Workshop on Radiative Corrections, MIT, July 30, 2011

Overview of the OLYMPUS Experiment

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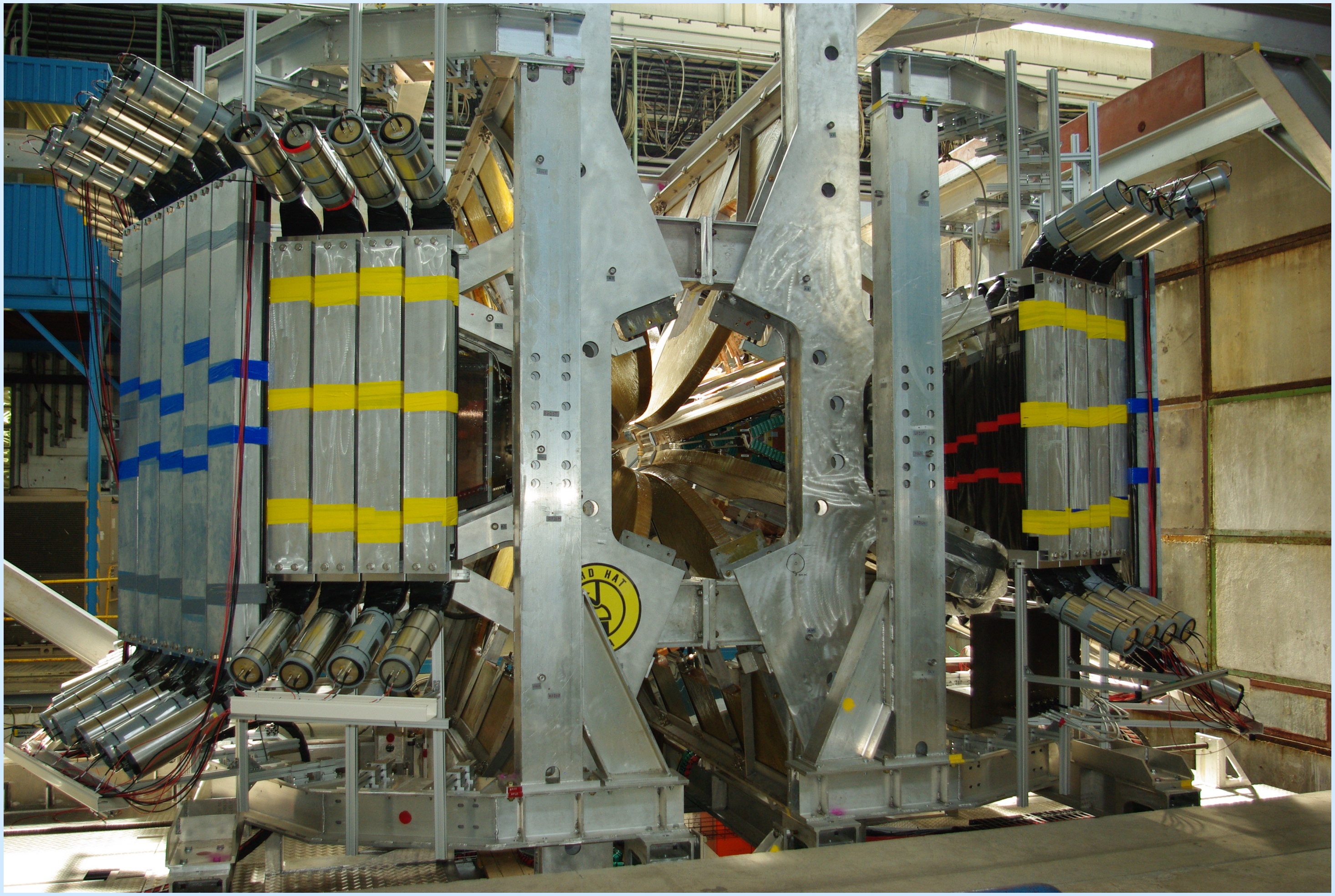
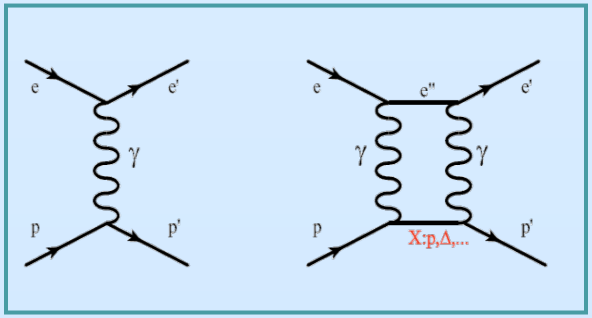
* Supported by NSF grants PHY-0855473 and 0959521, and DOE Early Career Award DE-SC0003884

The OLYMPUS Experiment

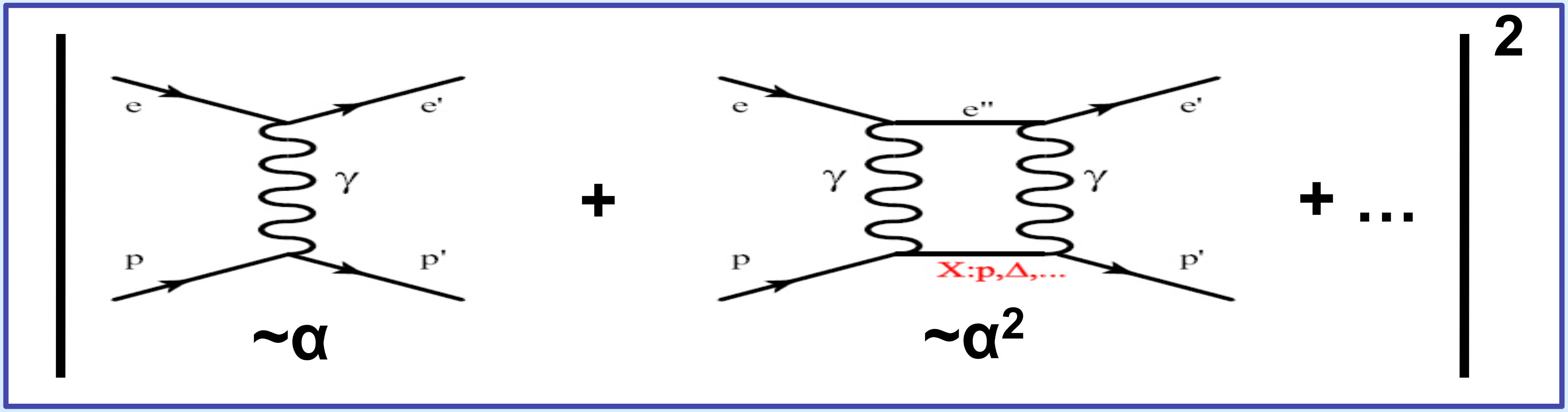
- Description of the OLYMPUS experiment
- Treatment of Radiative Corrections





OLYMPUS @ DESY

Lepton-Proton Elastic Scattering



$$\sigma = (1\gamma)^2\alpha^2 + (1\gamma)(2\gamma)\alpha^3 + ...$$

$$e^- \Longleftrightarrow e^+ \Rightarrow \alpha \Longleftrightarrow -\alpha$$

$$\sigma(\text{electron-proton}) = (1\gamma)^2\alpha^2 - (1\gamma)(2\gamma)\alpha^3 + ..$$

$$\sigma(\text{positron-proton}) = (1\gamma)^2\alpha^2 + (1\gamma)(2\gamma)\alpha^3 + ..$$

$$\frac{\sigma(e^+p)}{\sigma(e^-p)} = 1 + (2\alpha)\frac{2\gamma}{1\gamma}$$

σ-ratio to deviate from 1 due to interference of 1γ and 2γ proportional to TPE

Observables involving real part of TPE

$$P_t = -\sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}}\,\frac{G_M^2}{d\sigma_{red}}\left\{R + R\frac{\Re\left(\delta\tilde{G}_M\right)}{G_M} + \frac{\Re\left(\delta\tilde{G}_E\right)}{G_M} + Y_{2\gamma}\right\}$$

$$P_l = \sqrt{(1+\varepsilon)(1-\varepsilon)}\,\frac{G_M^2}{d\sigma_{red}}\left\{1 + 2\frac{\Re(\delta\tilde{G}_M)}{G_M} + \frac{2}{1+\varepsilon}\varepsilon Y_{2\gamma}\right\}$$

$$\frac{P_t}{P_l} = -\sqrt{\frac{2\varepsilon}{(1+\varepsilon)\tau}}\left\{R - R\frac{\Re\left(\delta\tilde{G}_M\right)}{G_M} + \frac{\Re\left(\delta\tilde{G}_E\right)}{G_M} + 2\left(1 - R\frac{2\varepsilon}{1+\varepsilon}\right)Y_{2\gamma}\right\}$$

E04-019
(Two-gamma)

$$d\sigma_{red}/G_M^2 = 1 + \frac{\varepsilon R^2}{\tau} + 2\frac{\Re(\delta\tilde{G}_M)}{G_M} + 2R\frac{\varepsilon\Re(\delta\tilde{G}_E)}{\tau G_M} + 2\left(1+\frac{R}{\tau}\right)\varepsilon Y_{2\gamma}$$

e^+/e^- x-section ratio
CLAS,VEPP3,OLYMPUS

Rosenbluth non-linearity
E05-017

$$\Re(\tilde{G}_E) = G_E(Q^2) + \Re(\delta\tilde{G}_E(Q^2,\varepsilon))$$

$$\Re(\tilde{G}_M) = G_M(Q^2) + \Re(\delta\tilde{G}_M(Q^2,\varepsilon))$$

$$R = G_E / G_M \qquad Y_{2\gamma} = 0 + \sqrt{\frac{\tau(1+\tau)(1+\varepsilon)}{1-\varepsilon}}\,\frac{\Re(\tilde{F}_3(Q^2,\varepsilon))}{G_M}$$

Born Approximation **Beyond Born Approximation**

P.A.M. Guichon and M.Vanderhaeghen, Phys.Rev.Lett. 91, 142303 (2003)

M.P. Rekalo and E. Tomasi-Gustafsson, E.P.J. A 22, 331 (2004)

Slide idea:
L. Pentchev

OLYMPUS @ DESY

Collaboration Organization

- Nov 2006 – Idea first formulated (D. Hasell, M.K., R. Milner)
  Jun 2007 – Letter of Intent; Sep 2008 – Full Proposal
  Sep 2009 – Technical review; Jan 2010 – Funded and officially approved
- Regular collaboration meetings since technical review
  Nov 30–Dec 1, 2009 Feb 23–24, 2010 Apr 26–27, 2010 Jun 28–29, 2010
  Aug 30–31, 2010 Nov 1–2, 2010 Jan 24–25, 2011 Apr 26–27, 2011
  Jun 27–28, 2011
- Elected management of OLYMPUS at June 2011 meeting:
  Spokesman: M.K. (Hampton U.)
  Deputy spokesman: Alexander Winnebeck (MIT)
  Technical coordinator: Douglas Hasell (MIT)
  Project manager: Uwe Schneekloth (DESY)
- Appointed coordinators:
  Target – Richard Milner (MIT)
  Tracking – Douglas Hasell (MIT)
  TOF Scintillators – Inti Lehmann (U. Glasgow)
  GEM Luminosity Monitor – Jürgen Diefenbach (Hampton U.)
  Multiwire Proportional Chambers – Alexander Kiselev (PNPI)
  Symmetric Moller Monitor – Roberto Perez Benito (U. Mainz)
  Data Acquisition – Christian Funke (U. Bonn)
  Trigger – Alexander Winnebeck (MIT)
  Slow Controls – Anton Izotov (PNPI)
  Offline Analysis and Simulation – Jan Bernauer (MIT)

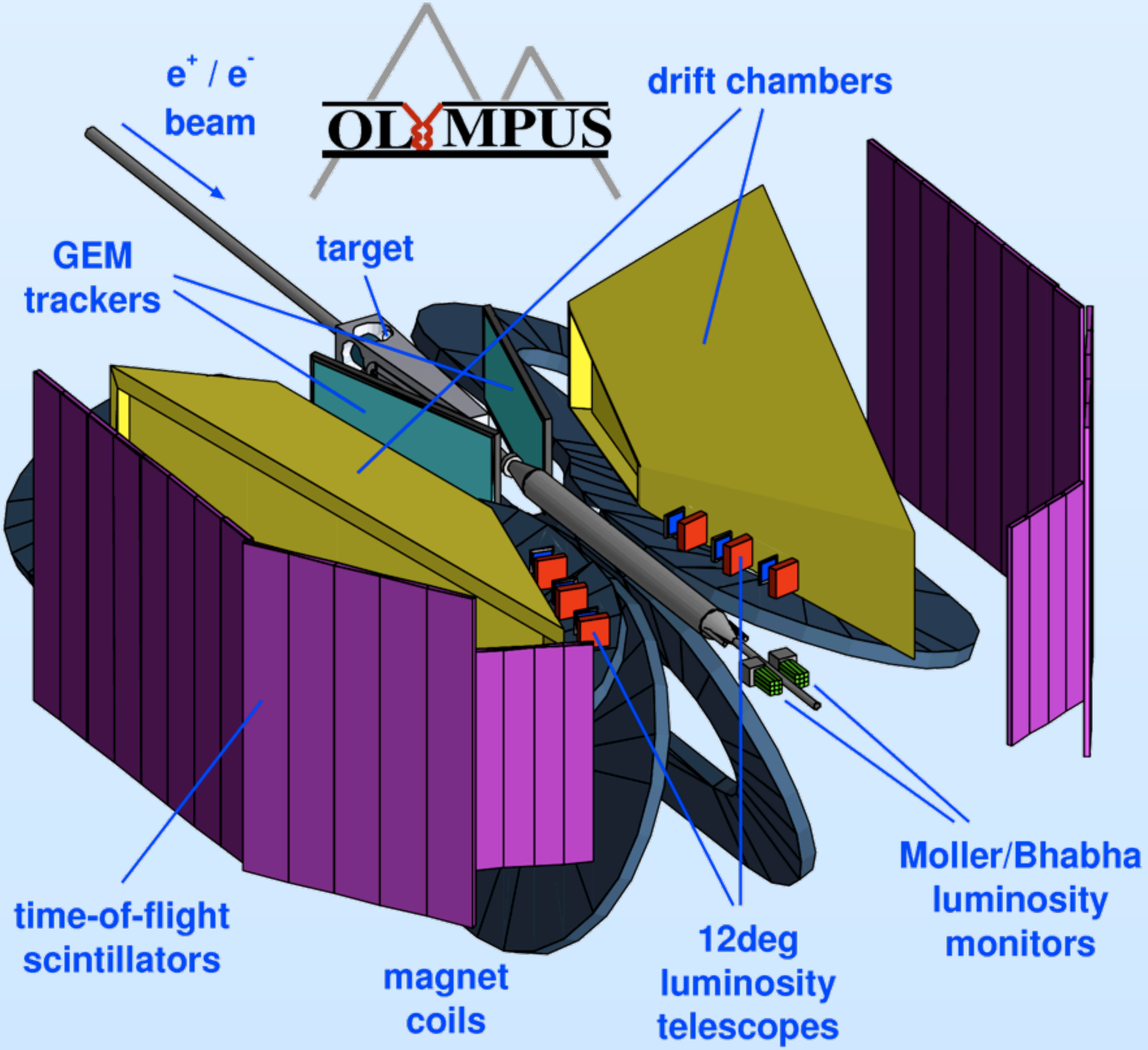
Institutional Responsibilities

- **Arizona State University:** TOF support, particle identification, magnetic shielding
- **DESY:** Modifications to DORIS accelerator and beamline, toroid support, infrastructure, installation
- **Hampton University:** GEM luminosity monitor, simulations
- **INFN Bari:** GEM electronics
- **INFN Ferrara:** Target
- **INFN Rome:** GEM electronics
- **MIT:** BLAST spectrometer, wire chambers, tracking upgrade, target and vacuum system, transportation to DESY, simulations
- **Petersburg Nuclear Physics Institute:** Slow controls, MWPC luminosity monitor
- **University of Bonn:** Trigger and data acquisition
- **University of Glasgow**: Particle Identification, TOF scintillators
- **University of Kentucky:** Simulations
- **University of Mainz:** Trigger, DAQ, Symmetric Moller/Bhabha monitor
- **University of New Hampshire:** TOF scintillators
- **Yerevan Physics Institute:** Removal of ARGUS, TOF system

The OLYMPUS Experiment

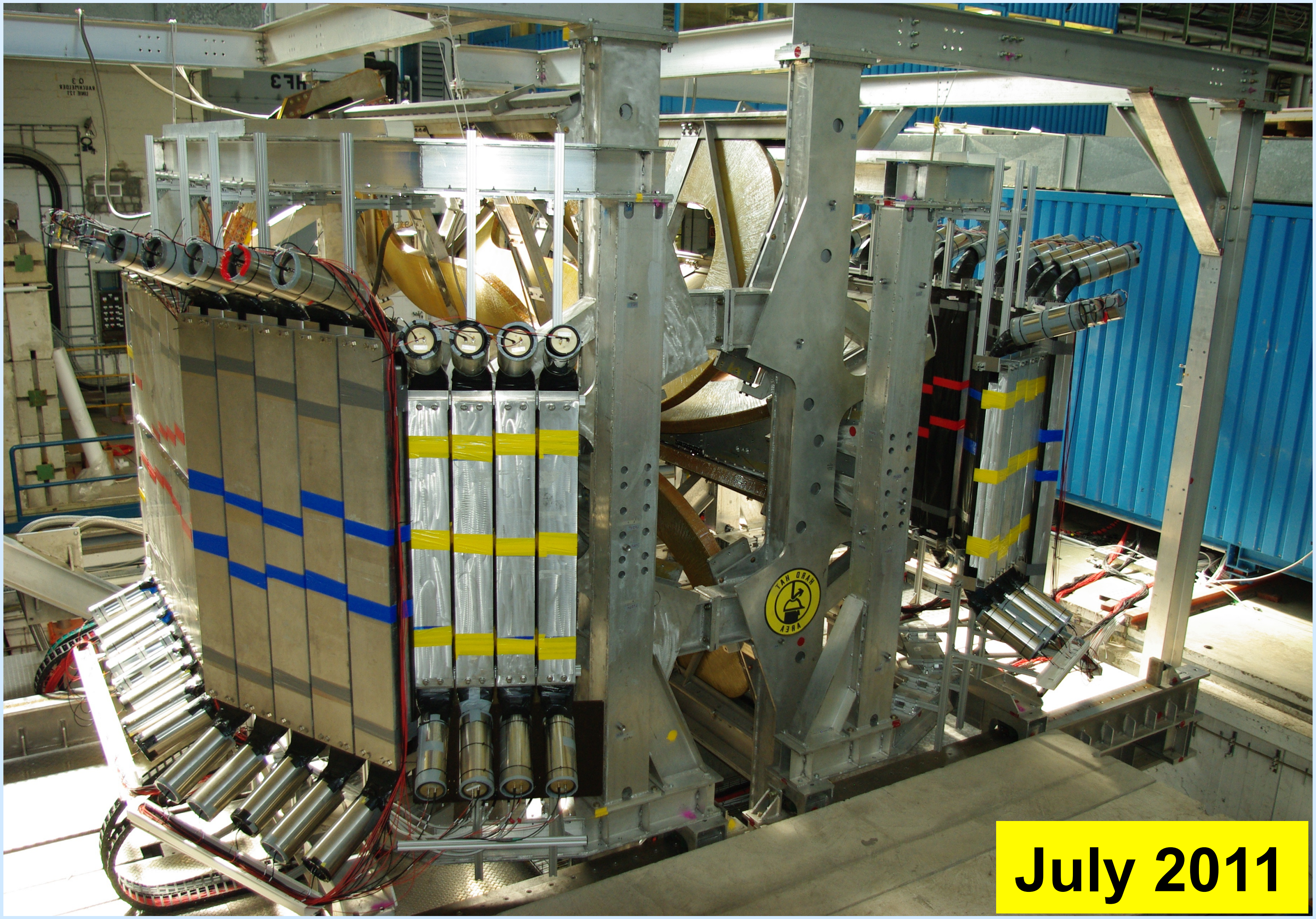
- Electrons/positrons (100mA) in multi-GeV storage ring
  DORIS at DESY, Hamburg, Germany
- Unpolarized internal hydrogen target (buffer system)
  3×10^{15} at/cm^2 @ 100 mA → $L = 2 \times 10^{33}$ / (cm^{2}s)
- Large acceptance detector for e-p in coincidence
  BLAST detector from MIT-Bates available
- Redundant monitoring of luminosity
  Pressure, temperature, flow, current measurements
  Small-angle elastic scattering at high epsilon / low Q^2
  Symmetric Moller/Bhabha scattering
- Measure ratio of positron-proton to electron-proton unpolarized elastic scattering to 1% stat.+sys.

The Proposed OLYMPUS Detector



The Realized OLYMPUS Detector

OLYMPUS



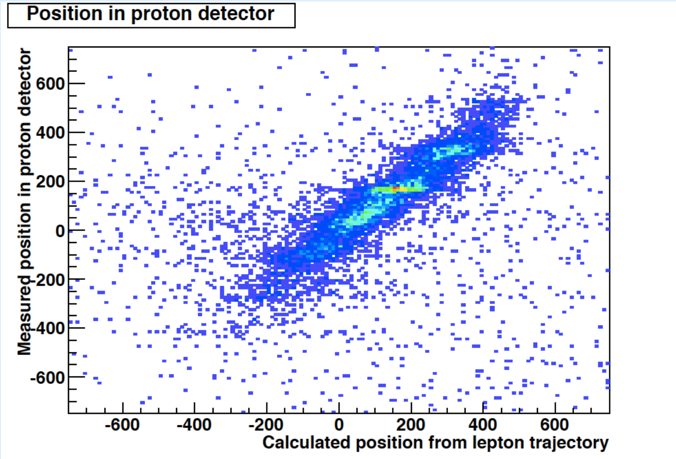
July 2011

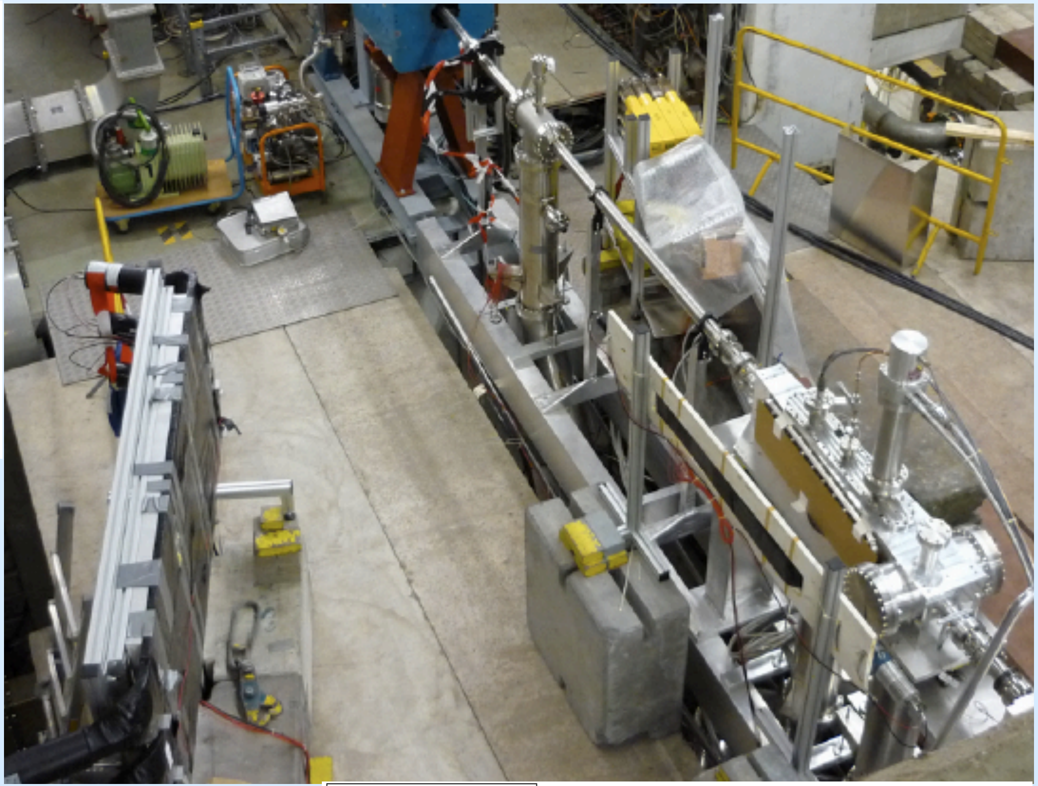
Preparation of OLYMPUS

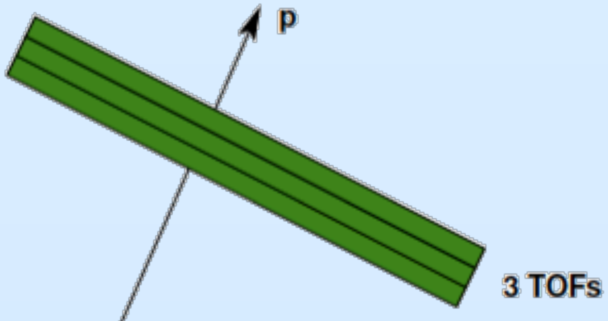
- Transfer of detector
  - ARGUS removed; BLAST disassembled and shipped (May-July 2010)
  - OLYMPUS assembly at DESY started in June 2010, completed by July 2011
- Target and vacuum system
  - New target chamber designed and machined (MIT), target cells by INFN Ferrara
  - Contructed and tested by Nov. 2010, shipped and installed in Jan. 2011
  - DORIS test run in Feb. 2011; improved target reinstalled in DORIS in July 2011
- Drift Chambers
  - Rewired drift chambers at DESY in summer 2010, installed April-May 2011
- TOFs
  - TOFs tested and calibrated at Bates in January 2010
  - Supports redesigned, coordinated by U. Glasgow, installed in May 2011
- Luminosity Monitoring
  - 12-degree elastic scattering telescopes (Hampton & PNPI), installed in Jun 2011
  - Symmetric Moller/Bhabha monitors (U. Mainz), to be installed by Oct 2011
  - Test of all elements at DESY testbeam facility in May-Jun 2011
- DAQ
  - U. Bonn coordinating, system brought into operation at DESY in summer 2010
- Slow Controls
  - Control system (PNPI) tested and commissioned in summer 2011

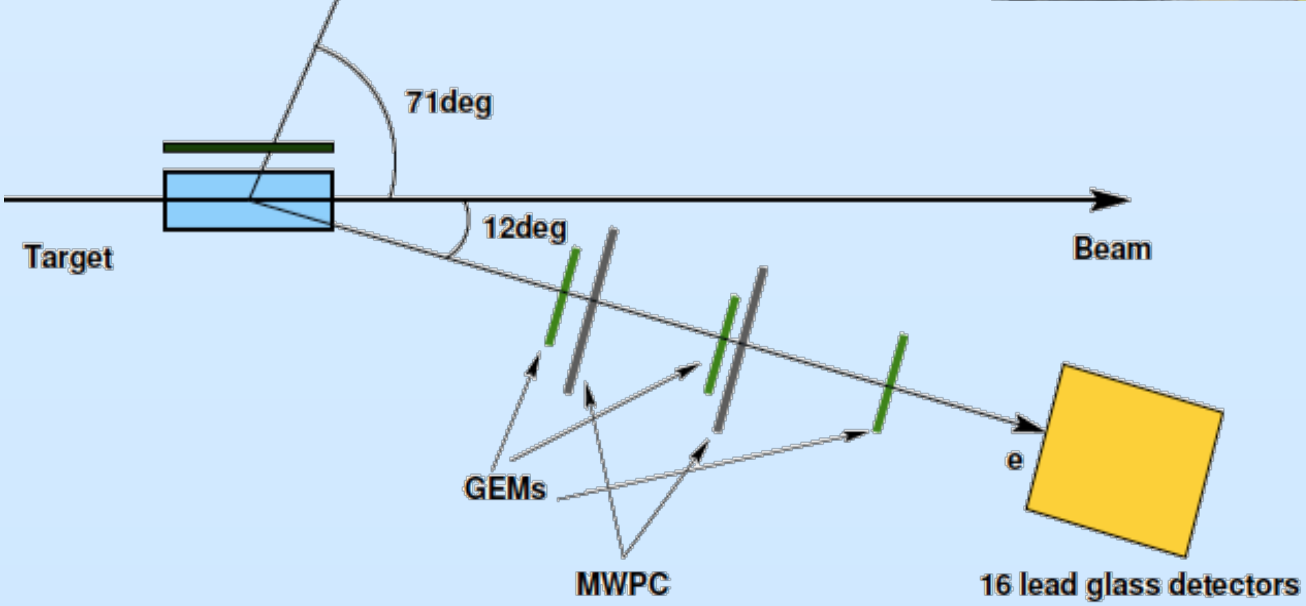
- **“ROLLING-IN” of final OLYMPUS detector into DORIS accomplished in July 2011**

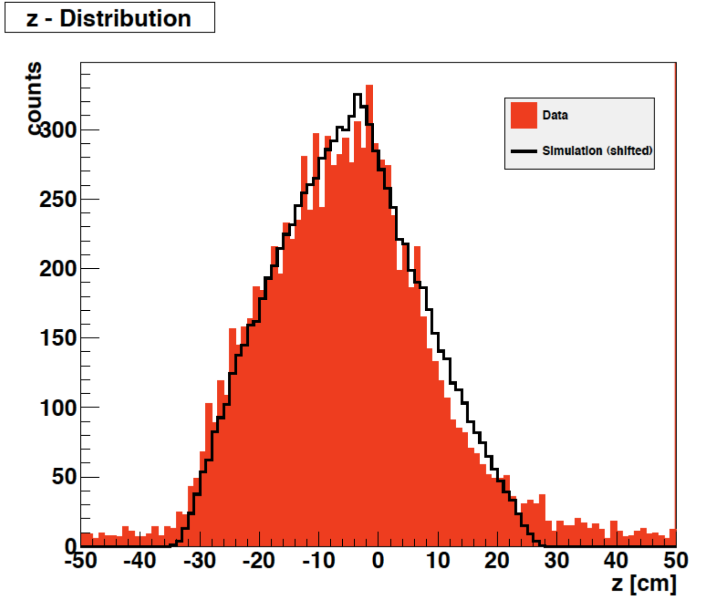
DORIS Test Experiment in Feb 2011











Kinematics vs. Statistics

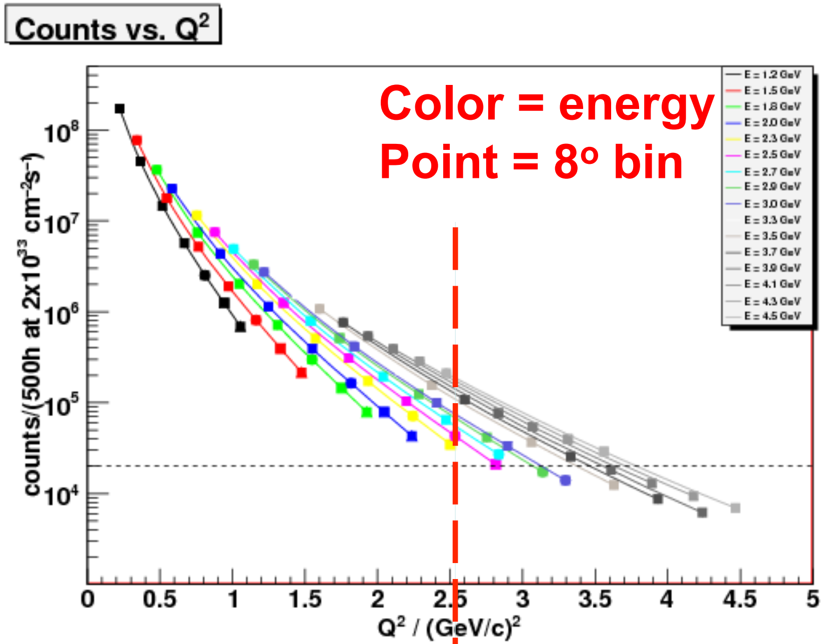
E_0 [GeV]	θ_e	$p_{e'}$ [GeV/c]	θ_p	p_p [GeV/c]	Q^2 [(GeV/c)^2]	ϵ	Counts
2.0	24	1.69	56.4	0.83	0.6	0.905	22613100
	32	1.51	48.1	1.08	0.9	0.828	4321570
	40	1.33	41.3	1.30	1.2	0.736	1141960
	48	1.17	35.7	1.50	1.6	0.636	389822
	56	1.03	31.0	1.66	1.8	0.538	162355
	64	0.91	27.1	1.80	2.0	0.447	78744
	72	0.81	23.8	1.91	2.2	0.367	42954

- E small enough for sufficient statistics within 500 hours e+,e- @ 2x10^{33} / cm^{2}s
- E large enough to maximize Q^2 / minimize ε

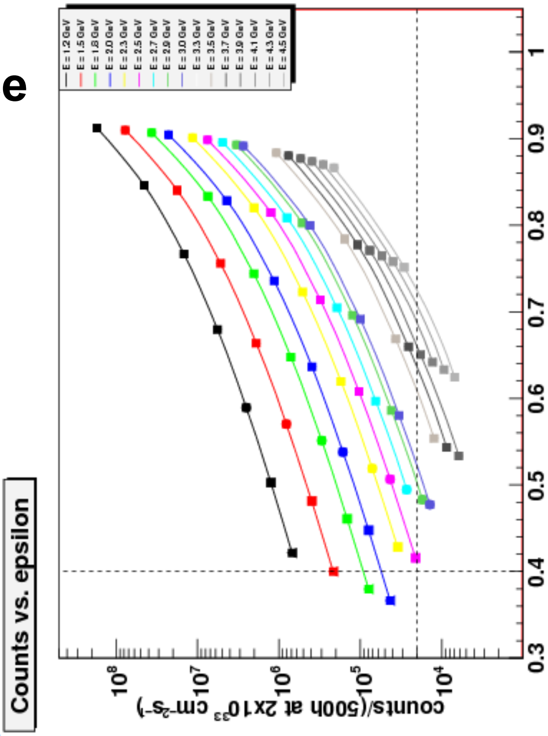
- E = 2 GeV best choice

- Impact on DORIS running cost

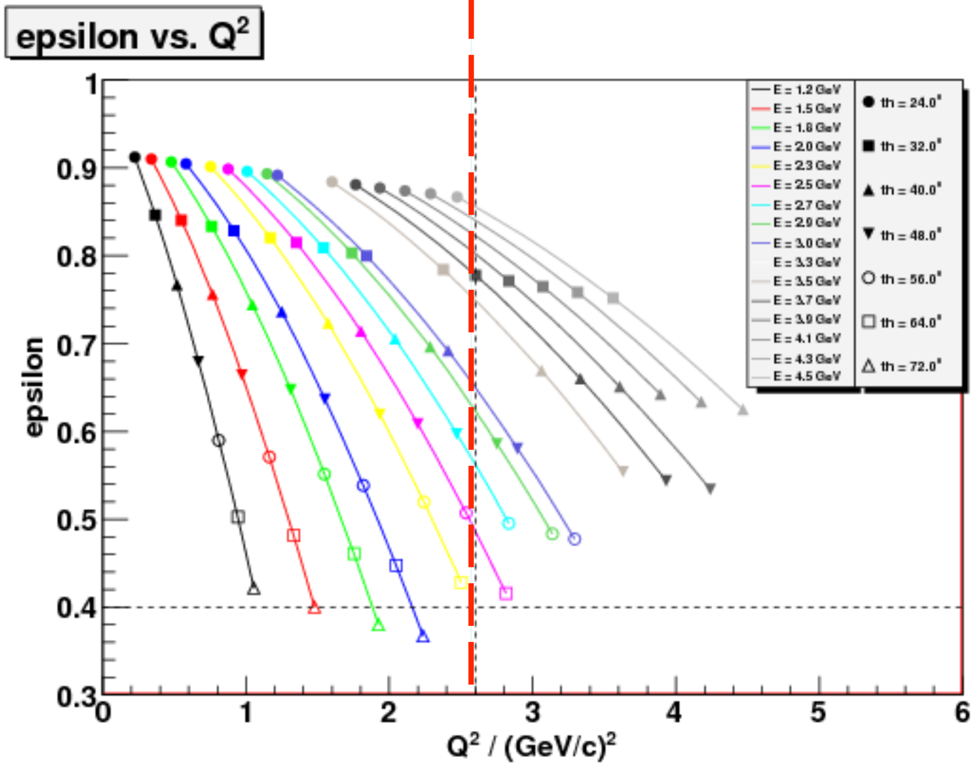
Counts vs. Q^2



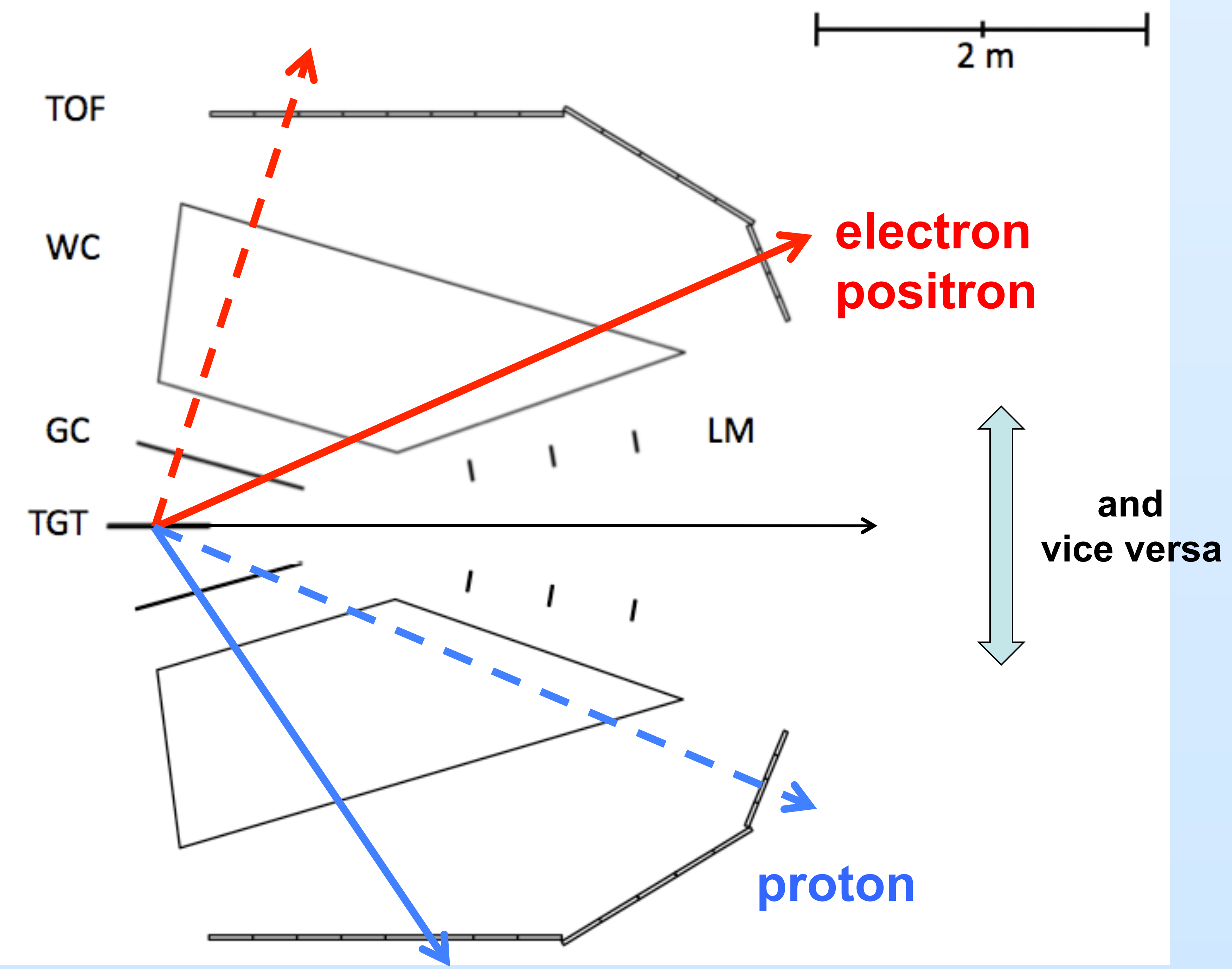
Counts vs. epsilon



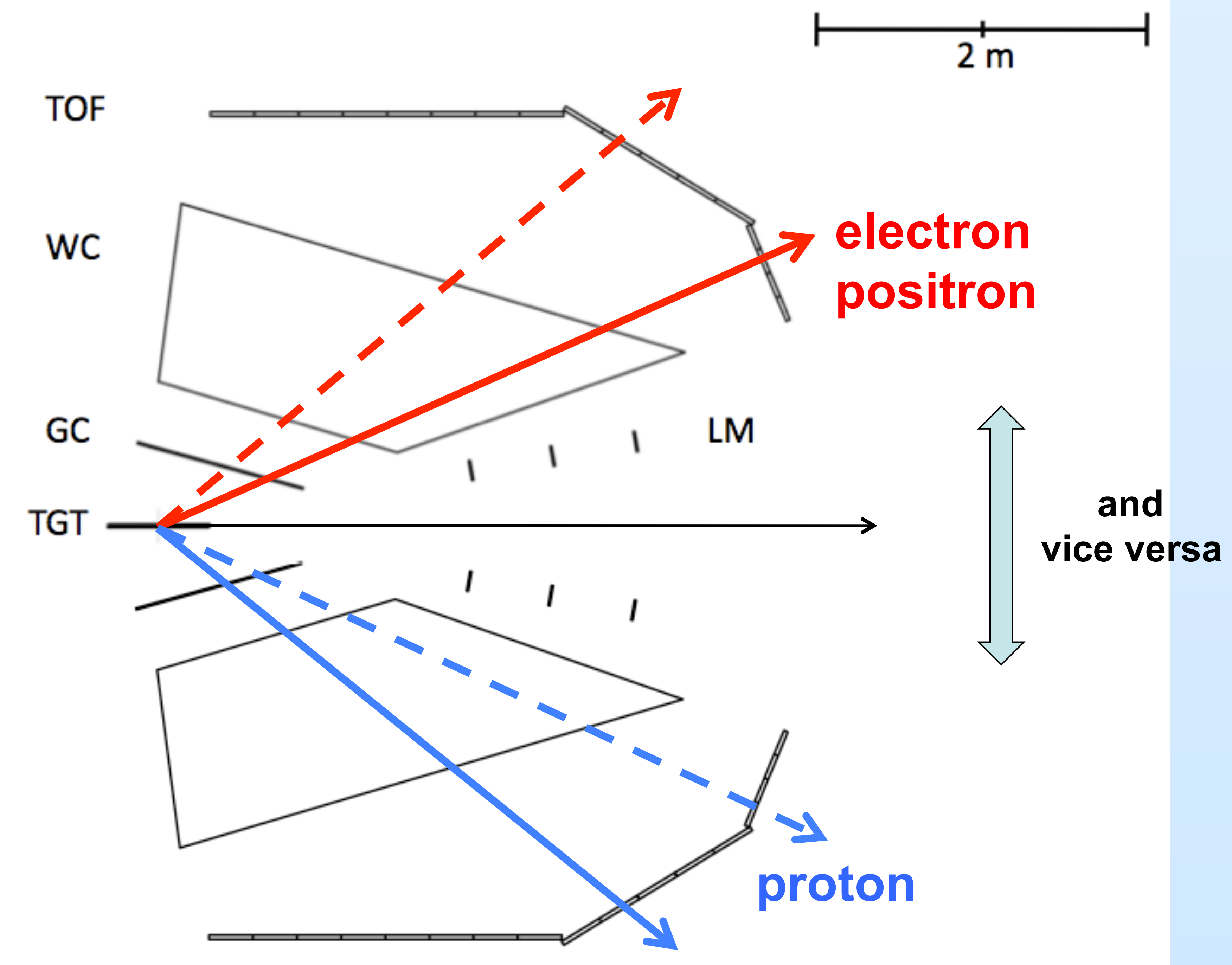
epsilon vs. Q^2



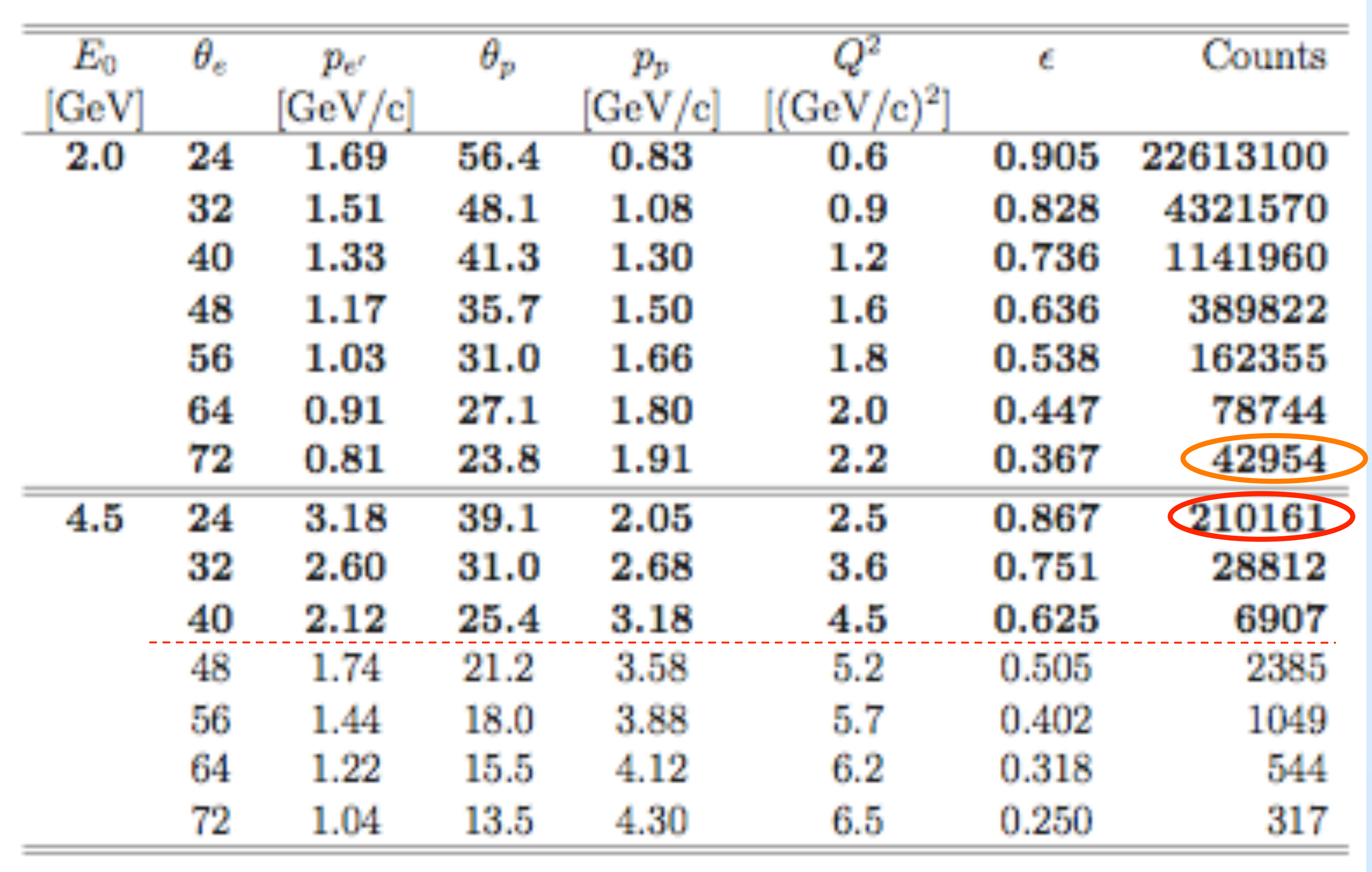
OLYMPUS Kinematics at 2 GeV



OLYMPUS Kinematics at 4.5 GeV



Expected OLYMPUS Statistics



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	64	0.91	27.1	1.80	2.0	0.447	78744
	72	0.81	23.8	1.91	2.2	0.367	42954
4.5	24	3.18	39.1	2.05	2.5	0.867	210161
	32	2.60	31.0	2.68	3.6	0.751	28812
	40	2.12	25.4	3.18	4.5	0.625	6907
	48	1.74	21.2	3.58	5.2	0.505	2385
	56	1.44	18.0	3.88	5.7	0.402	1049
	64	1.22	15.5	4.12	6.2	0.318	544
	72	1.04	13.5	4.30	6.5	0.250	317

e+,e- each
500h @ 2x10^{33} / cm^{2}s
8^o bins

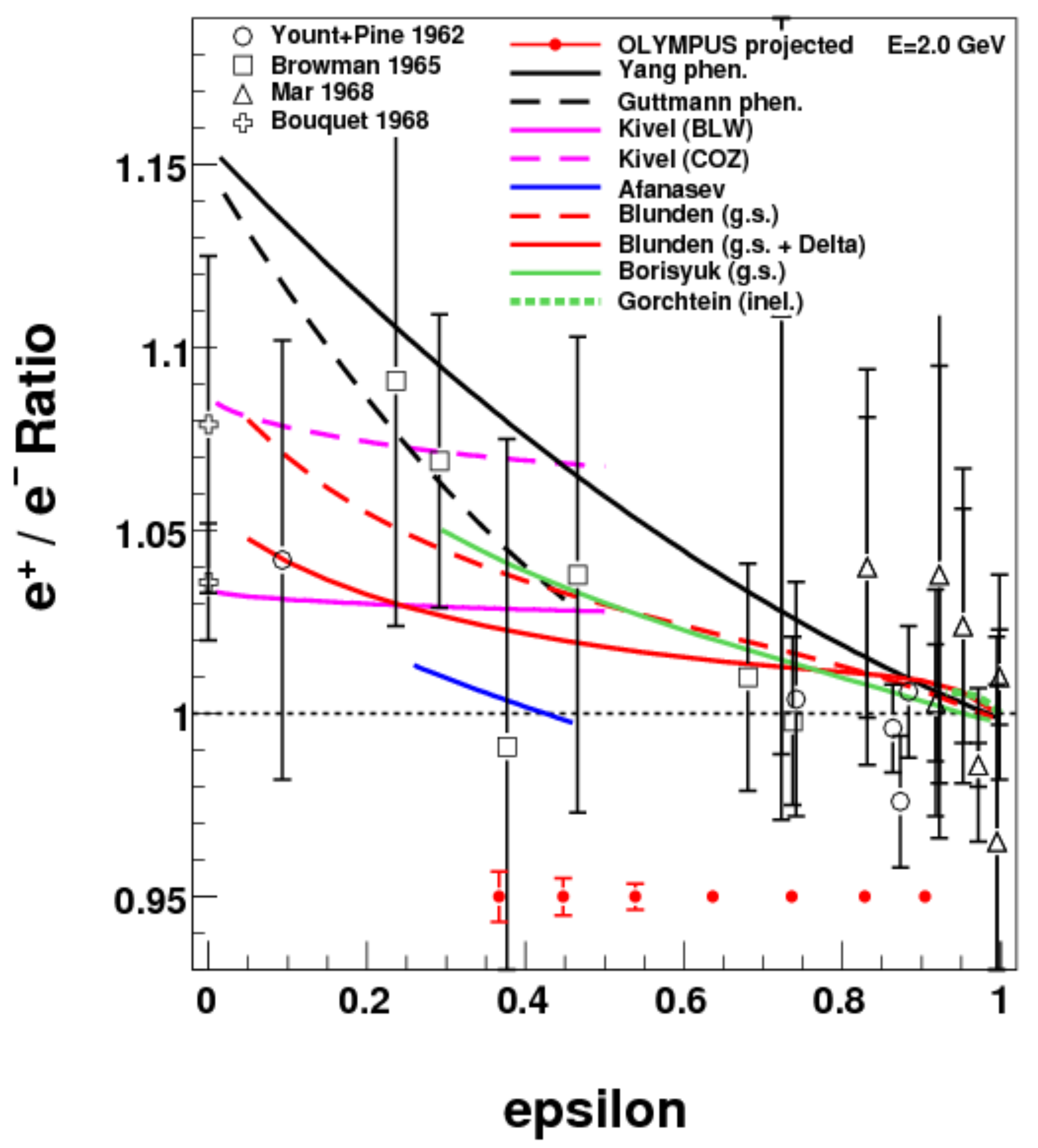
40k events total = 1% stat. precision for e+/e- ratio

Count rate at similar Q^2 factor 5-10 higher at 4.5 GeV -> 50 hours

"Quasi"-Rosenbluth separation of e^+/e^- vs. ε at $Q^2 \approx 2$–2.5 (GeV/c)^2 if running at 2.0 and 4.5 GeV (within beamtime budget)

Reach Q^2 ~ 3–4.5 (GeV/c)^2 with suitable statistics for E=4.5 GeV and intermediate ε (requires additional running time)

Projected Results for OLYMPUS



Data from 1960's

Many theoretical predictions with little constraint

OLYMPUS:
- **E = 2 GeV, ε = 0.37-0.9**
- **Q^2 = 0.6-2.2 $(GeV/c)^2$**
- **<1% projected uncertainties**
- **500h @ 2×10^{33} / cm^2s e+,e-**

to be run in 2012

Simplistic Analysis Scheme

$$N_{ij} = L_{ij}\sigma_i\kappa^p_{ij}\kappa^l_{ij}$$

i = e+ or e-

j= pos/neg polarity

Geometric proton **efficiency:** $\kappa^p_{e+j} = \kappa^p_{e-j}$

$$\frac{N_{e+j}/L_{e+j}}{N_{e-j}/L_{e-j}} = \frac{\sigma_{e+}}{\sigma_{e-}} \cdot \frac{\kappa^l_{e+j}}{\kappa^l_{e-j}}$$

Ratio in single polarity j

Geometric lepton **efficiency:** $\kappa^l_{e++} = \kappa^l_{e--}$ and $\kappa^l_{e+-} = \kappa^l_{e-+}$

Simplistic Analysis Scheme

Super ratio:

$$\left[\frac{N_{\mathrm{e}^+ +}/L_{\mathrm{e}^+ +}}{N_{\mathrm{e}^- +}/L_{\mathrm{e}^- +}} \cdot \frac{N_{\mathrm{e}^+ -}/L_{\mathrm{e}^+ -}}{N_{\mathrm{e}^- -}/L_{\mathrm{e}^- -}}\right]^{\frac{1}{2}} = \frac{\sigma_{\mathrm{e}^+}}{\sigma_{\mathrm{e}^-}}$$

Cycle of four states ij
Repeat cycle many times

- Change between electrons and positrons every other day
- Change toroid polarity every other day
- Left-right symmetry

In reality, need to take acceptances A_{ij} into account

Impact of Magnetic Field

- Magnetic Toroidal field: 1.6 MW
  - Dominates OLYMPUS running cost
  - Cleaning effect: prevent low-energy particles (Moller) from entering wire chambers
  - Momentum measurement, $\delta p/p \sim 3\%$ @ 1 GeV/c

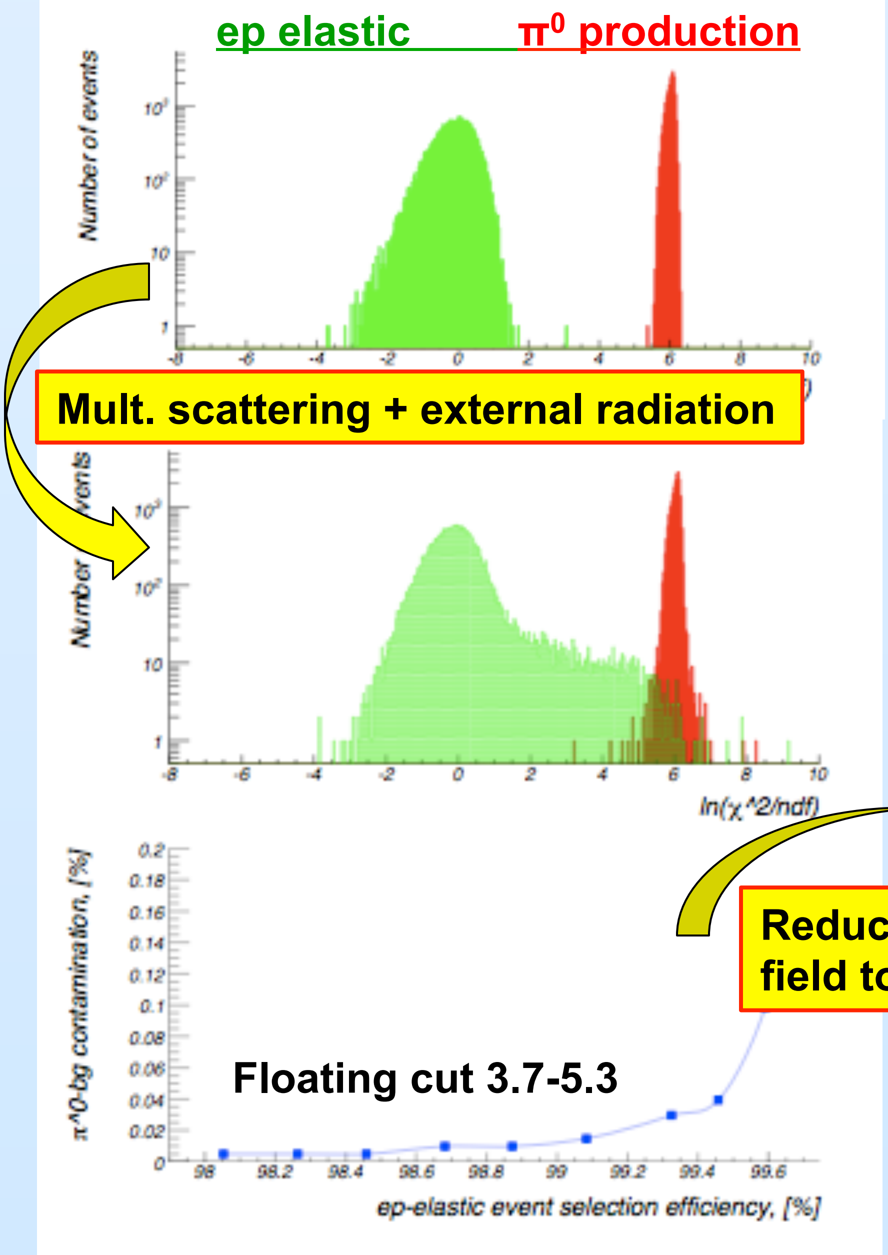
- Acceptance for e^+p / e^-p depending on magnetic field

- Radiative corrections dependent on radiative tails
  ➔ correction smaller w/o field, momentum cut

- Event selection less dependent on momentum, use of angular resolution more powerful

- Optimal toroidal field to be investigated experimentally
  “As large as necessary, as small as possible”

OLYMPUS Elastic Event Selection

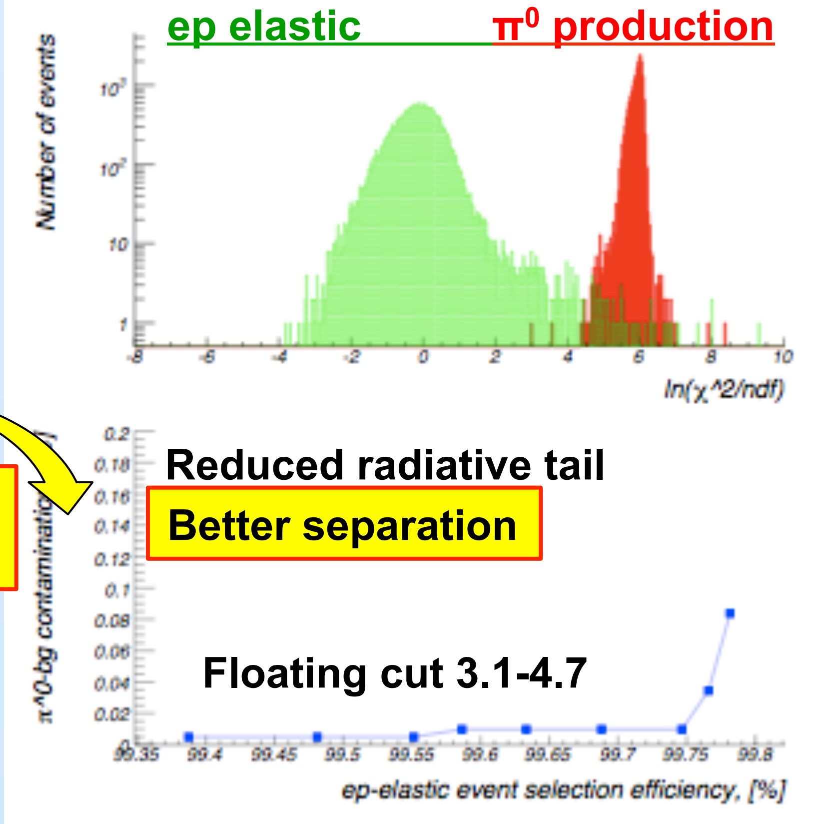


Mult. scattering + external radiation

Floating cut 3.7-5.3

Reduce toroidal field to 30%

- Elastic event selection governed by angular resolution
- Momentum resolution less relevant
- Radiative tails
- Plotted *ln(Chi^2/ndf)* for (recon-expected)



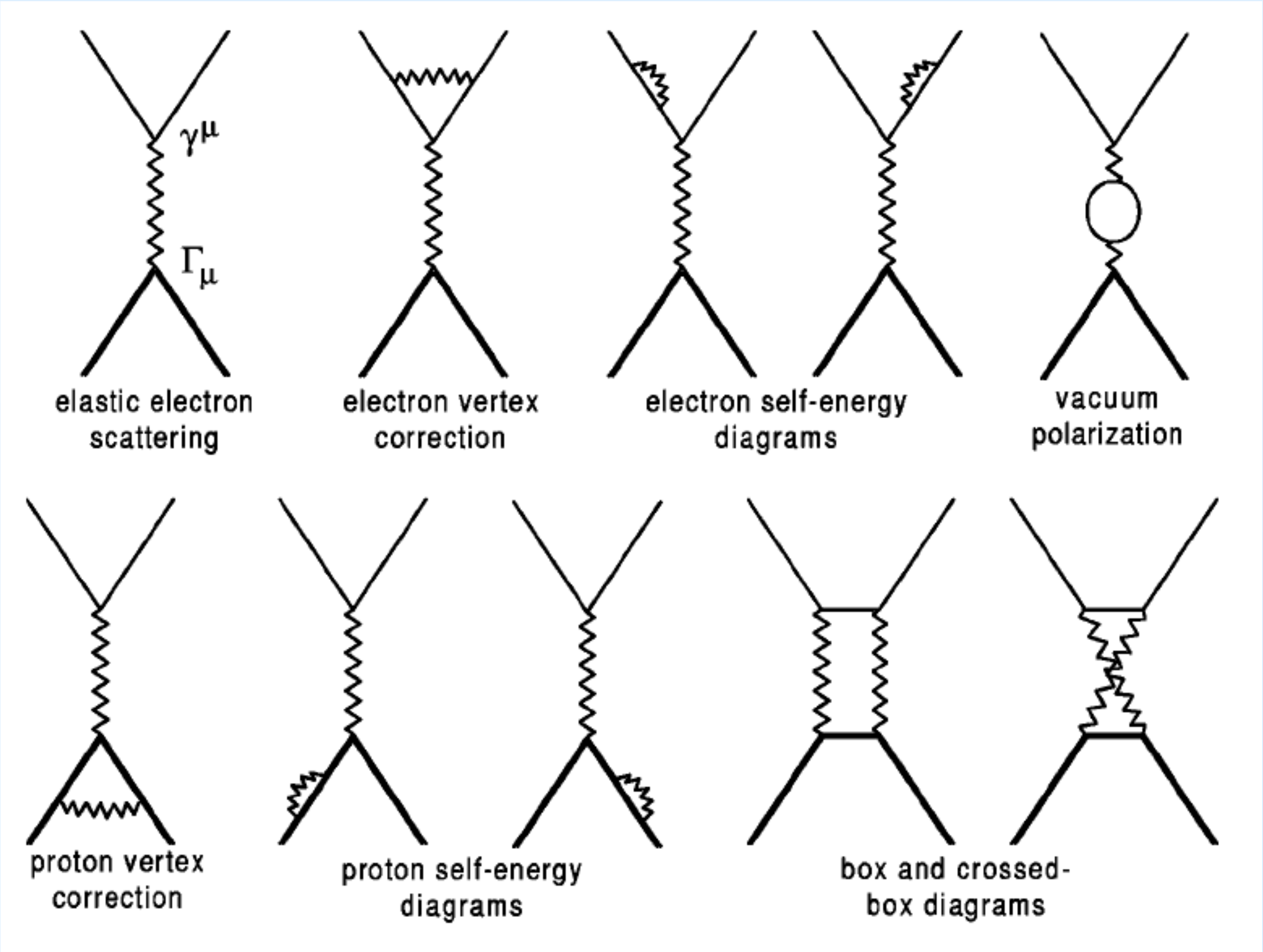
Reduced radiative tail

Better separation

Floating cut 3.1-4.7

Study by A. Kiselev, PNPI

Radiative Corrections for Elastic ep



L.C.. Maximon and J.A. Tjon, Phys. Rev. C62, 054320 (2001)
L. W. Mo and Y. S. Tsai, Rev. Mod. Phys. 41, 205 (1969)

Radiative Corrections for BLAST

MASCARAD, SIMC (Jlab)

$\sigma=\sigma_0(1+\delta)$ unpolarized

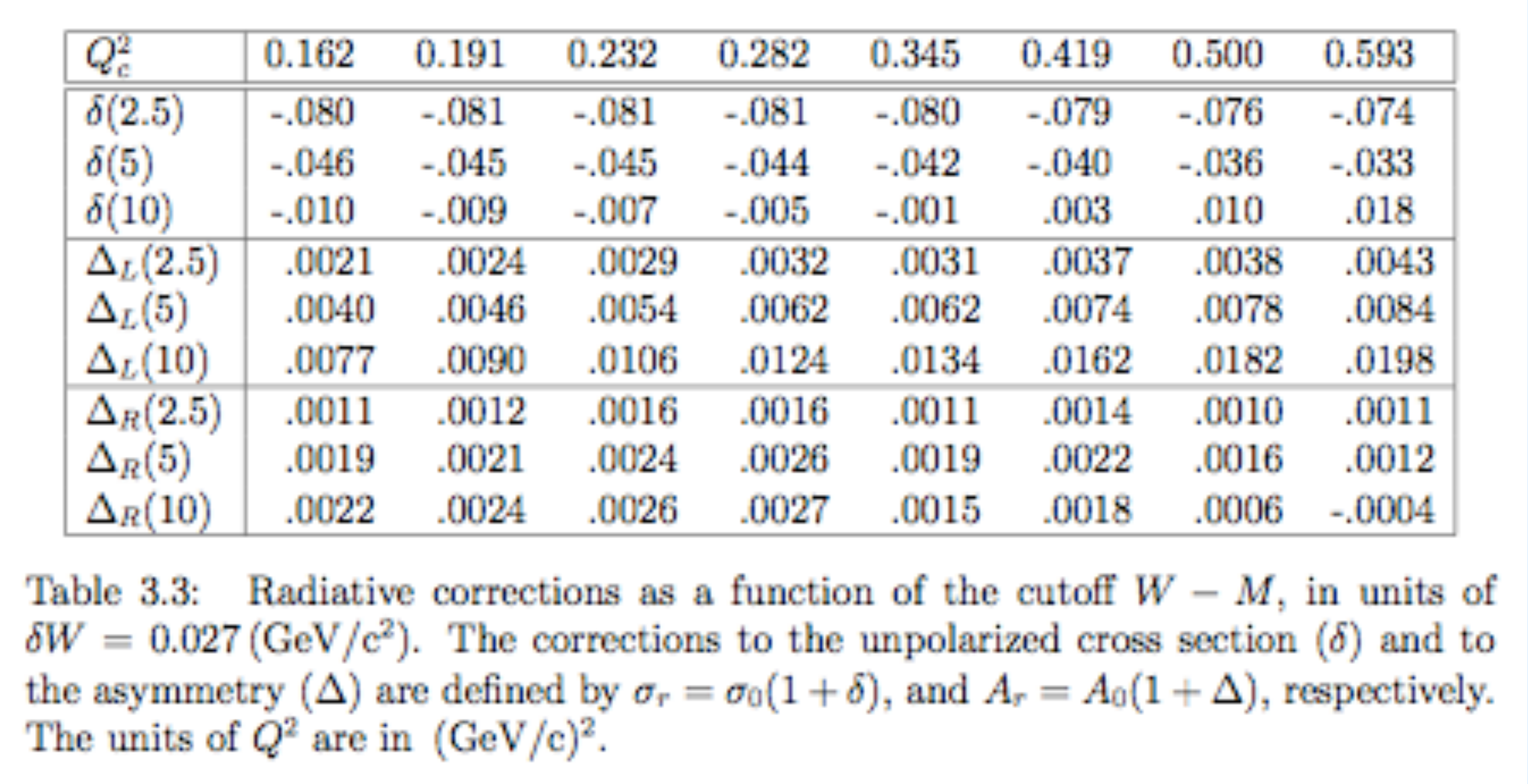
$A=A_0(1+\Delta)$ polarized

A. Afanasev, I. Akushevich, and N. Merenkov, Phys. Rev. D64, 113009 (2001)

Correction to spin asymmetries, Δ

- 2.5 sigma W cut: 0.2 – 0.4 %
- 5.0 sigma W cut: 0.4 – 0.8 %
- 7.5 sigma W cut: 0.6 – 1.3 %
- 10. sigma W cut: 0.8 – 2.0 %

(predominantly in the left sector)



Q^2_c	0.162	0.191	0.232	0.282	0.345	0.419	0.500	0.593
$\delta(2.5)$	-.080	-.081	-.081	-.081	-.080	-.079	-.076	-.074
$\delta(5)$	-.046	-.045	-.045	-.044	-.042	-.040	-.036	-.033
$\delta(10)$	-.010	-.009	-.007	-.005	-.001	.003	.010	.018
$\Delta_L(2.5)$	.0021	.0024	.0029	.0032	.0031	.0037	.0038	.0043
$\Delta_L(5)$	.0040	.0046	.0054	.0062	.0062	.0074	.0078	.0084
$\Delta_L(10)$	.0077	.0090	.0106	.0124	.0134	.0162	.0182	.0198
$\Delta_R(2.5)$	.0011	.0012	.0016	.0016	.0011	.0014	.0010	.0011
$\Delta_R(5)$	.0019	.0021	.0024	.0026	.0019	.0022	.0016	.0012
$\Delta_R(10)$	.0022	.0024	.0026	.0027	.0015	.0018	.0006	-.0004

Table 3.3: Radiative corrections as a function of the cutoff $W-M$, in units of $\delta W = 0.027\,(\mathrm{GeV/c^2})$. The corrections to the unpolarized cross section (δ) and to the asymmetry (Δ) are defined by $\sigma_r = \sigma_0(1+\delta)$, and $A_r = A_0(1+\Delta)$, respectively. The units of Q^2 are in $(\mathrm{GeV/c})^2$.

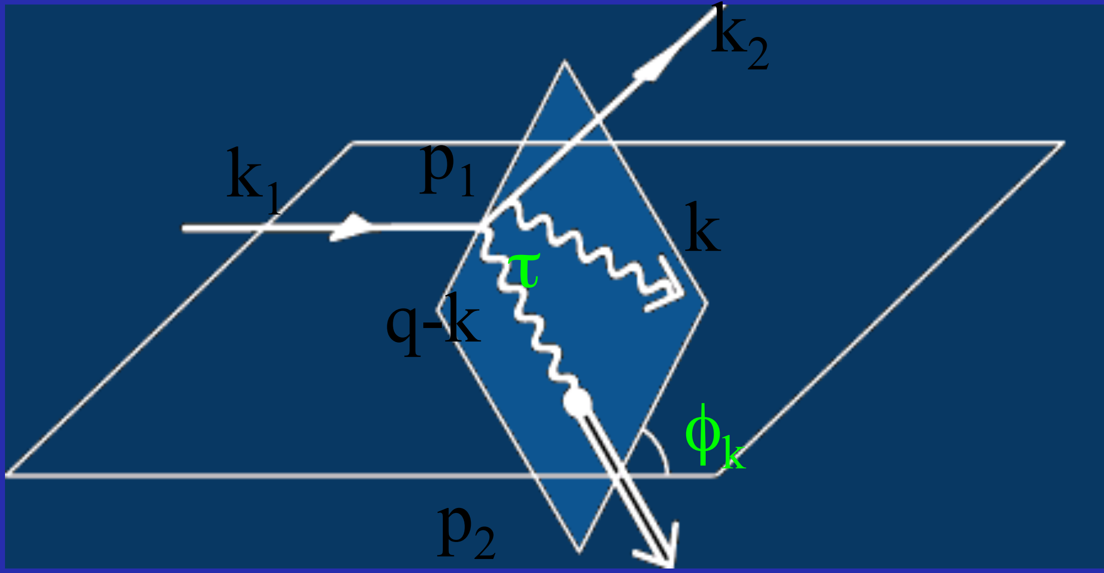
From C. Crawford, Ph.D. thesis, MIT (2005)

-> need to convolute with detector response

MASCARAD Phase Space

$$v \equiv 2k \cdot p_2$$

$$\tau \equiv \frac{k \cdot q}{p_1 \cdot q}$$



$$\int \frac{d^3k}{2k_0} = \int_0^{v_m} \frac{dv}{4\sqrt{\lambda_q}} \int_{\tau_{min}}^{\tau_{max}} \frac{d\tau_k \, v}{(1+\tau_k)^2} \int_0^{2\pi} d\phi_k$$

with limits

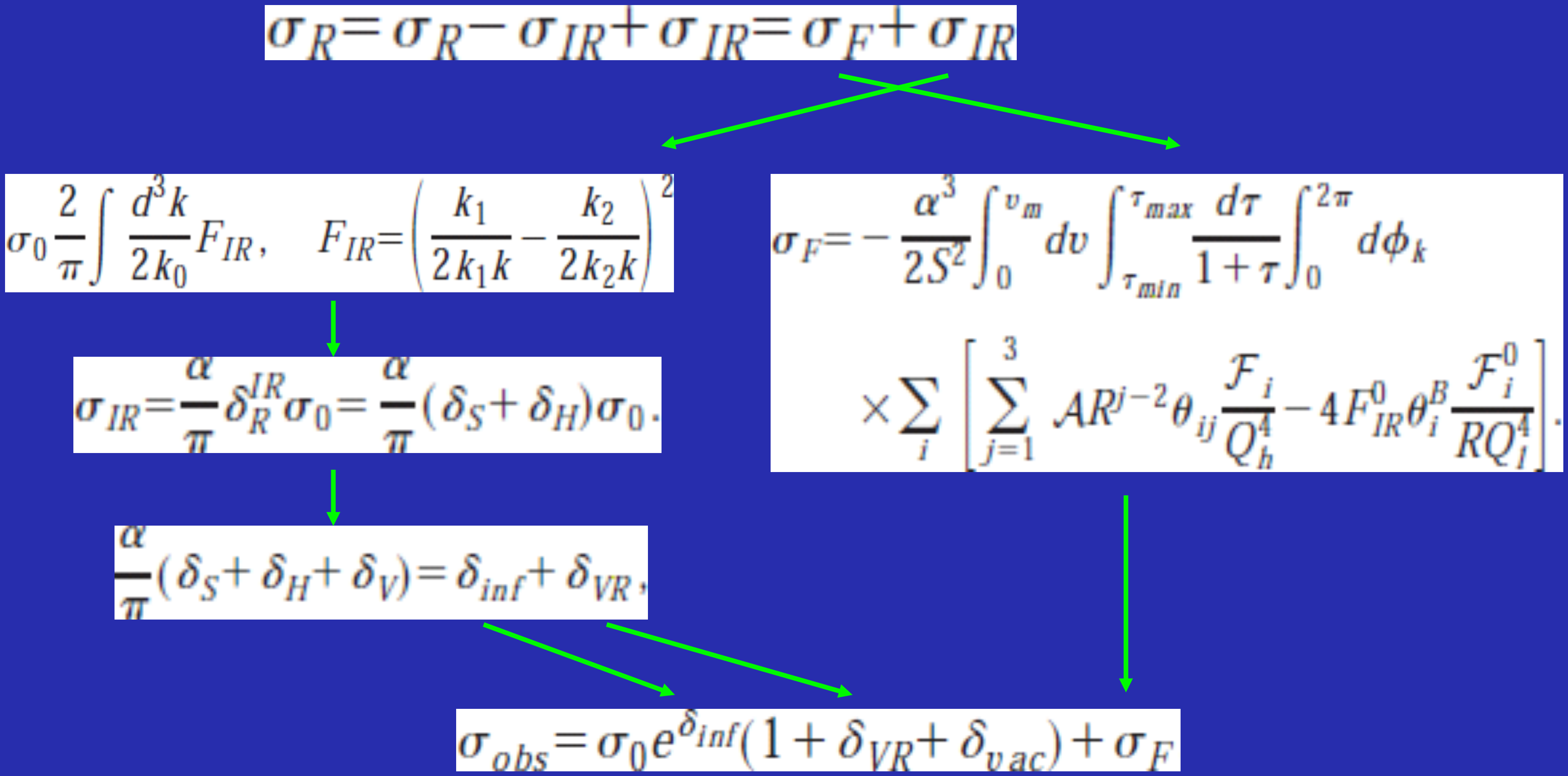
$$v_m = \frac{\sqrt{\lambda_s}\sqrt{\lambda_m} - 2m^2Q^2 - Q^2S}{2m^2},$$

$$\tau_{min}^{max} = \frac{v + Q^2 \pm \sqrt{\lambda_q}}{2M^2}$$

Details of MASCARAD

$$L_{\mu\nu} \Rightarrow L^{r}_{\mu\nu} \qquad \gamma^{\mu} \Rightarrow \Gamma^{\mu\alpha}$$

$$\Gamma^{\mu\alpha} = \left(\frac{k_1^{\alpha}}{k\cdot k_1} - \frac{k_2^{\alpha}}{k\cdot k_2}\right)\gamma^{\mu} - \frac{\gamma^{\alpha}\not{k}\gamma^{\mu}}{2k\cdot k_1} - \frac{\gamma^{\mu}\not{k}\gamma^{\alpha}}{2k\cdot k_2}$$



$$\sigma_R = \sigma_R - \sigma_{IR} + \sigma_{IR} = \sigma_F + \sigma_{IR}$$

$$\sigma_0 \frac{2}{\pi}\int \frac{d^3k}{2k_0} F_{IR}, \quad F_{IR} = \left(\frac{k_1}{2k_1k} - \frac{k_2}{2k_2k}\right)^2$$

$$\sigma_{IR} = \frac{\alpha}{\pi}\delta_R^{IR}\sigma_0 = \frac{\alpha}{\pi}(\delta_S + \delta_H)\sigma_0.$$

$$\frac{\alpha}{\pi}(\delta_S + \delta_H + \delta_V) = \delta_{inf} + \delta_{VR},$$

$$\sigma_F = -\frac{\alpha^3}{2S^2}\int_0^{v_m} dv \int_{\tau_{min}}^{\tau_{max}} \frac{d\tau}{1+\tau}\int_0^{2\pi} d\phi_k \times \sum_i \left[\sum_{j=1}^{3} \mathcal{A}R^{j-2}\theta_{ij}\frac{\mathcal{F}_i}{Q_h^4} - 4F_{IR}^0\theta_i^B\frac{\mathcal{F}_i^0}{RQ_i^4}\right].$$

$$\sigma_{obs} = \sigma_0 e^{\delta_{inf}}(1 + \delta_{VR} + \delta_{vac}) + \sigma_F$$

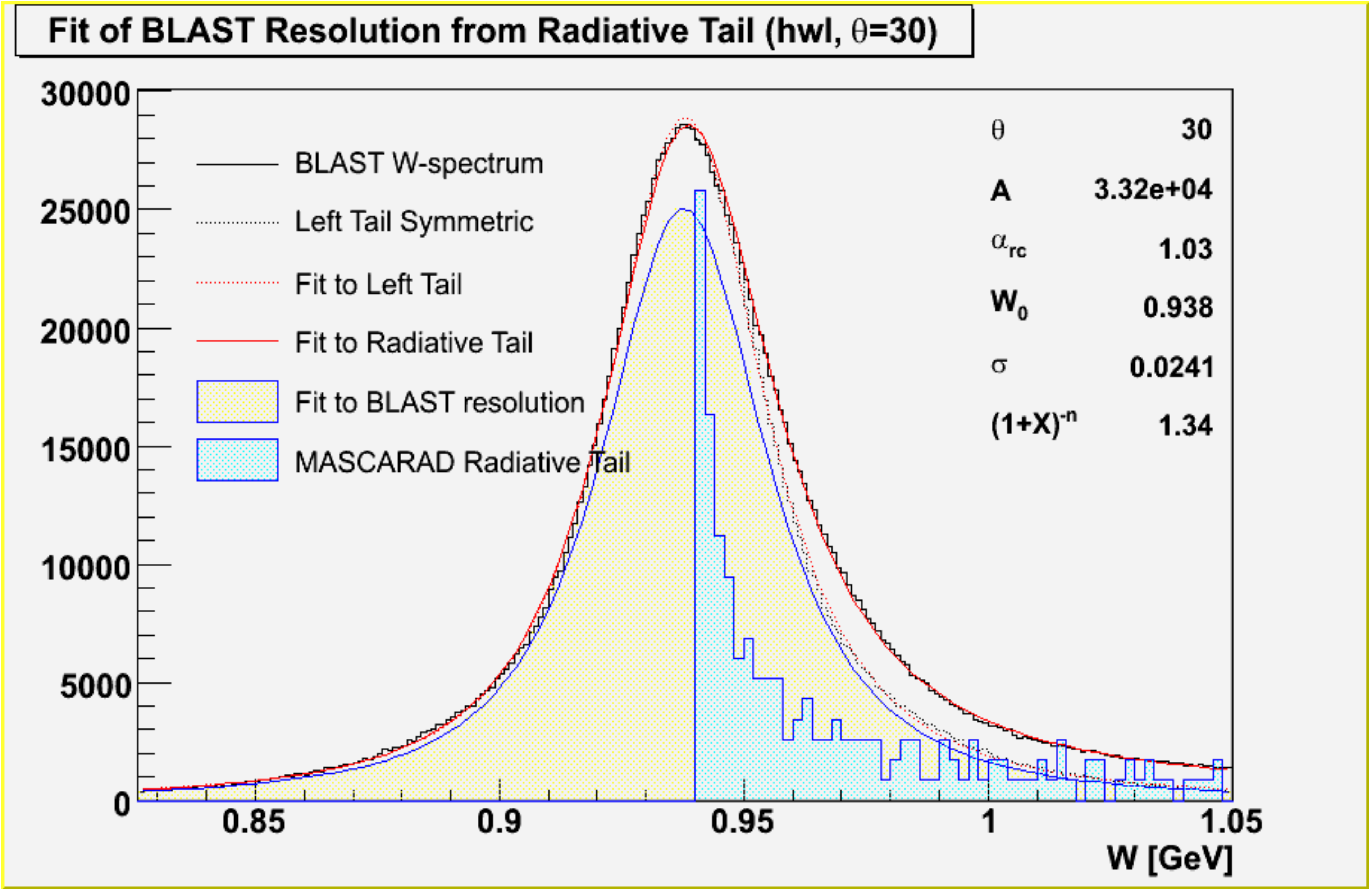
V. Ziskin, BLAST analysis meeting 2005/08/17

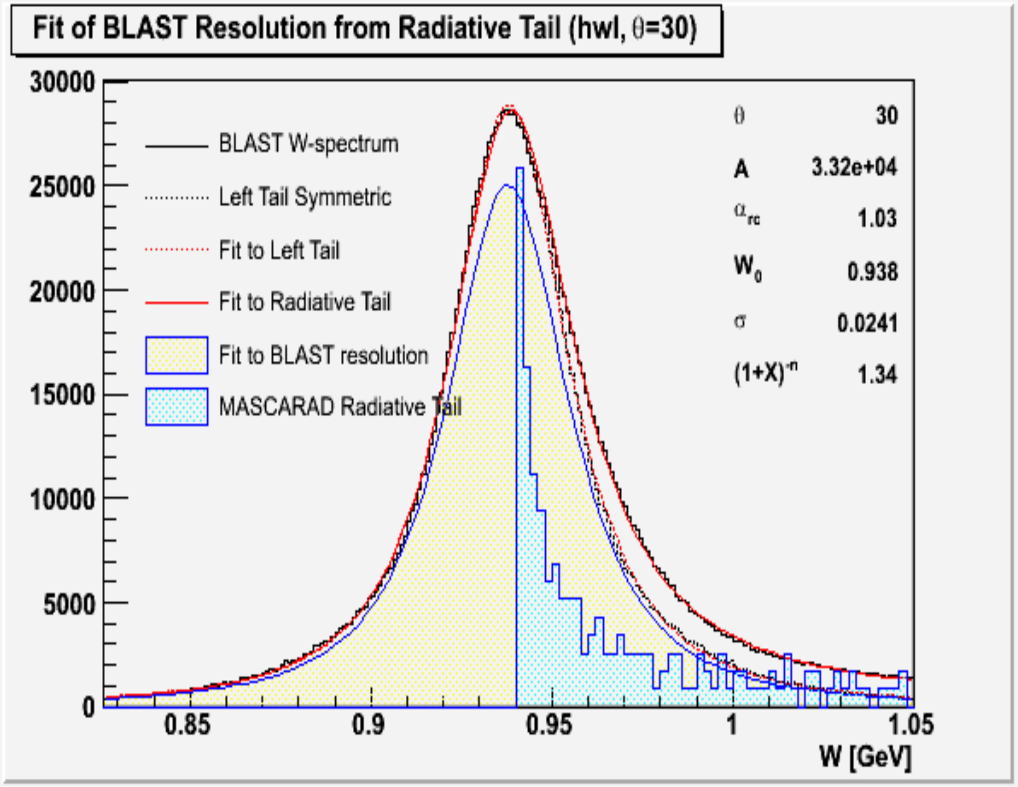
Radiative Corrections Applied to BLAST Data

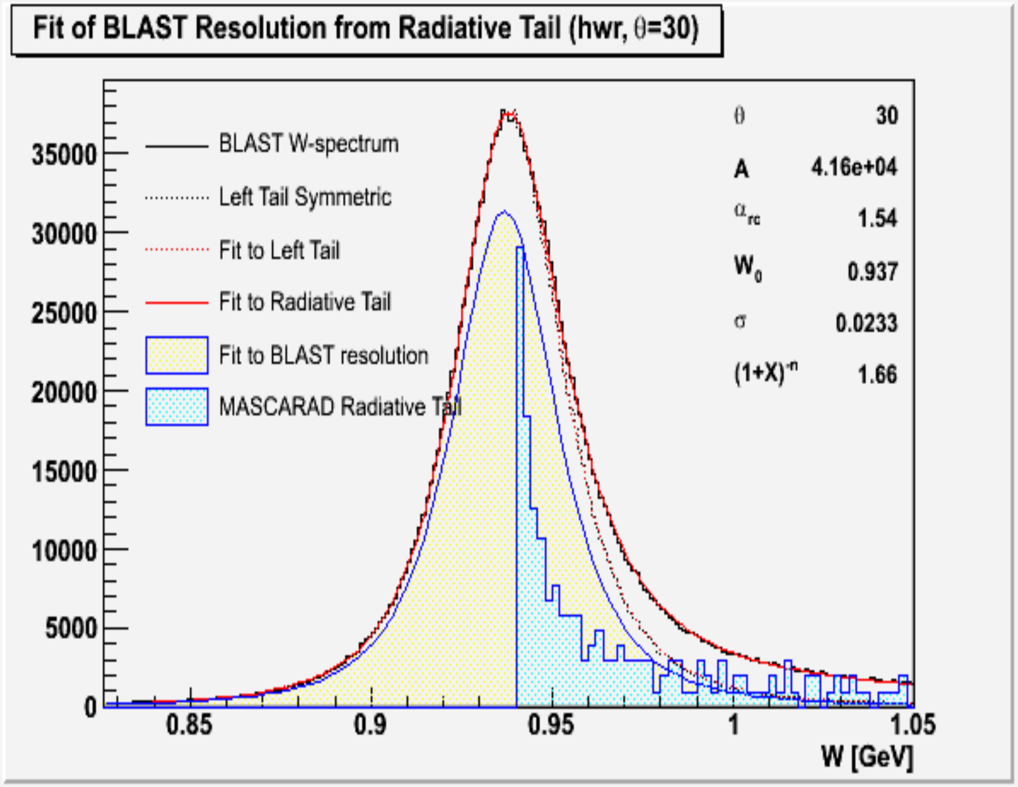
Chris Crawford

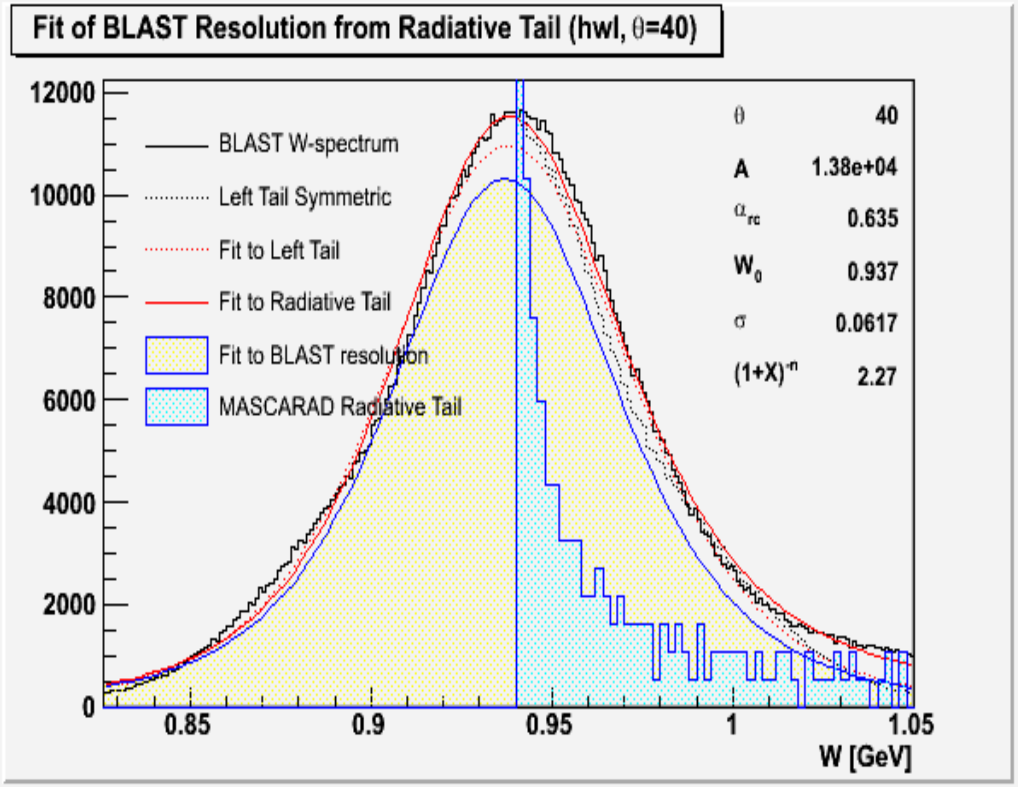
2006-04-19

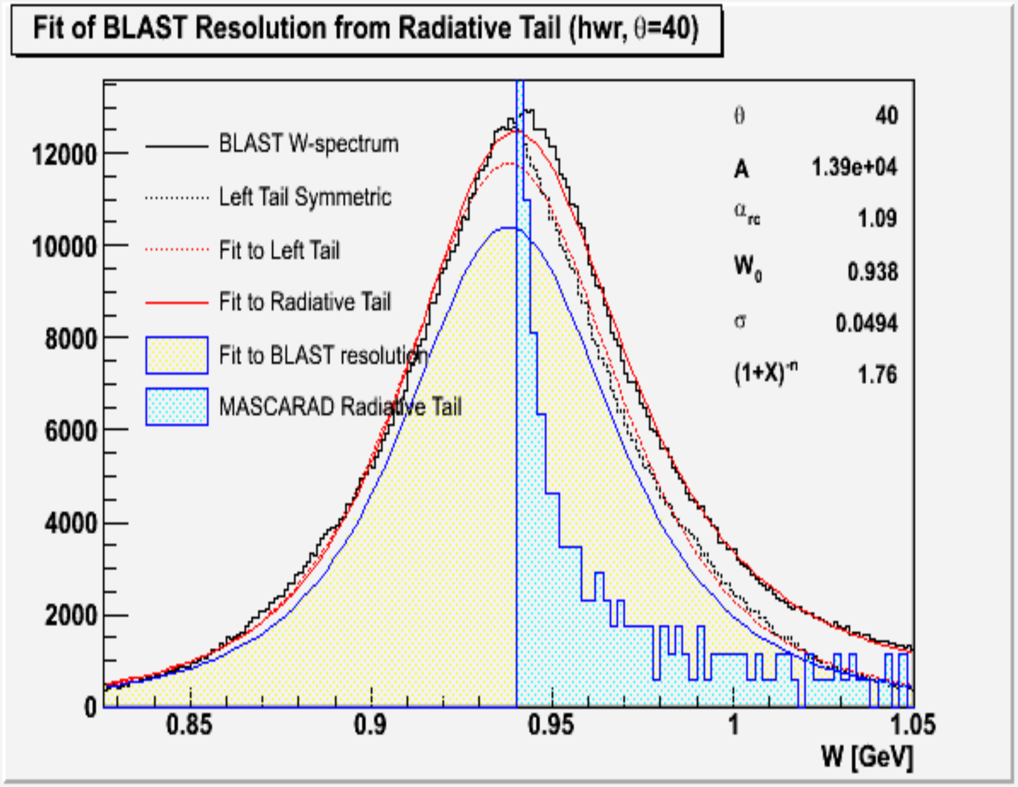
BLAST Resolution from W spectrum




Fit of BLAST Resolution from Radiative Tail (hwl, θ=30)
BLAST W-spectrum
Left Tail Symmetric
Fit to Left Tail
Fit to Radiative Tail
Fit to BLAST resolution
MASCARAD Radiative Tail
θ 30
A 3.32e+04
α_{rc} 1.03
W_0 0.938
σ 0.0241
$(1+X)^{-n}$ 1.34
30000
25000
20000
15000
10000
5000
0
0.85
0.9
0.95
1
1.05
W [GeV]


Fit of BLAST Resolution from Radiative Tail (hwr, θ=30)
BLAST W-spectrum
Left Tail Symmetric
Fit to Left Tail
Fit to Radiative Tail
Fit to BLAST resolution
MASCARAD Radiative Tail
θ 30
A 4.16e+04
α_{rc} 1.54
W_0 0.937
σ 0.0233
$(1+X)^{-n}$ 1.66
35000
30000
25000
20000
15000
10000
5000
0
0.85
0.9
0.95
1
1.05
W [GeV]


Fit of BLAST Resolution from Radiative Tail (hwl, θ=40)
BLAST W-spectrum
Left Tail Symmetric
Fit to Left Tail
Fit to Radiative Tail
Fit to BLAST resolution
MASCARAD Radiative Tail
θ 40
A 1.38e+04
α_{rc} 0.635
W_0 0.937
σ 0.0617
$(1+X)^{-n}$ 2.27
12000
10000
8000
6000
4000
2000
0
0.85
0.9
0.95
1
1.05
W [GeV]


Fit of BLAST Resolution from Radiative Tail (hwr, θ=40)
BLAST W-spectrum
Left Tail Symmetric
Fit to Left Tail
Fit to Radiative Tail
Fit to BLAST resolution
MASCARAD Radiative Tail
θ 40
A 1.39e+04
α_{rc} 1.09
W_0 0.938
σ 0.0494
$(1+X)^{-n}$ 1.76
12000
10000
8000
6000
4000
2000
0
0.85
0.9
0.95
1
1.05
W [GeV]

Peak Offsets from Rad. Tail

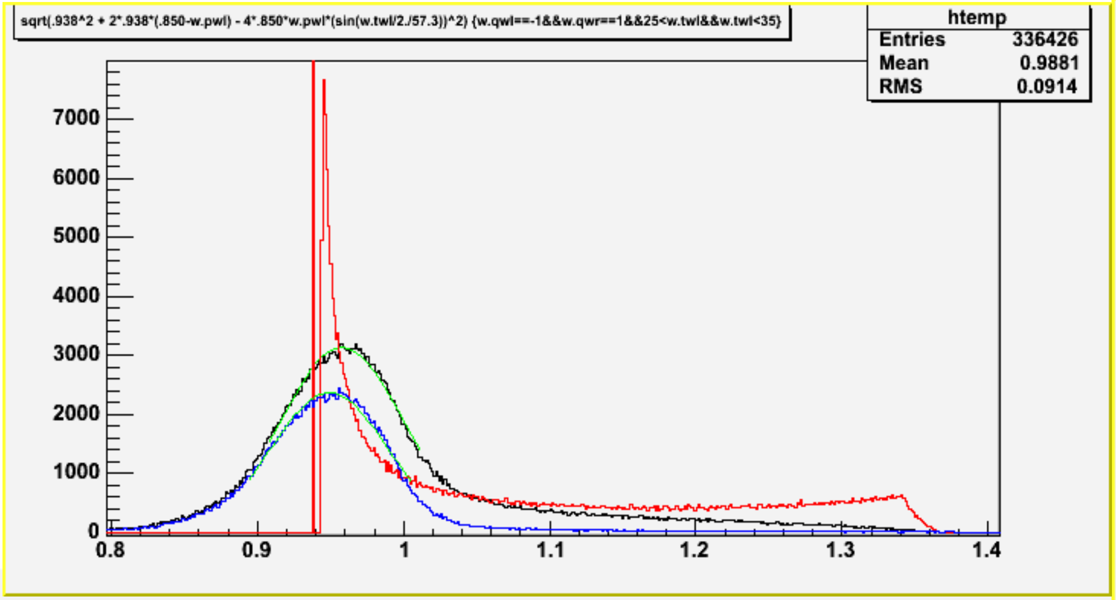
- **radiative corrections offset (peak):**
- th=30 0.90 MeV (left) 1.15 MeV (right)
- th=40 1.29 MeV (left) 1.90 MeV (right)

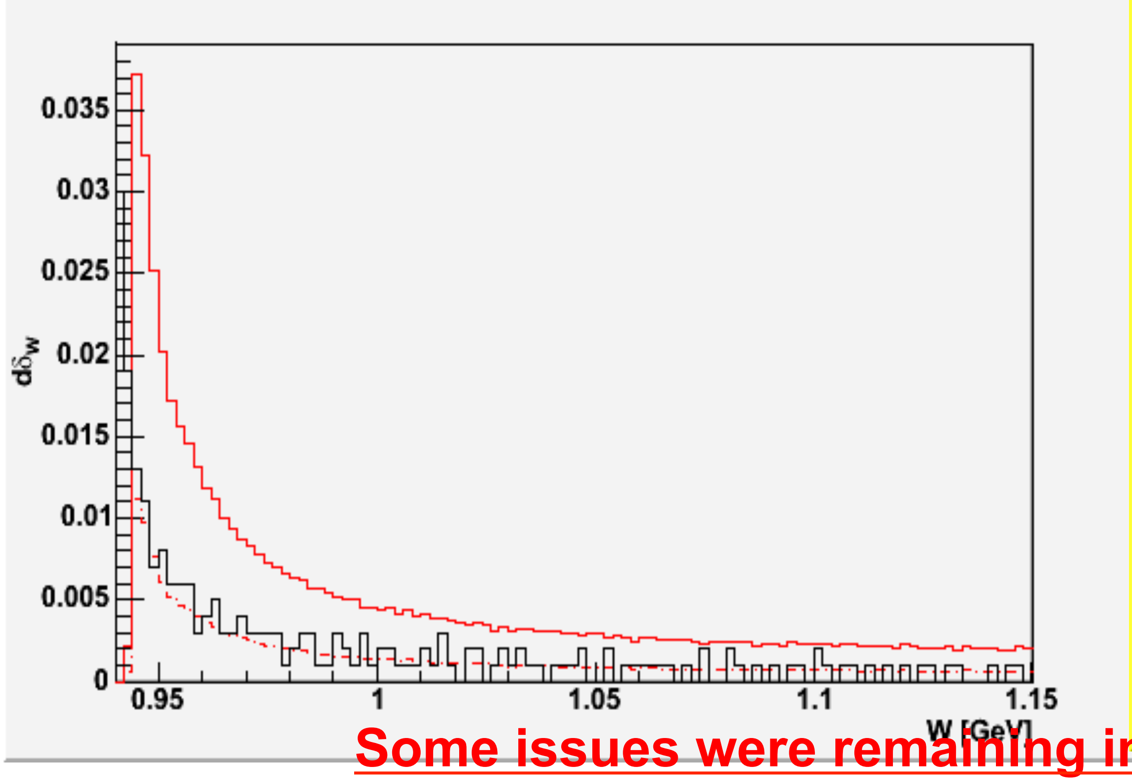
- **calc_peaks(sigma) [MeV]**

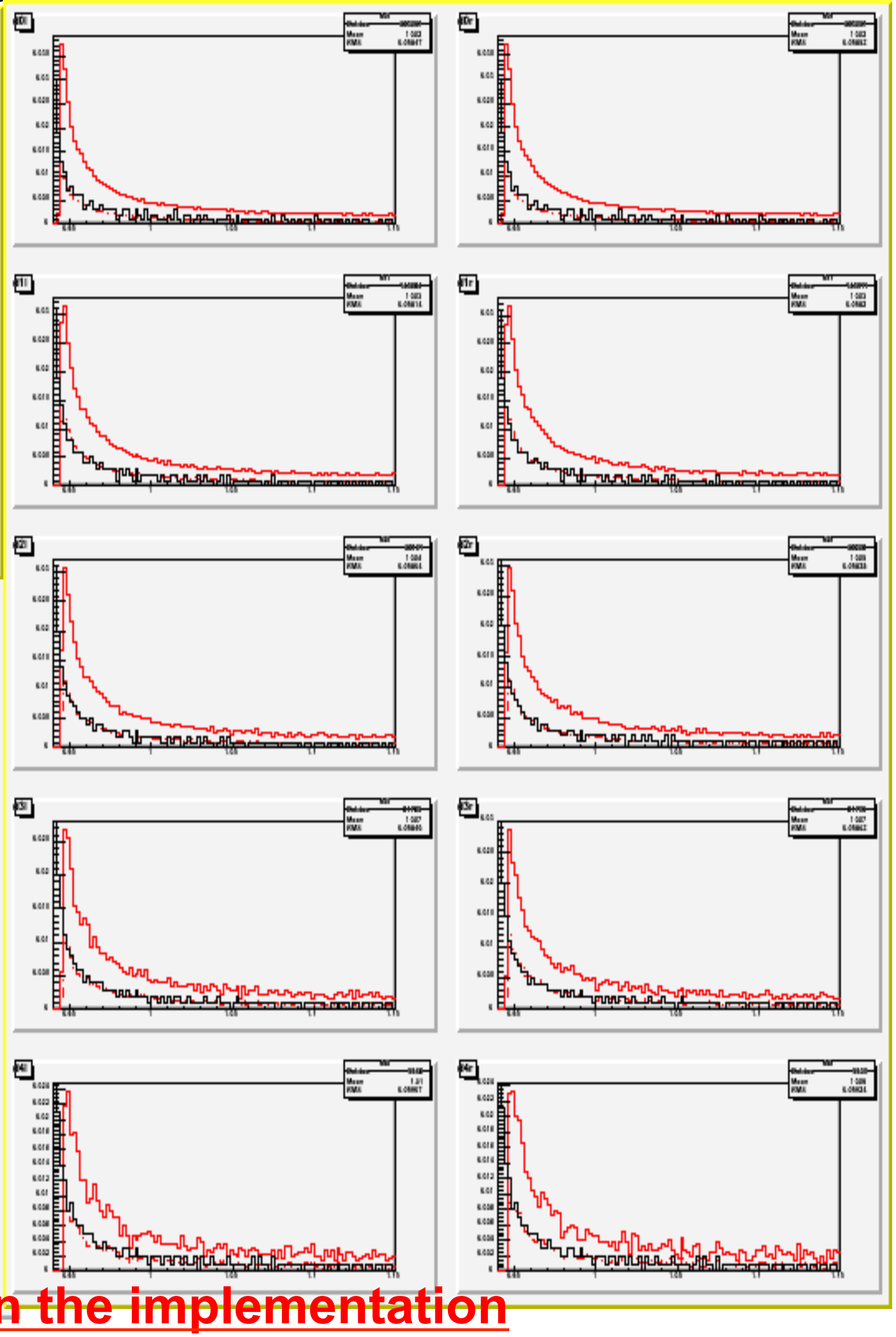
(assuming n=1.5)	**sigma=25 MeV**	**sigma=50 MeV**	**sigma=100 MeV**
offset(30 deg) =	0.868	1.823	3.640
offset(40 deg) =	0.907	1.906	3.808
offset(50 deg) =	0.934	1.962	3.937
offset(60 deg) =	0.954	2.009	4.053
offset(70 deg) =	0.973	2.046	4.151

Shift of peak is scaling with resolution (width of response function)

DGen + Mascarad



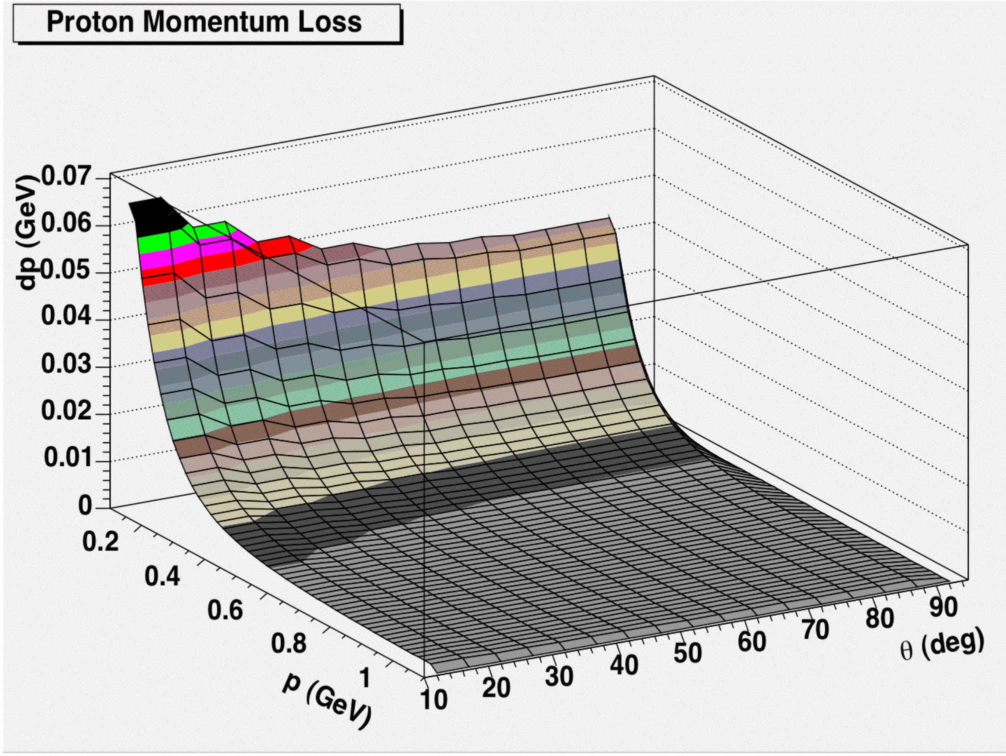




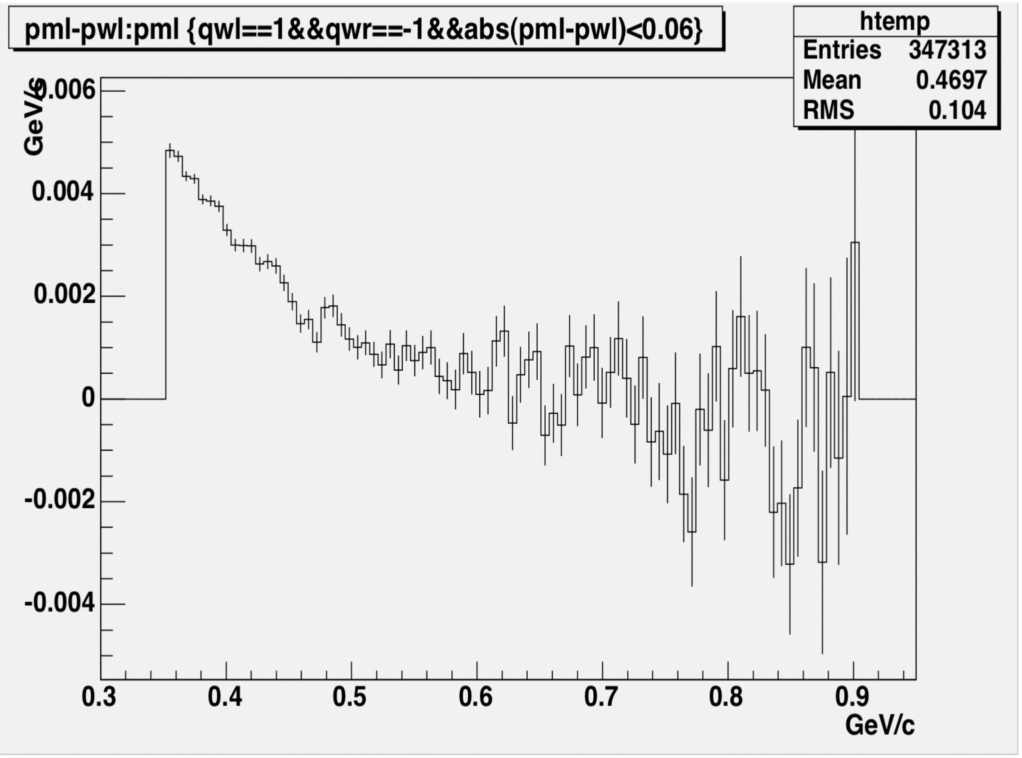
Some issues were remaining in the implementation of MASCARAD into the BLAST analysis

Energy Loss

Aaron, 2004-12-03



Eugene, 2006-02-22



Energy loss is a minor effect (internal target!)

Radiative Correction for e+/e-

- Radiative correction of cross section sizable, depending on momentum cutoff, the latter on resolution – correction is smaller if momentum is not measured
- Radiative correction of polarization observables very small (<1%) due to approximate factorization

- How big is the radiative correction for the e+/e- ratio?
- How does the correction for e+/e- depend on the momentum cutoff?
- How sensitive is it to the magnetic field used for momentum measurement?

- Need a common, suitable framework to account for radiative effects

Summary

- The limits of OPE have been reached with available today's precision
  ➔ Nucleon elastic form factors, particularly G_E^p under doubt

- The TPE hypothesis is suited to remove form factor discrepancy, however calculations of TPE are model-dependent

- Experimental probes: Real part of TPE –
  - ε-dependence of polarization transfer
  - ε-nonlinearity of cross sections
  - Comparison of positron and electron scattering

- Need both positron and electron beams for a definitive test of TPE
  OLYMPUS, CLAS, VEPP-3

- OLYMPUS has been installed into DORIS in July 2011 ("rolling-in")
  - Commissioning of OLYMPUS August – December 2011
  - Take data in two running blocks beginning and end 2012
  - Reach ε below 0.4 for $Q^2 \approx 2.2\ (\mathrm{GeV}/c)^2$ at $E = 2$ GeV
  - Can reach high ε for $Q^2 \approx 2.5\ (\mathrm{GeV}/c)^2$ at $E = 4.5$ GeV

Backup slides – OLYMPUS

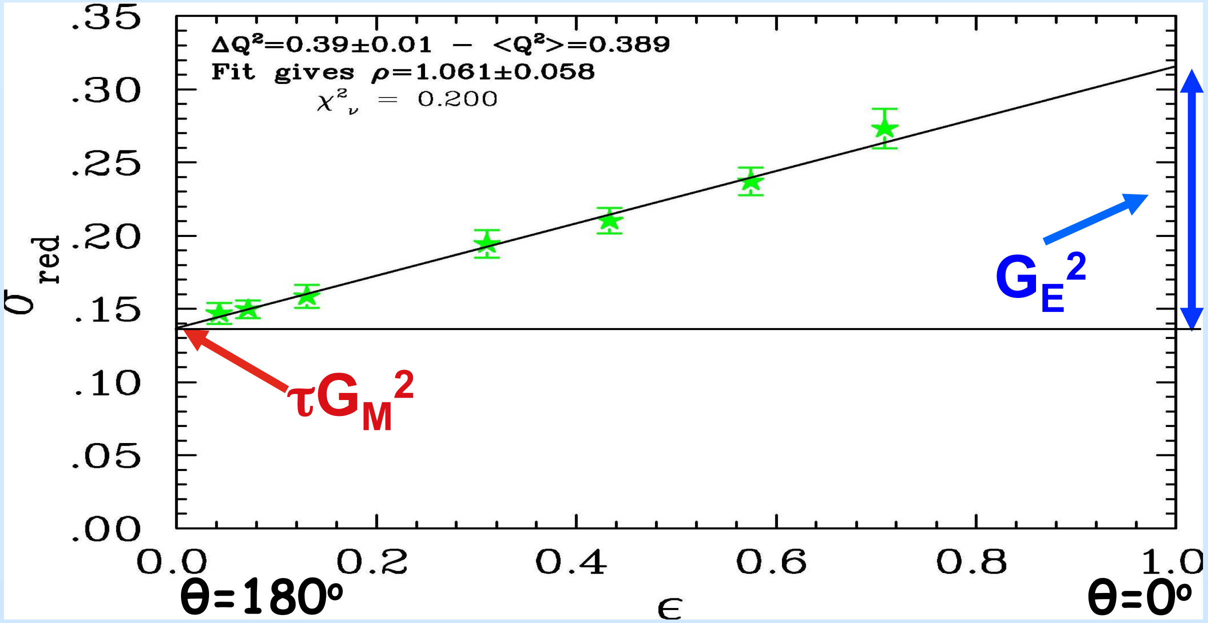
Form Factors from Rosenbluth Method

- In One-photon exchange approximation, elastic form factors are observables of elastic electron-nucleon scattering

$$\frac{d\sigma/d\Omega}{(d\sigma/d\Omega)_{Mott}} = S_0 = A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}$$

$$= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}$$

$$= \frac{\epsilon\, G_E^2 + \tau G_M^2}{\epsilon\,(1+\tau)}, \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$



$\sigma_{red} = \varepsilon G_E^2 + \tau G_M^2$

→Determine

$|G_E|$, $|G_M|$, $|G_E/G_M|$

Nucleon Form Factors and Polarization

- **Double polarization in elastic ep scattering:**
  Recoil polarization or (vector) polarized target

  $^1\mathrm{H}(\vec{e},e'\vec{p})$, $^1\vec{\mathrm{H}}(\vec{e},e'p)$

- **Polarized cross section / transferred polarization**

$$\sigma = \sigma_0 \left(1 + P_e\,\vec{P}_p\cdot\vec{A}\right)$$

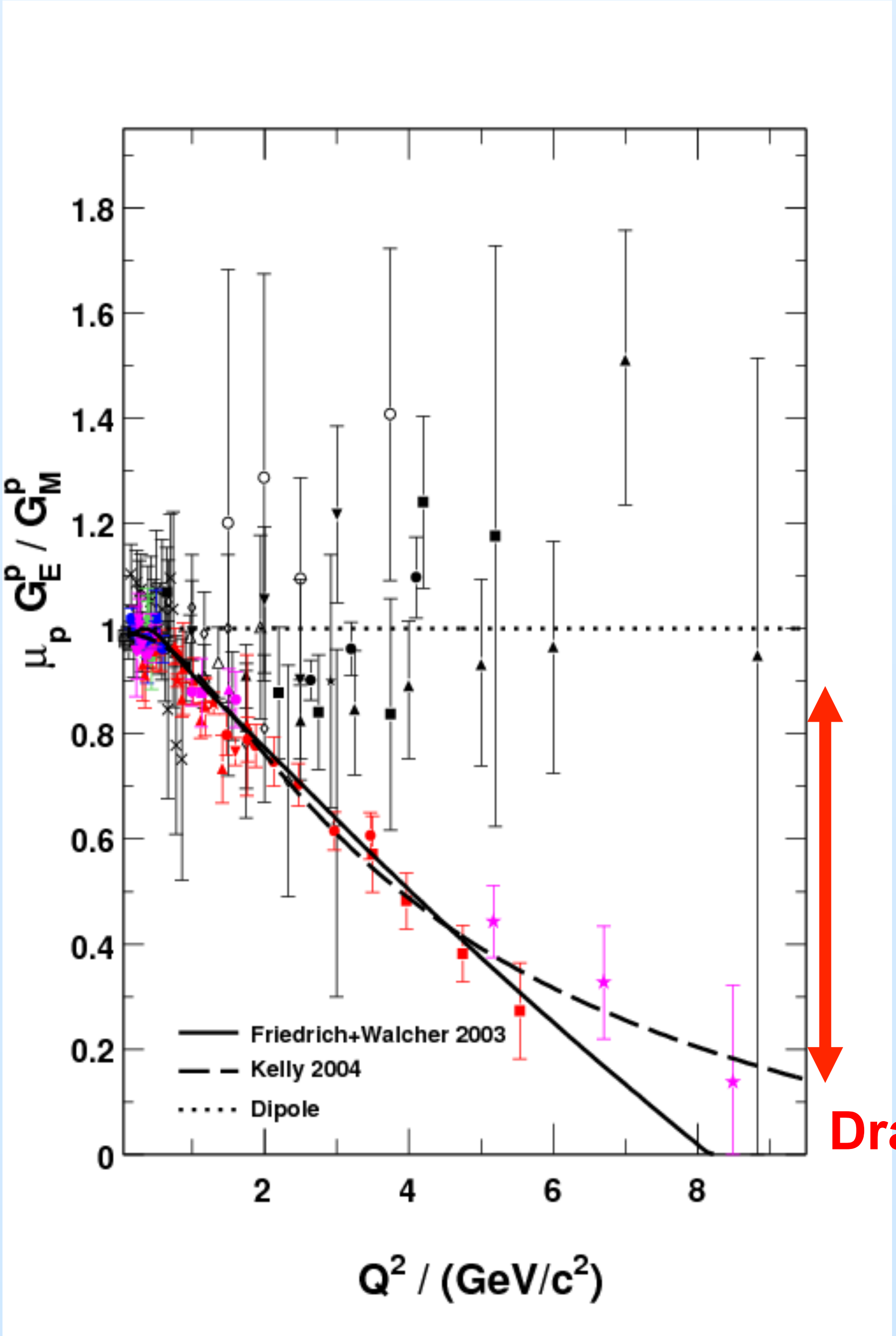
- **Double spin asymmetry = spin correlation**

$$\boxed{-\sigma_0\,\vec{P}_p\cdot\vec{A} = \sqrt{2\tau\epsilon(1-\epsilon)}\,G_E G_M \sin\theta^*\cos\phi^* + \tau\sqrt{1-\epsilon^2}\,{G_M}^2\cos\theta^*}$$

- **Asymmetry ratio ("Super ratio")** $\dfrac{P_\perp}{P_\parallel} = \dfrac{A_\perp}{A_\parallel} \propto \dfrac{G_E}{G_M}$

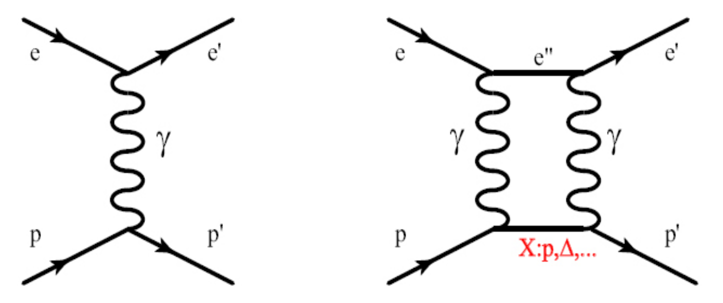
  independent of polarization or analyzing power

Proton Form Factor Ratio



Jefferson Lab 2000–today

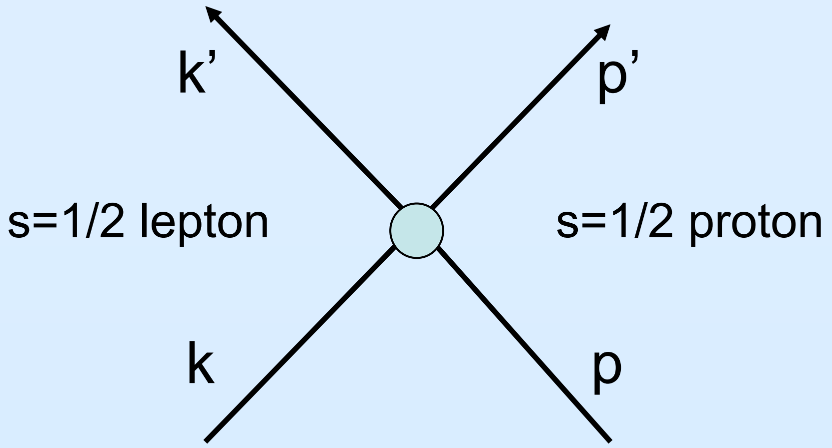
- All Rosenbluth data from SLAC and Jlab in agreement
- Dramatic discrepancy between Rosenbluth and recoil polarization technique
- Multi-photon exchange considered best candidate



Dramatic discrepancy!

>800 citations

Elastic ep Scattering Beyond OPE



$$P \equiv \frac{p+p'}{2}, \qquad K \equiv \frac{k+k'}{2}$$

Kinematical invariants :

$$\begin{aligned} Q^2 &= -(p-p')^2 \\ \nu &= K \cdot P = (s-u)/4 \end{aligned}$$

Next-to Born approximation:

$$\begin{aligned} T^{non-flip}_{h'\lambda'_N, h\lambda_N} &= \frac{e^2}{Q^2}\bar{u}(k',h')\gamma_\mu u(k,h) \\ (m_e = 0) \quad &\times \quad \bar{u}(p',\lambda'_N)\left(\tilde{G}_M\,\gamma^\mu - \tilde{F}_2\frac{P^\mu}{M} + \tilde{F}_3\frac{\gamma.K P^\mu}{M^2}\right)u(p,\lambda_N) \end{aligned}$$

The T-matrix still factorizes, however a new response term F_3 is generated by TPE
Born-amplitudes are modified in presence of TPE; modifications ~α^3

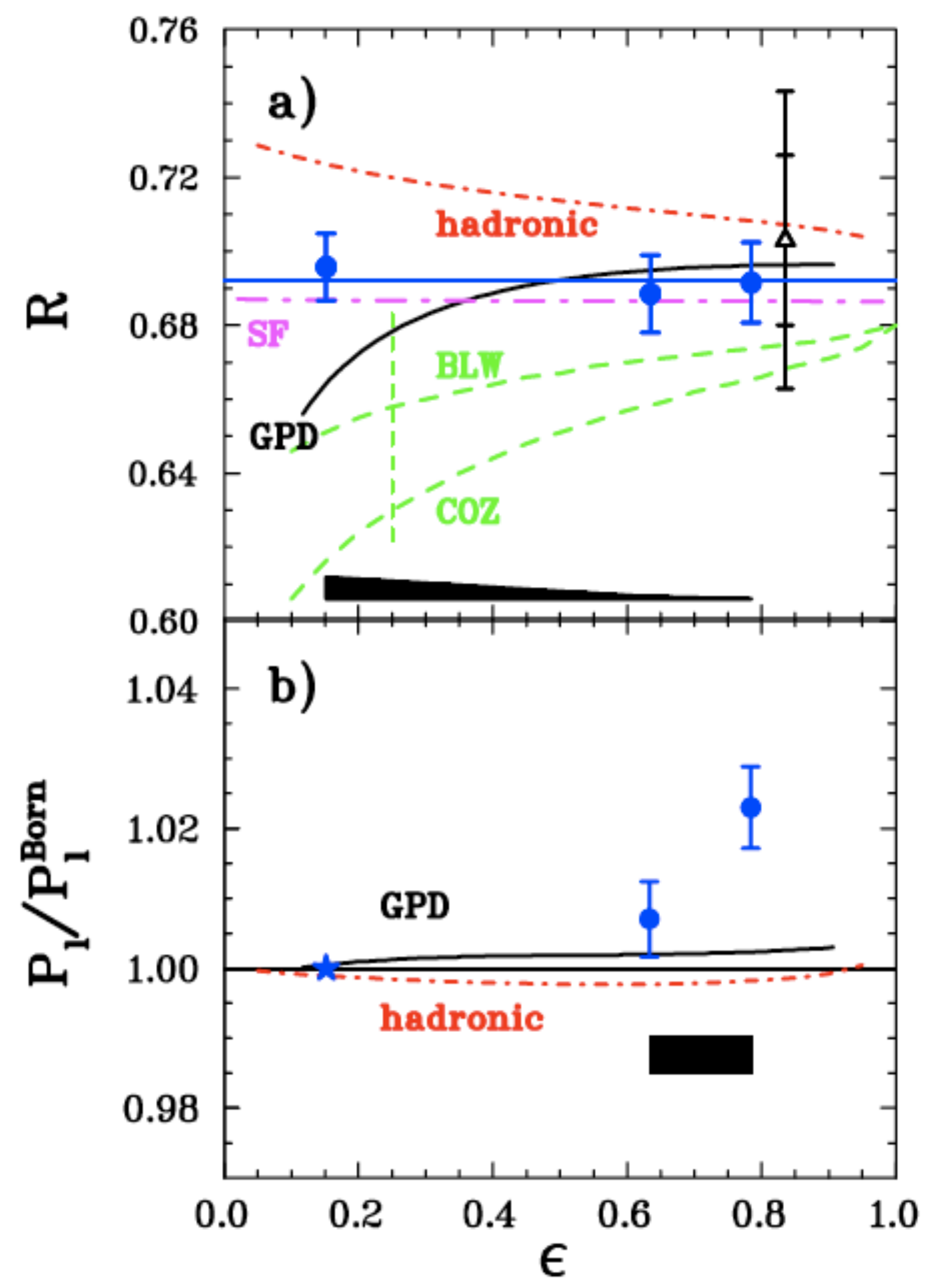
$$\begin{aligned} \tilde{G}_M(\nu,Q^2) &= G_M(Q^2) + \delta\tilde{G}_M \\ \tilde{F}_2(\nu,Q^2) &= F_2(Q^2) + \delta\tilde{F}_2 \\ \tilde{F}_3(\nu,Q^2) &= 0 + \delta\tilde{F}_3 \end{aligned}$$

$$\tilde{G}_E \equiv \tilde{G}_M - (1+\tau)\,\tilde{F}_2$$

$$\tilde{G}_E(\nu,Q^2) = G_E(Q^2) + \delta\tilde{G}_E$$

New amplitudes are complex!

Jefferson Lab E04-019 (Two-gamma)



Jlab – Hall C
$Q^2 = 2.5\ (GeV/c)^2$

G_E/G_M from P_t/P_l constant vs. ε

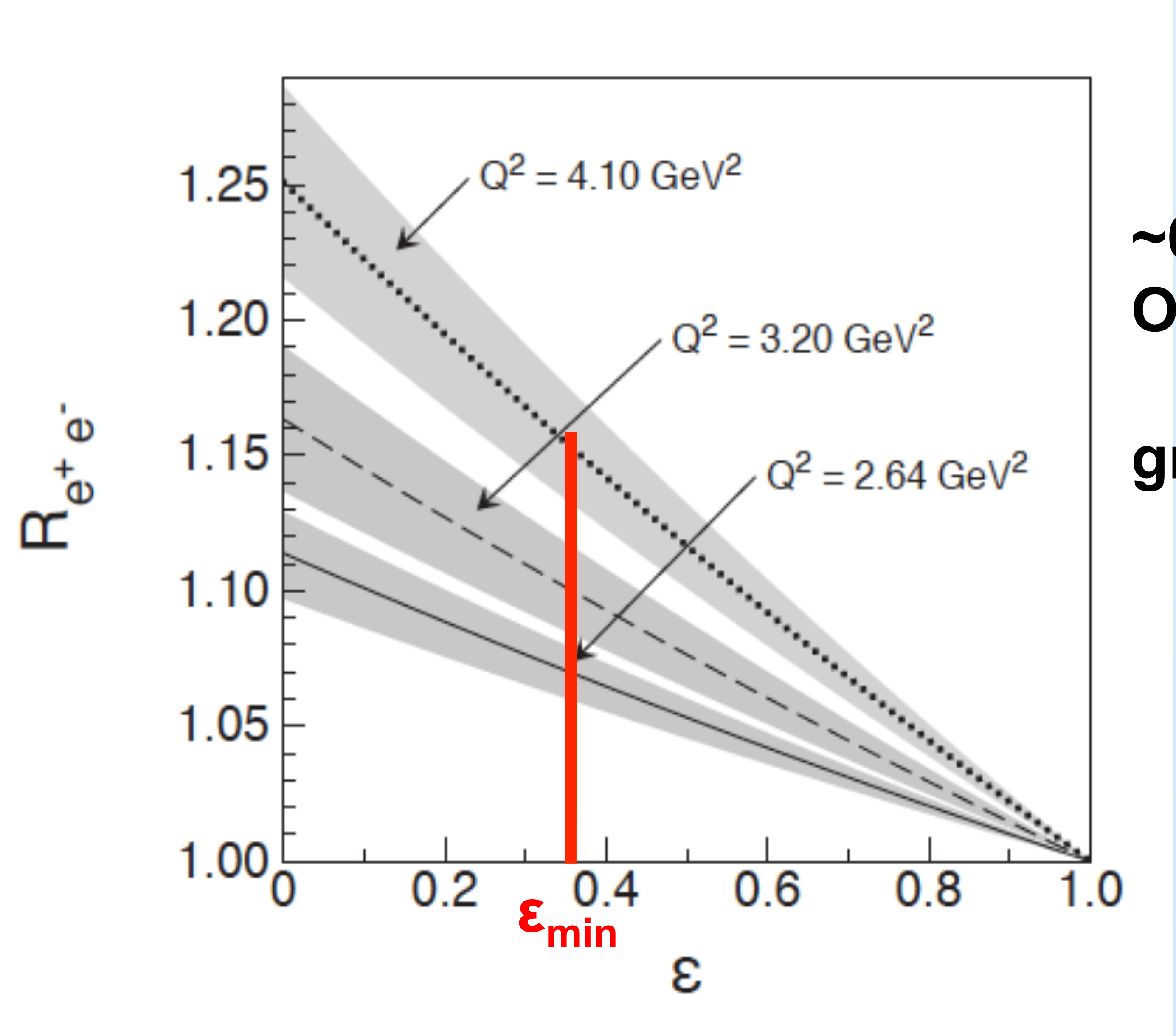
- ➔ **no effect in P_t/P_l**
- ➔ **some effect in P_l**

Expect larger effect in e+/e-!

M. Meziane et al., hep-ph/1012.0339v2
Phys. Rev. Lett. 106, 132501 (2011)

Empirical Extraction of TPE Amplitudes

J. Guttmann, N. Kivel, M. Meziane, and M. Vanderhaeghen, hep-ph/1012.0564v1



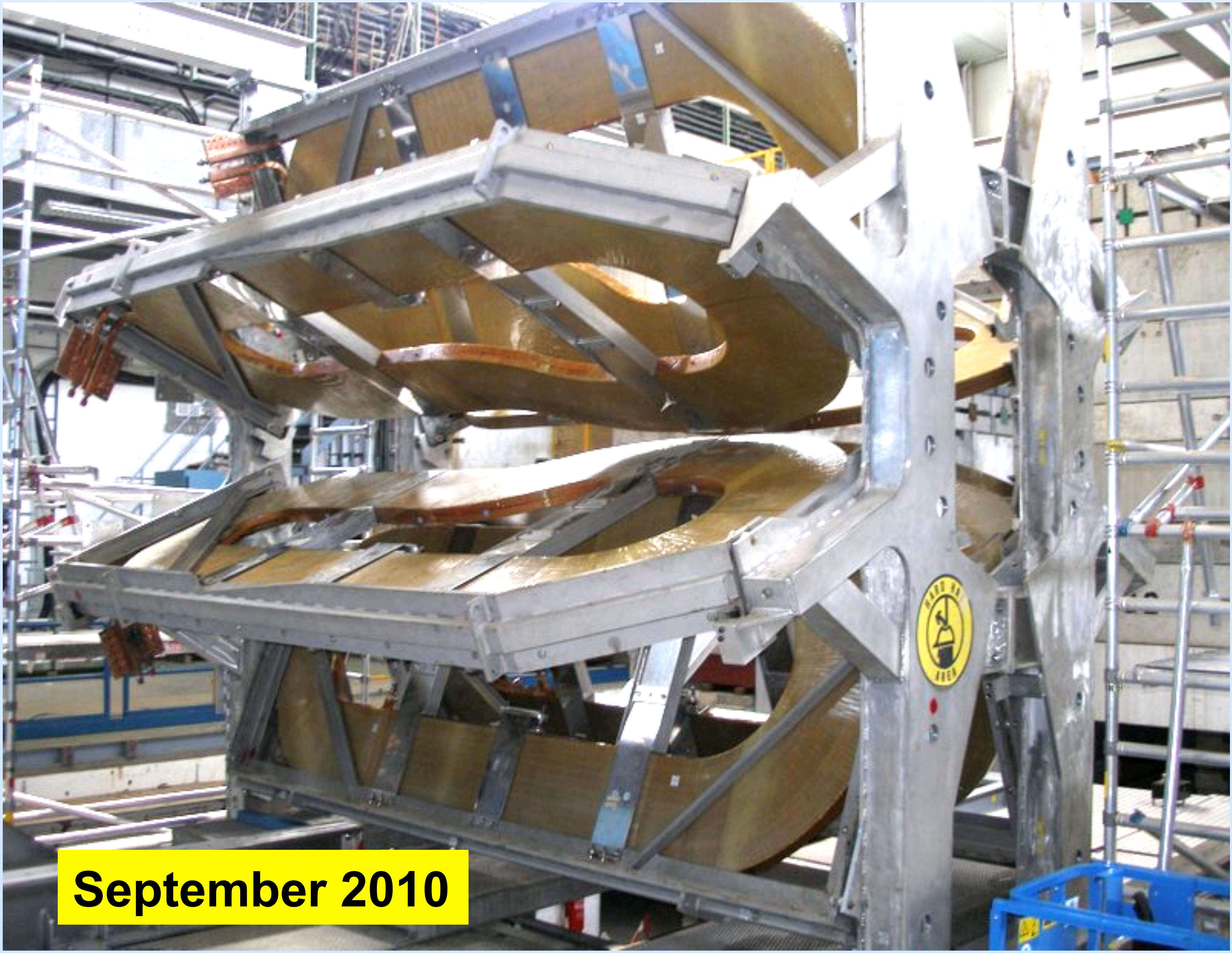
~6% effect for OLYMPUS@2.0GeV

grows with Q^2!

OLYMPUS: BLAST@DESY/DORIS

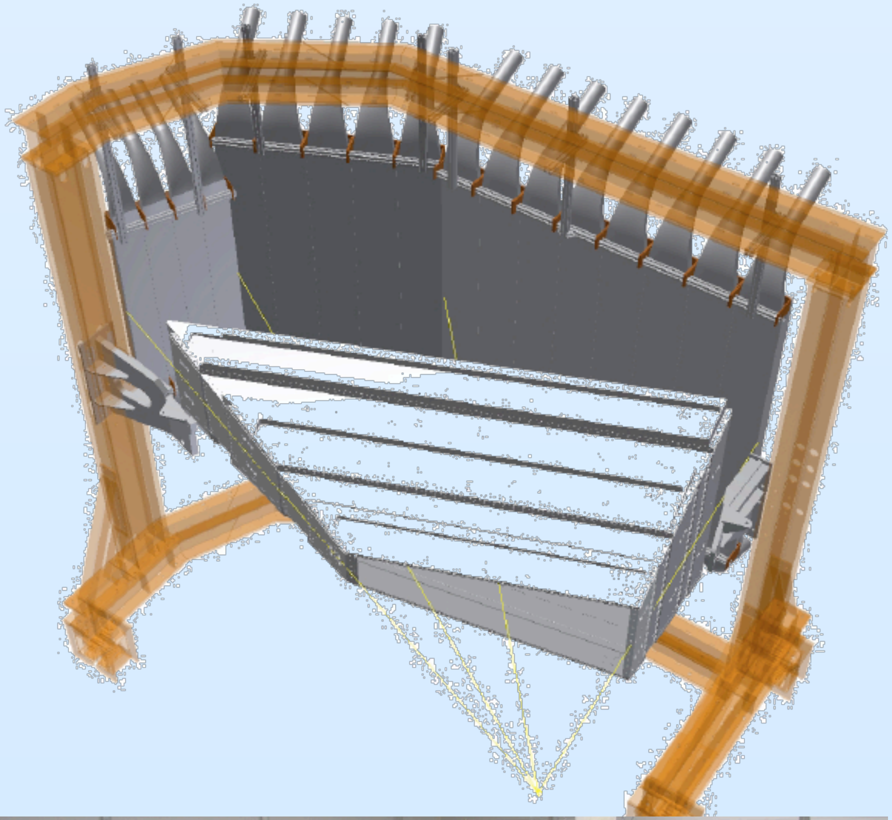
August 2010

OLYMPUS: BLAST@DESY/DORIS

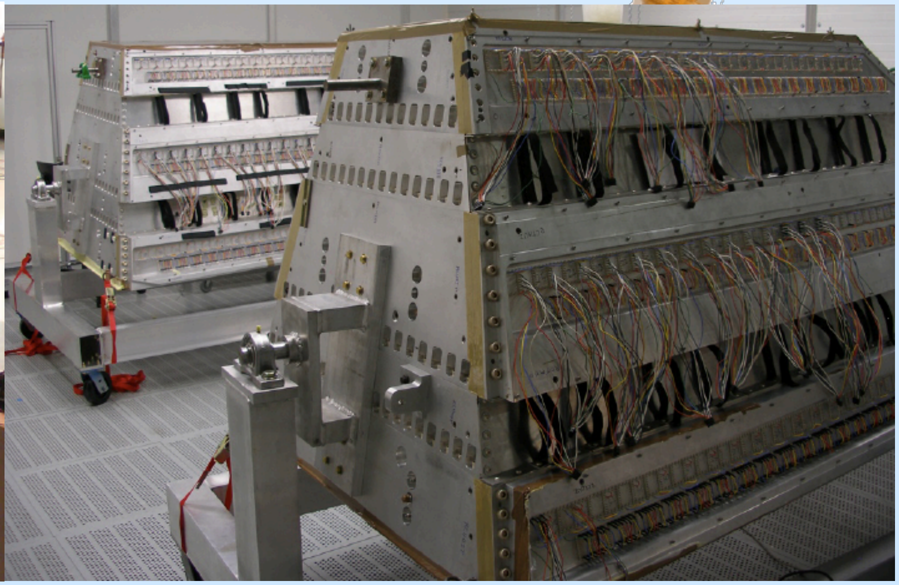


September 2010

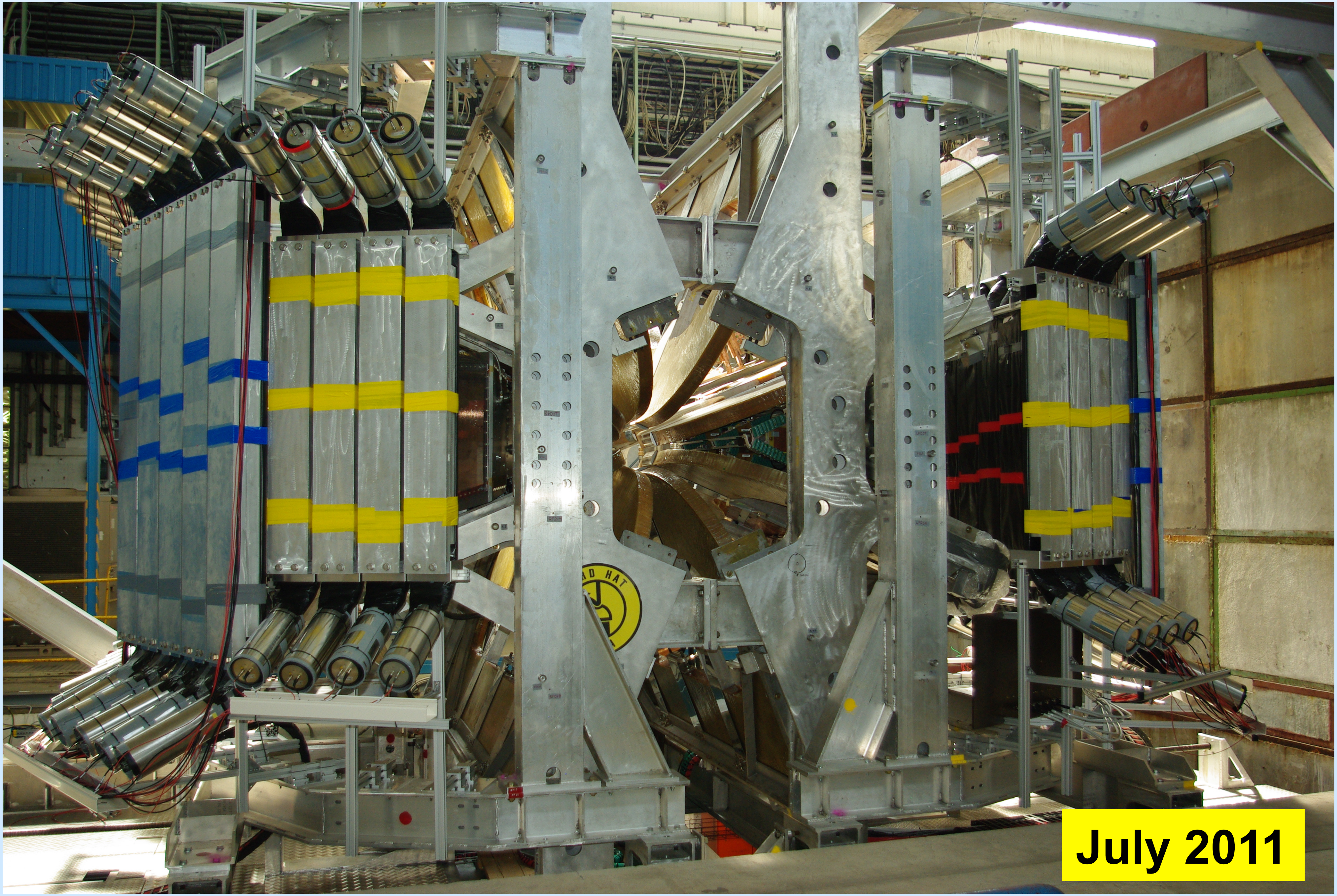
Wire Chambers and TOF Scintillators



- 2x18 TOFs for PID, timing and trigger
- 2 WCs for PID and tracking (z,θ,φ,p)
- WC and TOF refurbished from BLAST
  WC re-wired at DESY, now conditioned
  TOF rewrapped, efficiency tested
- Installed in OLYMPUS Apr-May 2011

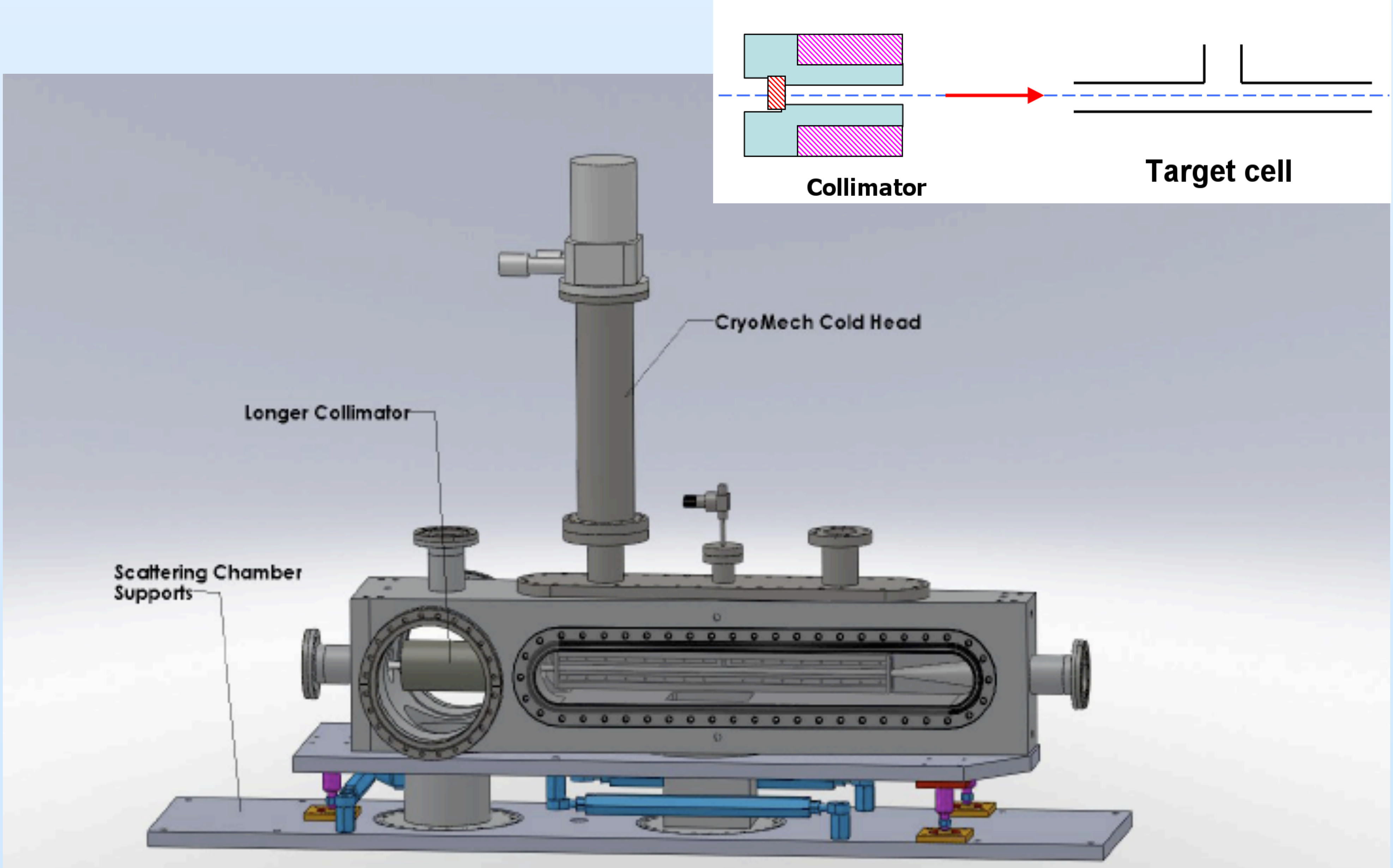


OLYMPUS: BLAST@DESY/DORIS



July 2011

Target and Vacuum System

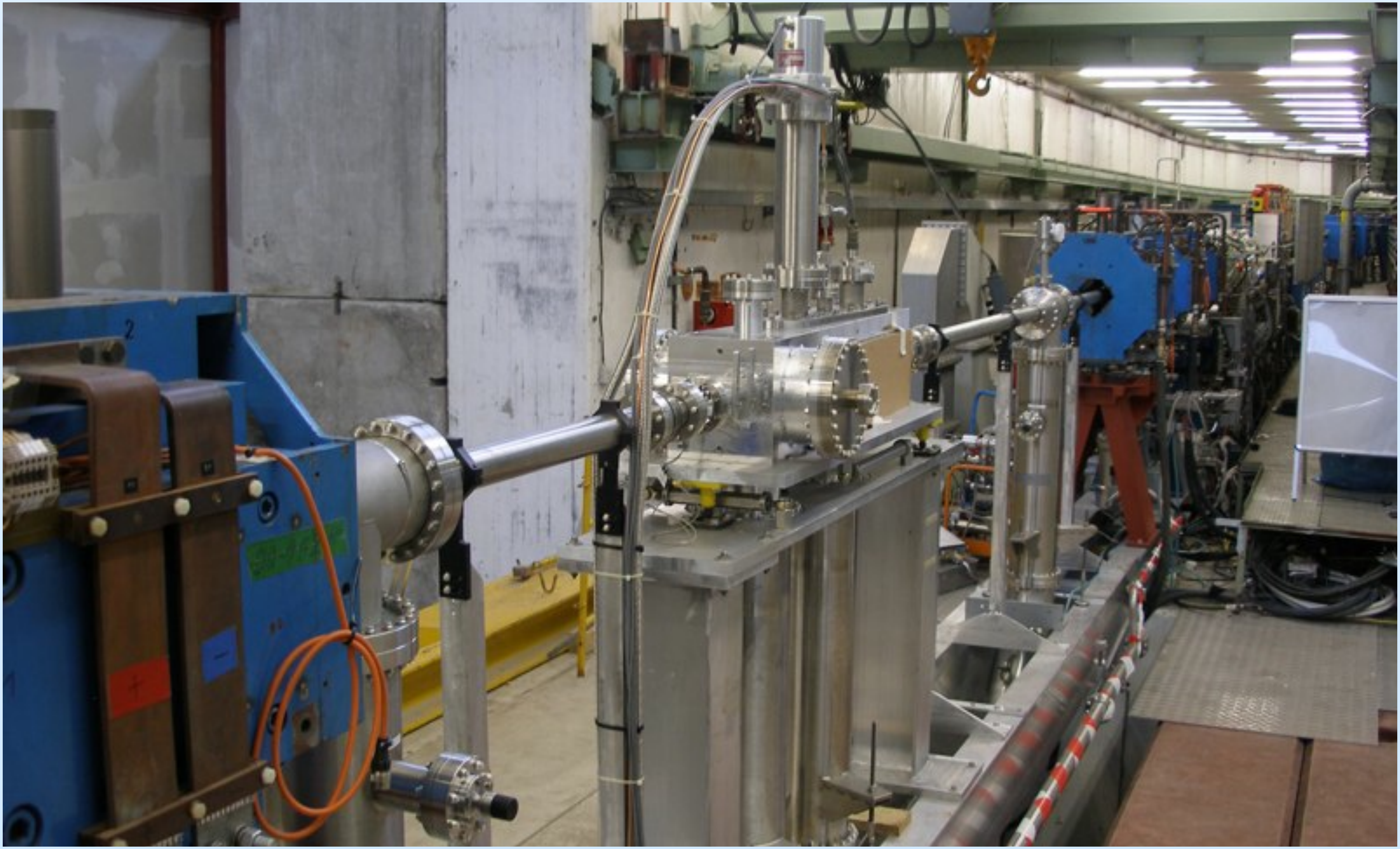


Designed until summer 2010

Target and Vacuum System

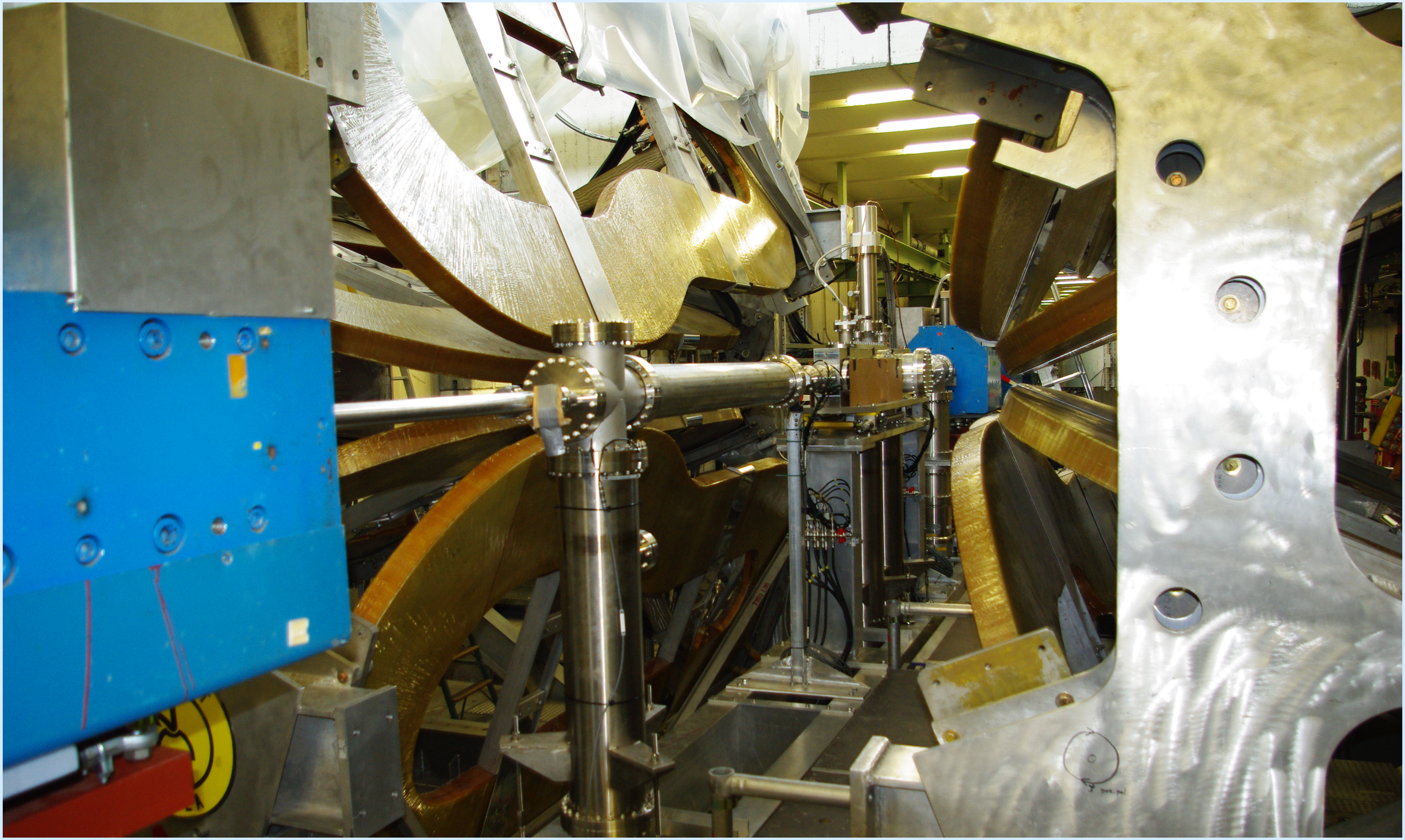
Target chamber machined by October 2010

Target and Vacuum System



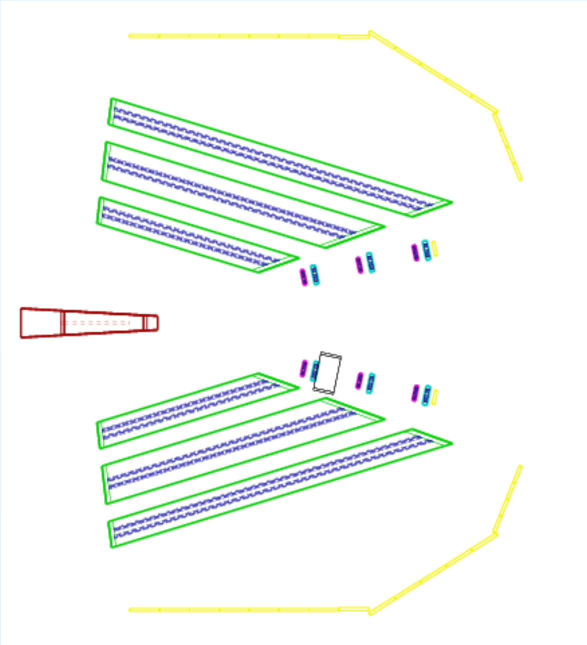
Installed in DORIS in January 2011

Target and Vacuum System

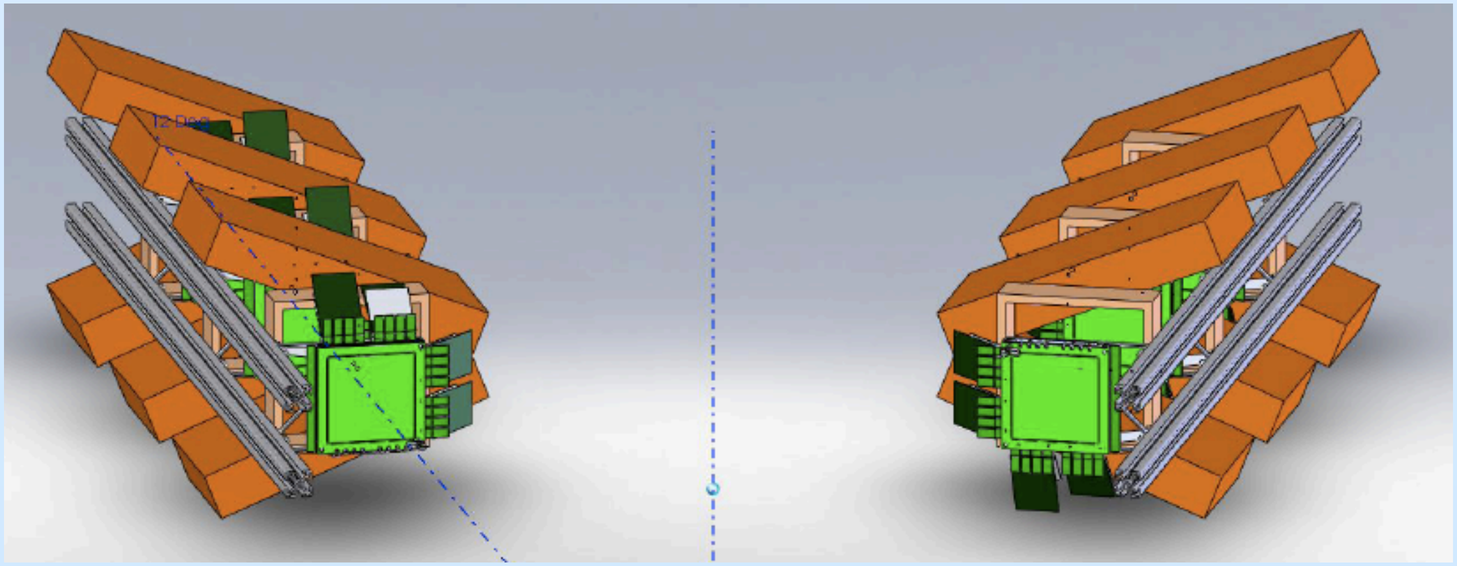


Re-installed in DORIS after roll-in in July 2011

Luminosity Monitors: GEM + MWPC

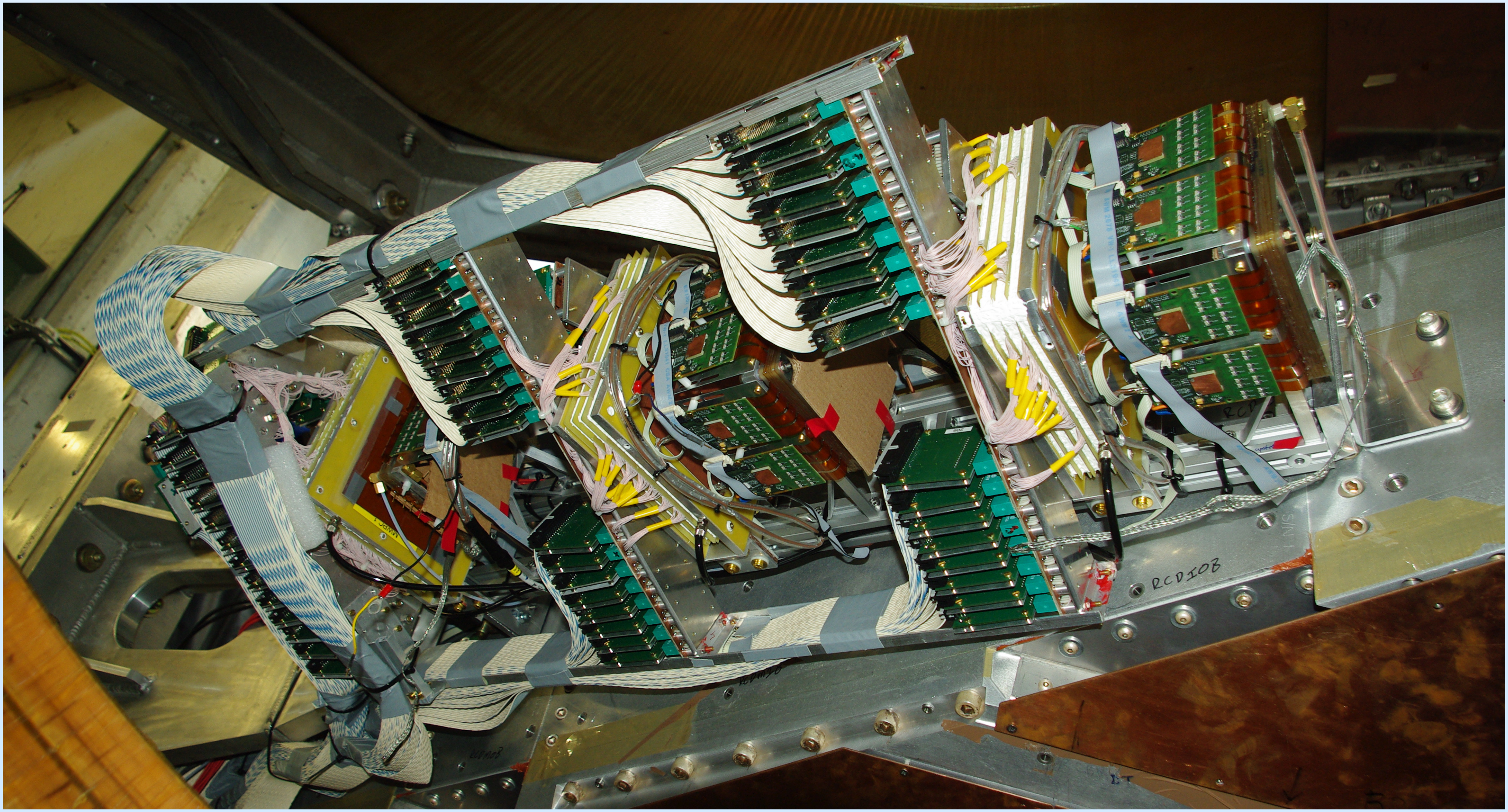


- Forward elastic scattering of lepton at 12° in coincidence with proton in main detector
- Two GEM + MWPC telescopes with interleaved elements operated independently
- Scintillator for triggering and timing
- Sub-percent (relative) luminosity measurement per hour at 2.0 GeV, per day at 4.5 GeV
- High redundancy – alignment, efficiency
  Two independent groups (Hampton, PNPI)



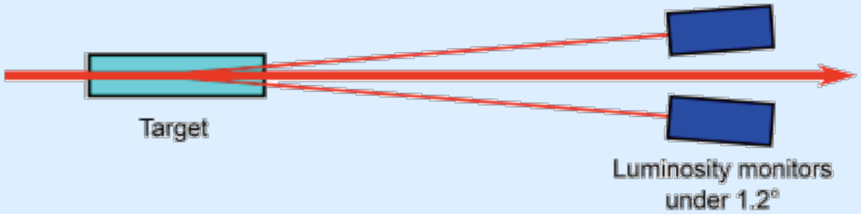
Designed to fit into forward cone

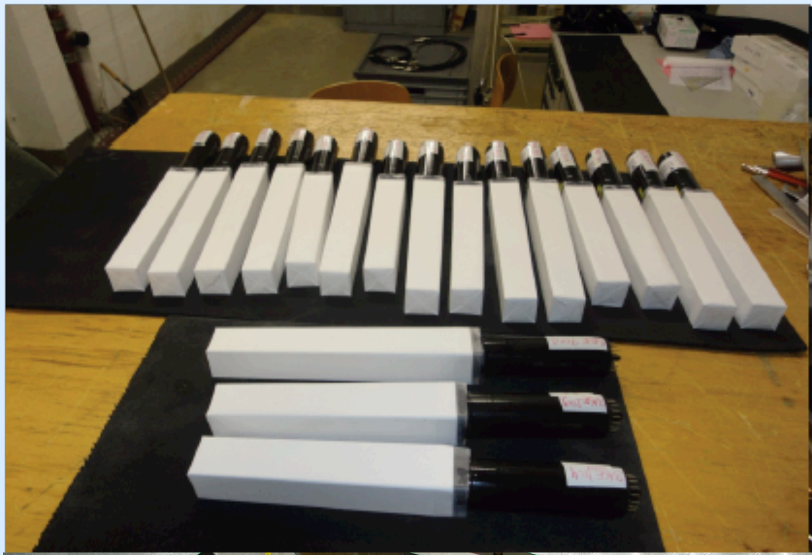
Luminosity Monitors: GEM + MWPC

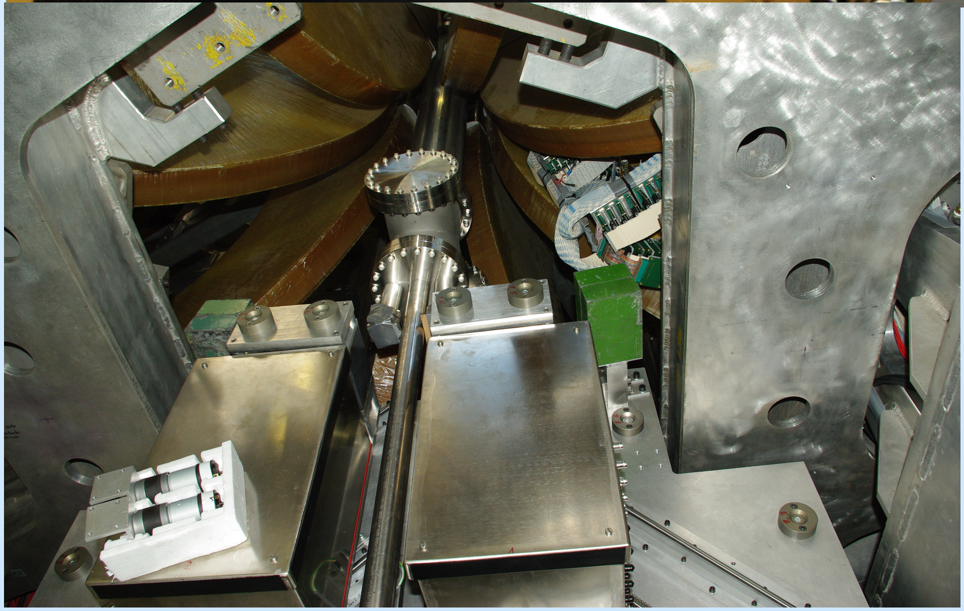


Telescopes of three GEMs and MWPCs interleaved
Mounted on wire chamber forward end plate
Extensively tested at DESY test beam facility

Symmetric Møller/Bhabha Monitor







- Symm. angle 1.3° @ 2 GeV
- Matrix of 3x3 PbF_2 crystals
- Tested at DESY and MAMI
- Supports installed July 2011