



University
of Glasgow



ZERO-DEGREE SPECTROMETER FOR μ CLAS12

μ CLAS12 Experiment workshop

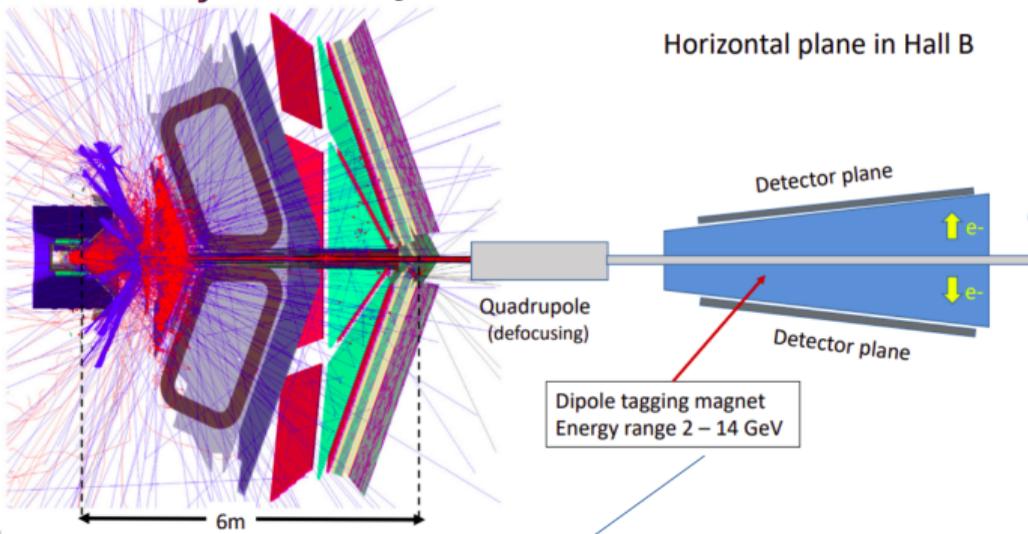
Derek Glazier
University of Glasgow

9th March 2026

* Derek.Glazier@Glasgow.ac.uk

Zero Degree Spectrometer

Courtesy: Burkert JFUTURE, Messina.

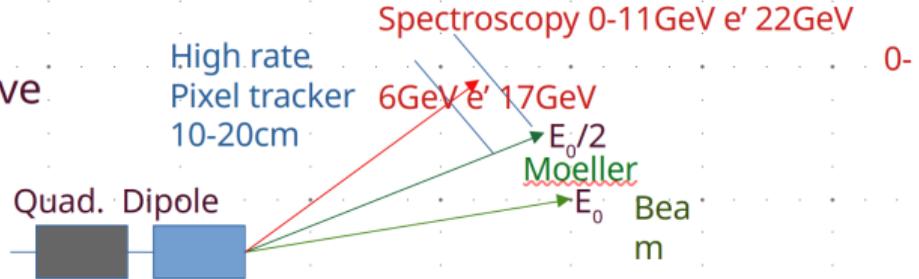


- Non-interacting electrons, Moller electrons, bremsstrahlung; electrons leave only accidental energy in CLAS12 detectors.
- Hadronically interacting electrons leave significant amount of energy and tracks in CLAS24, $O(10\text{GeV})$.
- The strategy would be to trigger on the event measured in CLAS24 detectors and tag those events with electrons measured in a 0-degree spectrometer.
- This should be studied in simulations to determine what magnitude in instantaneous luminosity can be achieved.
- Note that the Torus magnet open bore of $\sim 4\text{ cm}$ accommodates $\sim 0.5^\circ$ scattering angle without interfering materials. * have assumed here can be increased to 0.75°

High low energy threshold
Will reduce results shown
Here, particularly for 17GeV

Alternative

CLAS12



EPIC LOWQ2-TAGGER

EIC ePIC Low- Q^2 Tagger

- For precise measurements of photoproduction and vector mesons.
- Extends central detector reach down to effectively $Q^2 = 0$.
- Located after first group of beamline magnets.
- Scattered electrons follow a unique path through magnetic optics.
- 4-momentum of virtual photon interaction can be inferred.

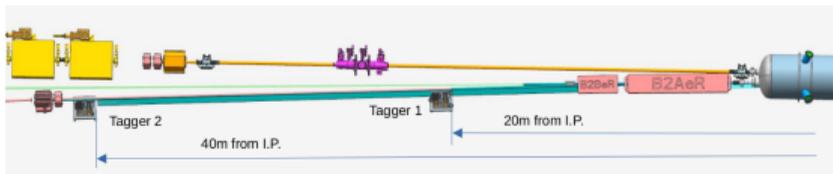


Figure 1: ePIC Low- Q^2 Tagger in Far Backward region.

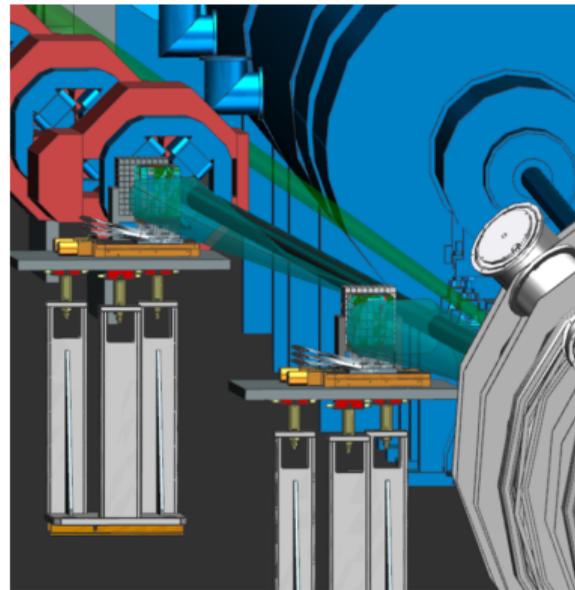


Figure 2: 2 Tagger stations beside the outgoing beamline.

Tagger Design

- Two tagger stations covering different energy ranges.
- Tracker consisting of 4 layers of Timepix4 detectors.
- Detector layer consisting of tiled Timepix4 ASICs using TSV.
- SPIDR4 readout.

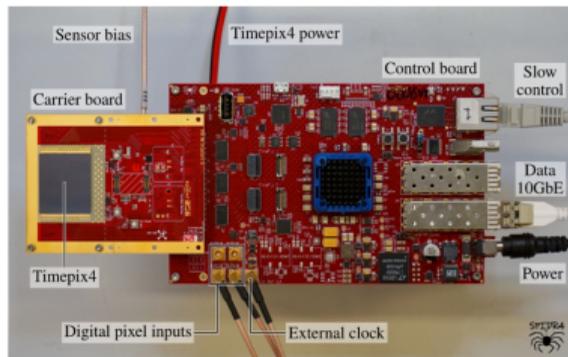


Figure 3: SPIDR4 readout - K. Heijhoff et al 2022

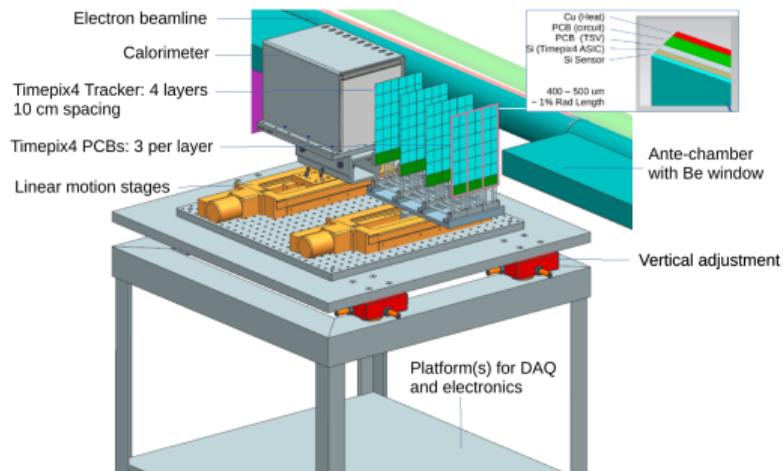
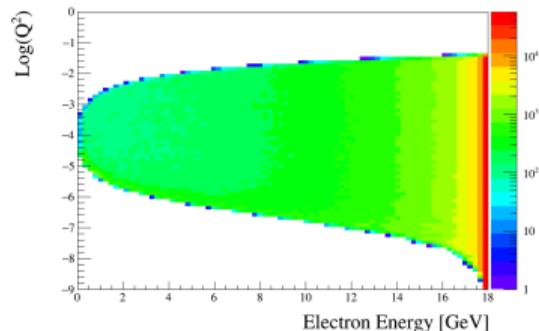


Figure 4: CAD model of a tagger station

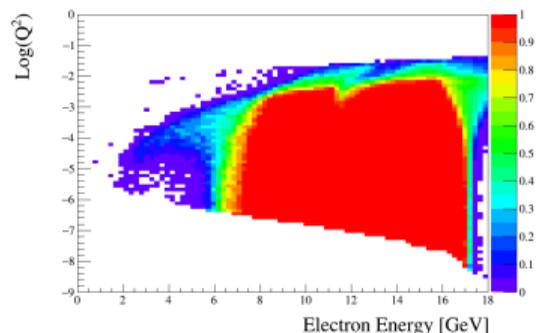
ACCEPTANCE, EFFICIENCY & RESOLUTION

Detector acceptance

Events - Theta < 10 mrad



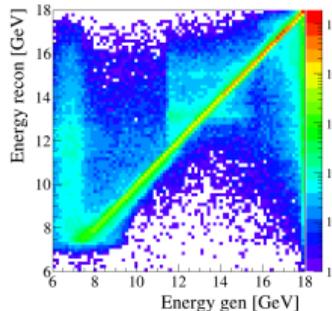
Acceptance



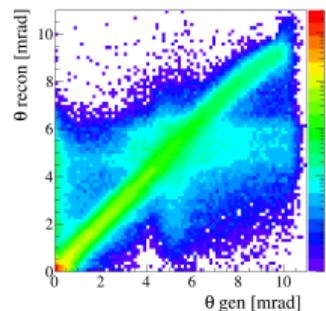
Integrated efficiency = 29%

Kinematic reconstruction (using neural network)

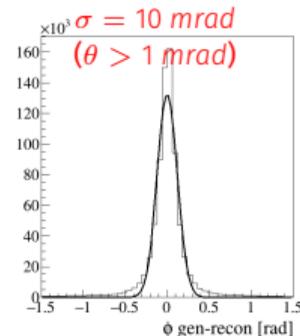
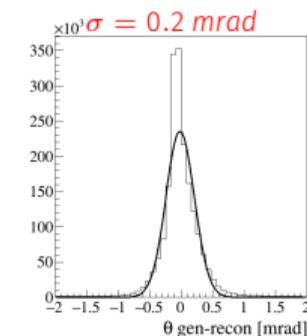
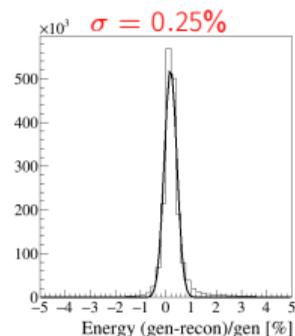
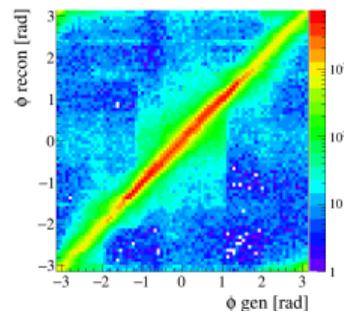
Energy Reconstruction



Theta Reconstruction



Phi Reconstruction (Theta > 1 mrad)



Resolutions

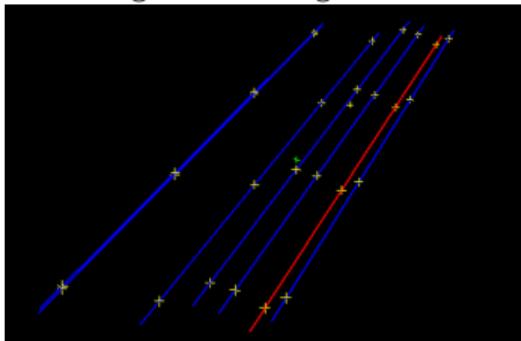
In vacuum tracker and reconstruction technique provides better energy resolution than baseline calorimeter with improved θ and ϕ .

Typical bunch crossing (18x275 maximum luminosity)

Contains ~ 12 electrons

~ 7 are accepted by Tagger 2

Clustering and tracking: 95% reconstruction efficiency



e^- from Quasi-Real scattering event among e^- from Bremsstrahlung

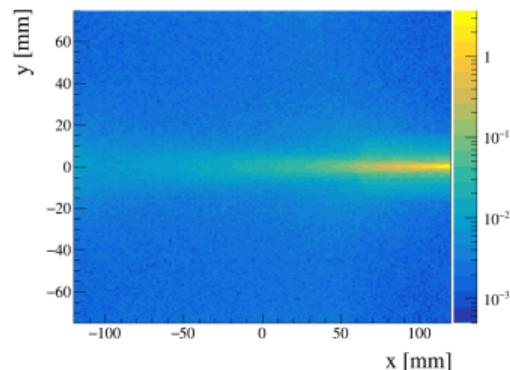
Rates

Maximum rate per $55\mu\text{m}$ pixel: 20 kHz

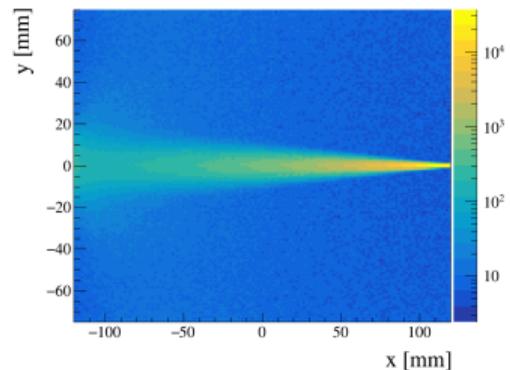
Maximum pixel rate per layer from MIPs: 2.5 GHz

At 64 bits per pixel = 320Gb/s. (Big but Timepix4 + SPIDR4 can do this)

Tagger 2 QR Hit Distribution [Hz/ $55\mu\text{m}$ pixel]



Tagger 2 Brem Hit Distribution [Hz/ $55\mu\text{m}$ pixel]



Hybrid pixel detector: Timepix ASIC + Sensor (Si)
 55 μm pixel pitch
 <1 ns timing resolution (Si limit)

Characteristic	Value
Technology	65 nm - 10 metal
Pixel size	55 x 55 μm
Sensor size	512 x 448 pixels, 4-side buttable
Sensitive area	6.94 cm ² (2.47 x 3.0 cm)
Packet size	64 bits
Readout method	data driven
Maximum rate / unit area	3.58 x 10 ⁶ hits / mm ² / s
Maximum rate / pixel	10.8 kHz / pixel
ToT Energy resolution	< 1 keV
Time resolution	195 ps
Readout bandwidth	163.84 Gb/s (16 x 10.24 Gb/s)

Table 3.66: Timepix4 ASIC characteristics. [176]

Store only MIPS clusters (x,y,time,energy,width) = **80 bits**

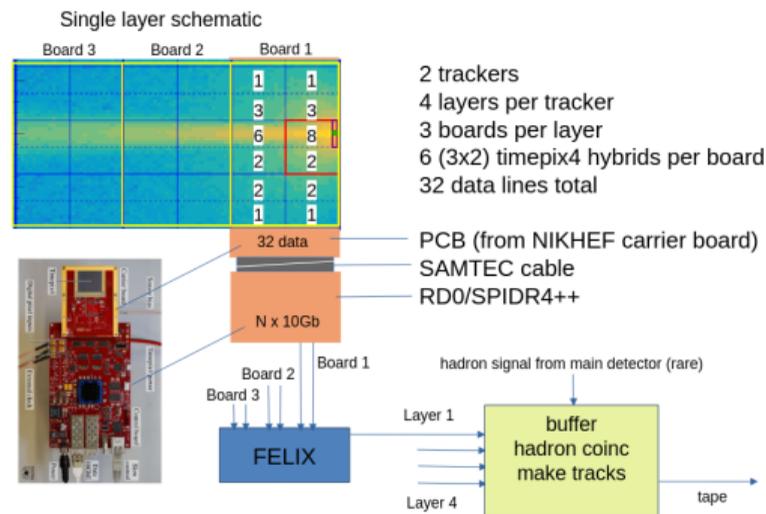
2 tagger modules, 4 layers

~200 Gb/s to DAQ

~1.5 Gb/s to disk, **DAQ trigger rate 500kHz**

Timepix4 + SPIDR4 an **off-the-shelf** solution

Next-gen sensors improve on Si timing limit: **i-LGAD** (link)



SPIDR4: <http://www.nikhef.nl/s01/SPIDR4-MF-GP-apr2020.pdf>

SPIDR4 DAQ: <https://indico.cern.ch/event/1215762/contributions/5137274/>

Timepix4: X. Llopert et al 2022 JINST 17 C01044

Hybrid pixel detector: Timepix ASIC + Sensor (Si)

55 μm pixel pitch

<1 ns timing resolution

Characteristic
Technology
Pixel size
Sensor size
Sensitive area
Packet size
Readout method
Maximum rate / unit area
Maximum rate / pixel
ToT Energy resolution
Time resolution
Readout bandwidth

Table 3.66: Timepix4

Store only MIPS clusters

2 tagger modules, 4 layers

~ 200 Gb/s to DAQ

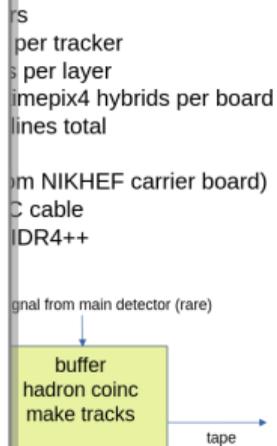
~ 1.5 Gb/s to disk, DAQ trigger rate 500kHz

Timepix4 + SPIDR4 an off-the-shelf solution

Next-gen sensors improve on Si timing limit: [i-LGAD \(link\)](#)

Glasgow Timepix4 Working Group

- Members of **Medipix** collaboration (required for using Timepix)
- **Simon Gardner** (lead)
- **Ken Livingston**(coordinator)
- **Derek Glazier**
- **Gary Penman** (hardware tests and simulations)
- **Richard Tyson** (tracking and machine learning)



F-GP-apr2020.pdf
 contributions/5137274/

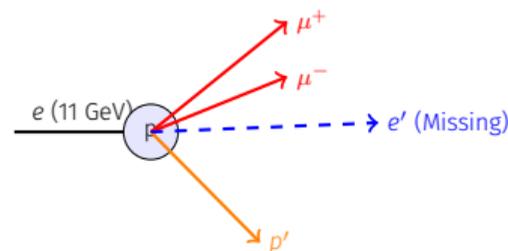
timepix4, X. Clouparet et al 2022 jinst 17 C01044

ZERO DEGREE SPECTROMETER FOR
 μ CLAS12

Reaction J/ψ & DDVCS: $ep \rightarrow e' \mu^+ \mu^- (p')$

- **Detected:** Scattered electron (e') in the new $PbWO_4$ calorimeter and the muon pair ($\mu^+ \mu^-$) in the forward spectrometer.
- **Inferred:** The recoil proton (p') is "missing" and identified through **Missing Mass analysis**:

$$M_X^2 = (k + p - k' - p_{\mu^+} - p_{\mu^-})^2 \approx M_p^2$$



Baseline μ CLAS12 utilizes missing particle analysis to fix kinematics.

Reaction TCS: $ep \rightarrow p' \mu^+ \mu^- (e')$

- **Detected:** The recoil proton (p') in the central recoil tracker and the muon pair ($\mu^+ \mu^-$) in the forward spectrometer.
- **Inferred:** The scattered electron (e') is "missing." Its kinematics are deduced via **Missing Momentum analysis**:
 - Assumes quasi-real photoproduction ($Q^2 \approx 0$).
 - $M_X^2 \approx M_e^2 \approx 0$.

- **Challenge:** High luminosity (10^{37}) makes detecting the recoil proton difficult due to background.
- **Limitation:** Most photoproduction occurs at $\theta \approx 0^\circ$ where e' is lost in the beam pipe.

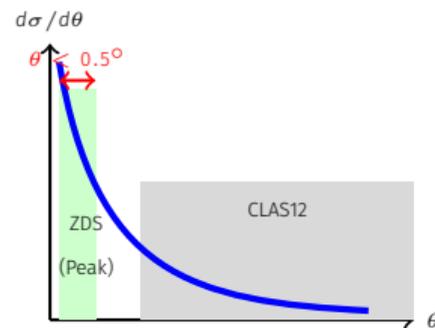
THE CASE FOR A ZERO-DEGREE SPECTROMETER (ZDS)

The "Missing" Physics at $10^{37} \text{ cm}^{-2} \text{ s}^{-1}$

- **Peak Photon Flux:** Photoproduction cross-sections peak at $\theta \approx 0^\circ$ and $Q^2 \rightarrow 0$.
- **Geometric Blind Spot:** In the baseline μCLAS12 , these electrons never exit the beam pipe or are lost in the first magnets.
- **CLAS12 Gap:** There is a forward hole in CLAS12 of around 0.5° . May be able to detect e^- after this...

ZDS: Transforming the Reach

- **Direct Tagging:** Detects electrons in the critical $\theta < 0.5^\circ$ range.
- **Kinematic Certainty:** Directly measuring $E_{e'}$ provides a precise E_γ for every event, removing missing-momentum ambiguity.
- **Polarisation** Measuring scattering plane gives transverse/linearly polarised photons - more physics.



- **Range:** $0.5 < E_{e'} < 3.5 \text{ GeV}$.
- **Impact:** High-resolution tagging enables precise GPD studies through TCS and J/ψ .

The EIC Heritage (ePIC)

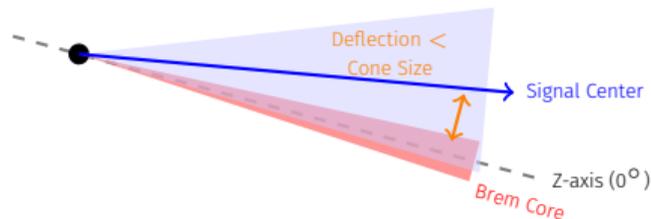
- **Spectrometer Design:** The ePIC Far-Backward region uses existing beamline steering magnets to bend scattered electrons.
- **Analysis:** The degree of bending allows for precise reconstruction of electron momentum and Q^2 . Track required to extract vertex 3-momentum.
- **Readout:** Requires high-granularity and <1 ns timing to separate signal.



ePIC Low- Q^2 Tagger geometry

Applying to μ CLAS12

- **Direct Analogue:** We introduce a dedicated dipole to bend electrons away from the 11 GeV primary beam.
- **High Rates:** At 10^{37} luminosity, we face greater background challenges to EIC.
- **Timepix4 Advantage:**
 - **Spacial resolution:** ($<55\mu m$) required to resolve momentum at very small angles ($\theta < 0.5^\circ$)
 - **Timing resolution:** (<1 ns) required for GHz scale backgrounds and to resolve beam bucket.
 - **Rate capability:** (GHz per layer) required for GHz scale backgrounds. It's the only pixel detector / readout combination that can handle this sort of rate.



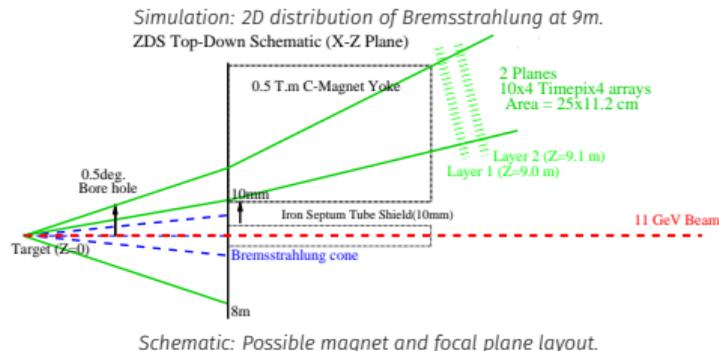
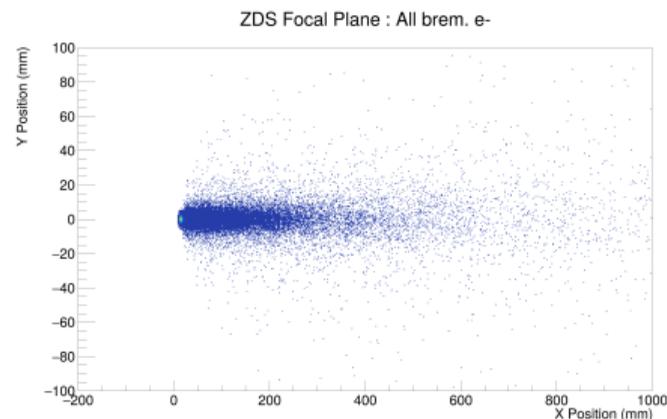
SIMULATION: BREMSSTRAHLUNG AT 9M FOCAL PLANE

The Separation Challenge

- **The "Firehose":** Bremsstrahlung produces a massive flux of electrons at extremely small angles.
- **Spatial Overlap:** At the 9m focal plane, the magnetic deflection is **less than the signal cone size**.
- **Consequence:** Deflection alone cannot cleanly separate signal electrons of different momenta from the background.

The Hardware Requirement

- **Problem 1:** A standard dipole would kick the primary beam and the Brem core into the detector.
- **Problem 2:** Beam is diverged from dump by some amount. Needs correcting and produces synchrotron radiation.
- **Solution: C-frame Dipole Septum (Lambertson).**
- **Function:** Provides a field-free bore for the "hot" core while maintaining a high-field region immediately adjacent for the signal.
- **Compromise** Lose acceptance for one side of our signal cone

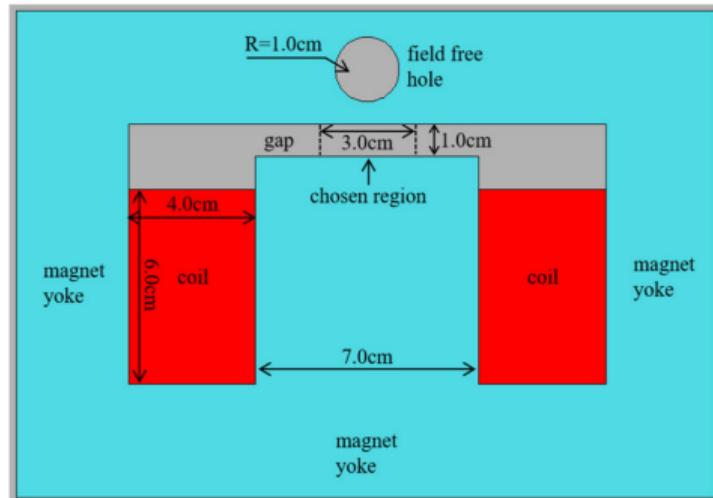


Magnet Design & Parameters

- **Type:** Normal-conducting C-frame Dipole Septum.
- **Integrated Field:** 0.5 T-m.
- **Septum Geometry:**
 - **Field-Free Bore:** 10 mm diameter for the 11 GeV primary beam and Bremsstrahlung core.
 - **Septum Material:** High-permeability iron to shield the bore from the dipole field.
- **Gap:** Ideally 25x11 cm.
- Is such a device possible? Is the field region too large?
What are the issues in the proposed environment?
- How can it interface to the beam vacuum pipe???

Lamberston References

- A new design of Lambertson magnet with true zero field region
- Development of Lambertson Magnet and Septum Magnets for Splitting 30-GeV Proton Beam in Hadron Experimental Facility at J-PARC



Basic two dimensional cross section profile of Lambertson magnet.

- **C-frame advantage:** Allows the magnet to be installed/serviced without breaking the primary beam vacuum.
- **Septum:** Reduces leakage field in the bore to $< 0.1\%$.

FOCAL PLANE DISTRIBUTIONS: IF NO MATERIAL, JUST FIELD

Simulation:

• **Generate:**

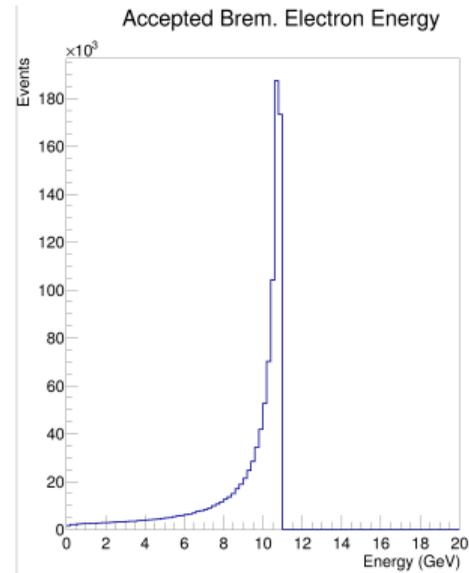
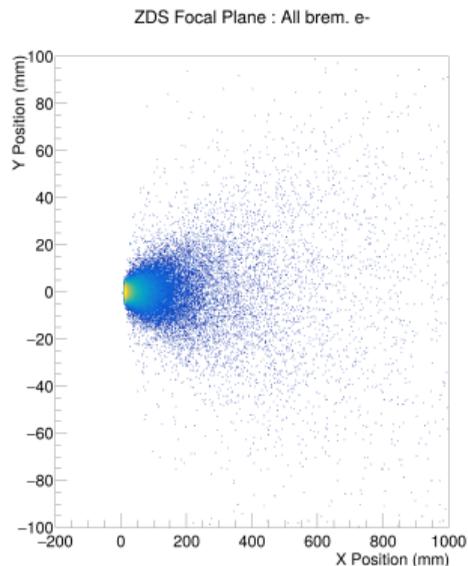
<https://github.com/adamjaro/GETaLM>

- Energy 11 GeV Bremsstrahlung
- Divergence = 0.1 mrad
- Beamspot = 100
- **Multiple scattering:** 5 cm liquid hydrogen target : ($x/X_0 \approx 0.0058$)
- modeled using the PDG Highland formula :

$$\theta_{MS} \approx \frac{0.000833}{\rho [\text{GeV}/c]} \text{ rad}$$

Relevant numbers

- **Bremsstrahlung:** Extremely high rate for $10^{37} \text{ cm}^{-2} \text{ s}^{-1}$ we get $> 1000\text{ GHz}$
Corresponds to $> 4000 \text{ e}^-$ per bunch
- **Extent:** Characteristic angle at 11 GeV is $50 \mu\text{rad}$.



Top: Bremsstrahlung Focal Plane (Energy vs. X-Y)

FOCAL PLANE DISTRIBUTIONS: IF NO MATERIAL, JUST FIELD

Simulation:

- **Generate:**

<https://github.com/adamjaro/GETaLM>

- Energy 11 GeV Virtual Photon Flux

- Divergence = 0.1 mrad

- Beamspot = 100

- **Multiple scattering:** 5 cm liquid hydrogen target : ($x/X_0 \approx 0.0058$)

- modeled using the PDG Highland formula :

$$\theta_{MS} \approx \frac{0.000833}{\rho [\text{GeV}/c]} \text{ rad}$$

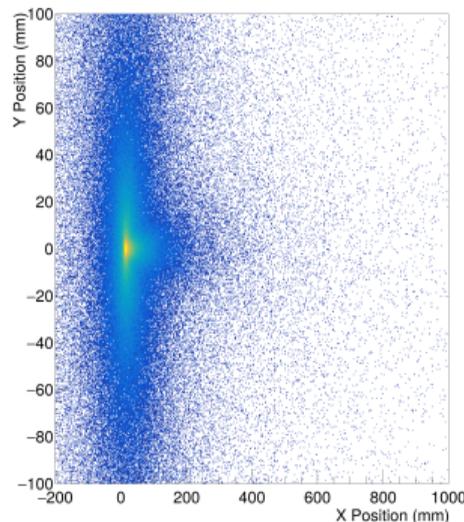
Relevant numbers

- **Quasi-real:** Rate for $10^{37} \text{ cm}^{-2} \text{ s}^{-1}$ we get 0.1 GHz

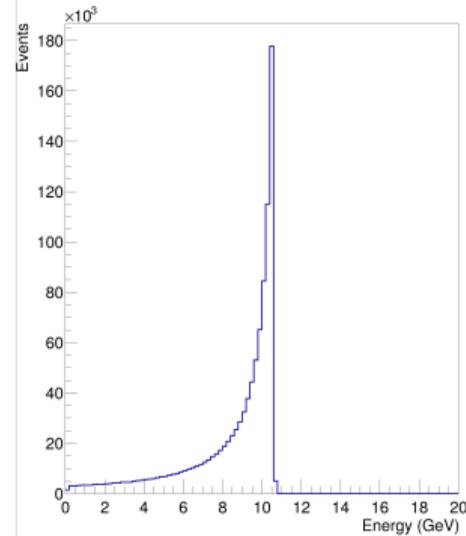
Corresponds to > 0.4 e- per bunch

- **Extent:** Characteristic angle at 11 GeV is $140 \mu\text{rad}$.

ZDS Focal Plane : All scattered e-



Accepted Scattered Electron Energy



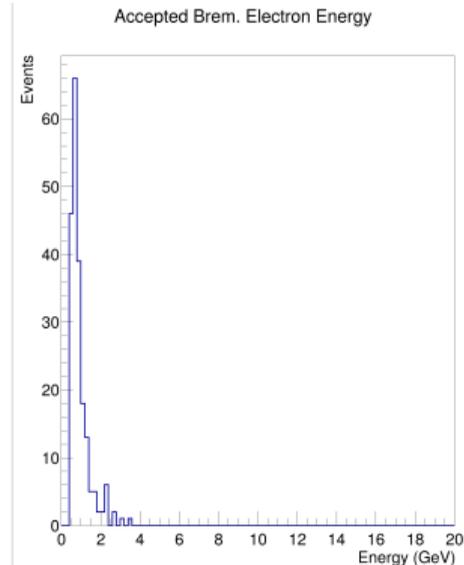
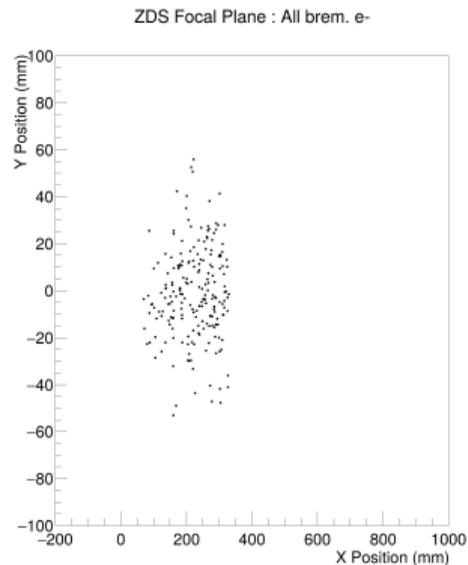
Top: Quasi-real Focal Plane (Energy vs. X-Y)

Simulation:

- Assume 30cm x 11cm Focal plane detectors

Relevant numbers

- **Bremsstrahlung:** Acceptance=0.0002 we get $> 0.2\text{GHz}$
Corresponds to $> 0.8\text{ e- per bunch}$.
Compare to EIC-lowQ2 : 2.5GHz and $12\text{ e- per crossing}$.



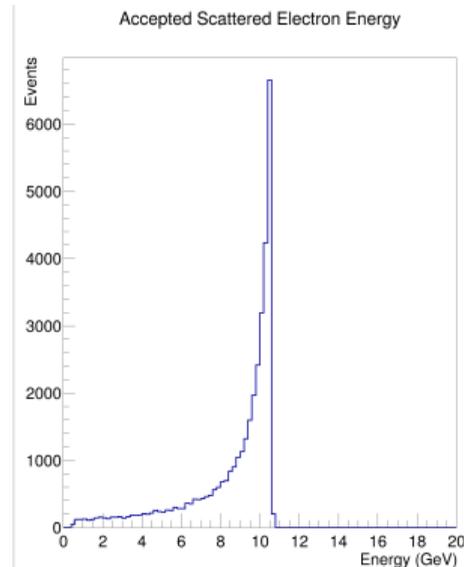
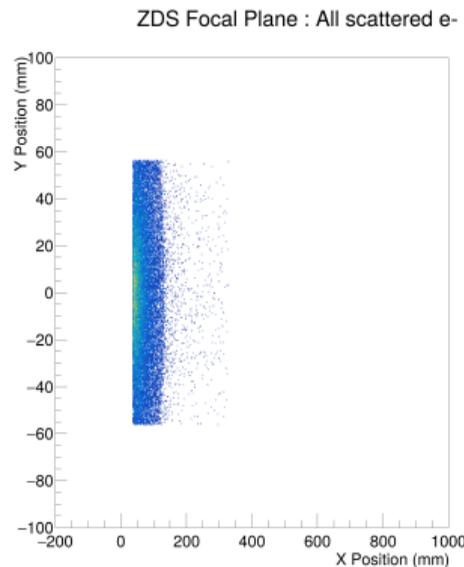
Top: Bremsstrahlung Focal Plane (Energy vs. X-Y)

Simulation:

- Assume 30cm x 11cm Focal plane detectors

Relevant numbers

- **Quasi-real:** Acceptance = 0.036 gives 3.6 MHz.
Corresponds to around 1 e⁻ per 70 bunches.



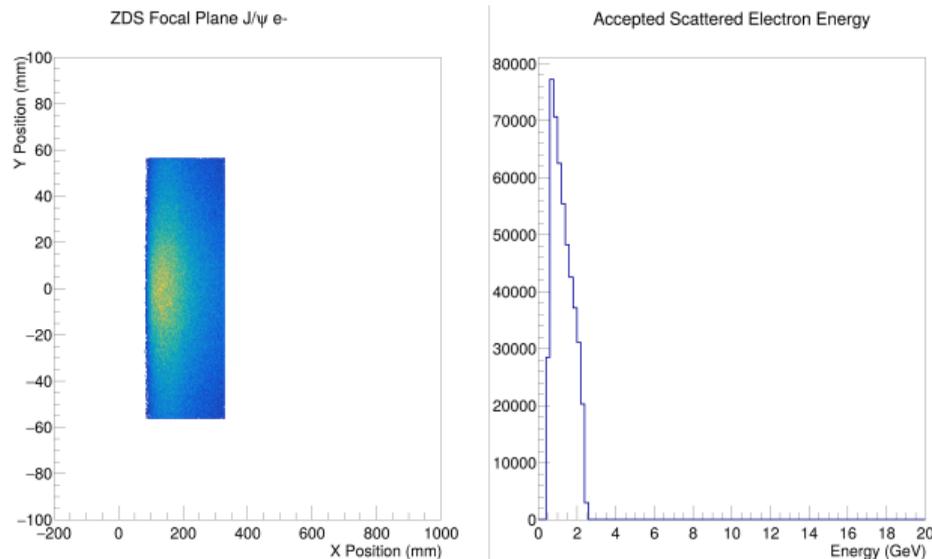
Top: Quasi-real Focal Plane (Energy vs. X-Y)

Simulation:

- Assume 30cm x 11cm Focal plane detectors.

Relevant numbers

- J/ψ : Acceptance ≈ 0.05
- Max photon energy = 10.5 GeV from 11 GeV electron beam.
- Assuming e^- scattering kinematics: $p > 0.5$ GeV; $7^\circ < \theta < 30^\circ$ gives acceptance ≈ 0.08 .
- Current design yields 60% of the rate of electron scattering J/ψ .



Top: Quasi-real Focal Plane (Energy vs. X-Y)

Simulation:

- Assume 30cm x 11cm detectors.

Relevant numbers

- J/ψ : Acceptance ≈ 0.0
- Max photon energy = 1.02 GeV electron beam.
- Assuming e^- scattering $p > 0.5$ GeV; $7^\circ < \theta < 10^\circ$ acceptance ≈ 0.08 .
- Current design yields 1000 electron scattering J/ψ events

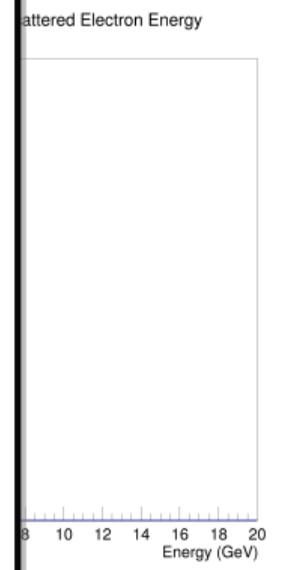
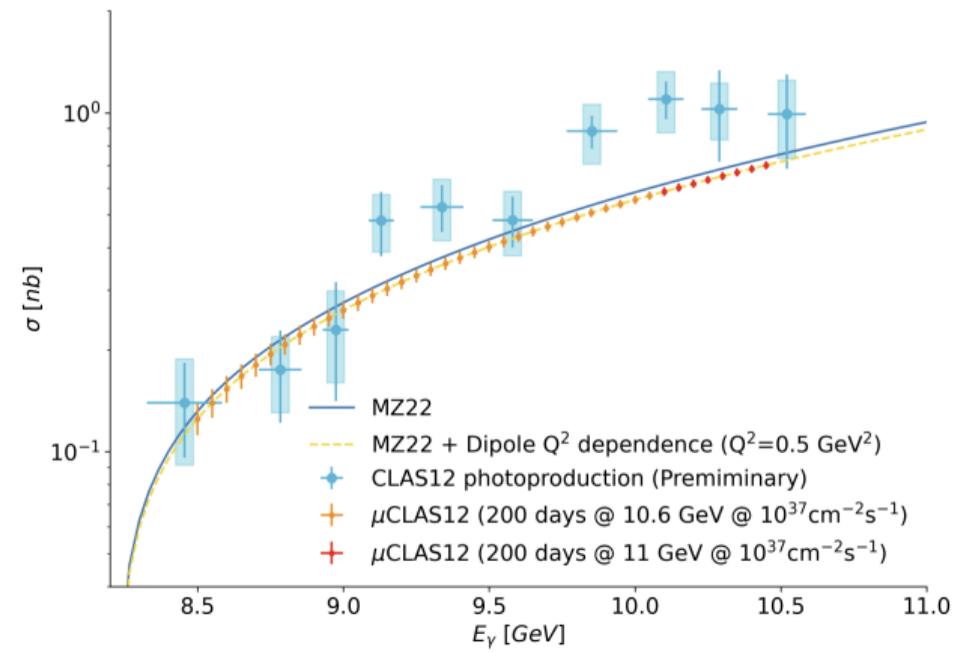


Figure 5: Comparison: μ CLAS12 Proposal J/ψ cross section

1. Primary Beam Envelope at Magnet Face ($Z = 8$ m)

- **RMS Spread:** ≈ 0.73 mm
- *Combines 50 μ rad intrinsic CEBAF divergence and 11 GeV target Multiple scattering*
- **Clearance:** Beam easily clears the 10 mm Lambertson bore.

2. ZDS Signal Electron (0.5 – 3.5 GeV)

- **Momentum Resolution ($\Delta p/p$):** $\leq 0.5\%$
- *Derived from Timepix4 0.2 mrad pointing resolution with 11cm layer separation over a magnetic kick of 50-150 mrad.*
- **Angular Resolution (σ_θ):** 0.24 – 1.67 mrad
- *Fundamentally limited by target Multiple Scattering, not the tracker.*

3. Standard μ CLAS12 Forward Electron (PbWO_4)

- **Energy Resolution ($\Delta E/E$):** $4\%/\sqrt{E}$ from proposal page 55.
- **Angular Resolution (σ_θ):** ≈ 2 mrad

PHYSICS PERFORMANCE: ZDS VS. PBWO₄ CALORIMETER

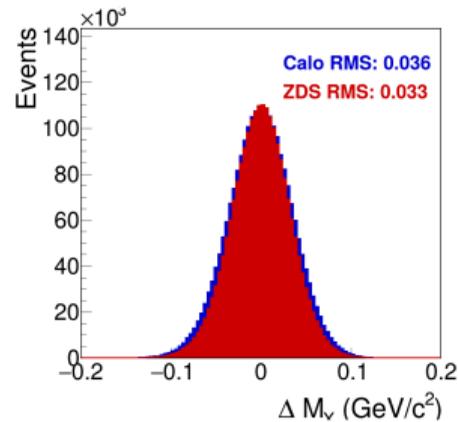
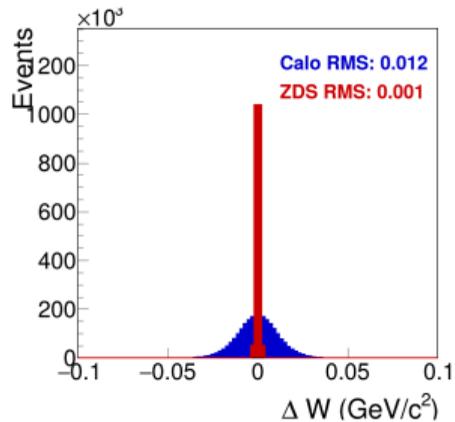
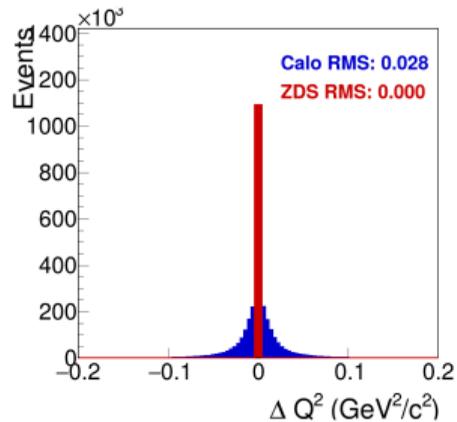
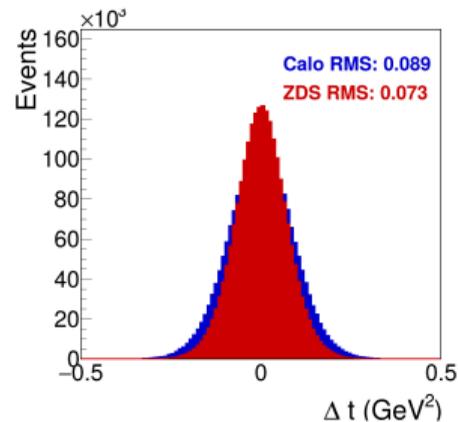
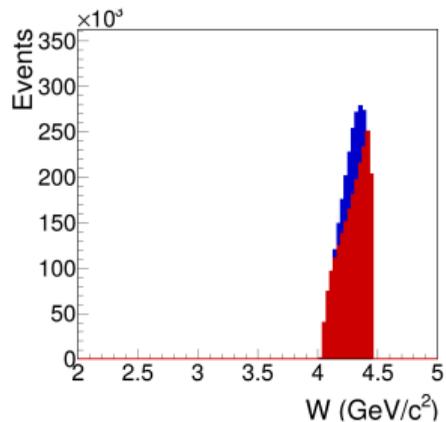
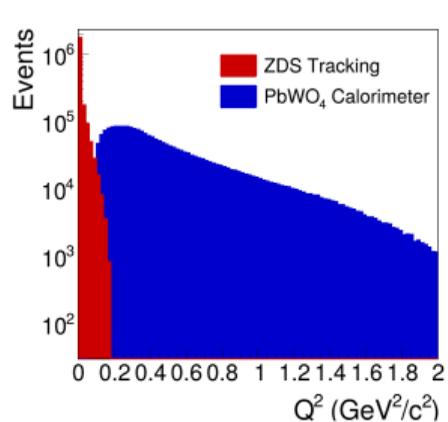


Table 1: Estimated Hardware and Development Costs. Note μ CLAS12 project conceptual design cost estimate \$5.78M.

Subsystem	Description	Cost (k\$)
Common Infrastructure		
Magnet System	Normal-Conducting C-Magnet (0.5 T·m)	85 – 95
Vacuum System	Straight Chamber + Flat Strongback Window	20 – 30
Shielding	Lambertson Iron Septum (10 mm bore)	5 – 10
Mechanics	Detector Support & Precision Movers	10 – 15
<i>Subtotal</i>		120 – 150
Tracking Detectors (Timepix4 Hardware)		
Timepix4	ASICs, Silicon, UBM, and Bonding	82
Front-End Electronics	PCBs for 3 × 2 Timepix4 and Cables	8
Backend DAQ & Power	Layer DAQ FPGAs, Felix, Server, Bias/HV/LV	93
Cooling	Monolithic Water-Cooled Cold Plates	4
<i>Subtotal</i>		187
Total System Cost		307 – 337

SUMMARY

Technology Heritage

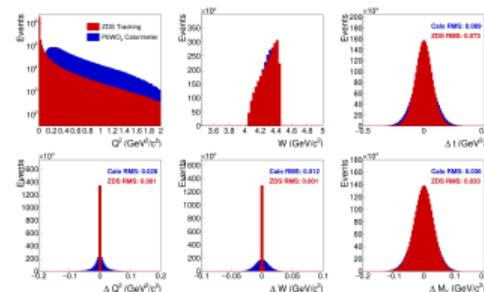
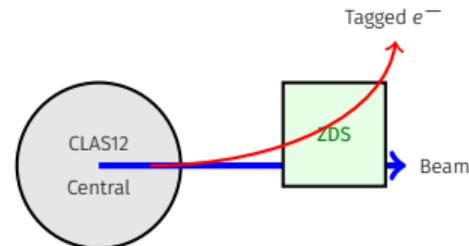
- Direct application of **Timepix4/SPIDR4** R&D from the EIC Low- Q^2 Tagger.
- Only detector combination capable of handling **GHz-scale rates** and **<1 ns timing** required for 10^{37} luminosity.

The ZDS Solution

- **Lambertson Magnet:** C-frame design provides a 10 mm field-free bore for the beam while analyzing signal electrons.
- **Tagging Reach:** Accesses the peak photon flux at $\theta < 0.5^\circ$, currently a "blind spot" for baseline CLAS12.
- **Performance:** Momentum resolution potentially very good, $\Delta p/p \leq 0.5\%$. Acceptance for electrons of around 5% for J/ψ quasi-real photoproduction.

Scientific Impact

- Enables a high-precision J/ψ **and TCS** photoproduction program, complementary to proposed electroproduction.



Technology Heritage

- Direct application
- Only detector con
- **timing** required for

The ZDS Solution

- **Lambertson Mag**
- the beam while a
- **Tagging Reach:** A
- "blind spot" for b
- **Performance:** Mo
- Acceptance for ele

Scientific Impact

- Enables a high-precision J/ψ and TCS photoproduction program, complementary to proposed electroproduction.

Current Technical Uncertainties

- **Magnet Design:** Detailed engineering of the C-frame septum and fringe field analysis is **completely uncertain**.
- **Vacuum Integration:** The mechanical interface between the ZDS chamber and the primary beam vacuum pipe remains to be designed.
- **General Engineering:** Support structures, alignment tolerances, and cooling requirements are at a preliminary conceptual stage.
- **Status:** While physics simulations are promising, the **hardware implementation** requires significant R&D.

