Double Deeply Virtual Compton Scattering with SoLIDμ spectrometer

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Jefferson Laboratory Hall A
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uCLAS12 collaboration meeting

U.S. DEPARTMENT OF ENERGY | Office of Science

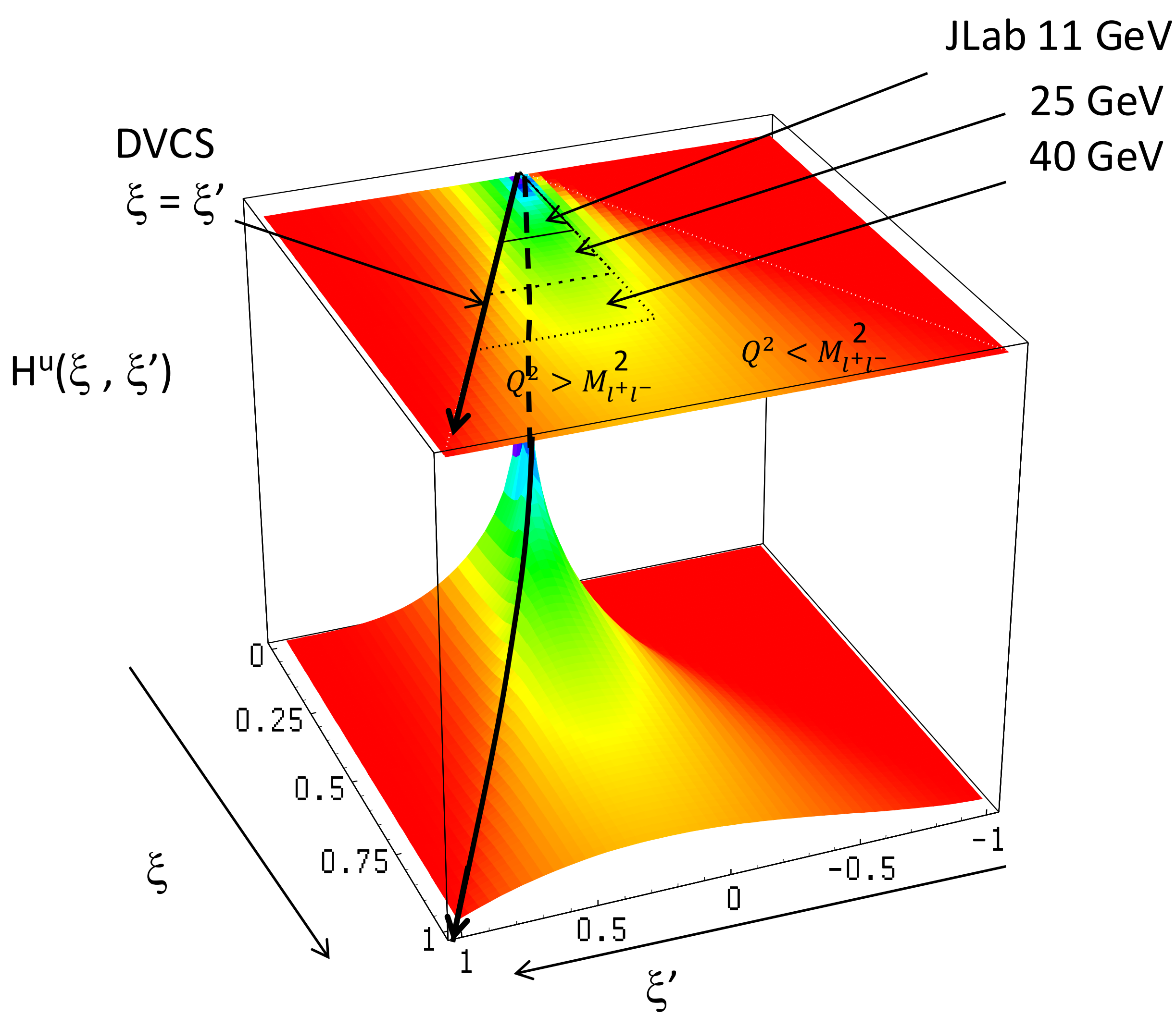
Jefferson Lab
Thomas Jefferson National Accelerator Facility

JSA

Overview

- Double Deeply Virtual Scattering
- SoLIDμ setup
- Muon detector
- Simulation study
- Physics projections
- Beam time request
- Possible dedicated experiment and developements
- Conclusion

Kinematical coverage

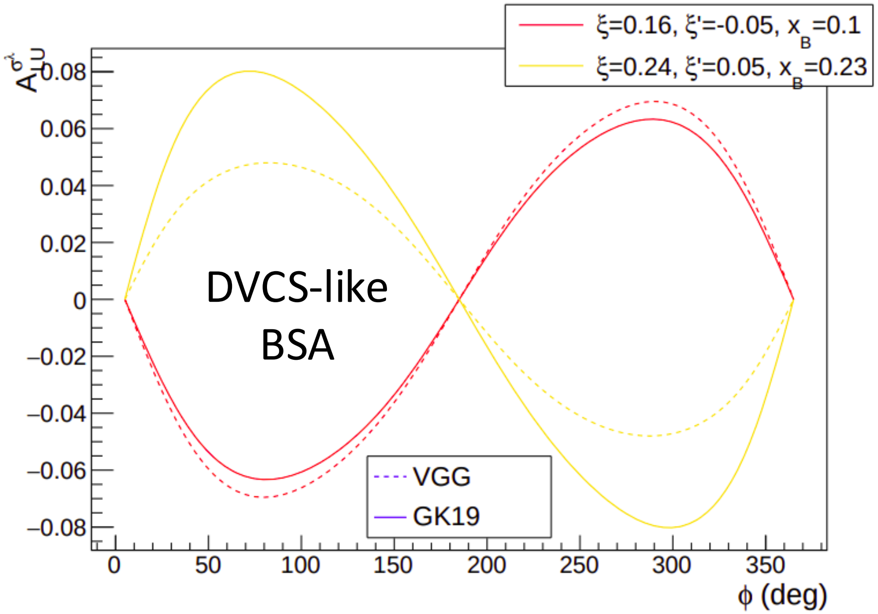


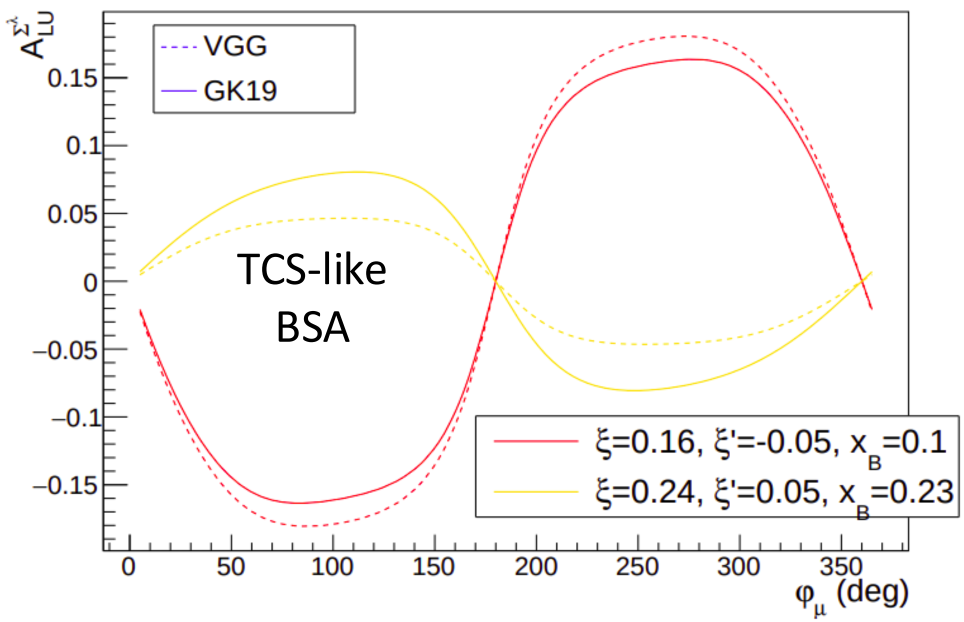
- DVCS only probes η = ξ line
- Example with model of GPD H for up quark
- Jlab : $Q^2>0$
- Kinematical range increases with beam energy (larger dilepton mass)

Experimental observables

$$\begin{Bmatrix} A_{\mathrm{LU}}^{\sin\phi} \\ A_{\mathrm{LU}}^{\sin\varphi_\mu}\end{Bmatrix} = \frac{1}{\mathcal{N}}\int_{\pi/4}^{3\pi/4} d\theta_\mu \int_0^{2\pi} d\varphi_\mu \int_0^{2\pi} d\phi \begin{Bmatrix} 2\sin\phi \\ 2\sin\varphi_\mu\end{Bmatrix} \frac{d^7\overrightarrow{\sigma} - d^7\overleftarrow{\sigma}}{dx_B\,dy\,dt\,d\phi\,dQ'^2\,d\Omega_\mu}$$

$$\propto \Im\mathrm{m}\left\{F_1\mathcal{H} - \frac{t}{4M_N^2}F_2\mathcal{E} + \xi(F_1+F_2)\widetilde{\mathcal{H}}\right\},$$



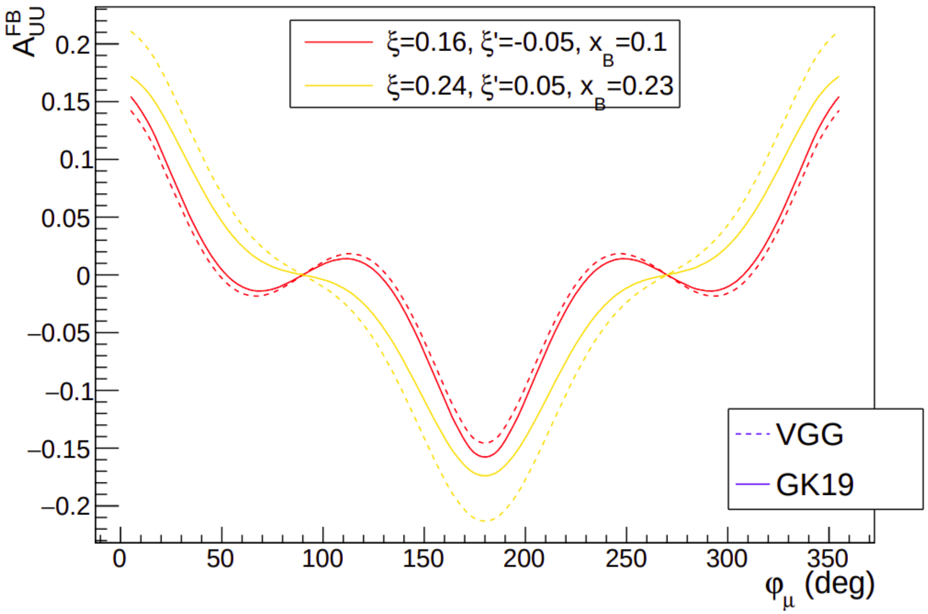


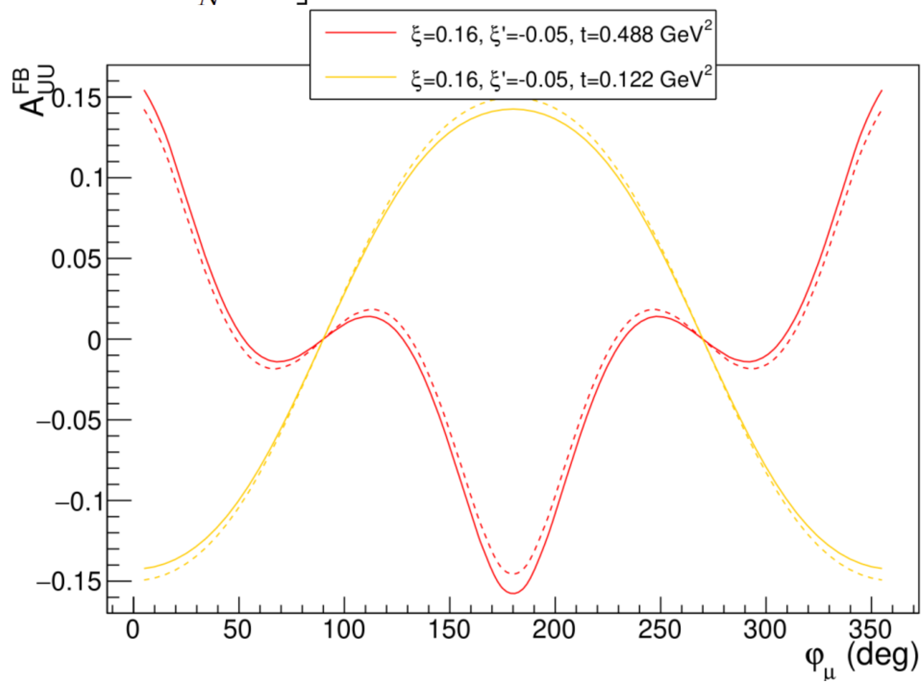
- Access to the imaginary part of CFFs.
- Sign change when transitioning from ξ'>0 ($Q^2>Q'^2$) to ξ'<0 ($Q^2<Q'^2$).
- TCS(DVCS)-like BSA enhances the amplitude in the ξ'<0(ξ'>0) region.

Experimental observables

$$\begin{Bmatrix} A_{\mathrm{CA}}^{\cos\varphi_\ell} \\ A^{\cos\varphi_\ell}\end{Bmatrix} = \frac{1}{\mathcal{N}}\int_{\pi/4}^{3\pi/4} d\theta_\ell \int_0^{2\pi} d\phi \int_0^{2\pi} d\varphi_\ell \; 2\cos\varphi_\ell \begin{Bmatrix} (d\sigma^+ + d\sigma^-)/2d\Omega_\ell d\phi \\ d\sigma^-/d\Omega_\ell d\phi \end{Bmatrix},$$

$$\propto -\frac{\xi'}{\xi}\,\Re\mathfrak{e}\left[F_1\mathcal{H} + \frac{\xi^2}{\xi'}(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4M_N^2}F_2\mathcal{E}\right] .$$





- Access to the real part of CFFs with angular asymmetries
- Curvature sign change is a highly-discriminating feature for models

Experimental observables

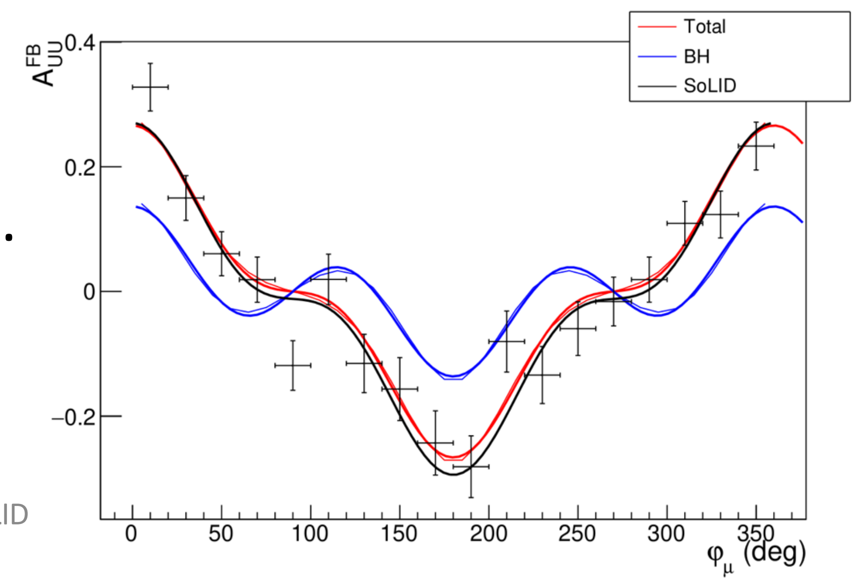
cosϕ moment can be accessed with the muon charge asymmetry

$$A_{UU}^{FB}(\varphi_\mu) = \frac{d^5\Sigma_{UU}(\varphi_{\mu^-}) - d^5\Sigma_{UU}(\varphi_{\mu^-}+\pi)}{d^5\Sigma_{UU}(\varphi_{\mu^-}) + d^5\Sigma_{UU}(\varphi_{\mu^-}+\pi)} = \frac{d^5\Sigma_{UU}(\varphi_{\mu^-}) - d^5\Sigma_{UU}(\varphi_{\mu^+})}{d^5\Sigma_{UU}(\varphi_{\mu^-}) + d^5\Sigma_{UU}(\varphi_{\mu^+})} = A_{UU}^{\mu^\pm}(\varphi_\mu)$$

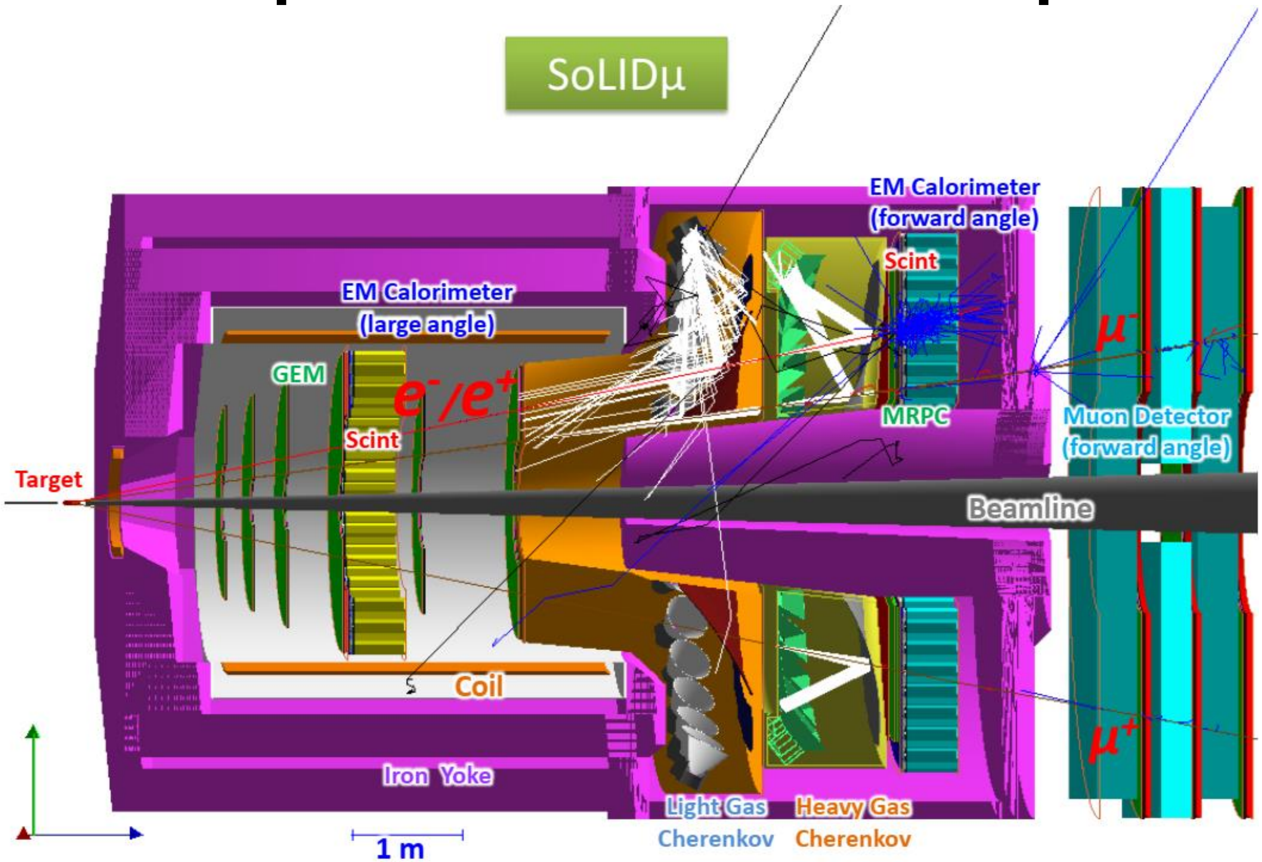
$$A_{UU}^{\mu^\pm}(\varphi_\mu) = \frac{d^5\Sigma_{BH_{12}} + d^5\Sigma_{\mathcal{I}_2}}{d^5\Sigma_{BH_1} + d^5\Sigma_{BH_2} + d^5\Sigma_{DDVCS} + d^5\Sigma_{\mathcal{I}_1}}$$

$$\frac{d^4\sigma_{INT}}{dQ'^2dtd\Omega} = -\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{m_p}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}[\cos(\phi)\frac{1+\cos^2(\theta)}{\sin(\theta)}\mathrm{Re}\tilde{M}^{--}$$
$$-\cos(2\phi)\sqrt{2}\cos(\theta)\mathrm{Re}\tilde{M}^{0-} + \cos(3\phi)\sin(\theta)\mathrm{Re}\tilde{M}^{+-} + O(\frac{1}{Q'})],$$

- There are contributions from cos(ϕ) and cos(3ϕ) modulations to the μCA.
- cos(ϕ) can be extracted from fits
- As BH is known, it can be subtracted

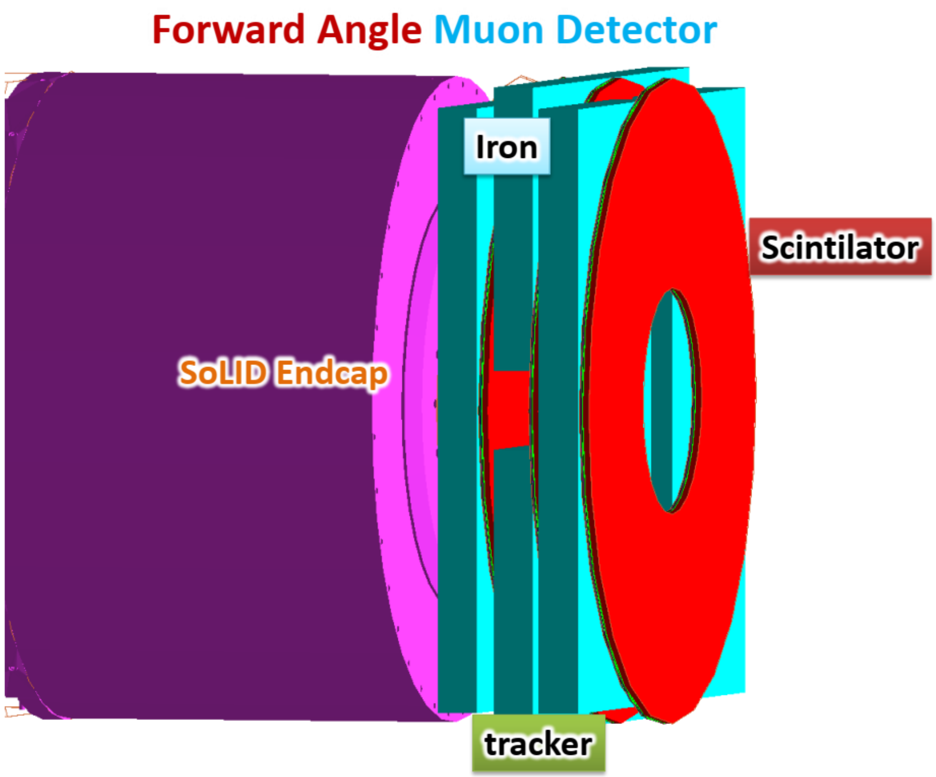


Experimental Setup



- Based on SoLID J/Psi and TCS setup with forward angle muon detector added
- Sharing beam time with added muon channels for J/Psi and TCS
- Forward Angle (FA) covers 8.5-16.5deg and Large Angle (LA) covers 18-30deg

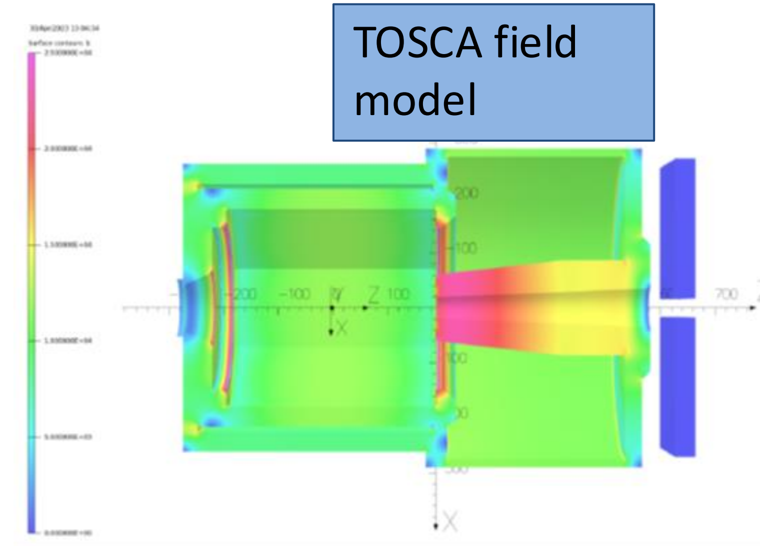
Forward Angle Muon Detector (FAMD)

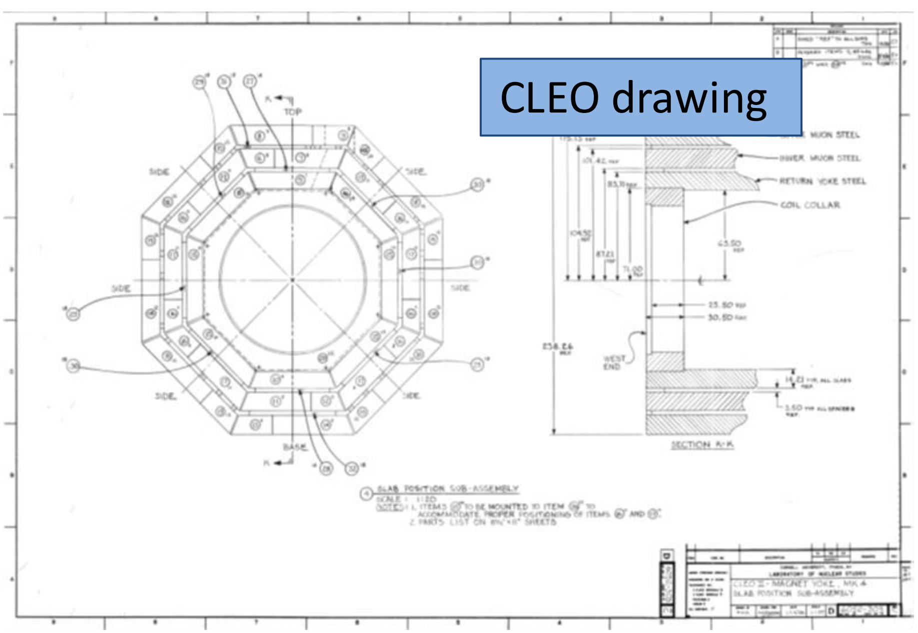


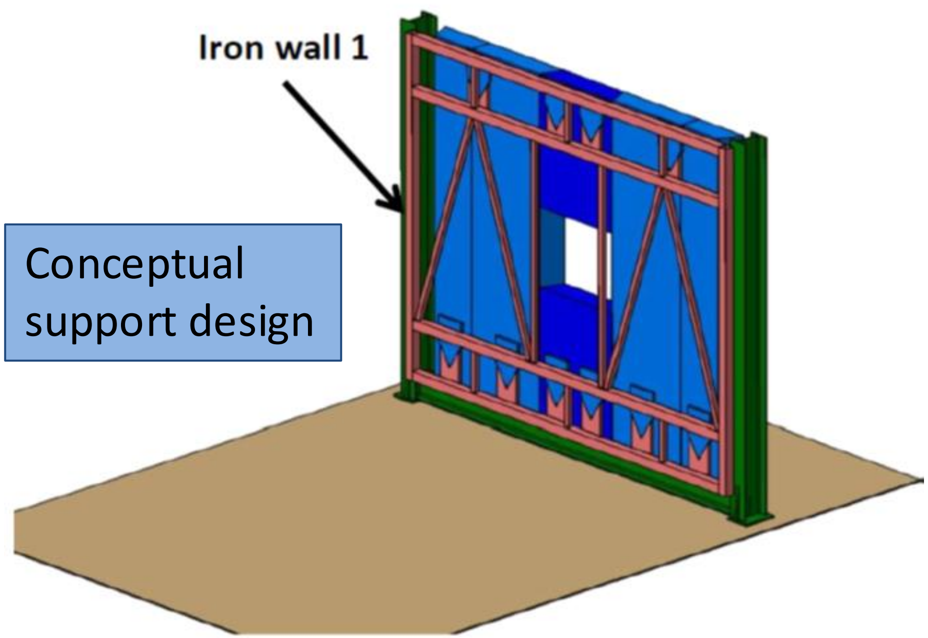
- 3 layers of iron for pion blocking
- 3 layers of μRWell trackers for tracks in FAMD to connect with tracks in SoLID inner GEM trackers
  - track resolution from SoLID inner trackers only
- 3 layers of scintillators for pion suppression and muon PID. And last layer for trigger

Iron of FAMD

- Reuse 6 of 8 CLEO octagon outer layer iron
- Each one is about 36x254x533cm
- No problem with space
- Field (<10G),force(<1N),torque(<2Nm) are small

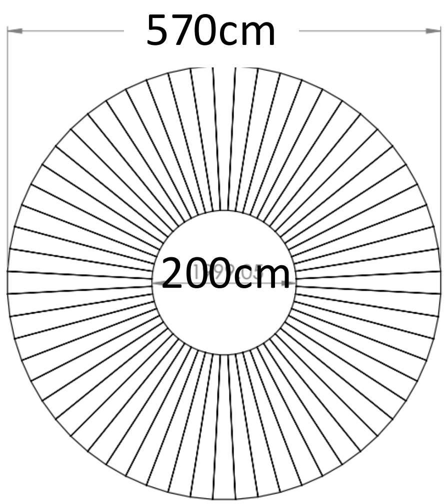




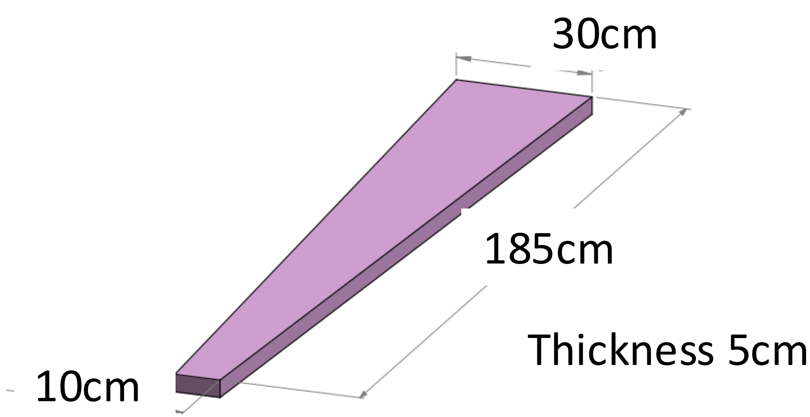


Scintillators of FAMD

- 3 layers of scintillator planes
- Each plane has 60 azimuthal segments
- Readout with light guide and PMTs from both inner and outer radial ends
- Design similar to CLAS12 forward scintillator and SoLID large angle scintillator with similar performance



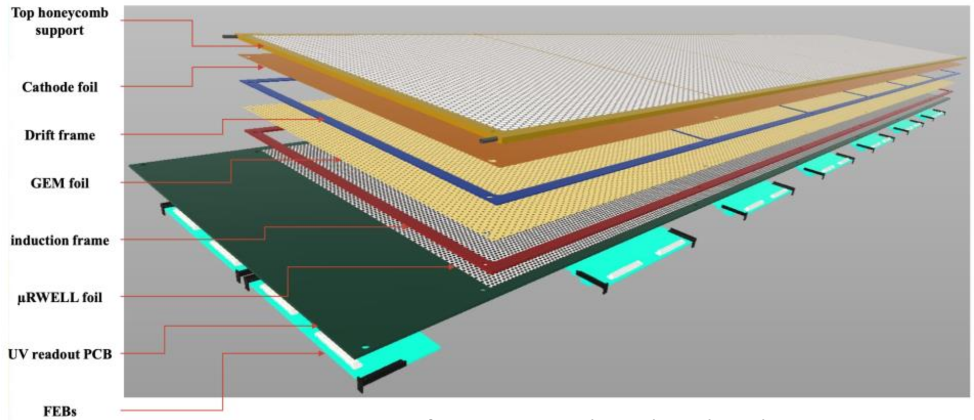
A plane of scintillator detector



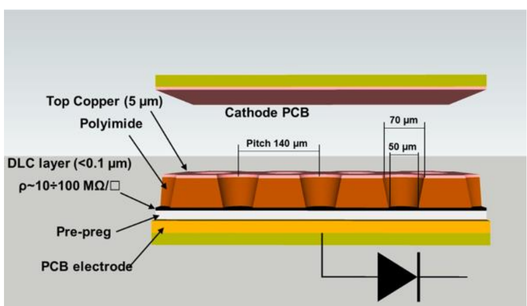
A module of scintillator detector

µRWell trackers of FAMD

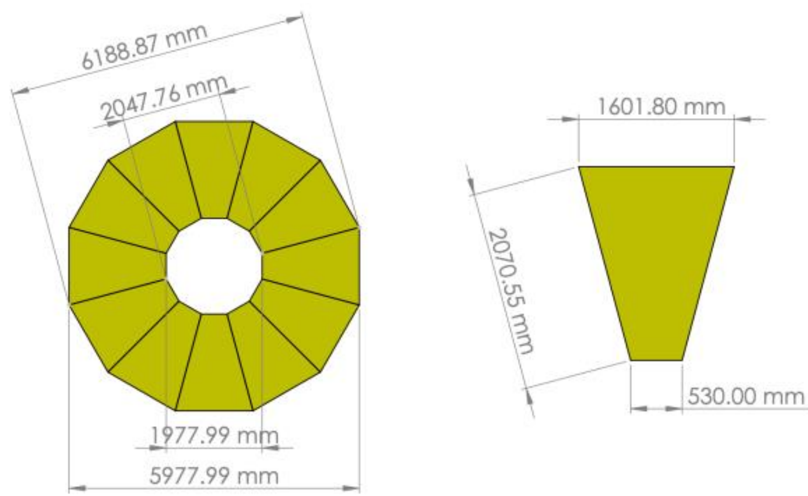
- µRWell with good rate capability and lower cost than GEM
- VMM electronics
- 2D UV strips with capacitive charge sharing to have rate 30KHz/cm2 and position resolution of 1 mm



μRWELL Detector for EPIC outer barrel tracking layer



μRWELL Detector – G. Bencivenni *et al* 2019 *JINST* **14** P05014



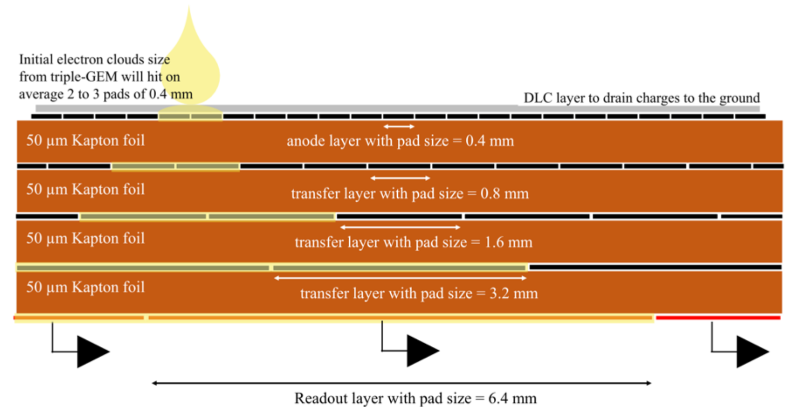
A plane of μRWELL detectors for muon detection

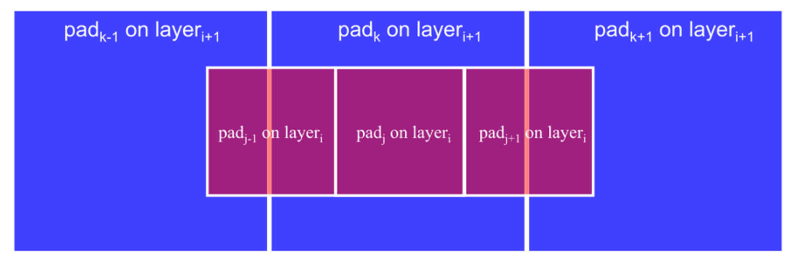
Muon Detector

- Use capacitive charge sharing technique to reduce total readout channels while maintain the same space resolution
- Works for all readout patterns – strip, pad, zigzag, …

With Capacitive charge sharing:

- Space resolution : 1 mm
- Total readout channel can be reduced to around 22K for all 3 layers combined
- Detector rate will be determined by the final readout strip width, larger strip width leads to lower detector rate capability
- For 22K readout channels, 1 mm space resolution, with capacitive charge sharing technique – rate capability: $\sim 30\ KHz/cm^2$ (assume 300 ns signal integral time)

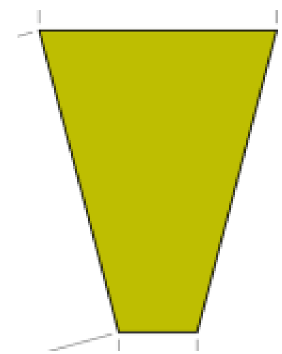




Concept for capacitive charge sharing – K. Gnanvo *et al, Nuclear Inst. and Methods in Physics Research, A 1047 (2023) 167782*

Scintillators of FAMD

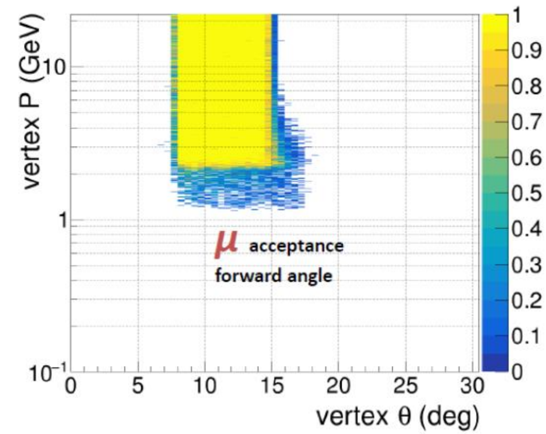
- Each plane has 60 azimuthal segments
- Readout with light guide and PMTs from both inner and outer radial ends
- Thickness 5cm and 150 ps time resolution
- Design similar to CLAS12 forward scintillator and SoLID large angle scintillator with similar performance

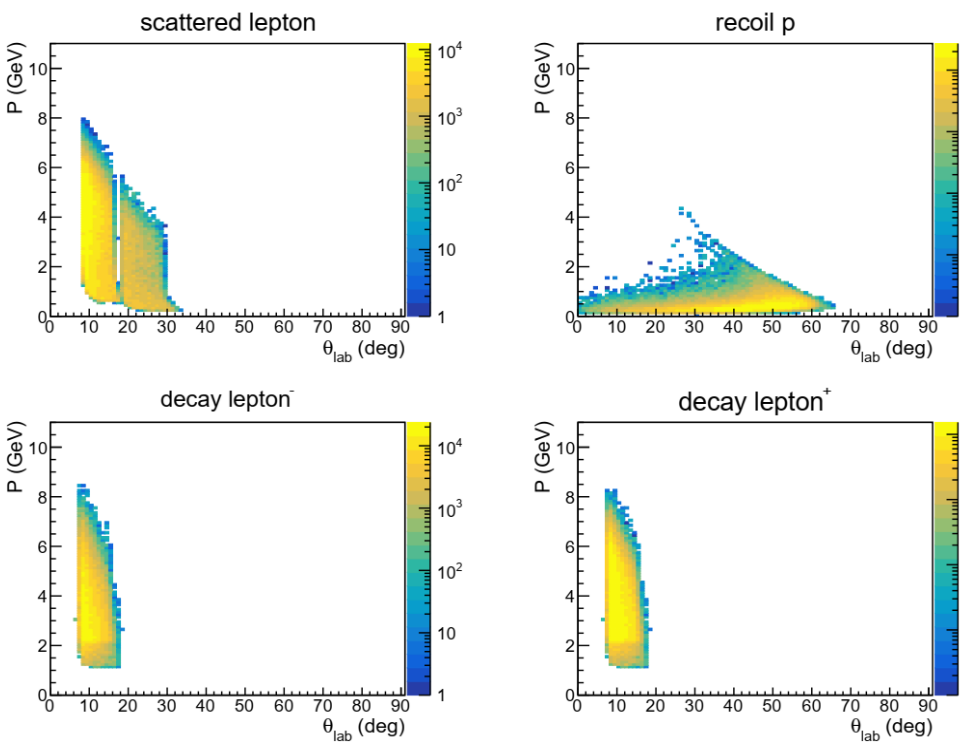


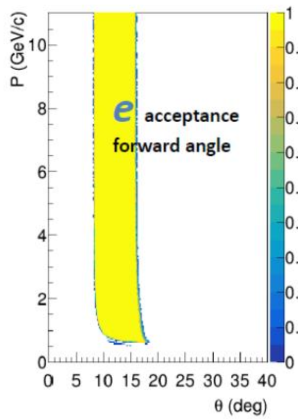
Event Acceptance

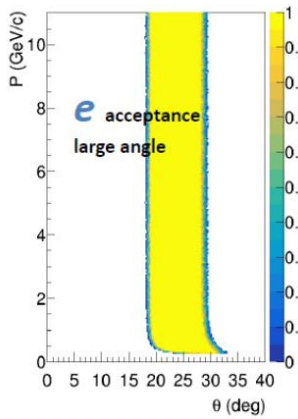
BH generator "grape-dilepton" used by HERA and verified by CLAS12

- Best topology 3fold(e+mu+mu): scattered e- at FA+LA, both muons at FA, proton not detected (shown below)
- Additional topology 4fold(e+mu+mu+p): scattered e- and recoil proton at FA+LA, both muons at FA





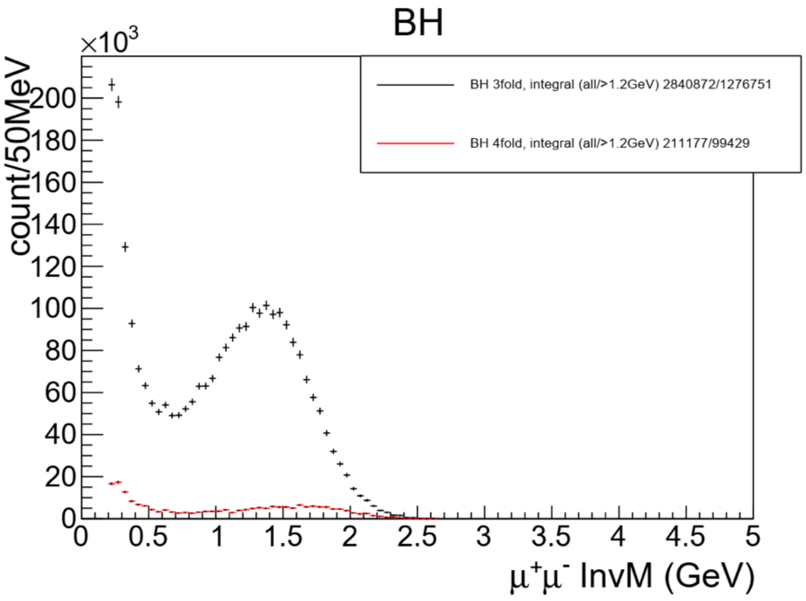


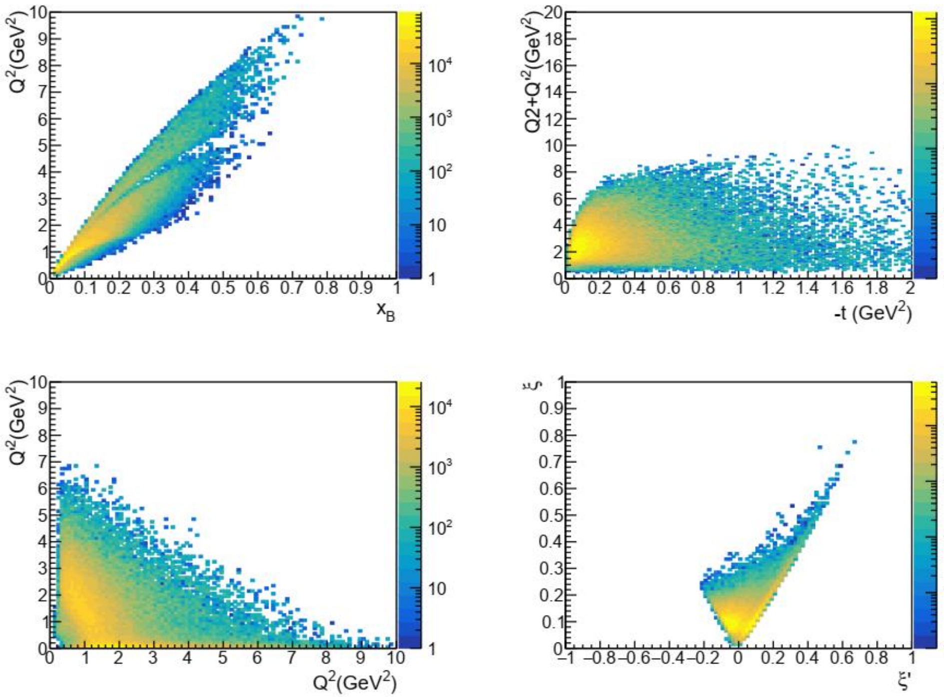


Event Distribution

BH generator "grape-dilepton" used by HERA and verified by CLAS12

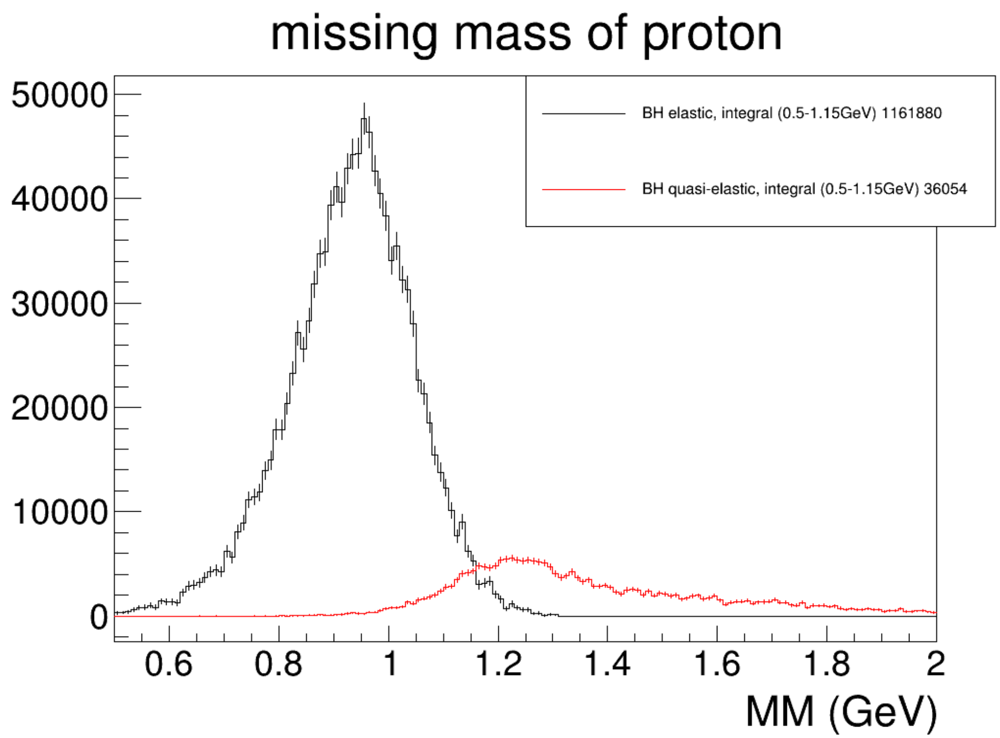
- 3fold BH events covers large kinematic range
- 0.7 overall detection efficiency
- Enough counts for 1.2e37/cm2/s lumi and 100 days to have multidimensional binning





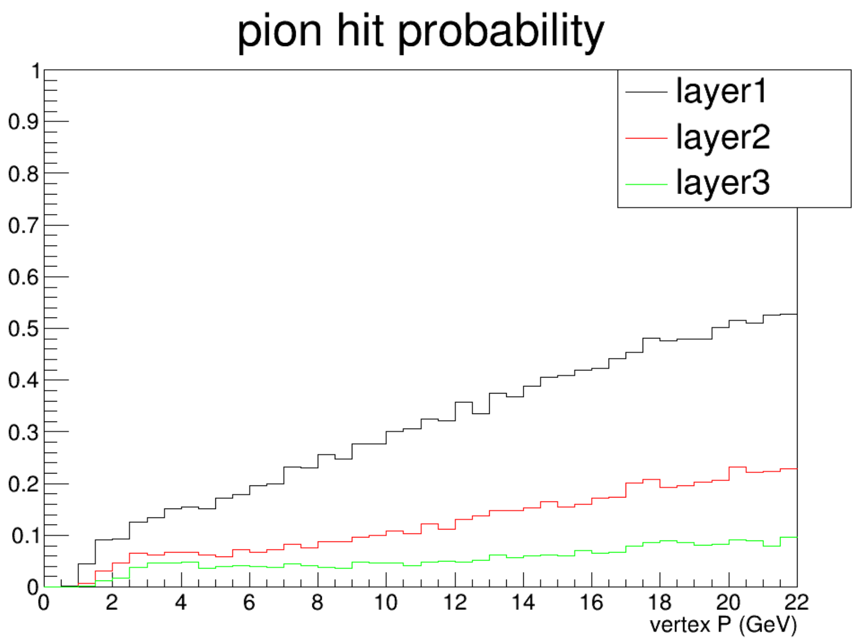
Exclusivity cut

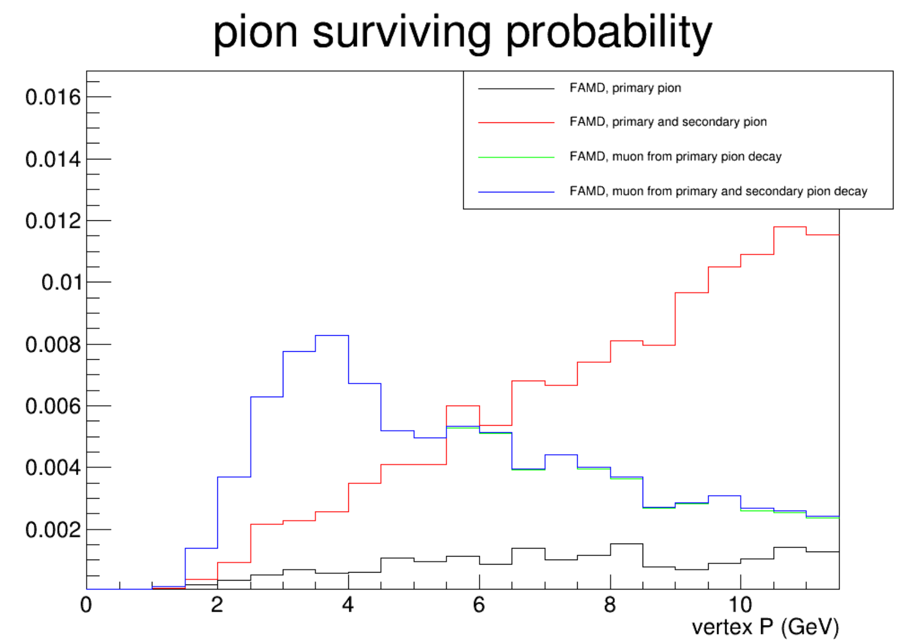
- Both BH with 4 final particles (elastic) and more than 4 particles (quasi-elastic) are generated by "grape-dilepton"
- Missing proton mass of 3 fold BH events with resolution from SoLID inner GEM trackers, for resonance free region (muon pair InvM>1.2GeV)
- 3-4% background left after cutting MM>1.15GeV



Pion blocking

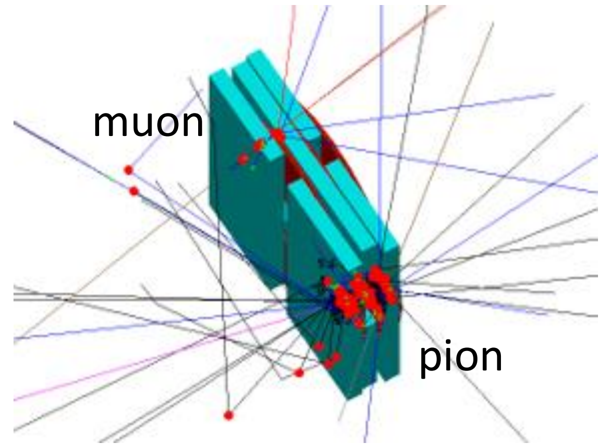
- Geant4 simulation of pions from target with some probabilities creating hits at FAMD
- "pion hit probability", hits of charged particles entering each layer, used for FAMD detector and trigger rate estimate
- "pion surviving probability", hits of pion and muon at the last layer of FAMD and a track passing all SoLID inner GEM trackers, used for physics event rate estimation

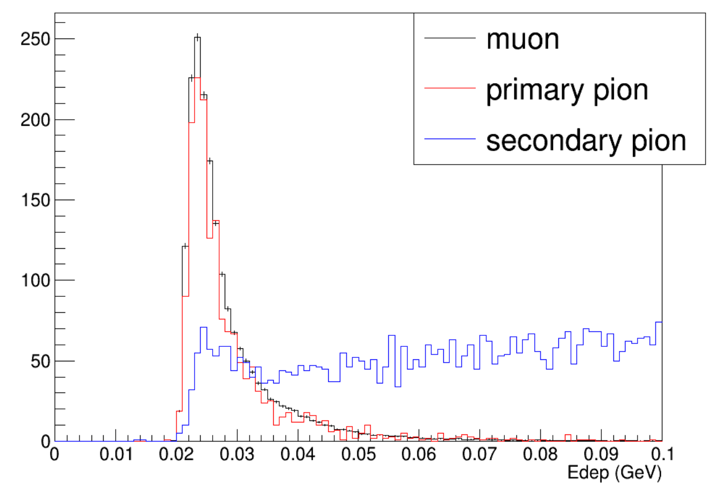




Pion suppression within FAMD

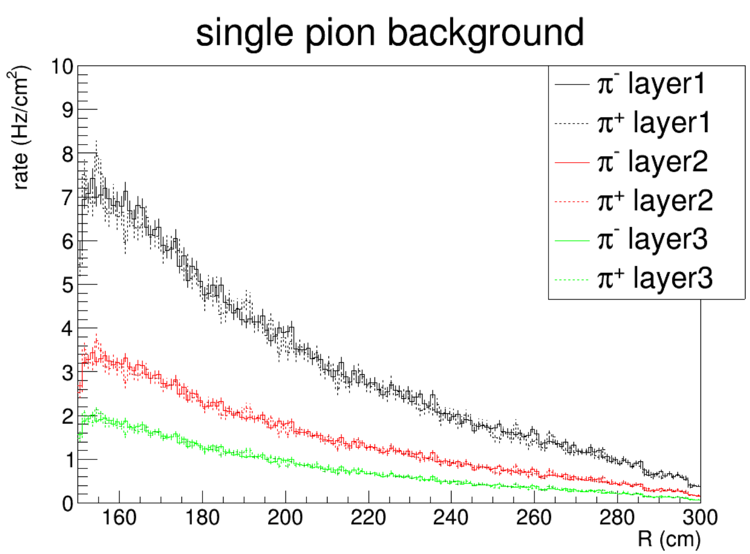
- Muons behave as Minimum Ionizing Particle (MIP)
- Pions often deposit more energy over 3 layers of scintillators.
- Use moderate pion suppression factor 2 from energy cut

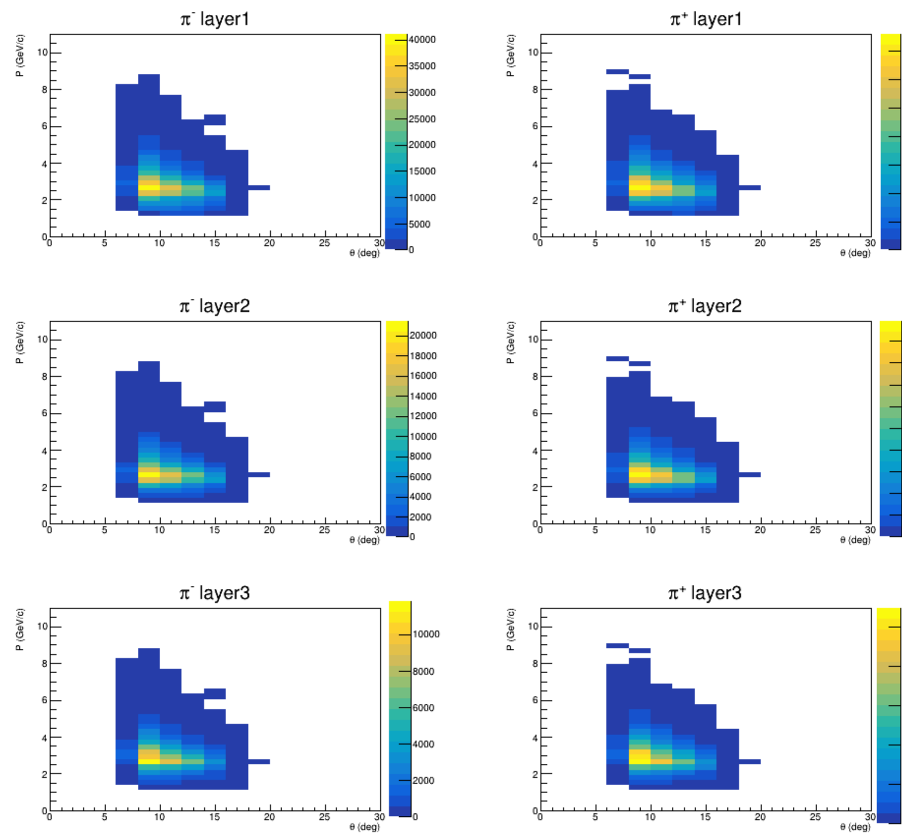




Single pion background

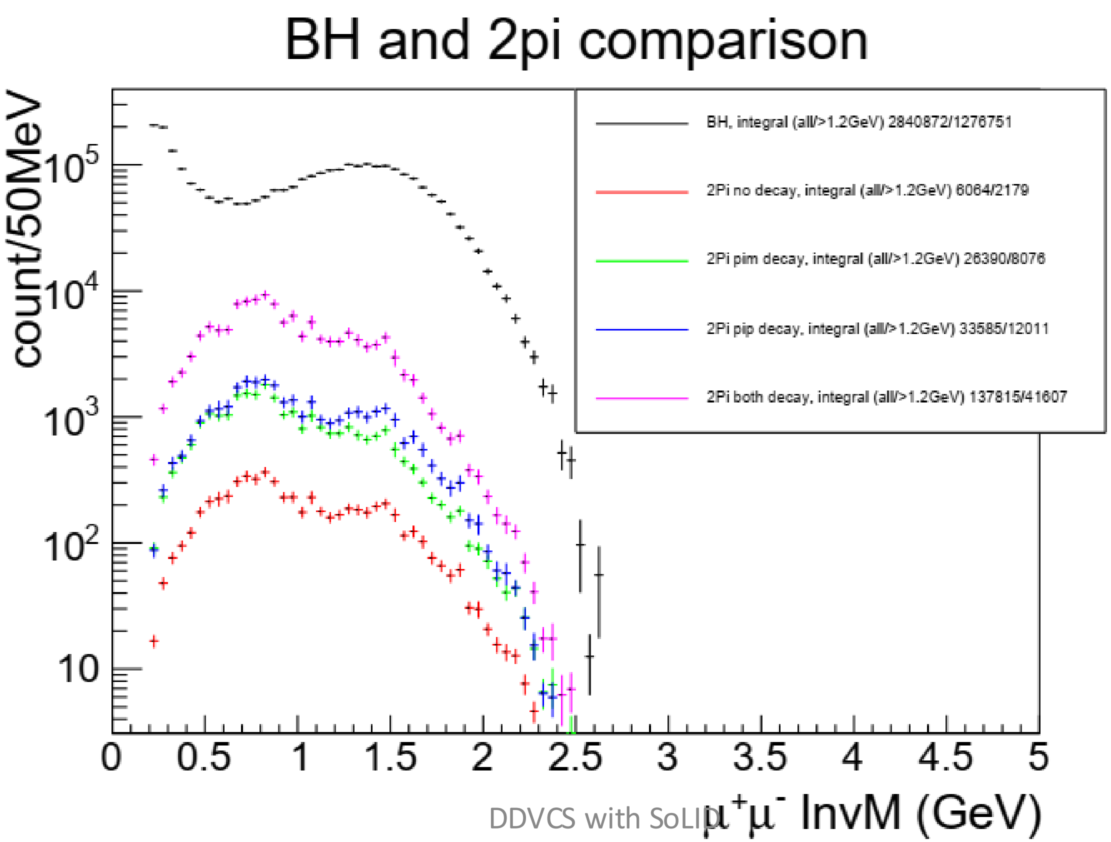
- Combining single pion generator "evgen_bggen" (pythia+MAID) events with "pion hit probability", study charged particle rate at 3 layers
- Adding a safety factor 2 to obtain single particle trigger 600khz rate at the last layer of scintillator. Coincidence of two hits from 2 different sectors (out of total 60 sectors) within 50ns time windows leads to 18khz final trigger rate
- Full simulation confirmed the result



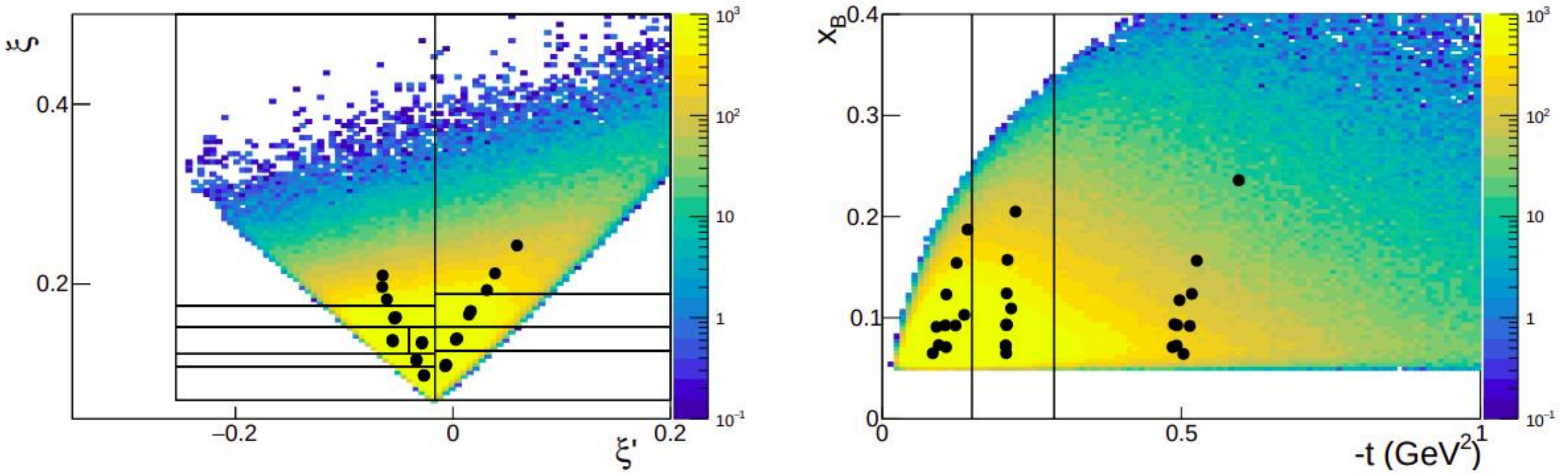


Two pion exclusive background

- Main physics background from two pion exclusive channel (missing mass cut won't reject it because pions and muons have similar mass)
- Combine event generator "twopeg" (fit to CLAS data) and "pion hit probability" with pion suppression factor 2, study "2pi" rate and compare to BH rate
- 5-7% background



Experimental projections

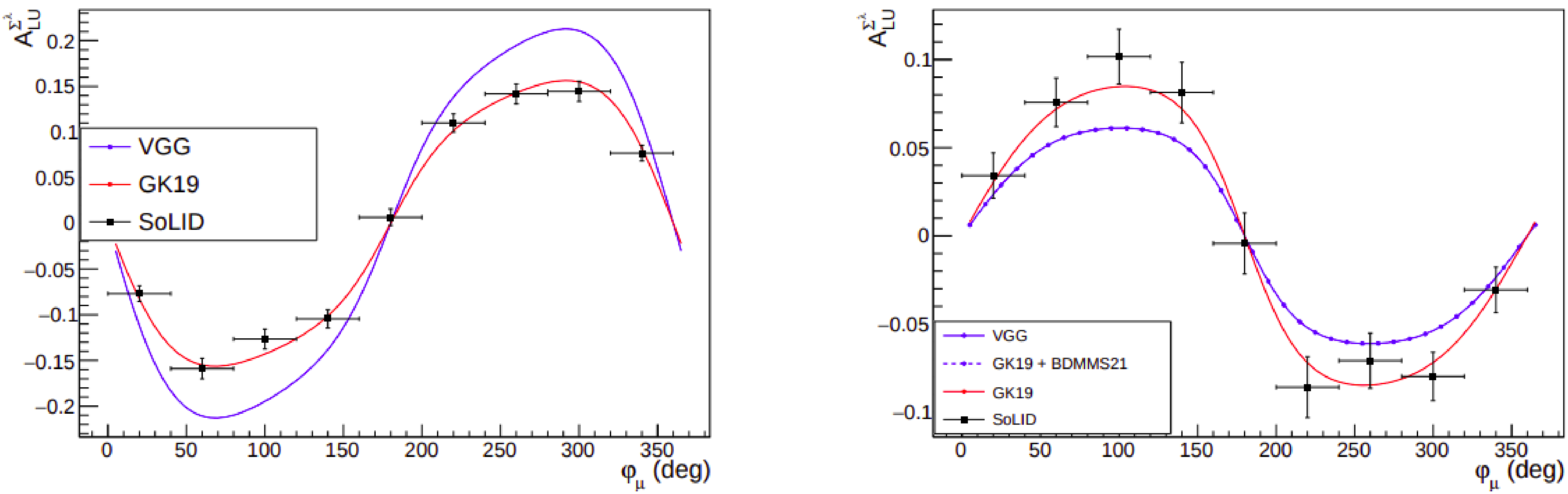


(a) (ξ', ξ) space.

(b) $(-t, x_B)$ space.

- 100 days would allow for exploratory measurements on a five-dimensional grid.

BSA experimental projections

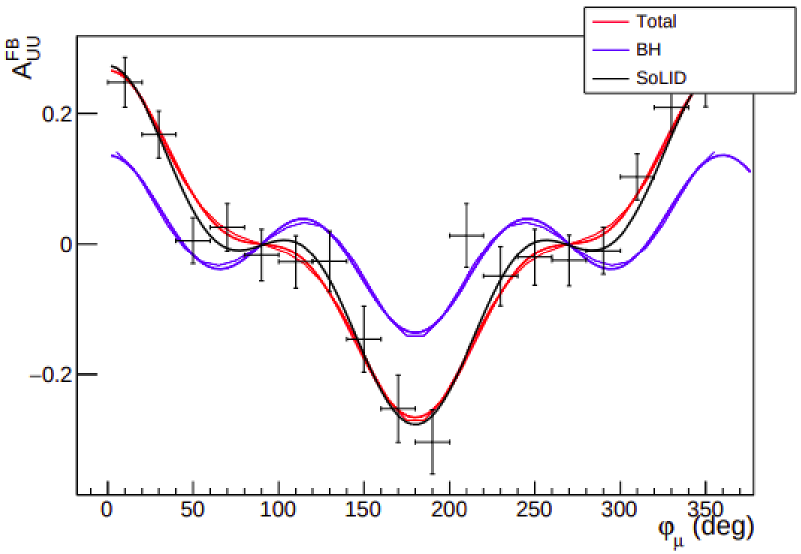


(a) TCS-like BSA in the TCS-like region (Bin 21). (b) TCS-like BSA in the full DVCS-like region.

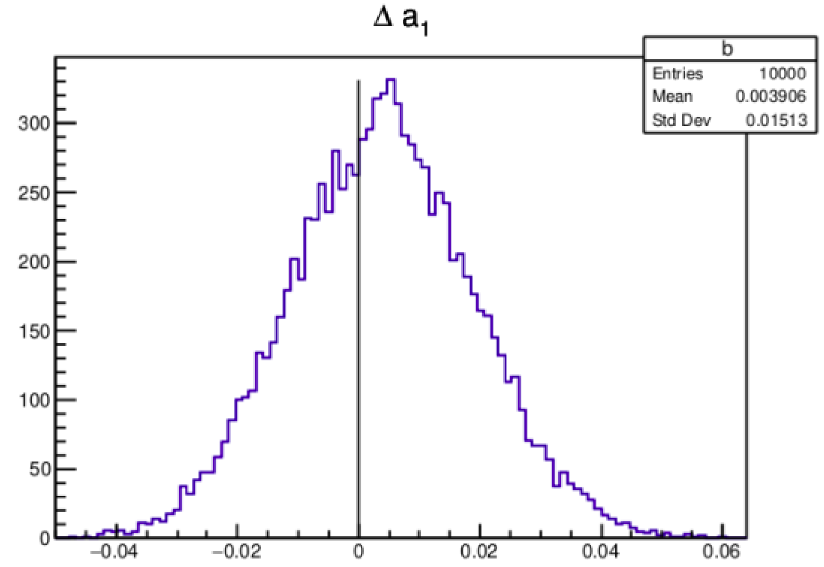
Figure 25: Sample TCS-like BSA projections.

- First-time measurements of the BSA sign change
- Possibility to constrain GPD models

μCA experimental projections



(a) μCA and the components entering the $\cos\varphi_\mu$ moment.

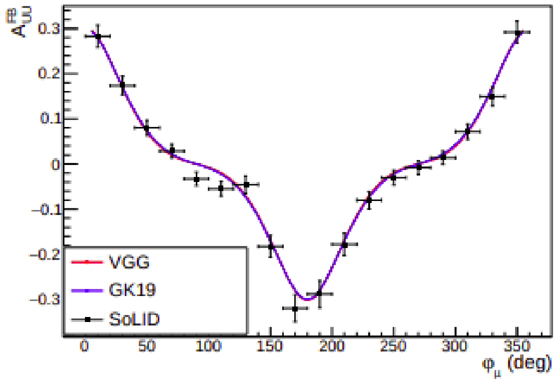


(b) Distribution of the $\cos\varphi_\mu$ moment of the μCA after 10k iterations.

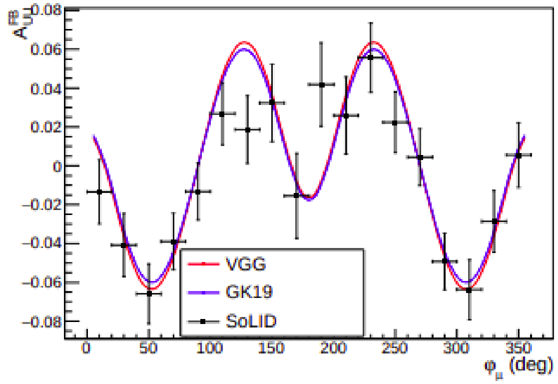
Figure 28: Extraction of $\cos\varphi_\mu$ moment of the μCA on bin 13.

Sample cos(ϕ) extraction with a 11% error.

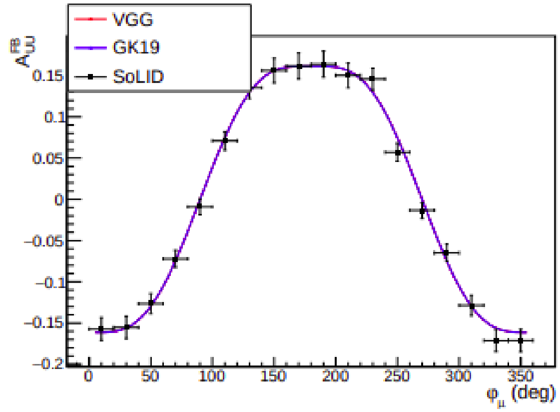
μCA experimental projections



(d) Bin 19.



(e) Bin 20.



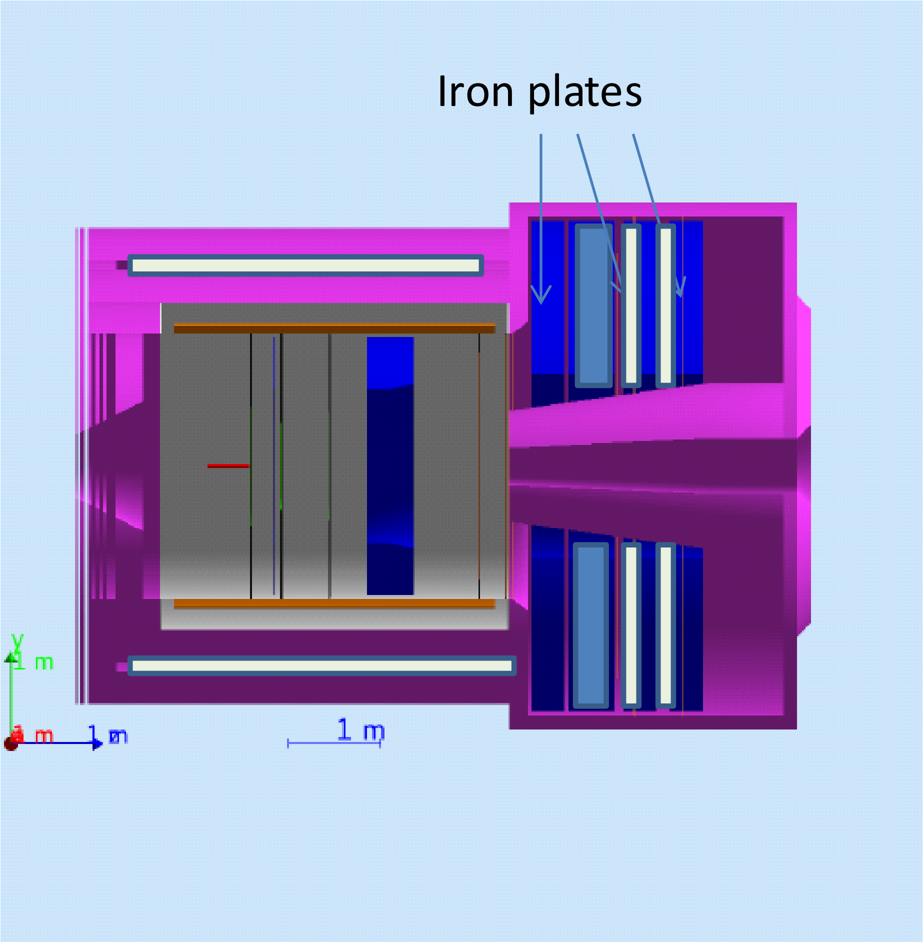
(f) Bin 21.

- Observation of the CFF real part curvature change

Beam time request

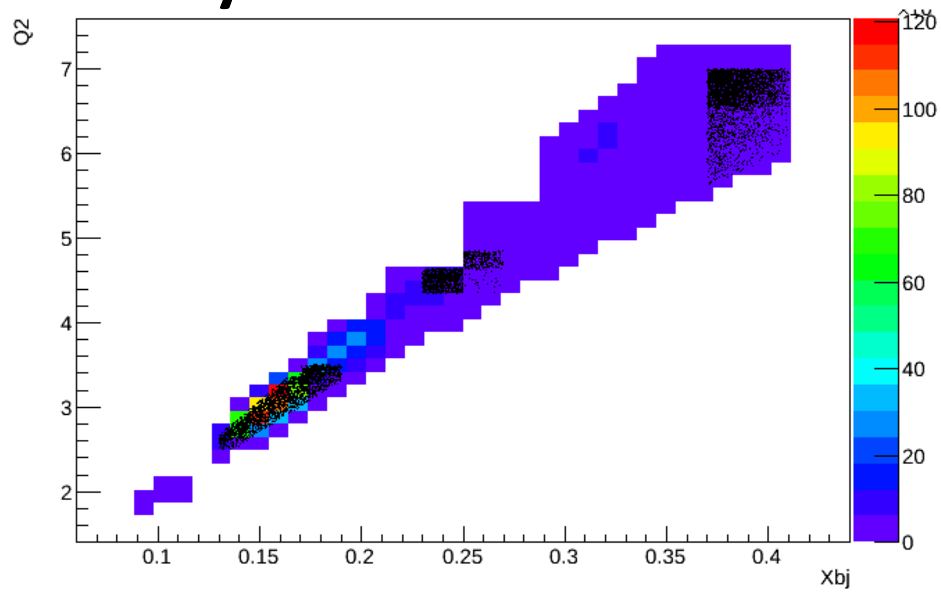
Beam Energy (GeV)	Beam Current (uA)	Beam Requirements	Target Material	Target Thickness (cm)	Beam time (days)
11	3	polarized (>85%)	LH2	15	
Run Group Calibration time					10
Run Group Production time					50
Requested Production time					50
Total Time					110

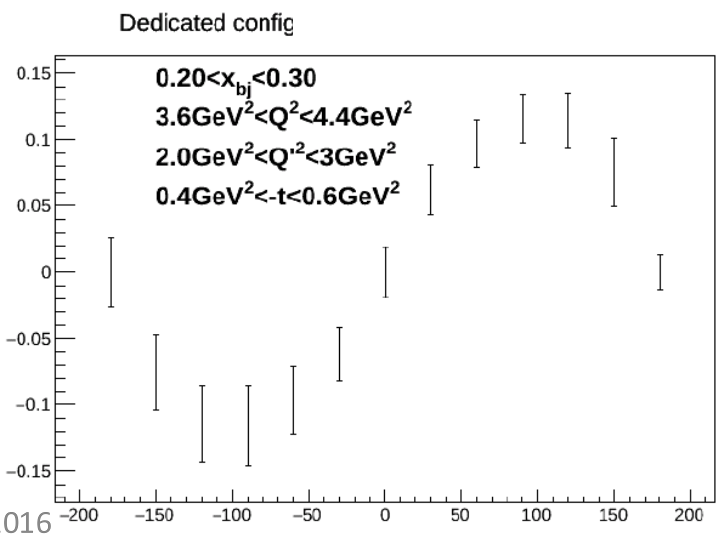
Possible future dedicated setup

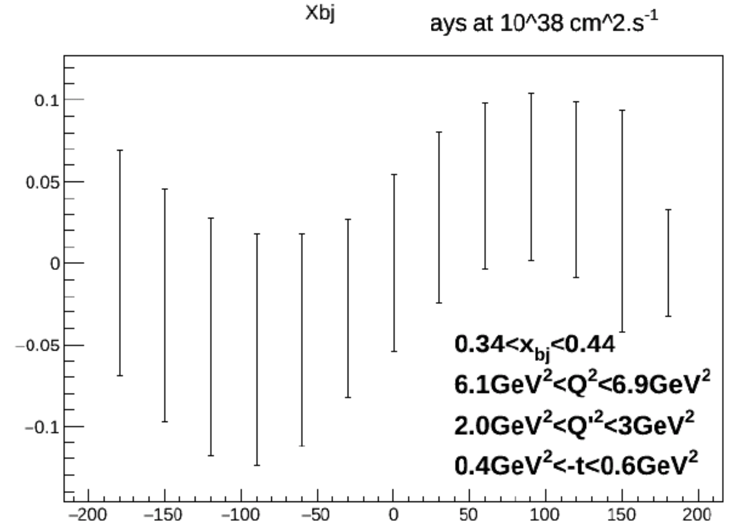


- Target moved 2m from Jpsi position inside and switch to 45 cm target
- Iron plate from 3rd layer yoke in front and behind calorimeter
- Remove Gas Cerenkov
- Try to reach 10^{38} $cm^{-2}s^{-1}$
- 10 uA on 45 cm target

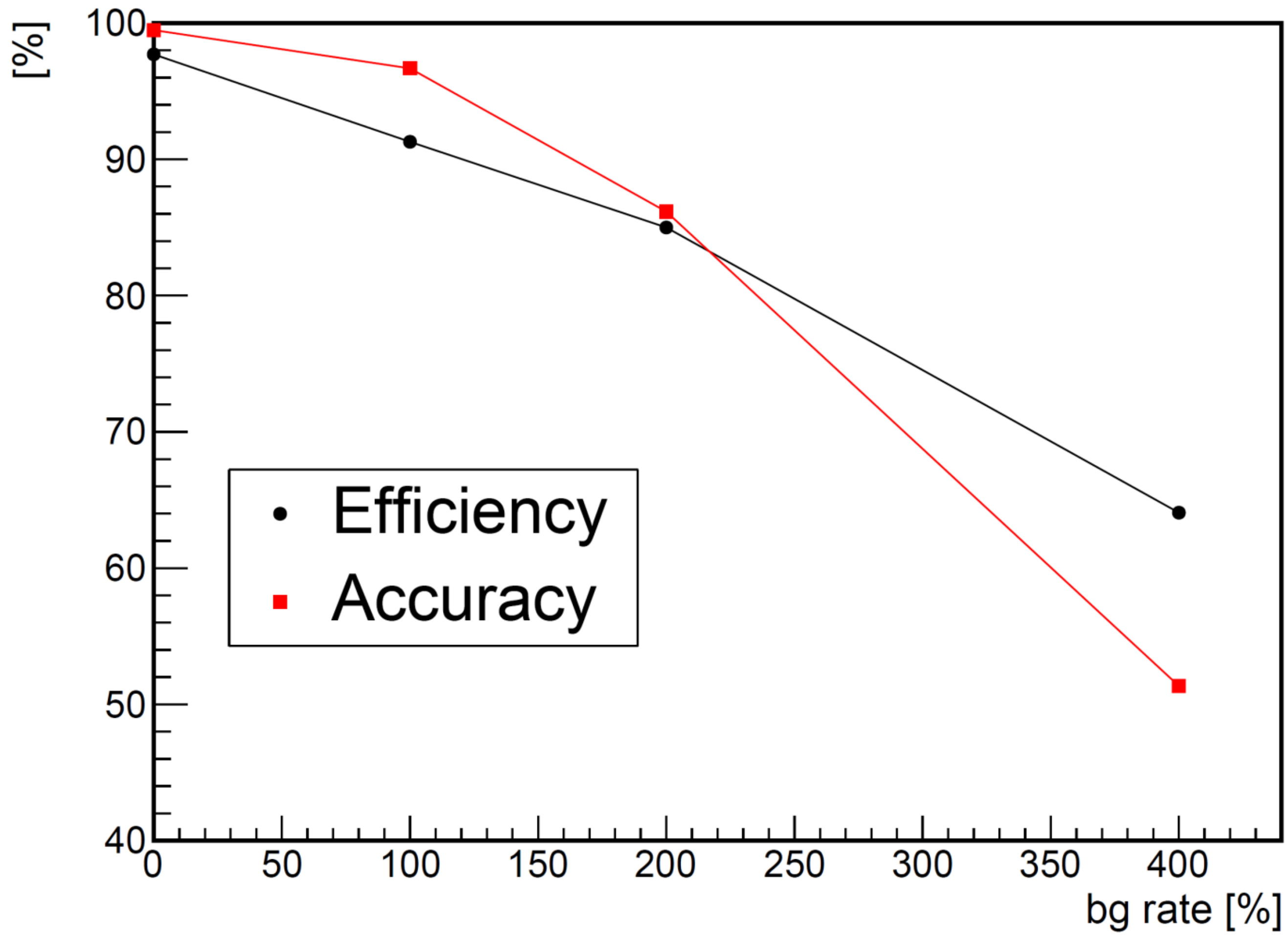
Expected accuracy dedicated setup 90 days at 10^{38} $cm^{-2}s^{-1}$







Higher luminosity J/Psi setup tracking study



Weizhi Xiong

Simple Kalman filter tracking

To be checked with future chip with faster shaping time

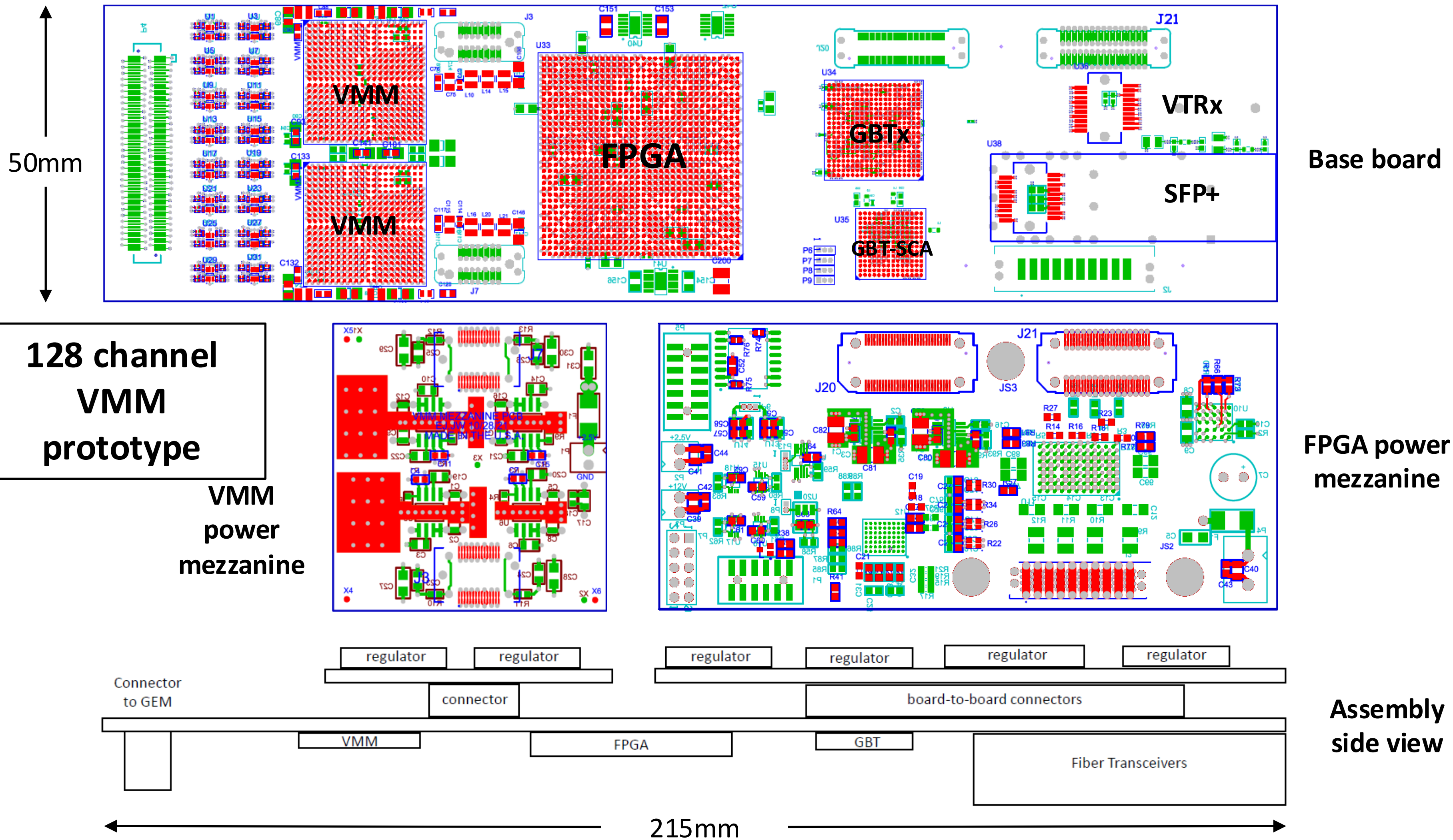
Higher luminosity ?

- Current could go up to 80 uA
- Target length up to 1 meter (~1.8 10^39 $cm^{-2}s^{-1}$)
- Tracker occupancy and photon background
  - Reduce amount of Copper in GEM
  - Micromegas option
  - Build smaller chambers and add more channels and tracking layers
  - Study complement with 2D pad readout
  - Superconducting tracker option
  - Radiation hardened silicon and MAPS
- Calorimetry
  - Study liquid scintillator and cryogenics calorimeter option
  - Superconducting detector to replace PMT (1 ns width pulse to increase rate capability)
- Cerenkov
  - Superconducting detector to replace PMT (1 ns width pulse to increase rate capability)
  - HBD type Cerenkov for Large Angle calorimeter

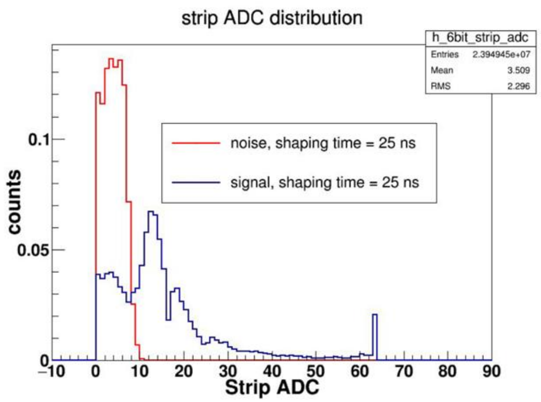
6. 10^38 $cm^{-2}s^{-1}$

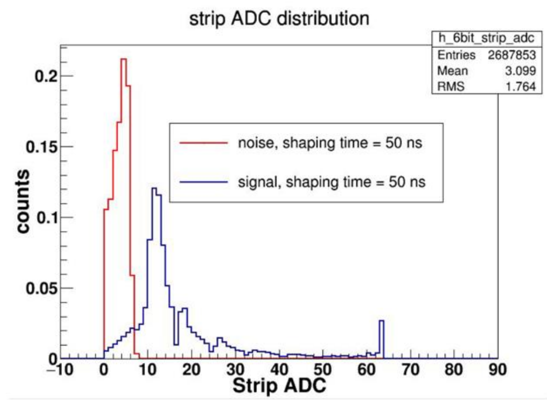
Technically doable mostly matter of cost

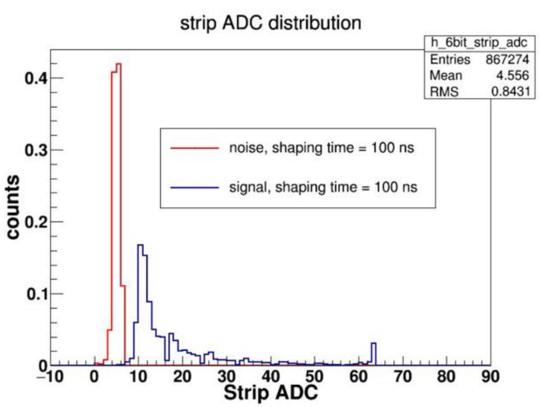
128 channel VMM prototype

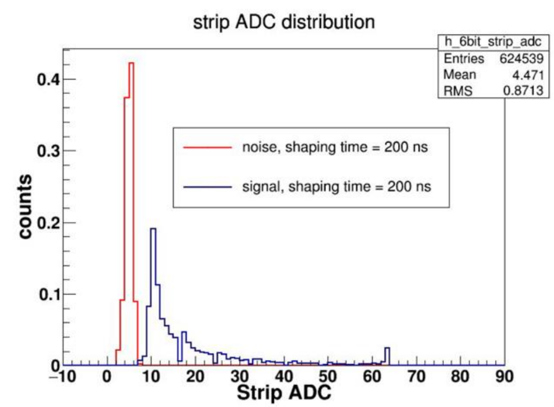


Noise 6 bit 16mV/fC Sr90



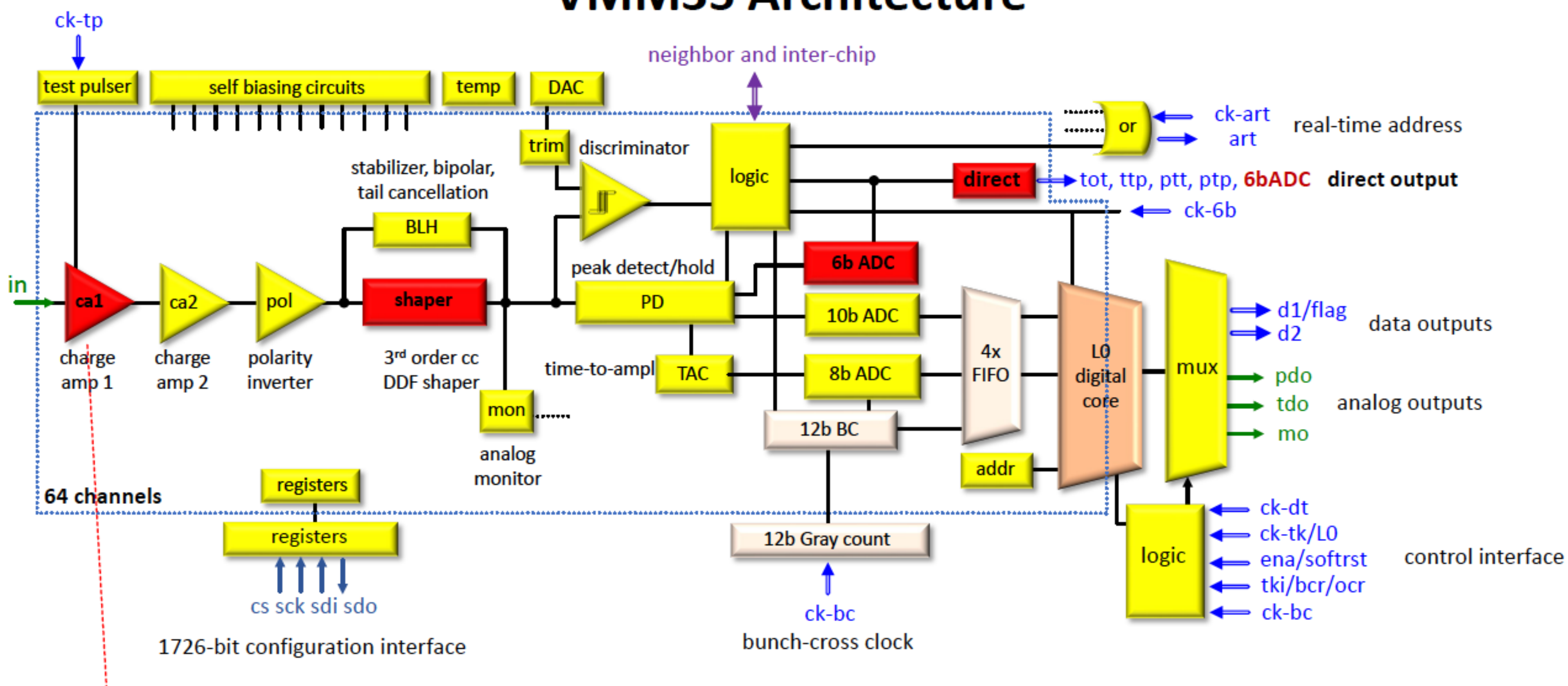






- Amplitude for MIP not change much
- Pedestal width dependent on peaking time

VMM3S Architecture



SoLID MPGDs will initially operate with charges up to ~100,000e$^-$:

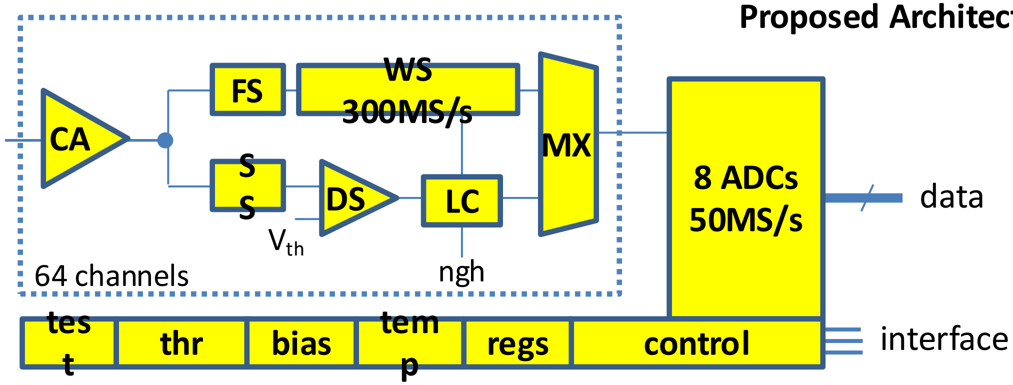
- will integrate a higher gain setting 64mV/fC
- will deliver ENC ~1,500e$^-$ @ 50pF, 25ns (ADC contribution ~450e$^-$)

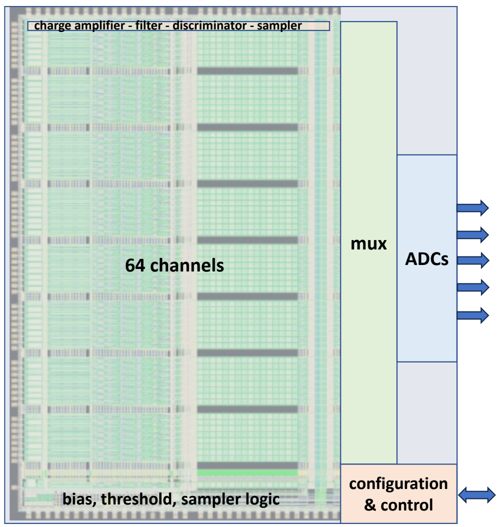
New potential dedicated ASIC

- High luminosity running need to run
- Pile-up and deadtime can be significant

- Dedicated chip
  - Optimized gain and dynamic range
  - Optimize shaping time for high rate operation : from 50 ns to 25 ns or better
  - Zero dead time
  - High speed links to allow streaming

Proposed Architecture





CA: charge amplifier
- optimized for 50-200pF
- programmable gain 25fC to 250fC

FS: fast shaper
- programmable 5-20ns

SS: slow shaper
- for discrimination (zero suppression)
- programmable 20-100ns

DS: discriminator
- trimmable per channel
- external trigger option

WS: waveform sampler
- 128 sampling cells (127 effective)
- continuous sampling until trigger
- 300MS/s → ~ 400ns waveform
- programmable pre-post trigger samples

LC: local control logic
- internal or external trigger
- neighbor (sub-threshold) logic

ADCs
- 8 operating at 10-bit 100MS/s
- waveform conversion time ~ 2.5µs

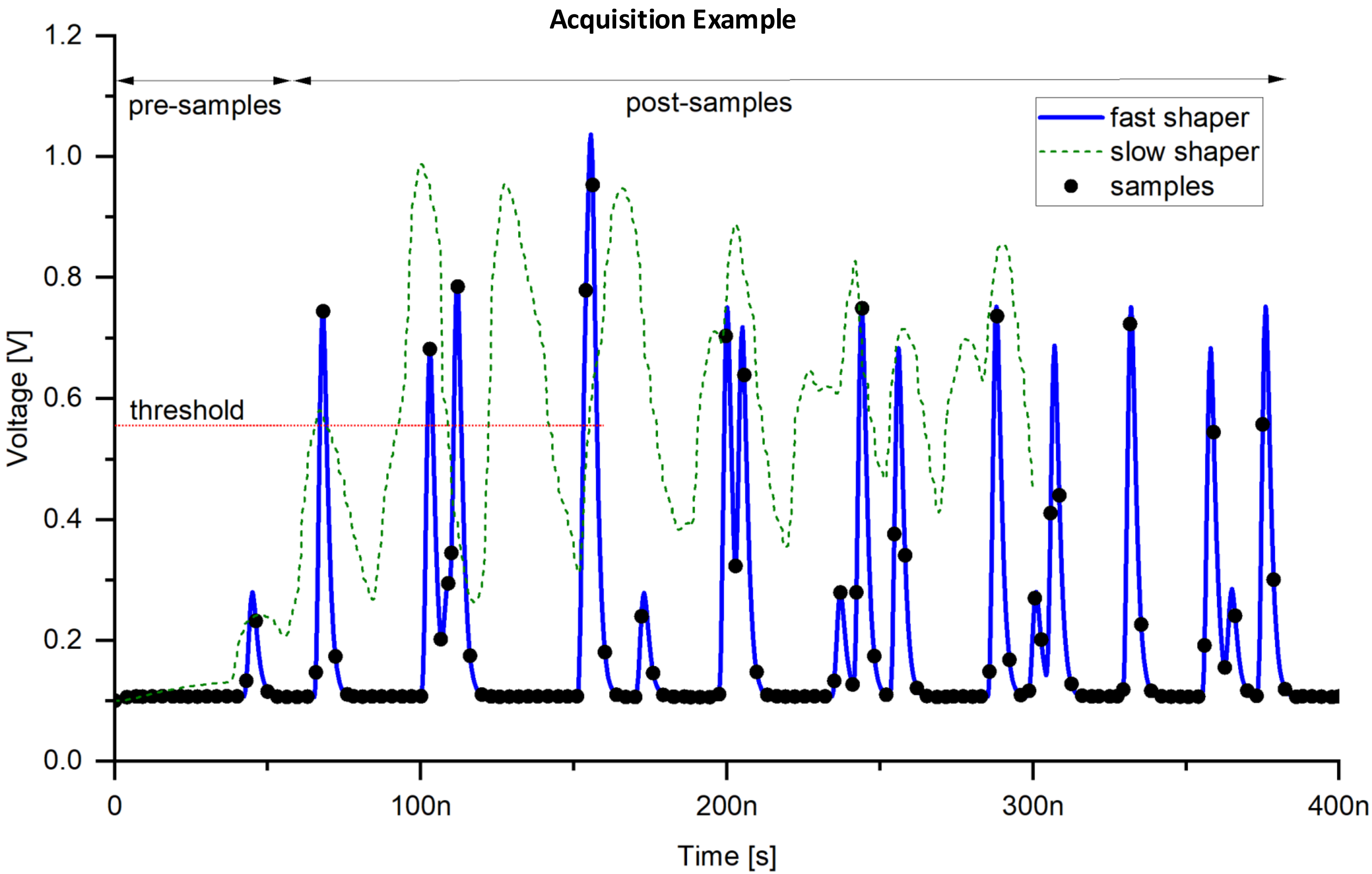
Data
- channel, trigger, 127 samples = 1,280 bits per waveform
- up to 8 waveforms with sub-threshold neighbors = 10,240 bits
- up to 8 SLVS outputs operating in DDR at ~ 500MS/s
- conversion/readout time (dead time) ~ 2.5µs per event
- maximum event rate ~ 330kHz
- maximum data rate ~ 4Gb/s

Architecture
- event-driven analog/digital with acquisition/readout
- SEU tolerant register and logic
- DSP-ready

Power, Size, Technology, Schedule
- power consumption below 3mW/channel
- anticipated die size ~ 6x8 mm^2
- technology TSMC 65nm 1.2V
- development time ~ 24 months (1st proto in 12 months)

Design
- charge amplifier, shapers and samplers based on verified architectures
- ADCs from collaborative effort
- first prototype design time
    - ~ 12-13 months plus ADCs
    - ADC can be parallel effort
- second prototype design time
    - ~ 4-5 months

Key Features
- power-efficient analog zero-suppression
- efficient data generation and transfer
- highly flexible, highly programmable

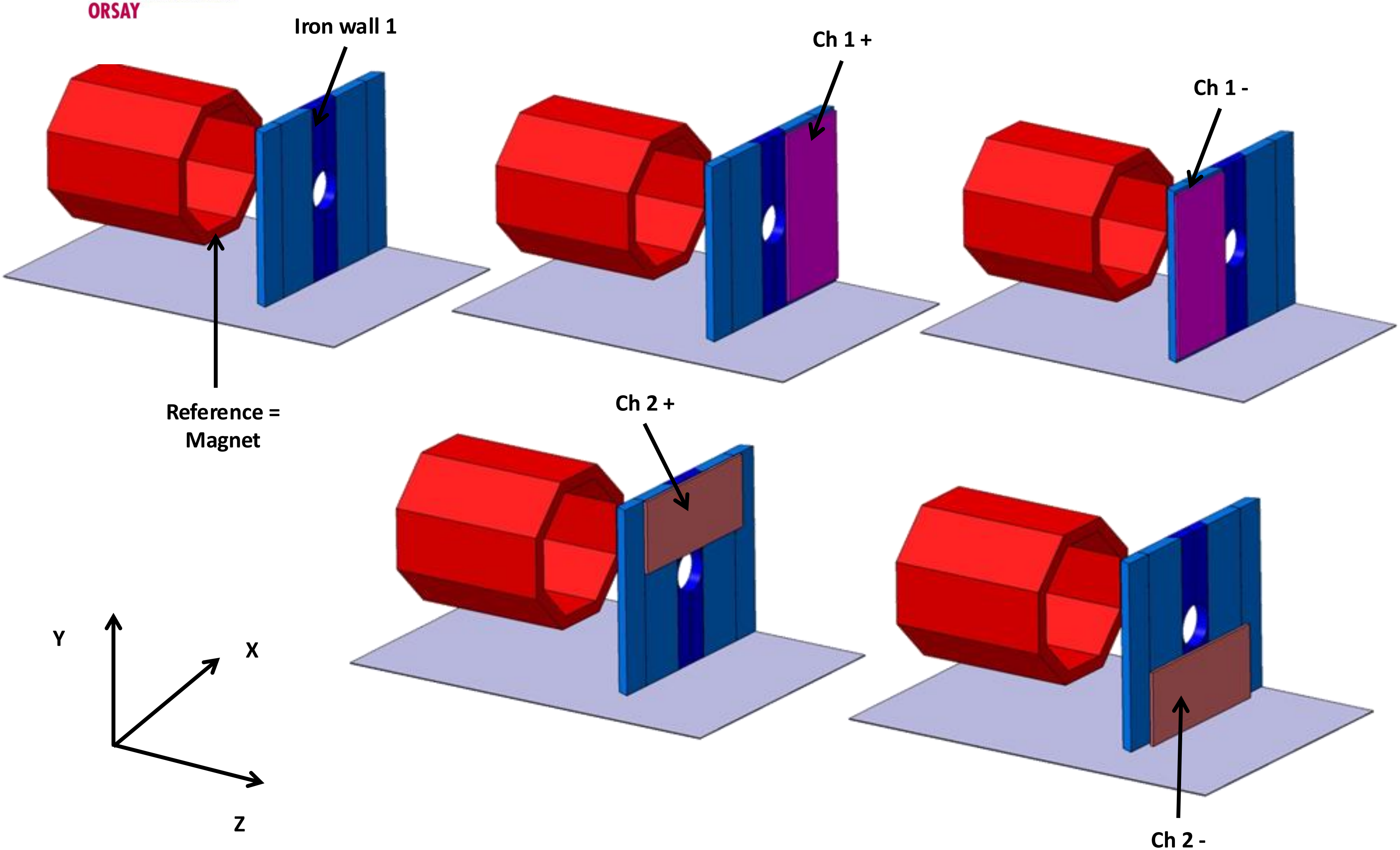


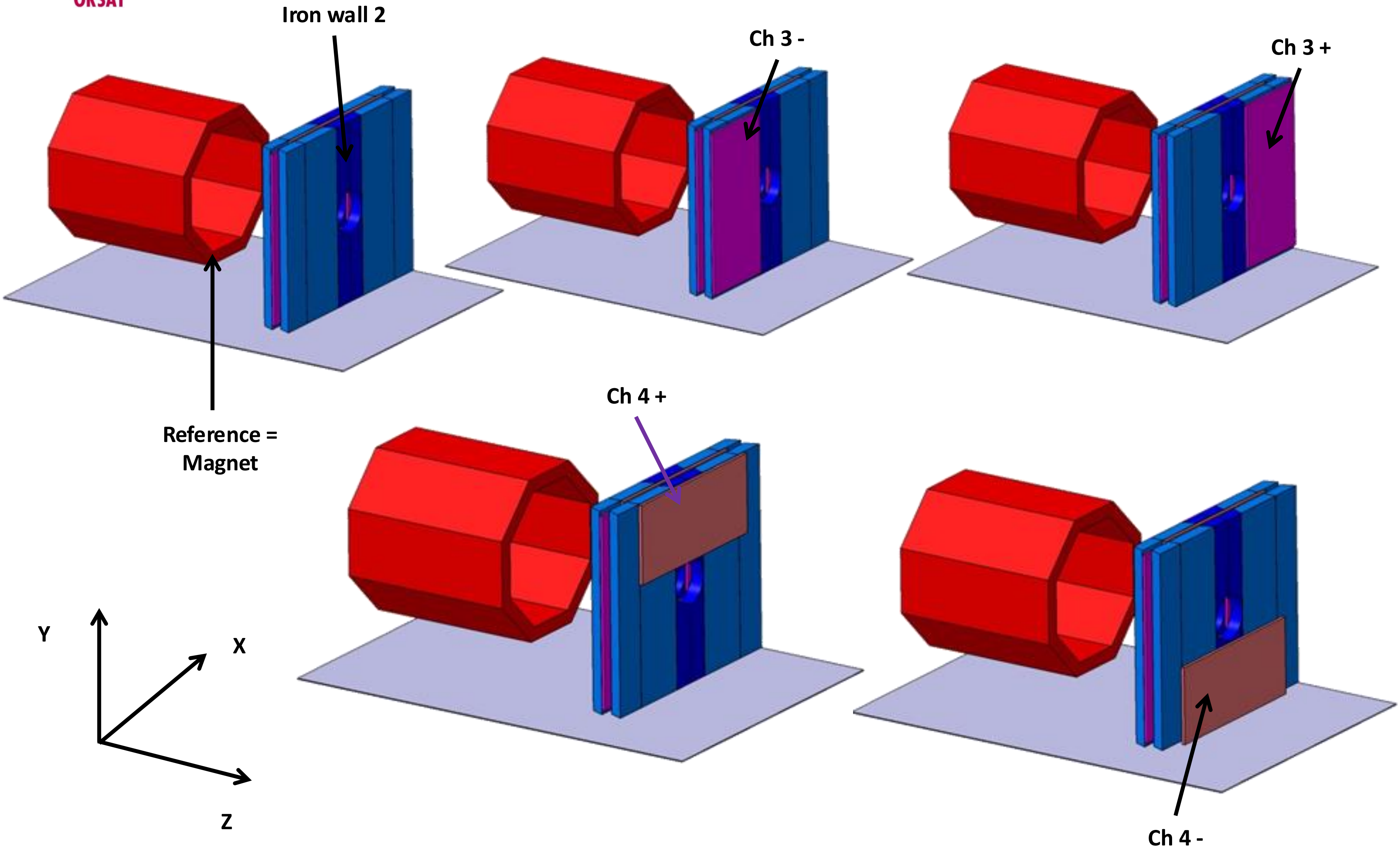
Acquisition Example
pre-samples
post-samples
threshold
fast shaper
slow shaper
samples
Voltage [V]
Time [s]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
100n
200n
300n
400n

Summary

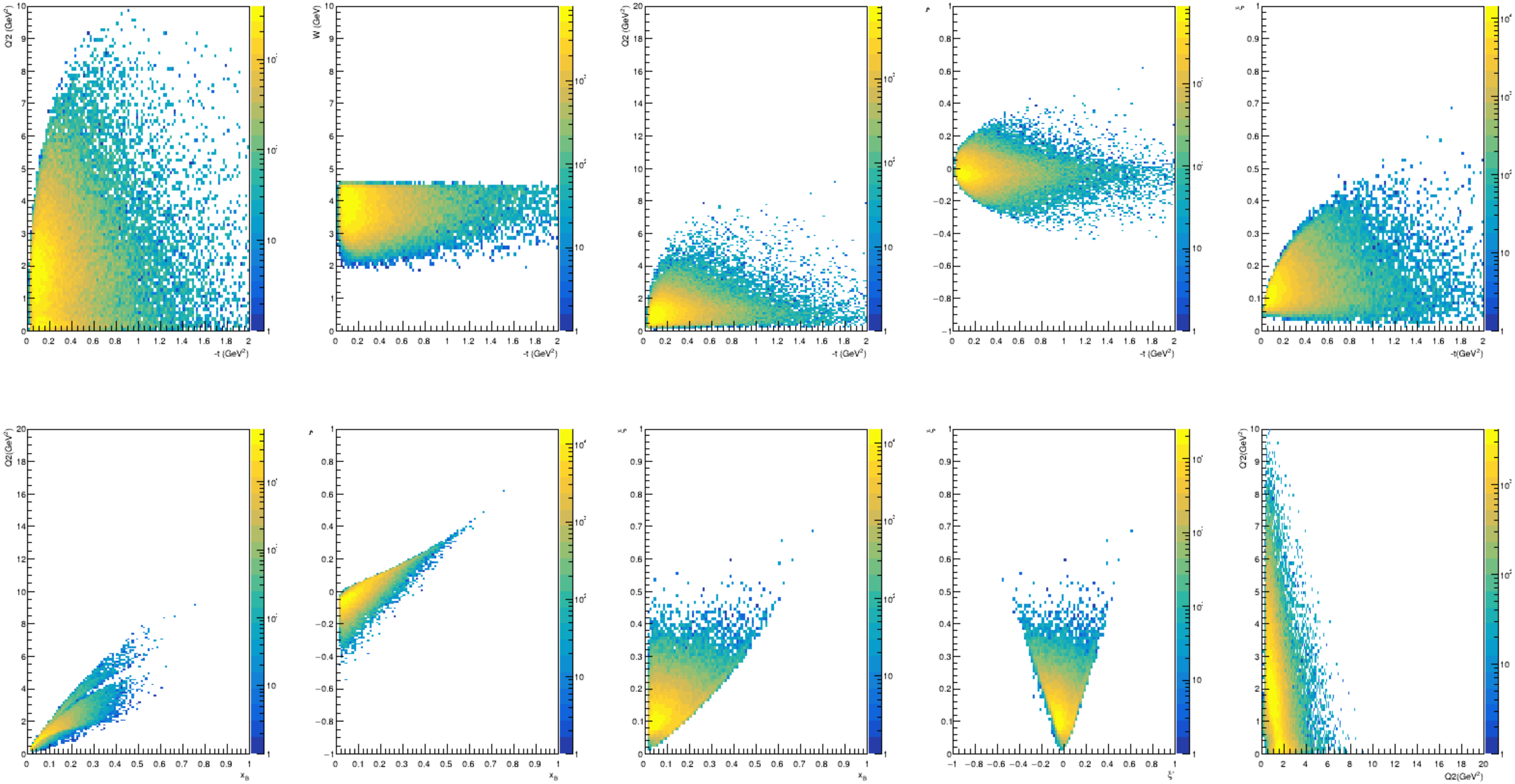
- We are proposing to complement the J/Psi SoLID setup with a muon detector
- This will allow us to measure DDVCS in the dimuons channel
- We will use the J/Psi beamtime and with additional 50 days to measure the DDVCS asymmetries : proposal approved conditional to SoLID detector
- Possible upgrade for dedicated increased luminosity setup
- Complementary measurement to uCLAS12 measurement

Backup


Iron wall 1
Ch 1 +
Ch 1 -
Reference =
Magnet
Ch 2 +
Ch 2 -
Y
X
Z

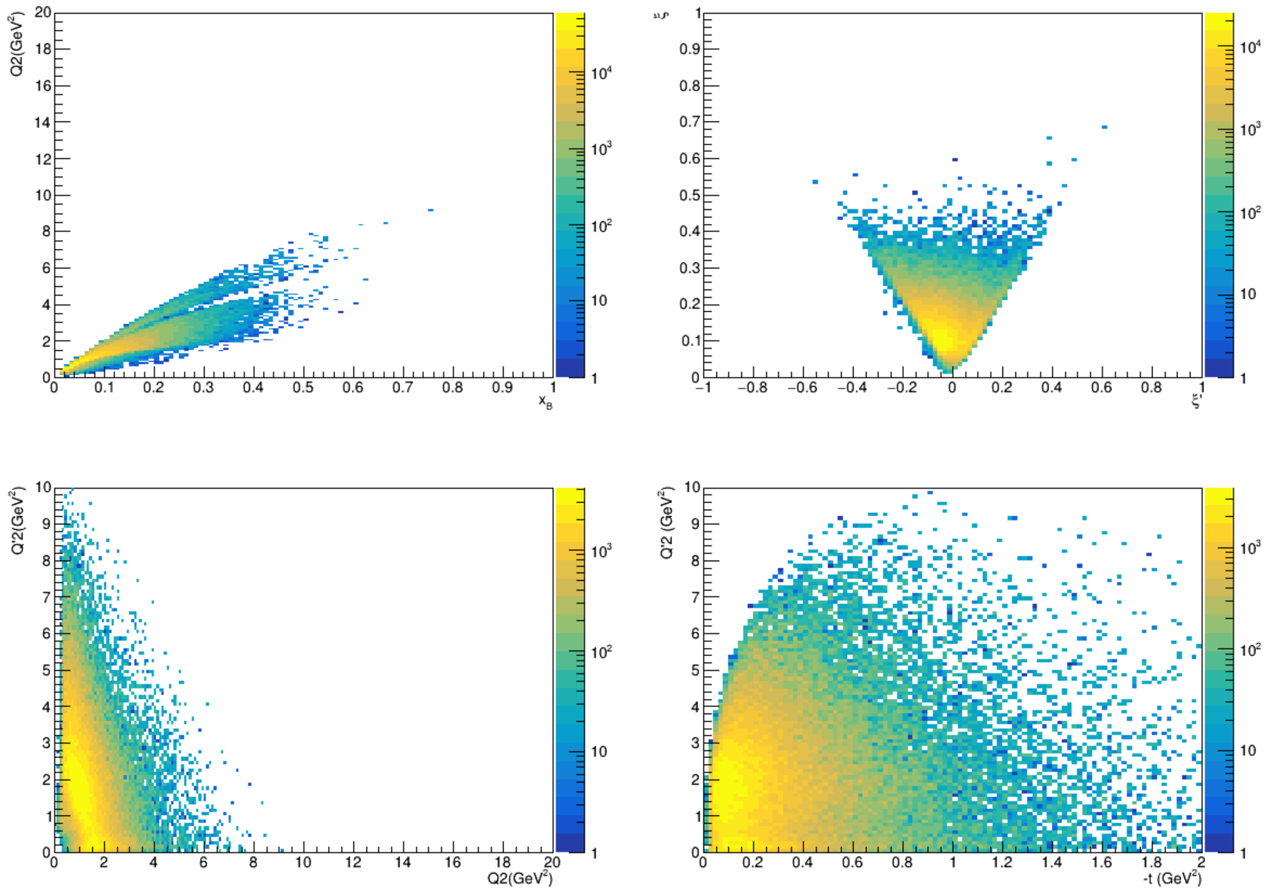

Iron wall 2
Ch 3 -
Ch 3 +
Reference = Magnet
Ch 4 +
Ch 4 -
Y
X
Z

Kinematical coverage 11 GeV



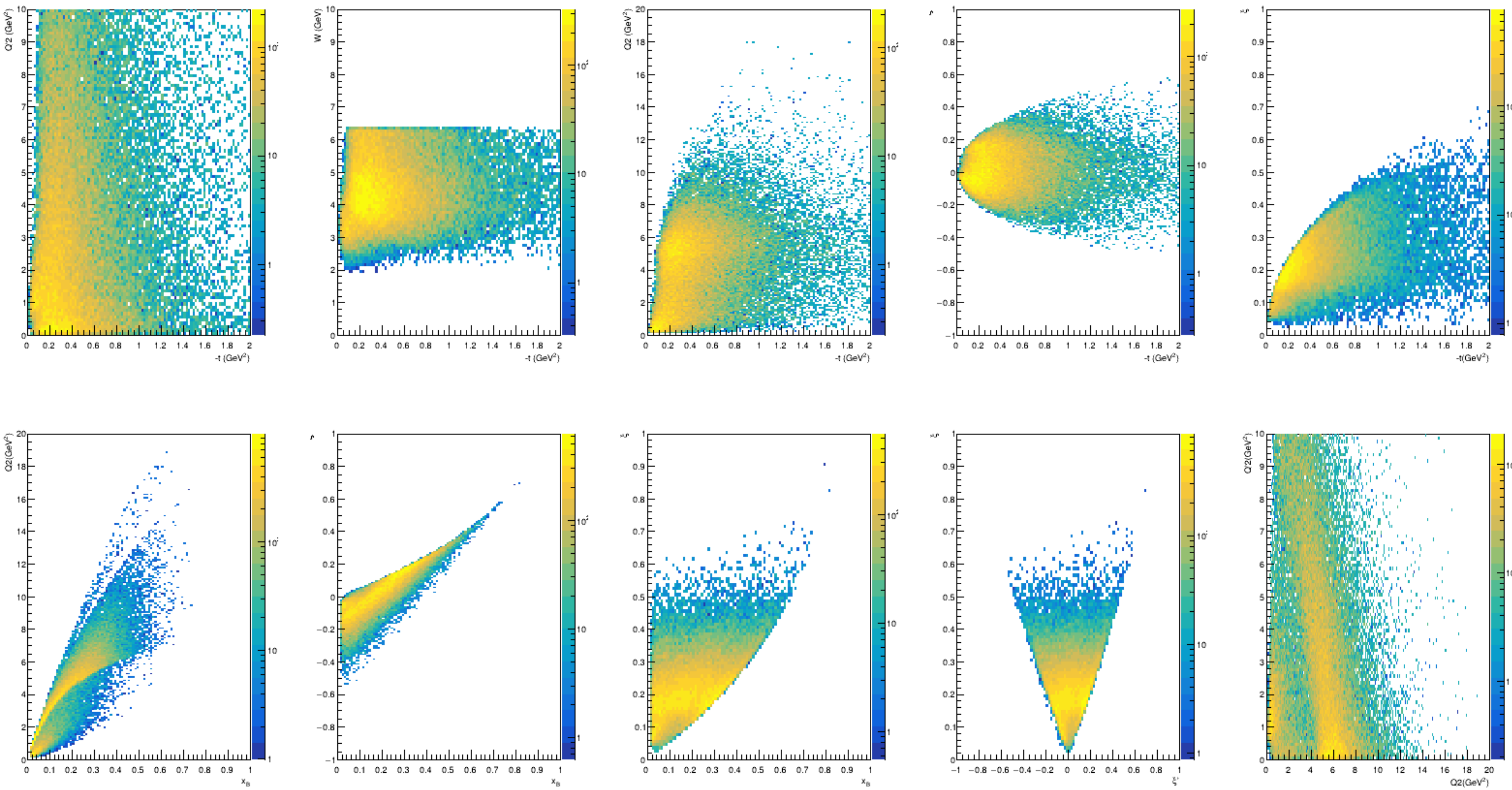
Zhiwen Zhao (GRAPE)

Kinematical coverage 11 GeV



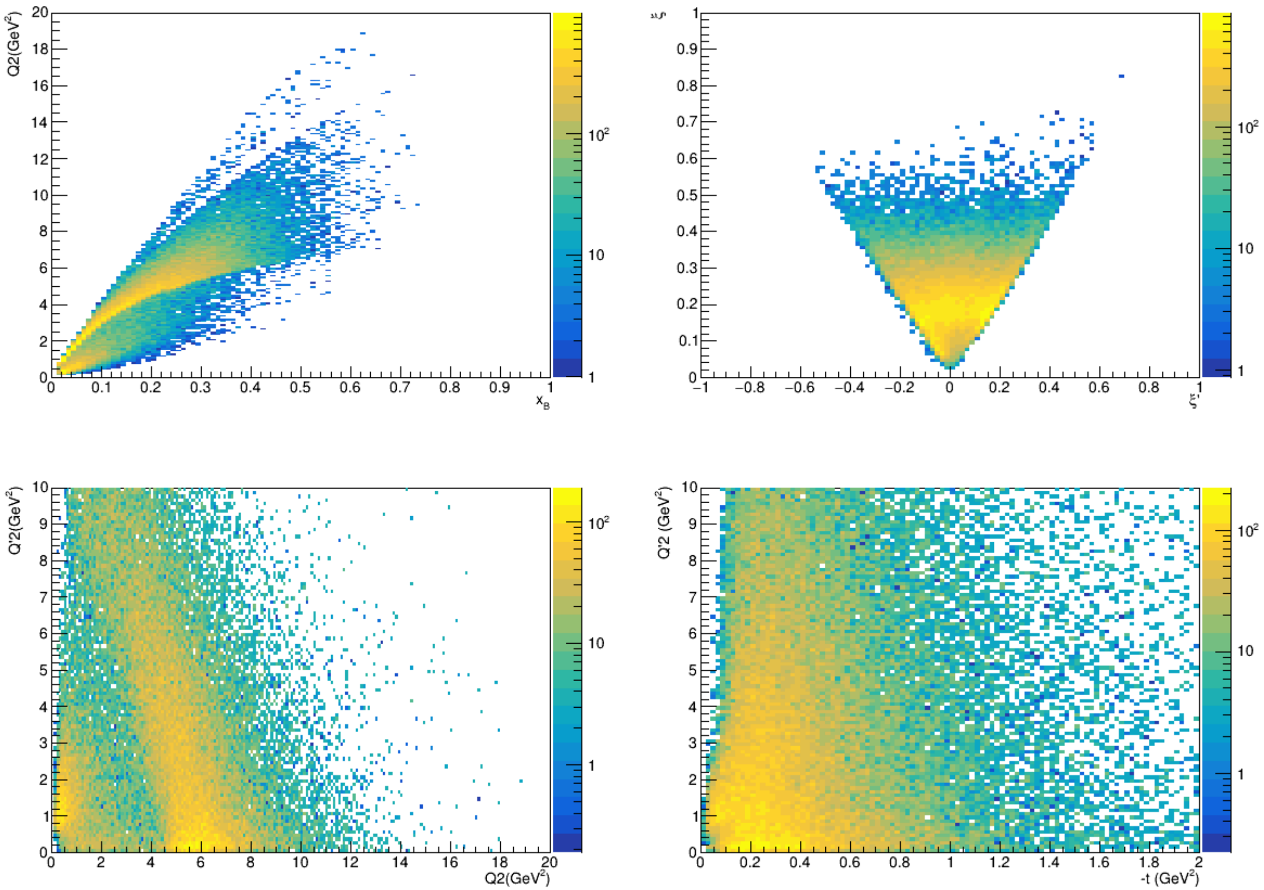
Zhiwen Zhao (GRAPE)

Kinematical coverage 22 GeV



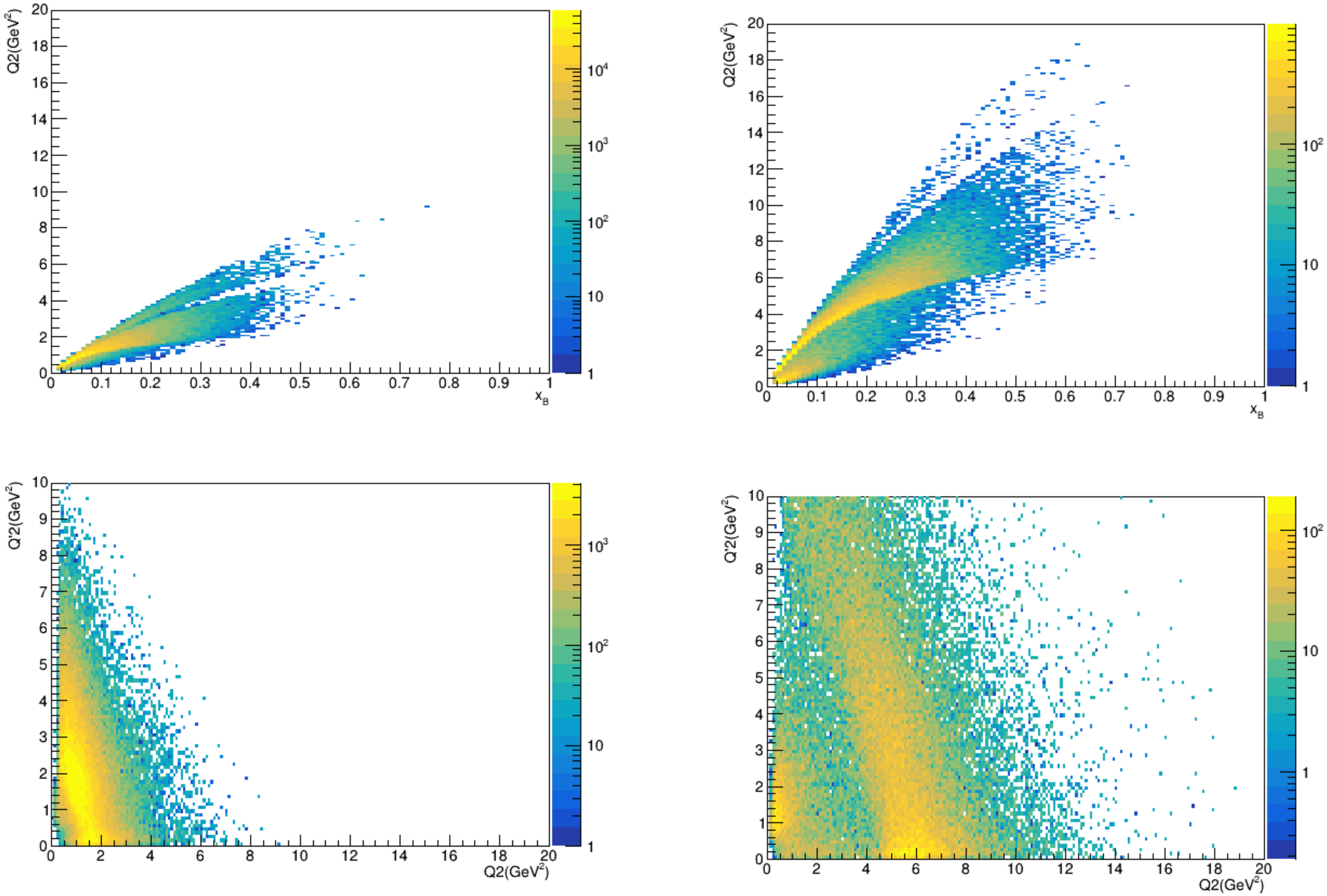
Zhiwen Zhao (GRAPE)

Kinematical coverage 22 GeV

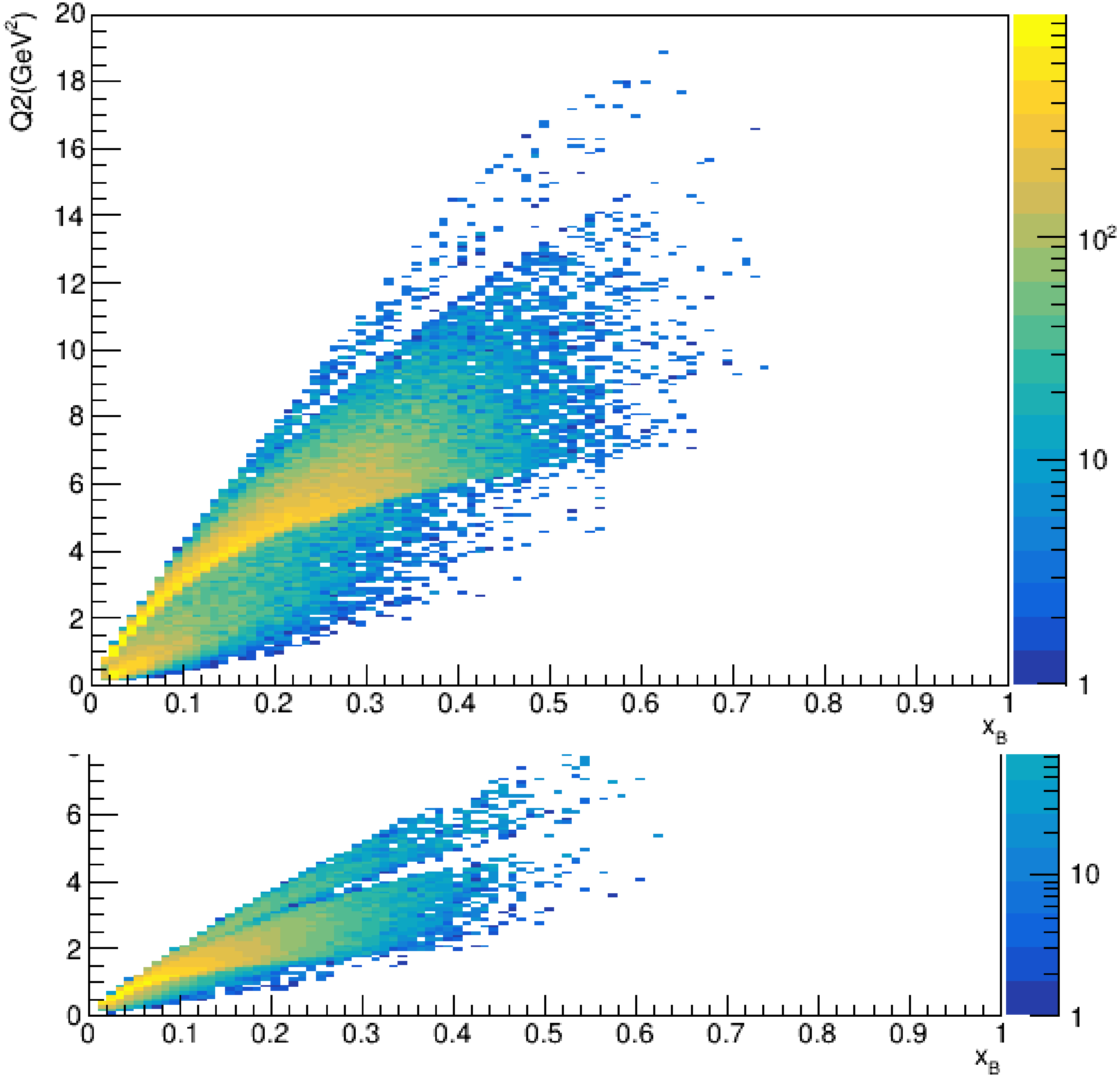


Zhiwen Zhao (GRAPE)

11 GeV vs 22 GeV

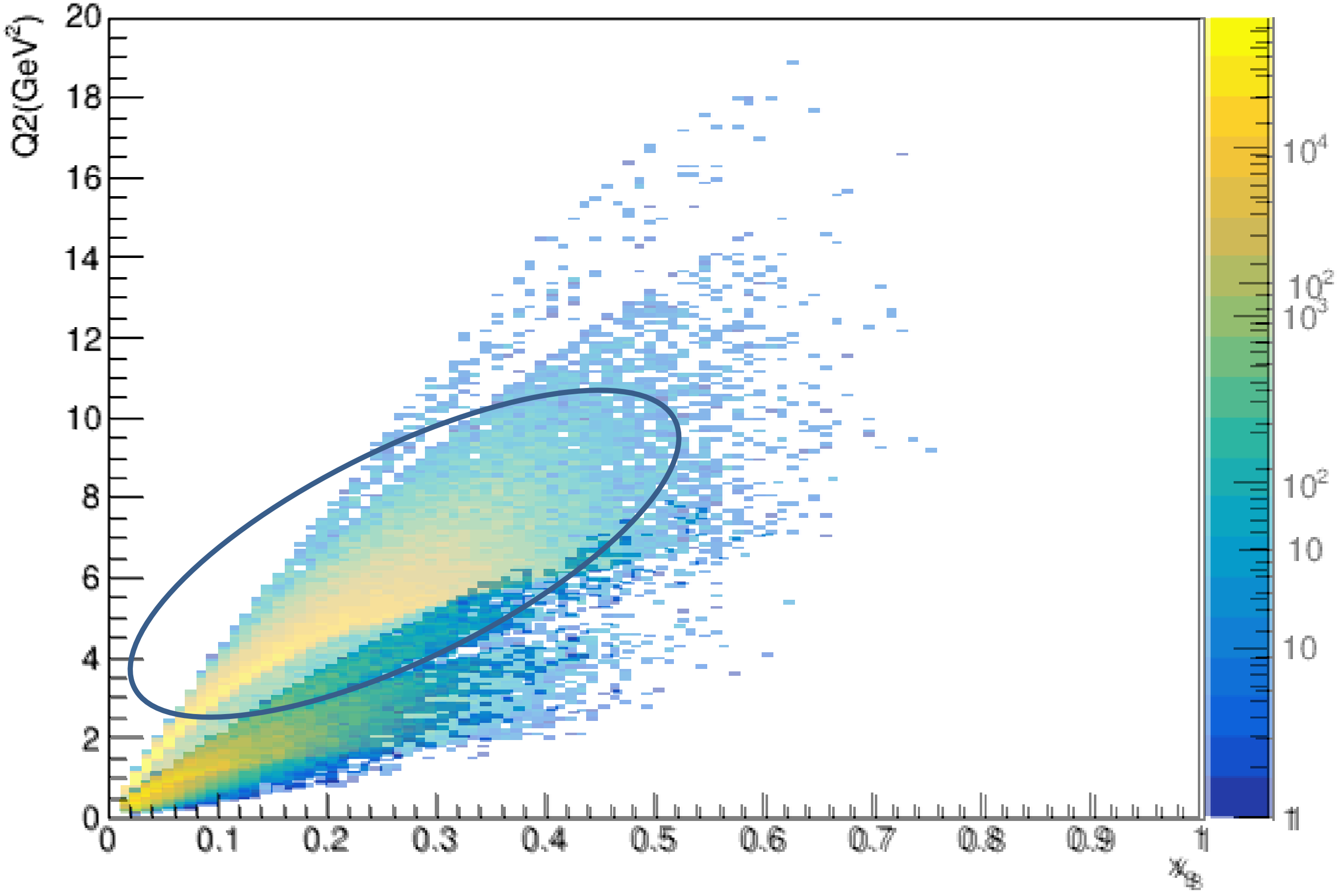


Zhiwen Zhao (GRAPE)



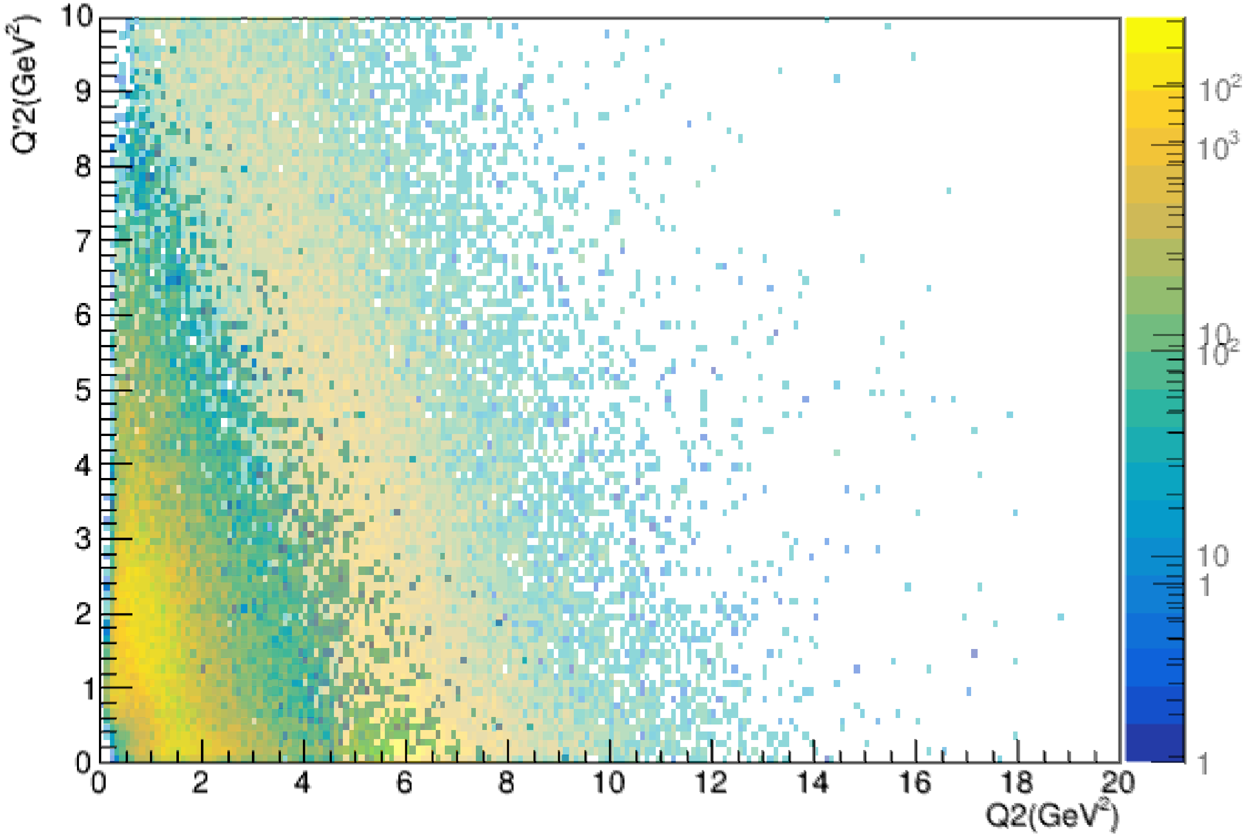
Zhiwen Zhao (GRAPE)

11 GeV vs 22 GeV



Zhiwen Zhao (GRAPE)

11 GeV vs 22 GeV



Much better Q2 Q’2 coverage

Want Q2 and Q’2 large enough for factorization

Quick numbers for J/Psi settings

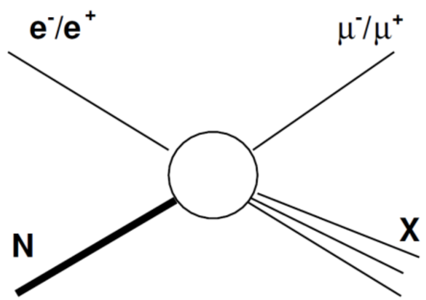
50 days at 10^37

Beam energy	e-mu-mu+	pmu-mu+
11	180156	1.37175e+06
22	51600	2.75867e+06

Cross section about 3 times lower : could run at 10 uA or with 45 cm target

Acceptance better when detecting proton but dominated by low Q2/Q'2

Charged Lepton Flavor Violation ($e^+ \to \mu^+$)



$$e^+ + N \to \mu^+ + X$$

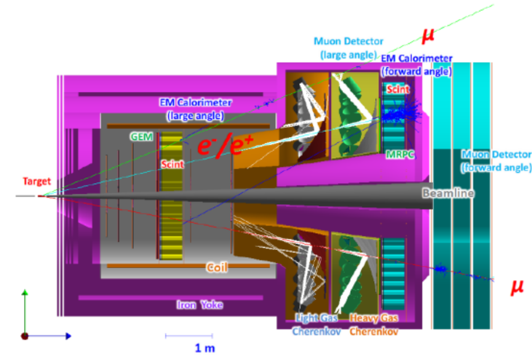


Fig. 3. The SoLID J/Ψ configuration with muon detectors [28]. Other sub-detectors are labeled.

- Low center of mass energy but high luminosity:

$$\sqrt{s} \sim 4.5 \text{ GeV}$$
$$\mathcal{L} \sim 10^{36} \text{ - } 10^{39} \text{ cm}^{-2} \text{ s}^{-1}$$

- Detectors should be equipped with muon detectors and a good tracker. Proposed SoLID spectrometer meets these requirements

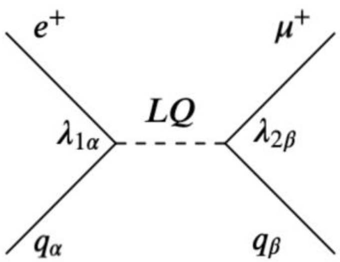
- High luminosity will allow for substantial improvement over HERA limits on CLFV.

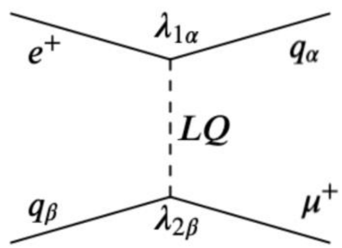
- For $\mathcal{L} \sim 10^{38}\ cm^{-2}s^{-1}$ one can expect two to three orders of magnitude improvement over HERA.

Yulia Furletova
and Sonny Mantry

Charged Lepton Flavor Violation via Leptoquarks

- Convenient to study CLFV in Leptoquark framework which mediates CLFV at tree-level:





$$\sigma^{e^+p}_{F=0} = \sum_{\alpha,\beta} \frac{s}{32\pi} \left[\frac{\lambda_{1\alpha}\lambda_{2\beta}}{M^2_{LQ}}\right]^2 \int dx \int dy \left\{ x q_\alpha(x, xs) f(y) + x\bar{q}_\beta(x, -u) g(y) \right\}$$

$$\sigma^{e^+p}_{|F|=2} = \sum_{\alpha,\beta} \frac{s}{32\pi} \left[\frac{\lambda_{1\alpha}\lambda_{2\beta}}{M^2_{LQ}}\right]^2 \int dx \int dy \left\{ x\bar{q}_\alpha(x, xs) f(y) + q_\beta(x, -u) g(y) \right\}$$

- 14 LQ states. Positron beam can help disentangle F=0 and |F|=2 LQ states. Polarized beams can help distinguish between left-handed and right-handed LQs.

Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
S_0^L	0	2	$-1/3$	$e_L^- u_L \to \ell^- u$	λ_L	1/2
				$\to \nu_\ell d$	$-\lambda_L$	1/2
S_0^R	0	2	$-1/3$	$e_R^- u_R \to \ell^- u$	λ_R	1
$\tilde{S}_0^R$	0	2	$-4/3$	$e_R^- d_R \to \ell^- d$	λ_R	1
S_1^L	0	2	$-1/3$	$e_L^- u_L \to \ell^- u$	$-\lambda_L$	1/2
				$\to \nu_\ell d$	$-\lambda_L$	1/2
			$-4/3$	$e_L^- d_L \to \ell^- d$	$-\sqrt{2}\lambda_L$	1
$V_{1/2}^L$	1	2	$-4/3$	$e_L^- d_R \to \ell^- d$	λ_L	1
$V_{1/2}^R$	1	2	$-1/3$	$e_R^- u_L \to \ell^- u$	λ_R	1
			$-4/3$	$e_R^- d_L \to \ell^- d$	λ_R	1
$\tilde{V}_{1/2}^L$	1	2	$-1/3$	$e_L^- u_R \to \ell^- u$	λ_L	1

Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
V_0^L	1	0	$+2/3$	$e_R^+ d_L \to \ell^+ d$	λ_L	1/2
				$\to \bar{\nu}_\ell u$	λ_L	1/2
V_0^R	1	0	$+2/3$	$e_L^+ d_R \to \ell^+ d$	λ_R	1
$\tilde{V}_0^R$	1	0	$+5/3$	$e_L^+ u_R \to \ell^+ u$	λ_R	1
V_1^L	1	0	$+2/3$	$e_R^+ d_L \to \ell^+ d$	$-\lambda_L$	1/2
				$\to \bar{\nu}_\ell u$	λ_L	1/2
			$+5/3$	$e_R^+ u_L \to \ell^+ u$	$\sqrt{2}\lambda_L$	1
$S_{1/2}^L$	0	0	$+5/3$	$e_R^+ u_R \to \ell^+ u$	λ_L	1
$S_{1/2}^R$	0	0	$+2/3$	$e_L^+ d_L \to \ell^+ d$	$-\lambda_R$	1
			$+5/3$	$e_L^+ u_L \to \ell^+ u$	λ_R	1
$\tilde{S}_{1/2}^L$	0	0	$+2/3$	$e_R^+ d_R \to \ell^+ d$	λ_L	1

Crossection proportional to center of mass energy ~ factor 2 at 22 GeV

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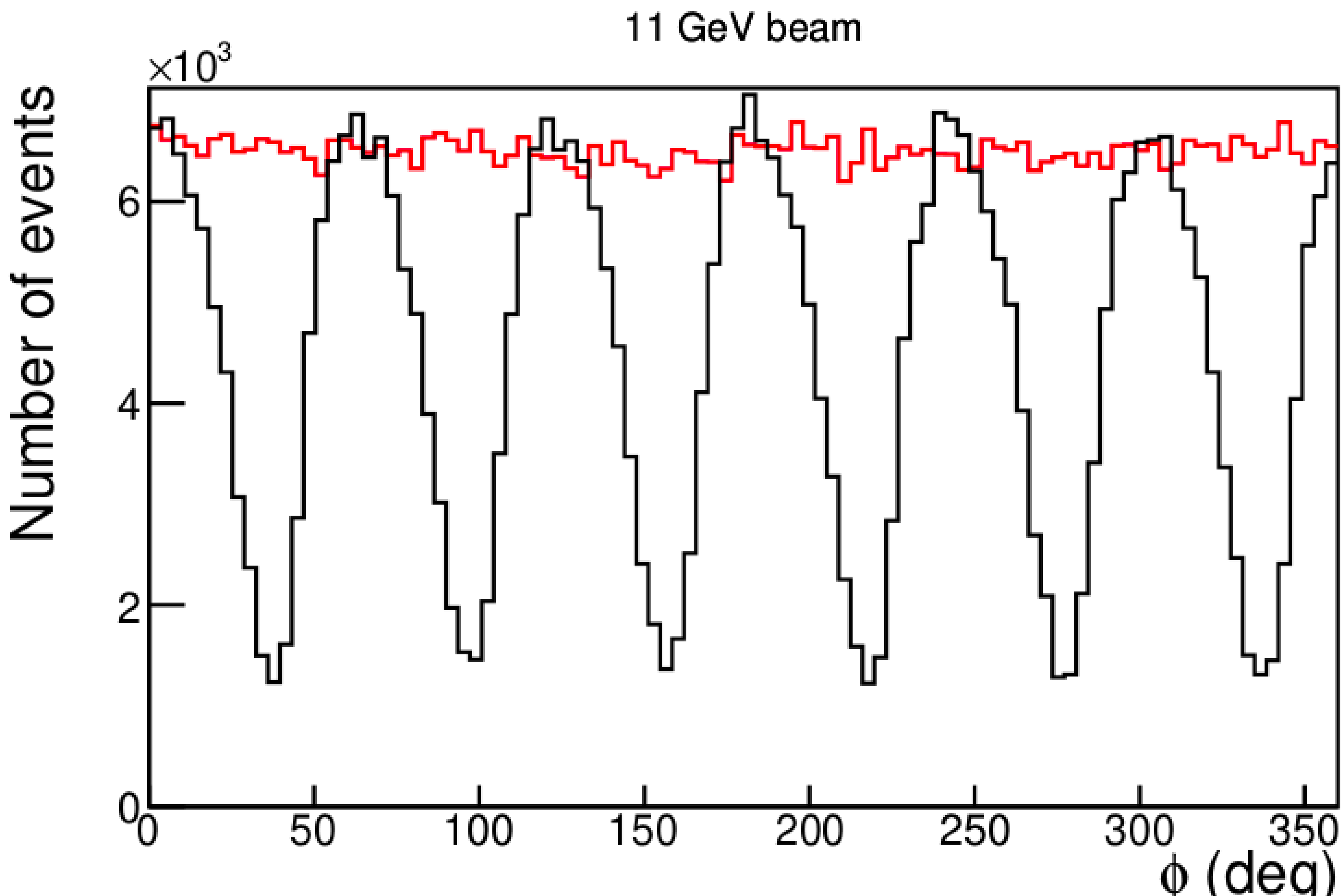
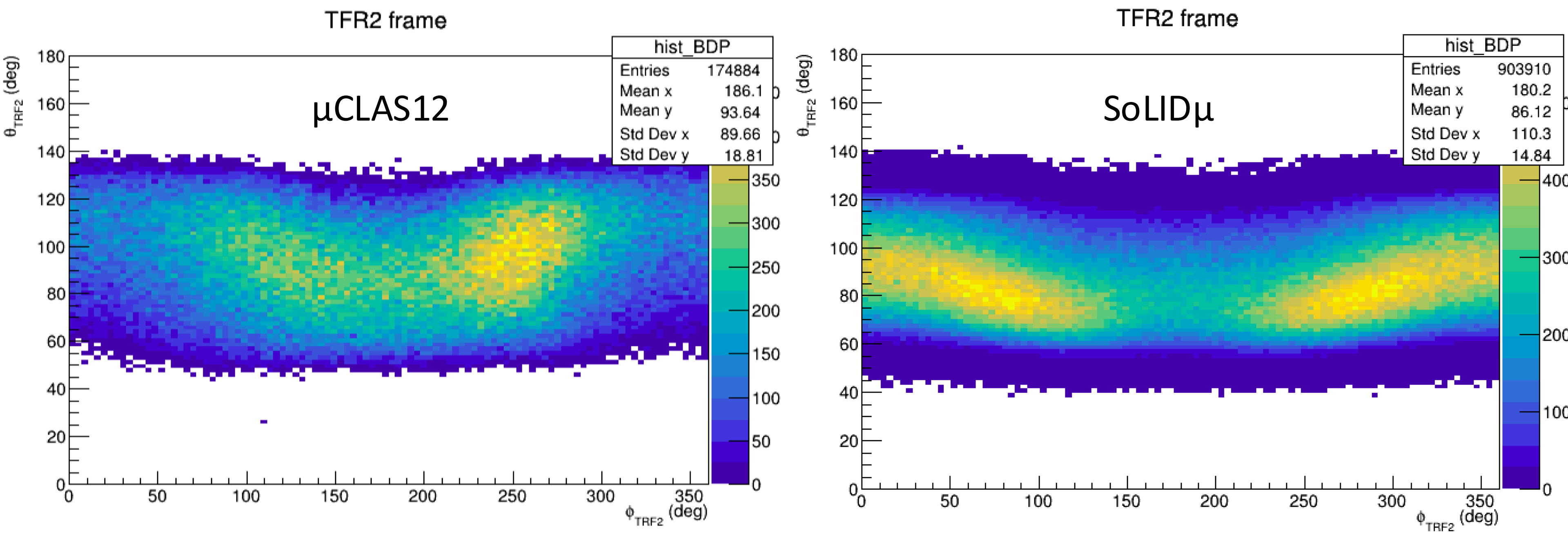
and Sonny Mantry

SoLIDμ vs μCLAS12



100 days comparison

SoLIDμ vs μCLAS12



- Angles in the muon center-of-mass frame
- Larger coverage with SoLIDμ

Systematics

	Correction/ accuracy	Systematic
Electron efficiency	30%	5%
Acceptance	3%	3%
Polarimetry	1%	1%
Beam charge	3%	3%
Single pion contamination	5%	5%
Di-pion contamination	5%	5%
Background subtraction	4%	2%

~ 10% systematic on cross section – 5% on assymetries depending on pion asymmetry