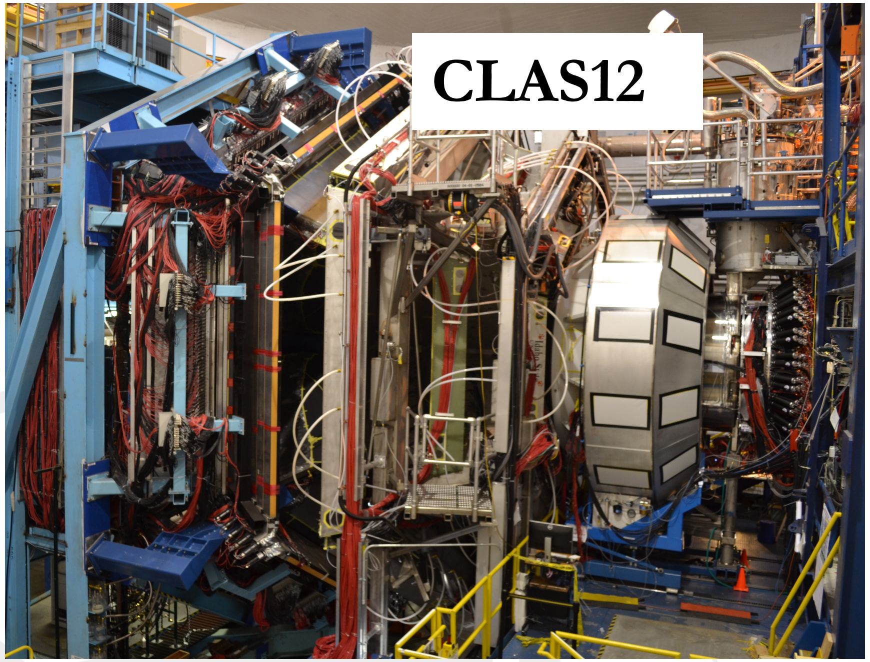
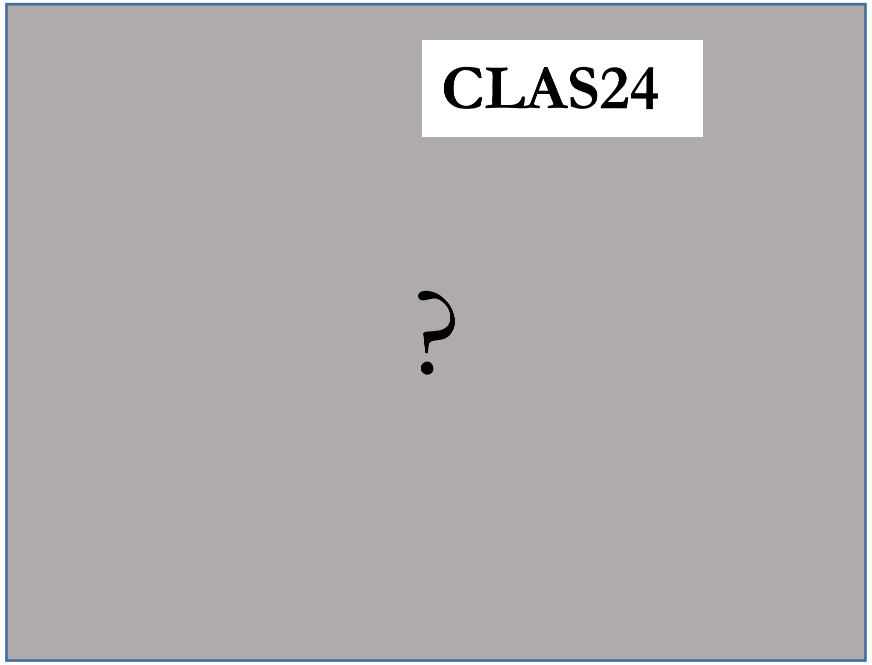
Hadron Physics with CLAS12 at 24 GeV



V.D. Burkert, L. Elouadrhiri, et al., Nuclear Inst. and Methods in Physics Research, A 959 (2020) 163419



Volker Burkert, Jefferson Lab

Based on talk at workshop "J-FUTURE" 28-30 March 2022, Jefferson Lab / Messina University

Why another detector upgrade?

- Optimize running the 12 GeV science program by improvements in tracking, photon detection, and charged particle identification
- Preparing for a 20+ GeV energy upgrade of JLab that expands on achievements from the 12 GeV science program (https://arxiv.org/pdf/2112.00060.pdf)
  - Entering new kinematics domains, sea-quarks, gluons.
  - Passing mass thresholds (J/ψ, ψ'(3700), exotic states) with sufficient phase space to explore new avenues, e.g. gluon structure of nucleons & nuclei
- Bridging the energy gap between 12 GeV and future Precision Studies of QCD at low center mass energy EIC operation. (CEBAF-24: W_{max} = 6.5 GeV; EIC: W = 20 - 140 GeV)

https://indico.bnl.gov/event/10677

https://indico.bnl.gov/event/11669

Science Program Highlights

Elements of a high impact program that drive detector and instrumentation requirements and specifications.

1) Systematic studies of the protons mechanical properties, through measurements of its gravitational form factors $M_2(t)$, $J(t)$, $d_1(t)$ in a large t-range.

- Use DVCS (with electrons and positrons) as a probe of GPDs (CFF) in the valence quarks and sea-quark domain.
- Use time-like Compton Scattering (TCS) as a probe of Re($\mathcal{H}$) and $d^q{}_1(t)$.

2) Use J/ψ production as a tool to probe the gluon structure (GPDs) of the nucleon.

- Measure J/ψ production off proton at threshold to study gluon content in mass, angular momentum, pressure; large t-range needed.

3) Search for new exotic mesons with heavy quarks to discover new states and the underlying systematics and production mechanism.

- Photoproduction cross sections are small O(1nb), widths O(100MeV) – require large acceptance, high luminosity, good momentum resolution, good vertex resolution. (Example is series of $Z_c(3900)$, $Z_c(4020)$, $Z_c(4200)$, ... all ccbar-qqbar states, decaying into J/ψ + pions)

4) Hard processes in backward meson production u-channel processes and TDA & 2–γ physics (new)

Systematic study of mechanical properties of the proton

Quick Science background

- Mechanical properties appear as gravitational form factors (GFF) in the proton matrix element of the EMT.

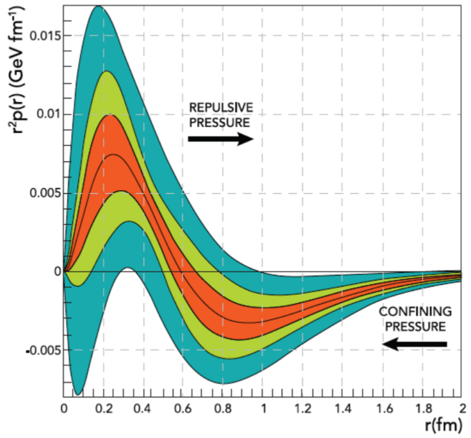
$$\langle p_2|\hat{T}^q_{\mu\nu}|p_1\rangle = \bar{u}(p_2)\left[M_2^{q,g}(t)\frac{P_\mu P_\nu}{M} + J^{q,g}(t)\frac{i(P_\mu\sigma_{\mu\rho}+P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M} + d_1^{q,g}(t)\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M}\right]u(p_1)$$

Example of the GFF $d_1^q(t)$:

Appears in 2nd x-moment of GPD H^q: $\int \mathrm{d}x\, x H^q(x,\xi,t) = M_2^q(t) + \frac{4}{5}\xi^2 d_1^q(t)$

$$\mathcal{F}(\xi,t;Q^2) = \int_{-1}^{1} dx \left[\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right] F(x,\xi,t;Q^2)$$

$$\mathrm{Re}\mathcal{H}^q(\xi,t) = \Delta^q(t) + \frac{1}{\pi}\mathcal{P}\int_0^1 \mathrm{d}x \left[\frac{1}{\xi - x} - \frac{1}{\xi + x}\right]\mathrm{Im}\mathcal{H}^q(x,t),$$

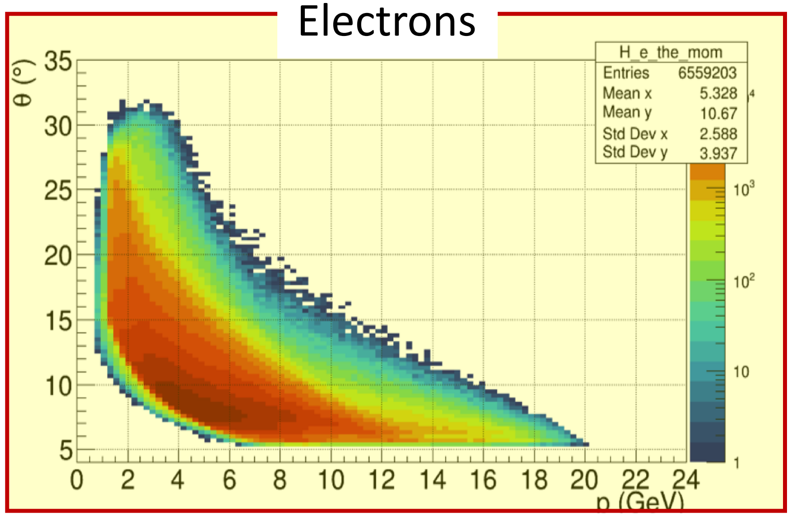


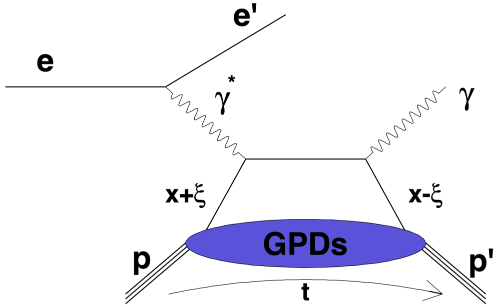
- **Dispersion relation** for CFF $\mathcal{H}$ contains subtraction term $\Delta^q(t)$ that relates to $d_1^q(t)$
- **Fourier transform** of $d_1^q(t)$ into coordinate space gives shear and pressure distribution.

DVCS on Proton @ 24 GeV - GEMC and reconstruction

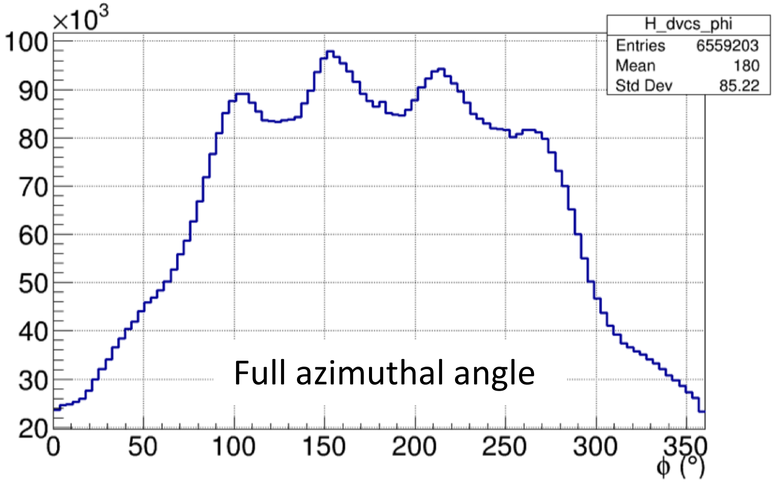
Statistics equivalent to few hrs @ 10^{35} $cm^{-2}s^{-1}$ data taking.

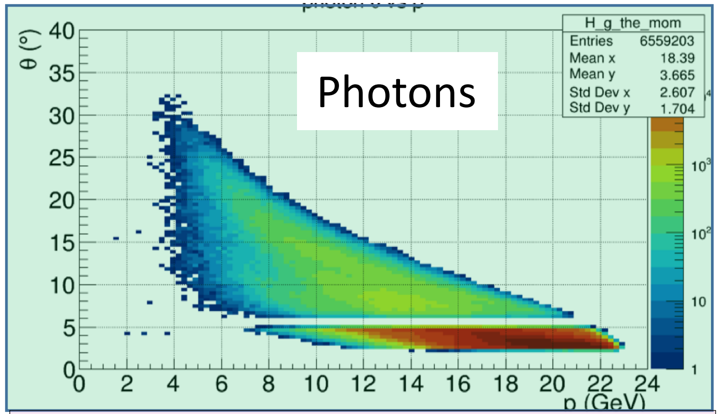
credit: F.X. Girod

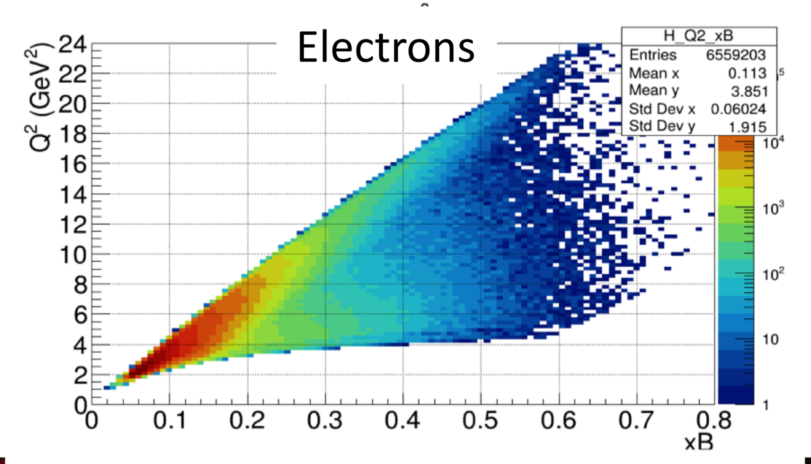


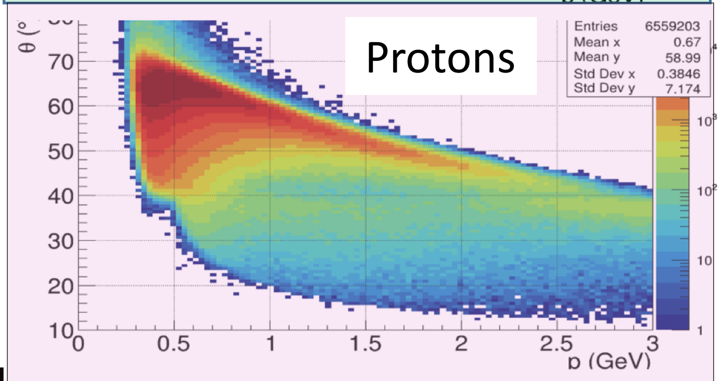


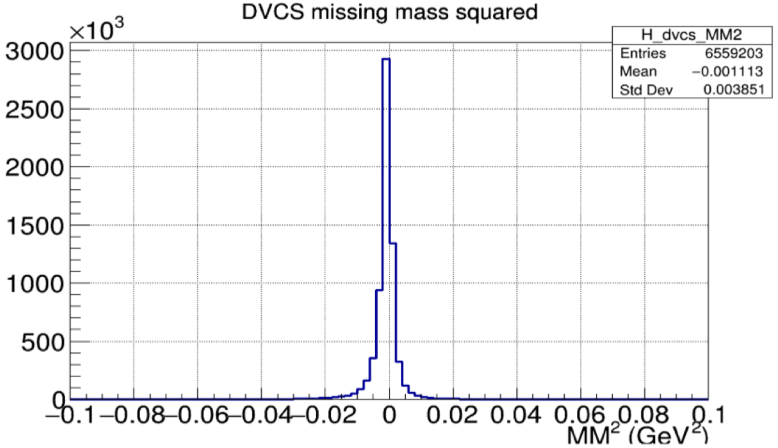
Exclusive DVCS events



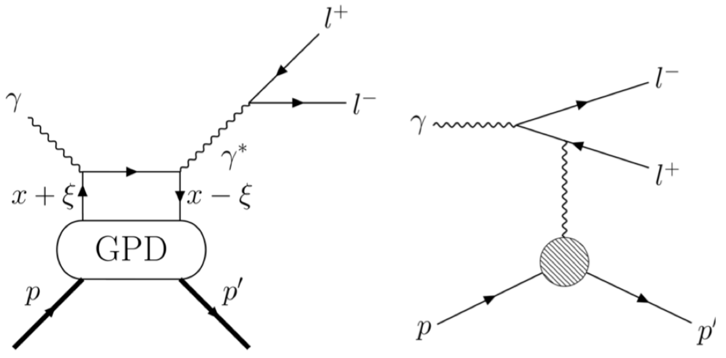


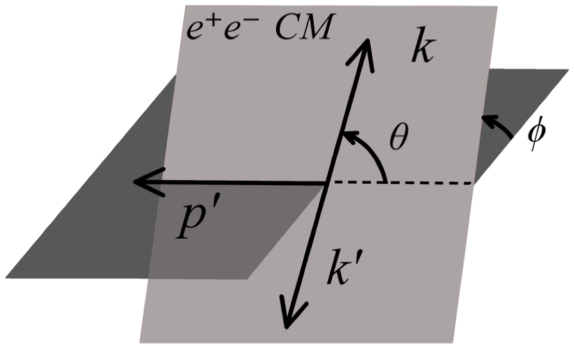


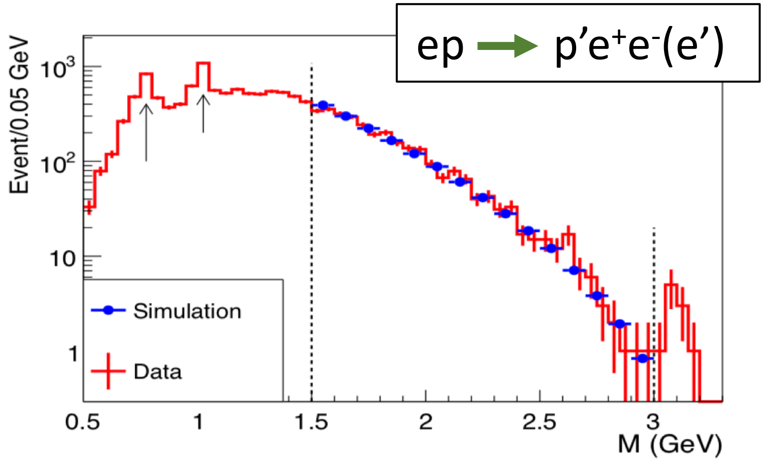




Time-like Compton Scattering at 10.6 GeV







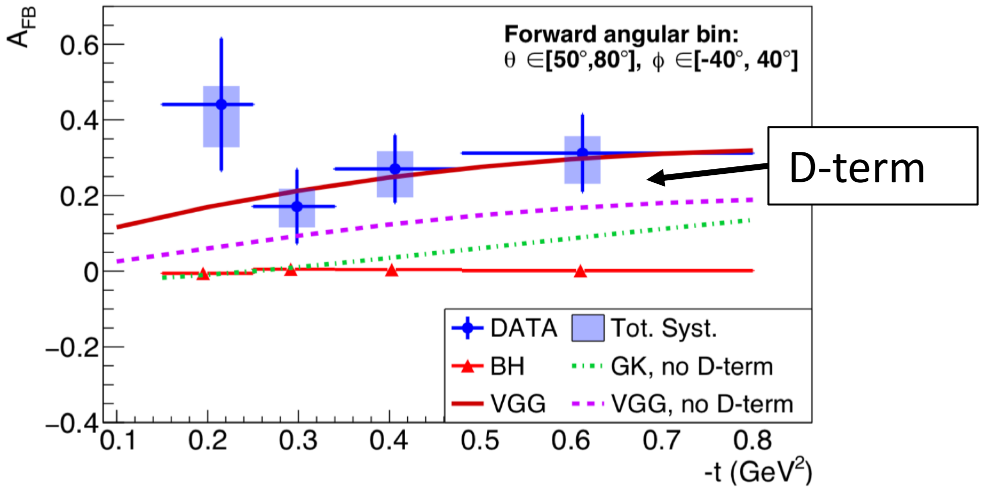
Eγ = 7.23 GeV; M = 1.81GeV

In addition to the BSA from the polarized beam, TCS has a forward-backward asymmetry, which **directly** relates to the CFF Re$\mathcal{H}(\xi, t)$ through the interference term with BH.

$$A_{FB}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ-\theta, 180^\circ+\phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ-\theta, 180^\circ+\phi)},$$

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} = A\frac{1+\cos^2\theta}{\sin\theta}\left[\cos\phi \,\mathrm{Re}\tilde{M}^{--} - \nu\cdot \sin\phi \,\mathrm{Im}\tilde{M}^{--}\right]$$

$$\tilde{M}^{--} = \left[F_1\mathcal{H} - \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4m_p^2}F_2\mathcal{E}\right]$$



P. *Chatagnon et al., Phys.Rev.Lett. 127 (2021) 26, 262501*

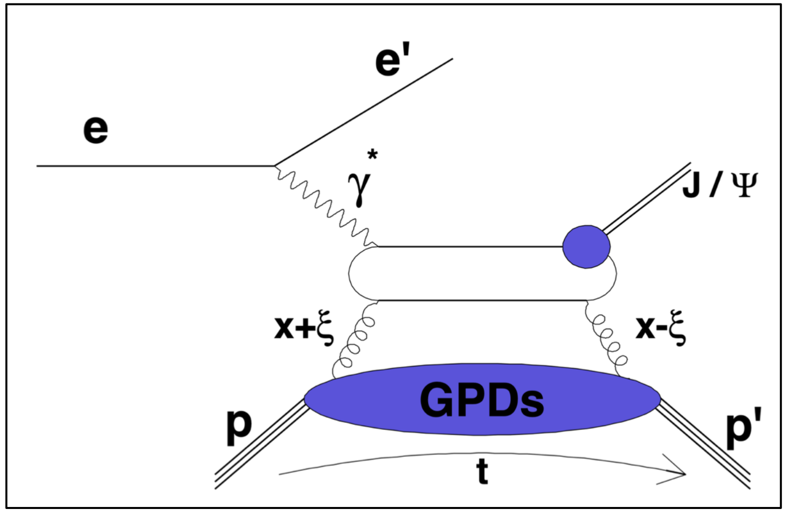
Conclusions from DVCS/TCS

- **DVCS @ 24** GeV is suitable to be measured in standard CLAS12 configuration
  - Most scattered electrons at $Q^2 > 2$ GeV^2 are measured at polar angles 5^o – 30^o
  - Nearly all protons are detected at $\Theta_p > 40^o$ in CVT
  - The DVCS photons reach in polar angle from 2.5^o to 25^o and should be reconstructed in ECAL & FTCal
  - The DVCS process is reconstructed with full coverage in azimuthal angle ϕ
  - Well reconstructed missing mass for exclusive DVCS production with fully exclusive process.
- Caveats
  - Electrons id at >5GeV/c and photons relies exclusively on ECAL information. Both calorimeters, ECAL and FTCAL will have some energy leakage at highest energies, but should be sufficient for exclusive DVCS.
  - Protons have momenta below 2 GeV/c at $\Theta > 40^o$, and should be easily separated from π^+, not from K^+ though. Improved PID would be helpful.
  - DVCS photon separation from π^0 at energy > 12 GeV may see 2-photon merging.

- **TCS @ 24** GeV would benefit from improved acceptance for e^- and e^+ at forward angles for forward-backward asymmetry.

Proton's gluon structure – GEMC & reconstruction

- Quasi-real photoproduction of J/ψ near threshold is sensitive to gluon structure. In leading twist the process is described by the handbag diagram.
- The heavy J/ψ mass of 3.1 GeV/c^2 ensures short distance scattering.
- Determination of the GFF and partial gluon contribution to the pressure and shear force distribution in coordinate space?
- Determination the mechanical gluon radius?



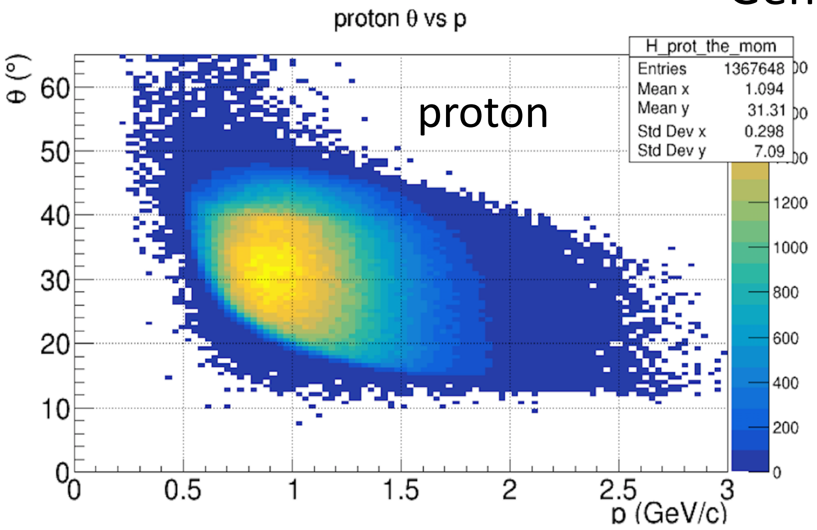
CLAS12 @ 24 GeV

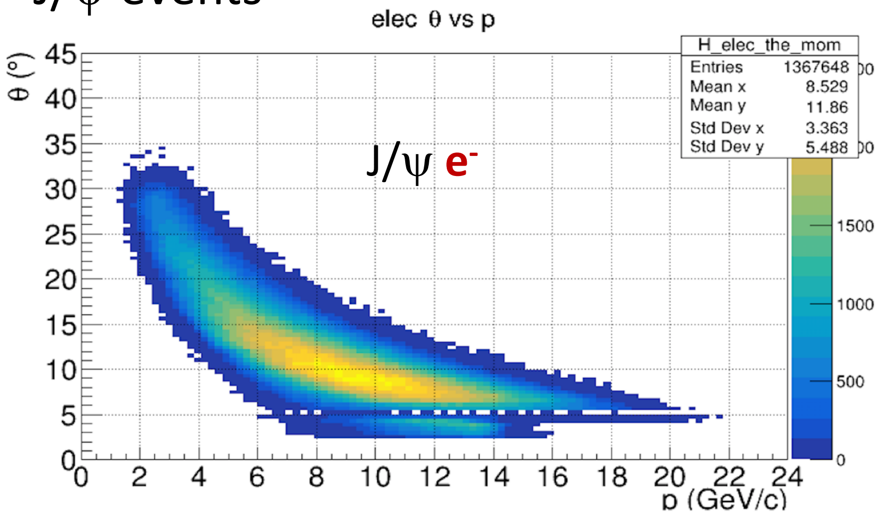
Reconstruction efficiency from simulations in CLAS12 configuration at 24 GeV is about 7%.

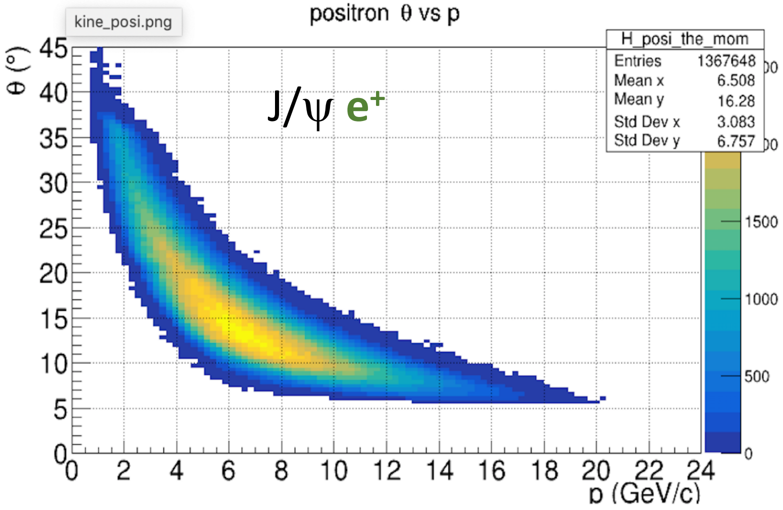
Can this be improved by extending acceptance for $e^+ e^-$ and improving vertexing? Extending to include $\mu^+\mu^-$ decay desirable.

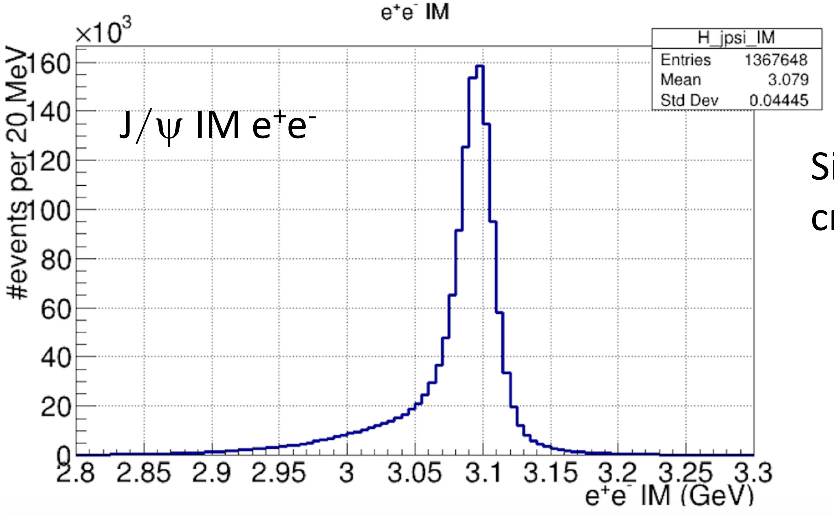
J/ψ MC events reconstructed in CLAS12 at 24 GeV

Generated 20×10^6 J/ψ events



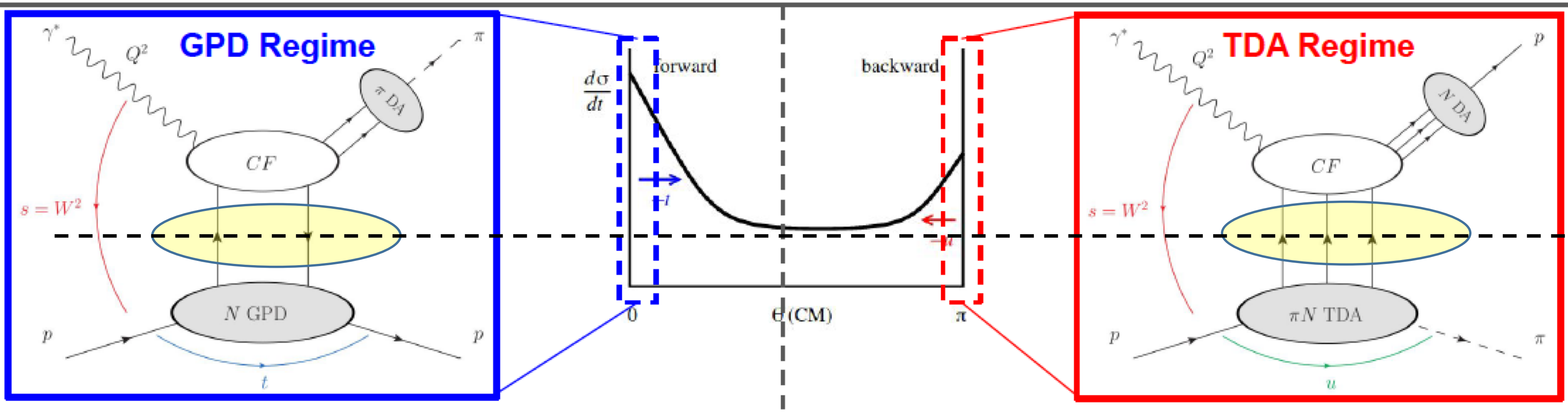






Simulation credit: F.X. Girod

U-channel short distance exclusive processes



B. Pire, L. Szymanowski, K. Semenov-Tian Shansky

Collinear Factorization

Slide: Wenliang 'Bill' Li

- **Factorization: $Q^2 \rightarrow$large, $-t \rightarrow$small, $-t/Q^2 \sim 0$**
- **Systematically study forward DVCS & DVMP**
- **Factorization indicator:**
  - $\sigma_L >> \sigma_T$
  - $d\sigma_L/dt \propto 1/Q^6$
- **Factorization conclusion results from most meson production channels.**

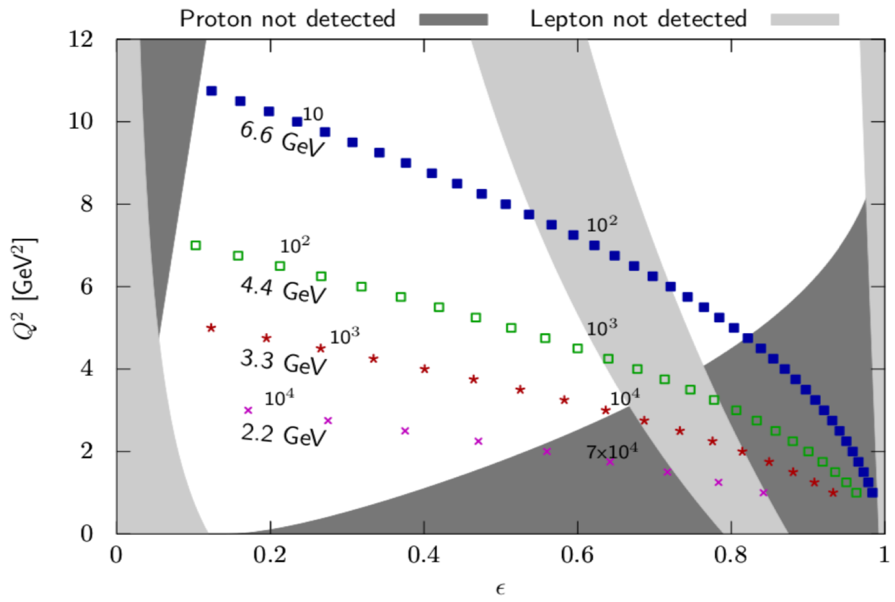
- **Factorization: $Q^2 \rightarrow$large, $-u \rightarrow$small, $-u/Q^2 \sim 0$**
- **Systematically study backward DVCS & DVMP?**
- **Factorization indicator:**
  - $\sigma_T >> \sigma_L$
  - $d\sigma_T/dt \propto 1/Q^{10}$ ($d\sigma_T/d\Omega \propto 1/Q^8$)
- **Factorization conclusion results from most meson production channels.**

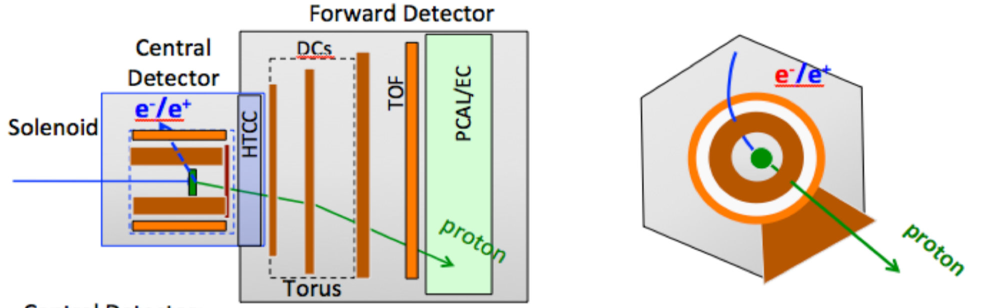
Needs high luminosity

5

For π^0 channel requires CLAS12 upgrade with backward angle e.m. calorimeter.

2-γ science in elastic e^+p/e^-p scattering

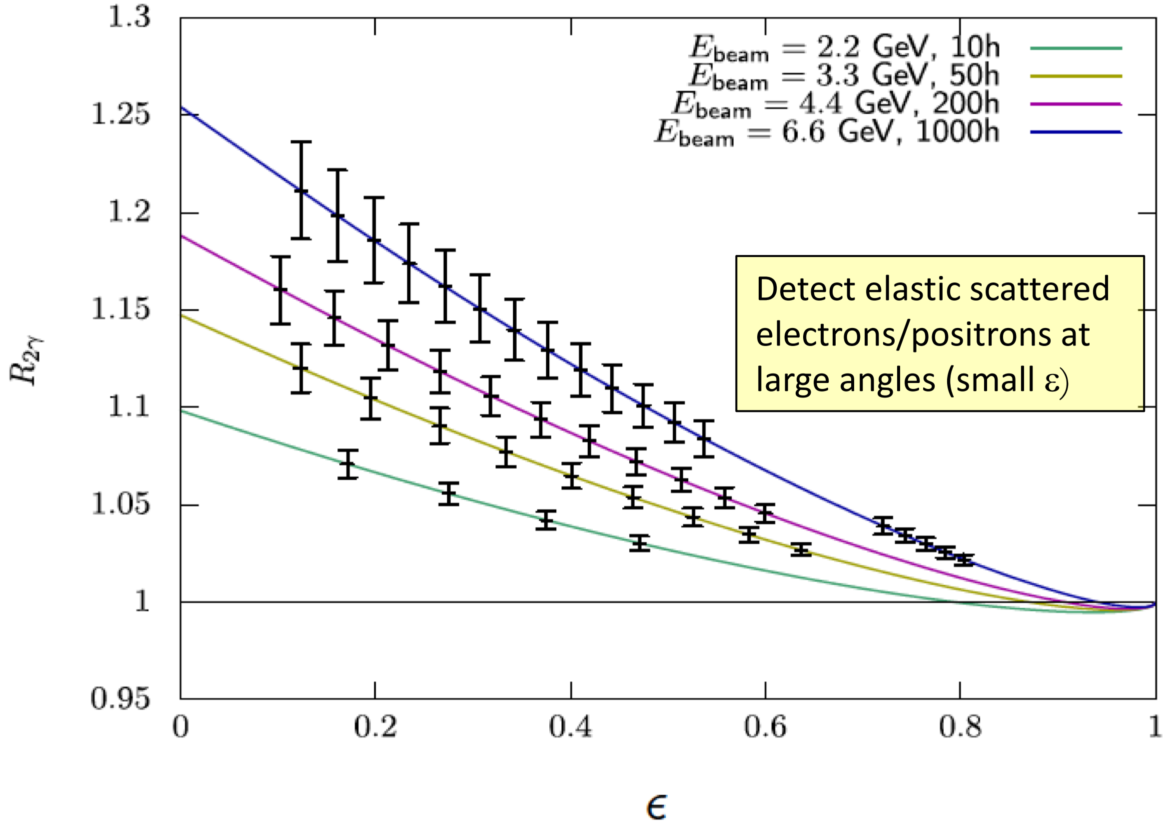




Central Detector:
- Charged particle tracking in solenoid field
- Polar angle range θ = 35 - 125°
- Azimuthal angle range Δϕ= 360°
- Particle ID by TOF for p < 1.5 GeV/c
- No direct electron/positron ID

Forward Detector:
- Charged particle tracking in Torus field
- Polar angle range θ = 6 - 35°
- Azimuthal angle range (0.6 – 0.9)x2π
- Particle ID by TOF for p < 6 GeV/c
- e⁻/e⁺ rejection in HTCC

J. Bernauer, V.B., E. Clyne, A. Schmidt, Y. Sharabian, Eur.Phys.J. A 57 (2021)



Detect elastic scattered electrons/positrons at large angles (small ε)

Energy upgrade is not needed.

Exotic heavy flavor spectroscopy (X,Y,Z)

See: Talk be Derek Glazier at Messina J-FUTURE for further motivation.

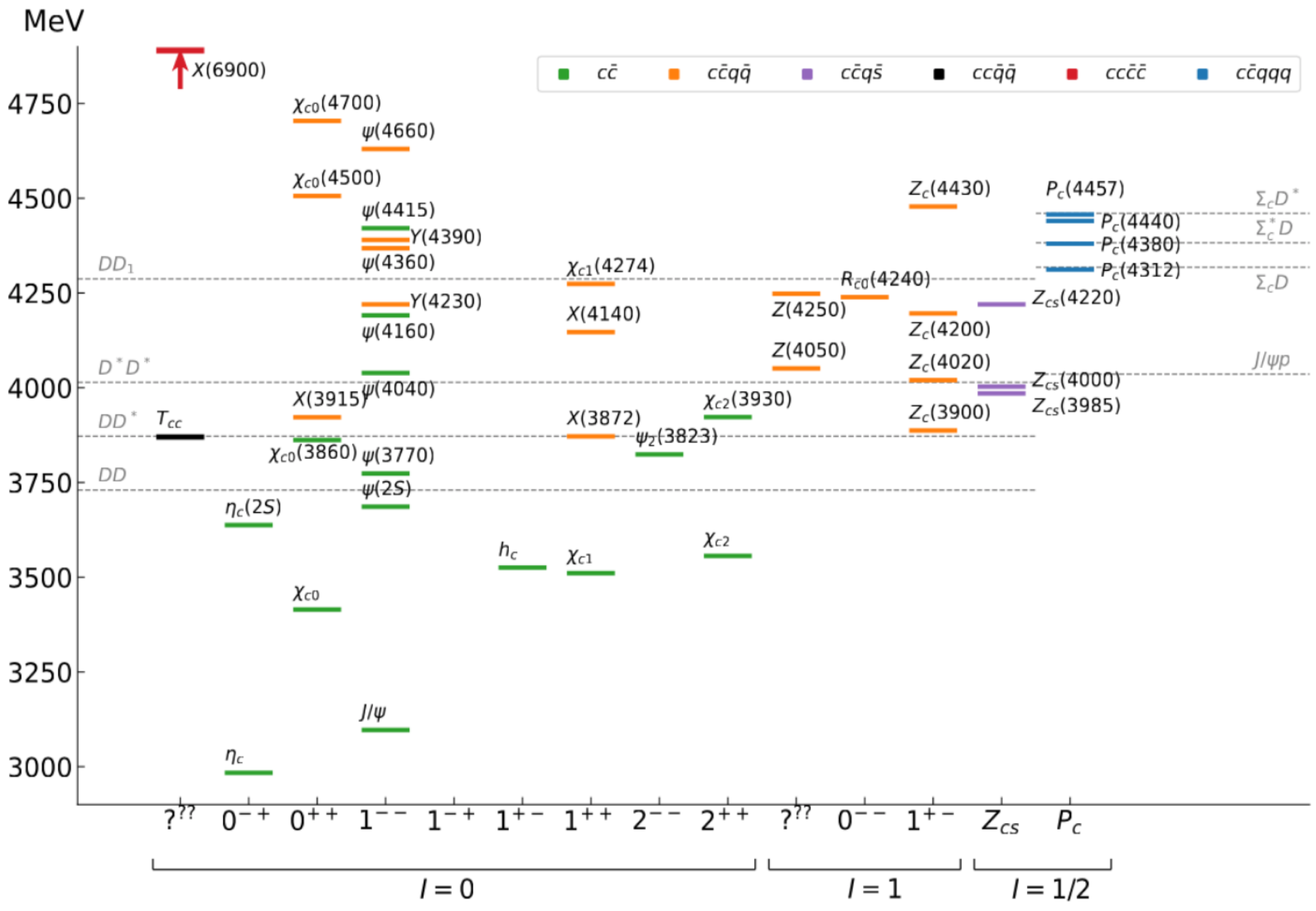
At 24 GeV electron beam energy many states with charmonium content are well within kinematic reach.

A series of them have been found in e^+e^- collisions (e.g. Belle, BESIII).

In electron-proton scattering all I, J^{PC} quantum numbers can be generated.

"It is clearly a great help to detect (tag) the scattered electrons with momentum in the range **0-14 GeV below 1 degree**." (Derek Glazier)

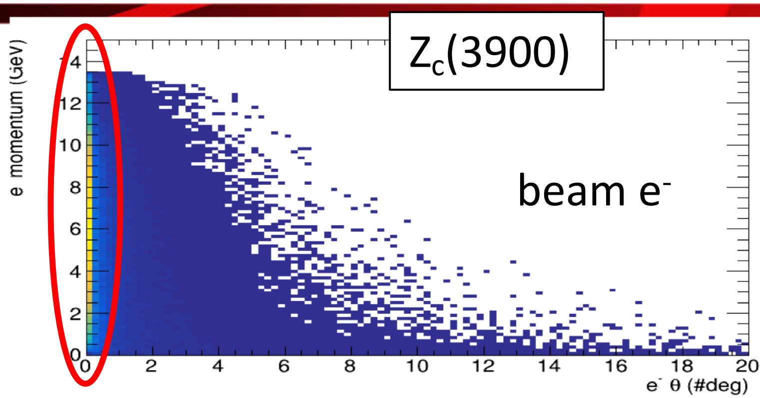
Is this a realistic possibility?

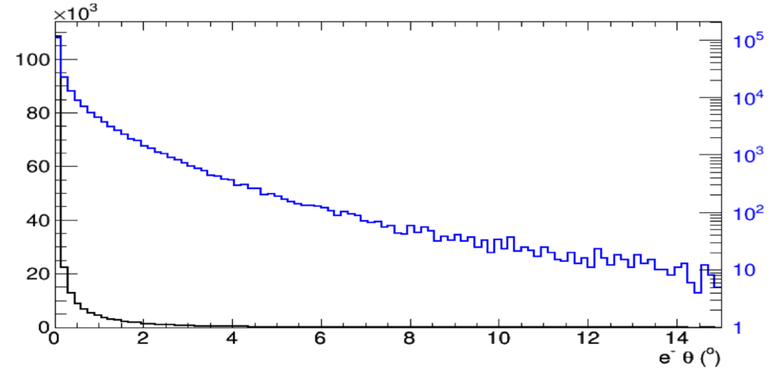


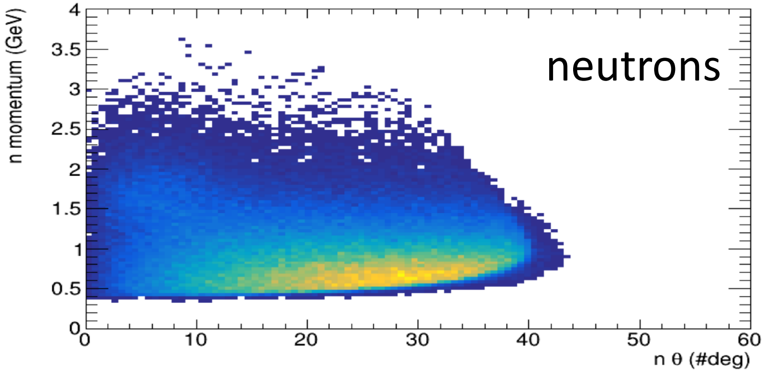
Constraints for X, Y, Z studies at 24 GeV

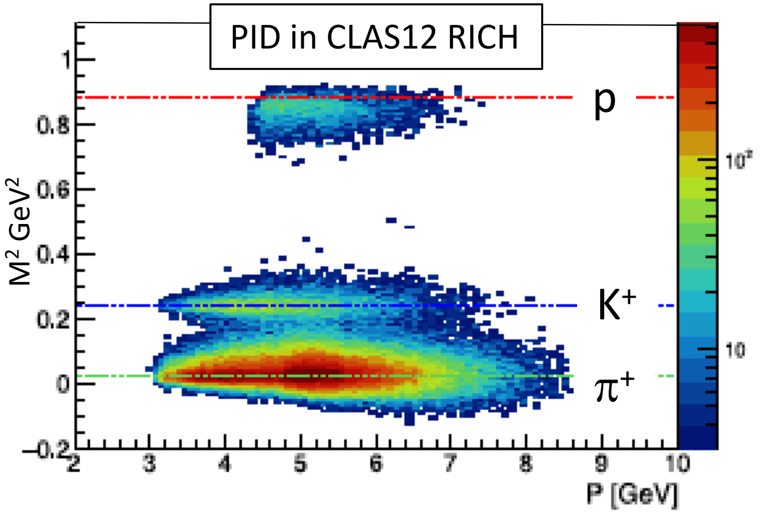
- **Electrons:** Most beam electrons are scattered at Θ_e **< 0.5°** with momenta up to 14 GeV/c.
  - **Requires close to 0-degree electron tagging to be viable.**
- **Pion** kinematics covers range from ~0.5 to 8 GeV in momentum, angle range from ~5° – 40°.
  - **CLAS12 tracking should be improved and extended with vertexing for heavy quark tagging**
  - **PID in 6 sectors with RICH (currently available in 2 sectors)**
- **Neutron** charge exchange process requires neutron detection with momenta 0.5 to 2.5 GeV, and angle range from ~5° to 40°, achievable in CLAS12 ECAL.

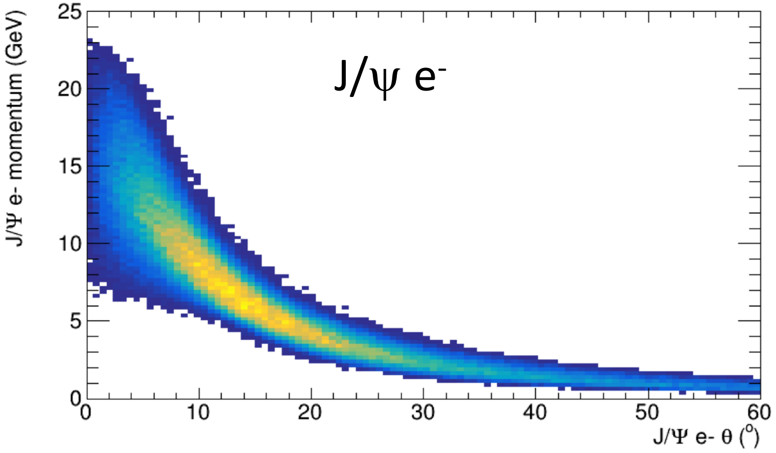
Credit: Derek Glazier







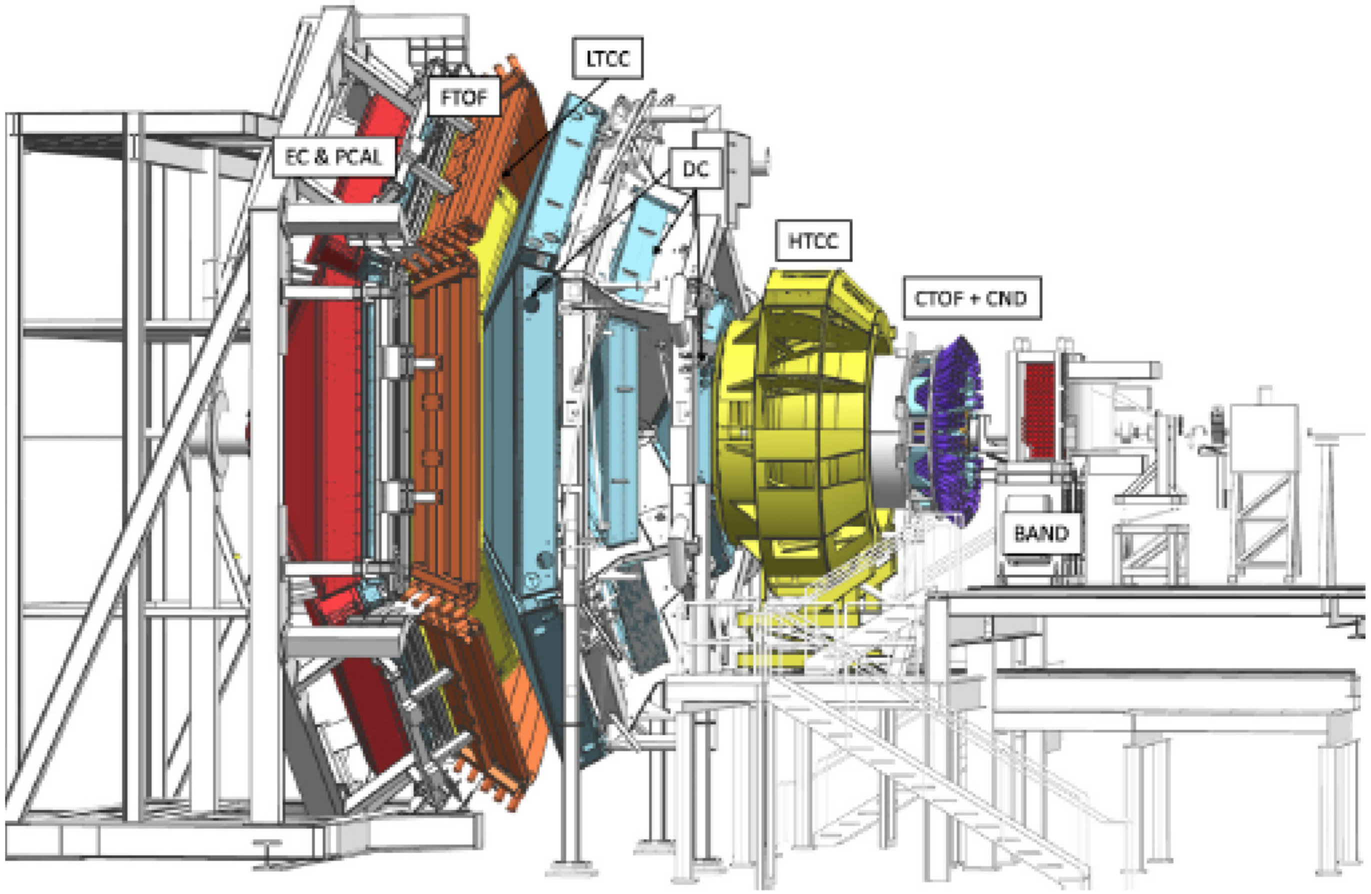




CLAS12 improvements to meet science requirements

- Increase CLAS12 luminosity by repositioning R1 drift chambers (x 2)
- Improve the tracking and vertexing in the CLAS12 forward detector region to accommodate requirements for resolution in spectroscopy and heavy quarks science
- Develop a robust 0-degree electron spectrometer for the energy range 1 – 14 GeV for exotic heavy quark spectroscopy. Could also be useful for TCS
- Provide π^0, γ, e^+/e^- detection in backward hemisphere (TDAs, 2γ–physics)
- Upgrade CLAS12 for charged particle ID in full momentum range & all forward sectors (RICH 3-6)
- Improve the PID in the Central Detector for K/π separation

The CLAS12 Spectrometer at Jefferson Lab



Nuclear Inst. and Methods in Physics Research, A 959 (2020) 163419
+ 17 NIM articles on all subsystems.

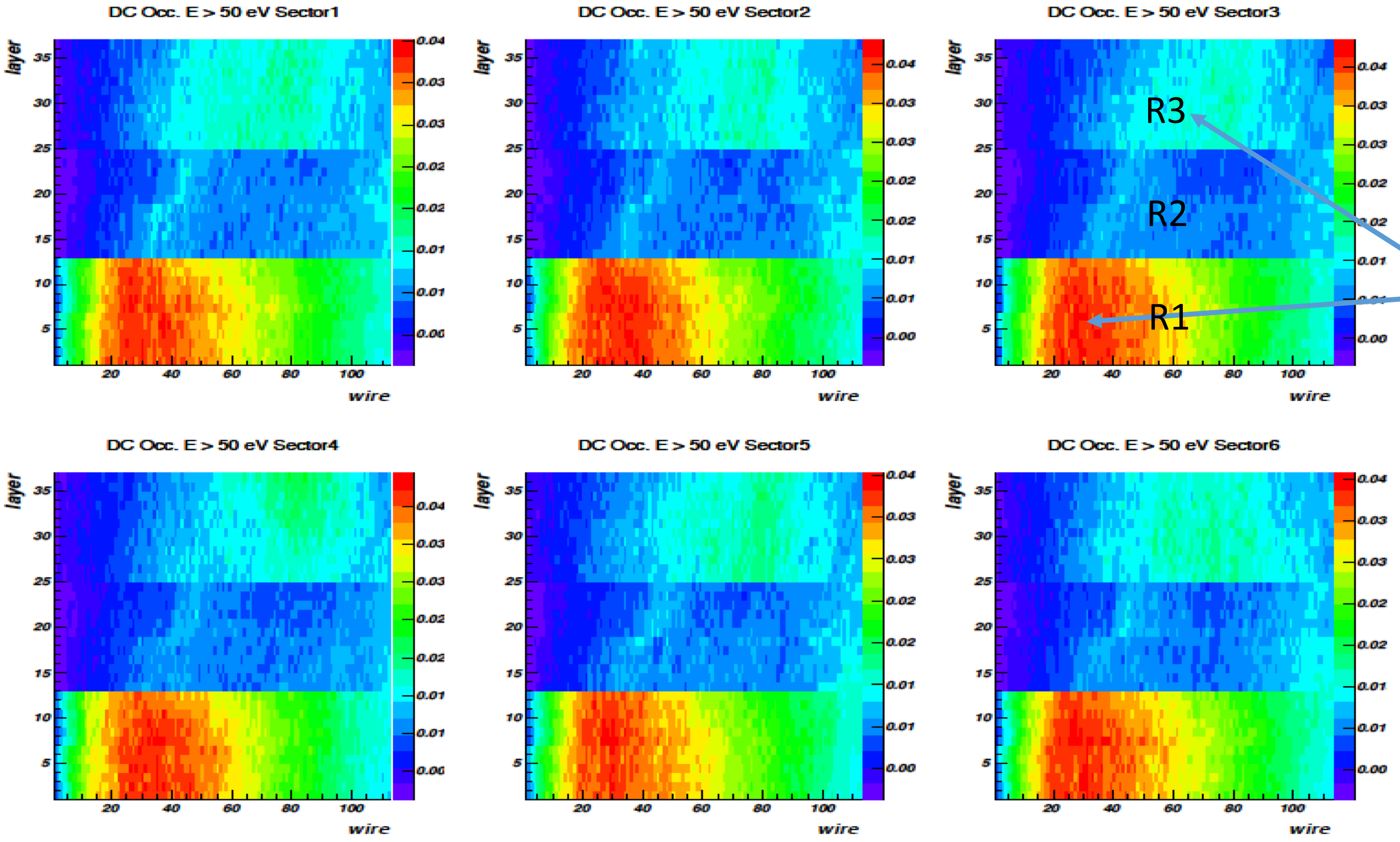
From CLAS to CLAS12 has been a major upgrade to accommodate science requirements from doubling the CEBAF beam energy.

- Focus on electron scattering and more forward particle production
- Replaced Torus magnet with shorter magnet for $5^o < \theta_e < 40^o$ coverage
- Improved PID and coverage at forward angles
- Added 5T Solenoid magnet for large angle tracking, PID, Moller trap, polarizing field for target

CLAS12 achieved design luminosity (for the nominal configuration)

Can CLAS12 @ 24GeV operate at 11 GeV luminosities?

- CLAS12 luminosity limited by accidental occupancy of DC R1.



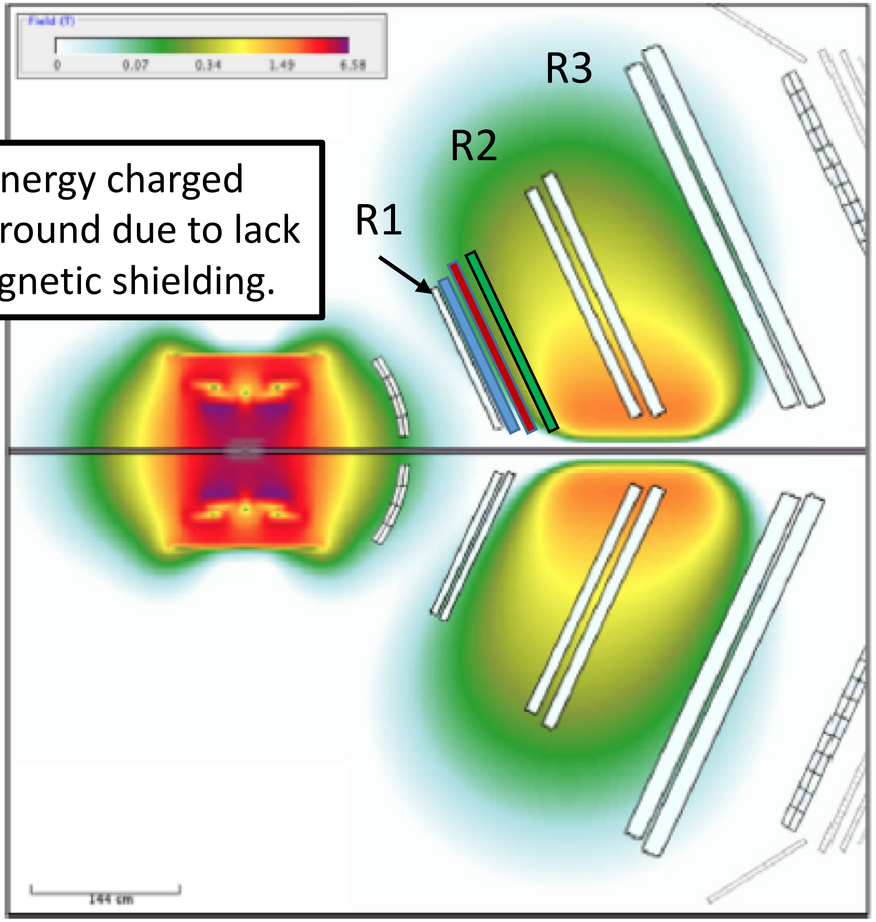
2 to 3 times higher occupancy in part of R1 than R3. Limits operating luminosity.

Credit: Z. Meador, L. Elouadrhiri

Reducing Drift Chamber Occupancy in R1

- CLAS12 will see <10% increase in occupancy in all drift chambers at 24GeV at same luminosity.
- Current operation of CLAS12 limited by accidental occupancy of the **R1** drift chambers

Low energy charged Background due to lack of magnetic shielding.



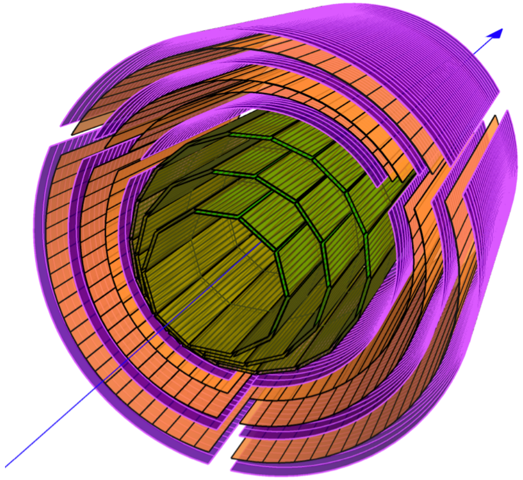
Occupancy (%)

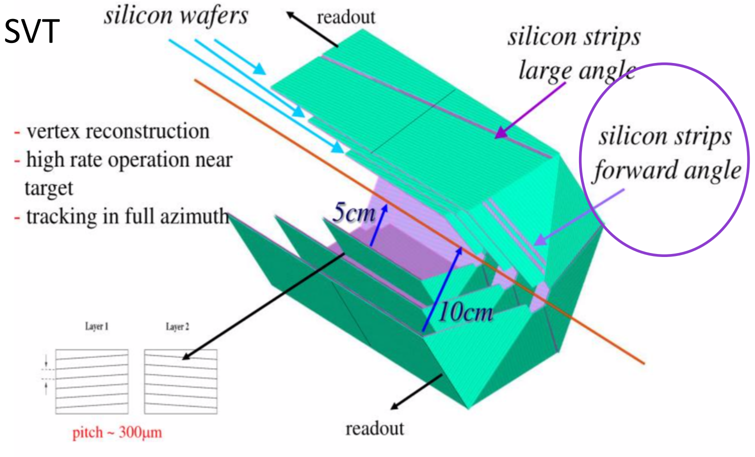
RI	Shift	R1	R2	R3
CLAS12 @ 11		**2.6**	**0.76**	**1.18**
CLAS12 @ 24		**2.8**	**0.77**	**1.23**
CLAS12 @ 24	**+20 cm**	**2.2**	**0.74**	**1.13**
CLAS12 @ 24	**+40 cm**	**1.5**	**0.75**	**1.13**
CLAS12 @ 24	**+60 cm**	**0.83**	**0.77**	**1.14**

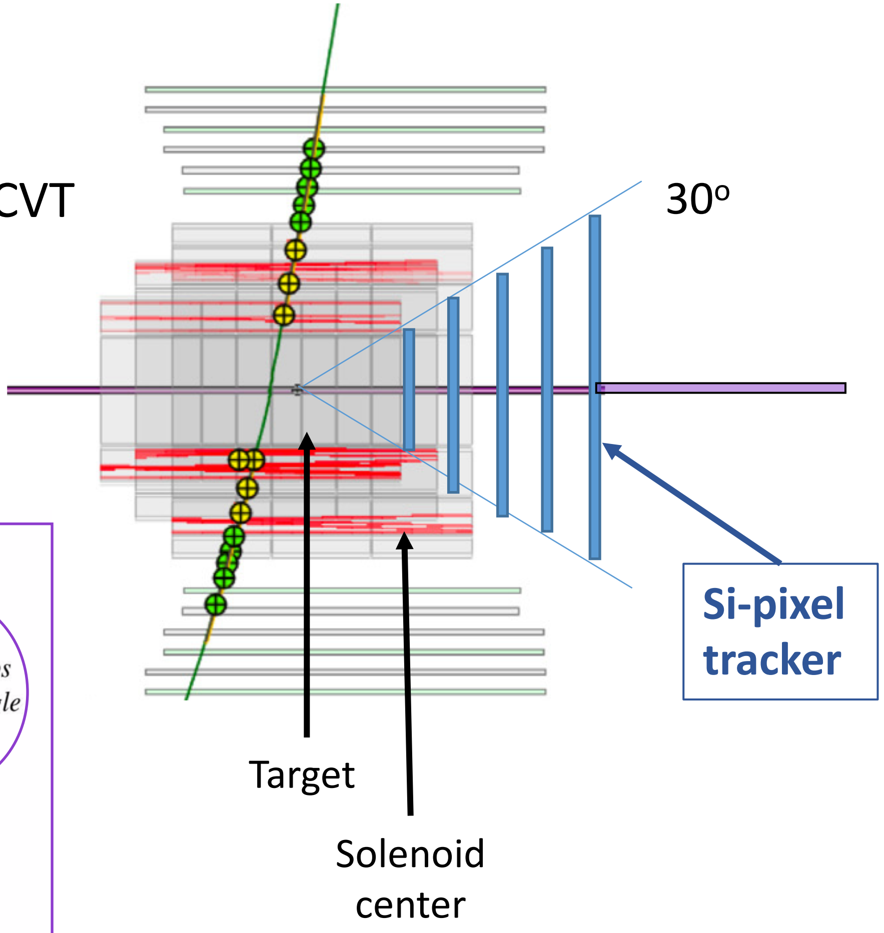
Shift R1 horizontally by ~ 50cm downstream for occupancy similar to R3. This should allow running CLAS12 at **twice luminosity** from current status.

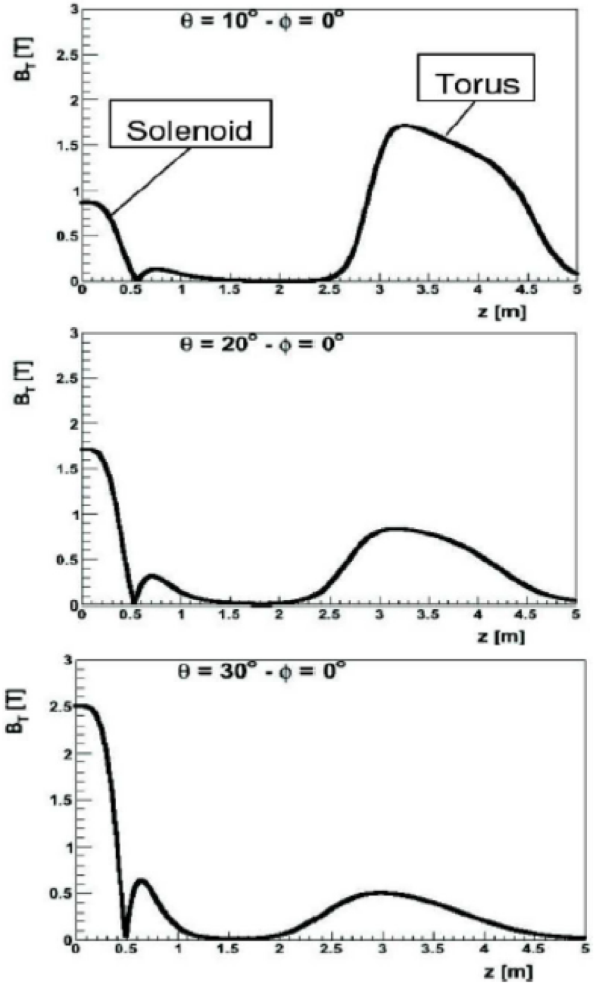
Courtesy: Z. Meador, L. Elouadrhiri

Improving forward tracking & vertexing (concept)









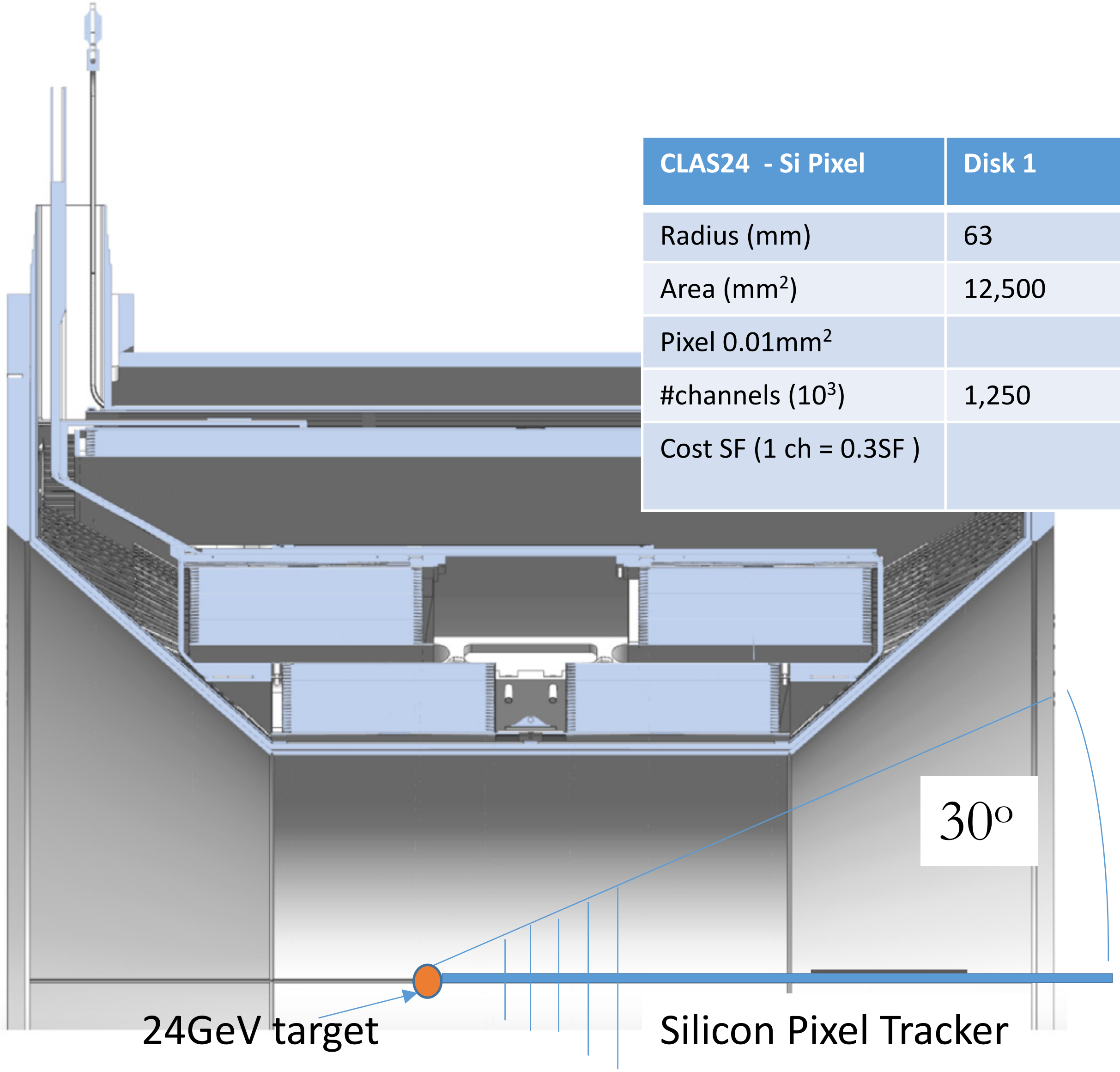
CLAS12 + Silicon pixel tracker

Silicon Pixel Tracker cost estimate
(CMS phase 2, upgrade)

Y. Gotra

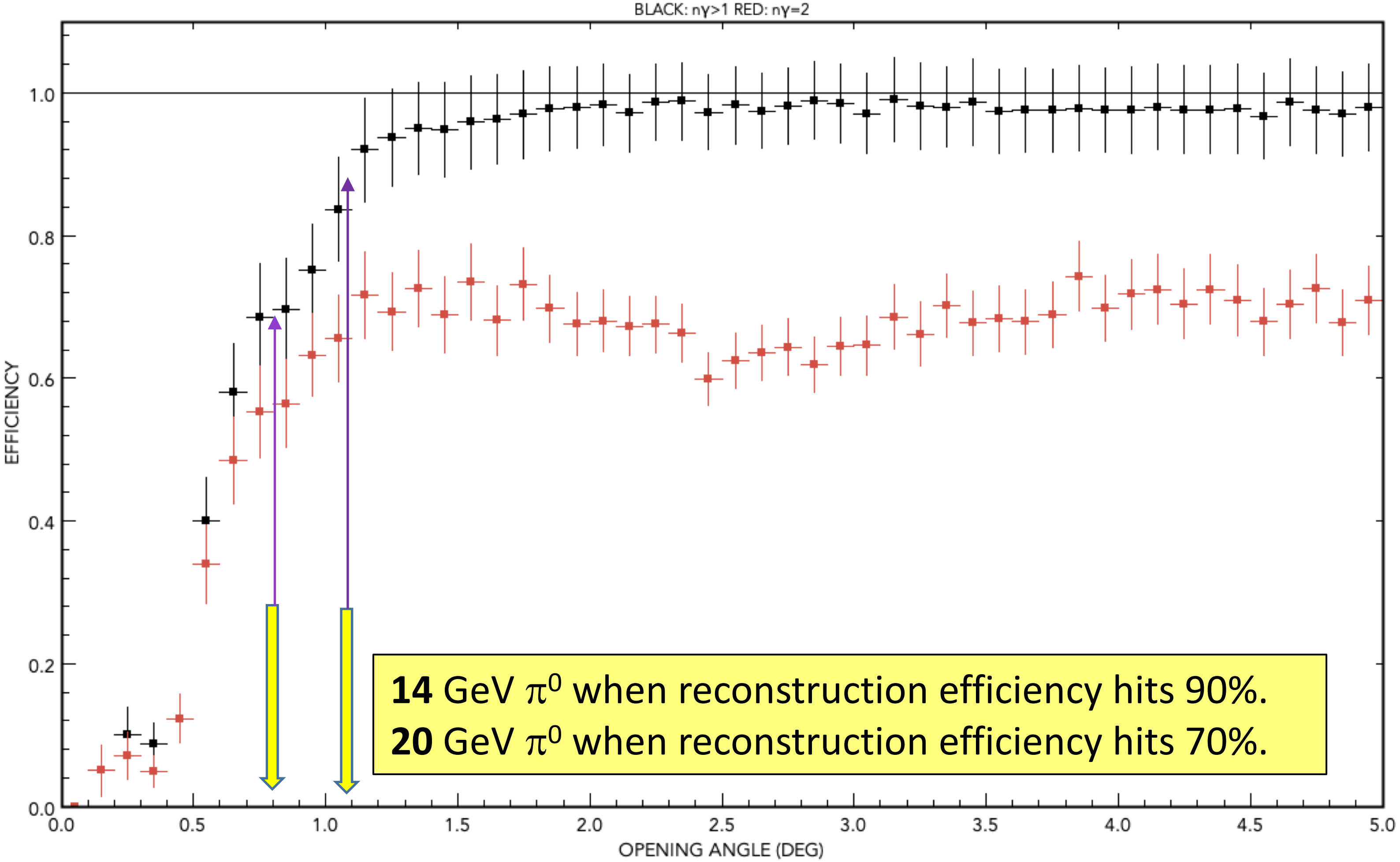
CLAS24 - Si Pixel	Disk 1	Disk 2	Disk 3	Disk 4	Disk 5	total
Radius (mm)	63	83	103	123	143	
Area (mm^2)	12,500	21,600	33,300	47,500	64,300	179,200
Pixel 0.01mm^2						
#channels (10^3)	1,250	2,160	3,330	4,750	6,430	17,920
Cost SF (1 ch = 0.3SF)						**5,376,000+ inflation**

Pixel size : 100 x 100 μm



π^o and γ detection in ECAL

GEMC simulations



2 or more photons are reconstructed

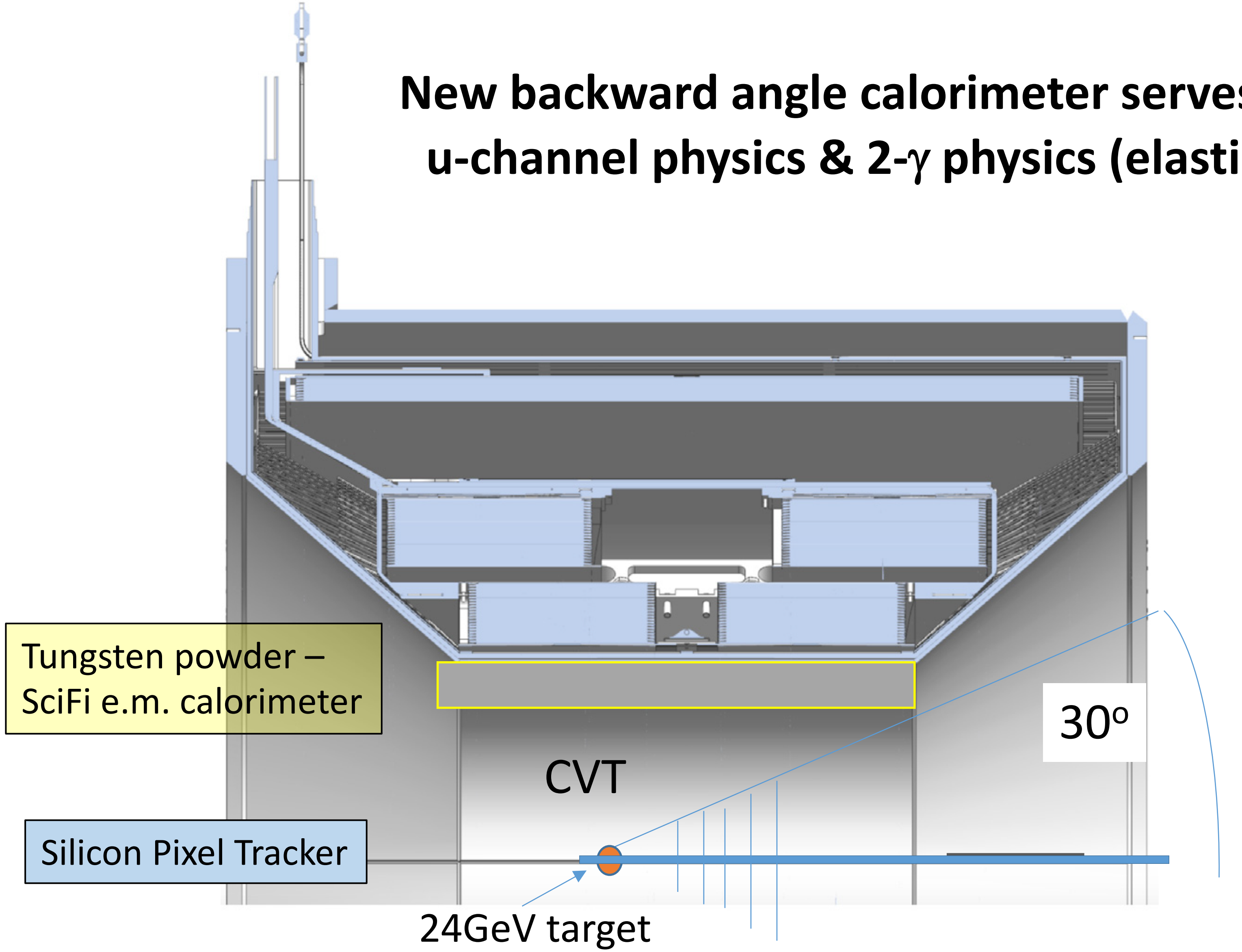
Exactly 2 photons are constructed

Courtesy: C. Smith

- At 24 GeV beam energy most π^0 events will be reconstructed in ECAL.

CLAS12 + $\gamma/e^{+/-}$ detection at large angles

New backward angle calorimeter serves both u-channel physics & 2-γ physics (elastic ep)



Prototype.
Y. Sharabian

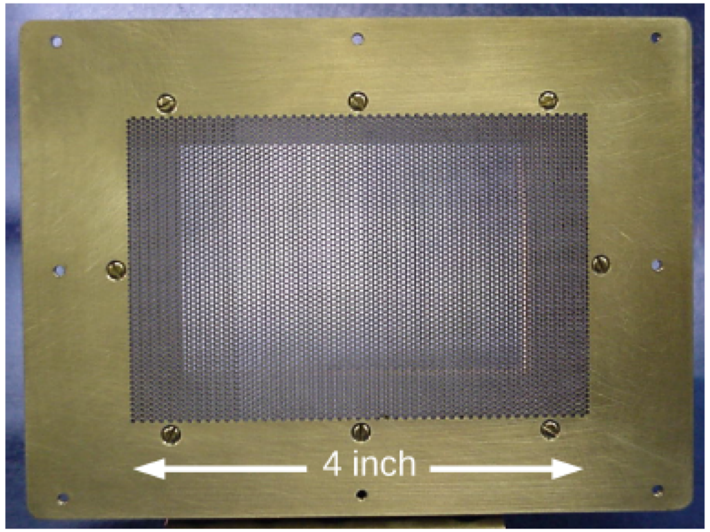


Figure 3: Active volume casing. Perforated area of $L \times H$ = 4"×2.626"

Electron detection at ~0 degrees?

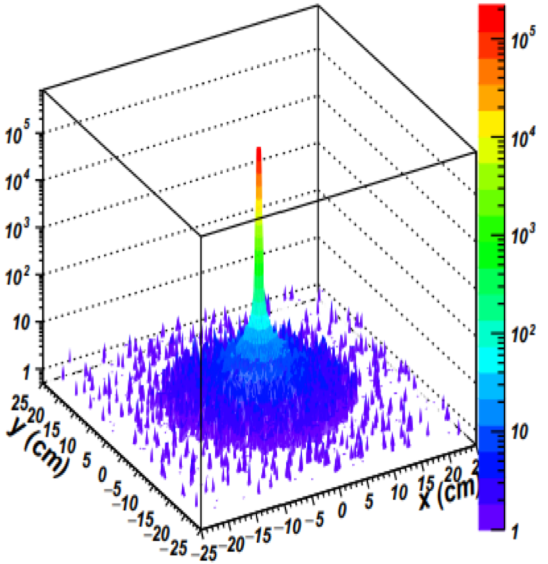
- We need to deal with several sources of electrons scattered at ~0 degrees.
  - **Non-interacting beam electrons** undergoing multiple scattering in target ~$\mathbf{5x10^{11}sec^{-1}}$
  - **Moller scattered electrons** – with energy range from $\mathbf{E_0/2 – E_0}$. This rate is orders of magnitude higher than electrons from hadronic interactions.
  - **Electron bremsstrahlung** in hydrogen target $\mathbf{E = E_0 – E_\gamma}$
  - **Hadronic interaction rate –** at luminosity 10^{35} $cm^{-2}s^{-1}$ this rate is $\mathbf{5x10^6sec^{-1}}$
  - **The events of interest** – hadronic events with cross sections of ~ 0.5nb. Scattered electron energy range: 2 to 14 GeV, to produce states above 4 GeV cc-bar + meson. For $\mathbf{Z_c(3900)}$ **~** $\mathbf{50sec^{-1}}$.

The electron rates are much too high to consider detecting all electrons at 0 degree.

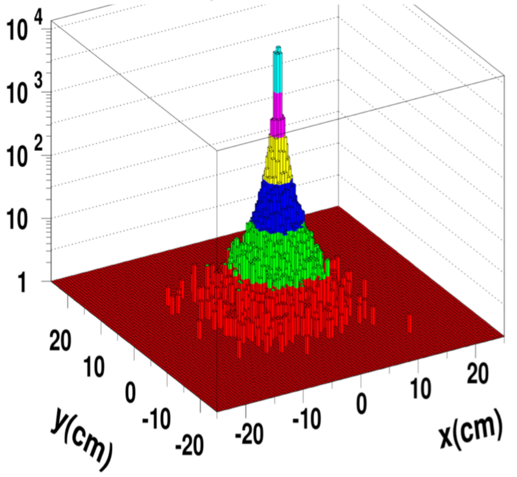
What are remedies that we may apply?

0-degree events are in 2 categories

- 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(10GeV).
- 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 in the range 1-14GeV.
- This should be studied in simulations to determine what magnitude in instantaneous luminosity can be achieved.
- Note that the Torus magnet open bore of ~ 6 cm accommodates ~0.75° scattering angle without interfering materials.



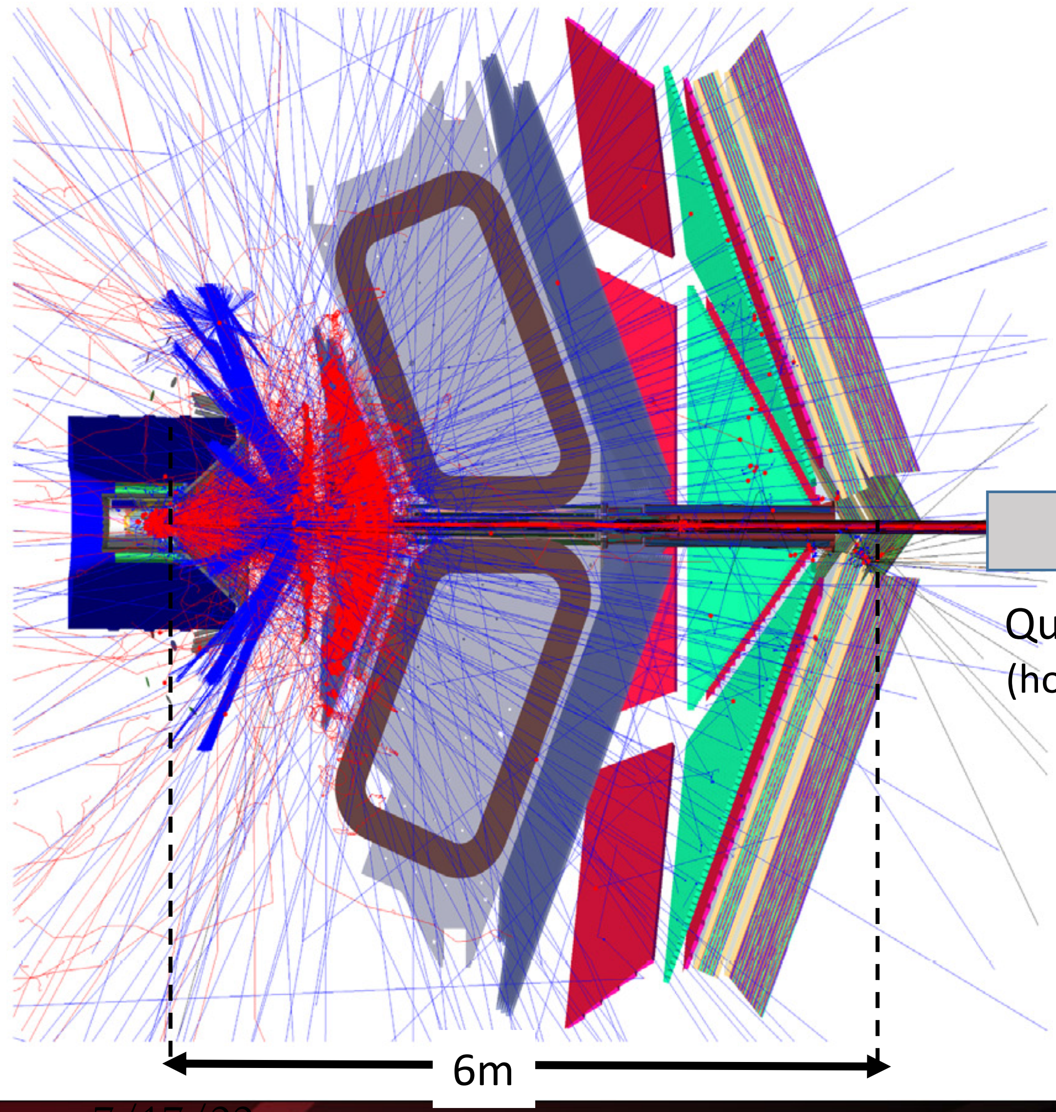
GEMC e.m. background



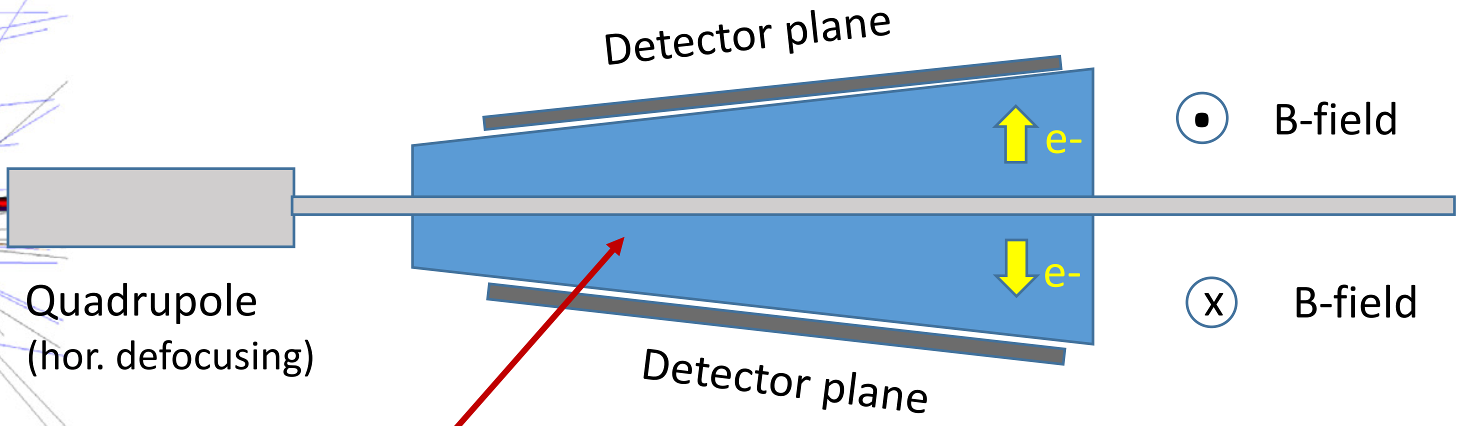
Pythia-8 for Q^2=0 events show broader central peak.

Courtesy: H. Avakian, Z. Meador , L. Elouadrhiri

0-degree energy tagging system (schematic)



Horizontal plane in Hall B



Dipole tagging magnet
Energy range 1 – 14 GeV

Summary

- **An energy upgrade of JLab to 20+ GeV would open up high impact science not reachable at the currently available 10.6 GeV beam energy. They include:**
  - A program related to quark and gluon GPDs and mechanical properties
    - DVCS at small x_B and in a large t-range
    - J/ψ production at threshold in a wide range of x_B and t
    - Time-like Compton scattering in wide kinematic range
  - Science with positron beam and u-channel processes
    - Both require CLAS12 upgrade with e.m. large angle calorimeter.
  - Spectroscopy involving heavy quarks (c-cbar)
    - Systematics of X, Y, Z states and pentaquarks, discussed on example of $Z_c(3900)$
- The first program would be an extension of the program with CLAS12 with improvements in tracking, vertexing and particle ID.
- The positron program and u-channel physics both require a new large angle e.m. calorimeter
- The exotic spectroscopy would require a near 0-degree electron tagging spectrometer in the energy range from about 1 to 14 GeV. The concept has been described, but it requires detailed simulations and a realistic layout of the spectrometer magnet and detectors to make a statement about achievable luminosity.
- No thorough cost estimate has been attempted for the 0-degree spectrometer. The Si-pixel tracking detector was estimated at < $10M for 100μm squared pixels (prototypes are been developed for EIC).