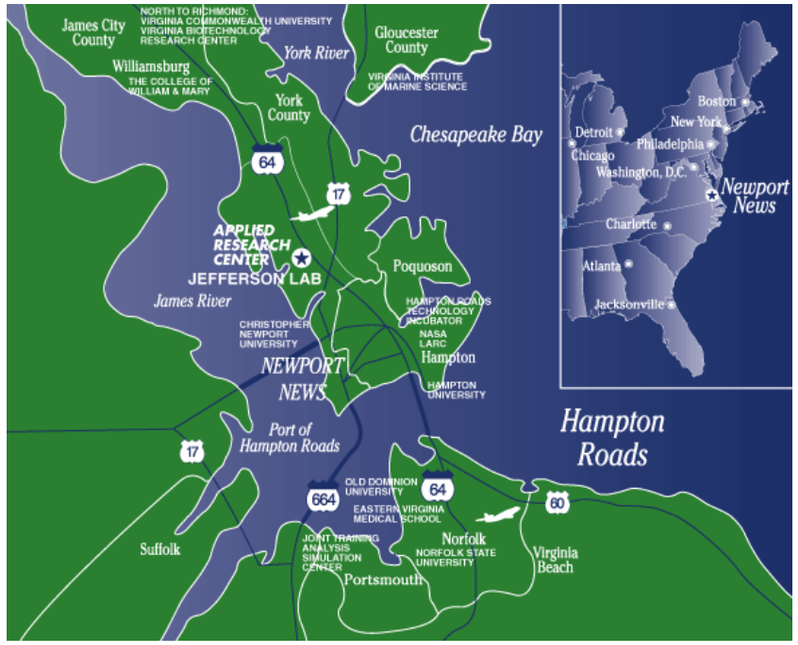
Program at CLAS/CLAS 12:

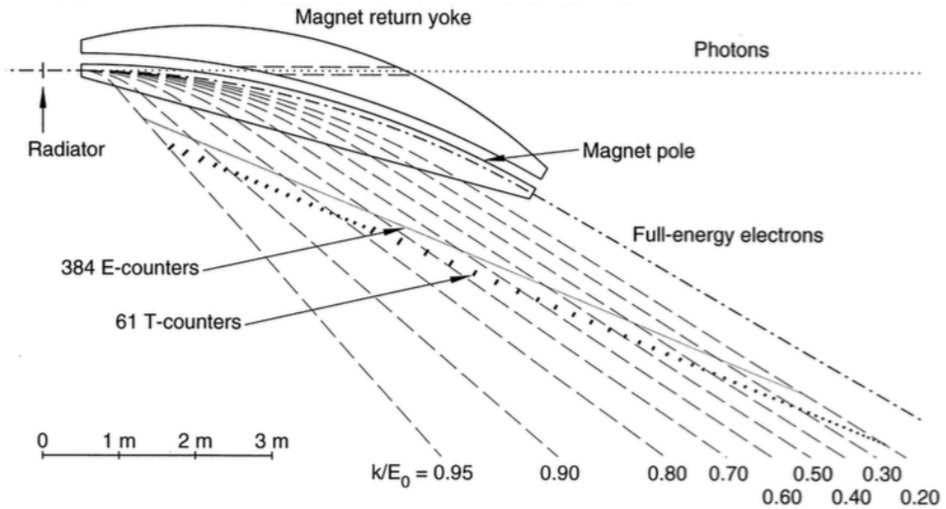
Lei Guo (郭磊), Florida International University
For the CLAS Collaboration
10th Workshop on Hadron Physics in China and Opportunities Worldwide
Weihai, Shandong, China
July 30th, 2018

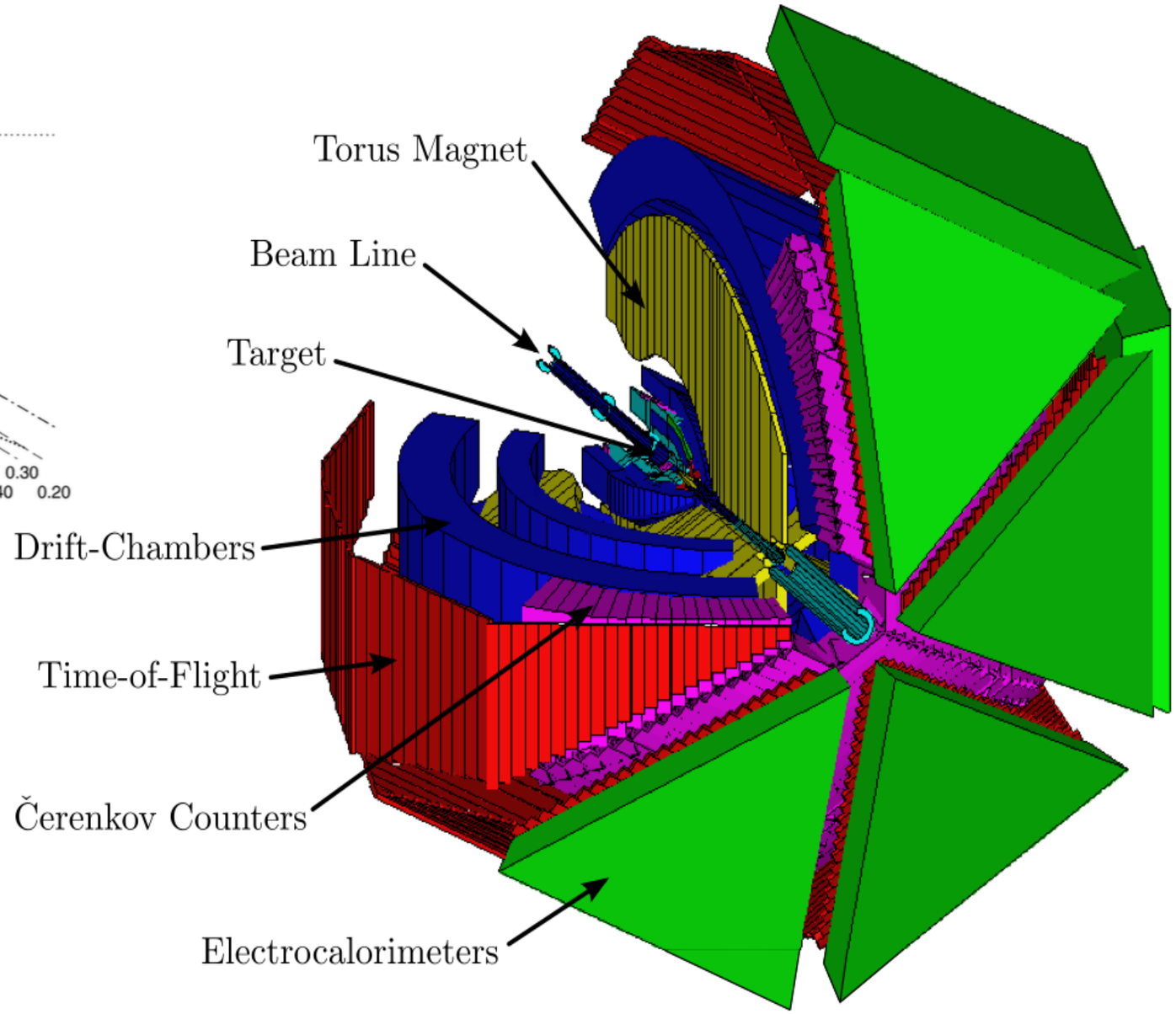
Jefferson Lab: Overview



- Located in Newport News?, Virginia
  - James Town: First Settlement
  - Yorktown: American+French > British
- Superconducting electron accelerating facility
- Simultaneous distribution to 4 experimental Halls (We did it!)
- 12GeV for Hall D
- Hall ABC ~11GeV
- Beam Polarization >85%

CLAS: CEBAF Large Acceptance Spectrometer

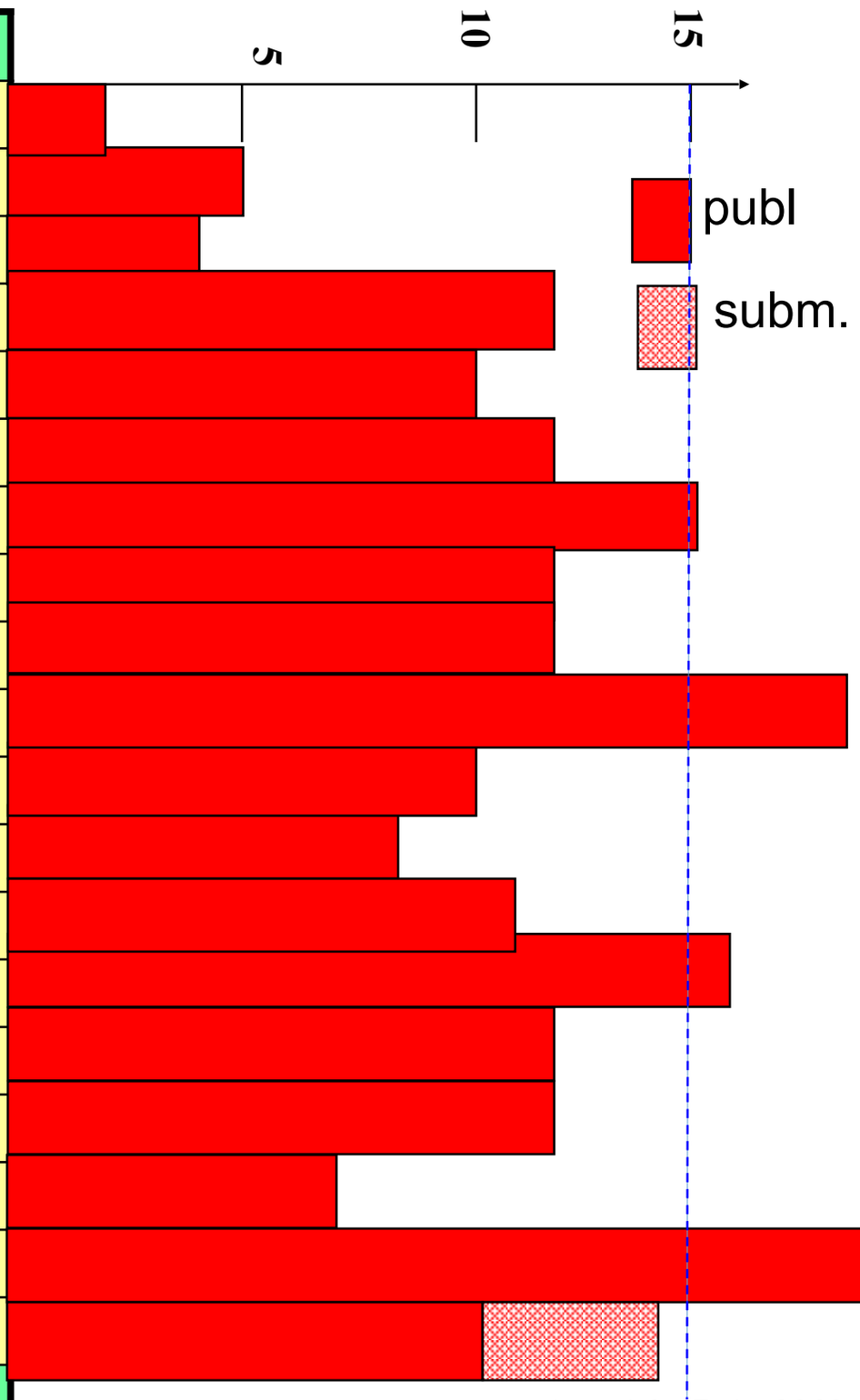




- CLAS:
  - Momentum Resolutinon
    - ~0.1%
  - Photon Tagging Range: 20-95%
  - Energy: Up to 5.7 GeV

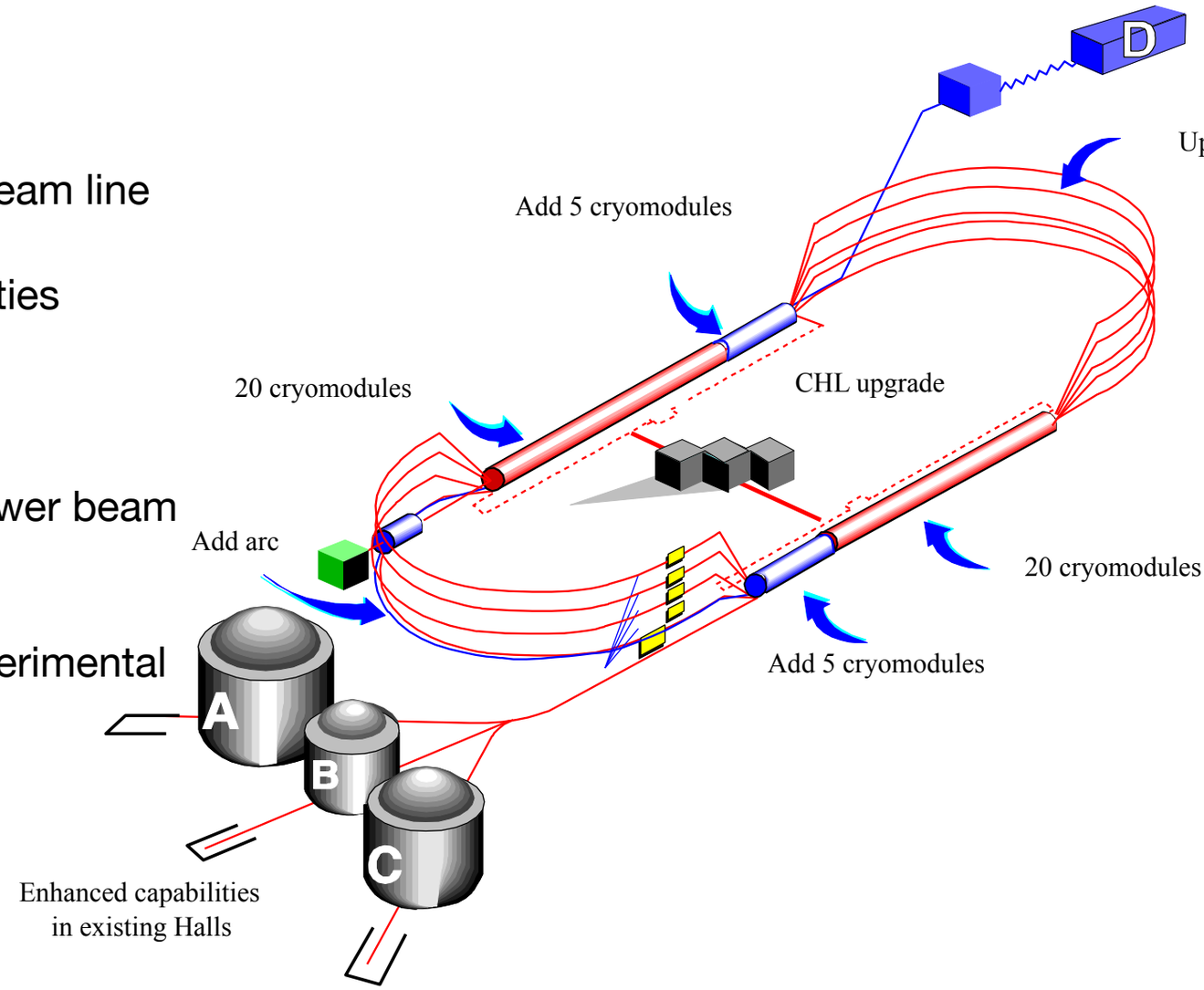
Hall B Physics Publications

	HSWG	DPWG	NPWG	ALL
2000	-	1	1	2
2001	2	3	-	5
2002	3	-	1	4
2003	7	4	1	12
2004	3	3	4	10
2005	7	3	2	12
2006	8	4	3	15
2007	7	2	3	12
2008	4	6	2	12
2009	8	7	4	19
2010	4	2	4	10
2011	3	1	4	8
2012	6	3	2	11
2013	8	6	2	16
2014	5	6	1	12
2015	4	5	3	12
2016	7			7
2017	12	7	1	20
2018	5	4	1	10 + 4
SUM	103	67	39	209+4



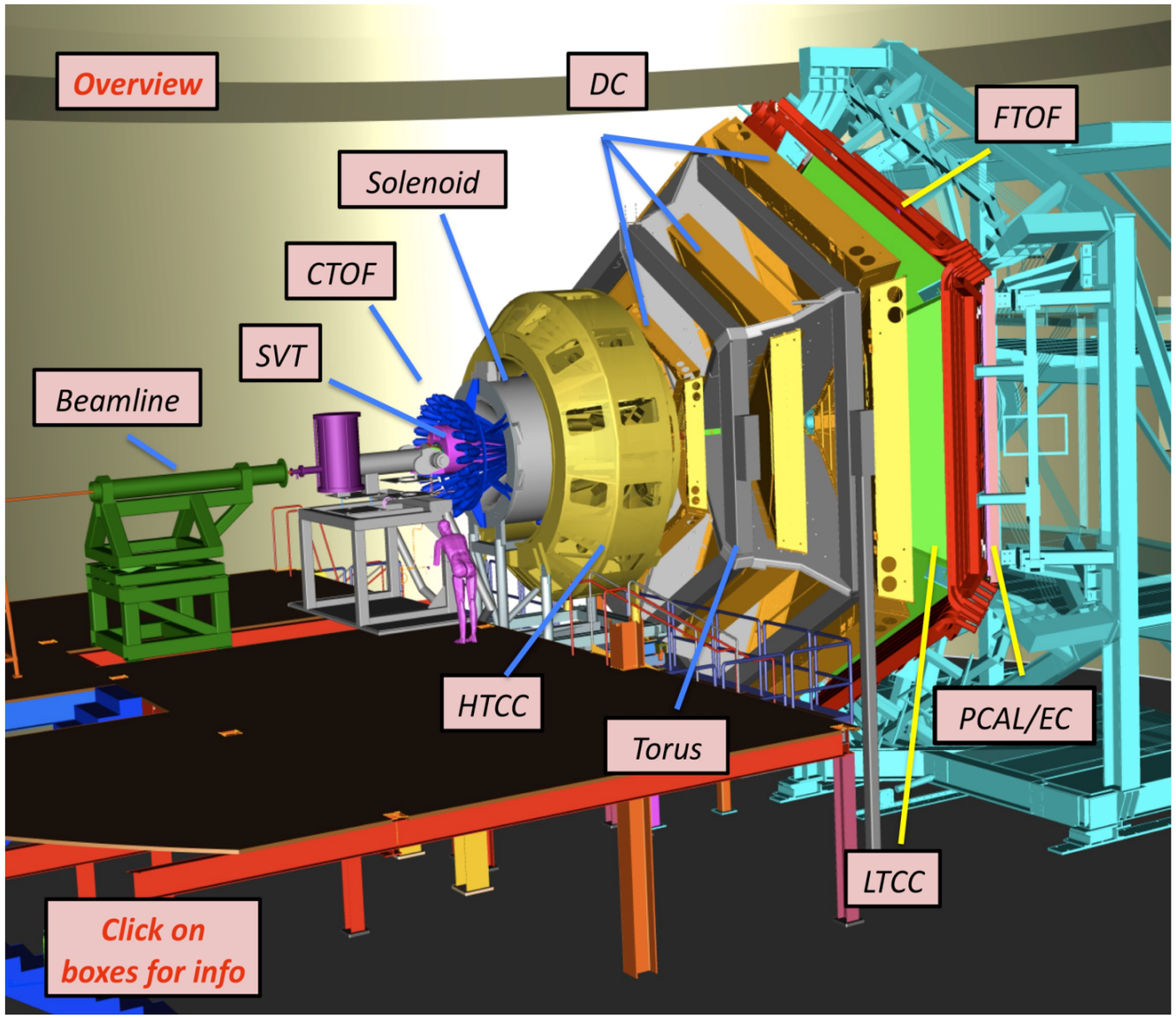
The 12GeV Upgrade: It's done

- Doubling beam energy
- New experimental Hall D and beam line
- Civil construction including utilities
- Upgrades to Halls B and C
- Maintain capability to deliver lower beam energies
- Majority of accelerator and experimental equipment are reused

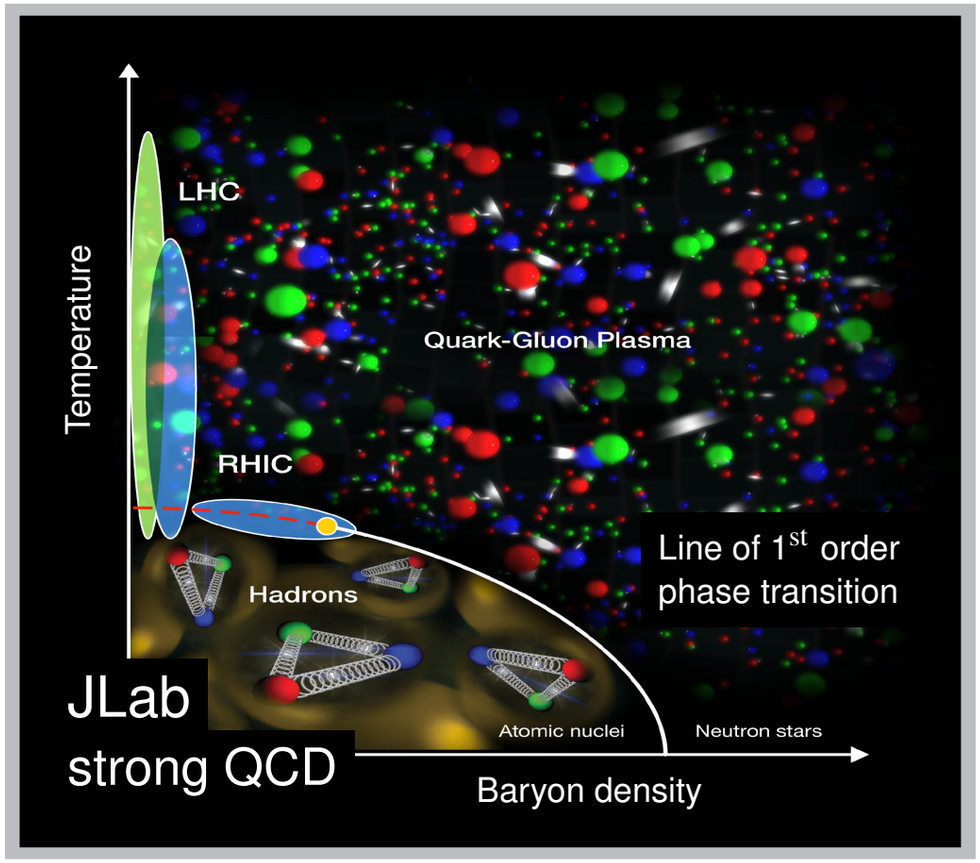


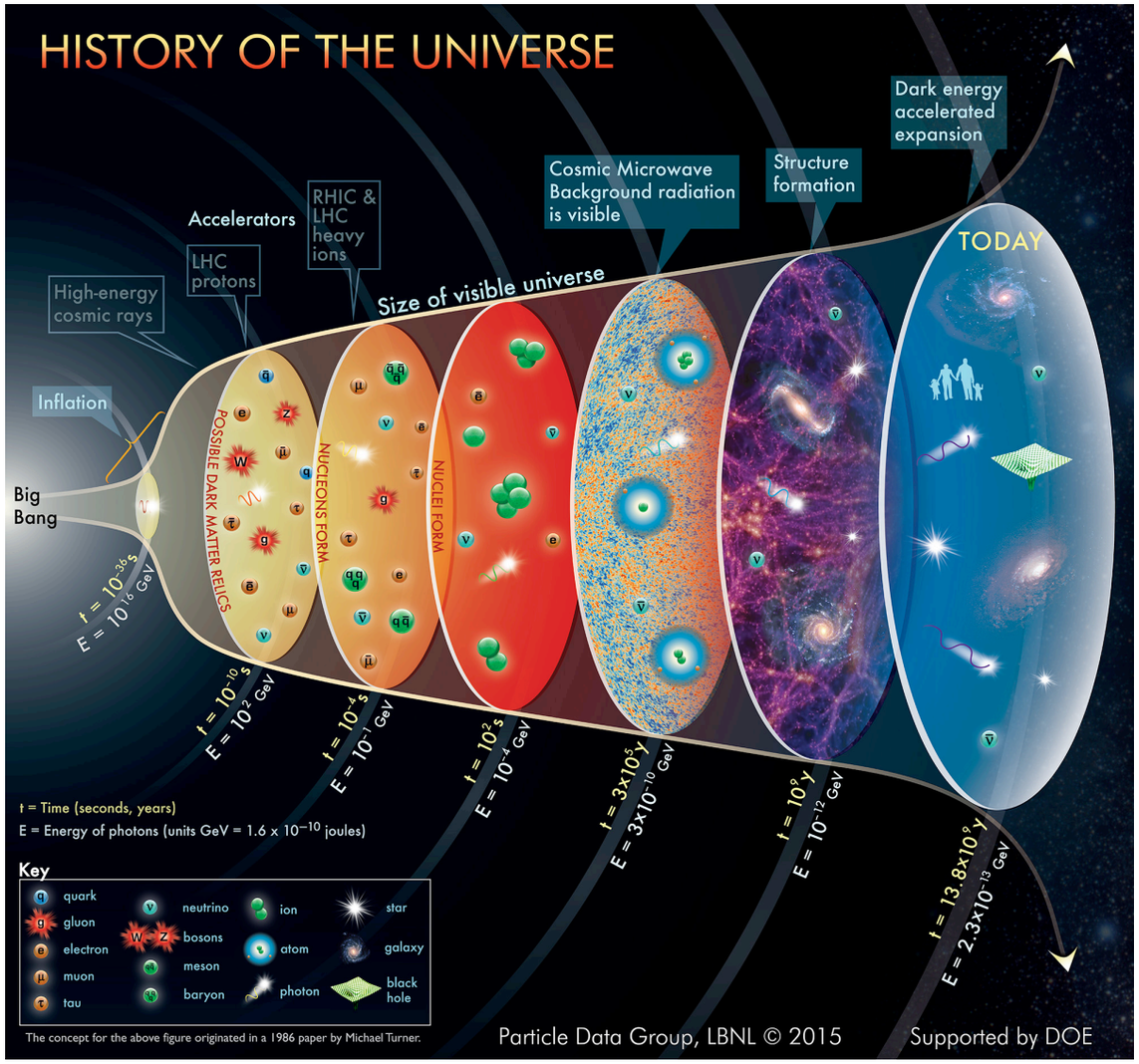
CLAS12 Overview

- Baseline Equipments:
  - Torus and Solenoid Magents
  - HT/LT Cerenkov Counter
  - Forward/Central TOF
  - Drift Chambers
  - Preshower and EM calorimeters
  - Silicon tracker
- Upgrades
  - Micromegas
  - Neutron detectors
  - RICH detectors (1 sector)
  - Forward Tagger



The Beginning of everything:Why Hadron Spectroscopy





- Atomic Spectrosopy —> QED
- Hadron Spectroscopy —> QCD

QGP —>Hadron
10^{-9} s —>10^{-4} s

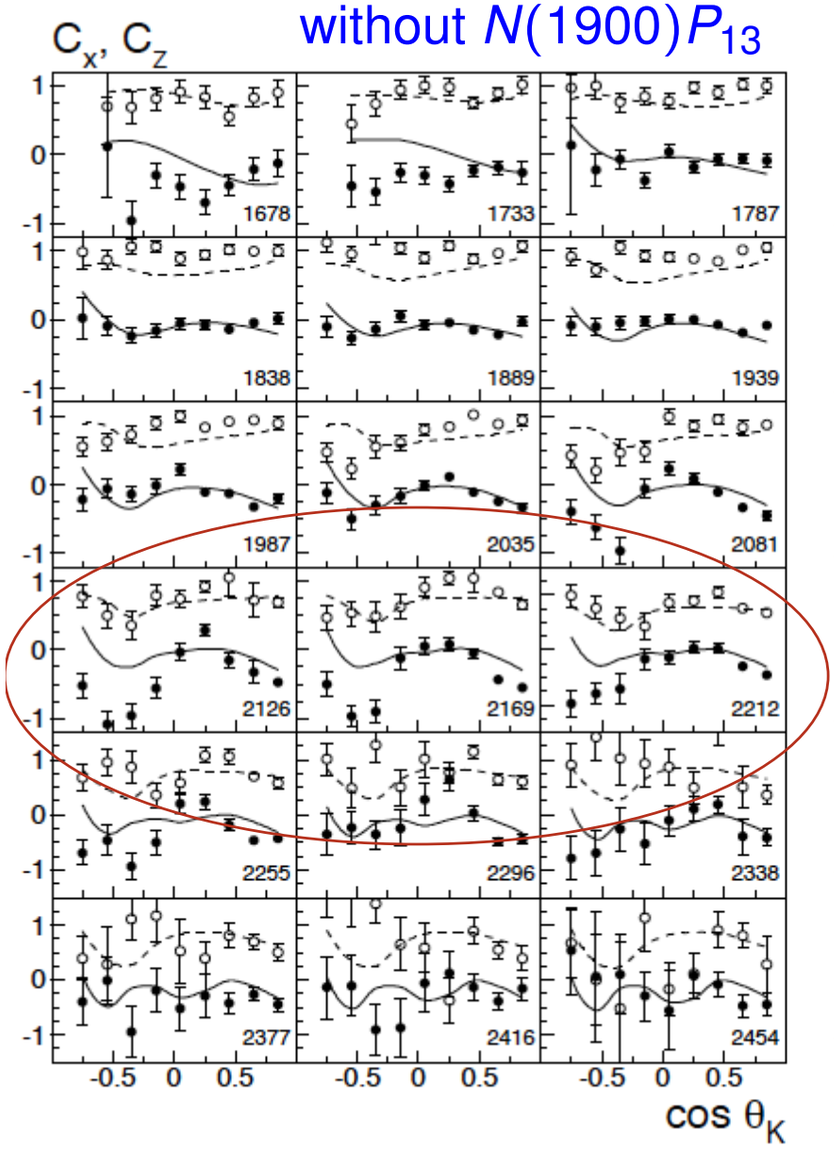
Polarization and Interferences: Key to the CLAS N* Program

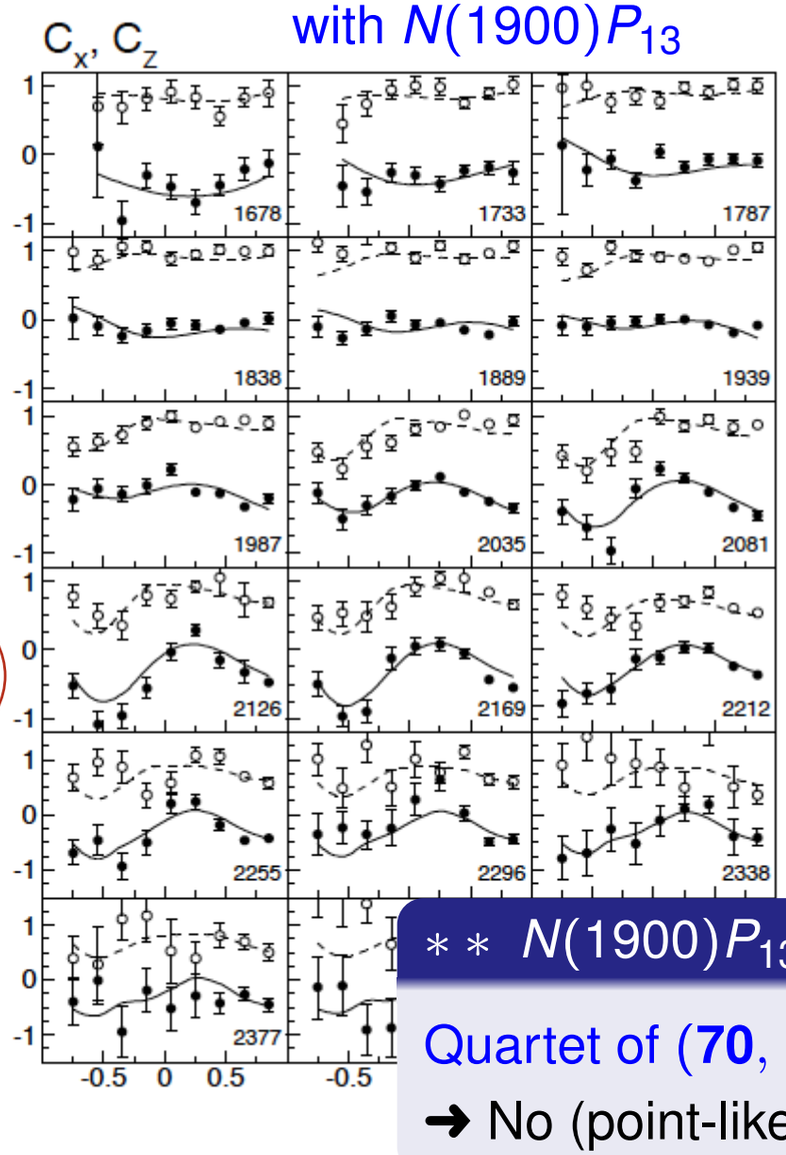
Without Polaroid. **With Polaroid**

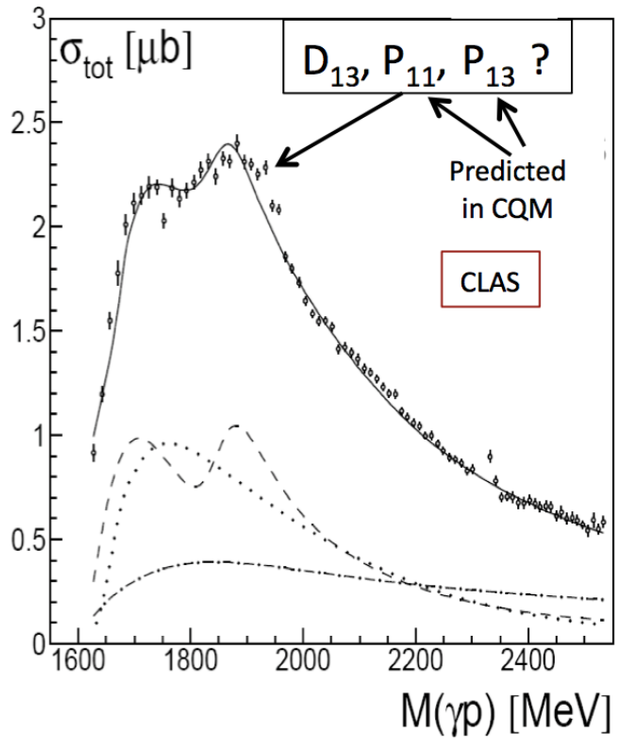
Isospin: Need proton/neutron targets
Coupled Channel Analysis:
Maid,Said, Bn-Ga
Many Results published;
Even More to come!!!
CLAS analysis still ongoing.

	σ	Σ	T	P	E	F	G	H	$T_{x'}$	$T_{z'}$	$L_{x'}$	$L_{z'}$	$O_{x'}$	$O_{z'}$	$C_{x'}$	$C_{z'}$
						Proton targets										
$p\,\pi^0$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$n\,\pi^+$	✓	✓	✓	(✓)	✓	✓	✓	✓		✓	published					
$p\,\eta$	✓	✓	✓	(✓)	✓	✓	✓	✓		✓	acquired or under analysis					
$p\,\eta'$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$p\,\omega/\phi$	✓	✓	✓	(✓)	✓	✓	✓	✓		Tensor polarization, SDMEs						
$K^+\,\Lambda$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^+\,\Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\,\Sigma^+$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
						Neutron (deuteron) targets										
$p\,\pi^-$	✓	✓			✓		✓									
$K^-\,\Sigma^+$	✓	✓	✓	✓	✓	✓	✓									
$K^0\,\Lambda$	✓	✓	✓	✓	✓*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\,\Sigma^0$	✓	✓	✓	✓	✓*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Polarization Observables (Cx and Cz) in Λ photoproduction







∗∗ $N(1900)P_{13}$, $N(2000)F_{15}$, $N(1990)F_{17}$

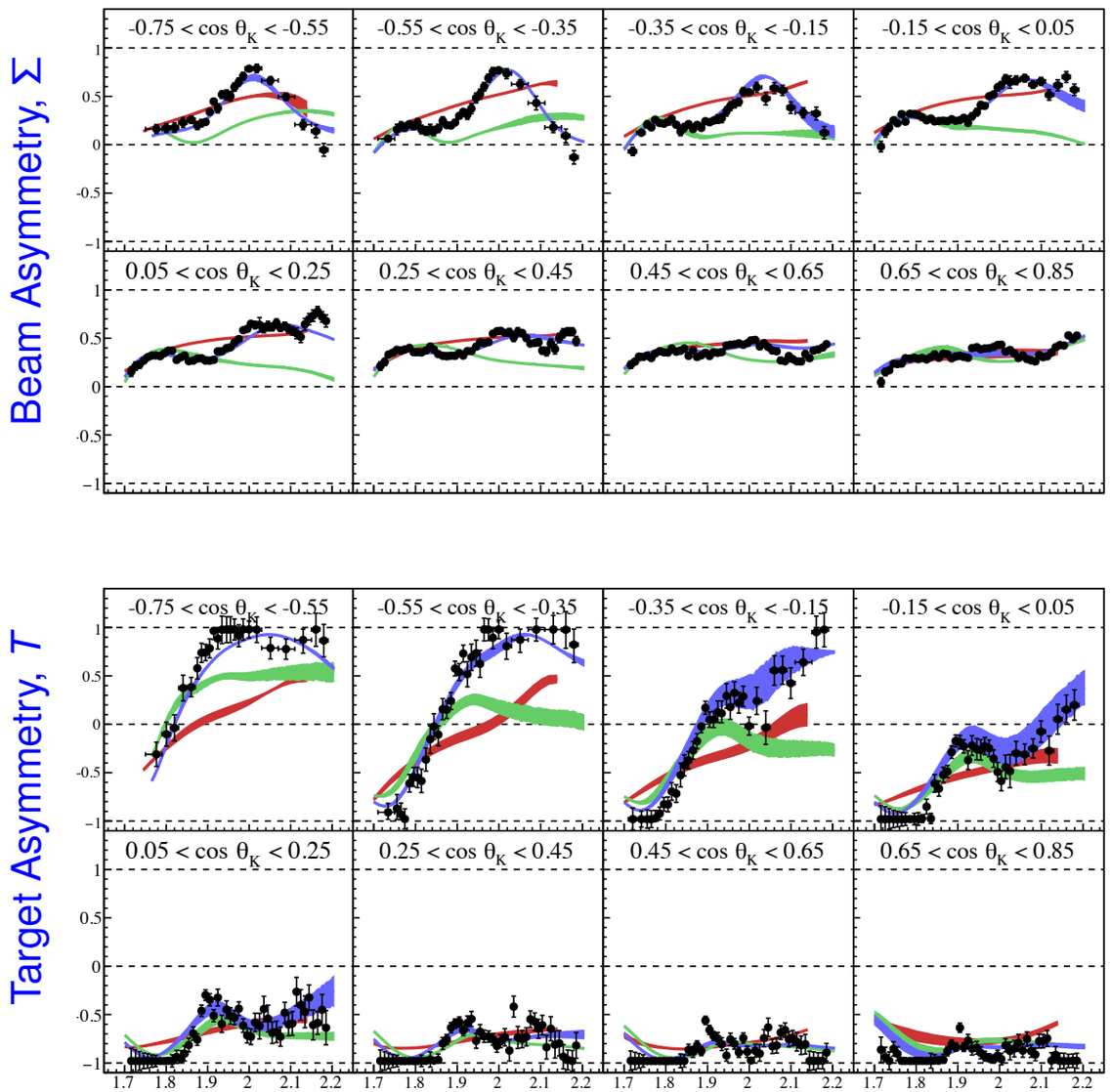
Quartet of (**70**, 2_2^+) with $S = \frac{3}{2}$

➜ No (point-like) quark-diquark oscillations!

R. Bradford *et al.* [CLAS Collaboration], PRC **75**, 035205 (2007)

Fits: BoGa-Model, V. A. Nikonov et al., PLB 662, 245 (2008)

More Polarization Observables: Λ photoproduction



C. A. Paterson (CLAS) et al., PRC 93, 065201 (2016)

— ANL-Osaka, —Bn-Ga14

—Bn-Ga14 Refit: Additional N* 3/2+ and 5/2+ Needed

From PDG 2004 to 2018: What changed

The impact of photoproduction on baryon resonances

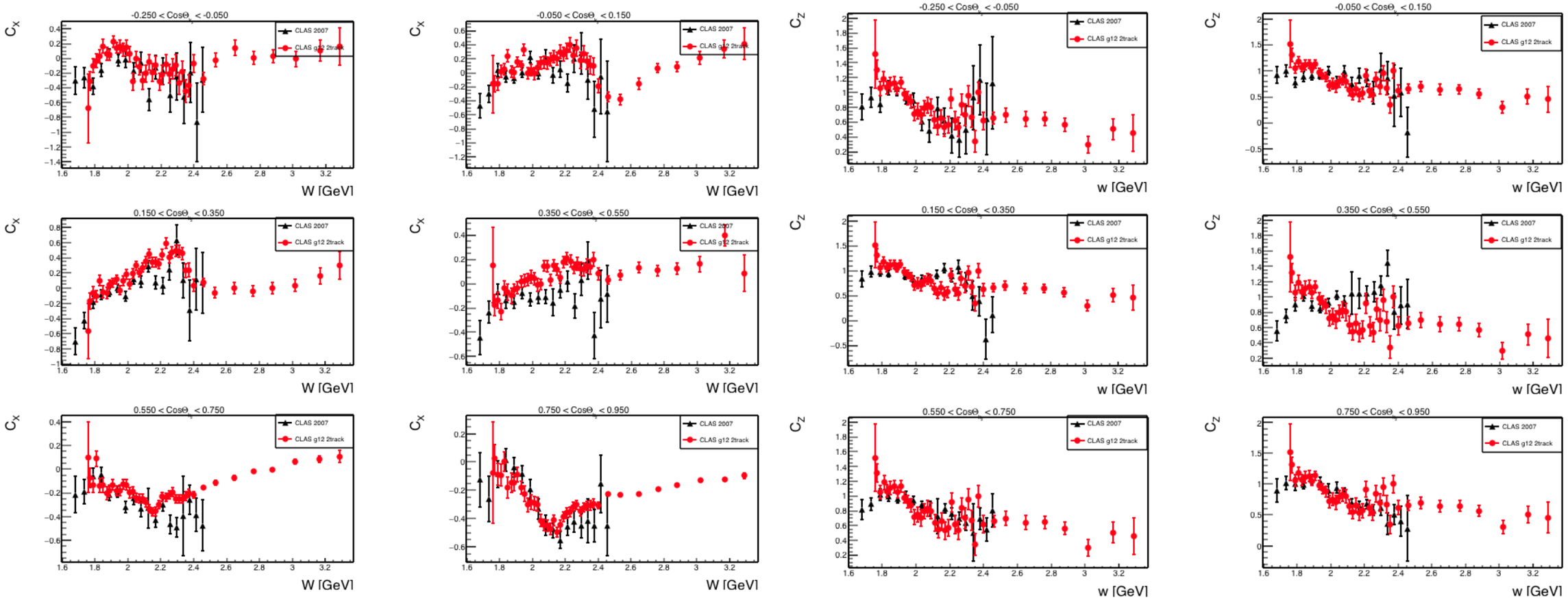
Decay modes of nucleon resonances
black: PDG 2004
red: PDG 2018
blue: BESIII resonances

∗∗∗∗	Existence is certain.
∗∗∗	Existence is very likely.
∗∗	Evidence of existence is fair.
∗	Evidence of existence is poor.

		overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$	$N_{1440}\pi$	$N_{1520}\pi$	$N_{1535}\pi$	$N_{1680}\pi$
N	$1/2^+$	∗∗∗∗														
$N(1440)$	$1/2^+$	∗∗∗∗	∗∗∗∗	∗∗∗∗	∗∗∗∗	∗∗∗										
$N(1520)$	$3/2^-$	∗∗∗∗	∗∗∗∗	∗∗∗∗	∗∗∗∗	∗∗	∗∗∗∗									
$N(1535)$	$1/2^-$	∗∗∗∗	∗∗∗∗	∗∗∗∗	∗∗∗	∗	∗∗∗∗									
$N(1650)$	$1/2^-$	∗∗∗∗	∗∗∗∗	∗∗∗∗	∗∗∗	∗	∗∗∗∗	∗∗					∗			
$N(1675)$	$5/2^-$	∗∗∗∗	∗∗∗∗	∗∗∗∗	∗∗∗∗	∗∗∗	∗	∗	∗	∗∗					∗	
$N(1680)$	$5/2^+$	∗∗∗∗	∗∗∗∗	∗∗∗∗	∗∗∗∗	∗∗∗	∗			∗∗∗∗						
$N(1700)$	$3/2^-$	∗∗∗	∗∗	∗∗∗	∗∗∗	∗	∗	∗∗	∗	∗						
$N(1710)$	$1/2^+$	∗∗∗∗	∗∗∗∗	∗∗∗∗	∗∗		∗∗∗	∗∗	∗	∗	∗			∗		
$N(1720)$	$3/2^+$	∗∗∗∗	∗∗∗∗	∗∗∗∗	∗∗∗	∗	∗	∗∗∗∗	∗	∗∗	∗					
$N(1860)$	$5/2^+$	∗∗	∗	∗∗		∗	∗									
$N(1875)$	$3/2^-$	∗∗∗	∗∗	∗∗	∗	∗∗	∗	∗	∗	∗	∗	∗	∗			
$N(1880)$	$1/2^+$	∗∗∗	∗∗	∗	∗∗	∗	∗	∗∗	∗∗		∗∗			∗		
$N(1895)$	$1/2^-$	∗∗∗∗	∗∗∗∗	∗	∗	∗	∗∗∗∗	∗∗	∗∗	∗	∗	∗∗∗∗	∗			
$N(1900)$	$3/2^+$	∗∗∗∗	∗∗∗∗	∗∗	∗∗	∗	∗	∗∗	∗∗	∗	∗	∗∗				
$N(1990)$	$7/2^+$	∗∗	∗∗	∗∗	∗	∗	∗	∗∗	∗∗							
$N(2000)$	$5/2^+$	∗∗	∗∗	∗∗	∗∗	∗	∗	∗	∗		∗					
$N(2040)$	$3/2^+$	∗		∗												
$N(2060)$	$5/2^-$	∗∗∗	∗∗∗	∗∗	∗	∗	∗	∗	∗	∗	∗		∗	∗		∗
$N(2100)$	$1/2^+$	∗∗∗	∗∗	∗∗∗	∗∗	∗∗	∗	∗		∗	∗	∗∗			∗∗∗	
$N(2120)$	$3/2^-$	∗∗∗	∗∗∗	∗∗∗	∗∗	∗∗		∗∗	∗		∗	∗	∗	∗	∗	
$N(2190)$	$7/2^-$	∗∗∗∗	∗∗∗∗	∗∗∗∗	∗∗∗∗	∗∗	∗	∗∗	∗	∗	∗					
$N(2220)$	$9/2^+$	∗∗∗∗	∗∗	∗∗∗∗			∗	∗	∗							
$N(2250)$	$9/2^-$	∗∗∗∗	∗∗	∗∗∗∗			∗	∗	∗							
$N(2300)$	$1/2^+$	∗		∗												
$N(2570)$	$5/2^-$	∗		∗												
$N(2600)$	$11/2^-$	∗∗∗		∗∗∗												
$N(2700)$	$13/2^+$	∗∗		∗∗												

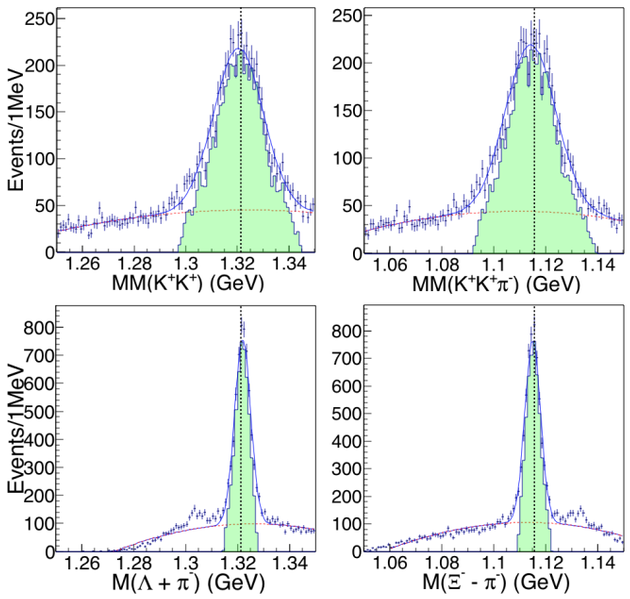
Based on results from CLAS, ELSA, MAMI ….

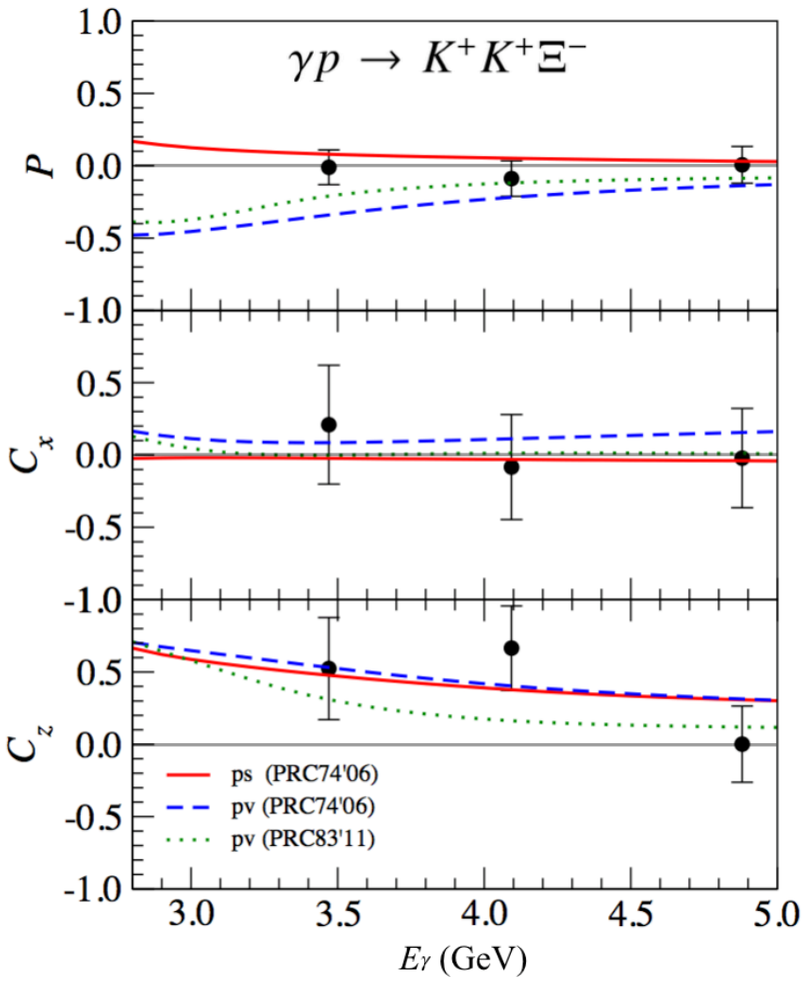
More Precise Measurements: Λ photoproduction

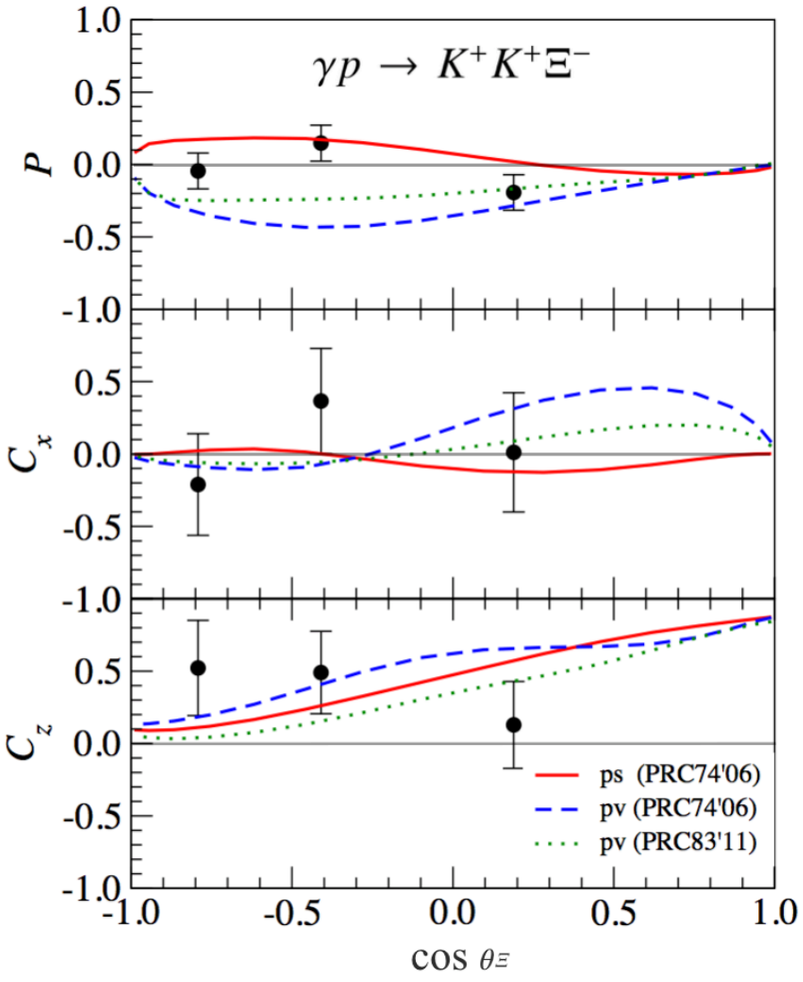


P, Cx, Cz extracted simultaneously: Maximum Log Likehood Method
Much Larger Statistics: uncertainties three times smaller
Extending to higher W range
Better Constraint on non-resonance contributions
Ph.D Thesis of Shankar Adhikari (FIU 2018)

CLAS6 Cascade Polarization results







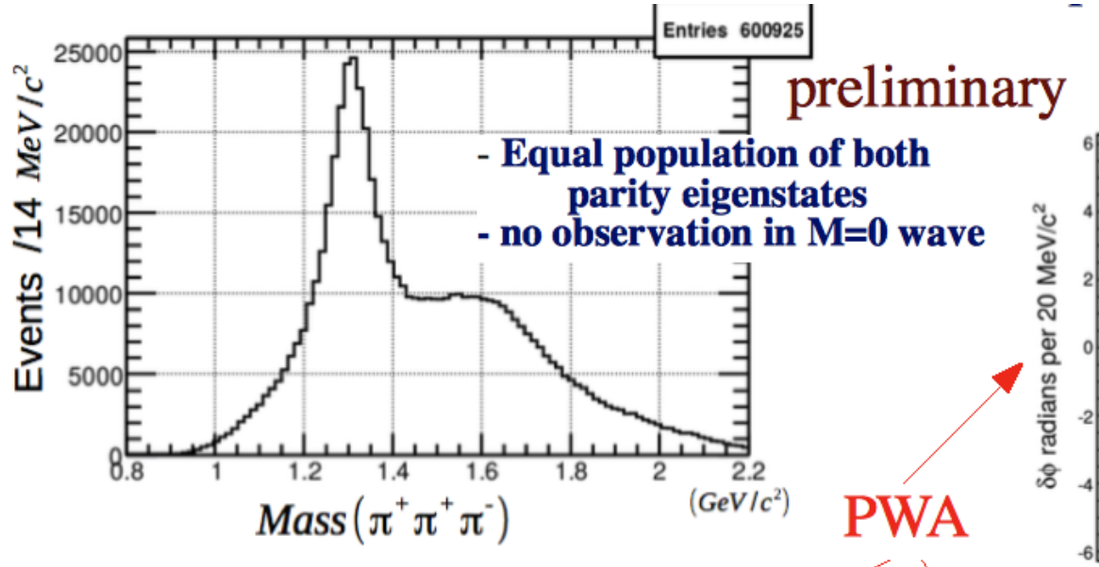
- Results VS prediction: Limited by statistics
  R~0.3
  vs R~1 for Λ results

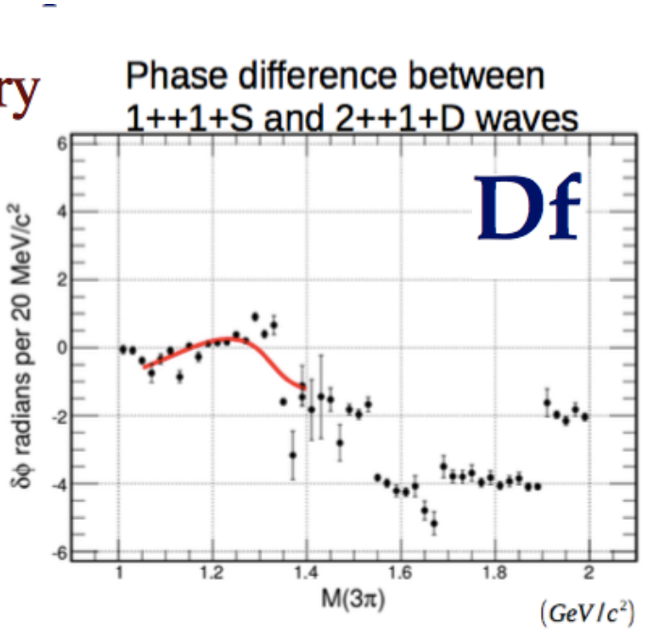
- Unable to distinguish models
  - (K or K* exchange? Higher-mass hyperon contribution)

- CLAS12 needed

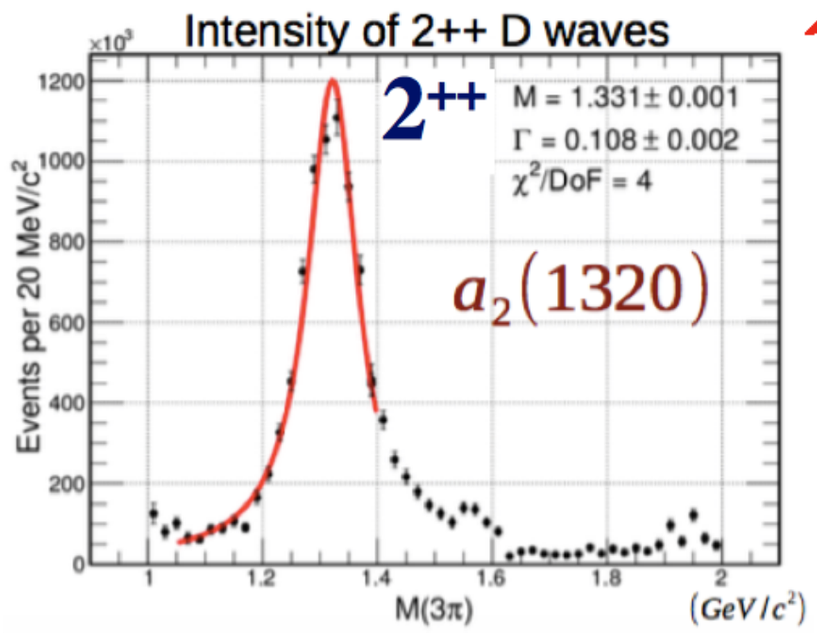
J. Bono (CLAS) et al.,PLB 783, 280 (2018)

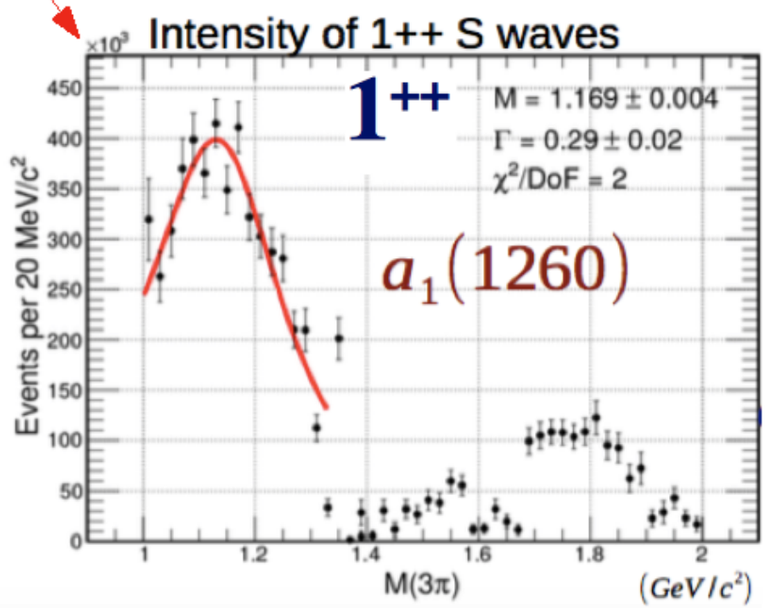
CLAS 6 (g12) results: $\gamma p \rightarrow n\, \pi^+\pi^+\pi^-$





PWA

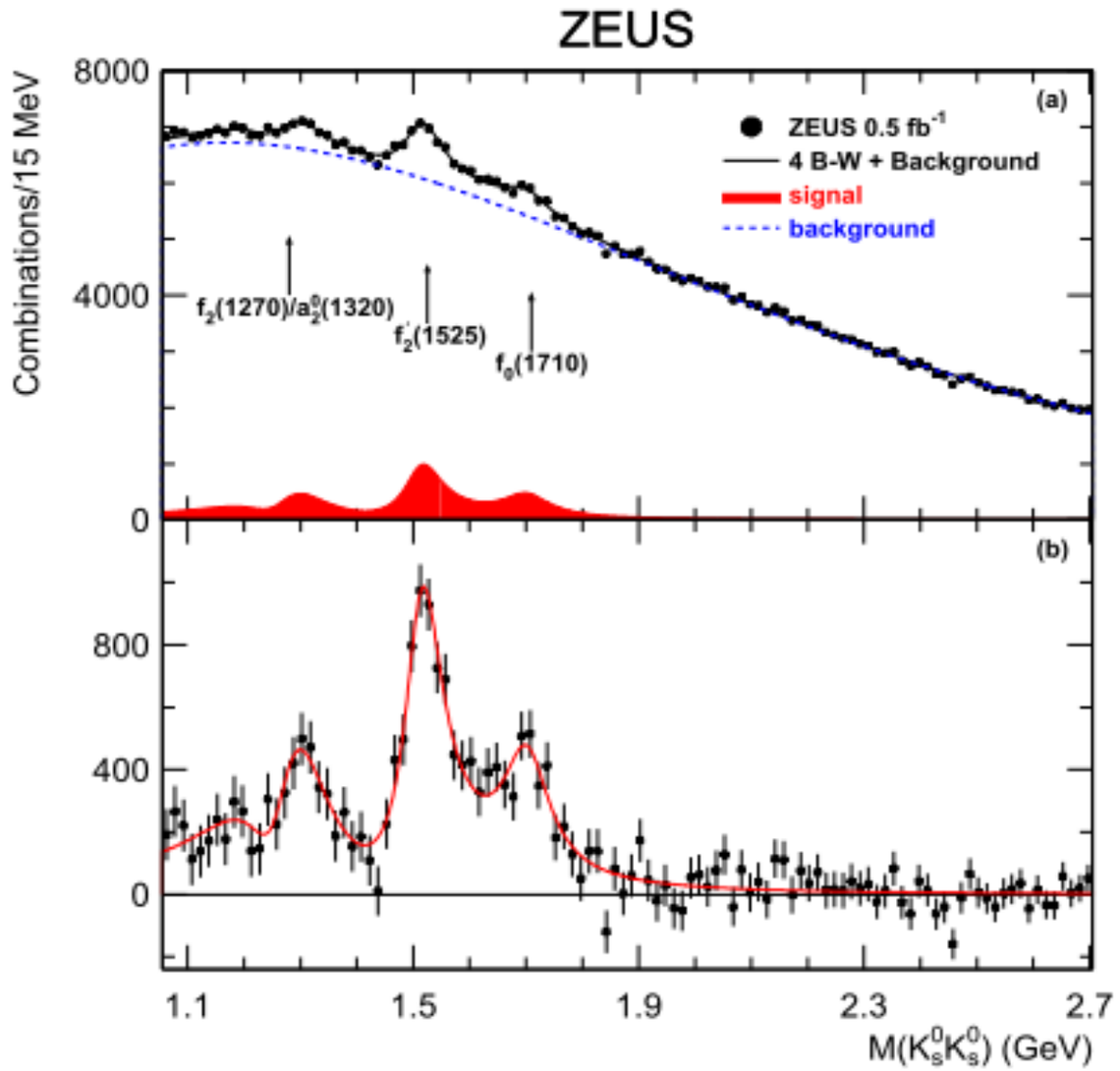




A. Tsaris (2016 FSU Dissertation)

No exotic wave required;
Results under review

CLAS 6 (g12) results: Scalar Mesons and Glueball candidates



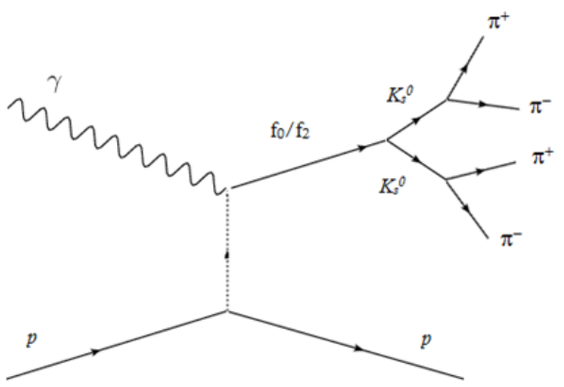
ZEUS Collaboration: S. Chekanov, et al, *Inclusive $K^0_S K^0_S$ resonance production in ep collisions at HERA, Phys.Rev.Lett. 101:112003,2008, arXiv:0806.0807v2*

Why choose strange decay?

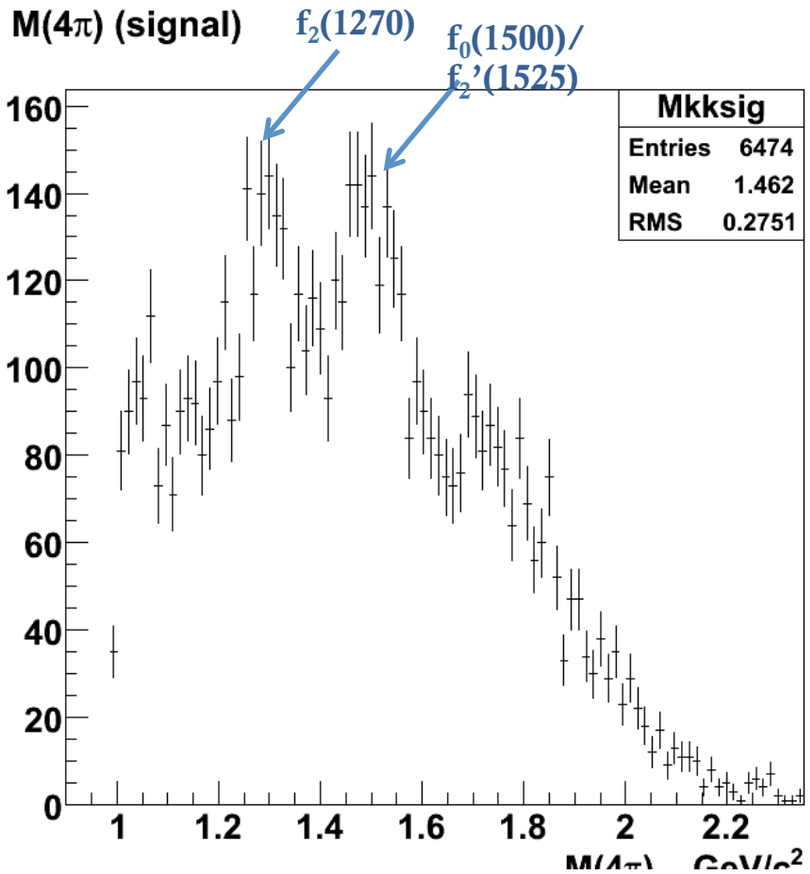
M.Chanowitz suggests in PRL 95, 172001 (2005) that glueballs are more likely to decay to strange channels

Why choose $K_s^0 K_s^0$?

Ensure that the final state has the same PC =++ as the lightest glueball



CLAS 6 (g12) results: Scalar Mesons and Glueball candidates

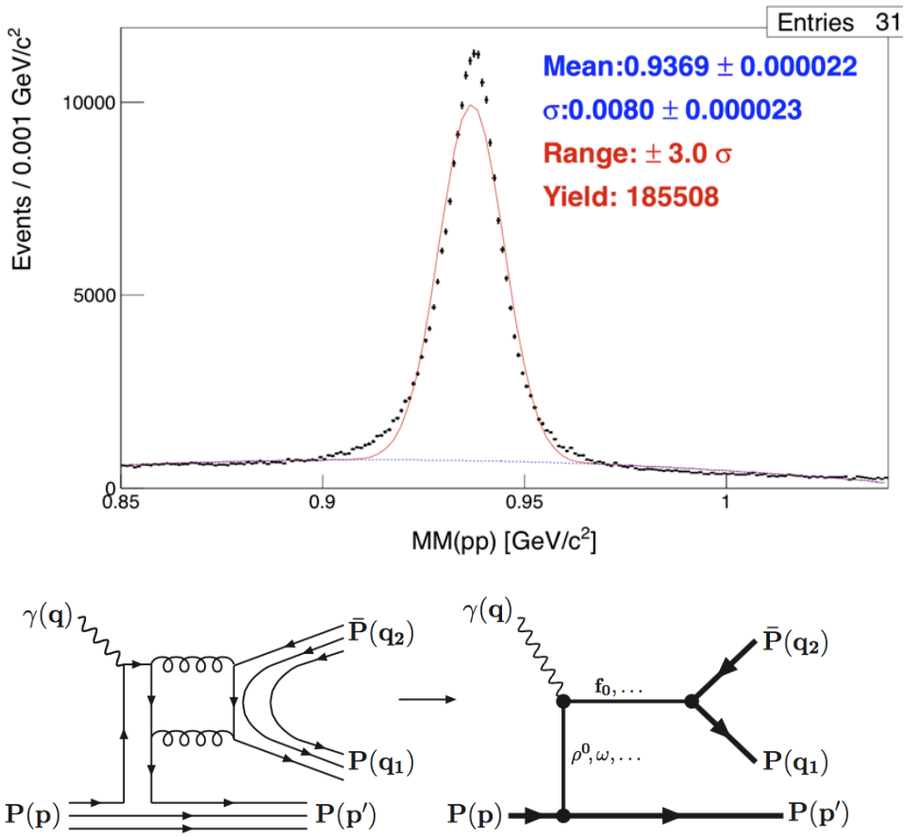


- Angular distributions analyzed and compared with simulaton
- S-wave dominates; No glueball evidence.

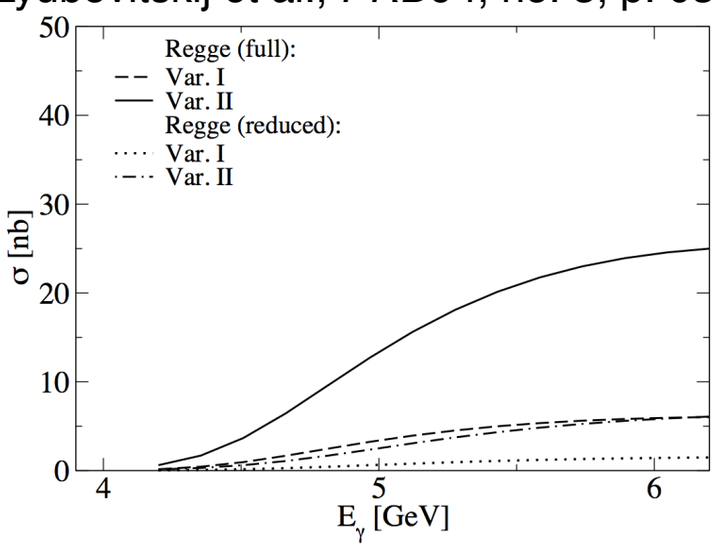
Mass Bin (MeV)	S-wave fraction (S+B region)	S-wave fraction (Sidebands)
1000-1050	1.000 ± 0.045	1.000 ± 0.031
1050-1100	1.000 ± 0.031	1.000 ± 0.029
1100-1150	0.973 ± 0.025	0.982 ± 0.018
1150-1200	1.000 ± 0.023	1.000 ± 0.015
1200-1250	1.000 ± 0.022	1.000 ± 0.011
1250-1300	1.000 ± 0.013	1.000 ± 0.063
1300-1350	1.000 ± 0.020	1.000 ± 0.011
1350-1400	1.000 ± 0.028	1.000 ± 0.026
1400-1450	1.000 ± 0.025	0.922 ± 0.019
1450-1500	0.928 ± 0.037	0.890 ± 0.023
1500-1550	0.903 ± 0.039	0.879 ± 0.021
1550-1600	0.803 ± 0.044	0.897 ± 0.024
1600-1650	0.791 ± 0.056	0.883 ± 0.032
1650-1700	0.762 ± 0.052	0.910 ± 0.031
1700-1750	0.660 ± 0.053	0.902 ± 0.033
1750-1800	0.690 ± 0.071	0.941 ± 0.041
1800-1850	0.845 ± 0.086	0.994 ± 0.096

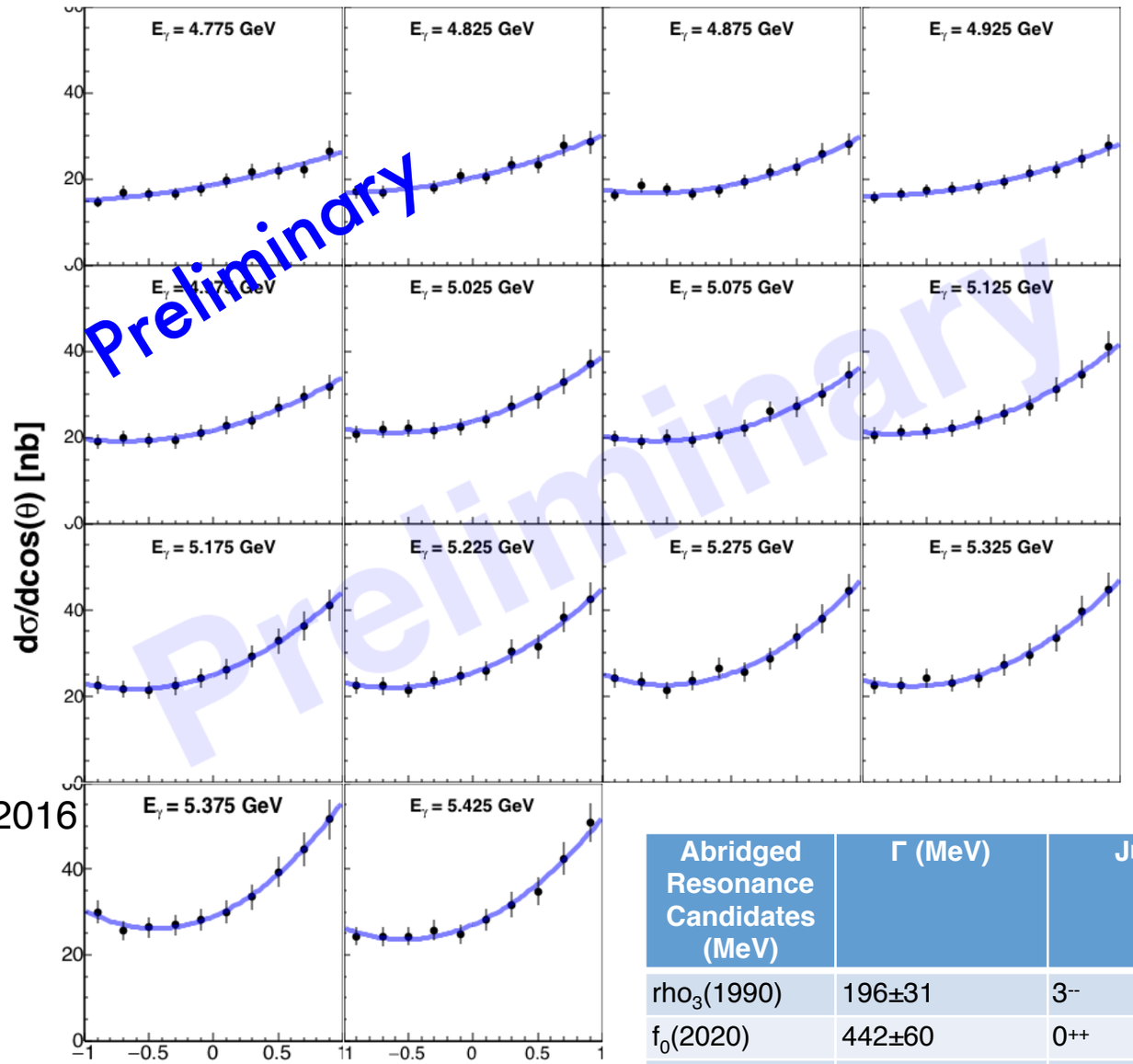
S. Chandavar *et al.* , Phys. Rev. C 97, 025203 (2018)

CLAS 6 results: Glueballs to proton-antiproton?



V. E. Lyubovitskij et al., *PRD*94, no. 3, p. 034010, 2016

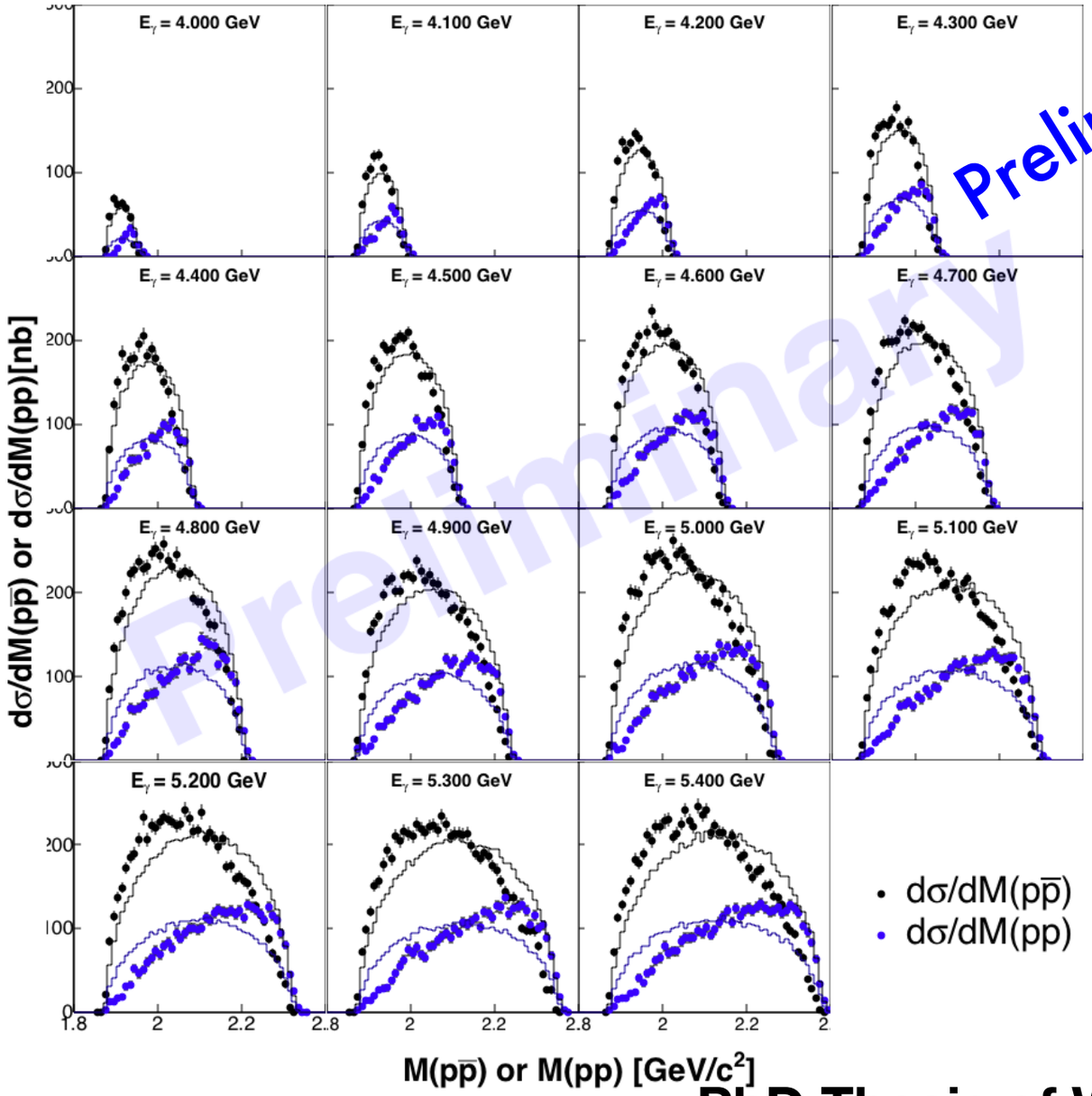


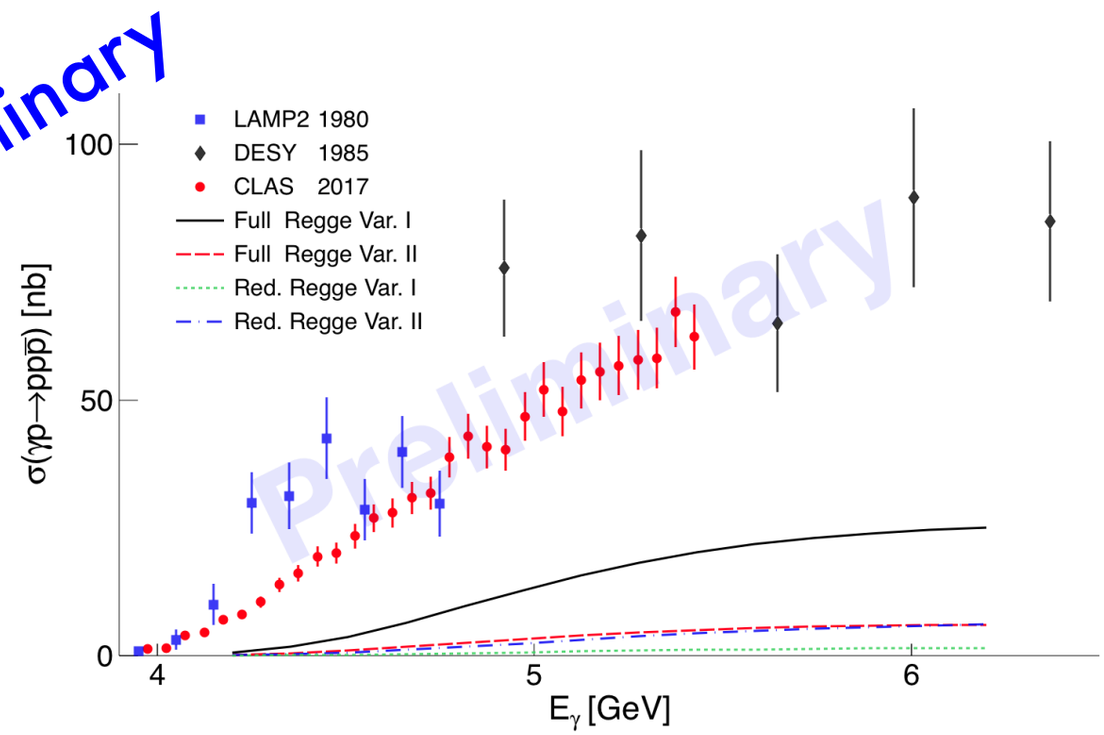


Intermediate Mesons (glueball candidates?) —> ppbar?

Abridged Resonance Candidates (MeV)	Γ (MeV)	J^{pc}
$rho_3(1990)$	196±31	3^{--}
$f_0(2020)$	442±60	0^{++}
$f_2(2150)$	152±30	2^{++}
rho(2150)	~250-320(?)	1^{--}
$rho_3(2250)$	~220	3^{--}
$rho_5(2350)$	400±100	5^{--}
$f_6(2510)$	283±40	6^{++}

CLAS 6 results: Mesons decay to proton-antiproton?



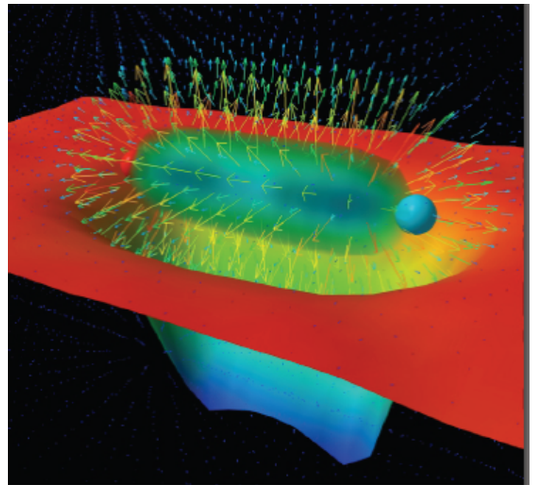


Glueball only predictions underestimates xsection
Mass distributions non-phase-space
No Narrow Peaks
Polarization Observables needs:
Beam Asymmetry (GlueX)
Beam Helicity Asymmetry (CLAS)

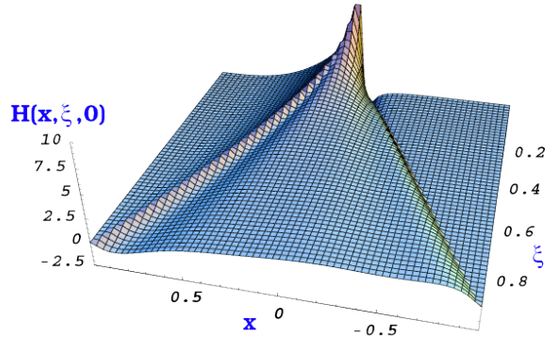
PhD Thesis of Will Phelps (FIU 2017)

Key Components of CLAS12 Science Program

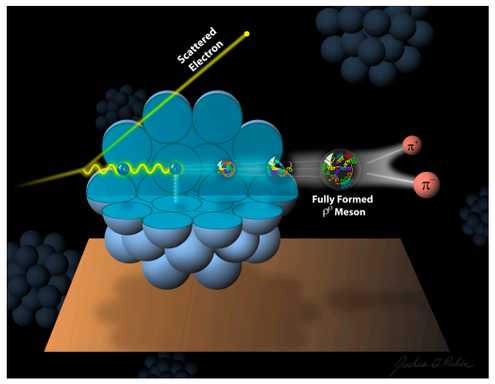
- **Quark confinement and the role of the glue in meson and baryon spectroscopy**



- The 3D structure of the nucleon – from form factors and PDFs to GPDs and TMDs



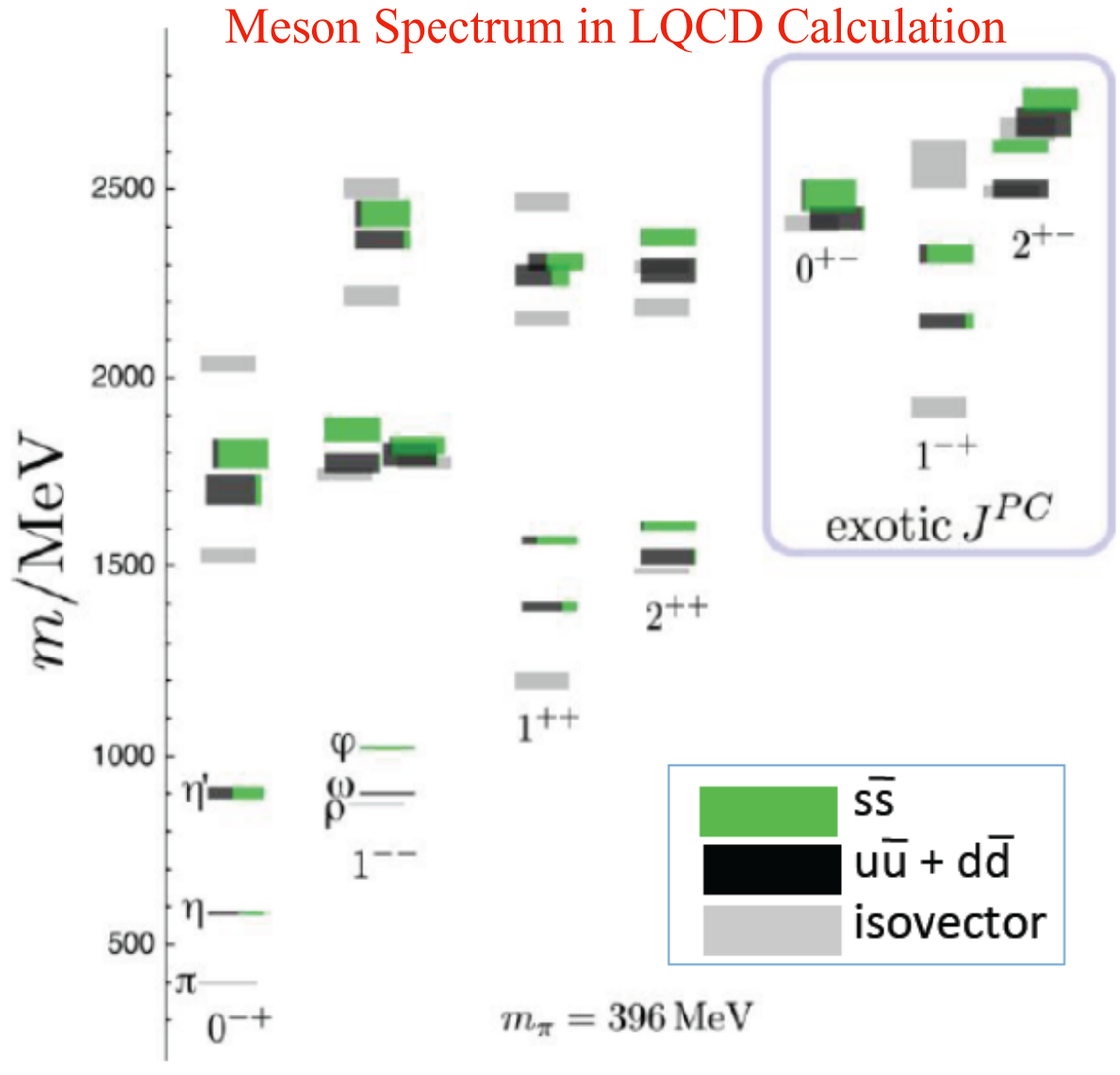
- The strong interaction in nuclei – evolution of quark hadronization, nuclear transparency of hadrons



CLAS12: MesonX experiment with FT
Search for exotic mesons

- New Lattice QCD calculations consistent with earlier quark-model and other calculations
  - Hybrid mesons should exist
- Exotic quantum numbers J^{PC}, cannot be accomplished by quark-antiquark configuration alone
  - $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$
- GlueX (Linearly polarized photon beam) dedicated to hybrid meson search
- CLAS12 search using quasi-real photon beam is complimentary

Meson Spectrum in LQCD Calculation



Dudek, Edwards, Guo and Thomas, PRD 88, 094505 (2013)

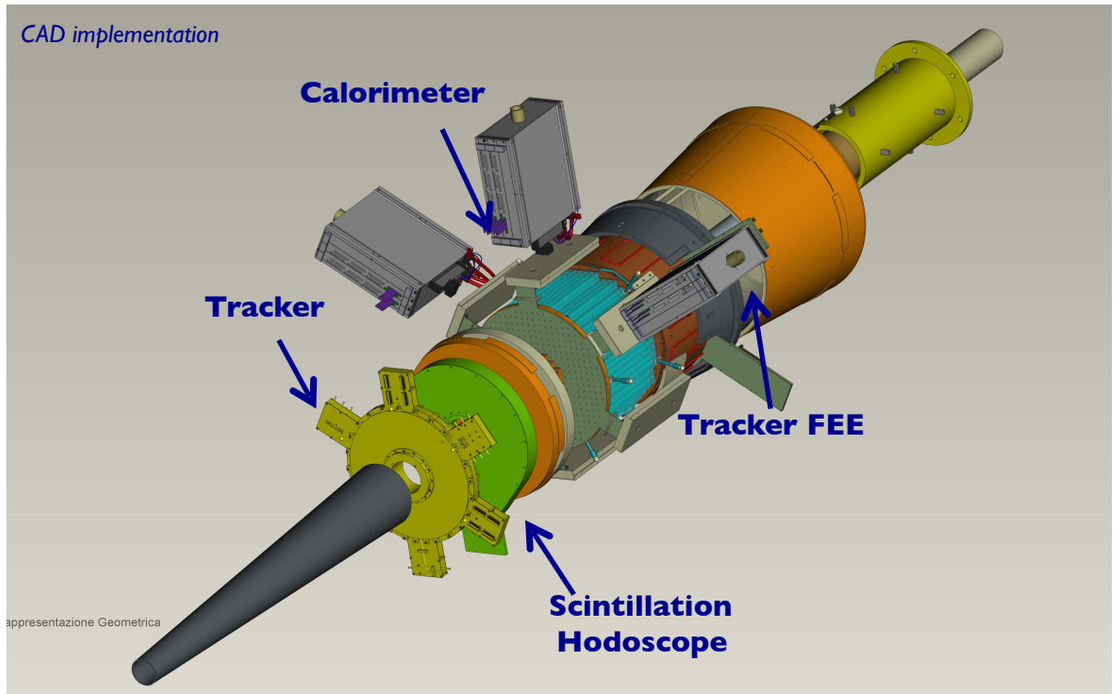
CLAS12 Upgrade: Forward Tagger

- **FT layout**
  - Calorimeter determine the electron energy using homogenous PbWO4 crystals
  - Tracker: Determines electron scattering plane, hence the photon polarization
  - Hodoscope: Distinguish photons from electrons

Forward Tagger	
E’	0.5-4.5 GeV
ν	7-10.5 GeV
θ	2.5-4.5 deg
Q^2	0.007 – 0.3 GeV^2
W	3.6-4.5 GeV
Photon Flux	5 x 10^7 γ/s @ $L_e=10^{35}$

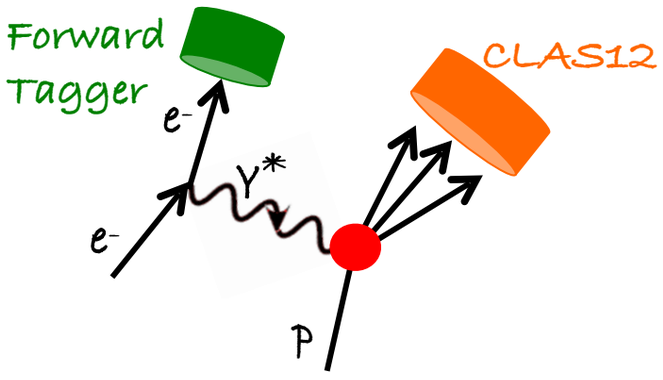
Why do we want FT:

- First of its kind
- Quasi-real photon production (FT) of multiple particle final states (CLAS12)
- Wide range of hadron spectroscopy programs
  - Hybrid meson and baryons
  - Multi-strangeness hyperons
  - ….

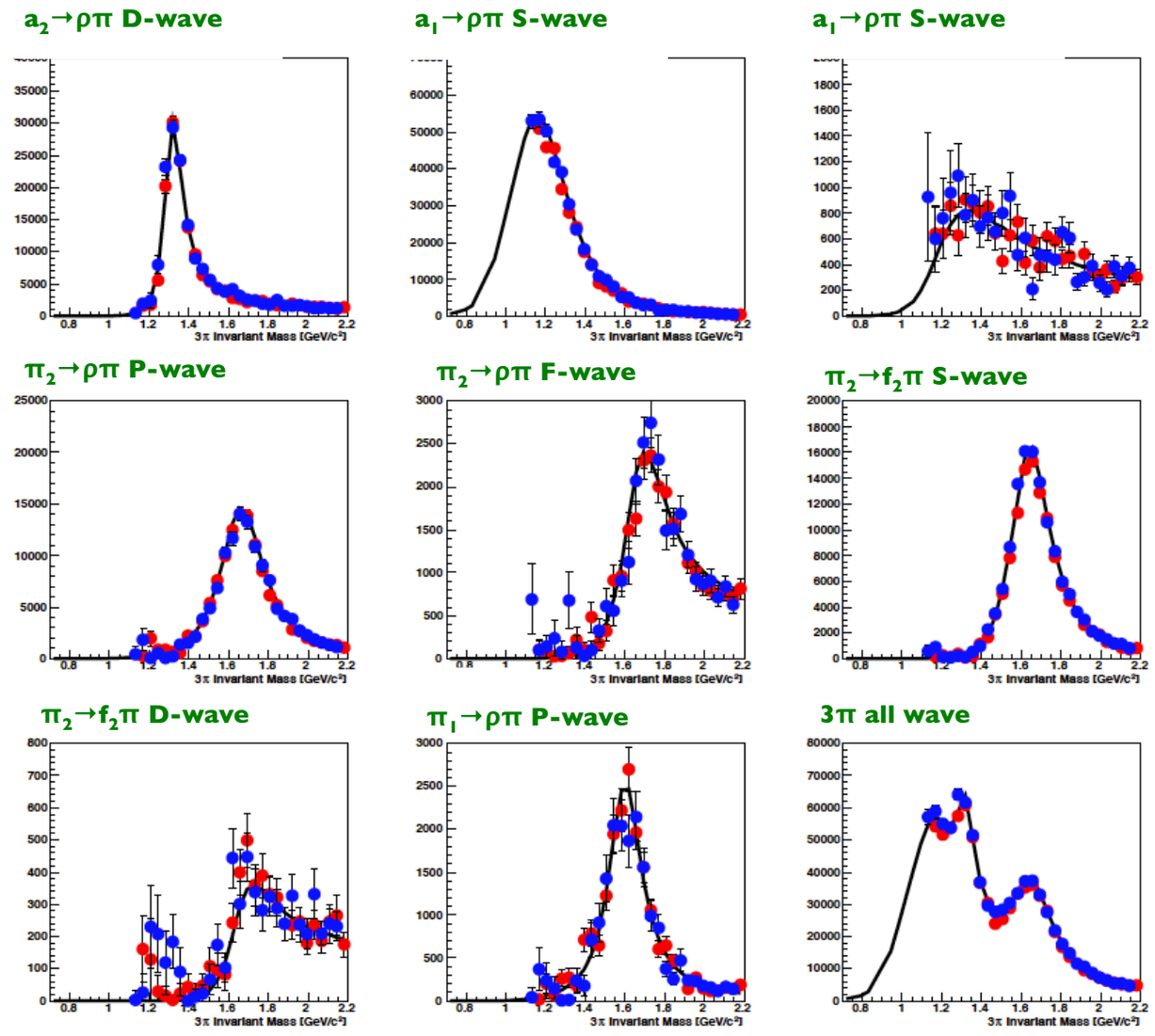


CLAS12: MesonX experiment with FT

Search for exotic mesons: $\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$



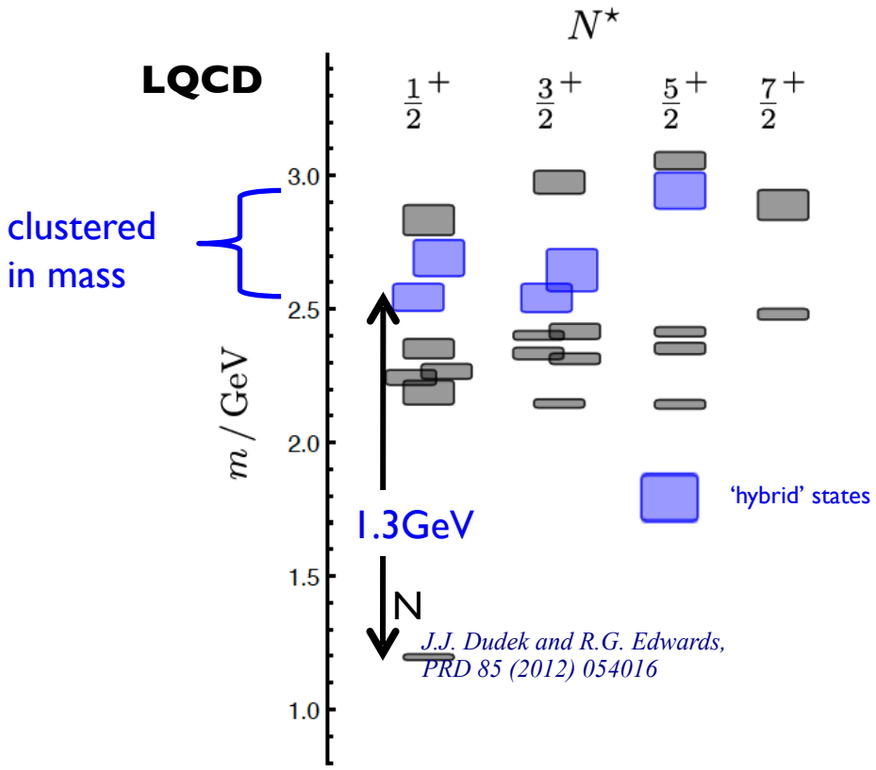
- Partial Wave Analysis:
  - Detector acceptance accounted
  - Event-based maximum log likelihood method
  - Various mesons can be successfully reconstructed
  - The exotic wave you see here is not real data!
- Other meson related program:
  - Vector meson: Beam asymmetry
  - Pseudoscalar mesons

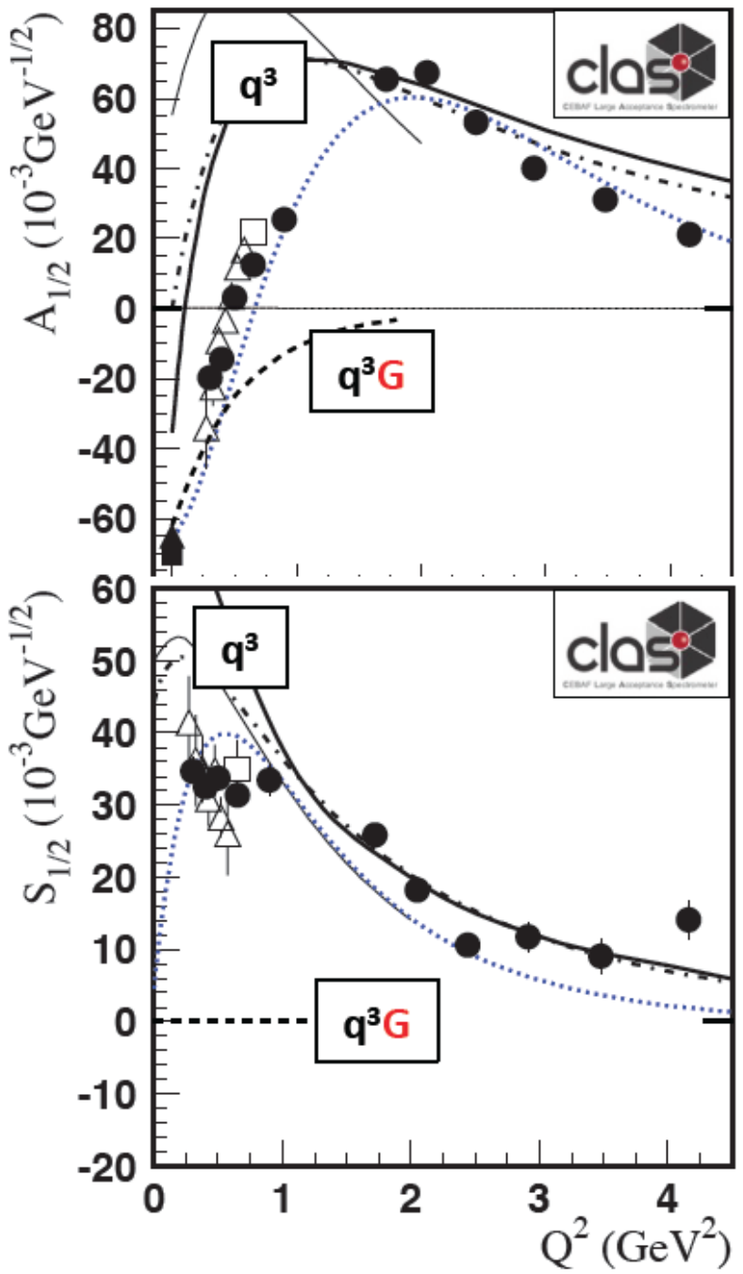


t=0.2(0.5)GeV²

Black: Generated

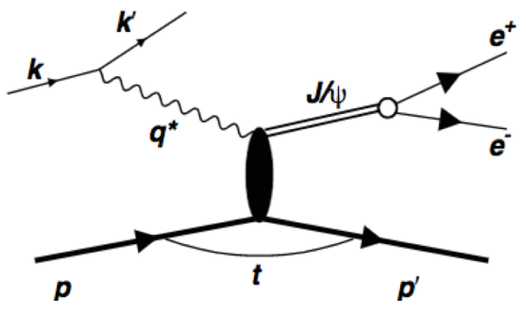
CLAS12:Search for Hybrid Baryons

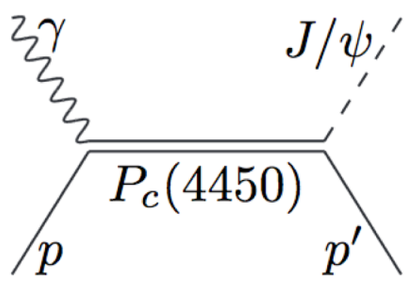


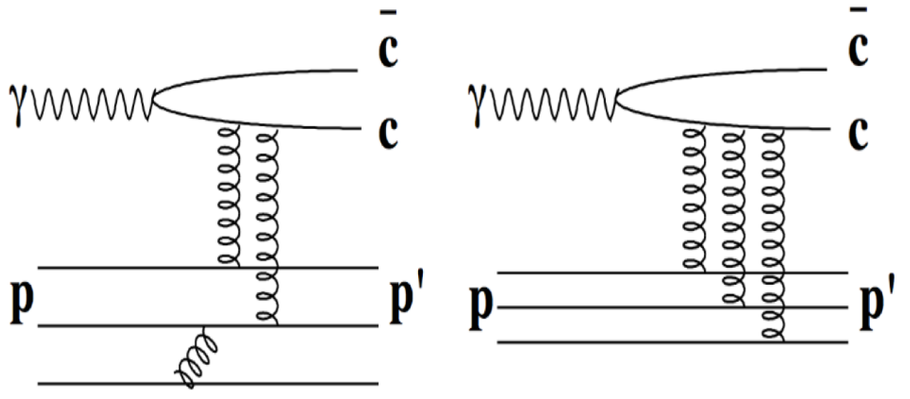


- Hybrid baryons have no "exotic" quantum numbers
- q^3G expected to be more extended objects
- Transition form factors have different Q^2 dependence for hybrid baryons (q^3G) from the "normal" (q^3)ones.

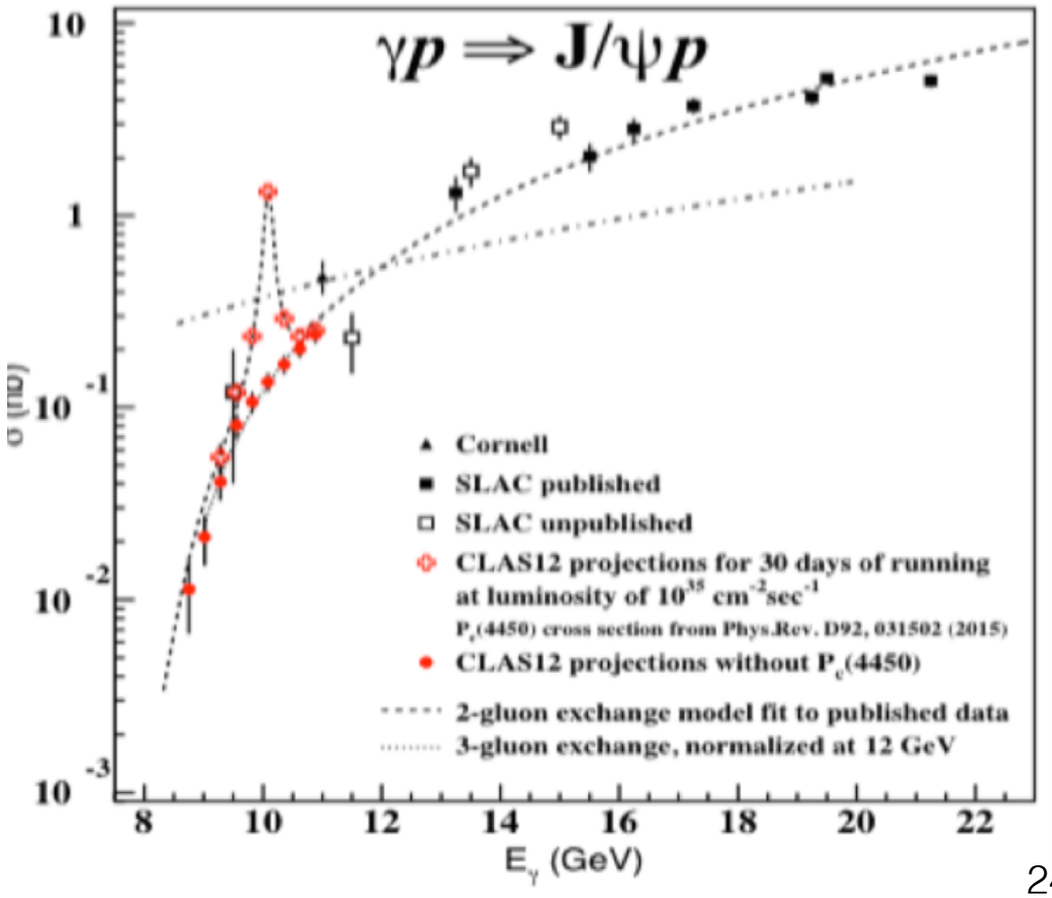
CLAS12:J/Ψ Photoproduction





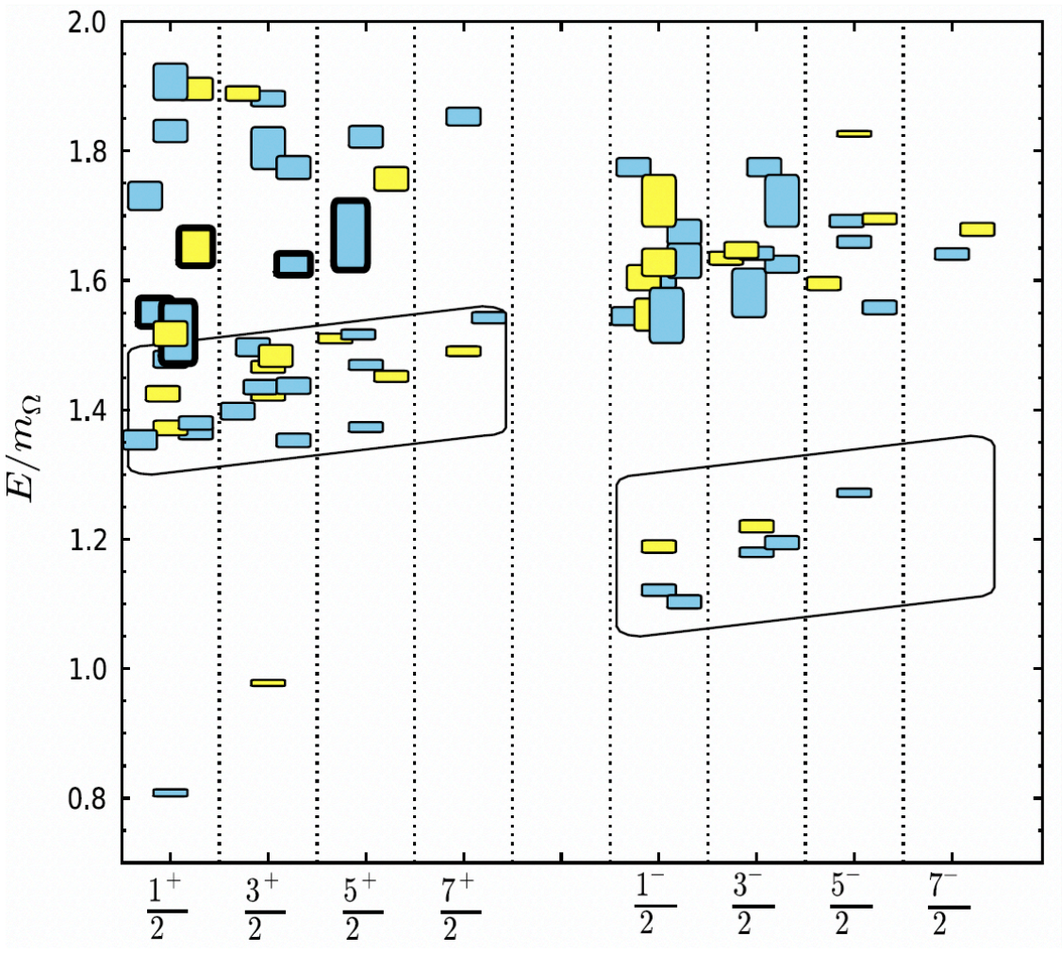


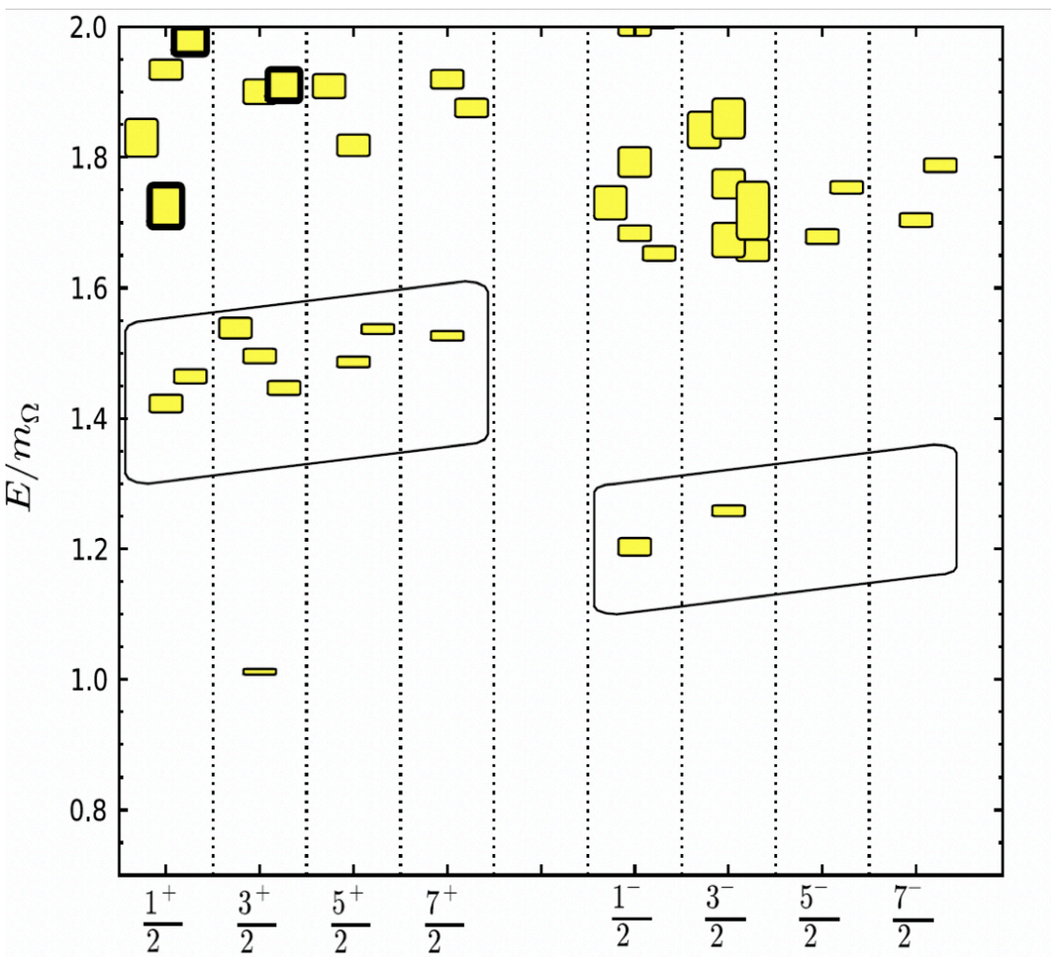
t-channel or s-channel?



- Photon couples to the gluon field via intermediate virtual charm-anticlharm pair according to VDM
- Near threshold J/Ψ production allows the study of gluonic form factors of the proton (t-dependence)
- Rate estimation: 45 J/Ψ per day (No pentaquark assumption)
- Similar search can be performed on deuteron target
- Tagged quasi-real photon or untagged photon

CLAS12: Very Strange Experiment
LQCD Calculation for the Ξ and Ω spectra





R. Edwards et al., PRD 87, 054506(2013)

Very few Ξ states established, with even fewer (only four) has J^P measured

CLAS12: Spin-Parity Determination of Ξ*

- Spin can be measured by angular distributions
  - Parity measurement challenge: Minami ambiguity
  - $\Xi^* \rightarrow Y\,(1/2^+) + M_1\,(0^-)$: two solutions J^P

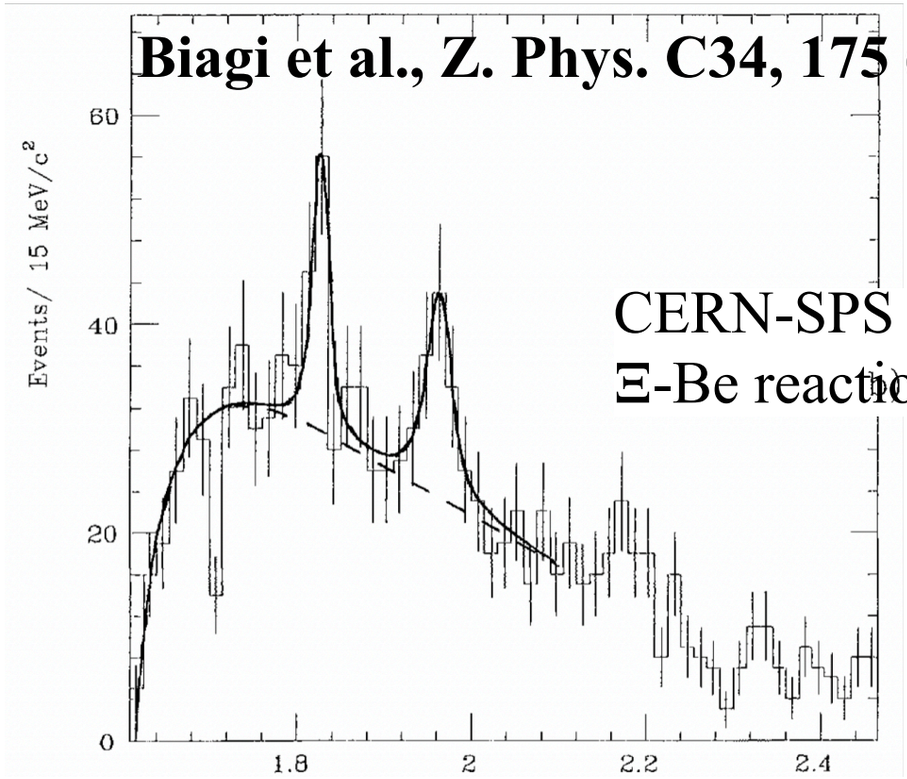
- DoubleMomentAnalysis(DMA)

  $Y\,(1/2^+) \rightarrow B\,(1/2^+) + M_2\,(0^-)$

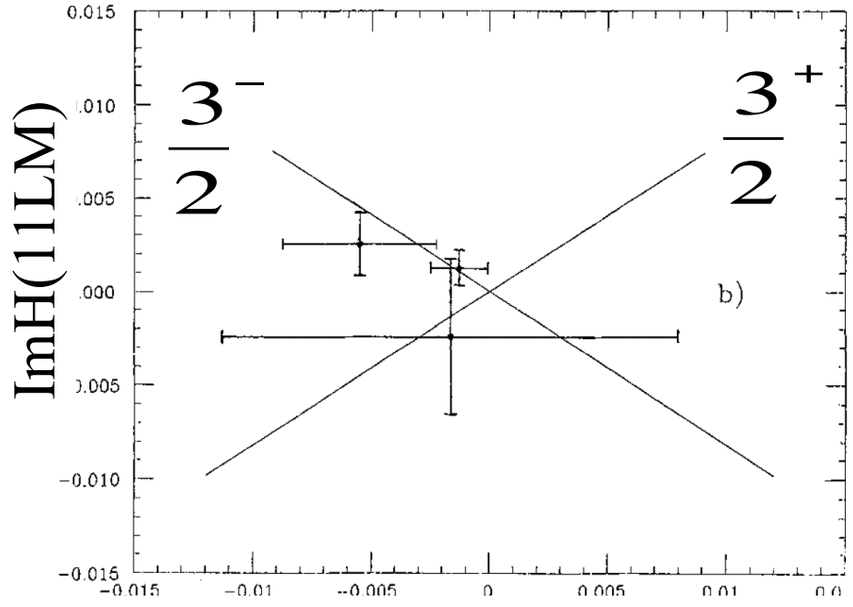
  Double moments:

  - $H(lmLM) = \Sigma\, D^L_{Mm}(\theta_1, \phi_1)\, D^1_{m0}(\theta_2, \phi_2)$

- Linear dependence gives simple, multiple tests for J, P for any odd $L \leq 2J$ and $M \leq L$



Needs corroboration



CLAS12: some expected Ξ results

- Ξ^- polarization measurement: (should be E_γ dependent)

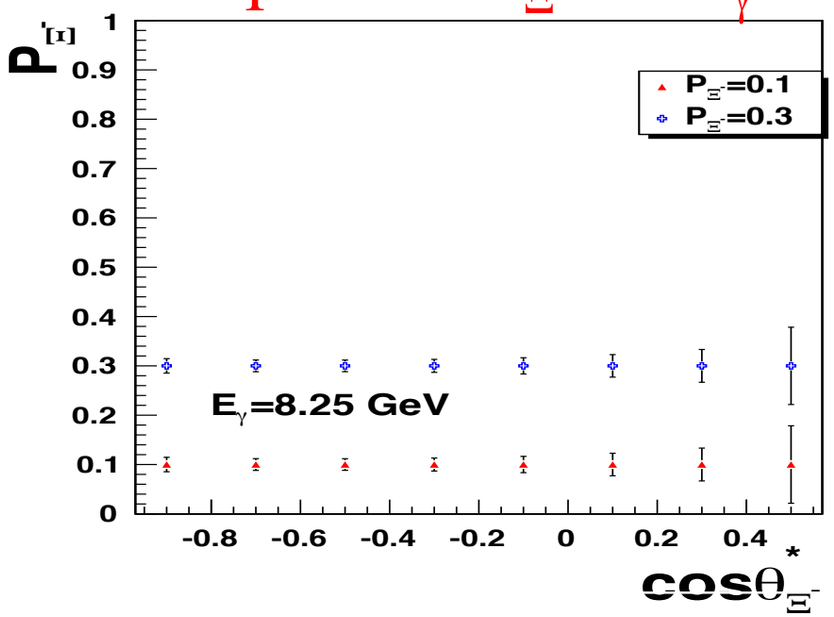
$$\gamma p \to K^+K^+\Xi^- \to K^+K^+\pi^-(\Lambda)$$

- $\Xi^-(1820)$ double moments

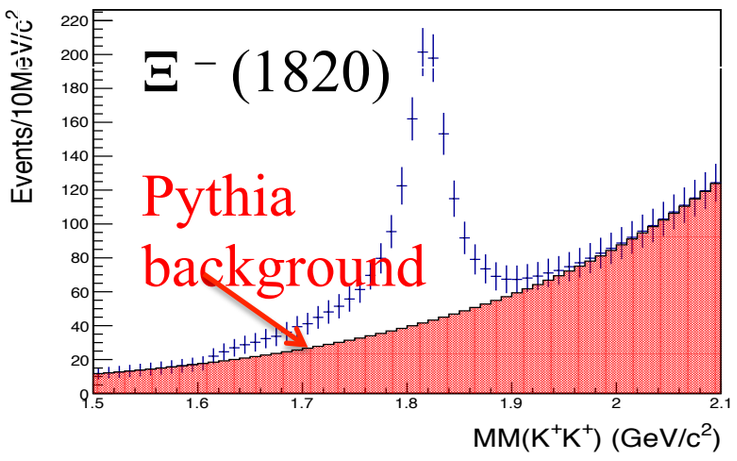
$$\gamma p \to K^+K^+\Xi^-(1820)$$

$$\Xi^-(1820) \to K^-(\Lambda \to \pi^- p)$$

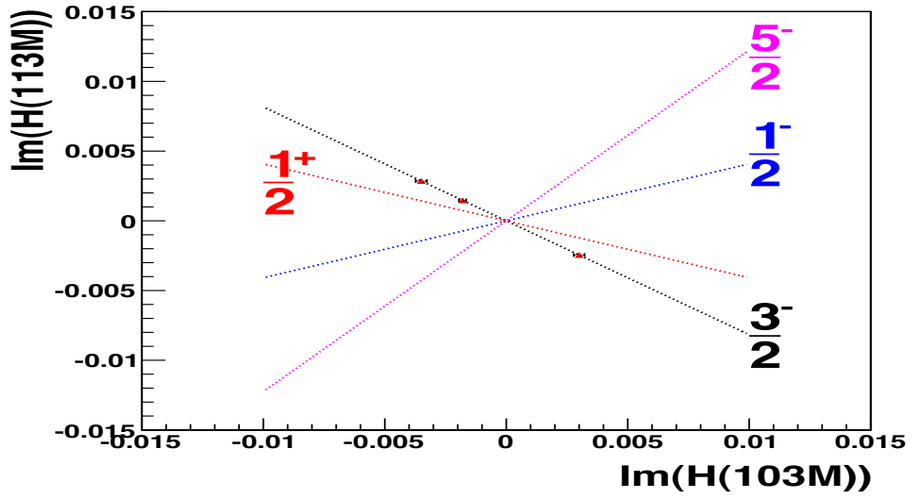
Expected P_{Ξ^-} vs E_γ



Expected $M(\Lambda K^-)$ spectrum



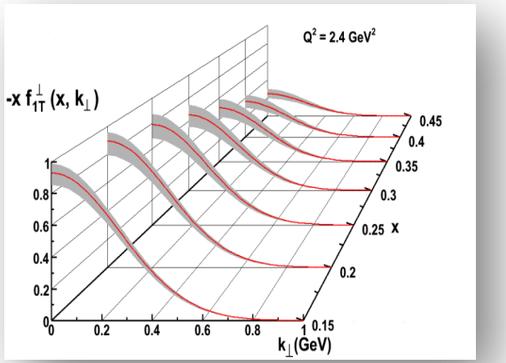
Expected double moments (L=3)



CLAS12: 3D-mapping of the nucleon

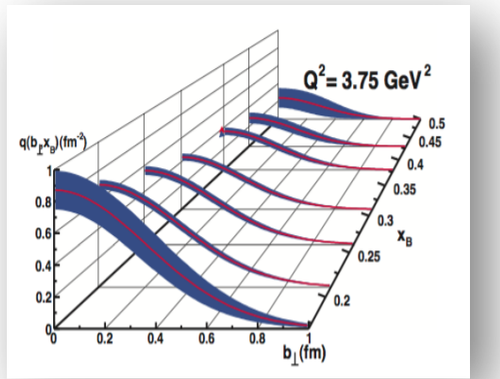
TMDs: Longitudinal momentum fraction x
and transverse momentum k

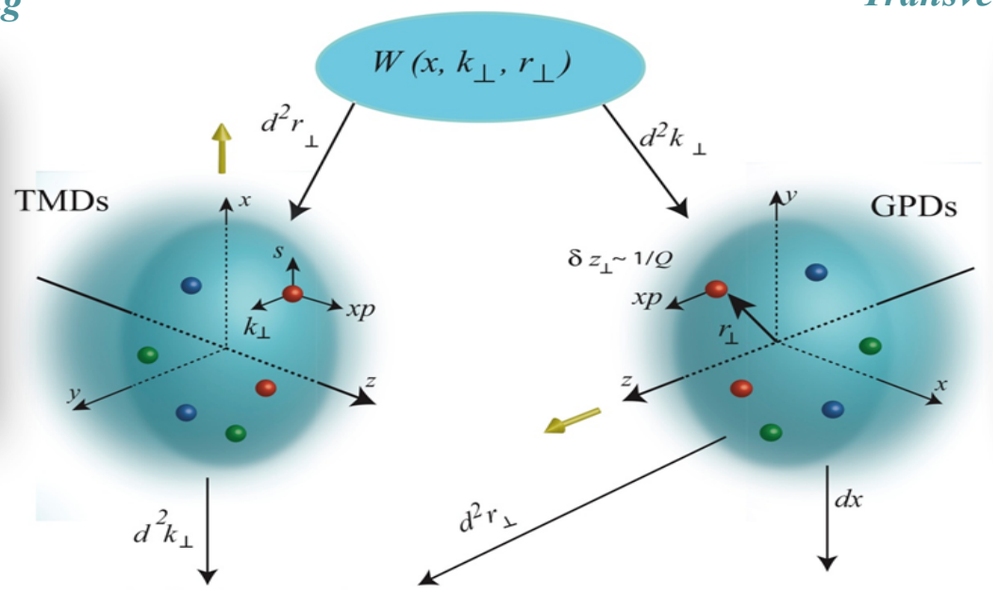
Transverse Momentum Imaging

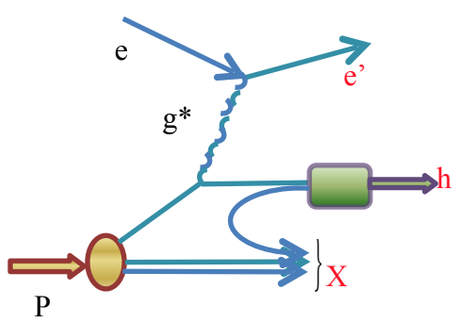


GPDs: Longitudinal momentum fraction x at transverse location b

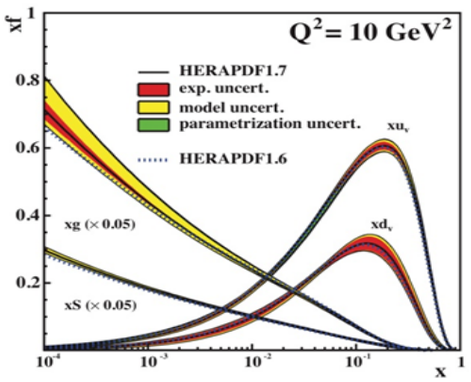
Transverse Spatial Imaging



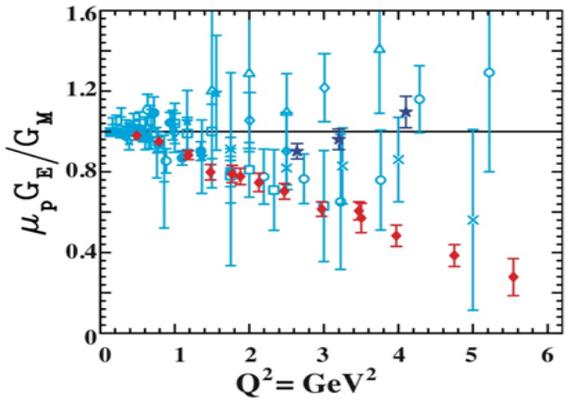


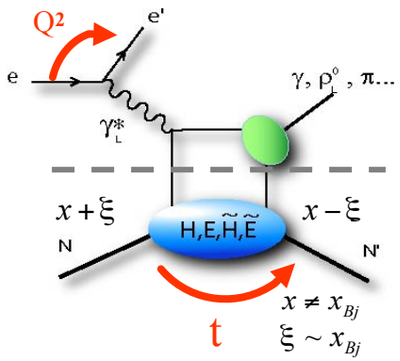


Parton Distribution Functions



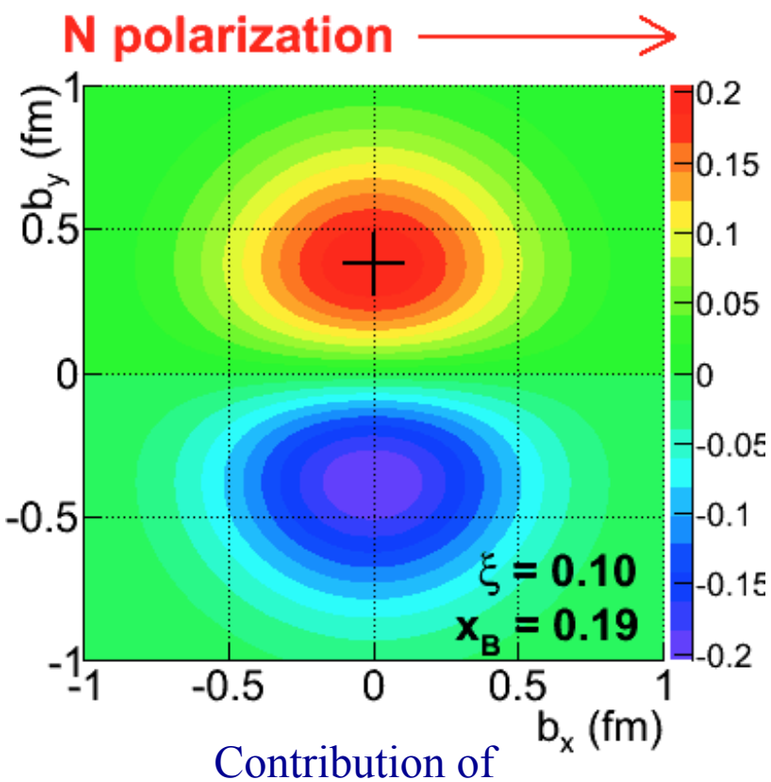
Form Factors





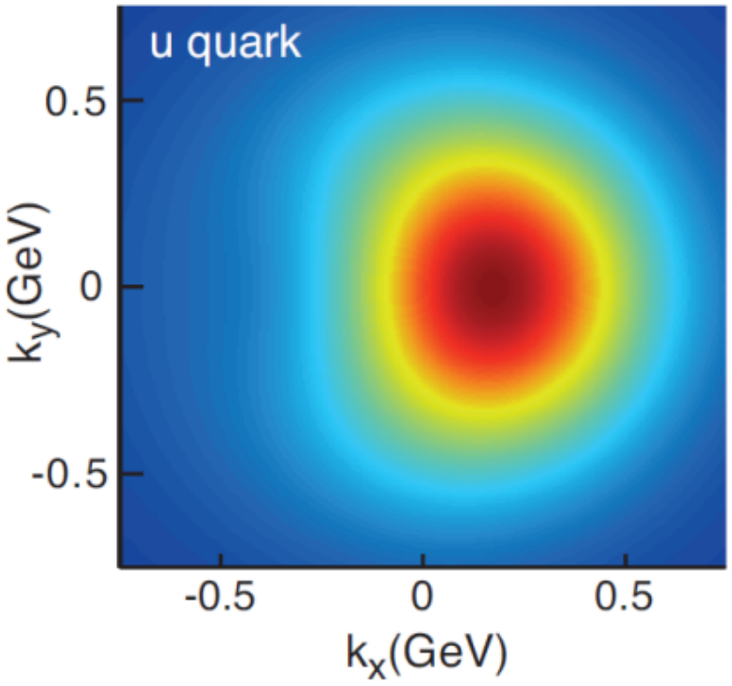
CLAS12: 3D-mapping of the nucleon

Spatial Imaging



Contribution of
GPD E

Momentum Imaging

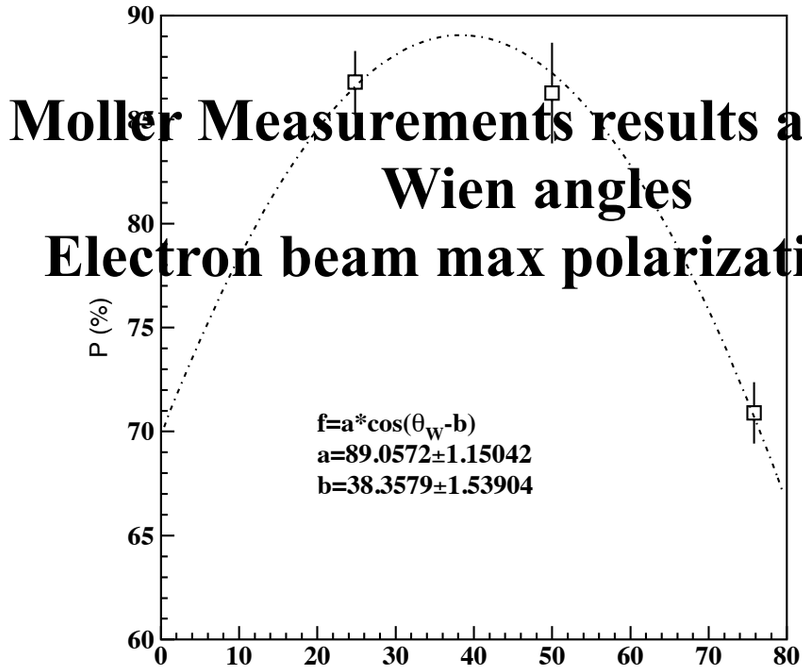


Contribution of
TMD f_{1T}

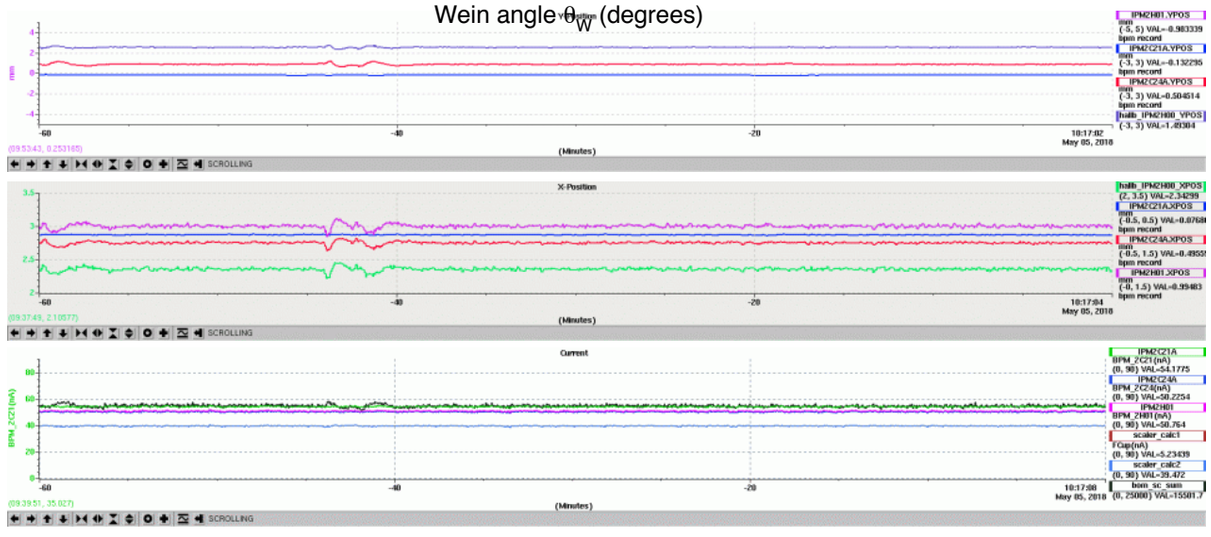
Various beam/target polarization, target types planned at CLAS12
For DVCS experiments (GPD)
Various SIDIS experiments also planned at CLAS12 for TMD

CLAS12 Data Collection Status

- Run Group A(proton target):
  - Five experimental groups
  - First running period: Feb -May 6 (~20% data collected)
- Second running period: RGA and RGK
  - Aug 20-Dec 21, 2018
- Third running period: RGB (Deuterium target)
  - Jan 28 - Mar 12, 2019

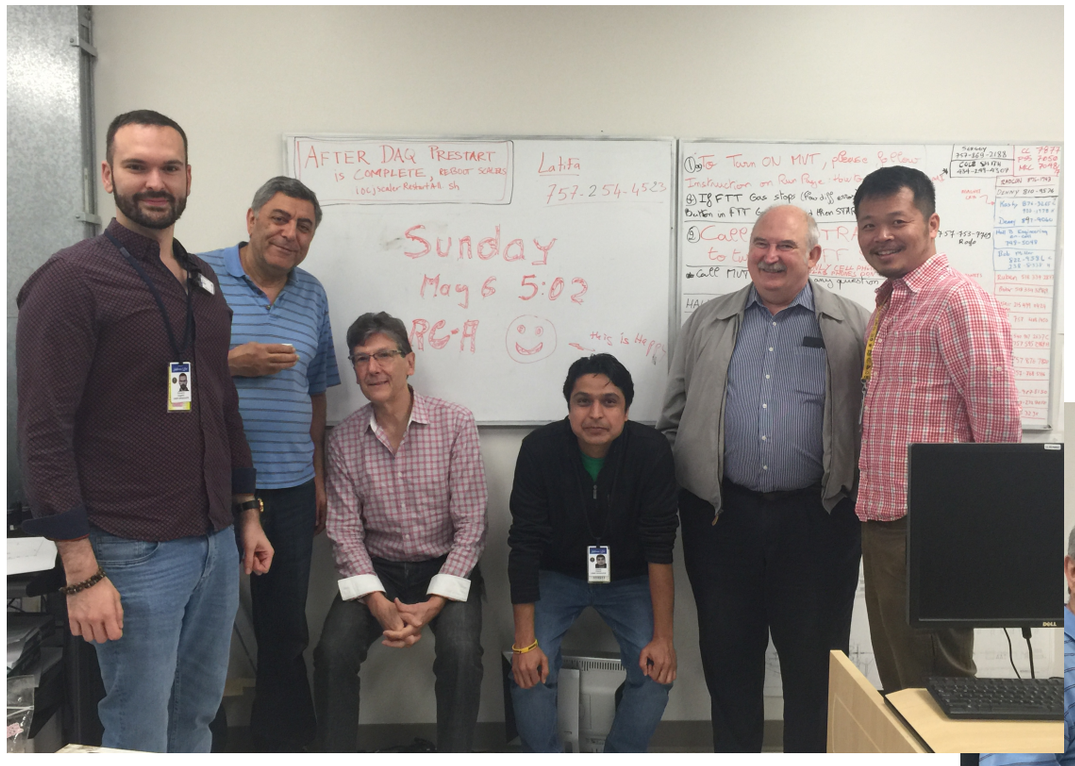


Moller Measurements results at different Wien angles
Electron beam max polarization: 89%



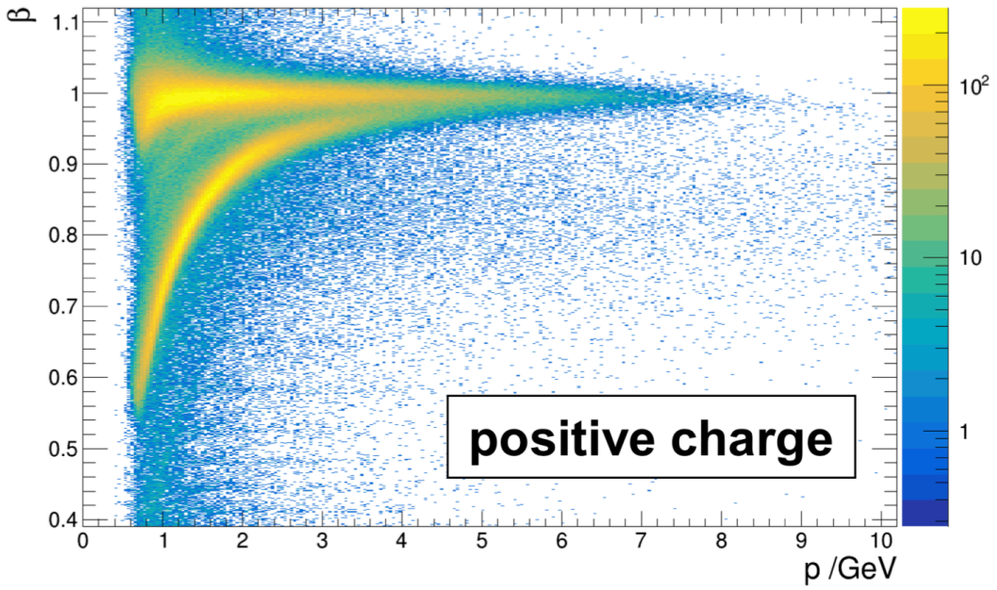
Beam quality during the last day shift
Disclaimer (Not representative)

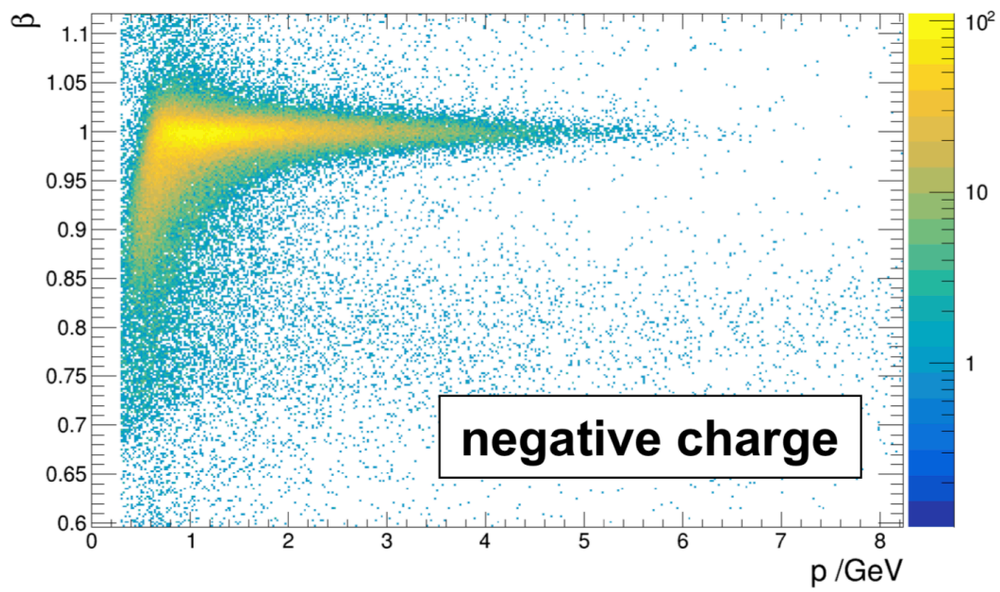
CLAS12:The survivors of the last hour of the spring run



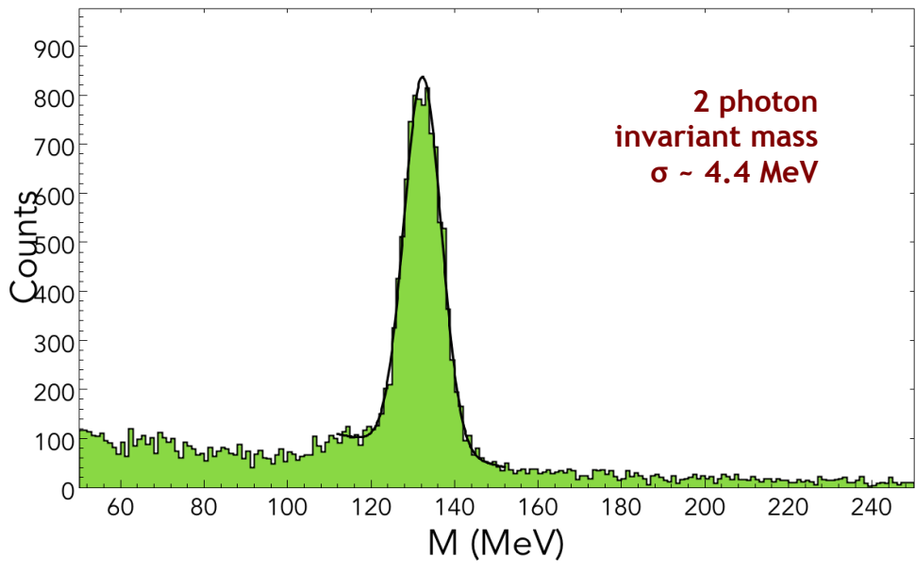
No Alchohol Involved!!!

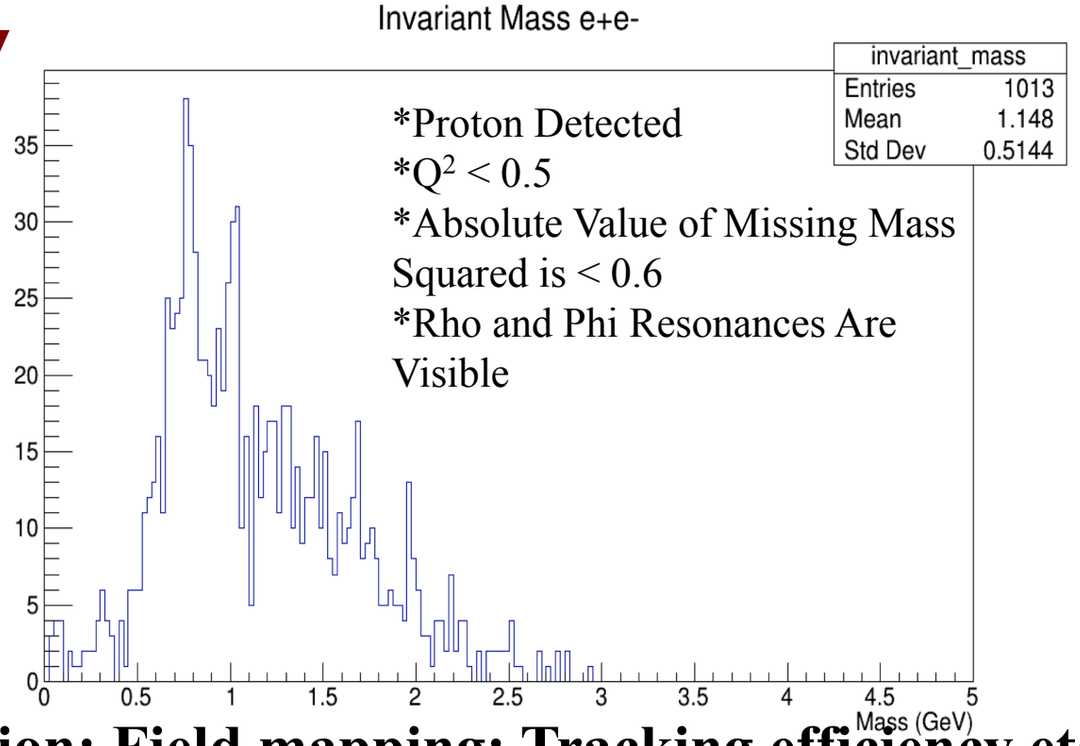
CLAS12 Status: Some basic data features





E=10.6 GeV

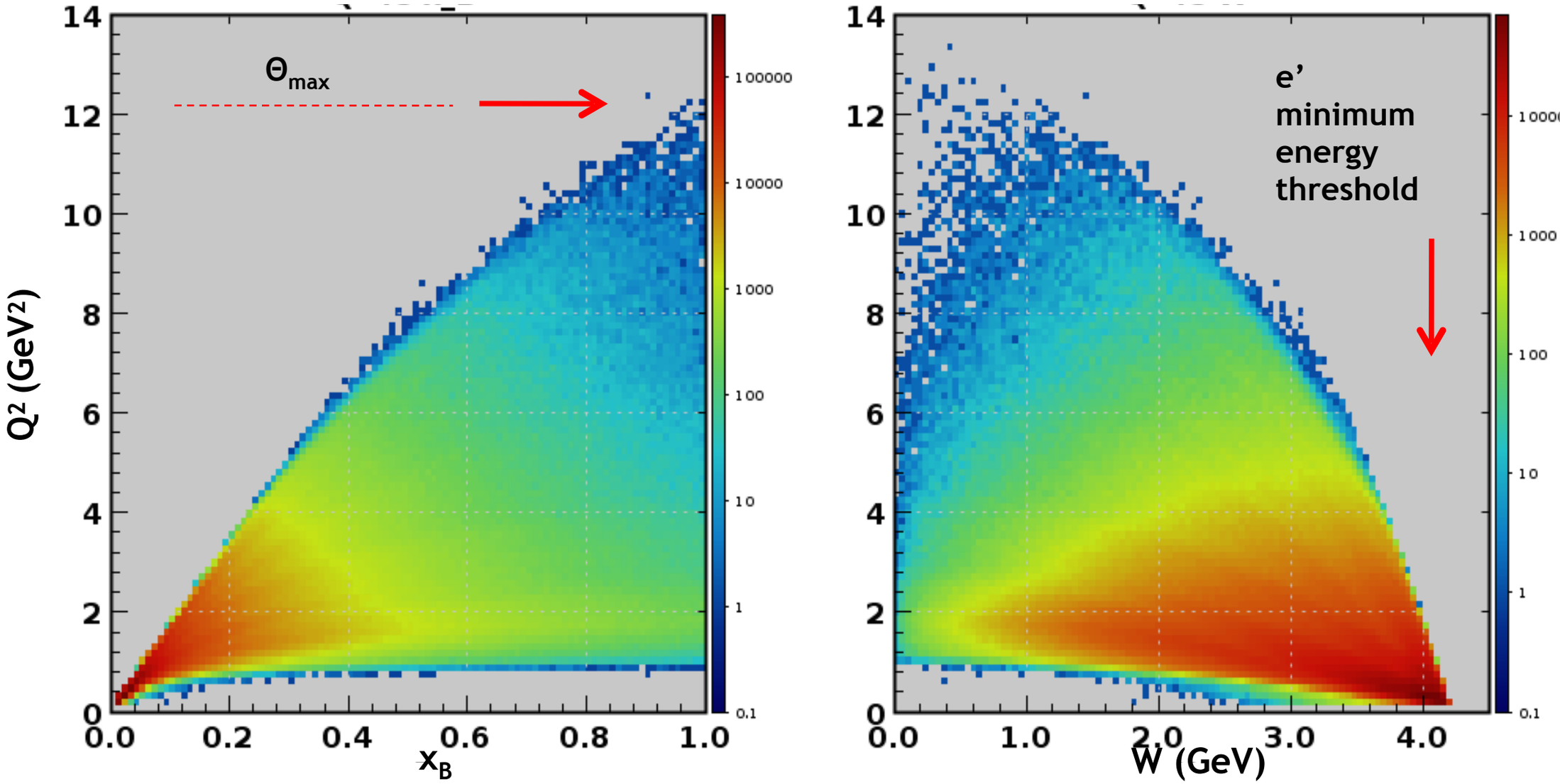




Many improvements expected: Calibration; Field mapping; Tracking efficiency etc

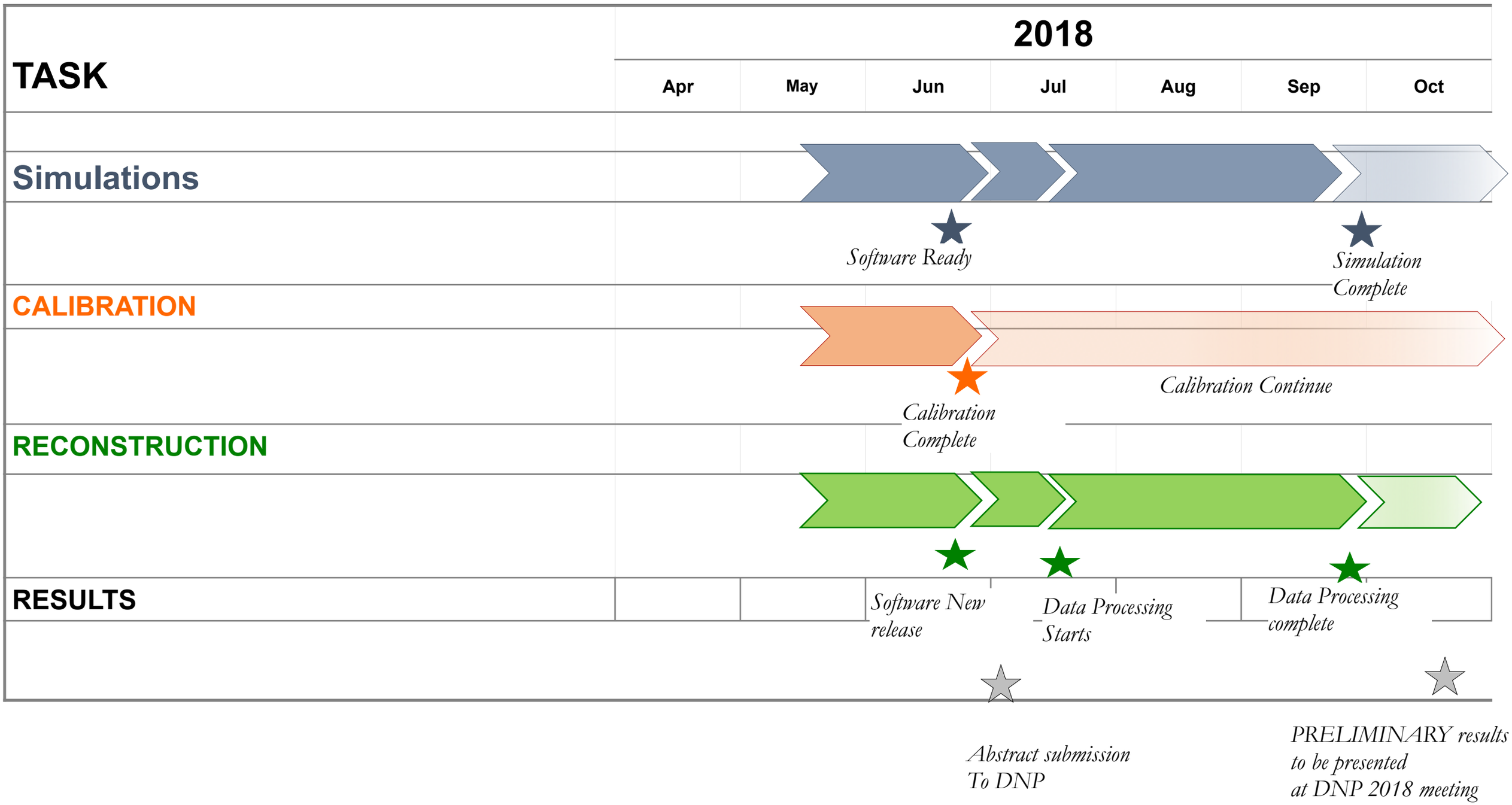
CLAS12:Kinematic Coverage

p(e,e')X



Beam energy at 10.6 GeV Torus current 3770 A, electrons out-bending, Solenoid magnet at 2416 A.

CLAS12: Towards first results and first publication



Acknowledgement: The CLAS Collaboration

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University of Connecticut, Storrs, CT
Edinburgh University, Edinburgh, UK
University of Ferrara, Ferrara, Italy
Florida International University, Miami, FL
Florida State University, Tallahassee, FL
George Washington University, Washington, DC
University of Genova, Genova, Italy
University of Glasgow, Glasgow, UK

University of Grenoble, Grenoble, France
Idaho State University, Pocatello, Idaho
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INFN, Sezione di Ferrara, Ferrara, Italy
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ITEP, Moscow, Russia
James Madison University, Harrisonburg, VA
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University of Massachusetts, Amherst, MA
Moscow State University, Moscow, Russia
University of New Hampshire, Durham, NH
Norfolk State University, Norfolk, VA

Ohio University, Athens, OH
Old Dominion University, Norfolk, VA
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Union College, Schenectady, NY
University Santa Maria, Valparaiso, Chile
Virginia Polytechnic Institute, Blacksburg, VA
University of Virginia, Charlottesville, VA
College of William and Mary, Williamsburg, VA
Yerevan Institute of Physics, Yerevan, Armenia
Brazil, Morocco and Ukraine,
, have individuals or groups involved with CLAS,
but with no formal collaboration at this stage.

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Slide Acknowledgement: Raffaella De Vita; Volker Crede; Volker BurkertWill Phelps; Shankar Adhikari

Summary

- CLAS has had a great run — more results still to come
- CLAS12 has successfully completed the upgrade
    - All detectors performed extremely well
    - Data acquisition upgrade should enable data taking at full luminosity very soon
- First data taking period ended on May 6th, 2018
- Many more experiments to come
- First results expected to be reported at DNP 2018 at the joint APS/JPS meeting in Hawaii
- First publication expected at the end of 2019
    - Stay tuned