Studying Nucleon Structure with Spin at BLAST

Overview

BLAST Experiment

Nucleon Form Factors

Deuterium

Nucleon Elastic Form Factors

Fundamental for understanding nucleon structure in non-perturbative regime.

Parameterises coherent scattering without exciting internal degrees of freedom with single photon exchange.

- for point-like, spin=1/2 particles QED gives:

$$\sigma_{Dirac} = \sigma_{Mott}\left(1 + 2\tau\tan^2\frac{\theta}{2}\right)$$

- for extended objects, like nucleons, require form factors:

$$\sigma_{lab} = \sigma_{Mott}\left[\left(\frac{{G_E^N}^2 + \tau {G_M^N}^2}{1+\tau}\right) + 2\tau {G_M^N}^2\tan^2\frac{\theta}{2}\right]$$

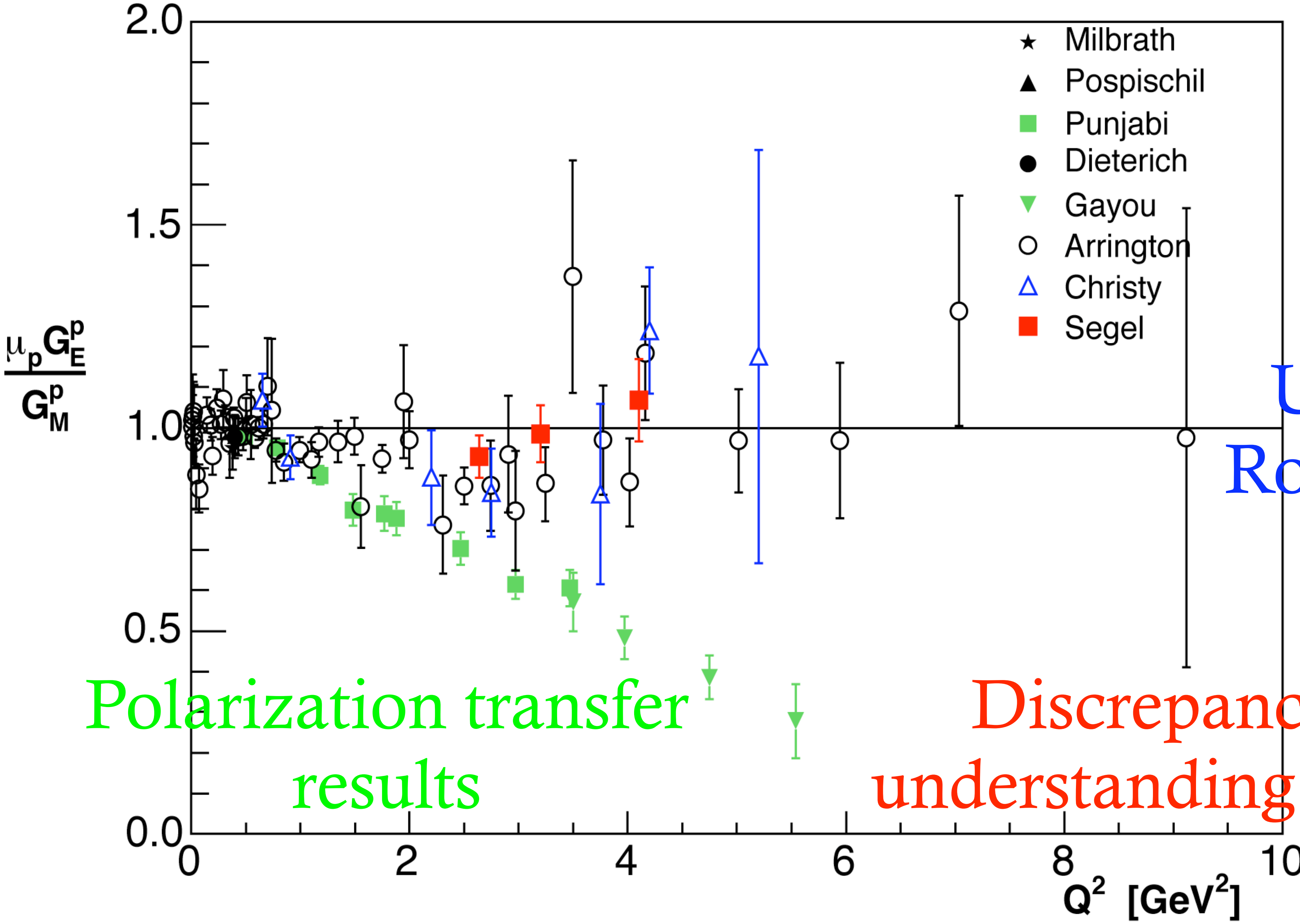
- traditionally measure using Rosenbluth technique

$$\sigma_{Rosenbluth} = \sigma_{Mott}\left(A^N(Q^2) + 2\tau B^N(Q^2)\tan^2\frac{\theta}{2}\right)$$

Discrepancy in Proton Form Factor Ratio

Polarization transfer results in striking discrepancy with unpolarized data

Possible explanation - two photon contributions



Unpolarised results Rosenbluth separation

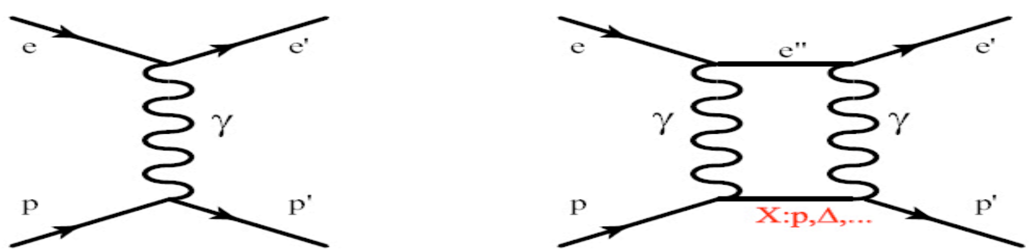
Polarization transfer results

Discrepancy fundamental to understanding of nucleon structure

Importance of Spin Measurements

JLAB results highlight the importance of using spin in studying nucleon structure

- more information
- more detailed information



A Definitive Experiment to Quantify Multi-photon Exchange in Lepton Scattering

M. Kohl, MIT

09:00 Thursday

Nucleon Elastic Form Factors

Parameterised as dipole distribution in momentum space.

- corresponds to a exponential distribution in position space
- single dipole describes G^p_E, G^p_M, and G^n_M
- G^n_E is the exception, order of magnitude smaller
  - traditionally hard to measure, small, no convenient neutron targets

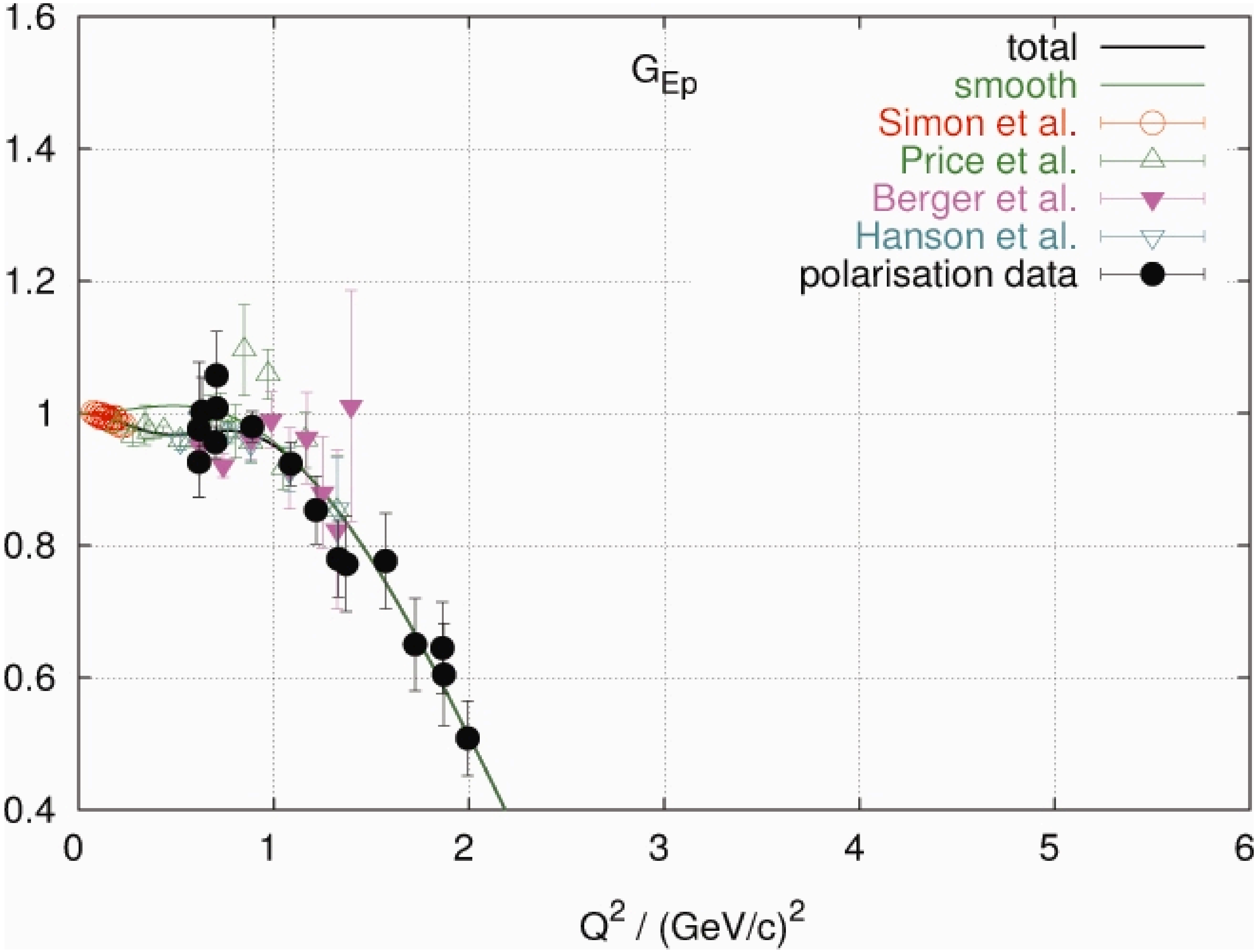
But dipole not perfect, does not describe details Q^2<1 $(\text{GeV}/c)^2$

Friedrich and Walcher have proposed a new parameterisation:

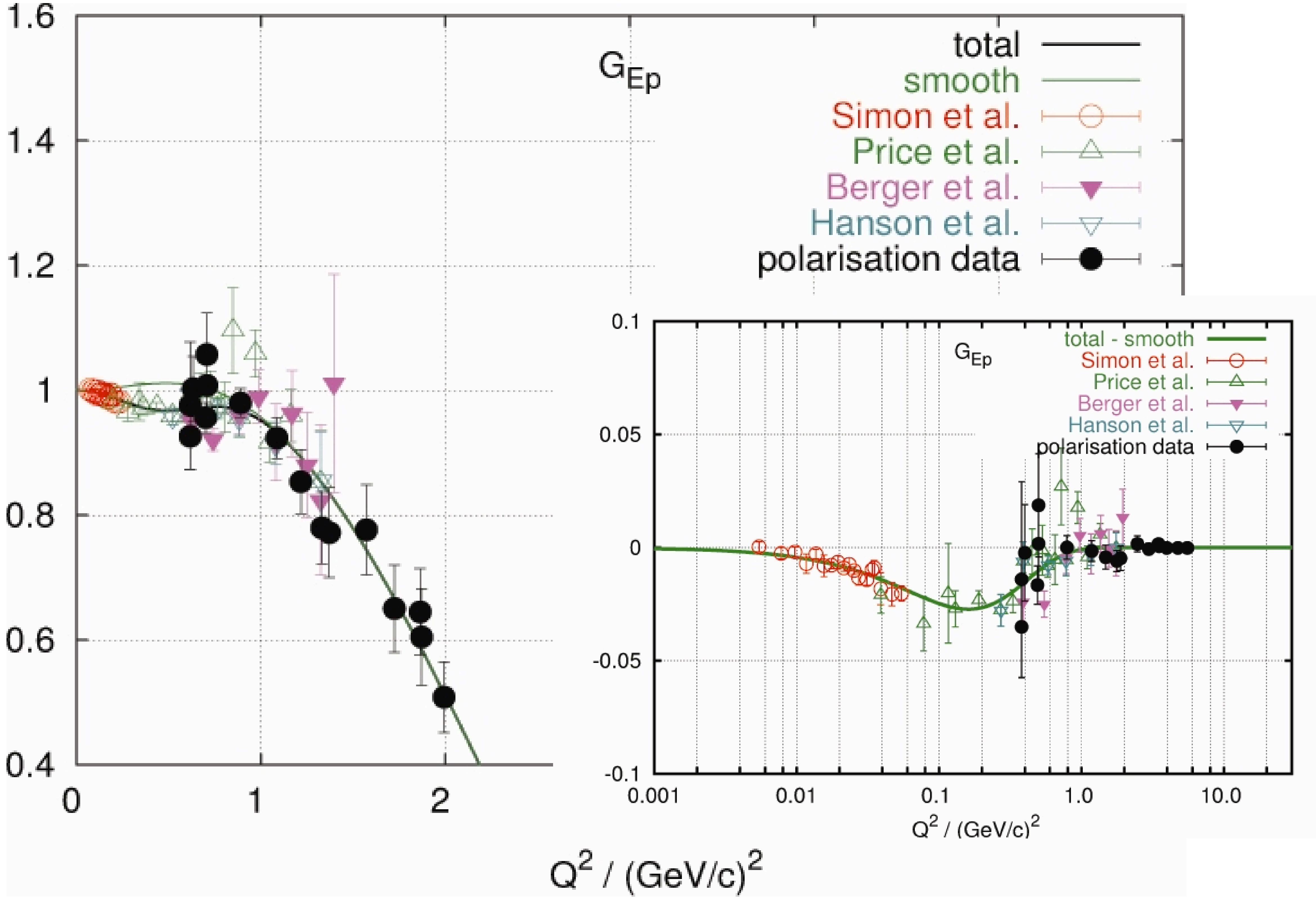
$$G^N(Q^2) = G^N_S(Q^2) + \alpha_B Q^2 G^N_B(Q^2)$$

  - S- smooth term of two dipoles
  - B - bump part of two gaussians
- fit to a collection of the world's data

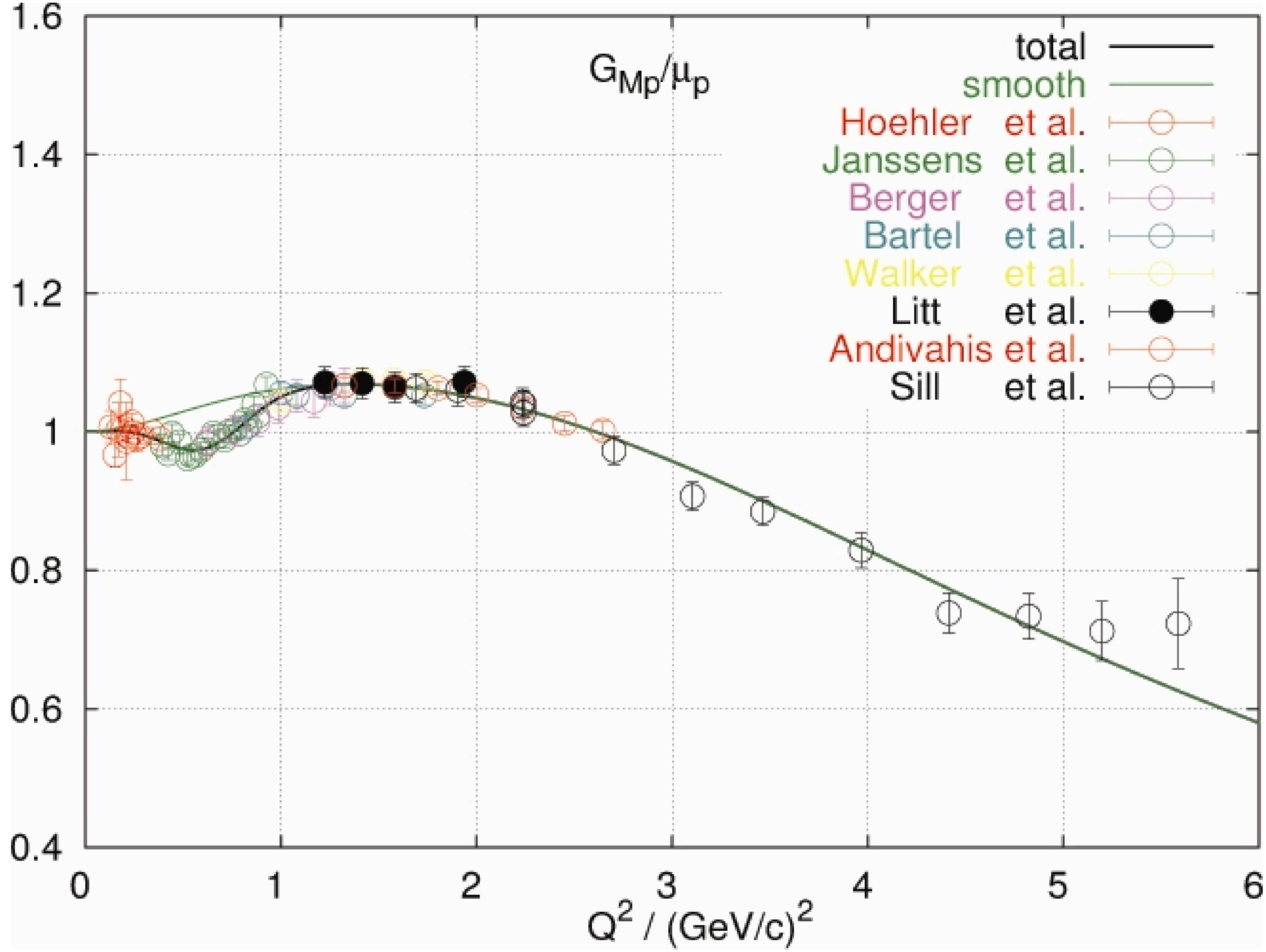
Friedrich and Walcher Fit to G^p_E



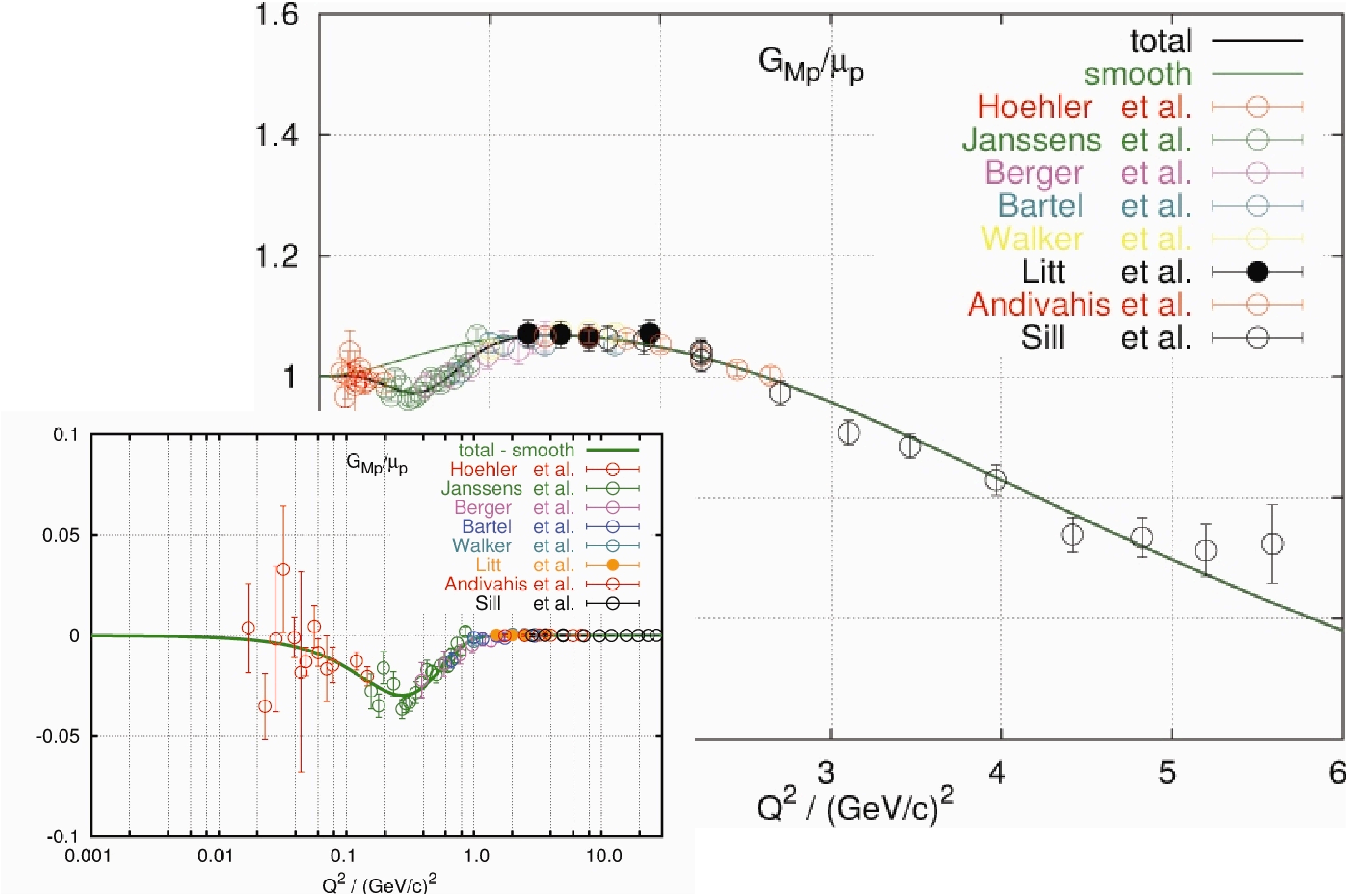
Friedrich and Walcher Fit to G^p_E



Friedrich and Walcher Fit to G^p_M



Friedrich and Walcher Fit to G^p_M



Bates Large Acceptance Spectrometer Toroid

Systematic study of spin-dependent electromagnetic interaction

Polarized electrons in MIT-Bates SHR storage ring

- 850 MeV, 200 mA (typical), 65% polarization (typical)

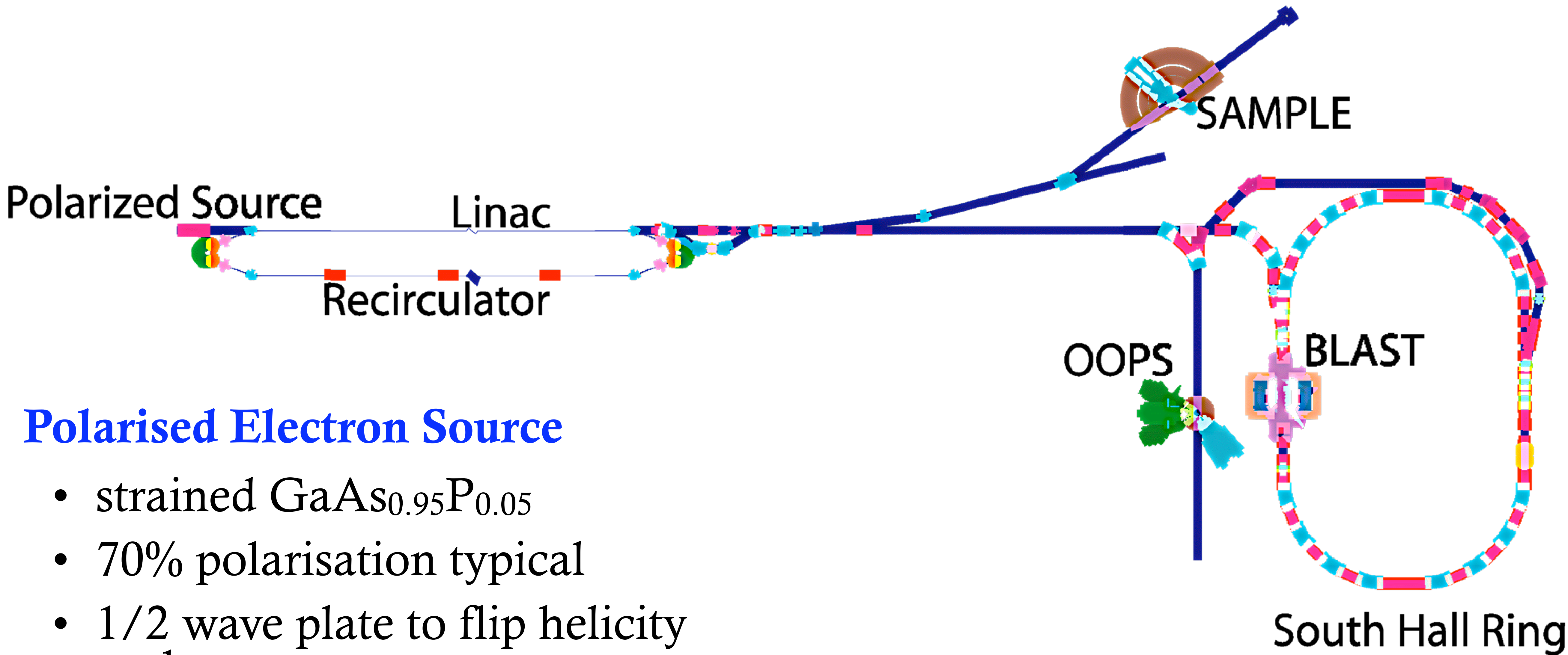
Highly polarized, internal gas target, isotopically pure H or D

- 6×10^{13} atoms/cm^2, 80% vector (H and D), 70% tensor (D) polarization

L/R Symmetric, large acceptance, general purpose detector

- 20°-80° polar, ±15° azimuthal, $0.1 < Q^2 < 0.8$ $(\mathrm{GeV}/c)^2$
- Simultaneous detection of $e^\pm$, $\pi^\pm$, p, n, d

MIT-Bates Linear Accelerator Center



Polarised Electron Source

- strained $GaAs_{0.95}P_{0.05}$
- 70% polarisation typical
- 1/2 wave plate to flip helicity each run

500 MeV Linac with recirculator

- polarised electrons up to 1 GeV

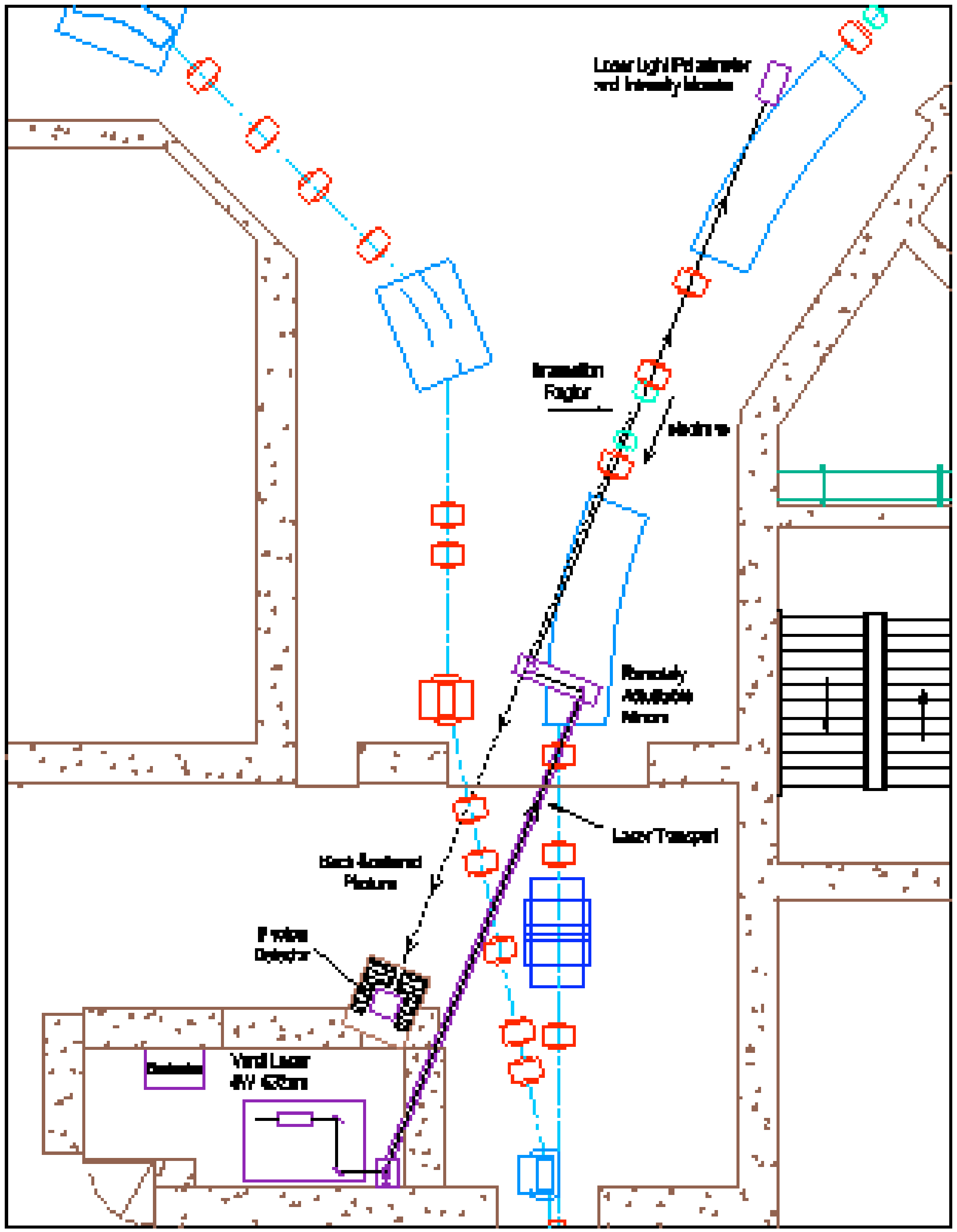
North and South Expt. Halls

- SAMPLE - north hall
- OOPS/BLAST - south hall

South Hall Ring

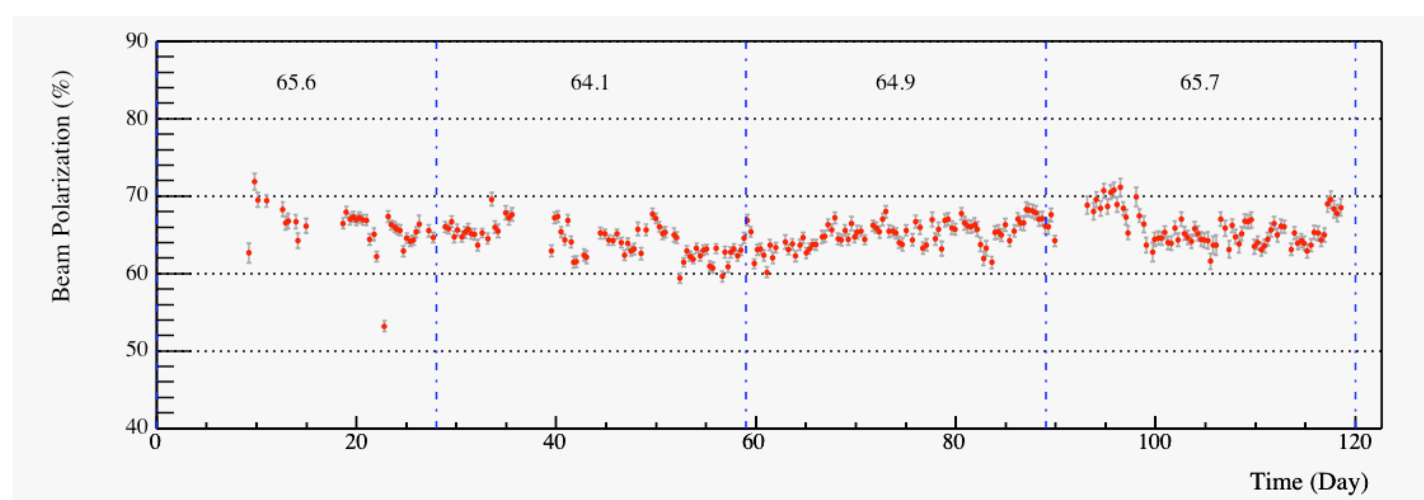
- stack to 225 mA typical
- 30 minute lifetime
- 65 % polarisation typical
- Siberian snake maintains longitudinal spin at target

Compton Polarimeter

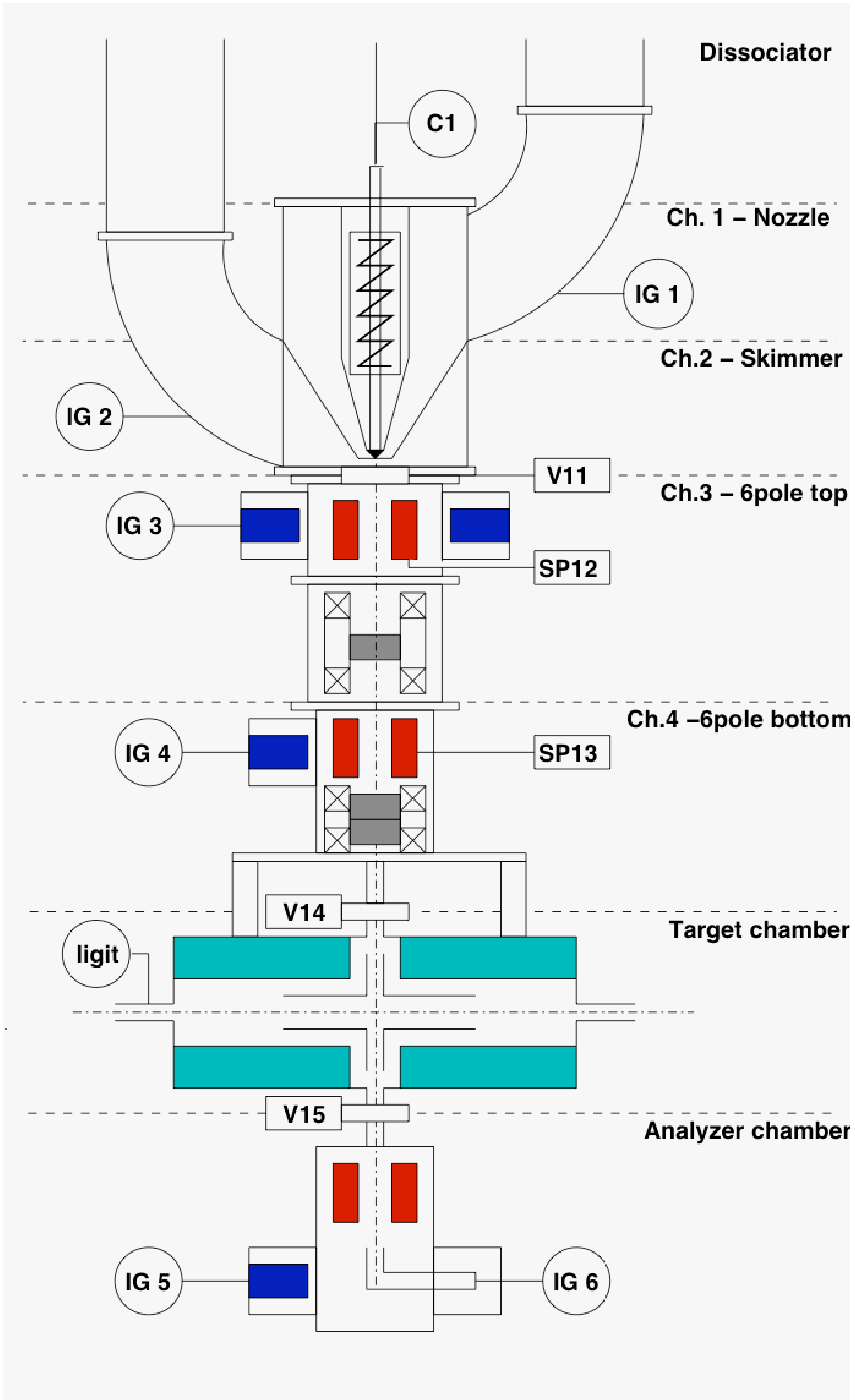


Monitor beam polarisation in ring

- 5 W laser, 532 nm, circularly polarised incident on oncoming electron beam
- Backscattered photons detected in CsI
- Laser helicity flipped in Pockels cell
- Asymmetry yields beam polarisation
- Chopper wheel allows simultaneous measure of background
- Typical beam polarisation 65 %
- Systematic uncertainty <3%



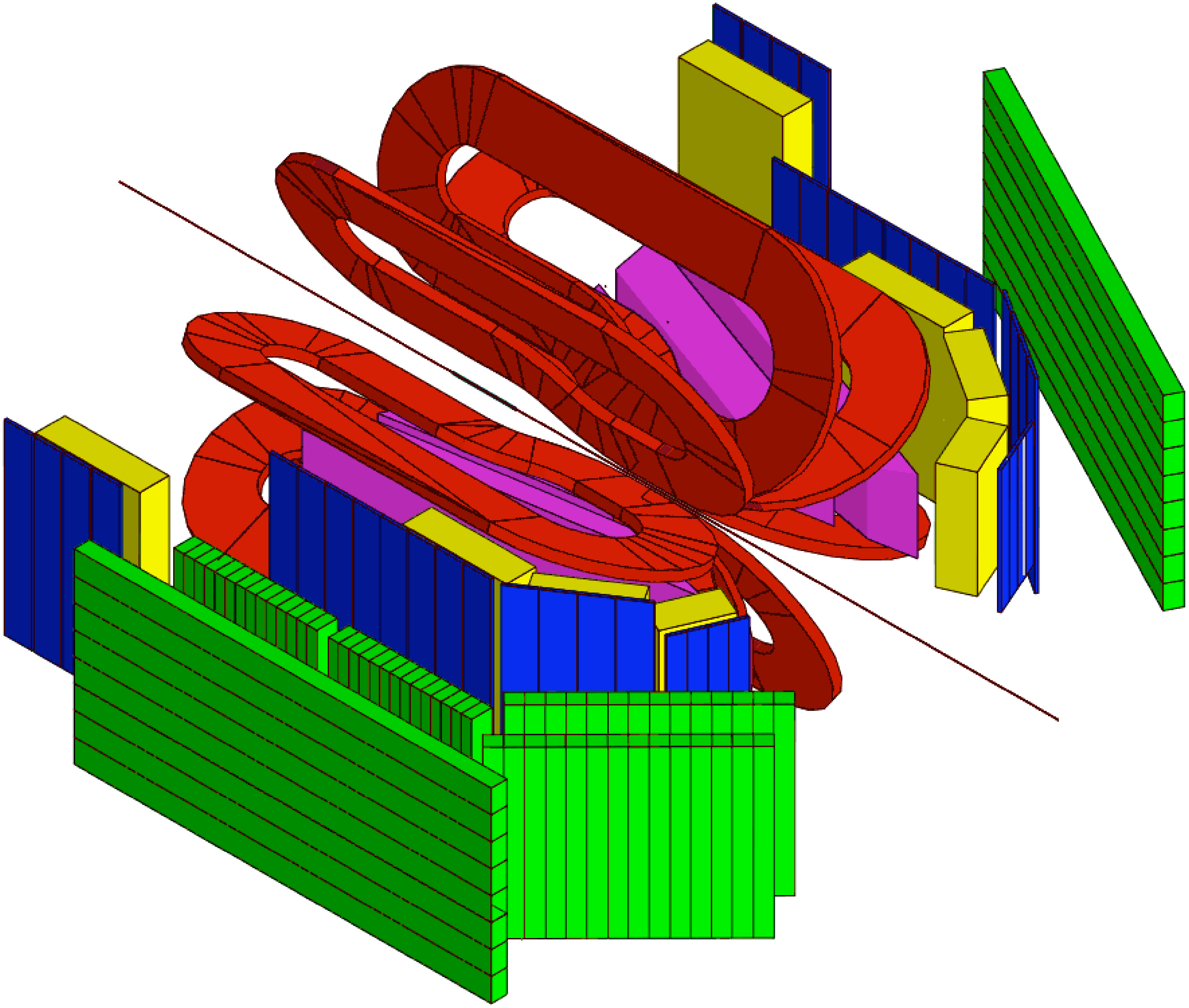
Internal, Polarised Gas Target



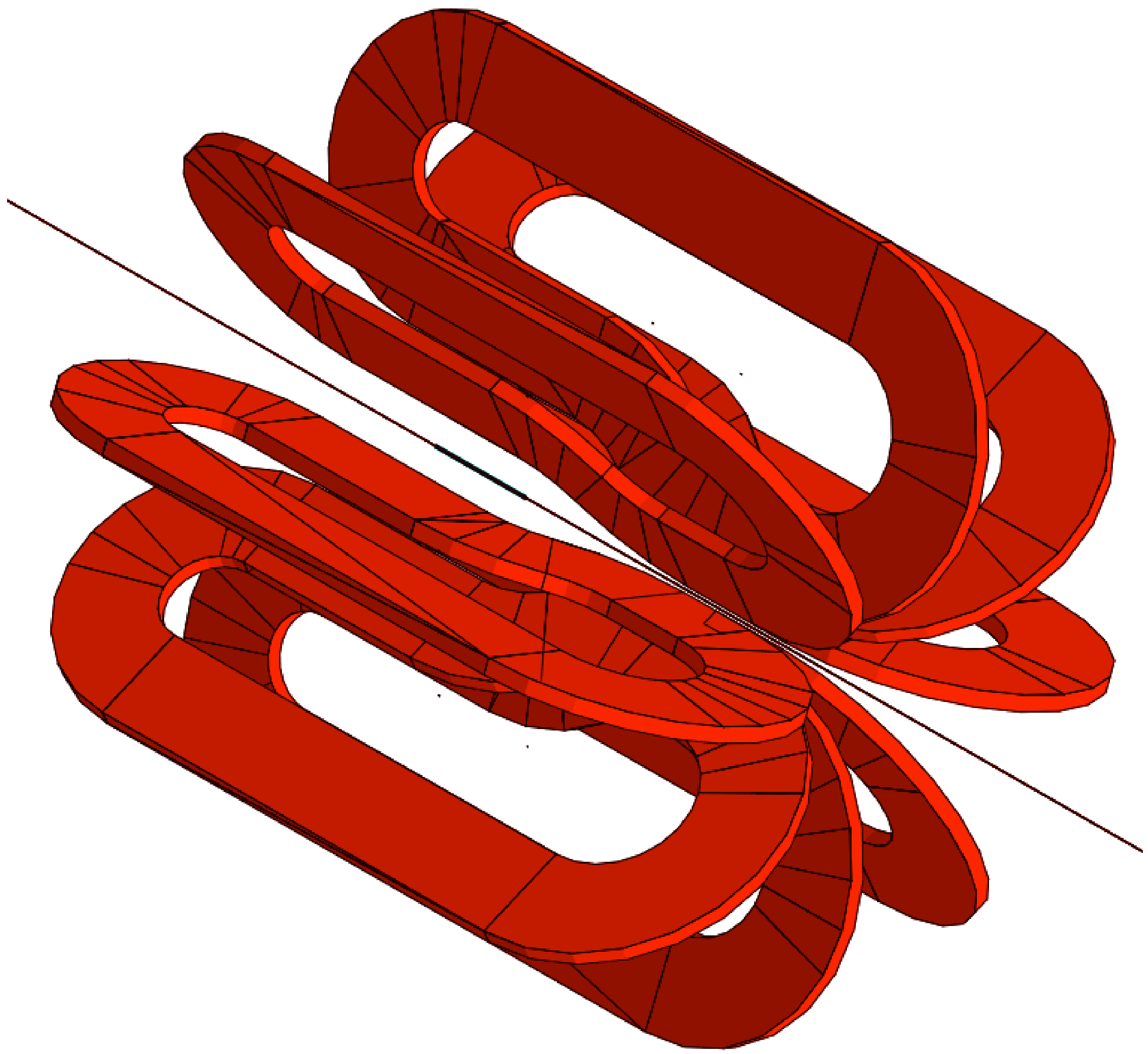
Atomic Beam Source

- series of focusing magnets and RF transition units populate and transport the desired spin state to the target cell
- target cell - thin walled, open ended tube, 60 cm long, ∅15 mm
- isotopically pure ^{1}H or ^{2}H
- vector polarised ^{1}H
- vector and tensor polarised ^{2}H
- randomly change spin state every 5′ during run
- target density 6×10^{13} atoms/cm^2
- vector polarisation 80 % typical
- tensor polarisation 68 % typical

BLAST Detector

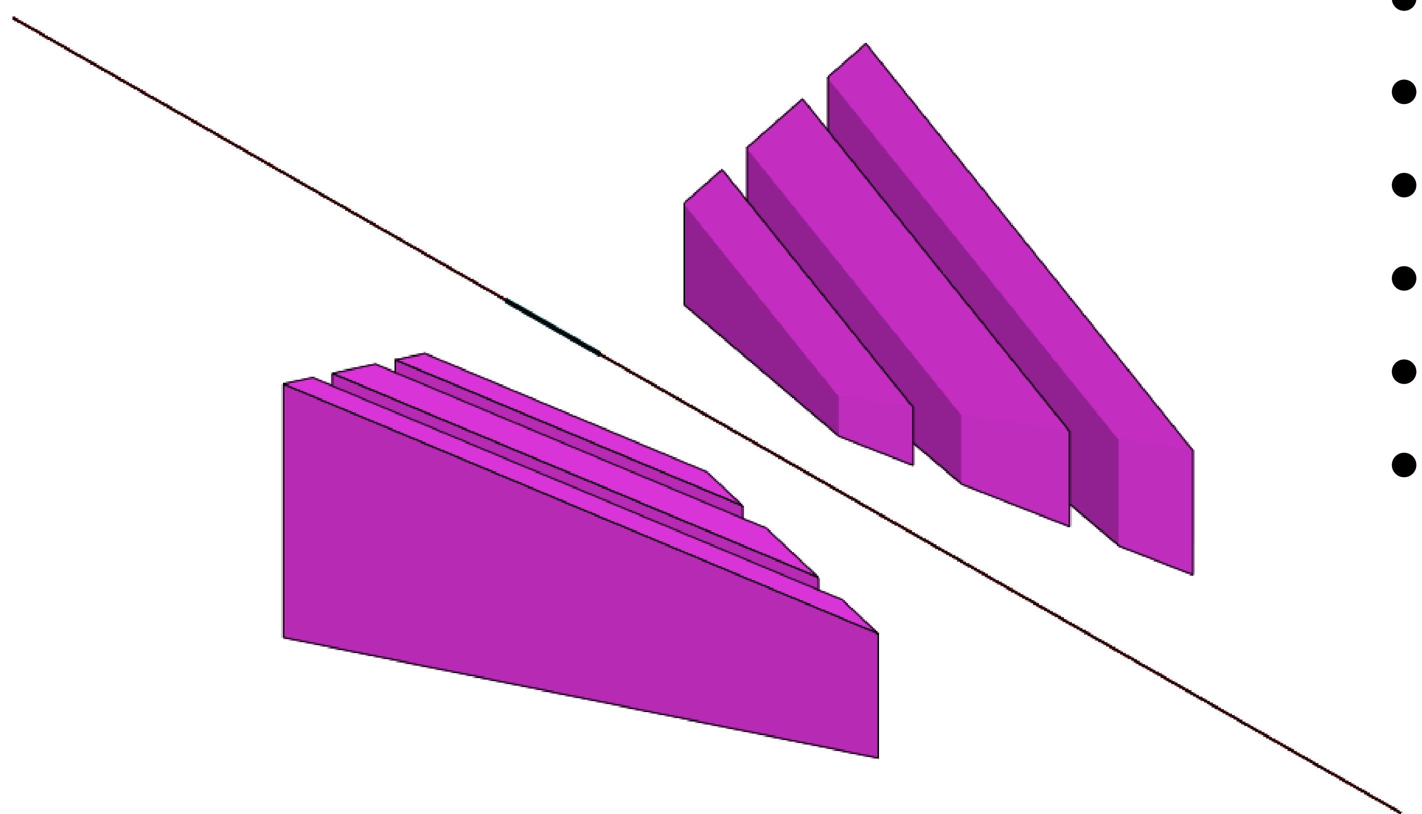


BLAST Detector



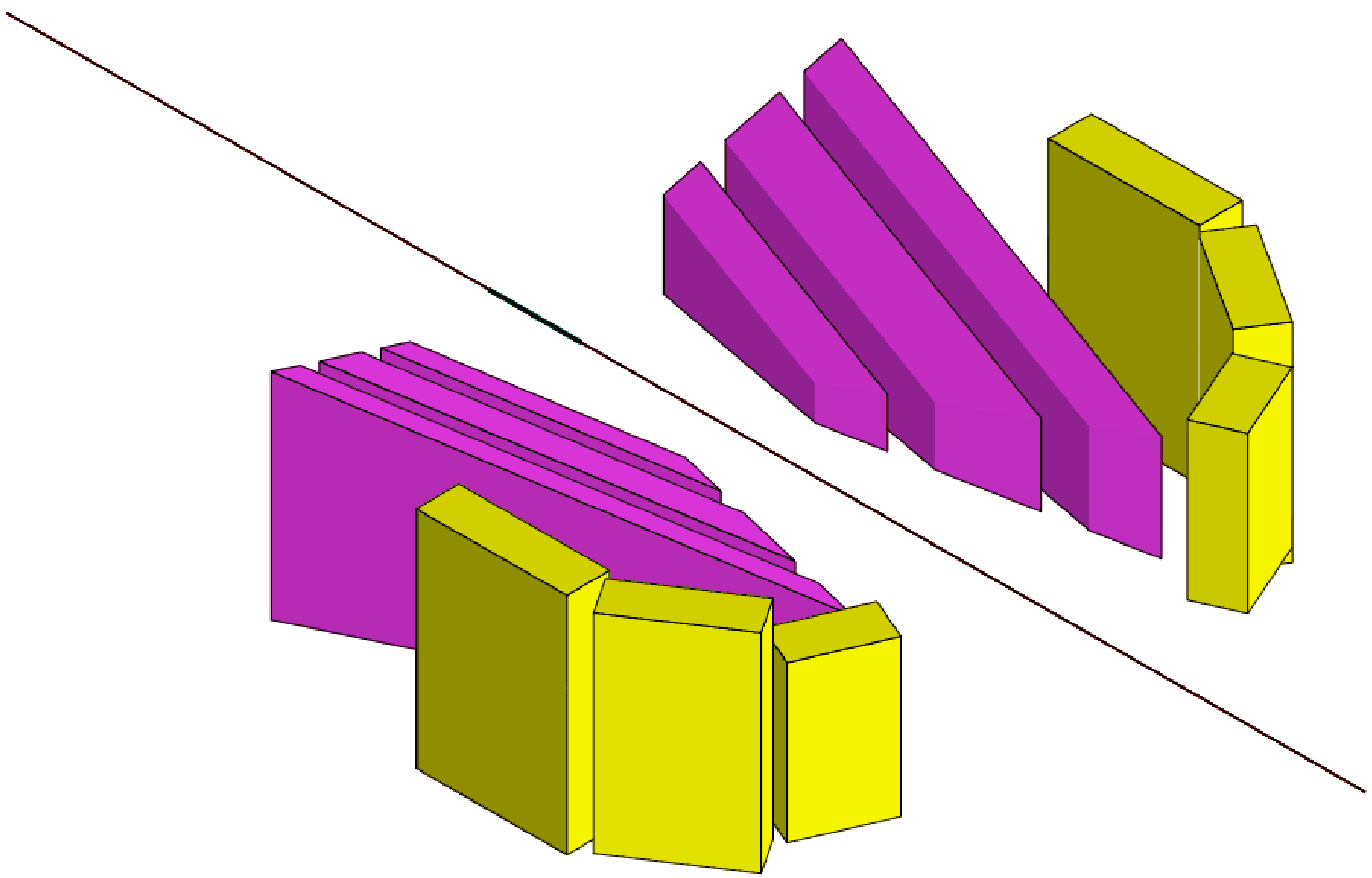
- 8 sector toroid magnet
  - minimise effect on beam and target polarisation
- 3.8 kG maximum field
- two horizontal sectors instrumented

BLAST Detector



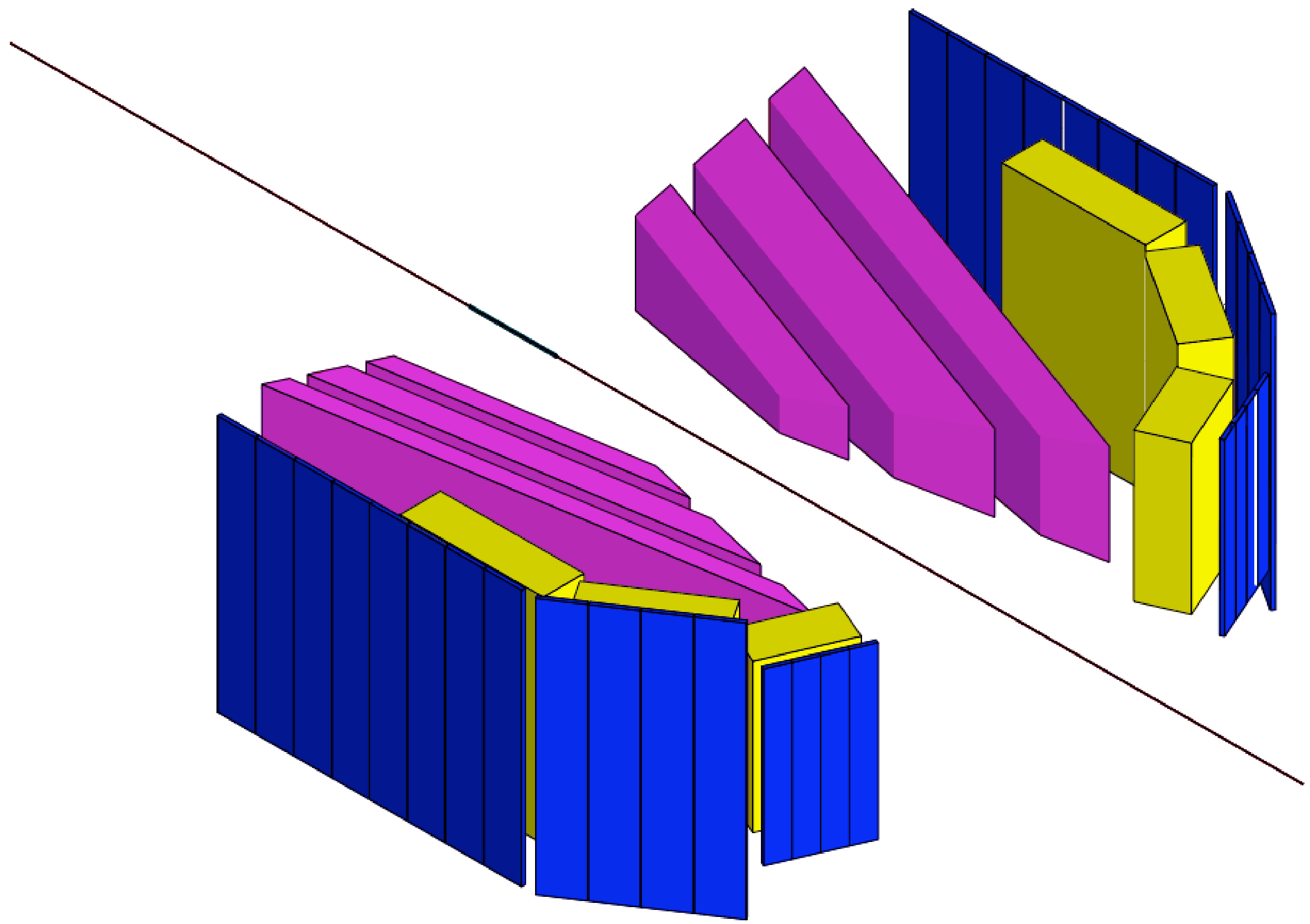
- 3 wire chambers / sector
  - single gas volume
- 2 superlayers / chamber
  - +/- 10° stereo
- 3 sense layers / superlayer
- total 18 layers of tracking
- momentum analysis
- scattering angles
- event vertex
- particle charge

BLAST Detector



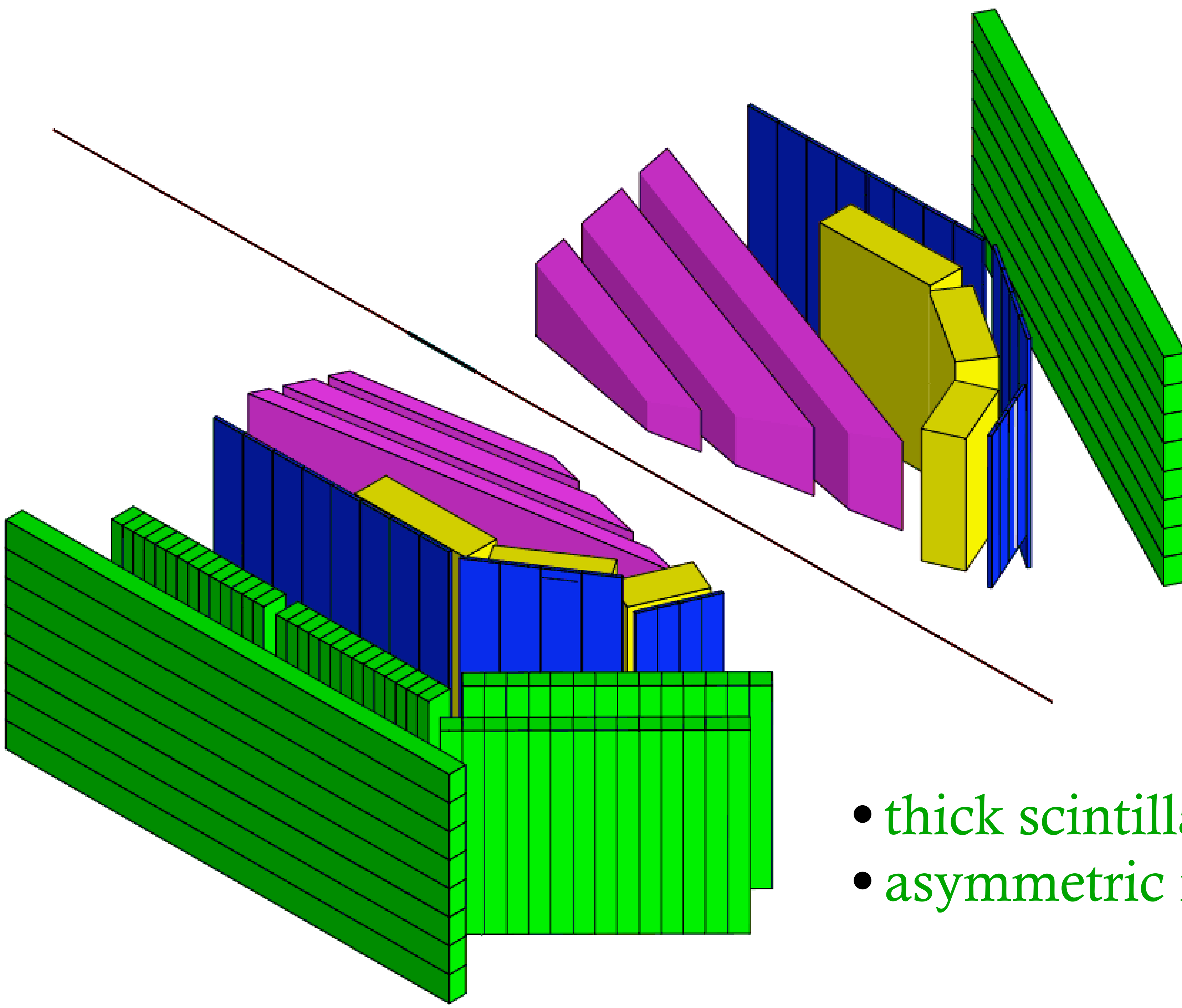
- Aerogel Cerenkov
- pion / electron separation

BLAST Detector



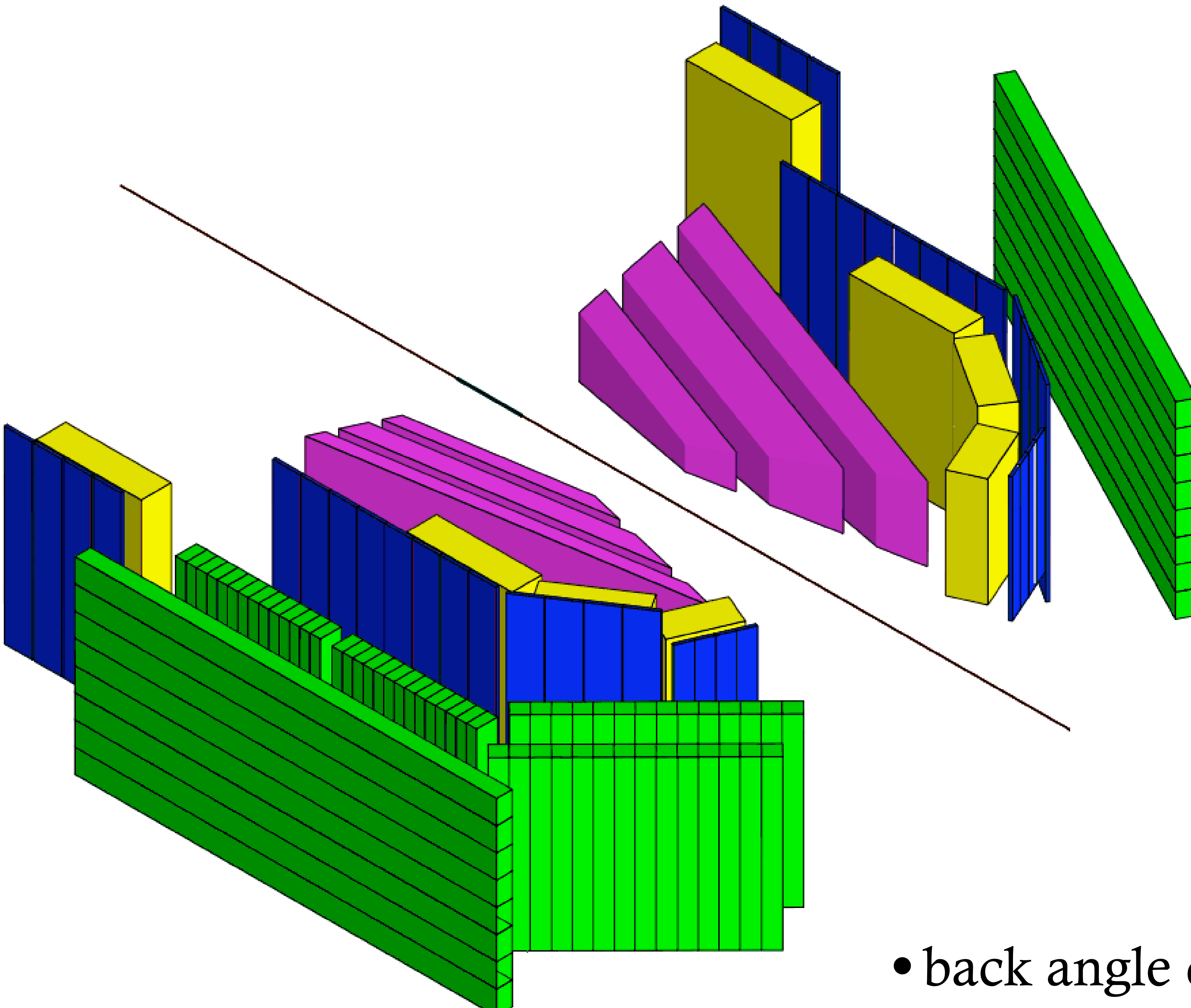
- time of flight scintillator walls
- relative timing
- trigger timing

BLAST Detector



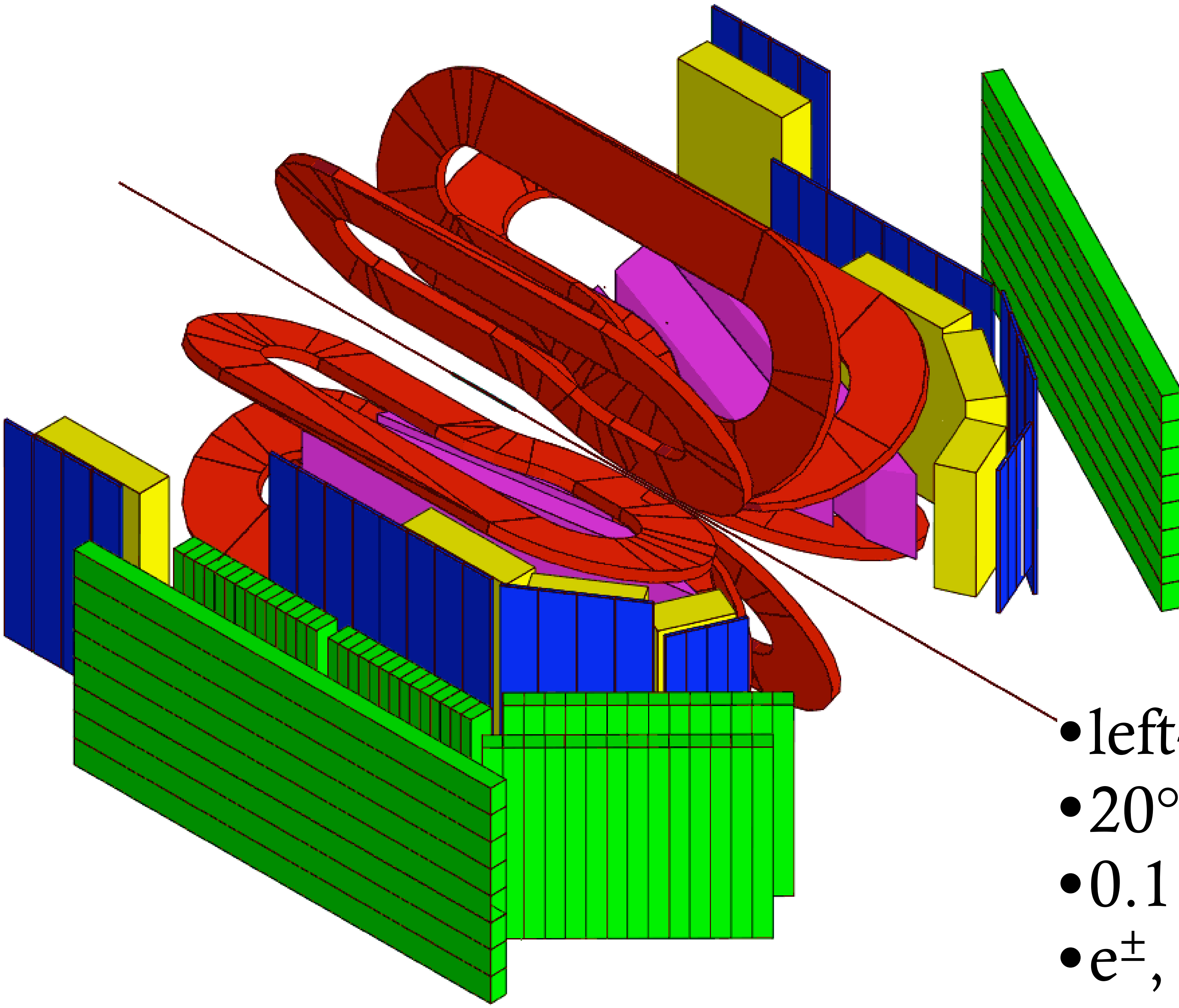
- thick scintillators for neutron detector
- asymmetric favouring right sector

BLAST Detector



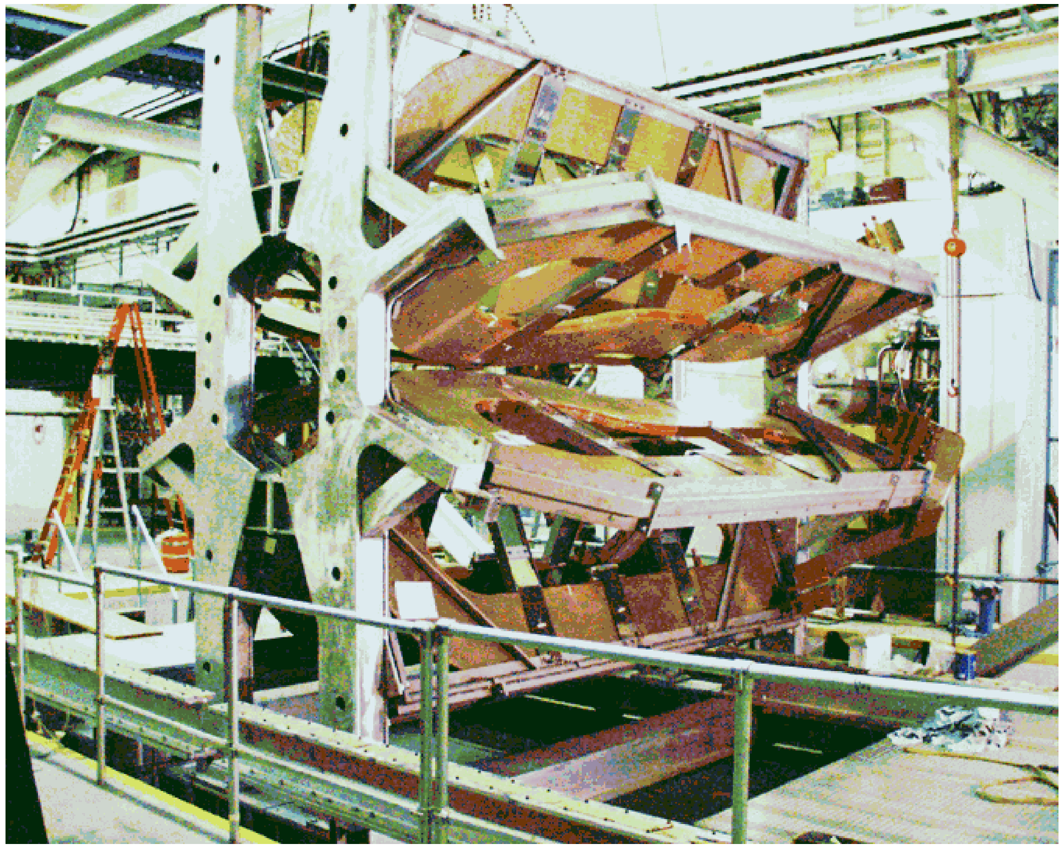
- back angle detectors
- extend coverage, no tracking

BLAST Detector



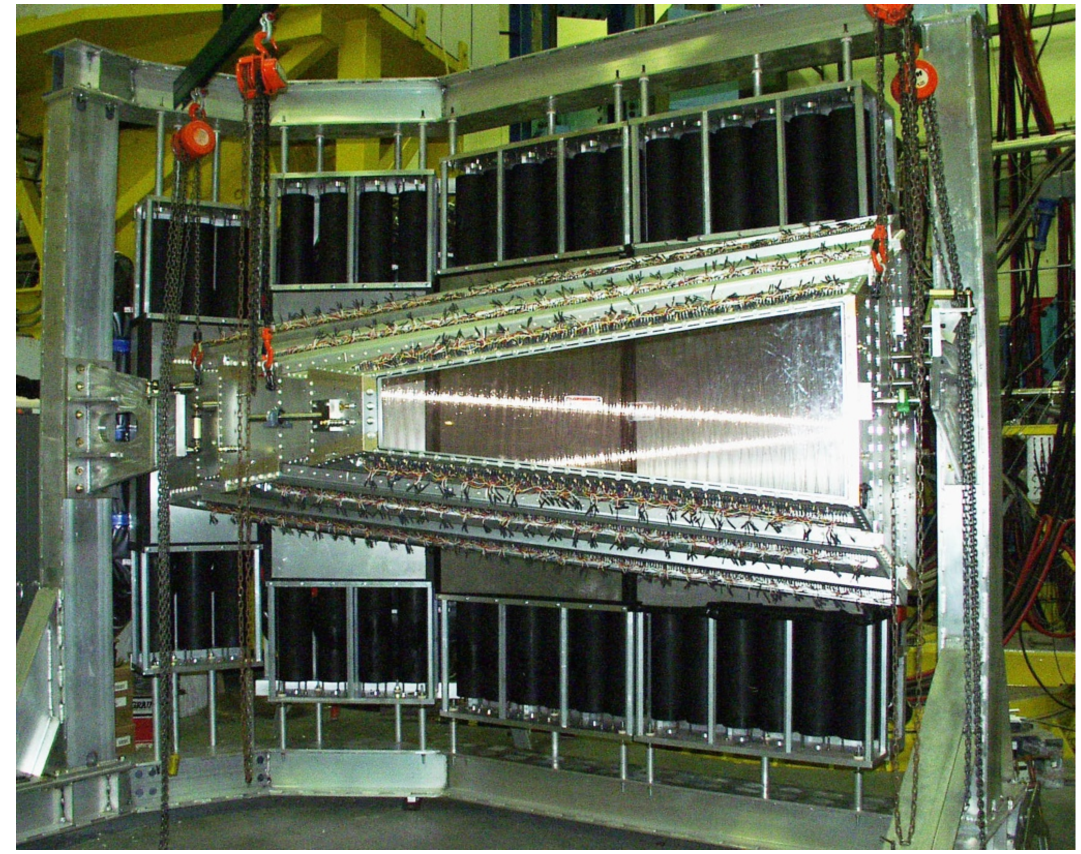
- left-right symmetric
- $20° - 80°\ \theta$, $\pm 15°\ \varphi$
- $0.1 < Q^2 < 0.8\ (GeV/c)^2$
- $e^{\pm}$, p, n, d, $\pi^{\pm}$

BLAST Detector Components



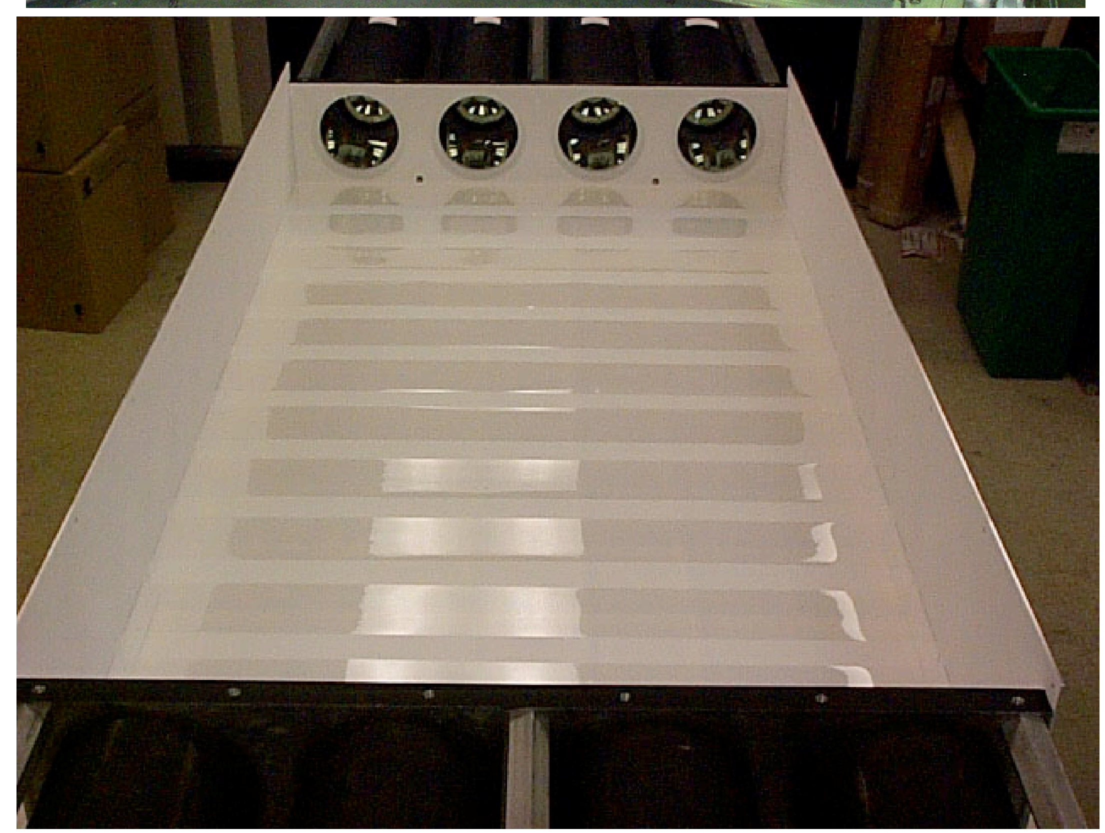
Bates

MIT



UNH

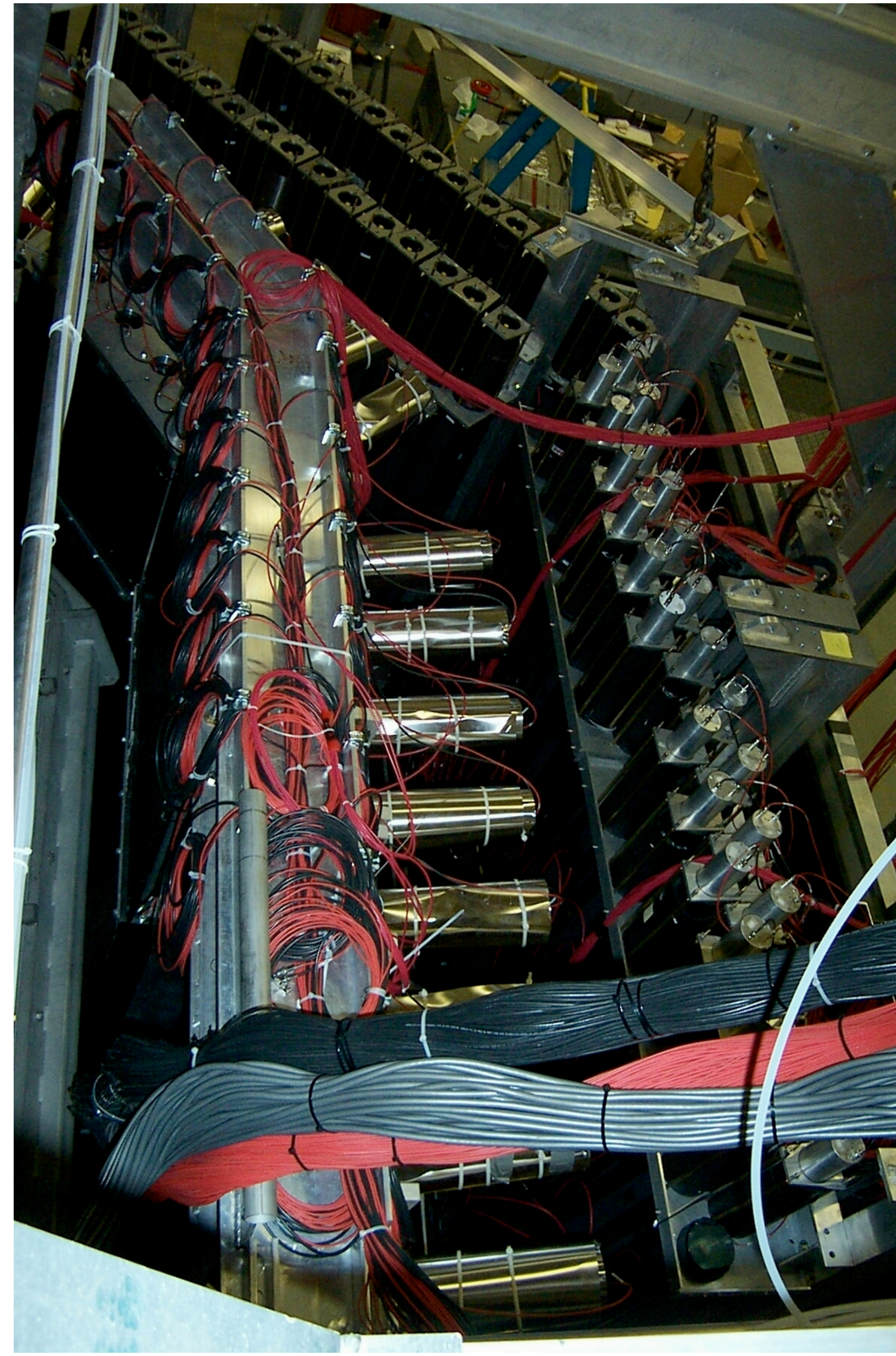
ASU



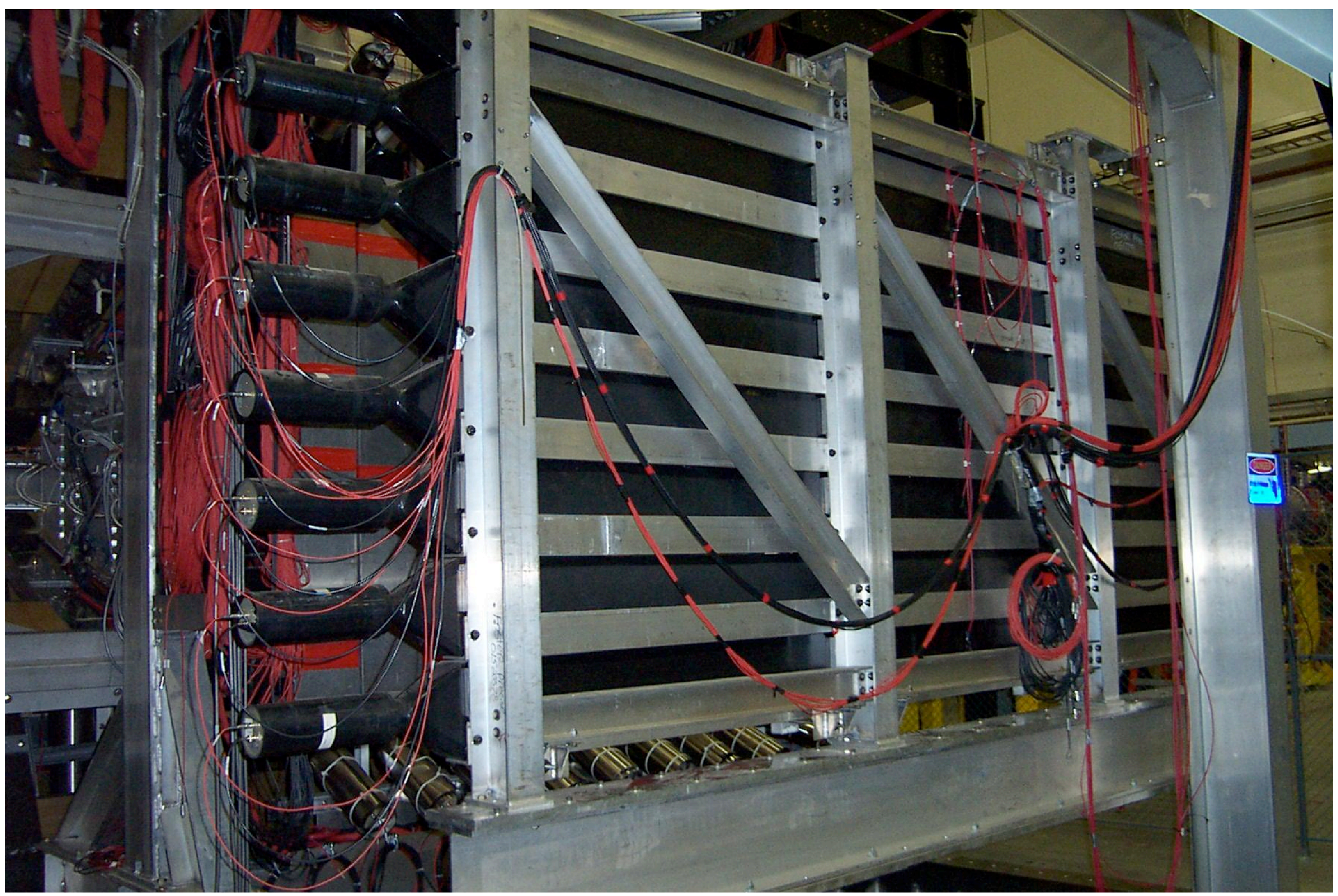
BLAST Detector Components

Neutron Detectors

MIT

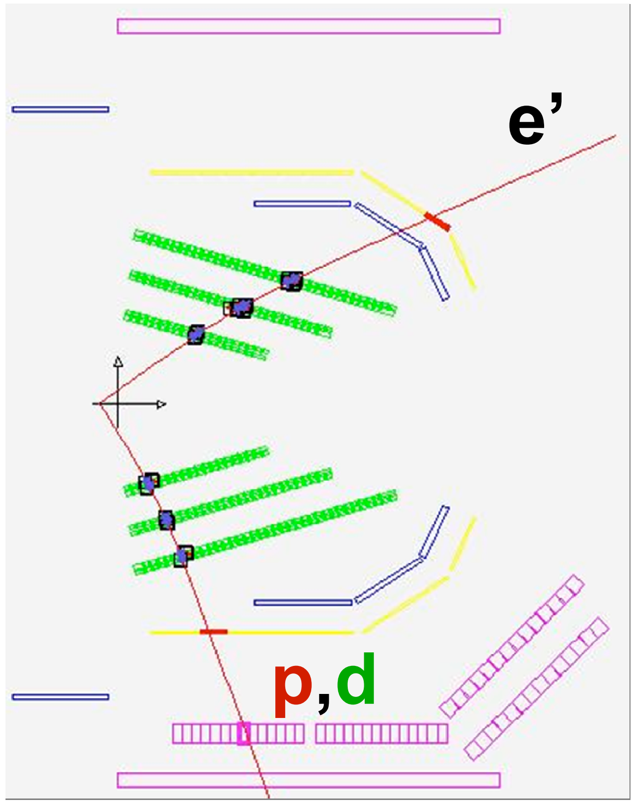


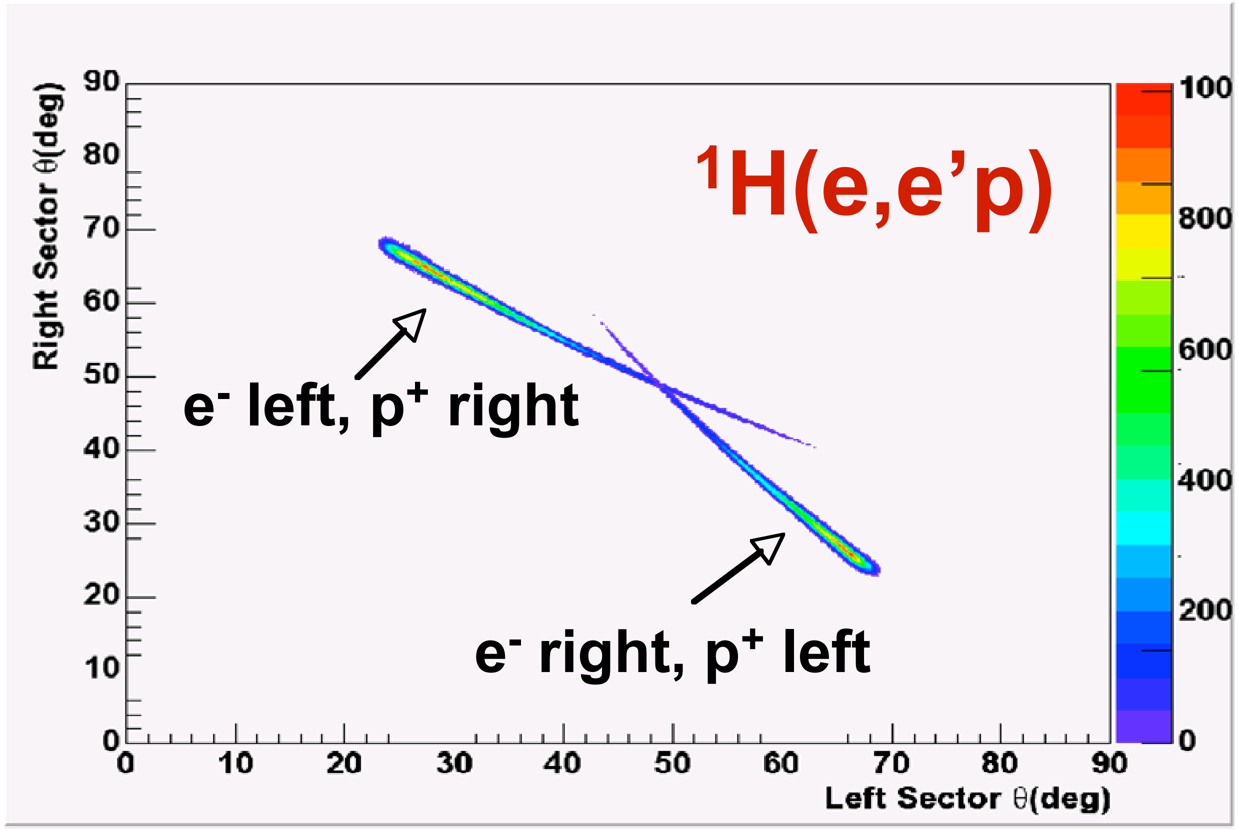
Ohio University

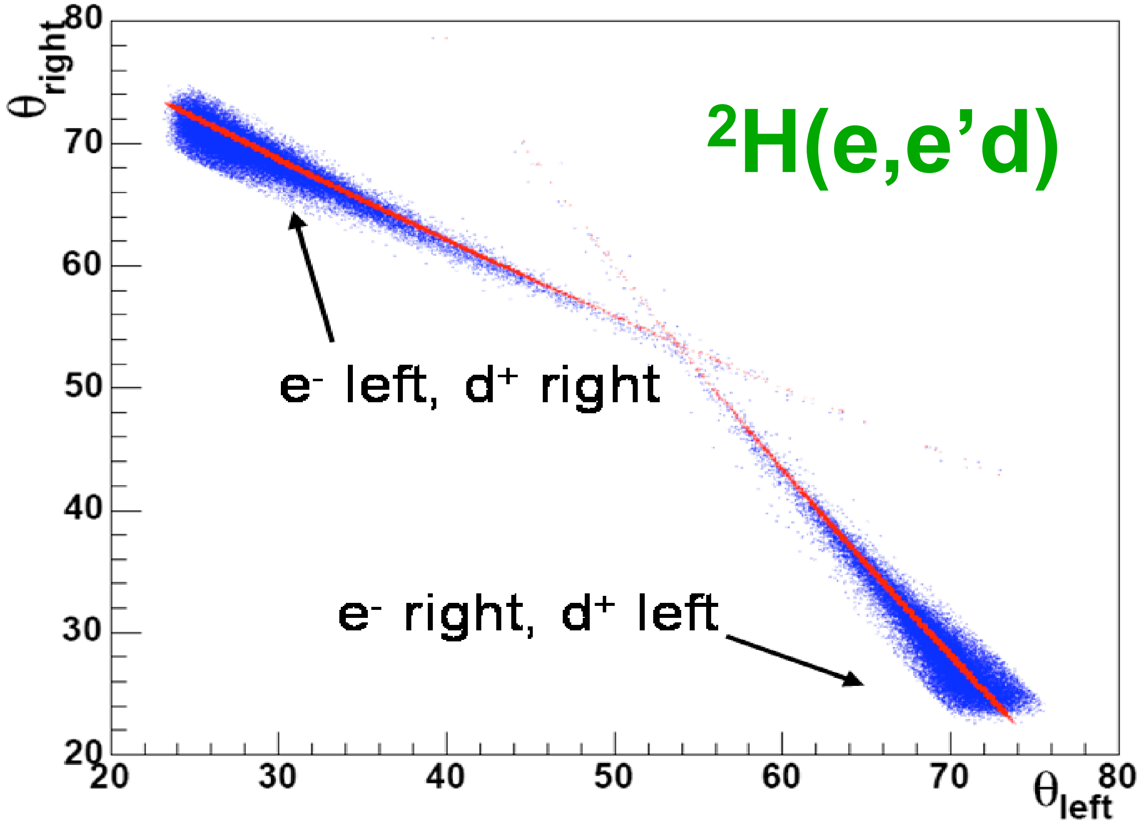


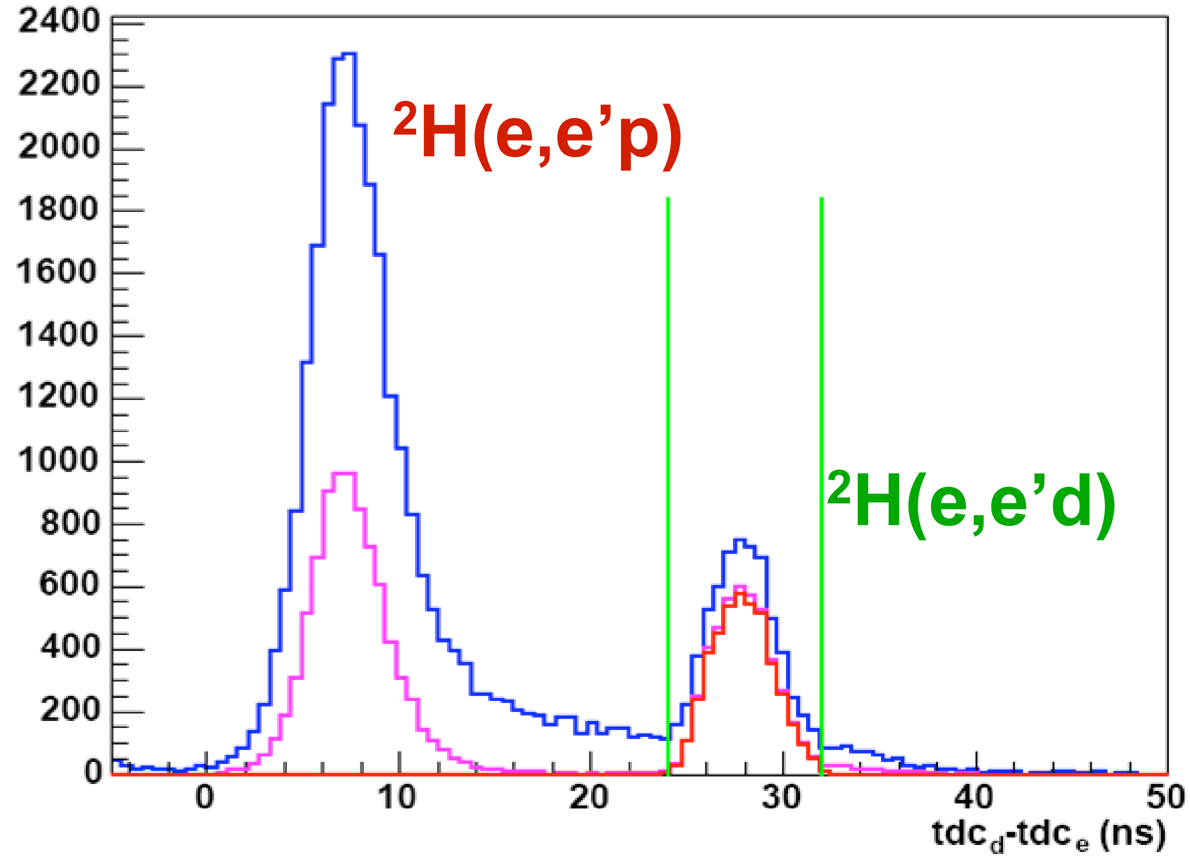
Event Selection

Charge+/-
Coplanarity
Kinematics
Timing

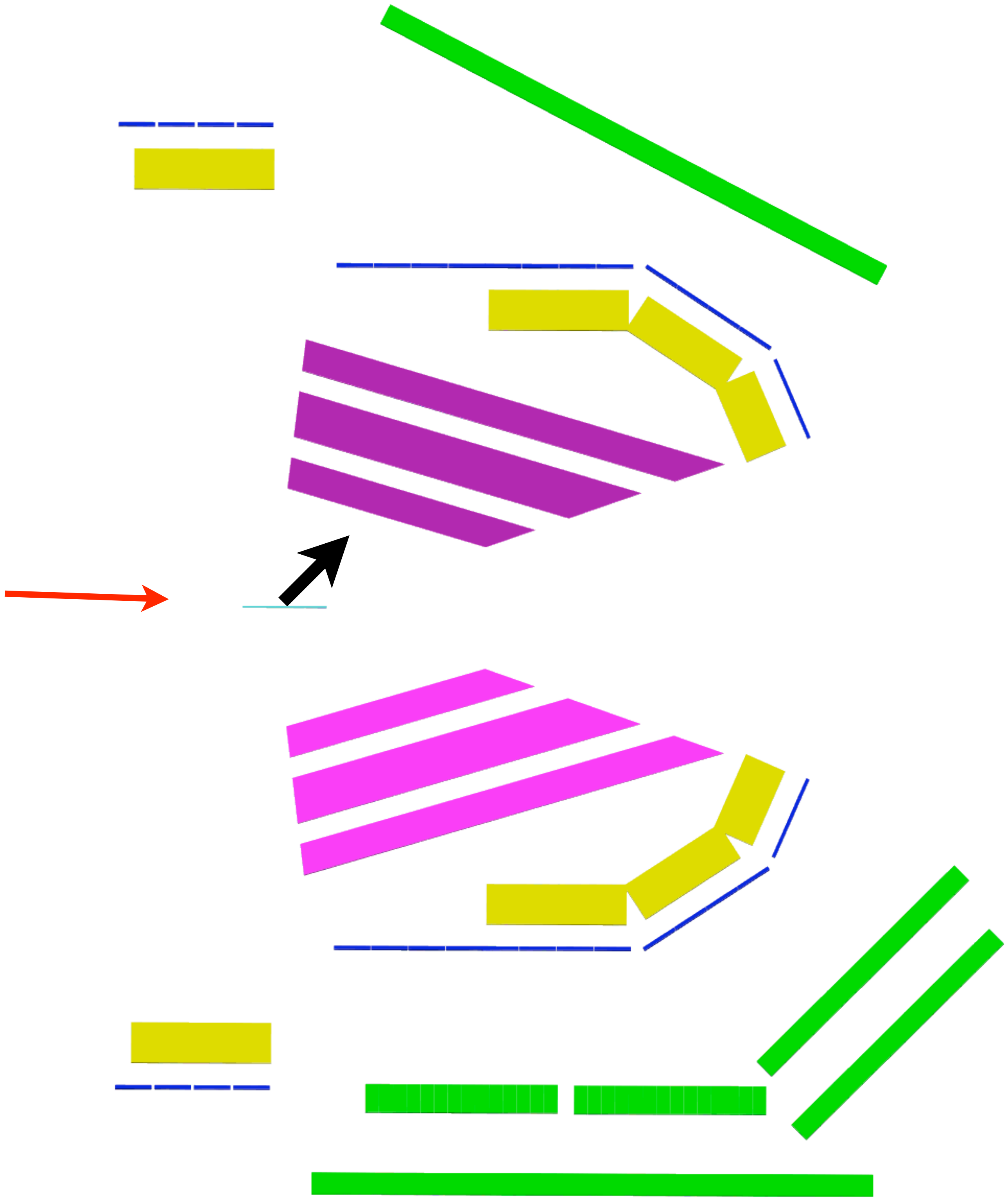








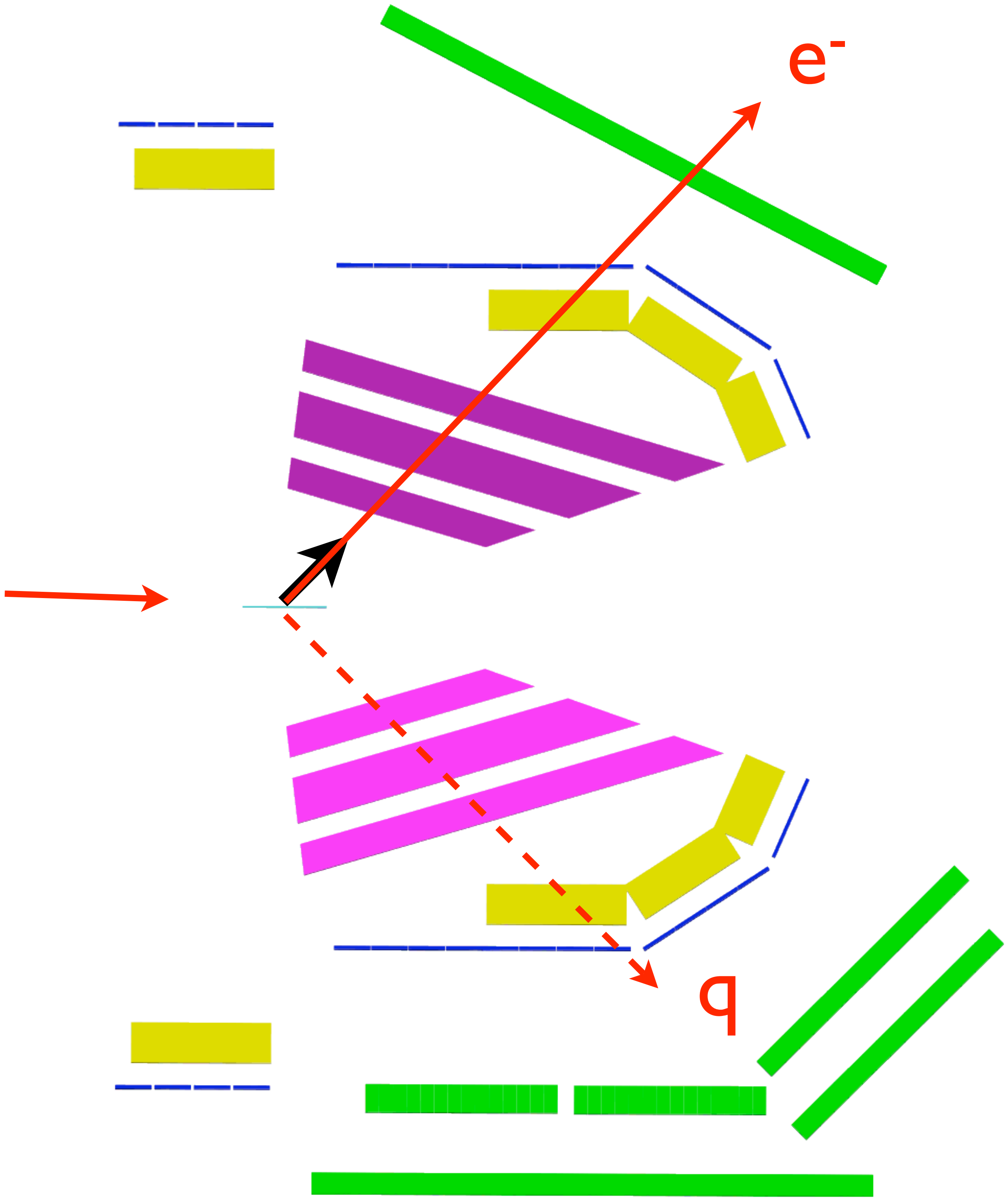
Orientation of Target Spin



Target spin angle

- 32° (2004) / 45° (2005)
- horizontal into the left sector

Orientation of Target Spin



Target spin angle

- 32° (2004) / 45° (2005)
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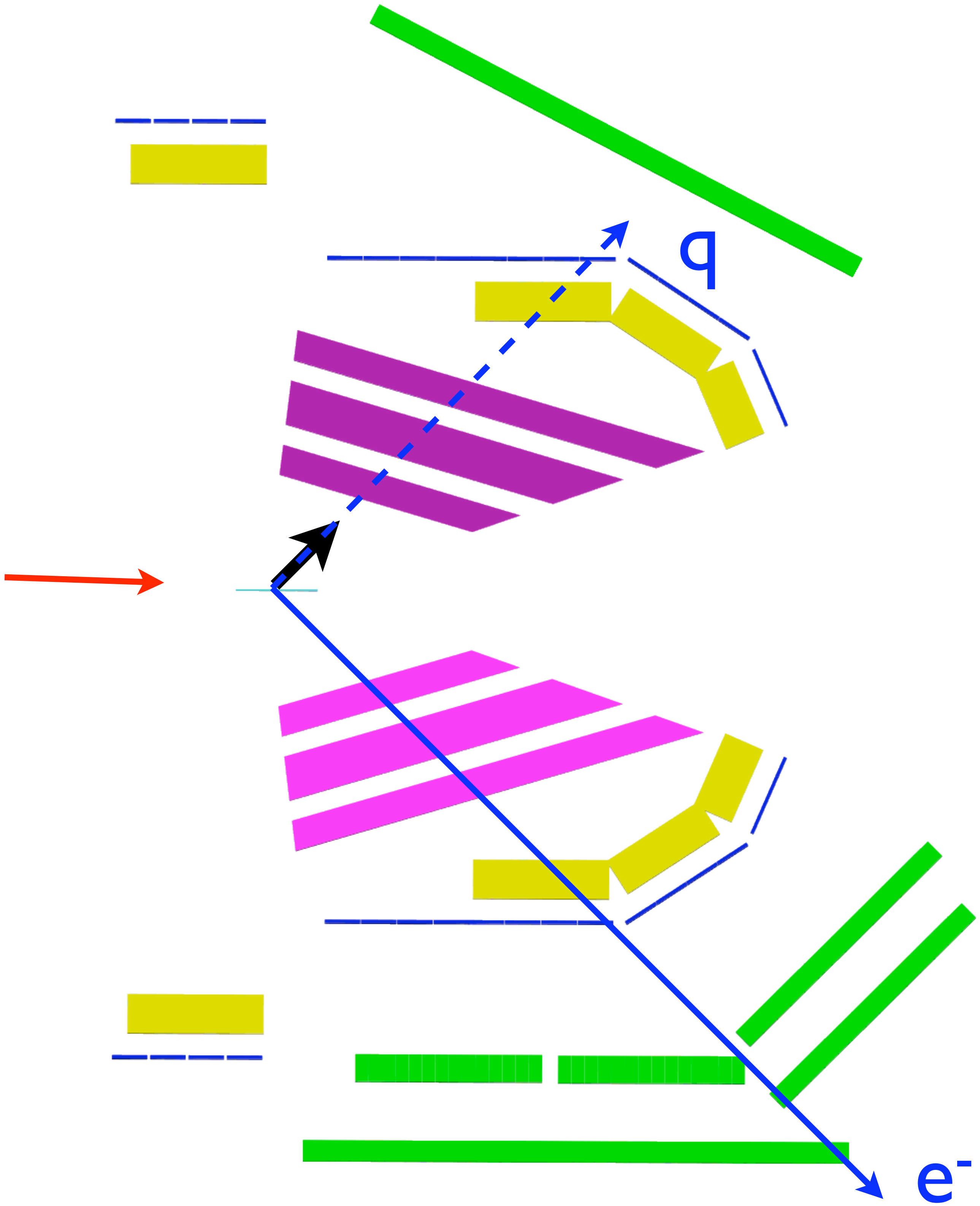
Electron scatters to left sector

- q ≈ perpendicular to target spin
- $\theta^* \approx 90°$
- "spin perpendicular" kinematics

Orientation of Target Spin



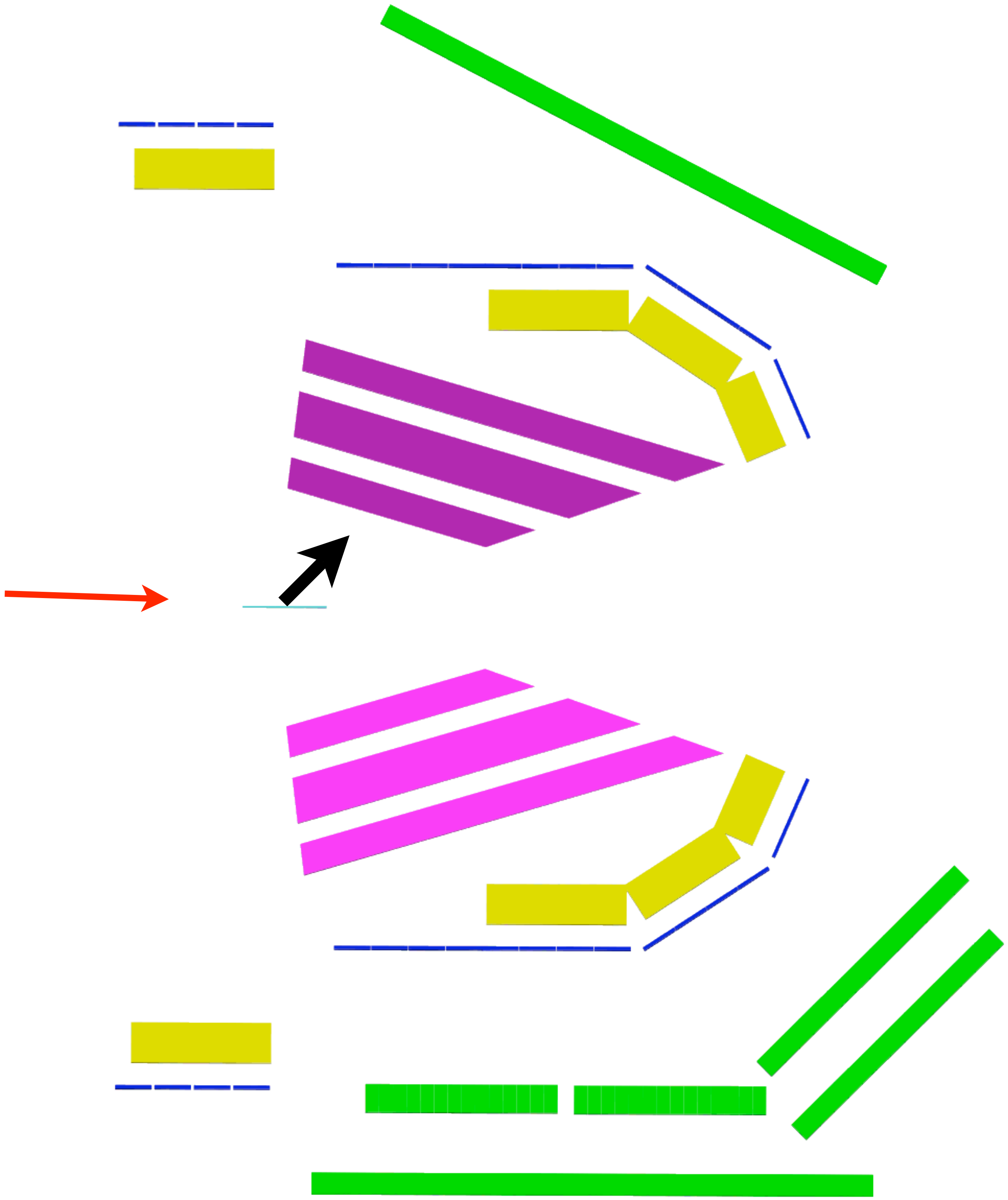
Target spin angle

- 32° (2004) / 45° (2005)
- horizontal into the left sector

Electron scatters to right sector

- q ≈ parallel to target spin
- $\theta^* \approx 0°$
- "spin parallel" kinematics

Orientation of Target Spin



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BLAST Physics

Polarised Hydrogen

$^1\vec{H}(\vec{e},e')$ $\quad ^1\vec{H}(\vec{e},e'p)$ $\quad ^1\vec{H}(\vec{e},e'p)\gamma,\pi^0$ $\quad ^1\vec{H}(\vec{e},e'\pi^+)n$ $\quad ^1\vec{H}(\vec{e},e'\pi^+n)$

Inclusive **G^p_E/G^p_M** **N-Δ : EMR, CMR** **Photoprod.**

Vector Polarised Deuterium

$^2\vec{H}(\vec{e},e')$ $\quad ^2\vec{H}(\vec{e},e'd)$ $\quad ^2\vec{H}(\vec{e},e'p)n$ $\quad ^2\vec{H}(\vec{e},e'n)p$ $\quad ^2\vec{H}(\vec{e},e'\pi^{\pm,0})$

G^n_M **T^e_{11} : G^d_M** **A^v_{ed} : L=2** **G^n_E** **N-Δ**

Tensor Polarised Deuterium

$^2\overleftrightarrow{H}(e,e'd)$ $\quad ^2\overleftrightarrow{H}(e,e'p)n$ $\quad ^2\overleftrightarrow{H}(e,e'n)p$ $\quad ^2\overleftrightarrow{H}(\gamma,pn)$ $\quad ^2\overleftrightarrow{H}(\vec{e},e'\pi^{\pm})$

T_{20} : G^d_Q **A^T_d : L=2** **photodisint.** **$^1S_0$**

Elastic Scattering from Hydrogen

With polarized beam and target can measure asymmetries

$$A_{exp} = P_b P_t \frac{-2\tau v_{T'} \cos\theta^* {G_M^p}^2 + 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta^* \cos\phi^* G_M^p G_E^p}{(1+\tau) v_l {G_E^p}^2 + 2\tau v_T {G_M^p}^2}$$

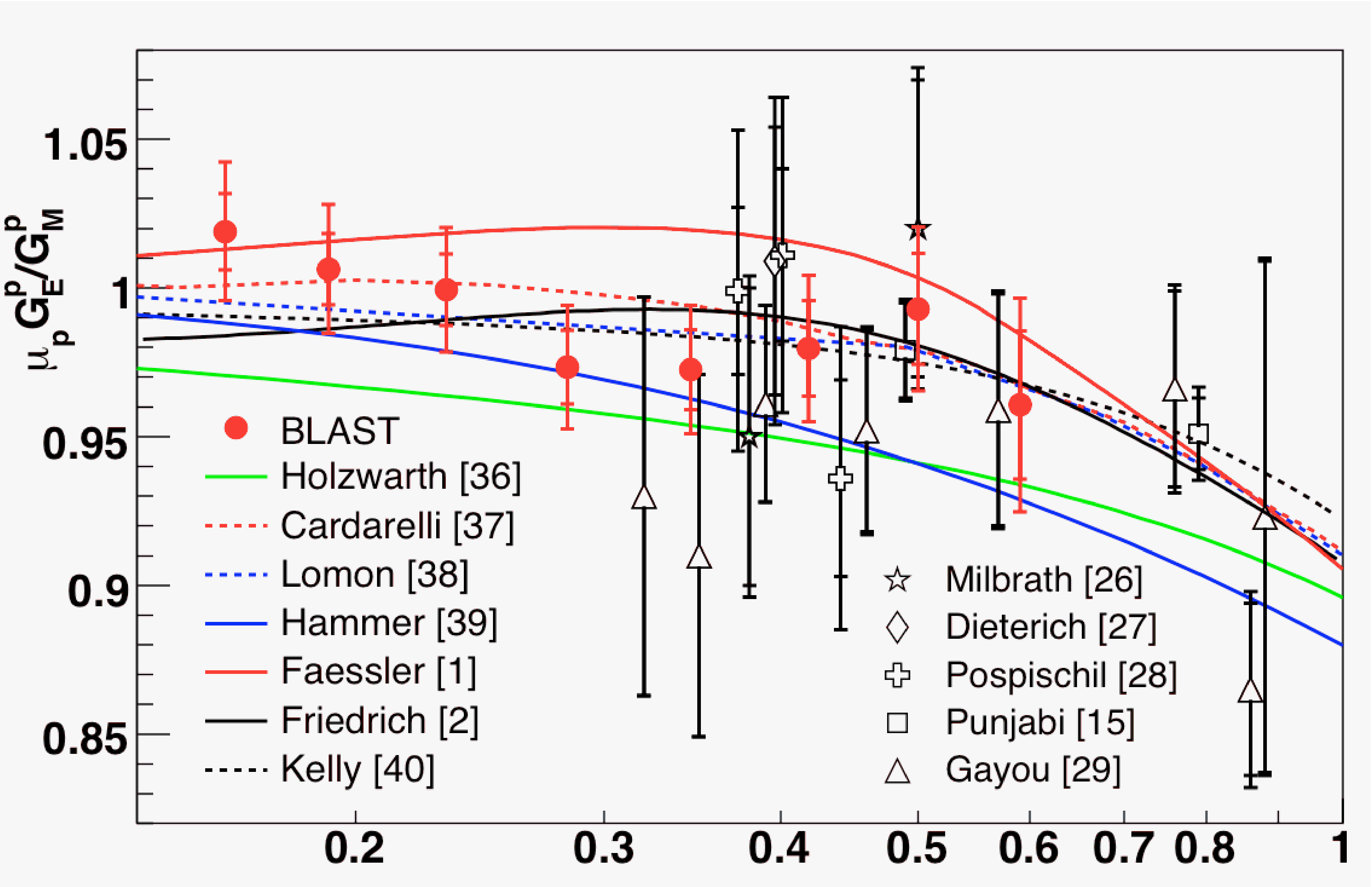
- note some terms vanish in perpendicular or parallel kinematics

With symmetric detector can form ratio of left/right asymmetries

$$R_A = \frac{A_L}{A_R} = \frac{z_L^* - x_L^* G_E^p / G_M^P}{z_R^* - x_R^* G_E^p / G_M^P}$$

- beam and target polarisations cancel
- all that remains is kinematic terms

Ratio of Proton Elastic Form Factors



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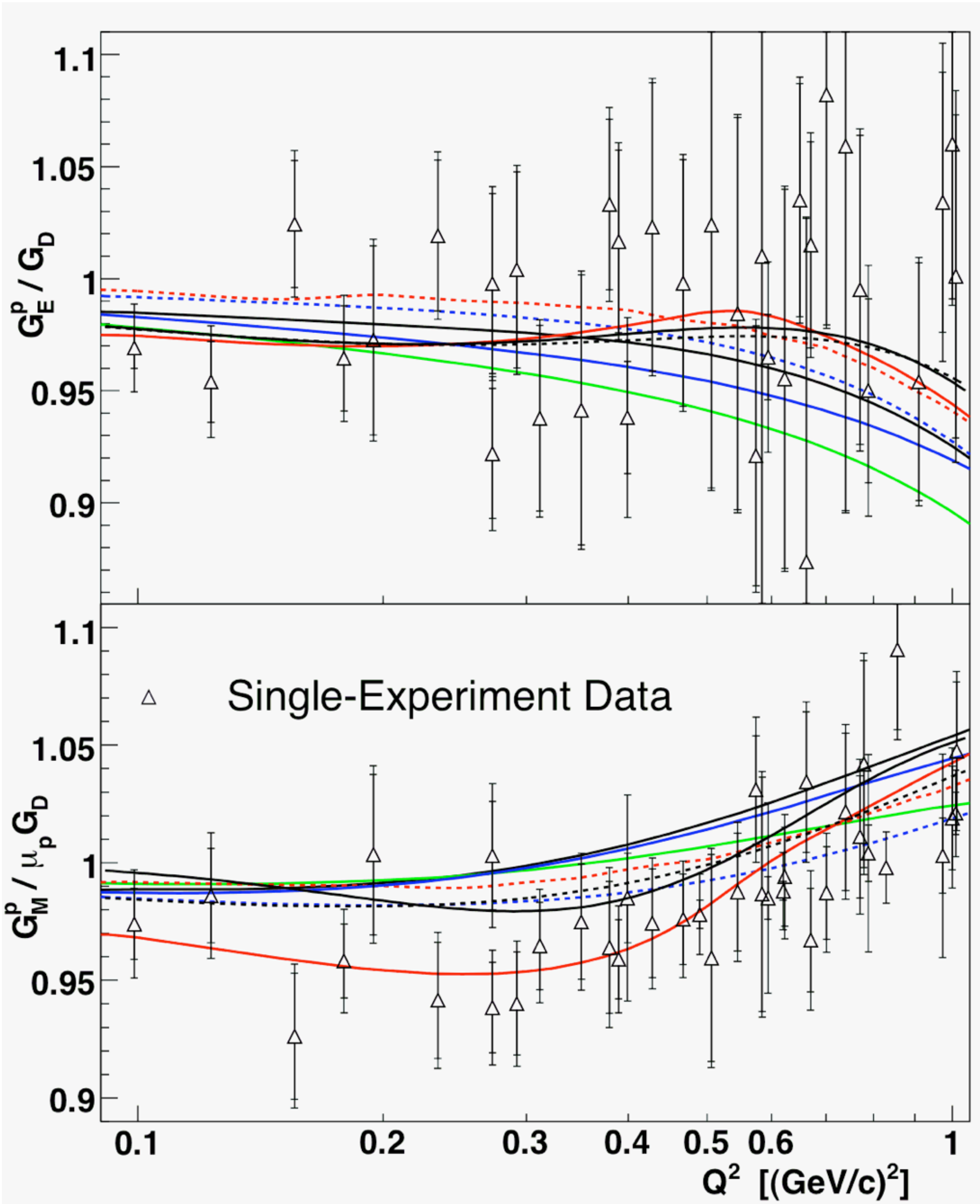
Impact of BLAST Results on World Data



Proton elastic form factors

- G^p_E and G^p_M
- divided by dipole
- collection of unpolarised data

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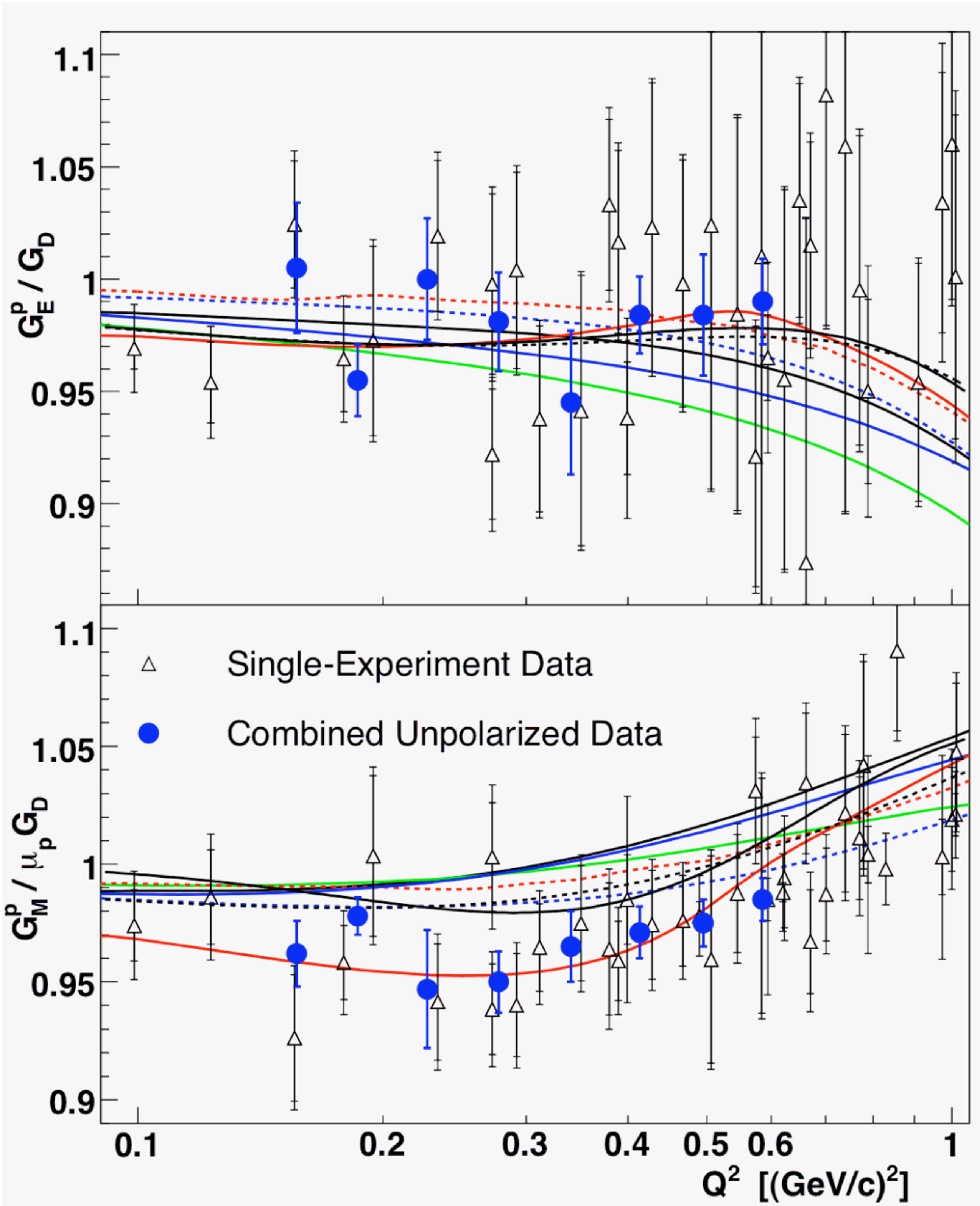

Proton elastic form factors

- $G^p{}_E$ and $G^p{}_M$
- divided by dipole
- collection of unpolarised data

World data combined

- averaged and rebinned
- over BLAST range

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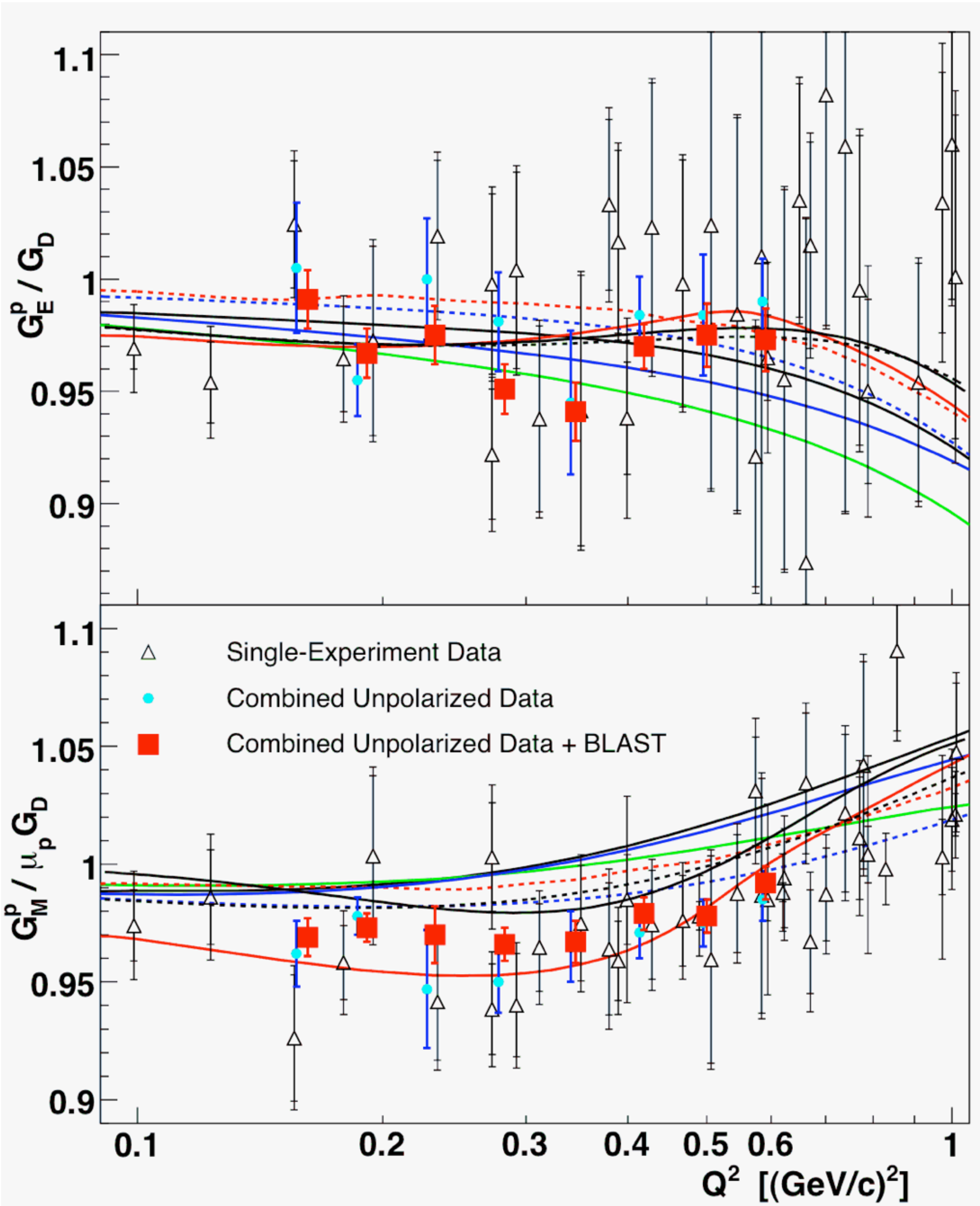

Proton elastic form factors

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World data combined

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- over BLAST range

Constraining with BLAST

- uncertainties reduced factor 2

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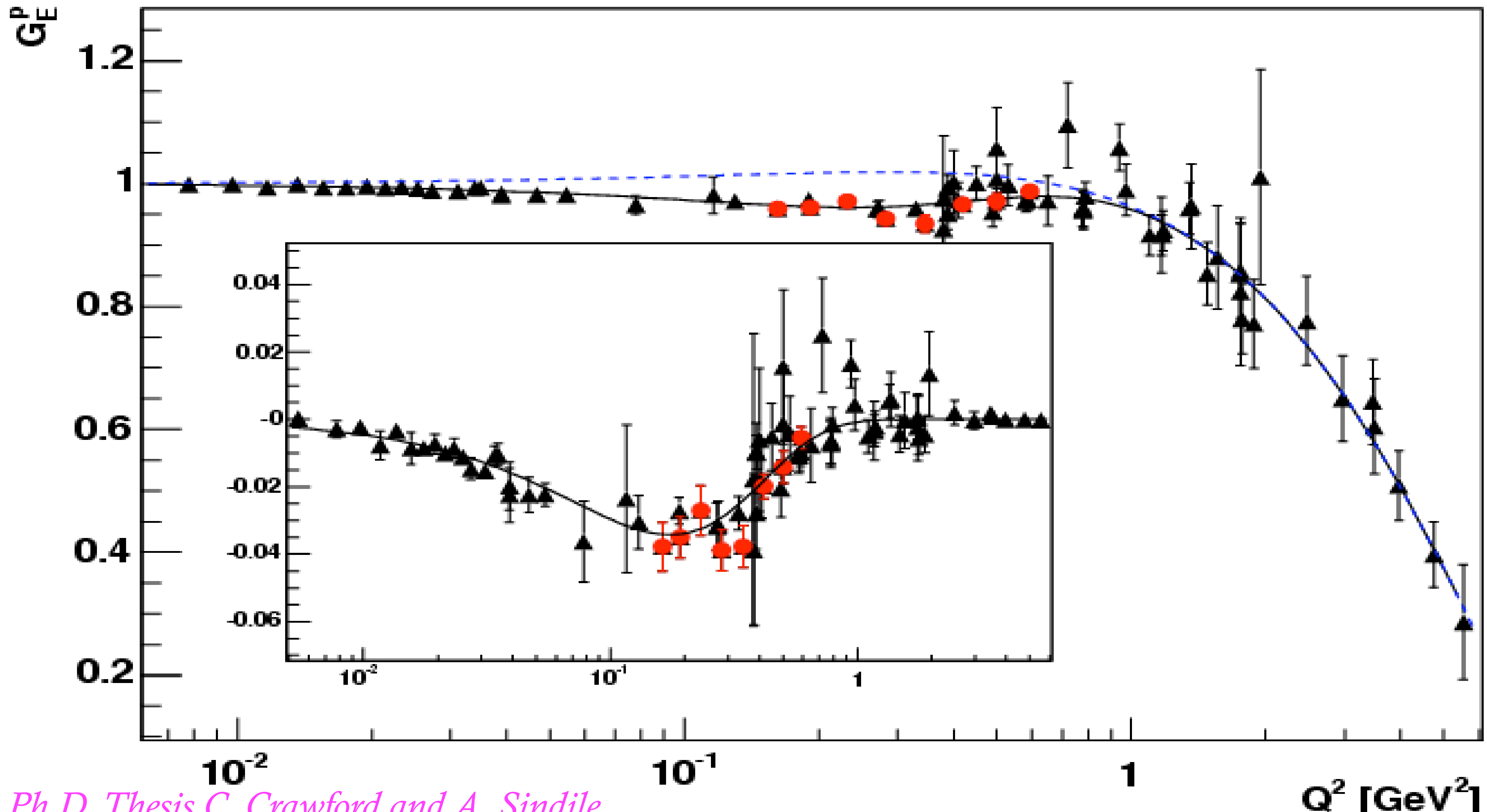
BLAST Data with Friedrich and Walcher



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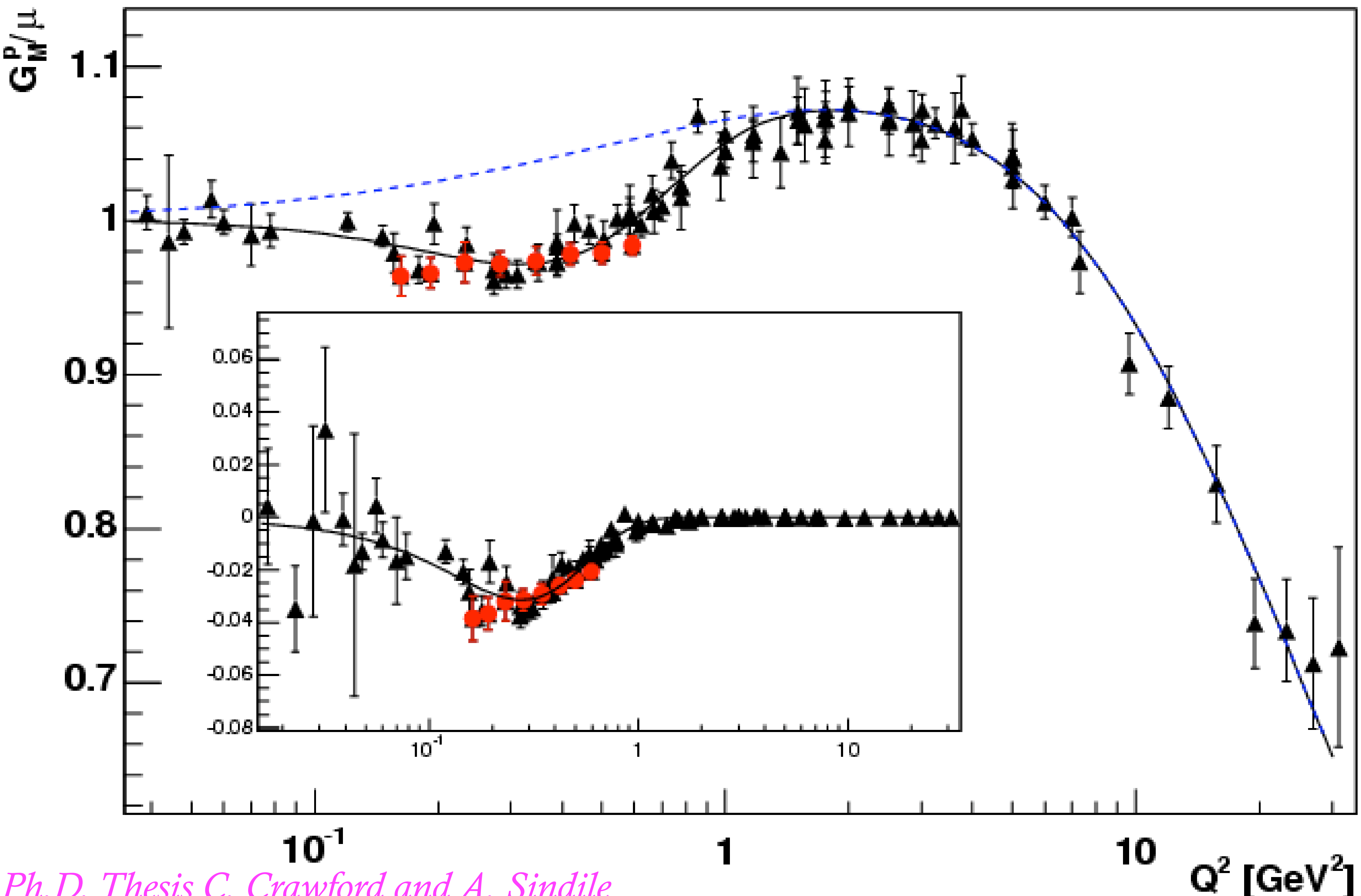
BLAST Data with Friedrich and Walcher



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Elastic Electron - Deuteron Scattering

Deuteron spin S = 1

- three form factors $G^d{}_C$, $G^d{}_M$, and $G^d{}_Q$
- $G^d{}_Q$ arises from tensor force, D-wave
- normalisation $G^d{}_Q(0)=M^2{}_d\, Q_d$

Unpolarised elastic cross section - insufficient

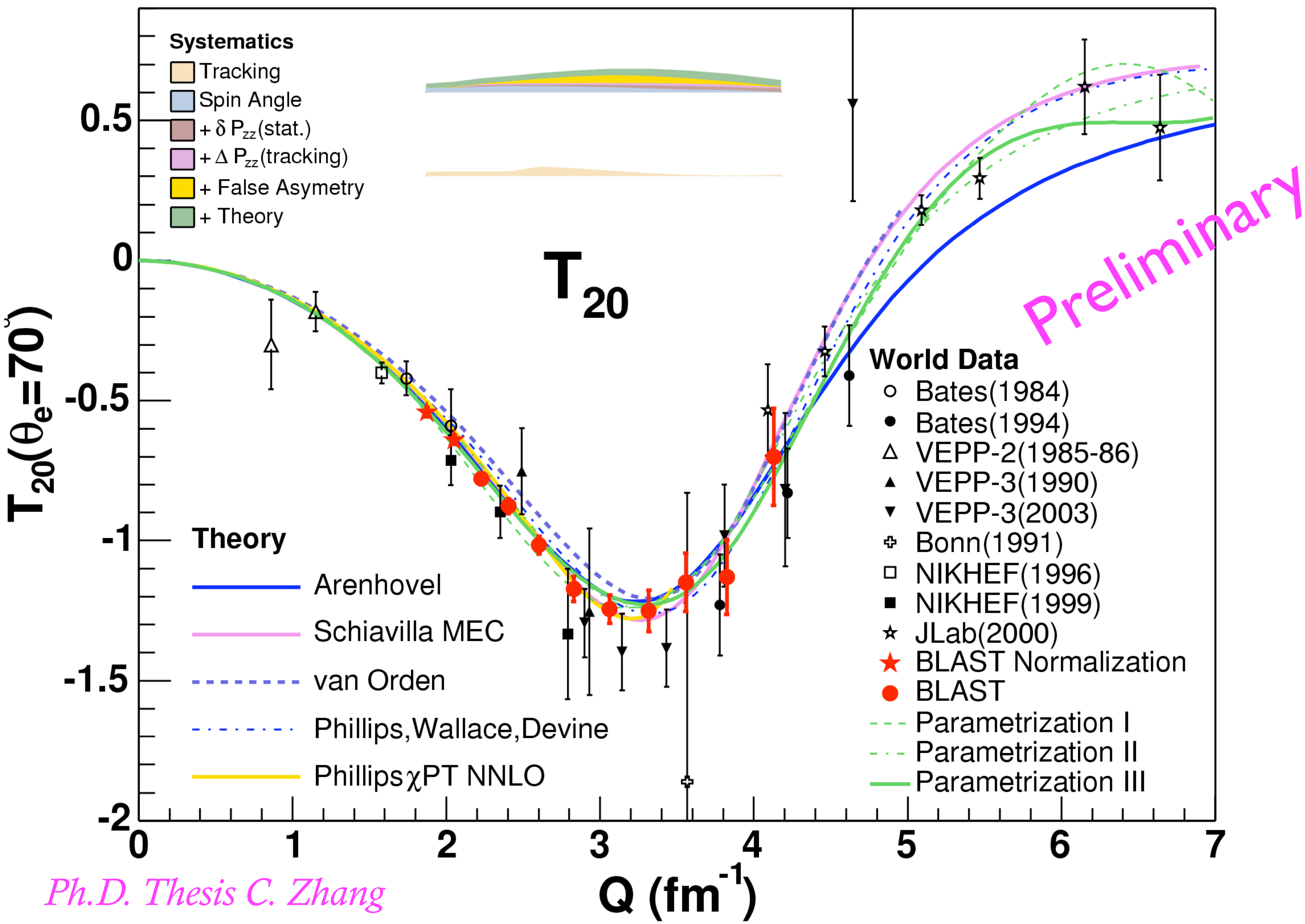
$$A(Q^2) = {G_C^d}^2 + \frac{8}{9}\eta^2 {G_Q^d}^2 + \frac{2}{3}\eta {G_M^d}^2$$

$$B(Q^2) = \frac{4}{3}\eta(1+\eta){G_M^d}^2; \qquad \eta = Q^2/(4M_d^2)$$

Need additional measurement - tensor asymmetry

$$T_{20} = -\frac{1}{\sqrt{2}S}\left[\frac{8}{3}\eta G_C G_Q + \frac{8}{9}\eta^2 {G_Q}^2 + \frac{1}{3}\eta[1+2(1+\eta)\tan^2(\frac{\theta}{2}){G_M}^2\right]$$

T_{20}



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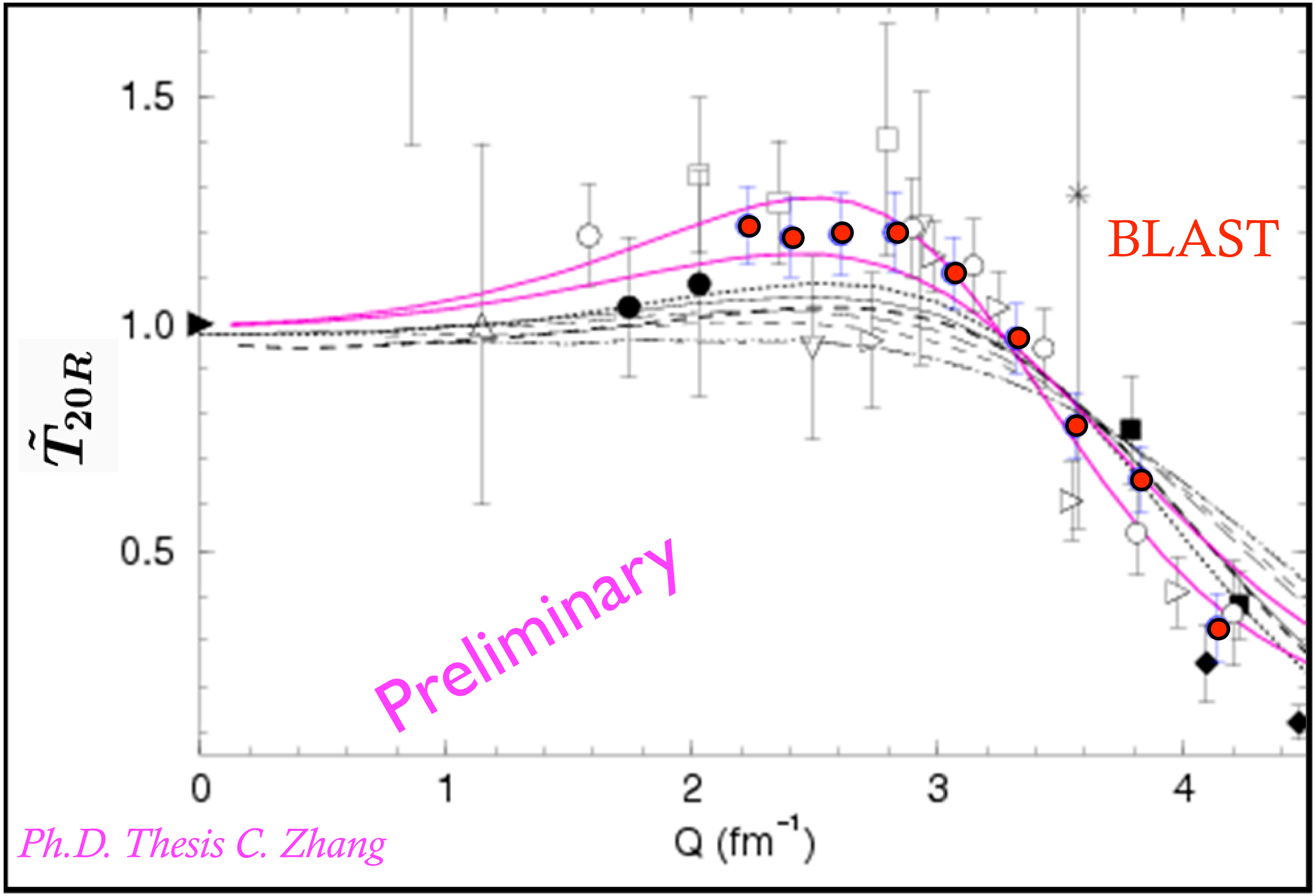
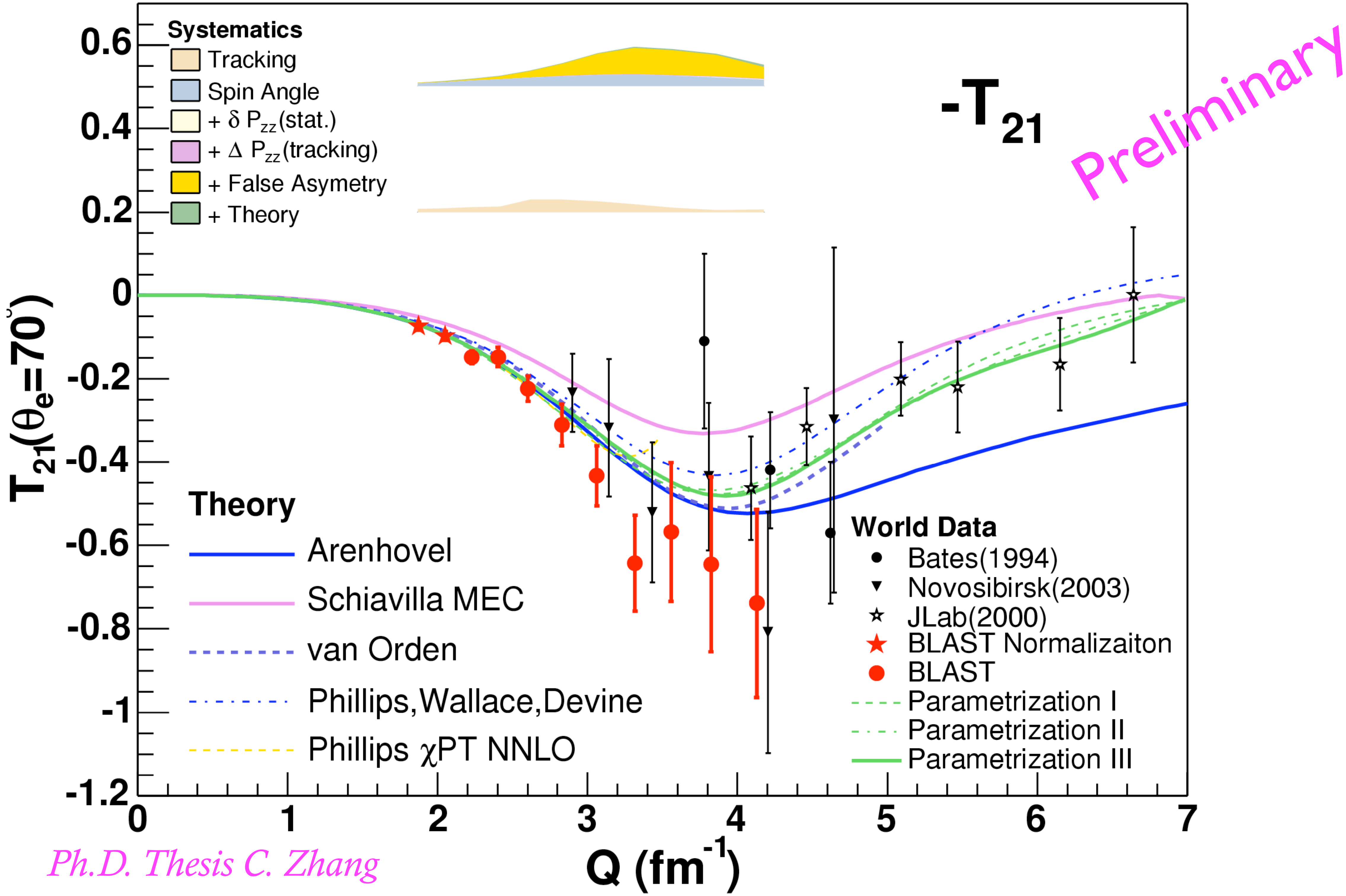
Reduced T_{20}

$$\tilde{T}_{20R} = -\frac{3}{\sqrt{2}Q_d Q^2}\tilde{T}_20$$

D. Phillips, J. Phys. G34, (2007) 365



T_{21}



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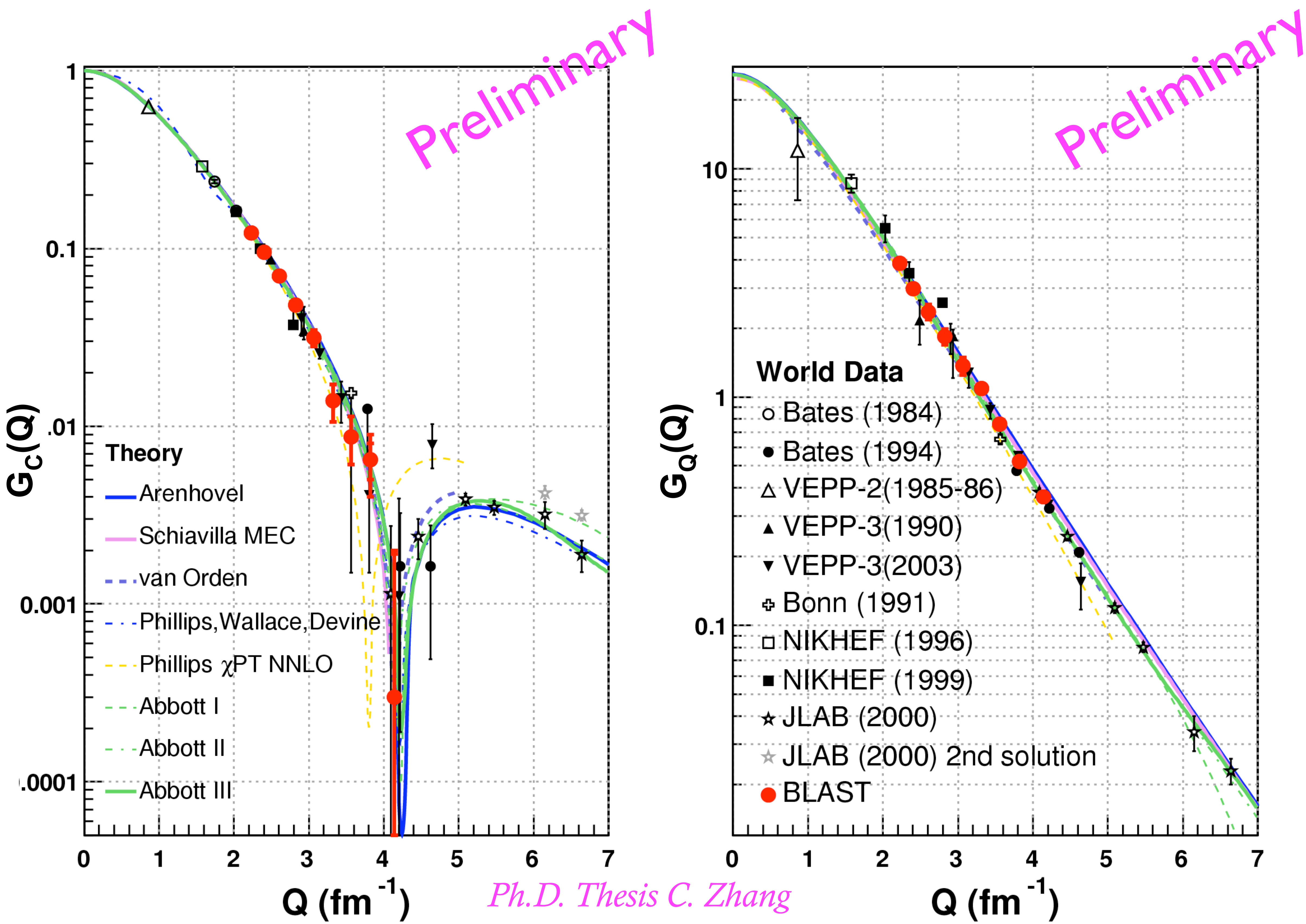
G_C and G_Q


Preliminary
Preliminary
$G_C(Q)$
$G_Q(Q)$
Q (fm^{-1})
Q (fm^{-1})
Theory
Arenhovel
Schiavilla MEC
van Orden
Phillips,Wallace,Devine
Phillips χPT NNLO
Abbott I
Abbott II
Abbott III
World Data
Bates (1984)
Bates (1994)
VEPP-2(1985-86)
VEPP-3(1990)
VEPP-3(2003)
Bonn (1991)
NIKHEF (1996)
NIKHEF (1999)
JLAB (2000)
JLAB (2000) 2nd solution
BLAST
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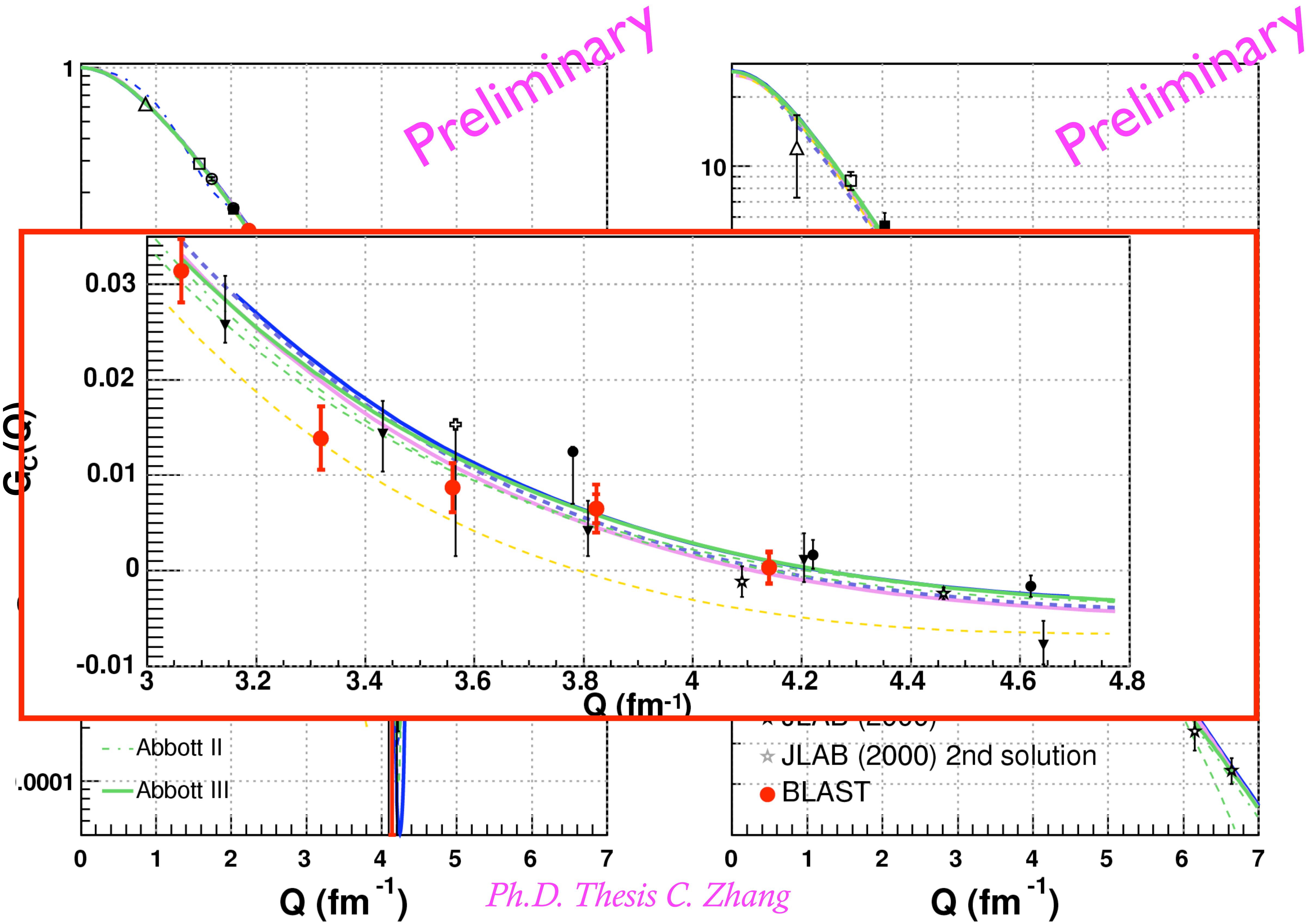
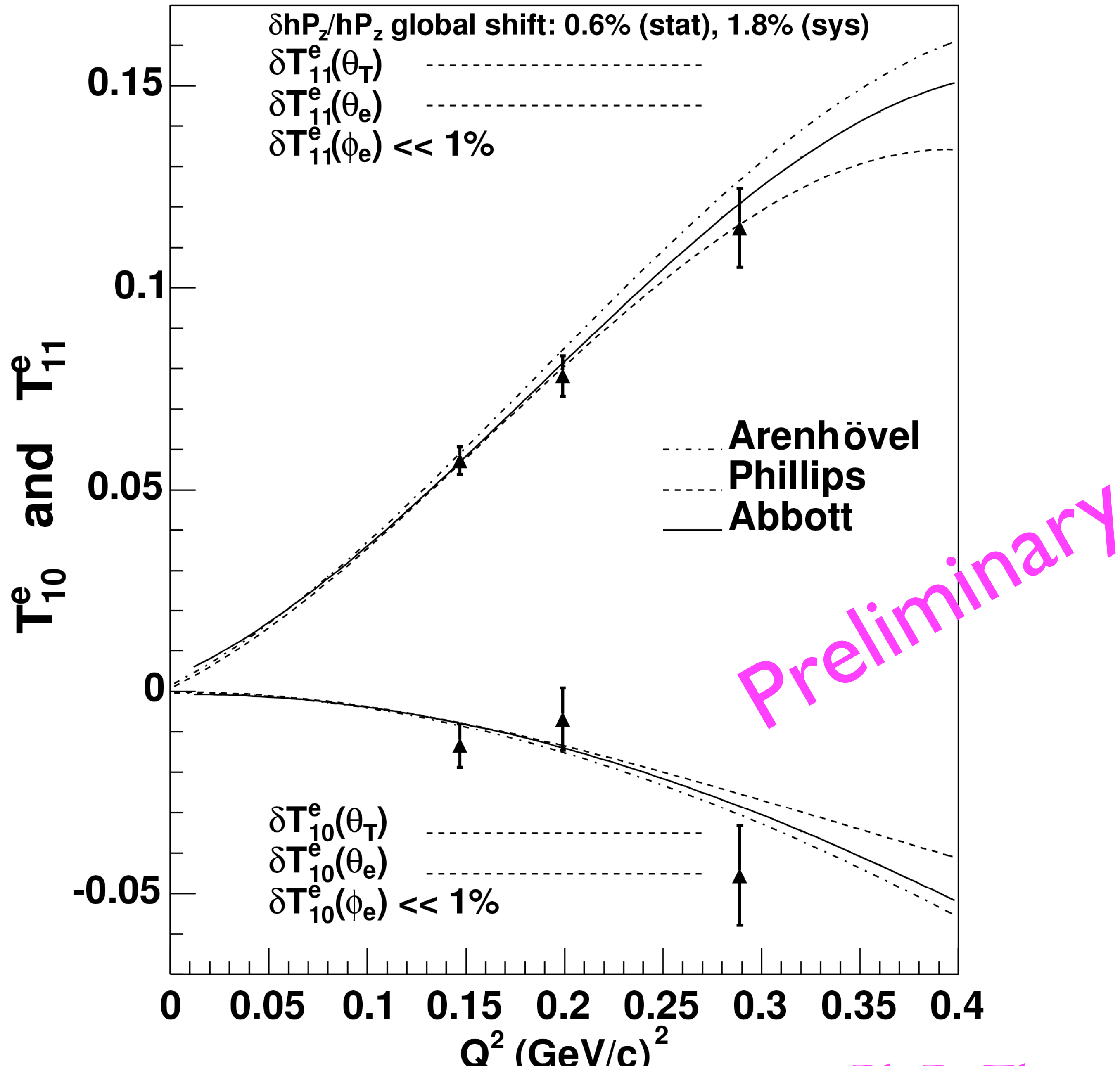
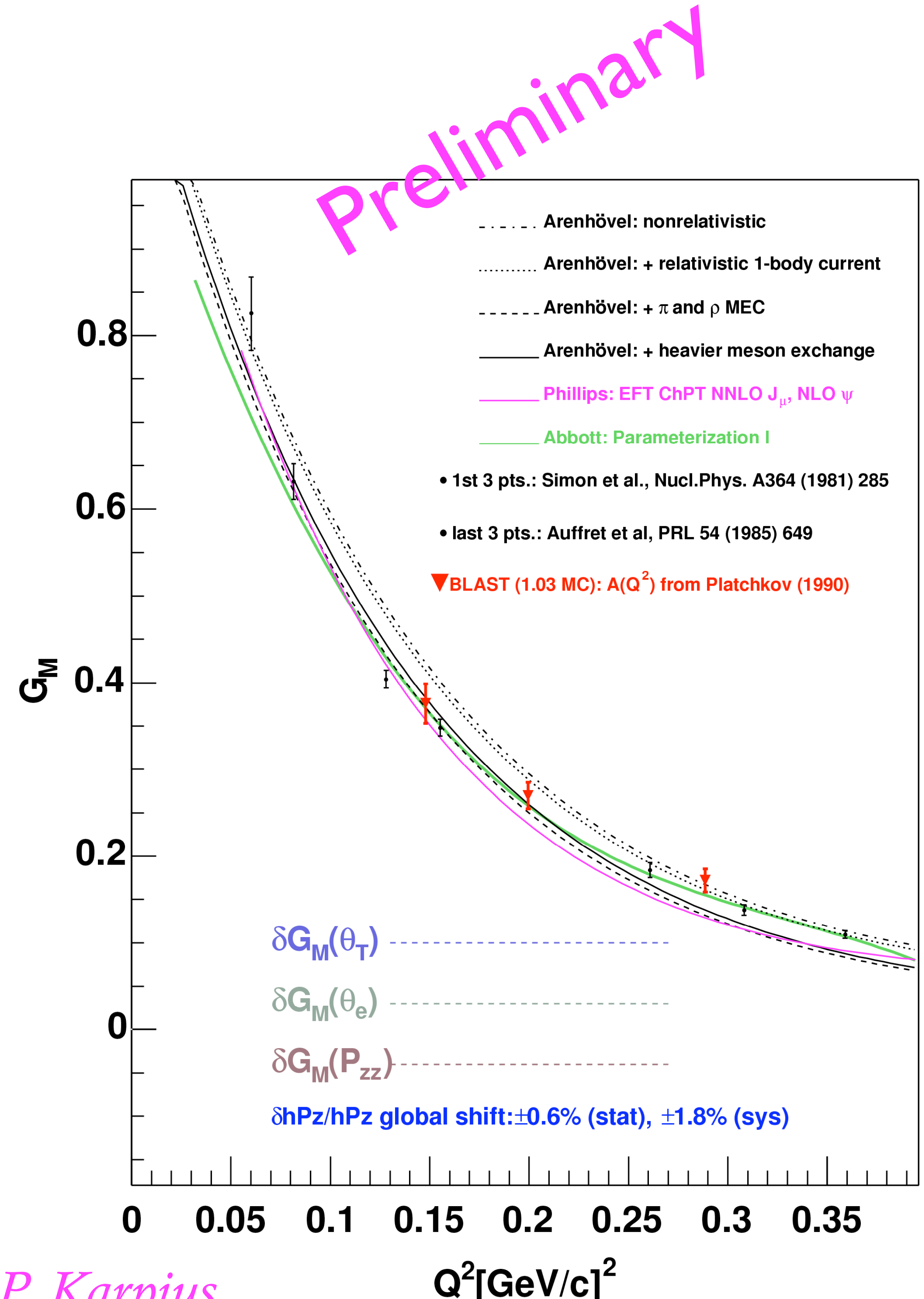
G_C and G_Q


Preliminary
Preliminary
1
10
0.03
0.02
0.01
0
-0.01
$G_C(Q)$
3
3.2
3.4
3.6
3.8
4
4.2
4.4
4.6
4.8
Q (fm-1)
Abbott II
Abbott III
.0001
JLAB (2000) 2nd solution
BLAST
0
1
2
3
4
5
6
7
Q (fm -1)
Ph.D. Thesis C. Zhang
Q (fm -1)

T^e_{10} and T^e_{11} and G^d_M



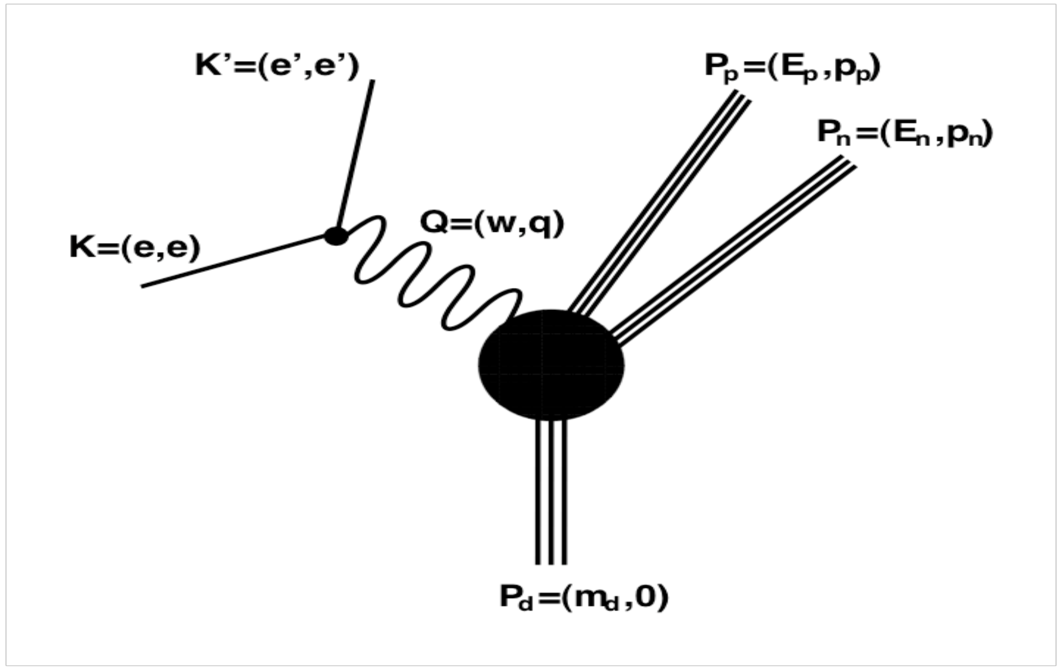


Ph.D. Thesis P. Karpius

Quasi-Elastic Scattering from Deuterium

Deuteron readily breaks up

- e + d → e′ + p + n
- electro-disintegration



Spin-dependent d(e,e′N) cross section can be written as:

$$S(h, P_Z, P_{ZZ}) = S_0\left[1 + P_Z A_d^V + P_{ZZ} A_d^T + h(A_e + P_Z A_{ed}^V + P_{ZZ} A_{ed}^T)\right]$$

In the Born approximation

$$A_d^V = A_e = A_{ed}^T = 0$$

Yielding:

$$S(h, P_Z, P_{ZZ}) = S_0\left[1 + P_{ZZ} A_d^T + h P_Z A_{ed}^V\right]$$

$A_{ed}^V \propto G_E/G_M$

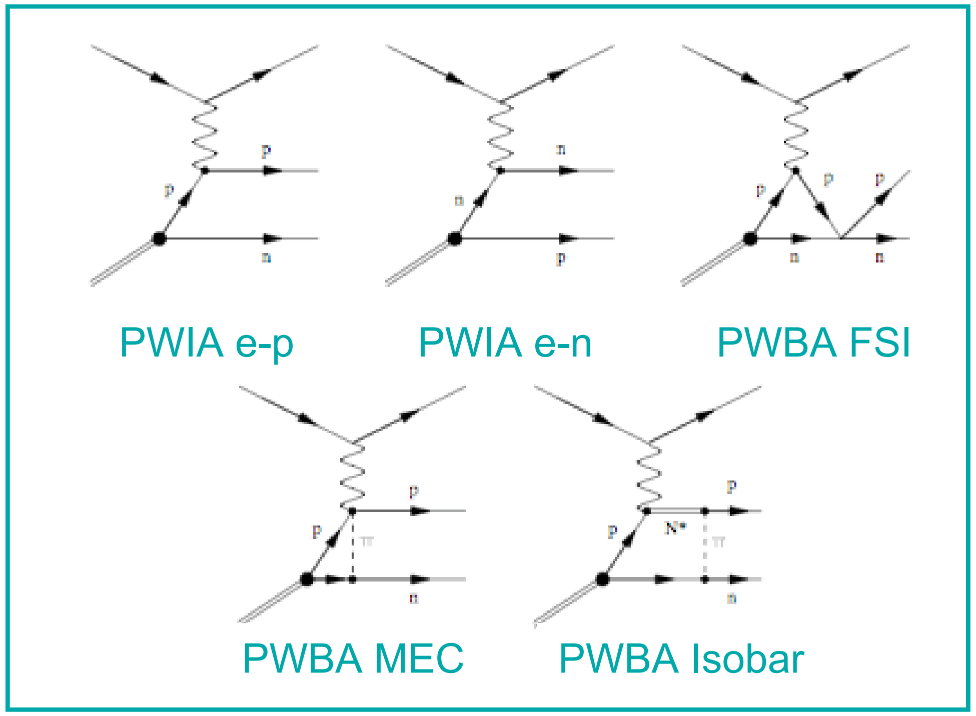
$A_d^T = 0$ for S state

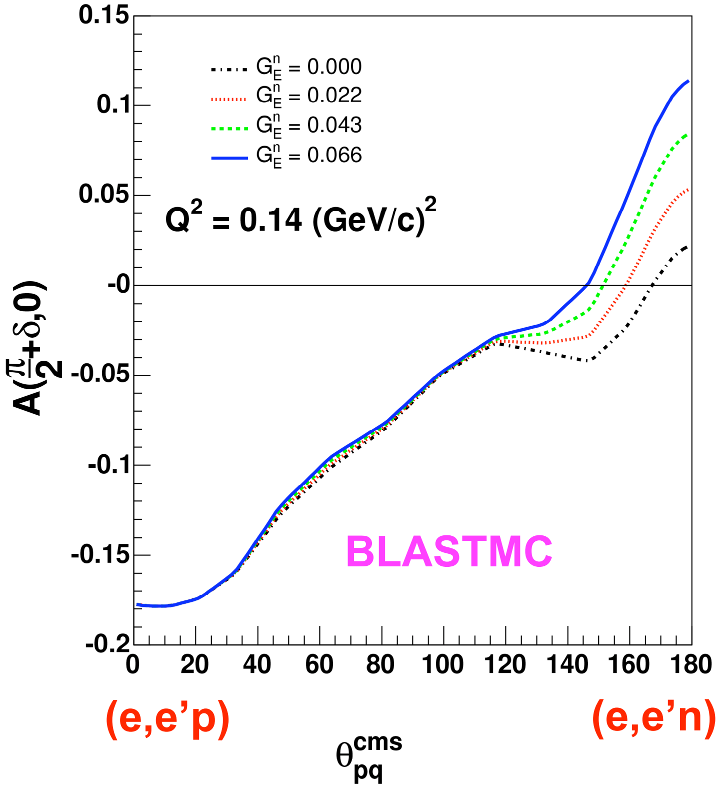
Extracting G^n_E from A^V_{ed}

$$A^V_{ed} = \frac{a {G^n_M}^2 \cos\theta^* + b G^n_E G^n_M \sin\theta^* \cos\phi^*}{c {G^n_E}^2 + {G^n_M}^2} \approx a \cos\theta^* + b \frac{G^n_E}{G^n_M} \sin\theta^* \cos\phi^*$$

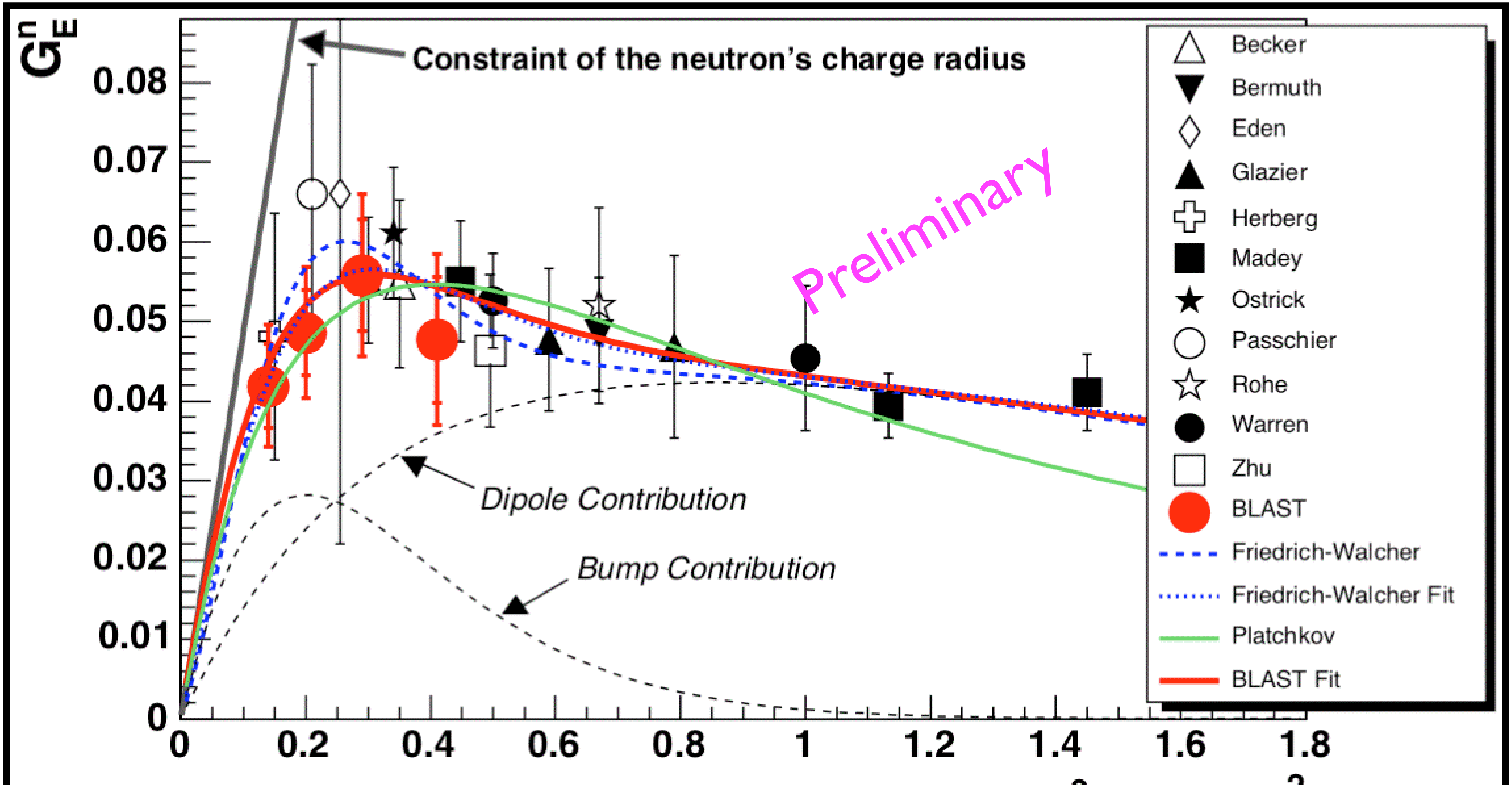
Beam-Target vector asymmetry gives G^n_E assuming G^n_M known

- full Monte Carlo simulation
- deuteron electro-disintegration by H. Arenhovel
- account for FSI, RC, IC, MEC
- "spin-perpendicular" kinematics shows largest effect



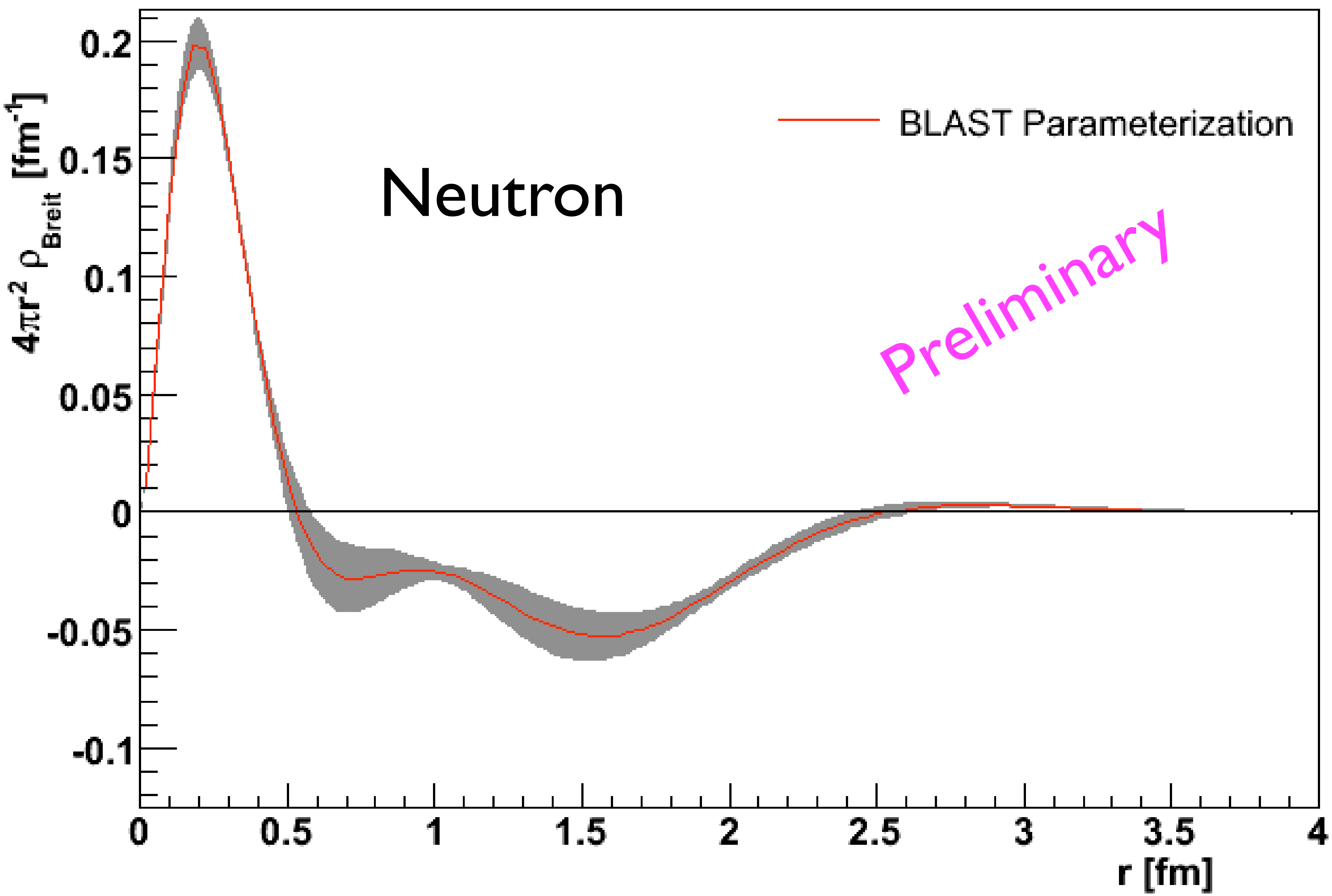


G^n_E from BLAST

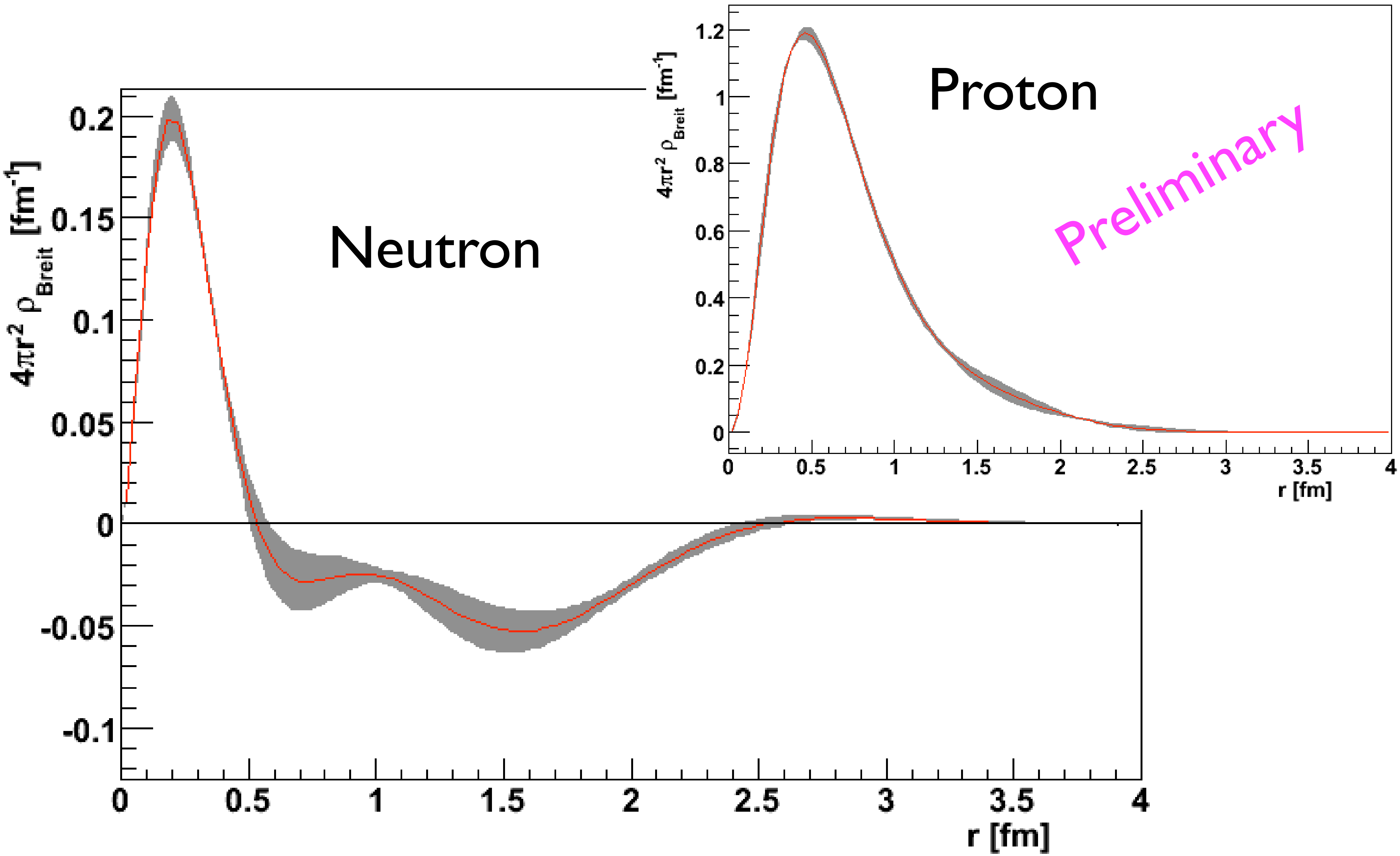


Ph.D. Thesis V. Ziskin and E. Geis

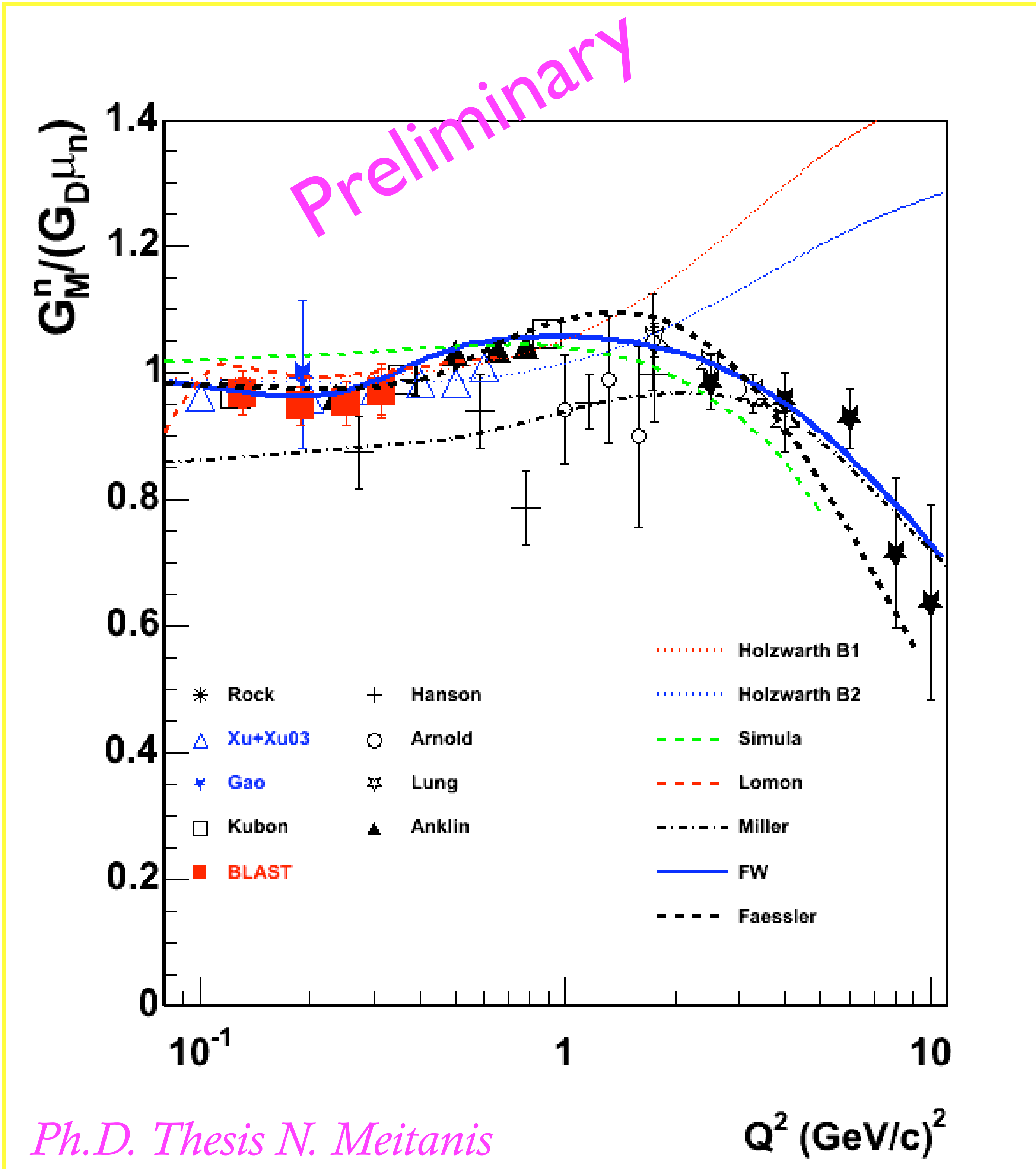
Charge Densities



Charge Densities



G^n_M from Inclusive Scattering



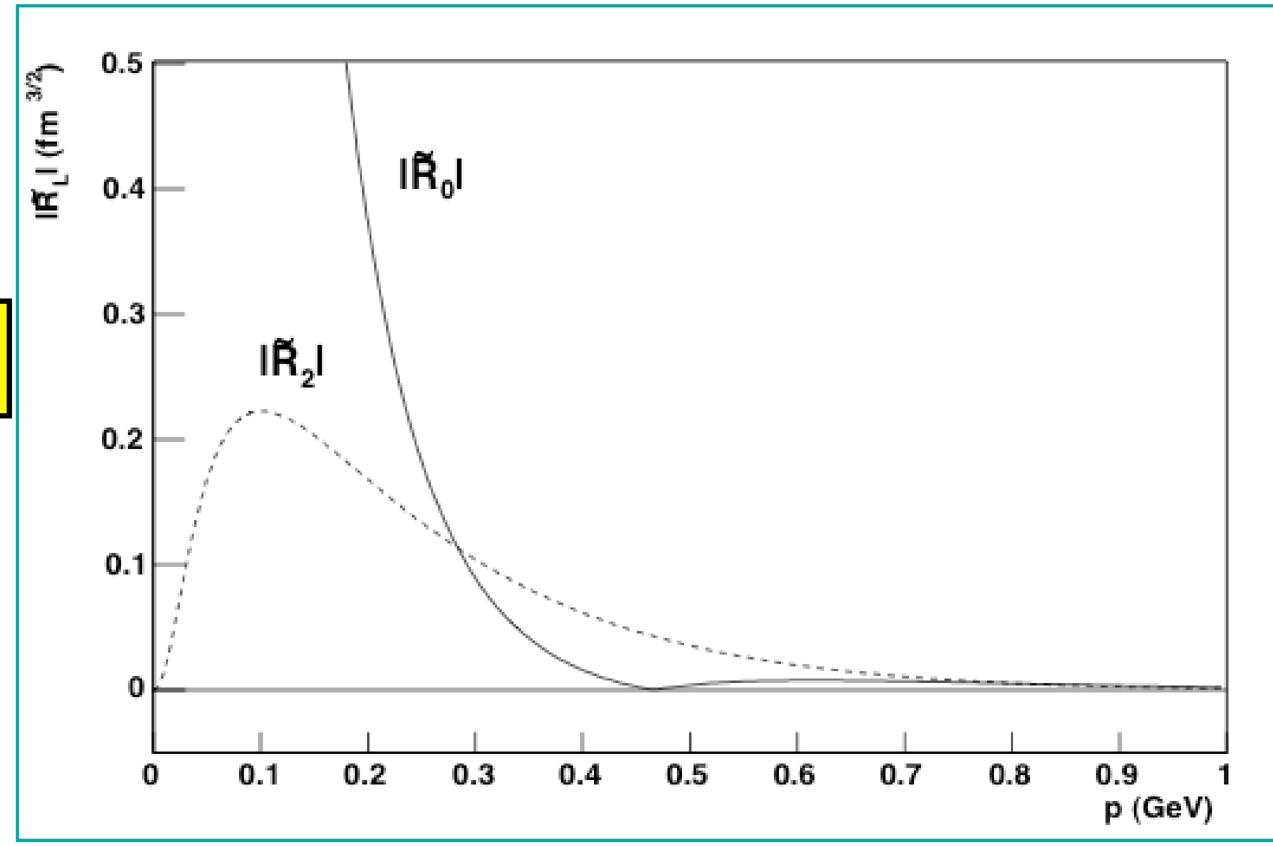
Deuteron Wavefunction

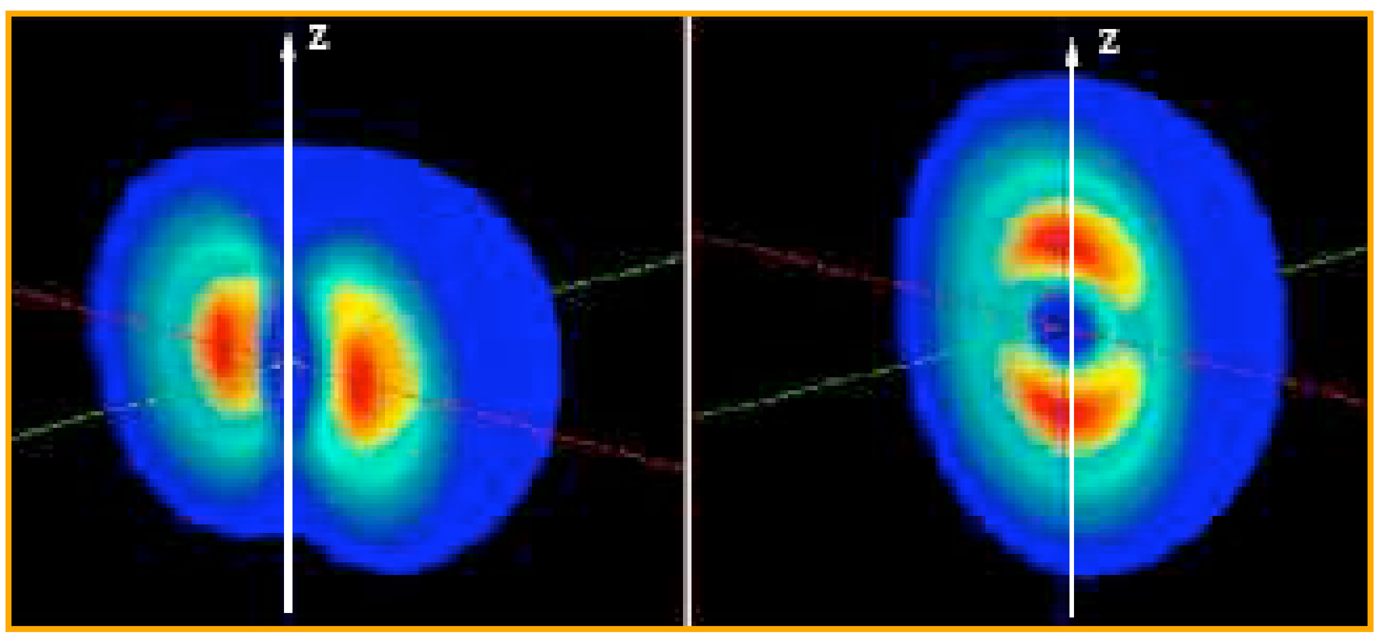
Deuteron wavefunction:

- L=0, 2 admixture

$$\psi^{m_d}(\vec{r}) = R_0(r)Y_{110}^{m_d}(\Omega_r) + R_2(r)Y_{112}^{m_d}(\Omega_r)$$

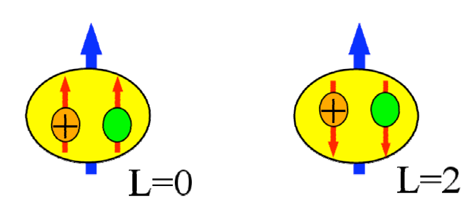
- S state minimum at p ~ 0.45 GeV
- D state significant at p > 0.3 GeV



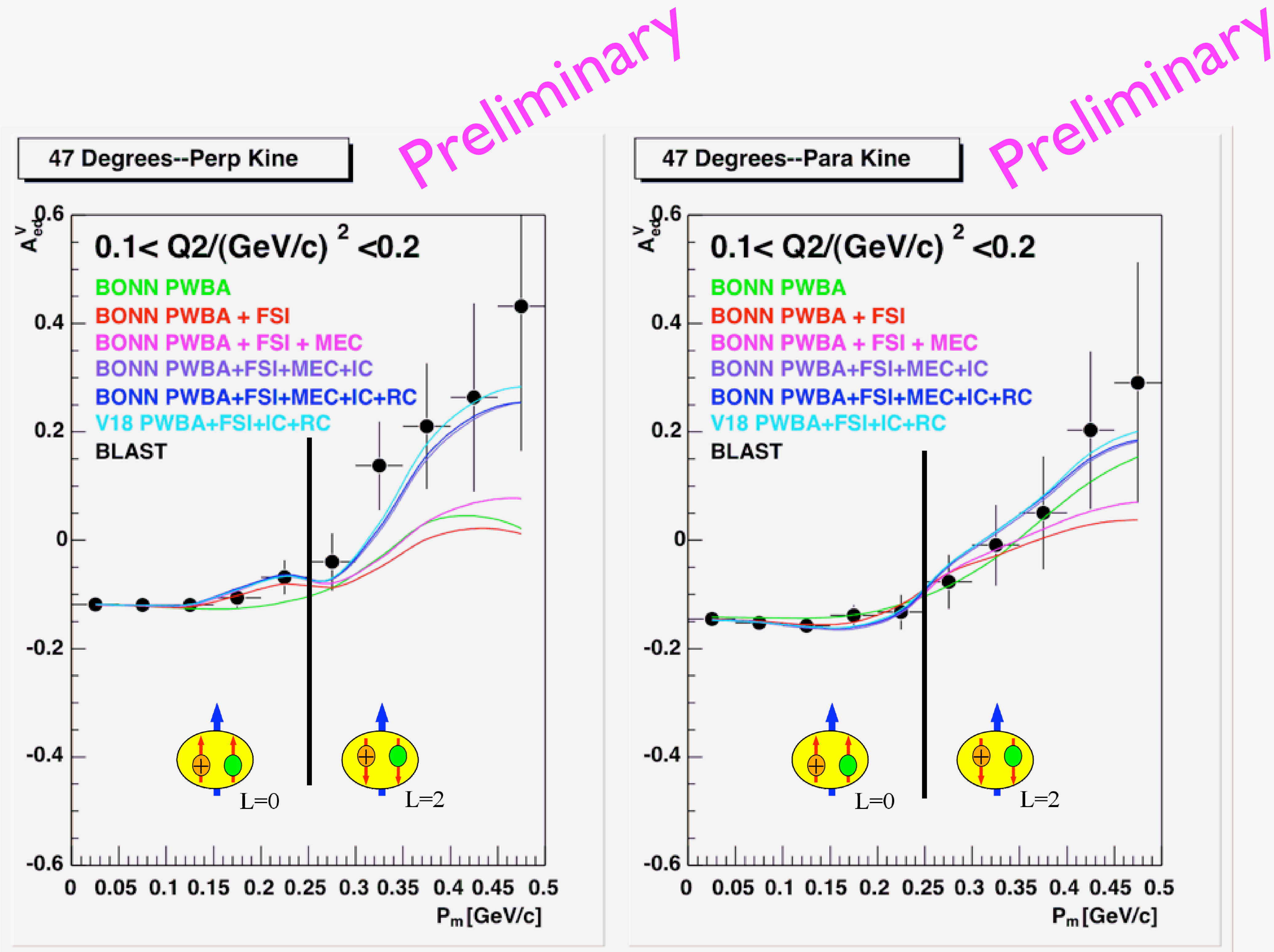


D state normally 4-6 %

- but beyond 0.3 GeV dominant
- provides a regime to study tensor force
- in D state nucleon spins flip

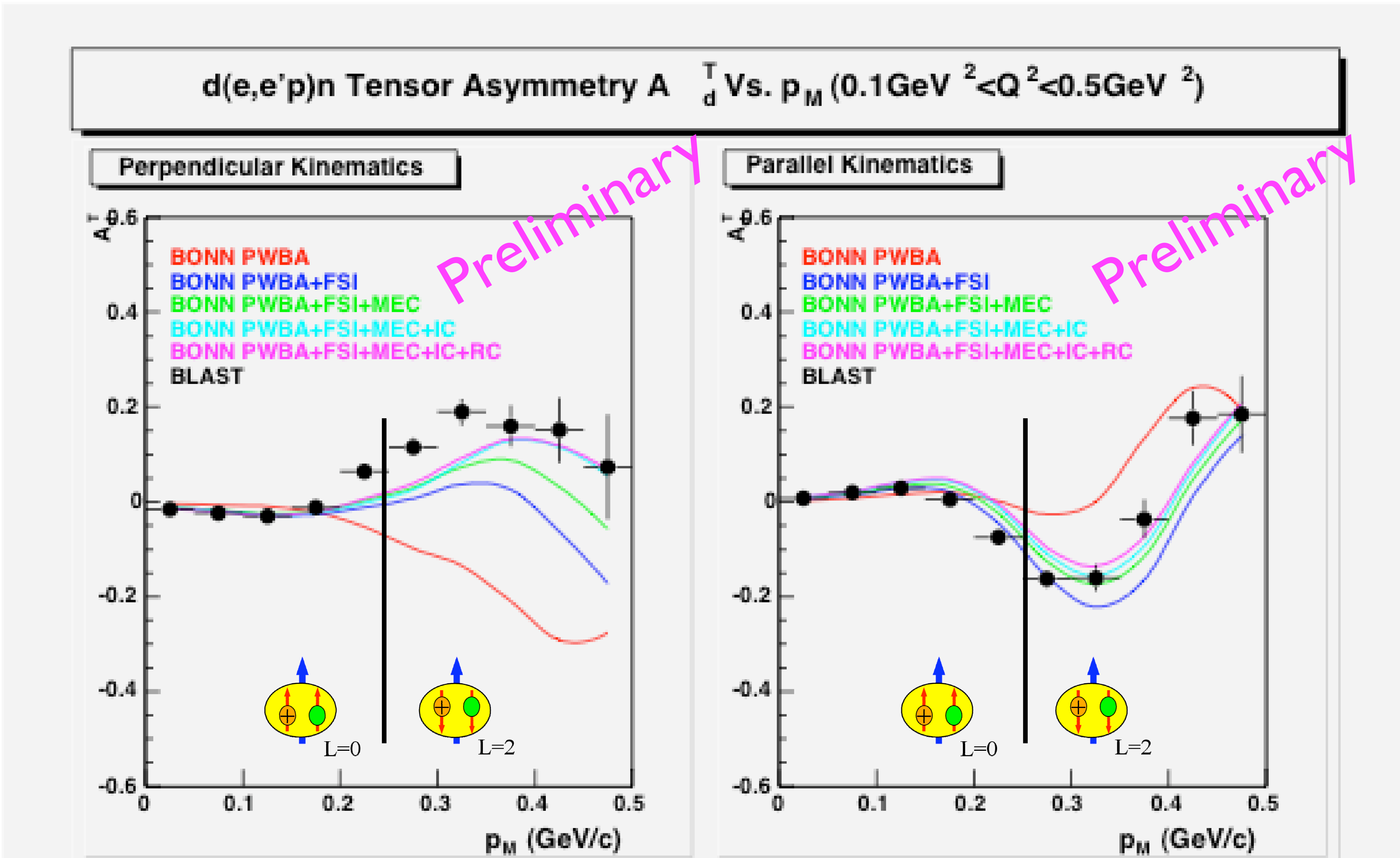


Quasi-Elastic e′p Scattering from Deuterium



Ph.D. Thesis A. DeGrush

Quasi-Elastic e′p Scattering from Deuterium



Ph.D. Thesis A. Maschinot

BLAST Collaboration