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Workshop in Frascati on strangeness - 16-17 October

Strange Matter

"K^-pp", a $\bar{K}$-meson nuclear bound state, observed in ^{3}He$(K^-, \Lambda p)n$ reactions

J-PARC E15 collaboration, S. Ajimura[a], H. Asano[b], G. Beer[c], C. Berucci[d], H. Bhang[e], M. Bragadireanu[f], P. Buehler[d], L. Busso[g,h], M. Cargnelli[d], S. Choi[e], C. Curceanu[i], S. Enomoto[j], H. Fujioka[k], Y. Fujiwara[l], T. Fukuda[m], C. Guaraldo[i], T. Hashimoto[n], R.S. Hayano[l], T. Hiraiwa[a], M. Iio[j], M. Iliescu[i], K. Inoue[a], Y. Ishiguro[o], T. Ishikawa[l], S. Ishimoto[j], K. Itahashi[b], M. Iwasaki[b,k,*], K. Kanno[l], K. Kato[o], Y. Kato[b], S. Kawasaki[a], P. Kienle[p,i], H. Kou[k], Y. Ma[b], J. Marton[d], Y. Matsuda[l], Y. Mizoi[m], O. Morra[g], T. Nagae[o], H. Noumi[a], H. Ohnishi[q,b], S. Okada[b], H. Outa[b], K. Piscicchia[i], Y. Sada[a], A. Sakaguchi[a], F. Sakuma[b,*], M. Sato[j], A. Scordo[i], M. Sekimoto[j], H. Shi[i], K. Shirotori[a], D. Sirghi[i,f], F. Sirghi[i,f], K. Suzuki[d], S. Suzuki[j], T. Suzuki[l], K. Tanida[n], H. Tatsuno[r], M. Tokuda[k], D. Tomono[a], A. Toyoda[j], K. Tsukada[q], O. Vazquez Doce[i,p], E. Widmann[d], T. Yamaga[b,a,*], T. Yamazaki[l,b], Q. Zhang[b], J. Zmeskal[d]

Future kaonic nuclear study based on J-PARC E15 result

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Nishina Center for Accelerator Based Science

Why a meson bound state is novel and peculiar quantum system?

hadron: <qqq> proton, neutron, … : <q̄q> π meson, K meson, …

existence form	Fermion one particle per one state Particle consisting matter	Boson as many for a state Particle generating field (nuclear foce)
	exists as particle at anywhere	particle in vacuum or meson field in nuclei (virtual particle)

key question **Can Kaon(meson) be bound in nuclei?**

Can <q̄q> be a "real particle" even in nuclei?

What is a role of meson DoF. in nuclei?

Meson predicted in 1935. Since then, it has been studied for ~80 years to identify <u>mesonic nuclear bound states</u>, but no definitive evidence was made before.

	$\Lambda(1405)$ as $\bar{K}N$ bound state	$\bar{K}NN$ bound state
Prediction	**1959**	**2002 ~**
Discovery	**1961**	**2019 ?**
Spin / parity	$1/2^-$ **(2014)**	$J^P = 0^-$ **???**
Interaction	**Chiral dynamics**	**Two-body** $\bar{K}N$ ***and*** NN **+ Three-body** $\bar{K}NN$ **?**
Component	$\bar{K}N$ **dominant in chiral D (2015 ~)**	$\bar{K}NN$ **dominant ???**
Peak position	**Depends on reaction**	**Depends on reaction**
Pole position	$(1415 - 1435) - (10 - 25)\,i$ MeV	**???**

What we have done at J-PARC?

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

by $\bar{K}N \rightarrow \bar{K}N$ reaction

"K^-pp" a tightly bound compact object?

Formation-reaction image illustrated by ÖEW Harald Ritsch

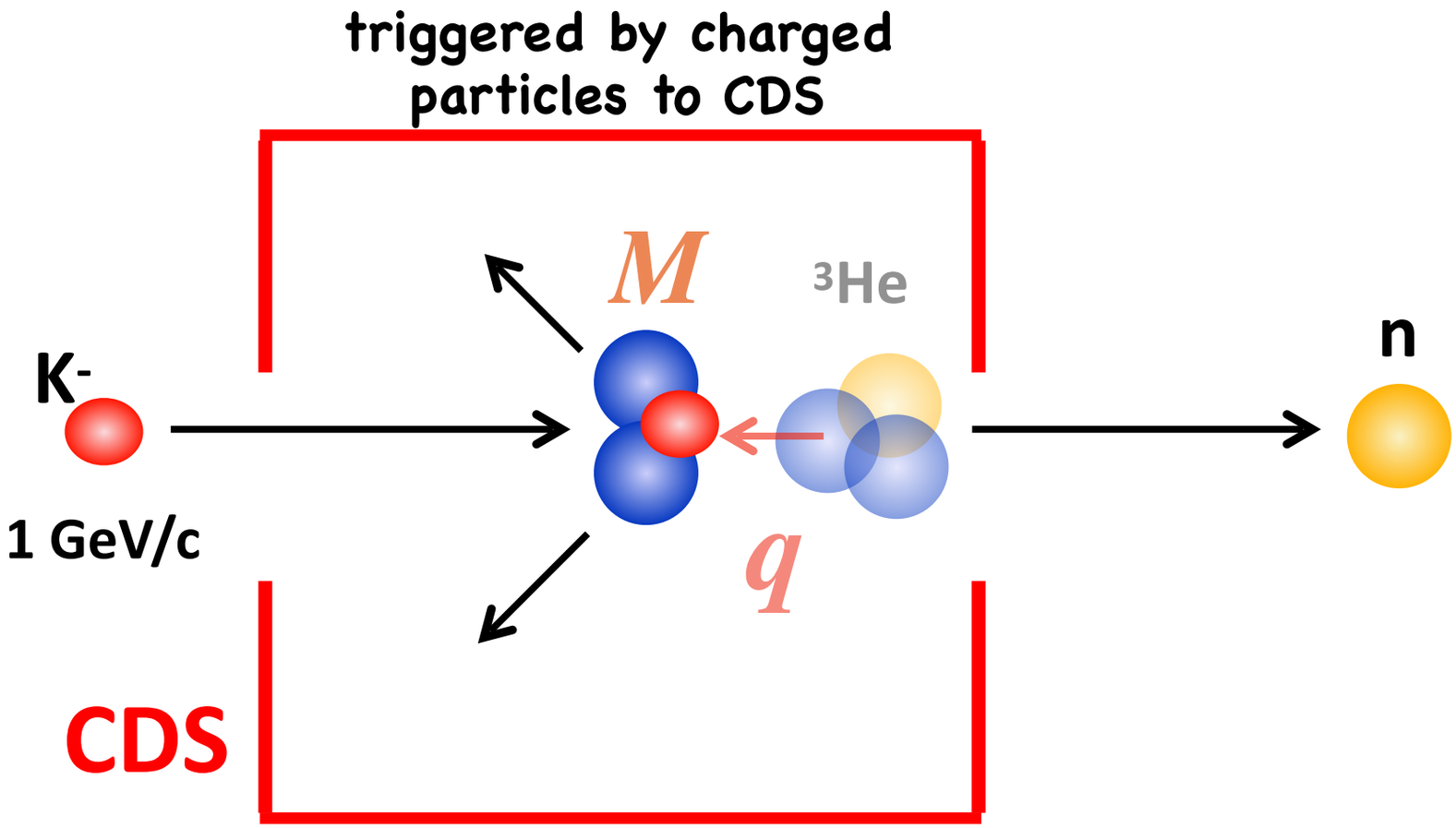
Semi-inclusive forward n

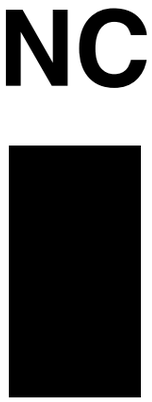
Prog. Theor. Exp. Phys. **2015**, 061D01 (11 pages)
DOI: 10.1093/ptep/ptv076

$$q = p_n - p_K$$

q: virtual kaon momentum

in spectators' frame

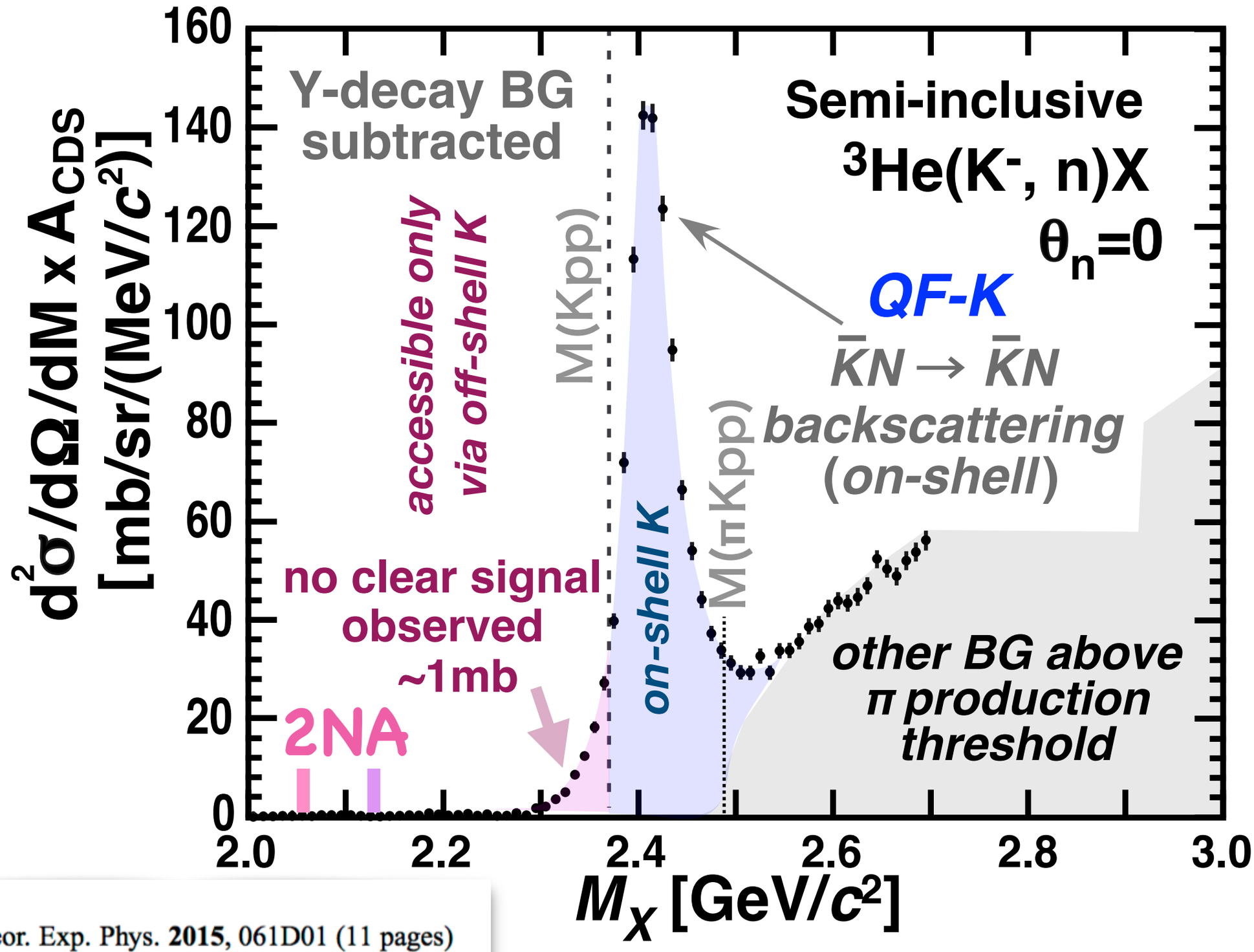




Does quasi-free kaon (= "virtual kaon") stick to two spectator proton?

@ q~200 MeV/c

Semi-inclusive forward n



Prog. Theor. Exp. Phys. **2015**, 061D01 (11 pages)
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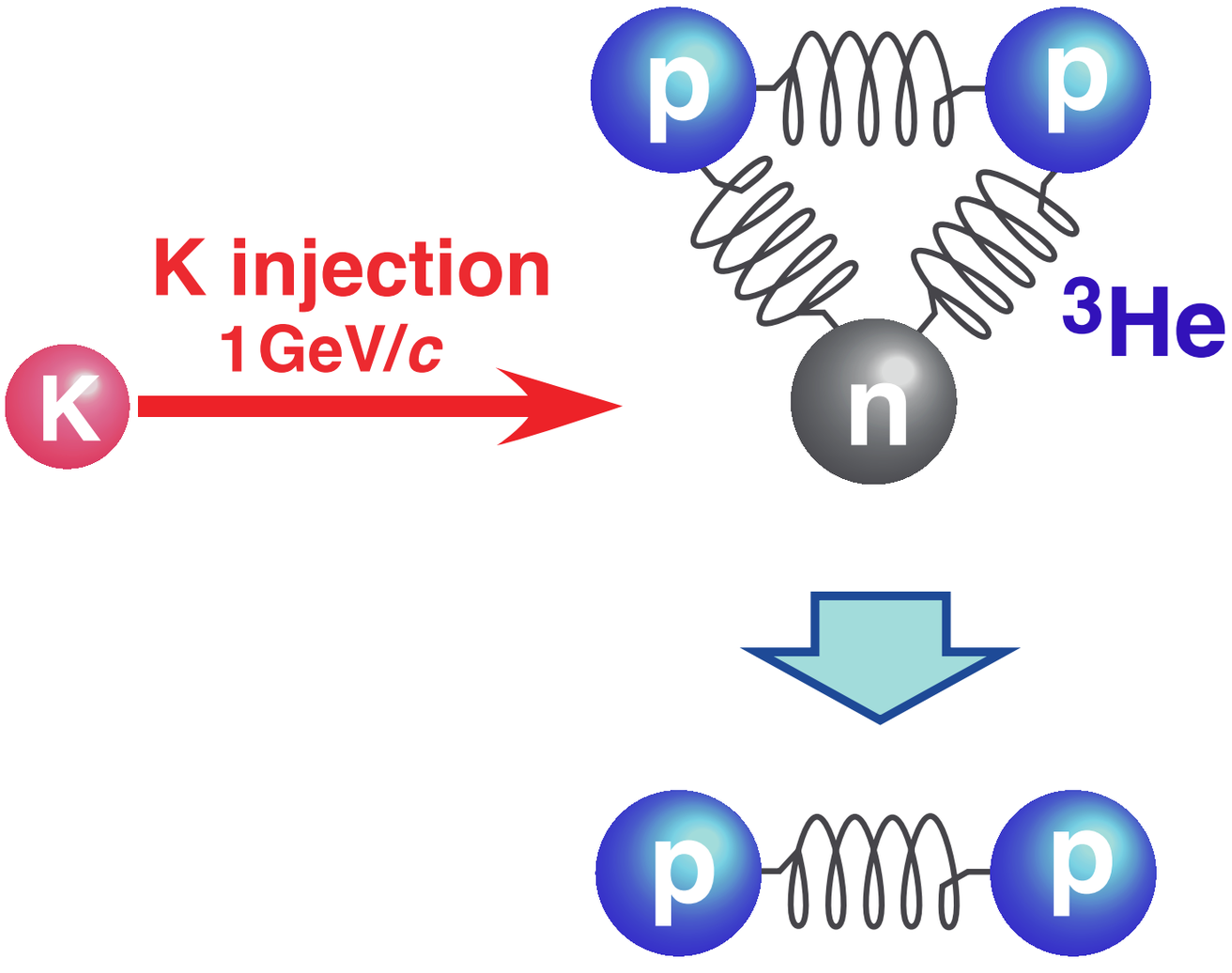
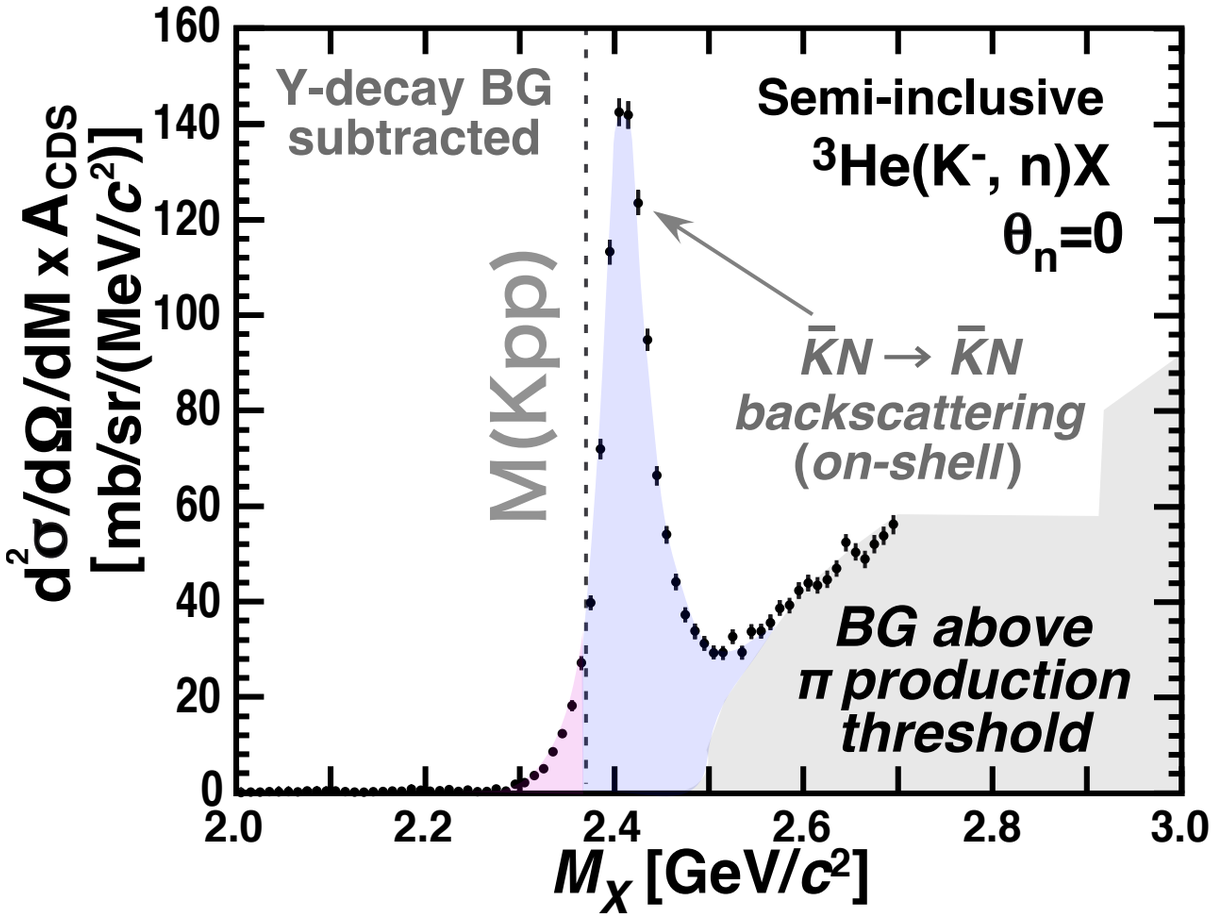
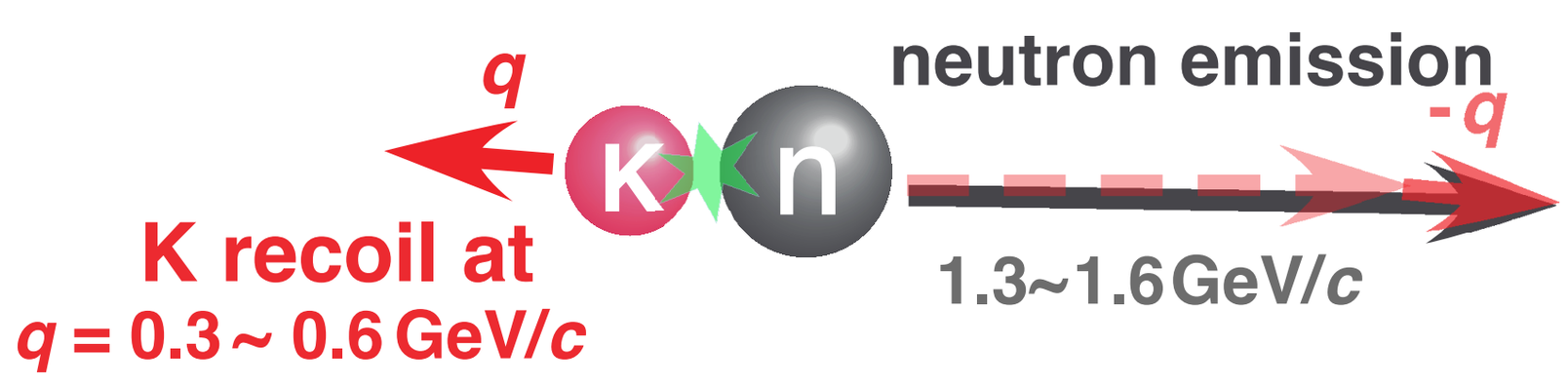
strong kaon back scattering is confirmed!

Semi-inclusive forward n

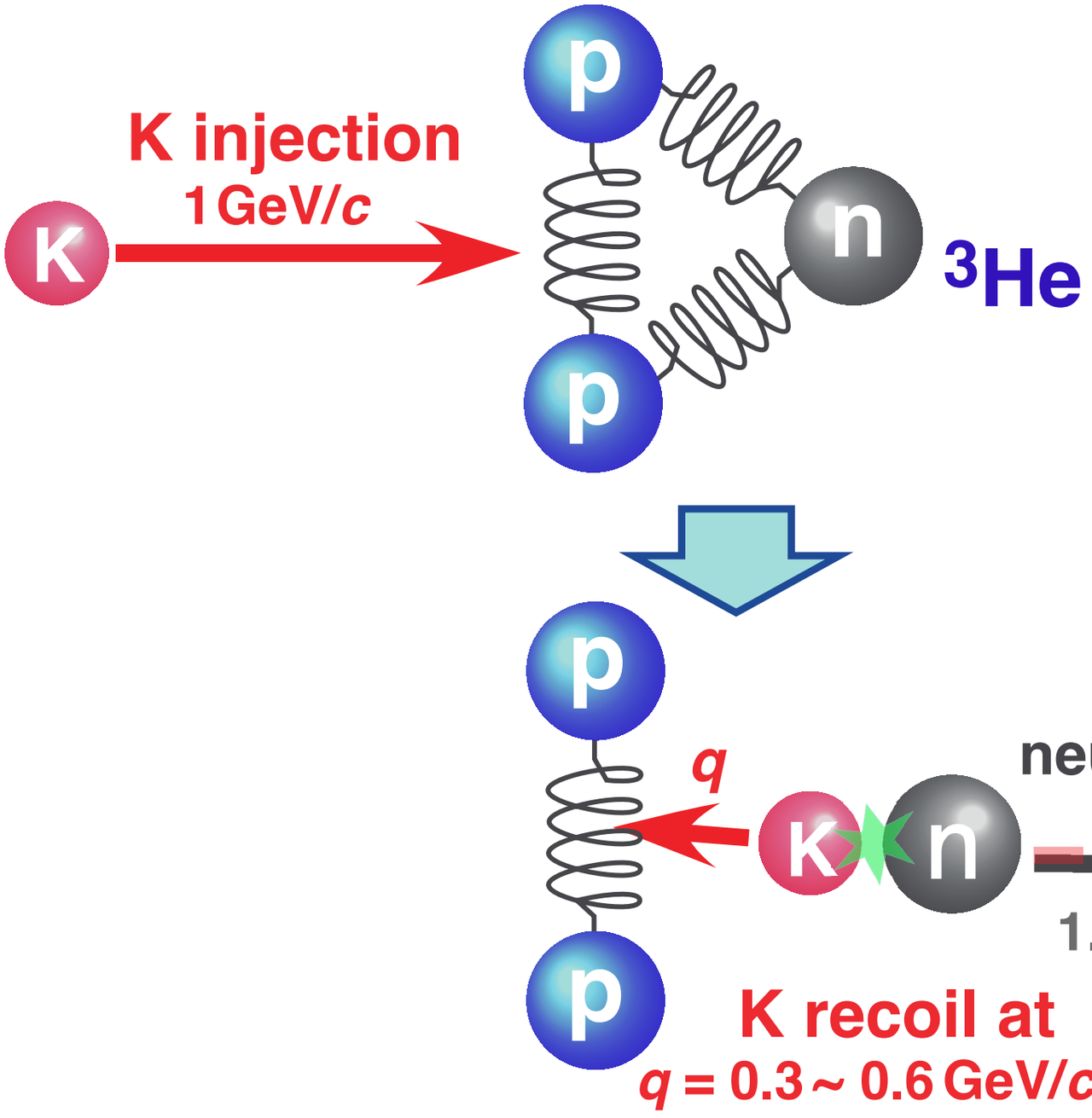


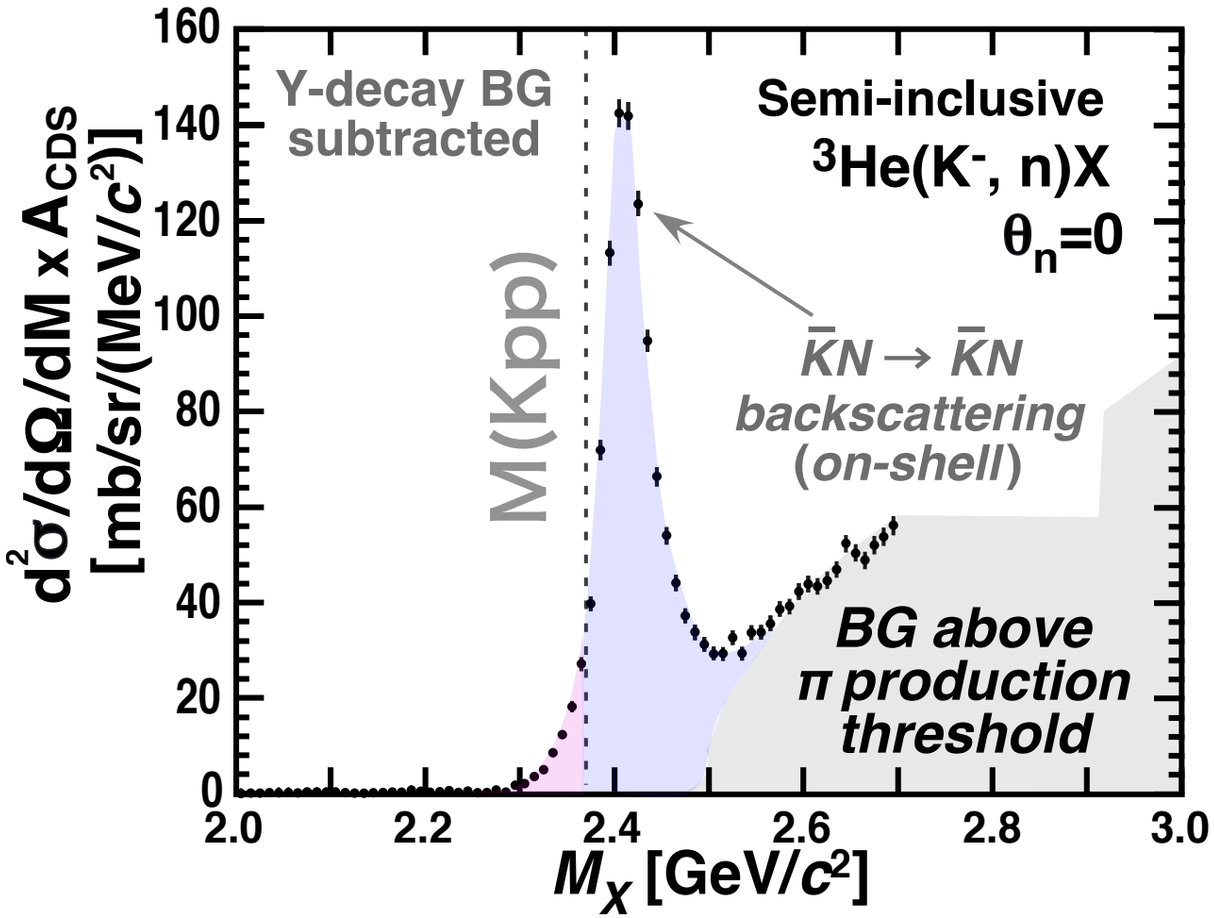




QF-K locate above M(Kpp) due to K's kinetic energy

Semi-inclusive forward n





virtual K can be accommodated by the successive reactions

QF-K tail masks "Kpp" formation

Semi-inclusive forward n

kaon back scattering

$$K^- + N \rightarrow \bar{K} + n$$

is clearly seen

kaon direct 2NA is weak

events in bound region

M < M(Kpp)

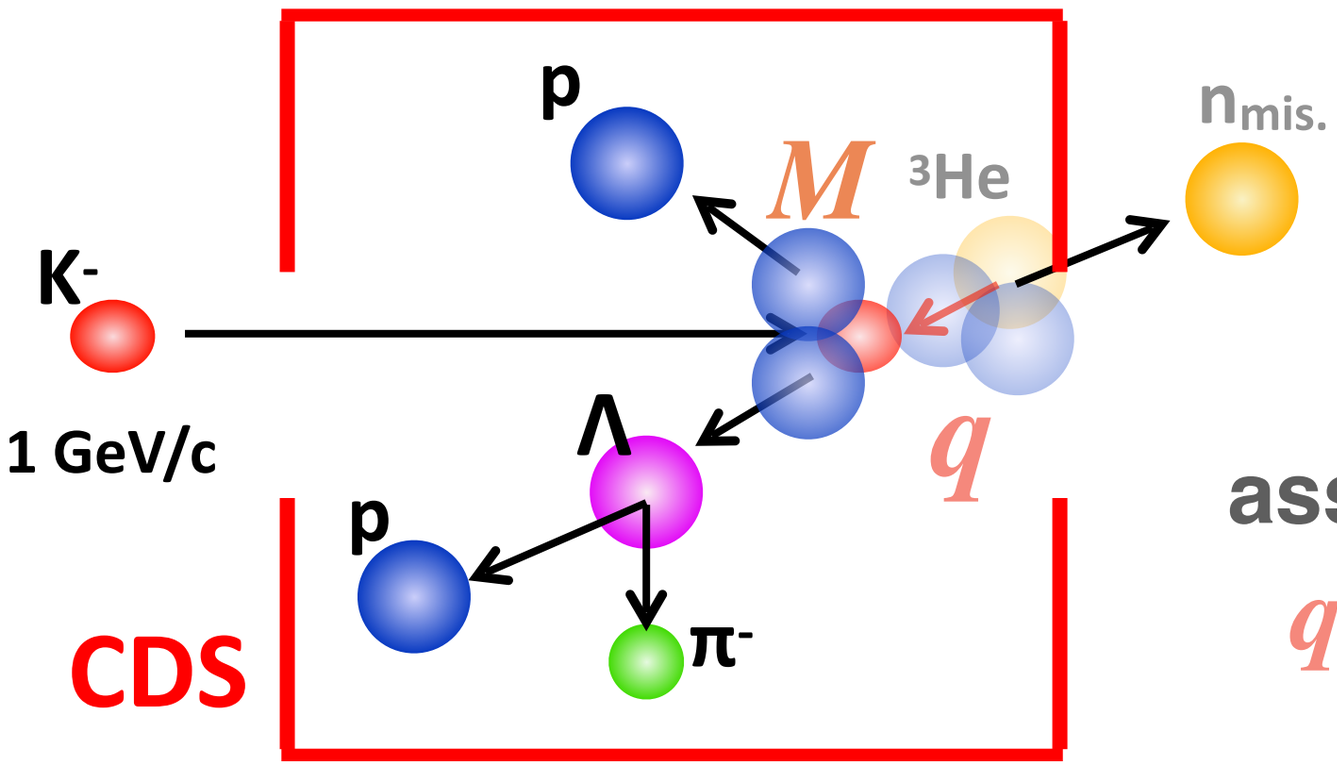
is large ~1 mb/sr

need more study

Exclusive: Λ p n

simplest final state

3 baryon w/ strangeness



assuming KN→KN

q: virtual kaon momentum

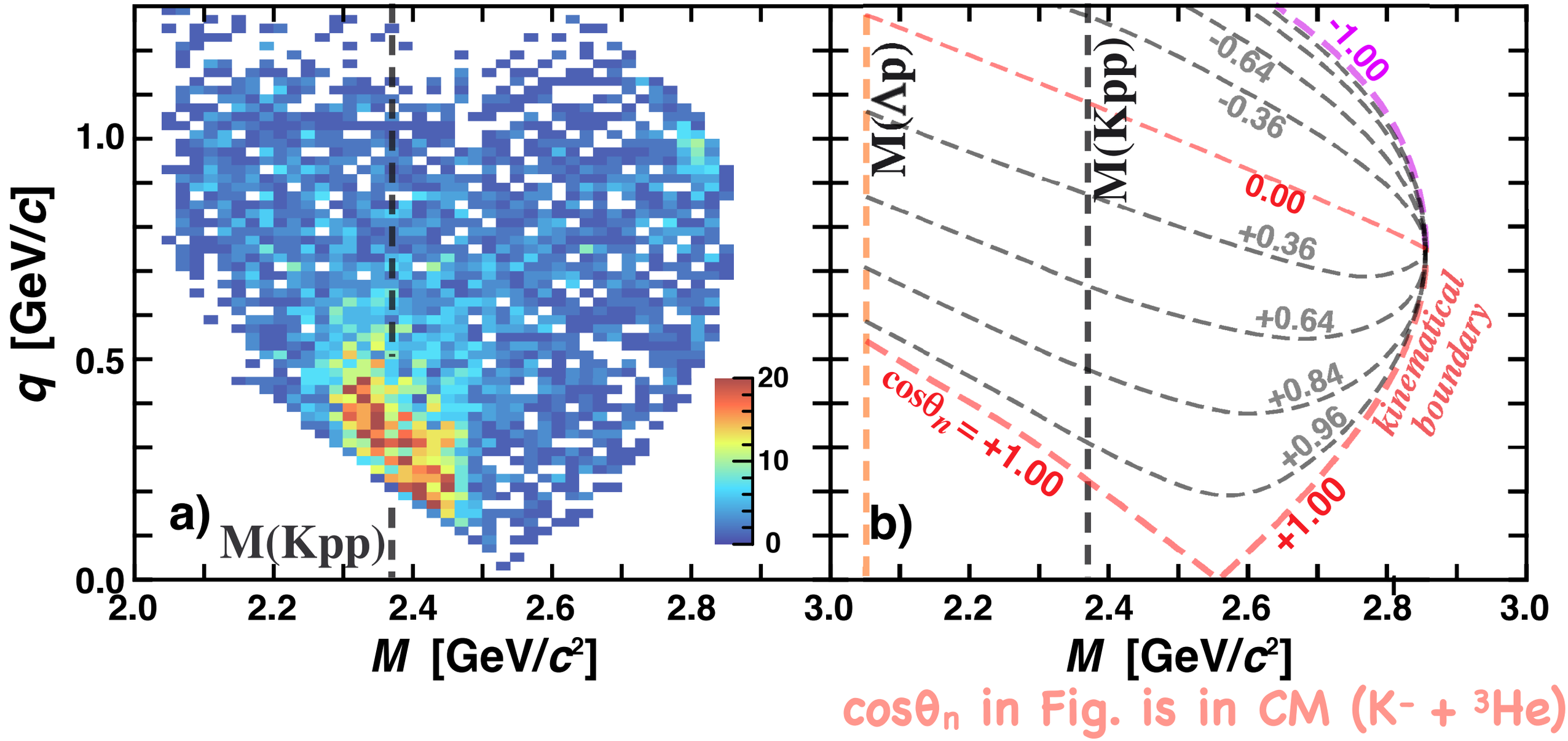
$$K^- + {}^3He \rightarrow (\Lambda + p) + n$$

M & *q* defines kinematics ⟷ (or *M* & θ_n)

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

$$\tan\theta_n^{Lab.} = \frac{-q\sin\theta}{p_K - q\cos\theta}$$

$$\begin{pmatrix} \sqrt{m_K^2 + p_K^2} \\ p_K \\ 0 \end{pmatrix} + \begin{pmatrix} M_{^3\mathrm{He}} \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} \sqrt{M^2 + q^2} \\ q\cos\theta \\ q\sin\theta \end{pmatrix} + \begin{pmatrix} \sqrt{m_n^2 + p_K^2 - 2p_K q\cos\theta + q^2} \\ p_K - q\cos\theta \\ -q\sin\theta \end{pmatrix}$$



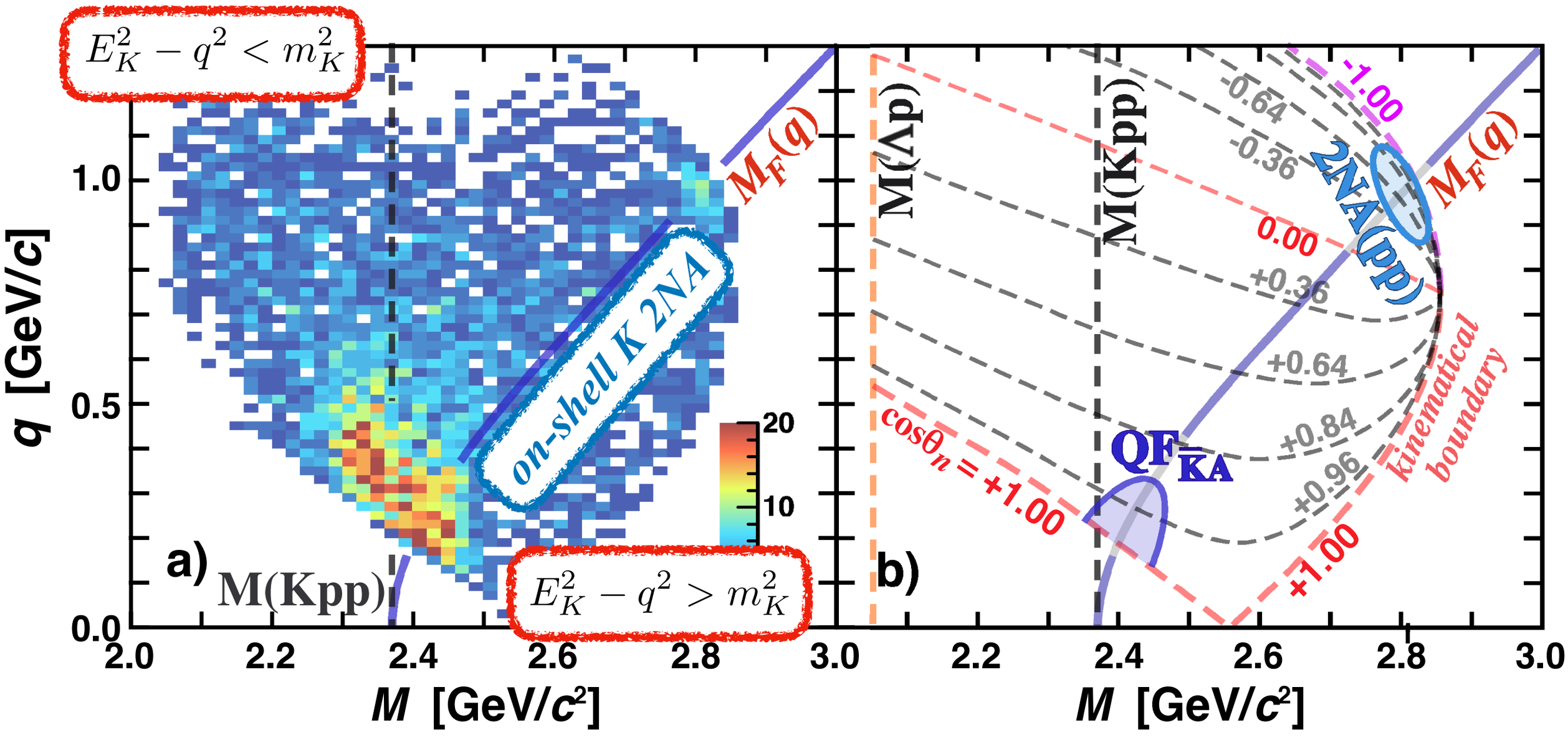
cosθn in Fig. is in CM (K^- + ^{3}He)

$QF_{\bar{K}A}$: $K^- + N \rightarrow \bar{K} + n$

2NA of on-shell scattered-K

$\bar{K} + N_s + N_s \rightarrow F\ (= \Lambda + p)$

$$\begin{pmatrix} \sqrt{m_K^2 + q^2} \\ q \end{pmatrix} + \begin{pmatrix} m_N \\ 0 \end{pmatrix} + \begin{pmatrix} m_N \\ 0 \end{pmatrix} = \begin{pmatrix} \sqrt{M_F^2 + q^2} \\ q \end{pmatrix}$$

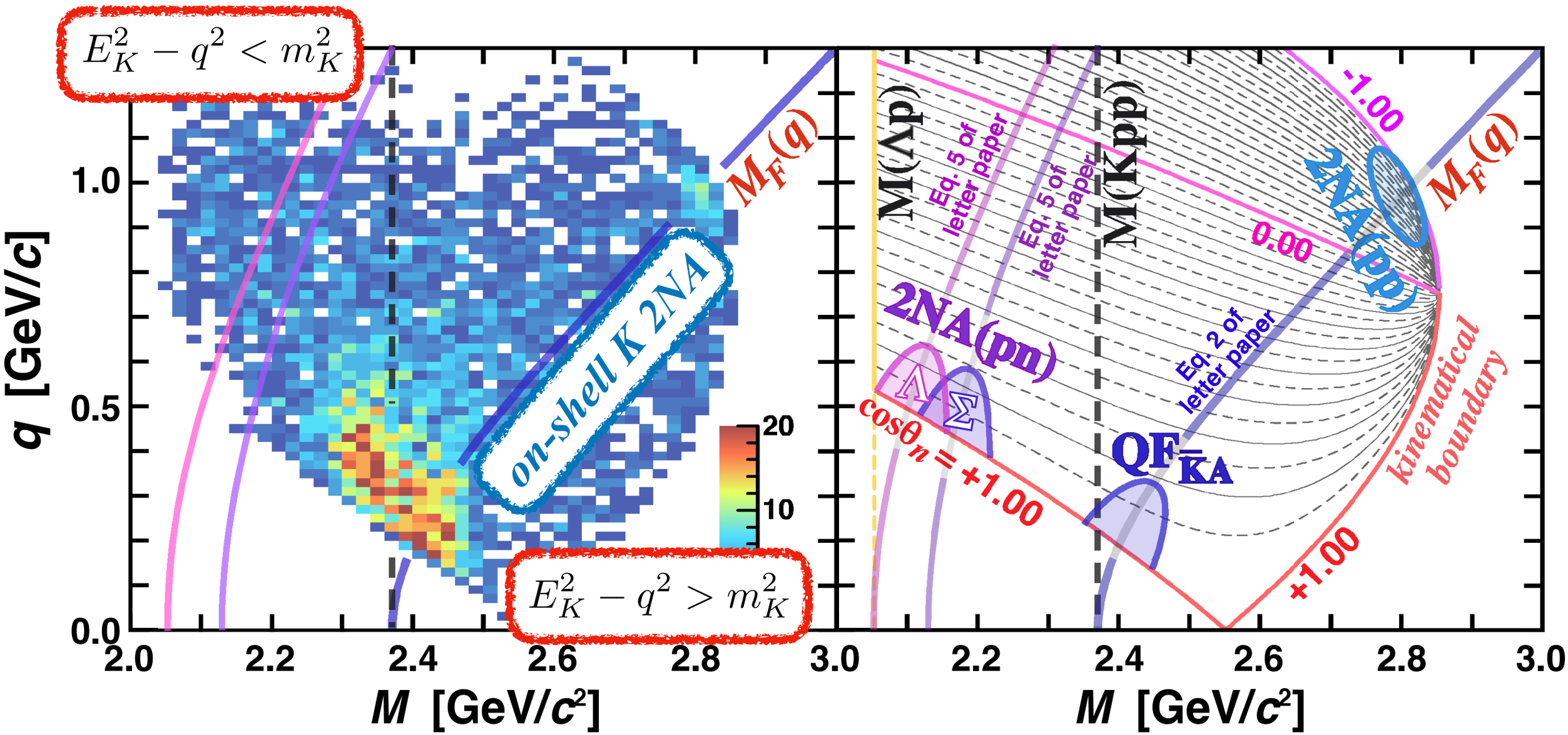


$QF_{\bar{K}A}$: $K^- + N \rightarrow \bar{K} + n$

2NA of on-shell scattered-K

$\bar{K} + N_s + N_s \rightarrow F\ (= \Lambda + p)$

$$\begin{pmatrix} \sqrt{m_K^2 + q^2} \\ q \end{pmatrix} + \begin{pmatrix} m_N \\ 0 \end{pmatrix} + \begin{pmatrix} m_N \\ 0 \end{pmatrix} = \begin{pmatrix} \sqrt{M_F^2 + q^2} \\ q \end{pmatrix}$$



after acceptance correction

q [GeV/c]

1.0

0.5

0.0

2.0

2.2

2.4

2.6

2.8

3.0

M [GeV/c^2]

$\theta_n = \pi$

$\theta_n = 0$

$\theta_n = 0$

$M_F(q)$

M(Kpp)

>5

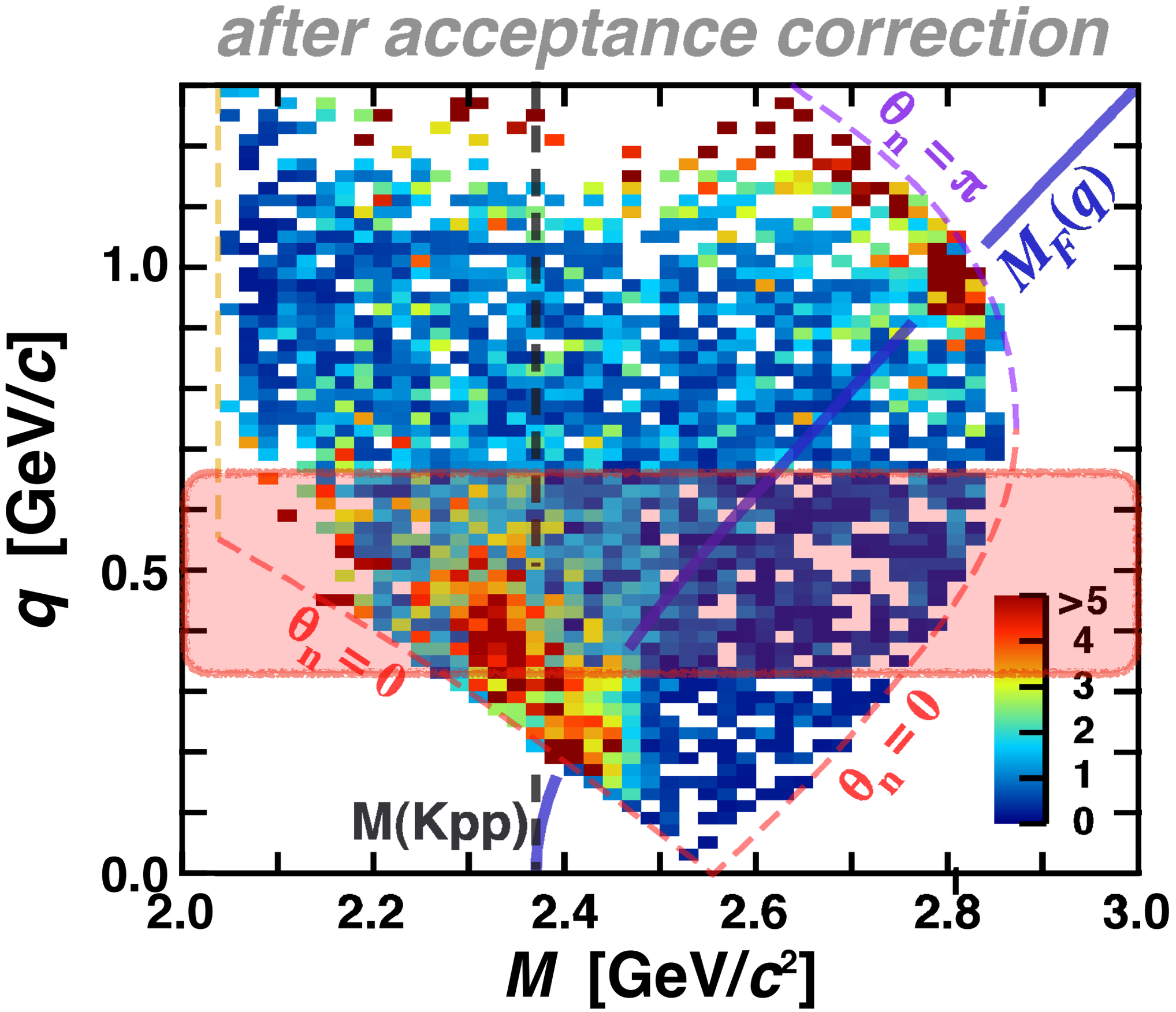
4

3

2

1

0


after acceptance correction
1.0
0.5
0.0
q [GeV/c]
2.0
2.2
2.4
2.6
2.8
3.0
M [GeV/c²]
θ = π
θ = 0
θ = 0
M_F(q)
M(Kpp)
>5
4
3
2
1
0

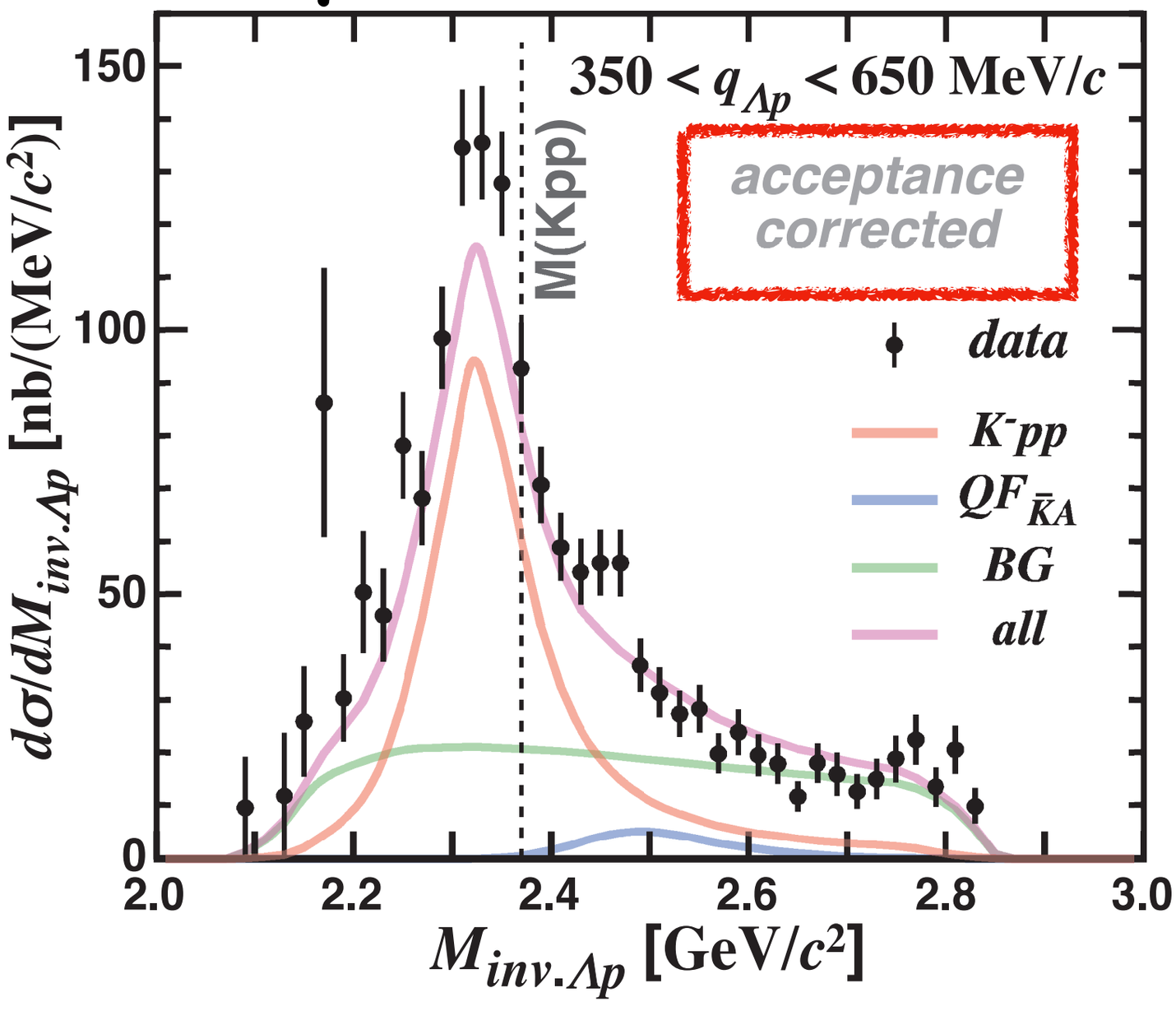
M: *q*-selected Λ p + $n_{mis.}$

PWIA w/ H.O.

$$\rho_{3B}(M,q) \times \frac{\left(\Gamma_{Kpp}/2\right)^2}{\left(M - M_{Kpp}\right)^2 + \left(\Gamma_{Kpp}/2\right)^2} \times \exp\left(-\frac{q^2}{Q_{Kpp}^2}\right)$$

energy (mass) *momentum*

M spectrum

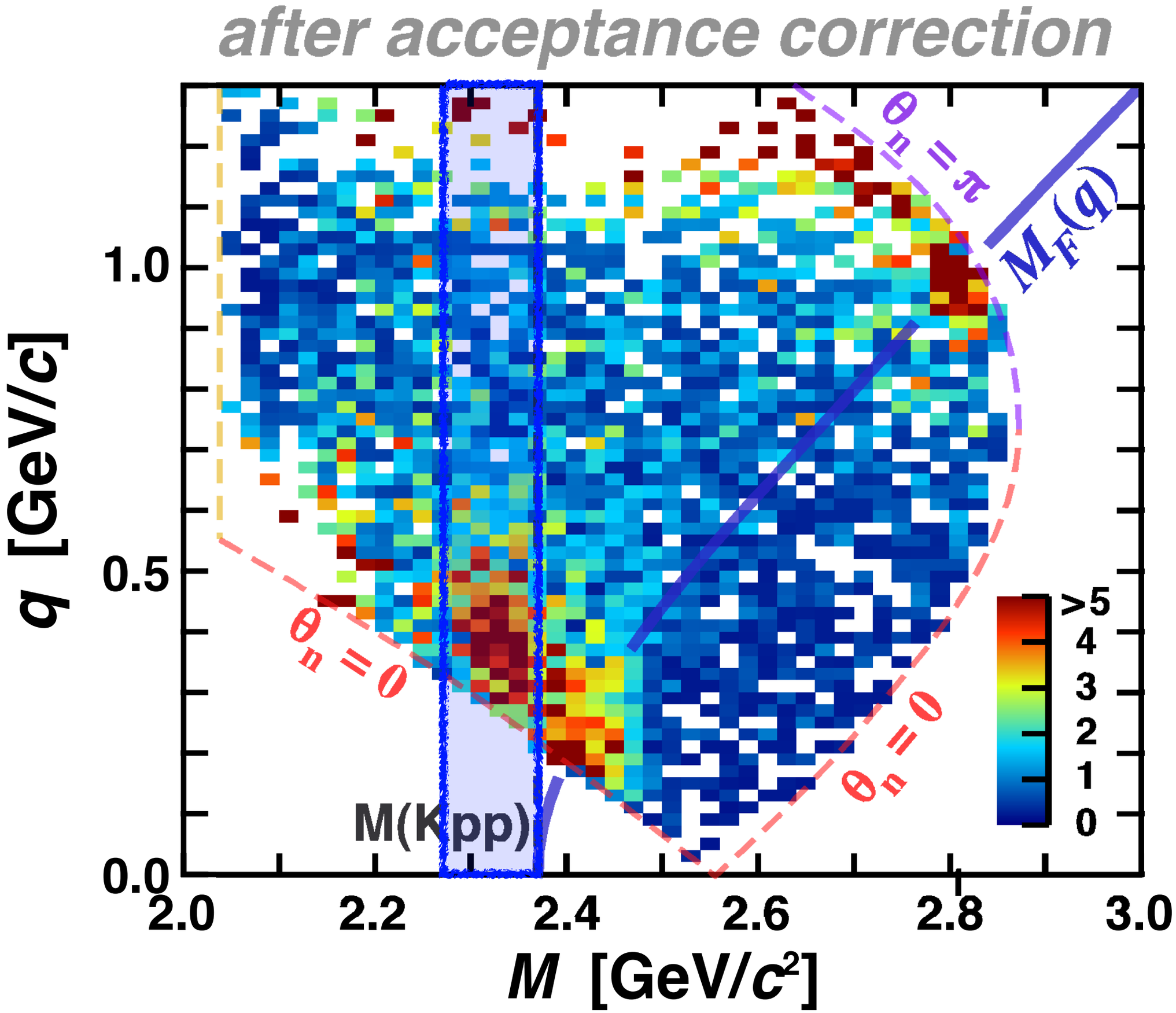


$\sigma_{Kpp} * Br_{\Lambda p}$ ~ 12 μb

B_{Kpp} ~ 50 MeV

Γ_{Kpp} ~ 100 MeV

$\sigma_M(\Lambda p)$ ~ 10 MeV/c^2

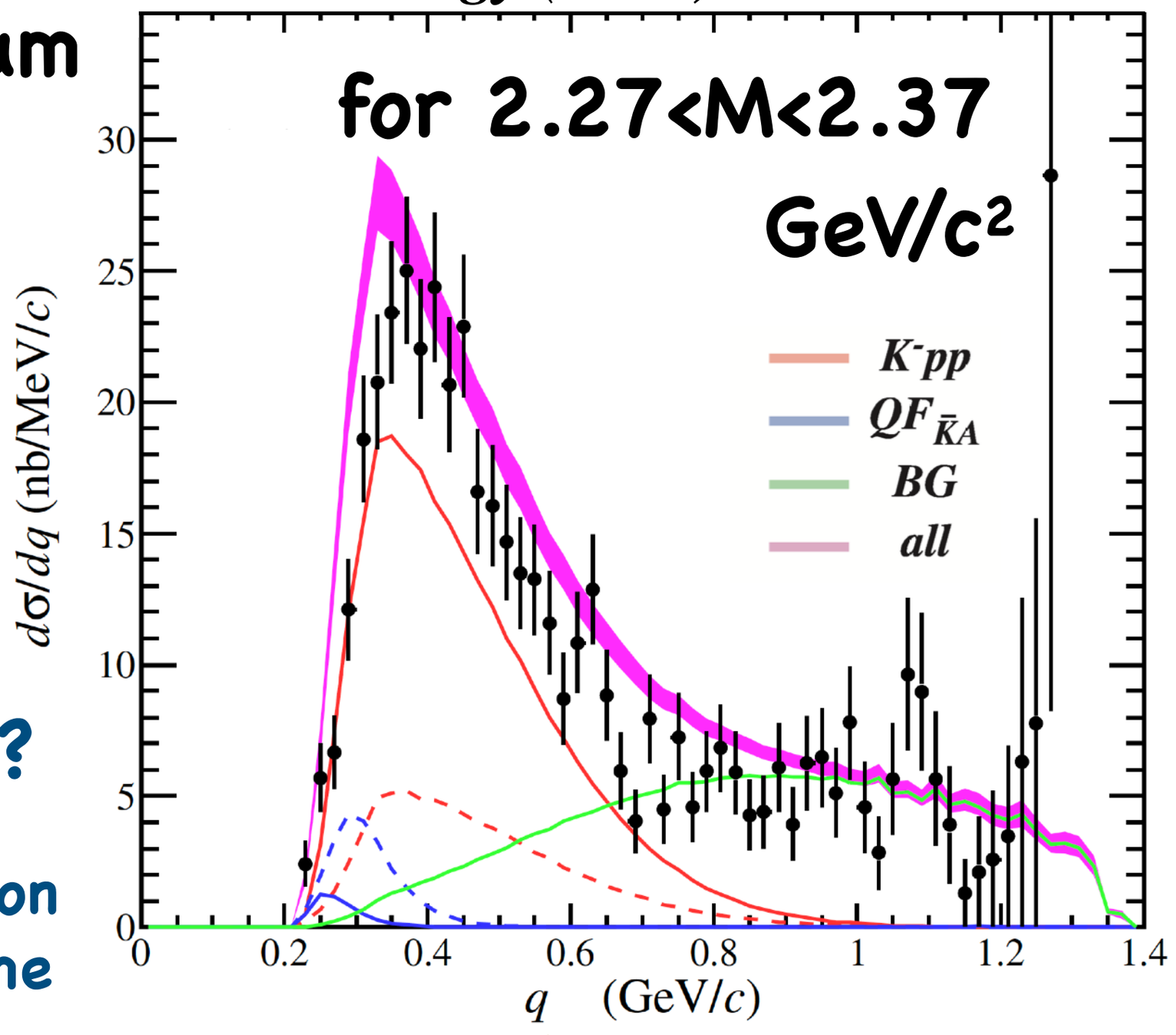

after acceptance correction
$\theta_n = \pi$
$M_F(q)$
$\theta_n = 0$
$\theta_n = 0$
M(Kpp)
>5
4
3
2
1
0
1.0
0.5
0.0
2.0
2.2
2.4
2.6
2.8
3.0
q [GeV/c]
M [GeV/c^2]

q: M-selected Λ p + $n_{mis.}$

$$\rho_{3B}(M,q) \times \mathcal{E}(M,q) \times \frac{\left(\Gamma_{Kpp}/2\right)^2}{\left(M - M_{Kpp}\right)^2 + \left(\Gamma_{Kpp}/2\right)^2} \times \exp\left(-\frac{q^2}{Q_{Kpp}^2}\right)$$

energy (mass) *momentum*

q spectrum



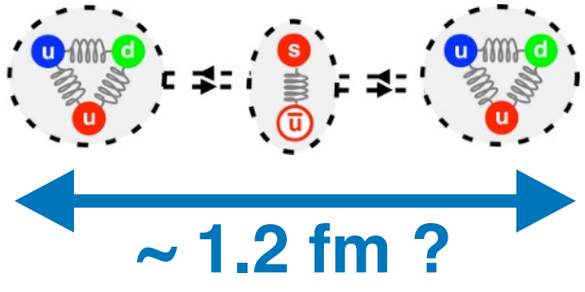
$Q_{Kpp} \sim 400$ MeV/c

$$R_{Kpp} \sim \frac{\hbar c}{Q_{Kpp}} \sim 0.5 \text{ fm?}$$

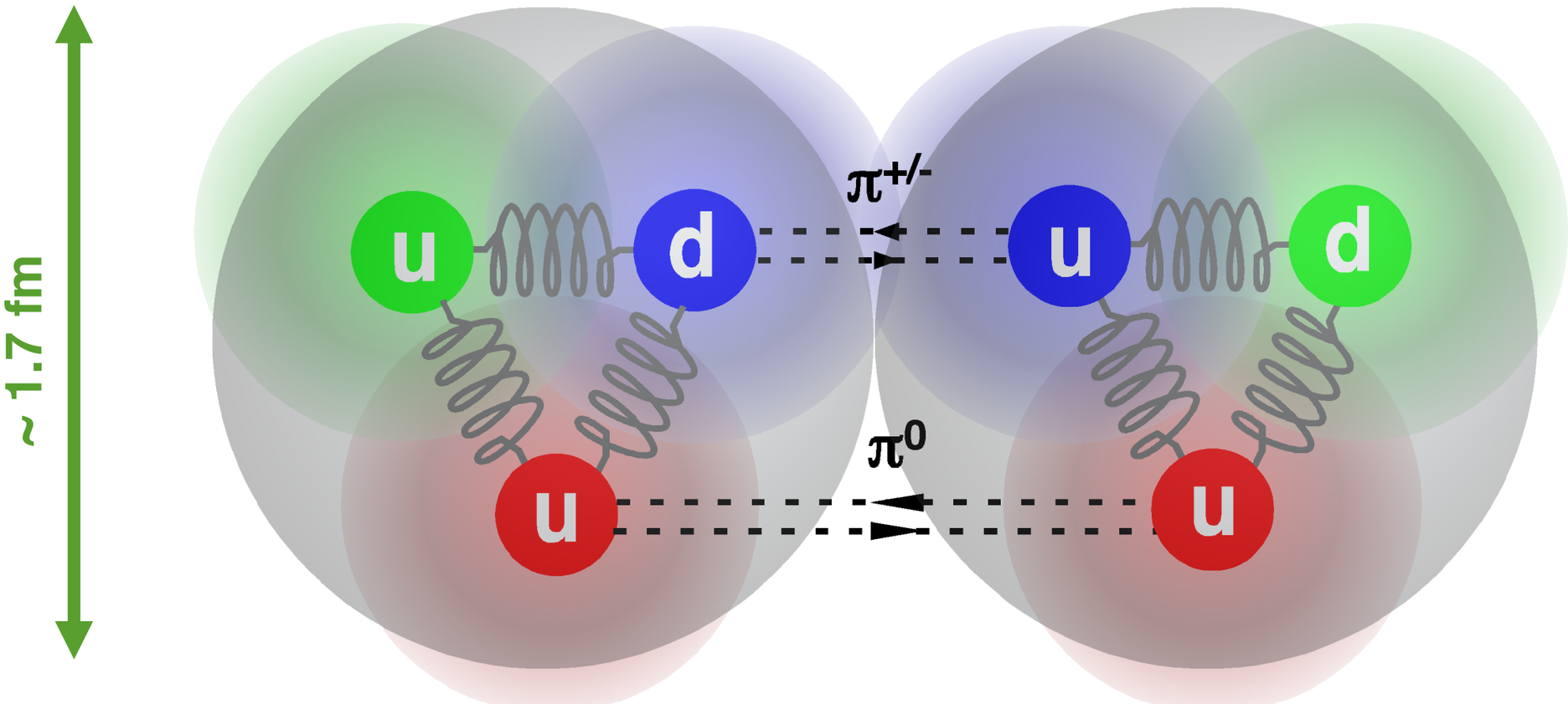
~0.6 fm relative K motion in Kpp CM-frame

Hierarchy inside nucleon?

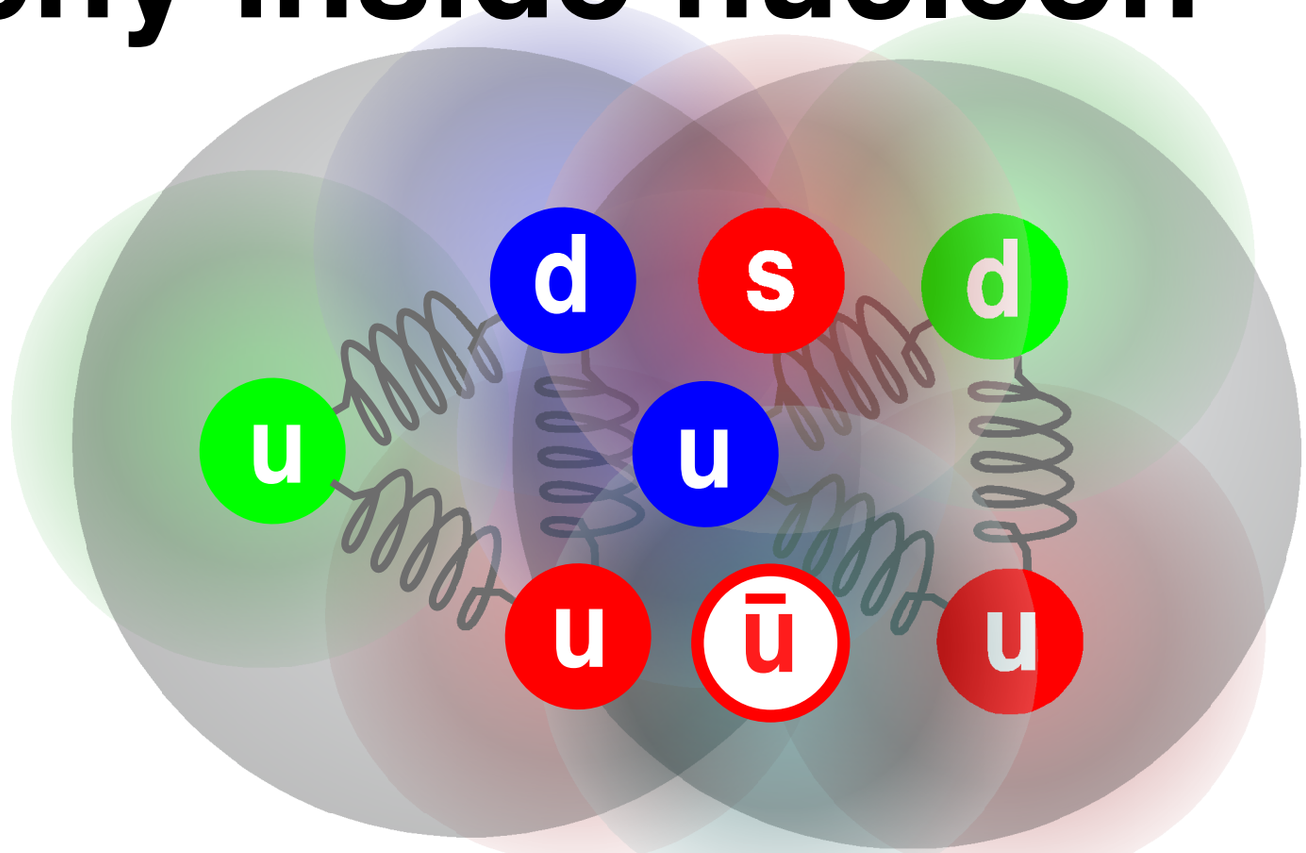
kaonic nucleus “Kpp” ~ composite of K+p+p?

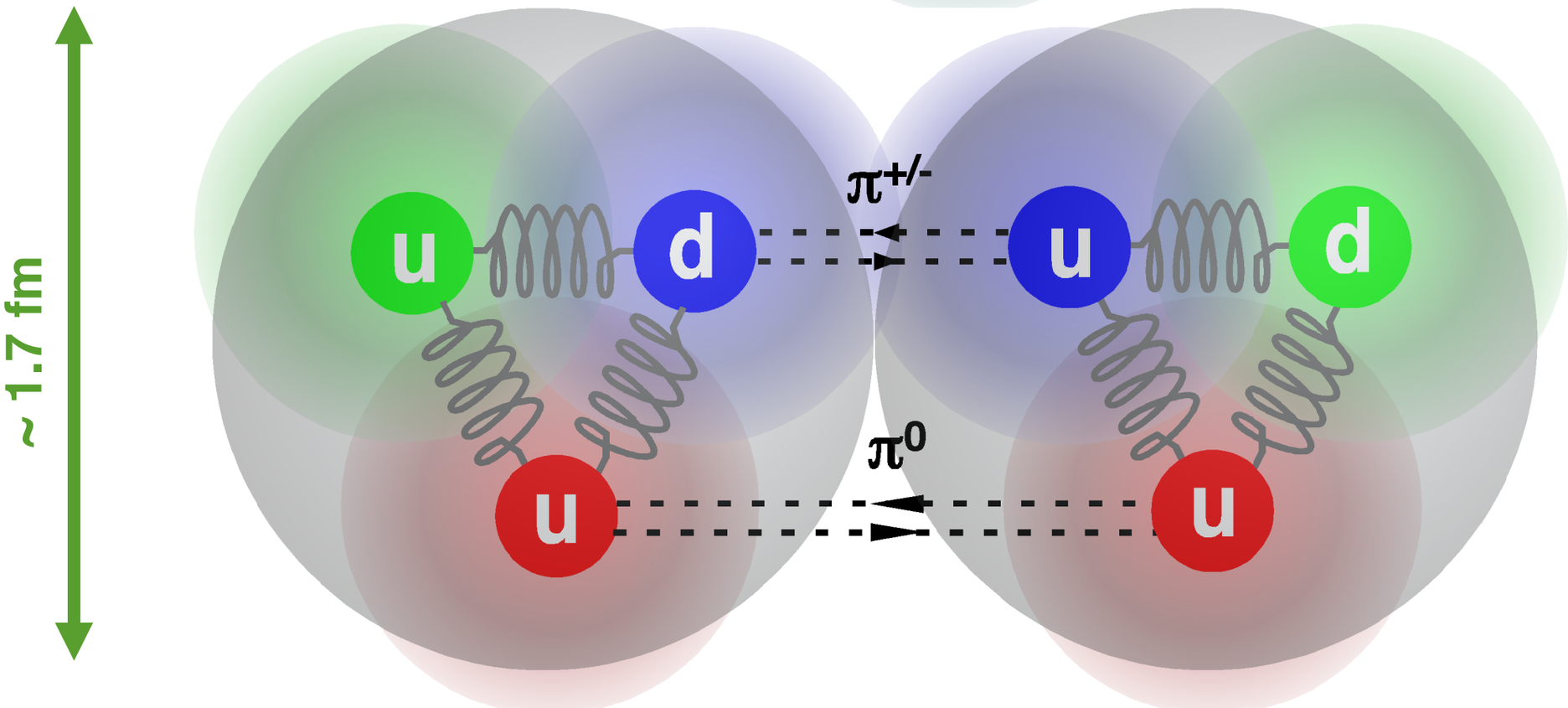


nucleon in nuclei / incompressibile

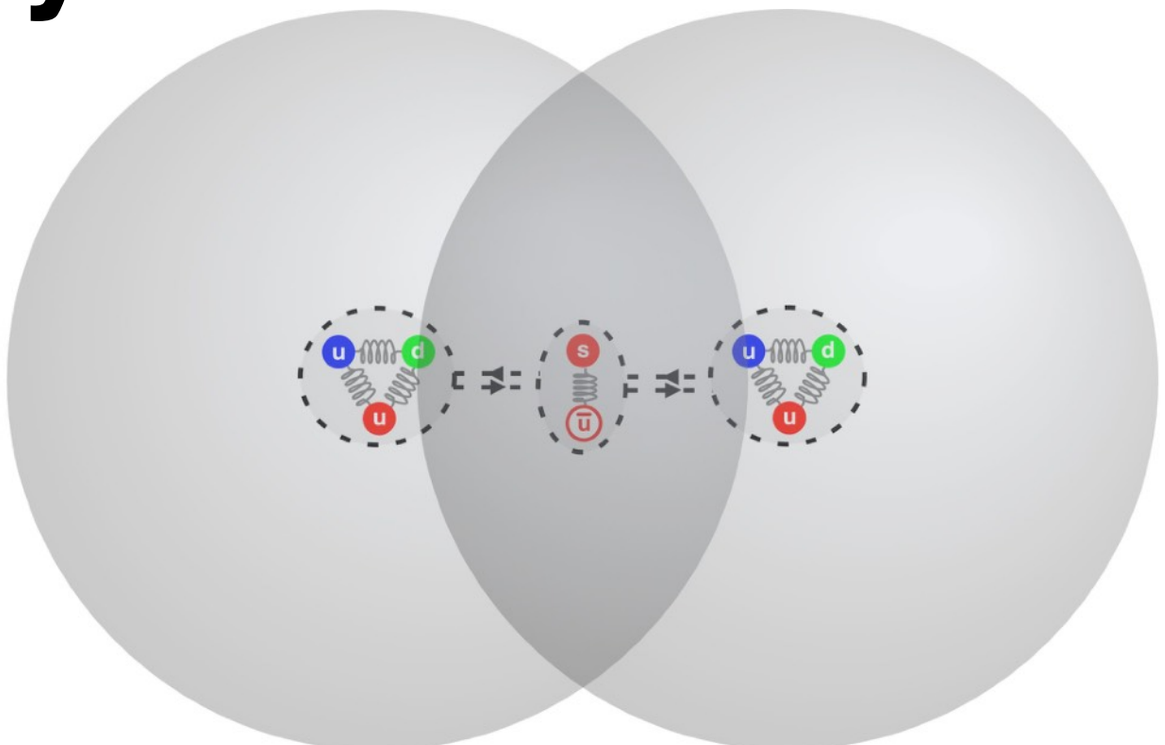


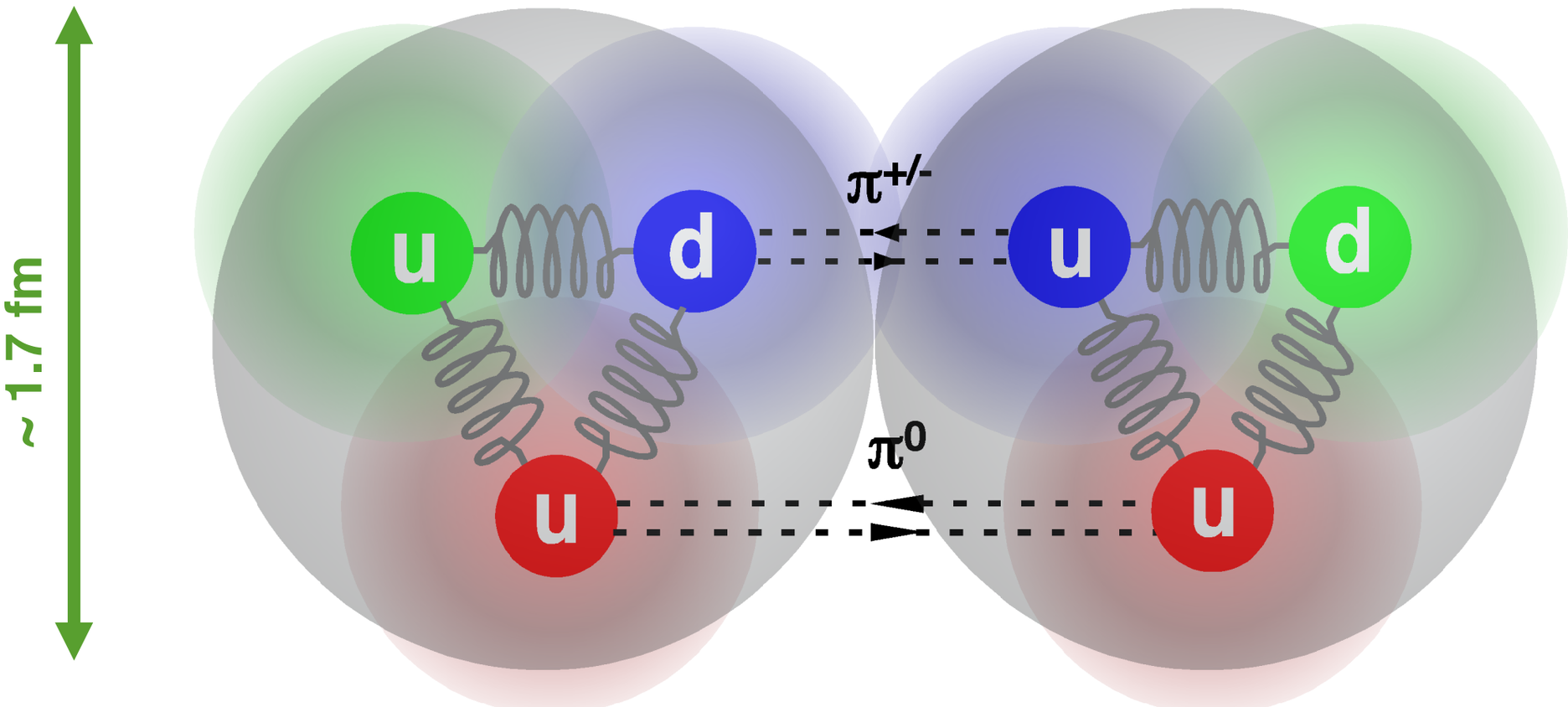
Hierarchy inside nucleon





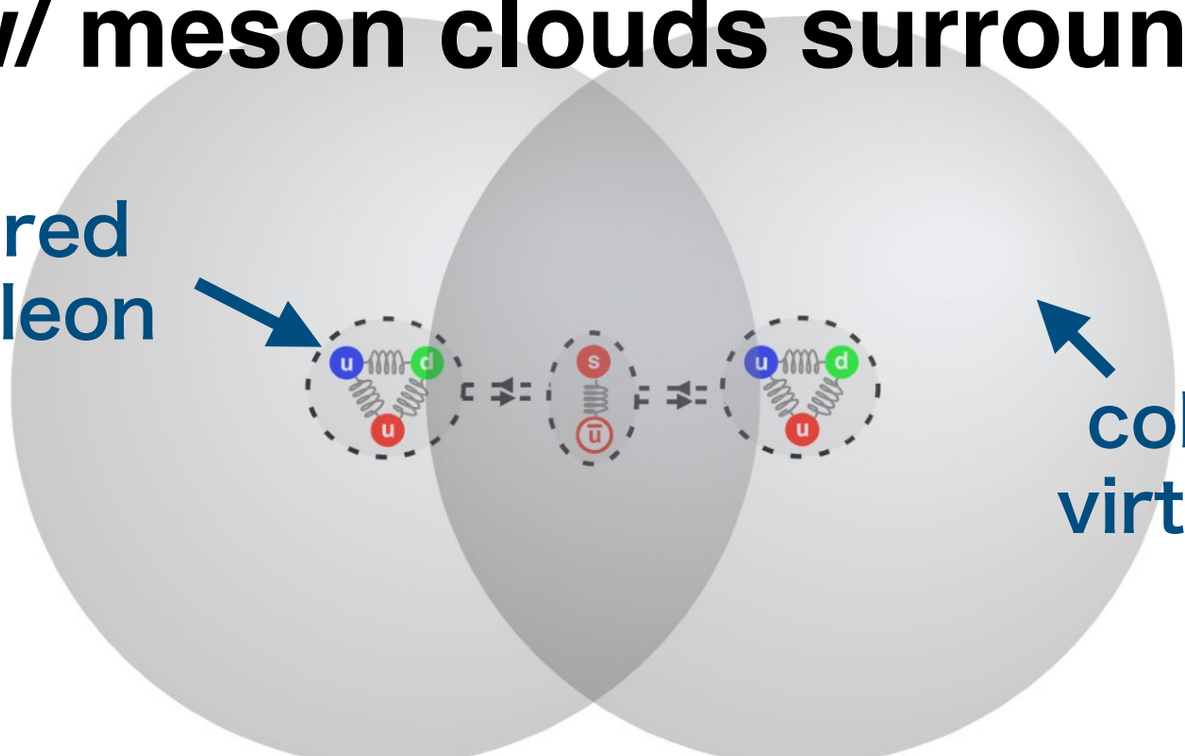
Hierarchy inside nucleon





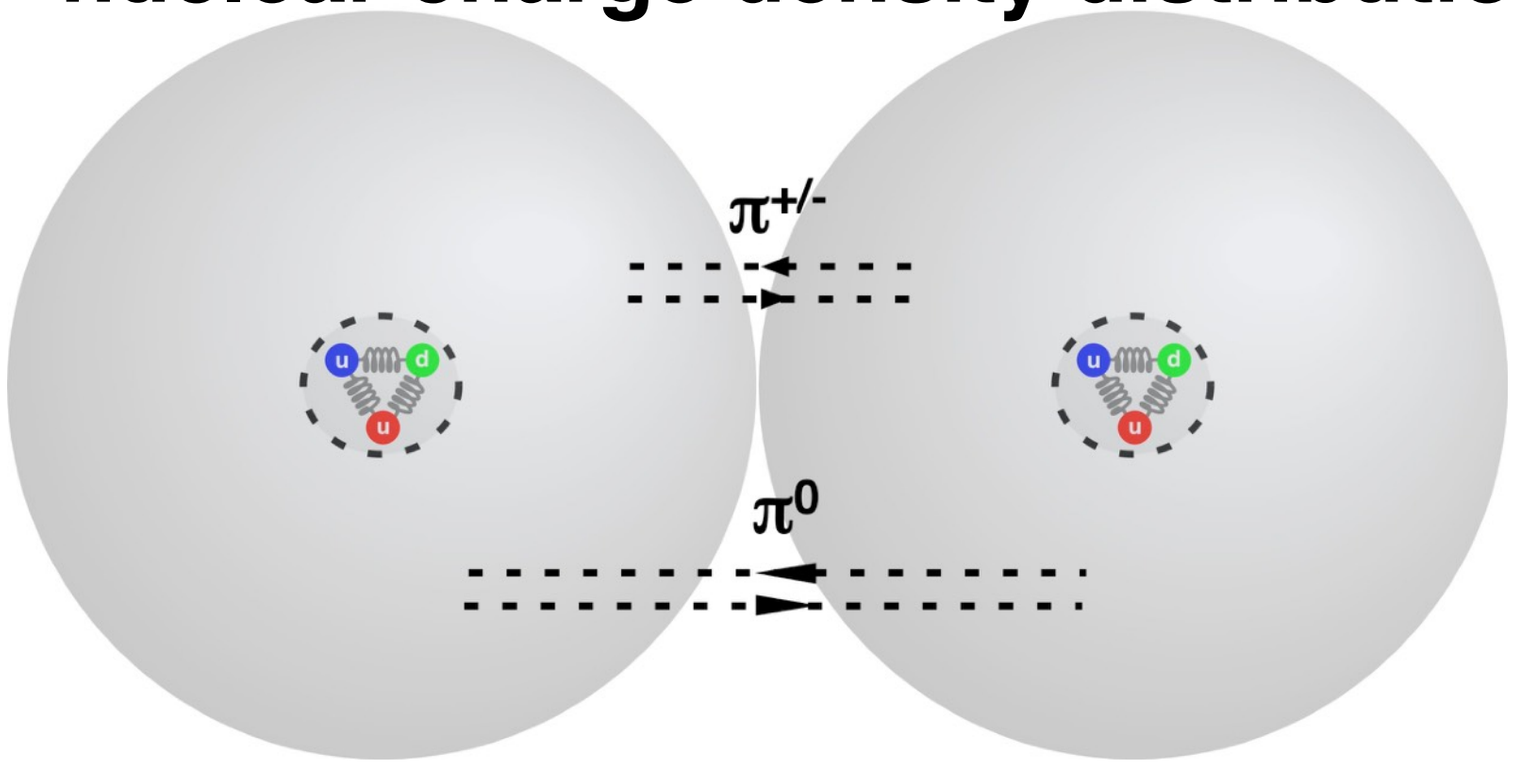
Is nucleon point-like?
w/ meson clouds surrounding around?

partially-colored
point-like nucleon
core



color-singlet shell:
virtual meson cloud

partially-colored core could be much compact than nuclear charge density distribution



E15 summary

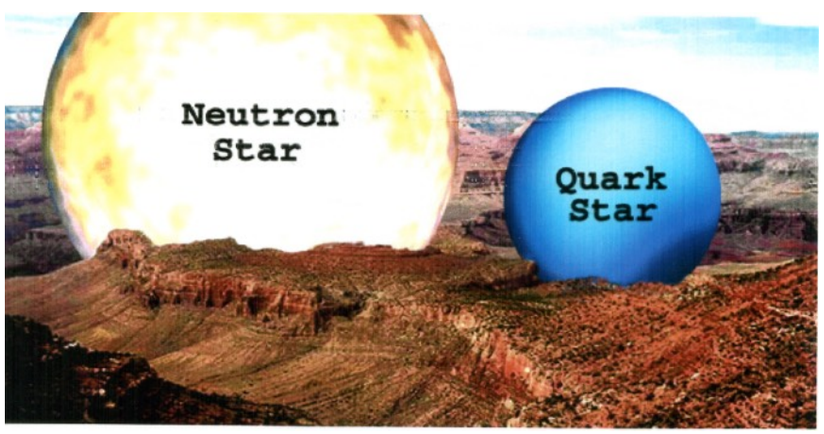
future to go

in-flight: $K^- + {}^3He \rightarrow (\Lambda + p) + n$

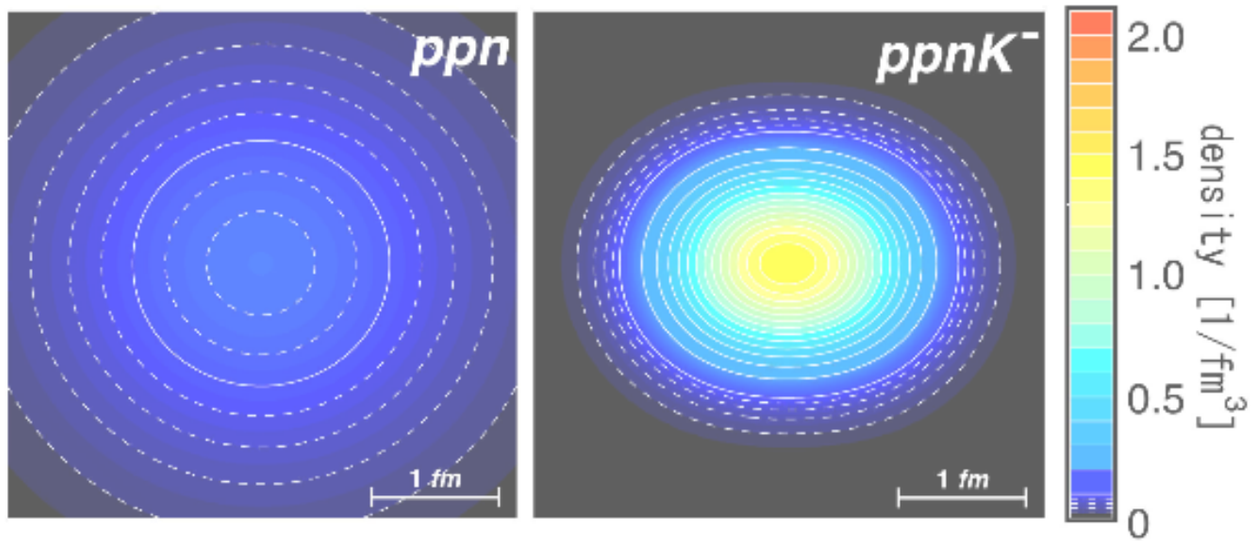
convincing Kpp signal obtained

systematic study on light kaonic nuclei

compact deep nuclear bound system ?



Dote et al., PLB 590 (2004) 51



Renewed key questions:

- How quark-composite particle can be "*a particle*" even in nuclear matter?

➡ **Mystery of "hadronization"**

- Dose K-meson change mass in nuclei?

➡ **Atomic number (A) dependence = *n* detector**

"K⁻p", "K⁻pp", "$\bar{K}^0$nn", "K⁻ppn", "K⁻ppnn", ...

- Spatial size?

➡ **precise angular dependence = *full coverage***

- Quantum state & decay?

➡ **Λp / Σ^0p / $\pi^0\Sigma^0$p = γ detector**

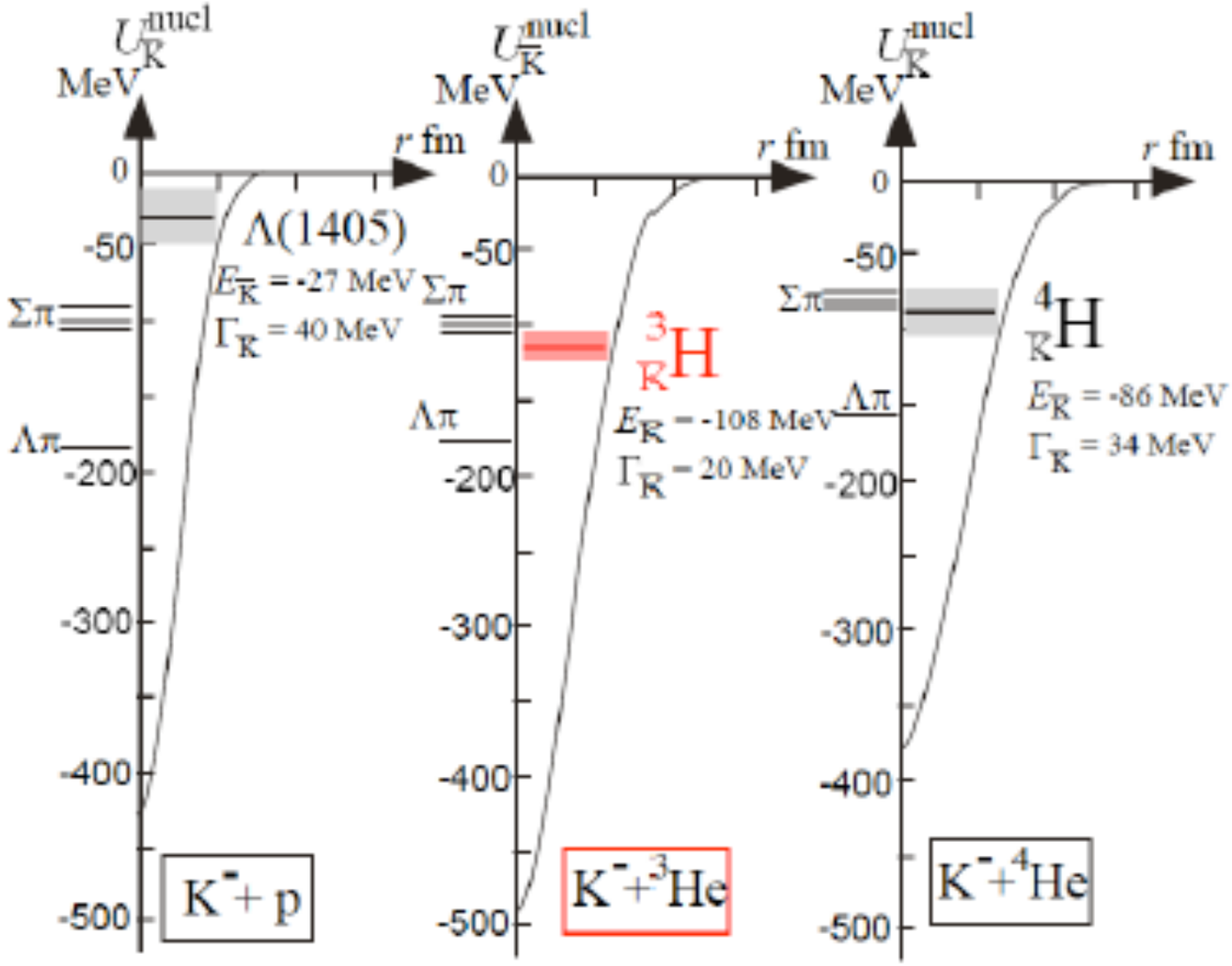
(if feasible: too expensive)

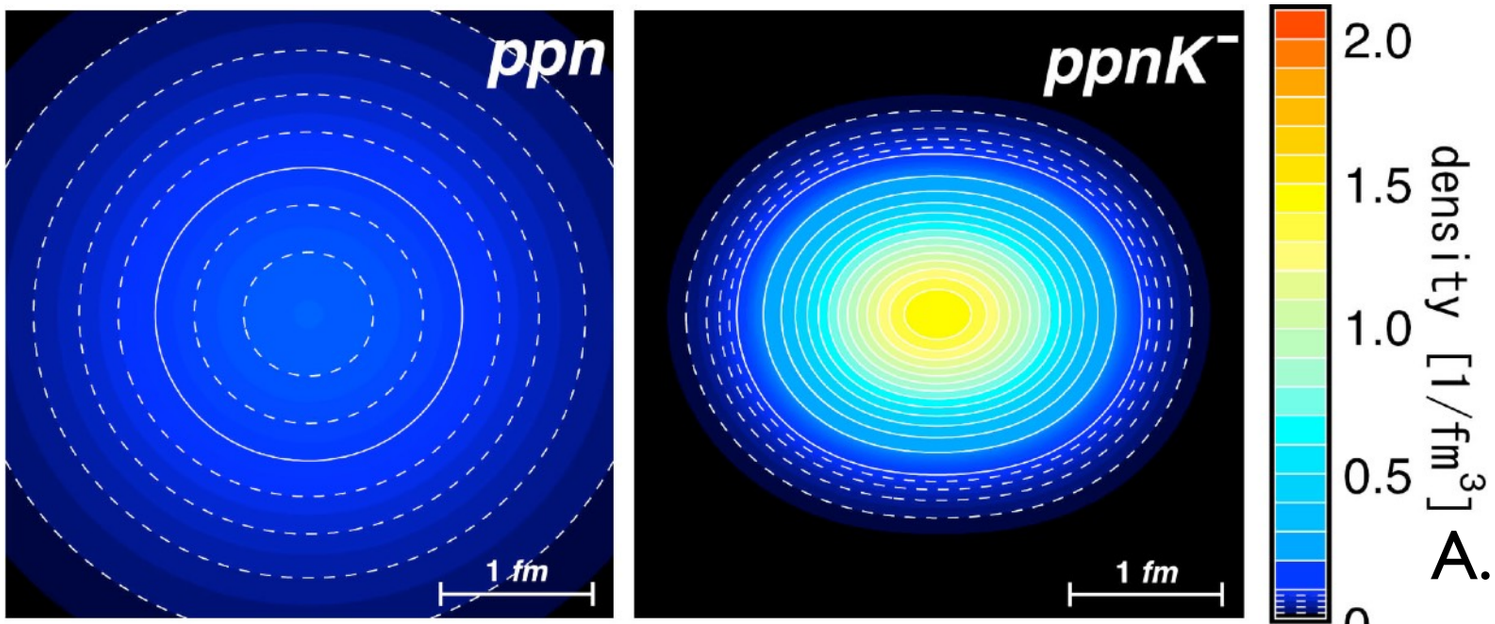
in-flight vs. at-rest

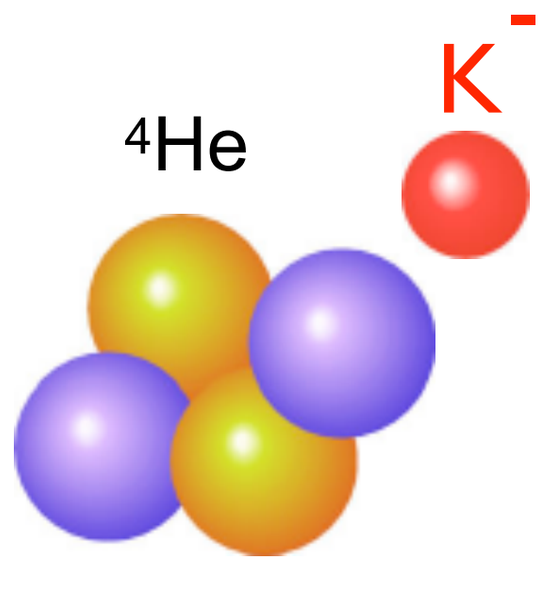
KEK PS-E471

Embedding K^- in nucleus via K at-rest?

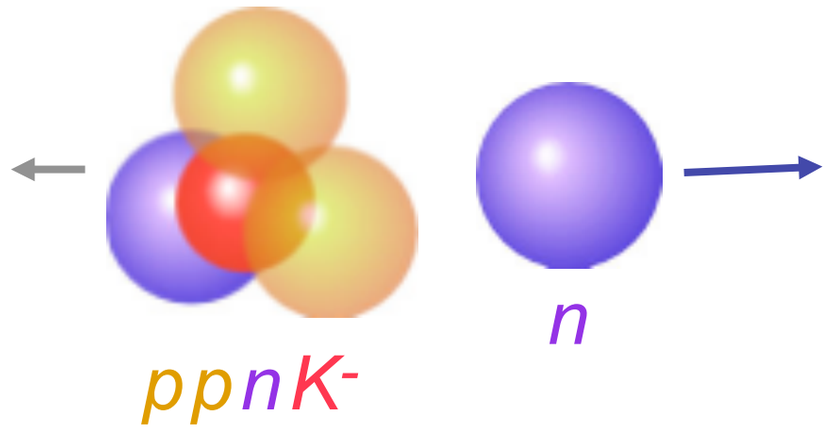
first trial to see K-nucl.







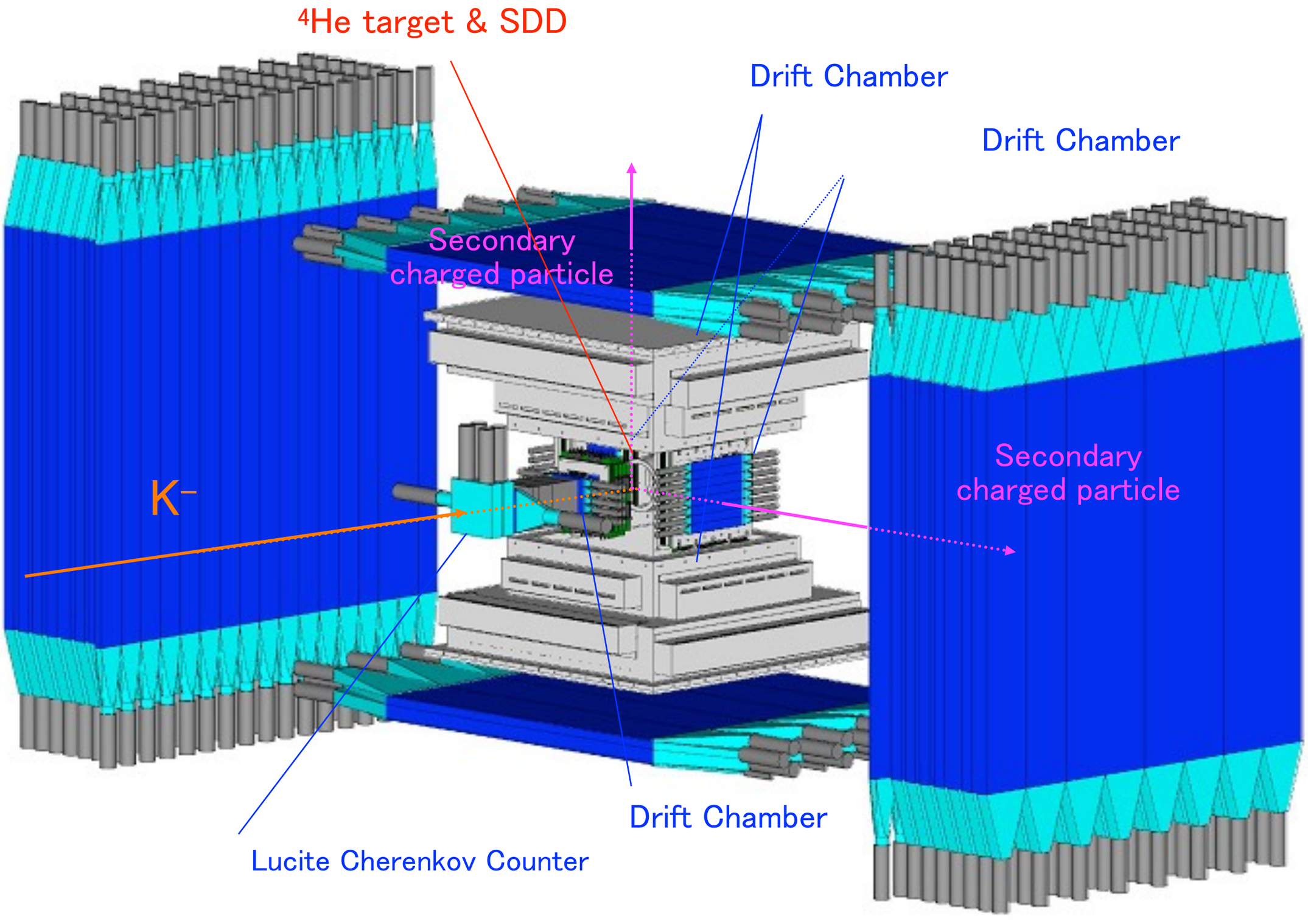
Z : +1
T : 0 *or* 1



^{4}He(stopped K^-, p)n

A. Dote et al. : PLB 590 (2004) 51

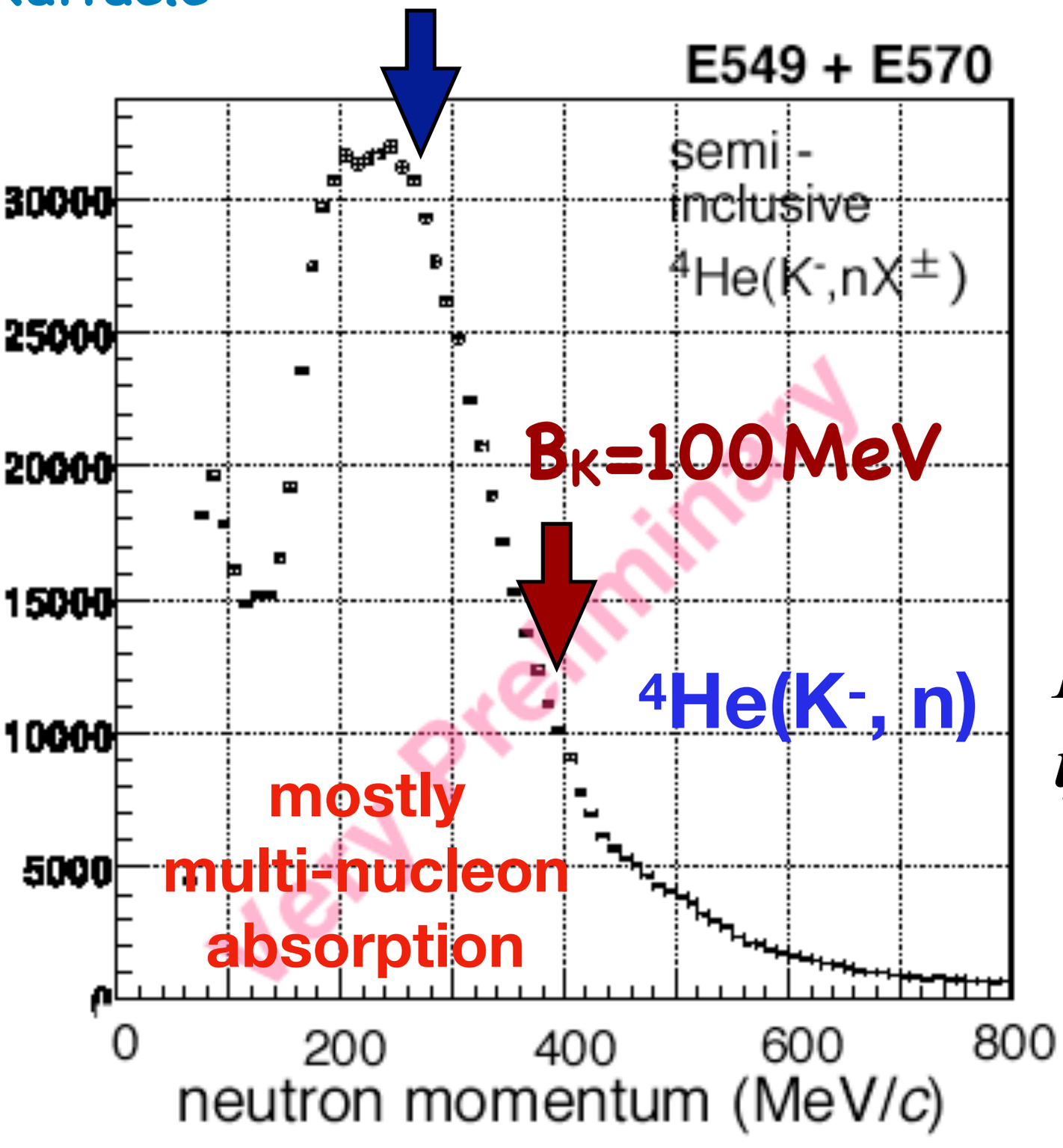
KEK 12GeV-PS E549 experimental setup



Neutron spectrum from K⁻ at-rest

inclusive

Raffaele



K⁻ at-rest

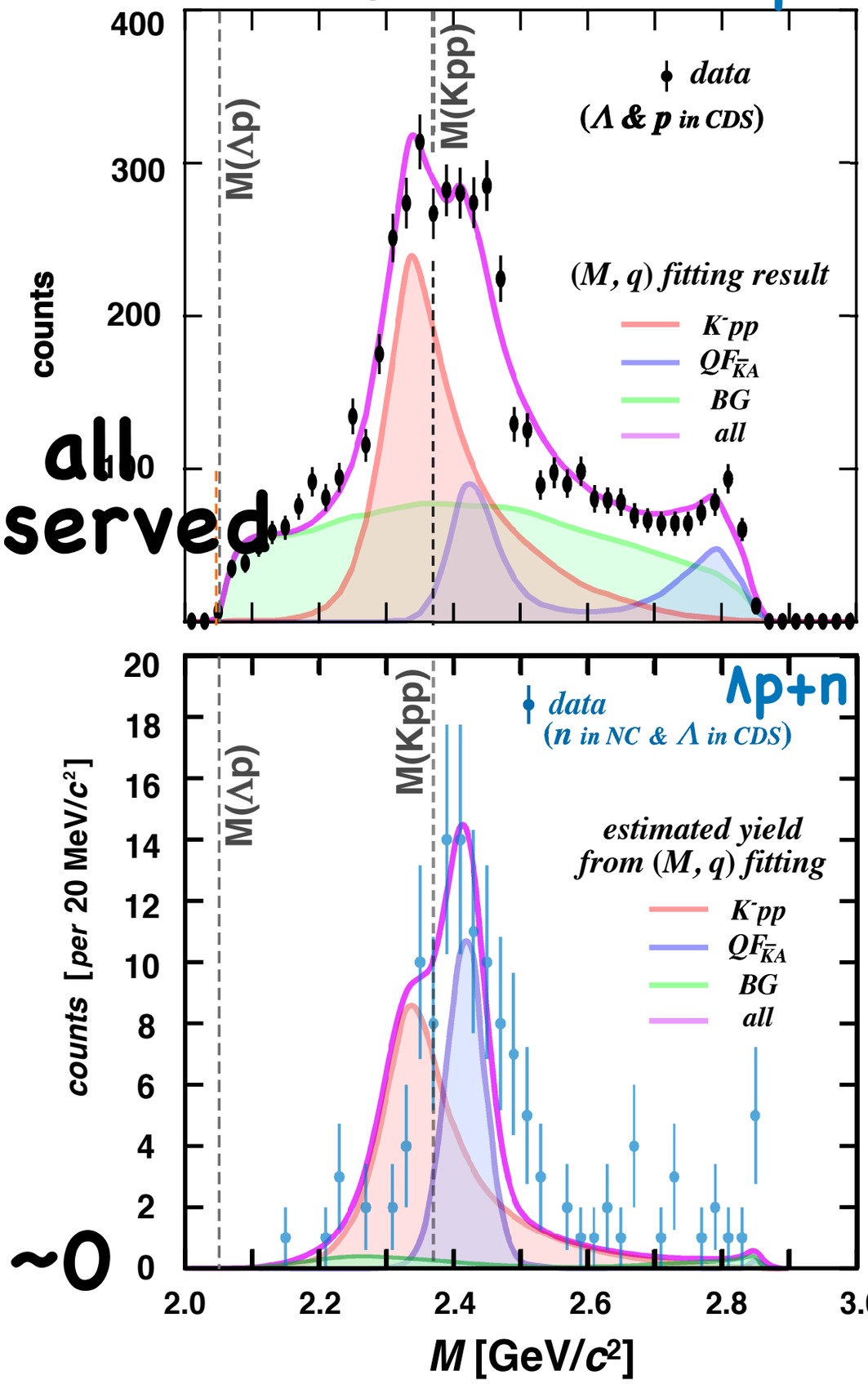
very severe in multi-nucleon absorption processes

I will be very surprised, if one can observe wide signal (~100 MeV/c²) over such a huge BG!

M Spectrum depending on detection condition

all observed

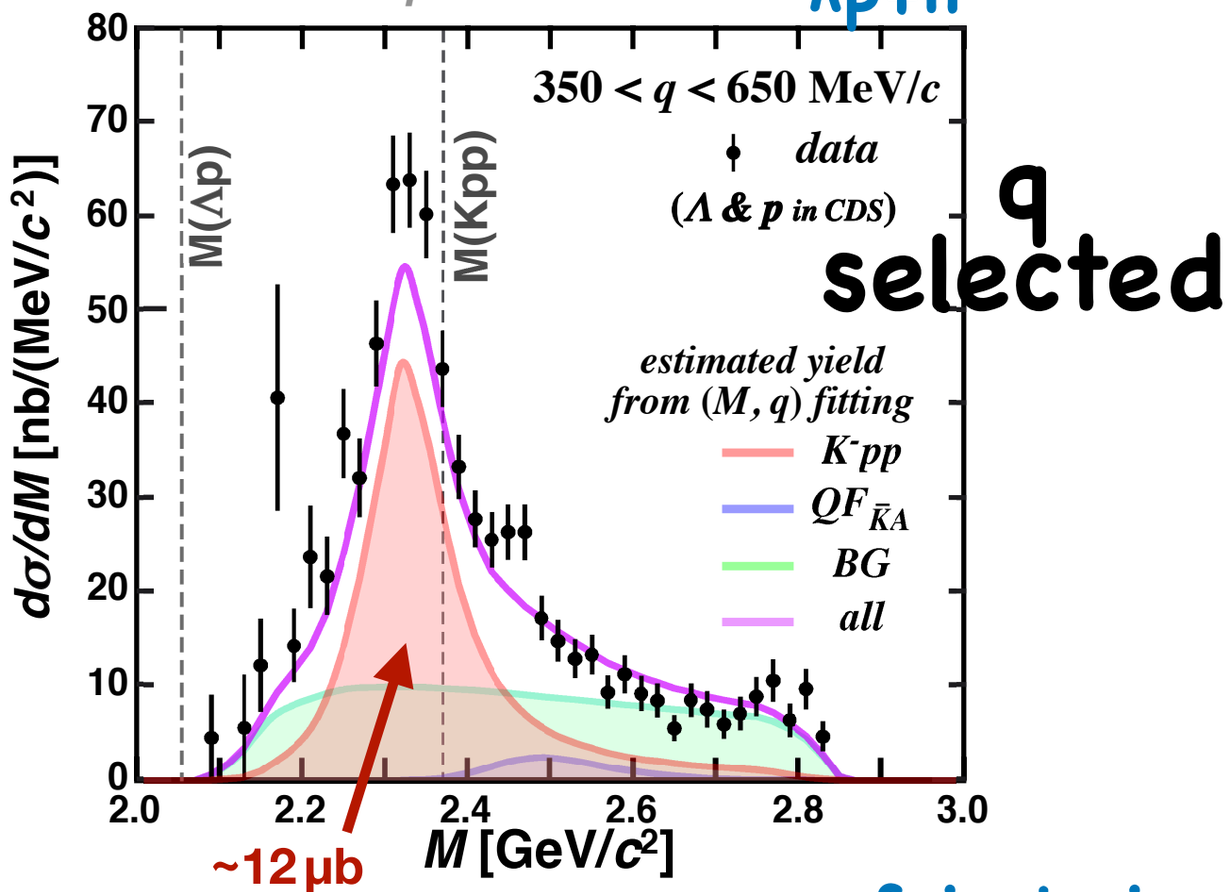
acceptance uncorrected Λp+n



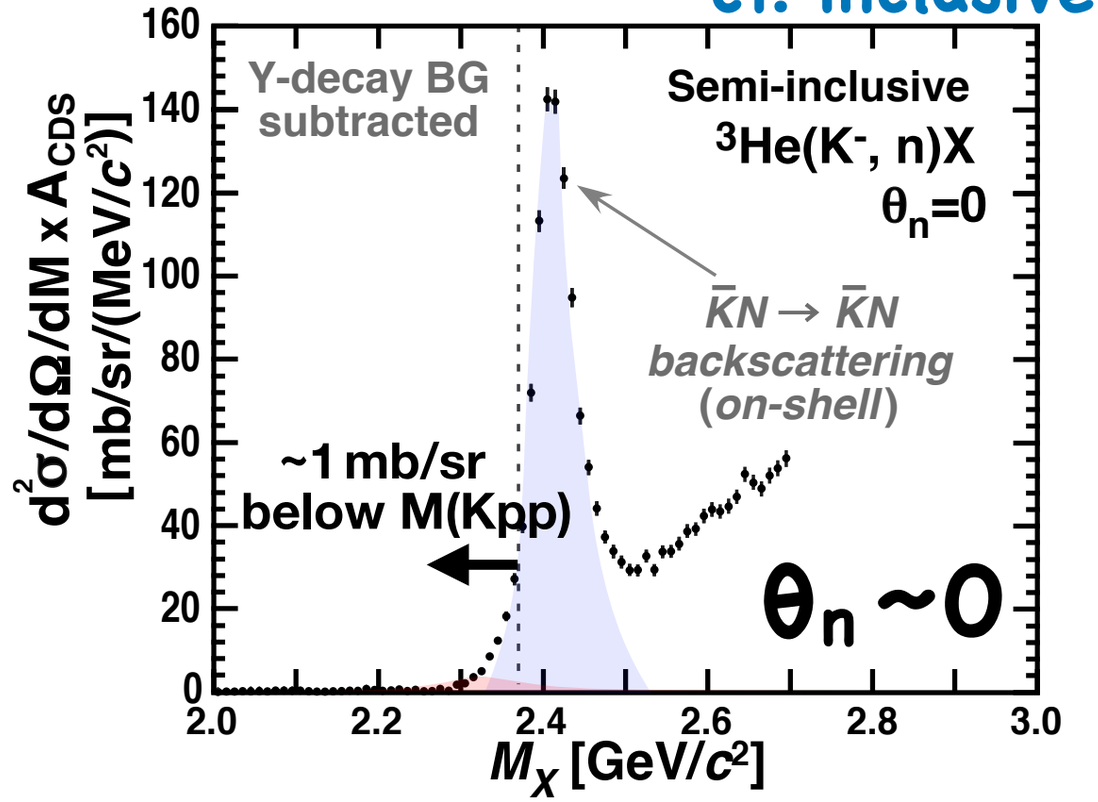
θn ~0

acceptance corrected Λp+n

q selected



cf. inclusive

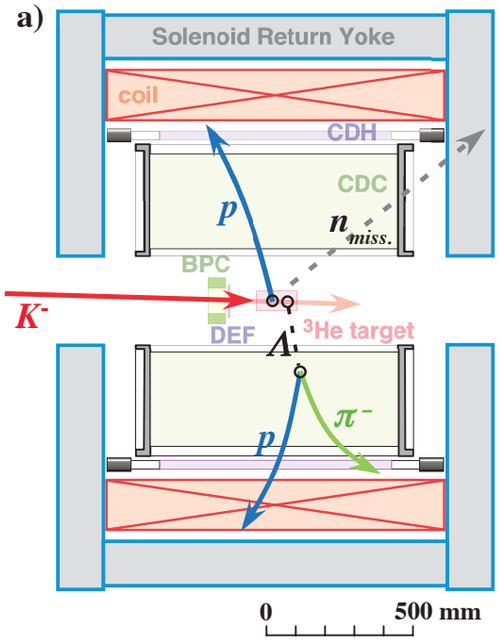


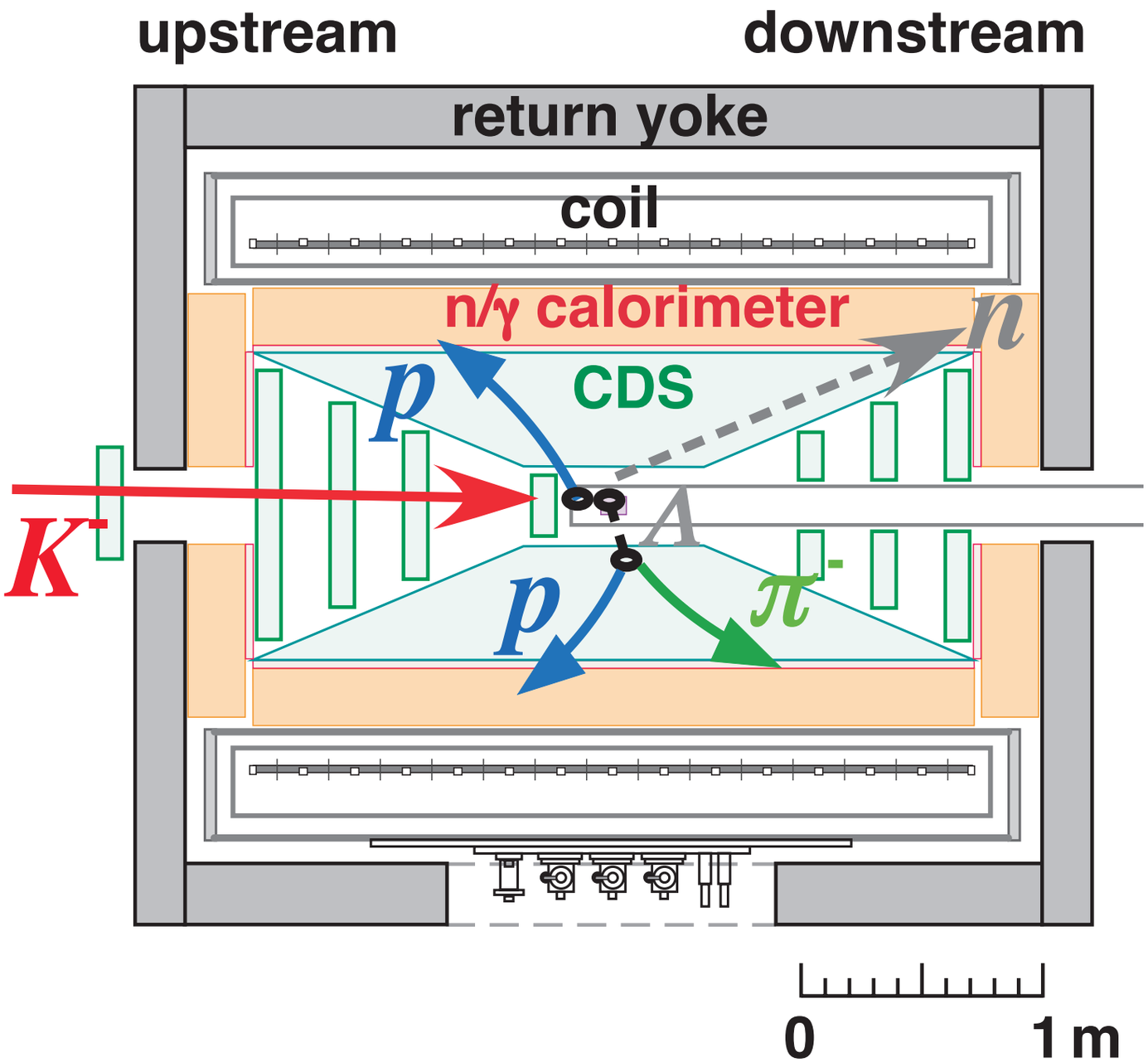
	in-flight	at-rest
source	off-shell kaon *via KN→KN*	on-shell kaon
(M, q)	uniquely defined	not easy to define
reaction kinematics	many Λp+n, Λ*p+n, … exclusive	many …
backgrounds	2NA separated QF separated 3NA?	severe 2NA QF unseparated

Future direction must be natural extension of E15 exclusive & in-flight

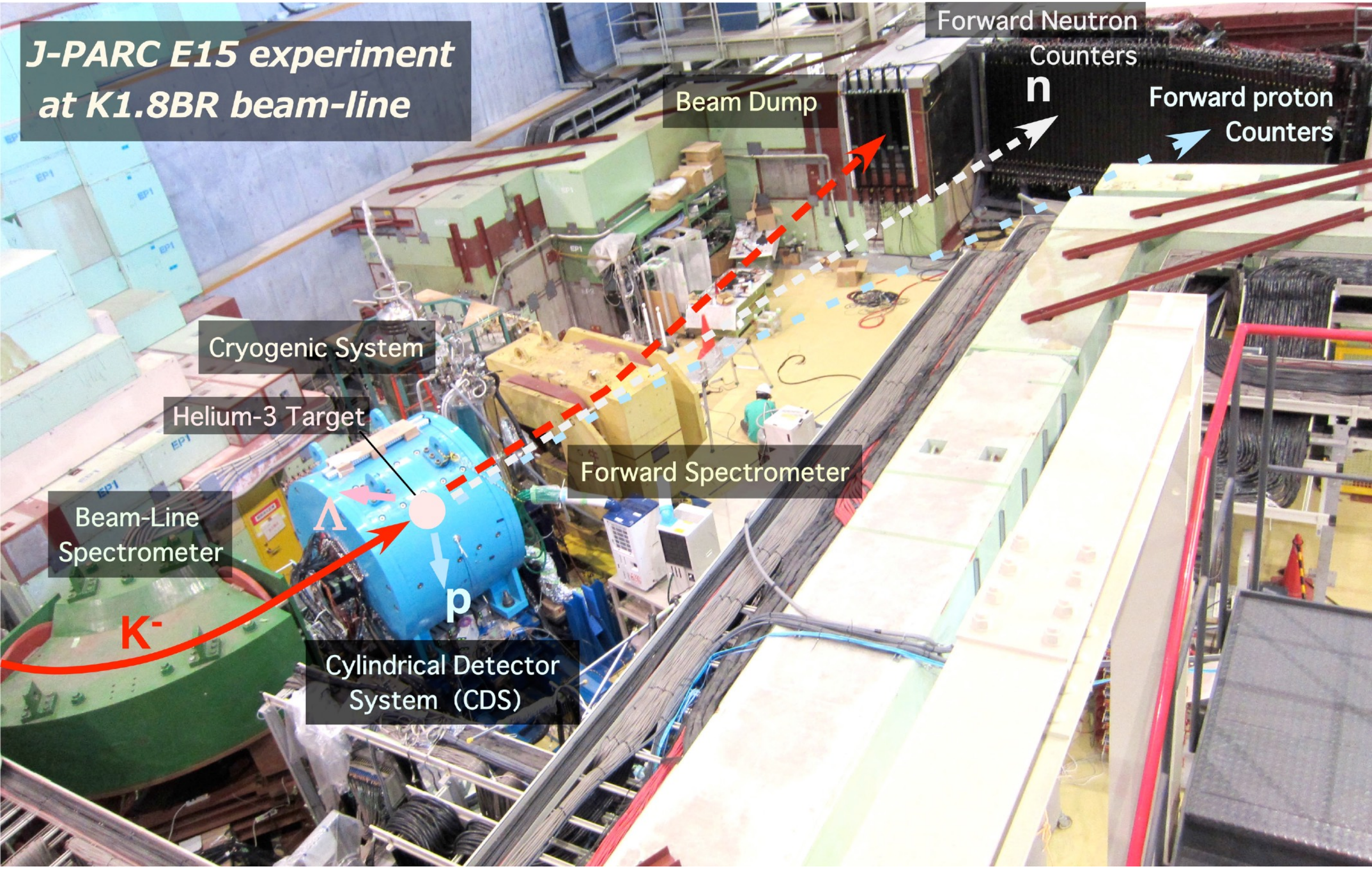
Upgrade Plan

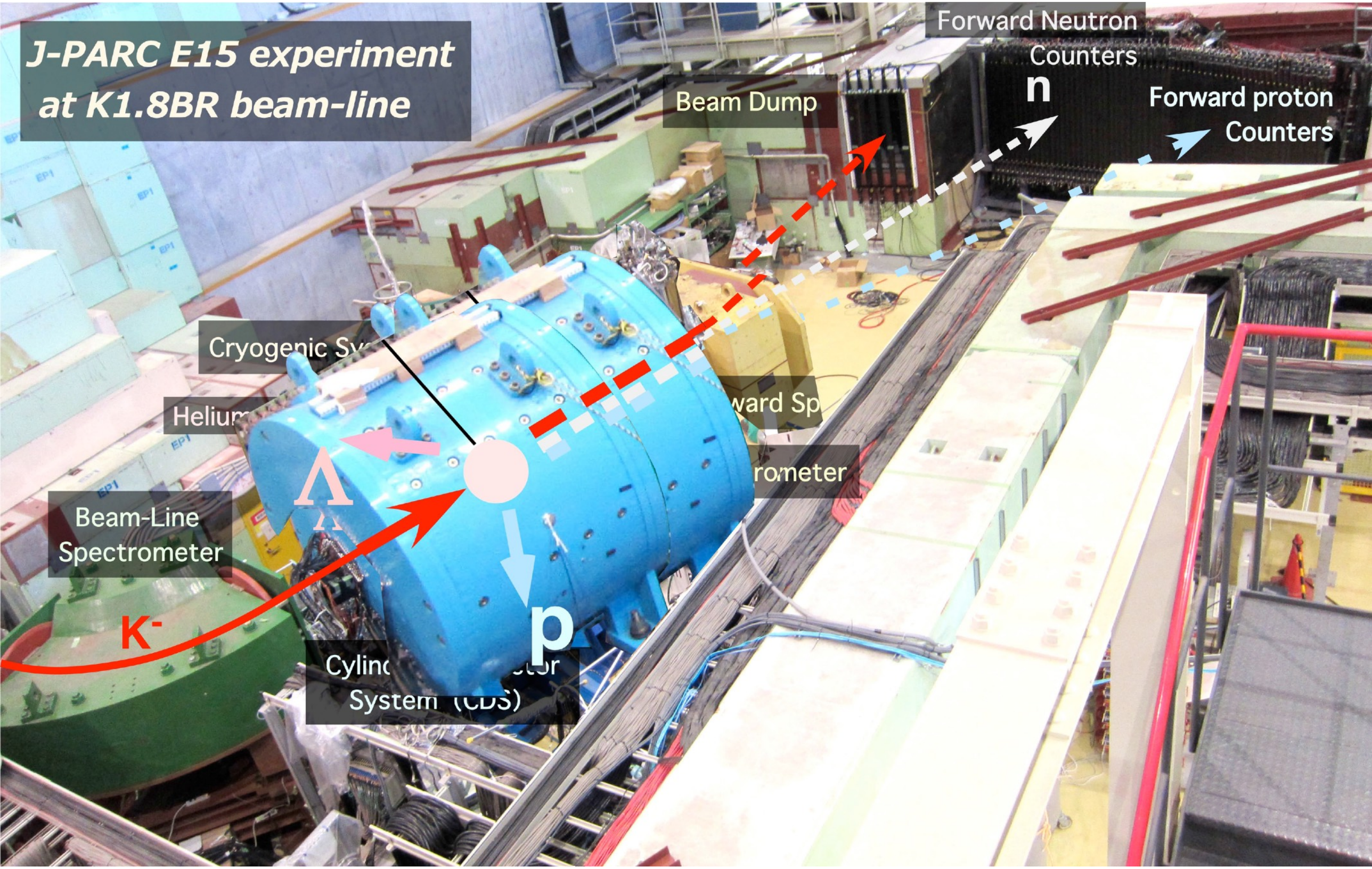
E15 setup





cf. $\Sigma^0 \rightarrow \Lambda + \gamma$!


J-PARC E15 experiment
at K1.8BR beam-line
Forward Neutron
Counters
n
Forward proton
Counters
Beam Dump
Cryogenic System
Helium-3 Target
Forward Spectrometer
Beam-Line
Spectrometer
Λ
p
K-
Cylindrical Detector
System (CDS)


J-PARC E15 experiment
at K1.8BR beam-line
Forward Neutron
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Cryogenic Sy
Helium
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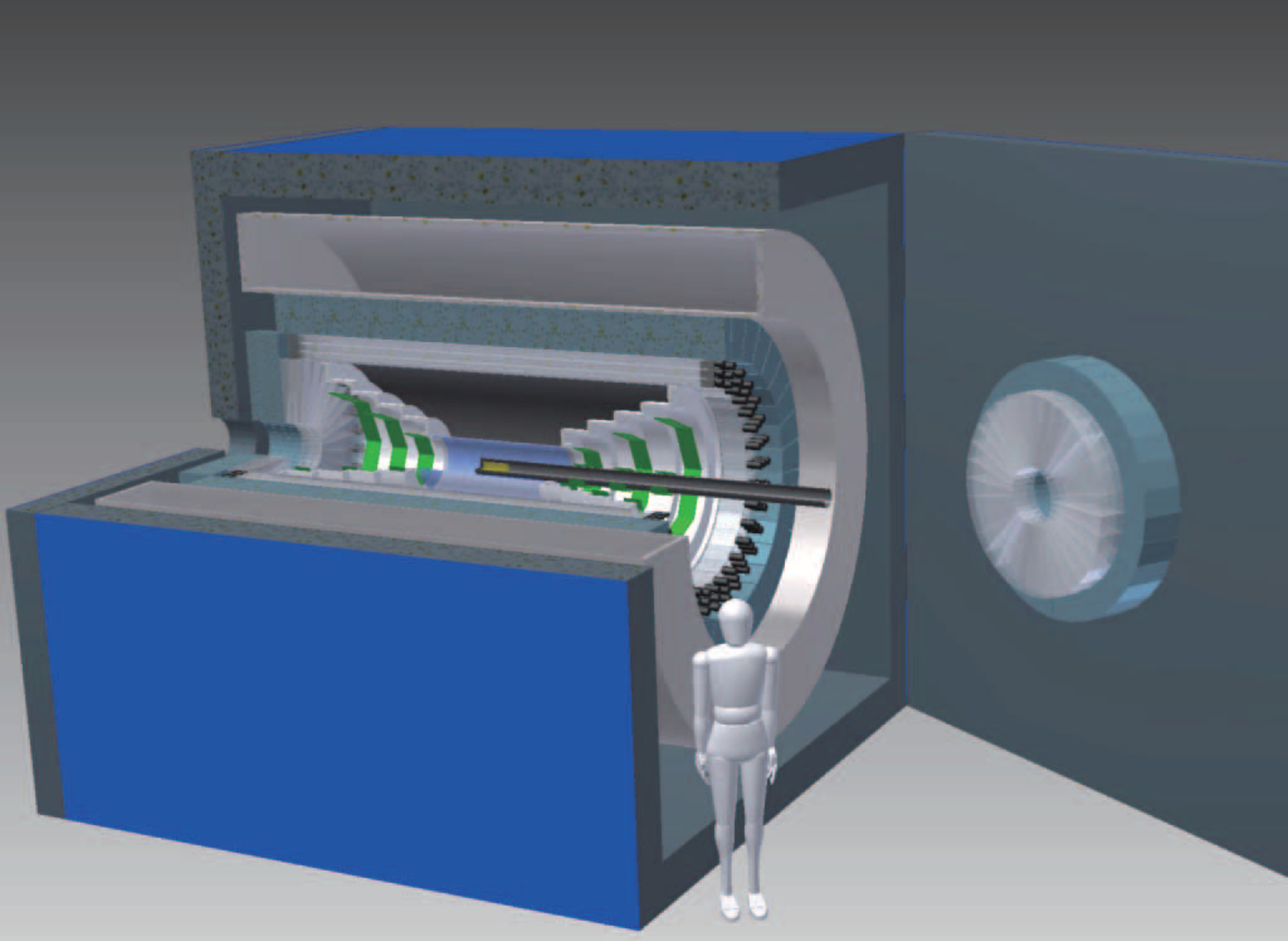
rometer
Λ
Beam-Line
Spectrometer
K-
p
Cylinc
System (CDS)

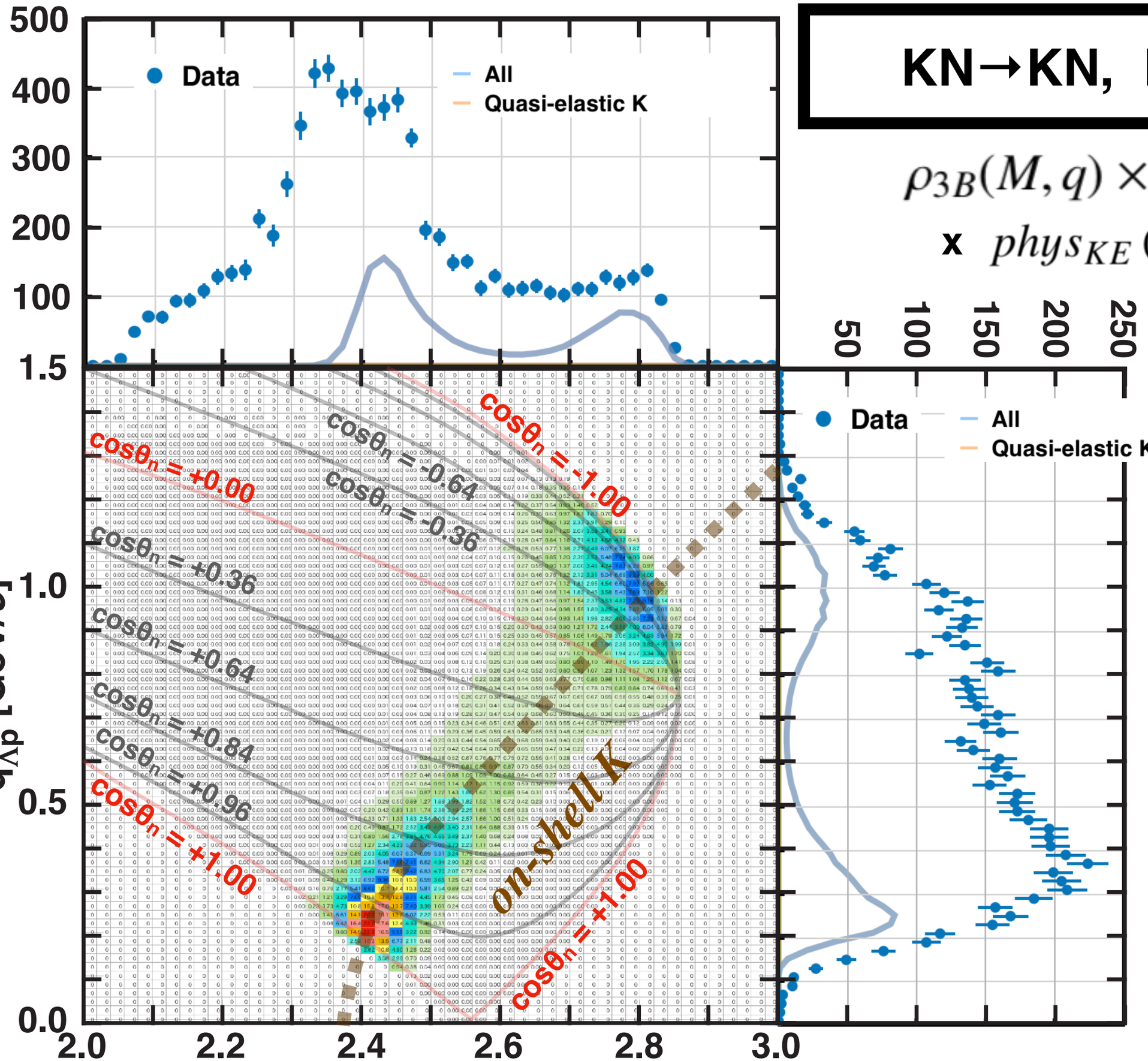


Thank you for attention!

KN→KN, KNN→Λp

$$\rho_{3B}(M,q) \times \mathcal{E}(M,q)$$

x $$phys_{KE}(M,q)$$



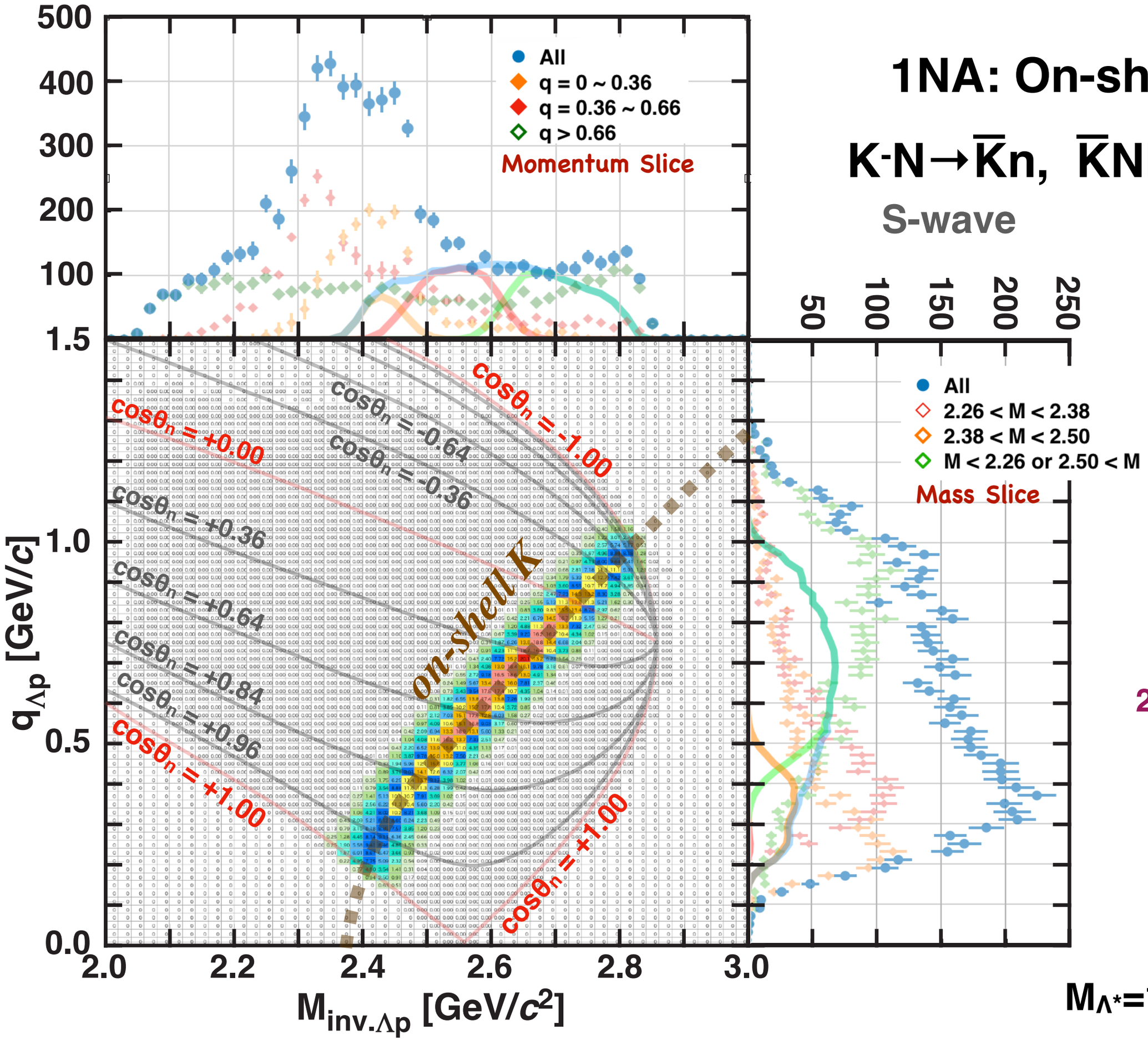
8 parameters

counts	color
24.2	
20	
16.2	
12.8	
9.8	
7.2	
5	
3.2	
1.8	
0.8	
0.2	
0	

1NA: On-shell K

$K^-N \to \bar{K}n$, $\bar{K}NN \to \Lambda p$

S-wave



2 parameters

width + yield

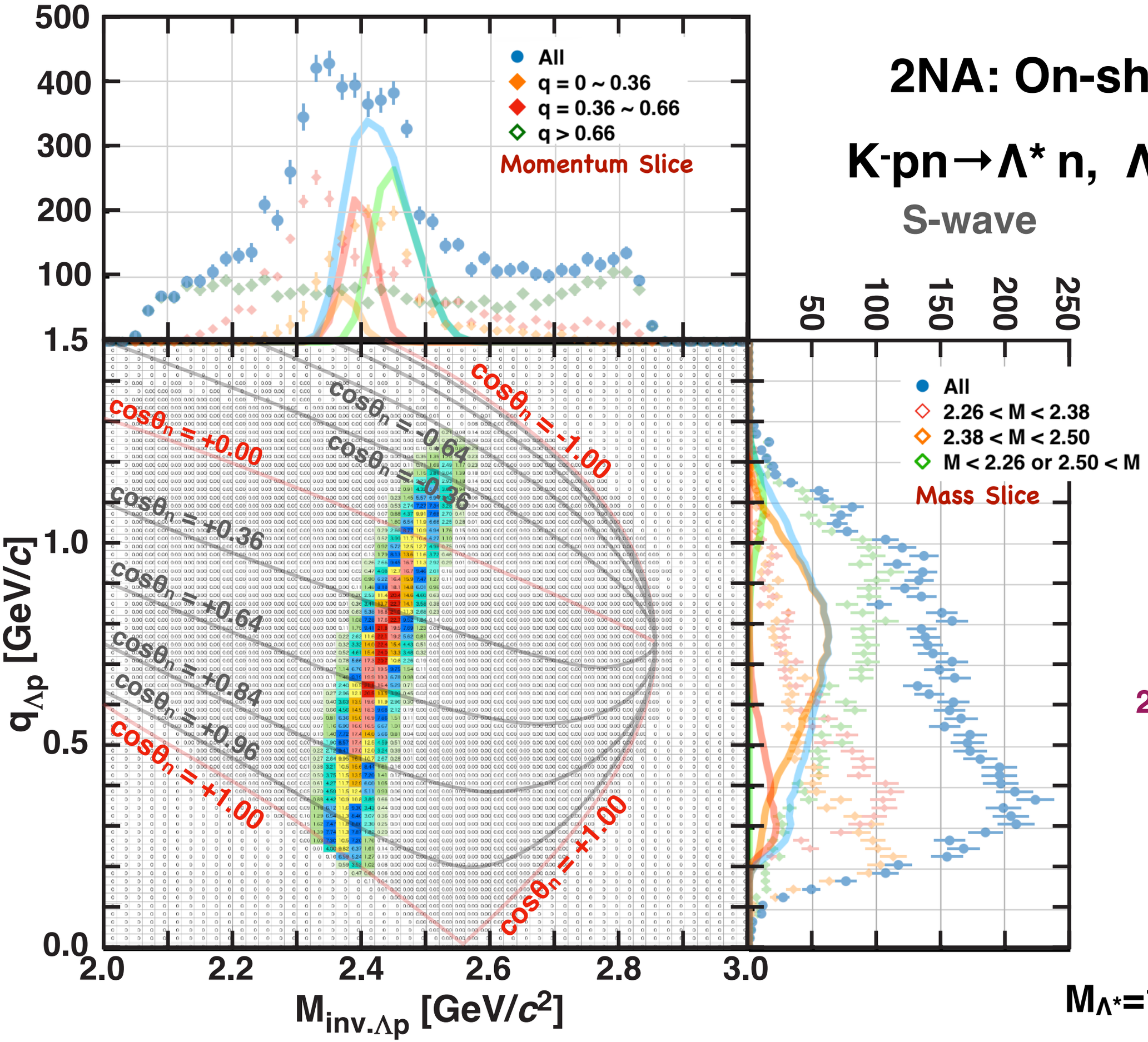
counts	color
24.2	
20	
16.2	
12.8	
9.8	
7.2	
5	
3.2	
1.8	
0.8	
0.2	
0	

M_{Λ^*}=1420 MeV/c^2

2NA: On-shell Λ*

$K^- pn \to \Lambda^* n,\ \Lambda^* p \to \Lambda p$

S-wave



2 parameters

width + yield

counts	color
24.2	
20	
16.2	
12.8	
9.8	
7.2	
5	
3.2	
1.8	
0.8	
0.2	
0	

M_{Λ^*}=1420 MeV/c²

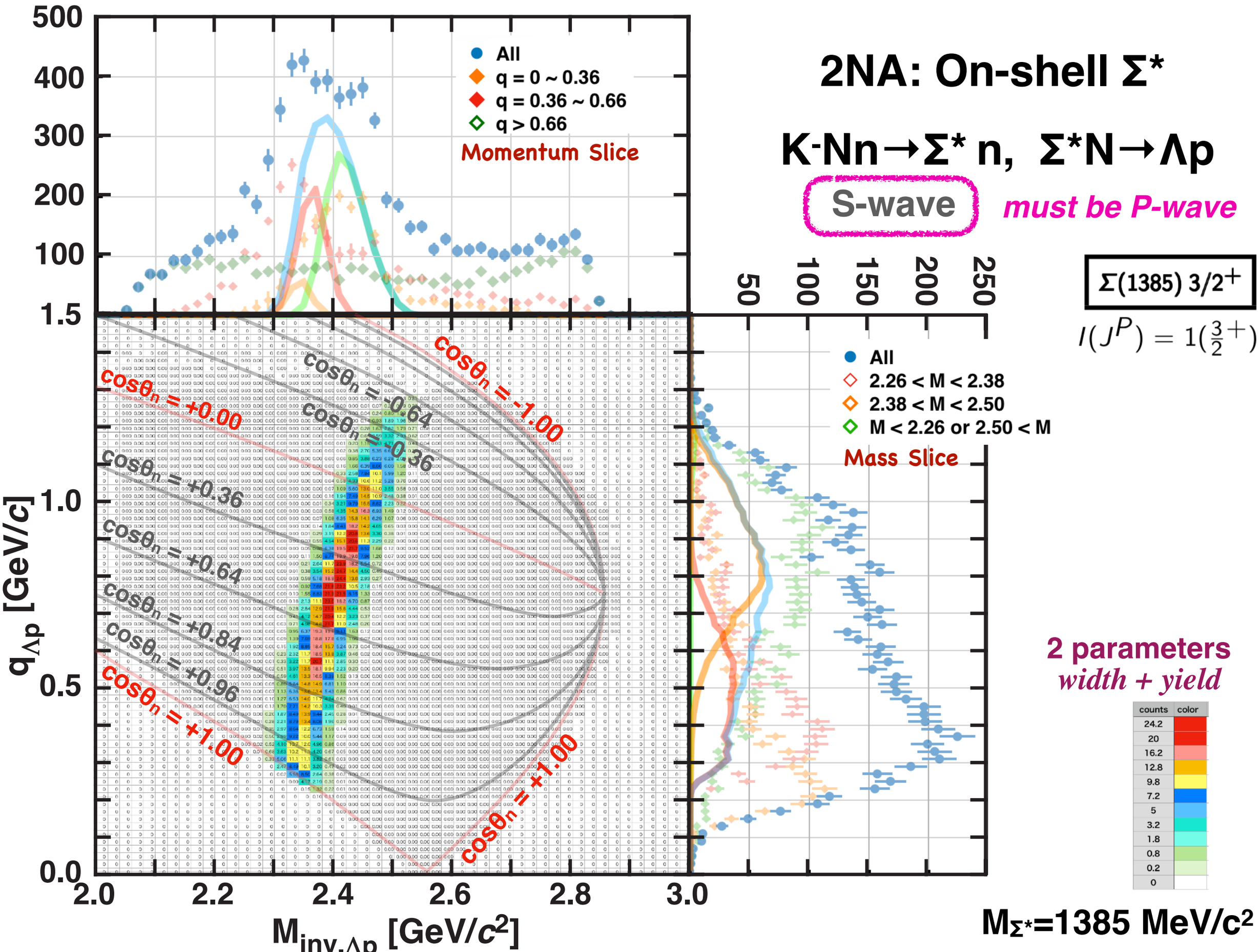
2NA: On-shell Σ*

K⁻Nn→Σ* n, Σ*N→Λp

S-wave *must be P-wave*

$\Sigma(1385)\ 3/2^+$

$I(J^P) = 1(\frac{3}{2}^+)$



2 parameters
width + yield

counts	color
24.2	
20	
16.2	
12.8	
9.8	
7.2	
5	
3.2	
1.8	
0.8	
0.2	
0	

M_{Σ^*}=1385 MeV/c²

2NA: On-shell Σ*

K⁻Nn→Σ* n, Σ*N→Λp

P-wave only by q^2 term

$\Sigma(1385)\ 3/2^+$

$I(J^P) = 1(\frac{3}{2}^+)$

All
q = 0 ~ 0.36
q = 0.36 ~ 0.66
q > 0.66
Momentum Slice

All
2.26 < M < 2.38
2.38 < M < 2.50
M < 2.26 or 2.50 < M
Mass Slice

$\cos\theta_n = +0.00$
$\cos\theta_n = +0.36$
$\cos\theta_n = +0.64$
$\cos\theta_n = +0.84$
$\cos\theta_n = +0.96$
$\cos\theta_n = +1.00$
$\cos\theta_n = -0.36$
$\cos\theta_n = -1.00$

2 parameters
width + yield

counts	color
24.2	
20	
16.2	
12.8	
9.8	
7.2	
5	
3.2	
1.8	
0.8	
0.2	
0	

M_{Σ^*}=1385 MeV/c²

$q_{\Lambda p}$ [GeV/c]

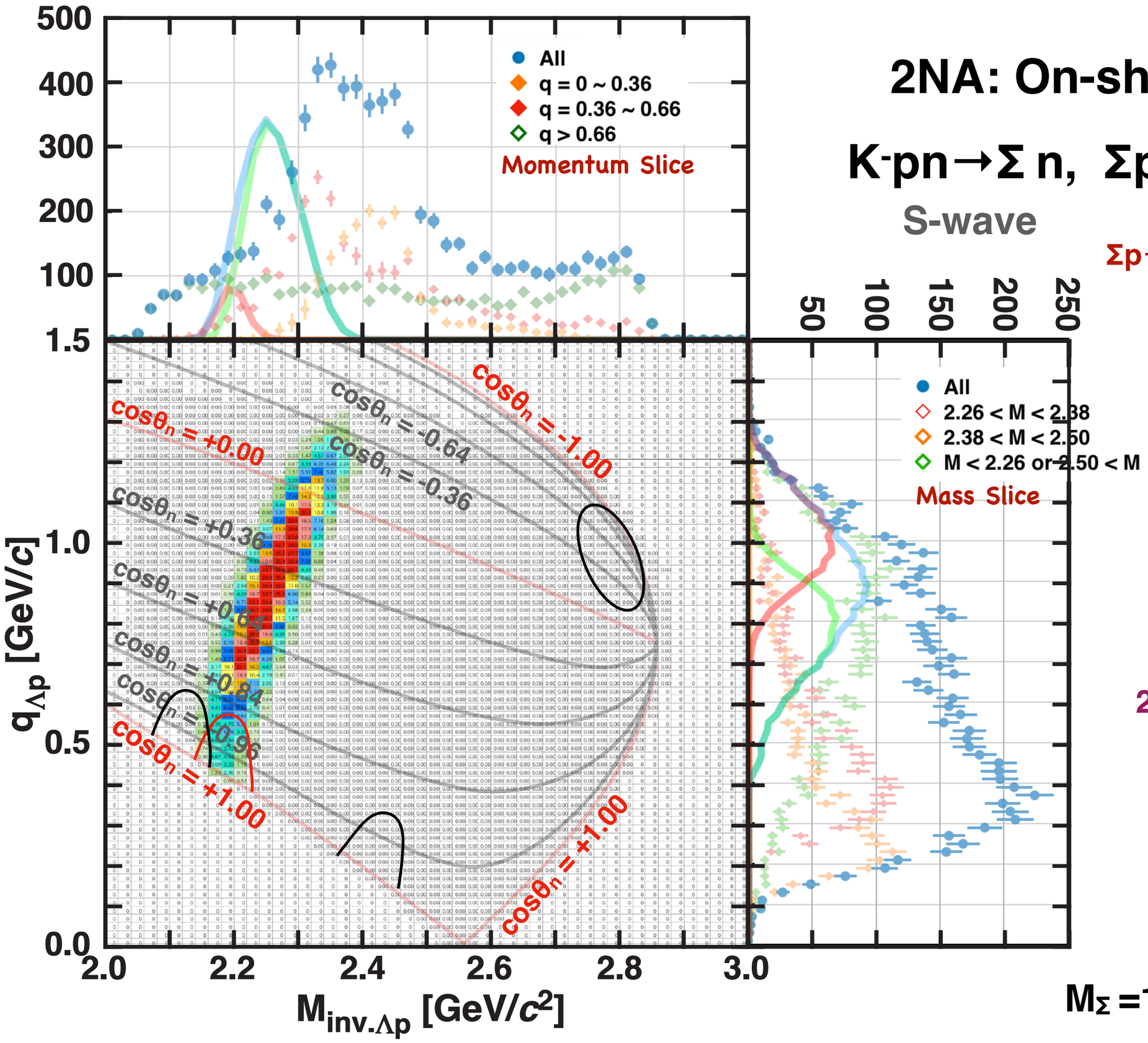
$M_{inv.\Lambda p}$ [GeV/c^2]

2NA: On-shell Σ

$K^- pn \to \Sigma n,\ \Sigma p \to \Lambda p$

S-wave

$\Sigma p \to \Lambda p$ conversion



2 parameters
width + yield

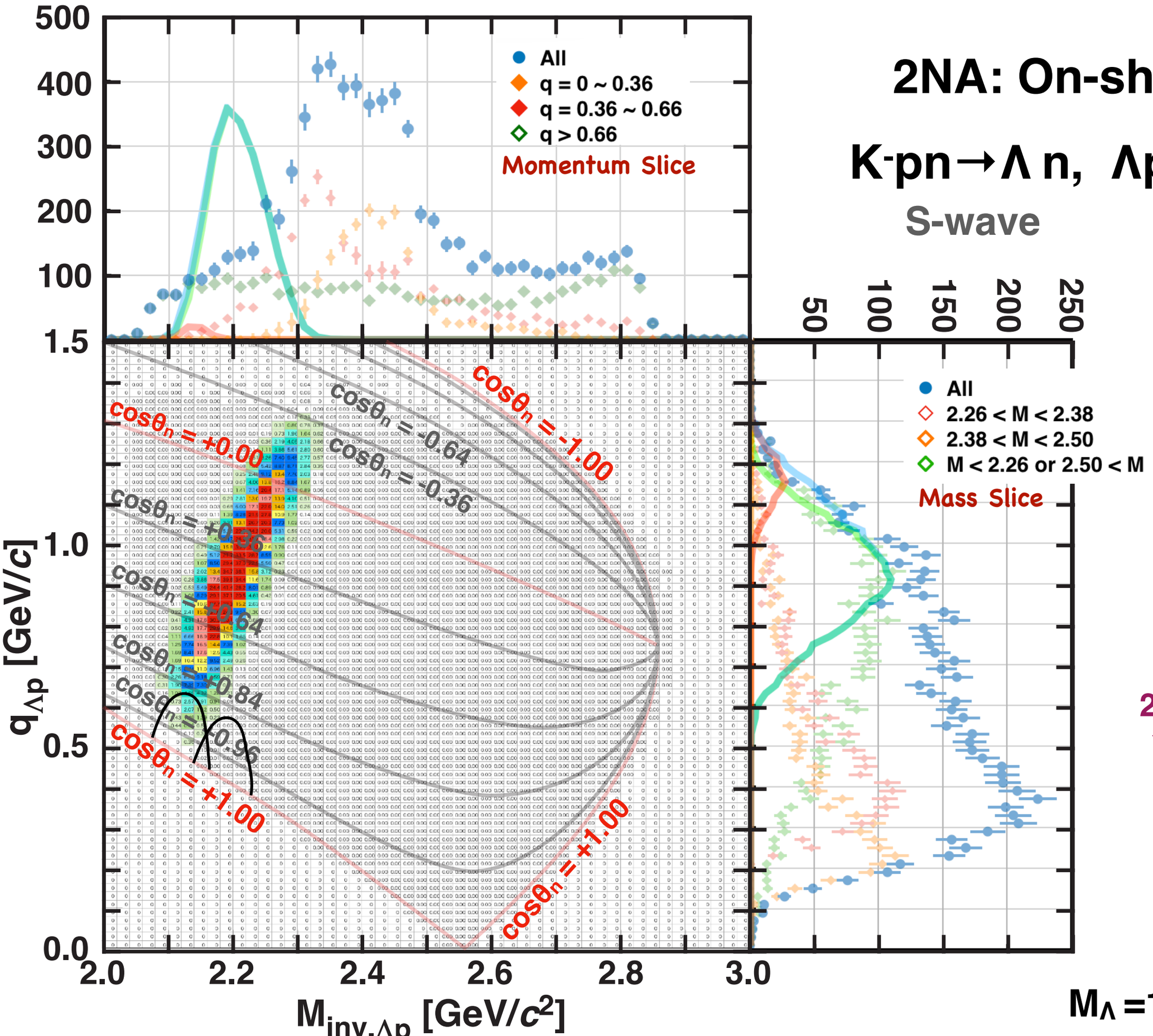
counts	color
24.2	
20	
16.2	
12.8	
9.8	
7.2	
5	
3.2	
1.8	
0.8	
0.2	
0	

M_Σ =1193 MeV/c²

2NA: On-shell Λ

$K^- pn \to \Lambda n$, $\Lambda p \to \Lambda p$

S-wave



2 parameters
width + yield

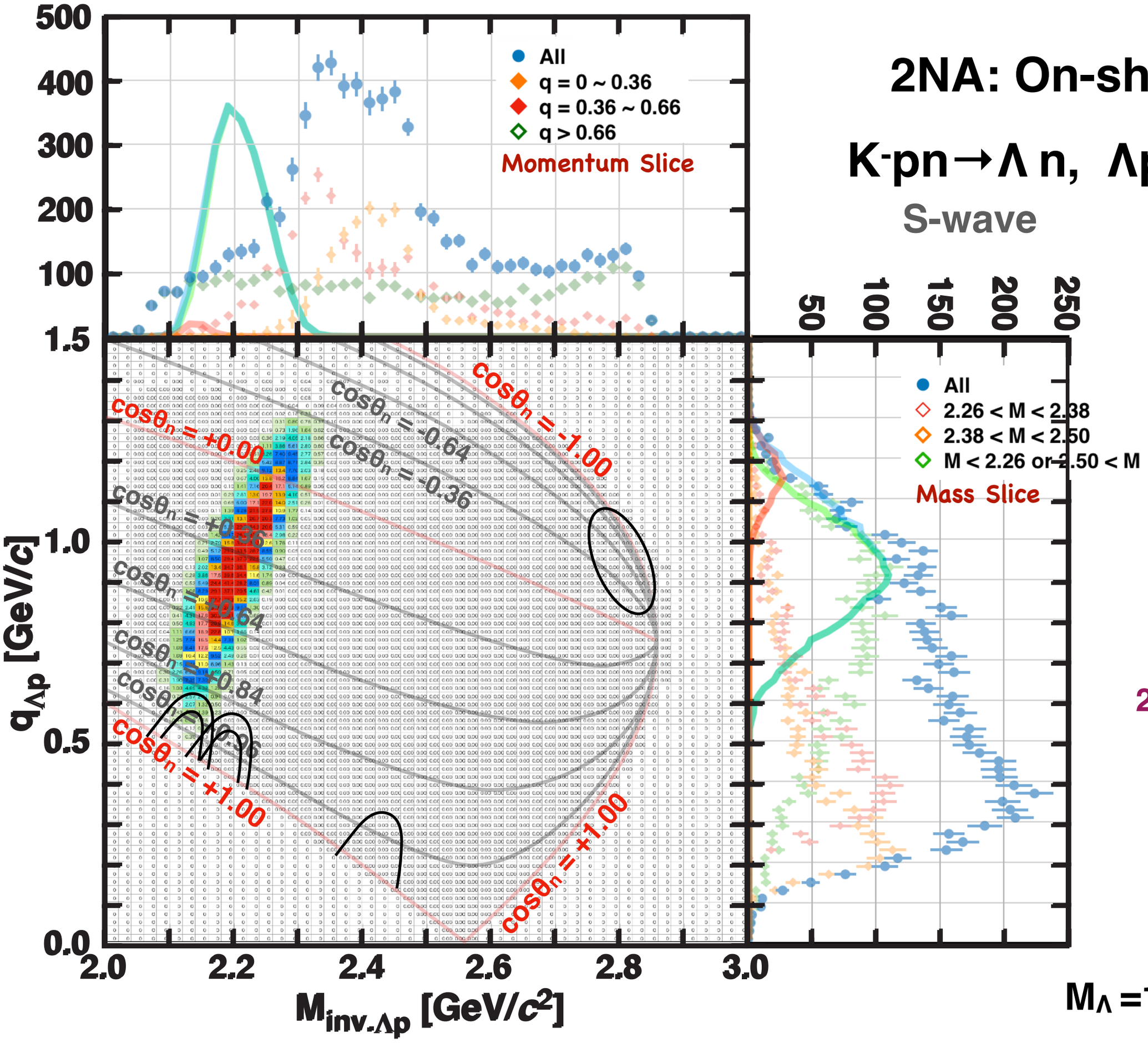
counts	color
24.2	
20	
16.2	
12.8	
9.8	
7.2	
5	
3.2	
1.8	
0.8	
0.2	
0	

M_Λ =1115 MeV/c²

2NA: On-shell Λ

$K^- pn \to \Lambda n$, $\Lambda p \to \Lambda p$

S-wave



2 parameters
width + yield

counts	color
24.2	
20	
16.2	
12.8	
9.8	
7.2	
5	
3.2	
1.8	
0.8	
0.2	
0	

M_Λ =1115 MeV/c²