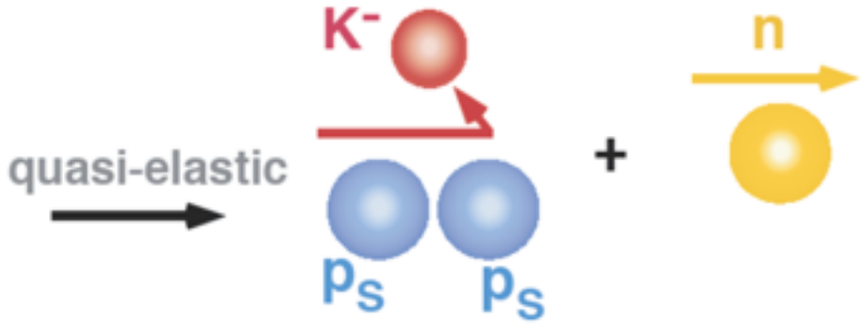


Kaonic nuclear state search by kaon reaction on ^{3}He target at 1GeV/c

M. Iwasaki

for E15 collaboration

MIN16 - Meson in Nucleus 2016, 31 Jul - 2 Aug

Objectives

Key questions :

- Can kaon be a member of nuclei?

- Kaon properties change in nuclear media?

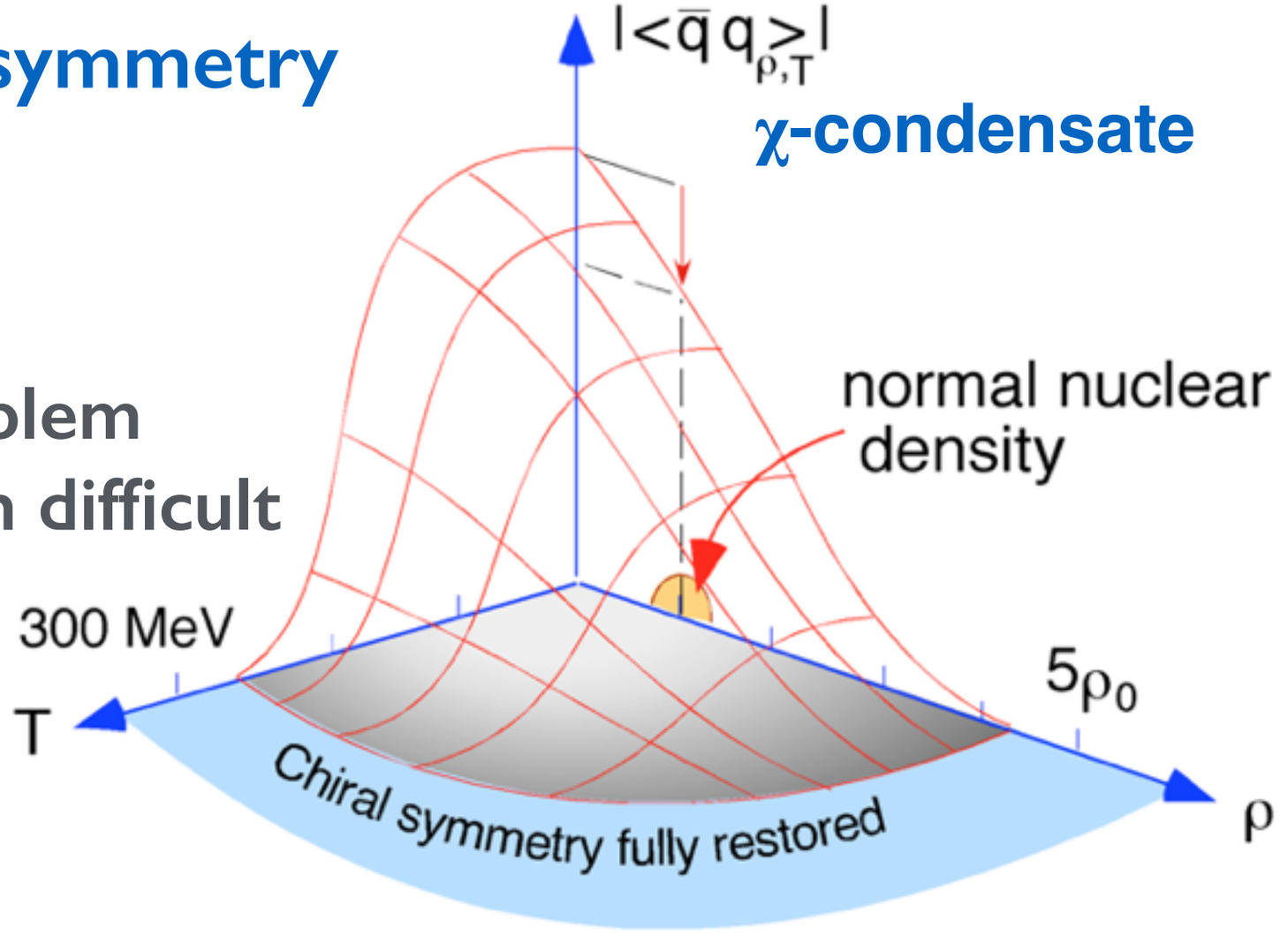
Hadron masses and χ-symmetry

Non-perturbative aspects

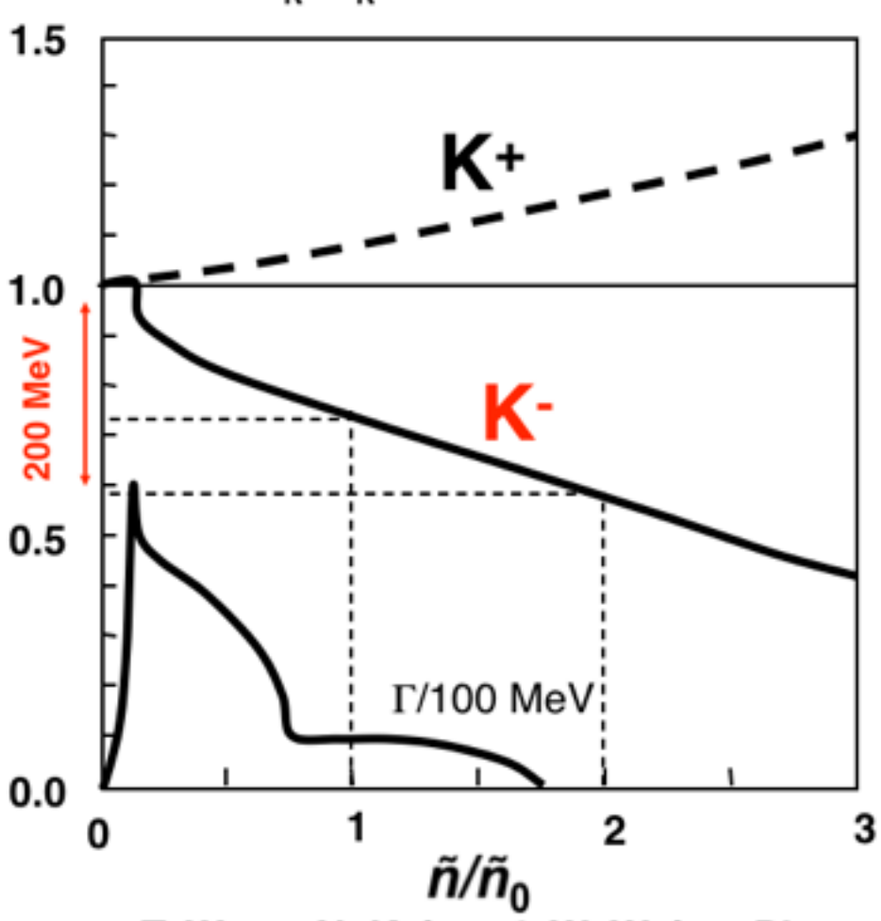
@ energy < Λ_{QCD}

Finite density → sign problem

Lattice-QCD approach difficult



Search for Kaonic nuclear states

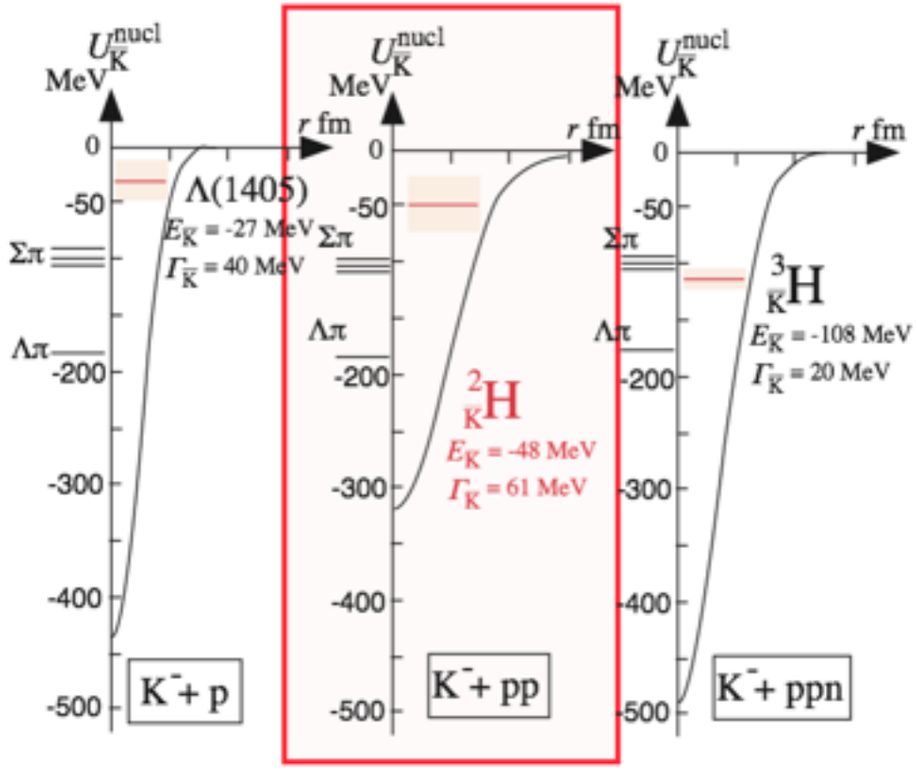


T. Waas, N. Kaiser & W. Weise, Phys. Lett. B379 (1996) 34.

strongly attractive in I=0 channel

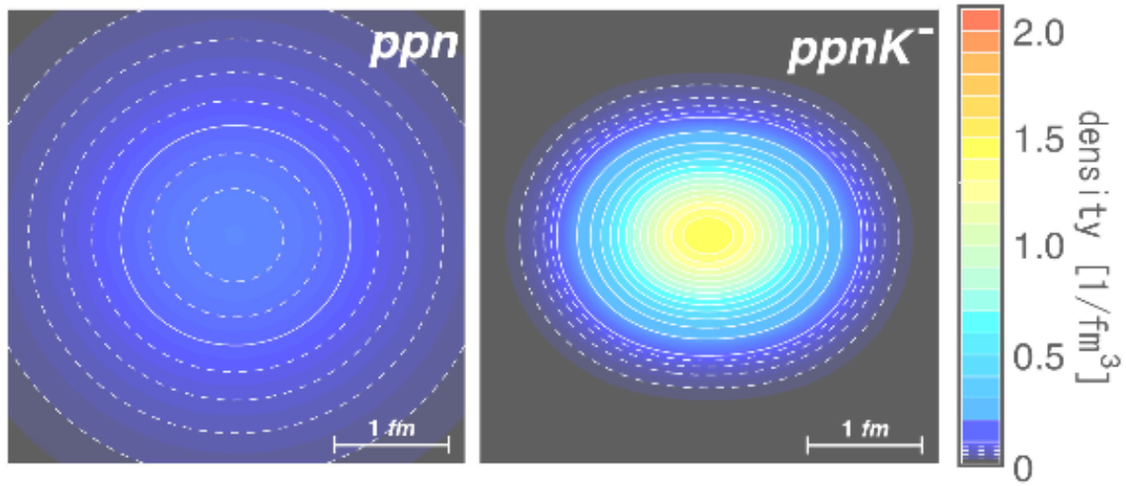
assuming $\Lambda(1405)$ = K^-p bound state ...

T. Yamazaki & Y. Akaishi, PLB 535 (2002) 70



$B_{\bar{K}}$ ~ 50 MeV!

Dote et al., PLB 590 (2004) 51



formation of high density matter?

nuclear state search

- simplest system K^-pp

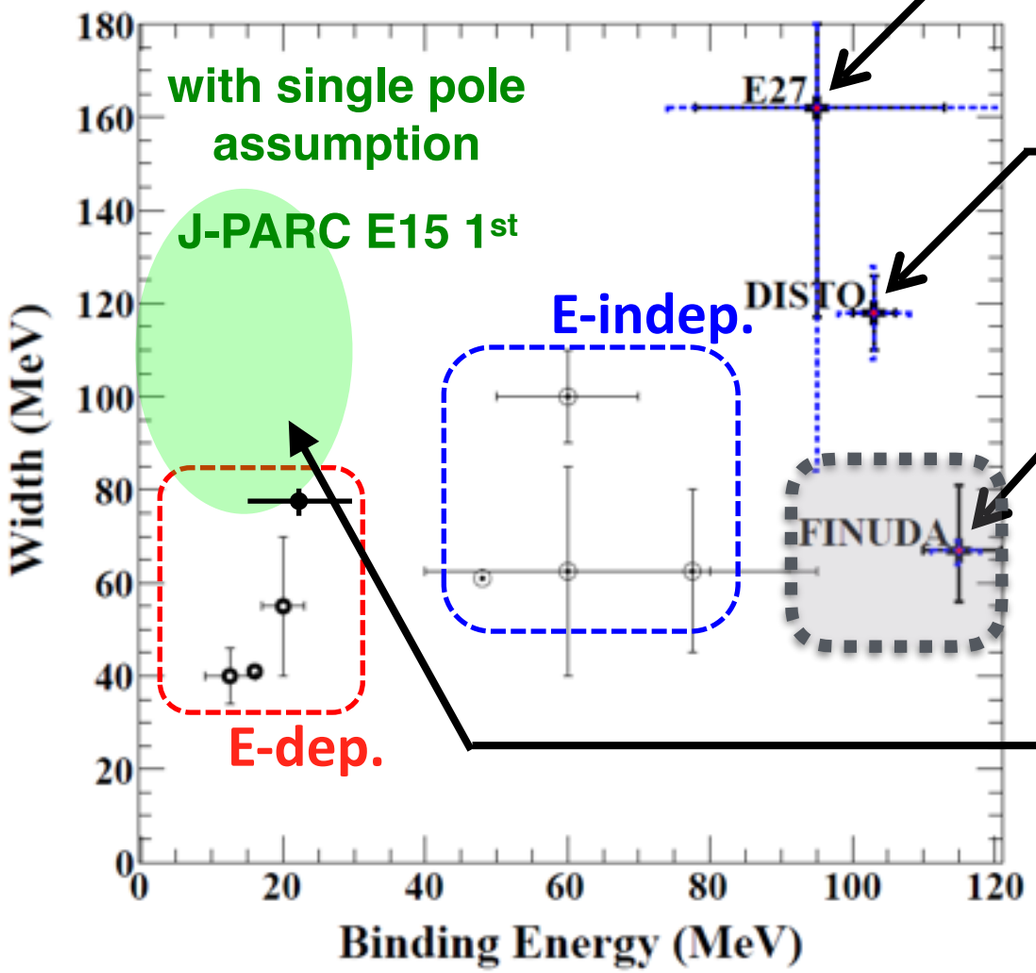
^{3}He(K^-, n) @ 1 GeV/c

Recent status of K^-pp bound state

- **Recent results**
  - **Theoretical calc.**
  - **Experiments**

$\bar{K}N$ interaction model

E-dep. / ***E-indep.***



Reports structure / *NO structure*

J-PARC E27
$d(\pi^+, K^+)X$

DISTO
$pp \to \Lambda p K^+$

FINUDA
$(stopped\ K^-, \Lambda p)$

J-PARC E15
$^3He(K^-, \Lambda p)n$:

LEPS
$p(\gamma, \pi^- K^+)X$

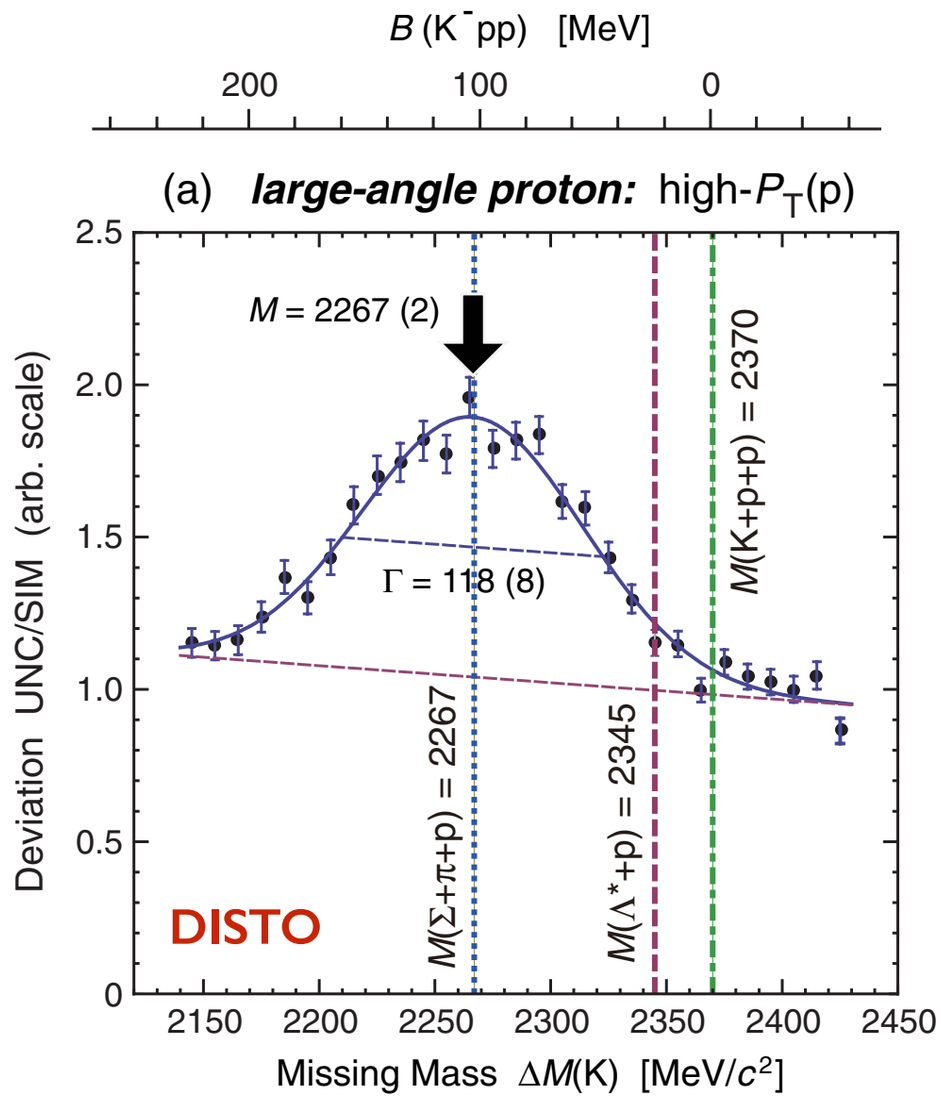
HADES
$pp \to \Lambda p K^+$

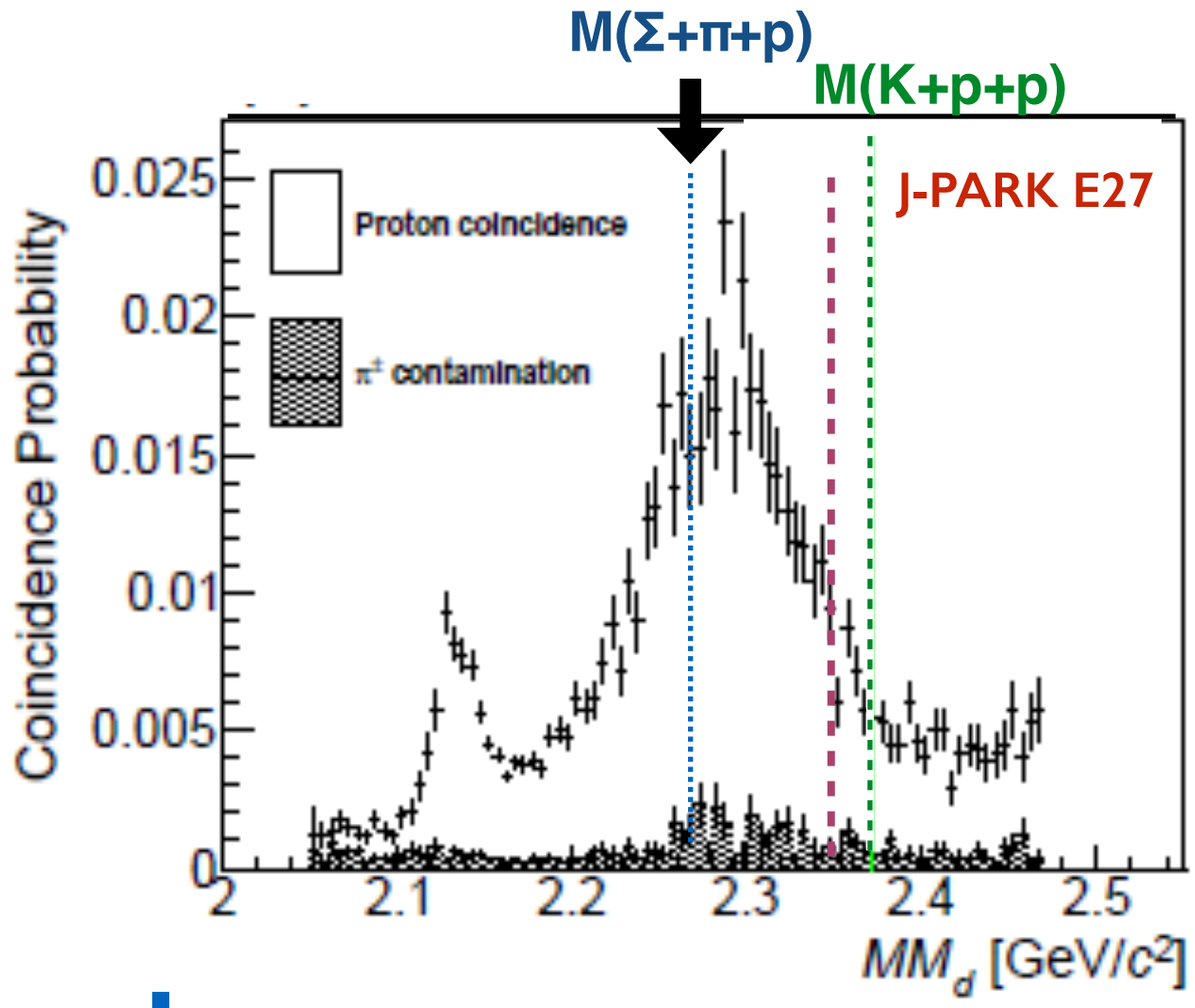
FINUDA ?

Kpp should be studied more

present “Kpp" candidates @ B_K~100 MeV

hyper deep ??





Many objections exist, though…

why no threshold ($\Sigma\pi$p) effect seen?

why no quasi-elastic K seen?

p+p → p+N⁺(1710) → p+(Λ+K⁺)

¿→ (p+Λ)+K⁺ ?

…

Published E15[1st] data

PTEP

Prog. Theor. Exp. Phys. **2015**, 061D01 (11 pages)
DOI: 10.1093/ptep/ptv076

Only 3 days!
(suspended by the earthquake)

^{3}He(K^-, n) — semi-inclusive

Letter

Search for the deeply bound $K^- pp$ state from the semi-inclusive forward-neutron spectrum in the in-flight K^- reaction on helium-3

J-PARC E15 Collaboration
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PTEP

Prog. Theor. Exp. Phys. **2016**, 051D01 (11 pages)
DOI: 10.1093/ptep/ptw040

^{3}He(K^-, Λp) n — exclusive

Letter

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Published E15[1st] data

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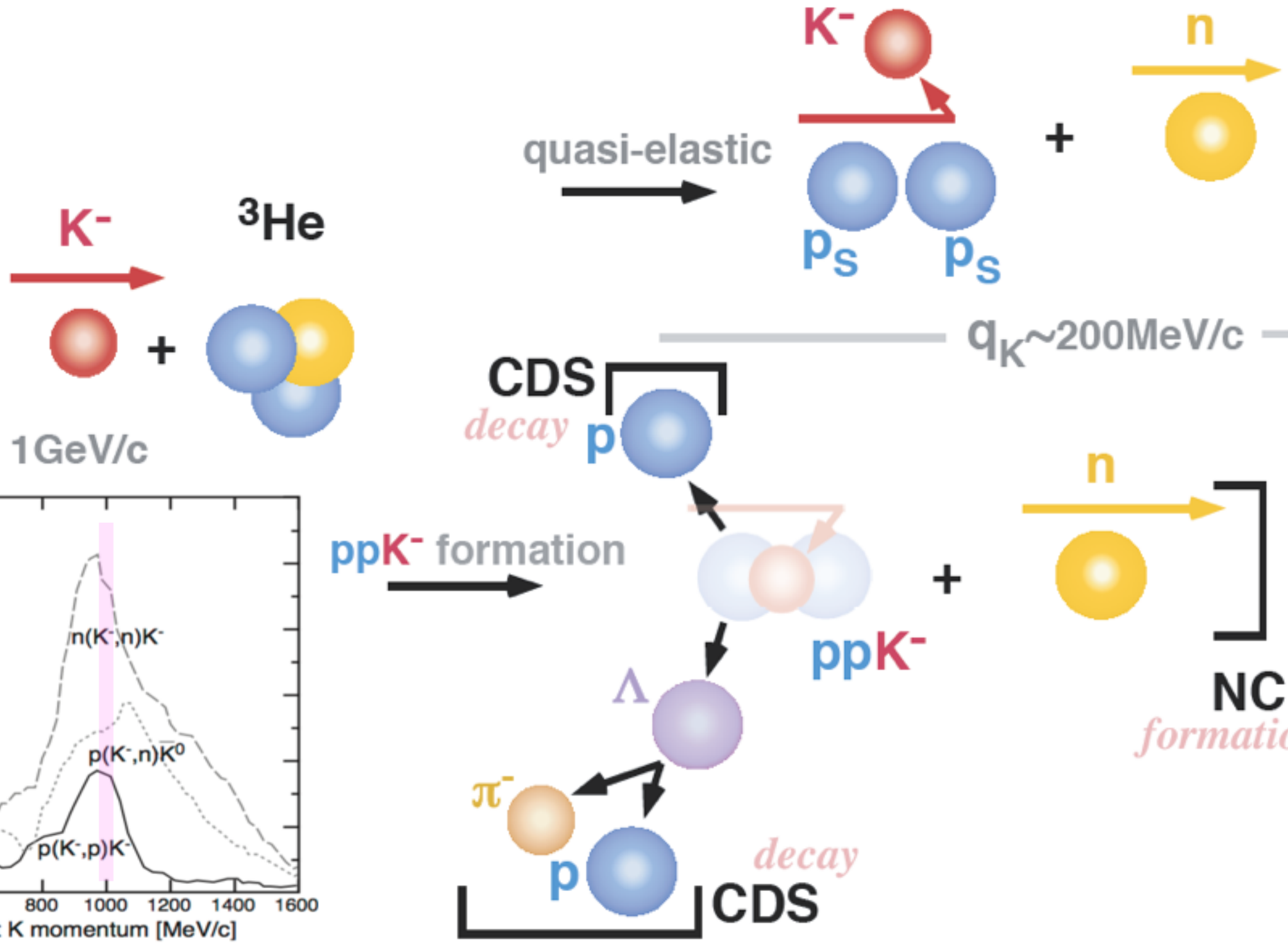
with new data!

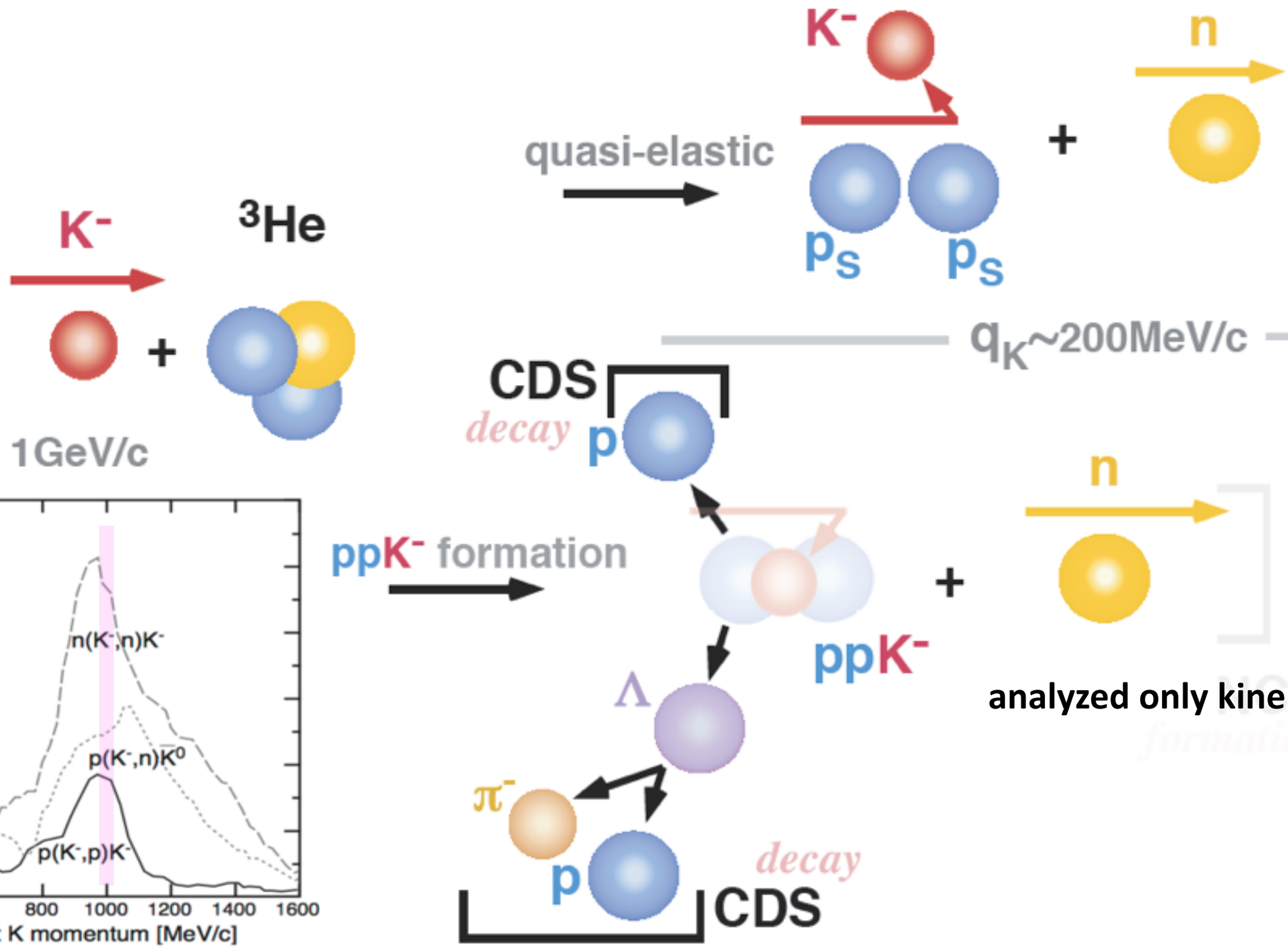
"K^-pp" search via $^3He(K^-,n)$ @p_K=1GeV/c

for efficient "ppK" formation $q_K \sim 200$ MeV/c



“K⁻pp” search via ^{3}He(K⁻,n) @p_K=1GeV/c

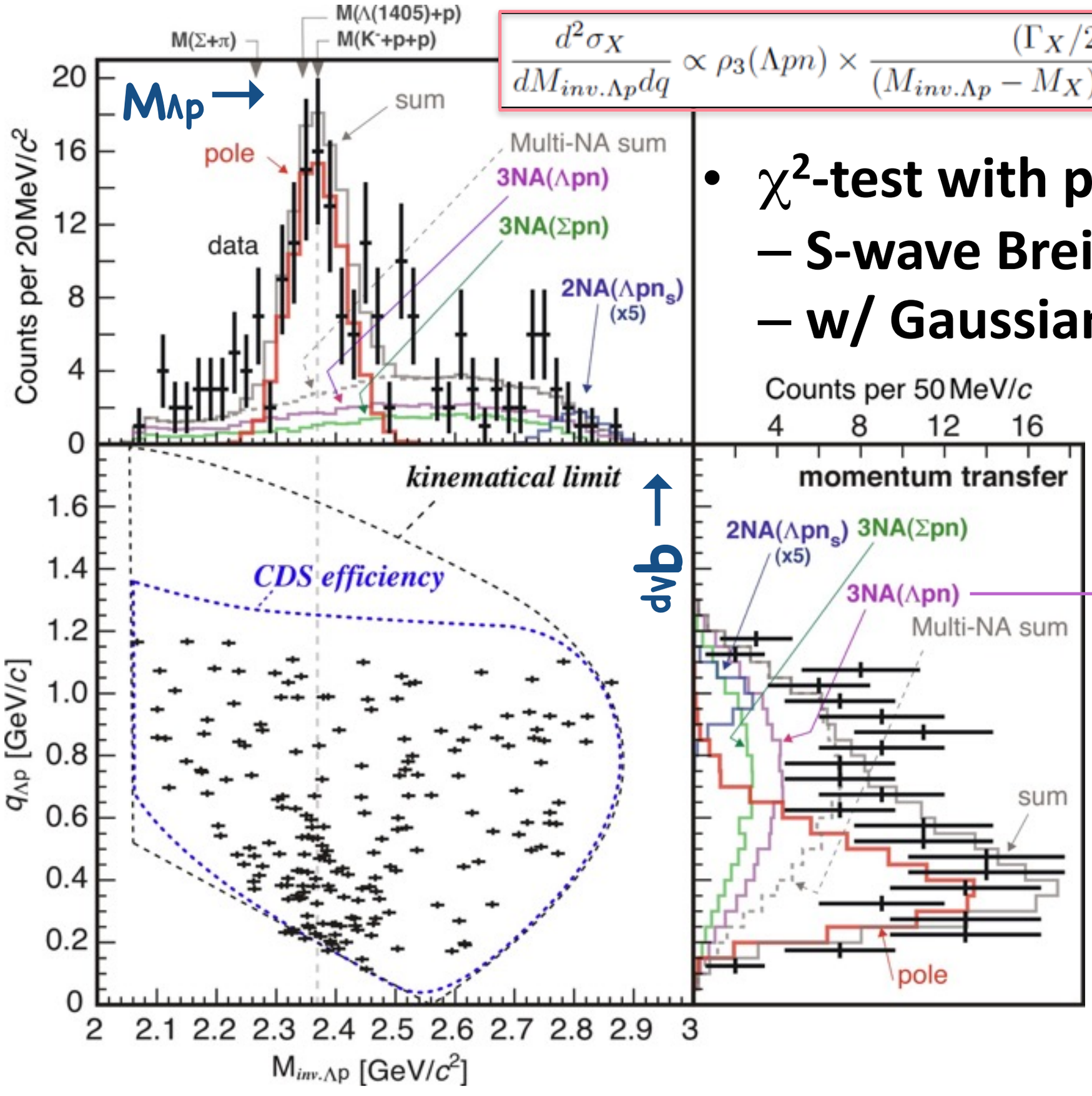
for efficient “ppK” formation $q_K \sim 200$ MeV/c



analyzed only kinematically

Assuming a Breit-Wigner $K^- + {}^3He \rightarrow \Lambda + p + n_{mis.}$

$$\frac{d^2\sigma_X}{dM_{inv.\Lambda p}dq} \propto \rho_3(\Lambda pn) \times \frac{(\Gamma_X/2)^2}{(M_{inv.\Lambda p} - M_X)^2 + (\Gamma_X/2)^2} \times |\exp(-q^2/2Q_X^2)|^2,$$



- χ^2-test with pole & 3NA(Ypn)
  - S-wave Breit-Wigner pole
  - w/ Gaussian form-factor

$$\frac{d^2\sigma_{3\mathrm{NA}(\Lambda\mathrm{pn})}}{dT_n^{CM}d\cos\theta_n^{CM}} \propto \rho_3(\Lambda pn)$$

B(X) ~ 15 MeV
Γ(X) ~ 110 MeV
Q(X) ~ 400 MeV/c

Assuming single pole (Breit-Wigner)

– introduce simplest assumption

S-wave pole & Breit-Wigner formula & Gaussian form-factor

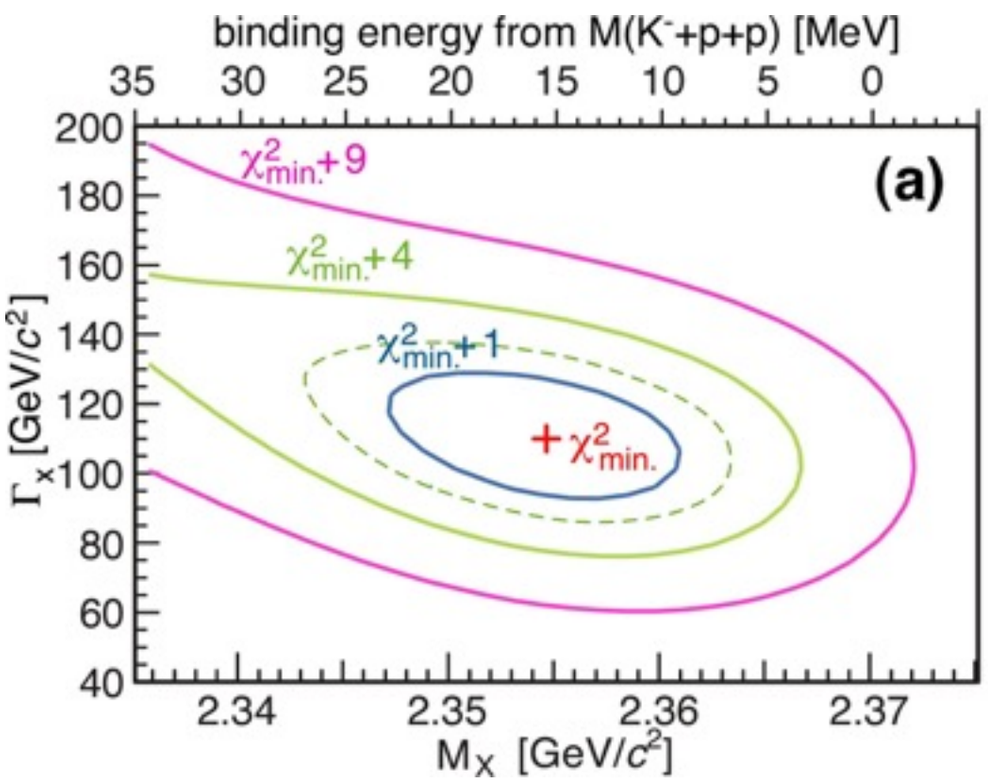
sticking probability to harmonic oscillator

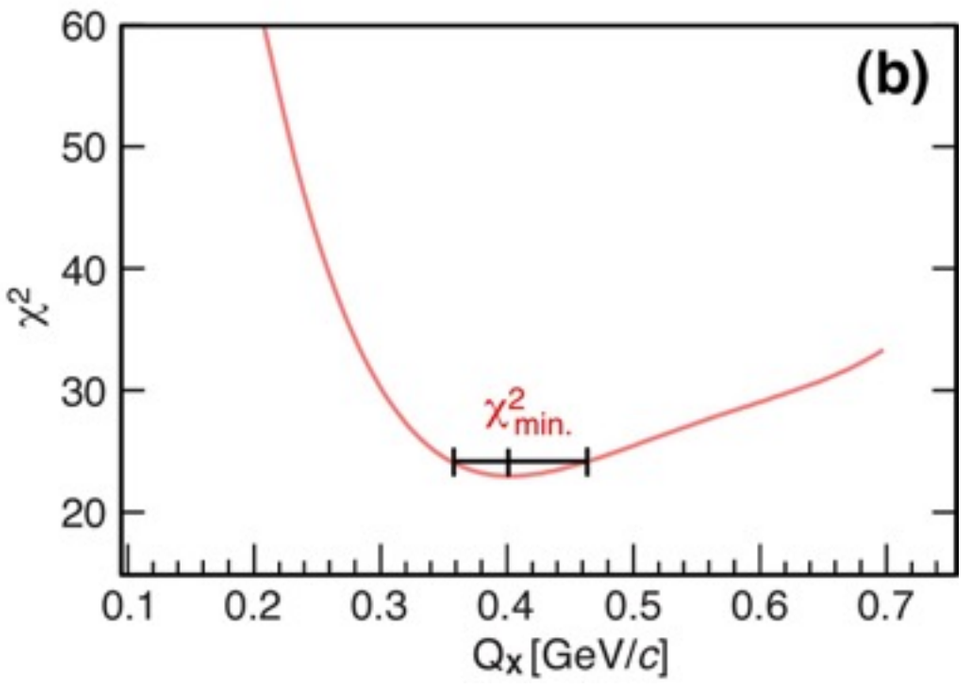
Breit-Wigner

$$\frac{d^2\sigma_X}{dM_{inv.\Lambda p}dq} \propto \rho_3(\Lambda pn) \times \frac{(\Gamma_X/2)^2}{(M_{inv.\Lambda p} - M_X)^2 + (\Gamma_X/2)^2} \times |\exp(-q^2/2Q_X^2)|^2,$$

Lorentz invariant phase-space

form-factor²





B(X) ~ 15 MeV, Γ(X) ~ 110 MeV, Q(X) ~ 400 MeV/c

What is the structure found in E15[1st] data?

Improving statistics via E15[2nd] data

3 days → 3 weeks w/ higher priority to Λp in CDS

E15[1st] E15[2nd]

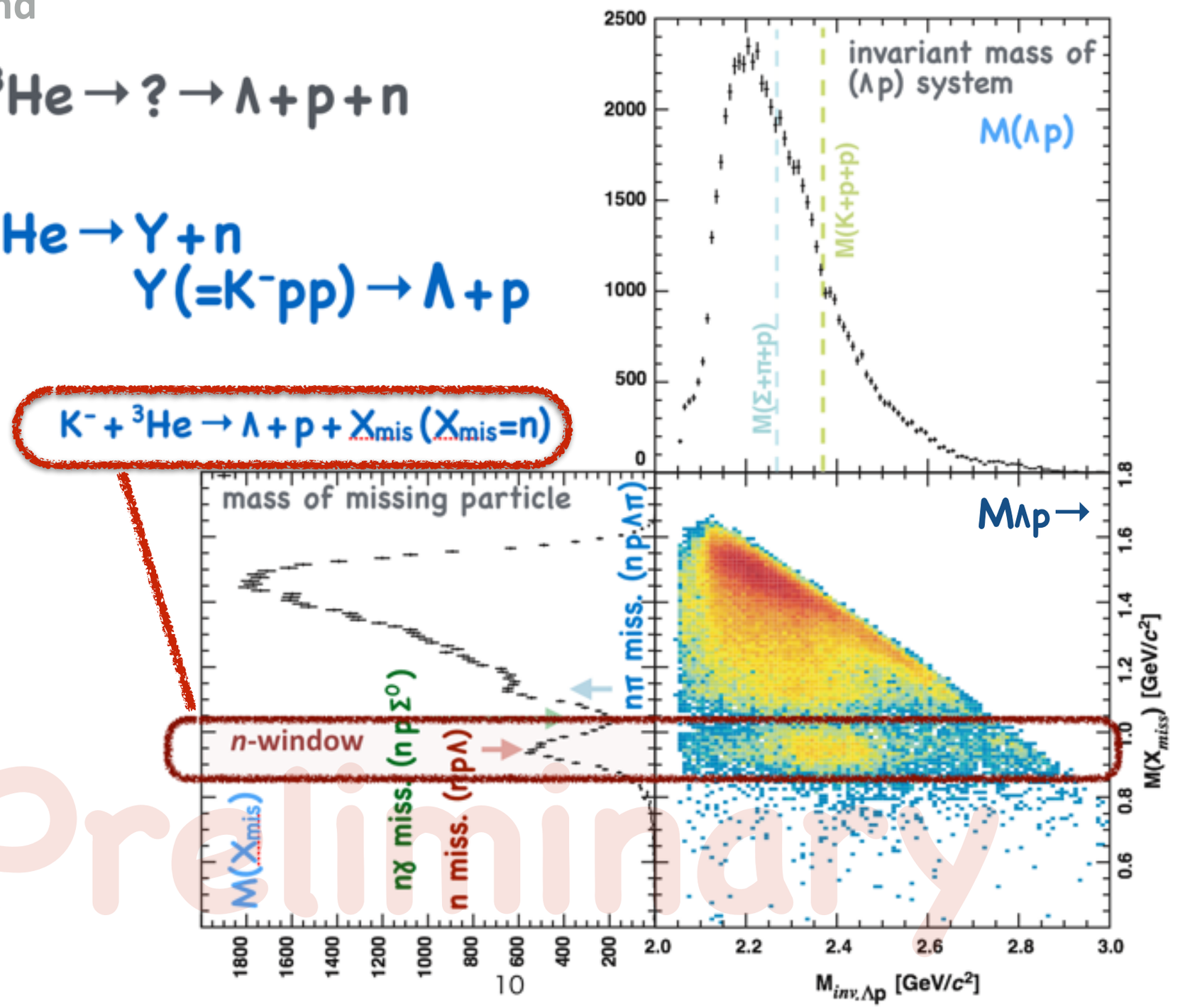
$K^- + {}^3He \rightarrow ? \rightarrow \Lambda + p + n$

$K^- + {}^3He \rightarrow Y + n$

$Y(=K^- pp) \rightarrow \Lambda + p$

~ 6 times more data for forward neutron

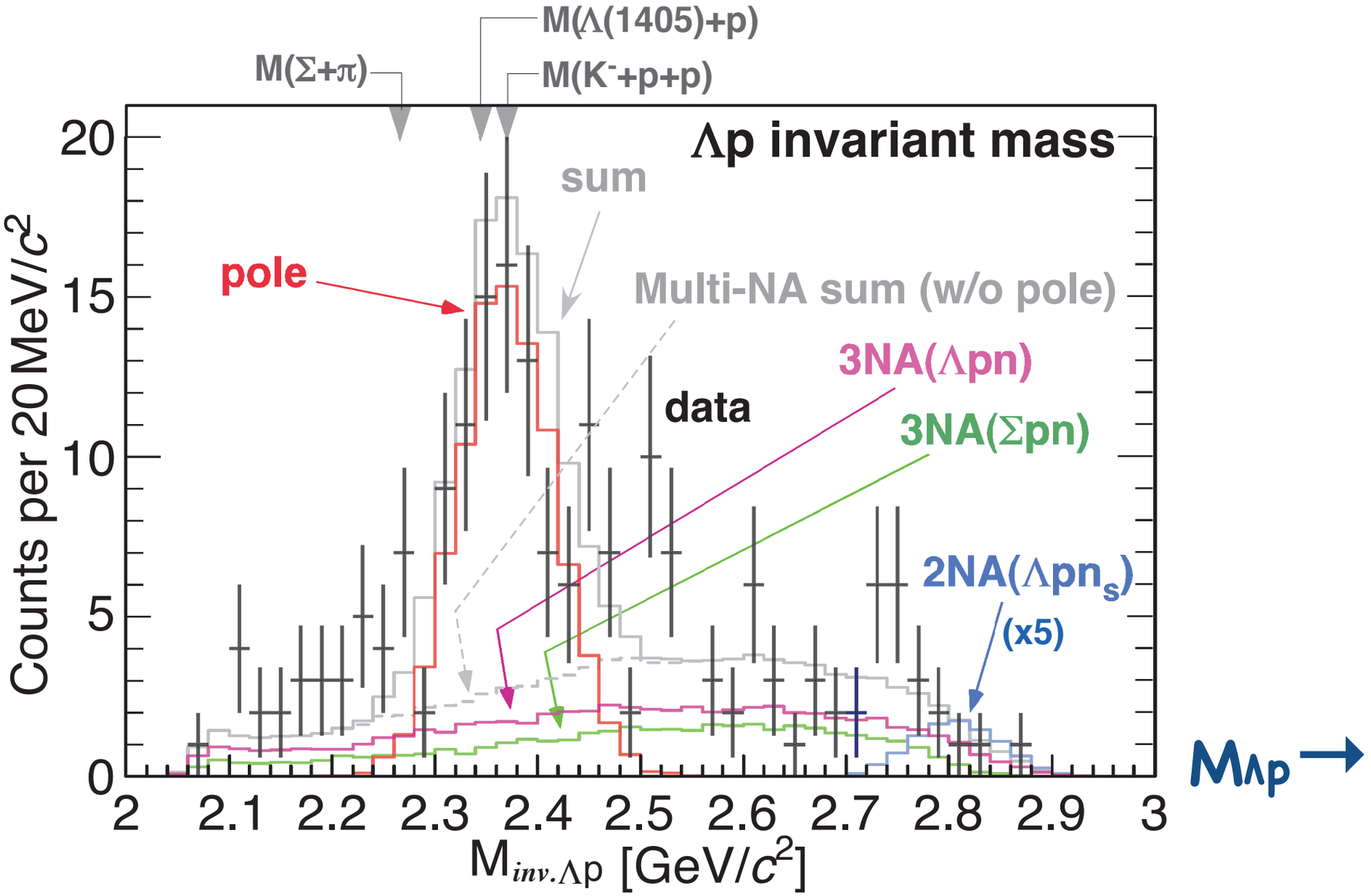
~ 30 times more data for Λpn final state



E15[1st] and E15[2nd] spectra consistent?

$K^- + {}^3He \rightarrow \Lambda + p + n_{mis.}$

$$\frac{d^2\sigma_X}{dM_{inv.\Lambda p}dq} \propto \rho_3(\Lambda pn) \times \frac{(\Gamma_X/2)^2}{(M_{inv.\Lambda p} - M_X)^2 + (\Gamma_X/2)^2} \times |\exp(-q^2/2Q_X^2)|^2,$$



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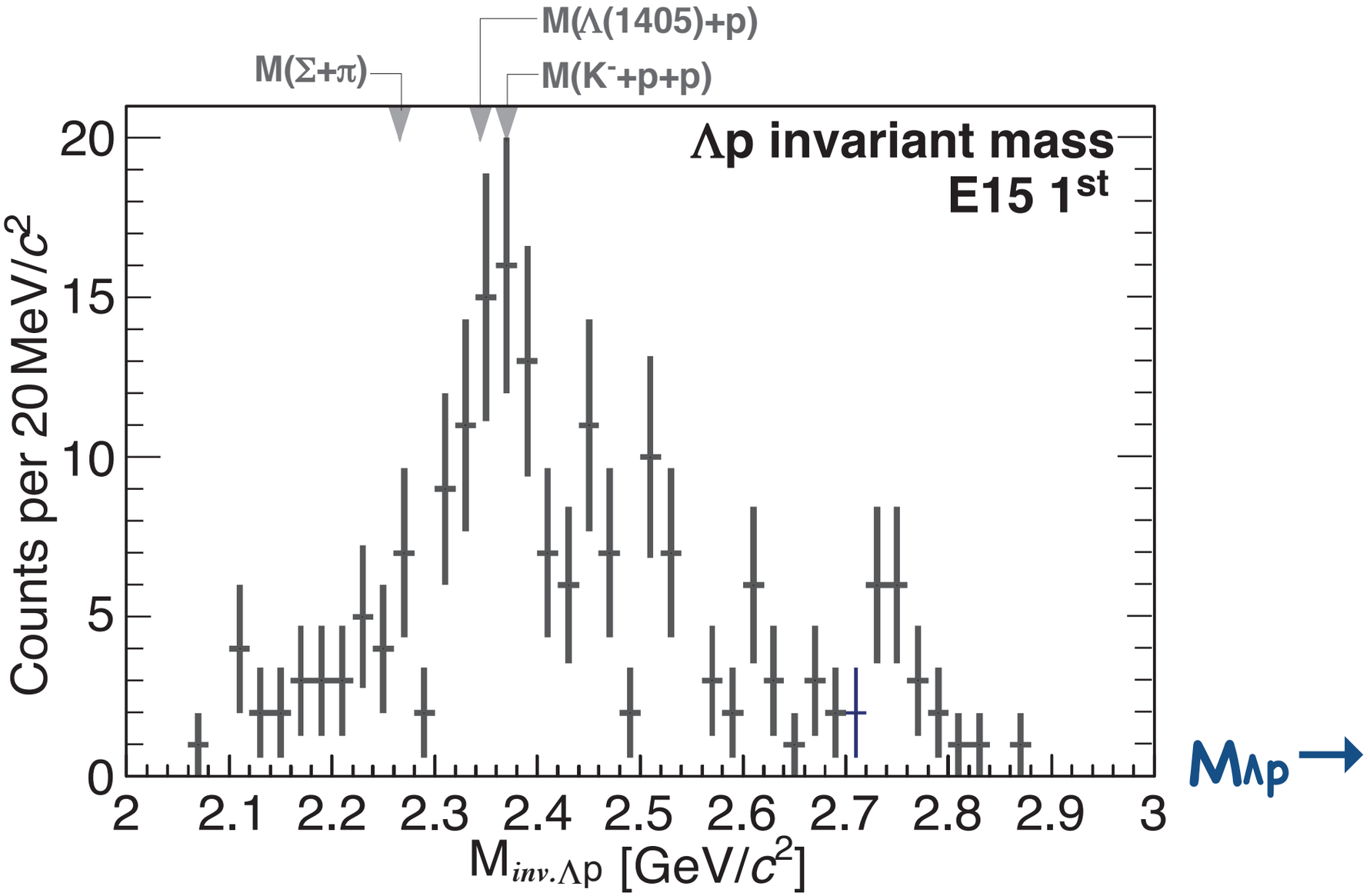
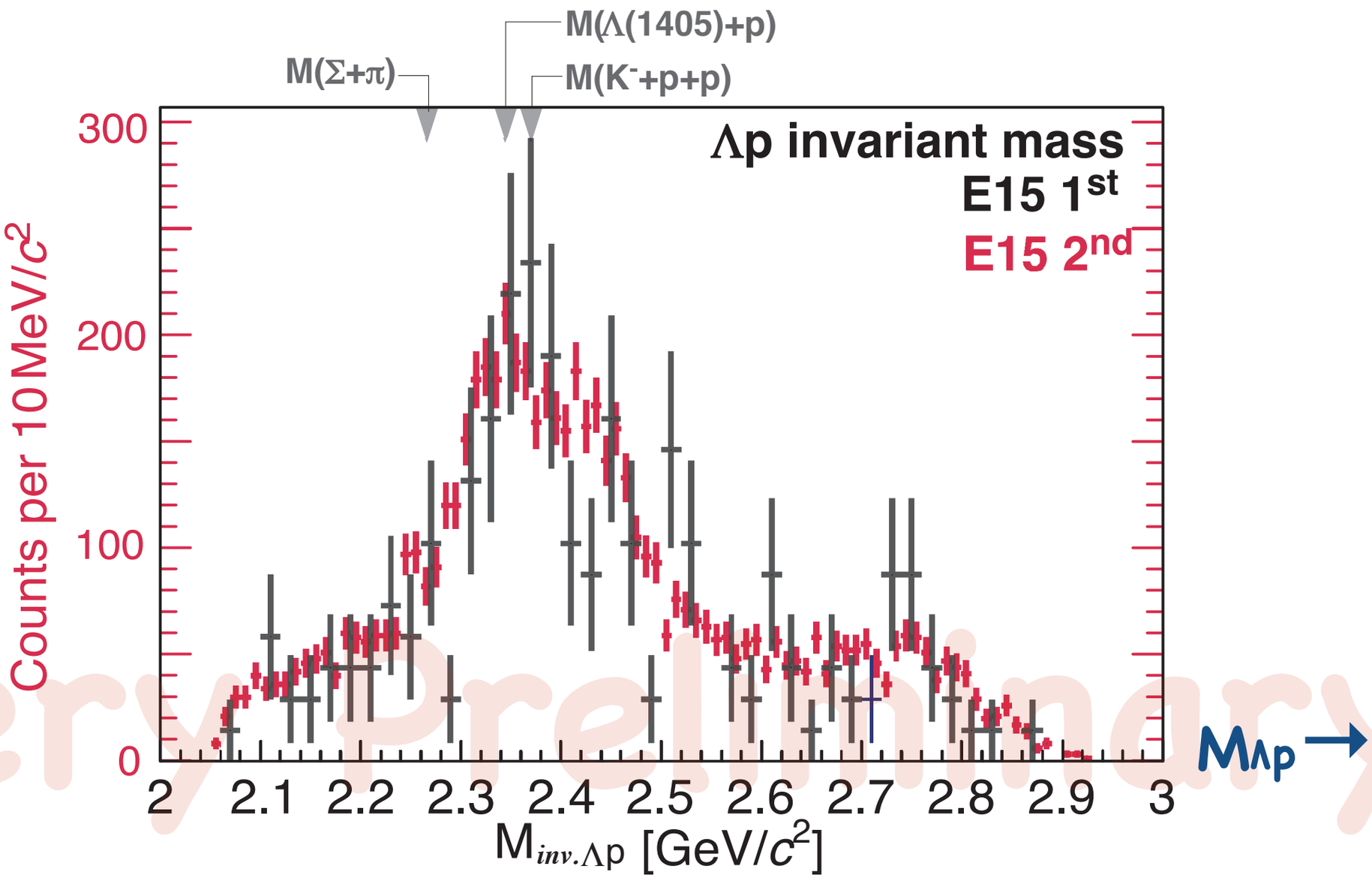


E15[1st] and E15[2nd] spectra consistent?

YES! They are consistent!

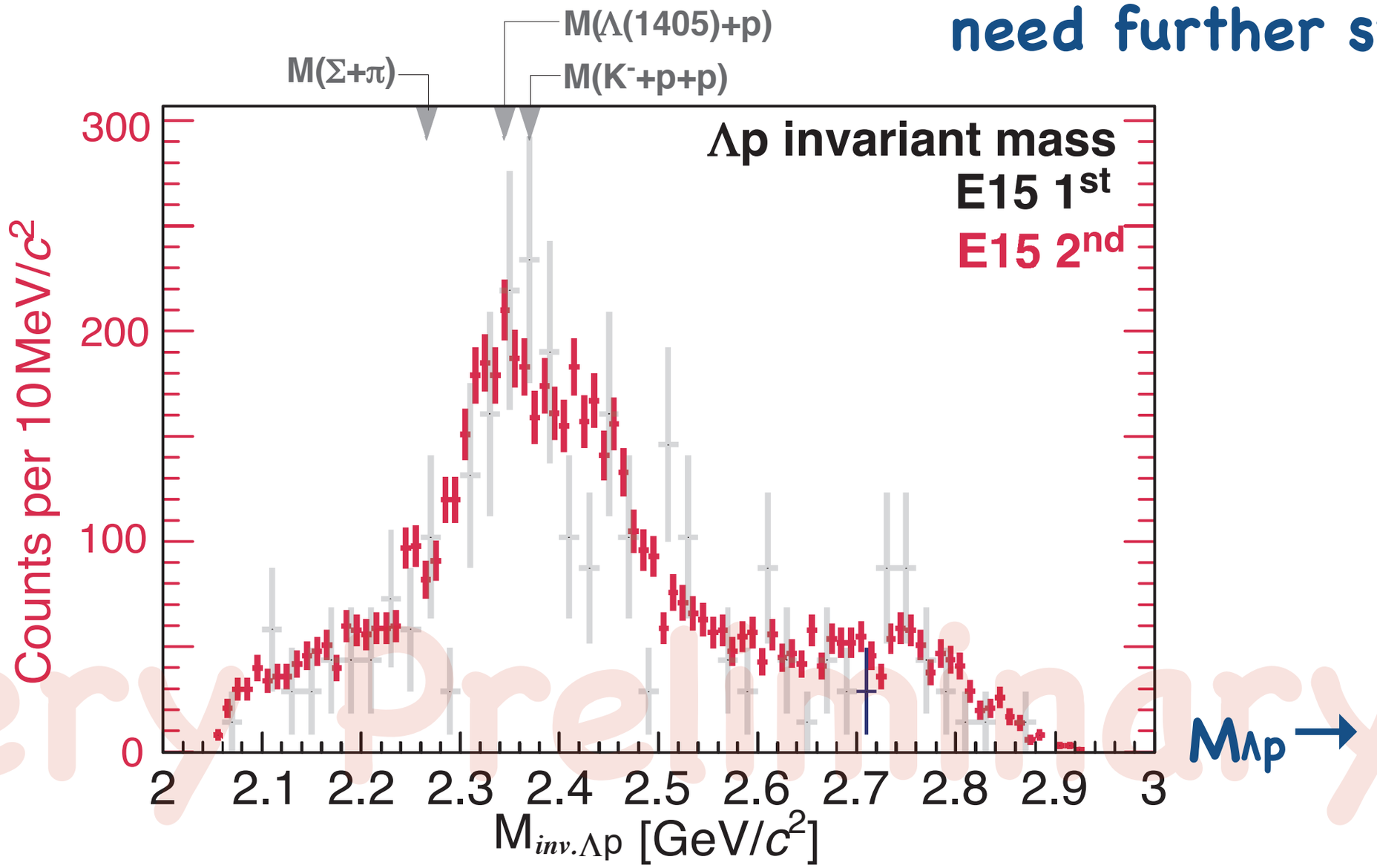


E15[1st] and E15[2nd] spectra consistent?

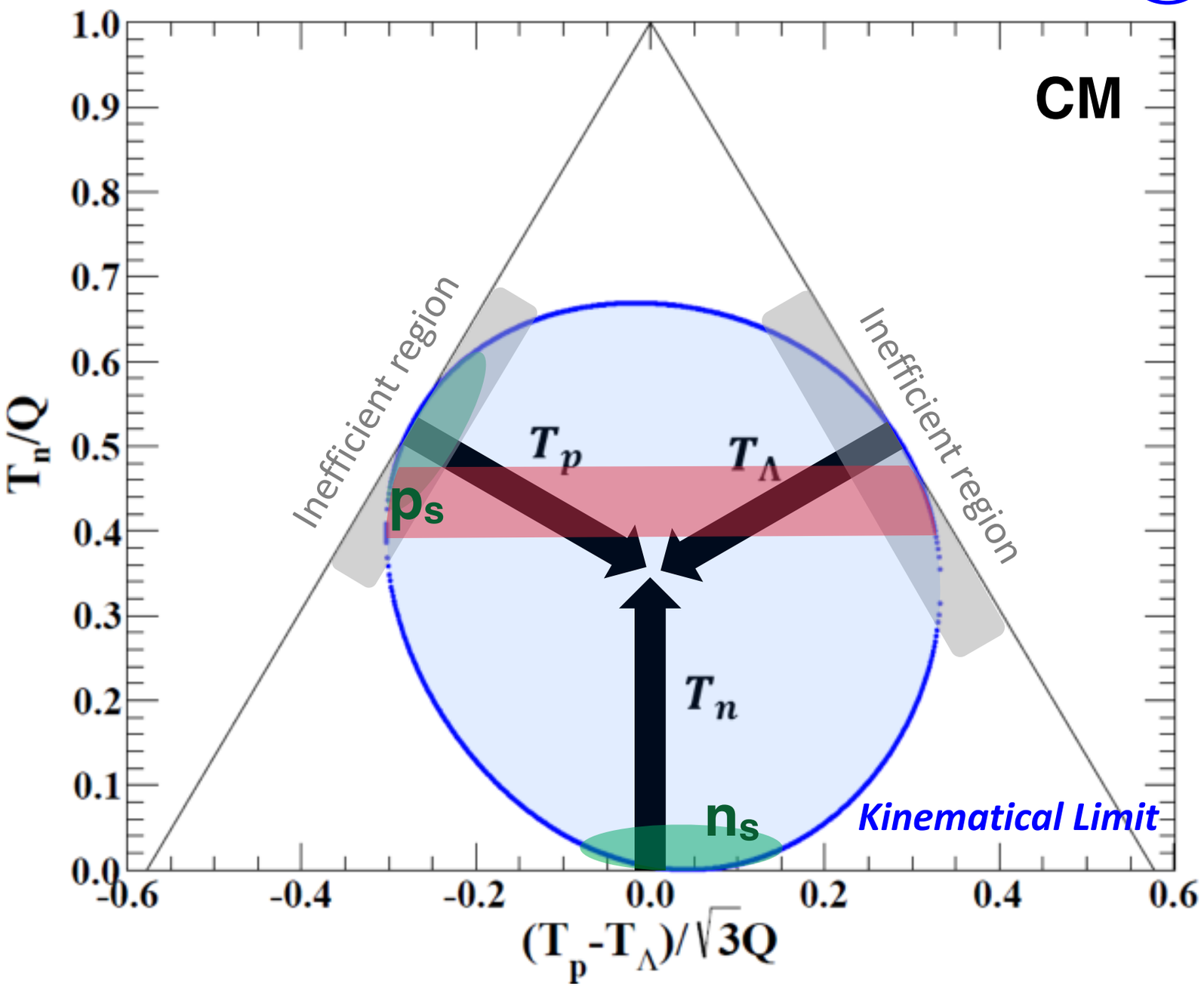
YES! They are consistent!

E15[2nd] spectrum does not allow single pole assumption

looks like trapezoidal??
need further study



Dalitz Plot of Λpn



kinematical limit

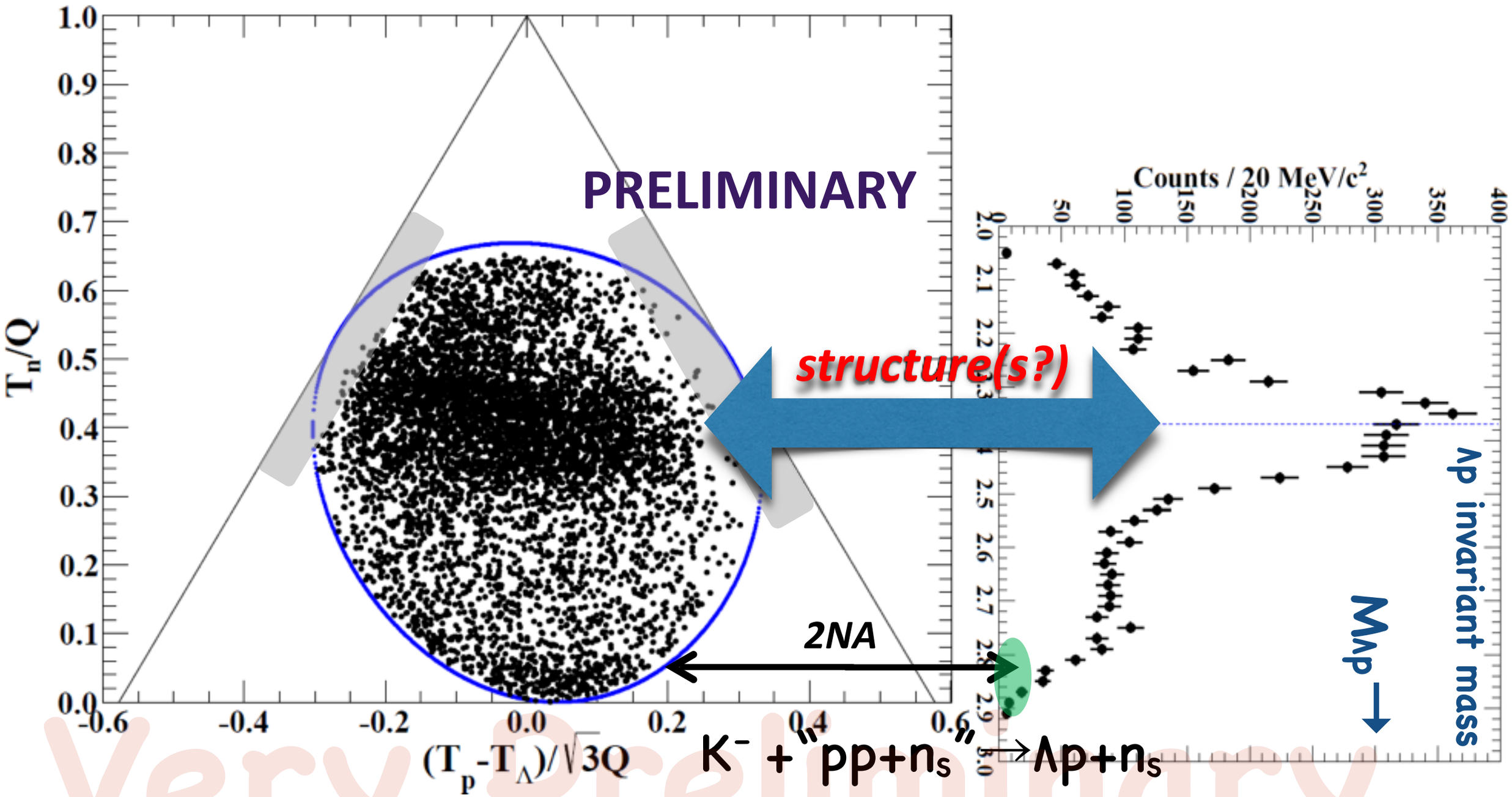
K⁻pp formation

flat for point-like 3NA

Is ^{3}He point-like?

2NA process
with spectator
n_s / p_s

Dalitz Plot of Λpn

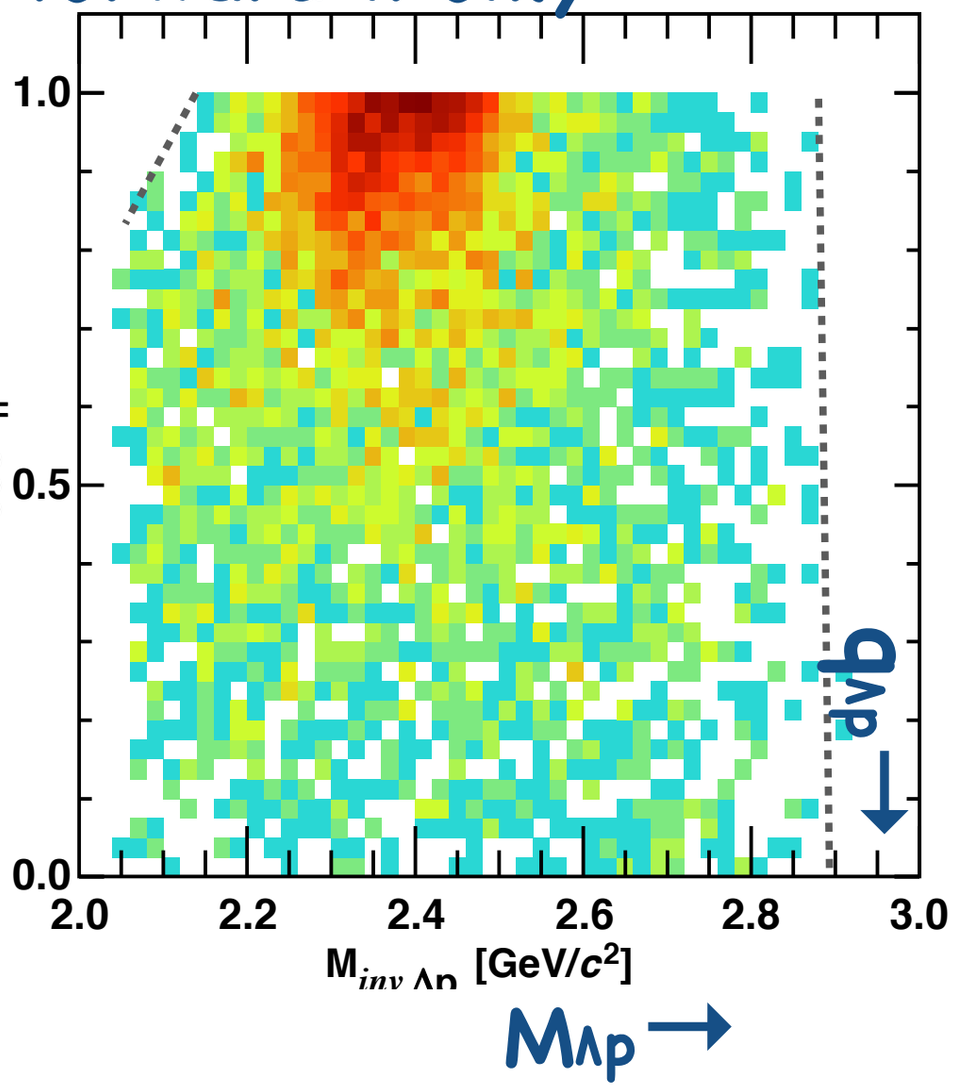


^{3}He(K^{-}, Λp)n:

Angular Dependence of n in CM

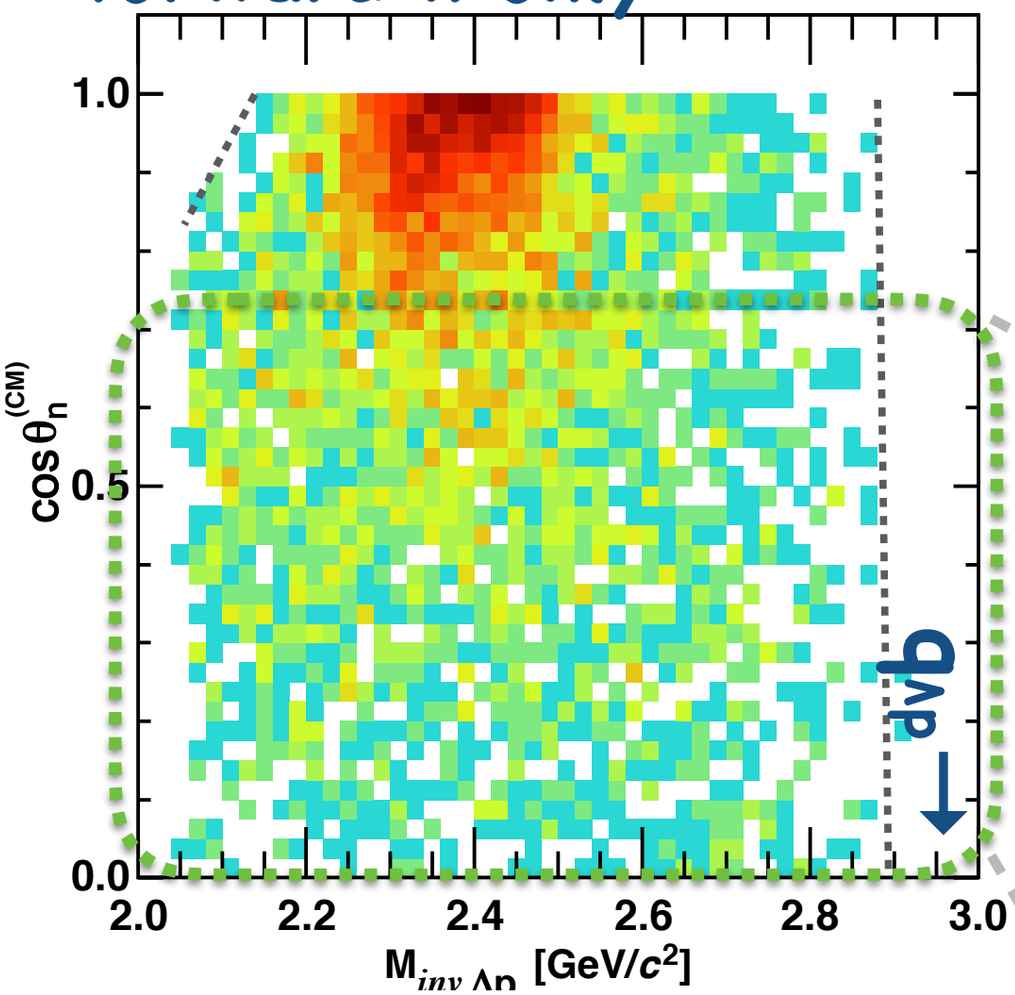
^{3}He(K^-, Λp)n: Angular Dependence

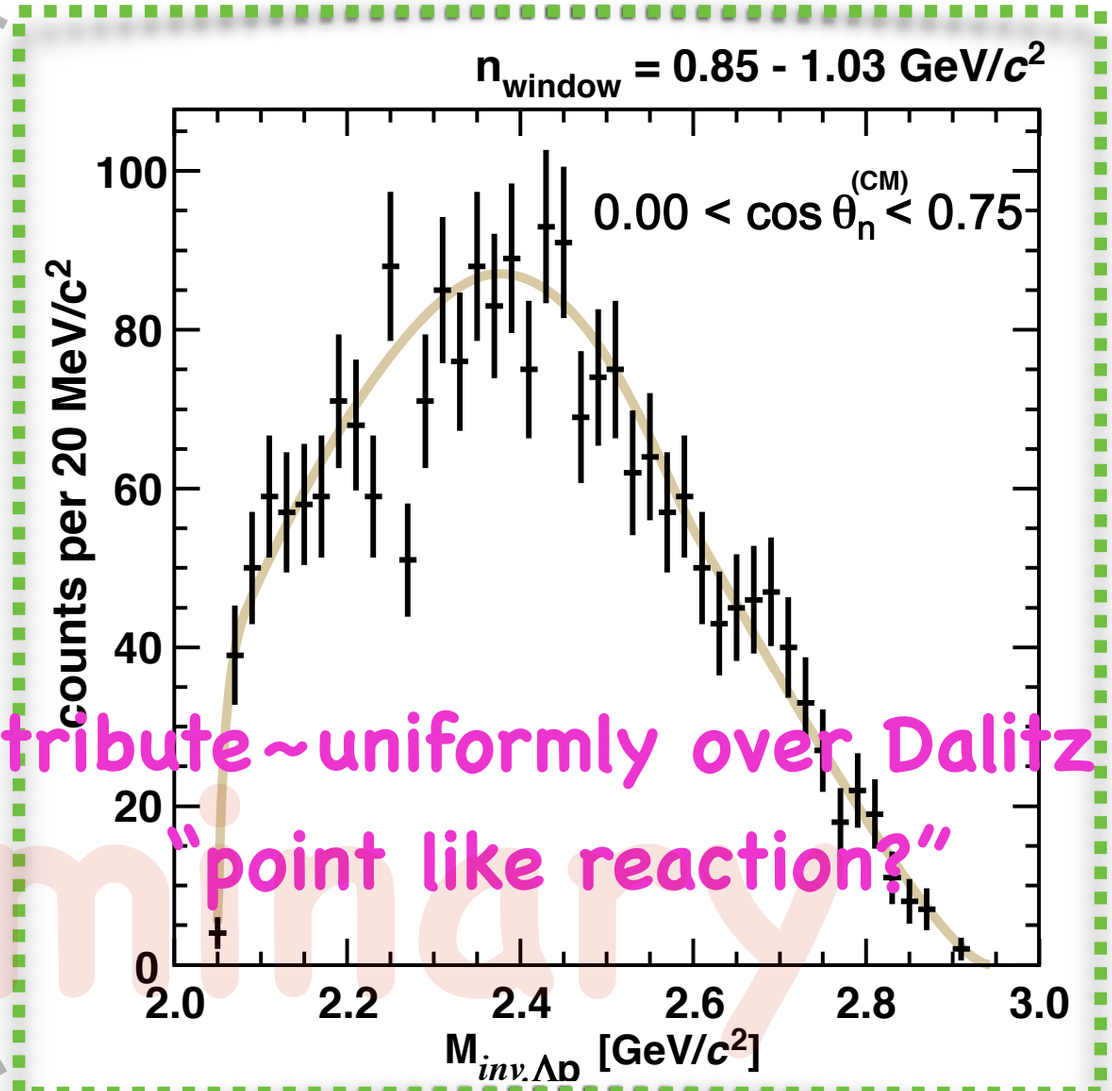
forward n only



^{3}He(K$^-$, Λp)n: Angular Dependence

forward n only



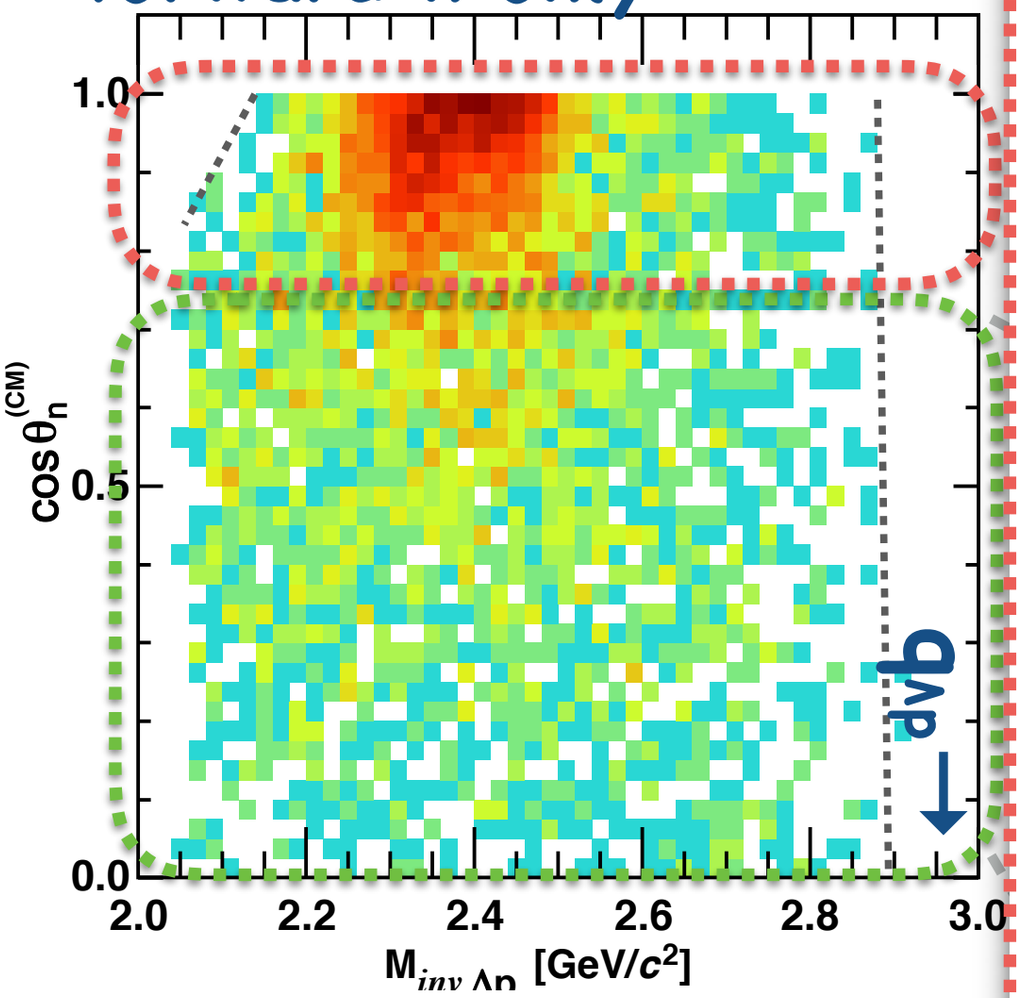


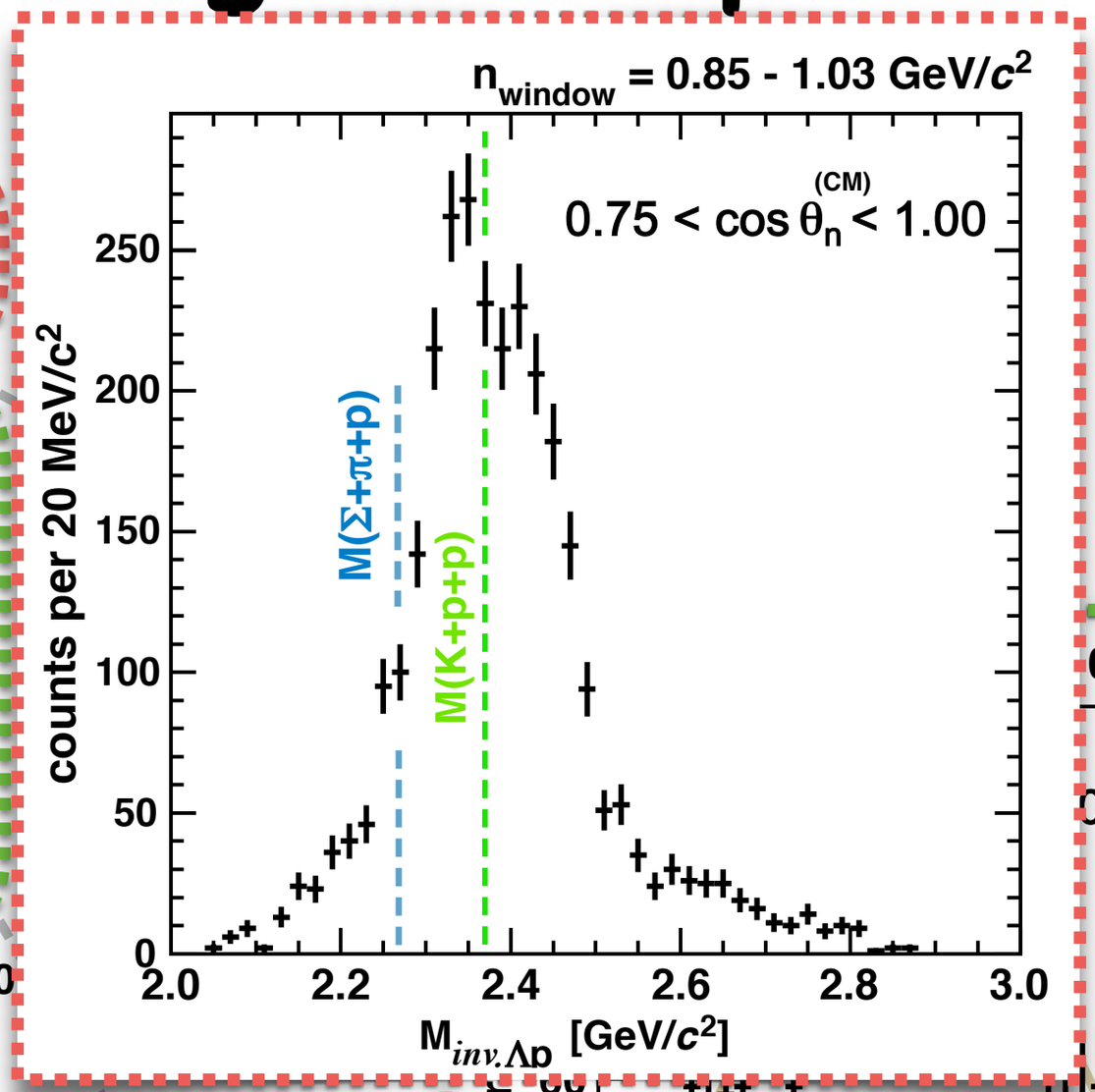
distribute~uniformly over Dalitz

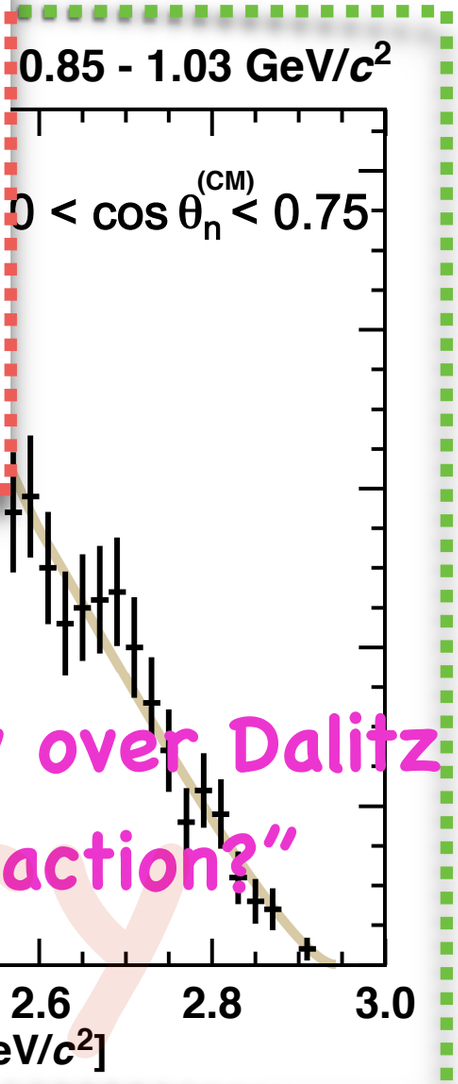
"point like reaction?"

^{3}He(K$^-$, Λp)n: Angular Dependence

forward n only





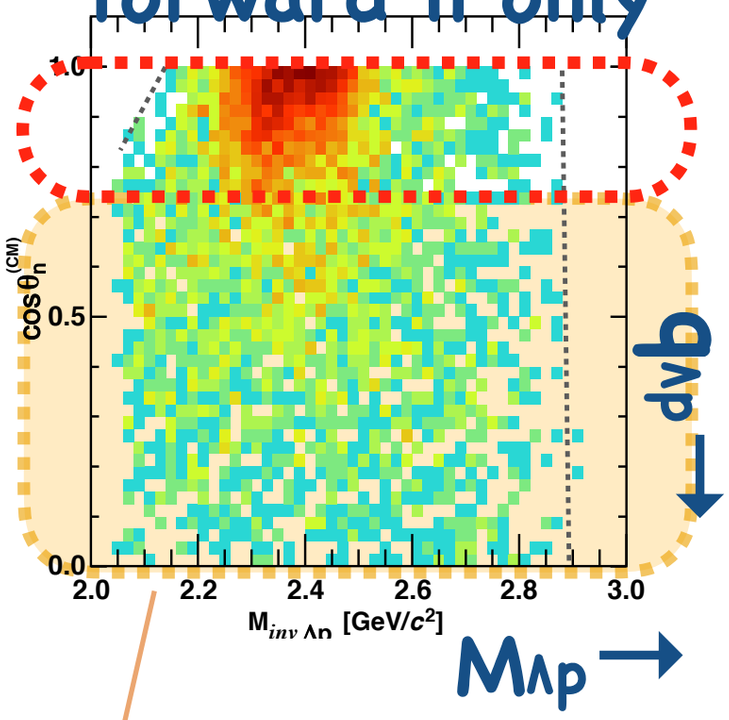


distribute~uniformly over Dalitz

"point like reaction?"

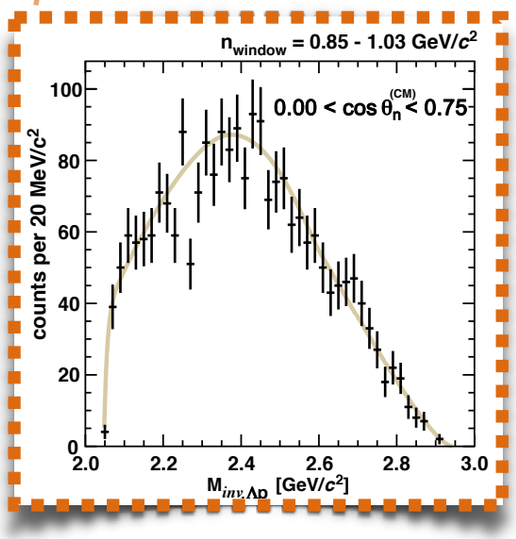
^{3}He(K$^-$, Λp)n: Angular Dependence

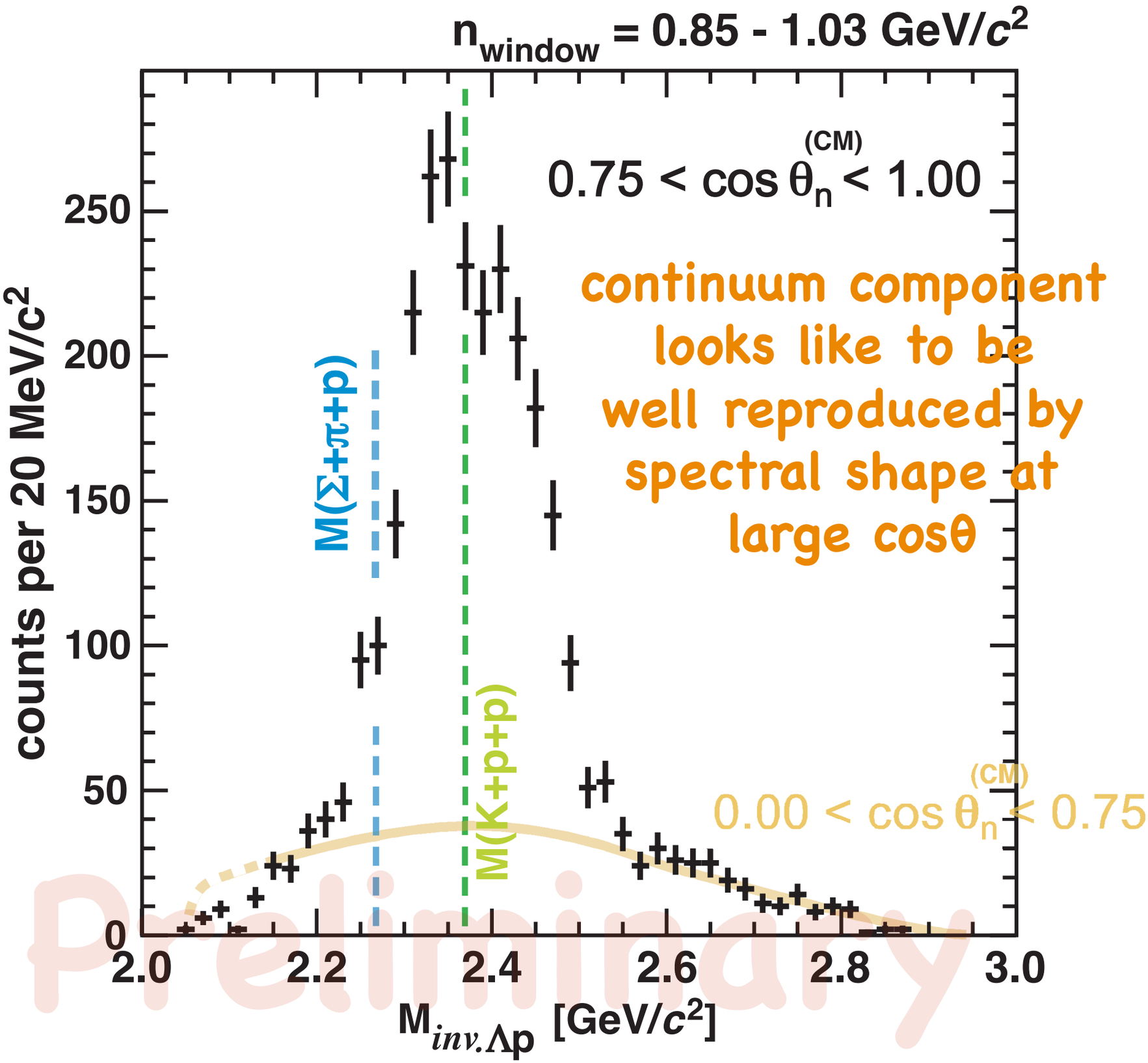
forward n only



dvb →

MΛp →





continuum component looks like to be well reproduced by spectral shape at large cosθ

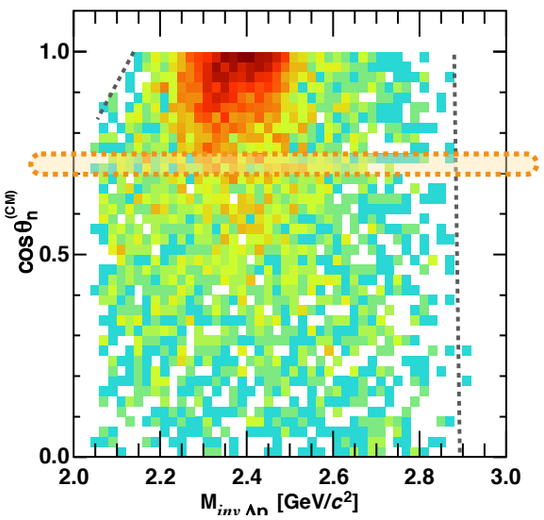
^{3}He(K^{-}, Λp)n:

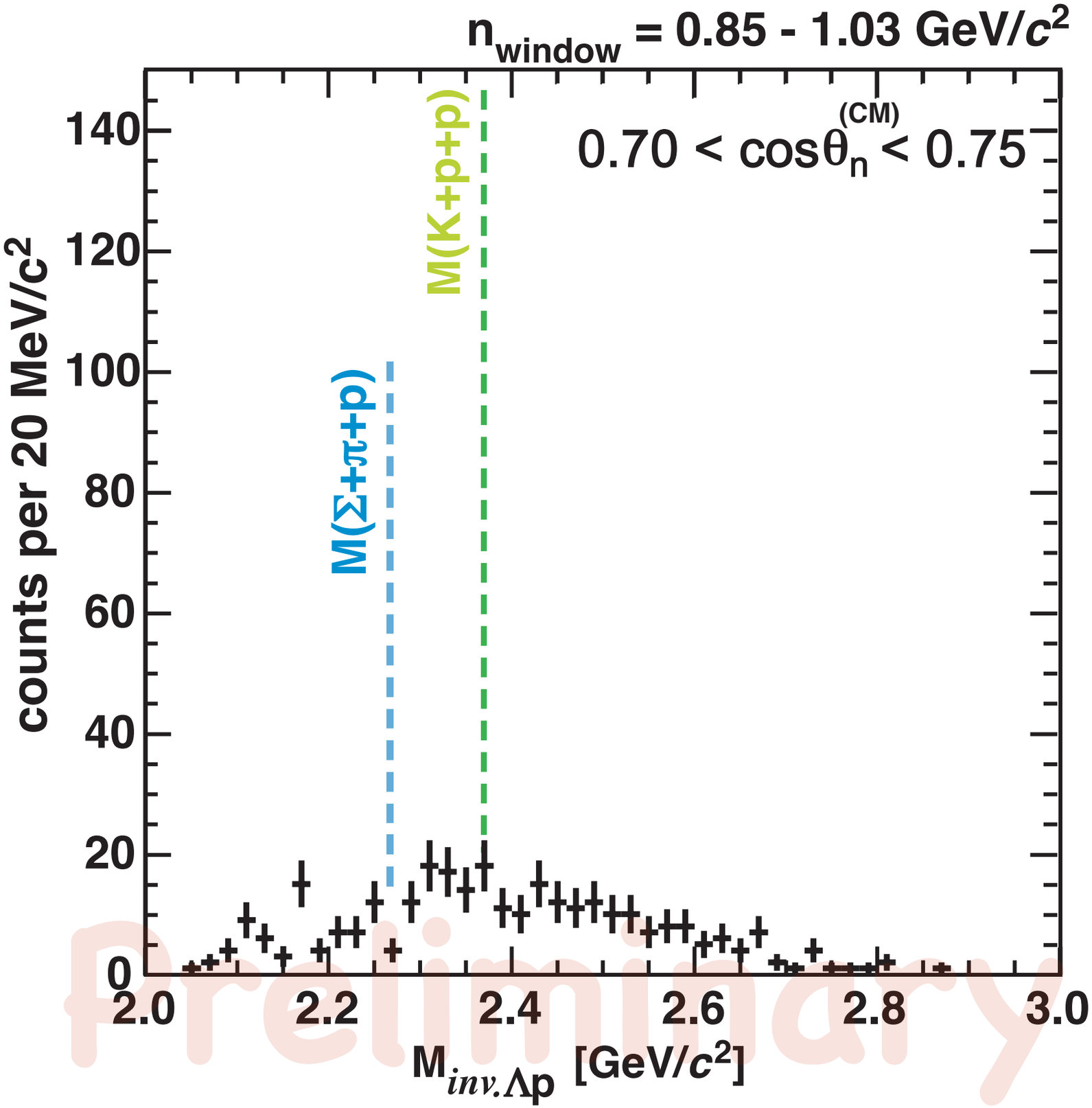
Angular Dependence of n in CM

in more detail

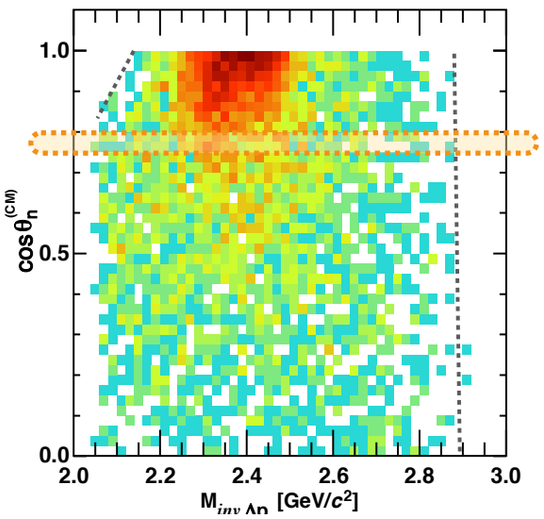
as a clue to understand

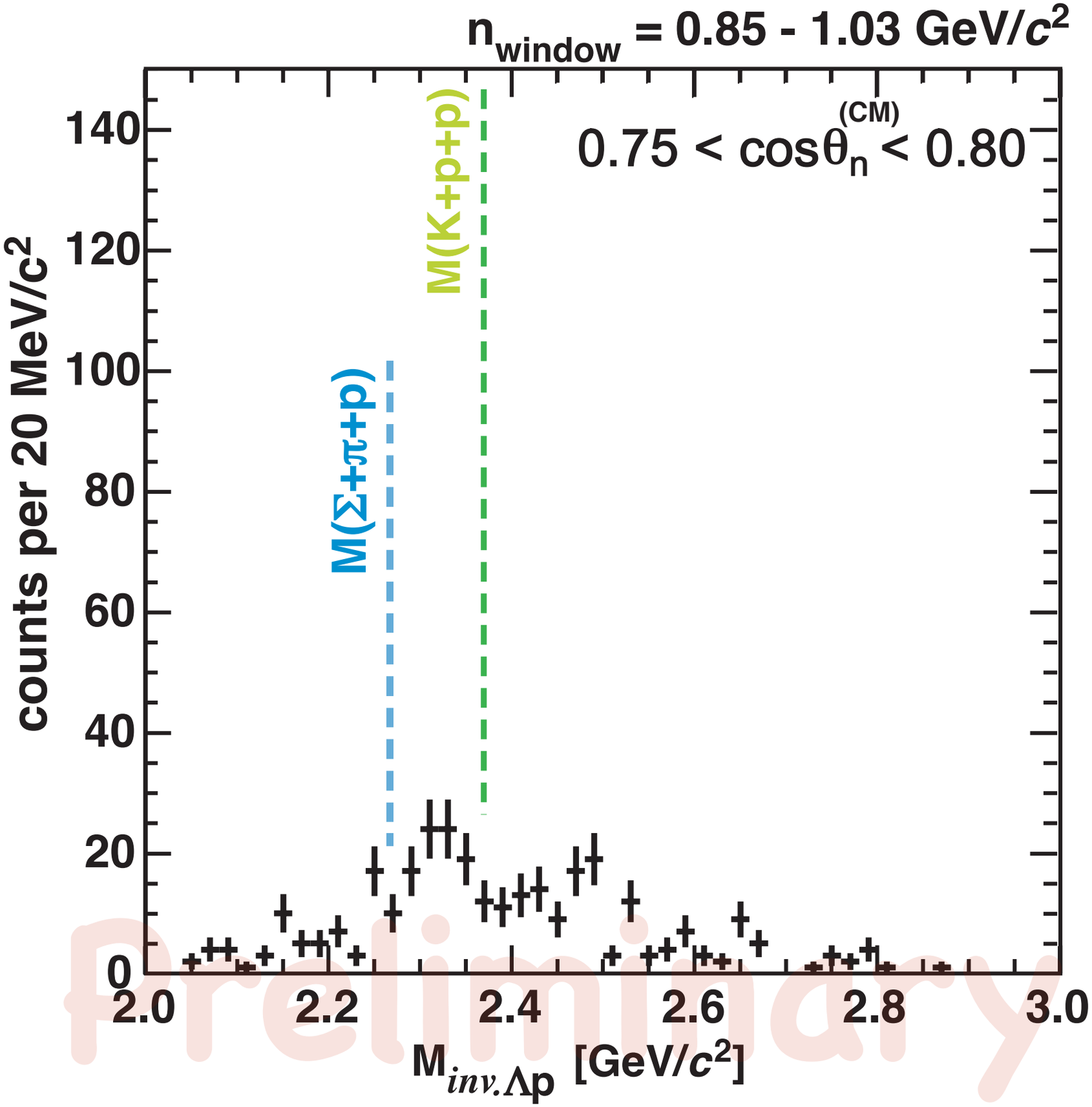
^{3}He(K^-, Λp)n: Angular Dependence



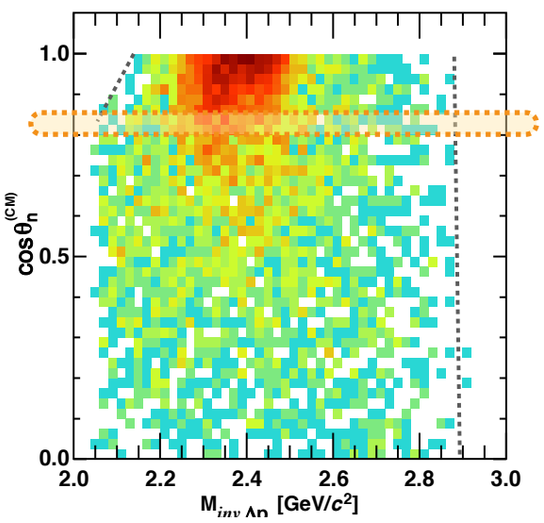


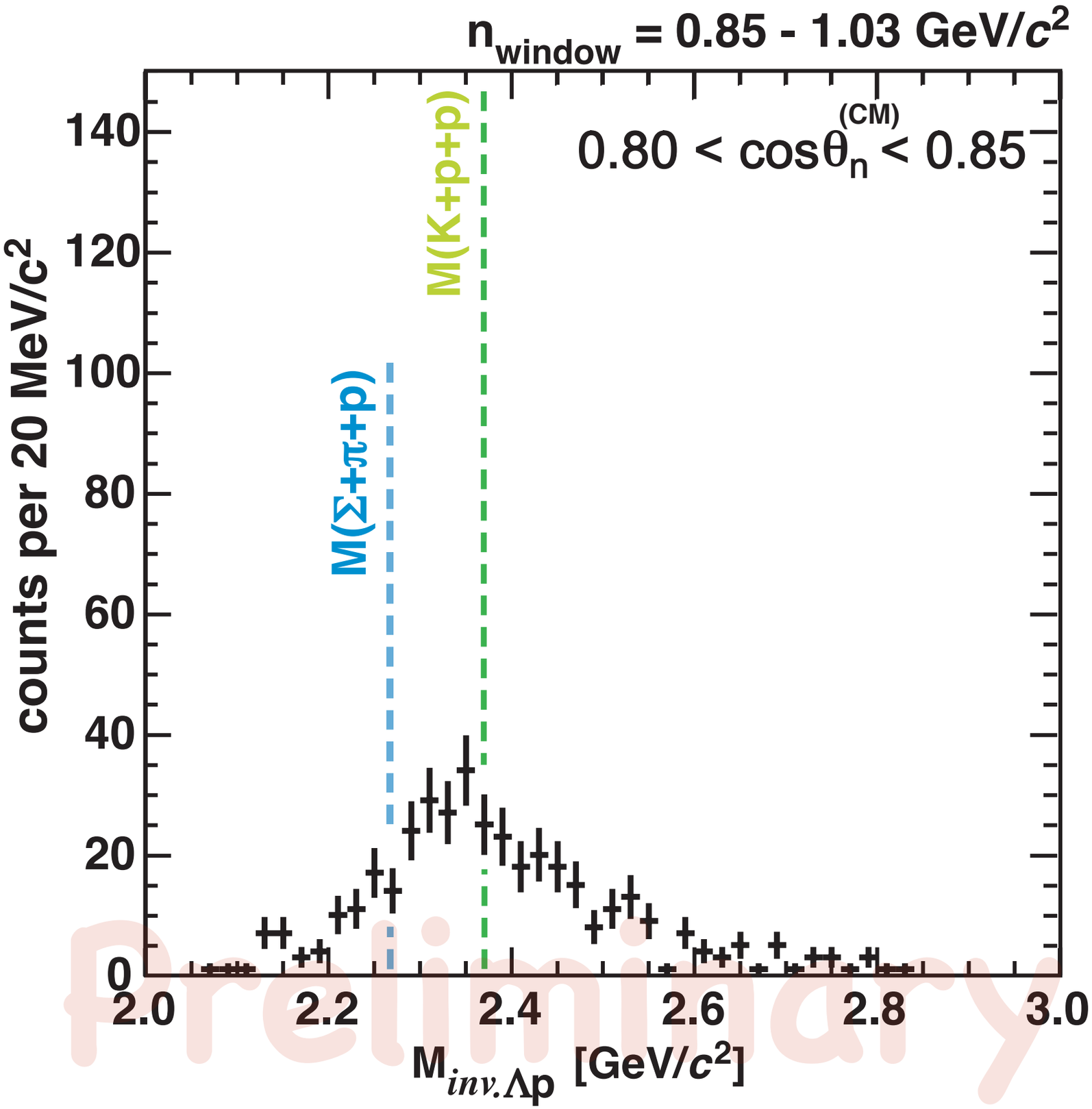
^{3}He(K$^-$, Λp)n: Angular Dependence



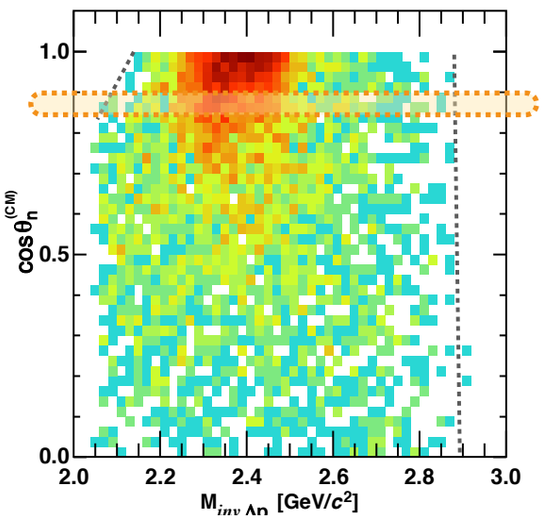


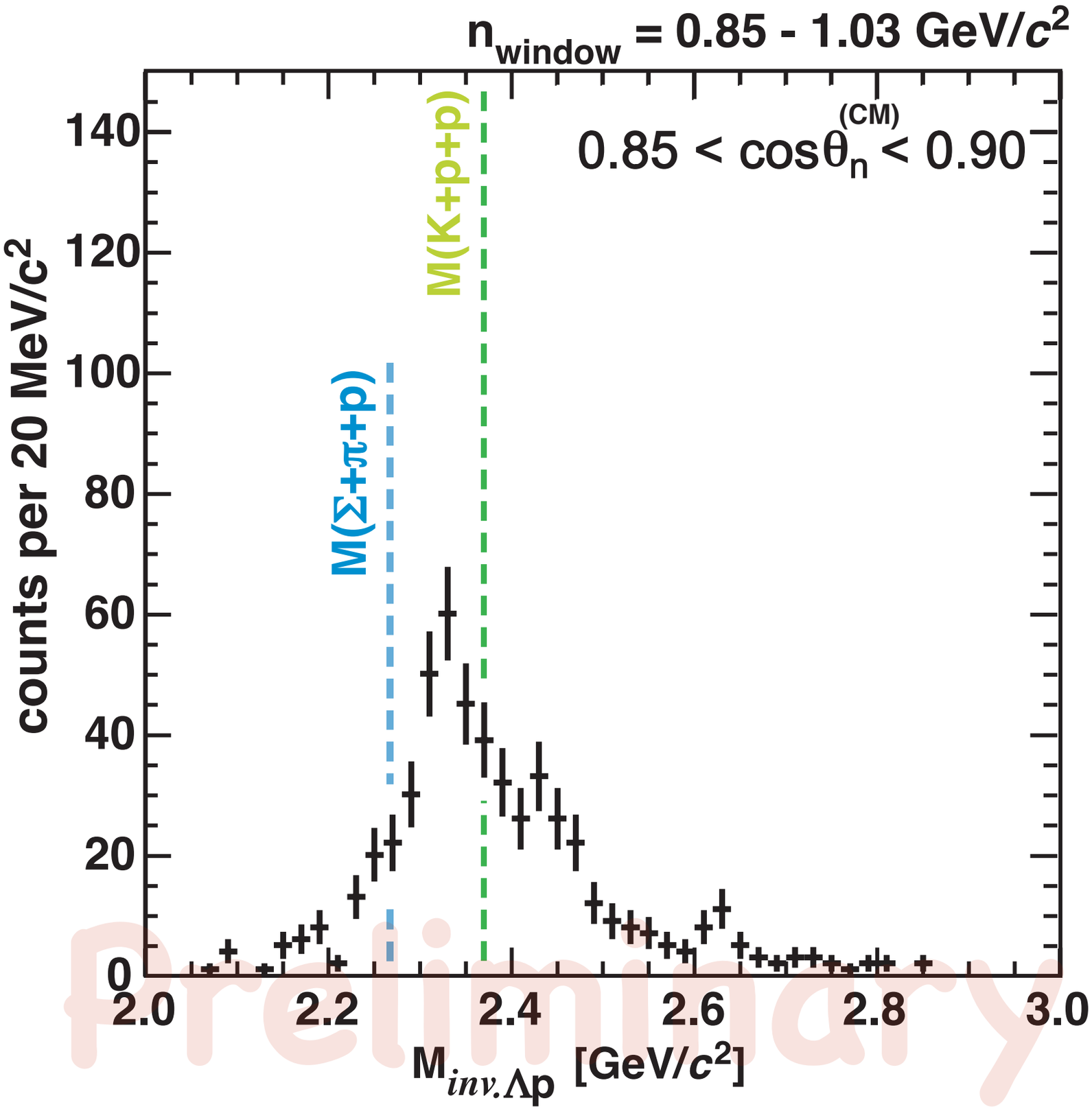
^{3}He(K$^-$, Λp)n: Angular Dependence



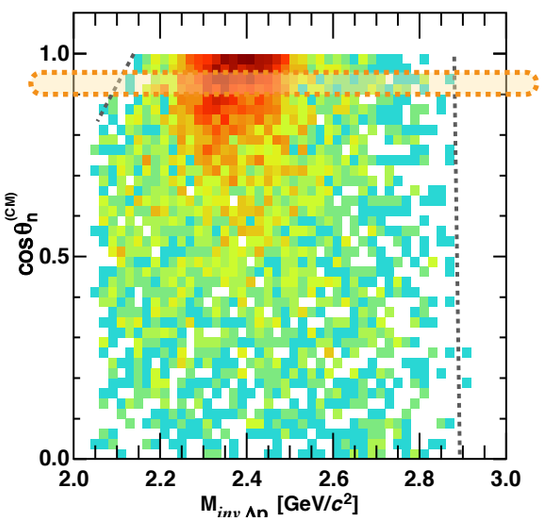


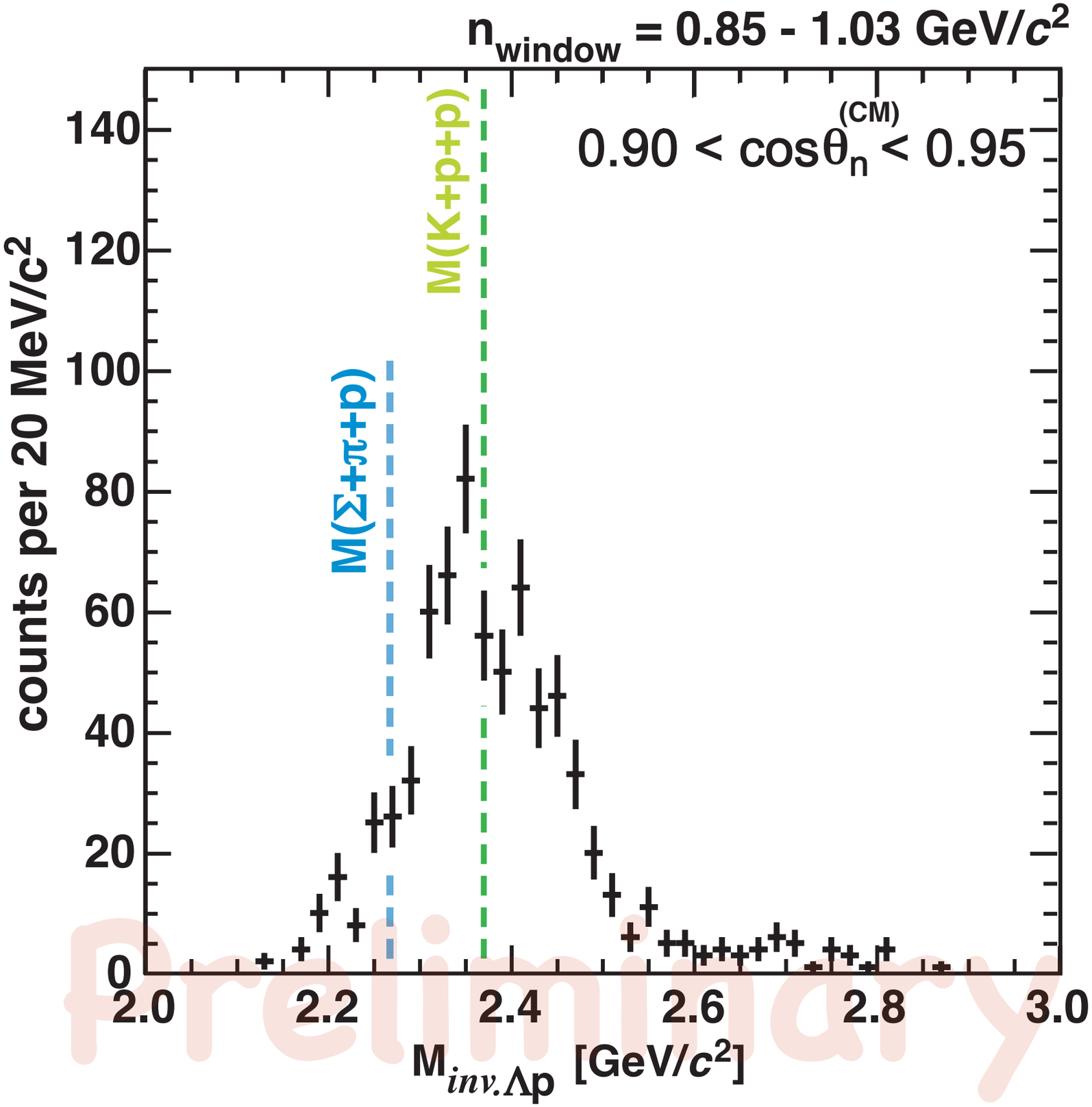
^{3}He(K$^-$, Λp)n: Angular Dependence



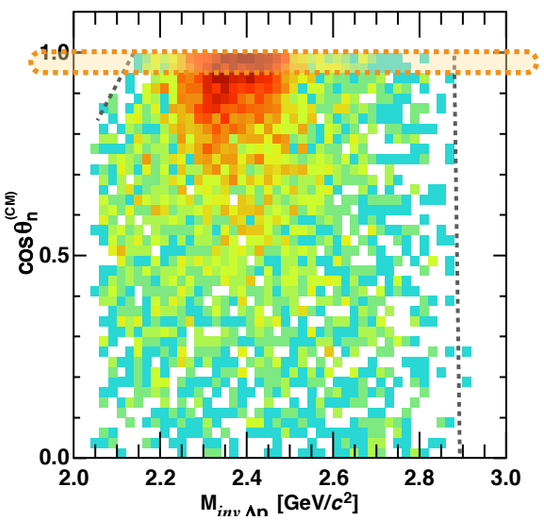


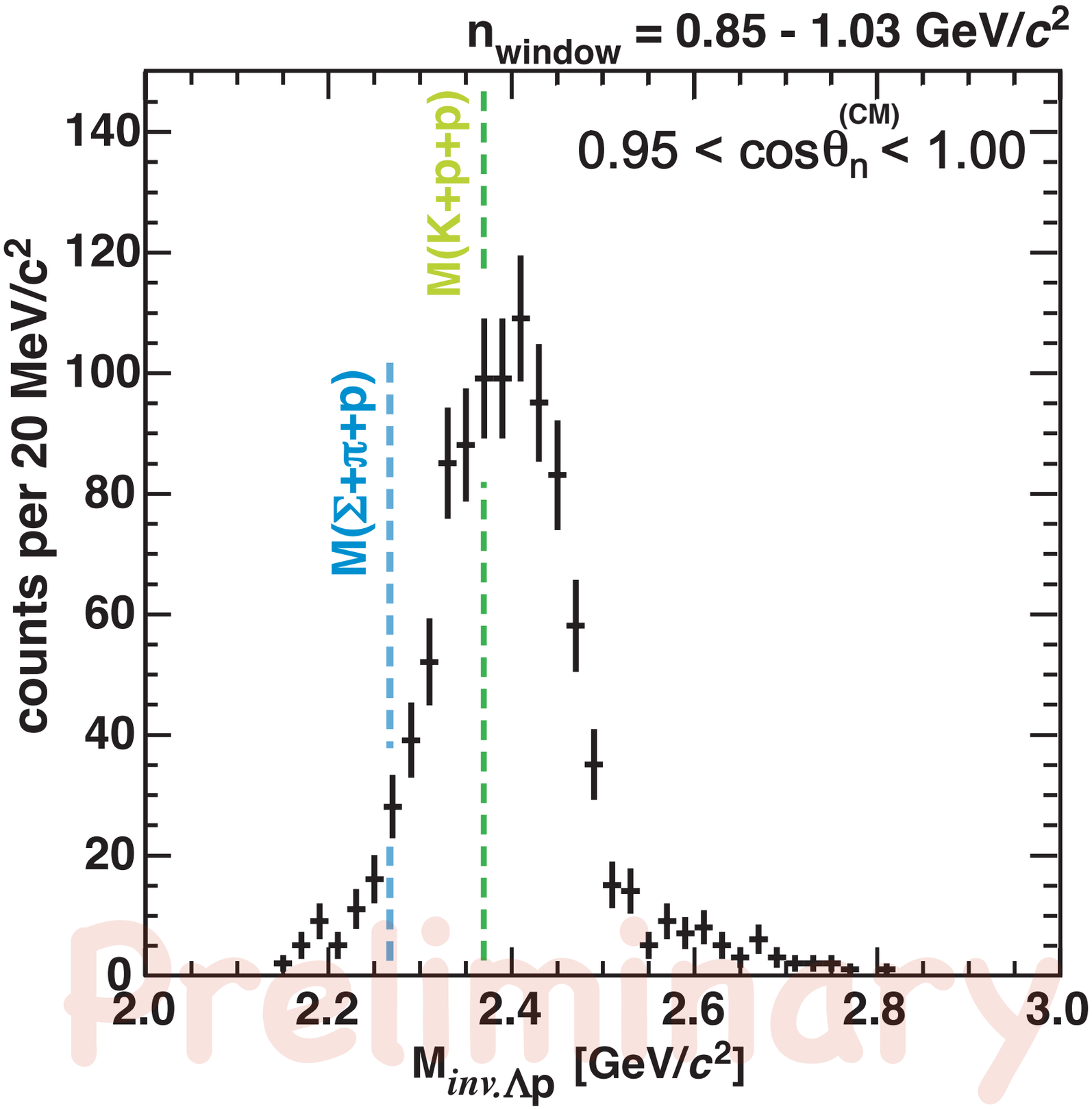
^{3}He(K$^-$, Λp)n: Angular Dependence





^{3}He(K$^-$, Λp)n: Angular Dependence





^{3}He(K$^-$, Λp)n:
Angular Dependence of n in CM

two components exist?

if that is the case,

bound region : forward peaking	unbound region : very forward peaking
S-wave would be OK	bit strongly depend to cosθ
weakly depend to cosθ	lower Q_K preferred

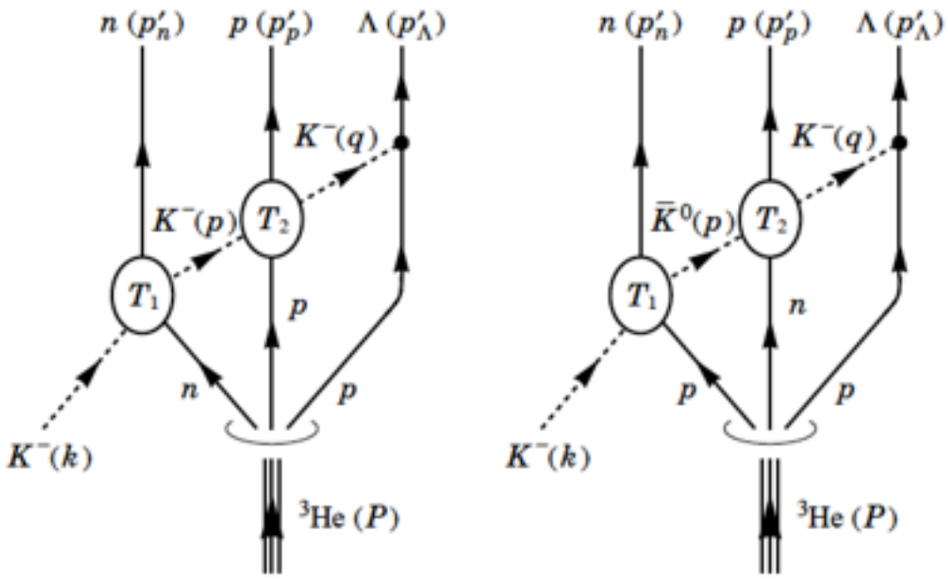
typical momentum transfer Q_K~400MeV/c

^{3}He(K^-, Λp)n:

Not like semi-inclusive spectrum,
"quasi-free K" excluded by the final state: Λpn,
but still need to ask …

Structure can be explained with quasi-elastic K scattering?

through uncorrelated $\Lambda(1405)$p channel



Sekihara Oset Ramos

PTEP
Prog. Theor. Exp. Phys. **2013**, 00000 (27 pages)
DOI: 10.1093/ptep/0000000000

On the structure observed in the in-flight ^{3}He(K^-, Λp)n reaction at J-PARC

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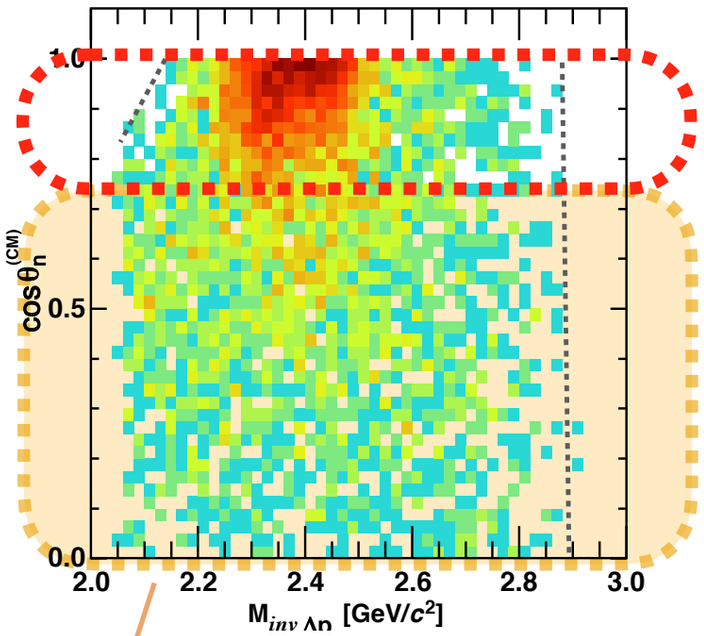
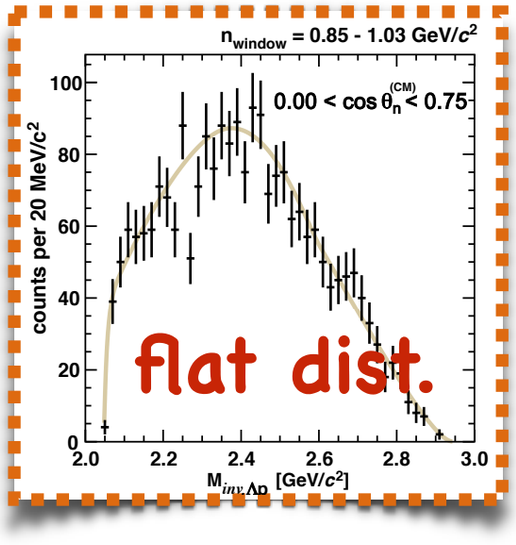
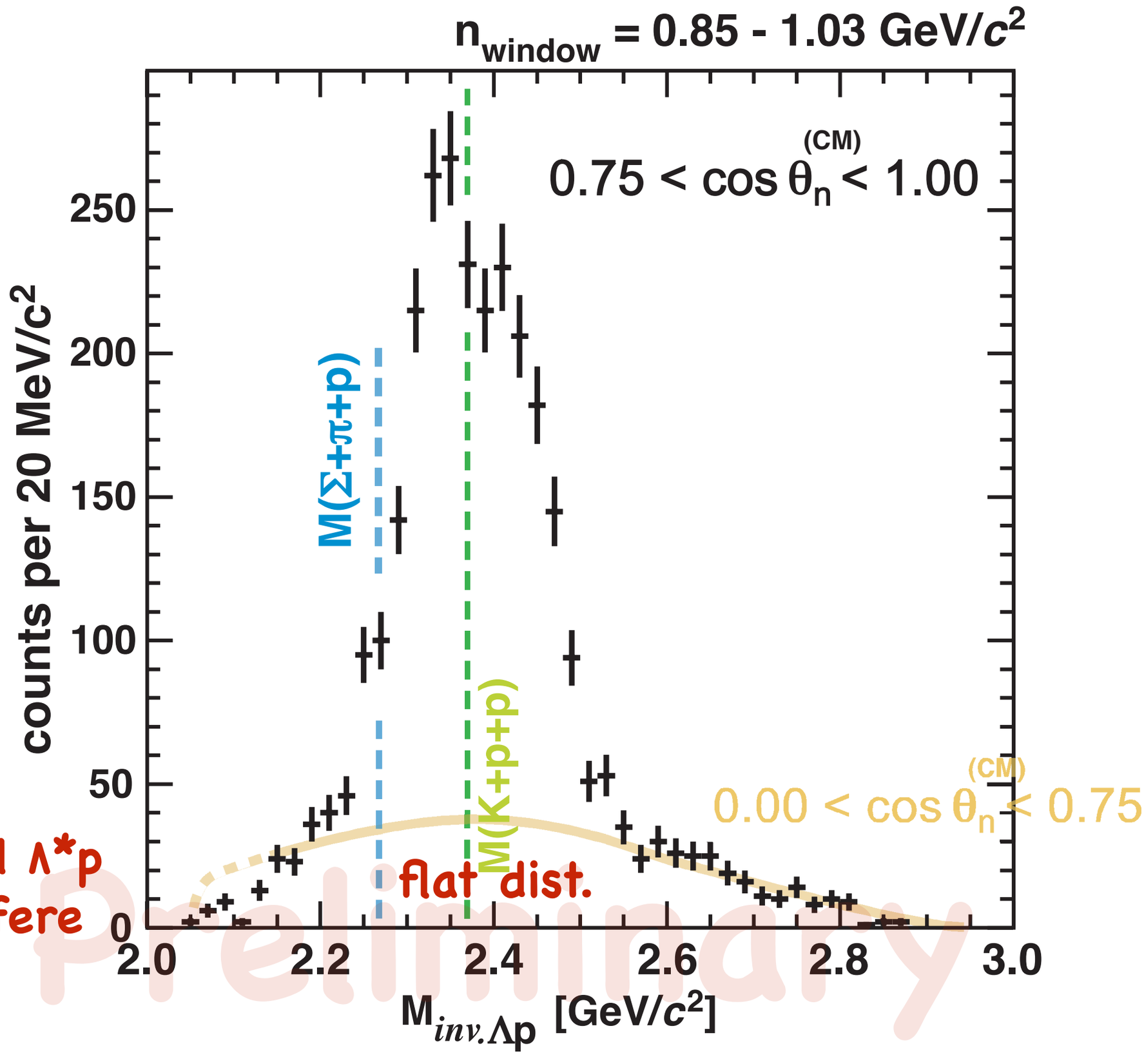
[2] *Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Aptdo. 22085, 46071 Valencia, Spain*
[3] *Departament de Física Quàntica i Astrofísica and Institut de Ciències del Cosmos, Universitat de Barcelona, Martí i Franquès 1, 08028 Barcelona, Spain*
[*] *E-mail: sekihara@post.j-parc.jp*

^{3}He(K$^-$, Λp)n:

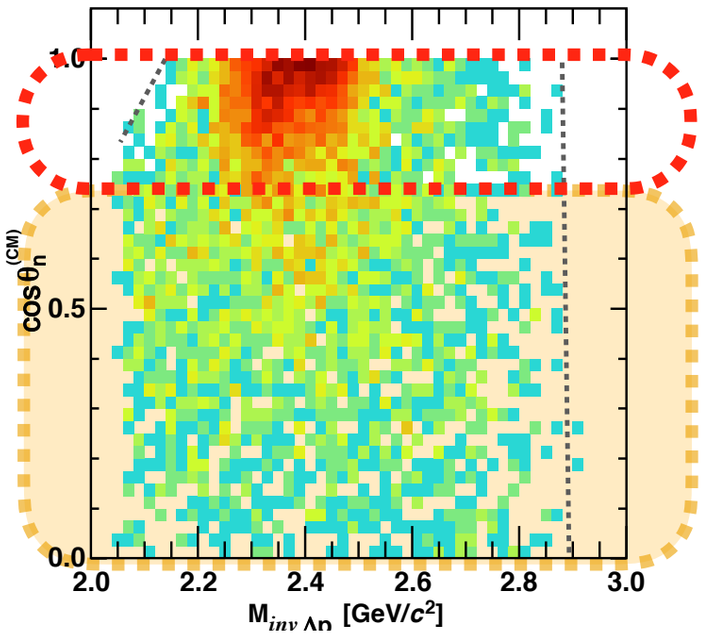




assuming uncorrelated Λ*p channel do not interfere with flat dist.

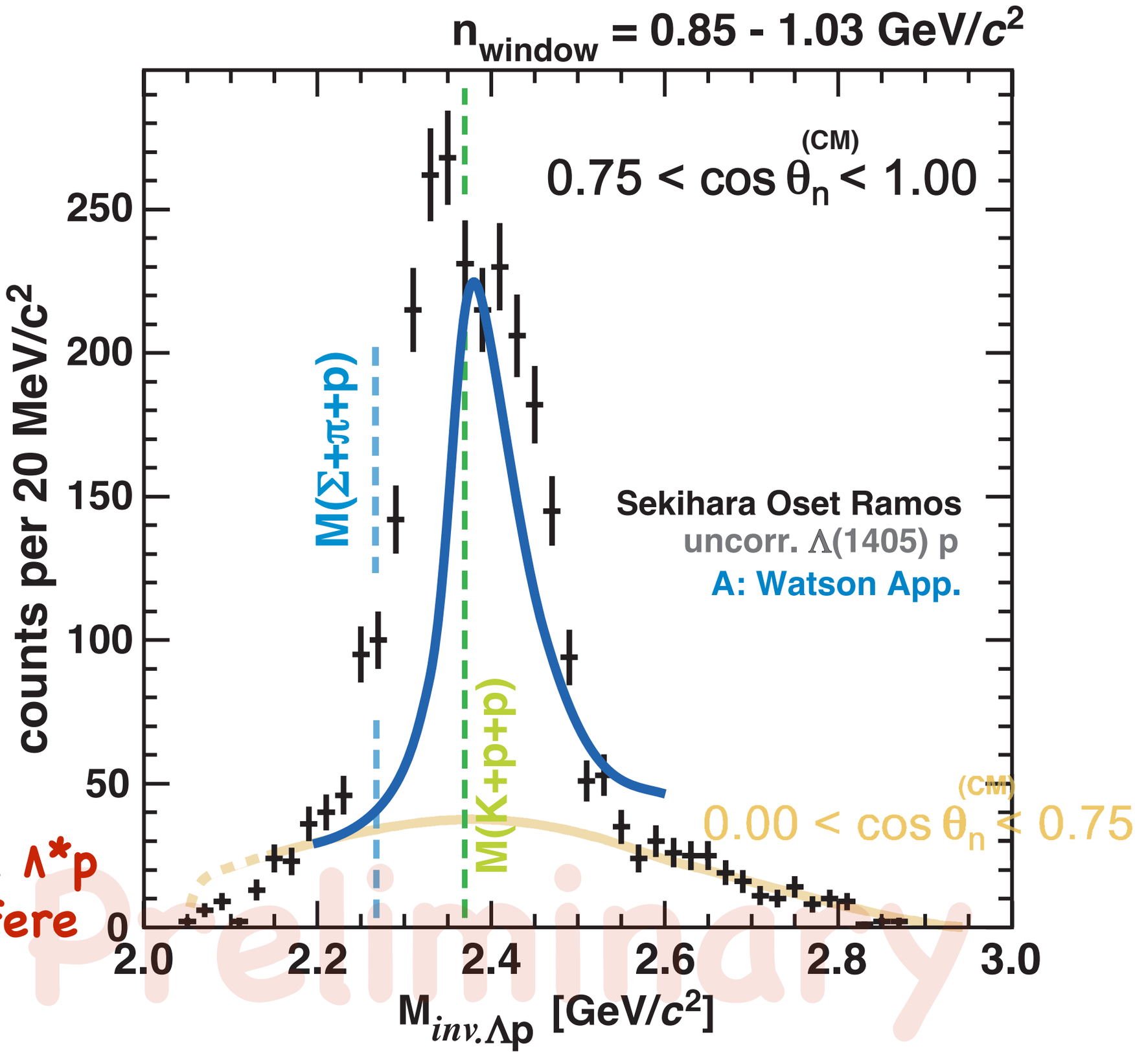


^{3}He(K$^-$, Λp)n: Quasi-elastic?

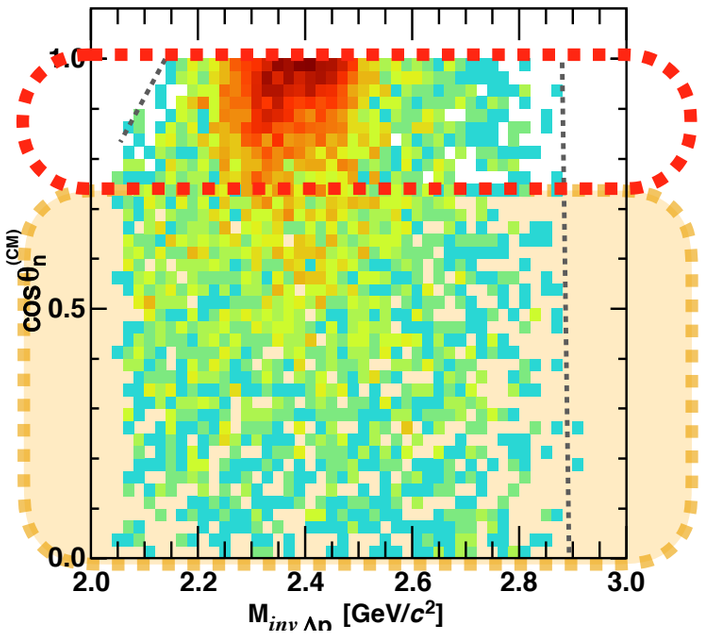


simple QE?

assuming uncorrelated Λ*p channel do not interfere with flat dist.



^{3}He(K$^-$, Λp)n: Quasi-elastic?



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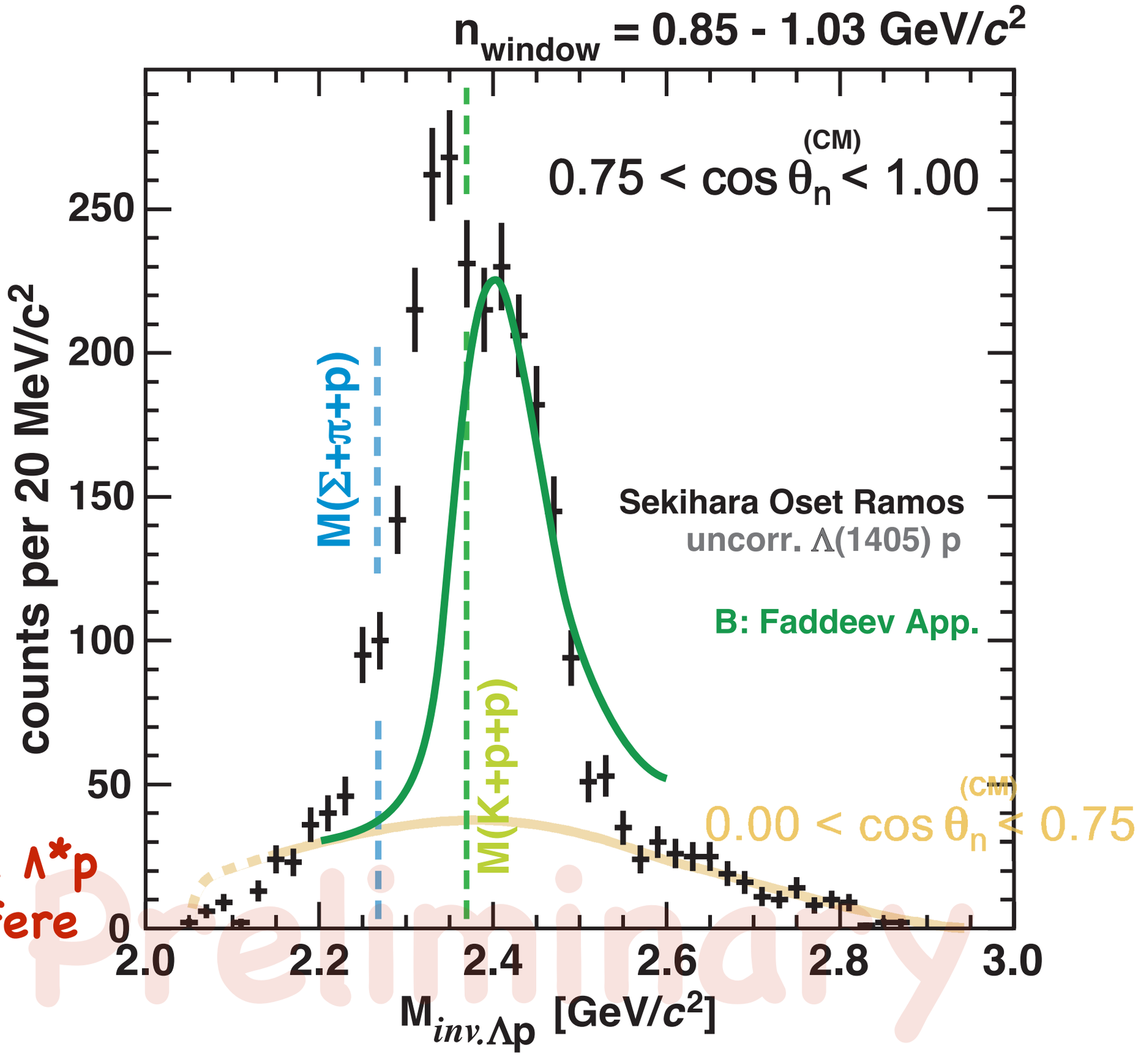
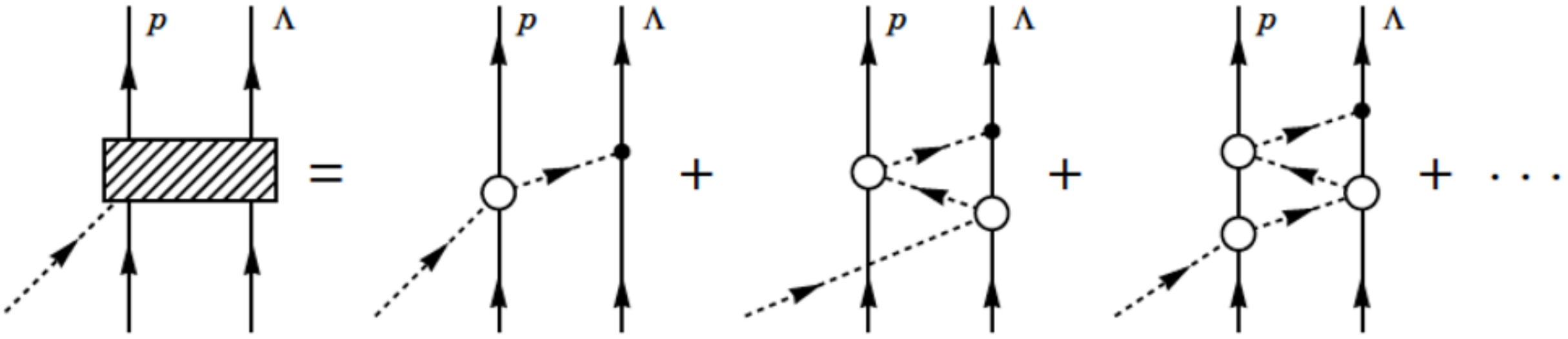


^{3}He(K^{-}, Λp)n:

Structure can be explained with "quasi-elastic K scattering" ? ➡ NO!

Need deeper strength!

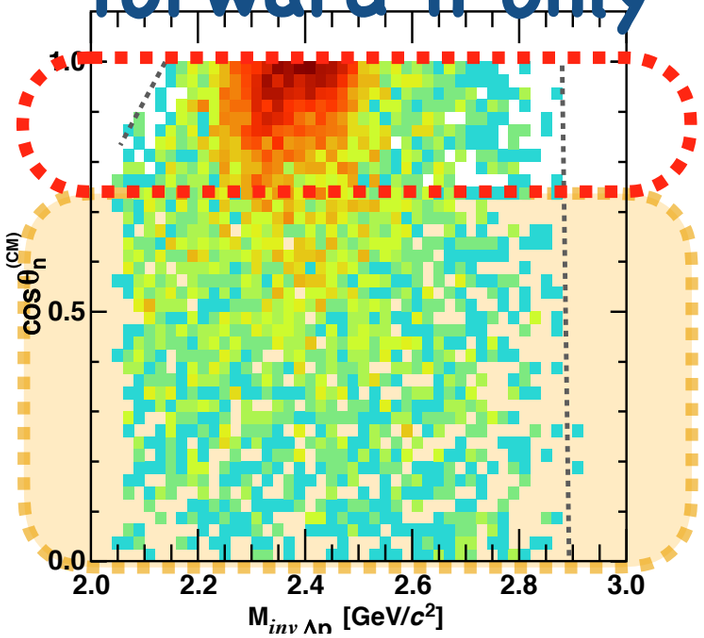
Sekihara Oset Ramos



K multiple scattering = "Kpp"

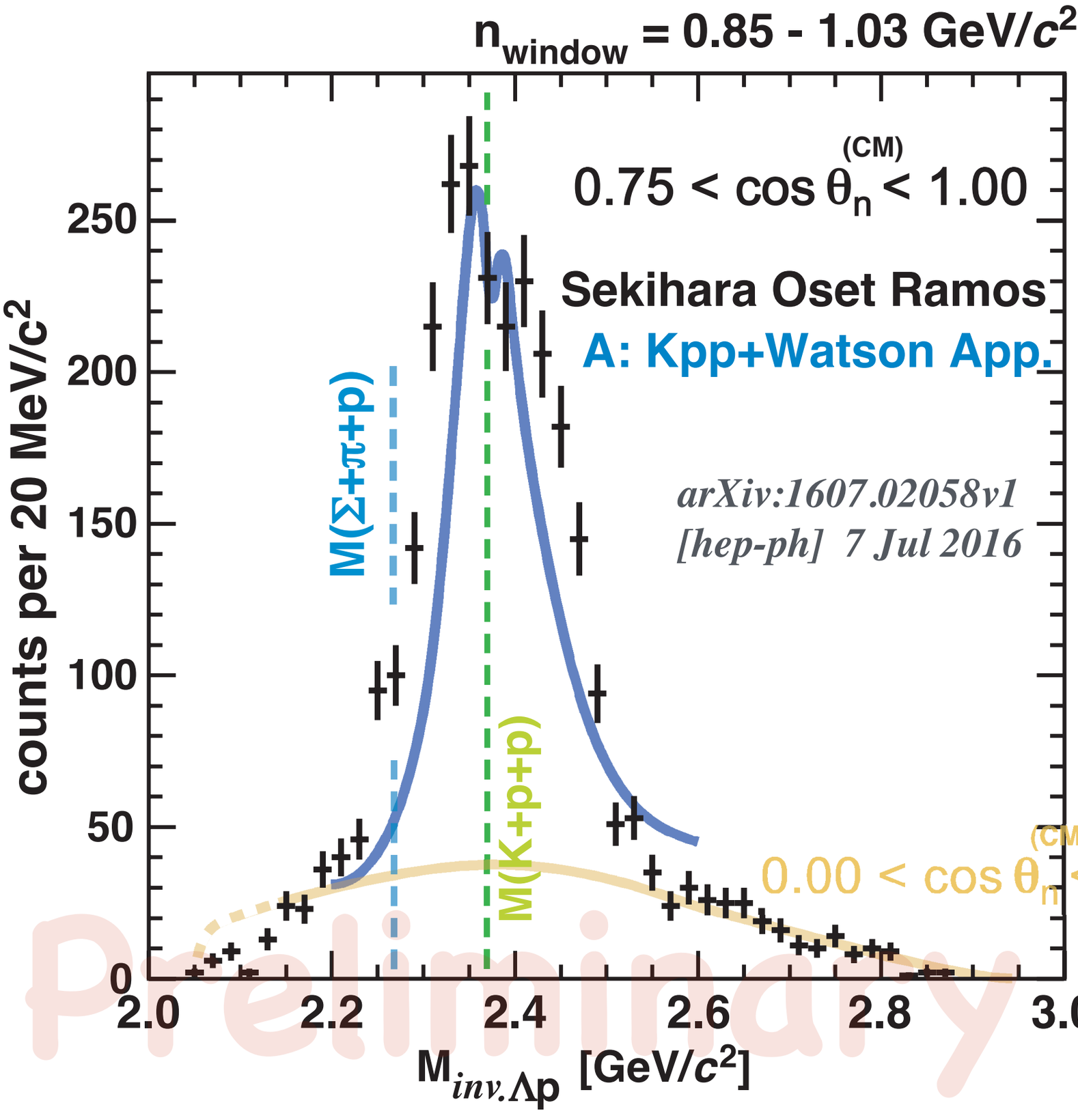
^{3}He(K$^-$, Λp)n: comparison with SOR

forward n only



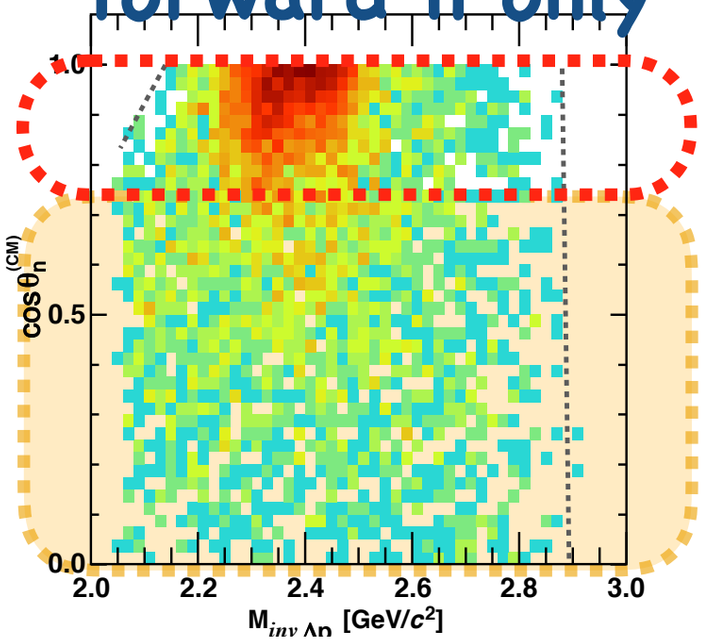
QE + "Kpp"

K multiple scattering



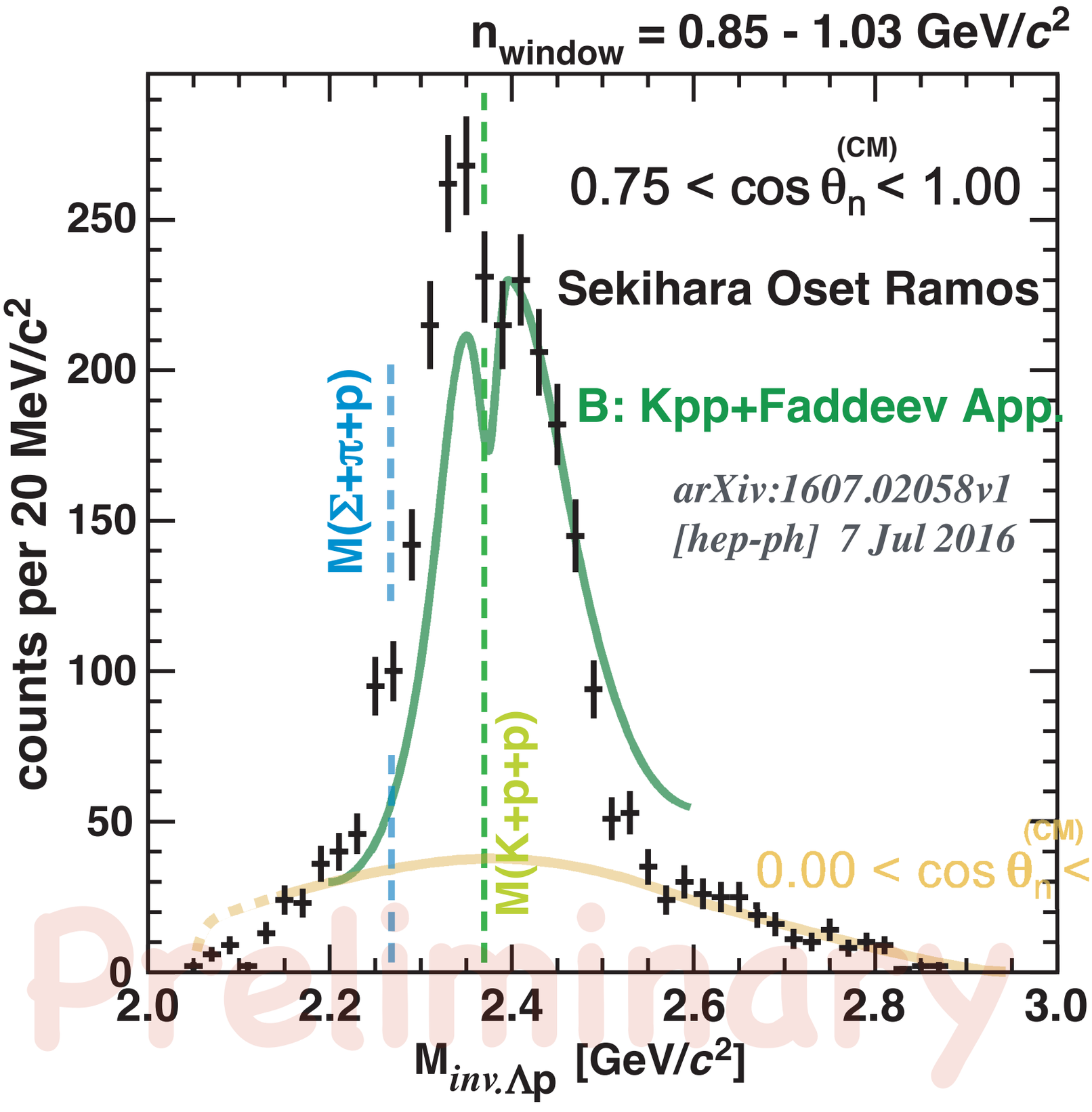
^{3}He(K$^-$, Λp)n: comparison with SOR

forward n only



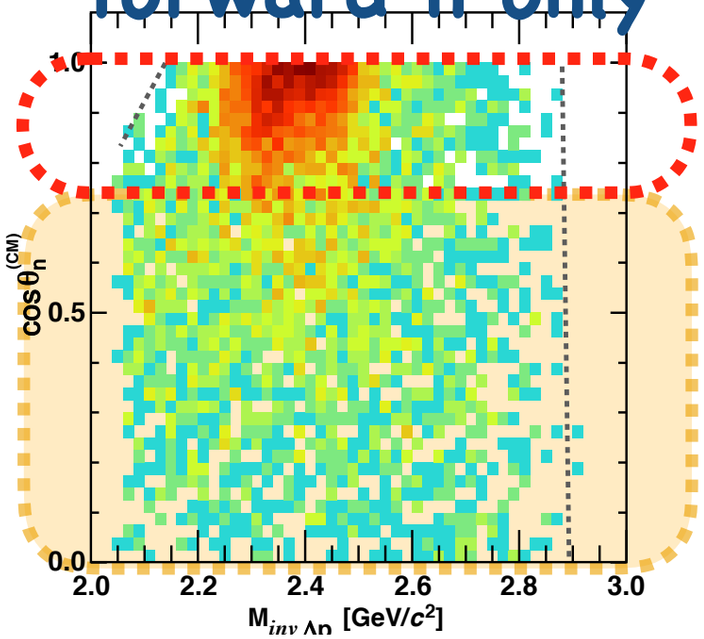
QE + "Kpp"

K multiple scattering



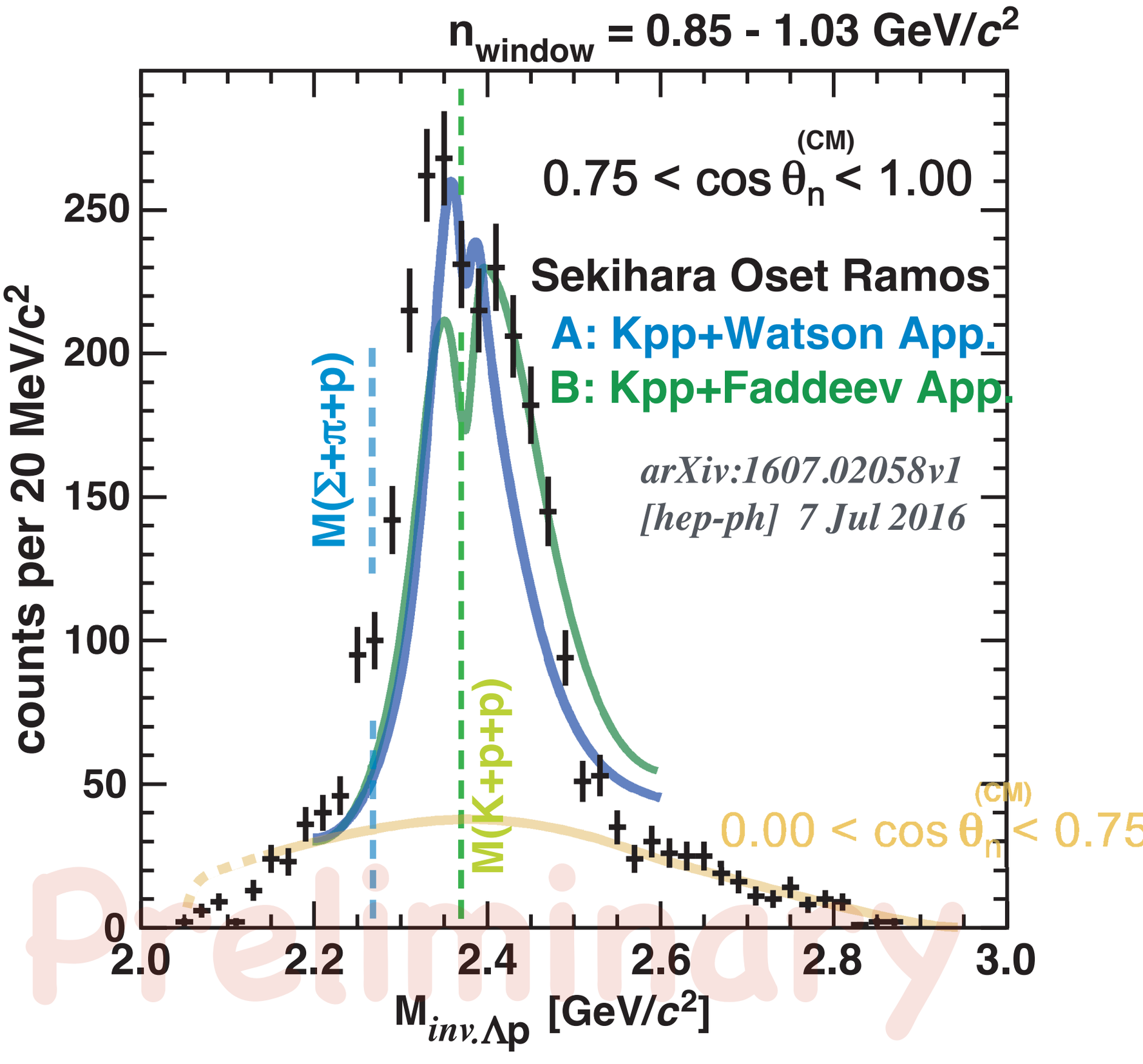
^{3}He(K$^-$, Λp)n: comparison with SOR

forward n only



Qualitatively in good agreement!

calculated without knowing E15 2nd spectrum



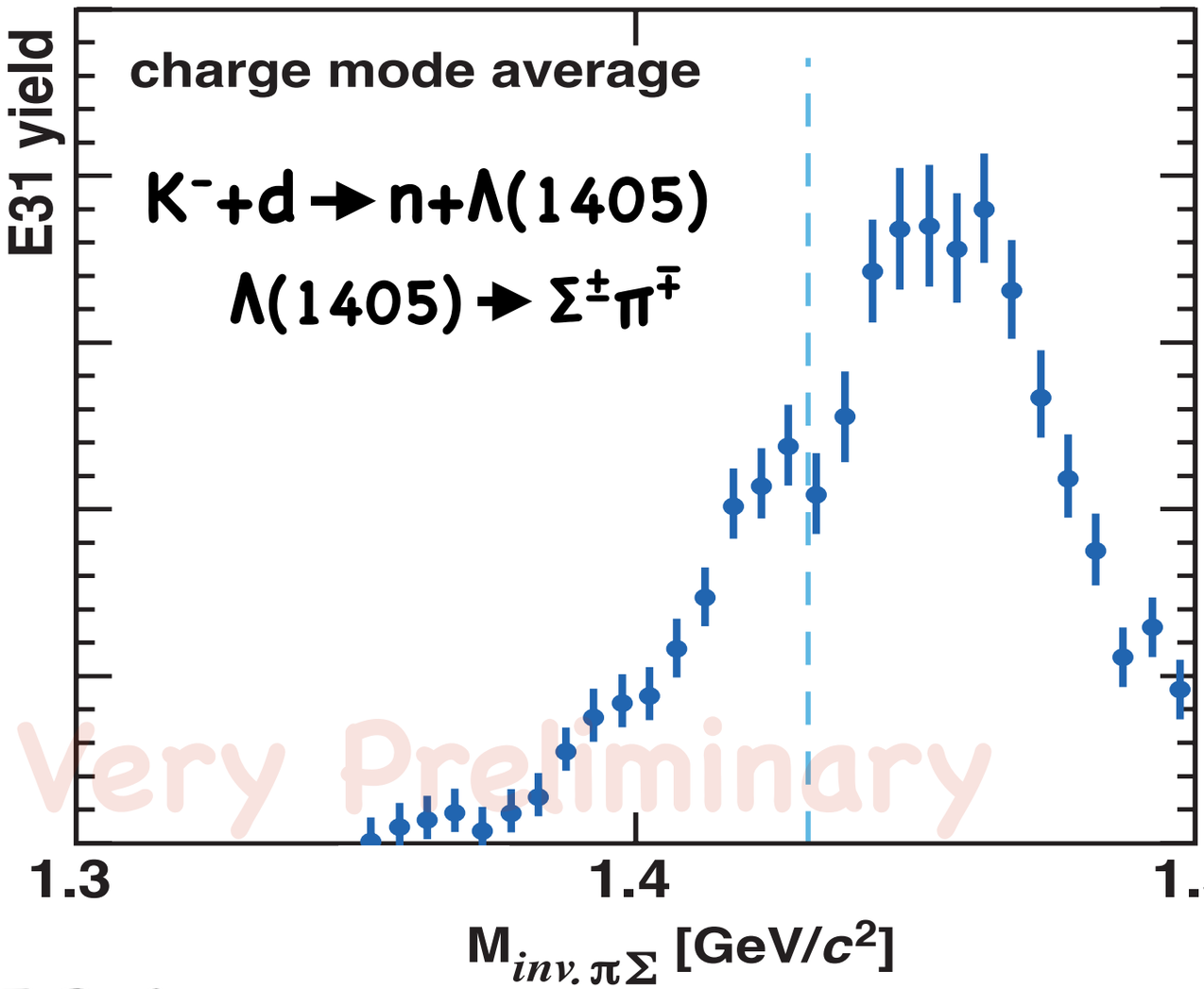
^{3}He(K^{-}, Λp)n:

Structure can be explained with quasi-elastic K scattering & Kpp @ x-UM?

qualitatively YES! but ...

Need even deeper strength!

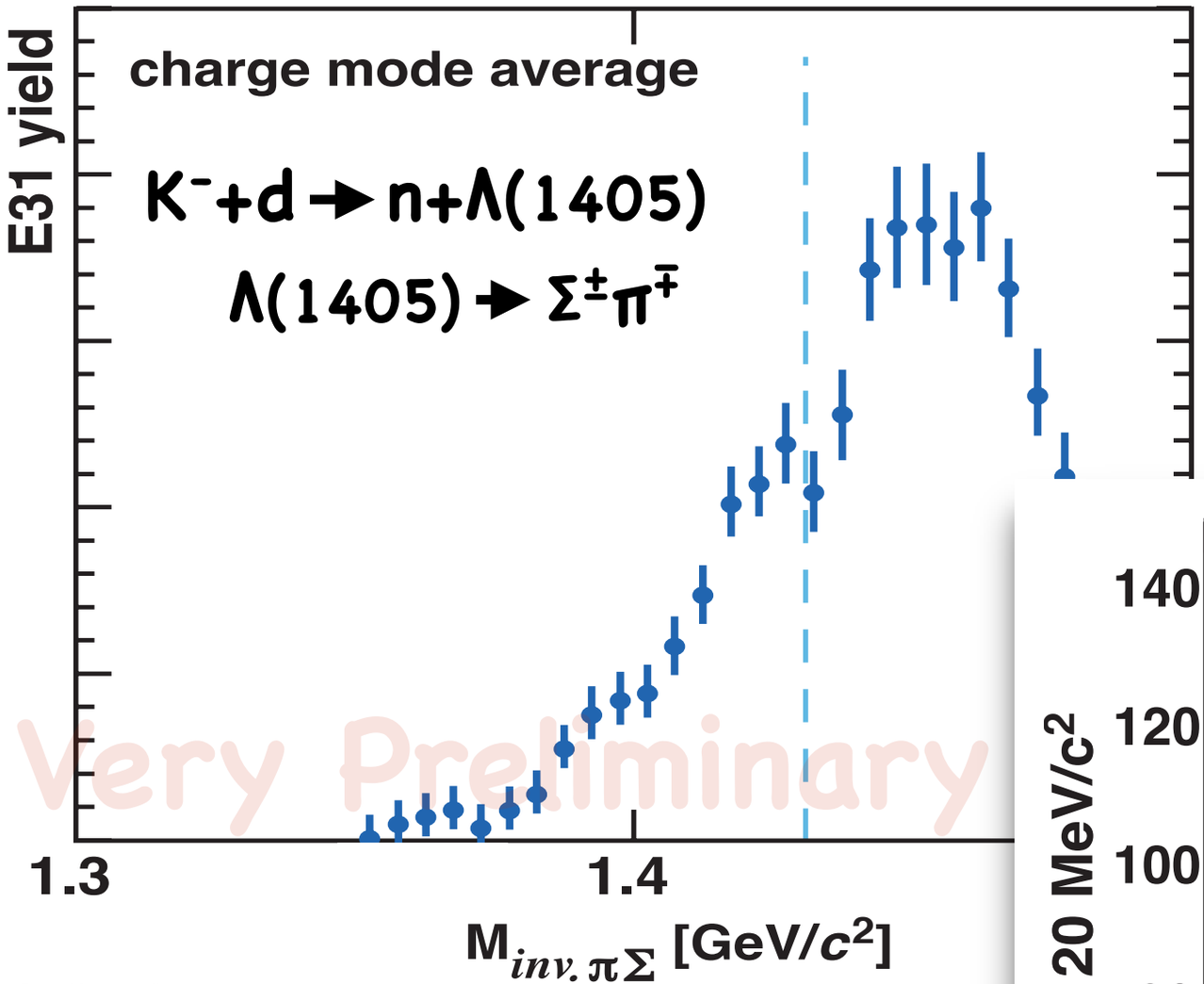
How to understand whole structure?



E31:

$K^-+d \rightarrow n+\Lambda(1405)$

$\Lambda(1405) \rightarrow \Sigma^{\pm}\pi^{\mp}$

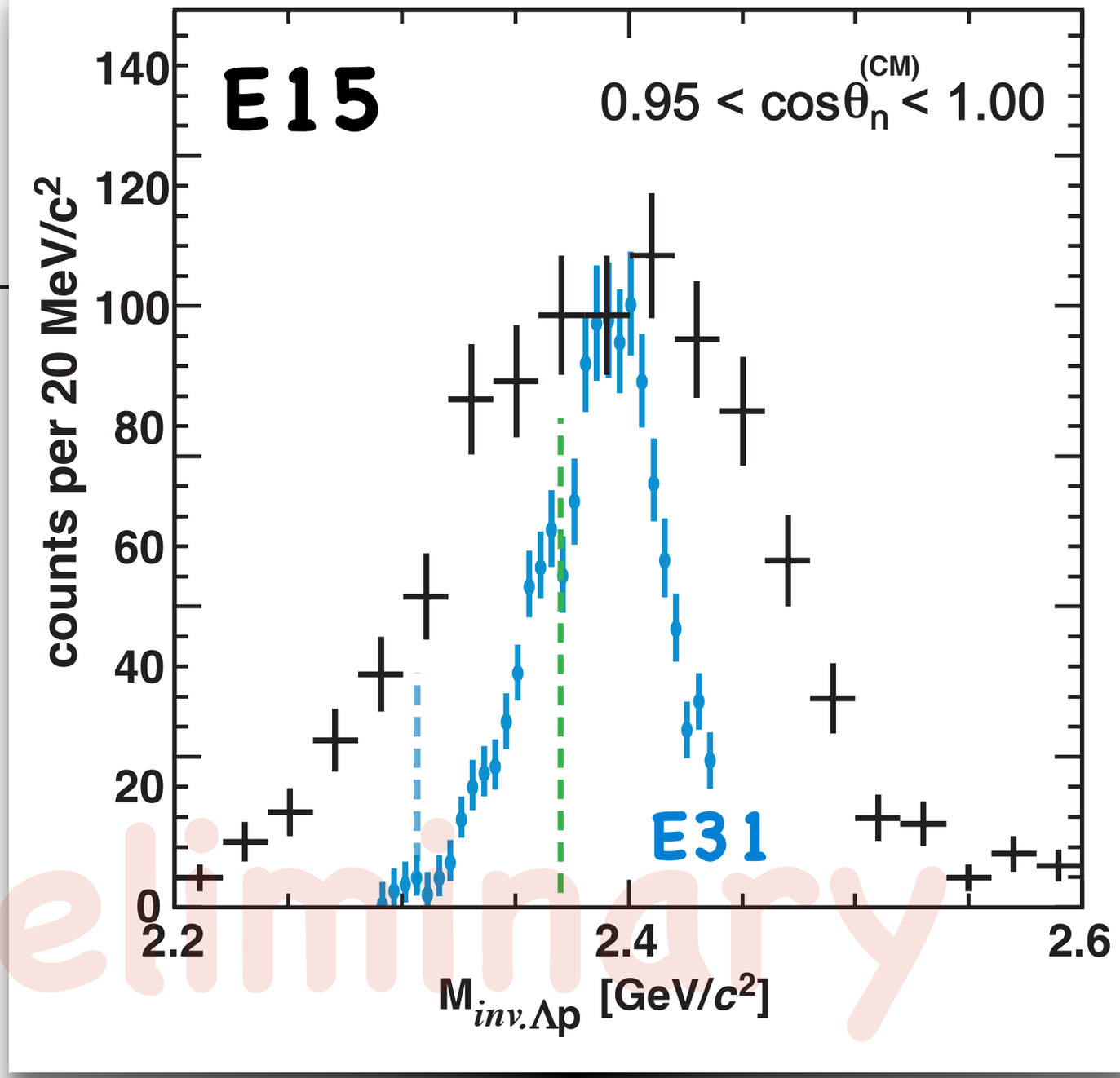


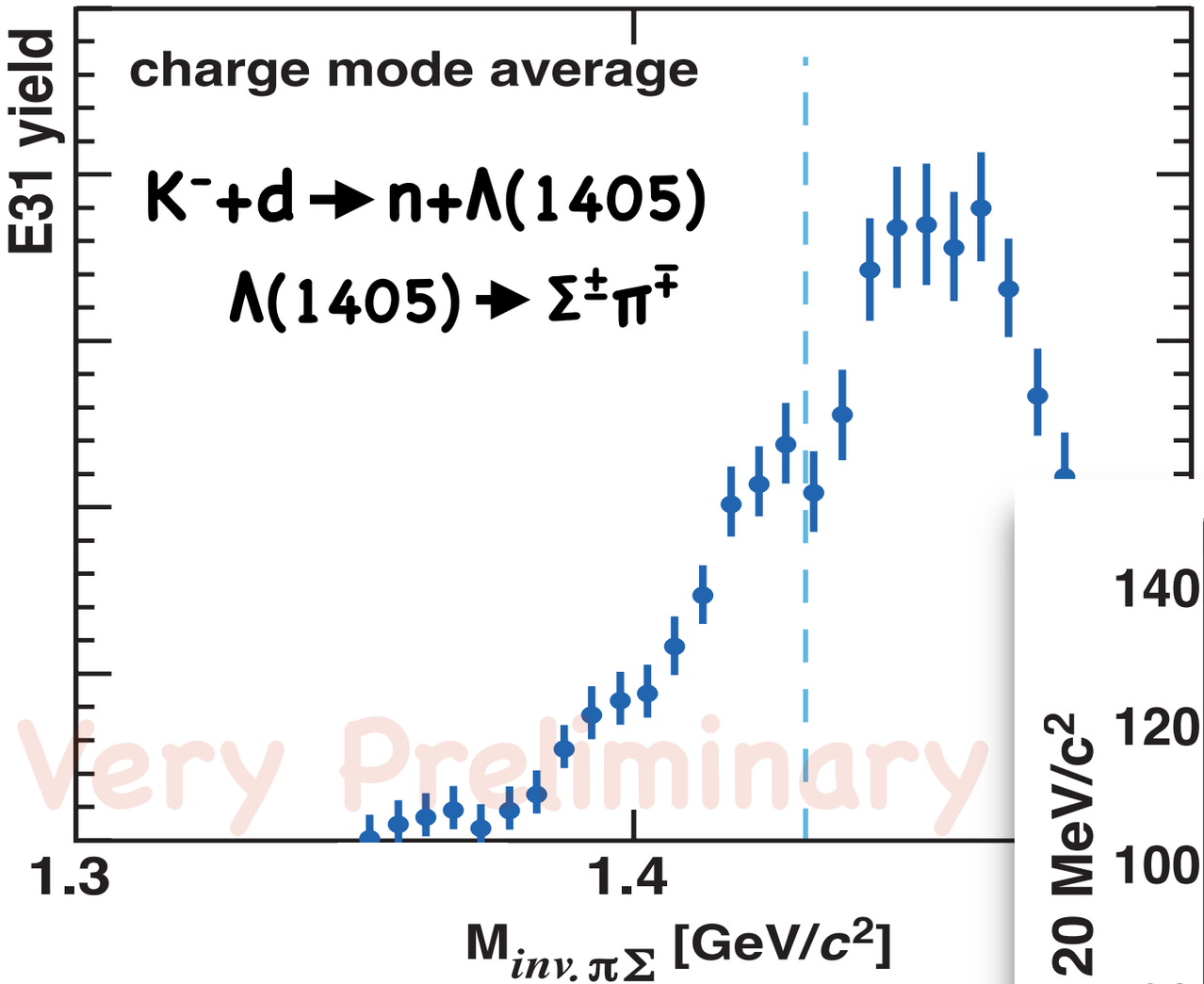
E31:

$K^-+d \rightarrow n+\Lambda(1405)$

$\Lambda(1405) \rightarrow \Sigma^{\pm}\pi^{\mp}$

Note: very forward n only





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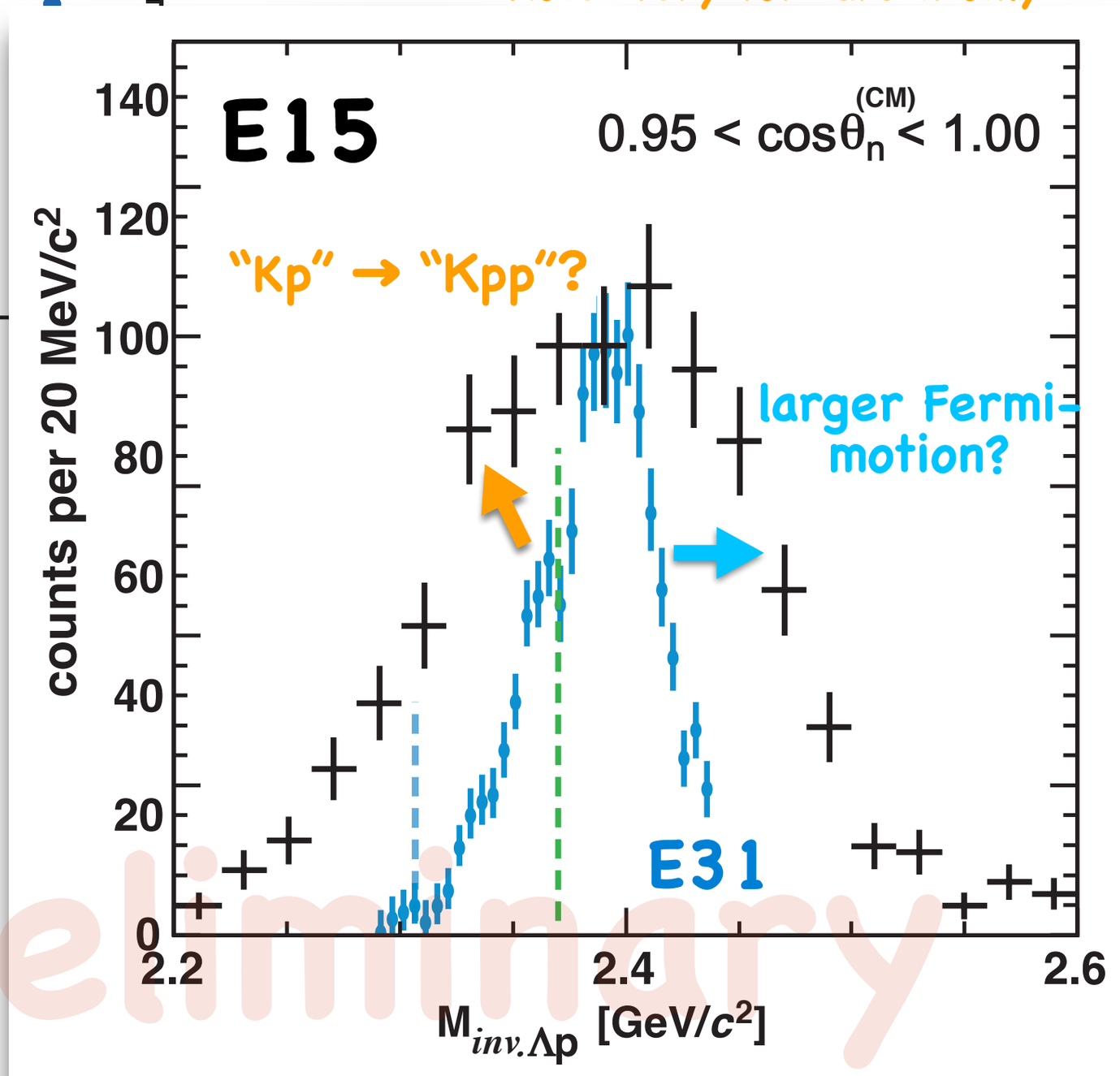
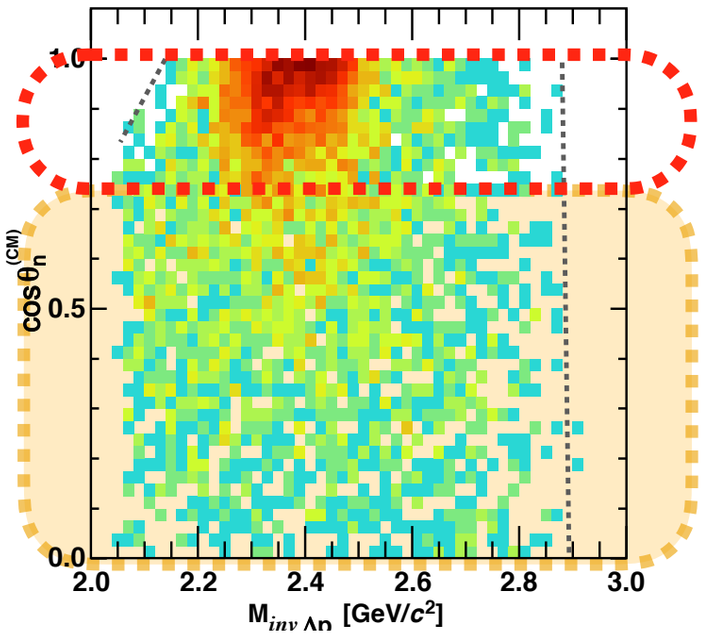
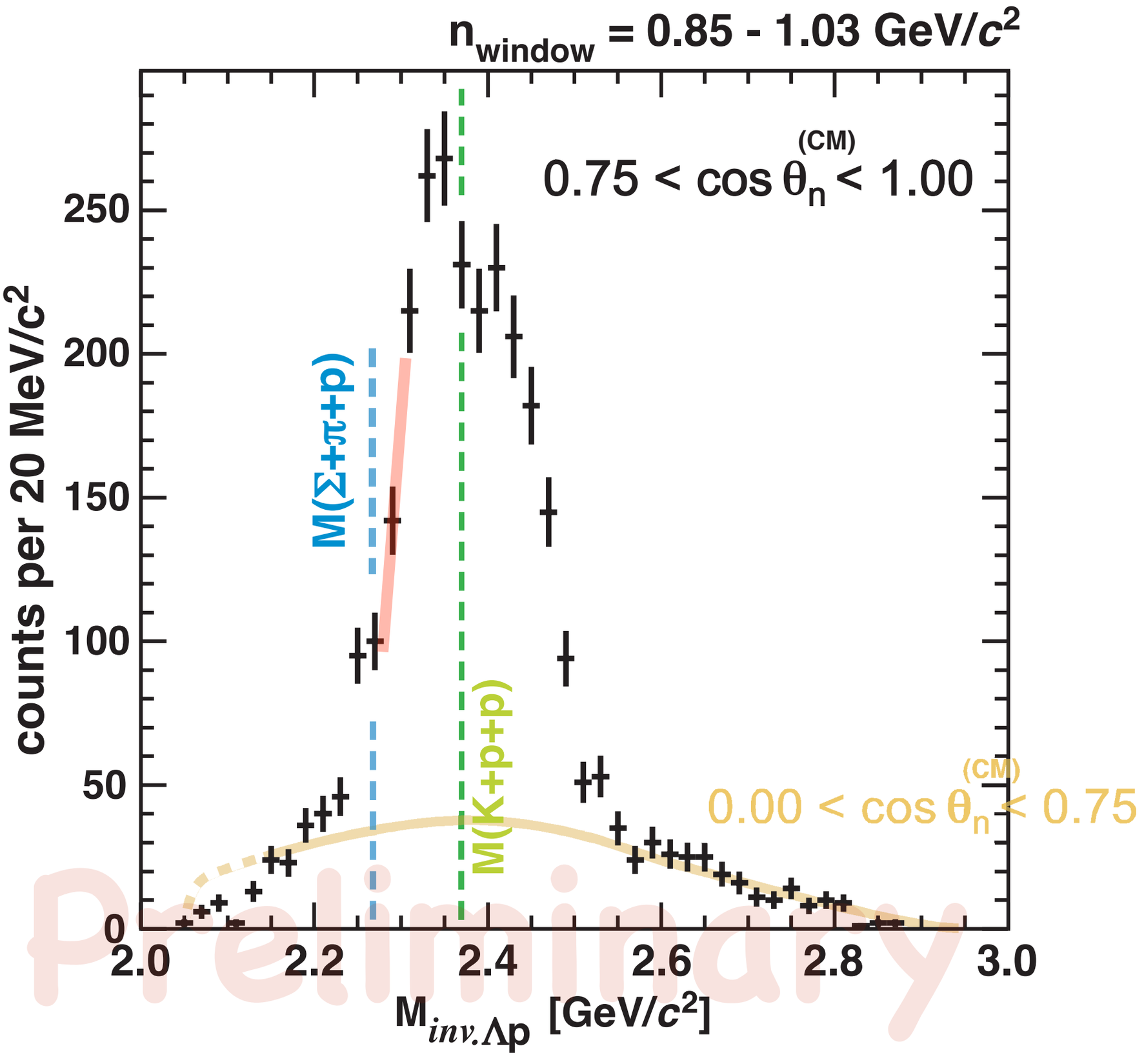


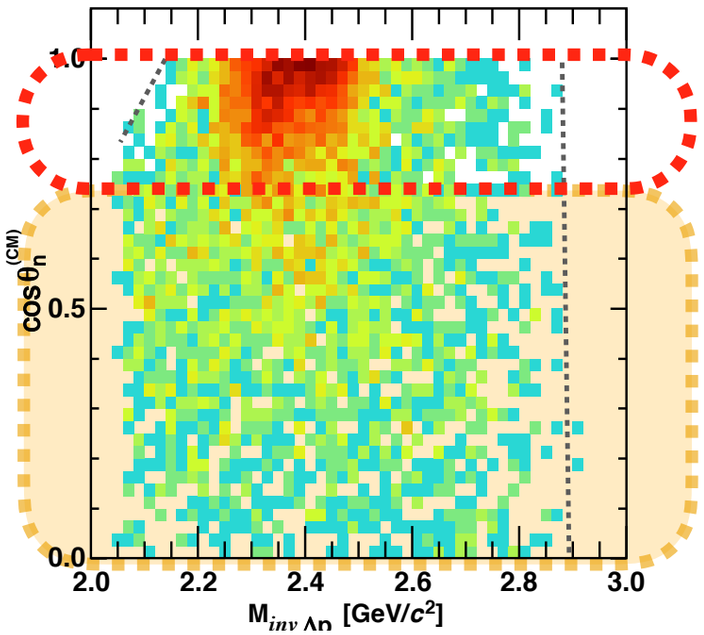
How to understand whole structure? ^{3}He(K^-, Λp)n:



from the shape of deeper region (sharp drop), the structure in bound region must be narrow (~60MeV)



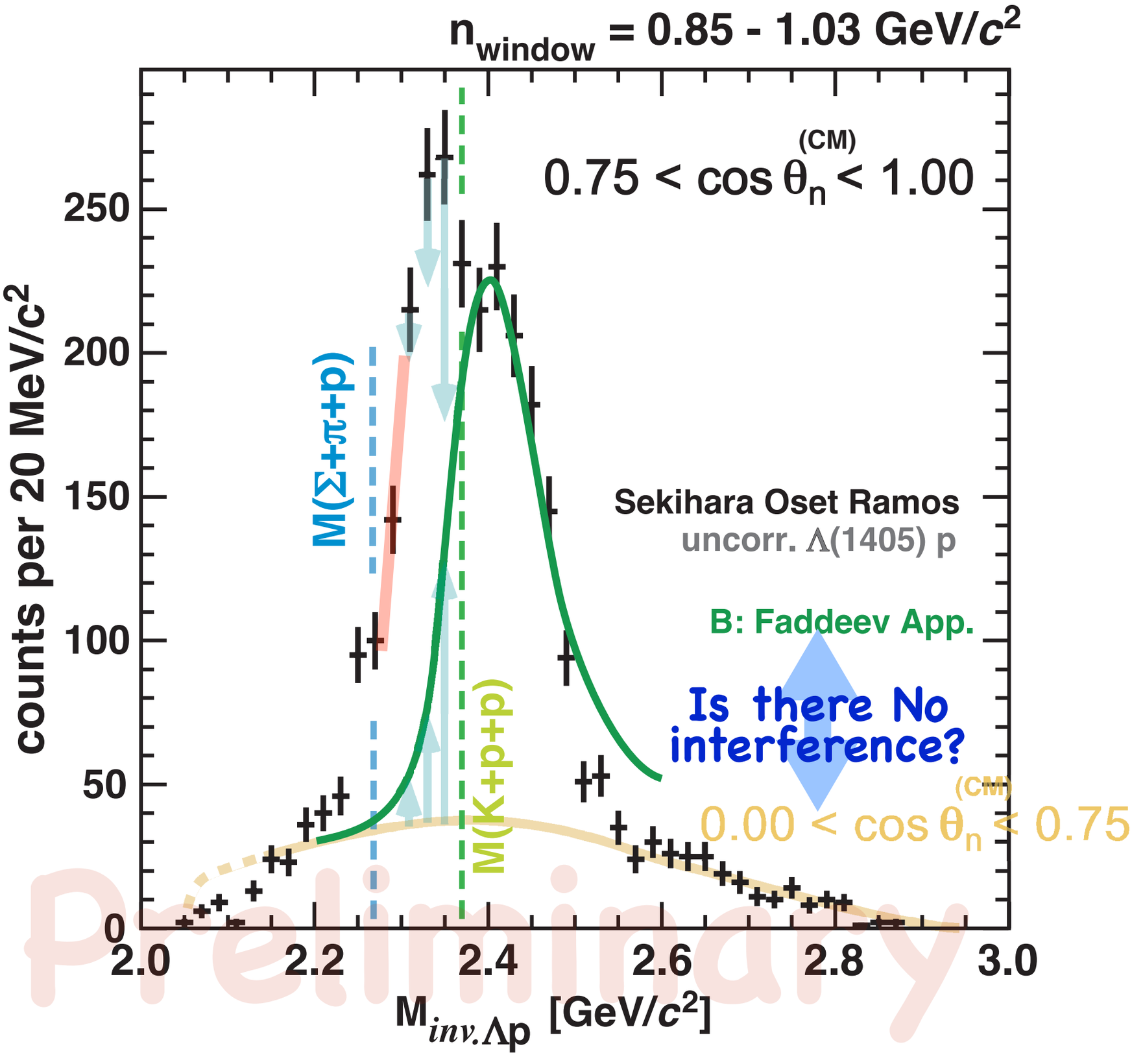
^{3}He(K$^-$, Λp)n: QE + ?



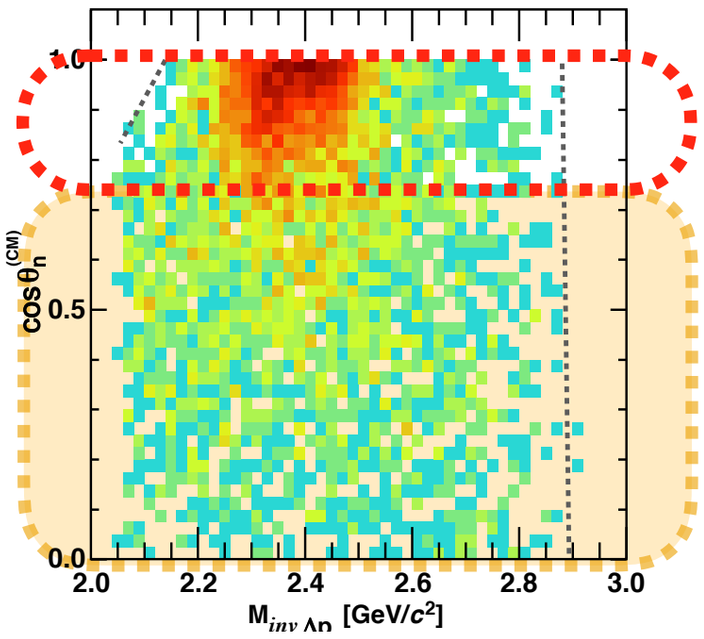
simple QE

+

?



^{3}He(K$^-$, Λp)n: QE + Kpp



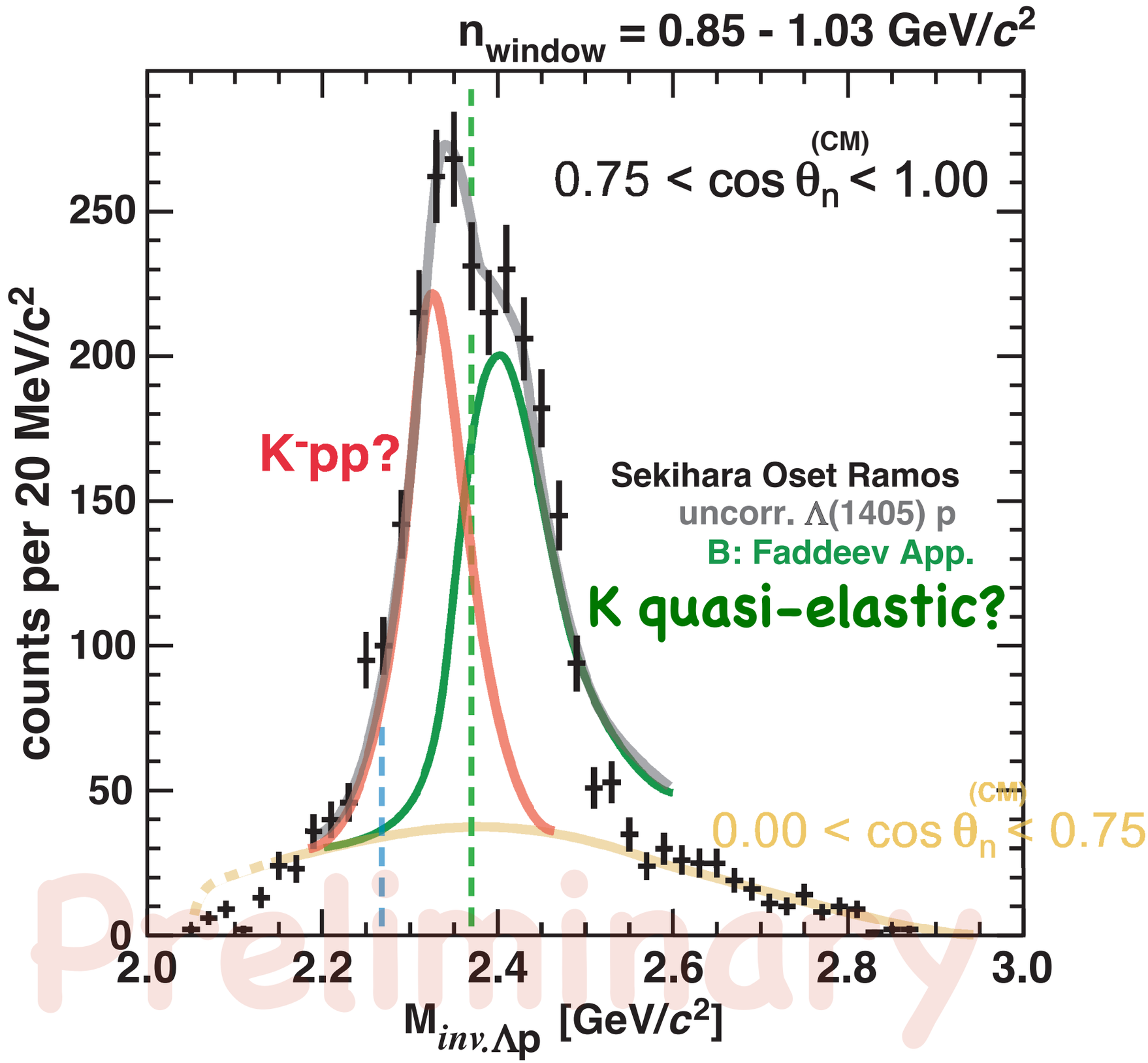
simple QE

+

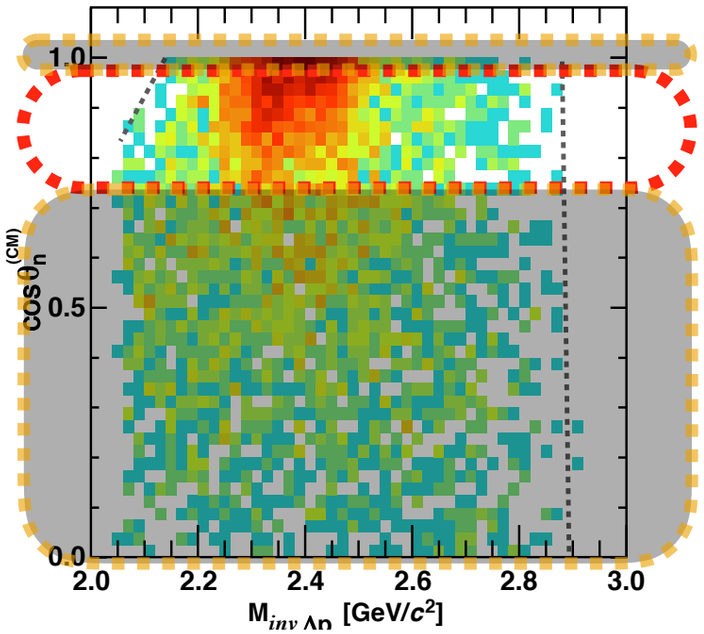
Kpp?

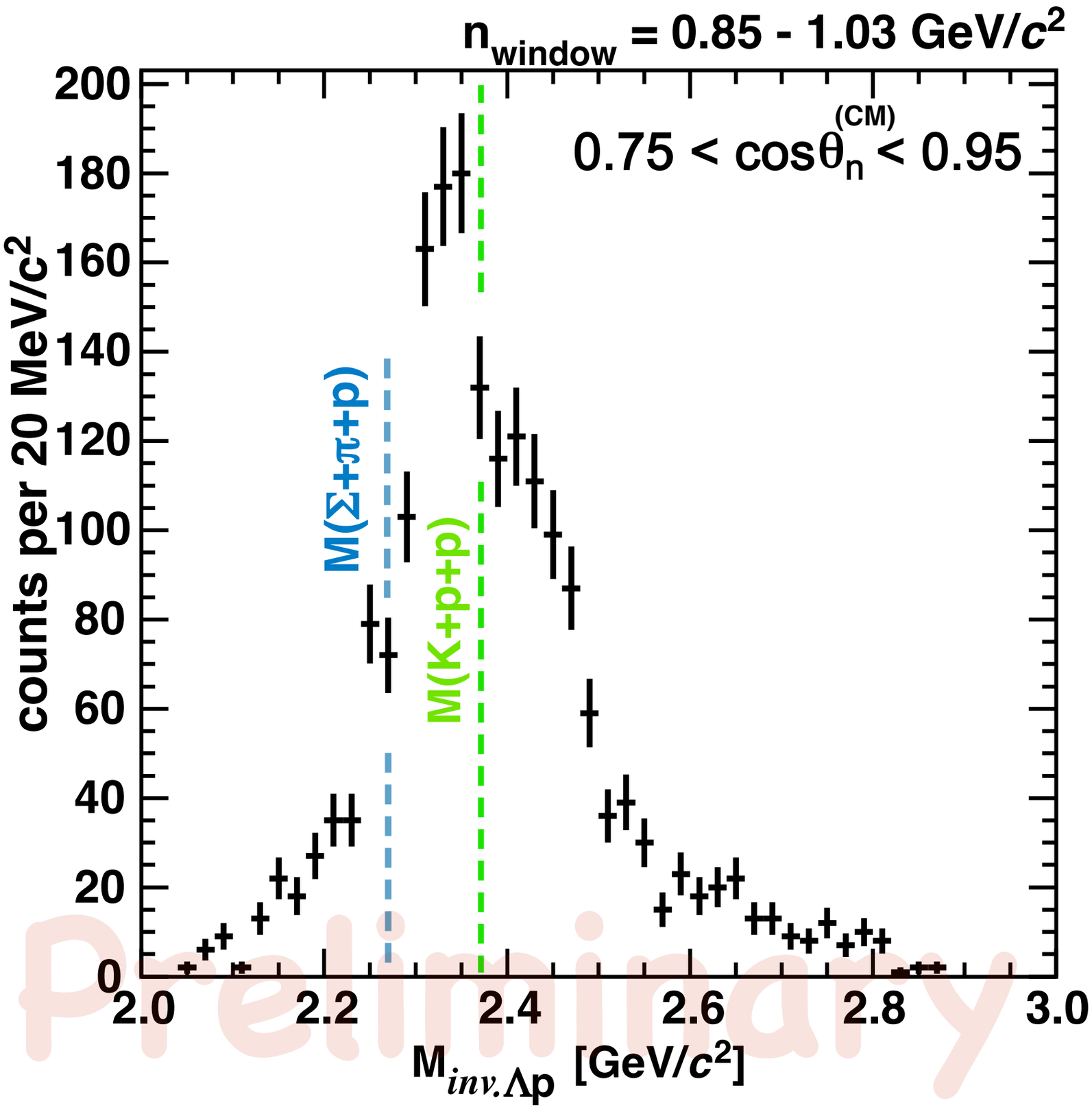
if we can neglect interference

rather deep & narrow in width

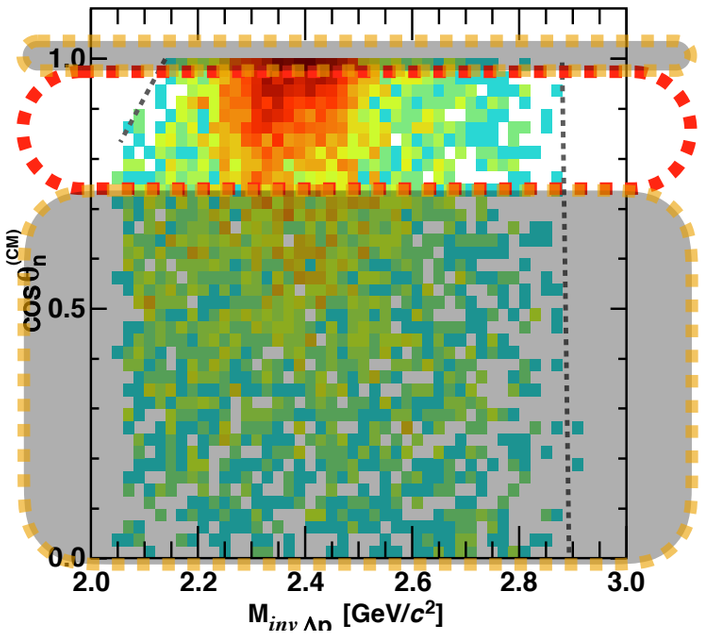


^{3}He(K$^-$, Λp)n:





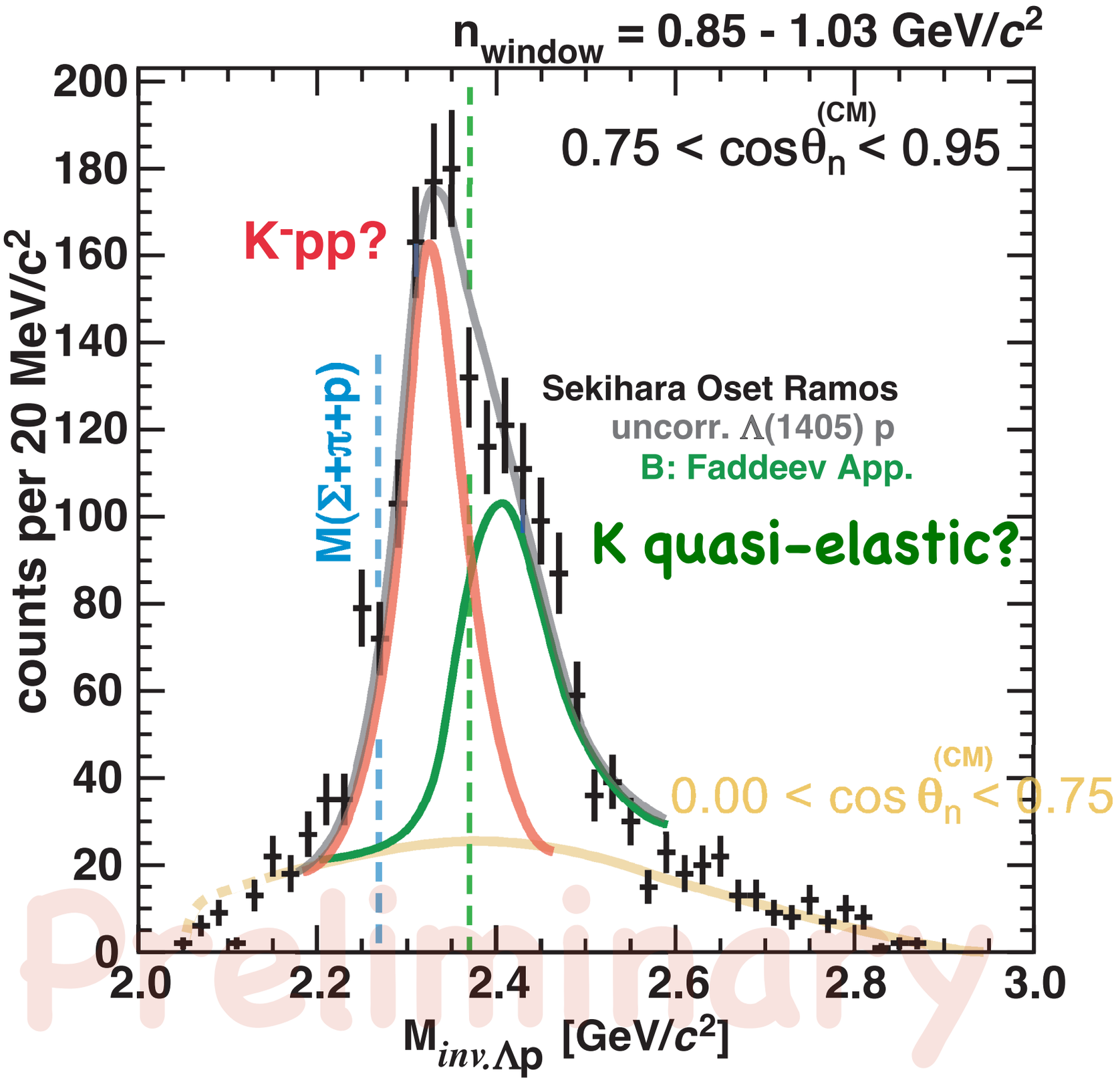
^{3}He(K$^-$, Λp)n:



if we can neglect interference

rather deep & narrow in width

could be OK

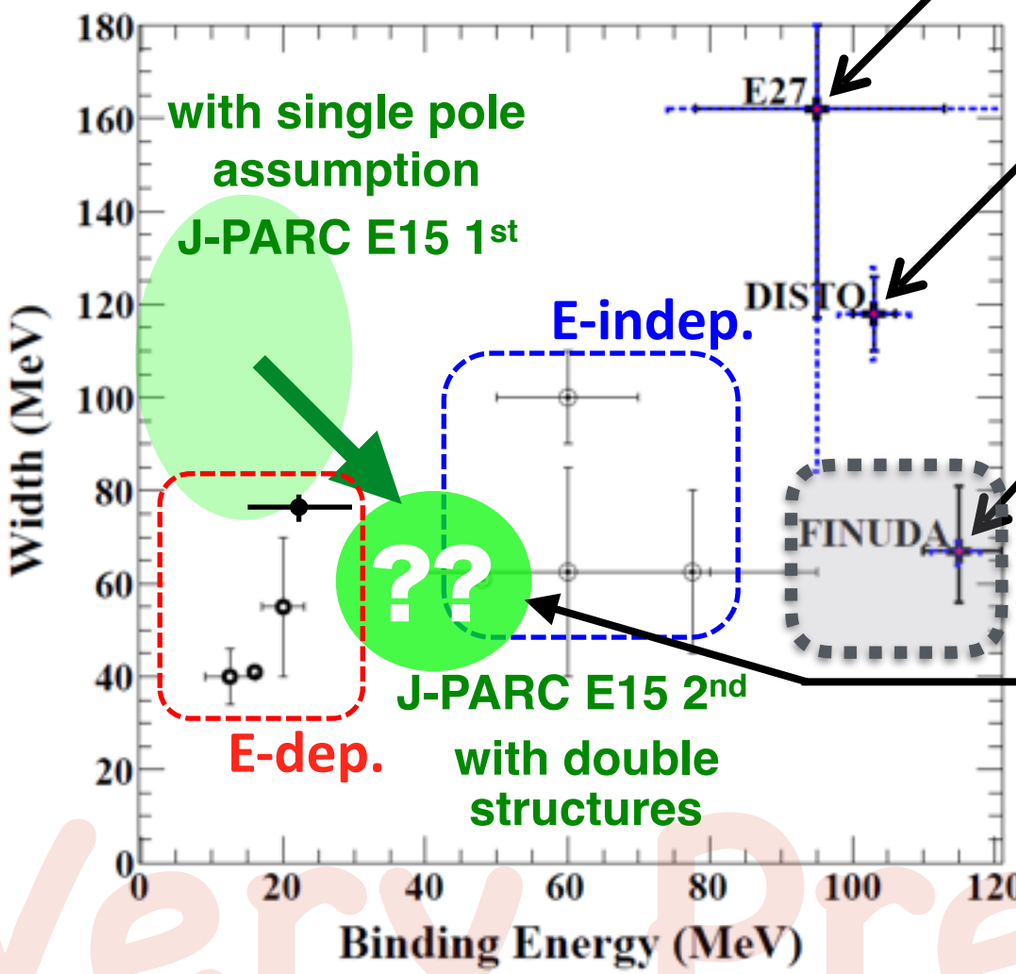


Recent status of K^-pp bound state

- **Recent results**
  - **Theoretical calc.**
  - **Experiments**

$\bar{K}N$ interaction model

E-dep. / ***E-indep.***



Reports structure / *NO structure*

J-PARC E27
$d(\pi^+, K^+)X$

DISTO
$pp \to \Lambda pK^+$

FINUDA
$(stopped\ K^-, \Lambda p)$

J-PARC E15
$^3He(K^-, \Lambda p)n$:

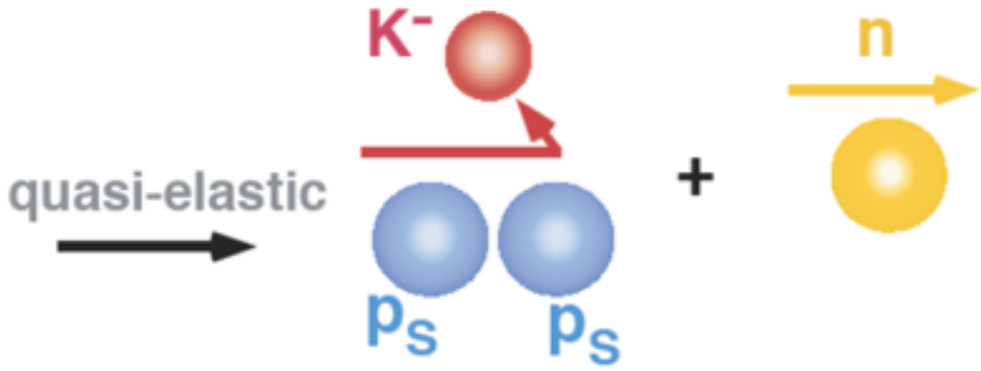
LEPS
$p(\gamma, \pi^- K^+)X$

HADES
$pp \to \Lambda pK^+$

FINUDA ?

could be the first convincing data
… after a long journey …

Summary



low q_K is key for the formation

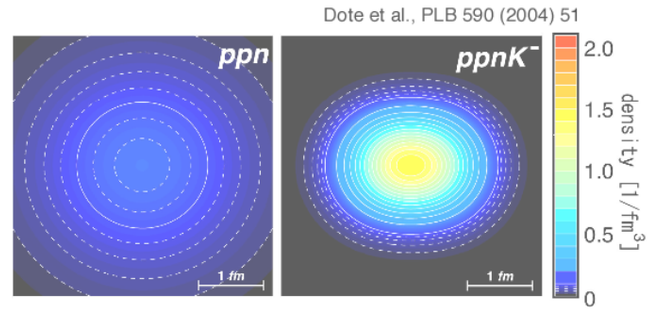
first convincing Kpp signal

probably, $B_K \sim 100$ MeV would be excluded

compact system ?

$Q_K \sim 400$ MeV/c → ~ 0.5 fm?

deeper than χ-UM ?



cf. arXiv:1607.02058 → $M_{\Lambda p} = 2354 - 36i$ MeV

B(K) ~ 15 MeV
Γ(K) ~ 70 MeV

what needed to be finalize?

what is flat dist. over Dalitz?

Λpn

finish analysis, *including* *E31?*

full kinematical refit / angular distributions …

further theoretical inputs? ***J^P?***

examine other possibilities: *uncorrelated Σ* p?*

University of Victoria | British Columbia Canada

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THANKS

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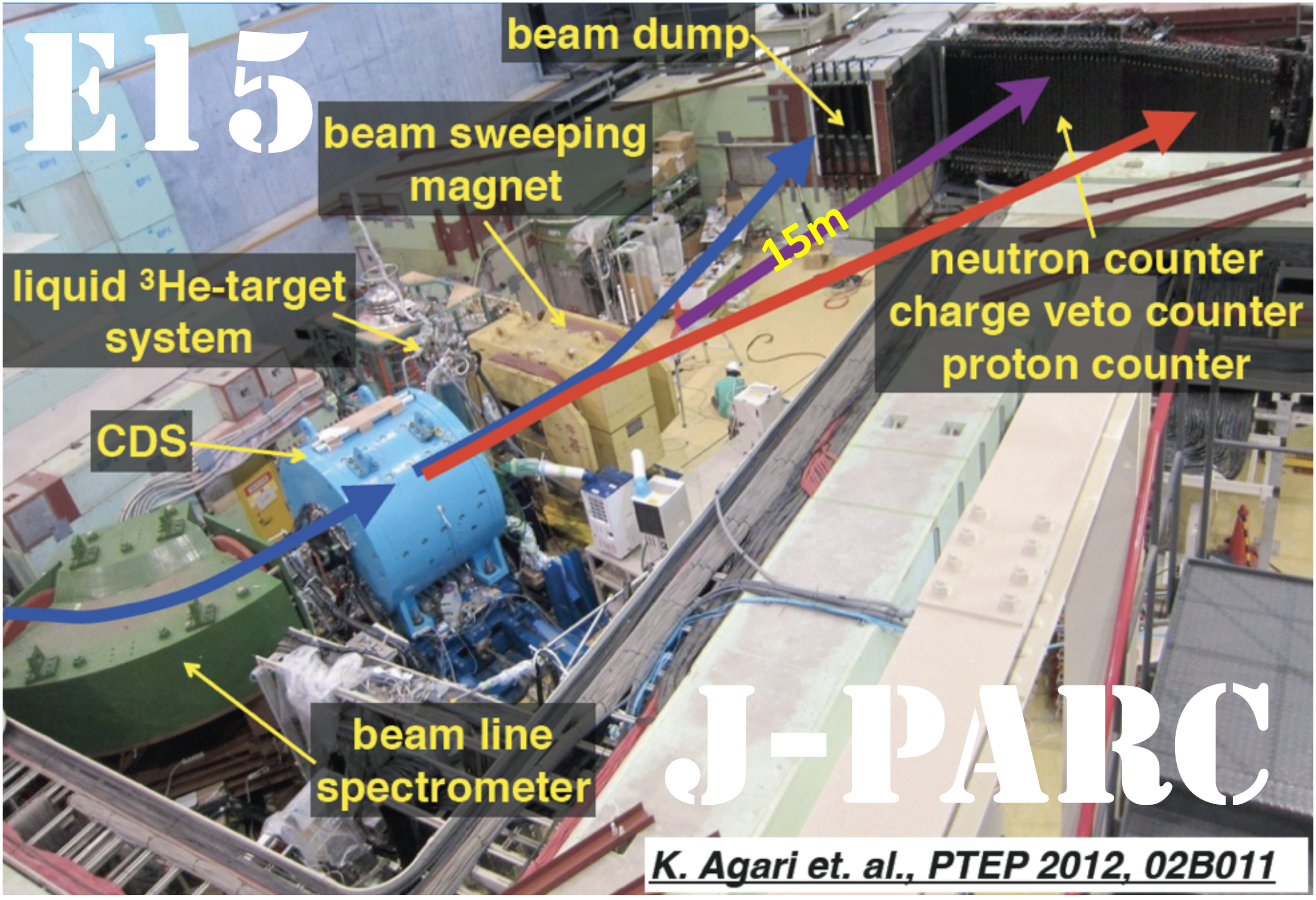
RIKEN

東北大学 TOHOKU UNIVERSITY

KEK

BACKUPS

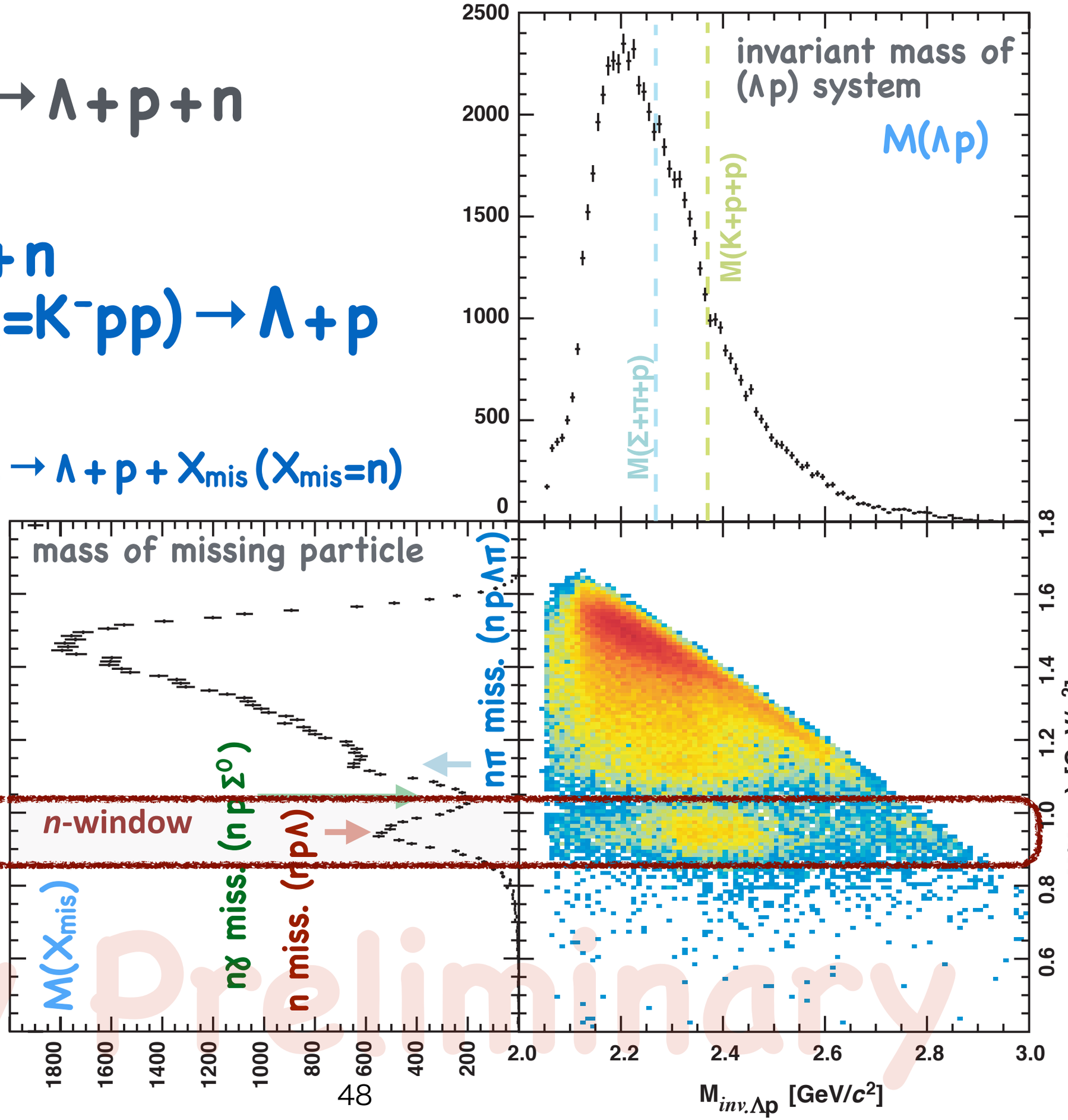

E15
beam dump
beam sweeping magnet
liquid ³He-target system
CDS
beam line spectrometer
15m
neutron counter
charge veto counter
proton counter
J-PARC
K. Agari et. al., PTEP 2012, 02B011

$K^- + {}^3He \rightarrow ? \rightarrow \Lambda + p + n$

$K^- + {}^3He \rightarrow Y + n$

$Y(=K^-pp) \rightarrow \Lambda + p$

$K^- + {}^3He \rightarrow \Lambda + p + X_{mis}\ (X_{mis}=n)$



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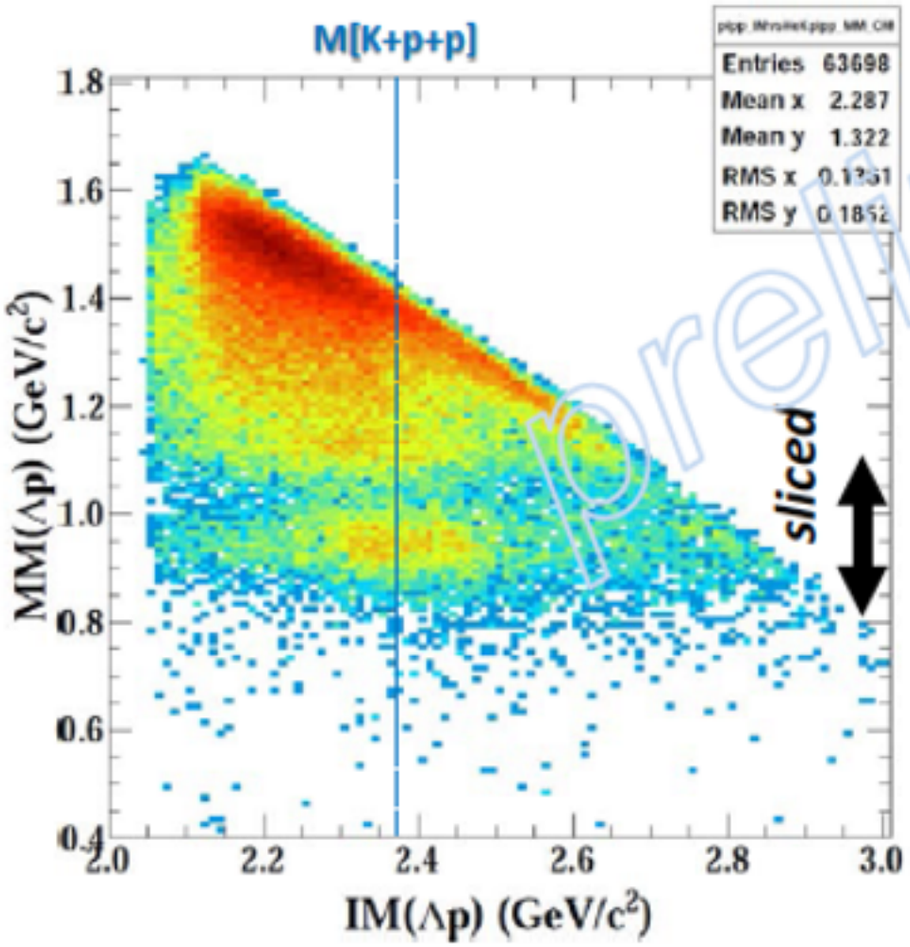
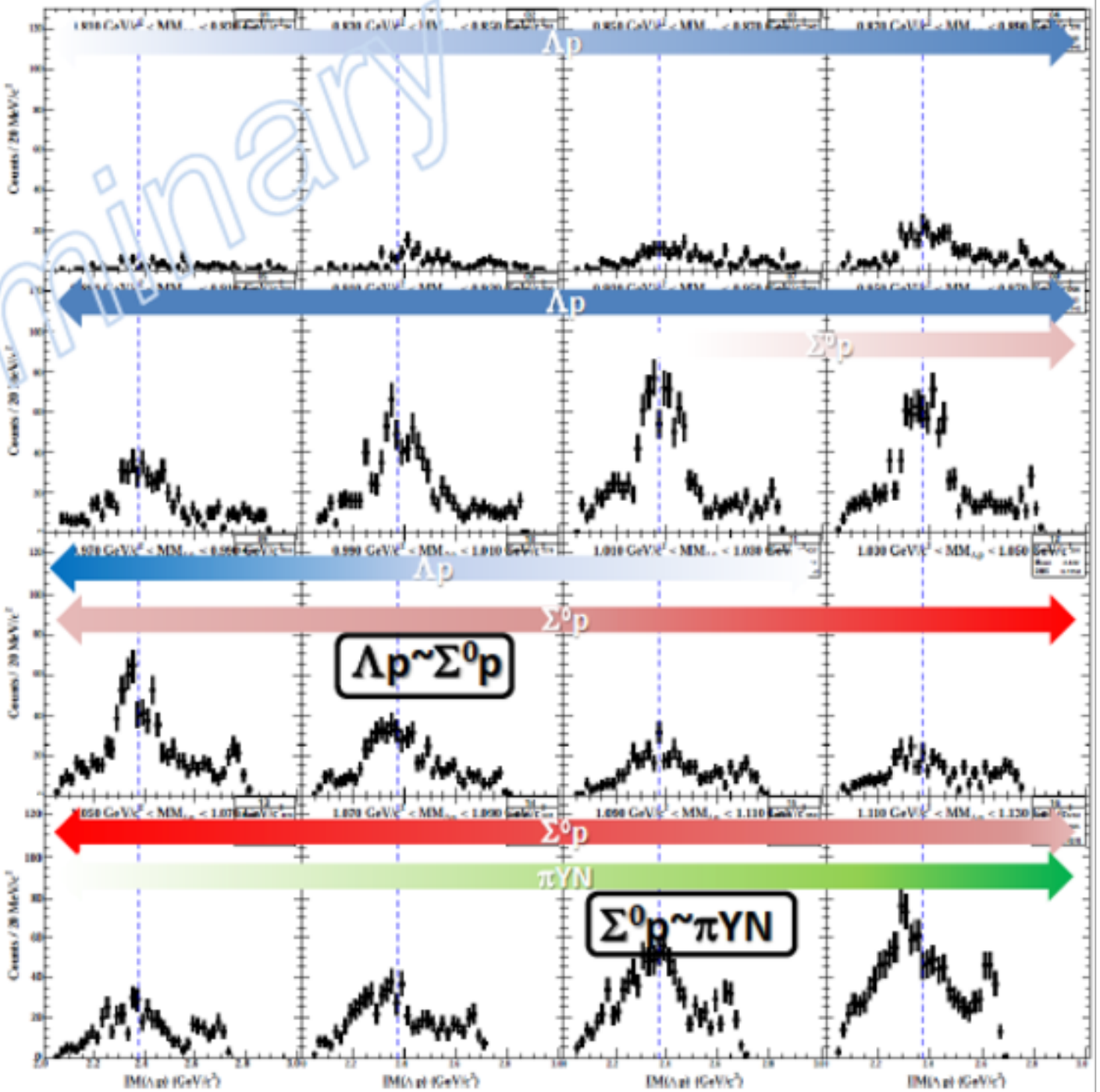
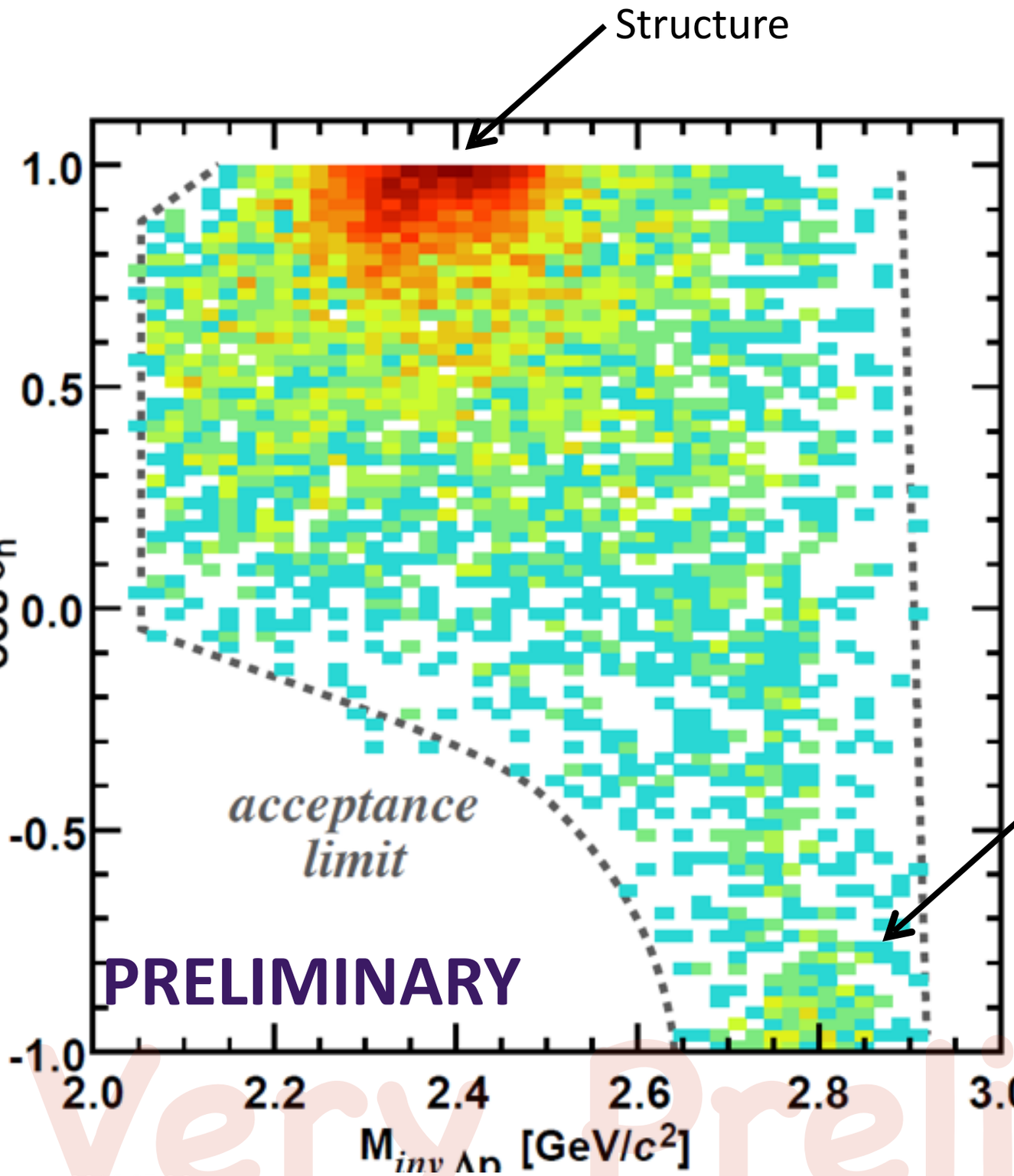
^{3}He(K$^-$,Λp)n: Decay Channel

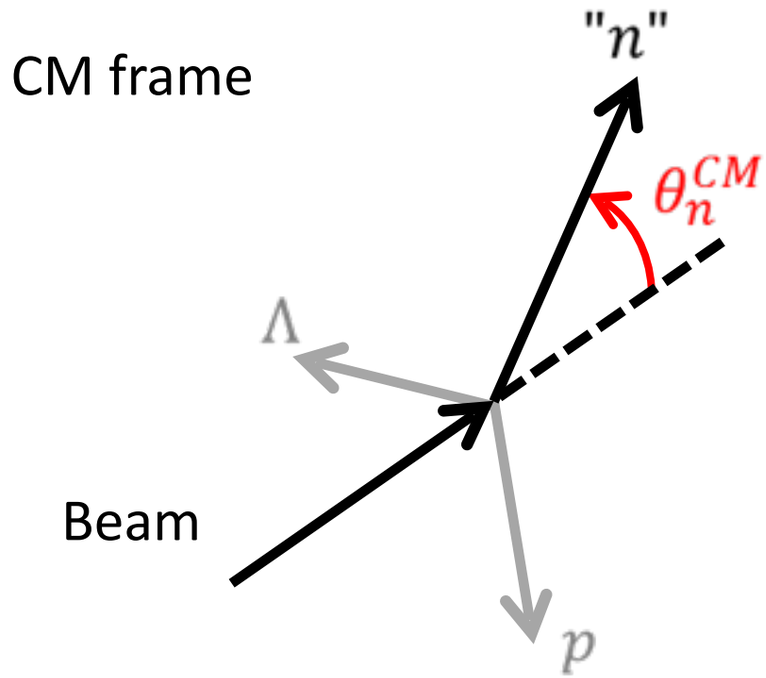




Γ(Λp) > Γ(Σ^{0}p) !?

$IM(\Lambda p)$ vs. $\cos\theta_n{}^{CM}$ Plot





2NA process

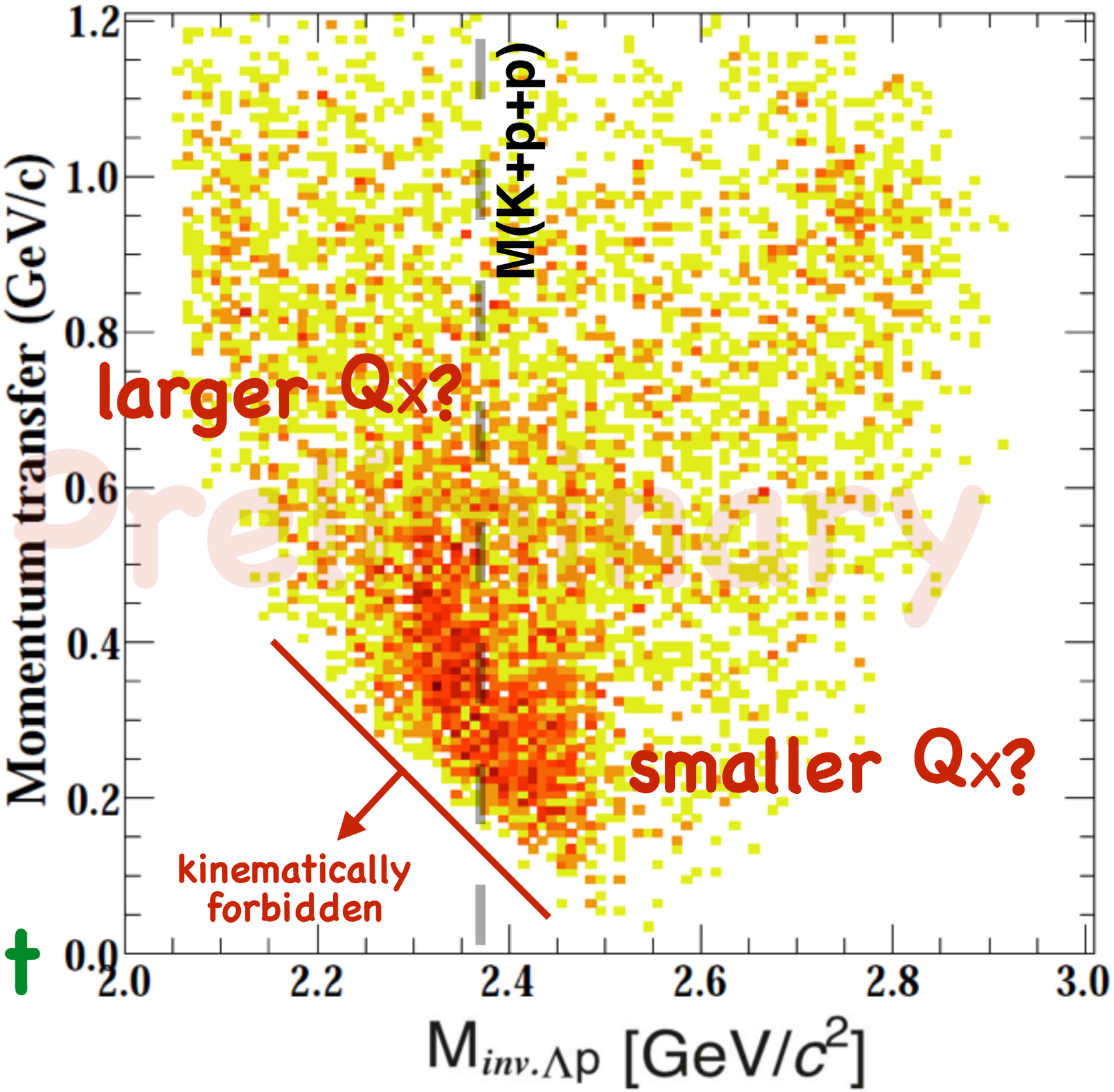
$K^- + {}^3He$:

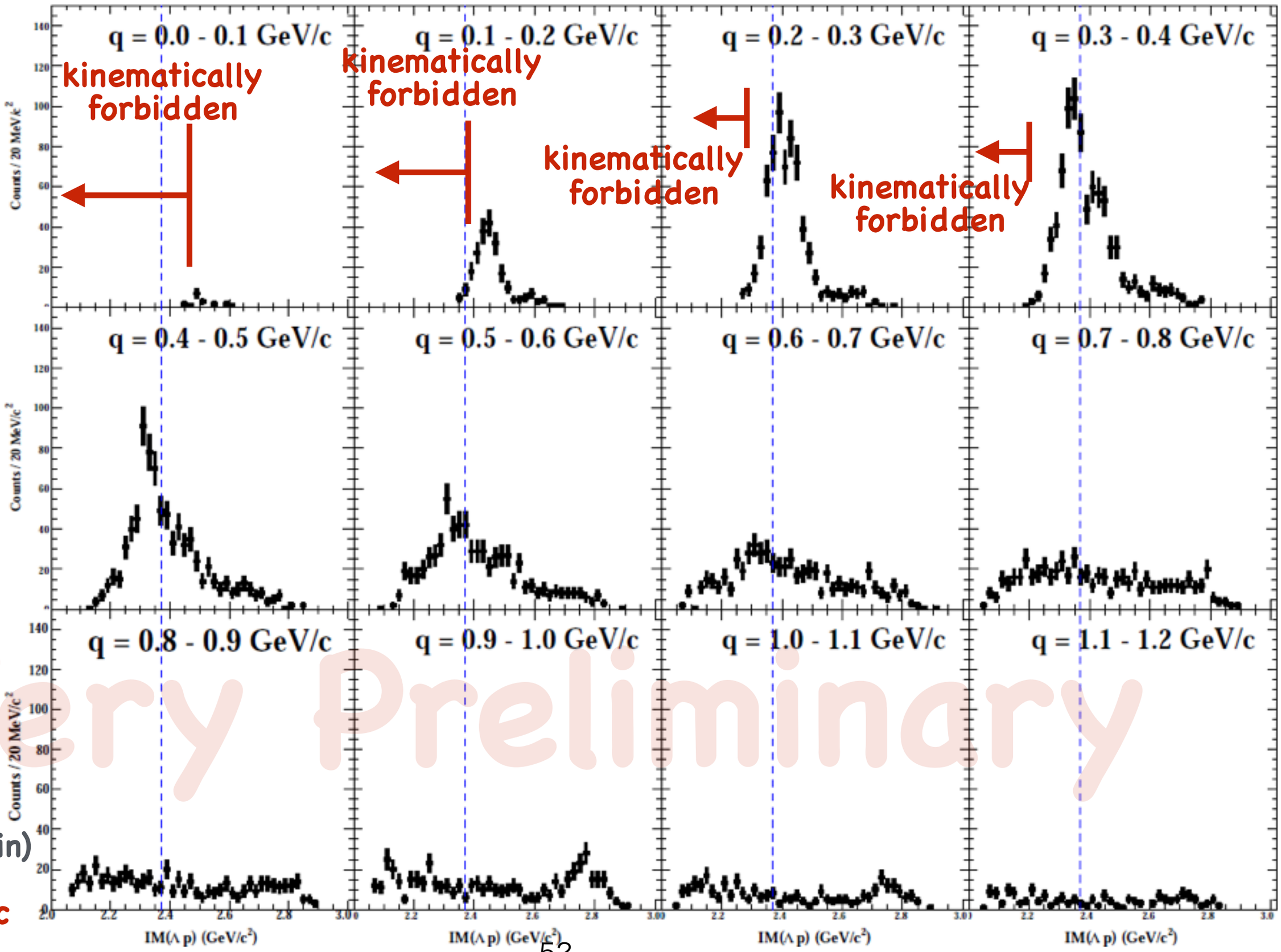
$K^- + \text{“}pp+n_s\text{”} \rightarrow \Lambda p + n_s$

backward

qx dependence

two components? with different qx?





(40 MeV bin)
slice =
0.1 GeV/c

^{3}He(K$^-$, Λp)n

T. Hashimoto et al., PTEP (2015) 061D01.

n : semi-inclusive

Y. Sada et al., PTEP (2016) 051D01.

Λpn : single-pole?

E15^{1st} B(X) ~ 15 MeV
Γ(X) ~ 110 MeV
Q(X) ~ 400 MeV/c

$$\frac{d^2\sigma_X}{dM_{inv.\Lambda p}dq} \propto \rho_3(\Lambda pn) \times \frac{(\Gamma_X/2)^2}{(M_{inv.\Lambda p} - M_X)^2 + (\Gamma_X/2)^2} \times |\exp(-q^2/2Q_X^2)|^2,$$

E15^{2nd} two structures & Kpp for deeper one!!

B(X) ~ 50 ?? MeV … very deep (not hyper deep, though)
Γ(X) ~ 60 ?? MeV … rather narrow
Q(X) ~ 400 ?? MeV/c … very compact (< 0.5 fm ?)

remaining mystery "point like reaction in Λpn final state"

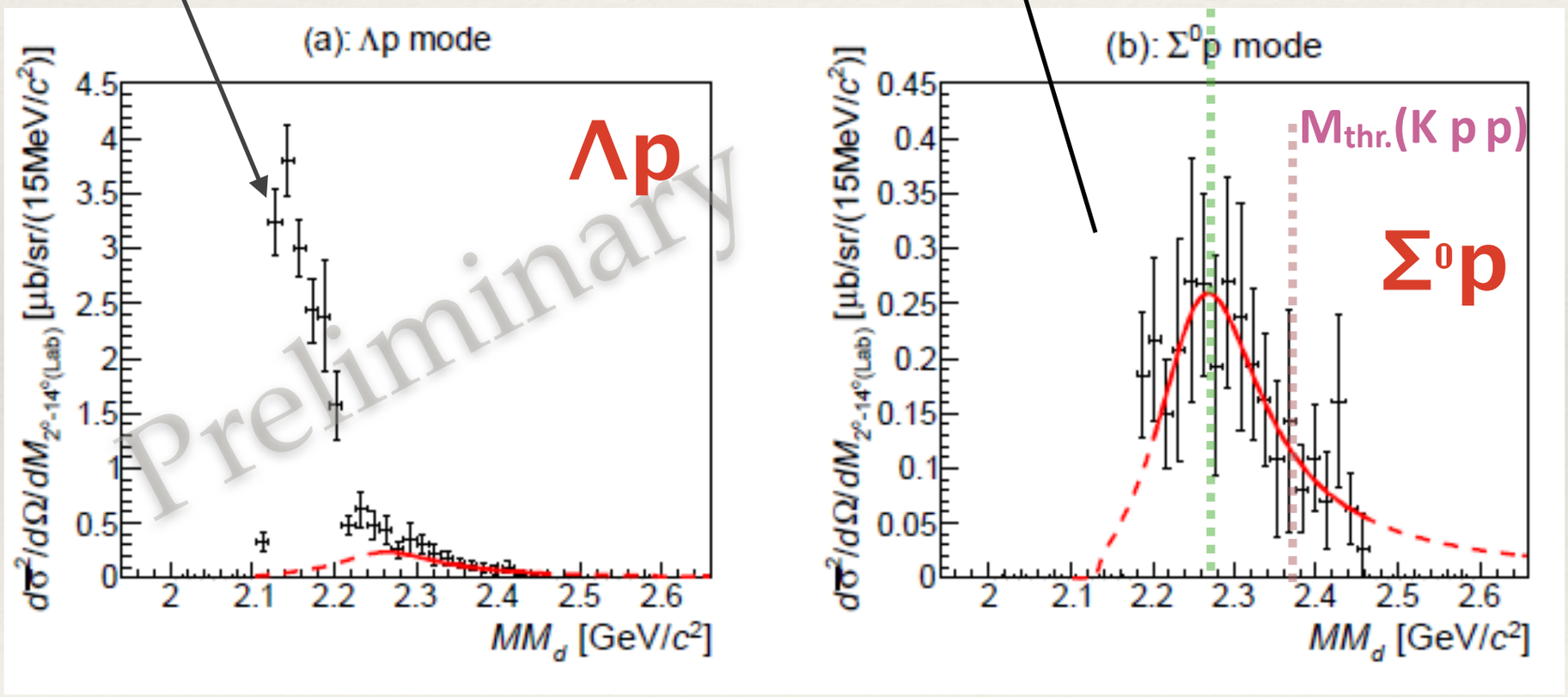
T. Nagae

K^-pp-like structure in $\Sigma^0 p$

$\Lambda p / \Sigma^0 p$

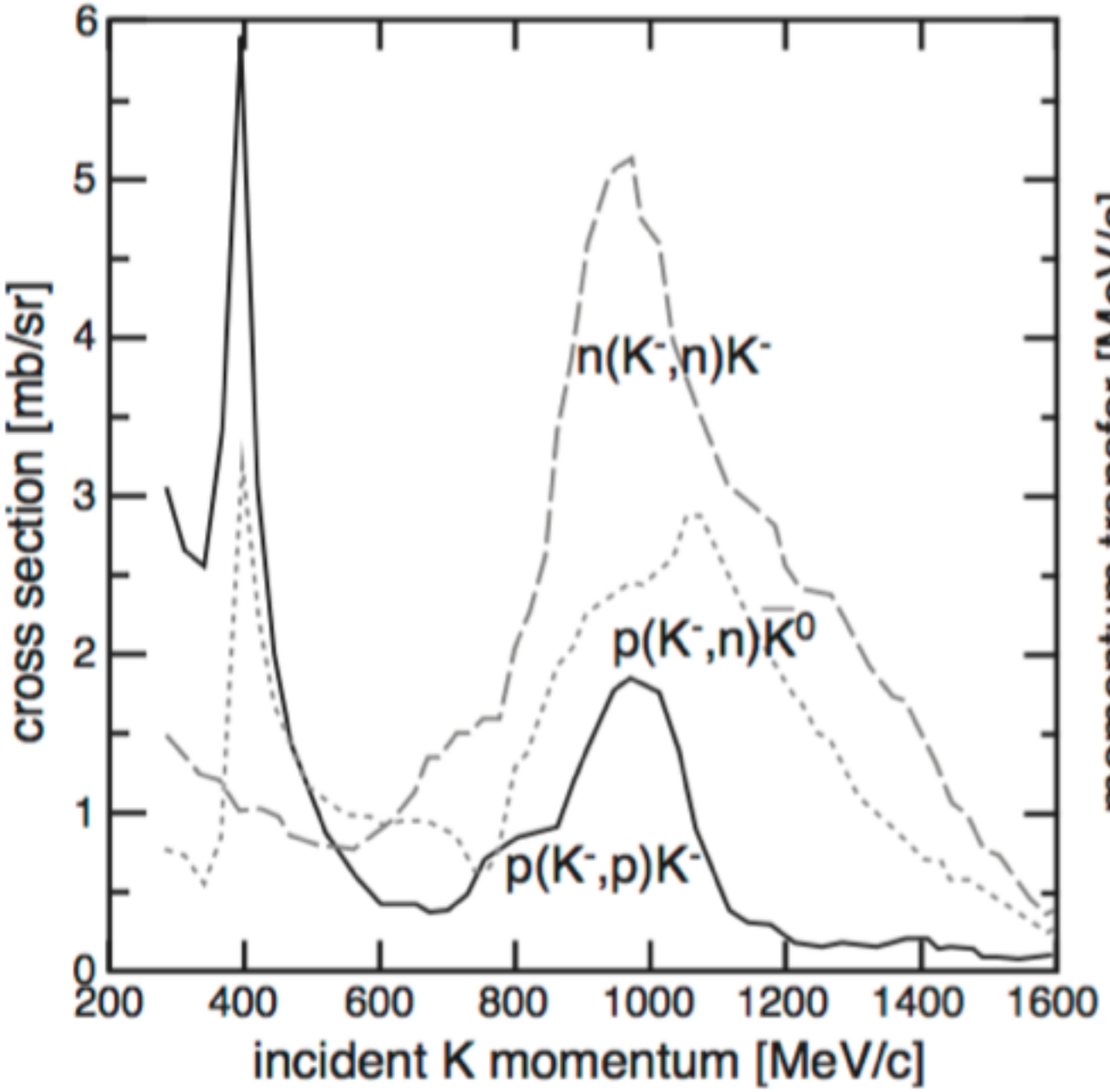
- **Mass :** $2275^{+17}_{-18}(\mathrm{stat.})^{+21}_{-30}(\mathrm{syst.})\ \mathrm{MeV}/c^2$
- **Width :** $162^{+87}_{-45}(\mathrm{stat.})^{+66}_{-78}(\mathrm{syst.})\ \mathrm{MeV}$
- **Binding Energy** $95\ ^{+18}_{-17}\ (\mathrm{stat.})\ ^{+30}_{-21}\ (\mathrm{syst.})\ \mathrm{MeV}$

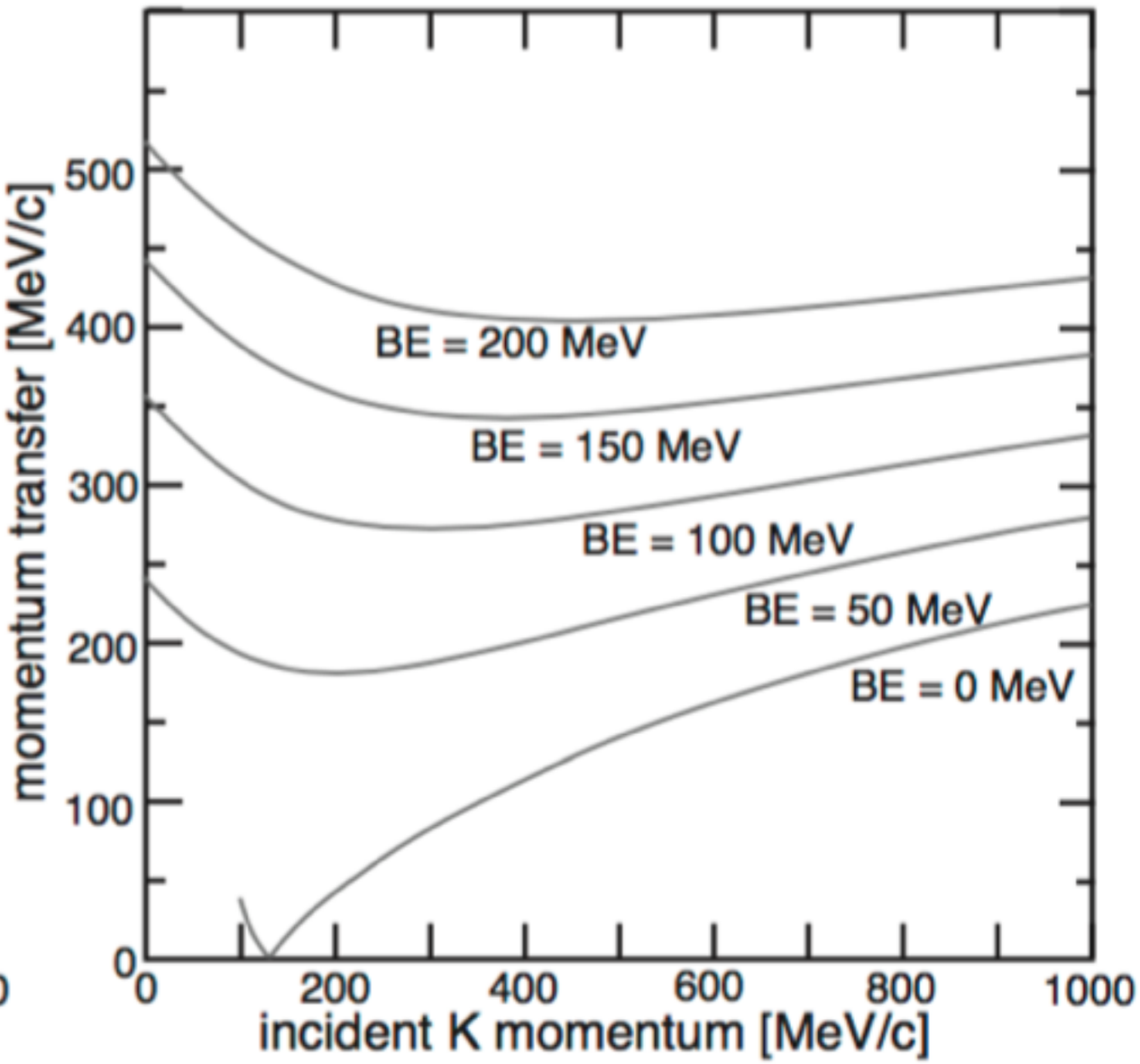
ΣN cusp +
ΣN→ΛN conversion



$$\frac{\Gamma_{\Lambda p}}{\Gamma_{\Sigma^0 p}} = 0.92^{+0.16}_{-0.14}(stat)^{+0.60}_{-0.42}(syst)$$

No threshold effect seen?!


n(K⁻,n)K⁻
p(K⁻,n)K⁰
p(K⁻,p)K⁻
cross section [mb/sr]
incident K momentum [MeV/c]
0
1
2
3
4
5
6
200
400
600
800
1000
1200
1400
1600


BE = 200 MeV
BE = 150 MeV
BE = 100 MeV
BE = 50 MeV
BE = 0 MeV
momentum transfer [MeV/c]
incident K momentum [MeV/c]
0
100
200
300
400
500
0
200
400
600
800
1000