Studying the Nucleon Structure with Spin

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:

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

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

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

- traditionally measure using Rosenbluth technique

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

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

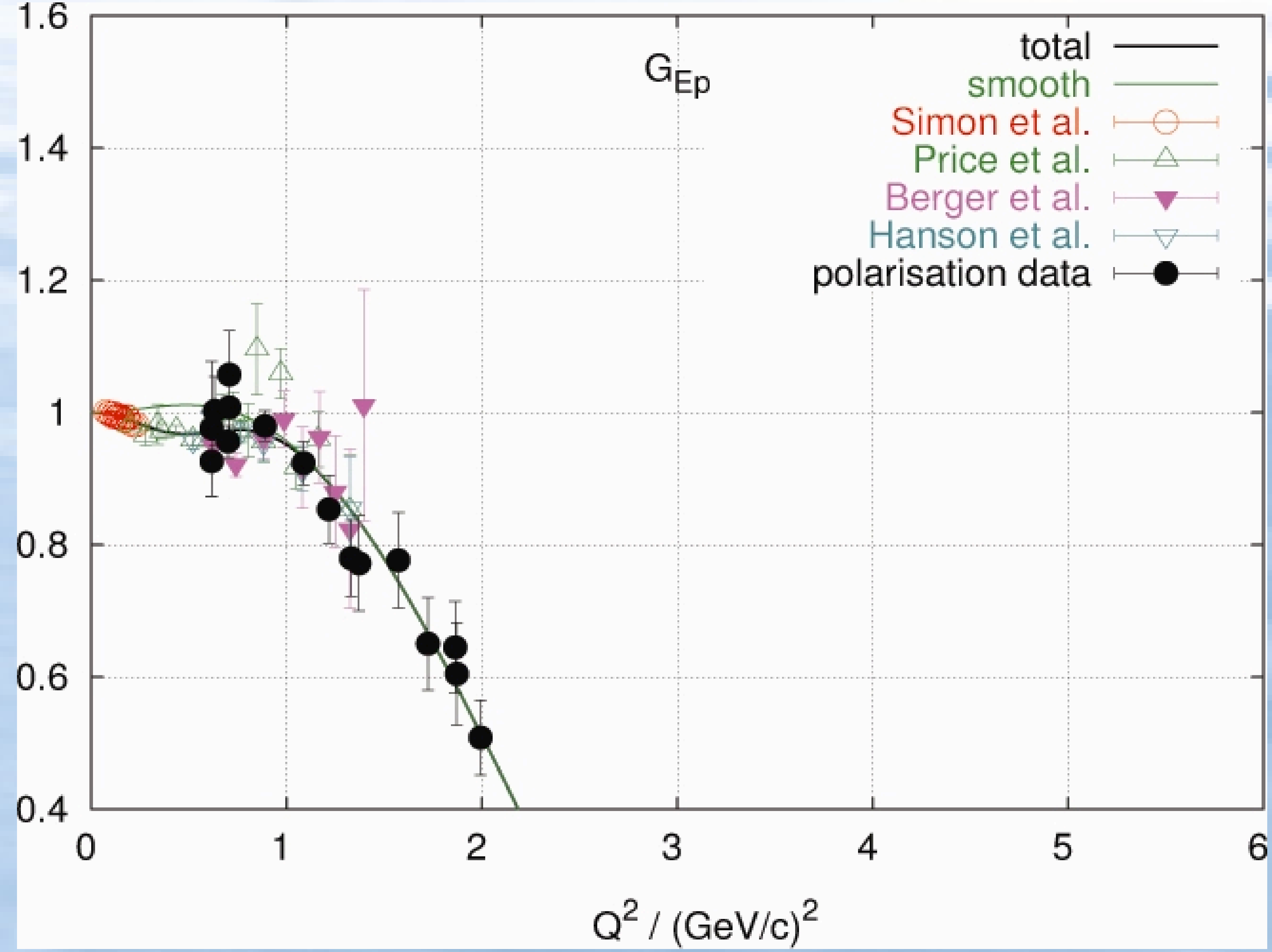
But dipole not perfect, does not describe details Q^2<1 (GeV/c)^2

Friedrich and Walcher have proposed a new parameterisation:

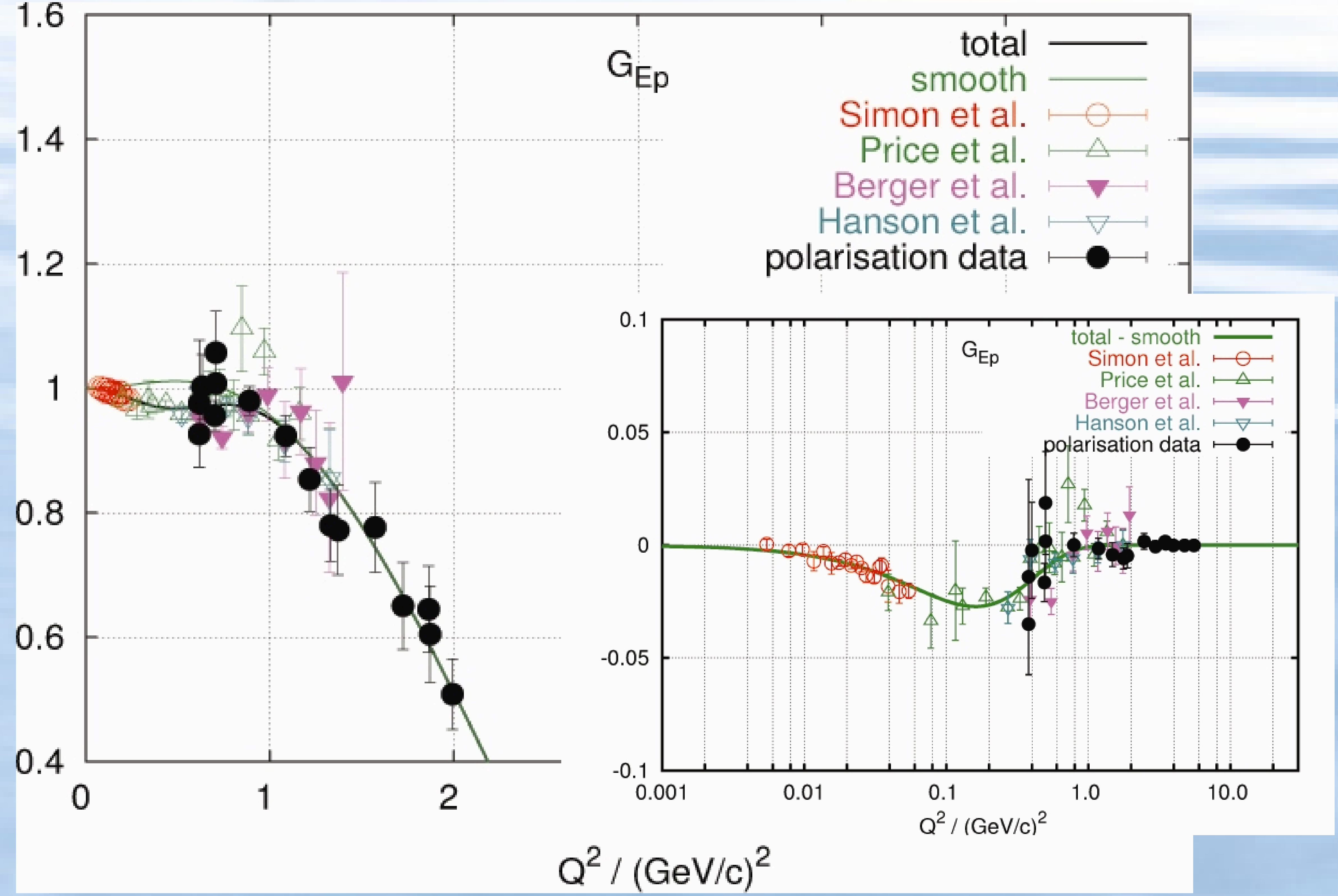
$$\boxed{G^N(Q^2) = G_S^N(Q^2) + \alpha_B Q^2 G_B^N(Q^2)}$$

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

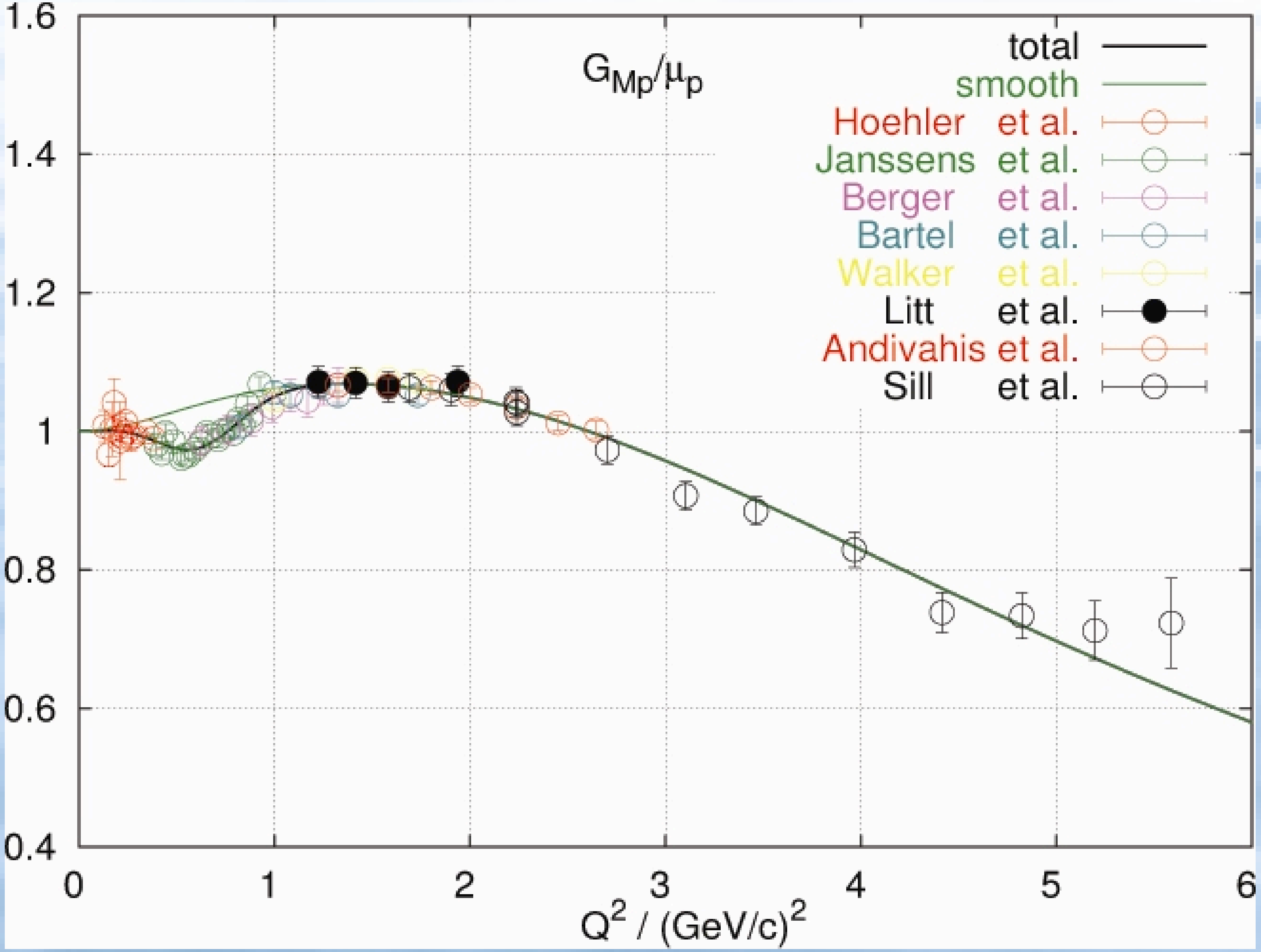
Friedrich and Walcher Fit to G^p_E



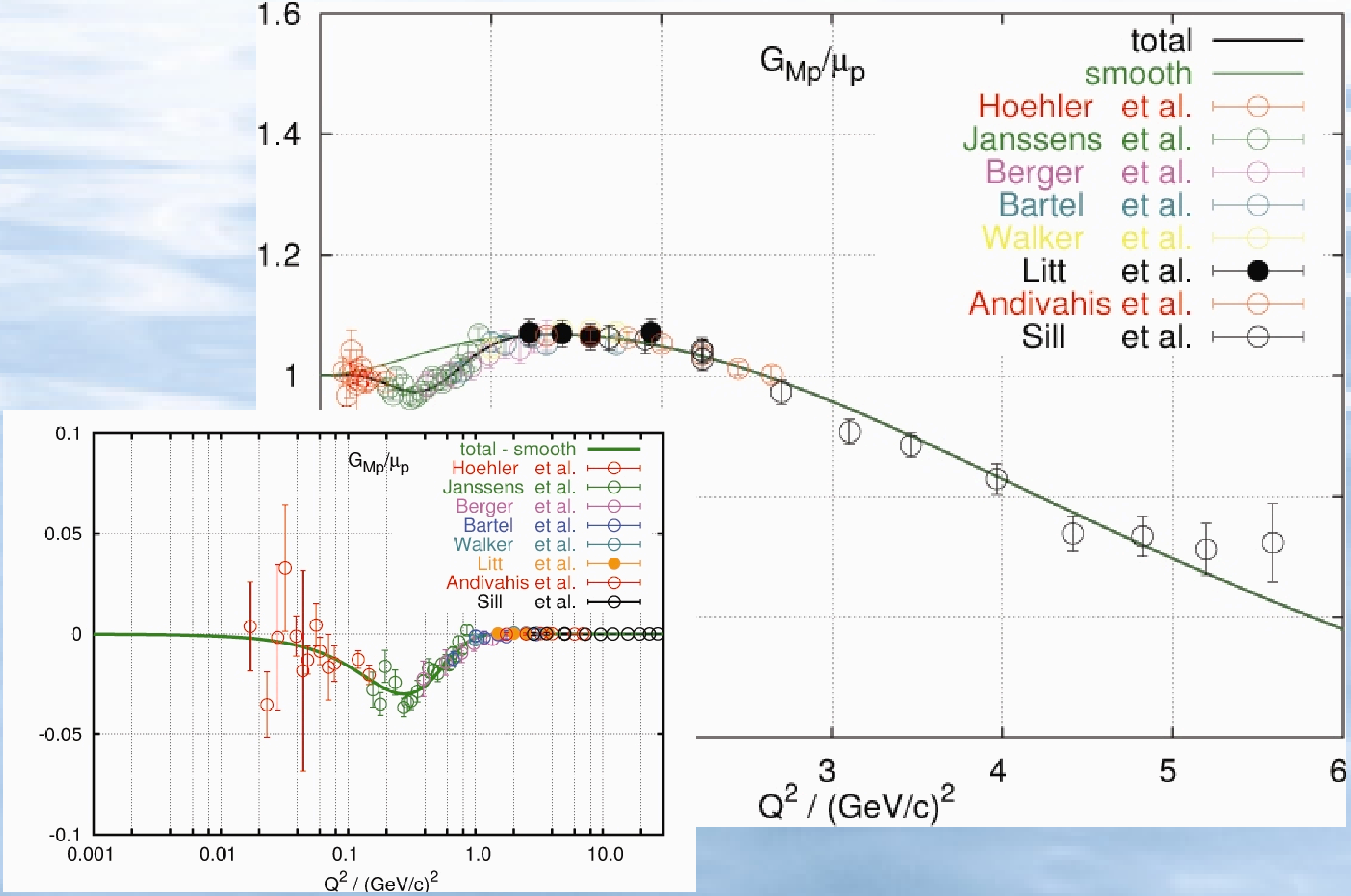
Friedrich and Walcher Fit to G^p_E



Friedrich and Walcher Fit to G^p_M



Friedrich and Walcher Fit to G^p_M



Discrepancy in Ratio $\mu_p G^p_E / G^p_M$

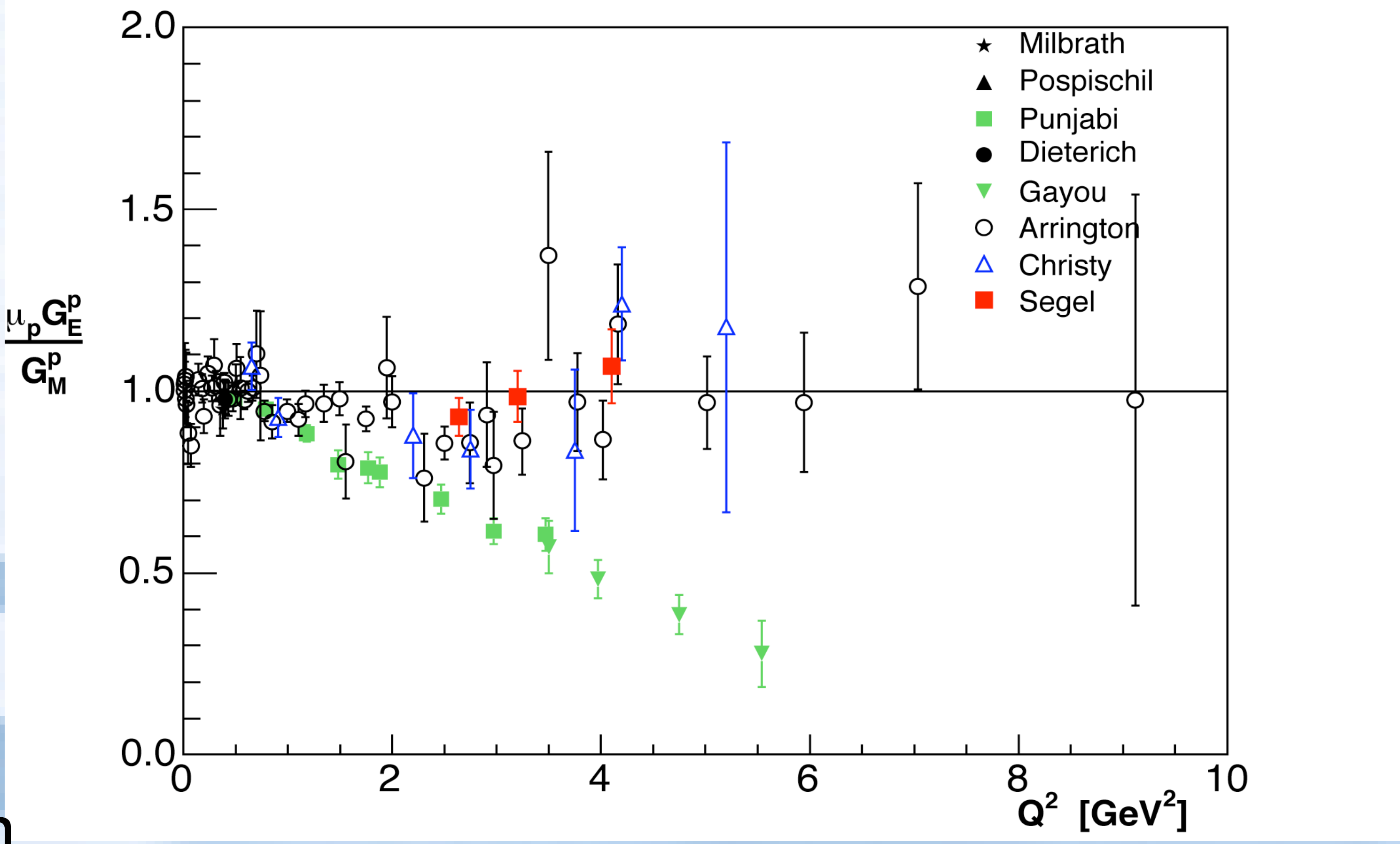
But details of bump not only interesting topic with nucleon form factors.

Recent results from JLAB

- polarisation transfer measurements disagree with Rosenbluth separation

Possible explanation by two photon effects

- calls into question present interpretation of data and understanding of nucleon form factors
- requires a re-interpretation of all Rosenbluth data
- more later



Bates Large Acceptance Spectrometer Toroid

Systematic study of spin-dependent electromagnetic interaction

Longitudinally polarised electrons MIT-Bates storage ring

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

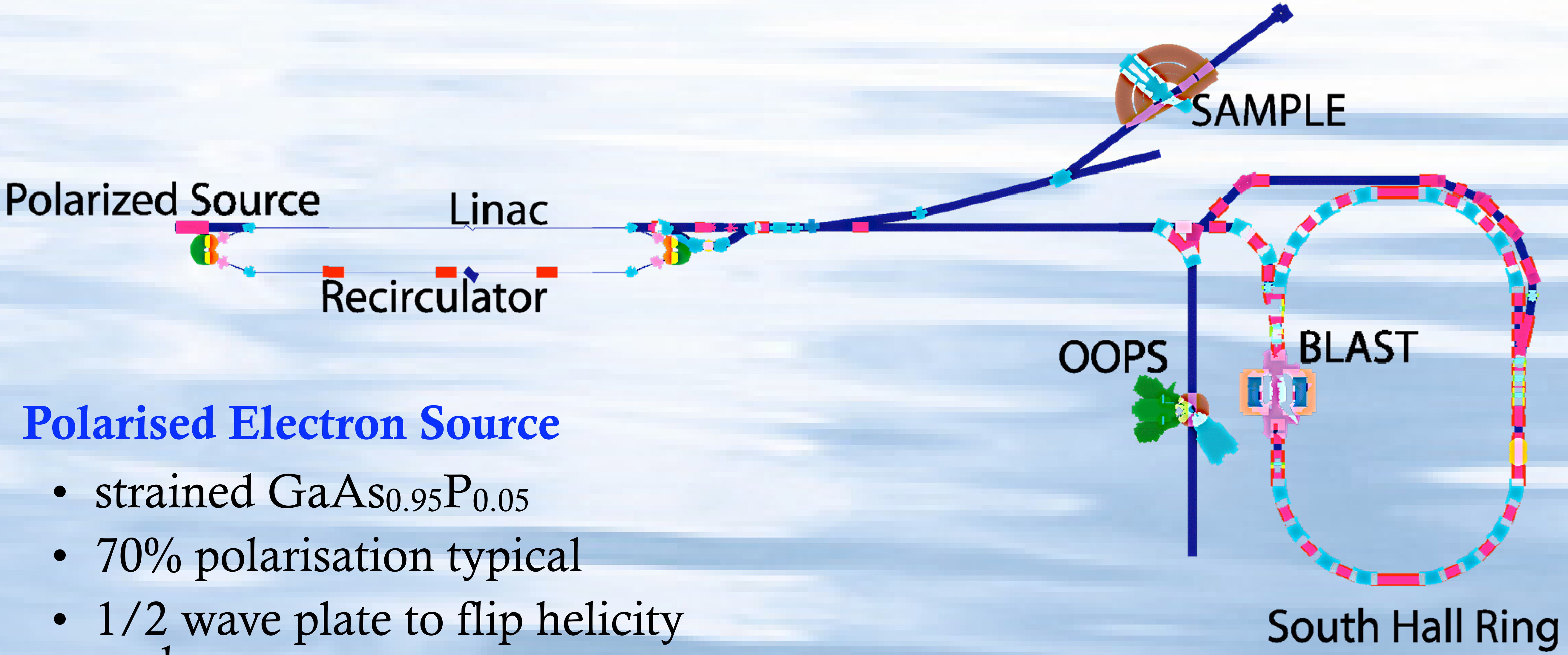
Highly polarised, internal gas target of isotopically pure H or D

- 6×10^{13} atoms/cm^2, 80% polarisation (typical)

Symmetric, large acceptance, general purpose detector

- 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

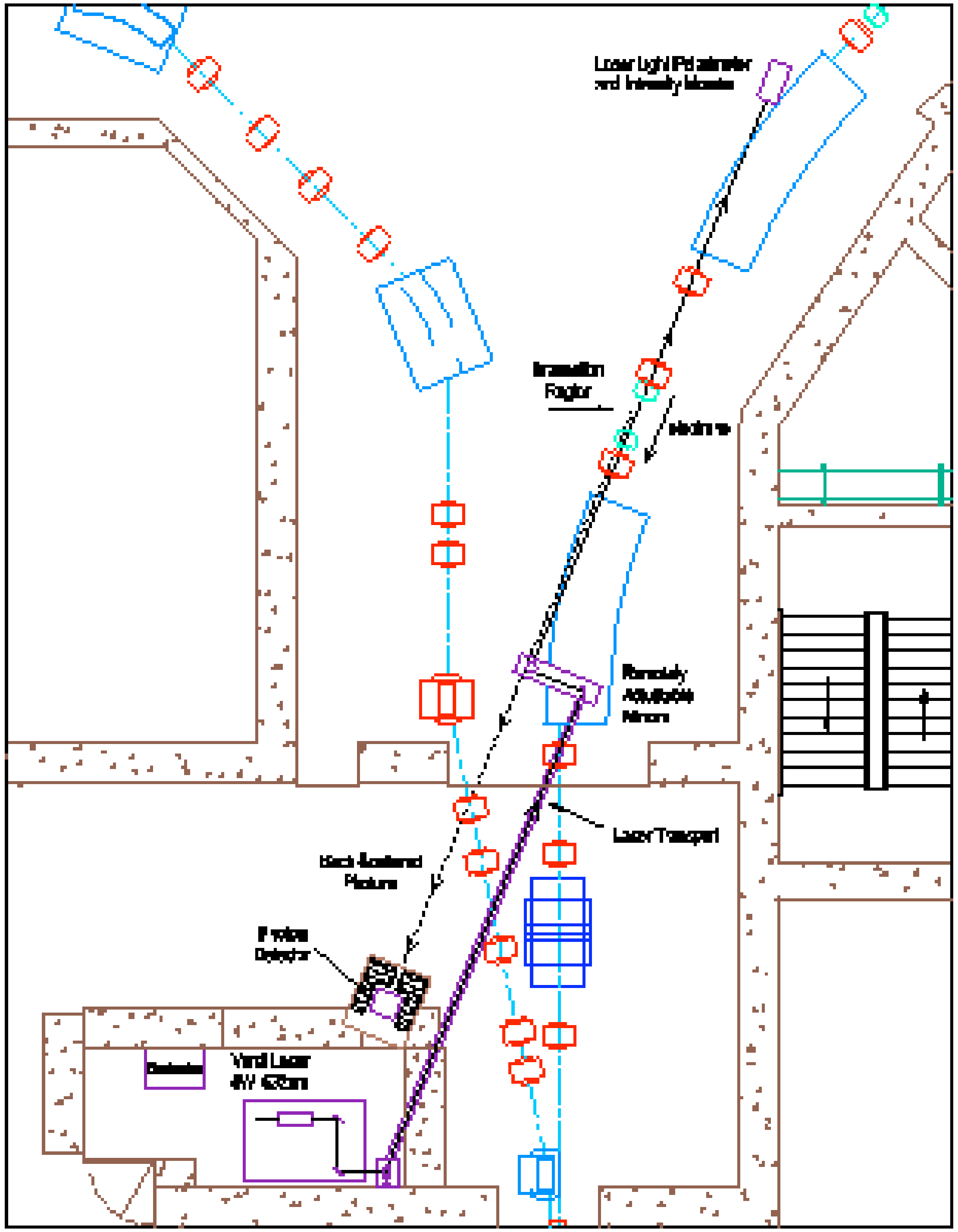
North and South Expt. Halls

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

South Hall Ring

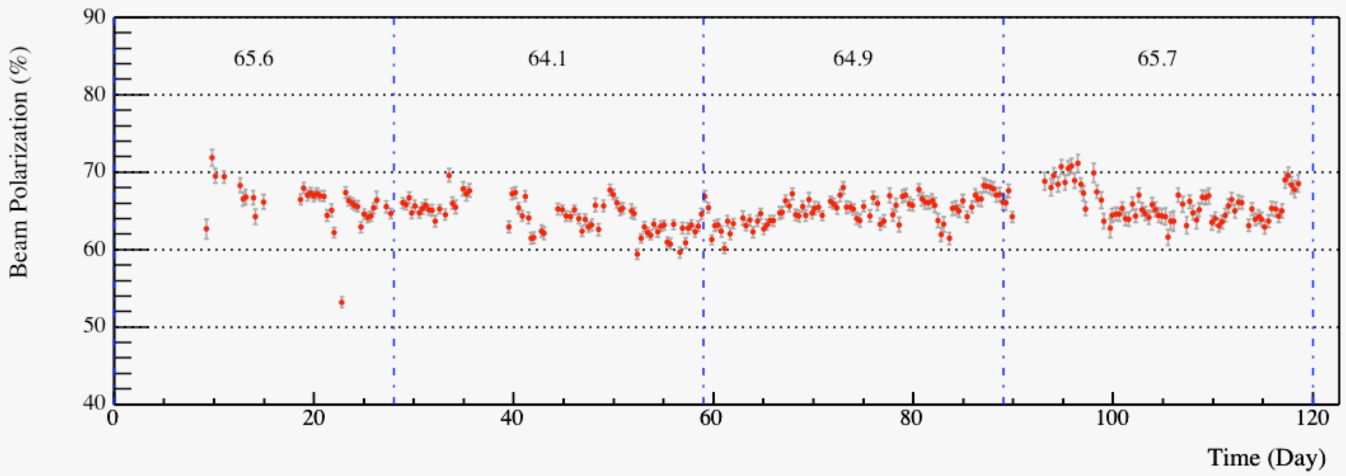
- stack to 225 mA typical
- 30 minute lifetime
- 65 % polarisation typical
- Siberian snake maintains longitudinal spin at target

Compton Polarimeter

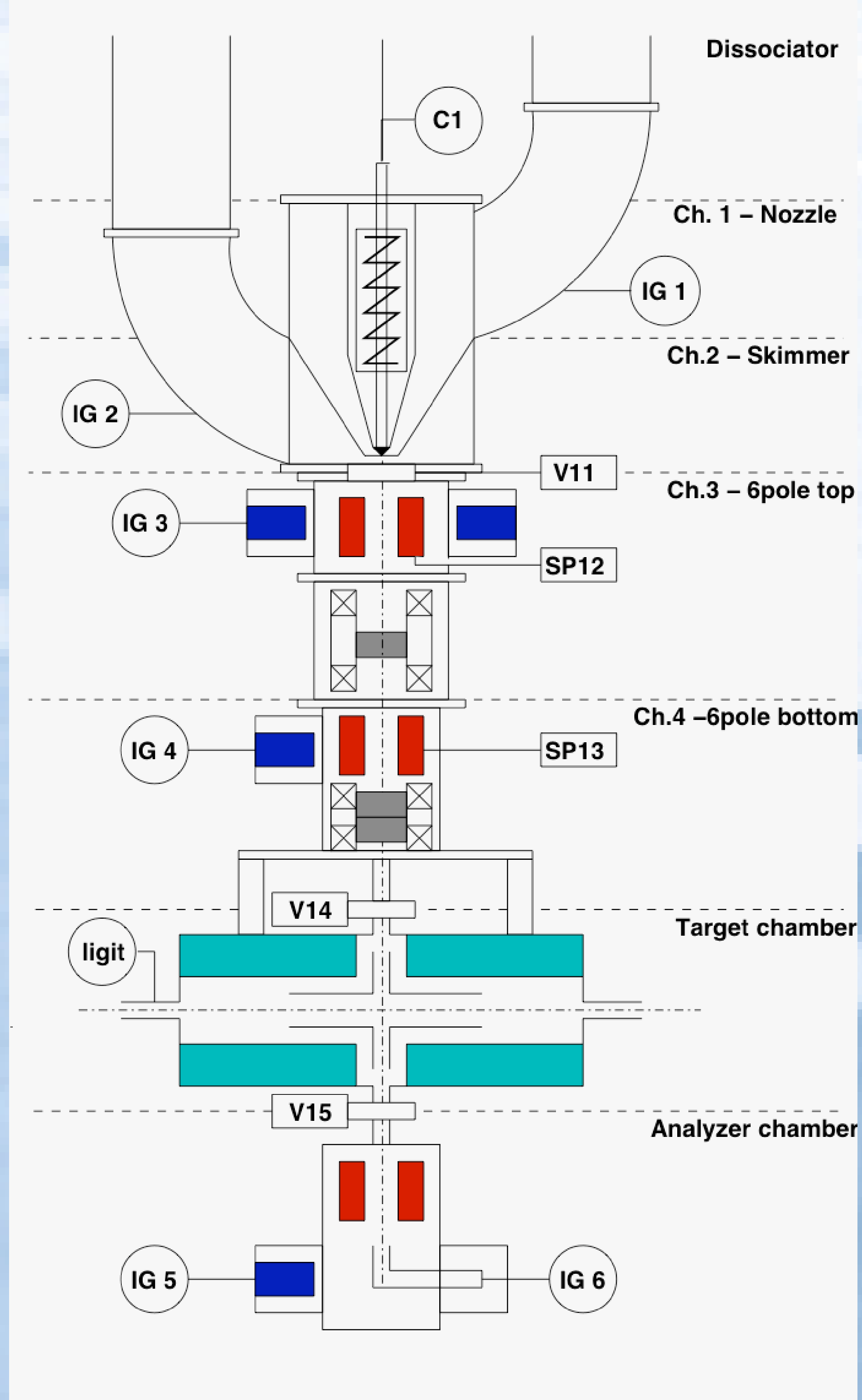


Monitor beam polarisation in ring

- 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%



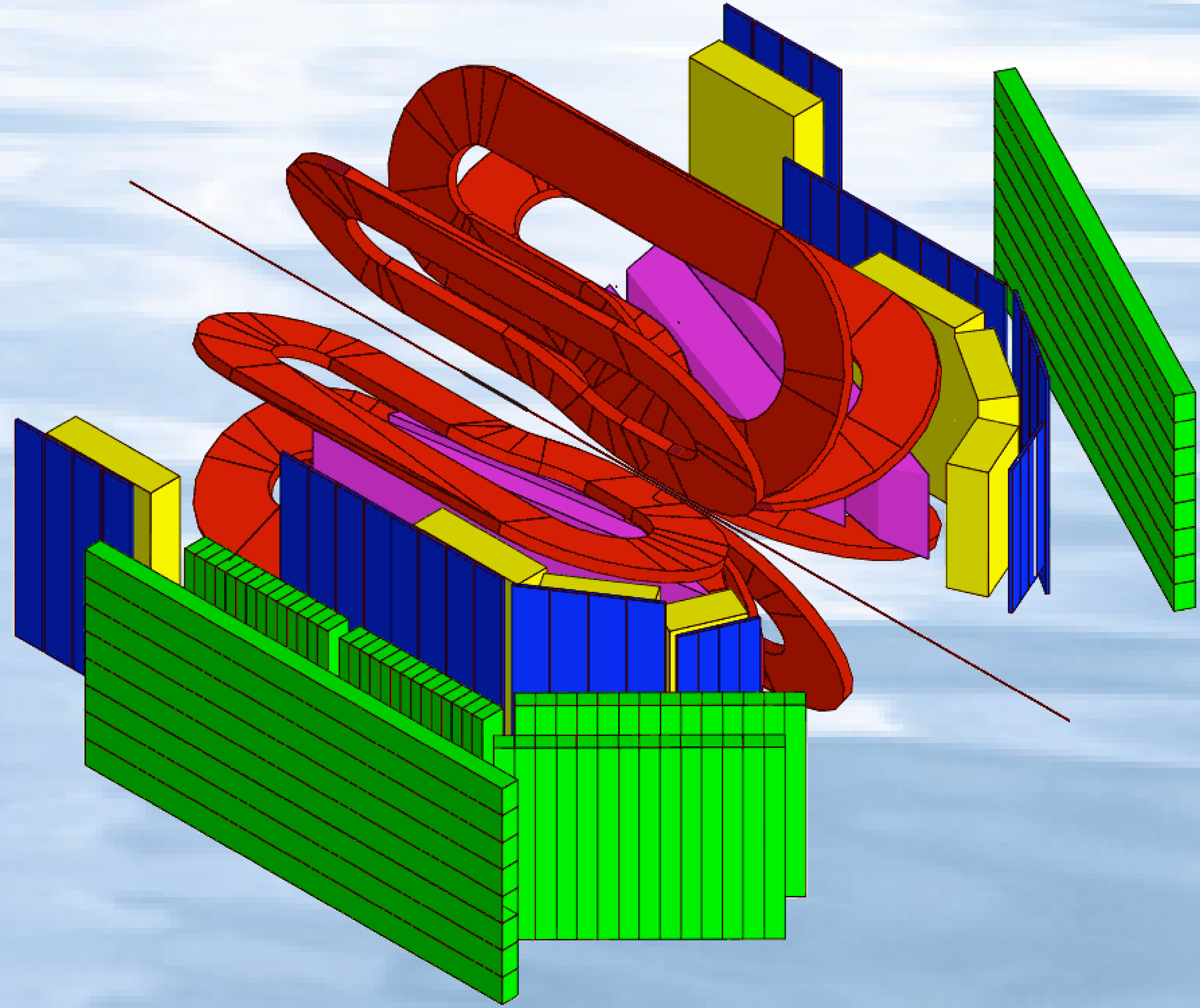
Internal, Polarised Gas Target



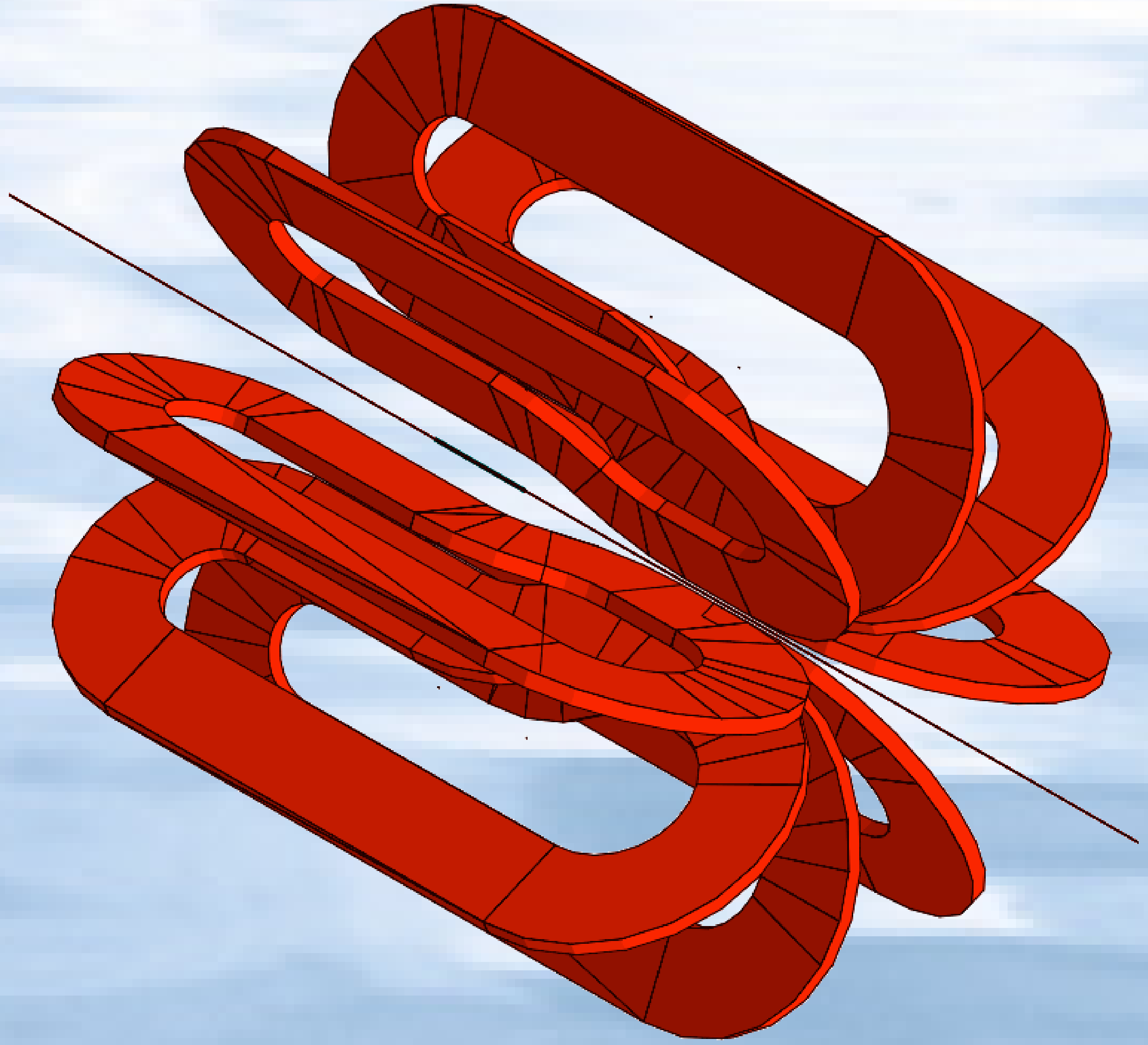
Atomic Beam Source

- 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

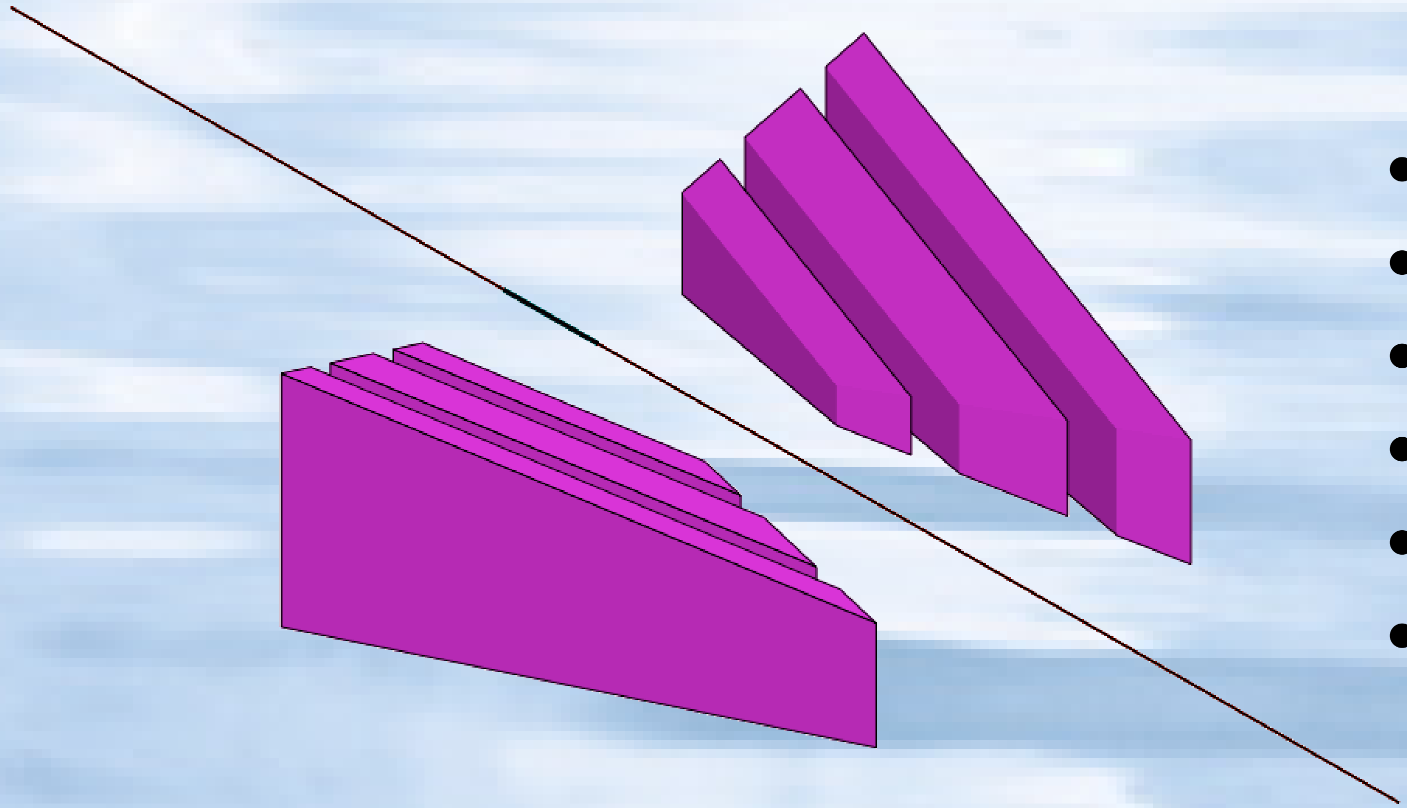


BLAST Detector



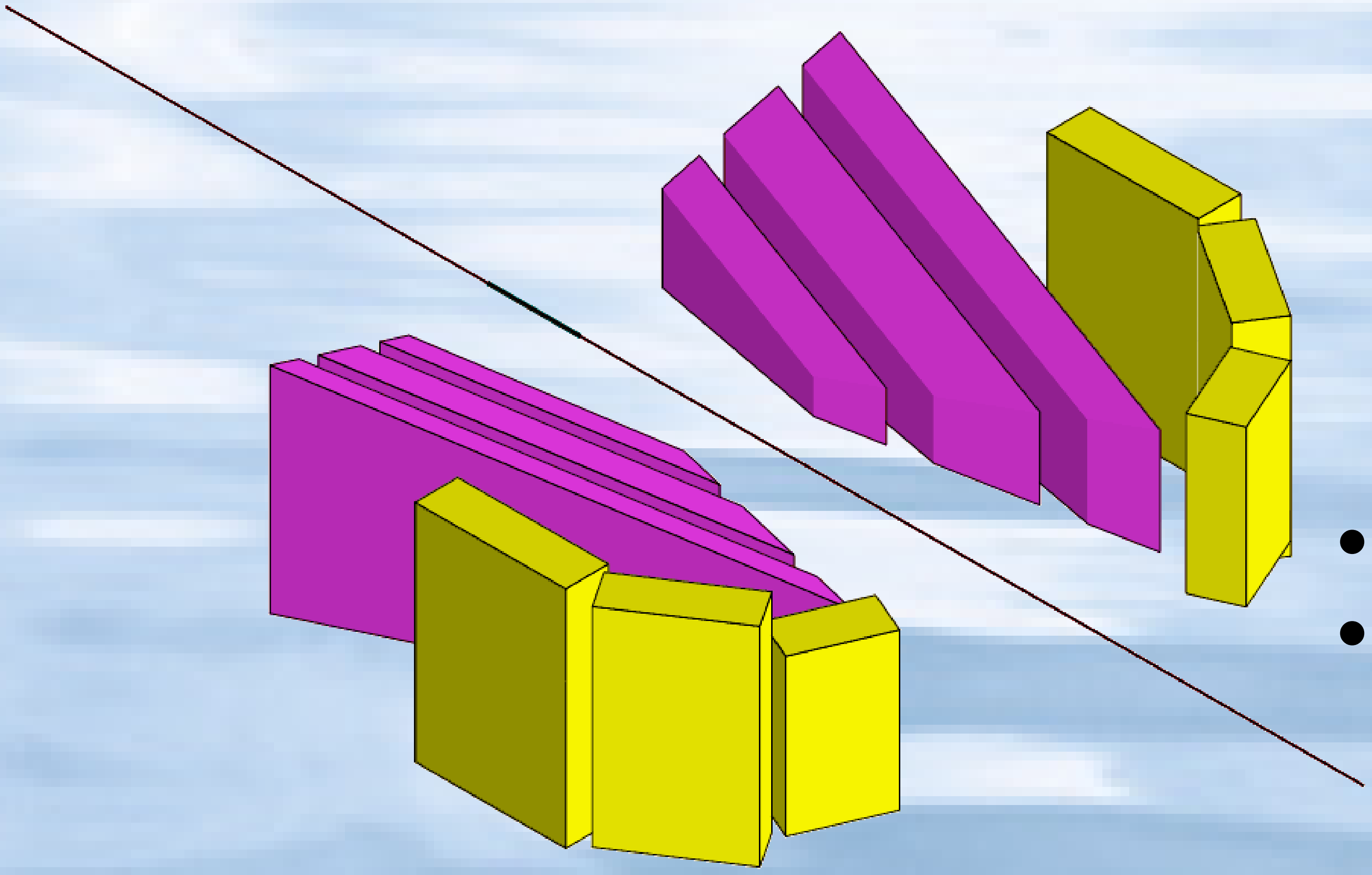
- 8 sector toroid magnet
  - minimise effect on beam and target polarisation
- 3.8 kG maximum field
- two horizontal sectors instrumented

BLAST Detector



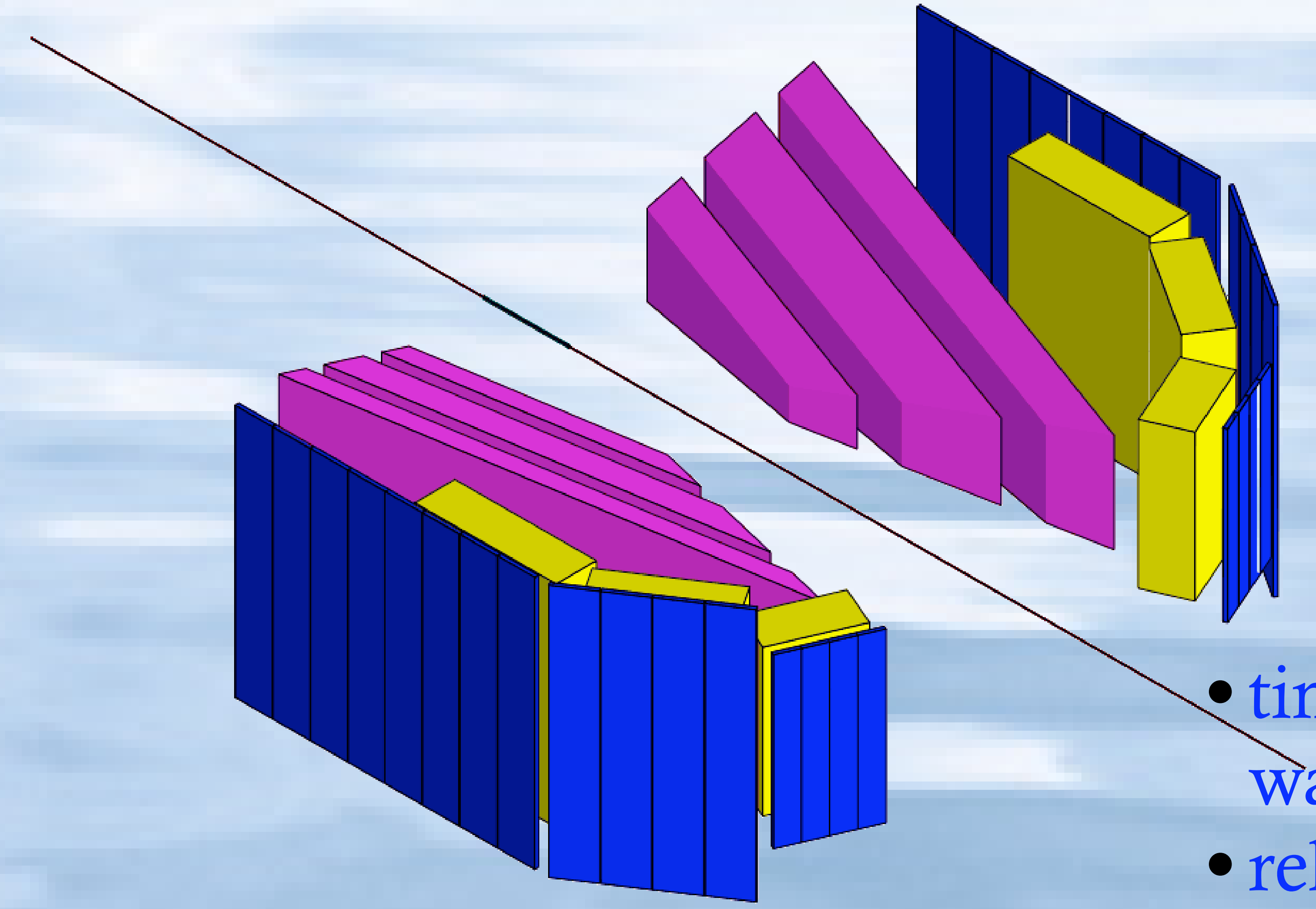
- 3 wire chambers / sector
  - single gas volume
- 2 superlayers / chamber
  - +/- 10° stereo
- 3 sense layers / superlayer
- total 18 layers of tracking
- momentum analysis
- scattering angles
- event vertex
- particle charge

BLAST Detector



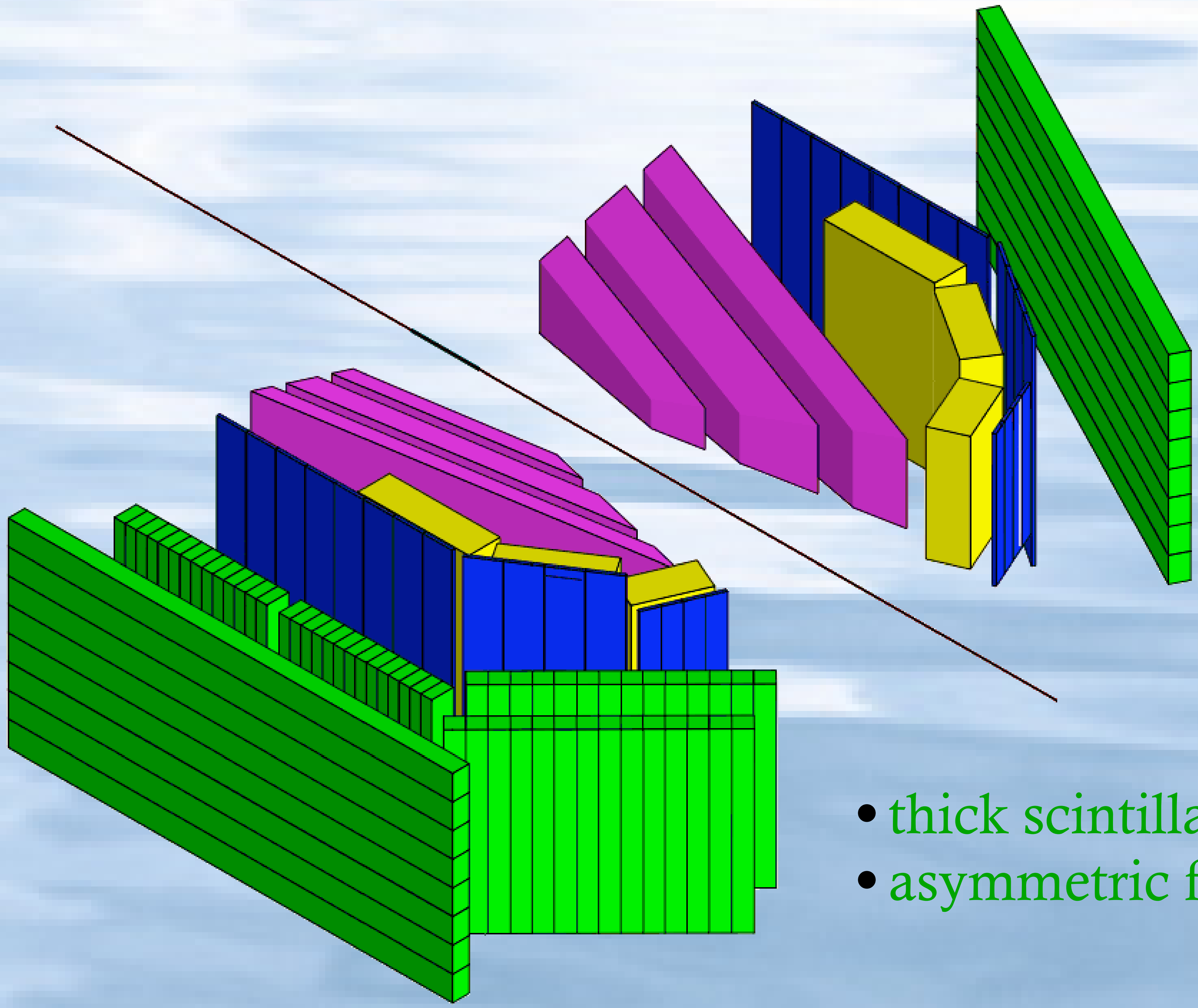
- Aerogel Cerenkov
- pion / electron separation

BLAST Detector



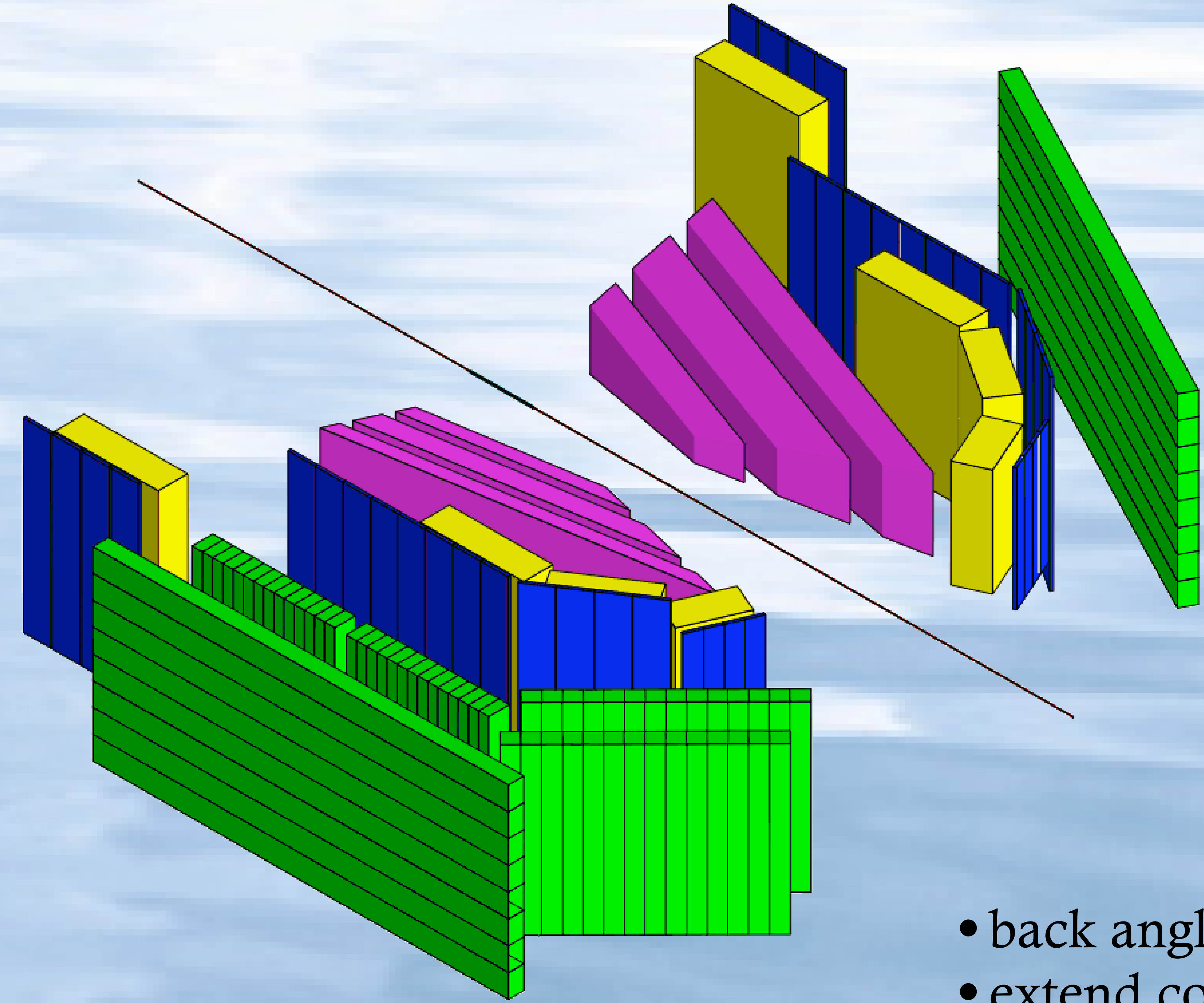
- time of flight scintillator walls
- relative timing
- trigger timing

BLAST Detector



- thick scintillators for neutron detector
- asymmetric favouring right sector

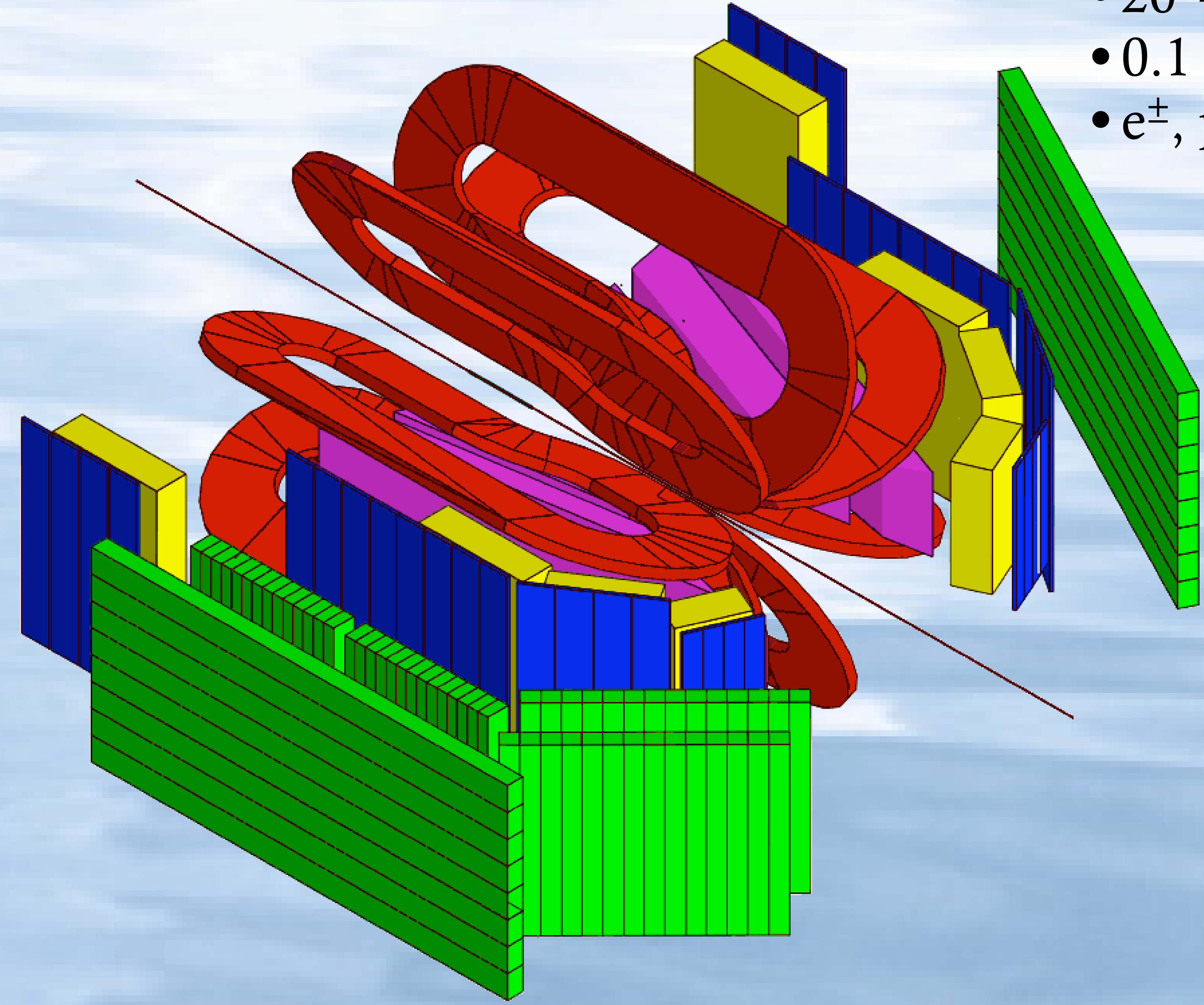
BLAST Detector



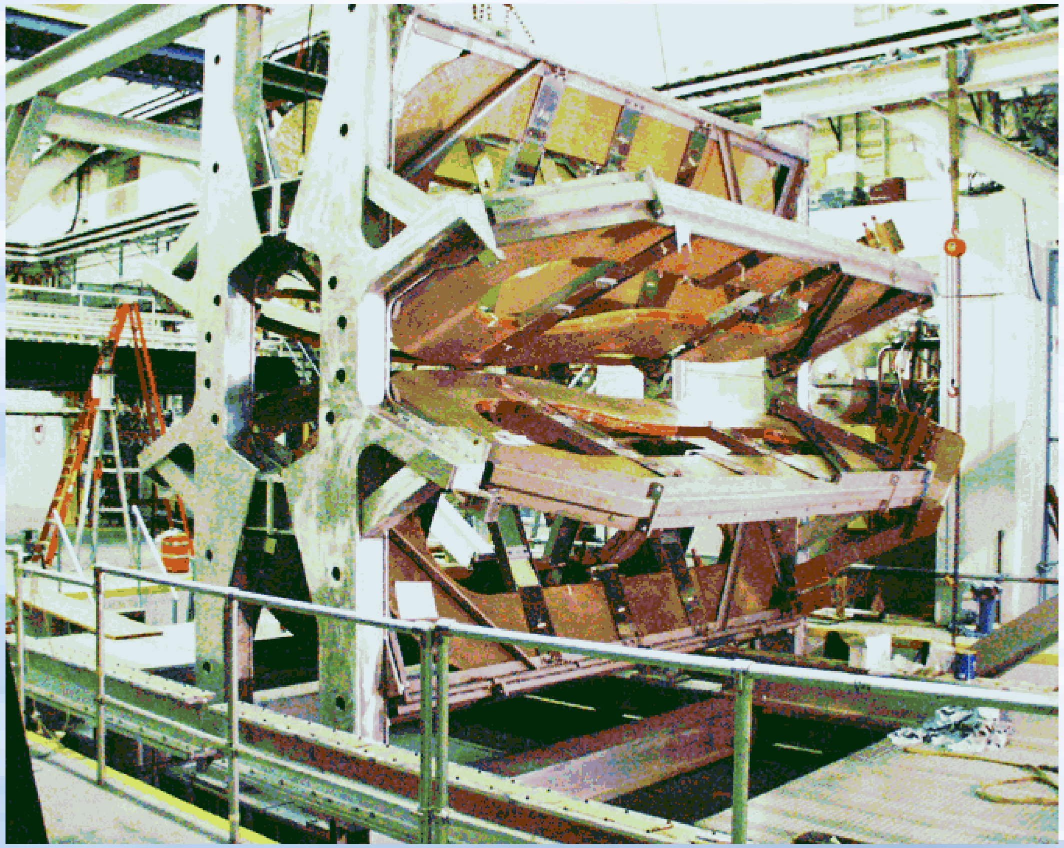
- back angle detectors
- extend coverage, no tracking

BLAST Detector

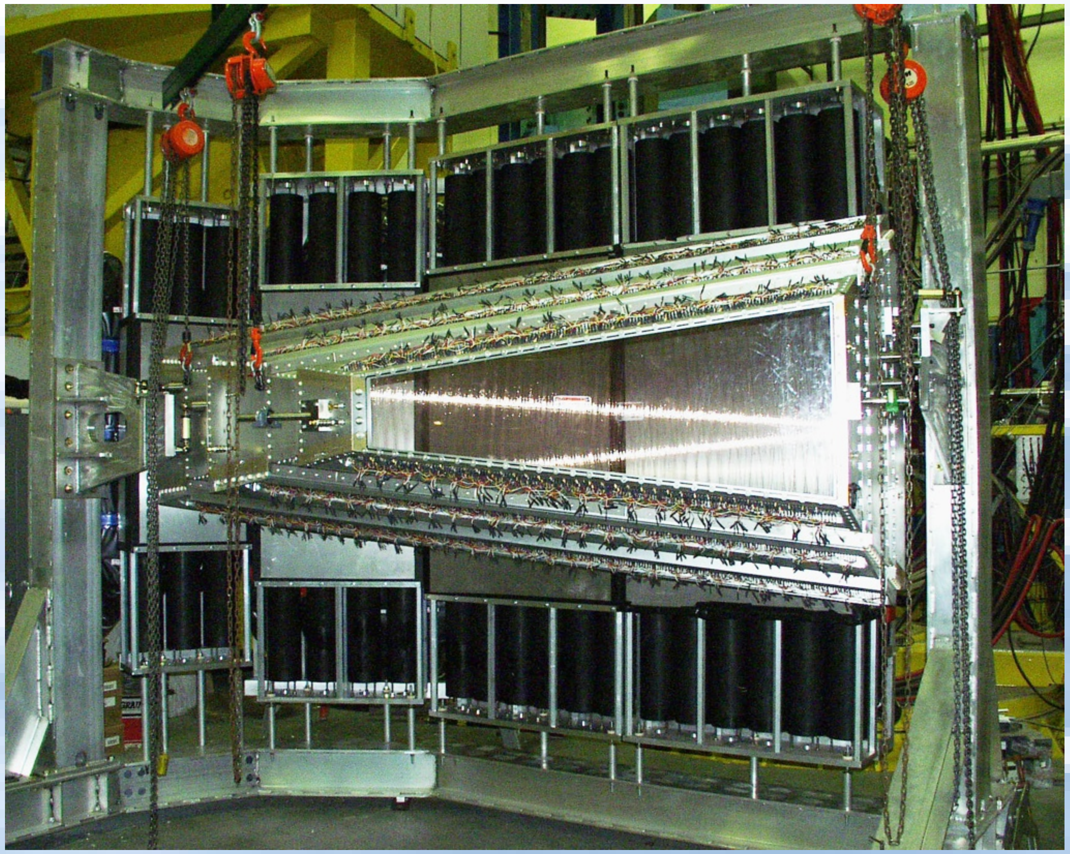
- left-right symmetric
- 20°- 80° θ, ±15° φ
- $0.1 < Q^2 < 0.8\ (\mathrm{GeV}/c)^2$
- $e^{\pm}$, p, n, d, $\pi^{\pm}$



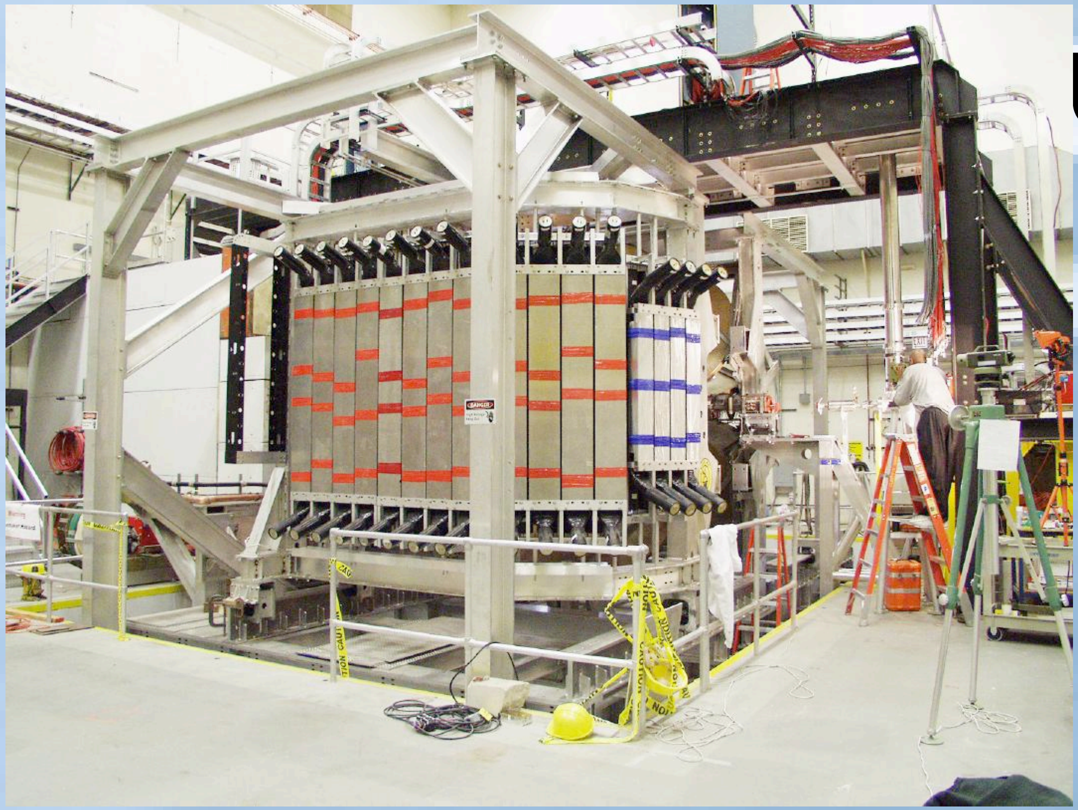
BLAST Detector Components



Bates



MIT



UNH

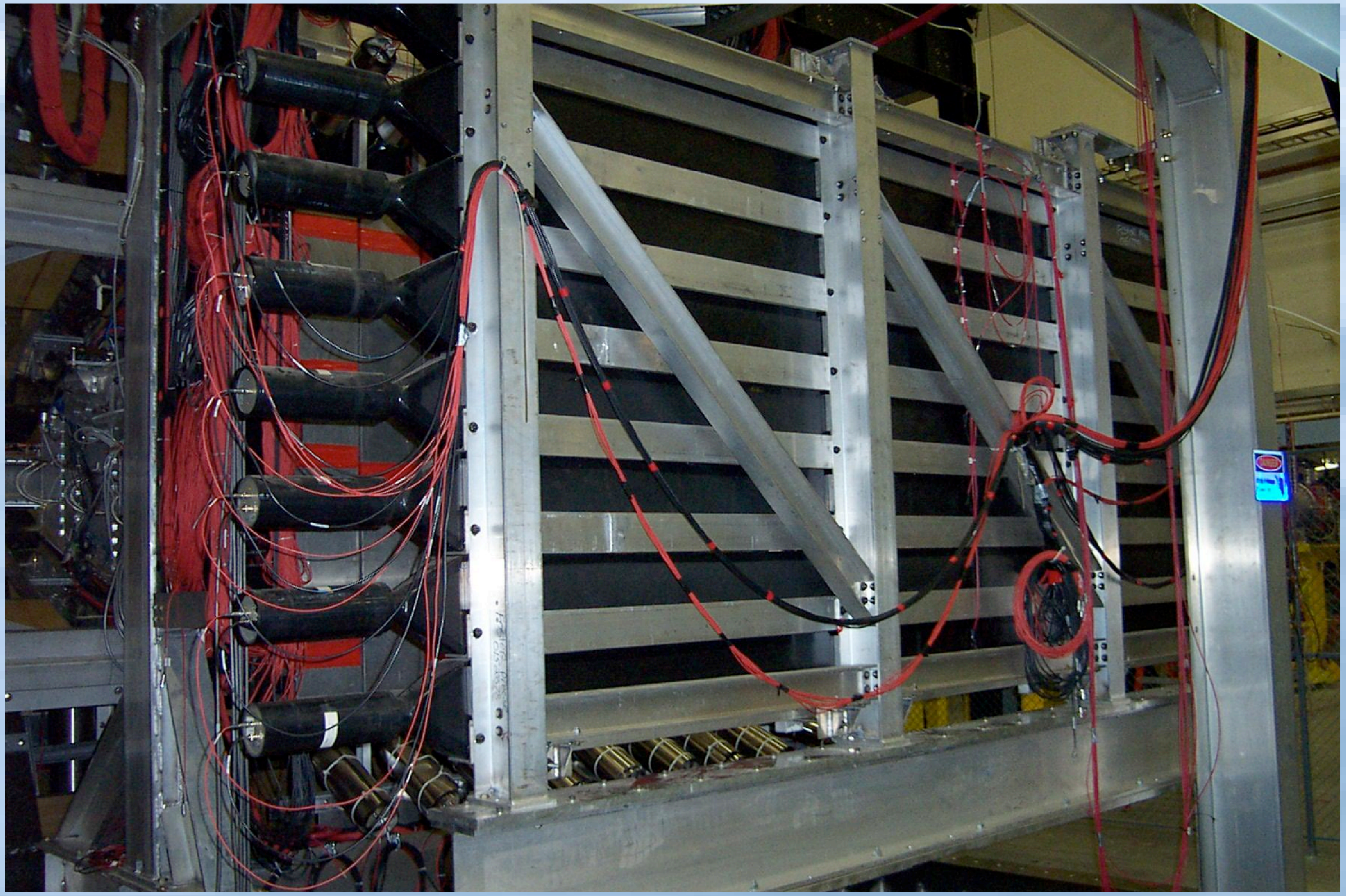
ASU

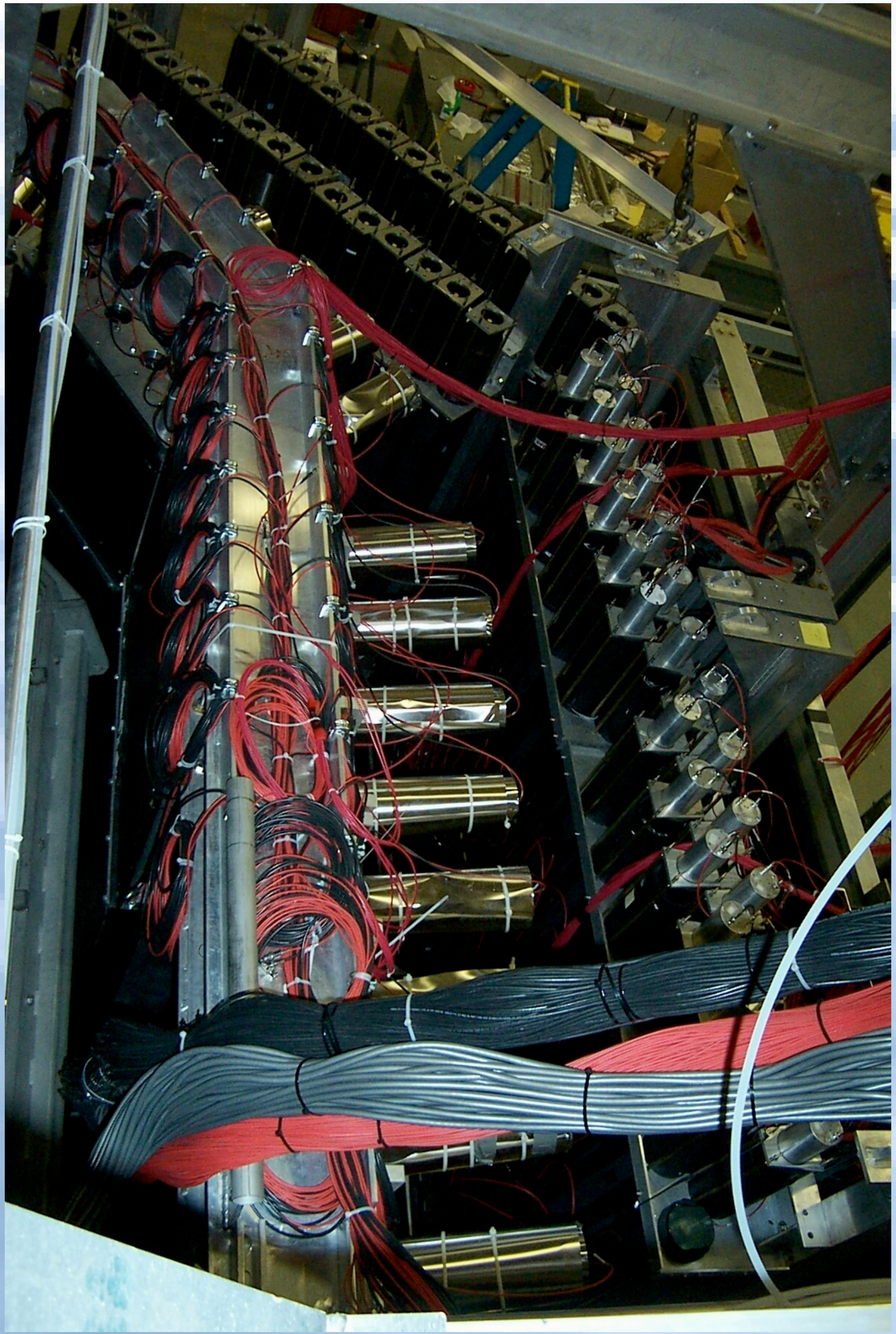
BLAST Detector Components

Neutron Detectors

MIT

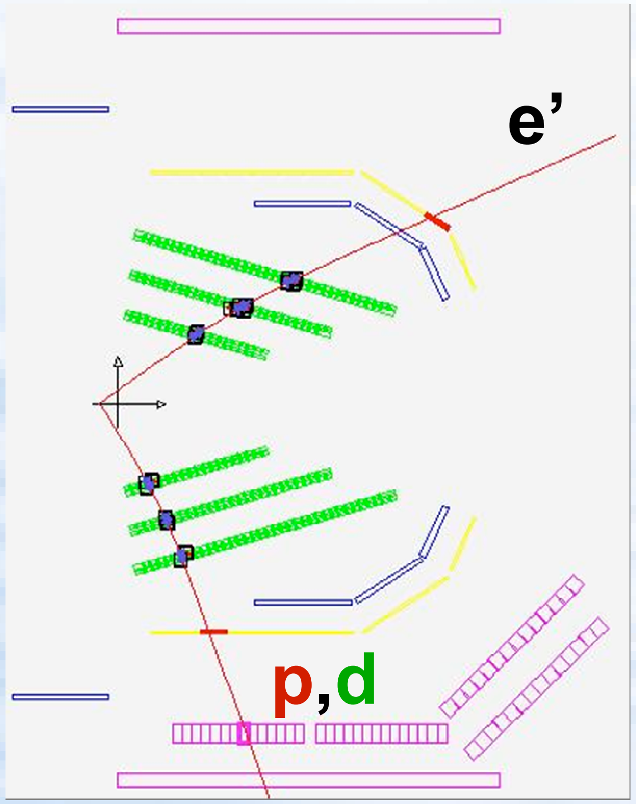
Ohio University

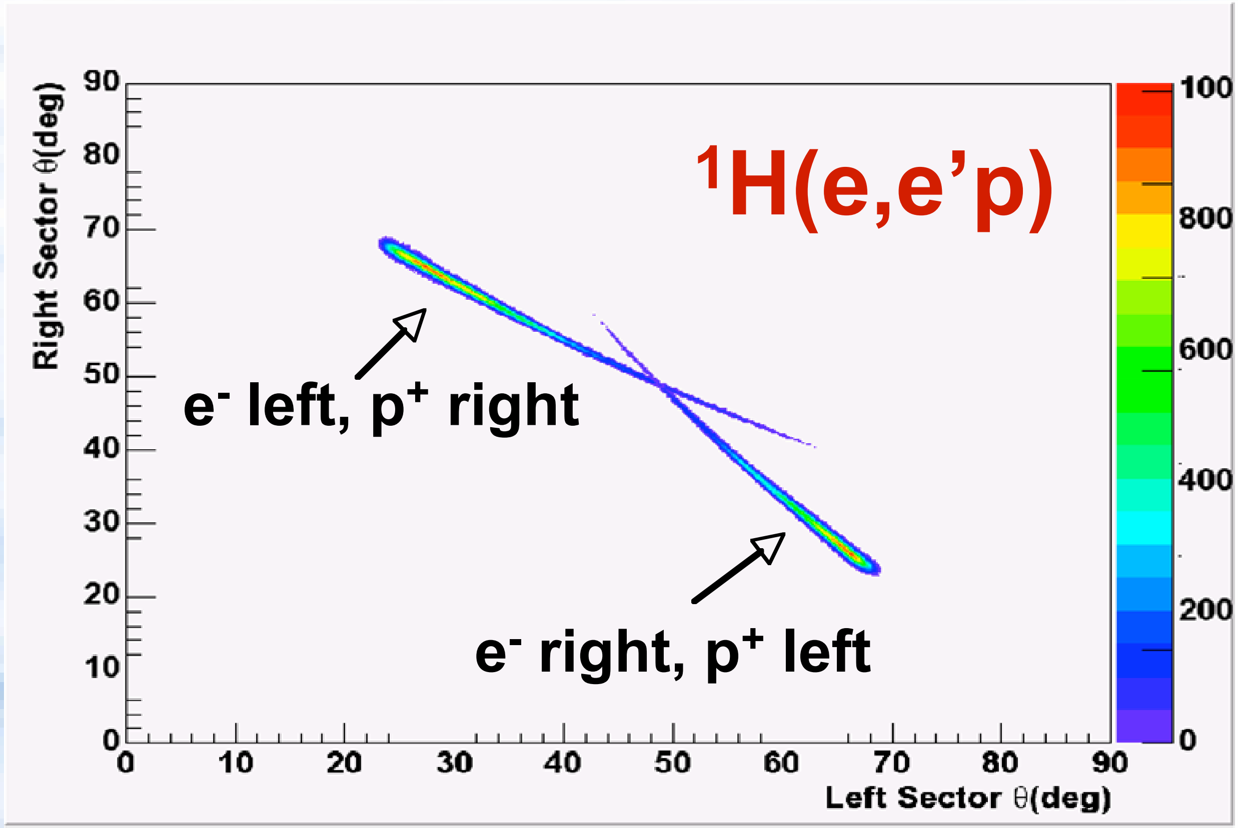


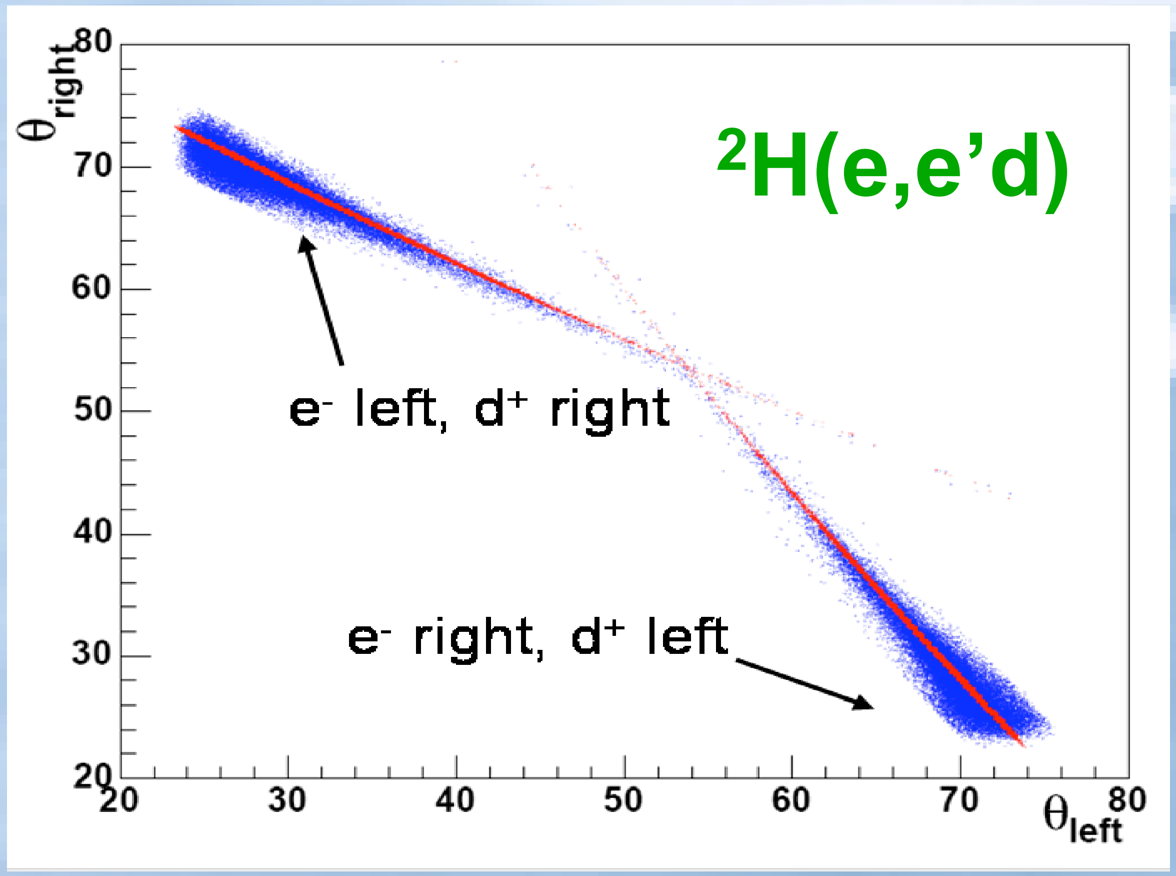


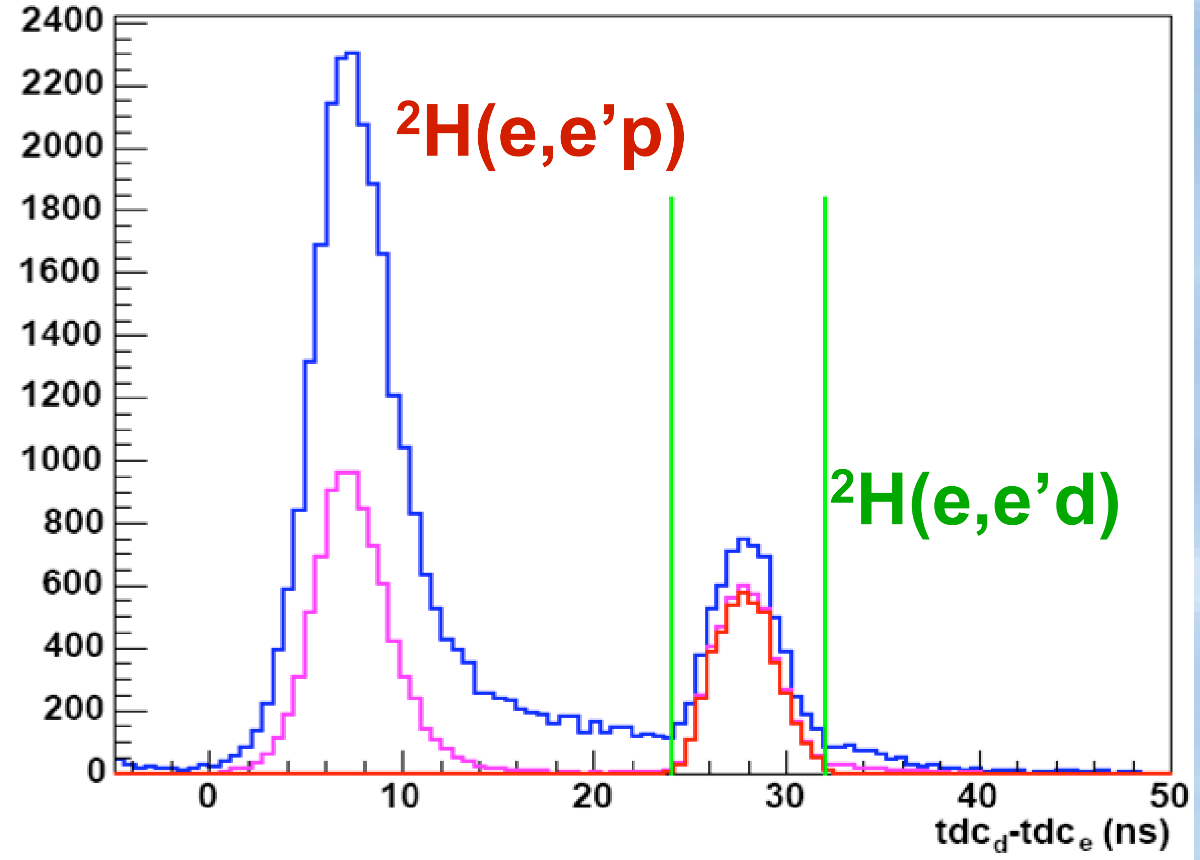
Event Selection

Charge+/-
Coplanarity
Kinematics
Timing

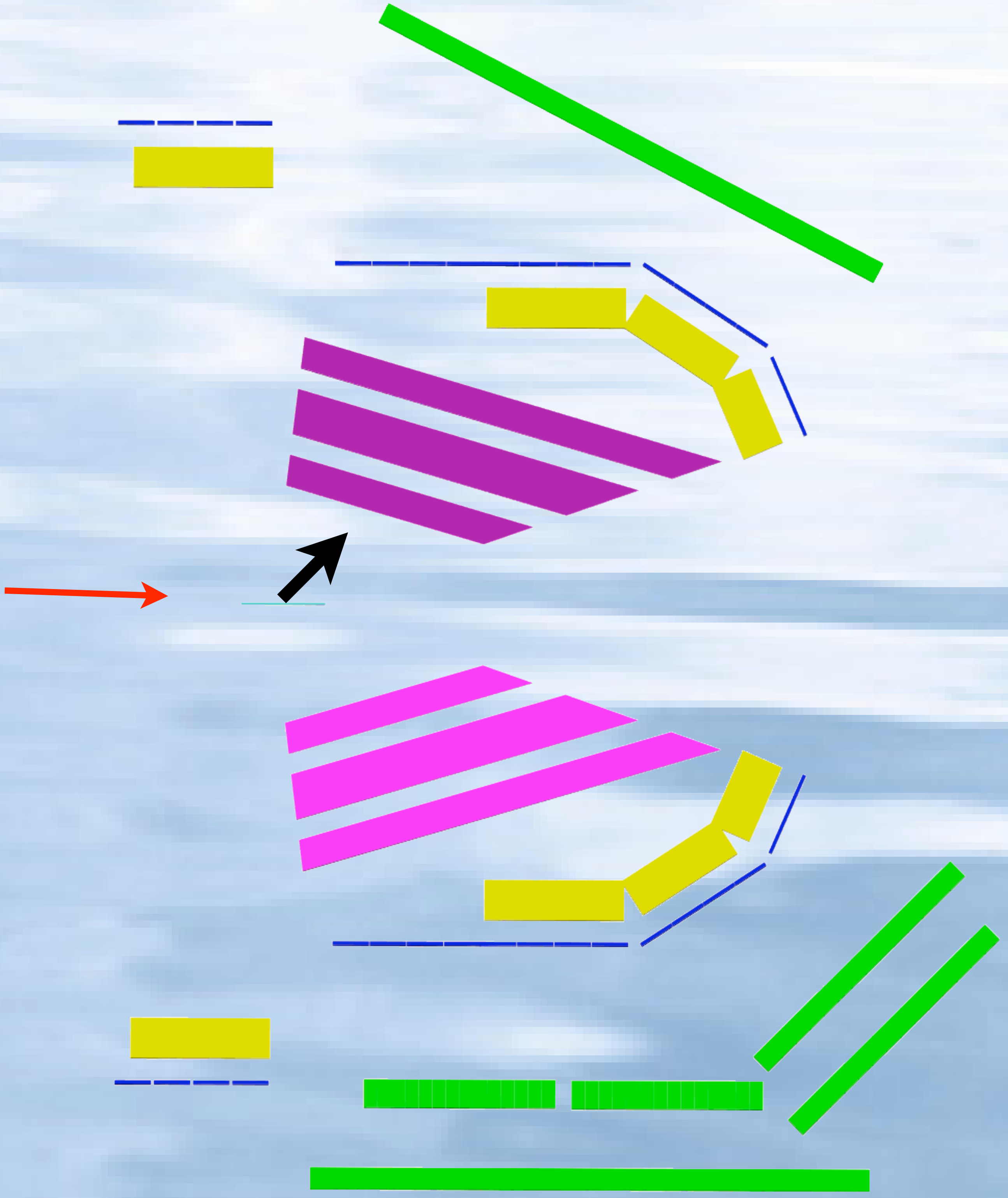








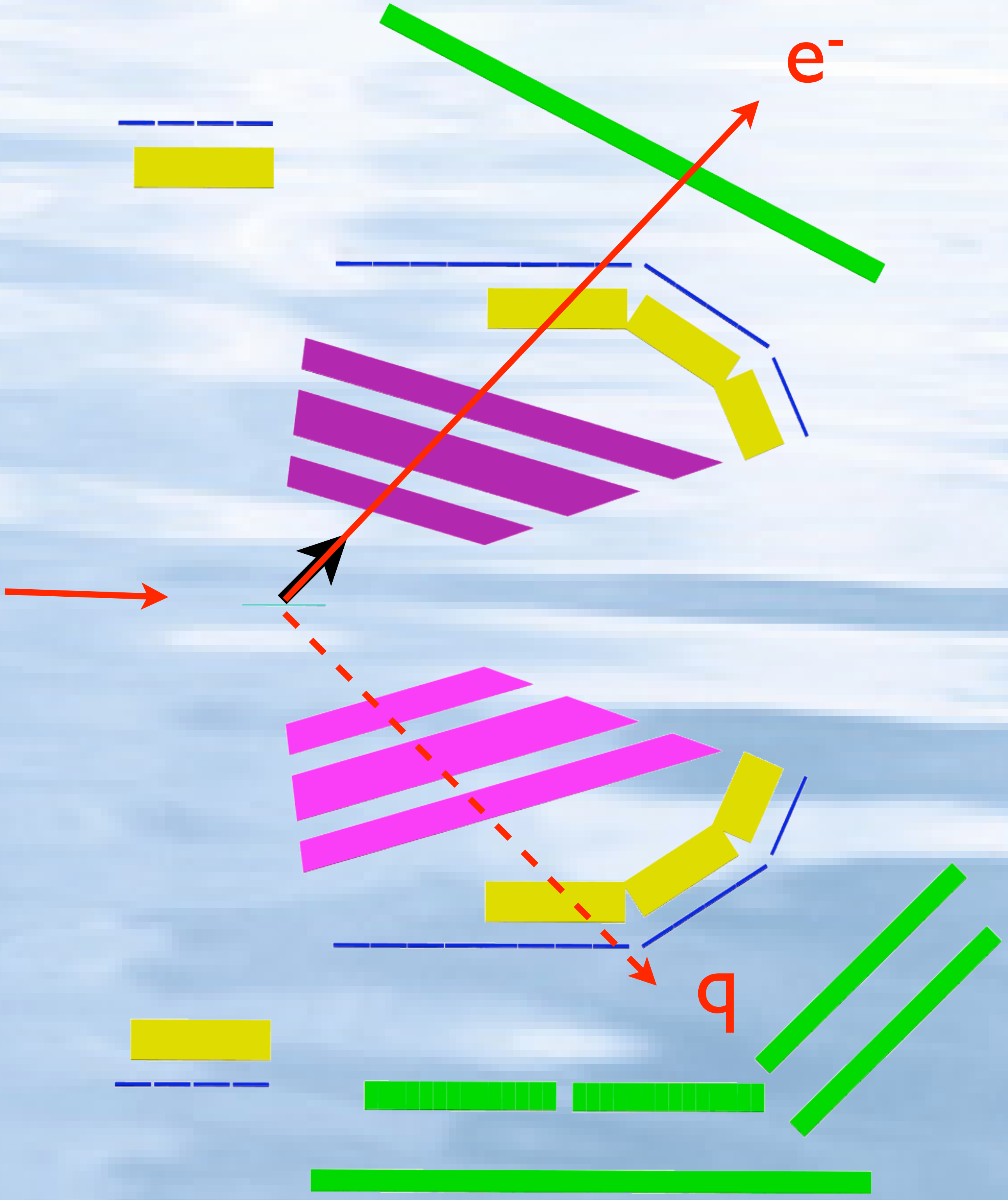
Orientation of Target Spin



Target spin angle

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

Orientation of Target Spin



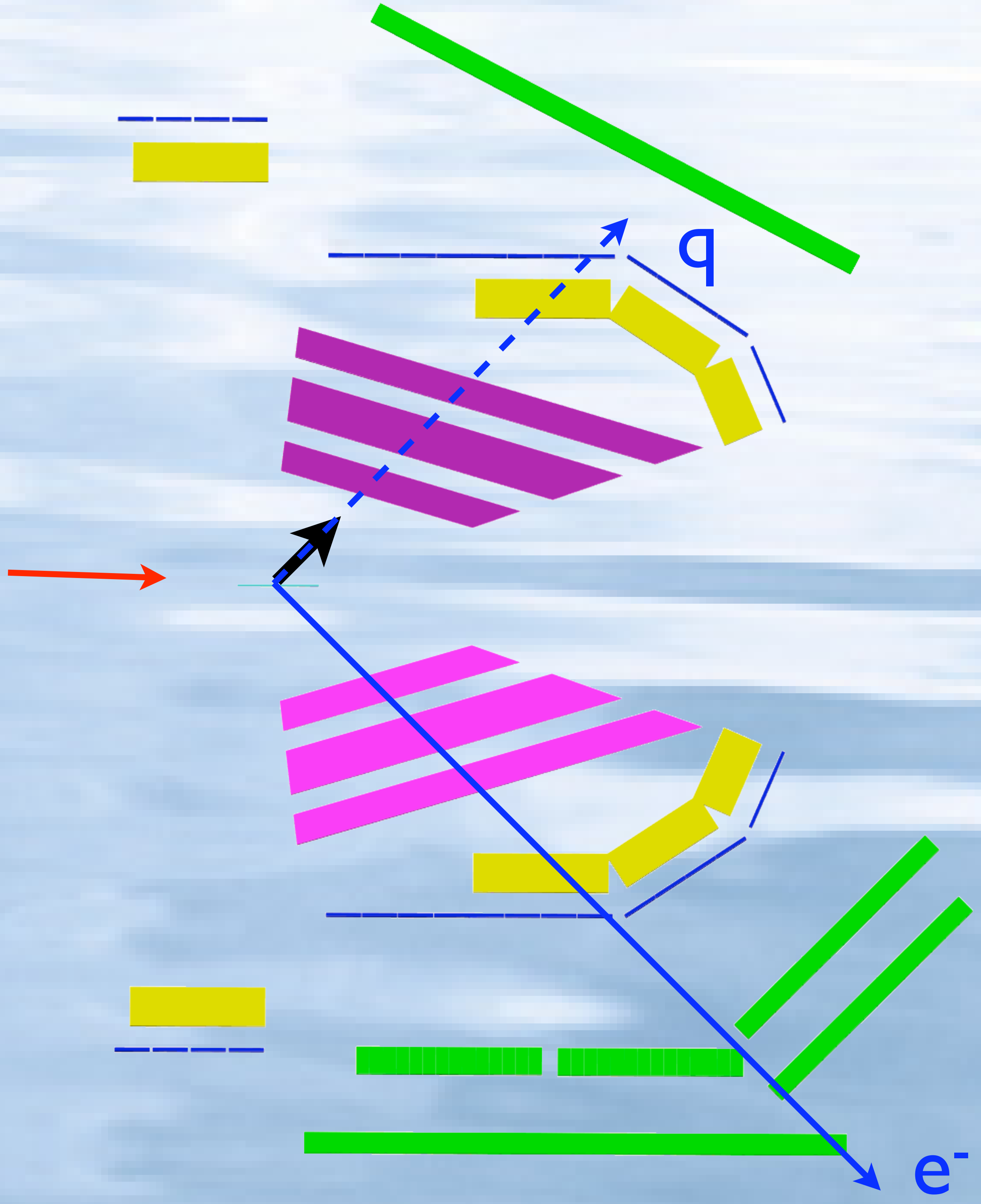
Target spin angle

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

Electron scatters to left sector

- q ≈ perpendicular to target spin
- θ* ≈ 90°
- "spin perpendicular" kinematics

Orientation of Target Spin



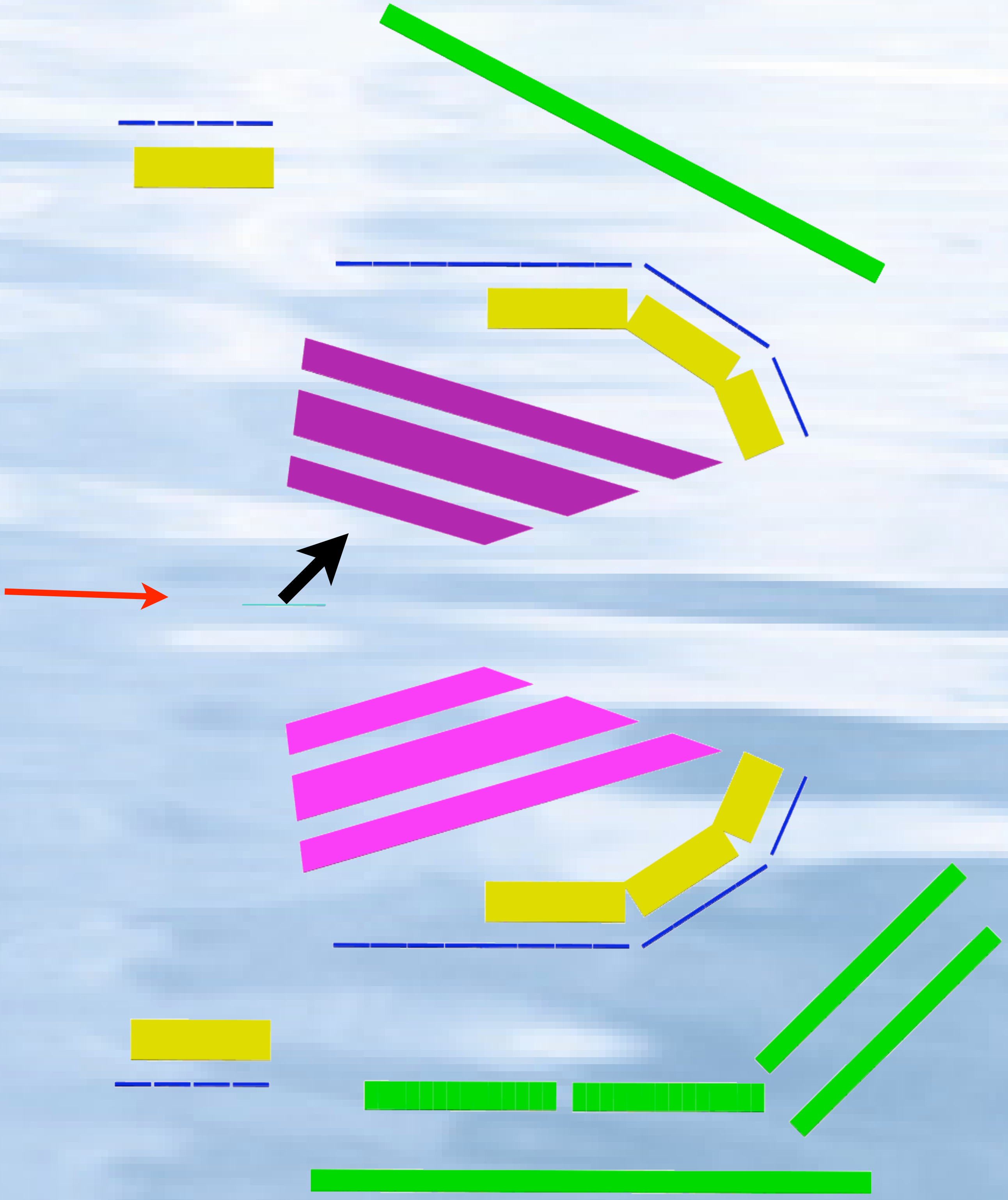
Target spin angle

- 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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- θ* ≈ 0°
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BLAST Physics

Polarised Hydrogen

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

Inclusive **G^{p}_{E}/G^{p}_{M}** **N-Δ : EMR, CMR** **Photoprod.**

Vector Polarised Deuterium

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

G^{n}_{M} **T^{e}_{11} : G^{d}_{M}** **A^{v}_{ed} : L=2** **G^{n}_{E}** **N-Δ**

Tensor Polarised Deuterium

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

T_{20} : G^{d}_{Q} **A^{T}_{d} : L=2** **photodisint.** **$^{1}S_{0}$**

Elastic Scattering from Hydrogen

With polarised beam and target can measure asymmetries

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

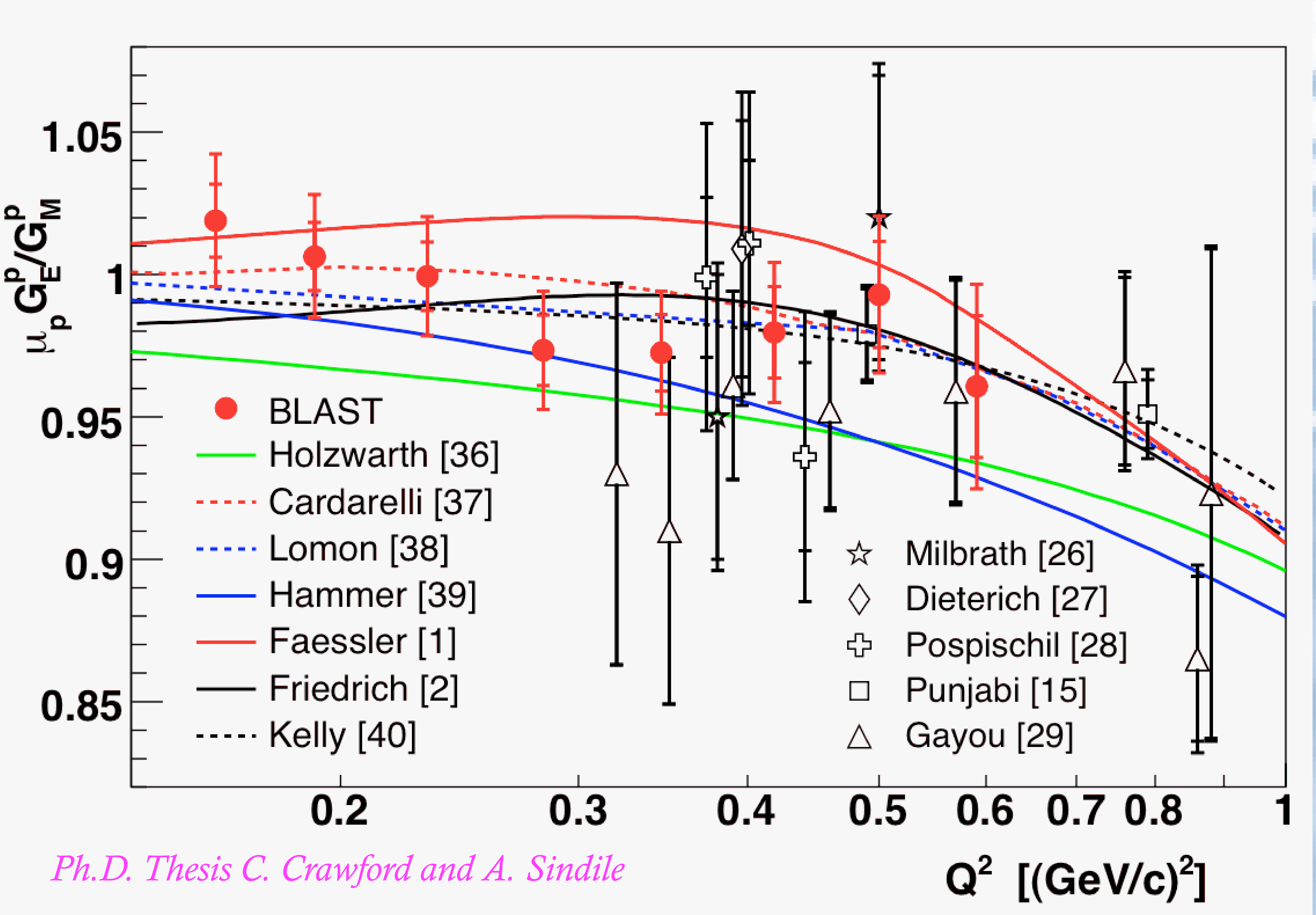
- note some terms vanish in perpendicular or parallel kinematics

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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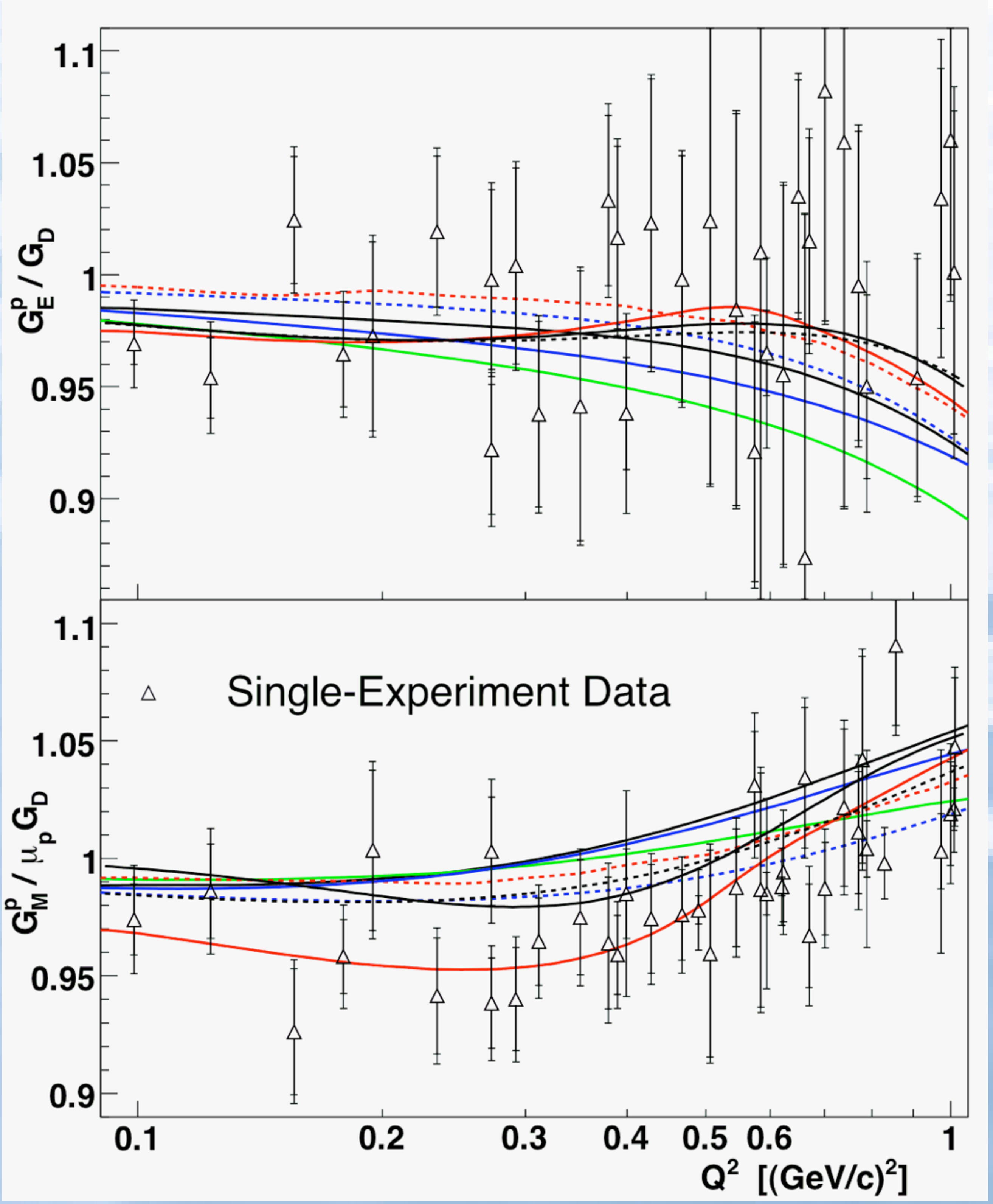
Impact of BLAST Results on World Data



Proton elastic form factors

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

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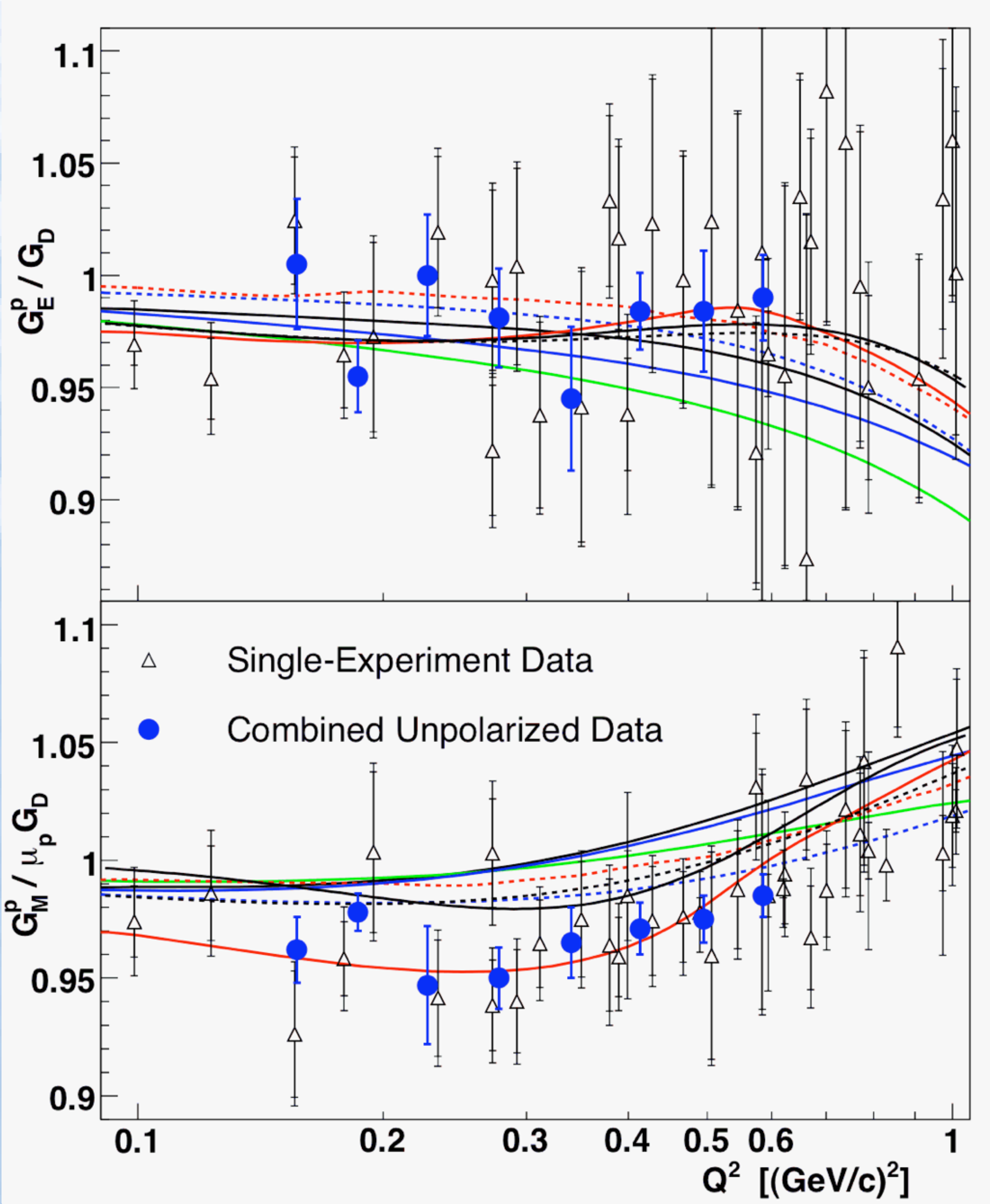
Impact of BLAST Results on World Data



Proton elastic form factors

- G^p_E and G^p_M
- divided by dipole
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World data combined

- averaged and rebinned
- over BLAST range

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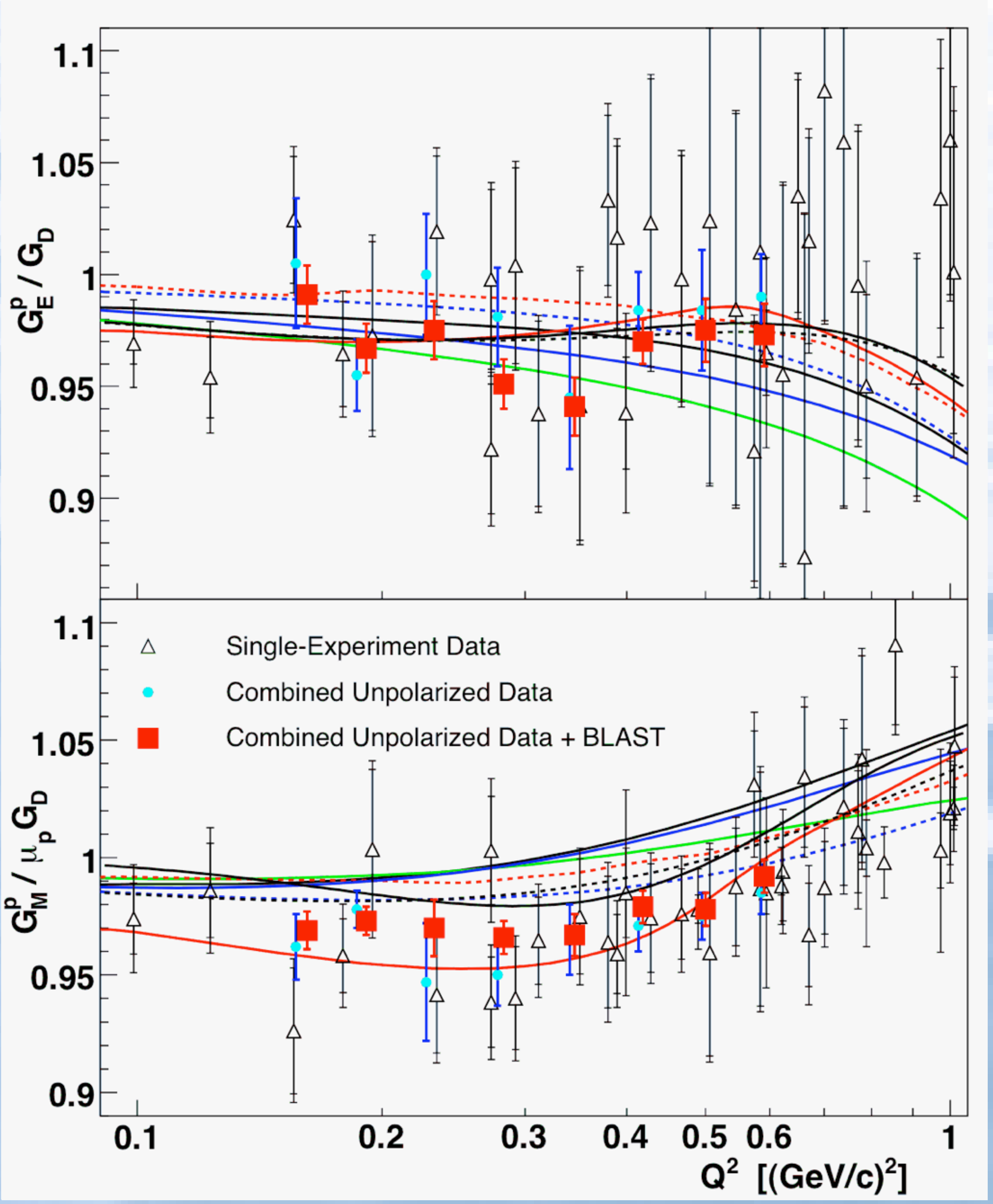
Impact of BLAST Results on World Data



Proton elastic form factors

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

World data combined

- averaged and rebinned
- over BLAST range

Constraining with BLAST

- uncertainties reduced factor 2

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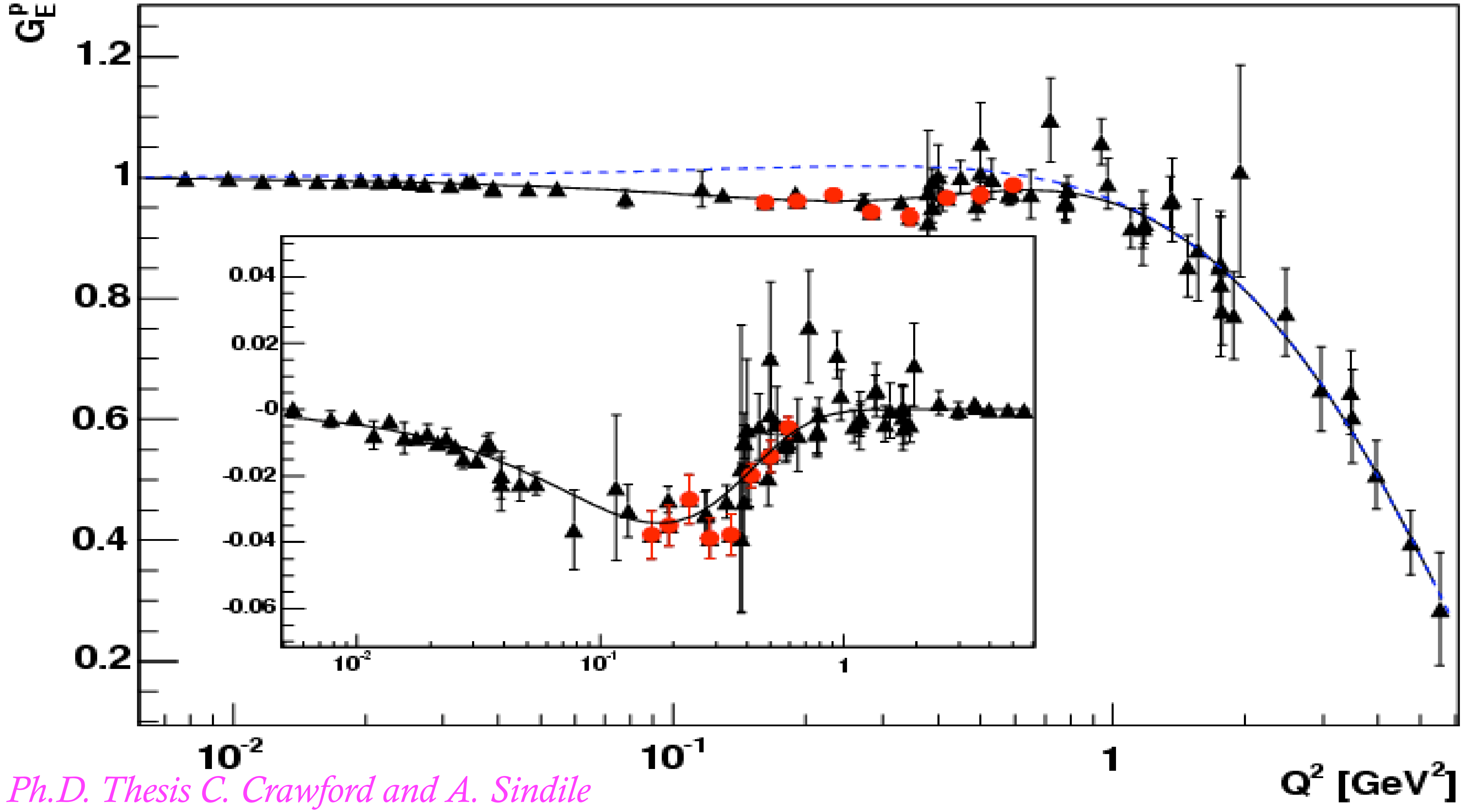
BLAST Data with Friedrich and Walcher



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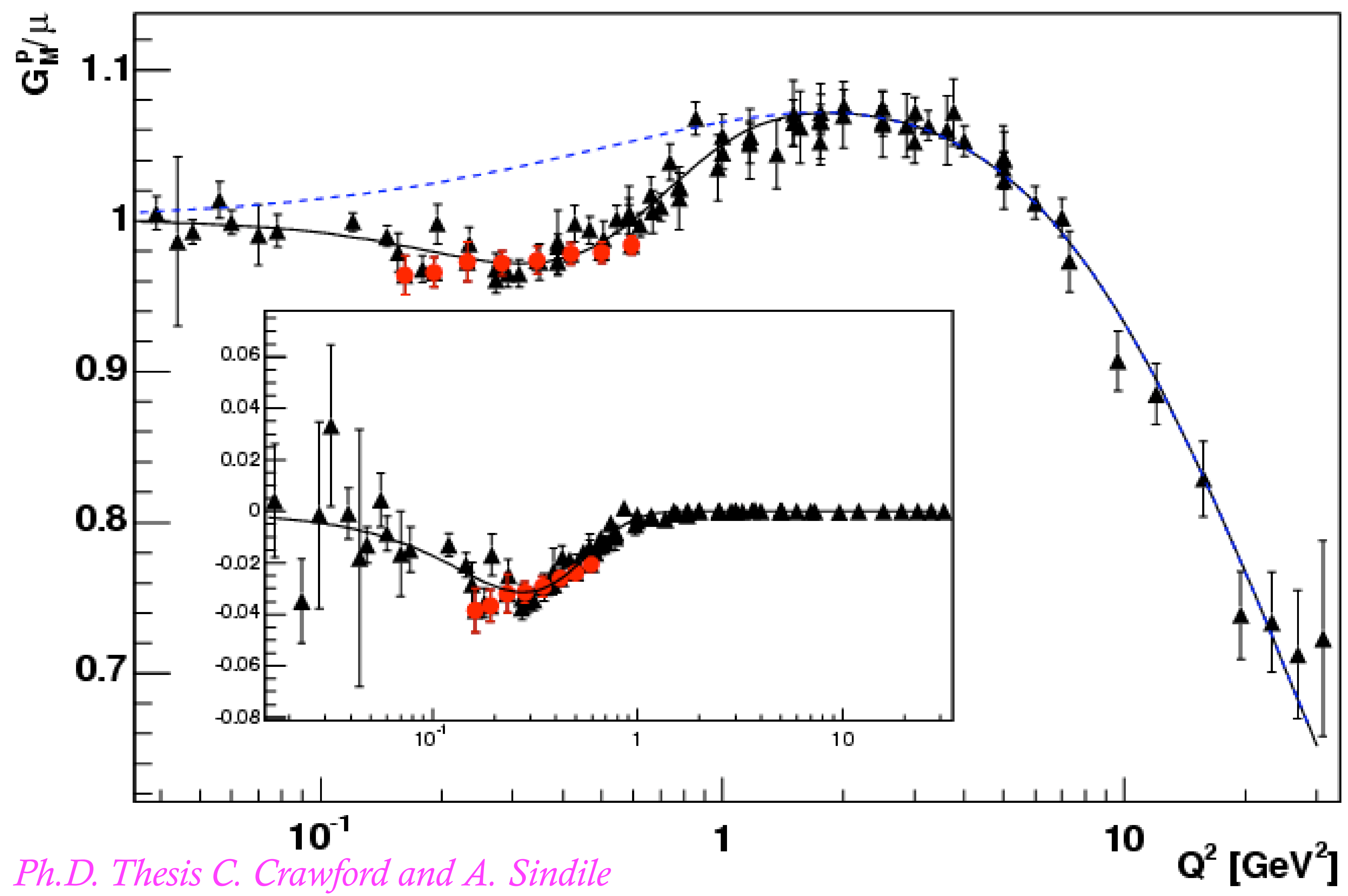
BLAST Data with Friedrich and Walcher



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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

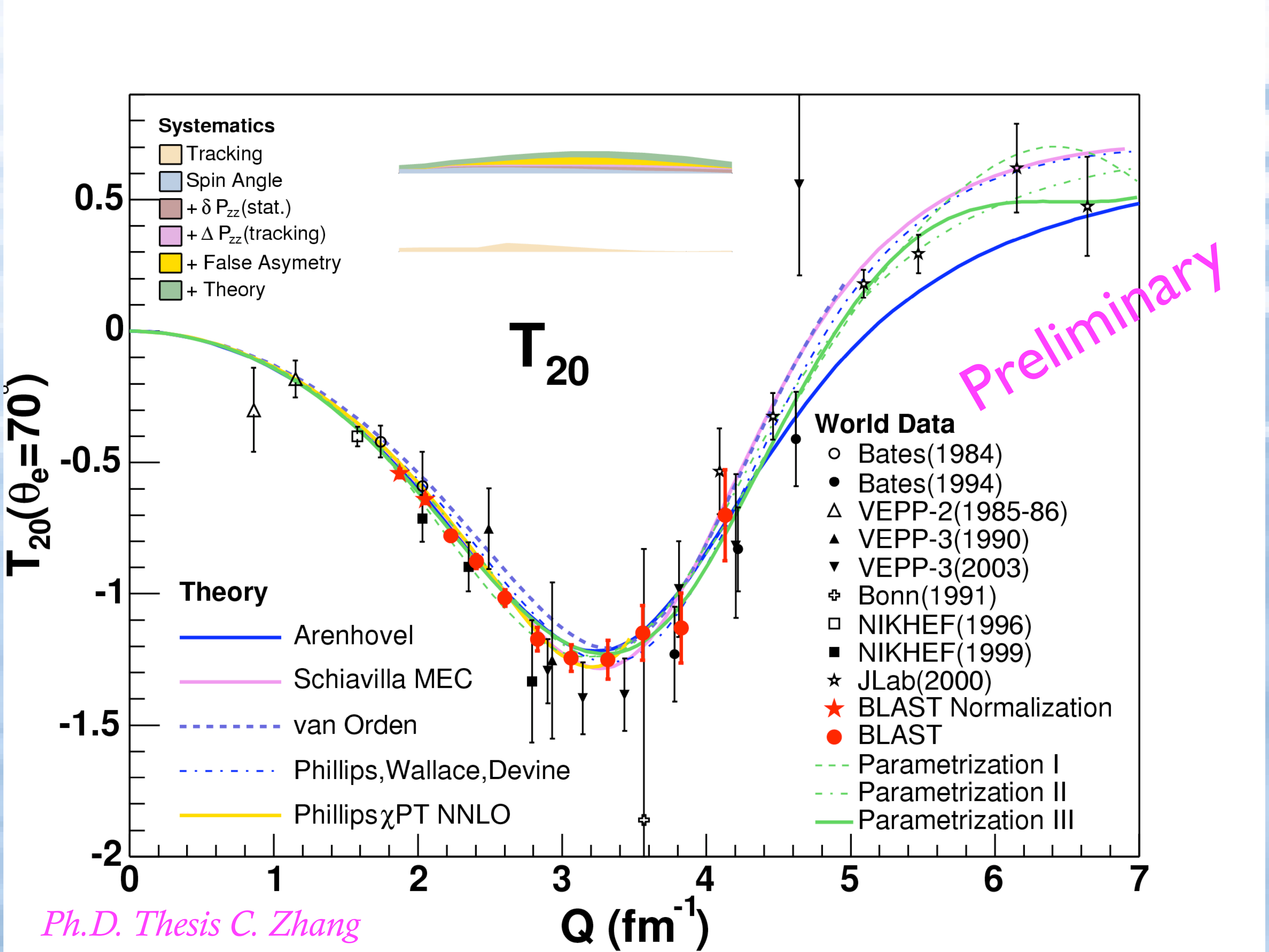
$$A(Q^2) = {G_C^d}^2 + \frac{8}{9}\eta^2 {G_Q^d}^2 + \frac{2}{3}\eta {G_M^d}^2$$

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

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}


Systematics
Tracking
Spin Angle
+ δ P_zz(stat.)
+ Δ P_zz(tracking)
+ False Asymetry
+ Theory
T_20
Preliminary
World Data
Bates(1984)
Bates(1994)
VEPP-2(1985-86)
VEPP-3(1990)
VEPP-3(2003)
Bonn(1991)
NIKHEF(1996)
NIKHEF(1999)
JLab(2000)
BLAST Normalization
BLAST
Parametrization I
Parametrization II
Parametrization III
Theory
Arenhovel
Schiavilla MEC
van Orden
Phillips,Wallace,Devine
Phillips χPT NNLO
T_20(θ_e=70°)
0.5
0
-0.5
-1
-1.5
-2
0
1
2
3
4
5
6
7
Q (fm^-1)
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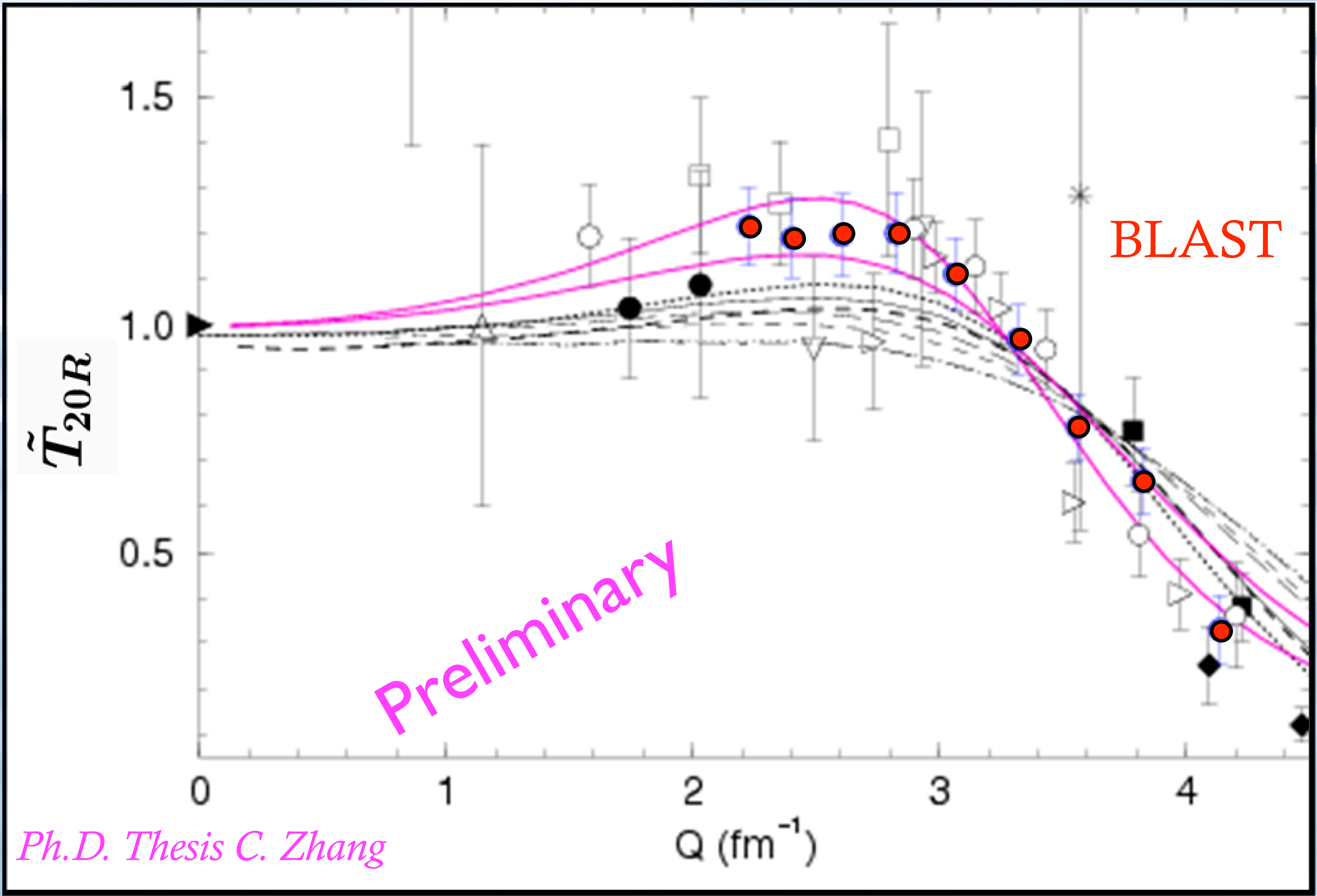
Reduced T_{20}

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

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



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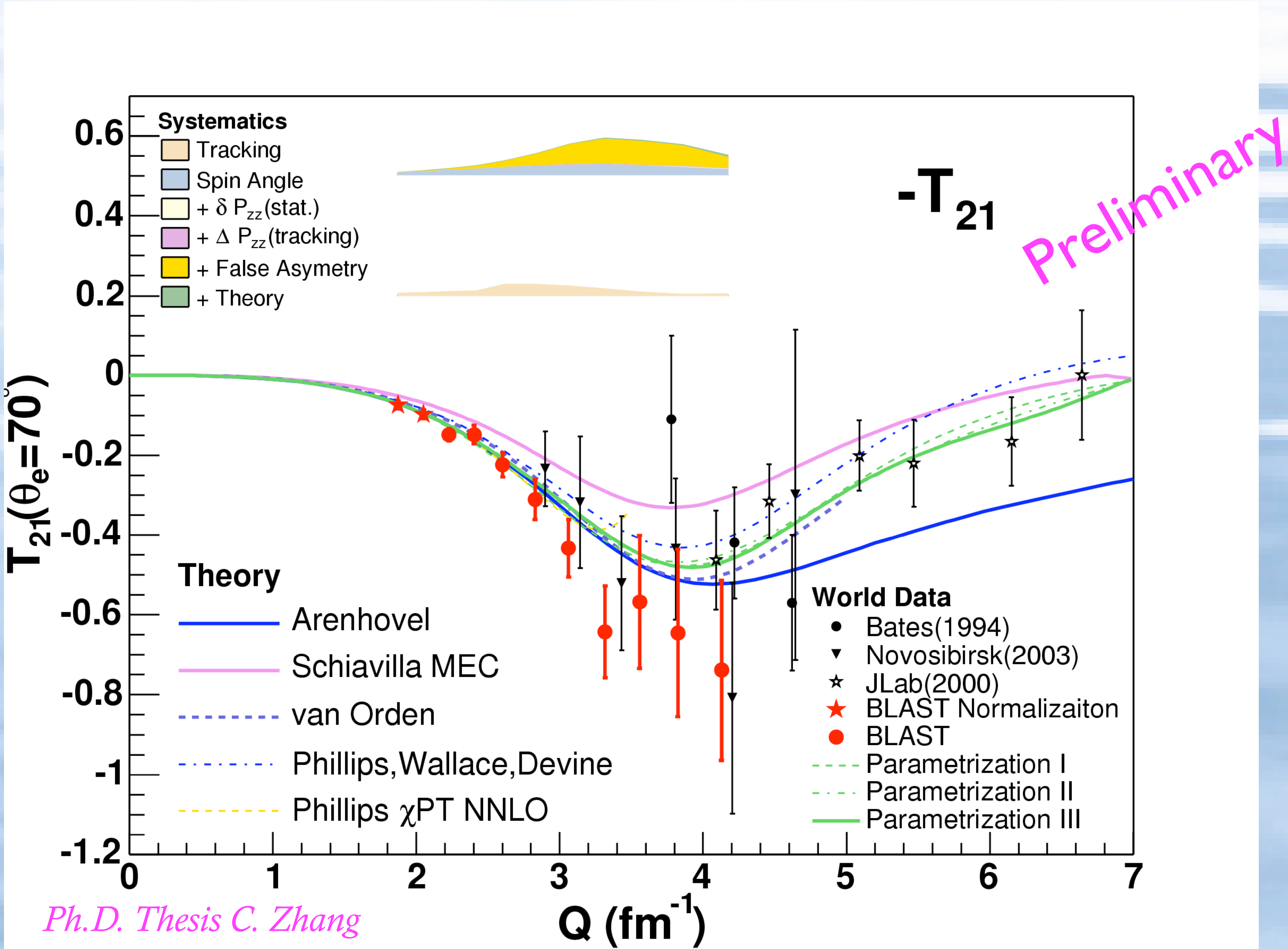
T_{21}



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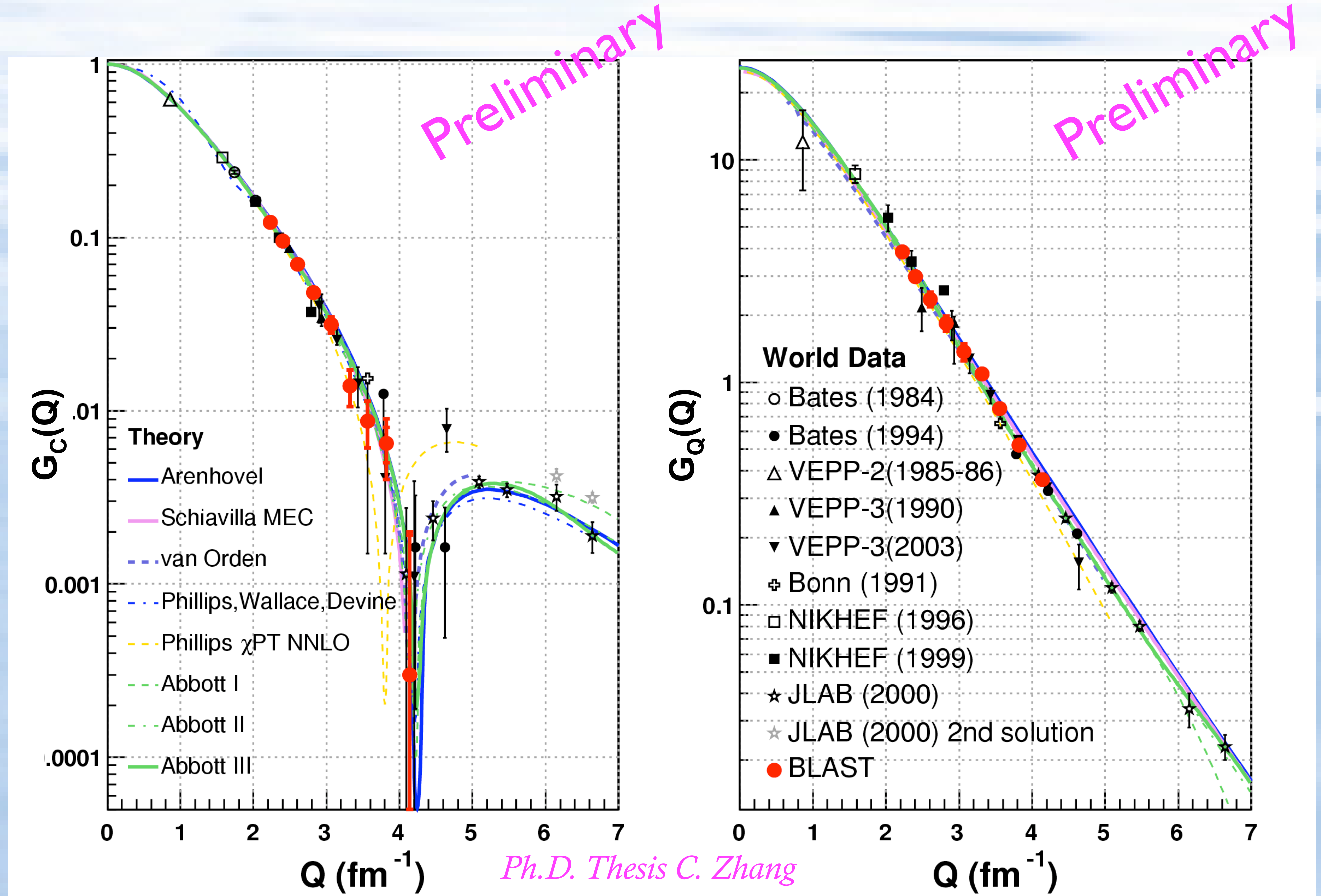
G_C and G_Q



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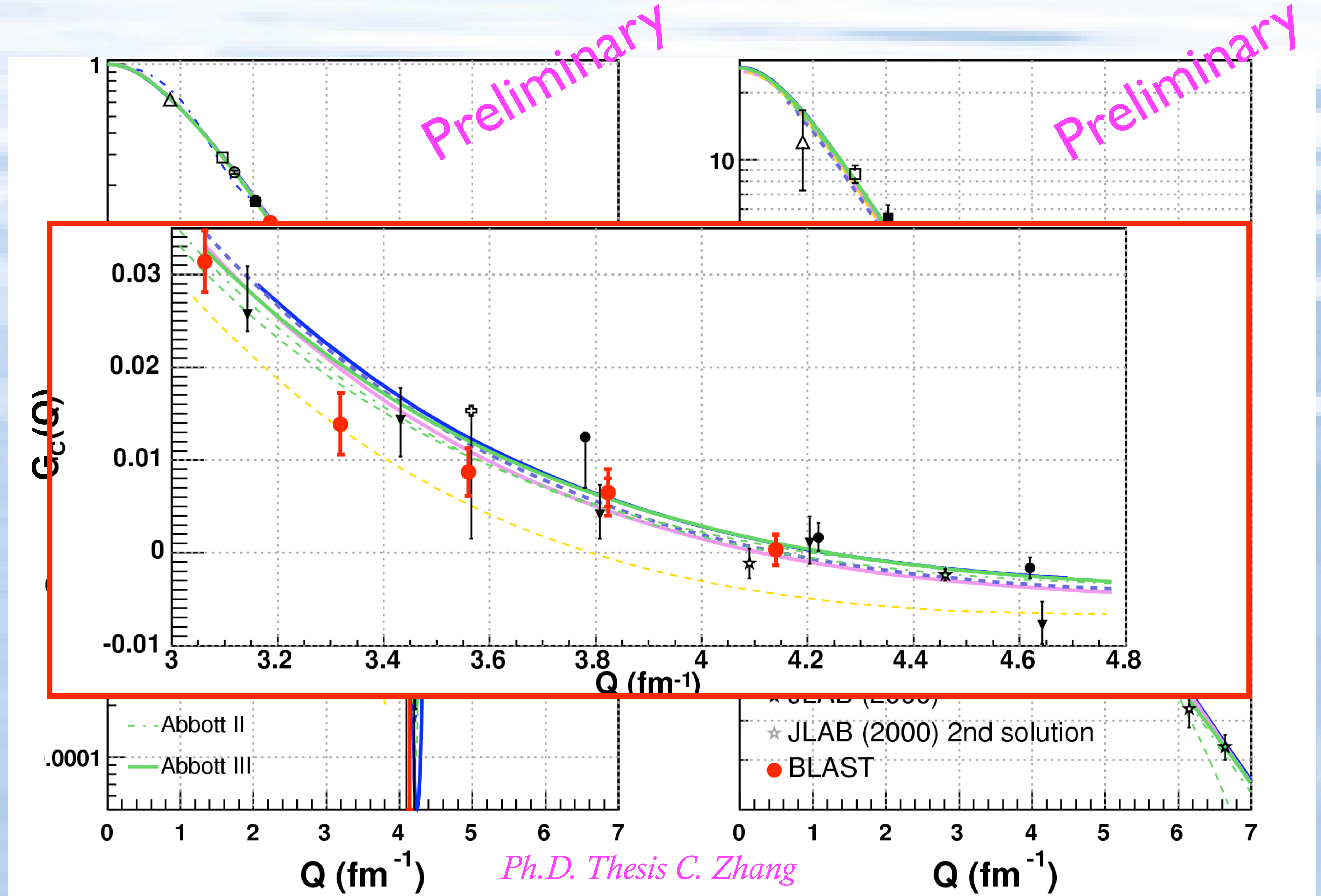
G_C and G_Q



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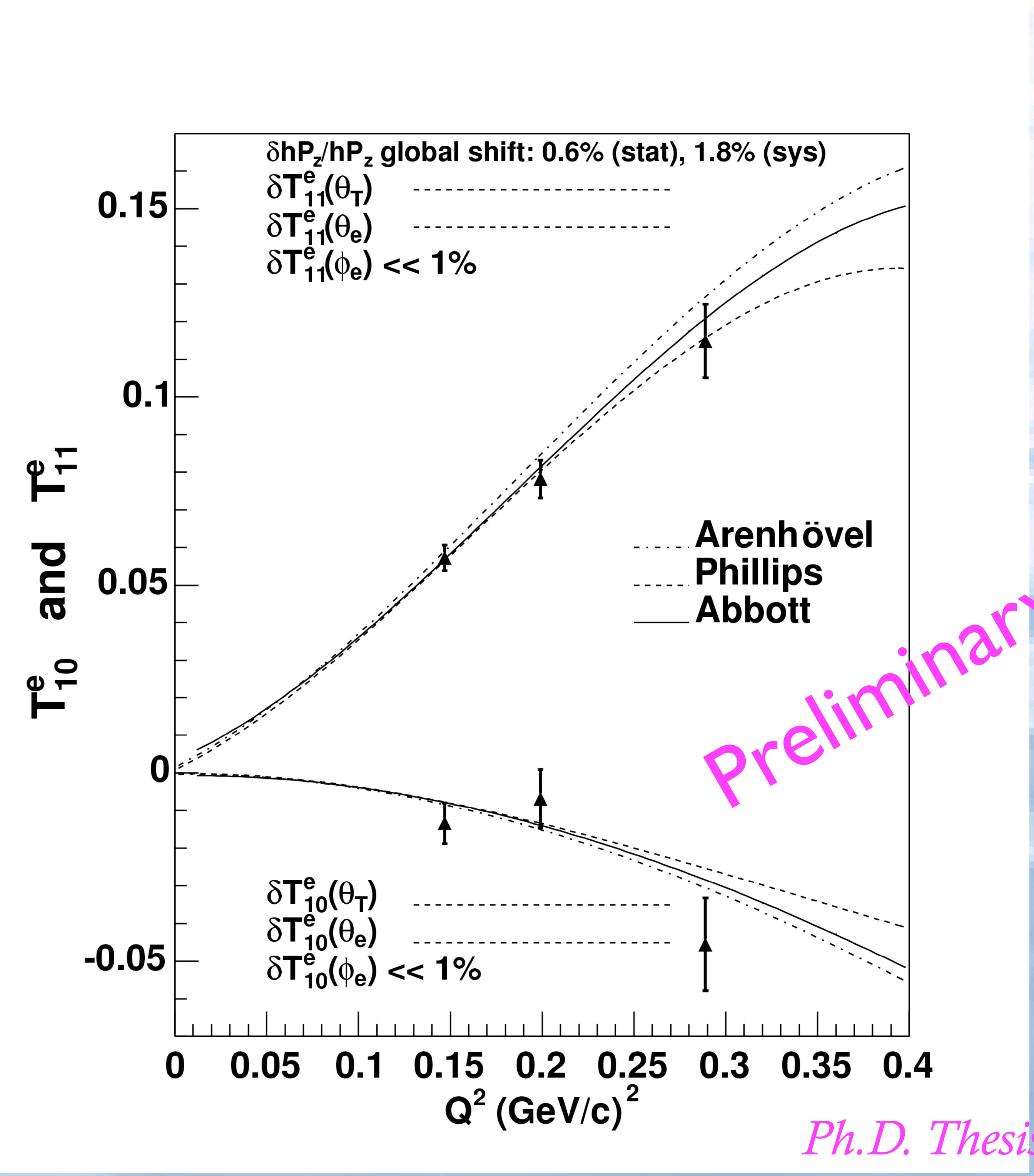
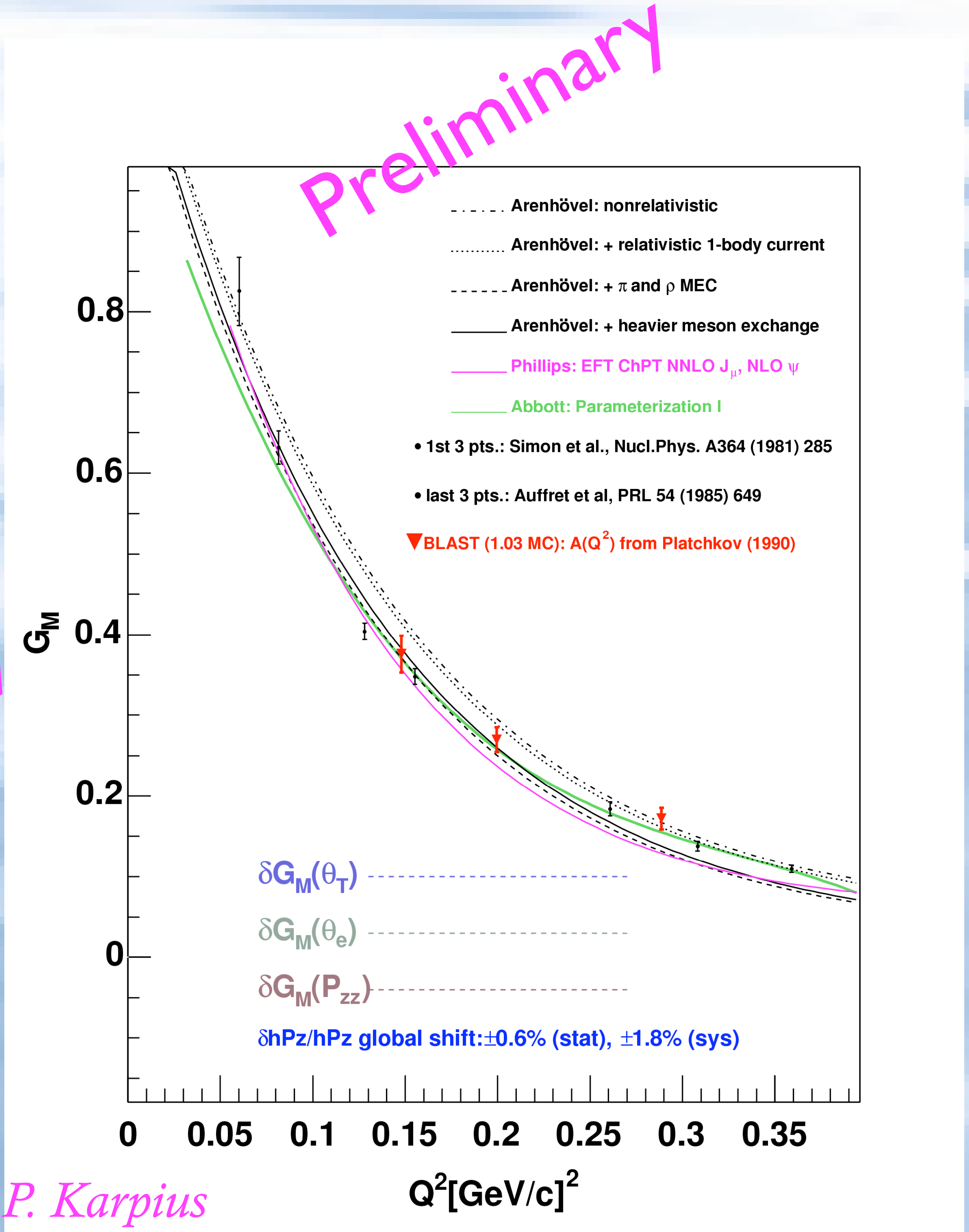
T^e_{10} and T^e_{11} and G^d_M





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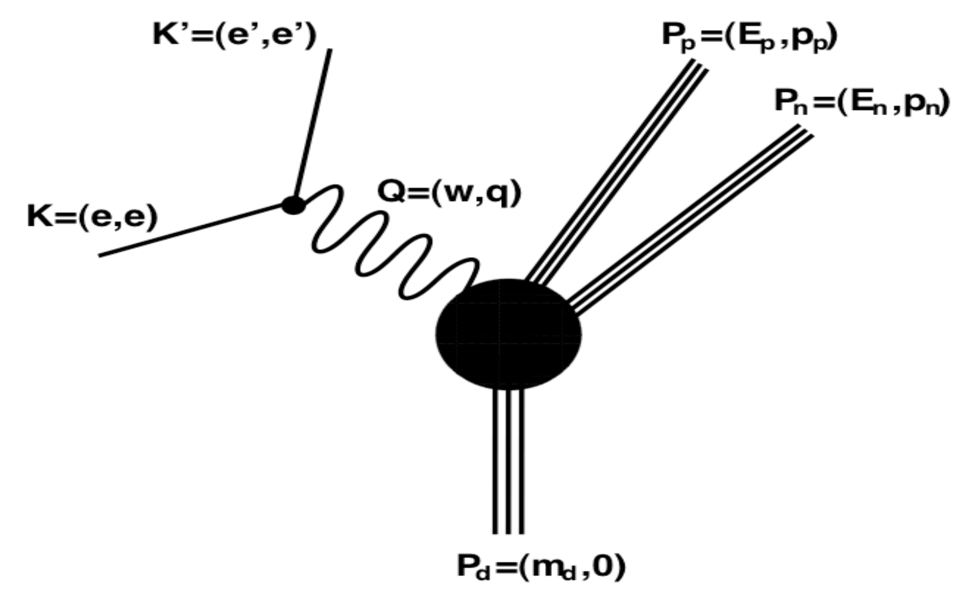
Quasi-Elastic Scattering from Deuterium

Deuteron readily breaks up

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



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

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

In the Born approximation

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

Yielding:

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

∝G$_E$/G$_M$

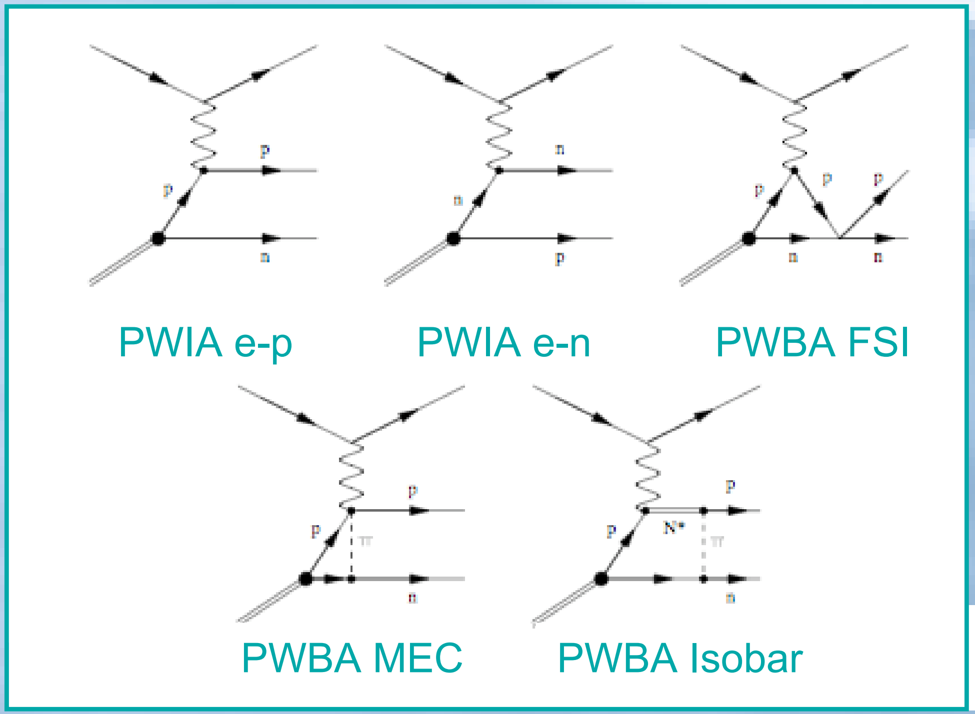
=0 for S state

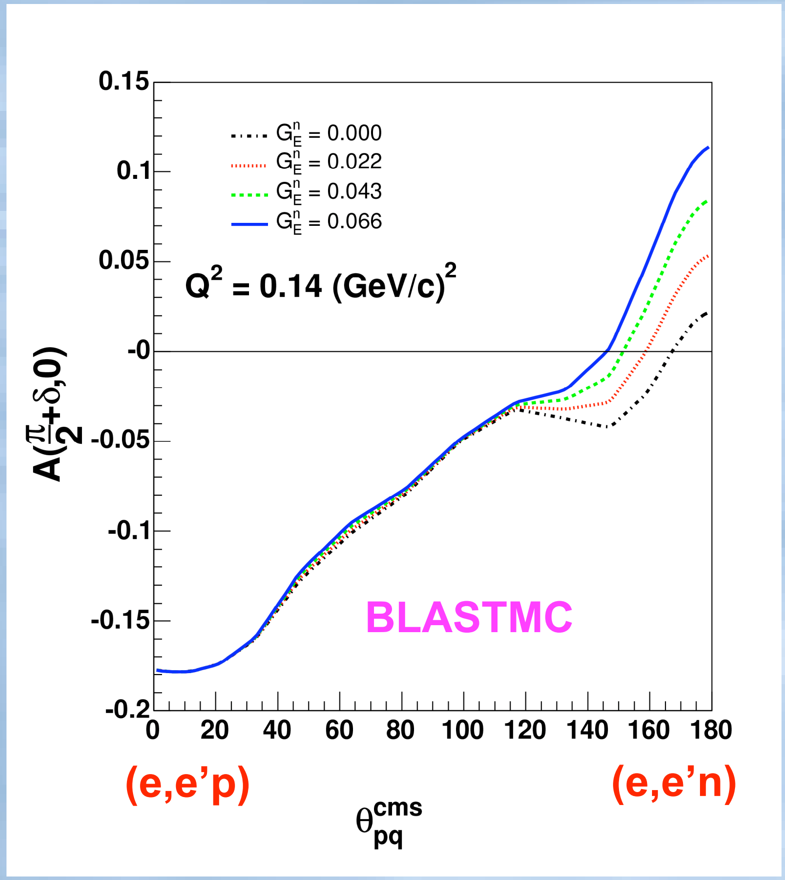
Extracting G^n_E from A^V_{ed}

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

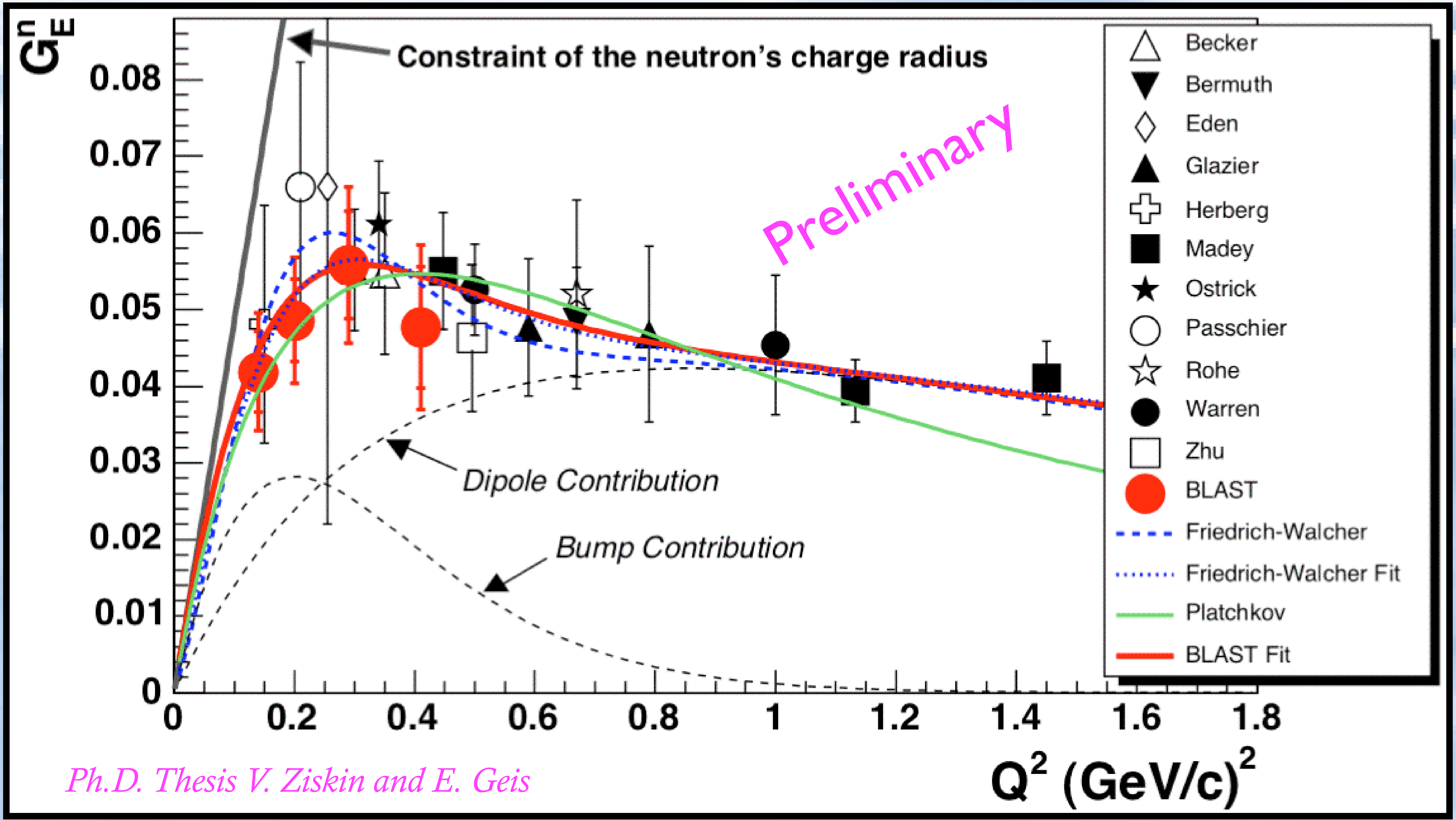
Beam-Target vector asymmetry gives G^n_E assuming G^n_M known

- 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



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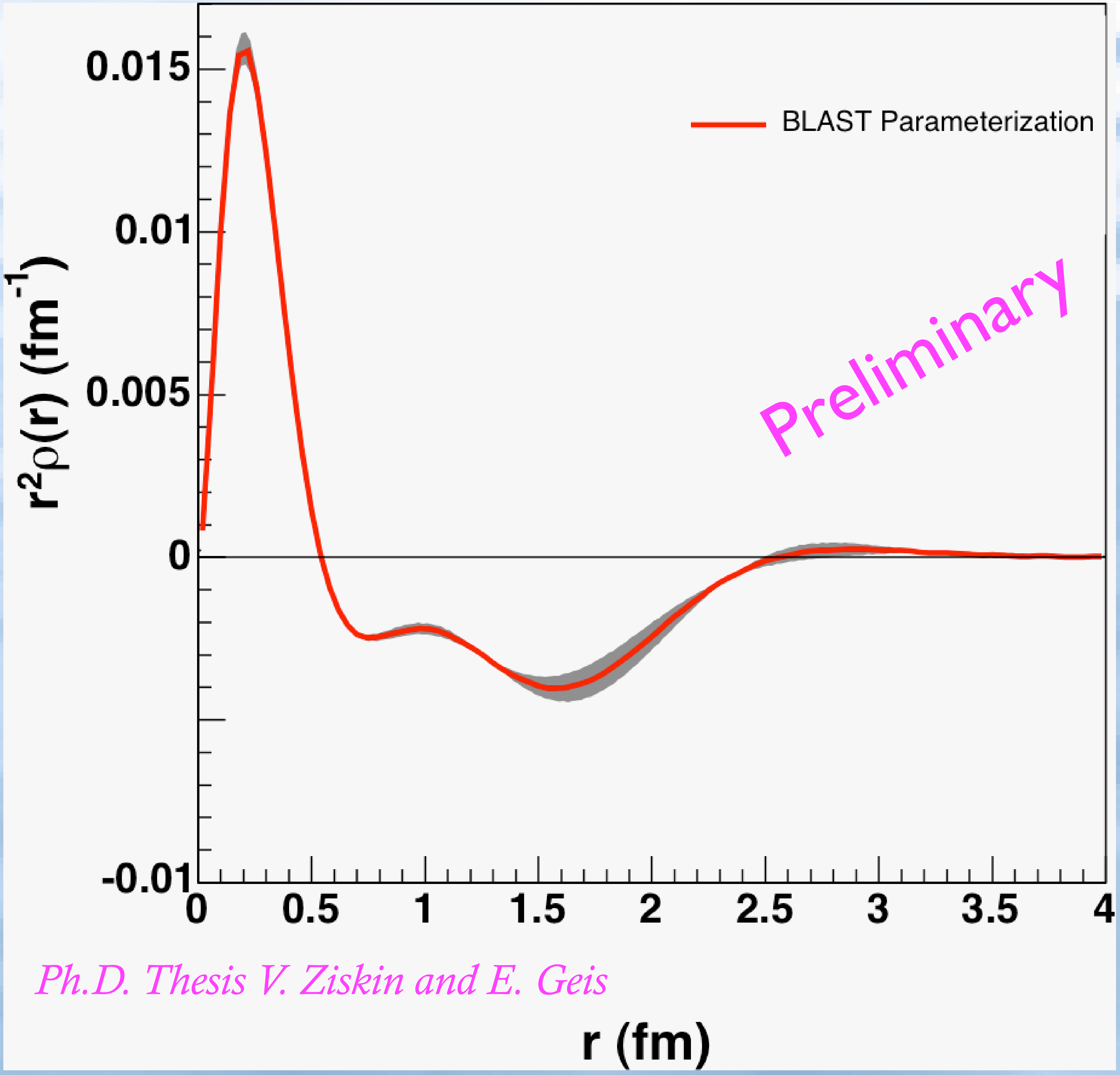
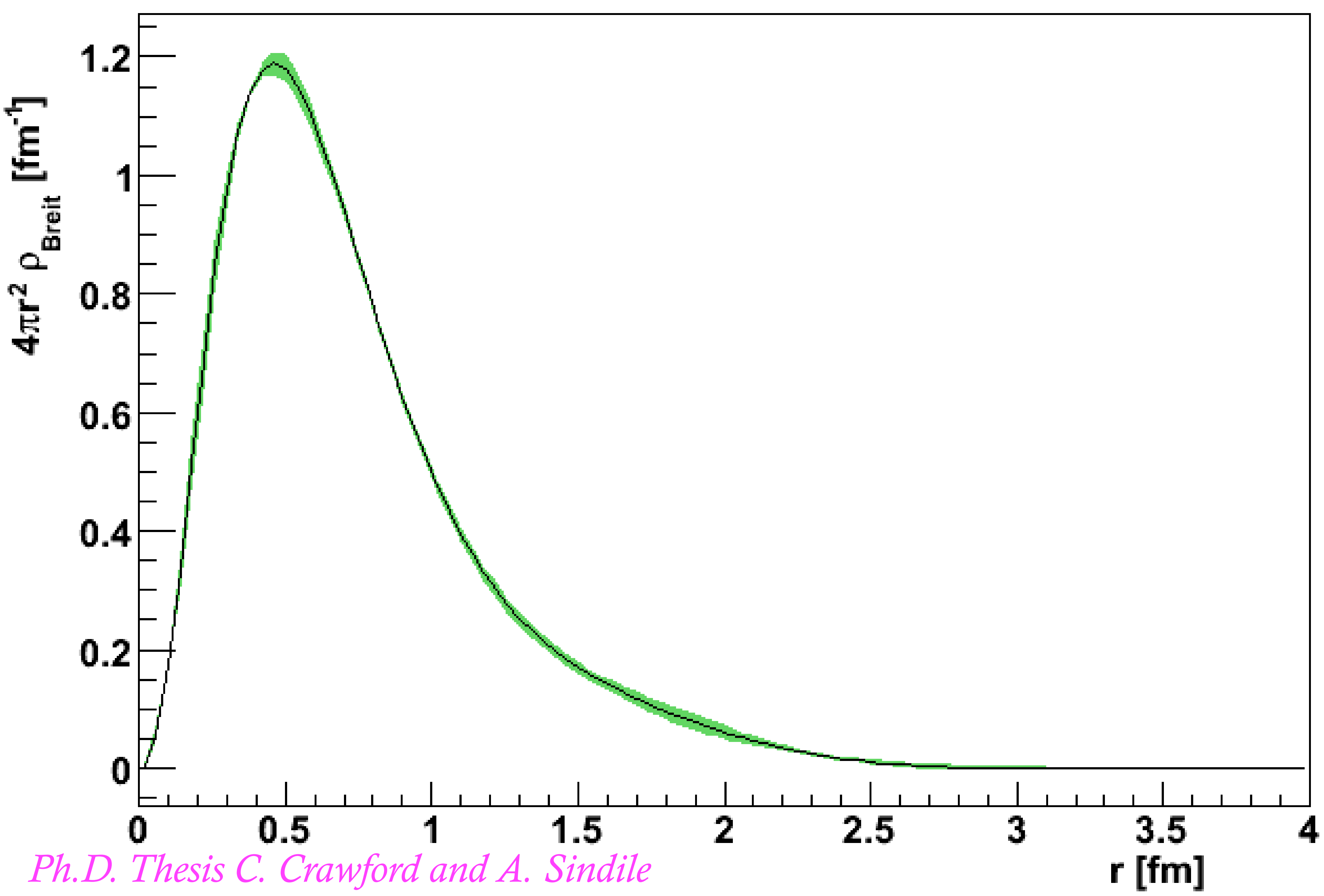
Neutron Charge Density



Proton Charge Density



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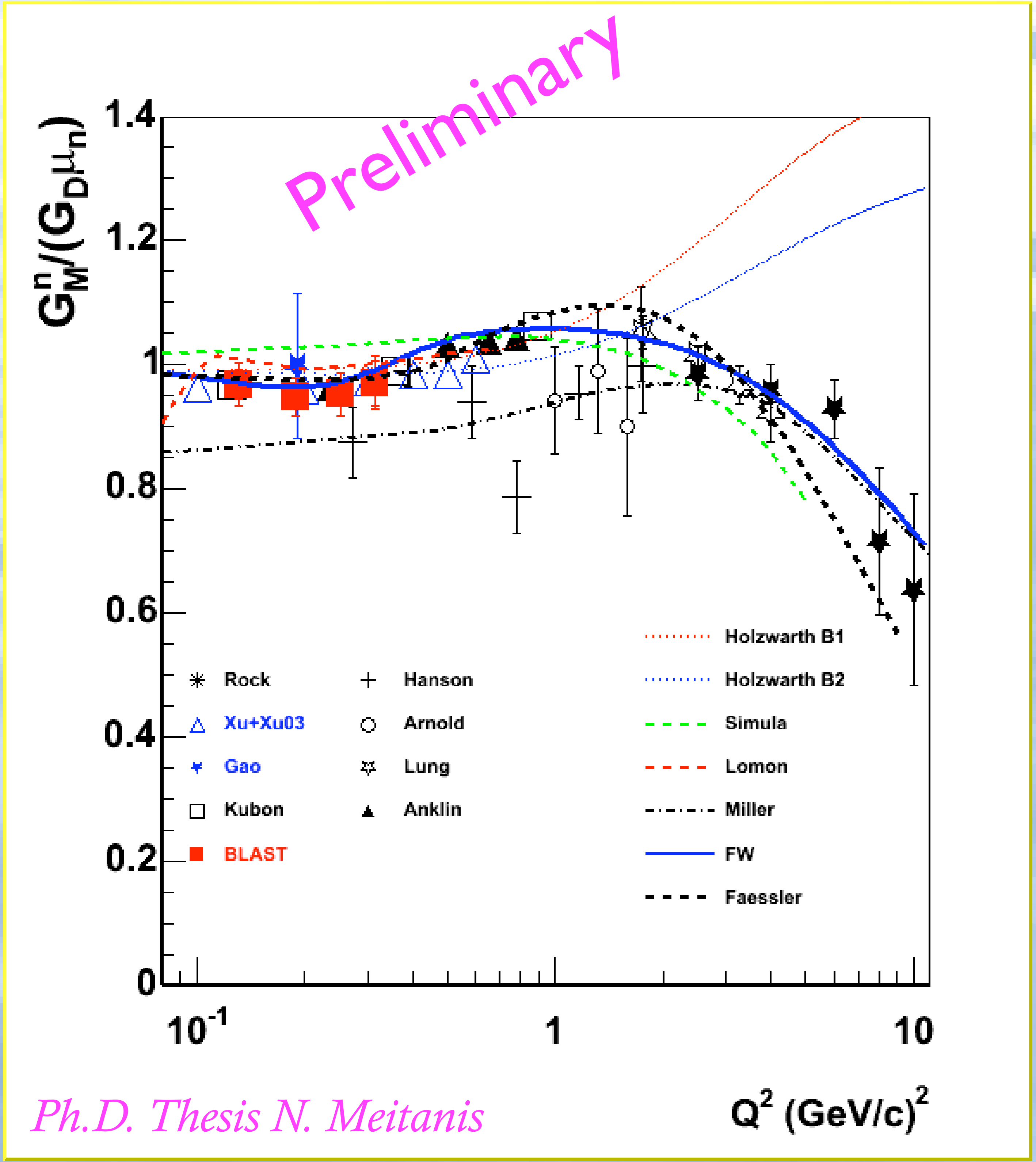
G^n_M



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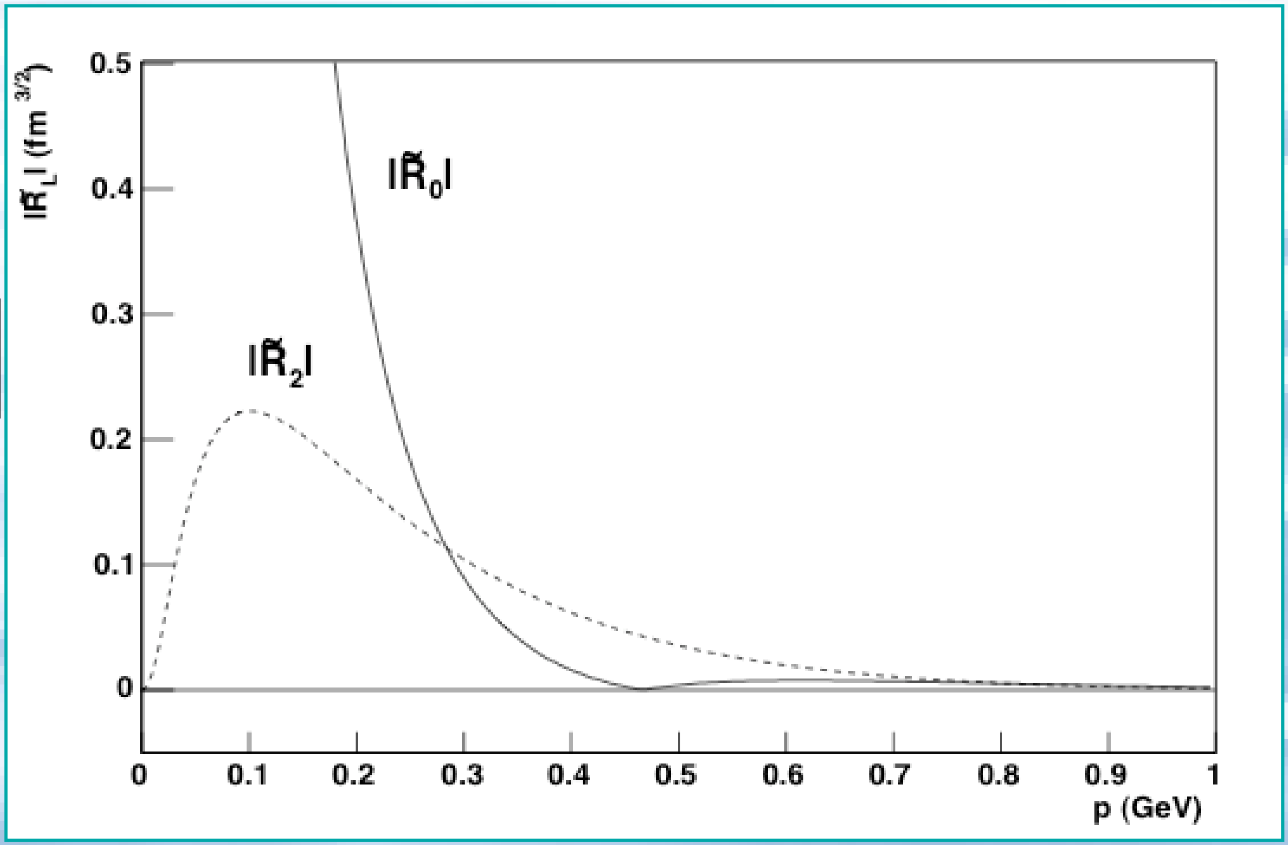
Deuteron Wavefunction

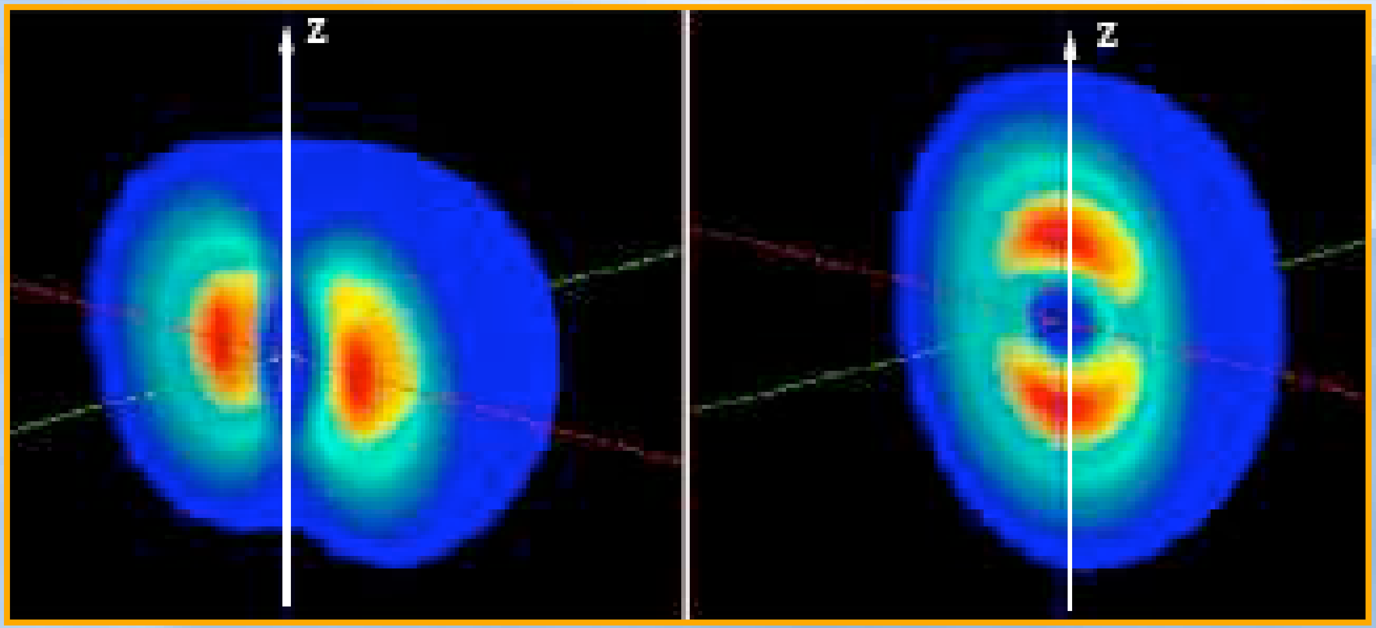
Deuteron wavefunction:

- L=0, 2 admixture

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

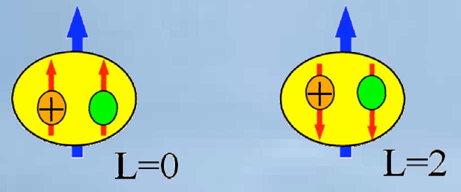
- S state minimum at p~ 0.45 GeV
- D state significant at p > 0.3 GeV



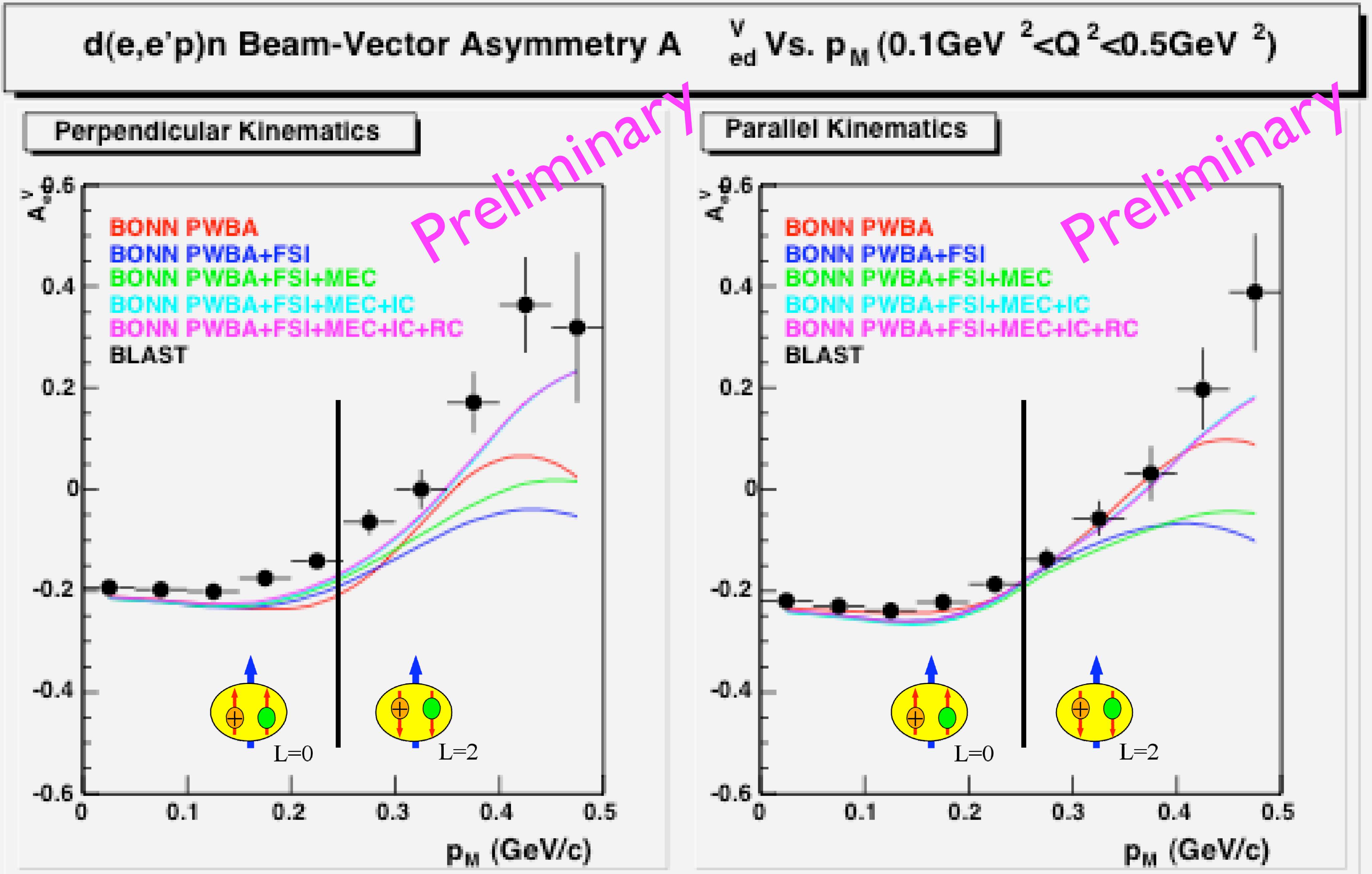


D state normally 4-6 %

- 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



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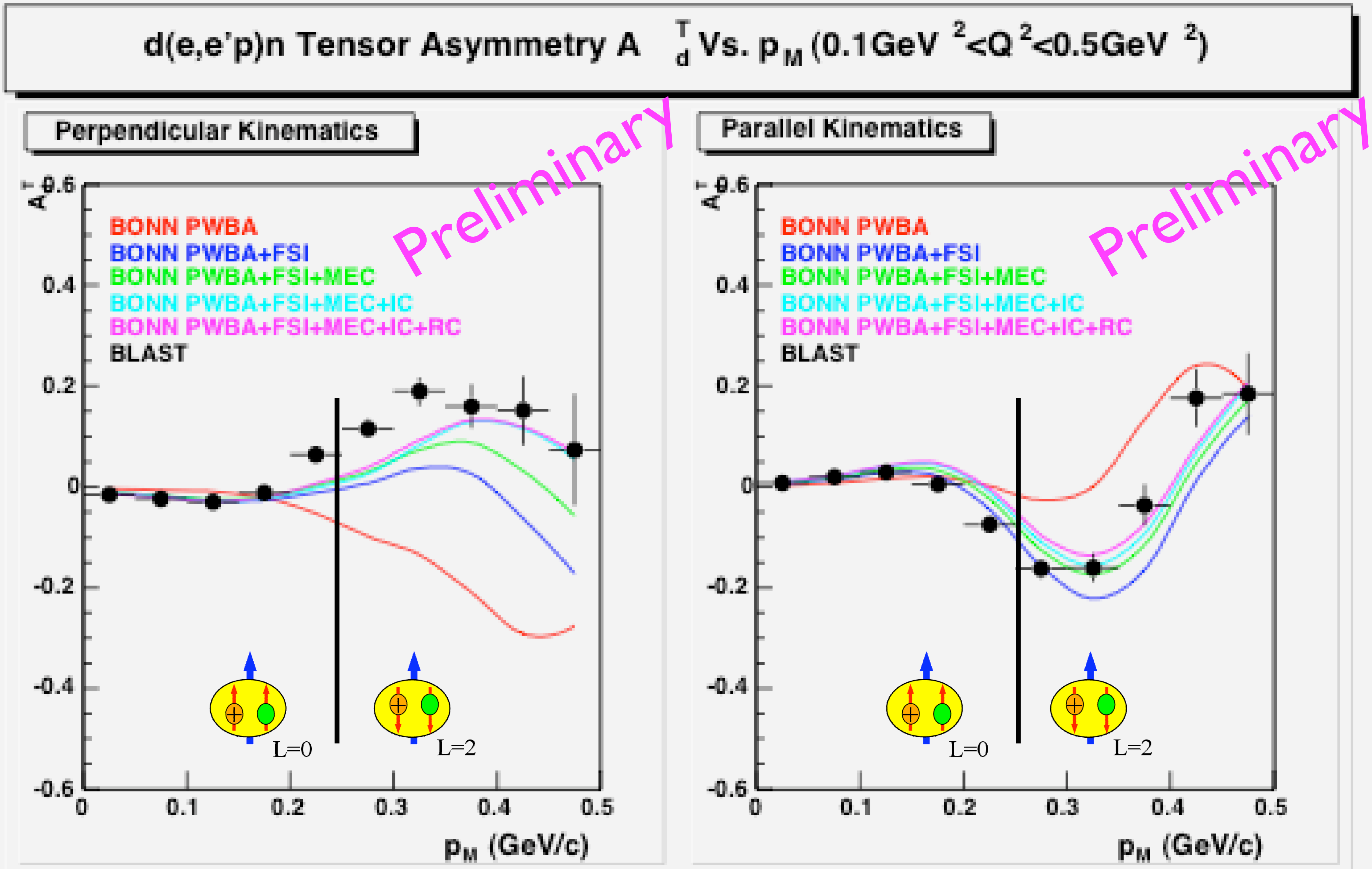
Quasi-Elastic e′p Scattering from Deuterium



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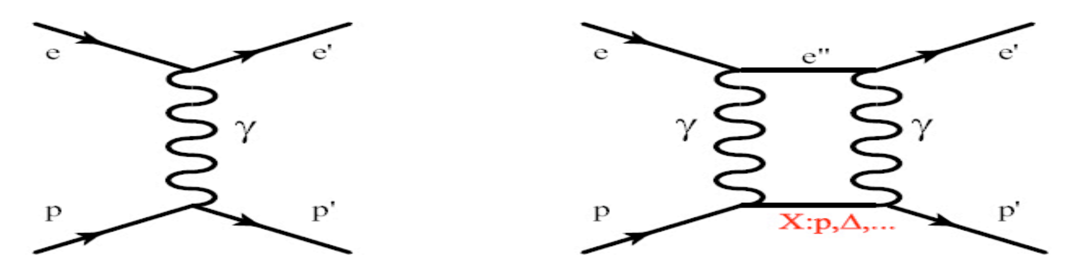
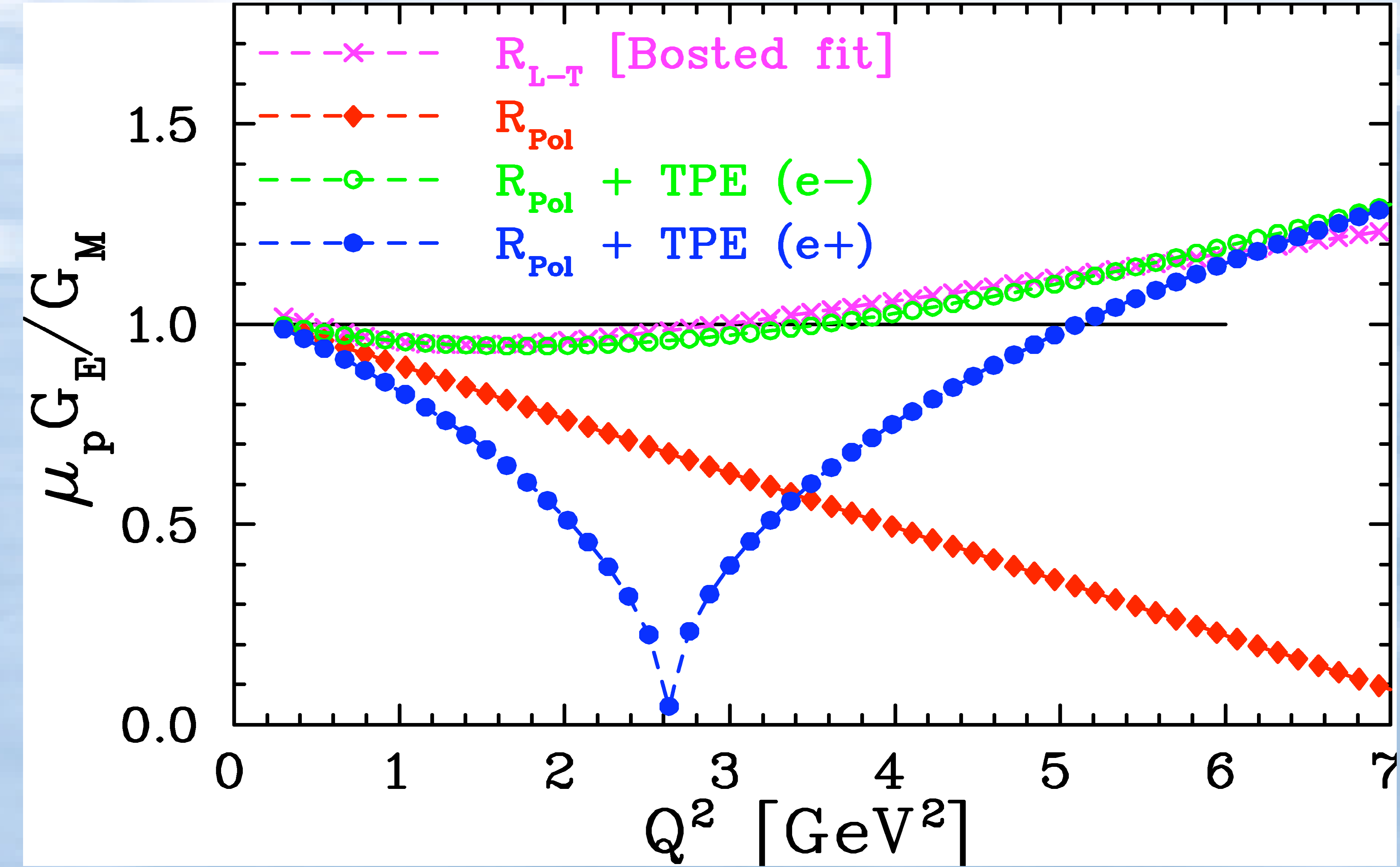
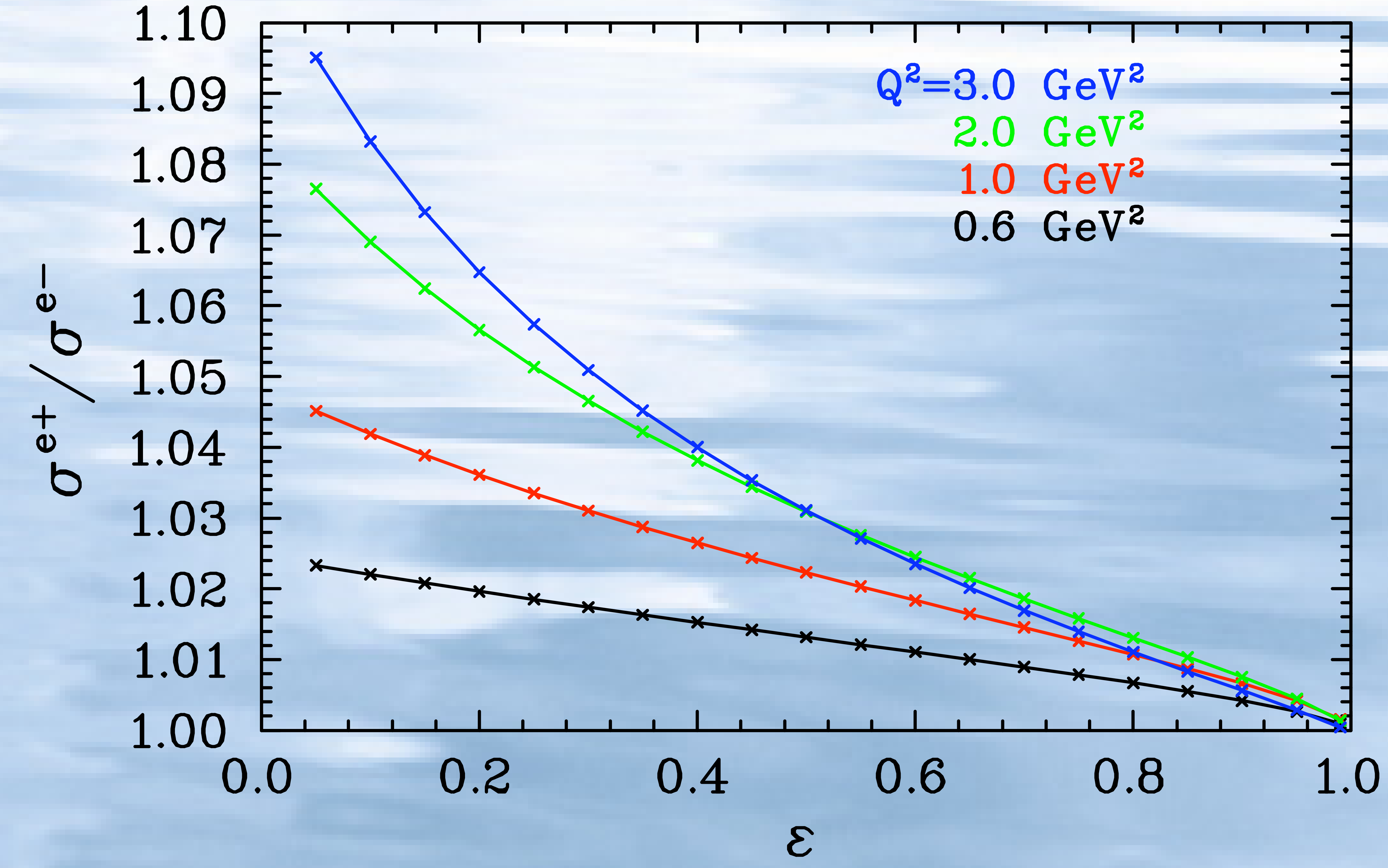
Two Photon Effect





Interference in e^-p/e^+p Cross Sections



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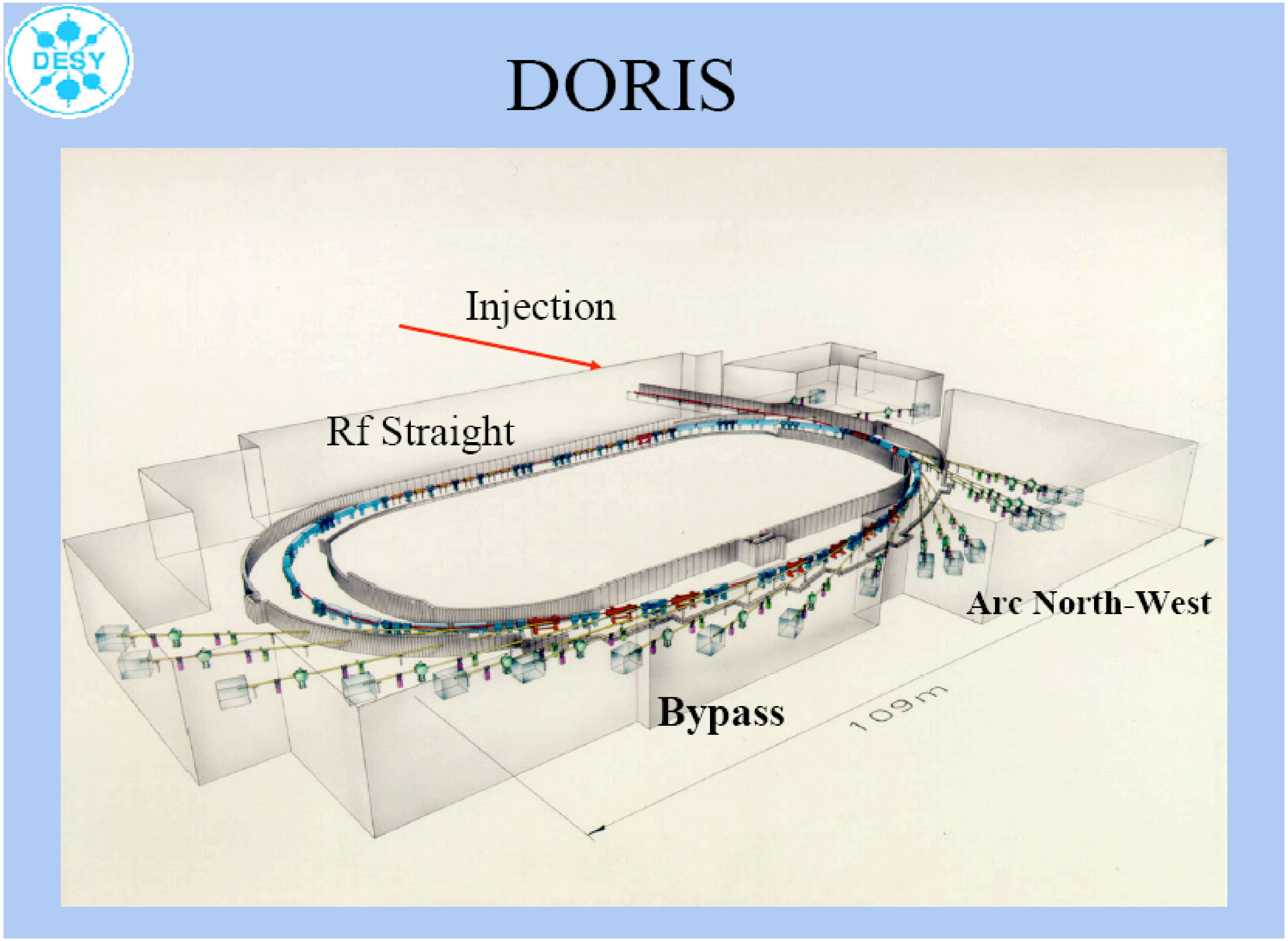

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