HADRON23, 5 - 9 June, Genova

UNIVERSITY OF SOUTH CAROLINA

Measurements of Cross Sections and Polarizations of ΛN and Λd Elastic Scattering with the CLAS Detector

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Research supported in part by the U.S. National Science Foundation

Why YN and YNN Scattering?

YN interaction as not as well known as the NN

- not all free parameters of the YN potential can be obtained from the NN potential via flavor SU(3) symmetry

- example: large uncertainties of ΛN scattering lengths:

  $a(^1S_0) = -0.7 - -2.6$ fm,

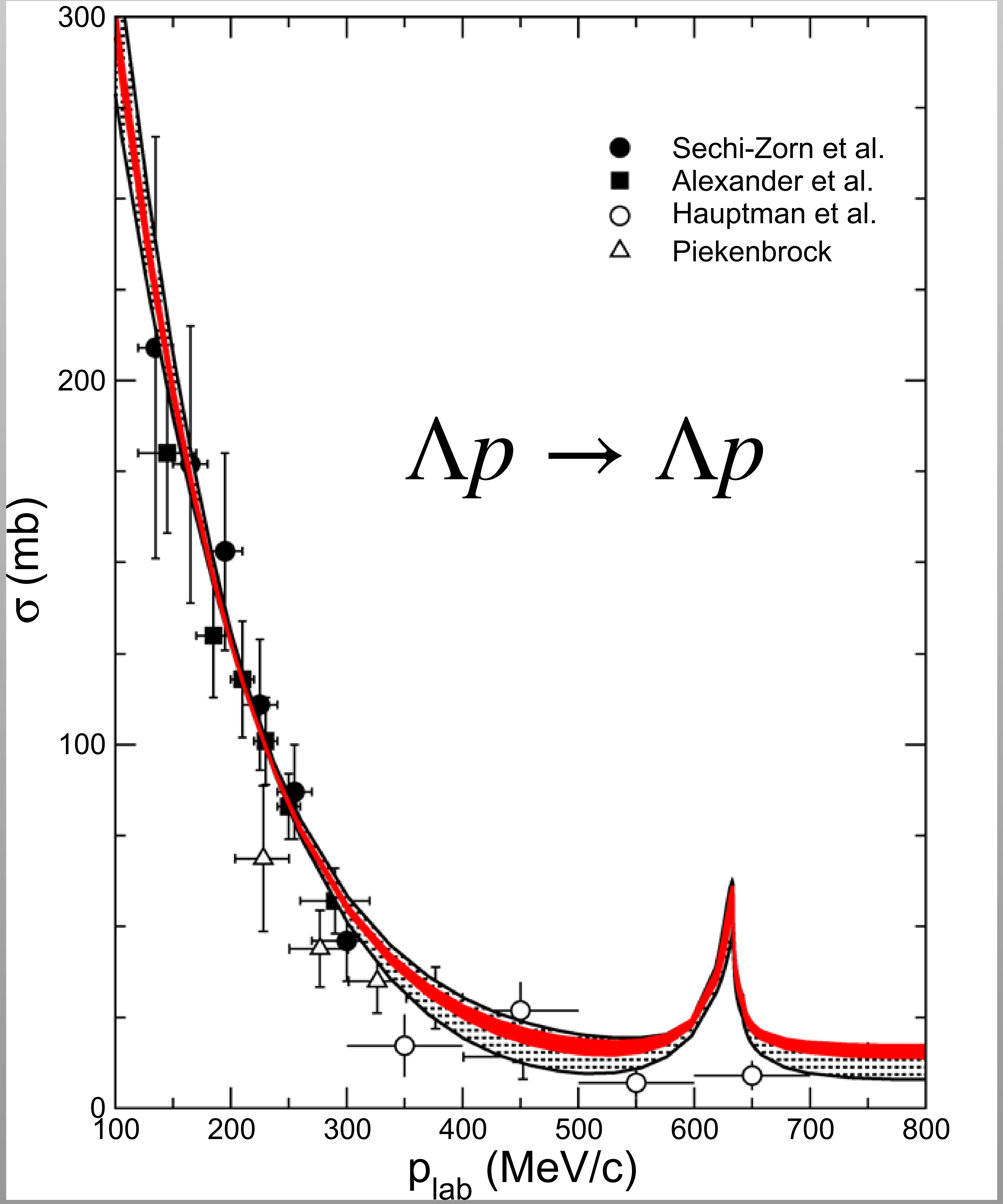
  $a(^3S_1) = -1.4 - 2.55$ fm

- YN elastic scattering database poor

  Pre-2022: 36 data points, total cross sections only, all from the 1960s; 10 new data points, from KEK-PS E251 collaboration (2000)

  for comparison: 4000 NN data for Elab < 350 MeV

- No YY, YNN, YYN, or YYY scattering data



J. Haidenbauer et al., Eur. Phys. J. A 59, 63 (2023)

Relevance of the YN Potential

Impact on resolving the "hyperon puzzle" for neutron stars

- The appearance of hyperons in the core of neutron stars , softens the Equation of State (EoS) and leads to a reduction of the predicted mass. The observation of neutron stars with masses ≳2M⊙ is incompatible with such a soft EoS

- Repulsive ΛNN interaction could stiffen the EOS (W. Weise, EPJ Web of Conferences 271, 06003 (2022)) - relative strength of ΛNN to ΛN forces needs to be quantified

Impact on hyper nuclear calculations

- Charge-Symmetry Breaking in A=4 hypernuclei:

$$\Delta E(0^+) = E_\Lambda^{0^+}({}^4_\Lambda\text{He}) - E_\Lambda^{0^+}({}^4_\Lambda\text{H}) = 233 \pm 92 \text{ keV}$$
$$\Delta E(1^+) = E_\Lambda^{1^+}({}^4_\Lambda\text{He}) - E_\Lambda^{1^+}({}^4_\Lambda\text{H}) = -83 \pm 94 \text{ keV}$$

F. Schulz et al., Null. Phys. A 954, 149 (2016); A. Esser et al., Phys. Rev. Lett. 114, 232501 (2105)

T.O. Yamamoto et al., Phys. Rev. Lett. 115, 222501 (2015)

$$\Delta a^{CSB}({}^1S_0) = a_{\Lambda p} - a_{\Lambda n} = 0.62 \pm 0.08 \text{ fm}$$
$$\Delta a^{CSB}({}^3S_1) = a_{\Lambda p} - a_{\Lambda n} = -0.10 \pm 0.02 \text{ fm}$$

J. Haidenbauer et al., Few-Body Syst 62, 105 (2021)

Recent Developments in YN Scattering

New experimental results

- **Final-State YN interaction (FSI) in production experiments**

  COSY TOF: $pp \to K^+ \Lambda p$ F. Hauenstein et al. (COSY-TOF Collaboration), Phys. Rev. C 95, 034001 (2017)

- **Direct YN Scattering Experiments**

  J-PARC: $\Sigma^- p \to \Sigma^- p$, $\Sigma^+ p \to \Sigma^+ p$, $\Sigma^- p \to \Lambda n$ (J-PARC E40 Σp Scattering Experiment) next talk

  K. Miwa et al., Phys. Rev. C 104, 045204 (2021); K. Miwa et al., Phys. Rev. Lett. 128, 072501 (2022); T. Nanamura et al., Progr. Theoret. Exp. Phys 2022, 093D01 (2022)

  CLAS JLab: $\Lambda p \to \Lambda p$ this talk J. Rowley et. al., Phys. Rev. Lett. 127, 272303 (2021)

Why YN and YNN Scattering?

Summary

While SU(3) symmetry and hypernuclear spectroscopy provide valuable constraints on YN potentials, there is a clear need for low-energy scattering YN data.

Clear need of YNN scattering data to constrain the three-body YNN force.

Need for experimental information of Λn scattering.

Complementary, but dynamically and experimentally different, means to access YN interaction to hypernuclear spectroscopy

Experimental Facility: The CLAS at JLab

E04-005, E04-017, E08-003 (g12)

- LH_2 target, 40-cm long
- E_e = 5.715 GeV
- triggers: ~26×10^9 triggers

E06-103 (g13)

- LD_2 target, 40-cm long
- Circularly (g13a) and Linearly Polarized (g13b) Photons
- E_e = 2 GeV; 2.65 GeV (g13a)
- triggers: ~50×10^9 triggers

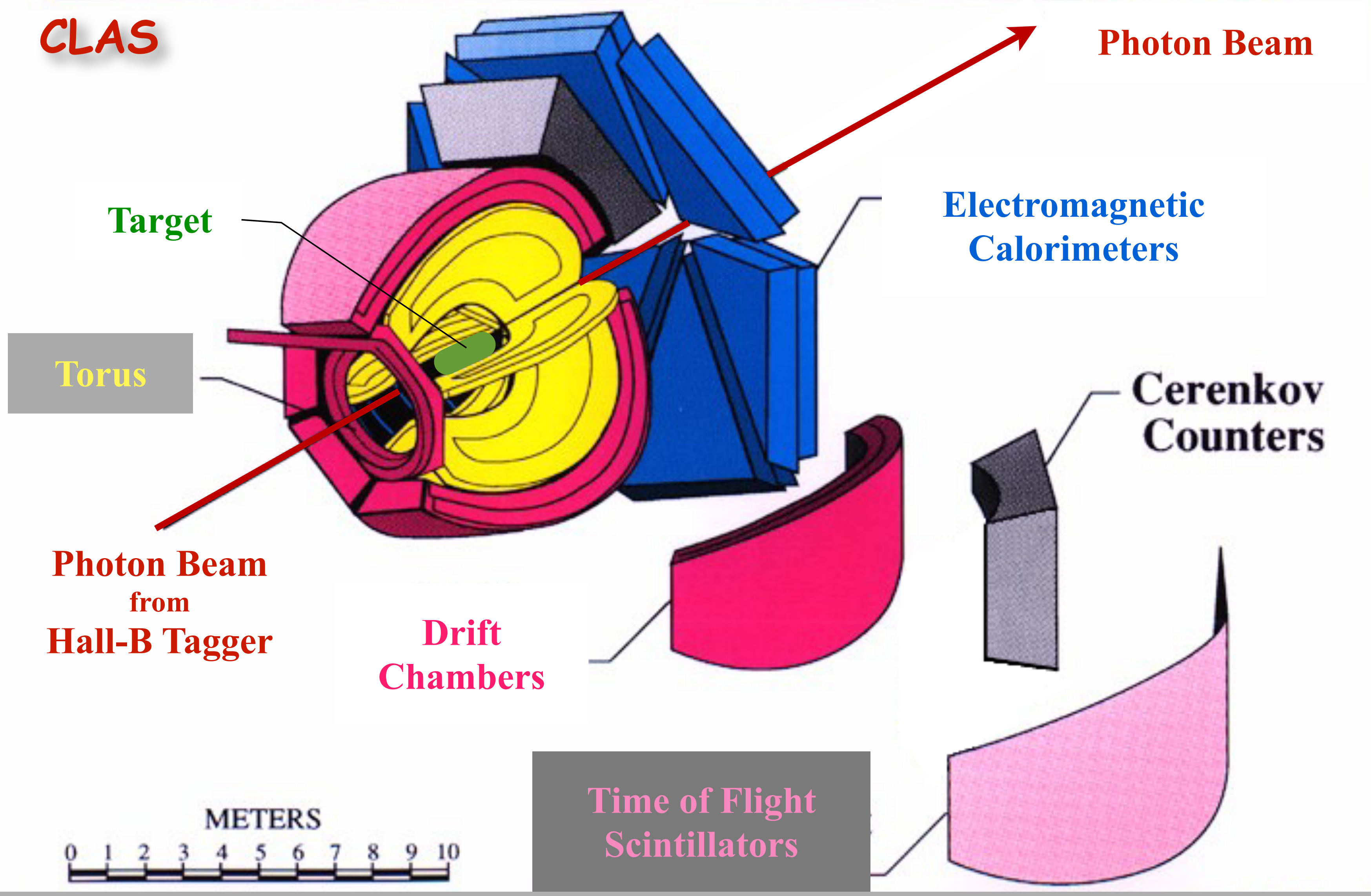
$8^\circ < \theta < 140^\circ$

$0^\circ < \phi < 360^\circ$

$\sigma_\theta \sim 1$ mrad

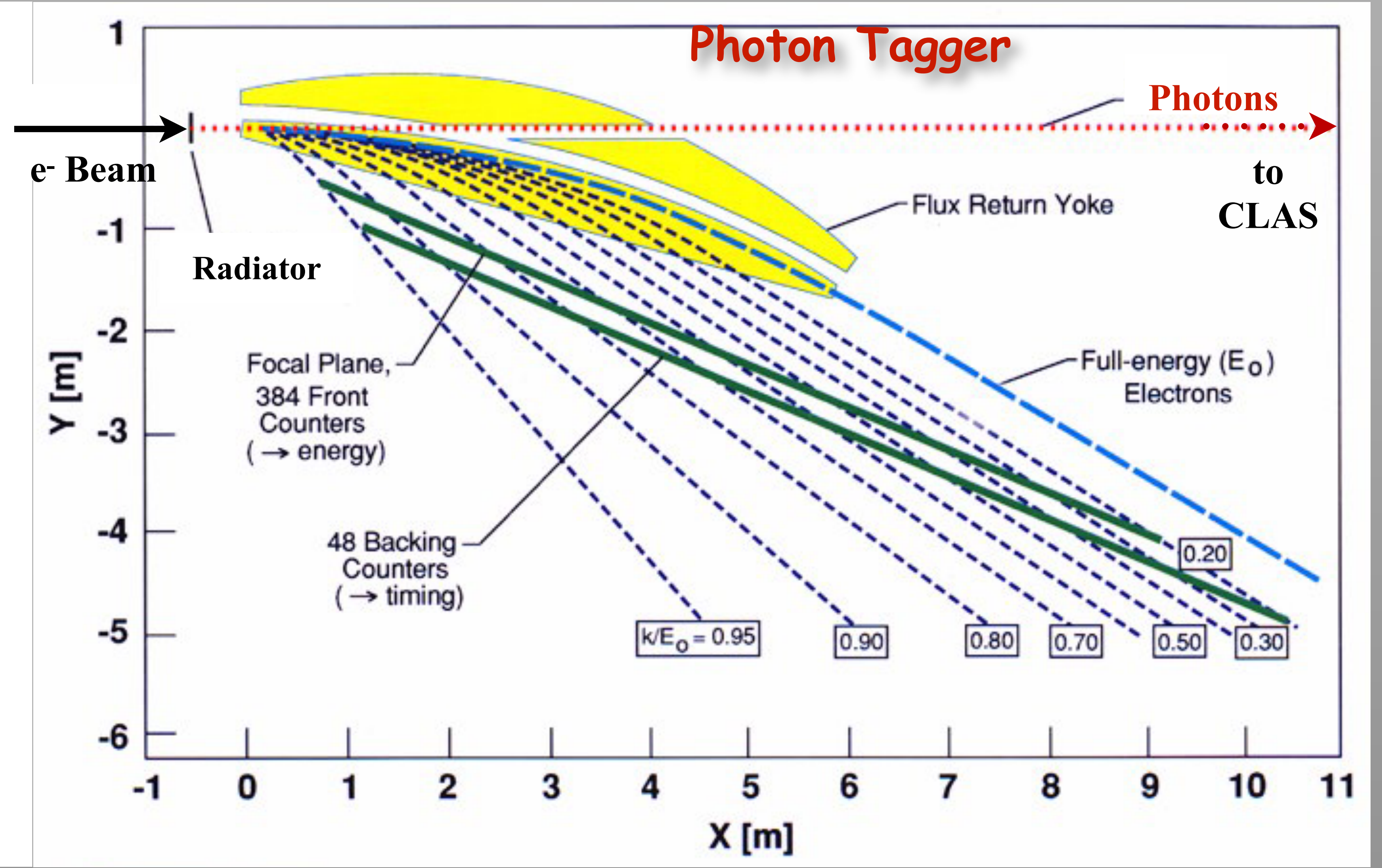
$\sigma_\phi \sim 4$ mrad

$\frac{\sigma_p}{p} \sim 1\,\%$



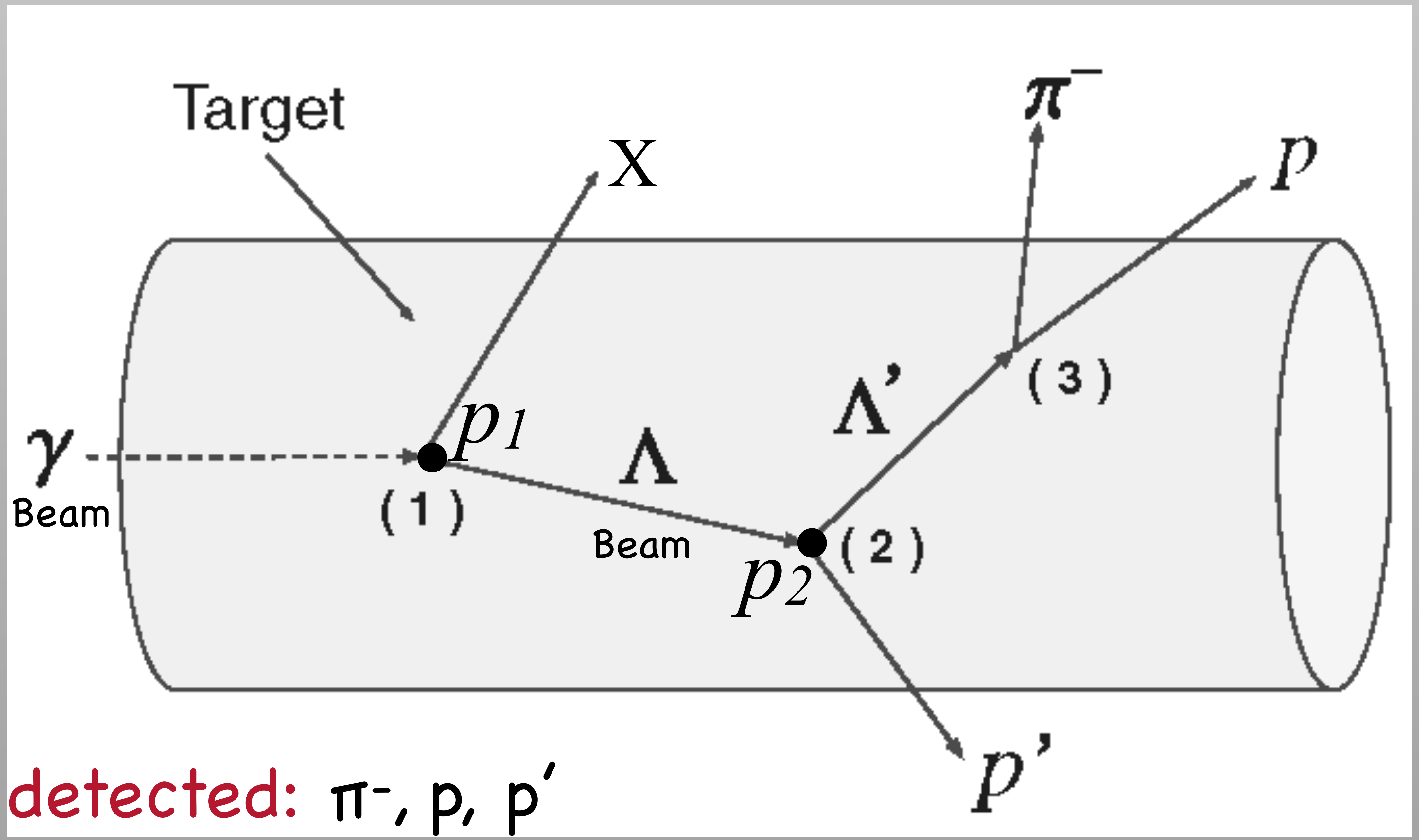
$E_\gamma : 0.2E_e,\ 0.95E_e$

$\frac{\sigma_{E_\gamma}}{E_\gamma} \sim 0.1\,\%$



Accessing YN scattering in Photoproduction

Technique 1: Rescattering off different nucleon/nucleus in same target cell



(1) Λ beam is produced in: $\gamma p_1 \to \Lambda X$

(2) Λ beam scatters off elastically: $\Lambda p_2 \to \Lambda' p'$

(3) Scattered Λ decays: $\Lambda' \to p\pi^-$

Advantages:

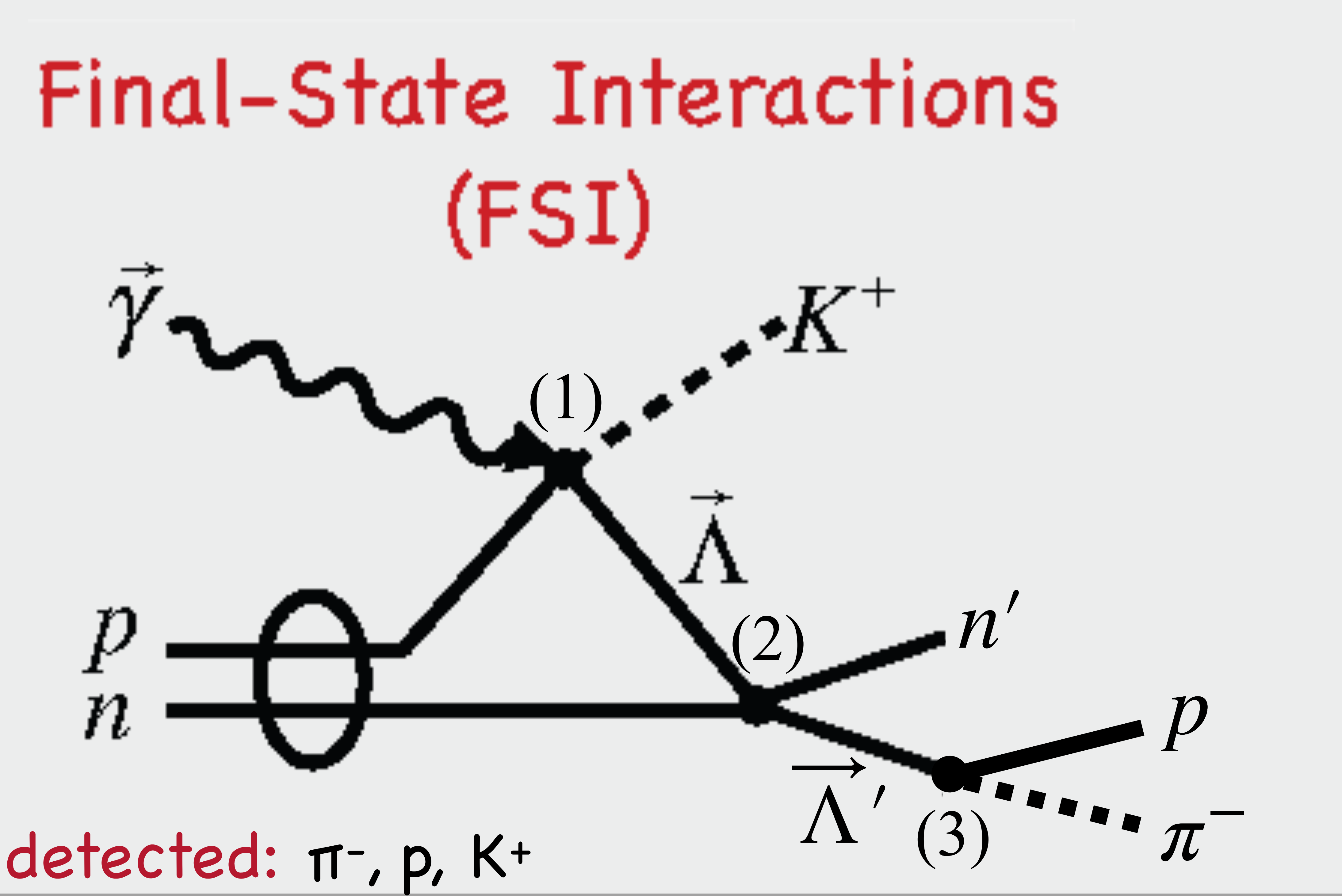
- Exclusive measurement of (2) - clean reaction selection
- Both target nucleons in (1) and (2) are at rest and on-shell — no Fermi smearing

Challenges:

- Luminosity determination for (2)
- Statistics of (2)
- Λ beam momentum cannot be arbitrarily low

Accessing YN scattering in Photoproduction

Technique 2: Rescattering off a nucleon in the same deuteron nucleus (FSI)



(1) Λ beam is produced in: $\vec{\gamma}N \to \vec{\Lambda}K$

(2) Λ beam scatters off elastically: $\vec{\Lambda}N \to \vec{\Lambda}'N'$

(3) Scattered Λ decays: $\vec{\Lambda}' \to p\pi^-$

Advantages:

- High statistics
- Exclusive measurement overall - clean reaction selection $\vec{\gamma}d \to K\vec{\Lambda}'N'$
- FSI selection by means of large $p_{N'}$
- Access to several polarization observables
- Access to Λp and Λn

Challenges:

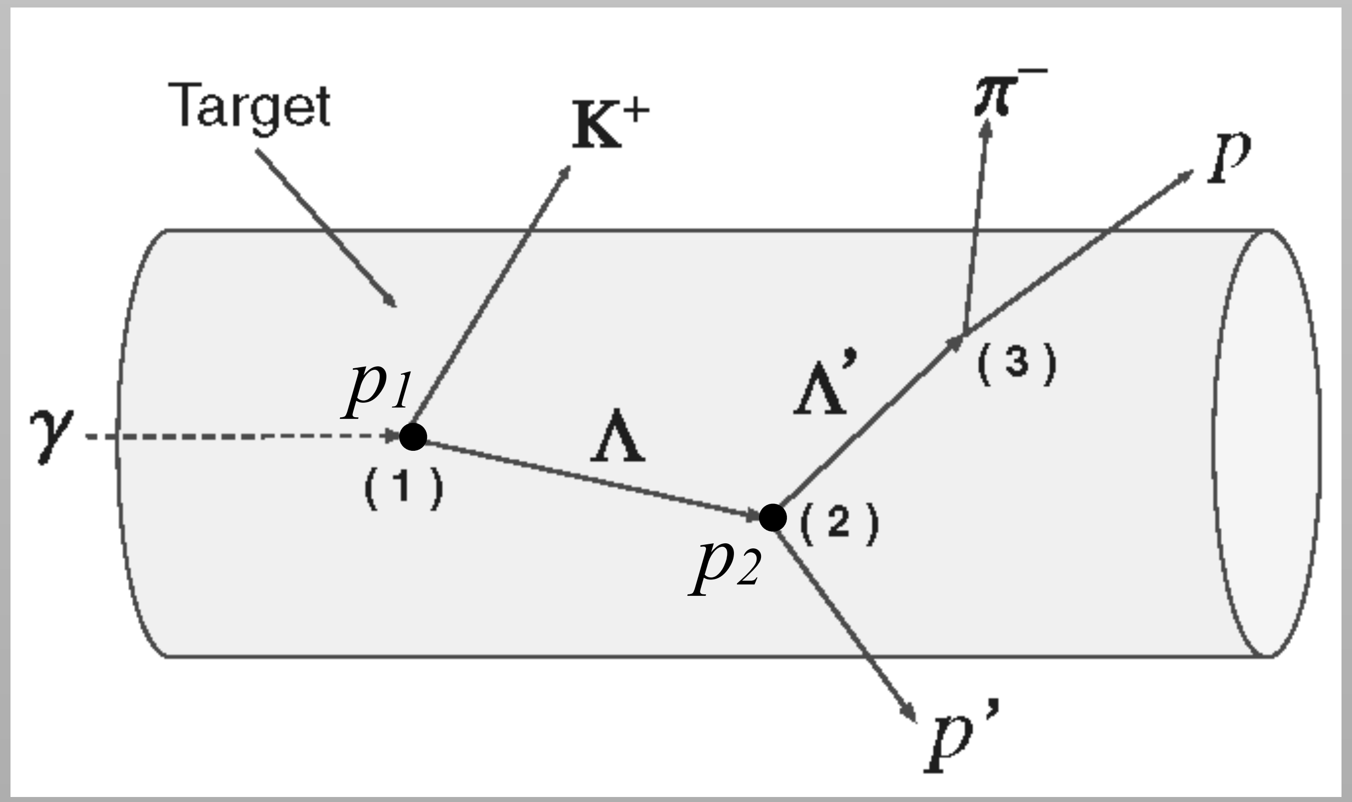
- Separation of physics background from other FSIs (KN, pion-mediated) - model dependence
- Target nucleon momentum unknown

Measurement of $\Lambda p \to \Lambda p$ Cross Section

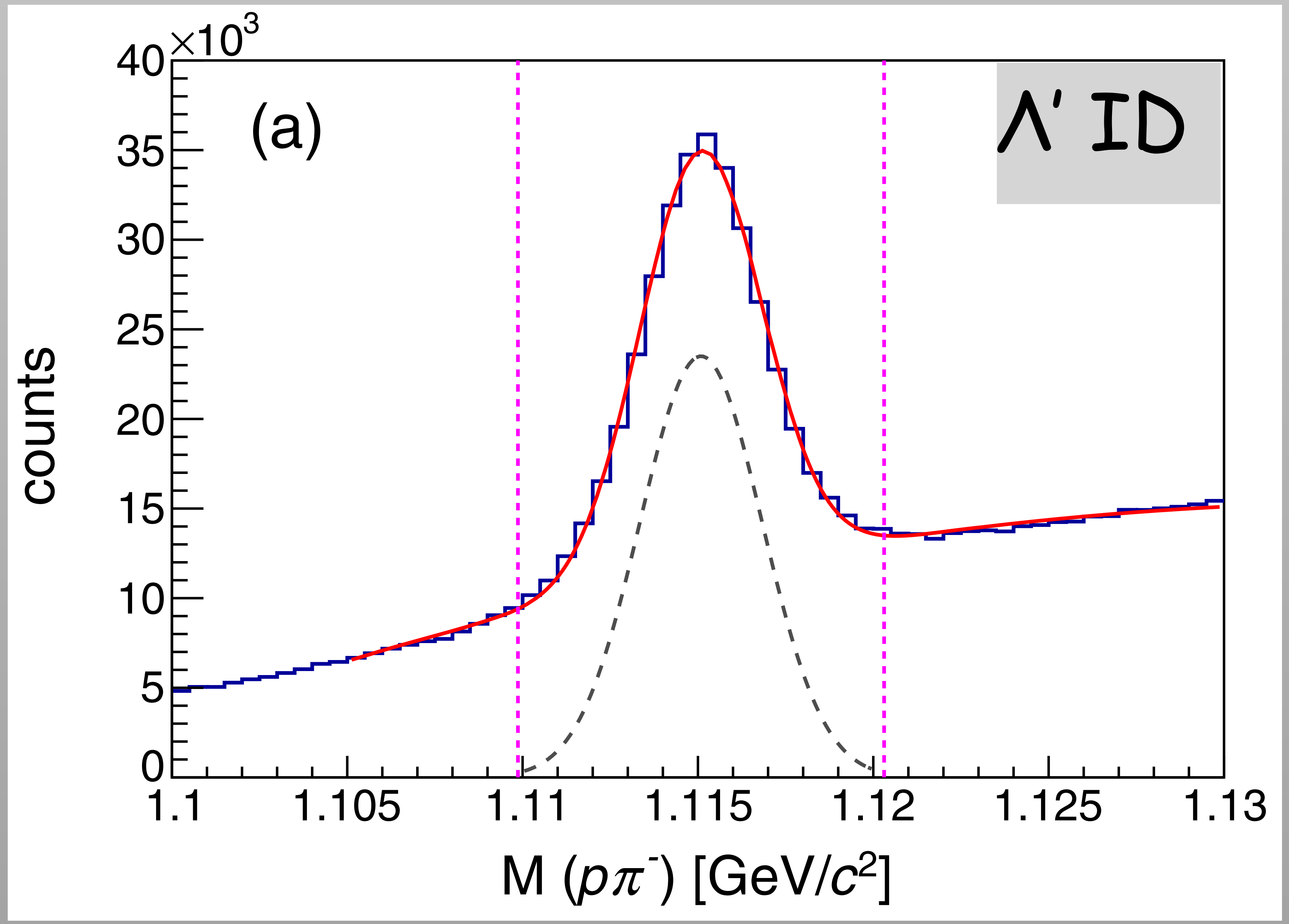
Technique 1: Applied to g12 data set

J. Rowley et. al., Phys. Rev. Lett. **127**, 272303 (2021)

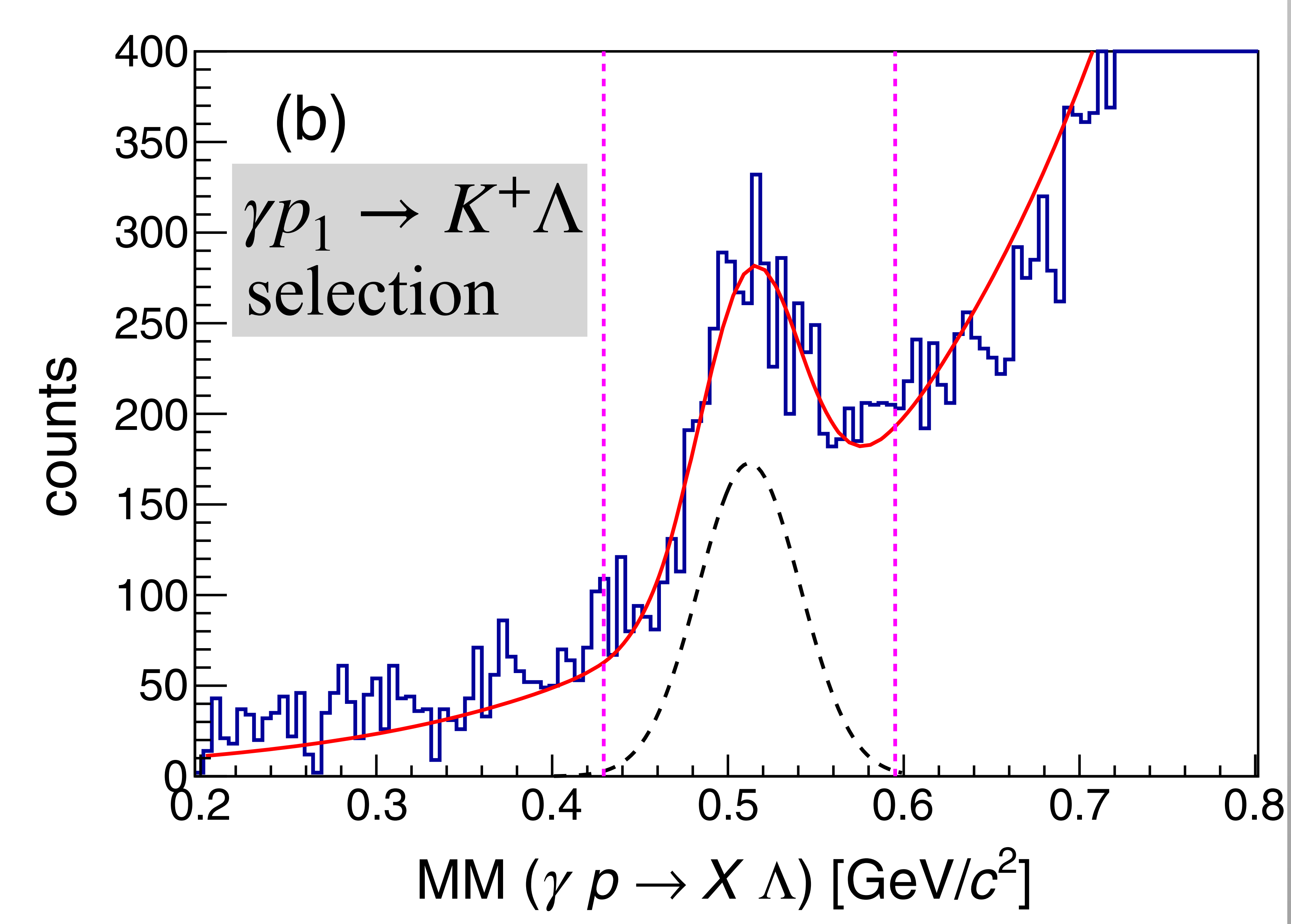
Event Selection



detected: π^-, p, p′



$$\tilde{p}_{\Lambda'} = \tilde{p}_{\pi^-} + \tilde{p}_p$$



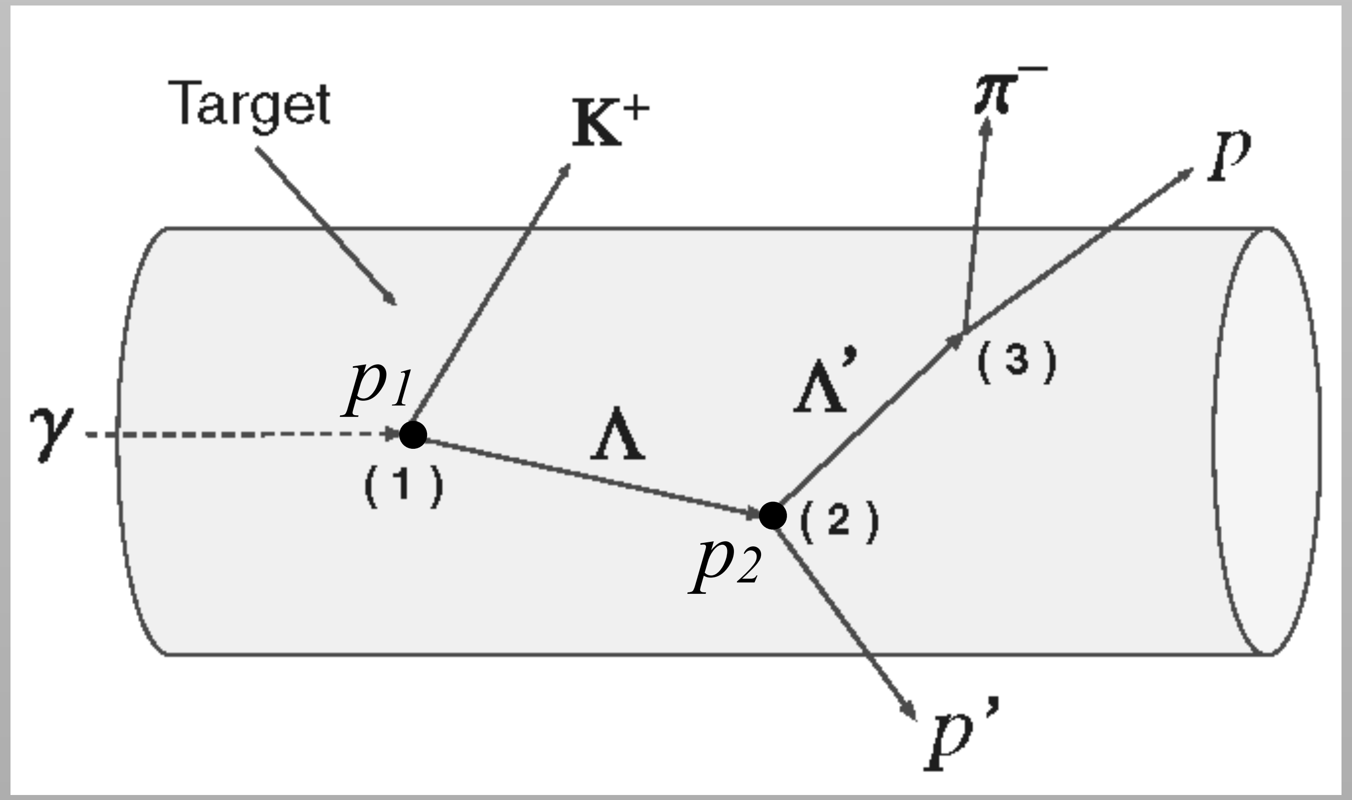
$$\tilde{p}_{K^+} = \tilde{p}_\gamma + \tilde{p}_{p_1} + \tilde{p}_{p_2} - \tilde{p}_{\Lambda'} - \tilde{p}_{p'}$$

Measurement of $\Lambda p \to \Lambda p$ Cross Section

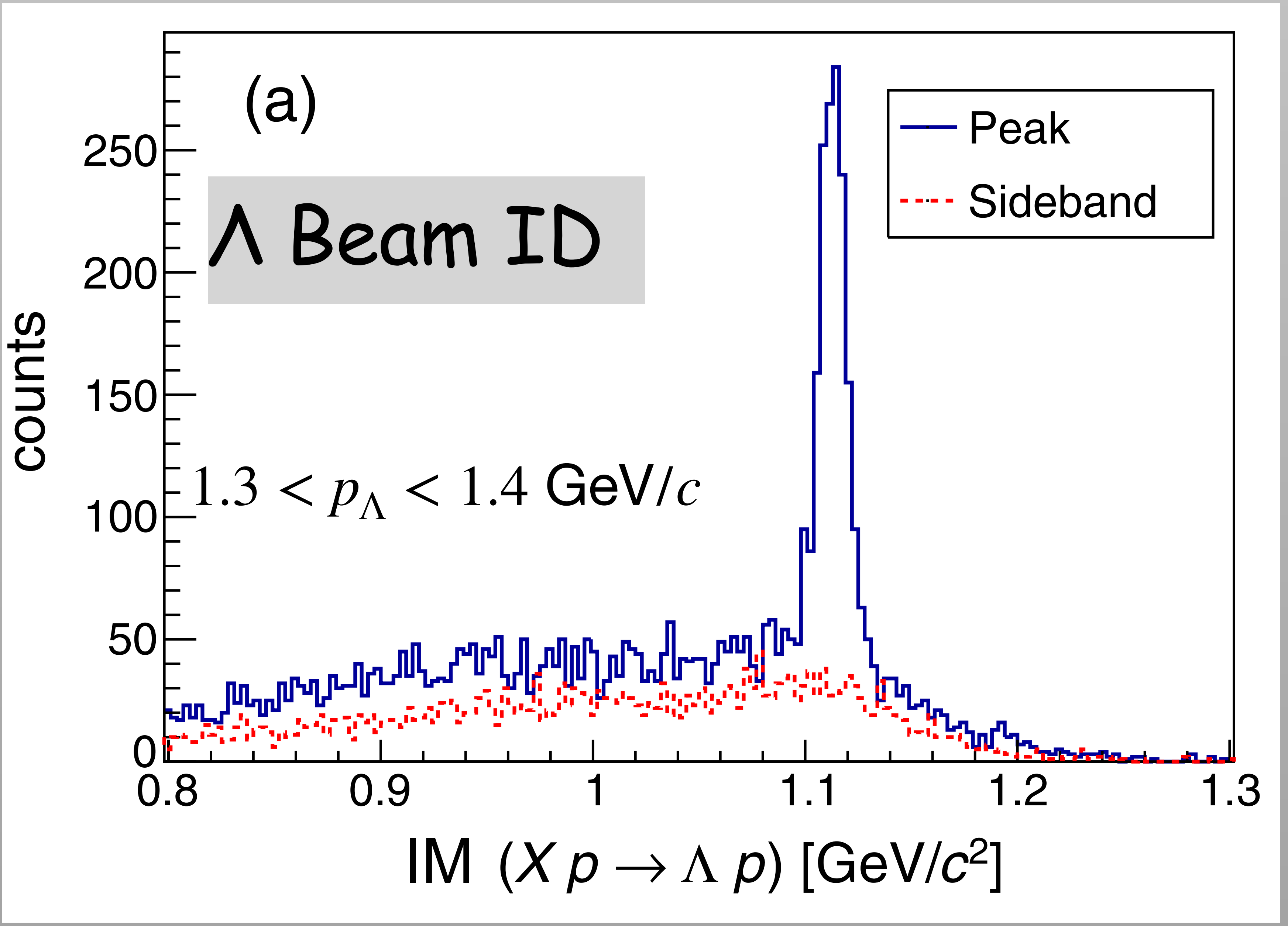
Technique 1: Applied to g12 data set

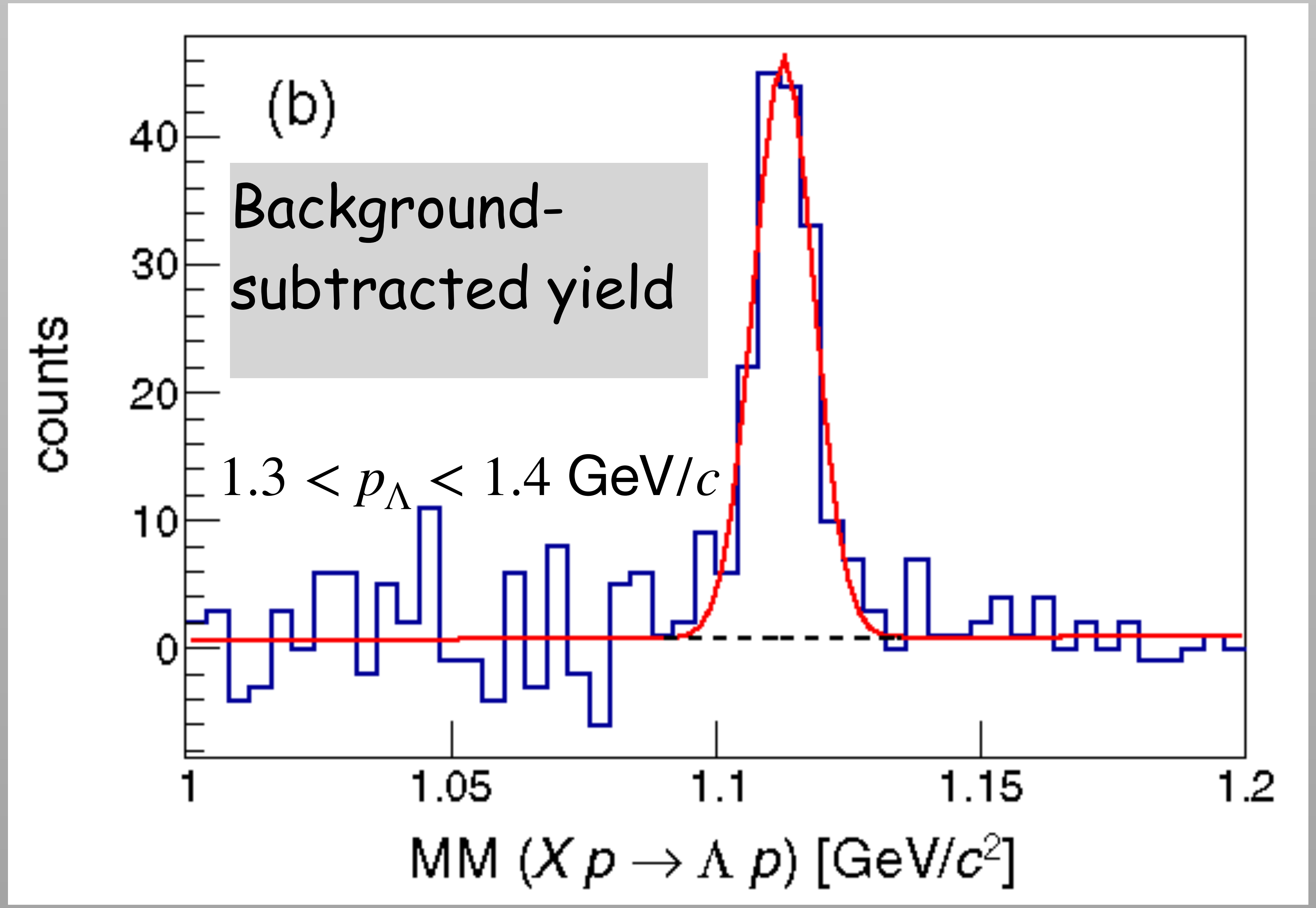
J. Rowley et. al., Phys. Rev. Lett. **127**, 272303 (2021)

Event Selection



detected: π^-, p, p′





$$\tilde{p}_{\Lambda} = \tilde{p}_{\Lambda'} + \tilde{p}_{p'} - \tilde{p}_{p_2}$$

Measurement of $\Lambda p \to \Lambda p$ Cross Section

Technique 1: Applied to g12 data set

J. Rowley et. al., Phys. Rev. Lett. **127**, 272303 (2021)

Total Cross Section Determination

$$\sigma(p_\Lambda) = \frac{Y(p_\Lambda)}{\mathscr{A}(p_\Lambda)\mathscr{L}(p_\Lambda)\Gamma_{\Lambda\to p\pi^-}}$$

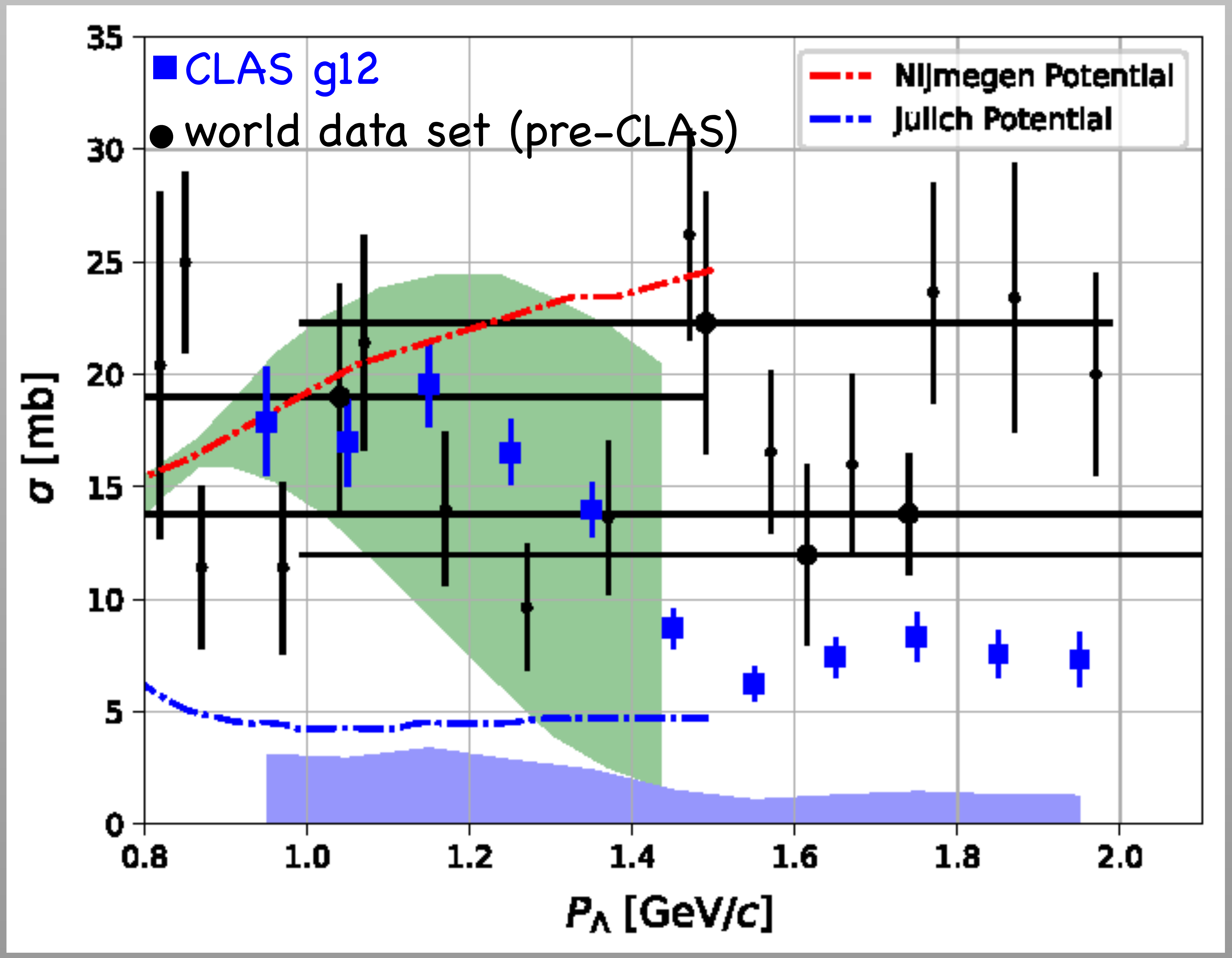
$$\mathscr{L}(p_\Lambda) = \frac{N_A \rho_T L}{M} N_\Lambda(p_\Lambda)$$

$$L: \; P(x) = \exp\left[-\frac{m_\Lambda}{p_\Lambda}\frac{x - x_0}{\tau}\right]$$

$$N_\Lambda(p_\Lambda) = \mathscr{L}_\gamma \frac{d\sigma}{d\Omega_{\gamma p\to K\Lambda}}(2\pi)(\Delta\cos\theta^*{}_K)$$

Simulations: $\mathscr{A}(p_\Lambda)$, L

Results



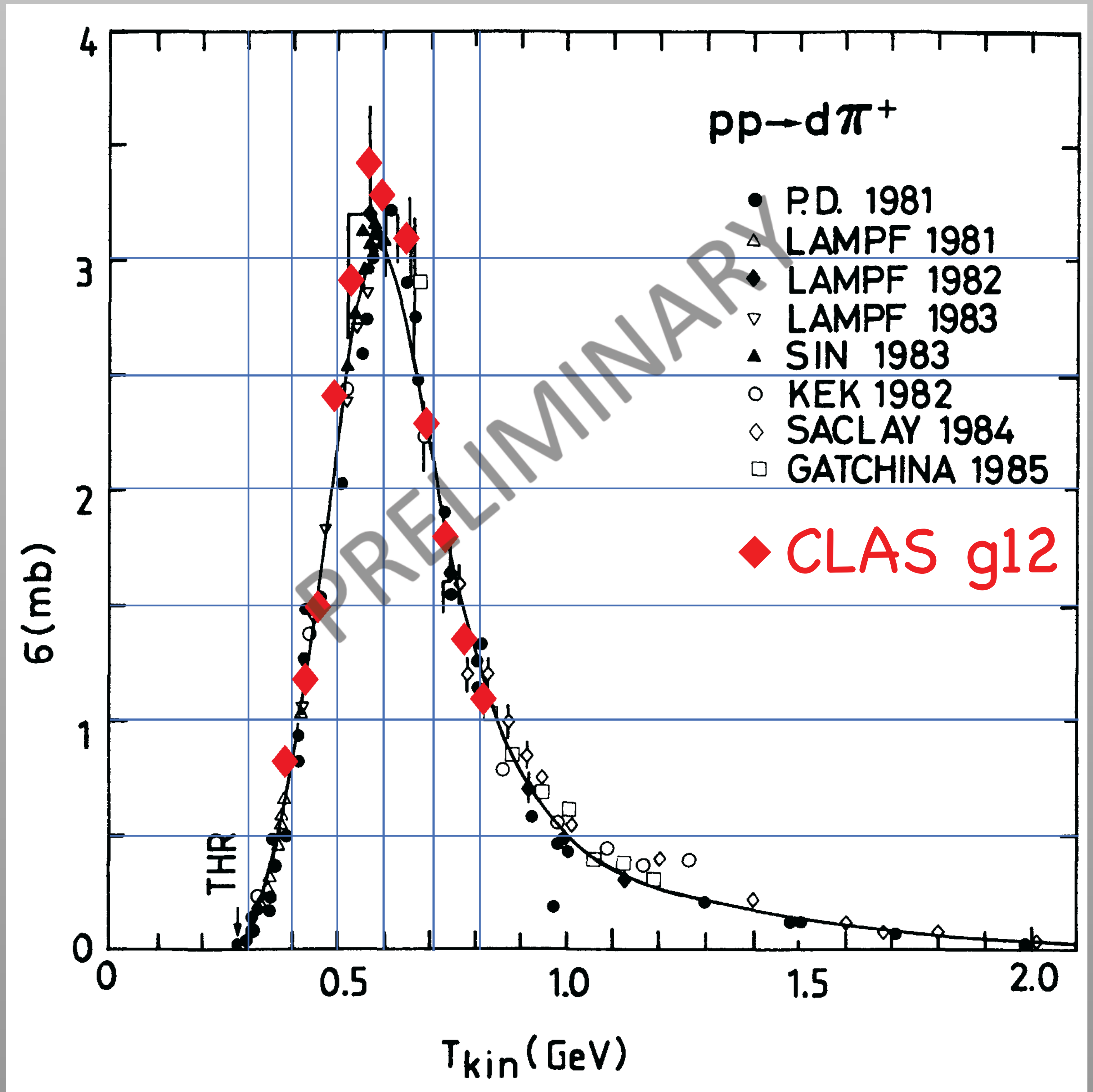
J. Haidenbauer and U.-G. Meißner, Phys. Rev. C 72, 044005 (2005)

T. A. Rijken, V. G. J. Stoks, and Y. Yamamoto, Phys. Rev. C 59, 21 (1999)

J. Haidenbauer, U.-G. Meißner, and A. Nogga, Eur. Phys. J. A 56, 91 (2020).

Measurement of $pp \rightarrow d\pi^+$ Cross Section

Technique 1: Validation



Work by Joe Rowley, Ken Hincks, Nick Zachariou

(1) $\gamma p \rightarrow p\pi^0$

(2) $pp \rightarrow d\pi^+$

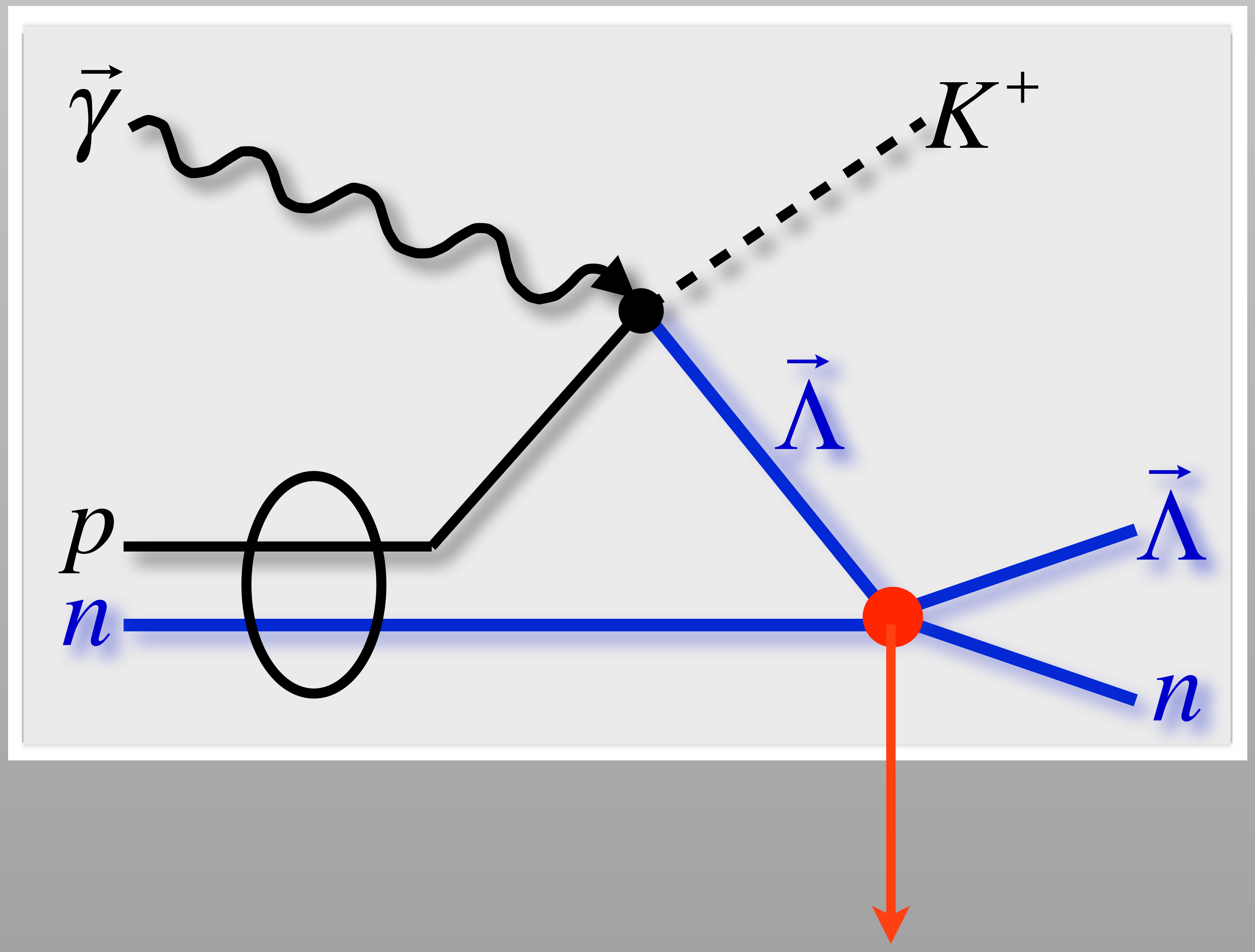
detected: d, π^+

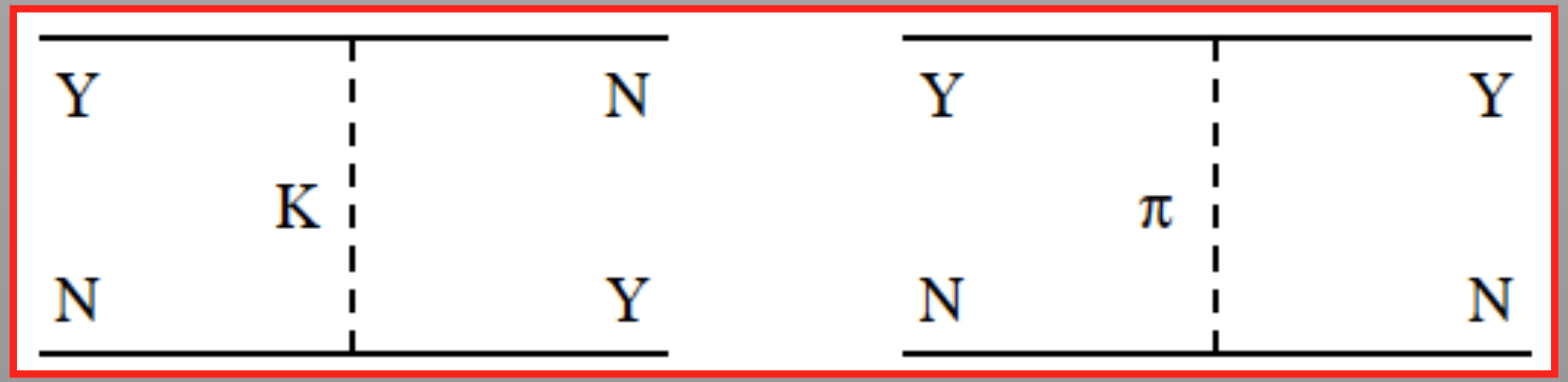
- statistical uncertainties: size of marker
- Systematic uncertainties: about 10%

Good agreement with previous data

Accessing $\Lambda n \to \Lambda n$ via FSI in Exclusive Photoproduction

Technique 2: Applied to g13 data set (indirect method)





Λn potential is accessed by means of the effect that Λn rescattering mechanism has on the observables defined for the first vertex.

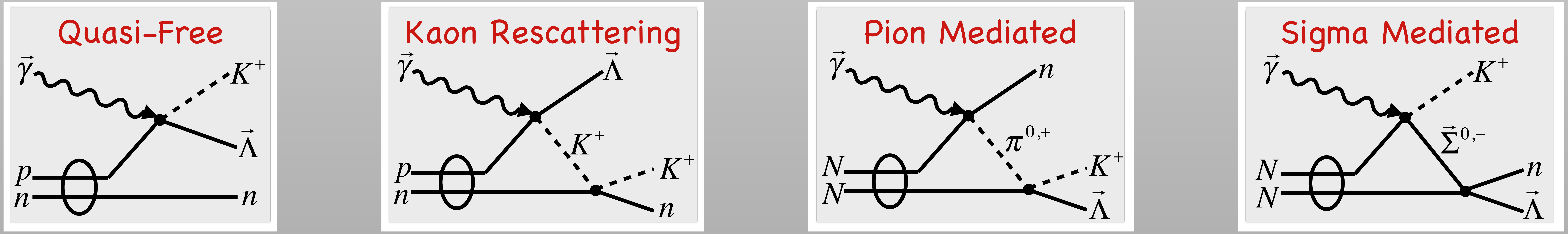
Theoretical Studies

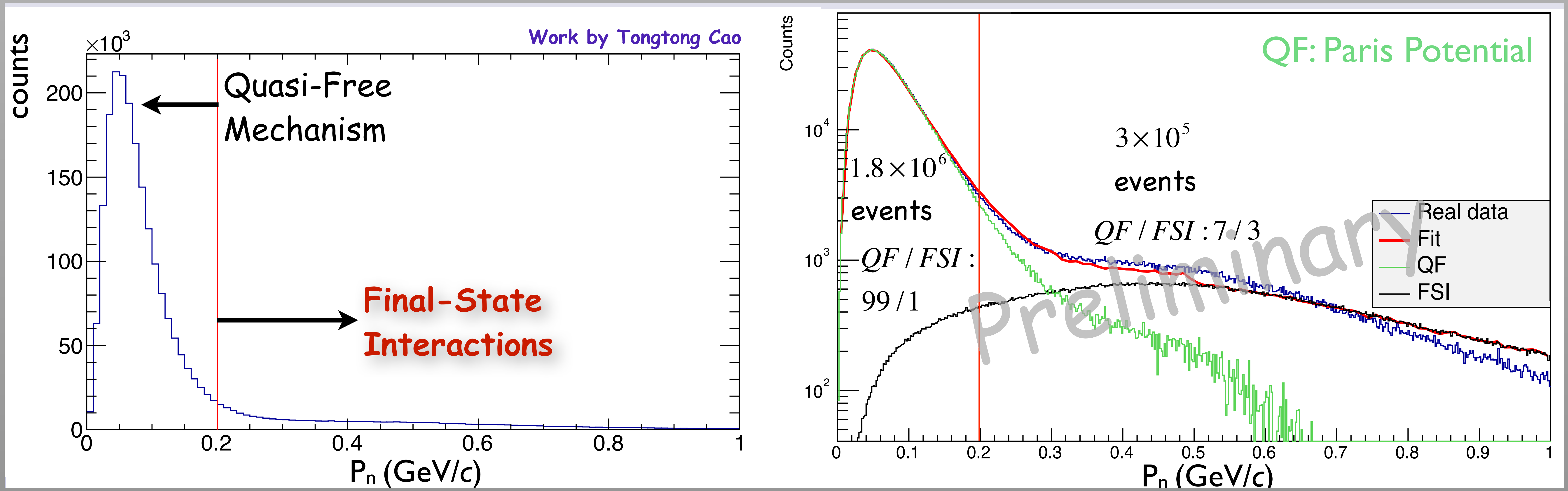
- Observables sensitive to YN potentials at certain kinematics at a level of ~10% (K. Miyagawa et al., Phys. Rev. C **74**, 034002 (2006); A. Salam et al., Phys. Rev. C **74**, 044004 (2006); H. Yamamura et al., Phys. Rev. C **61**, 014001 (1999))
- A combination of $^1S_0$ and $^3S_1$ scattering lengths can be extracted from data close to threshold (A.Gasparian et al., Phys. Rev. C 69, 034006 (2004))

Accessing $\Lambda n \to \Lambda n$ via FSI in Exclusive Photoproduction

Technique 2: Applied to g13 data set

Background Mechanisms



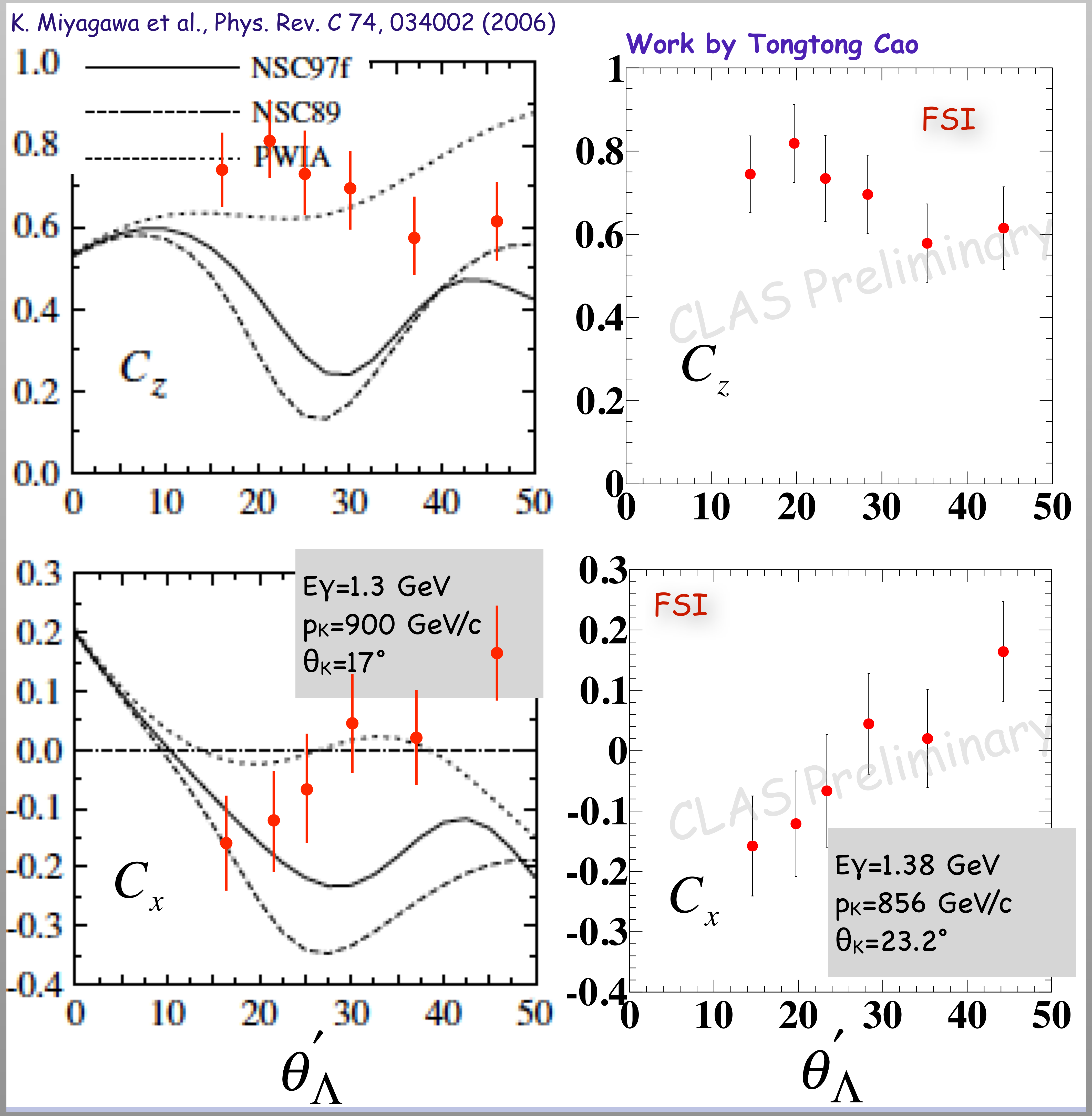


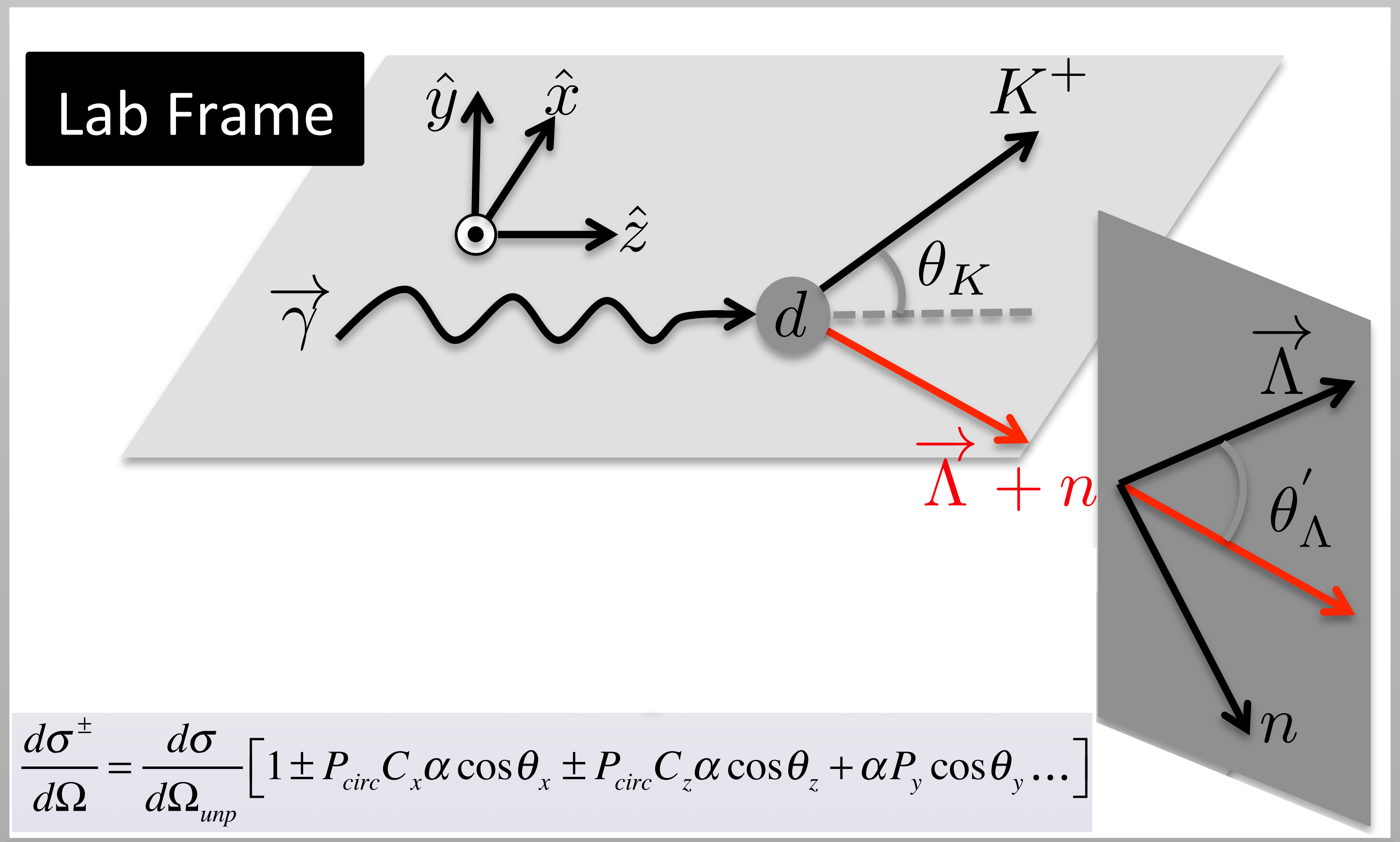
The removal of events with $P_n < 0.2$ GeV/c provides a sample that is by far dominated by FSI events.

Paris Potential describes well low P_n data. High-momentum tail drops off at $\sim$0.6 GeV/c: effect on data interpretation.

Accessing $\Lambda n \to \Lambda n$ via FSI in Exclusive Photoproduction

Technique 2: Applied to g13 data set



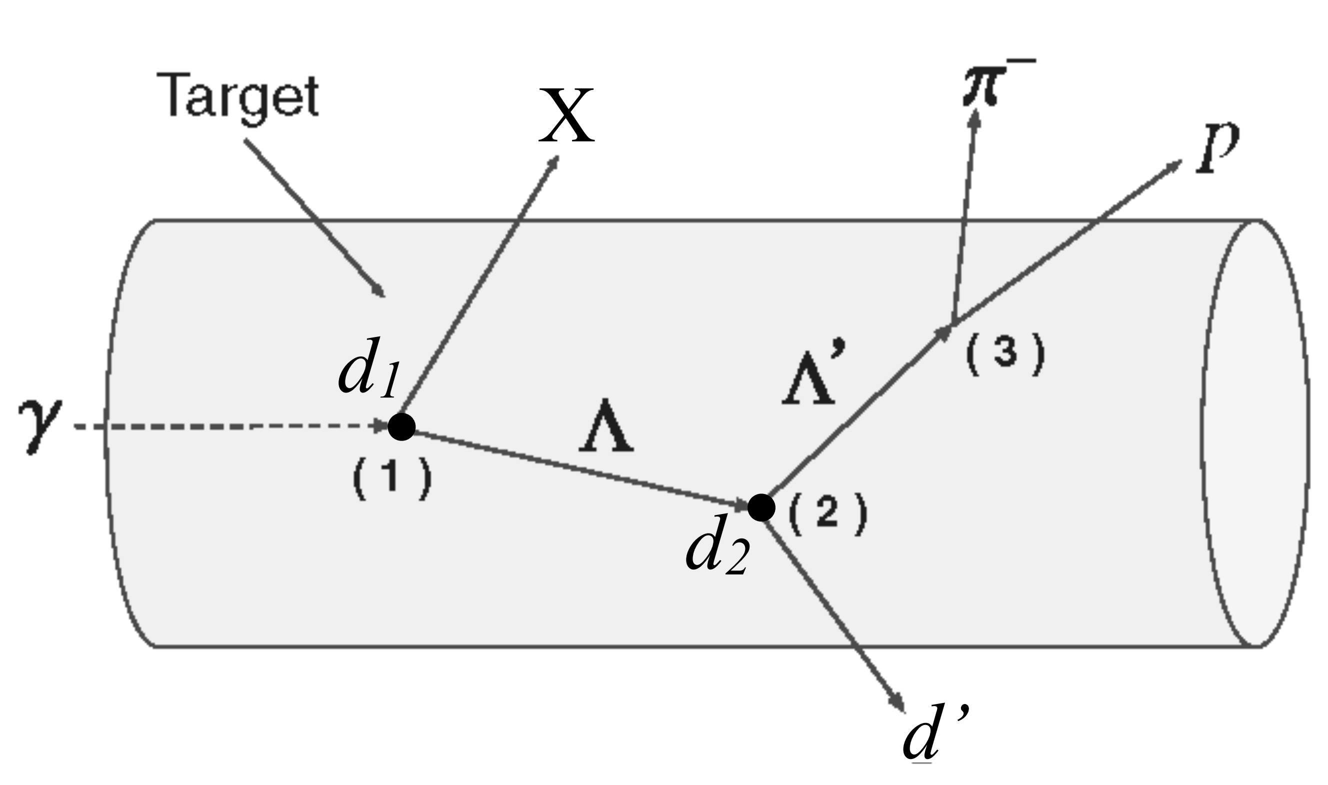


C_x, C_z: polarization transfers from the circularly polarized photon to the final-state Λ

- One-, …, four-fold differential FSI observables have been extracted
- Experimental observables are integrated over the CLAS acceptance
- FSI cross sections are being extracted
- The parameters of the Λn potential accessed by means of comparison with theoretical models (reaction dynamics dependence)
- Model dependence can be reduced by analyzing the unique effects various FSIs have on the polarization observables - in progress

Measurement of $\Lambda d \to \Lambda d$ Cross Section

Technique 1: Applied to g13 data set



Theoretical Studies

- Elastic cross section can be used to extract $^2S_{1/2}$ and $^4S_{3/2}$ scattering lengths

  $a(^4S_{3/2}) = -7.6 \div -31.9$ fm - directly constrains $a(^3S_1)$ for ΛN

  (J. Haidenbauer, Phys. Rev. C 102, 034001 (2020))

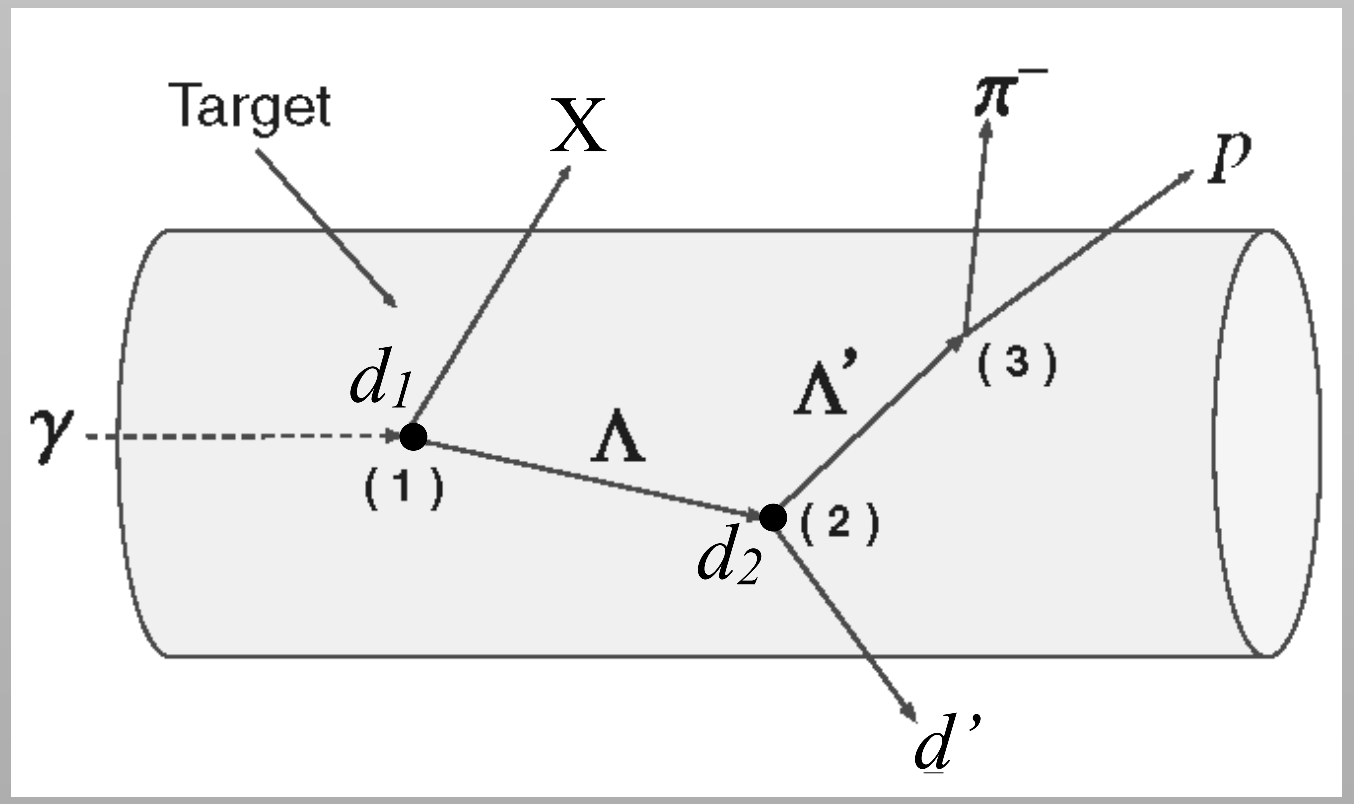
- Studies of Nd elastic cross sections at energies of our data show increased sensitivity to 3-body mechanisms→theoretical formalisms to extract the relative strength of these mechanisms will be applied to Λd cross sections to gain access to ΛNN

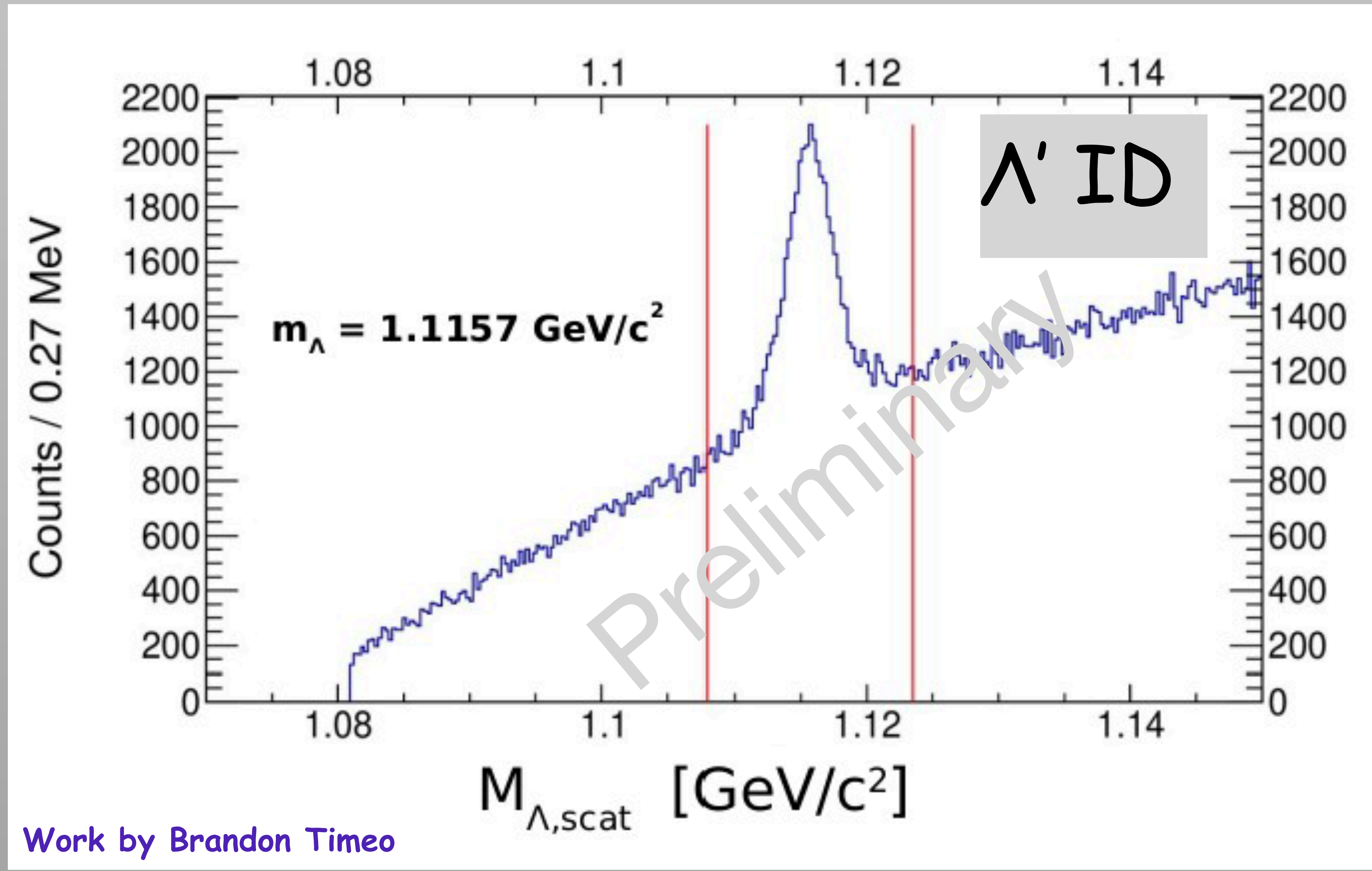
  (H. Garcilazo et al, Phys. Rev. C 75, 034002 (2007); B. Ghaffary Kashef, L. Schick, Phys. Rev. D 3, 2661 (1971), J. Hetherington, L. Schick, Phys. Rev. 139, B1164 (1965))

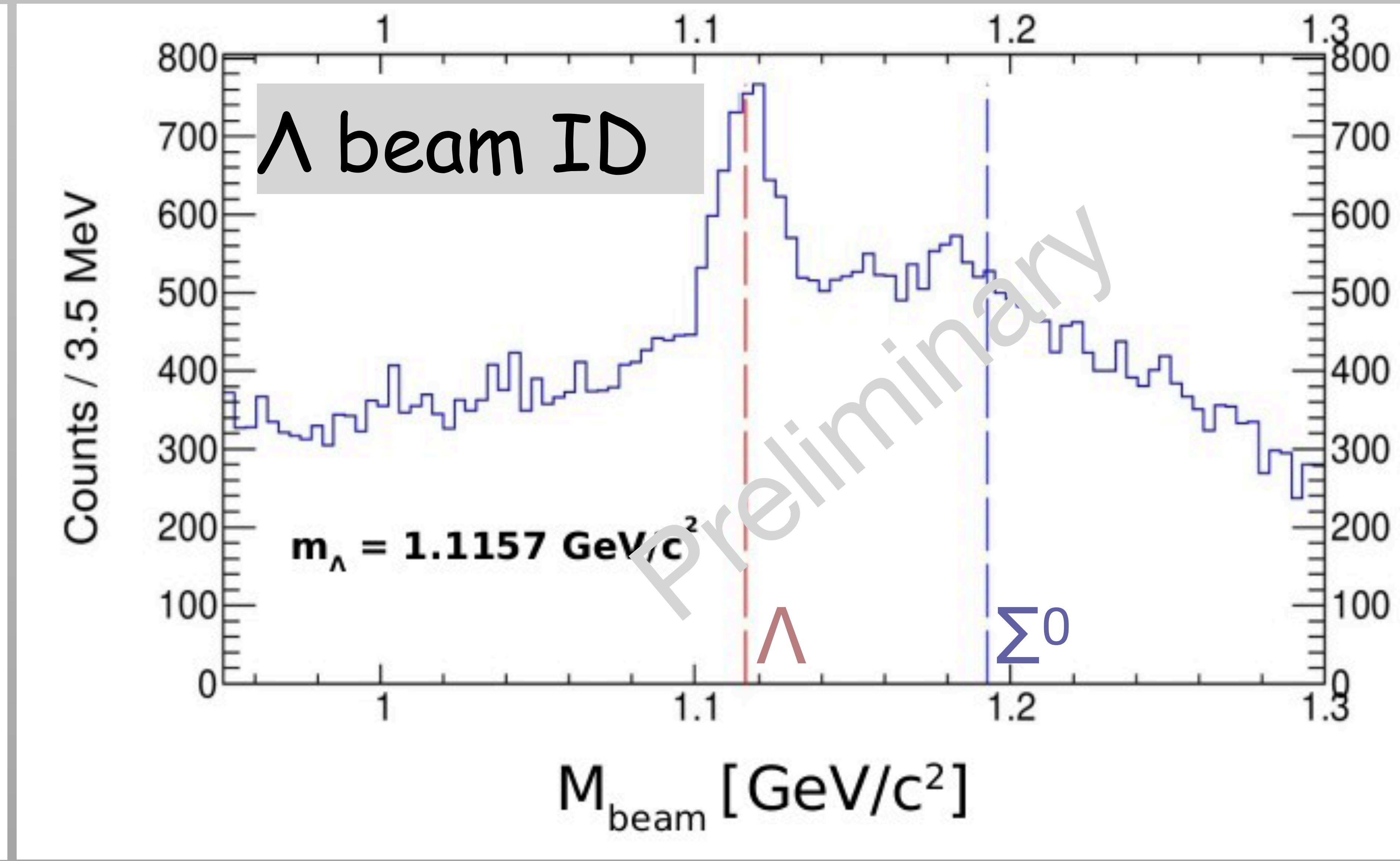
Measurement of $\Lambda d \to \Lambda d$ Cross Section

Technique 1: Applied to g13a data set

Event Selection







detected: π^-, p, d'

$$\tilde{p}_{\Lambda'} = \tilde{p}_{\pi^-} + \tilde{p}_p$$

$$\tilde{p}_{\Lambda} = \tilde{p}_{\Lambda'} + \tilde{p}_{d'} - \tilde{p}_{d_2}$$

At (1): inclusive Λ photo production to increase luminosity for (2)

Parallel analysis to extract $N_\Lambda(p_\Lambda)$ for $\gamma d \to \Lambda X$

Technique allows for adding circularly- and linearly-polarized data sets in a coherent way.

Measurement of $\Lambda d \to \Lambda d$ Cross Section

Technique 1: Applied to g13 data set

Expected Results

About 4000 elastic Λd events

Total Cross section

p_Λ(GeV/c)	$\delta_\sigma^{stat}/\sigma$(%)
0.6, 0.7	4
0.7, 0.8	4
0.8, 0.9	5
0.9, 1.0	5

For each momentum bin, differential cross section over $-0.6 < \cos\theta^*_{\Lambda'} < 0.8$

S-wave differential cross sections extracted by means of Legendre Polynomial Fits

Λ' induced polarization will be determined

Conclusion

The CLAS Collaboration has been carrying a robust experimental program to study the YN interaction in YN and YNN scattering using high-statistics photoproduction experiments.

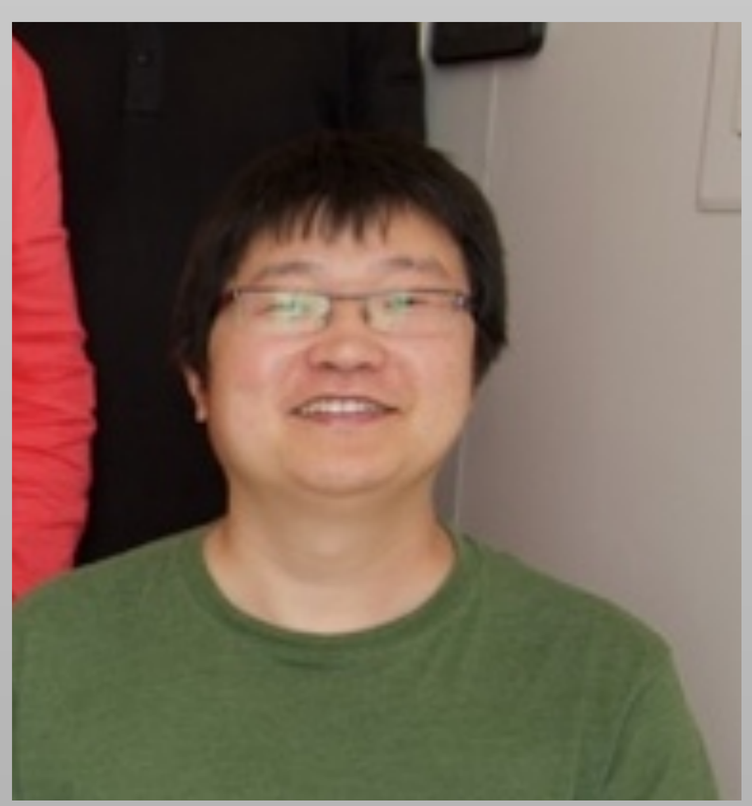
Λp elastic total cross sections for $p_\Lambda = 0.9 \div 2.0$ GeV/c are now published. Direct-scattering technique established.

Large set of polarization observables for Λn FSI has been determined. Work on reducing model dependence of interpretation in progress.

Feasibility of extraction of Λd elastic cross section established. Work on extracting cross sections and Λ induced polarization in progress.

The People

Nick
Zachariou



Tongtong
Cao

Joey
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