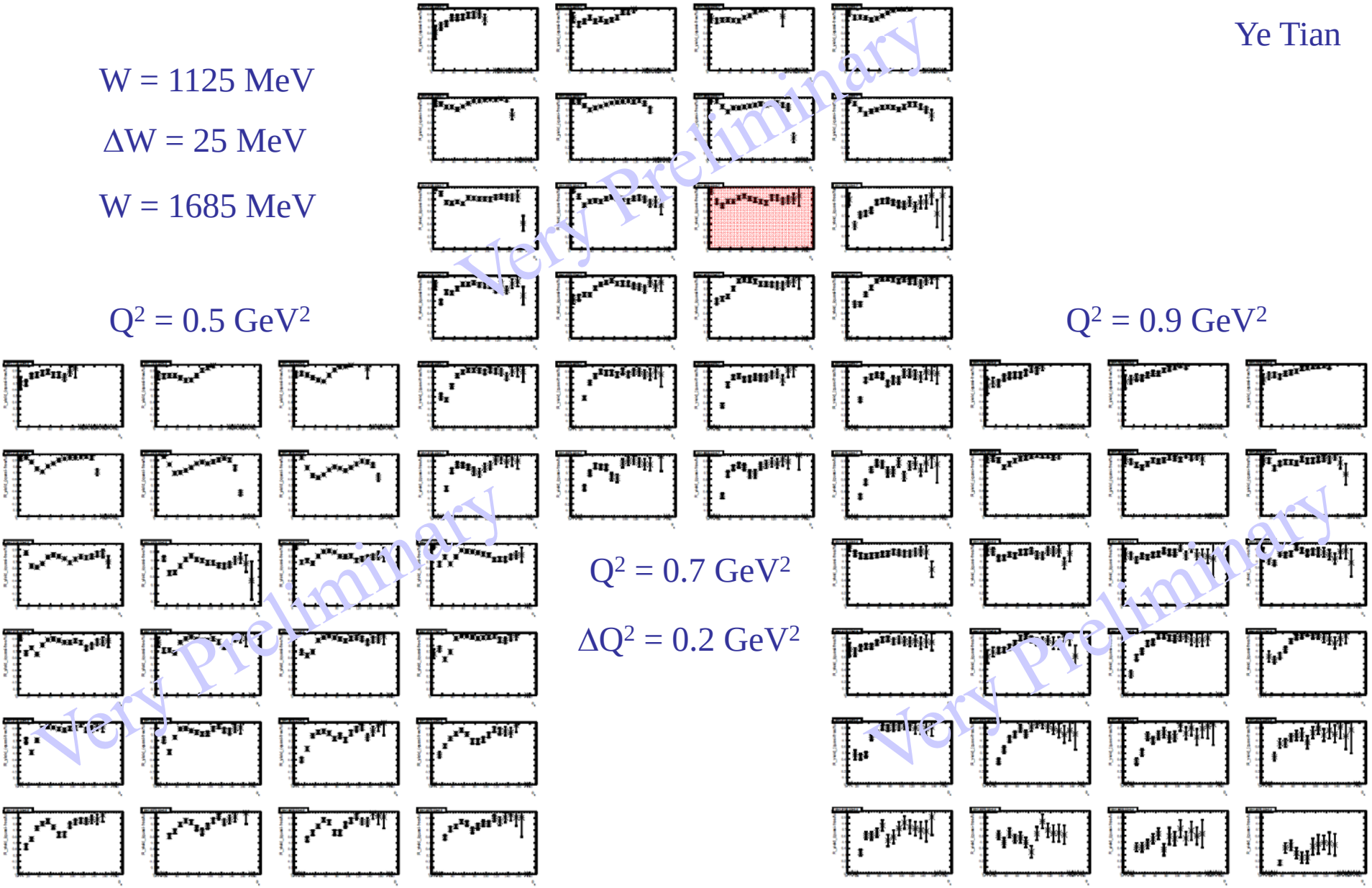
Ye Tian

W = 1125 MeV

ΔW = 25 MeV

W = 1685 MeV

Q^2 = 0.5 GeV^2



Q^2 = 0.7 GeV^2

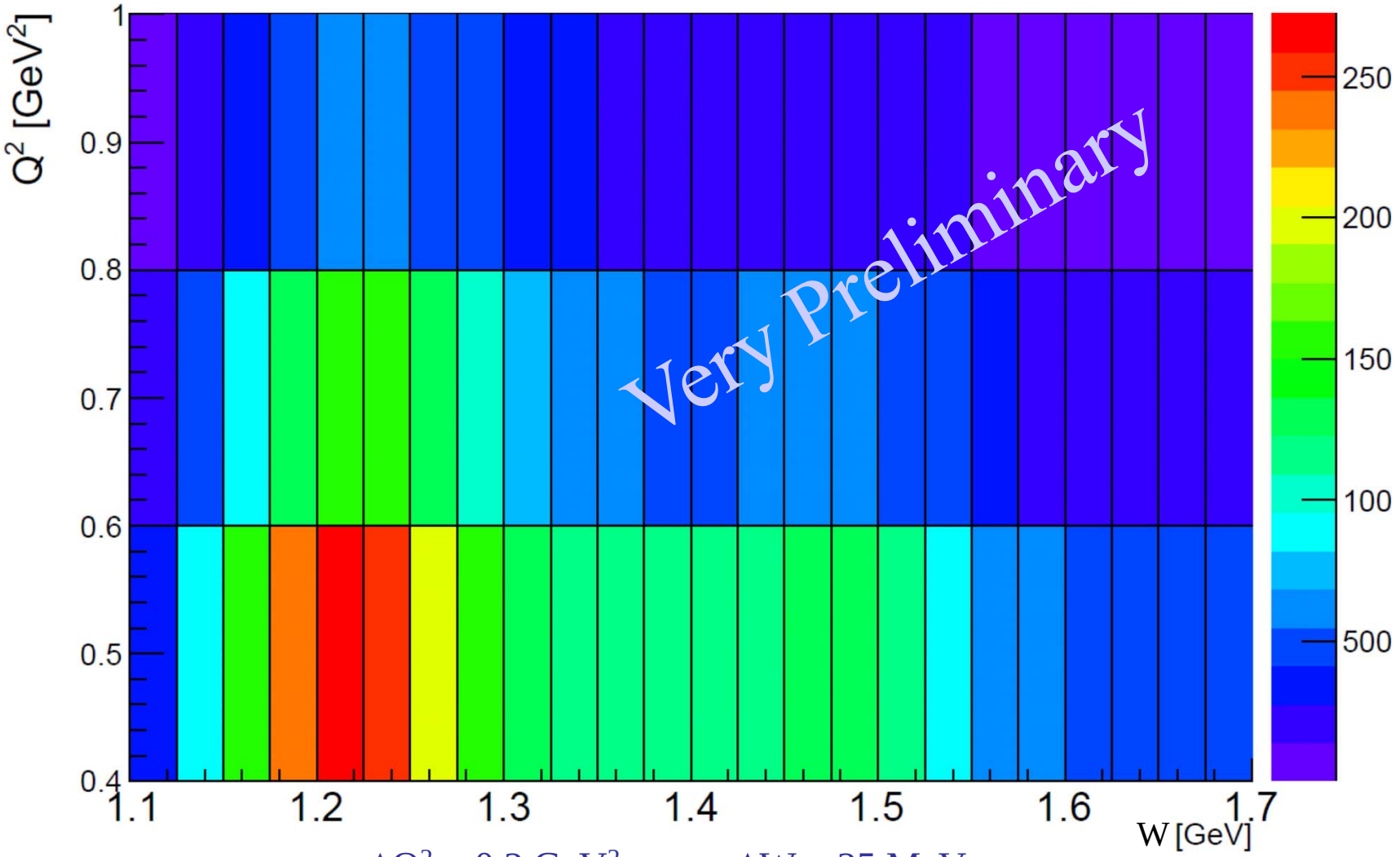
ΔQ^2 = 0.2 GeV^2

Q^2 = 0.9 GeV^2

Single π^- Electroproduction off the Deuteron

$\gamma d \rightarrow \pi^- p(p)$

Ye Tian



$\Delta Q^2 = 0.2$ GeV^2 $\Delta W = 25$ MeV

Single π^- Electroproduction off the Deuteron

Ye Tian

W = 1212 MeV

ΔW = 25 MeV

Q^2 = 0.5 GeV^2

ΔQ^2 = 0.2 GeV^2

cos(θ) = -0.7

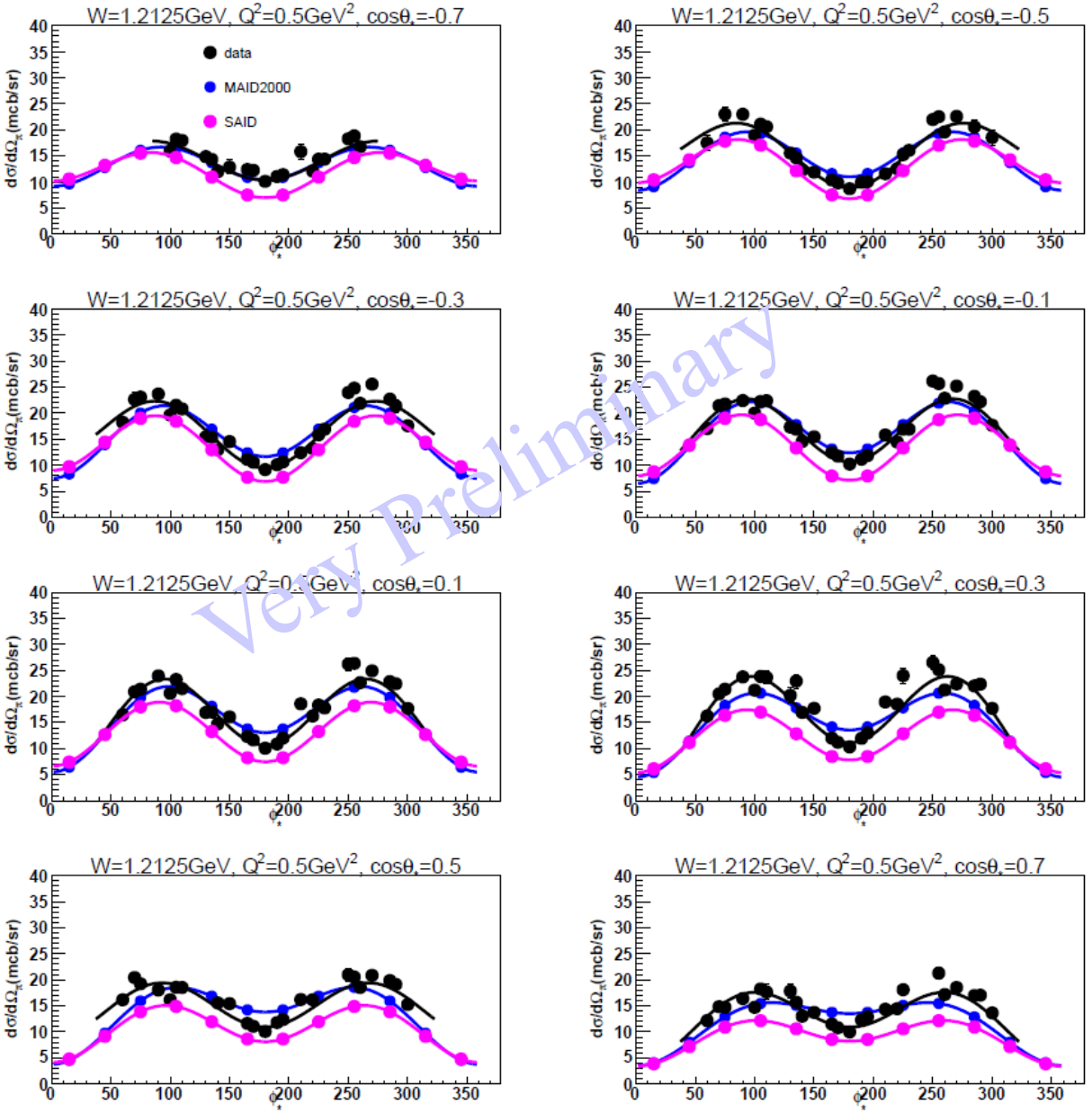
Δcos(θ) = 0.2

cos(θ) = 0.7

ϕ = 15°

Δϕ = 30°

ϕ = 345°



Single π^- Electroproduction off the Deuteron

Ye Tian

W = 1212 MeV

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Q^2 = 0.7 GeV^2

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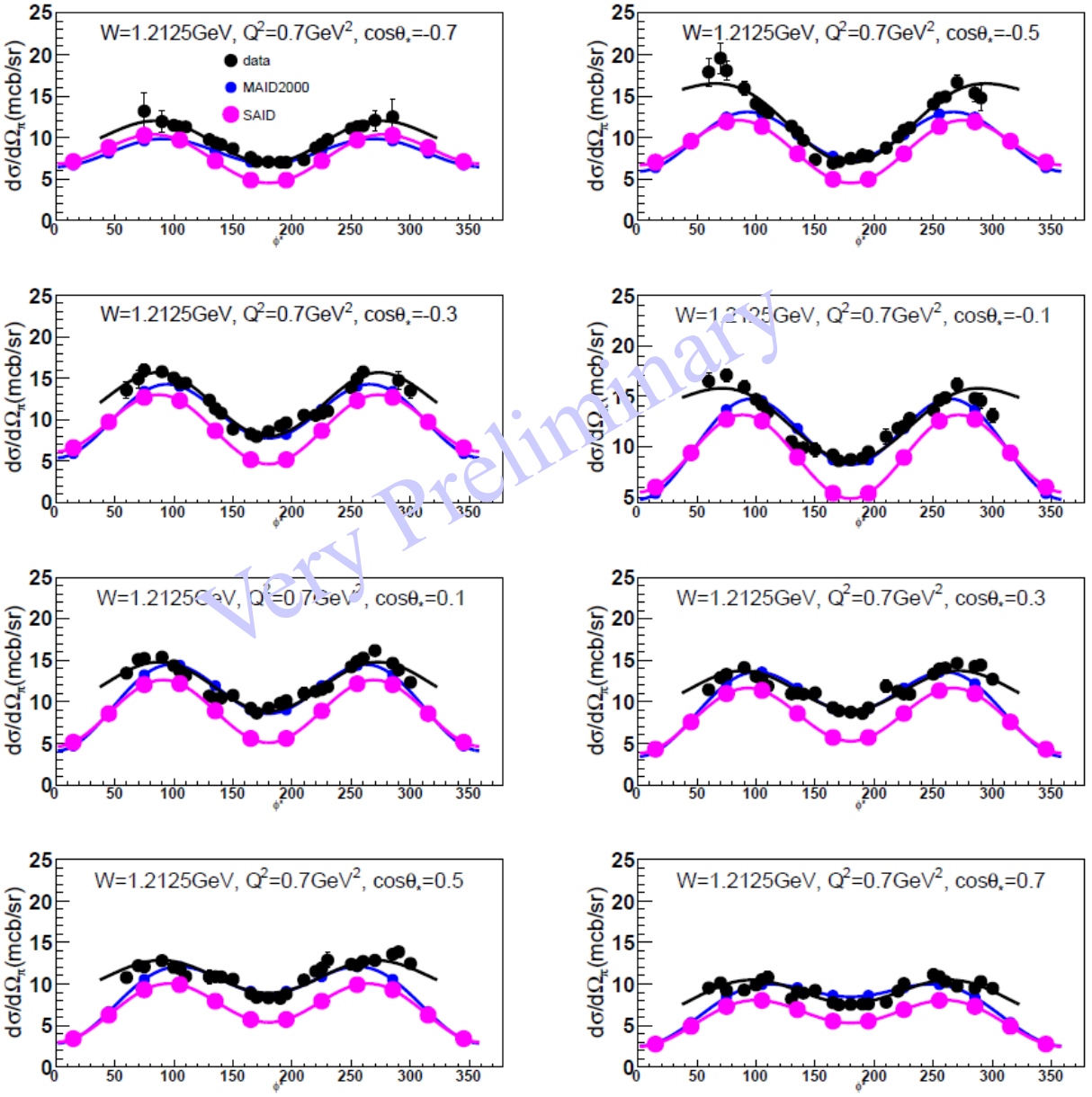


Single π^- Electroproduction off the Deuteron

Ye Tian

W = 1212 MeV

ΔW = 25 MeV

Q^2 = 0.9 GeV^2

ΔQ^2 = 0.2 GeV^2

cos(θ) = -0.7

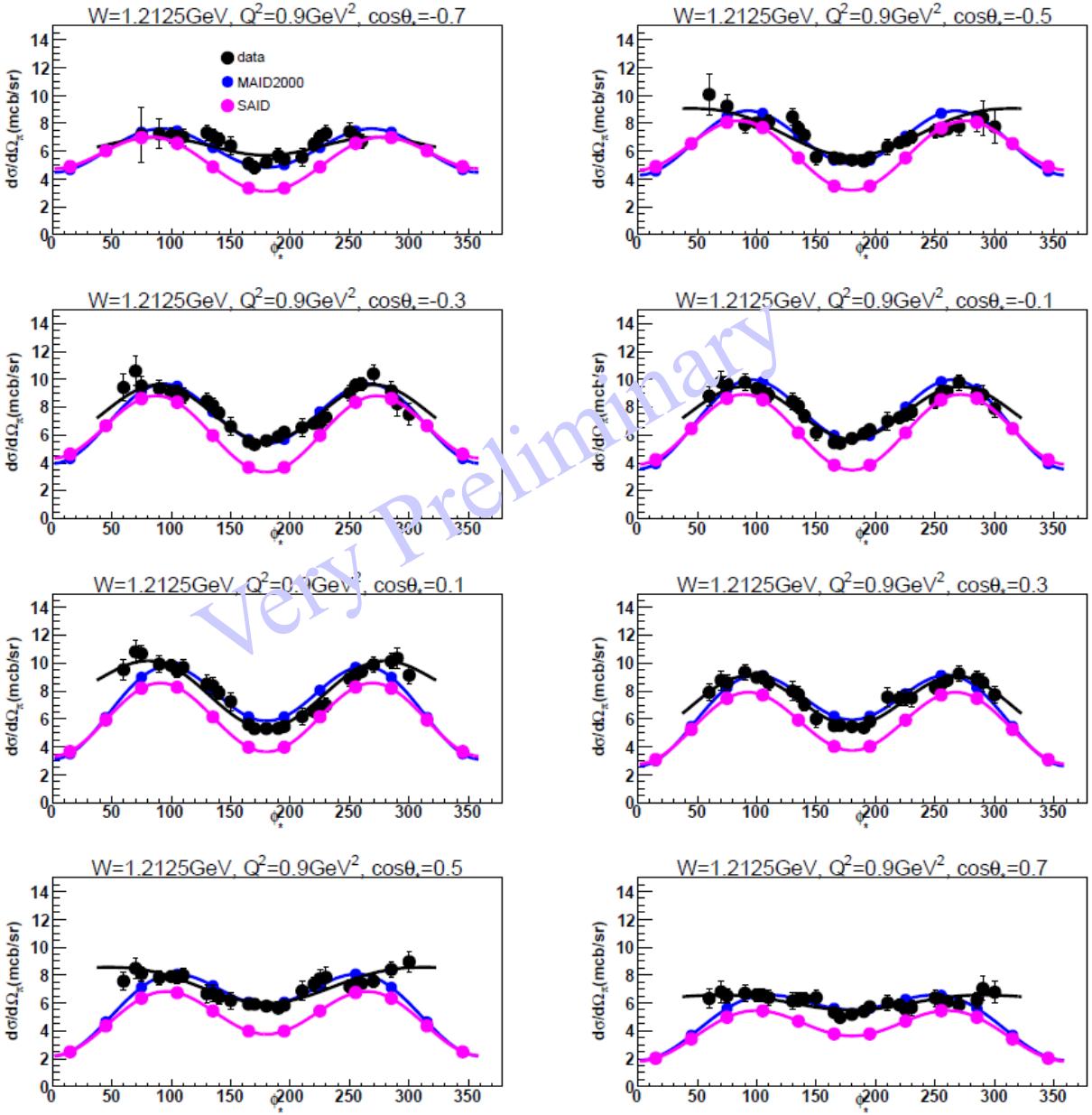
Δcos(θ) = 0.2

cos(θ) = 0.7

ϕ = 15°

Δϕ = 30°

ϕ = 345°



Single π^- Electroproduction off the Deuteron

Ye Tian

W = 1212 MeV

ΔW = 25 MeV

Q^2 = 0.5 GeV^2

ΔQ^2 = 0.2 GeV^2

cos(θ) = -0.7

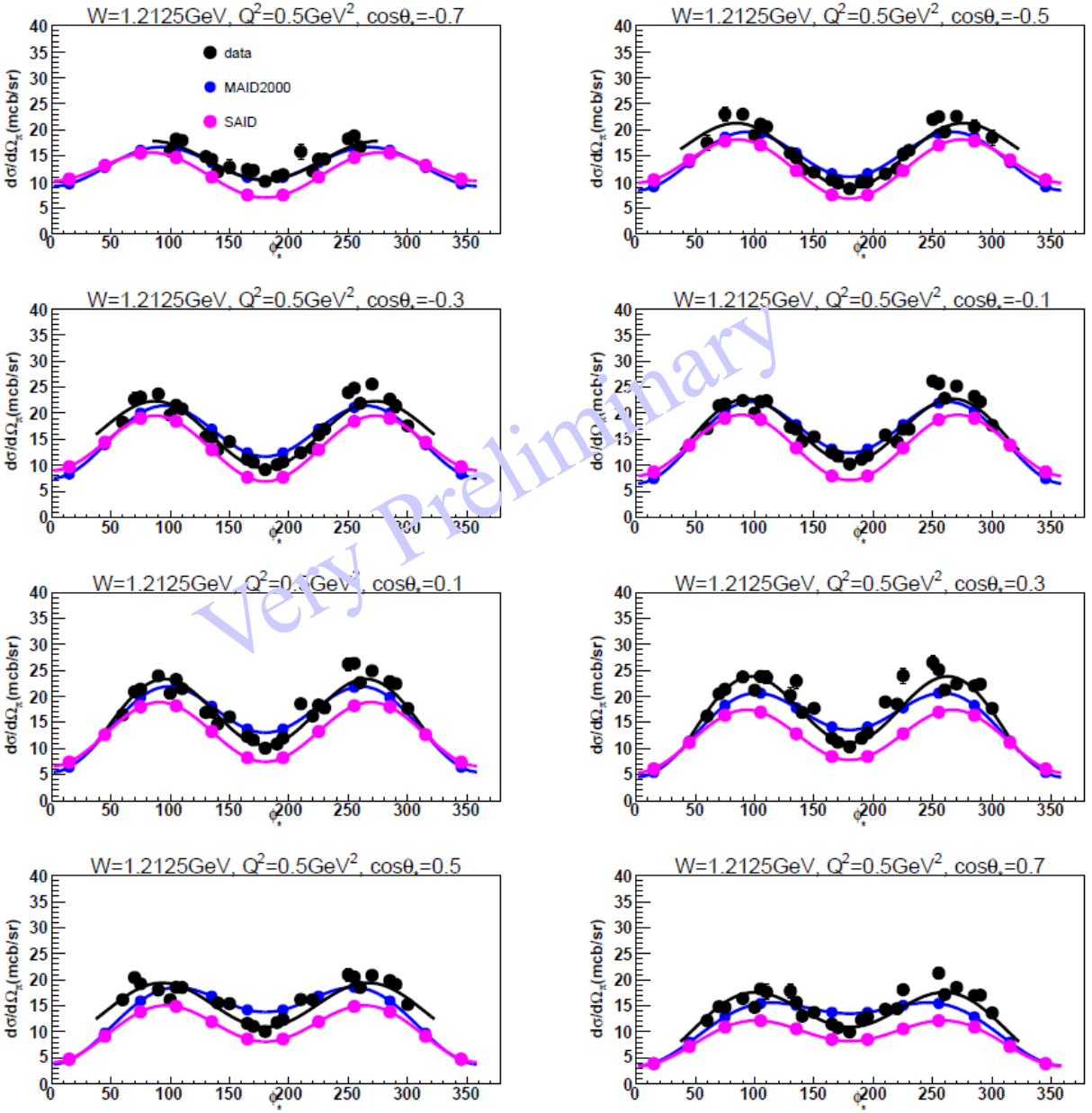
Δcos(θ) = 0.2

cos(θ) = 0.7

ϕ = 15°

Δϕ = 30°

ϕ = 345°



Single π^- Electroproduction off the Deuteron

Ye Tian

W = 1488 MeV

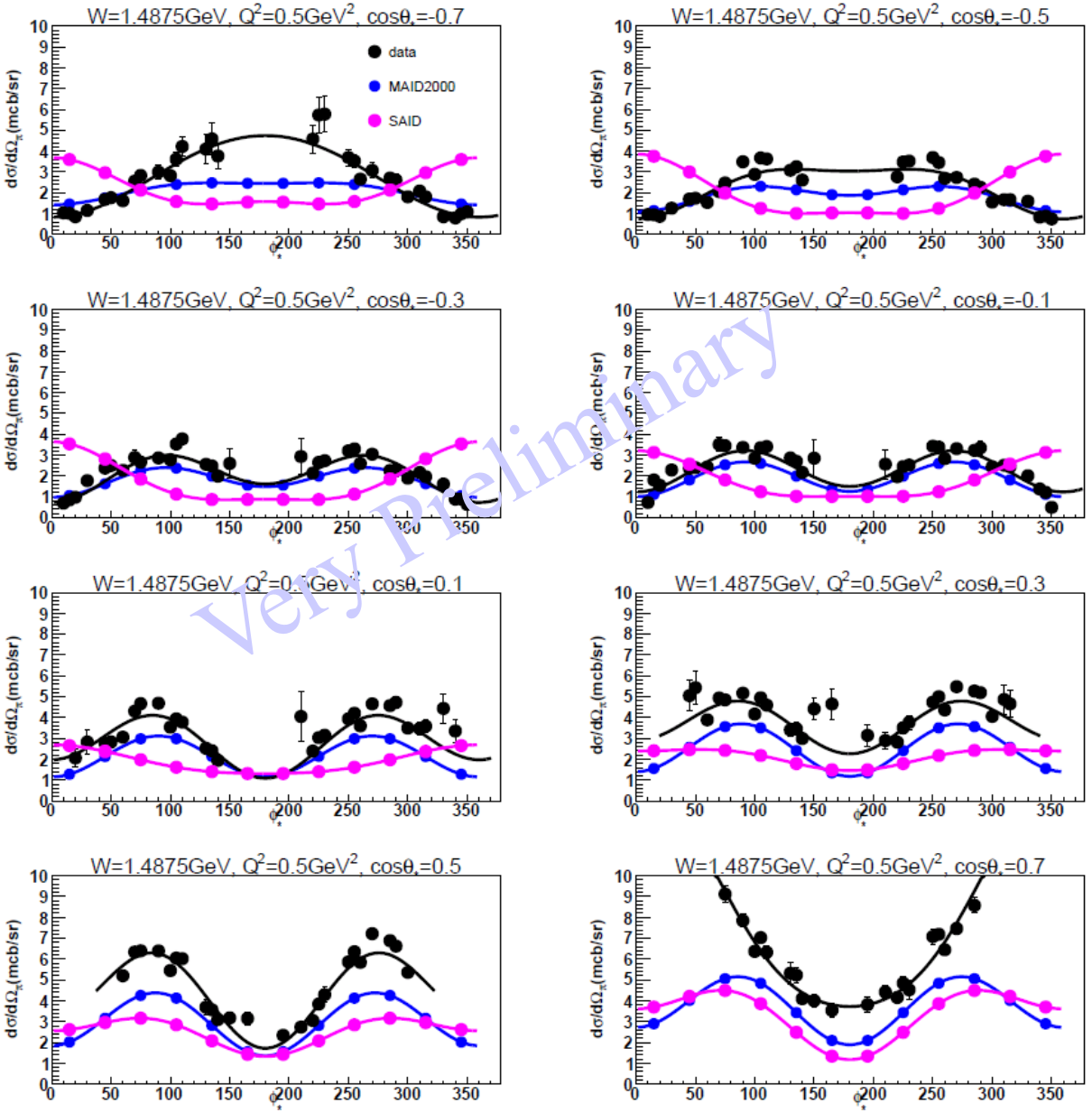
ΔW = 25 MeV

Q^2 = 0.5 GeV^2

ΔQ^2 = 0.2 GeV^2

cos(θ) = -0.7
Δcos(θ) = 0.2
cos(θ) = 0.7

ϕ = 15°
Δϕ = 30°
ϕ = 345°



Single π^- Electroproduction off the Deuteron

Ye Tian

W = 1612 MeV

ΔW = 25 MeV

Q^2 = 0.5 GeV^2

ΔQ^2 = 0.2 GeV^2

cos(θ) = -0.7

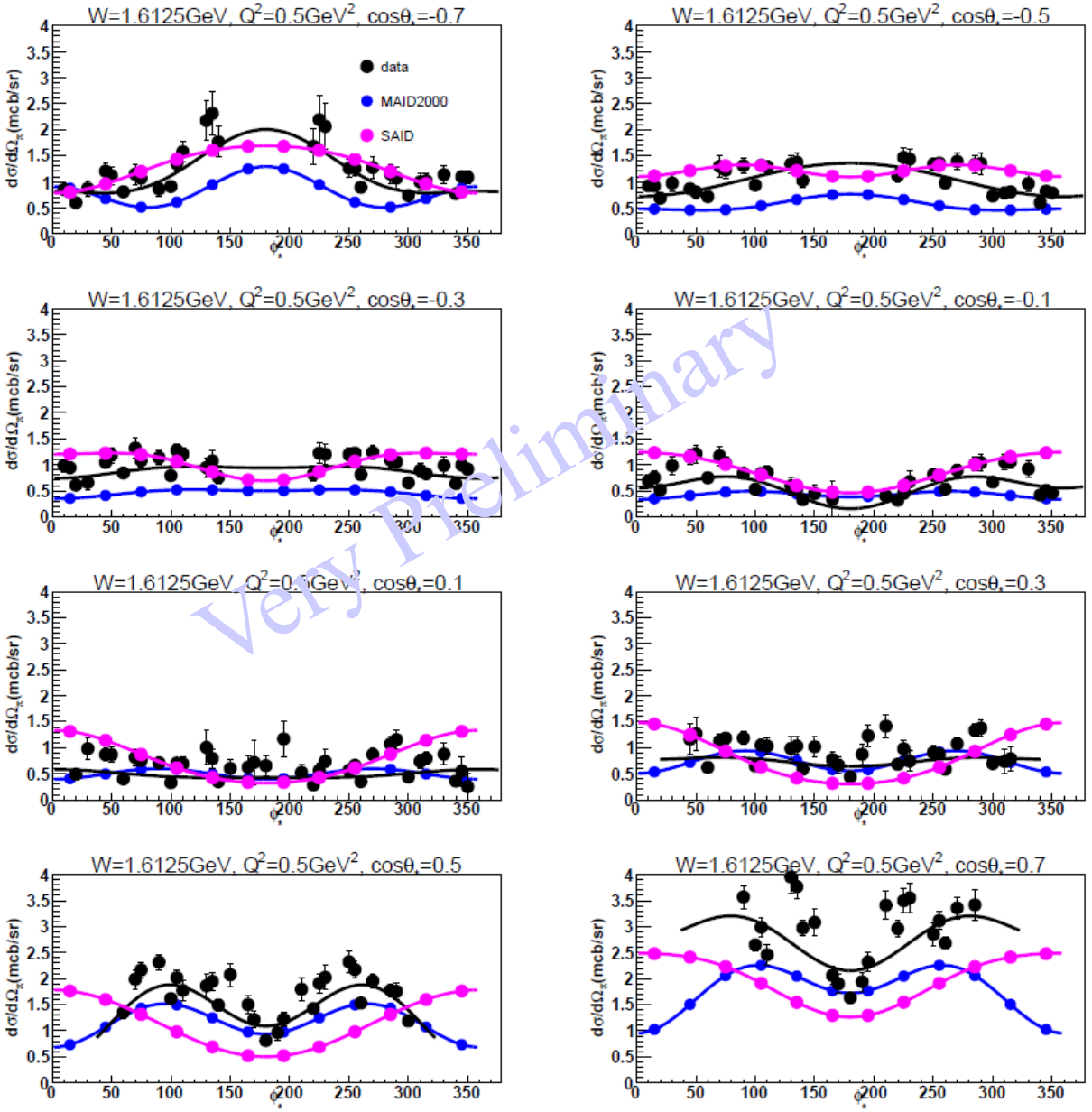
Δcos(θ) = 0.2

cos(θ) = 0.7

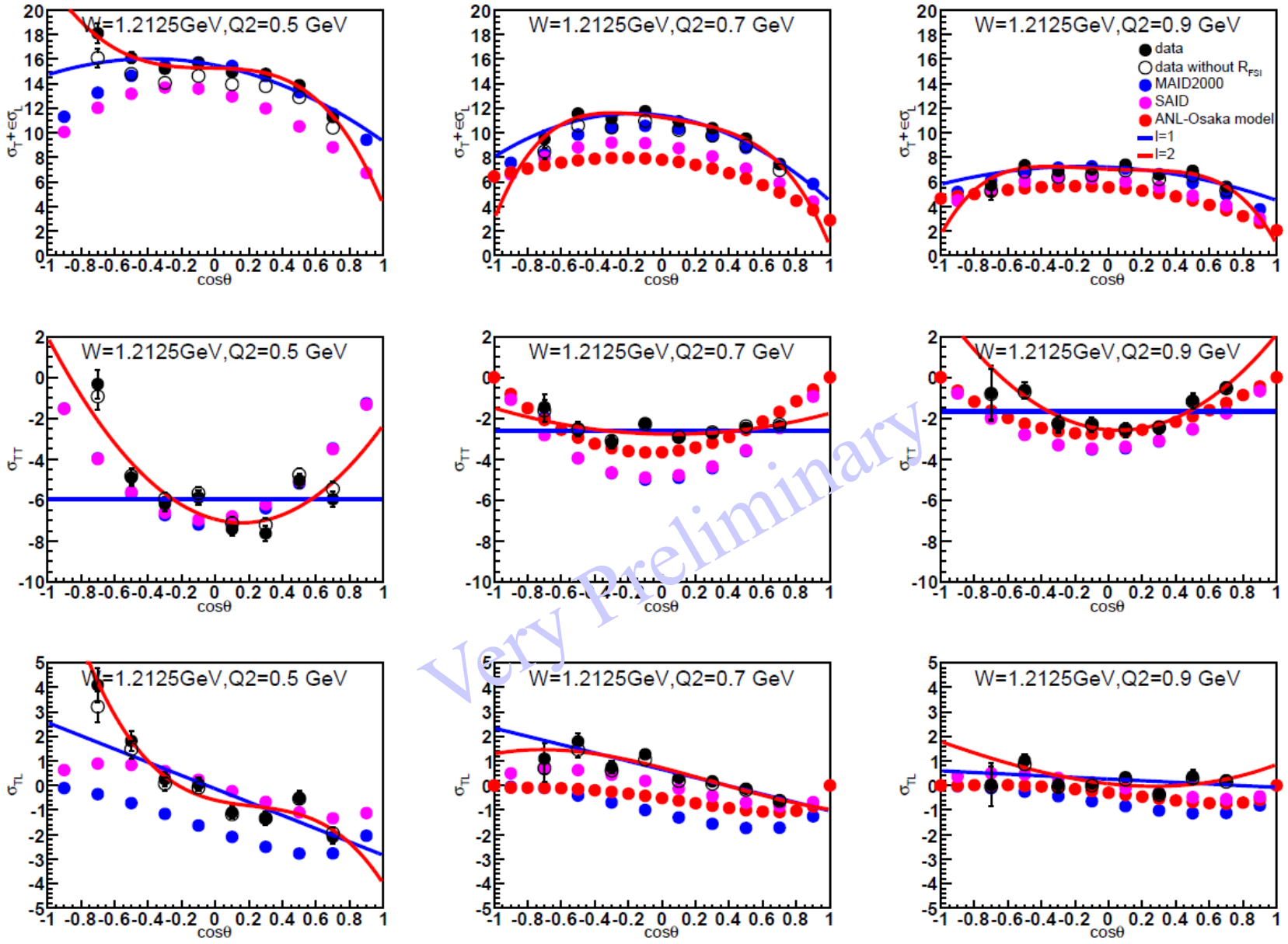
ϕ = 15°

Δϕ = 30°

ϕ = 345°



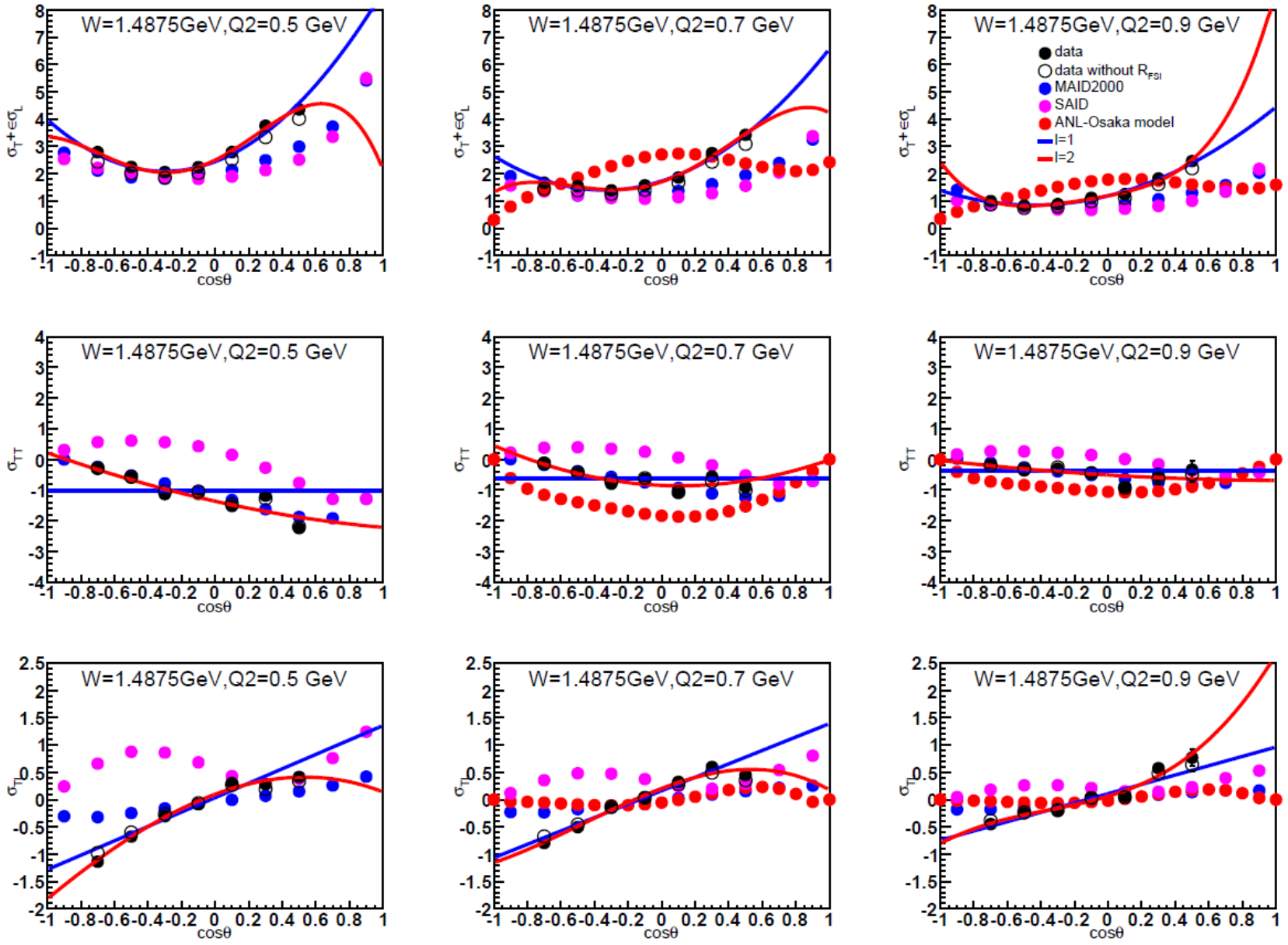
Single π^- Electroproduction off the Deuteron



Ye Tian

Very Preliminary

Single π^- Electroproduction off the Deuteron



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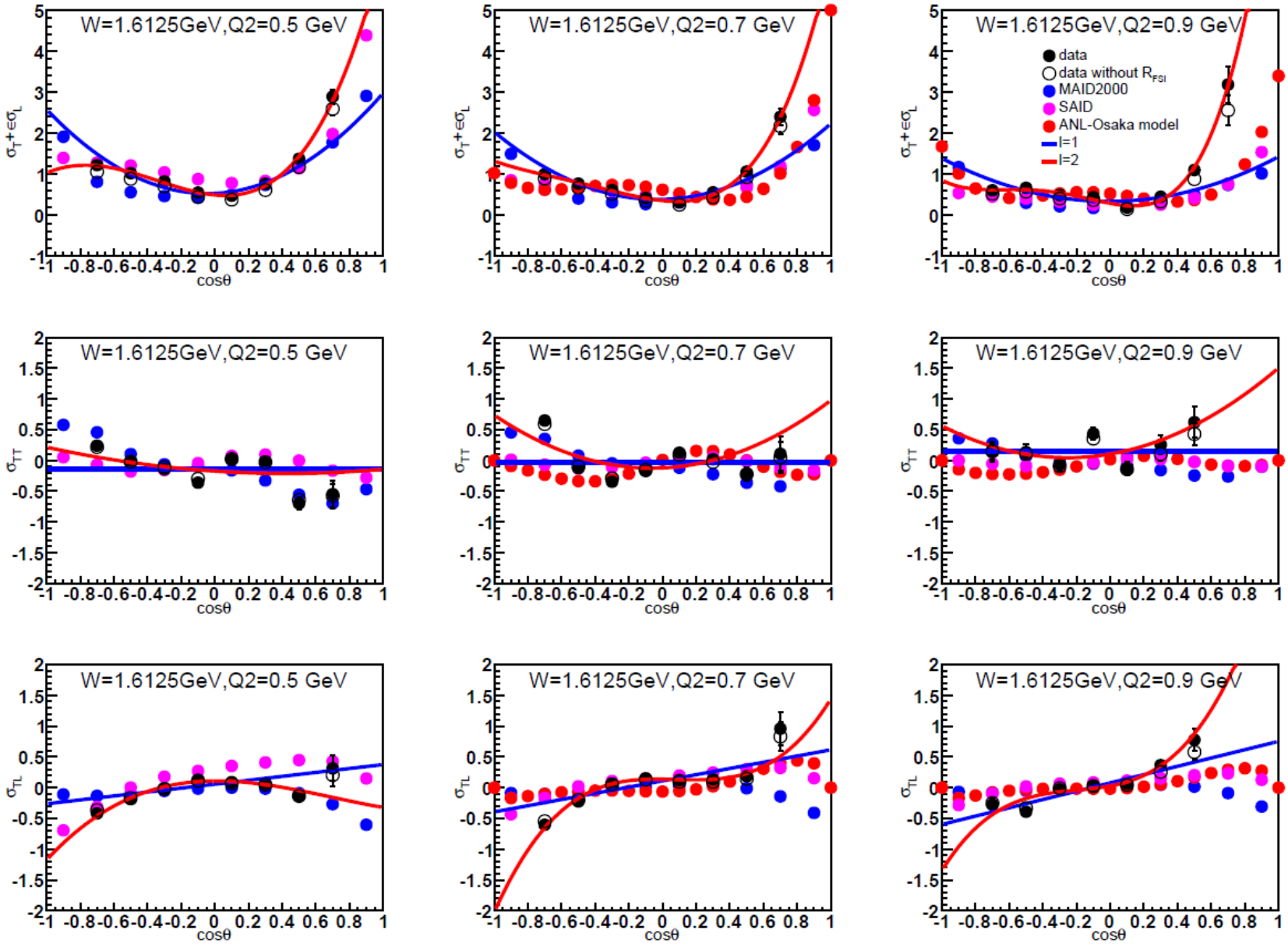
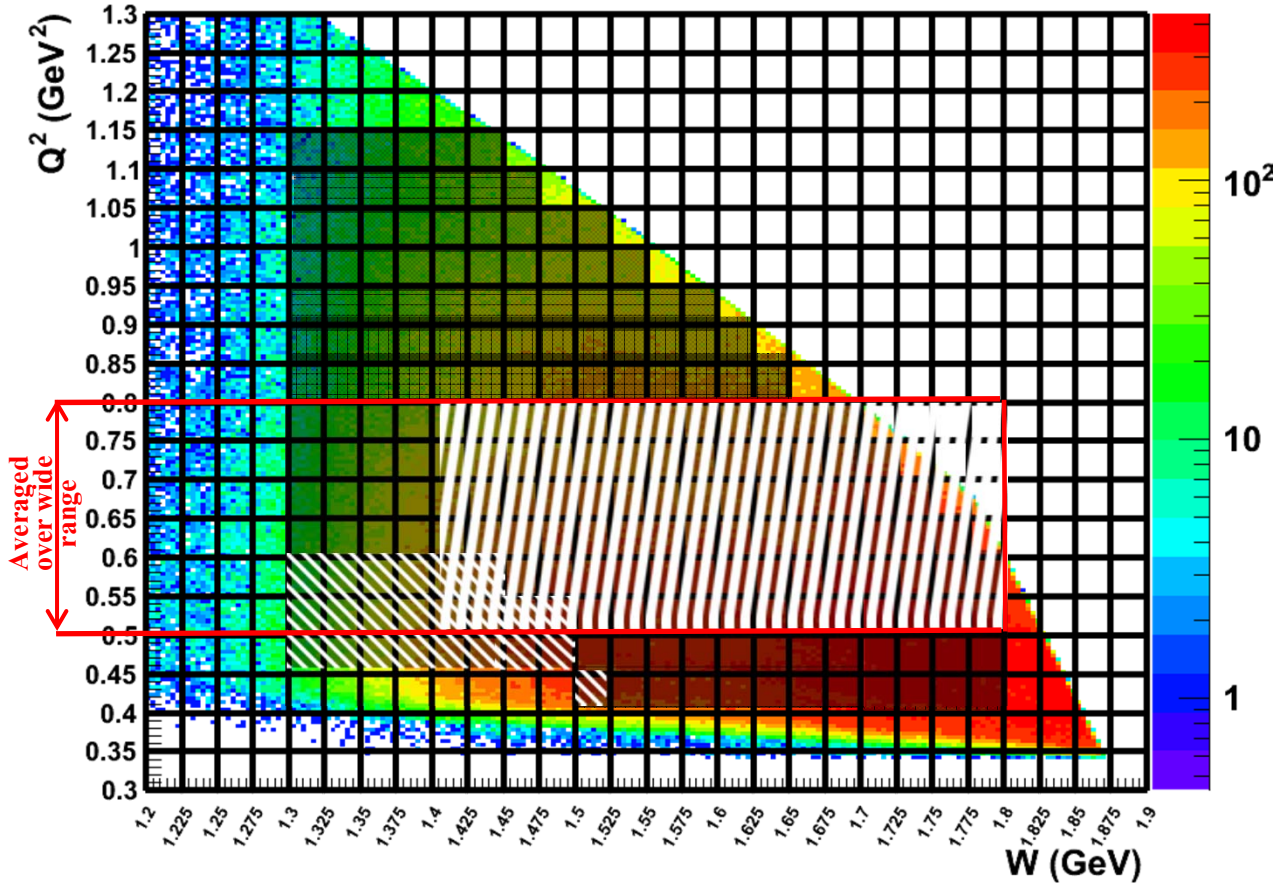
Single π^- Electroproduction off the Deuteron



Ye Tian

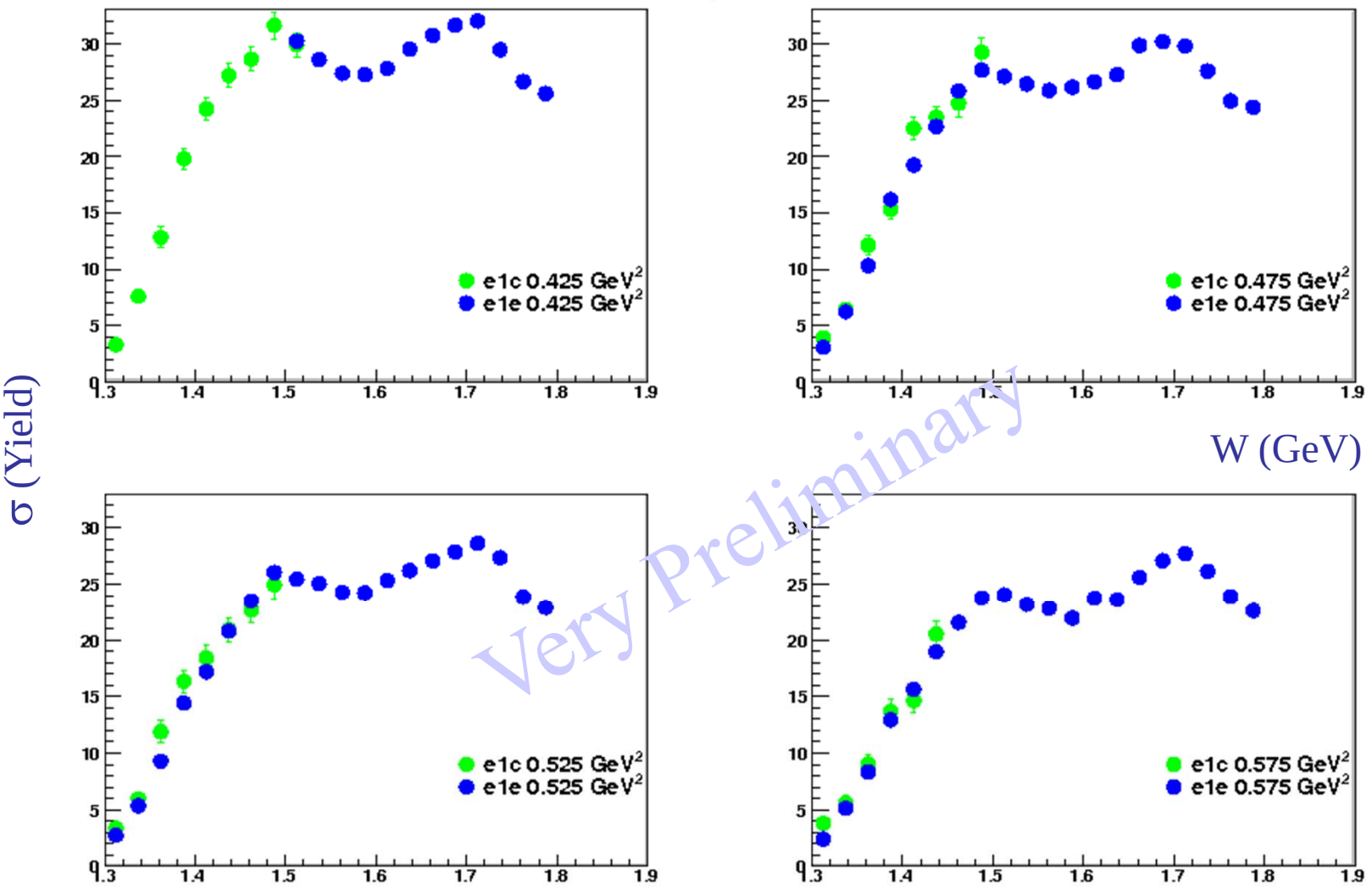
$N\pi^+\pi^-$ Electroproduction Kinematic Coverage

Gleb Fedotov



$p\pi^+\pi^-$ event yields over W and Q^2. Gray shaded area new e1e data set, hatched area at low Q^2 already published e1c data G. by Fedotov *et al.* and hatched area at higher Q^2 already published data in one large Q^2 bin by M. Ripani *et al.*.

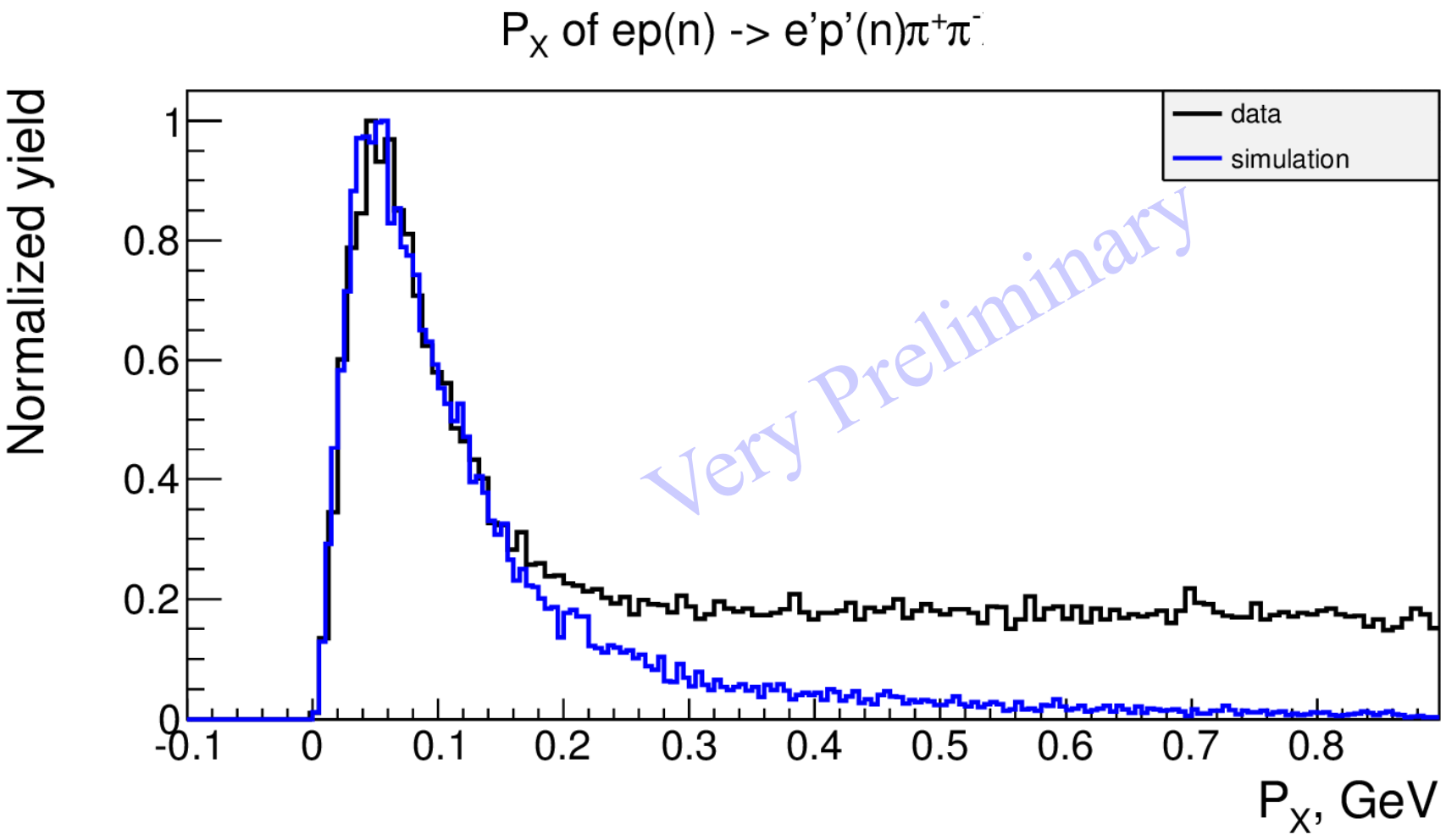
Integrated Nππ Cross Sections Compared to Existing Data



Green already published data (Fedotov *et al.*, PRC79, 015204 (2009)) and blue new e1e data in the overlap region.

Double π Electroproduction off the Deuteron

Iuliia Skorodomina



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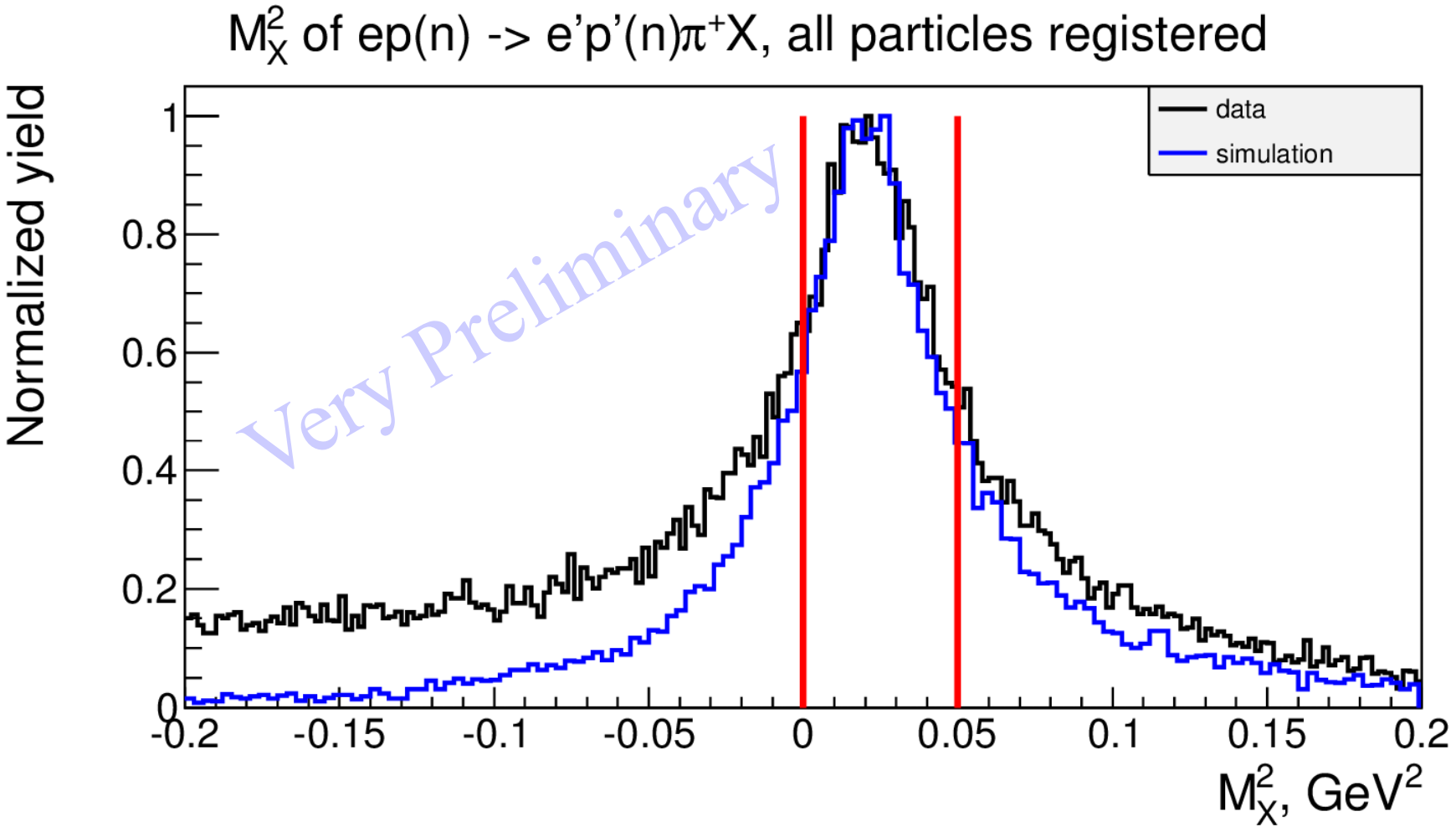

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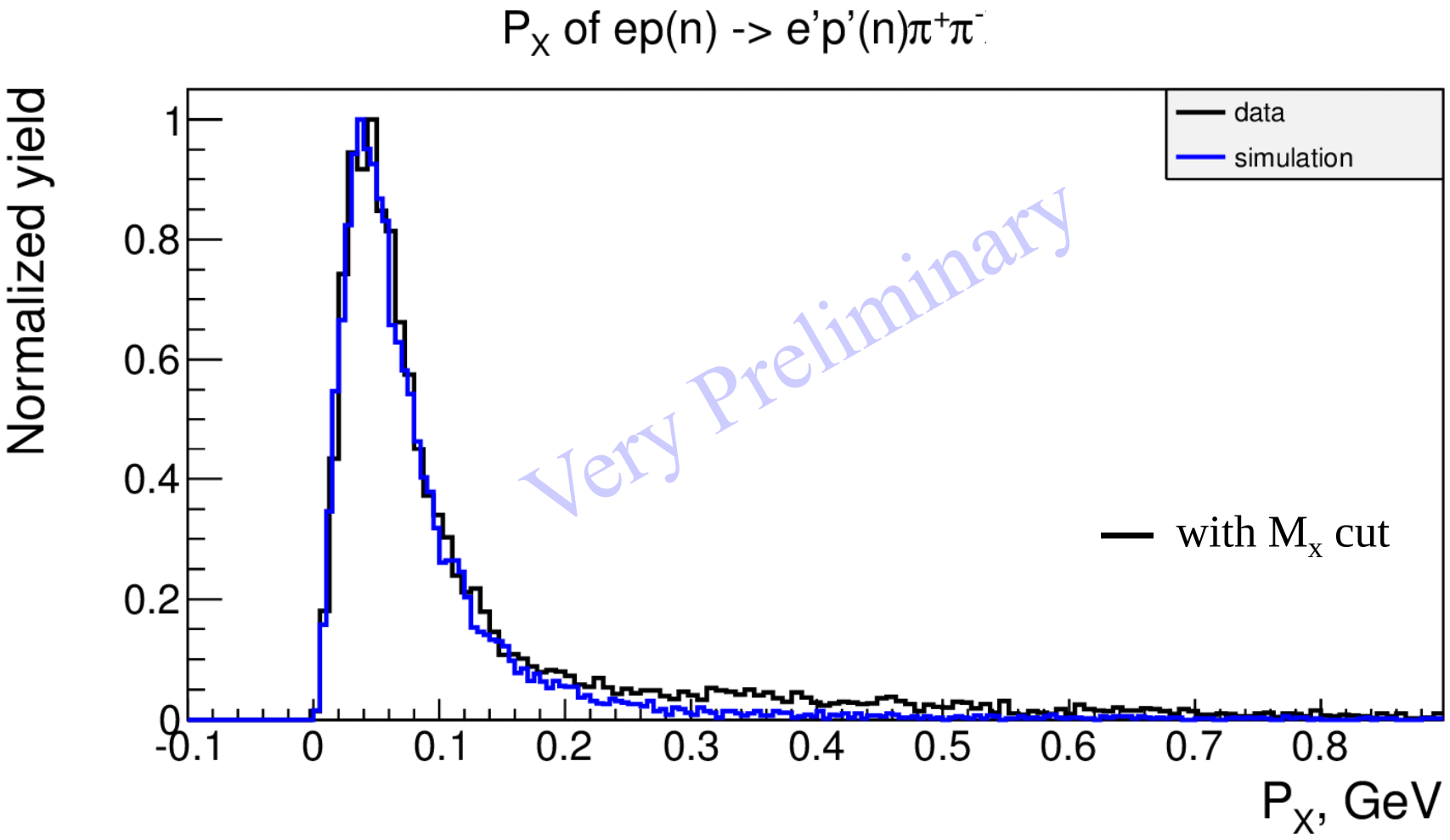

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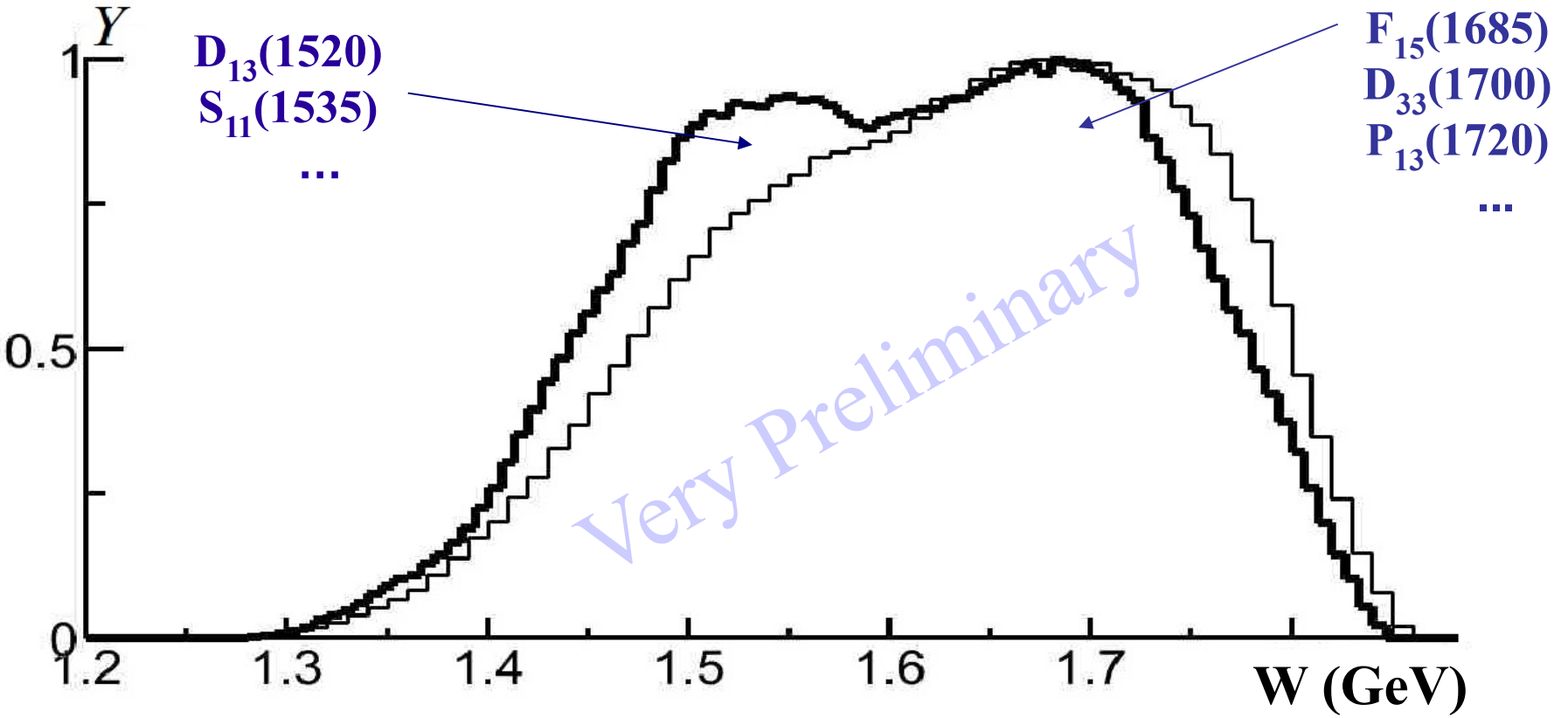
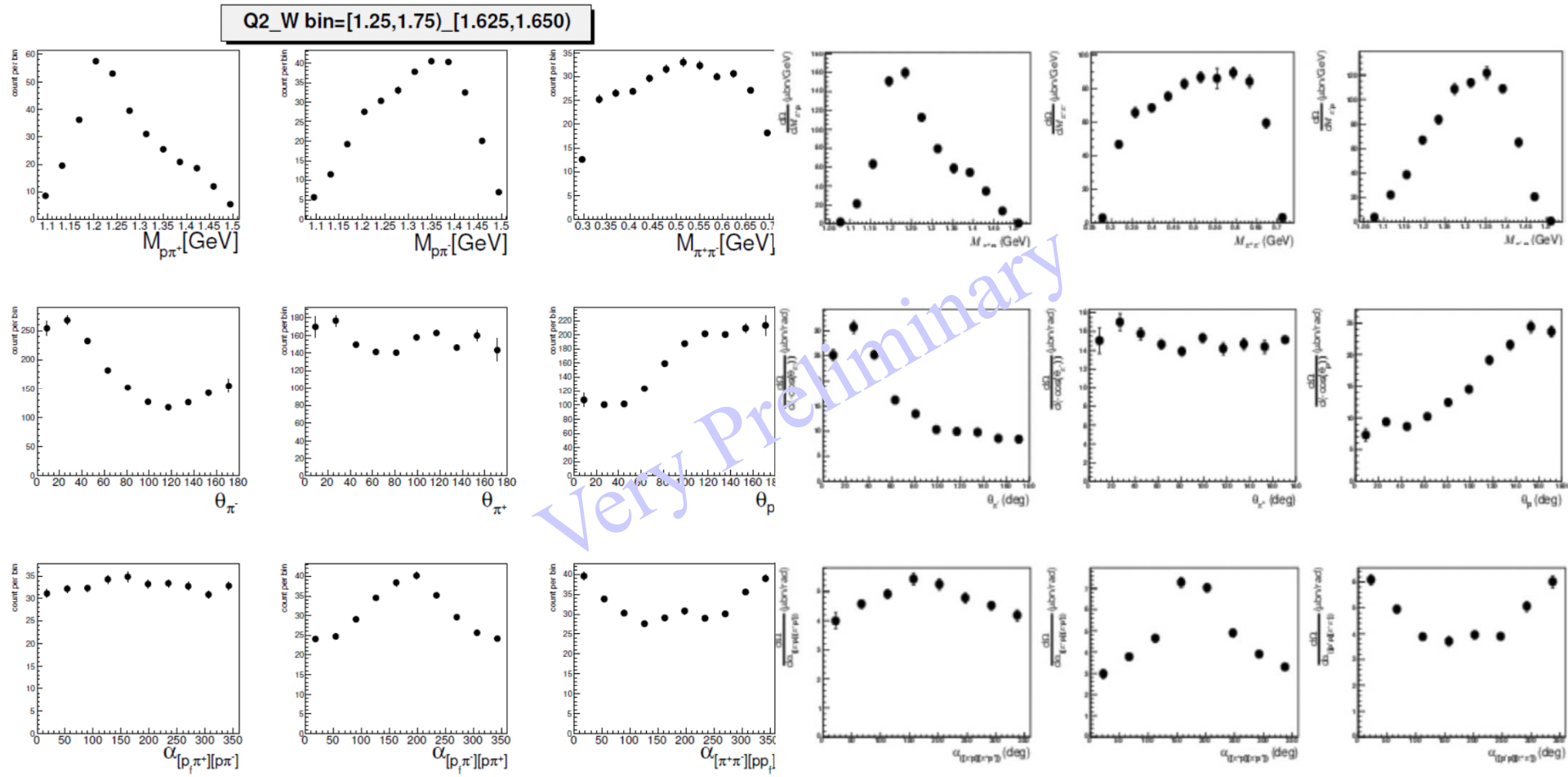


Bold curve W calculated from four-momenta of the final particles and **thin curve** W calculated from four-momenta of initial particles under the assumption that the target is at rest.

φ-dependent Nππ Single-Differential Cross Sections

Q^2, W bin $= [1.25, 1.75)GeV^2, [1.625, 1.650)GeV$ Arjun Trivedi



φ-integrated

$Q^2 = 0.425GeV^2$ Gleb Fedotov

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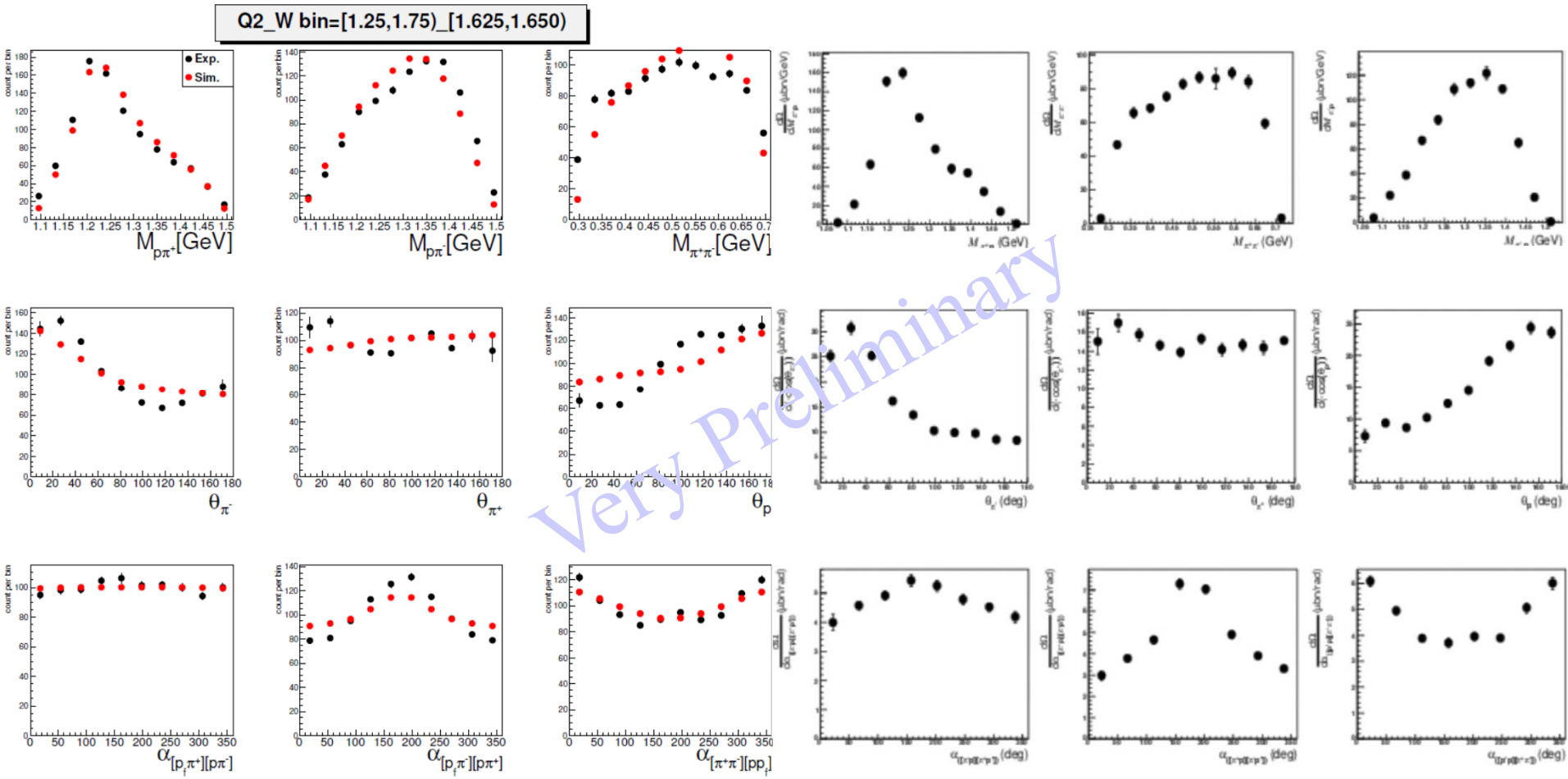

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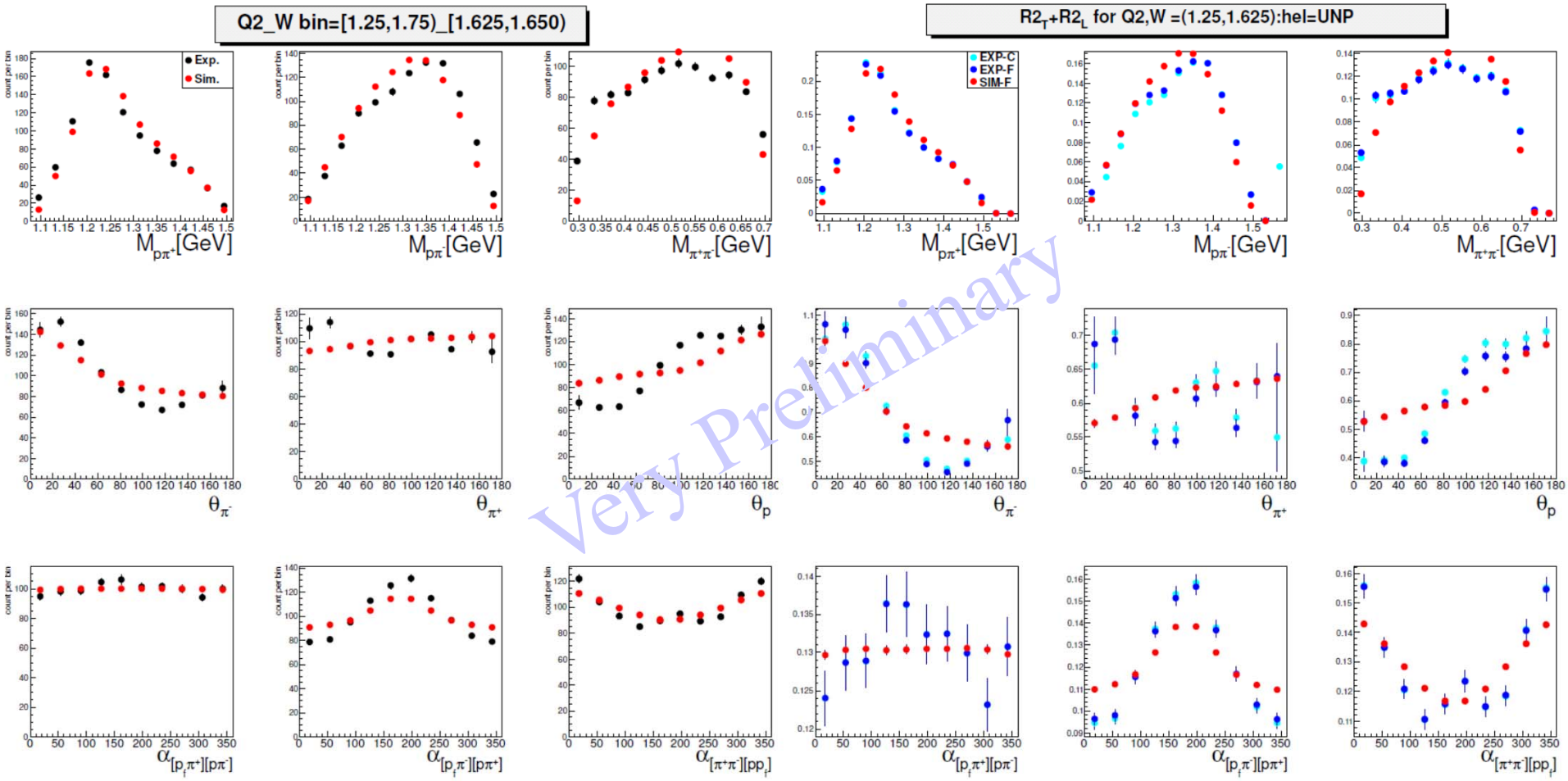

φ-integrated φ-independent

φ-dependent Nππ Single-Differential Cross Sections

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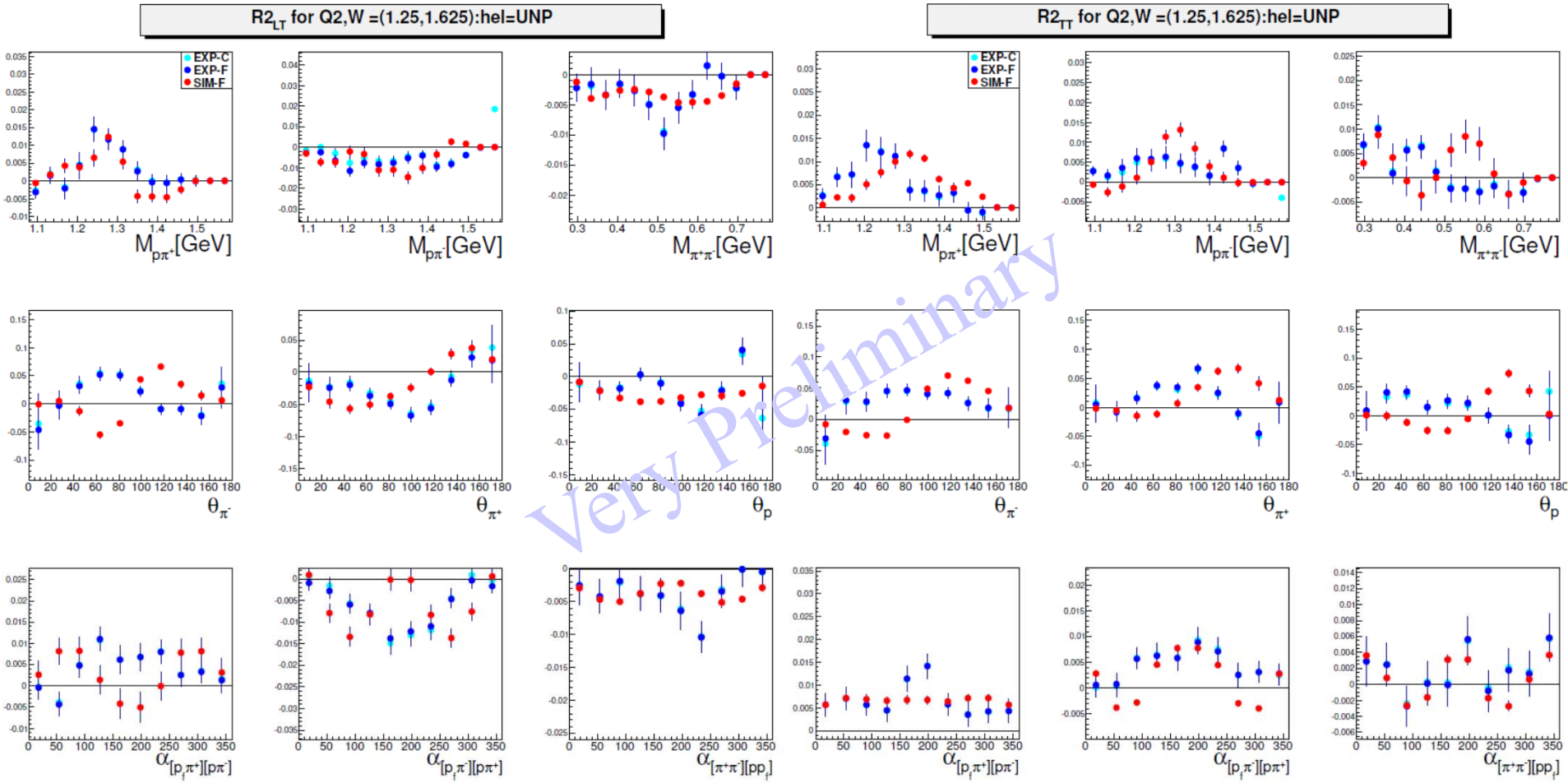

$$\left(\frac{d^2\sigma}{dX^{ij}d\phi^j}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + R2_{LT}{}^{X_{ij}} \cos\phi_j + R2_{TT}{}^{X_{ij}} \cos 2\phi_j$$

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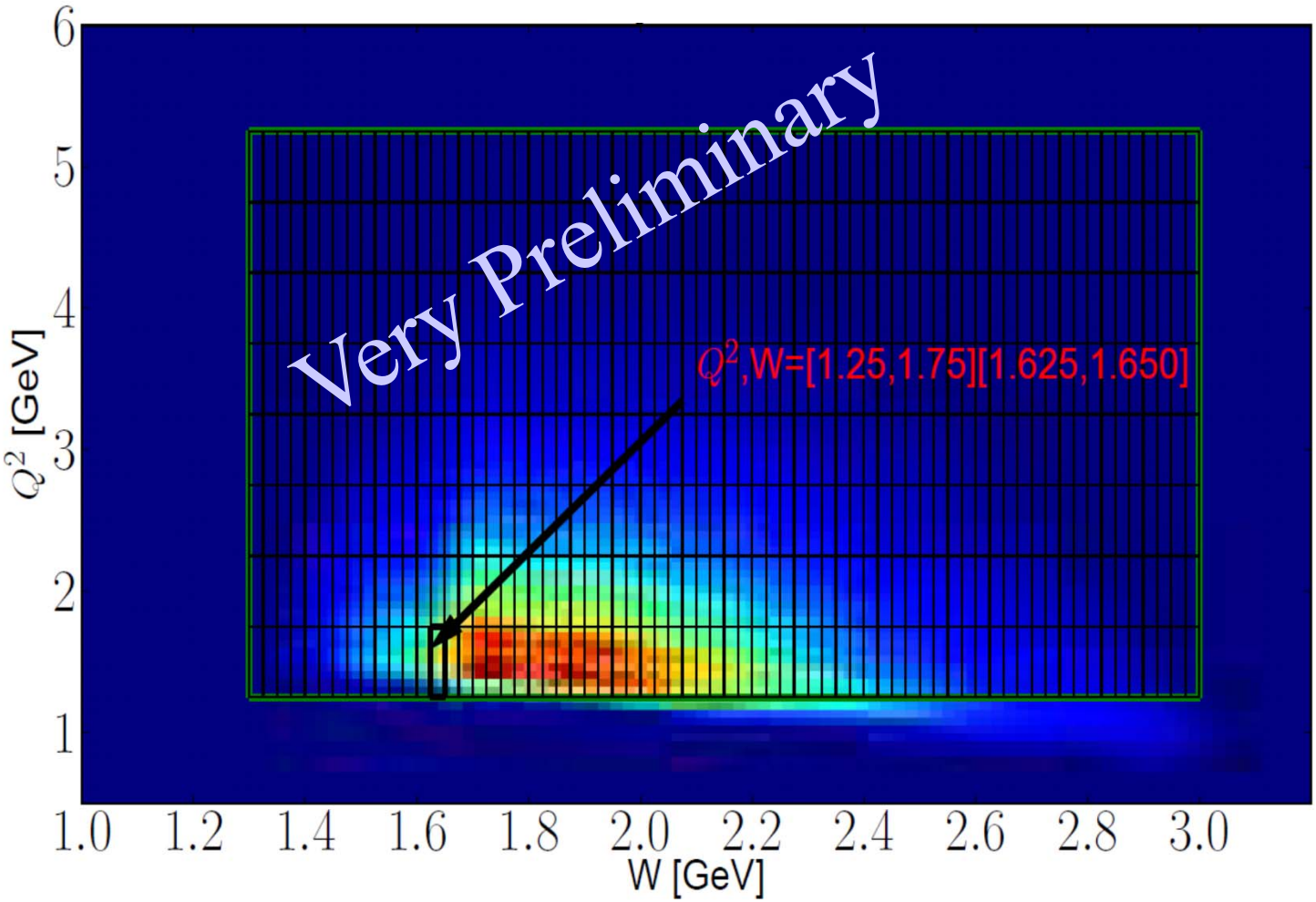

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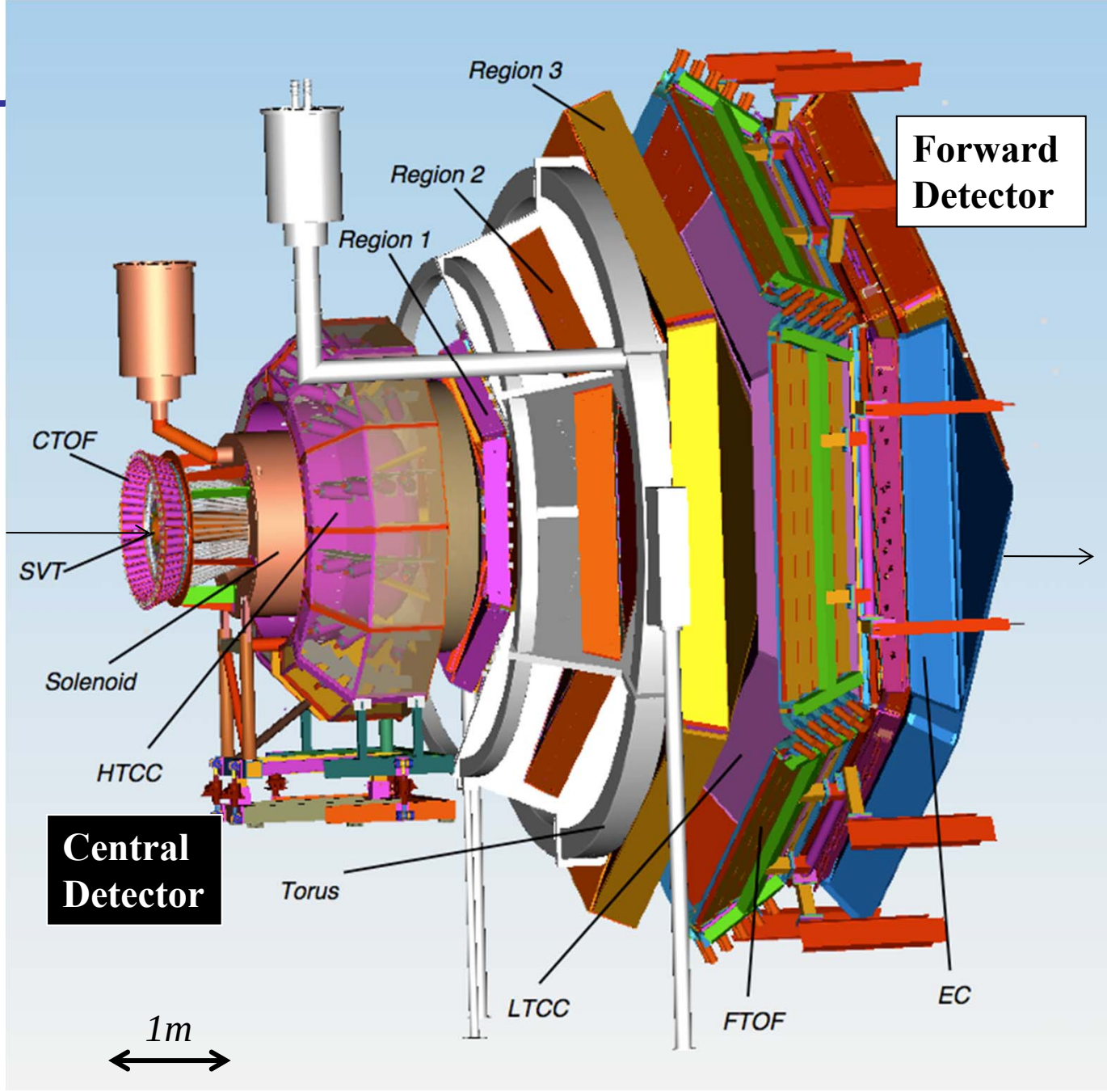
CLAS12

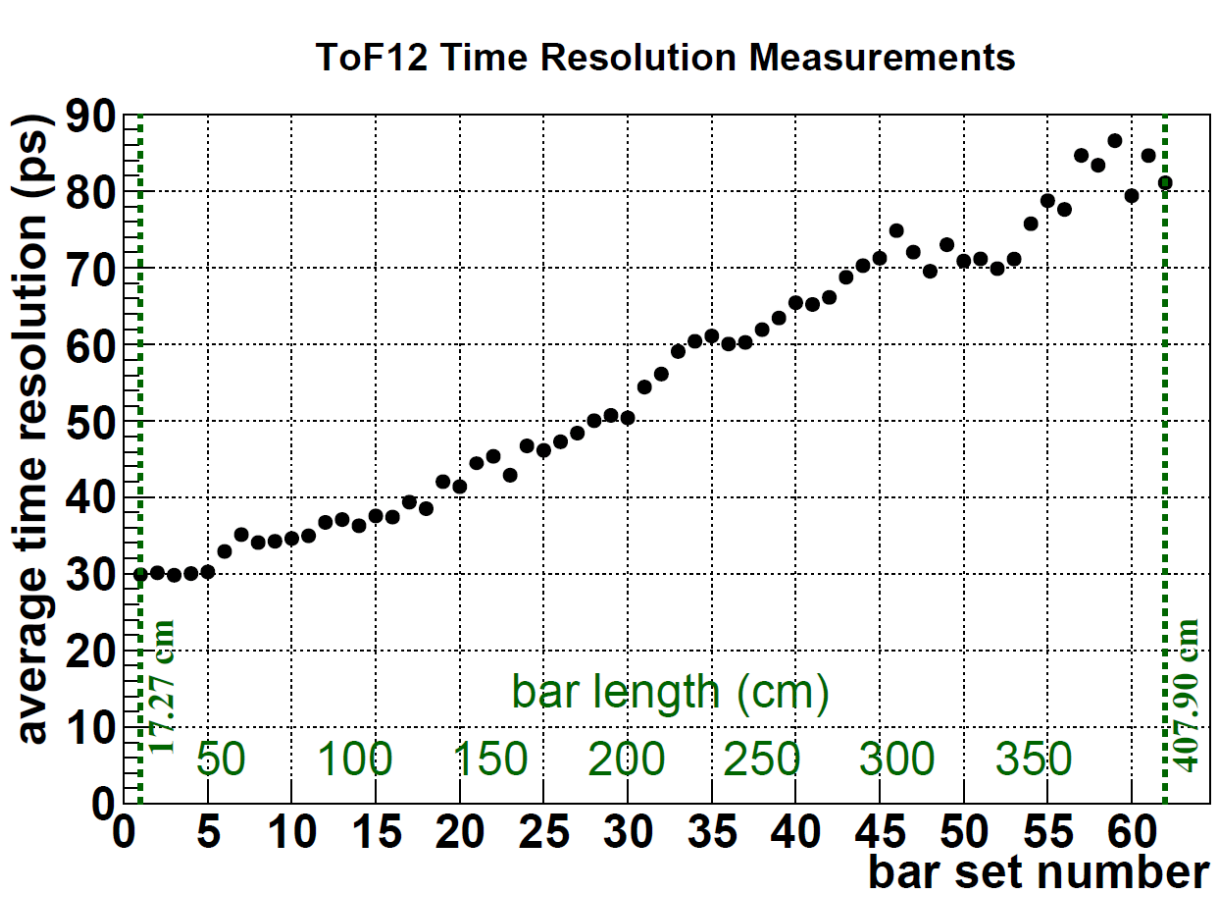
CLAS12

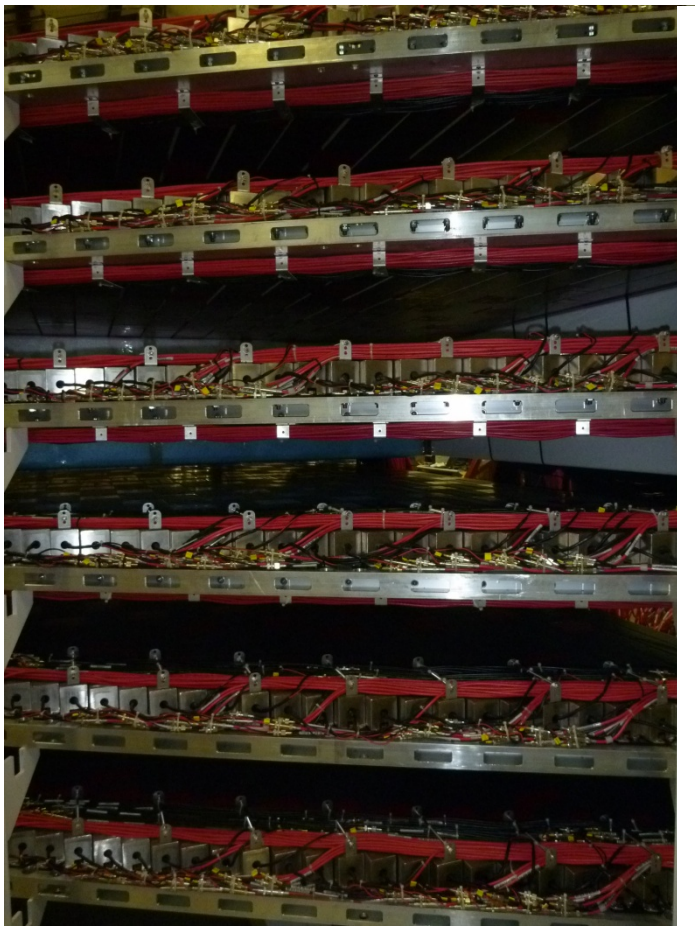
- Luminosity > 10^{35} $cm^{-2}s^{-1}$
- Hermeticity
- Polarization

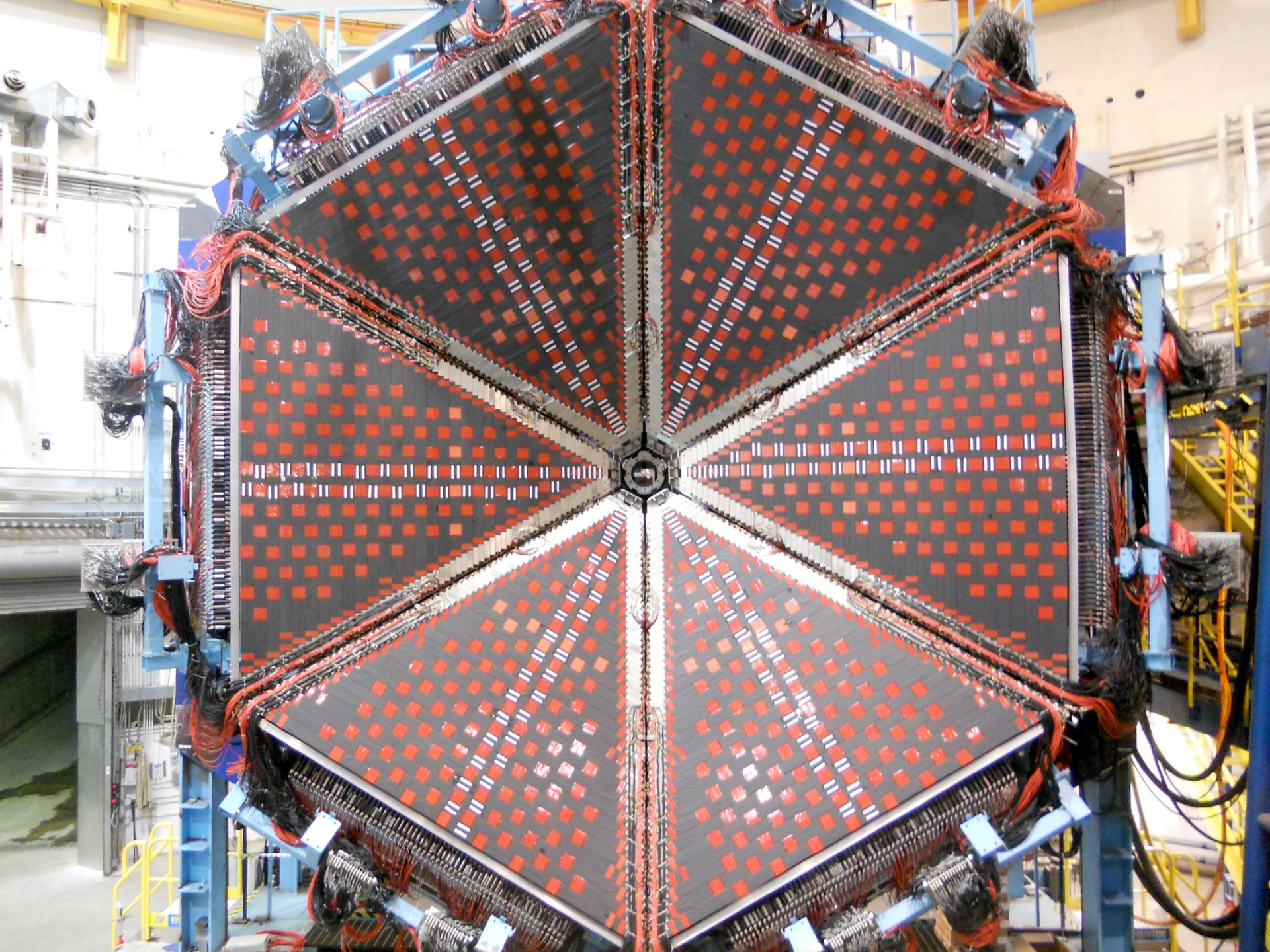
- Baryon Spectroscopy
- Elastic Form Factors
- N to N* Form Factors
- GPDs and TMDs
- DIS and SIDIS
- Nucleon Spin Structure
- Color Transparency
- …



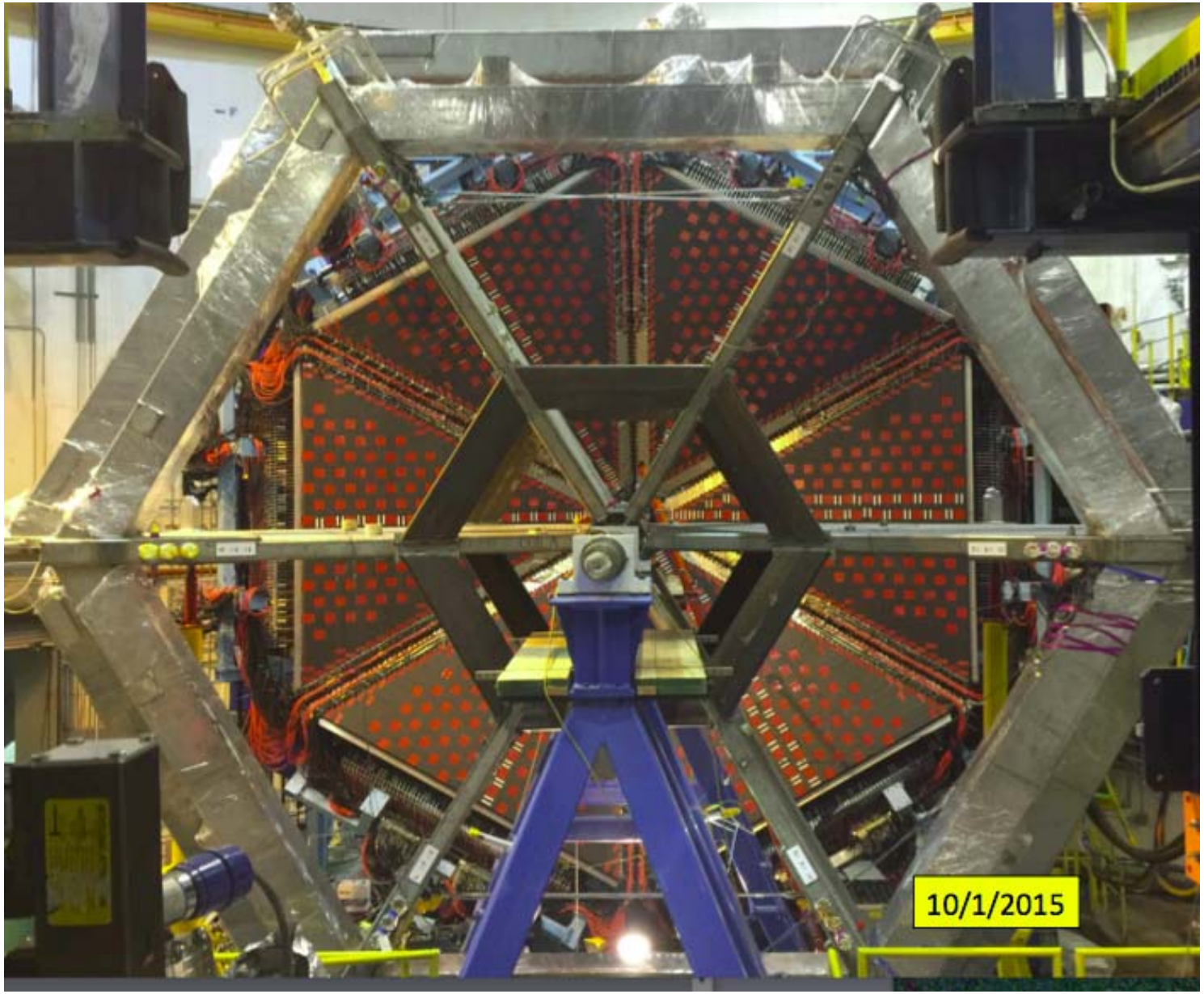
New Forward Time of Flight Detector for CLAS12



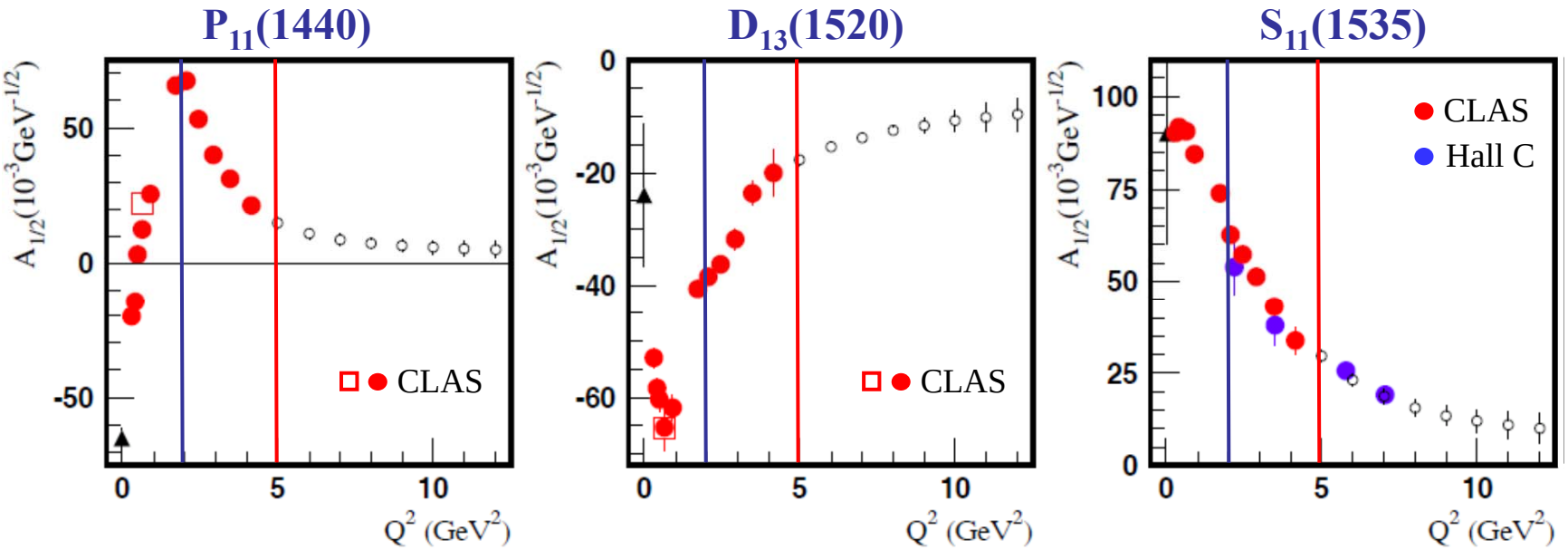




All Torus and Vacuum Cambers Installed



Anticipated N* Electrocouplings from Combined Analyses of Nπ/Nππ



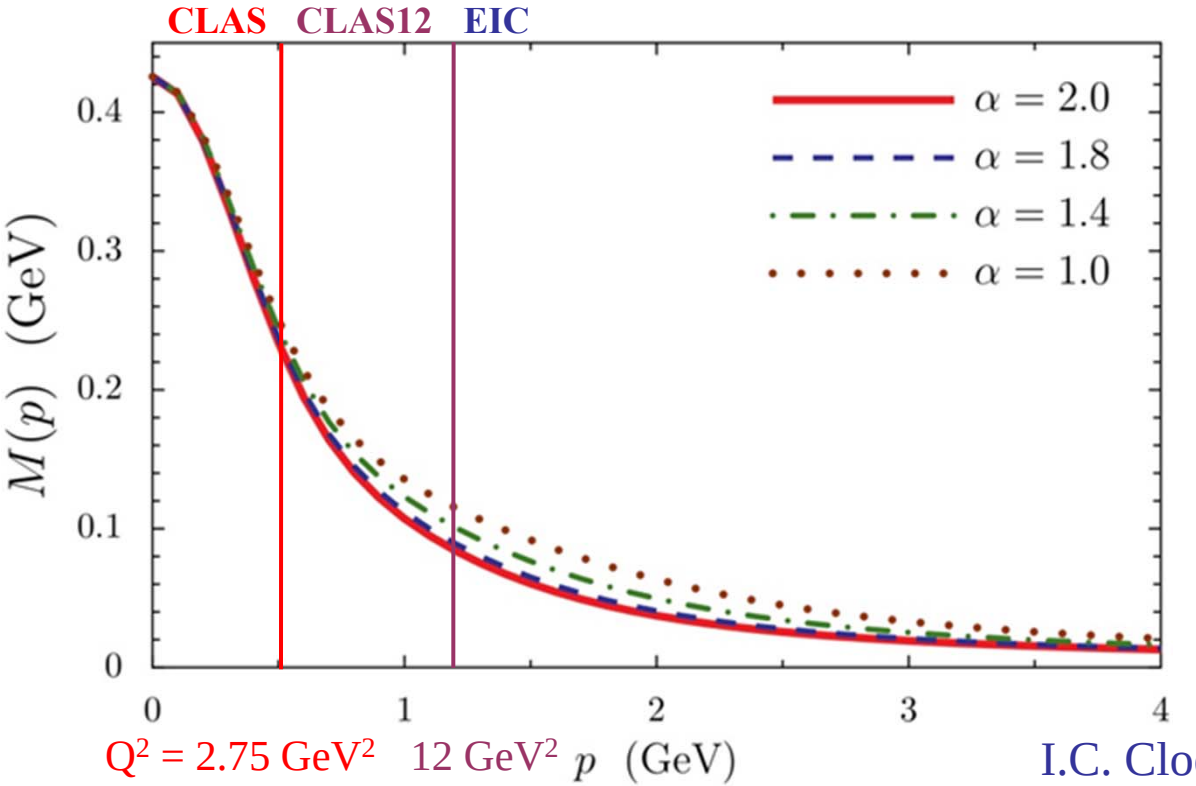
Open circles represent projections and all other markers the available results with the 6-GeV electron beam

➢ Examples of published and projected results obtained within 60d for three prominent excited proton states from analyses of Nπ and Nππ electroproduction channels. Similar results are expected for many other resonances at higher masses, e.g. $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1700)$, $P_{13}(1720)$, …

➢ The approved CLAS12 experiments E12-09-003 (NM, Nππ) and E12-06-108A (KY) are currently the only experiments that can provide data on γ_vNN* electrocouplings for almost all well established excited proton states at the highest photon virtualities ever achieved in N* studies up to Q^2 of 12 GeV^2, see http://boson.physics.sc.edu/~gothe/research/pub/whitepaper-9-14.pdf.

Dyson-Schwinger Equation (DSE) Approach

DSE approaches provide links between dressed quark propagators, form factors, scattering amplitudes, and QCD.



N* electrocouplings can be determined by applying Bethe-Salpeter / Faddeev equations to 3 dressed quarks while the properties and interactions are derived from QCD.

Impact of a modified momentum dependence of the dressed-quark propagator.

I.C. Cloet et al., arXiv:1304.0855[nucl-th]

DSE electrocouplings of several excited nucleon states will become available as part of the commitment of the Argonne NL.

Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99

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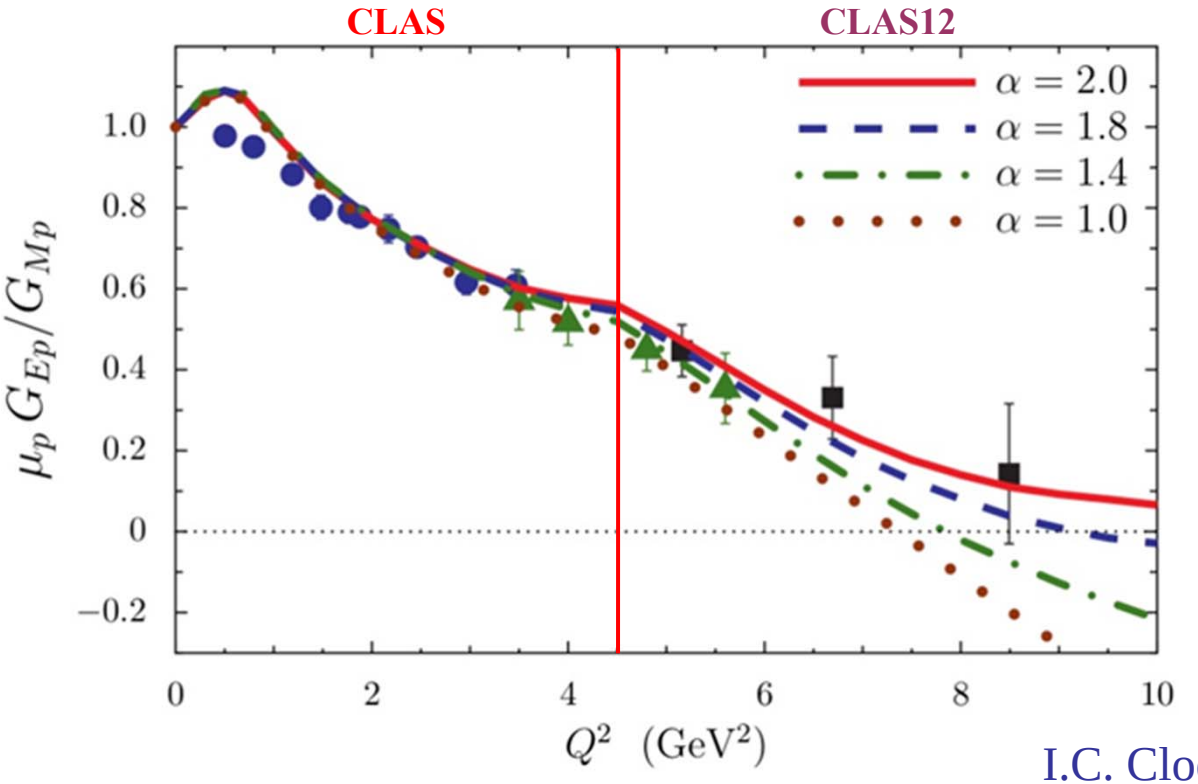

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DSE calculations of elastic and transition form factors are very sensitive to the momentum dependence of the dressed-quark propagator.

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Summary

- First high precision photo- and electroproduction data have become available and led to a new wave of significant developments in reaction and QCD-based theories.
- New high precision hadro-, photo-, and electroproduction data off the proton and the neutron will stabilize coupled channel analyses and expand the validity of reaction models, allowing us to
  - investigate and search for baryon hybrids,
  - establish a repertoire of high precision spectroscopy parameters, and
  - measure light-quark-flavor separated electrocouplings over an extended Q^2-range, both to lower and higher Q^2, for a wide variety of N* states.
- Comparing these results with DSE, LQCD, LCSR, and rCQM will build insights into
  - the strong interaction of dressed quarks and their confinement,
  - the emergence of bare quark dressing and dressed quark interactions from QCD, and
  - the QCD β-function and the origin of 98% of nucleon mass.
- A close collaboration of experimentalists and theorists has formed and is needed to push these goals, see Review Article Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99, that shall lead to a QCD theory that describes the strong interaction from current quarks to nuclei. **ECT*2015 and INT2016.**