Seminar at RCNP, Osaka University
7-9 March, 2019

How are hadrons formed from quarks?

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Part I: Introduction

Part II: Experimental Study of Hadrons

II-1: Λ(1405) and $K^{bar}N$ Interaction

II-2: Charmed Baryons

Form of Hadrons

Observable	Relevant Physics Quantity	What we learn	
Mass Spectrum	Mass, Width (pole: $M_R - i\Gamma/2$)	Particle state Resonant state	Classification
Angular Correl. (decay)	Spin, Parity		
Level structure		Internal (effective) DoF	Form (Dynamics of effective DoF in Hadron)
Production Rate (Diff. Cross Sect.)	Response Function (Transition) Form Factor	Reaction Mechanism Internal Motion/Corr.	
Partial Width	Internal Correlation (Wave function)	Decay Mechanism Internal Motion/Corr.	

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Part I: Introduction

I-1: Standing Point of this Lecture

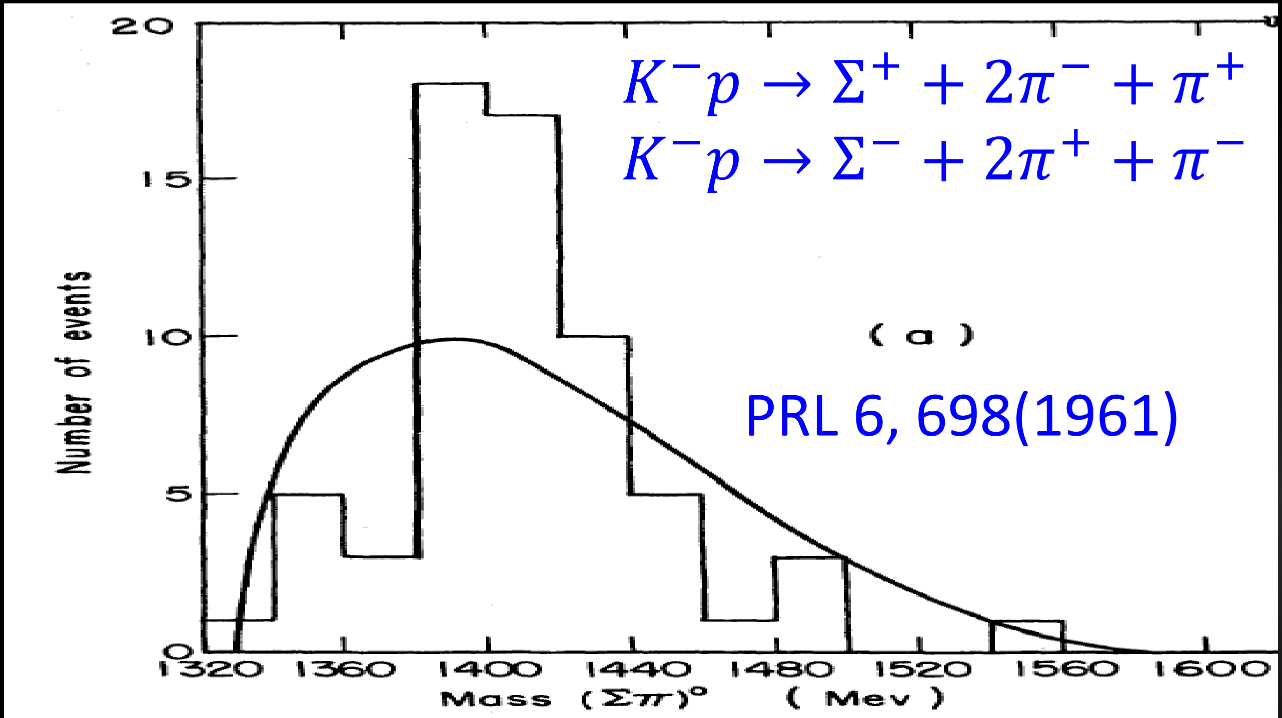
I-2: Basic Introduction of Hadrons

Part II: Experimental Study of Hadrons

II-1: Λ(1405) and $K^{bar}N$ Interaction

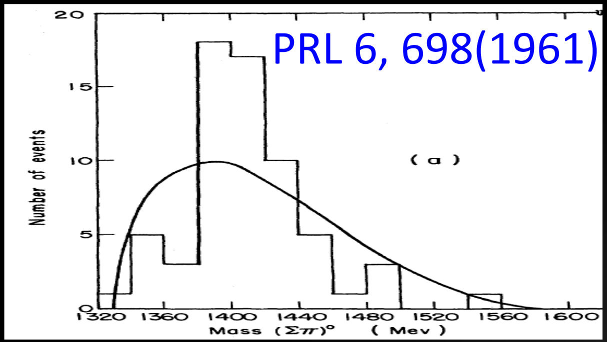
II-2: Charmed Baryon and diquark correlation

$\Lambda(1405)$ since 1961



- Well-known lightest Hyperon Resonance w/ a negative parity

Λ(1405) since 1961

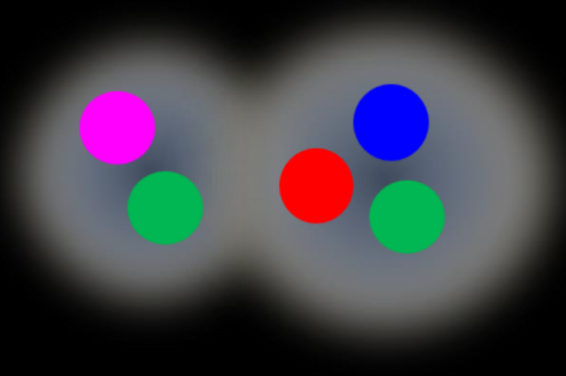


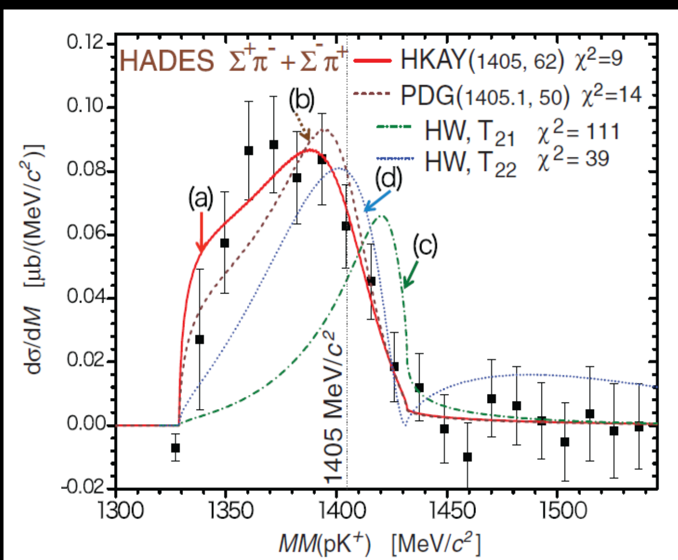
- $K^{bar}N$ int. and its pole position are still unclear.
  - Basic information on Kaonic Nuclei
- Not yet demonstrated if it is a molecular state.
  - To establish it as an exotic state
    - Hadron Picture in excited states
    - New question related to classification in CQM
  - Formation probability in hadronization
    - ExHIC (Phys.Rev. C84 (2011) 064910)

Important to study Low Energy $K^{bar}N$ scattering

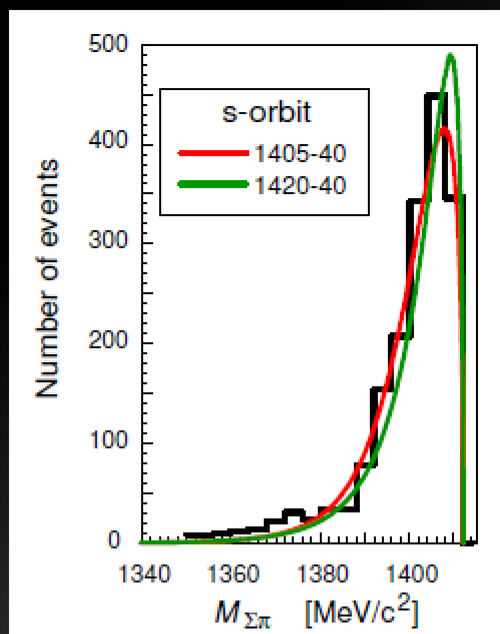
$\Lambda(1405)$: $1405.1^{+1.3}_{-0.9}$ MeV (PDG in 2019)

$J^P = \frac{1}{2}^-$, $I = 0$, $M_{\Lambda(1405)} < M_{\bar{K}N}$, lightest in neg. parity baryons

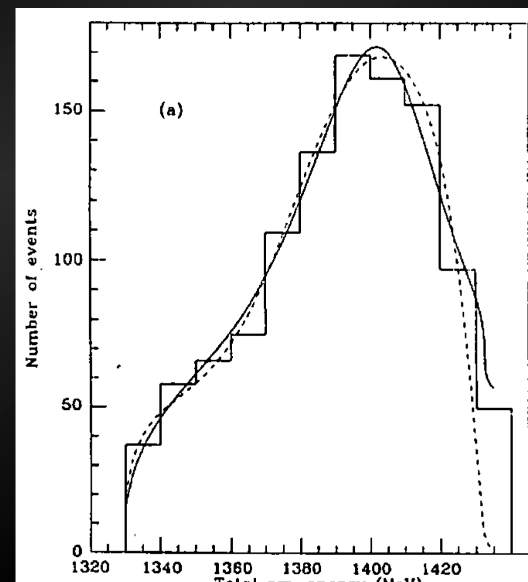




M. Hassanvand et al: πΣ IM Spec. of pp→K⁺πΣ



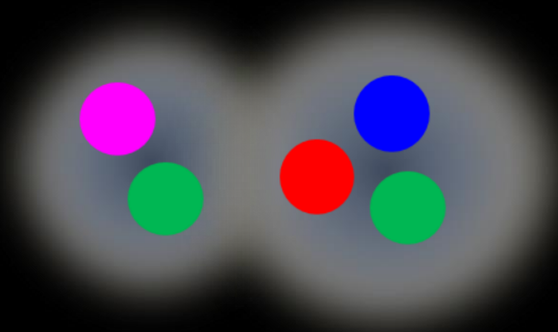
J. Esmaili et al: πΣ IM Spec. of Stopped K⁻ on ⁴He

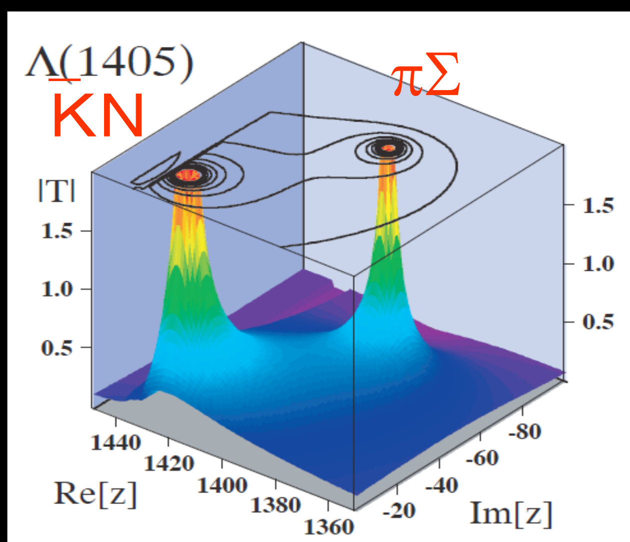


R.H. Dalitz et al: πΣ IM Spec. in K-p→ππΣ w/ M-matrix

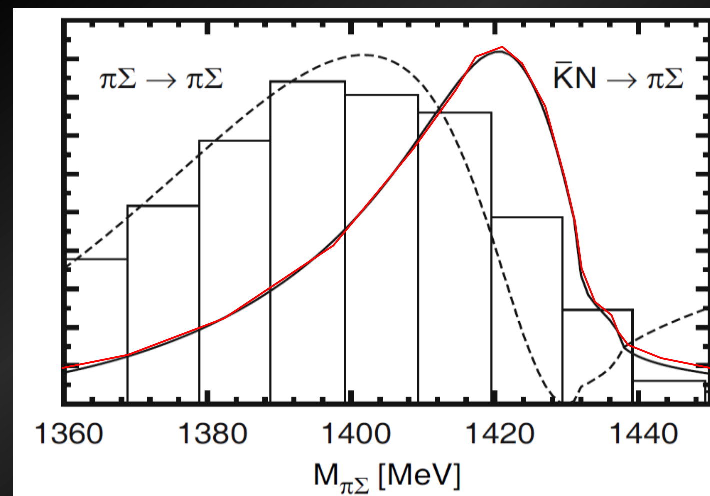
Λ(1405) : Double pole?

$J^P = \frac{1}{2}^-$, $I = 0$, $M_{\Lambda(1405)} < M_{\bar{K}N}$, lightest in neg. parity baryons





ChU model, T. Hyodo



Chiral Unitary Model:
D. Jido et al., NPA725(03)181

Pole Structure of the Lambda(1405) Region

PDG Reviews: Ulf-G. Meissner and T. Hyodo (Nov. 2015)

Table 1: Comparison of the pole positions of $\Lambda(1405)$ in the complex energy plane from next-to-leading order chiral unitary coupled-channel approaches including the SIDDHARTA constraint.

approach	pole 1 [MeV]	pole 2 [MeV]
Refs. 11,12, NLO	$1424^{+7}_{-23} - i\,26^{+3}_{-14}$	$1381^{+18}_{-6} - i\,81^{+19}_{-8}$
Ref. 14, Fit II	$1421^{+3}_{-2} - i\,19^{+8}_{-5}$	$1388^{+9}_{-9} - i\,114^{+24}_{-25}$
Ref. 15, solution #2	$1434^{+2}_{-2} - i\,10^{+2}_{-1}$	$1330^{+4}_{-5} - i\,56^{+17}_{-11}$
Ref. 15, solution #4	$1429^{+8}_{-7} - i\,12^{+2}_{-3}$	$1325^{+15}_{-15} - i\,90^{+12}_{-18}$

$\Lambda(1405)$: $1405.1^{+1.3}_{-1.0}$ MeV (Part. Listing in '19)

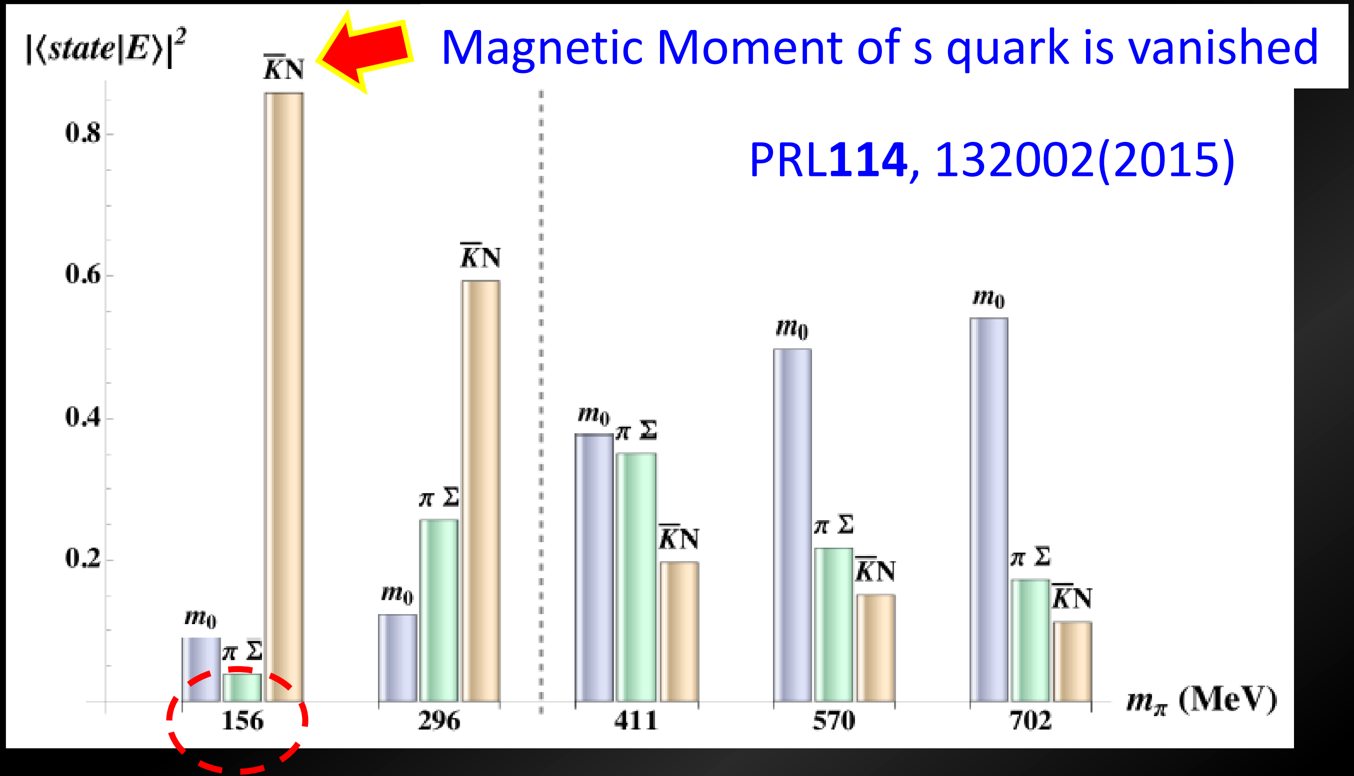
$J^P = \frac{1}{2}^-$, $I = 0$, $M_{\Lambda(1405)} < M_{\bar{K}N}$, lightest in neg. parity baryons

M. Hassanvand et al: $\pi\Sigma$ IM Spec. of $pp \rightarrow K^+\pi\Sigma$

J. Esmaili et al: $\pi\Sigma$ IM Spec. of Stopped K^- on ^4He

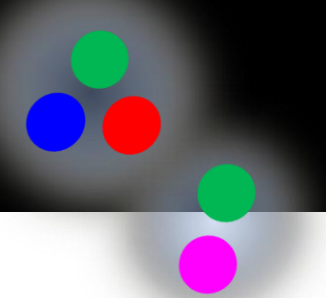
R.H. Dalitz et al: $\pi\Sigma$ IM Spec. in $K^-p \rightarrow \pi\pi\Sigma$ w/ M-matrix

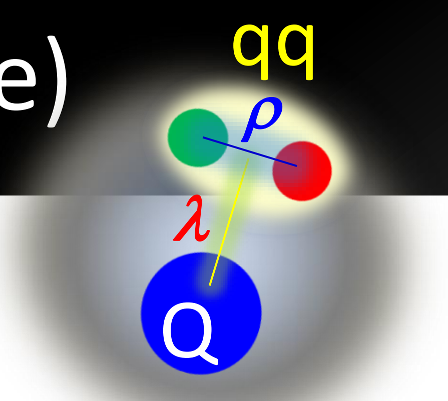
LQCD Evidence that $\Lambda(1405)$ is a $K^{bar}N$ molecule

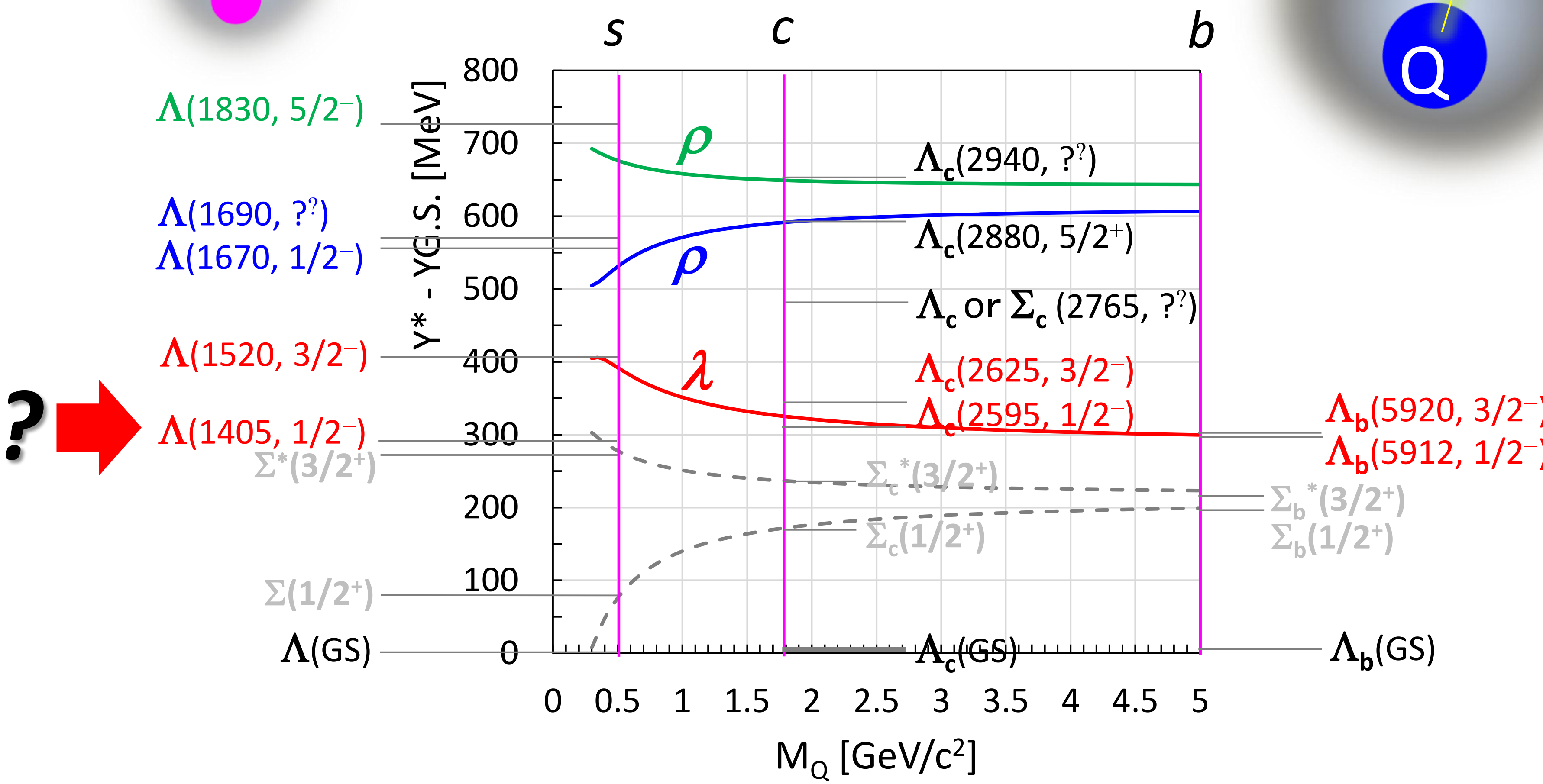


- Study of $K^{bar}N$ scattering below the $K^{bar}N$ thres. are important.

Lambda Baryons (P-wave)





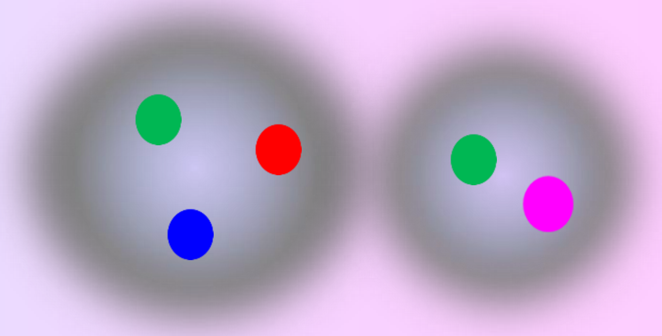


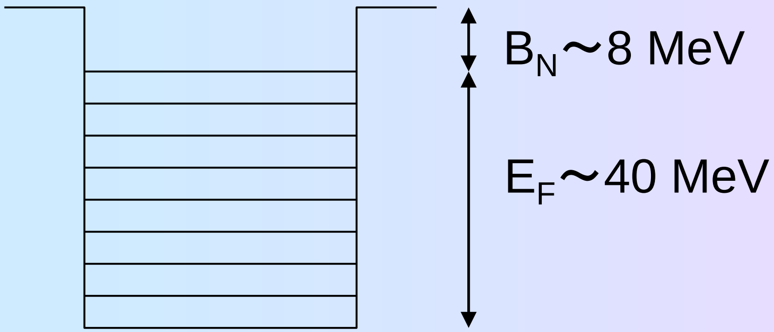
non-rel. QM: $H=H_0+V_{conf}+V_{SS}+V_{LS}+V_T$
ρ–λ mixing (cal. By T. Yoshida)

T. Yoshida et al.,
Phys. Rev. D**92**, 114029(2015)

If Λ(1405) is deeply bound $K^{bar}N$ state...

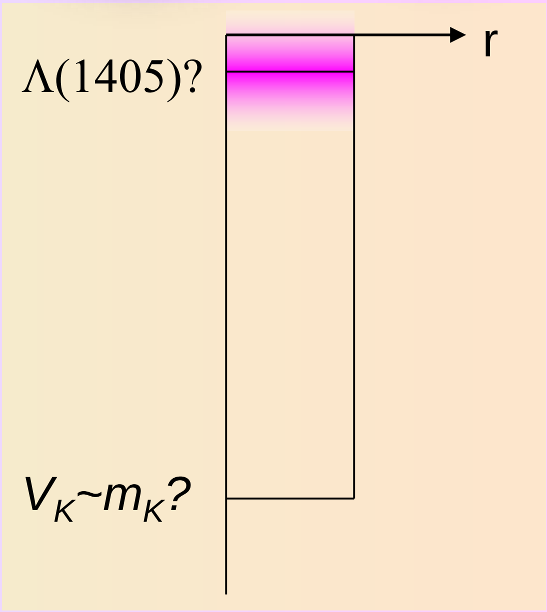
$K^{bar}N$ molecule?





Nuclear Potential

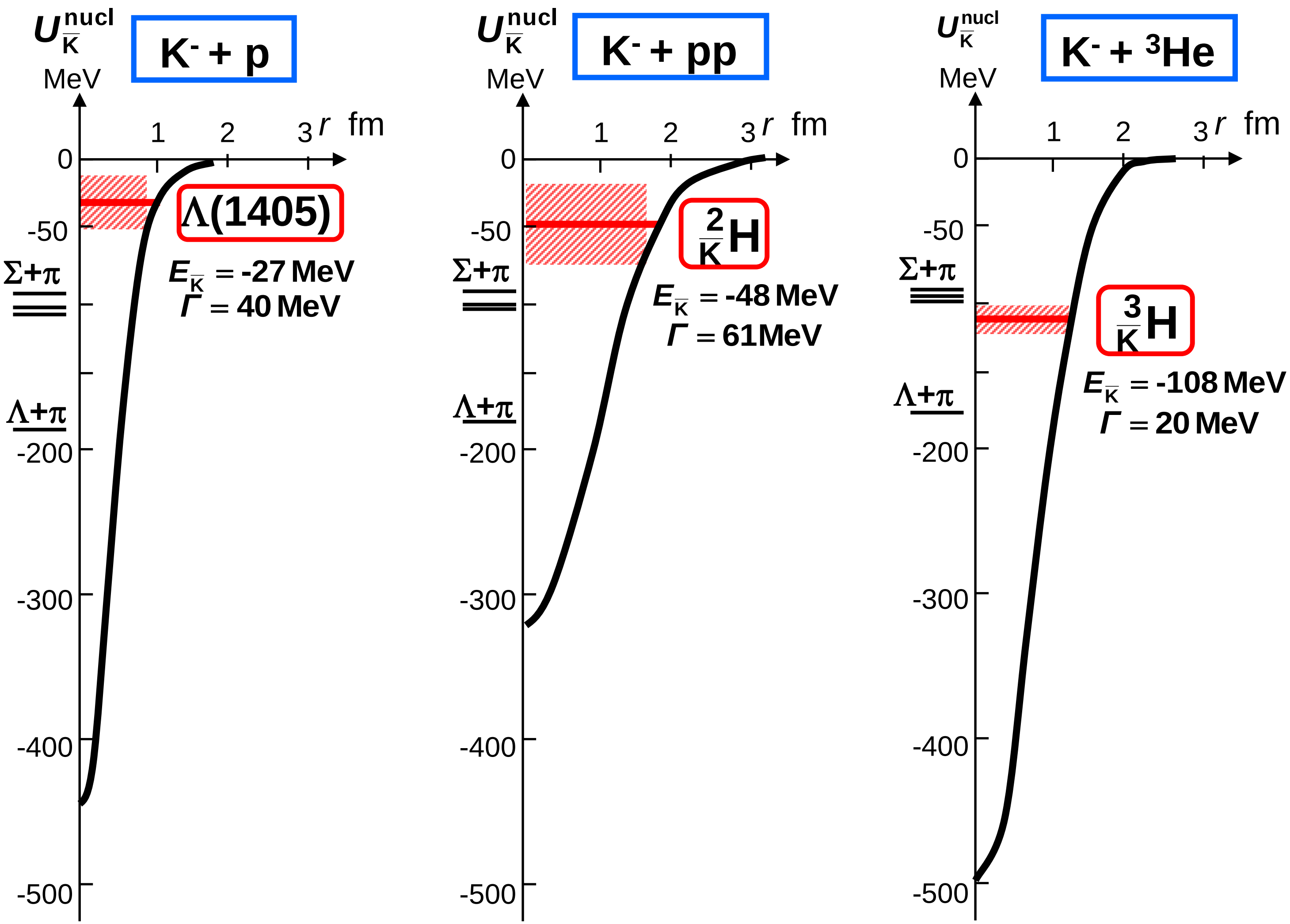
50 MeV



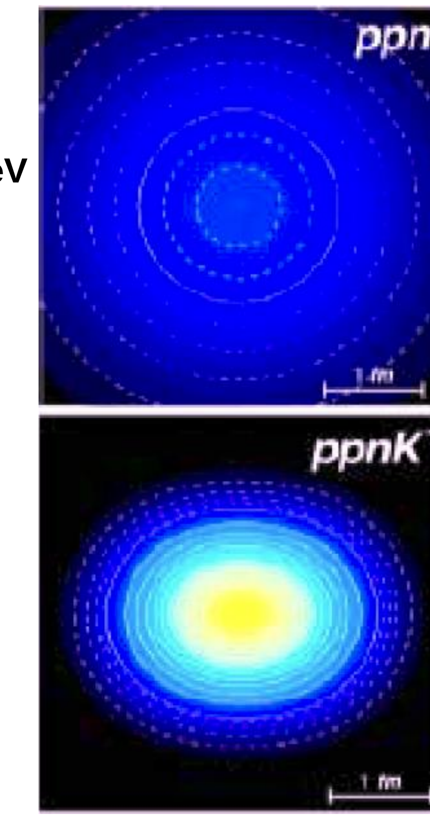
500 MeV !

Deeply Bound K^--Nucleus System ?

Kp散乱長を再現



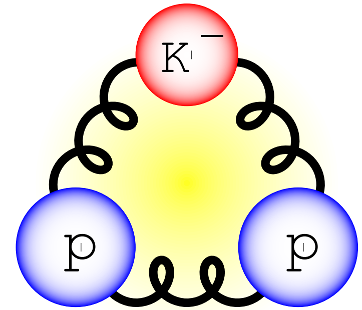
Dote et al.

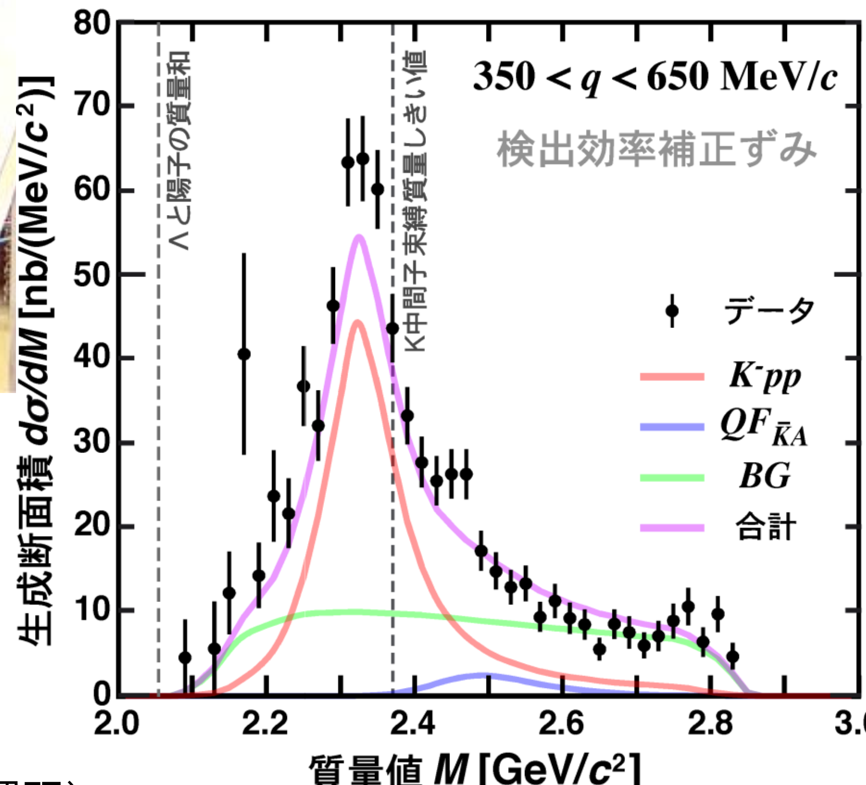


Y. Akaishi & T. Yamazaki, Phys. Rev. C65 (2002) 044005.

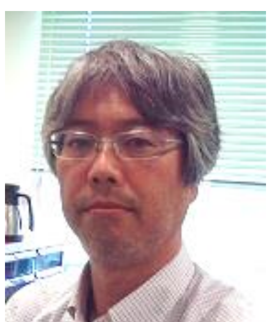
Y. Akaishi & T. Yamazaki, Phys. Lett. B535 (2002) 70.

クォークと反クォークが共存する奇妙な原子核の発見





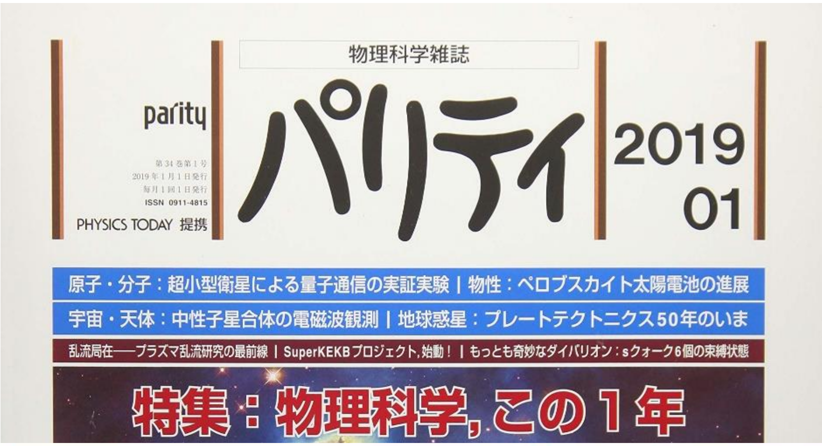

岩崎（理研）


野海（阪大）


山我（阪大→理研）

クォークと反クォークが共存する奇妙な原子核の発見

- 大阪大学博士論文（理学）山我拓巳　2018年6月
- Physics Letters B789(2019)620　2019年2月
  （オンライン出版2018年12月）
- 雑誌パリティ1月号　岩崎、野海
- プレスリリース　1月24日
  （理研，阪大，J-PARC，KEK，JAEA，東北大，INFN，SMI）



原子核物理

クォークと反クォークが共存する原子核：K中間子核の世界

岩﨑雅彦，野海博之

原子核は有限個の核子（陽子や中性子の総称）の集合体である。湯川秀樹は，核内に核子をつなぎ止める“糊”として中間子の存在を予言した。“糊”として核内を満たす中間子は，“力の場”（原子核ポテンシャル）を形成し，核子を束縛させ，原子核をつくる。この中間子は不確定性原理に従って現れては消える“仮想粒子”であ

Physics Letters B 789 (2019) 620–625

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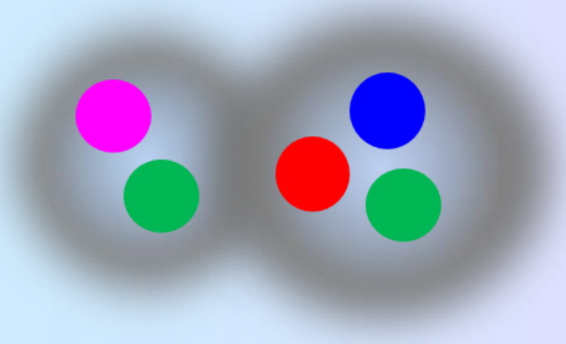
“K^-pp”, a $\bar{K}$-meson nuclear bound state, observed in ^{3}He$(K^-, \Lambda p)n$ reactions

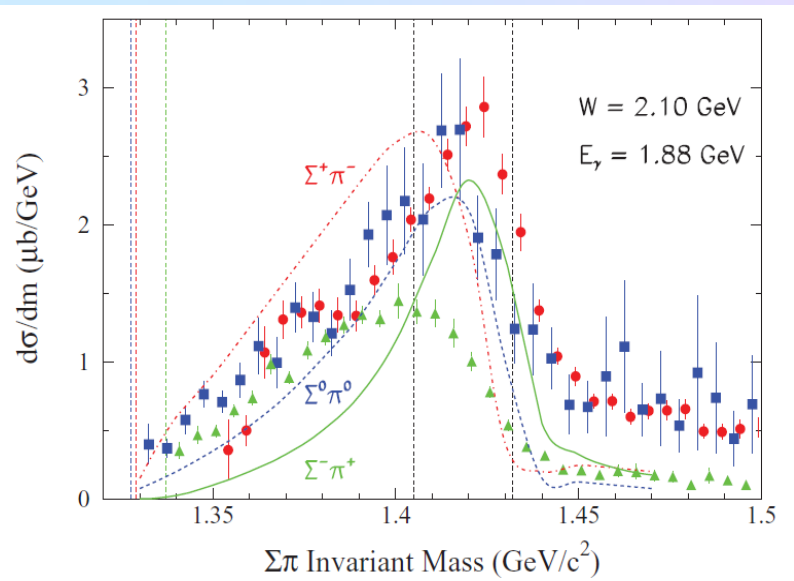
J-PARC E15 collaboration, S. Ajimura[a], H. Asano[b], G. Beer[c], C. Berucci[d], H. Bhang[e], M. Bragadireanu[f], P. Buehler[d], L. Busso[g,h], M. Cargnelli[d], S. Choi[e], C. Curceanu[i], S. Enomoto[j], H. Fujioka[k], Y. Fujiwara[l], T. Fukuda[m], C. Guaraldo[i], T. Hashimoto[n], R.S. Hayano[l], T. 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,1], 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]

Λ(1405) : Controversial Experimental Data?

$J^P = \frac{1}{2}^-$, $I = 0$, $M_{\Lambda(1405)} < M_{\bar{K}N}$, lightest in neg. parity baryons

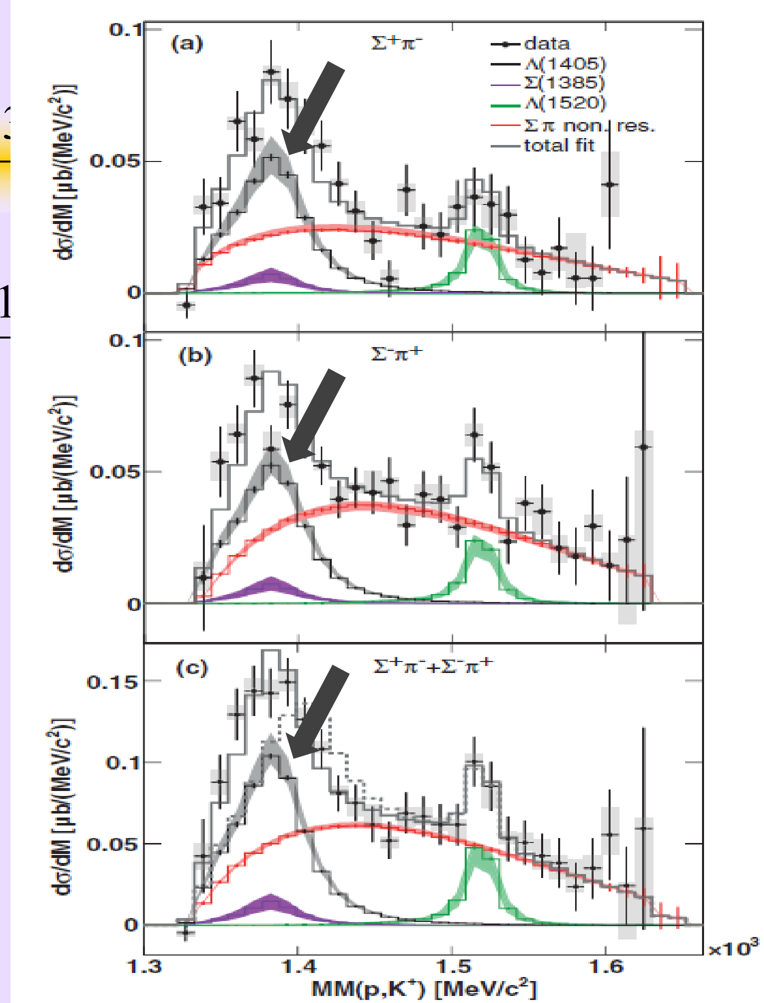


$\gamma p \rightarrow K^+\pi^-\Sigma^+, K^+\pi^0\Sigma^0, K^+\pi^+\Sigma^-$



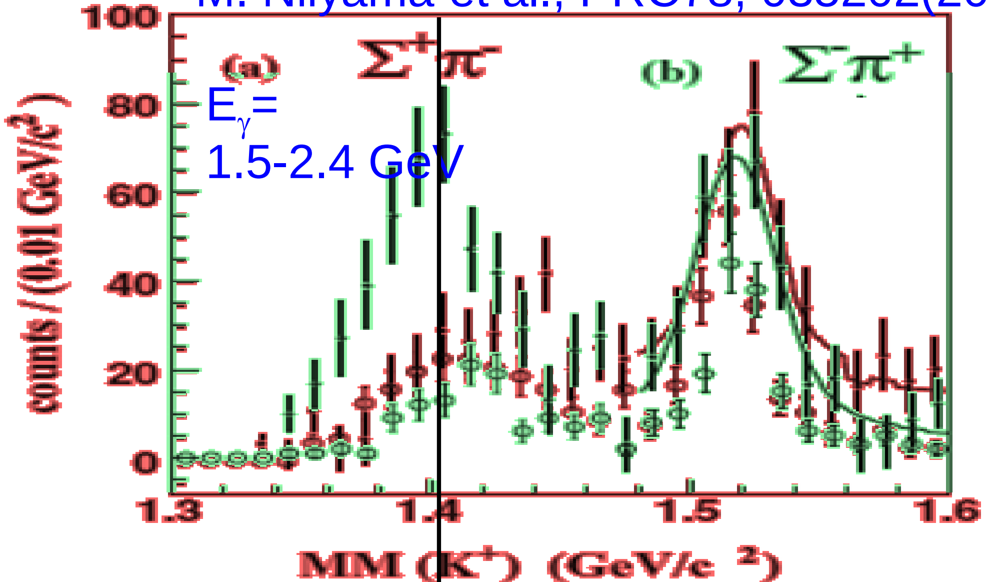
CLAS collaboration: PRC87, 035206

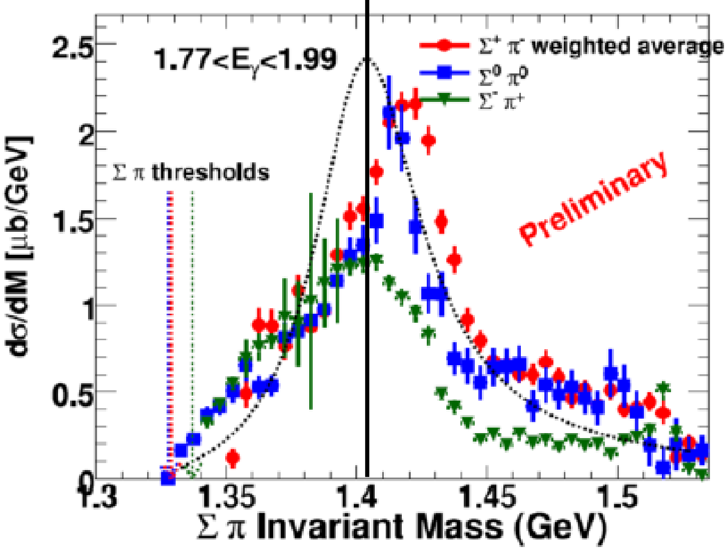
$pp \rightarrow K^+p\pi^-\Sigma^+, K^+p\pi^+\Sigma^-$



HADES collaboration: PRC87, 025201

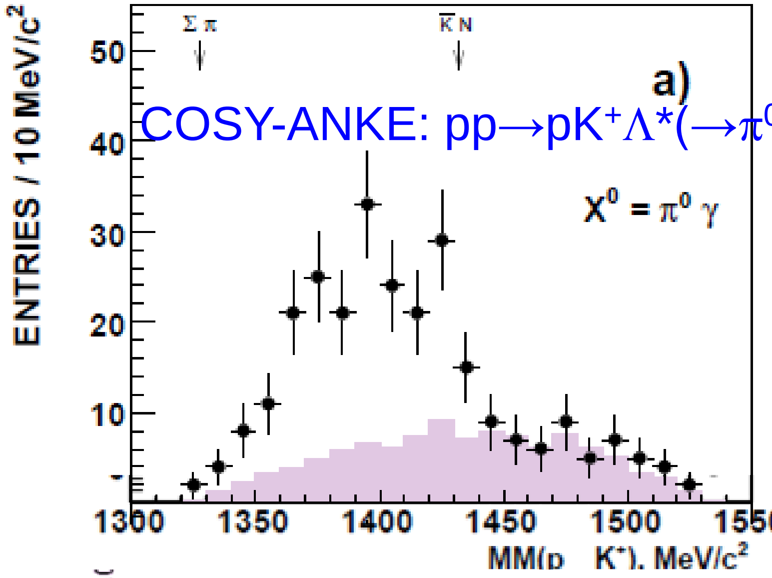
LEPS:
M. Niiyama et al., PRC78, 035202(2008)

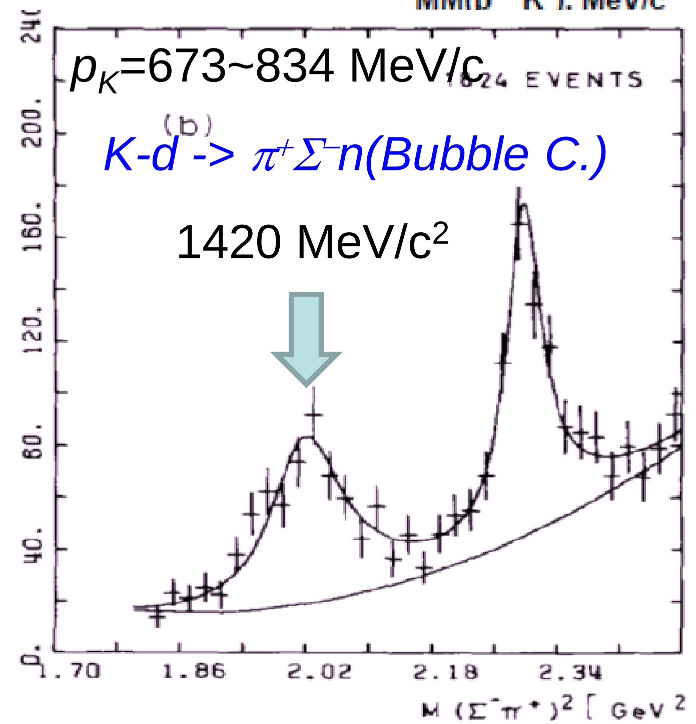




CLAS:
K. Moriya et al., NPA835, 325(2010)

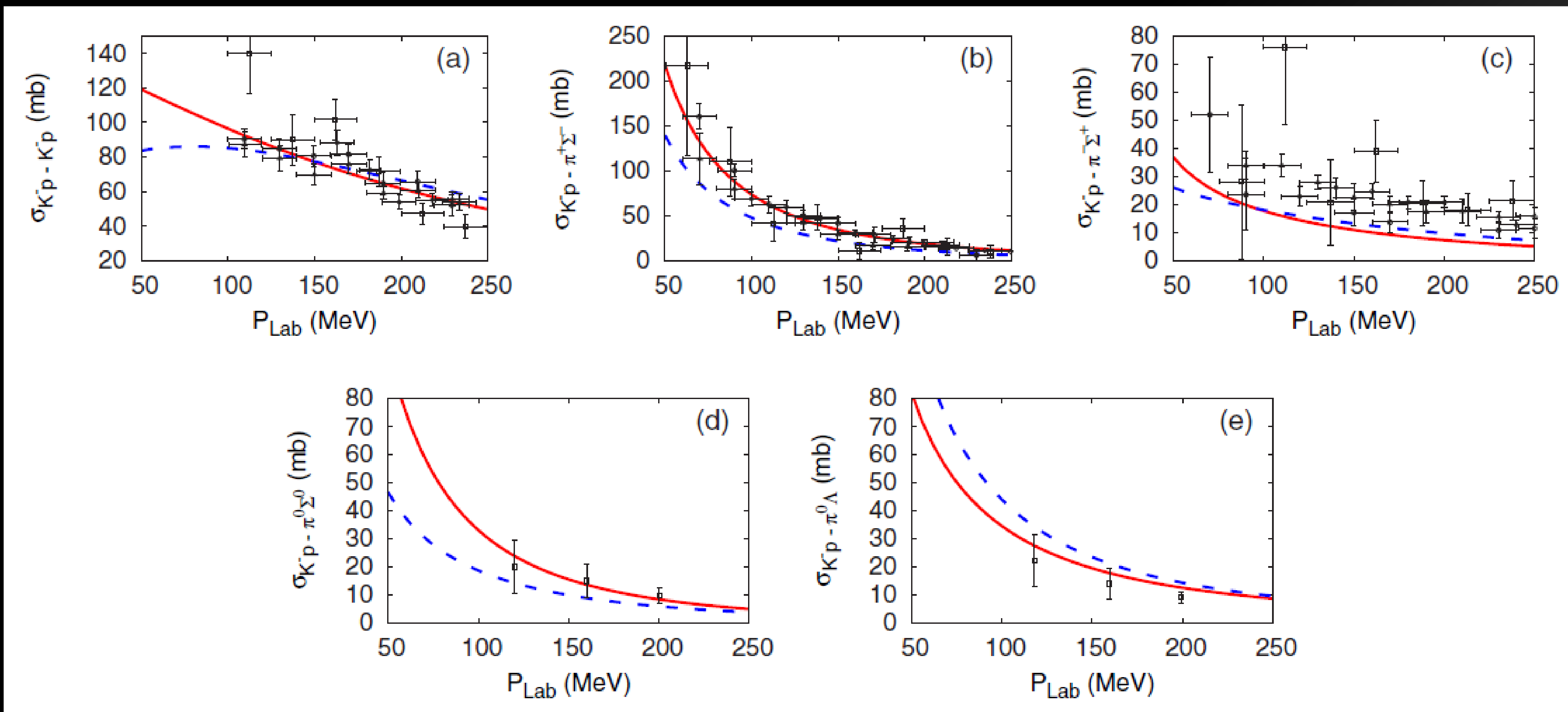
I. Zychor et al. PLB660, 167(2008)





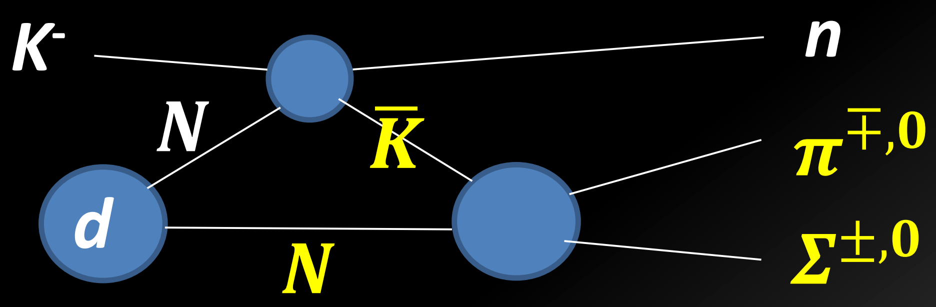
O. Braun et al., NPB129, 1(1977)

$K^{-}p$ scattering data



$K^{bar}N$ scattering below the $K^{bar}N$ thres. (J-PARC E31)

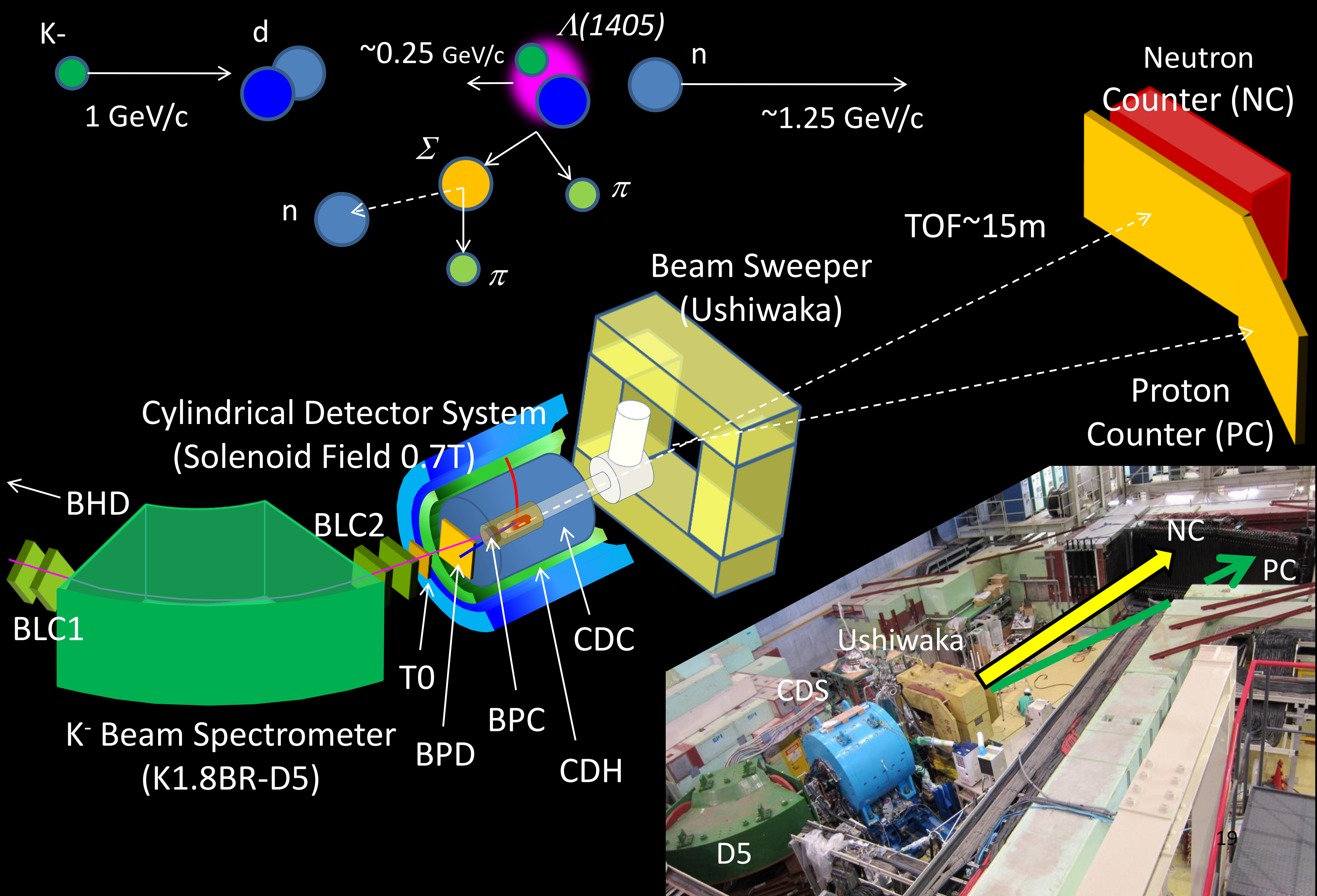
- measuring an *S*-wave $\bar{K}N \to \pi\Sigma$ scattering below the $\bar{K}N$ threshold in the $d(K^-,n)\pi\Sigma$ reactions at a forward angle of *n*.



- ID's all the final states to decompose the I=0 and 1 ampl's.

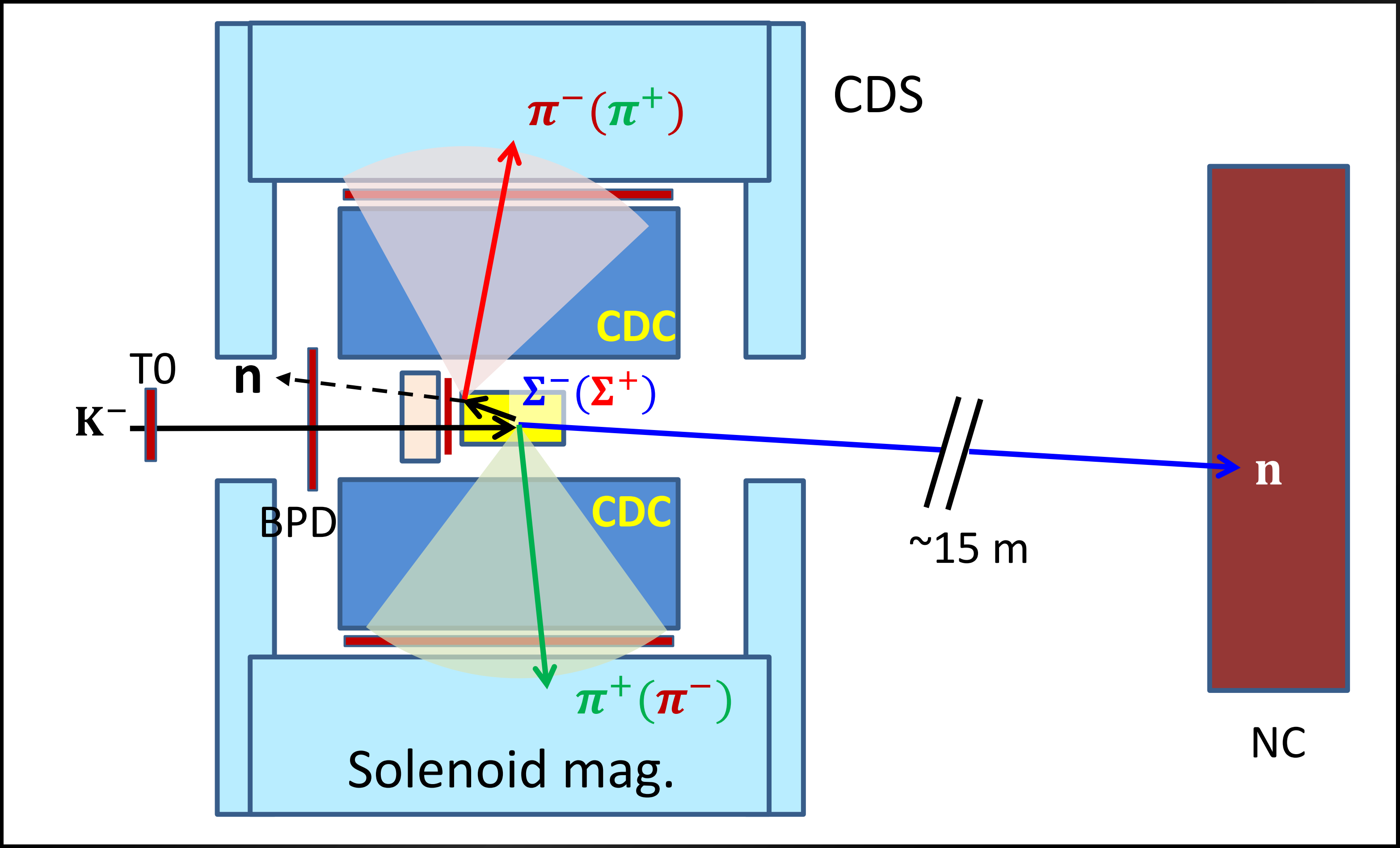
$\pi^{\pm}\Sigma^{\mp}$	**I=0, 1**	**Λ(1405) (I=0, S wave),** non-resonant[I=0/1] **(Σ(1385) (I=1, P wave) to be suppressed)**
$\pi^{-}\Sigma^{0}$ $[\pi^{-}\Lambda]$	I=1	non-resonant (Σ(1385) to be suppressed) $d(K^-,p)\pi^-\Sigma^0$ $[\pi^-\Lambda]$
$\pi^{0}\Sigma^{0}$	**I=0**	**Λ(1405) (I=0, S wave)**, non-resonant

Experimental Setup for E31

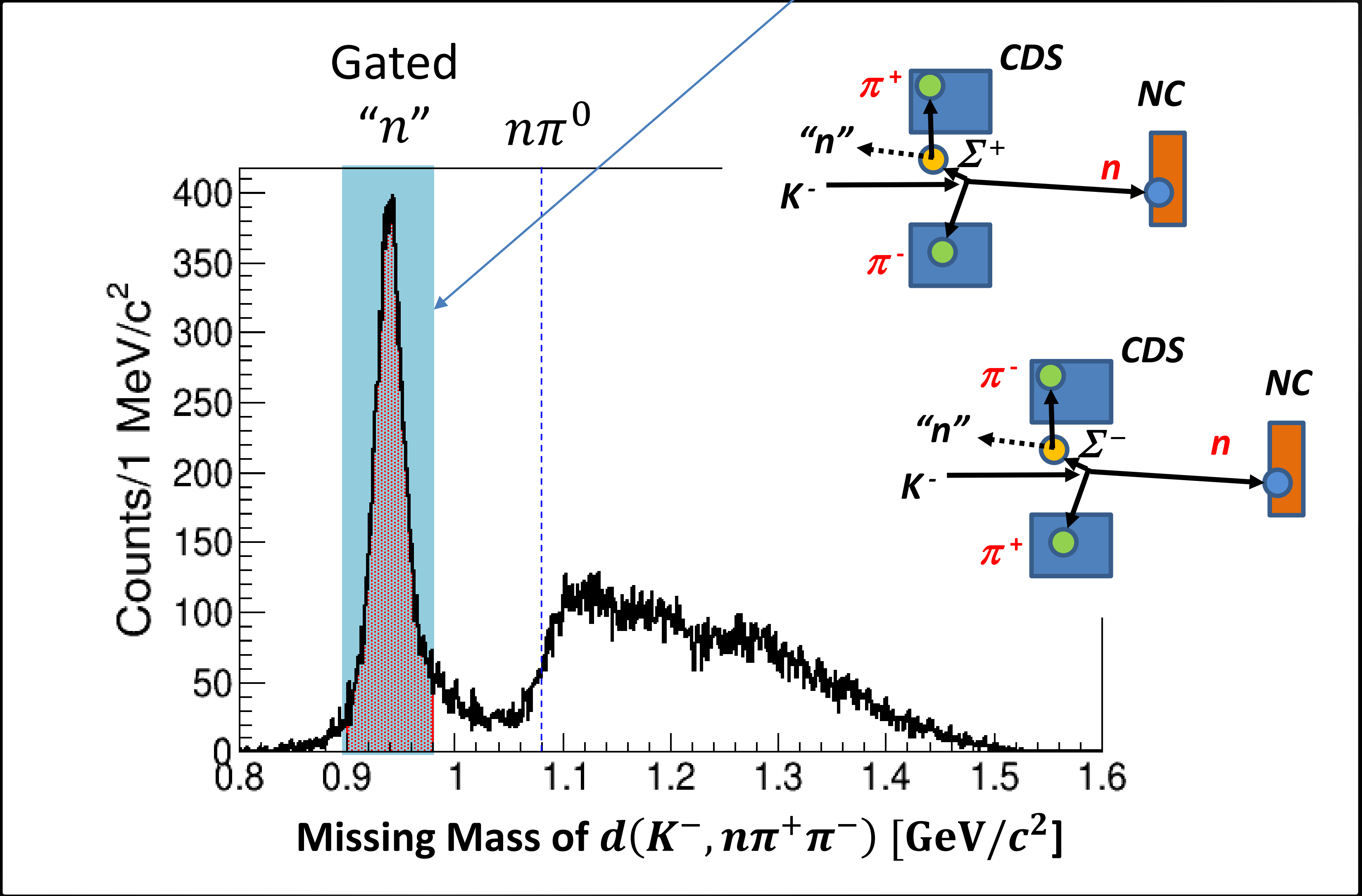


Schematic Drawings of Detectors

- Event topology of $d(K^-, n)X_{\pi^\pm\Sigma^\mp}$



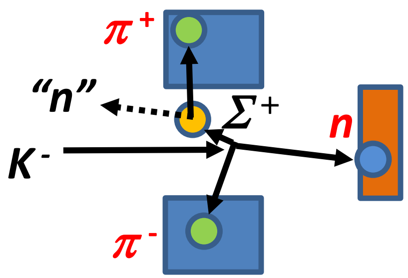
$d(K^-, n\pi^+\pi^-)n_{missing}$

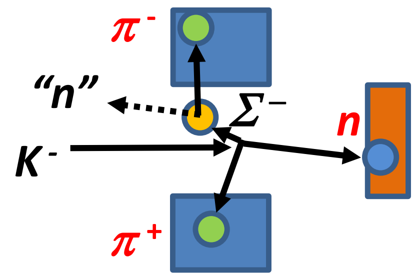


$d(K^-, n\pi^+\pi^-)$"n“ samples contain...

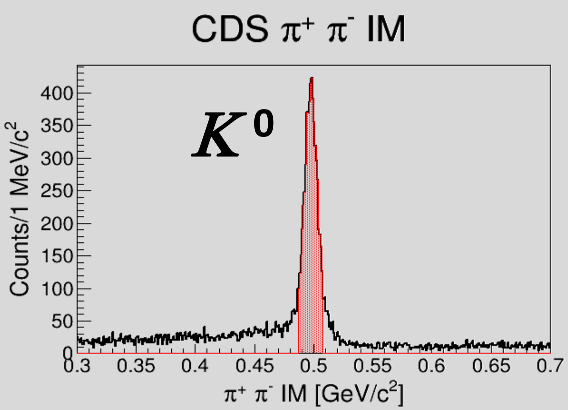
Signal Events

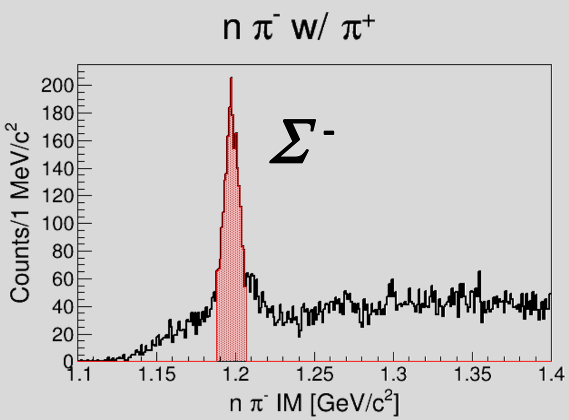
$$d(K^-, n)X_{\pi^\pm\Sigma^\mp}$$

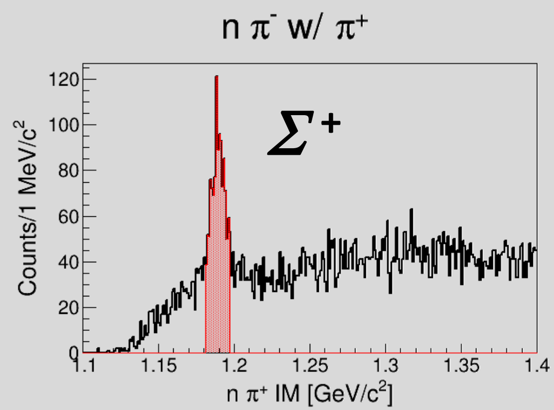


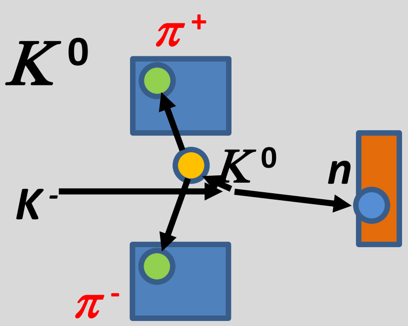


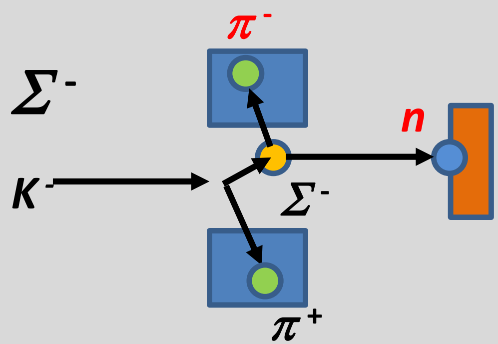
Background Events

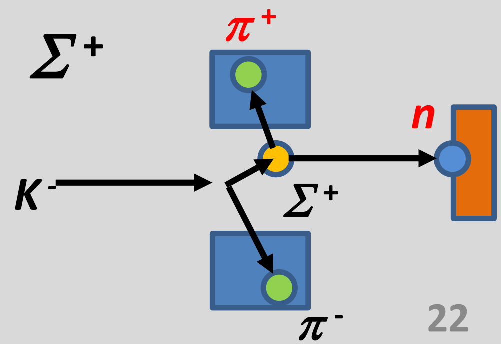


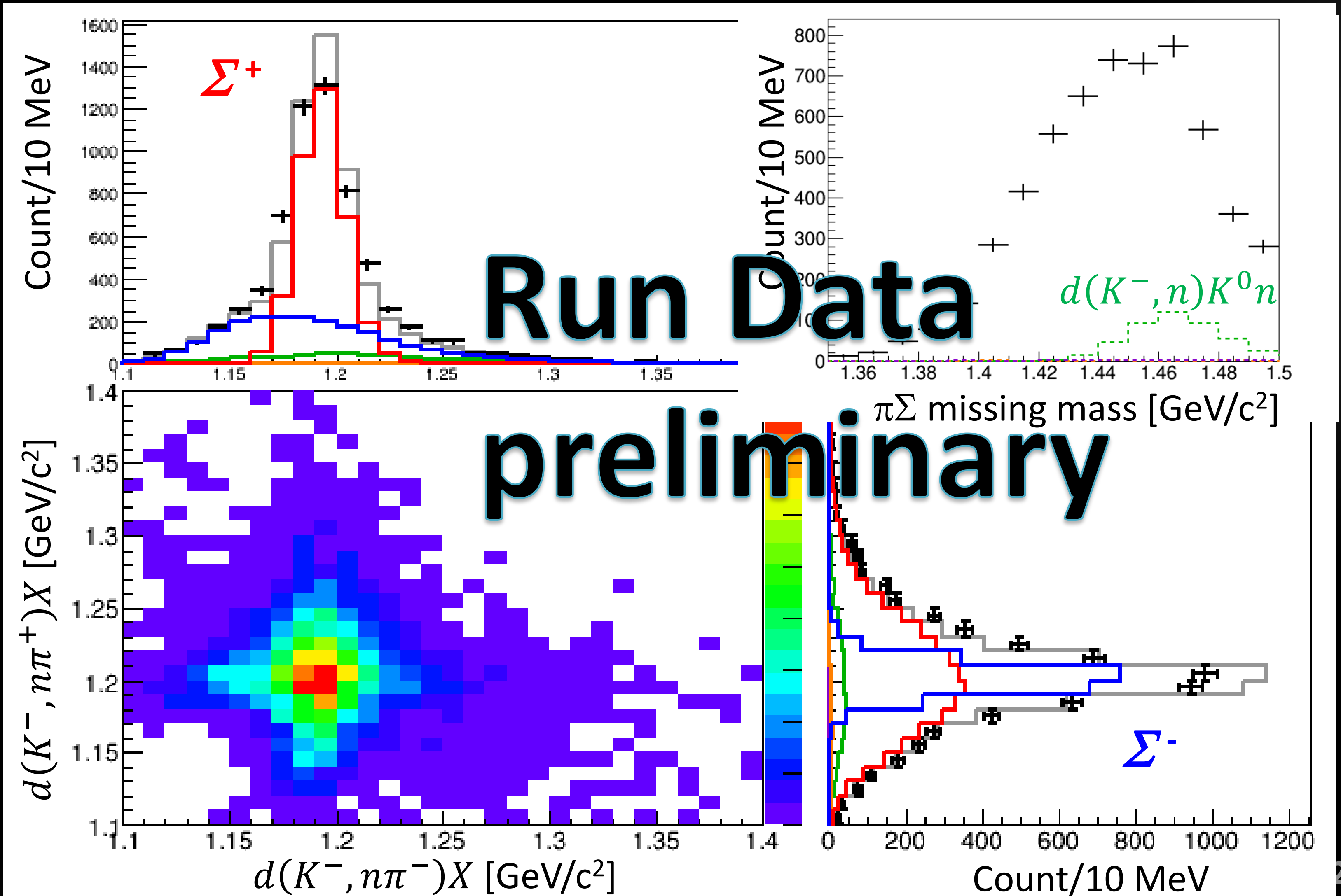








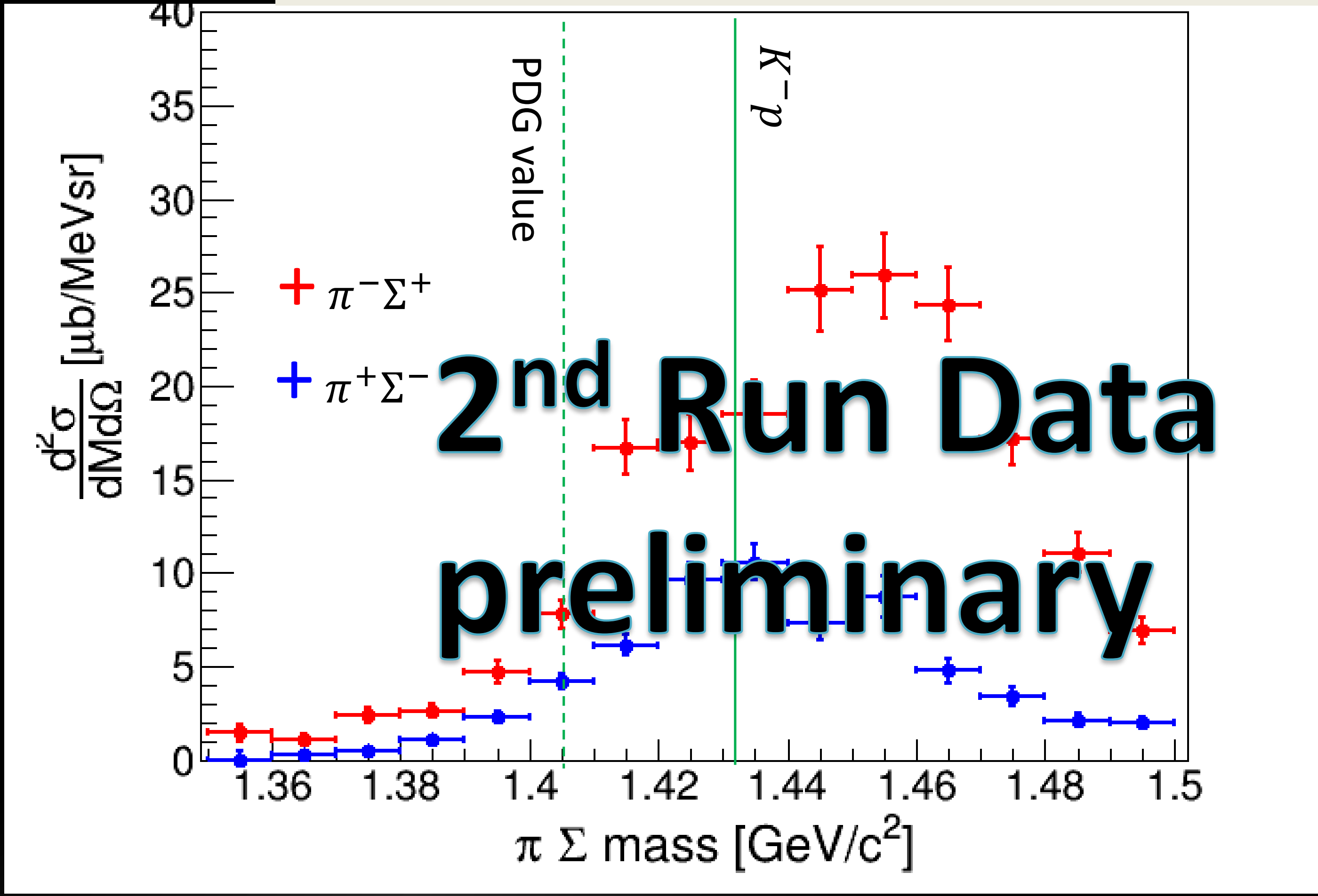




Count/10 MeV
Σ+
Run Data
preliminary
πΣ missing mass [GeV/c2]
d(K−,n)K0n
d(K−,nπ+)X [GeV/c2]
d(K−,nπ−)X [GeV/c2]
Count/10 MeV
Σ-

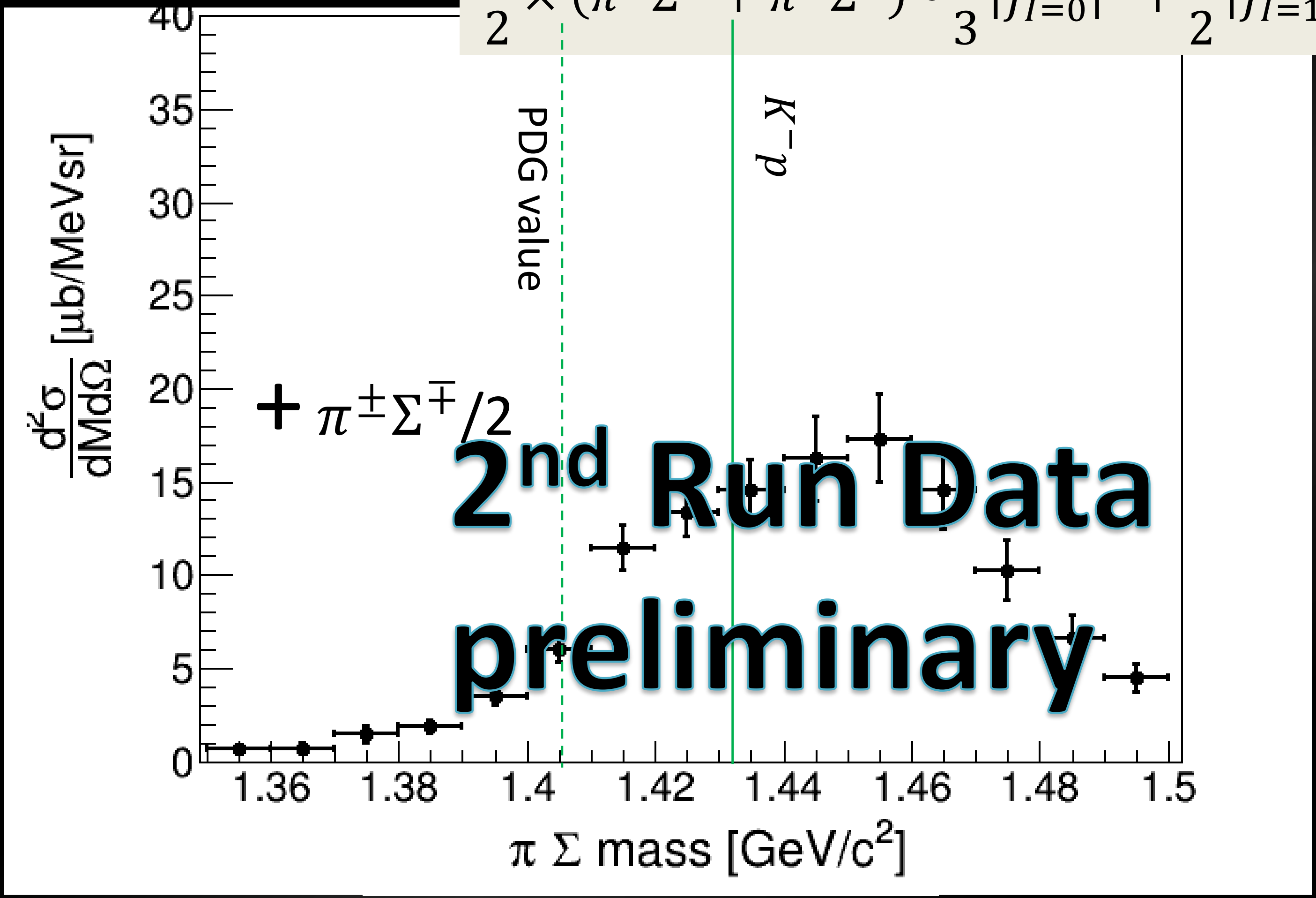
$\pi^+\Sigma^-/\pi^-\Sigma^+$ Mode ($I = 0, 1$)

$$\frac{d\sigma}{d\Omega}(\pi^\pm\Sigma^\mp) \propto \frac{1}{3}|f_{I=0}|^2 + \frac{1}{2}|f_{I=1}|^2 \pm \frac{\sqrt{6}}{3}Re(f_{I=0}f^*_{I=1})$$

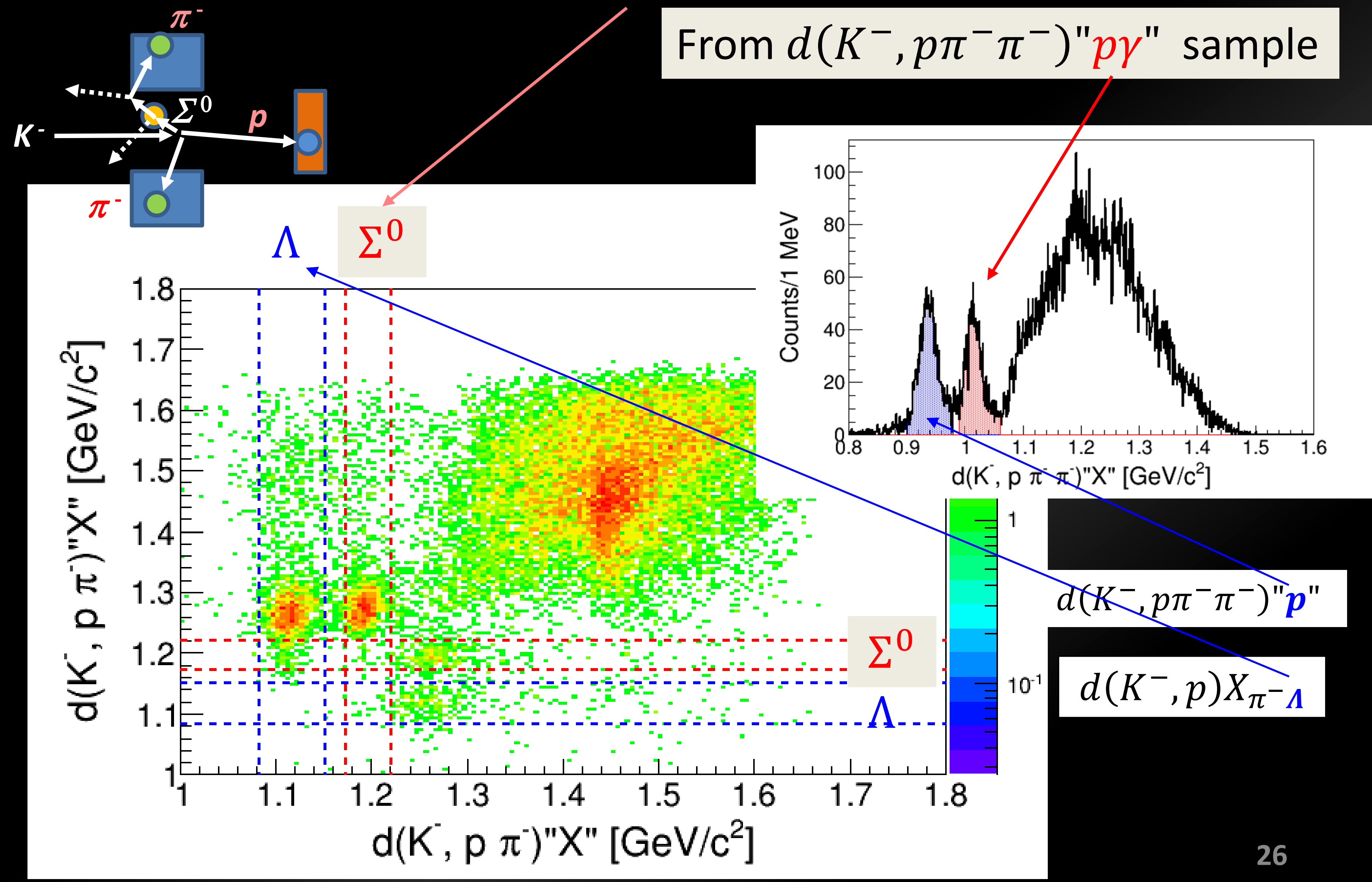


$$\frac{1}{2}\times(\pi^+\Sigma^- + \pi^-\Sigma^+)\ \ (I = 0, 1)$$

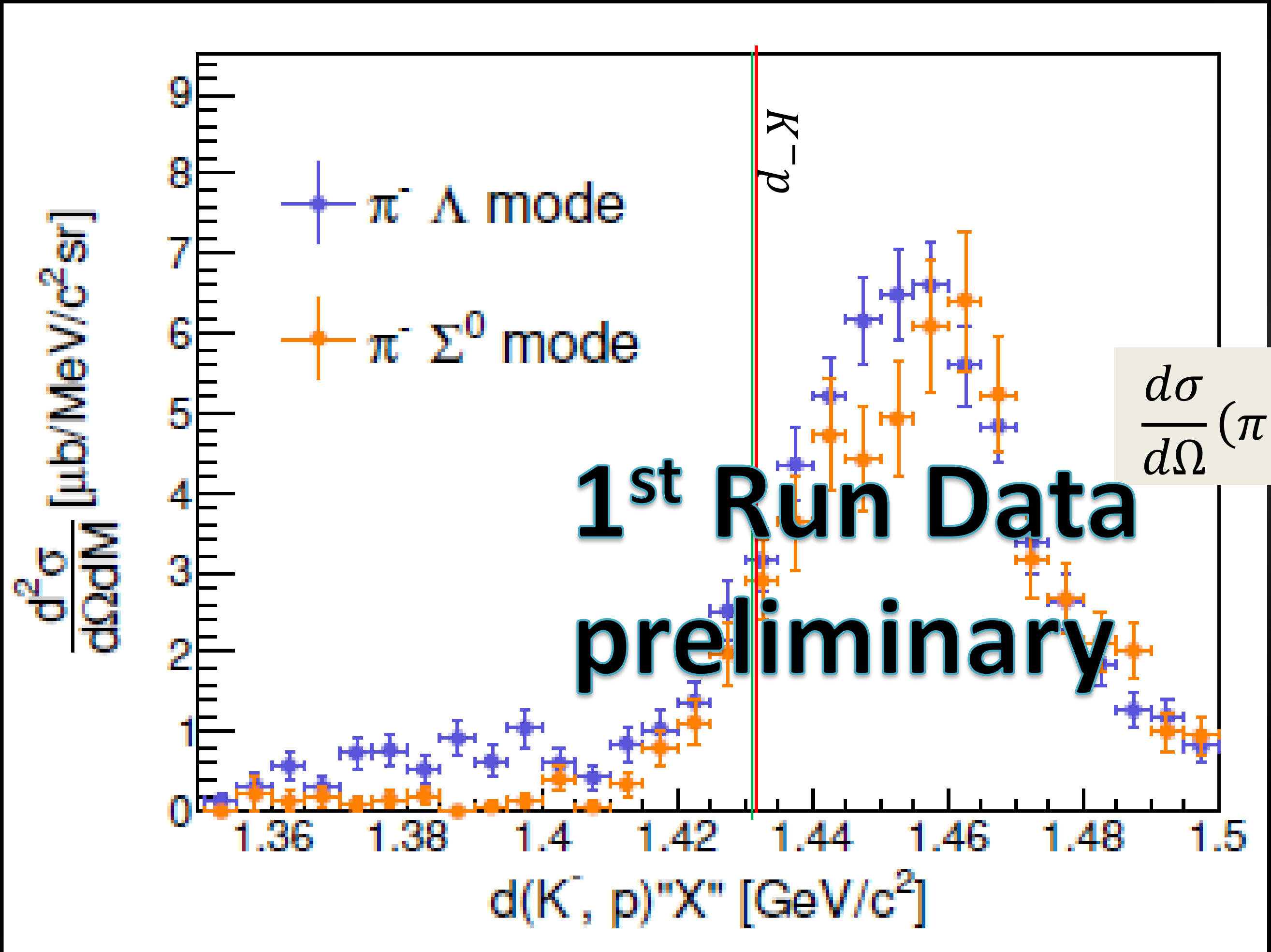
$$\frac{1}{2}\times(\pi^+\Sigma^- + \pi^-\Sigma^+) \sim \frac{1}{3}|f_{I=0}|^2 + \frac{1}{2}|f_{I=1}|^2$$



$d(K^-, p)X_{\pi^-\Sigma^0}$ Mode ($I = 1$)

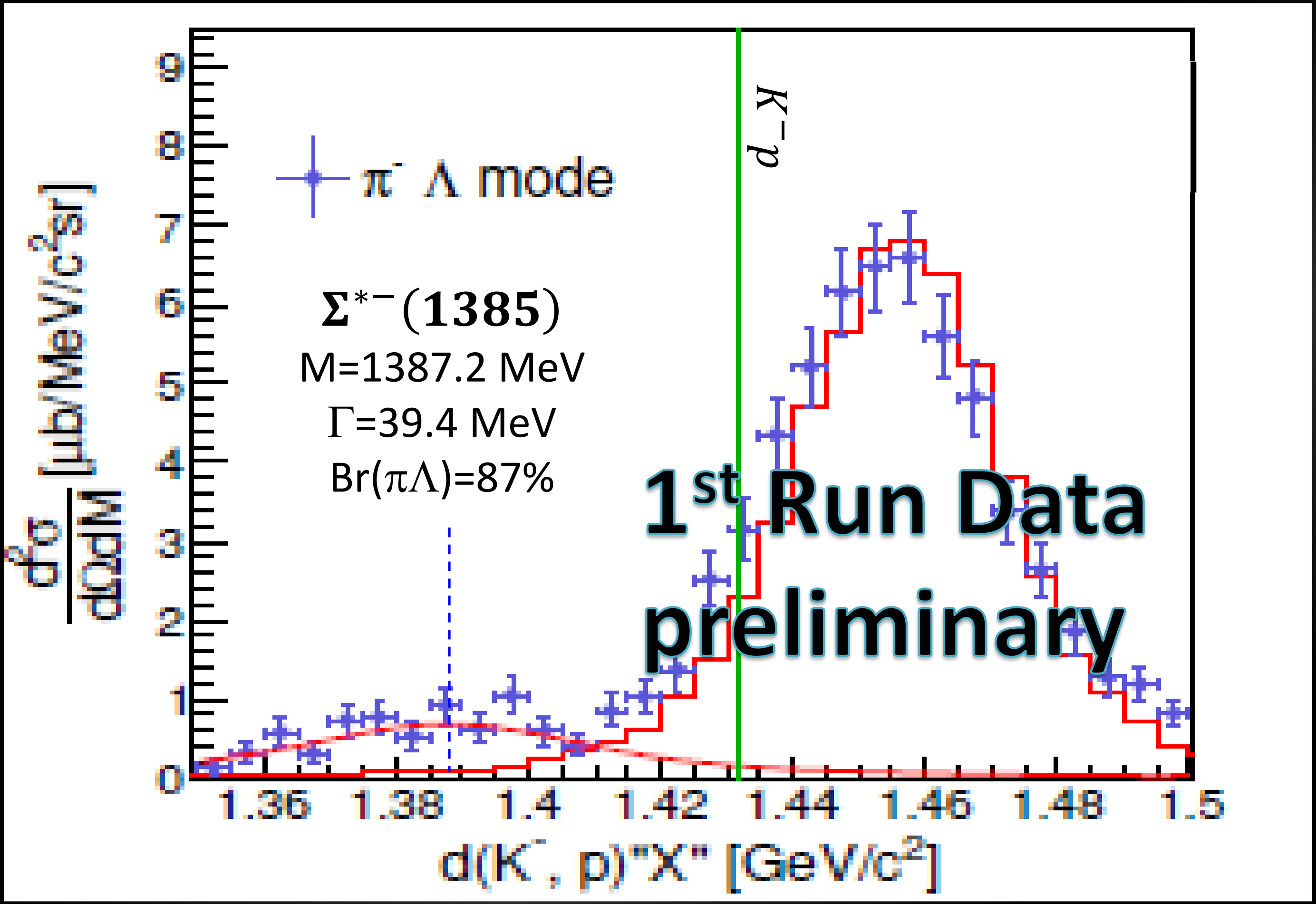


$\pi^-\Sigma^0/\pi^-\Lambda$ Mode ($I = 1$)



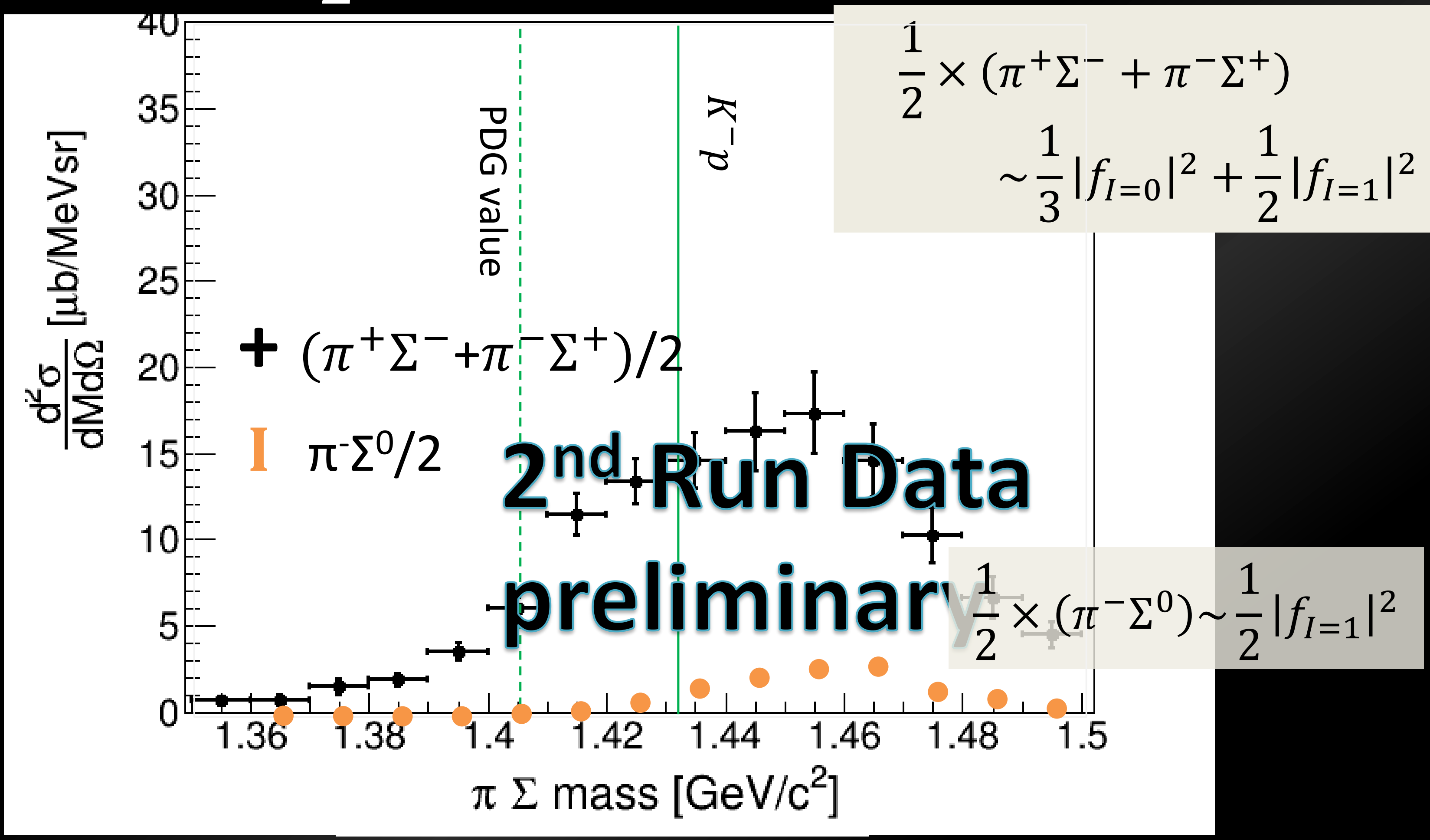
$$\frac{d\sigma}{d\Omega}(\pi^-\Sigma^0) \propto |f_{I=1}|^2$$

$\pi^-\Sigma^0/\pi^-\Lambda$ Mode ($I = 1$)



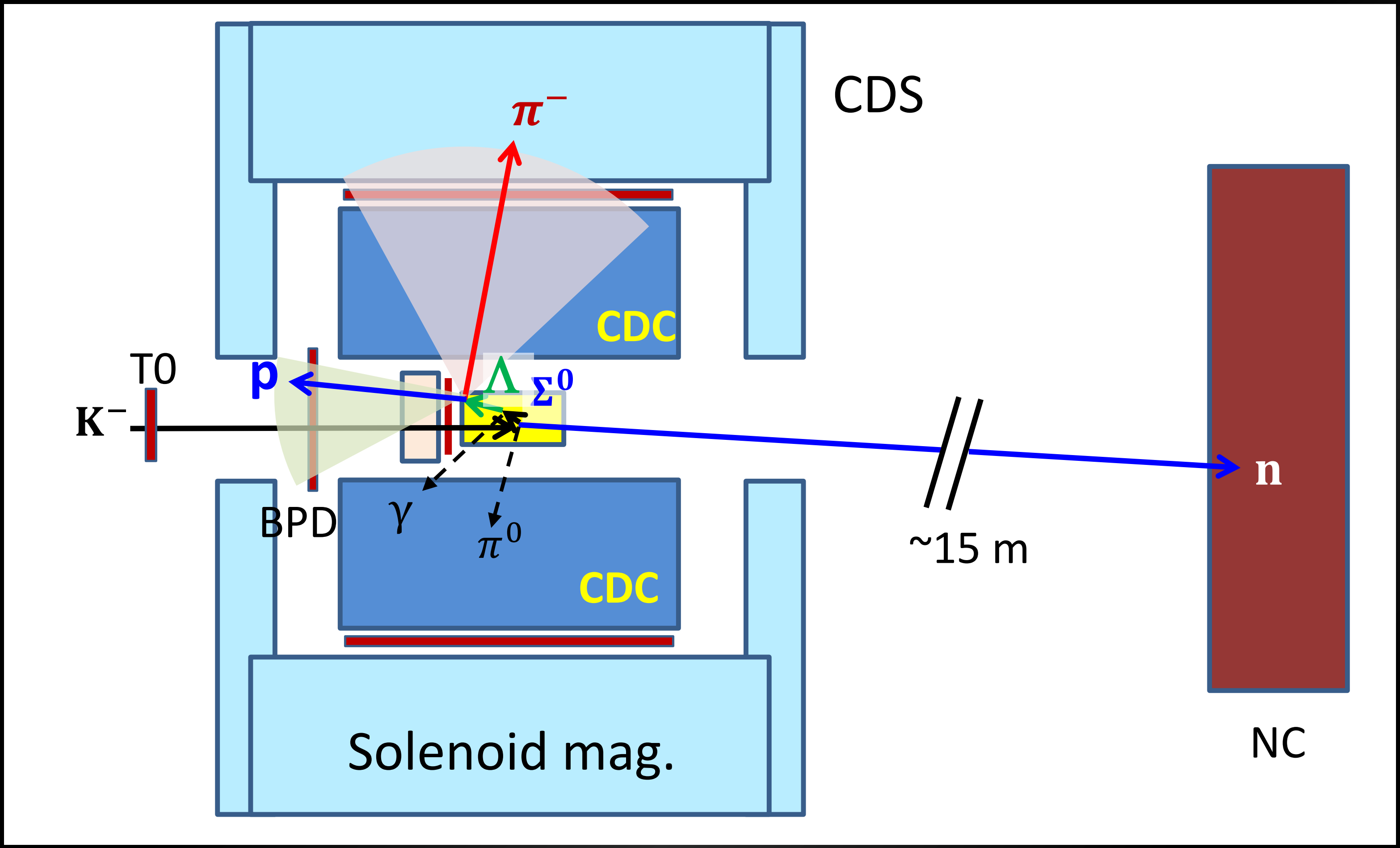
$$\frac{1}{2} \times (\pi^+\Sigma^- + \pi^-\Sigma^+) \ (I = 0, 1)$$

$$v.s. \quad \frac{1}{2} \times \pi^-\Sigma^0 \ (I = 1)$$



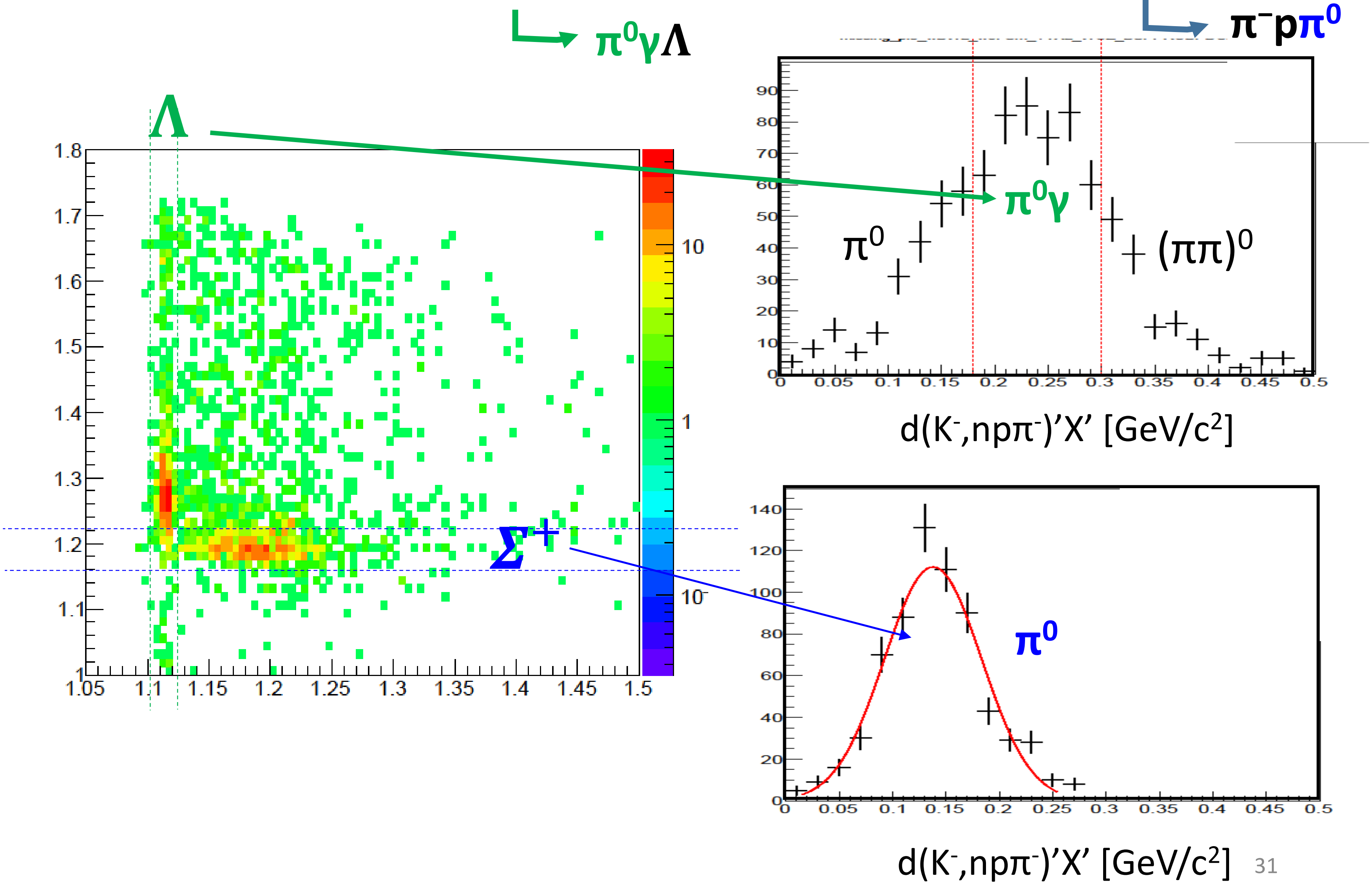
- *The I=0 amplitude is dominant.*

Event topology of $d(K^-, n)X_{\pi^0\Sigma^0}$



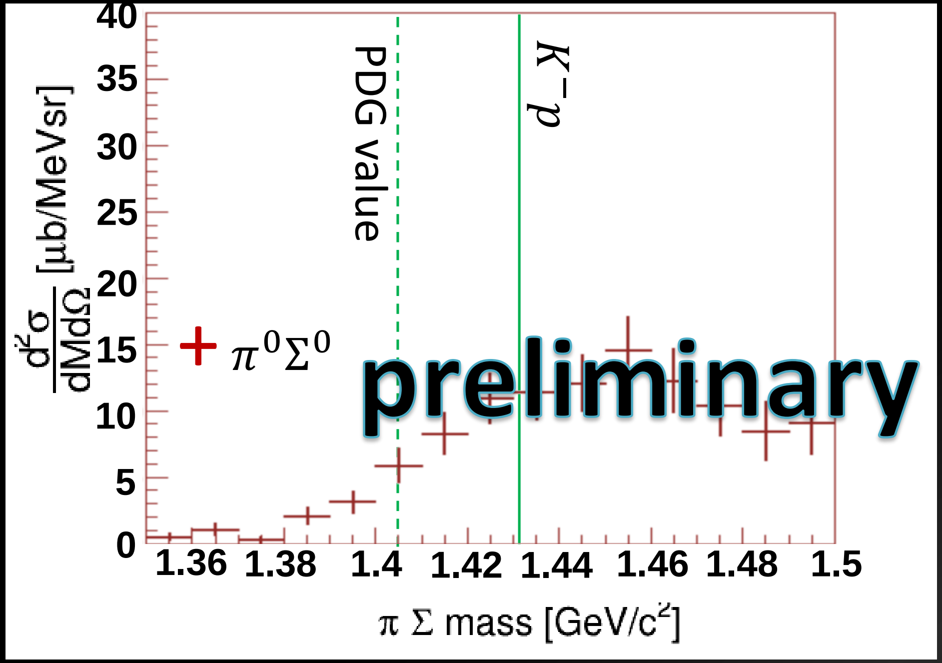
BG Process: $d(K^-, n)X_{\pi^0\Lambda}$, $d(K^-, n)X_{\pi^0\pi^0\Lambda}$,
$d(K^-, n)X_{\pi^-\Sigma^+}$, $d(K^-, \Sigma^- p)X$

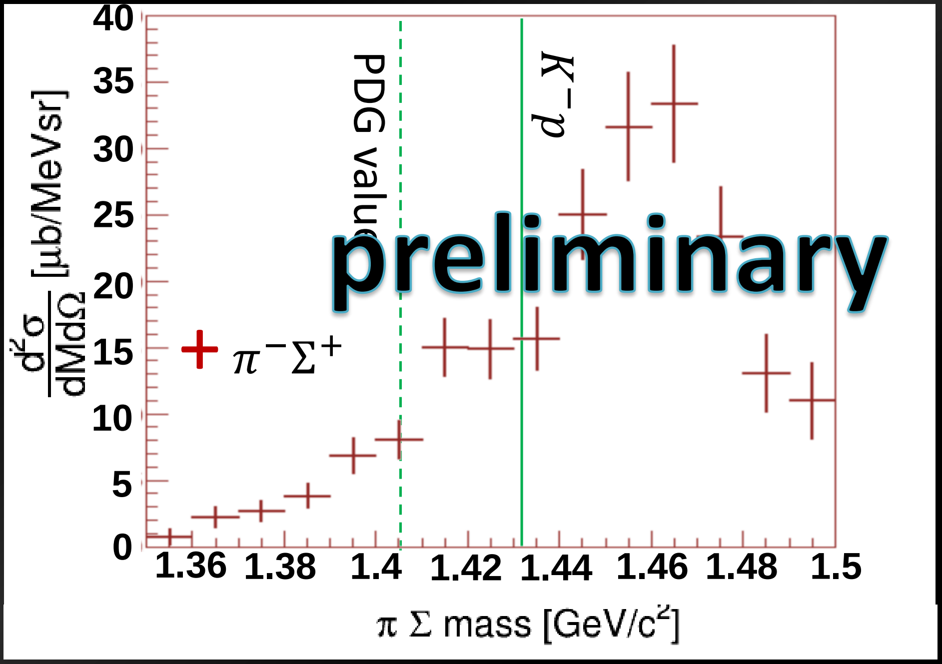
$d(K^-,n)\pi^0\Sigma^0$ vs $d(K^-,n)\pi^-\Sigma^+$



$\pi^0\Sigma^0(I=0)$ $\pi^-\Sigma^+$ Mode

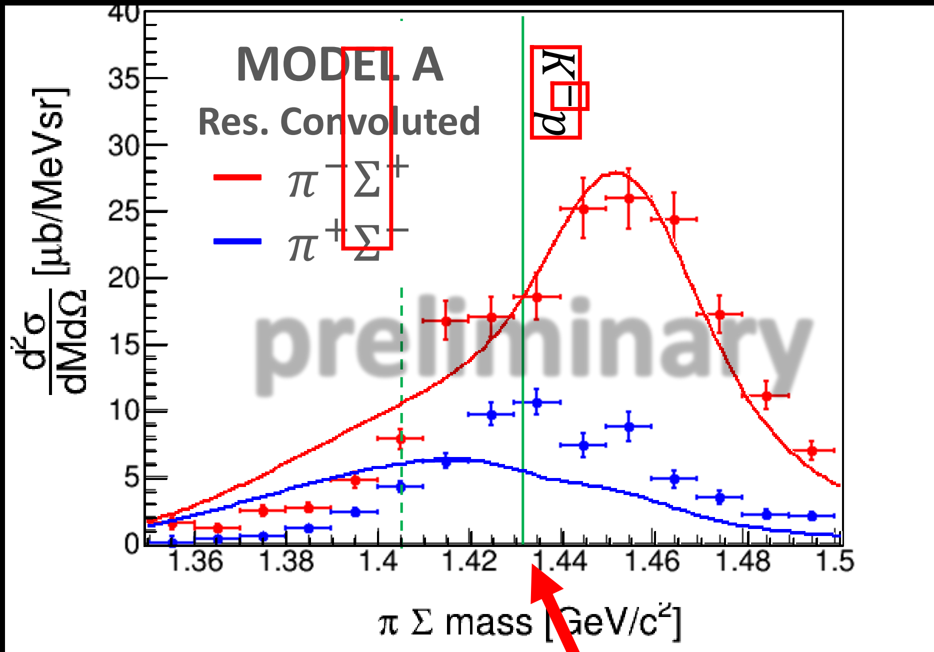
2nd Run Data preliminary

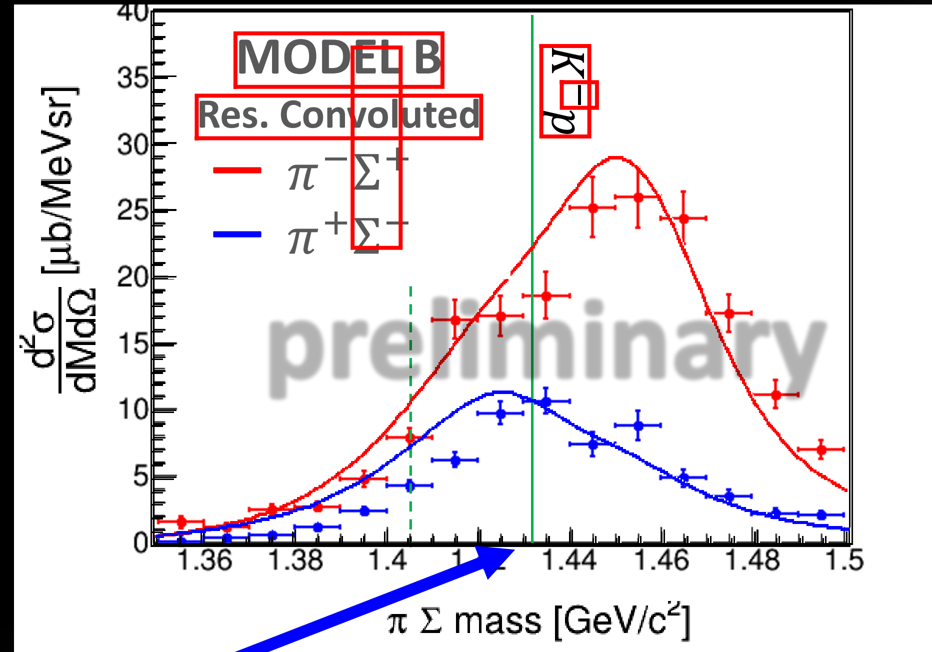


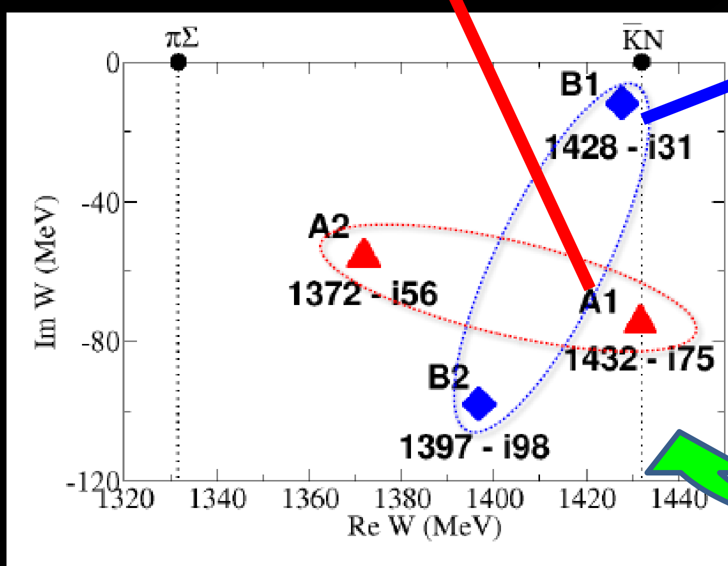


$$\frac{d\sigma}{d\Omega}(\pi^0\Sigma^0) \sim \frac{1}{3}|f_{I=0}|^2$$

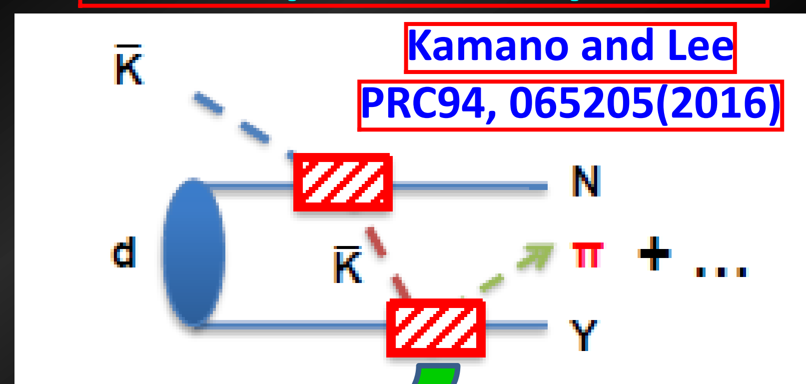
Comparison w/ theory







Two step reaction process



Kamano and Lee
PRC94, 065205(2016)

Resonance Poles

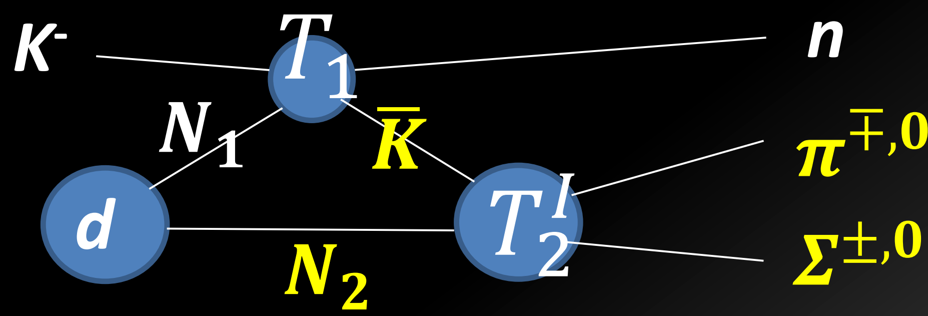
c.f. PTEP043D02('12)
Yamagata-Sekihara, Sekihara, Jido

Remarks

- Structures below and above the $\bar{K}N$ threshold are observed in $d(K^-,n)X_{\pi^\pm\Sigma^\mp}$
  - Interference btw I=0 and 1.
  - I=0 amp. seems dominant in $\pi^\pm\Sigma^\mp$ modes.
    - From measured pure I=1 channel, $d(K^-,p)X_{\pi^-\Sigma^0}$.
- How to decompose the I=0 and 1 amps. ?
  - Significant yield nearby the $K^{bar}N$ threshold but no clear peak structure
  - A simple "BW + Some plausible function" seems too naïve to explain the spectra…

Decompose the Spectra…

- 2-step process



$$\frac{d\sigma}{dM_{\pi\Sigma}}\bigg|_{\theta_n=0} \sim \left|\langle n\pi\Sigma \middle| T_2^I(\overline{K}N,\pi\Sigma)G_0T_1(K^-N,\overline{K}N)\middle|K^-\Phi_d\rangle\right|^2$$

$$\sim \left|T_2^I\right|^2 f_{QF}(M_{\pi\Sigma})$$

Factorization!

$$\left|T_2^I\right|^2 \sim \frac{1}{3}|f_{I=0}|^2 + \frac{1}{2}|f_{I=1}|^2 \pm \frac{\sqrt{6}}{3}Re(f_{I=0}f_{I=1}^*)$$

$$f_{QF}(M_{\pi\Sigma}) \sim \left|\int_0^\infty dq_{N_2}^3\, T_1 \frac{1}{E_{\overline{K}} - E_{\overline{K}}(q_{\overline{K}}) + i\epsilon}\Phi_d(q_{N_2})\right|^2, q_{\overline{K}} + q_{N_2} = q_{\pi\Sigma}$$

E31: Response Function, $F_{QF}(M_{\pi\Sigma})$

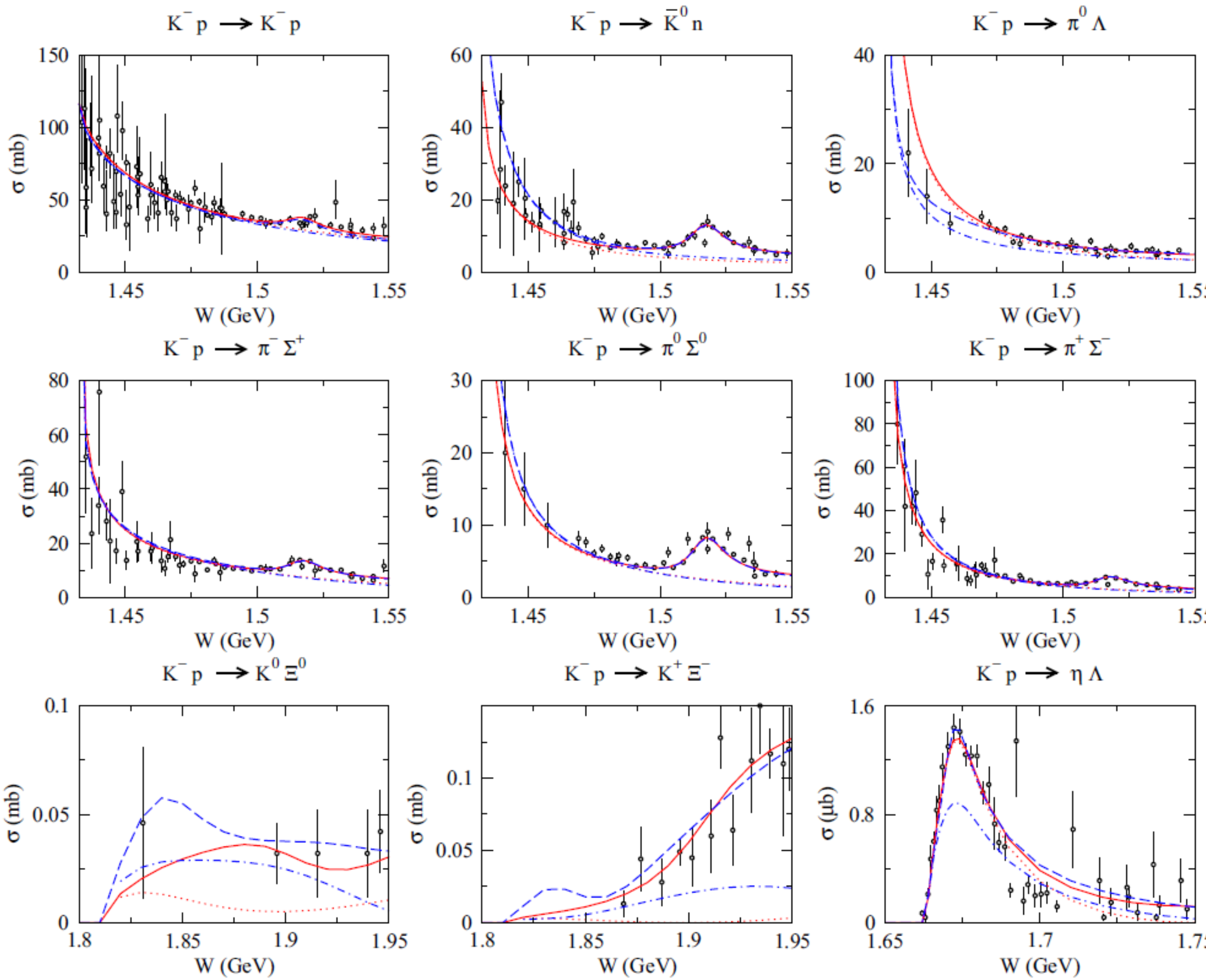
- $F_{QF}(M_{\pi\Sigma}) = \left| \int G_0(q_2, q_1) T_1 \Phi_d(q_2)\, d^3 q_2 \right|^2$
  - $G_0(q_2, q_1) = \frac{1}{q_0^2 - q'^2 + i\varepsilon} f(q_0, q') \frac{\left(\sqrt{P_{\pi\Sigma}^2 + M_{\pi\Sigma}^2} + \sqrt{P_{\pi\Sigma}^2 + W(q')^2}\right)}{M_{\pi\Sigma} + W(q')},$
    $f(q_0, q')^{-1} = [E_1(q_0) + E_1(q')]^{-1} + [E_2(q_0) + E_2(q')]^{-1}$
    Miyagawa and Haidenbauer, PRC85, 065201(2012)
  - T_1: $K^- n \to K^- n\ (I = 1), K^- p \to \bar{K}^0 n (I = 0{,}1)$ amplitude, Gopal et al., NPB119, 362(1977)
    - $T(K^- n \to K^- n) = f(I = 1)$
    - $T(K^- p \to \bar{K}^0 n) = [f(I = 1) - f(I = 0)]/2$
  - $\Phi_d(q_2)$: deuteron wave function, PRC63, 024001(2001)

S-wave contributions in the threshold region

K⁻ p → MB total cross sections

HK, Nakamura, Lee, Sato, PRC90(2014)065204

Kamano-san's slide



Red: Model A

Full

S wave only

Blue: Model B

Full

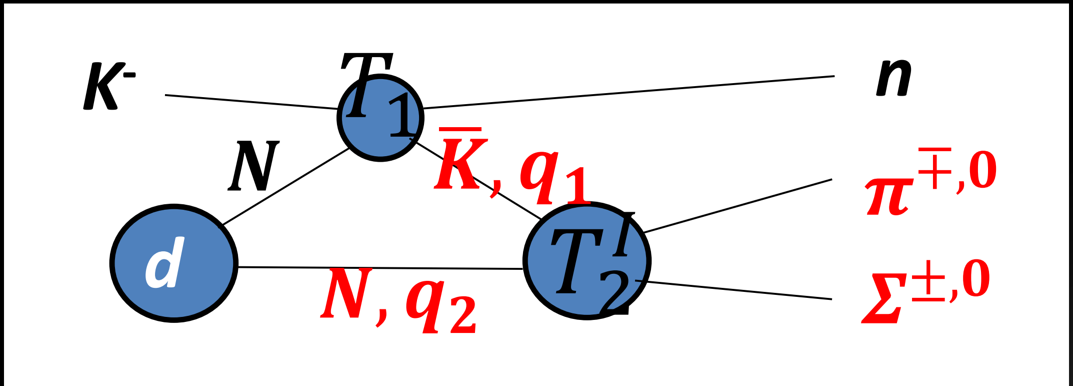
S wave only

Scattering Amplitude

L. Lensniak, arXiv:0804.3479v1(2008)

- $T_{22} = \frac{A}{1 - iAk_2 + \frac{1}{2}ARk_2^2} \quad (\bar{K}N \rightarrow \bar{K}N)$
- $T_{12} = \frac{1}{\sqrt{k_1}} e^{i\delta_0} \frac{\sqrt{ImA - \frac{1}{2}|A|^2 ImRk_2^2}}{1 - iAk_2 + \frac{1}{2}ARk_2^2} \quad (\bar{K}N \rightarrow \pi\Sigma)$
- $T_{11} = \frac{e^{i\delta_0}}{k_1} \frac{\left(\sin\delta_0 + iIm\left(e^{-i\delta_0}A\right)k_2 - \frac{1}{2}Im\left(e^{-i\delta_0}AR\right)k_2^2\right)}{1 - iAk_2 + \frac{1}{2}ARk_2^2}$ $(\pi\Sigma \rightarrow \pi\Sigma)$
- ５つの実数パラメータ
  - A:散乱長、R:有効レンジ、δ_0:位相

To deduce $\bar{K}N$ scattering amplitude



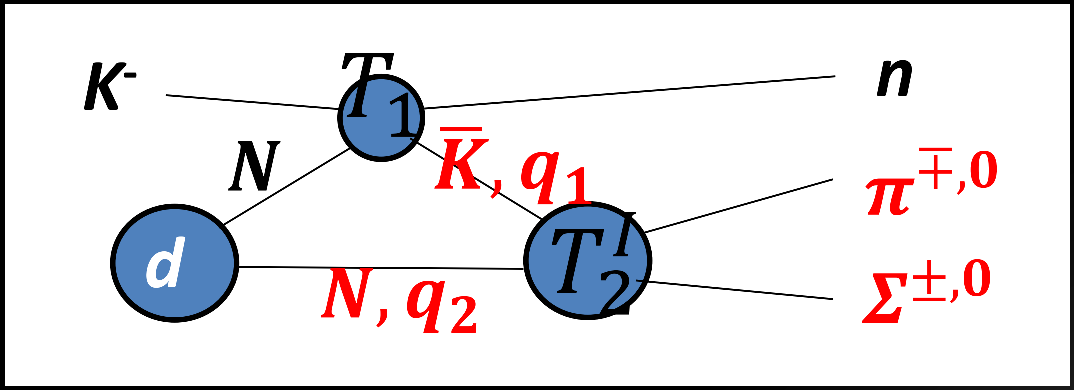
$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=0} \sim |\langle n\pi\Sigma| T_2^I(\bar{K}N,\pi\Sigma) g_2 G_0 g_1 T_1(K^- N,\bar{K}N) |K^-\Phi_d\rangle|^2$$

$$\sim \left|T_2^I\right|^2 F_{QF}(M_{\pi\Sigma})$$

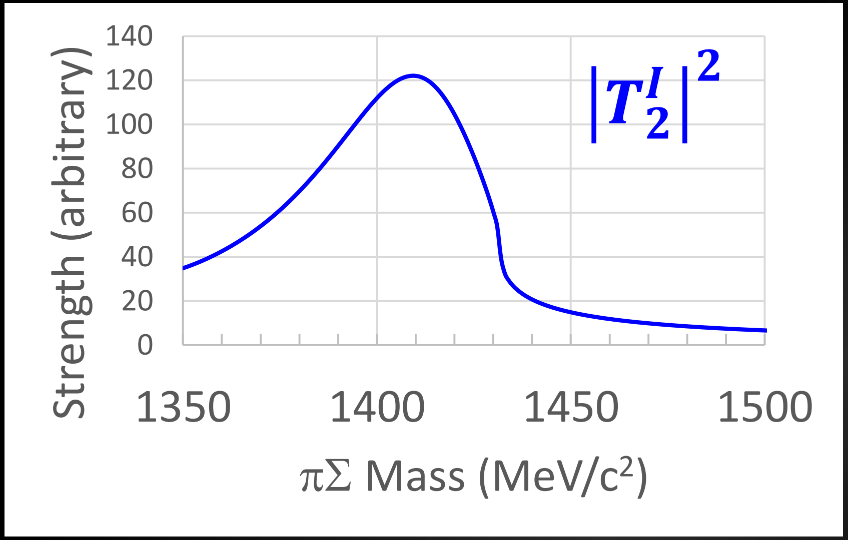
$$T_{12} = \frac{1}{\sqrt{k_1}} e^{i\delta_0} \frac{\sqrt{ImA - \frac{1}{2}|A|^2 ImRk_2^2}}{1 - iAk_2 + \frac{1}{2}ARk_2^2} \quad (\bar{K}N \to \pi\Sigma)$$

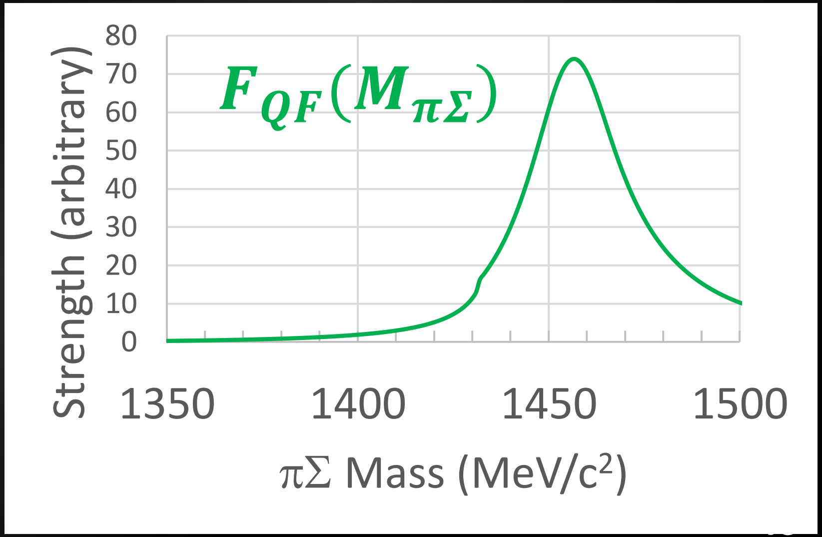
$$T_{22} = \frac{A}{1 - iAk_2 + \frac{1}{2}ARk_2^2} \quad (\bar{K}N \to \bar{K}N)$$

To deduce $\bar{K}N$ scattering amplitude

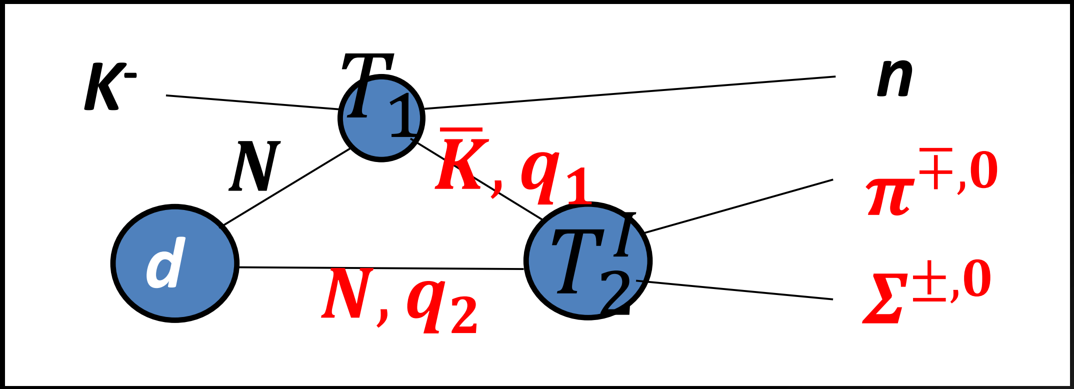


$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=0} \sim \left|T_2^I\right|^2 F_{QF}(M_{\pi\Sigma})$$

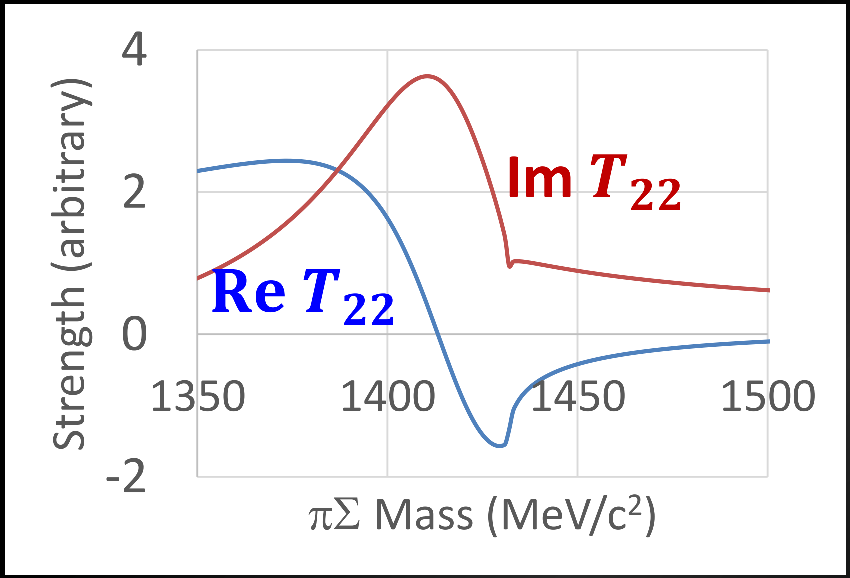


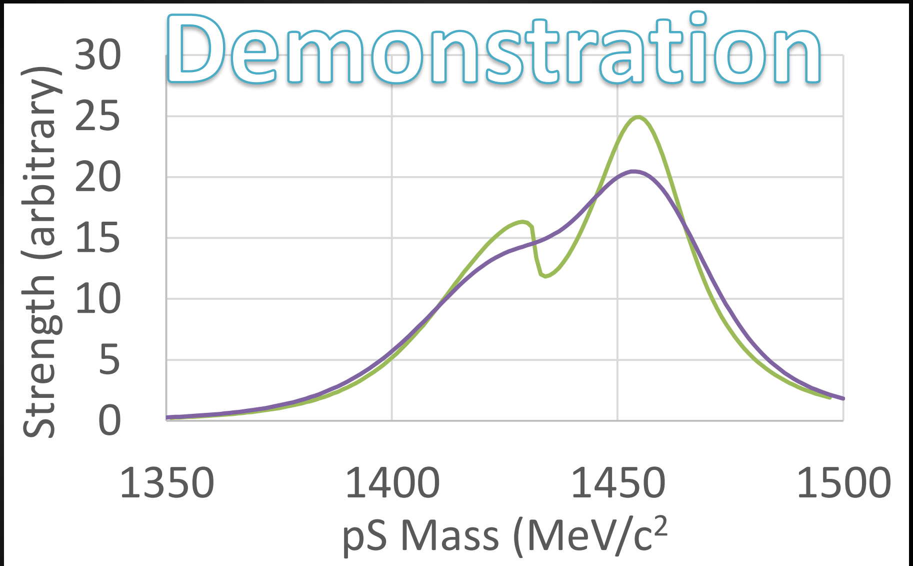


To deduce $\bar{K}N$ scattering amplitude



$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=0} \sim \left|T_2^I\right|^2 F_{QF}(M_{\pi\Sigma})$$

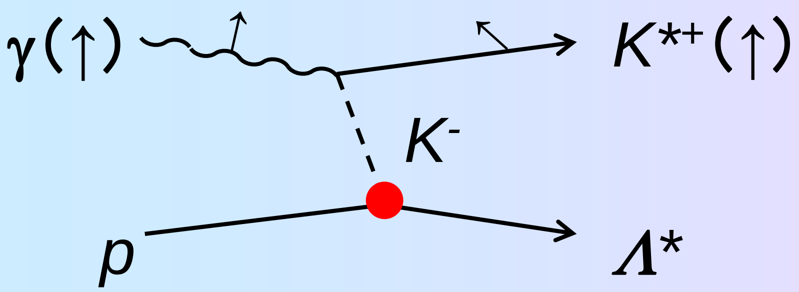




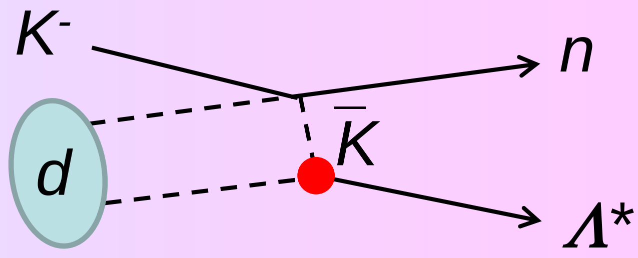
Further Studies of Λ(1405) : $K^{bar}N$ molecule?

<u>Measurement of $K^{bar}N \rightarrow \pi\Sigma$ transition **below $K^{bar}N$ threshold**</u>

Reactions coupled to the $\bar{K}N\Lambda^*$ vertex ($\bar{K}N \rightarrow \pi\Sigma$ channel)



LEPS2
(4π Detector)



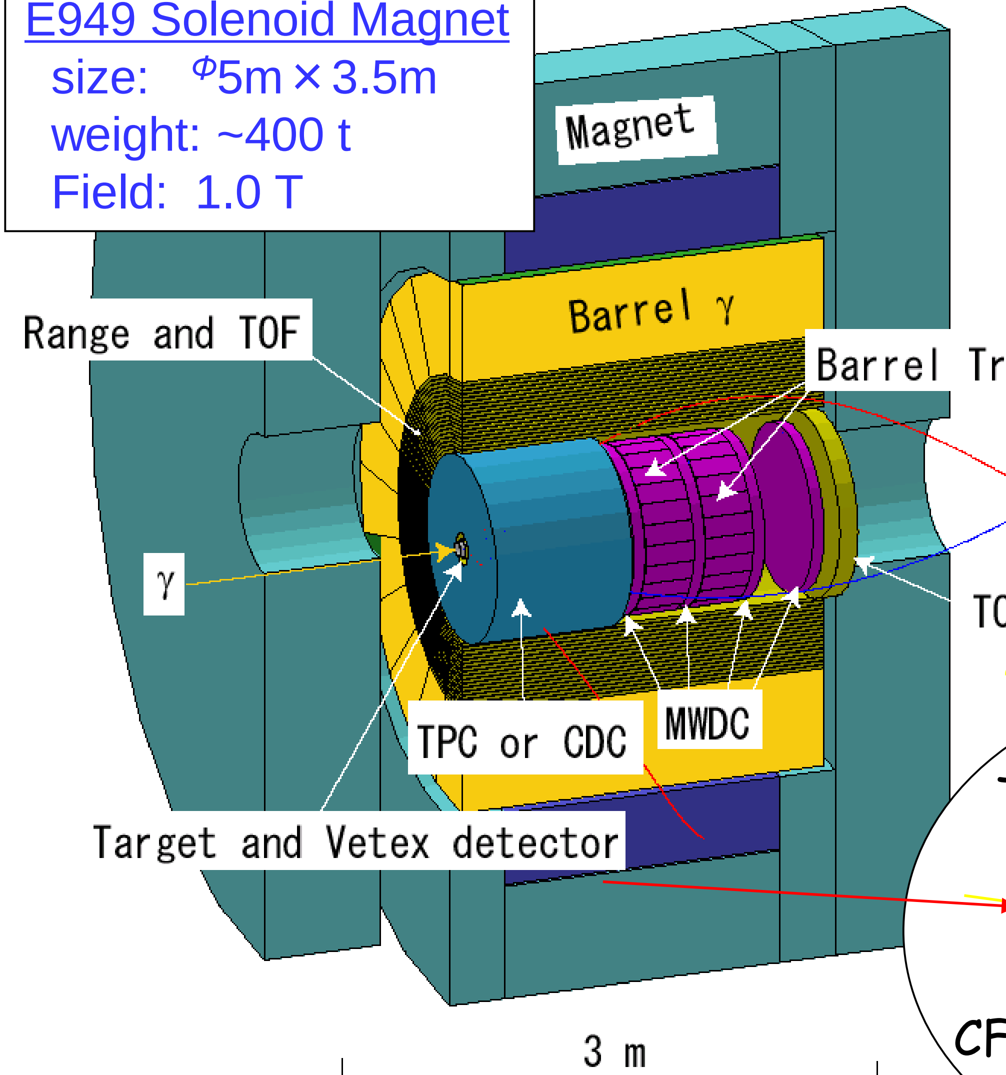
J-PARC
(FWD(n)+CDS)

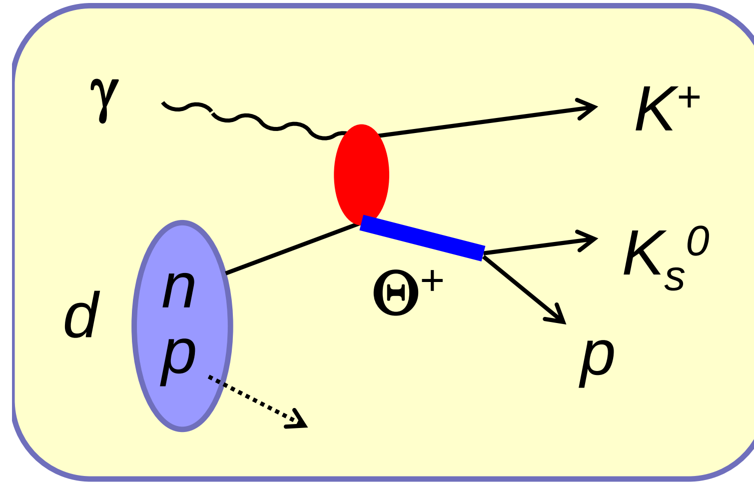
Identification of the Spin-Isospin states

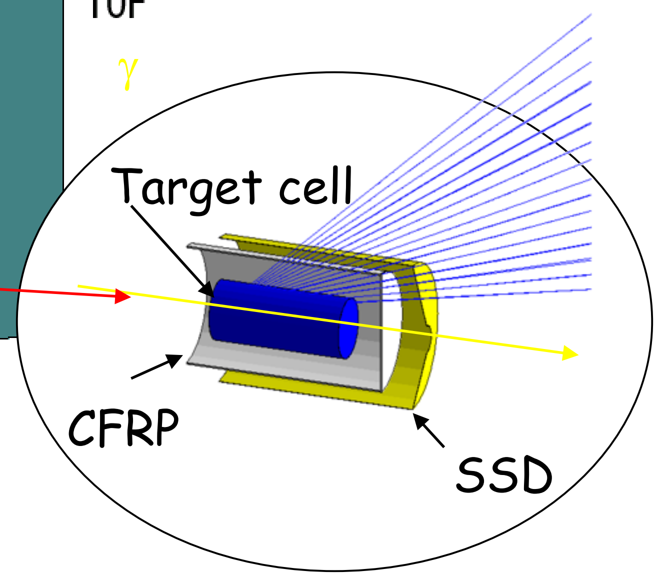
Λ(1405)	S-wave, I=0	$\pi^0\Sigma^0$, $\pi^{+/-}\Sigma^{-/+}$
Non-resonant	S-wave, I=1	$\pi^0\Lambda$, $\pi^{+/-}\Sigma^{-/+}$
Σ^*(1385)	P-wave, I=1	

4π Detector developed for LEPS2

E949 Solenoid Magnet
size: Φ5m × 3.5m
weight: ~400 t
Field: 1.0 T







Contents

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I-1: Standing Point of this Lecture

I-2: Basic Introduction of Hadrons

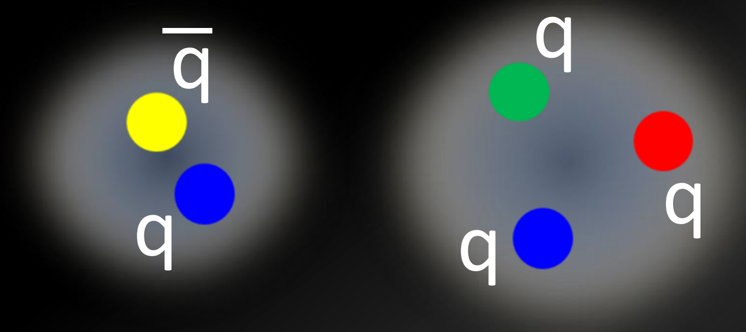
Part II: Experimental Study of Hadrons

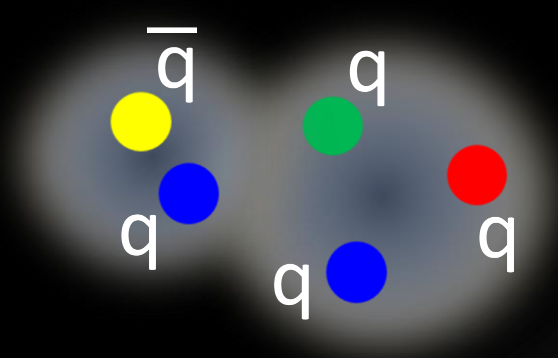
II-1: Λ(1405) and $K^{bar}N$ Interaction

II-2: Charmed Baryon and diquark correlation

What are good building blocks of Hadrons?

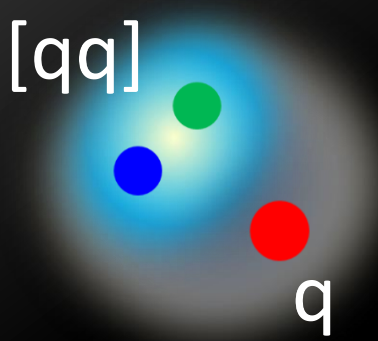
Constituent Quark





hadron (colorless cluster)

Diquark?
(Colored cluster)



Diquarks

Color-Magnetic Interaction of two quarks

$V_{CMI} \sim [\alpha_s/(m_i m_j)]*(\lambda_i,\lambda_j)(\sigma_i,\sigma_j)$

$\rightarrow 0$ if $m_{i,j} \rightarrow \infty$

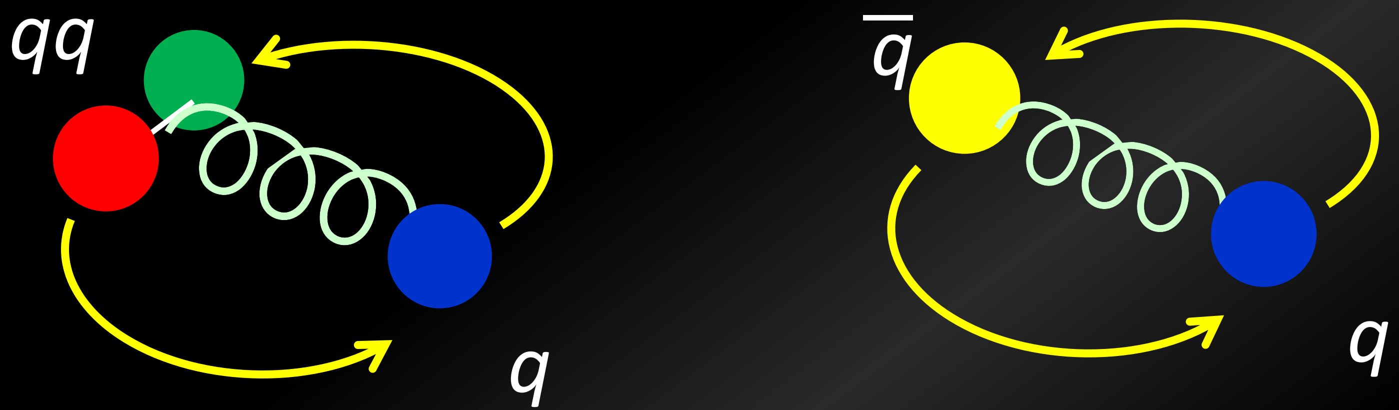
"Good Diquark": Strong Attraction

$V_{CMI}(^1S_0, \overline{3}_c) = 1/2 * V_{CMI}(^1S_0, 1_c)$

[qq] [$\overline{q}$q]

Emergent Diquarks

Baryons as well as Mesons seem to be well described by a Rotating String Configuration with a universal string tension.

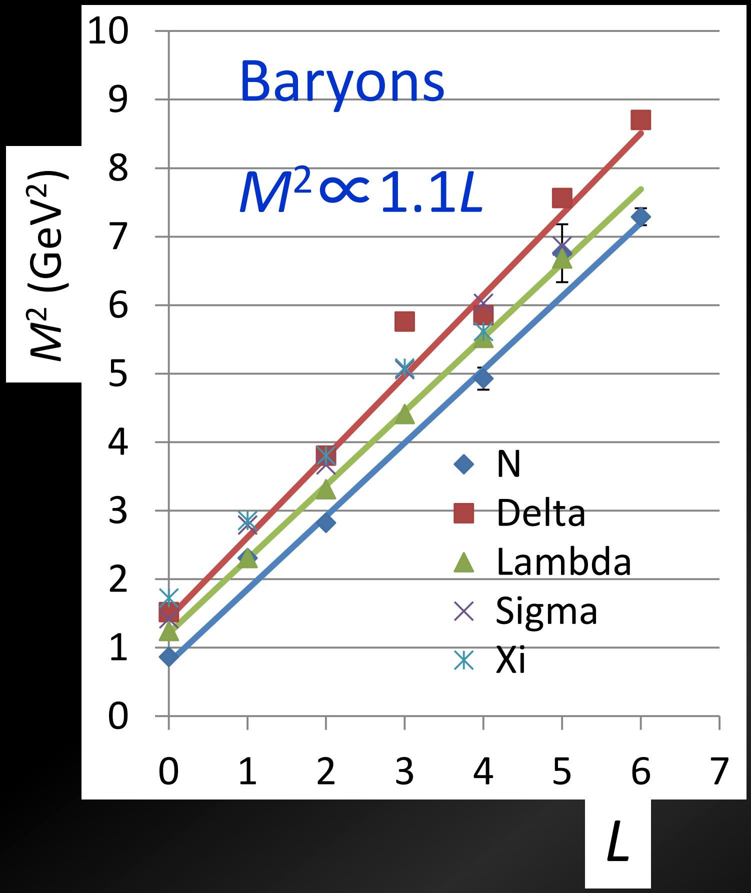


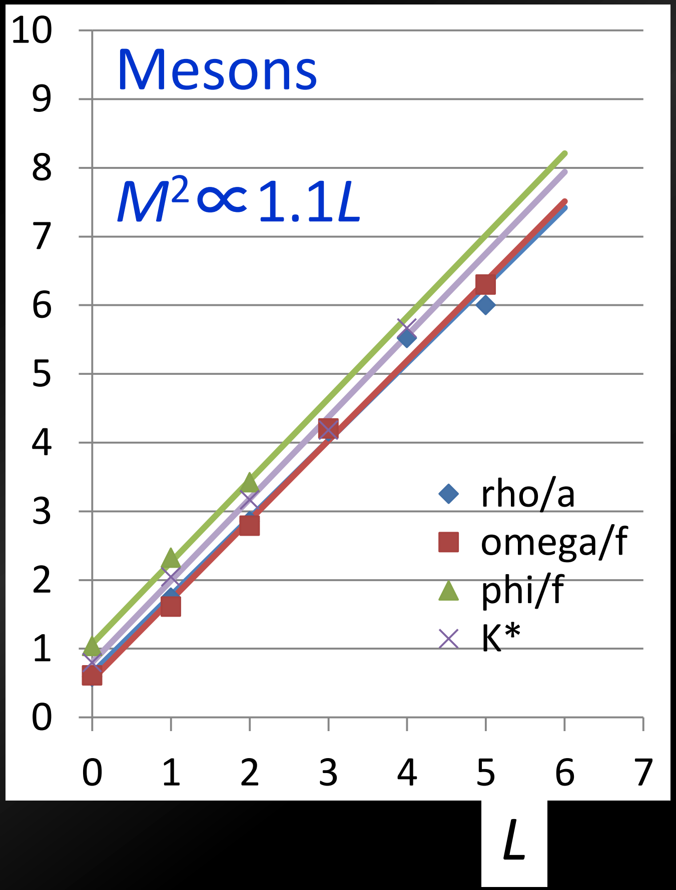
$M^2 \sim \Omega * L$

A distance of [qq]-q/$\bar{q}$-q increases as L increases.

Emergent Diquarks

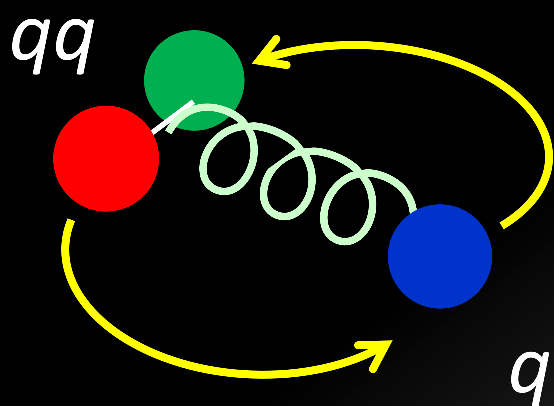
Baryons as well as Mesons seem to be well described by a Rotating String Configuration with a universal string tension.



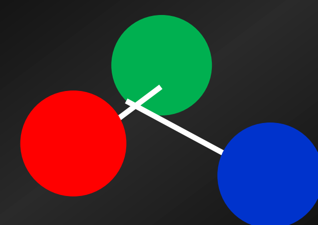


Emergent Diquarks

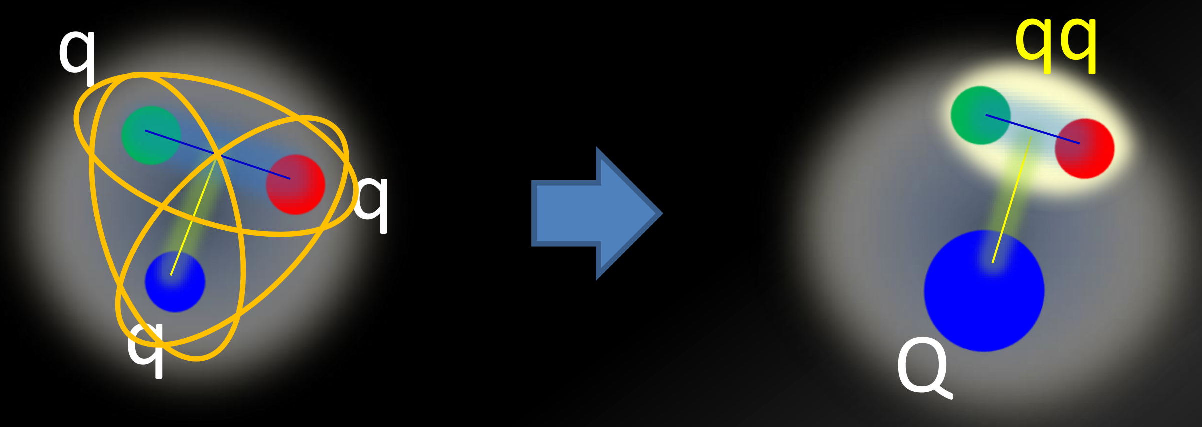
Baryons as well as Mesons seem to be well described by a Rotating String Configuration with a universal string tension.



"diquark"
in low-lying modes



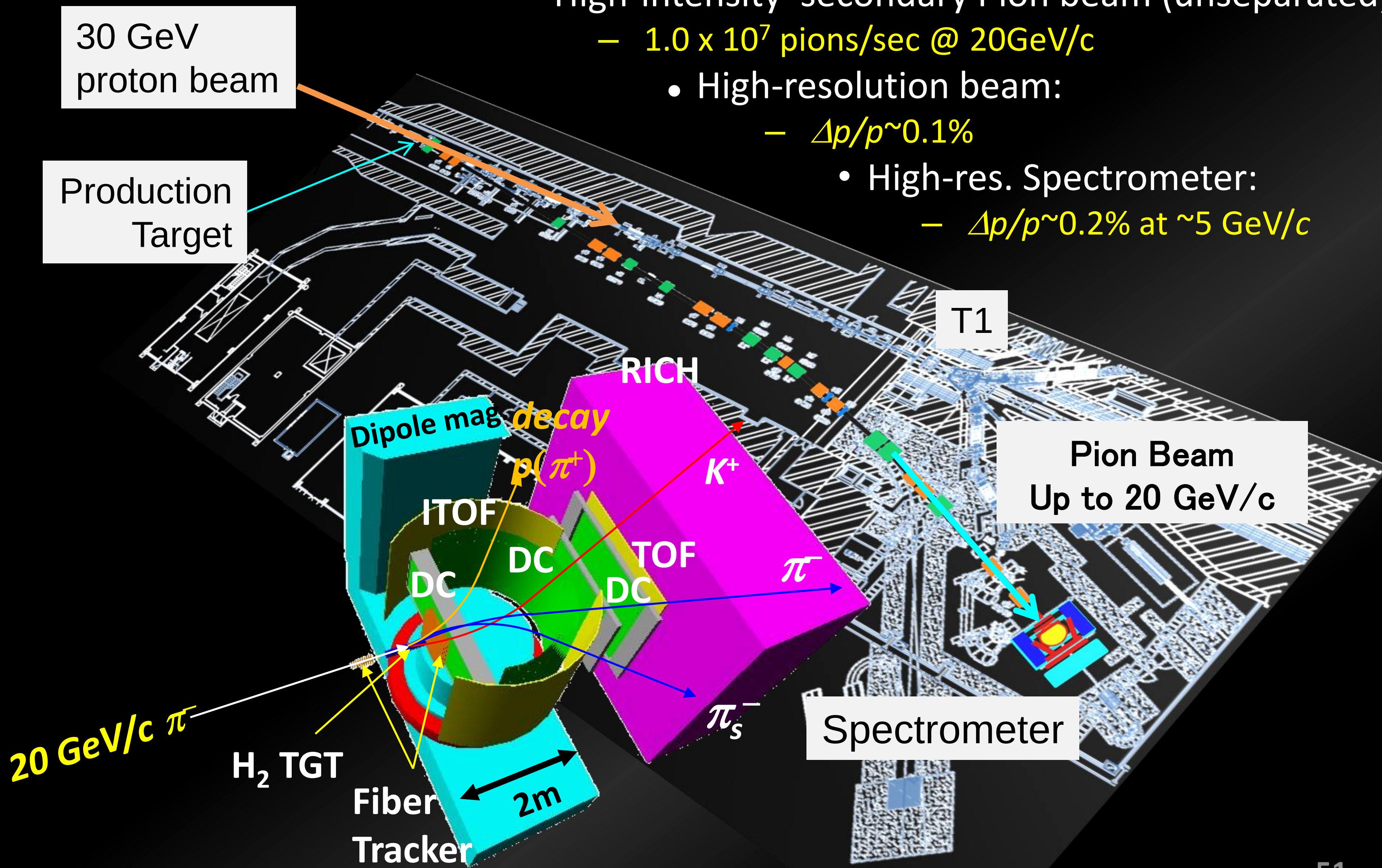
What we can learn from baryons with heavy flavors



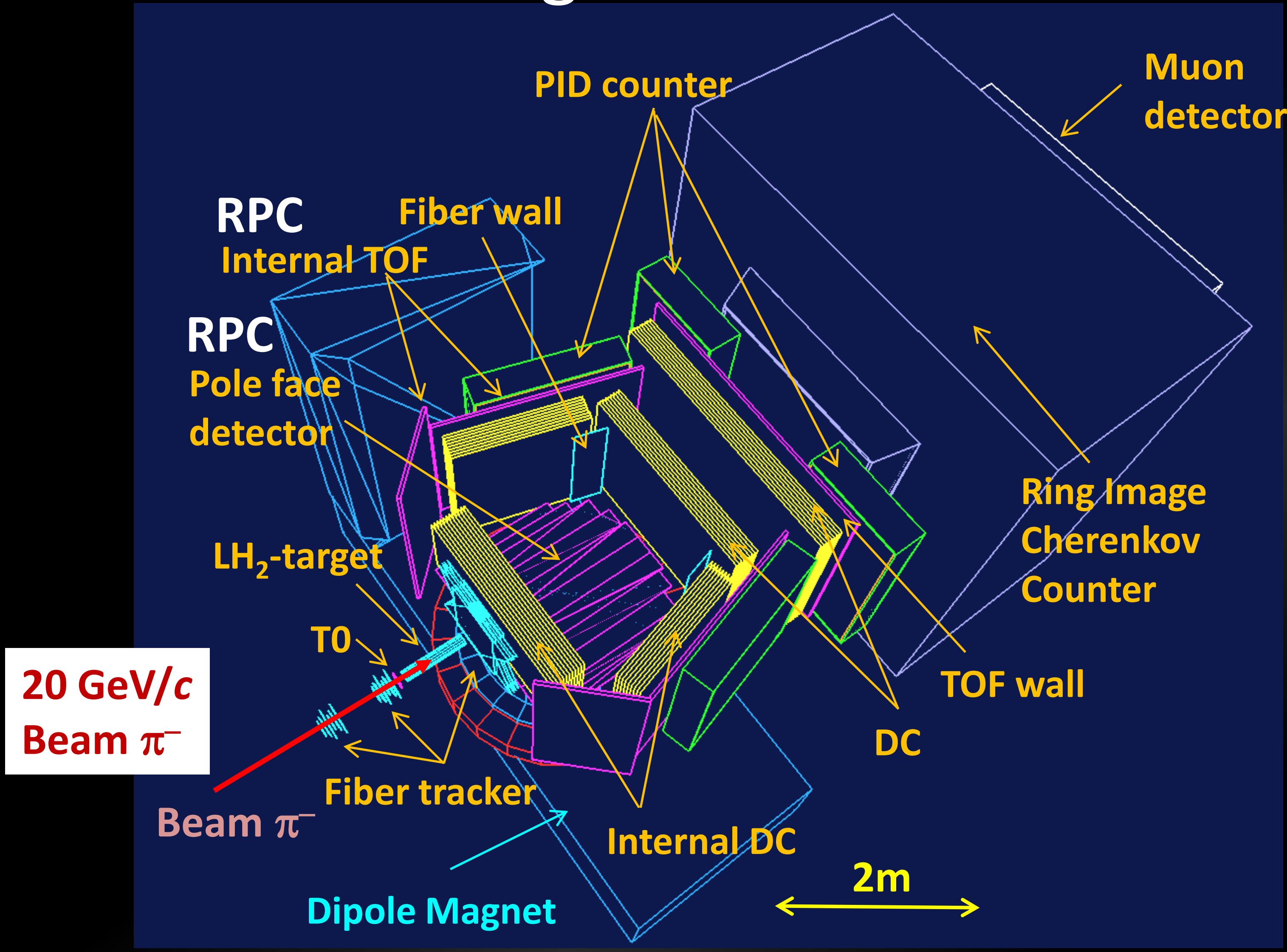
- Quark motion of “qq” is singled out by a heavy Q
  - Diquark correlation
- Level structure, Production rate, Decay properties
  - sensitive to the internal quark(diquark) WFs.
- Properties are expected to depend on a Q mass.

High-res., High-momentum Beam Line

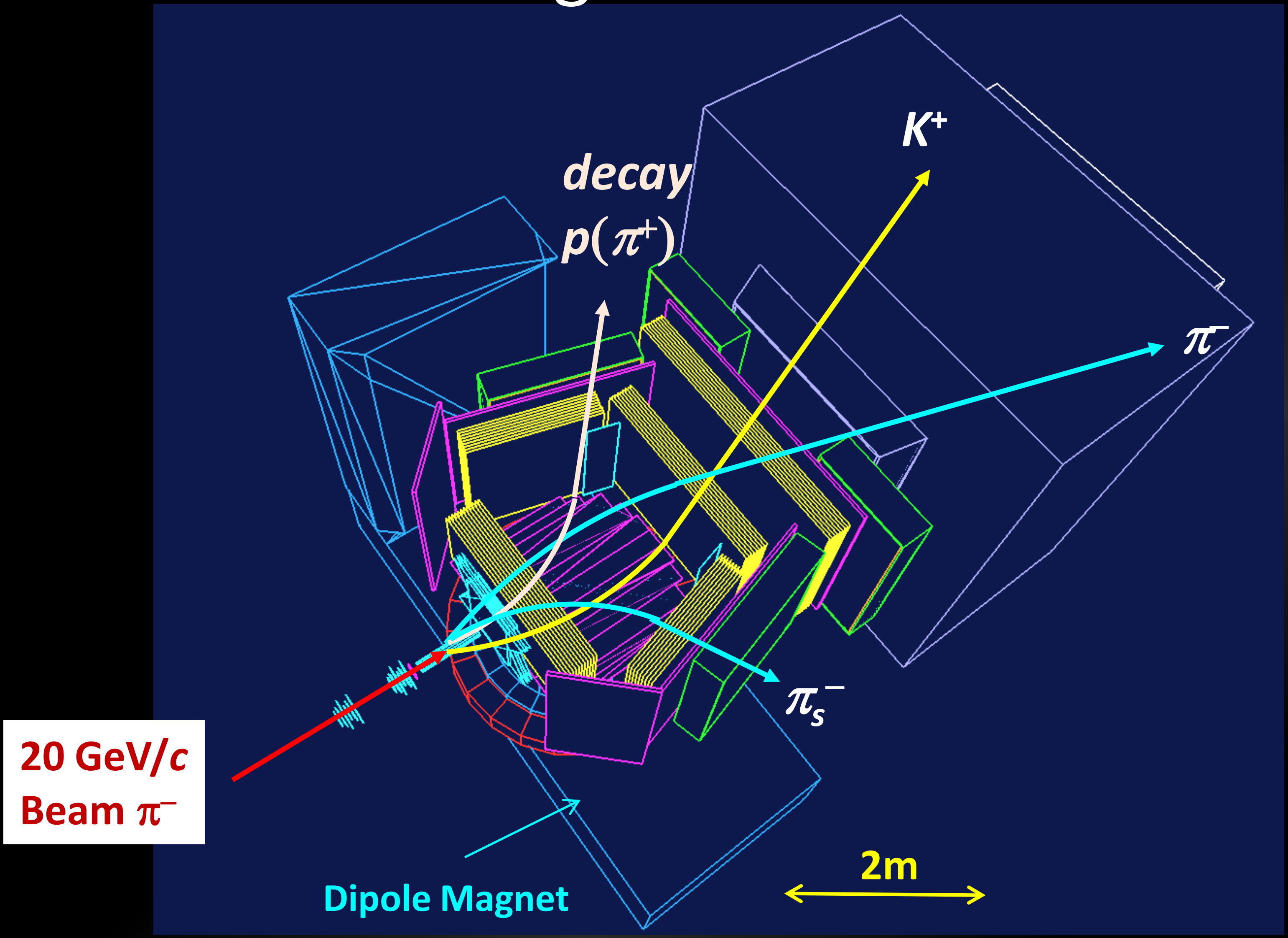
- High-intensity secondary Pion beam (unseparated)
  - 1.0 x 10^7 pions/sec @ 20GeV/c
- High-resolution beam:
  - $\Delta p/p$~0.1%
- High-res. Spectrometer:
  - $\Delta p/p$~0.2% at ~5 GeV/c



Spectrometer Design



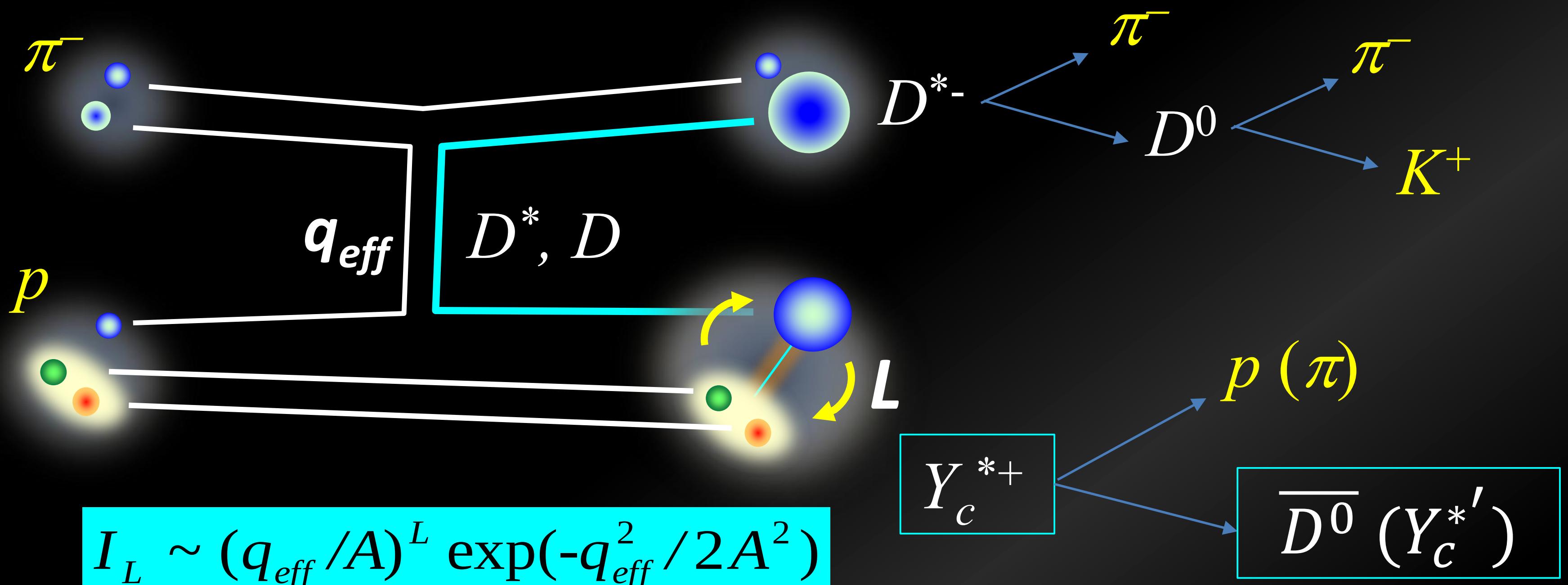
Spectrometer Design



Acceptance: ~ 60% for D^*, ~ 80% for decay π^+

Resolution: $\Delta p/p$~0.2% at ~5 GeV/c（Rigidity：~2.1 Tm)

Charmed Baryon Spectroscopy Using Missing Mass Techniques



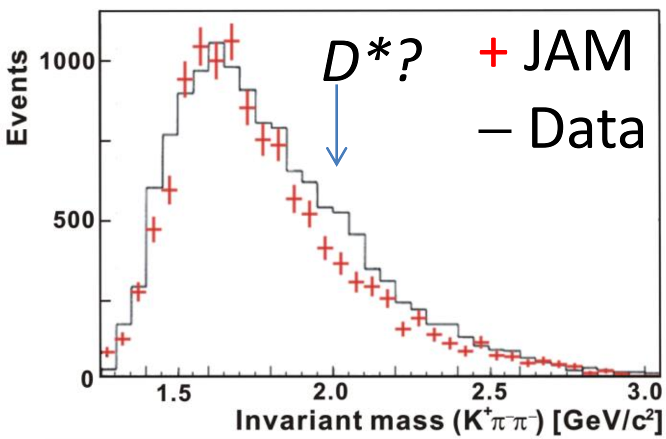
$$I_L \sim (q_{eff}/A)^L \exp(-q_{eff}^2/2A^2)$$

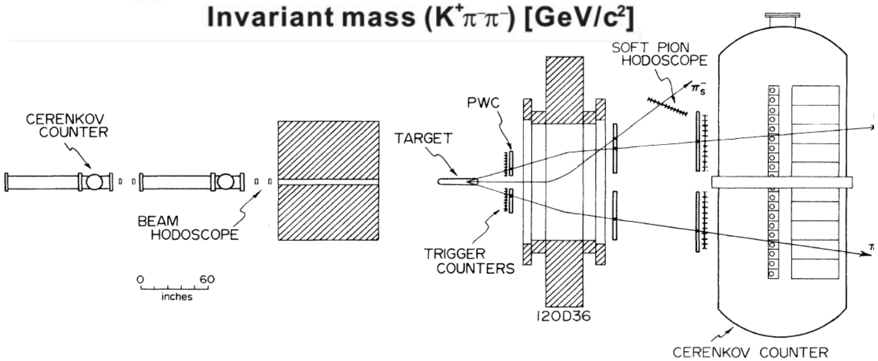
- ✓ Production and Decay reflect [qq] correlation in Excited Y_c^*
- ✓ C.S. DOES NOT go down at higher L when q_{eff}>1 GeV/c.

S.H. Kim, A. Hosaka, H.C. Kim, and HN, PTEP, (2014) 103D01,
S.H. Kim, A. Hosaka, H.C. Kim, and HN, Phys.Rev. D92 (2015) 094021

Production Cross Section

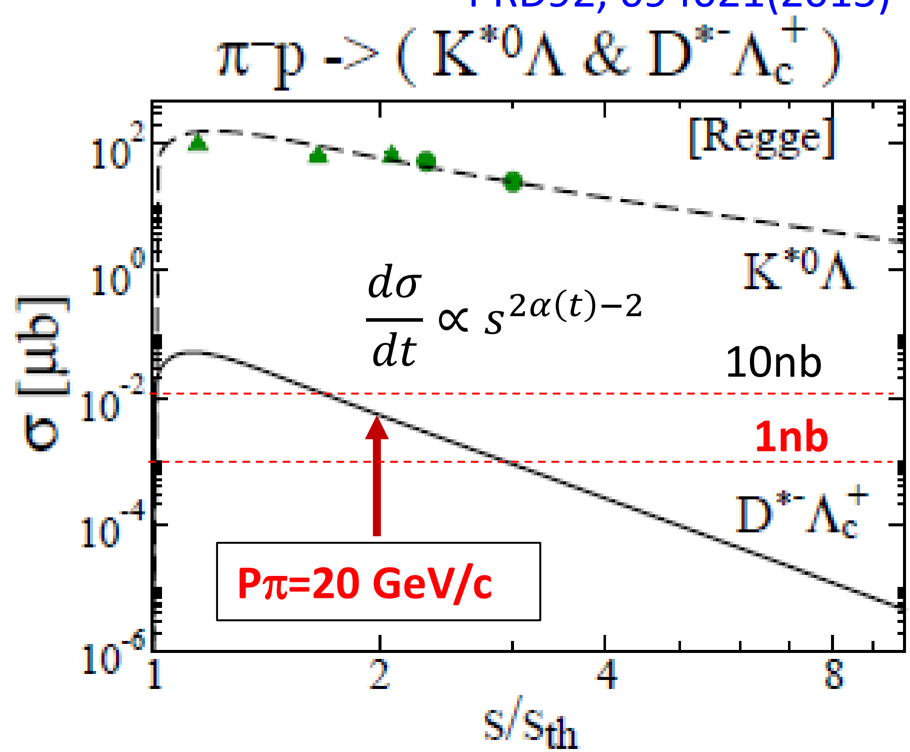
- Experimental data:
  - $\sigma(p(\pi^-,D^{*-})\Lambda_c) < 7$ nb (68%CL) (BNL exp., 1985)
  - BG spectrum is well reproduced by a MC simulation w/ JAM
- Regge Theory suggests 10^{-4} of the hyperon production
  - $\sigma(p(\pi^-,D^{*-})\Lambda_c) \sim$ a few nb





J.H. Christensen et al., PRL55, 154(1985)

S.H. Kim, A. Hosaka, H.C. Kim, and HN PRD92, 094021(2015)



discussed with A. Hosaka

Revisit the Regge Theory

- shows the typical s-dependence of binary reaction cross sections at the large s region;

$$\frac{d\sigma}{dt} = \frac{1}{64\pi s (p_\pi^{cm})^2} \left| \langle f | T | i \rangle \right|^2 \qquad \langle f | T | i \rangle = g_1 g_2 \Gamma(-\alpha(t)) (s/s_0)^{\alpha(t)}$$

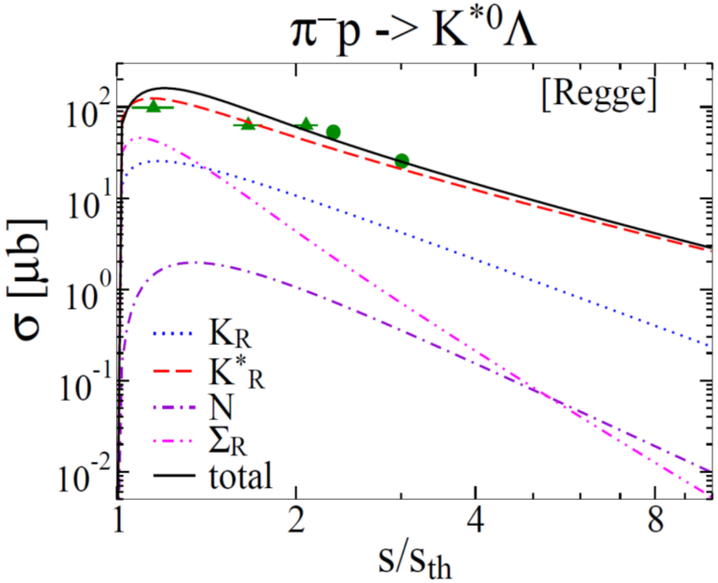
  - Regge trajectory: $\alpha(t) = \alpha(0) - \gamma[\sqrt{T} - \sqrt{t-T}\,]$
  - scale parameter s_0 :

    s at the threshold energy of the reaction AB → CD

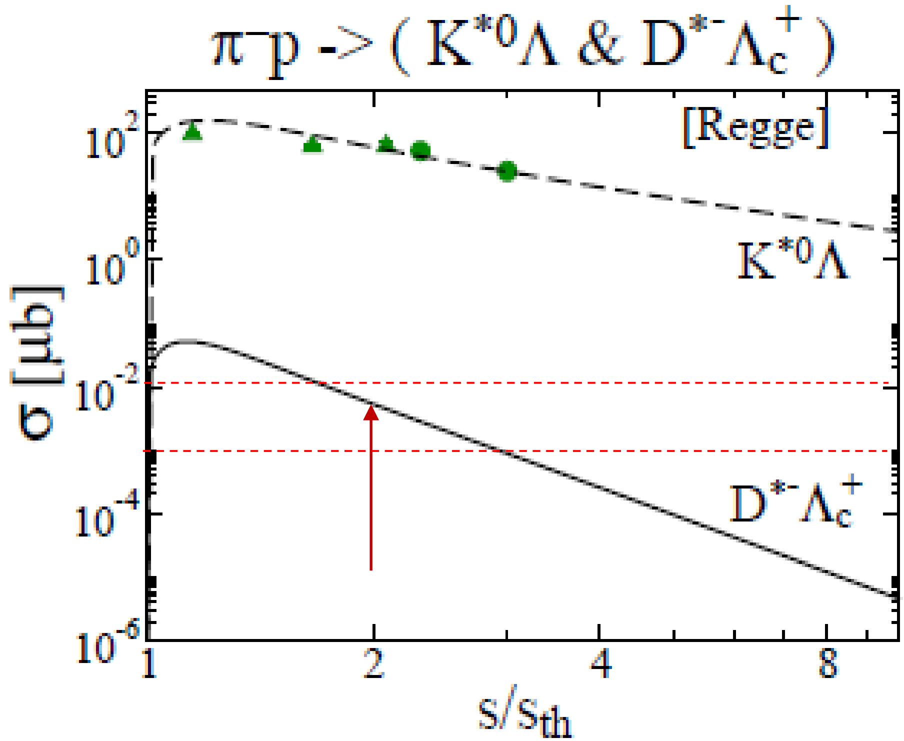
    (*In Kaidalov's Model: $s_0^{2(\alpha_{D^*}(0)-1)} = s_{CD}^{\alpha_\rho(0)-1} * s_{CD}^{\alpha_{J/\psi}(0)-1}$

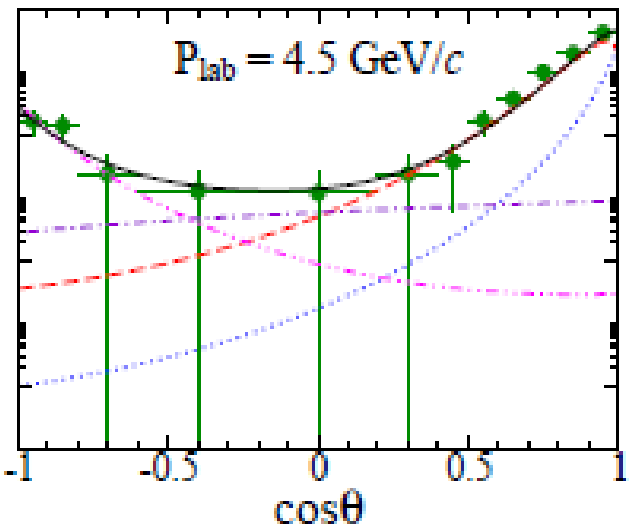
    $s_{AB} = (\Sigma m_i)_A * (\Sigma m_j')_B$, m_i:transversal masses of the consituent quark)

Production Cross Section

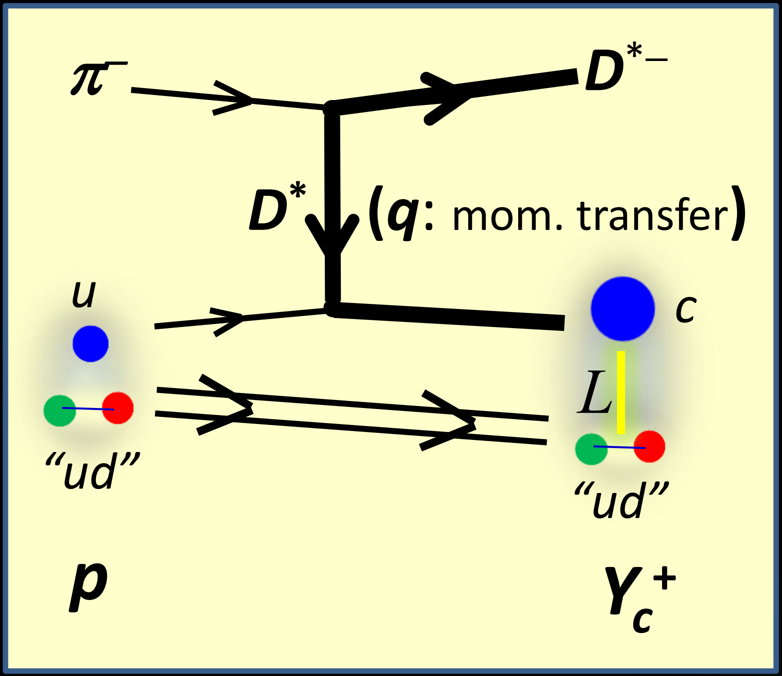


S.H. Kim, A. Hosaka, H.C. Kim, and HN
PRD92, 094021(2015)





Production Rate



- t-channel D^* *Reggeon* at a forward angle

S. H. Kim, et al., PTEP, 2014, 103D01(2014)

Production Rates are determined by the overlap of WFs

$$R \sim \langle \varphi_f | \sqrt{2}\sigma_- \exp(i\vec{q}_{eff}\vec{r}) | \varphi_i \rangle$$

and depend on:

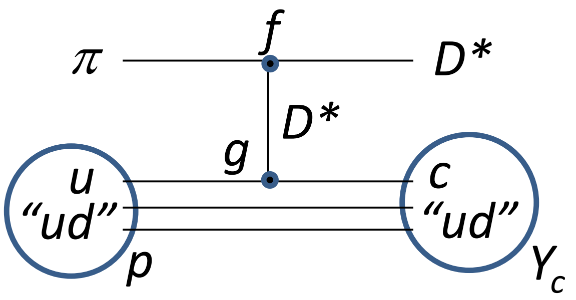
1. Spin/Isospin Config. of Y_c
   Spin/Isospin Factor
2. Momentum transfer (q_{eff})

$$I_L \sim (q_{eff}/A)^L \exp(-q_{eff}^2/2A^2)$$

A~0.42 GeV ([Baryon size]$^{-1}$)
q_{eff}~1.4 GeV/c

discussed by A. Hosaka

Excitation Energy Dependence



- Production Rate in a quark-diquark model:
  - *D** exchange at a forward angle

$$R \sim \gamma C \, | K \cdot I |^2 \; p_B$$

  - Radial integral of wave functions

$$I \sim \sqrt{2} \int d\vec{r}^{\,3} [\varphi_f^*(\vec{r}) \exp(\vec{q}_{eff} \vec{r}) \varphi_i(\vec{r})]$$

$$q_{eff} = \vec{p}_p \times m_d / M_p - \vec{p}_{Y_c} \times m_d / M_{Y_c},$$

m_d :"ud" diquak mass

Taking Harmonic Oscillator Wave Functions

- $I \sim (q_{eff}/A)^L \exp(-q_{eff}^2/2A^2)$, where A: oscillator parameter (0.4~0.45 GeV)
- For larger q_{eff}, the relative rate of a higher L state to the GS increases as $\sim (q_{eff}/A)^L$

  - Spectroscopic Factor: γ
    - pick up good/bad diquark configuration in a proton
    - A residual "*ud*" diquark acts as a spectator

→ γ=1/2 for Λ_c's
=1/6 for Σ_c's

  - Kinematic Factor w/ a propagator :

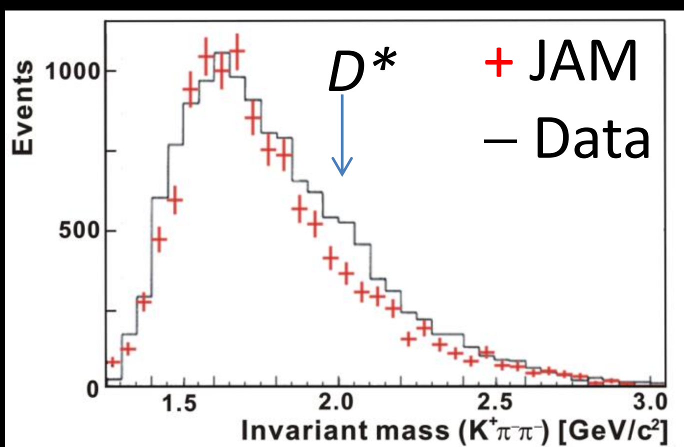
$$K \sim k_{D*}^0 k_\pi (|\,\vec{p}_B\,| / 2m_B - 1) / (q^2 - m_{D*}^2)$$

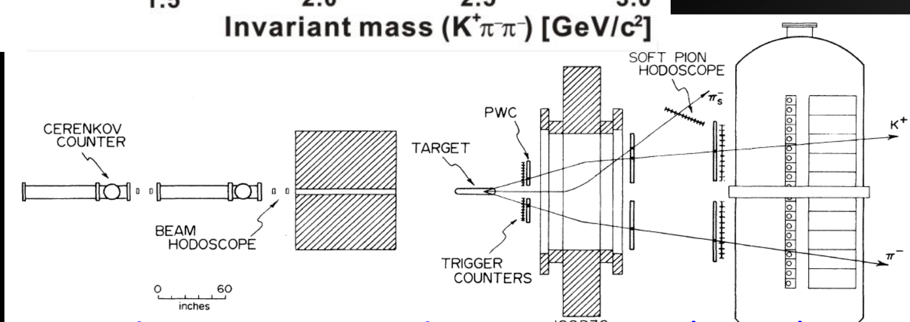
  - Spin Dependent Coefficient, *C*:
    - Products of CG coefficients based on quark-diquark spin configuration
    - Characterized by the spin operator in the vector meson exchange, $\vec{e}_{D*}^{\,\perp} \cdot \vec{\sigma}$

Production Cross Section

A. Hosaka et al.

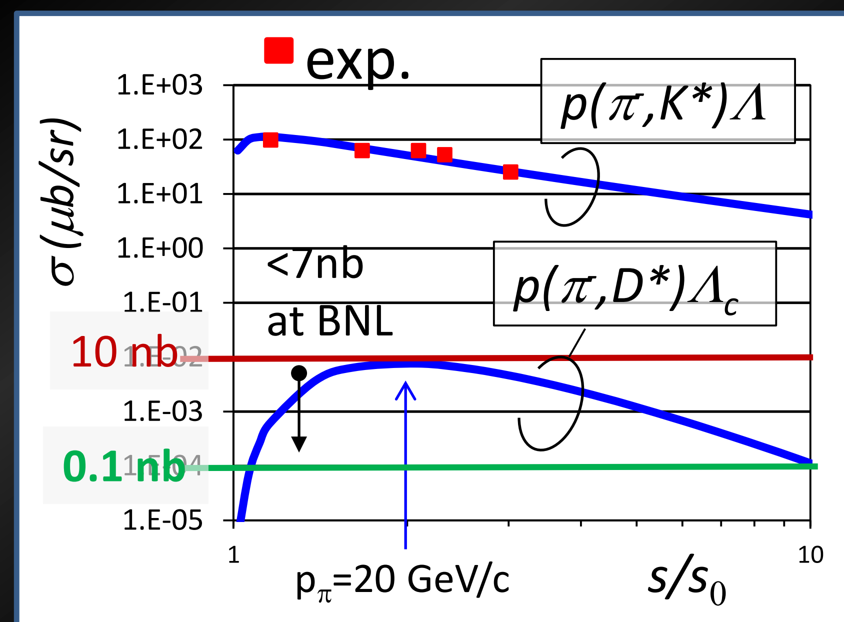
- Experimental data:
  - $\sigma(p(\pi^-,D^{*-})\Lambda_c)$ < 7 nb (68%CL) (BNL exp., 1985)
  - BG spectrum is well reproduced by a MC simulation w/ JAM
- Regge Theory suggests 10^{-4} of the hyperon production
  - $\sigma(p(\pi^-,D^{*-})\Lambda_c)$ ~ a few nb





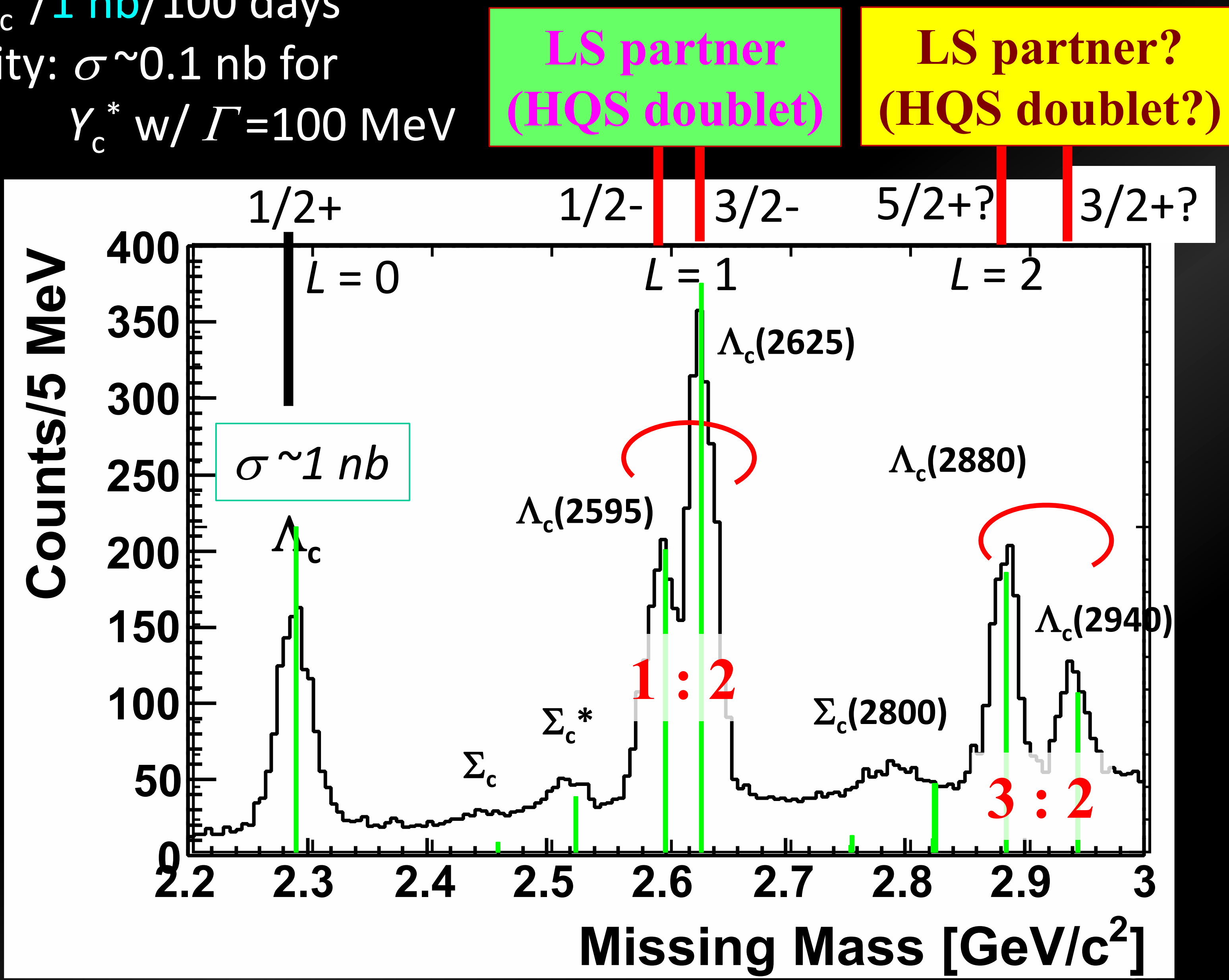
J.H. Christensen et al., PRL55, 154(1985)

Regge Theory



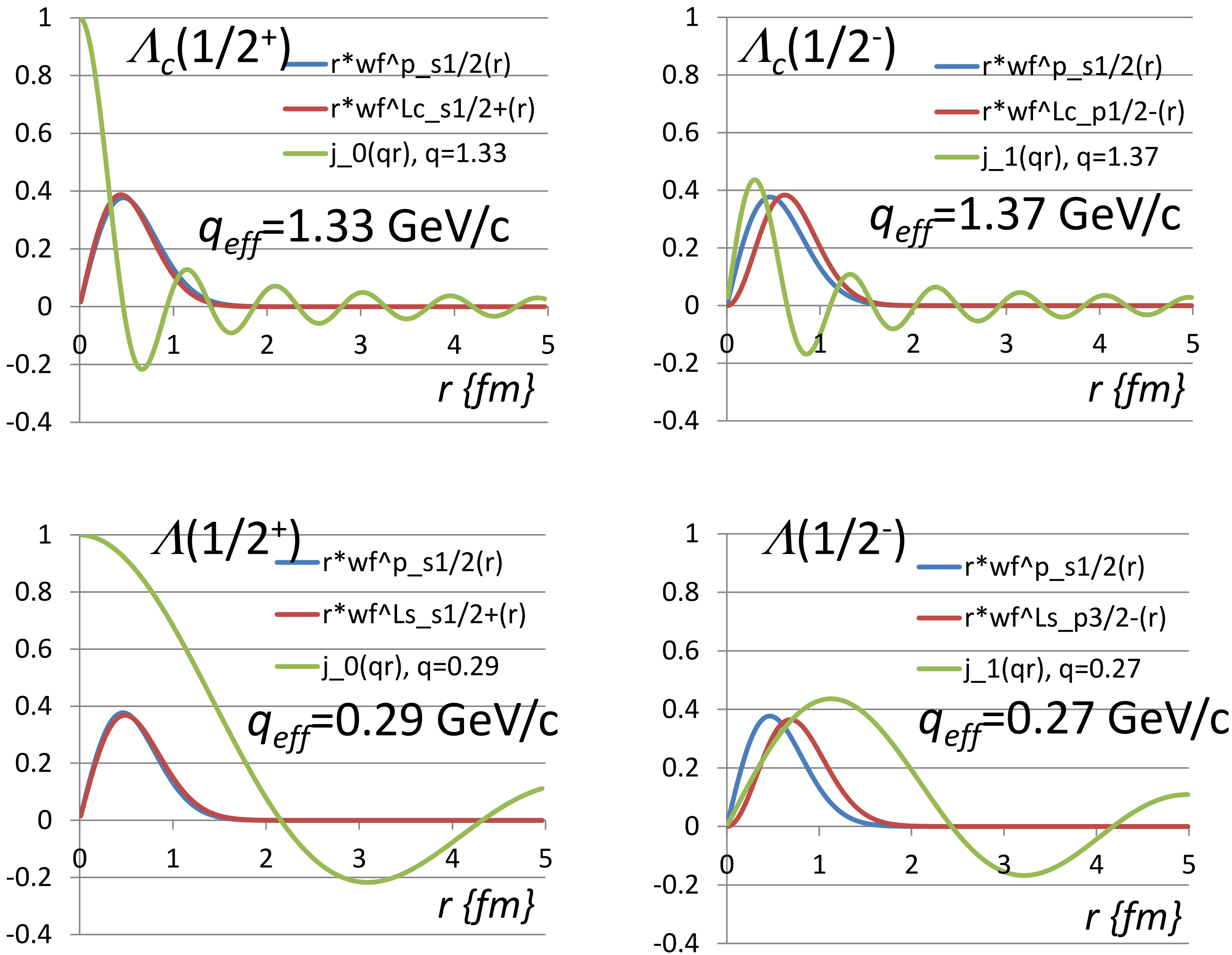
Missing Mass Spectrum (Sim.)

- ~1000 Y_c^*/1 nb/100 days
- Sensitivity: σ~0.1 nb for Y_c^* w/ Γ=100 MeV



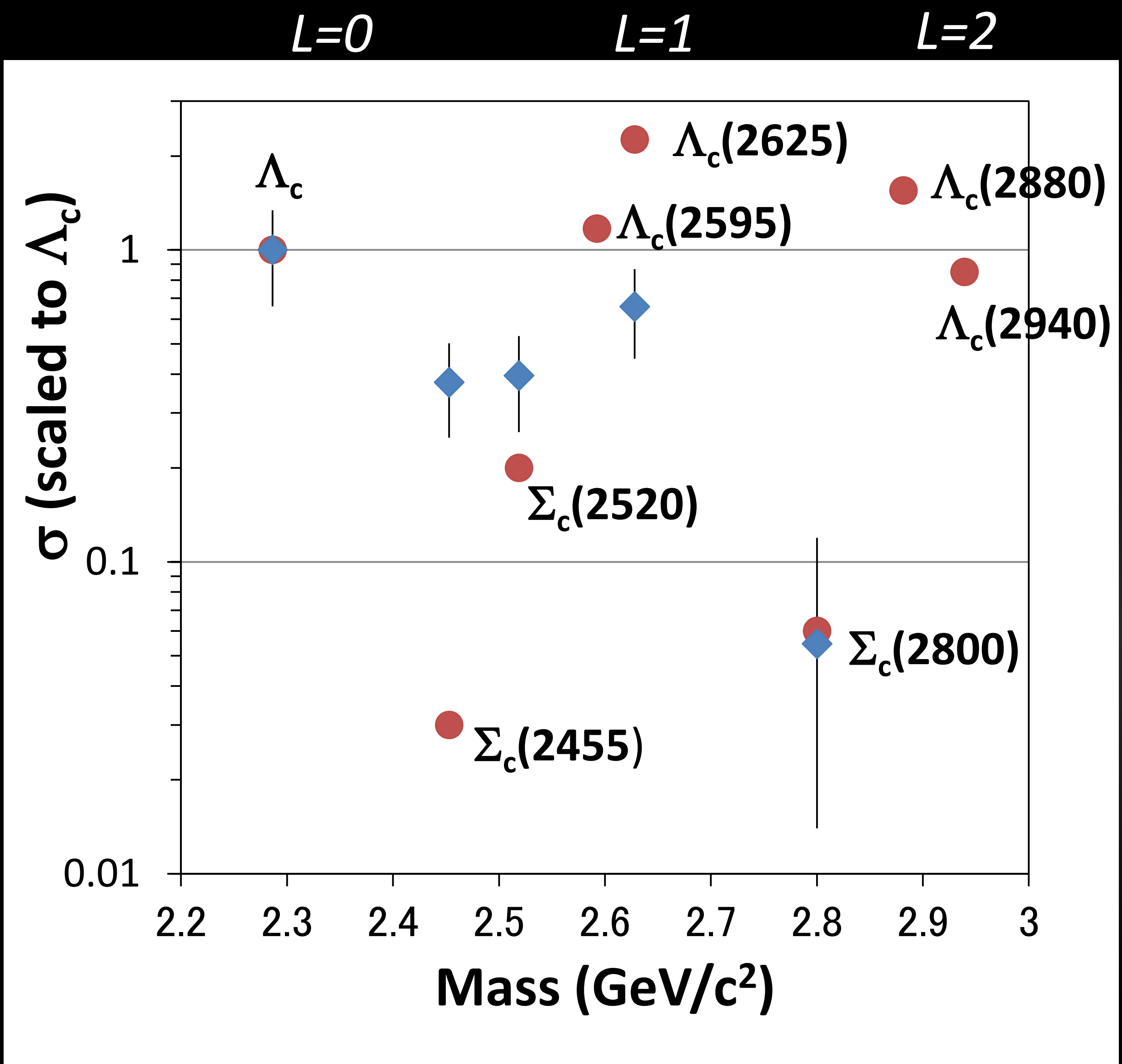
charm

strange



L=0 *L*=1

Comparison of production rates



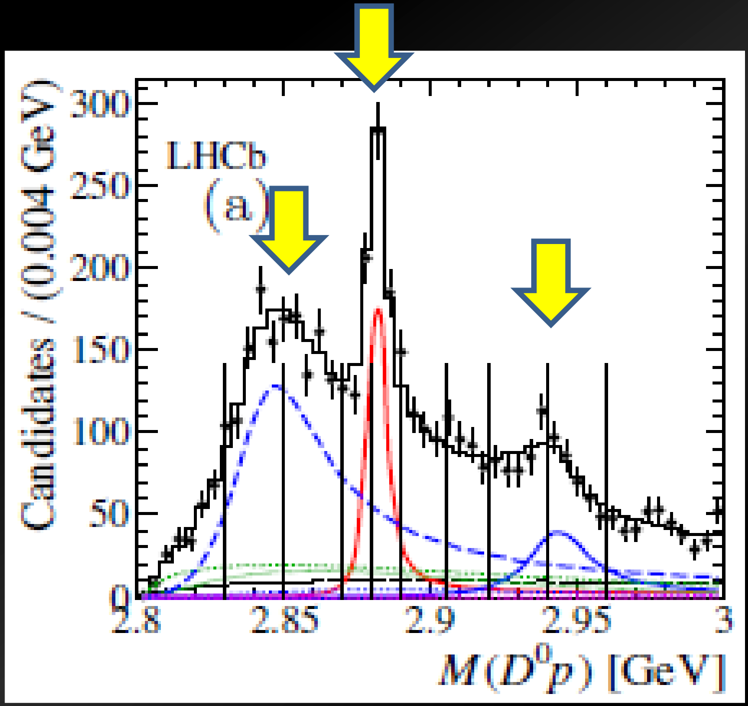
● $p(\pi^-, D^{*-})Y_c^*$ (Calculation)

◆ e^+e^- *Belle Data* (Hadron2013)

New data from LHCb

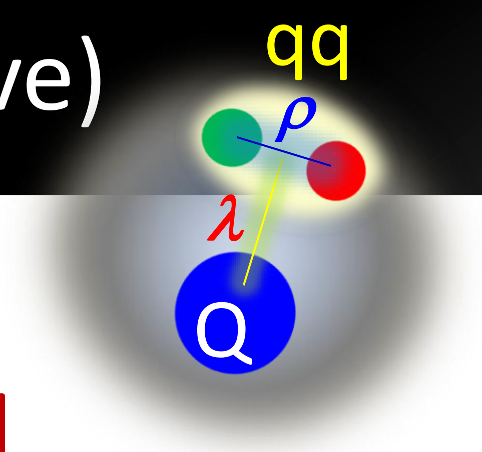
J. High Energ. Phys. (2017) 2017

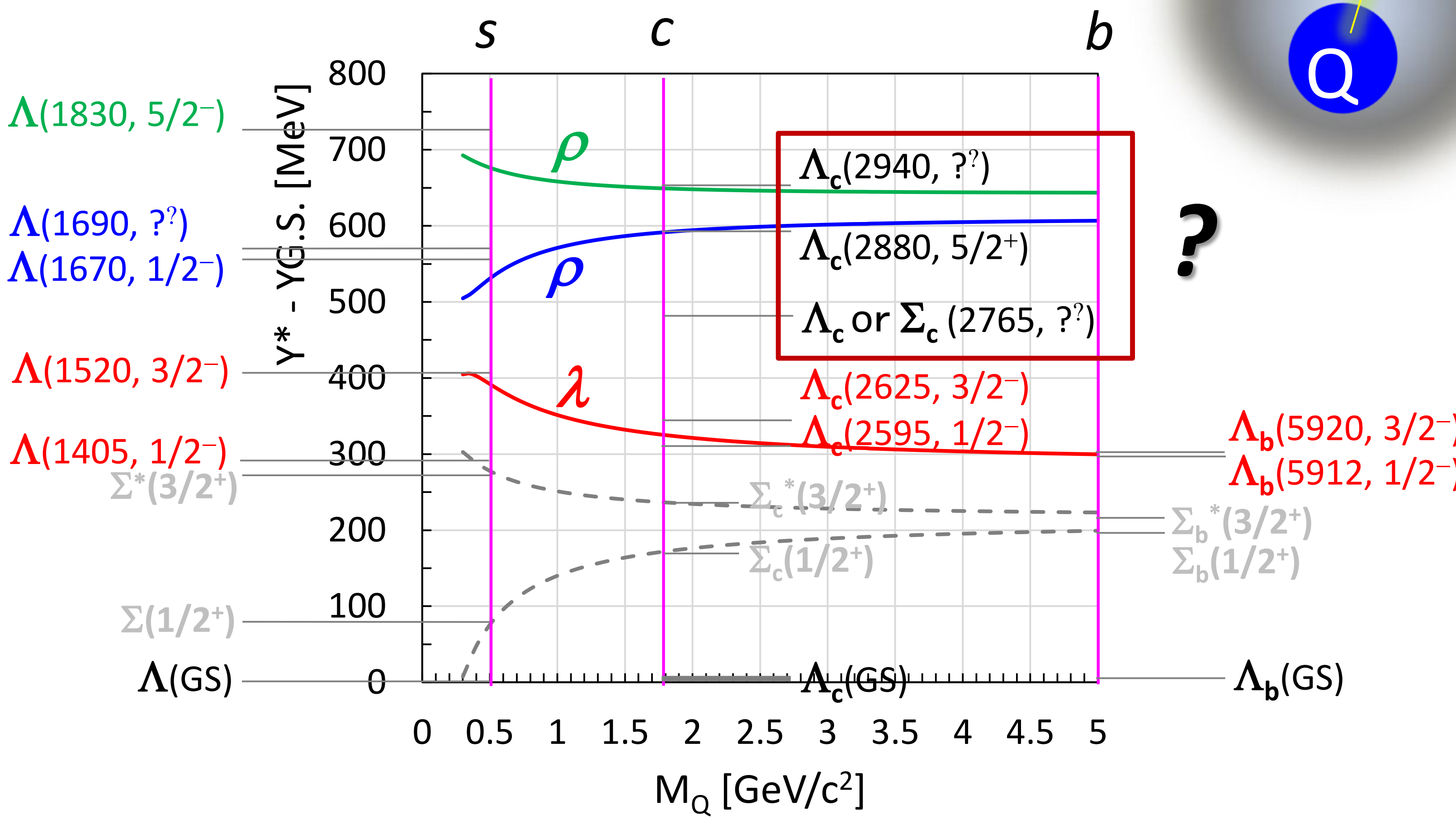
- $D^0 p$ invariant mass in $\Lambda_b \to D^0 p \pi^-$
  - $\Lambda_c(2940)$
    - likely 3/2-, (acceptable 1/2, 7/2)
  - $\Lambda_c(2880)$
    - 5/2+ confirmed
  - $\Lambda_c(2860)$
    - likely 3/2+, new D-wave resonance?



- Production rates of these states in $p(\pi^-, D^{*-})Y_c^*$ tell us:
  - if $\Lambda_c(2940)$ is an *L*=3 state (λ mode).
  - if $\Lambda_c(2880)$ and $\Lambda_c(2860)$ are *LS* partners of *L*=2 (λ modes).

Lambda Baryons (P-wave)

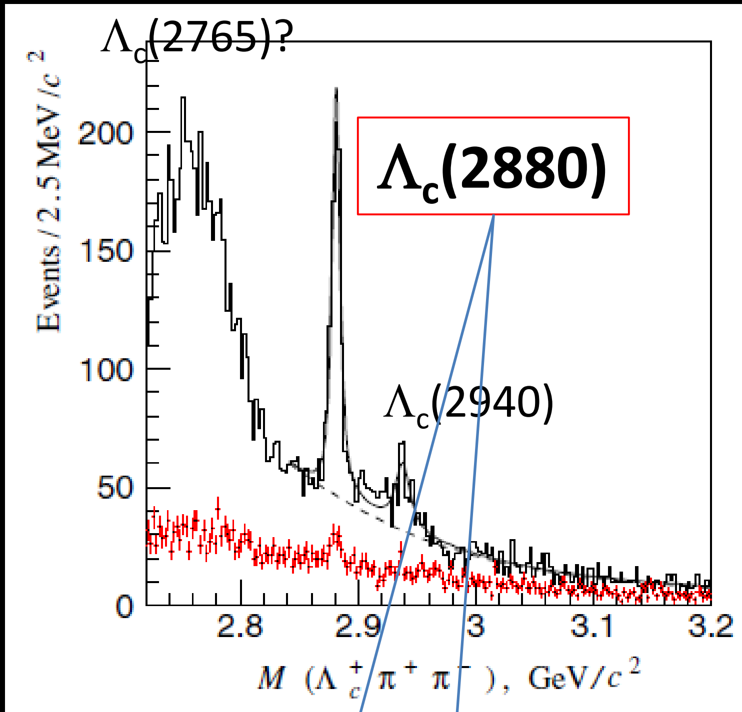


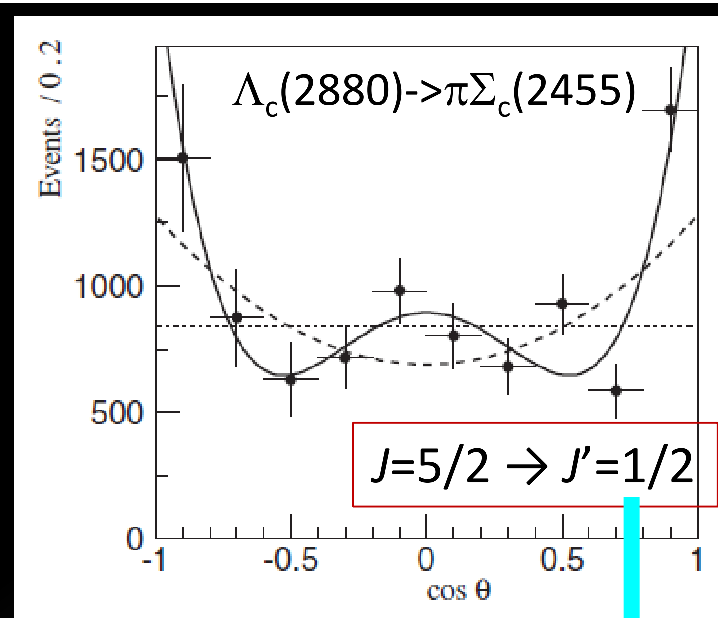


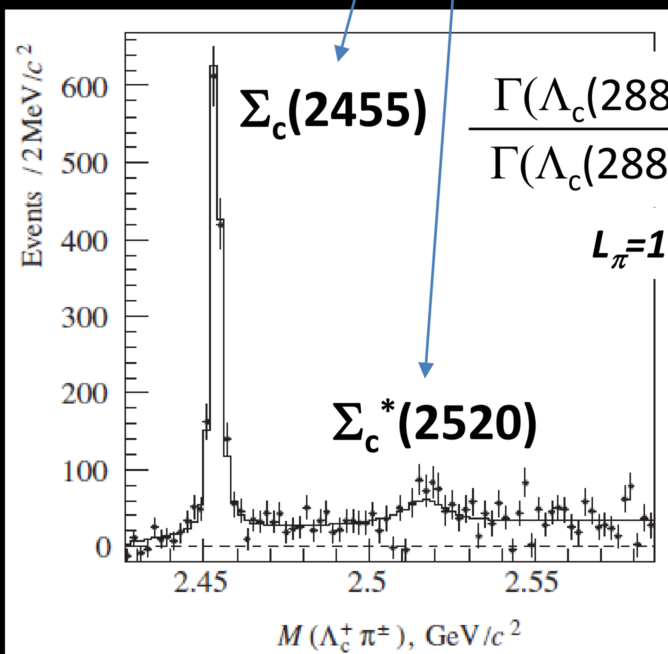
non-rel. QM: $H=H_0+V_{conf}+V_{SS}+V_{LS}+V_T$

ρ–λ mixing (cal. By T. Yoshida)

Lc(2880)Belle, PRL98, 262001('07)







$$\frac{\Gamma(\Lambda_c(2880)\to\pi\Sigma_c^*(2520))}{\Gamma(\Lambda_c(2880)\to\pi\Sigma_c(2455))} = \mathbf{0.23}$$

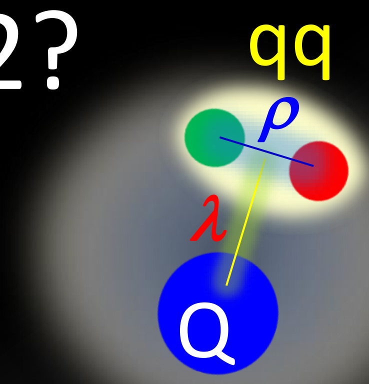
$L_\pi=1$ contribution may affect…

$L_\pi=3$ transition

$J^P=5/2^+$ for $\Lambda_c(2880)$

Is it a D-wave Lambda-c Baryon?
If so, where is a spin partner ?

Does Λ(2880) have L=2?



- P-wave transition seems to be suppressed in $\Lambda_c(2880)^{\frac{5}{2}+} \rightarrow \Sigma_c^*(2520)^{\frac{3}{2}+} + \pi(0^-)$.
- It would be forbidden only in the case of $J_{BM}^P = 3^+$:
  - Negative party states "5/2-" have large widths.

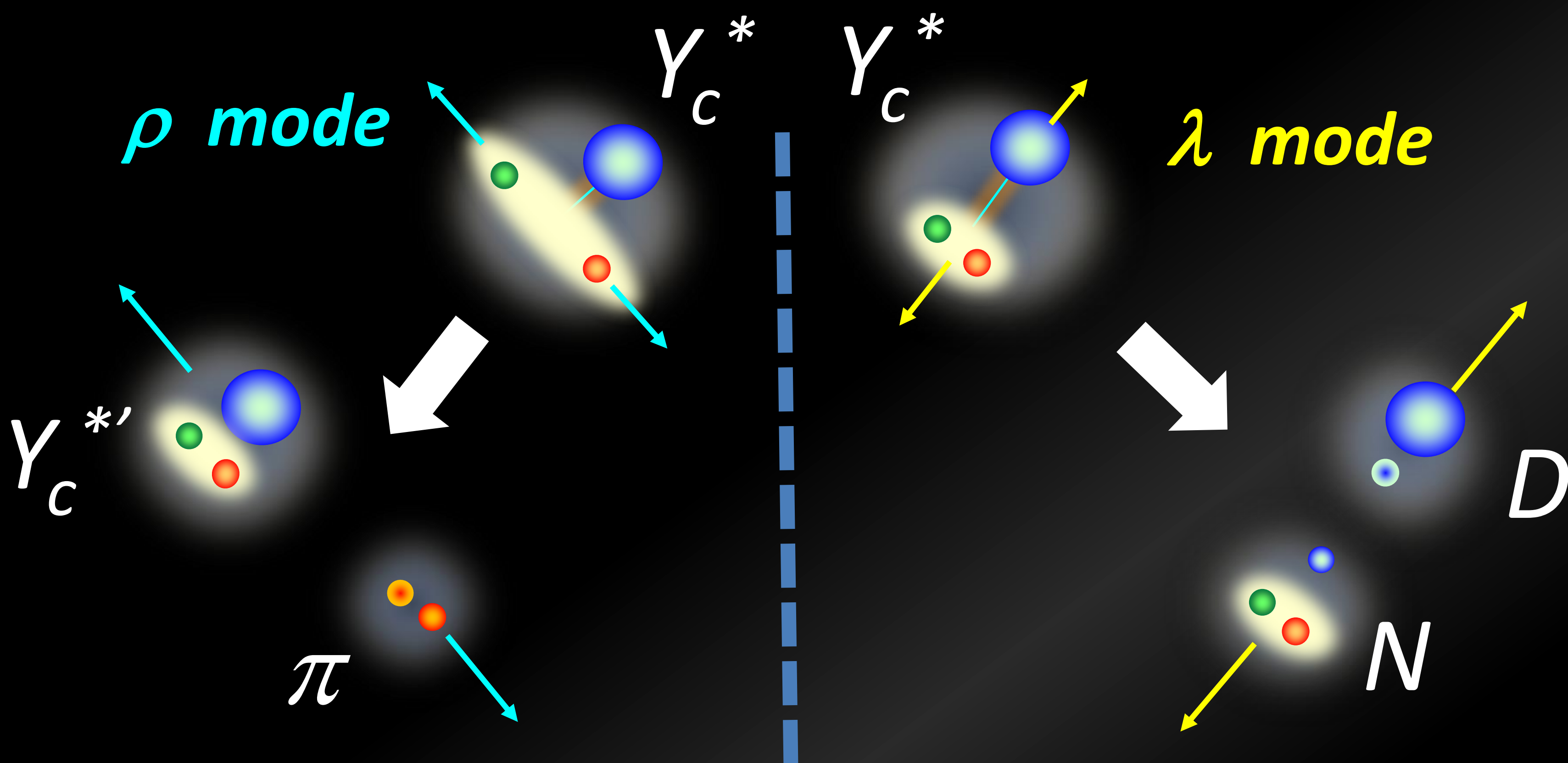
    (H. Nagahiro et al., PRD95 (2017) no.1, 014023)

Λ_c(2880) 5/2+	λλ	λρ	ρρ
color	Asymm.		
Isospin	Asymm. (I=0)		
Diquark spin Diquark orbit	Asymm. 0 Symm. 0	Symm. 1 Asymm. 1	Asymm. 0 Symm, 2
Lambda orbit	2	1	0
J_{BM}^P	2+	1+, 2+, 3+	2+

Σ_c^*(2520) 3/2+
Asymm
Symm. (I=1)
Symm. 1 Symm, 0
0
1+

- $\Lambda_c(2880)^{\frac{5}{2}+}$ is likely to be λρ mode (λ=1, ρ=1).
  - Since, Naively, Ex(λλ)<Ex(λρ), Ex(2880) is too low if it is a λρ state.
- This can be tested by measuring its production rate.

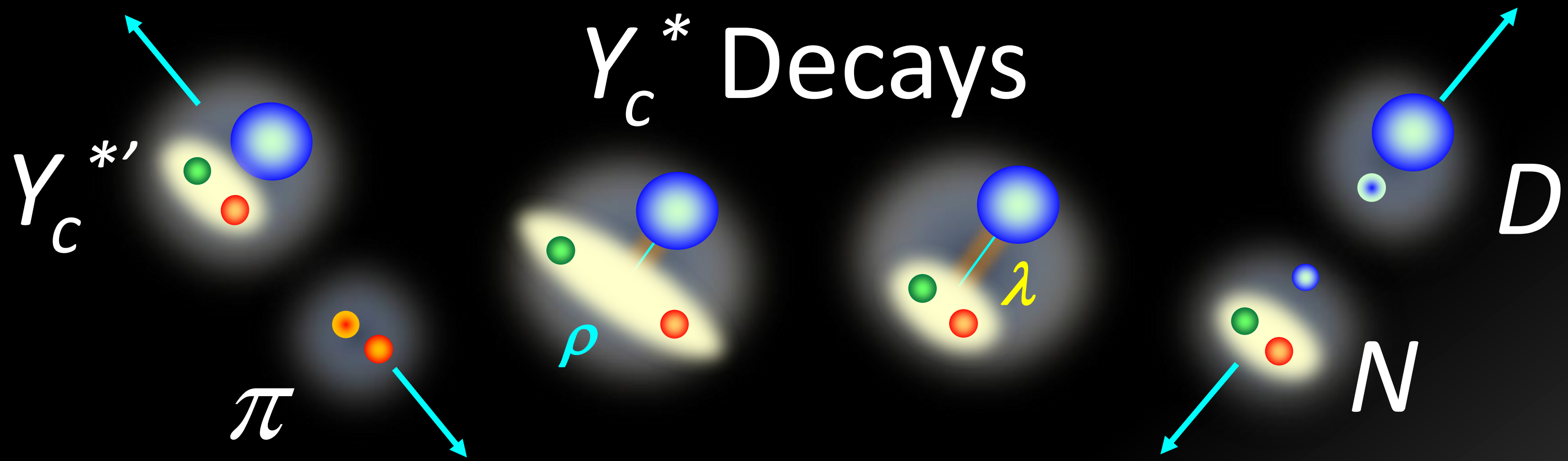
Y_c^* Decay Branching Ratio



$\Gamma(Y\pi) > \Gamma(DN)$

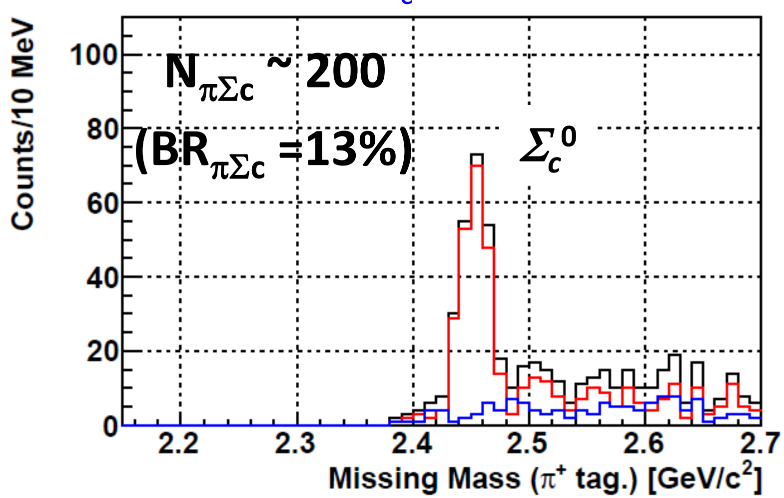
$\Gamma(DN) > \Gamma(Y\pi)$

$Y_c{}^*$ Decays

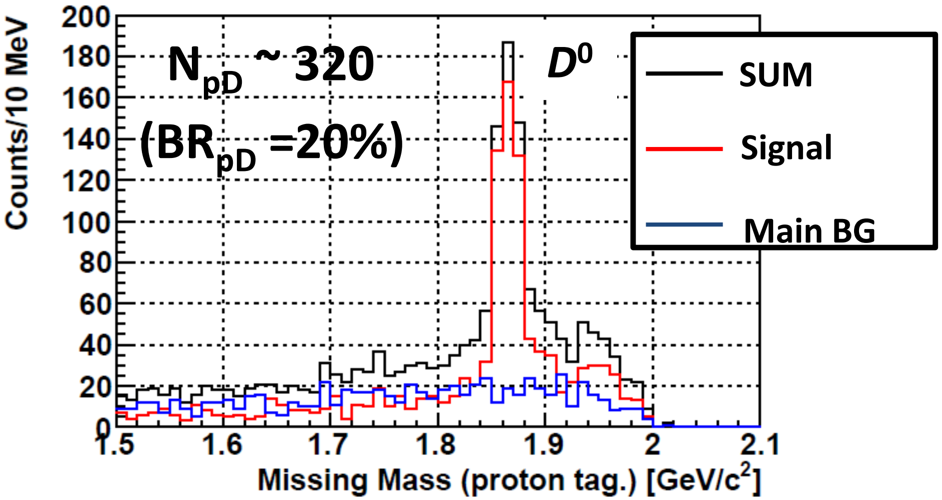


$\Lambda_c(2940) \to \Sigma_c{}^0\,\pi^+$

with $\Lambda_c{}^+ \pi^+ \pi^-$ selected



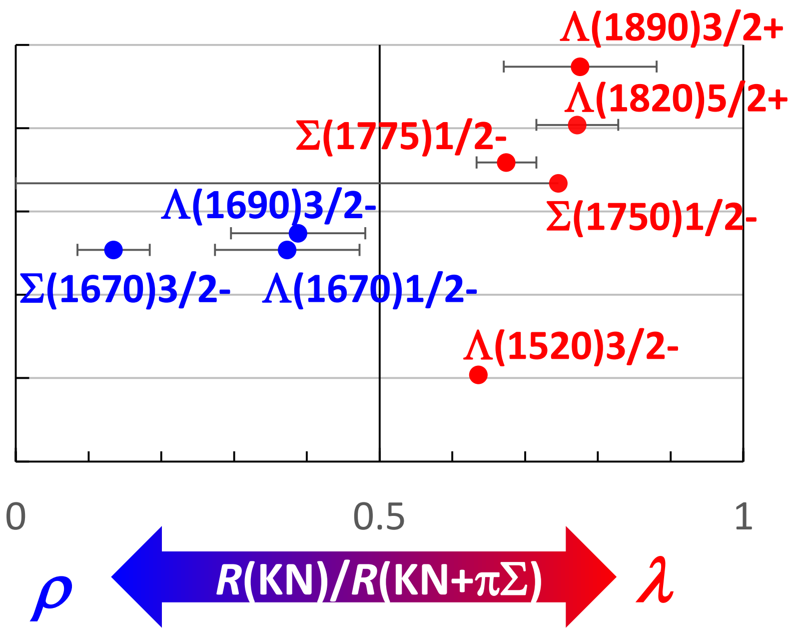
$\Lambda_c(2940) \to p\, D^0$



* Branching ratios: Diquark corr. affects $\Gamma(\Lambda_c{}^* \to pD)/\Gamma(\Lambda_c{}^* \to \Sigma_c\pi)$.

Hint in $R(NK)/R(\pi\Sigma)$

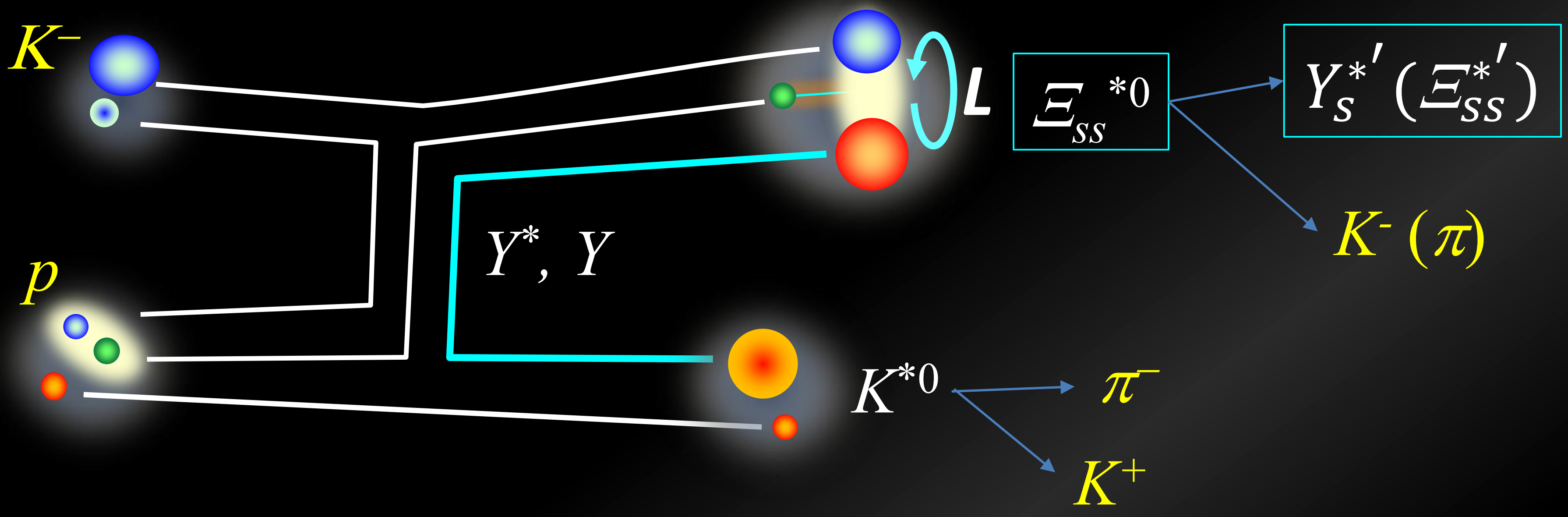
PDG Data



- Decay ratios in known hyperons SUGGEST the λ/ρ mode states
- λ/ρ mode ID by productions correlate w/ Decay Ratios
  → to be established

- Hyperon data indicate mode dependence
  → Errors should be improved.
- No data in charmed baryons

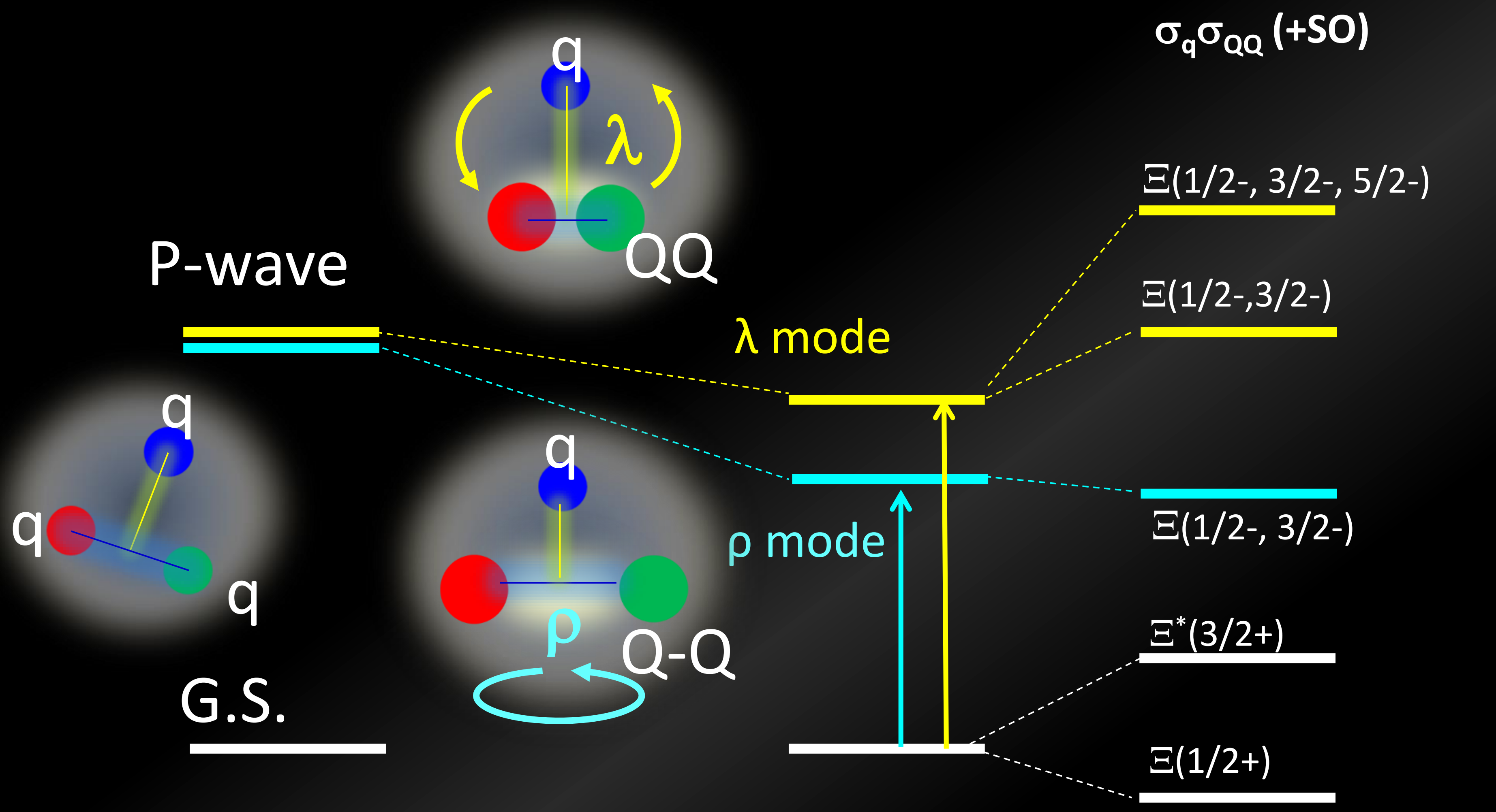
Double Strange Baryon Spectroscopy Using Missing Mass Techniques



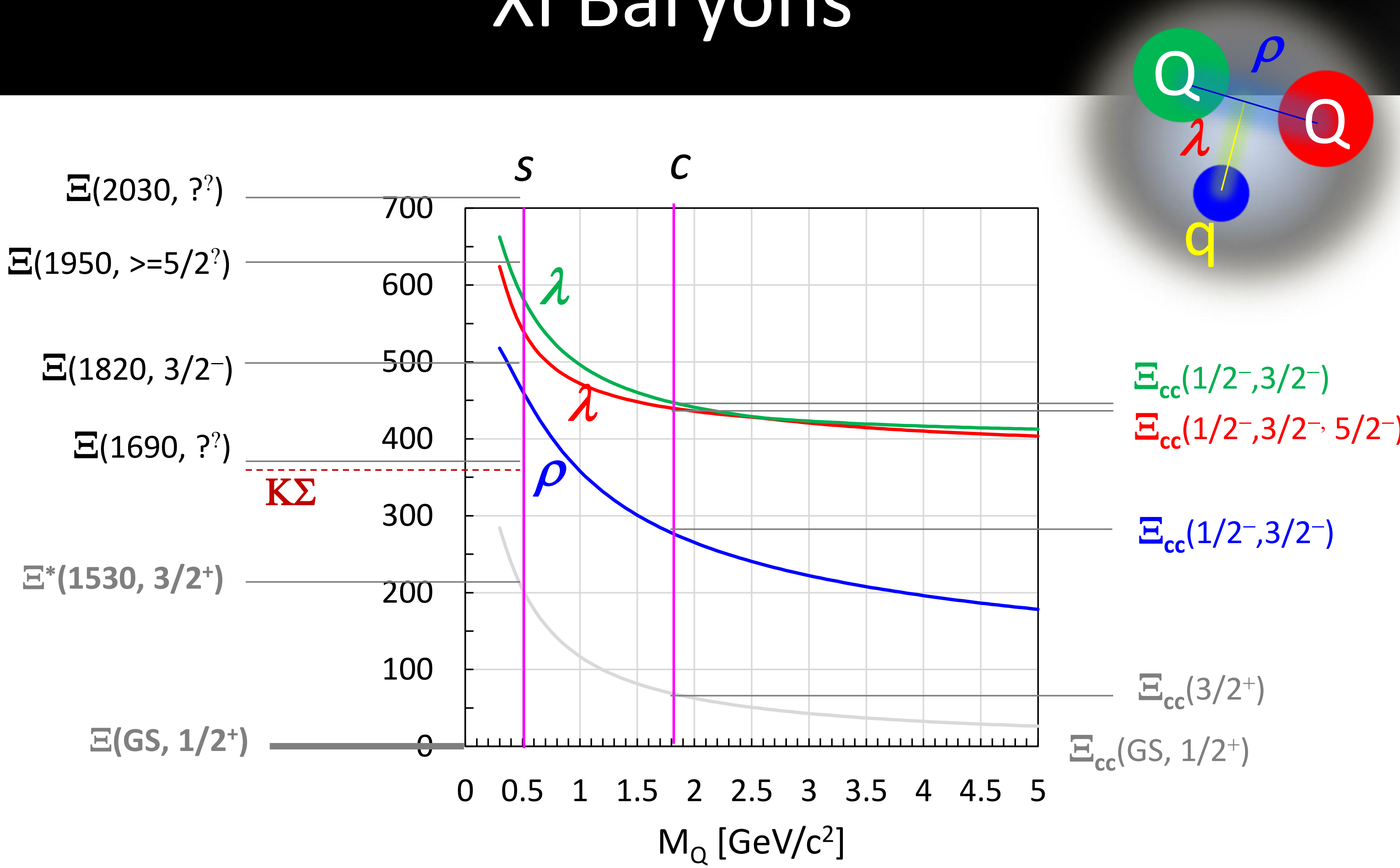
- ✓ Production and Decay reflect [QQ] correlation…
- ✓ *U-channel production may be dominant…*

Level Structure of double-Q baryons

- λ and ρ mode excitations interchange



Xi Baryons



non-rel. QM: $H=H_0+V_{conf}+V_{SS}+V_{LS}+V_T$

ρ–λ mixing (cal. By T. Yoshida)

Little is known for Ξ

Threshold

ΩK(2166)

ΣK*(1983)

Σ*K(1878) ΛK*(1908)

Ξ*π(1665) ΣK(1685)

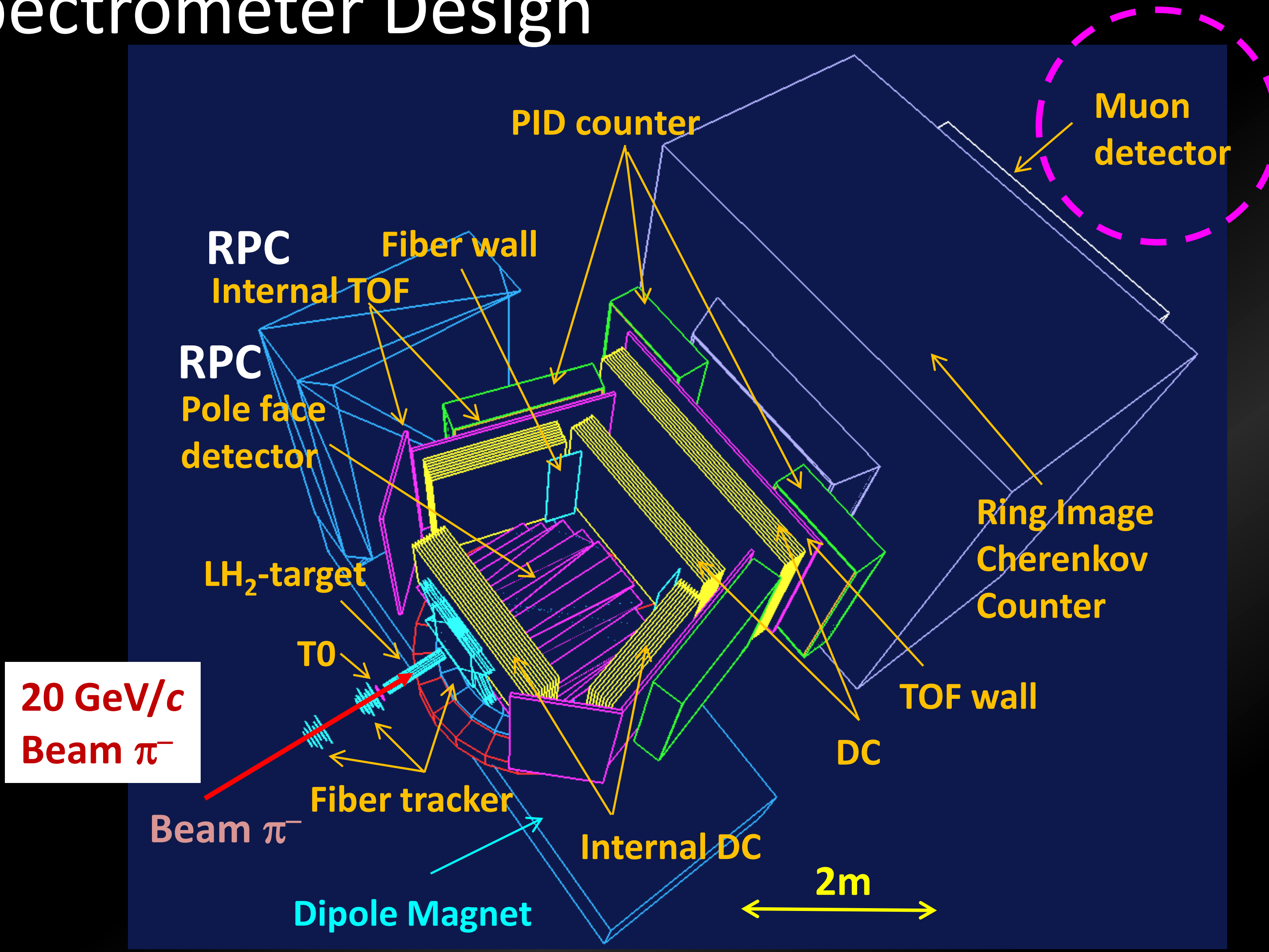
ΛK(1610)

Ξπ(1450)

	JP	rating	Width [MeV]	→Ξπ [%]	→ΛK [%]	→ΣK [%]	
Ξ(2500)	??	1*	150?				
Ξ(2370)	??	2*	80?				ΩK~9±4
Ξ(2250)	??	2*	47+-27?				
Ξ(2120)	??	1*	25?				
Ξ(2030)	>=5/2?	3*	20^{+15}_{-5}	small	~20	~80	
Ξ(1950)	??	3*	60+-20	seen	seen		
Ξ(1820)	3/2-	3*	24^{+15}_{-10}	small	Large	Small	
Ξ(1690)	??	3*	<30	seen	seen	seen	
Ξ(1620)	??	1*	20~40?				
Ξ(1530)	3/2+	4*	19	100			

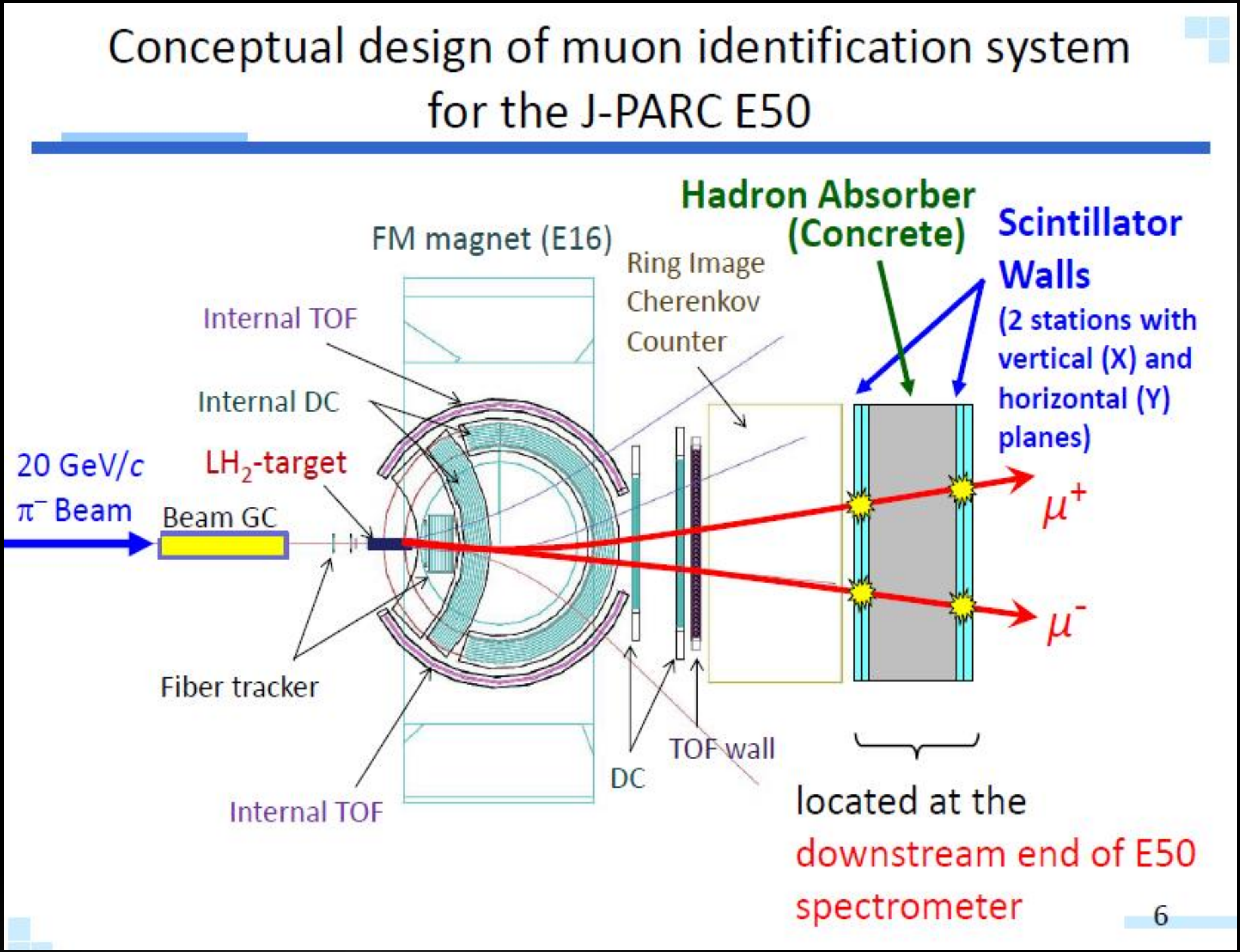
- Narrow width: ~ a few 10 MeV
- Large production cross section: ~ 1 μb

Spectrometer Design



Muon ID

By W.C. Chang, T. Sawada (Academia Sinica)

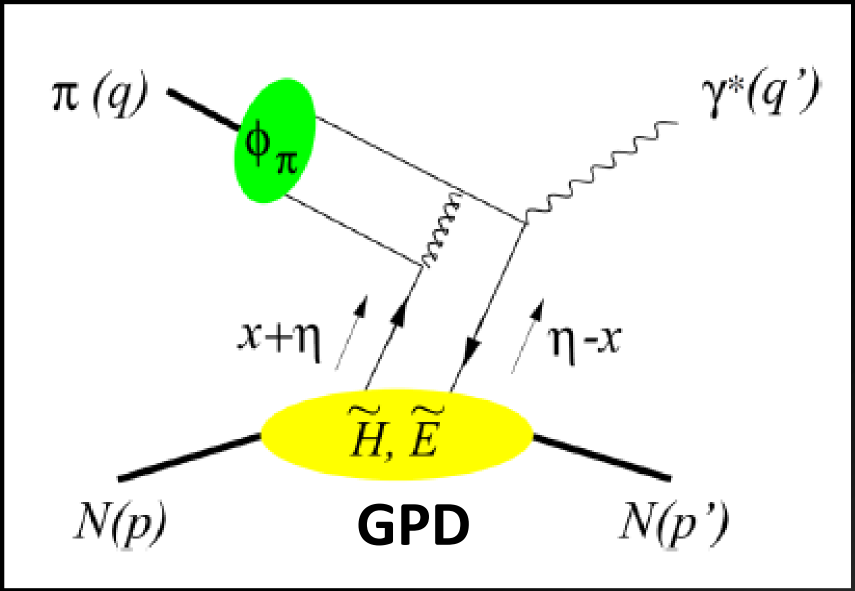


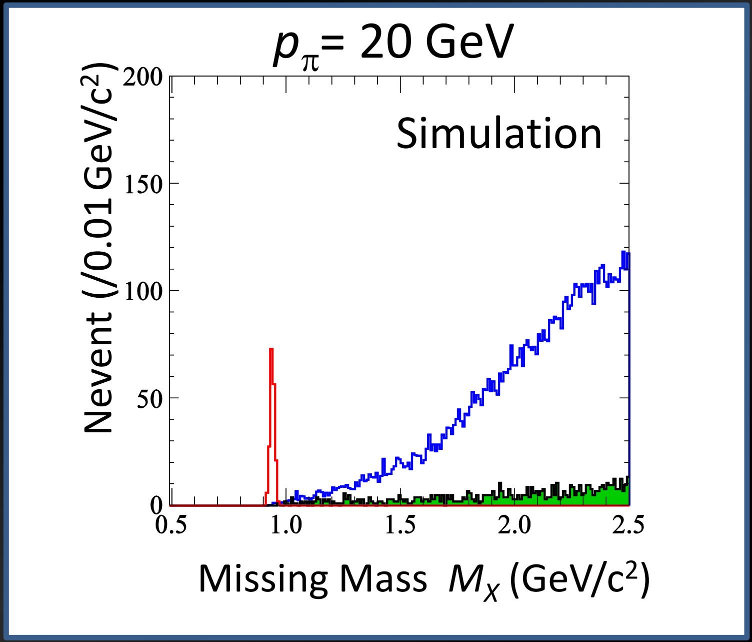
T. Sawada, W.C. Chang et al., PRD93, 114034(2016)

Hadron Tomography w/ Exclusive Drell-Yan

CHARM Spectrometer + Muon Detector at High-p BL

$$\pi^- + p \rightarrow \mu^+ + \mu^- + n$$





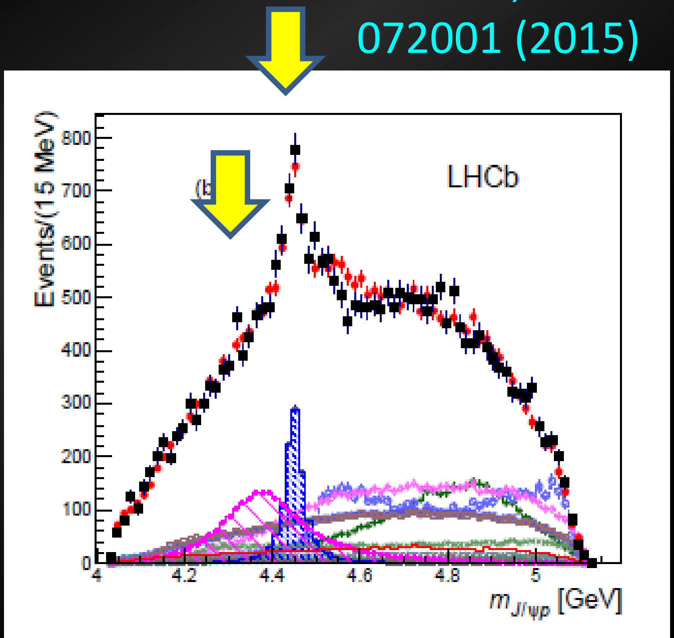
$$\pi^- + p \rightarrow \mu^+ + \mu^- + \Delta^0$$
$$K^- + p \rightarrow \mu^+ + \mu^- + Y^*$$

$N \rightarrow \Delta$ (Y^*) TDA

$P_c(4380), P_c(4450)$ *from LHCb*

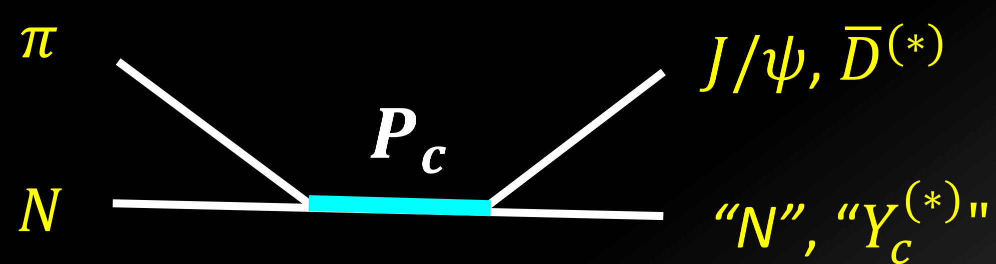
- Found in $J/\psi p$ invariant mass in $\Lambda_b \to J/\psi p K^-$
  - $m_{4380} = (4380 \pm 8 \pm 29)\mathrm{MeV},\ \Gamma = (205 \pm 18 + 86)\mathrm{MeV}$
    $m_{4450} = (4449.8 \pm 1.7 \pm 2.5)\mathrm{MeV},\ \ \Gamma = (39 \pm 5 + 19)\mathrm{MeV}$
  - J^P: (3/2-, 5/2+) most likely, respectively
    - (3/2+, 5/2-), (5/2+,3/2-) are acceptable.
  - Hidden $c\bar{c}$ state, P_c^0 may exist.
- decay branch?
  - $J/\psi + N, \bar{D}^{(*)} + Y_c^{(*)}$
- Its spin family?

PRL 115, 072001 (2015)



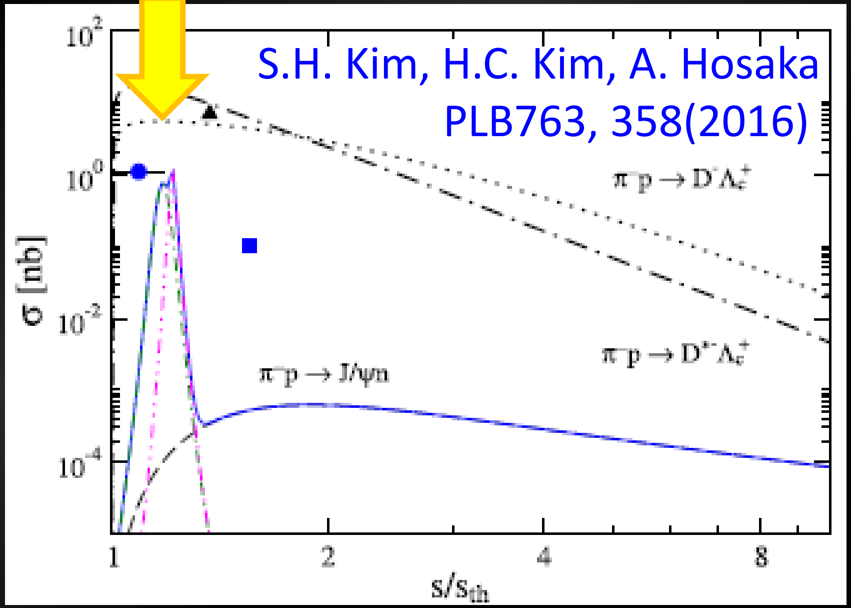
$P_c(4380), P_c(4450)$ *at J-PARC*

- P_c^0 : s-channel formation with 10 GeV/c π^- on p



- Cross Section: <1 nb?
  - $\Gamma_{\pi N}/\Gamma_{tot}$~ 10^{-5}
  - $\Gamma_{j/\psi p}/\Gamma_{tot}$~0.05

$$\sigma_L = (2L+1)\frac{\pi}{k^2}\frac{\Gamma_{\pi N}\Gamma_{J/\psi p}}{(E-m)^2+\Gamma_{tot}^2/4}$$



Thank you for your attention