Study of mesonic decay of $\bar{K}NN$ using J-PARC E15 data

Takumi Yamaga (RIKEN)
for the J-PARC E15 collaboration

ECT* workshop (2023.10.9–13)

$\bar{K}N$ interaction

$I_{\bar{K}N} = 0$	$\frac{1}{\sqrt{2}}\left(-K^- p + \bar{K}^0 n\right)$	Strong attractive
$I_{\bar{K}N} = 1$	$\bar{K}^0 p$ $\frac{1}{\sqrt{2}}\left(K^- p + \bar{K}^0 n\right)$ $K^- n$	attractive

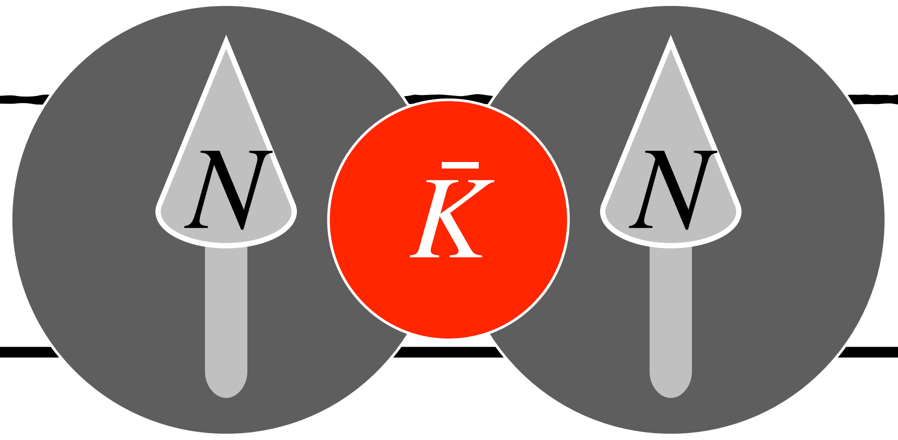
Possible to make quasi-bound state with $I_{\bar{K}N} = 0$

$\Lambda(1405)$

$\bar{K}$-nuclei

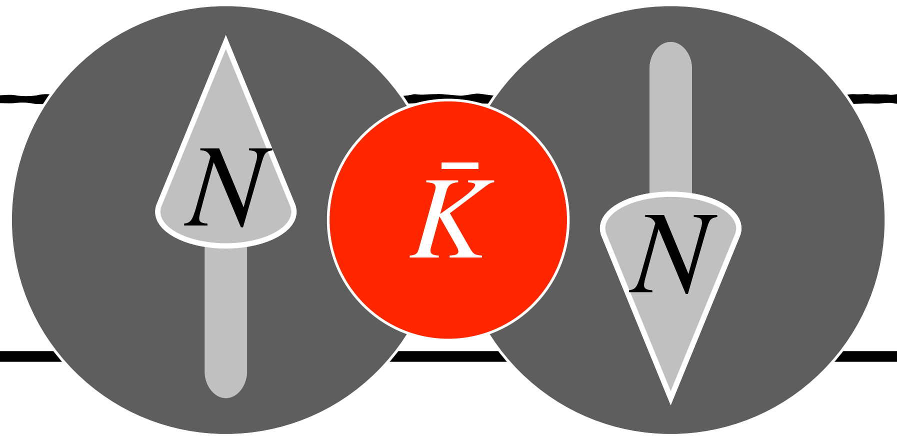
$\bar{K}NN$

The lightest $\bar{K}$-nucleus



$J^\pi = 1^-$

$$-\sqrt{\frac{1}{4}}[\bar{K}N]^{I=0}N + \sqrt{\frac{3}{4}}[\bar{K}N]^{I=1}N$$



$J^\pi = 0^-$

$$\sqrt{\frac{3}{4}}[\bar{K}N]^{I=0}N + \sqrt{\frac{1}{4}}[\bar{K}N]^{I=1}N$$

No theoretical study doubts the existence of $\bar{K}NN$,

but predicted BE & Γ highly depend on model.

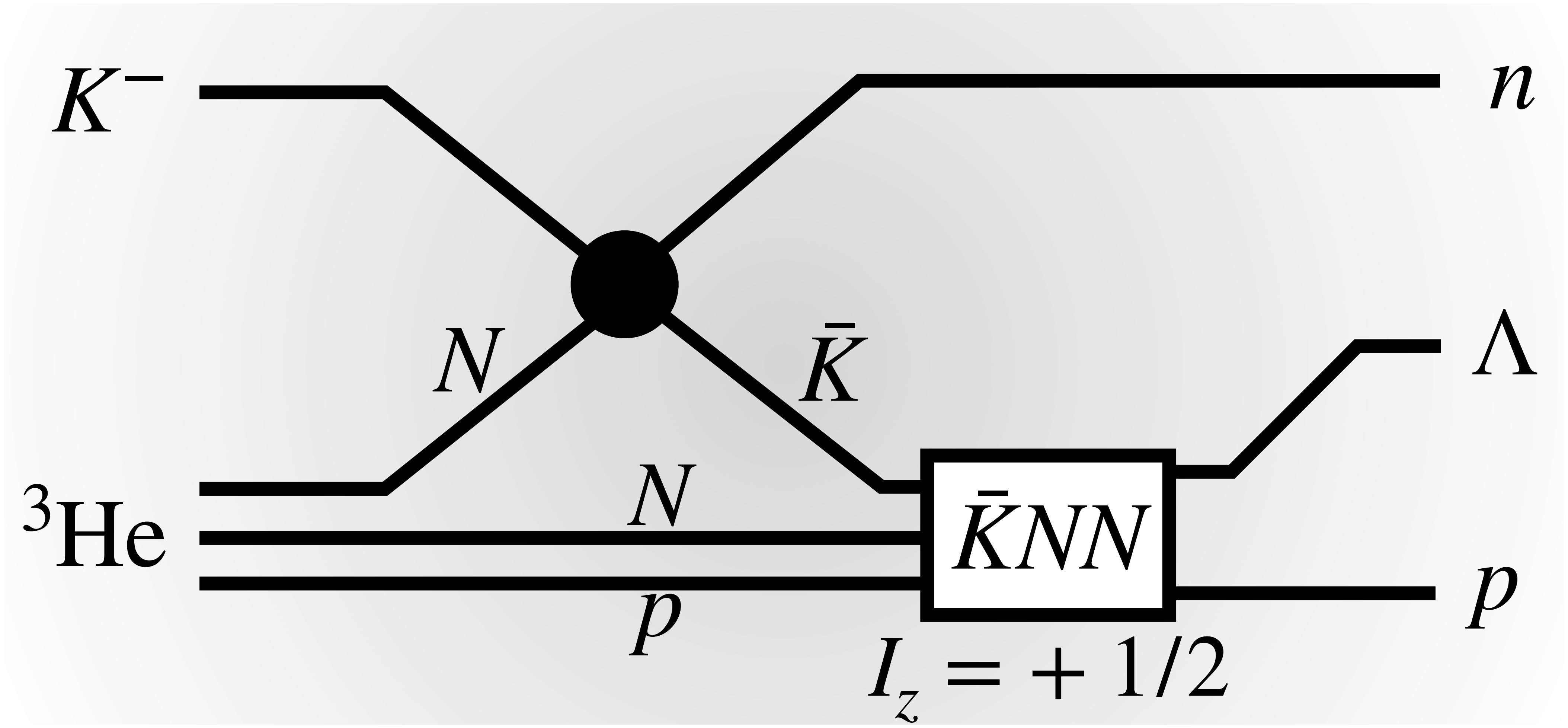
BE = 9 – 95 MeV Γ = 16 – 110 MeV

L. Tolos & L. Fabbietti, Prog.Part.Nucl.Phys. 112 (2020) 103770

We conducted an experimental search for $\bar{K}NN$ @ J-PARC (E15 experiment)

J-PARC E15

Production reaction

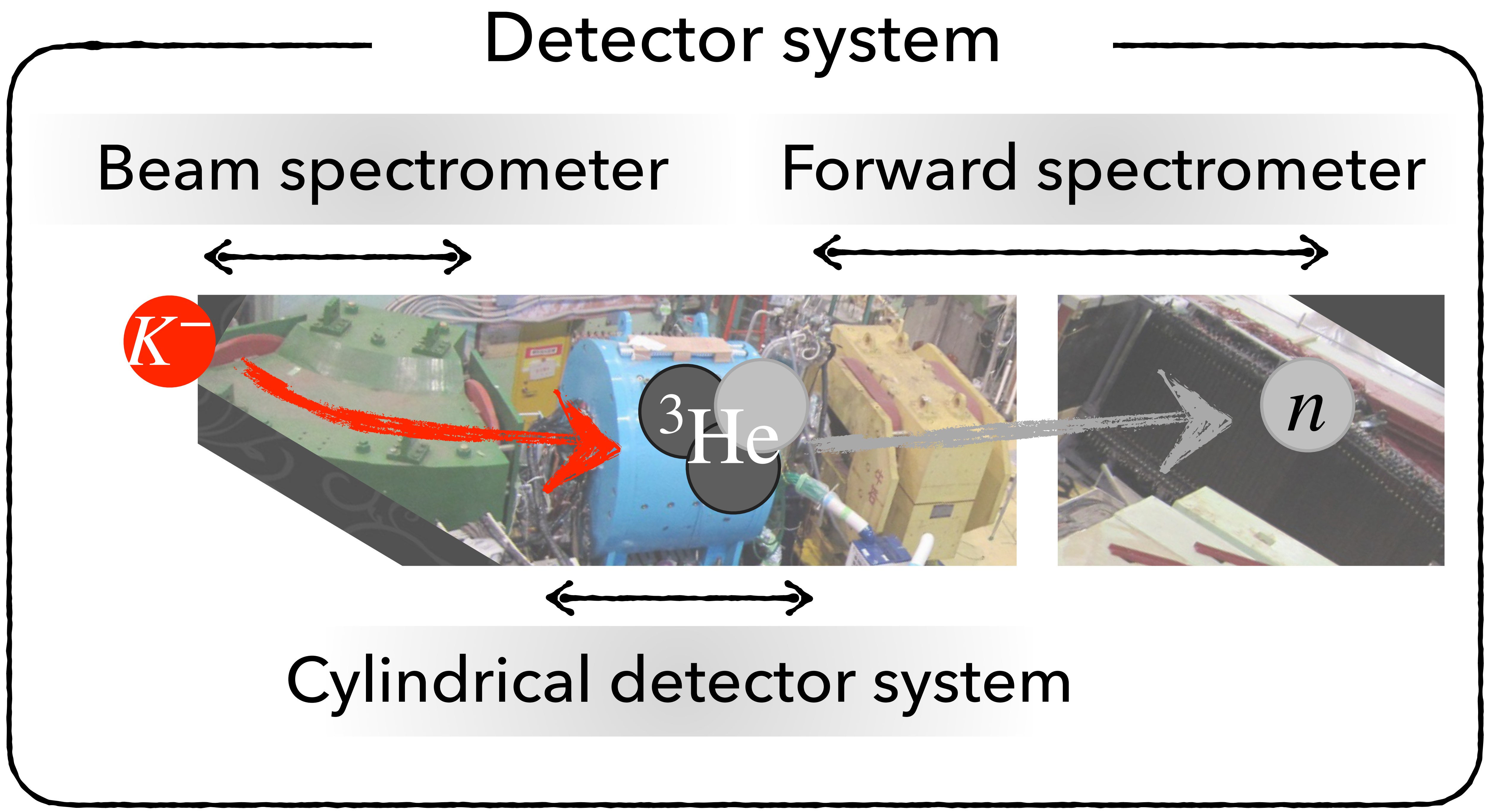


Exclusive Invariant-mass spectroscopy

To select Λpn final state

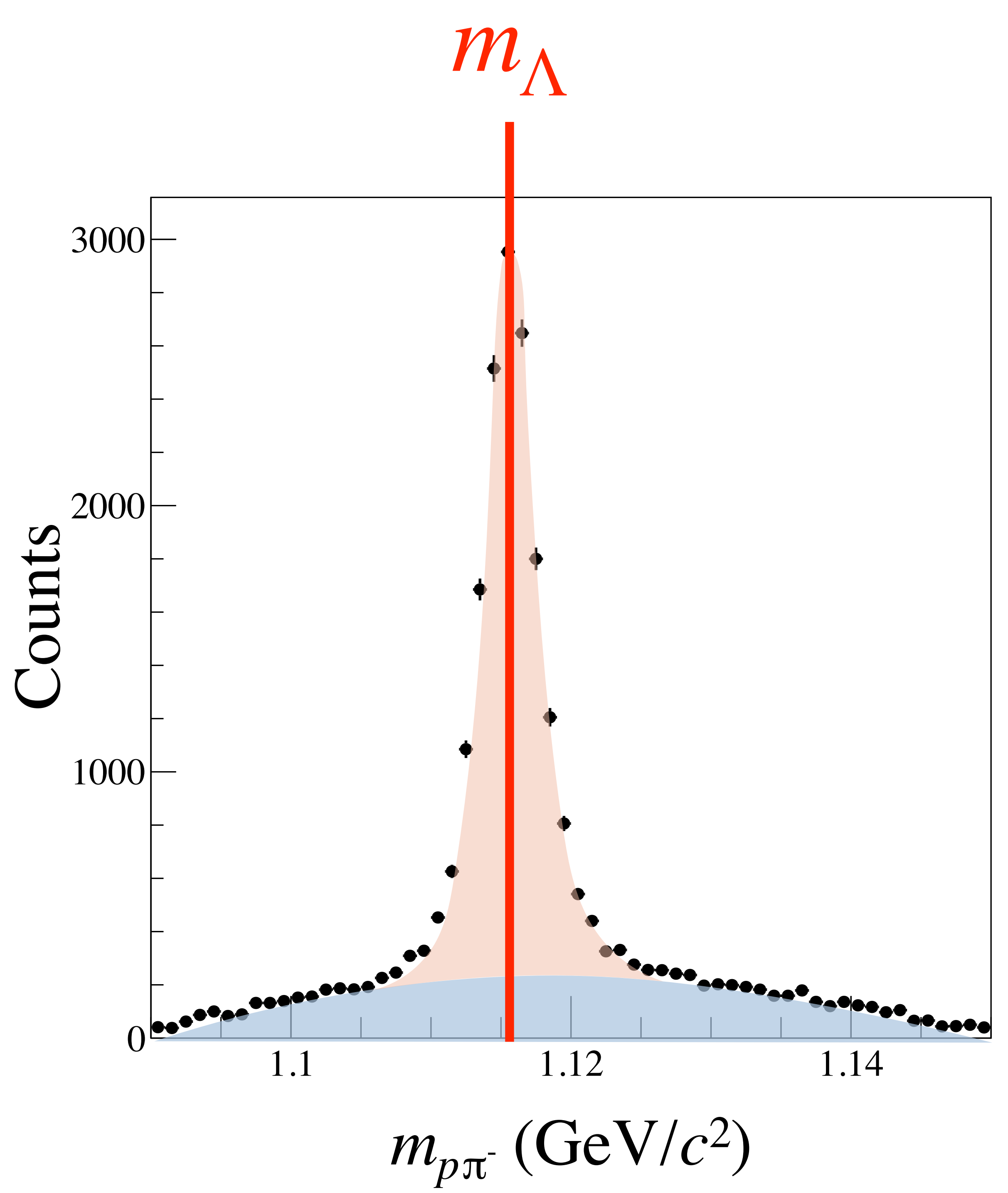
To measure Λp invariant-mass & momentum transfer

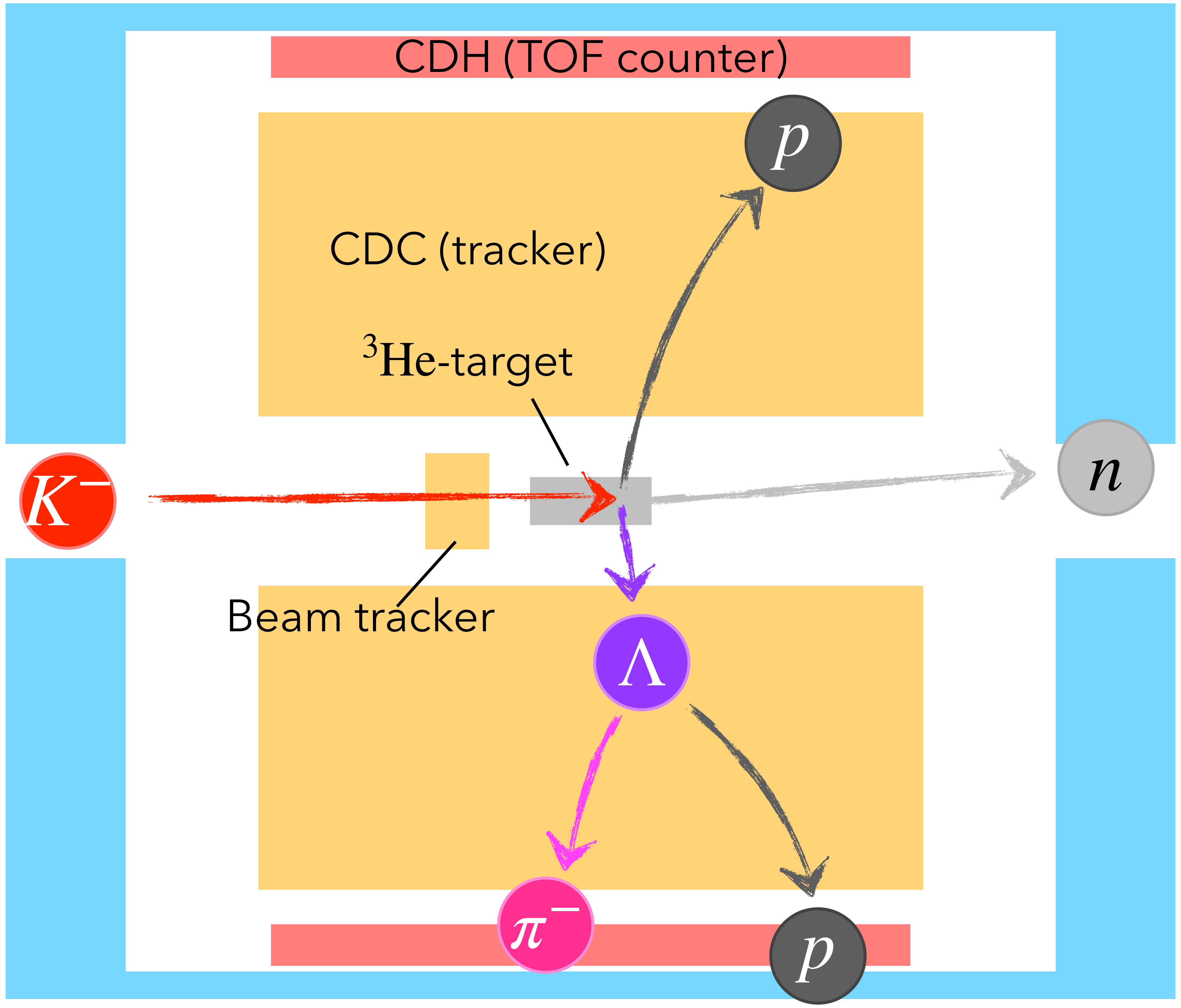
J-PARC E15


Detector system
Beam spectrometer
Forward spectrometer
K^-
^{3}He
n
Cylindrical detector system

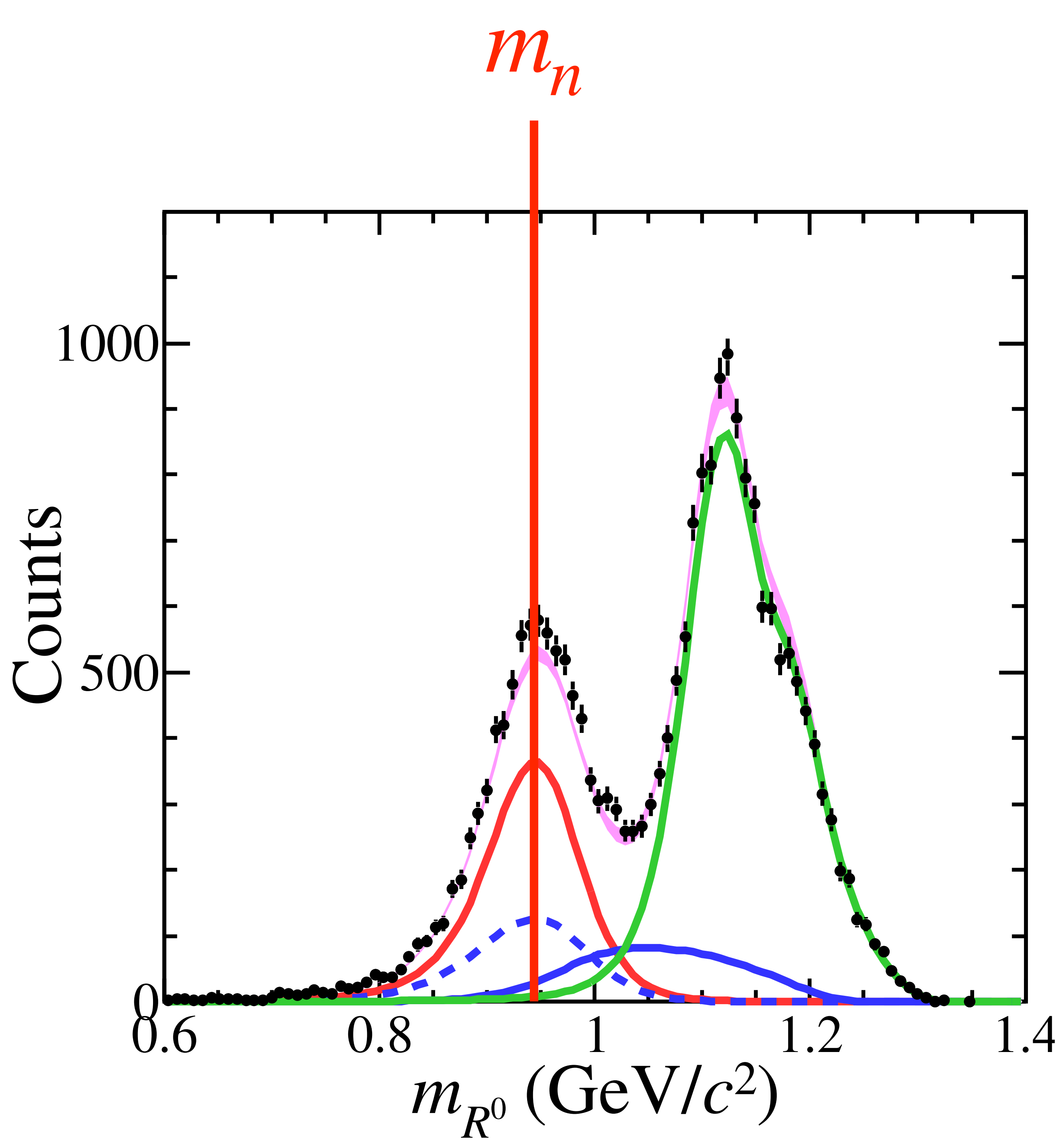
J-PARC E15

Reconstruction of Λ



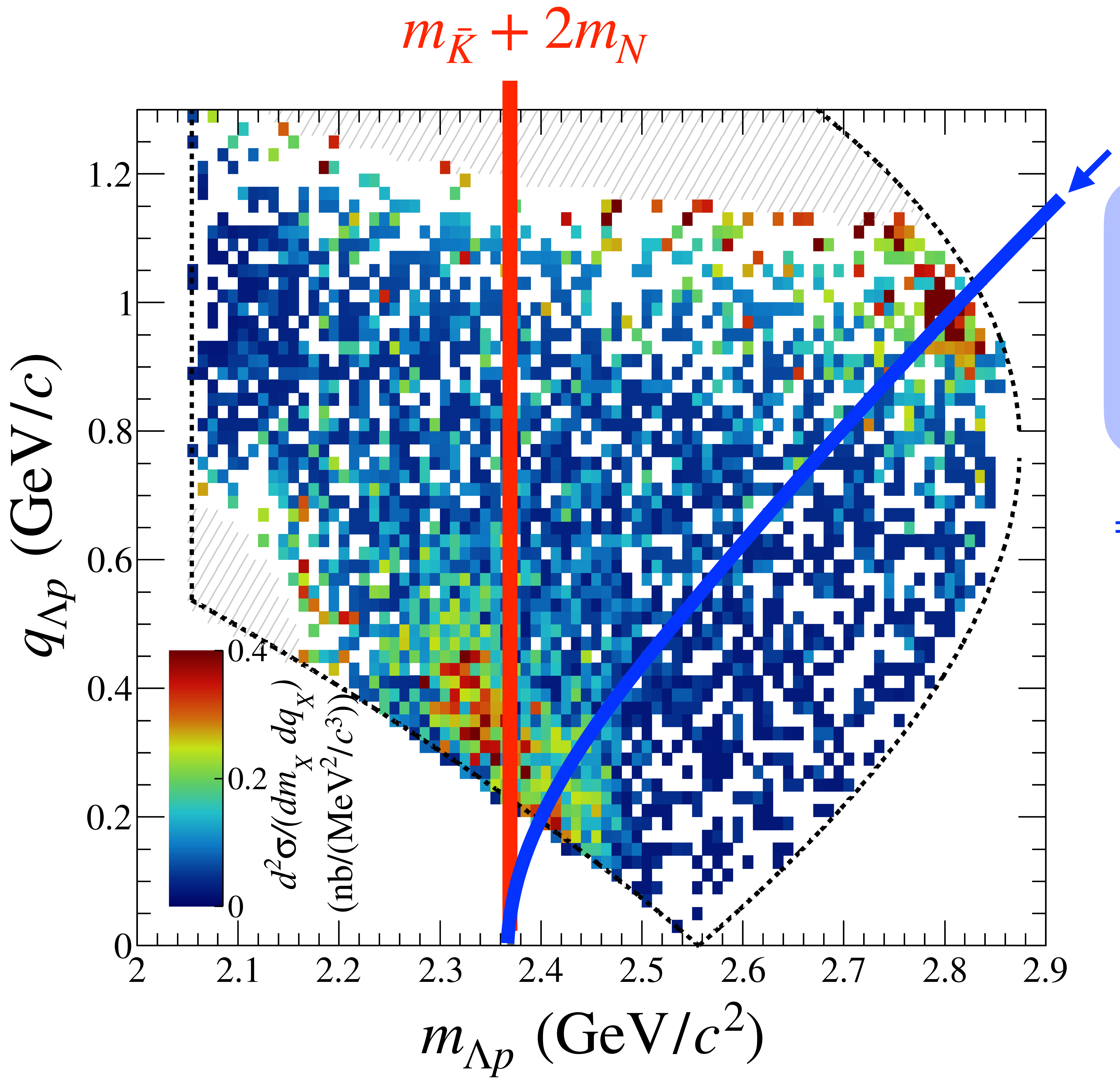


Identification of n_{miss}

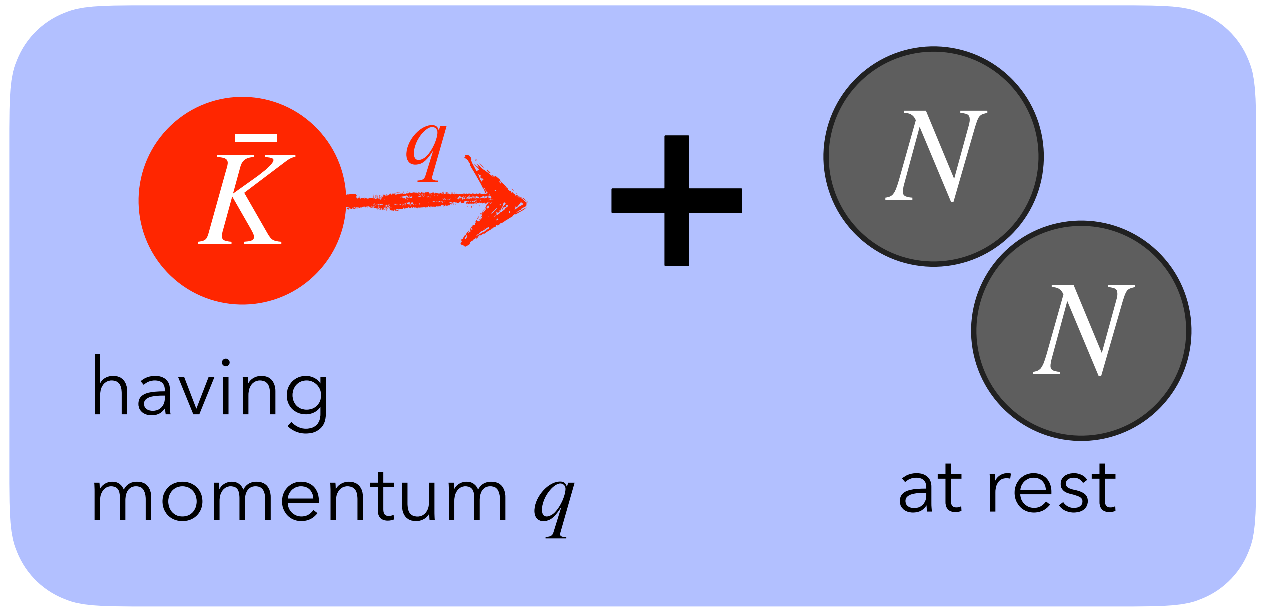


Purity of the Λpn final state $\sim 80\,\%$

Obtained 2D distribution



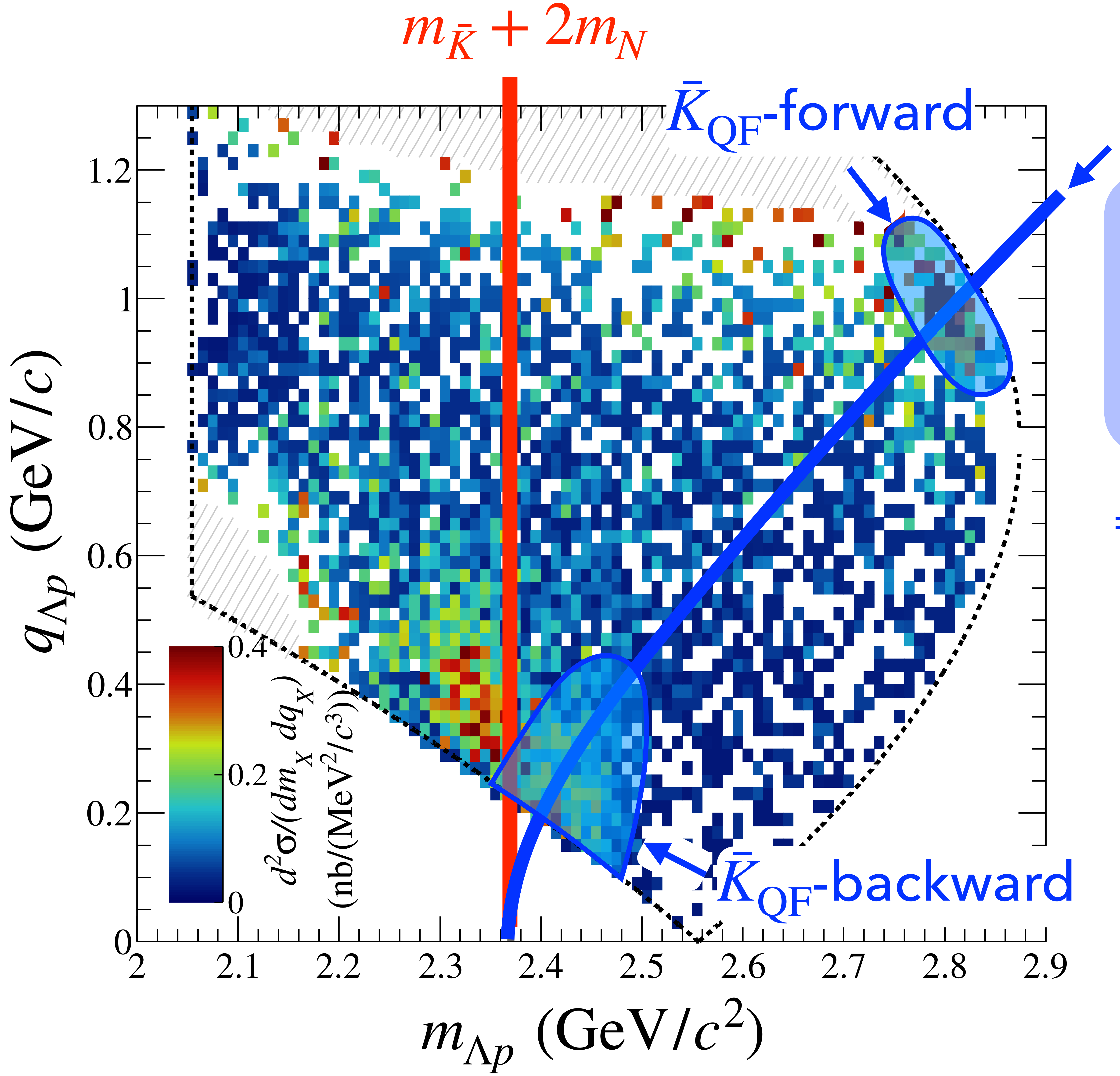
Mass of



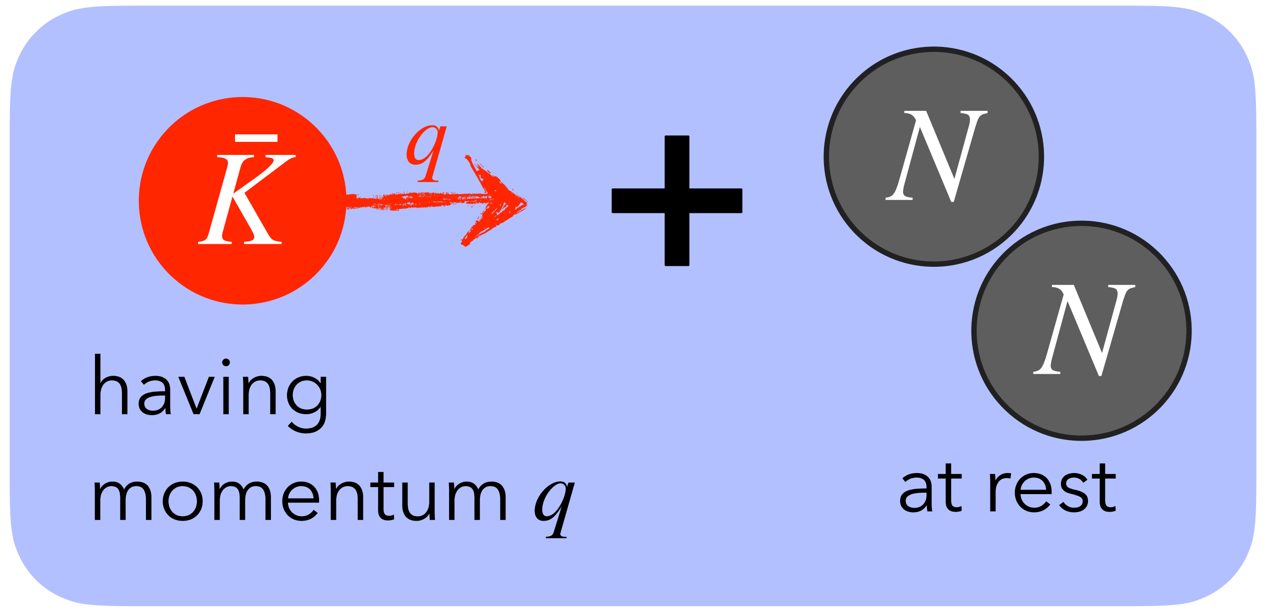
$$= \sqrt{4m_N^2 + m_{\bar{K}}^2 + 4m_N\sqrt{m_{\bar{K}}^2 + q^2}}$$

Quasi-free $\bar{K}$ absorption

Obtained 2D distribution



Mass of



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⇩

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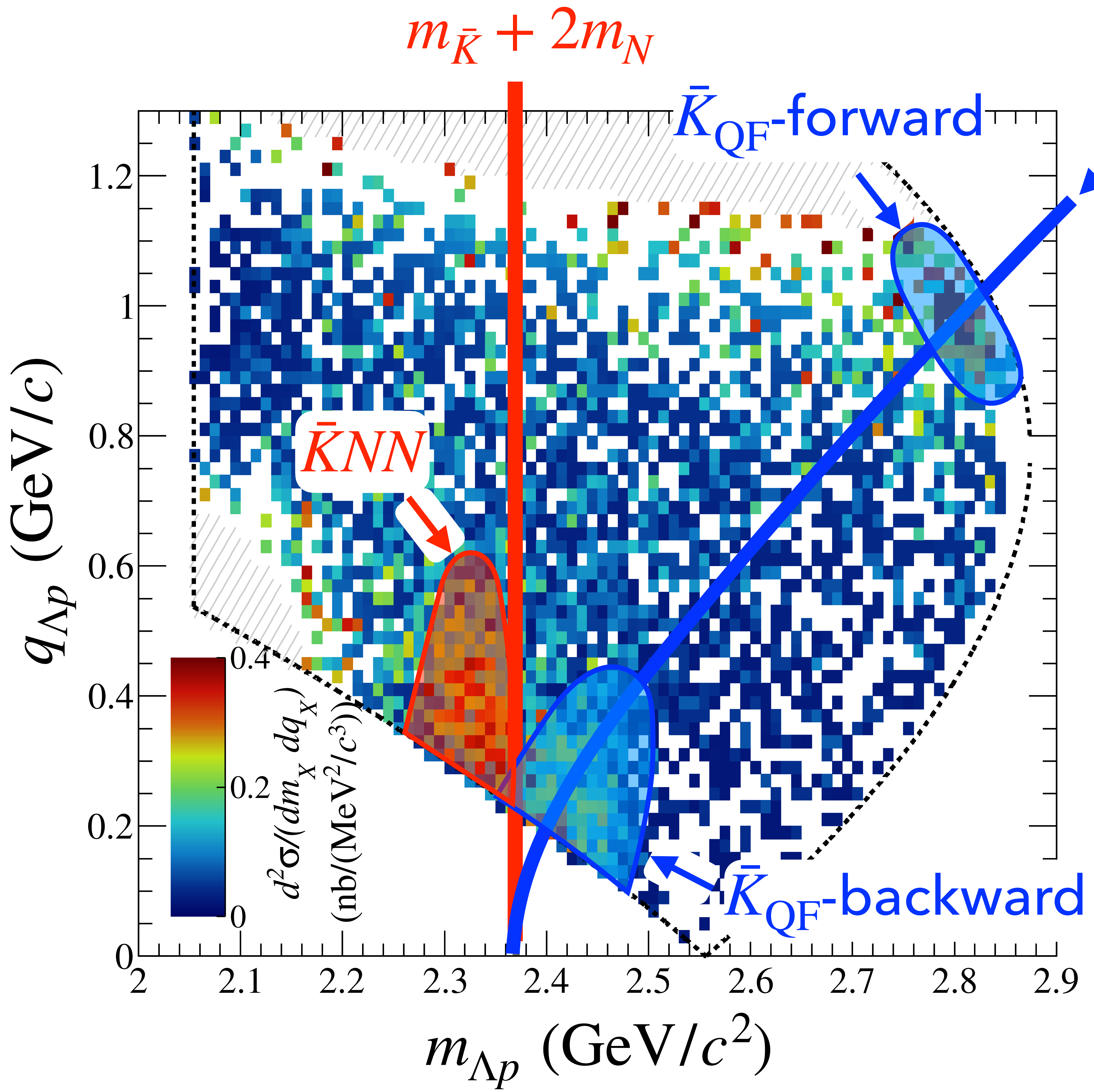
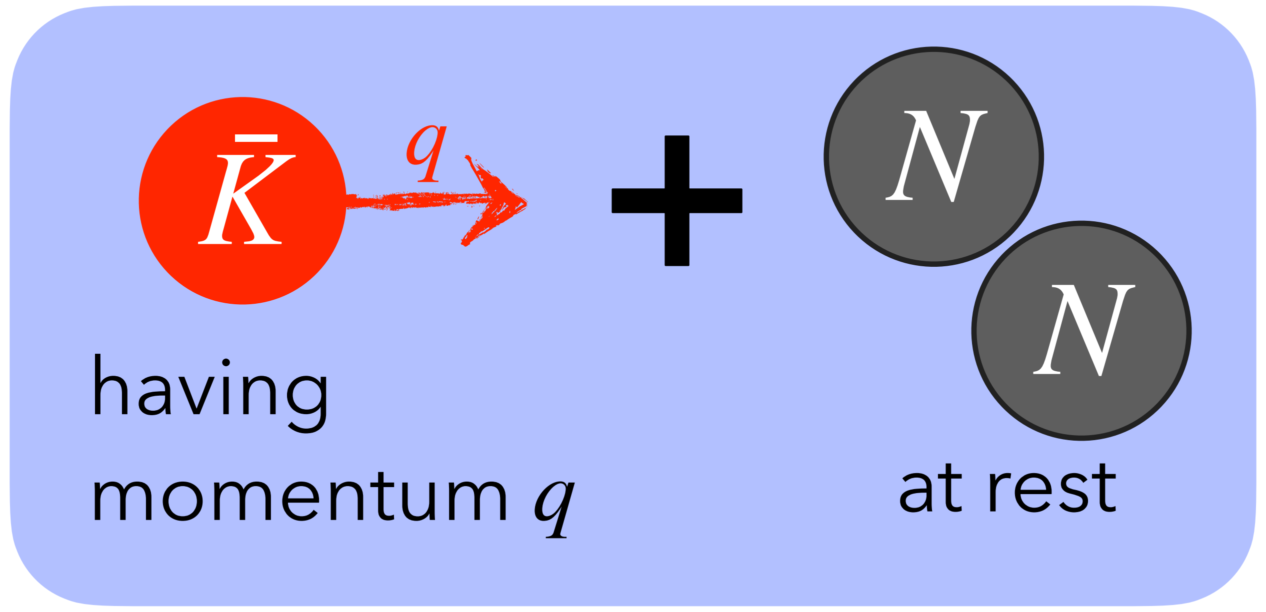


Mass of



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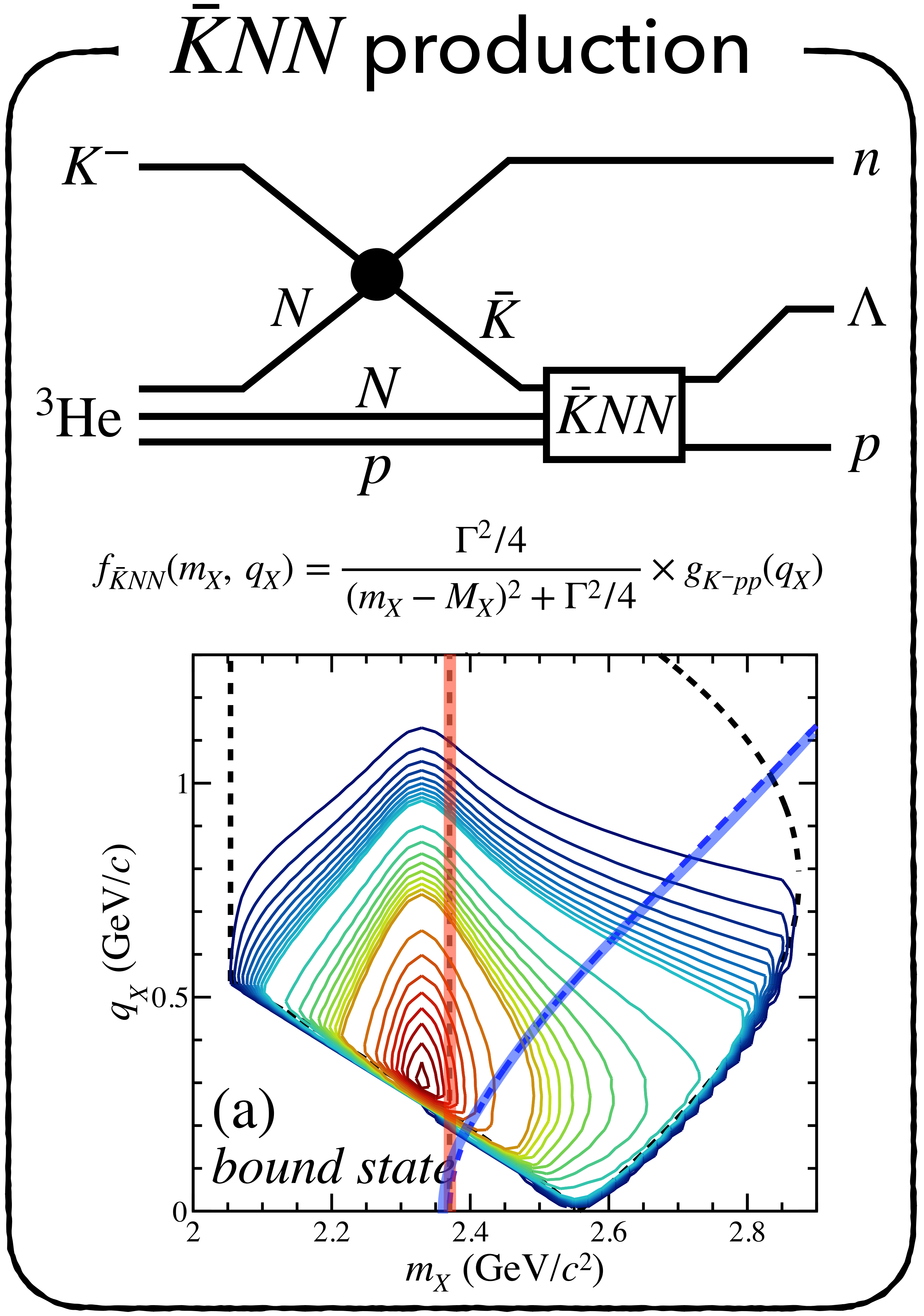
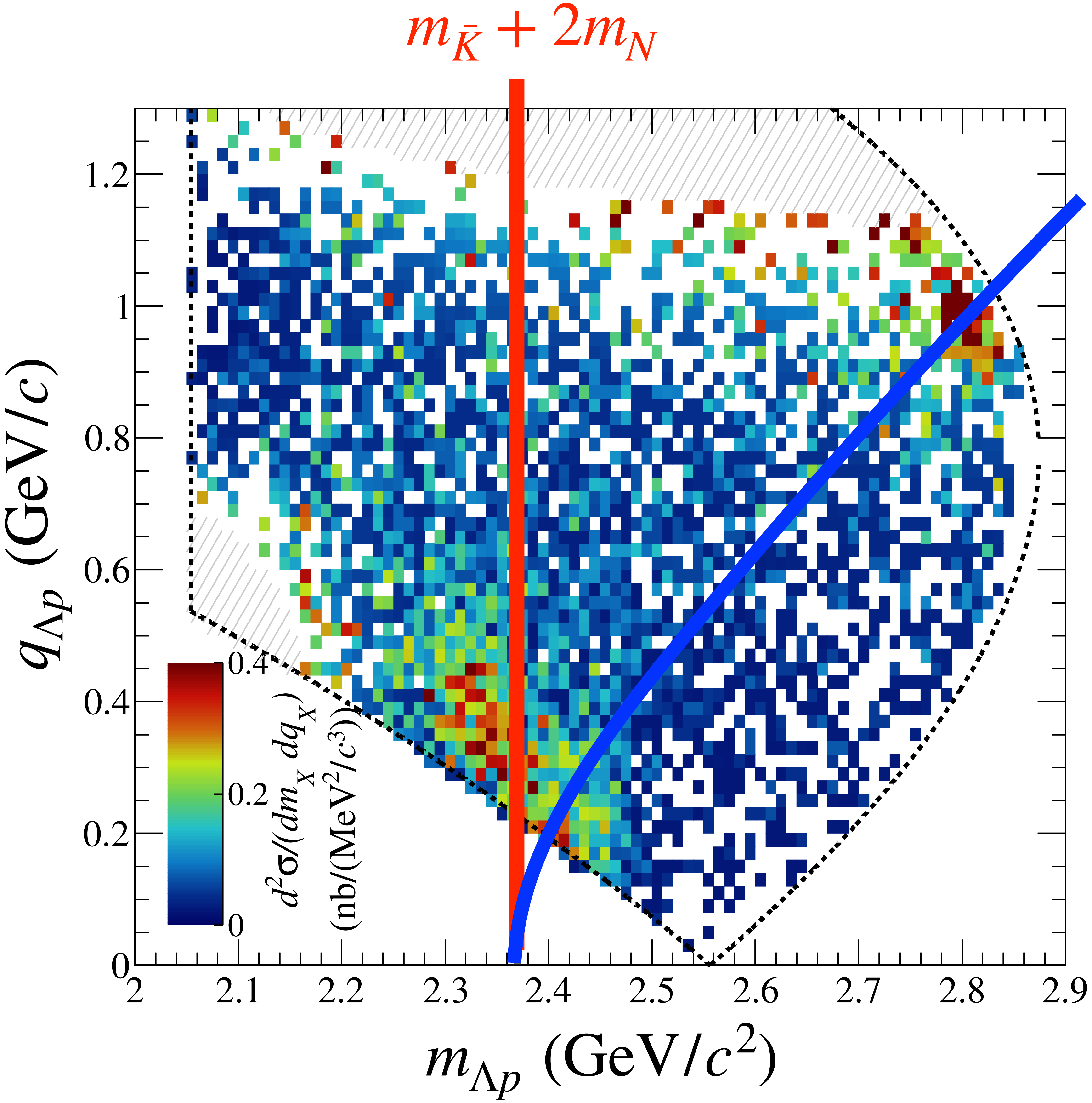
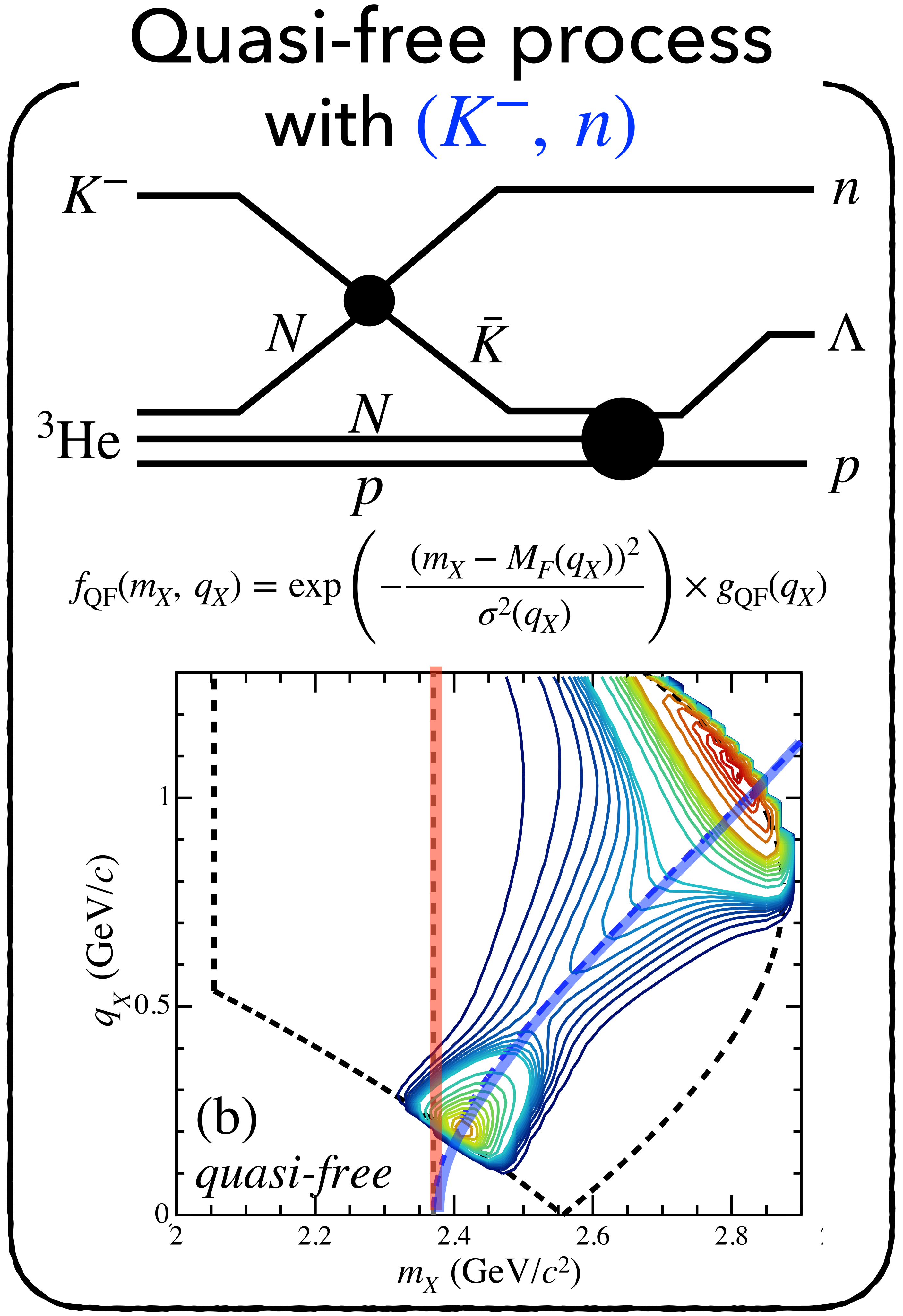
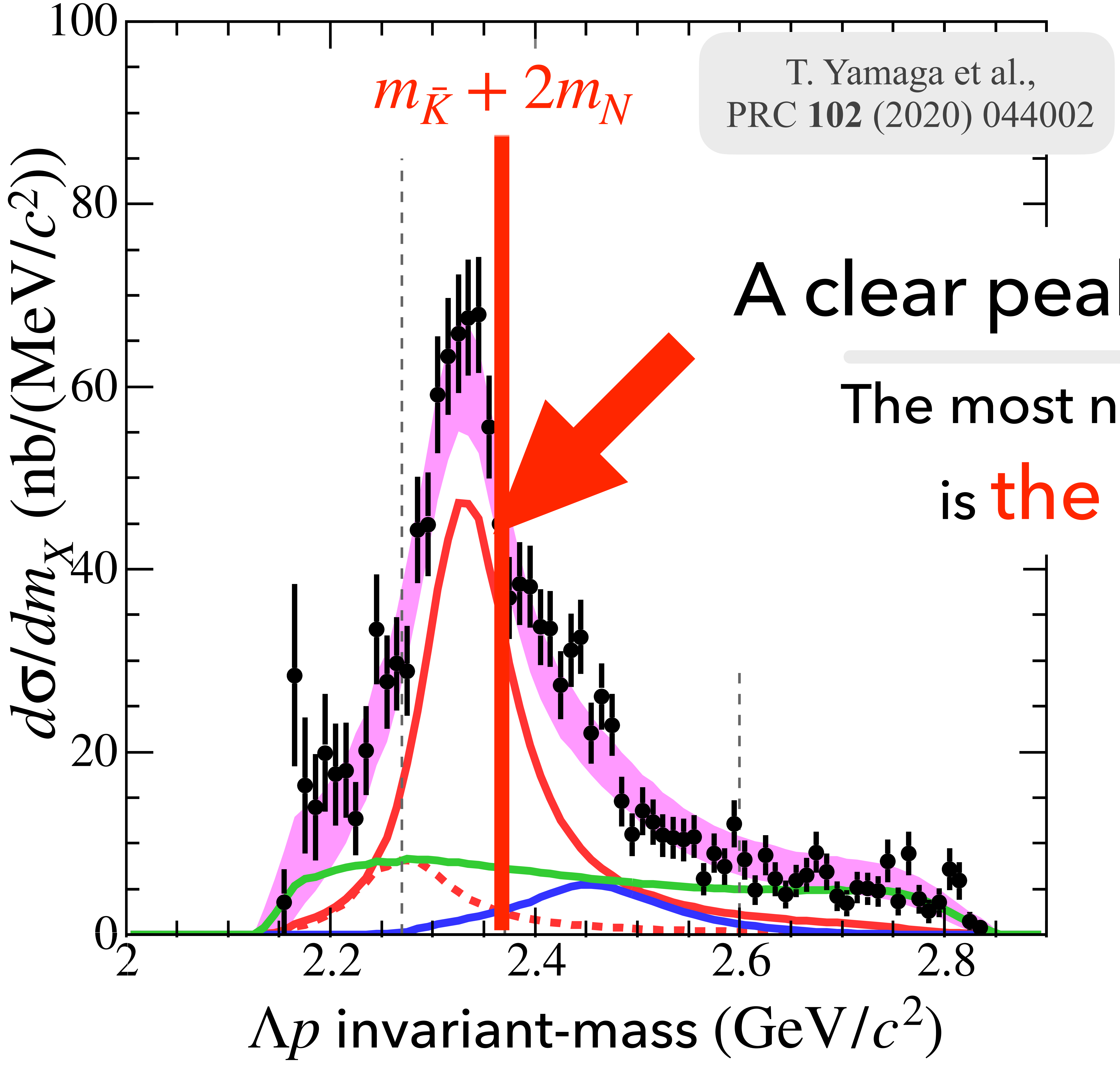






Signal of the $\bar{K}NN$



A clear peak below $m_{\bar{K}} + 2m_N$

The most natural interpretation is the $\bar{K}NN$ signal.

Mass and Width of $\bar{K}NN$

	BE	Γ
J-PARC E15 PRC **102** (2020) 044002	42 ± 3 (stat.) $^{+3}_{-4}$ (syst.) MeV	100 ± 7 (stat.) $^{+19}_{-9}$ (syst.) MeV

Theoretical predictions with chiral SU(3) based $\bar{K}N$ interaction

	BE	Γ
S. Ohnishi et al., Phys. Rev. C **95** (2017) 065202	26 – 28 MeV	31 – 59 MeV
N. Shevchenko, Few-Body Syst. **61** (2020) 27	29 – 30 MeV	46 – 47 MeV
A. Dote et al., Phys. Lett. B **784** (2018) 405	14 – 59 MeV	16 – 38 MeV

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T Consistent chi Exp > Theor on

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* Obtained as peak position & width of simple Breit-Wigner

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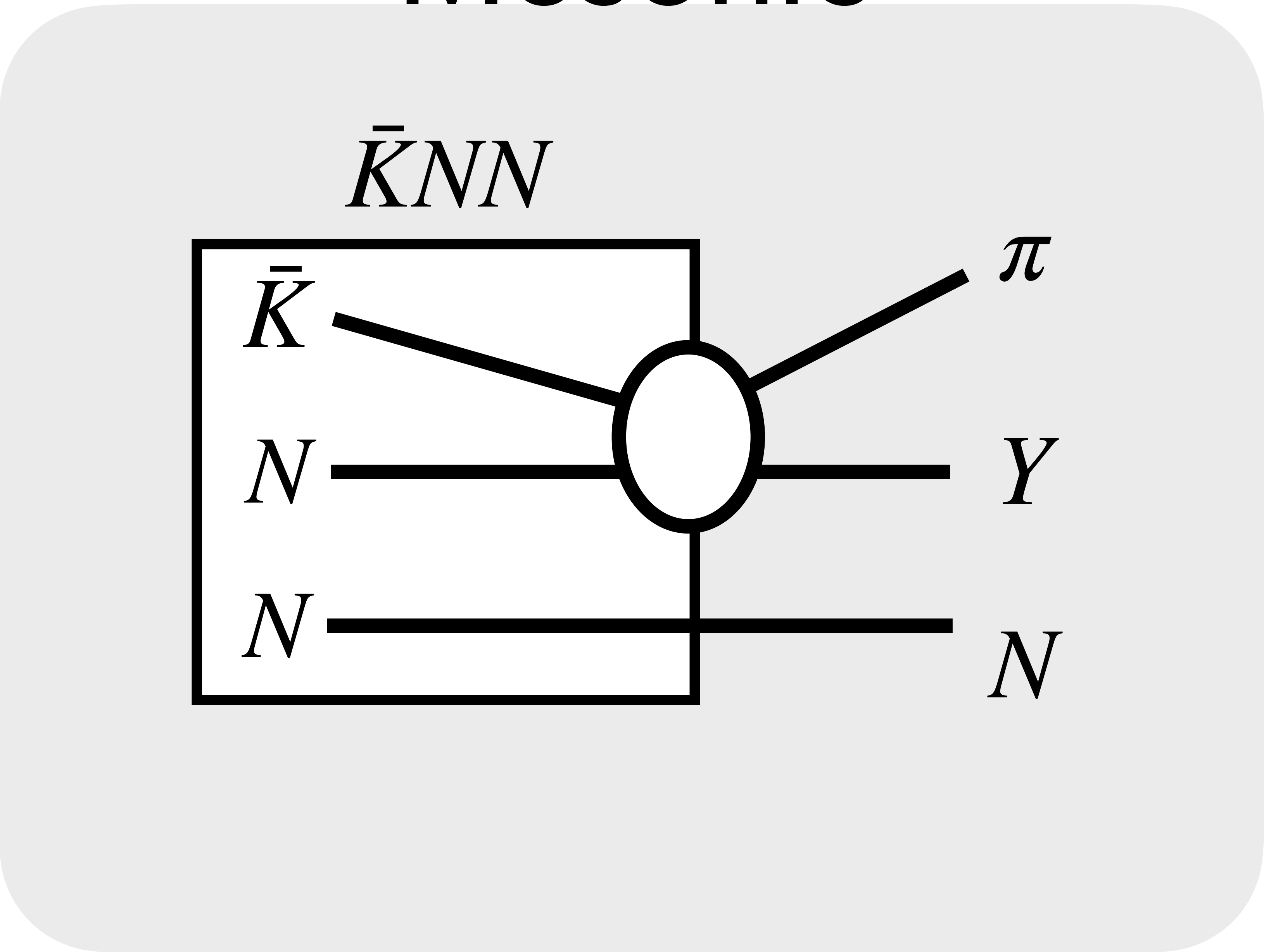
* Mesonic decay width only

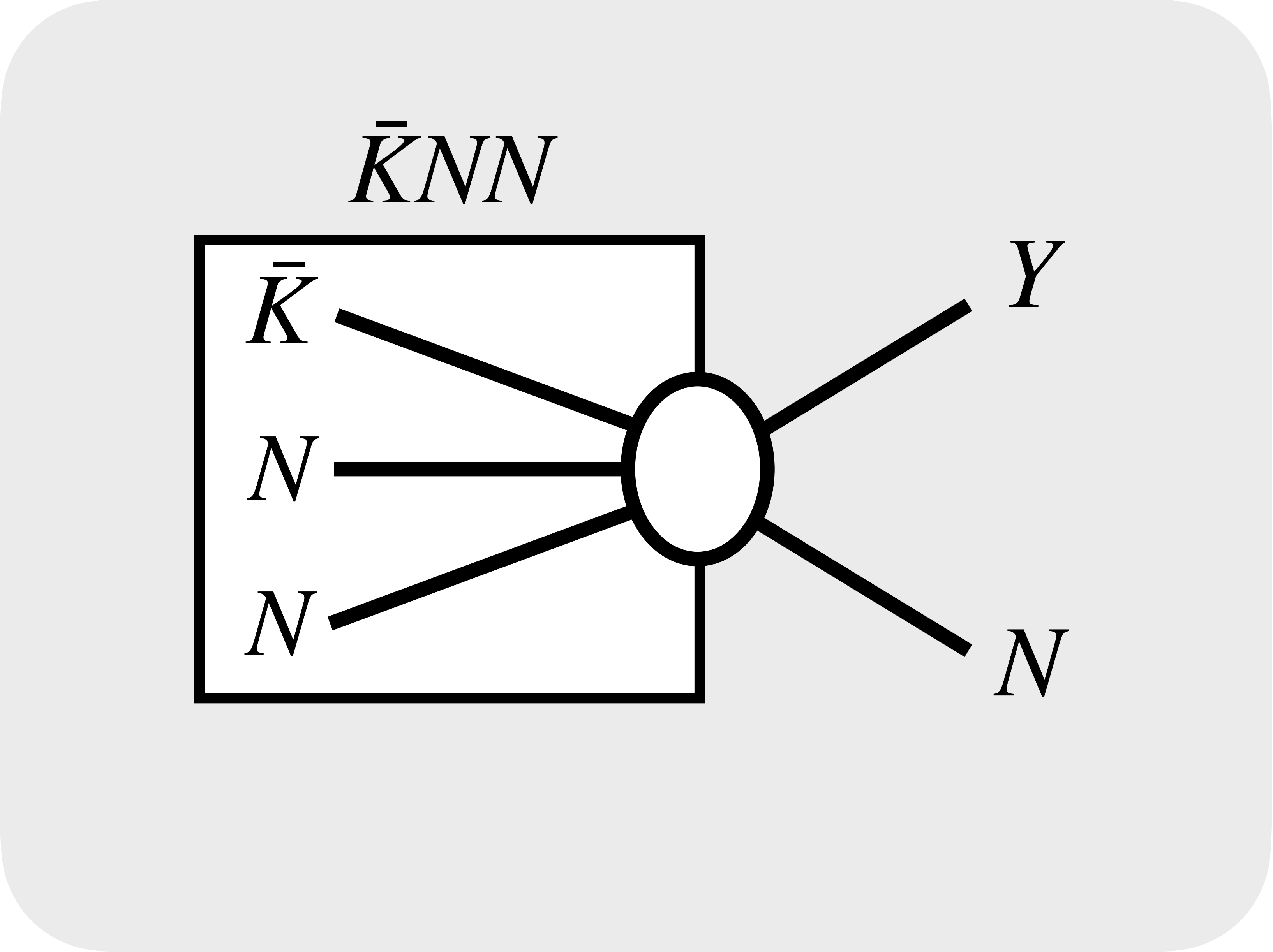
$\bar{K}NN$ decay

Mesonic



1N absorption

Non-mesonic



2N absorption

The non-mesonic fraction

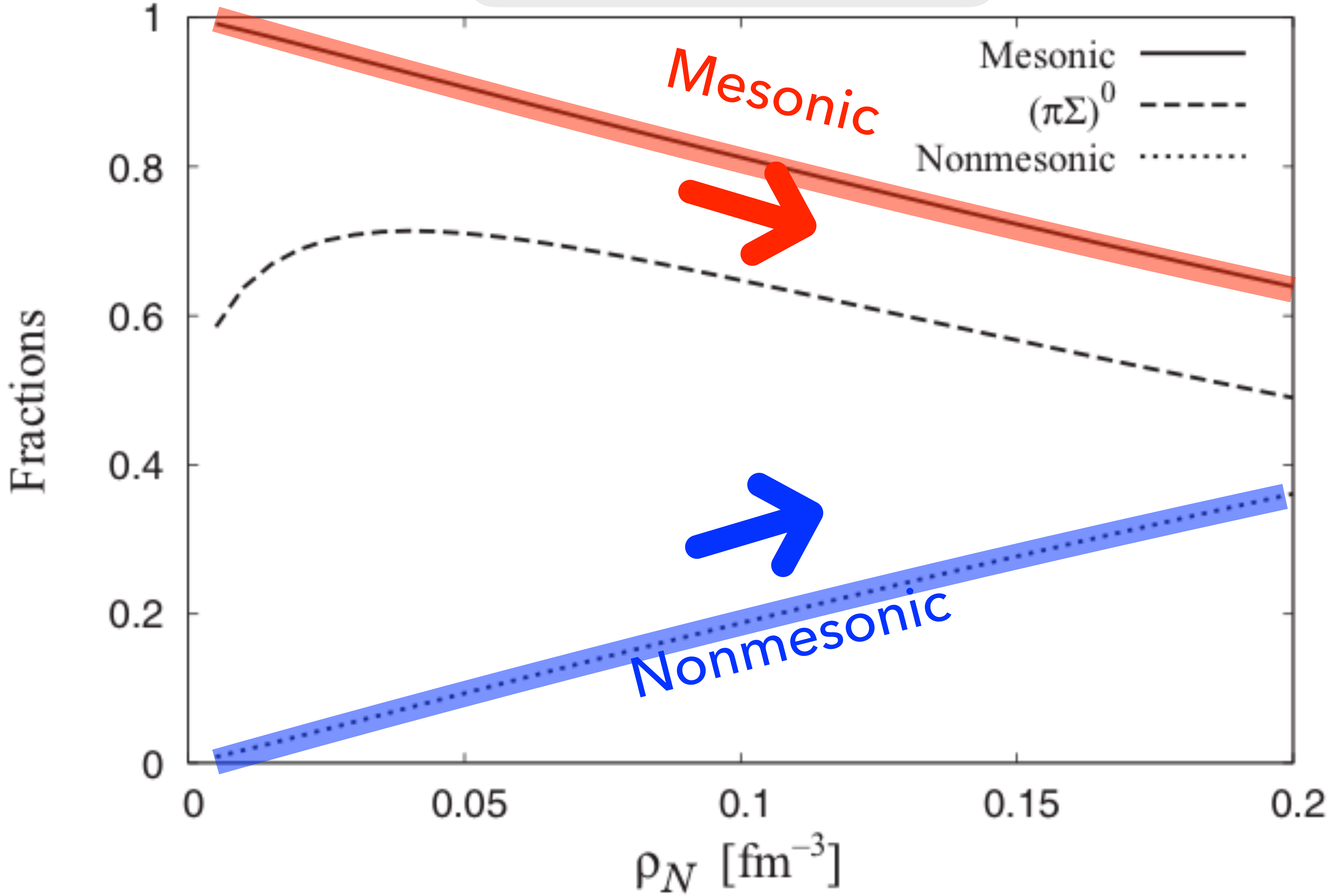
in stopped-K^- experiments

Target	Non-mesonic / mesonic ratio	
p	$100\,\%$ mesonic	Nucl. Phys. B **33**, (1971) 493. Nucl. Phys. B **139**, (1978) 61.
d	$\sim 1\,\%$	Phys.Rev.D**1**, (1970) 1883.
^{4}He	$\sim 20\,\%$	Phys.Rev.D**1**, (1970) 1267.

The non-mesonic fraction

theoretical calculation

T. Sekihara *et al.*,
Phys. Rev. C **86** (2012) 065205



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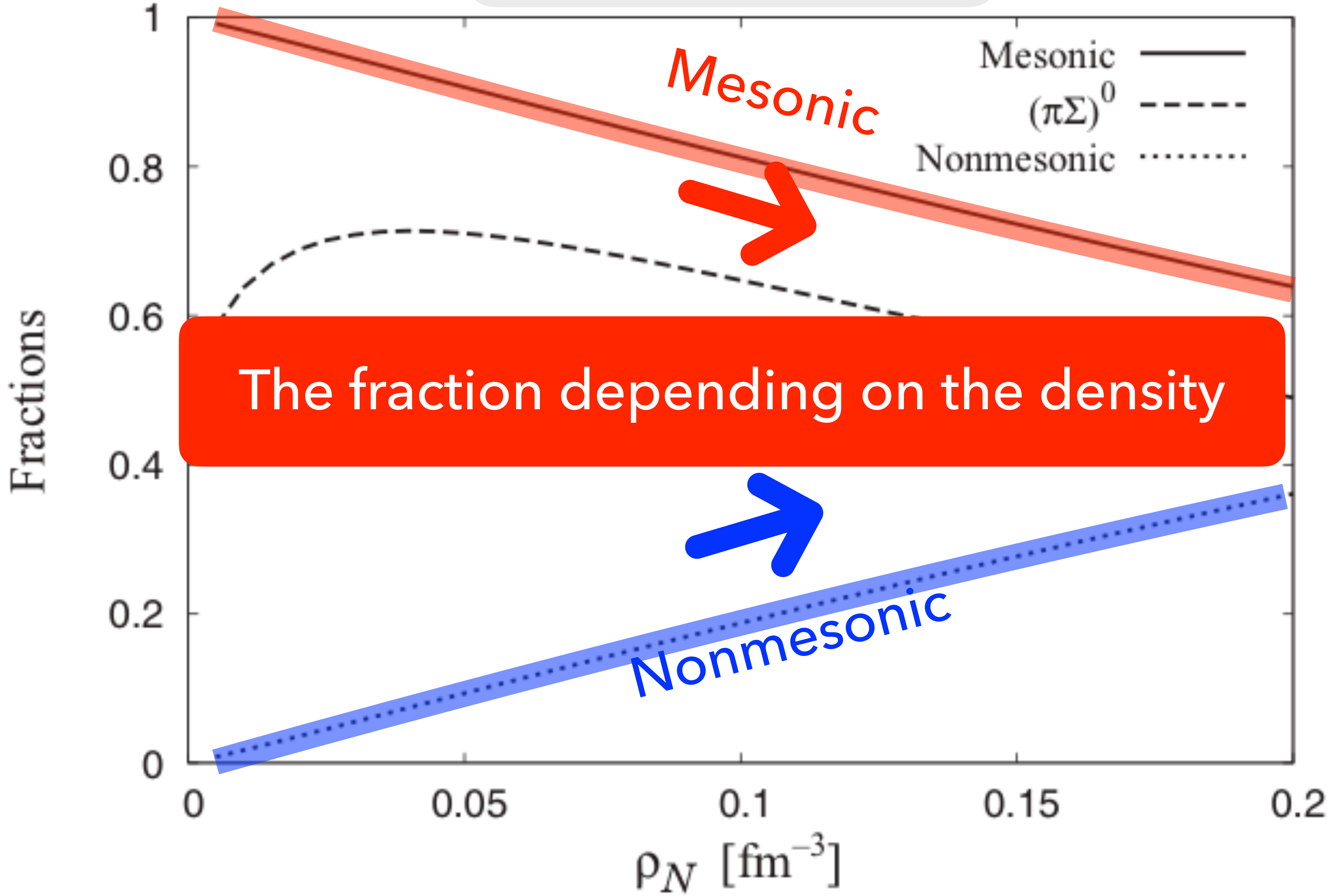
Phys. Rev. C **86** (2012) 065205



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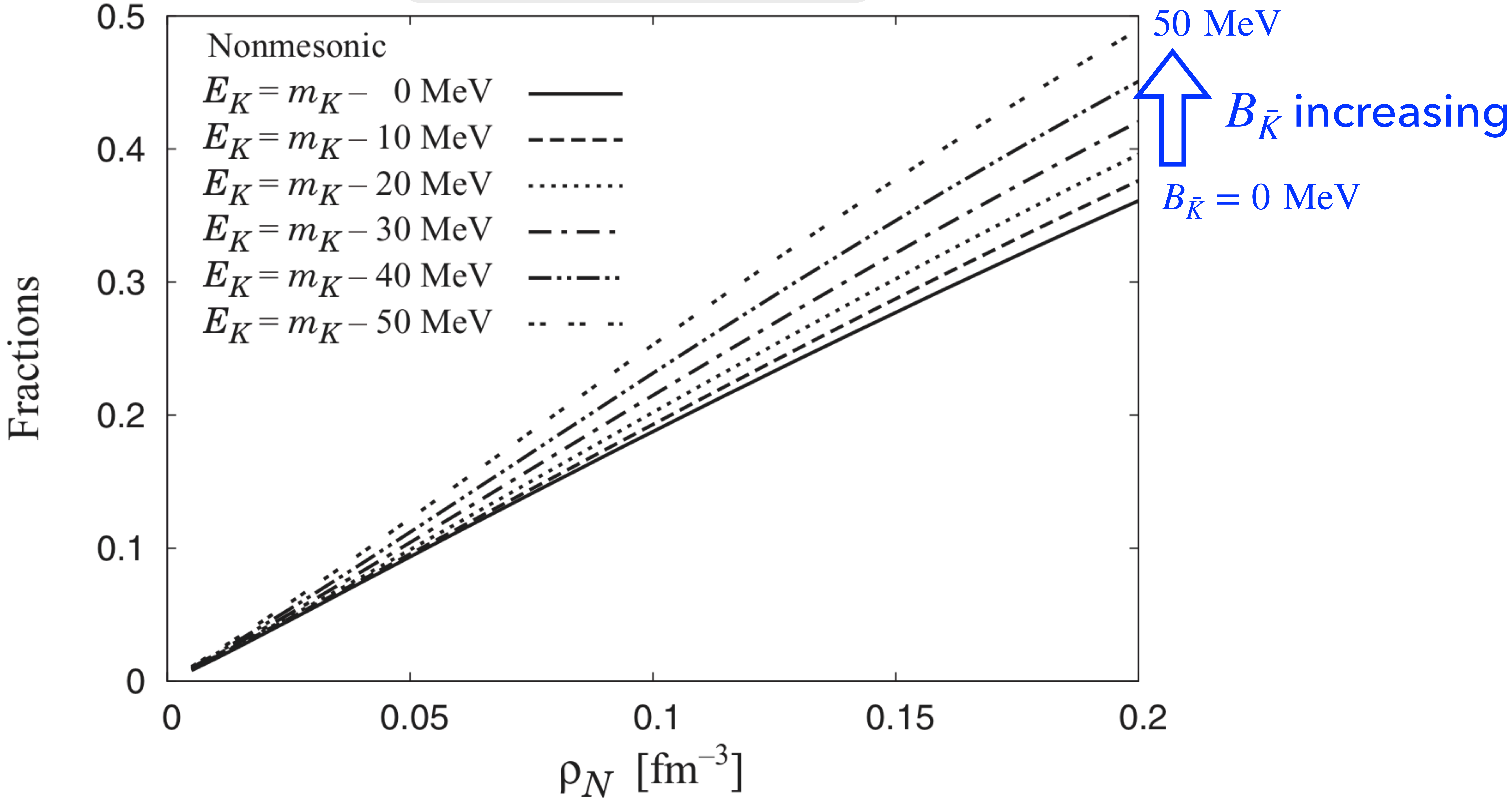
Phys. Rev. C **86** (2012) 065205



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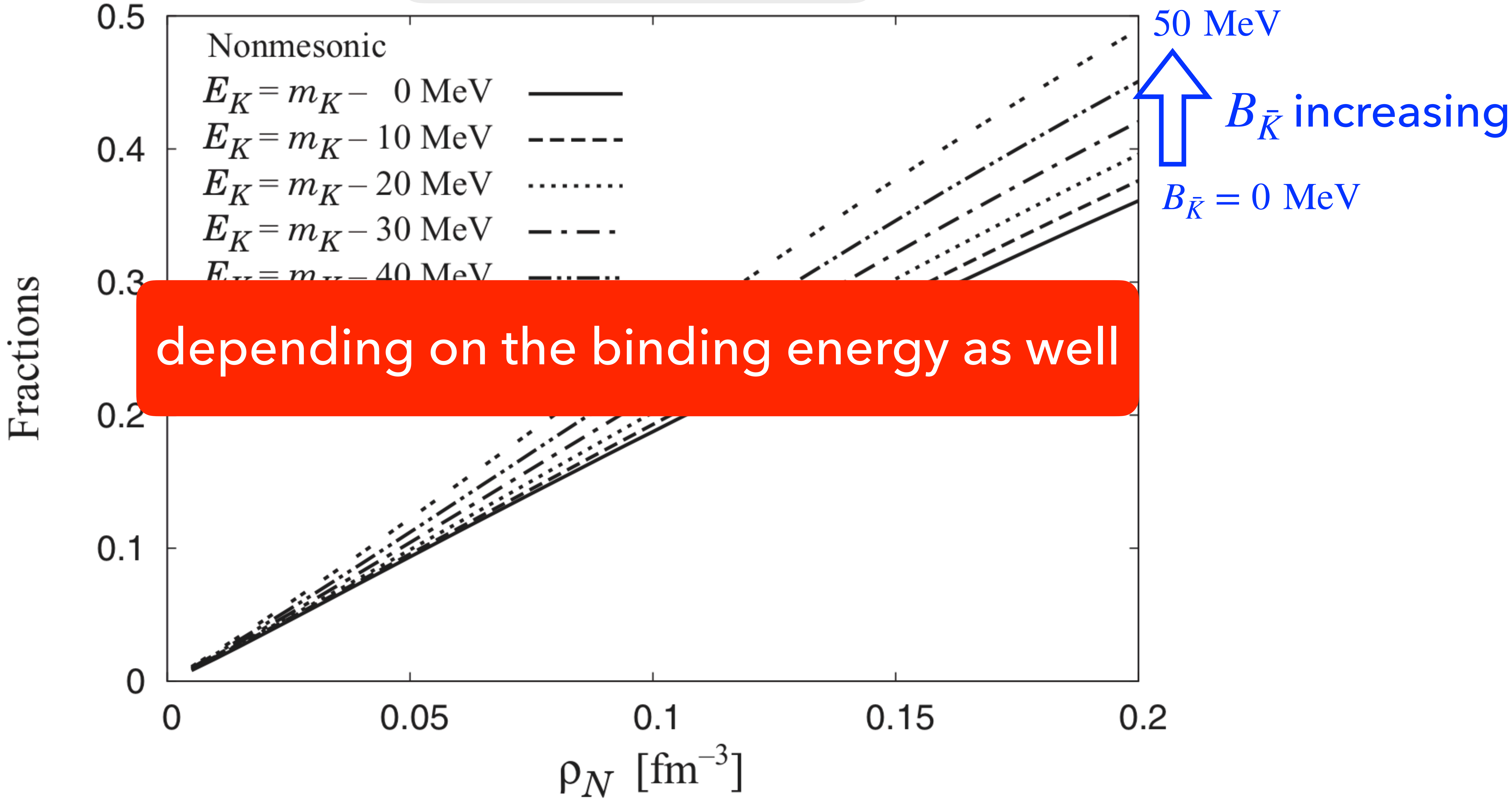
Phys. Rev. C **86** (2012) 065205



depending on the binding energy as well

The non-mesonic fraction

Calculated decay width of $\bar{K}NN$

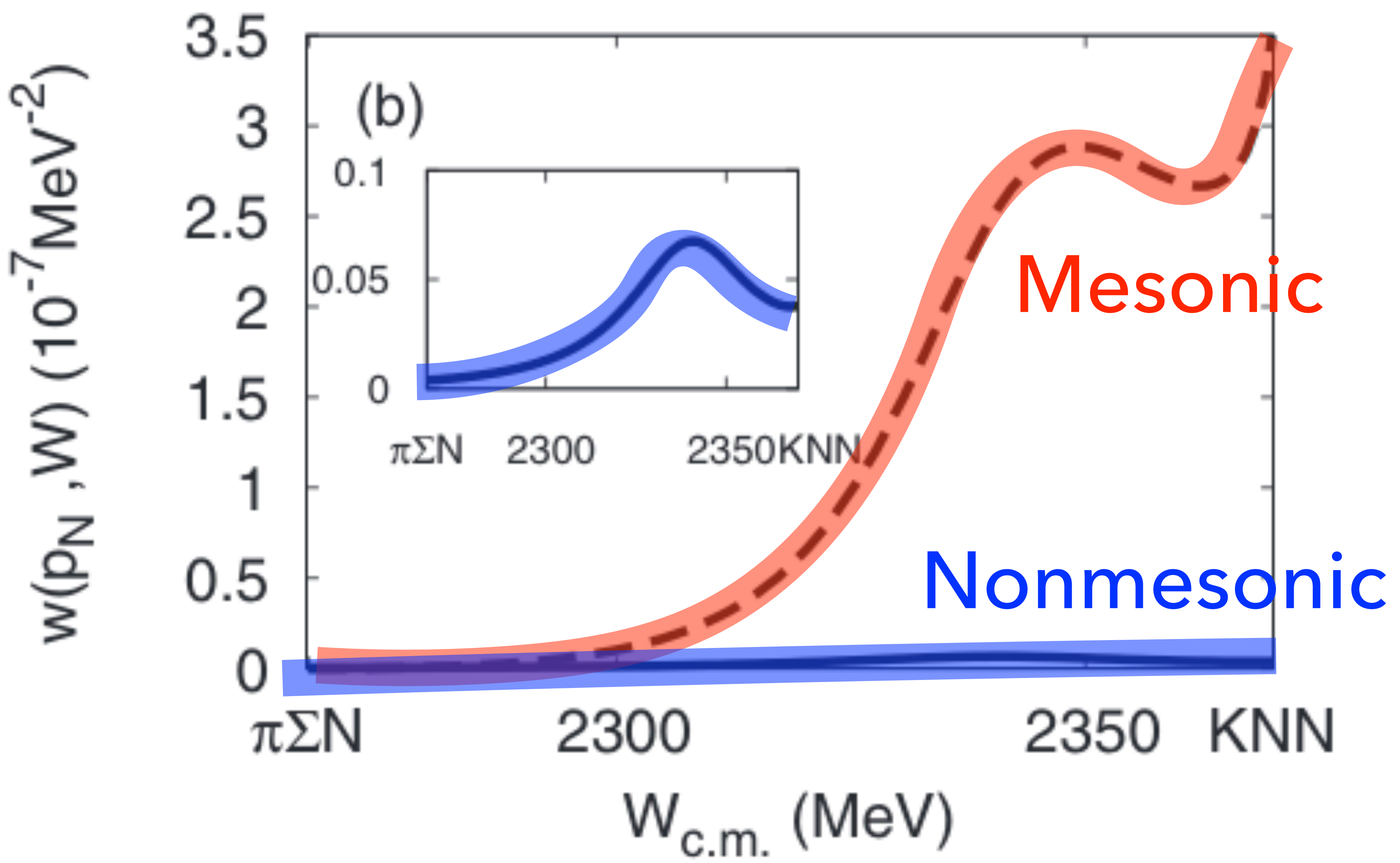
M. Bayar and E. Oset,
Phys. Rev. C 88 (2013) 044003

$\Gamma_{YN} \sim 30$ MeV

$\Gamma_{\pi YN} \sim 40 - 50$ MeV

S. Ohnishi, et al.,
Phys. Rev. C 88 (2013) 025204.

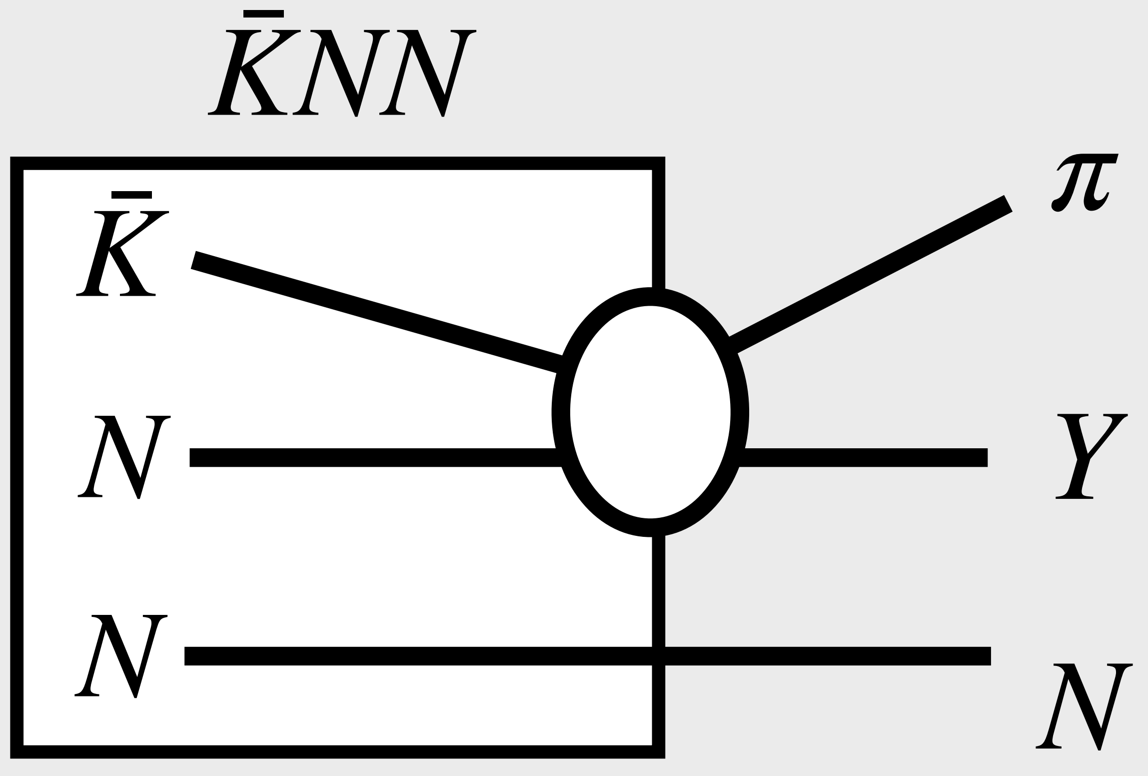
$\Gamma_{YN} \ll \Gamma_{\pi YN}$



$\bar{K}NN$ decay

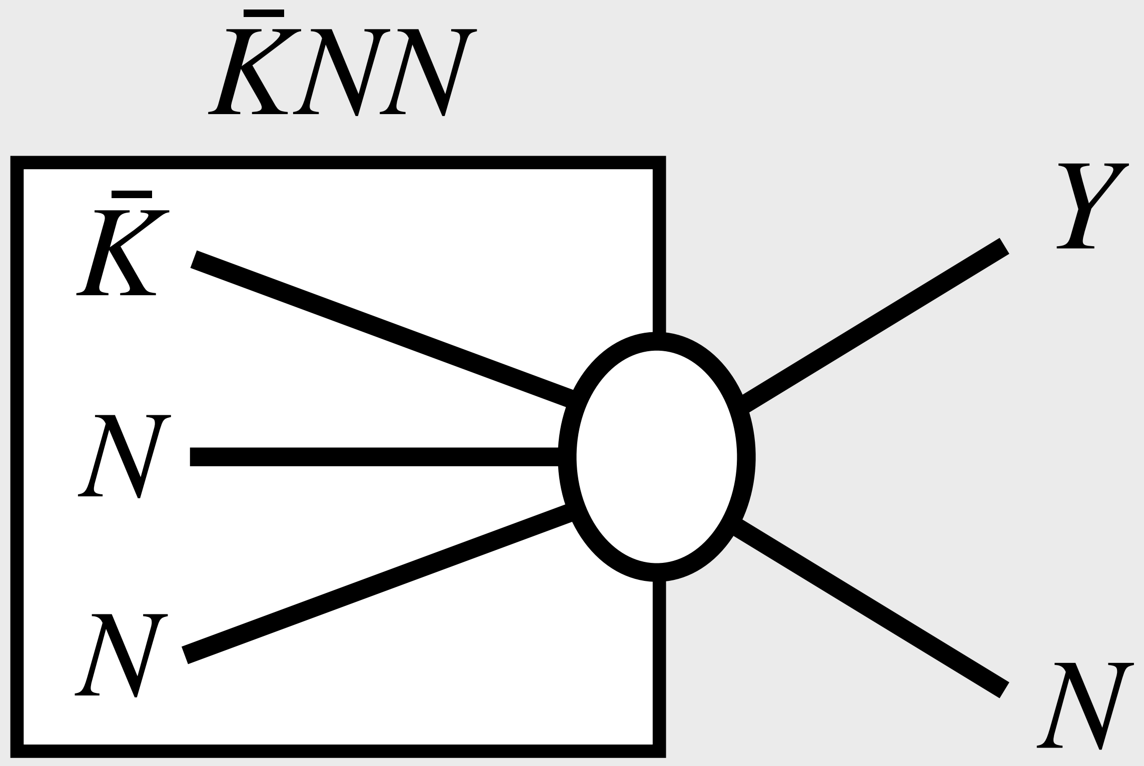
Fraction ∝ (Internal structure) ⊗ ($\bar{K}N$ interaction)

Mesonic



1N absorption

Non-mesonic

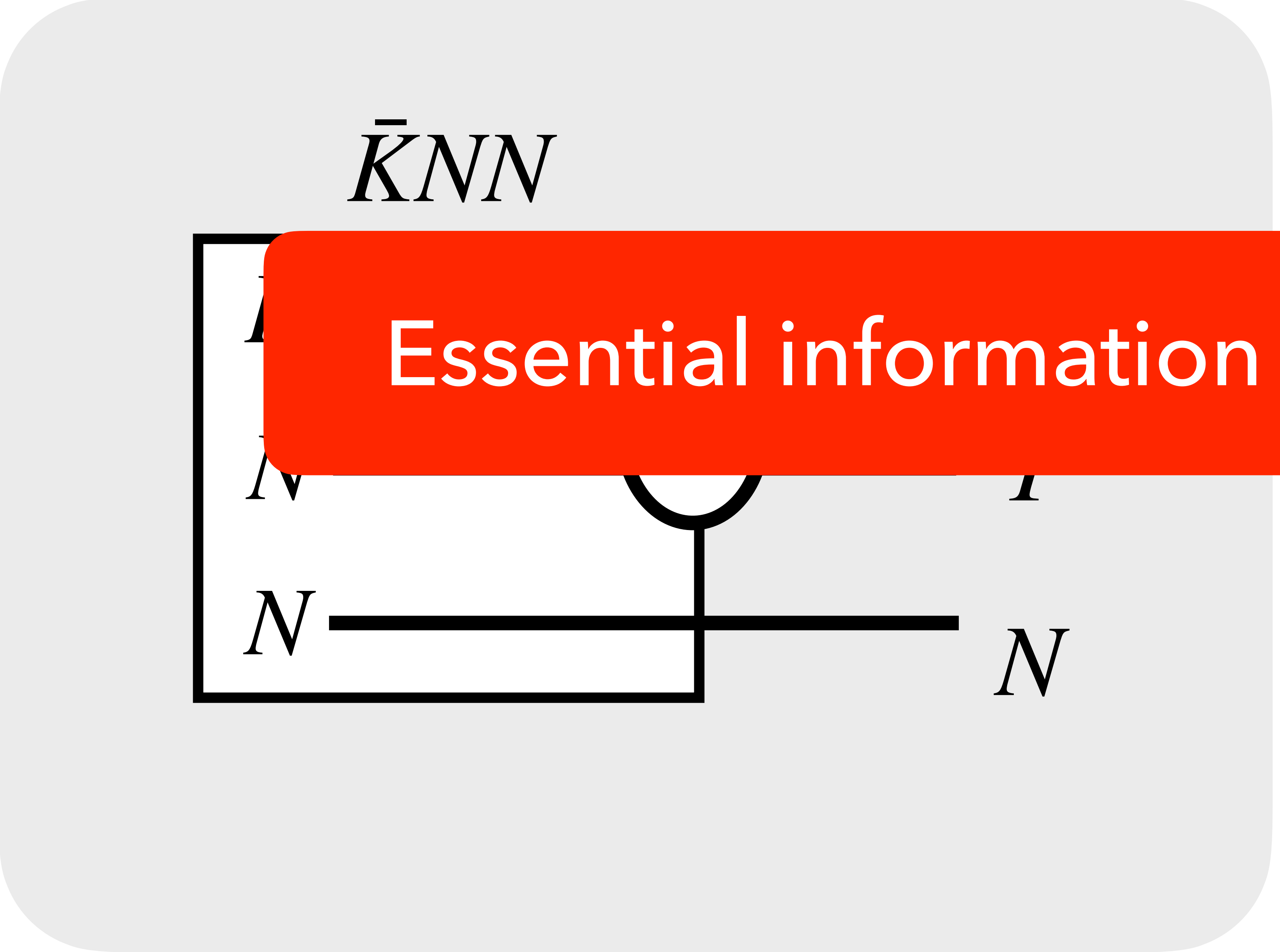


2N absorption

$\bar{K}NN$ decay

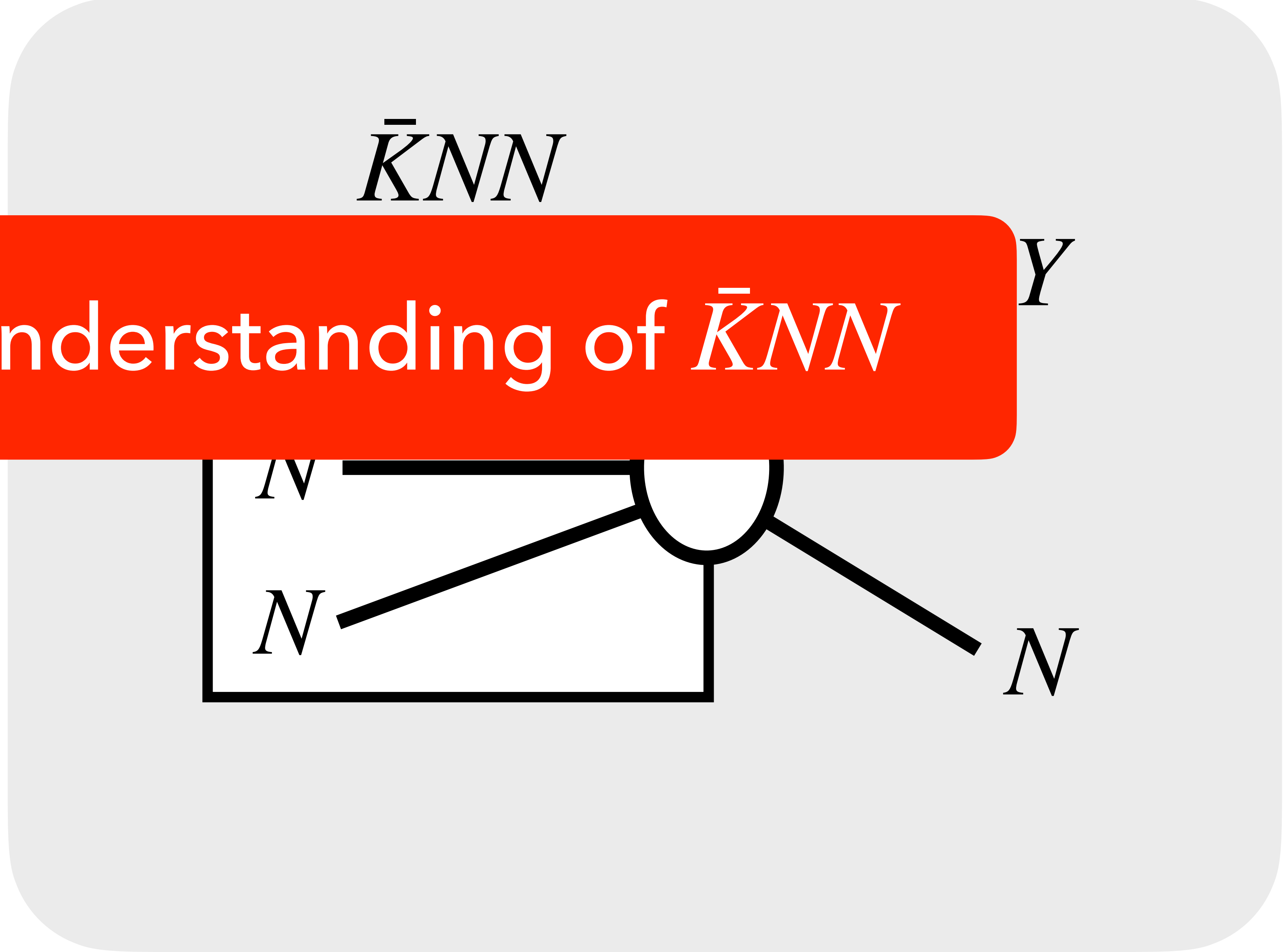
Fraction ∝ (Internal structure) ⊗ ($\bar{K}N$ interaction)

Mesonic



1N absorption

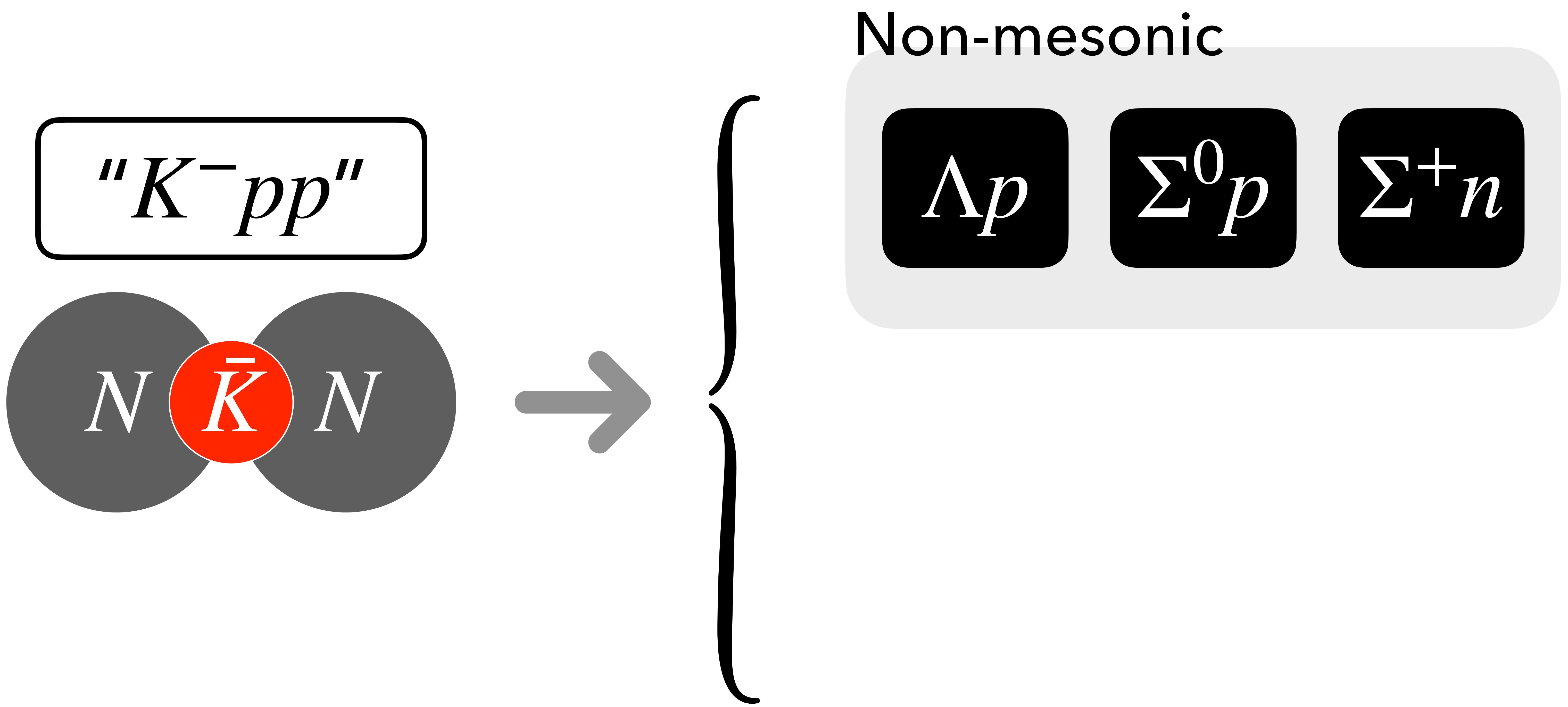
Non-mesonic



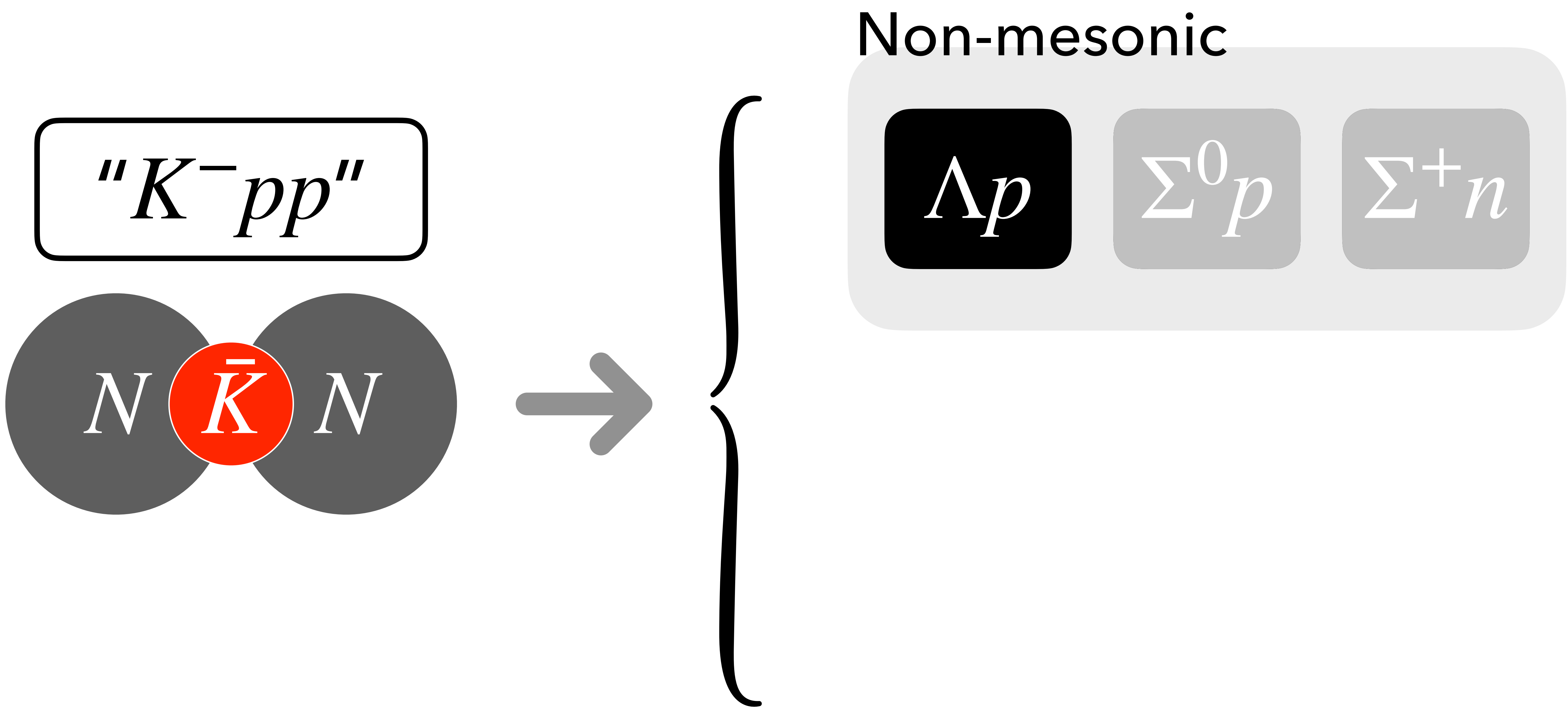
2N absorption

Essential information for further understanding of $\bar{K}NN$

Decay channels of $\bar{K}NN$



Decay channels of $\bar{K}NN$



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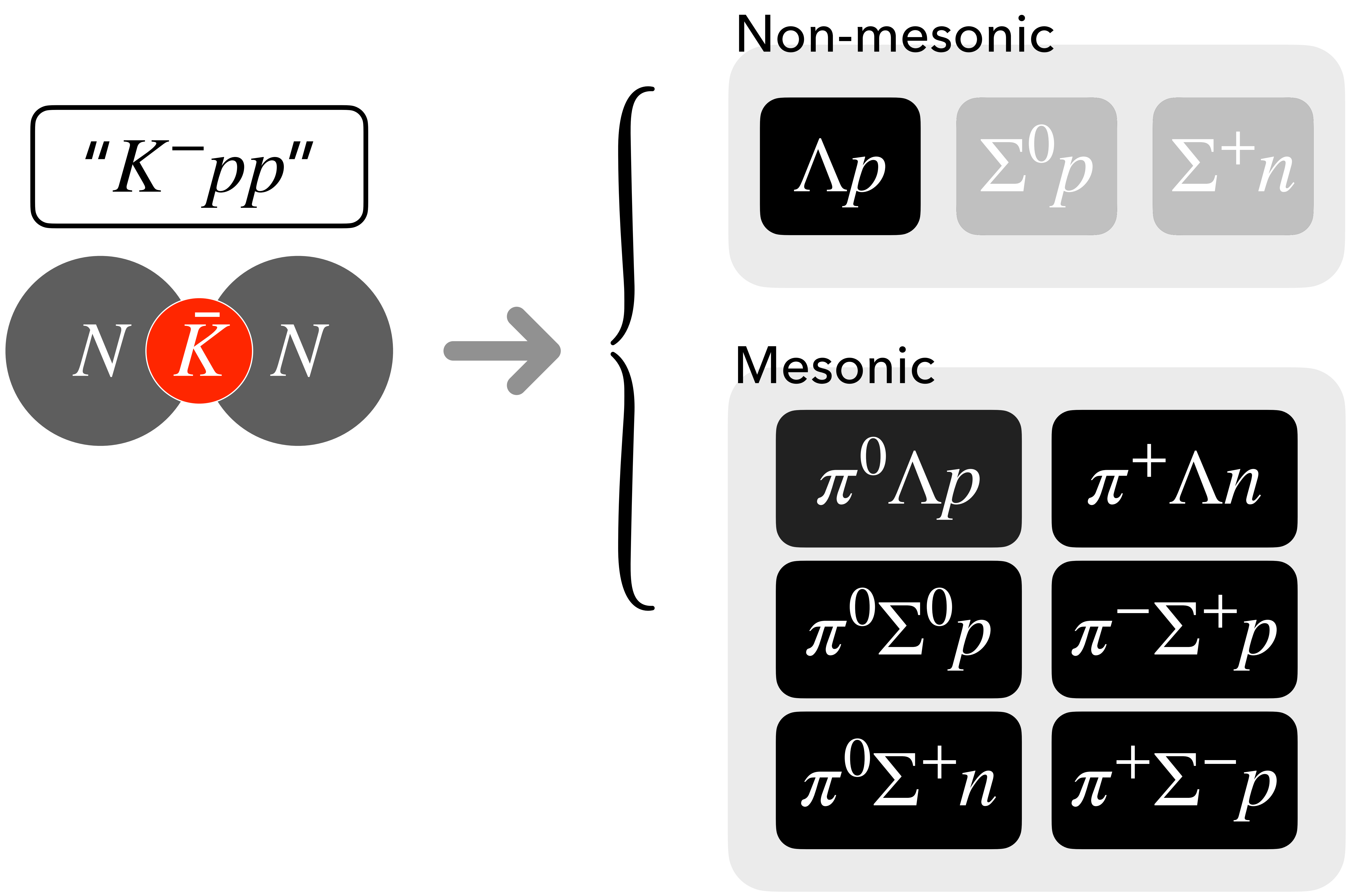
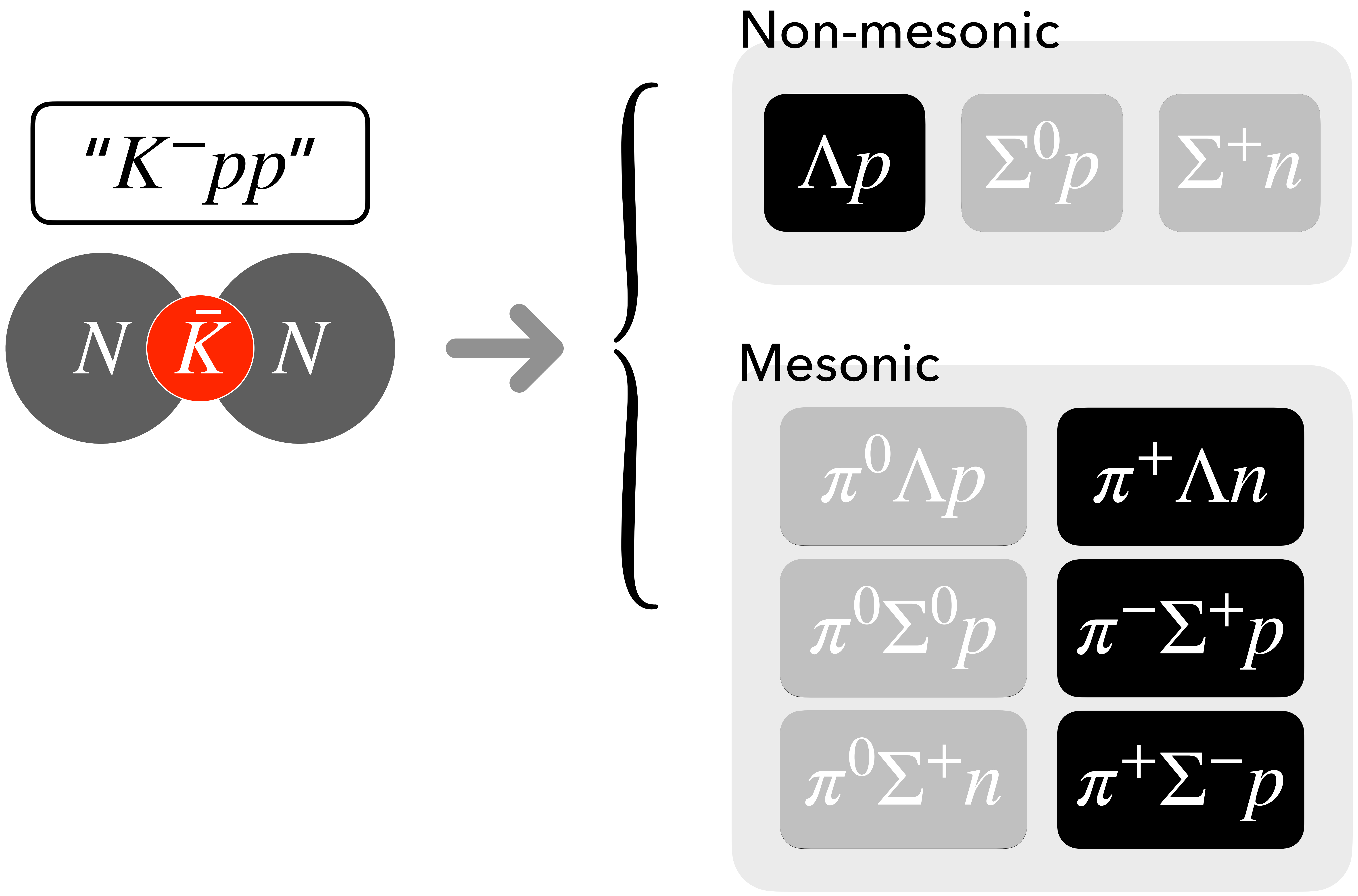
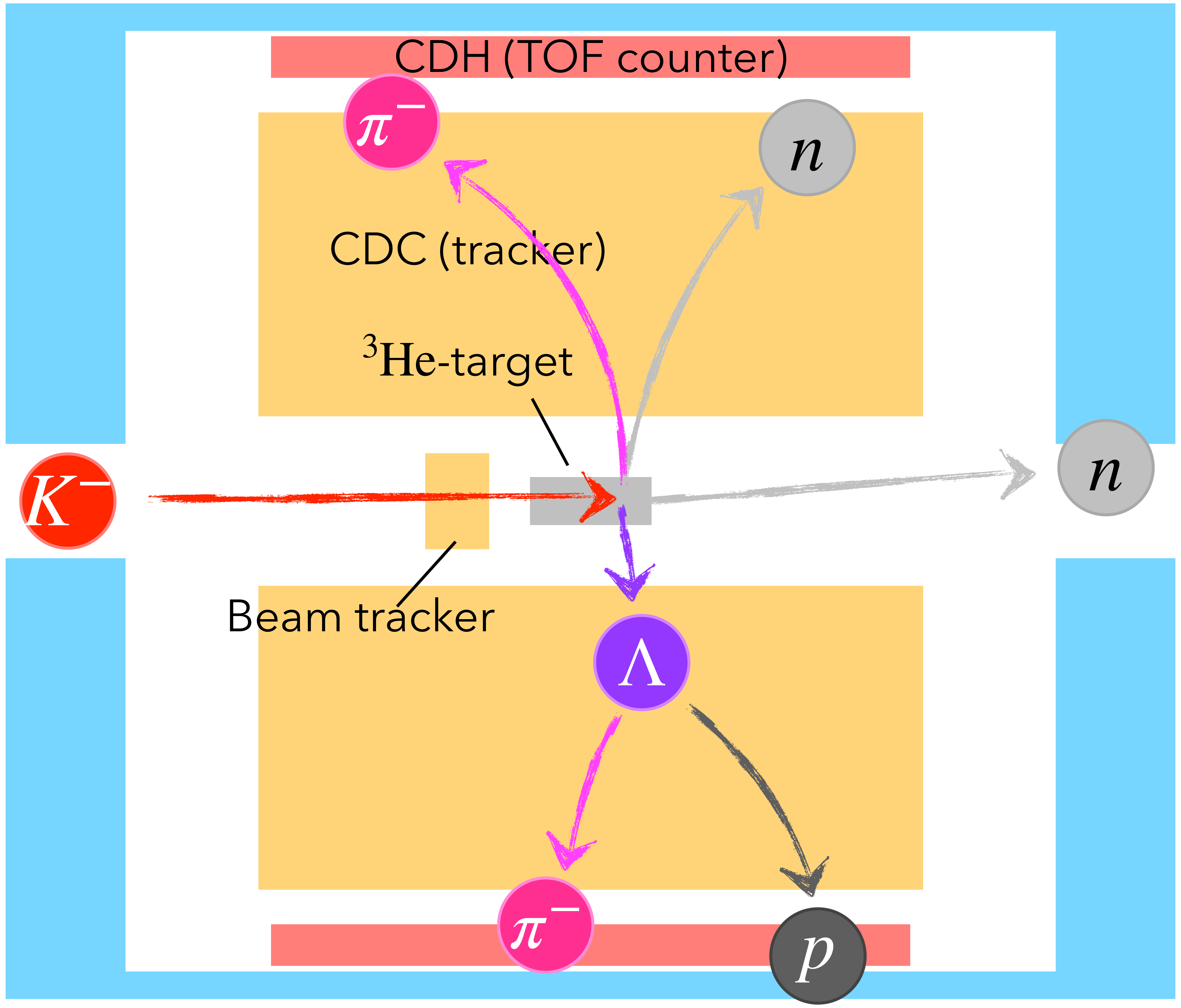


Decay channels of $\bar{K}NN$

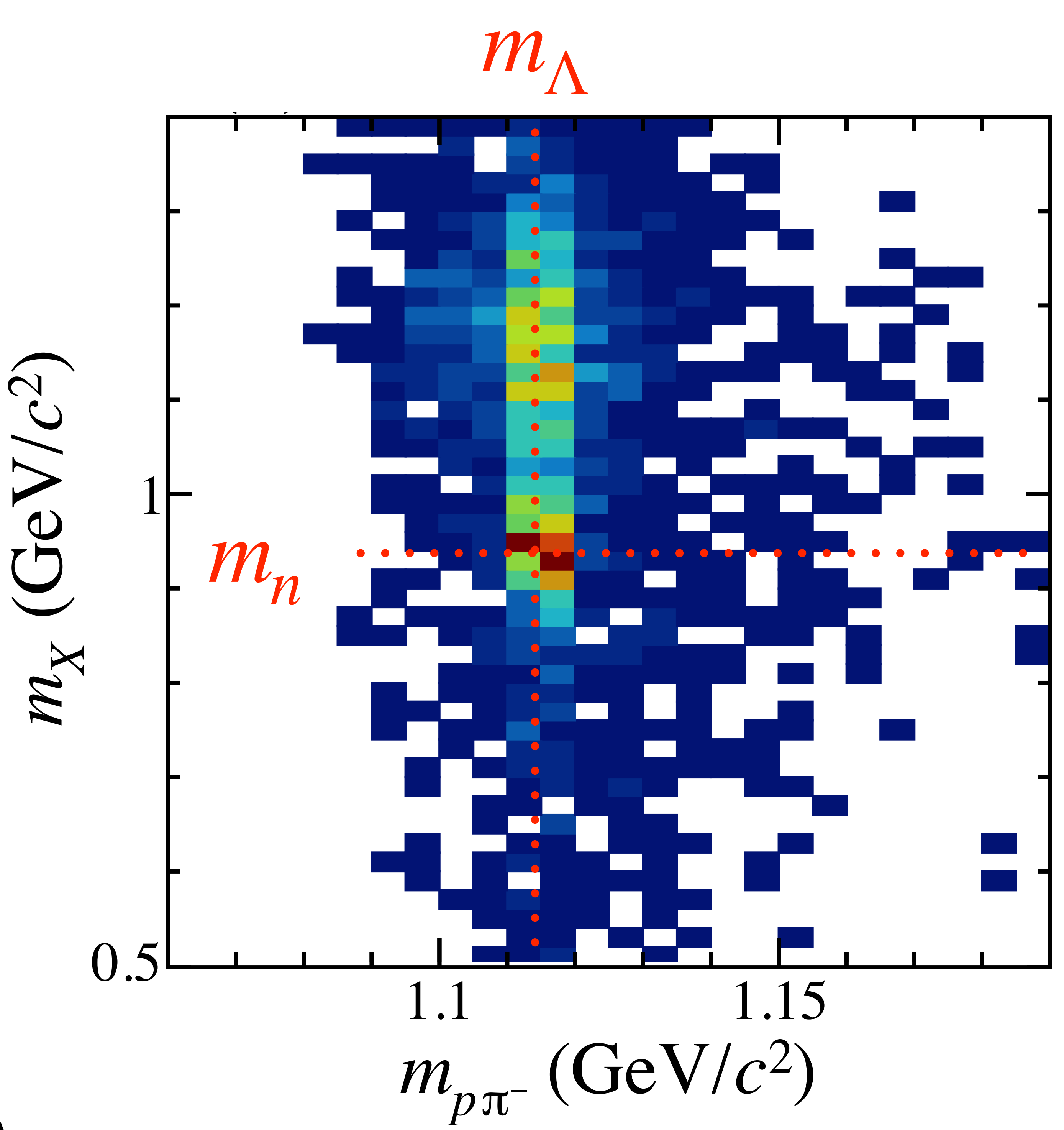


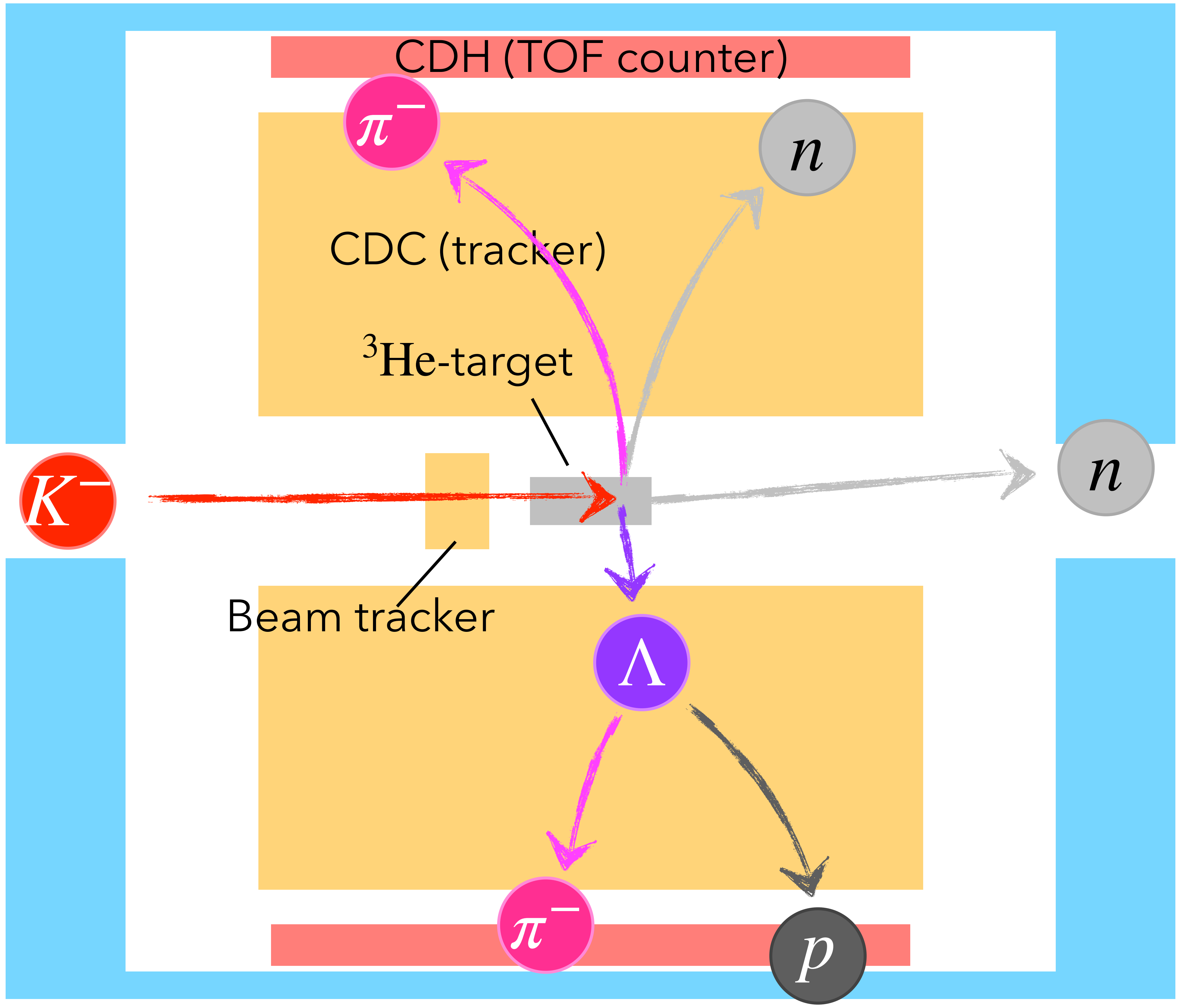
Event selection



Event selection

For the $\pi^+\Lambda nn$ final state





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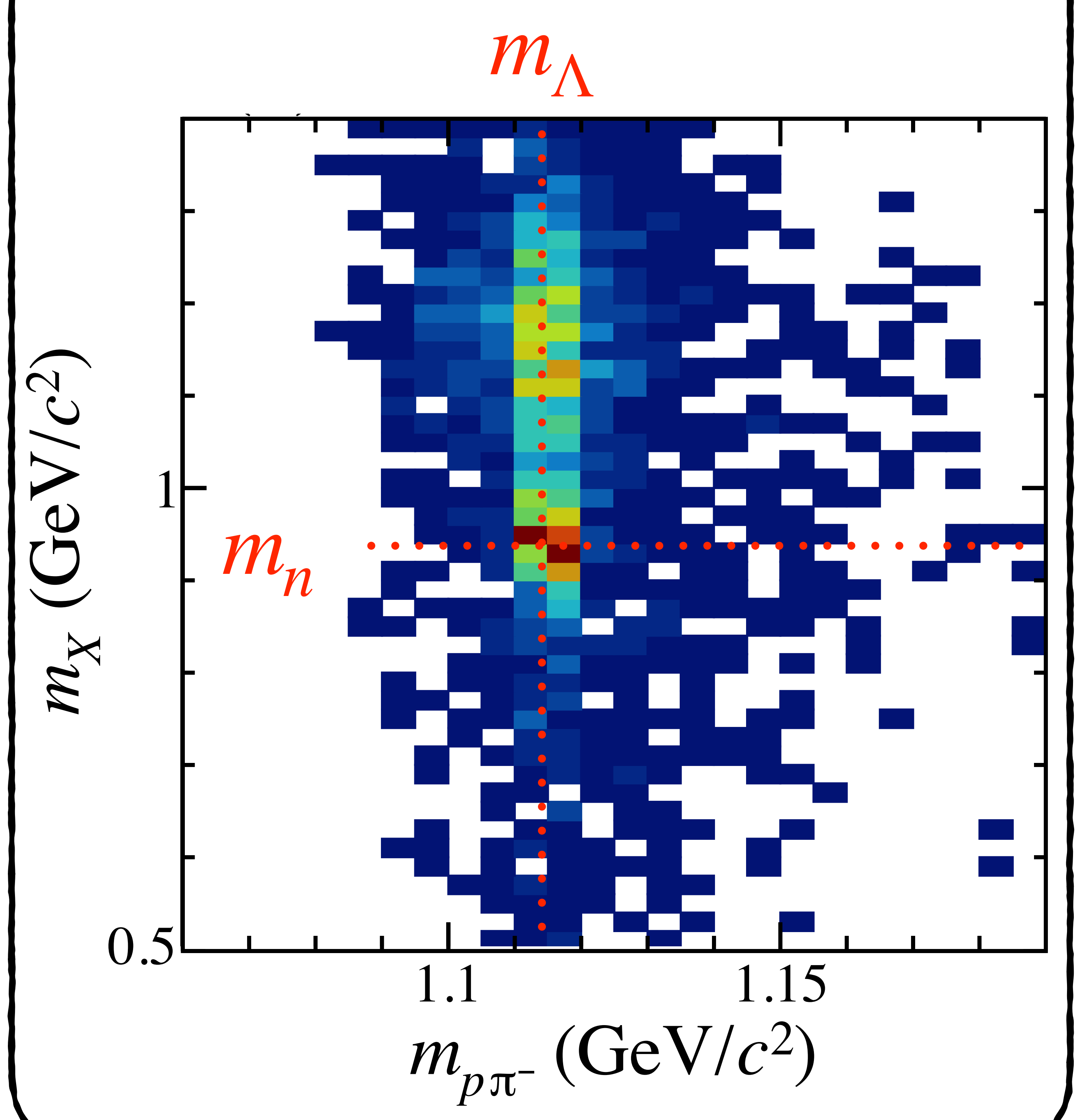

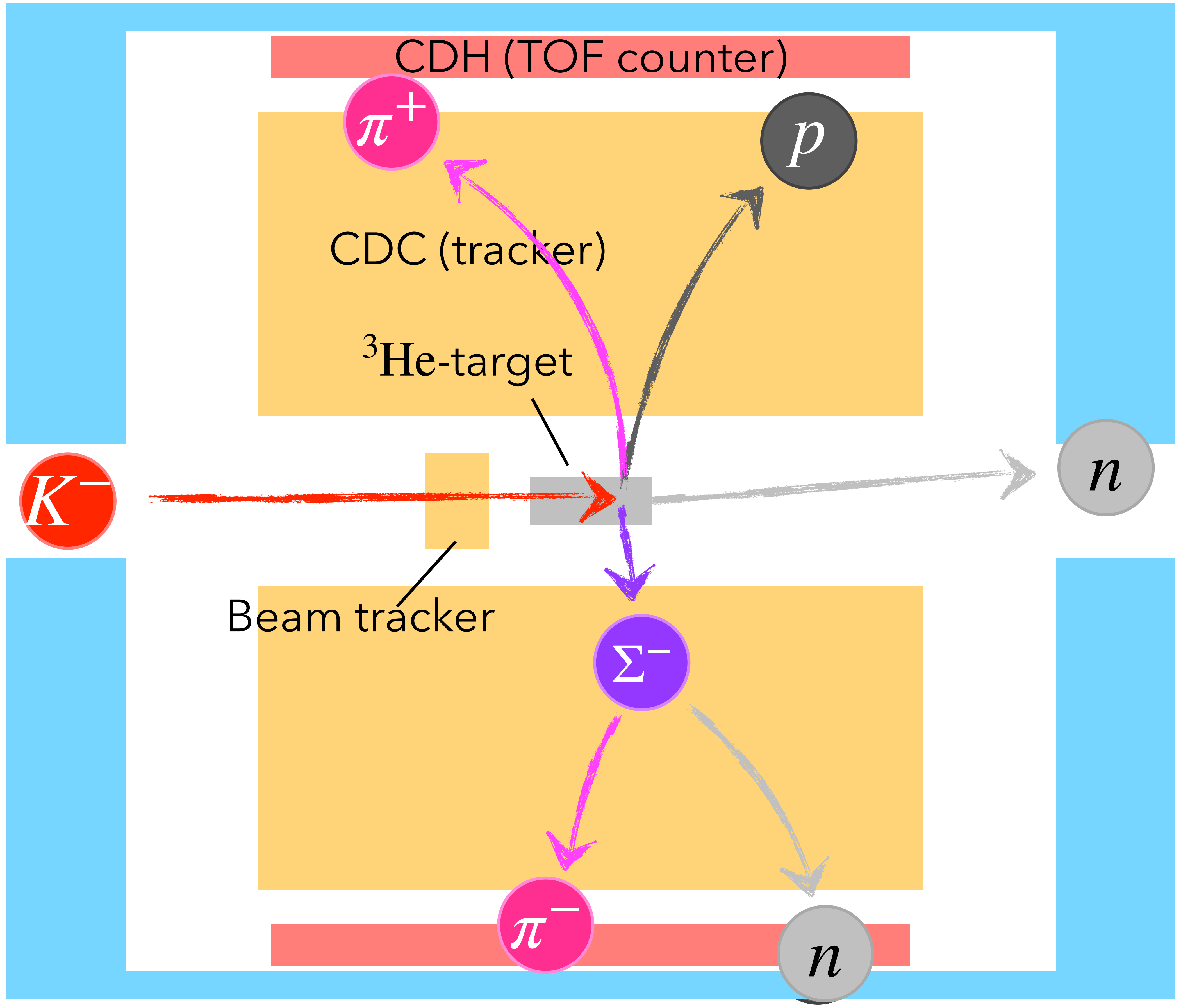

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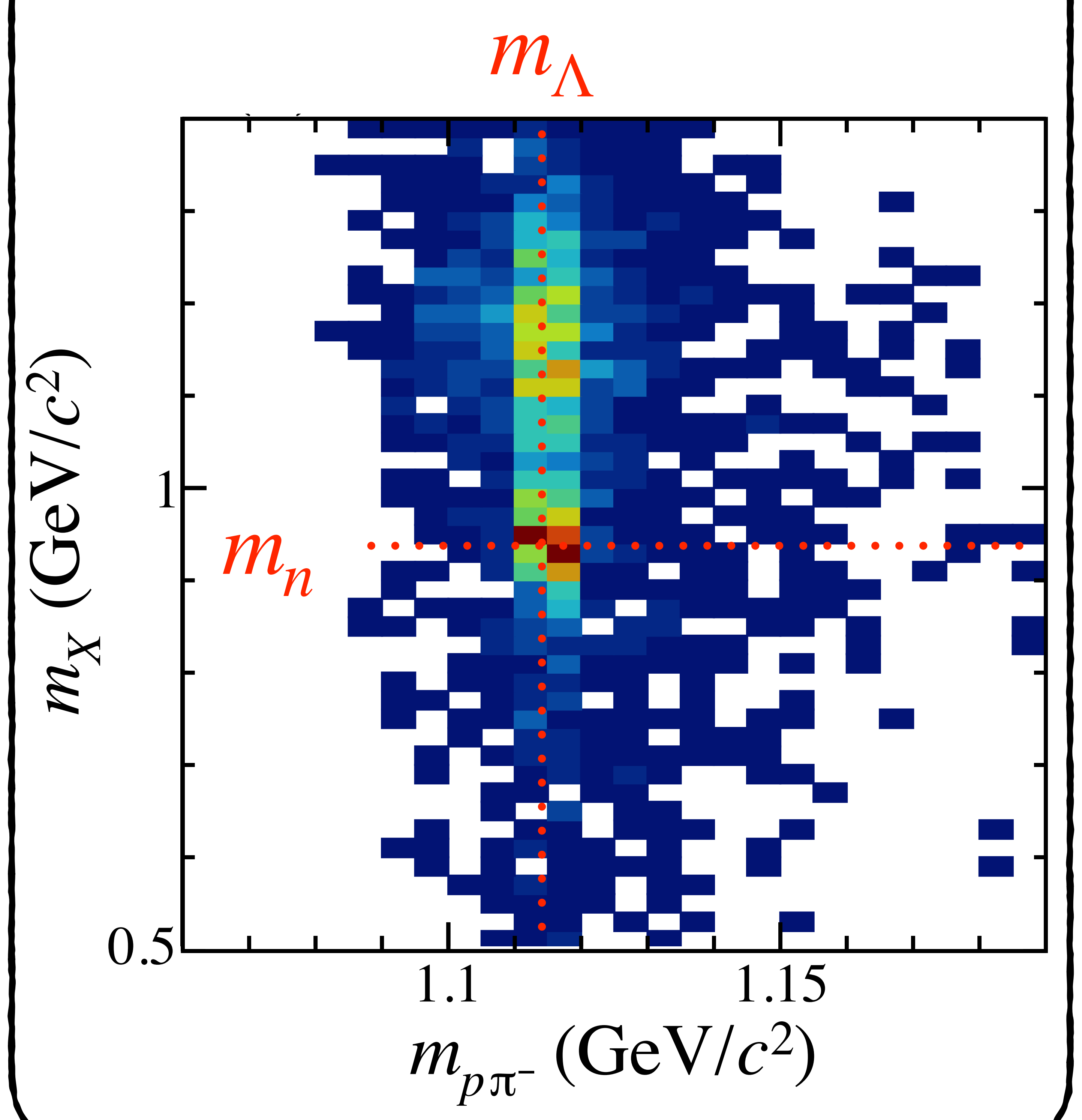
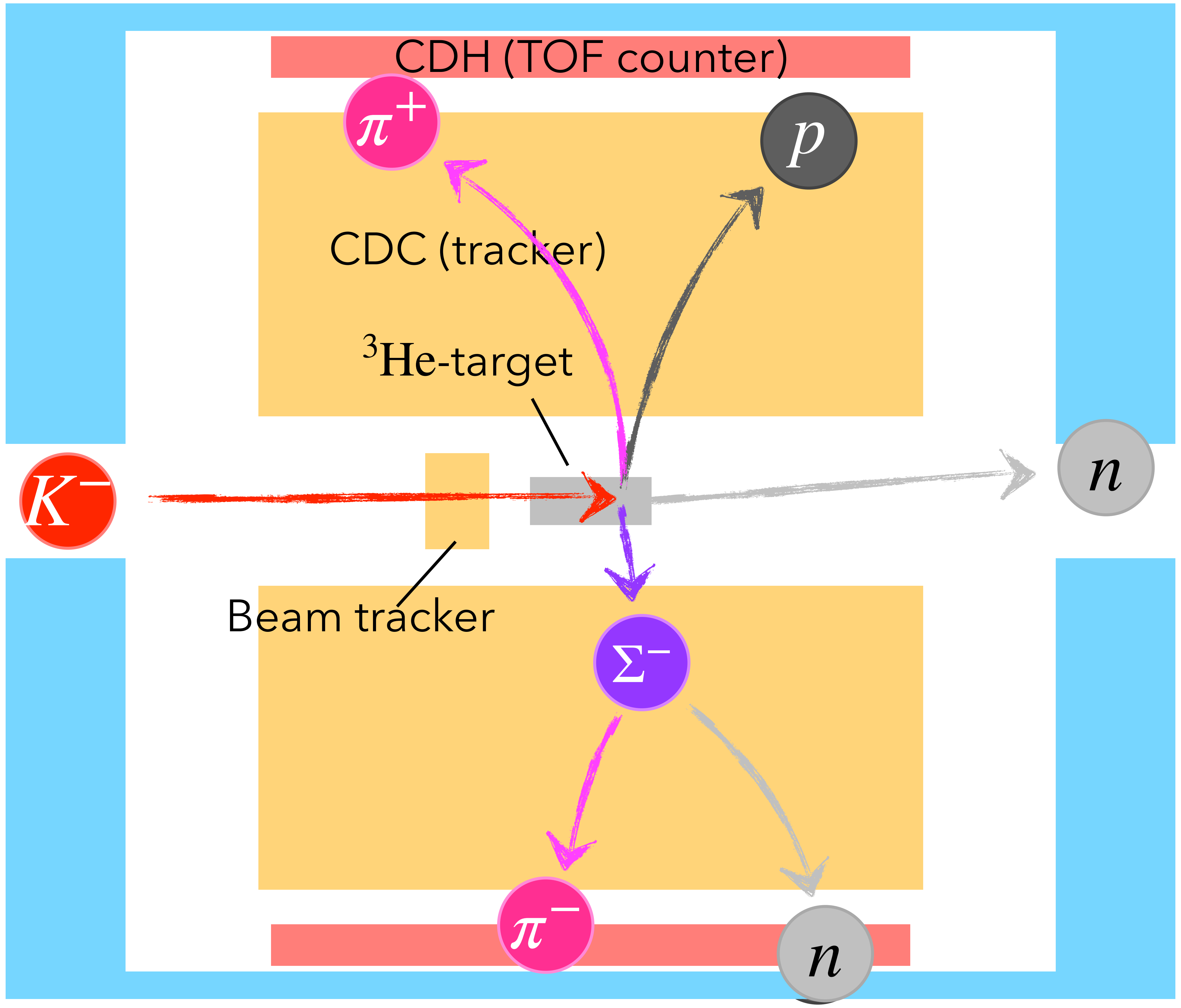
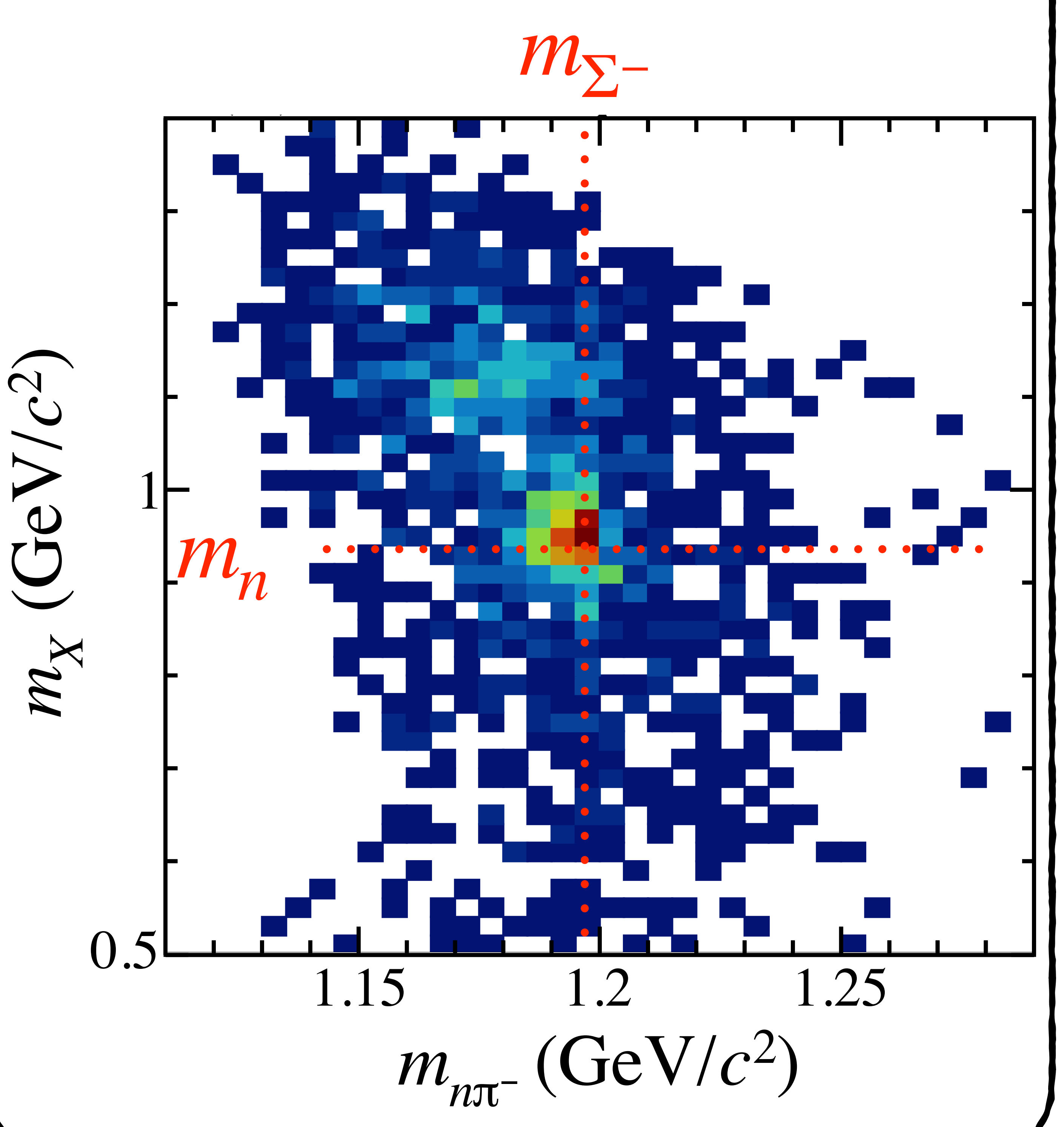


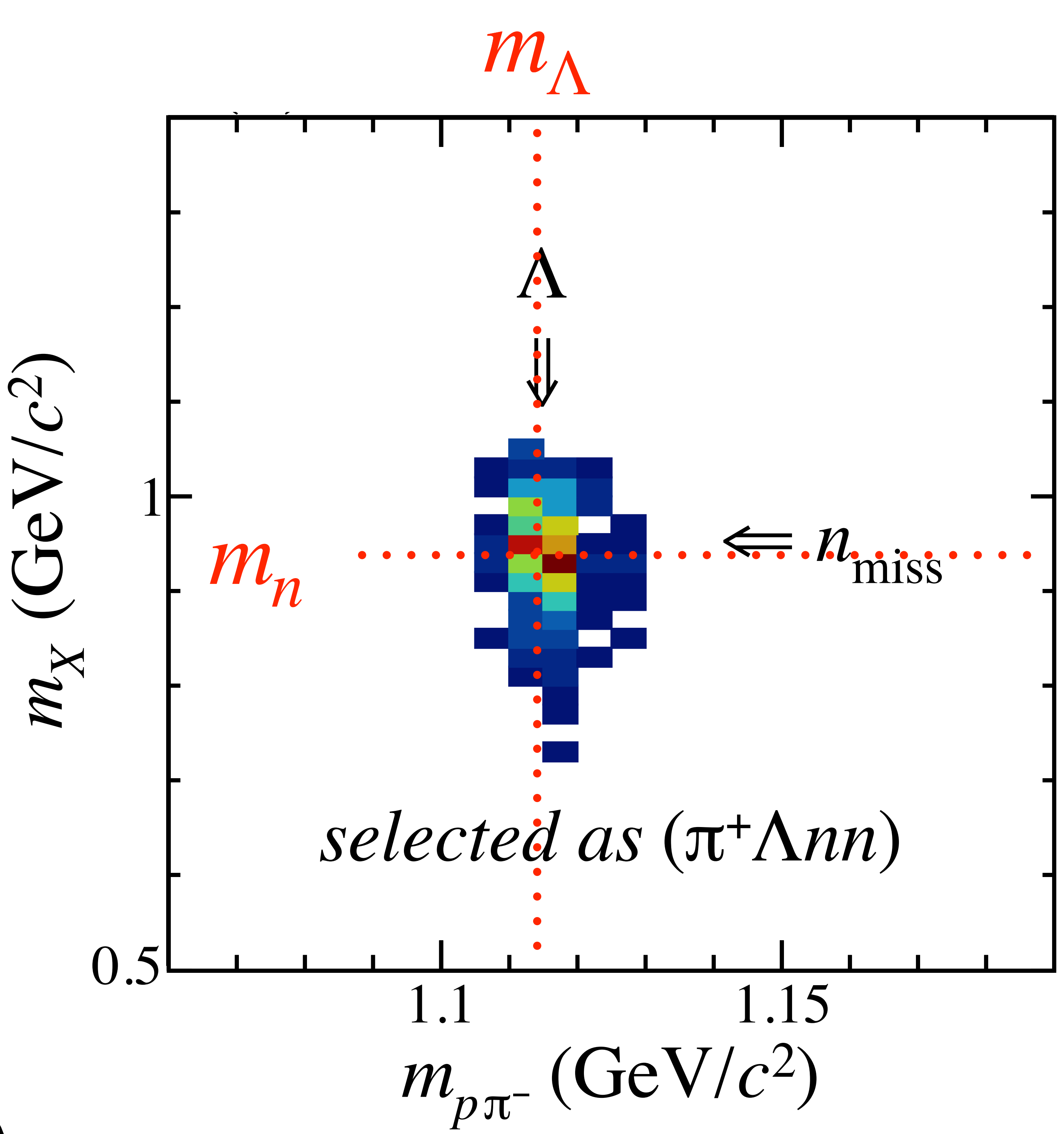


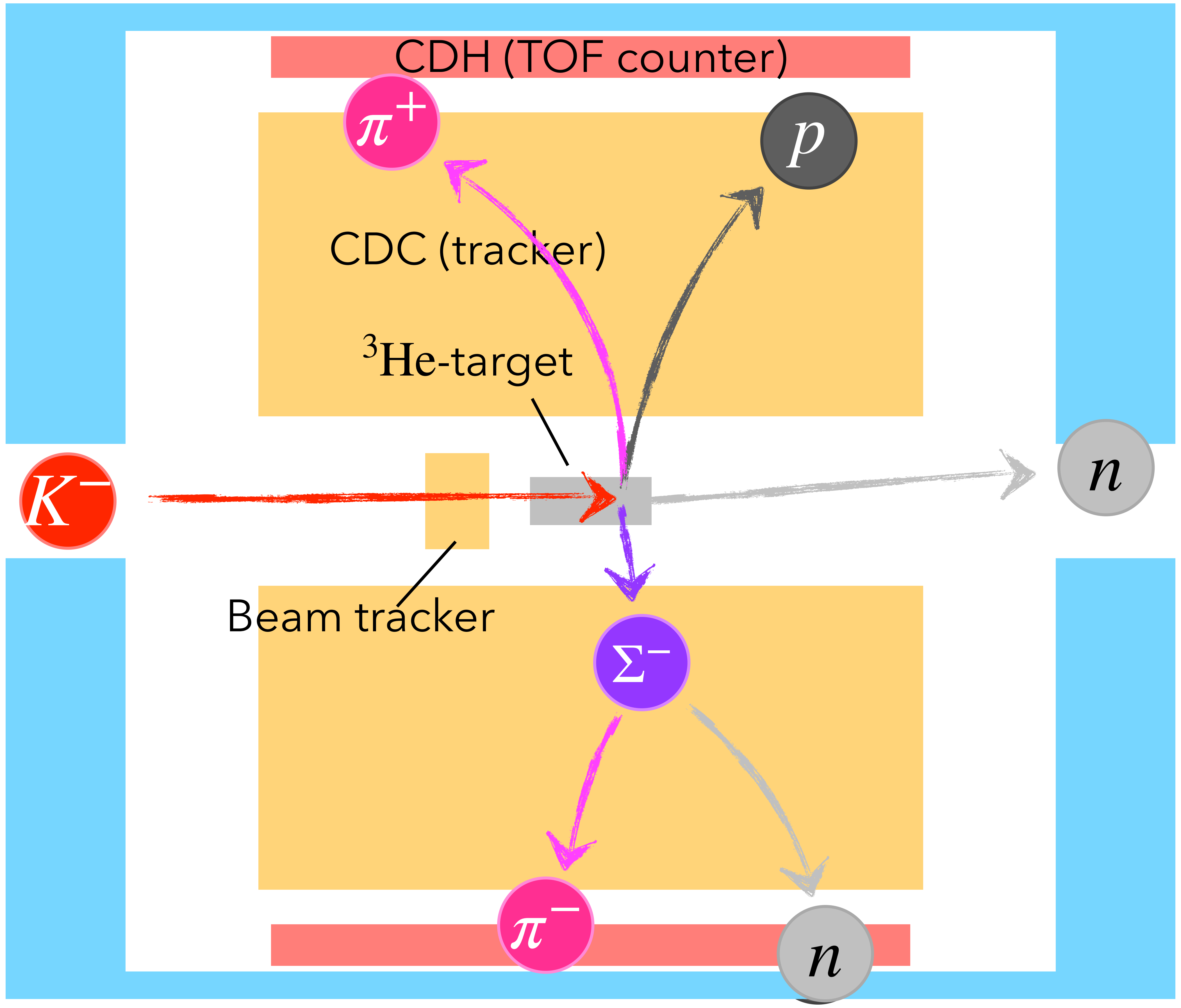
For the $\pi^+\Sigma^-pn$ final state



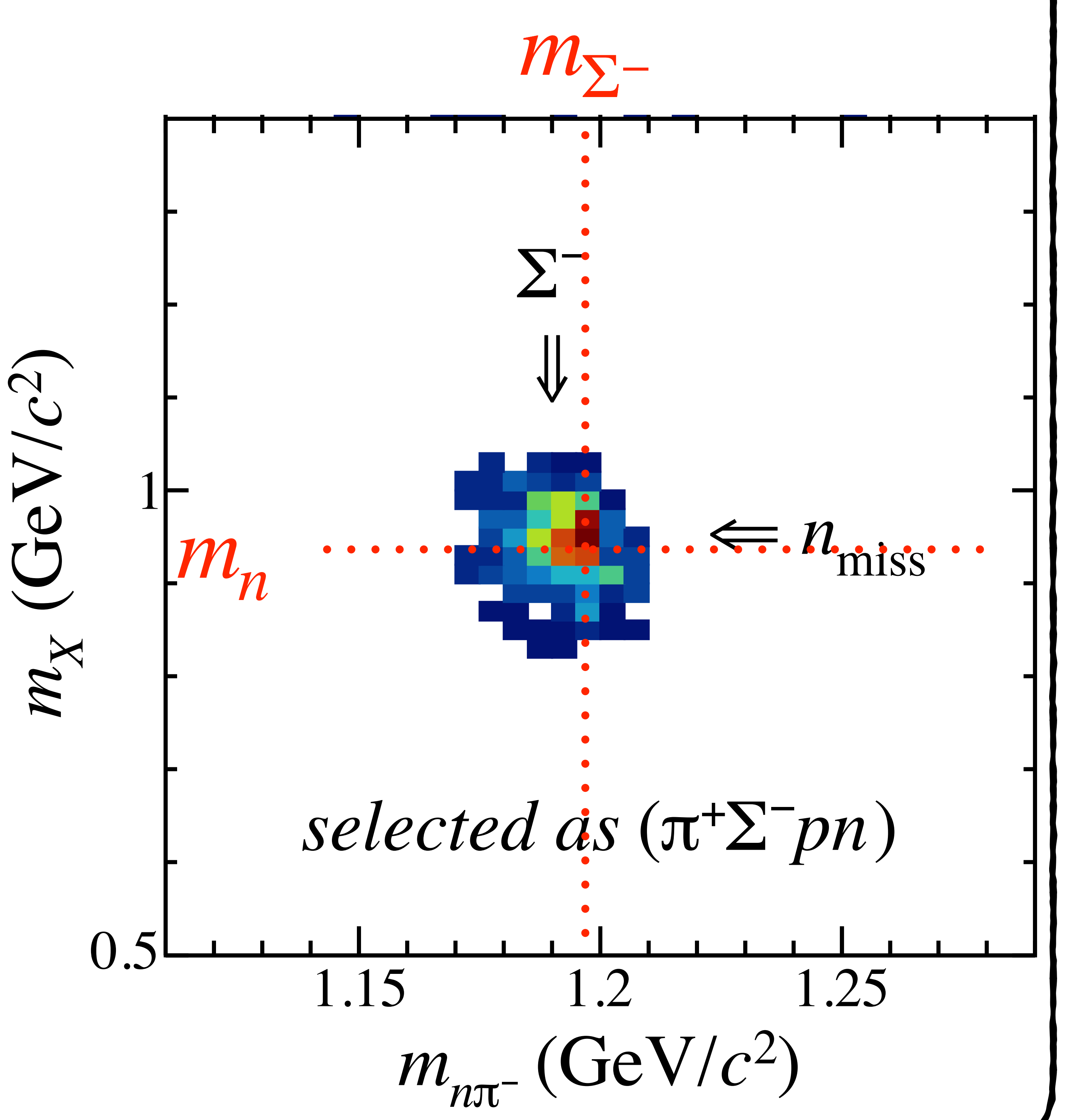
Event selection

For the $\pi^+\Lambda nn$ final state





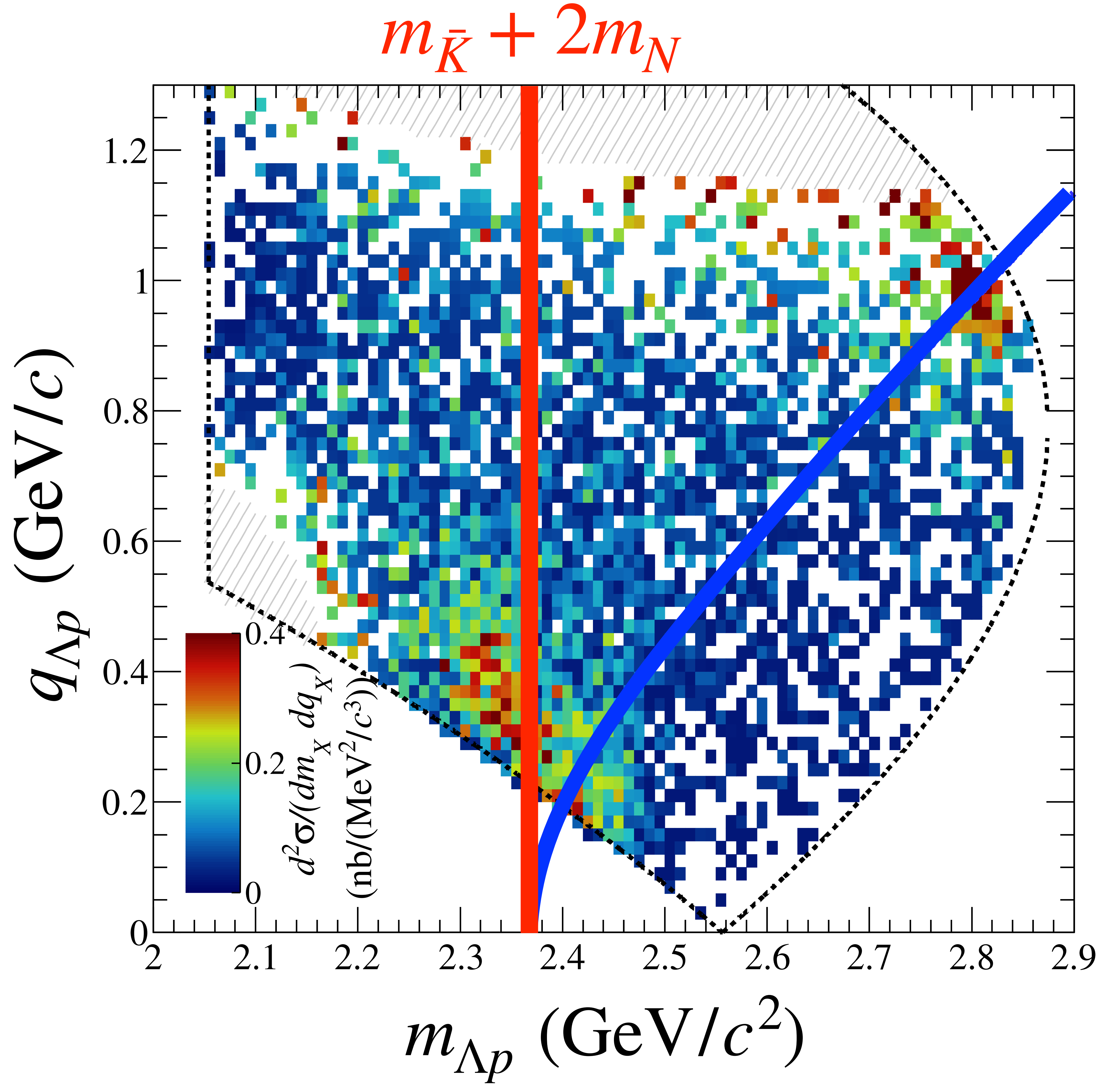
For the $\pi^+\Sigma^- pn$ final state

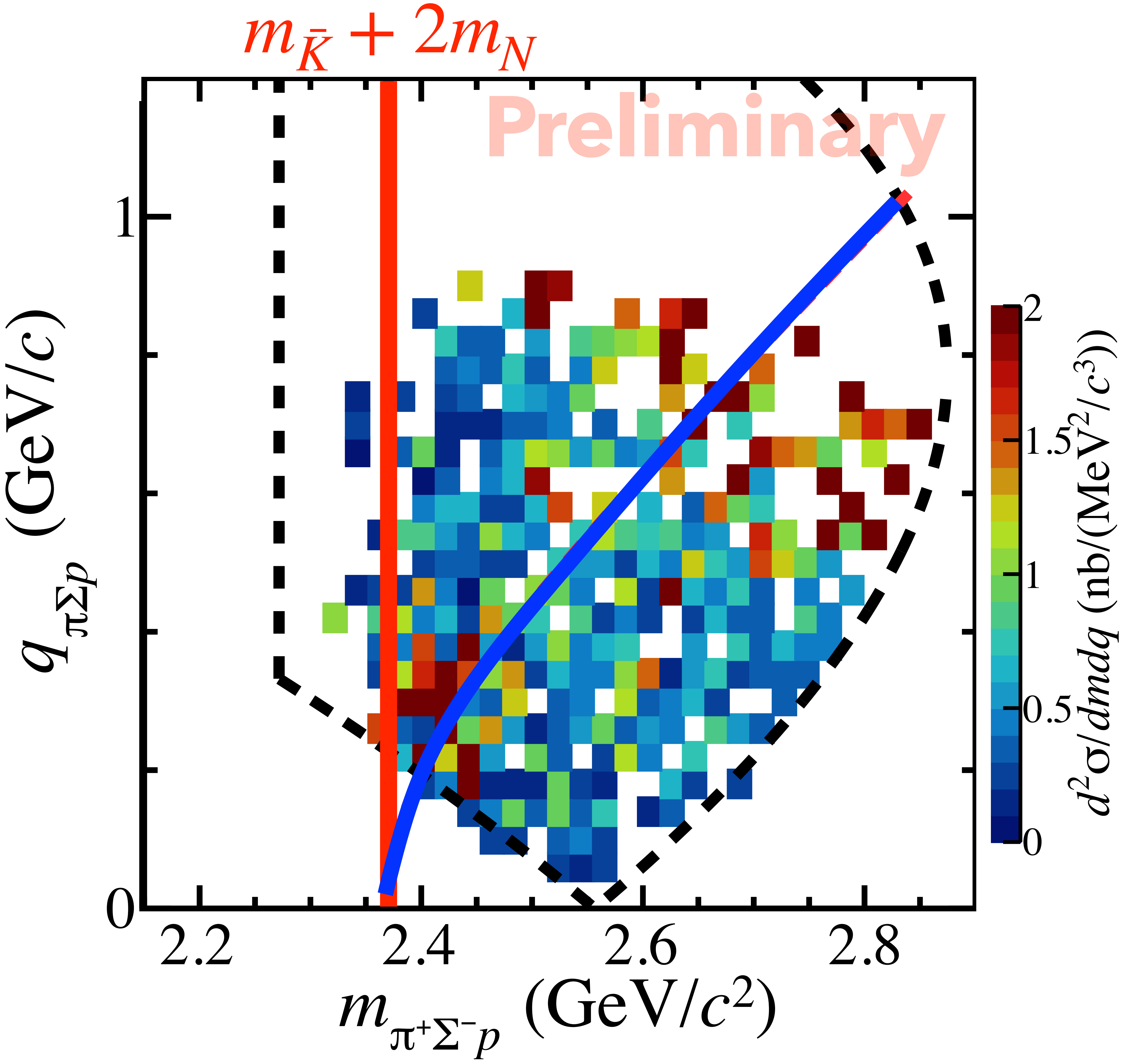


Purity of the πYNN final states $\sim 80\,\%$

Λp $+n_{\text{miss}}$

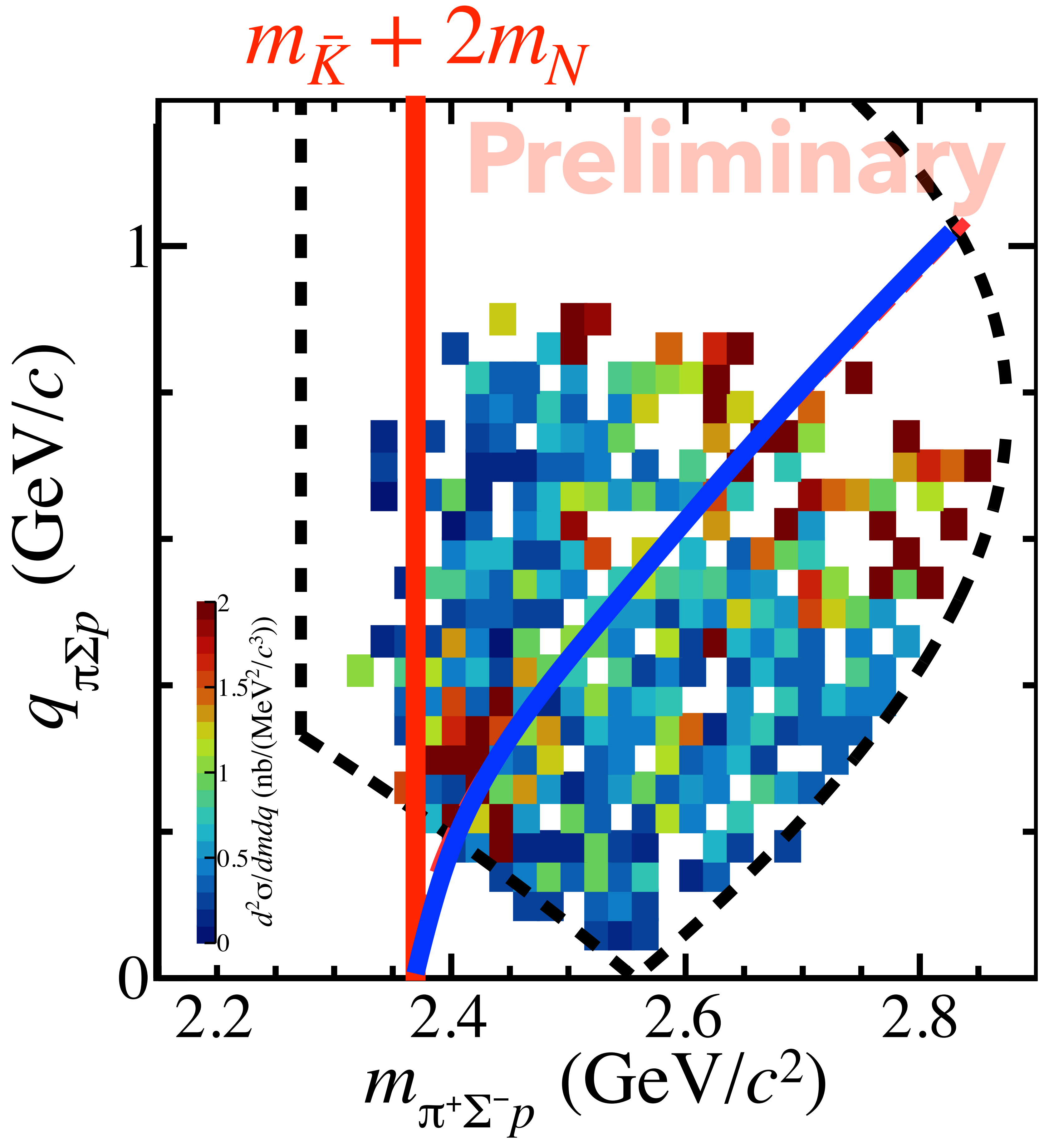
$\pi^+\Sigma^- p$ $+n_{\text{miss}}$





Similar but not clear peak below $m_{\bar{K}} + 2m_N$ due to the phase space

$\pi^+\Sigma^-p_{+n_{miss}}$



$\pi^-\Sigma^+p$ $+n_{miss}$ | $\pi^+\Sigma^-p$ $+n_{miss}$ | $\pi^+\Lambda n$ $+n_{miss}$

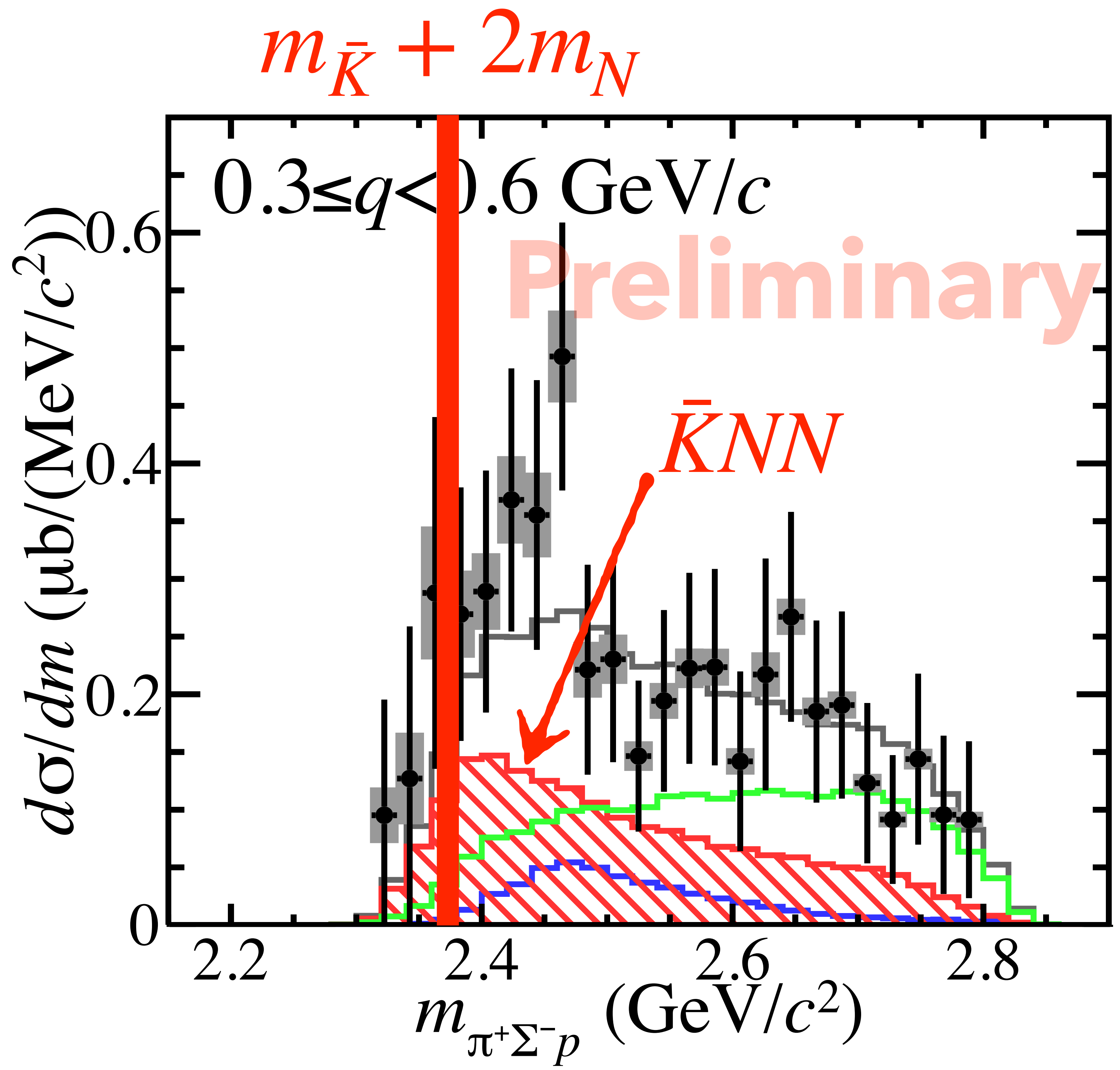
Fitting πYN distribution with the same model function applied to the Λp distribution

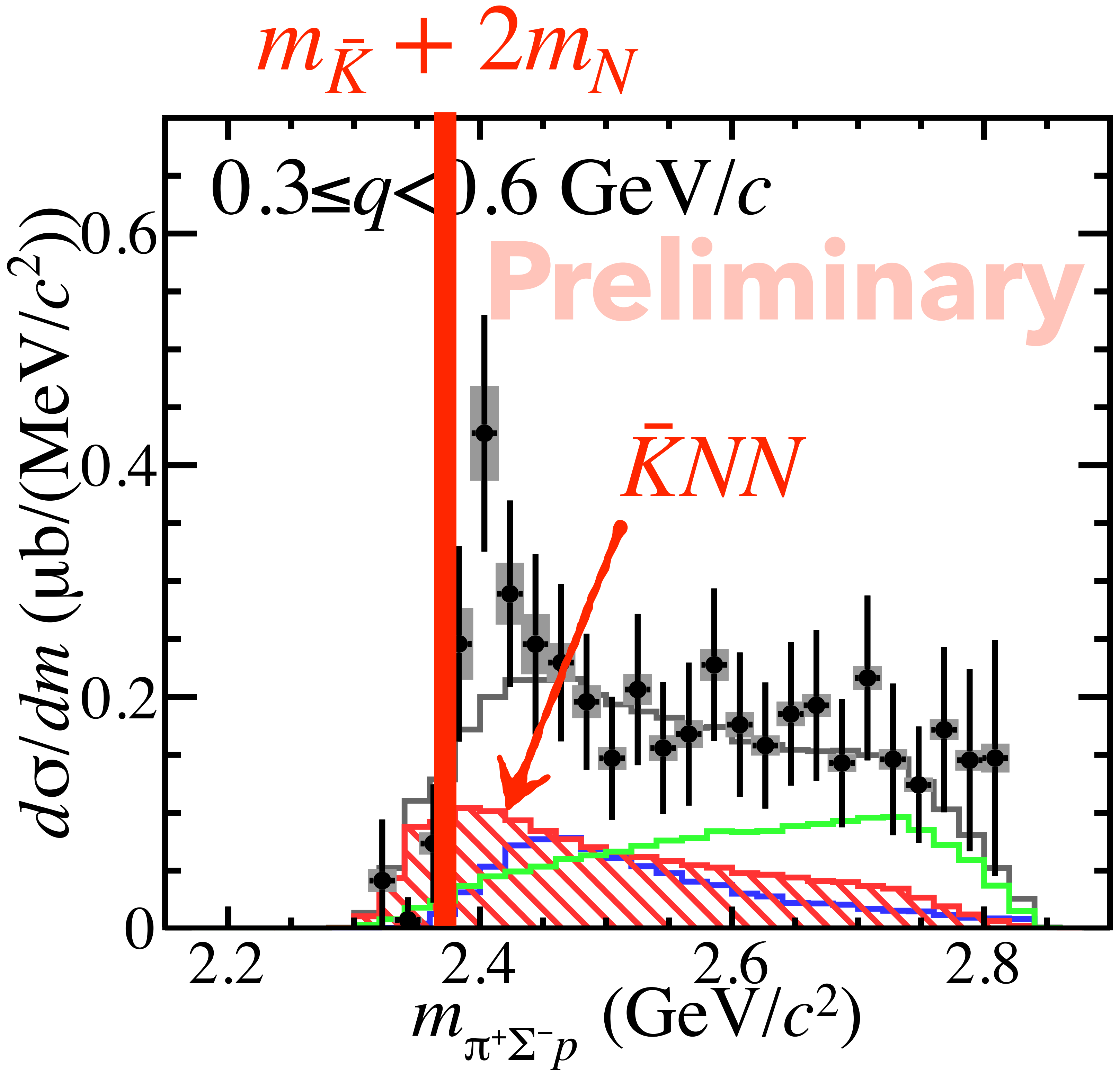
Fitting πYN distribution with the same model function applied to the Λp distribution

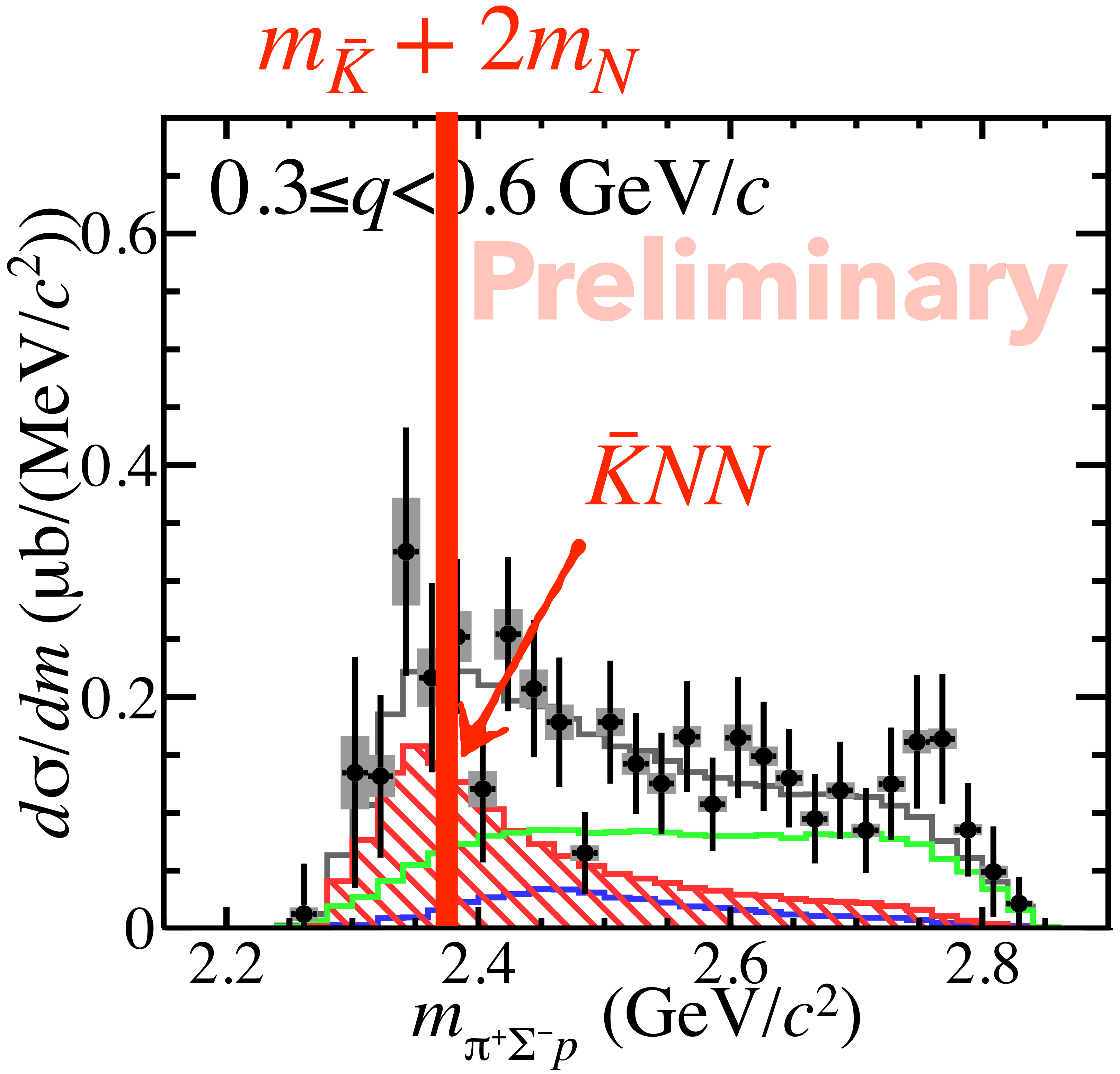
$\pi^-\Sigma^+ p$ $+n_{\text{miss}}$

$\pi^+\Sigma^- p$ $+n_{\text{miss}}$

$\pi^+\Lambda\, n$ $+n_{\text{miss}}$







Well reproduced although statistics is limited.

$\sigma_{\bar{K}NN} \times \mathrm{BR}$

※Statistical error only

$\pi^{-}\Sigma^{+}p$ $+n_{\mathrm{miss}}$	Preliminary $110 \pm 8\ \mu\mathrm{b}$
$\pi^{+}\Sigma^{-}p$ $+n_{\mathrm{miss}}$	Preliminary $38 \pm 3\ \mu\mathrm{b}$
$\pi^{+}\Lambda\, n$ $+n_{\mathrm{miss}}$	Preliminary $62 \pm 11\ \mu\mathrm{b}$
c.f. Λp $+n_{\mathrm{miss}}$	$9.3 \pm 0.8^{+1.4}_{-1.0}\ \mu\mathrm{b}$

$\sigma_{\bar{K}NN} \times \mathrm{BR}$

※Statistical error only

$\pi^-\Sigma^+p$ $+n_{\mathrm{miss}}$	Preliminary $110 \pm 8\ \mu\mathrm{b}$
$\pi^+\Sigma^-p$ $+n_{\mathrm{miss}}$	Preliminary $38 \pm 3\ \mu\mathrm{b}$
$\pi^+\Lambda n$ $+n_{\mathrm{miss}}$	Preliminary $62 \pm 11\ \mu\mathrm{b}$
c.f. Λp $+n_{\mathrm{miss}}$	$9.3 \pm 0.8^{+1.4}_{-1.0}\ \mu\mathrm{b}$

$$\Gamma_{YN} \ll \Gamma_{\pi YN}$$

$\Gamma_{\pi YN}$ would be $\mathcal{O}(10)$ times larger than Γ_{YN}.

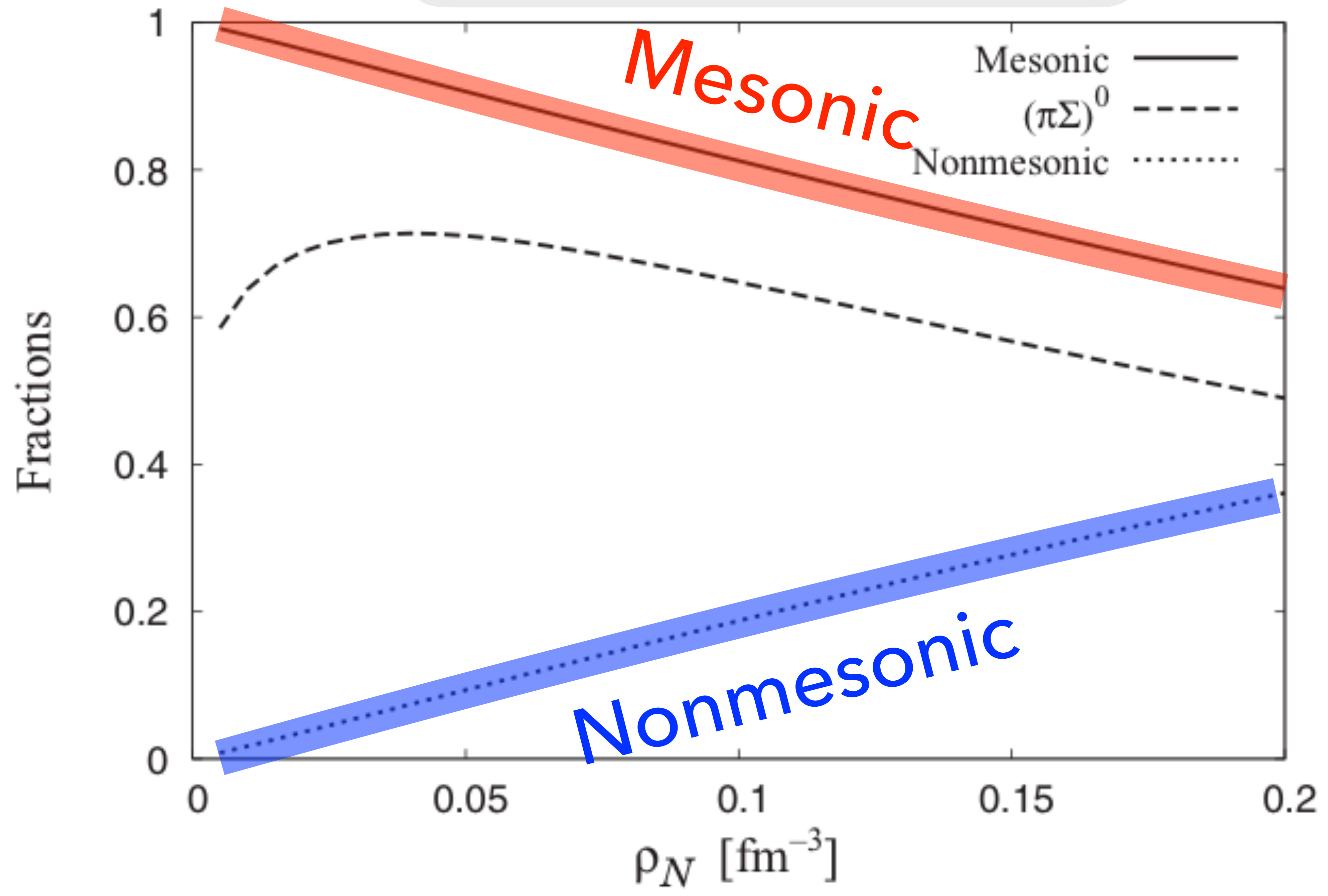
$$\Gamma_{\pi^+\Lambda n} \sim \Gamma_{\pi^\mp\Sigma^\pm p}$$

$$\Gamma_{YN} \ll \Gamma_{\pi YN}$$

$\Gamma_{\pi YN}$ would be $\mathcal{O}(10)$ times larger than Γ_{YN}.

$$\Gamma_{\pi^+\Lambda n} \sim \Gamma_{\pi^\mp\Sigma^\pm p}$$

T. Sekihara *et al.*,
Phys. Rev. C **86** (2012) 065205



$$\Gamma_{YN} \ll \Gamma_{\pi YN}$$

$$\Gamma_{\pi^+\Lambda n} \sim \Gamma_{\pi^\mp\Sigma^\pm p}$$

Non-mesonic fraction seems to be smaller than calc.

T. Sekihara *et al.*,
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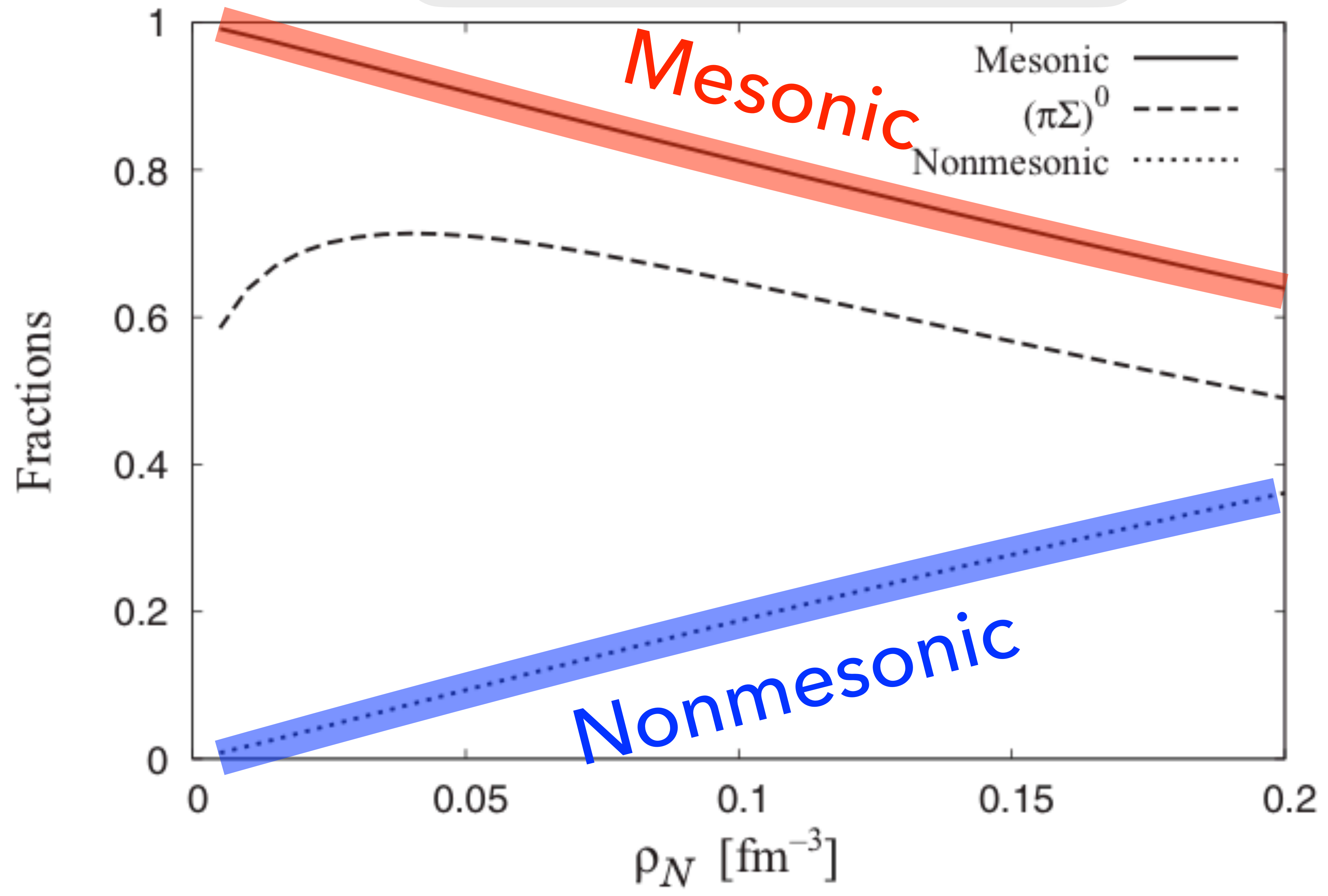

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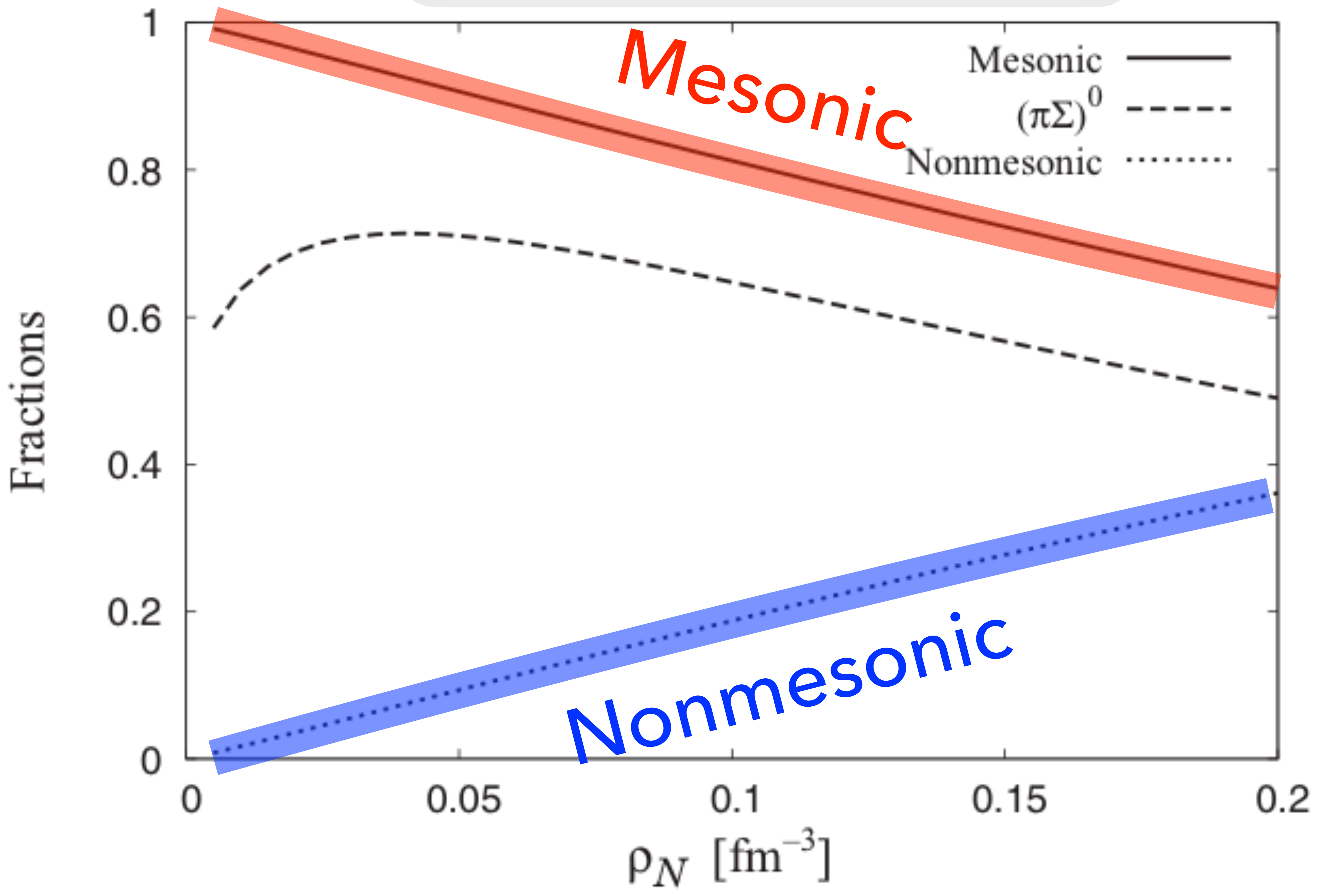
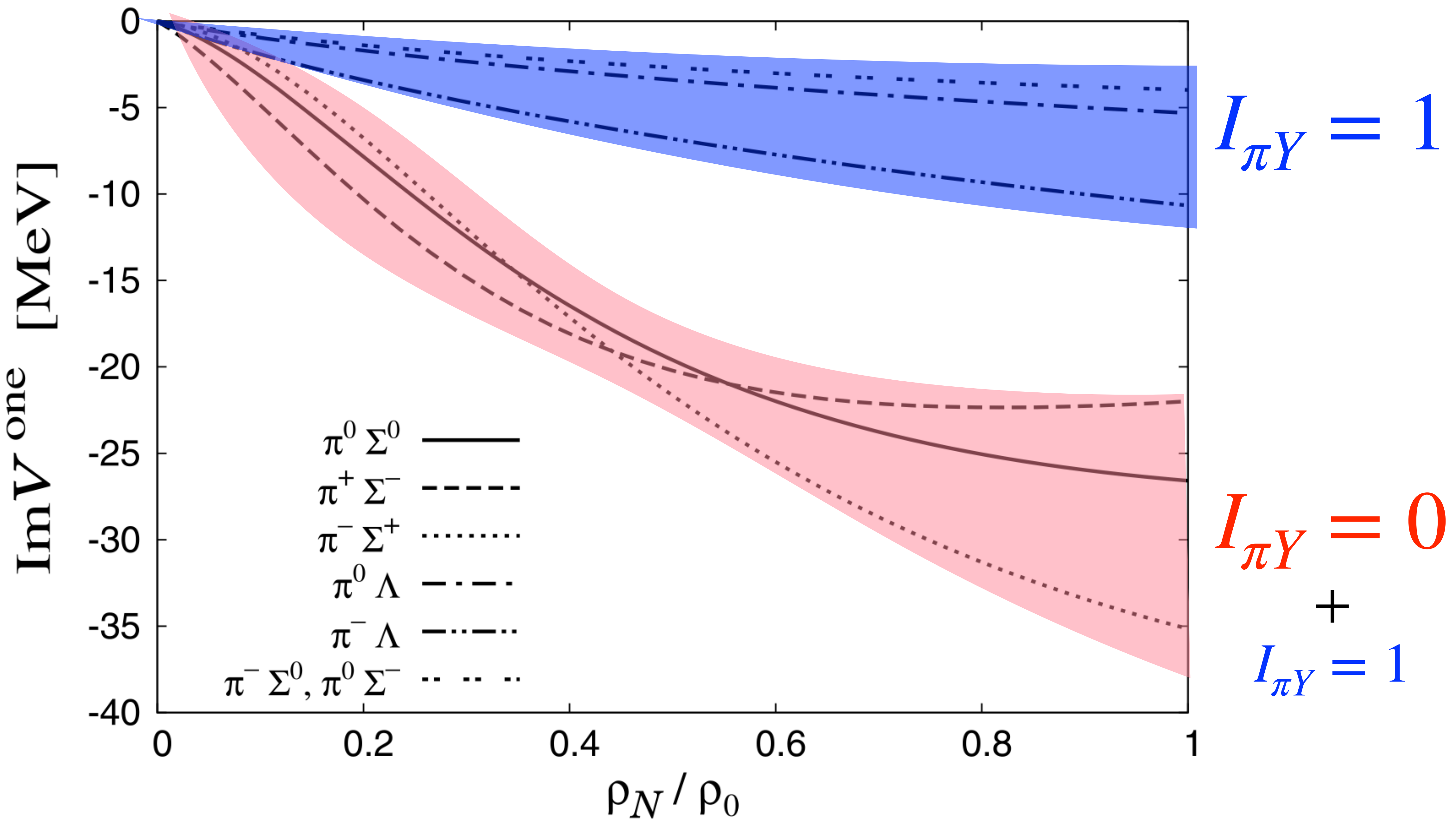


T. Sekihara *et al.*, Nucl. Phys. A **914** (2013) 338



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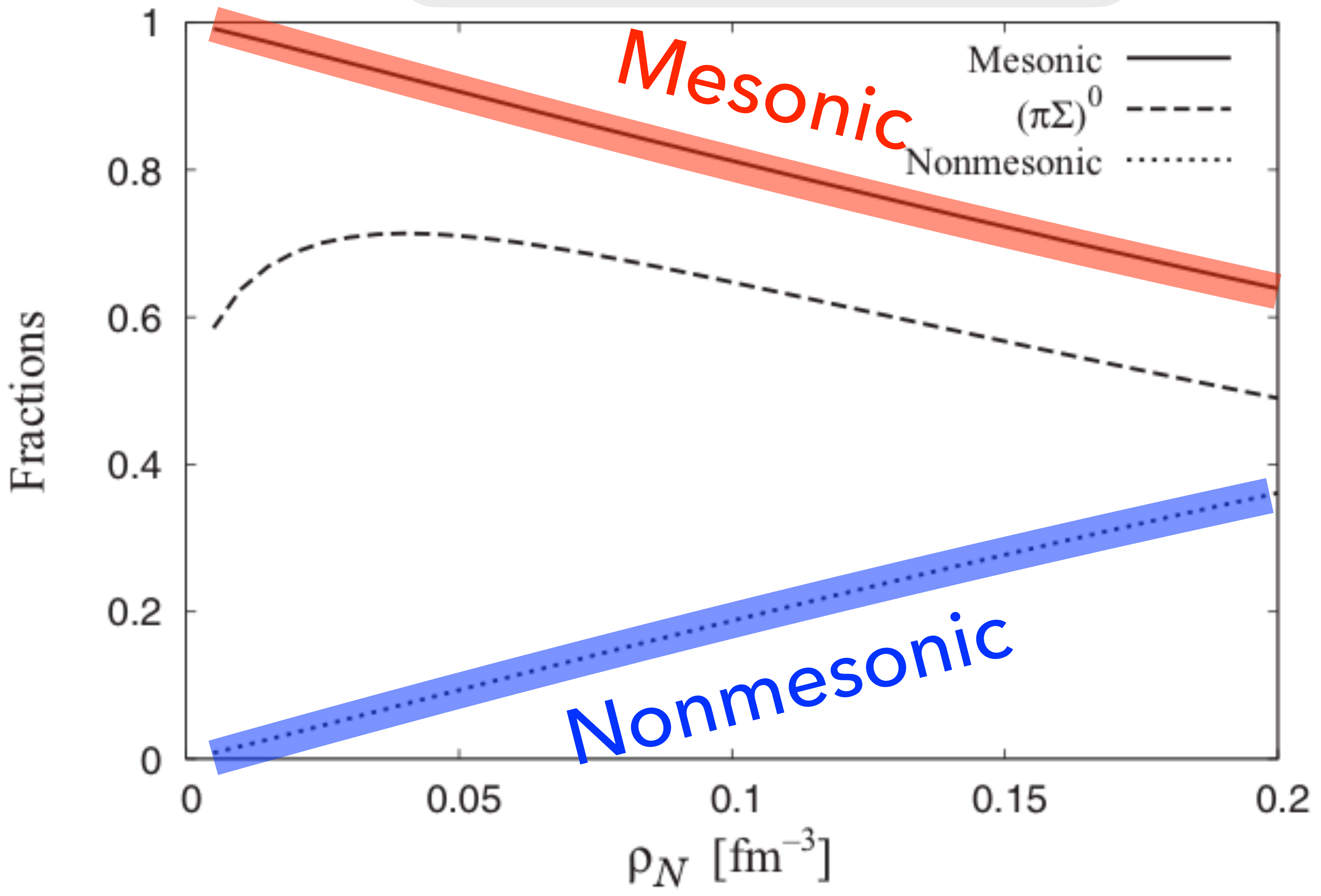
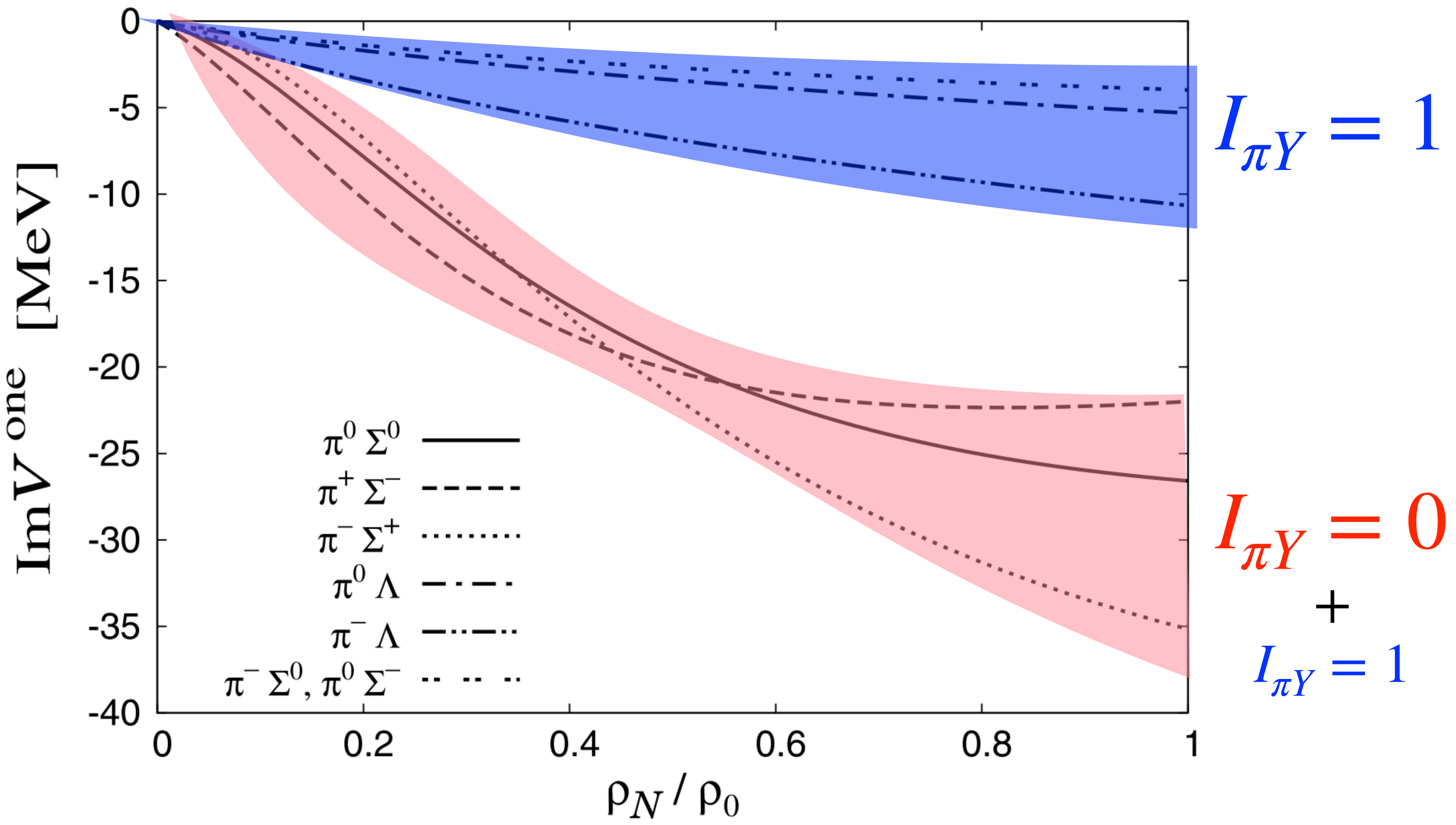


$\Gamma_{\pi^+\Lambda n} \sim \Gamma_{\pi^\mp\Sigma^\pm p}$

$I_{\pi Y} = 1$ fraction seems to be larger than calc.

T. Sekihara *et al.*, Nucl. Phys. A **914** (2013) 338



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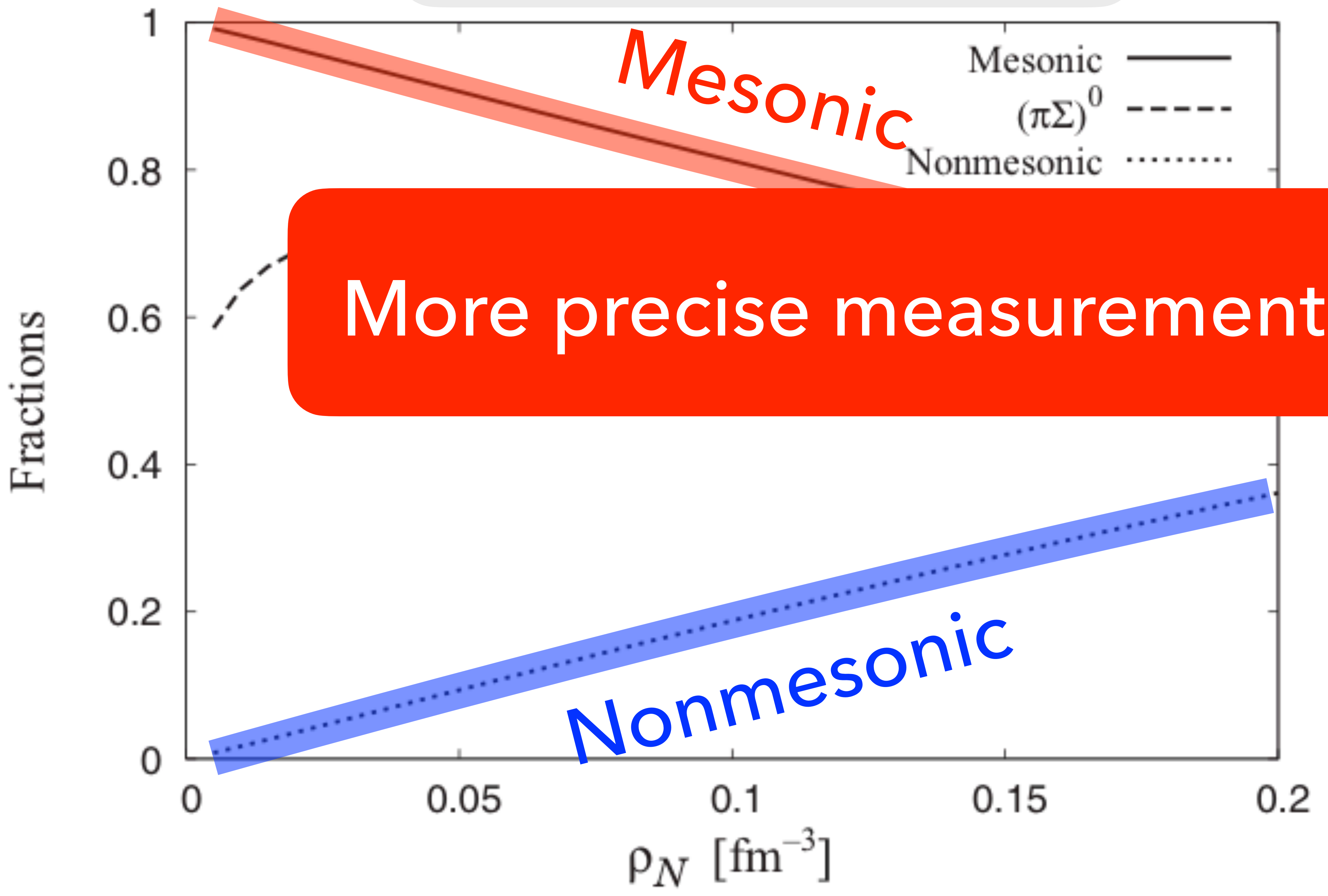
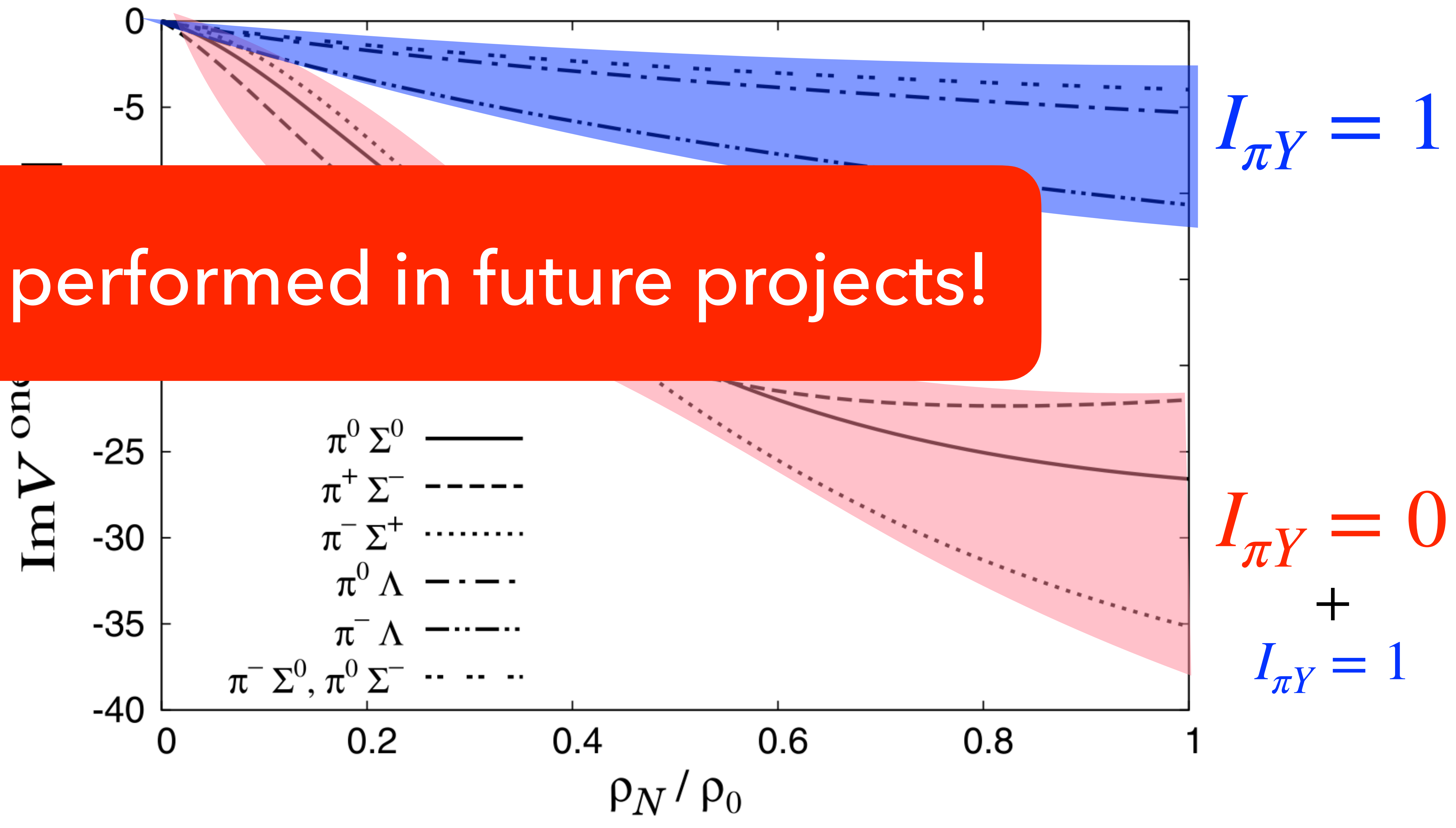
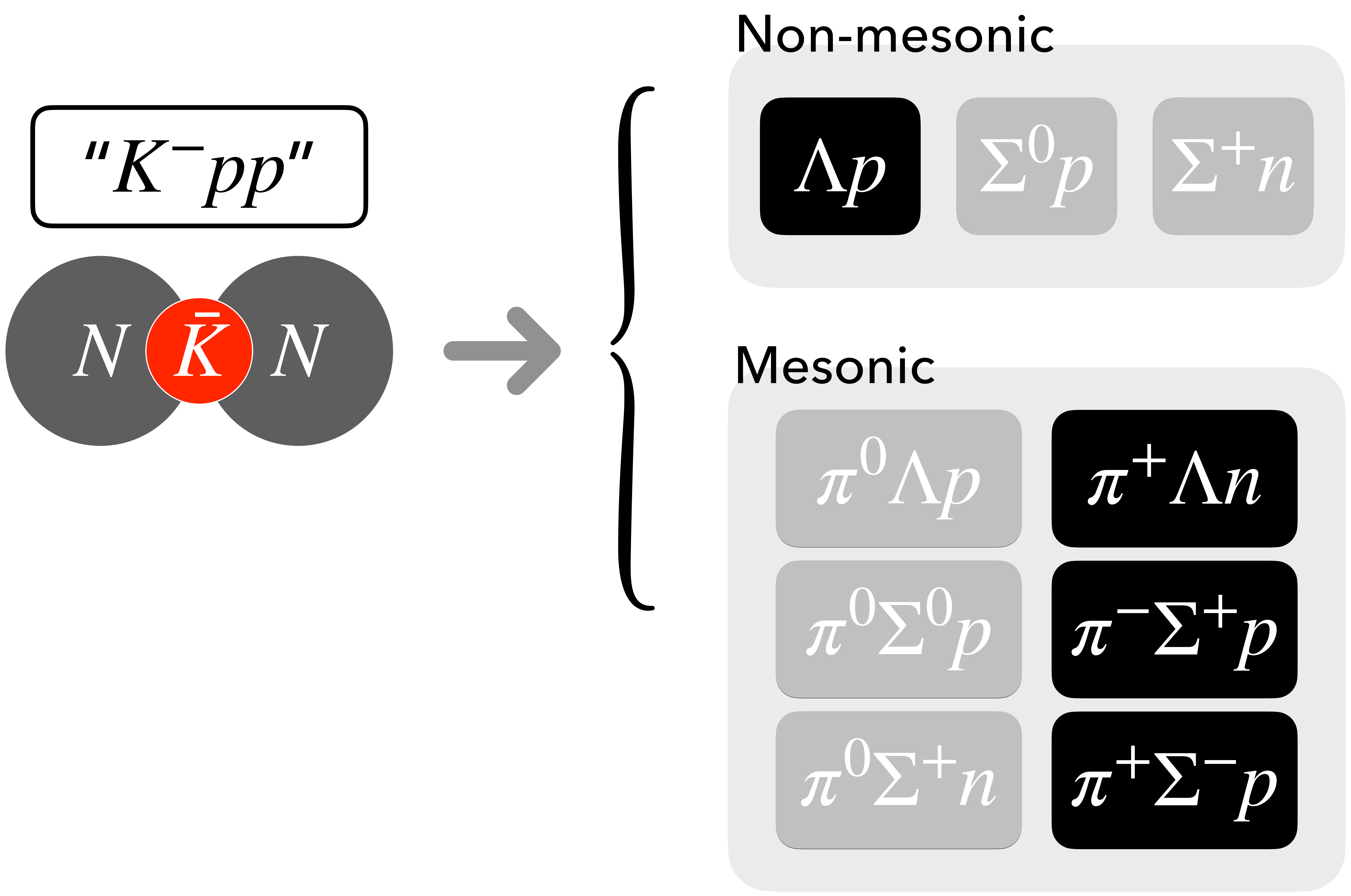


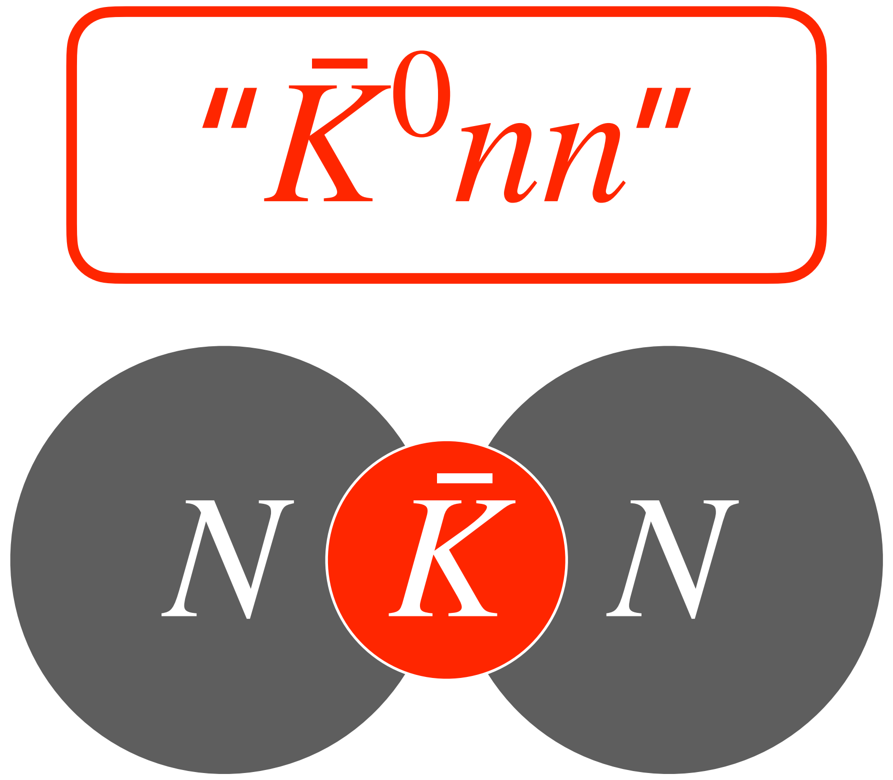


More precise measurement will be performed in future projects!

Decay channels of $\bar{K}NN$



Decay channels of $\bar{K}NN$



Non-mesonic

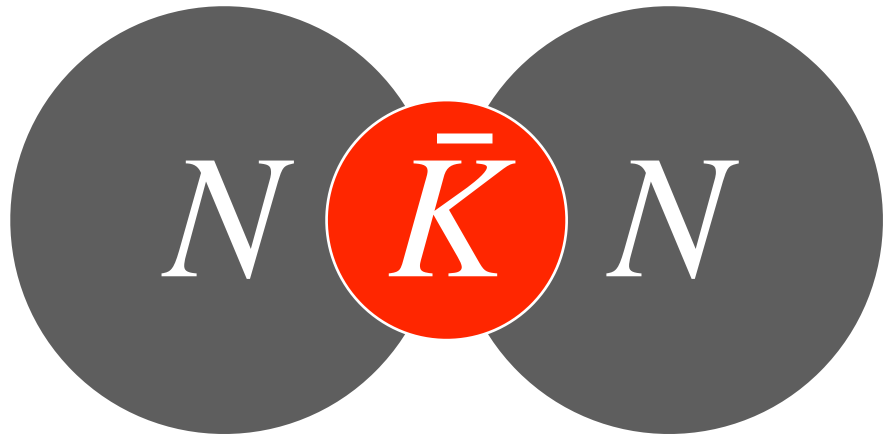
- Λn
- $\Sigma^0 n$
- $\Sigma^- p$

Mesonic

- $\pi^0 \Lambda n$
- $\pi^- \Lambda p$
- $\pi^0 \Sigma^0 n$
- $\pi^- \Sigma^+ n$
- $\pi^0 \Sigma^- p$
- $\pi^+ \Sigma^- n$

Decay channels of $\bar{K}NN$

"$\bar{K}^0 nn$"



Non-mesonic

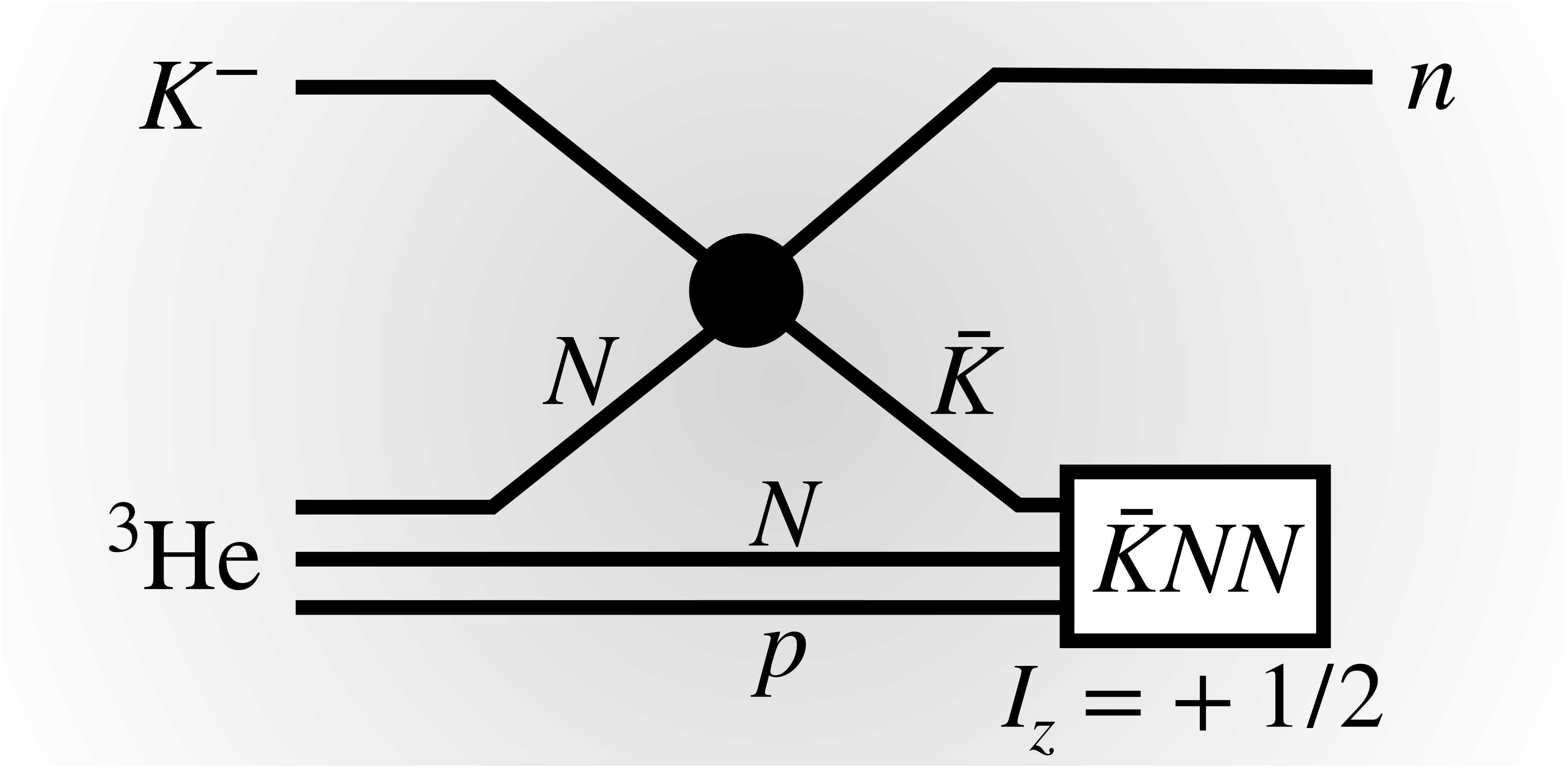
- Λn
- $\Sigma^0 n$
- $\Sigma^- p$

Mesonic

- $\pi^0 \Lambda n$
- $\pi^- \Lambda p$
- $\pi^0 \Sigma^0 n$
- $\pi^- \Sigma^+ n$
- $\pi^0 \Sigma^- p$
- $\pi^+ \Sigma^- n$

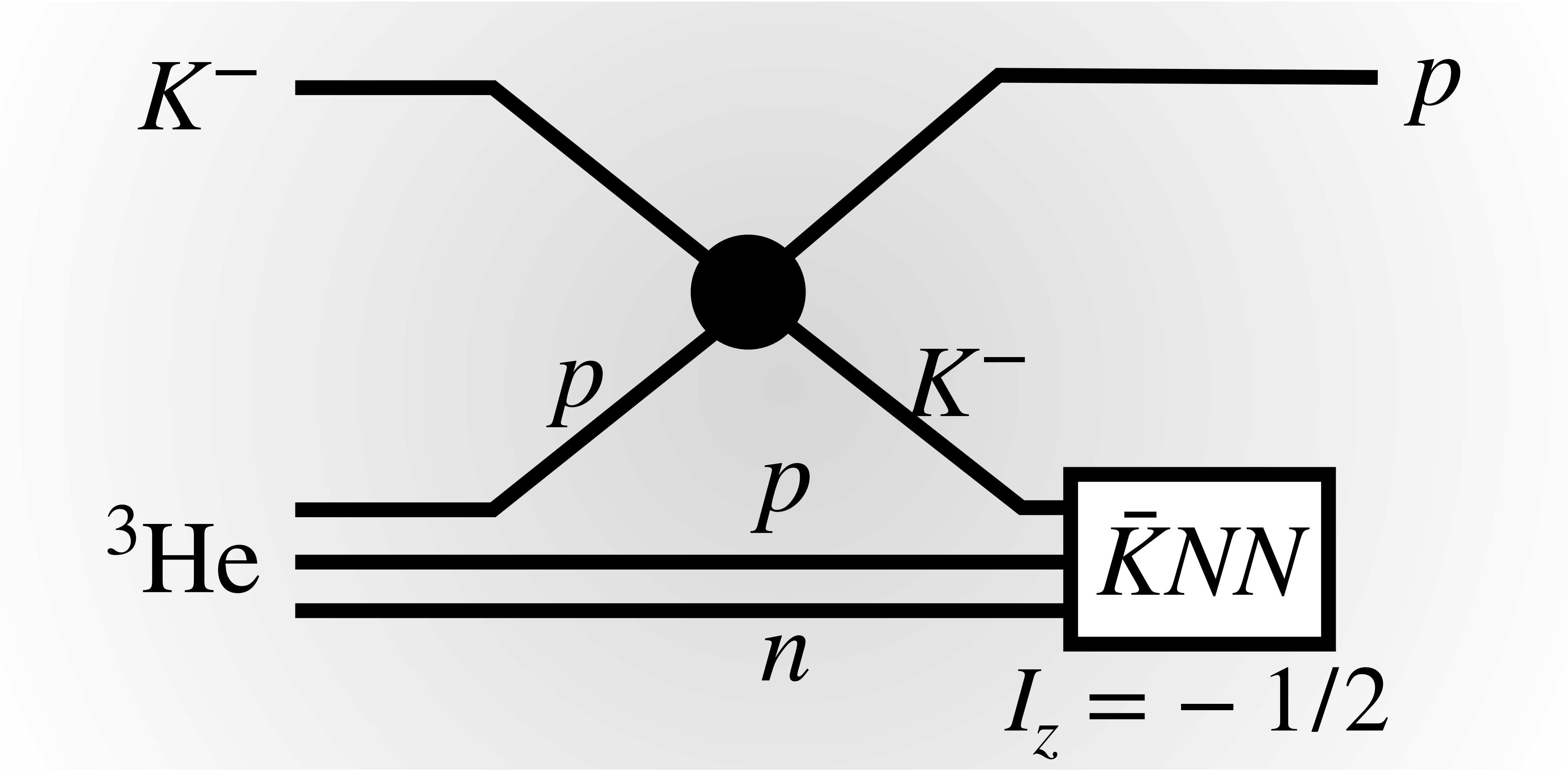
$\bar{K}NN$ production by $^3\mathrm{He}(K^-, N)$ reaction

with (K^-, n) reaction

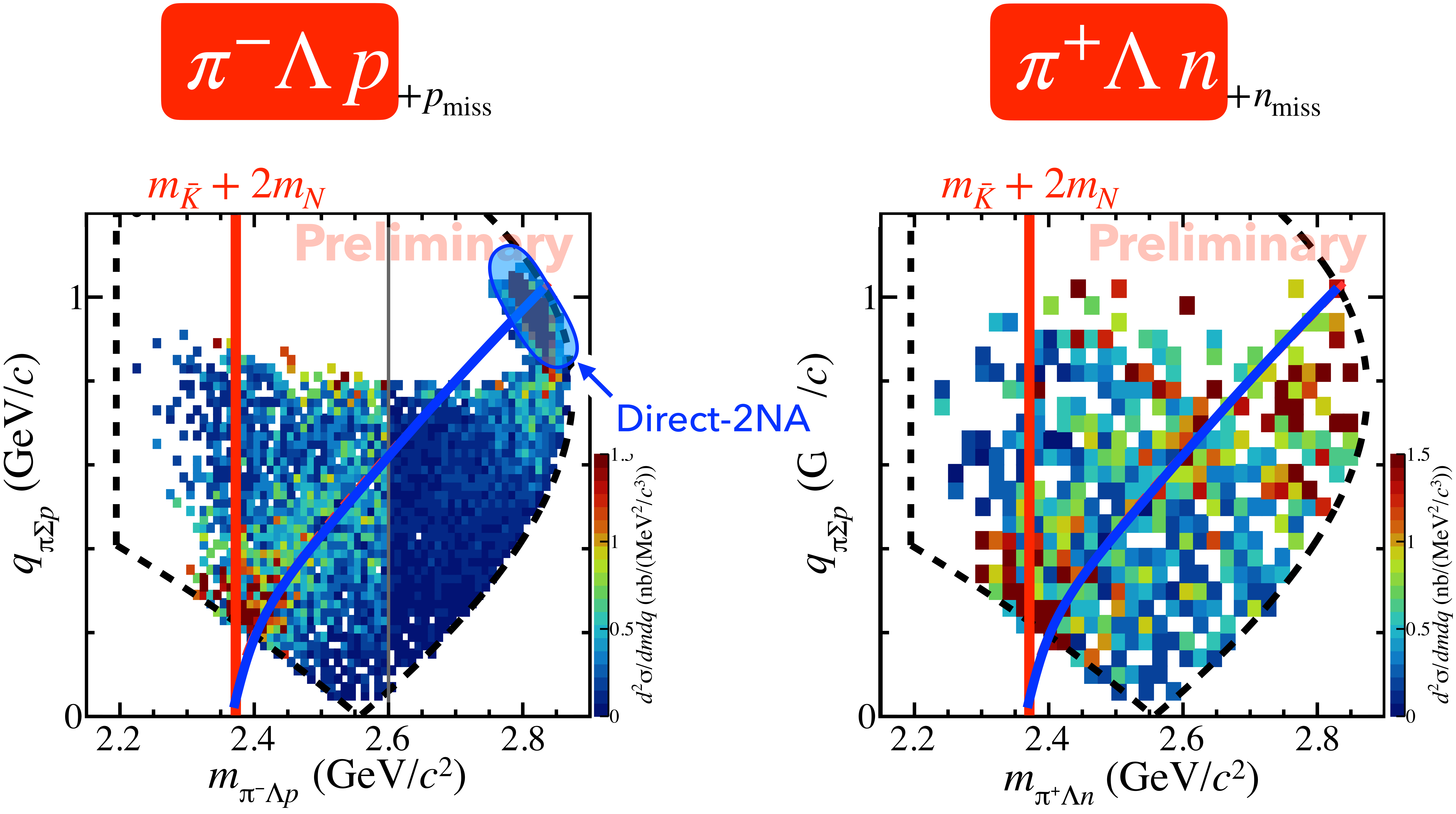


"$K^- pp$" is produced.

with (K^-, p) reaction

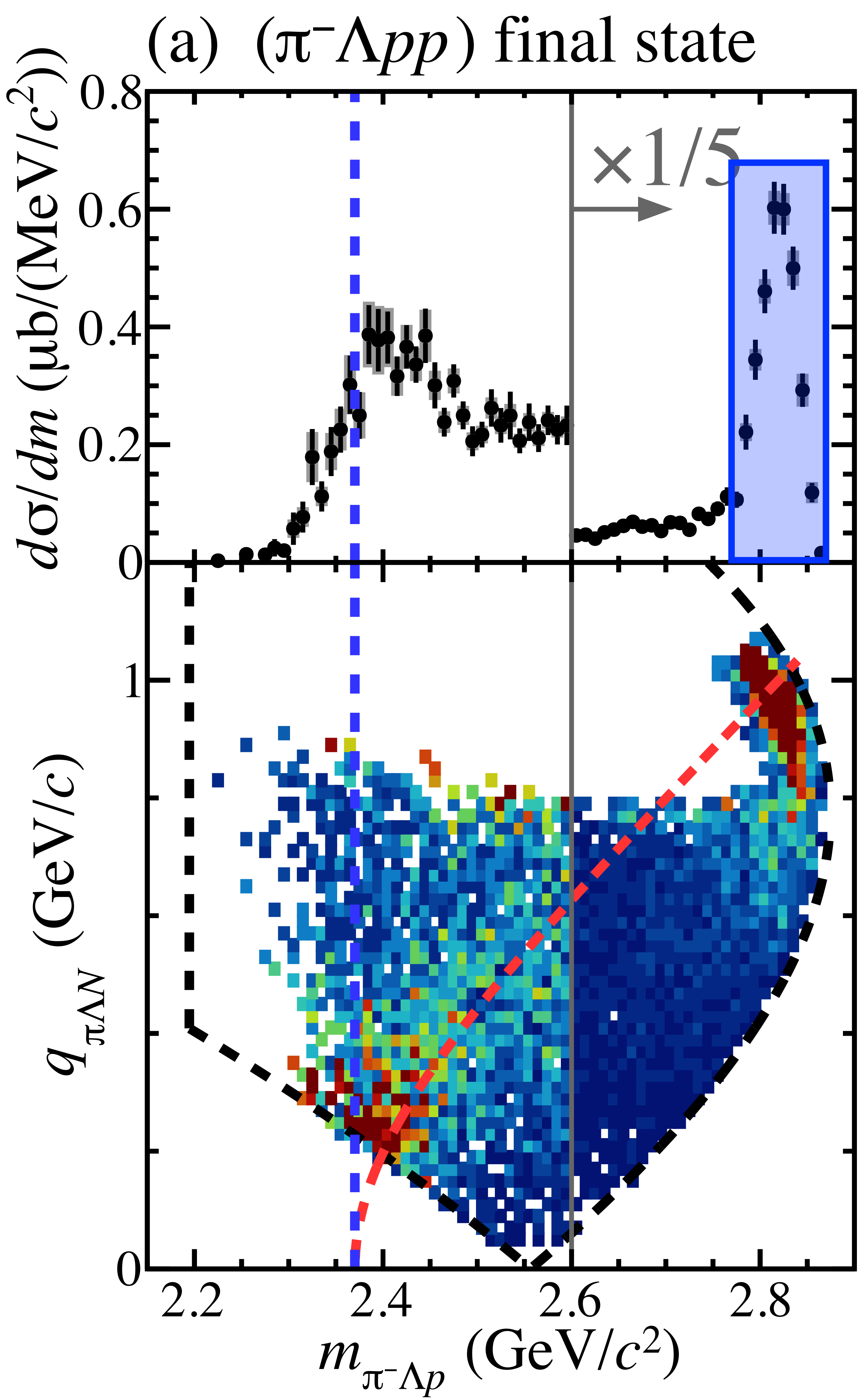


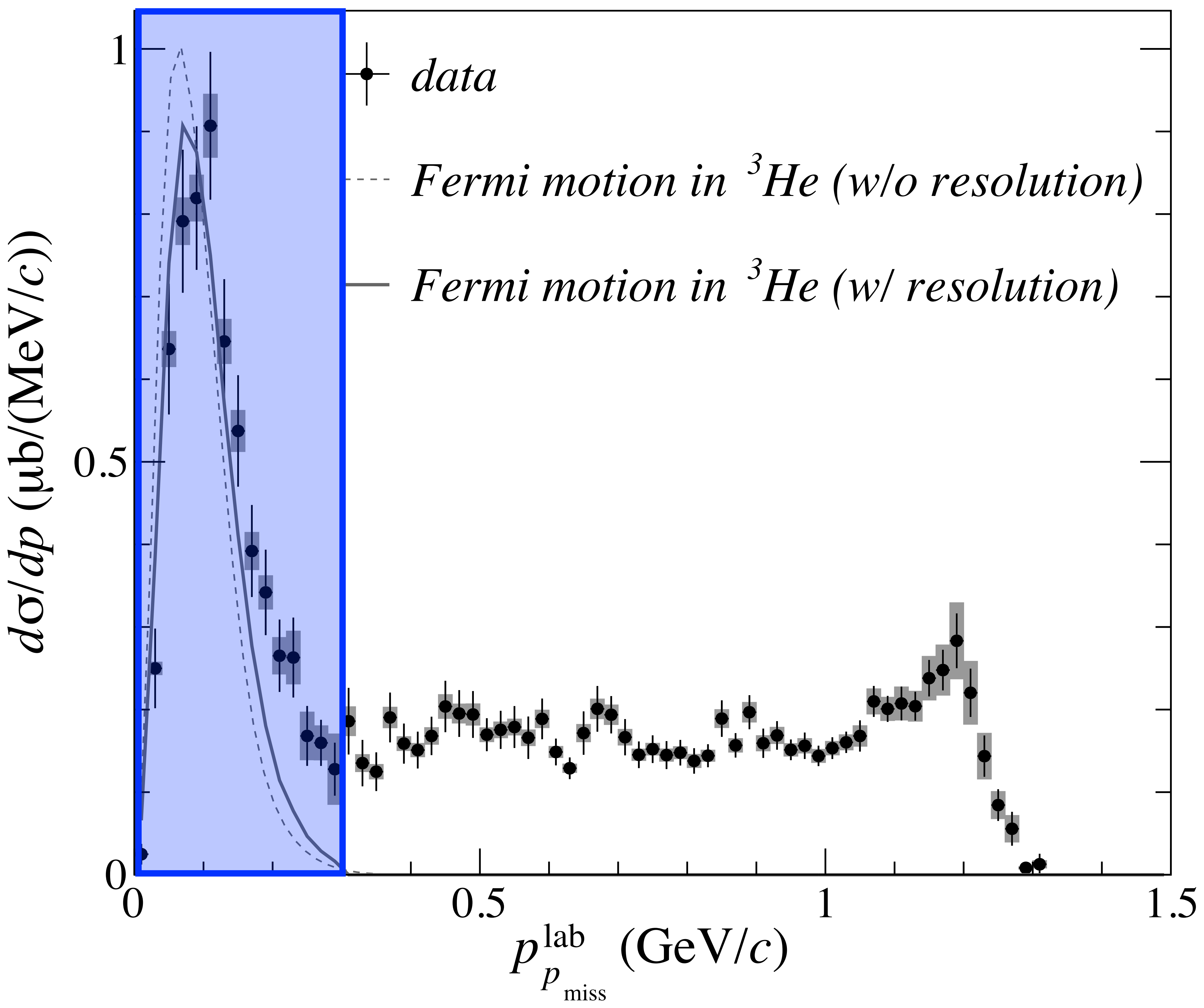
"$\bar{K}^0 nn$" is produced.



$\pi^-\Lambda p$ $+p_{\mathrm{miss}}$
$\pi^+\Lambda n$ $+n_{\mathrm{miss}}$
$m_{\bar{K}} + 2m_N$
$m_{\bar{K}} + 2m_N$
Preliminary
Preliminary
Direct-2NA
$q_{\pi\Sigma p}$ (GeV/c)
$m_{\pi^-\Lambda p}$ (GeV/c^2)
$m_{\pi^+\Lambda n}$ (GeV/c^2)
$d^2\sigma/dmdq$ (nb/(MeV^2/c^3))
0
1
2.2
2.4
2.6
2.8
0.5
1.5

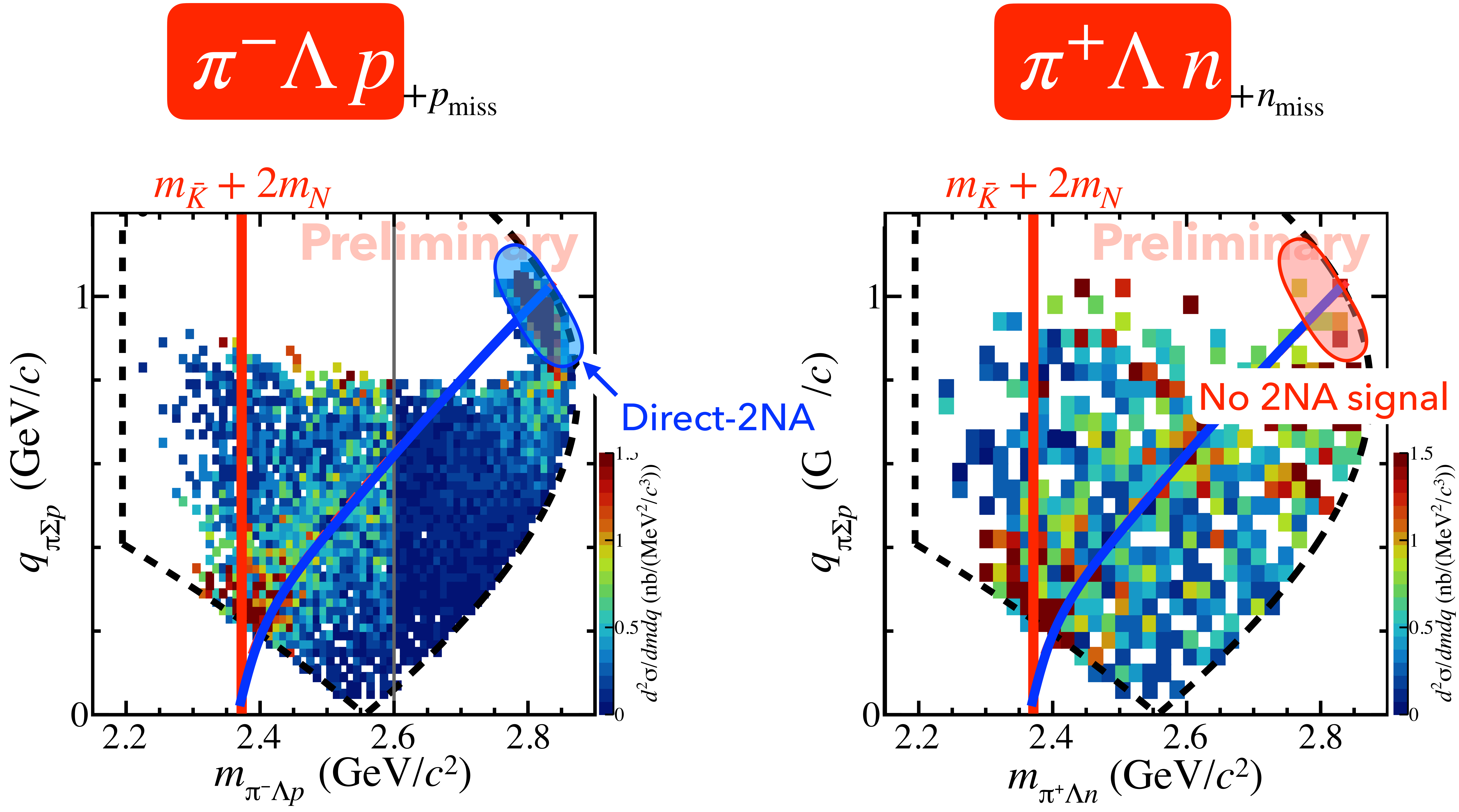
Direct 2NA observed in $\pi^{-}\Lambda pp'$





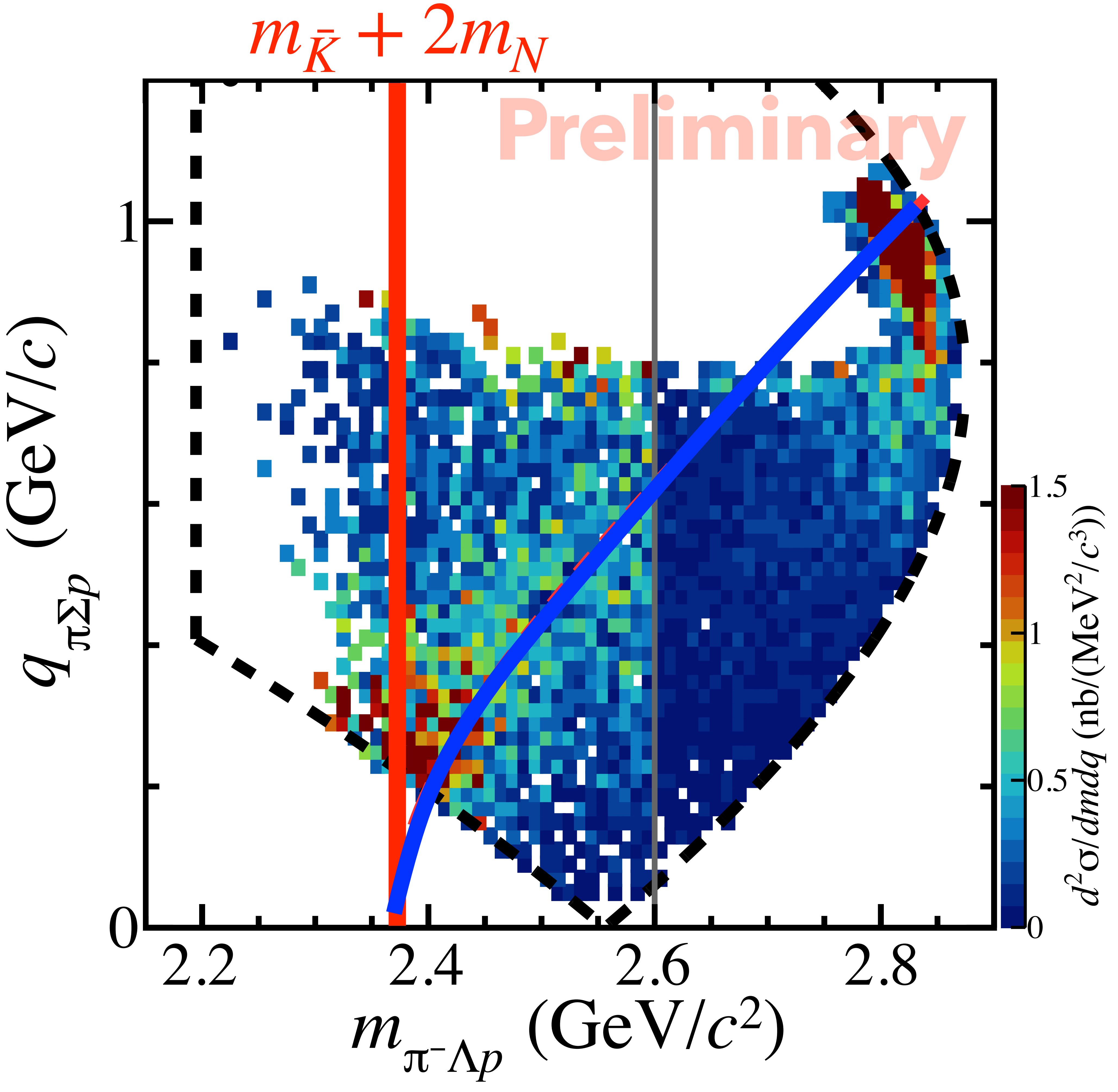
Missing proton has only fermi momentum.

⇨ The events-concentration produced by the direct-2NA process.

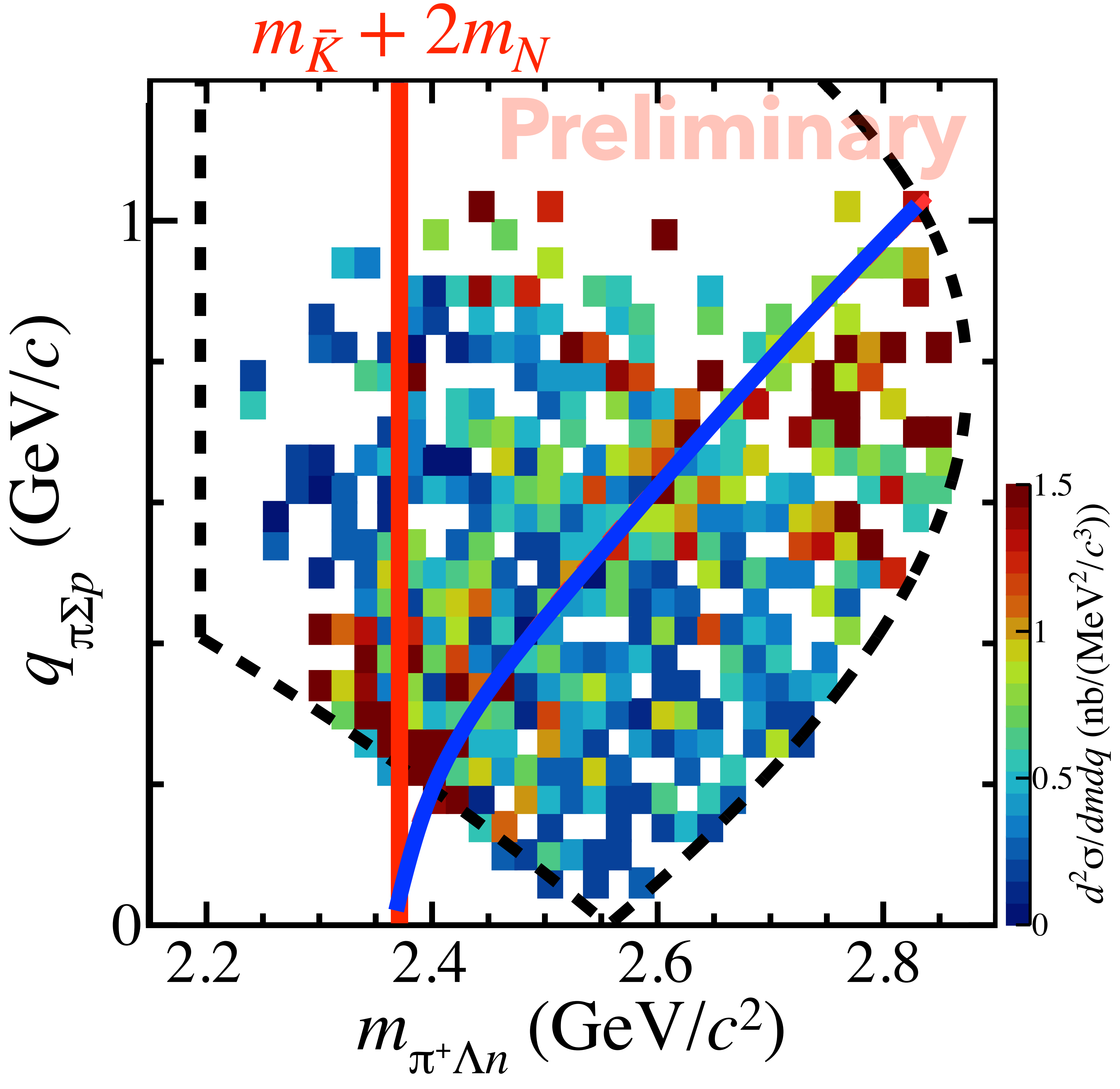


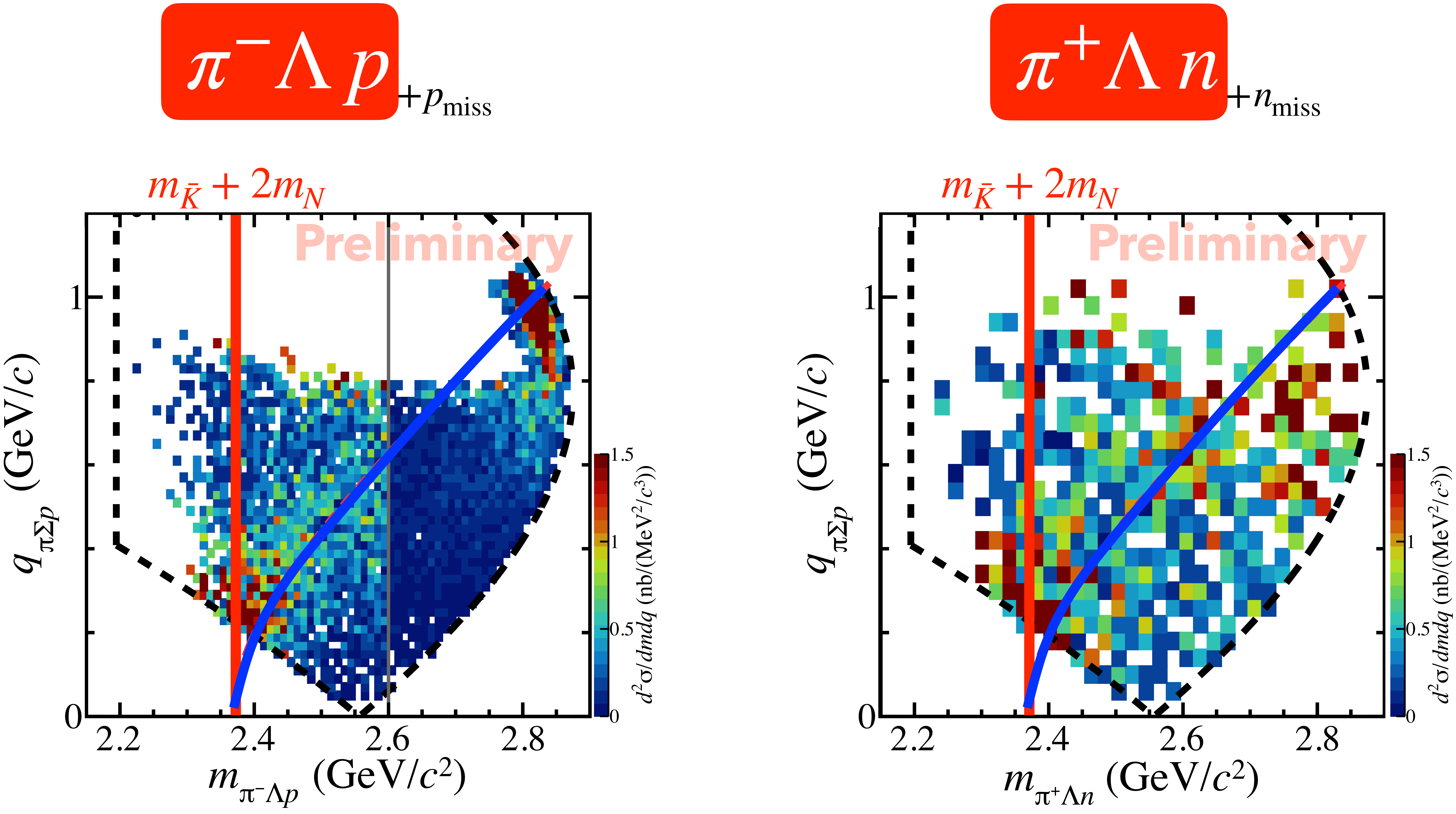
K^--beam is less likely absorbed by (pp)-pair compared to (pn)-pair.

$\pi^{-}\Lambda p$ $+p_{\text{miss}}$



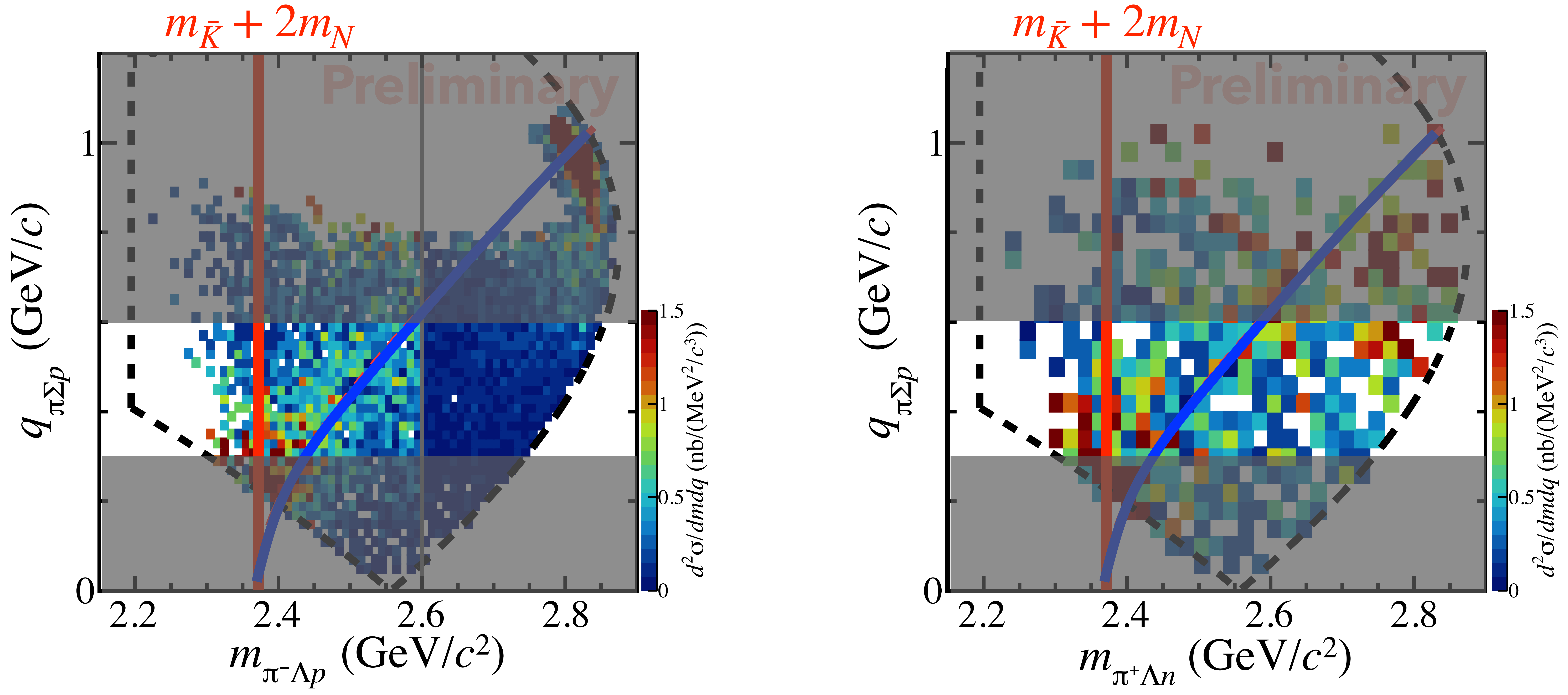
$\pi^{+}\Lambda n$ $+n_{\text{miss}}$





Fitting the $\pi^-\Lambda p$ distribution with the same model functions.

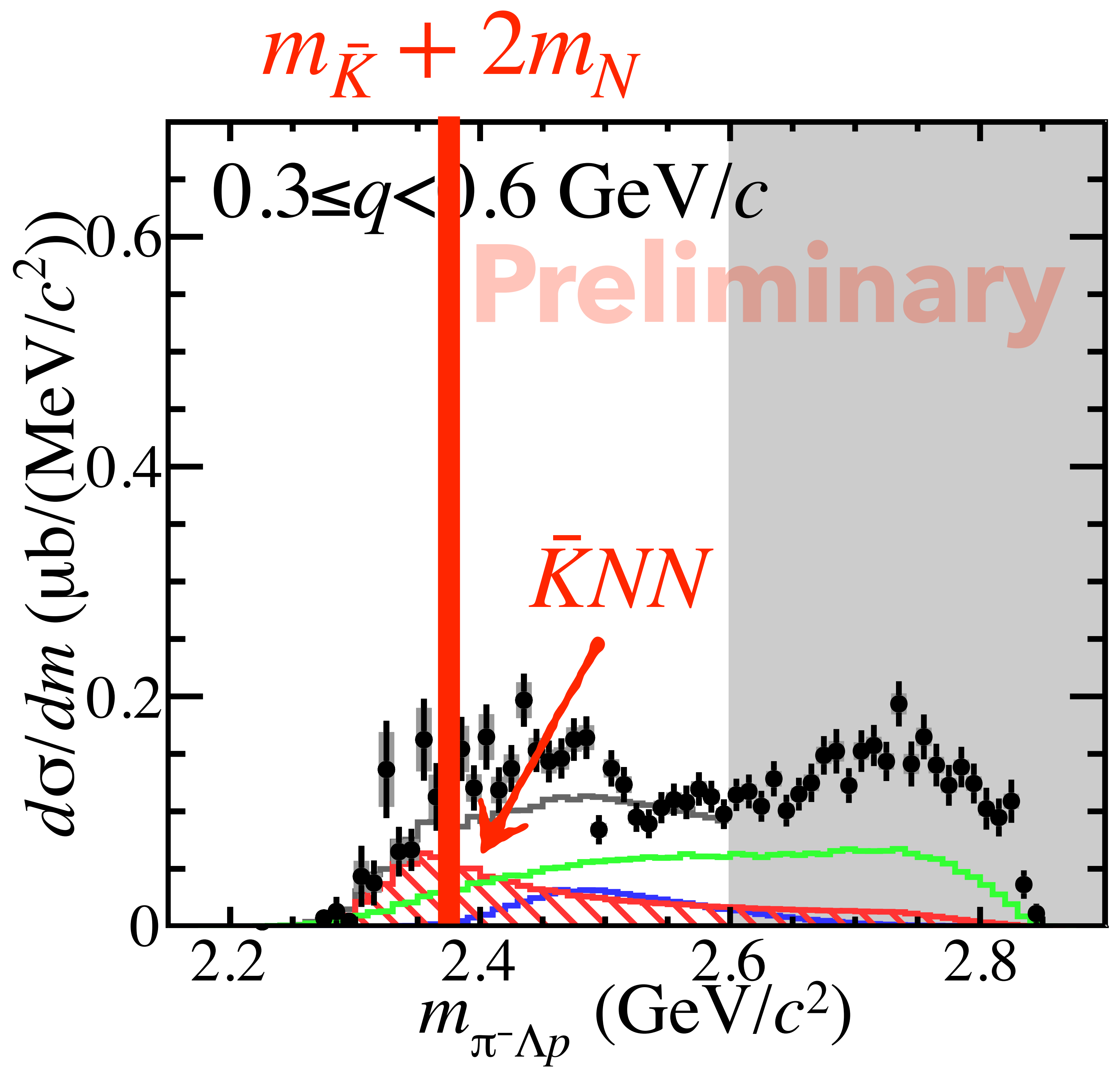
$\pi^- \Lambda p_{+p_{\text{miss}}}$ $\pi^+ \Lambda n_{+n_{\text{miss}}}$

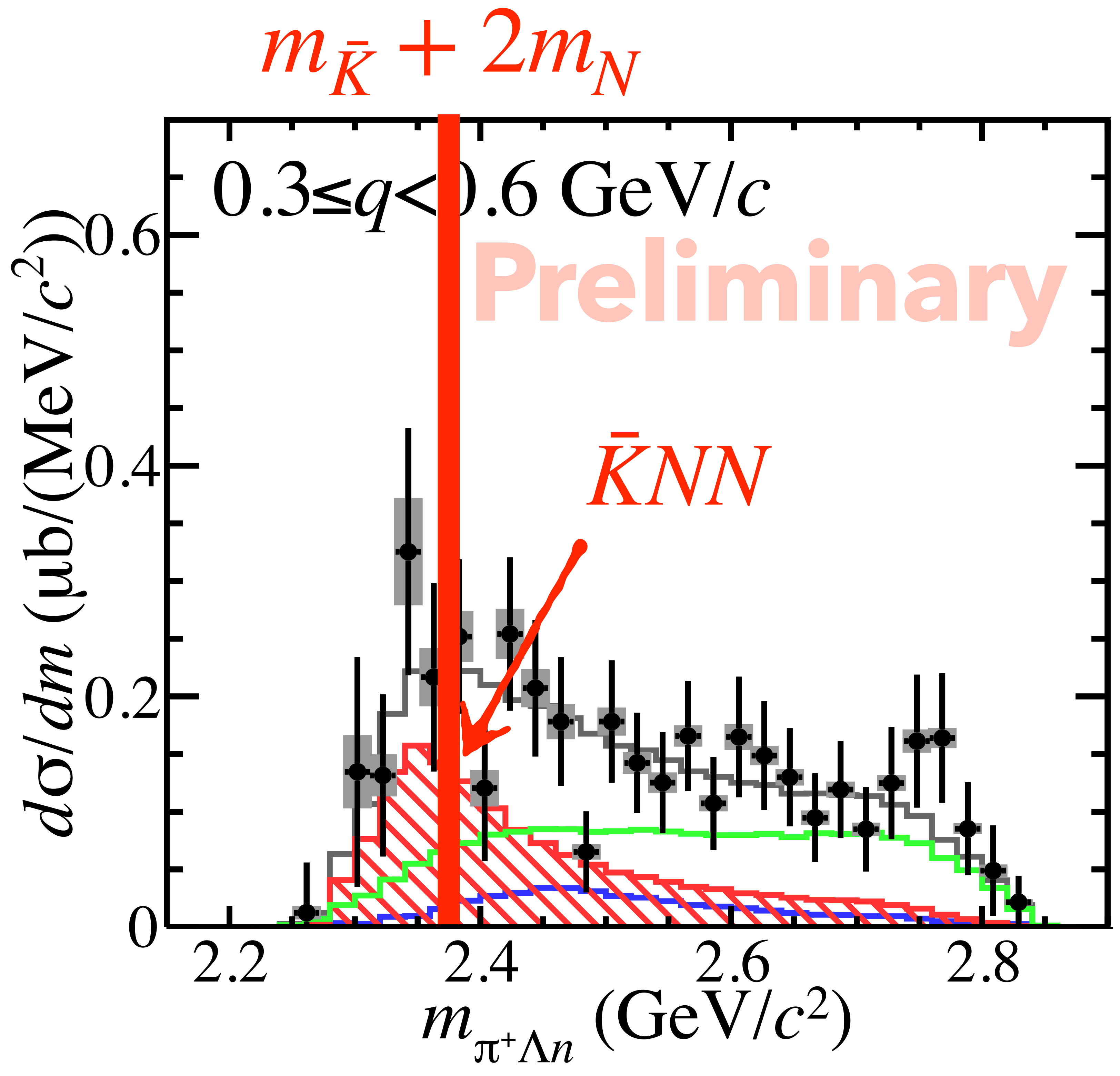


Fitting the $\pi^-\Lambda p$ distribution with the same model functions.

$\pi^{-}\Lambda p$ $+p_{miss}$

$\pi^{+}\Lambda n$ $+n_{miss}$





The $\pi^{-}\Lambda p$ distribution is explained by the model,
but difference between data & model is also seen.

	"K^-pp"	"$\bar{K}^0nn$"	
$\pi^-\Sigma^+p_{+n_{miss}}$	Preliminary $110 \pm 8\ \mu$b		
$\pi^+\Sigma^-p_{+n_{miss}}$	Preliminary $38 \pm 3\ \mu$b		
$\pi^+\Lambda\, n_{+n_{miss}}$	Preliminary $62 \pm 11\ \mu$b	Preliminary $29 \pm 3\ \mu$b	$\pi^-\Lambda\, p_{+p_{miss}}$

$\sigma_{\bar{K}^0nn}/\sigma_{K^-pp} \sim 1/2$ if we assume $\mathrm{BR}_{\pi^+\Lambda n} = \mathrm{BR}_{\pi^-\Lambda p}$

Summary

– Study of mesonic decay of $\bar{K}NN$ using J-PARC E15 data –

- We measured three mesonic decay channel of "$K^- pp$".
  - $\pi^{\mp}\Sigma^{\pm}p$ & $\pi^+\Lambda n$ channels
- Branching ratios were obtained to be
  - $\Gamma_{\pi YN}/\Gamma_{YN} \sim \mathcal{O}(10)$: Mesonic decay is dominant.
  - $\Gamma_{\pi\Lambda N} \sim \Gamma_{\pi\Sigma N}$: $I_{\bar{K}N} = 1$ $\bar{K}$-absorption in $\bar{K}NN$ would be significant.
- We measured a mesonic decay channel of "$\bar{K}^0 nn$".
  - $\pi^-\Lambda p$ channel
- The direct-2NA process was observed only in the $\pi^-\Lambda pp'$ channel not in the $\pi^+\Lambda nn'$ channel, which indicates K^--beam is less likely absorbed by (pp)-pair compared to (pn)-pair.
  - Can K^- be probe of internal structure (clustering) of nuclei? Need more study.
- Ratio of production cross sections of $\bar{K}^0 nn$ & $K^- pp$ was obtained to be
  - $\sigma_{\bar{K}^0 nn}/\sigma_{K^- pp} \sim 1/2$ (by assuming branching ratio of $\pi\Lambda N$ is the same for $\bar{K}^0 nn$ & $K^- pp$)

- Need to do / Open questions
  - Measuring all of other decay modes of $\bar{K}NN$
  - Connection between branching ratio and internal structure of $\bar{K}NN$
  - Why is $I_{\bar{K}N} = 1$ absorption significant in the $\bar{K}NN$ decay ? Is it related to the internal structure of $\bar{K}NN$?
  - Measuring "non-mesonic decay" of $\bar{K}^0 nn$ (such as Λn) to observe a clear signal (peak).

Thank you for your attention!

= Collaboration =

Experimentalists

RIKEN: H. Asano, K. Itahashi, M. Iwasaki, Y. Ma, R. Murayama, H. Outa, F. Sakuma, T. Yamaga

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