JLab CLAS12における Λ 共鳴状態の電磁生成の研究

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Contents

Λ resonances

Non-relativistic constituent quark models

$$H = \underbrace{H_{si}}_{\text{spin-independent}} + \underbrace{H_{sd}}_{\text{spin-dependent}}$$

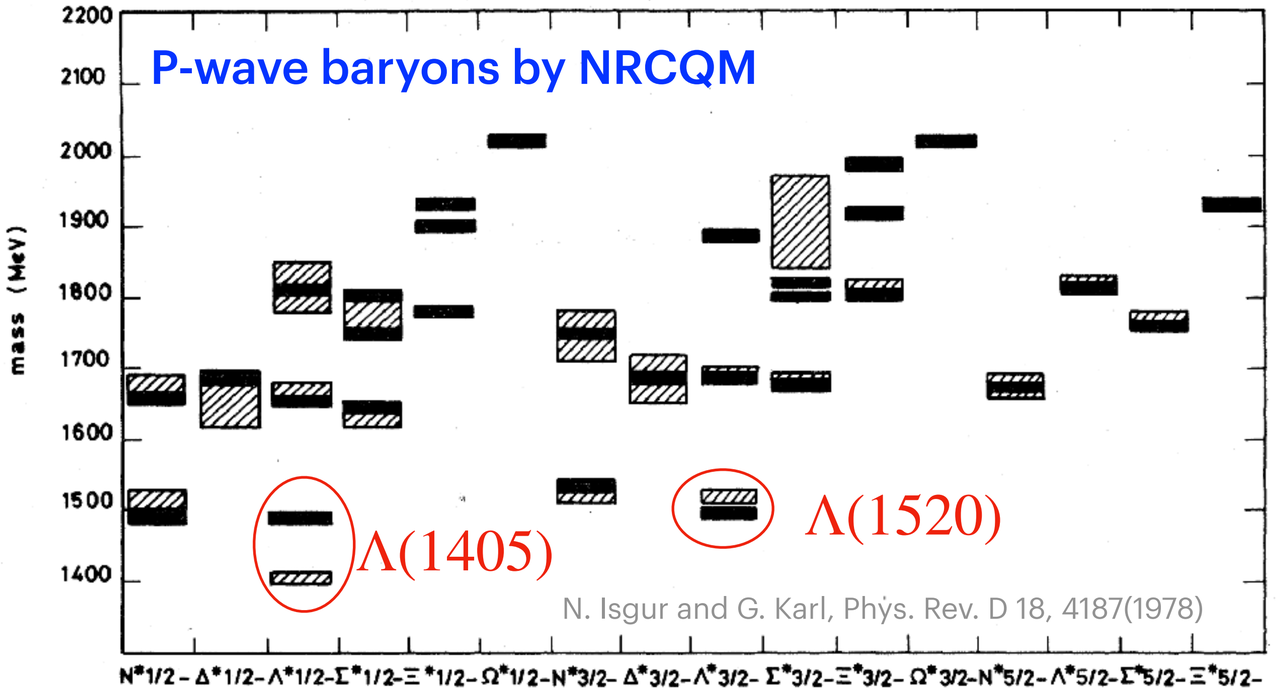
$$H_{si} = \sum\left(m_i + \frac{p_i^2}{2m_i}\right) + \sum\left(\frac{1}{2}br_{ij} + c - \frac{2\alpha_s}{3r_{ij}}\right)$$

Assumption:

- ✦ The quark masses (m_u, m_d, m_s)
- ✦ strong coupling constant
- ✦ the spring constant for the harmonic oscillator

P-wave Λ resonance $(S = 1/2,\ l = 1)$

→ Spin-orbit partners: $\Lambda(1405)(1/2)^-$, $\Lambda(1520)(3/2)^-$

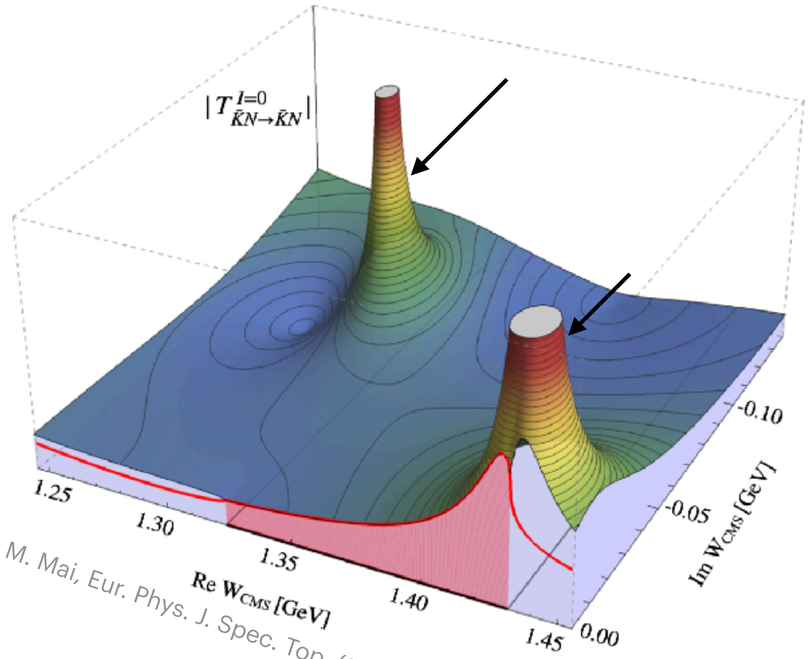


Why is there a discrepancy by ~80 MeV on Λ(1405)?

→ Exotic state such as a hadron molecule?

Two-pole structure of $\Lambda(1405)$

Scattering amplitude of $|T^{I=0}_{\bar{K}N\to\bar{K}N}|$ by ChUM

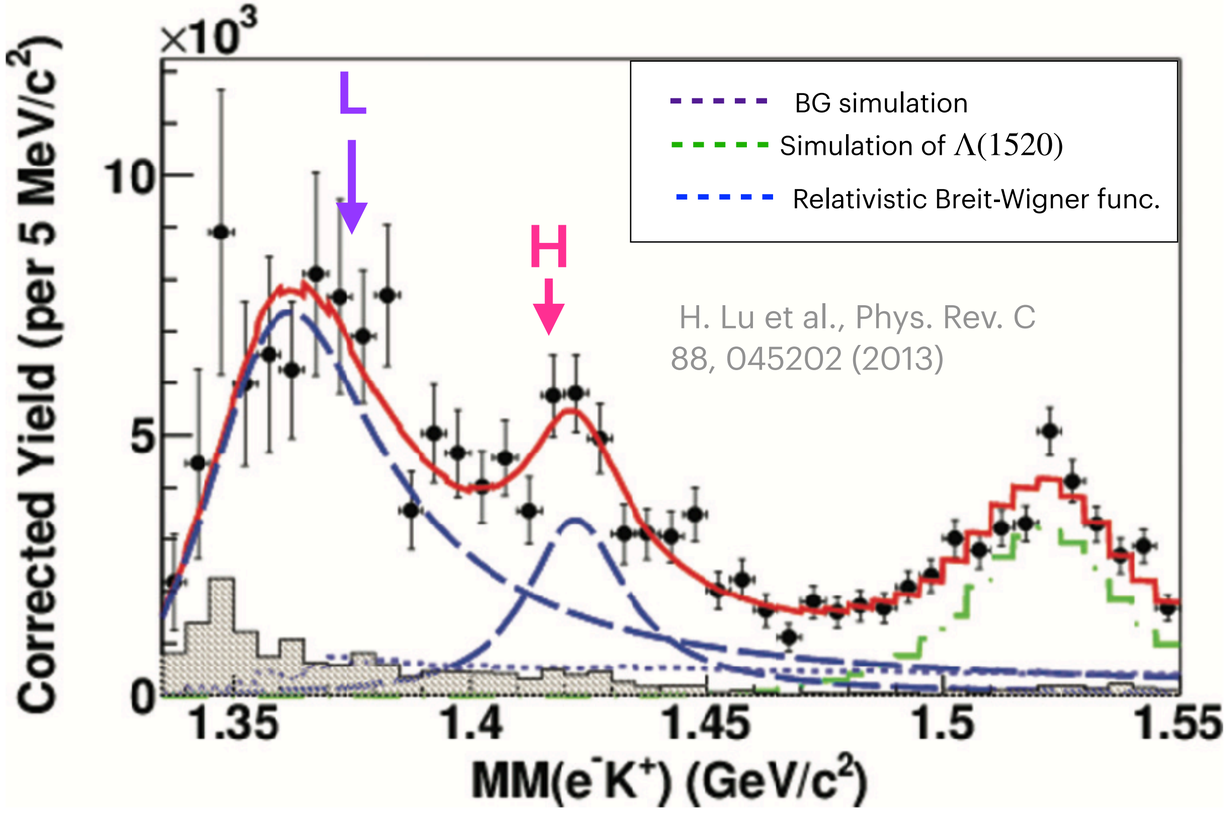


M. Mai, Eur. Phys. J. Spec. Top. (2021) 230:1593-1607

Two poles couple to different hadron molecules

Is there any evidence of that structure?

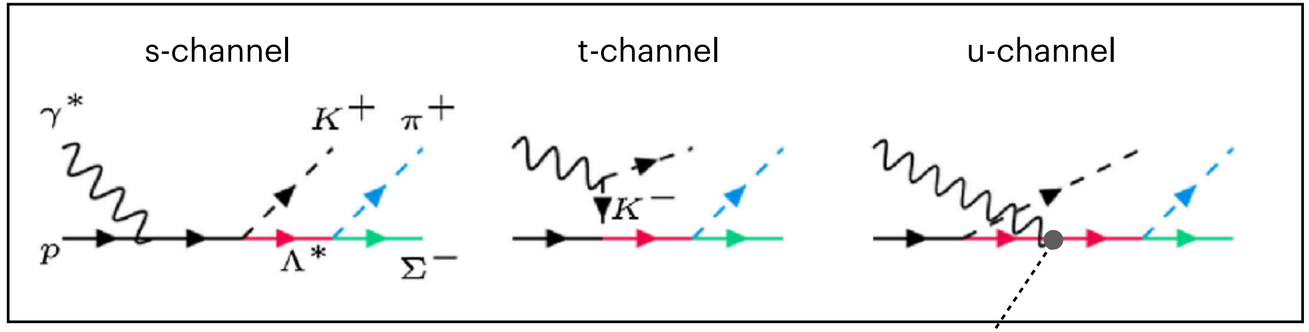
Λ(1405) electroproduction at CLAS e1f experiment



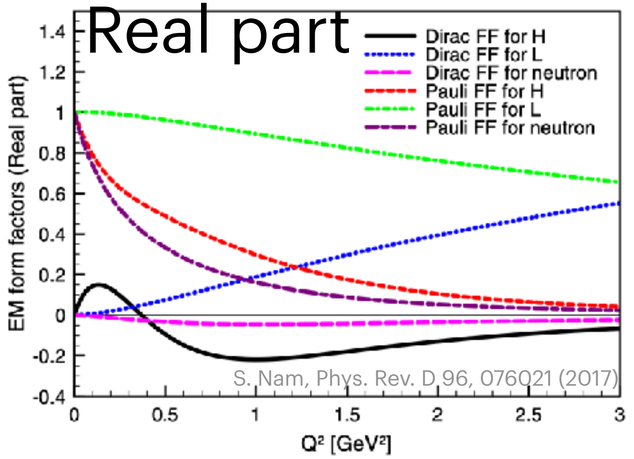
- There are evidences that supports two-pole structure, but no size information
- No Q2 slice due to statistics limitation→ Size of the molecule states?

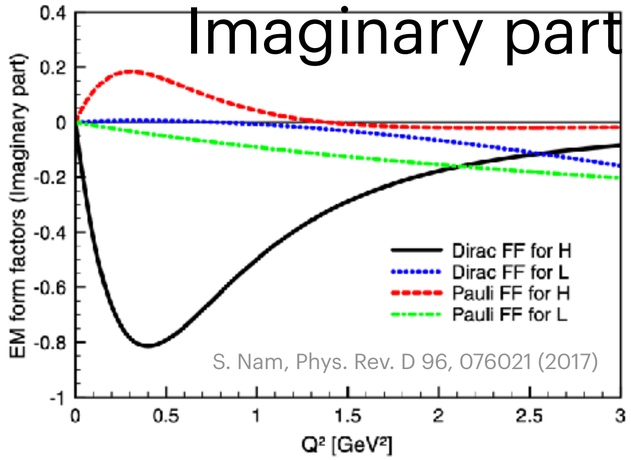
Q2 dependence approach

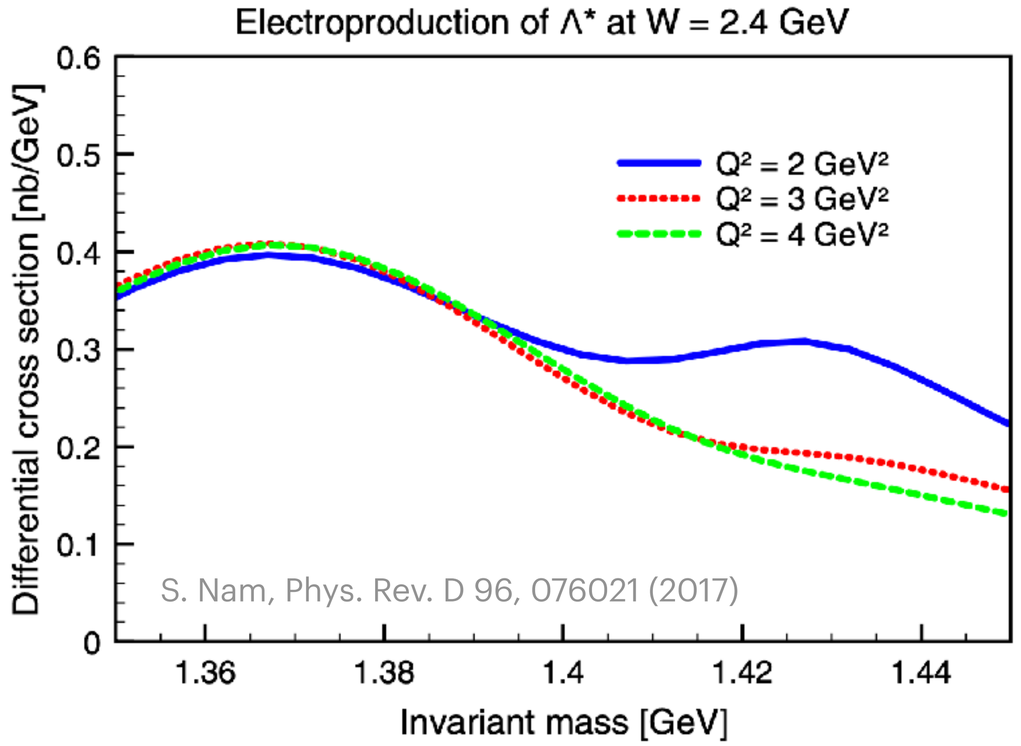
Feynman diagrams of Λ* electroprodction



Include Λ* Dirac and Pauli form factor using charge rms radii by ChUM

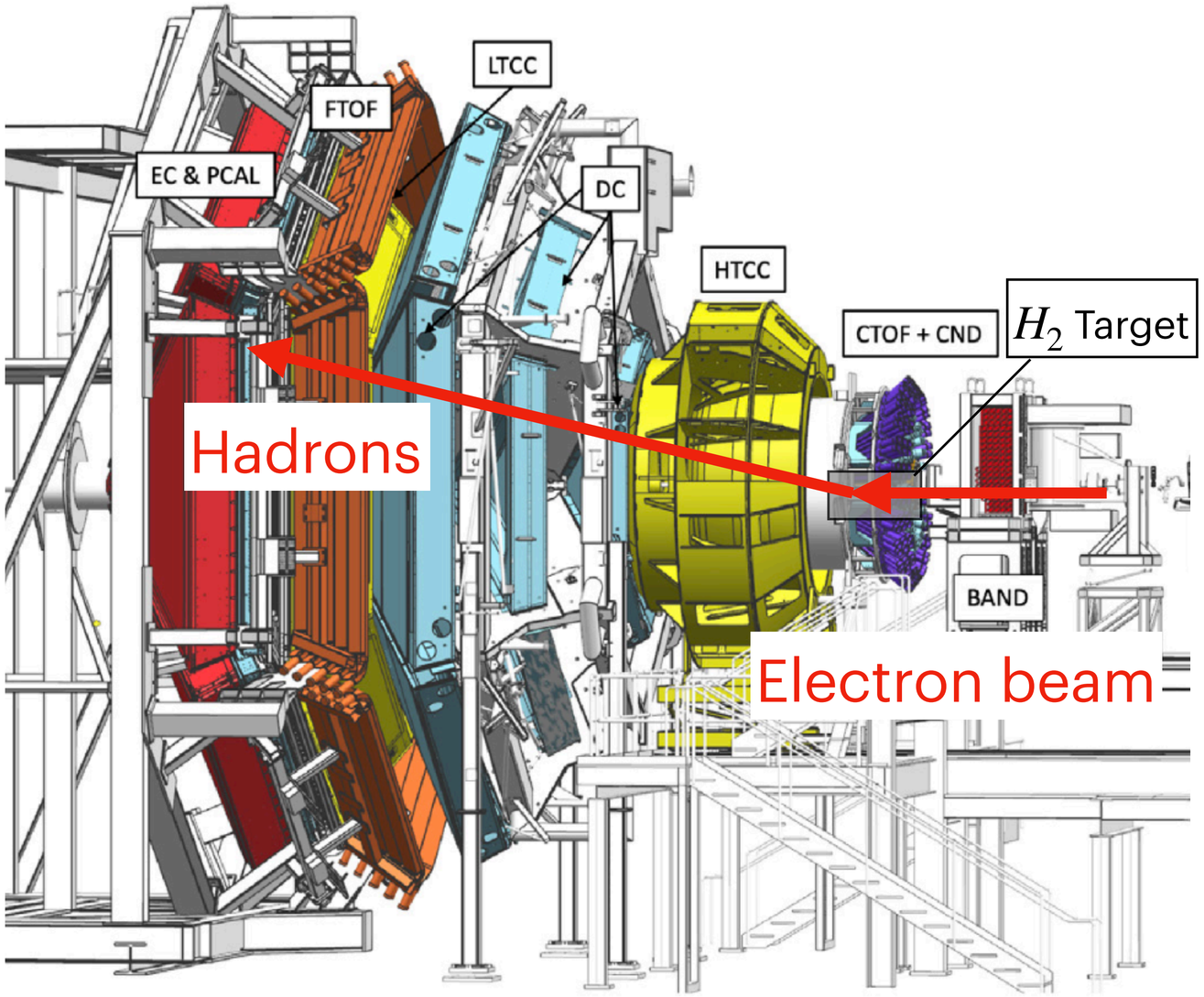






- There should be Q2 dependence of the cross section if form factor is as predicted
- My research is to get information about Λ^* size by Q^2 dependence

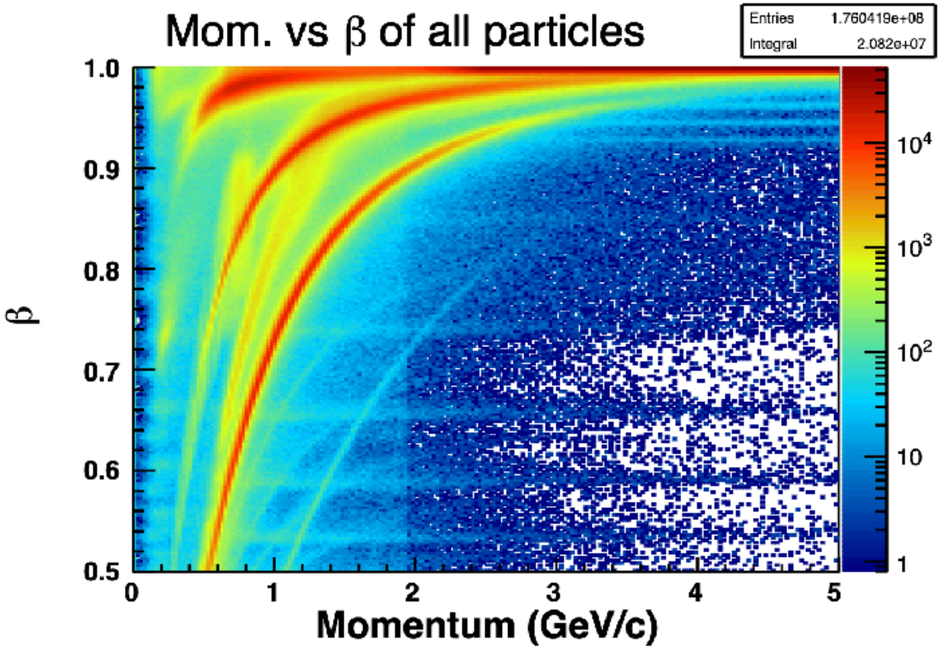
CLAS12 at JLab



Nuclear Inst. and Methods in Physics Research, A 959 (2020) 163419

CLAS upgraded detectors, CLAS12 specs:

- luminosity ... $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Coverage ... $5^\circ < \theta < 35^\circ$ @ FD, $\Delta\phi = 2\pi$
- momentum resolution ... $\sigma_p/p \sim 0.7\,\%$
- streaming data taking ... 15 kHz



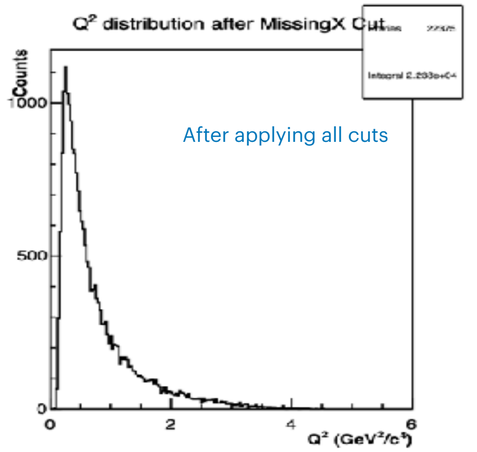
Run Group K

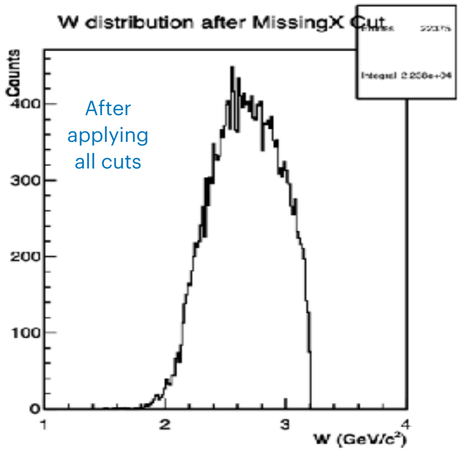
What is Run Group K experiment?

Run Group K encompasses the following three approved experiments, which share the same CLAS12 configuration and address complementary aspects of strong QCD:

- E12-16-010 - A Search for Hybrid Baryons in Hall B with CLAS12
- E12-16-010A - Nucleon Resonance Structure Studies Via Exclusive KY Electroproduction
- E12-16-010B - Deeply Virtual Compton Scattering with CLAS12 at 6.6 GeV and 8.8 GeV

Cited from E12-16-010 proposal for PAC48 at JLab

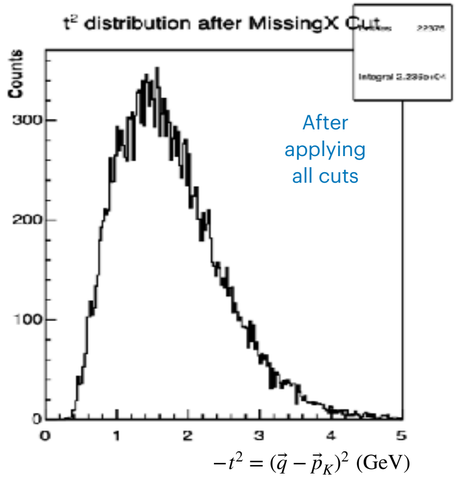


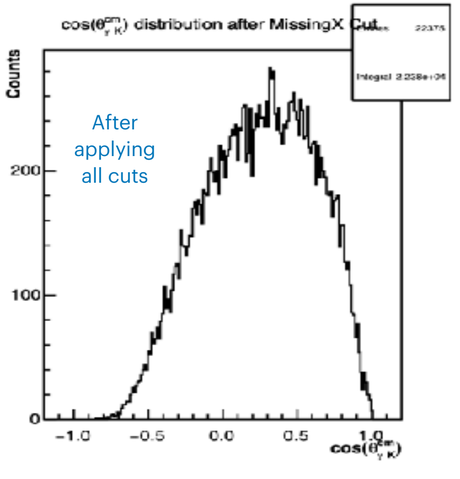


Dataset summary of RG-K

Run Period	Beam Energy (GeV)	Target	Collected Charge (mC)	Calibration status
Spr2024	6.394	LH_2	91.35	Not yet
Spr2024	8.477	LH_2	81.77	Not yet
Dec2018	6.535	LH_2	18.23	Done
Dec2018	7.546	LH_2	10.77	Done

←





Using 6-GeV datasets of 2018, started to research on Λ* electroproduction. After 2024 datasets calibrated, I'm going to integrate all data.

Event Selection

Y^* electroproduction

$$e + p \rightarrow e' + K^+ + X\,(X = Y, Y^*)$$

$$Y^* = \begin{matrix}\Lambda(1405)\\ \Lambda(1520)\end{matrix} \begin{cases} \xrightarrow{33\%} \Sigma^+\pi^- \rightarrow (\pi^+ n)\pi^- \\ \rightarrow (\pi^0 p)\pi^- \\ \xrightarrow{} \Sigma^-\pi^+ \rightarrow (\pi^- n)\pi^+ \end{cases}$$

Select the events

- Selection Steps

✓Final state selection … Select $\{e', K^+, \pi^-, p\}$

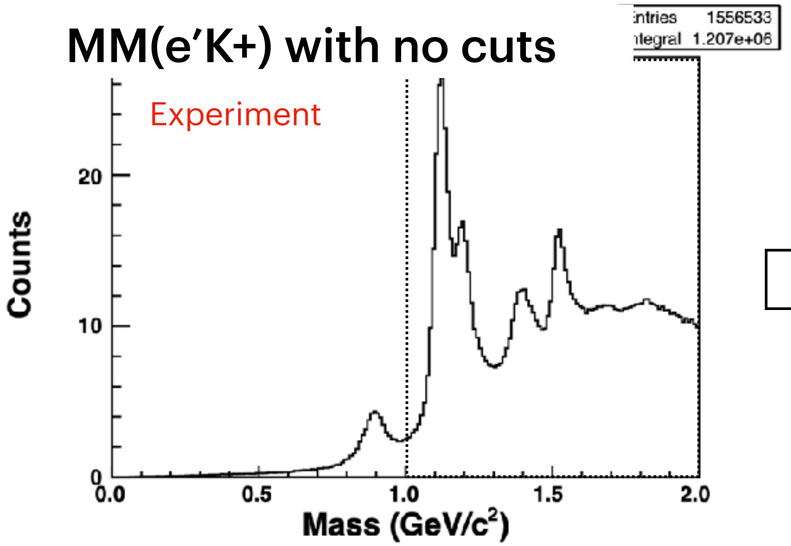
✓Z-vertex cut … Vertex peaks with 3σ range

✓PID cut … Good identification for mom vs ΔTOF

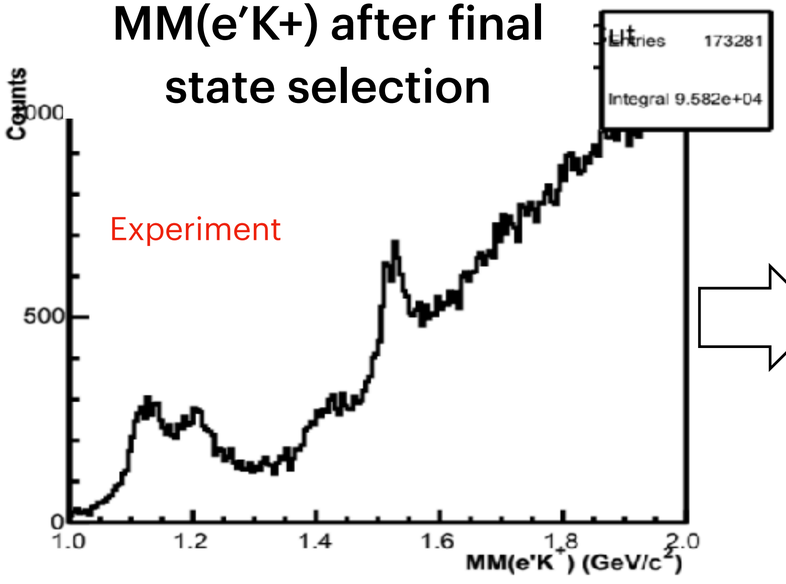
✓Missing particle cut … Missing π^0 peak with 3σ range

✓Σ cut … Missing Σ^+ peak with 3σ range

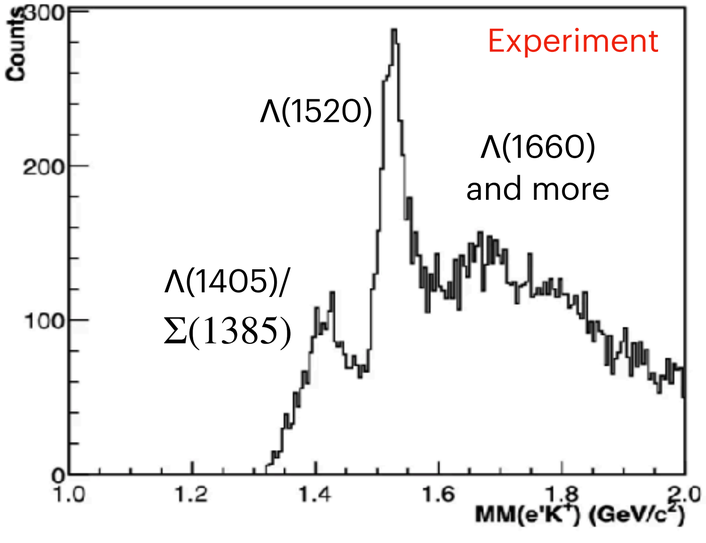
MM(e'K+) with no cuts



MM(e'K+) after final state selection



MM(e'K+) after Σ cut

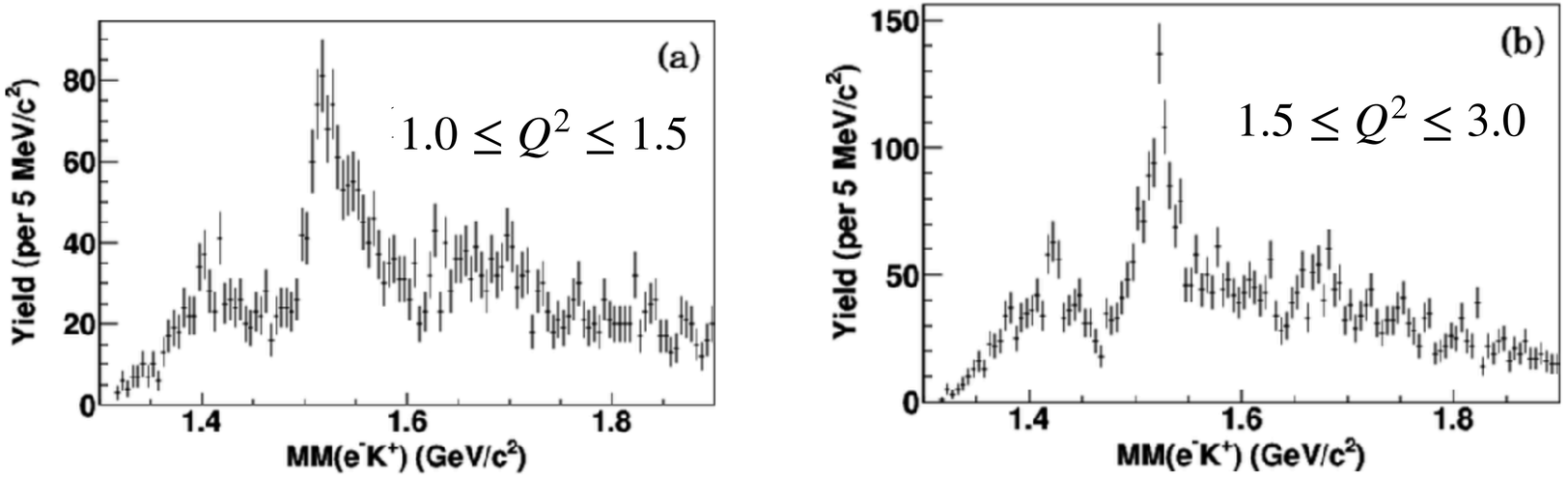


Comparison with previous study

Previous study

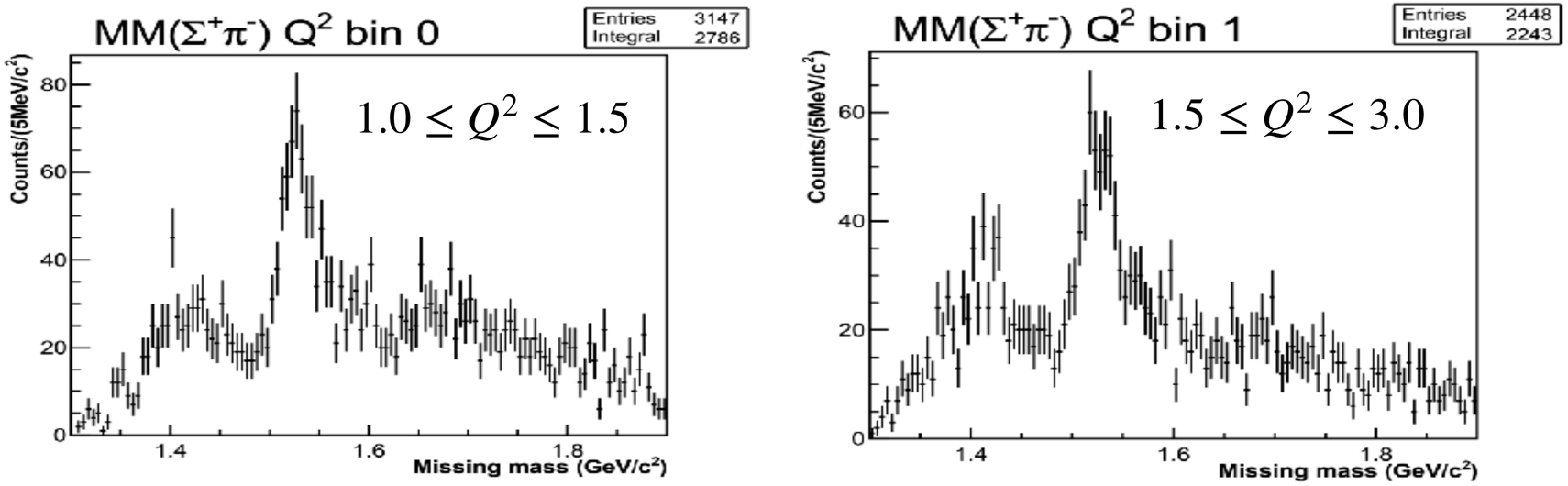
H. Lu et al., Phys. Rev. C 88, 045202 (2013)

- Two bins by Q^2
- Decay mode: $\Sigma^+\pi^- \rightarrow (\pi^0 p)\pi^-$



Present study

- Binning in the same way to the previous study
- Consistent with shape trend
- ~20 % less statistics than the previous data



Background estimation in progress

Resonant backgrounds

$\Sigma(1385)$

$$K^+ + \Sigma(1385) \rightarrow K^+ + \Lambda + \pi^0 \rightarrow K^+ + p + \pi^- + (\pi^0)$$

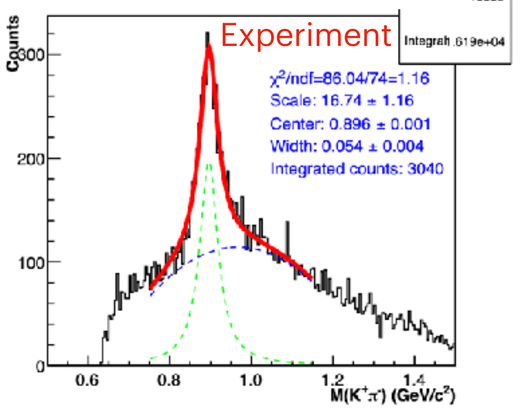
Invariant mass

K^{*0}

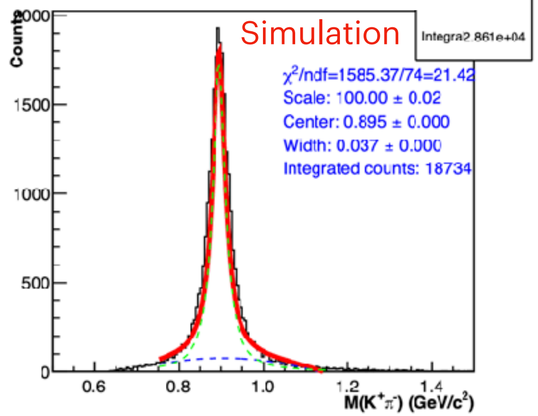
$$K^{*0} + \Sigma^+ \rightarrow K^+ + \pi^- + p + \pi^0$$

Invariant mass

Invariant mass of K^{*0}



Invariant mass of K^{*0}



Other backgrounds

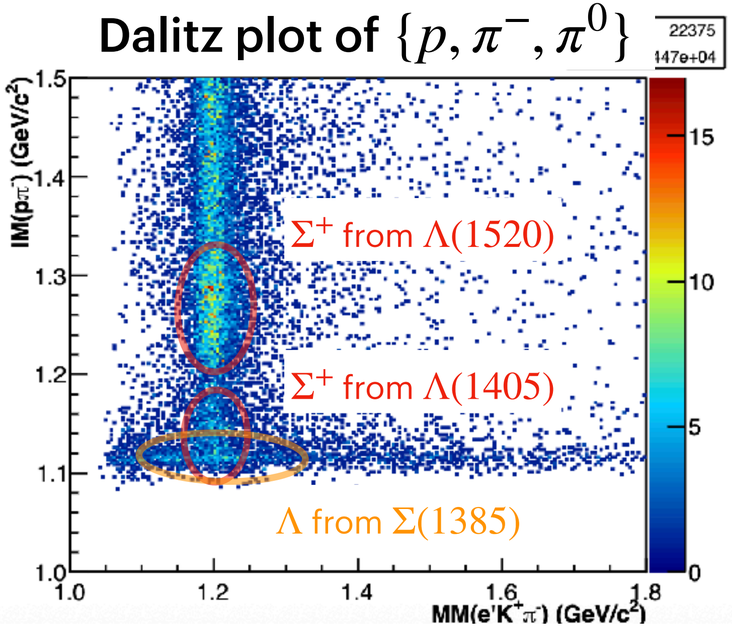
Non-resonant

$$K^+ + \Sigma^+ + \pi^0 \rightarrow K^+ + p + (\pi^0) + \pi^-$$

Uncorrelated events

$$\{e', K^+, p, \pi^-\}$$

Dalitz plot of $\{p, \pi^-, \pi^0\}$



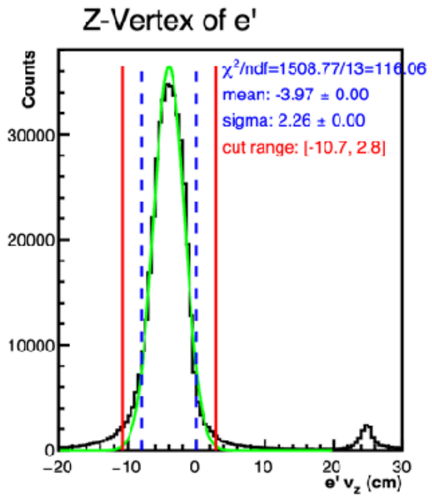
Summary

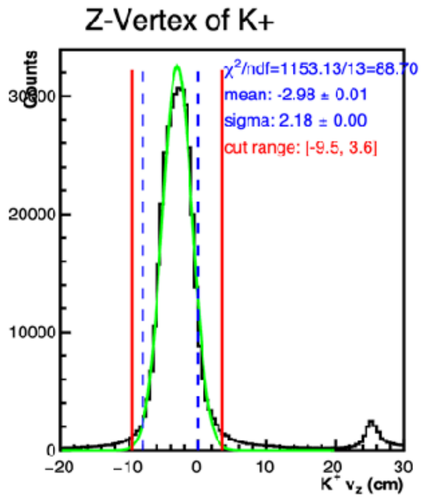
- Λ* electroproduction at CLAS12
  - ✦ Λ(1405/1520) are spin-orbit partners and Λ(1520) can be explained by CQM
  - ✦ Λ(1405) is supposed to have two-pole structure, but no size information obtained
  - ✦ CLAS12 has high luminosity, high statistics

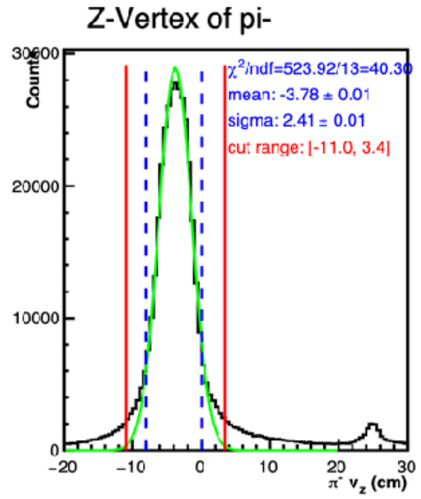
- Analysis
  - ✦ Event selection was performed and checked the consistency with previous data
  - ✦ Background estimation is ongoing

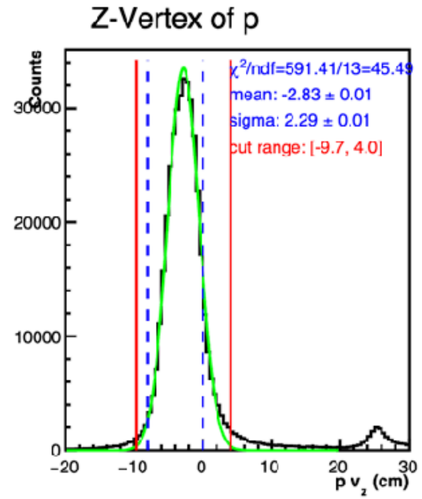
Backup

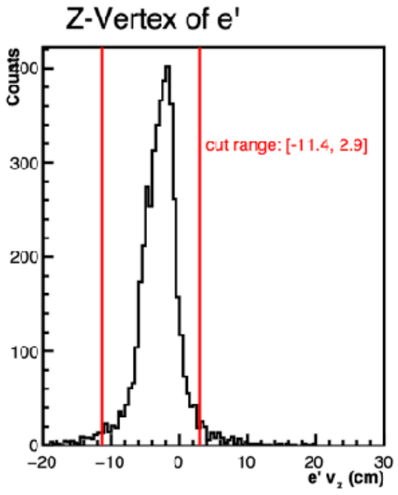
Z-vertex cut

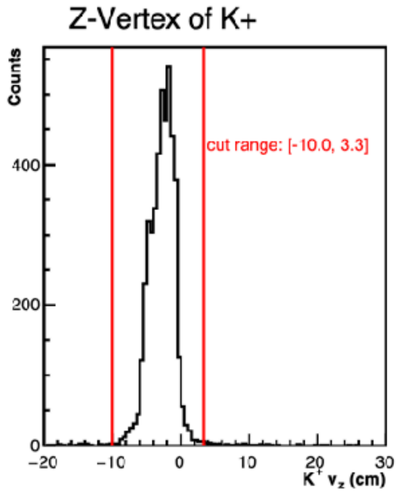

Z-Vertex of e'
χ²/ndf=1508.77/13=116.06
mean: -3.97 ± 0.00
sigma: 2.26 ± 0.00
cut range: [-10.7, 2.8]
Counts
e' v_z (cm)

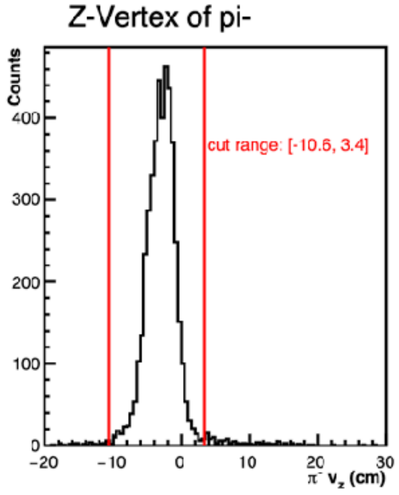

Z-Vertex of K+
χ²/ndf=1153.13/13=88.70
mean: -2.98 ± 0.01
sigma: 2.18 ± 0.00
cut range: [-9.5, 3.6]
Counts
K⁺ v_z (cm)

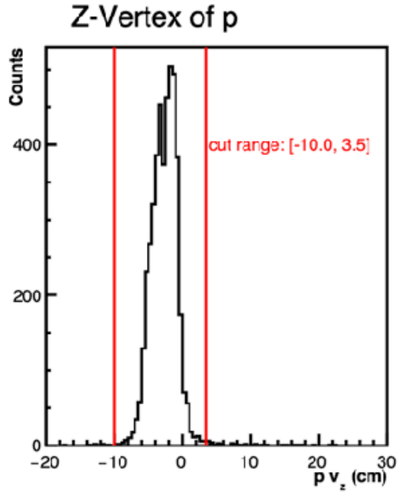

Z-Vertex of pi-
χ²/ndf=523.92/13=40.30
mean: -3.78 ± 0.01
sigma: 2.41 ± 0.01
cut range: [-11.0, 3.4]
Counts
π⁻ v_z (cm)


Z-Vertex of p
χ²/ndf=591.41/13=45.49
mean: -2.83 ± 0.01
sigma: 2.29 ± 0.01
cut range: [-9.7, 4.0]
Counts
p v_z (cm)


Z-Vertex of e'
cut range: [-11.4, 2.9]
Counts
e' v_z (cm)


Z-Vertex of K+
cut range: [-10.0, 3.3]
Counts
K⁺ v_z (cm)


Z-Vertex of pi-
cut range: [-10.6, 3.4]
Counts
π⁻ v_z (cm)

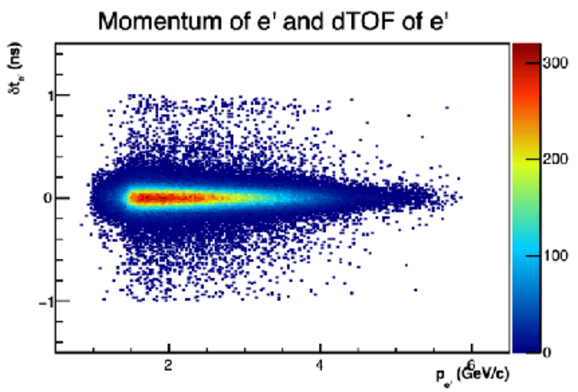

Z-Vertex of p
cut range: [-10.0, 3.5]
Counts
p v_z (cm)

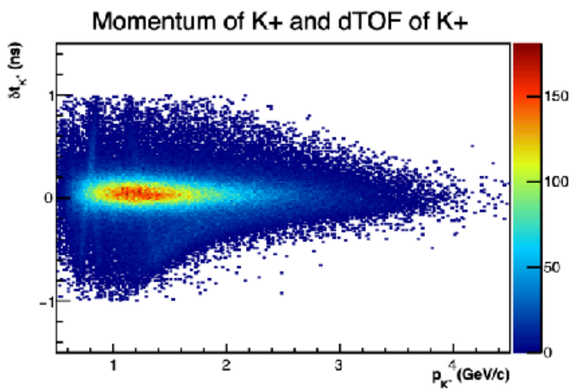
PID cut

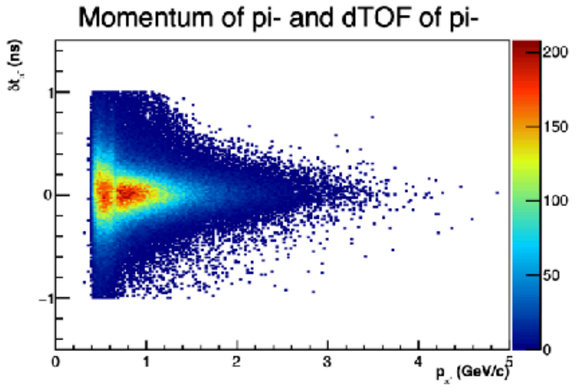
- Purpose
  - ✦ Remove the events near particle boundary regions
  - ✦ Events of all particles(e,K,p,pi-) are applied
- Use momentum dependence of $\delta_t = (t_{reach} - t_{start}) - \frac{l}{c\beta(p)}$
  - ✦ Slicing momentum and Project to δ_t
  - ✦ Fitting the peak with gaussian → Plot 3σ points
  - ✦ Boundaries of 6th-order polynomial by fitting 3σ points

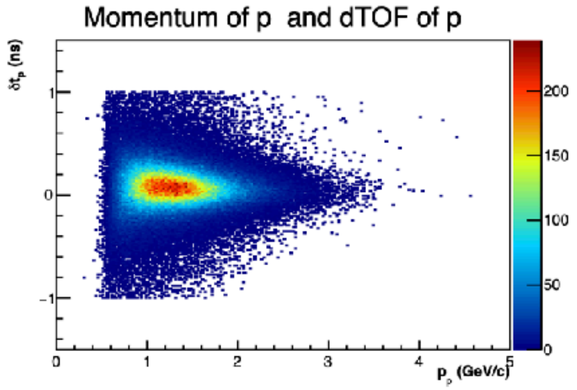
PID cut for all particles (data)

Before PID cut

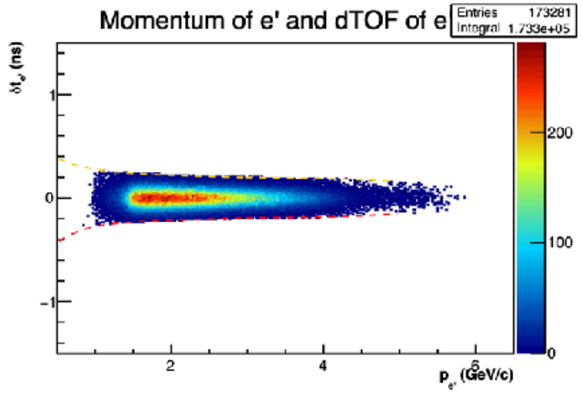


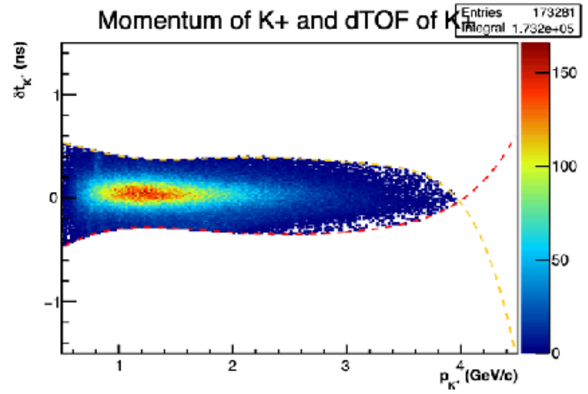


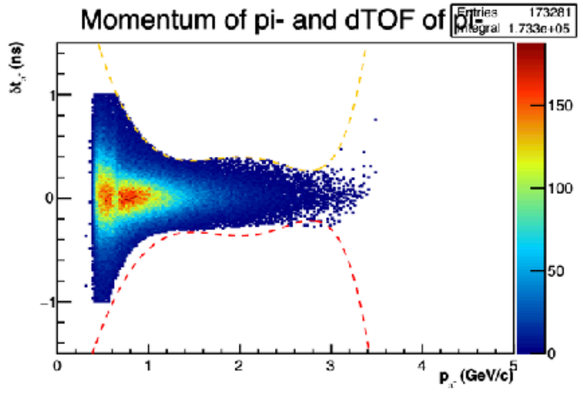


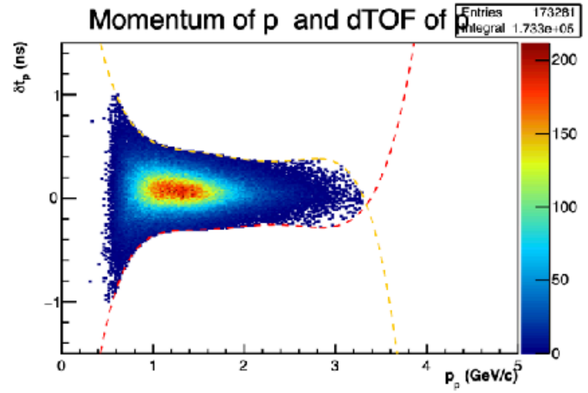


After PID cut



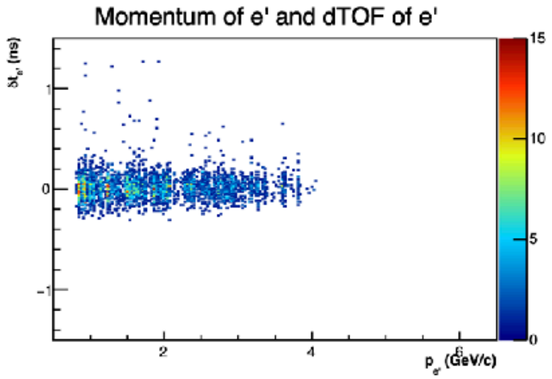


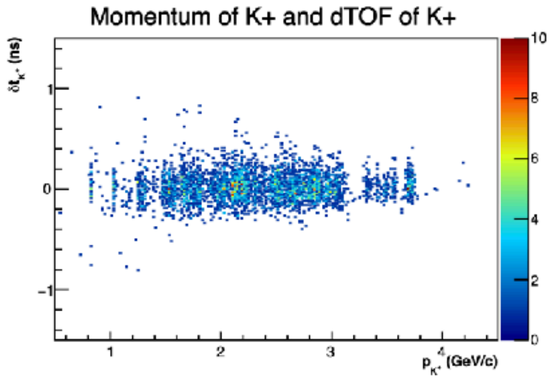


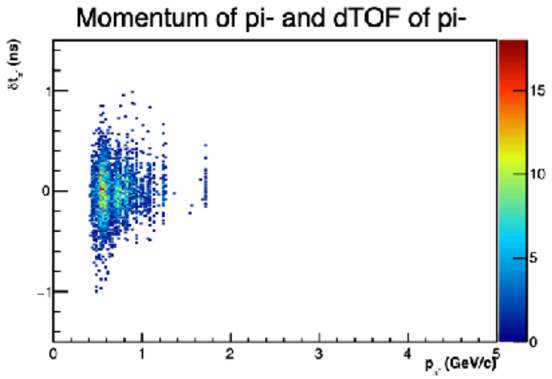


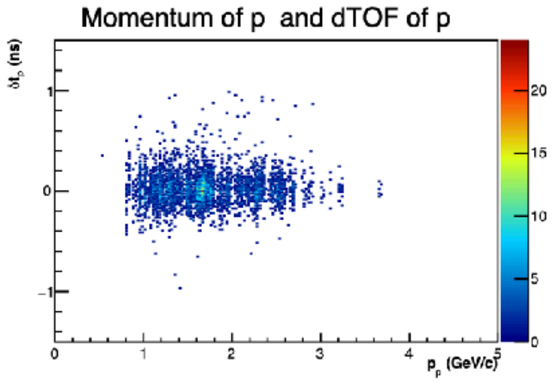
PID cut for all particles(simulation)

Before PID cut

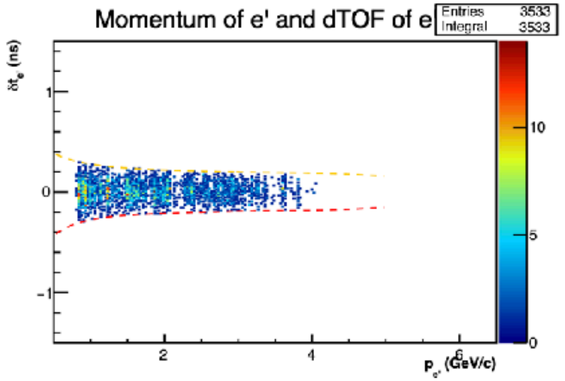


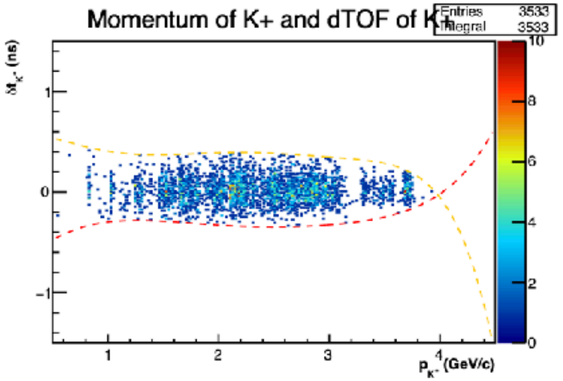


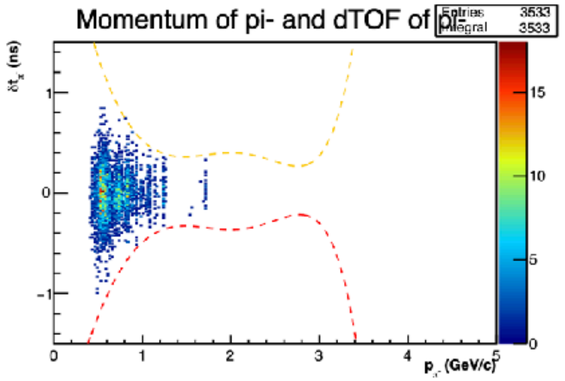


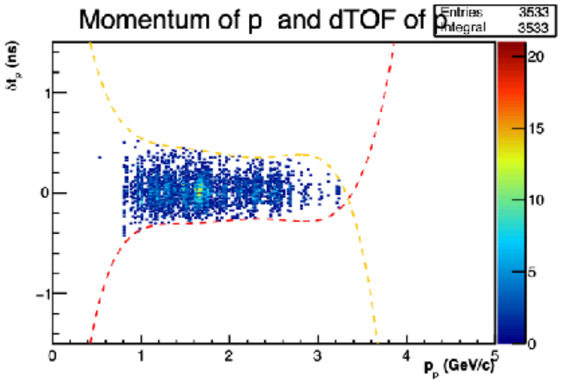


After PID cut

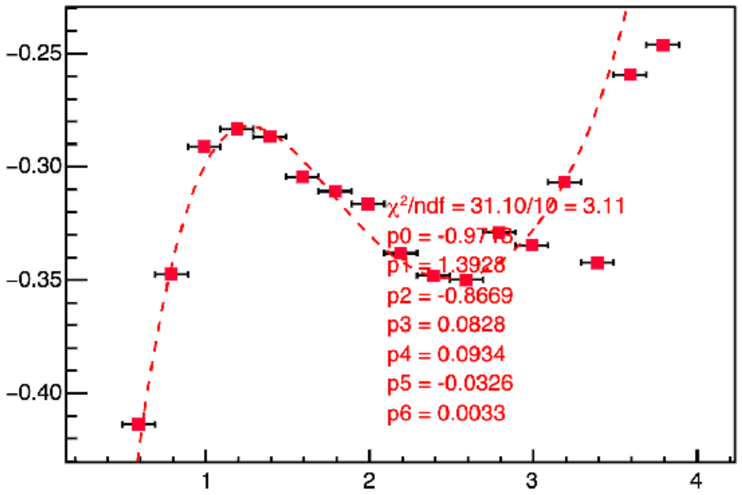


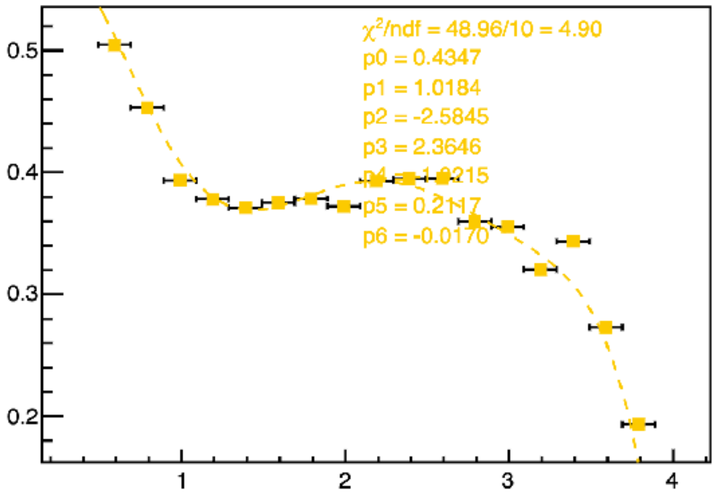


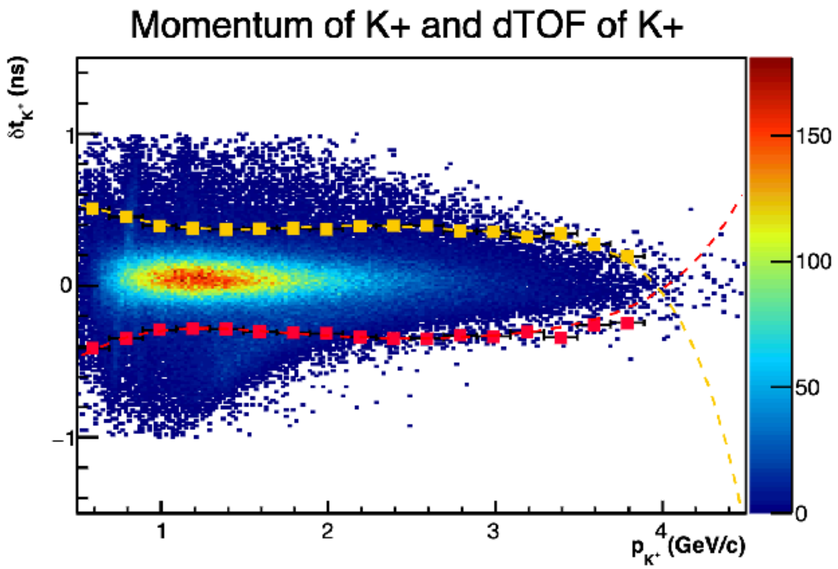




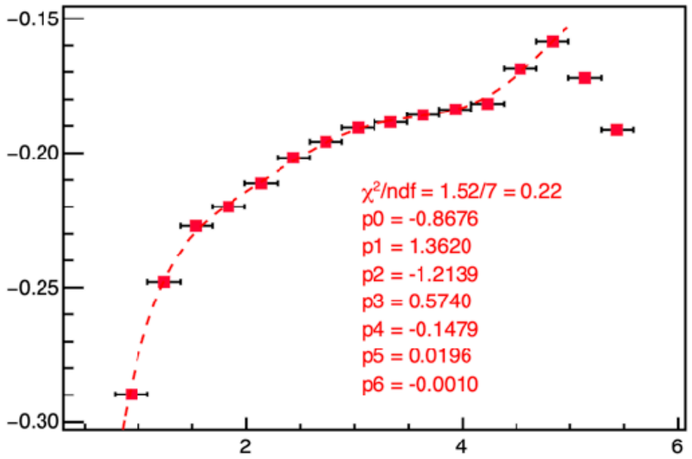
PID cut (data)

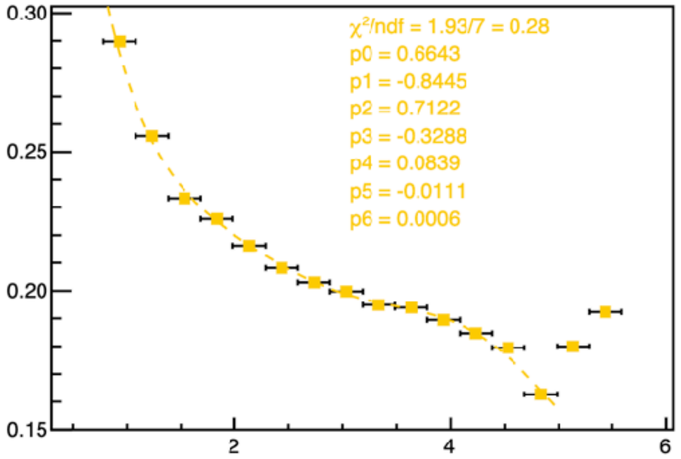

χ²/ndf = 31.10/10 = 3.11
p0 = -0.9716
p1 = 1.3928
p2 = -0.8669
p3 = 0.0828
p4 = 0.0934
p5 = -0.0326
p6 = 0.0033

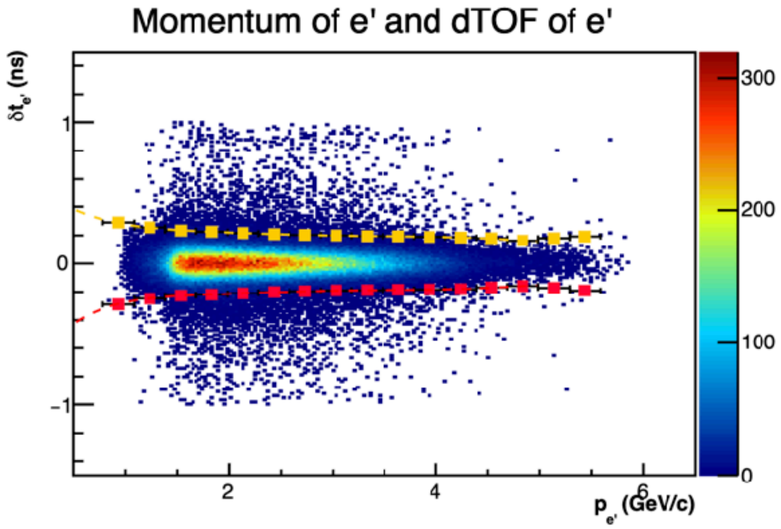

χ²/ndf = 48.96/10 = 4.90
p0 = 0.4347
p1 = 1.0184
p2 = -2.5845
p3 = 2.3646
p4 = -1.0215
p5 = 0.2117
p6 = -0.0170


Momentum of K+ and dTOF of K+
δt_K+ (ns)
p_K+ (GeV/c)

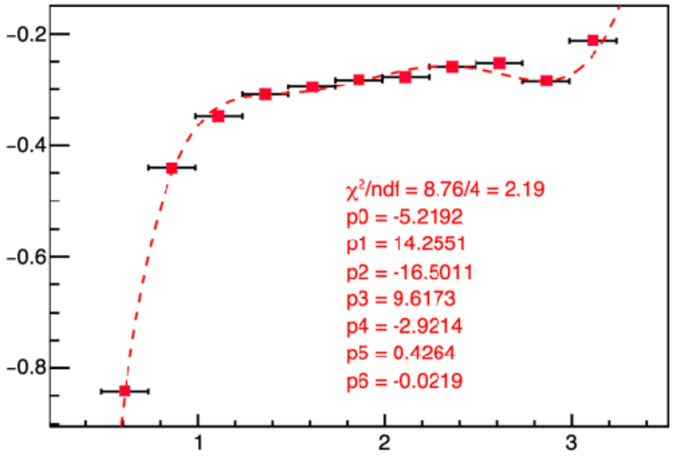
PID cut (data)

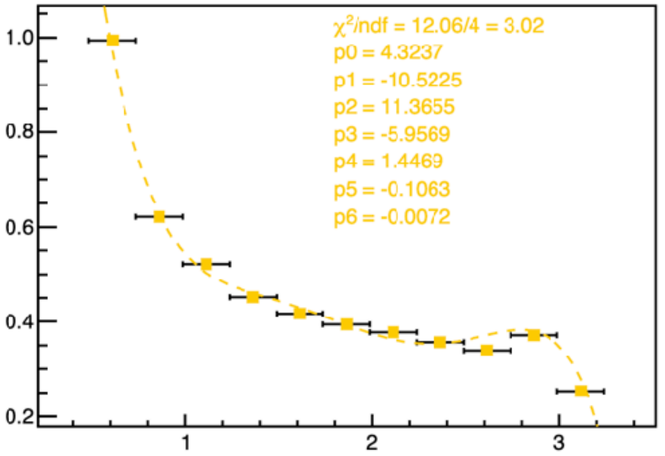

χ²/ndf = 1.52/7 = 0.22
p0 = -0.8676
p1 = 1.3620
p2 = -1.2139
p3 = 0.5740
p4 = -0.1479
p5 = 0.0196
p6 = -0.0010

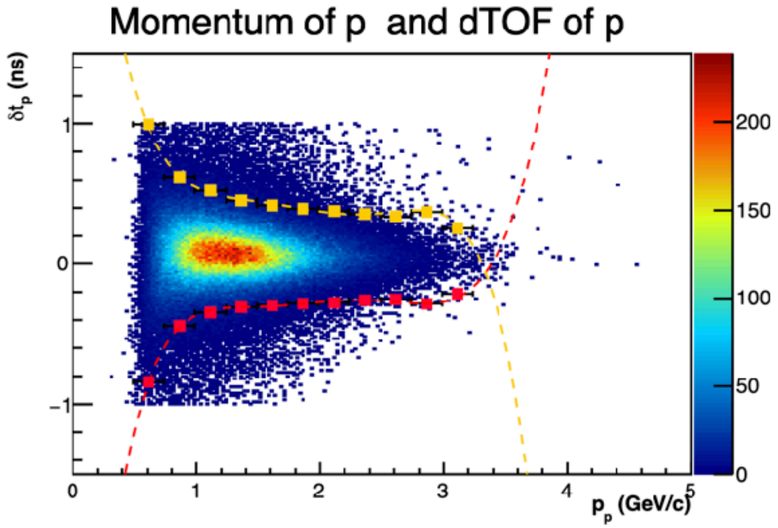

χ²/ndf = 1.93/7 = 0.28
p0 = 0.6643
p1 = -0.8445
p2 = 0.7122
p3 = -0.3288
p4 = 0.0839
p5 = -0.0111
p6 = 0.0006


Momentum of e' and dTOF of e'
δt_e' (ns)
p_e' (GeV/c)

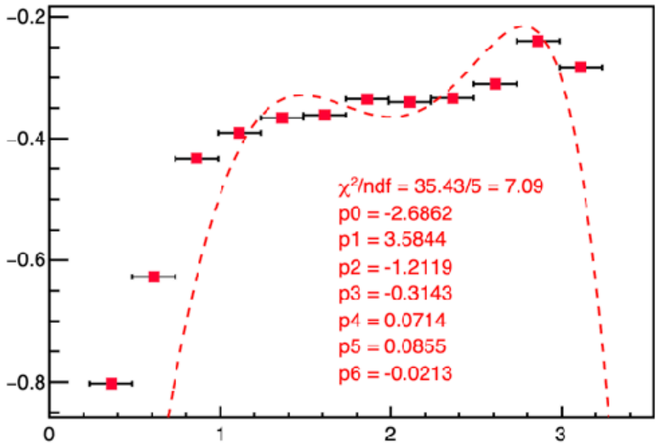
PID cut (data)

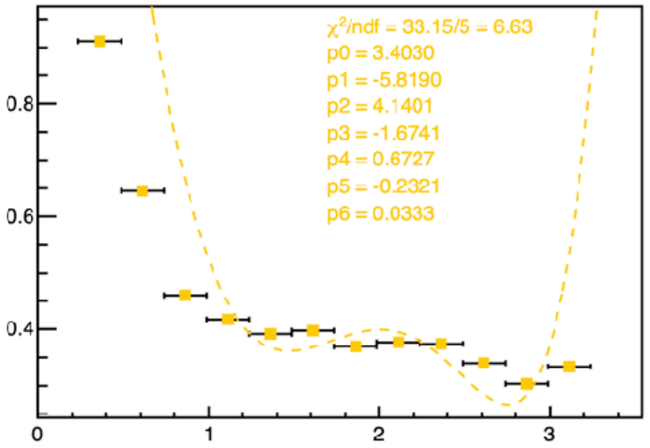

χ²/ndf = 8.76/4 = 2.19
p0 = -5.2192
p1 = 14.2551
p2 = -16.5011
p3 = 9.6173
p4 = -2.9214
p5 = 0.4264
p6 = -0.0219

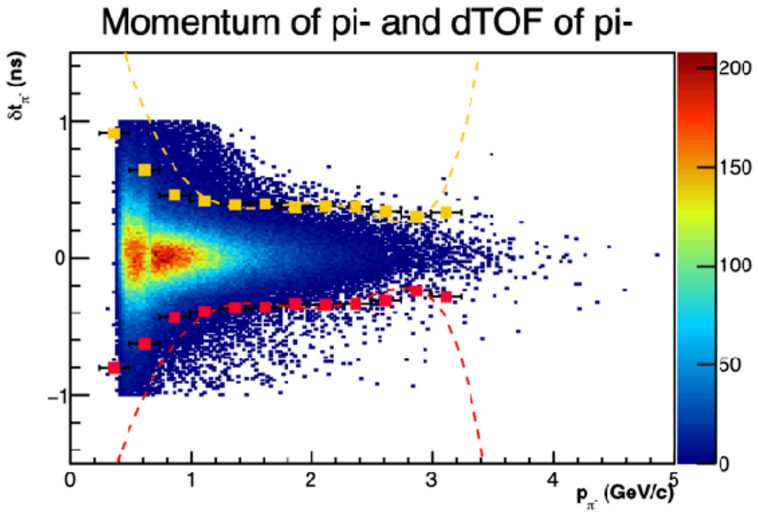

χ²/ndf = 12.06/4 = 3.02
p0 = 4.3237
p1 = -10.5225
p2 = 11.3655
p3 = -5.9569
p4 = 1.4469
p5 = -0.1063
p6 = -0.0072


Momentum of p and dTOF of p
δt_p (ns)
p_p (GeV/c)

PID cut (data)


χ^2/ndf = 35.43/5 = 7.09
p0 = -2.6862
p1 = 3.5844
p2 = -1.2119
p3 = -0.3143
p4 = 0.0714
p5 = 0.0855
p6 = -0.0213


χ^2/ndf = 33.15/5 = 6.63
p0 = 3.4030
p1 = -5.8190
p2 = 4.1401
p3 = -1.6741
p4 = 0.6727
p5 = -0.2321
p6 = 0.0333


Momentum of pi- and dTOF of pi-
δt_{π^-} (ns)
p_{π^-} (GeV/c)

Survival ratio

```
------------------------------------------------------------------
| Step                                  | Event Count|  Percent |
------------------------------------------------------------------
| Total events processed                |     5000000| 100.0000 |
| After final state selection           |       43571|   0.8714 |
| After Z-vertex cut                    |       39555|  90.7829 |
| After PID cut                         |       35003|  88.4920 |
| After Missing Particle cut            |       19855|  56.7237 |
| After Sigma cut                       |       19749|  99.4661 |
------------------------------------------------------------------
```

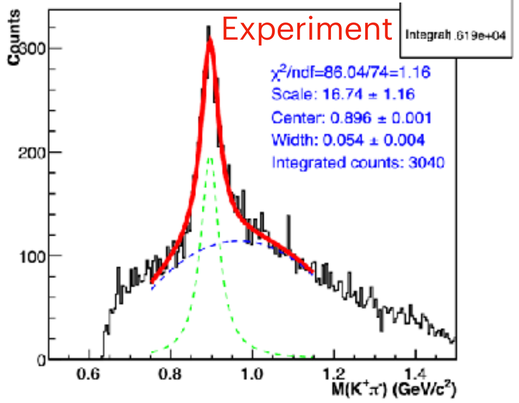
Survival ratio using Λ(1405) simulated data

Selection Step	Event Count	Efficiency	Survival ratio
No cut	5.00 M	-	1.0
Final state	43.6 k	0.008	0.0087
Z-vertex	39.6 k	0.90	0.0079
PID	35.0 k	0.88	0.007
Missing particle	19.9 k	0.57	0.004
Σ	19.7 k	0.99	0.0039

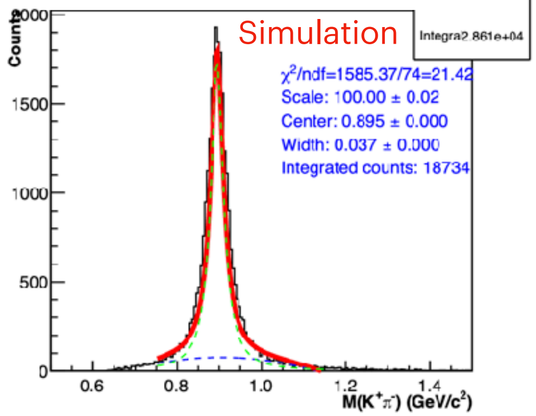
Resonant Backgrounds

K^{*0} events

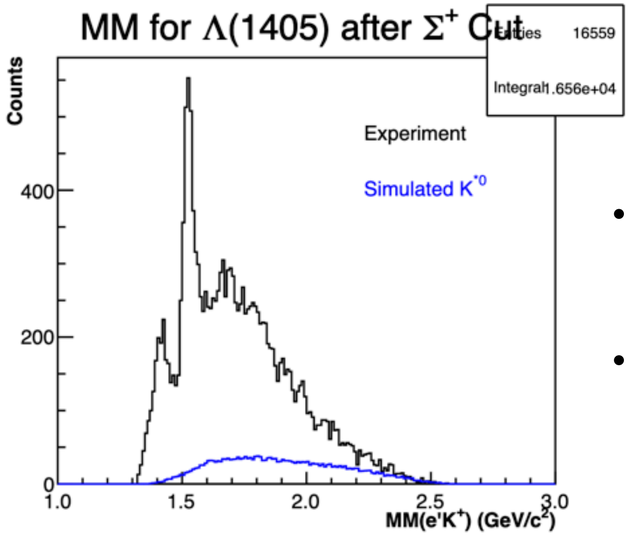
Invariant mass of K^{*0}



Invariant mass of K^{*0}



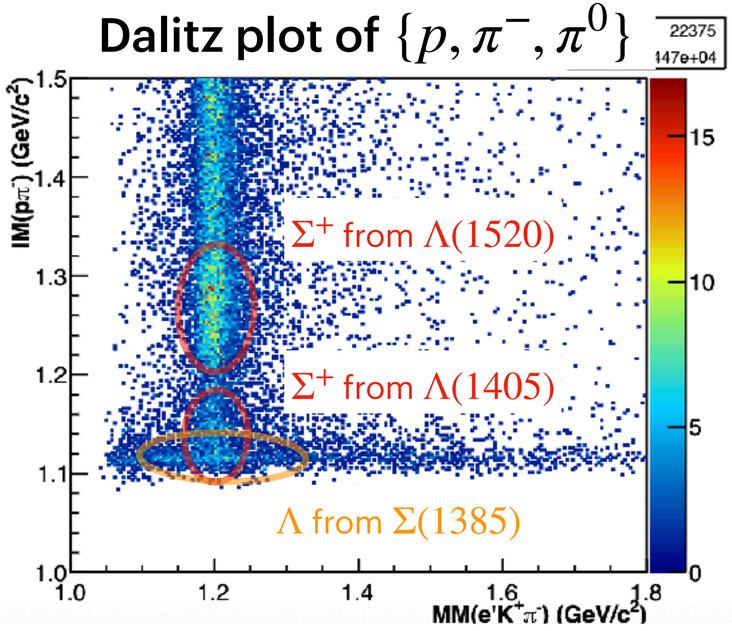
MM for Λ(1405) after Σ^+ Cut



- Derive K^{*0} count ratio of exp./sim.
- Scaling simulated background by the ratio

$\Sigma(1385)$ events

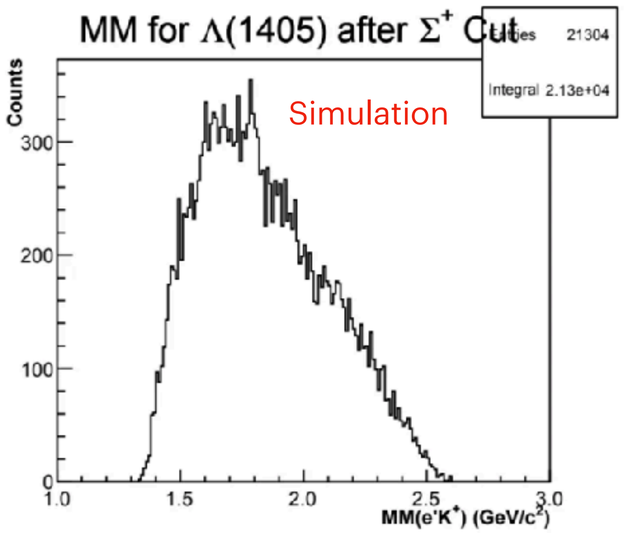
Dalitz plot of $\{p, \pi^-, \pi^0\}$

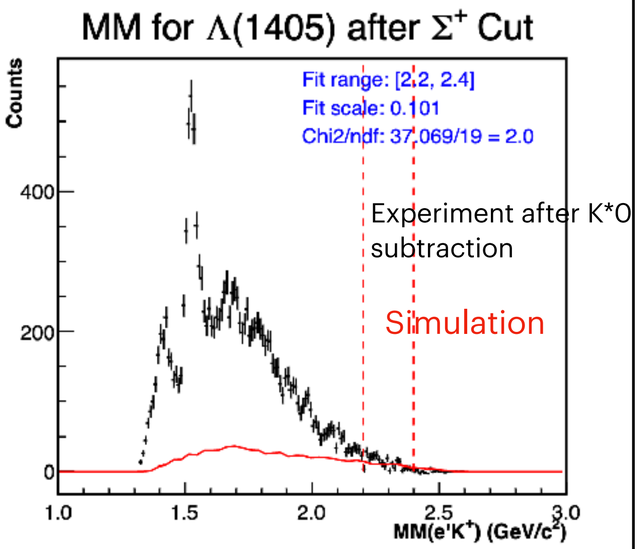


- Λ band and Σ+ band can be seen
- Events of Λ(1405) and Σ(1385) overlaying
- → Difficult to separate them by using only cuts
- Simulation estimation is needed

Other backgrounds

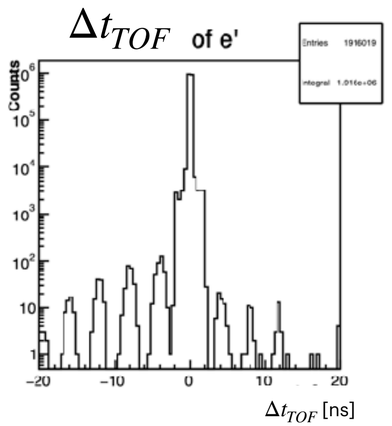
Non-resonant events

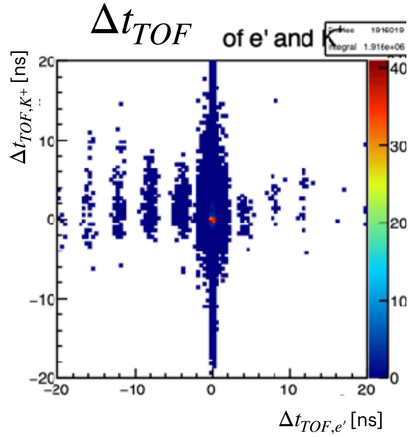


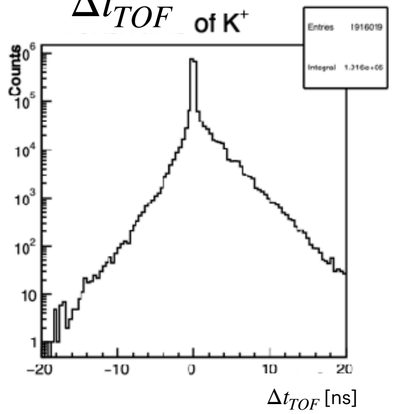


- Simulate non-resonant events
- Subtract K*0 events in advance
- Fitting to adjust higher-mass tail ([2.2, 2.4] GeV) with simulated shape

Accidental events

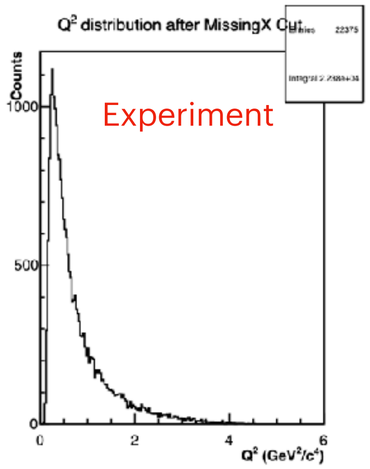


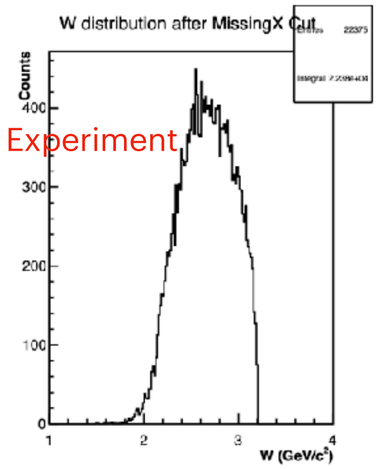


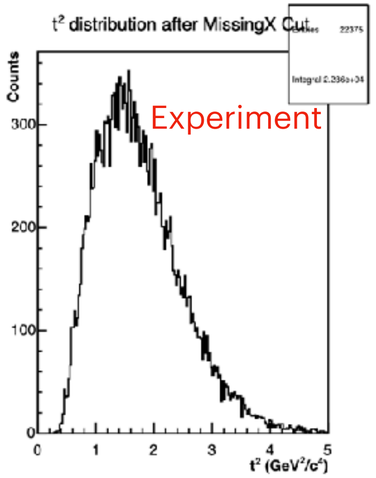


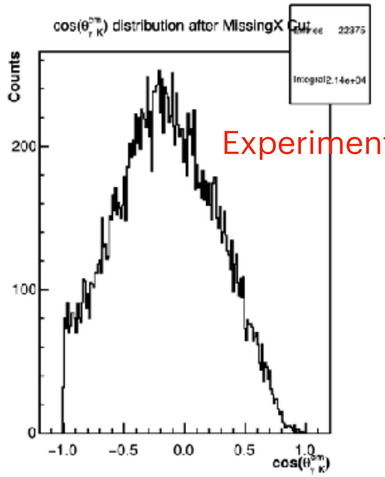
- $\Delta t_{TOF} = t_{time} - t_{mom.} = (t_{\mathrm{hit}} - t_{\mathrm{vertex}}) - \dfrac{d}{c\beta_{mom.}}$
- →True events are centered around 0 ns
- ΔTOF correlation between e' and K^+
  - ✦ Another bunch clusters can be seen
  - ✦ (Acc. coin. events) / (true coin. events) ~ 10^{-3} → The accidental events are negligible

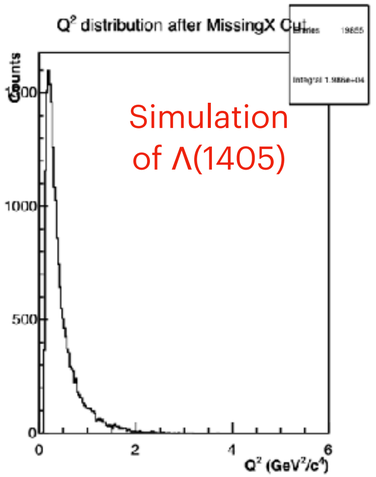
Reproducibility of Simulation

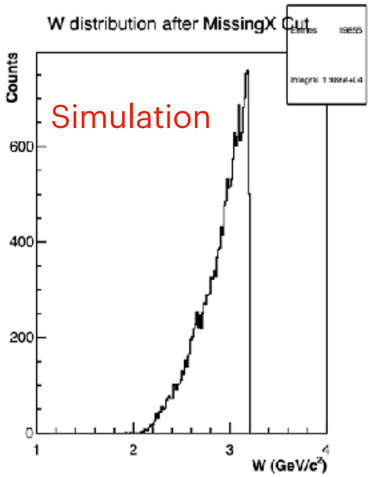


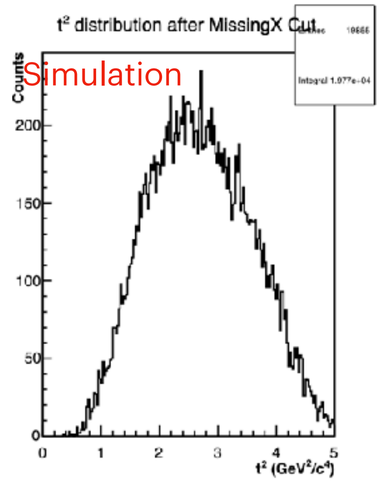


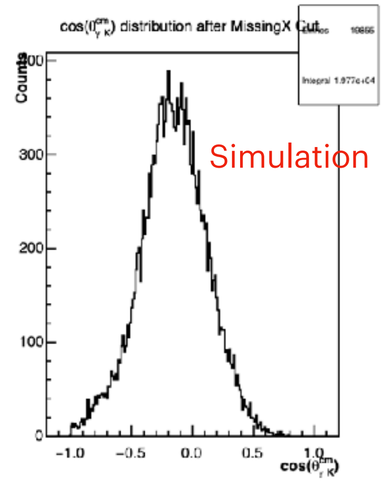












- Generator: clas12-elSpectro
- GEMC & COATJAVA: latest version

- Compare kinematics of experiment and Λ(1405) simulation
- Simulated kinematics doesn’t match well
- →Effect on background shape of non-resonant events
- Need to adjust it