# Photoproduction of Λ* Resonances using the CLAS detector

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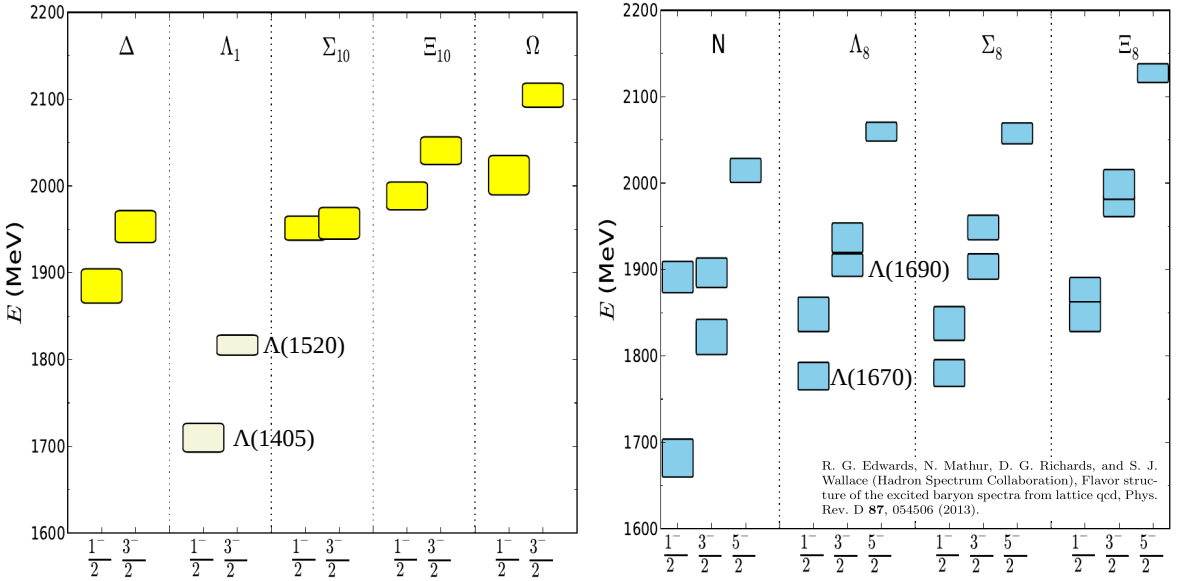
# Introduction

## The Quark Model

| $J^P$ | $(D, L_N^P)\,S$ | Octet members | | | Singlets |
|---|---|---|---|---|---|
| $1/2^+$ | $(56,0_0^+)\ 1/2\ N(939)$ | $\Lambda(1116)$ | $\Sigma(1193)$ | $\Xi(1318)$ | |
| $1/2^+$ | $(56,0_2^+)\ 1/2\ N(1440)$ | $\Lambda(1600)$ | $\Sigma(1660)$ | $\Xi(1690)^\dagger$ | |
| $1/2^-$ | $(70,1_1^-)\ 1/2\ N(1535)$ | $\boxed{\Lambda(1670)}$ | $\Sigma(1620)$ | $\Xi(?)$ | $\boxed{\Lambda(1405)}$ |
| | | | $\Sigma(1560)^\dagger$ | | |
| $3/2^-$ | $(70,1_1^-)\ 1/2\ N(1520)$ | $\boxed{\Lambda(1690)}$ | $\Sigma(1670)$ | $\Xi(1820)$ | $\boxed{\Lambda(1520)}$ |
| $1/2^-$ | $(70,1_1^-)\ 3/2\ N(1650)$ | $\Lambda(1800)$ | $\Sigma(1750)$ | $\Xi(?)$ | |
| | | | $\Sigma(1620)^\dagger$ | | |
| $3/2^-$ | $(70,1_1^-)\ 3/2\ N(1700)$ | $\Lambda(?)$ | $\Sigma(1940)^\dagger$ | $\Xi(?)$ | |
| $5/2^-$ | $(70,1_1^-)\ 3/2\ N(1675)$ | $\Lambda(1830)$ | $\Sigma(1775)$ | $\Xi(1950)^\dagger$ | |
| $1/2^+$ | $(70,0_2^+)\ 1/2\ N(1710)$ | $\Lambda(1810)$ | $\Sigma(1880)$ | $\Xi(?)$ | $\Lambda(1810)^\dagger$ |
| $3/2^+$ | $(56,2_2^+)\ 1/2\ N(1720)$ | $\Lambda(1890)$ | $\Sigma(?)$ | $\Xi(?)$ | |
| $5/2^+$ | $(56,2_2^+)\ 1/2\ N(1680)$ | $\Lambda(1820)$ | $\Sigma(1915)$ | $\Xi(2030)$ | |
| $7/2^-$ | $(70,3_3^-)\ 1/2\ N(2190)$ | $\Lambda(?)$ | $\Sigma(?)$ | $\Xi(?)$ | $\Lambda(2100)$ |
| $9/2^-$ | $(70,3_3^-)\ 3/2\ N(2250)$ | $\Lambda(?)$ | $\Sigma(?)$ | $\Xi(?)$ | |
| $9/2^+$ | $(56,4_4^+)\ 1/2\ N(2220)$ | $\Lambda(2350)$ | $\Sigma(?)$ | $\Xi(?)$ | |

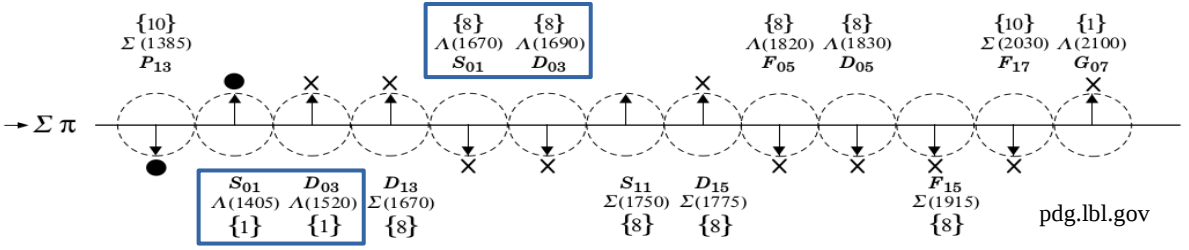
## Lattice QCD Calculations



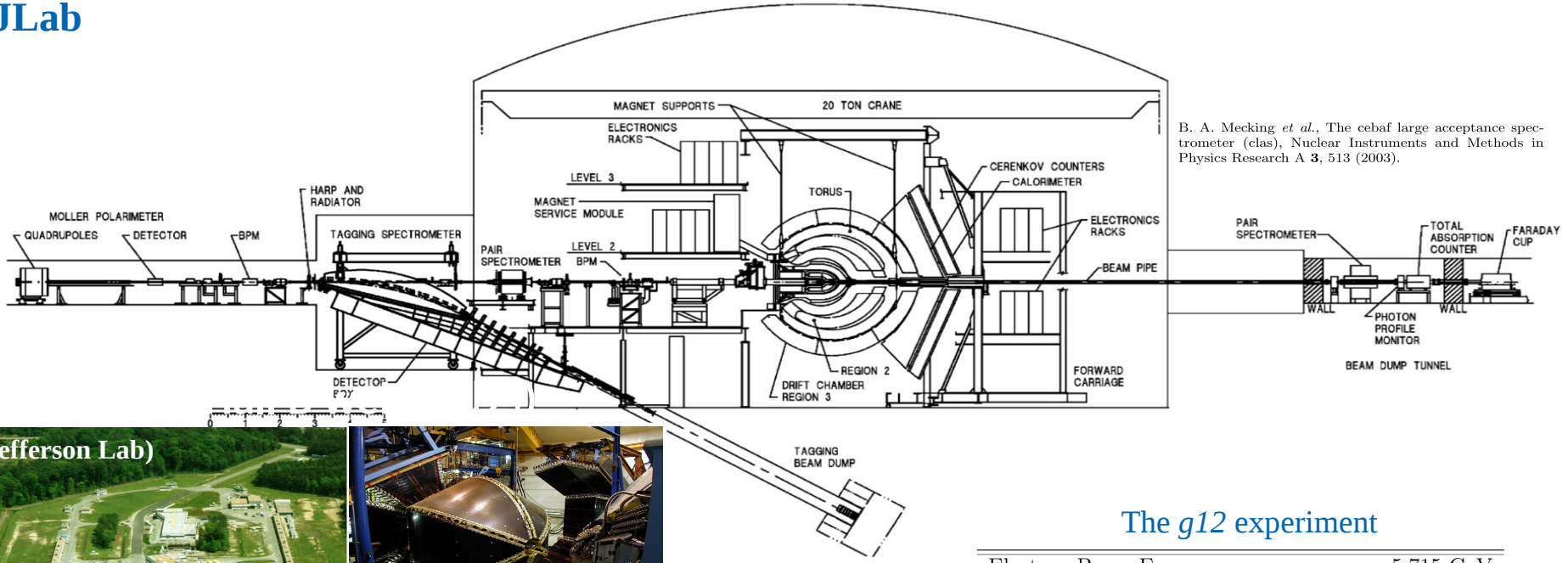

## The Particle Data Group Summary

| Particle | $J^P$ | PDG rating | Status as seen in $N\bar{K}$ | $\Lambda\pi$ | $\Sigma\pi$ | Other Channels |
|---|---|---|---|---|---|---|
| $\Lambda(1405)$ | 1/2- | **** | **** | | **** | |
| $\Lambda(1520)$ | 3/2- | **** | **** | Forbidden | **** | $\Lambda\pi\pi$, $\Lambda\gamma$ |
| $\Lambda(1670)$ | 1/2- | **** | **** | | **** | $\Lambda\eta$ |
| $\Lambda(1690)$ | 3/2- | **** | **** | | **** | $\Lambda\pi\pi$, $\Sigma\pi\pi$ |

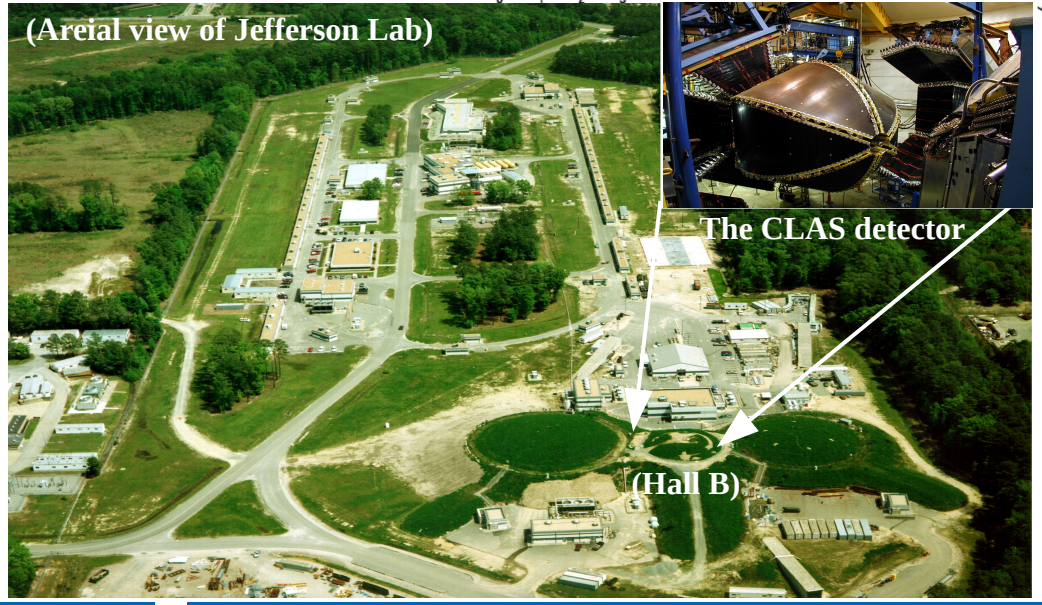
## Phase at Resonances in Σπ Channel



# CLAS @ JLab



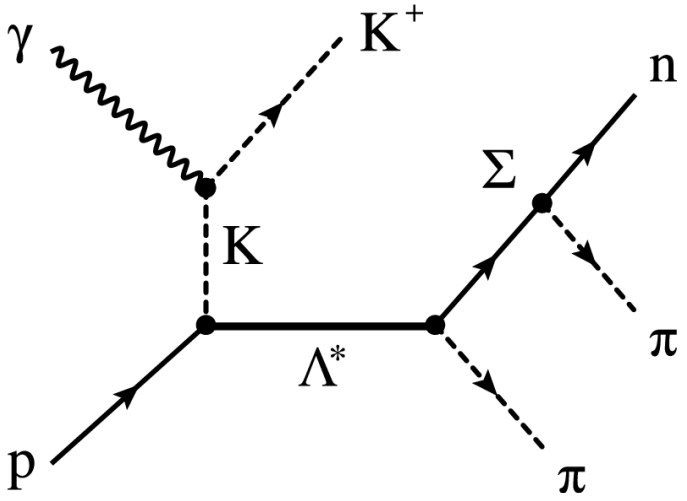

B. A. Mecking *et al.*, The cebaf large acceptance spectrometer (clas), Nuclear Instruments and Methods in Physics Research A **3**, 513 (2003).

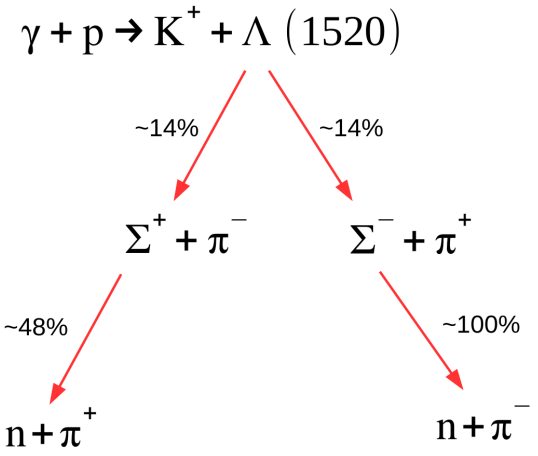



## The *g12* experiment

| | |
|---|---|
| Electron Beam Energy | 5.715 GeV |
| Beam Polarization | Circular |
| $e^-$ Current | 60–65 nA |
| Tagger Range | 20% - 95% of $e^-$ energy |
| Tagger Trigger Range | 3.6 - 5.441 GeV |
| Torus Magnet | $\frac{1}{2}B_{max}(1930A)$ |
| Target Length | 40 cm |
| Target Center (z location) | -90 cm |
| Target Material | $LH_2$ |
| Target Polarization | None |
| Start Counter Offset | 0 cm |
| Radiator Thickness | $10^{-4}$ radiation lengths |
| Collimator Radius | 6.4 mm |

# The Reaction

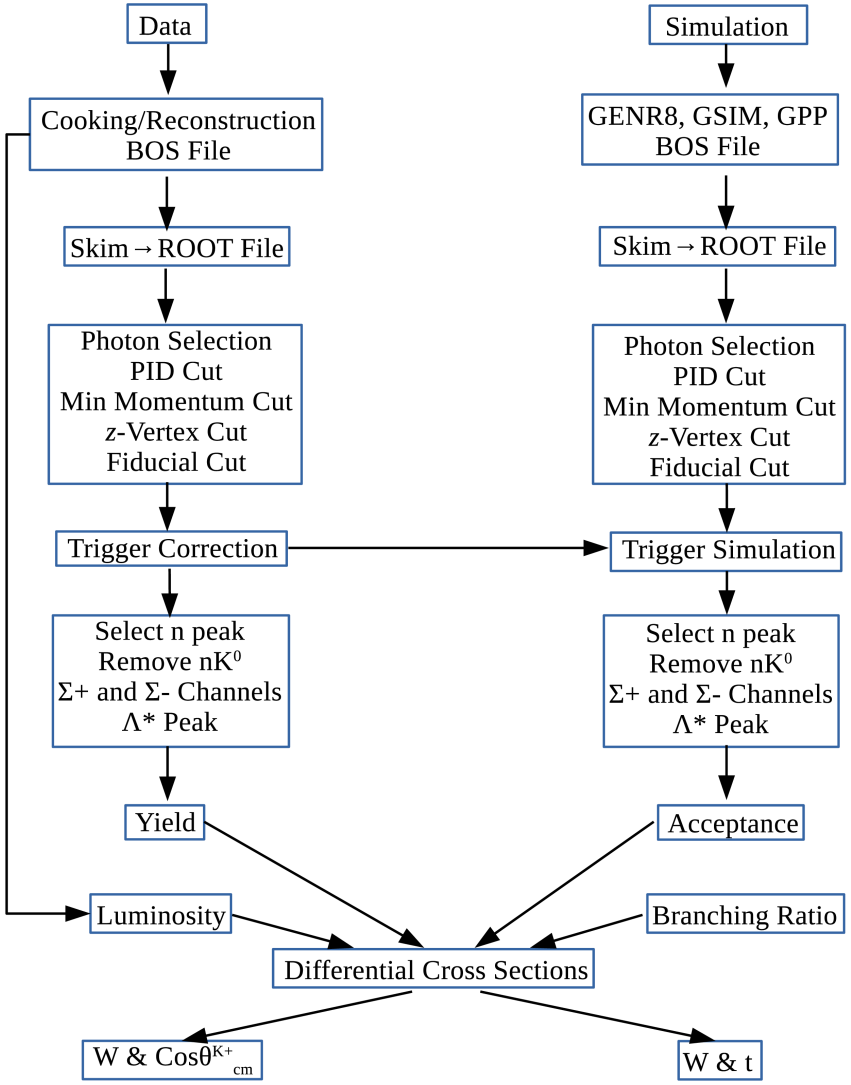


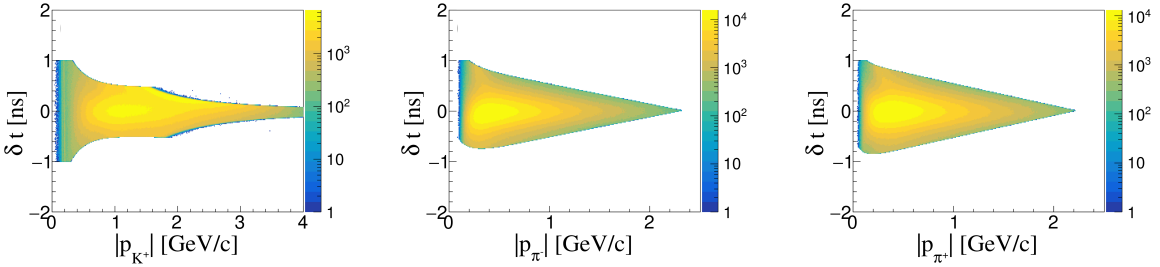

$$\gamma p \rightarrow K^+\Lambda(1520) \rightarrow K^+\Sigma^\pm\pi^\mp$$

$$\Lambda(1520) \rightarrow \Sigma^\pm\pi^\mp \rightarrow n\pi^\pm\pi^\mp$$

# Data Analysis

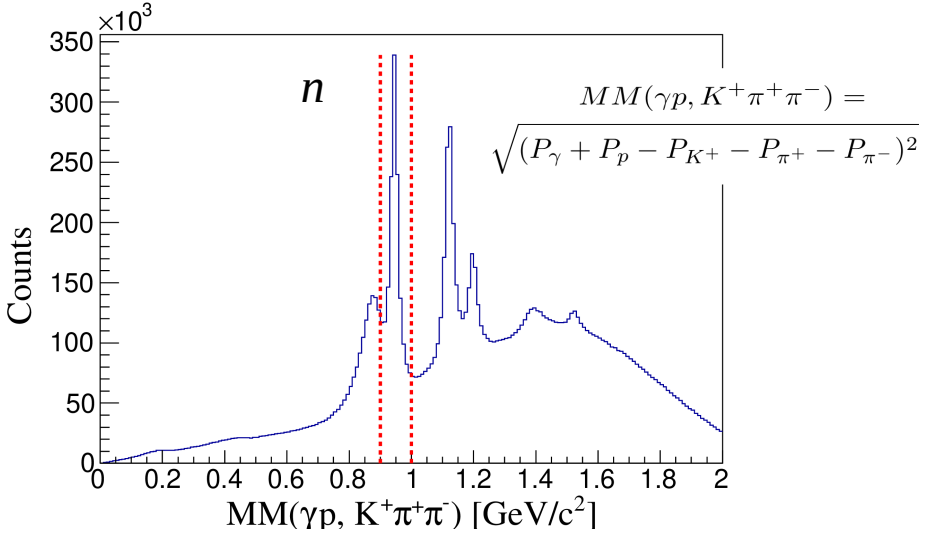


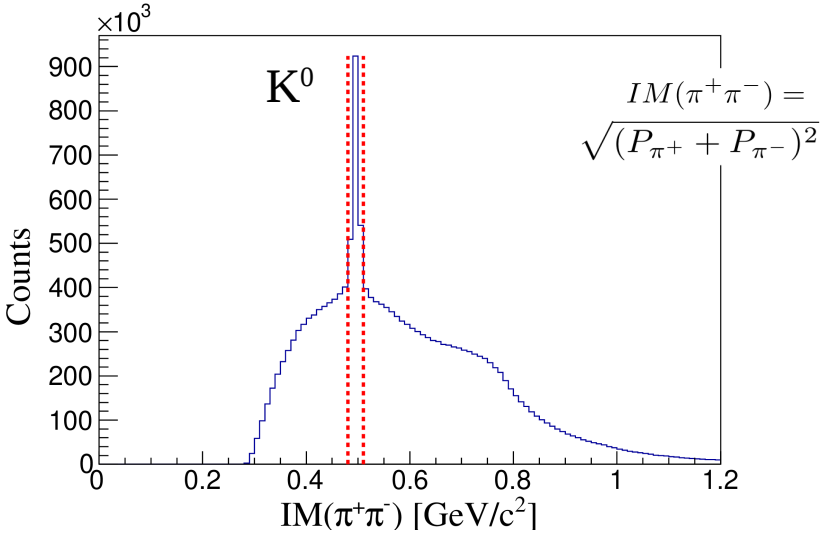

$$\delta t = t_{meas} - t_{calc} = t_{meas} - \frac{d_{path}}{c}\frac{E}{p} = \frac{d_{path}}{c}\left(\frac{1}{\beta_{meas}} - \frac{1}{\beta_{calc}}\right)$$

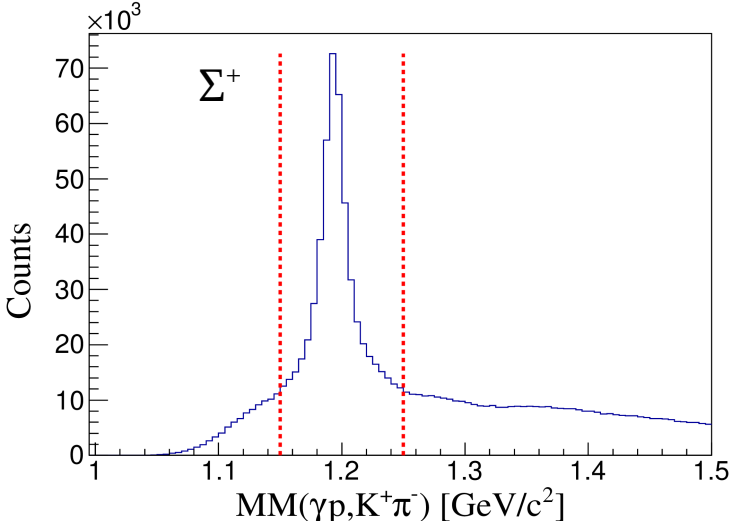


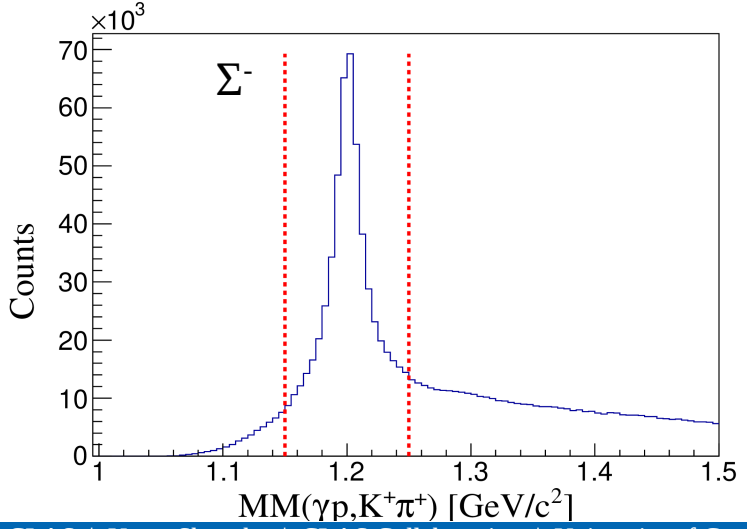

| | |
|---|---|
| $0.9 \leq MM(K^+\pi\pi) \leq 1.0$ | Select neutron events |
| $0.48 \leq IM(\pi^+\pi^-) \leq 0.51$ | Remove $nK^0$ channel |
| $1.15 \leq MM(K^+\pi^-) \leq 1.25$<br>$1.15 \leq MM(K^+\pi^+) \leq 1.25$ | Select $\Sigma^+$ and $\Sigma^-$ events for exclusive $\Sigma\pi$ channels |
| $1.44 \leq MM(K^+) \leq 1.6$ | Fitting Range $\Lambda(1520)$ |
| $2.25 \leq W \leq 3.25$ GeV<br>$-0.9 \leq cos\theta^{K+}_{cm} \leq 0.9$<br>$-2.7 \leq t \leq -0.3$ | Binning Scheme |

# Data Analysis

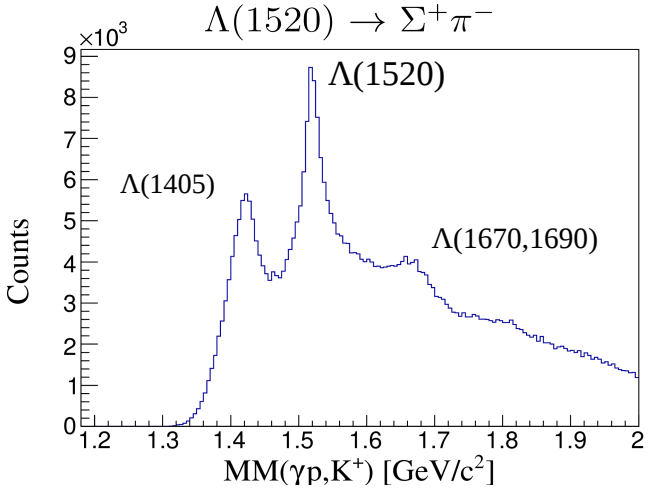


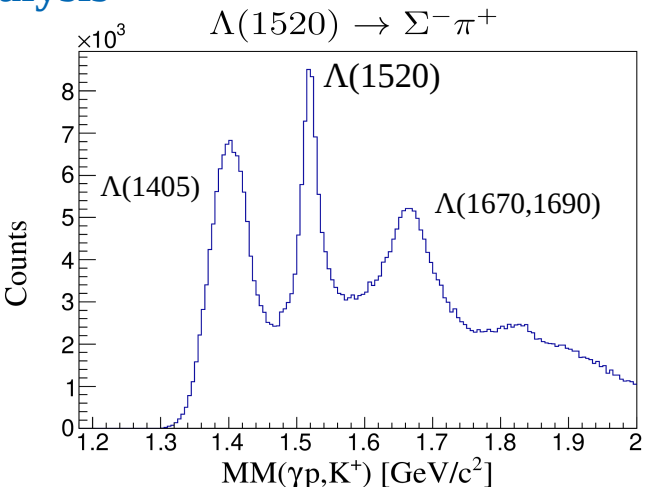



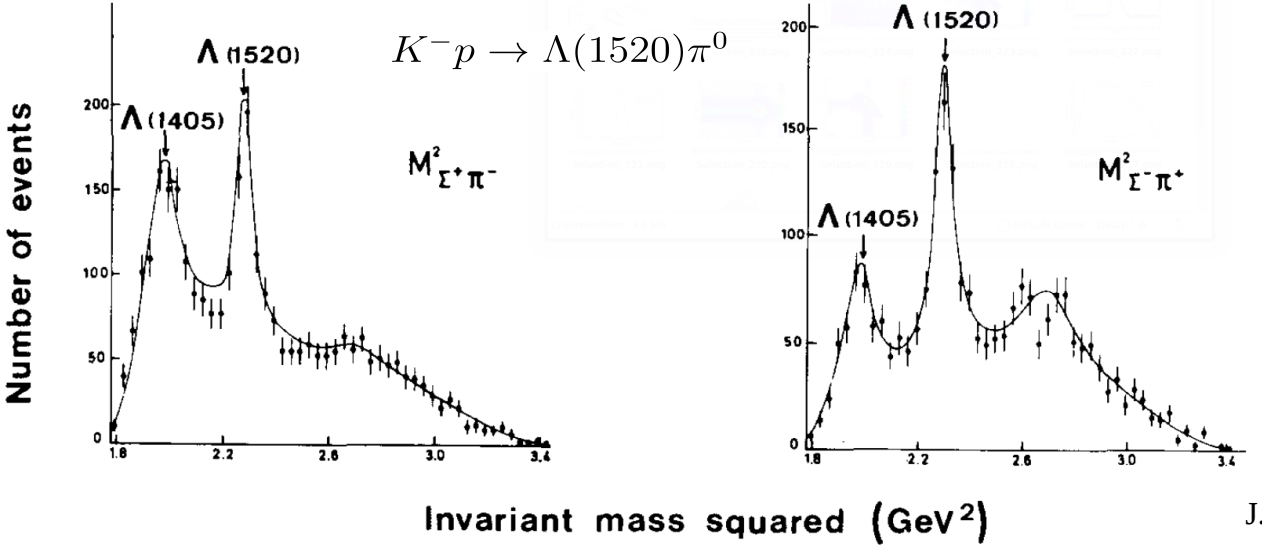



# Data Analysis

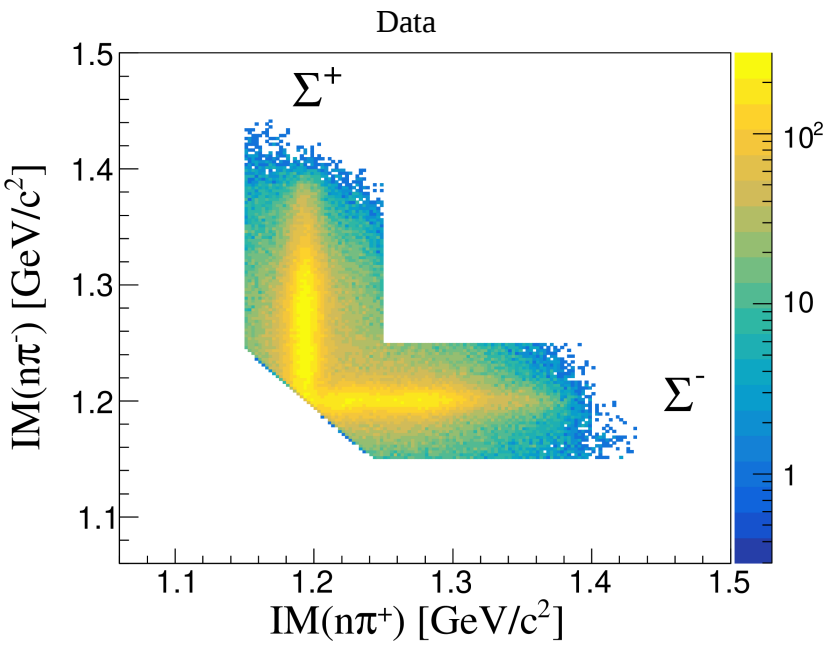


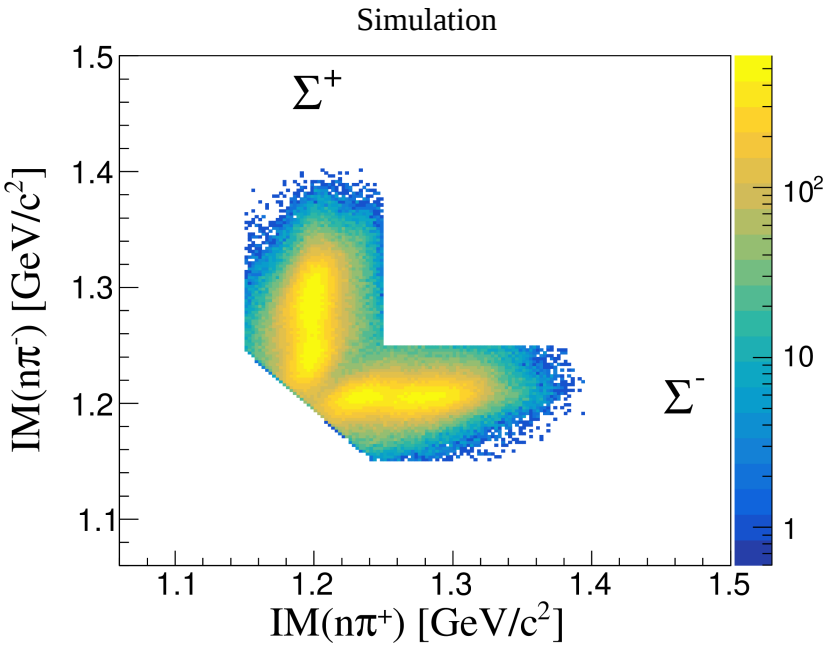




J. Griselin *et. al.*, 1975

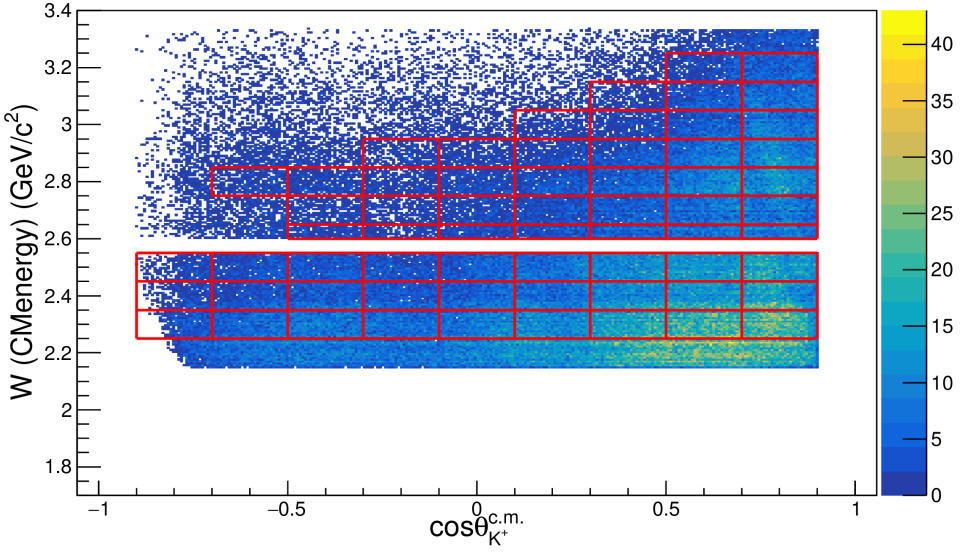
# Data Analysis



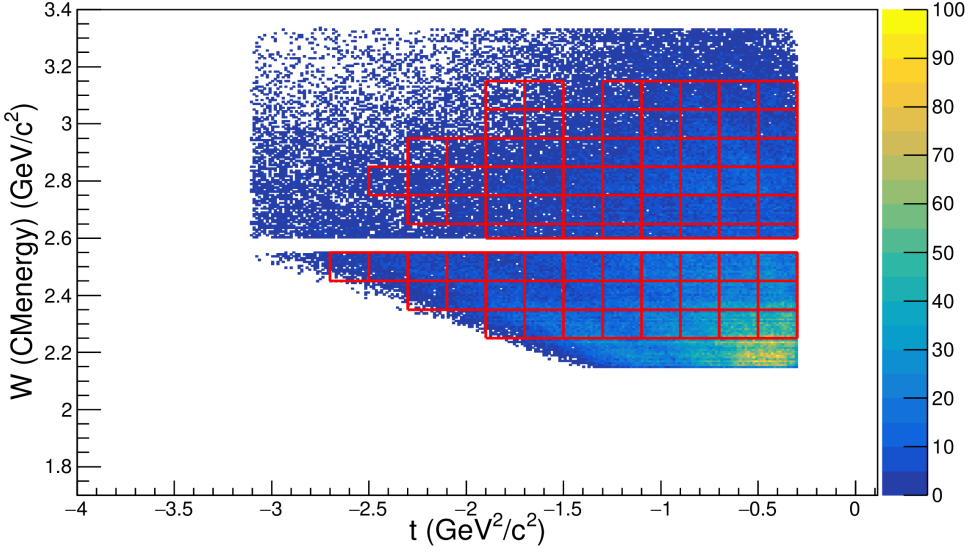



# Data Analysis

Binning Scheme in $W$ & $cos\theta^{cm}_{K+}$




Binning Scheme in $W$ & $t$

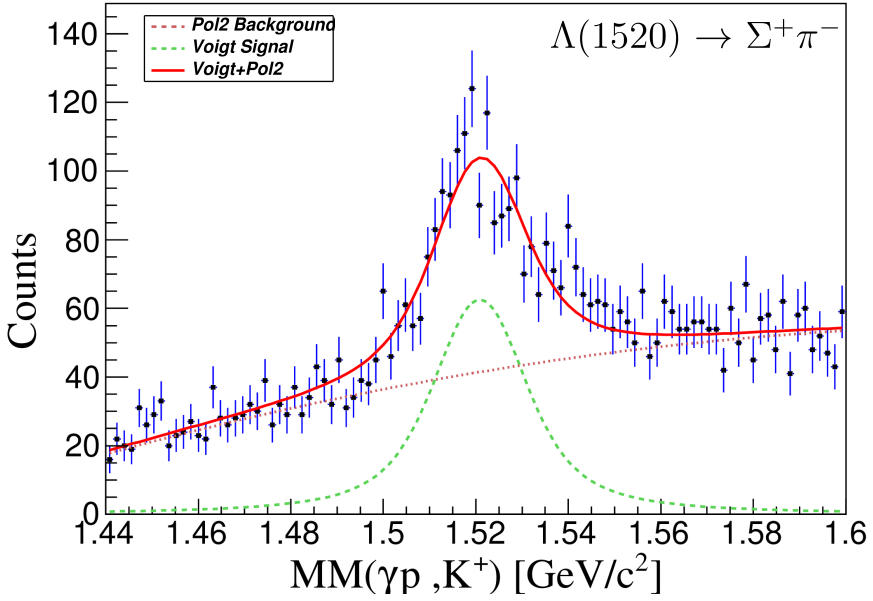


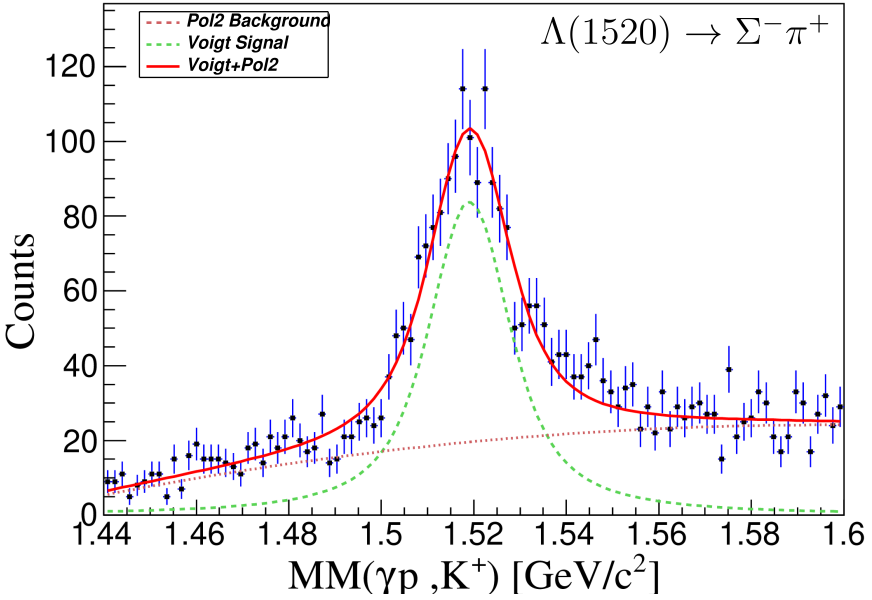
# Data Analysis

$$V(x-\mu,\sigma_G,\sigma_L) = G(x,\sigma_G) \otimes L(x,\sigma_L)$$

$$G(x,\sigma_G) = \frac{1}{\sqrt{2\pi}\sigma_G} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \qquad L(x,\sigma_L) = \frac{1}{\pi}\frac{\sigma_L/2}{(x-\mu)^2+(\sigma_L/2)^2}$$

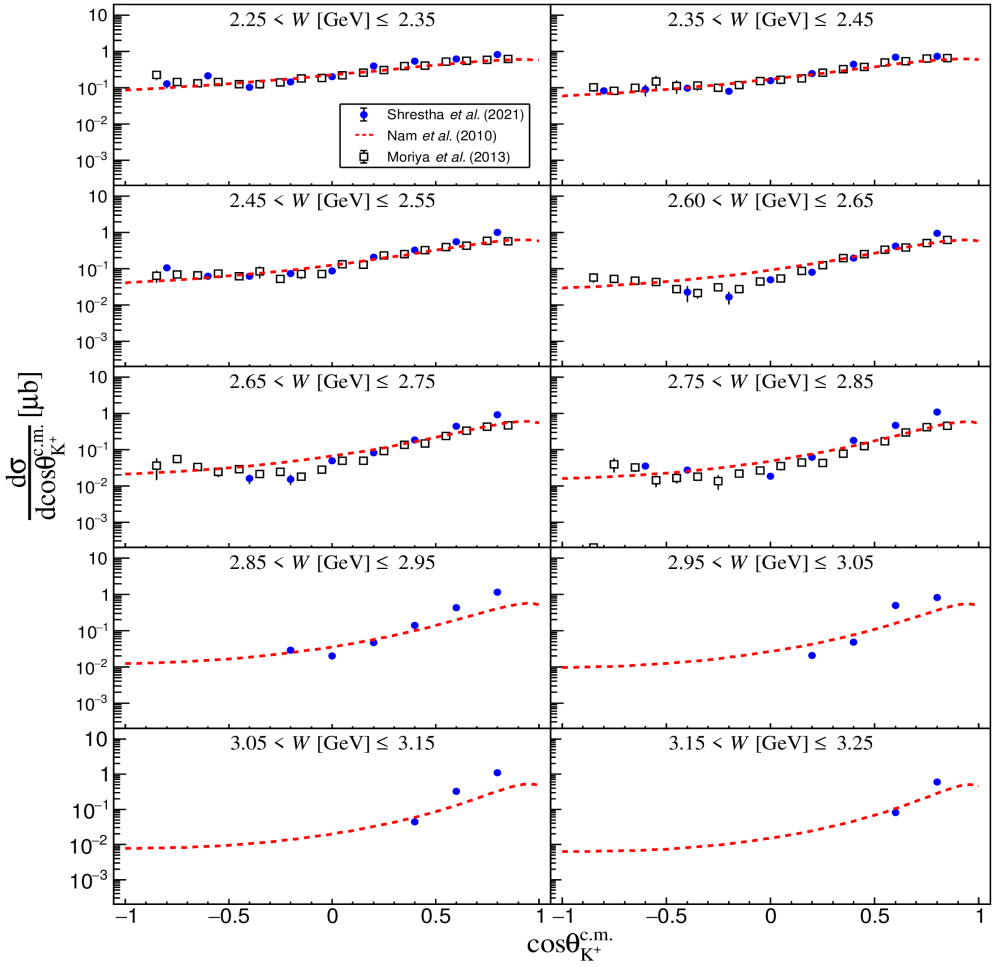
$$\sigma_L = \Gamma_{\Lambda(1520)} = 15.6 \text{ MeV}$$



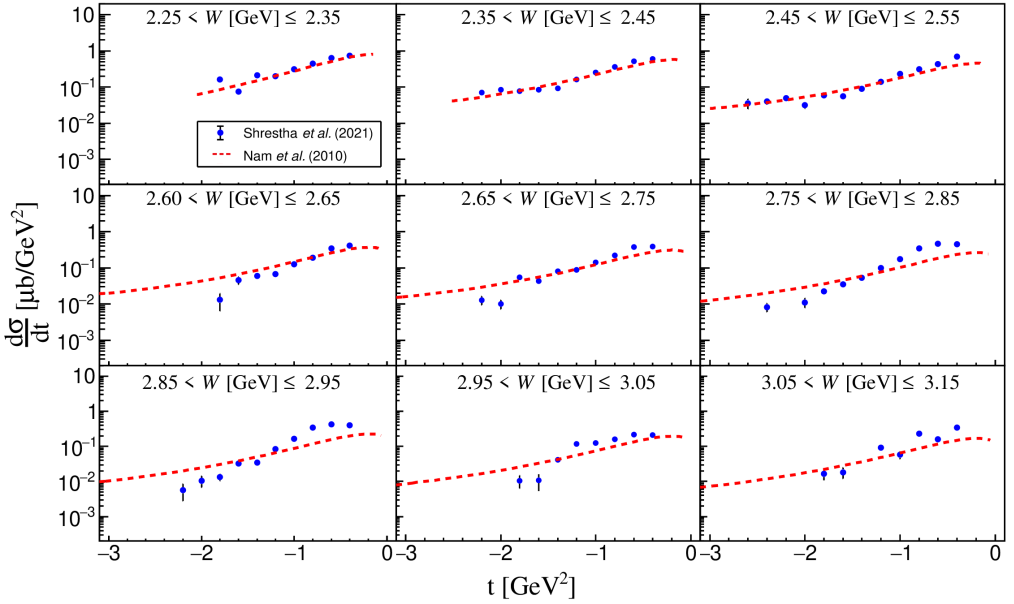



# Differential Cross-sections

$$\frac{d\sigma}{d\cos\theta^{c.m.}_{K^+}} = \frac{Y(W, \cos\theta^{c.m.}_{K^+})}{\tau\Delta\cos\theta^{c.m.}_{K^+} A(W, \cos\theta^{c.m.}_{K^+}) L(W)}$$



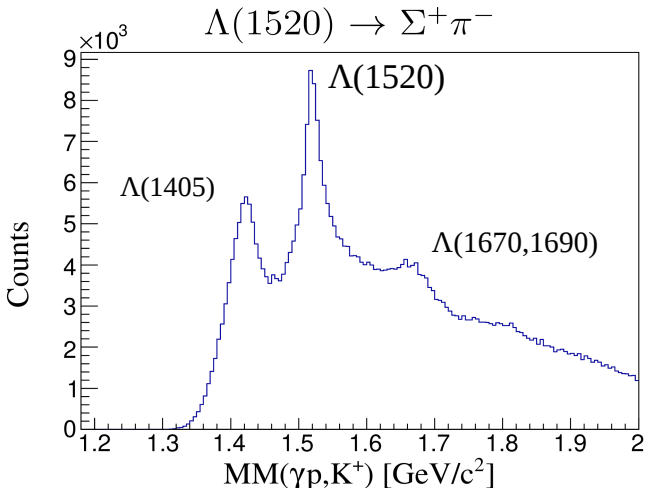

$$\frac{d\sigma}{dt} = \frac{Y(W, t)}{\tau\Delta t A(W, t) L(W)}$$

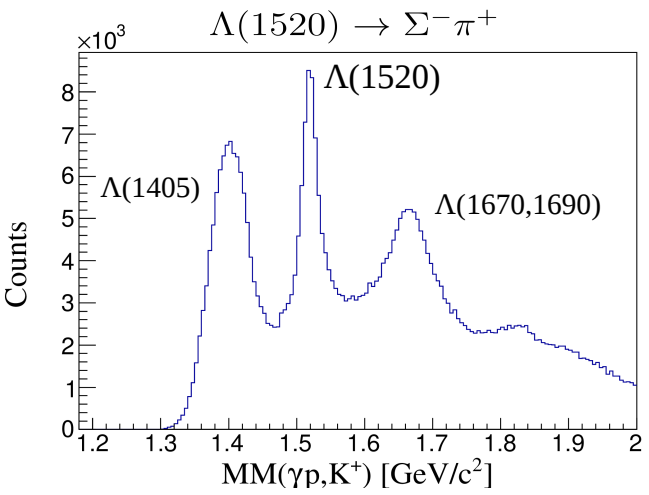



| Source | Uncertainty |
|---|---|
| *t*-slope dependence | 0.78% |
| Timing Cut | 4.11% |
| Minimum $\lvert p \rvert$ cut | 0.20% |
| *z*-Vertex Cut | 1.28% |
| Fiducial Cut | 3.13% |
| Background Function | 2.07% |
| Signal Integration Range | 0.43% |
| Flux Consistency/Luminosity | 5.70% |
| Sector by Sector | 5.90% |
| Target | 0.50% |
| **Total Systematic Uncertainty** | 10.05% |

# Λ(1670) & Λ(1690)

| Particle | $J^P$ | PDG rating | Status as seen in | | | |
|---|---|---|---|---|---|---|
| | | | $N\overline{K}$ | $\Lambda\pi$ | $\Sigma\pi$ | Other Channels |
| Λ(1405) | 1/2- | **** | **** | Forbidden | **** | |
| Λ(1520) | 3/2- | **** | **** | | **** | $\Lambda\pi\pi$, $\Lambda\gamma$ |
| Λ(1670) | 1/2- | **** | **** | | **** | $\Lambda\eta$ |
| Λ(1690) | 3/2- | **** | **** | | **** | $\Lambda\pi\pi$, $\Sigma\pi\pi$ |



# Interference: Σ(1670) & Λ(1670)

$\Lambda^* \rightarrow \Sigma^+\pi^-$ or $\Sigma^-\pi^+$

$\langle 0\ 0 \mid 1\ +1\ 1\ -1 \rangle = 1/\sqrt{3}$ **+**

$\langle 0\ 0 \mid 1\ -1\ 1\ +1 \rangle = 1/\sqrt{3}$ **+**

**Σ(1670) 3/2⁻** $I(J^P) = 1(\frac{3}{2}^-)$

Mass $m$ = 1665 to 1685 (≈ 1670) MeV
Full width Γ = 40 to 80 (≈ 60) MeV

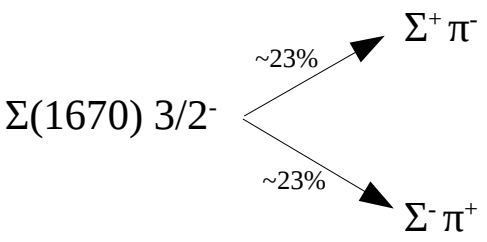
Σ coupling to the decay of $\Sigma^+\pi^-$ & $\Sigma^-\pi^+$

$\Sigma \rightarrow \Sigma^+\pi^-$ or $\Sigma^-\pi^+$

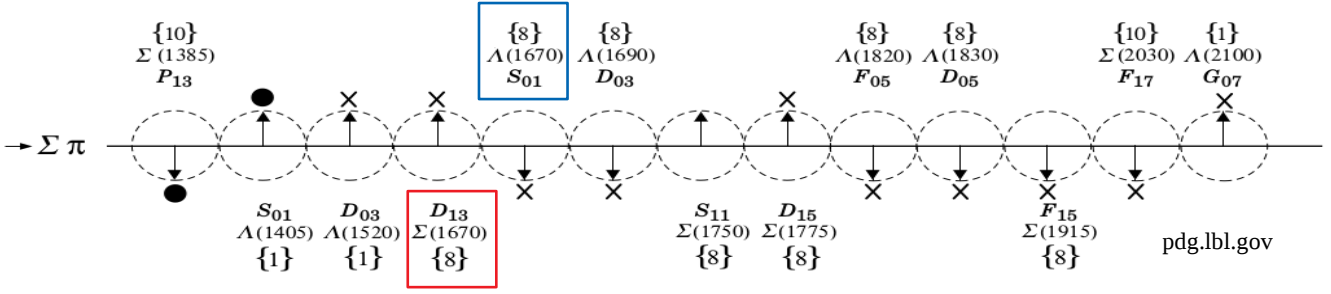
$\langle 1\ 0 \mid 1\ +1\ 1\ -1 \rangle = 1/\sqrt{2}$ **+**

$\langle 1\ 0 \mid 1\ -1\ 1\ +1 \rangle = -1/\sqrt{2}$ **-**

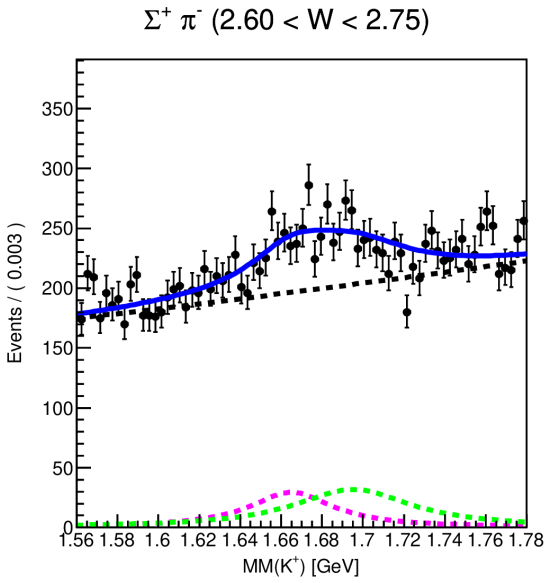
| **Σ(1670) DECAY MODES** | Fraction $(\Gamma_i/\Gamma)$ | $p$ (MeV/$c$) |
|---|---|---|
| $N\overline{K}$ | 7–13 % | 414 |
| $\Lambda\pi$ | 5–15 % | 448 |
| $\Sigma\pi$ | 30–60 % | 394 |

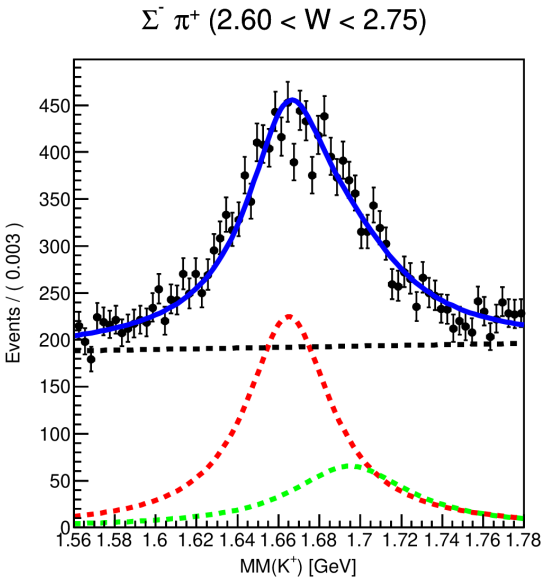



Phase at Resonances in Σπ Channel



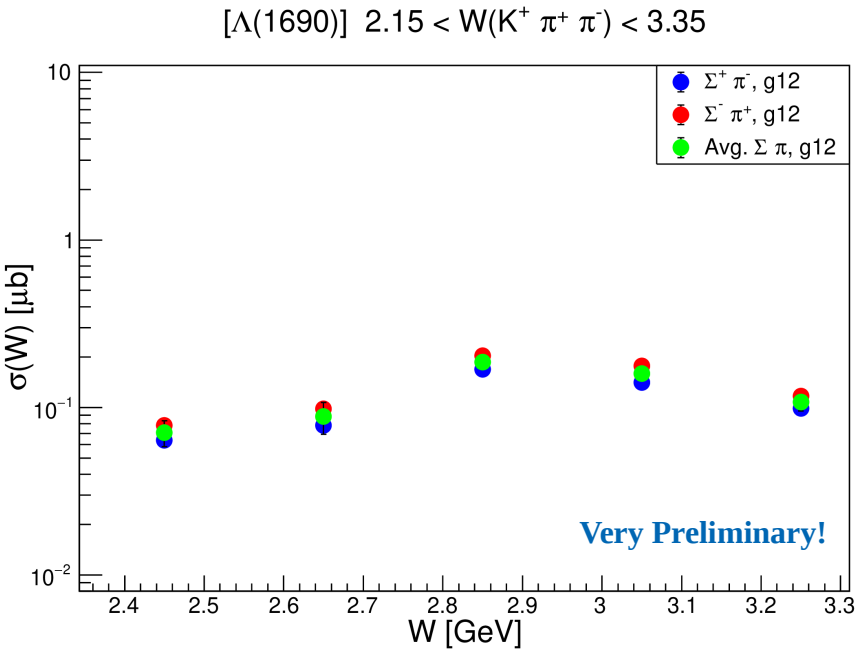
# Interference: Σ(1670) & Λ(1670)




- Simultaneous Fitting of Σ(1670) & Λ(1670) combined peak and Λ(1690) in the two decay channels.
- Λ(1690) signal is constrained with its branching ratio for the fit.

# Λ(1670) & Λ(1690)


[Λ(1690)] 2.15 < W(K+ π+ π-) < 3.35
Σ+ π-, g12
Σ- π+, g12
Avg. Σ π, g12
Very Preliminary!
σ(W) [μb]
W [GeV]
10
1
10−1
10−2
2.4
2.5
2.6
2.7
2.8
2.9
3
3.1
3.2
3.3

# Discussion and Conclusion : Λ(1520)

- The Λ(1520) differential cross sections are measured as a function of CM angle and invariant 4-momentum transfer *t*, and extented for higher *W*. They are found in good agreement with model calculations.

- The theory calculations are the numerical results without the $N^*$ contribution, and conserve gauge invariance. Theoretical study has concluded that the $K^*$-$N$-Λ(1520) coupling must be very small to explain the data. Calculations with $N^*$ show very small contribution, just above threshold, and is limited to the first W bin. Such calculations include only $N^*$ resonances with mass below 2.2 GeV.

- The simplest theoretical model with a pseudoscalar *K*-meson exchange, assuming *t*-channel dominance, is sufficient to explain our data, without other processes like Regge, $K^*$ and hyperon resonances. No new $N^*$ resonances decaying into $K^+$Λ(1520) final state are found. This theoretical model can be used to study higher $N^*$ resonances as well. DOI: 10.1103/PhysRevC.103.025206.

- Full partial wave analysis will be employed for the interference between the Σ(1670) and Λ(1670). Preliminary cross sections will be measured for the higher mass excited resonances, Λ(1670) and Λ(1670). This will provide first ever photoproduction data on these excited Λ* resonances.

**Thank You!**

# Extras

# Photoproduction of Λ* Resonances

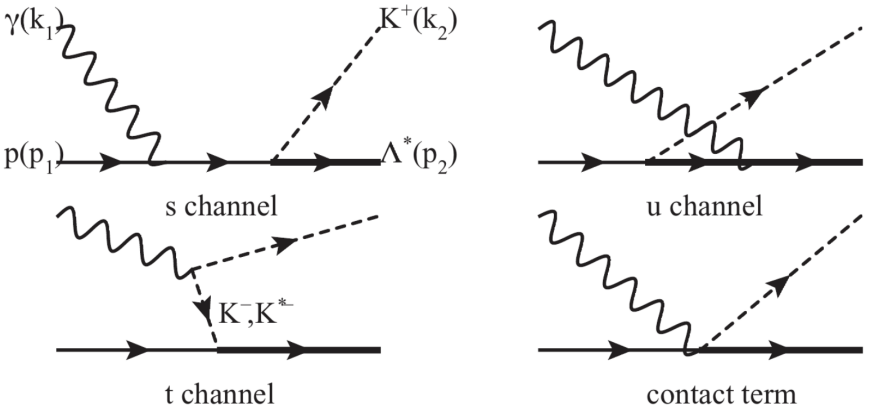
$$\gamma(k_1) + N(p_1) \rightarrow K(k_2) + \Lambda^*(p_2)$$

*s*-channel: nucleon-pole and nucleon-resonance contribution

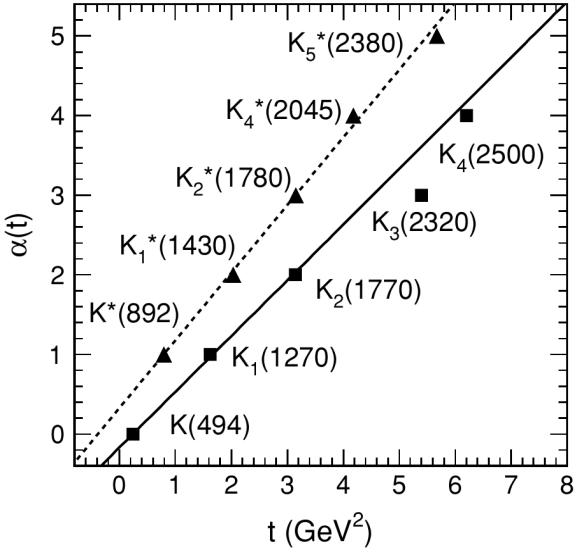
*u*-channel: Λ*-pole contribution

*t*-channel: *K* and *K** exchange phenomena

Contact term contribution




- Nam *et al.* (2010) used an effective-Lagrangian approach using Born terms with Rarita-Schwinger formalism to account for the spin 3/2-fermion field.
- Hadron form factors are introduced to represent spatial distribution for hadrons (physical non-point like structure).
- A contact term is included to preserve gauge invariance, the Lorentz invariance and the crossing symmetry.
- For higher energies, the formalism used the pseudoscalar strange-meson Regge trajectories.




S.-i. Nam and C.-W. Kao, Λ(1520) photoproduction off a proton target with regge contributions, Phys. Rev. C **81**, 055206 (2010).

# Normalization

$$\frac{d\sigma}{d\cos\theta^{c.m.}_{K^+}} = \frac{Y(W,\cos\theta^{c.m.}_{K^+})}{\tau\Delta\cos\theta^{c.m.}_{K^+} A(W,\cos\theta^{c.m.}_{K^+})L(W)}$$

$$\frac{d\sigma}{dt} = \frac{Y(W,t)}{\tau\Delta t A(W,t)L(W)}$$

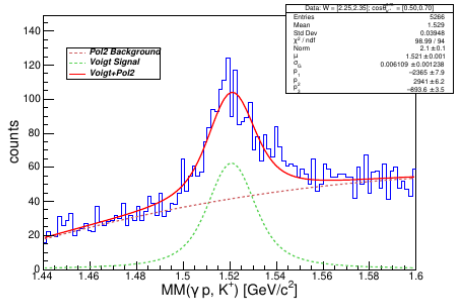
$$A(W,\cos\theta^{c.m.}_{K^+}) = \frac{Y_{acc}}{N_{gen}}$$

$$L(W) = \frac{\rho_p N_A l_t}{A_p} N_\gamma(W)$$

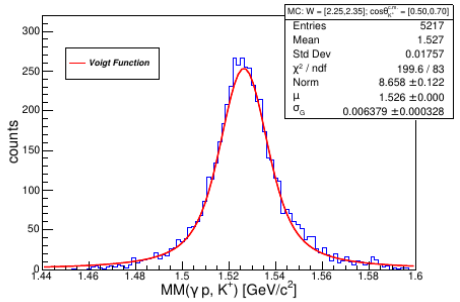
$$l_t = 40 \text{ cm}$$
$$\rho_p = 0.07114 \text{ g/cm}^3$$
$$A_p = 1.00794 \text{ g/mol}$$
$$N_A \text{ is Avogadro's number}$$

| $W$-range [GeV] | $N_\gamma$ | $\sigma_{N_\gamma}$ | $L\ [pb^{-1}]$ | $\sigma_L\ [pb^{-1}]$ |
|---|---|---|---|---|
| 2.25 - 2.35 | 8.18339e+12 | 2.86066e+06 | 1.39127e+37 | 4.86346e+30 |
| 2.35 - 2.45 | 6.66974e+12 | 2.58258e+06 | 1.13393e+37 | 4.39069e+30 |
| 2.45 - 2.55 | 7.13676e+12 | 2.67147e+06 | 1.21333e+37 | 4.54181e+30 |
| 2.60 - 2.65 | 2.50865e+12 | 1.58387e+06 | 4.2650e+36 | 2.69277e+30 |
| 2.65 - 2.75 | 5.44055e+12 | 2.3325e+06 | 9.24957e+36 | 3.96552e+30 |
| 2.75 - 2.85 | 6.06547e+12 | 2.46282e+06 | 1.0312e+37 | 4.18708e+30 |
| 2.85 - 2.95 | 5.72811e+12 | 2.39335e+06 | 9.73846e+36 | 4.06897e+30 |
| 2.95 - 3.05 | 5.08008e+12 | 2.2539e+06 | 8.63673e+36 | 3.83190e+30 |
| 3.05 - 3.15 | 5.37342e+12 | 2.31806e+06 | 9.13544e+36 | 3.94098e+30 |
| 3.15 - 3.25 | 5.42785e+12 | 2.32977e+06 | 9.22797e+36 | 3.96089e+30 |

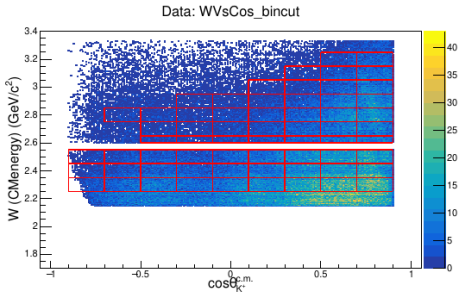
# Yield and Acceptance

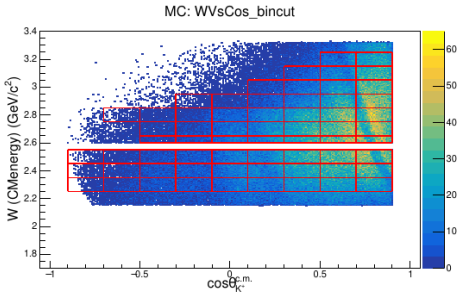


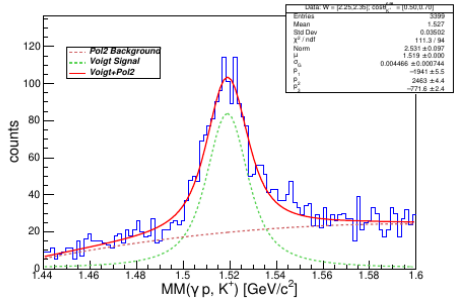

(a) Data: Signal fitting in $W = (2.25,2.35)$[GeV], $\cos\theta^{c.m.}_{K^+} = (0.5,0.7)$ bin for $\Sigma^+\pi^-$ channel.



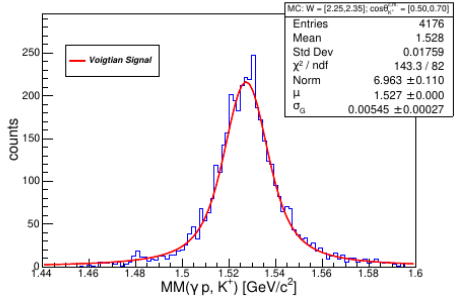

(b) MC: Signal fitting in $W = (2.25,2.35)$[GeV], $\cos\theta^{c.m.}_{K^+} = (0.5,0.7)$ bin for $\Sigma^+\pi^-$ channel.



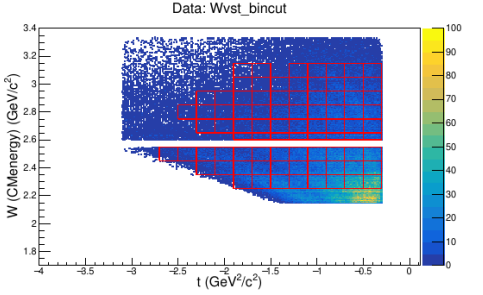



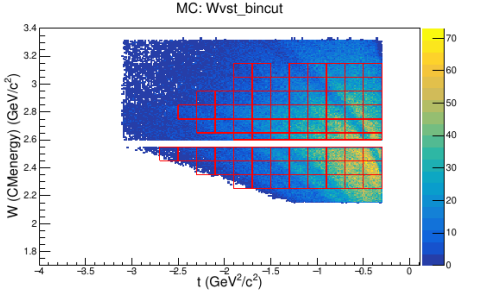




(c) Data: Signal fitting in $W = (2.25,2.35)$[GeV], $\cos\theta^{c.m.}_{K^+} = (0.5,0.71)$ bin for $\Sigma^+\pi^-$ channel.



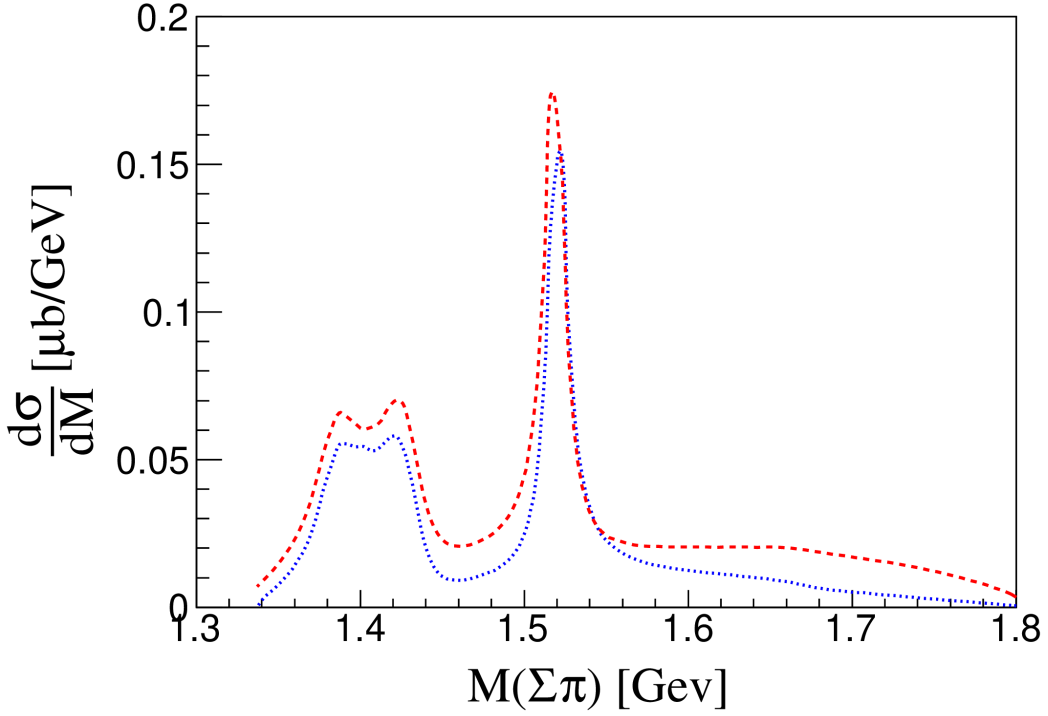

(d) MC: Signal fitting in $W = (2.25,2.35)$[GeV], $\cos\theta^{c.m.}_{K^+} = (0.5,0.7)$ bin for $\Sigma^+\pi^-$ channel.



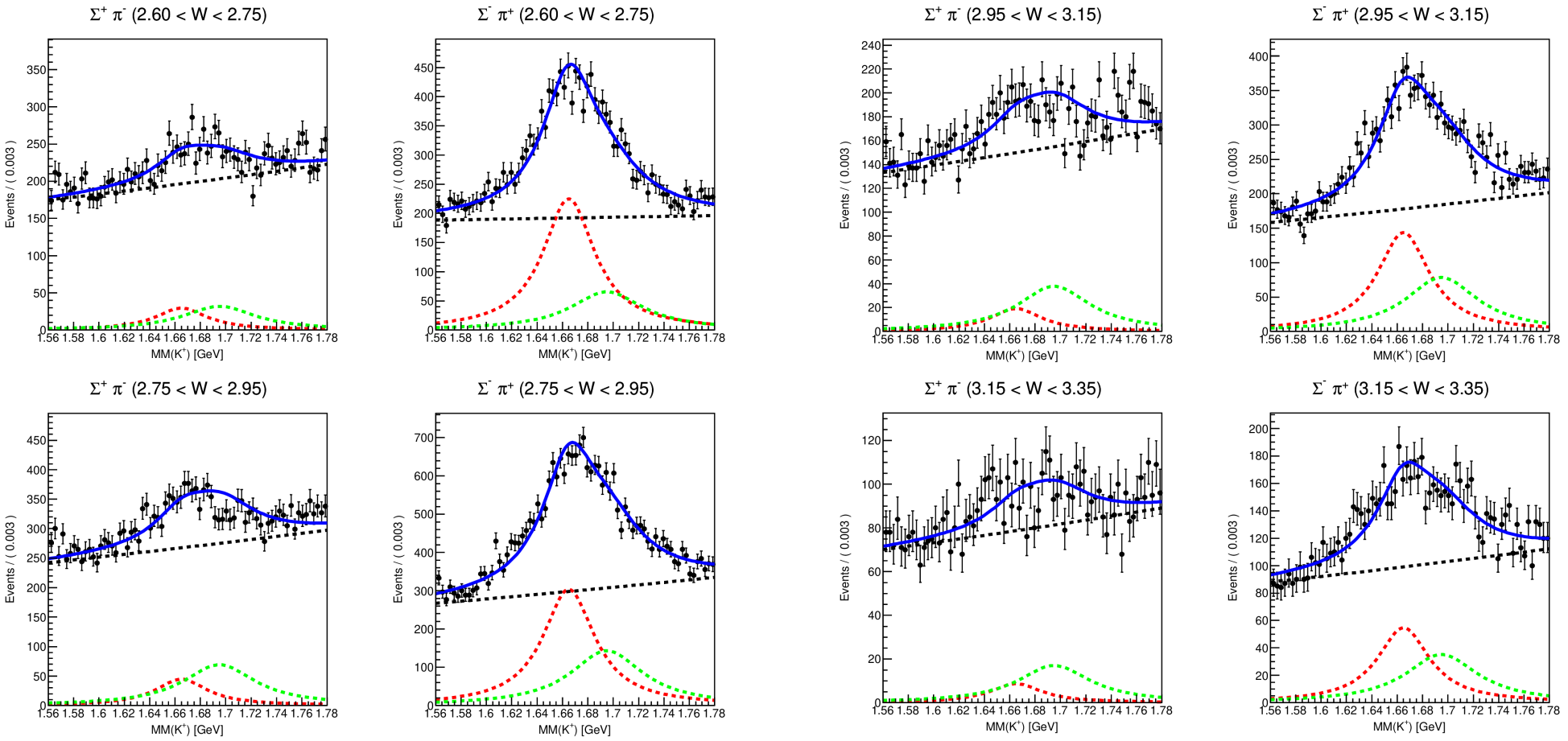



# $K^{*0} \rightarrow K^{+}\pi^{-}$ Backgound

Model prediction showing the difference in $K^{*0}$ background contributions to the decay of $\Lambda^*$ into two channels $\Sigma^{+}\pi^{-}$ (red) and $\Sigma^{-}\pi^{+}$ (blue).



# Λ(1670) & Λ(1690)


Σ⁺ π⁻ (2.60 < W < 2.75)
Σ⁻ π⁺ (2.60 < W < 2.75)
Σ⁺ π⁻ (2.95 < W < 3.15)
Σ⁻ π⁺ (2.95 < W < 3.15)
Σ⁺ π⁻ (2.75 < W < 2.95)
Σ⁻ π⁺ (2.75 < W < 2.95)
Σ⁺ π⁻ (3.15 < W < 3.35)
Σ⁻ π⁺ (3.15 < W < 3.35)
Events / ( 0.003 )
MM(K⁺) [GeV]

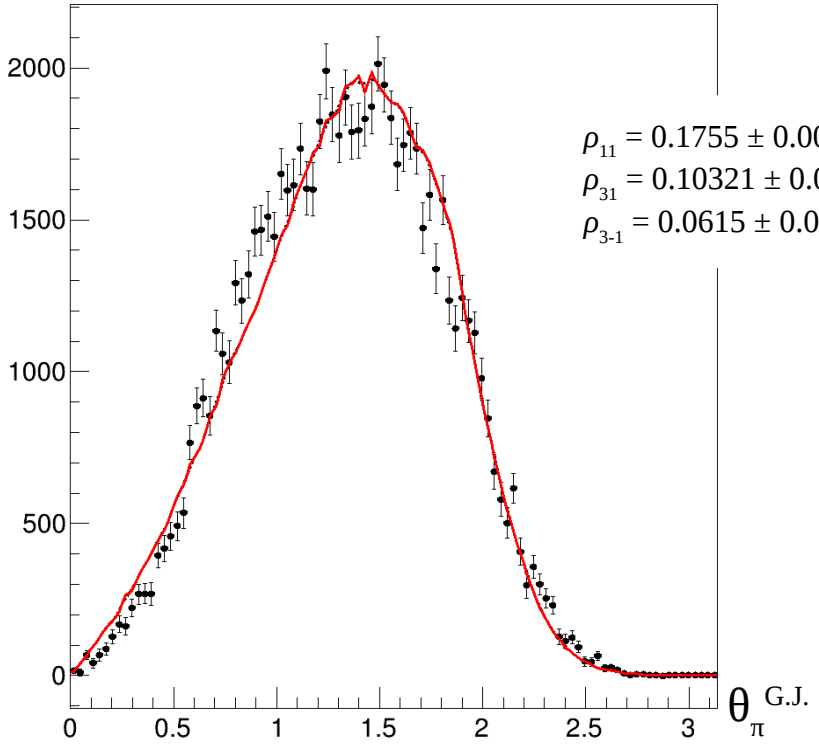
# Λ(1520) SDME

Barber *et. al.*, (1980)

$\Lambda(1520) \rightarrow \Sigma\,\pi$

$3/2^- \rightarrow 1/2^+\,0^-$

$$I(\cos\theta,\phi) = \frac{3}{4\pi}\left\{\varrho_{33}\sin^2\theta + \varrho_{11}(\tfrac{1}{3}+\cos^2\theta) - \frac{2}{\sqrt{3}}\mathrm{Re}\,\varrho_{31}\sin 2\theta\cos\phi - \frac{2}{\sqrt{3}}\mathrm{Re}\,\varrho_{3-1}\sin^2\theta\cos 2\phi\right\}$$




$\rho_{11} = 0.1755 \pm 0.0050$

$\rho_{31} = 0.10321 \pm 0.0045$

$\rho_{3\text{-}1} = 0.0615 \pm 0.0043$