The Very Strange Experiment and Cascade Spectroscopy at CLAS12

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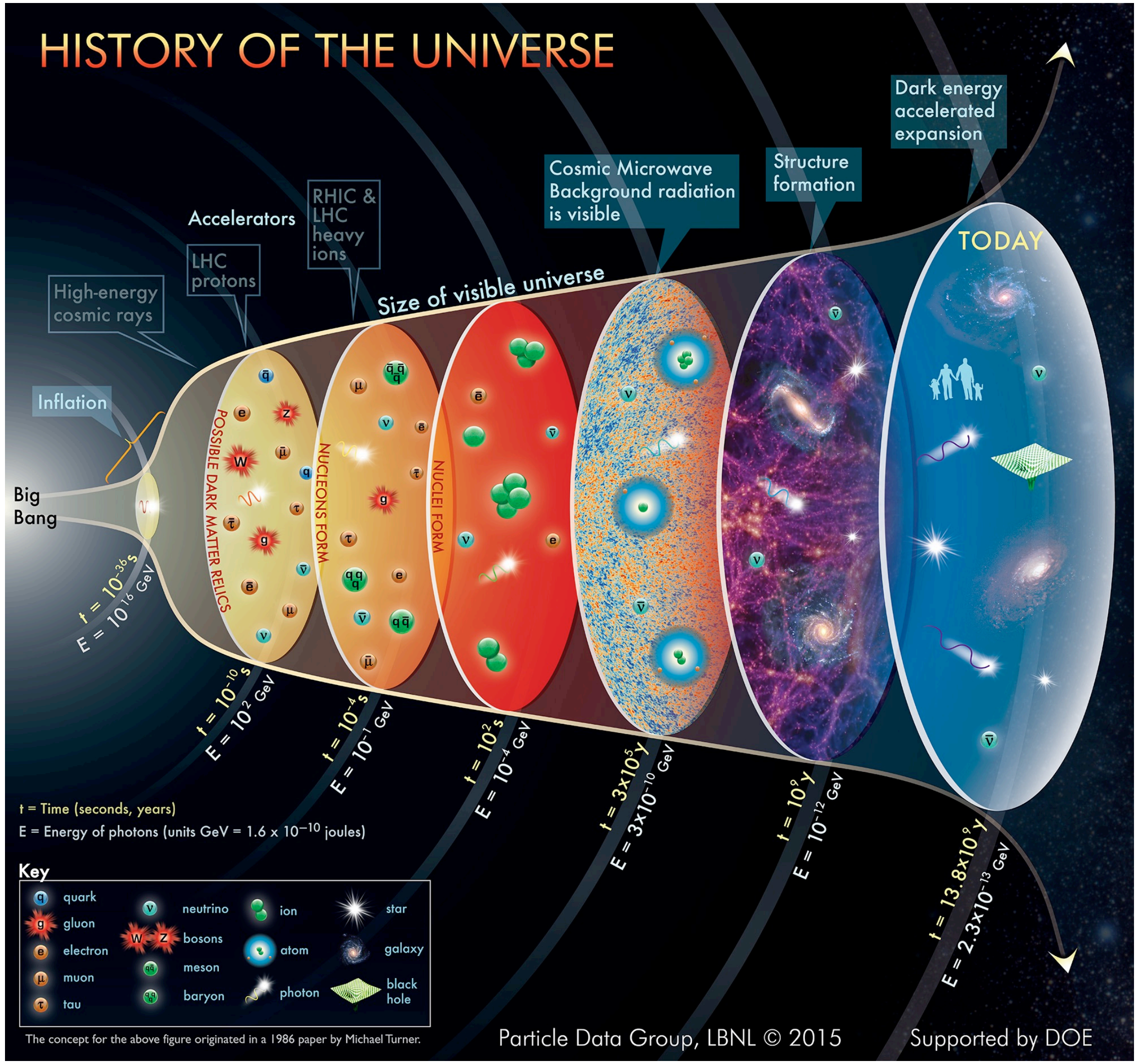
A Brief History Of the Universe: Motivation



"Density" of hadron states important shortly after the big bang:
Missing $N^*/Y*/\Xi^*\ldots$

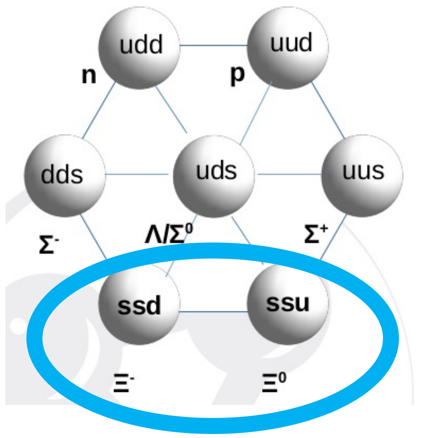
Hyperons related to neutron star (Hyperon-Nucleon Interaction)

Production Mechanisms:
Polarization variables essential

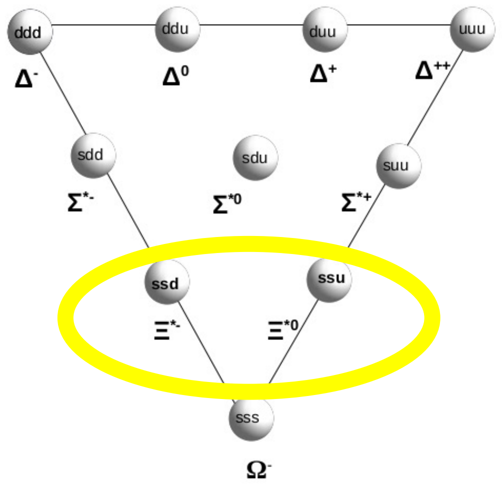
(Some people want to be in PDG)

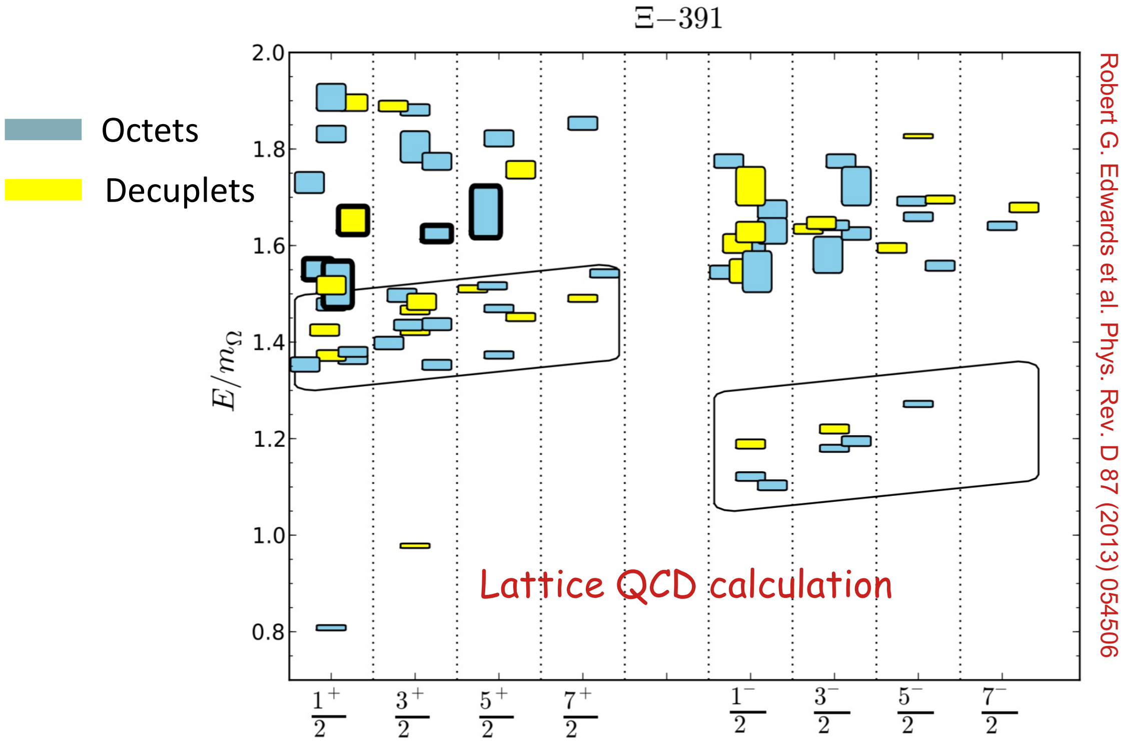
Motivation

Baryon Octets (J = 1/2)



Baryon decuplets (J = 3/2)

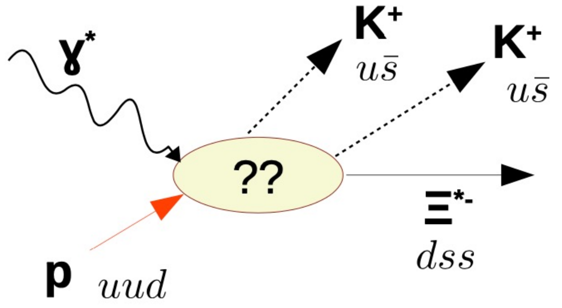




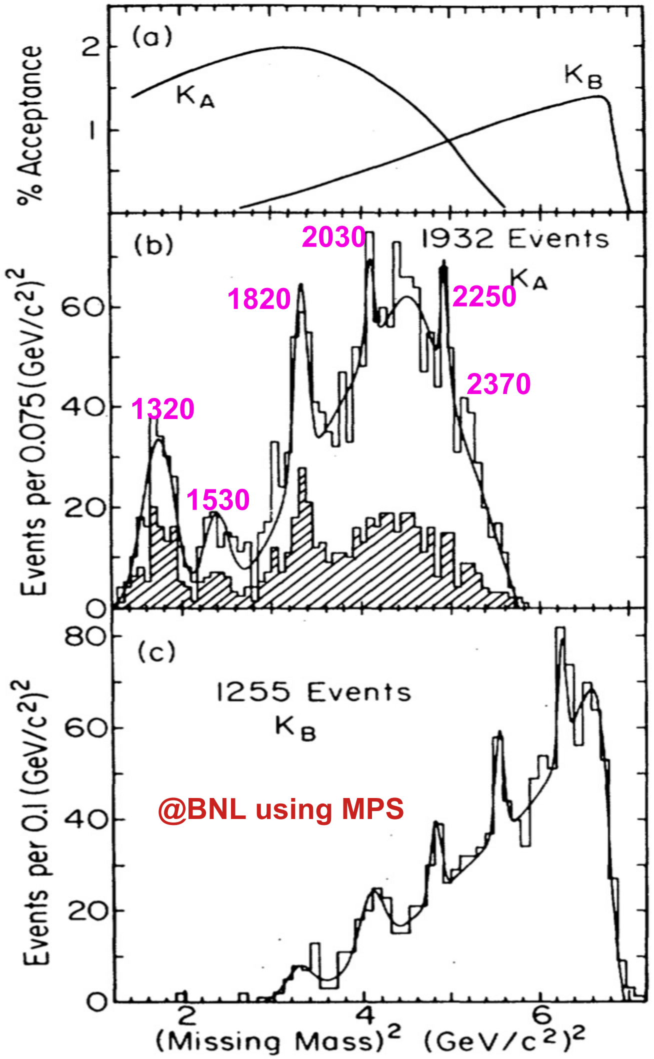
Particle	J^P	Overall status
$\Xi(1320)$	$\frac{1}{2}^+$	****
$\Xi(1530)$	$\frac{3}{2}^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$\frac{3}{2}^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\frac{5}{2}^?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*

2022 PDG status table

- Experimentally underexplored
- Many states expected to be narrow
- Production mechanism interesting to explore



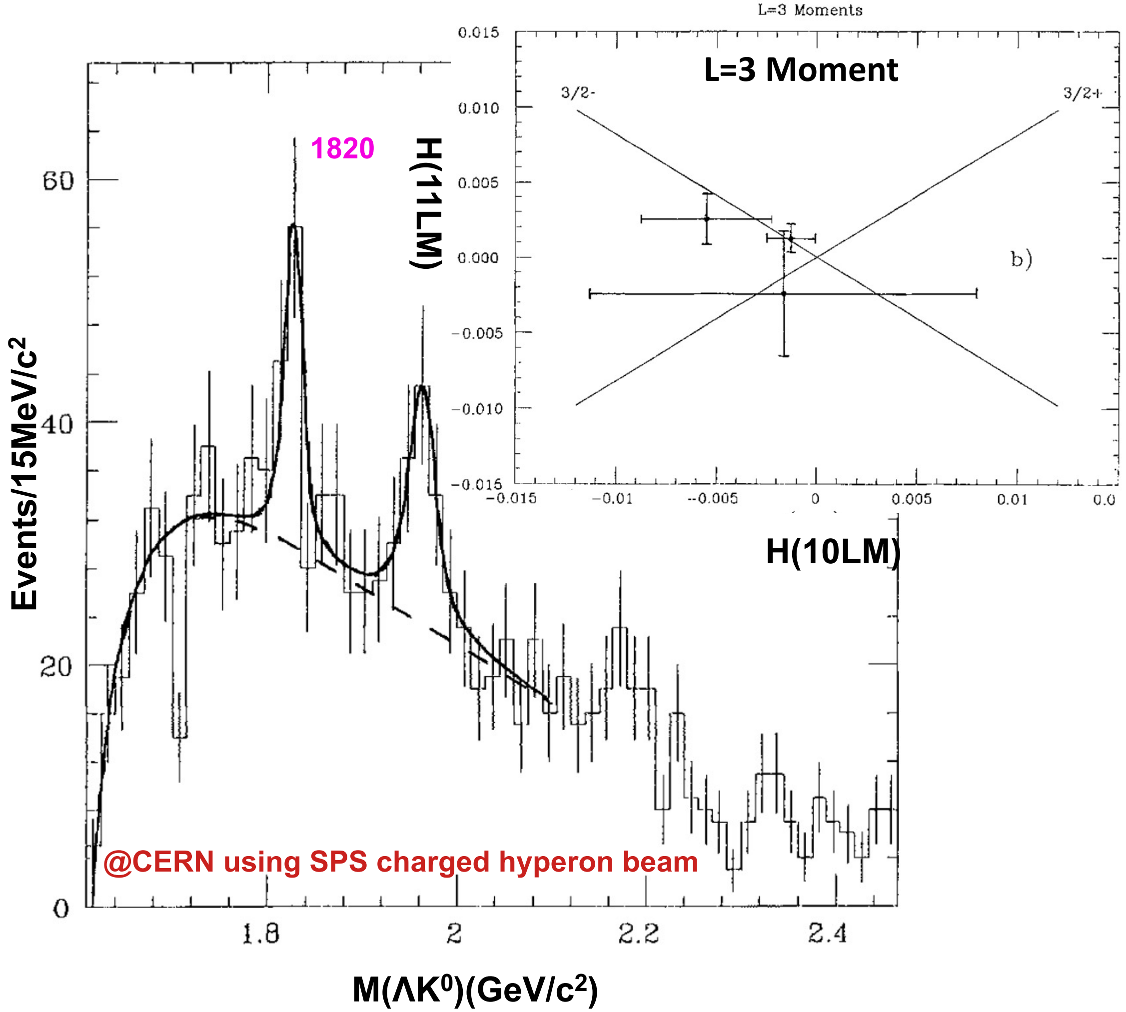
Early Experiments on Ξ Search



$K^{-}\mathrm{p} \rightarrow K^{+}\,(X^{-})$

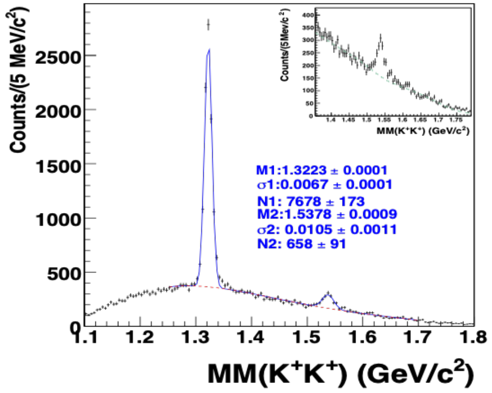
Jenkins, Charles M. et al. Phys.Rev.Lett. 51 (1983)

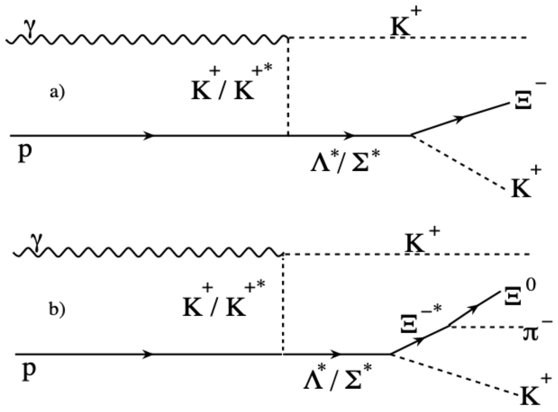
- Early experiments in 1960's used K^{-} **beam** on low-sensitive hydrogen bubble chamber (LRL, ANL, BNL)
- SPS (super proton synchrotrons) **charged hyperon beam** at CERN studied Ξ^{-}N interaction. Analysis of Ξ^{-}Be interaction concluded spin parity of $\Xi^{*-}(1820)$ with ~50 data events.
- **Kaon production** experiment in 1980's at BNL with MPS using Missing Mass technique ($K^{-}\mathrm{p} \rightarrow K^{+}\,(X^{-})$) claimed multiple Ξ states



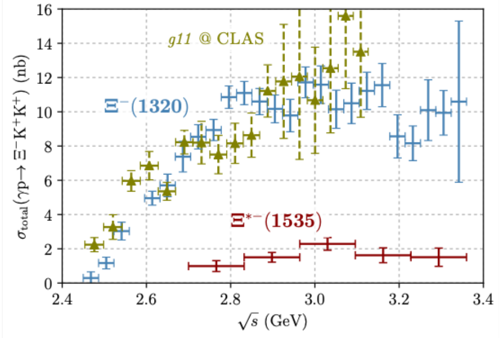
S. F. Biagi et al. Z. Phys. C 34, 175 (1987)

CLAS6 (Not so long ago): Cascade Cross Sections



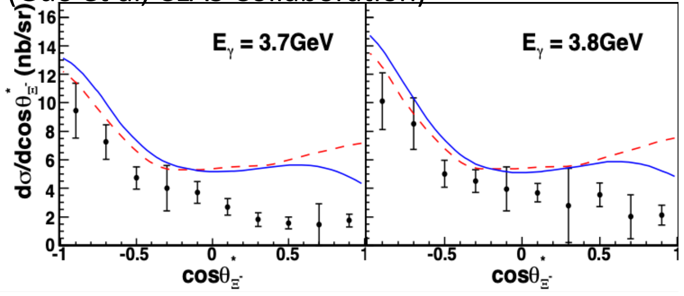


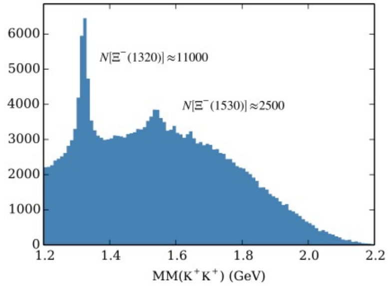
Production Mechanism?

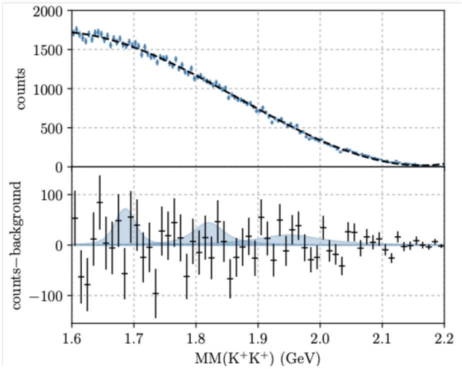


Phys.Rev. C98 (2018) no.6, 062201
Goetz et al, CLAS Collaboration

PRC76,025208 (2007)
(Guo et al, CLAS Collaboration)



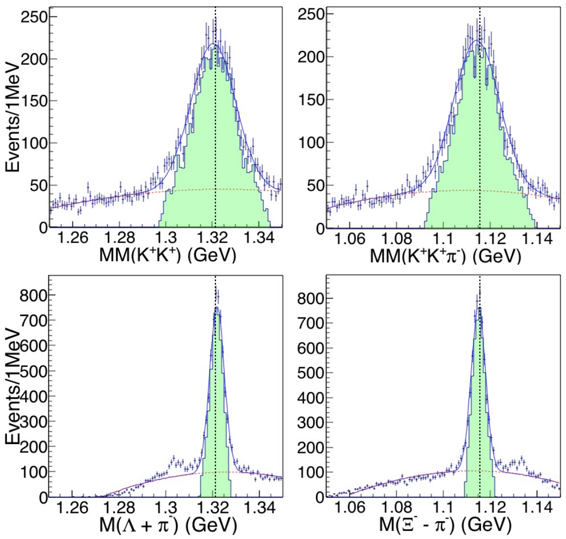




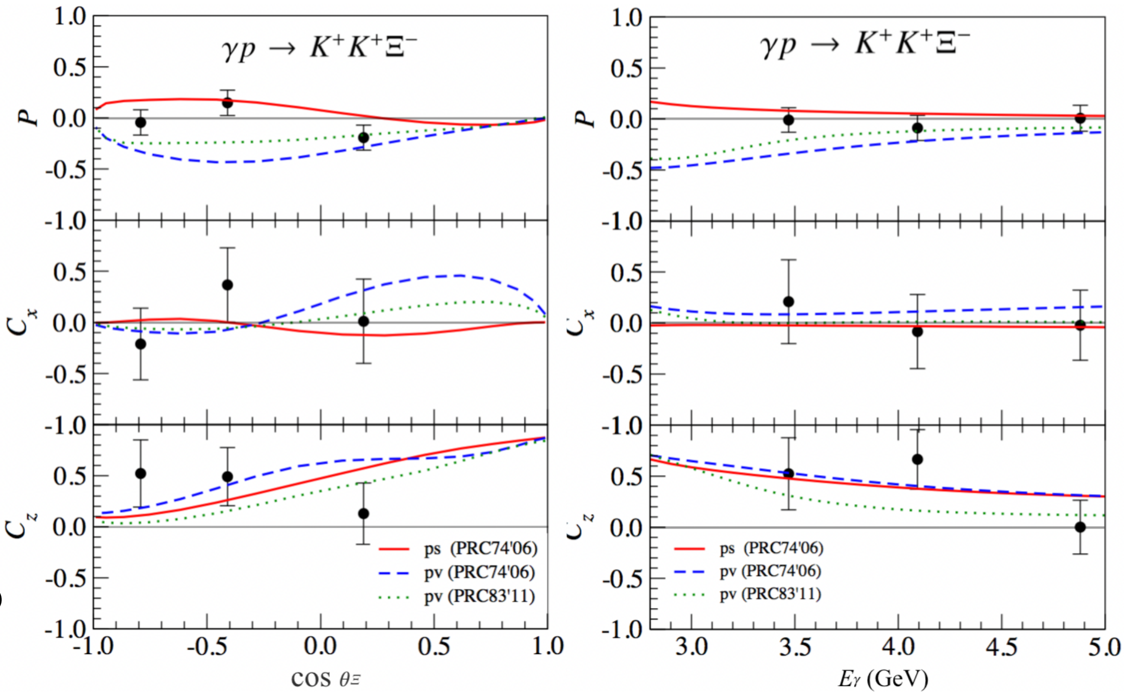
Backwards cascade:
Intermediate Hyperon?
Models: PRC74, 035205 (Nakayama et al)

Excited Cascades Upper limits:
~1nb

CLAS6 (Not so long ago): Cascade Polarization



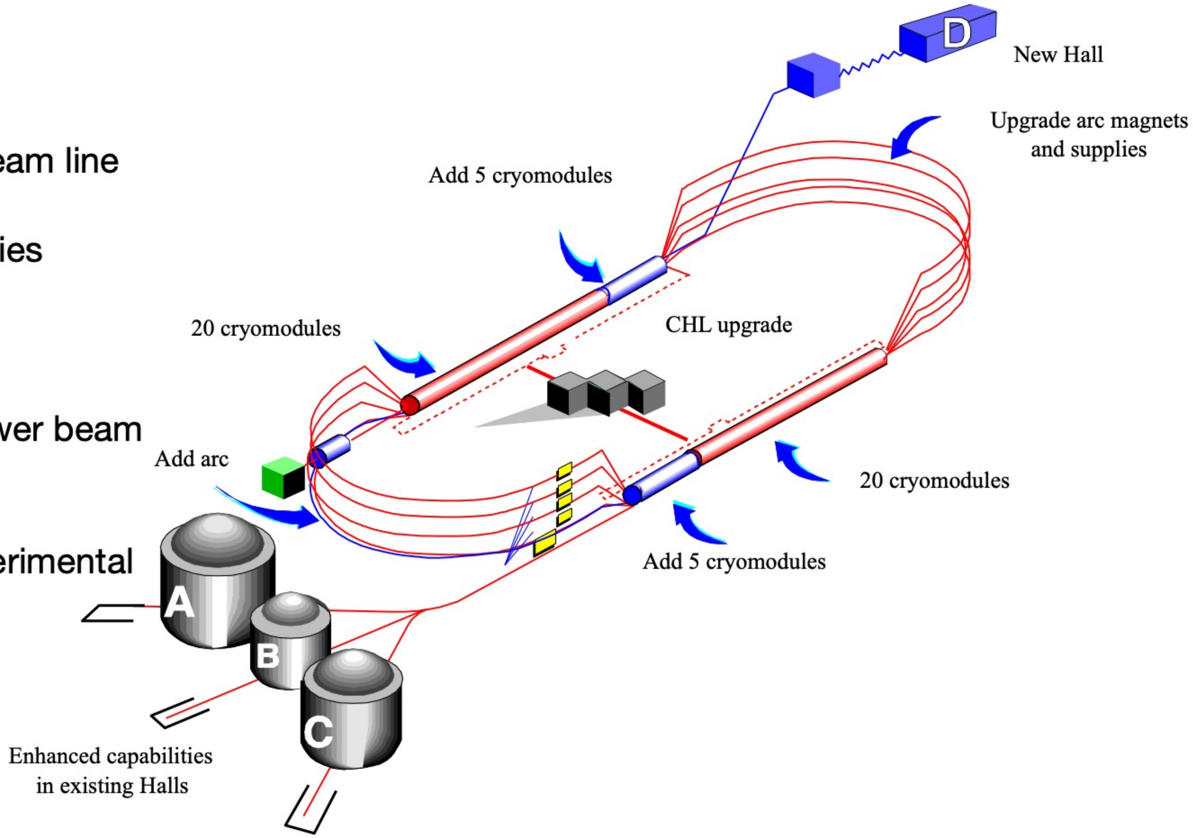
Bono et al (CLAS),Phys. Lett. B 783, 280 (2018)



Results VS Predictions (Nakayama et al):
R~0.3
Model Variance: K or K* exchange?
Higher mass hyperon contribution (PRC83, 2011)

JLab 12 GeV 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 Spectrometer

Forward Detector:

$(5^o \leq \theta \leq 35^o)$

- *TORUS magnet*
- *HT Cherenkov Counter*
- *Drift chamber system*
- *LT Cherenkov Counter*
- *Forward ToF System*
- *Preshower calorimeter*
- *E.M. calorimeter (EC)*

Central Detector:

$(35^o \leq \theta \leq 125^o)$

- *SOLENOID magnet*
- *Barrel Silicon Tracker*
- *Central Time-of-Flight*

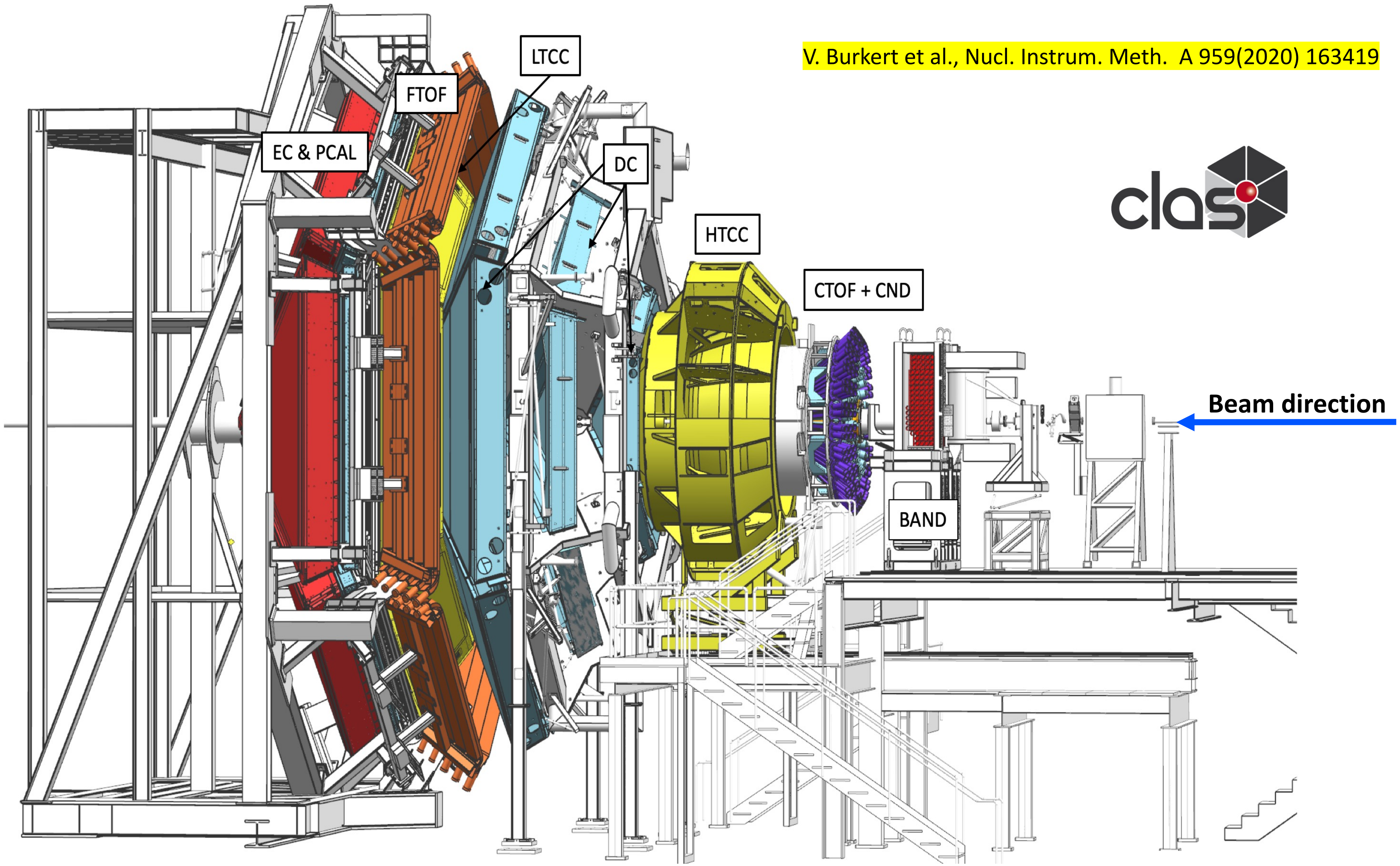
Upgrades:

- *Micromegas (CD)*
- *Neutron detector (CD)*
- *RICH detector (FD)*

Forward Tagger (FT)

$(2^o < \theta < 5^o)$

V. Burkert et al., Nucl. Instrum. Meth. A 959(2020) 163419



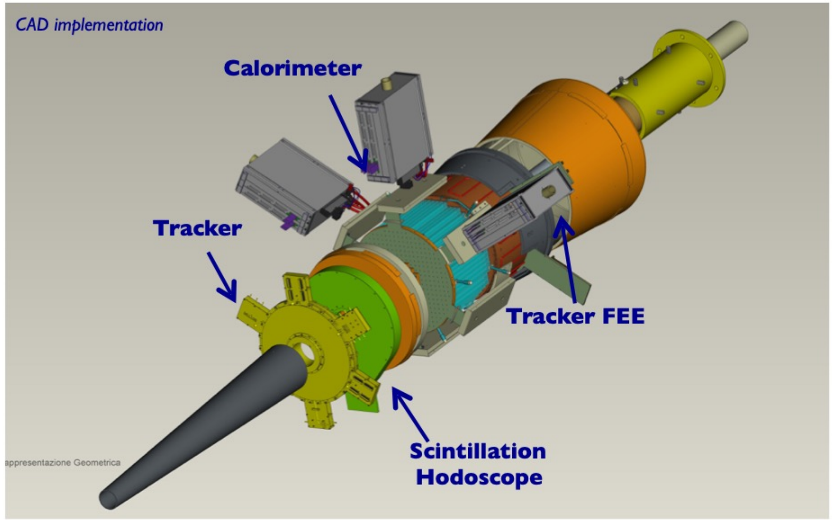
CLAS12: Forward Tagger and RGA

- **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
  - ….



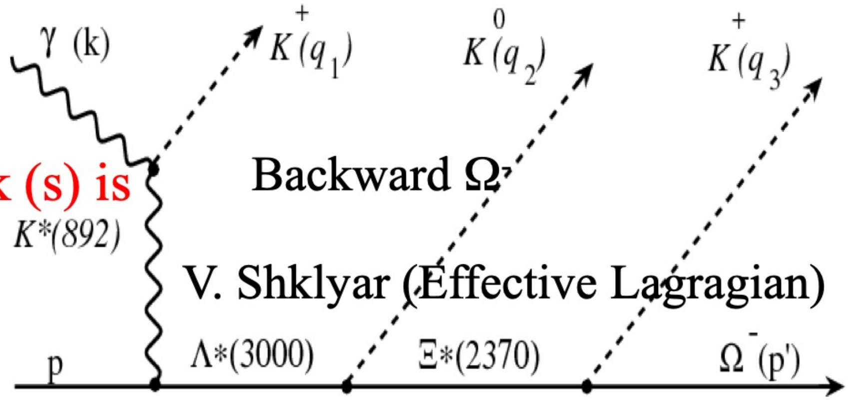
- Electron beam:: **10.6 GeV** and **10.2 GeV** Longitudinally polarized electron beam from CEBAF
- Target :: **5 cm unpolarized liquid hydrogen (LH2) target**
- Beam Current:: **5nA to 75nA**
- **Fall 2018 in**, **Fall 2018 out**, **Spring 2019 in** datasets available to analyze. The Spring 2018 dataset is not ready to analyze

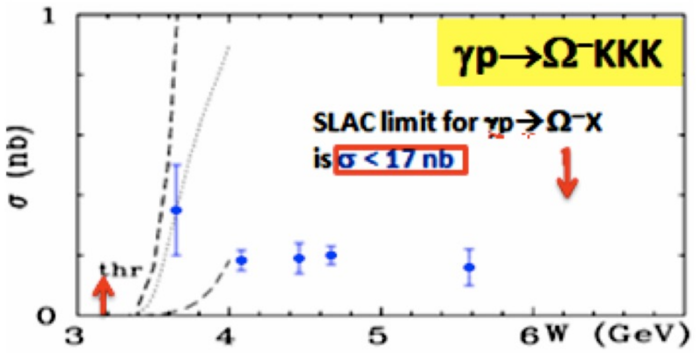
The Very Strange Experiment @ CLAS12 (RGA)

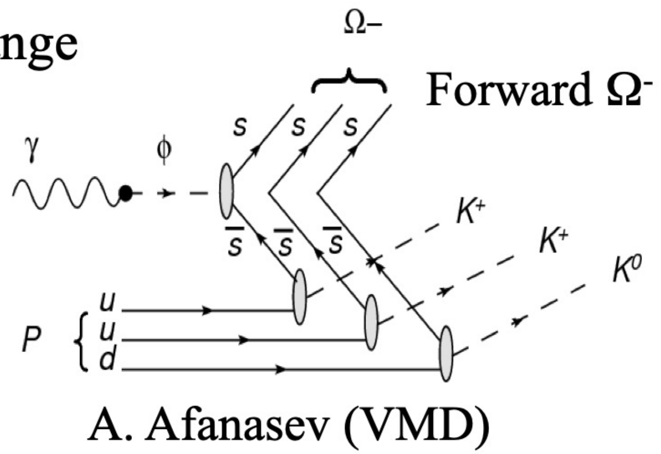
What is so "strange" about Ω^- photoproduction?

Mechanism totally unknown

- None of the constituent quark (s) is from the target ($\Delta S=-3$)
- Different models predicts opposite angular preferences
- Cross section predictions are consistent: $\sigma \sim 1$nb at GlueX/CLAS12 energy range







The Very Strange Experiment: Cascade Spectroscopy at CLAS12

- IF we want to search for Ω^-, we better seen cascades first
  - This talk:
  - $ep \rightarrow eK^+K^+ \, (\Xi^{-*})$
  - $ep \rightarrow eK^+K^+ \, K^-(\, \Lambda \,/\Sigma \,), \, \Xi^{-*} \rightarrow K^-\Lambda/\Sigma$

- Scattered electron $\boldsymbol{e'}$ detected in two different regions

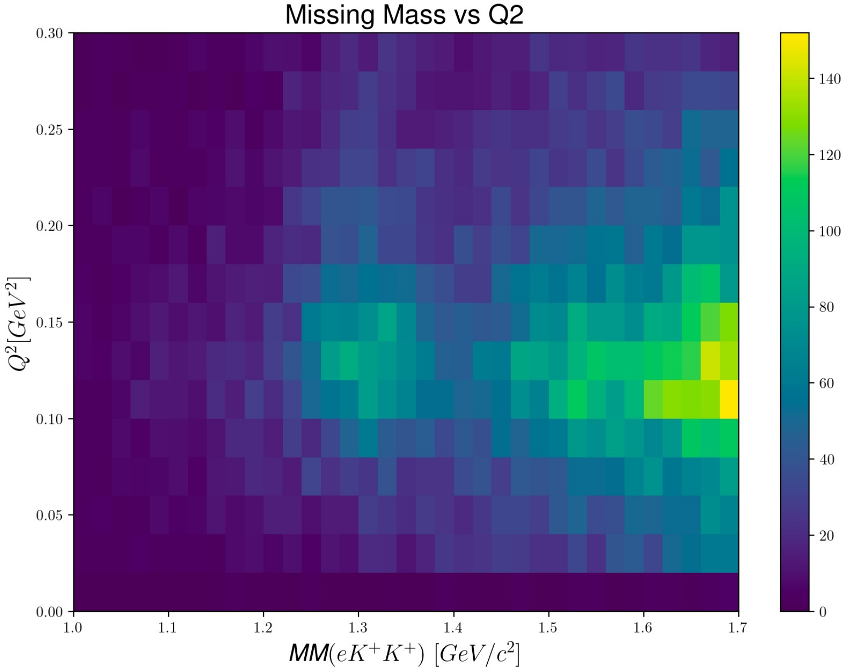
  - **Low-Q^2**(0.03 – 0.13 GeV^2) region to study quasi-real photoproduction - $\boldsymbol{e'}$ detected in the **FT** system which covers a very forward polar angle range of 2^o to 5^o

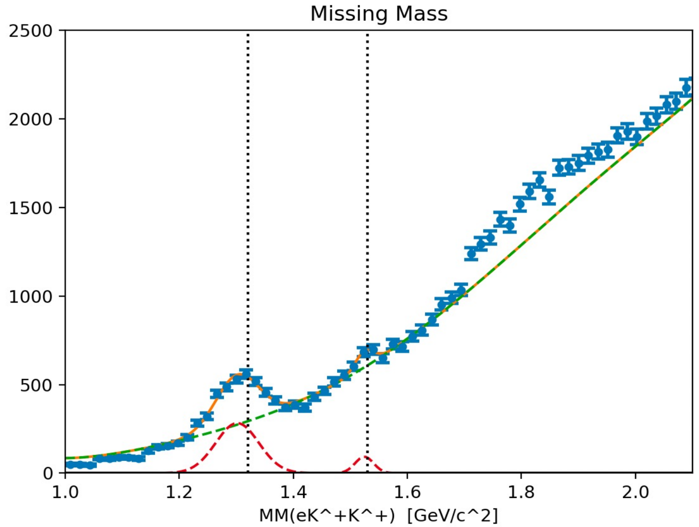
  - **Large-Q^2**(0.16 – 1.28 GeV^2(out-bending) / 1.28 – 2.88 GeV^2(in-bending)) region to study electroproduction - $\boldsymbol{e'}$ detected in the **FD** system which covers a forward polar angle range of 5^o to 35^o

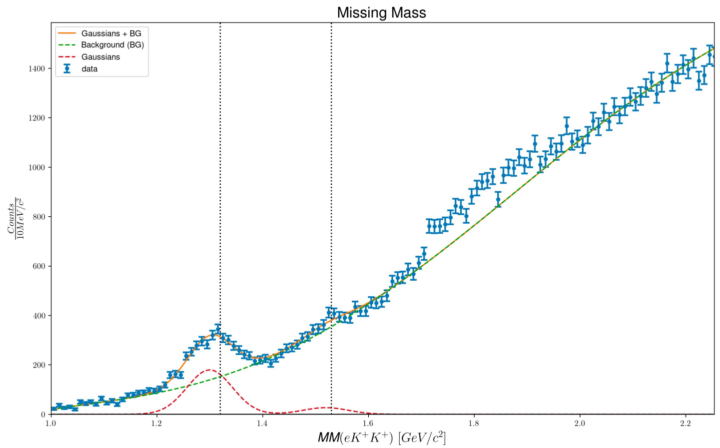
- **Charged Kaons** detected in the CLAS12 detector (**FD**) in coincidence with scattered electrons.

- Analyzed Fall2018(in/out) and Spring2019(in) data. Total **six data sets** analyzed with **FT/FD electron separately** (in/out torus)

CLAS12 cascade quasi-real photoproduction: $ep \rightarrow eK^+K^+ \left(\Xi^{-(*)}\right)$, ELECTRON in FT

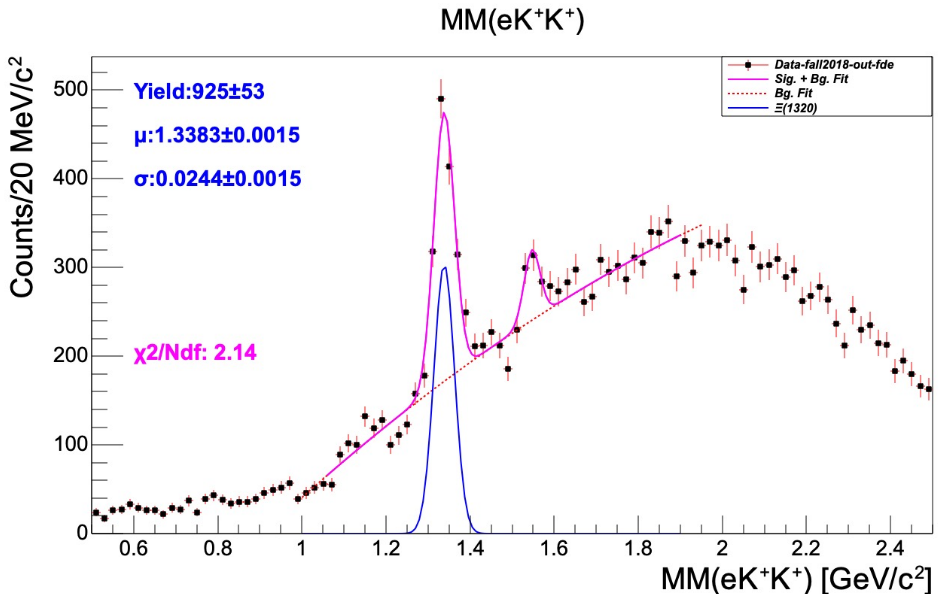


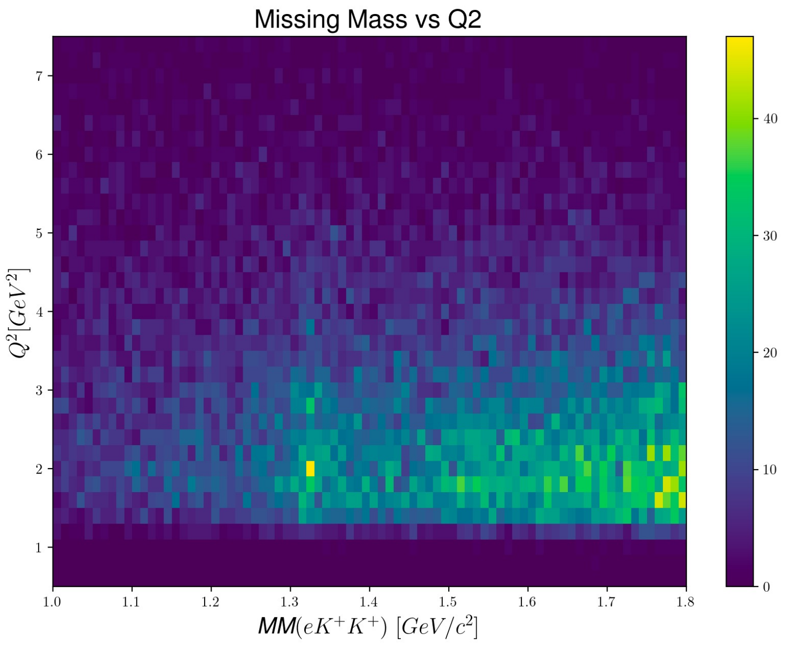




- Background shaped fixed by mixed events technique
- Event excess seen around 1.8GeV region
- 1.8-2GeV region excluded from the fit
- Excess persist when Ξ^-(1530) resolution fixed
- Work done by FIU Ph.D student Jose Carvajal

CLAS12 cascade electroproduction: $ep \rightarrow eK^+K^+\ (\Xi^{-(*)})$, ELECTRON in FD



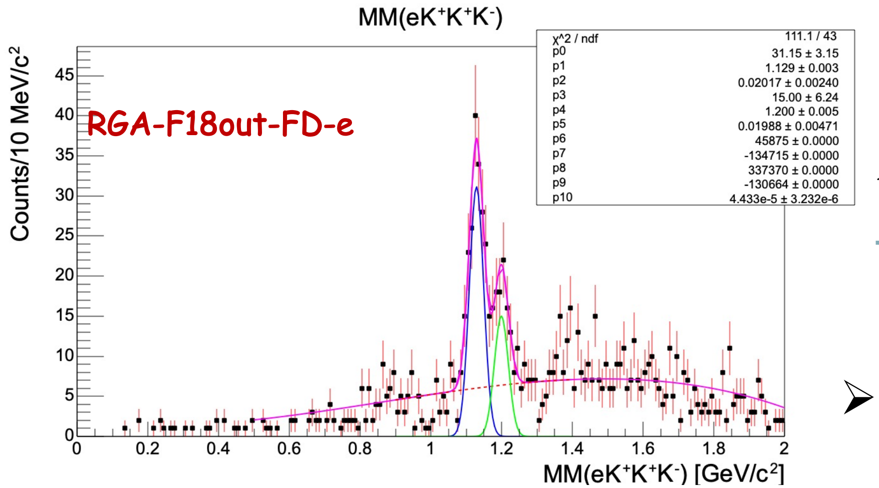


All particles (including electron) detected in FD;
Central detector data to come!
FD resolution better then FT electron

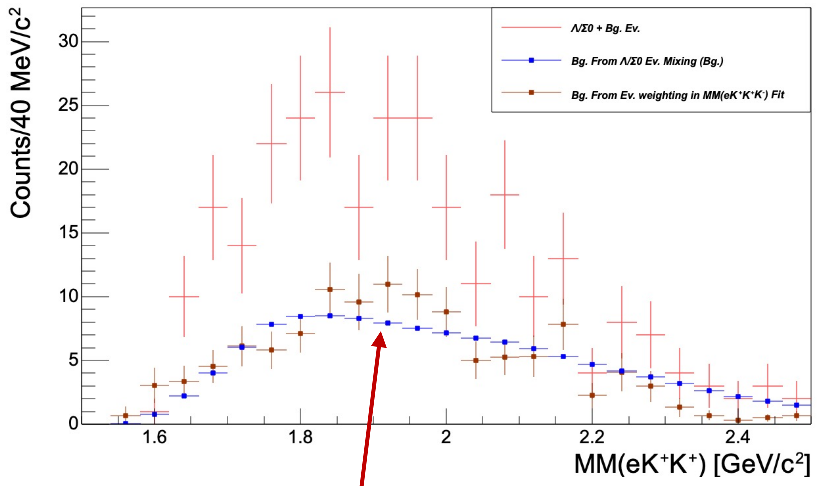
Q^2-dependency of the ground states cross section
To be extracted

- $\Xi^-(1320)$/ $\Xi^-(1530)$ First time seen in electroproduction

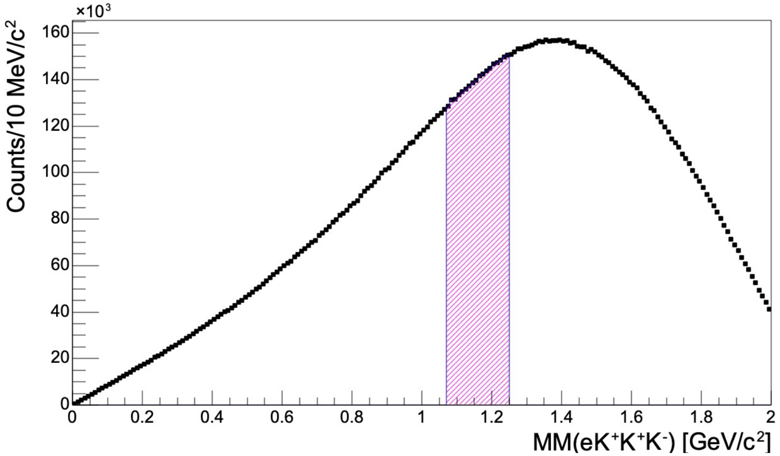
CLAS12 cascade electroproduction: $ep \rightarrow eK^{+}K^{+}K^{-}(\Lambda/\Sigma)$, ELECTRON in FD



Λ/Σ^0 Cut=[1.07, 1.25]

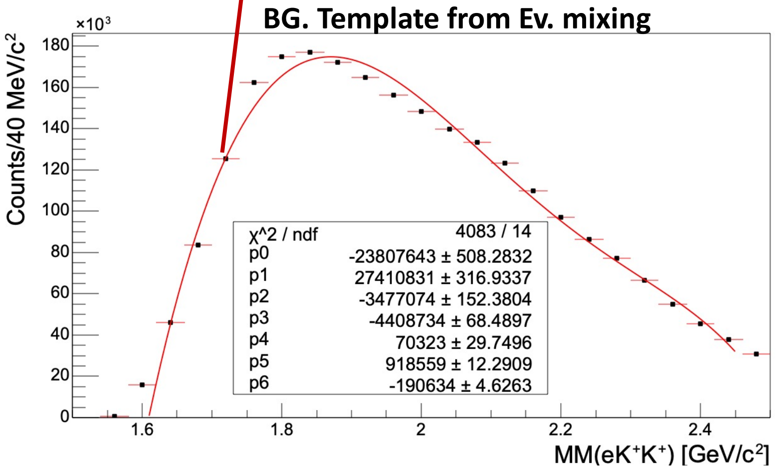


Mix events

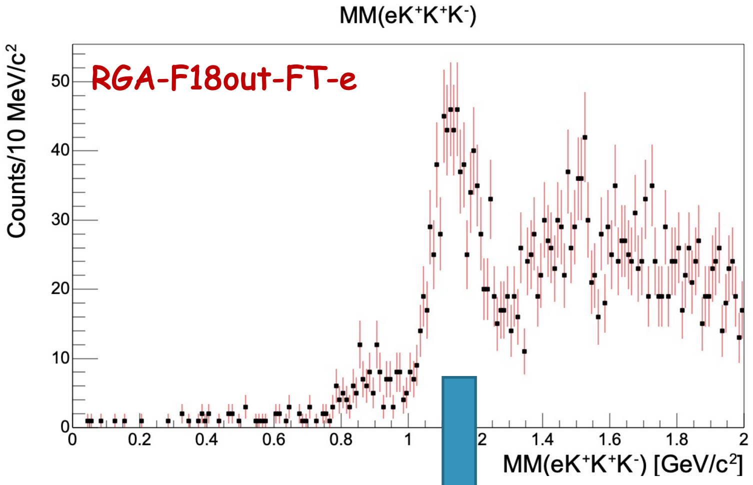


- ➢ Data driven background shape fix mixed events
- ➢ FIU Ph.D Thesis by Dr. Achyut K (Oct 11,2022)
- ➢ The event mixing background consistent with event-by-event weighting

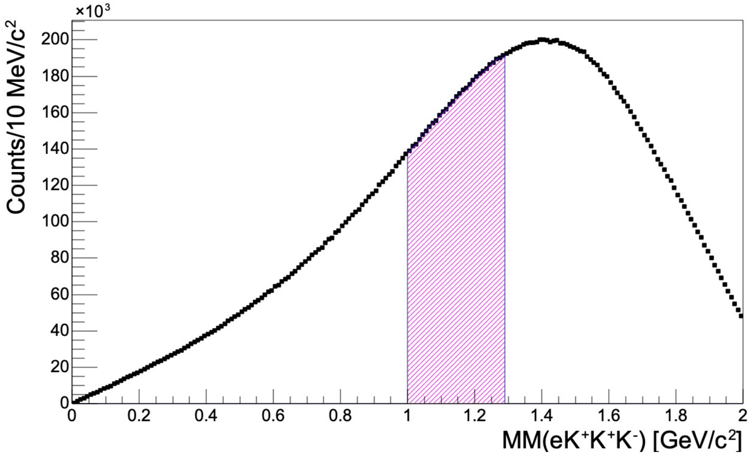
Λ/Σ^0 Cut=[1.07, 1.25]



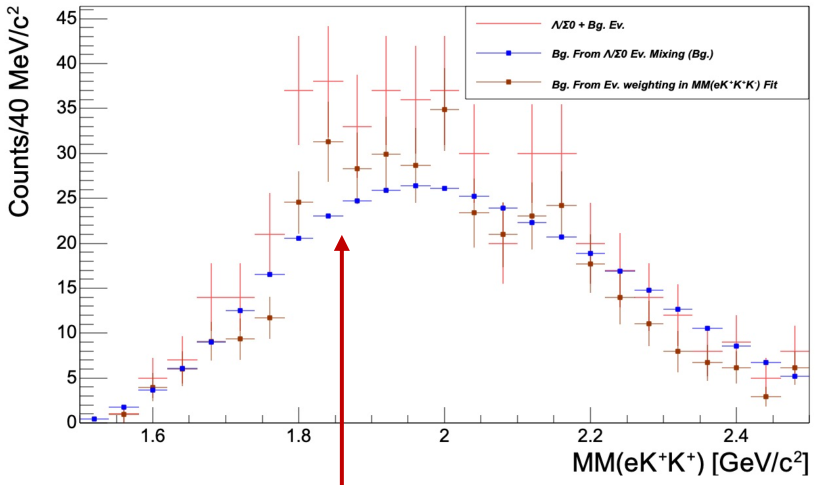
CLAS12 cascade electroproduction: $ep \rightarrow eK^{+}K^{+}K^{-}(\Lambda/\Sigma)$, ELECTRON in FT



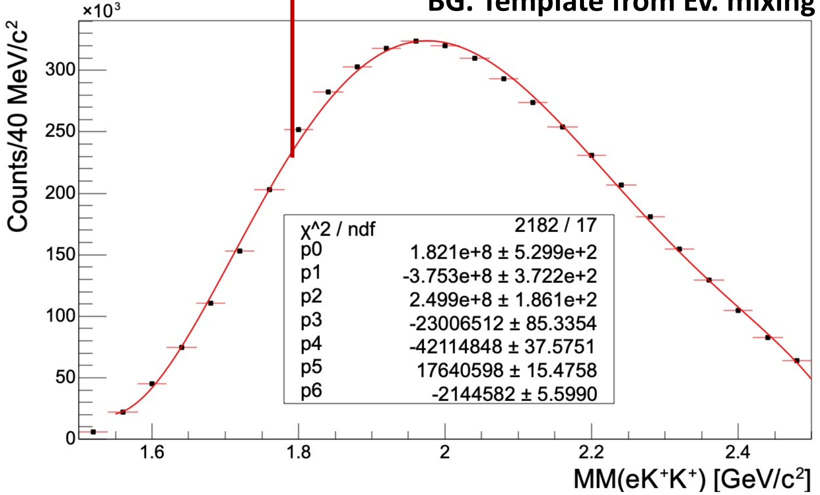
Mix events



Λ/Σ^0 Cut =[1.0, 1.29]



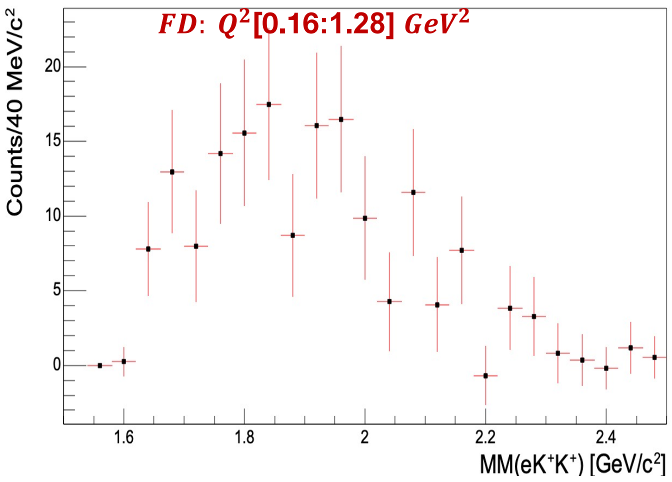
BG. Template from Ev. mixing

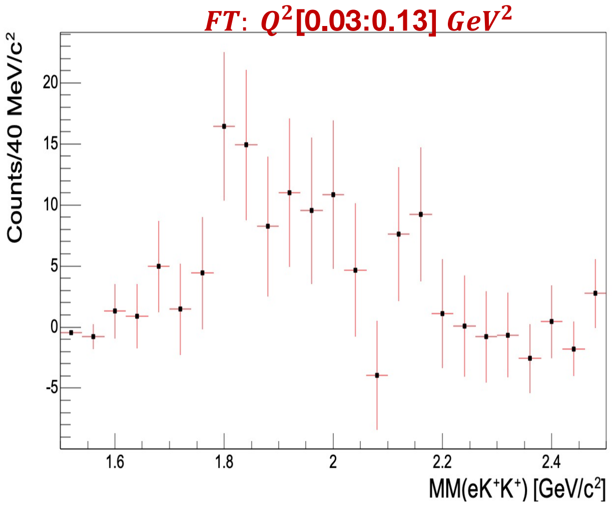


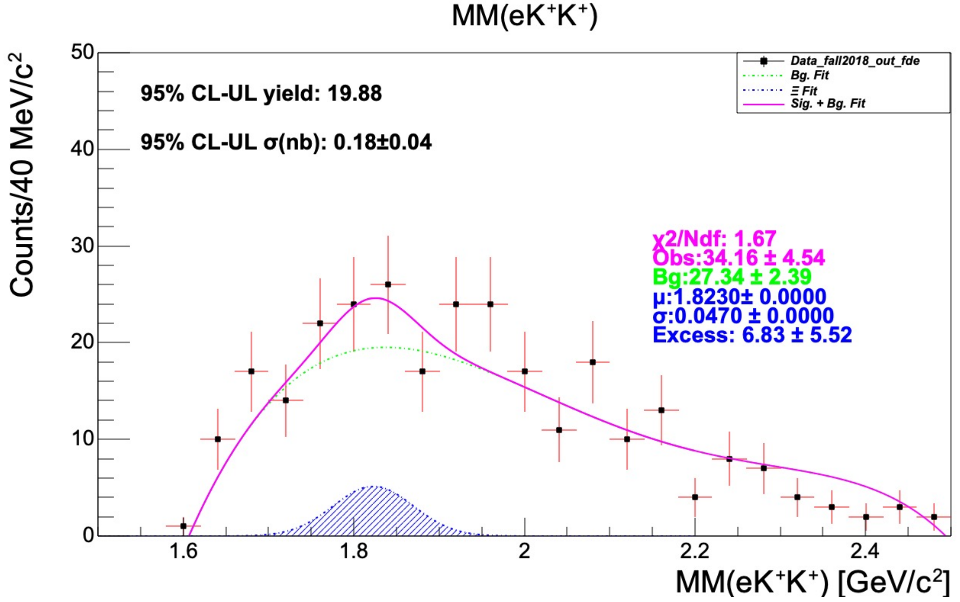
Same Cut=[1.0, 1.29]

CLAS12 cascade electroproduction: $ep \rightarrow eK^+K^+K^-(\Lambda/\Sigma)$, $\Xi^{-*} \rightarrow K^-\Lambda/\Sigma$, cross section uppder limit

Background subtracted distributions







Particle	$K^-\Lambda$	$K^-\Sigma^0$
Ξ (1690)	seen	seen
Ξ (1820)	**large (dominant)**	**small**
Ξ (1950)	seen	possibly seen
Ξ (2030)	~ 0.2	~0.8
Ξ (2120)	seen	N/A

No statistically significant states seen so far

Upper Limit Extraction ($\Xi^{*-}(1820)$):

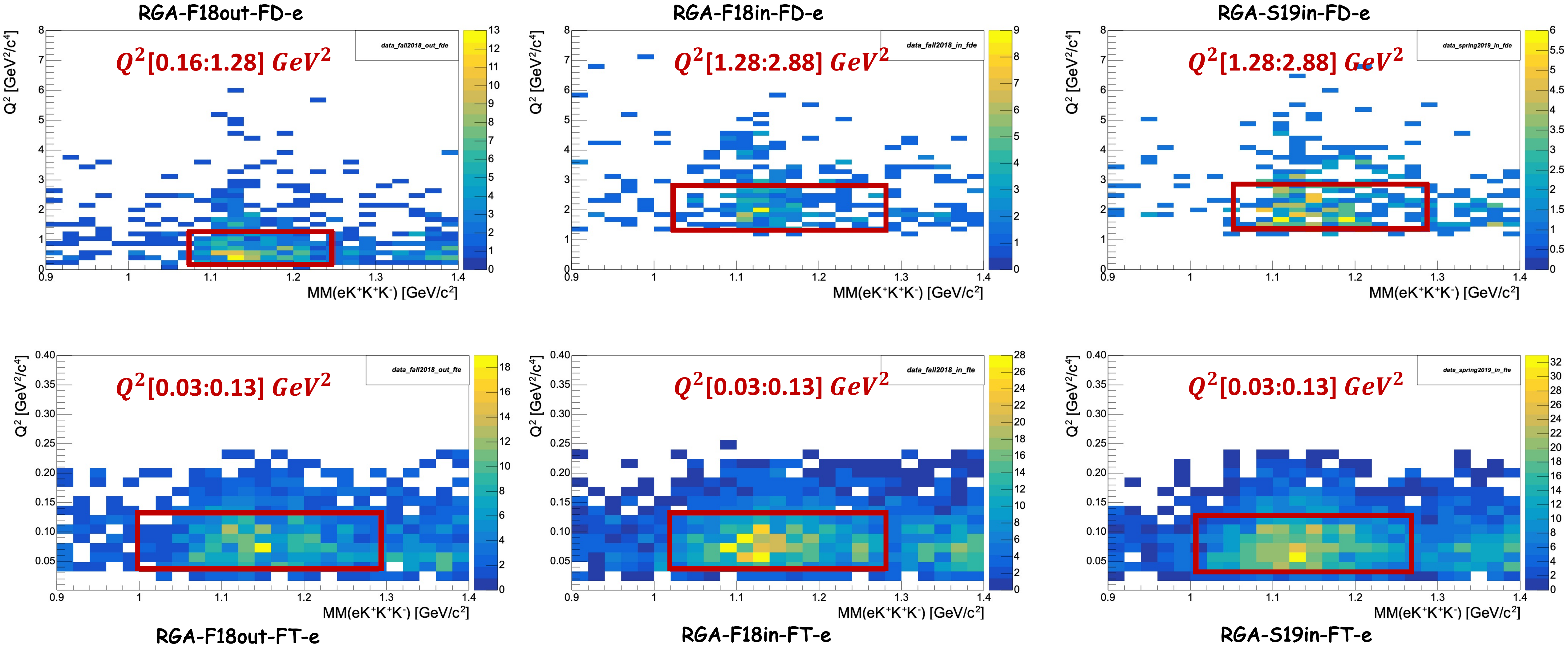
Mass/Width fixed from PDG/Simulation

Two methods used

- Naïve background+Gaussian fits
- Maximum log-likelihood method
- Both methods consistent with each other

Similar procedure performed as a function of eKK missing mass

CLAS12 cascade electroproduction: $ep \to eK^+K^+ K^-(\Lambda/\Sigma)$, $\Xi^{-*} \to K^-\Lambda/\Sigma$, cross section uppder limit : $Q^2 -$ Range



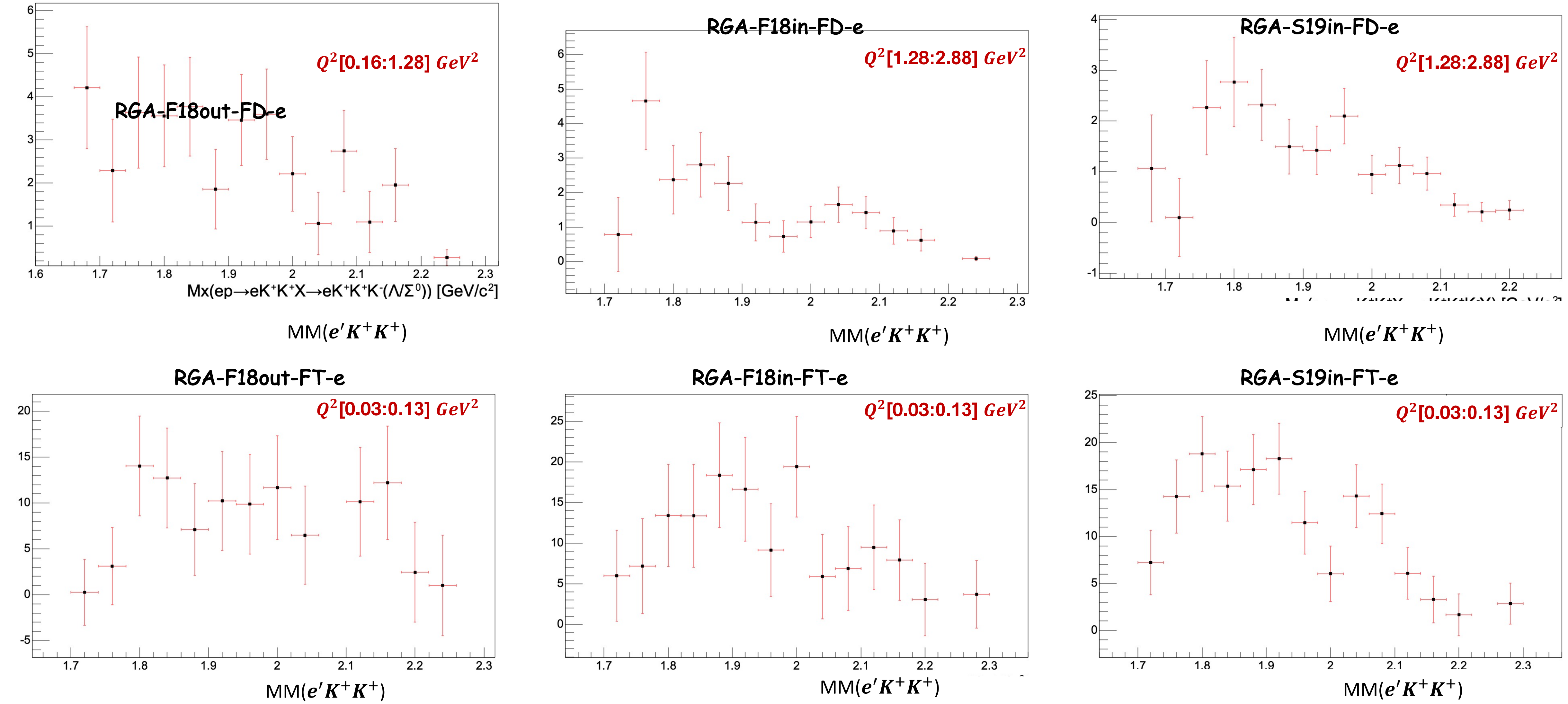
CLAS12 cascade electroproduction: $ep \rightarrow eK^{+}K^{+}K^{-}(\Lambda/\Sigma)$, $\Xi^{-*} \rightarrow K^{-}\Lambda/\Sigma$, $\Xi^{*-}(1820)$ 95% CL Upper Limit Yield

Fit result	F18 FT-e out	F18 FT-e in	S19 FT-e in	F18 FD-e out	F18 FD-e in	S19 FD-e in
Excess Yield	17.19	18.96	46.78	6.83	7.76	9.48
Yield uncertainty	7.67	8.09	10.18	5.84	5.14	5.32
TS	6.27	6.85	30.89	1.58	2.85	4.49
√TS	2.50	2.62	5.56	1.26	1.69	2.12
p-value	**0.0061**	**0.0044**	**0.0001**	**0.1045**	**0.0456**	**0.0170**
95%-CL range of yield excess	(3.142, **33.897**)	(4.080, **36.505**)	(27.730, **68.487**)	(-3.571, **19.884**)	(-1.237, **19.424**)	(0.480, **21.860**)

- **p-value** signifies how likely the data sample is consistent with the null hypothesis. A higher **p-value** implies that the data sample is highly consistent with the null hypothesis (H_0).

- 95%-Cl upper limit **yield from** the **maximum likelihood ratio test method** is **compatible with** the number obtained from the **naïve fit method** (yield + 2* yield-uncertainty)

CLAS12: $ep \rightarrow e'K^+K^+K^-(\Lambda/\Sigma^0)$ Preliminary "Differential Cross Section"



Acceptance Corrected/Flux Normalized; Data/Simulation resolution matched; Arbitrary units ☺

SUMMARY

- First look at CLAS12 RGA data on cascades promising
  - $ep \to eK^+K^+$ (Ξ^{-*})
  - $ep \to eK^+K^+$ $K^-(\Lambda/\Sigma)$, $\Xi^{-*} \to K^-\Lambda/\Sigma$; Both channels consistent with each other and expectation
  - Ground states seen first time in electroproduction
- Current statistics limited (central detector data not used)
  - Major tracking efficiency and resolution improvement underway
  - Order of magnitude more statistics soon
- Higher mass states do not have statistically significant signals
  - Preliminary Cross section upper limit (not shown) consistent with earlier results
  - Preliminary Reaction differential cross section derived
- Other reactions will be investigated with improved RGA data set
  - $ep \to eK^+K^+$ $(\Xi^{-*}), \Xi^{-*} \to K^-\Lambda, \Lambda \to p\pi^-$
  - $ep \to eK^+K^+\pi^-(\Xi^0)$
  - $ep \to eK^+K^+K^{-0}(\Omega^-), \Omega^- \to K^-\Lambda$
  - Others (S=-1 hyperons, etc)
- Probing production mechanisms
  - Polarization measurement possible if statistics allows
  - Q^2 dependency of cross section measurements
- Acknolwdgement: CLAS Collaboration/Nstar2022 Organanizers/Supported by DOE grant 800004726

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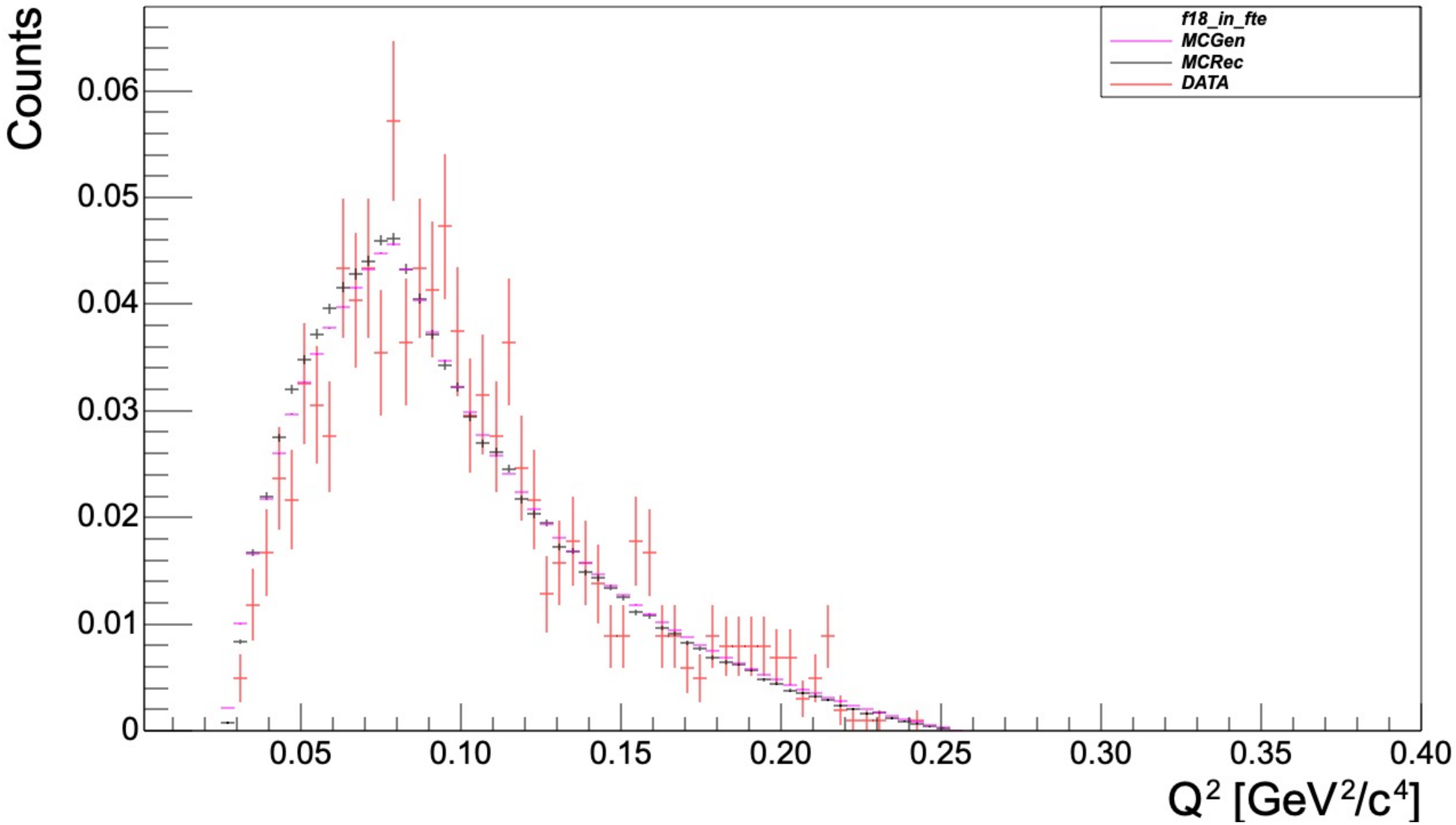
Backup Slides

Quality Control of Simulation

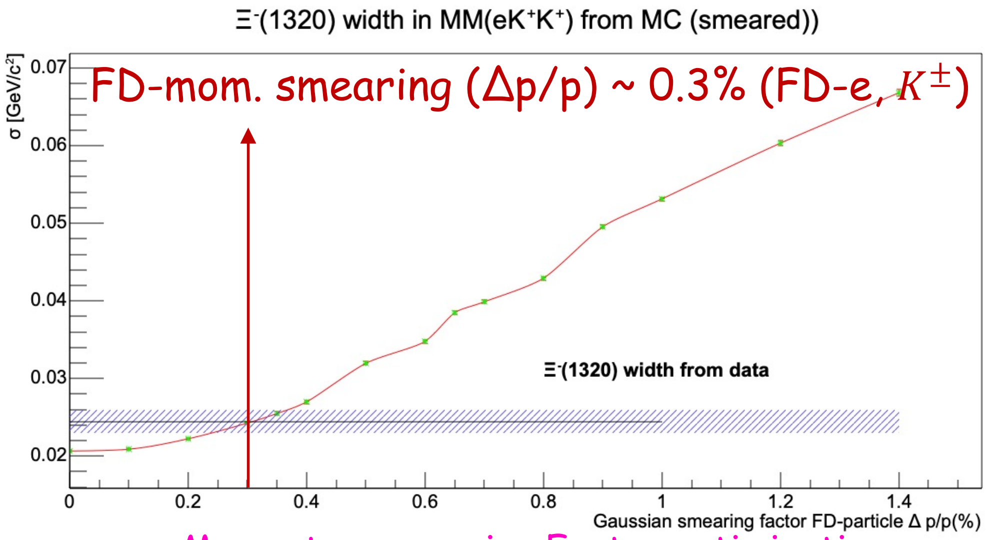
- The shape of Q^2 distribution from MC Events and Ξ^{*-} data sample were matched by weighting generated events if needed.



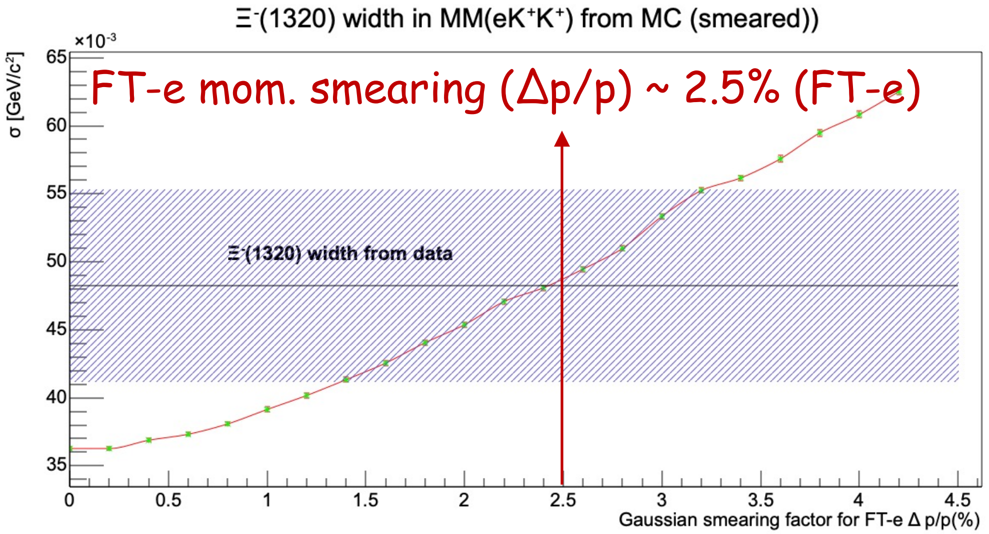
- Histograms normalized to one to compare the overall shape

- Similar comparisons were performed for all the data sets to ensure simulation best mimics data distributions

Knowledge of Ξ^{*-}(1820) Experimental Mass Resolution



Momentum smearing Factor optimization

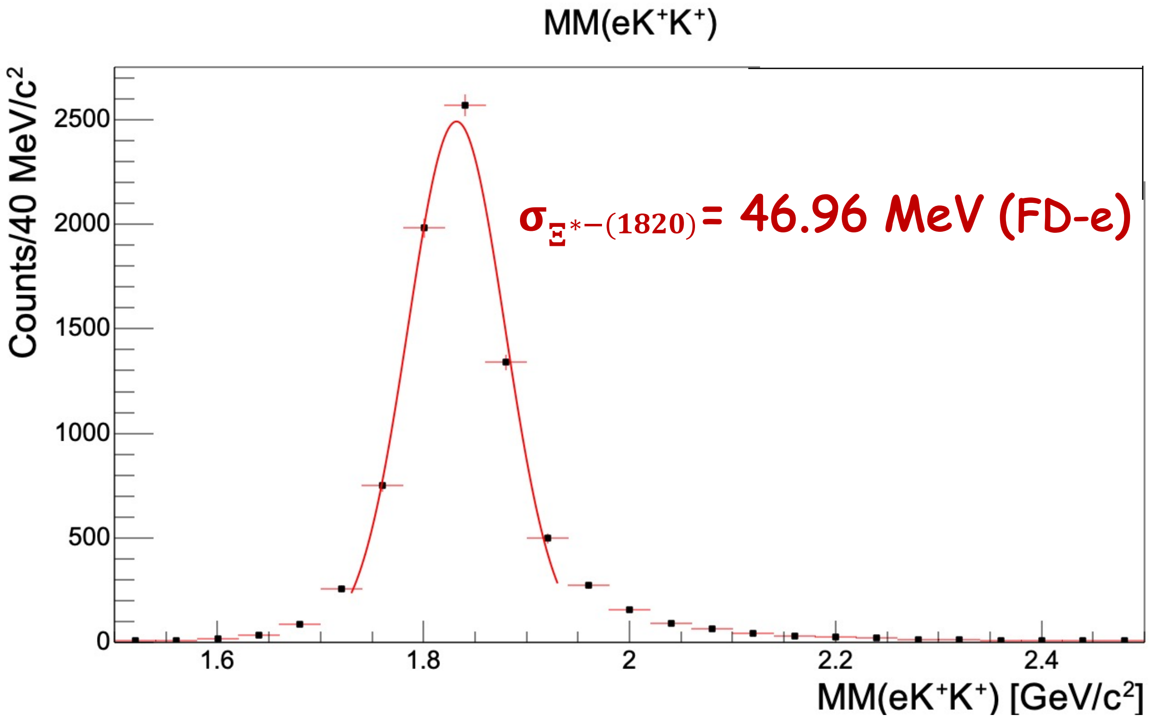


- Ξ^{*-}(1820) Mass resolution **inferred from MC** by applying proper momentum smearing to MC for data vs MC matching
- Compared observed **Ξ^-(1320) signal width** in the MM(**eK^+ K^+**) distribution to derive MC smearing factor for FD and FT
- The smearing factor for FD and FT derived with two independent processes by running **MC simulation for Ξ^-(1320)** exclusive reaction:

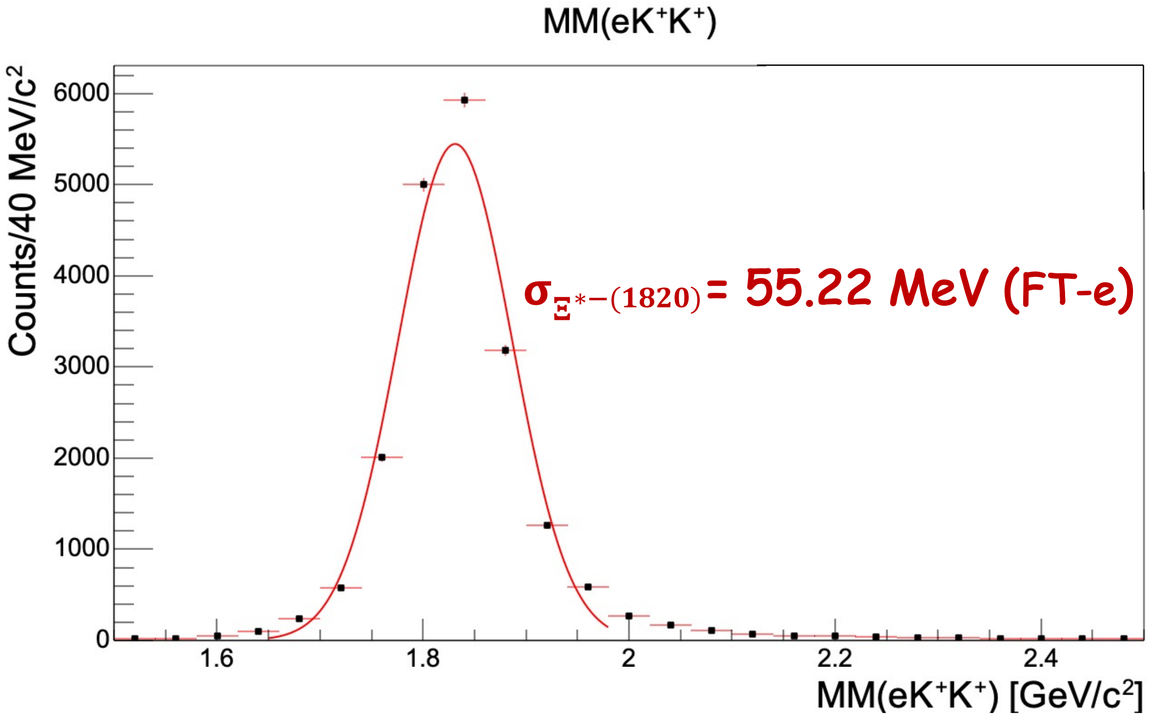
$$\mathbf{ep} \rightarrow e'K^+K^+\,\Xi^-(1320) \rightarrow e'K^+K^+\,\pi^-\Lambda$$

- Used 0.3% Δp/p($K^{\pm}$) to derive Δp/p for FT-e

Knowledge of Ξ^{*-}(1820) Experimental Mass resolution



- Generated $ep \rightarrow e'K^+K^+\Xi^{*-} \rightarrow e'K^+K^+(\Lambda/\Sigma^0)$ with intrinsic Ξ^{*-}**(1820)** mass (**1823 MeV**) / resolution (24 MeV) from PDG
- Applied momentum smearing to reconstructed momenta
- Fitted MM($e'K^+K^+$) distribution to get the Expt. Resolution

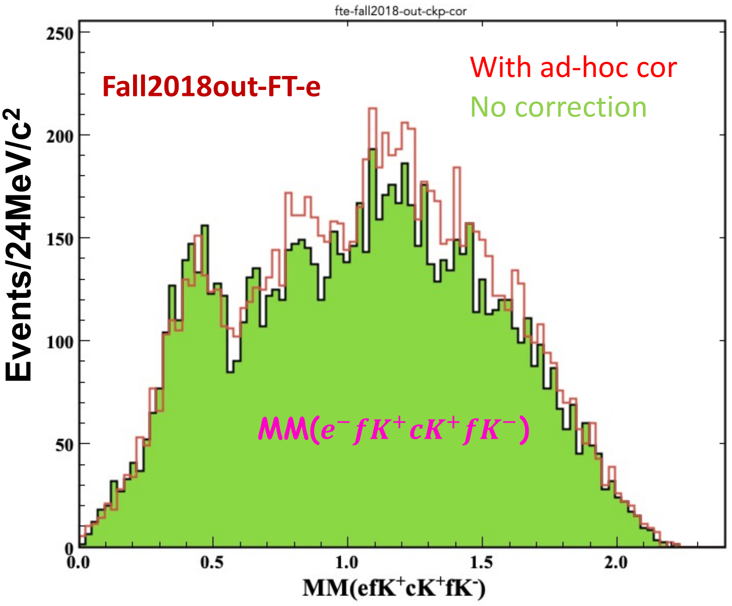


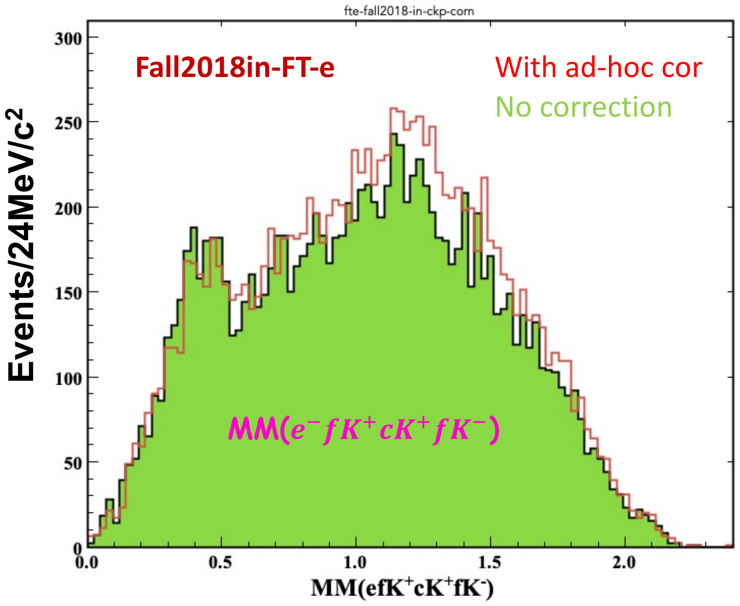
<u>Expt. Mass resolution with MC smearing</u>

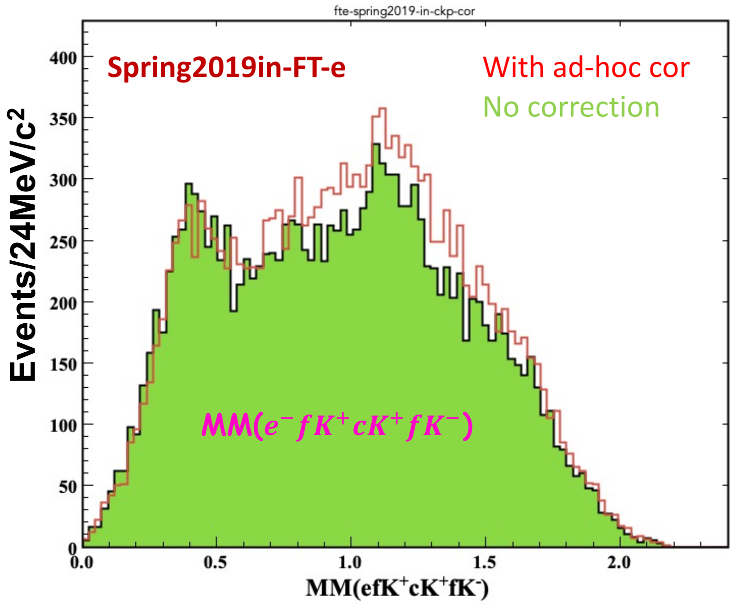
Sources of Systematic Uncertainties

Systematics	F18 FD-e outbending (δ_i)	F18 FT-e outbending (δ_i)
Momentum smearing factor ($\Xi^{*-}(1820)$ resolution choice)	4.4%	2.9%
BG. Fit function choice	4.5%	5.8%
Bin shift study	0.9%	1.3%
BG. Template choice (Ev. Mixing vs. Signal excluding Technique)	26%	16%

Why Central Detector Data has not been used yet







- Correction derived using $\boldsymbol{e'p\pi^+\pi^-}$ events with $\boldsymbol{e', p}$ and, $\boldsymbol{\pi^-}$ detected in FD and $\boldsymbol{\pi^+}$ detected in CD (Details back up slide)
- Treating $\boldsymbol{\pi^+}$ in CD as missing particle and used missing particle four-momentum to calibrate $\boldsymbol{\pi^+}$ in CD
- Used same correction for K^+ in CD. **Results were not so encouraging -> Decided to work on the FD only**