Search for the “$\bar{K}NN$” bound state in $d(K^-, \Lambda p)\pi^-$ reaction at K1.8BR E31 exp.

Rie MURAYAMA
RIKEN

For the J-PARC E31 collaboration

Outline
1. “KNN” at E31
2. Approach beyond significant reactions
3. Current understanding

Kaonic nuclei "K̄NN"

- Nuclear system with Kbar mesons.
- Based on Strong KbarN (I=0) attraction.

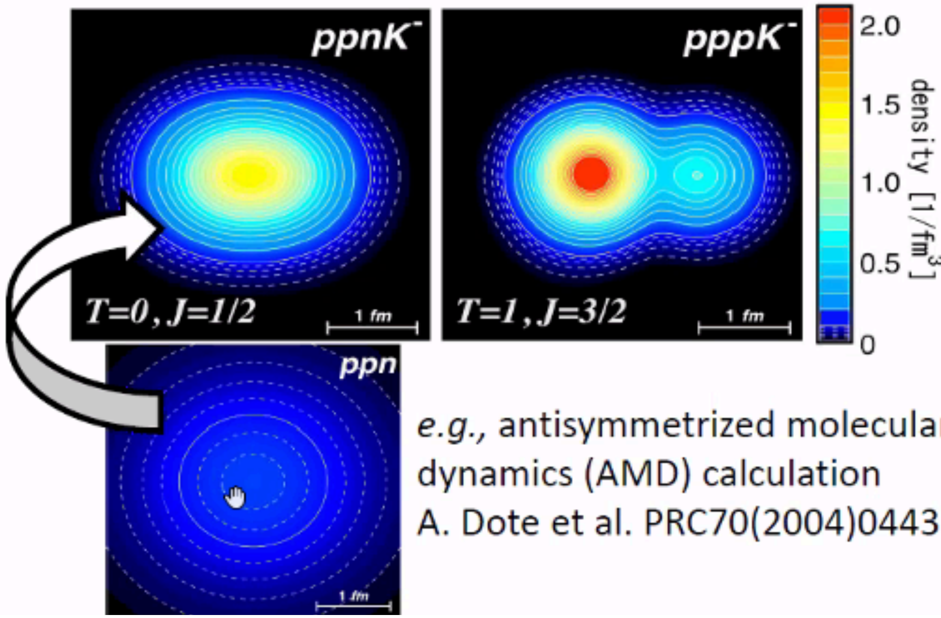
Excited hyperon Λ(1405) as KbarN quasi-bound state

  - Kbar meson should bound in a nucleus with large binding energy.
  - "KbarNN" is the simplest Kaonic nucleus to investigate.

Expected as

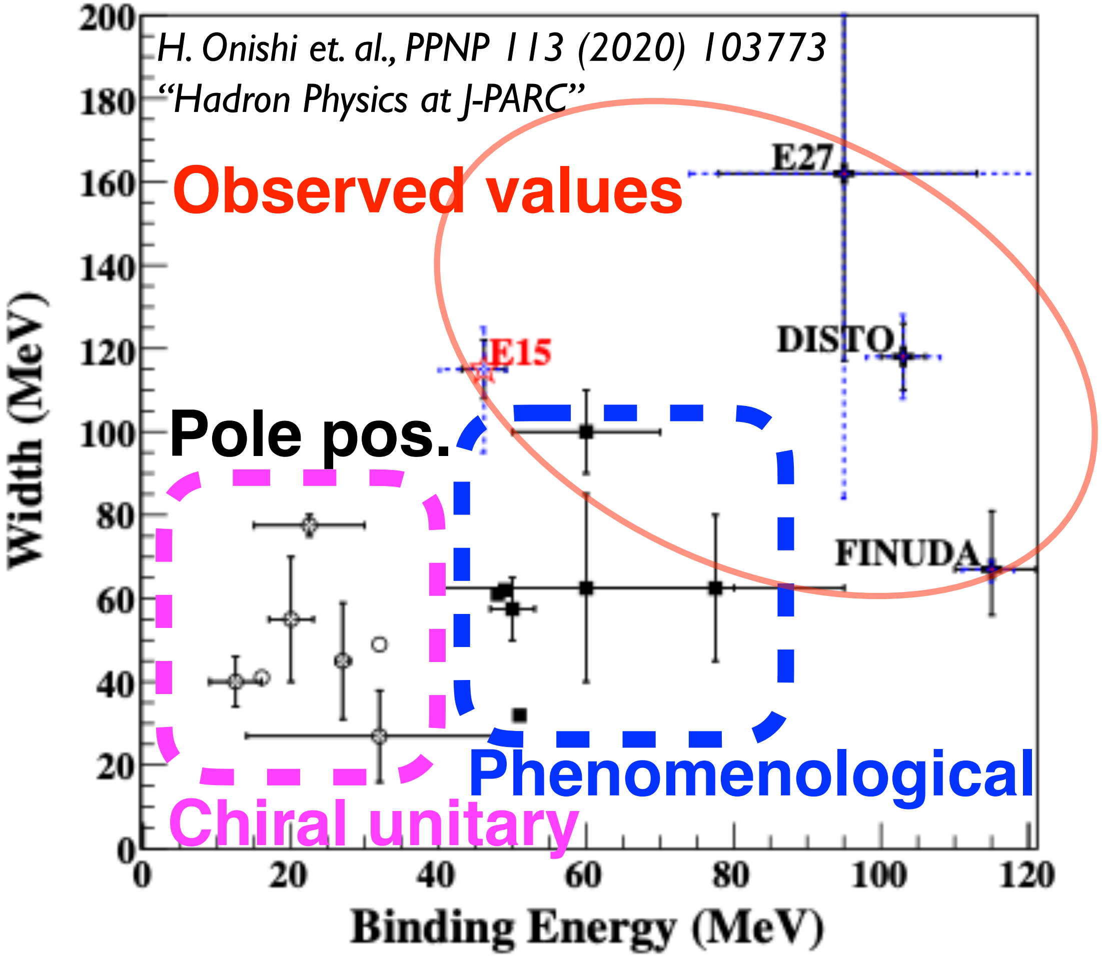
- "Cold and Dense" state.
- Anti-quark in matter.

Good probe for low energy QCD.



e.g., antisymmetrized molecular dynamics (AMD) calculation
A. Dote et al. PRC70(2004)044313.

Theories and experiments on "$\bar{K}NN$"



- E15 at K1.8BR J-PARC

  $^3He(K^-, \Lambda p)n$

- E27 at K1.8 J-PARC PTEP(2015)021D01.

  $d(\pi^+, K^+)\Lambda p \, / \, \Sigma^0 p$

  Inverse reaction $dK^- \rightarrow \Lambda p \pi^-$ has be taken at K1.8BR.

- DISTO PRL**104**(2010)132502

  Intermediate $N^* \rightarrow pK^+$?

  $pp \rightarrow p\Lambda K^+$

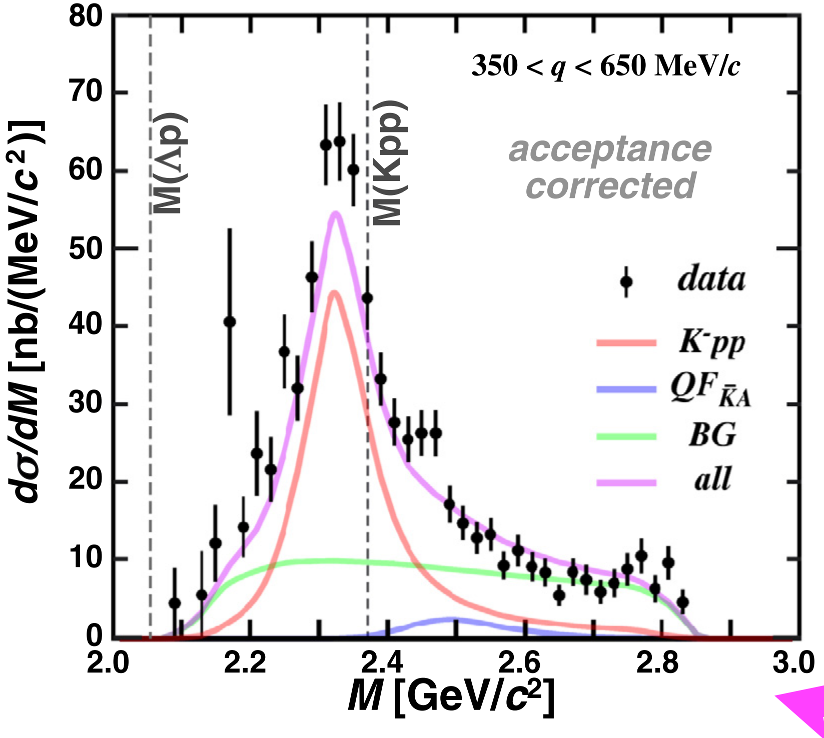
- FINUDA PRL**94**(2005)212303

  Multi-NA processes?

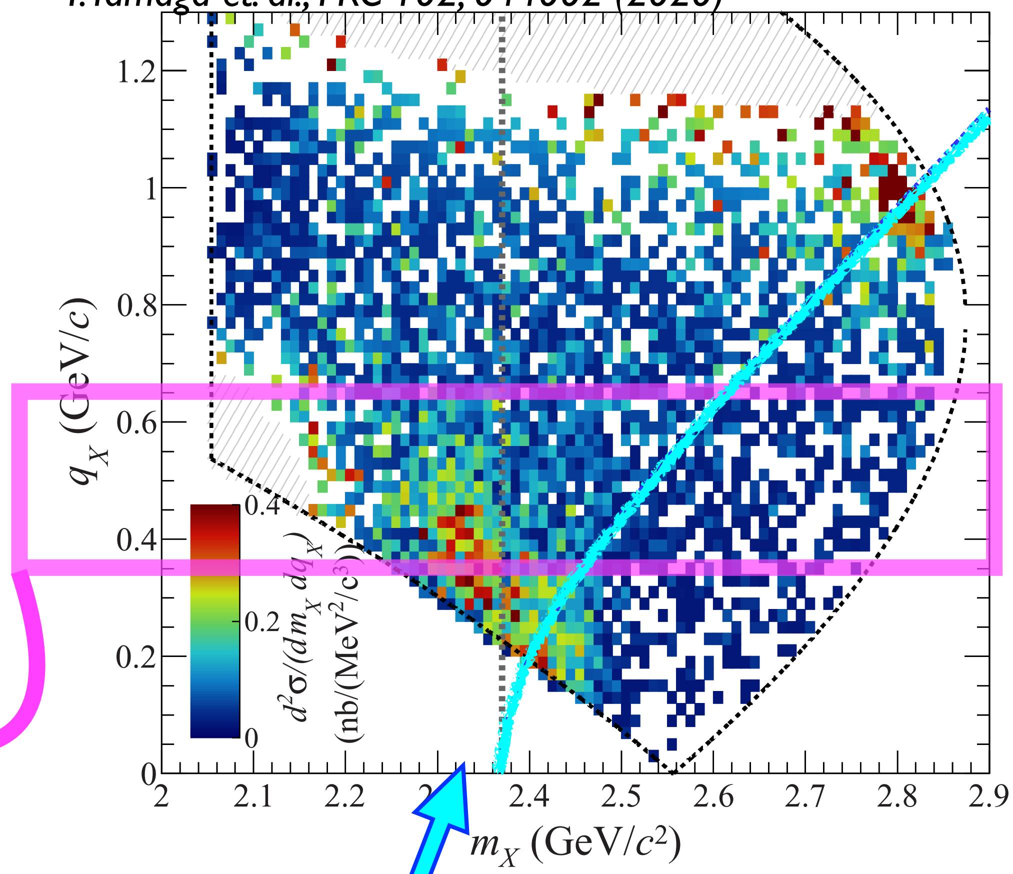
  $(K_{stop}^+, \Lambda p)$

Result of J-PARC E15

J-PARC E15 exp. ^{3}He(K$^-$,Λp)n
S. Ajimura et. al., PLB 789, 620 (2019)



J-PARC E15 exp. ^{3}He(K$^-$,Λp)n
T. Yamaga et. al., PRC 102, 044002 (2020)



0.35<q_x<0.65
Projection

Quasi-free KN→Kn, KNN→Λp

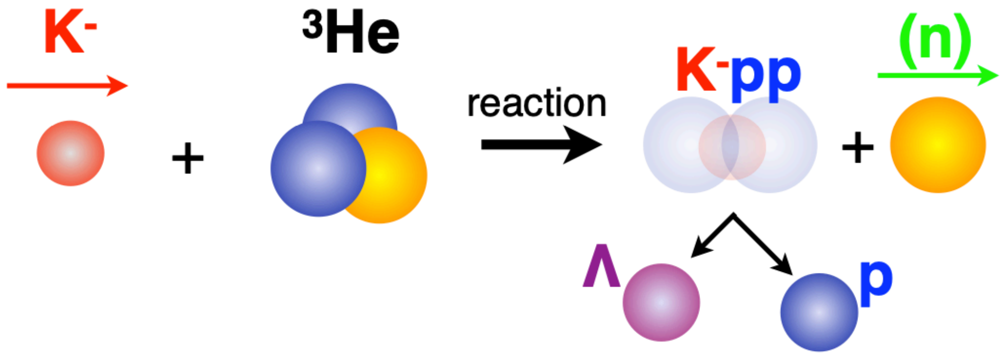
$$M_F(q) = \sqrt{4m_N^2 + m_K^2 + 4m_N\sqrt{m_K^2 + q^2}},$$

- Momentum transfer q
  $q(\Lambda p) = p_k - p_n$

The advantage is the q dependence to understand background processes.

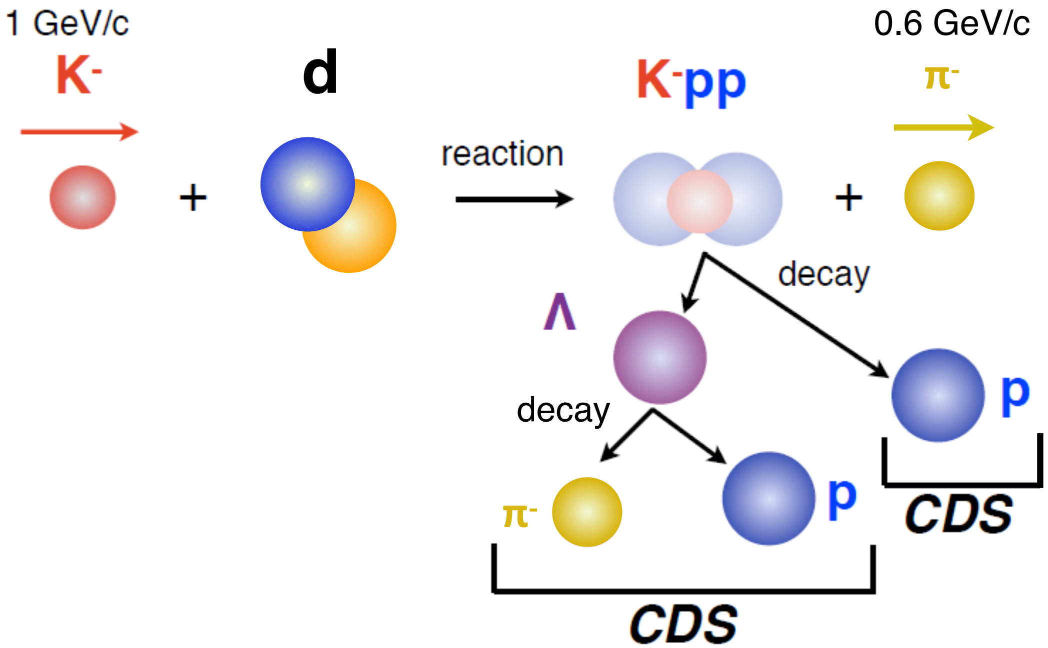
d(K⁻, Λp)π⁻ reaction

J-PARC E15



J-PARC E31

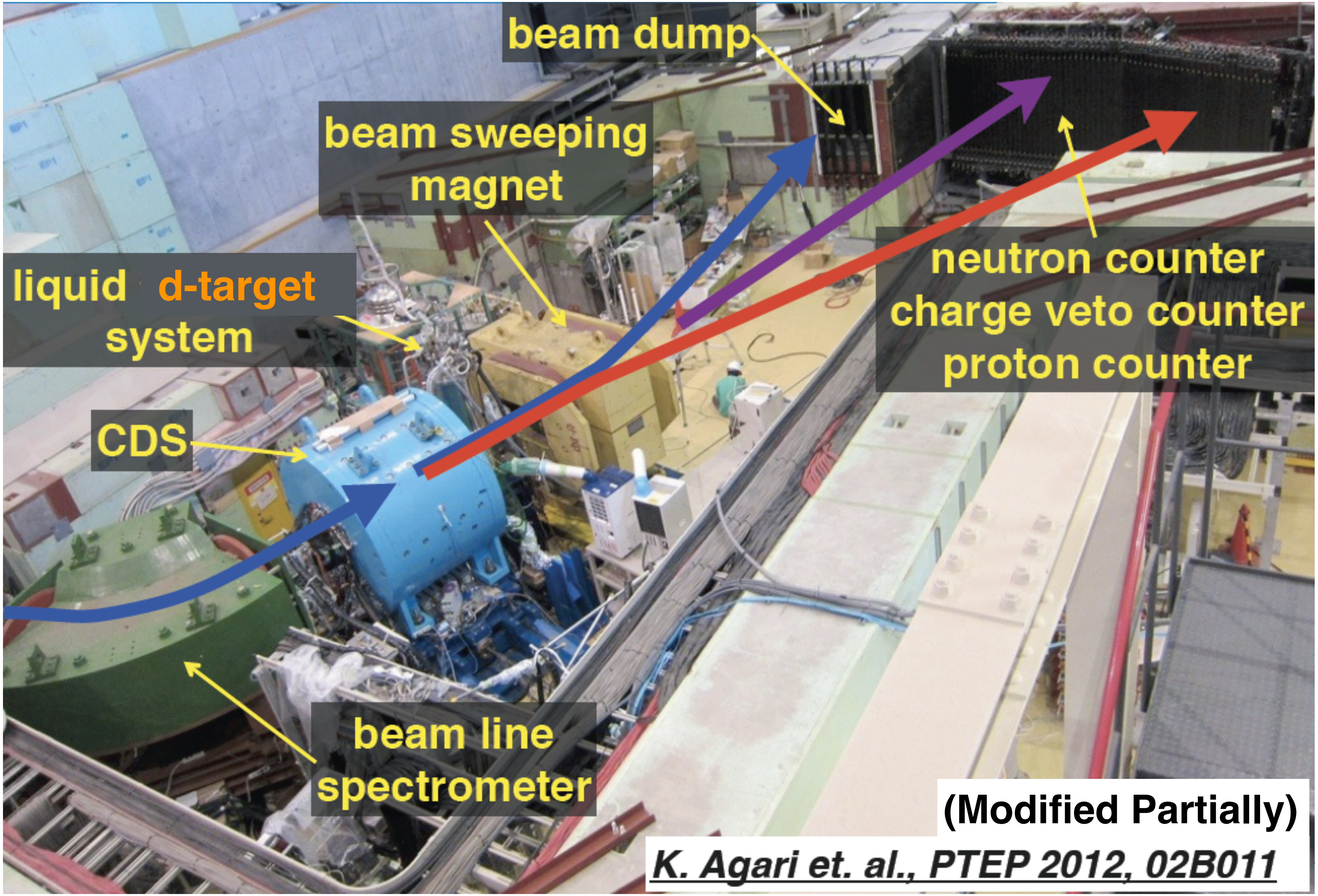
This talk.



Missing.

Tracking and time-of-flight.

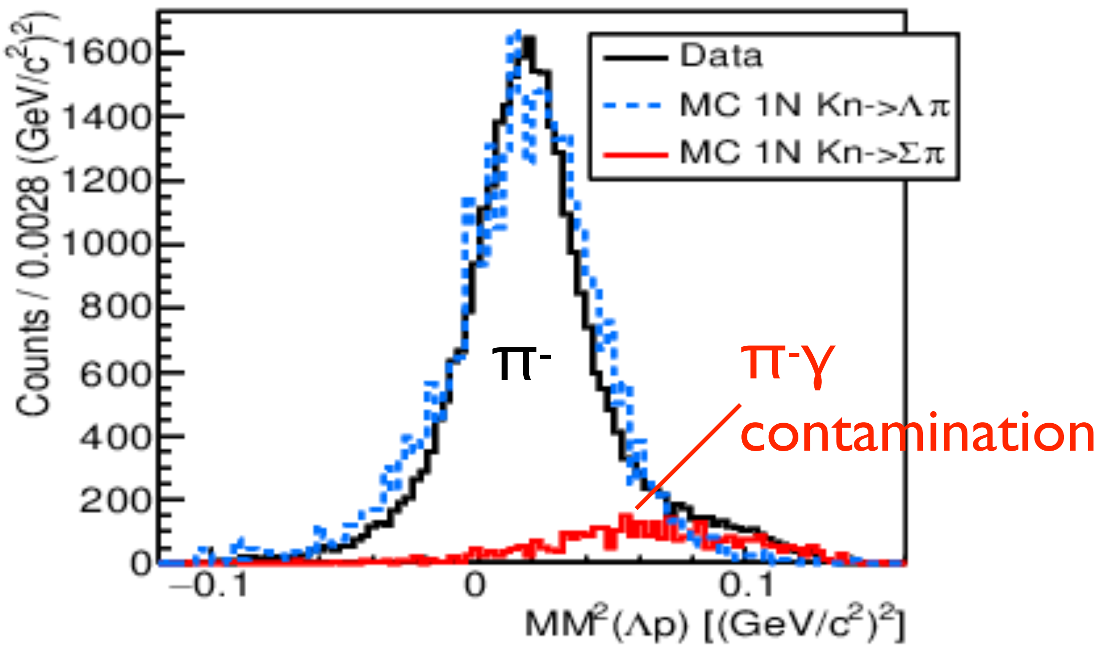
Experimental Setup at K1.8BR



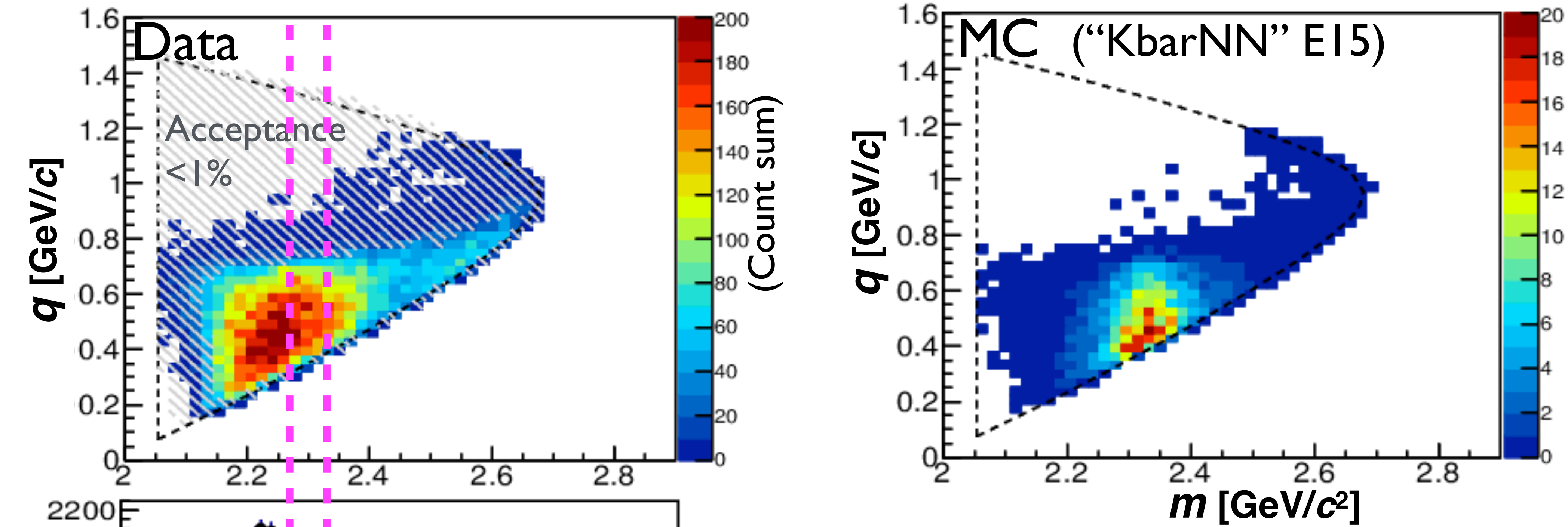
Event selections

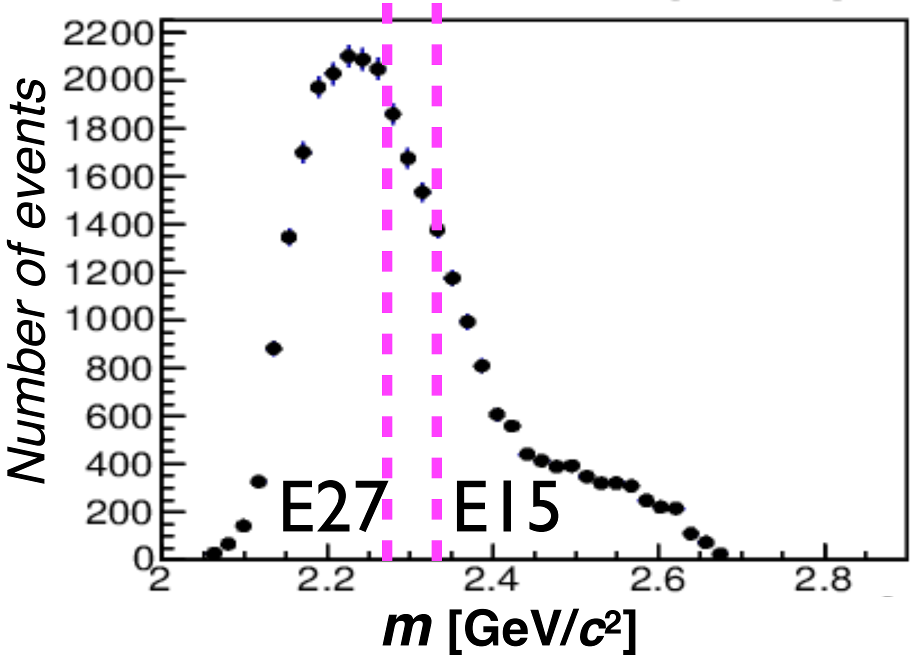
- $pp\pi$ event selection in CDS.
- $\Lambda \rightarrow p\pi^-$ pairs selection: Likelihood method on closest distance approach.
- Missing pion selection: χ^2 method on kinematical refit to conserve energy-momentum.

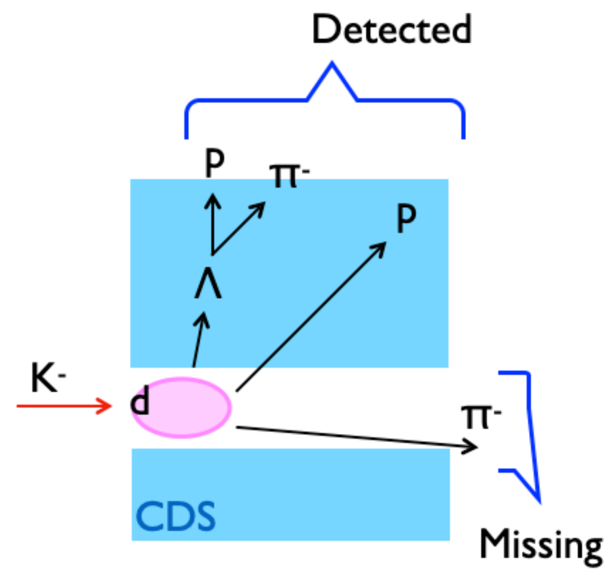
Square of Λp missing mass after applying all the event selections



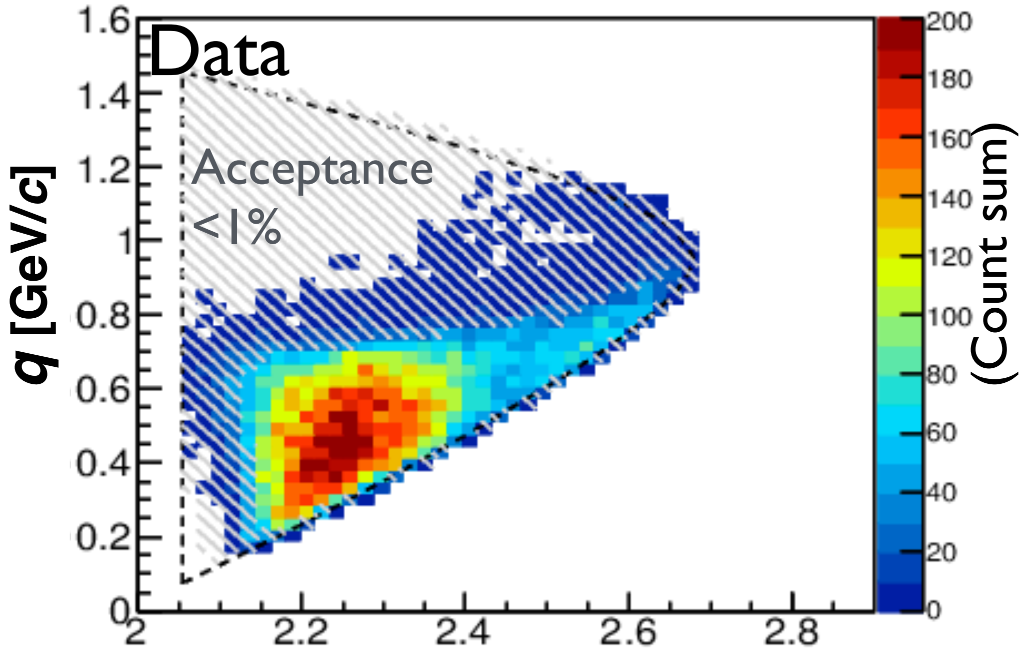
Λp distribution (1/2)

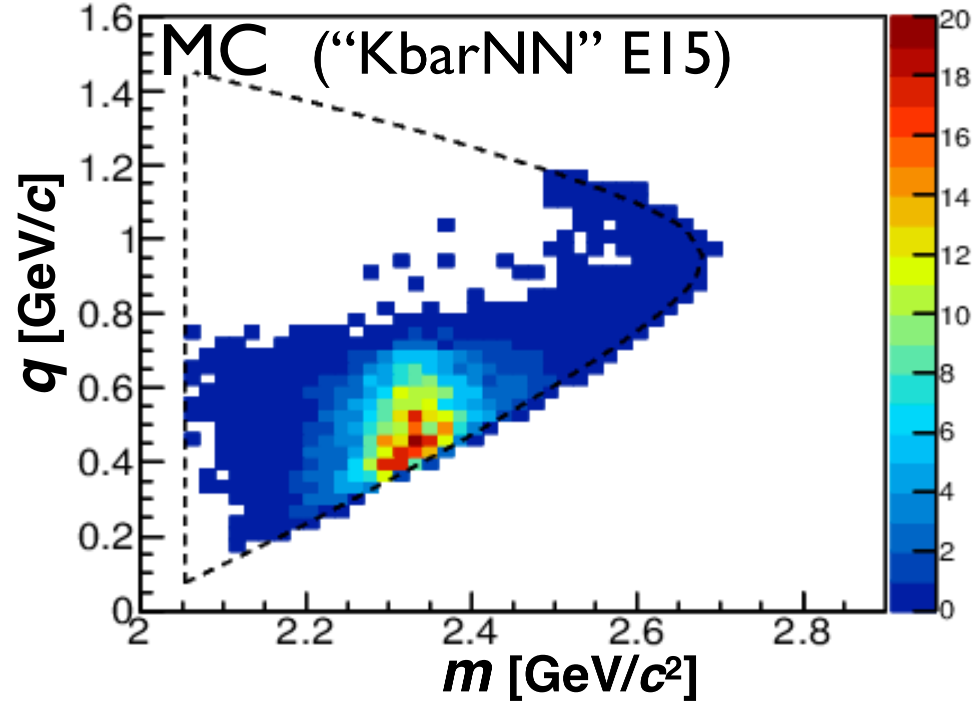


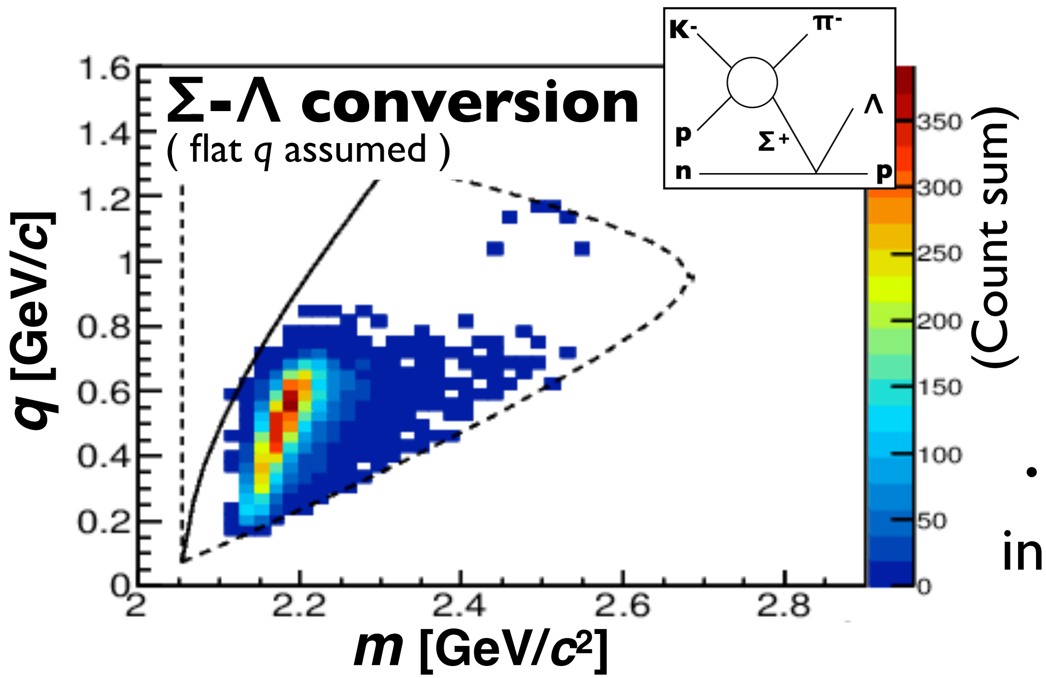




Λp distribution (2/2)







・ Σ-Λ conversion was not significant in “KbarNN” region.

Event distribution of $\Lambda p \pi^-$ final state

kinematical Degree-of-Freedom = 4

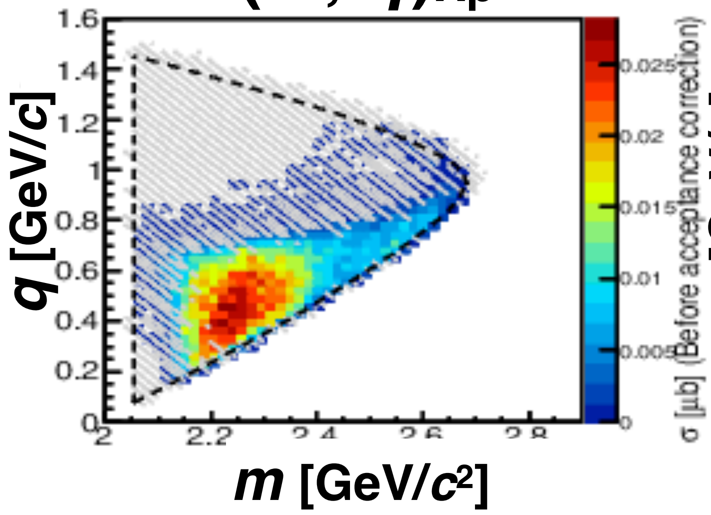
9 (3 on-shell particles) - 4 (energy-momentum conservation) - 1 (ϕ symmetry)

3 (m, q)-plots are ***more than sufficient*** to identify the event kinematics

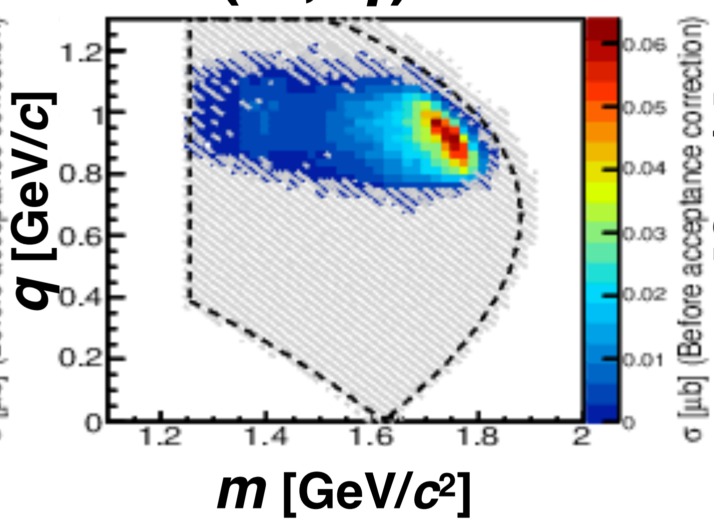
➡ We can specify reaction dynamics by these 3 plots

m : invariant mass of a pair ***q*** : momentum transfer to the pair

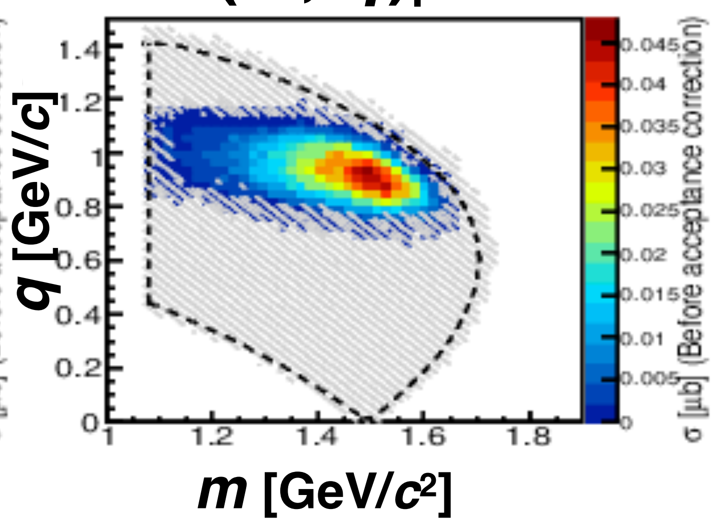
$(m, q)_{\Lambda p}$



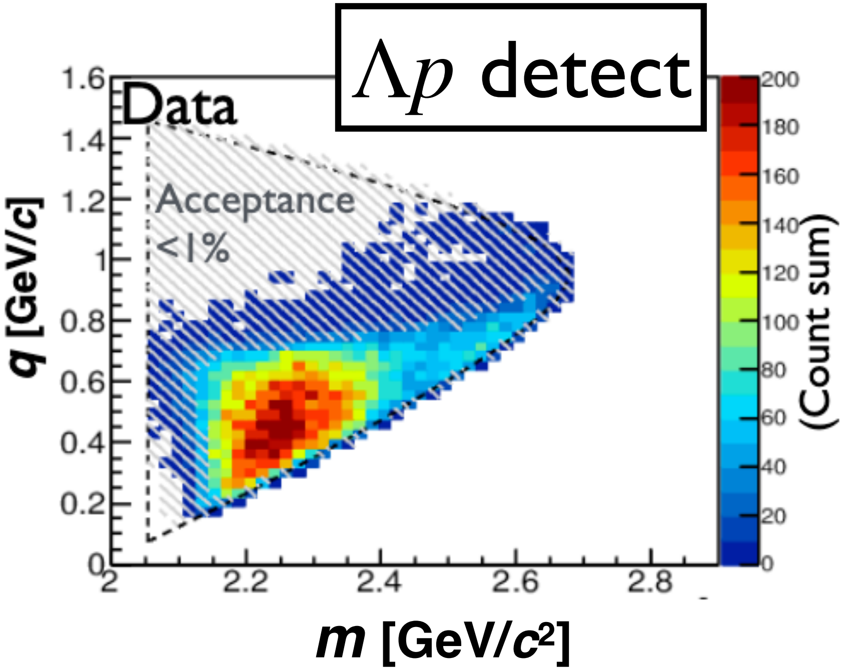
$(m, q)_{\Lambda \pi^-}$

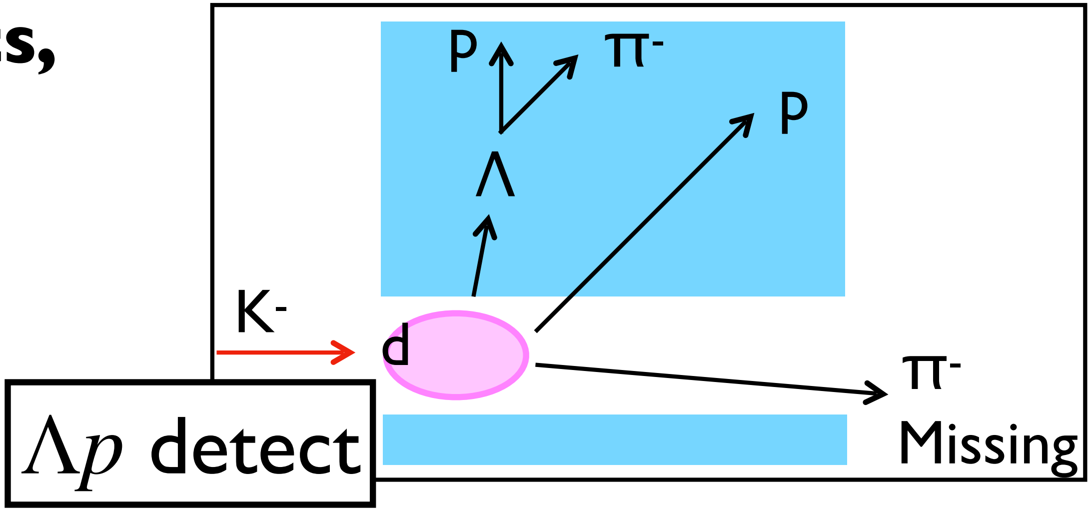


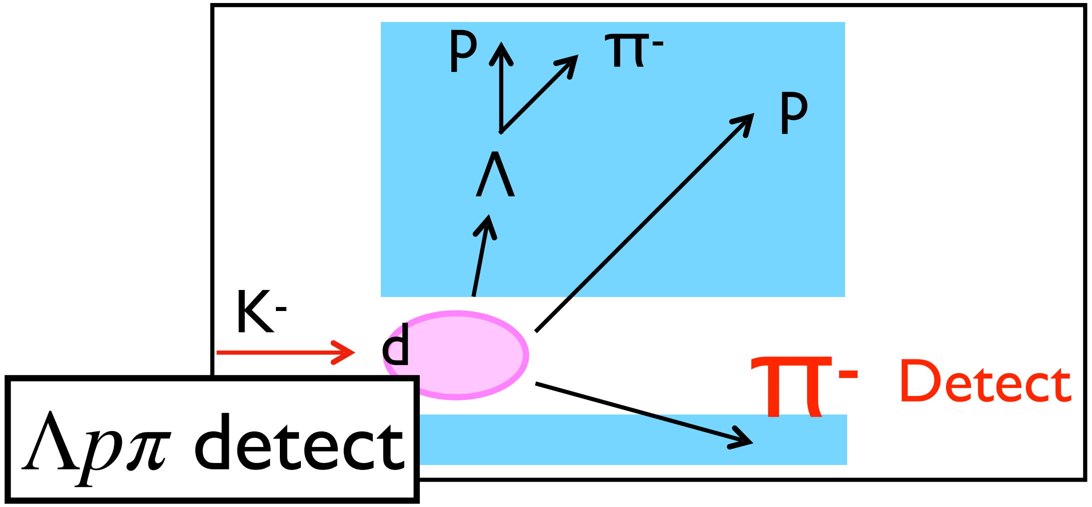
$(m, q)_{p \pi^-}$

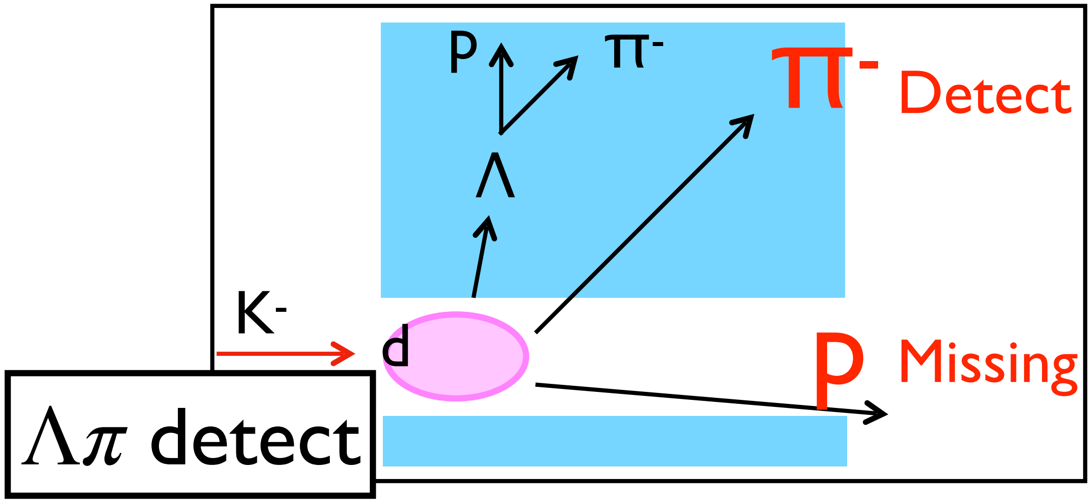


To know reaction dynamics, we need to expand the acceptance on (m, q).

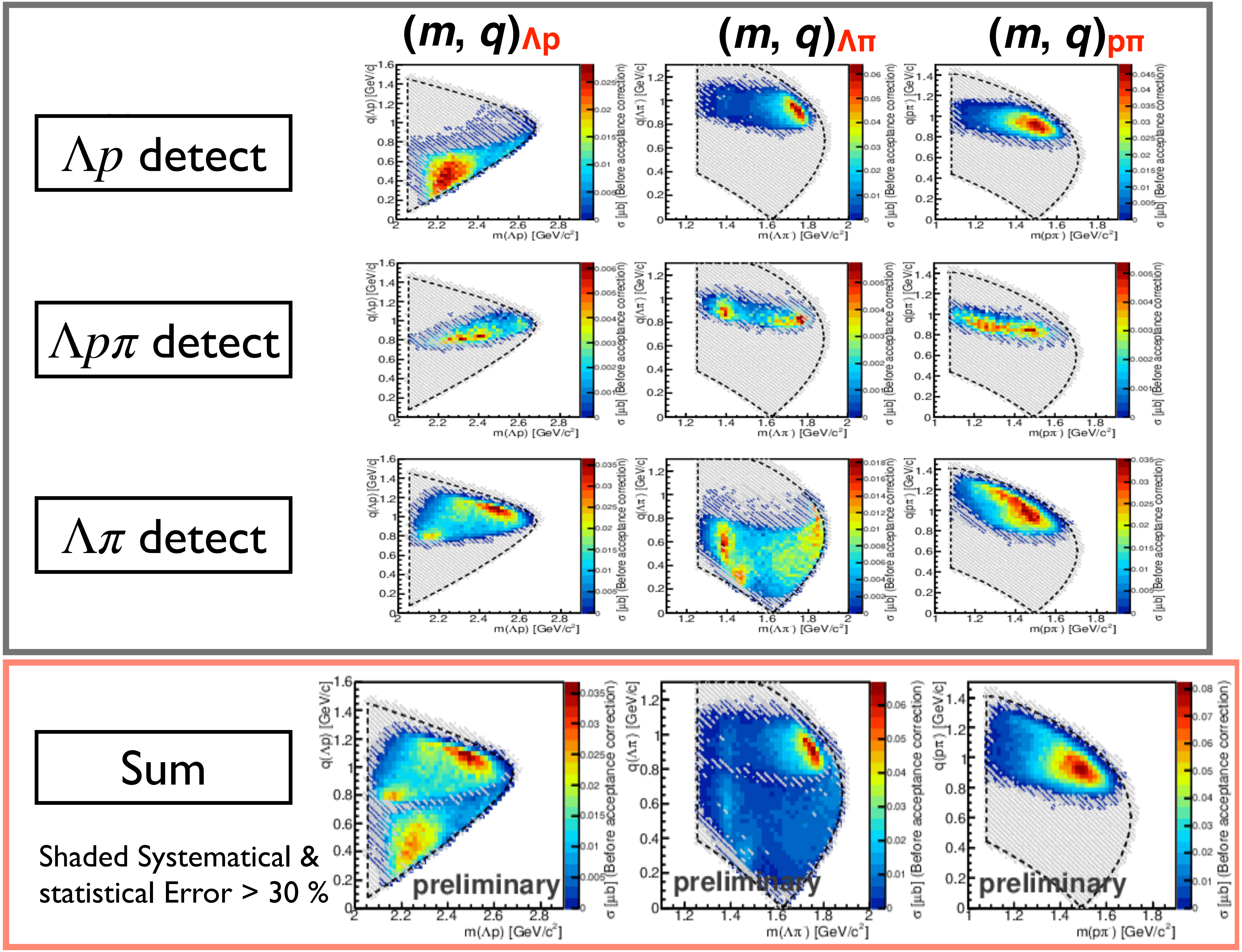








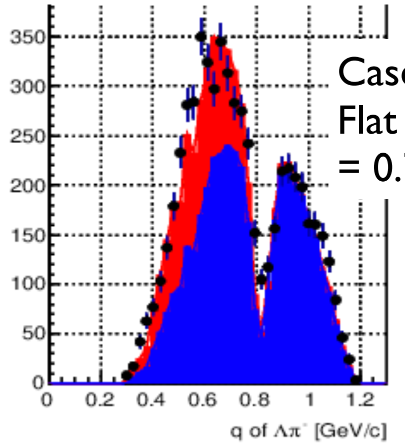
When we require Λ detection, there are three possible event geometries to identify $\Lambda p \pi^-$ final state.



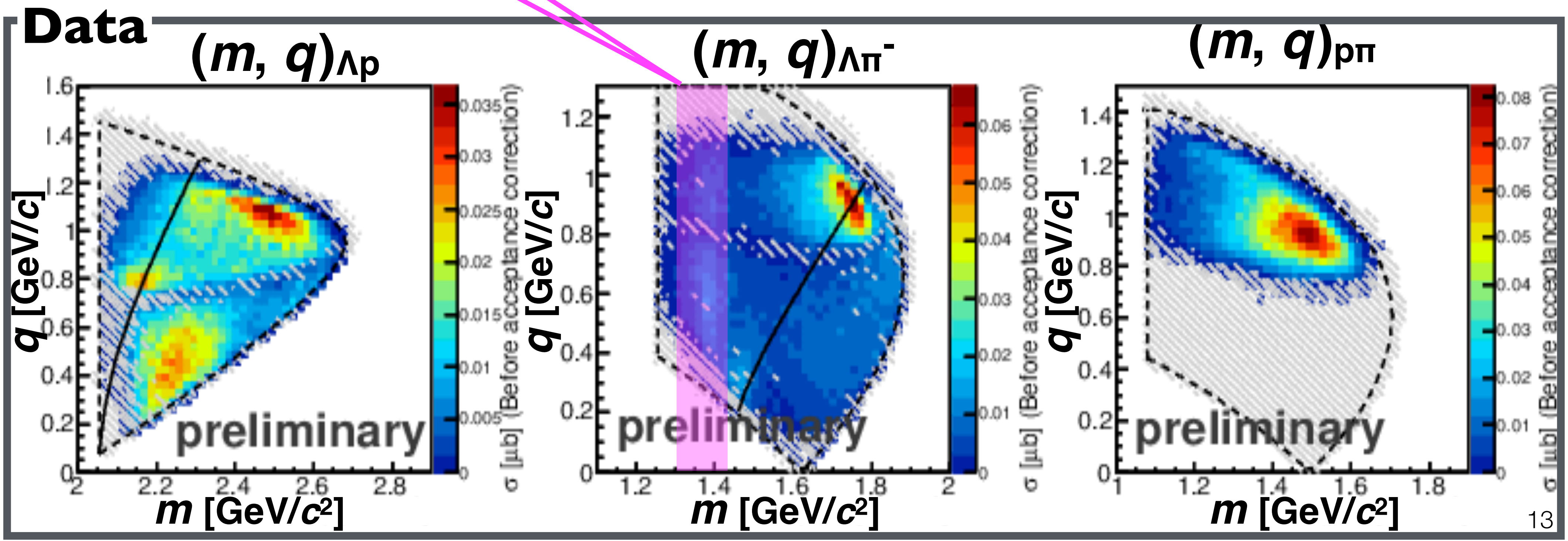
(m, q)Λp
(m, q)Λπ
(m, q)pπ
Λp detect
Λpπ detect
Λπ detect
Sum
Shaded Systematical & statistical Error > 30 %
preliminary
preliminary
preliminary
m(Λp) [GeV/c²]
q(Λp) [GeV/c]
m(Λπ⁻) [GeV/c²]
q(Λπ⁻) [GeV/c]
m(pπ⁻) [GeV/c²]
q(pπ⁻) [GeV/c]
σ [μb] (Before acceptance correction)

Knowledge from reaction dynamics (m, q)

$K^- d \rightarrow \Sigma(1385)p$

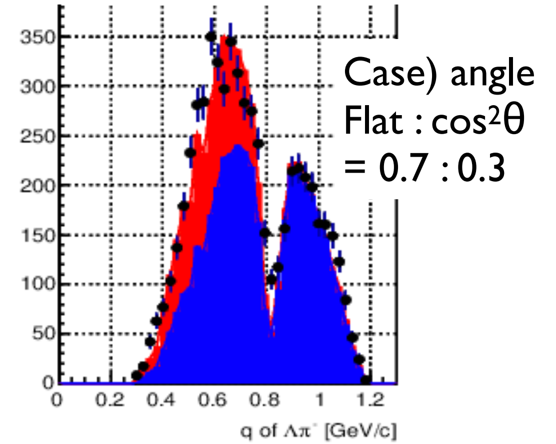


- Clearly identified.



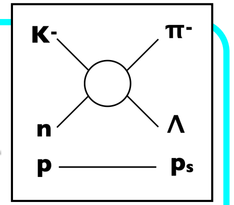
Knowledge from reaction dynamics (m, q)

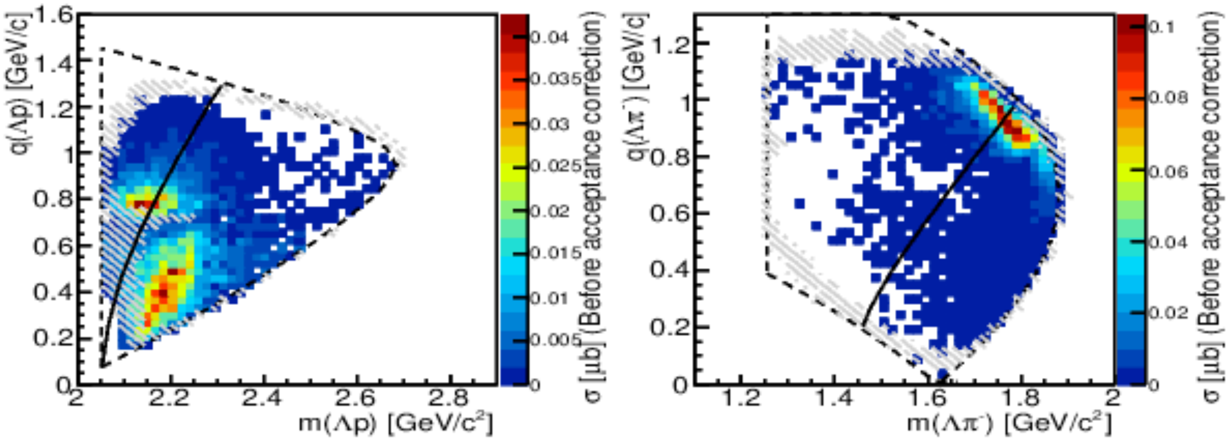
$K^- d \to \Sigma(1385)p$



・Clearly identified.

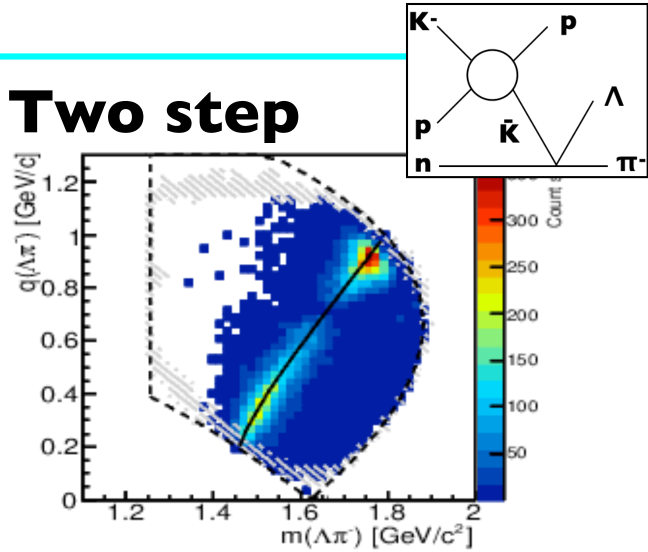
$\bar{K} N \to \Lambda\pi^-$ One nucleon





・Seems dominant.

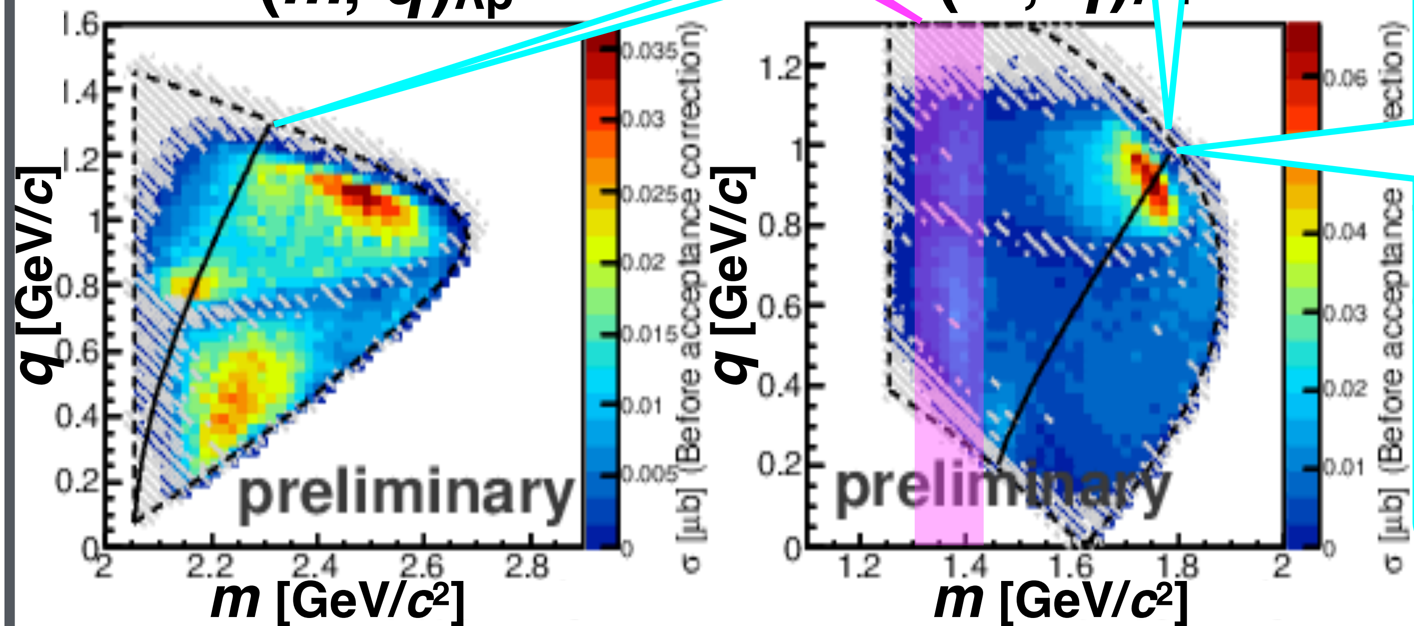
Two step



・Not dominant.

・Not just angle of elementary processes.

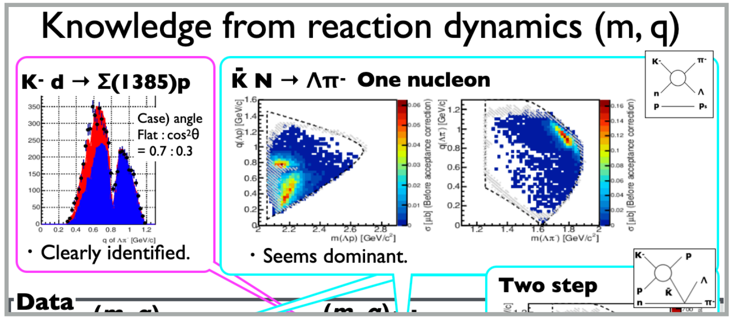
Data



Approach for further estimation

1) **Rely on clear reactions**
2) **Assume reactions near “KbarNN” region**
3) **Evaluate w/ momentum transfer dependence**

Approach (1/3)



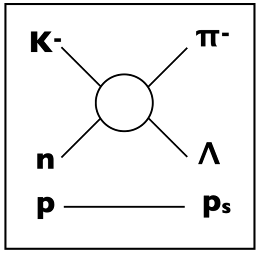
1) Rely on clear reactions

K- d → Σ(1385)p

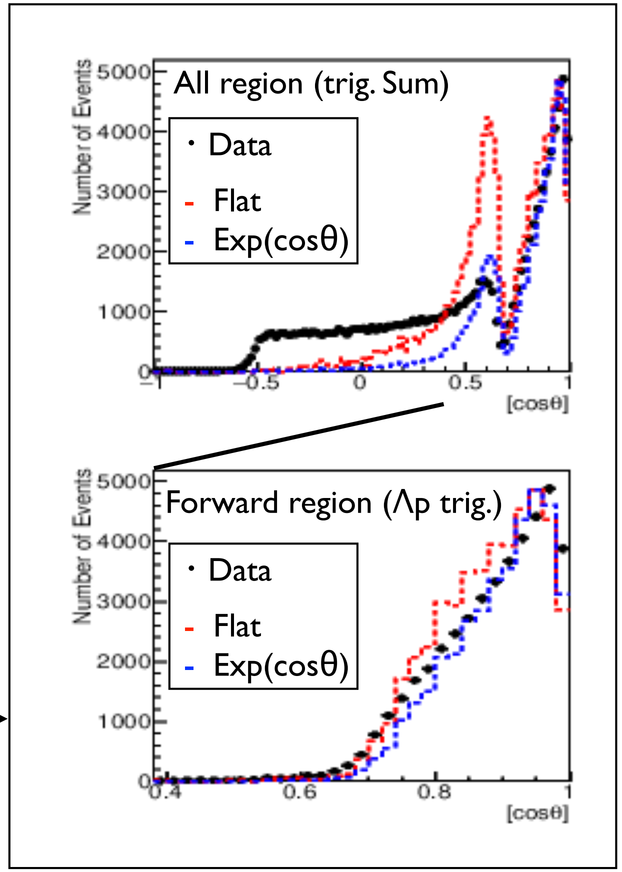
- Creation angle distribution.

K̄ N → Λπ-

One nucleon



- Tail component of fermi-motion including D-wave.
- π- angle to reproduce data.



Approach (2/3)

2) Assume reactions near "KbarNN" region

- Σ*s … M and Γ based on PDG

Σ(1660) 1/2$^+$ $I(J^P) = 1(\frac{1}{2}^+)$

Re(pole position) = 1585 ± 20 MeV
−2Im(pole position) = 290^{+140}_{-40} MeV
Mass m = 1640 to 1680 (≈ 1660) MeV
Full width Γ = 100 to 300 (≈ 200) MeV

Σ(1775) 5/2$^-$ $I(J^P) = 1(\frac{5}{2}^-)$

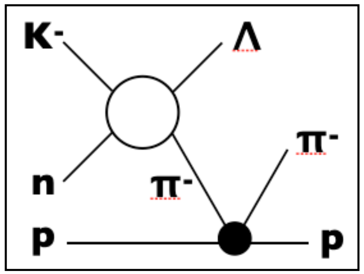
Mass m = 1770 to 1780 (≈ 1775) MeV
Full width Γ = 105 to 135 (≈ 120) MeV

Particle	J^P	Overall status	Status as seen in — $N\overline{K}$	$\Lambda\pi$	$\Sigma\pi$
Σ(1193)	1/2$^+$	****			
Σ(1385)	3/2$^+$	****		****	****
Σ(1580)	3/2$^-$	*	*	*	*
Σ(1620)	1/2$^-$	*	*	*	*
Σ(1660)	1/2$^+$	***	***	***	***
Σ(1670)	3/2$^-$	****	****	****	****
Σ(1750)	1/2$^-$	***	***	**	***
Σ(1775)	5/2$^-$	****	****	****	**
Σ(1780)	3/2$^+$	*	*	*	*
Σ(1880)	1/2$^+$	**	**	*	
Σ(1900)	1/2$^-$	**	**	*	**
Σ(1910)	3/2$^-$	***	*	*	**
Σ(1915)	5/2$^+$	****	***	***	***

https://pdg.lbl.gov/2022/reviews/contents_sports.html

Or

- pπ scatter

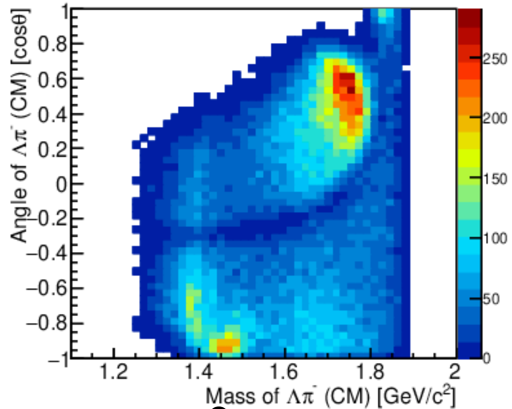


I skip today.

Approach (3/3)

3) Evaluate w/ momentum transfer dependence

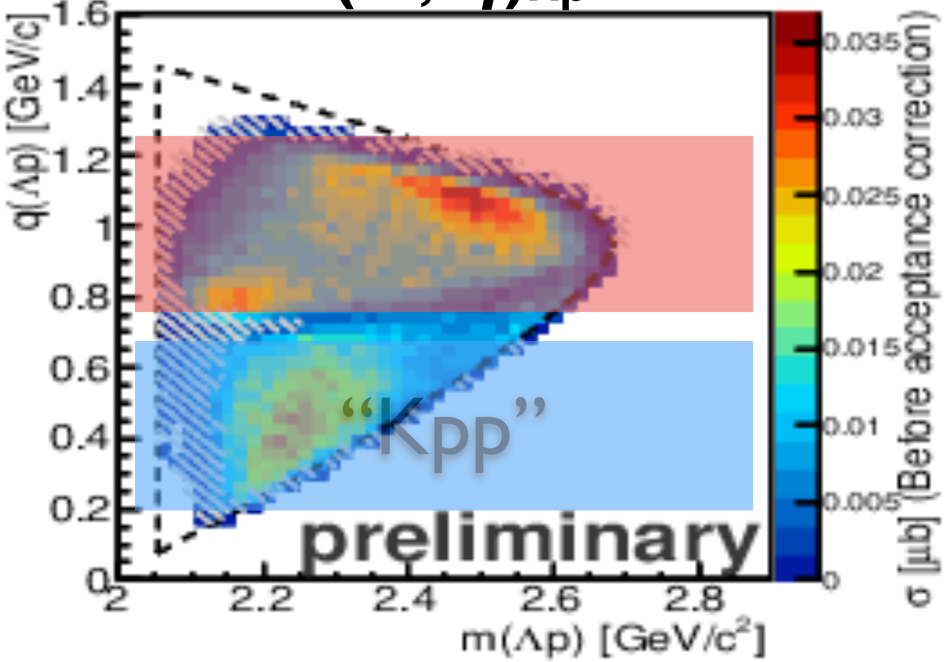
- Large $\boldsymbol{q}$ in Λp system corresponds to low $\boldsymbol{q}$ in Λπ system. The reactions in both systems and their consistencies are evaluated w/ the $\boldsymbol{q}$ dependence.



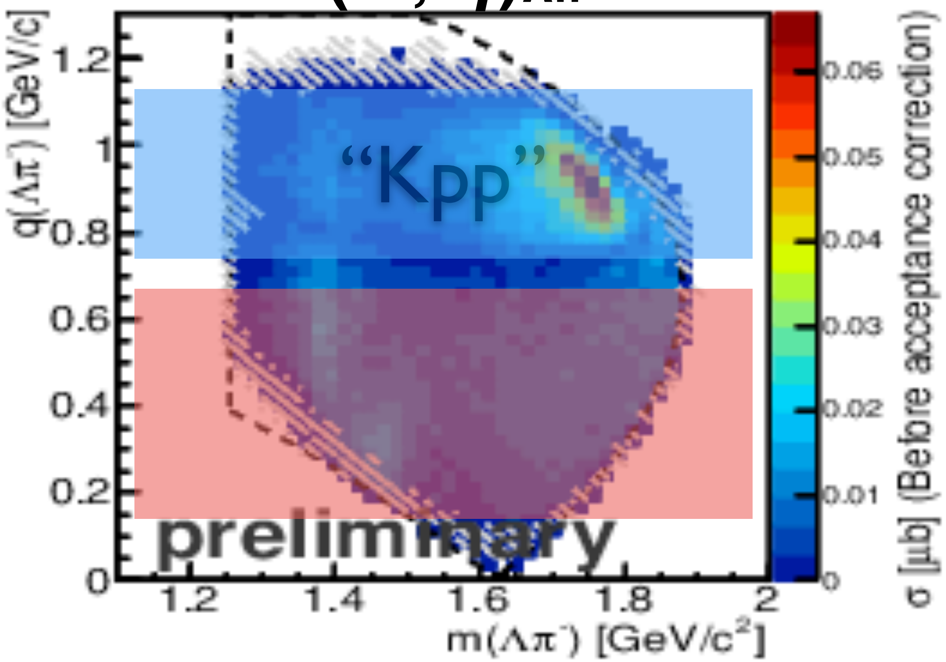
Cf) Cosθ dependence of Λπ system

Data

$(m, q)_{\Lambda p}$



$(m, q)_{\Lambda\pi^-}$

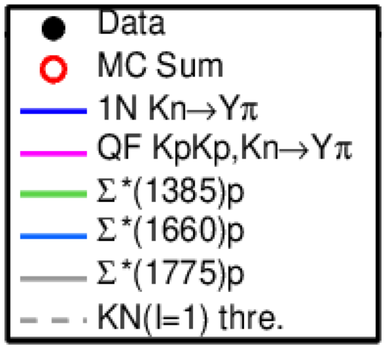


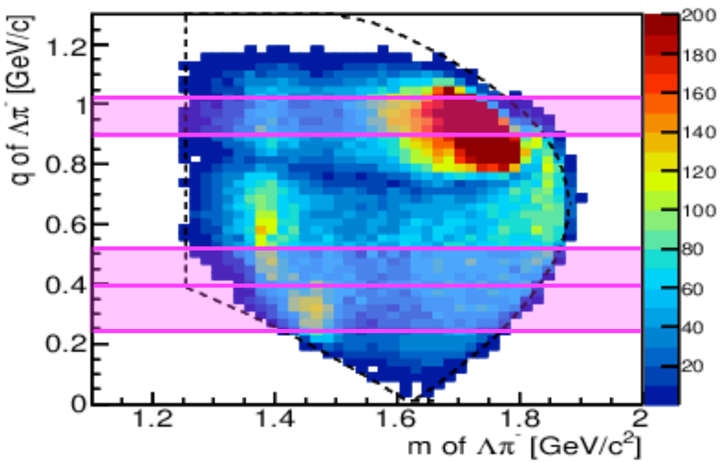
q sliced Λπ system

Σ* resonances
W/ KN threshold state

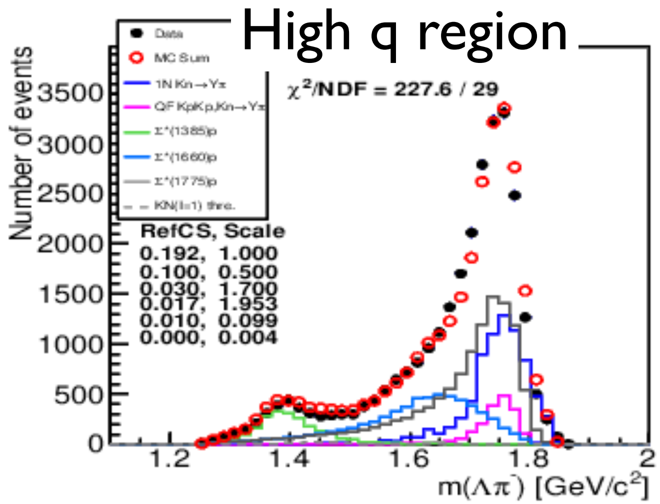
- Events in high ***q*** region are well reproduced with assumed reactions.
- In low ***q*** regions, peak near KN threshold is essential. The mass and width is under investigation.

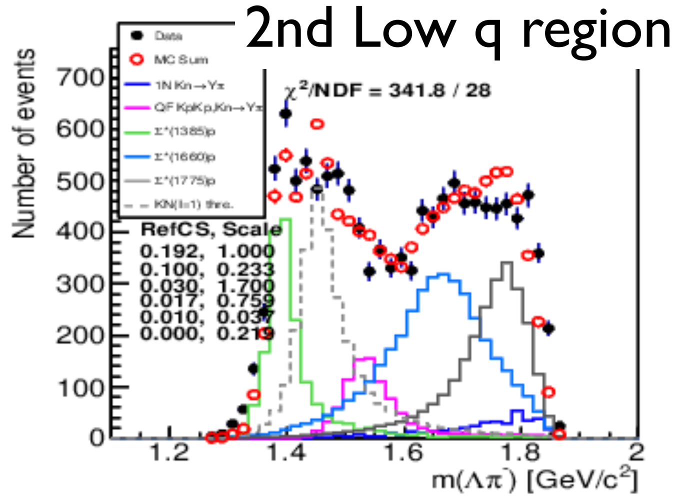
KN (I=1)… B.W. at m=1450, Γ=70 MeV

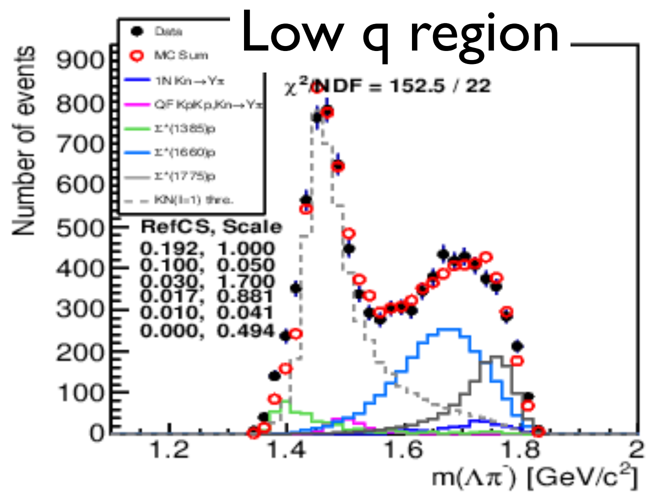




q [GeV/c]
Up: 0.88 < q < 1.04
Middle: 0.37 < q < 0.52
Down: 0.23 < q < 0.39





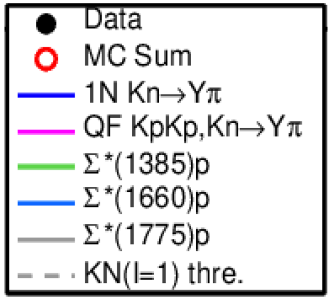


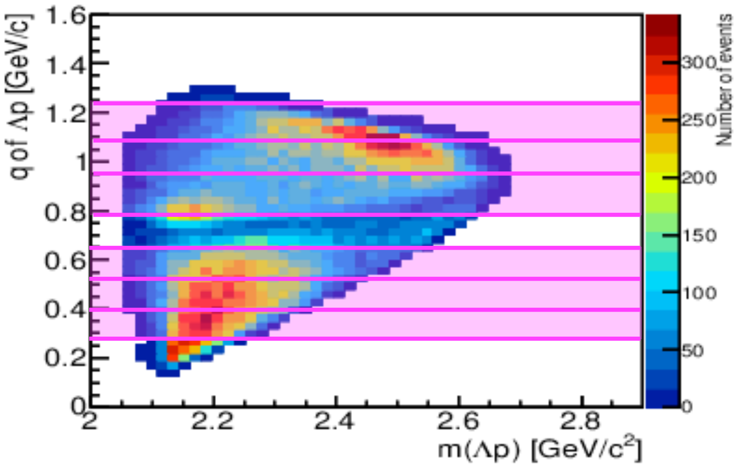
q dependence of Λp system

Σ* resonances
W/ KN threshold state

Left: low q [GeV/c]
Up: 0.51 < q < 0.64
Middle: 0.38 < q < 0.51
Down: 0.26 < q < 0.38

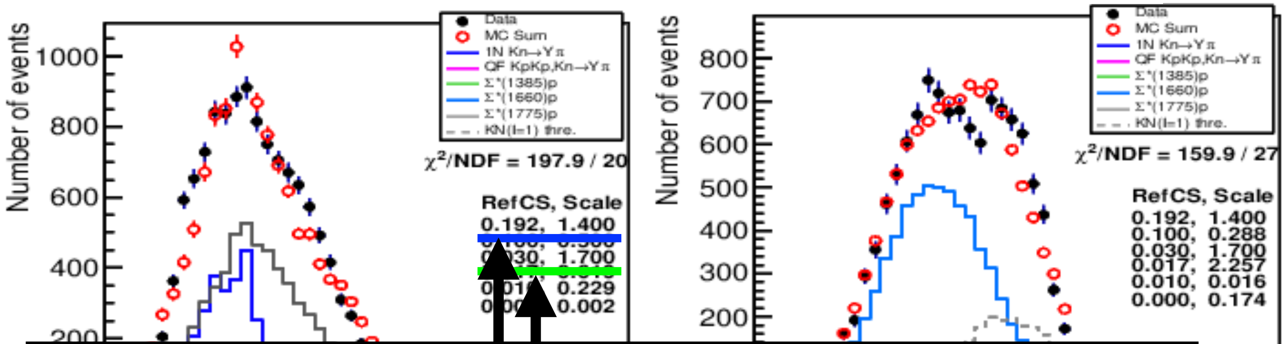
Right: high q [GeV/c]
Up: 1.09 < q < 1.25
Middle: 0.93 < q < 1.09
Down: 0.77 < q < 0.93



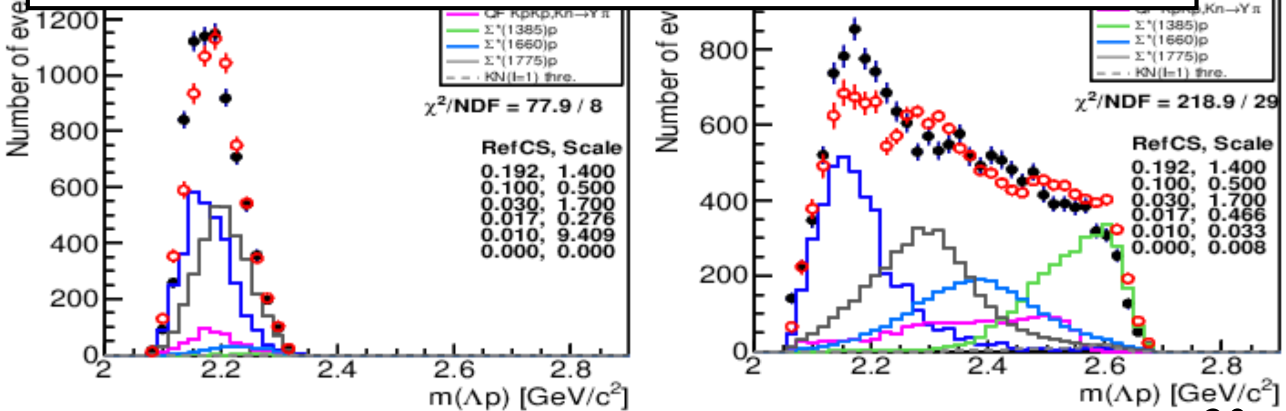


Low q region

High q region



- Cross-sections (CS) of relied reactions (1N and Σ(1385)p) are set constants in all region.
- CS of other reactions are treated as free parameters because of unknown angle distributions.

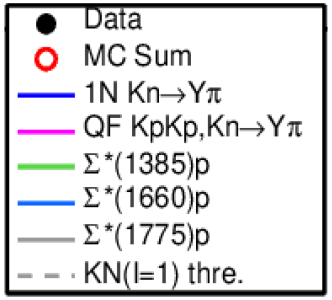


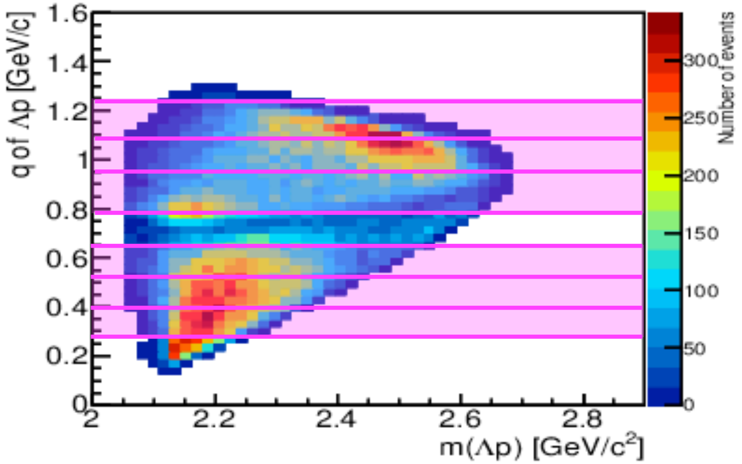
q dependence of Λp system

Σ* resonances
W/ KN threshold state

Left: low q [GeV/c]
Up: $0.51 < q < 0.64$
Middle: $0.38 < q < 0.51$
Down: $0.26 < q < 0.38$

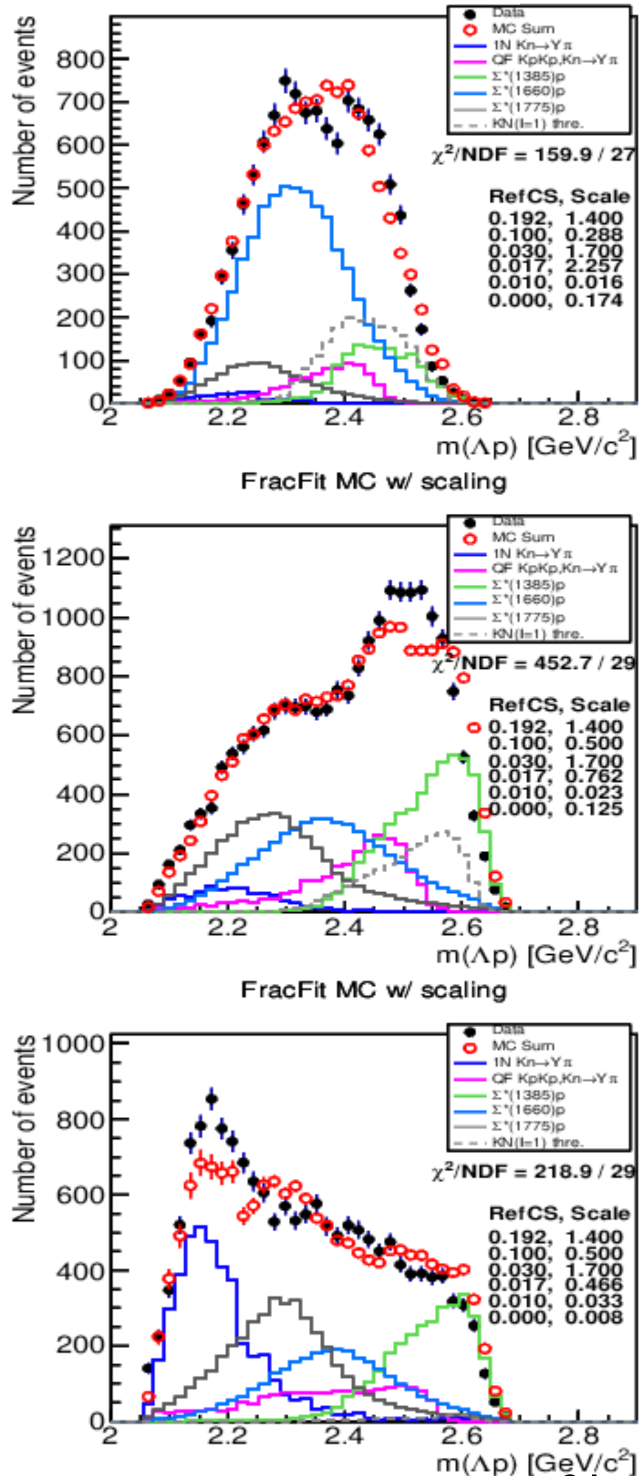
Right: high q [GeV/c]
Up: $1.09 < q < 1.25$
Middle: $0.93 < q < 1.09$
Down: $0.77 < q < 0.93$





- Due to ambiguity of shape near KN threshold seen in Λπ system, MC fitting does not reproduce data well.

High q region



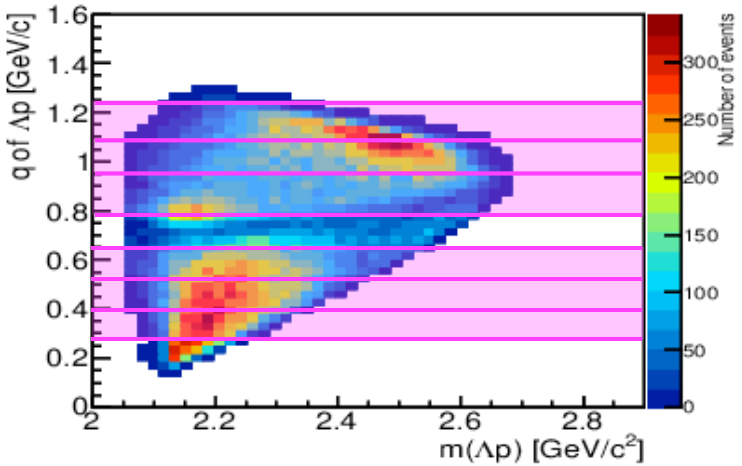
q dependence of Λp system

Σ* resonances
W/ KN threshold state

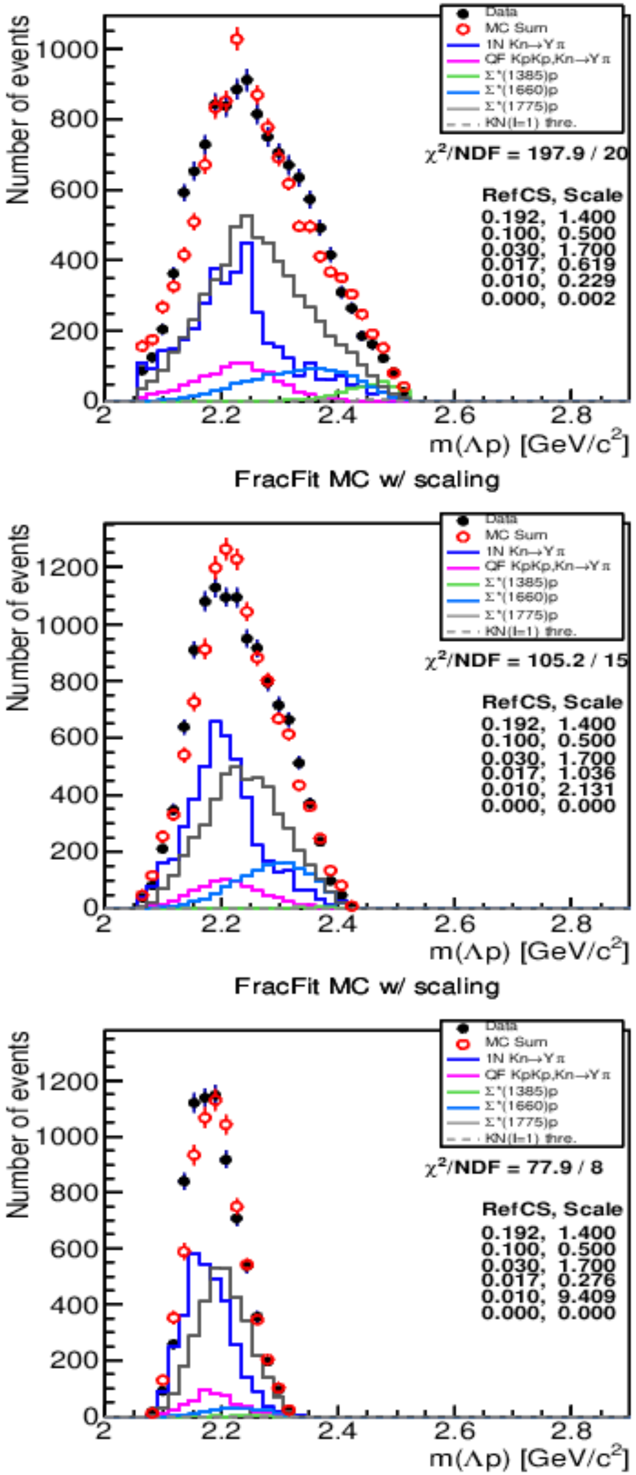
Left: low q [GeV/c]
Up: $0.51 < q < 0.64$
Middle: $0.38 < q < 0.51$
Down: $0.26 < q < 0.38$

Right: high q [GeV/c]
Up: $1.09 < q < 1.25$
Middle: $0.93 < q < 1.09$
Down: $0.77 < q < 0.93$

- ● Data
- ○ MC Sum
- 1N Kn→Yπ
- QF KpKp,Kn→Yπ
- Σ*(1385)p
- Σ*(1660)p
- Σ*(1775)p
- KN(I=1) thre.



Low q region



- Distributions are explained mainly with 1N and Σ*s in total ~1mb.

Summary

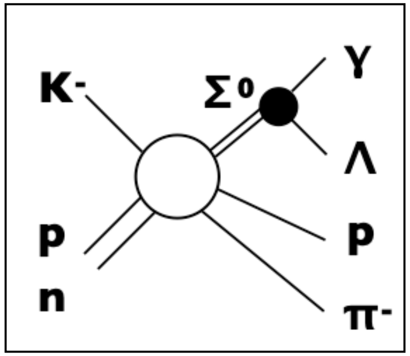
- E31 collaboration is investigating "KbarNN" bound state using d(K^-, Λp)π^- reaction with the confirmation of all the kinematical freedoms. Reaction dynamics are determined by the momentum transfer and invariant mass of Λp, $\Lambda\pi^-$ and $p\pi^-$ systems.

- The reaction processes identified clearly are one nucleon reaction $Kn\to\Lambda\pi^-$, two nucleon reaction $Kp\to Kp$, $Kn\to\Lambda\pi^-$ and none-mesonic Y* production $Kd\to\Sigma(1385)p$.

- "KbarNN" interested region is mostly explained with one nucleon reaction $Kn\to\Lambda\pi^-$ and additional reactions having broad distribution. Possible reactions as the broad distribution are $p\pi$ scattering and higher mass none-mesonic Y* productions. We are trying to apply the global event fitting with q dependence to identify the contributions of each reaction and "KbarNN" state.

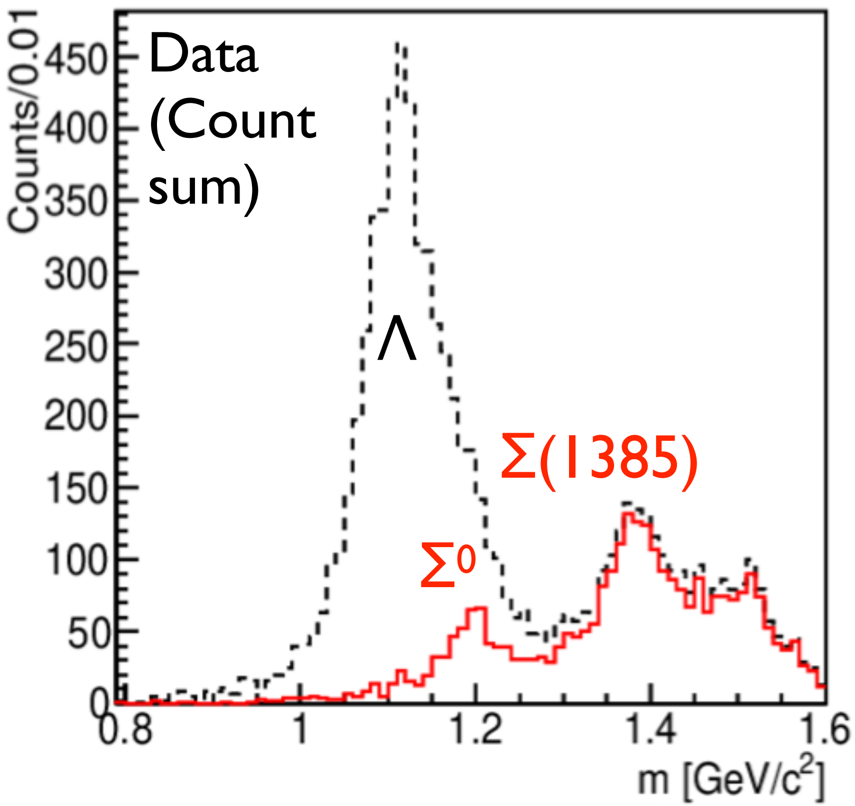
Backup

Analysis of Σp final state

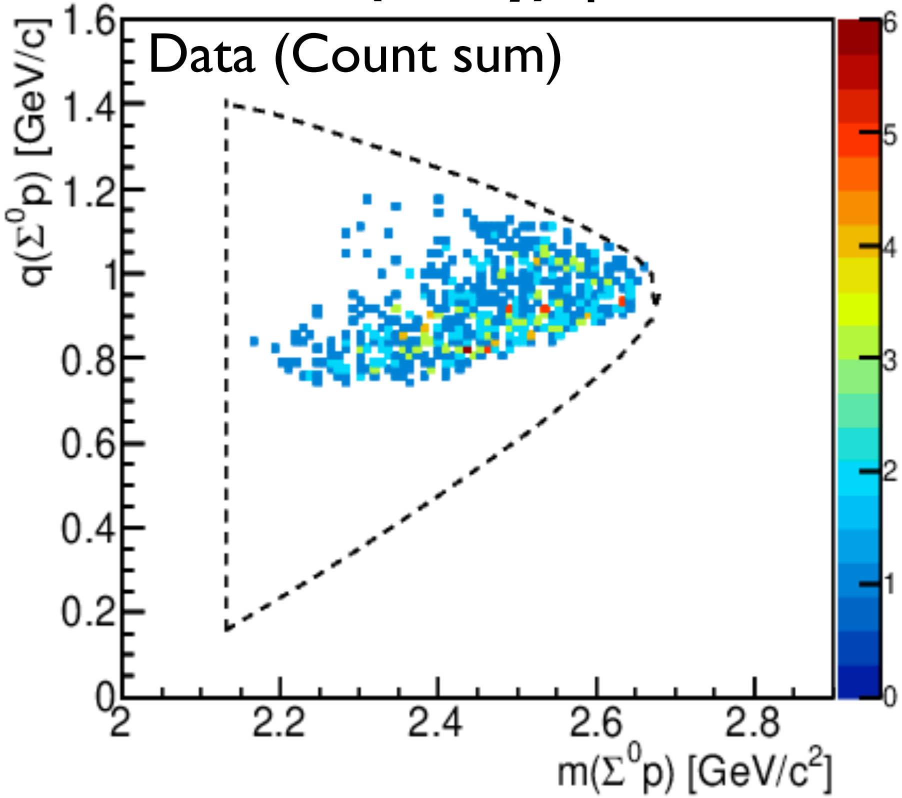


- $\Lambda p \pi^-$ detect.
- p_γ ~ 70 MeV/c.
- Require missing momentum in $\Lambda p \pi$ system.

pπ missing mass



$(m, q)_{\Sigma p}$



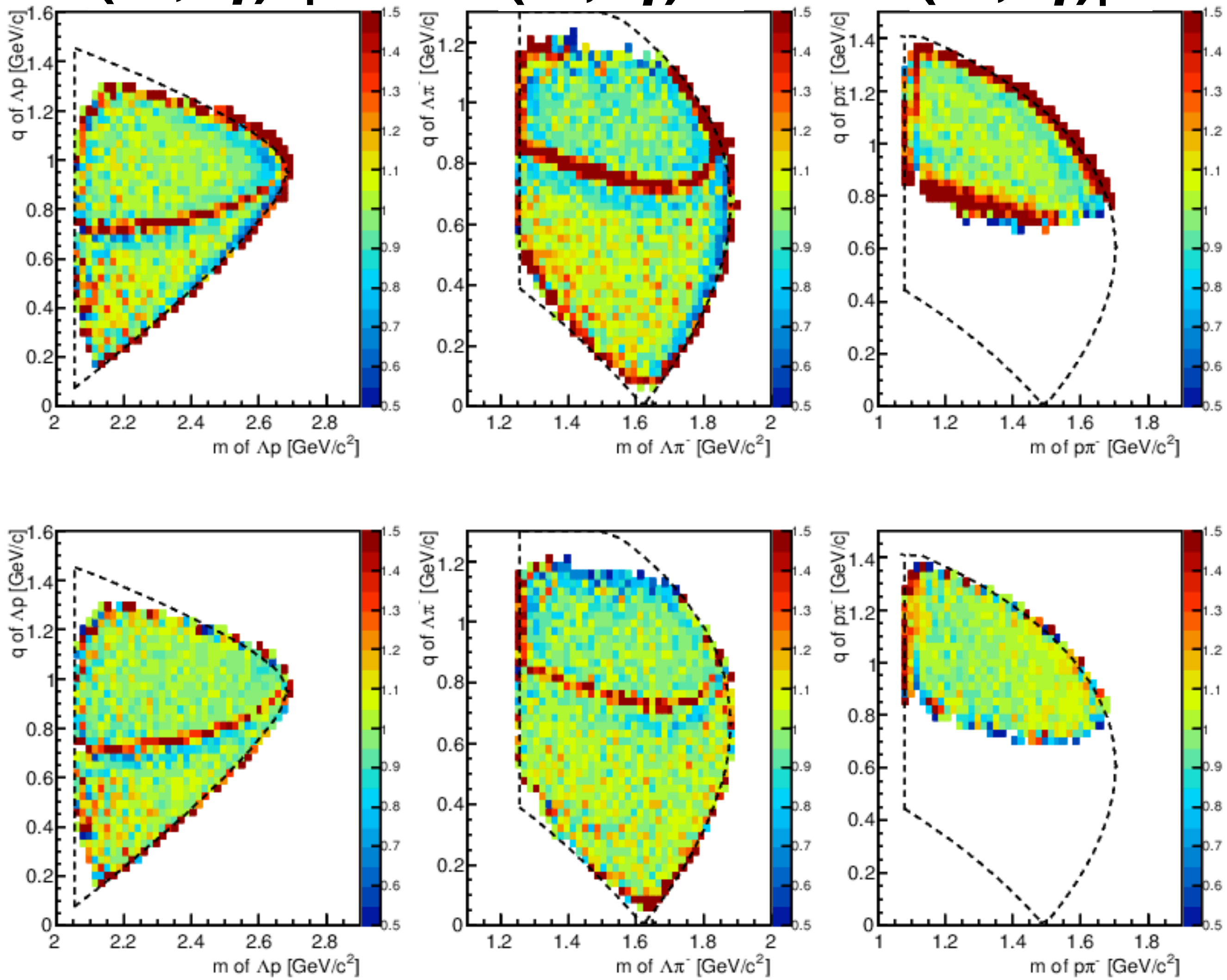
Kinematical anomaly estimated w/ MC PS $Kd \to \Lambda p \pi^-$

Detecting system dependence on event kinematics N_{rec}/N_{tr} where number of reconstructed events N_{rec} and true-kinematic events N_{tr} .

$(m, q)_{\Lambda p}$ $(m, q)_{\Lambda \pi^-}$ $(m, q)_{p \pi^-}$

Before kinematical refit

After kinematical refit



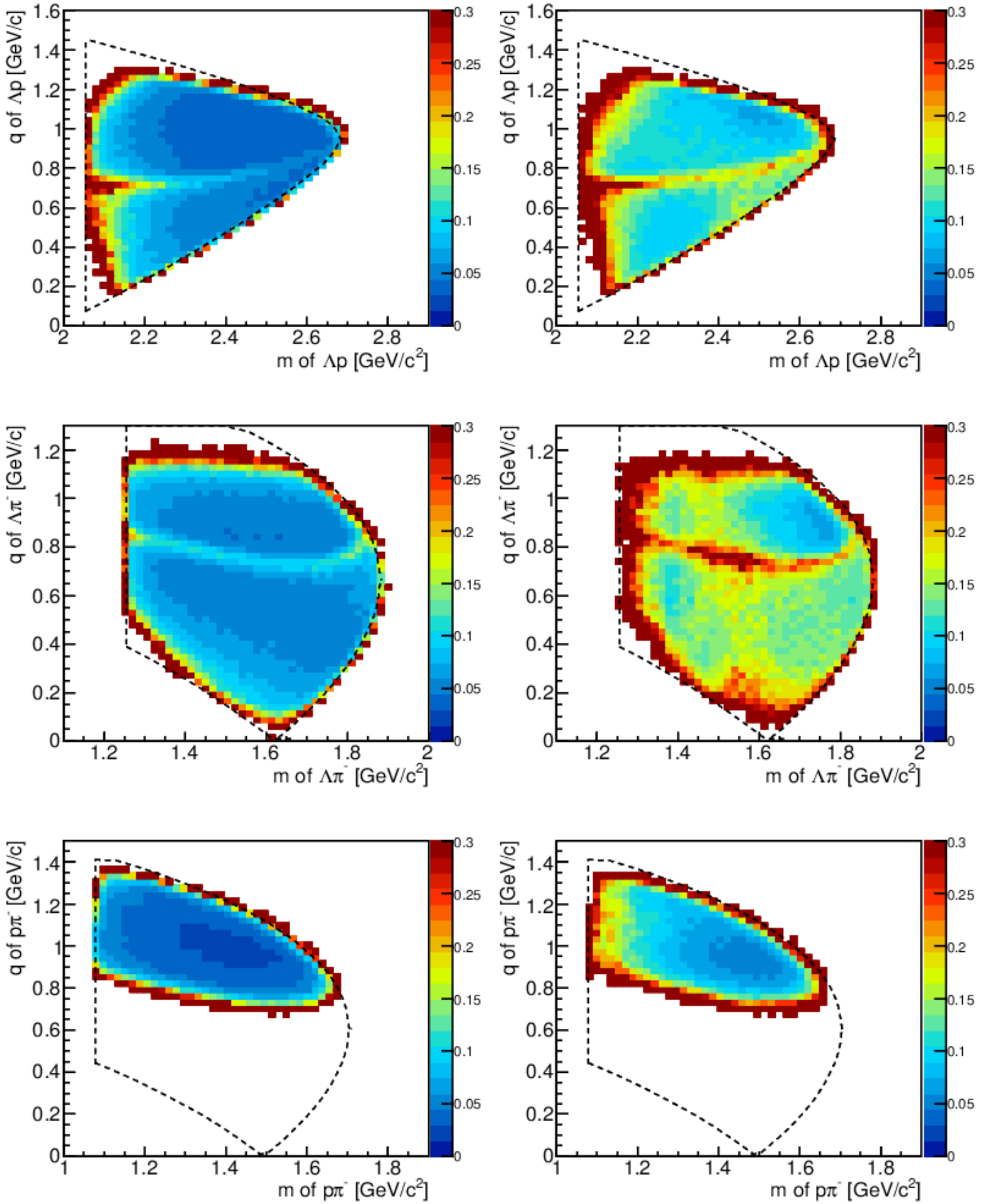
With kinematical refit, kinematical inconsistency coming from detecting bias is reduced.

Remaining effect are appropriated in the systematic errors.

Errors coming from acceptance correction using PS Kd→Λpπ⁻

Errors from acceptance a_{err}/a

Errors from cross-section σ_{err}/σ



Cross-section

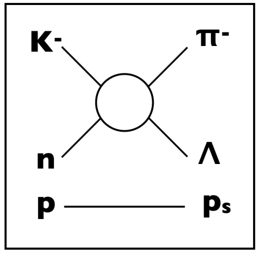
$(\sigma \pm \sigma_{err}) = (N \pm N_{err})/(a \pm a_{err})$

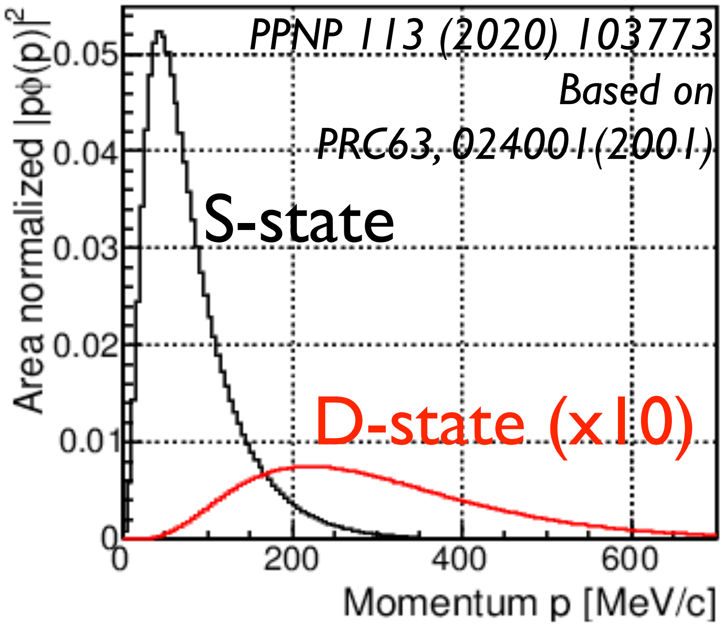
where number of reconstructed events $(N \pm N_{err})$ and acceptance $(a \pm a_{err})$.

Values of left plots are smaller than those of Right plots.

Statistics is large enough to neglect the error of acceptance.

One nucleon reaction: $K^- n \rightarrow \Lambda \pi^-$ (1/2)



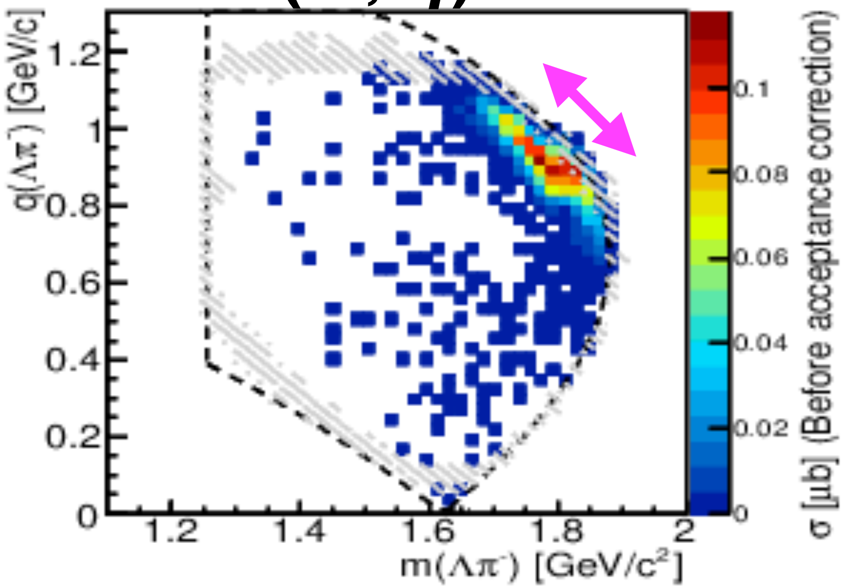


- Spectator-proton w/ large ***p*** fires trigger. Tail component of Fermi-motion affect the distribution.

Effect of large Fermi-momentum tail on Λπ distribution

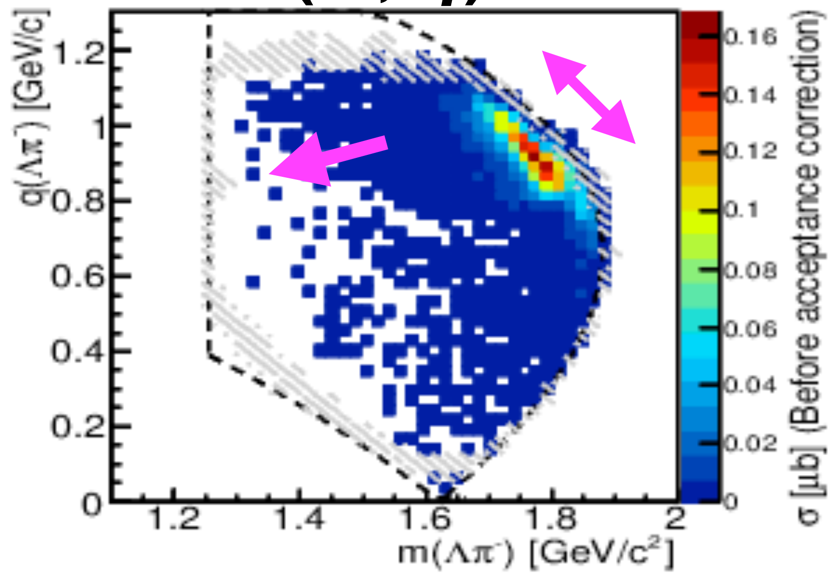
MC **w/o** D-state

***(m, q)*Λπ**



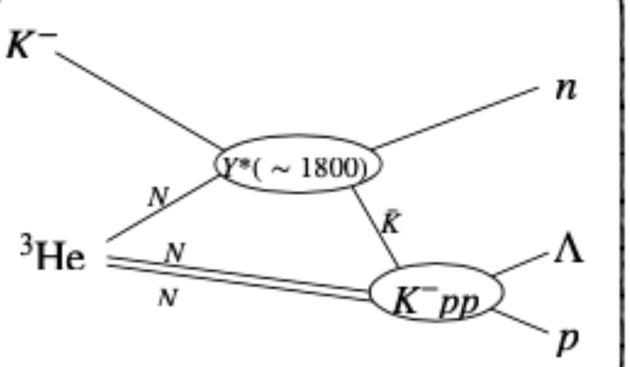
MC **w/** D-state

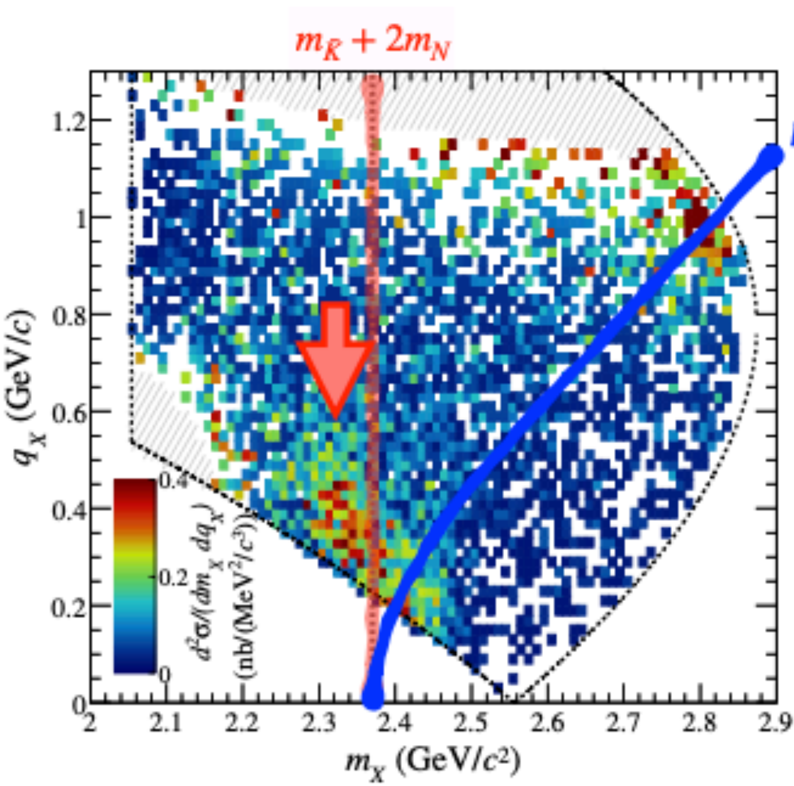
***(m, q)*Λπ**



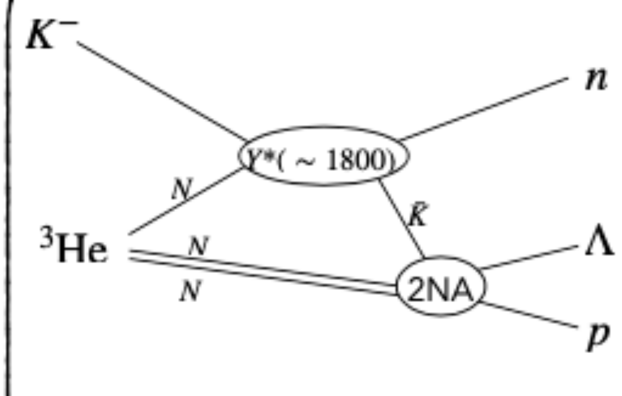
Result of E15

Bound state





Quasi-free

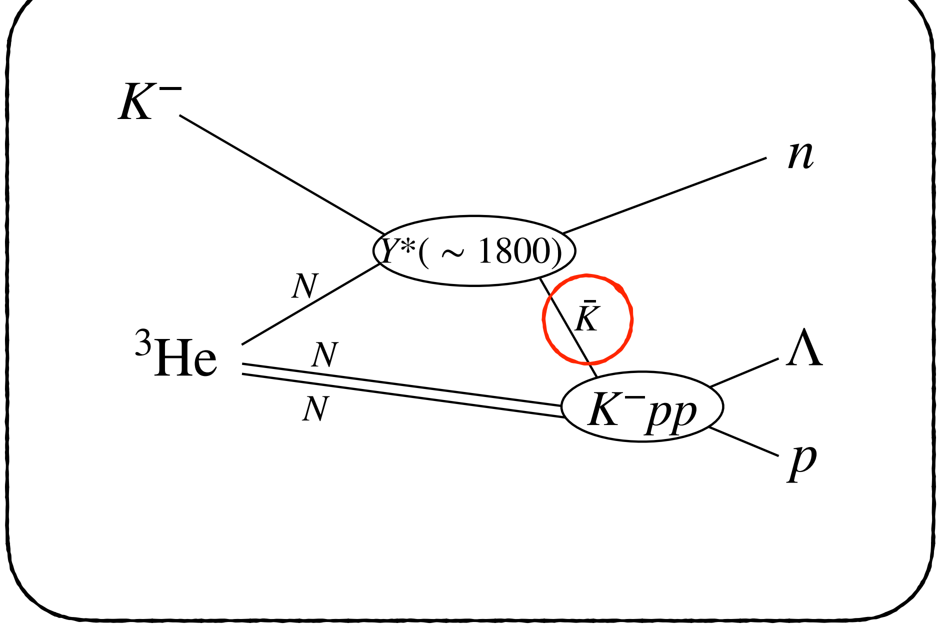


$$M_F(q_X) = \sqrt{4m_N^2 + m_{\bar{K}}^2 + 4m_N\sqrt{m_{\bar{K}}^2 + q_X^2}}$$

2022.02.16 HEF-ex workshop 山我さんスライド

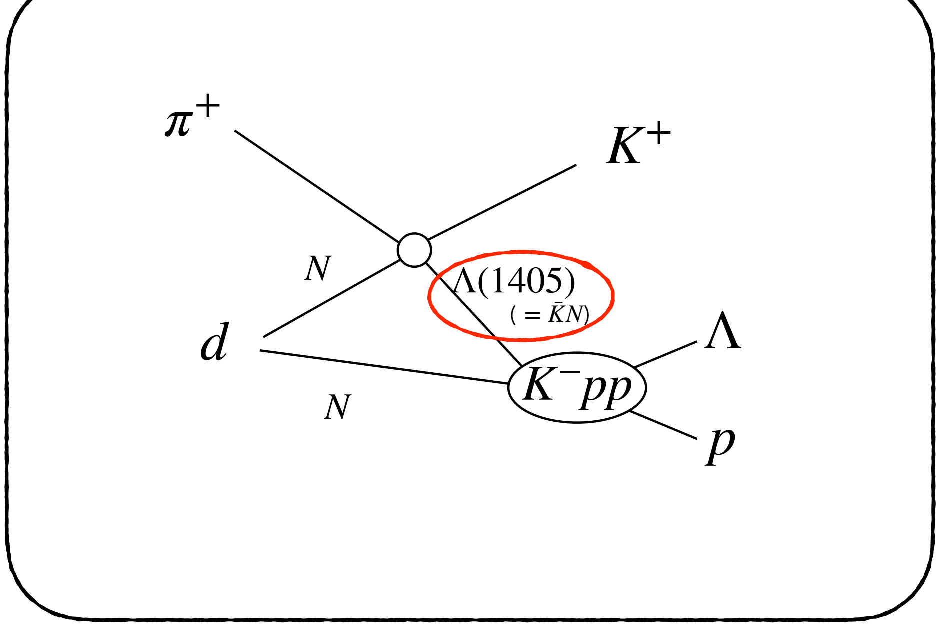
J-PARC E15

$^3\mathrm{He}(K^-, n)\Lambda p$



J-PARC E27

$d(\pi^+, K^+)\Lambda p/\Sigma^0 p$



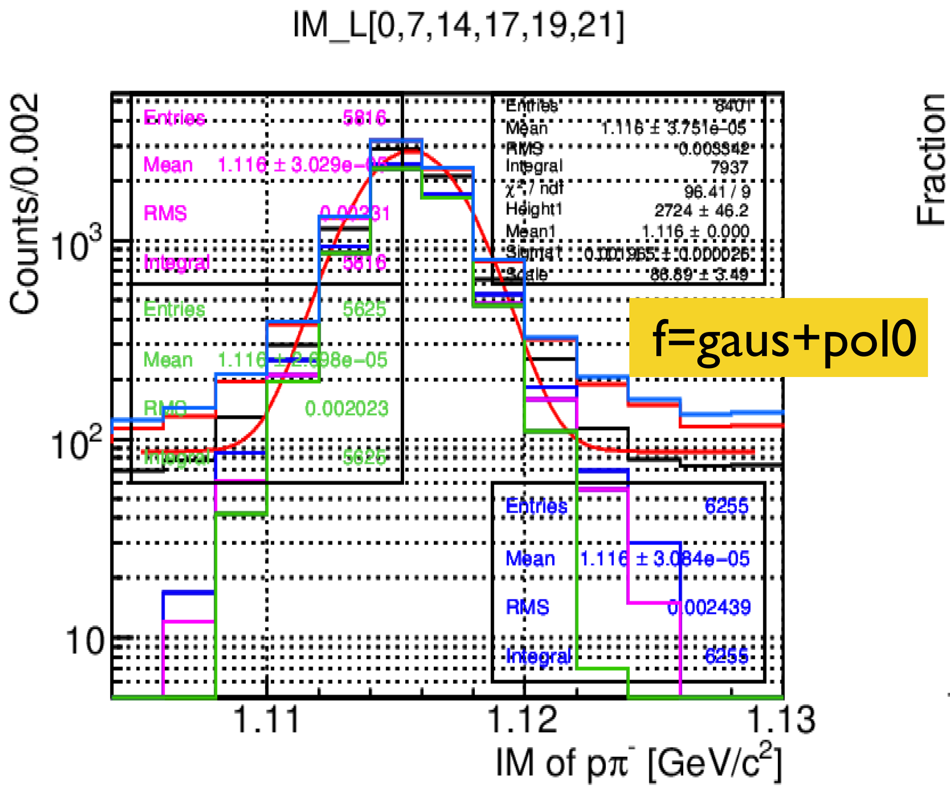
Production of K^-pp is essentially the same.
Occurred by intermediate $\bar{K}$ or $\bar{K}N$

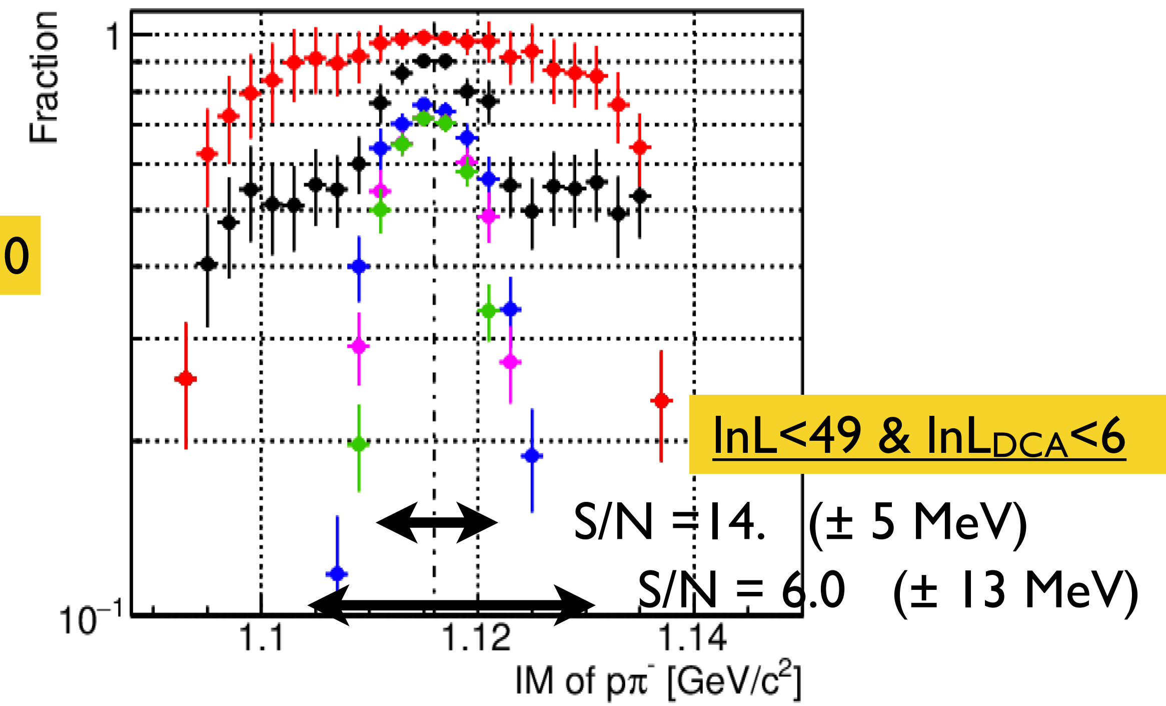
2022.02.16 HEF-ex workshop 山我さんスライド

W/ each cut

Data
(1/5 of Run78)

— base condition
— lnL<49
— lnL<49 & lnL$_{DCA}$<6 (Fit)
— lnL<49 & kf_chi2<15
— lnL<49 & lnL$_{DCA}$<6 & kf_chi2<15
— lnL<6 (& lnL$_{DCA}$<6) & kf_chi2<15





- S/N =14 in signal region (L mass ± 5 MeV) w/o Lambda mass selection.
- W/ Lambda mass selection, the selections show similar number of events and distributions.

Dalitz plot $m^2(\Lambda p)$ vs $m^2(\Lambda\pi)$