UNIVERSITY OF MICHIGAN

TPEX@DESY - A Two-Photon Exchange Experiment at DESY Test Beam

on behalf of the TPEX collaboration

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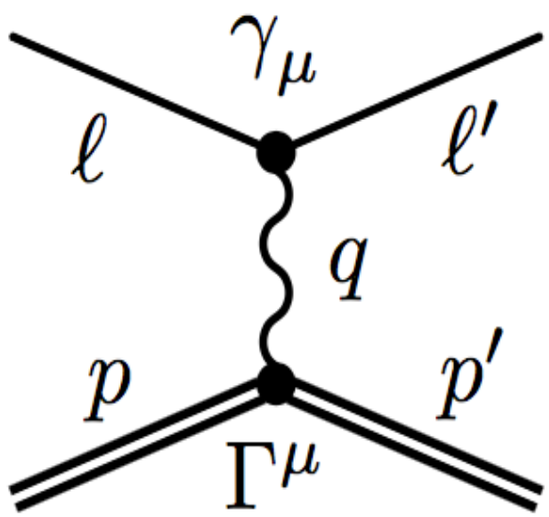
Introduction to ep Scattering

QED theory is perturbative! ➡ Born (One Photon) Approximation!



Electrons (positrons) are an ideal probe for studying the structure of the proton:

- point-like,
- spin 1/2 ,
- purely electromagnetic interaction,
- well described to high precision by QED.

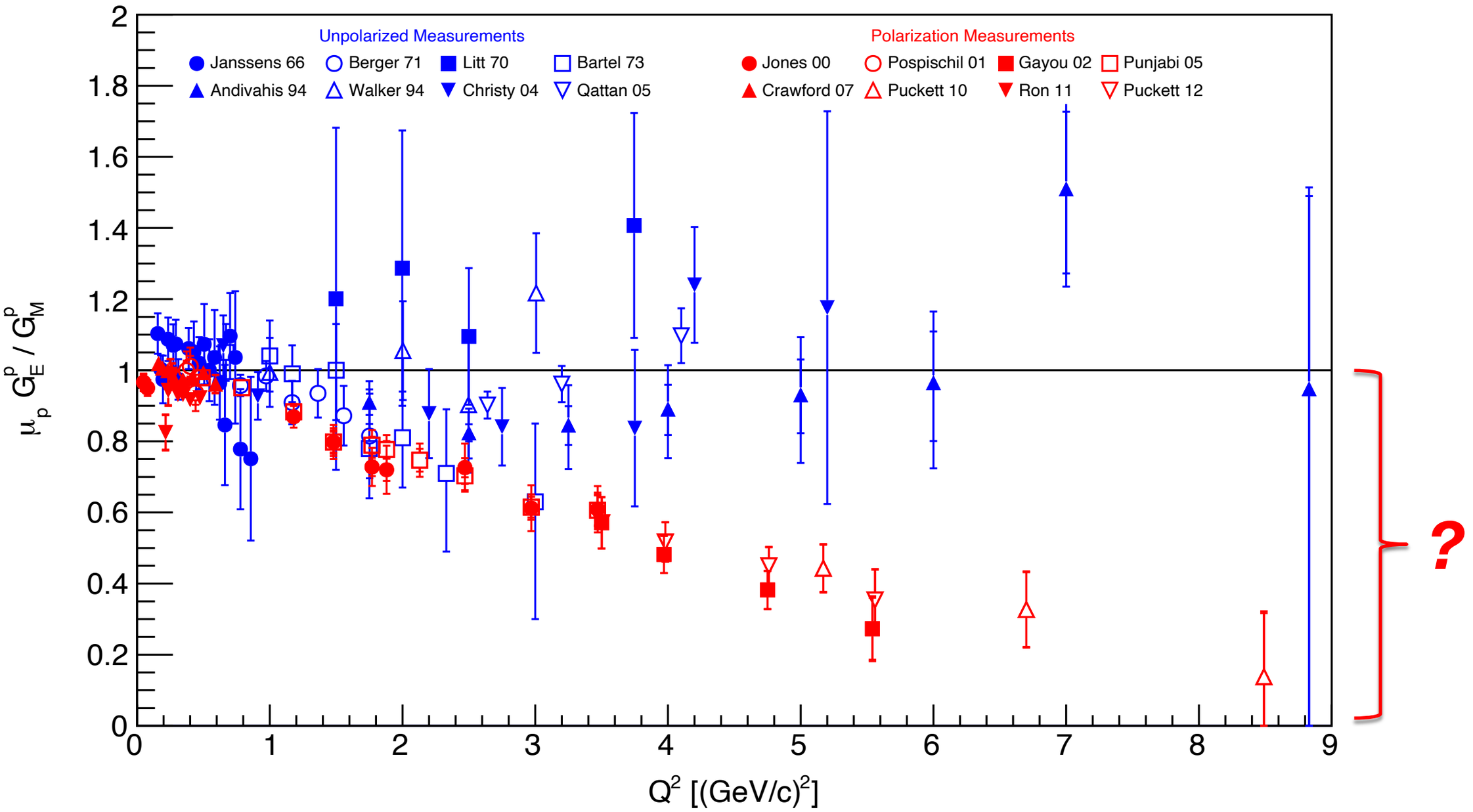
Differential Cross Section is proportional to the scattering amplitude squared:

structure of proton

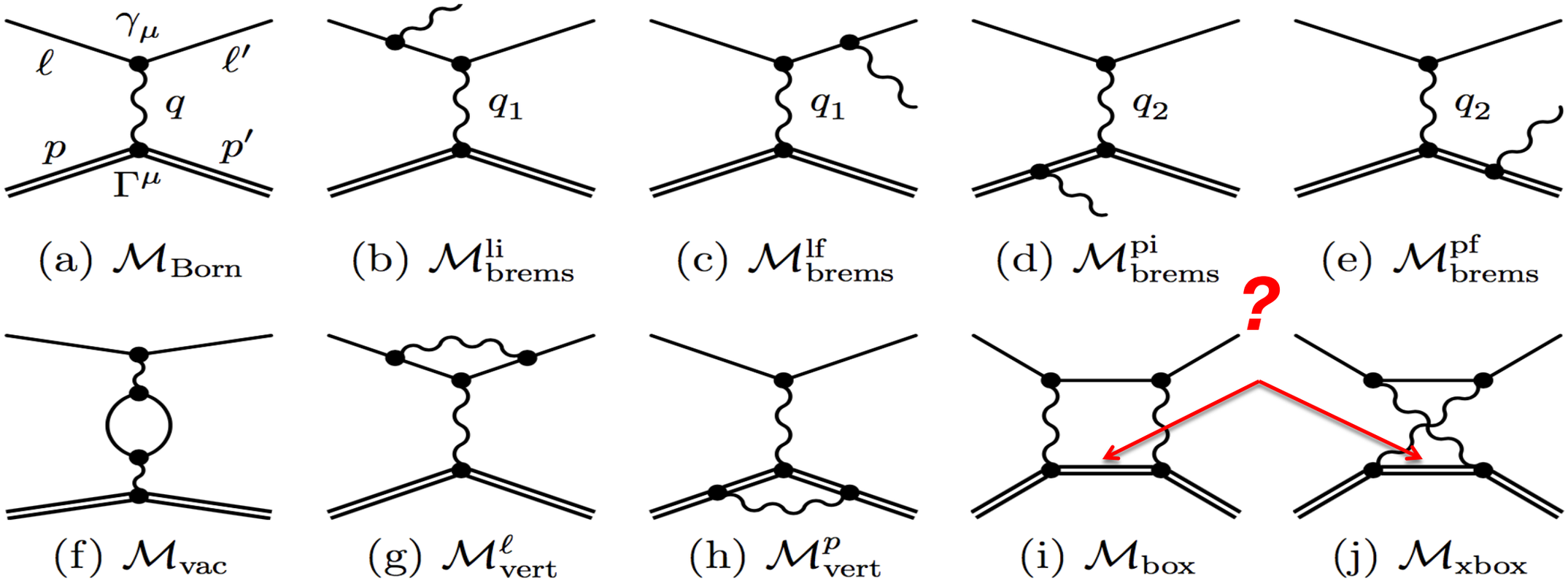
$$\frac{d\sigma}{d\Omega}^{Born} = \left(\frac{\alpha}{4\,m_p Q^2}\frac{E'}{E}\right)\left|M_\gamma\right|^2 = \frac{d\sigma}{d\Omega}^{Mott}\frac{\epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)}{\epsilon\,(1+\tau)}$$

The Proton Form Factor Puzzle

Large Discrepancy at high Q^2



Beyond Born Approximation (L and NL order)



(a) $\mathcal{M}_{\mathrm{Born}}$ (b) $\mathcal{M}^{\mathrm{li}}_{\mathrm{brems}}$ (c) $\mathcal{M}^{\mathrm{lf}}_{\mathrm{brems}}$ (d) $\mathcal{M}^{\mathrm{pi}}_{\mathrm{brems}}$ (e) $\mathcal{M}^{\mathrm{pf}}_{\mathrm{brems}}$

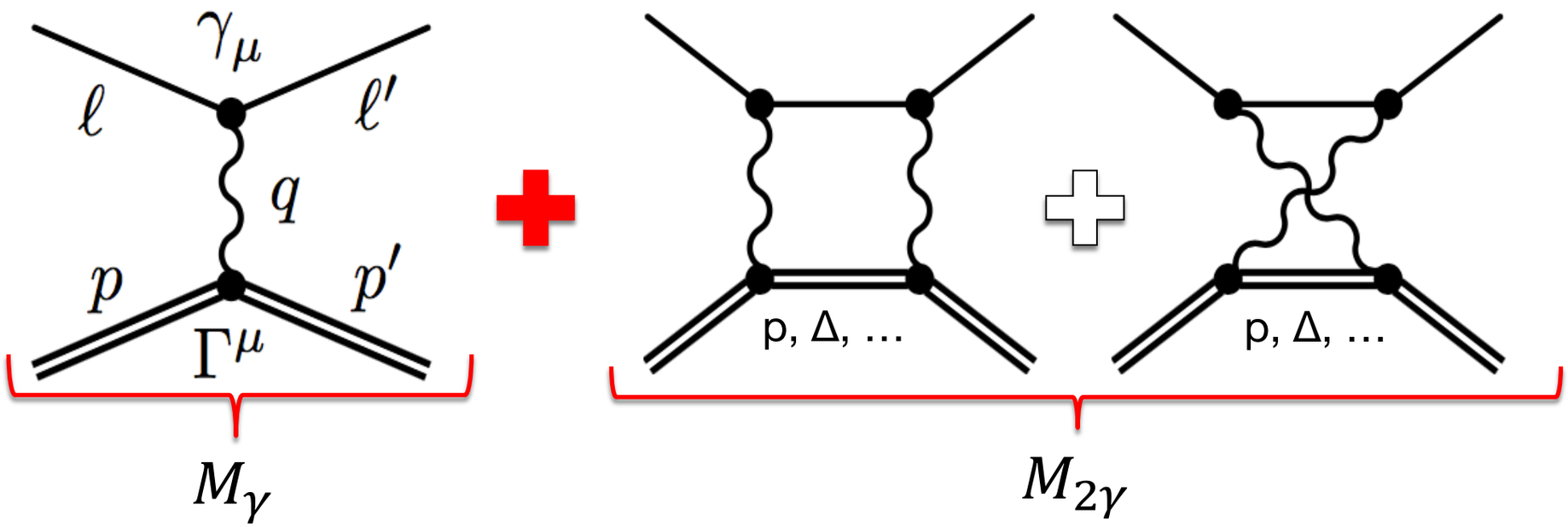
(f) $\mathcal{M}_{\mathrm{vac}}$ (g) $\mathcal{M}^{\ell}_{\mathrm{vert}}$ (h) $\mathcal{M}^{p}_{\mathrm{vert}}$ (i) $\mathcal{M}_{\mathrm{box}}$ (j) $\mathcal{M}_{\mathrm{xbox}}$

$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha}{4m_p}\frac{E'}{E}\right)^2 \left| M_{Born} + \sum_{NL} M_{NL} \right|^2 = \left(\frac{\alpha}{4m_p}\frac{E'}{E}\right)^2 |M_{Born}|^2 \left| 1 + \frac{\sum_{NL} M_{NL}}{M_{Born}} \right|^2$$

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma^{Born}}{d\Omega} \left| 1 + \sum_{NL} \delta_{NL} \right|^2$$

Proposed Explanation: Two-Photon Exchange (TPE)

Two Photon Exchange ***(TPE)*** is the next-to-leading order correction that depends on nucleon structure:



- "soft" TPE correction is included in calculations:
  ⇨ removes the divergence term from bremsstrahlung correction.
- "hard" TPE is difficult to calculate:
  intermediate state (p, Δ, …) ⇨ model dependent!

$$\delta_{2\gamma} = \frac{2\mathrm{Re}(M_\gamma^{\ *} M_{2\gamma})}{\left|M_\gamma\right|^2}$$

Need to measure "hard" TPE

Direct Measurement of TPE

The differential cross section of elastic lepton-proton scattering is proportional to the square of the matrix element:

$$\frac{d\sigma}{d\Omega} \propto |M|^2 = |M_{Born} + M^l_{brems} + M^p_{brems} + M_{virtual} + M_{2\gamma}|^2$$

Considering only terms up to 4^{th} order:

$$\frac{d\sigma}{d\Omega} \propto [M_{Born}]^2 + \left[M^l_{brems}\right]^2 + 2\Re\left[(M^l_{brems})^\dagger M^p_{brems}\right] + \left[M^p_{brems}\right]^2 + \\ + 2\Re\left[M^\dagger_{Born} M_{virtual}\right] + 2\Re\left[M^\dagger_{Born} M_{2\gamma}\right] + \mathcal{O}(\alpha^4)$$

The sign of a QED vertex $(= -iQ|e|\gamma^\mu)$ depends on the change of the lepton that scatters off the proton.

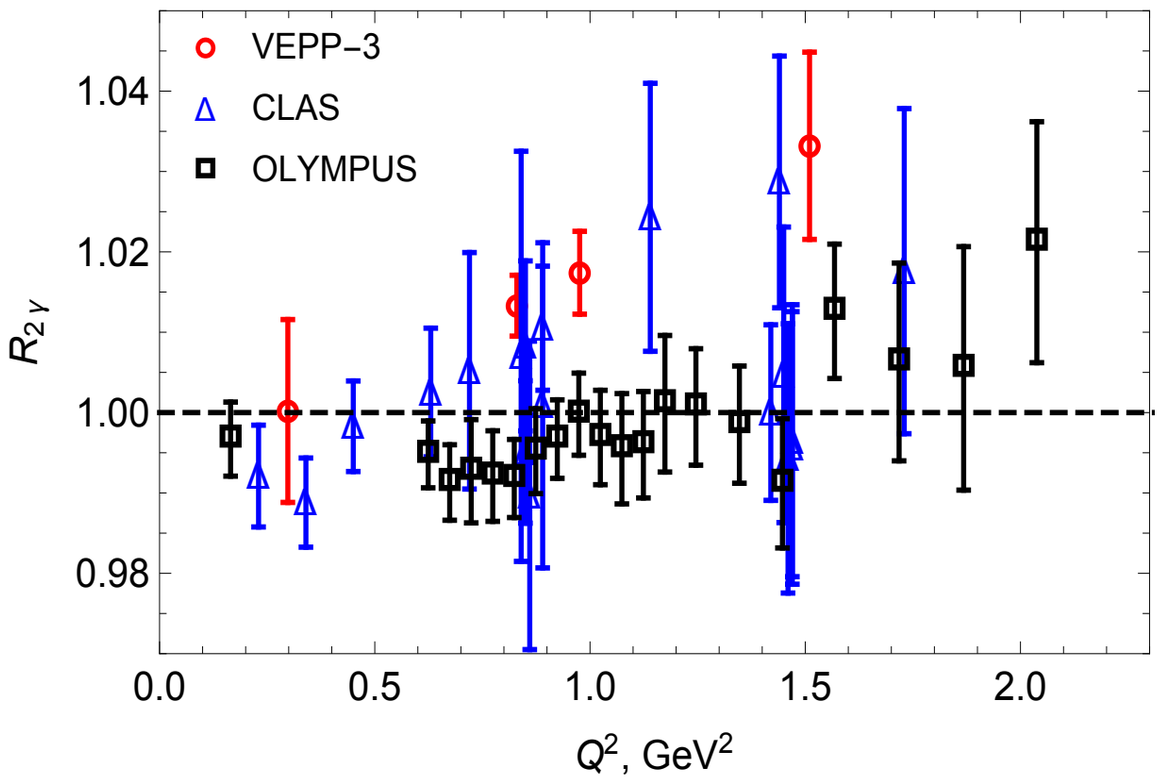
Cross Section Ratio:

$$R = \frac{\sigma(l^+p)}{\sigma(l^-p)} = \frac{1 + \delta_{even} - \delta_{2\gamma} - \delta_{brems}}{1 + \delta_{even} + \delta_{2\gamma} + \delta_{brems}} \approx 1 - 2 \cdot \frac{\delta_{2\gamma} + \delta_{brems}}{1 + \delta_{even}}$$

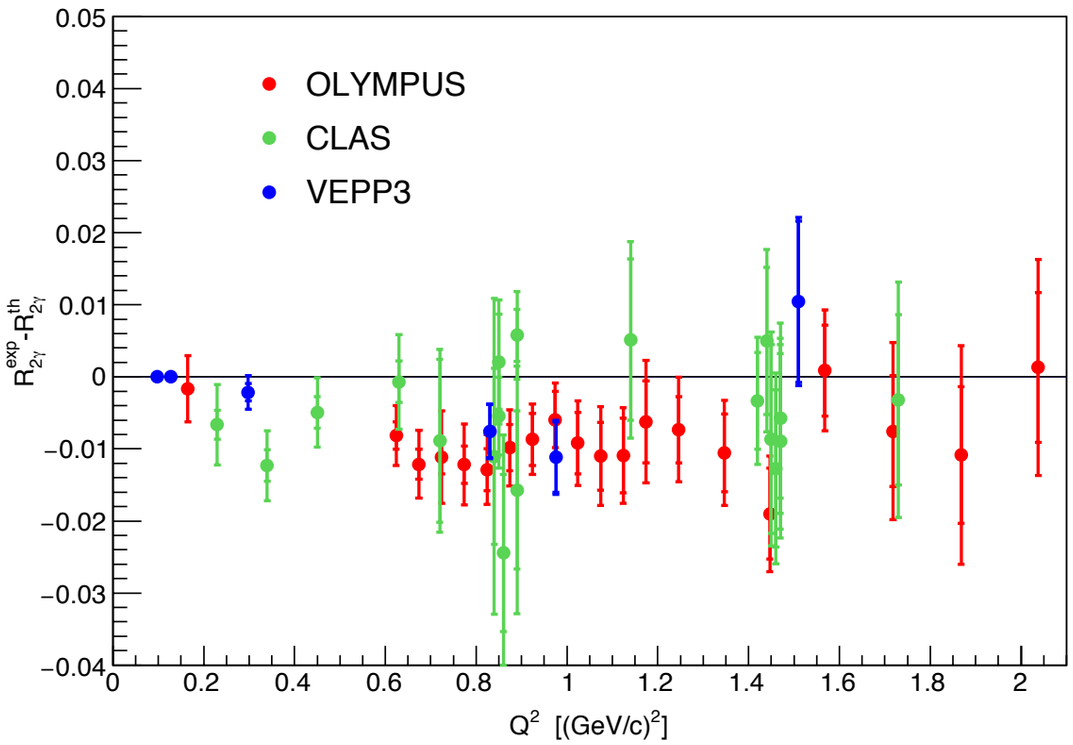
!

Recent Experimental Results Overview

Recent Experiments $Q^2 < 2.1$ (GeV/c)^2:



Difference with respect to Blunden ND vs Q^2

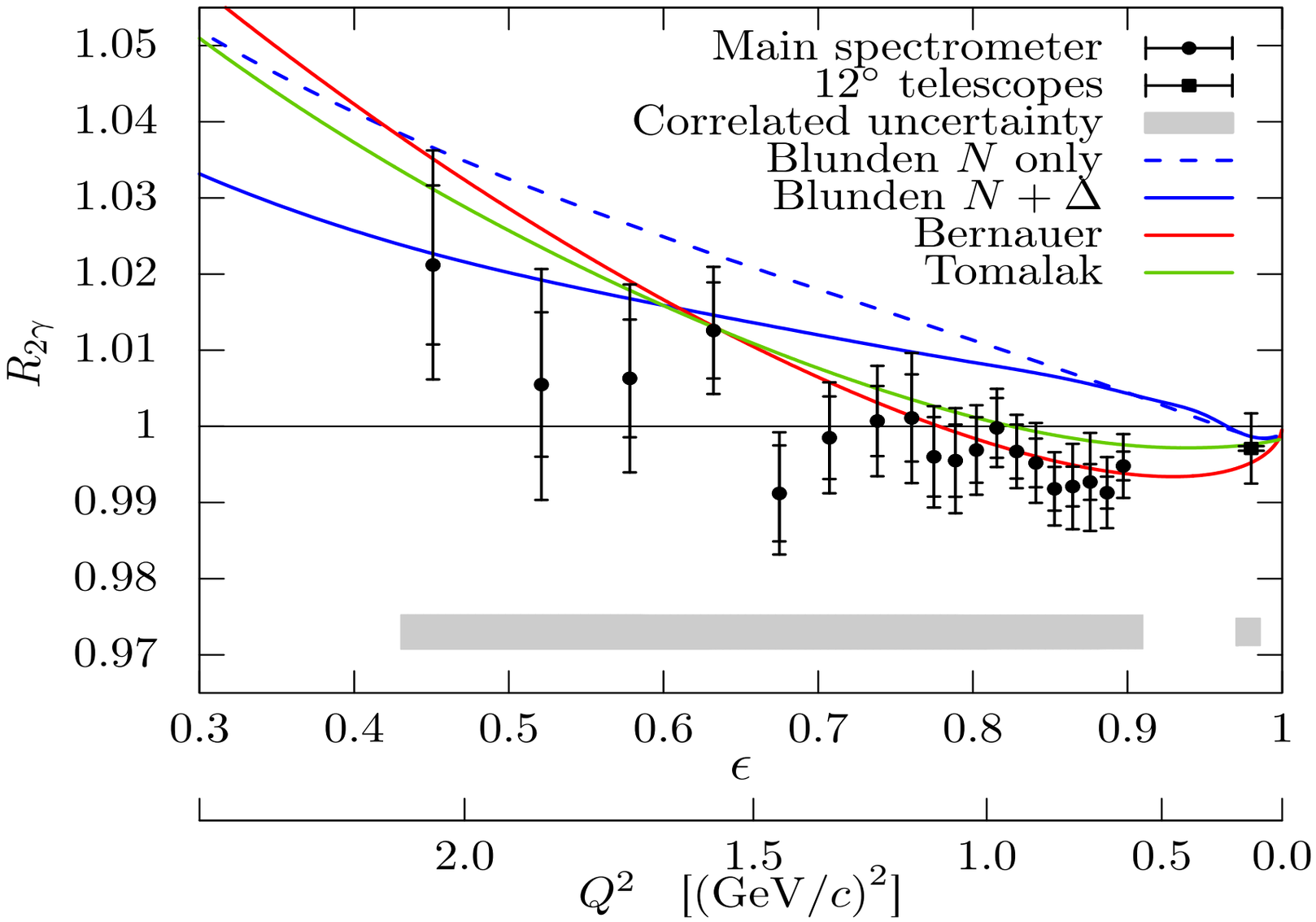


- VEPP – 3 (Novosibirsk, Russia, 2009);
- CLAS TPE experiment (Jefferson Lab's Hall B, USA, 2015);
- OLYMPUS (DESY, Germany, 2016);

$$R_{2\gamma} = \frac{\sigma_{e^+p}}{\sigma_{e^-p}}$$

OLYMPUS Results

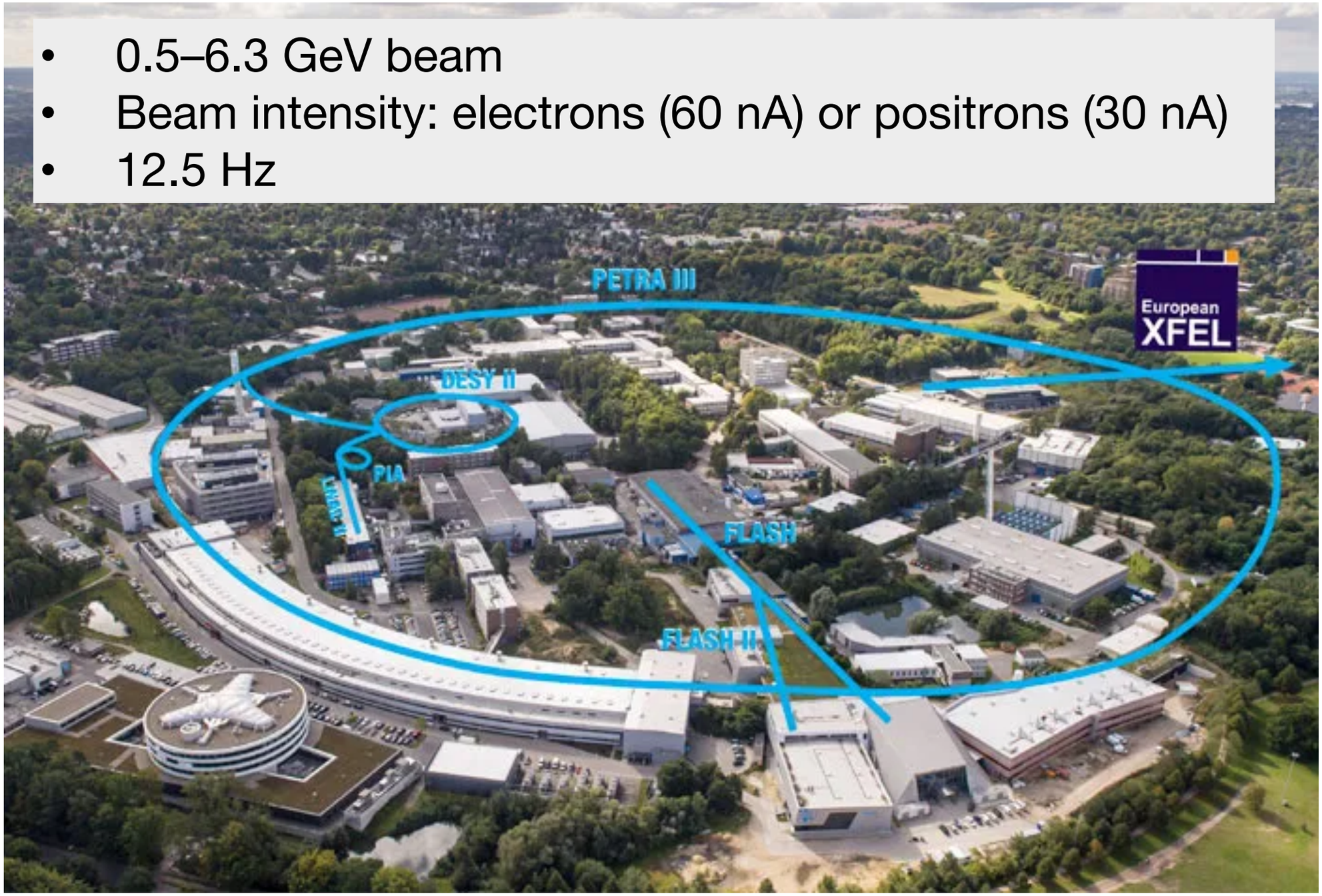
- Region $Q^2 < 1$ GeV^2 not understood in terms of QED theory
- Further theoretical effort needed Experiments at higher energy required.



[B. Henderson et al. Phys. Rev. Lett. 118 092501 (2017)]

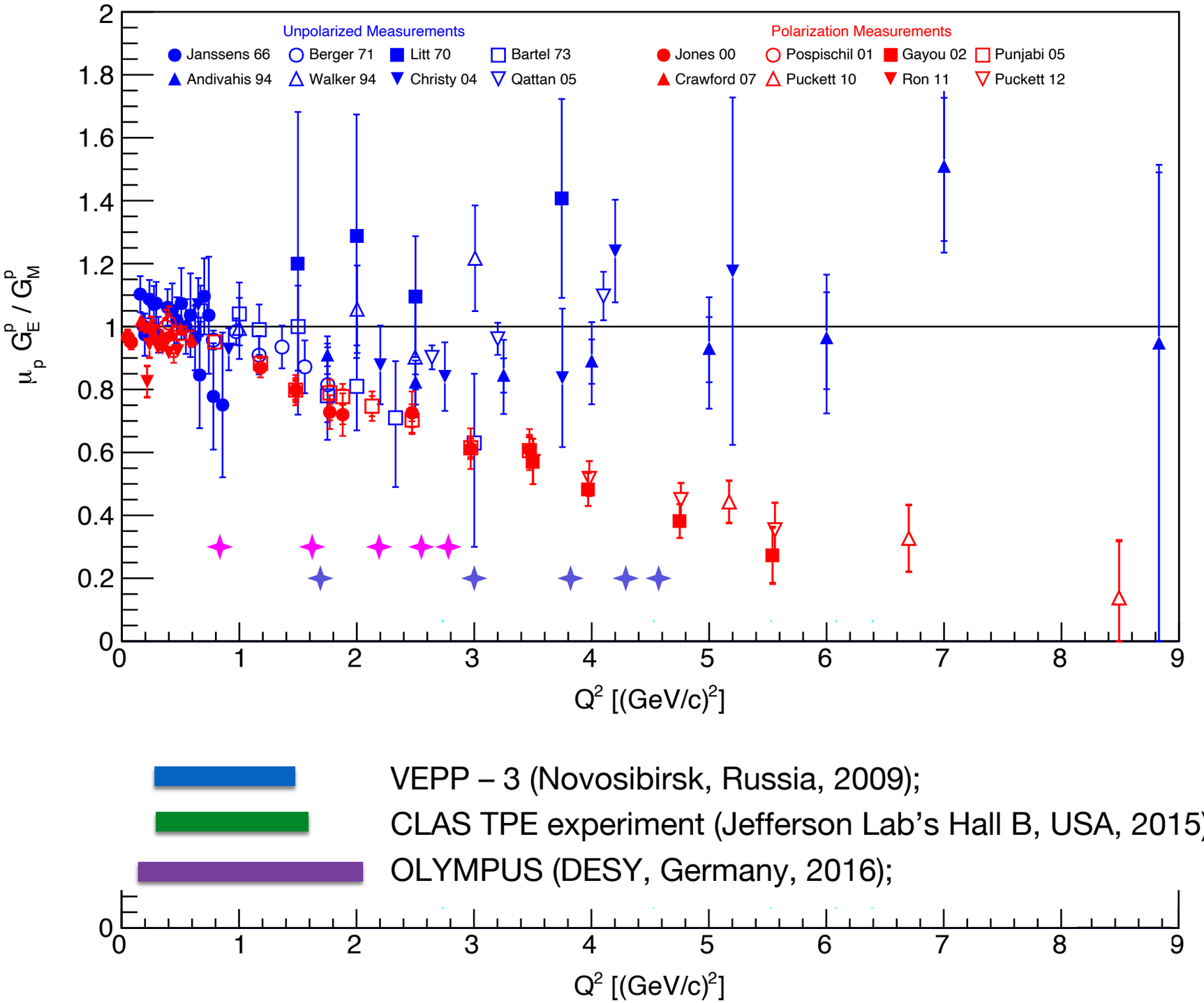
The *T*wo-*P*hotons *E*xchange e*X*periment @ DESY

- 0.5–6.3 GeV beam
- Beam intensity: electrons (60 nA) or positrons (30 nA)
- 12.5 Hz



DESY the only facility with intense electron and positron beams!

The Proton Form Factor Puzzle and TPEX



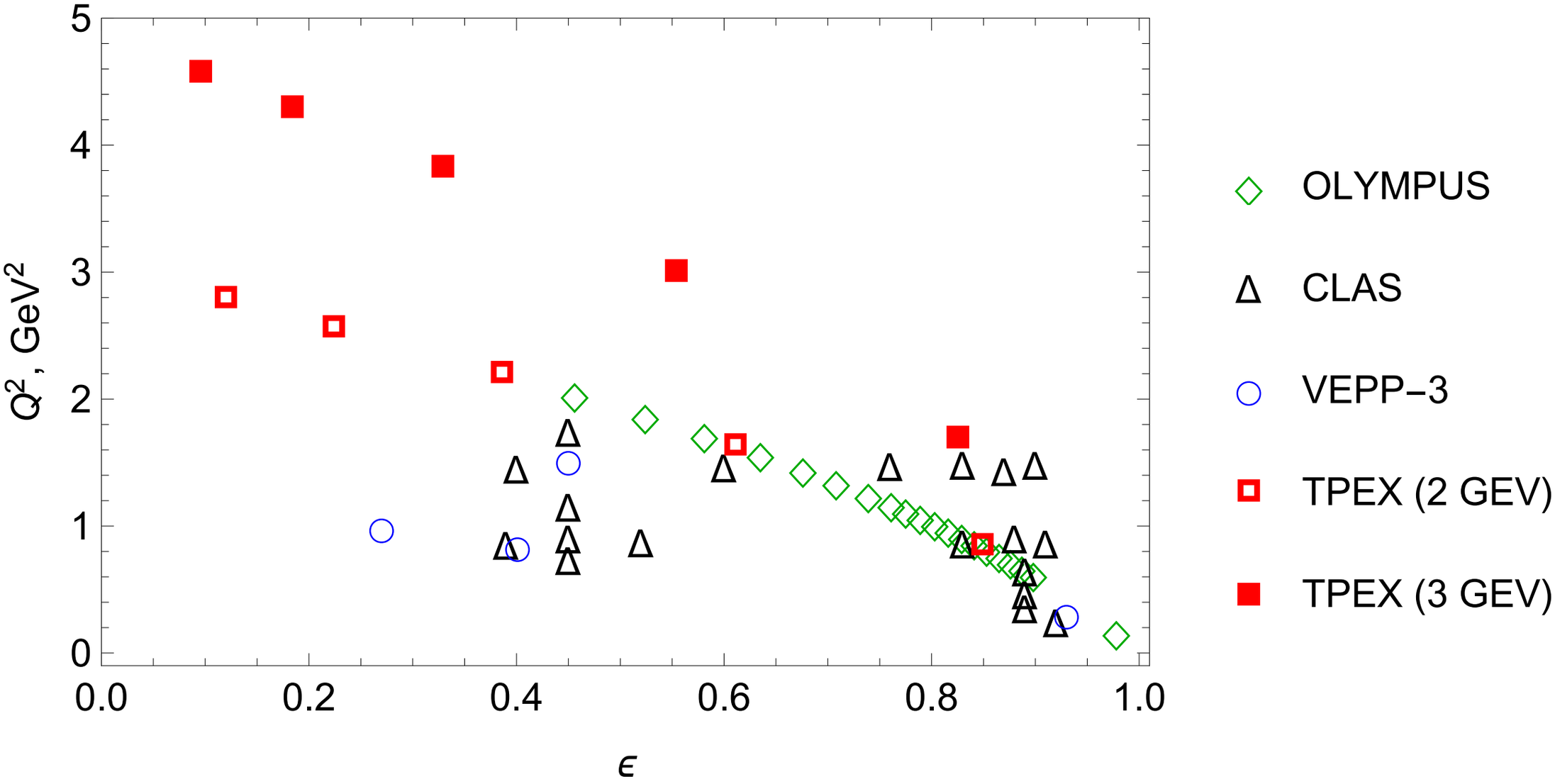
$$R_{2\gamma} = \frac{\sigma_{e^+p}}{\sigma_{e^-p}}$$

Future of TPEX:

- TPEX(2 GeV): $Q^2 < 2.7$ (GeV/c)^2
- TPEX(3 GeV): $Q^2 < 4.6$ (GeV/c)^2

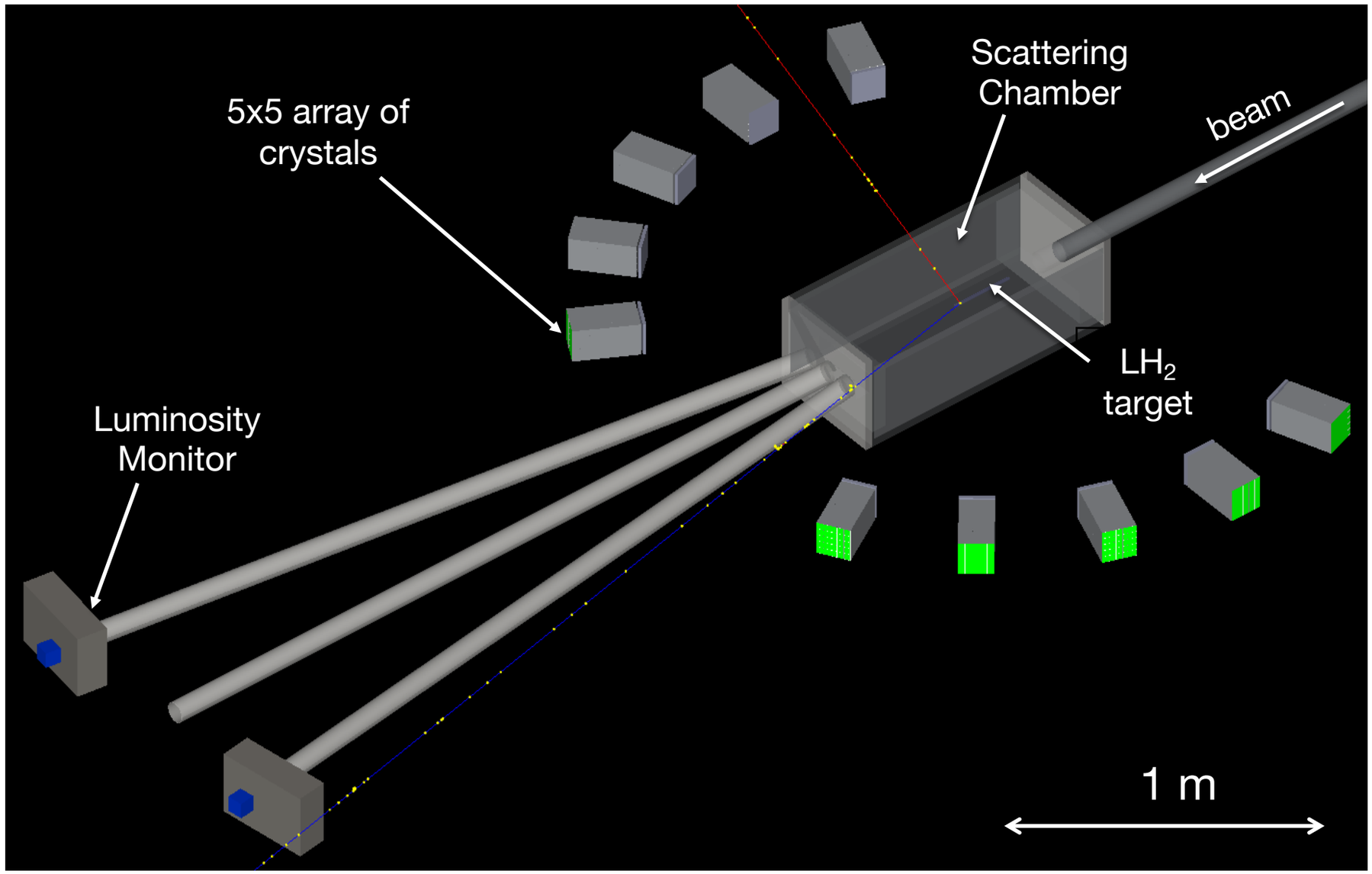
Recent TPE Experiments: $Q^2 < 2.1$ (GeV/c)^2

TPEX Kinematic Coverage



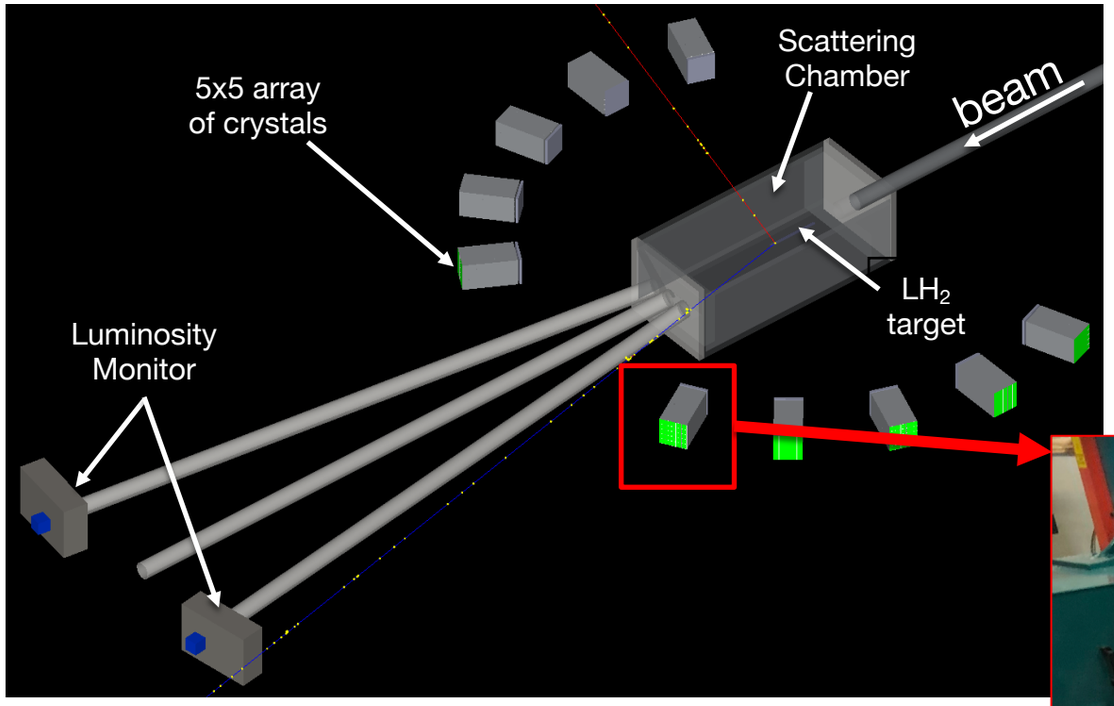
- Commission @ 2 GeV beam (2 weeks): $Q^2 \leq 2.7$ (GeV/c)^2 .
- Run @ 3.0 GeV beam (6 weeks): $Q^2 \leq 4.57$ (GeV/c)^2.

TPEX Apparatus



- Scattering: 5x5 arrays Calorimeter at 30°, 50°, 70°, 90°, and 110°.
- Beam Luminosity: Luminosity Monitor (Quartz Cherenkov Counter)

TPEX Apparatus: 5x5 Calorimeter (MIT)



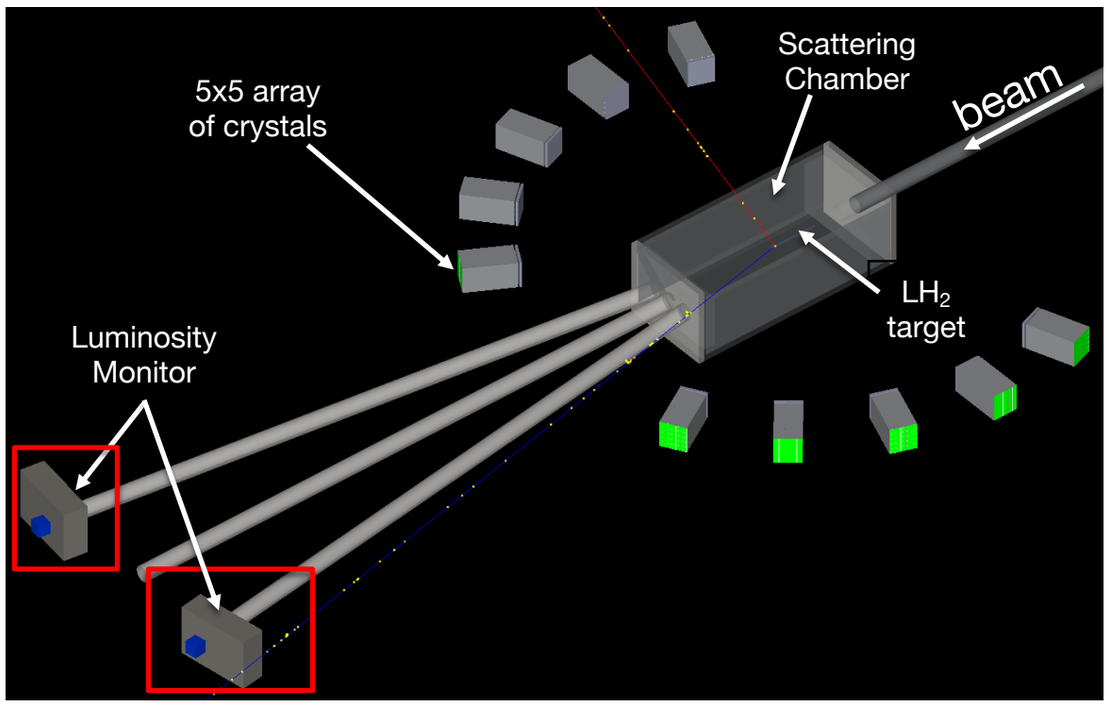
[credit to Douglas K. Hasell - MIT]

- 10 detectors of 5 × 5 calorimeters (PbWO4).
- Density: ρ=8.3g/cm^3

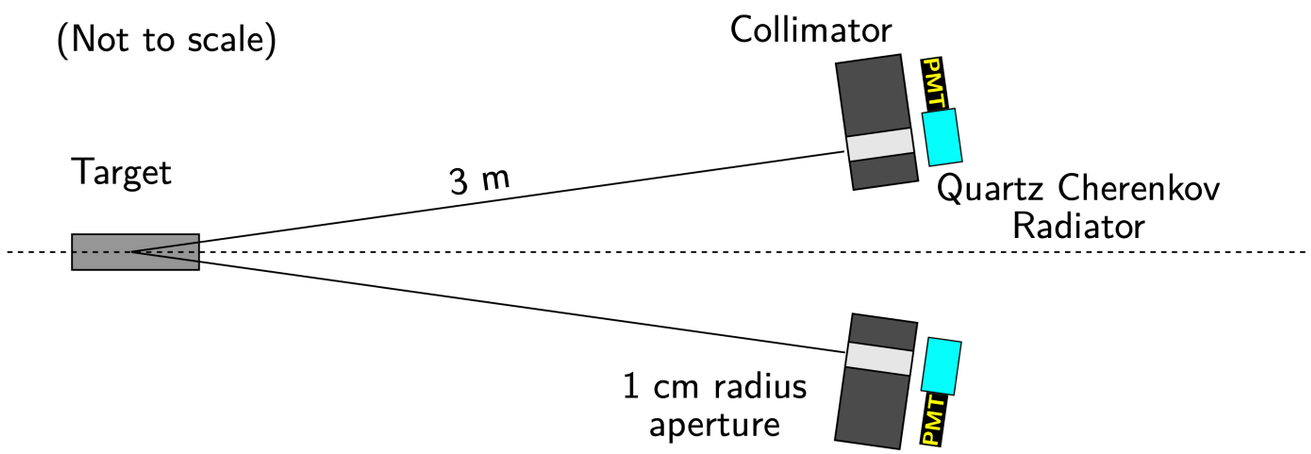
  ⇒ 2×2×20 cm^3 crystal=0.664kg.
- energy loss dE/dx = 10.2 MeV/cm.
- Moliere radius = 1.959 cm.

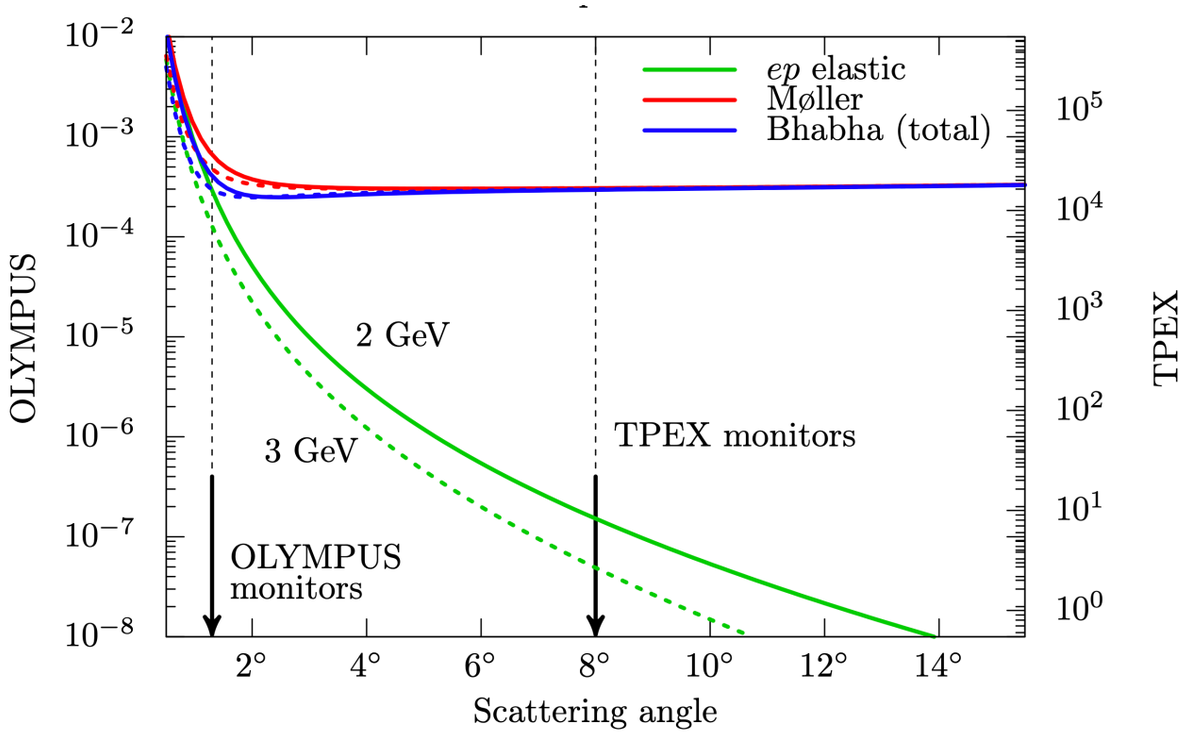
TPEX Test Calorimeter 5×5 version:

TPEX Apparatus: Luminosity Monitor (GWU)



[credit to Axel Schmidt - GWU]





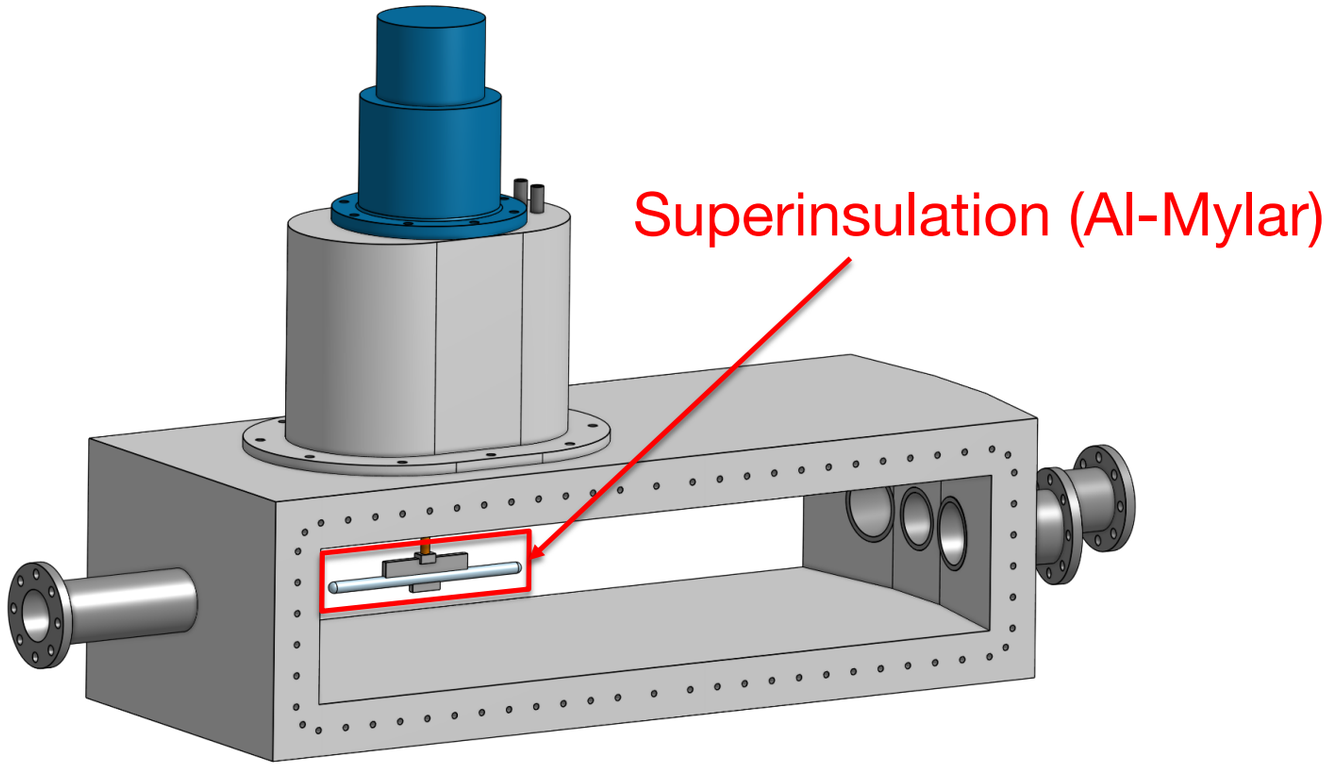
TPEX luminosity systematics:

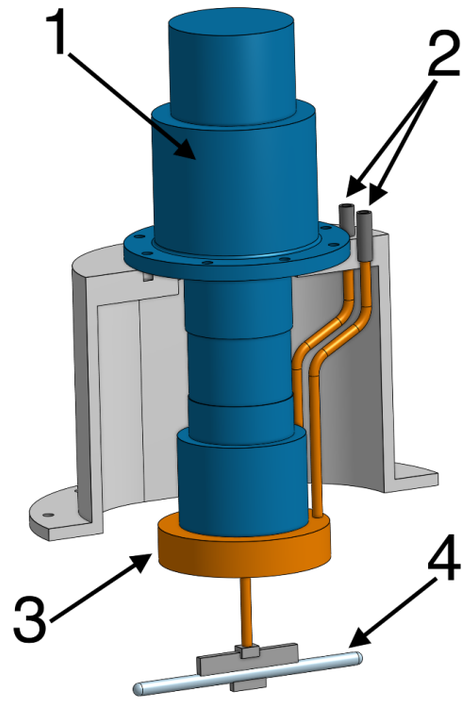
- Magnetic Field → not relevant
- Beam position: ~ 1/ sin θ

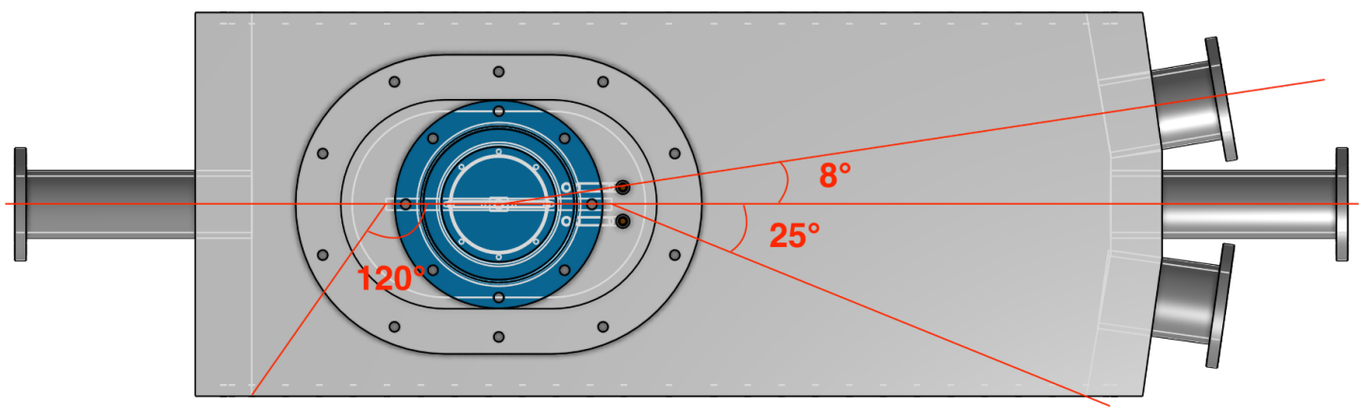
  (0.21± 0.01 %/mm)
- Monitor position: ~ 1/ sin θ

  (0.0235 ± 0.0004 %/mm)

TPEX Apparatus: Vacuum Chamber (UMICH)



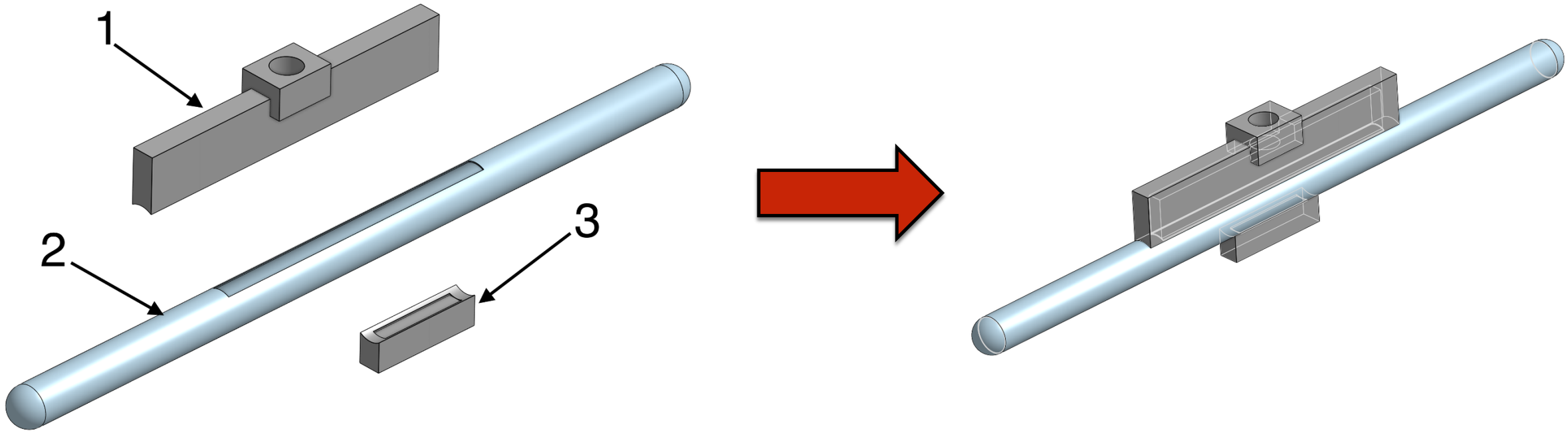




1. CH110-LT cryocooler (25 W at 20 K)
2. hydrogen supply and exhaust lines
3. condenser with a cooling loop
4. target cell

Total heat load (Radiation + Beam) < 4 W

TPEX Apparatus: LH_2 Target (UMICH)



1. top block with liquid hydrogen **level sensor**;
2. **target cell** with long channel on top to help the release of bubbles from LH_2;
3. bottom block with **temperature sensor** and **heater**

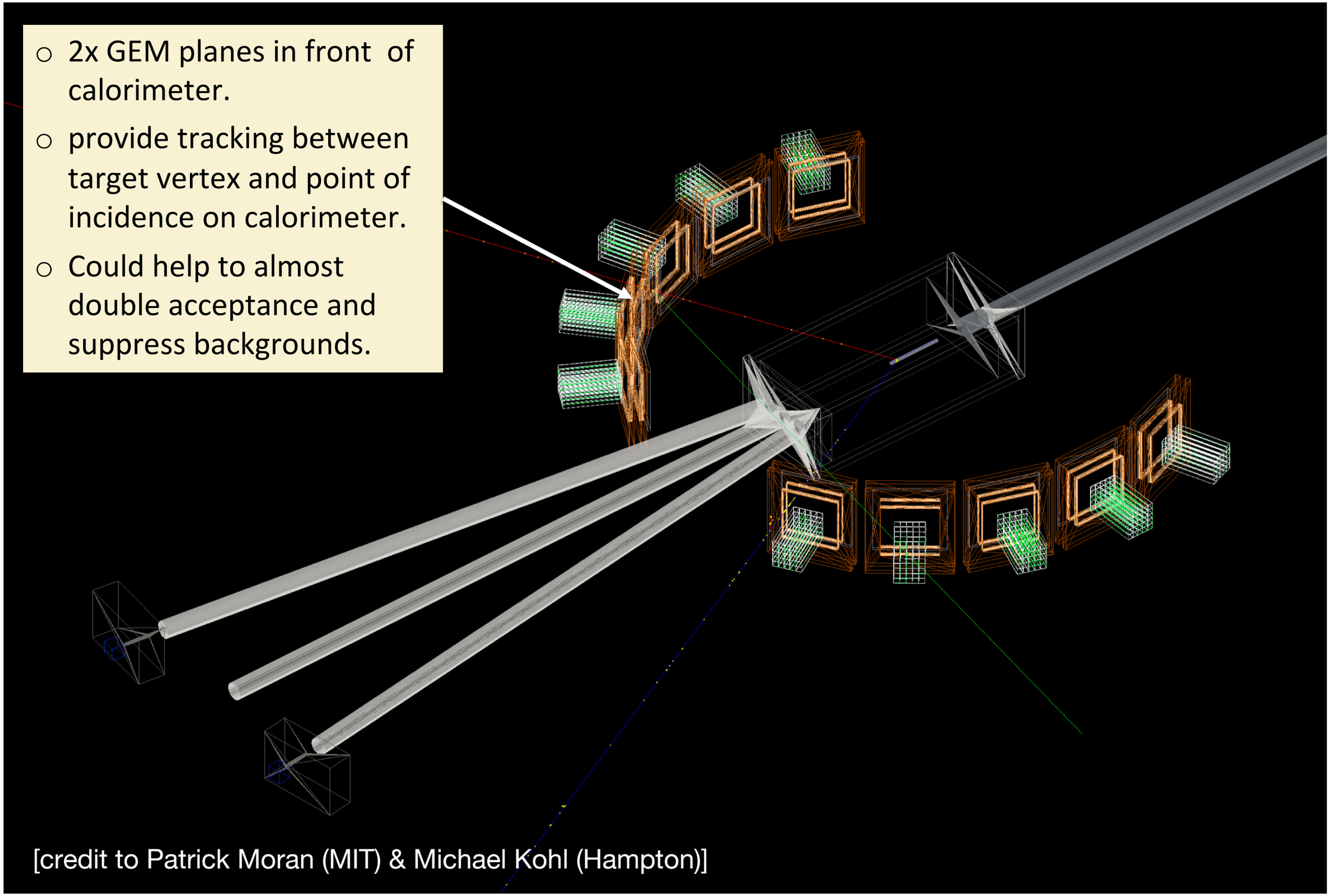
$Q^2 \leq 4.57$ (GeV/c)^2 requires LH_2 target:

- max beam current:
  60 nA (e–), 30 nA (e+)
- 20-cm long LH2 target:
  L_{avg} = 2.1×10-4 fb-1·s-1 (~200 x OLYMPUS)

all components are made of aluminum!

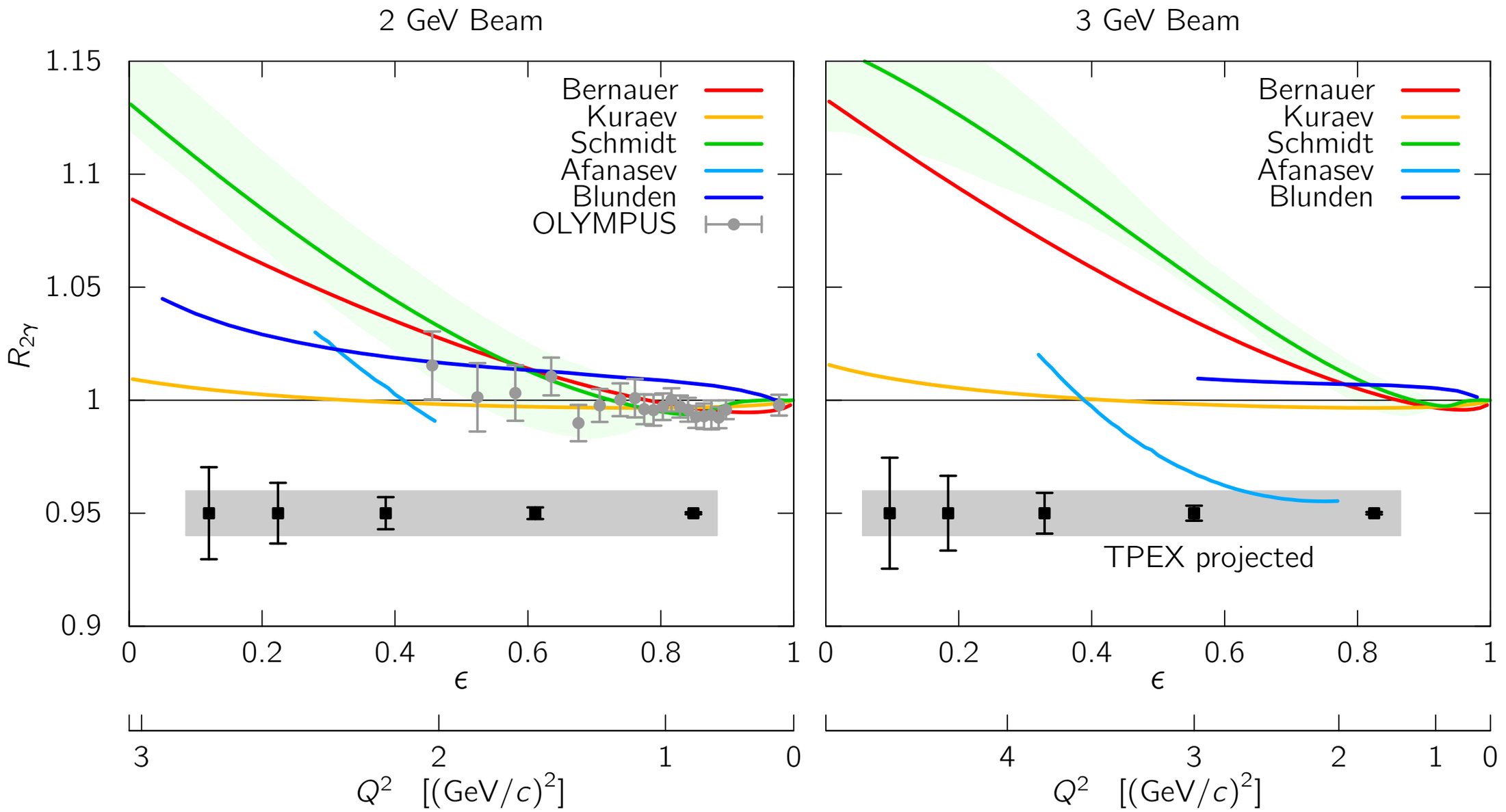
Further TPEX Design Upgrade: GEMs (Hampton)

- 2x GEM planes in front of calorimeter.
- provide tracking between target vertex and point of incidence on calorimeter.
- Could help to almost double acceptance and suppress backgrounds.



[credit to Patrick Moran (MIT) & Michael Kohl (Hampton)]

TPEX Expectations/ Uncertainties



TPEX Collaboration - 15 Institutions, 40 Collaborators (13 OLYMPUS)

- Arizona State University, Tempe, AZ, USA
- Catholic University of America, Washington, DC, USA
- Charles University, Prague, Czech Republic
- Deutsches Elektronen-Synchrotron, Hamburg, Germany
- Friedrich Wilhelms Universitat, Bonn, Germany
- George Washington University, Washington, DC, USA
- Hampton University, Hampton, VA, USA
- Johannes Gutenberg Universitat, Mainz, Germany
- Massachusetts Institute of Technology, Cambridge, MA, USA
- Riken BNL Research Center, Upton, NY, USA
- Stony Brook University, Stony Brook, NY, USA
- University of Glasgow, Glasgow, Scotland
- University of Michigan, Ann Arbor, MI, USA
- University of Zagreb, Zagreb, Croatia
- University of Manitoba, Winnipeg, Canada

Thank you!