Exclusive Analysis of the in-flight $^3He(K^-, \Lambda p)n_{missing}$ reaction to search for the $K^{bar}NN$ bound state

Few body 21
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2015/05/21

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- Introduction
  - Strange and exotic matter
  - $K^{bar}NN$
  - E15 experiment
- Analysis of $^3He(K^-, \Lambda p)n$ reaction
- Conclusion

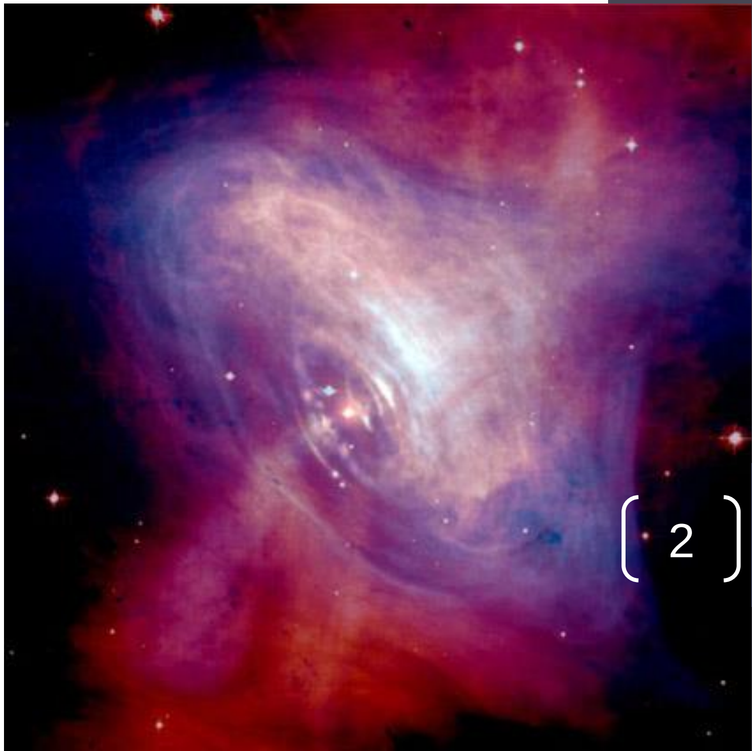
Strange and exotic matter

- Hadron with strangeness
  - Kaon (meson)
  - Λ, Σ, $\Lambda(1405)$(baryon)

- What happens if strange matter is in nuclei??
  - Λ in nuclei => hyper nuclei
  - Kaon in nuclei => kaonic nuclei **exotic!**

- To investigate these exotic matter,
  we can extract information of interaction
  of YN ,YY and KN

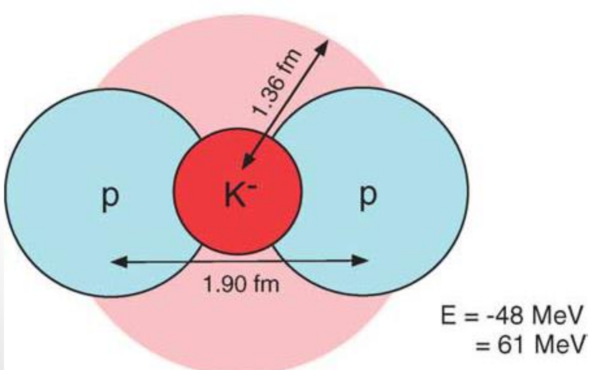
- **structure of neutron star,**
  or new high density matter??

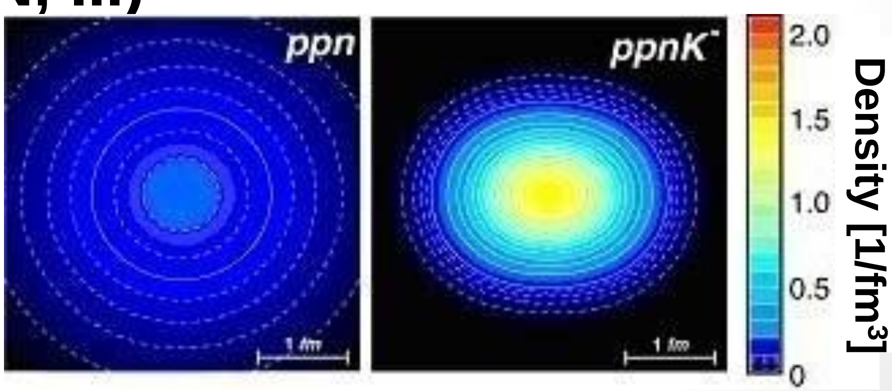


K^{bar} in nucleus

- K^{bar}-N interaction
  - Expected to be strongly attractive when I=0
    - Low energy KN scattering experiments
    - Kaonic-atom experiments
      (KpX@KEK, DEAR/SIDDHARTA @DAΦNE)

  - What happens if K^{bar} is embedded in nucleus?
    - K^{bar}-nucleus bound state?
    - high density?
  - **Kaonic nucleus is a bound state of nucleus and anti-kaon (K^{bar}NN, K^{bar}NNN, ...)**





T.Yamazaki, A.Dote, Y.Akiaishi, PLB587, 167 (2004).

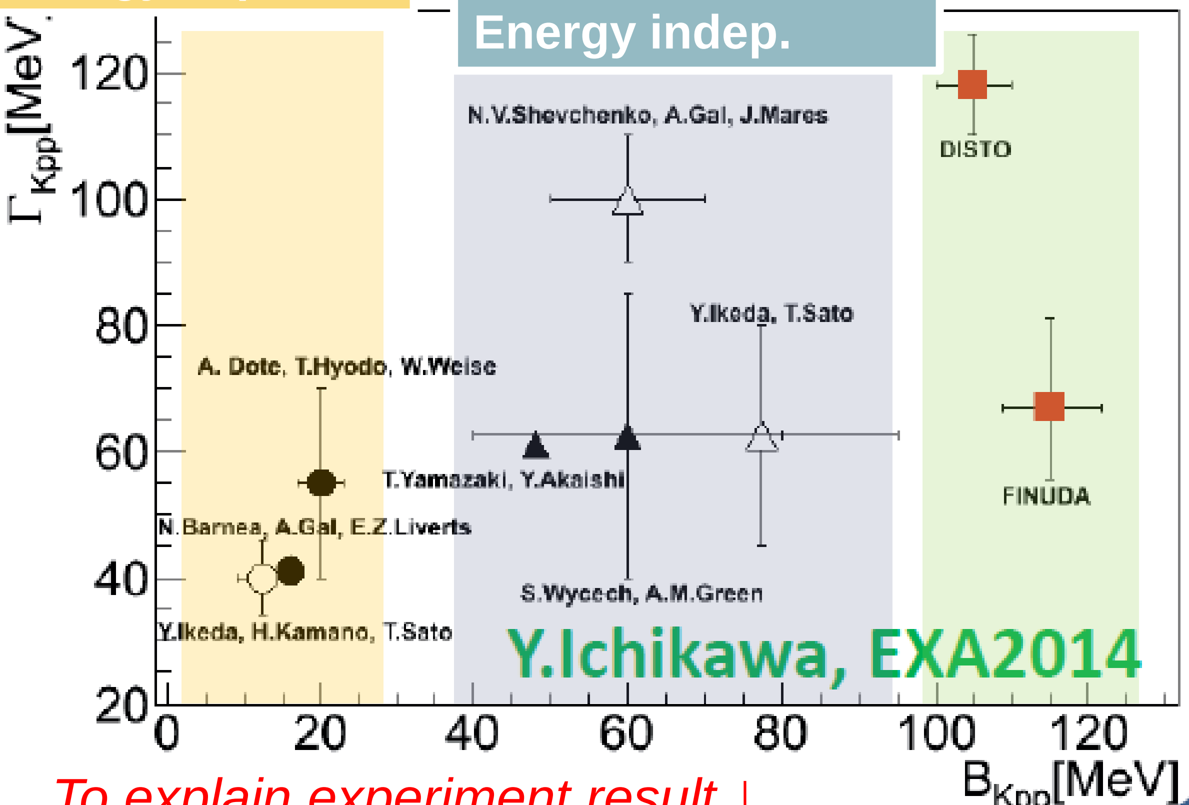
Situation of $K^{bar}NN$

$K^{bar}NN$: the simplest K^{bar}-nuclear state

Chiral base Calc. Energy dep.

Phenomenological Calc. Energy indep.

Experiment



- There are large discrepancy in theoretical models and experiments
- Energy dependent models suggest shallow bound??

- *To explain experiment result ↓*

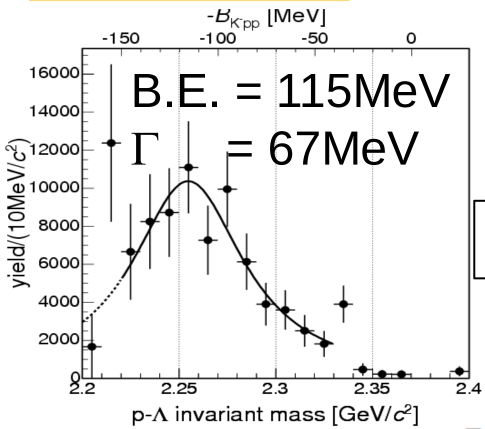
･*Enhanced KN intaction in nuclui?* Y. Akaish,T.Yamazaki, S.Maeda Proc.Jpn.Acad.,Ser.B89(2013)

･*π assisted dibaryon $\pi\Sigma N$-$\pi\Lambda N$?* *A. Gal, arXiv:1412.0198 (Proceeding of EXA2014)*

･Double pole structure of KNN? *Y. Ikeda, H. Kamano, T. Sato, PTP124, 533 (2010)*
A. Dote, T. Inoue, T Myo, PTEP 2015, 043D02 (2015)

Deeply bound $K^{bar}NN$

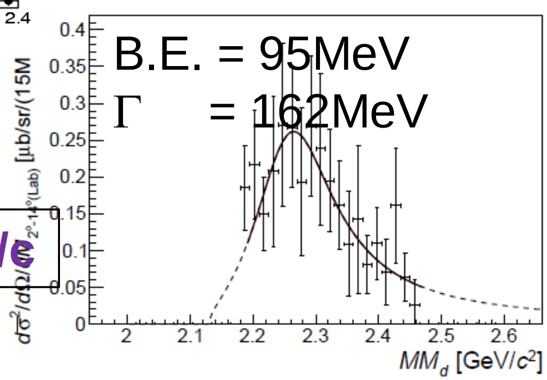
Positive



FINUDA@DAΦNE

PRL**94**(2005)212303

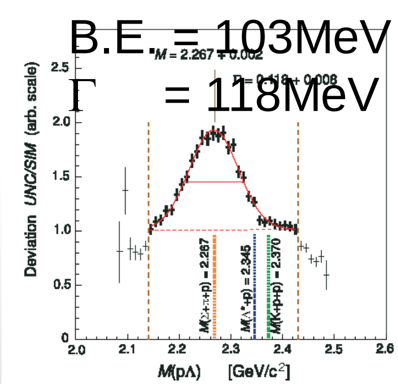
A(*stopped* K⁻, Λp)



E27@J-PARC

PTEP(2015)021D01

d(π⁺, K⁺) @ 1.7GeV/c



DISTO@SATURNE

PRL**104**(2010)132502

p + p → (Λ + p) + K⁺ @ 2.85GeV

Negative

LEPS @Spring-8

Phys. Lett B728(2014) 616

photon -induced reaction

E15 @J-PARC

arXiv:1408.5637v2 (Accepted by PTEP)

3He(K-, n)X @1.0GeV/c (inclusive)

HADES@GSI

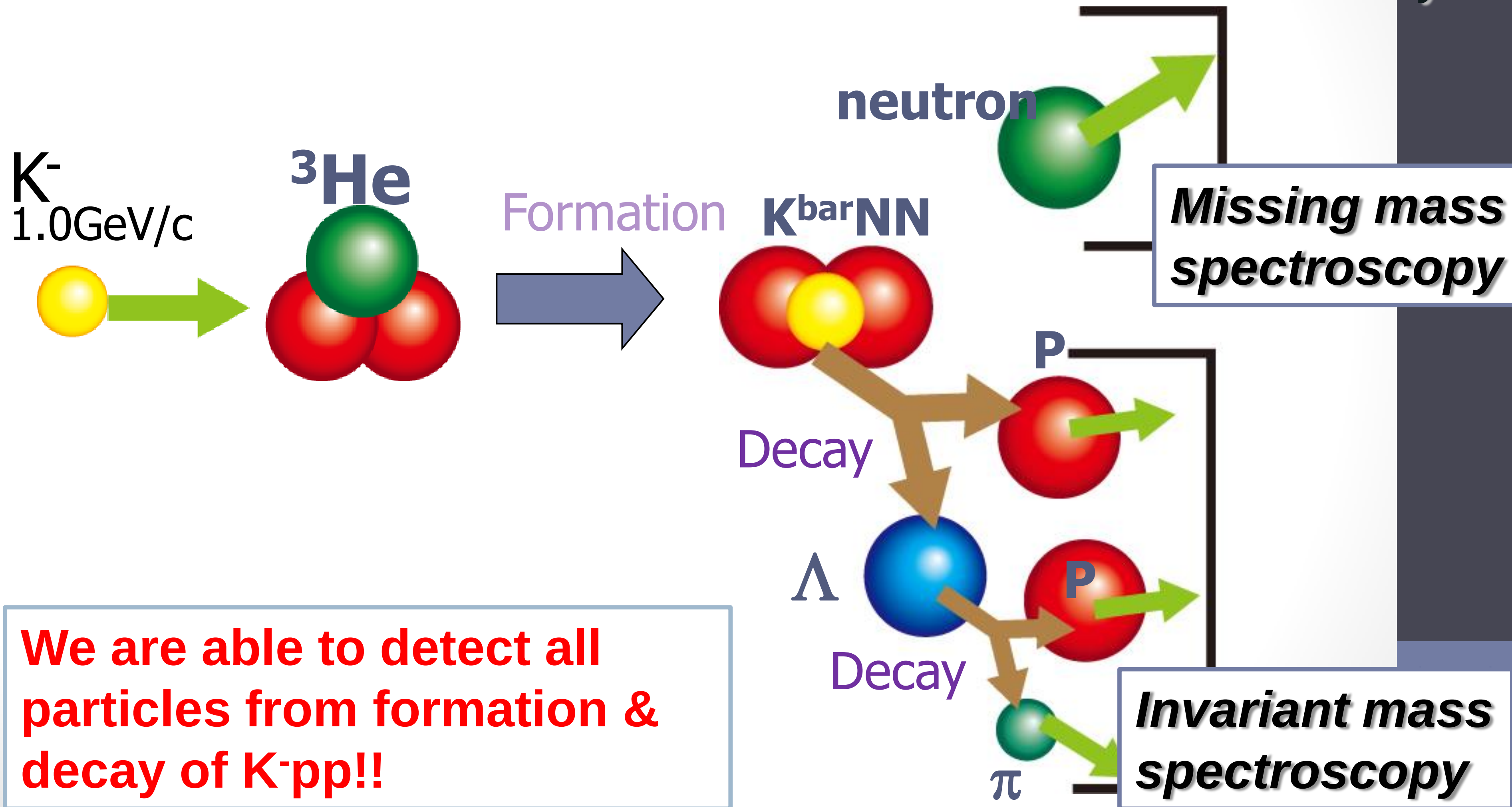
NP**A914**(2013)60

p + p → (Λ + p) + K⁺ @ 3.5GeV

J-PARC E15 experiment

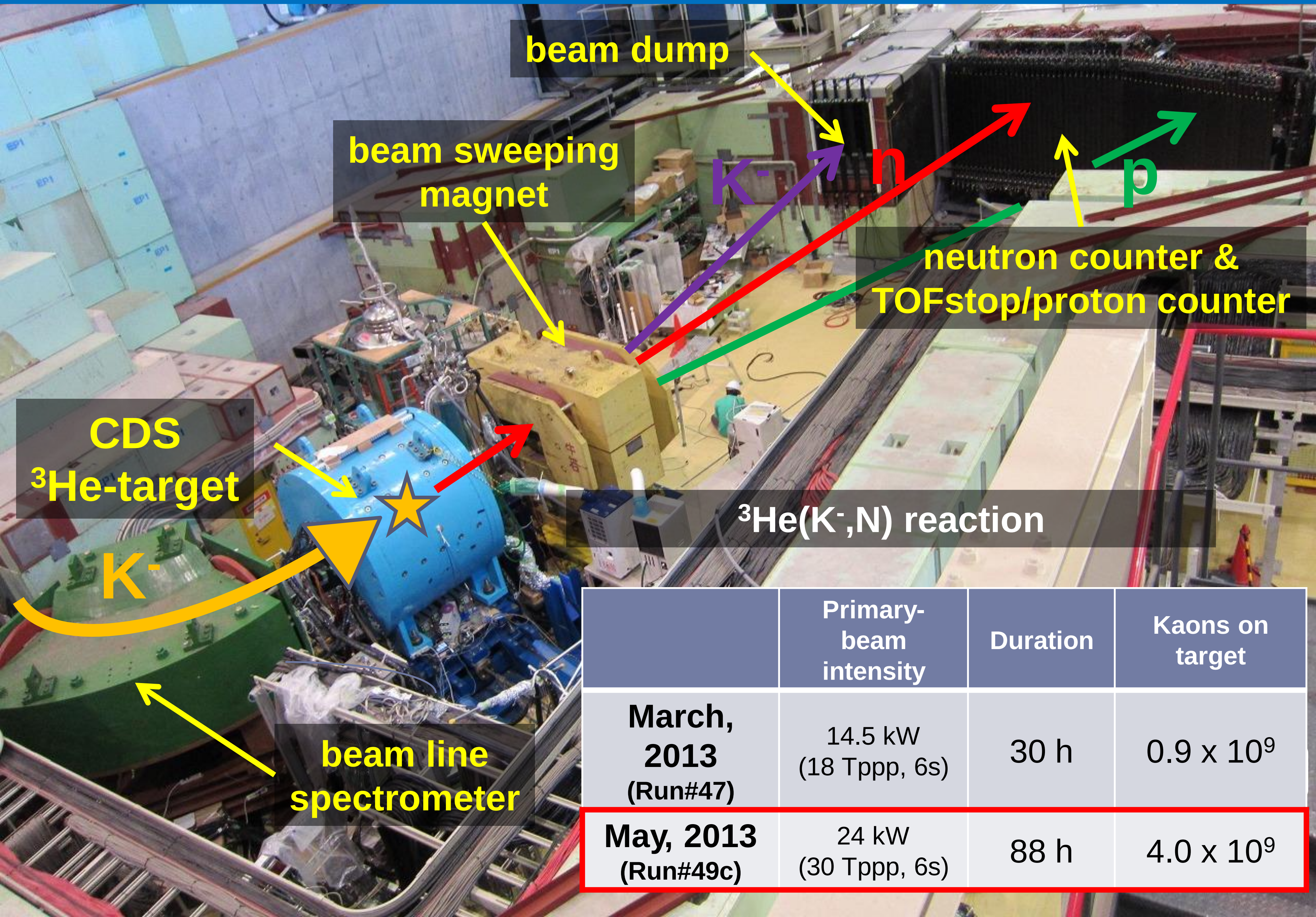
in-flight ^{3}He(K$^-$, n) reaction & its exclusive measurement

=> Search for K^{bar}NN bound states both via formation & Decay



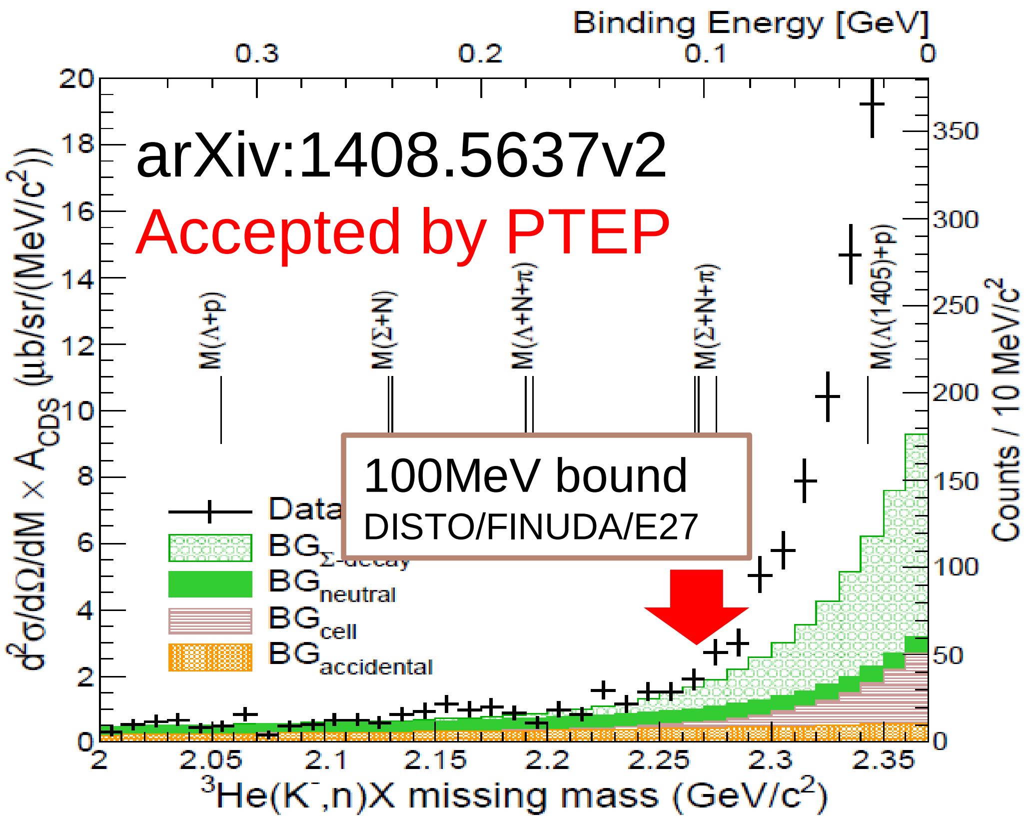
We are able to detect all particles from formation & decay of K$^-$pp!!

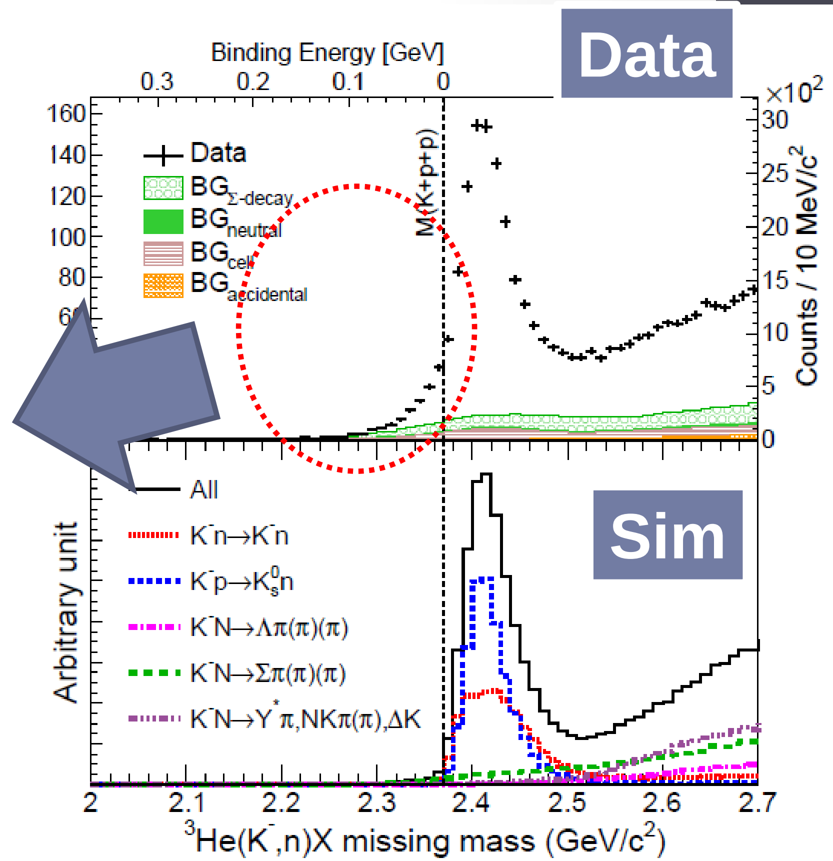
J-PARC K1.8BR beam line[Jun. 2012]



	Primary-beam intensity	Duration	Kaons on target
March, 2013 (Run#47)	14.5 kW (18 Tppp, 6s)	30 h	0.9×10^9
May, 2013 (Run#49c)	24 kW (30 Tppp, 6s)	88 h	4.0×10^9

Semi- inclusive analysis of ^{3}He(K^{-},n)X

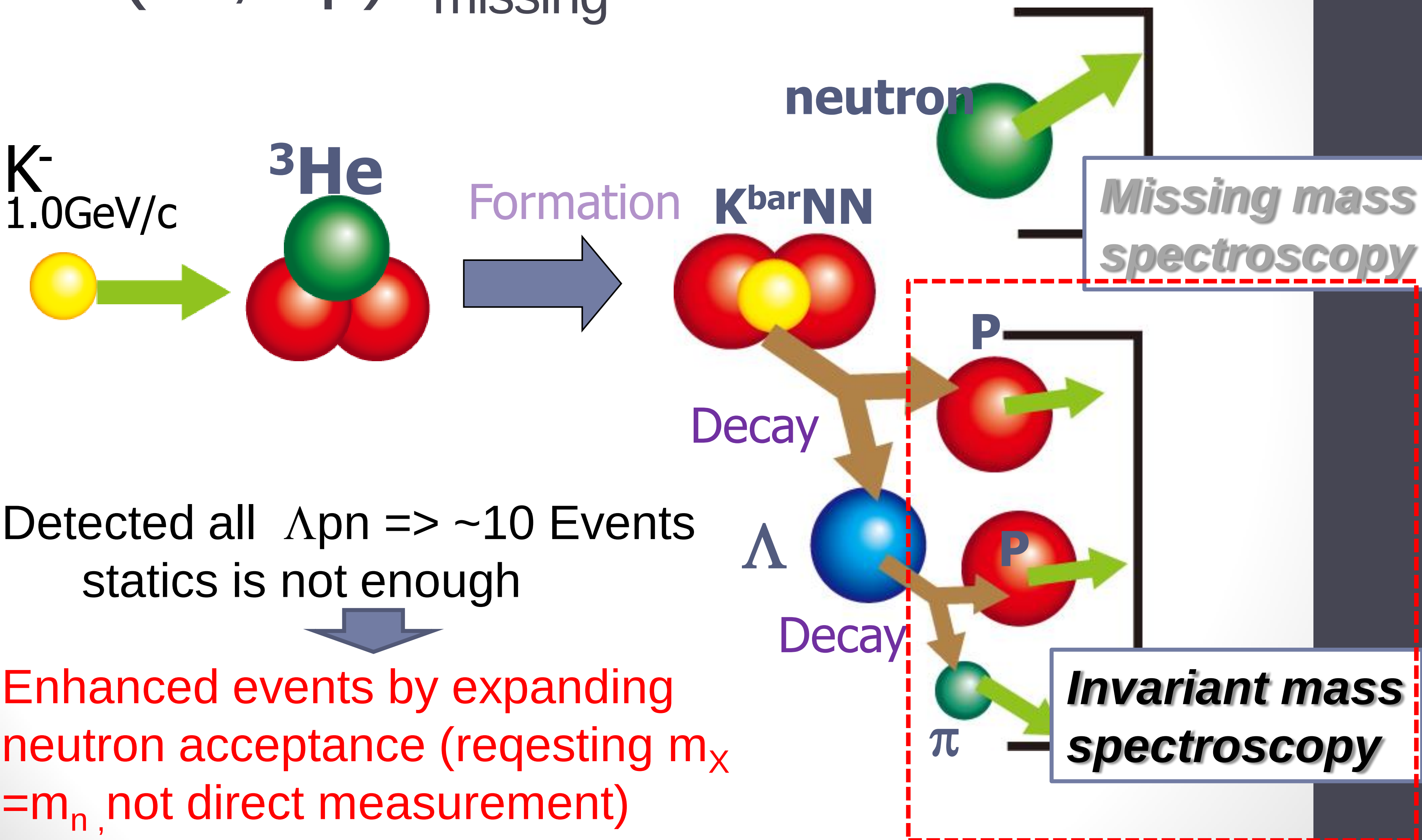




- No significant excess over 2.25GeV/c^2
  - Kaon induced reaction doesn't generate deeply bounded K^{bar}NN state?
- Excess near Kpp threshold
  - loosely K^{bar}NN state? Λ(1405)N 2body reaction? New resonance?

Exclusive analysis of the in-flight via. ^{3}He(K^-, Λp)$n_{missing}$ reaction

Exclusive Analysis of the in-flight $^{3}He(K^{-}, \Lambda p)n_{missing}$ reaction



Detected all Λpn => ~10 Events
statics is not enough

Enhanced events by expanding neutron acceptance (reqesting $m_X = m_n$, not direct measurement)

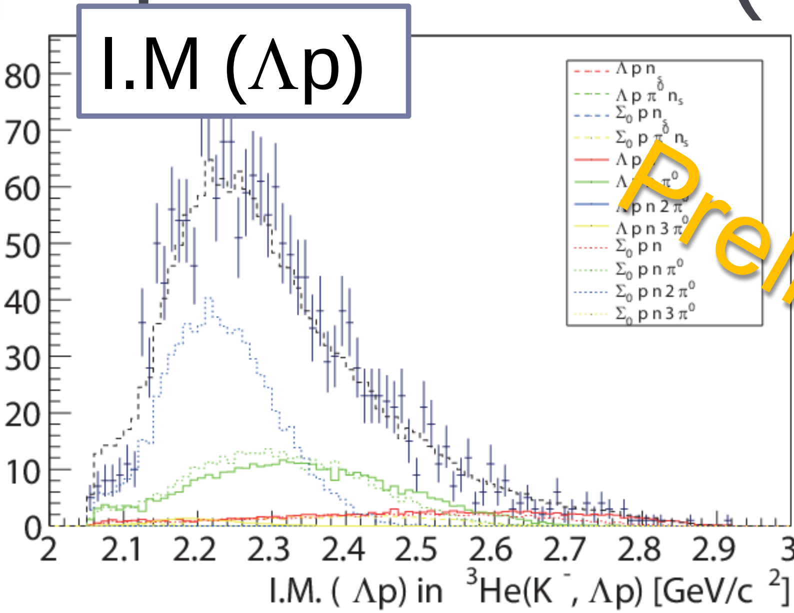
Monte Calro simulation of known elementary processes

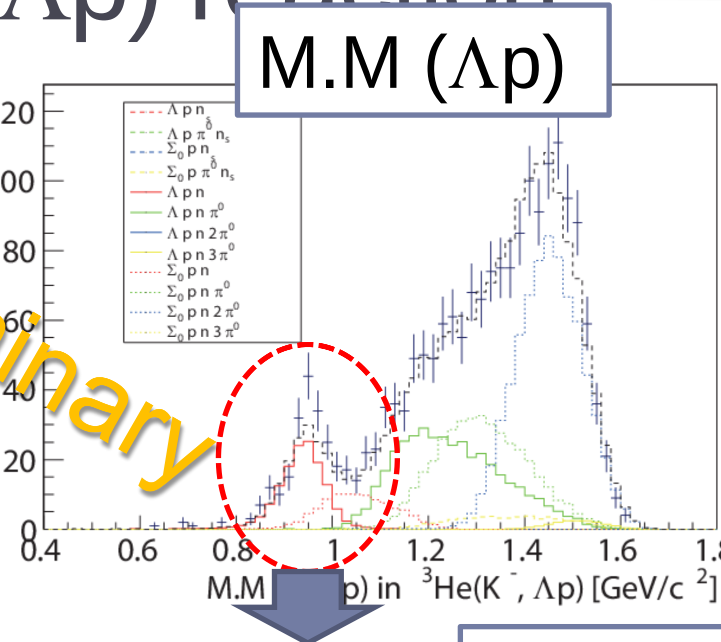
- Kaon multi nucleon absorption and π emission(YNN + π)
- generated each process via PWIA, namely final state simply follows its phase space (with spectator, if any).

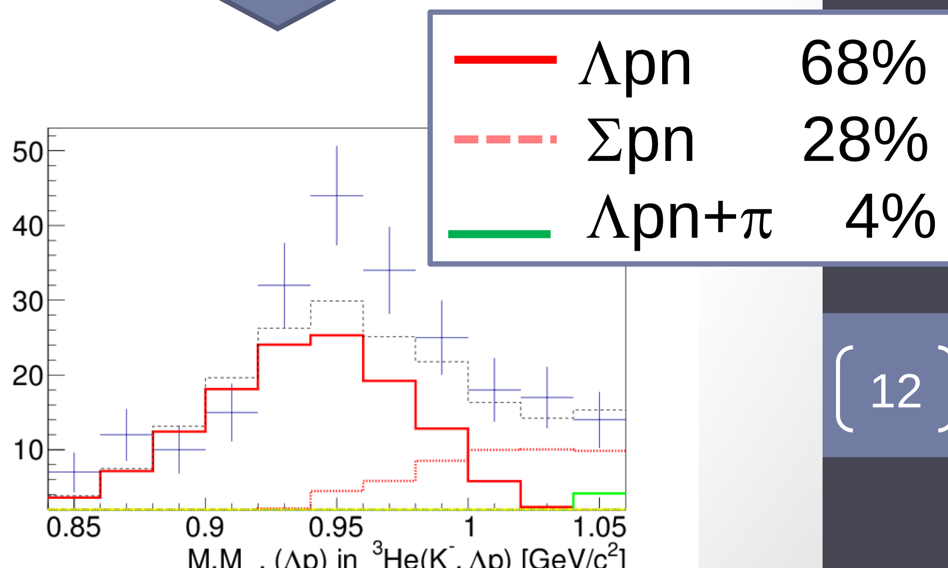
- Can we reproduce data spectrum with these processes？

process
Λp ns
Λp ns+π
Σp ns
Σp ns +π
Λpn
Λpn+π
Λpn+2π
Λpn+3π
Σpn
Σpn+p
Σpn+2π
Σpn+3π

Invariant mass and missing mass spectra in ^{3}He(K^{-},Λp) reaction

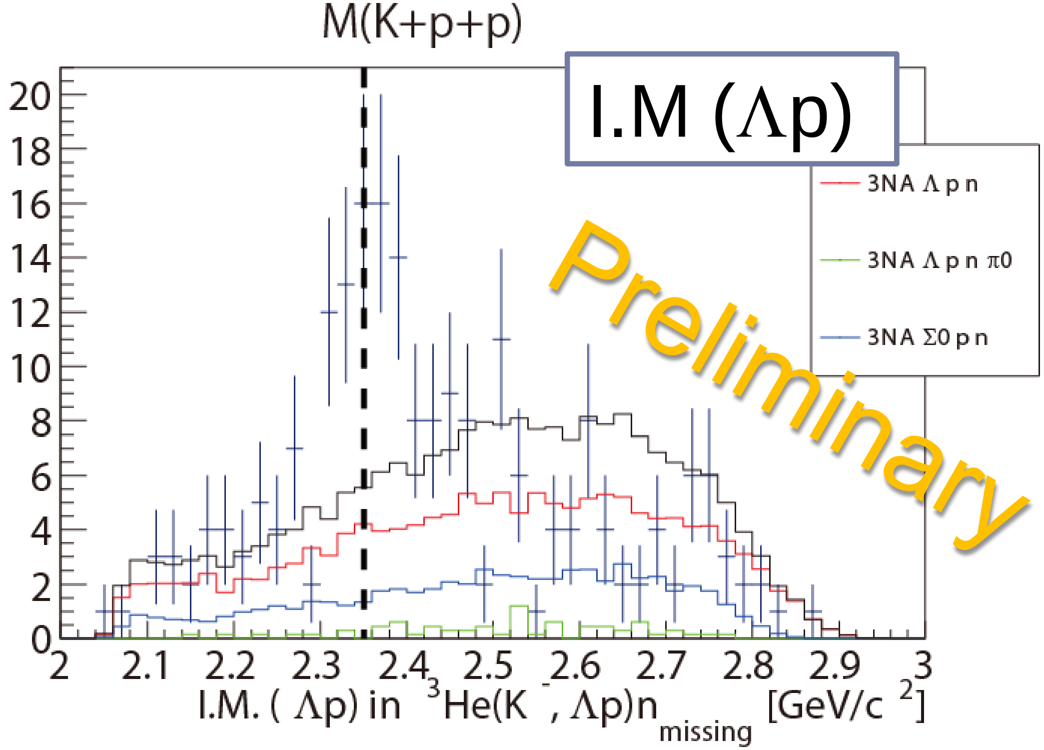


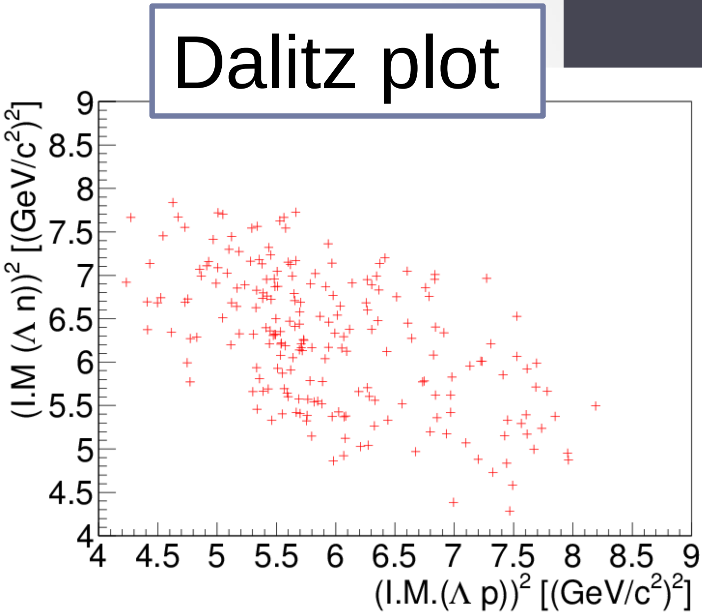




- χ^2 /NDF =142.577 / 158 =0.902
- Ratio of Λ:Σ in final state under missing neutron peak is evaluated to be about 70:30.

$^{3}He(K^{-},\Lambda p)n$ data and 3NA(sim)

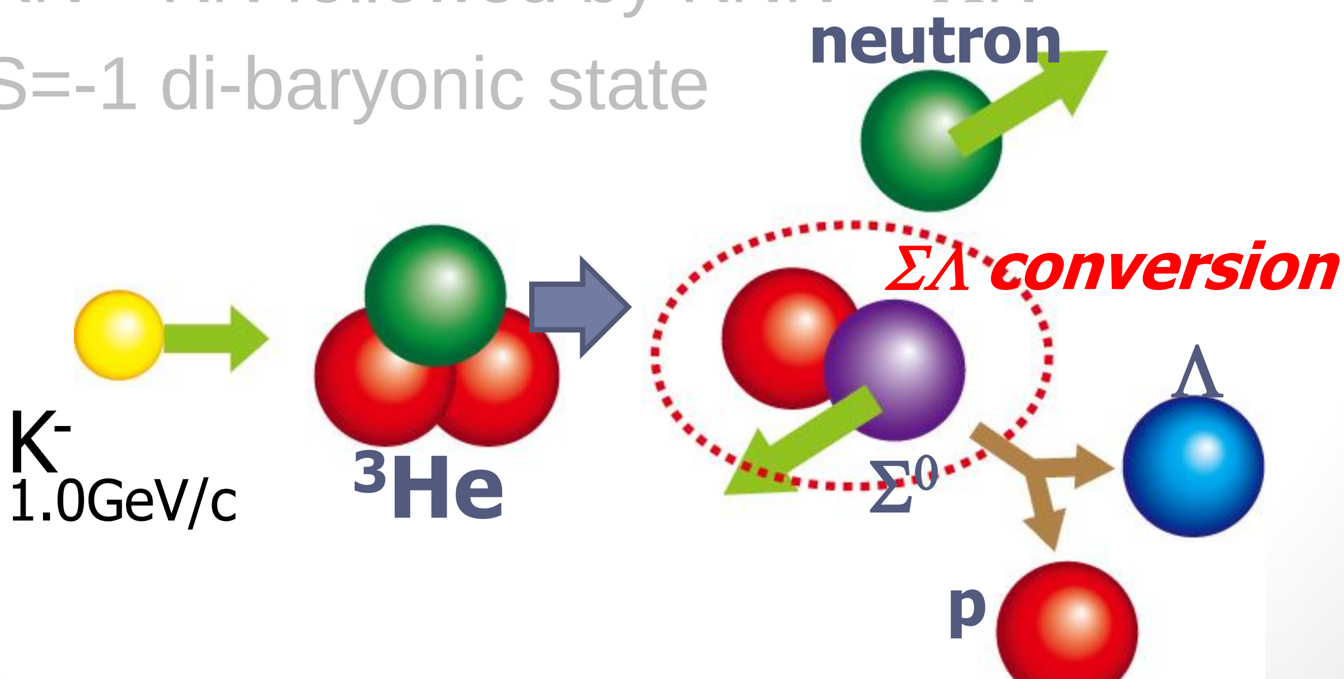




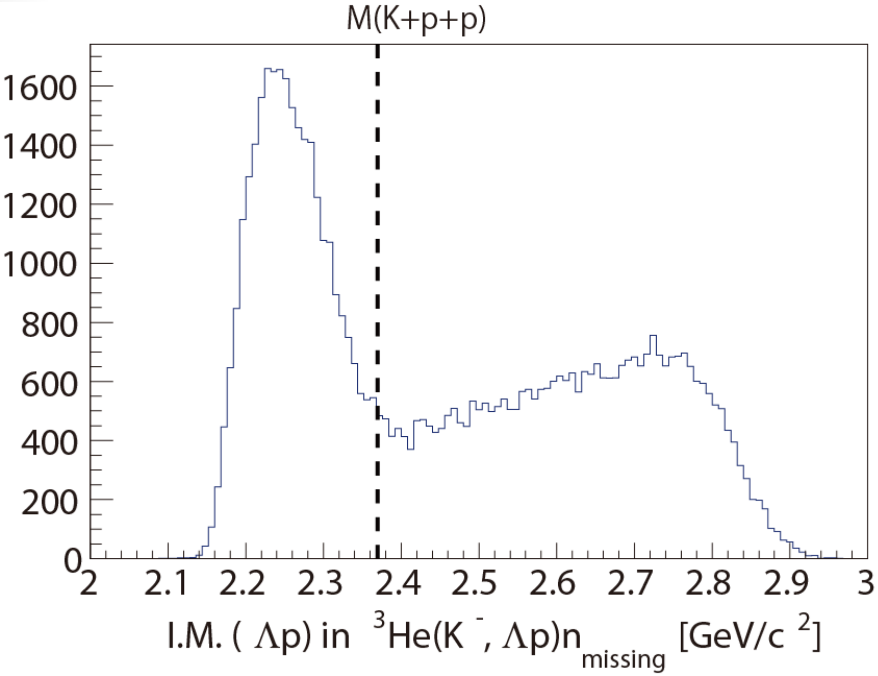
- **Prominent peak structure is seen above known processes.** Especially, peak structure near Kpp threshold.
  - χ^2 /NDF =171 / 49 (~200 events)
- To understand peak structure, following 3 candidates are examined

Examination of possible candidates

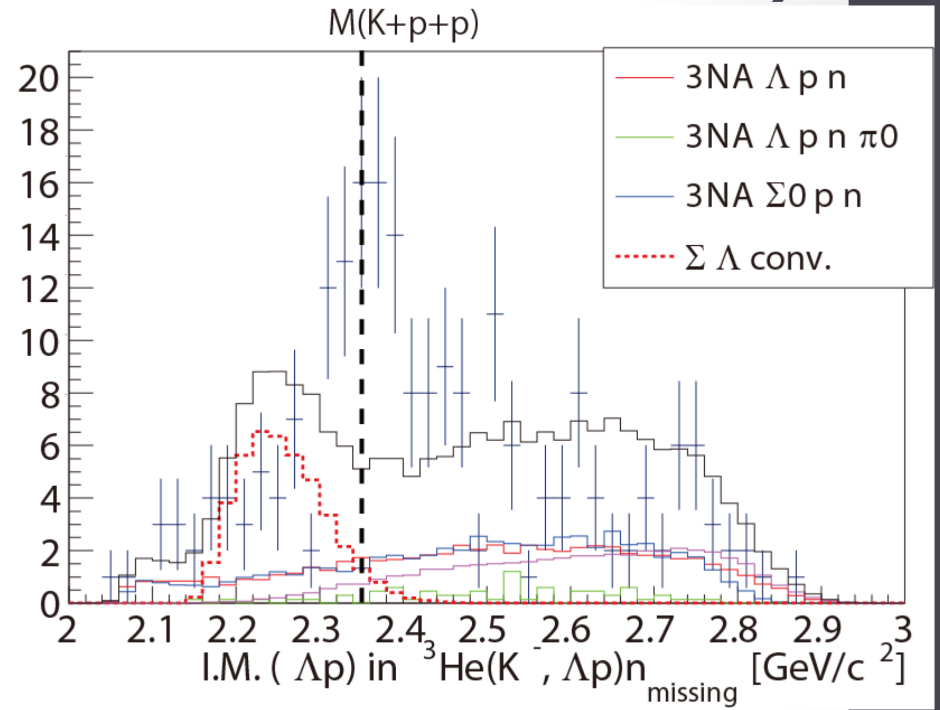
1. Known elementary process (previous slide)
2. **2 step reactions**
   - **2NA followed by ΣΛ conversion**
   - 2NA followed by $\Lambda_{(1405)}$N conversion
   - KN→KN followed by KNN→ ΛN
3. S=-1 di-baryonic state



$\Sigma\ \Lambda$ conversion (2NA + ΣN->ΛN)



Only $\Sigma\Lambda$ conversion



3NA+$\Sigma\Lambda$ conv.

Peak position ~2.25GeV /c^2 => too small

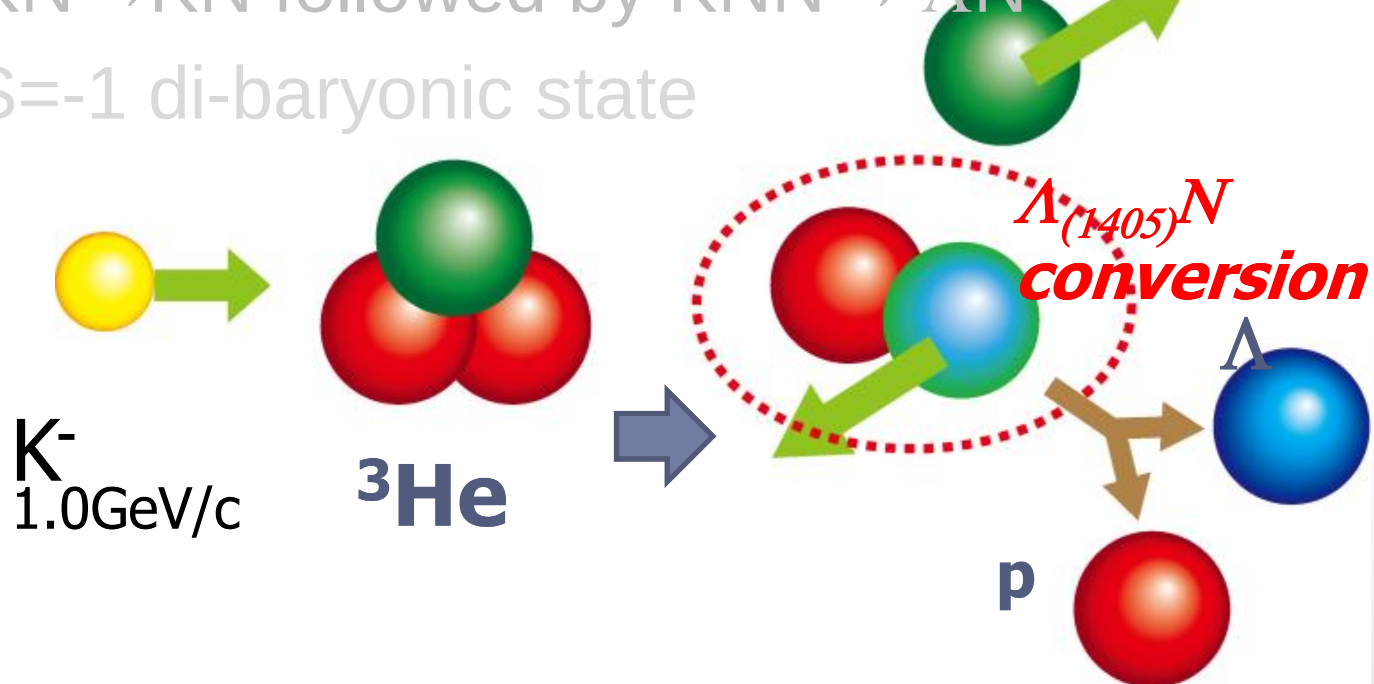
χ^2 /NDF =150 / 49

Not consistent

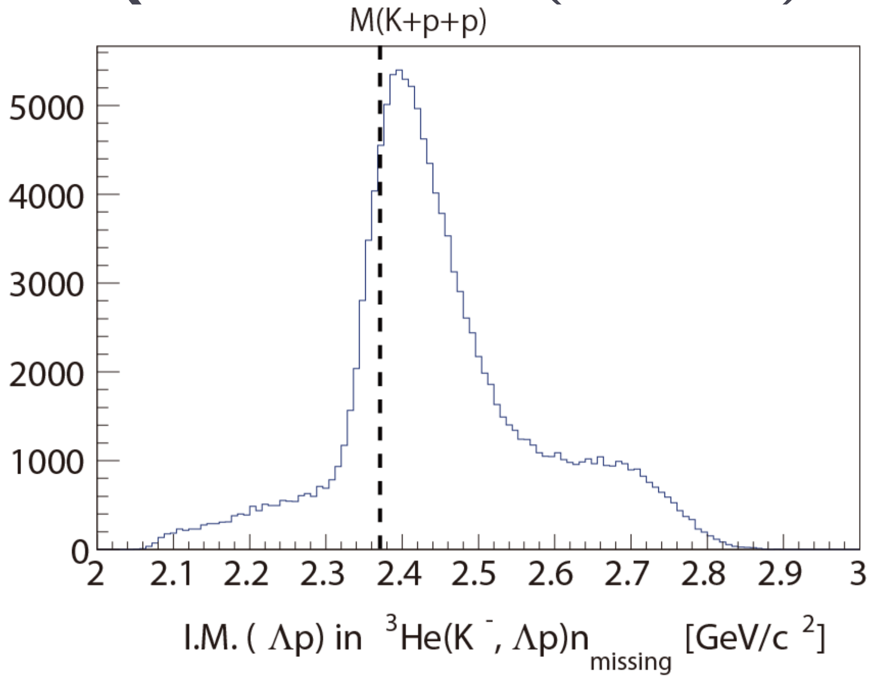
Notice:
2NA itself is not observed in our data
=> 2NA should be weak

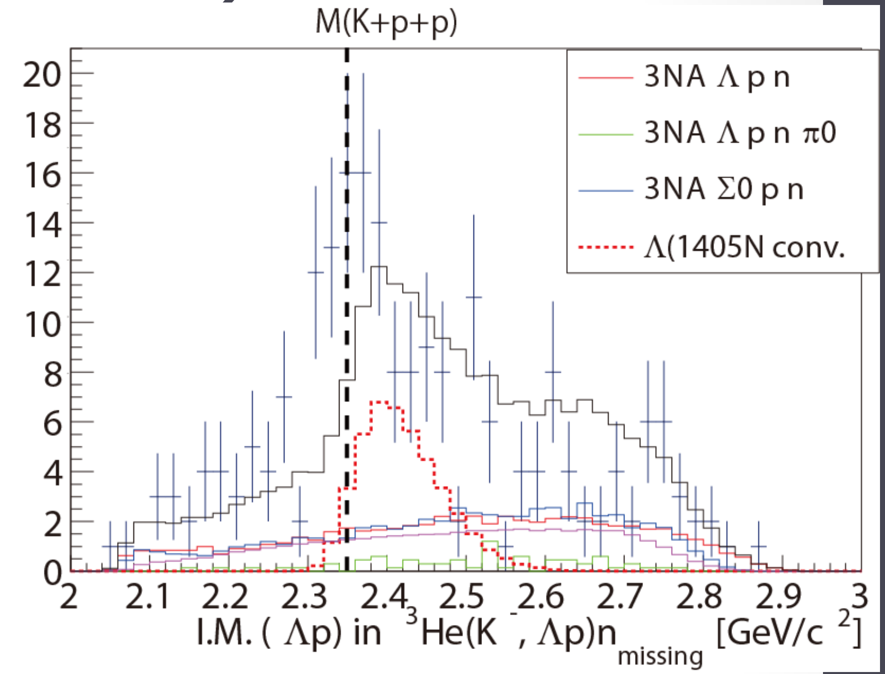
Examination of possible candidates

1. Known elementary process (previous slide)
2. **2 step reactions**
   - 2NA followed by ΣΛ conversion
   - **2NA followed by $\Lambda_{(1405)}$N conversion**
   - KN→KN followed by KNN→ ΛN
3. S=-1 di-baryonic state



Λ(1405)N conversion (2NA + Λ(1405)N->ΛN)





Only Λ(1405)N conversion

3NA+Λ*N conv.

Peak position ~2.40GeV /c^2

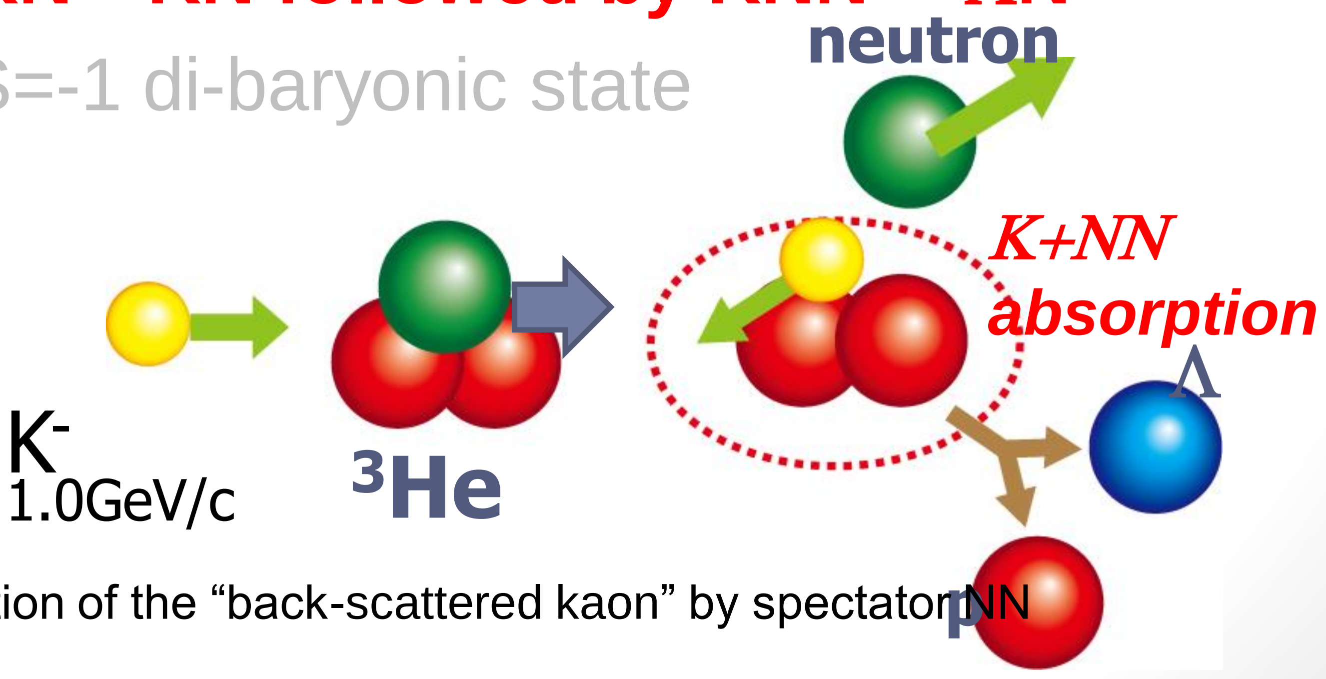
χ^2 /NDF =123 / 49

Not consistent

Notice:
2NA itself is not observed in our data
=> 2NA should be weak

Examination of possible candidates

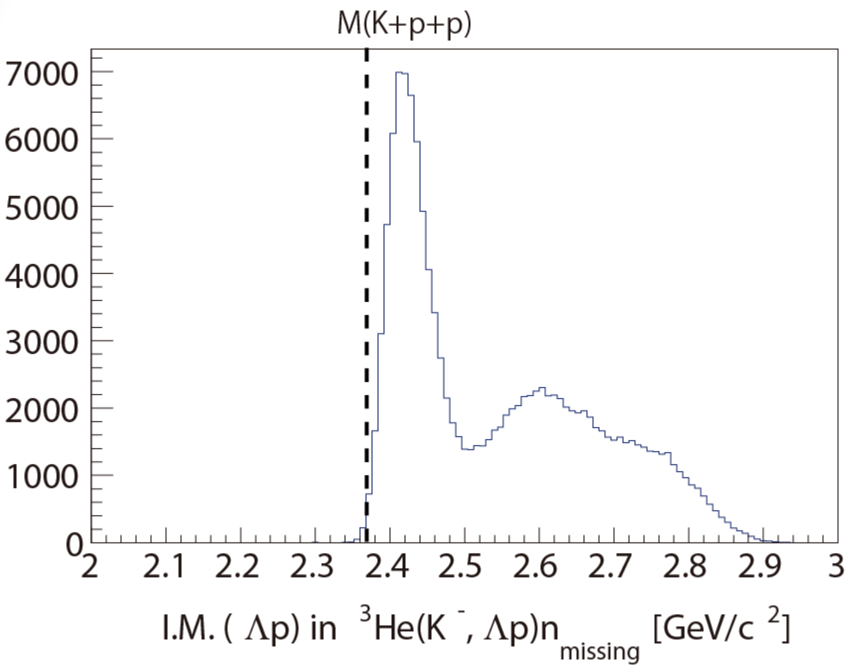
1. Known elementary process (previous slide)
2. **2 step reactions**
   - 2NA followed by ΣΛ conversion
   - 2NA followed by $\Lambda_{(1405)}$N conversion
   - **KN→KN followed by KNN→ ΛN**
3. S=-1 di-baryonic state

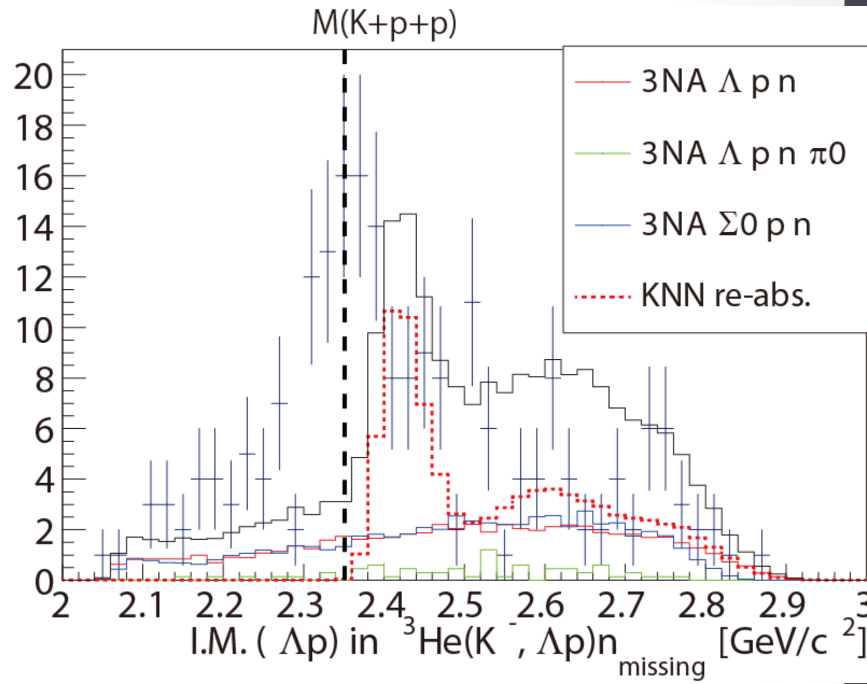


Re-absorption of the "back-scattered kaon" by spectator NN

"$K^{-}p \rightarrow K^{0}n$" + "$K^{0}d \rightarrow \Lambda p$" (2step)

Re-absorption of the "back-scattered kaon" by spectator NN





Only KNN absorption

3NA+KNN re-abs.

KNN absorption events exist over Kpp threshold.

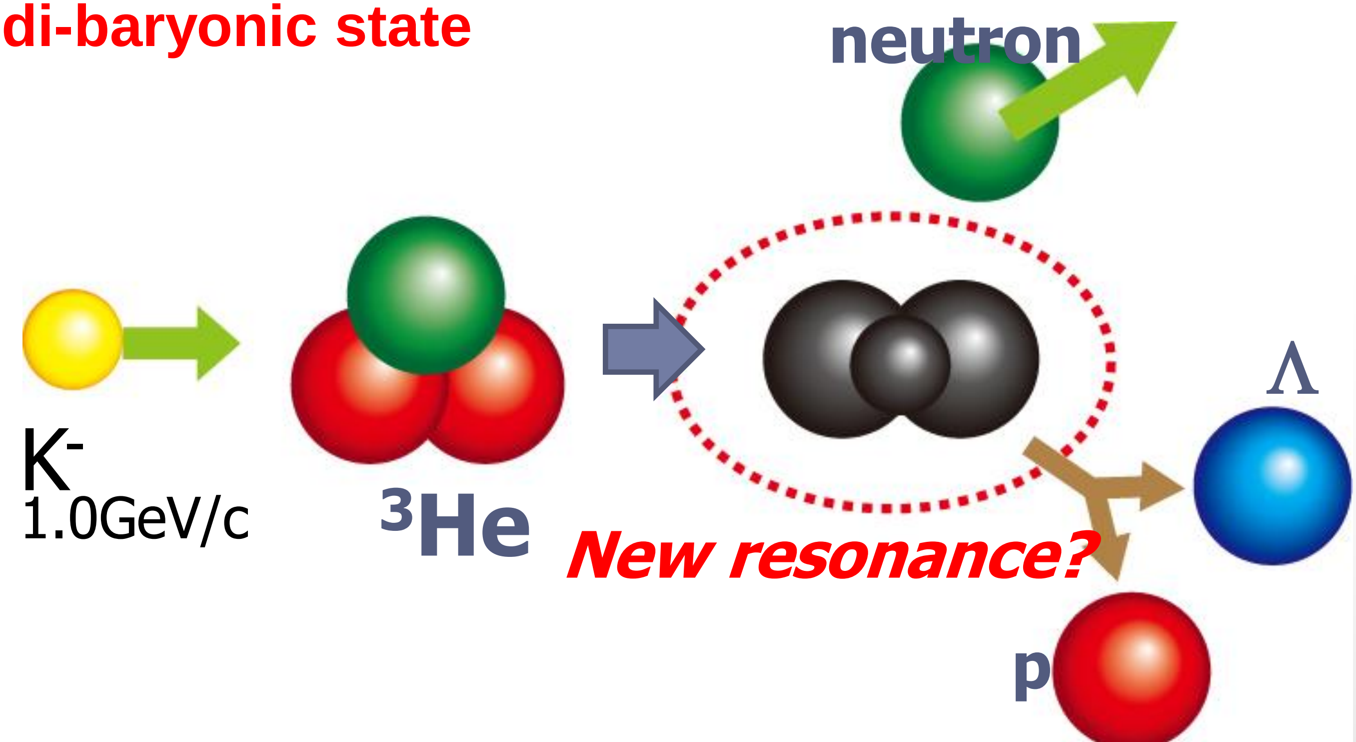
χ^2 /NDF =183 / 49

Not consistent.

Examination of possible candidates

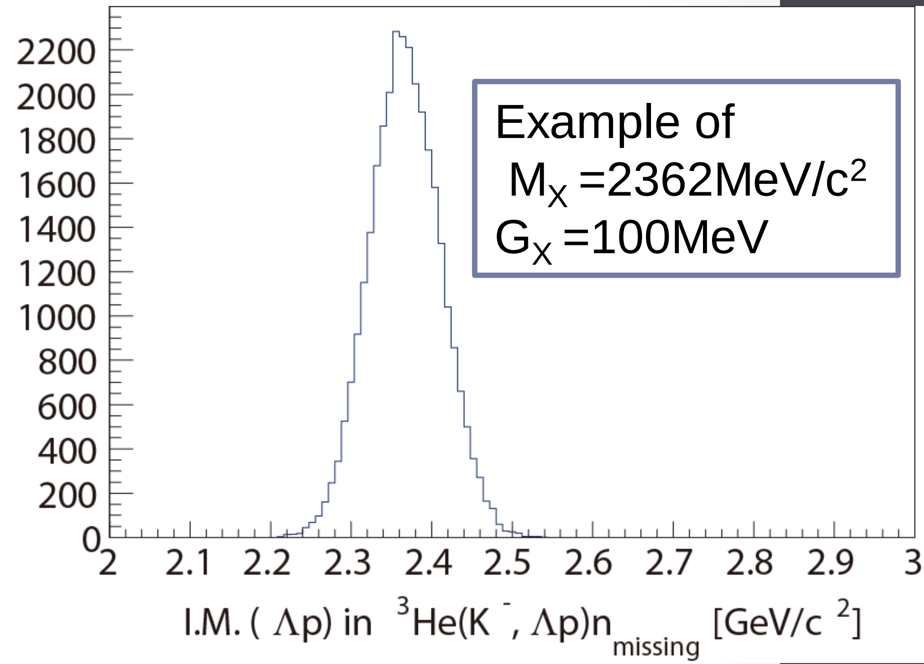
1. Known elementary process (previous slide)
2. **2 step reactions**
   - ~~2NΛ + ΣΛ conversion~~
   - ~~KN →KN + KNN → ΛN~~
   - ~~2NΛ + $\Lambda_{(1405)}$N conversion~~
3. **S=-1 di-baryonic state**

Peak structures from these processes are not consistent of our data spectrum !!



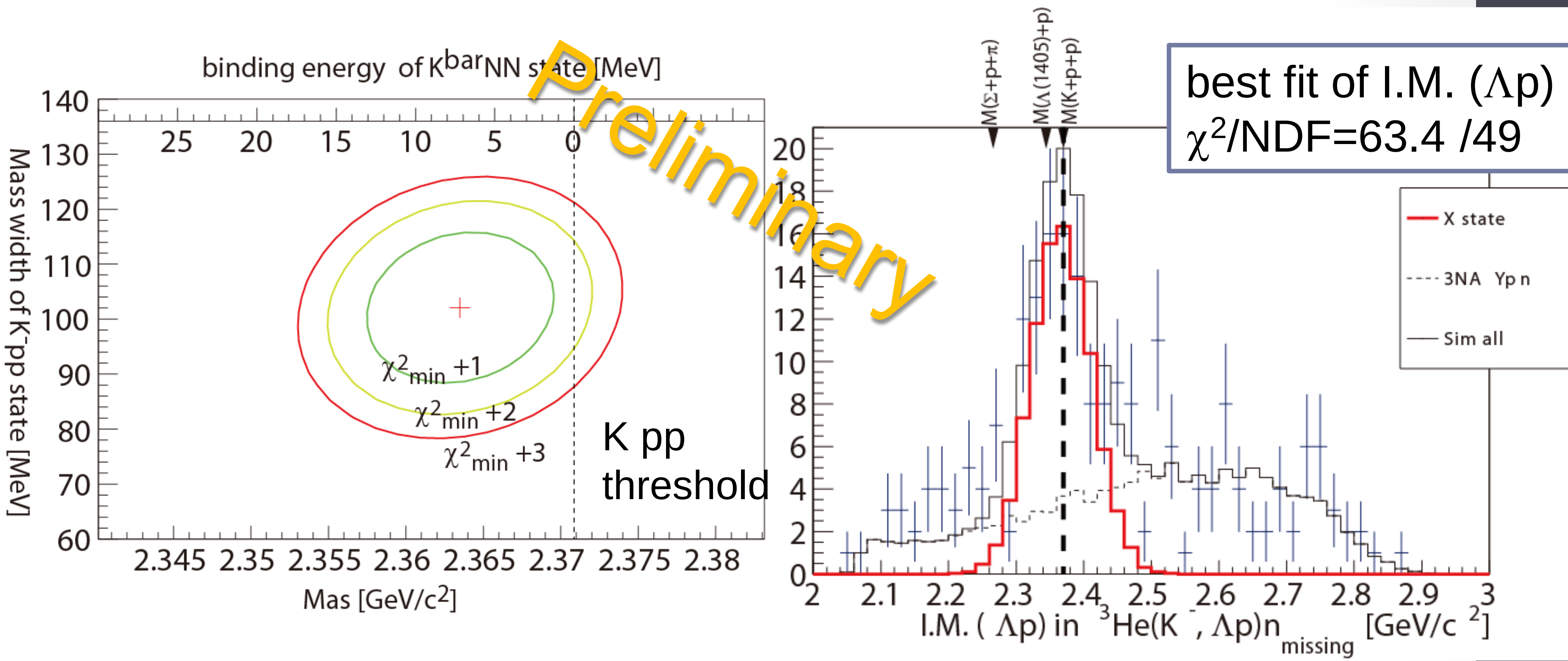
S=-1 di-baryonic state

- Assumption of a resonance state X (S=-1, baryon number =2)
- X state has been generated as a function of mass of X M_X and decay width Γ_X.
  - Width of the peak is assumed to be Bright-Wigner shape
  - $K^-+{}^3He$=> X n(in phase space)
  - X decay to Λp in uniformly angle distribution

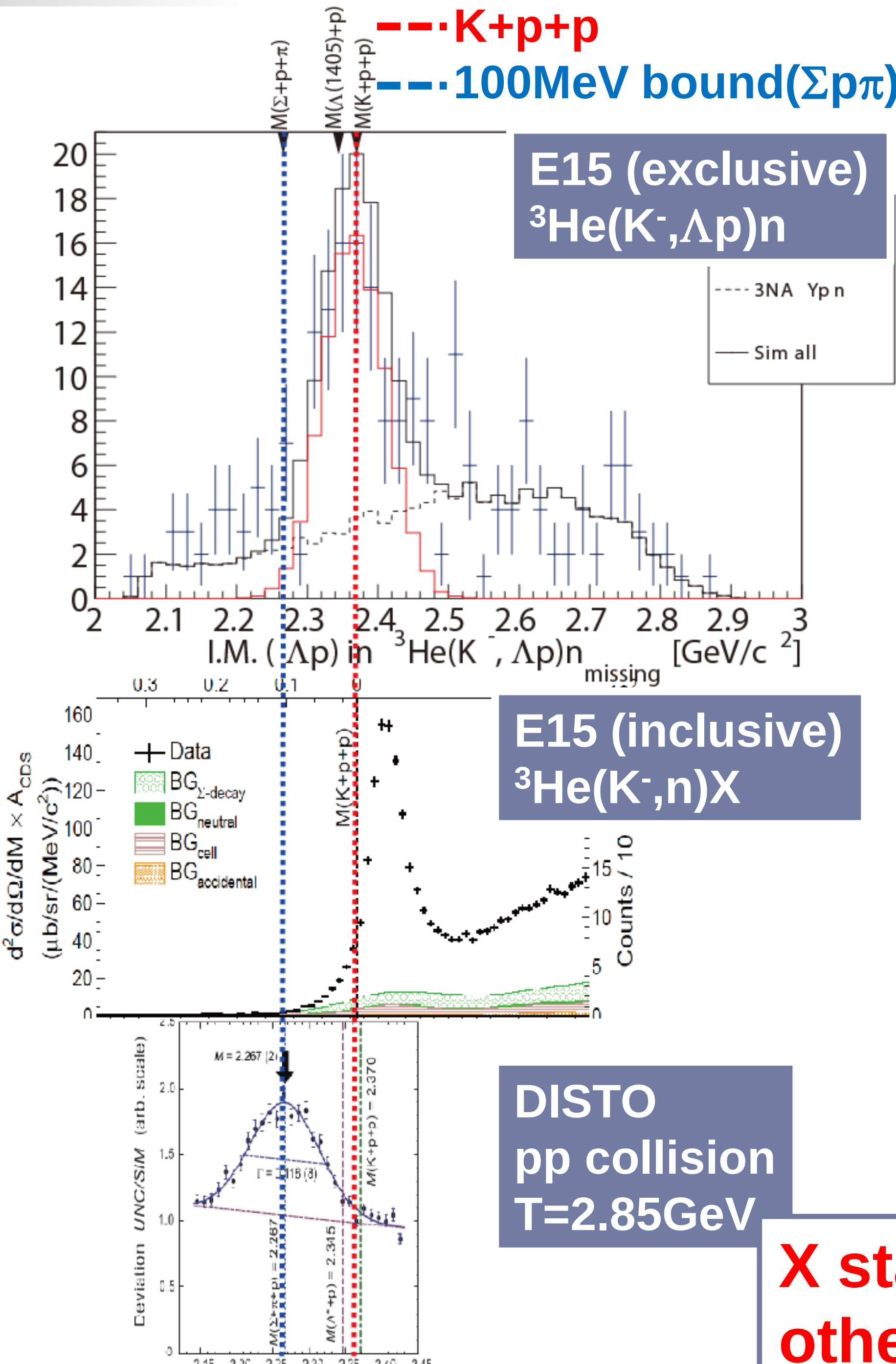


To evaluate Mass and width,
Minimum position on χ^2 map was searched.

Mass and width of X state



- From χ^2 map, it is shallow and having large width, if it is K^{bar}NN.
- In I.M, significance of X state(sig/sqrt(sig+bg)) =8.0



- In E15 experiment
  - Region of X state in I.M. (Λp) is consistent to excess in missing mass of ^{3}He(K$^-$,n)X
- Deeply bound K^{bar}NN
  - In our experiment (induced Kaon reaction), bump structure of 100MeV bound K^{bar}NN is not seem
- 100MeV bound K^{bar}NN formation is strongly depends on reaction?
  - K / π induced?
  - Momentum transfer??

X state is shallow bound K^{bar}NN? or other state?

Conclusion

- First Physics run of the E15 experiment has been performed
  - Data statics is enough to analyze $^3He(K^-, \Lambda p)n$ reaction
- Data spectra of $^3He(K^-, \Lambda p)n$ can not be reproduced by known elementary process
- Λp invariant mass spectra could be explained shallow and wide S=-1 di-baryonic resonance.
  - Mass of the resonance state is very near K+p+p threshold
  - Full width is about 100 MeV
- Is it surely resonance state? $K^{bar}NN$?

  =>We need more information (i.e. spin / isospin)

We will obtain 10 times statics of this data in next E15 run

  - *=> Full kinematics data / other final state (i.e. $\pi\Sigma N$)*

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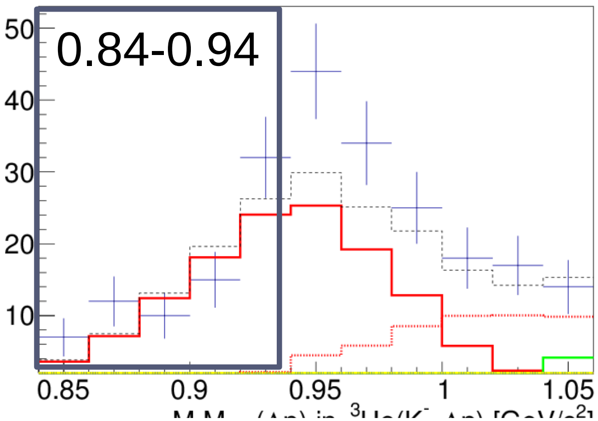
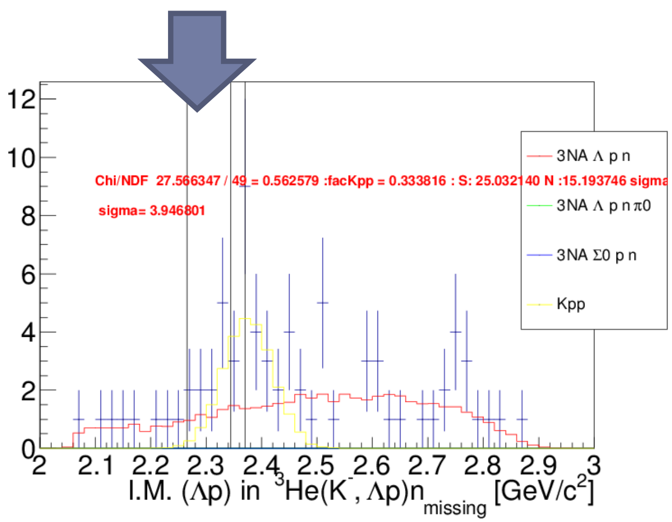
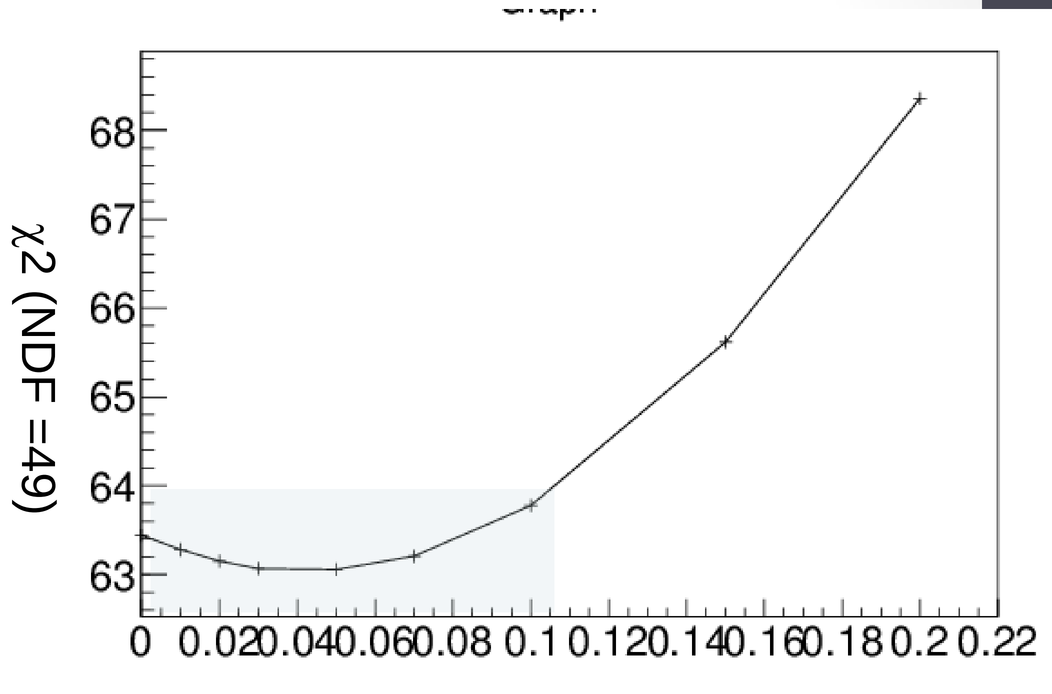
Thank for your attention!!





Only Lpn contribution
There is peak



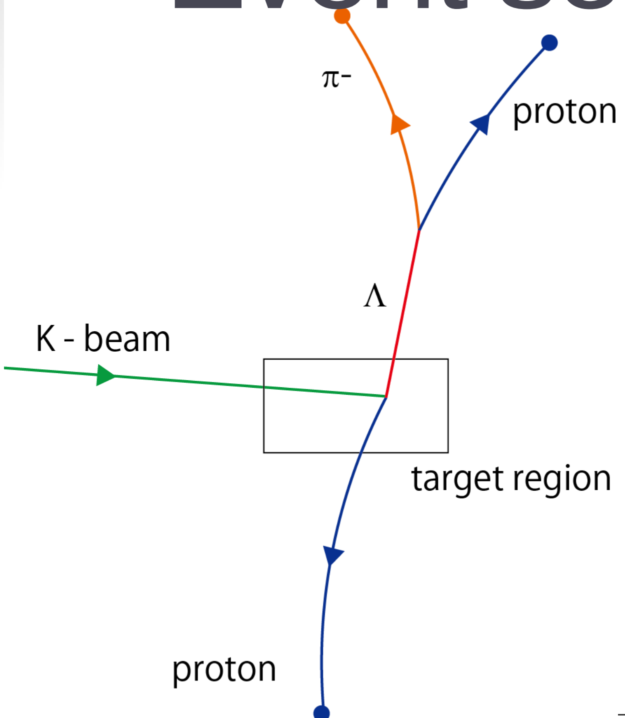
- Fitted I.M. (Lp) with Σ^0p decay mode
- χ2 is minimum in M vs Γ map
- 0 consistent :
- Σ^0p decay <11%

List of expected spectra

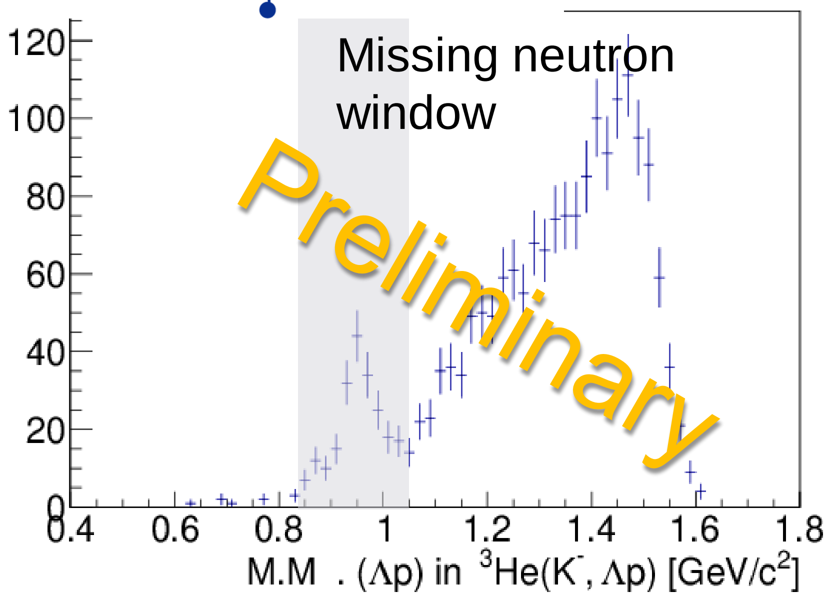
Process ID	process	Ratio [%]
1600	Λp ns	**2.91E−09**
1603	Λp ns+π	1.45E−07
1610	Σp ns	**1.22E−09**
1613	Σp ns +π	3.01896
2100	Λpn	7.39825
2102	Λpn+π	21.1222
2103	Λpn+2π	3.24E−07
2104	Λpn+3π	0.000215
2110	Σpn	5.27836
2112	Σpn+p	20.2813
2113	Σpn+2π	39.4892
2114	Σpn+3π	4.92E−08

Contribution from two-nucleon absorption processes, *i.e.* one nucleon is as spectator, are almost negligible in this reaction.
(10^{-9} % level)

Event selection



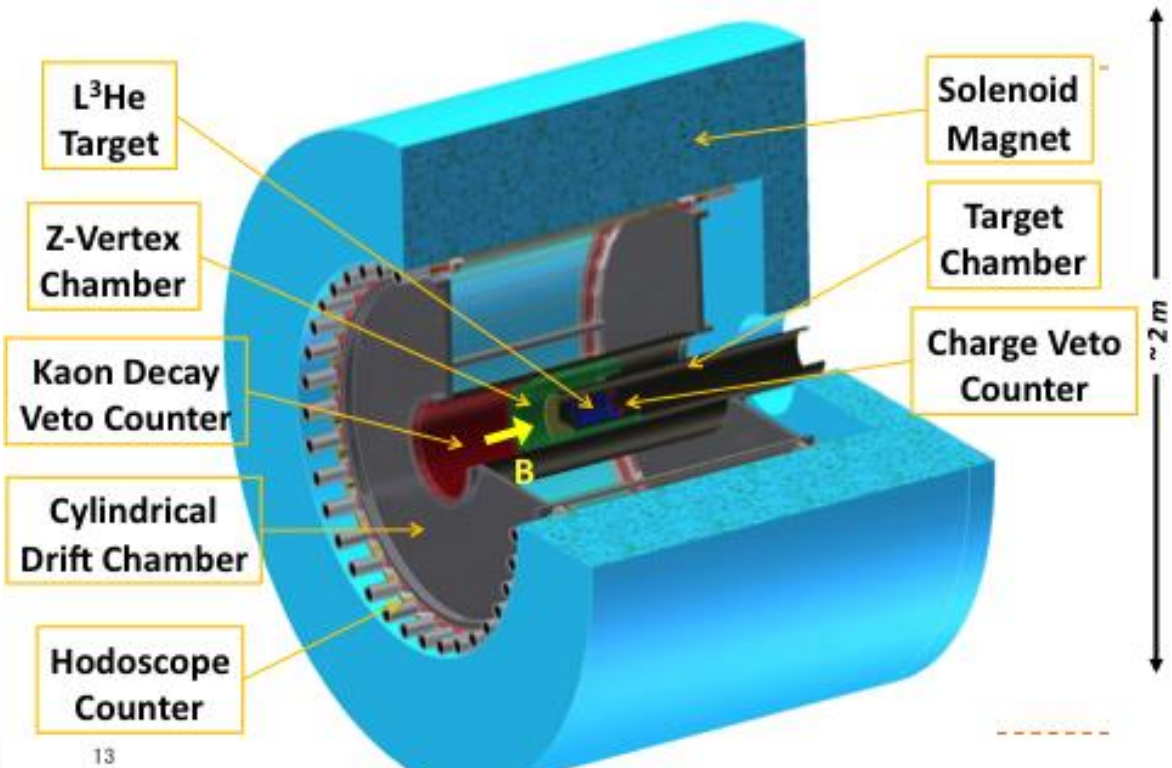
1. Event tagged by ppπ- @CDS
2. Requested no forward charged particle
3. Defined Λ decay pair by using Likelihood method.
4. Selected missing neutron

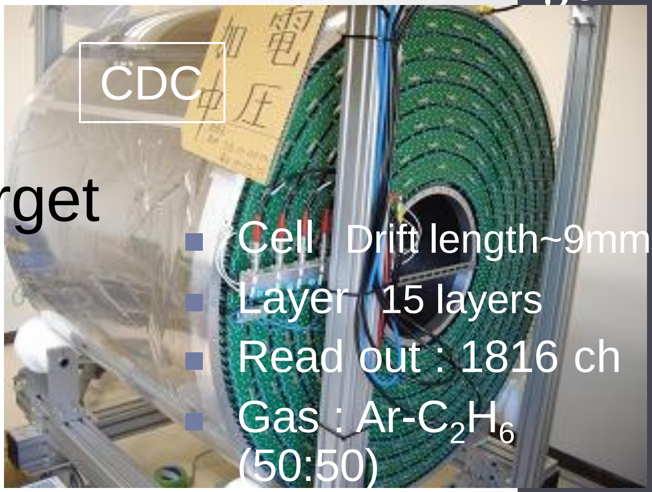


- To ensure Λpn final state, missing neutron (0.84-1.04GeV/c^2) selected

Cylindrical Detector System

- To detect the decay particles from ^{3}HeTarget
  - Momentum reconstruction
  - Particle identification





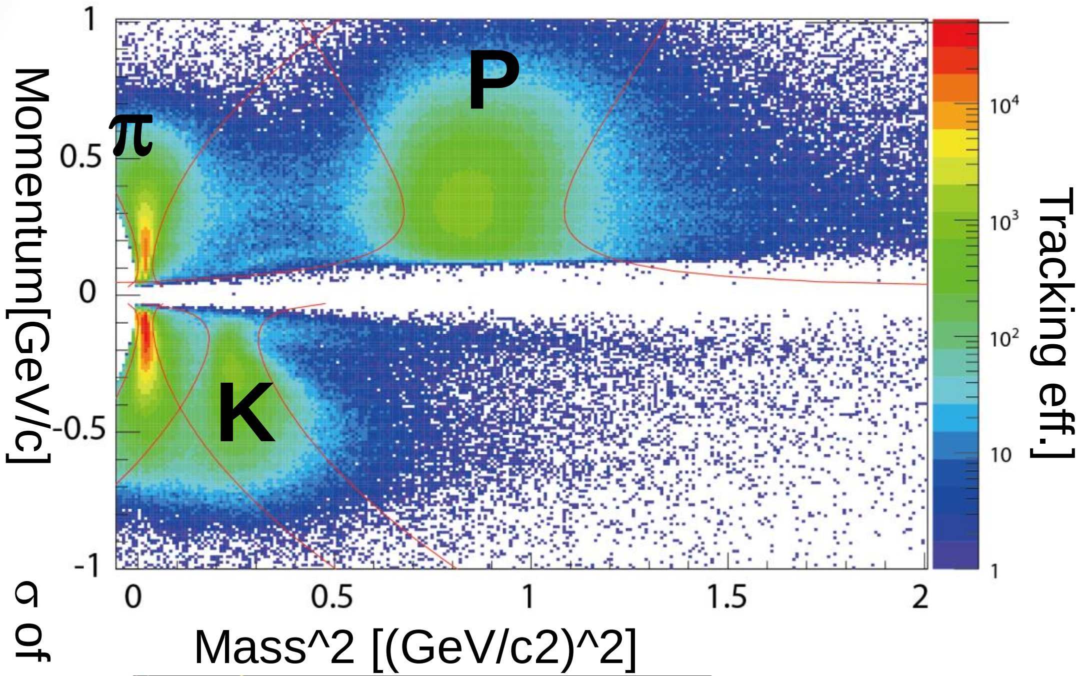
CDC (15 layers, 1816ch) + CDH (36 seg) + 0.7T

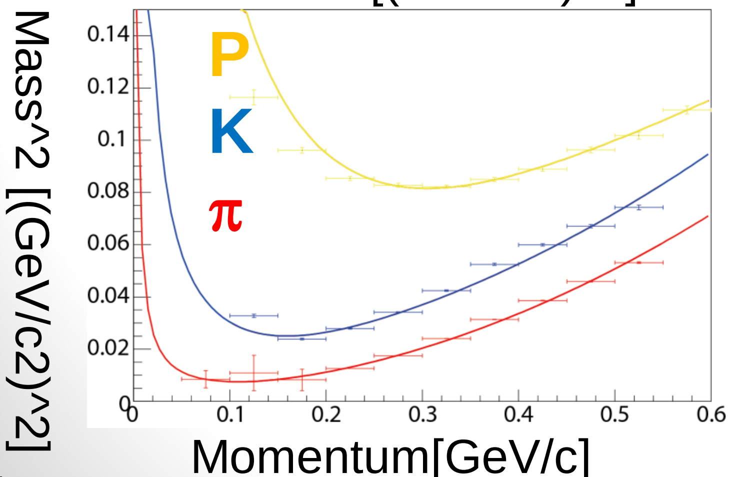
solid angle: 60% of 4π

Mass resolution (Kpp) ~10MeV/c^2

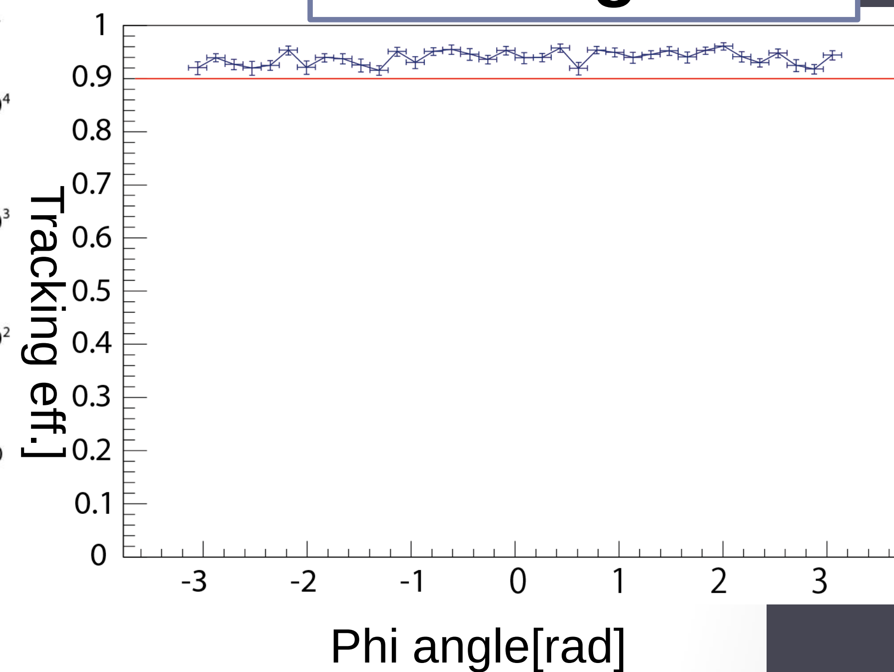
PID & Tracking efficiency

π/K/p/d are clearly separated





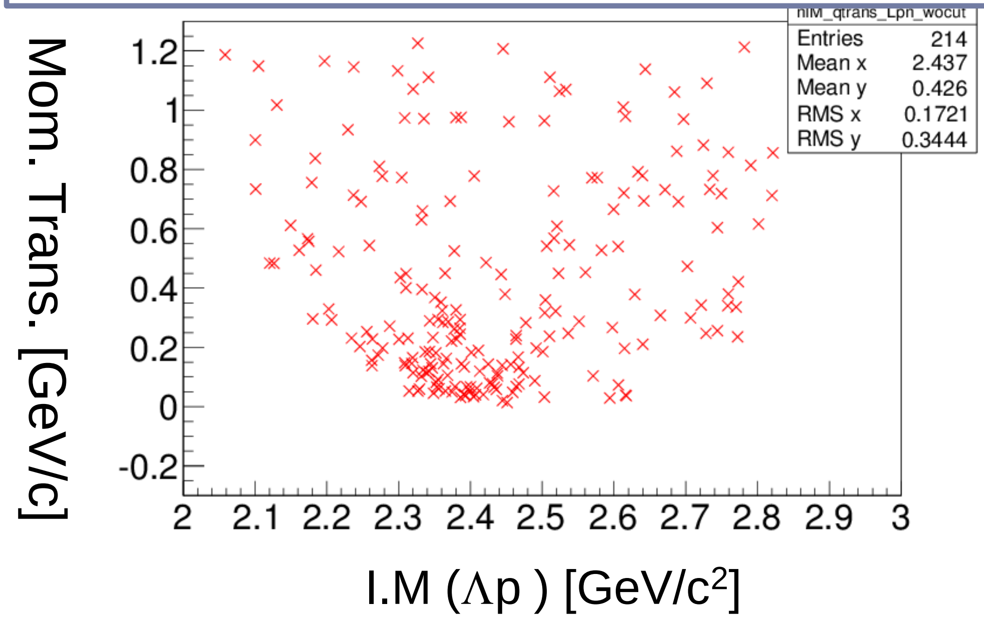
Tracking eff



- Total eff =94.0%
- There is no geometrical asymmetry!

Peak structure and Momentum transfer of $^{3}He(K^{-},\Lambda p)n$

I.M (Λp) vs momentum transfer

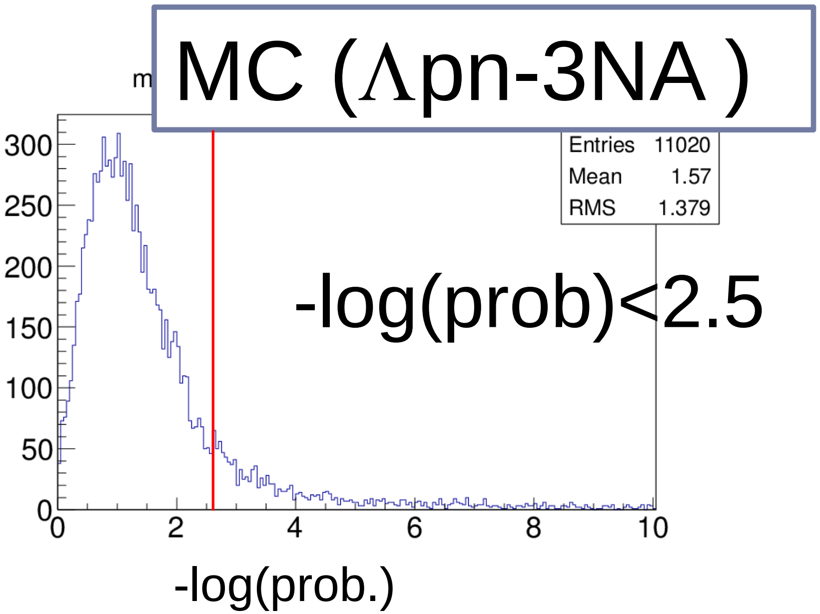


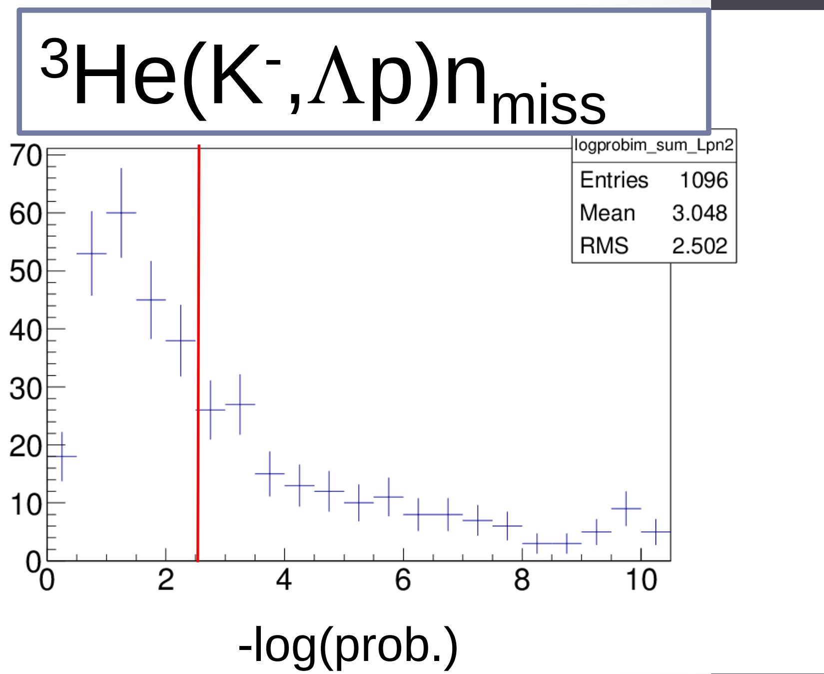
Momentum transfer :
$(\boldsymbol{P}^{2}_{beam} - \boldsymbol{P}^{2}_{n}) / (\boldsymbol{P}_{beam} * \boldsymbol{P}_{n})$

- Peak structure seems enhanced in small momentum transfer region.
- **Process which make peak structure is enhanced in small momentum transfer region?**

Back up of Λp selection

Probability fuction





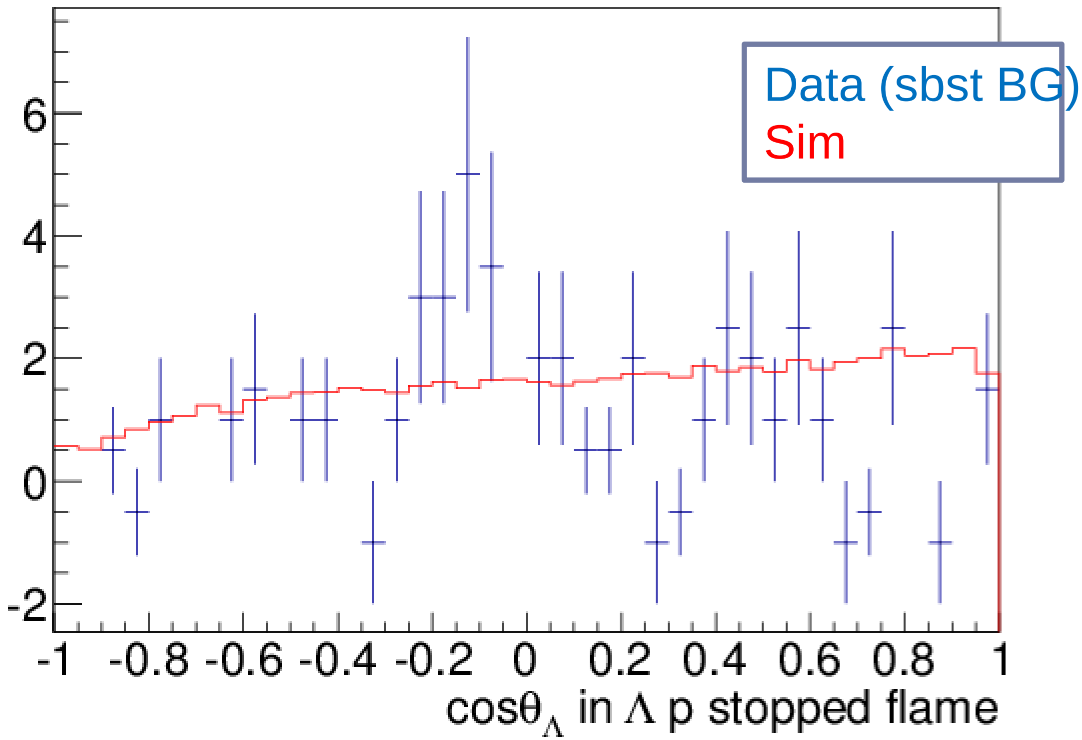
- Cut -log(prob)<2.5

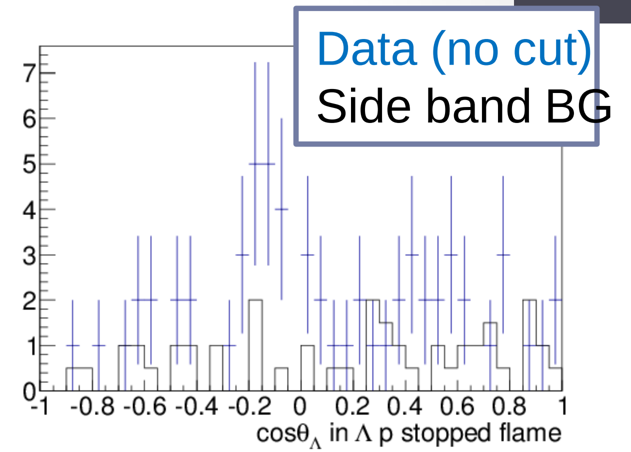
missID <0.5% @3NA Λpn

=>miss ID @2NA (Λpn_{sp} , $\Sigma^0 pn_{sp}$) & 3NA (Σ^0pn) also less than 0.5%.

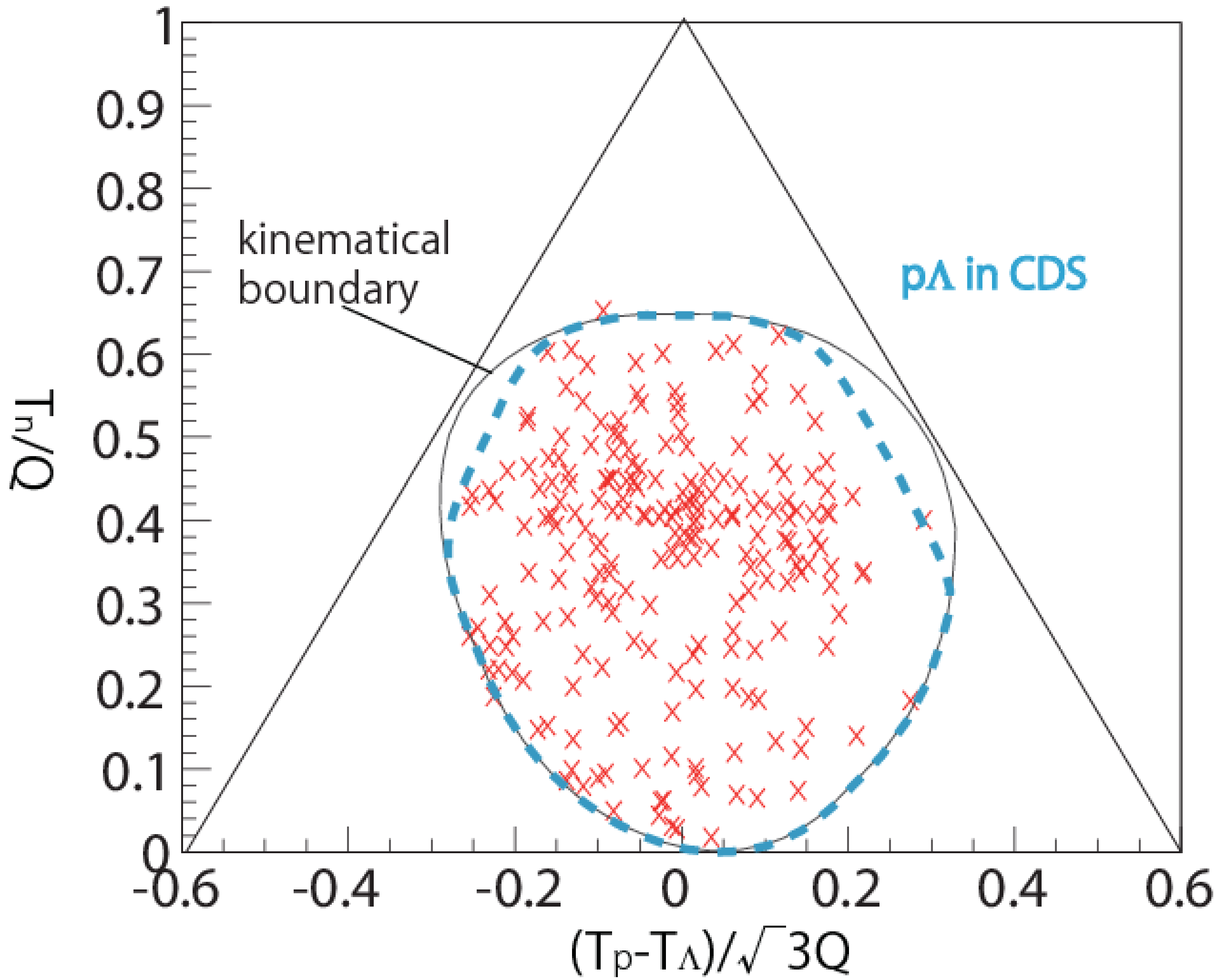
Detail of fitting of DCAs and IM(Lp) is in Backup slide.

$\cos\theta_\Lambda$ in Λp stopped flame





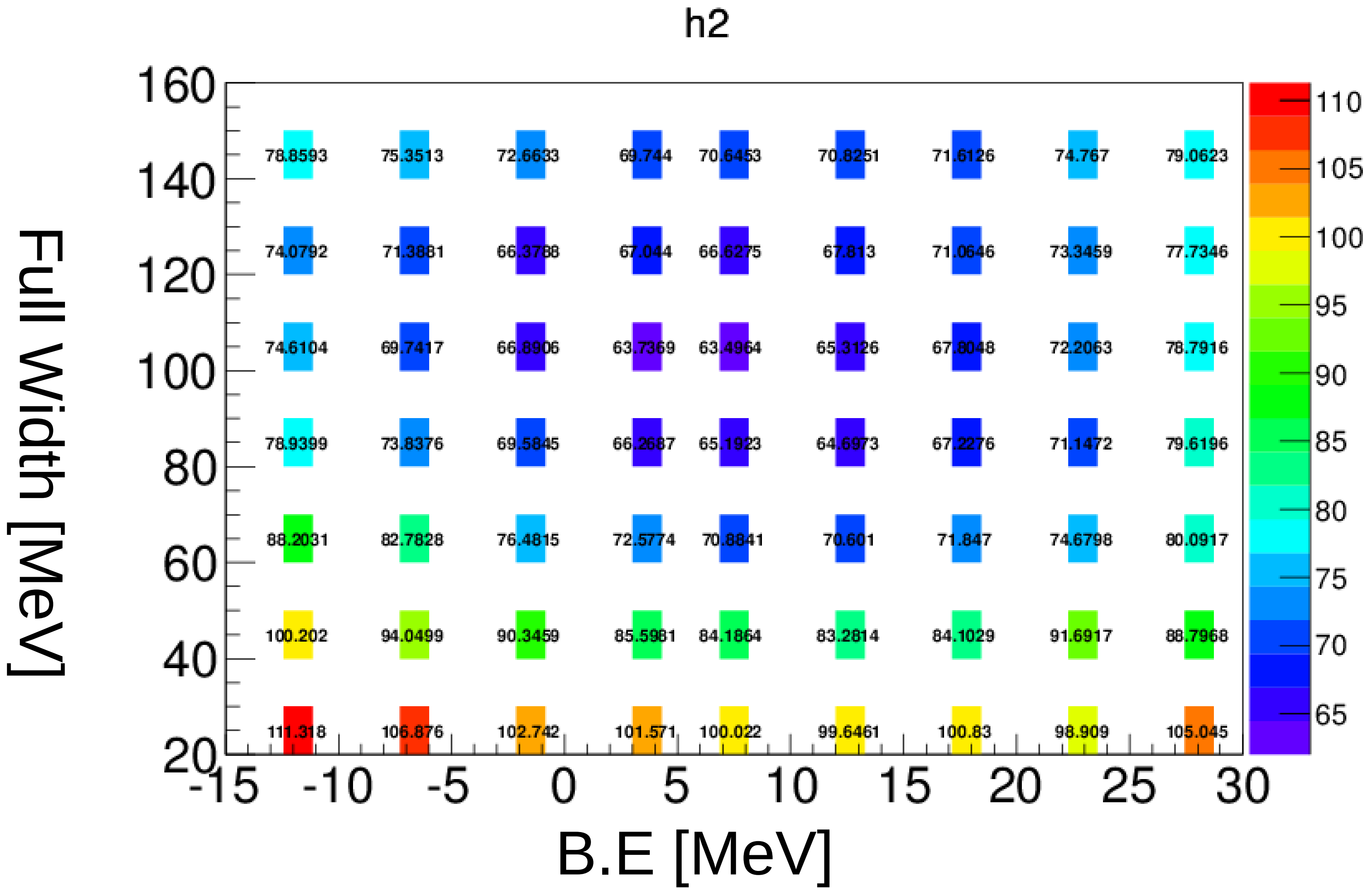
- Data spectra is subtracted with Side band background .
- Red line is simulation of X state (S-wave)
- Data (cut in $\text{mean}_{\text{Xstate}} \pm 1\sigma$) is almost consist to sim.
- =>X state is S-wave state?


kinematical
boundary
pΛ in CDS
T_n/Q
$(T_p-T_\Lambda)/\sqrt{3}Q$

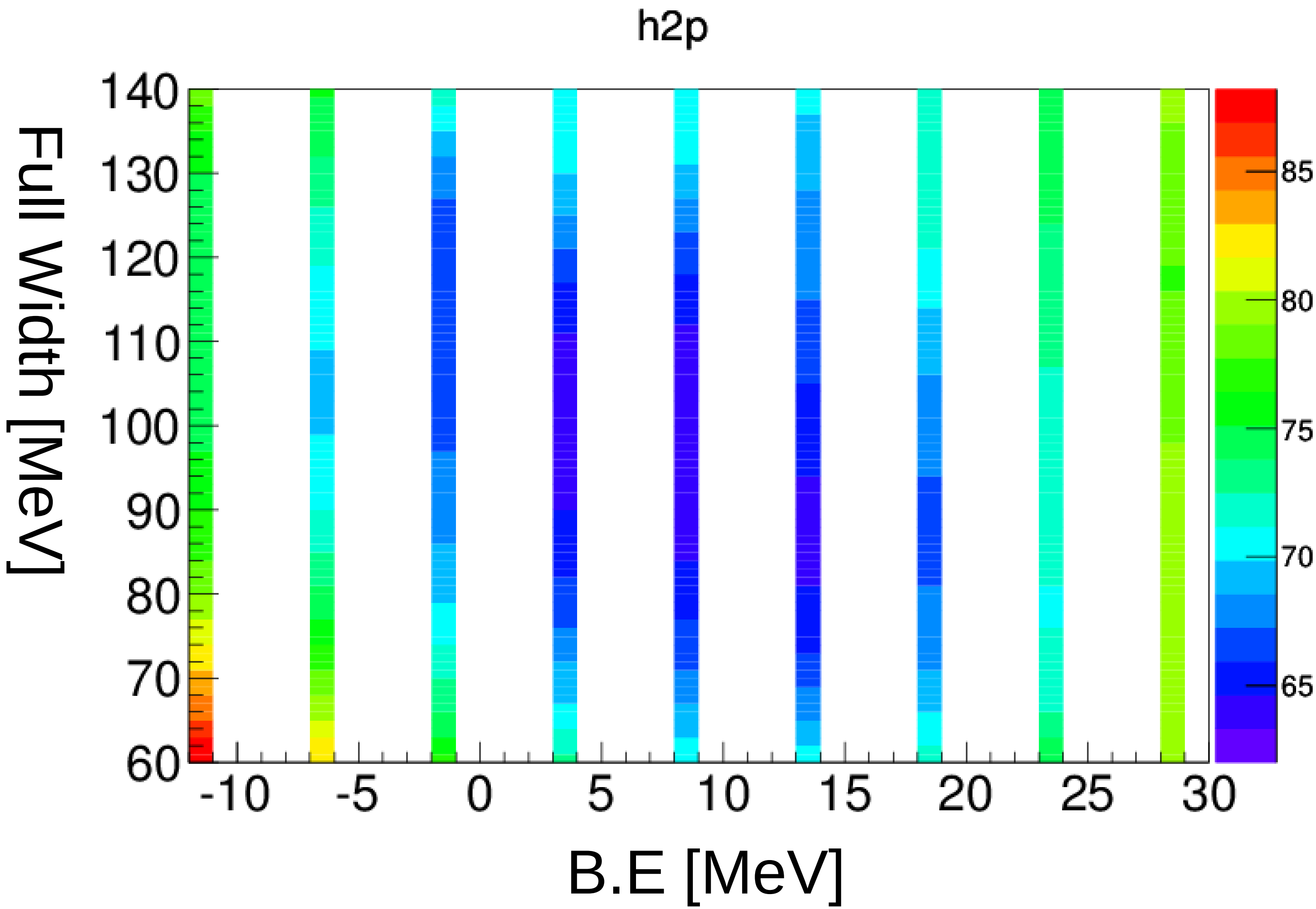
$\chi 2$ mapping of X state (sim)

1. Generated X state in some B.E and width
2. Fitting 6th polynomial to x2 v.s width in certain B.E
3. Making continues plot of $\chi 2$ map
4. Fitting map with 2nd order XY function ($z=p_0+p_1x^2+p_2y^2+p_3xy+p_4x+p_5y$)

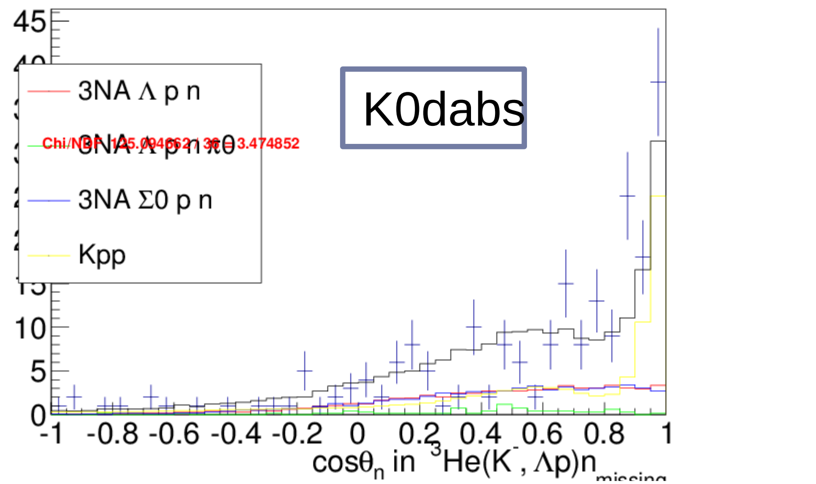
Generated X state in some B.E and width

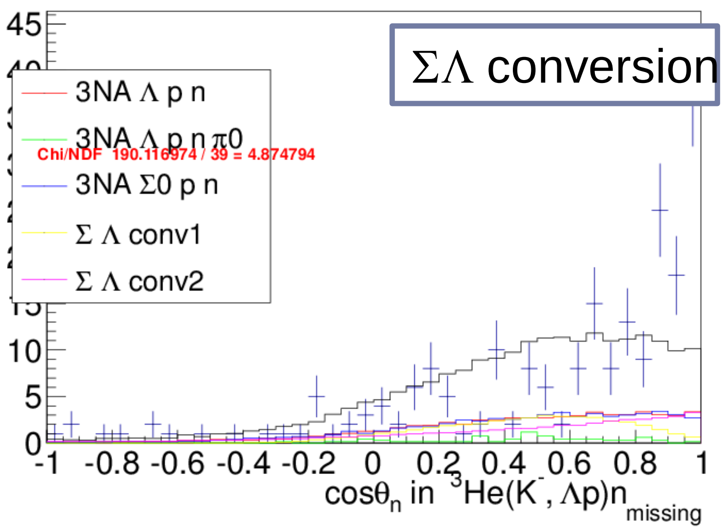


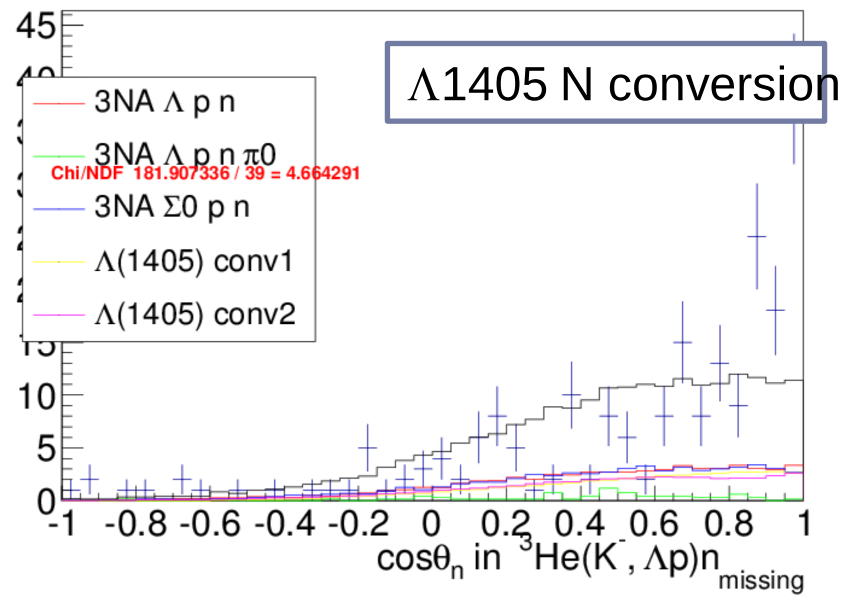
Making continues plot of $\chi 2$ map



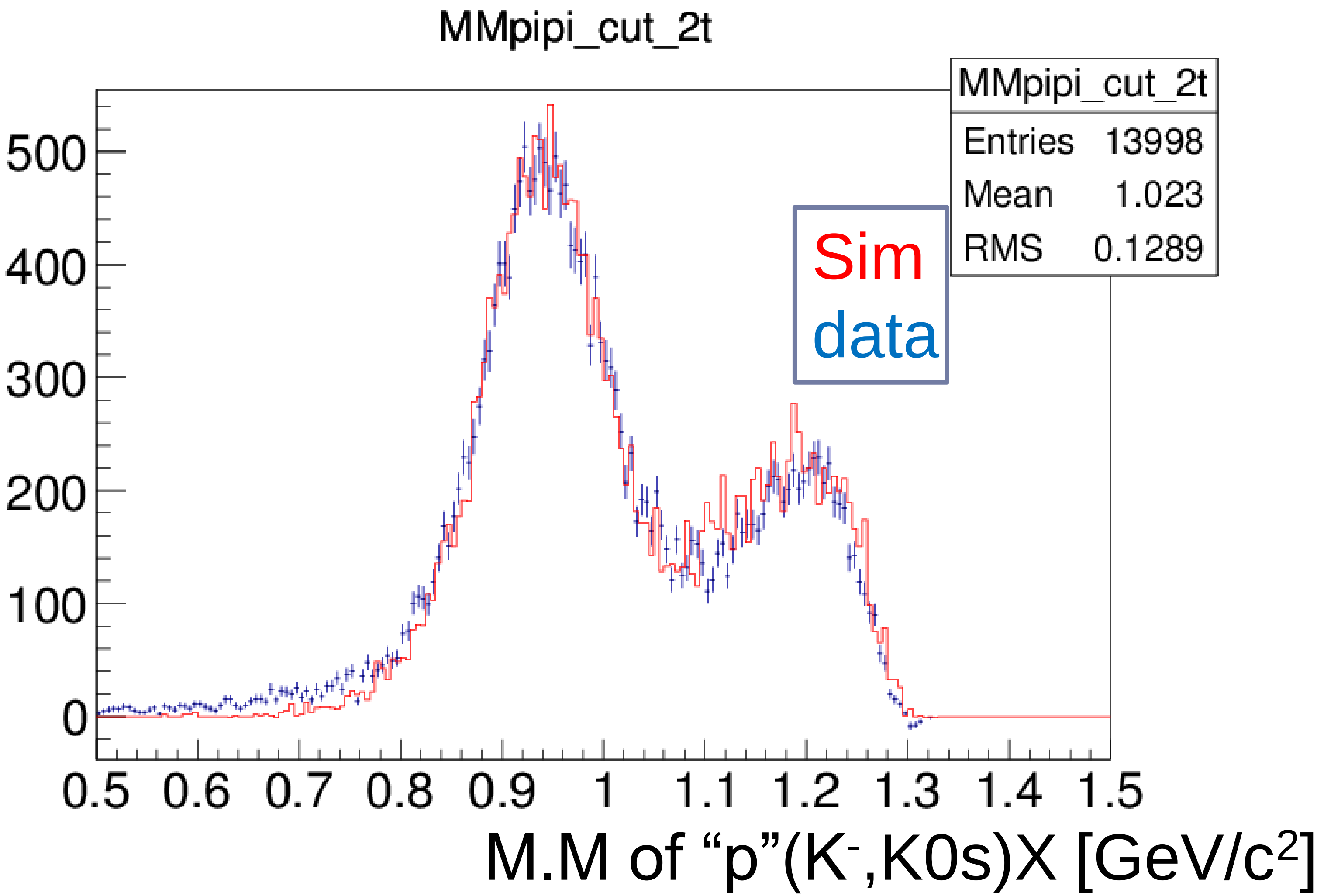
Cos n plot of Sim







M. M. of K^0s



Data and sim are consistent => missing mass resolution and center value is good

I add offsell correction (considering 3He binding energy) to sim

And chage distribution of Fermi motion (almost no effect to MM of

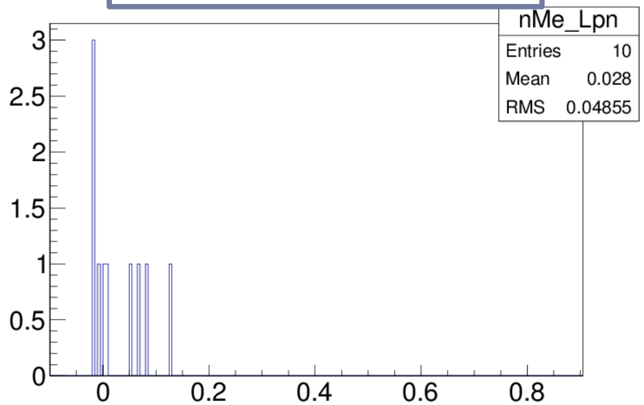
$^3He(K^-,\Lambda p)n^{NC}$

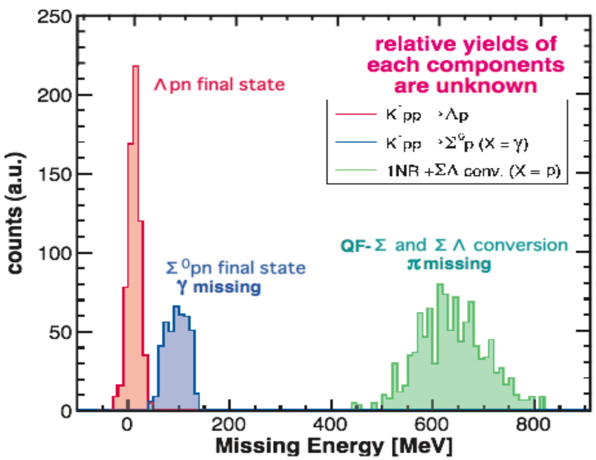
- Expected missing n in NC ~60events
- => 60 x 0.25(eff^{NC}) =15
- Detected event =10events

- In missing energy spec., ~4events from Σ^0 (estimation of Σ^0pn ~30%)

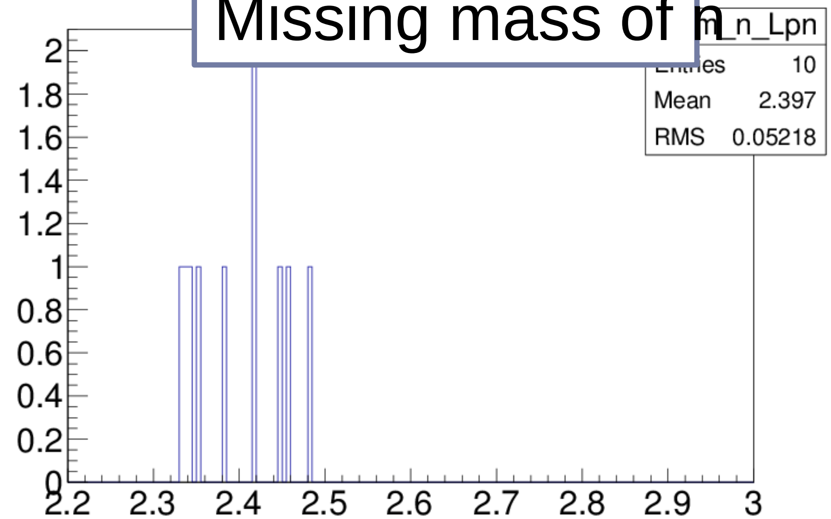
Consistent!!!

Missing energy

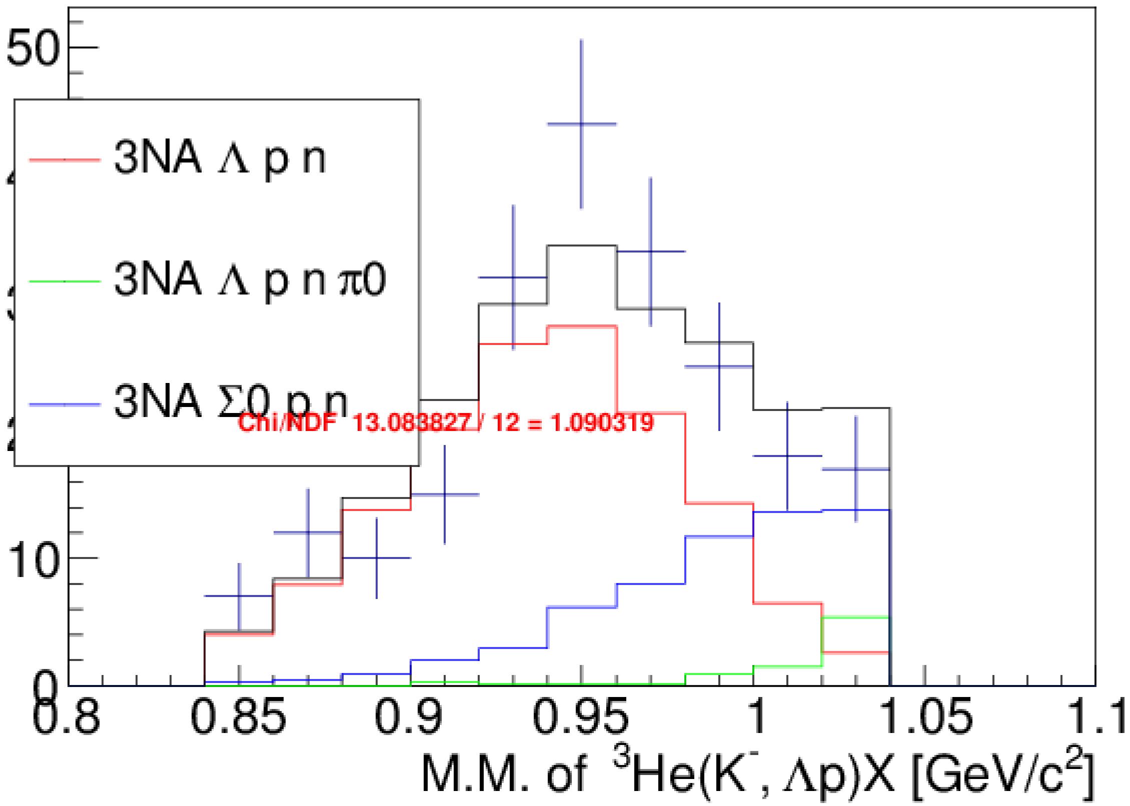




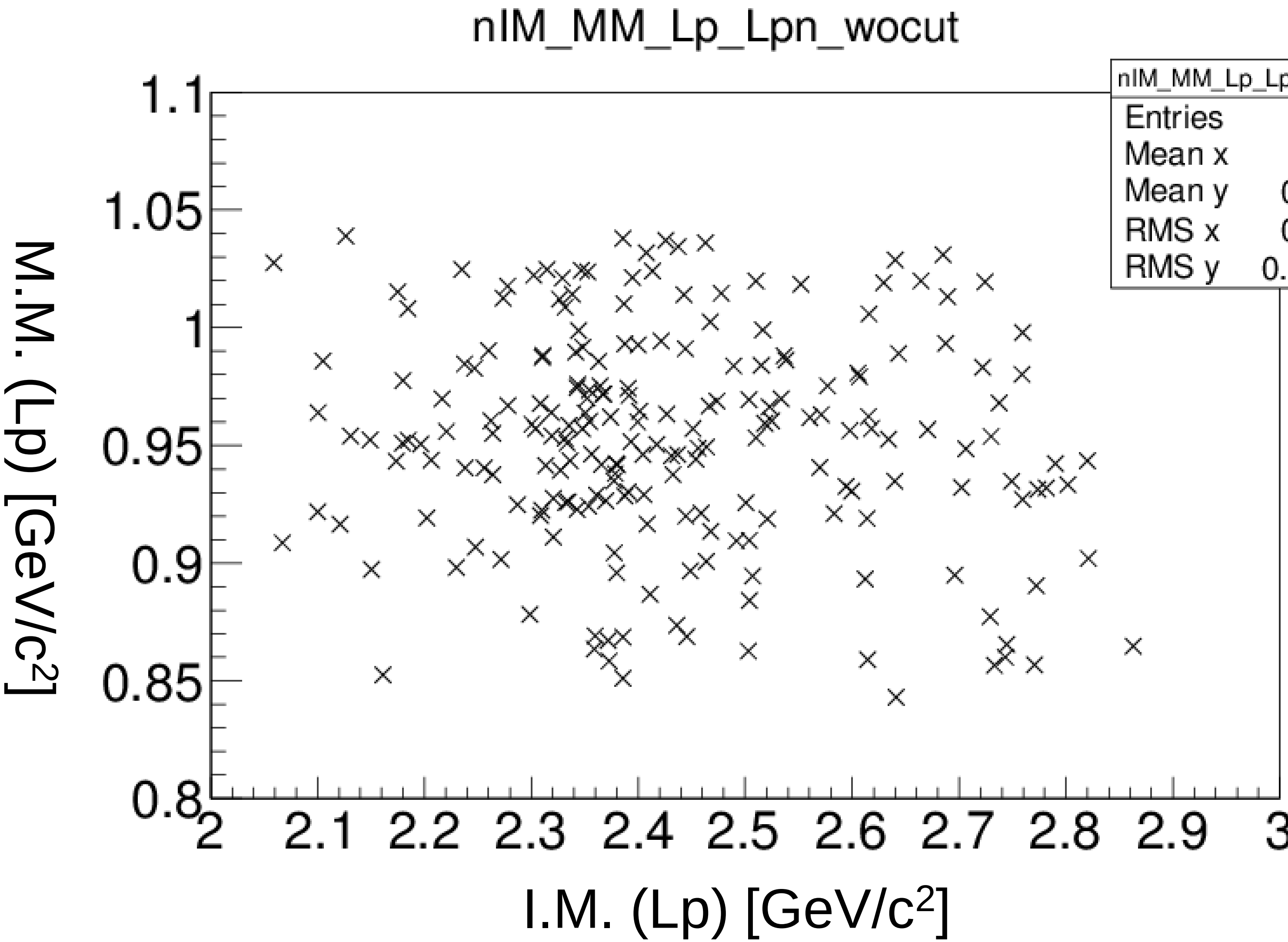
Missing mass of n



Missing neutron

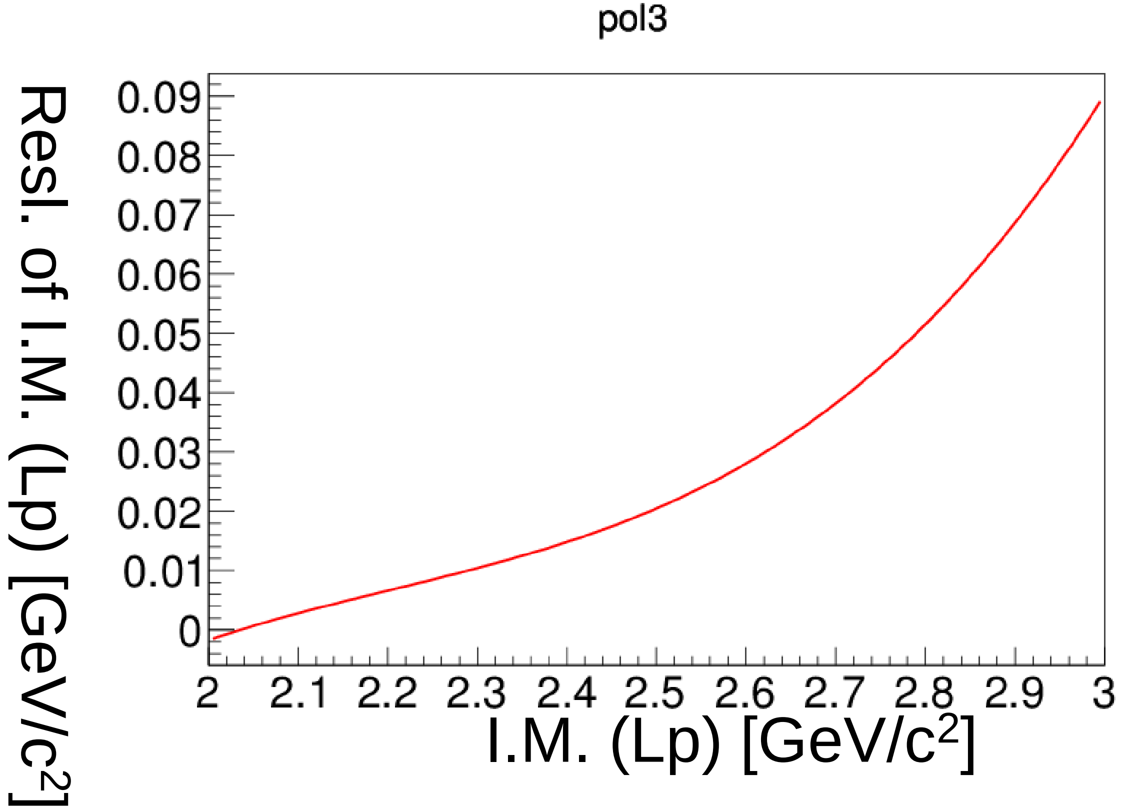


- Reduced $\chi^2 \sim 1$
- Fitting is not bad



- Peak structure of X state is on missing n peak
- => almost X state events seem not to be come from Σ^0

Resolution of I.M (Lp)



- Estimated with sim of 3NA(Lpn)
- At Kpp th, resl is ~10MeV