THEIA-REIMEI Web seminar, 2nd Dec. 2020

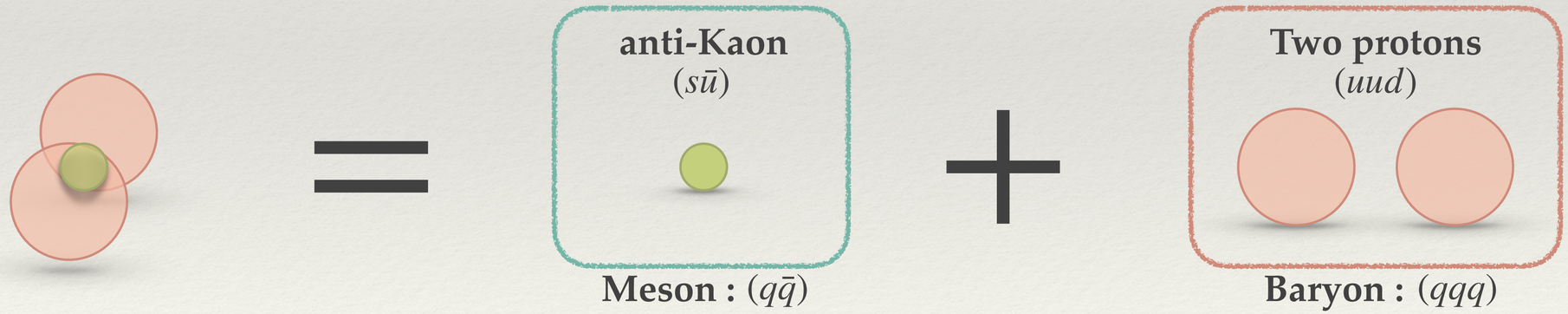
K^-pp bound state in $^3\mathrm{He}(K^-, \Lambda p)n$ reaction

Takumi Yamaga, RIKEN
For the E15 collaboration

(Expected) Property of K^-pp

- K^-pp is the $I_Z = +\frac{1}{2}$ state of the simplest kaonic nucleus $\bar{K}NN$.

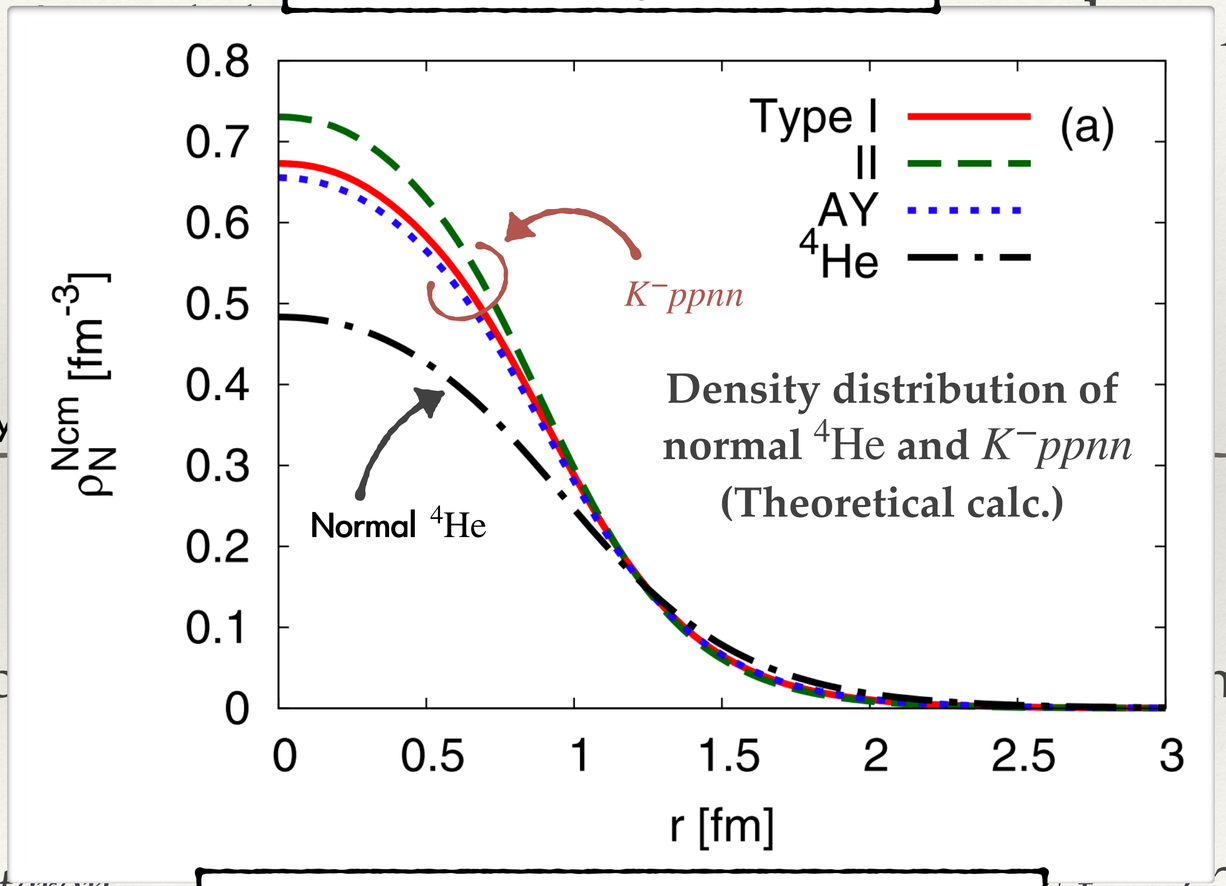
Meson as a component of nucleus



(Expected) Property of K^-pp

- K^-pp is the $I_Z =$ 1 [illegible] $\bar{K}NN$.

Calculated density distributions



S. Ohnishi et al., Phys. Rev. C**95** (2017) 065202

Calculated binding energy

Chiral SU(3)
~ 20 MeV

Phenomenologic
~ 50 MeV

c.f. ~ 2 MeV for deuteron

Calculated NN distance

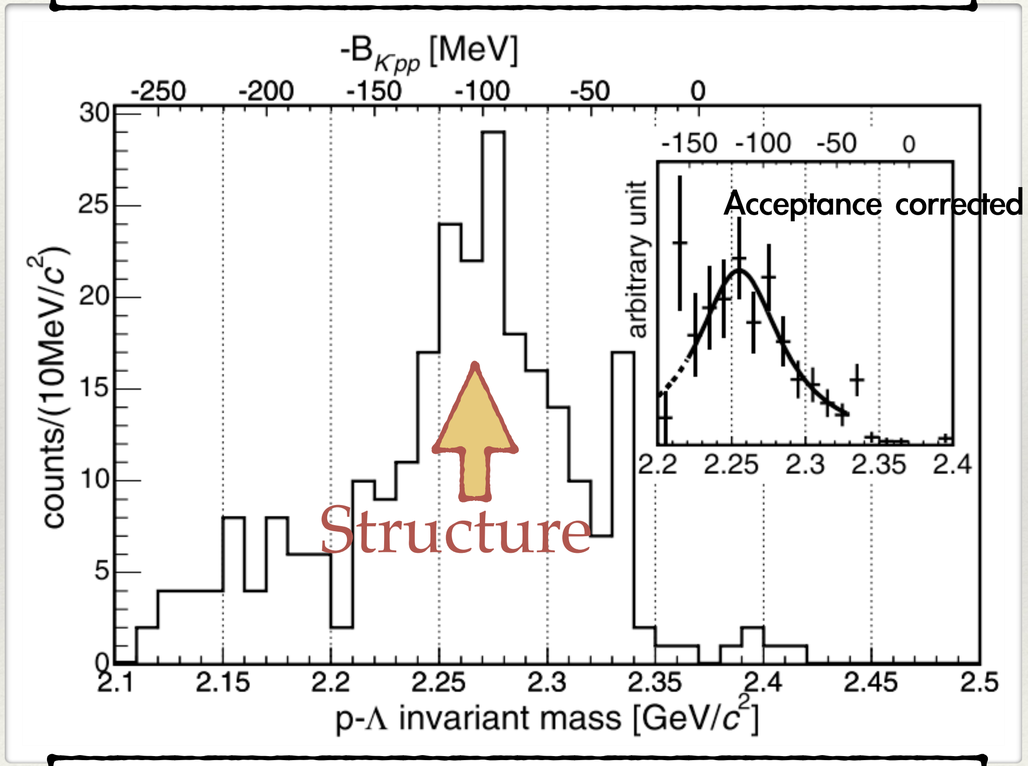
Chiral SU(3)
~ 2.1 fm

henomenological
~ 1.8 fm

c.f. ~ 2.2 fm for normal nucleus

Searching for K^-pp so far

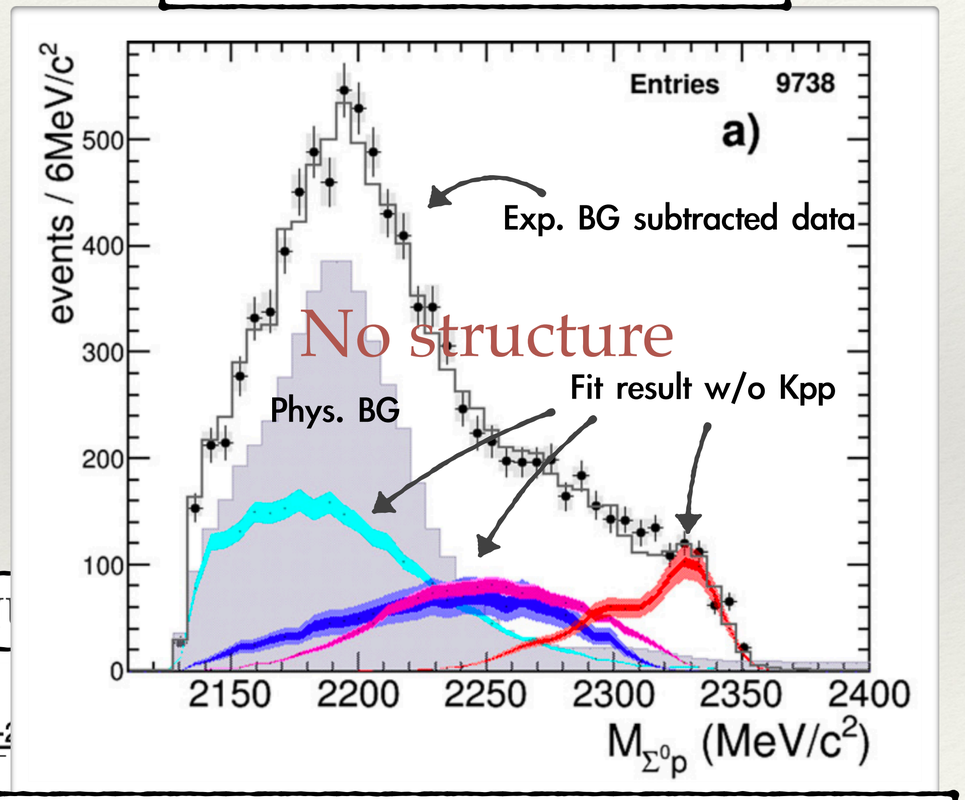
FINUDA (Stopped K^- on light nucleus target)



M. Agnello et al., Phys. Rev. Lett. 94 (2005) 212303.

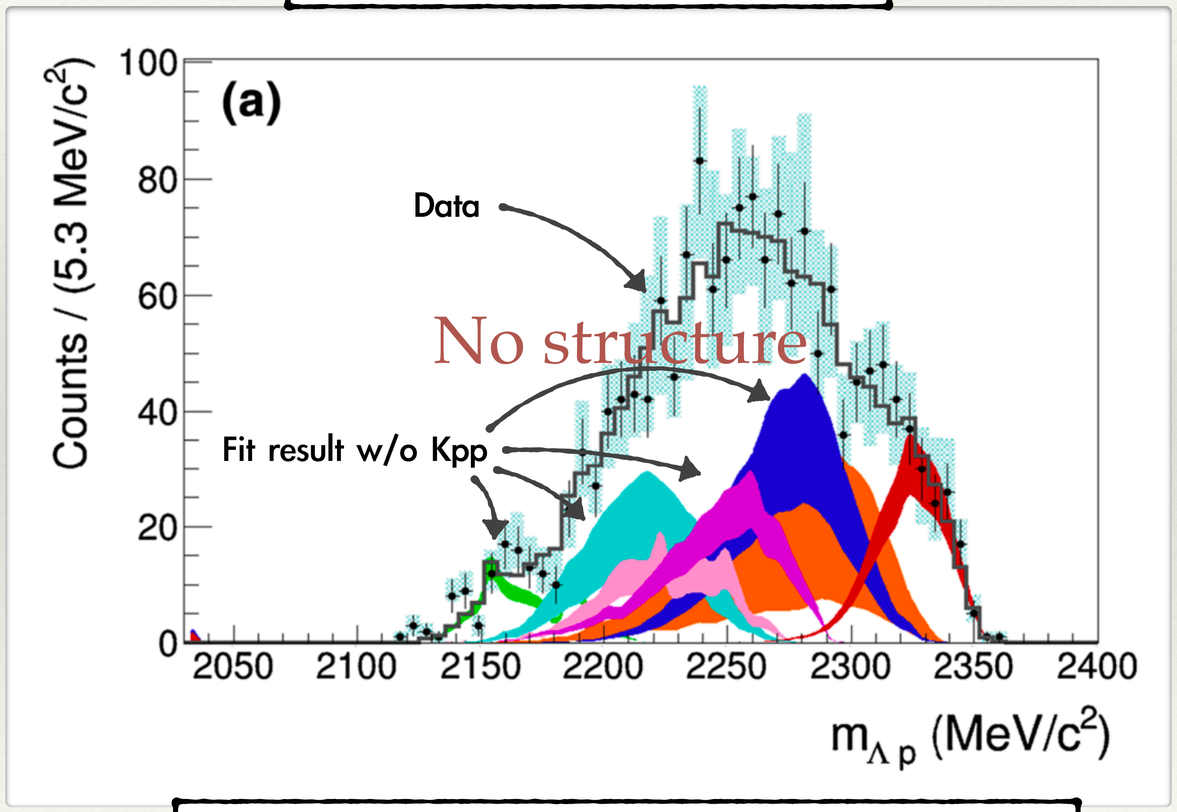
Searching for K^-pp so far

AMADEUS (Stopped K^- , $\Sigma^0 p$)



O. Vázquez Doce et al., Phys. Lett. B **758** (2016) 134.

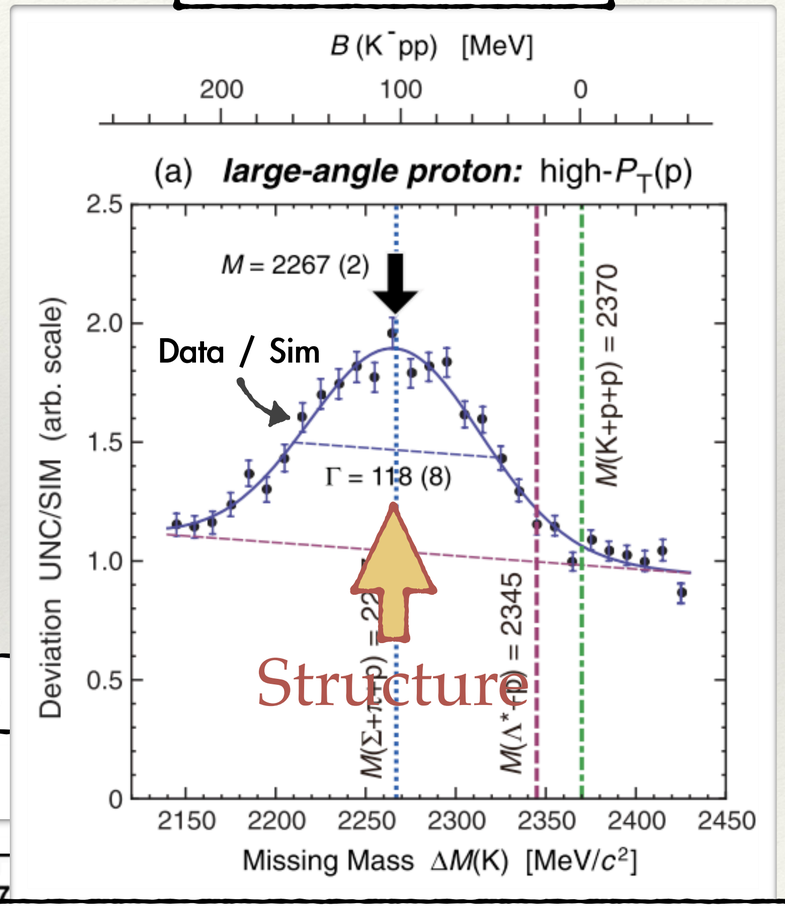
AMADEUS (Stopped K^-, Λp)



R. Del Grande et al., Eur. Phys. J. C **79** (2019) 190.

Searching for K^-pp so far

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

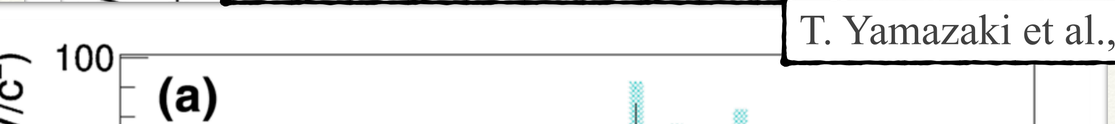


Structure

FINUDA (Stopped K^- on light nucleus

AMADEUS (Stopped K^- , $\Sigma^0 p$)

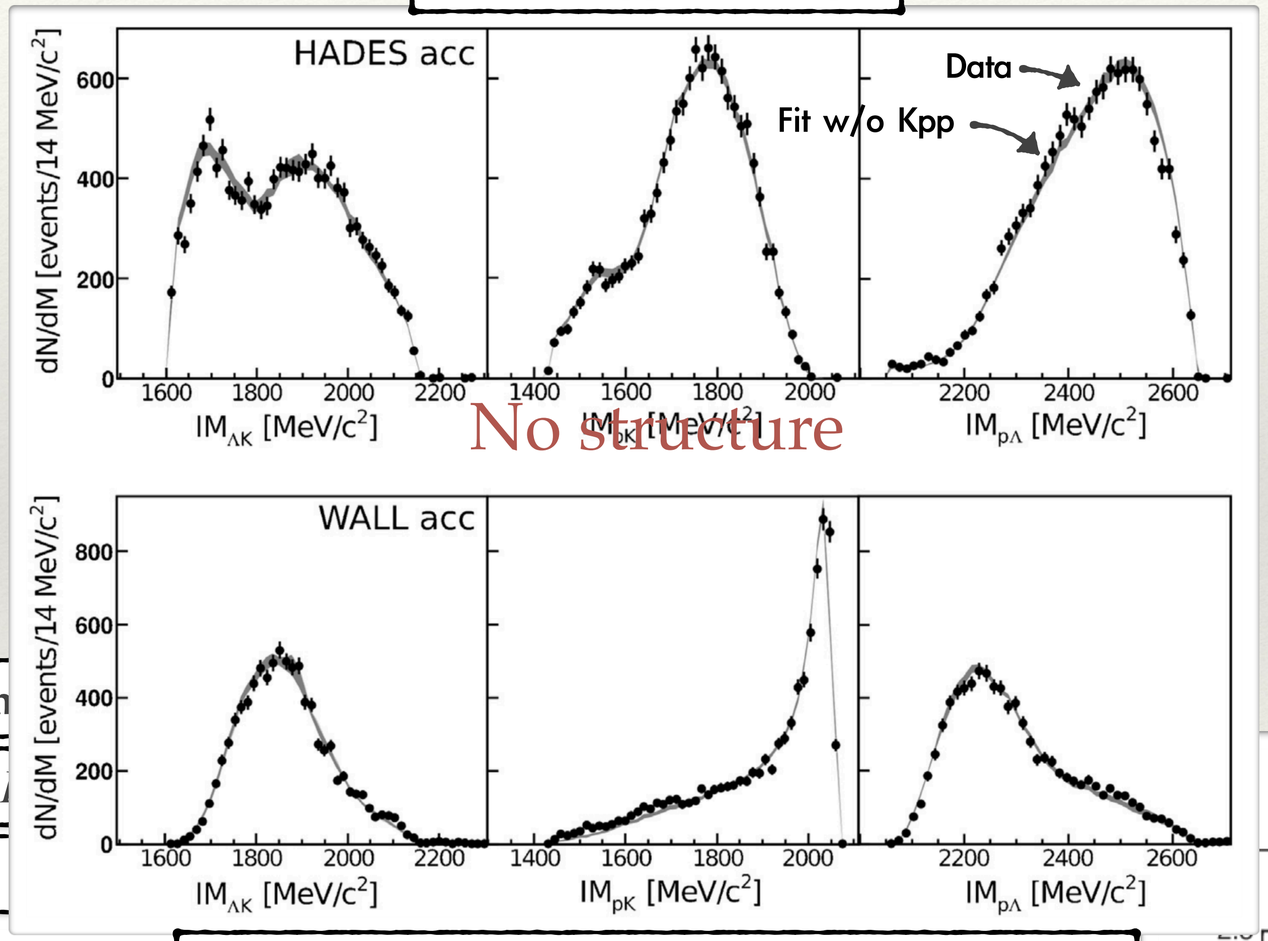
AMADEUS (Stopped K^-, Λp)



T. Yamazaki et al., Phys. Rev. Lett. **10** (2010) 132502.

Searching for $K^- pp$ so far

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



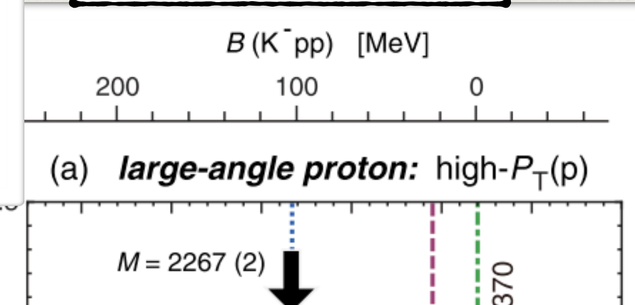
No structure

FINUDA (Stopped K^- on ligh

AMADEUS (Stopped

AMADEUS (Stopped

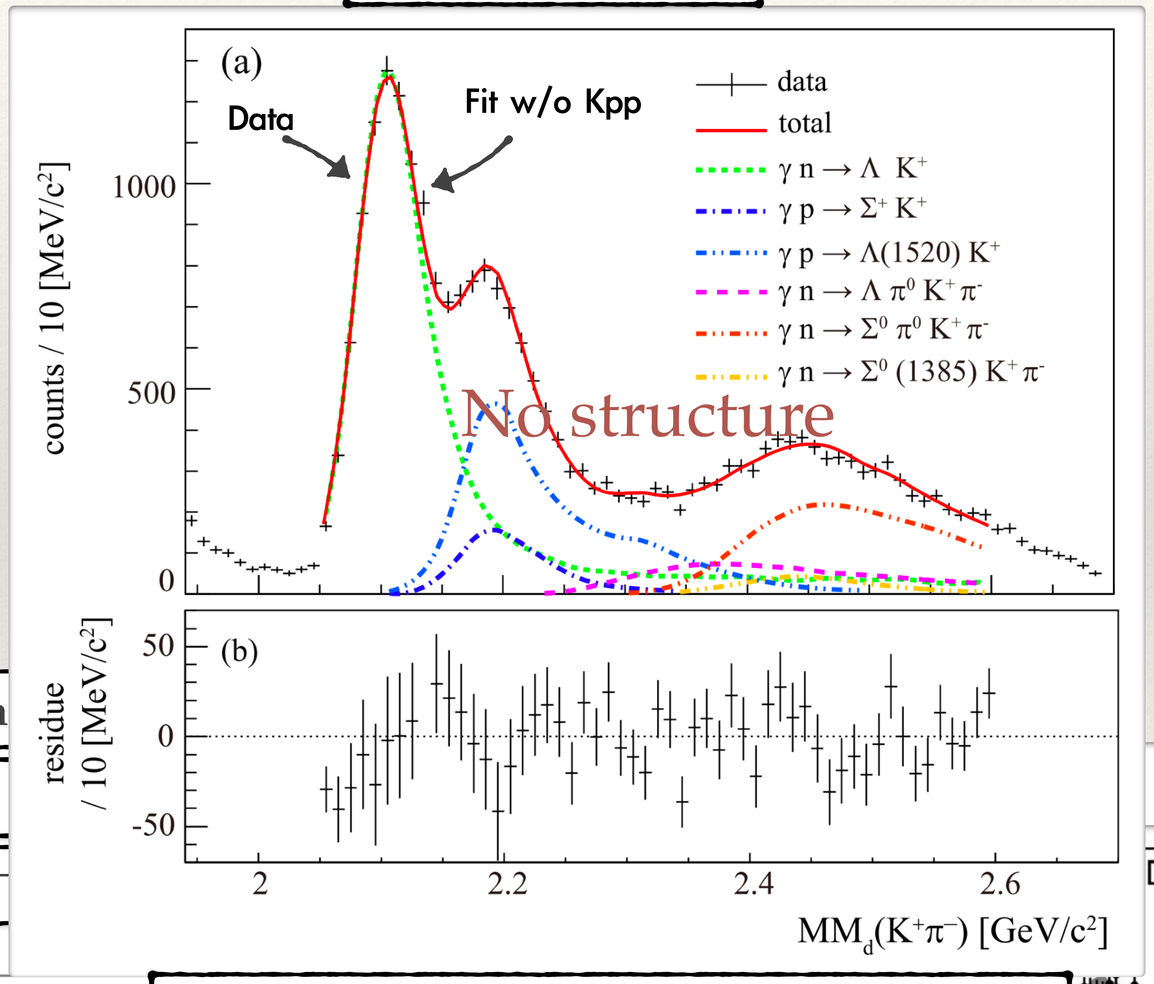
DISTO ($pp \to K^+\Lambda p$)



G. Agakishiev,, Phys. Lett. B **742** (2015) 242.

Searching for K^-pp so far

LEPS ($\gamma d \to \pi^- K^+ X$)



FINUDA (Stopped K^- on light n

AMADEUS (Stopped K^-

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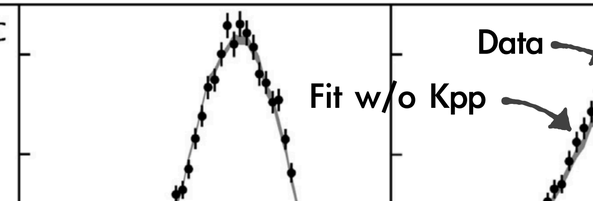
DISTO ($pp \to K^+\Lambda p$)

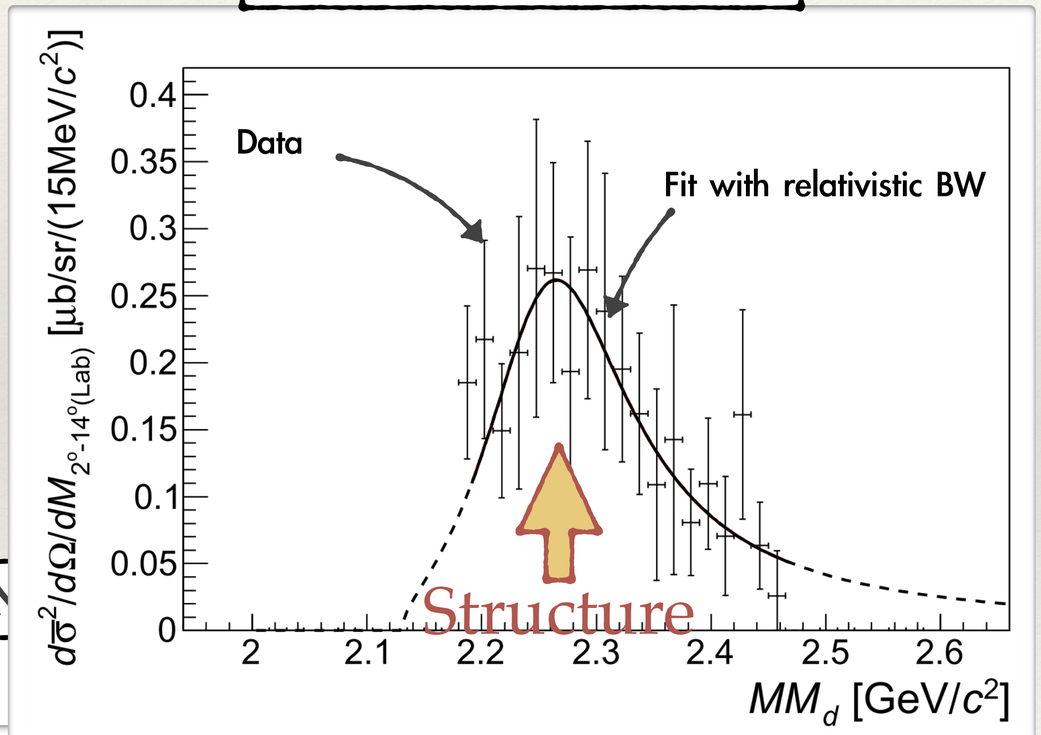
HADES ($pp \to K^+\Lambda p$)



A. O. Tokiyasu et al., Phys. Lett. B **728**, (2014) 616.

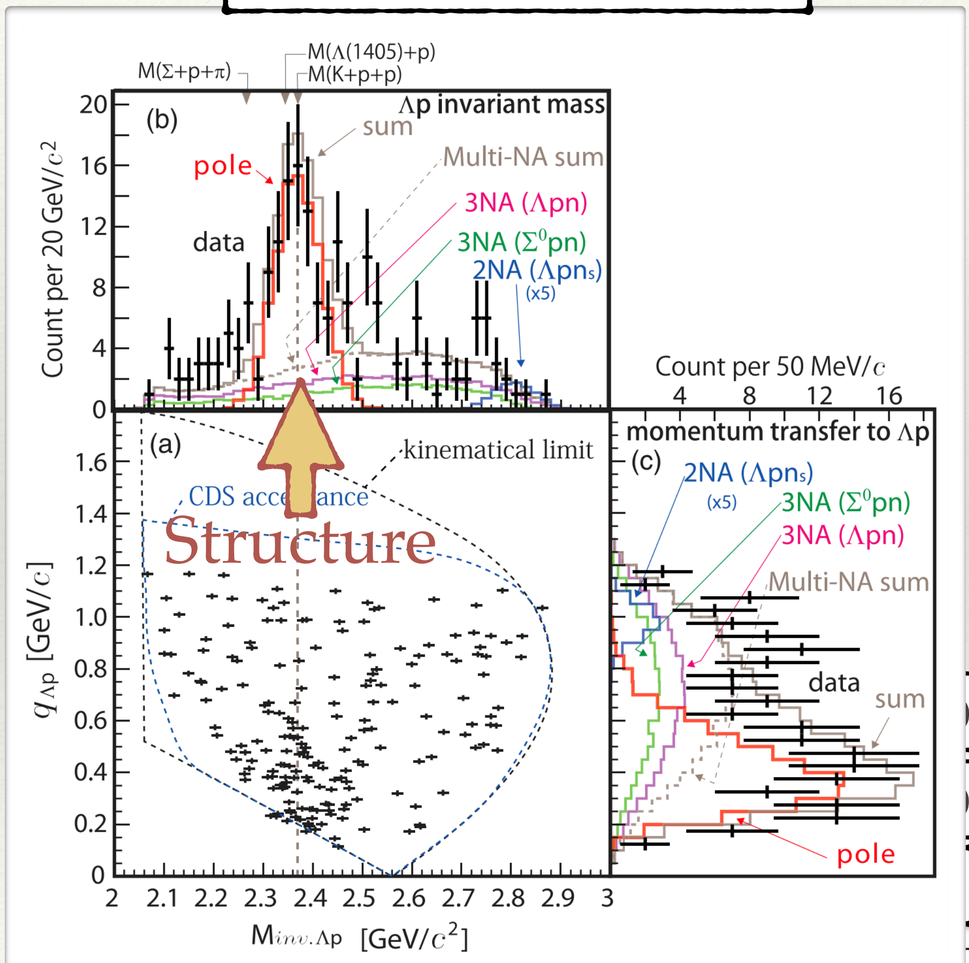
Searching for K^-pp so far

J-PARC E27 ($\pi^+ d \to K^+ \Sigma^0 p$)



Y. Ichikawa et al., Prog. Theor. Exp. Phys. **2015** (2015).

J-PARC E15 (K^- ^{3}He $\to \Lambda pn$)

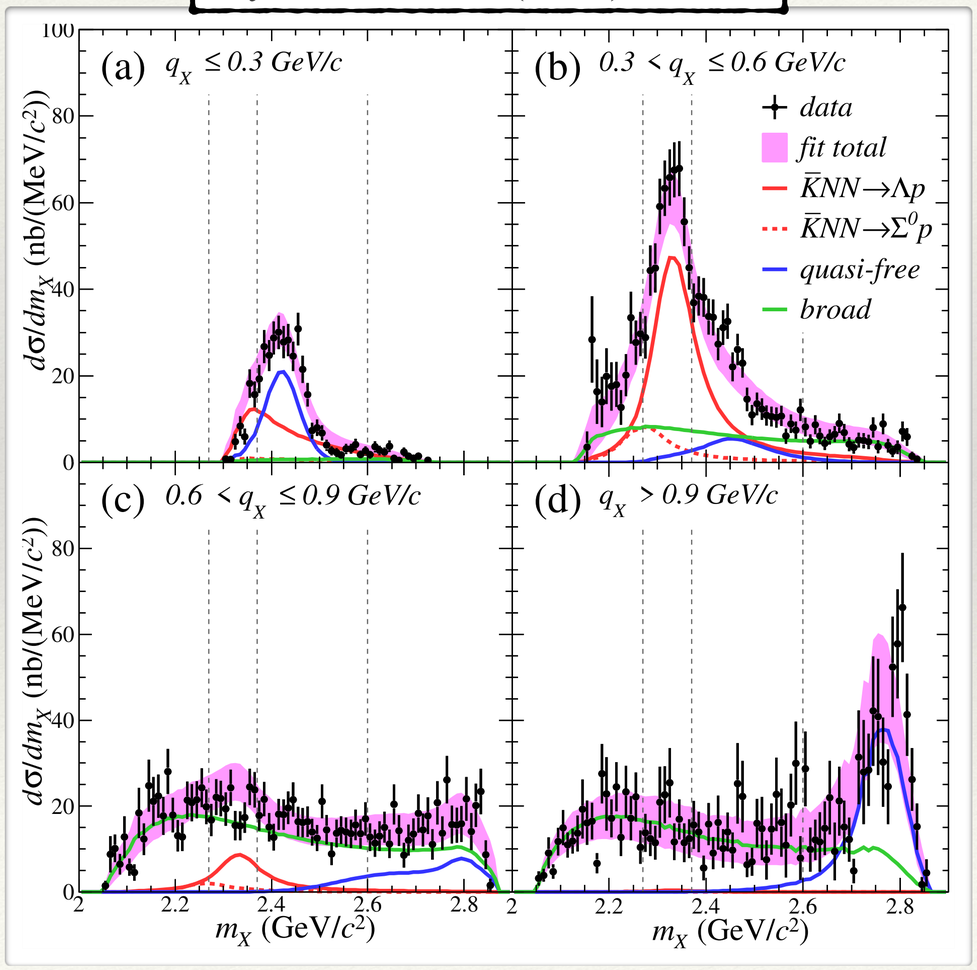


Y. Sada et al., Prog. Theor. Exp. Phys. **2016** (2016) 051D01.

Today's topics

Phys. Lett. B **789** (2019) 620.

Phys. Rev. C **102** (2020) 044002.



First topic Result of E15

- $K^- pp$ existence has been confirmed.
  - B . E . $\sim$ 40 MeV
  - $\Gamma \sim$ 100 MeV

Second topic Future plan

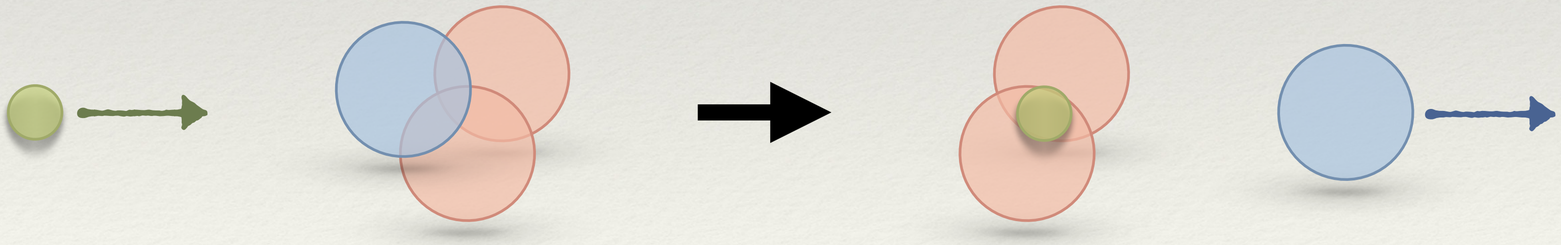
- To search for $\bar{K}^0 nn$
- To determine J^P of $K^- pp$
- Systematic study of $A \geq 3$ systems

E15 experiment

In-flight (K^-, n) reaction to generate KbarNN bound state

$$p_K = 1 \text{ GeV}/c$$

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

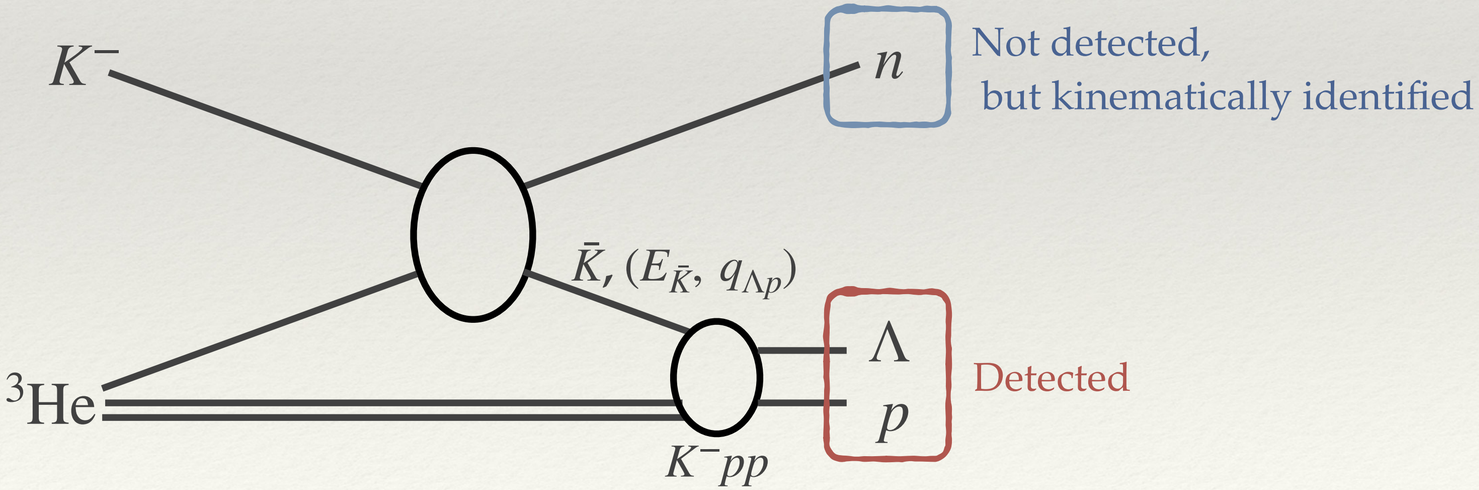


E15 experiment

In-flight (K^-, n) reaction to generate KbarNN bound state

$$p_K = 1 \text{ GeV}/c$$

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

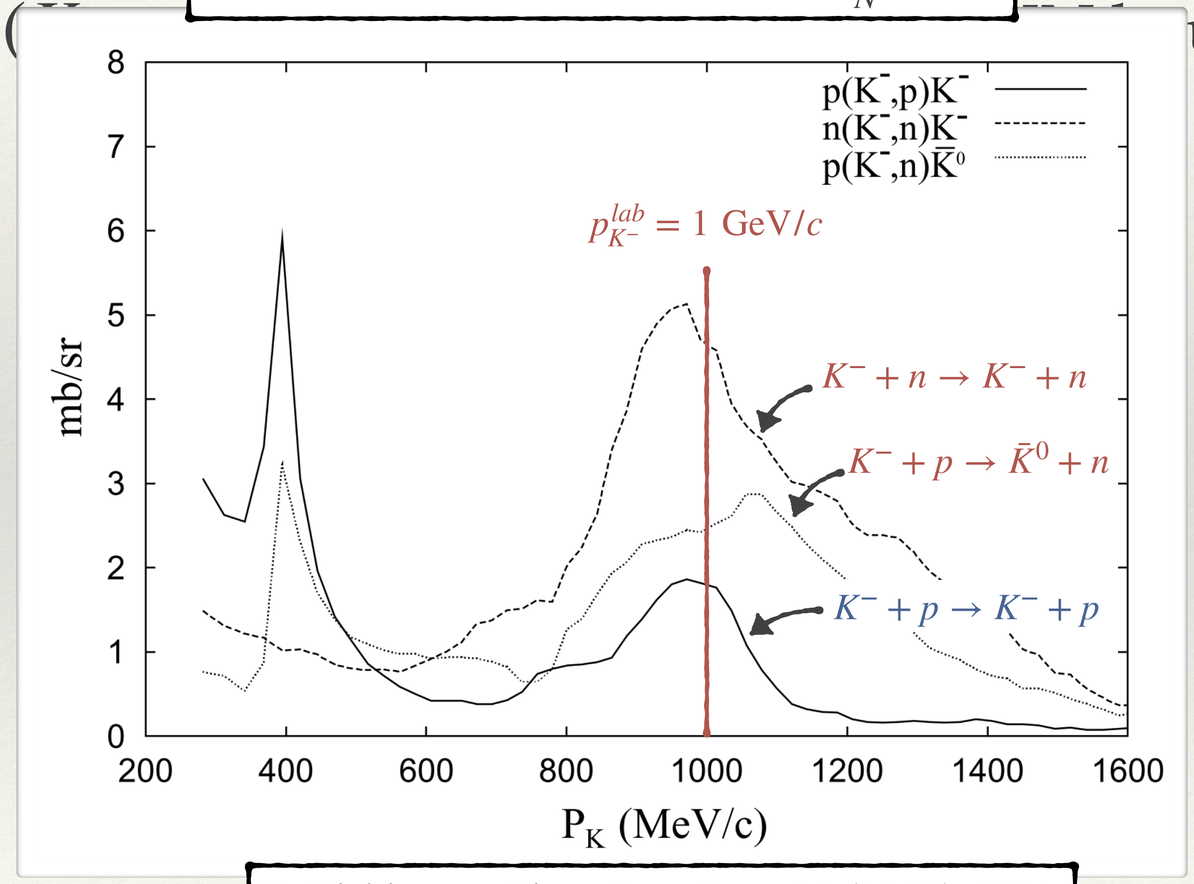


E15 experiment

In-flight (

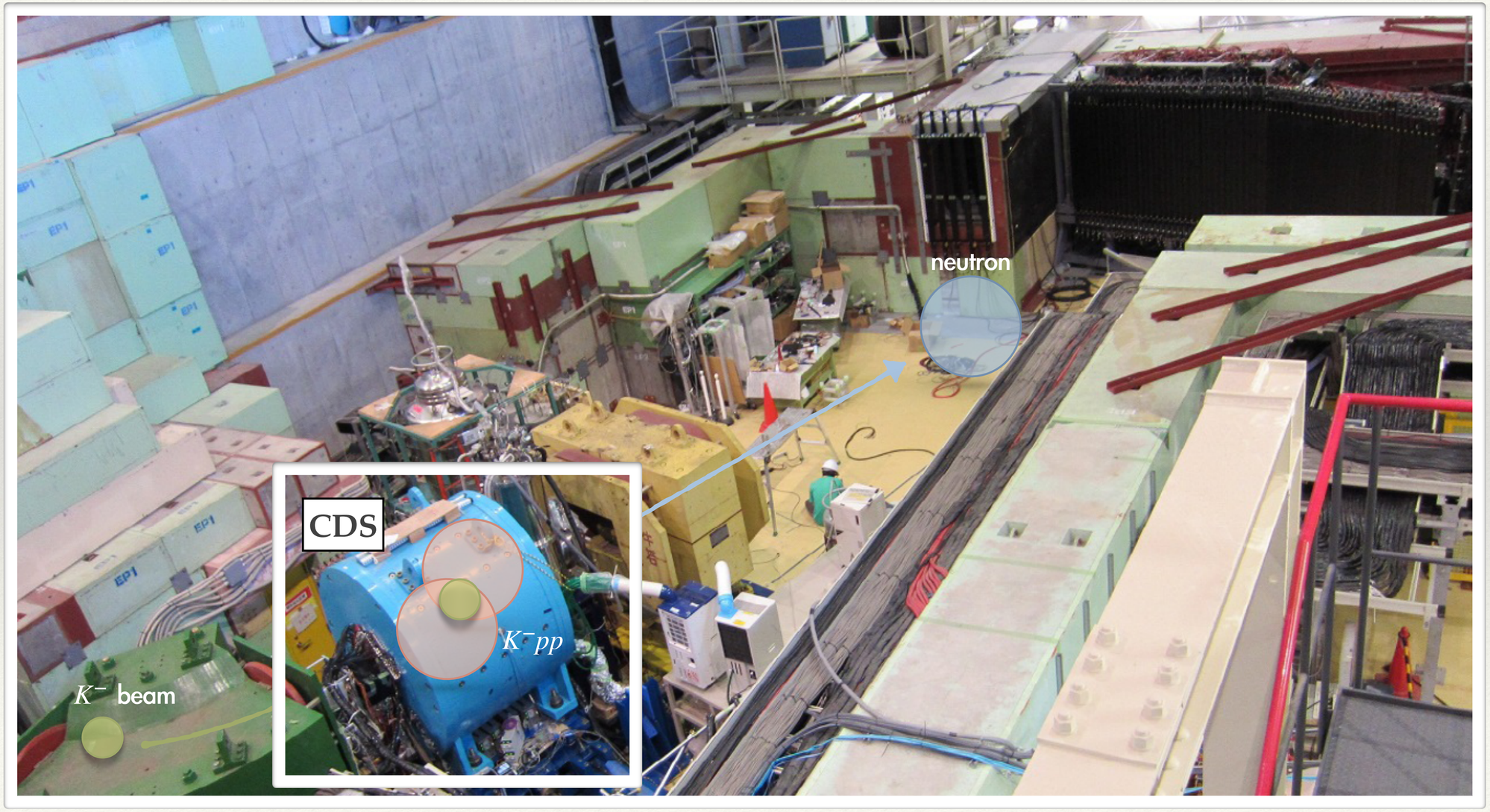
und state

Cross section of $K^- N \to \bar{K} N$ at $\theta_N = 0°$

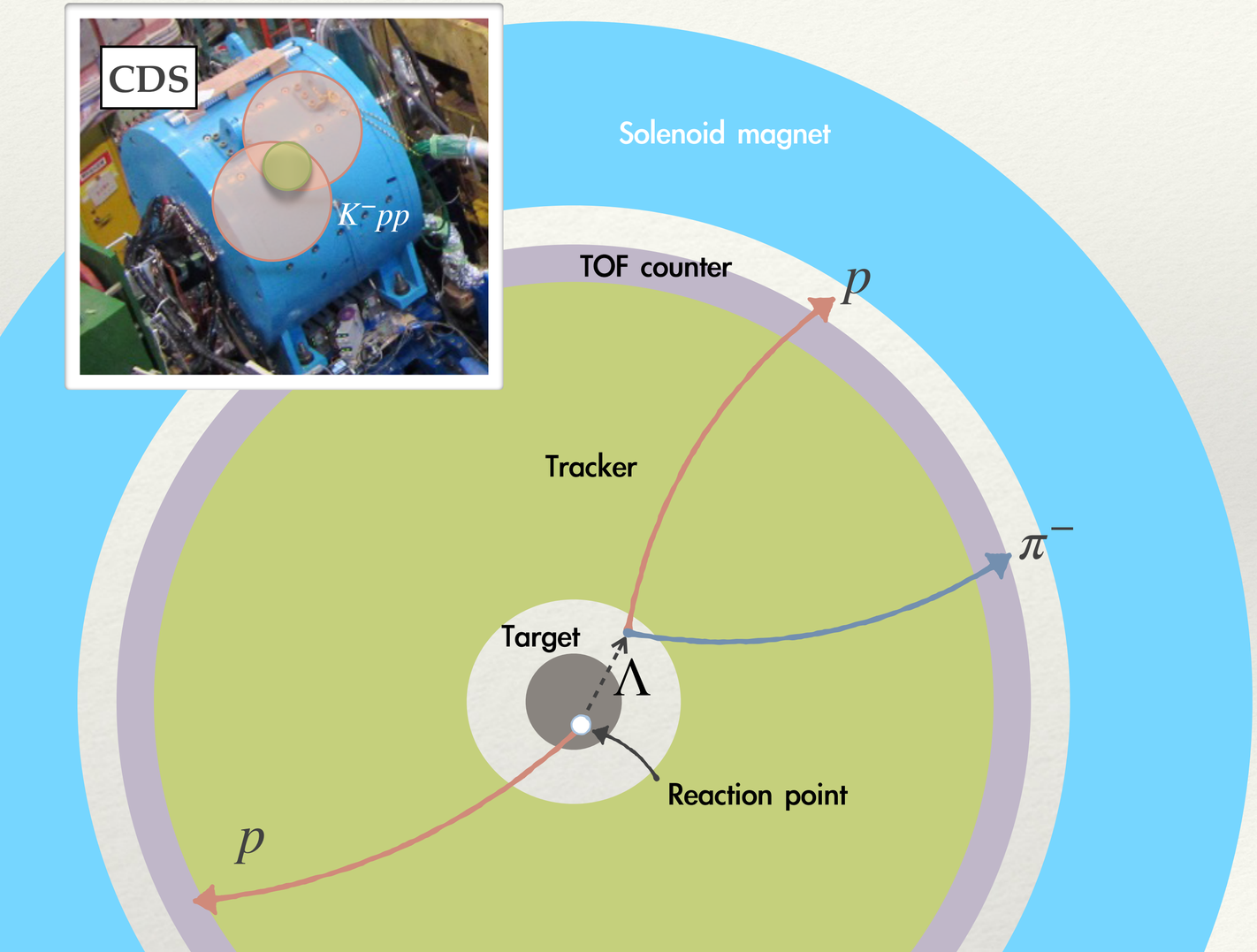


T. Kishimoto, Phys. Rev. Lett. **83** (1999) 4701.

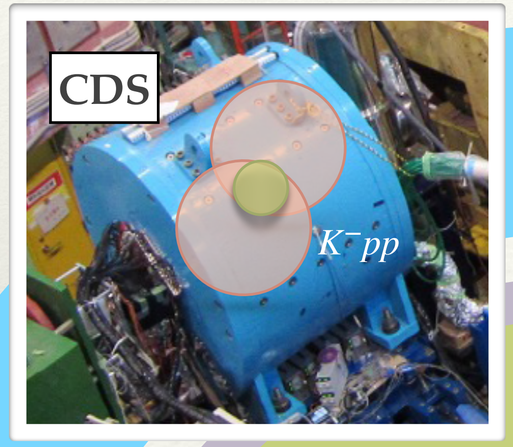
E15 experiment



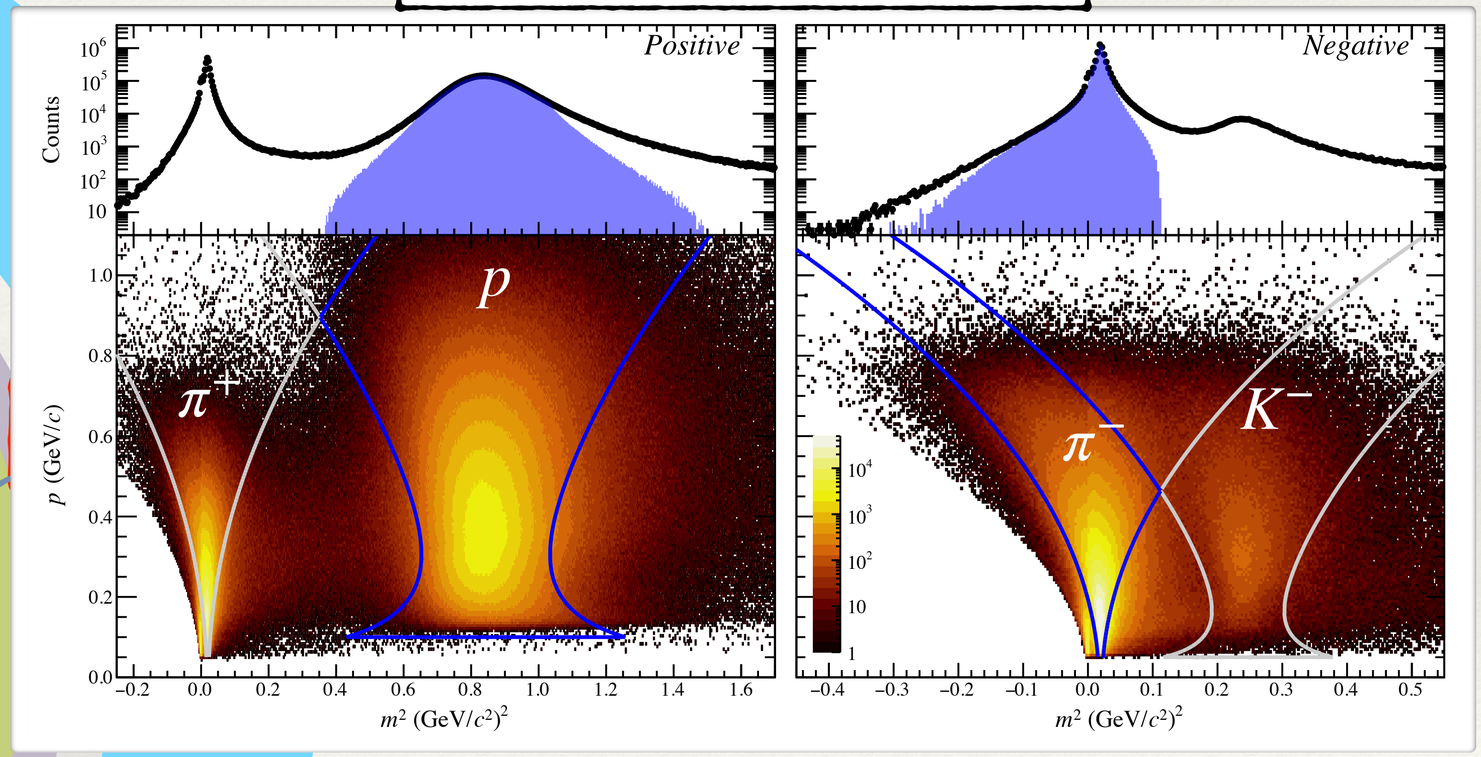
E15 experiment



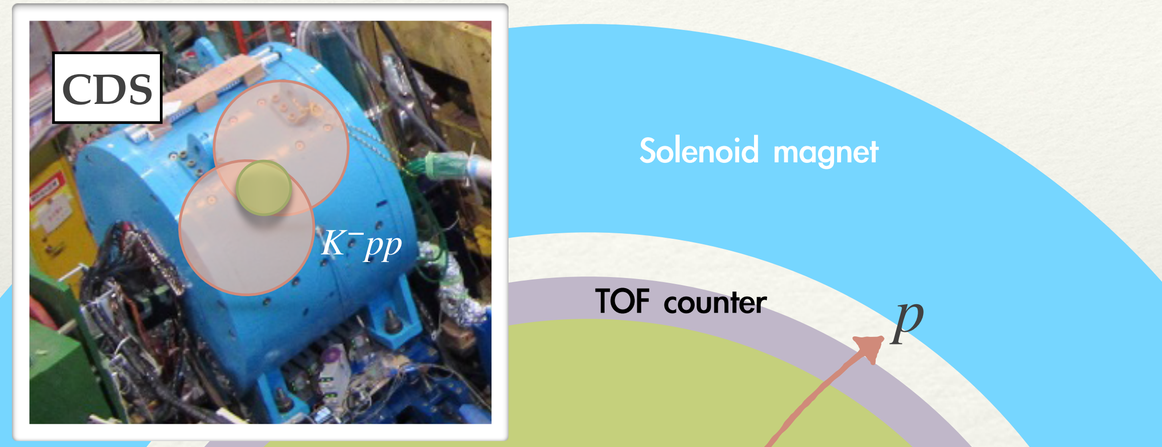
E15 experiment

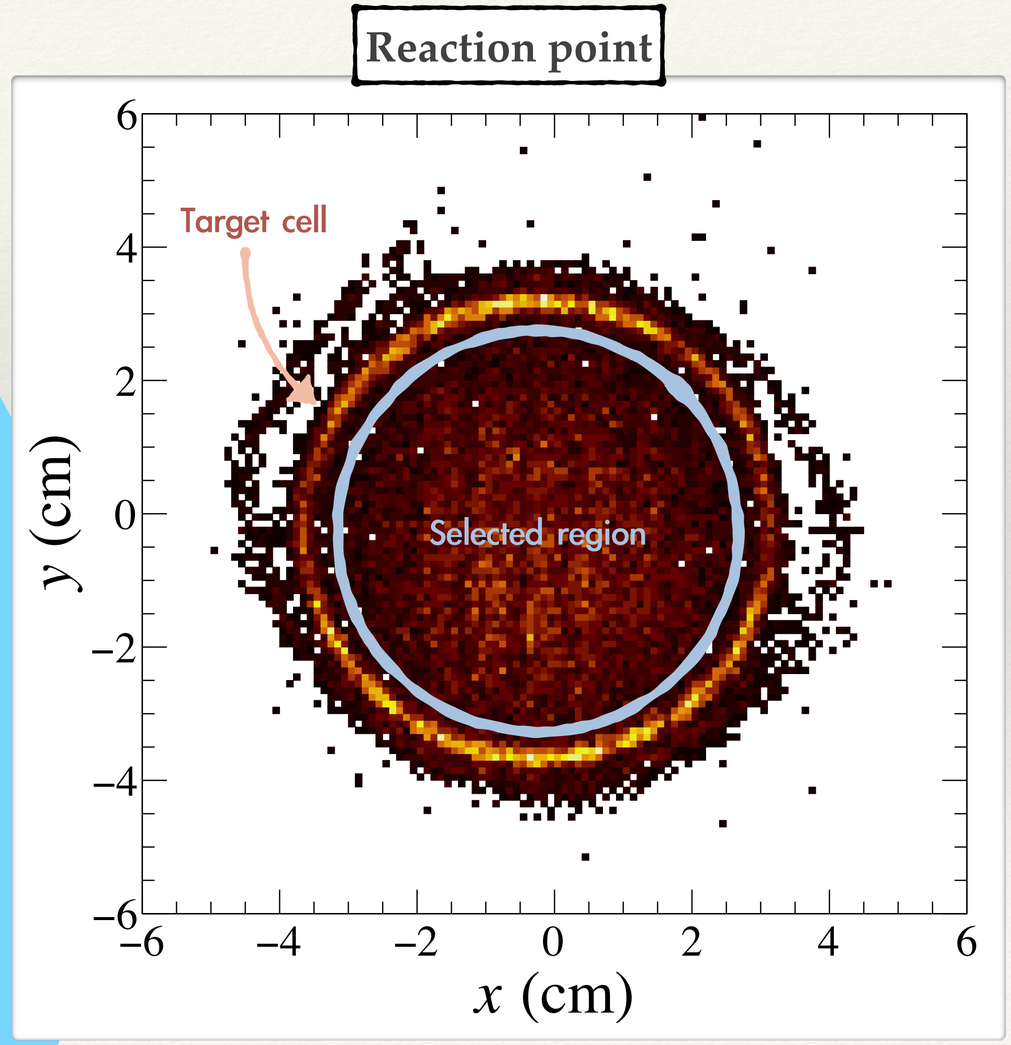


Identification of detected particles



E15 experiment





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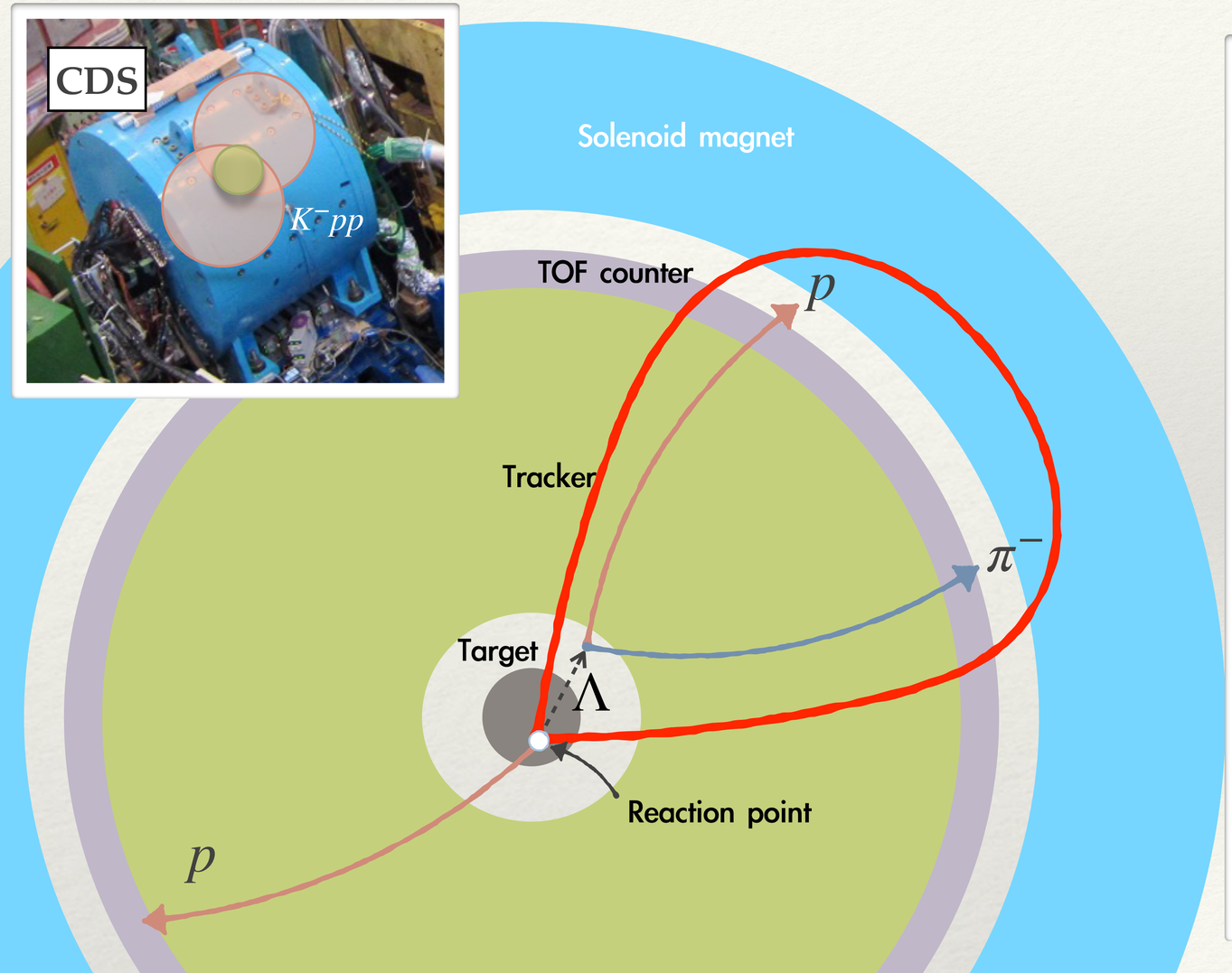
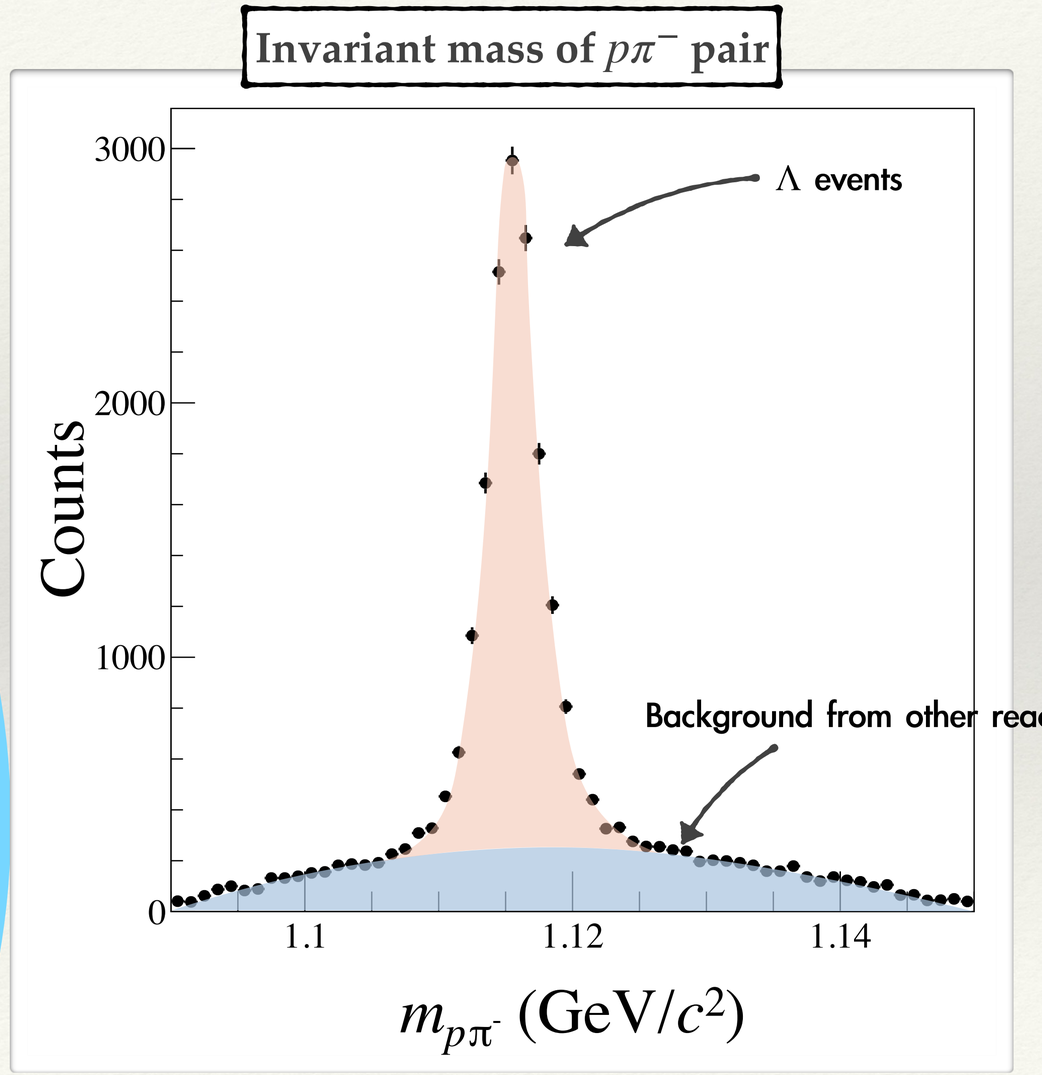
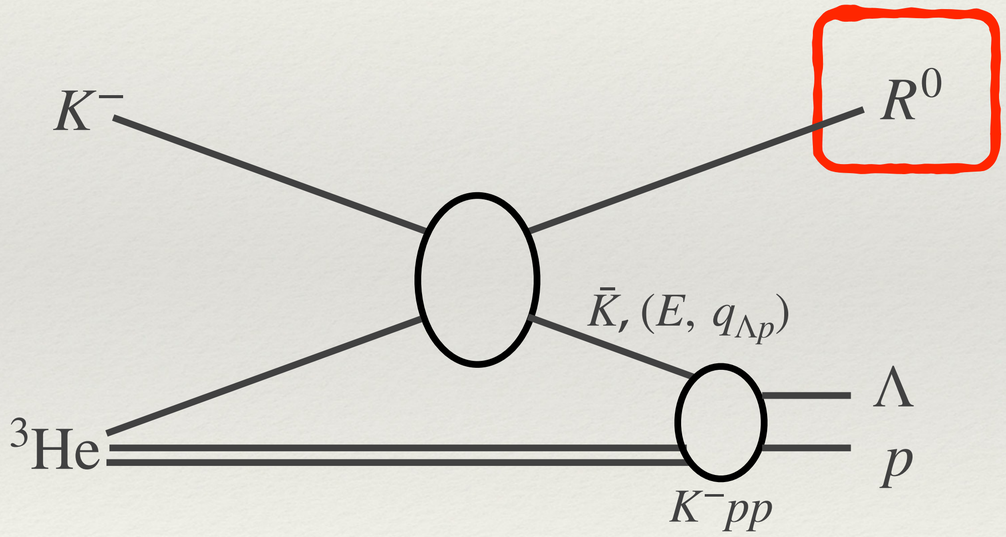
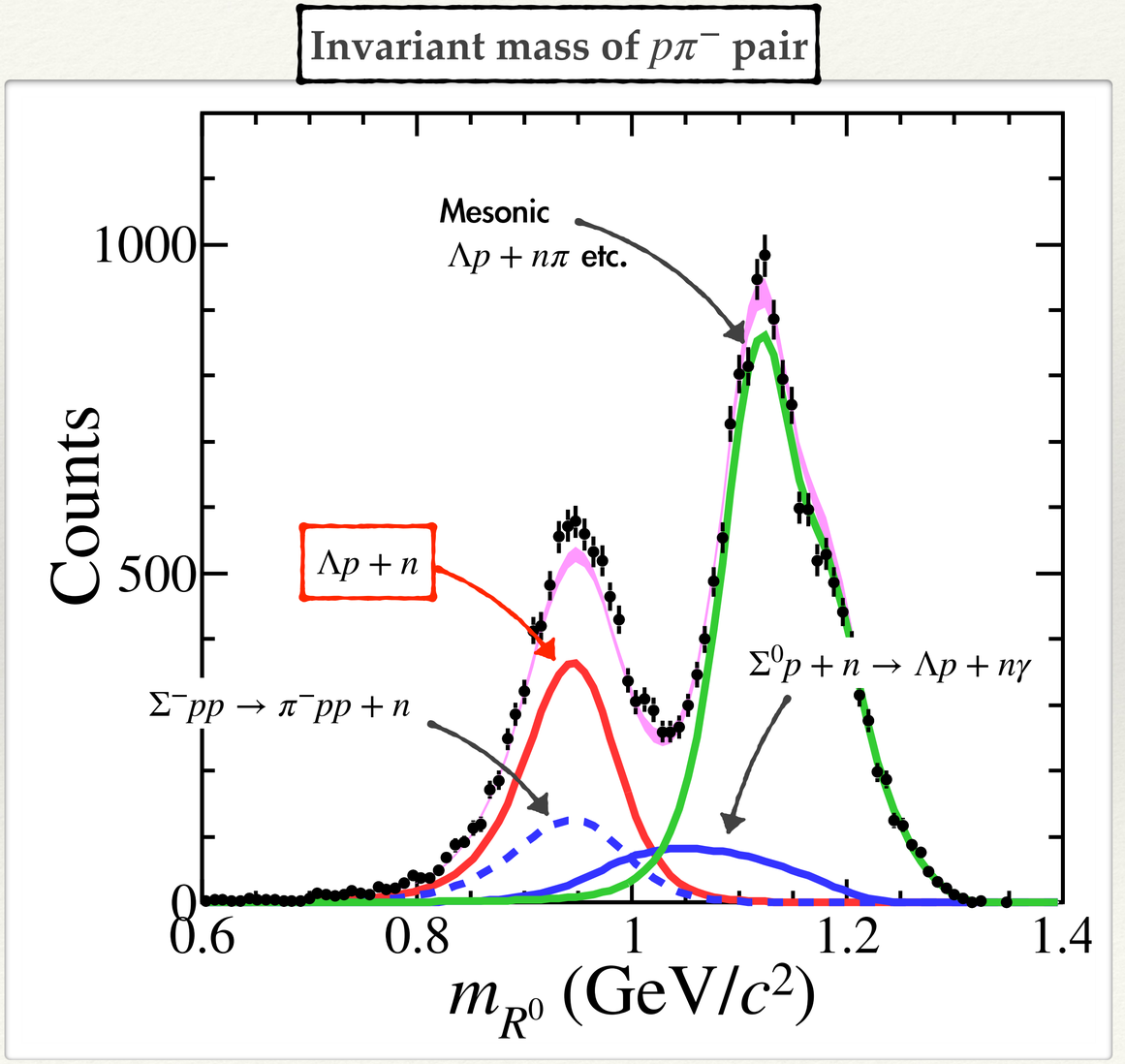




E15 experiment

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





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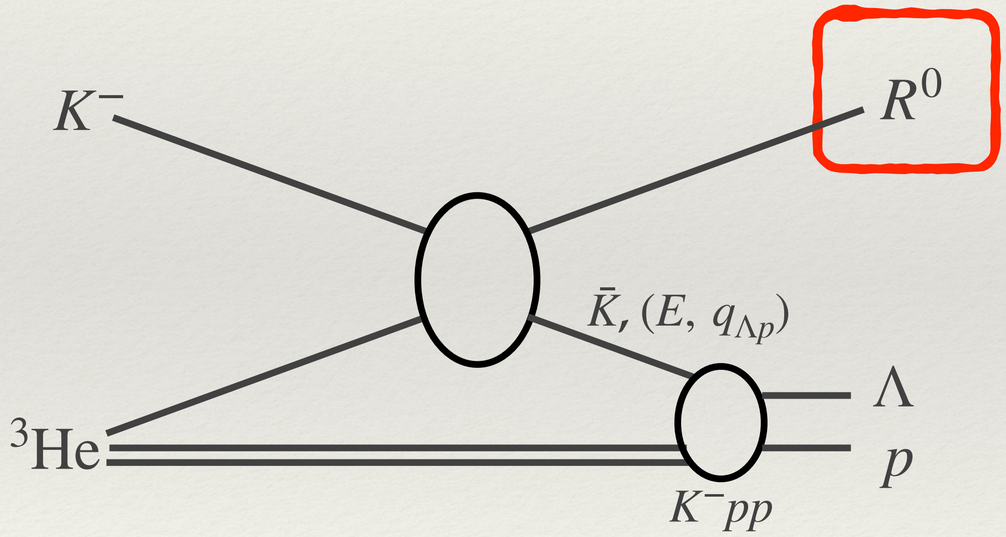
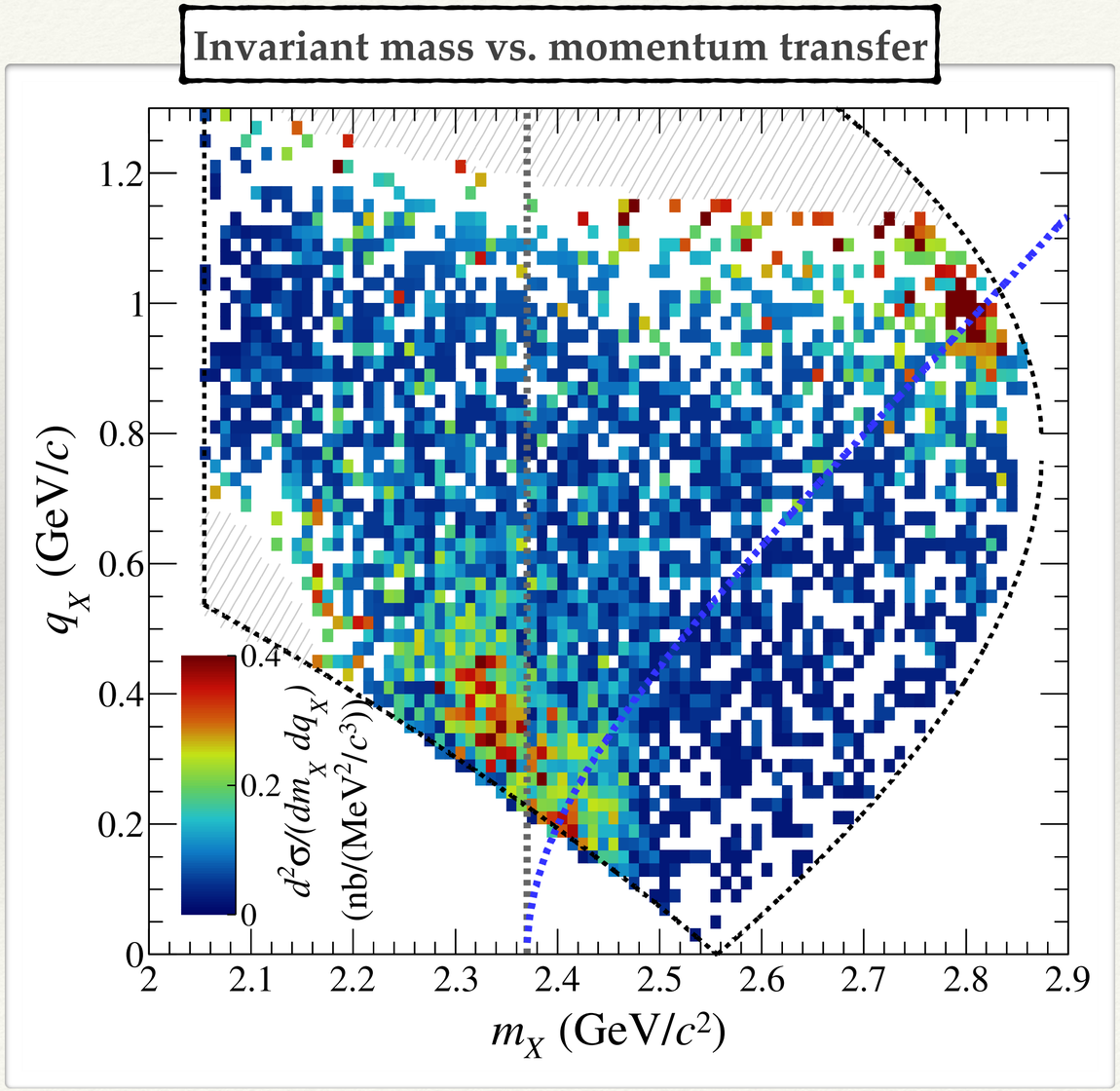


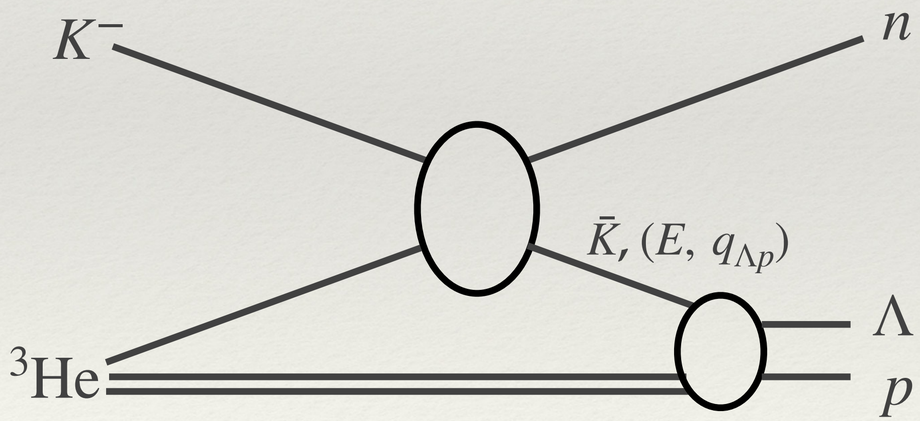
Data purity	
Signal	
Λpn final state	$\sim 80\,\%$
Backgrounds	
$\Sigma^0 pn$ final state	$\sim 10\,\%$
$\Sigma^- pp$ final state	$\sim 10\,\%$
$\Lambda pn + \pi$ final state	Negligible
Exp. background	Negligible

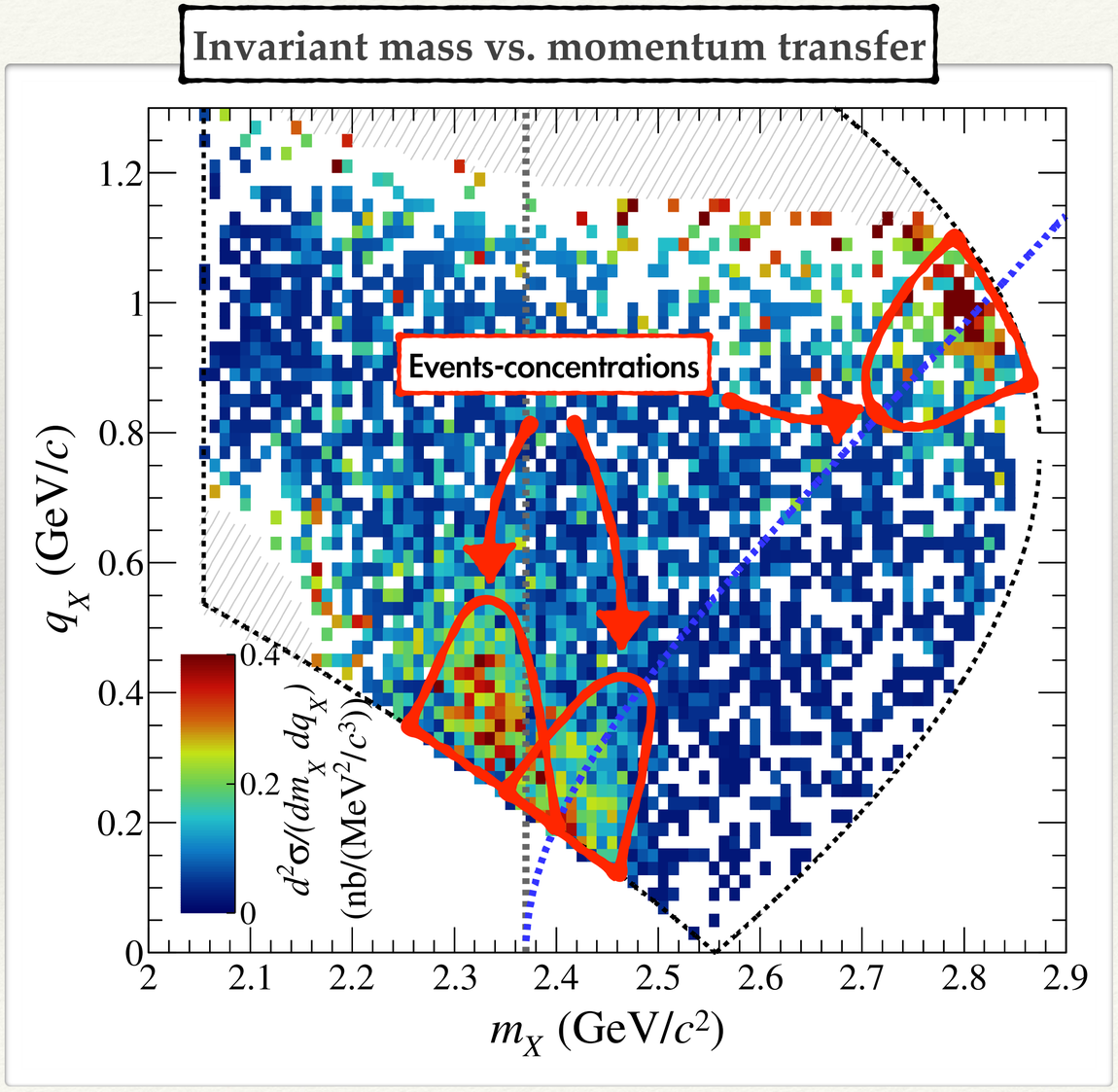
Result of E15



Result of E15

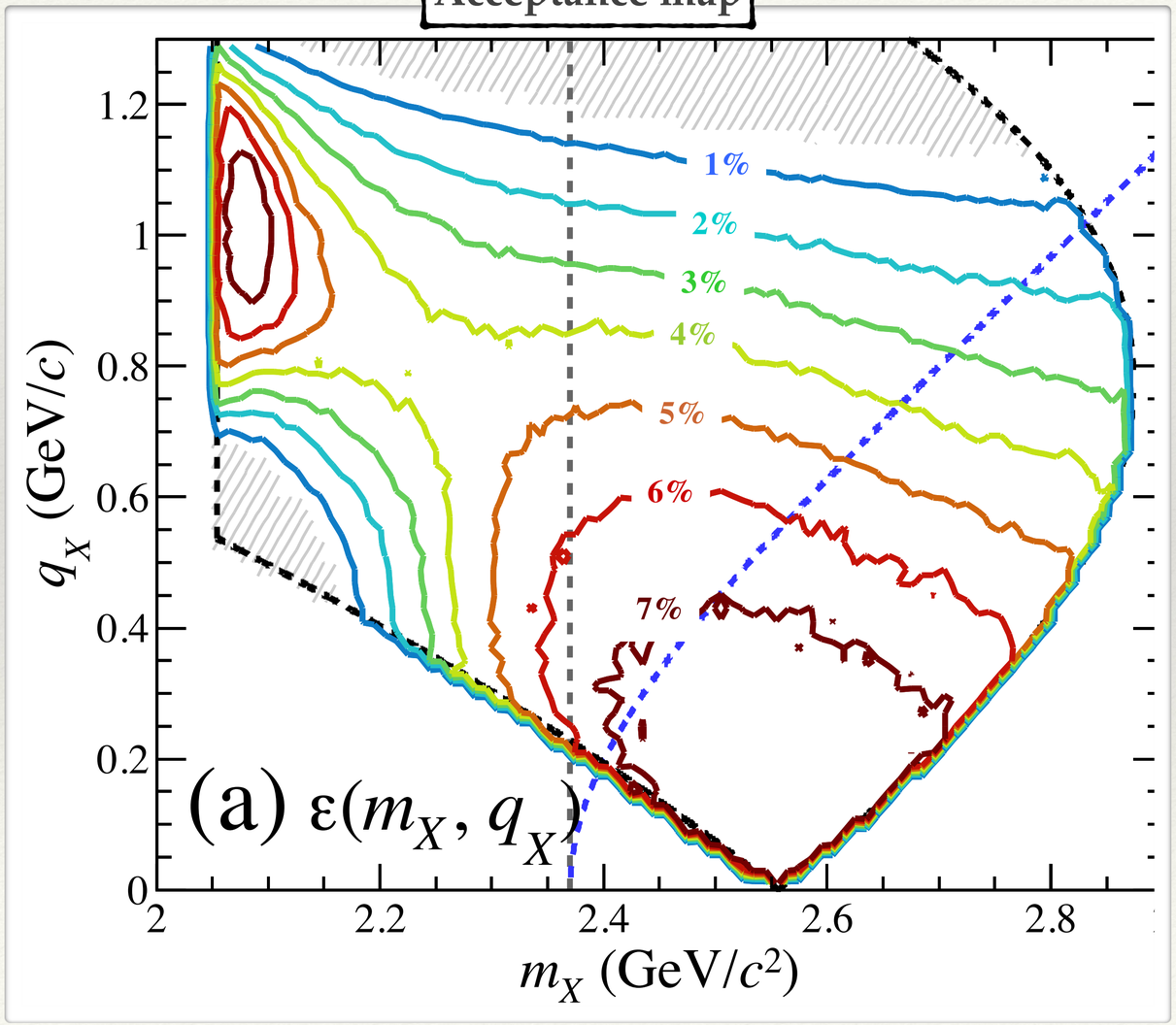
$$K^- + {}^3\mathrm{He} \rightarrow \Lambda p + n$$



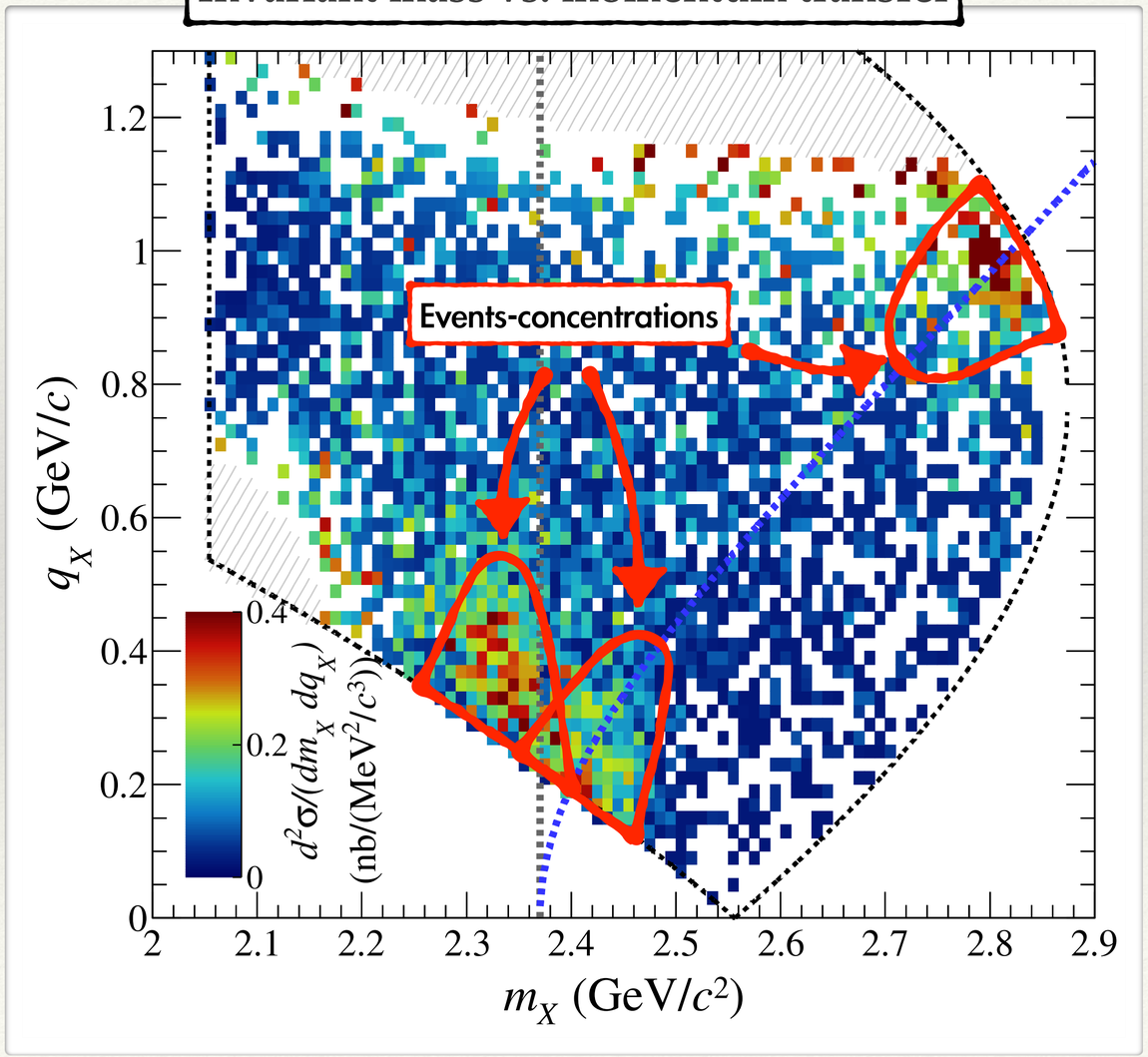


Result of E15

Acceptance map



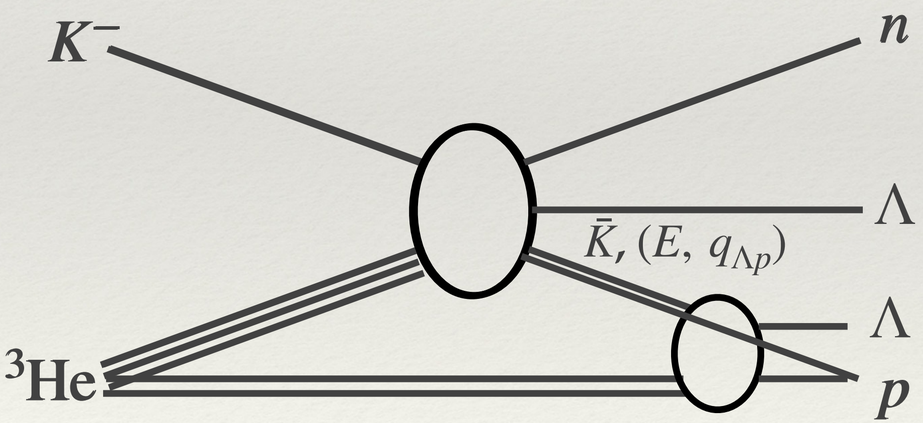
Invariant mass vs. momentum transfer

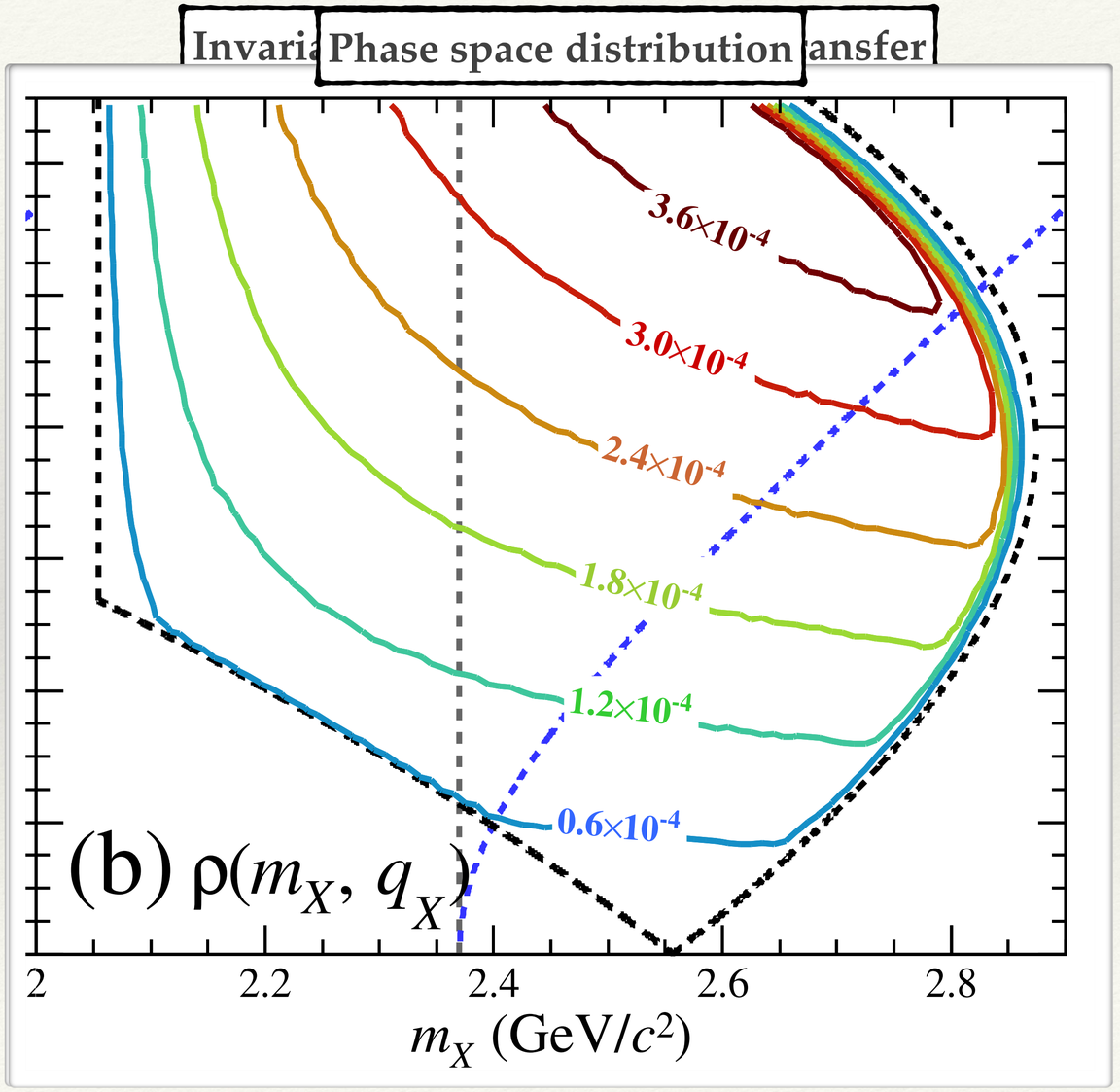


Result of E15

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

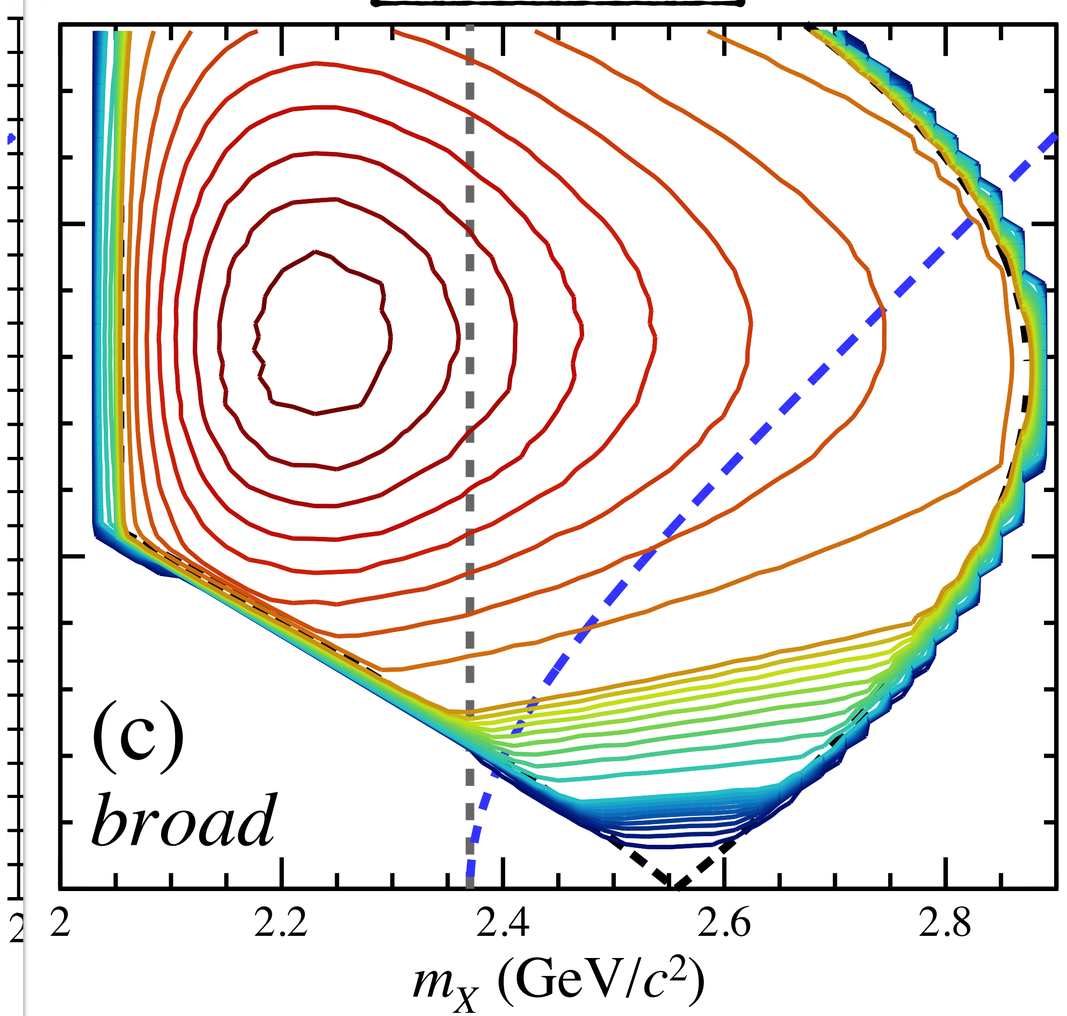
Point like interaction
(Kaon absorption by three nucleons; 3NA)





Result of E15

Ph Broad component on



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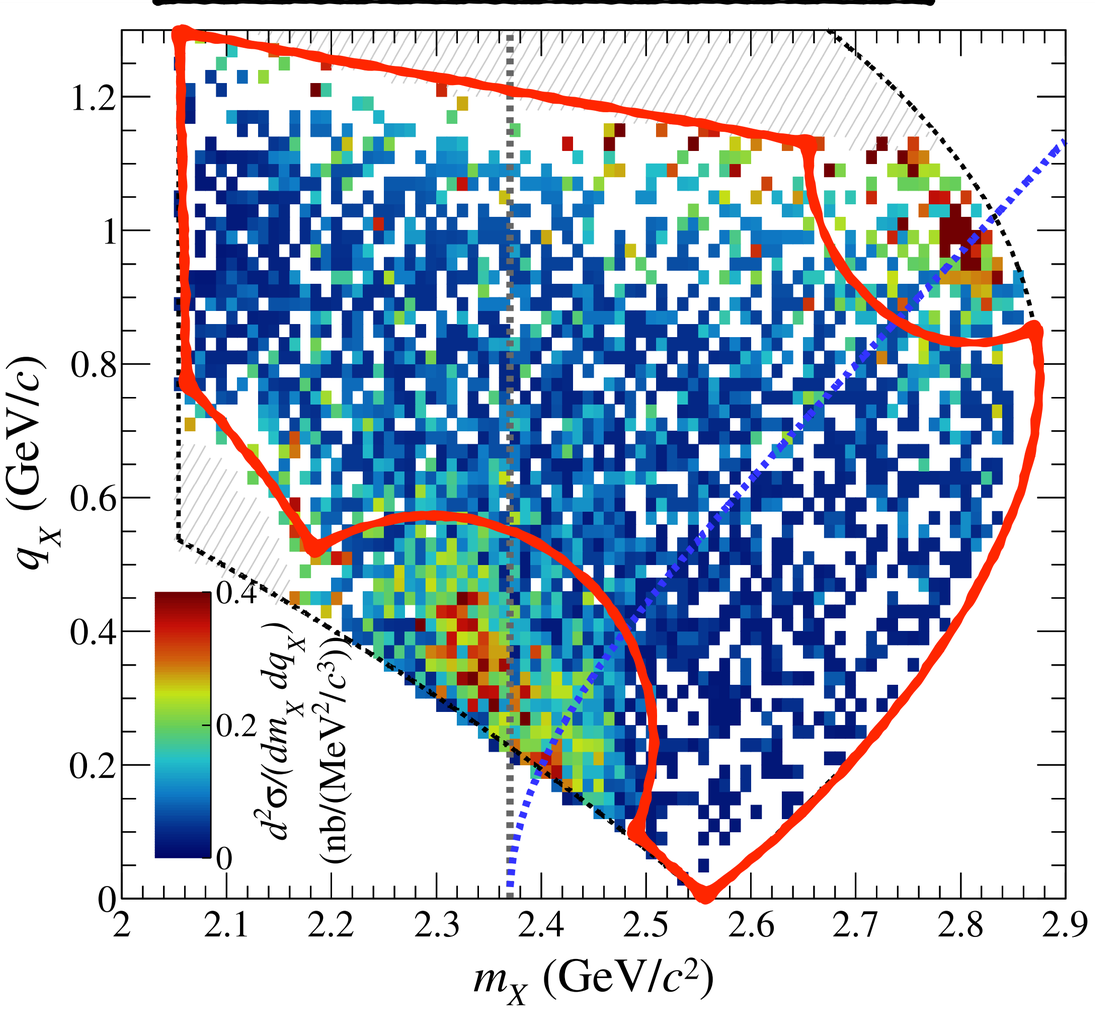
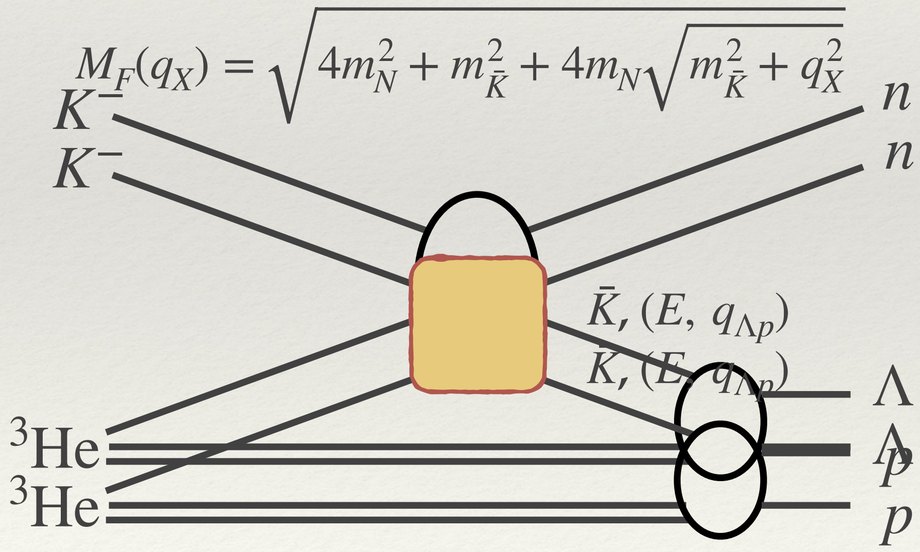


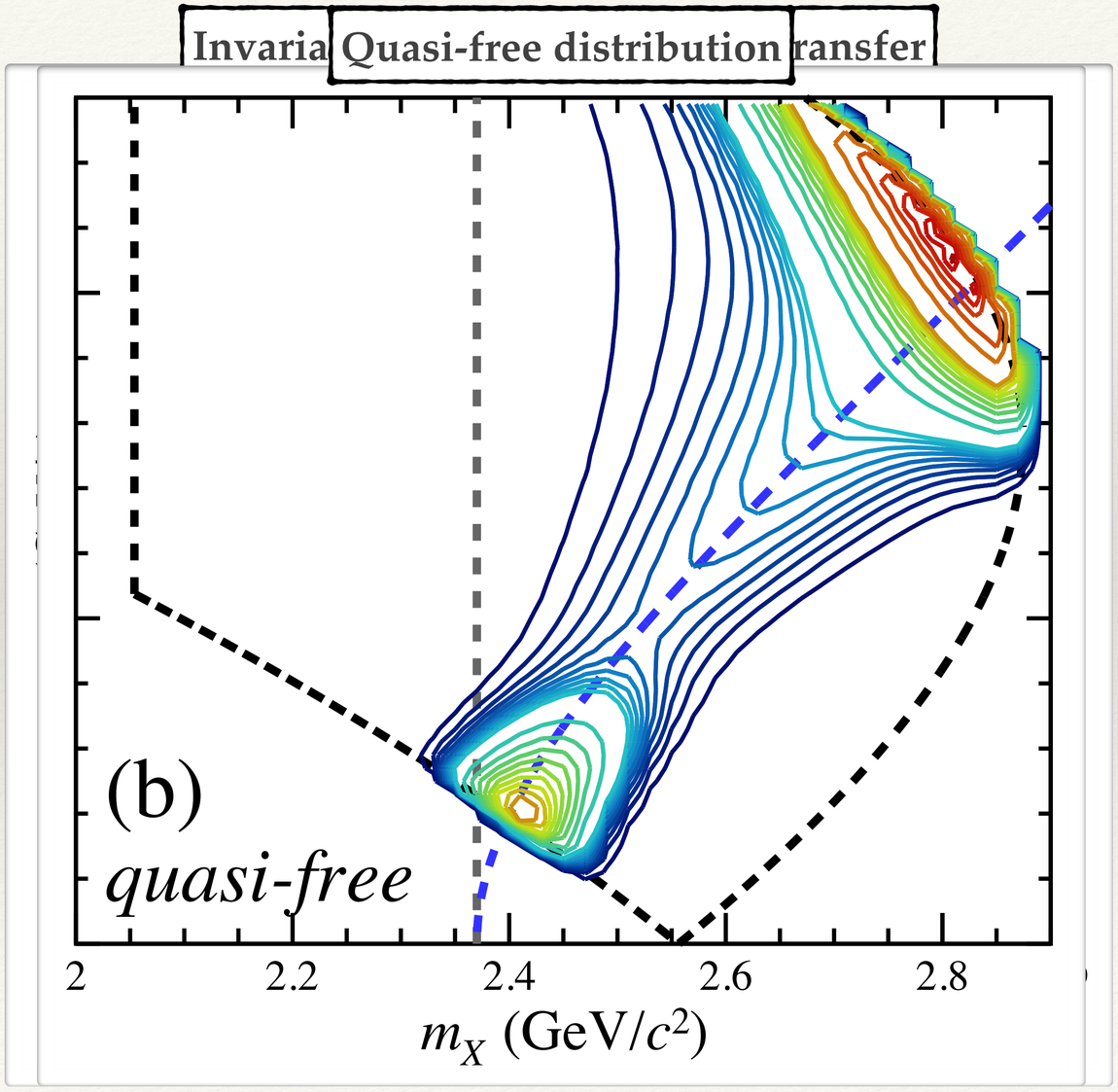
Result of E15

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

QF-K absorption by two residual nucleons

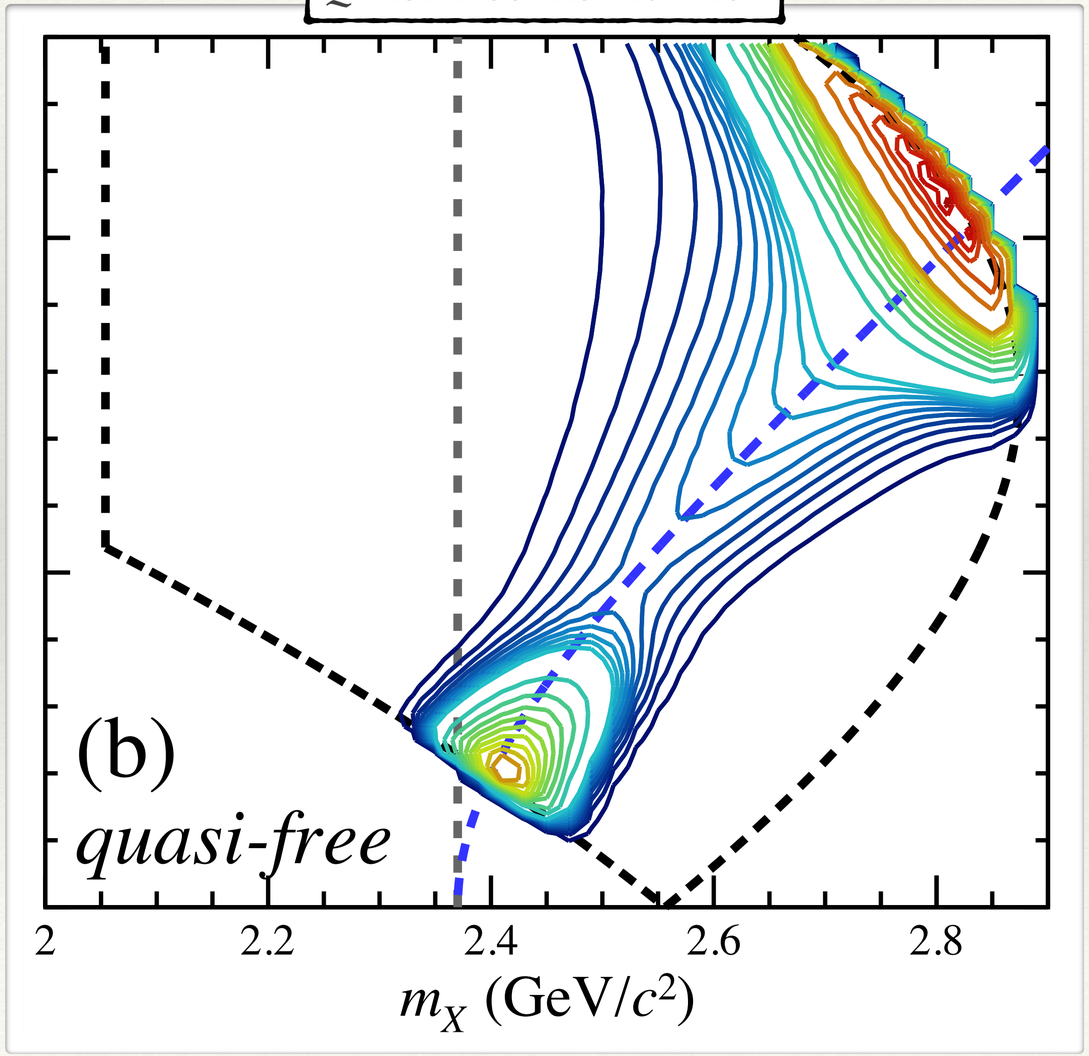


$\bar{K}$: **on-shell**



Result of E15

Quasi-free distribution



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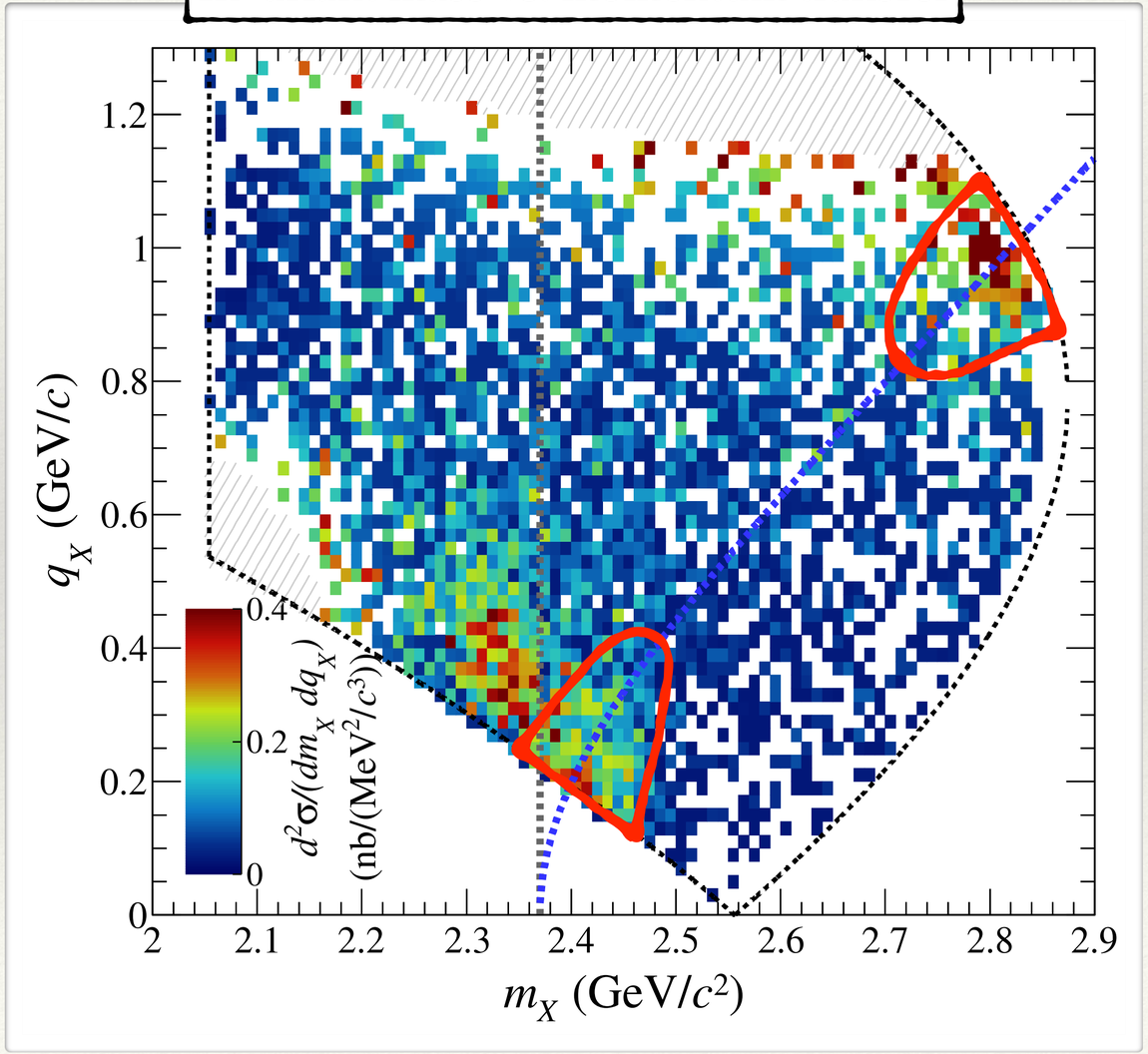
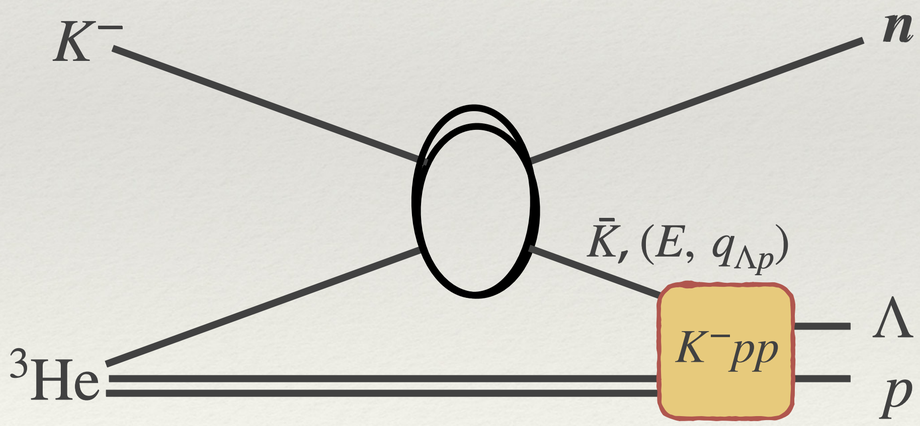
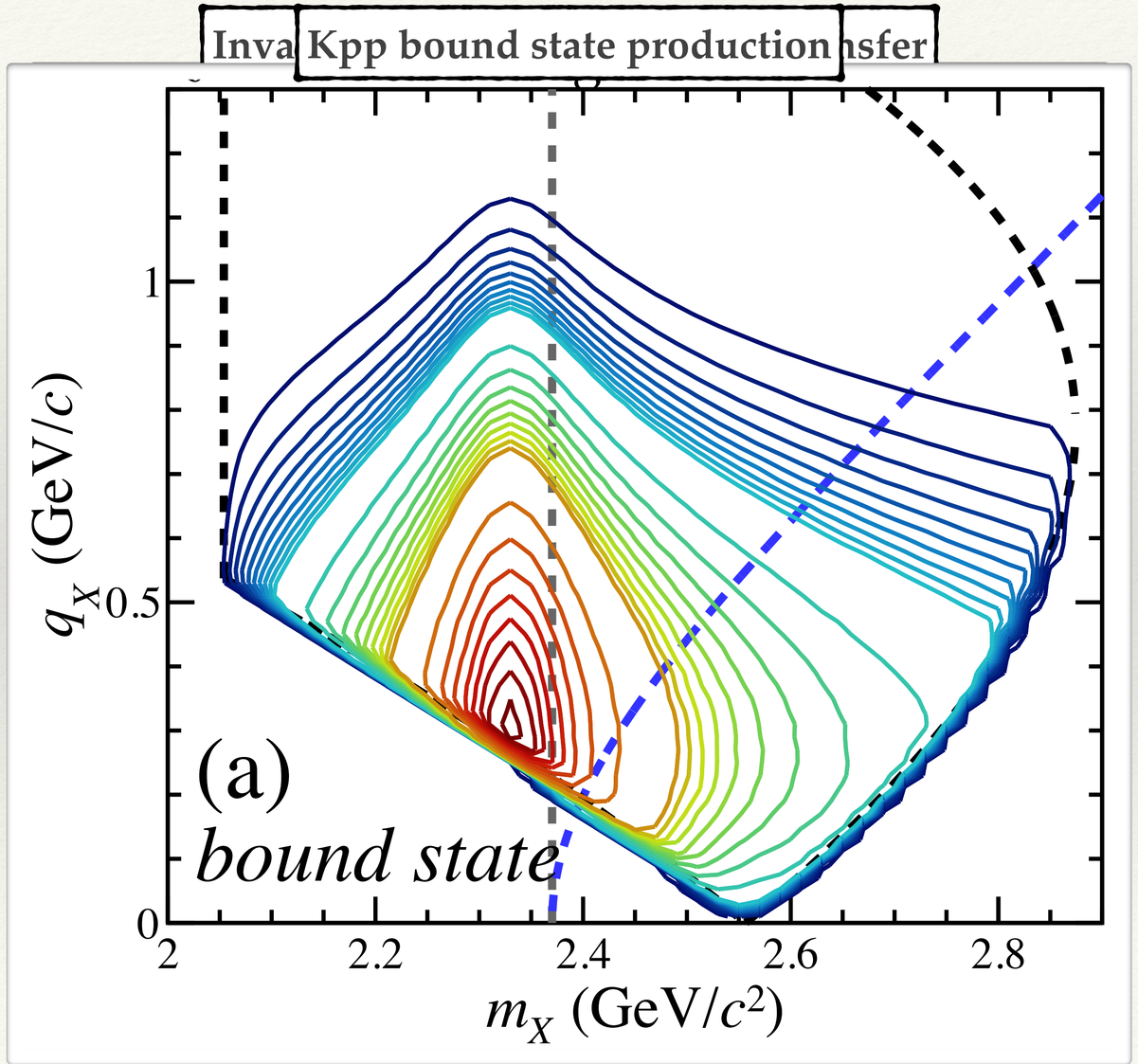


Result of E15

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

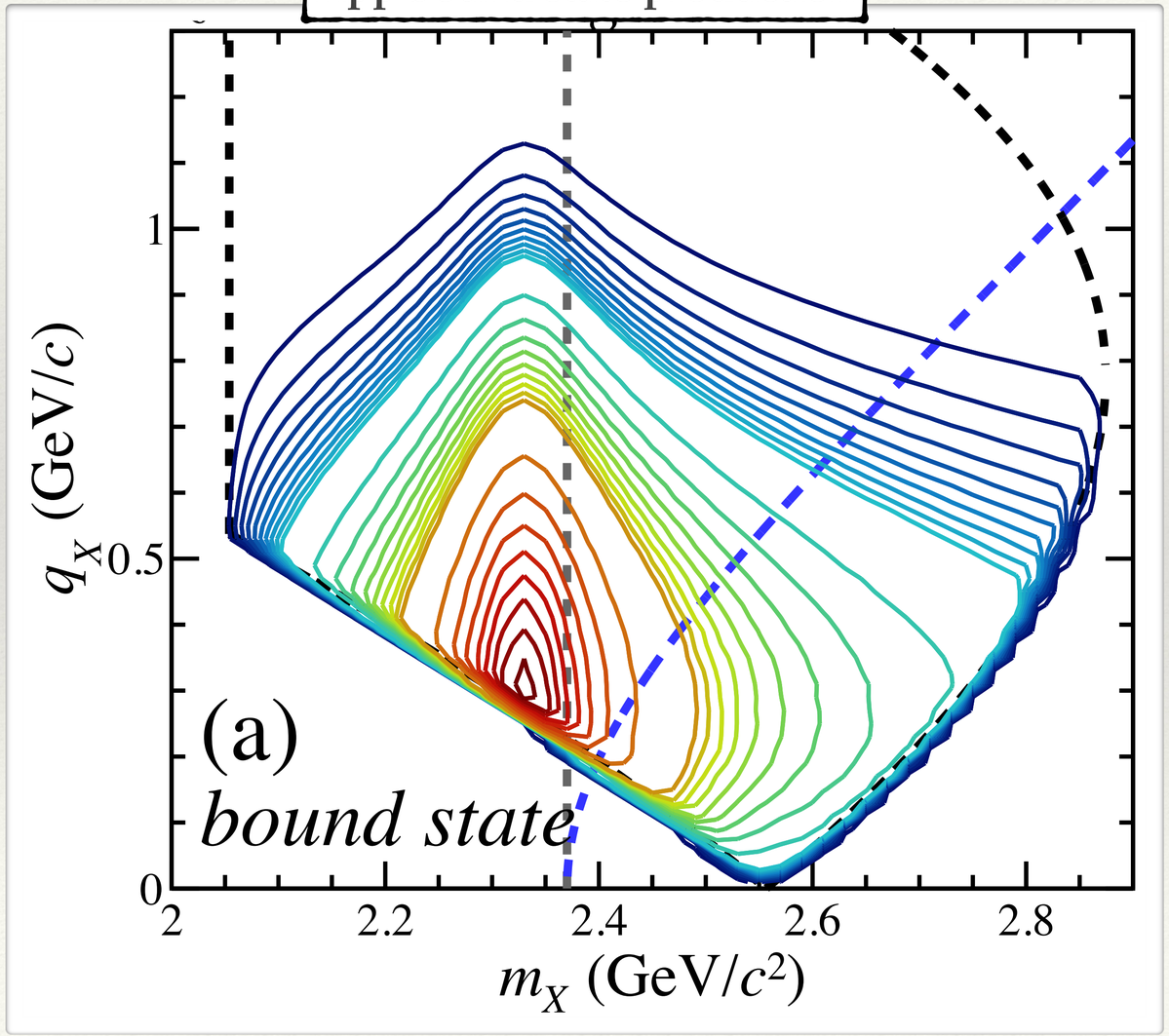
K^-pp production





Result of E15

Kpp bound state production



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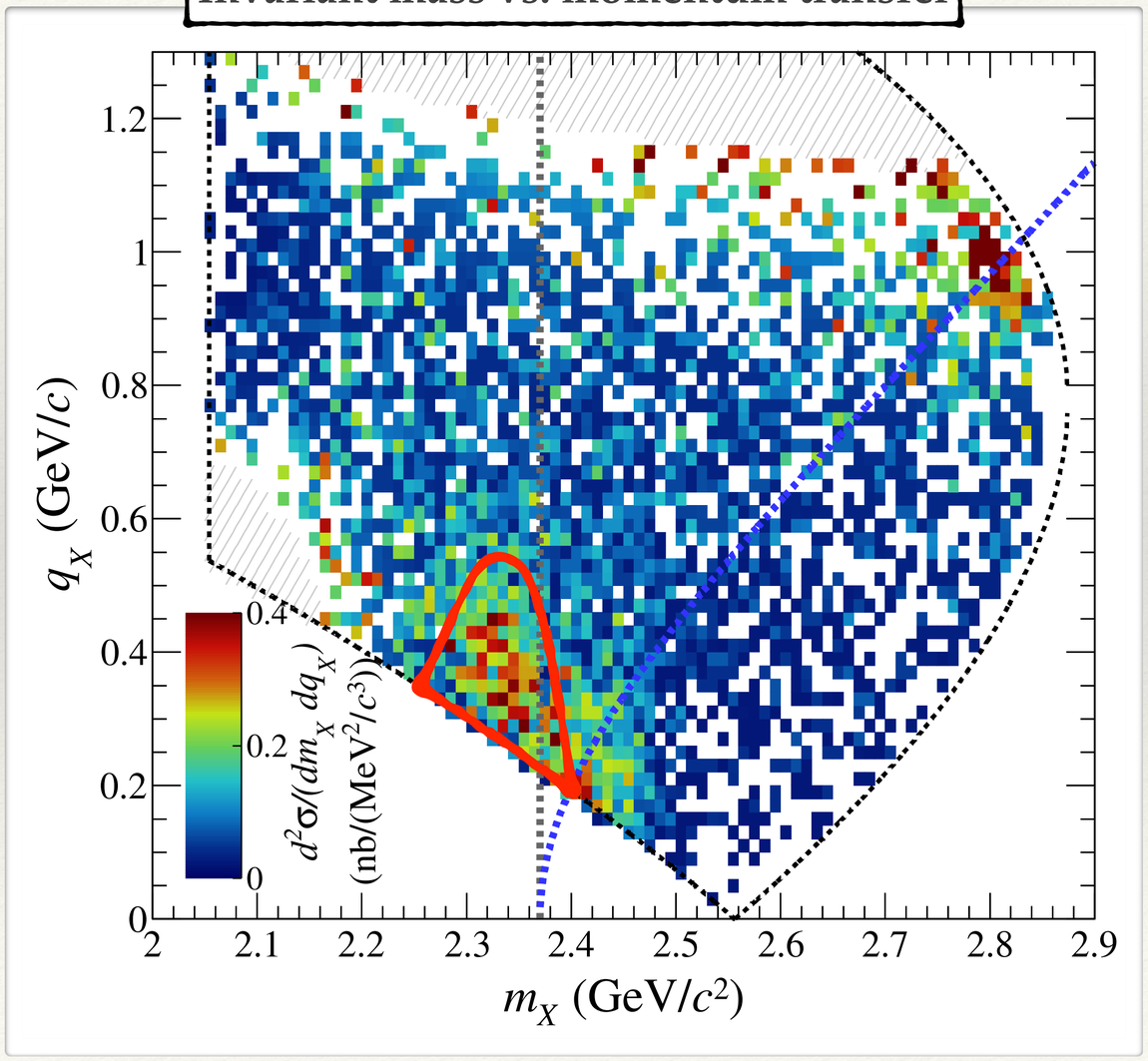

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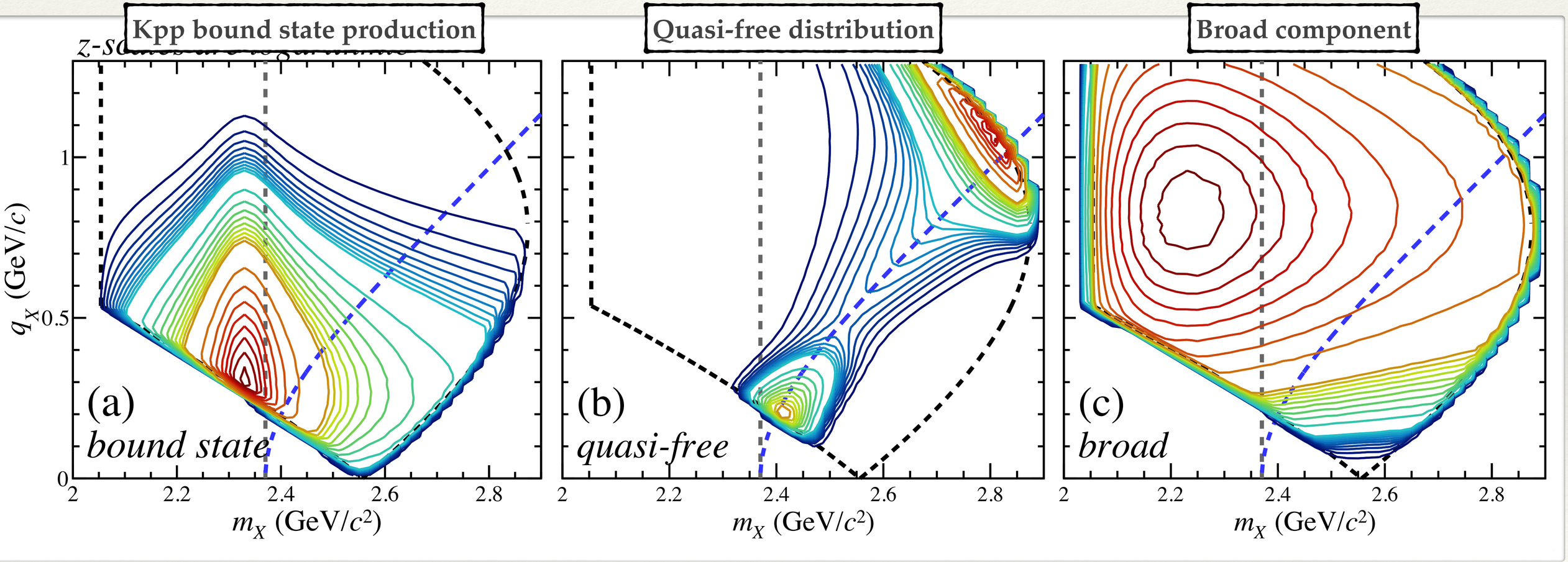
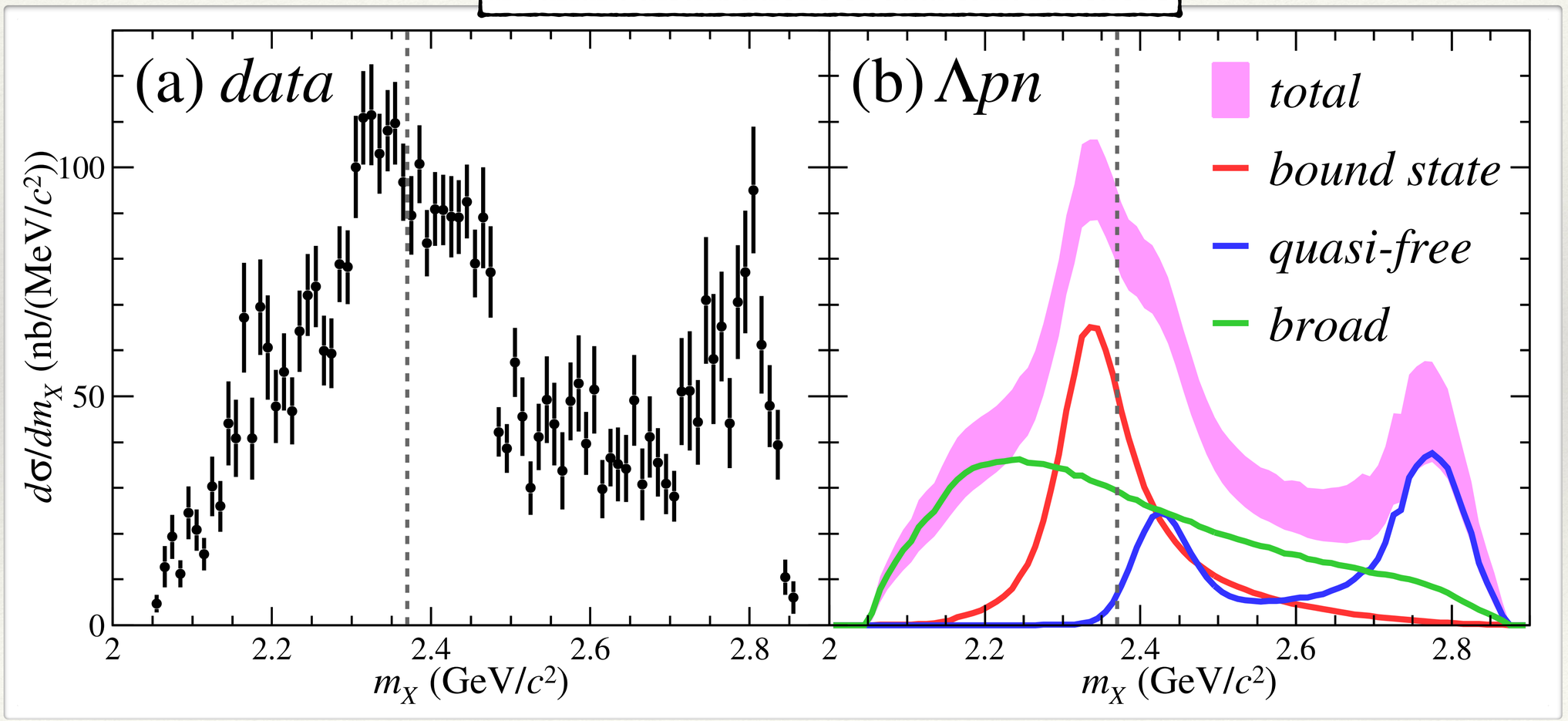


Result of E15

Invariant distributions of data & fit functions



Result of E15

Data purity	
Signal	
Λpn final state	$\sim 80\,\%$
Backgrounds	
$\Sigma^0 pn$ final state	$\sim 10\,\%$
$\Sigma^- pp$ final state	$\sim 10\,\%$
$\Lambda pn + \pi$ final state	Negligible
Exp. background	Negligible

Result of E15

Data purity

Signal

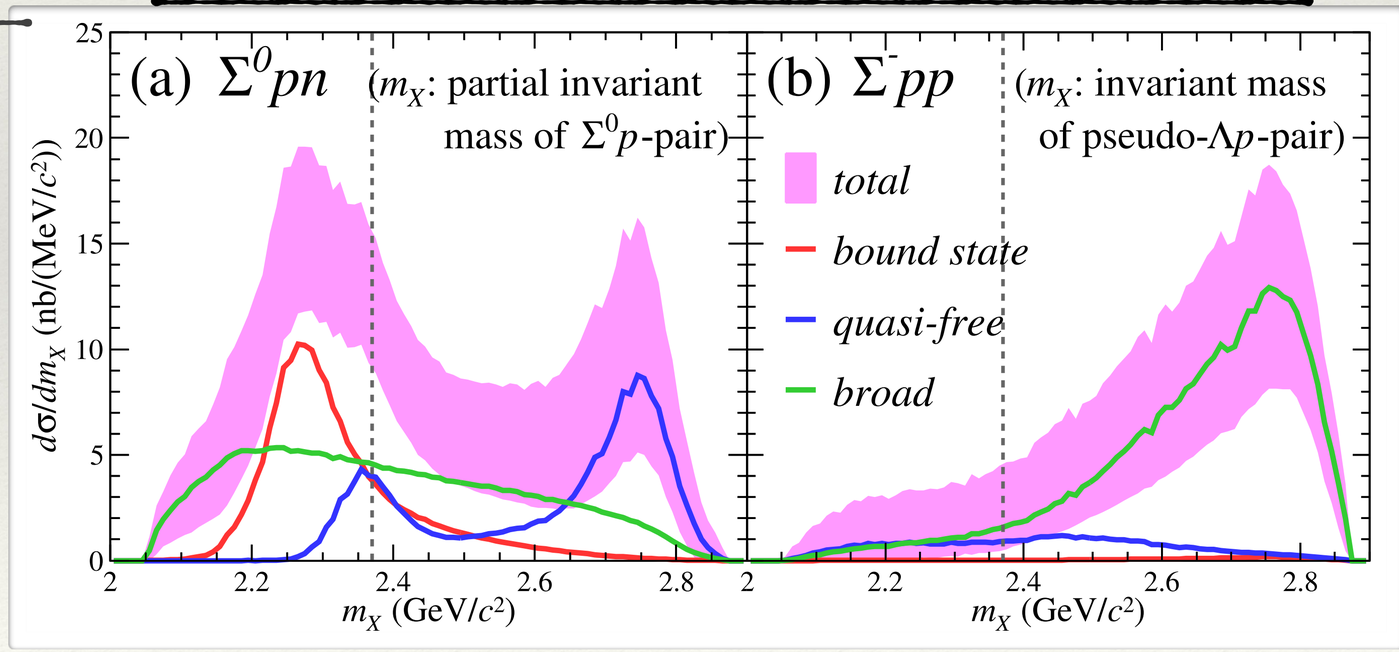
Λpn final state	~ 80 %

Backgrounds

$\Sigma^0 pn$ final state	~ 10 %
$\Sigma^- pp$ final state	~ 10 %
$\Lambda pn + \pi$ final state	Negligible
Exp. background	Negligible

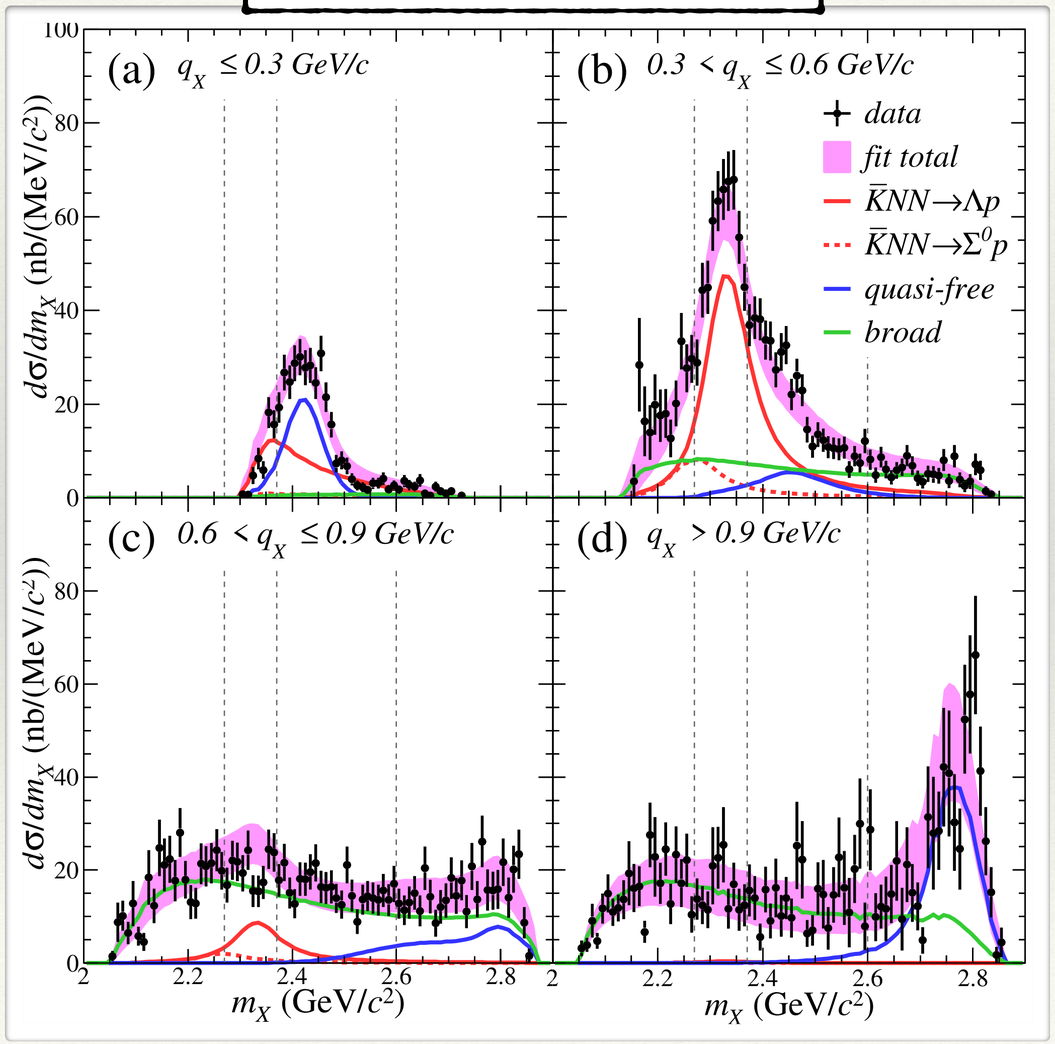
Assuming the same spectral functions

Invariant mass distributions of $\Sigma^0 pn$ & $\Sigma^- pp$ backgrounds

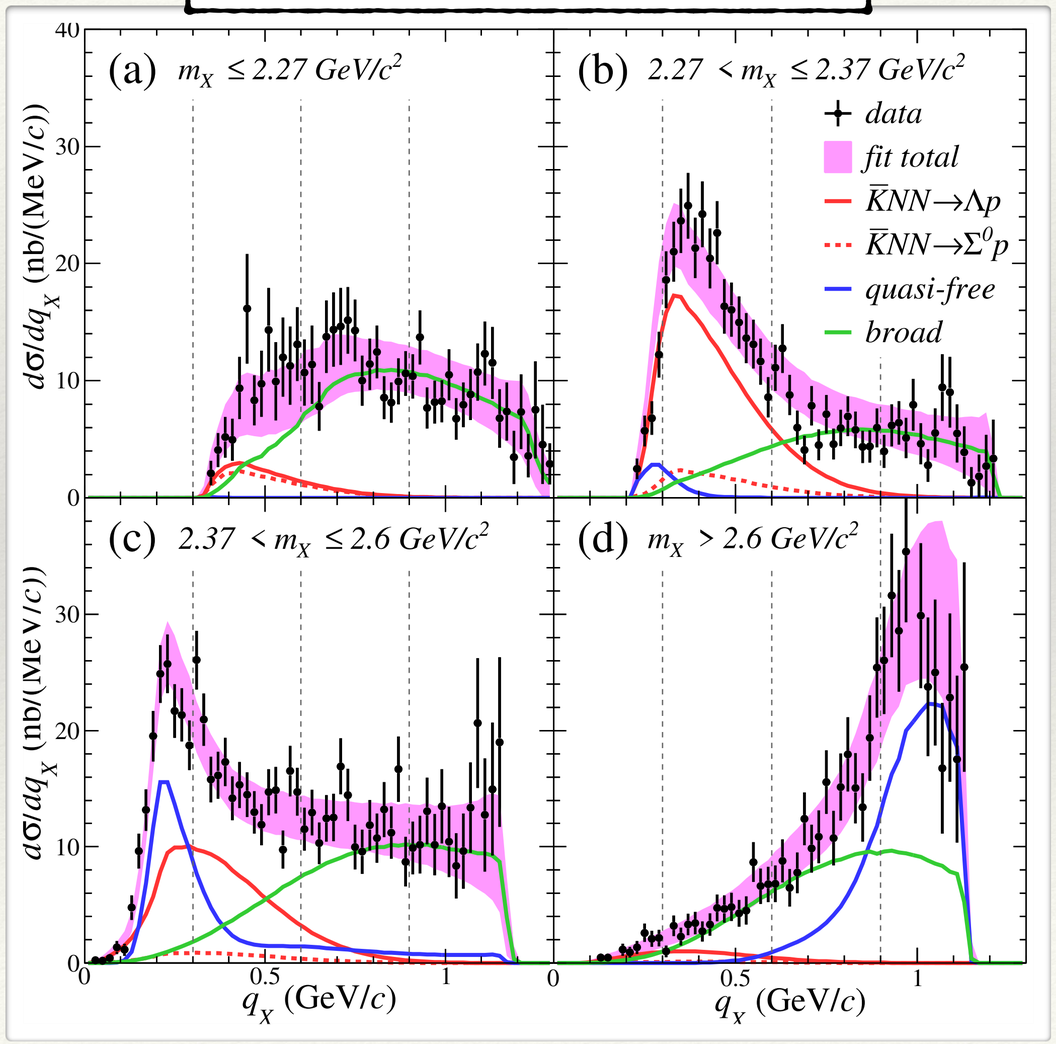


Result of E15

Invariant mass distributions

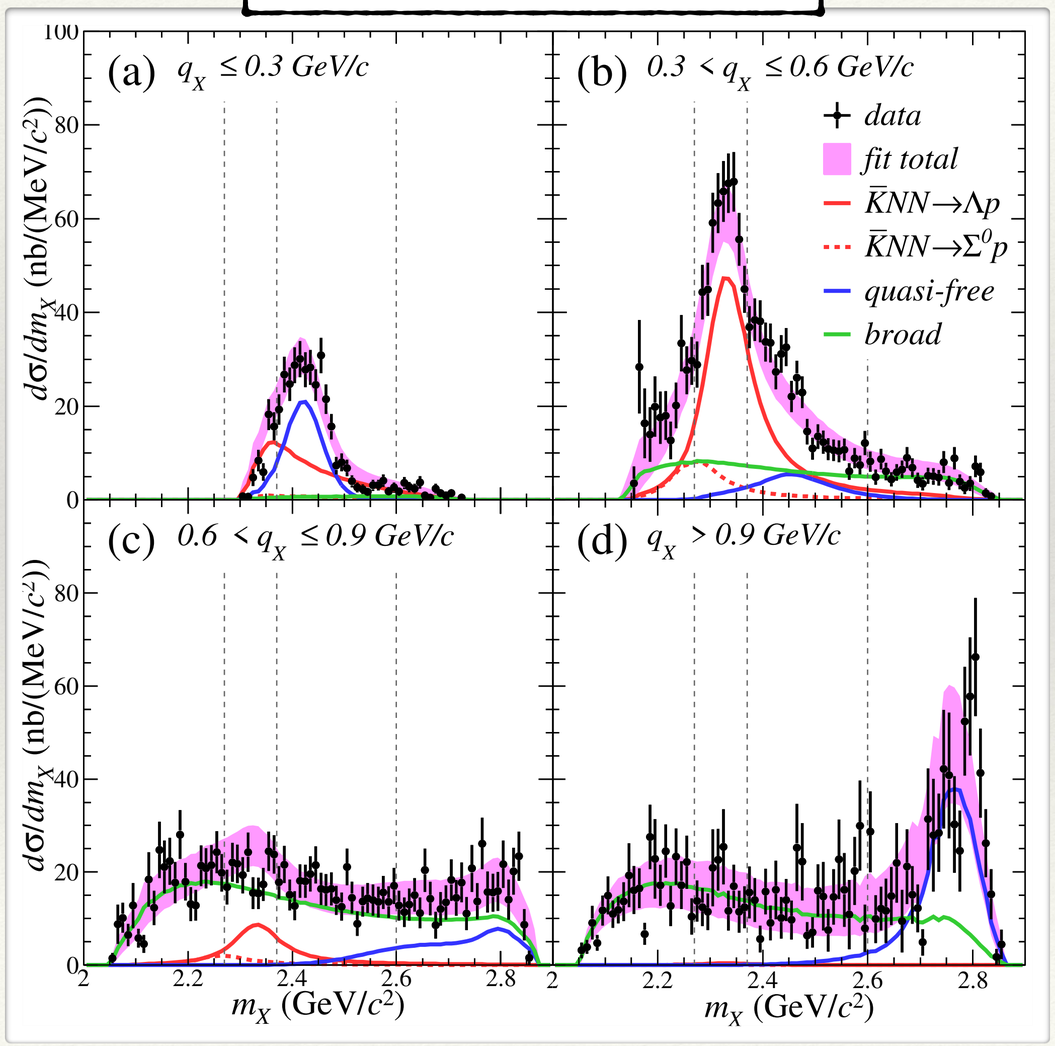


Momentum transfer distributions

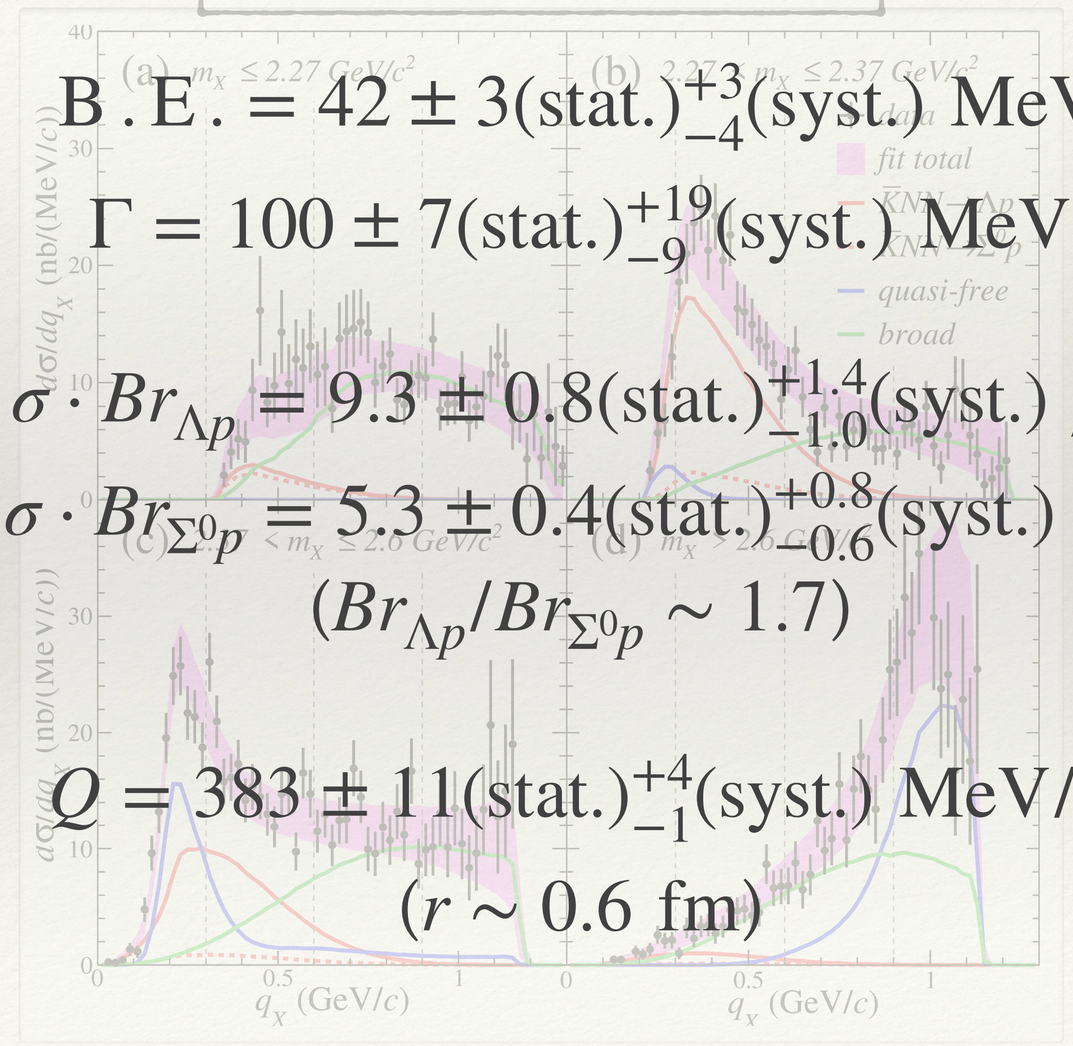


Result of E15

Invariant mass distributions



Momentum transfer distributions



$$\mathrm{B.E.} = 42 \pm 3(\mathrm{stat.})^{+3}_{-4}(\mathrm{syst.})\ \mathrm{MeV}$$

$$\Gamma = 100 \pm 7(\mathrm{stat.})^{+19}_{-9}(\mathrm{syst.})\ \mathrm{MeV}$$

$$\sigma \cdot Br_{\Lambda p} = 9.3 \pm 0.8(\mathrm{stat.})^{+1.4}_{-1.0}(\mathrm{syst.})\ \mu\mathrm{b}$$

$$\sigma \cdot Br_{\Sigma^0 p} = 5.3 \pm 0.4(\mathrm{stat.})^{+0.8}_{-0.6}(\mathrm{syst.})\ \mu\mathrm{b}$$

$$(Br_{\Lambda p}/Br_{\Sigma^0 p} \sim 1.7)$$

$$Q = 383 \pm 11(\mathrm{stat.})^{+4}_{-1}(\mathrm{syst.})\ \mathrm{MeV}/c$$

$$(r \sim 0.6\ \mathrm{fm})$$

Result of E15

E15 result

$$\mathrm{B.E.} = 42 \pm 3(\mathrm{stat.})^{+3}_{-4}(\mathrm{syst.})\ \mathrm{MeV}$$

$$\Gamma = 100 \pm 7(\mathrm{stat.})^{+19}_{-9}(\mathrm{syst.})\ \mathrm{MeV}$$

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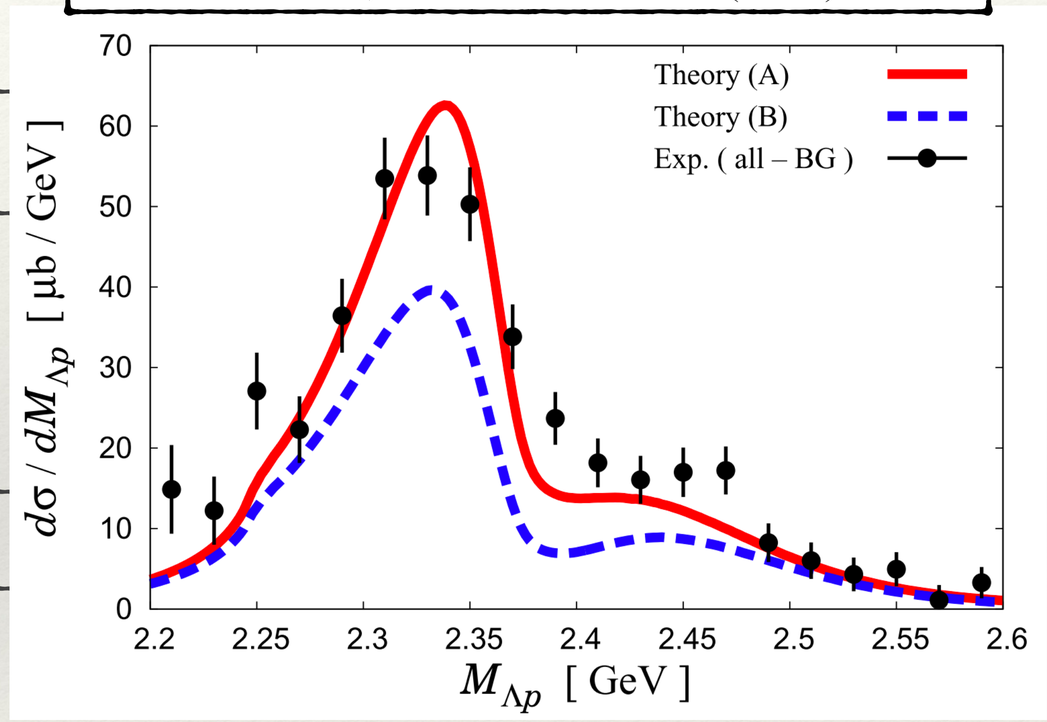
$$(r \sim 0.6\ \mathrm{fm})$$

T. Sekihara et al., JPS Conf. Proc. **26** (2019) 023009



/sr

Large difference between E15 & E27

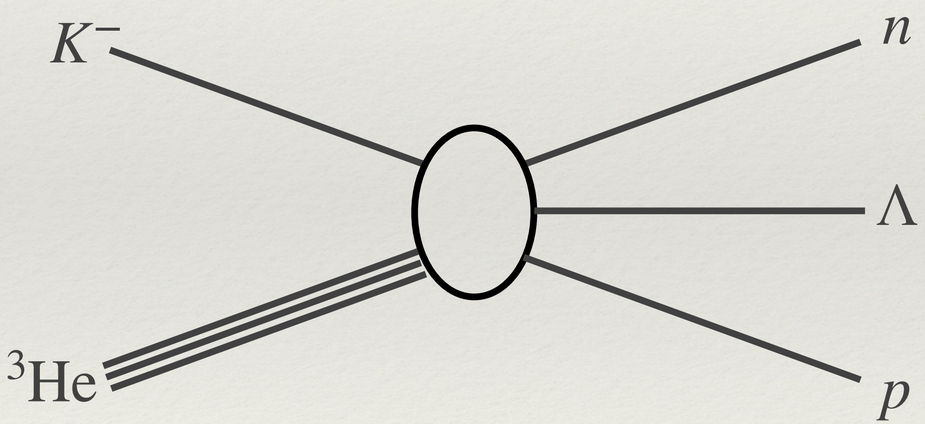
~~Good agreement with theoretical calc.~~

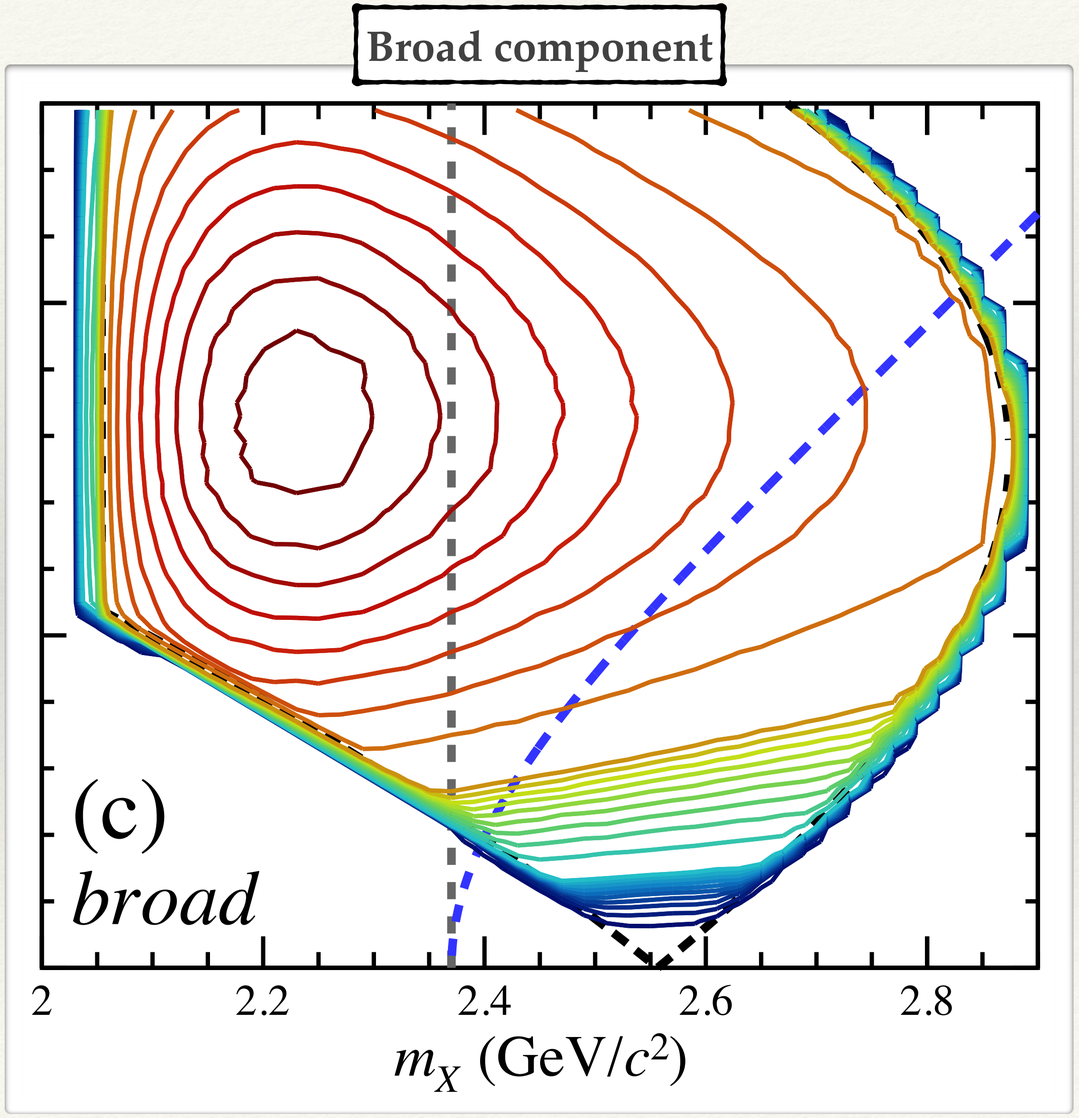
Different state?

~~Where is broad?~~

What is origin of broad component?

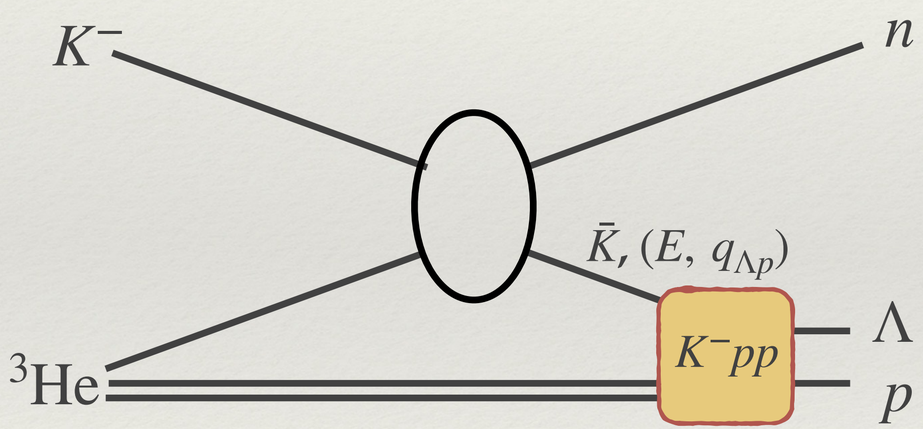
3NA-like process?



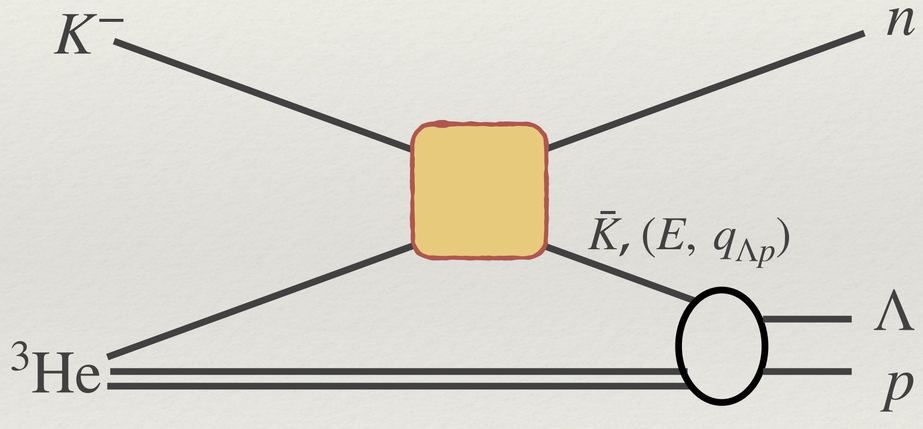


What is origin of broad component?

Kpp production

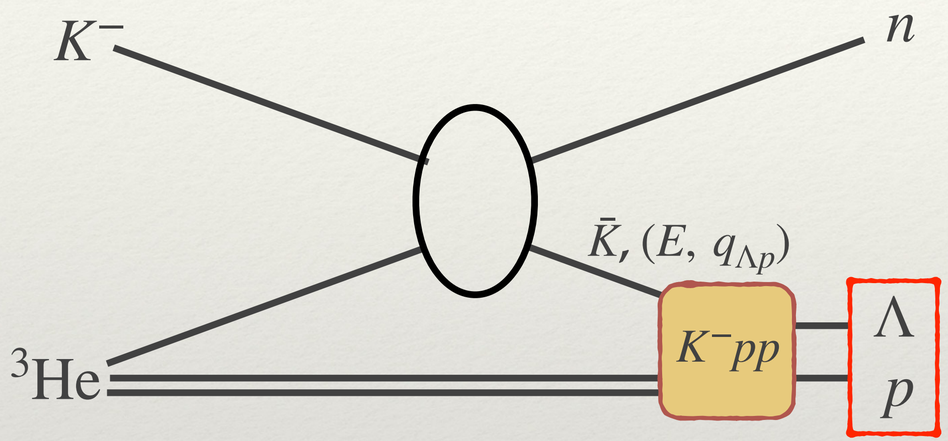


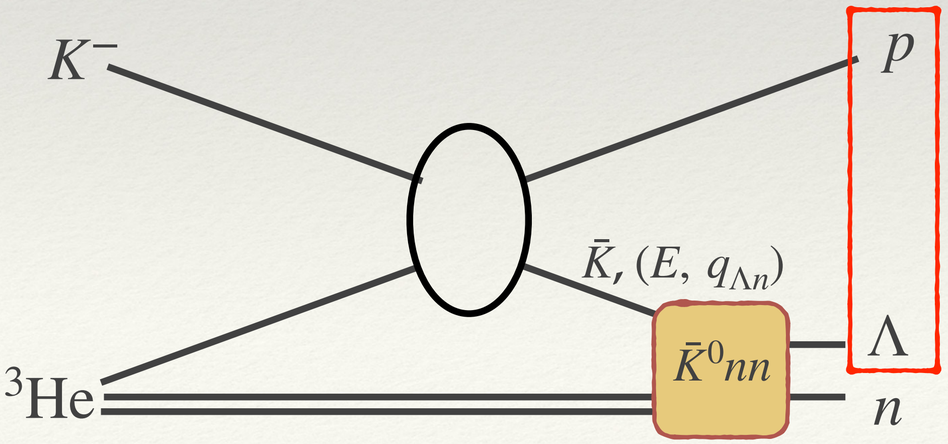
QF-K absorption by two residual nucleons



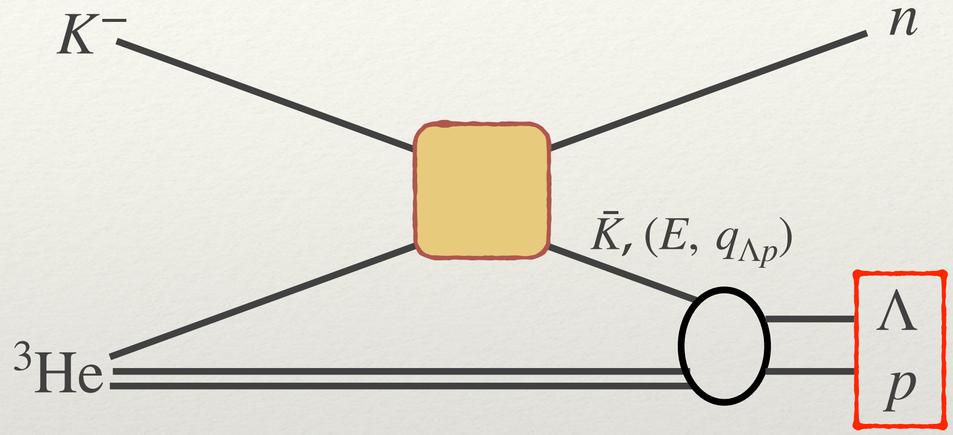
What is origin of broad component?

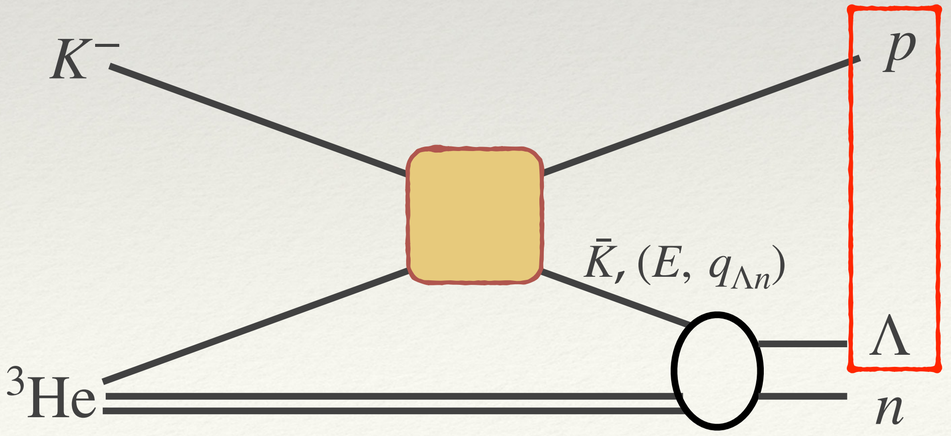
Kpp production





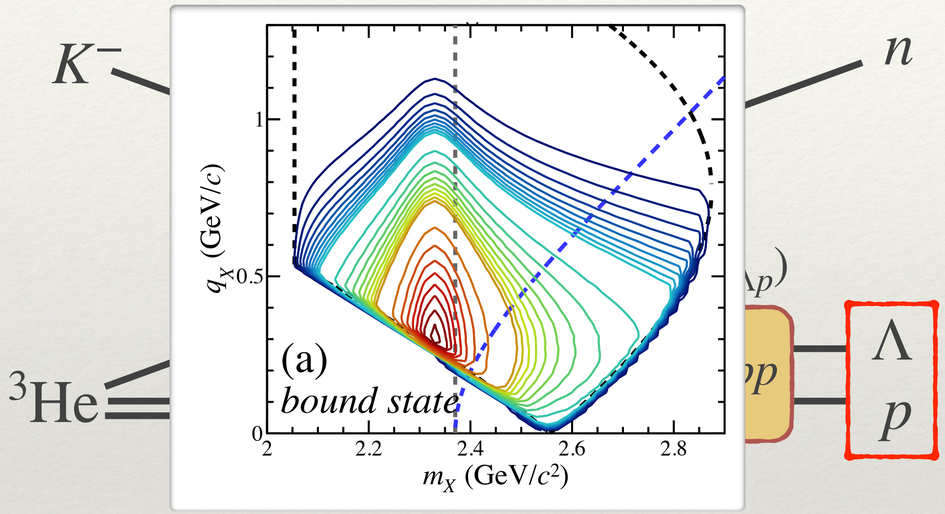
QF-K absorption by two residual nucleons



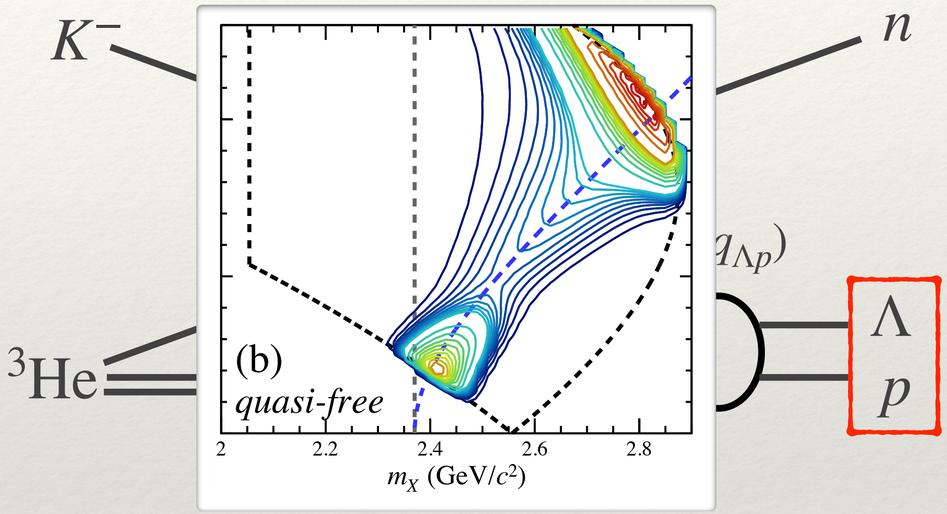


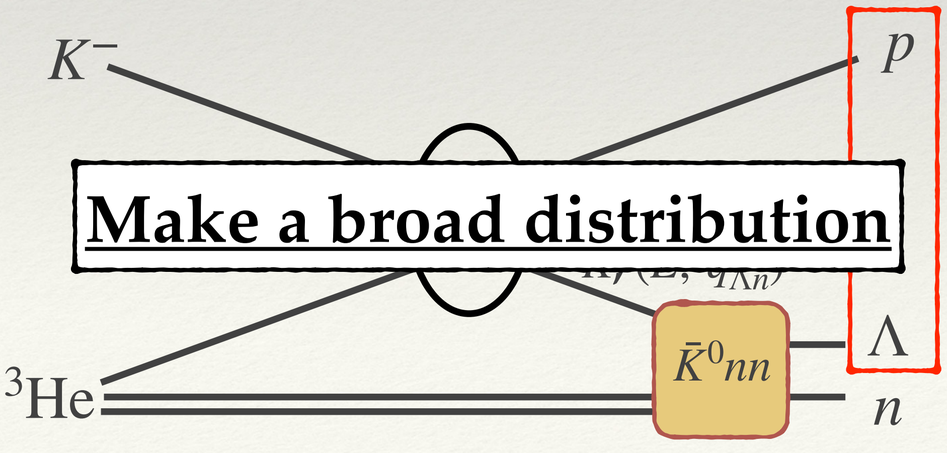
What is origin of broad component?

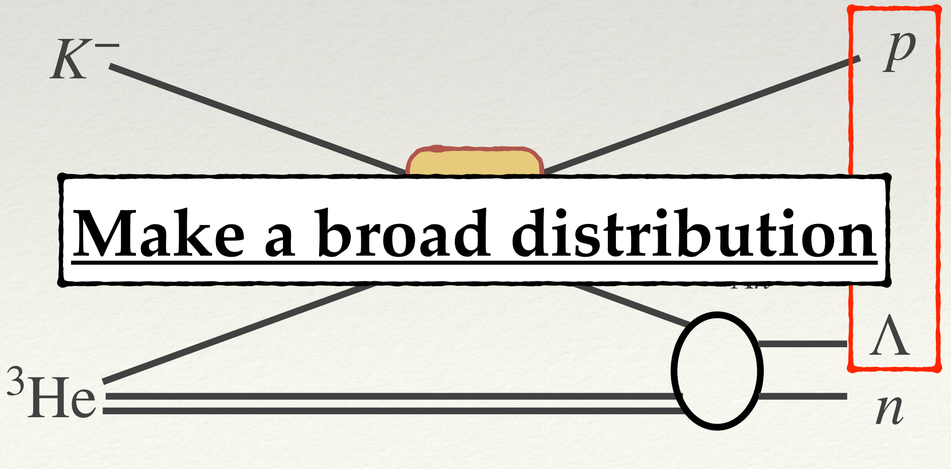
Kpp production



QF-K absorption by two residual nucleons

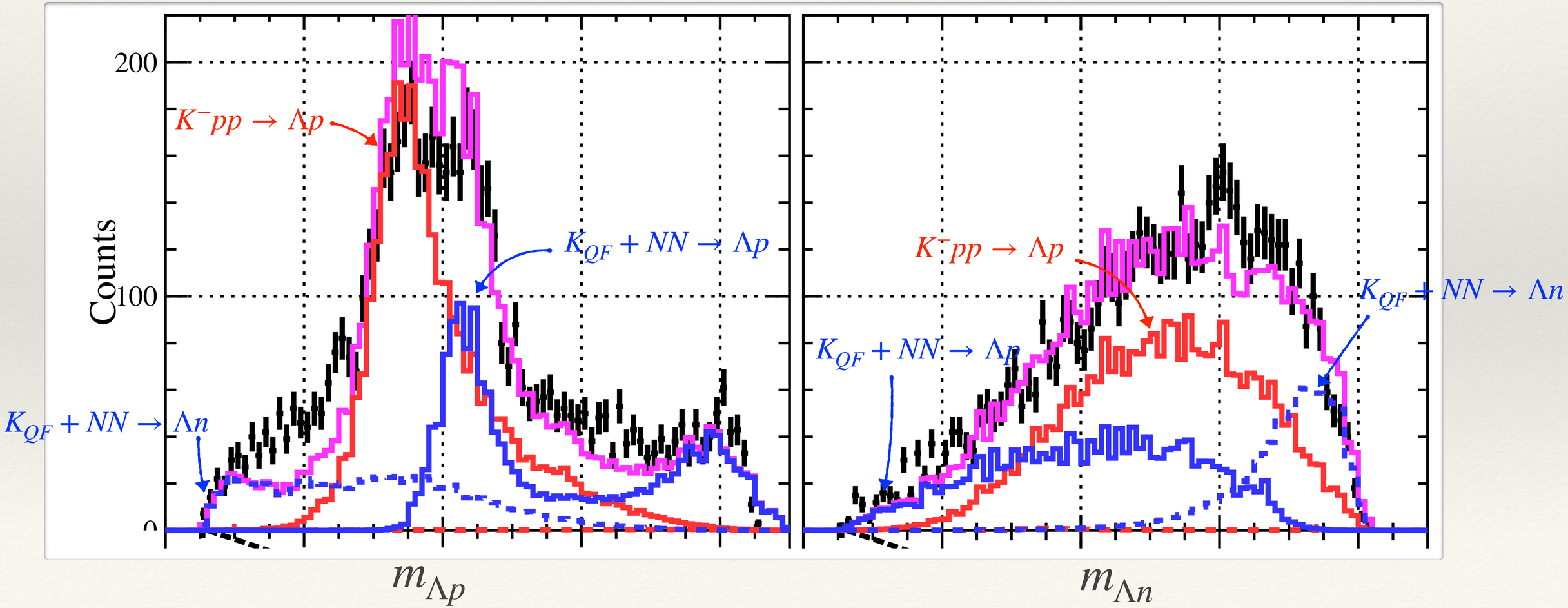






What is origin of broad component?

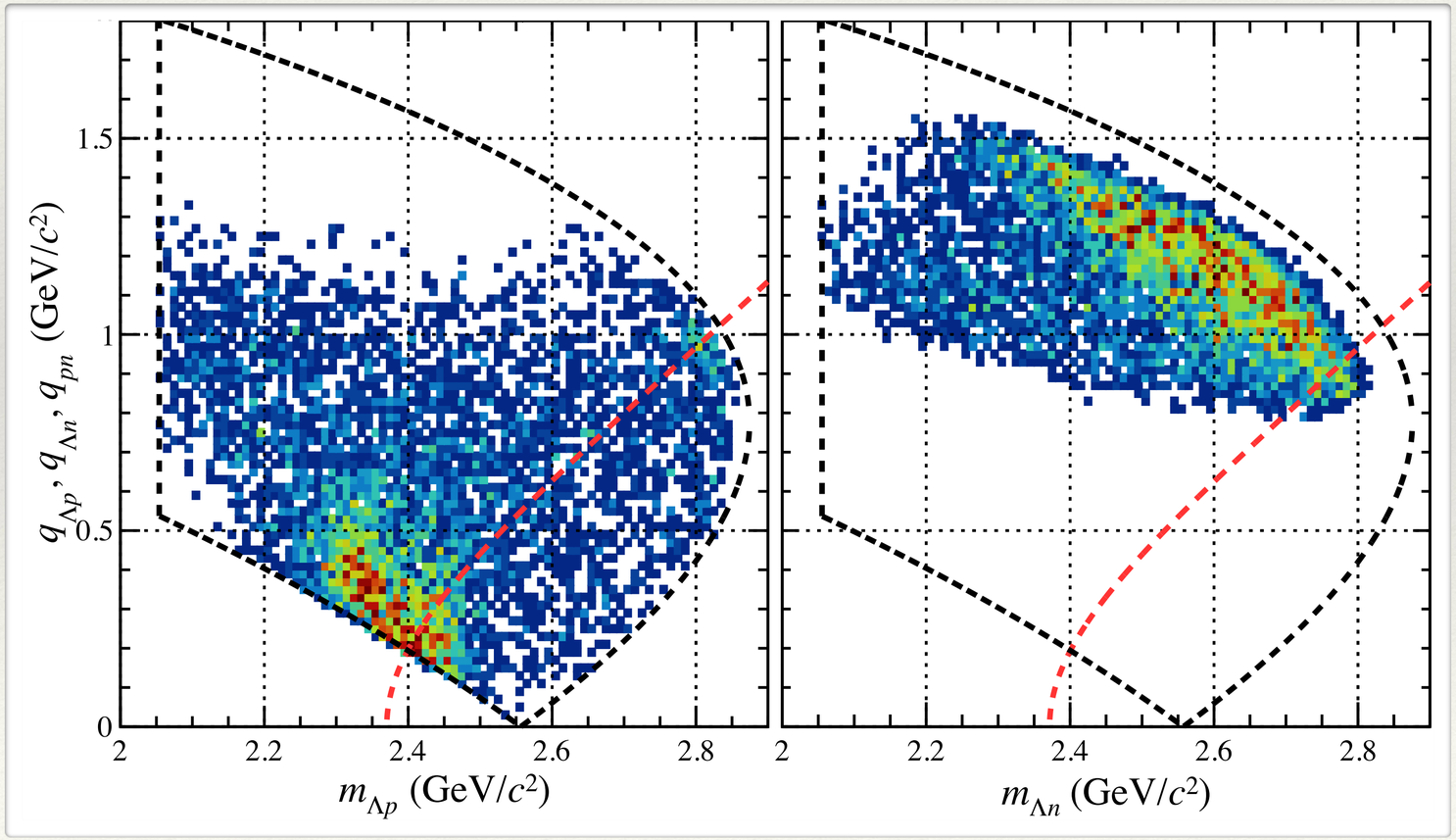
Well reproduced although eye fit only



What is origin of broad component?

Acceptances are much different between Λp & Λn

Need additional measurement with larger acceptance



Size of K^-pp

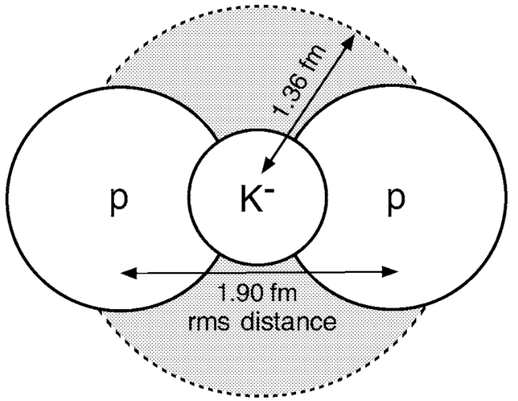
$$Q = 383 \pm 11(\text{stat.})^{+4}_{-1}(\text{syst.})\ \text{MeV}/c$$

⇩

$$r \sim 0.6\ \text{fm}$$

Quite compact!

But, we need more discussions…
Theoretical calculation is very helpful.



T. Yamazaki and Y. Akaishi, Phys. Lett. B. **535** (2002) 70.

S. Ohnishi et al., Phys. Rev. C**95** (2017) 065202

Model	Kyoto		AY
	Type I	Type II	
B (MeV)	27.9	26.1	48.7
Γ (MeV)	30.9	59.3	61.9
$\delta\sqrt{s}$ (MeV)	$-61.0 - i25.0$	$-30.2 - i23.7$	
P_{K^-}	0.65	0.65	0.64
$P_{\bar{K}^0}$	0.35	0.35	0.36
$\sqrt{\langle r^2_{NN}\rangle}$ (fm)	2.16	2.07	1.84
$\sqrt{\langle r^2_{\bar{K}N}\rangle}$ (fm)	1.80	1.73	1.55
$\sqrt{\langle r^2_{N}\rangle}$ (fm)	1.12	1.08	0.958
$\sqrt{\langle r^2_{\bar{K}}\rangle}$ (fm)	1.14	1.10	0.988
$\langle T\rangle^{K^-}_G$ (MeV)	$117 + i28.8$	$124 + i53.1$	$102 + i31.4$
$\langle V\rangle^{K^-}_G$ (MeV)	$-113 - i33.7$	$-120 - i63.9$	$-102 - i47.0$
$\langle T\rangle^{\bar{K}^0}_G$ (MeV)	$74.3 + i18.4$	$76.3 + i33.1$	$63.1 + i15.5$
$\langle V\rangle^{\bar{K}^0}_G$ (MeV)	$-62.0 - i19.1$	$-64.3 - i35.6$	$-48.6 - i21.6$
$2\langle V\rangle^{K^-\bar{K}^0}_G$ (MeV)	$-44.1 - i9.76$	$-41.9 - i16.4$	$-64.0 - i9.24$
$P^{I=0}_{\bar{K}N}$	0.72	0.73	0.73
$P^{I=1}_{\bar{K}N}$	0.28	0.27	0.27

<u>Additional experiment is desired to understand the internal structure.</u>

Future plan

Remaining questions on K^-pp

- Does $\bar{K}^0nn$ state exist?
- What is J^P of the observed K^-pp state?
- What is decay branch of other channels?
- Why is Γ_{K^-pp} so large? (about twice of theoretical expectations)
  - substructure?
- What is the origin of the broad distribution?
  - $\bar{K}_{QF} + NN \rightarrow \Lambda n$?
- What is the internal structure of K^-pp?
- What is the size of K^-pp?

Spin-parity of K^-pp

- What is J^P of the observed K^-pp state?

$\bar{K}: J^P = 0^-, I = \frac{1}{2}$

$N: J^P = \frac{1}{2}^+, I = \frac{1}{2}$

Spin-parity of $\bar{K}NN$ $(I = 1/2)$

I_{NN}	S_{NN}	L_{NN}	$L_{\bar{K}}$	J^P
1	0	0	0	0^-
1	0	0	1	1^+
0	1	0	0	1^-
0	1	0	1	0^+

$I_{NN} = 0$state is less bound

Spin-parity of K^-pp

- What is J^P of the observed K^-pp state?

$\bar{K}: J^P = 0^-, I = \frac{1}{2}$

$N: J^P = \frac{1}{2}^+, I = \frac{1}{2}$

$\Lambda^*: J^P = \frac{1}{2}^-, I = 0$

Spin-parity of $\bar{K}NN$ $(I = 1/2)$

I_{NN}	S_{NN}	L_{NN}	$L_{\bar{K}}$	J^P
1	0	0	0	0^-
1	0	0	1	1^+
0	1	0	0	1^-
0	1	0	1	0^+

$I_{NN} = 0$state is less bound

Spin-parity of $\Lambda(1405)N$

S_{Λ^*N}	L_{Λ^*N}	J^P
0	0	0^-
0	1	1^+
1	0	1^-
1	1	0^+

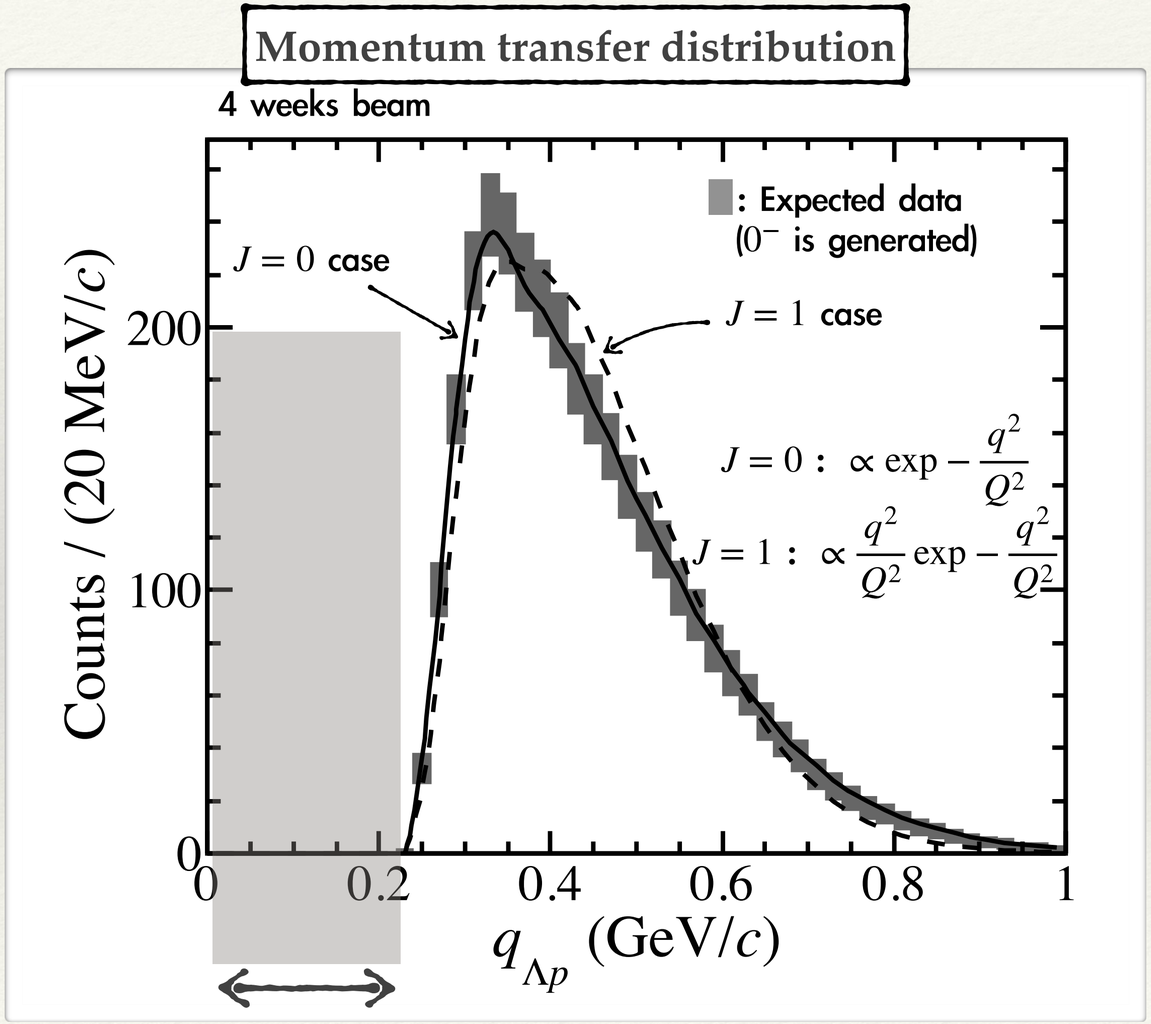
Spin-parity of K^-pp

- What is J^P of the observed K^-pp state?

Spin-parity of $\bar{K}NN$ $(I = 1/2)$

I_{NN}	S_{NN}	L_{NN}	$L_{\bar{K}}$	J^P
1	0	0	0	0^-
1	0	0	1	1^+
0	1	0	0	1^-
0	1	0	1	0^+

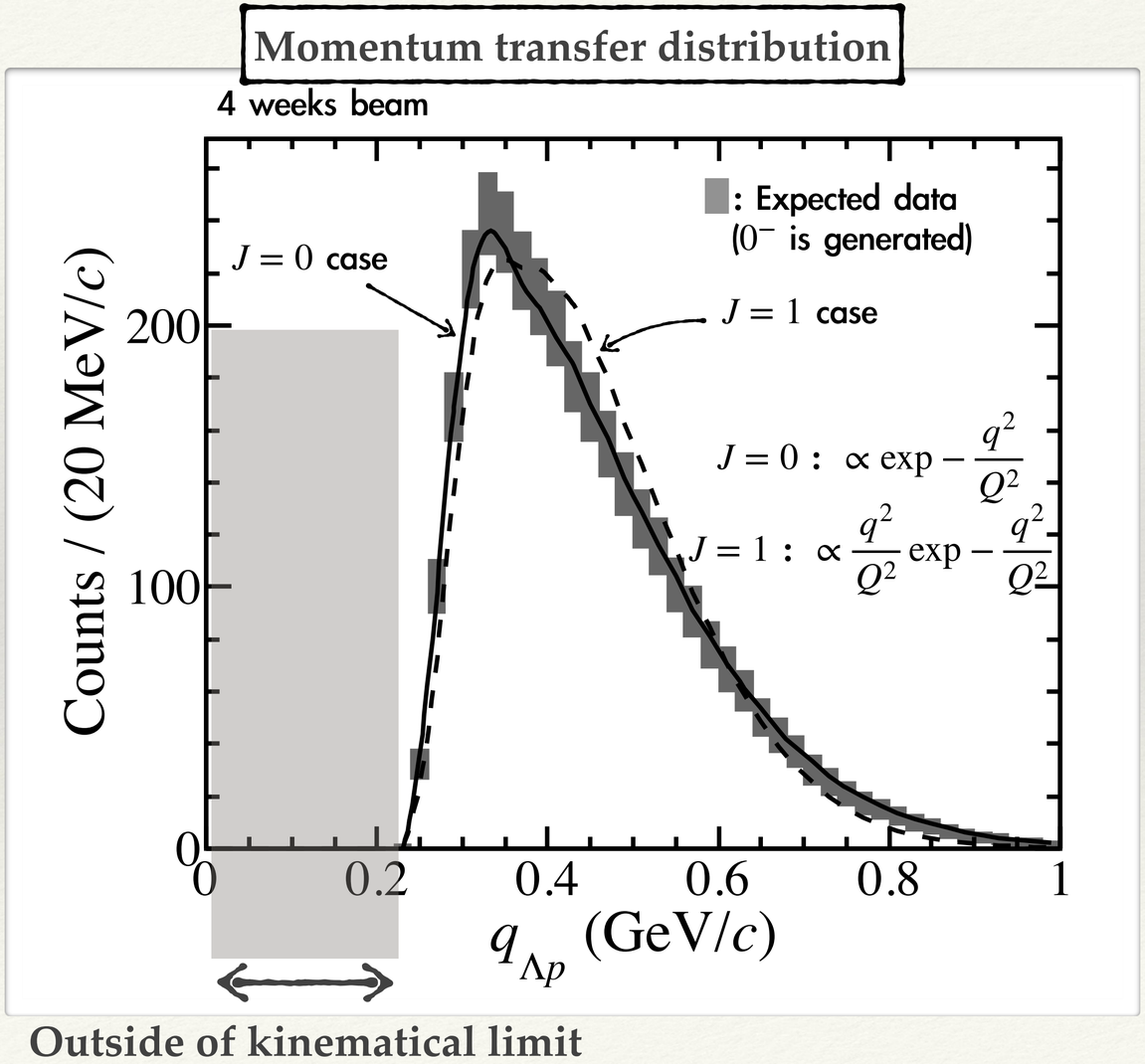
$I_{NN} = 0$state is less bound



Spin-parity of K^-pp

- Momentum transfer distribution has $J = 0$ / 1 information.
  - However, very higher statistics is necessary to determine J.
    - Because of kinematical limit
  - No information on P is obtained.

<u>Need statistics & additional measurement</u>



Spin-parity of K^-pp

Spin-parity of $\bar{K}NN$ ($I = 1/2$)

I_{NN}	S_{NN}	L_{NN}	$L_{\bar{K}}$	J^P
1	0	0	0	0^-
1	0	0	1	1^+
0	1	0	0	1^-
0	1	0	1	0^+

$I_{NN} = 0$state is less bound

Spin-spin correlation of Λp pair

P-wave decay

$$|0^-\rangle = \frac{1}{\sqrt{3}}|1,+1\rangle_L \left|-\frac{1}{2}\right\rangle_\Lambda \left|-\frac{1}{2}\right\rangle_p \quad \text{parallel}$$

$$-\frac{1}{\sqrt{6}}|1,0\rangle_L \left|+\frac{1}{2}\right\rangle_\Lambda \left|-\frac{1}{2}\right\rangle_p \quad \text{anti-parallel}$$

$$-\frac{1}{\sqrt{6}}|1,0\rangle_L \left|-\frac{1}{2}\right\rangle_\Lambda \left|+\frac{1}{2}\right\rangle_p \quad \text{anti-parallel}$$

$$+\frac{1}{\sqrt{3}}|1,-1\rangle_L \left|+\frac{1}{2}\right\rangle_\Lambda \left|+\frac{1}{2}\right\rangle_p \quad \text{parallel}$$

S-wave decay

$$|0^+\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_L \left|+\frac{1}{2}\right\rangle_\Lambda \left|-\frac{1}{2}\right\rangle_p - |0\rangle_L \left|-\frac{1}{2}\right\rangle_\Lambda \left|+\frac{1}{2}\right\rangle_p\right).$$

anti-parallel anti-parallel

Spin-parity of K^-pp

Spin-parity of $\bar{K}NN$ ($I = 1/2$)

I_{NN}	S_{NN}	L_{NN}	$L_{\bar{K}}$	J^P
1	0	0	0	0^-
1	0	0	1	1^+
0	1	0	0	1^-
0	1	0	1	0^+

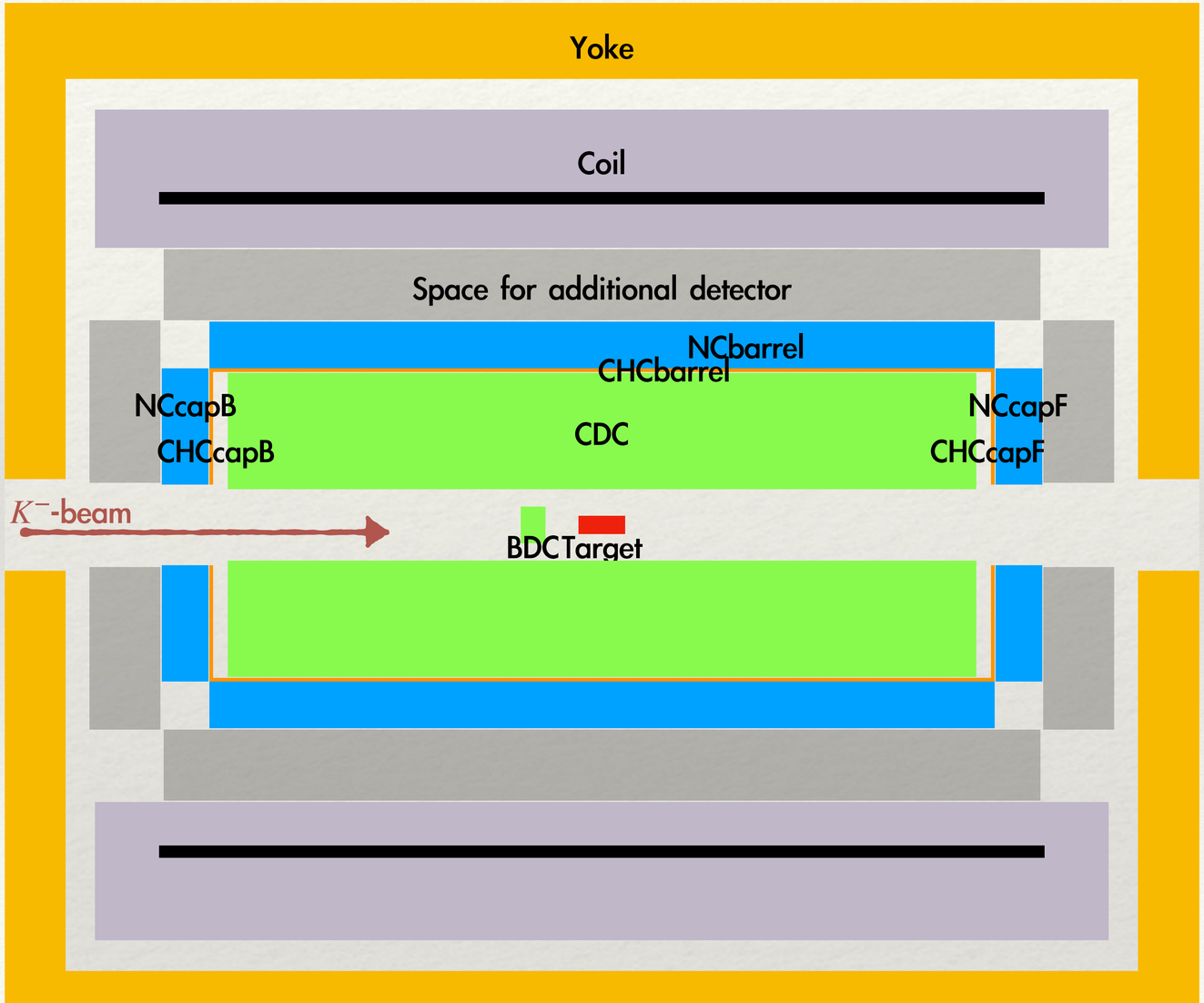
$I_{NN} = 0$state is less bound

Spin-spin correlation of Λp pair

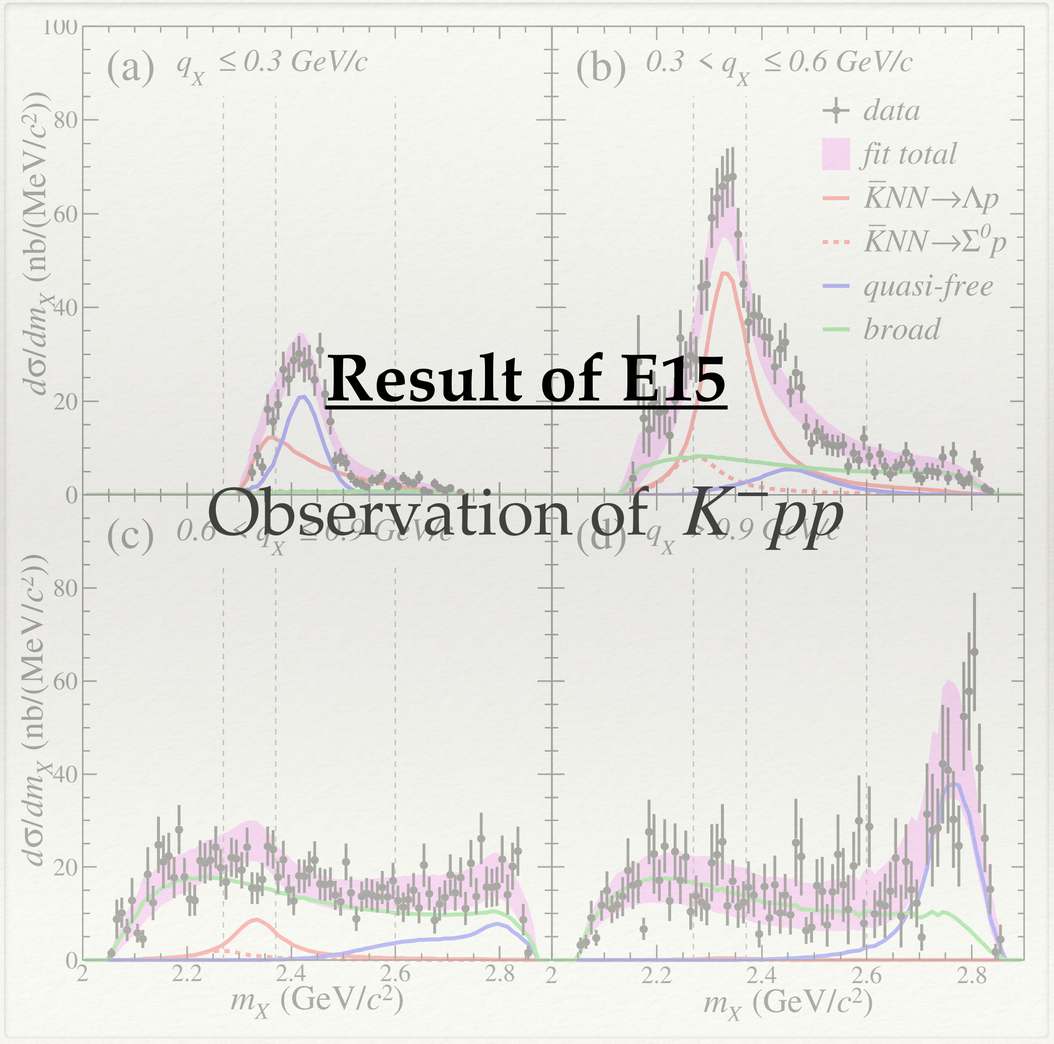
$\alpha_{\Lambda p}$
$+1/3$
$+1/3$
$-2/3$
-1

- Spin-spin correlation of Λp pair has parity information.
  - Also need higher statistics

New CDS

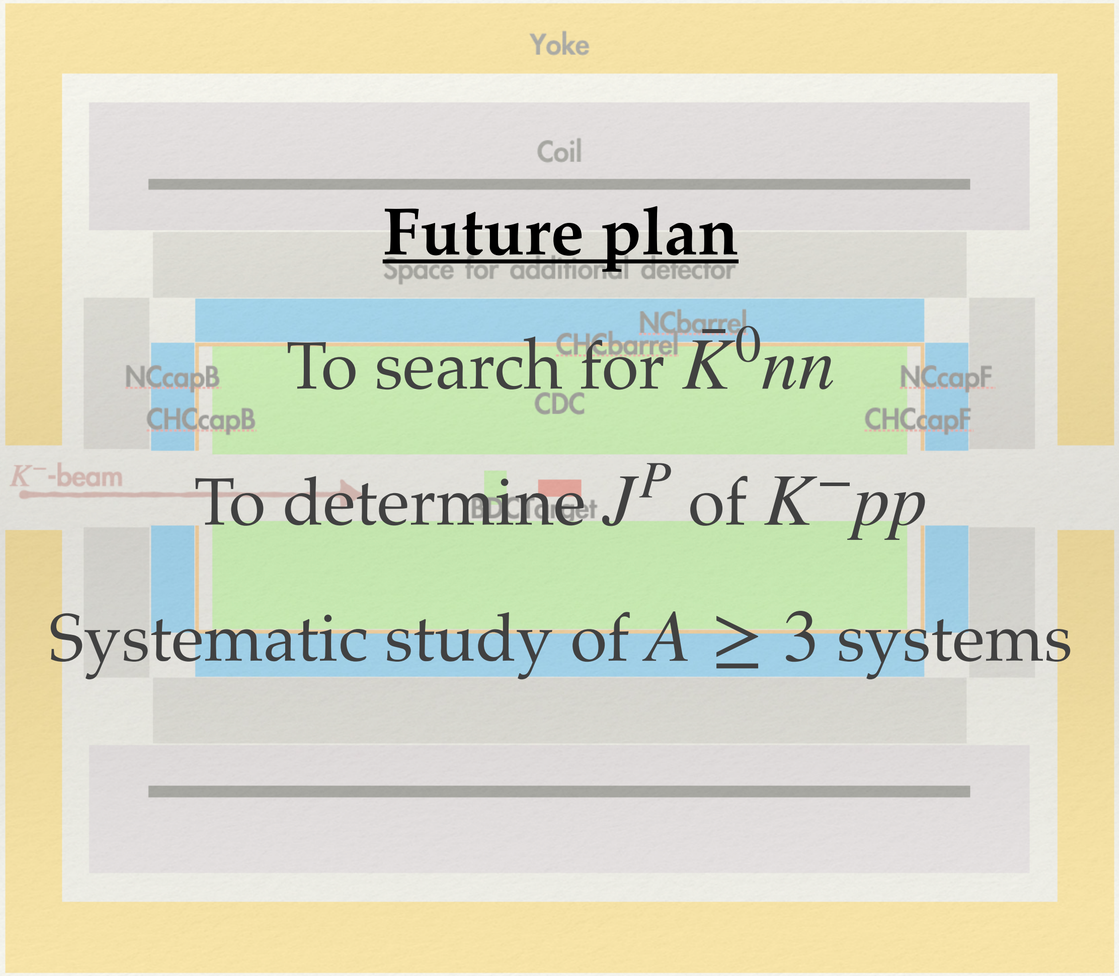

Yoke
Coil
Space for additional detector
NCbarrel
CHCbarrel
NCcapB
CHCcapB
CDC
NCcapF
CHCcapF
K^--beam
BDCTarget

Summary



Result of E15

Observation of K^-pp



Future plan

To search for $\bar{K}^0nn$

To determine J^P of K^-pp

Systematic study of $A \geq 3$ systems

Thank you for your attention

J-PARC E15 collaboration

S. Ajimura[1], H. Asano[2], G. Beer[3], C. Berucci[4], H. Bhang[5], M. Bragadireanu[6], P. Buehler[4], L. Busso[7,8], M. Cargnelli[4], S. Choi[5], C. Curceanu[9], S. Enomoto[10], H. Fujioka[11], Y. Fujiwara[12], T. Fukuda[13], C. Guaraldo[9], T. Hashimoto[14], R. S. Hayano[12], T. Hiraiwa[1], M. Iio[10], M. Iliescu[9], K. Inoue[1], Y. Ishiguro[15], T. Ishikawa[12], S. Ishimoto[10], K. Itahashi[2], M. Iwasaki[2,11],* K. Kanno[12], K. Kato[15], Y. Kato[2], S. Kawasaki[1], P. Kienle[16],† H. Kou[11], Y. Ma[2], J. Marton[4], Y. Matsuda[12], Y. Mizoi[13], O. Morra[7], T. Nagae[15], H. Noumi[1], H. Ohnishi[17,2], S. Okada[2], H. Outa[2], K. Piscicchia[9], Y. Sada[1], A. Sakaguchi[1], F. Sakuma[2],‡ M. Sato[10], A. Scordo[9], M. Sekimoto[10], H. Shi[9], K. Shirotori[1], D. Sirghi[9,6], F. Sirghi[9,6], K. Suzuki[4], S. Suzuki[10], T. Suzuki[12], K. Tanida[14], H. Tatsuno[18], M. Tokuda[11], D. Tomono[1], A. Toyoda[10], K. Tsukada[17], O. Vazquez Doce[9,16], E. Widmann[4], T. Yamaga[2,1],§ T. Yamazaki[12,2], Q. Zhang[2], and J. Zmeskal[4]

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[11] *Tokyo Institute of Technology, Tokyo, 152-8551, Japan*
[12] *The University of Tokyo, Tokyo, 113-0033, Japan*
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[14] *Japan Atomic Energy Agency, Ibaraki 319-1195, Japan*
[15] *Kyoto University, Kyoto, 606-8502, Japan*
[16] *Technische Universität München, D-85748, Garching, Germany*
[17] *Tohoku University, Sendai, 982-0826, Japan and*
[18] *Lund University, Lund, 221 00, Sweden*

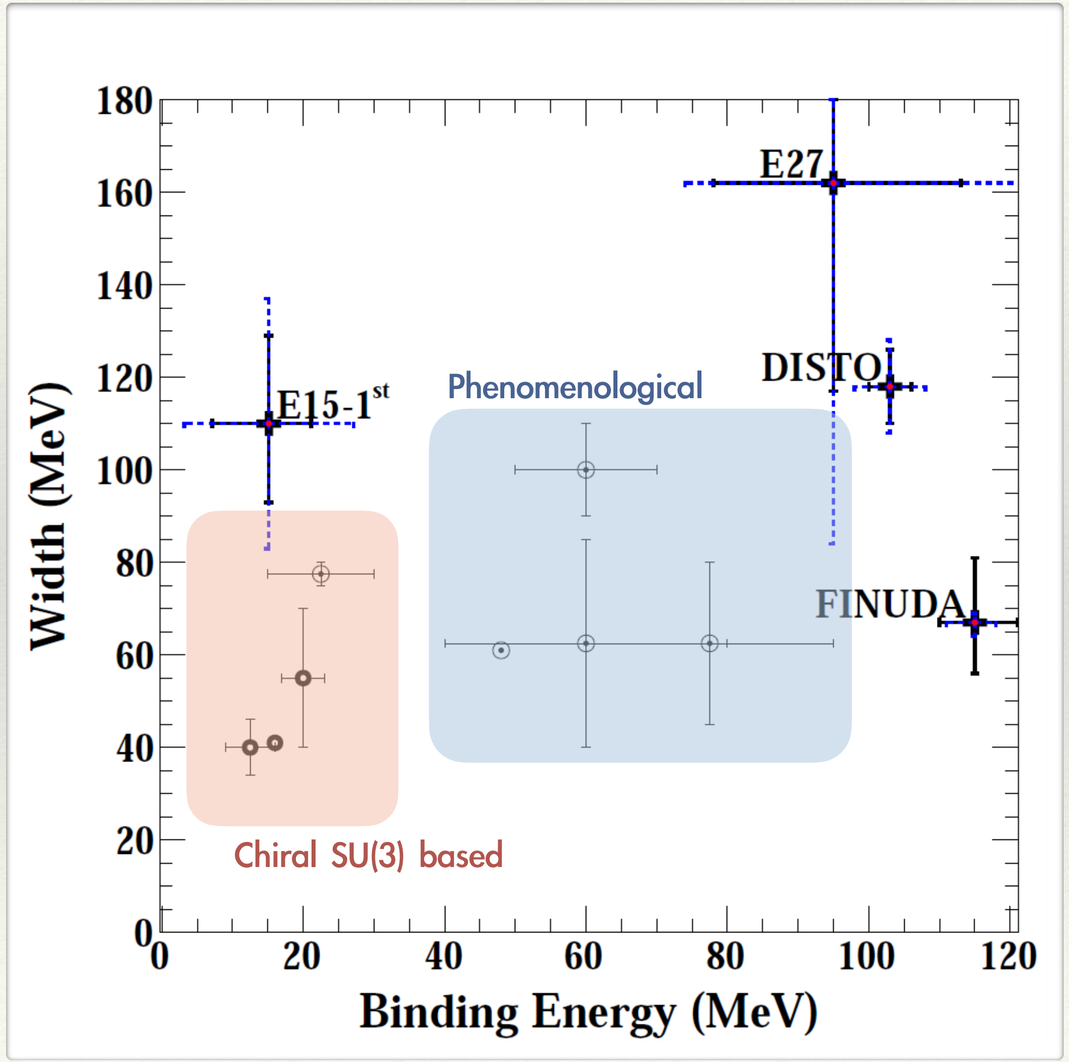
Backup

Theoretical studies

From F. Sakuma NFQCD2018 slide

KbarN interaction	**Chiral SU(3)**			**Phenomenological**			
Method	Variational		Faddeev	Variational		Faddeev	
	Barnea, Gal, Liverts	Dote, Hyodo, Weise	Ikeda, Kamano, Sato	Yamazaki, Akaishi	Wyceck, Green	Shevchenko, Gal, Mares	Ikeda, Sato
B.E. (MeV)	16	17 - 23	9 - 16	48	40 - 80	50 - 70	60 - 95
Width (MeV)	41	40 - 70	34 - 46	61	40 - 85	90 - 110	45 - 80

Searching for K^-pp so far



Expected spectrum of $\bar{K}^0nn$ search

Λn detection mode, Λn system measurement

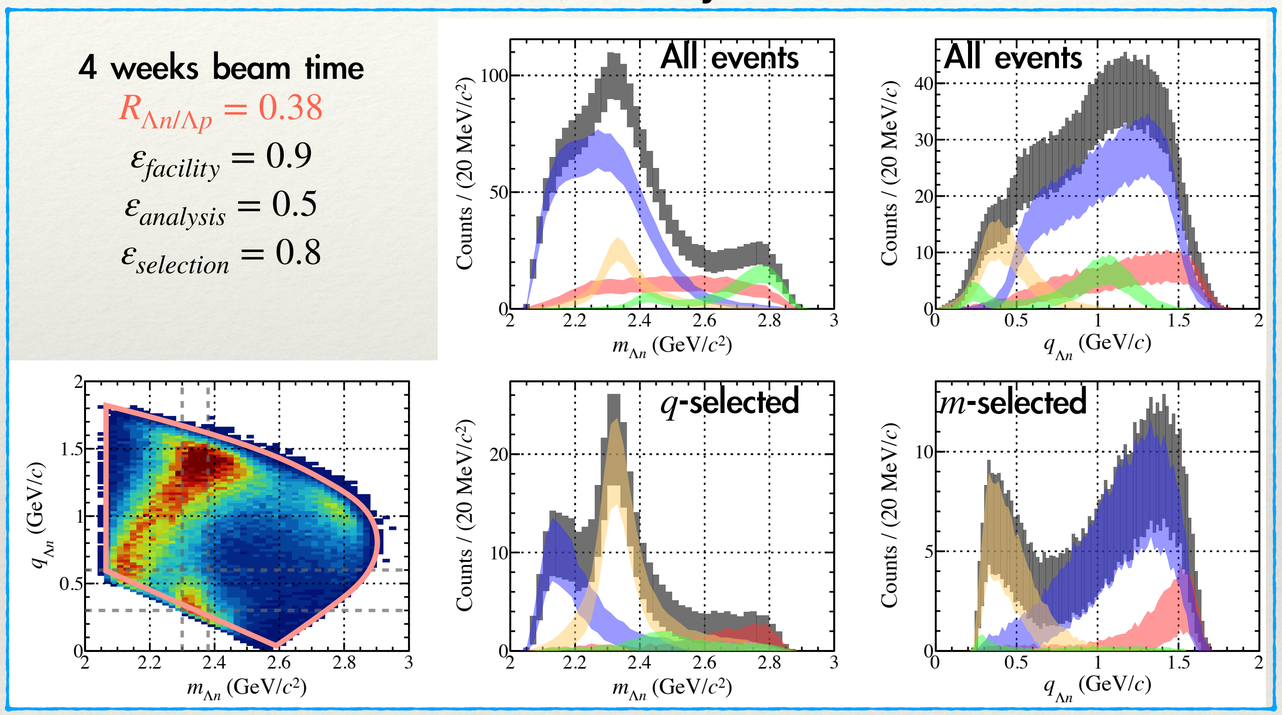
4 weeks beam time

$R_{\Lambda n/\Lambda p} = 0.38$

$\varepsilon_{facility} = 0.9$

$\varepsilon_{analysis} = 0.5$

$\varepsilon_{selection} = 0.8$



~ 1/10 statistics of E15-2nd is expected.

Error band is statistical error.

: $K^-pp \to \Lambda p$

: $\bar{K}^0nn \to \Lambda n$

: $\bar{K}_{QF} + NN \to \Lambda p$

: $\bar{K}_{QF} + NN \to \Lambda n$

Expected spectrum of $\bar{K}^0nn$ search

Λp detection mode, Λn system measurement

4 weeks beam time

$R_{\Lambda n/\Lambda p} = 0.38$

$\varepsilon_{facility} = 0.9$

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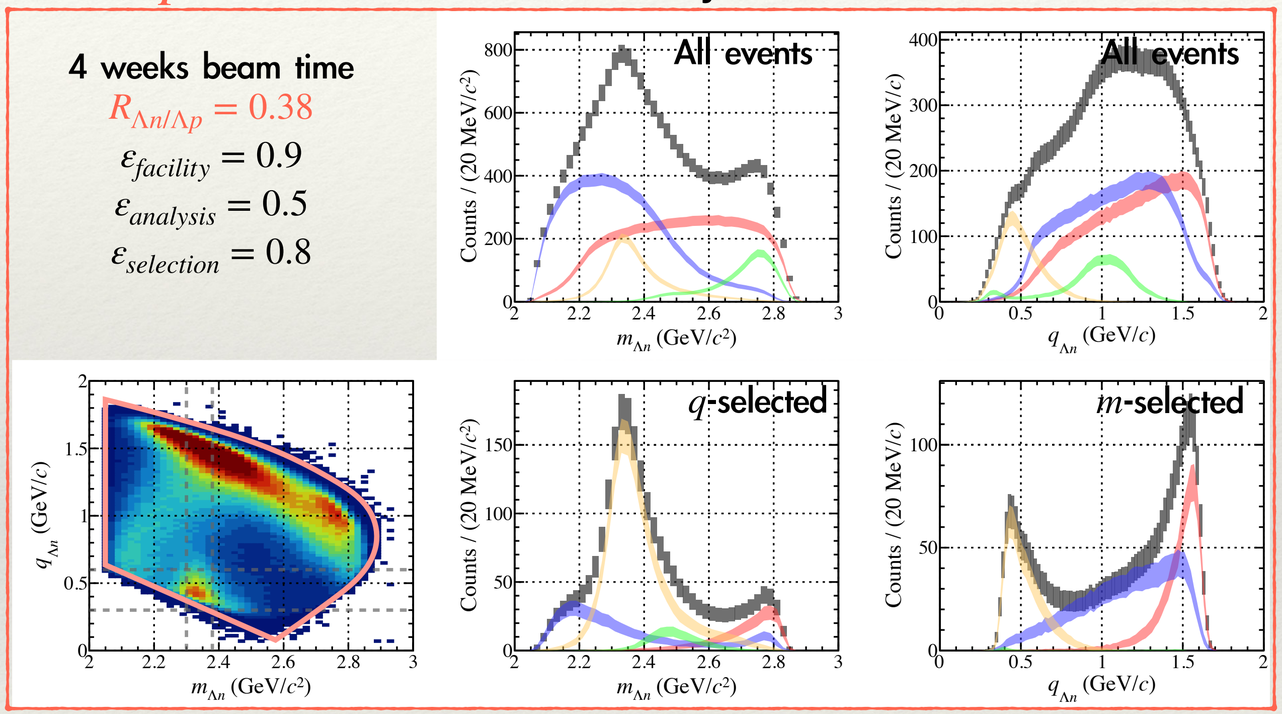
$\varepsilon_{selection} = 0.8$



~ 1/2 times statistics of E15-2nd is expected.

Error band is statistical error.

: $K^-pp \to \Lambda p$

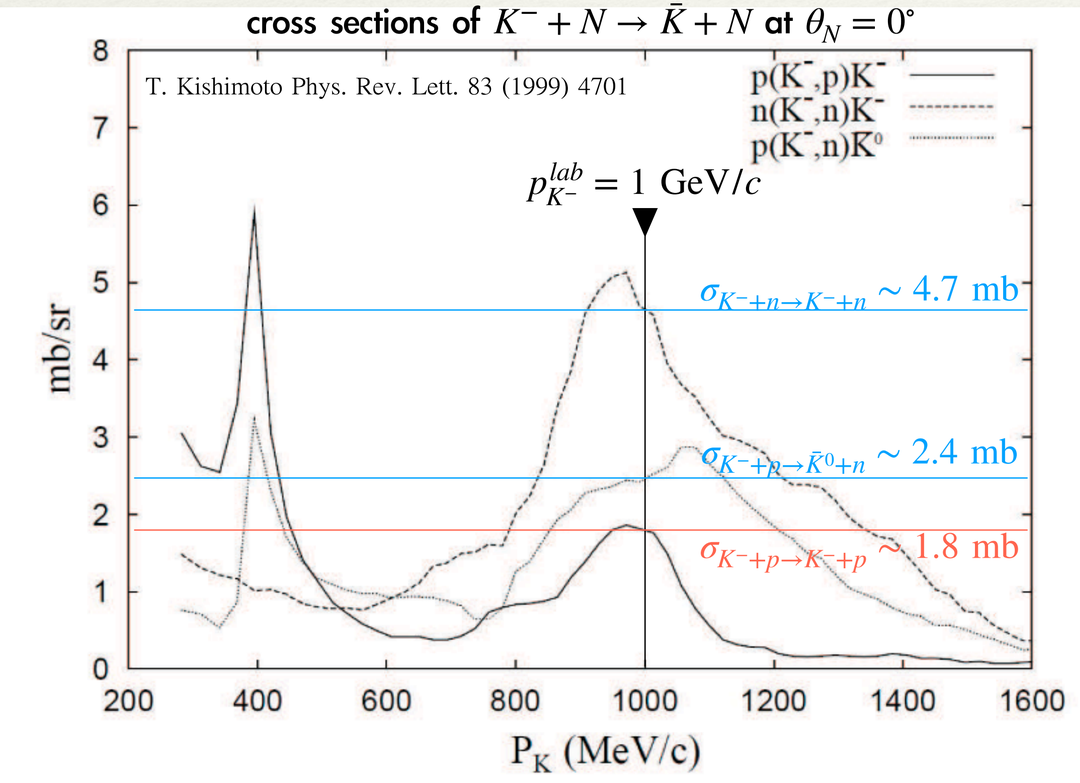
: $\bar{K}^0nn \to \Lambda n$

: $\bar{K}_{QF} + NN \to \Lambda p$

: $\bar{K}_{QF} + NN \to \Lambda n$

Expected spectrum of $\bar{K}^0nn$ search

*$R_{\Lambda n/\Lambda p} \sim 0.38$ is assumed from simple considering of elementary cross sections in very forward angle.



$\sigma_{\Lambda n} \propto 2 \times \sigma_{K^-+p\to K^-+p} \sim 3.6$ mb

$\sigma_{\Lambda p} \propto 2 \times \sigma_{K^-+p\to \bar{K}^0+n} + \sigma_{K^-+n\to K^-+n} \sim 9.5$ mb ($^3\mathrm{He} = ppn$)

- Luminosity (90 kW beam power)
  - $\mathscr{L} = 1.9$ /nb /week *With shorten beam line
- Cross sections
  - Bound state
    - $\sigma_{K^-pp} \cdot Br_{\Lambda p} = 9.29\ \mu$b ⟵ E15 result
    - $\sigma_{\bar{K}^0nn} \cdot Br_{\Lambda n} = R_{\Lambda n/\Lambda p} \cdot \sigma_{K^-pp} \cdot Br_{\Lambda p} = 3.10\ \mu$b
  - Quasi-free
    - $\sigma_{QF}\ Br_{\Lambda p} = 10.7\ \mu$b ⟵ E15 result
    - $\sigma_{QF} \cdot Br_{\Lambda n} = R_{\Lambda n/\Lambda p} \cdot \sigma_{QF} \cdot Br_{\Lambda p} = 3.57\ \mu$b