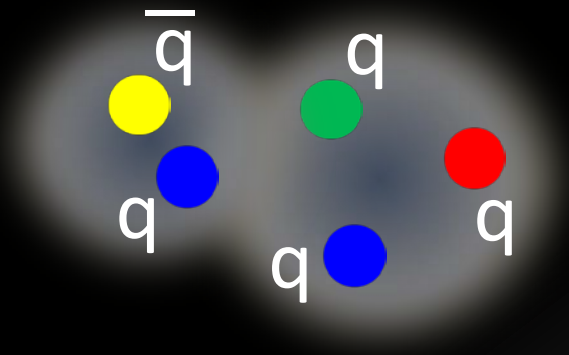
Charmed Baryon Spectroscopy via the (π, D^{*-}) reactions

H. Noumi
Research Center for Nuclear Physics
Osaka University
for the P50 collaboration

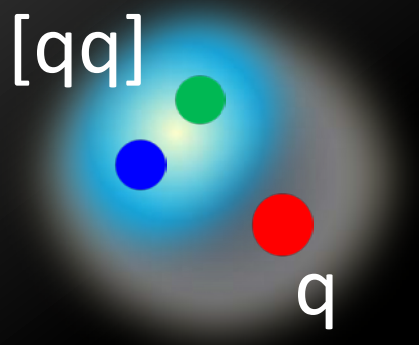
What are good building blocks of Hadrons?

Constituent Quark



hadron (colorless cluster)

Diquark?
(Colored cluster)



Diquarks

Color-Magnetic Interaction of two quarks

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

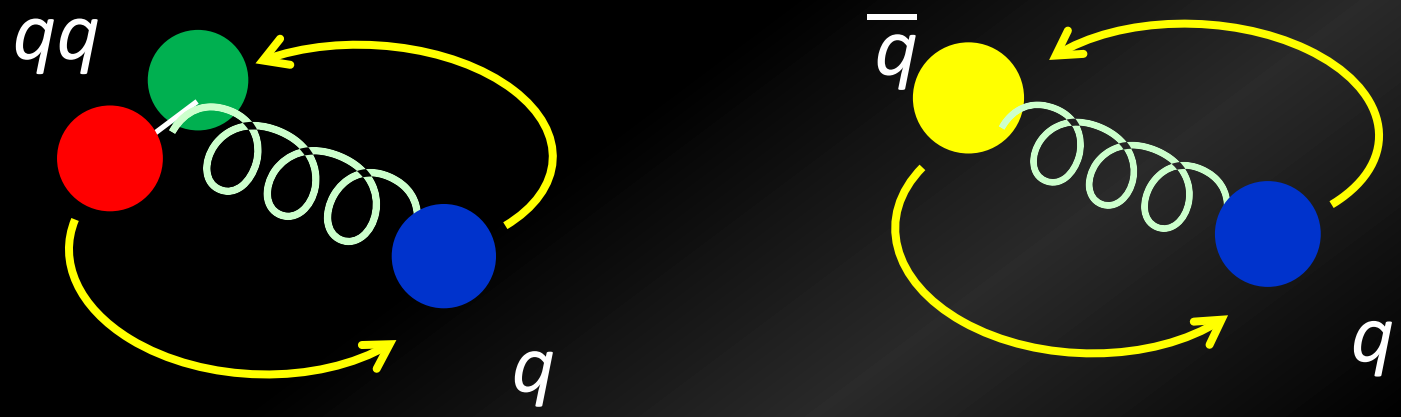
"Good Diquark": Strong Attraction

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

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

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/$\overline{q}$-q increases as L increases.

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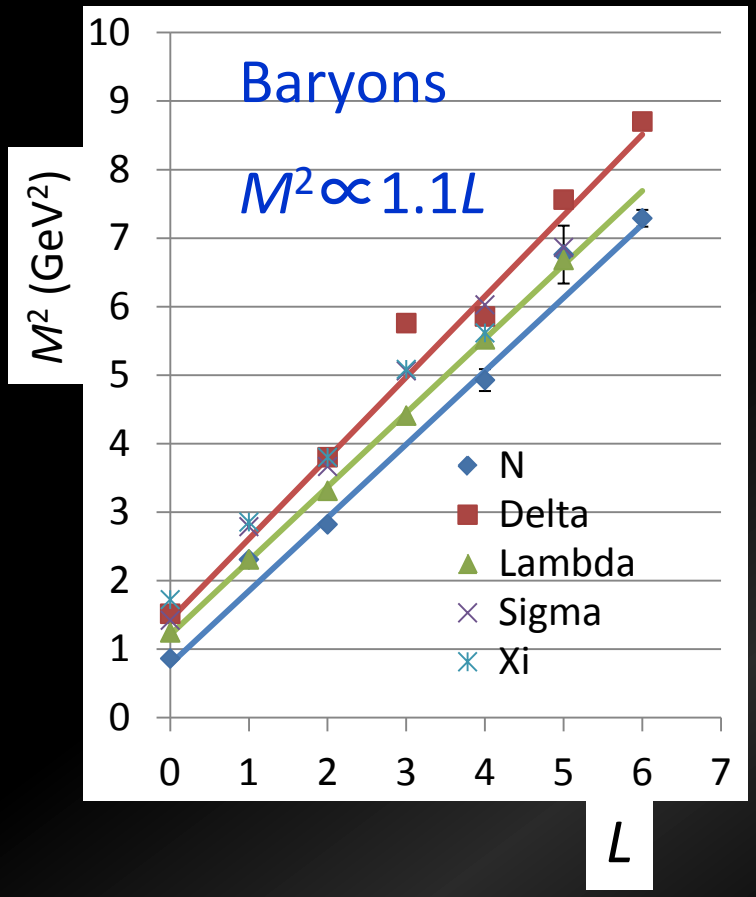

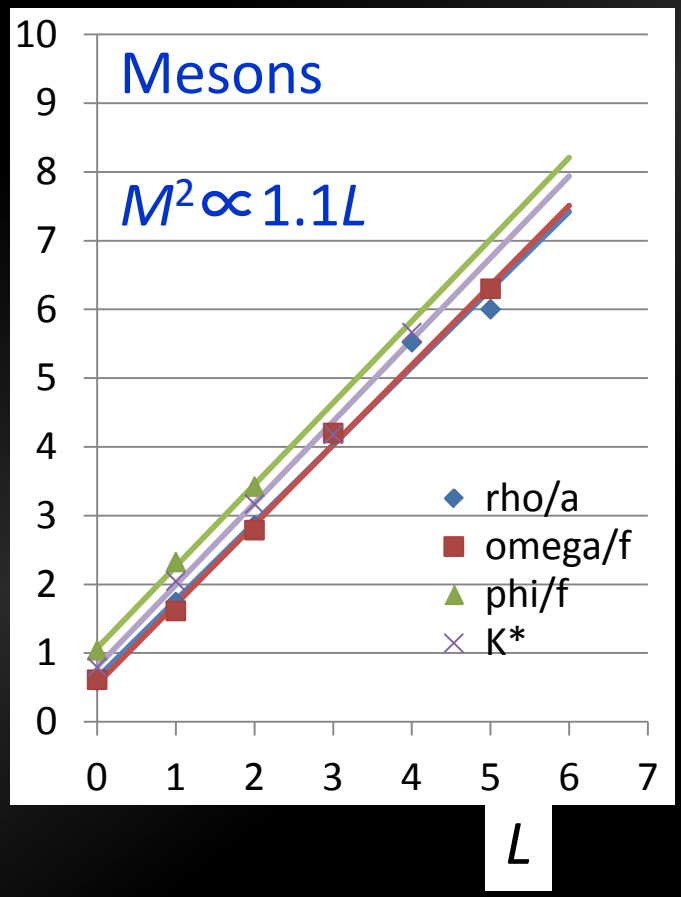

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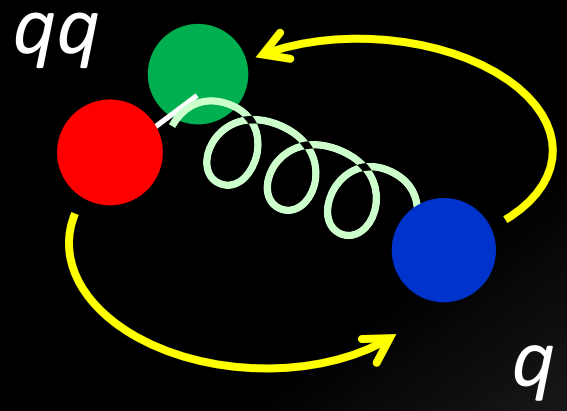
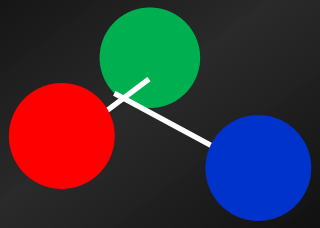
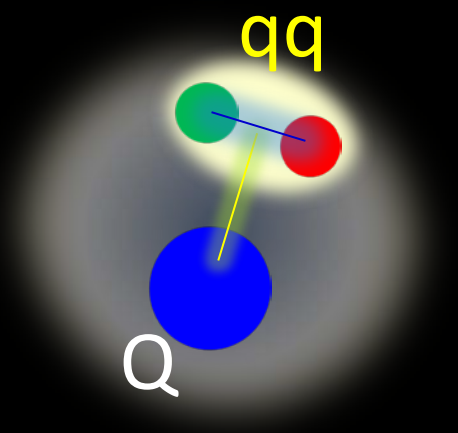


"diquark"
in low-lying modes



Charmed Baryon



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

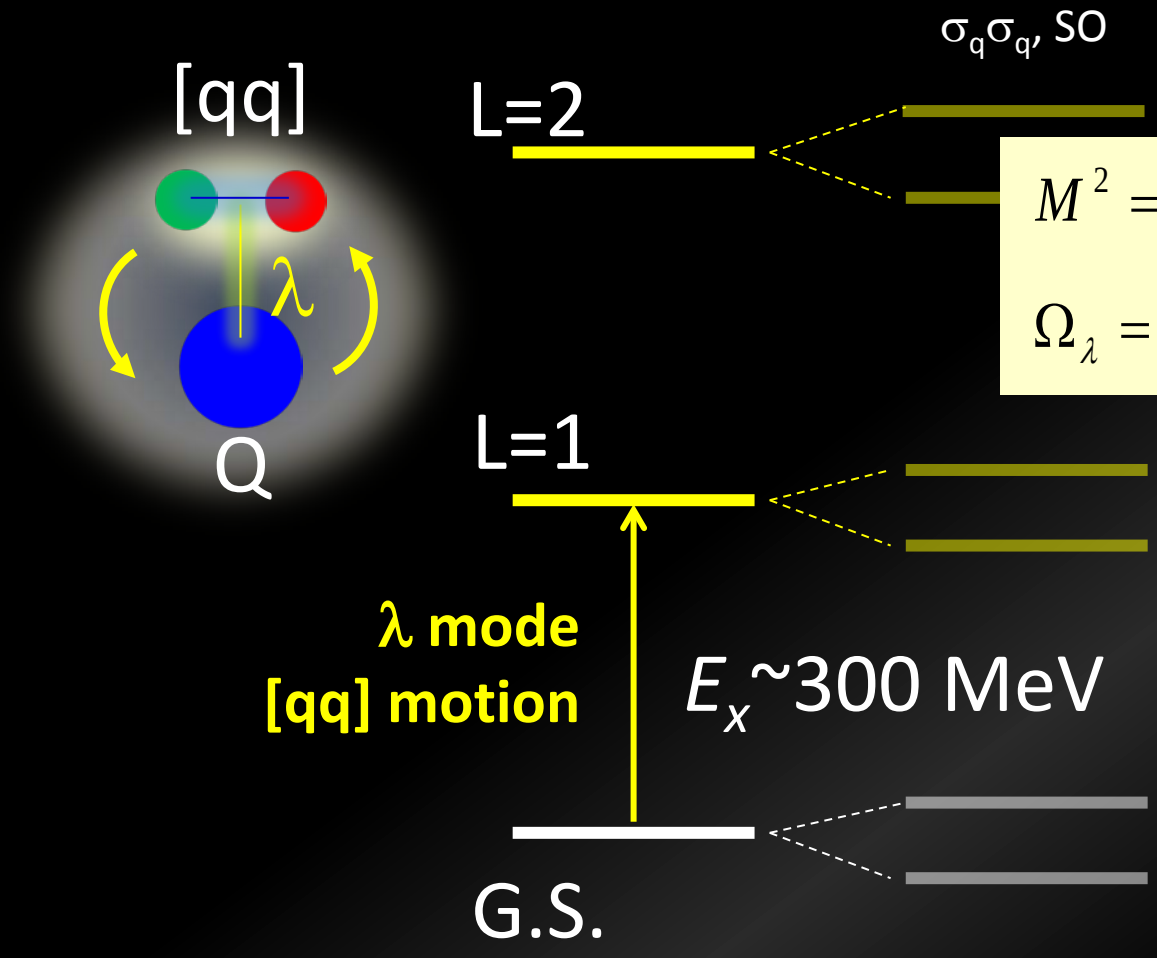
Weak CMI with a heavy Quark

- [qq] is well Isolated and developed

- Level structure of Y_c^* provides diquark properties
  - "diquark mass"

Precision measurement of collective [qq] orbital E_x gives a [qq] mass

Covariant Oscillator QM w/ Universal Spring [PTP 91, 775('94)]



$$M^2 = \Omega_\lambda L + \Omega_\rho L + M_0$$

$$\Omega_\lambda = 2K^{1/2}\sqrt{2(M_Q + m_{qq})^3/(M_Q m_{qq})}$$

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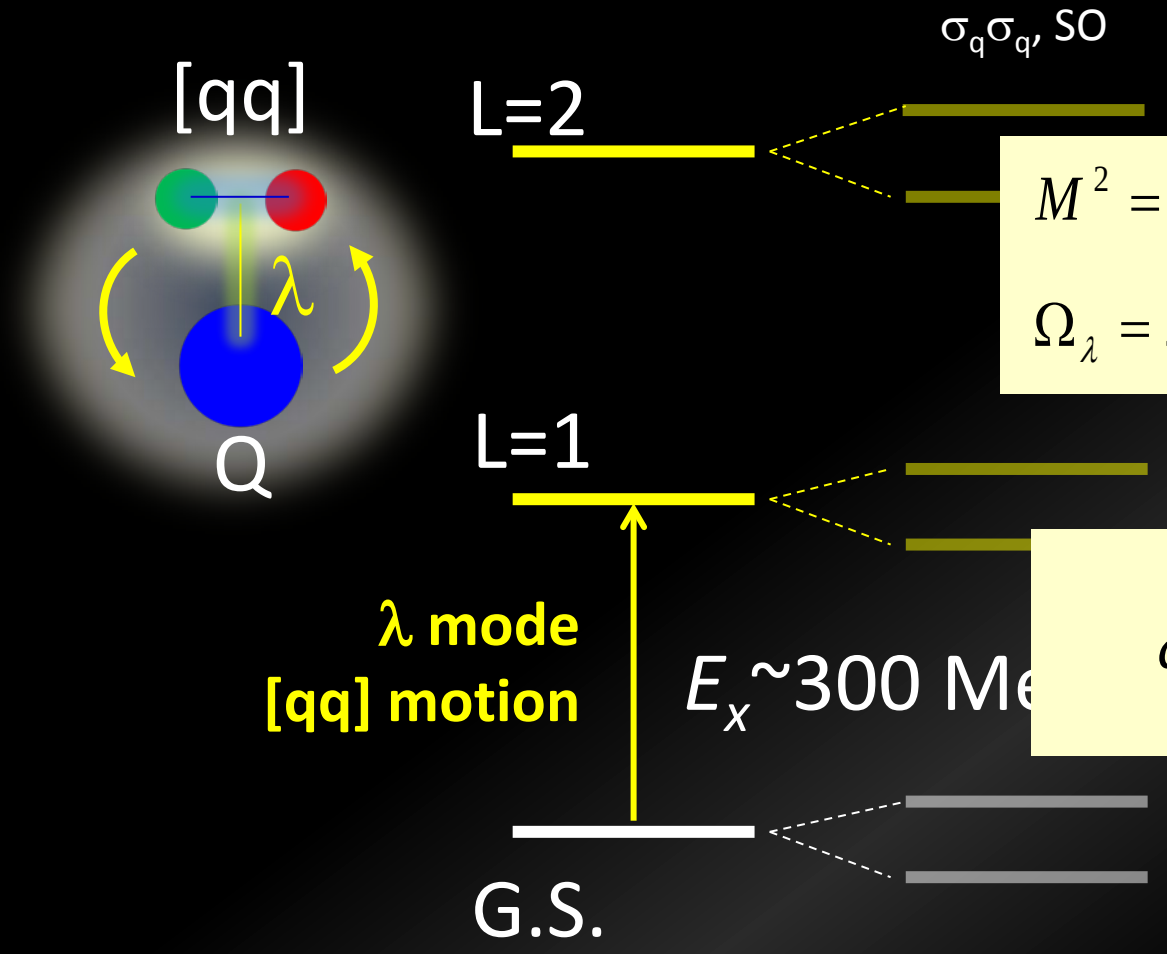

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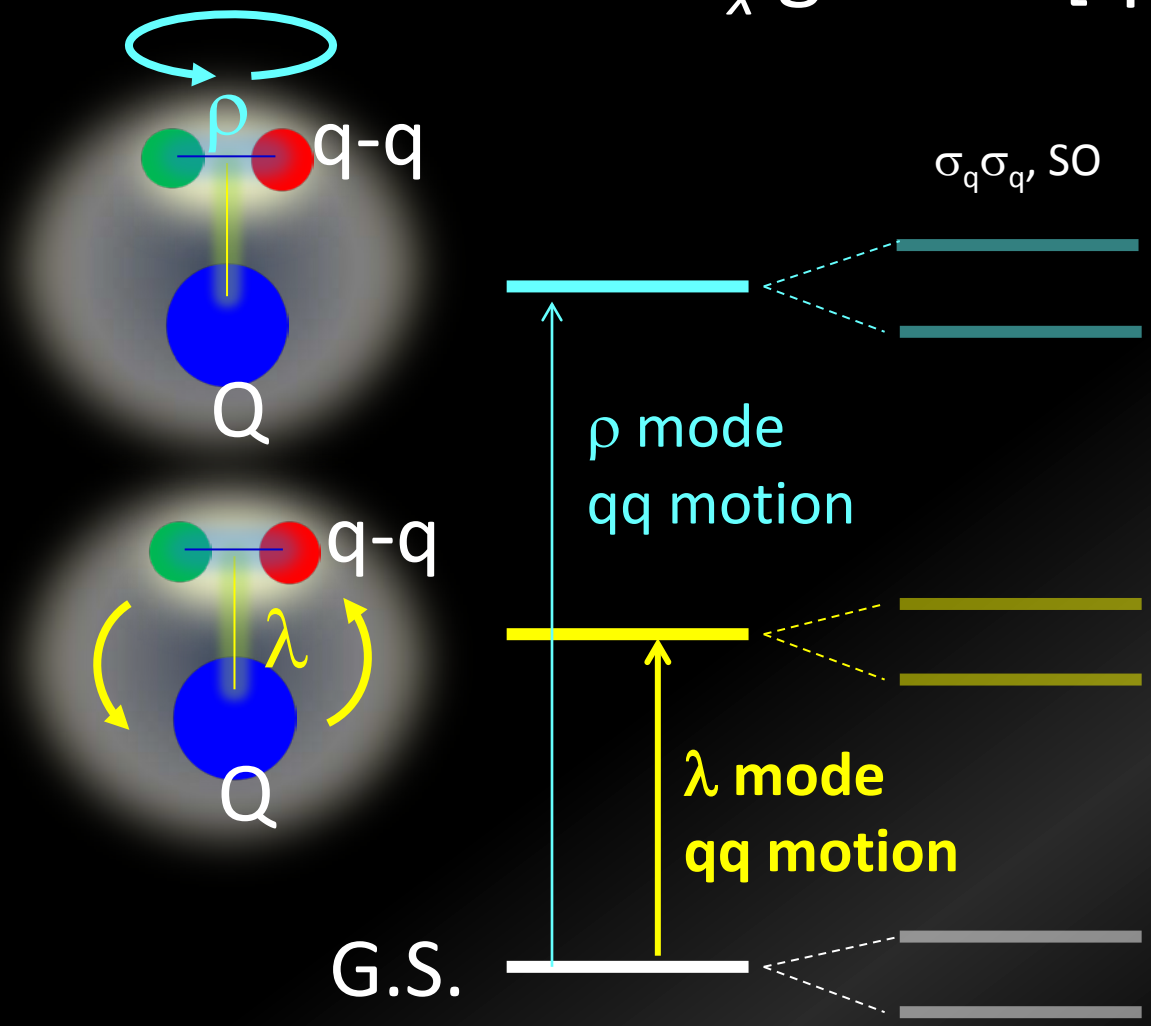
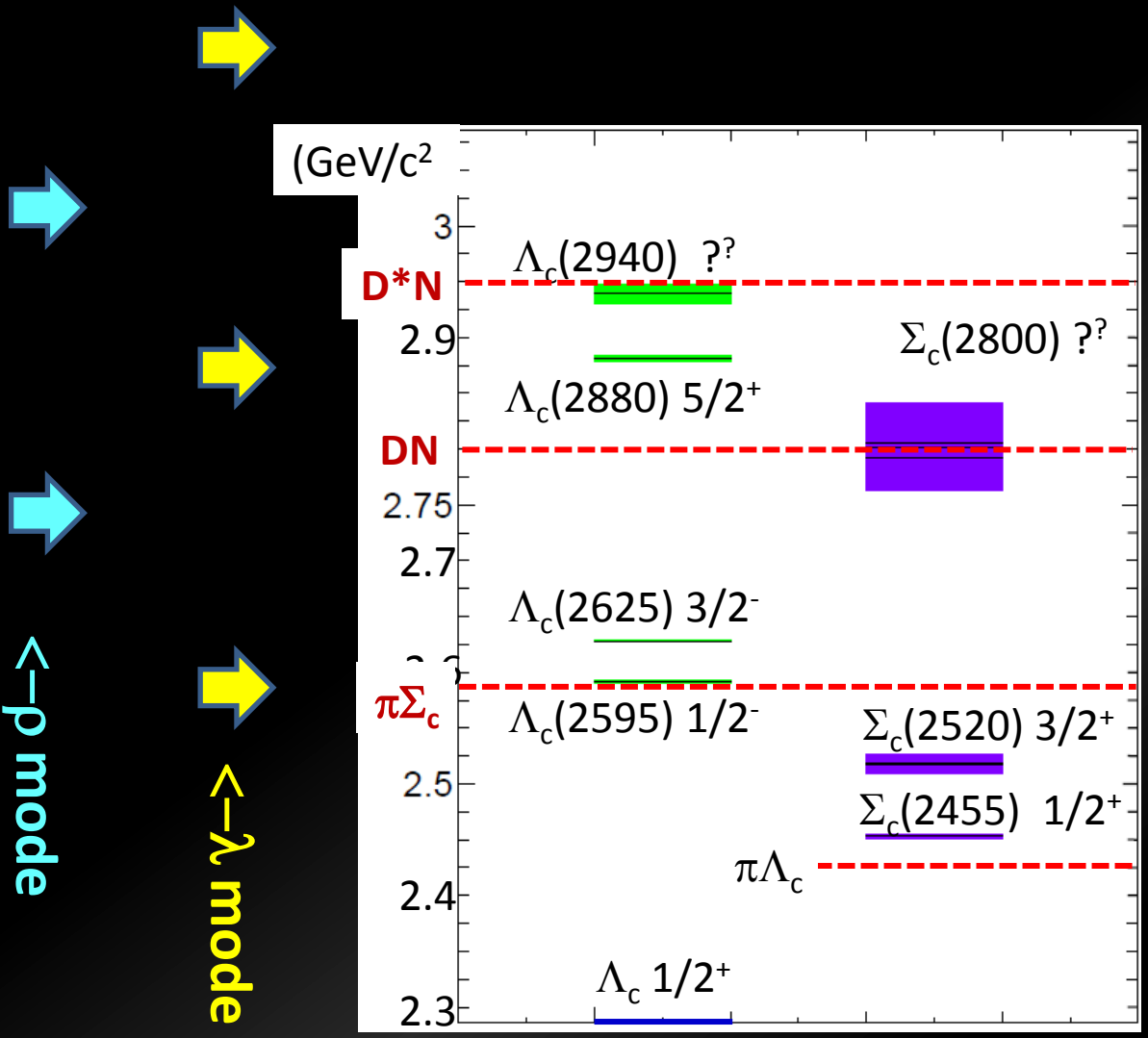
$$dE_x \sim dm_{qq}/30\,[\mathrm{MeV}]$$

Precision measurement of Collective [qq] orbital E_x gives a [qq] mass



Limited # of Charmed Baryons have yet been observed.



What we will measure…

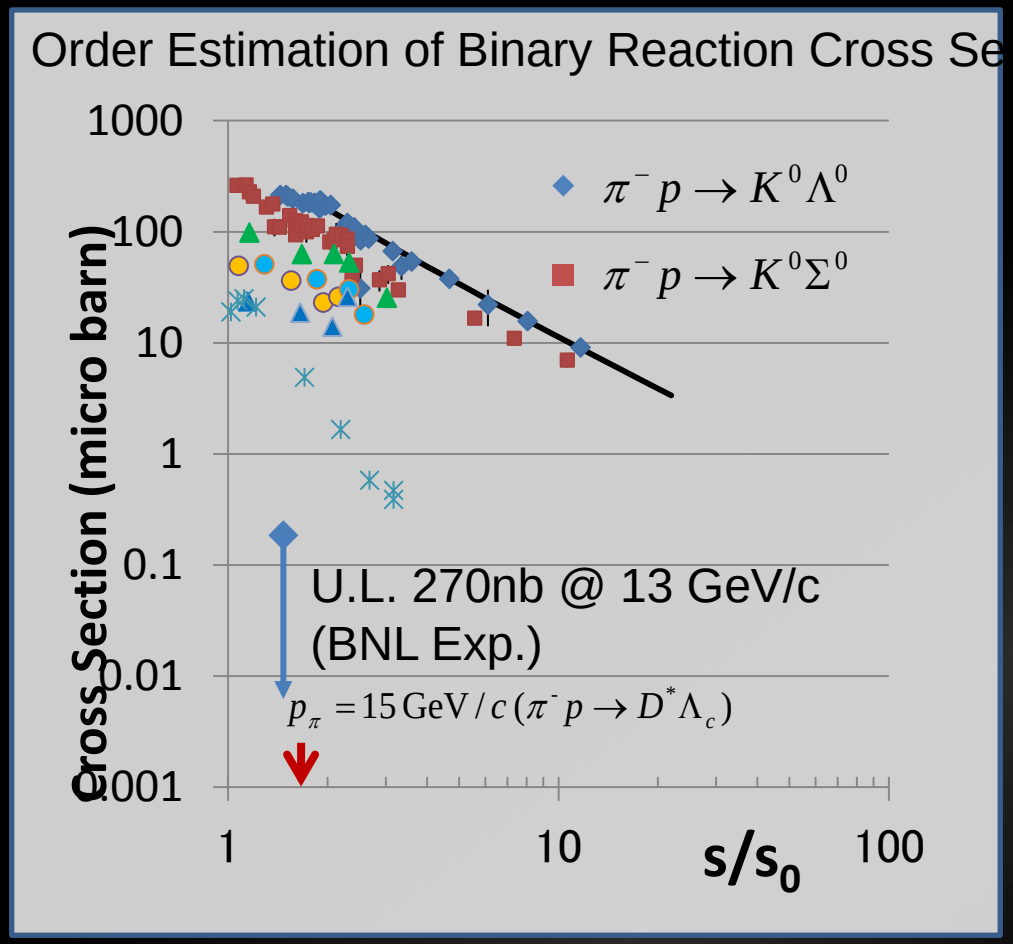
Missing mass spectroscopy via the (π,D*-) reactions.

- Excitation Energies and widths of charmed baryons
  - From the G.S. to highly E.S. of E_x>1 GeV w/ ~5.5 MeV res.
  - Independent of decay final states
- Decay properties of the populated states
  - Strong BG suppressions for the parent states
  - Decay branching ratios (Partial widths)
  - Possible assignment of spins

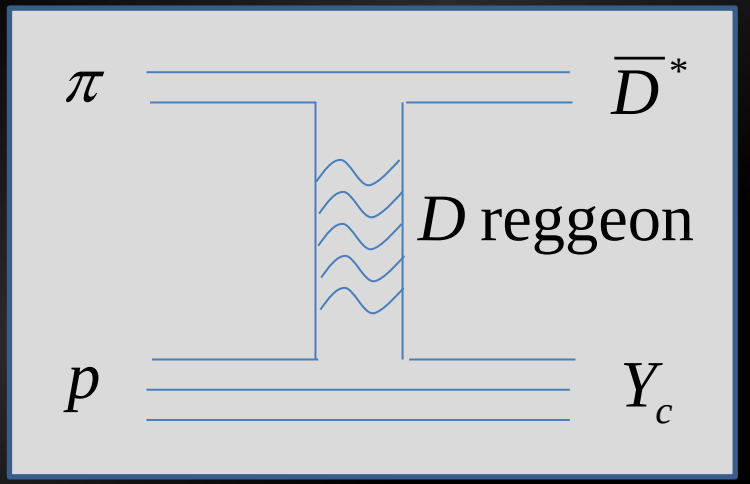
Production Cross Section

No exp. data : σ<270nb@13 GeV/c (PRL55, 154(1985))

Estimation: $10^{-4\sim-5}$ of $\sigma(\pi^- p \to K\Lambda, K\Sigma) \sim 1$ nb



Binary Reaction at High E is well described as quark planar diagram.



A.B. Kaidalov, ZPC12, 63(1982)

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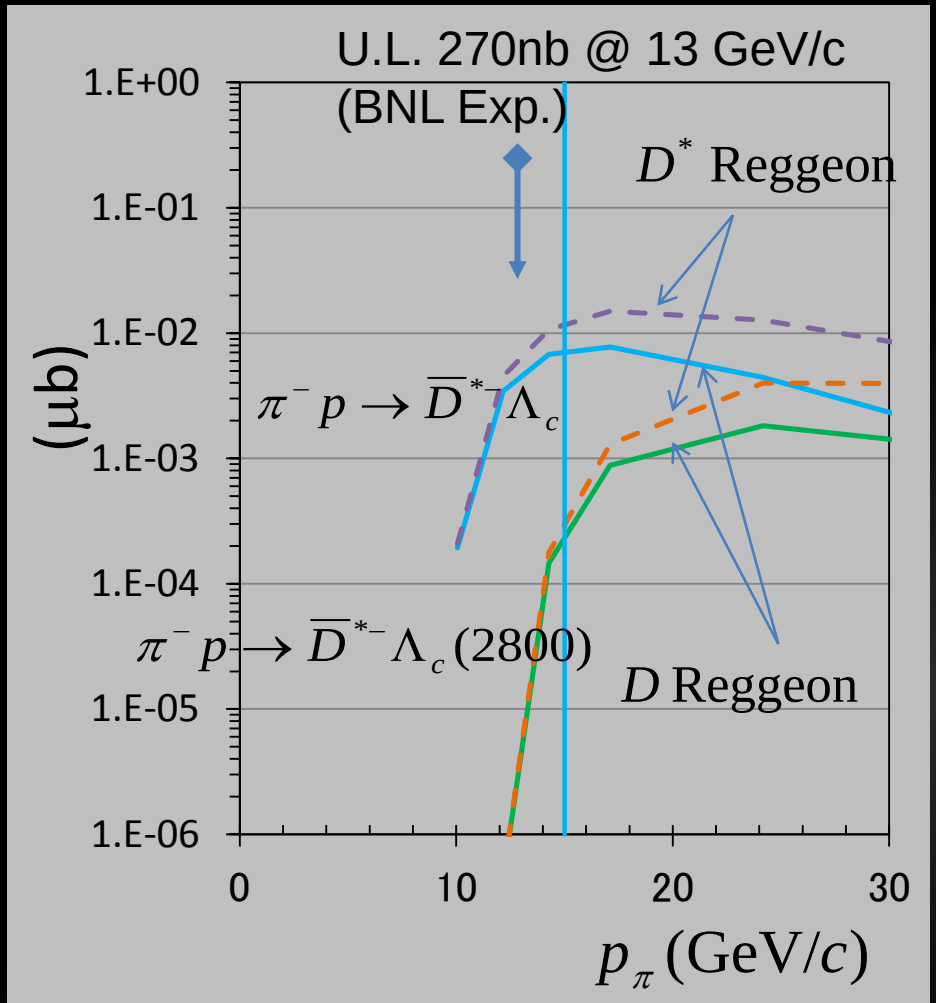

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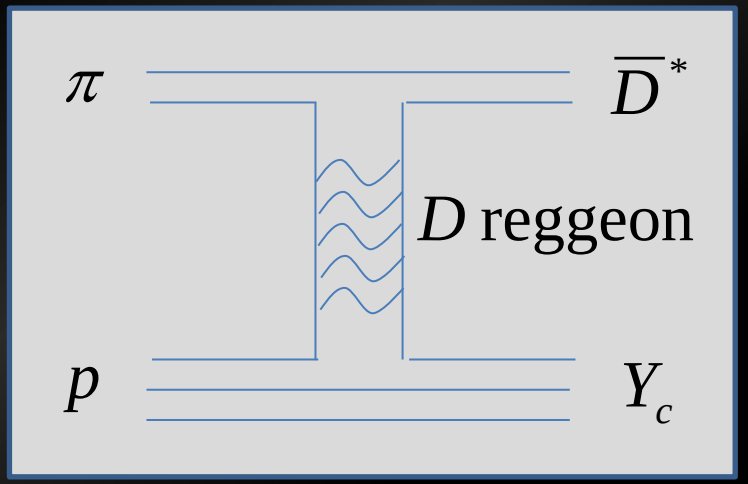

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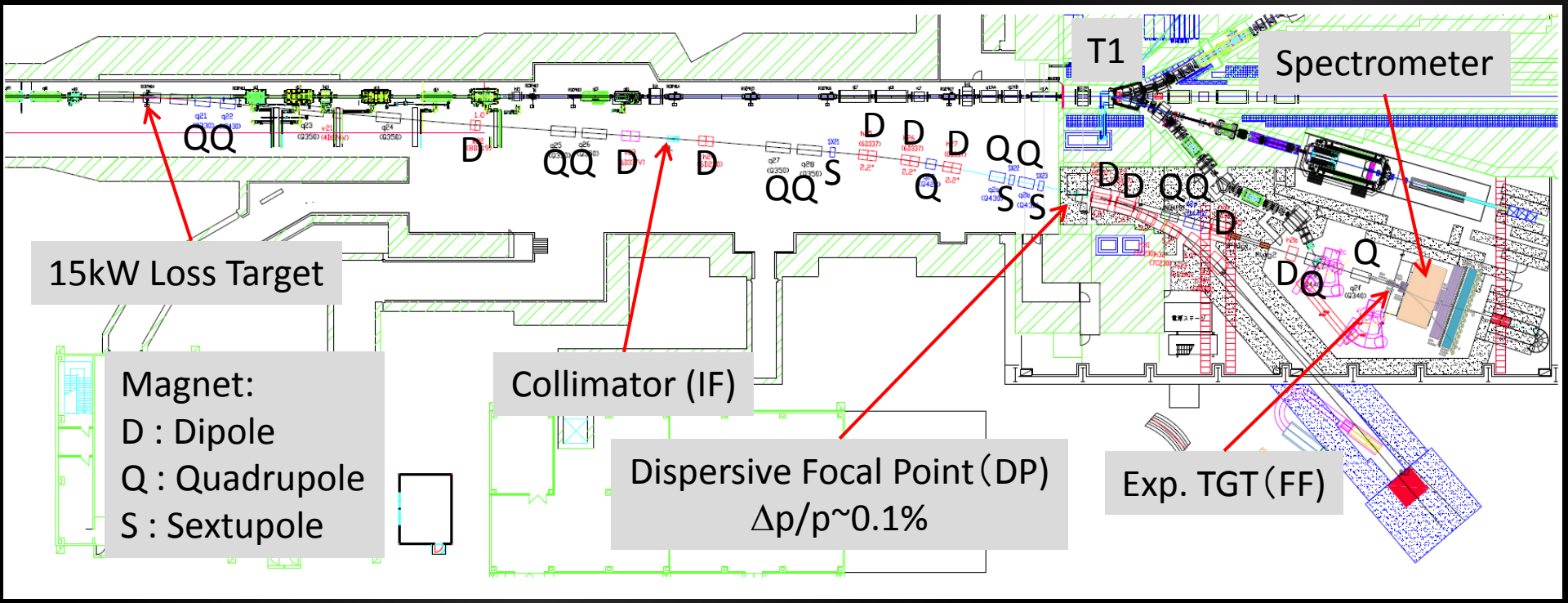
High-res., High-mom. Pion Beam

- High-intensity secondary Pion beam can be delivered.
  - 2 msr･%、1.0 x 10^7 Hz @ 15GeV/c π
- High-resolution beam: $\Delta p/p$~0.1%
  - Momentum dispersion and eliminate 2nd order aberrations



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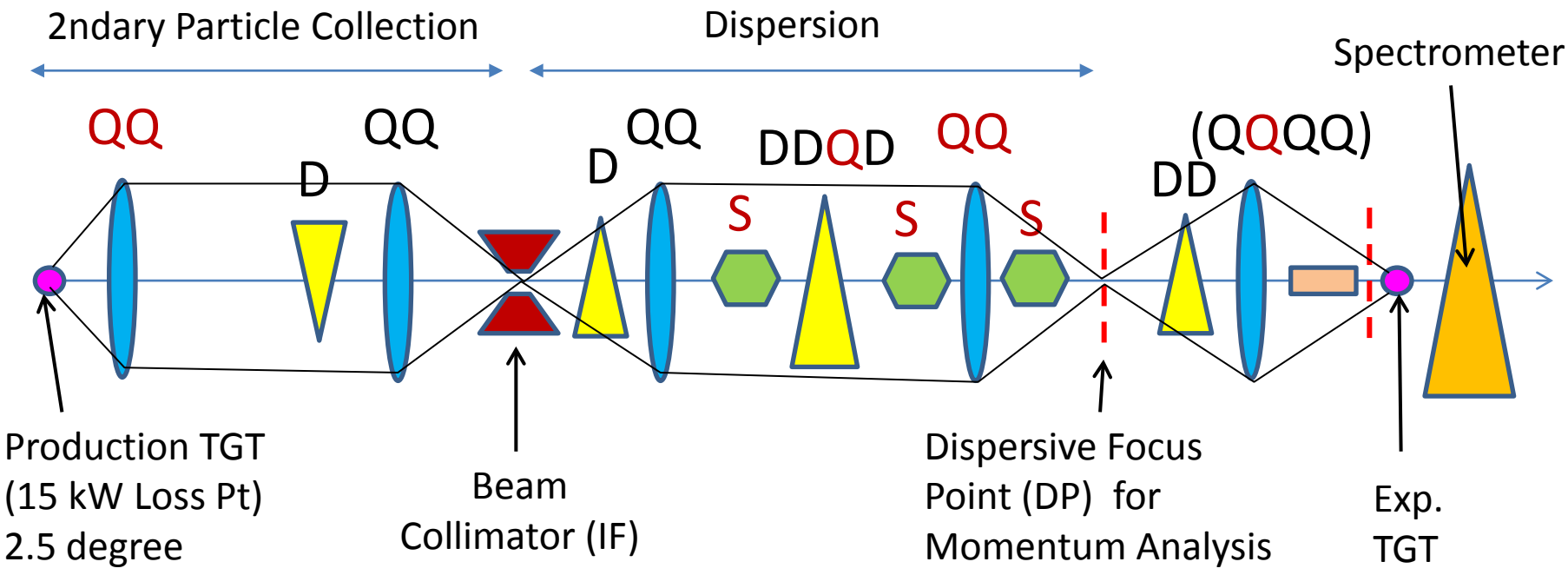
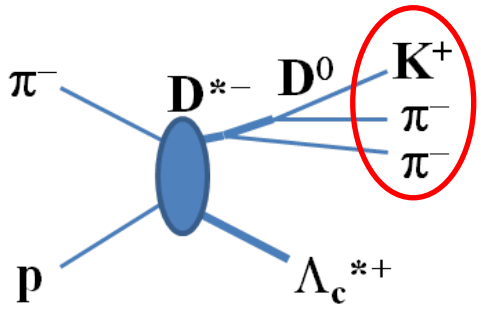
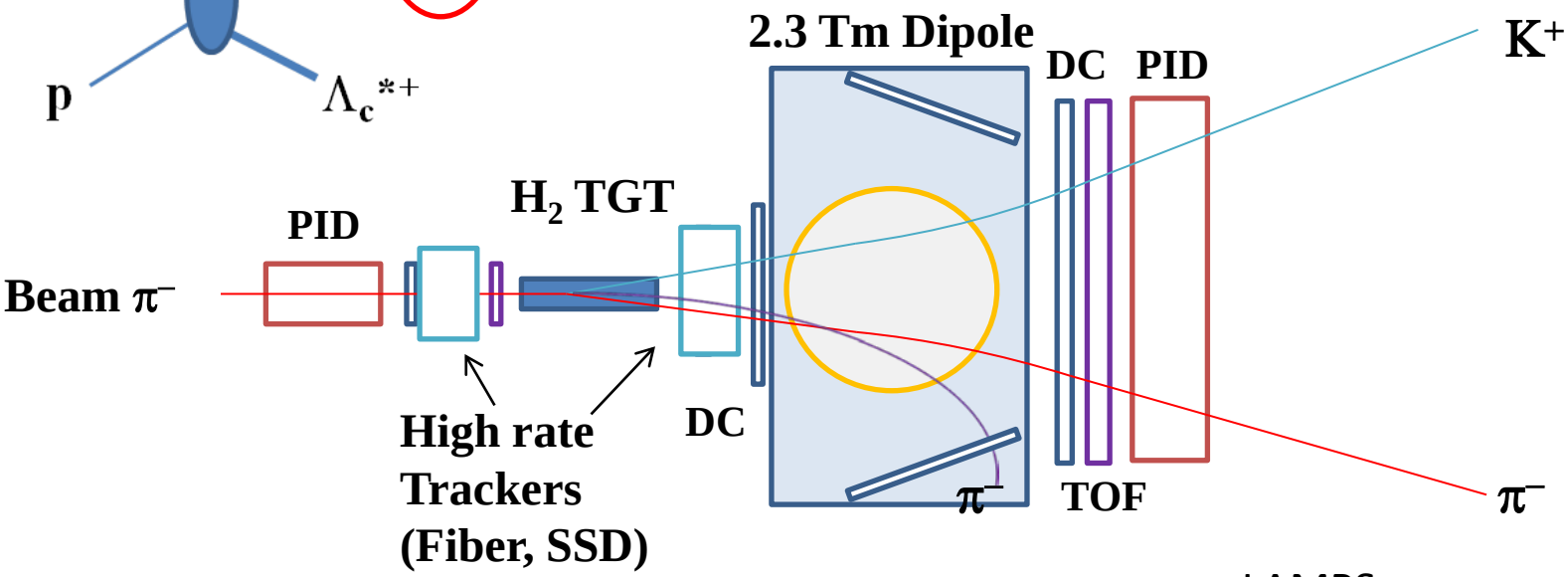
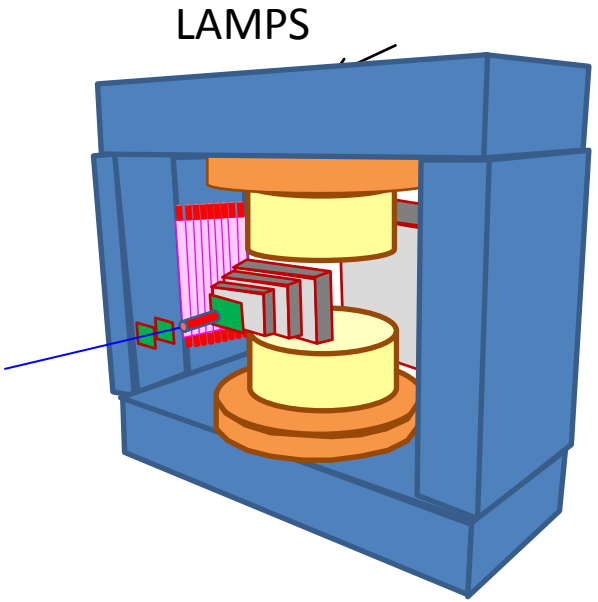


Spectrometer Concept

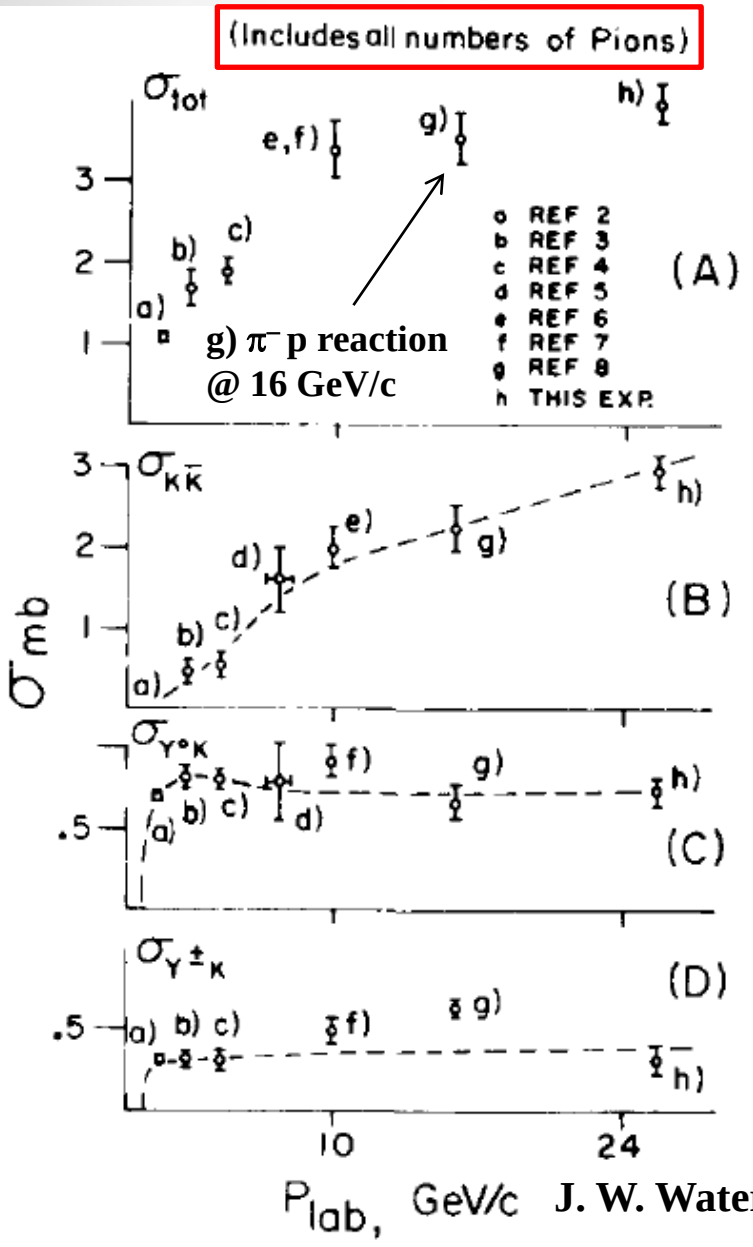




- Large Acceptance, Multi-Particle
  - *K*, π from D^0 decays
  - Soft π from D^{*-} decays
  - (Decay products from Y_c^*)
- High Resolution
- High Rate
  - SFT/SSD op. >10M/spill at K1.8



Background Reduction



(A) Any s-production: 3.4(4) mb

(B) K-pair production: 2.1(3) mb

- $K^+ K^-$, $K_1^0 K_2^0$, $K_2^0 K_2^0$

(C) Y^0 production: 0.7(2) mb

- ΛK^0, ΛK^+, $\Sigma^0 K^0$, $\Sigma^0 K^+$

(C) $Y^\pm$ production: 0.6(1) mb

- $\Sigma^+ K^0$, $\Sigma^+ K^+$, $\Sigma^- K^0$, $\Sigma^- K^+$

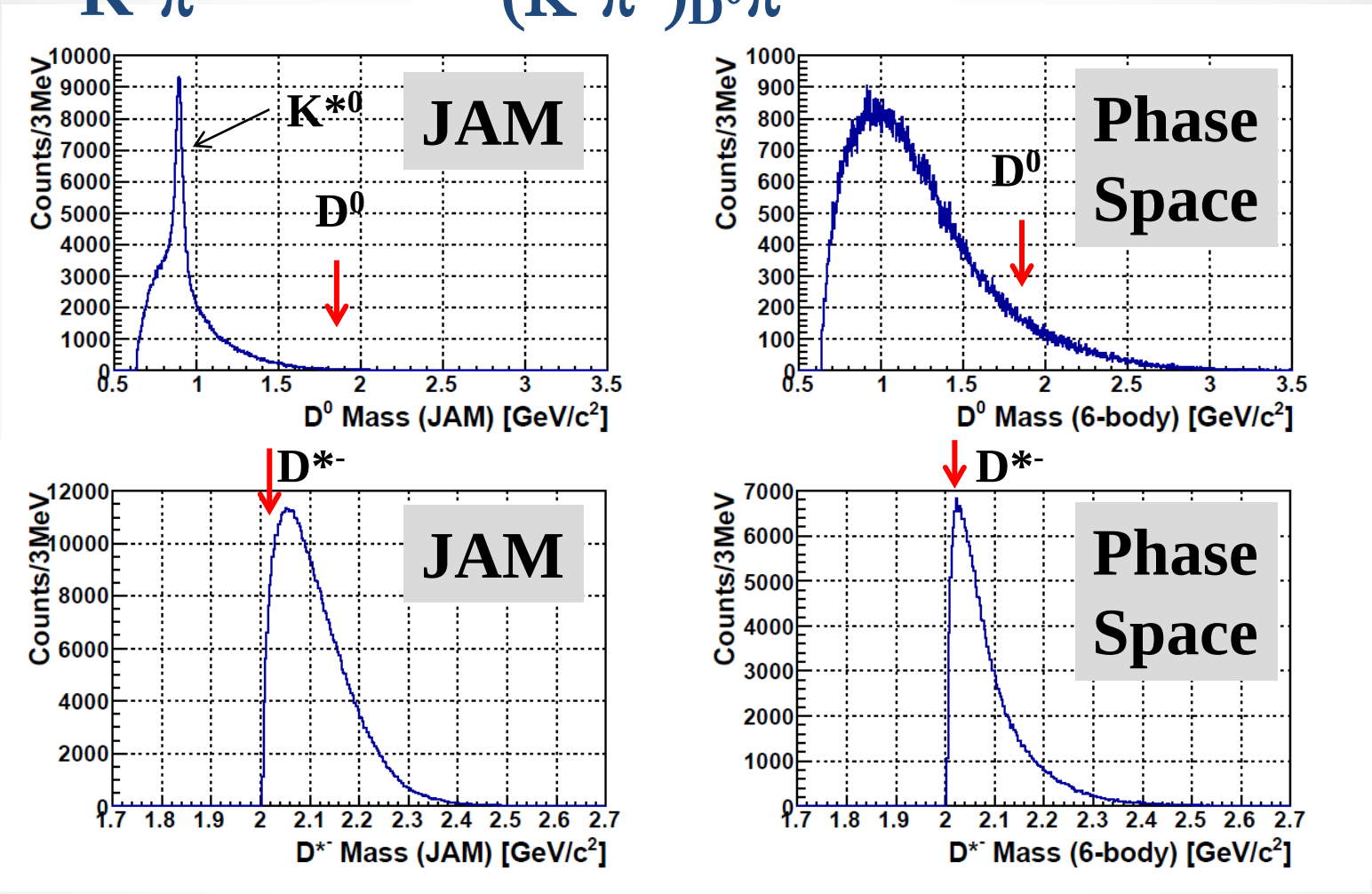
- **$\sigma(K_1^0 X) = 1.15 \pm 0.12$ mb**
  - 前ページのK^0 inclusiveと同じ

σ_{BG}=3.4mb at most (A)

Mission:
Pick up ~nb signals out of ~mb BG

J. W. Waters et al, NPB17 (1970) 445

$IM_{K^-\pi^+}$ & $IM_{(K^-\pi^+)_{D^0}\pi^-}$ reconstruction



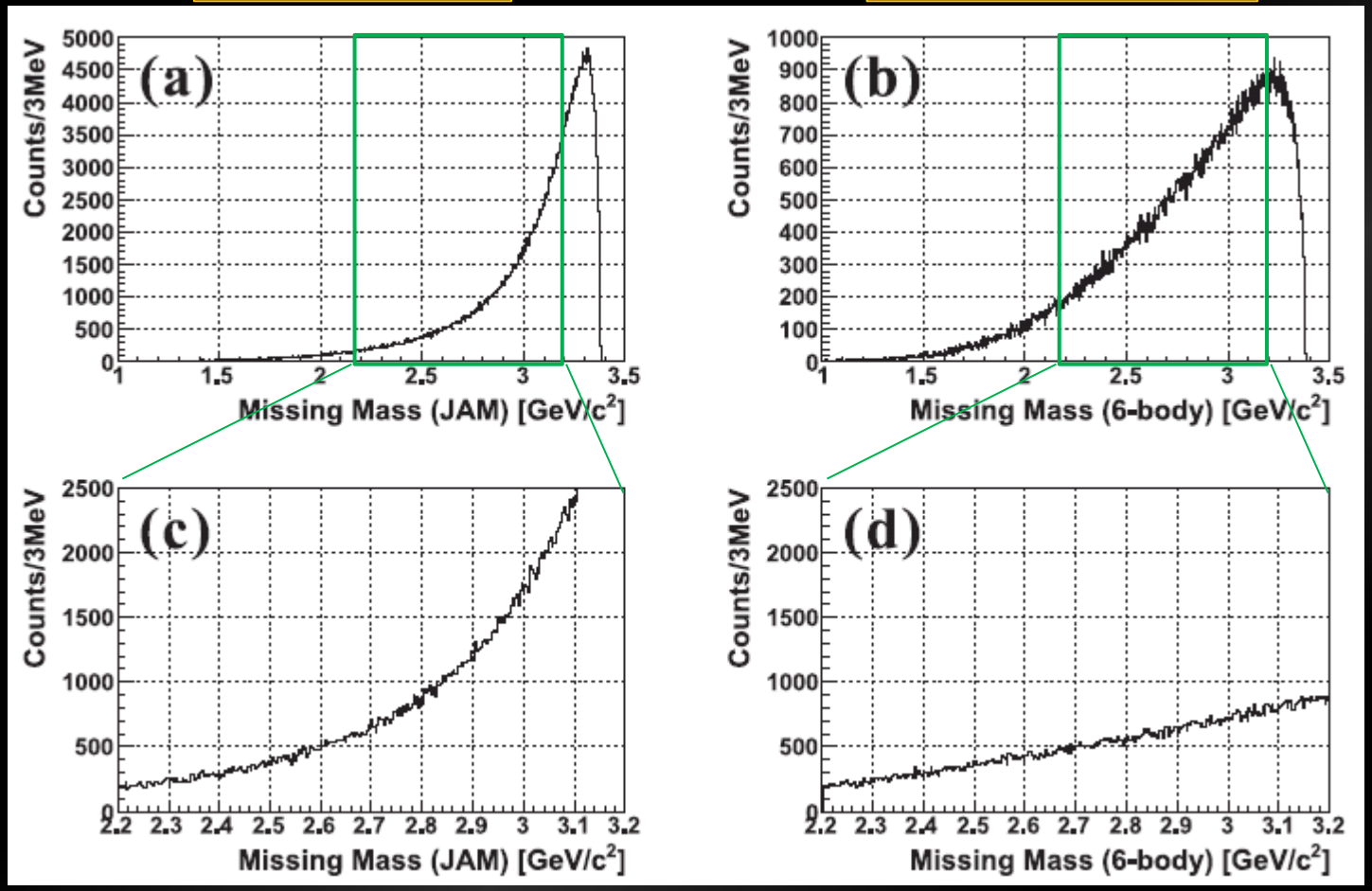
JAM: Simulation Code for ultra-rel. Nucl. Collision

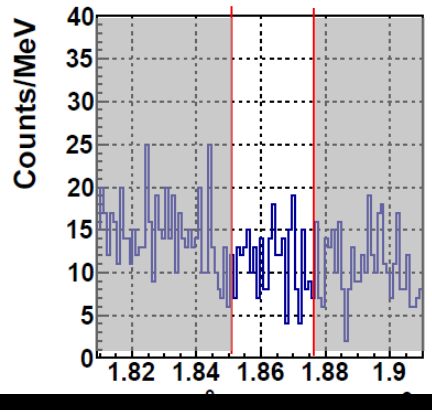
Phase Space: Isotropic distribution in multi-body P.S.

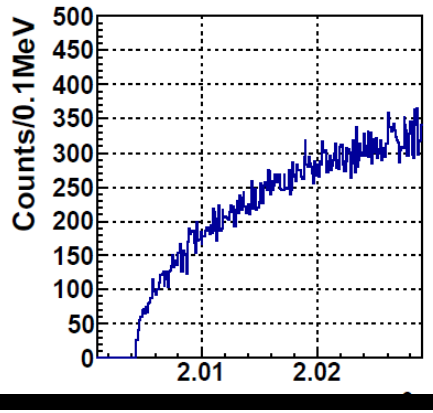
Background Shapes in $MM_{\pi^- p \to D^{*-} X}$

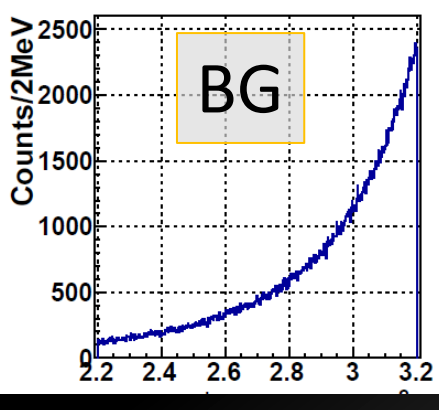
JAM code

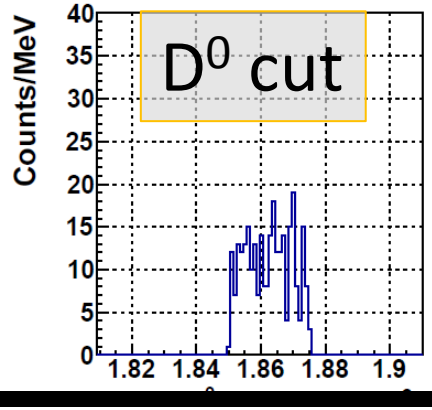
Phase space

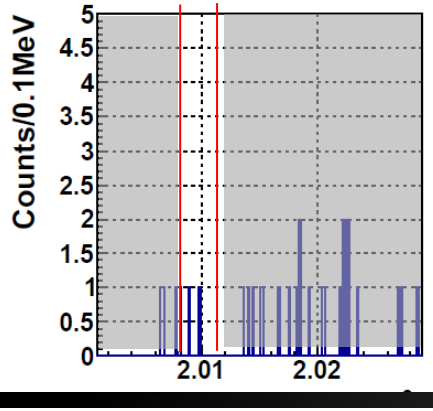


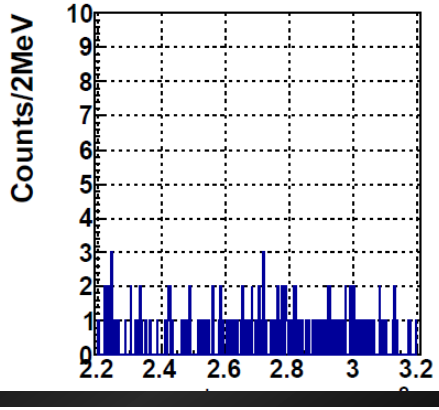


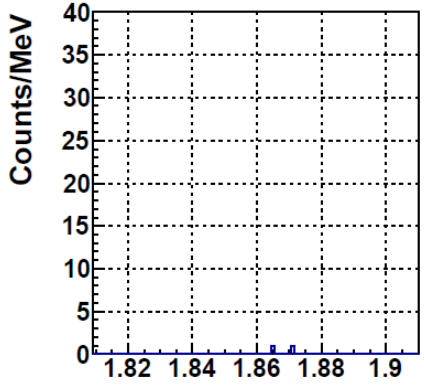


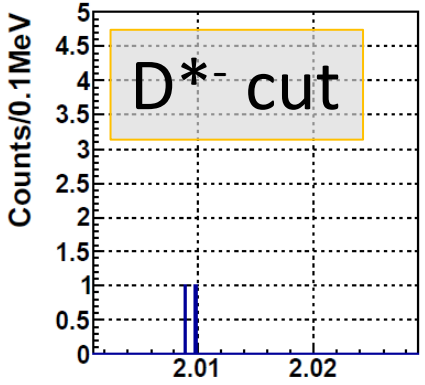


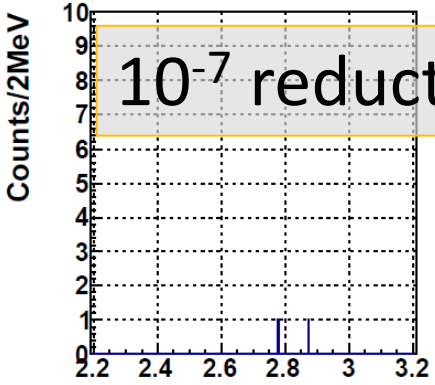










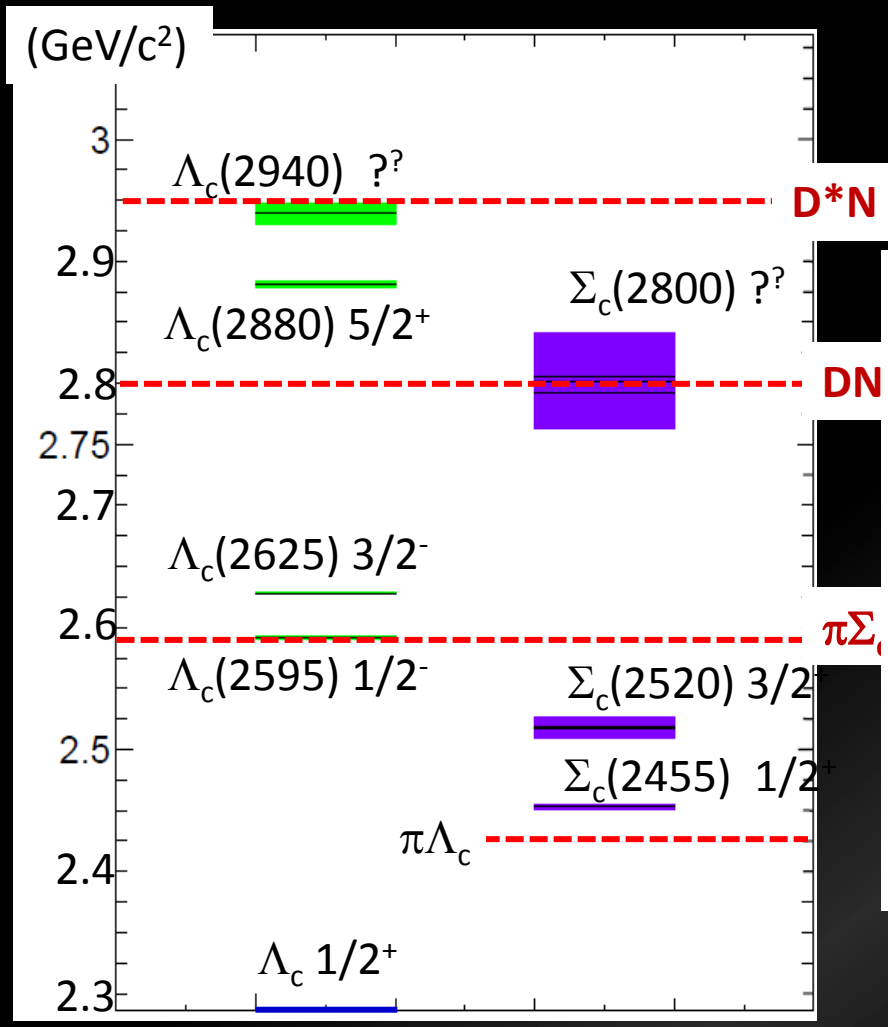


IM($K^-\pi^+$) [GeV/c^2]

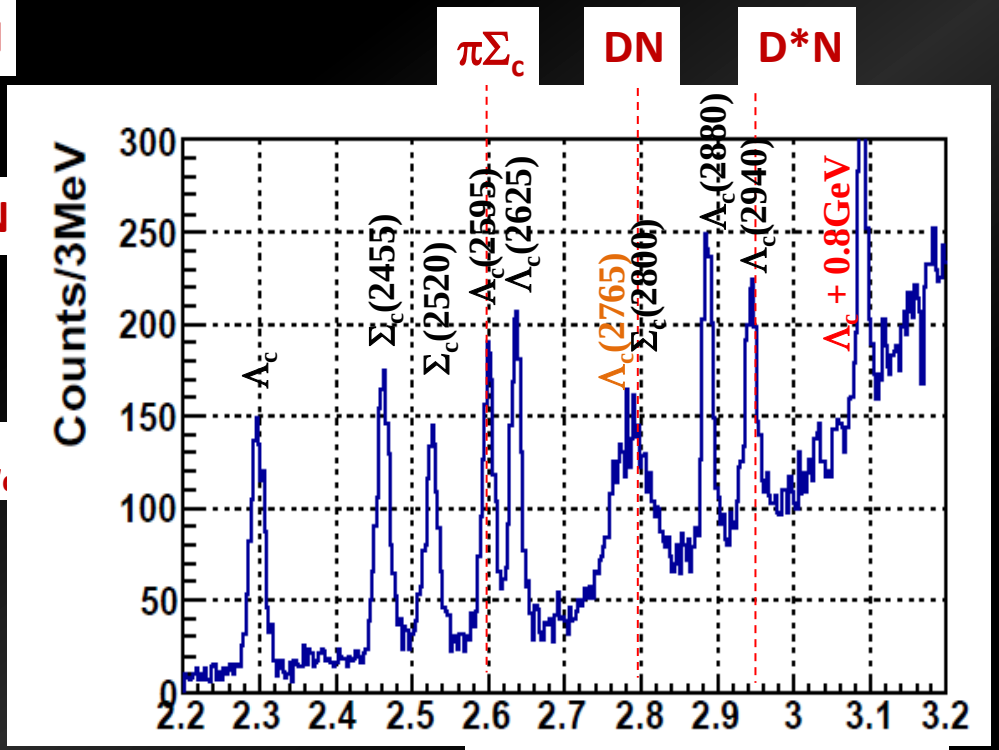
IM($K^-\pi^+\pi^-$) [GeV/c^2]

MM((π^-,D^{*-})) [GeV/c^2]

Expected Spectrum in the (π,D*$^-$) reaction

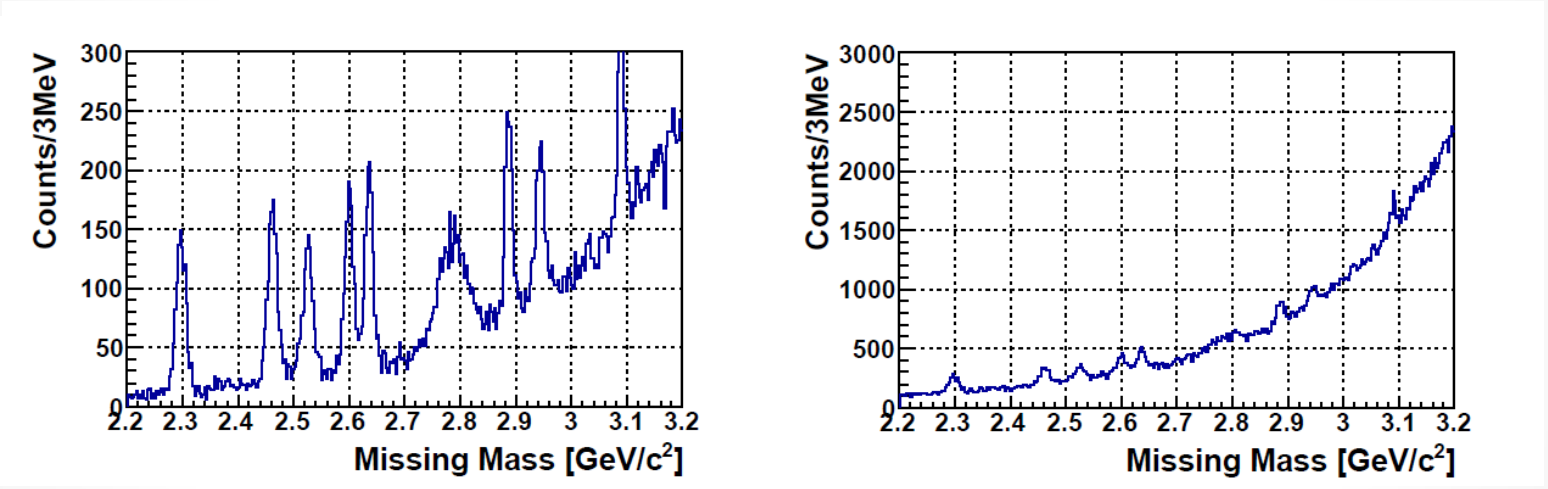


Signal: 1 nb/Yc* :~1000 events
BG: 1.8 mb (JAM)



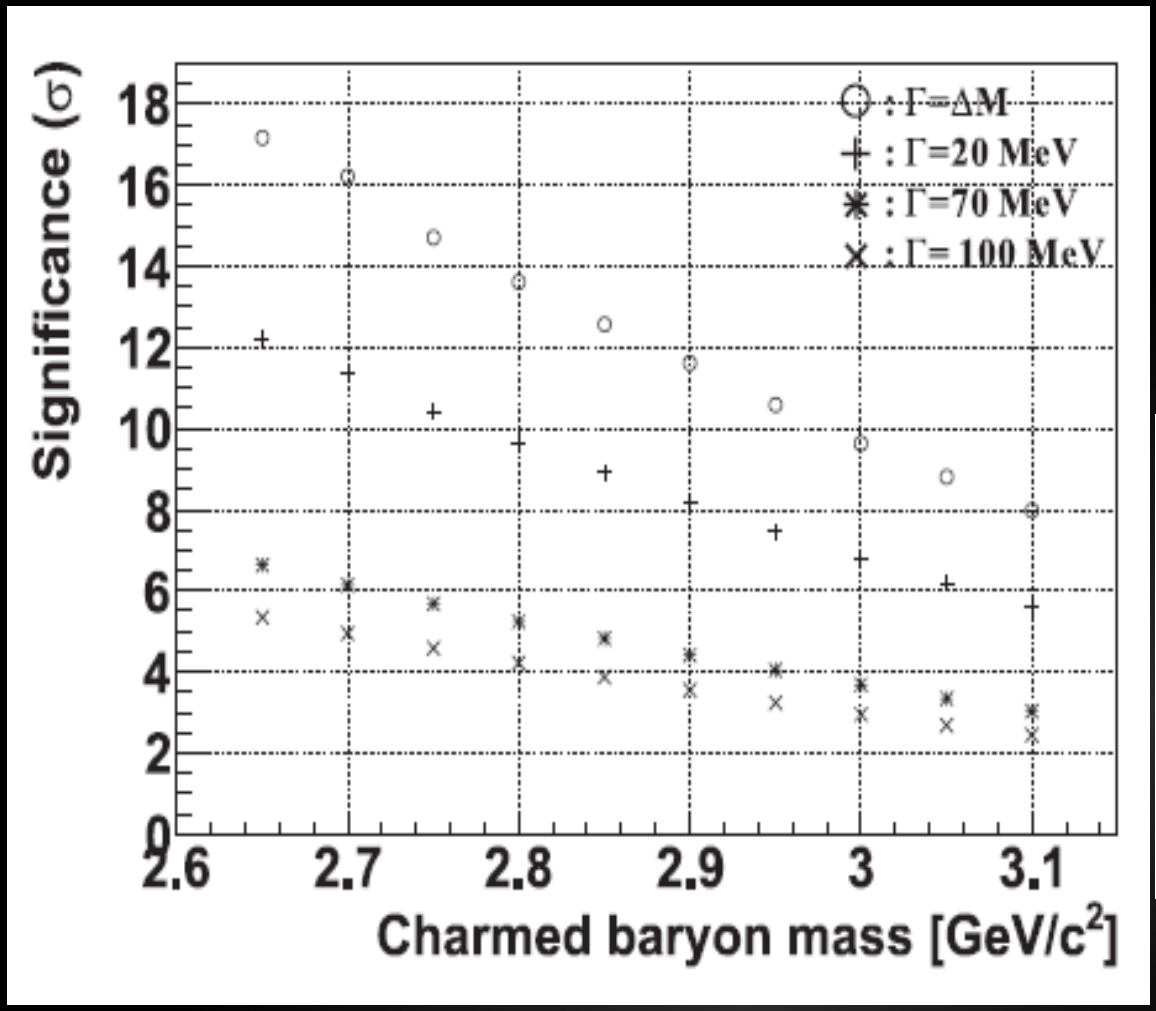
Missing mass spectra w/ Y_c*

10^{-7} BG eduction → **10 times more BG**



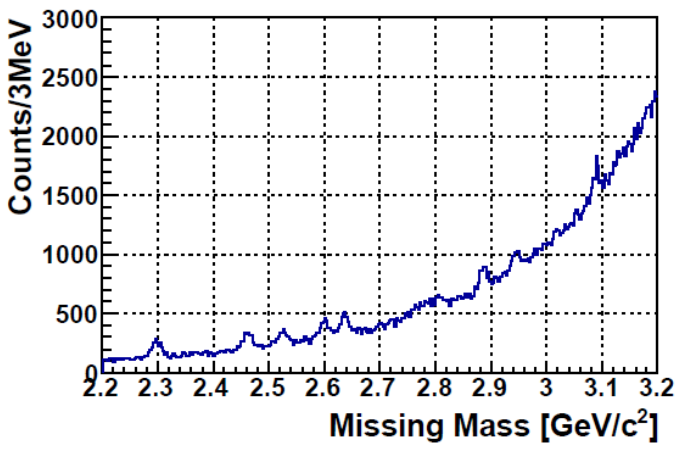
- **Assuming 10^{-7} and 10^{-6} BG reduction, generated by using the JAM code**
  - **BG: σ_{tot} = 1.8 mb**
- **For each Y_c*, production cross section of 1 nb, mass and width from PDG**
  - **~1000 counts for each Y_c***

Signal Sensitivity



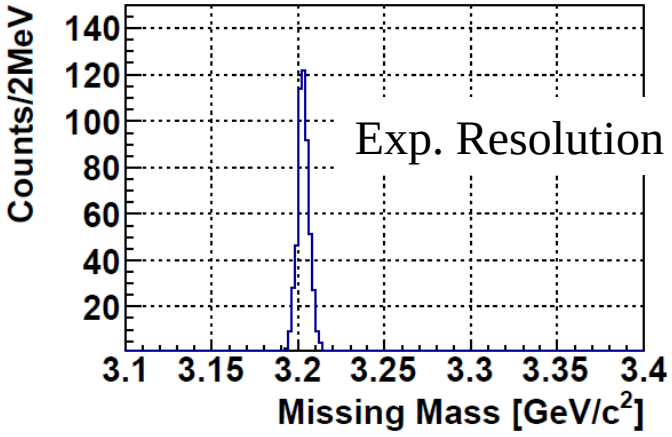
Signal: 1000 events

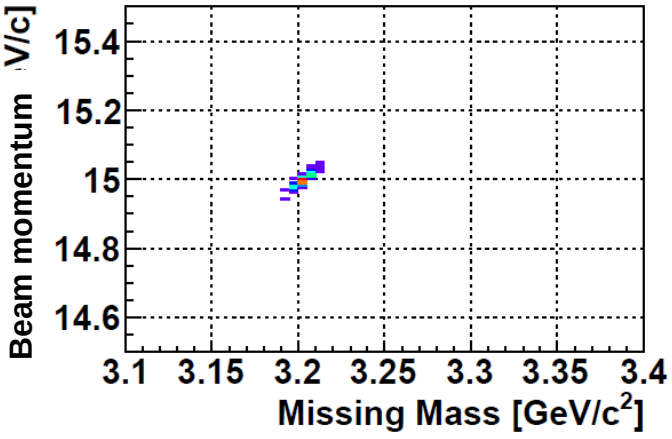
BG: 10^{-6} reduction



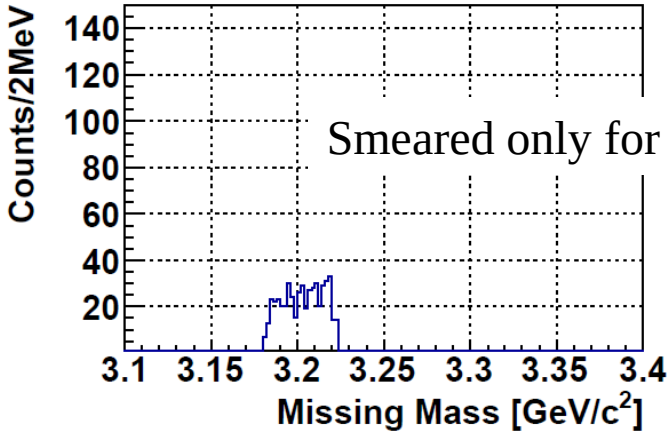
Reflection: $\pi^- p \rightarrow (D^{*-} D^{*+})_X n$

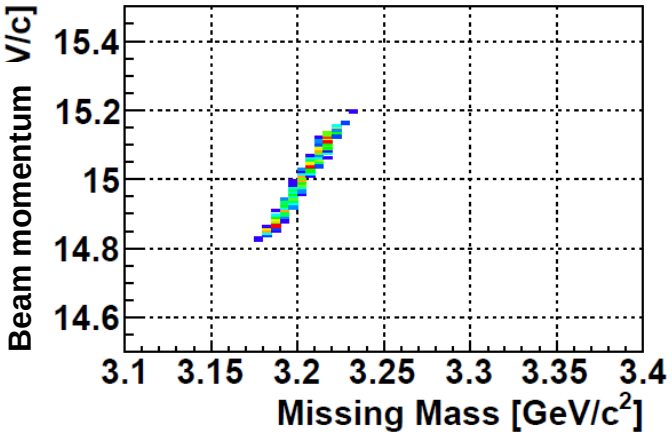
Mono-chromatic beam





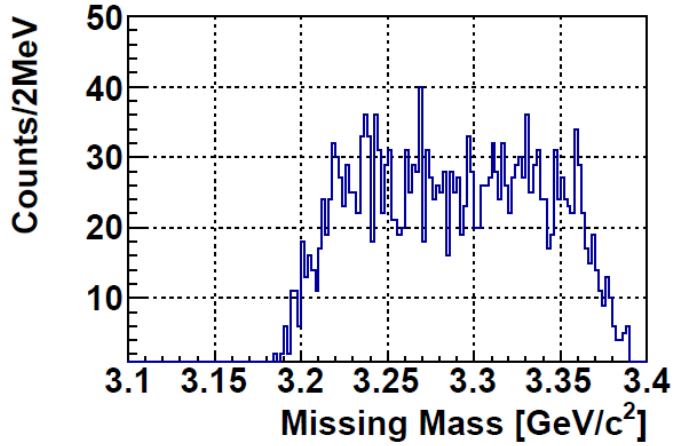
Dispersive beam



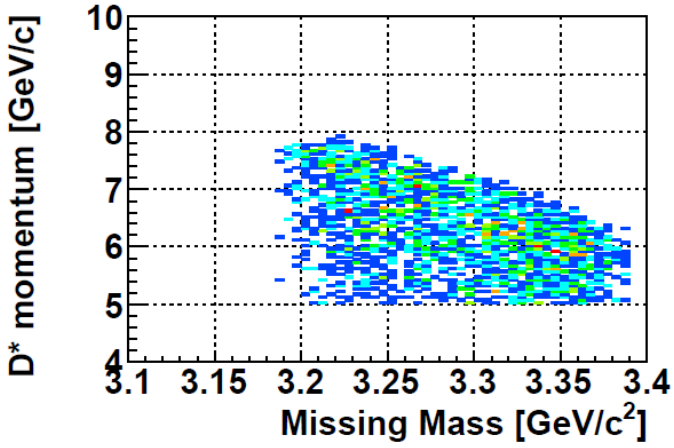


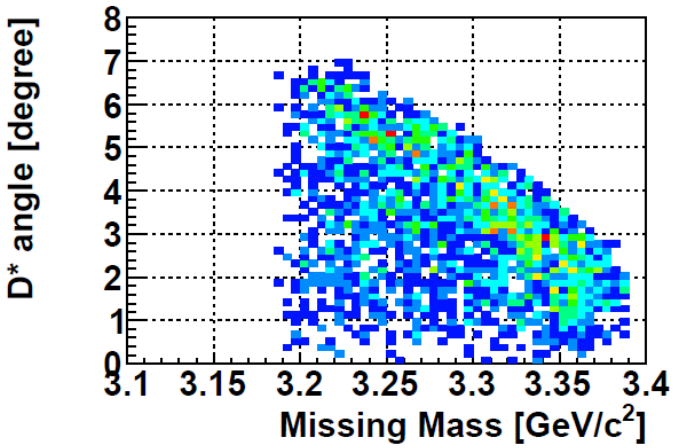
D*- scattering angle fixed ($\theta = 0^\circ$, $\phi = 0^\circ$)

Reflection: $\pi^- p \rightarrow (D^{*-} D^{*+})_X n$



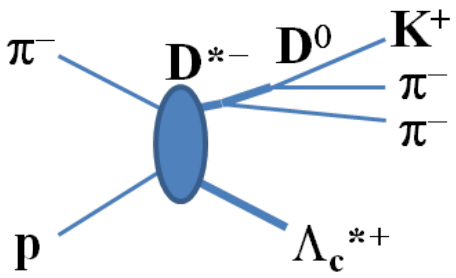
Isotropic angular distribution:
Smeared ~150 MeV in the MM spectrum

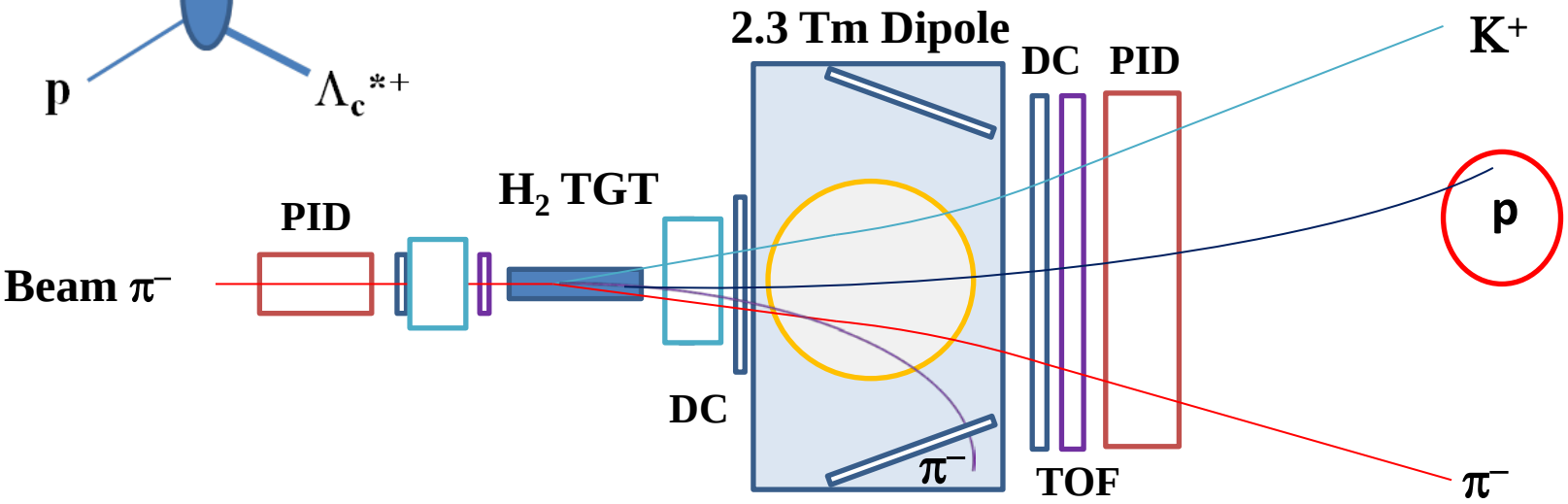




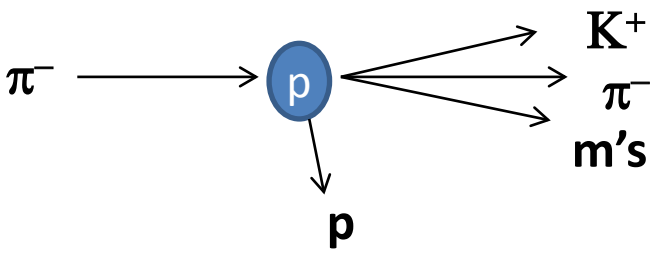
- **MM has Correlation w/ Momentum transfer (angular correlation)**
- **Bump position changes as an incident momentum.**

Spectrometer Concept

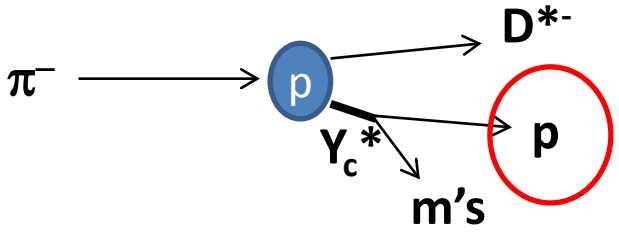




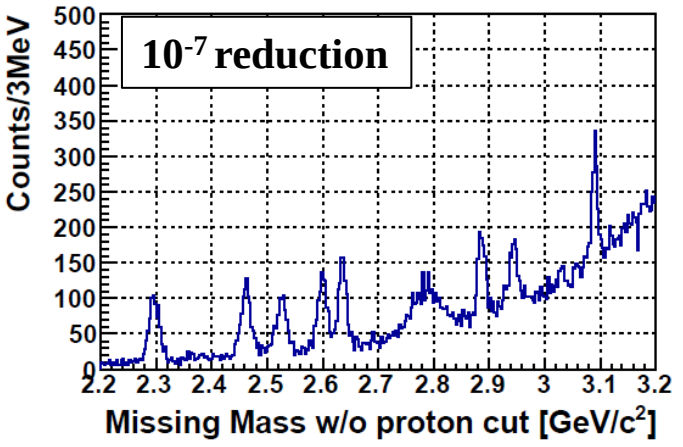
Multi-meson productions (BG)

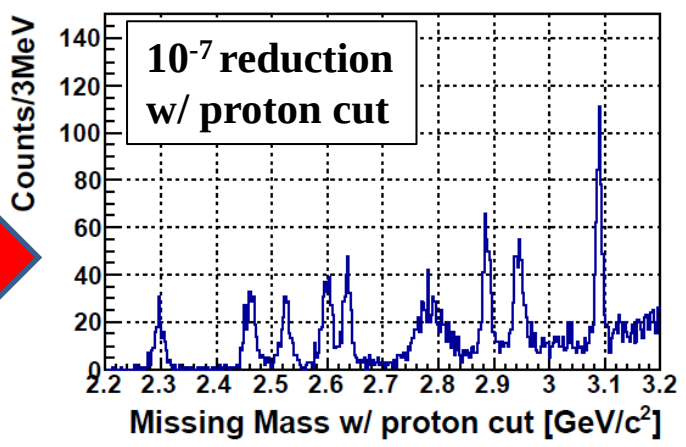


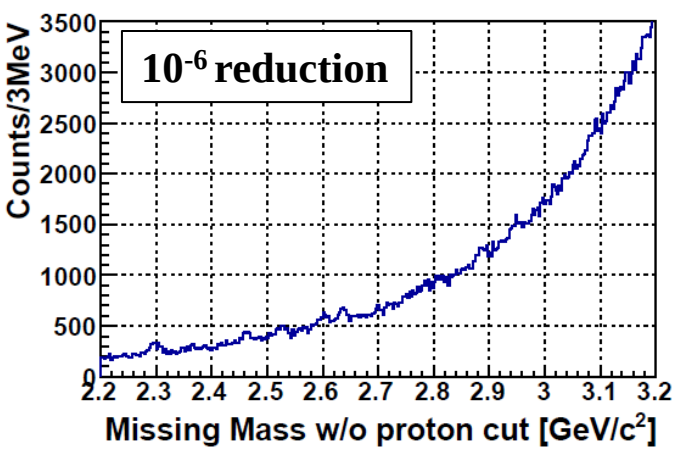
Y_c* production (Signal)

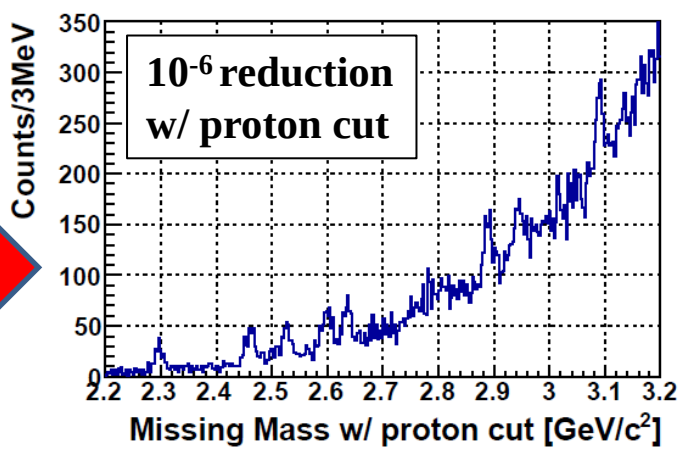


Forward proton detection



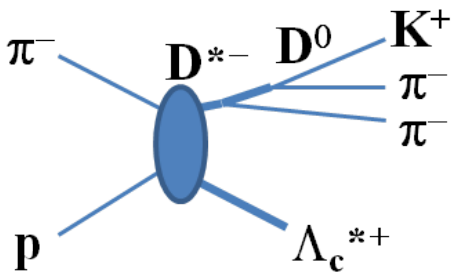


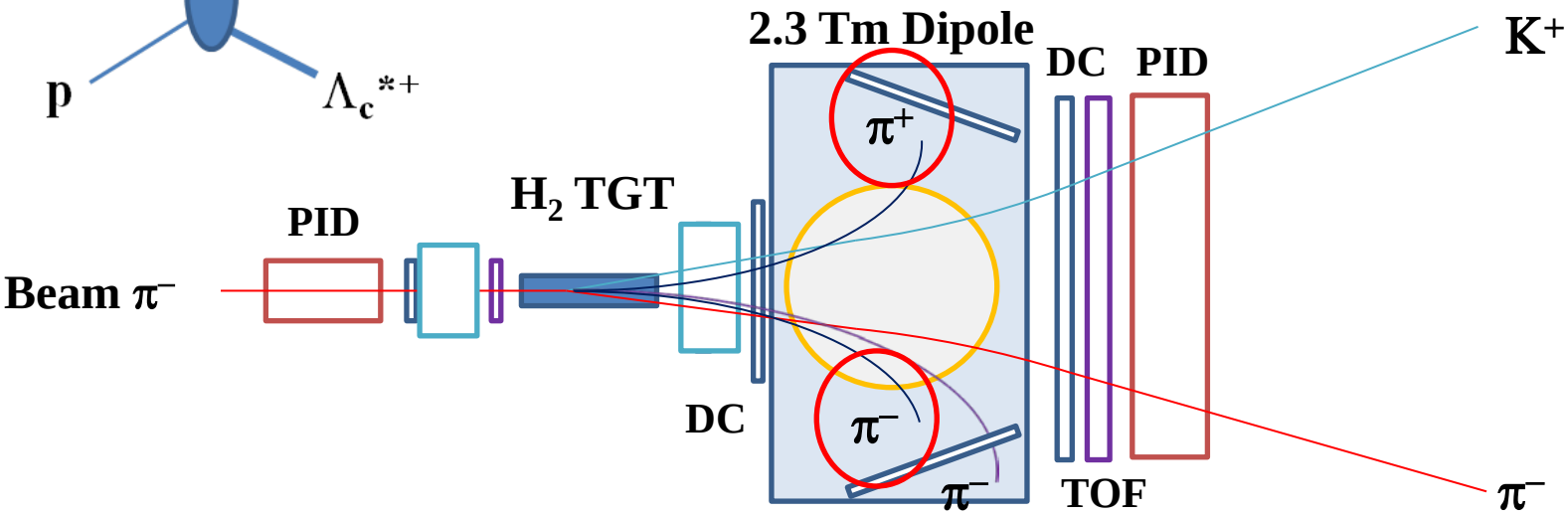




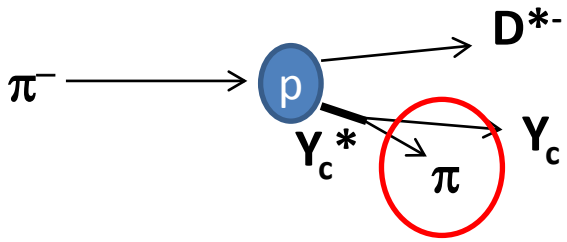
- **Further BG reduction (significance ⇒ × 1.5)**
  - **Yied for Y_c* is reduced to be 1/4**
  - **S/N is improved from 1:15 ⇒ 1:6 @ $\Lambda_c(2880)$**

Spectrometer Concept

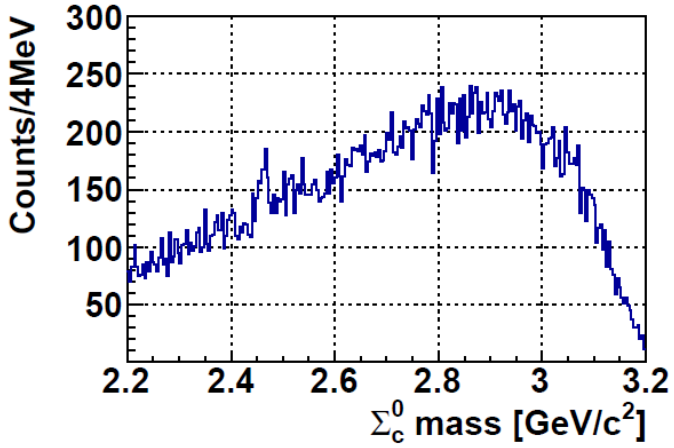


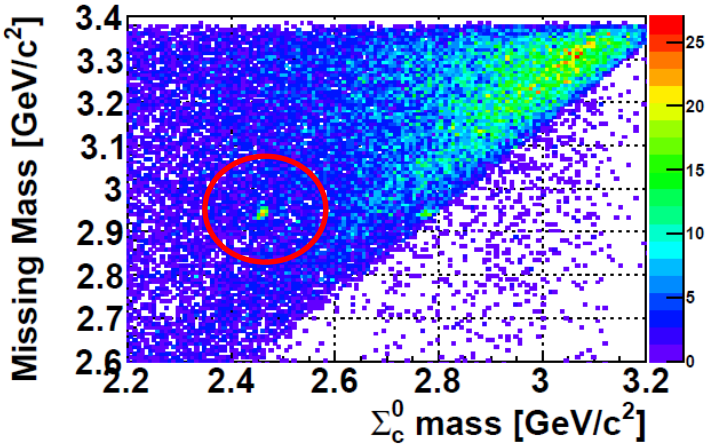


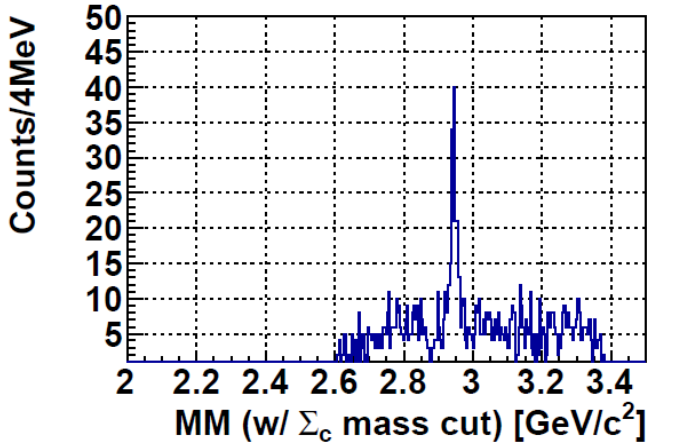
Y_c^*->Y_c+π decay process

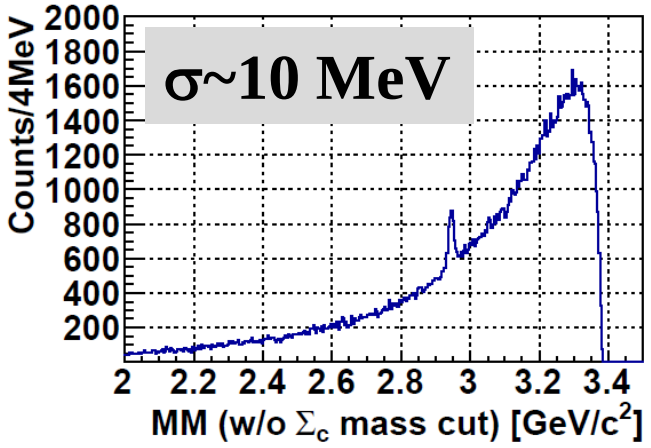


$\Lambda_c(2940)$->$\Sigma_c(2455)^0+\pi^+$ decay



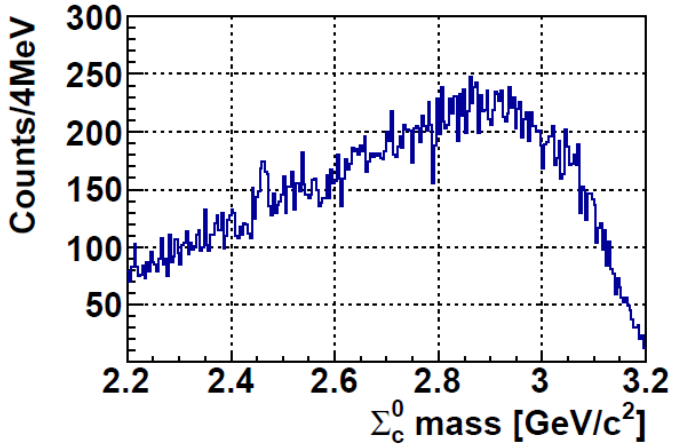


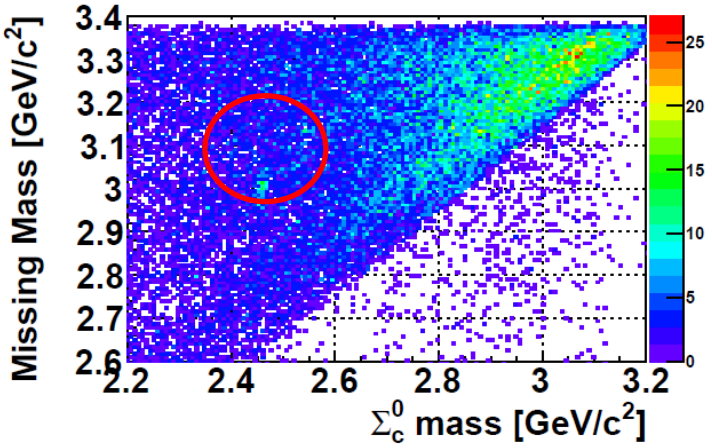


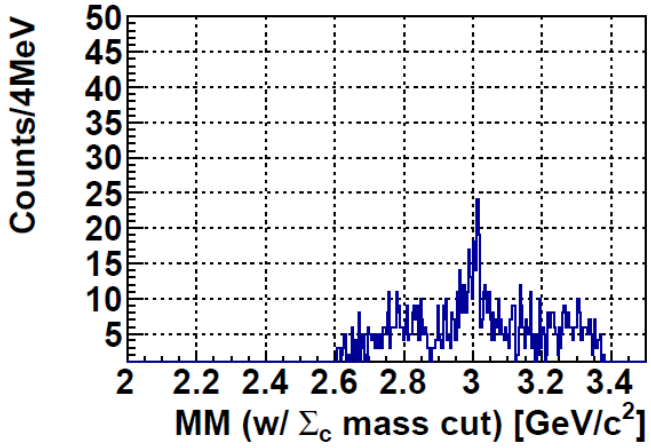


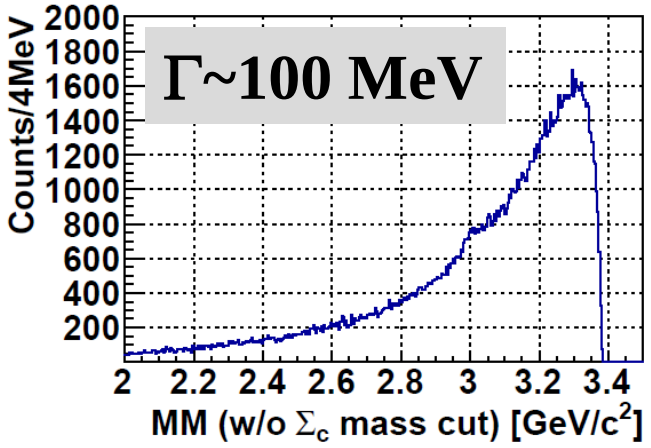
Further Reduction of BG in coin. w/ a decay pion

$\Lambda_c(3000)$->$\Sigma_c(2455)^0+\pi^+$ decay









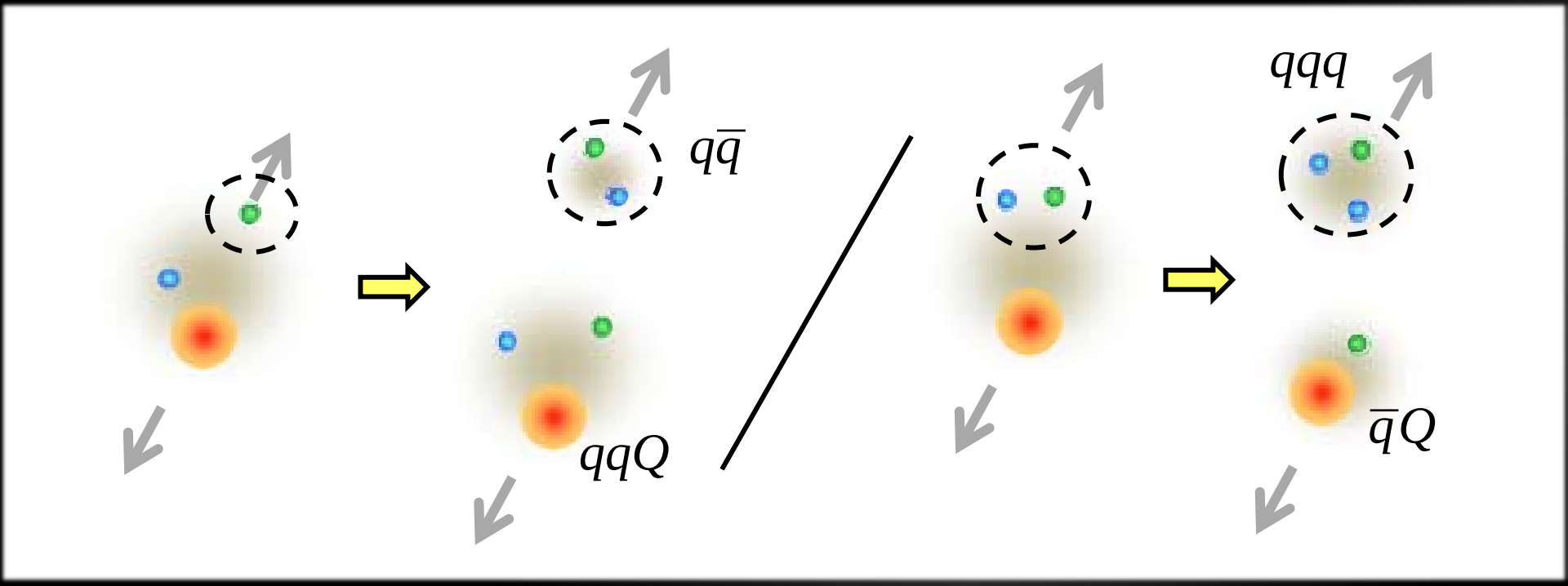
Further Reduction of BG in coin. w/ a decay pion

What we will measure…

Missing mass spectroscopy via the (π,D*-) reactions.

- Excitation Energies and widths of charmed baryons
  - From the G.S. to highly E.S. of E_x>1 GeV w/ ~5.5 MeV res.
  - Independent of decay final states
- Decay properties of the populated states
  - Strong BG suppressions for the parent states
  - Decay branching ratios (Partial widths)
  - Possible assignment of spins

Structure and Decay Partial Width



Excited (qq) Good [qq]

- $\Lambda(1520)$ -> NK (D wave!)>$\pi\Sigma$, similarly $\Lambda(1820)$, $\Lambda(2100)$
- Possible explanation of narrow widths of Charmed Baryons

Yield Estimation/Beam Time Request

- $I_{beam}=10^7$ π/s, $n_{TGT}=4$ g/cm^2, $\Delta\Omega/\Omega$~14%

  br($D^{*-}\rightarrow\pi^- D^0$, $D^0\rightarrow K^+\pi^-$)=0.67*0.039

  ε(DAQ,Tracking,PID)=0.9*0.7*0.9

  → 4.5 events/day/nb

- Missing Mass Resolution σ_{MM}~ 5.5 MeV

  If a Peak Res. $\delta\sigma_{MM}$ <5 MeV for dm_{qq}~100 MeV,

  Keep sensitivity for excited states w/ Γ~100 MeV

  → >1000 events, >200 days

Summary

- Charmed Baryon Spectroscopy via the (π,D*-) reactions
  - Shed light on "diquark": colored object in hadrons
  - Clarify a Level Structure of the charmed baryons
    - From the ground state to highly excited states of E_x~1 GeV
    - Independent of decay final states
  - Decay Branching Ratios (Partial Widths)
    - Suppressions of [qq^{bar}]-[qqQ] decays if "Good diquark" in Y_c*
    - Possible assignment of spins
- A New Project of Hadron Physics at J-PARC, High-p BL
  - High-res., High-intensity 2ndary Beam
  - Large Acceptance, Multi-Particle Spectrometer

Backup

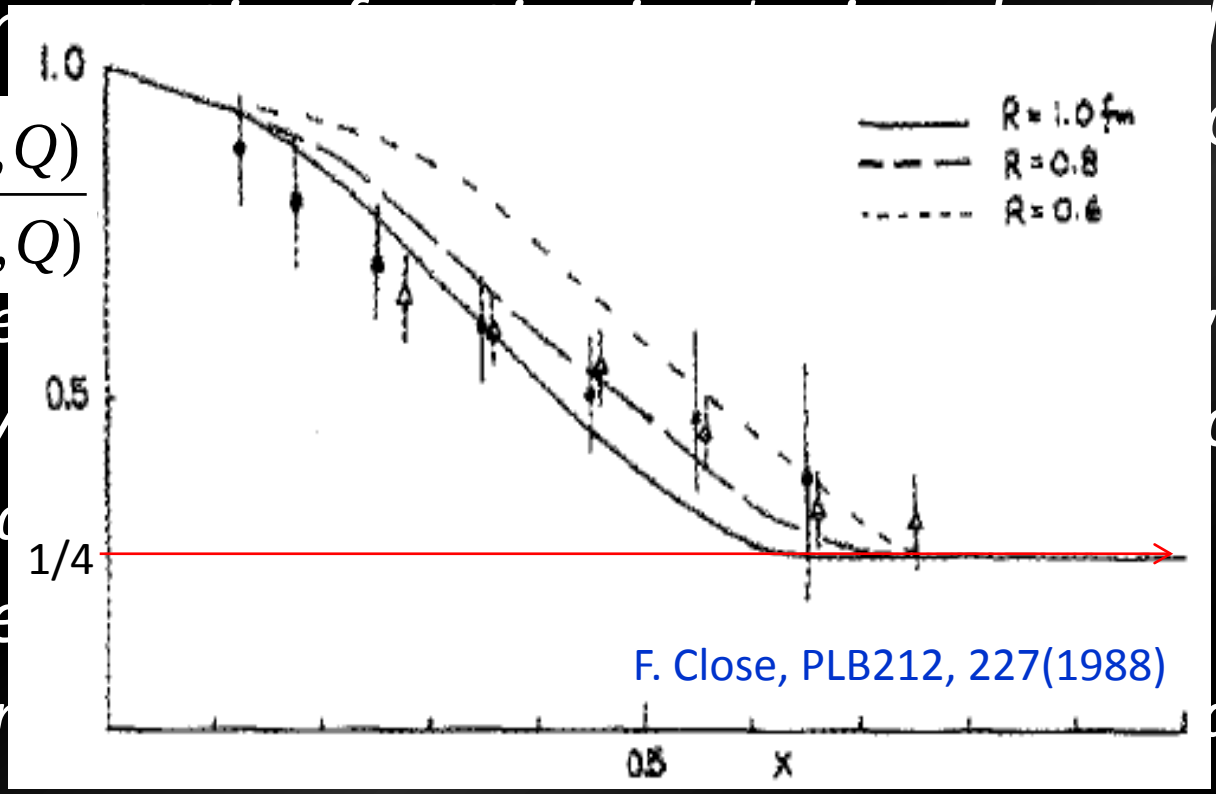
Indications of Diquarks

- Λ - Σ (80 MeV), Λ_c - Σ_c (215 MeV) mass difference
  - Energy difference of Good "[ud]" to Bad "(qq)"
- Λ Fragmentation function in e^+e^- is enhanced.
  - $\Lambda:\Sigma = 0.08:0.023$, $\Lambda_c:\Sigma_c = 0.074:0.014$ [$s^{1/2}$=10 GeV]
- EM FF Ratio at x=1 in DIS on n/p
  - Converging into 1/4 ($=e_d^2/e_u^2$), where [ud] tightly bound
- $|\Delta I|$=1/2 in non-lept'c decay of strange hadrons
  - "ud" antisymmetric pair is favored.
- Possible explanation of Hadron spectra
  - missing 20plet, Light Scalar Meson Nonet: $\{[qq][qq]^{bar}\}_{GS,}$ …

Indications of Diquarks

- Λ - Σ (80 MeV), Λ_c - Σ_c (215 MeV) mass difference
  - Energy difference of Good "[ud]" to Bad "(qq)"
- Λ Fragr… …d.
  - … …GeV]
- EM… …
  - Conve… …bound
- $|\Delta I|=1/$… …ons
  - "ud" …
- Possible…
  - missi… …$qq]^{bar}\}_{GS,}$
    …

$$\frac{F_2^n(x,Q)}{F_2^p(x,Q)}$$



Covariant Oscillator Quark Model

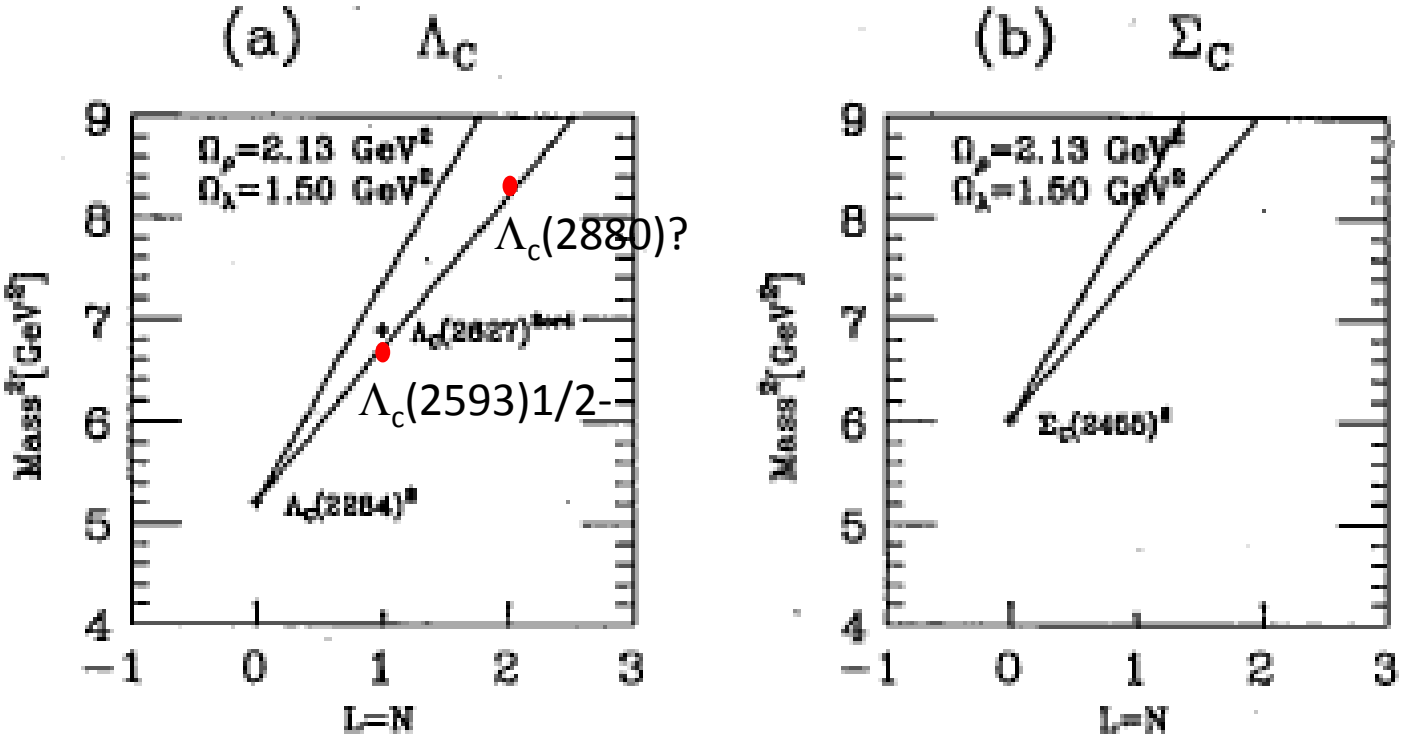
S. Ishida et al, PTP91, 775(1994)

Mesons : $M^2 = \Omega L + M_0^2$,

$$\Omega_\rho = 2(2m + M)\left(\frac{3K_3}{m}\right)^{1/2},$$

Baryons : $M^2 = \Omega_\rho L_\rho + \Omega_\lambda L_\lambda + M_0^2$.

$$\Omega_\lambda = 2(2m + M)\left(\frac{K_3}{m} + \frac{2K_3}{M}\right)^{1/2}.$$



Diquarks in Lattice QCD

Diquark correlation function

$$C(\boldsymbol{r}_u,\boldsymbol{r}_d;t)=\langle 0|J_\Gamma(0,2t)\rho_u(\boldsymbol{r}_u,t)\rho_d(\boldsymbol{r}_d,t)J_\Gamma^\dagger(0,0)|0\rangle$$

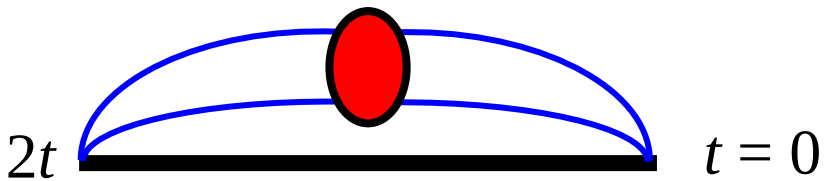
$$\rho(\boldsymbol{r},t)=\bar{q}_f\gamma_0 q_f,\quad f=u,d$$

$$J_\Gamma(x)=\varepsilon^{abc}[u_a^T(x)C\Gamma d_b(x)\pm d_a^T(x)C\Gamma u_b(x)]s_c(x)$$

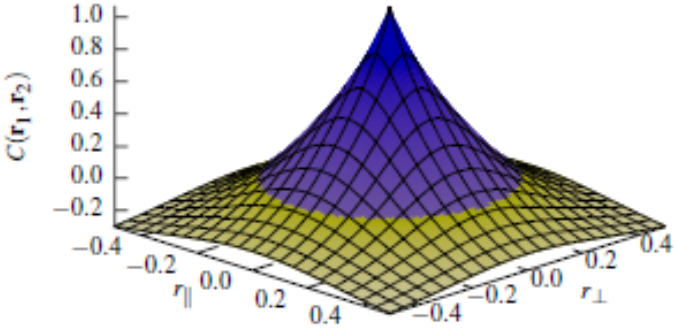
ud-diquark

"Static" quark (heavy quark)

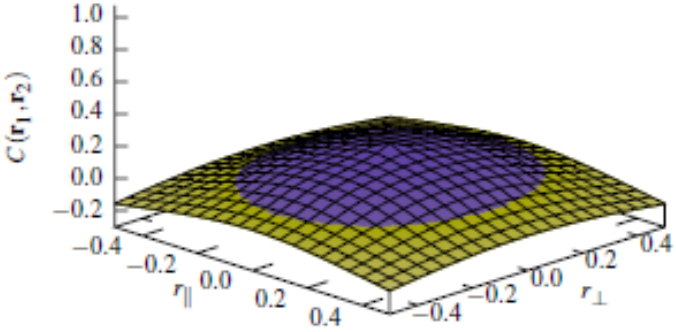
$\rho_u(\boldsymbol{r}_u,t)\rho_d(\boldsymbol{r}_d,t)$



good $m_\pi = 293$ MeV

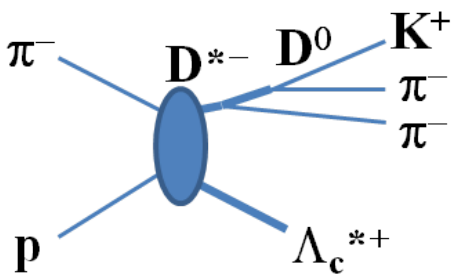


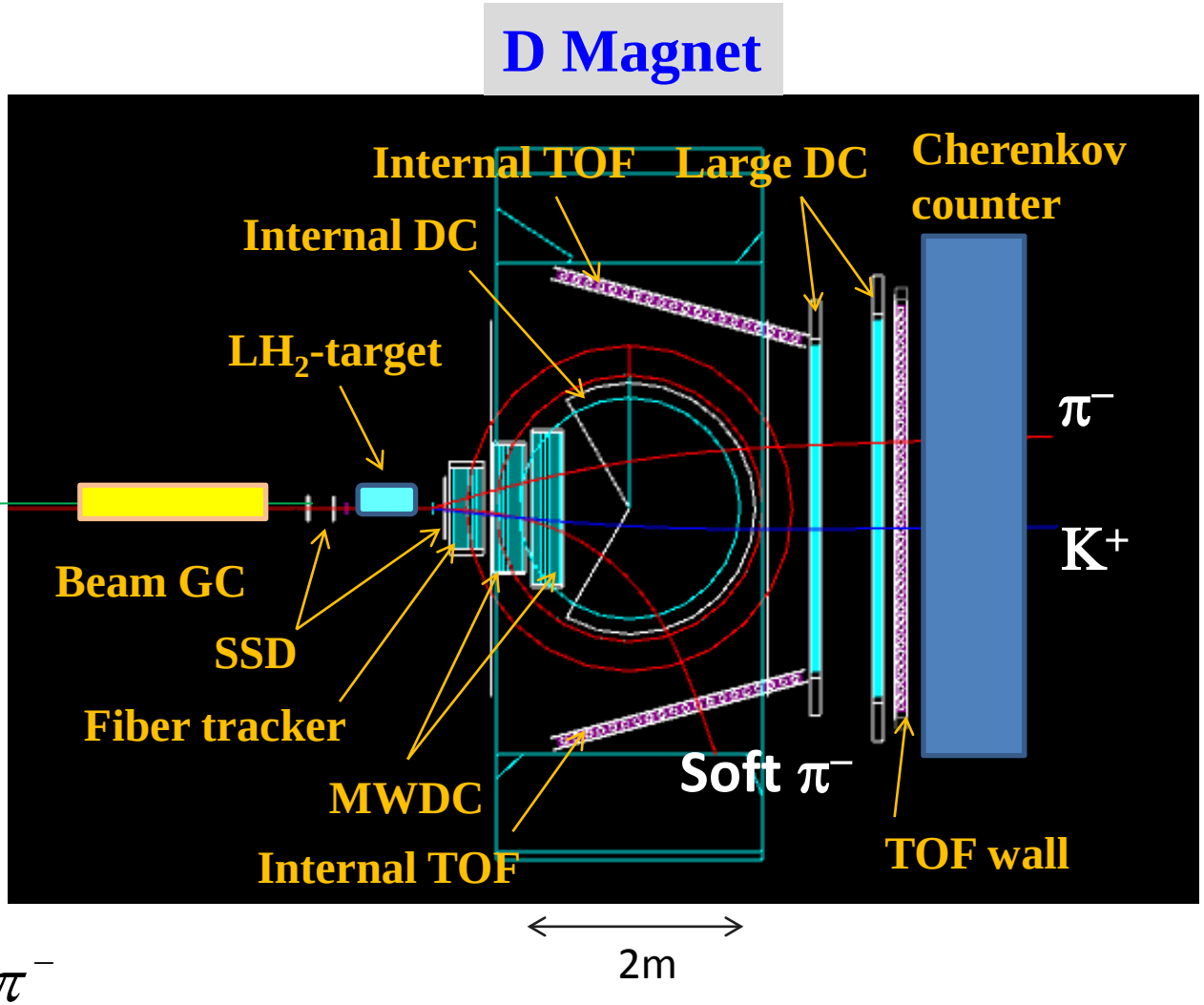
bad $m_\pi = 293$ MeV



J. Green, M. Engelhardt, J. Negele, and P. Varilly, AIP Conf. Proc. 1441, 172(2012)

Simulation



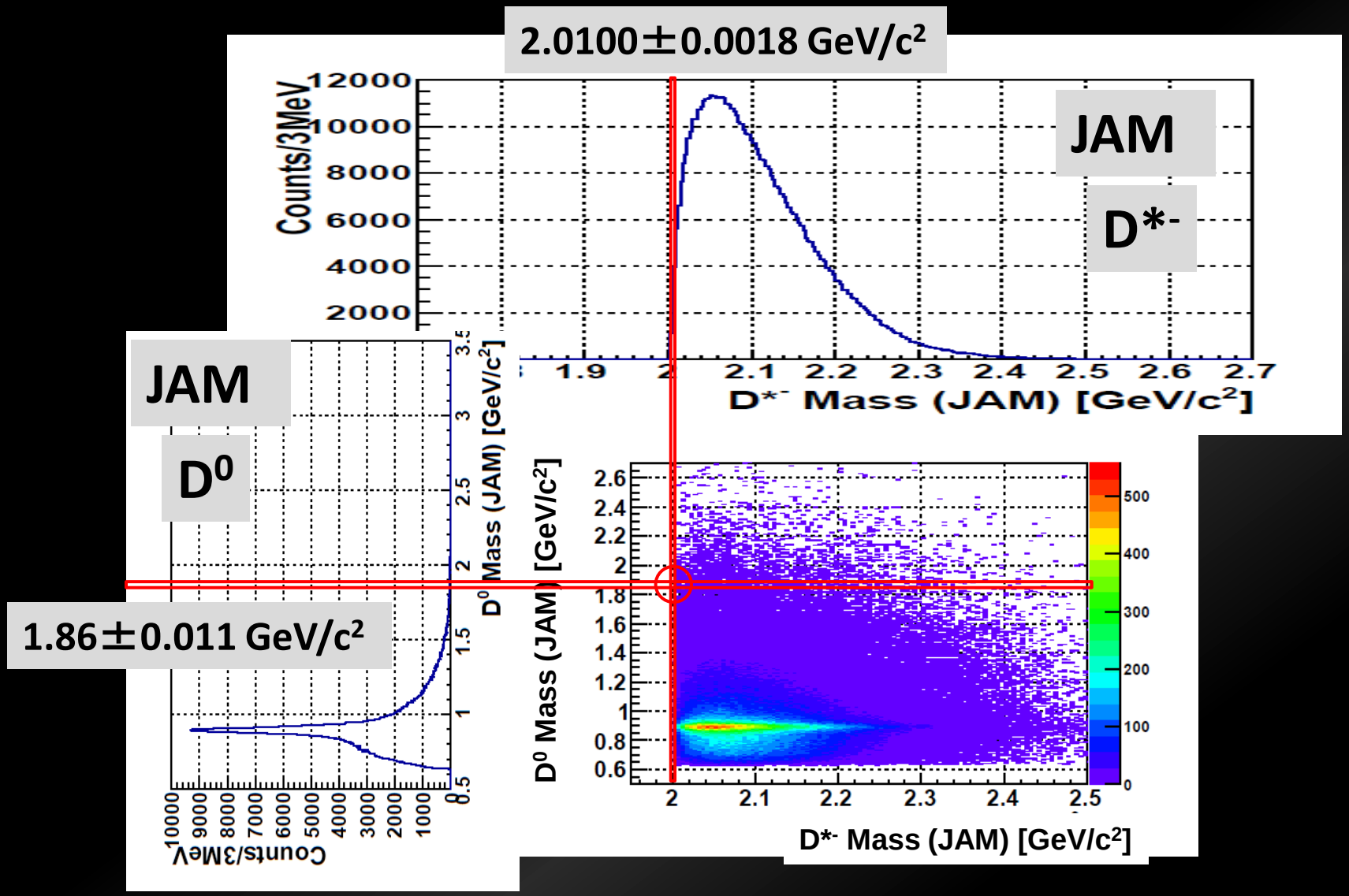


6x10^7 π/pulse
@15 GeV/c

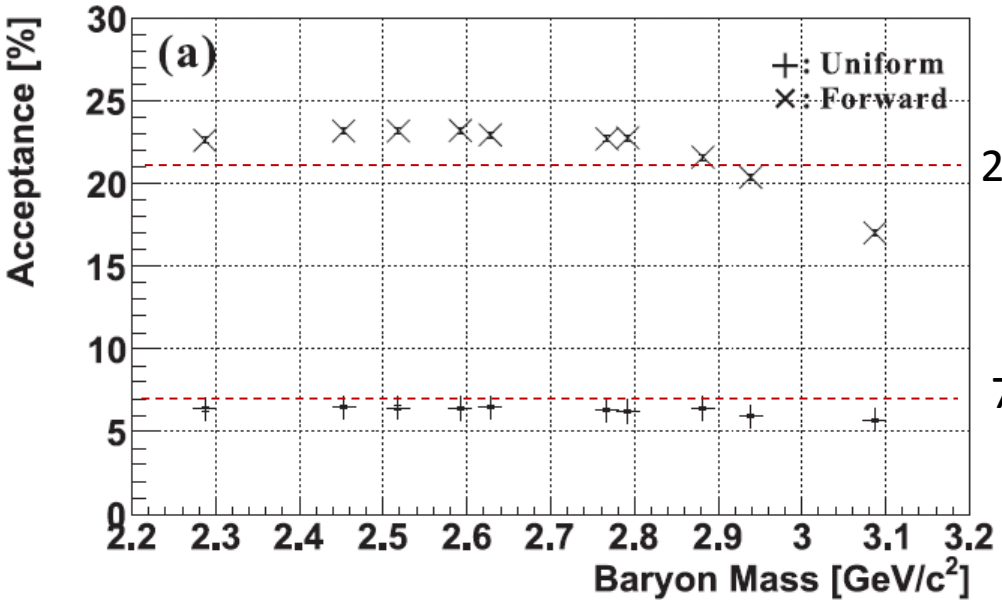
$$\pi^- p \to \overline{D}^{*0} Y_c$$
$$\mapsto \overline{D}^0 \pi^-$$
$$\mapsto K^+ \pi^-$$

Expected Resolution: ΔE_{MM}=5~6 MeV/c^2

BG reduction by D^{*-} and D^0 mass cuts

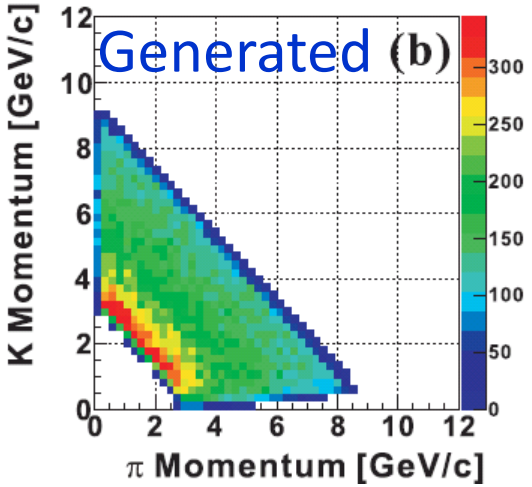


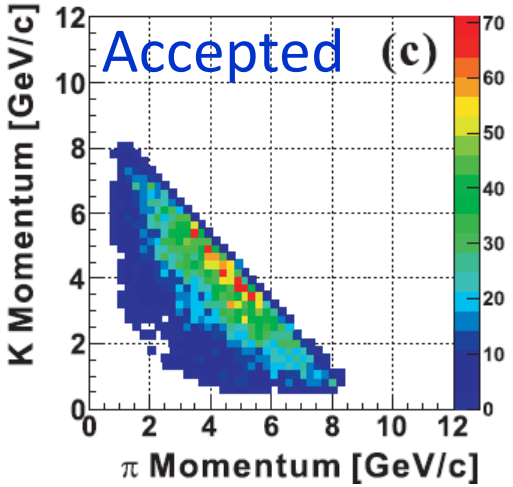
D^{*-} Acceptance



21% (t-channel scat.)

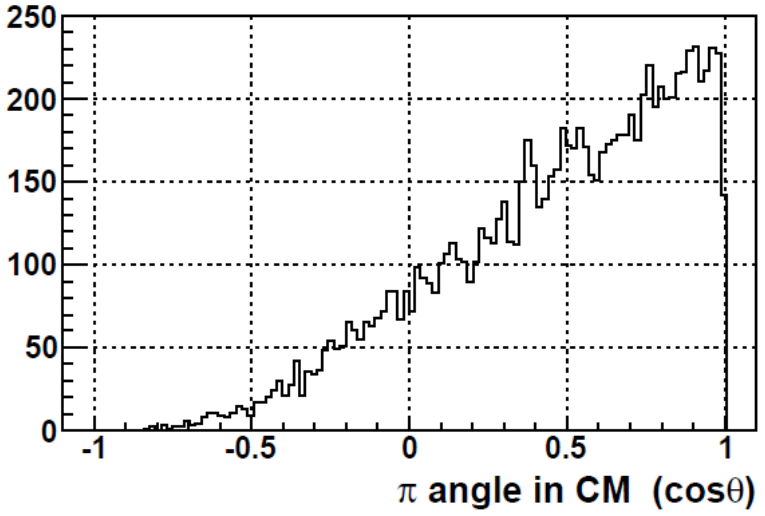
7% (isotropic scat.)

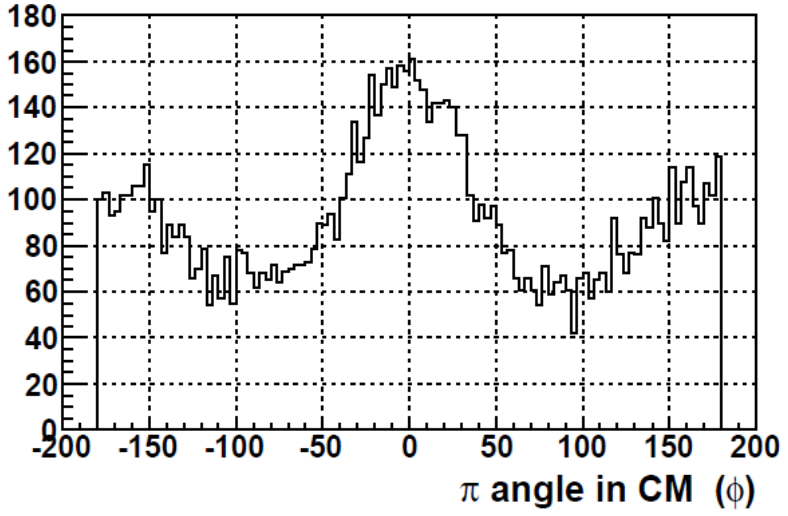




Acceptance for a Decay Pion

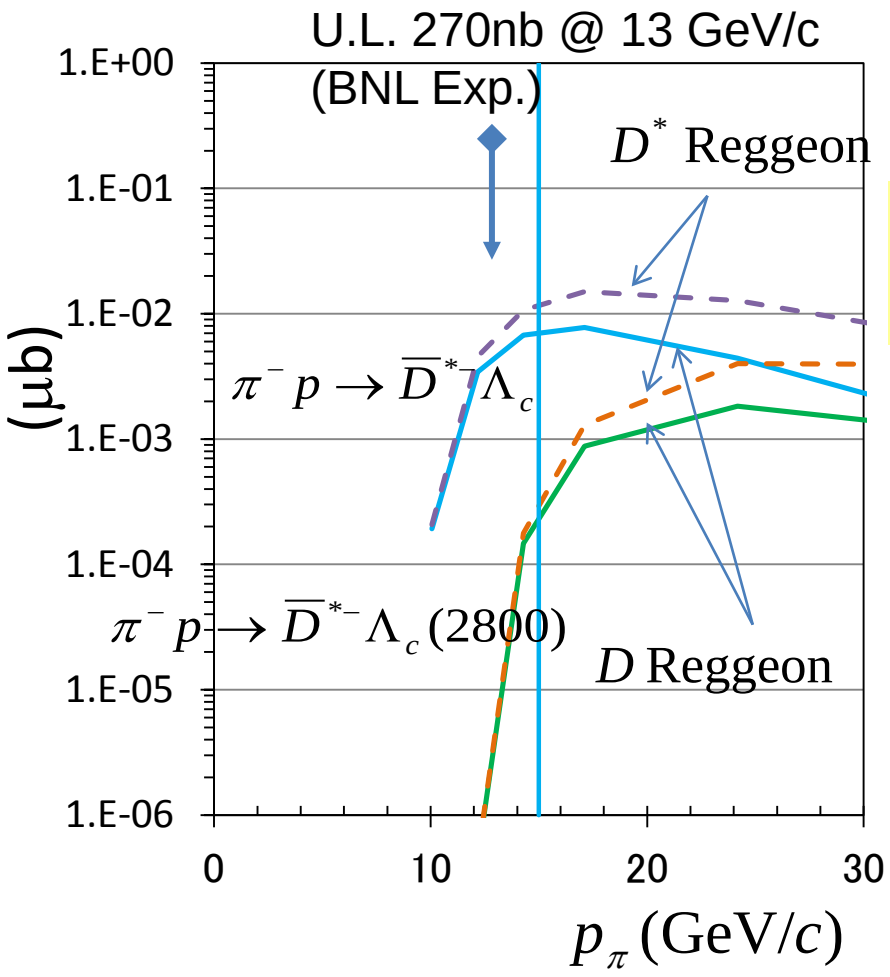
Default entrance detector size





Large entrance detector size

- **$Y_c^* \rightarrow \Sigma_c(2455) + \pi$**
  G-J frame of Y_c^*
  θ: polar angle
  ϕ: azimuthal angle
- ~50% acceptance



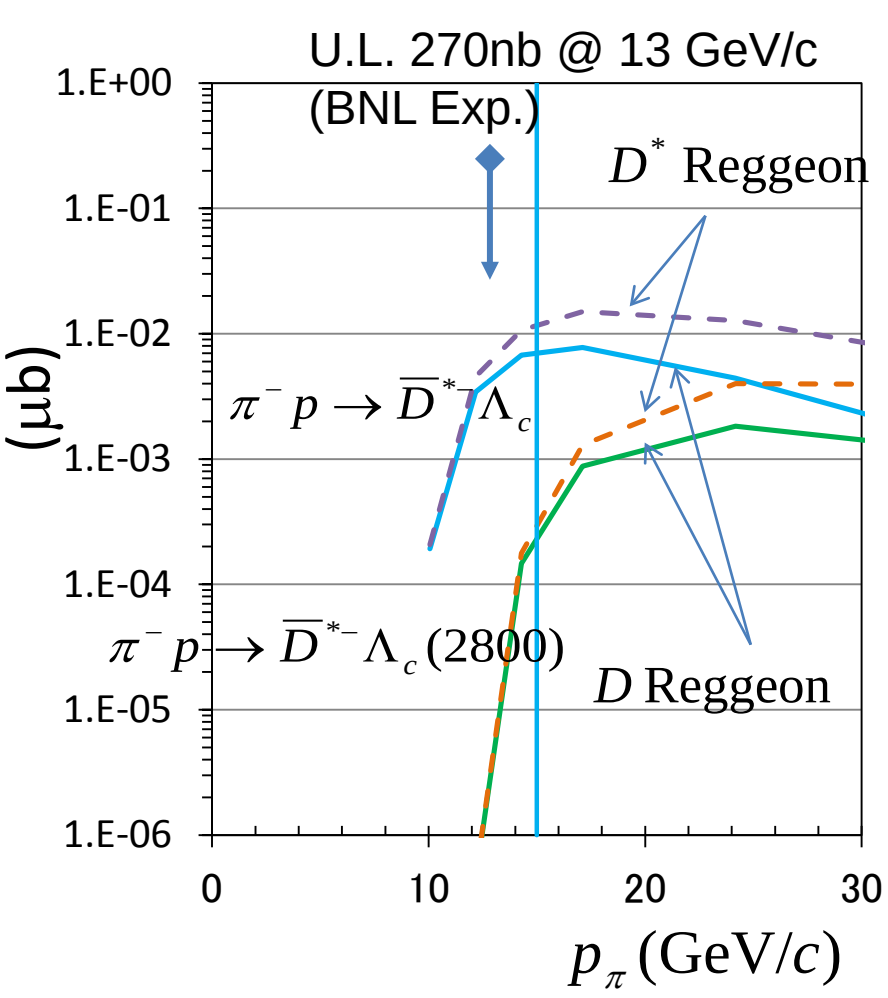
$$\sigma(s) = C\int_{t_0}^{t_1} dt \left[\frac{1}{64\pi s (p_m^{cm})^2} g_1^2 g_2^2 \, |F(t)|^2 \, |s/s_0|^{2\alpha(t)} \right]$$

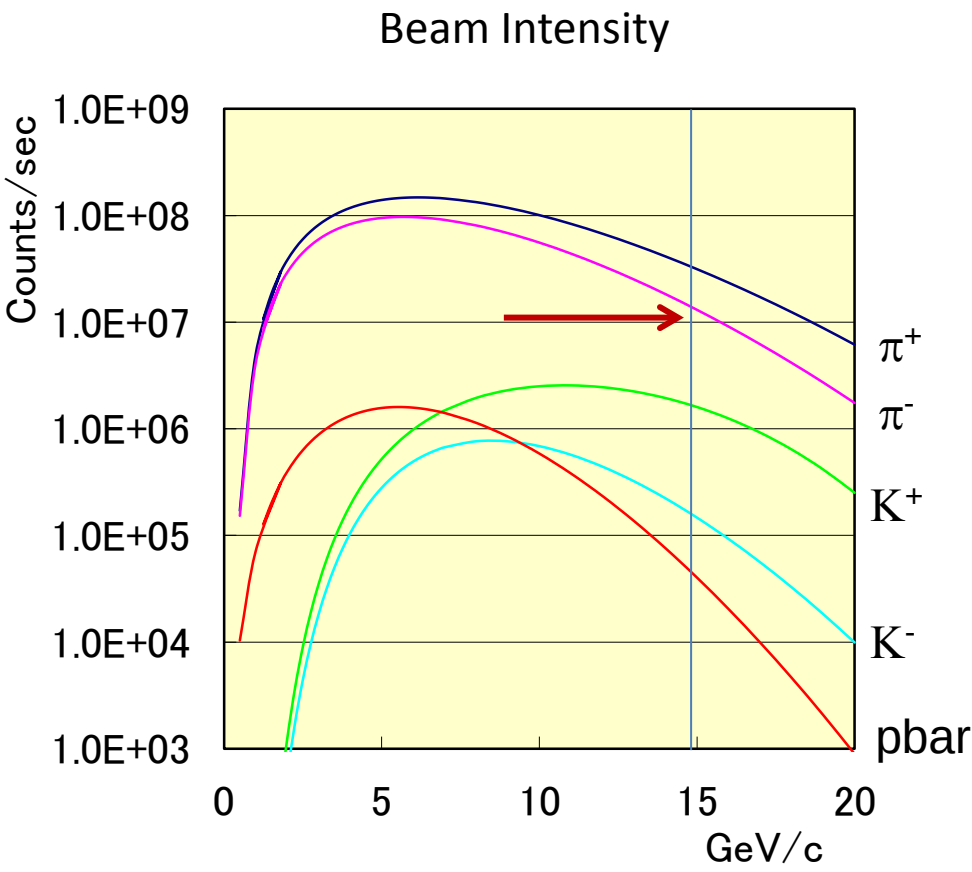
$|F(t)|^2 = \exp(2R^2 t)$, R^2 : slope parameter

$\alpha(t)$: Regge Trajectory

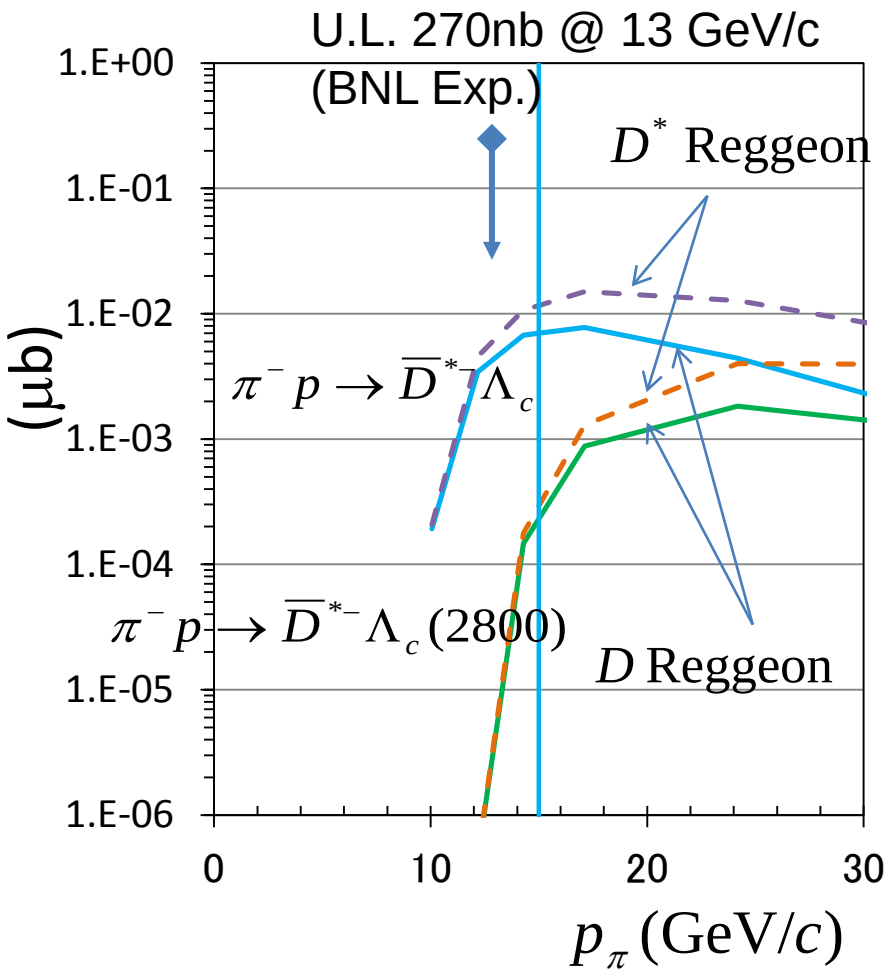
$s_0 = (m_M + m_B)^2$: scale parameter

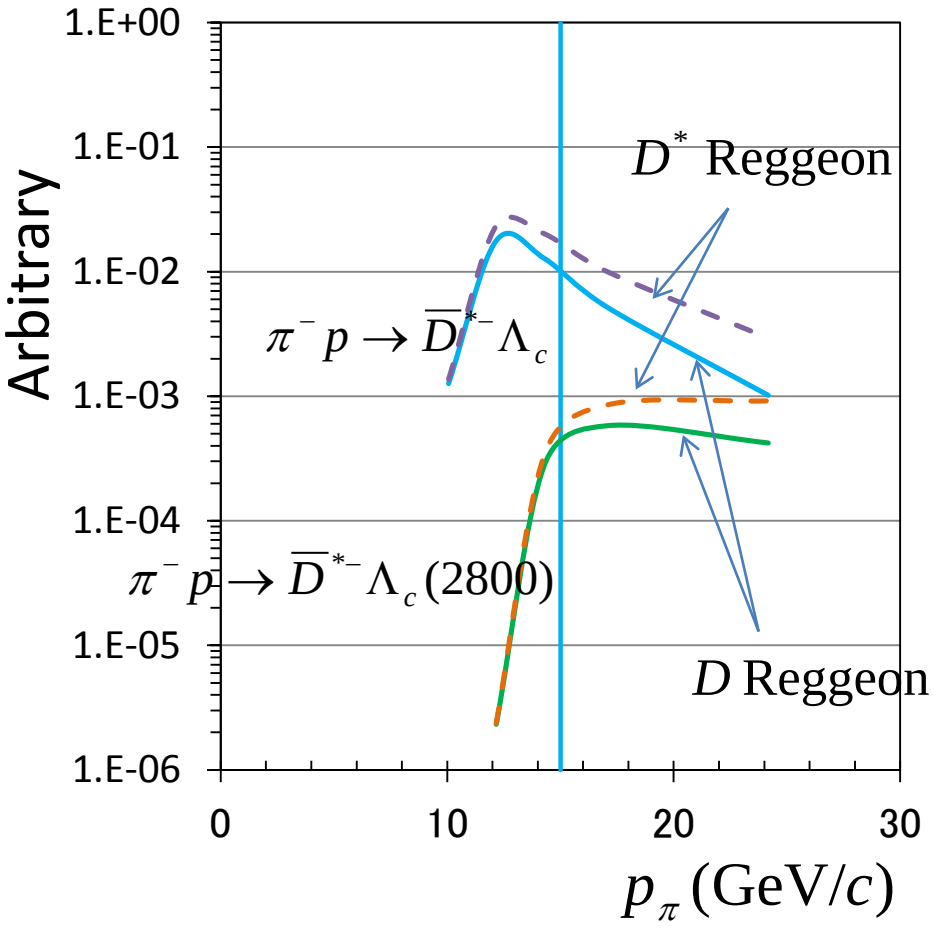
$R^2 = 2.13\,\mathrm{GeV}^{-2}$





Sanford-Wang formula
15 kW loss Pt TGT,
Acceptance: 2 msr%
BL Length: 132 m,


U.L. 270nb @ 13 GeV/c
(BNL Exp.)
D^* Reggeon
$\pi^- p \to \overline{D}^{*-} \Lambda_c$
$\pi^- p \to \overline{D}^{*-} \Lambda_c(2800)$
D Reggeon
(μb)
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
0
10
20
30
p_π (GeV/c)


Arbitrary
D^* Reggeon
$\pi^- p \to \overline{D}^{*-} \Lambda_c$
$\pi^- p \to \overline{D}^{*-} \Lambda_c(2800)$
D Reggeon
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
0
10
20
30
p_π (GeV/c)

Background cross section

TABLE II. Neutral strange particles, inclusive cross sections in μb for $\pi^- p \to K_S^0 + X$, $\Lambda + X$, $\bar{\Lambda} + X$, $K_S^0 K_S^0 + X$, $K_S^0 \Lambda + X$, $\Lambda\bar{\Lambda} + X$, and $K_S^0 \bar{\Lambda} + X$.

π⁻ p reaction @ 16 GeV/c

No. of charged secondaries	K_S^0	Λ	$\bar{\Lambda}$	$K_S^0 K_S^0$	$K_S^0 \Lambda$	$\Lambda\bar{\Lambda}$	$K_S^0 \bar{\Lambda}$
0	122.5 ± 22.4	92.5 ± 16.8	6.6 ± 2.5	17.0 ± 6.0	38.9 ± 11.7	5.3 ± 2.9	1.1 ± 1.1
2	713.6 ± 43.7	465.9 ± 30.0	23.9 ± 3.6	74.5 ± 9.6	117.8 ± 13.8	7.9 ± 2.6	3.1 ± 1.8
4	787.2 ± 48.8	479.7 ± 31.3	15.8 ± 3.0	52.5 ± 7.9	76.7 ± 10.4	5.3 ± 2.4	···
6	266.3 ± 29.1	199.5 ± 22.6	1.2 ± 0.8	6.6 ± 2.8	22.7 ± 5.8	1.1 ± 1.1	···
8	45.2 ± 15.7	26.6 ± 10.1	0.8 ± 0.8	4.2 ± 4.2	···	···	···
10	2.4 ± 1.6	1.8 ± 1.5	···	···	···	···	···
Total inclusive	1937.2 ± 76.7	1266.0 ± 52.7	48.3 ± 5.4	154.8 ± 15.0	256.1 ± 21.6	19.6 ± 4.7	4.2 ± 2.2

F. Barreiro et al, PRD 17(1978)669

R. Honecker et al, NPB 13(1969)571

π⁻ p reaction @ 16 GeV/c

n_{ch}	Final state a)	σ(mb)	n_{ch}	Final state	σ(μb)
2	$p\pi^-$	4.36 ± 0.15	8	$p\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-$	94 ± 23
	$p\pi^-\pi^0$	0.30 ± 0.10		$p\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-\pi^0$	126 ± 24
	$n\pi^+\pi^-$	0.27 ± 0.10		$n\pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-$	114 ± 25
	$p\pi^-Z^0$	1.58 ± 0.09		$p\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-Z^0$	523 ± 63
	$\pi^+\pi^-Z^0$	2.49 ± 0.15		$\pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-Z^0$	393 ± 51
4	$p\pi^+\pi^-\pi^-$	0.99 ± 0.05	10	$p\pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-\pi^-$	9 ± 6
	$p\pi^+\pi^-\pi^-\pi^0$	0.70 ± 0.04		$p\pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-\pi^-\pi^0$	65 ± 17
	$n\pi^+\pi^+\pi^-\pi^-$	0.29 ± 0.05		$n\pi^+\pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-\pi^-$	26 ± 12
	$p\pi^+\pi^-\pi^-Z^0$	2.94 ± 0.16		$p\pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-Z^0$	75 ± 22
	$\pi^+\pi^+\pi^-\pi^-Z^0$	2.81 ± 0.16		$\pi^+\pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-\pi^-Z^0$	65 ± 20
6	$p\pi^+\pi^+\pi^-\pi^-\pi^-$	0.25 ± 0.02	12	$p\pi^+\pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-\pi^-\pi^-$	<6
	$p\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0$	0.55 ± 0.03		$p\pi^+\pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-\pi^-\pi^-\pi^0$	3 ± 3
	$n\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$	0.19 ± 0.05		$n\pi^+\pi^+\pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-\pi^-\pi^-$	8 ± 5
	$p\pi^+\pi^+\pi^-\pi^-\pi^-Z^0$	2.00 ± 0.11		$p\pi^+\pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-\pi^-\pi^-Z^0$	8 ± 6
	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-Z^0$	1.18 ± 0.07		$\pi^+\pi^+\pi^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-\pi^-\pi^-\pi^-\pi^-Z^0$	5 ± 4

a) Z^0 represents a system of two or more neutral particles.

Strangeness production data

- $K^0_s \to K^+$とする
- 4 track以上が$K^+ \pi^- \pi^-$を含む

⇒~1.1 mb

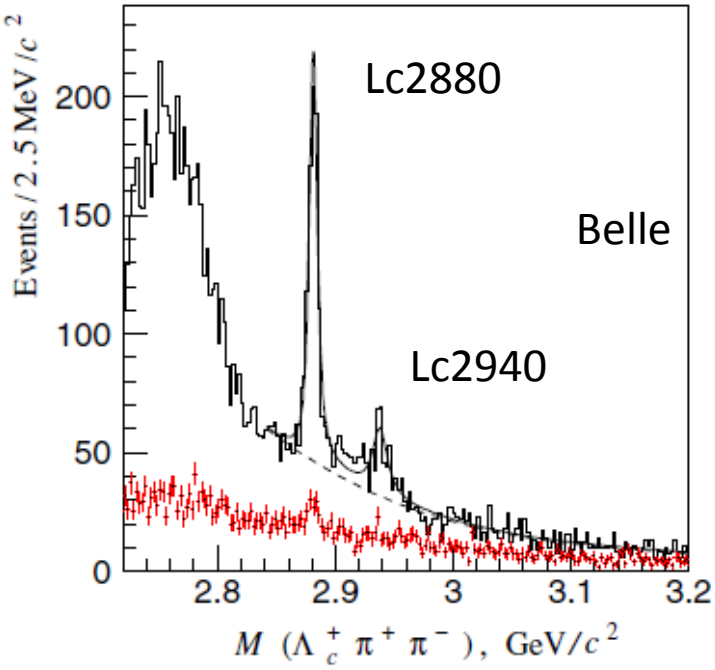
π production data

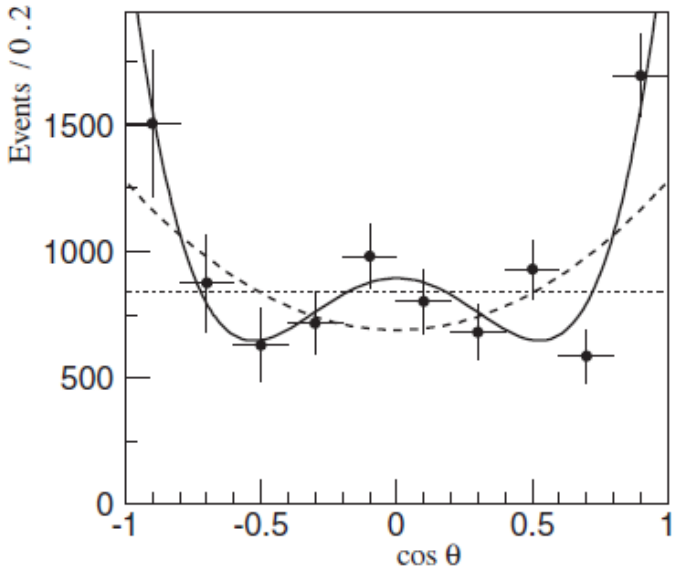
- 終状態に$\pi^- \pi^0(K^+) \pi^- \pi^-$等を含む
- Strangeness生成は1/10程度と仮定

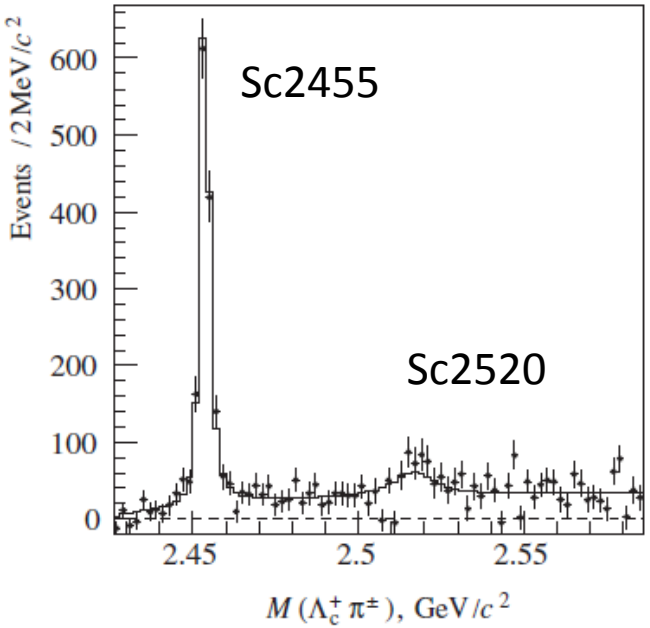
⇒~0.5 mb

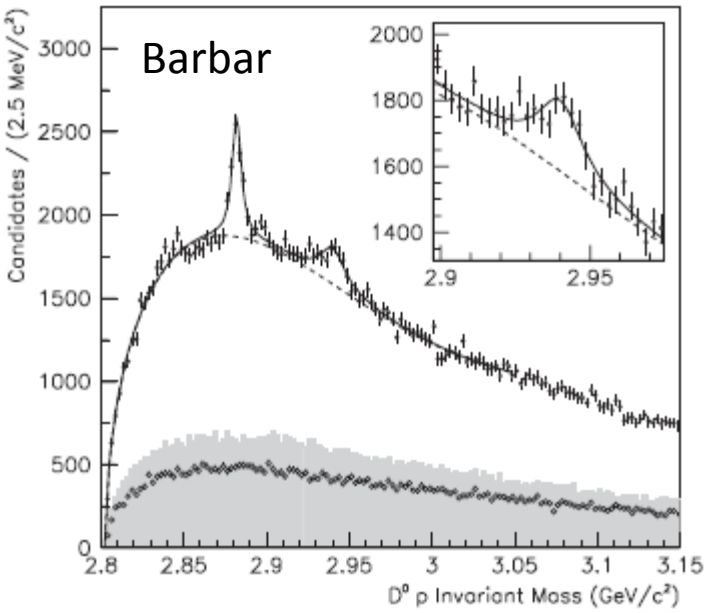
＊ $K^+ \pi^- \pi^-$になるものは0.5~1 mb程度か?

Shirotori's Slide

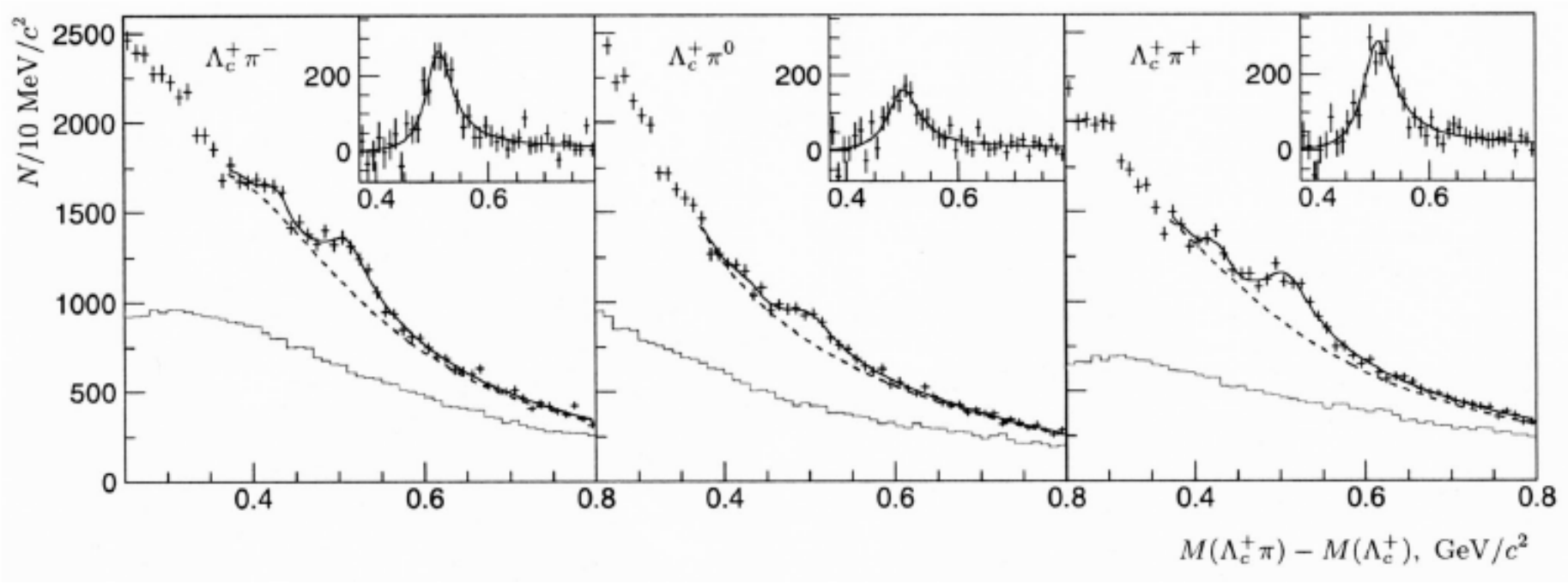

Lc2880
Belle
Lc2940
Events / 2.5 MeV/c²
M (Λc+ π+ π−), GeV/c²


Events / 0.2
cos θ


Sc2455
Sc2520
Events / 2 MeV/c²
M (Λc+ π±), GeV/c²


Barbar
Candidates / (2.5 MeV/c²)
D⁰ p Invariant Mass (GeV/c²)

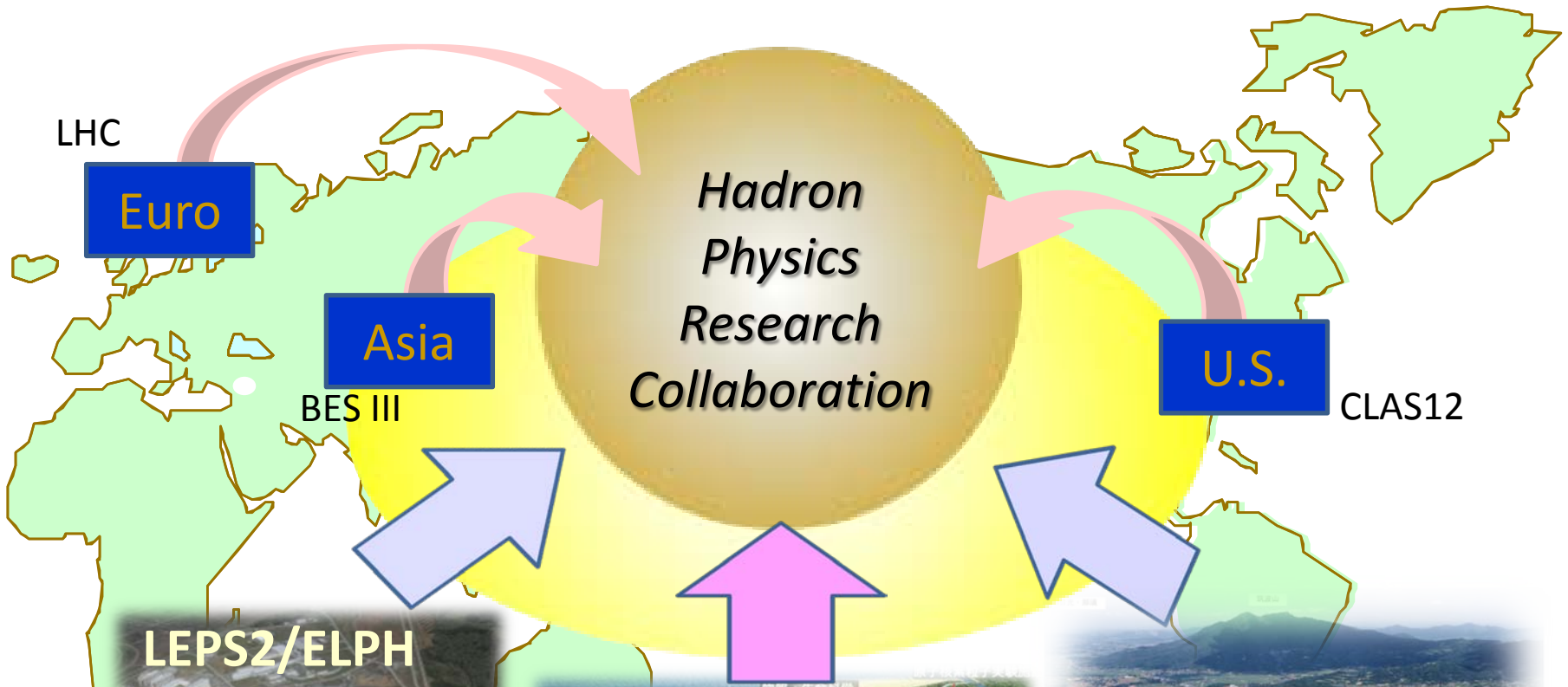
Belle


$N/10\ \mathrm{MeV}/c^2$
2500
2000
1500
1000
500
0
$\Lambda_c^+\pi^-$
$\Lambda_c^+\pi^0$
$\Lambda_c^+\pi^+$
200
0
0.4
0.6
0.8
$M(\Lambda_c^+\pi) - M(\Lambda_c^+),\ \mathrm{GeV}/c^2$

A new research project in High-res., High-p Beam Line at J-PARC

- Proposed by RCNP, Osaka U. under the MOU on research cooperation among RCNP, IPNS/KEK, and the J-PARC Center
- Role of RCNP
  - Collect research ideas and collaborators
  - Introduce new methods/techniques
    - High-resolution, high-p Secondary Beam Line
    - Large Acceptance, Multi-Particle Spectrometer
      → Multi-Purpose System for Hadron/Nuclear Physics
  - Conduct hadron/nuclear physics with a leader ship of RCNP
    a platform for a research collaboration in Hadron Physics
- Charmed Baryon Spectroscopy at the High-p BL
  - RCNP-PPAC Project Review on 9/Nov/2012
  - Proposal submitted to the J-PARC PAC

Extension of Research Collaboration in Hadron Physics



photon beams

hadron beams

Belle/Belle II

e^+e^- collider

Schedule

Fiscal Year	2012	2013	2014	2015	2016	2017	2018
Accelerator	10kW	50kW	Toward 100kW			100kW	
Beam Line		Manufacturing		Install			
E16							
Magnet	Construction						
Detector		1/3 ready		Full install			
Beam Time					Experiment		
Charmed Baryon							
High Res. Beam	Design	Manufacturing		Install			
Detector	Design	R&D		Production		Install	
Beam Time							Exp.

GSI/FAIR	Construction	Install	Start