Two-photon exchange in lepton-proton elastic scattering

Jan C. Bernauer

Jefferson Lab Nuclear Physics Seminar
January 2016

Massachusetts Institute of Technology

Cross section and form factors for elastic lepton-proton scattering

The cross section:

$$\frac{\left(\frac{d\sigma}{d\Omega}\right)}{\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}} = \frac{1}{\varepsilon\left(1+\tau\right)}\left[\varepsilon G_E^2\left(Q^2\right) + \tau G_M^2\left(Q^2\right)\right]$$

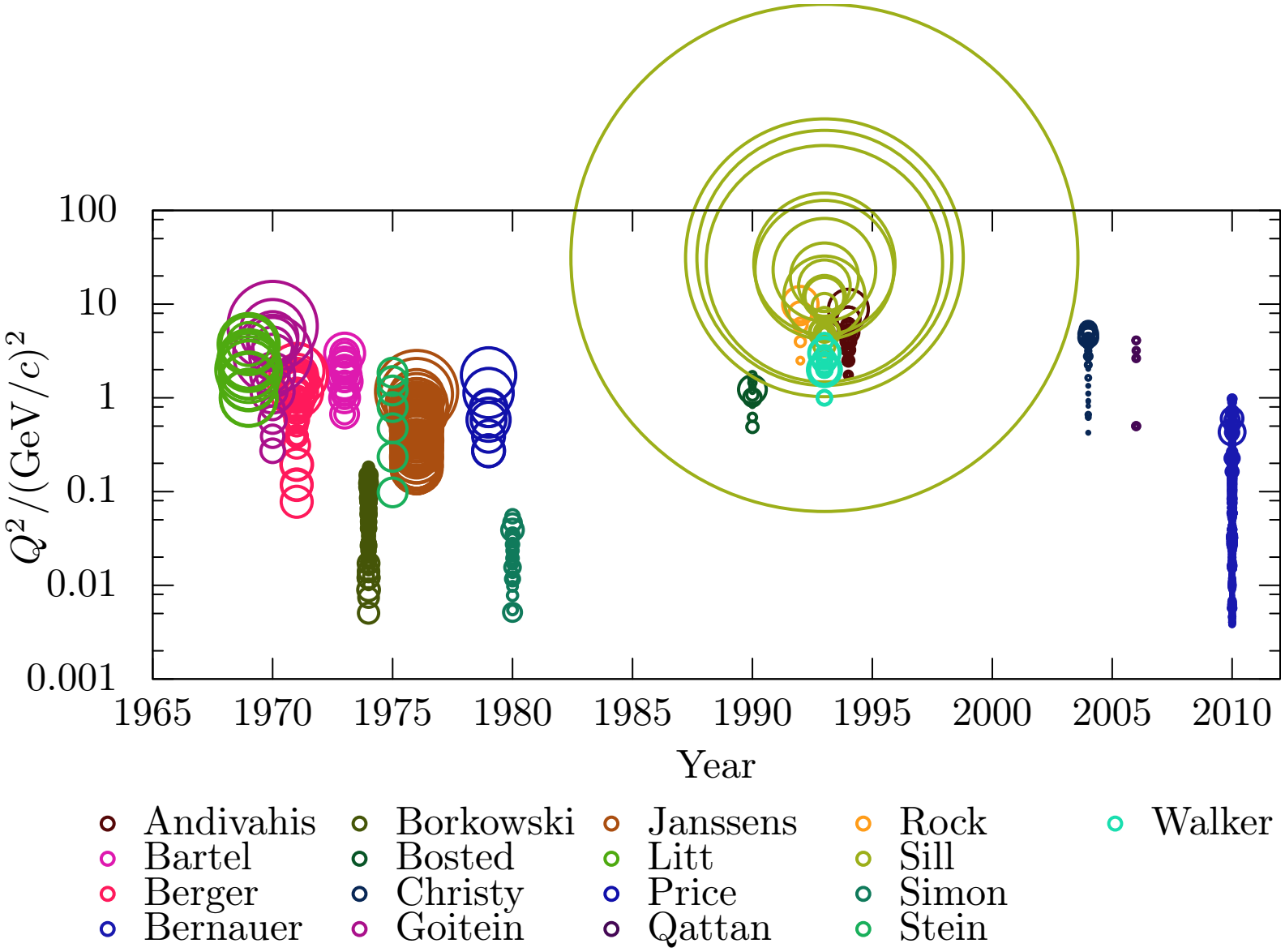
with:

$$\tau = \frac{Q^2}{4m_p^2}, \quad \varepsilon = \left(1 + 2\left(1+\tau\right)\tan^2\frac{\theta_e}{2}\right)^{-1}$$

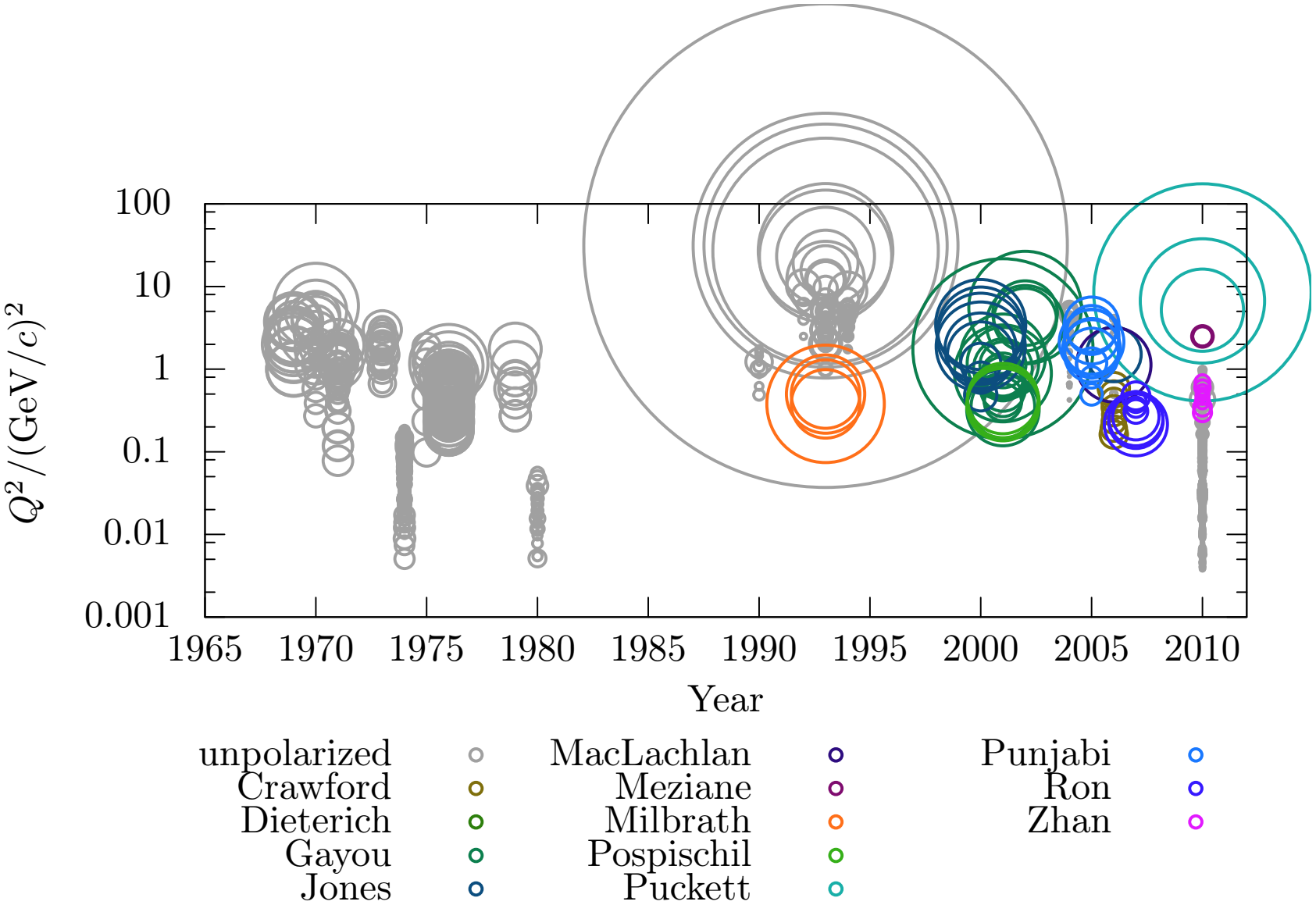
Fourier-transform of G_E, G_M $\longrightarrow$ spatial distribution (Breit frame)

$$\left\langle r_E^2 \right\rangle = -6\hbar^2 \left.\frac{\mathrm{d}G_E}{\mathrm{d}Q^2}\right|_{Q^2=0} \qquad \left\langle r_M^2 \right\rangle = -6\hbar^2 \left.\frac{\mathrm{d}\left(G_M/\mu_p\right)}{\mathrm{d}Q^2}\right|_{Q^2=0}$$

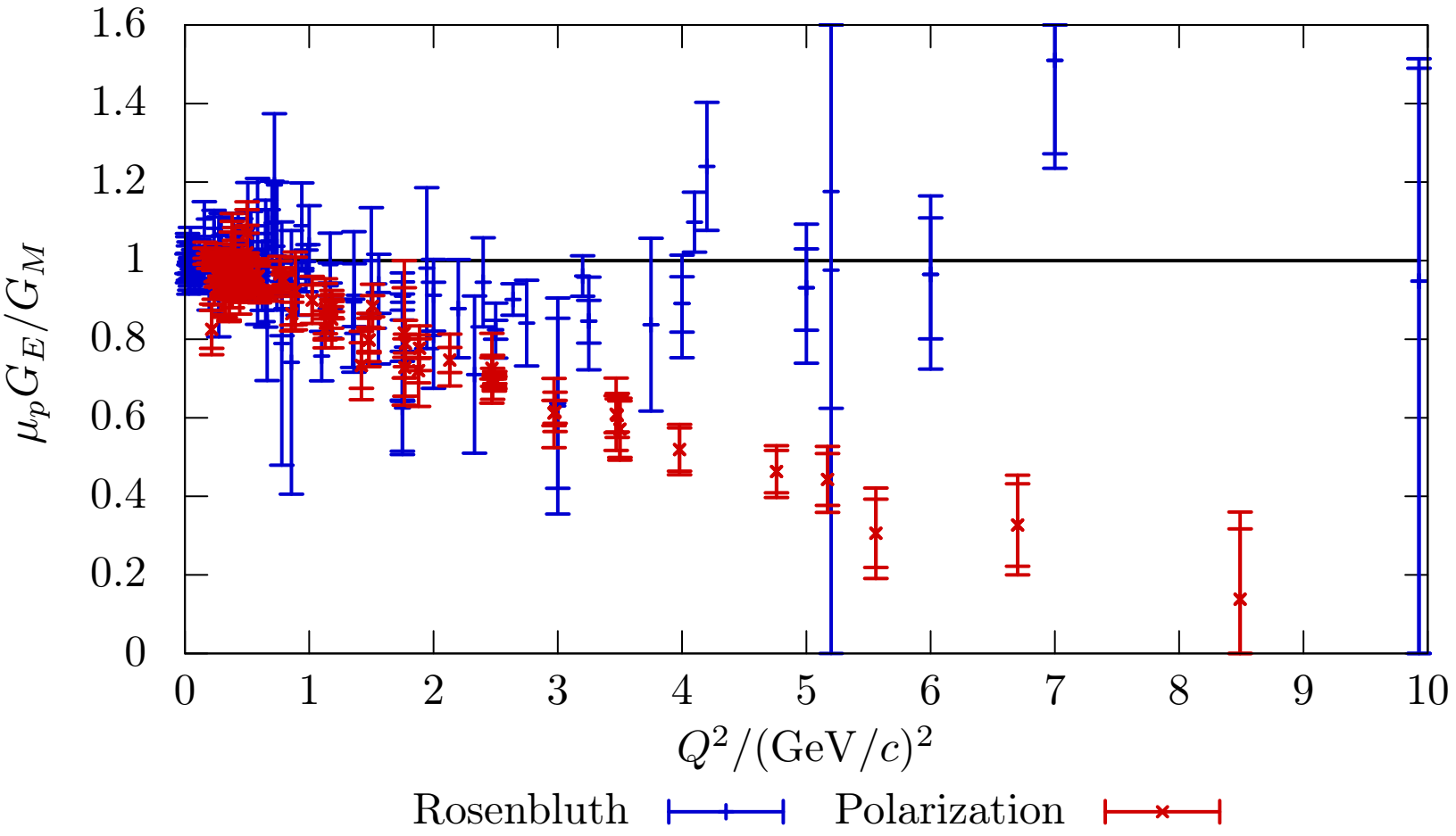
History of unpolarized electron-proton scattering



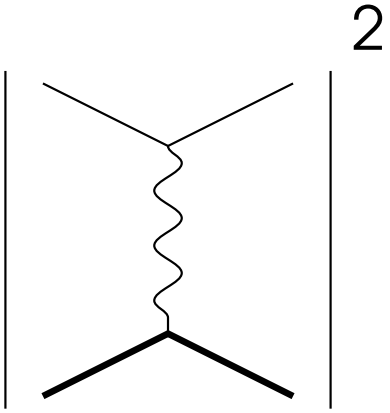
Measurements with polarization: FF ratio



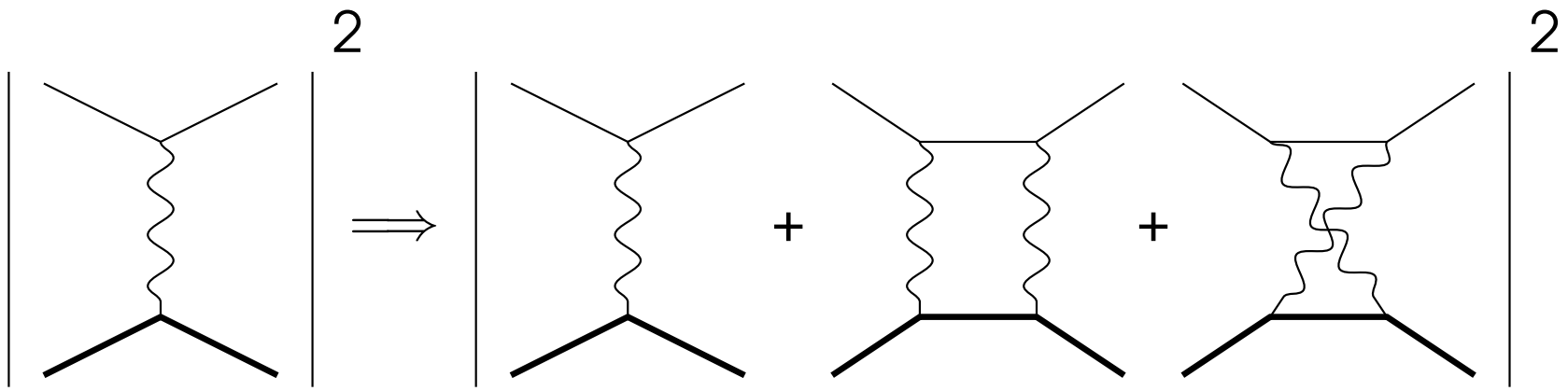
Ratio: Difference!



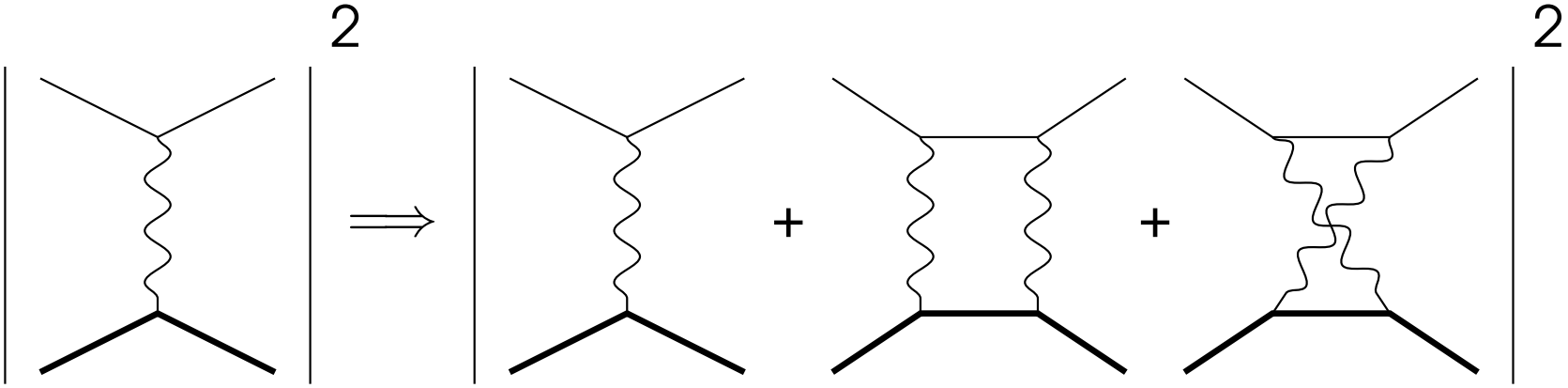
Most likely explanation: Two Photon Exchange



Most likely explanation: Two Photon Exchange



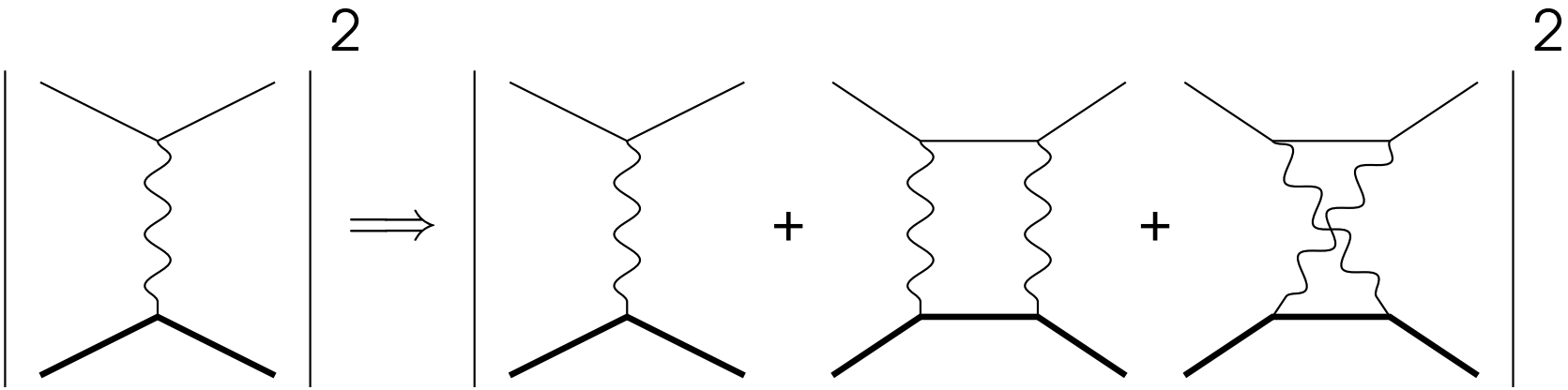
Most likely explanation: Two Photon Exchange



Impact of direct measurement

- Reconcile Rosenbluth and polarized data?
- How to treat (off-shell) hadron line?

Most likely explanation: Two Photon Exchange



Method

- Mixed term changes sign with lepton sign:

$$\sigma(e^{\pm}p) \propto \left|M_{1\gamma}\right|^2 \pm 2\Re\left\{M_{1\gamma}^{\dagger}M_{2\gamma}\right\} + \ldots$$

$$R_{2\gamma} = \frac{N_{exp}^{e^+}}{N_{exp}^{e^-}} / \frac{N_{MC}^{e^+}}{N_{MC}^{e^-}}$$

- MC contains luminosity, acceptance, soft radiative corrections

Direct measurement: Three modern experiments

VEPP-3

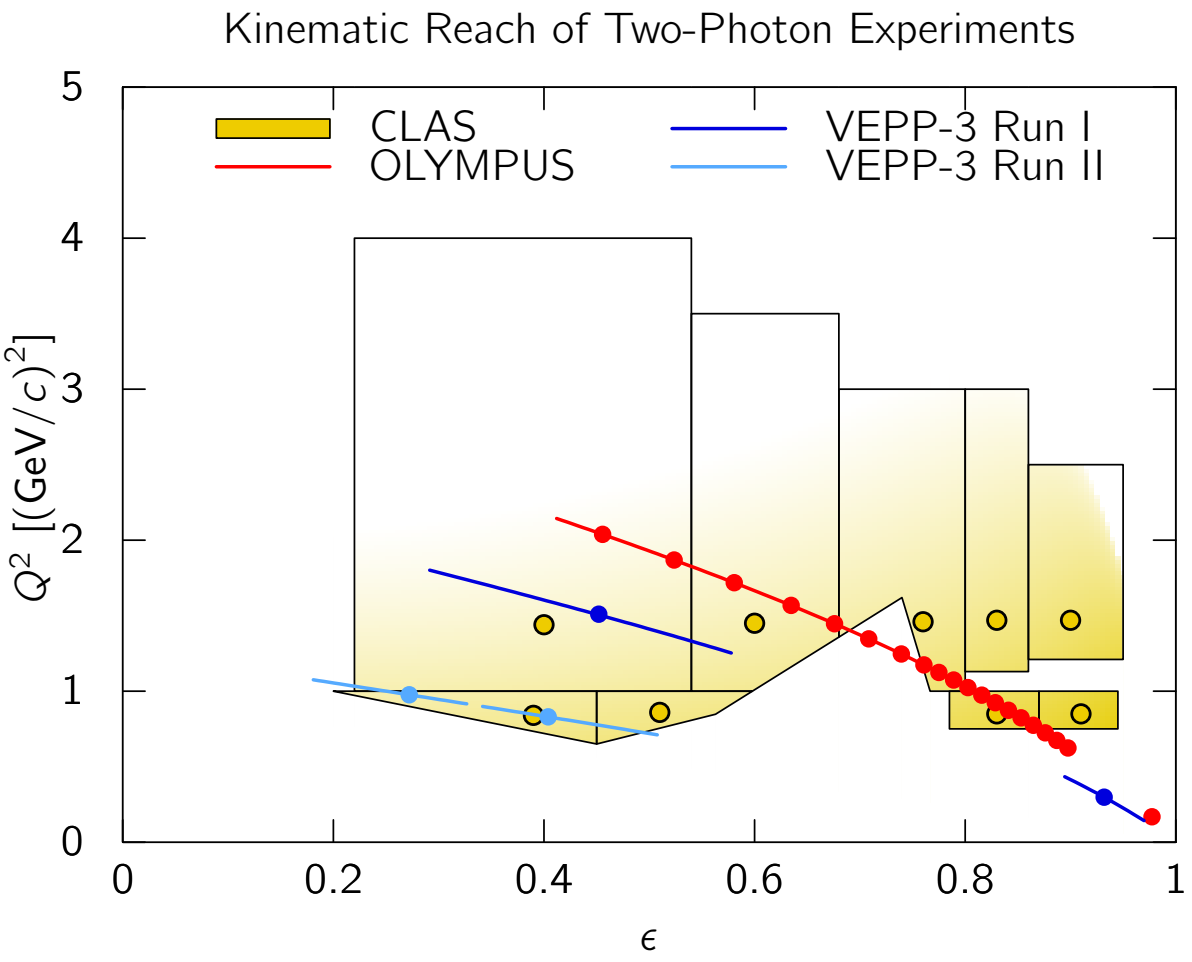
- 1.6/1 GeV beam
- no field
- PRL 114, 062005

CLAS

- e^- to γ to $e^{+/-}$ -beam
- PRL 114, 062003

OLYMPUS

- DORIS @ DESY
- 2 GeV beam
- PRL accepted



The OLYMPUS collaboration

- Arizona State University, USA
- DESY, Hamburg, Germany
- Hampton University, USA
- INFN, Bari, Italy
- INFN, Ferrara, Italy
- INFN, Rome, Italy
- MIT Laboratory for Nuclear Science, Cambridge, USA
- Petersburg Nuclear Physics Institute, Gatchina, Russia
- University of Bonn, Bonn, Germany
- University of Glasgow, United Kingdom
- University of Mainz, Mainz, Germany
- University of New Hampshire, USA
- Yerevan Physics Institute, Armenia

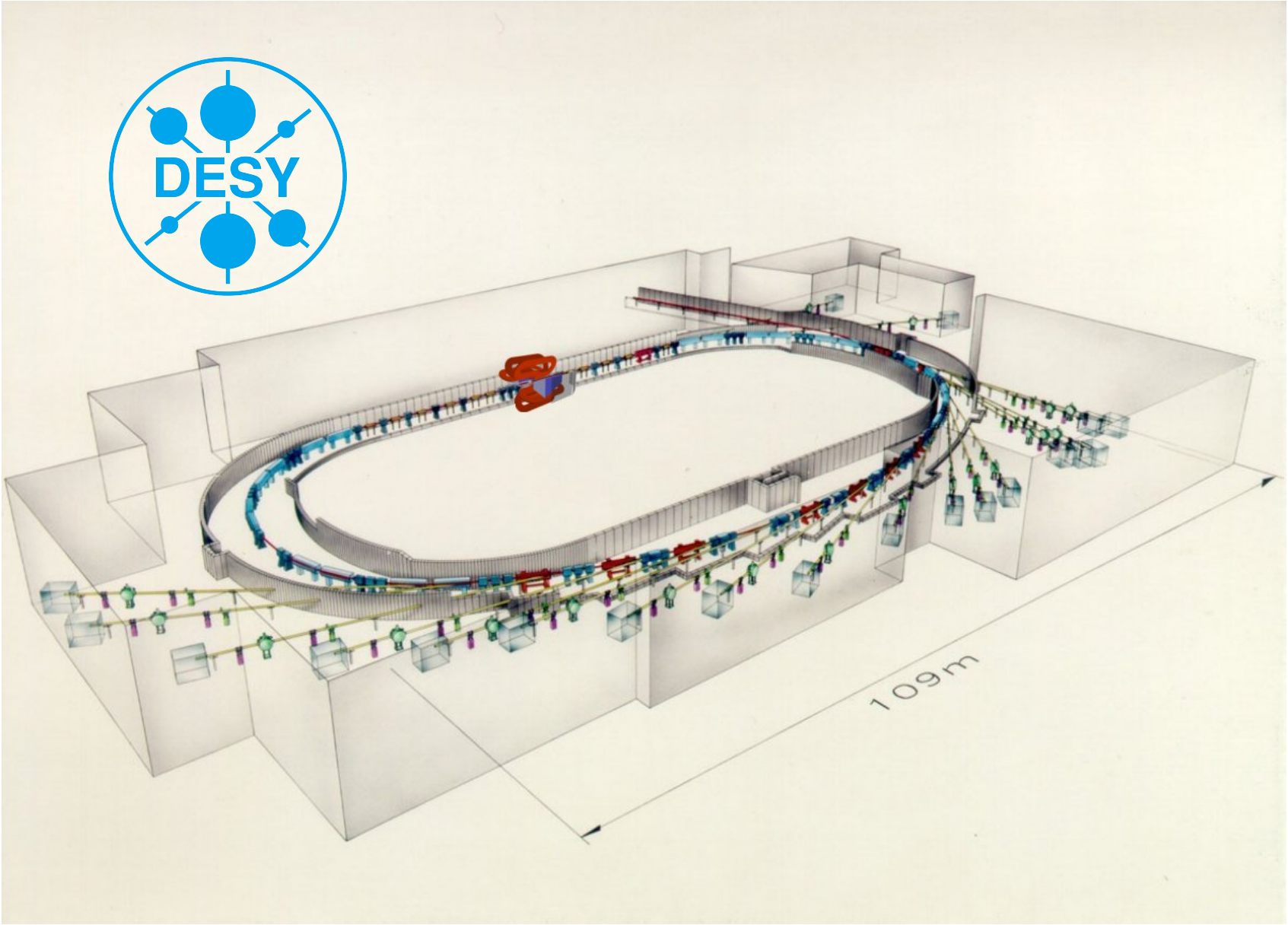
The OLYMPUS collaboration

- Arizona State University, USA
- DESY, Hamburg, Germany
- Hampton University, USA
- INFN, Bari, Italy
- INFN, Ferrara, Italy
- INFN, Rome, Italy

Analysis effort carried by students

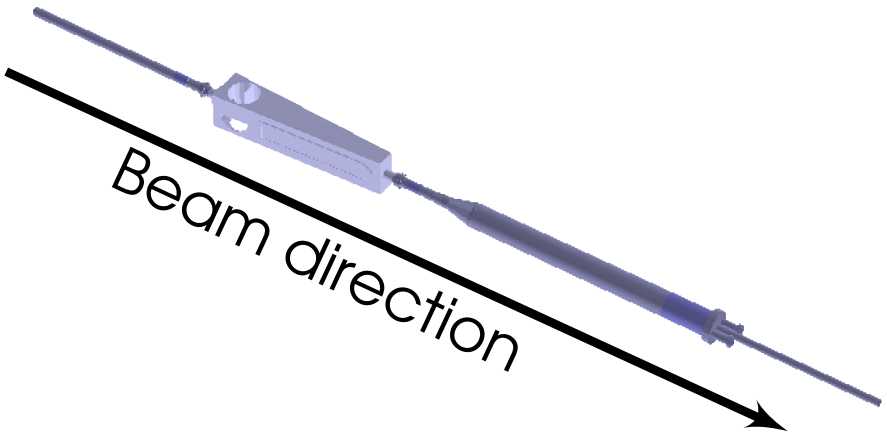
Lauren Ice (ASU)
Dmitry Khaneft (Mainz)
Colton O'Connor (MIT)
Brian Henderson (MIT)
Rebecca Russell (MIT)
Axel Schmidt (MIT)

At DESY: DORIS



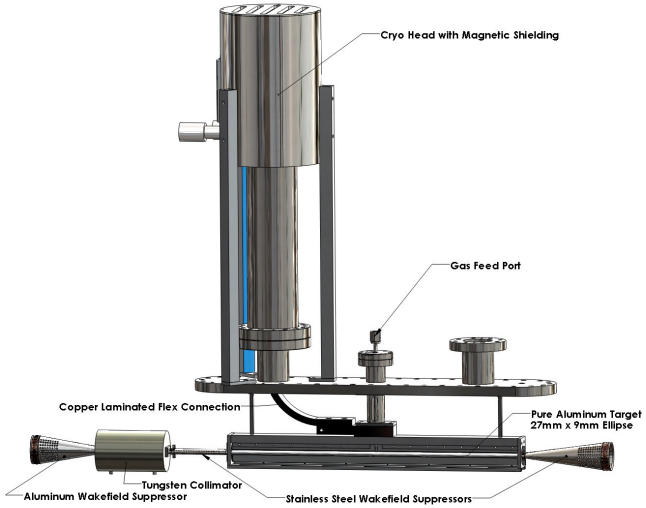
Anatomy of the OLYMPUS detector

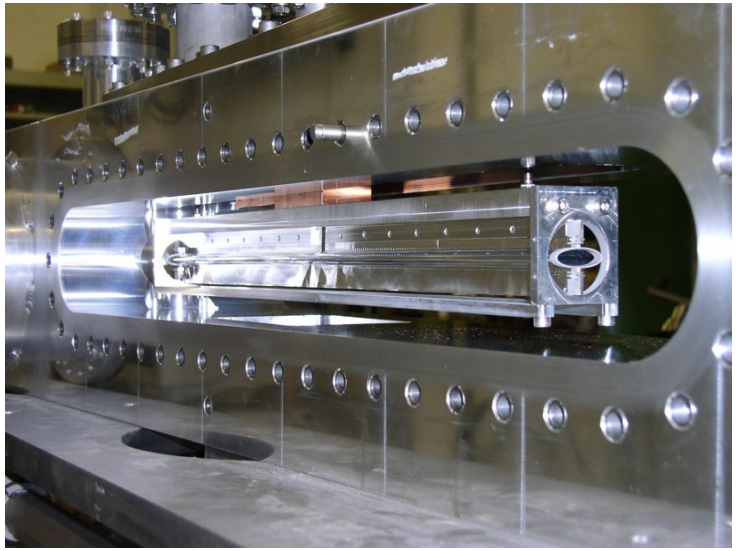
- Target chamber with target cell



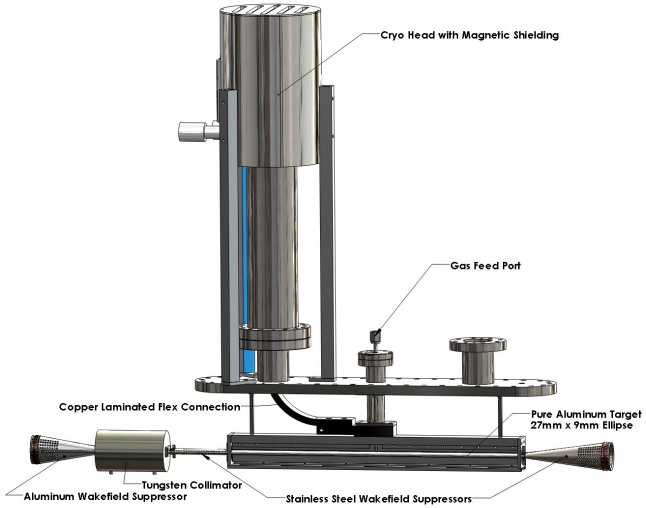
R. Milner et al., NIMA 741 (2014) 1-17

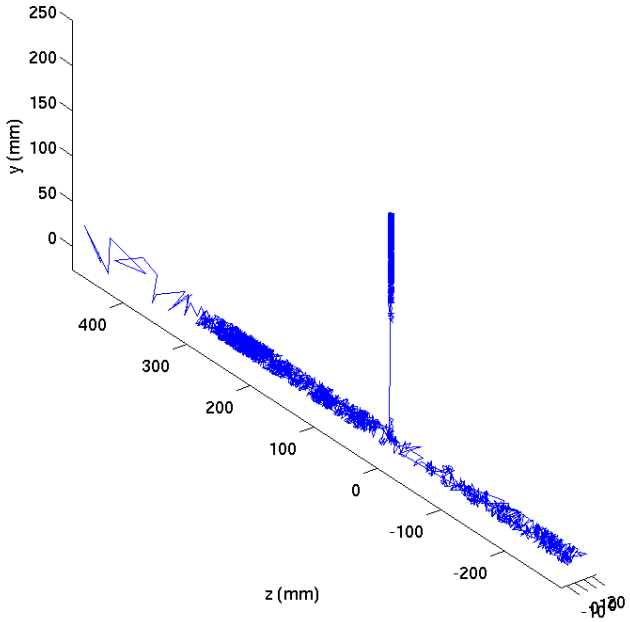
Target

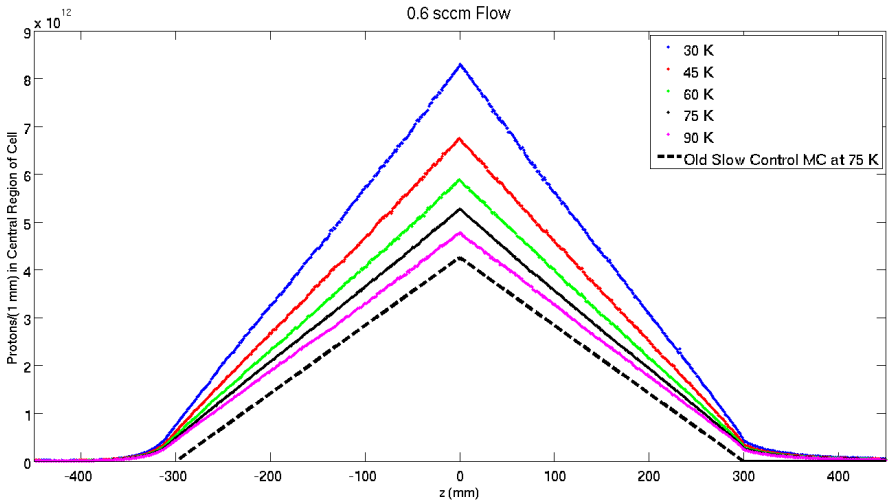

Cryo Head with Magnetic Shielding
Gas Feed Port
Copper Laminated Flex Connection
Pure Aluminum Target
27mm x 9mm Ellipse
Tungsten Collimator
Aluminum Wakefield Suppressor
Stainless Steel Wakefield Suppressors



Target

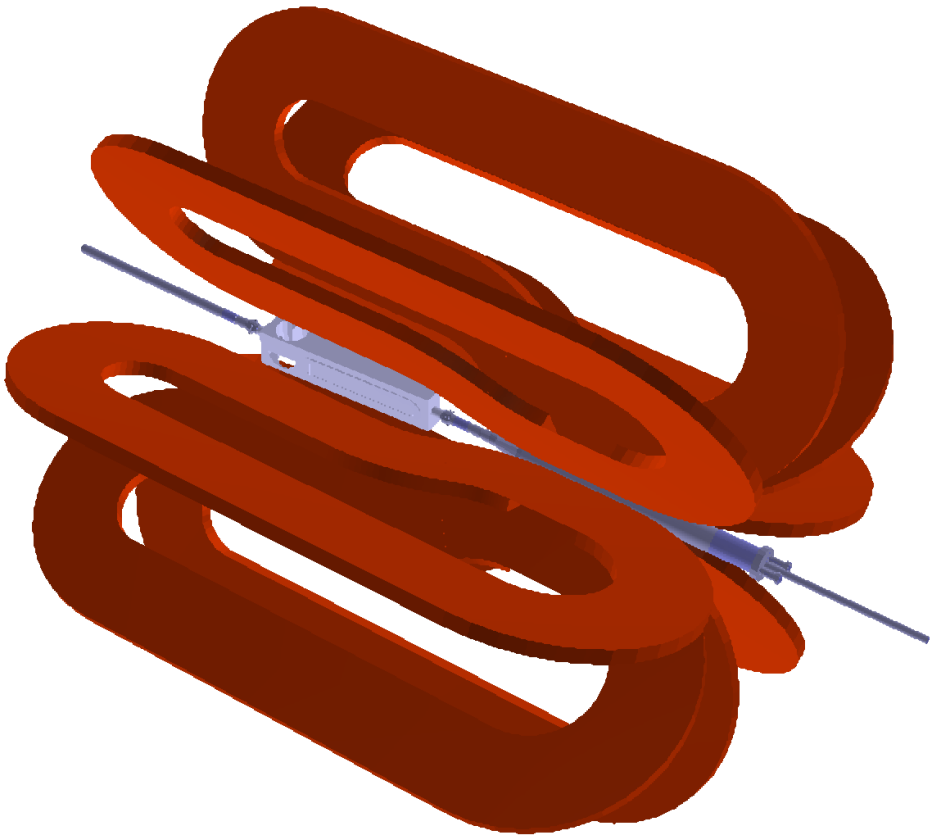






Simulation by B. Henderson (thesis). For constr. see NIMA 755 20 (2014)

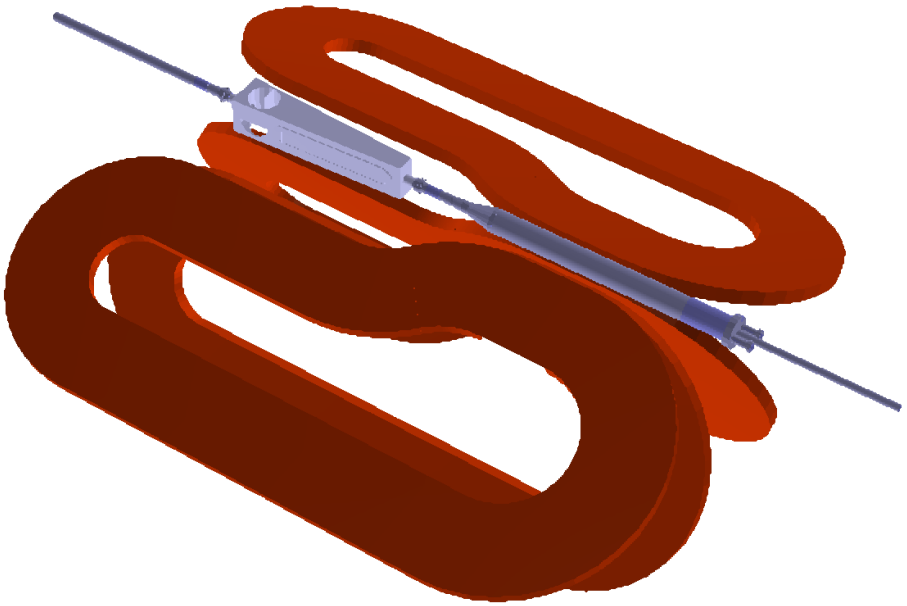
Anatomy of the OLYMPUS detector



- Target chamber with target cell
- Toroid magnet coils

R. Milner et al., NIMA 741 (2014) 1-17

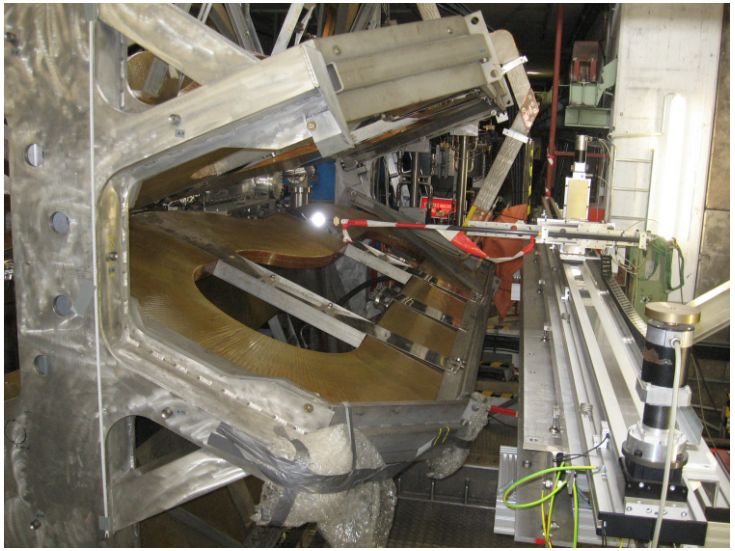
Anatomy of the OLYMPUS detector

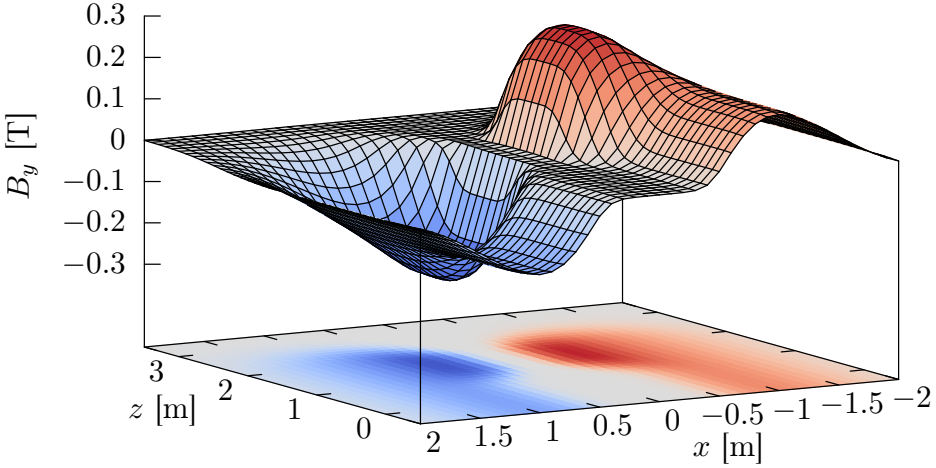


- Target chamber with target cell
- Toroid magnet coils (half shown)

R. Milner et al., NIMA 741 (2014) 1-17

Toroid magnet system

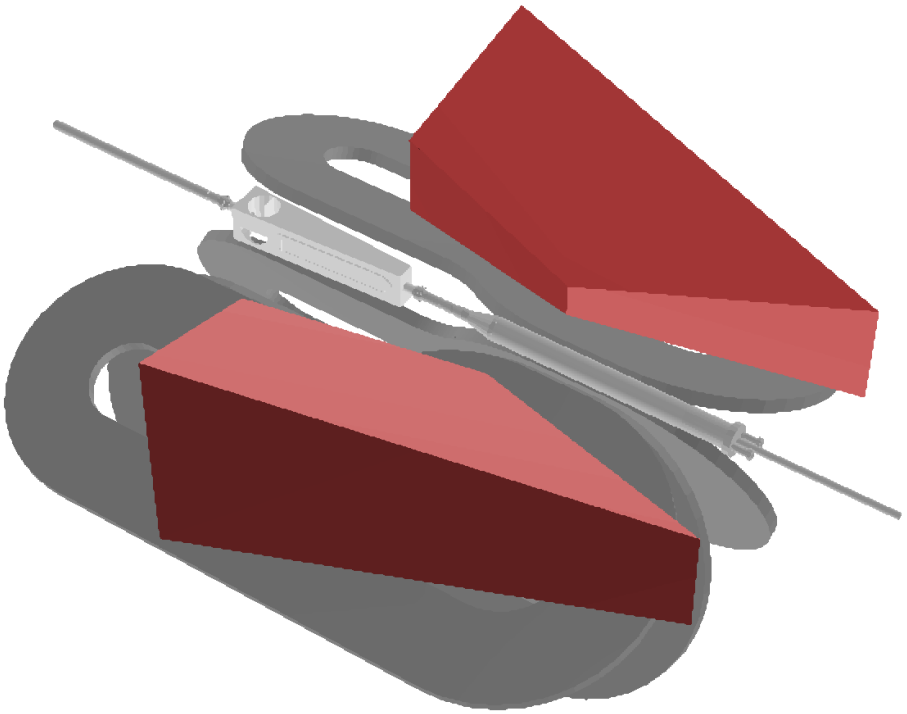




- Fit measurements with model of coil field
- Evaluate model for full volume
- Special form of spline interpolation

NIM A 823, 9 (2016) doi:10.1016/j.nima.2016.03.115

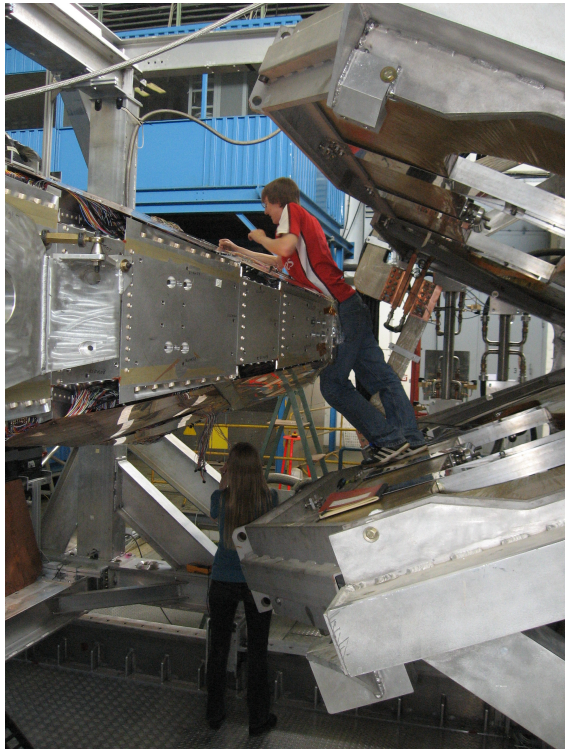
Anatomy of the OLYMPUS detector

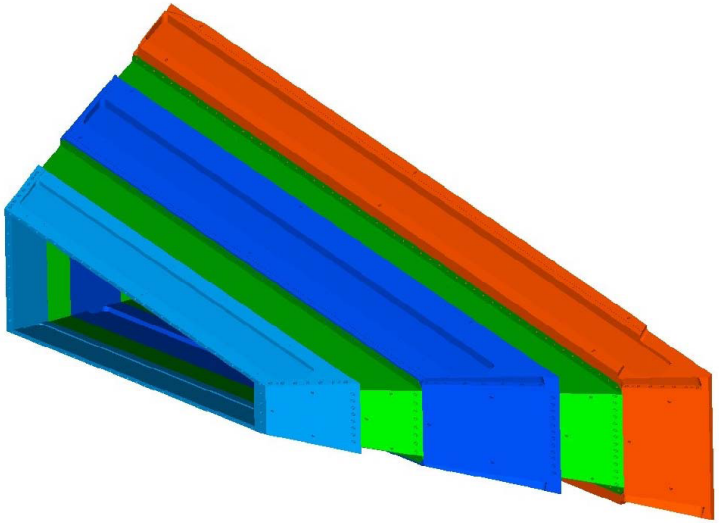


- Target chamber with target cell
- Toroid magnet coils (half shown)
- Drift chambers

R. Milner et al., NIMA 741 (2014) 1-17

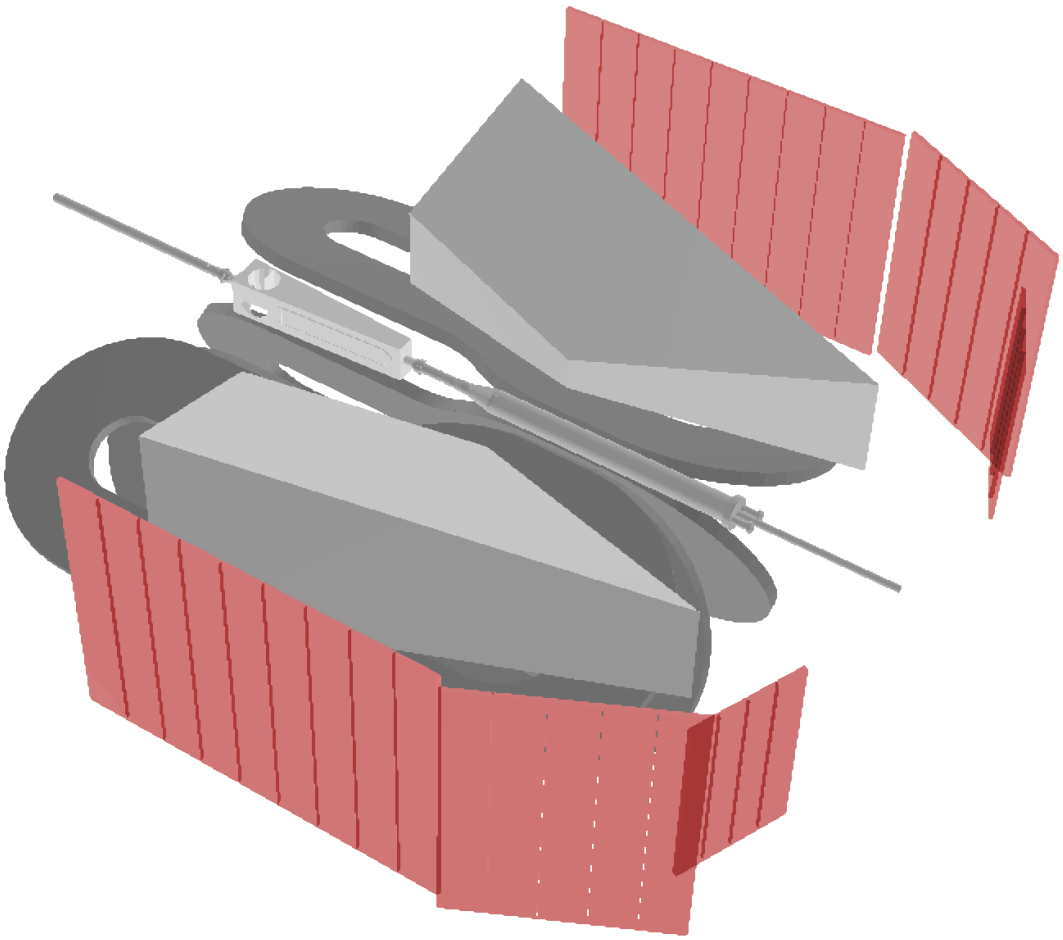
Drift chambers





- 3 chambers,
  2 planes each
- Tracking is *hard*
- Wrote three trackers!

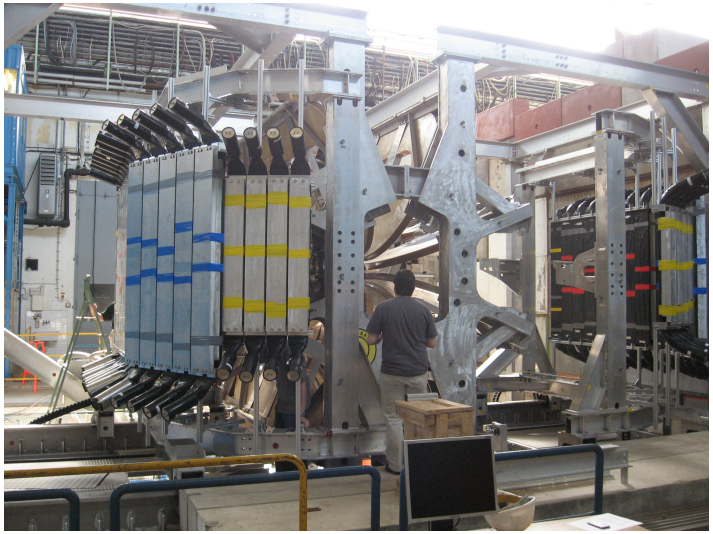
Anatomy of the OLYMPUS detector

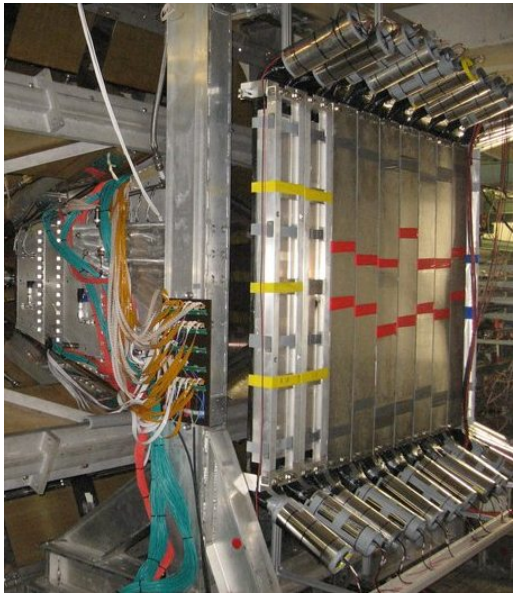


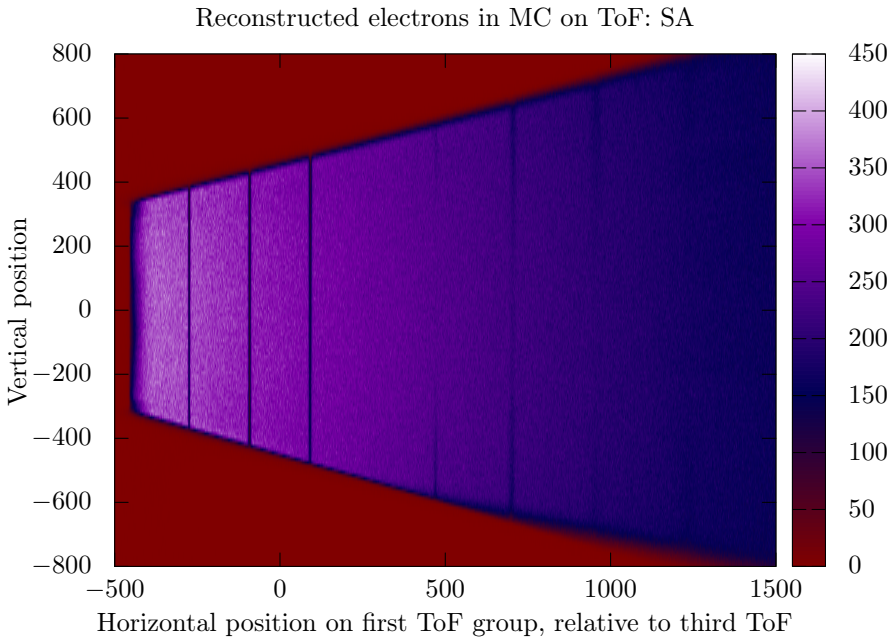
- Target chamber with target cell
- Toroid magnet coils (half shown)
- Drift chambers
- Time of flight scintillators

R. Milner et al., NIMA 741 (2014) 1-17

Time-of-flight scintillators

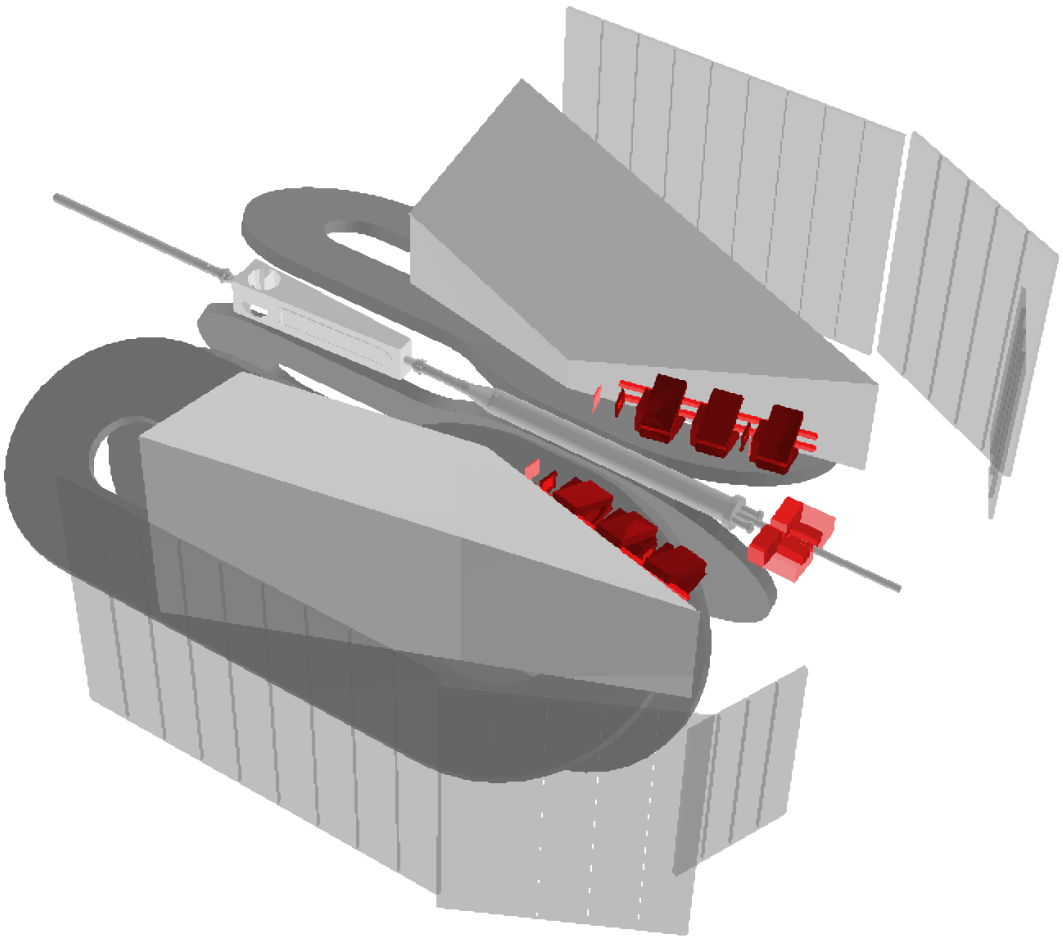






- Trigger + particle ID
- Sophisticated simulation (see theses by L. Ice and R. Russell)
- The curse of old detectors

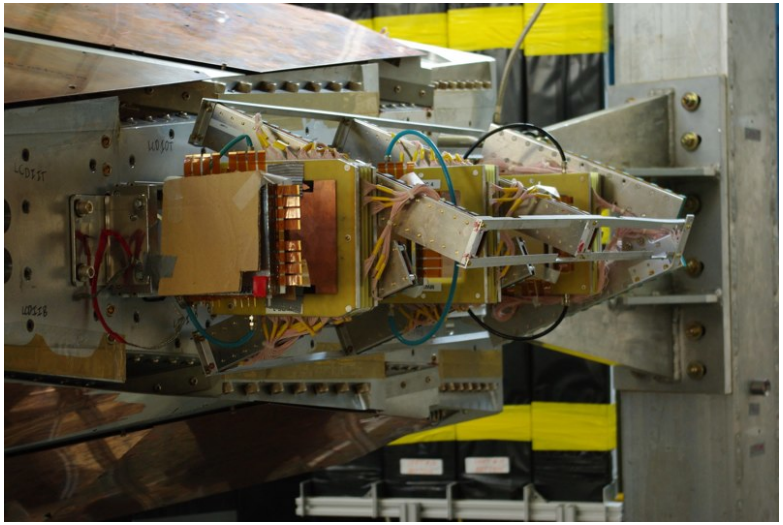
Anatomy of the OLYMPUS detector

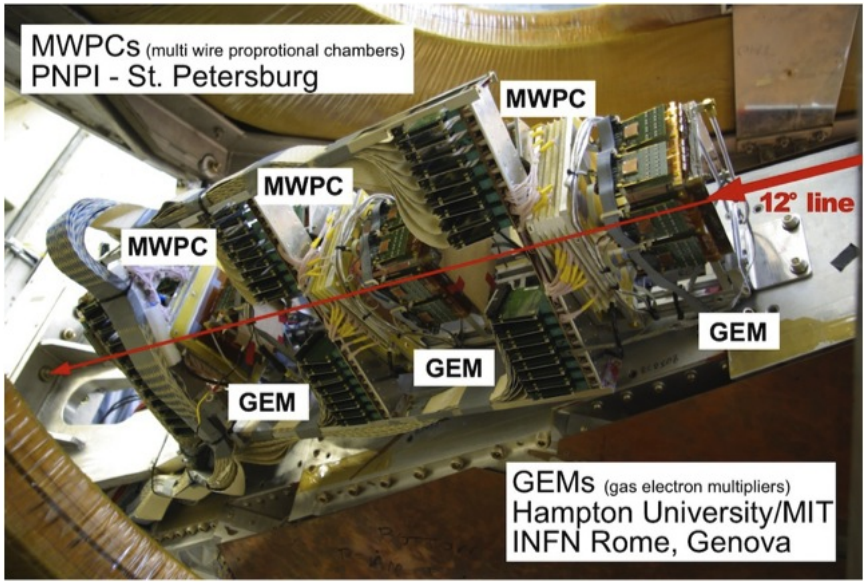


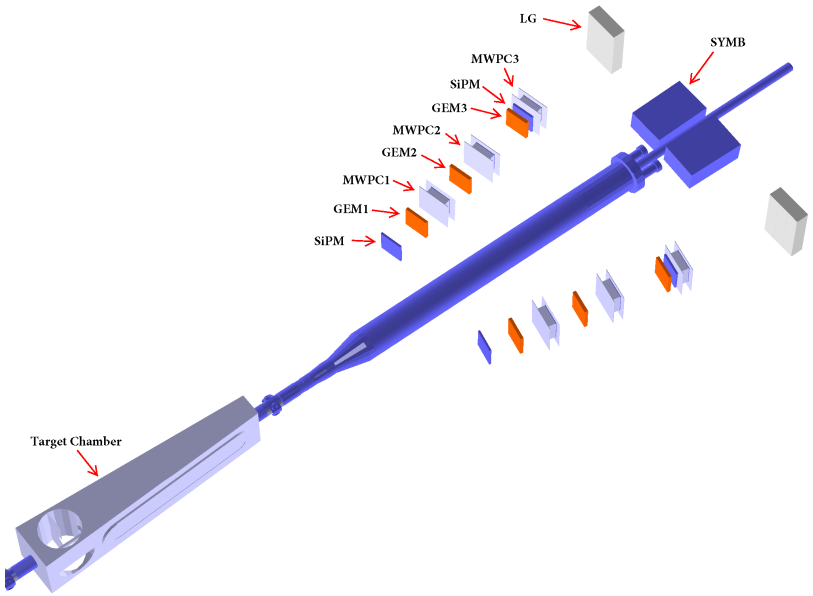
- Target chamber with target cell
- Toroid magnet coils (half shown)
- Drift chambers
- Time of flight scintillators
- Dual luminosity monitors
  - 12°-detector
  - Symmetric Møller/Bhabha

R. Milner et al., NIMA 741 (2014) 1-17

12° telescopes

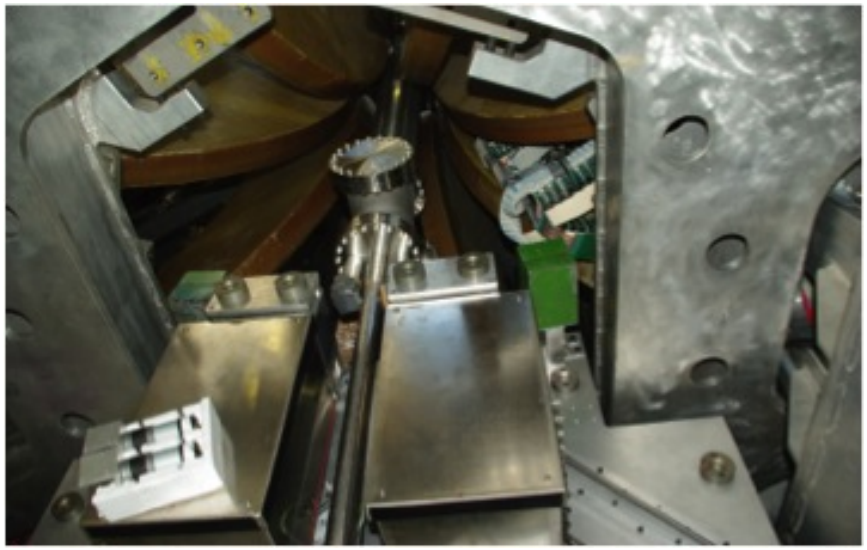


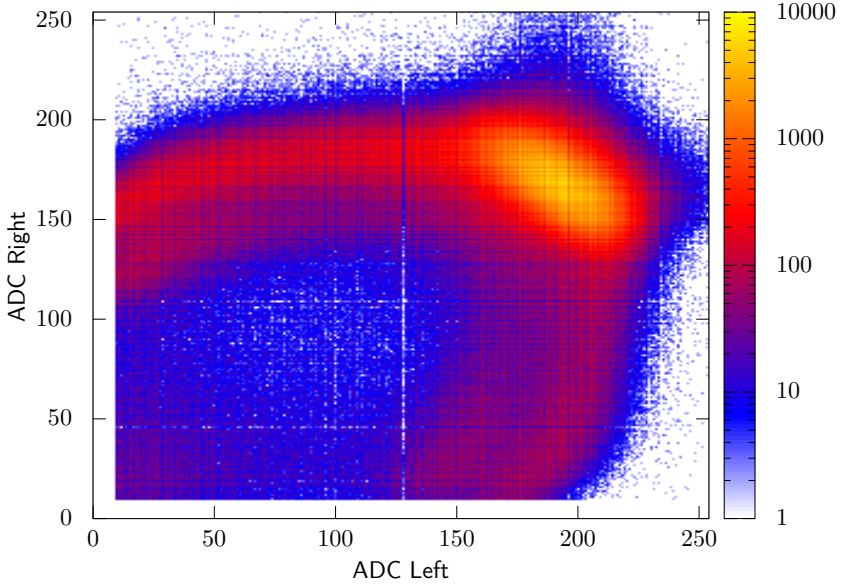




- Interleaved MWPCs + GEMs
- Scintillator+SiPM trigger
- Independent readout

Symmetric Møller-Bhabha





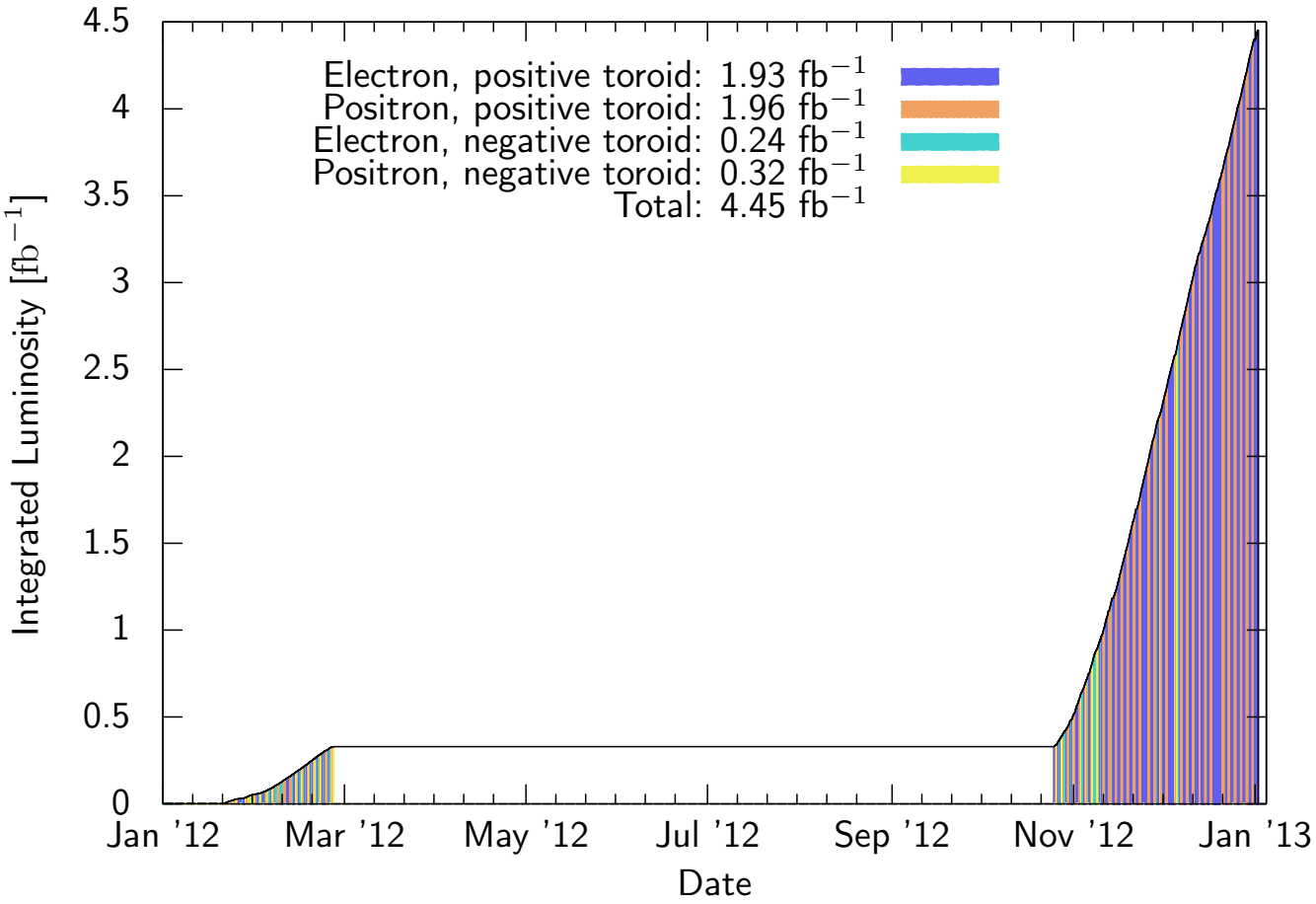
- A4 histogramming cards
- dead-time free
- no event-by-event readout

NIM A 826, 6 (2016) doi:10.1016/j.nima.2016.04.071

Timeline

OLYMPUS full proposal	September 2008
Experiment funded by DOE	January 2010
BLAST moved to Germany	Spring 2010
Target test experiment	February 2011
Drift chambers installed	Spring 2011
Luminosity monitors installed	Summer 2011
OLYMPUS roll-in	July 2011
First full OLYMPUS test	August 2011
Sym. Møller/Bhabha installed	Fall 2011
First data run	January 2012
Second data run	October-December 2012
DORIS shut down	January 2013

Total data taken

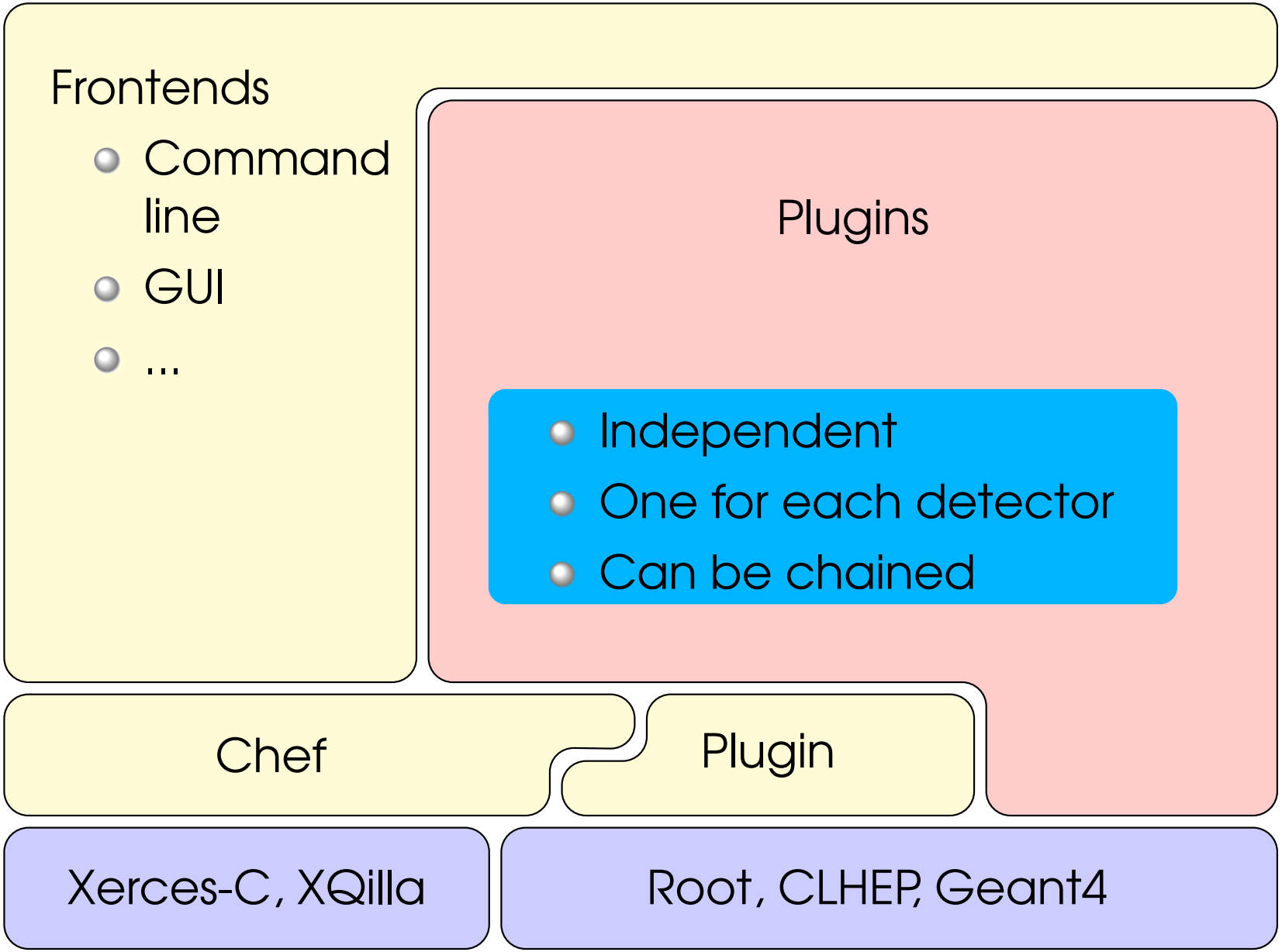


- $> 4\,\mathrm{fb}^{-1}$ data taken
- Selected $3.2\,\mathrm{fb}^{-1}$ high quality subset

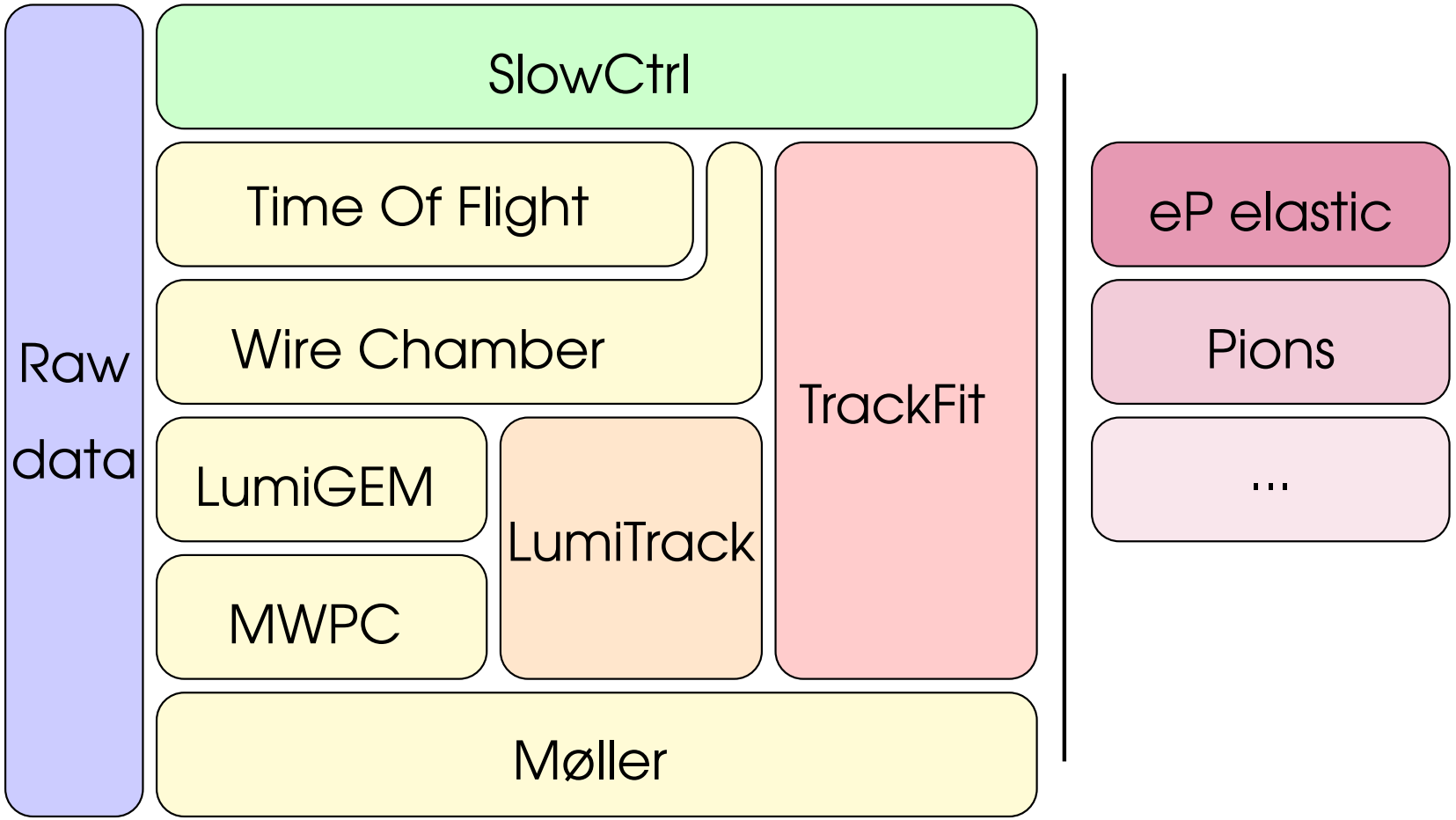
Analysis

Goal: $R_{2\gamma}$

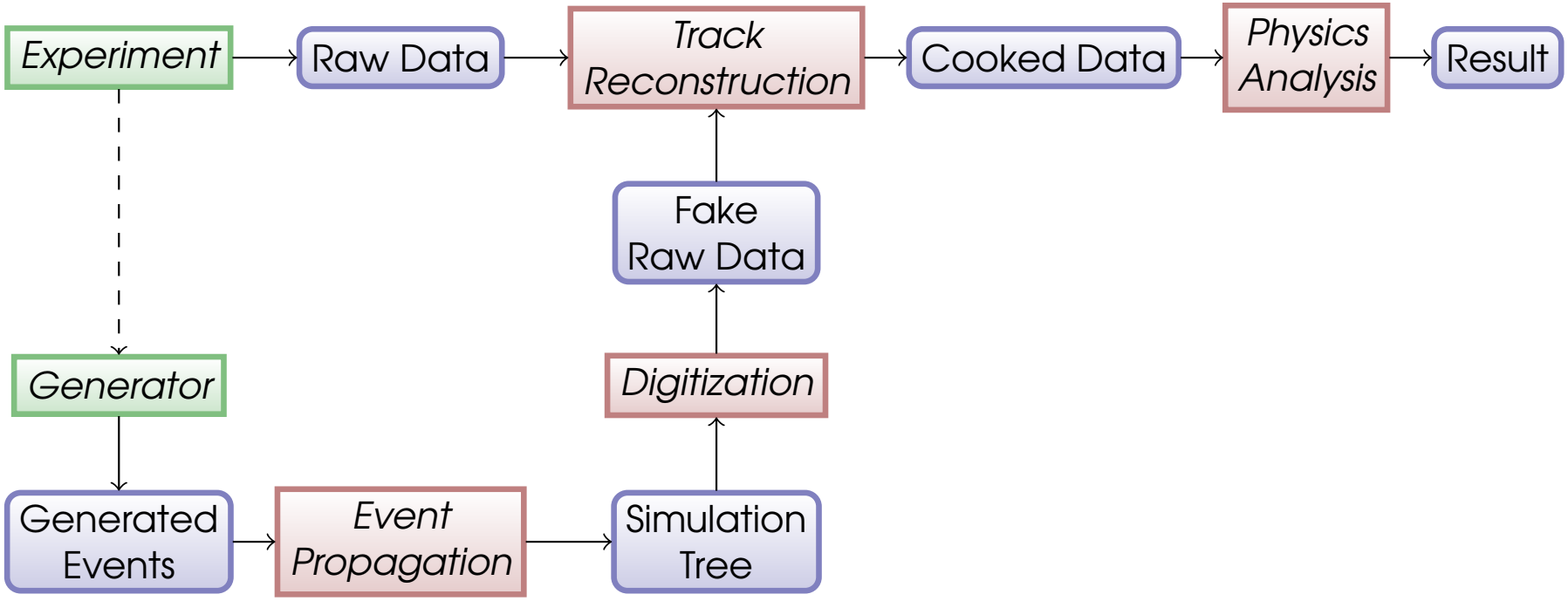
Analysis software stack: Cooker



Plugin System



Analysis approach



"Straight forward" analysis

- Measure data
- Model experiment in simulation
- Generate pseudo data
- Track data + pseudo data
- Define cuts
- Background subtraction
- Build ratio

$$R_{2\gamma} = \frac{N_{exp}^{e^+}}{N_{exp}^{e^-}} / \frac{N_{MC}^{e^+}}{N_{MC}^{e^-}}$$

The crux: systematics

- Measure data
- Model experiment in simulation
- Generate pseudo data
- Track data + pseudo data
- Define cuts
- Background subtraction
- Build ratio

$$R_{2\gamma} = \frac{N^{e^+}_{exp}}{N^{e^-}_{exp}} / \frac{N^{e^+}_{MC}}{N^{e^-}_{MC}}$$

The crux: systematics

- Measure data Lumi. asymmetry? Time stability?
- Model experiment in simulation
- Generate pseudo data
- Track data + pseudo data
- Define cuts
- Background subtraction
- Build ratio

$$R_{2\gamma} = \frac{N^{e^+}_{exp}}{N^{e^-}_{exp}} / \frac{N^{e^+}_{MC}}{N^{e^-}_{MC}}$$

The crux: systematics

- Measure data Lumi. asymmetry? Time stability?
- Model experiment in simulation Reality matched?
- Generate pseudo data Radiative corrections? F.F.?
- Track data + pseudo data
- Define cuts
- Background subtraction
- Build ratio

$$R_{2\gamma} = \frac{N^{e^+}_{exp}}{N^{e^-}_{exp}} / \frac{N^{e^+}_{MC}}{N^{e^-}_{MC}}$$

The crux: systematics

- Measure data Lumi. asymmetry? Time stability?
- Model experiment in simulation Reality matched?
- Generate pseudo data Radiative corrections? F.F.?
- Track data + pseudo data Tracker efficiency?
- Define cuts
- Background subtraction
- Build ratio

$$R_{2\gamma} = \frac{N^{e^+}_{exp}}{N^{e^-}_{exp}} / \frac{N^{e^+}_{MC}}{N^{e^-}_{MC}}$$

The crux: systematics

- Measure data Lumi. asymmetry? Time stability?
- Model experiment in simulation Reality matched?
- Generate pseudo data Radiative corrections? F.F.?
- Track data + pseudo data Tracker efficiency?
- Define cuts Cut bias?
- Background subtraction Background model?
- Build ratio

$$R_{2\gamma} = \frac{N^{e^+}_{exp}}{N^{e^-}_{exp}} / \frac{N^{e^+}_{MC}}{N^{e^-}_{MC}}$$

How to check systematics

- Redundancy
  - Multiple luminosity monitors
  - Multiple MC generators
  - Multiple trackers
  - Multiple analyses
- Associated quantities
  - Lepton left vs. lepton right by species
  - Charge average: $\frac{\sigma^{e^+}_{exp}+\sigma^{e^-}_{exp}}{\sigma^{e^+}_{MC}+\sigma^{e^-}_{MC}} \approx 1$

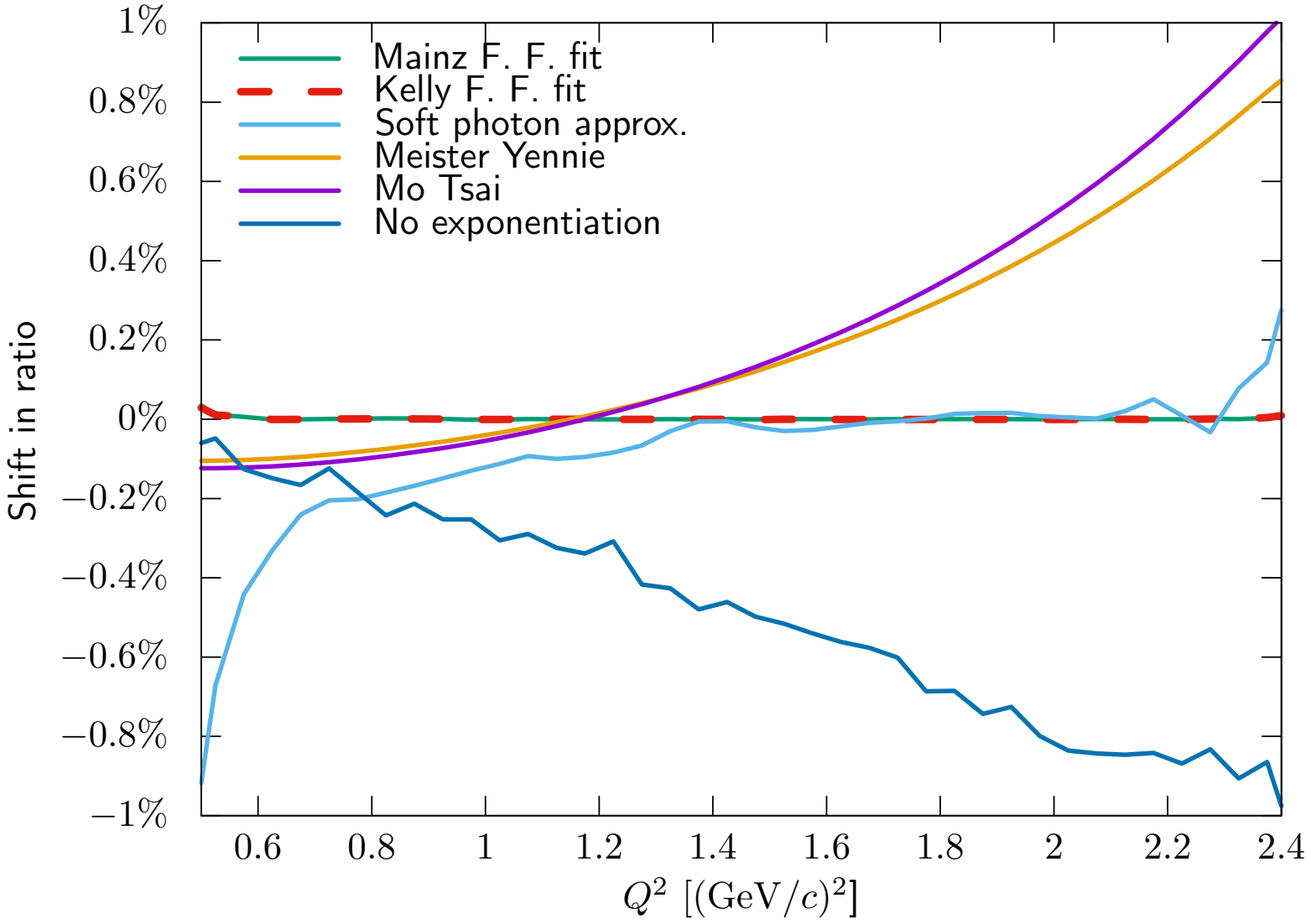
    $\Longrightarrow$ TPE cancels in first order

The crux: systematics

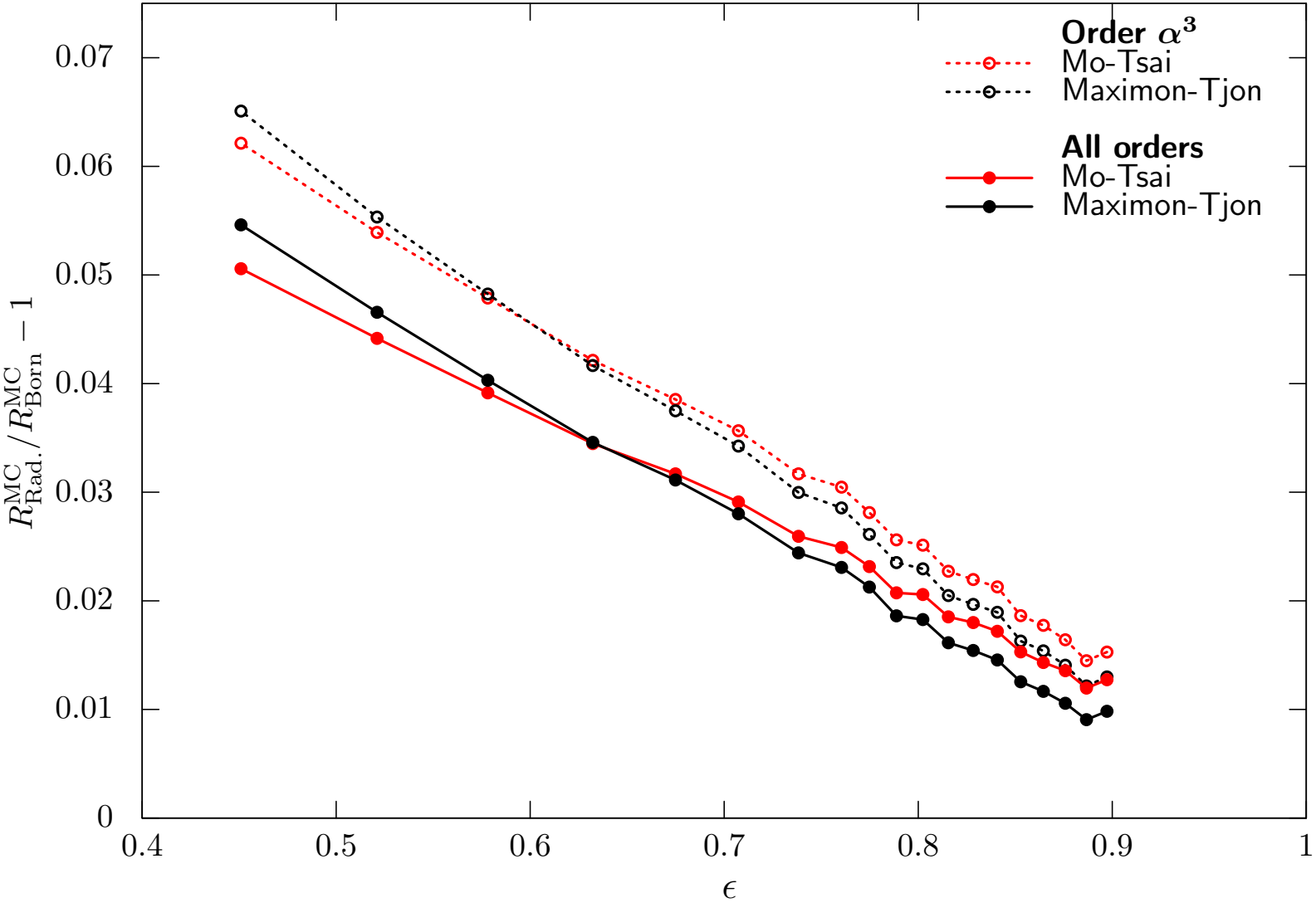
Effect	Appears in			Verdict
	charge avg.	left/right	ratio	
TPE	no	no	yes	signal
Soft TPE model	no (1st ord.)	no		
F. F. model	yes	no		
Luminosity				
Total eff.				
Local eff.				
Proton accept.				
Lepton accept.				
Cuts				
Bkgd. subtr.				

MC model / form factor effects

Baseline: Dipole F. F., Maximon Tjon rad. corrections



Soft-photon corrections are sizeable



Upcoming workshop on two-boson diagrams at Amherst Center for Fundamental Interactions! Interested? Talk to Michael Ramsey-Musolf, Richard Milner, or me.

The crux: systematics

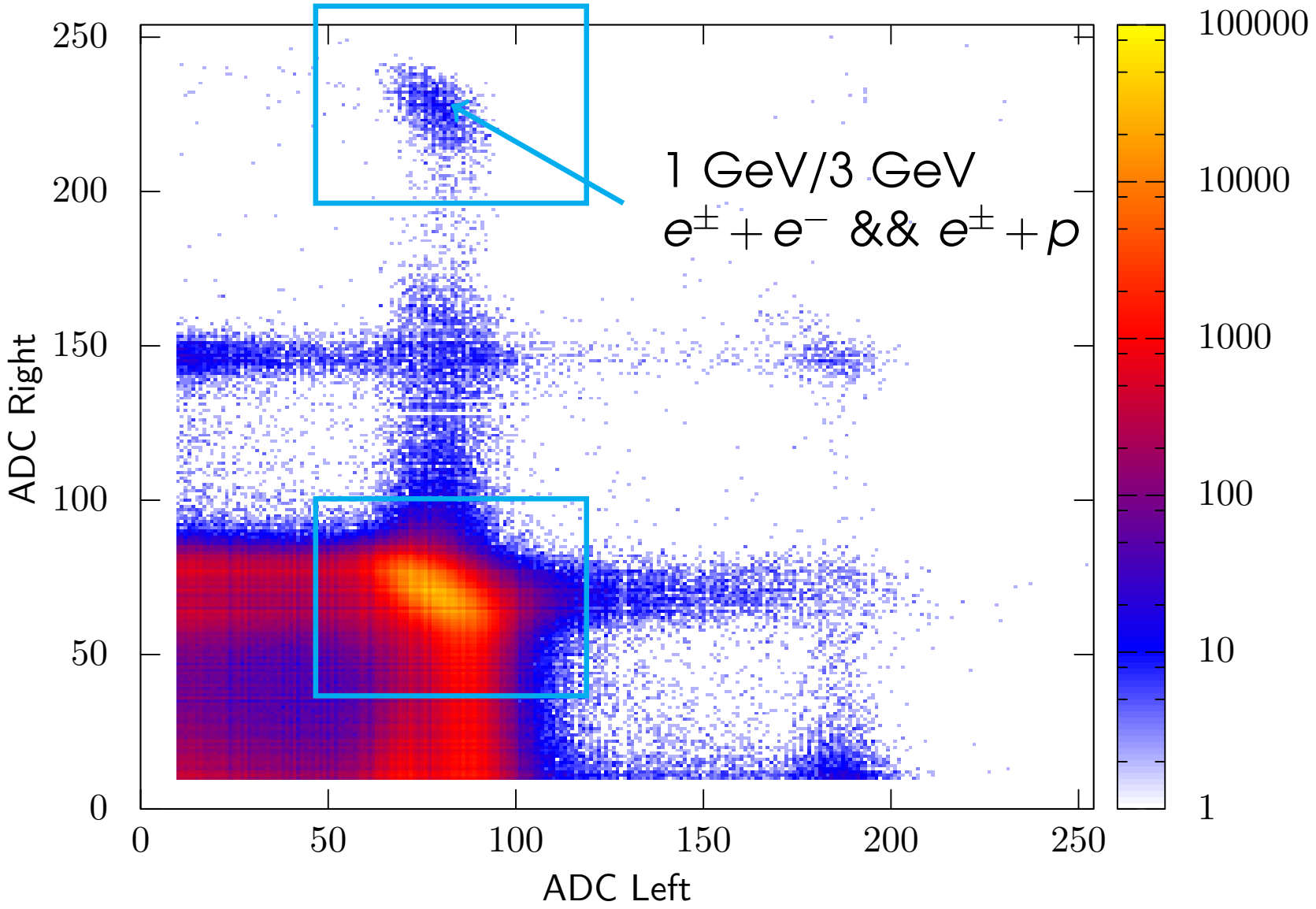
Effect	Appears in			Verdict
	charge avg.	left/right	ratio	
TPE	no	no	yes	signal
Soft TPE model	no (1st ord.)	no	yes	use all
F. F. model	yes	no	no	✓
Luminosity	yes	no	asymmetry	
Total eff.				
Local eff.				
Proton accept.				
Lepton accept.				
Cuts				
Bkgd. subtr.				

Luminosity measurements

Redundant systems:

- Slow control luminosity
  - beam current, target flow, temperature
- Symmetric Møller/Bhabha monitor
  - MC of both processes
- $e^{\pm}e^{-} + e^{\pm}p$ double coincidence in symmetric Møller/Bhabha detector (multi-interaction events, MIE)
- 12° monitor
  - two independent $e^{\pm}p$ measurements

Symmetric Møller/Bhabha monitor

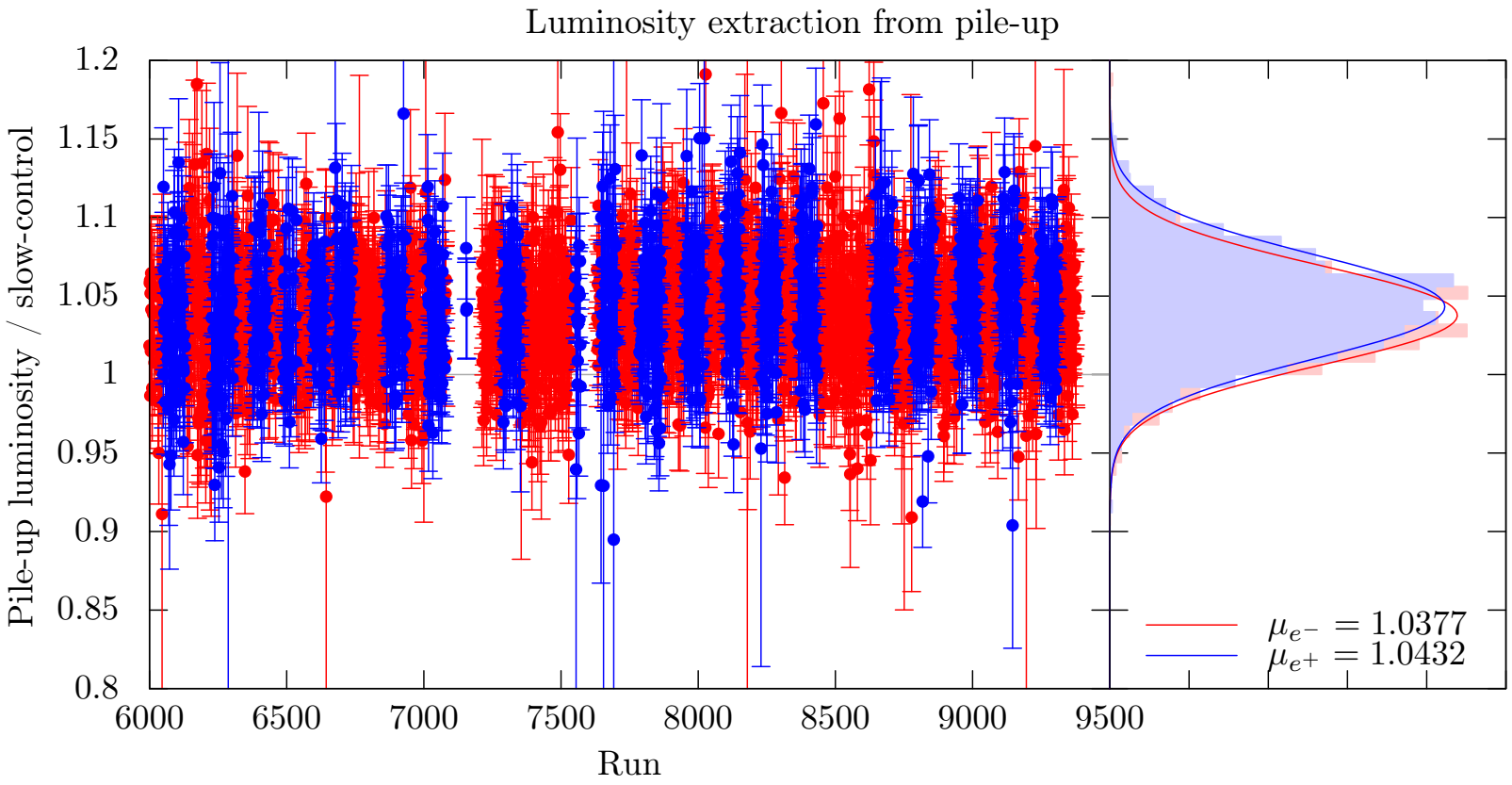


See thesis by O'Connor, Dmitry, Schmidt

$e^{\pm}e^{-} + e^{\pm}p$ double coincidence

- Calculate coincidence rate from $e^{\pm}p$ simulation and $e^{\pm}e^{-}$ rate measurement
- Correct for luminosity variance (time / bunch charge)
- Result is independent of:
  - detector efficiency
  - Møller / Bhabha cross section
- Reduced sensitivity on beam position, geometry

$e^{\pm}e^{-} + e^{\pm}p$ double coincidence

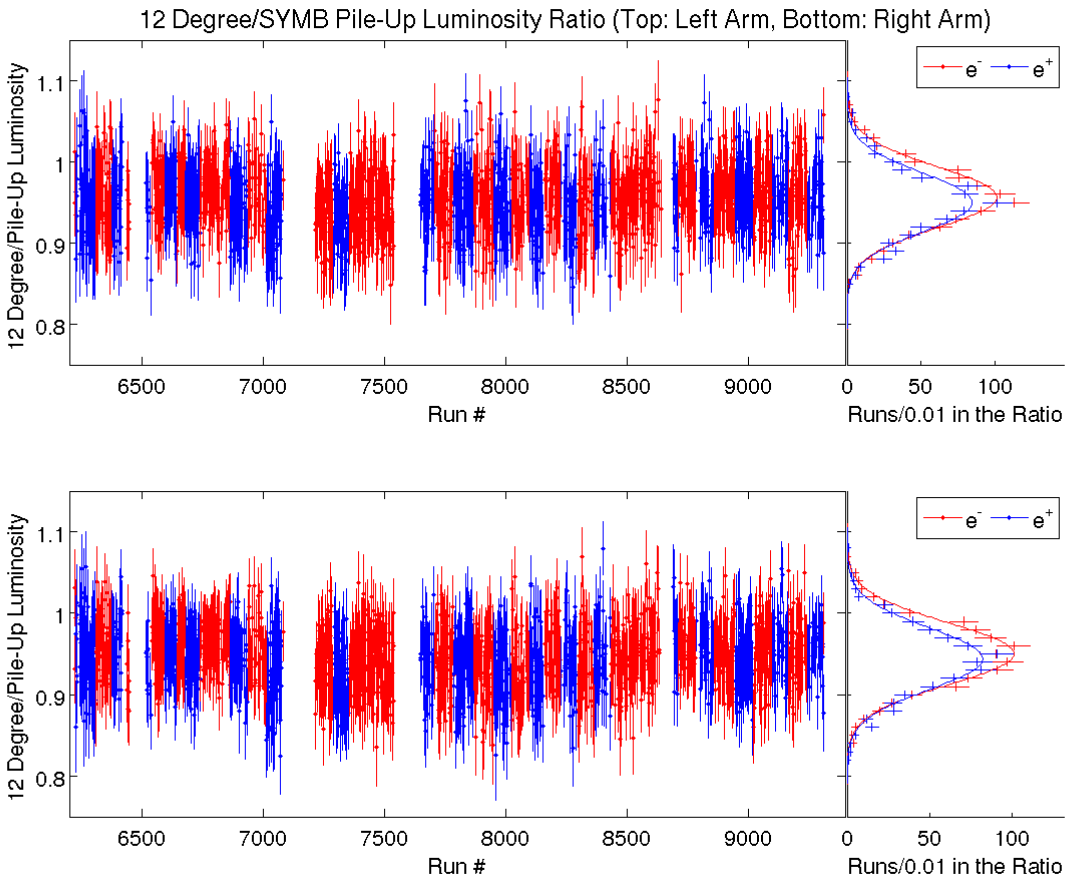


Analysis by Axel Schmidt

- Slow control luminosity induced asymmetry: $\sim 0.55\%$
- Uncertainty: 0.10% stat. 0.35% syst.
- $< \varepsilon >= 0.99975$, $< Q^2 >= 0.002\,(\mathrm{GeV}/c)^2$

12° luminosity monitor

- Yields using SM double coinc. luminosity
- Left and right agrees to within 0.1%
- TPE at $Q^2 = 0.168\,(\mathrm{GeV}/c)^2$?
- Uncertainty: 0.03% stat., 0.46% syst.

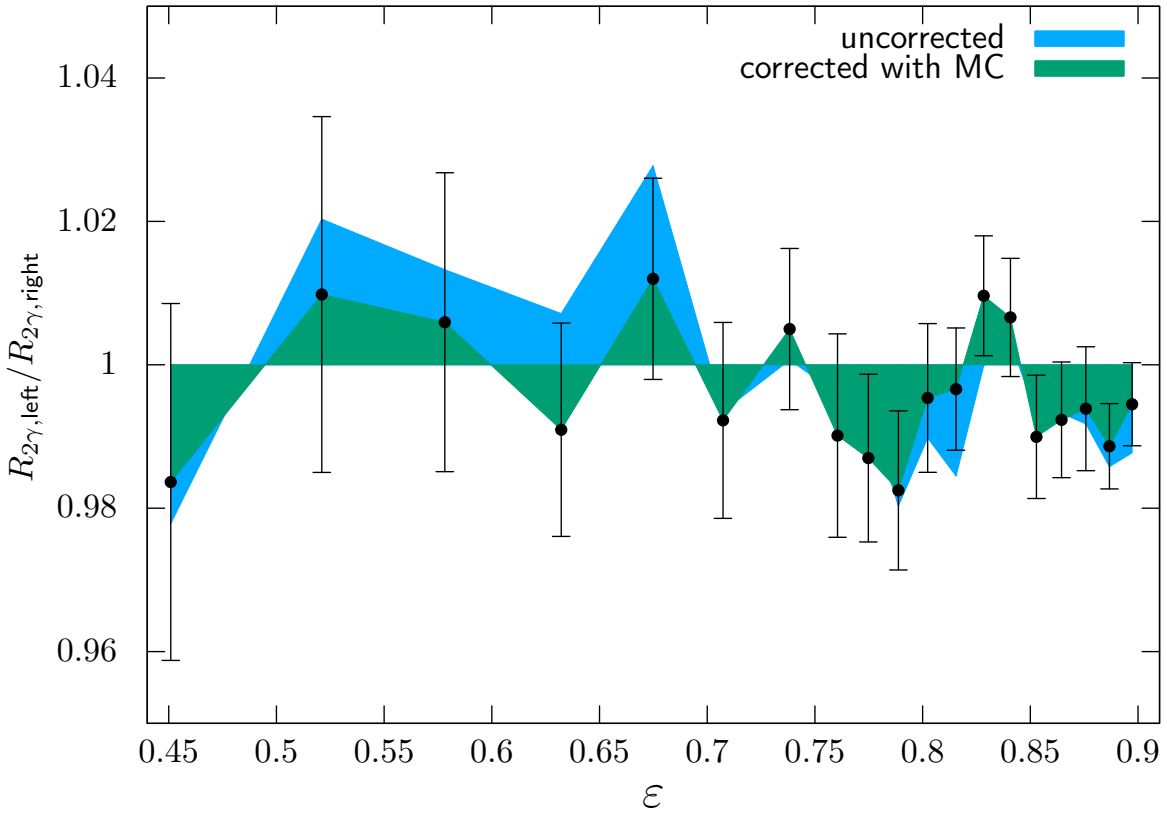


Analysis by Brian Henderson

The crux: systematics

Effect	Appears in			Verdict
	charge avg.	left/right	ratio	
TPE	no	no	yes	signal
Soft TPE model	no (1st ord)	no	yes	use all
F. F. model	yes	no	no	✓
Luminosity	yes	no	asymmetry	✓
Total eff.	yes	no	no	
Local eff.	yes	(yes)	reduced	
Proton accept.	yes	(yes)	no	
Lepton accept.	yes	(yes)	reduced	
Cuts				
Bkgd. subtr.				

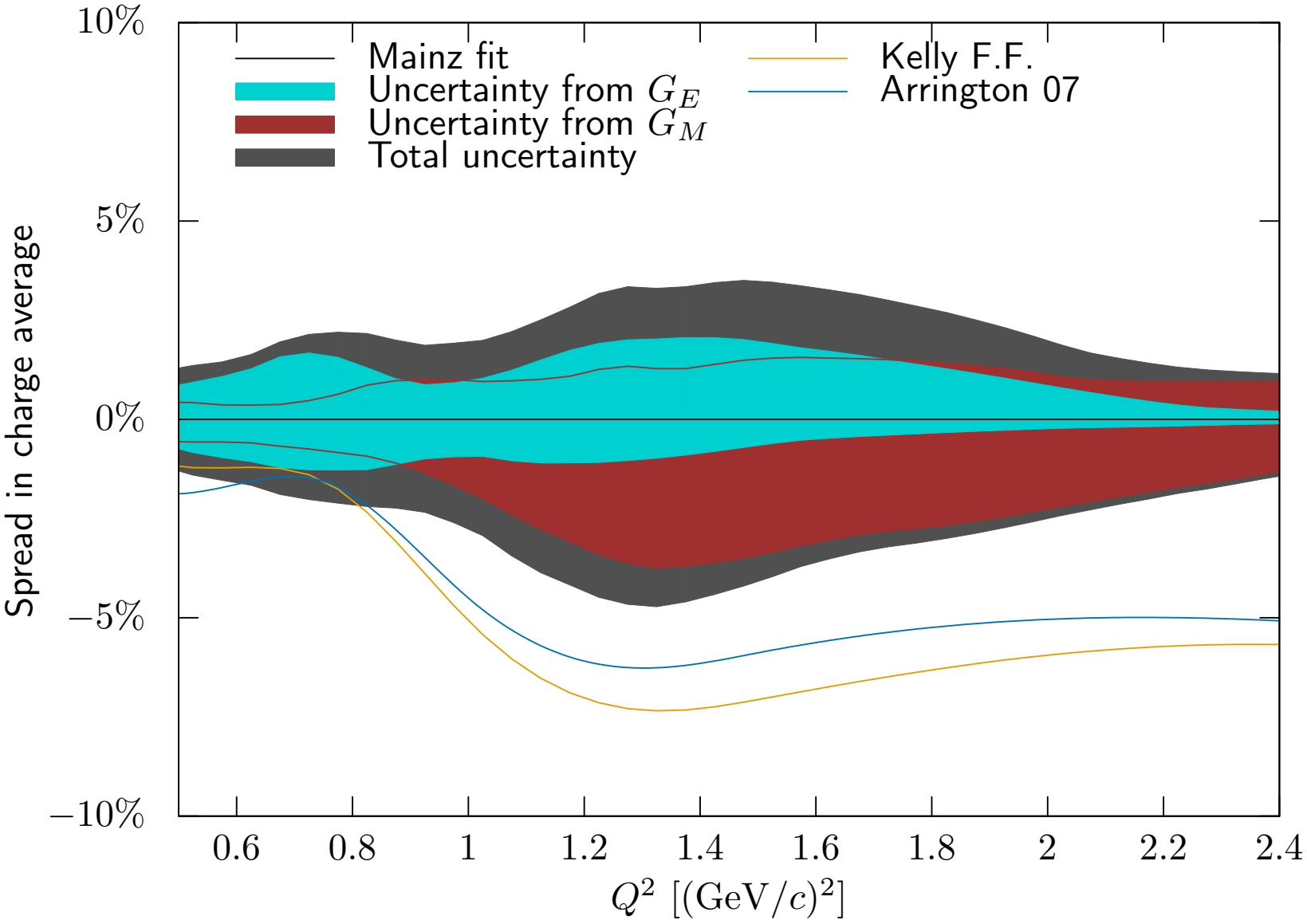
Left/right comparison



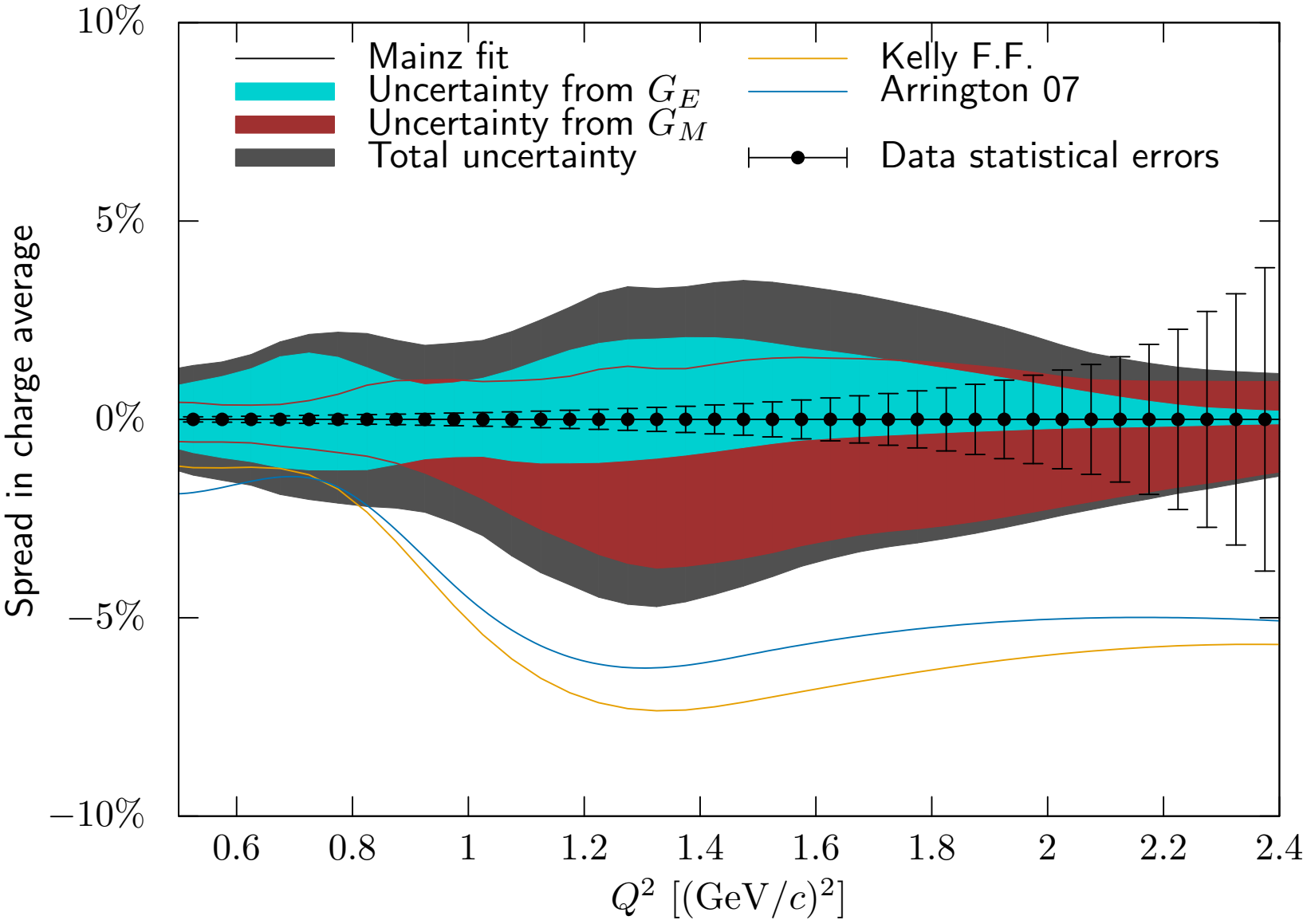
- Calculate $R_{2\gamma}$ for lepton left/right
- Ratio should be 1
- MC corrects acceptance difference

Few deviations bigger than statistical. Take worst case as global systematic error.

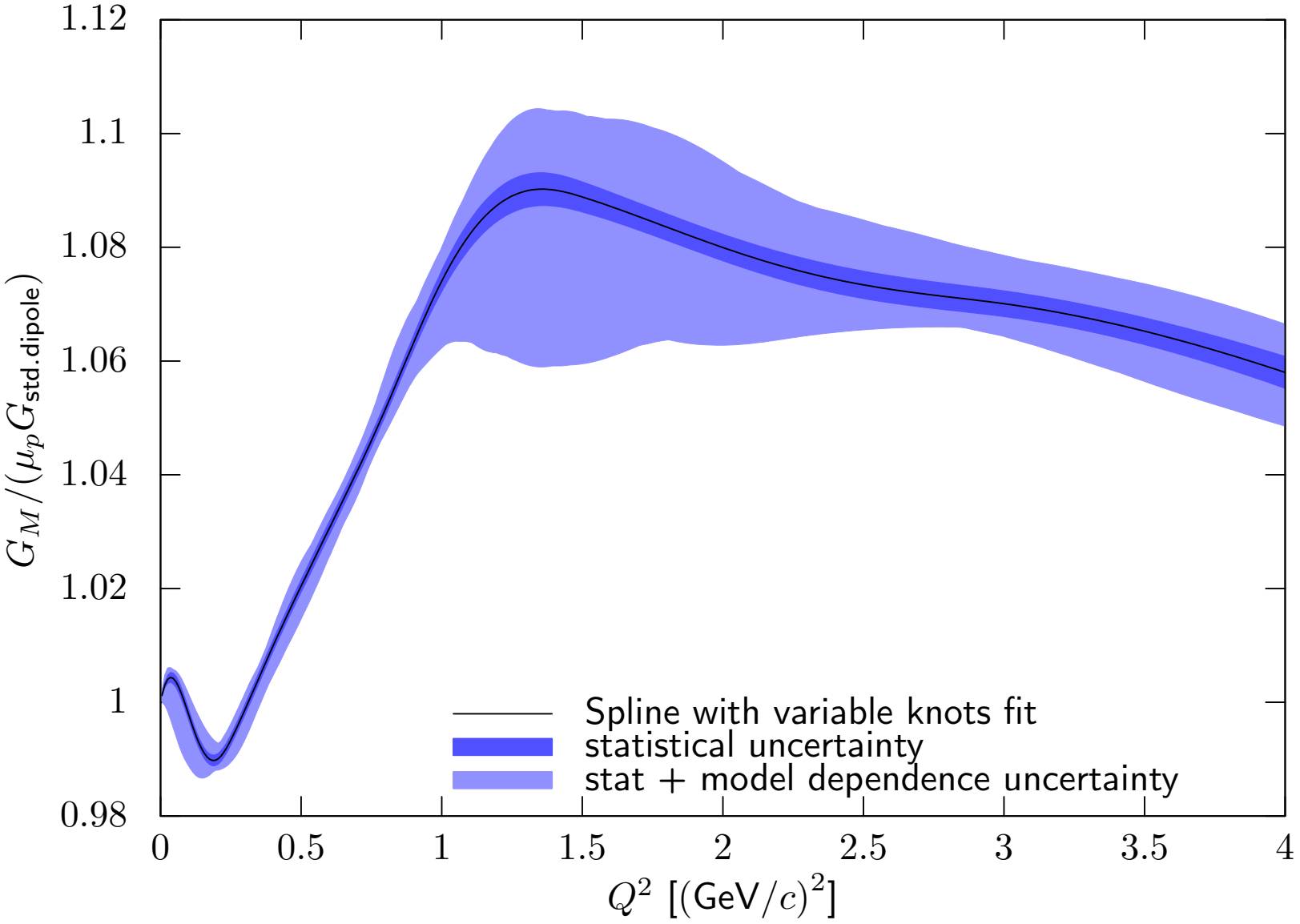
Charge average



Charge average



Bonus physics



The crux: systematics

Effect	Appears in			Verdict
	charge avg.	left/right	ratio	
TPE	no	no	yes	signal
Soft TPE model	no (1st ord)	no	yes	use all
F. F. model	yes	no	no	✓
Luminosity	yes	no	asymmetry	✓
Total eff.	yes	no	no	limited knowledge
Local eff.	yes	(yes)	reduced	✓
Proton accept.	yes	(yes)	no	✓
Lepton accept.	yes	(yes)	reduced	✓
Cuts	yes	reduced	reduced	
Bkgd. subtr.	yes	reduced	reduced	

Cuts and Background subtraction

- Multiple independent analyses of the same data set
- Different approaches in
  - Particle ID
  - Track / Event selection
  - Background subtraction
- Methods different, results similar!

Cuts and Background subtraction

- Multiple independent analyses of the same data set
- Different approaches in
  - Particle ID
  - Track / Event selection
  - Background subtraction
- Methods different, results similar!

Meta-analysis

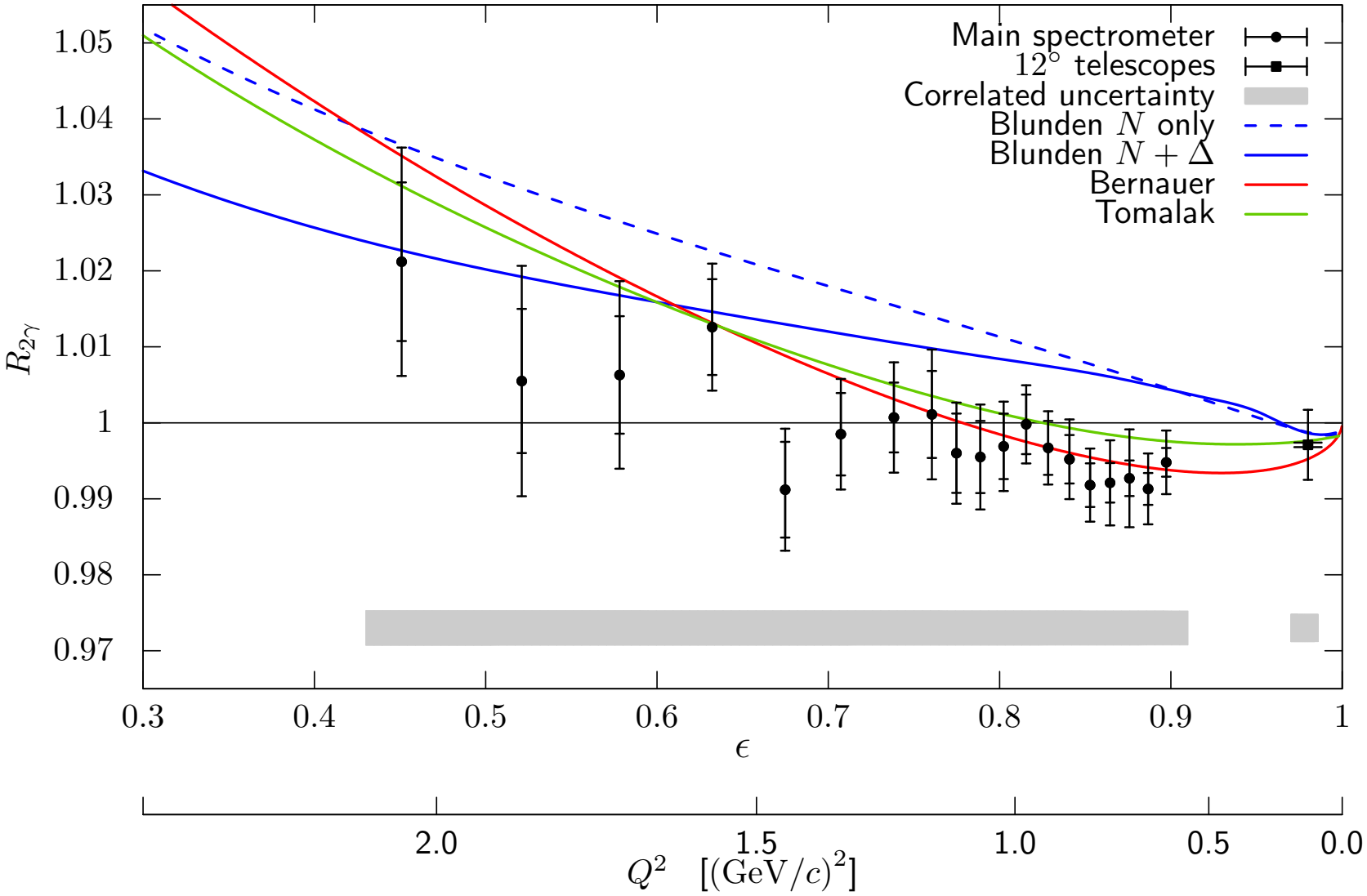
- Take average of all analyses
- Standard deviation as systematic uncertainty

The crux: systematics

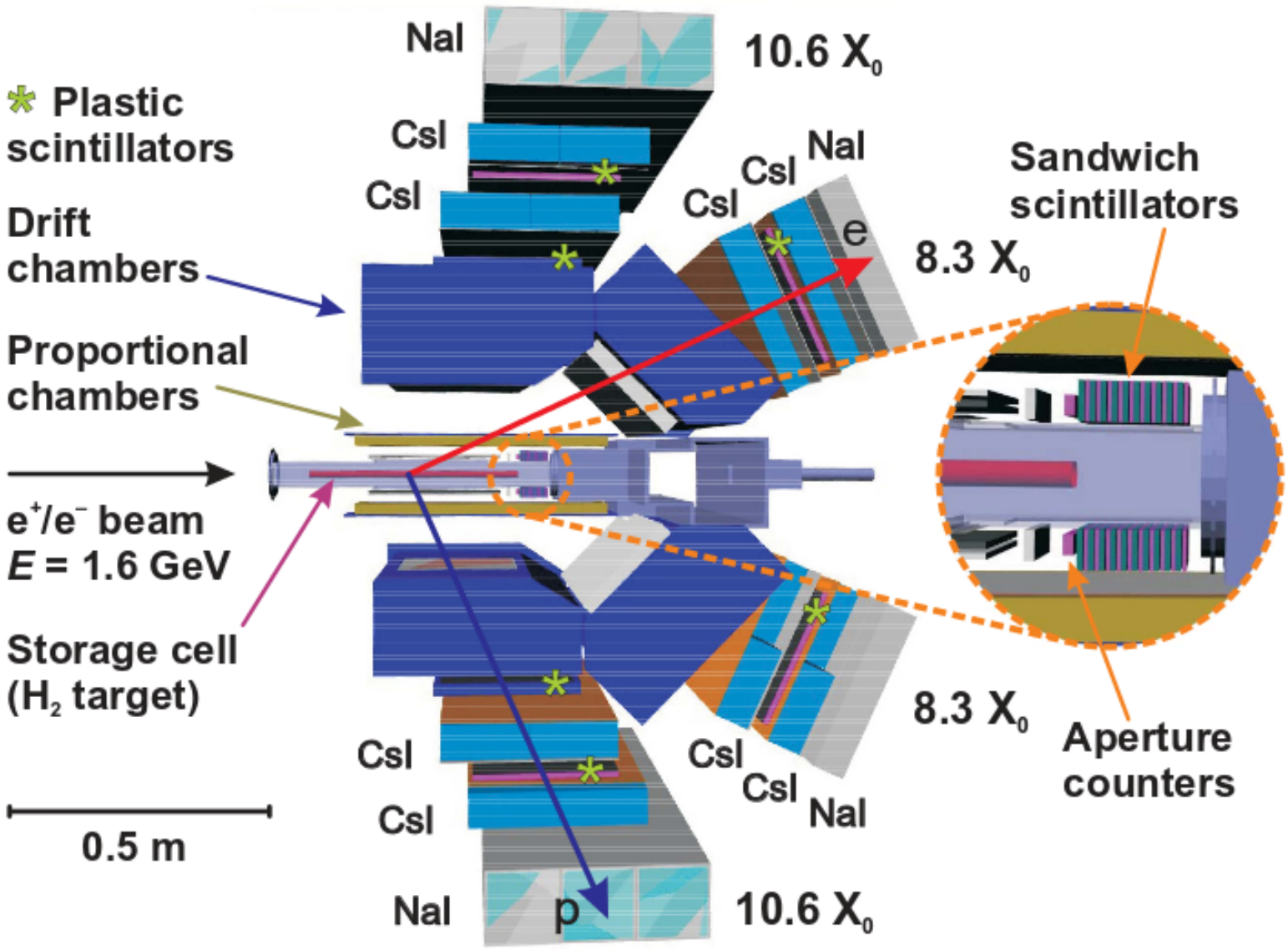
Effect	Appears in			Verdict
	charge avg.	left/right	ratio	
TPE	no	no	yes	signal
Soft TPE model	no (1st ord)	no	yes	use all
F. F. model	yes	no	no	✓
Luminosity	yes	no	asymmetry	✓
Total eff.	yes	no	no	limited knowledge
Local eff.	yes	(yes)	reduced	✓
Proton accept.	yes	(yes)	no	✓
Lepton accept.	yes	(yes)	reduced	✓
Cuts	yes	reduced	reduced	✓
Bkgd. subtr.	yes	reduced	reduced	✓

OLYMPUS results (B. Henderson et al., arXiv:1611.04685 (nucl-ex))

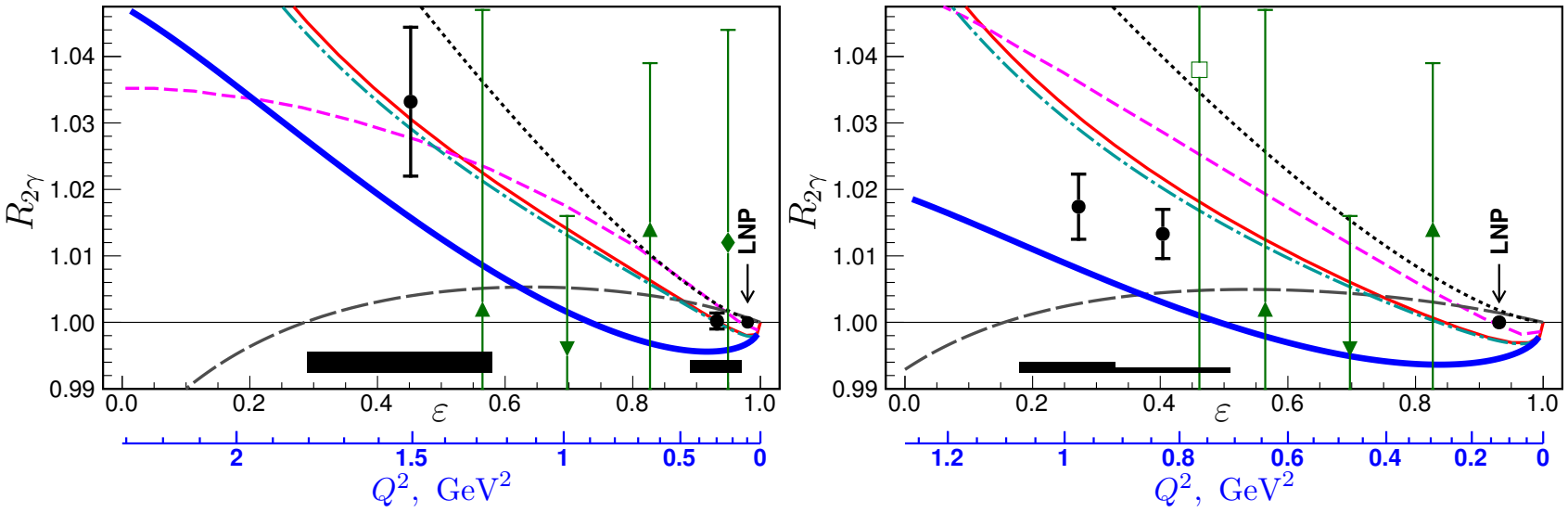
- With exponentation, using Mo-Tsai soft photon calc.



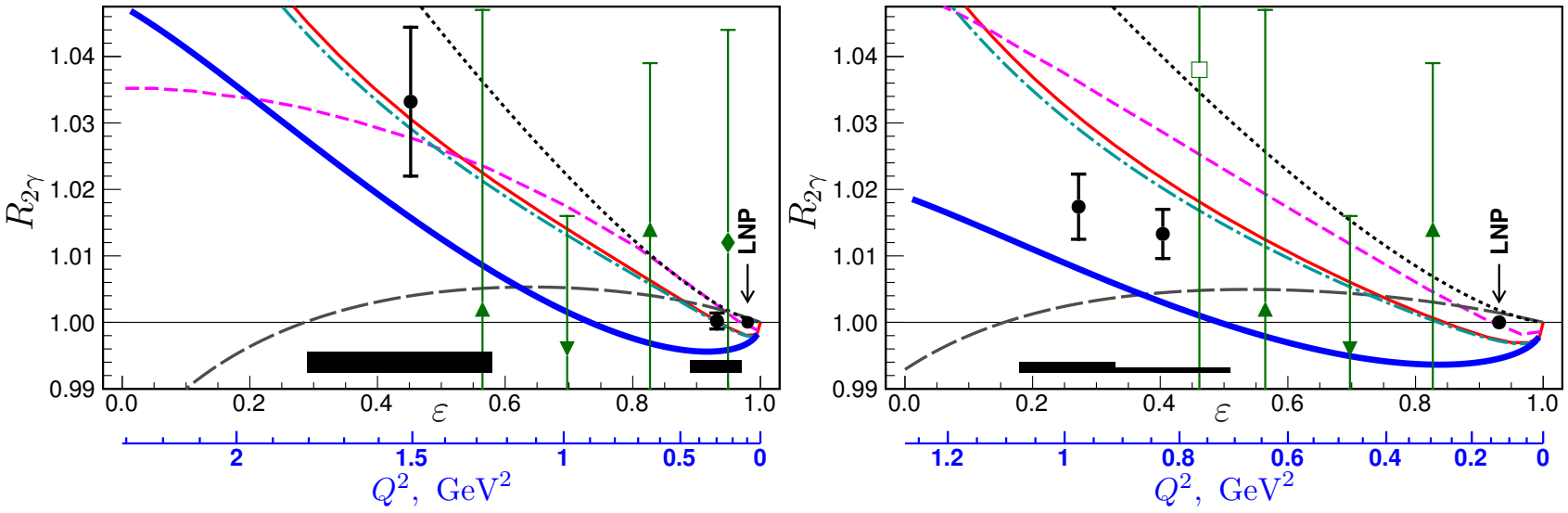
VEPP-3 results (I. A. Rachek et al., Phys. Rev. Lett 114, 062005)



VEPP-3 results (I. A. Rachek et al., Phys. Rev. Lett 114, 062005)

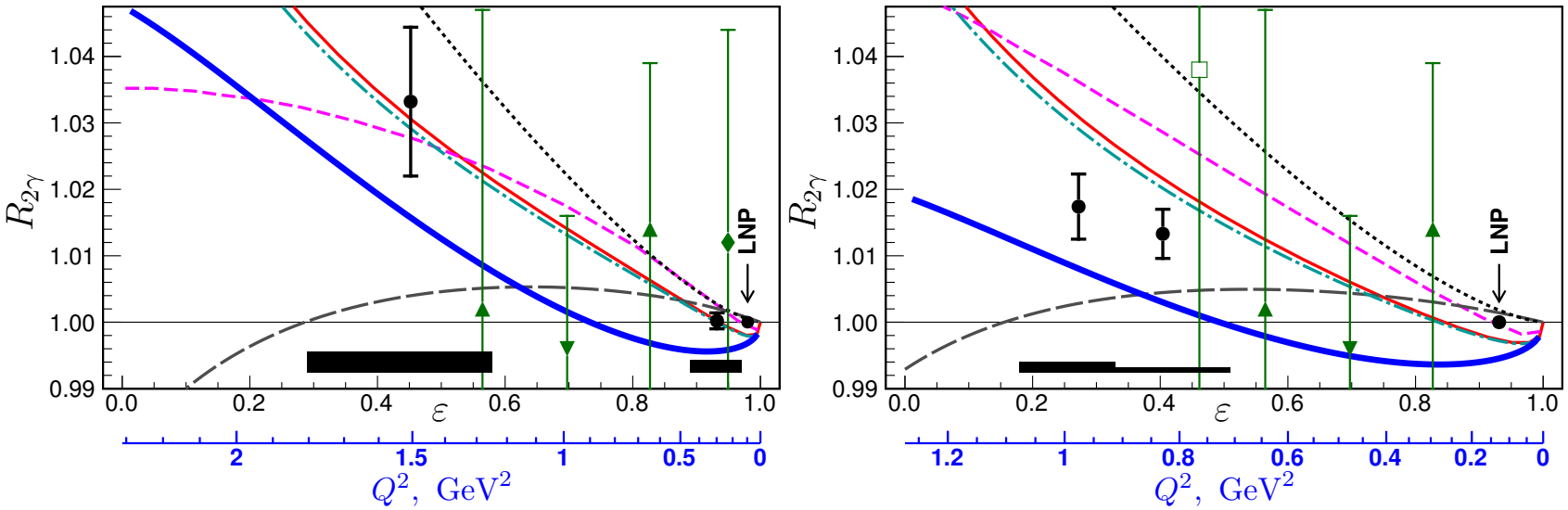


VEPP-3 results (I. A. Rachek et al., Phys. Rev. Lett 114, 062005)



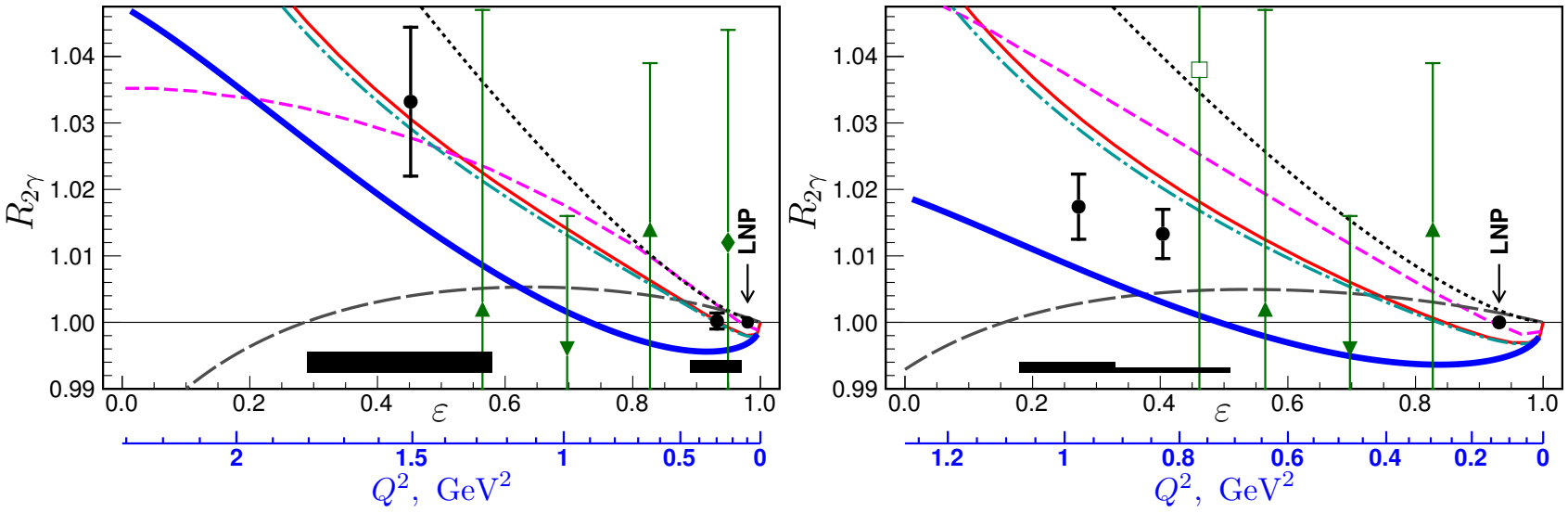
	$R_{2\gamma}^{\text{LNP}}$	$\frac{\chi^2}{n_{\text{d.f.}}}$
Borisyuk and Kobushkin	1	2.14
Blunden, et al.	1	2.94
Bernauer, et al.	1	4.19
Tomasi-Gustafsson, et al.	1	5.09
Arrington and Sick	1	7.72
Qattan, et al.	1	25.0
No hard TPE ($R_{2\gamma} \equiv 1$)	1	7.97

VEPP-3 results (I. A. Rachek et al., Phys. Rev. Lett 114, 062005)



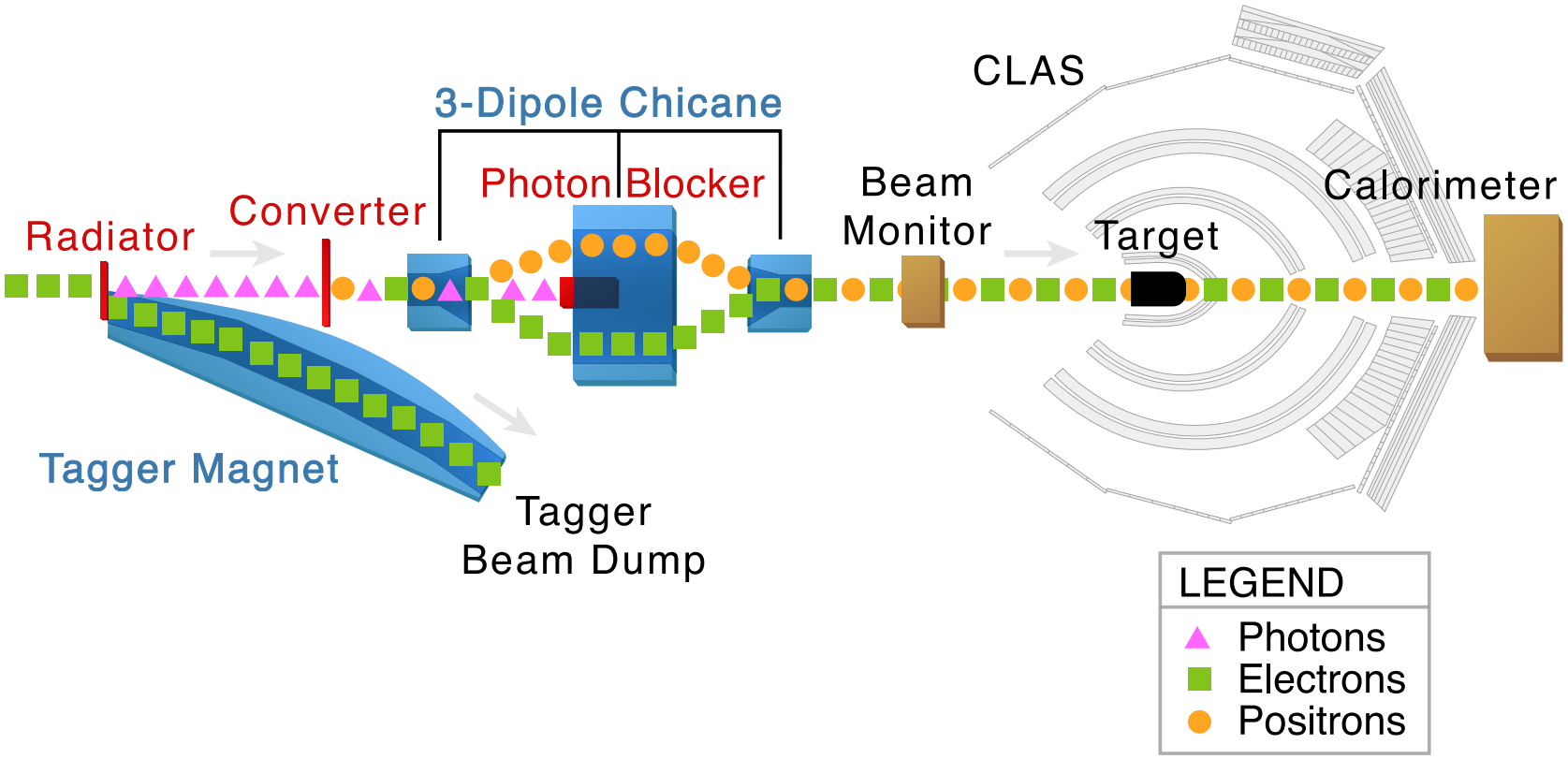
	$R_{2\gamma}^{\text{LNP}}$	$\frac{\chi^2}{n_{\text{d.f.}}}$	$R_{2\gamma}^{\text{LNP}}$ Run-I	$R_{2\gamma}^{\text{LNP}}$ Run-II	$\frac{\chi^2}{n_{\text{d.f.}}}$
Borisyuk and Kobushkin	1	2.14	0.998	0.997	3.80
Blunden, et al.	1	2.94	0.998	0.997	4.75
Bernauer, et al.	1	4.19	0.997	0.995	1.00
Tomasi-Gustafsson, et al.	1	5.09	1.001	1.001	5.97
Arrington and Sick	1	7.72	1.000	1.000	8.18
Qattan, et al.	1	25.0	1.000	1.002	22.0
No hard TPE ($R_{2\gamma} \equiv 1$)	1	7.97	1	1	7.97

VEPP-3 results (I. A. Rachek et al., Phys. Rev. Lett 114, 062005) Fixed

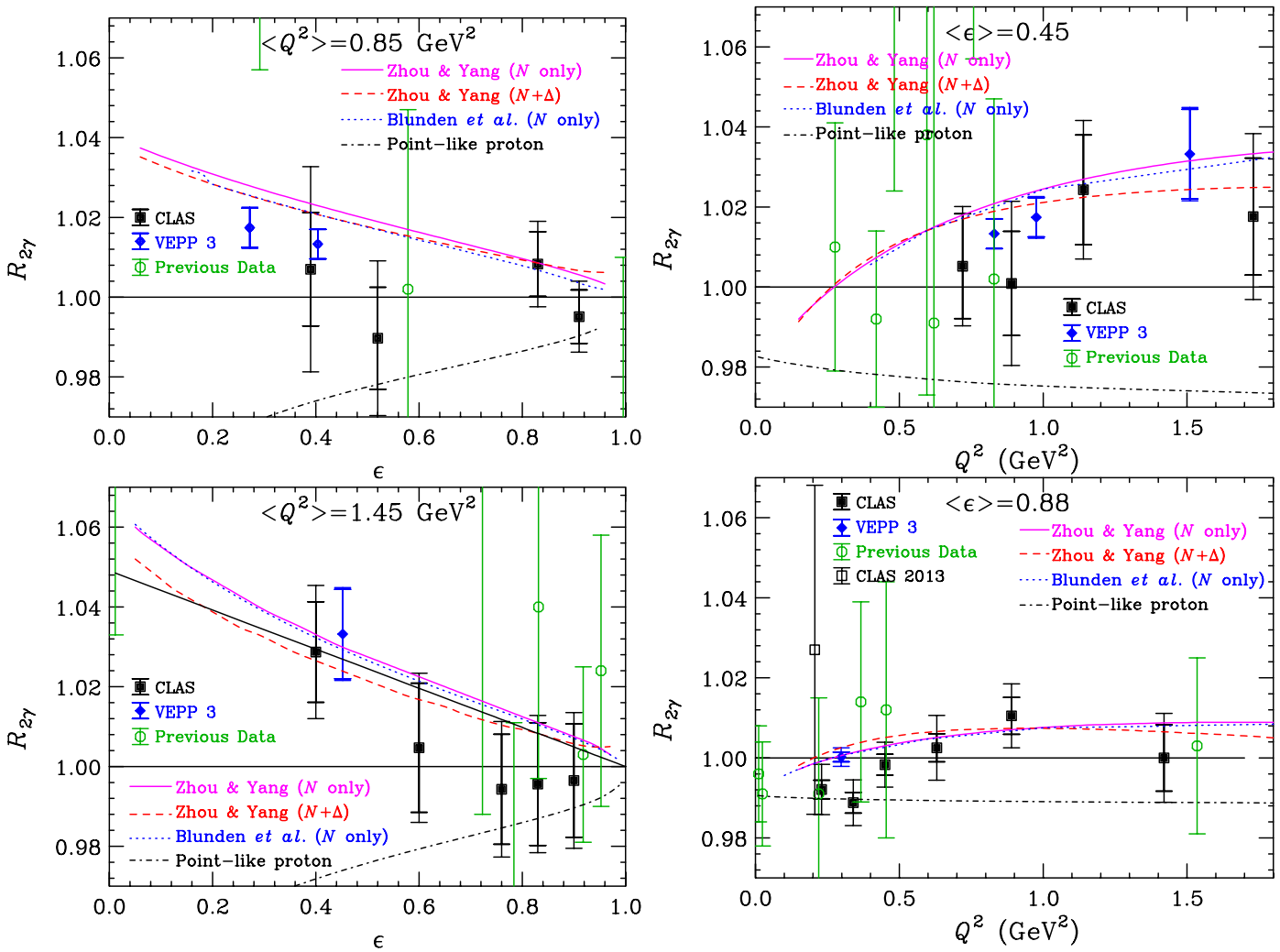


	$R_{2\gamma}^{\text{LNP}}$	$\frac{\chi^2}{n_{\text{d.f.}}}$	$R_{2\gamma}^{\text{LNP}}$ Run-I	$R_{2\gamma}^{\text{LNP}}$ Run-II	$\frac{\chi^2}{n_{\text{d.f.}}}$
Borisyuk and Kobushkin	1	2.14	0.998	0.997	3.80
Blunden, et al.	1	2.94	0.998	0.997	4.75→4.01
Bernauer, et al.	1	4.19	0.997	0.995	1.00→1.95
Tomasi-Gustafsson, et al.	1	5.09	1.001	1.001	5.97
Arrington and Sick	1	7.72	1.000	1.000	8.18
Qattan, et al.	1	25.0	1.000	1.002	22.0
No hard TPE ($R_{2\gamma} \equiv 1$)	1	7.97	1	1	7.97

CLAS (D. Rimal et al., arXiv:1603.00315 , D. Adikaram et al., Phys. Rev. Lett 114, 062003)



CLAS (D. Rimal et al., arXiv:1603.00315 , D. Adikaram et al., Phys. Rev. Lett 114, 062003) (color adjusted)

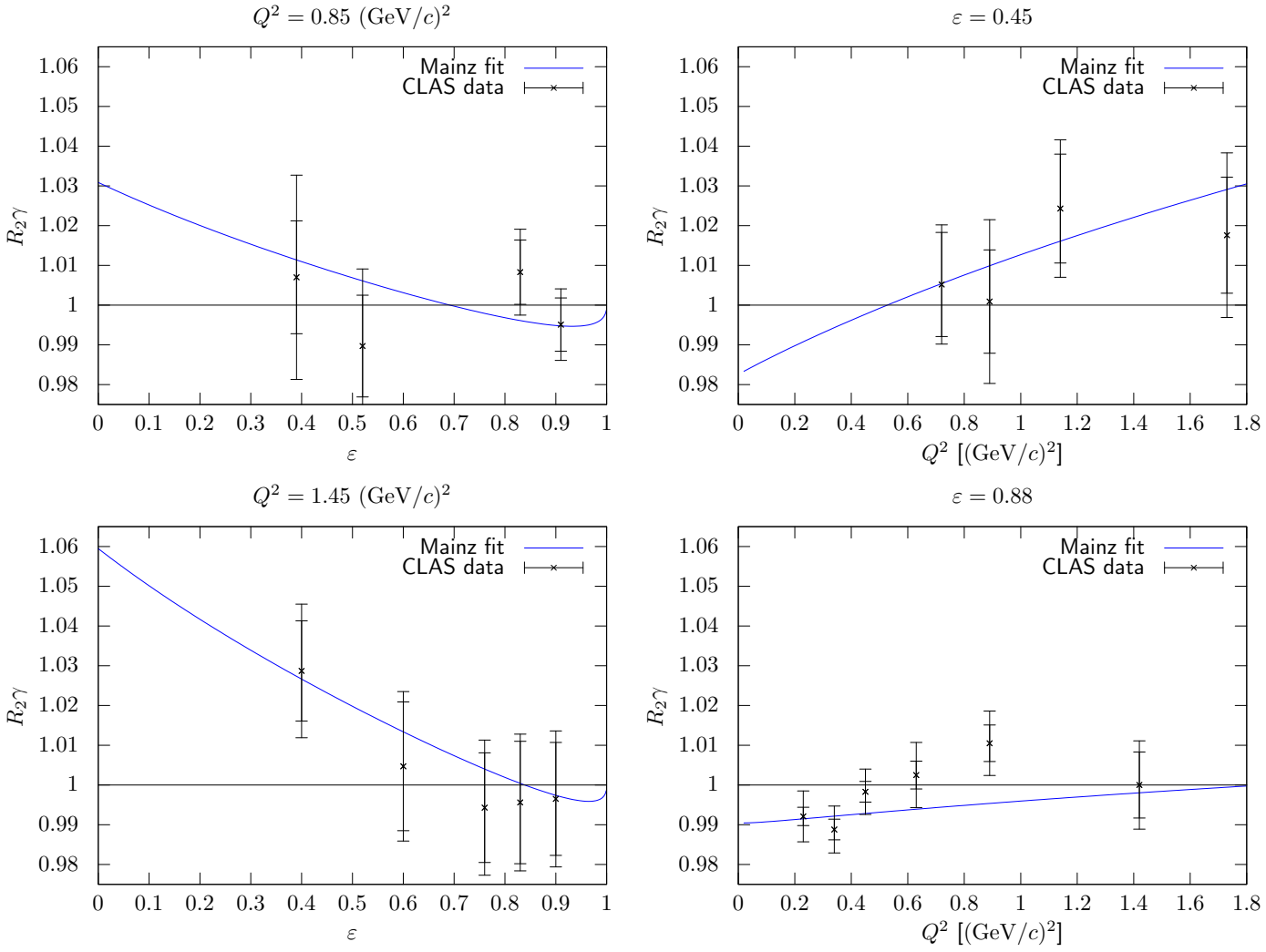


Fit to world data set:

- 12 non-overlapping points from CLAS
- 4 Vepp-3 points

	$\frac{\chi^2}{n_{d.f.}}$
Z & Y (N)	1.09
Z & Y (N+Δ)	1.03
Blunden (N)	1.06
No TPE	2.10
Point-proton	6.96

CLAS data + Mainz fit



Fit to world data set:

- 12 non-overlapping points from CLAS
- 4 Vepp-3 points

	$\frac{\chi^2}{n_{\text{d.f.}}}$
Z & Y (N)	1.09
Z & Y (N+Δ)	1.03
Blunden (N)	1.06
No TPE	2.10
Point-proton	6.96
Mainz	0.919

χ^2 of the world data set

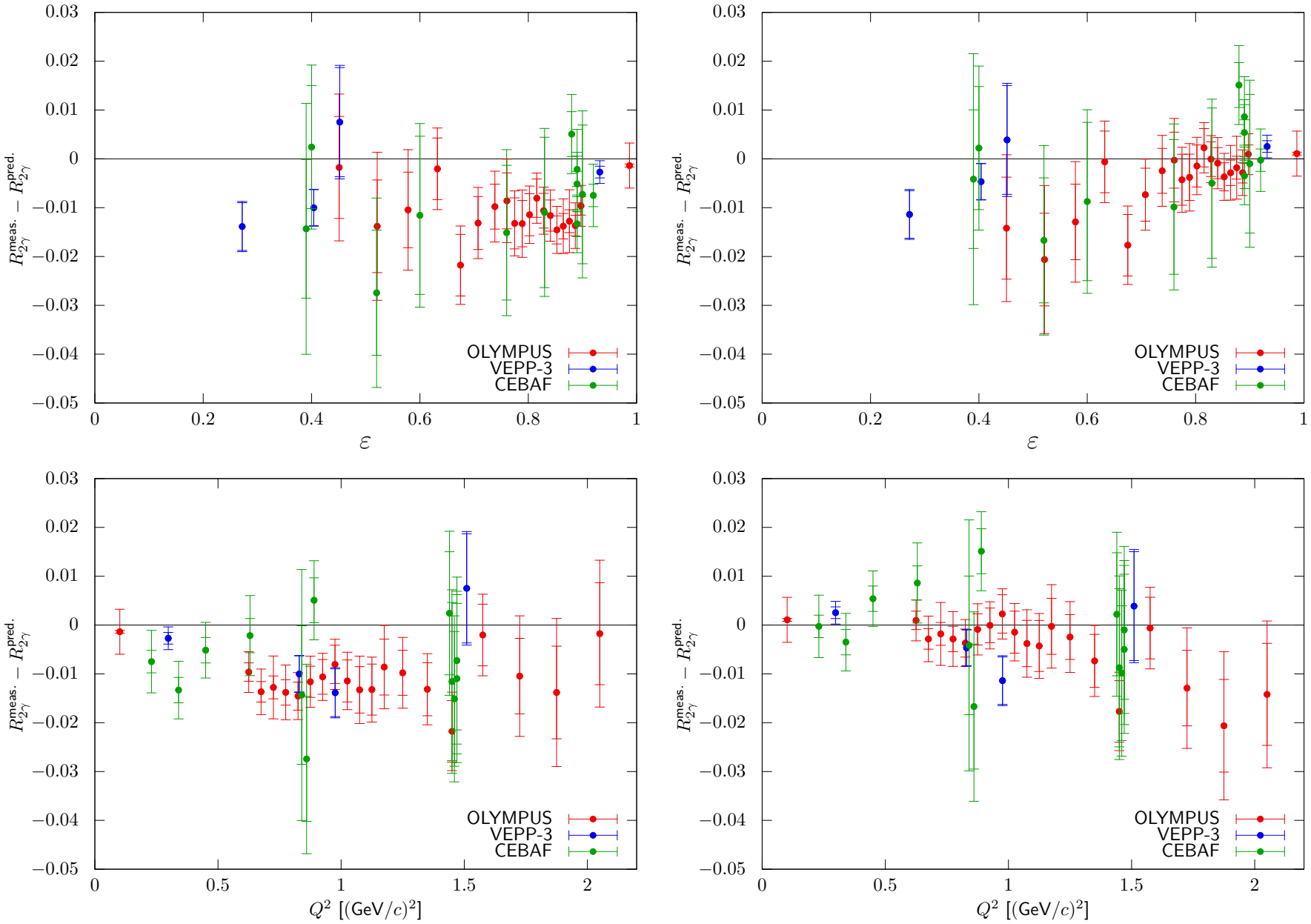
	VEPP-3	CLAS		OLYMPUS		World
	$\frac{\chi^2}{n_{\text{d.f.}}}$	$\frac{\chi^2}{n_{\text{d.f.}}}$	N.	$\frac{\chi^2}{n_{\text{d.f.}}}$	N.	
Blunden	4.01	0.70	1.23σ	0.73	3.278σ	1.088
Bernauer	1.95	0.57	-0.36σ	0.49	0.45σ	0.679

- Large normalization shifts for Blunden
- Point-wise syst. errors too large in CLAS/OLYMPUS?
- Need to check other models
- Non-trivial: Map to same soft-photon description

Difference data to prediction

Blunden

Bernauer



Take away / my interpretation

In measured region

- Data agrees with Mainz extraction
  $\Longrightarrow$TPE dominant effect for f.f. ratio discrepancy
- Blunden has "better" slope, but scale is ruled out.

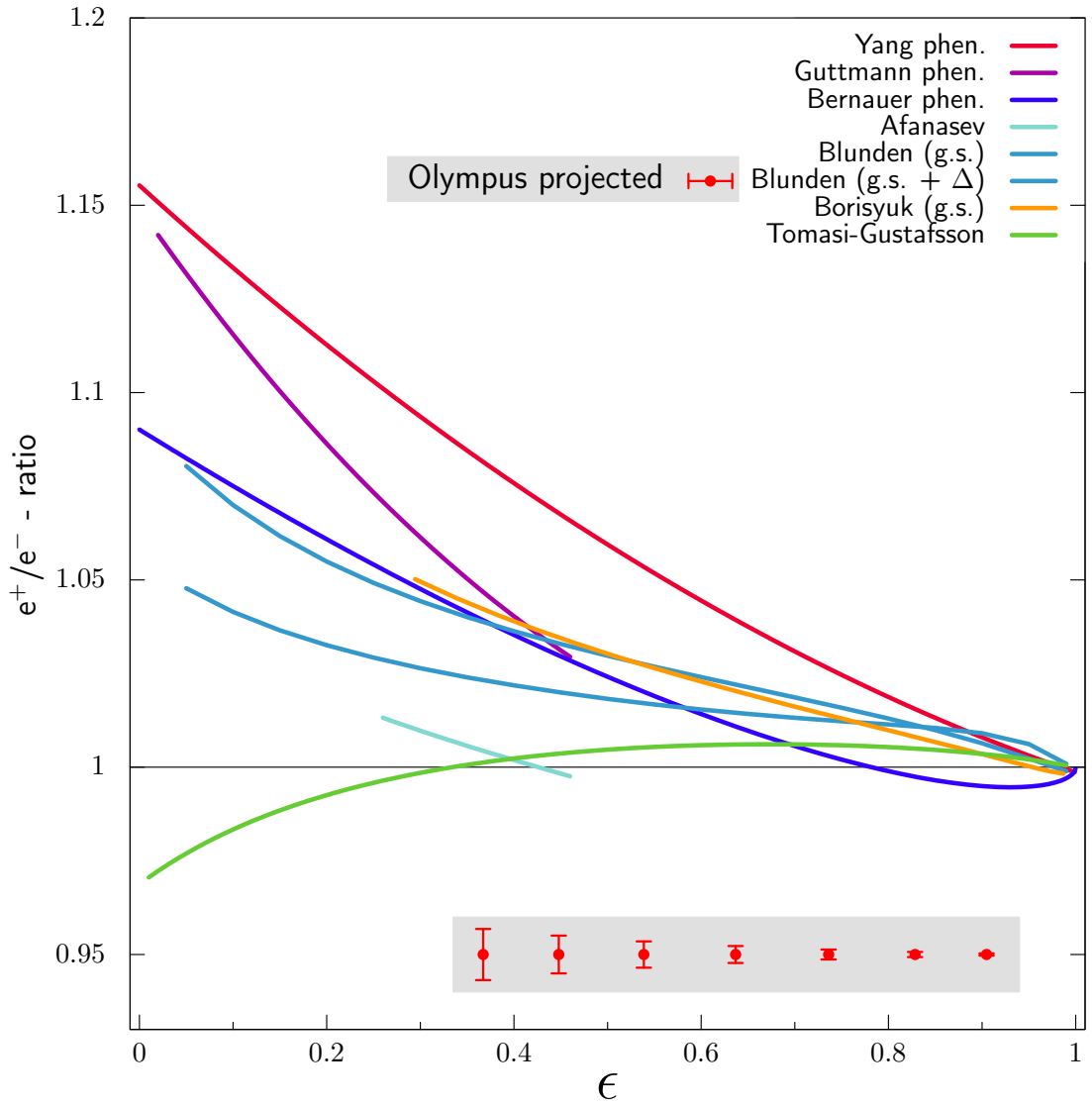
At larger Q^2

- Slight hint that Mainz fit overpredicts slope
  $\Longrightarrow$TPE might not explain full discrepancy at larger Q^2
- Cannot trust theoretical predictions if off for measured Q^2

The book isn't closed on this one

- Direct TPE measurement at large Q^2 needed!

OLYMPUS: Projected performance



2 GeV beam, Q^2-range: 0.6 to 2.2 $(\mathrm{GeV}/c)^2$

Cuts (slice at $Q^2 = 1.175\,(\mathrm{GeV/c})^2$)