Vector Polarization Observables of the Deuteron and a New Measurement of the Magnetic Dipole Form Factor G_M

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University of New Hampshire Nuclear Physics Group
and the BLAST Collaboration

Ph.D. Thesis Defense
18 October 2005

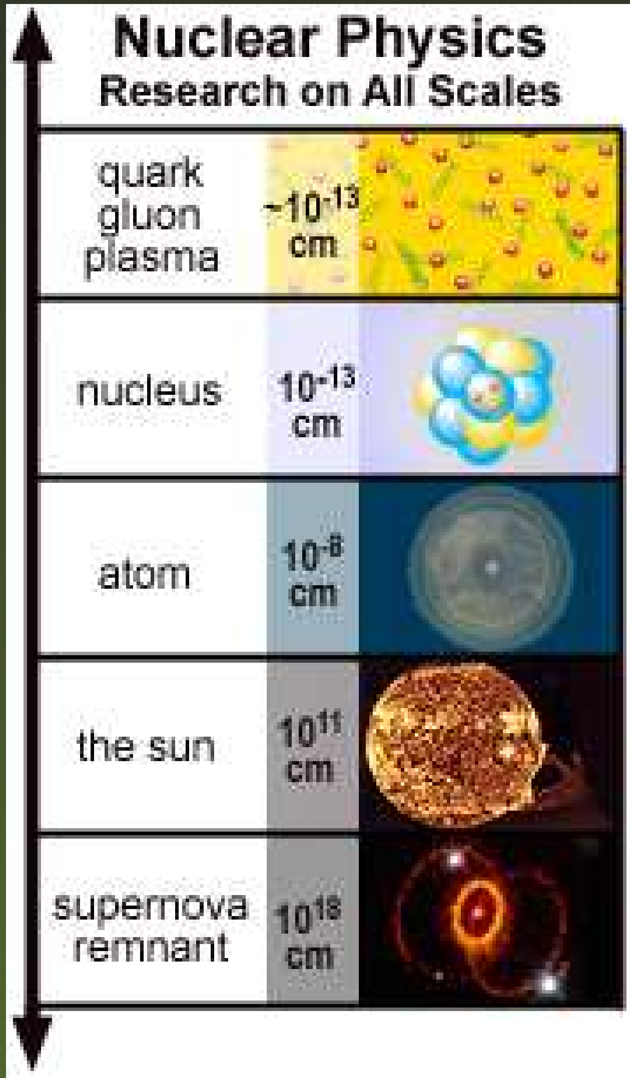
An Invitation . . .

Exploring the Electromagnetic Structure of the Deuteron:

- Beam-Target Asymmetry A_{ed}^{V}
- 1^{st} Measurement of the Vector Analyzing Power T_{11}^{e}
- New Measurement of the Magnetic Dipole Form Factor G_M

The Scale of Things

- Matter is made of atoms . . .
- The heart of the atom is the nucleus
- Nuclei contain protons and neutrons, or collectively, nucleons.



The Big Picture at UNH & MIT-Bates

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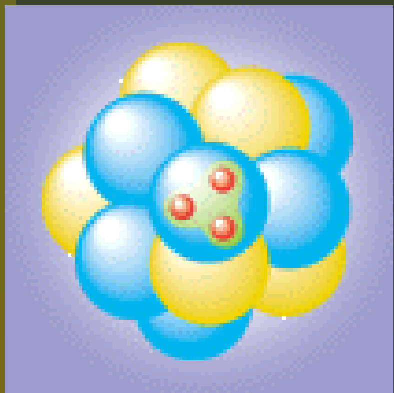

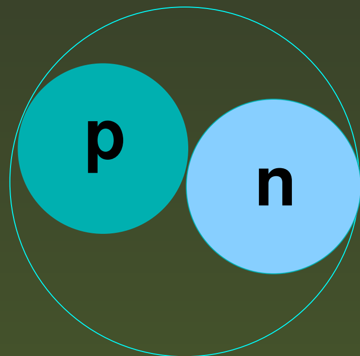

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- ${}^{2}_{1}H$ is ideal for addressing this question.

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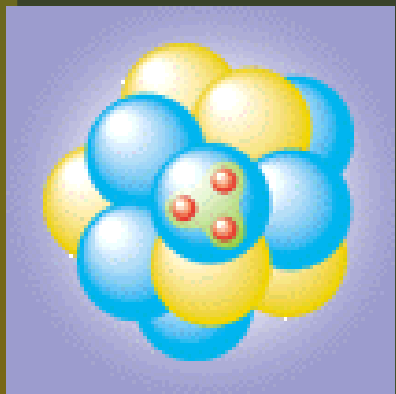

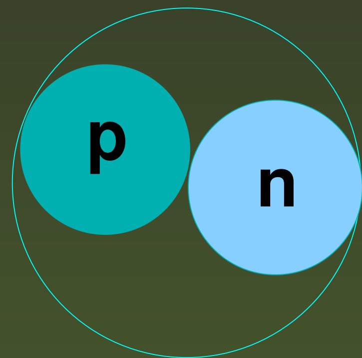

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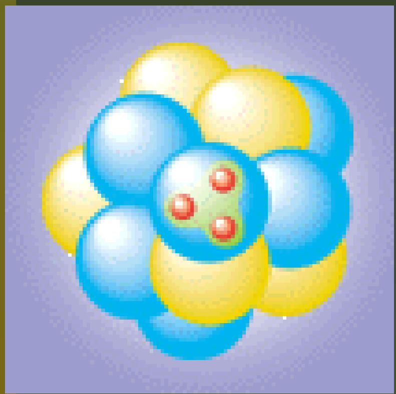

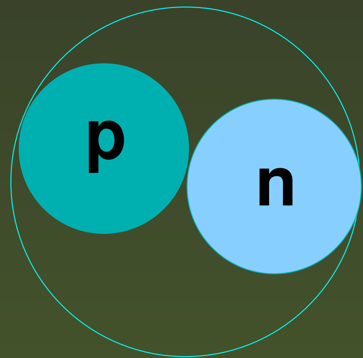

The Deuteron!

- ${}^2_1H$ is ideal for addressing this question.
- How do we describe nuclear shape and boundaries?
- $\longrightarrow$ electricity and magnetism in the nucleus

Polarization of Spins

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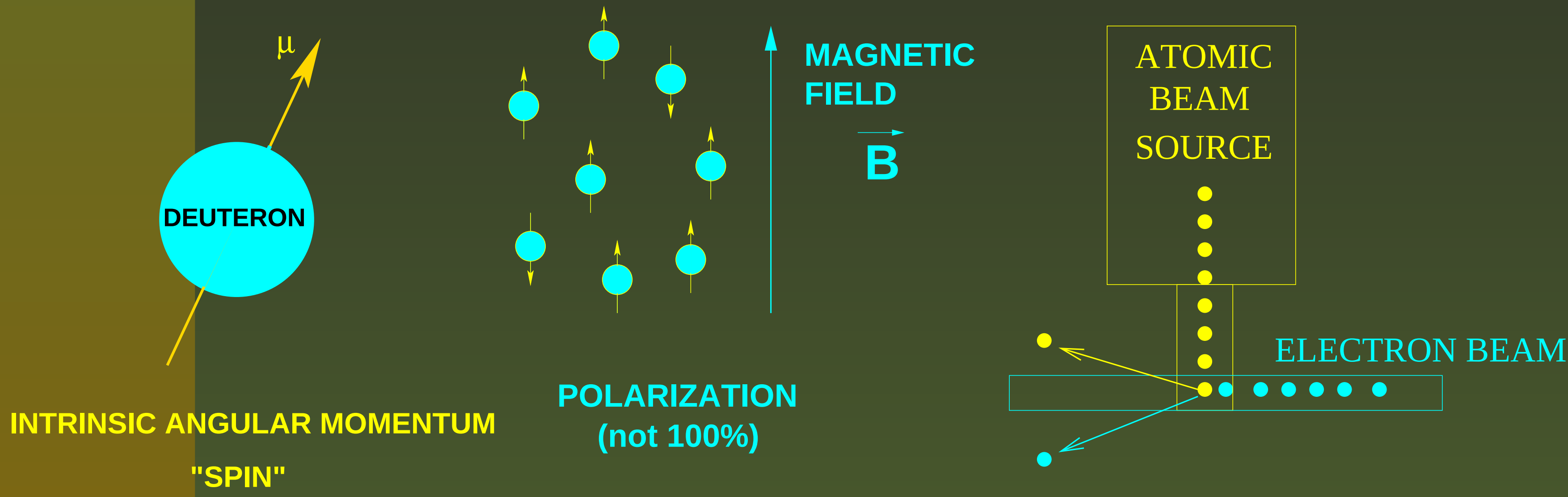

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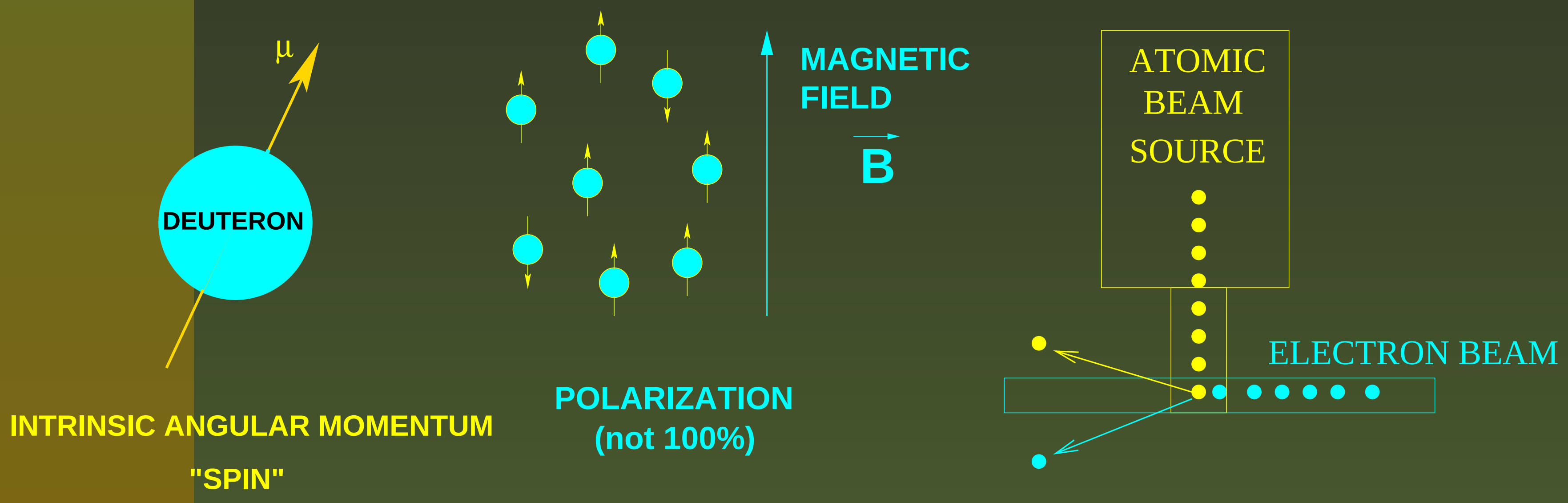
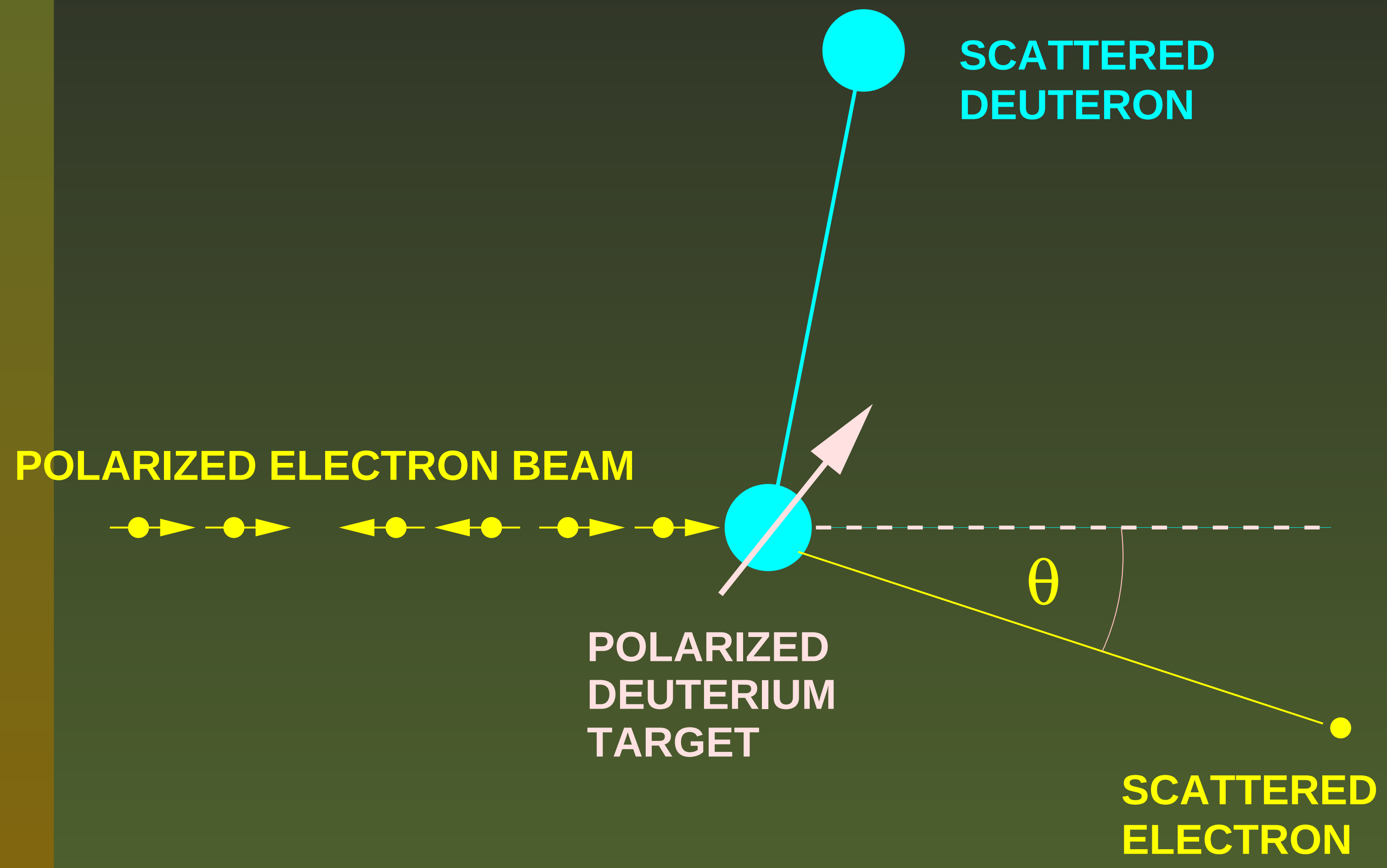
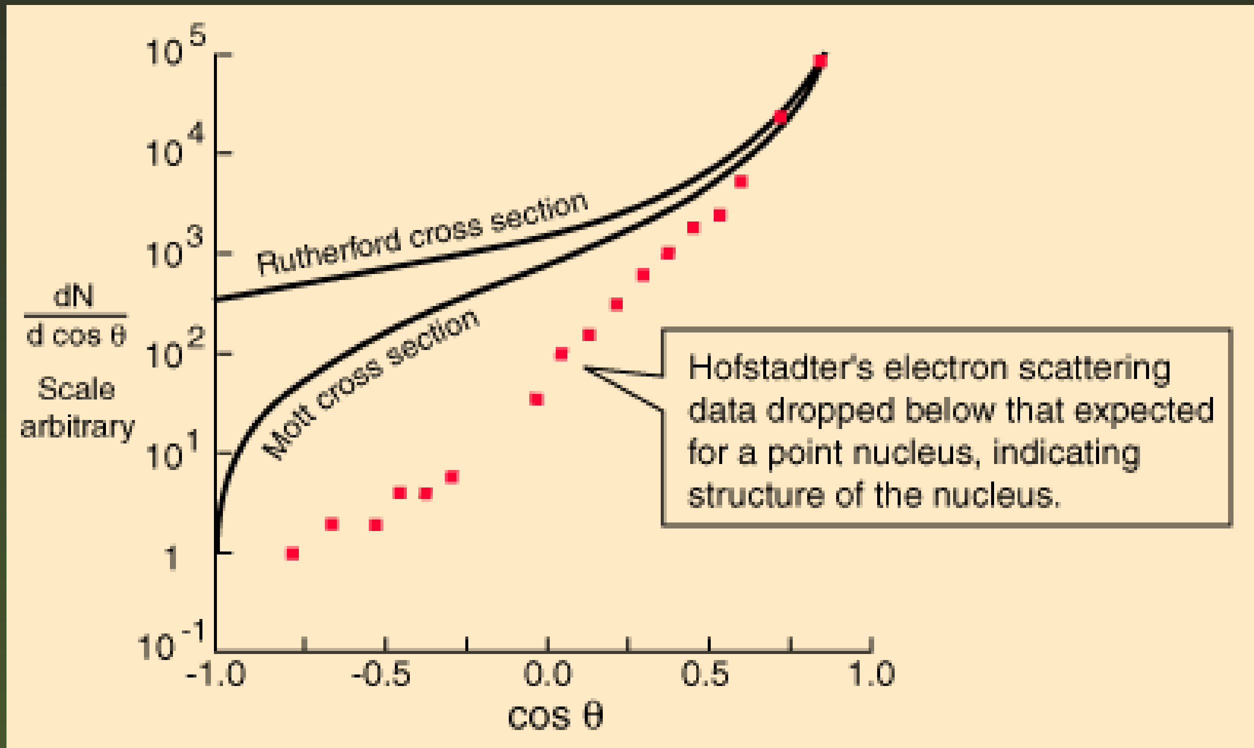


- Polarization observables will manifest themselves

Polarized ed-Elastic Scattering



Hoftstadter’s Watershed



- Electron Scattering is a time tested method

Electromagnetic Structure

Unpolarized Scattering Cross Section

$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot f_{rec}^{-1} \cdot S$$

- $S = A(Q^2) + B(Q^2) tan^2 \frac{\theta_e}{2}, \qquad \tau = \frac{Q^2}{4M_d^2}$

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

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  - can separate A and B, and from B get G_M
  - can not separate G_C and G_Q

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We need another observable!

Polarization Observables

Polarized Scattering Cross Section

$$\frac{d\sigma}{d\Omega}(h, P_z, P_{zz}) = \Sigma + h\Delta$$

- $\Sigma = (\frac{d\sigma}{d\Omega})_0[1 + \Gamma] \quad \rightarrow \quad \Gamma$ contains tensor terms T_{2q}

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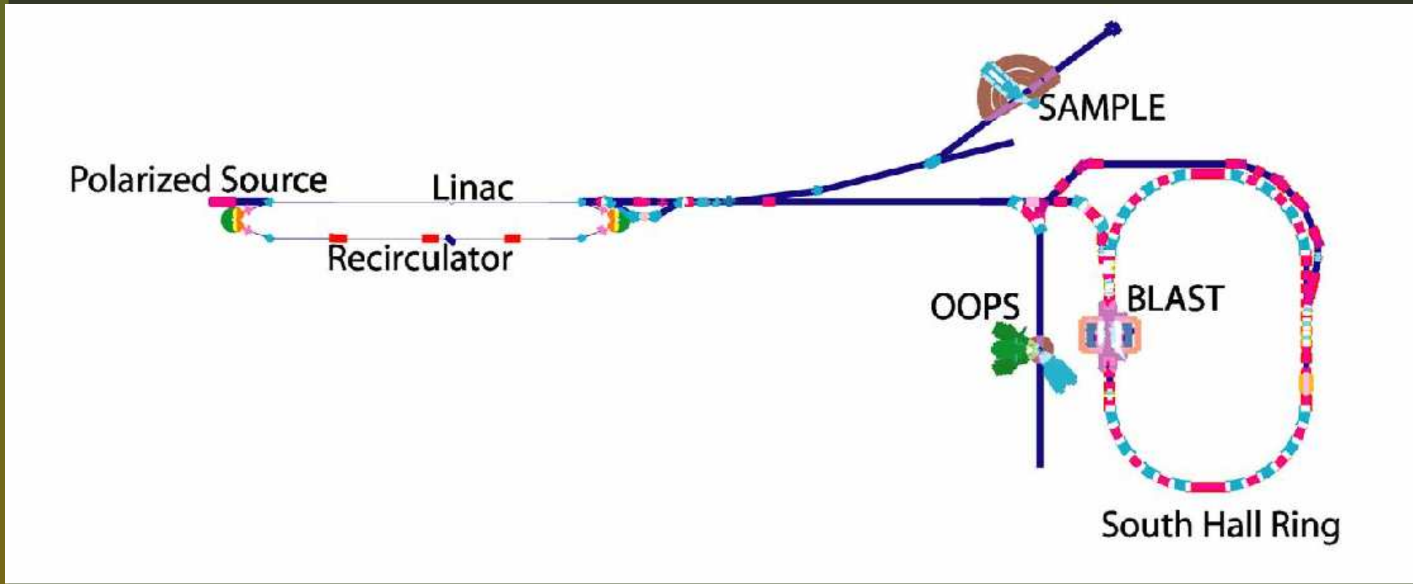
$$T^e_{11}(Q^2, \theta_e) = \sqrt{\frac{3}{2}}\frac{1}{S}\frac{4}{3}[\tau(1+\tau)]^{1/2} G_M(G_C + \frac{\tau}{3}G_Q) tan\frac{\theta_e}{2}$$

$$T_{20}(Q^2, \theta_e) = -\sqrt{2}\frac{1}{S}\tau\left(\frac{4}{3}G_C G_Q + \frac{4}{9}G_Q^2 + \frac{1}{6}(1+(\tau+1)tan^2(\theta_e/2))G_M^2\right)$$

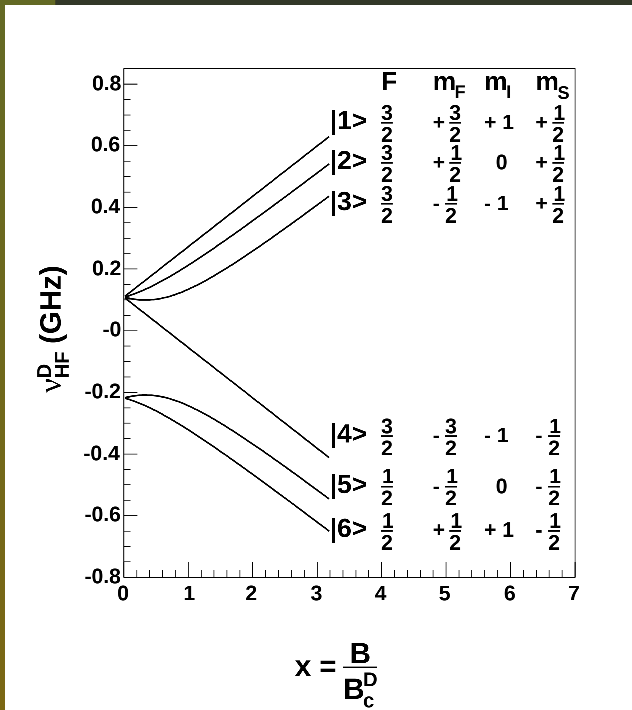
$$T_{21}(Q^2, \theta_e) = -\frac{2}{\sqrt{3}}\frac{1}{S}\tau\left(\tau + \tau^2 sin^2(\theta_e/2)\right)^{1/2} G_M G_Q sec\frac{\theta_e}{2}$$

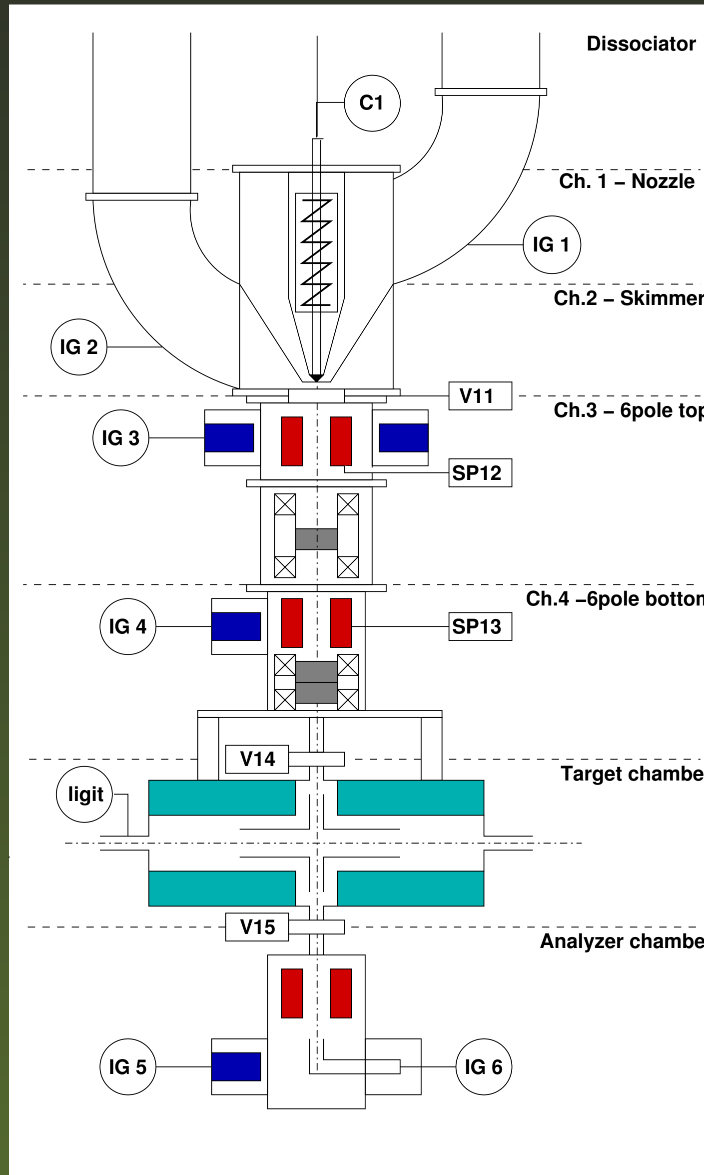
The MIT-Bates Linac



- Beam Energy of 850 MeV
- Beam Polarization of $65 \pm 4\%$
- Average / Max Injection Current = $100 \; / \; 200$ mA

The Polarized ABS Target

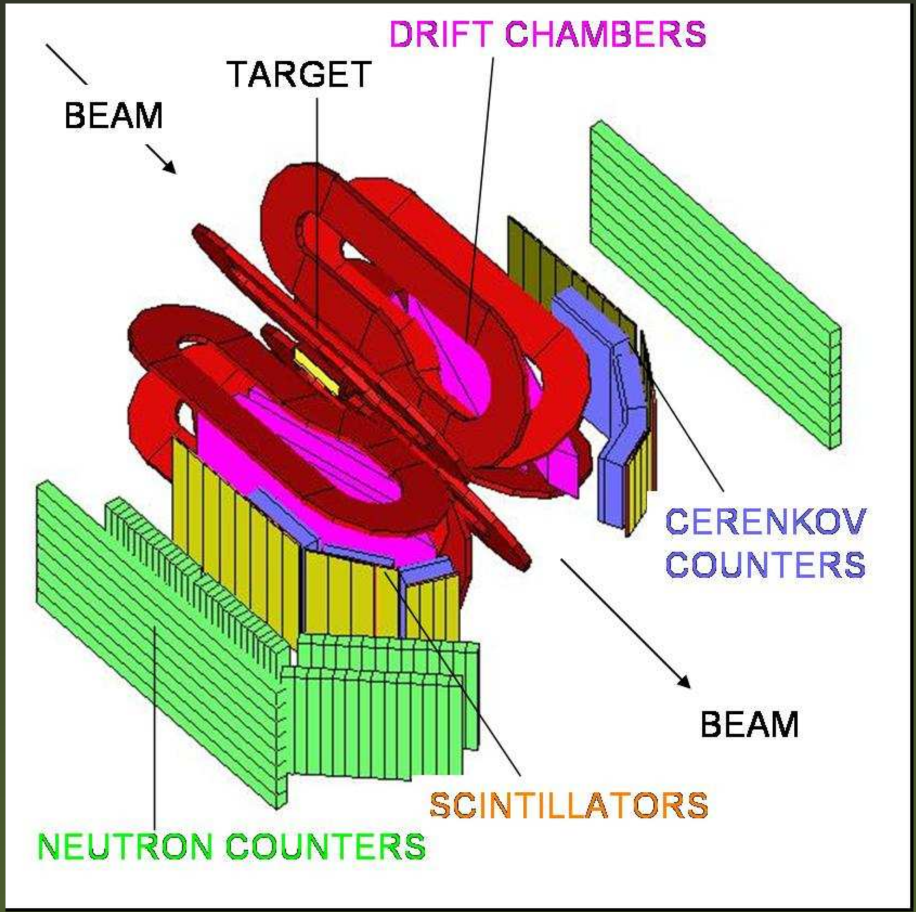




- RF dissociator produces atomic deuterium
- Sextupoles to select atomic states
- RF transitions to access nuclear polarizations
- Average Intensity $\sim\ 2.6\times10^{16}\ atoms\cdot s^{-1}$

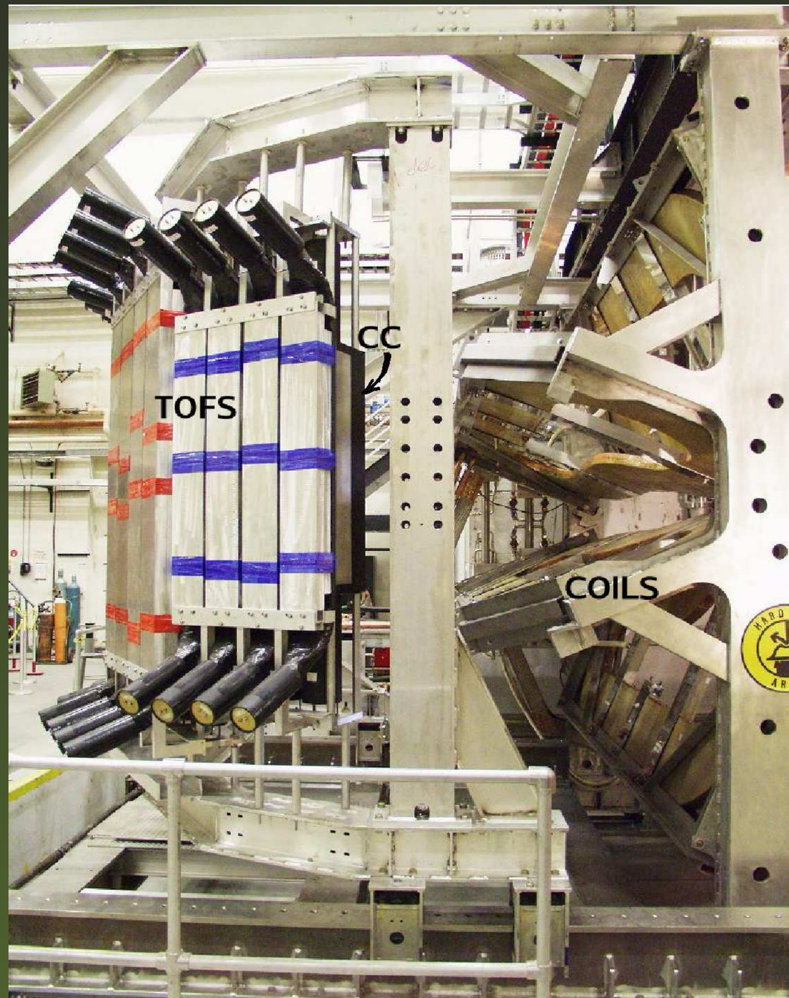
The BLAST Detector

- **Large Acceptance:**
  - $20° < \theta_e < 80°$
  - $0.1 < Q^2 < 0.8\ [GeV/c]^2$
  - $-22° < \phi < 22°$
- **BLAST Field**
  - $B_{max} = 3.8\ [kG]$
- **Drift Chamber Tracking:**
  - $\frac{\Delta p}{p} = 3\%$
  - $\Delta\theta_e = 0.5°$



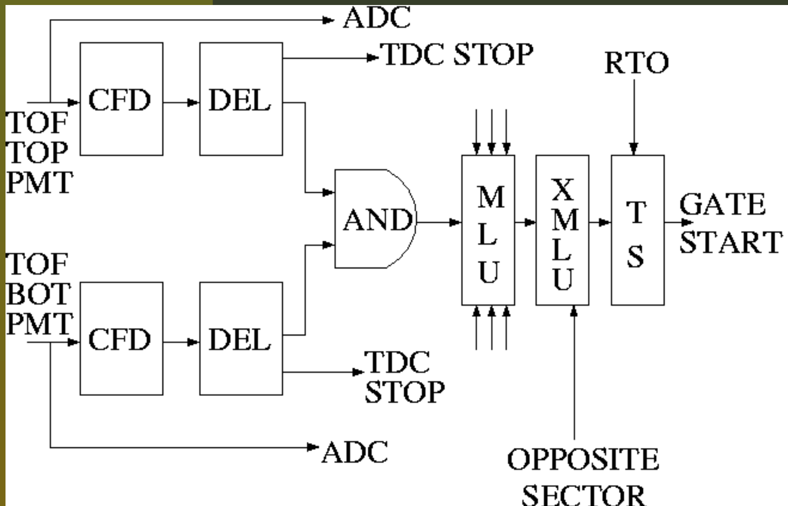
Time-of-Flight Scintillators

- **Fast Timing Information**
  - TDC 50 $[ps/ch]$
  - Key to BLAST Trigger
- **Energy Information**
  - ADC 50 $[fC/ch]$
- **Performance**
  - $\delta_T < 500\ [ps]\ (FWHM)$
  - Efficiency $> 99\%$



The BLAST DAQ

- • NIM & CAMAC electronics
- • 16 bit sector MLU
- • XMLU and Trigger Supervisor
- • Fastbus TDCs and ADCs



Simplified Trigger

showing TOF logic

Beam-Target Vector Asymmetry

$$A^V_{ed\ theory} \equiv \frac{\Delta}{\Sigma} = \sqrt{3}\,[\ \frac{1}{\sqrt{2}} cos\theta^*\ T^e_{10}(Q^2,\theta_e)\ \ -\ sin\theta^* cos\phi^*\ T^e_{11}(Q^2,\theta_e)\ ]$$

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target polarization angles w.r.t. $\vec{q}$ are θ^* and ϕ^*

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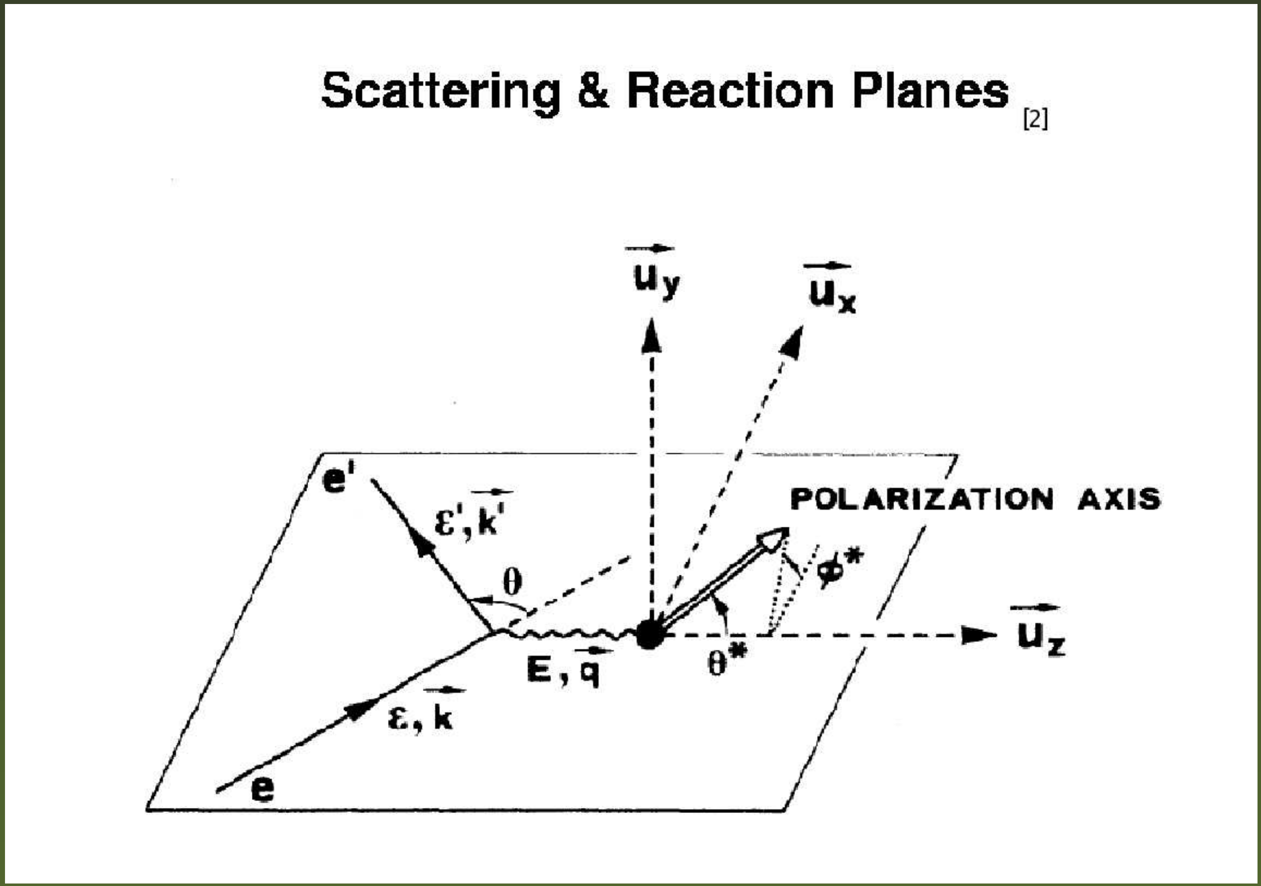
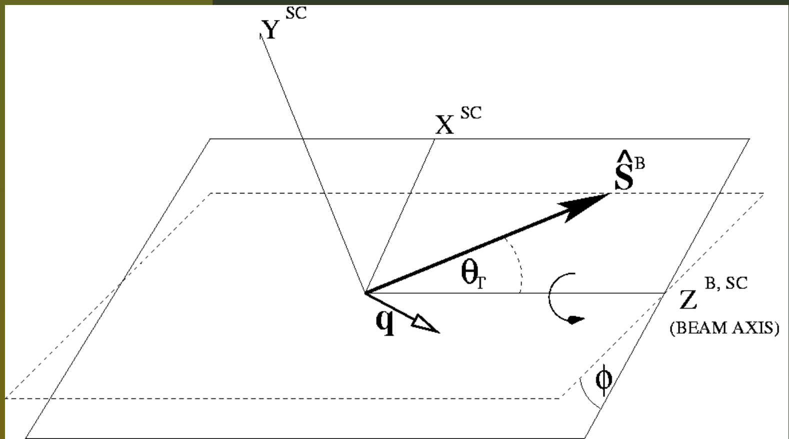


Defining θ^* and ϕ^*

$R_z^{SC}(\phi_e)\text{BLAST}_{c/s} \rightarrow \text{Scat}_{c/s}$



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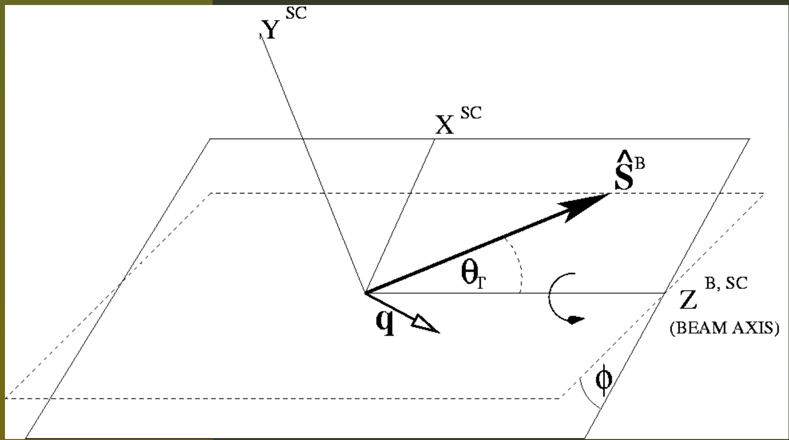
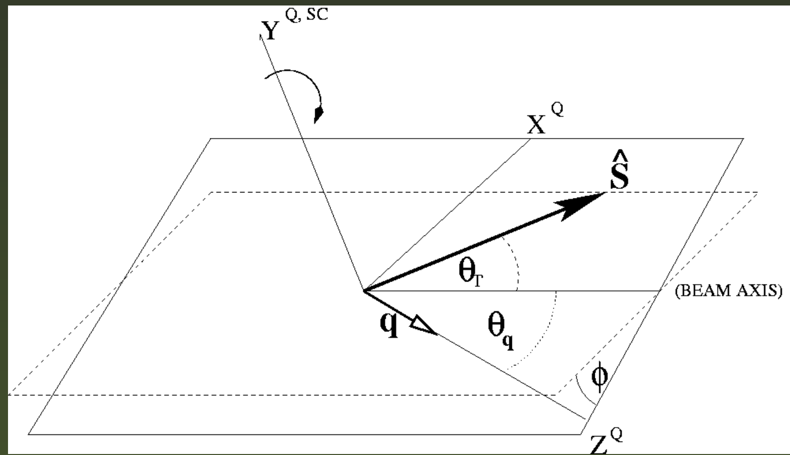
$$R_z^{SC}(\phi_e)\mathrm{BLAST}_{c/s} \rightarrow \mathrm{Scat}_{c/s} \quad + \quad R_y^{Q}(\theta_{\vec{q}})\mathrm{Scat}_{c/s} \rightarrow \mathrm{Physics}_{c/s}$$





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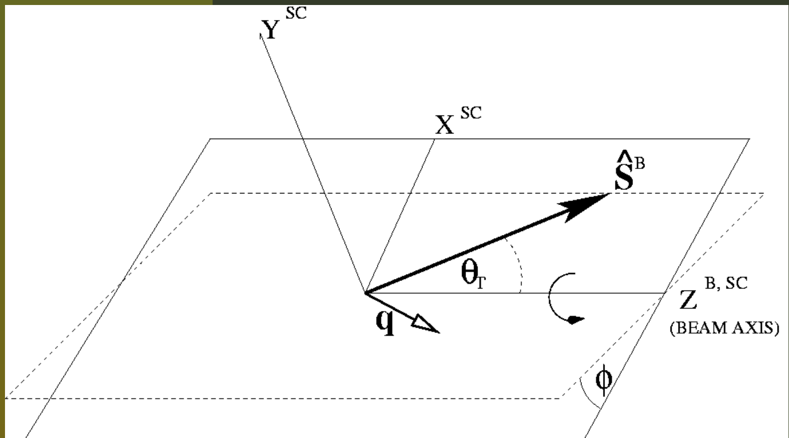

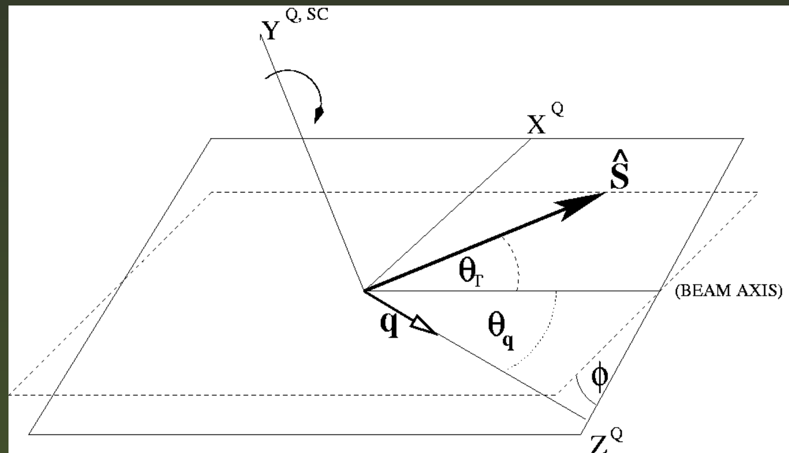

$$\theta^* = \cos^{-1}(-\sin\theta_{\vec{q}}\ \cos\phi_e \sin\theta_T + \cos\theta_{\vec{q}}\ \cos\theta_T)$$

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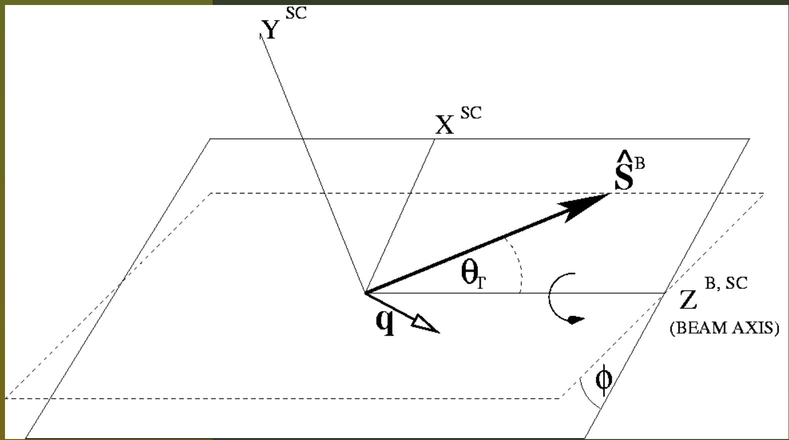

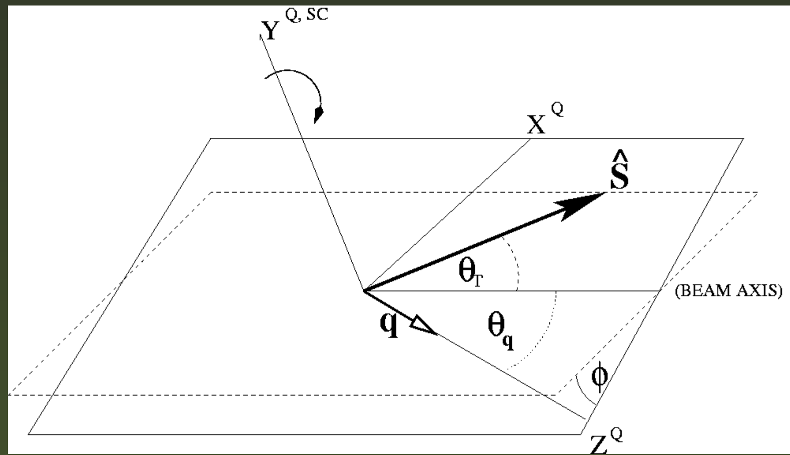

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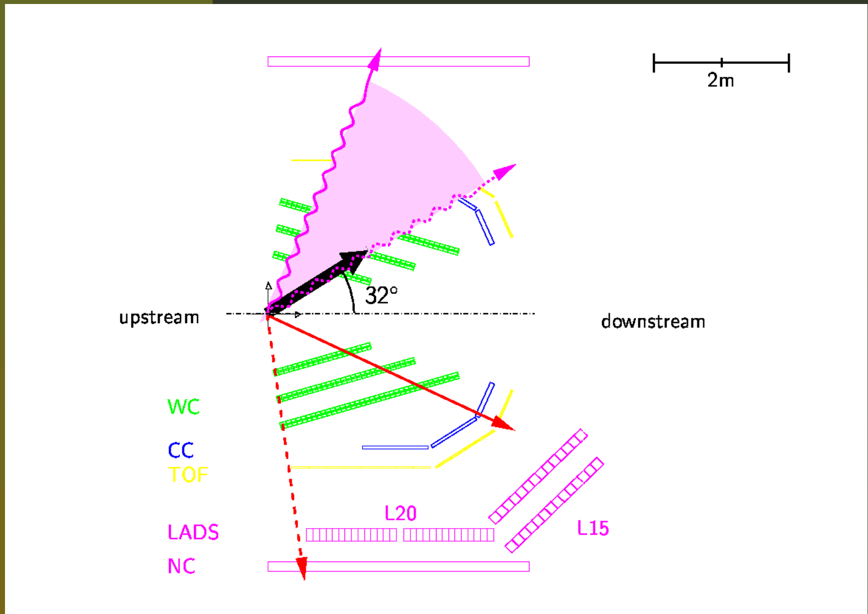
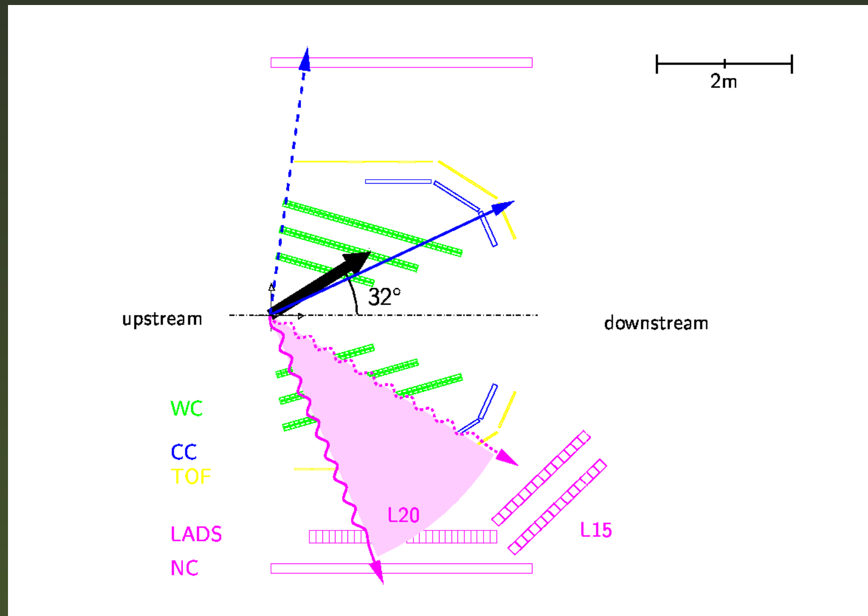
Elastic $\rightarrow$ $\theta_{\vec{q}}$ depends only on θ_e

- $\theta_{\vec{q}} = \tan^{-1}\left(\frac{k'\sin\theta_e}{k-k'\cos\theta_e}\right), \qquad k' = \frac{E_{beam}}{1+\frac{2E_{beam}\sin^2\theta_e/2}{M_d}}$

Parallel & Perpendicular Kinematics





Parallel Kinematics:

Electron Right

$\vec{q}$ Left & $\sim \parallel \theta_T$

Perpendicular Kinematics:

Electron Left

$\vec{q}$ Right & $\sim \perp \theta_T$

Extracting T_{10}^{e} and T_{11}^{e}

- Exploit the symmetrical geometry of BLAST!

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- Extract the vector analyzing powers T_{10}^{e} and T_{11}^{e}

Extracting T^e_{10} and T^e_{11}

- Exploit the symmetrical geometry of BLAST!
- Measure $A^V_{ed,\perp}$ and $A^V_{ed,\parallel}$ simultaneously
- Extract the vector analyzing powers T^e_{10} and T^e_{11}

$$T^e_{10} = \sqrt{\frac{2}{3}}\left[\frac{sin\theta^*_\parallel cos\phi^*_\parallel A_\perp - sin\theta^*_\perp cos\phi^*_\perp A_\parallel}{cos\phi^*_\parallel sin\theta^*_\perp cos\phi^*_\perp - cos\theta^*_\perp sin\theta^*_\parallel cos\phi^*_\parallel}\right]$$

$$T^e_{11} = \frac{\sqrt{3}}{3}\left[\frac{cos\theta^*_\parallel A_\perp - cos\theta^*_\perp A_\parallel}{cos\theta^*_\perp sin\theta^*_\parallel cos\phi^*_\parallel - cos\theta^*_\parallel sin\theta^*_\perp cos\phi^*_\perp}\right]$$

Theory $\Longleftrightarrow$ Experiment

$$A^V_{ed,\ theory} \ \equiv \ \frac{\Delta}{\Sigma} = \sqrt{3}\,[\ \frac{1}{\sqrt{2}} cos\theta^*\ T^e_{10}(Q^2) \ \ - \ sin\theta^* cos\phi^*\ T^e_{11}(Q^2)\ ]$$

$$A^V_{ed,\ exp} \ \equiv \ \frac{1}{4hP_z\sigma_0}[\sigma(+,+,+1) - \sigma(-,+,+1) - \sigma(+,-,+1) + \sigma(-,-,+1)]$$

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BEAM-TARGET POLARIZATION STATES $\sigma(h, V, T)$

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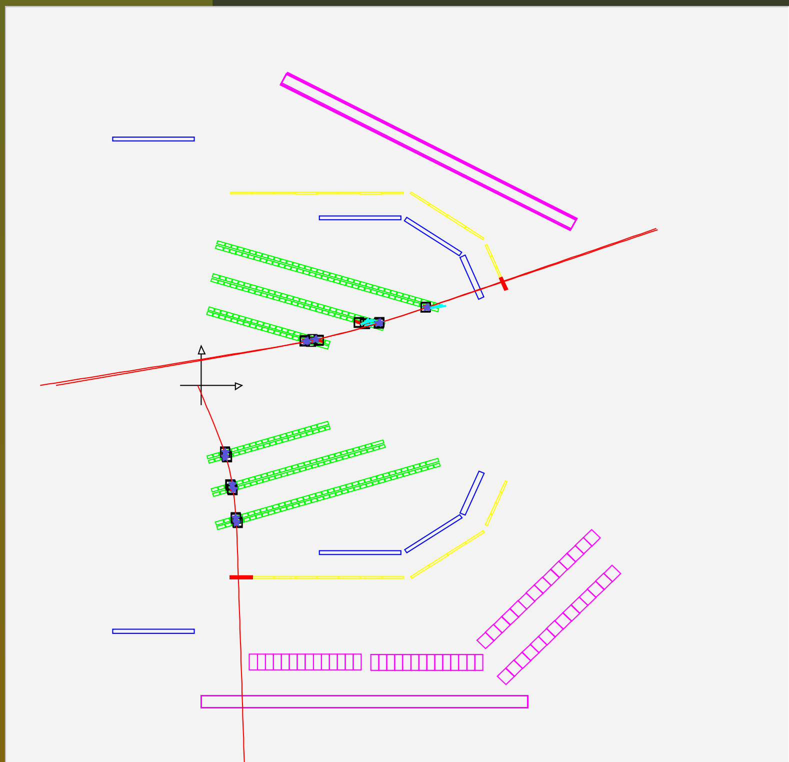
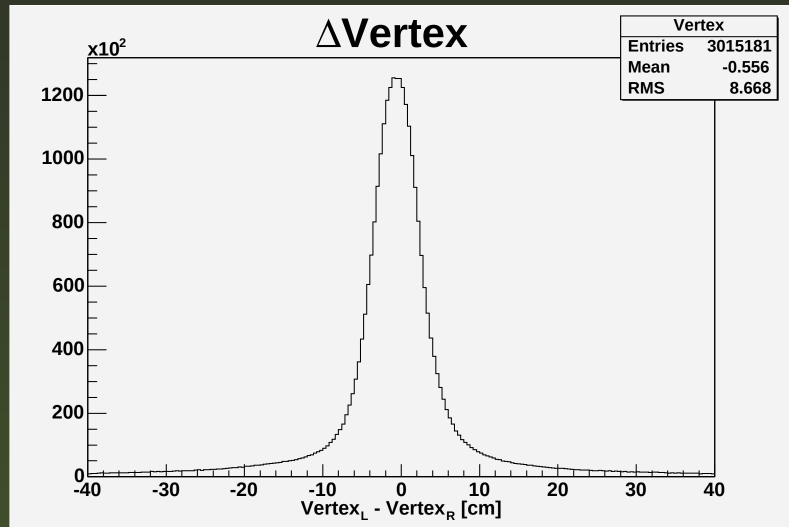
Summary and Preview:

- Measure $A^{ed}_{V,\perp}$ and $A^{ed}_{V,\parallel}$
- Extract T^{e}_{10} and T^{e}_{11} !
- Use BLAST $\&$ World Data in a $\chi^2_{\nu}(G_C, G_Q, G_M)$ analysis

General Event Selection

e.g. a poor candidate:

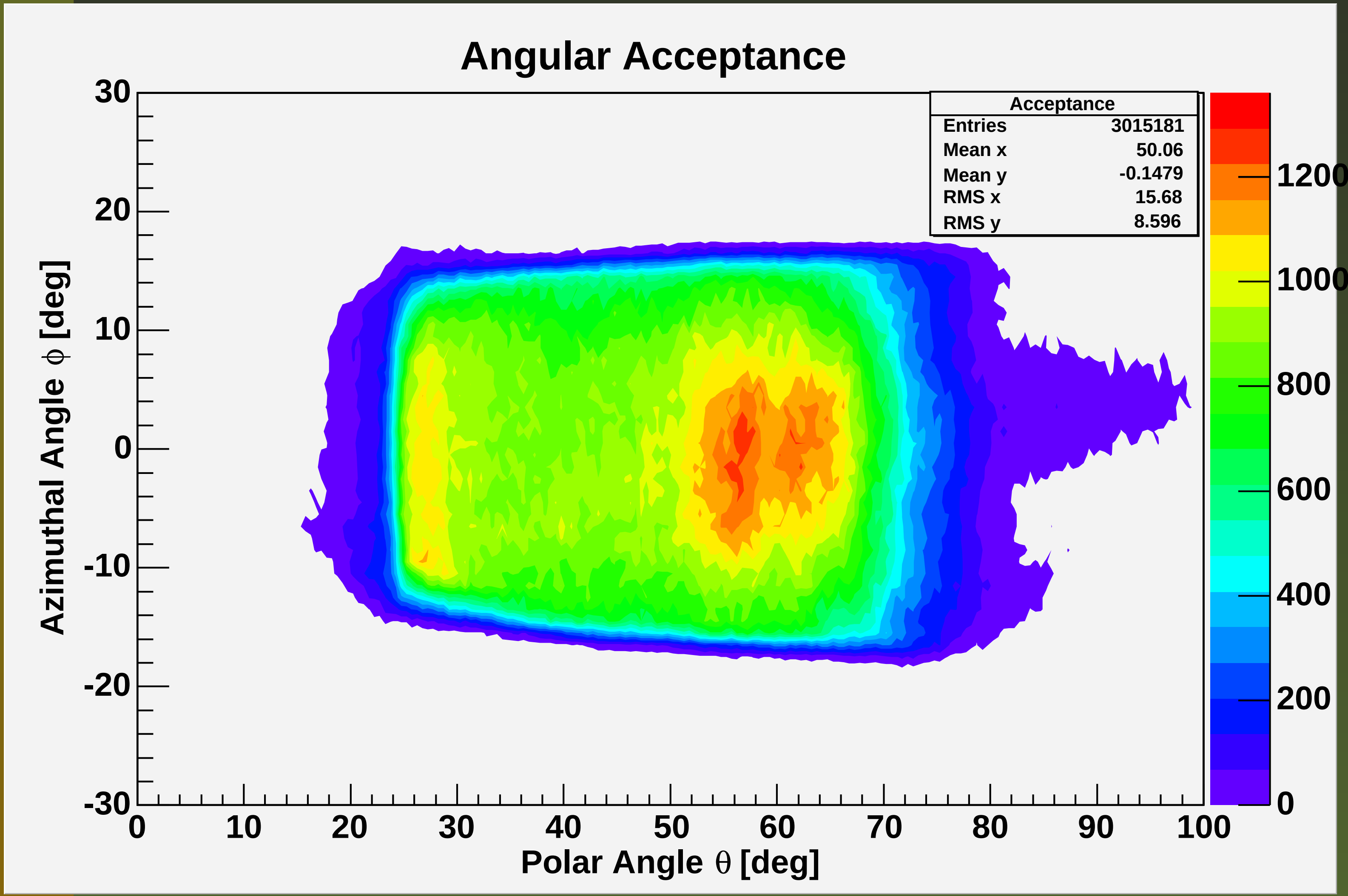




Vertex Cuts

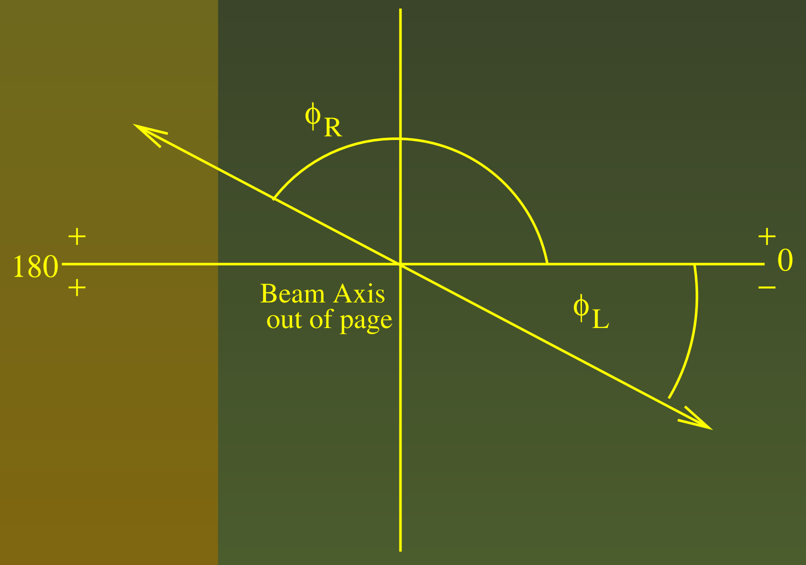
- common vertex
- target region

General Event Selection

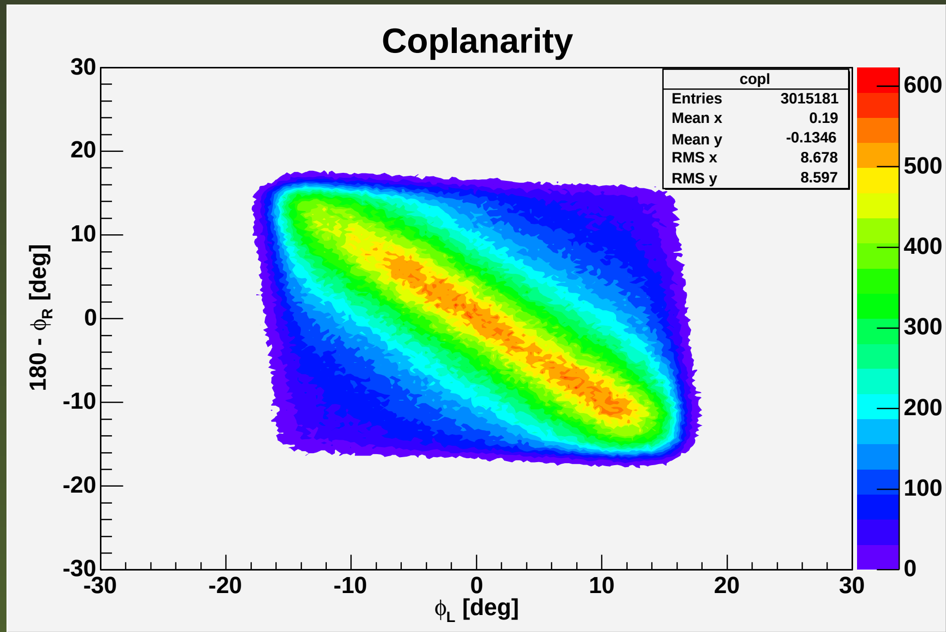


Selection of Elastic Deuterons

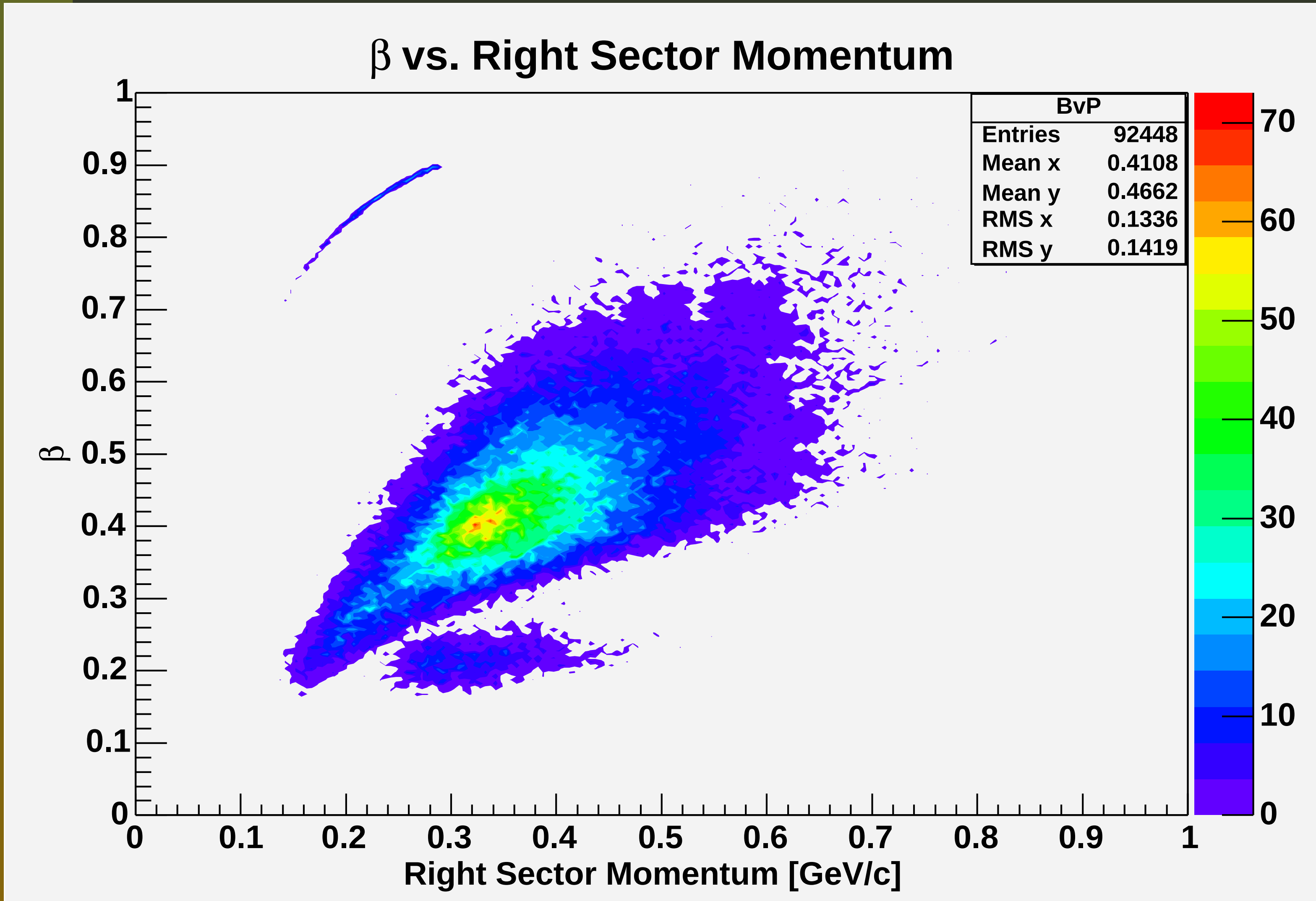
- Two-body final state is coplanar with beam axis
- Cut on coplanarity!



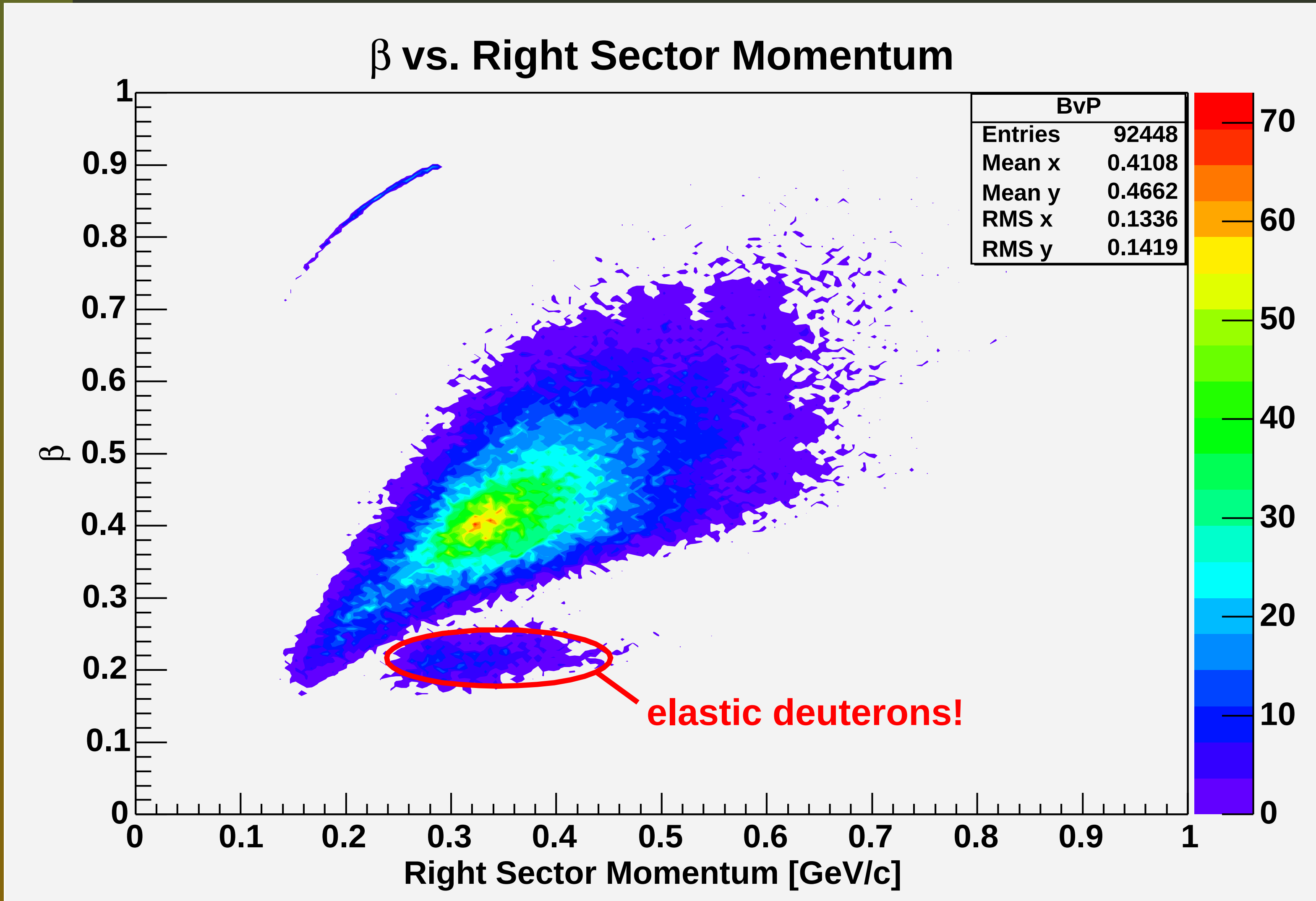
$180 - \phi_R + \phi_L = 0$



Selection of Elastic Deuterons



Selection of Elastic Deuterons



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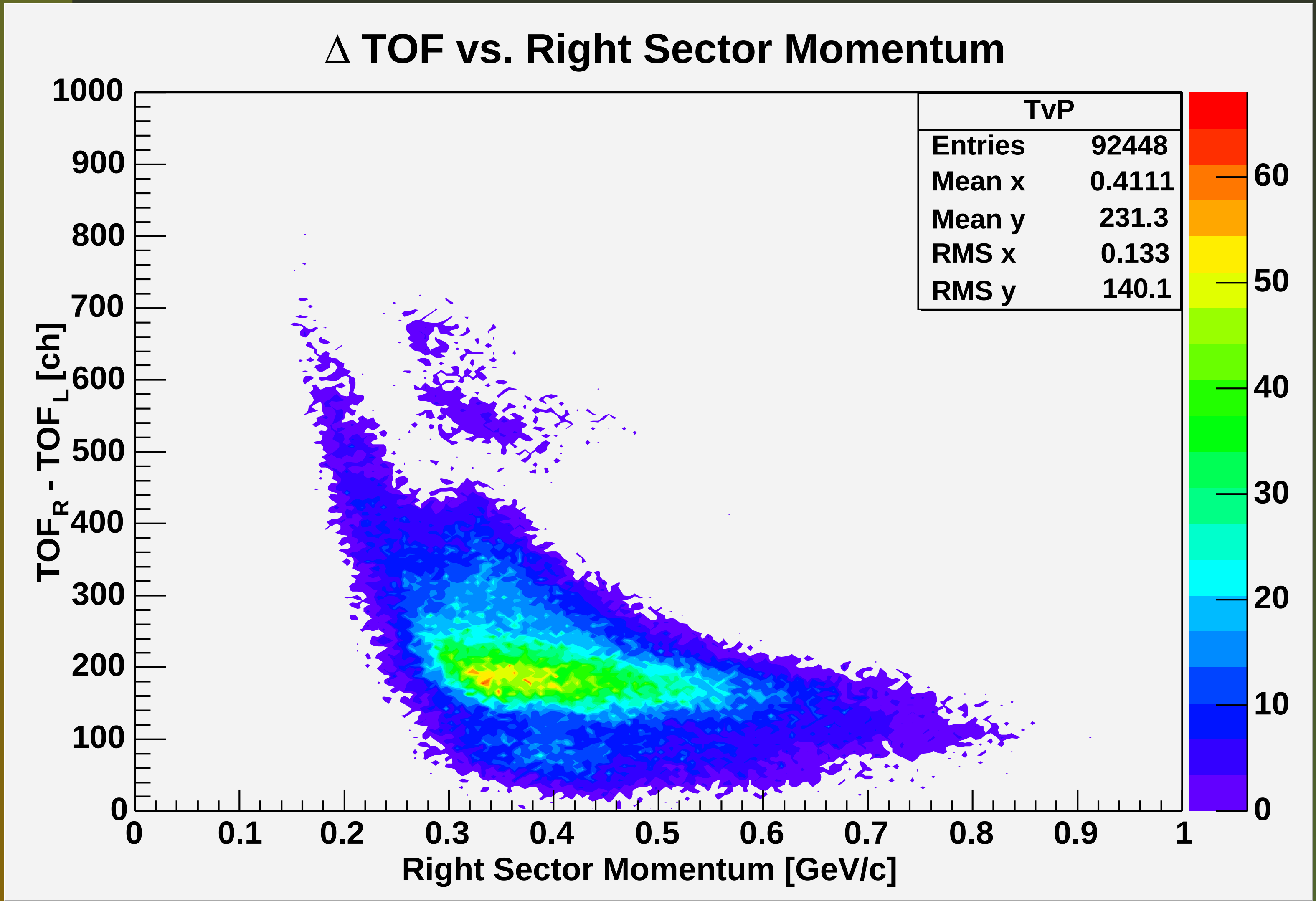

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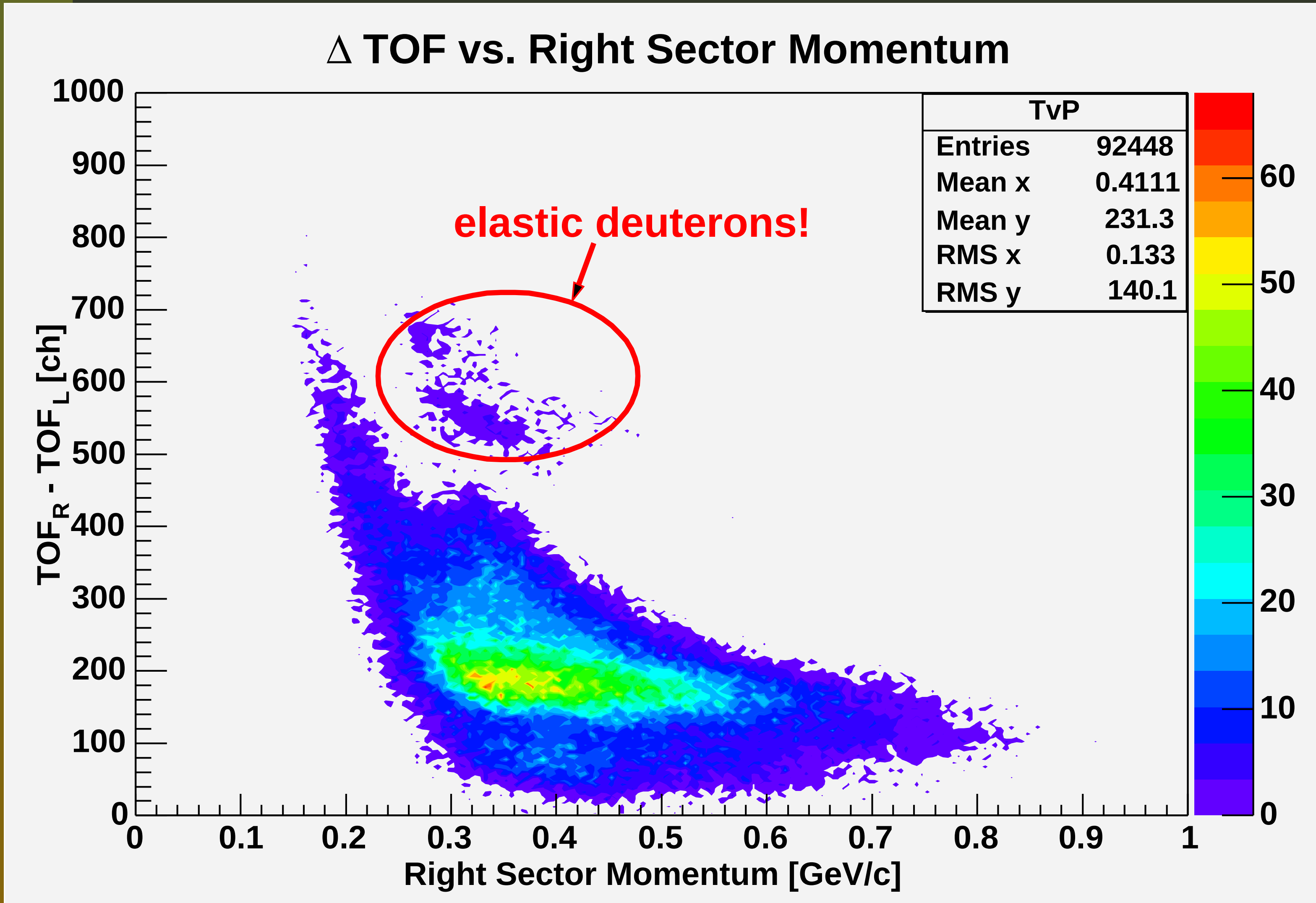
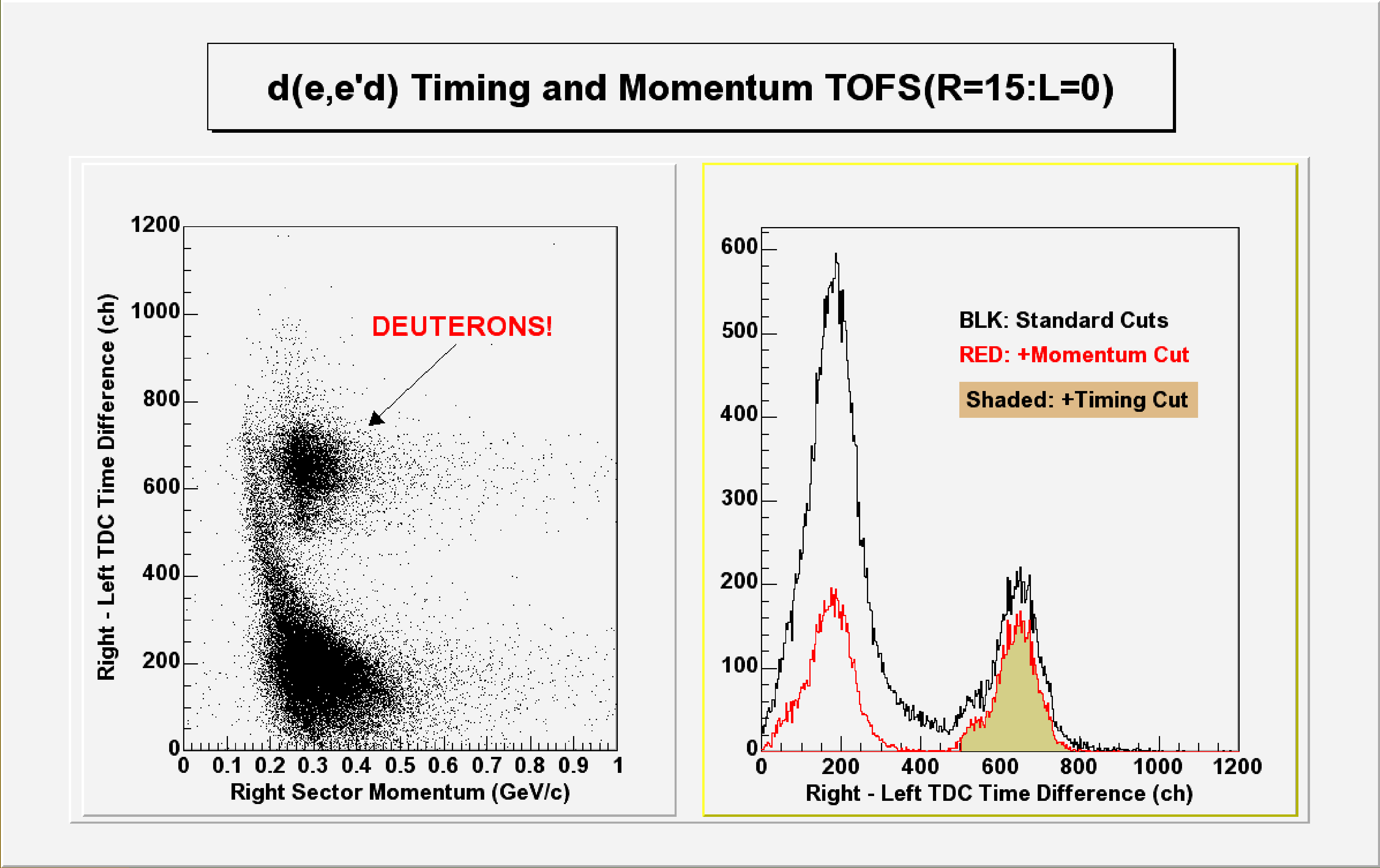
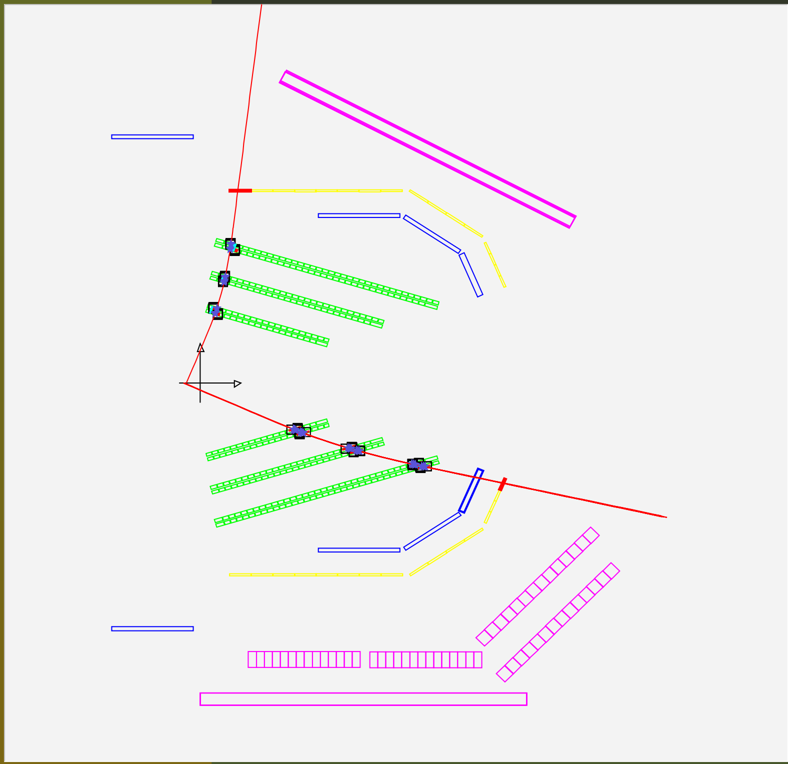
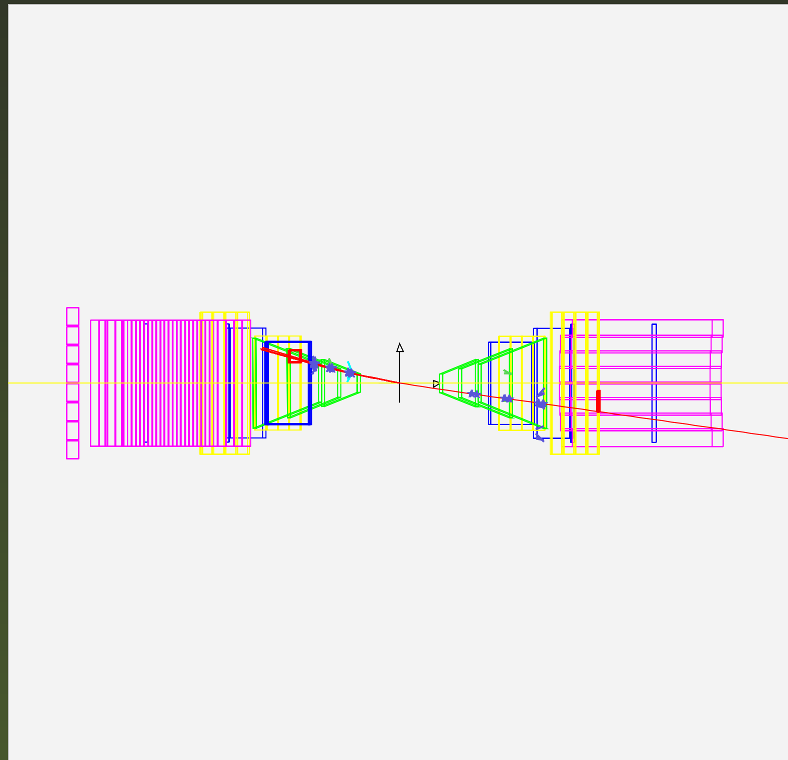


Selection of Elastic Deuterons



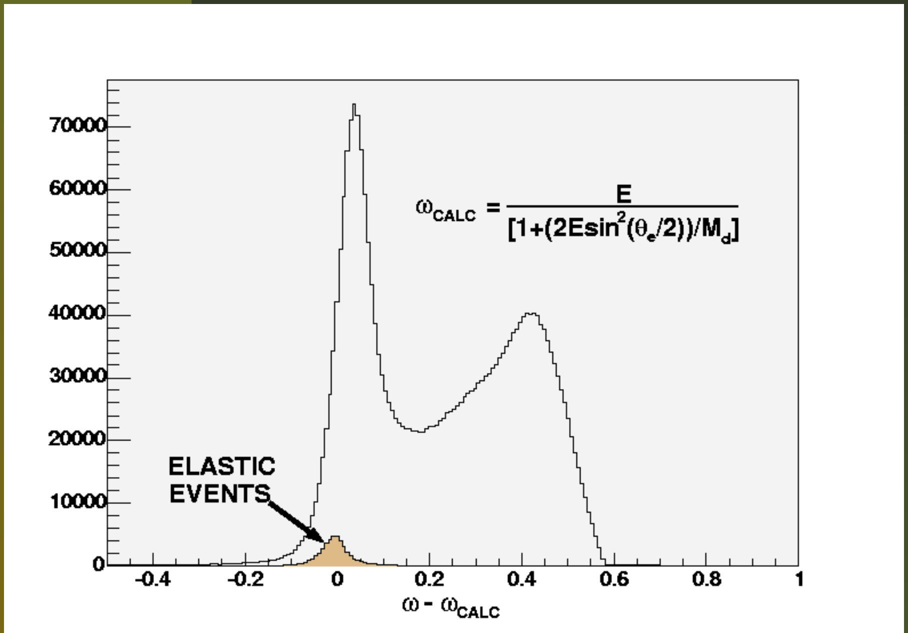
Good Elastic Candidate

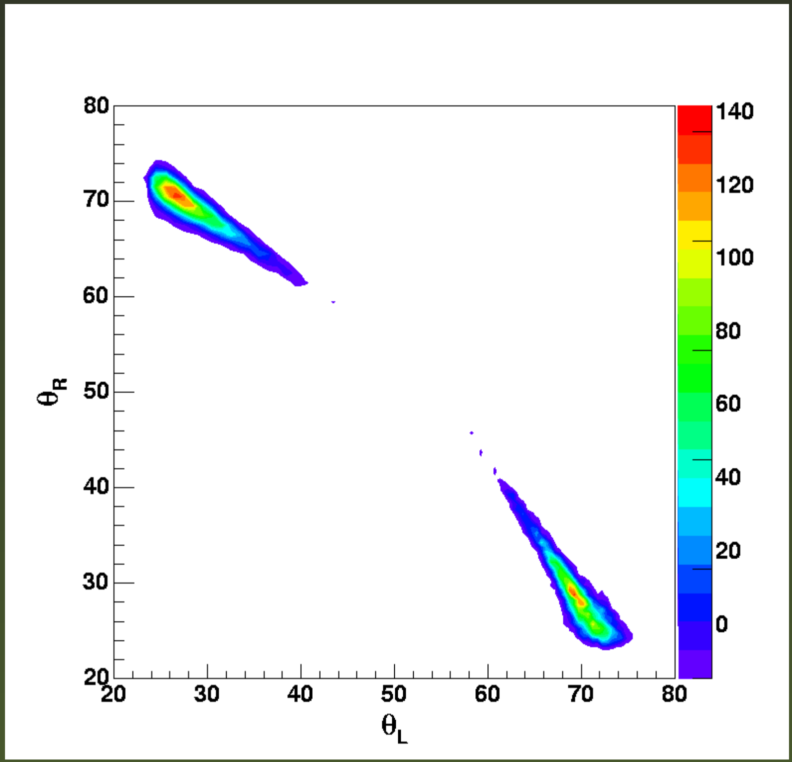




- General data quality cuts satisfied
- Elastic kinematics and timing cuts satisfied

Quality of the Data

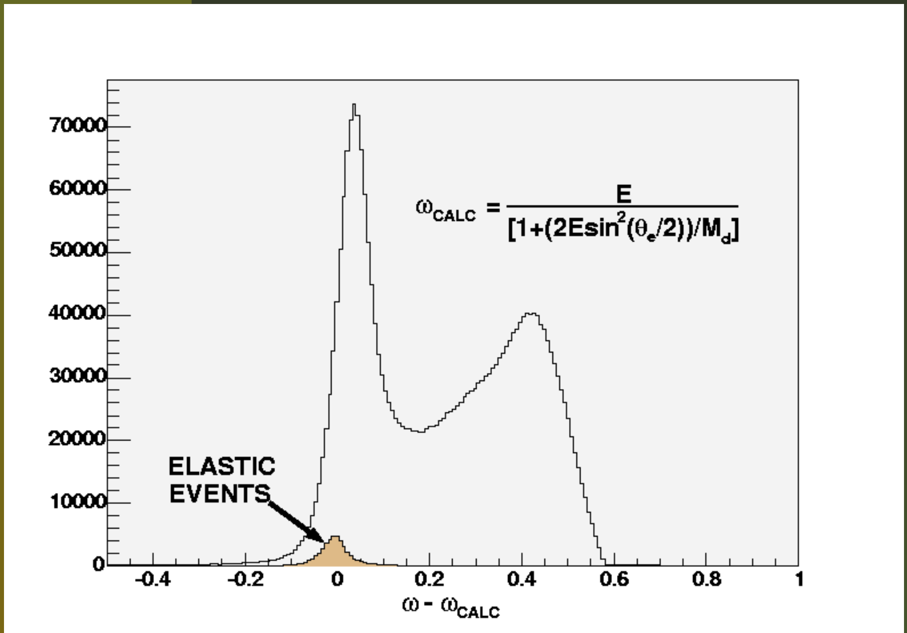


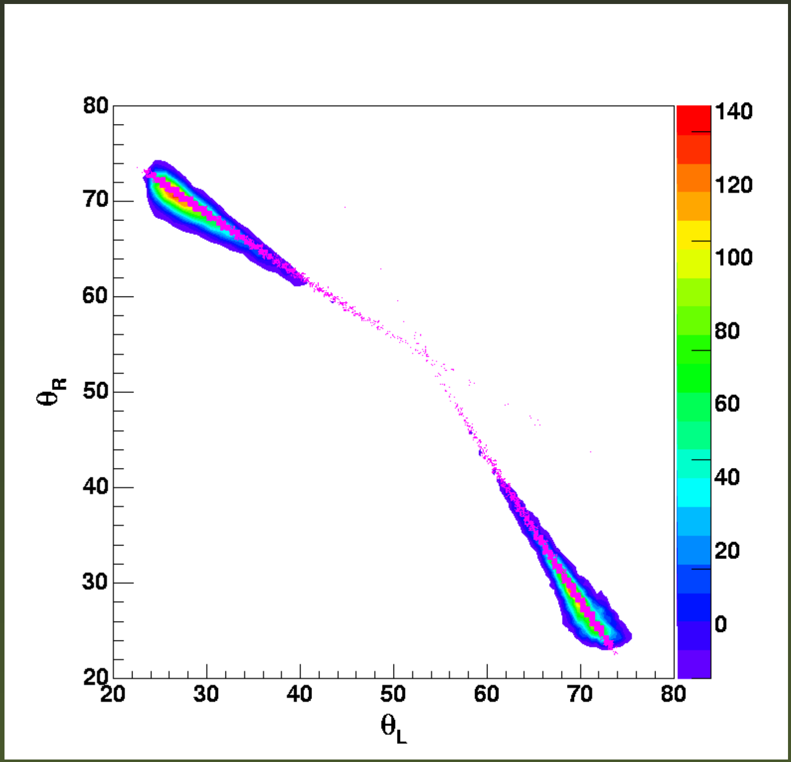


Check of $\omega - \omega_{CALC}$

Check of θ_e vs θ_q

Quality of the Data

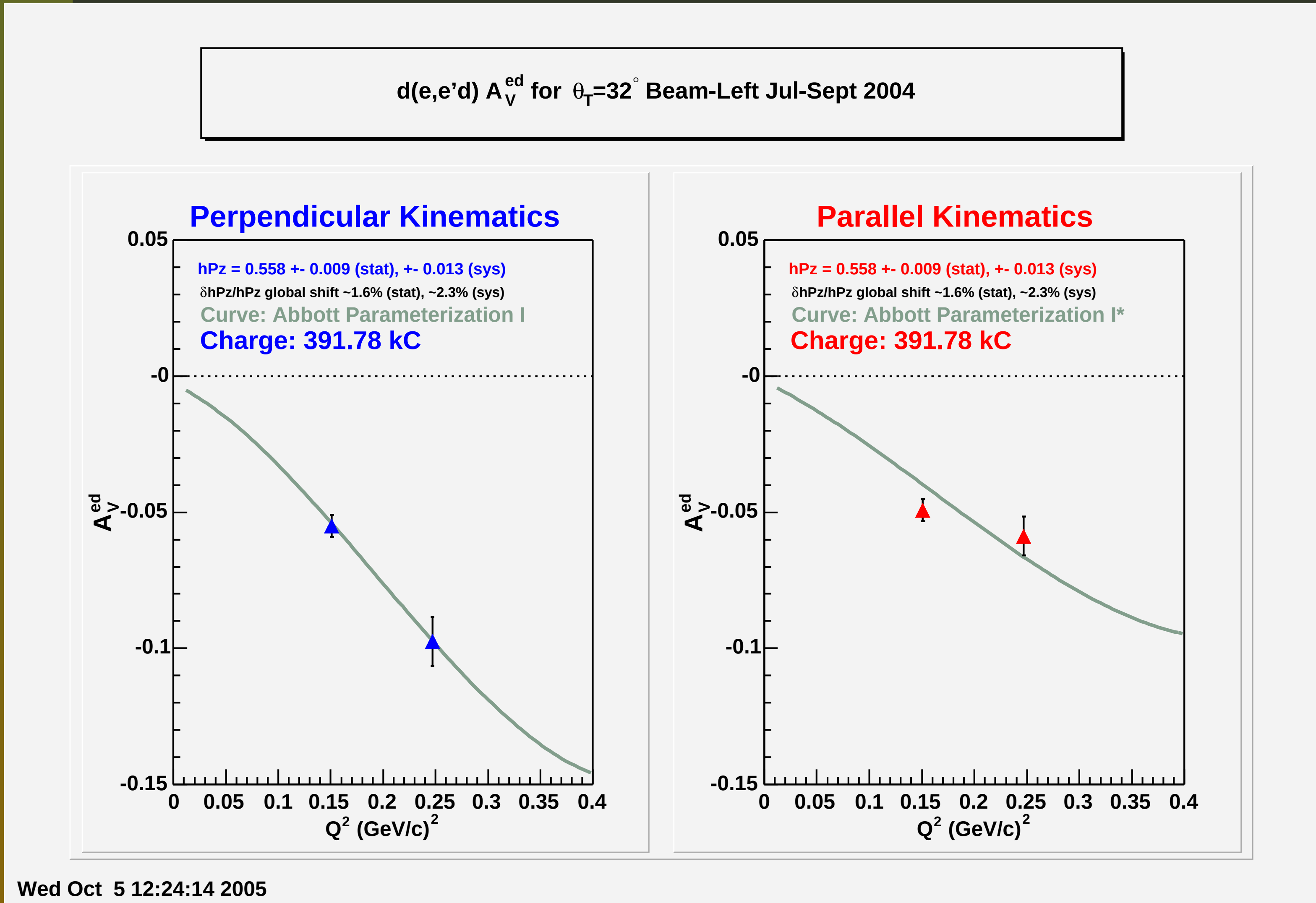




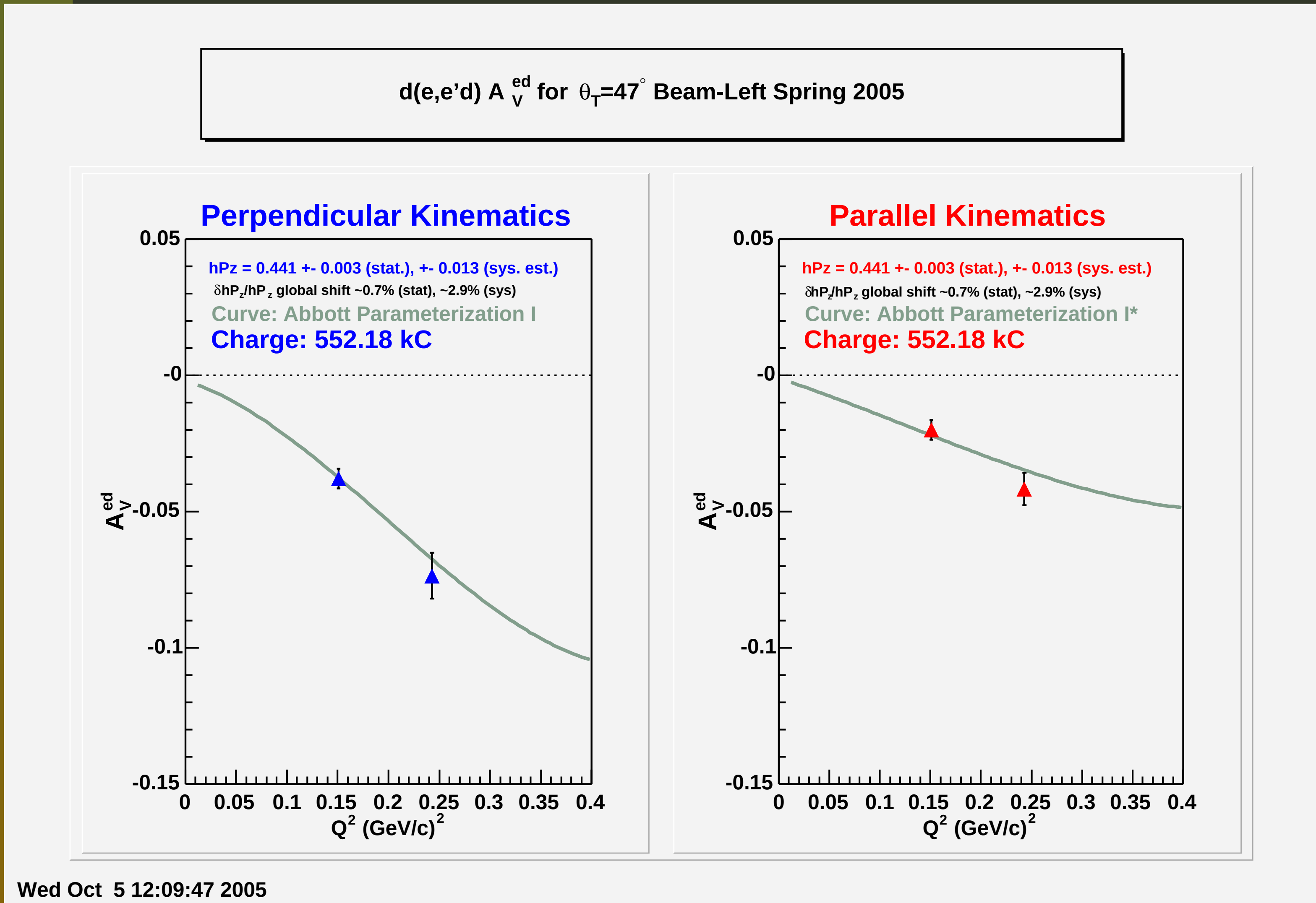
Check of $\omega - \omega_{CALC}$

Check of θ_e vs θ_q

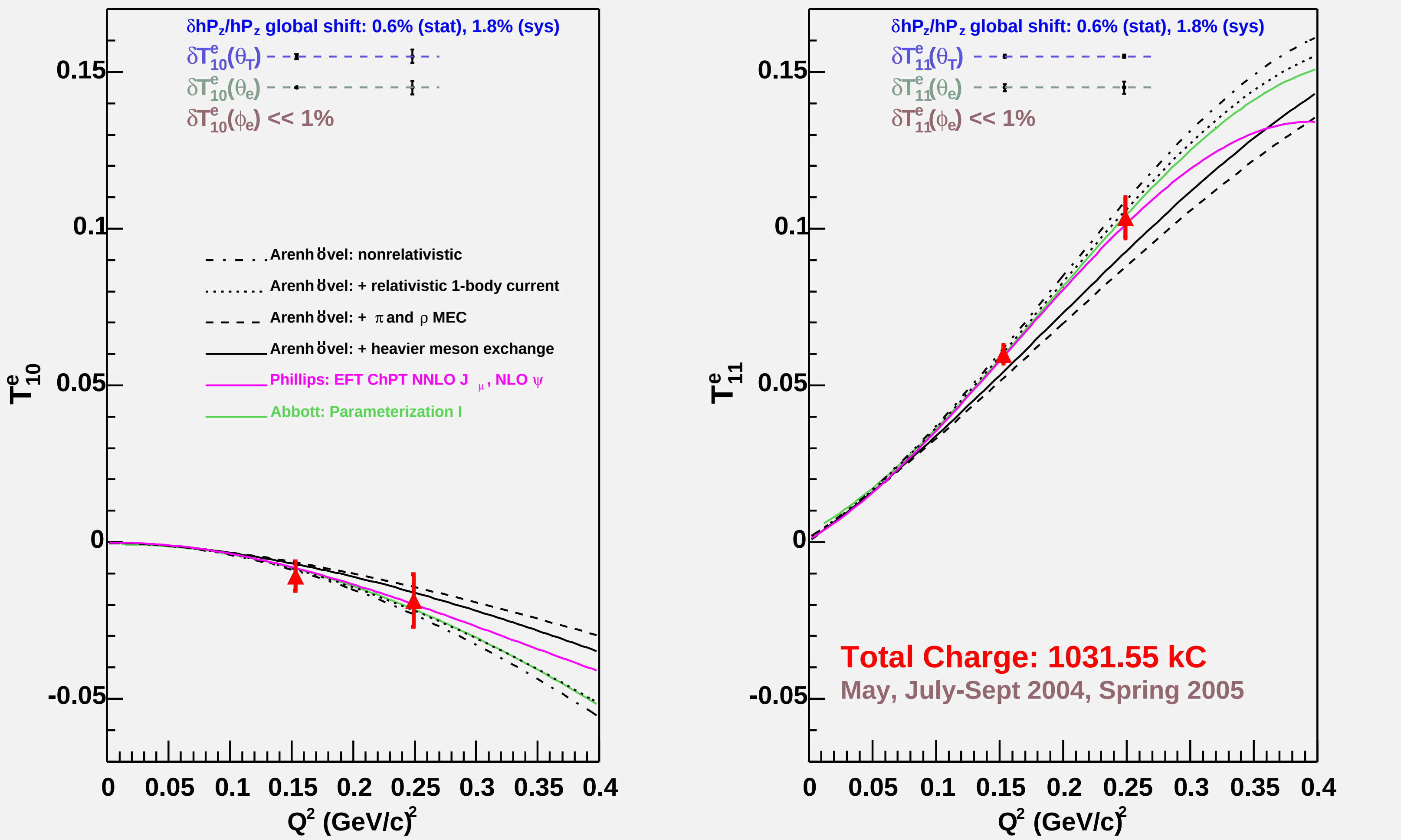
Vector Asymmetry A_{ed}^{V}



Vector Asymmetry A_{ed}^{V}



Vector Analyzing Powers



Extracting the Form Factors

- We have T_{20}, T_{21}, and T_{11}^{e} from BLAST.

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- Use only $A(Q^2)$ from world data

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$$
\begin{aligned}
T_{11}^e &= \sqrt{\frac{3}{2}}\frac{1}{S}\frac{4}{3}[\tau(1+\tau)]^{1/2}G_M(G_C+\frac{\tau}{3}G_Q)tan\frac{\theta_e}{2} \\
T_{20} &= -\sqrt{2}\frac{1}{S}\tau\left(\frac{4}{3}G_CG_Q+\frac{4}{9}G_Q^2+\frac{1}{6}(1+(\tau+1)tan^2(\theta_e/2))G_M^2\right) \\
T_{21} &= -\frac{2}{\sqrt{3}}\frac{1}{S}\tau\left(\tau+\tau^2sin^2(\theta_e/2)\right)^{1/2}G_MG_Qsec\frac{\theta_e}{2} \\
A(Q^2) &= G_C^2(Q^2)+\frac{8}{9}\tau^2G_Q^2(Q^2)+\frac{2}{3}\tau G_M^2(Q^2)
\end{aligned}
$$

Extracting the Form Factors

- We have T_{20}, T_{21}, and T_{11}^e from BLAST.
- Use only $A(Q^2)$ from world data

$$\begin{aligned}
T_{11}^e &= \sqrt{\frac{3}{2}}\frac{1}{S}\frac{4}{3}[\tau(1+\tau)]^{1/2}G_M(G_C+\frac{\tau}{3}G_Q)tan\frac{\theta_e}{2} \\
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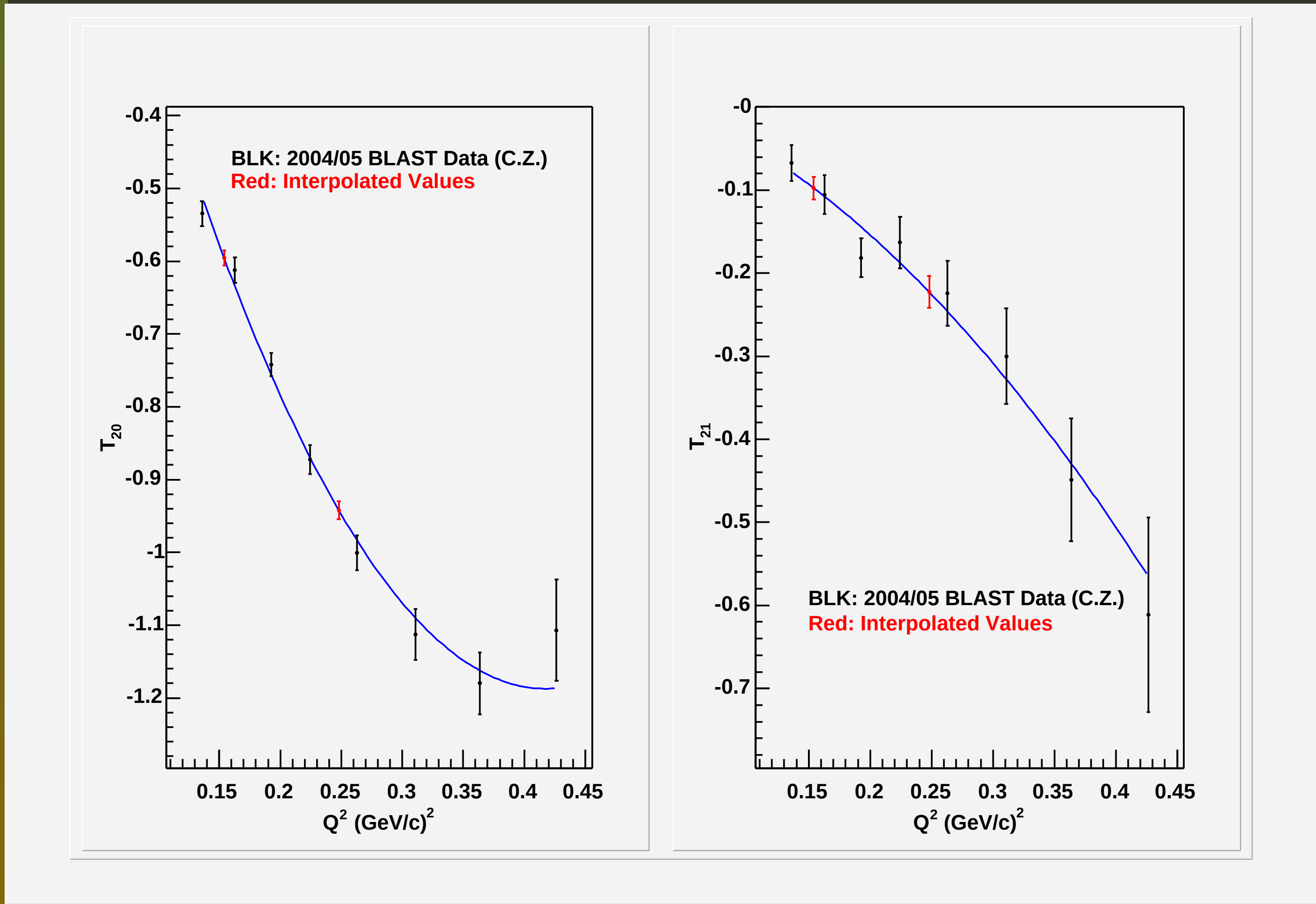
A(Q^2) &= G_C^2(Q^2)+\frac{8}{9}\tau^2G_Q^2(Q^2)+\frac{2}{3}\tau G_M^2(Q^2)
\end{aligned}$$

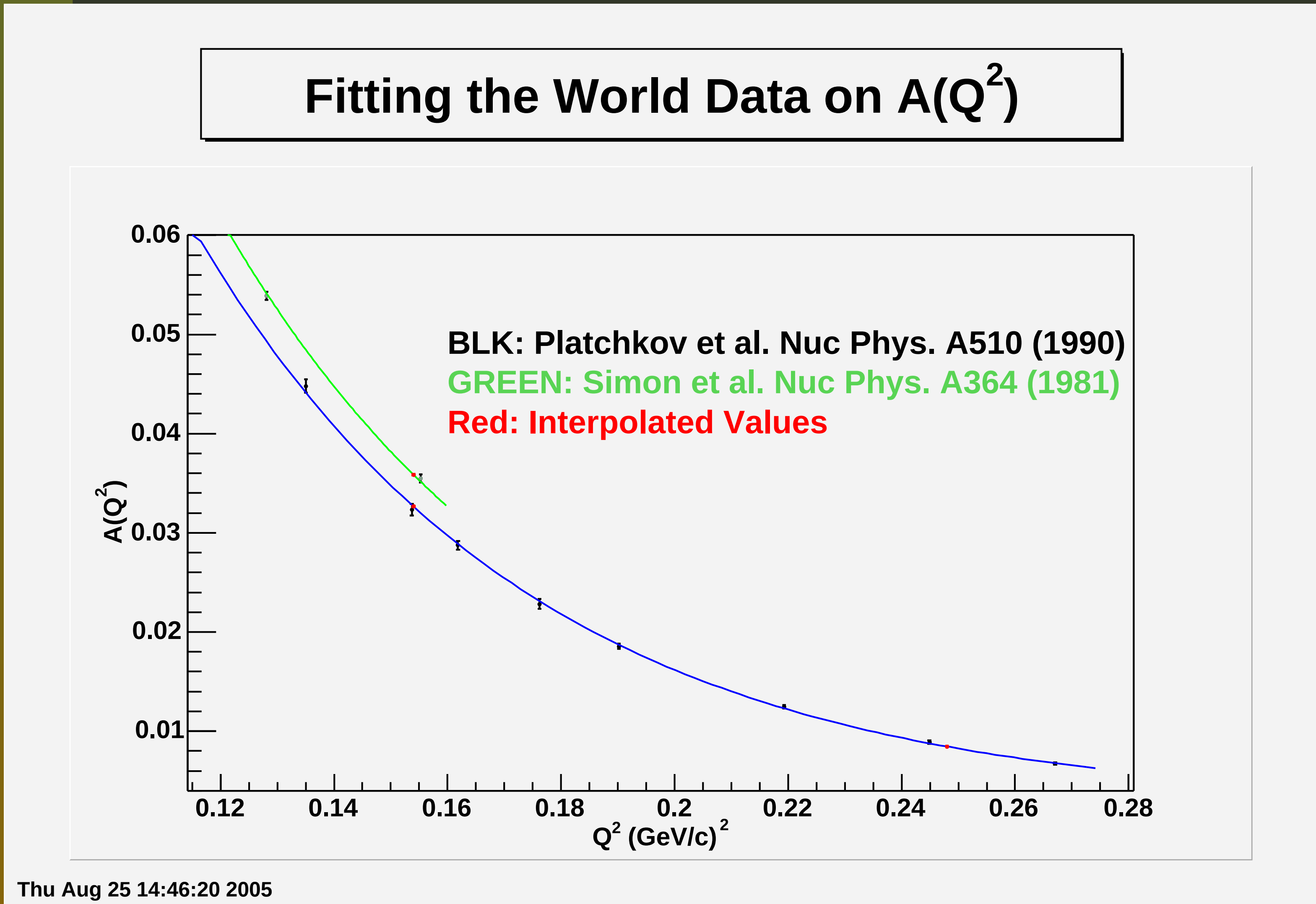
- 4 equations - 3 parameters $\longrightarrow$ 1 D.O.F.

Fitting Chi's T_{20} and T_{21}

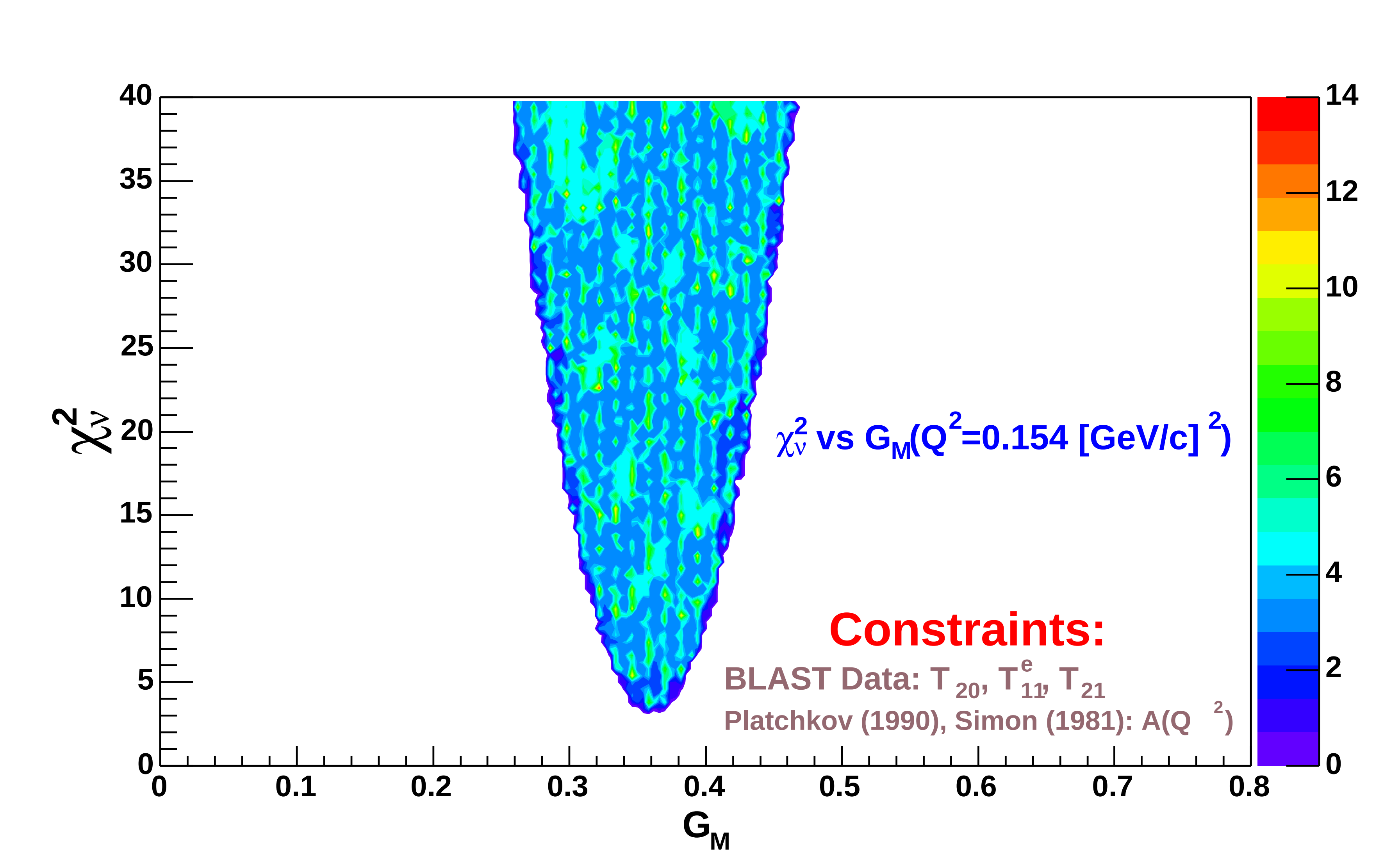


- Courtesy of Chi Zhang, MIT

Saclay & Mainz Discrepo!



χ^2_ν v. G_M



χ^2_ν vs $G_M(Q^2=0.154\ [GeV/c]^2)$
Constraints:
BLAST Data: T_{20}, T^e_{11}, T_{21}
Platchkov (1990), Simon (1981): $A(Q^2)$
G_M
χ^2_ν
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
5
10
15
20
25
30
35
40
0
2
4
6
8
10
12
14

Parameters and Errors

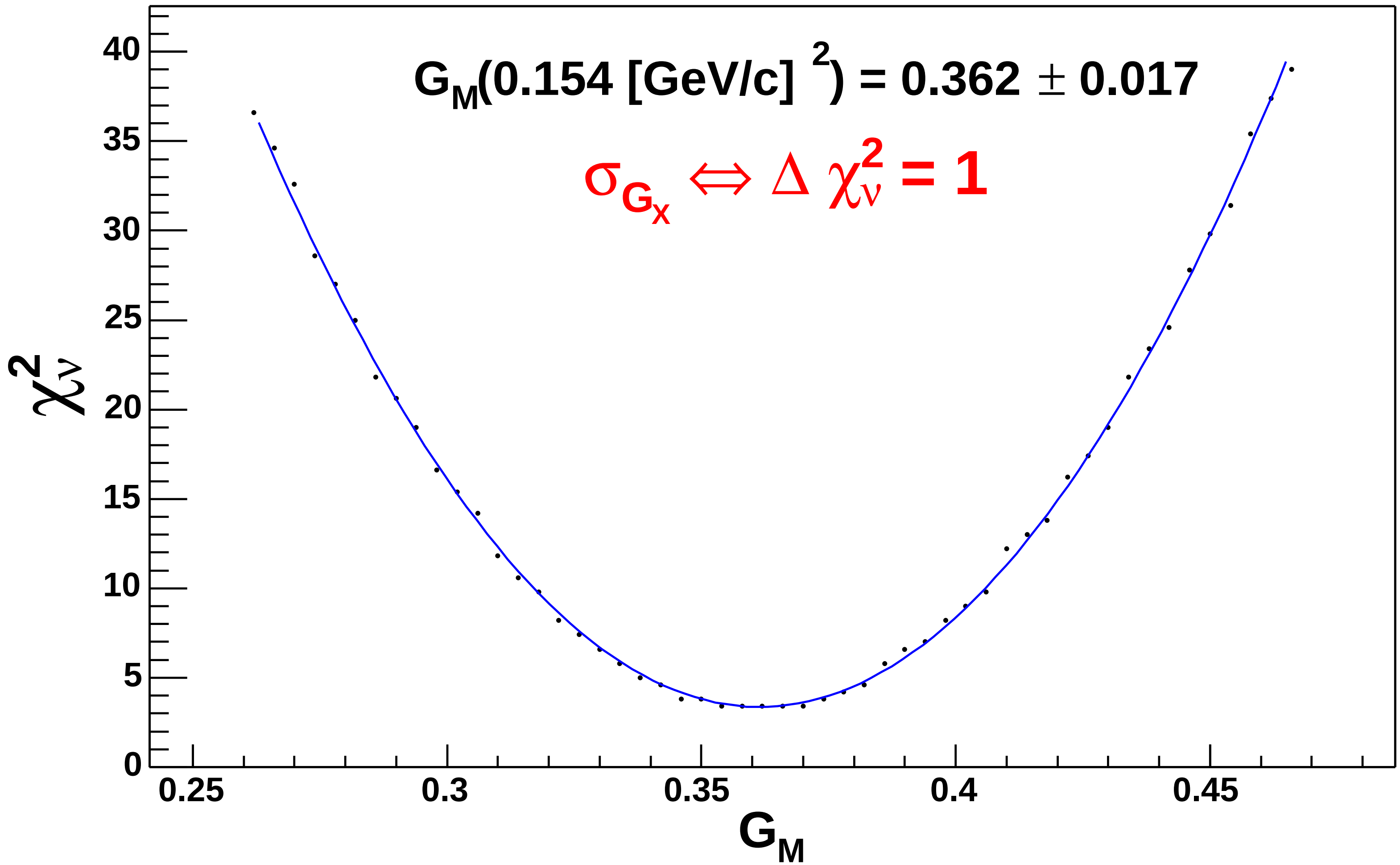
- Fit local minima of χ^2_ν distributions
- Take parameters from global minima

- Errors from $\Delta\chi^2_\nu = 1$

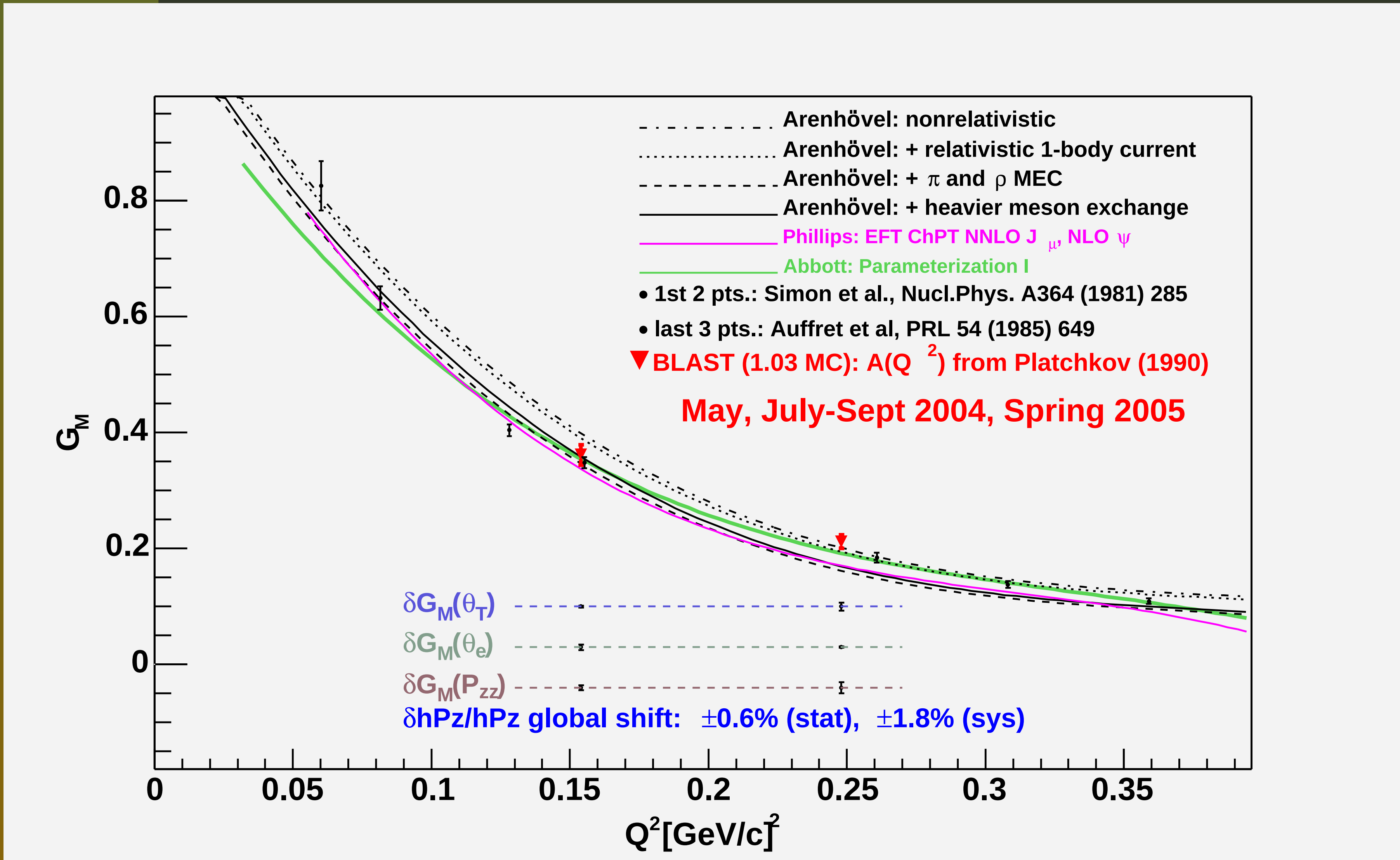
$$\sigma_j = \Delta a_j \sqrt{2(\chi^2_1 - 2\chi^2_2 + \chi^2_3)^{-1}}$$

Bevington (2003) Equation 8.13

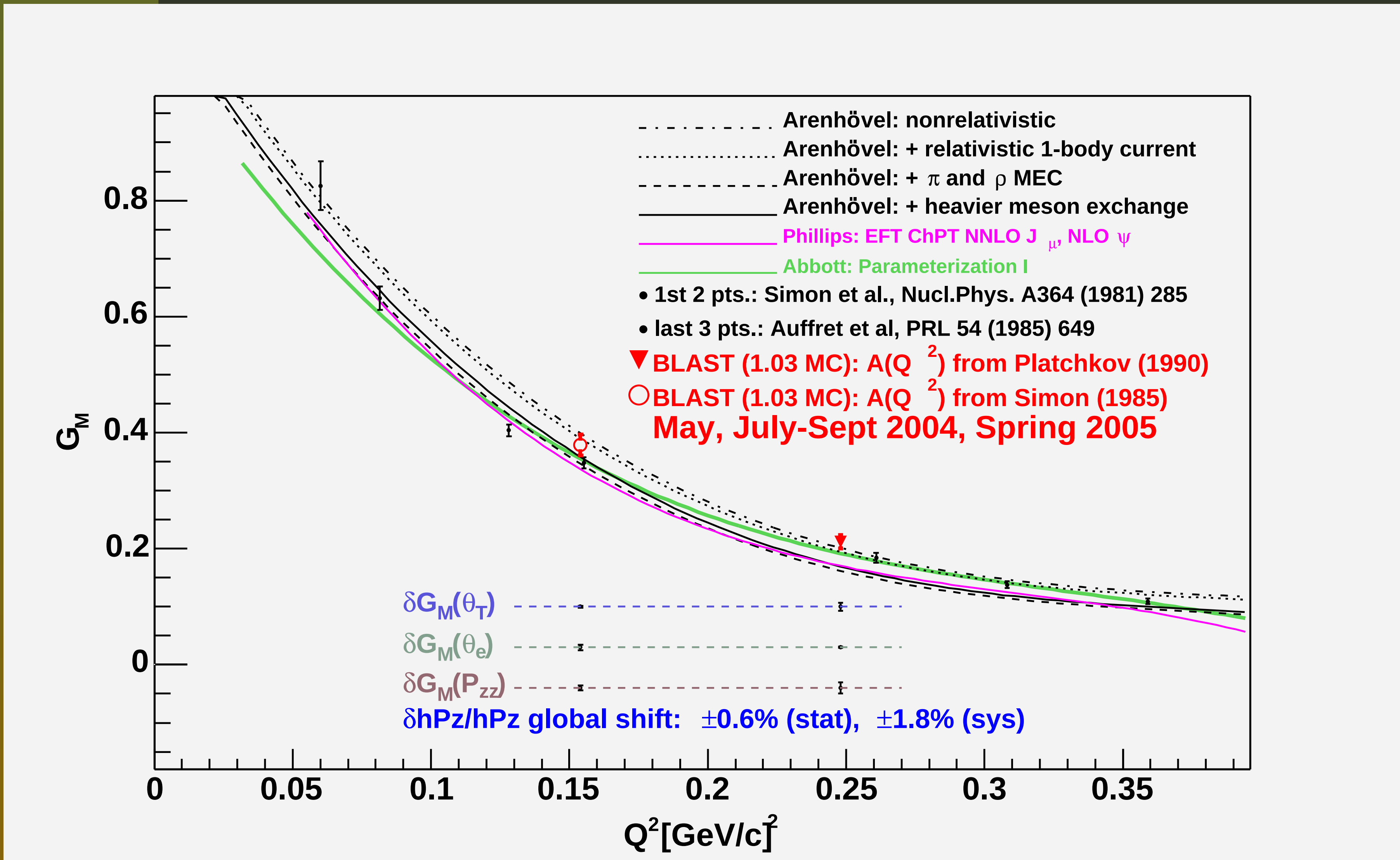
Fitting 'Local Minima'



G_M with Saclay $A(Q^2)$



G_M: Mainz & Saclay $A(Q^2)$



Sensitivity of the Form Factors

$Q^2\left[\frac{GeV}{c}\right]^2$	Varied Parameter	ΔG_C [%]	ΔG_Q [%]	ΔG_M [%]
0.154	T_{11}^e	0.17	0.02	4.70
0.248	T_{11}^e	0.40	0.15	3.90
0.154	T_{20}	0.30	5.00	0.40
0.248	T_{20}	0.70	5.60	1.70
0.154	T_{21}	0.40	0.07	0.02
0.248	T_{21}	1.60	0.20	0.20
0.154	$A(Q^2)$	2.50	2.50	2.50
0.248	$A(Q^2)$	2.40	2.50	2.50

Sensitivity of G_C, G_Q, G_M with respect to an independent 5% change in each of the parameters T_{11}^e, T_{20}, T_{21}, $A(Q^2)$

Preliminary Results Summary

$$Q^2 = 0.154\ [GeV/c]^2$$
$$T^e_{11} = 0.0599 \pm 0.0029$$
$$G_M = 0.3615 \pm 0.0172 \text{ (Saclay } A(Q^2))$$
$$G_M = 0.3787 \pm 0.0180 \text{ (Mainz } A(Q^2))$$

$$Q^2 = 0.248\ [GeV/c]^2$$
$$T^e_{11} = 0.1035 \pm 0.0066$$
$$G_M = 0.2119 \pm 0.0120$$

Preliminary Results Summary

$$\begin{aligned} Q^2 &= 0.154\ [GeV/c]^2 \\ T_{11}^e &= 0.0599 \pm 0.0029 \\ G_M &= 0.3615 \pm 0.0172 \text{ (Saclay } A(Q^2)) \\ G_M &= 0.3787 \pm 0.0180 \text{ (Mainz } A(Q^2)) \end{aligned}$$

$$\begin{aligned} Q^2 &= 0.248\ [GeV/c]^2 \\ T_{11}^e &= 0.1035 \pm 0.0066 \\ G_M &= 0.2119 \pm 0.0120 \end{aligned}$$

- First measurement of T_{10}^e and T_{11}^e
- Unique measurement of G_M from spin observables
- Motivation for new $A(Q^2)$ data at low Q^2

The BLAST Collaboration

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The BLAST Collaboration

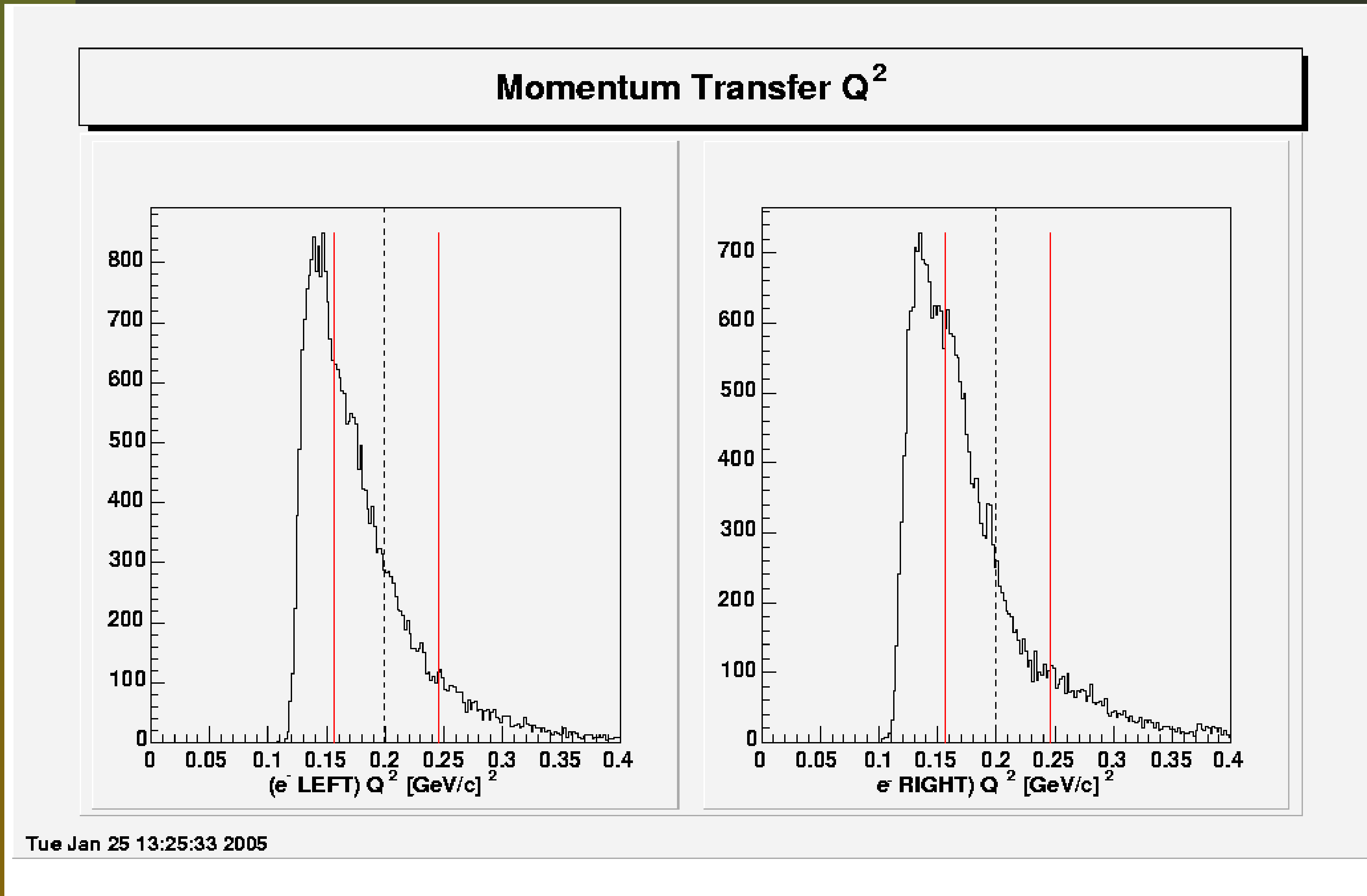
To my friends and colleagues

Reference Slides Only

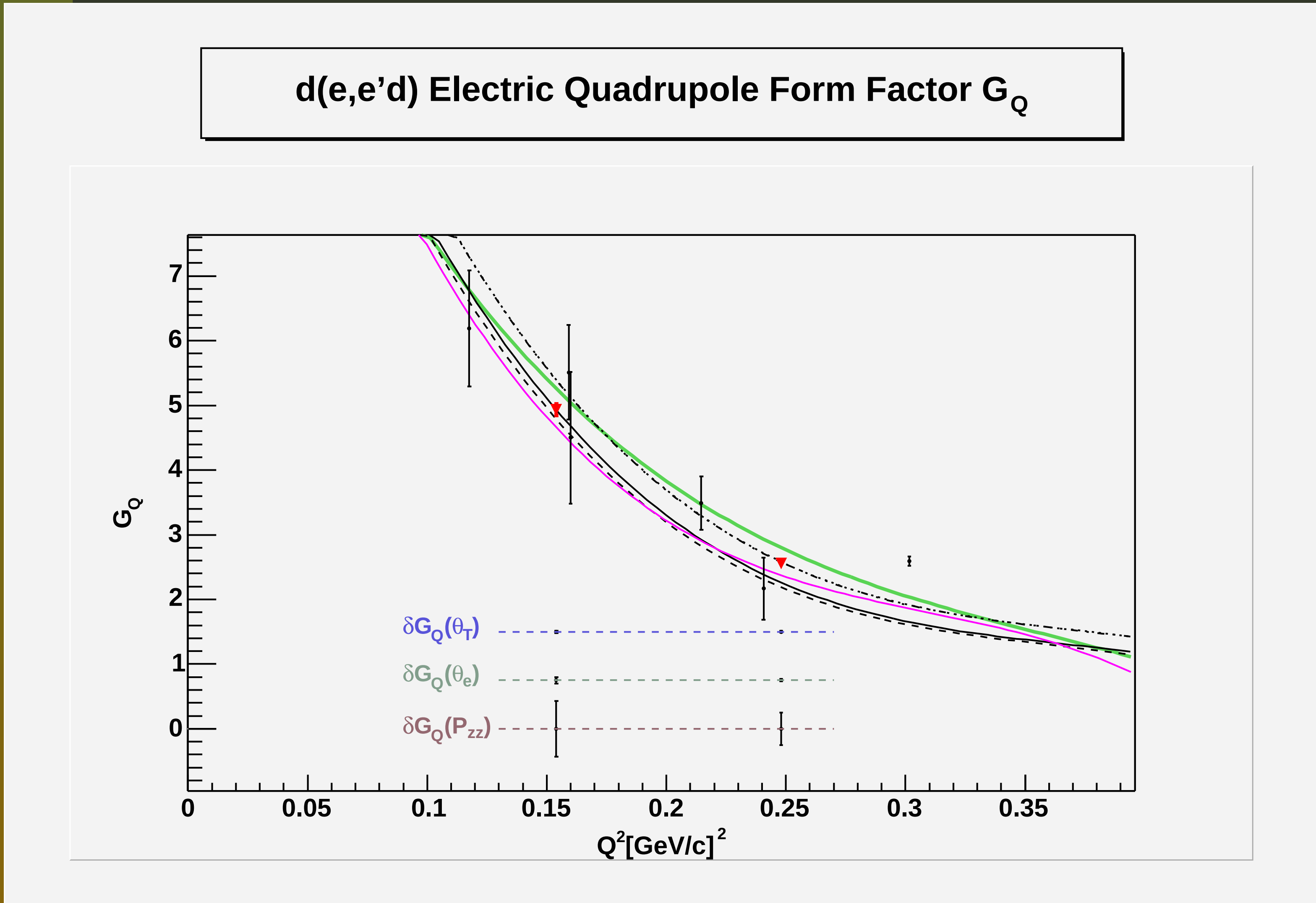
The following slides are for reference only.

They are not considered part of the talk proper.

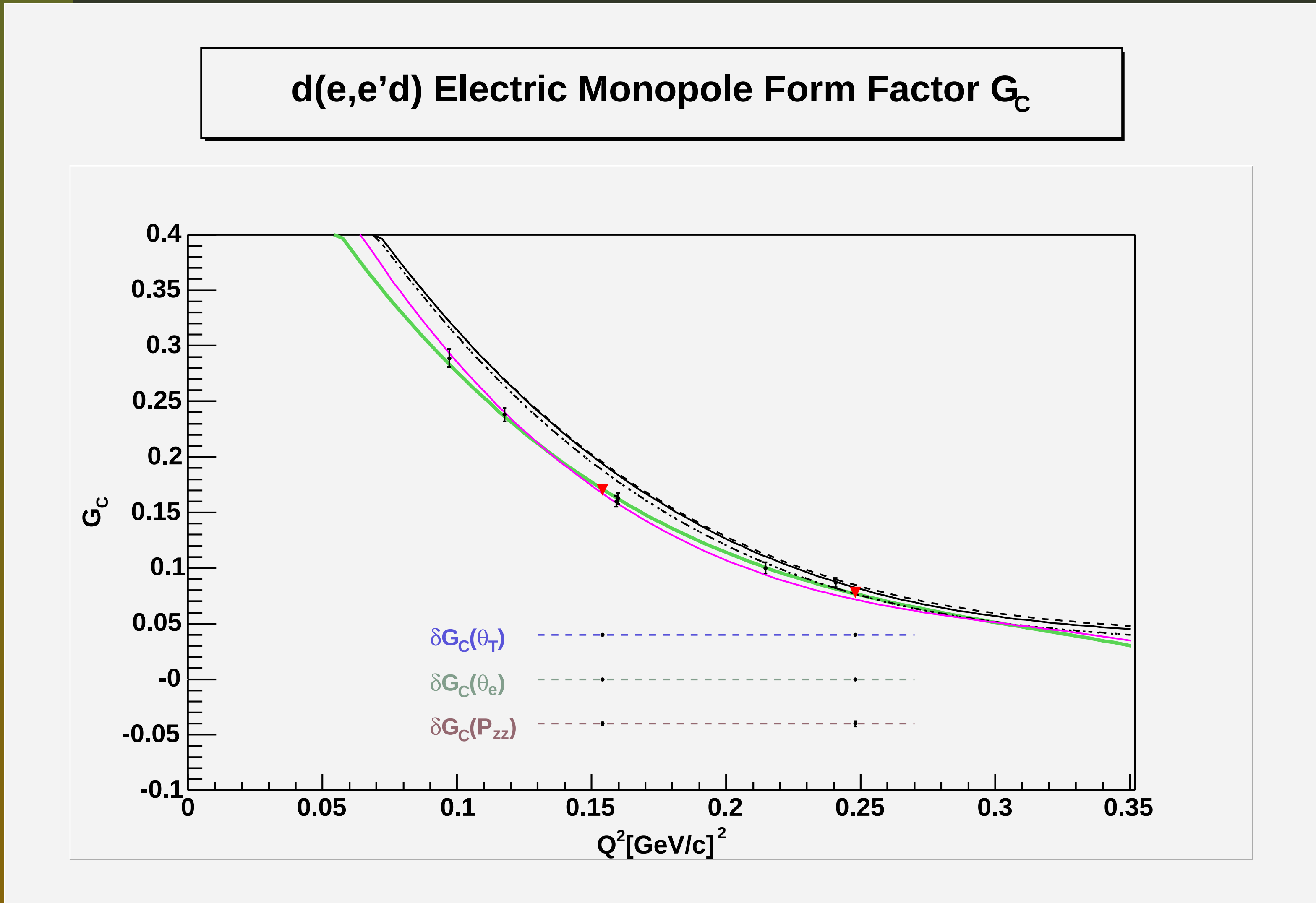
Binning in Q^2



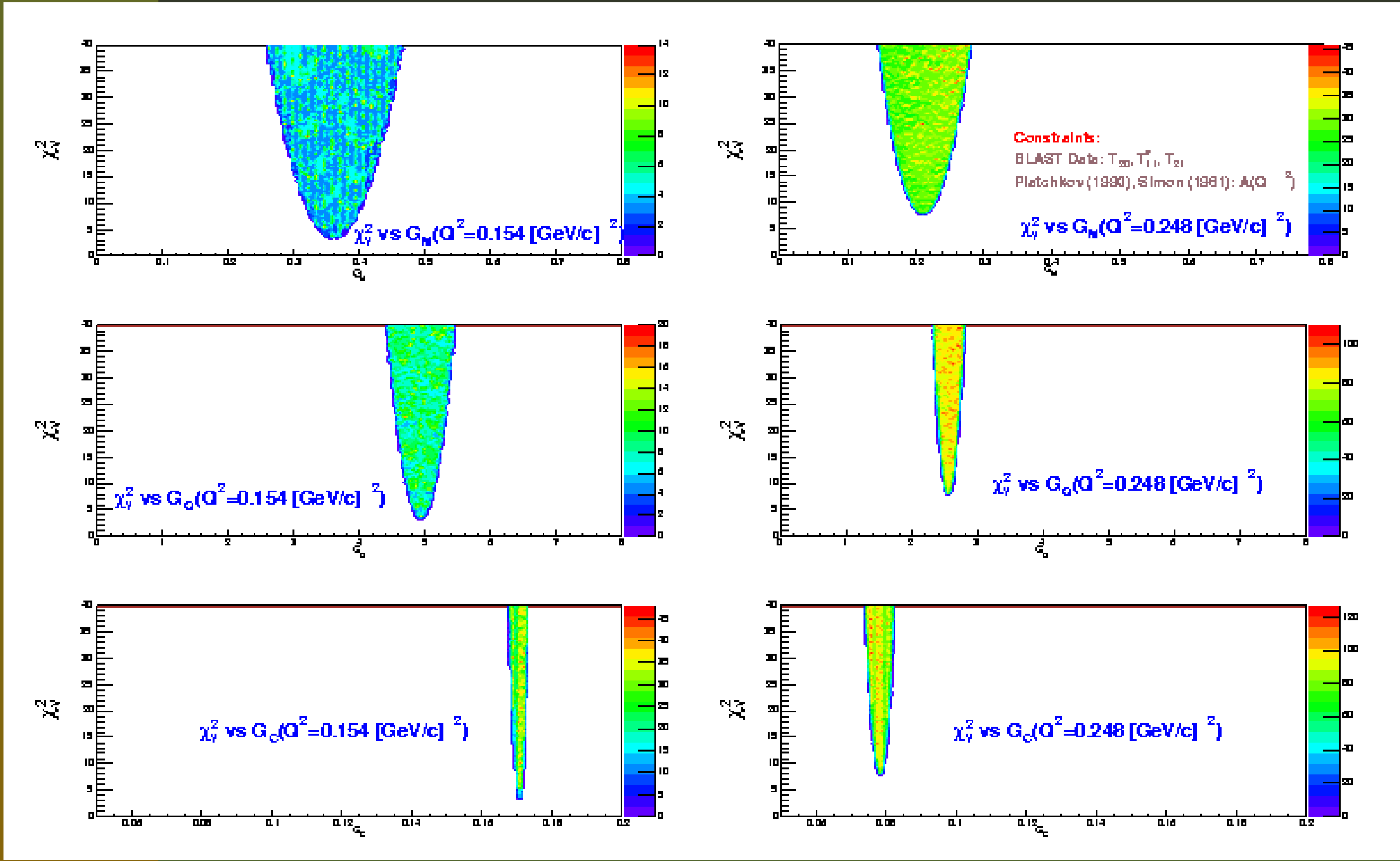
G_Q with Saclay $A(Q^2)$



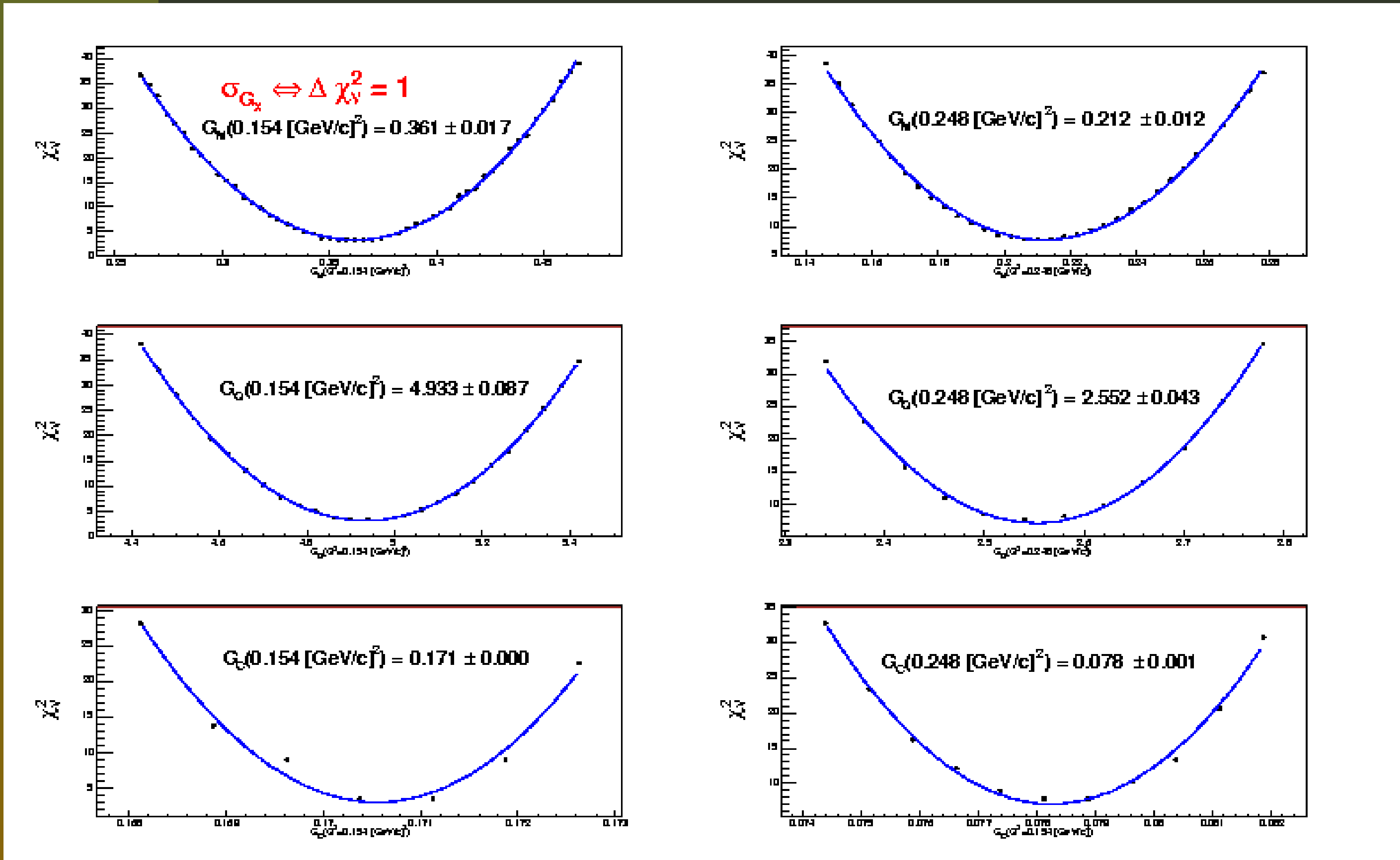
G_C with Saclay $A(Q^2)$



χ^2_ν v. G_M, G_Q, G_C



Fitting 'Local Minima'



Radiative Corrections

Modify Mascarad per Merenkov

- JETP, V.98, p.403-416, (2004)

  i) Scale the hadron tensor

  ii) Map the form factors

RCs: Unpolarized Mapping

Hadron Tensor

- Scale $H_{\mu\nu}^{d(unpol)} = \frac{4\tau+xyr}{4\tau} H_{\mu\nu}^{p(unpol)}$

Form Factors

- $G_{M,(p)}^2 \longrightarrow \frac{2}{3} G_{M,(d)}^2$
- $G_E^2 \longrightarrow G_C^2 + \frac{8x^2y^2r^2}{9(4\tau)^2} G_Q^2$

... where

$$x = \frac{Q^2}{2p_1(k_1-k_2)}, \quad y = \frac{k_1-k_2}{k_1}, \quad r = \frac{-q^2}{Q^2}, \quad \tau = \frac{M^2}{2p_1k_1}$$

RCs: Polarized Mapping

Hadron Tensor

- Scale $H_{\mu\nu}^{d(\parallel,\perp)} = \frac{-4\tau+xyr}{8\tau} H_{\mu\nu}^{p(\parallel,\perp)}$

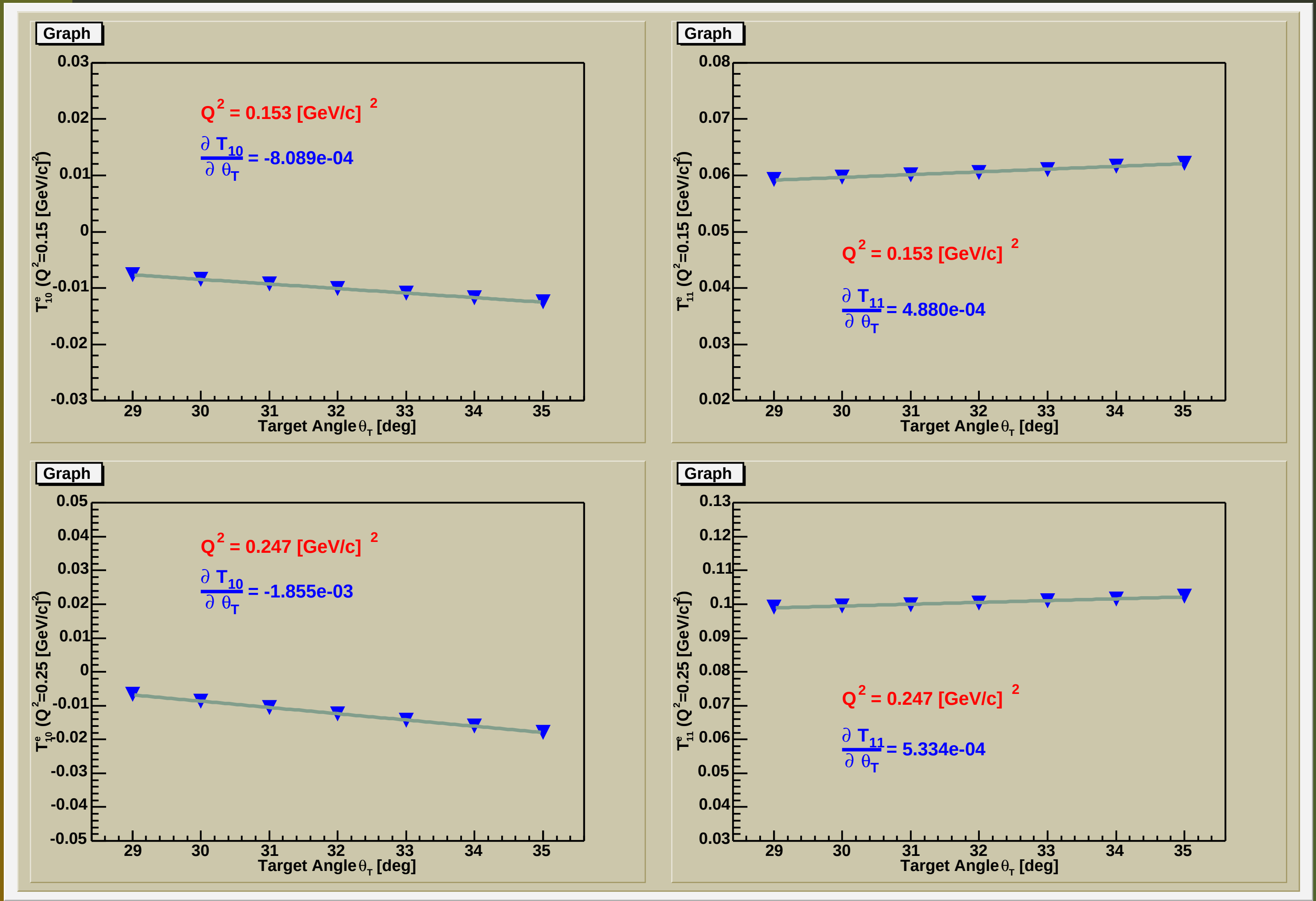
Form Factors

- $G_{M,(p)} \longrightarrow G_{M,(d)}$
- $G_E \longrightarrow 2G_C + \frac{xyr}{6\tau} G_Q$

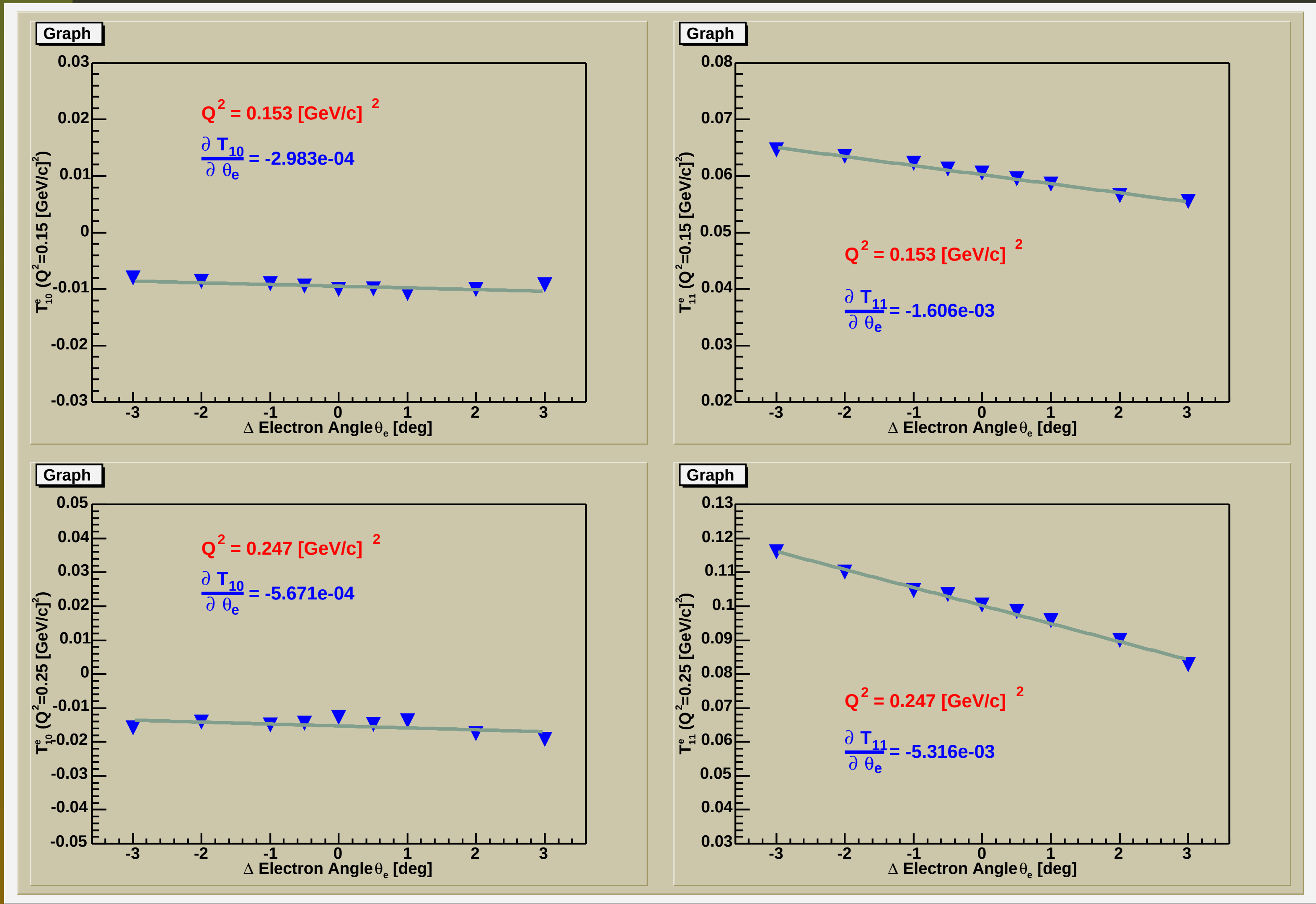
... where

$$x = \frac{Q^2}{2p_1(k_1-k_2)}, \quad y = \frac{k_1-k_2}{k_1}, \quad r = \frac{-q^2}{Q^2}, \quad \tau = \frac{M^2}{2p_1k_1}$$

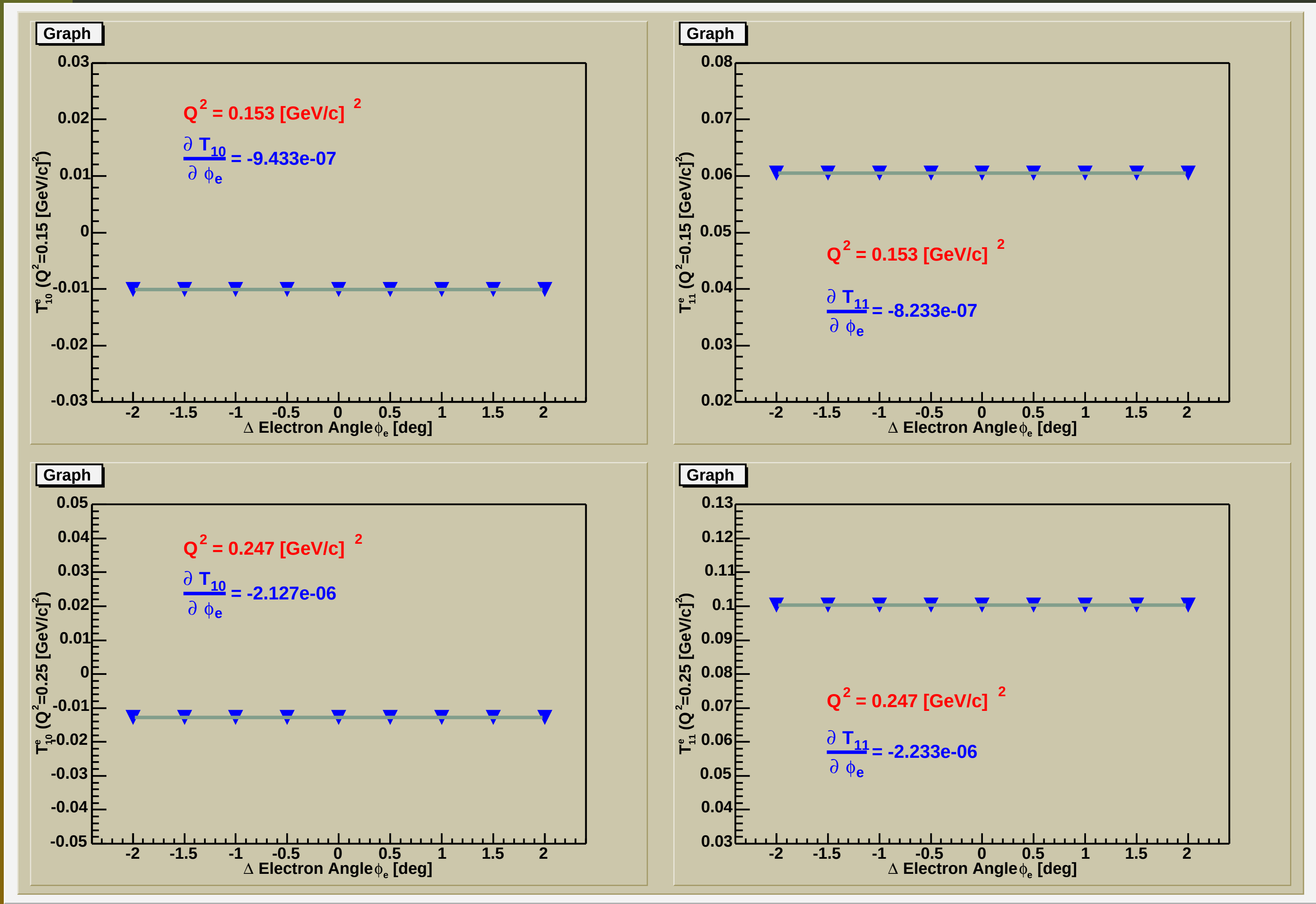
Systematic Errors: $\delta T^e_{1q}(\theta_T)$



Systematic Errors: $\delta T^{e}_{1q}(\theta_e)$



Systematic Errors: $\delta T^e_{1q}(\phi_e)$



Scaling Abbott by hPz