Baryon spectroscopy at Belle and future prospects for Belle II and J-PARC

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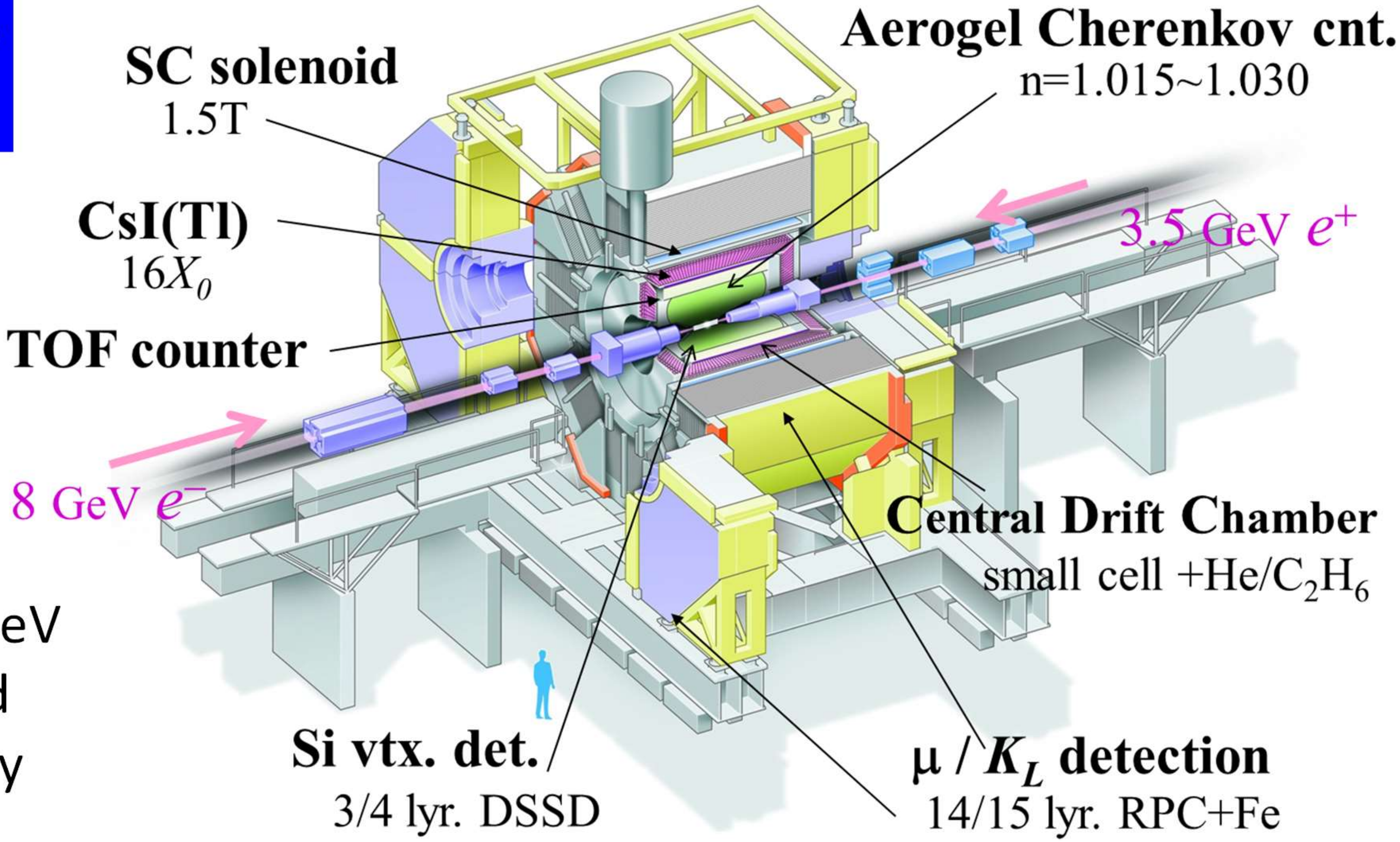
Baryon spectroscopy
at Belle

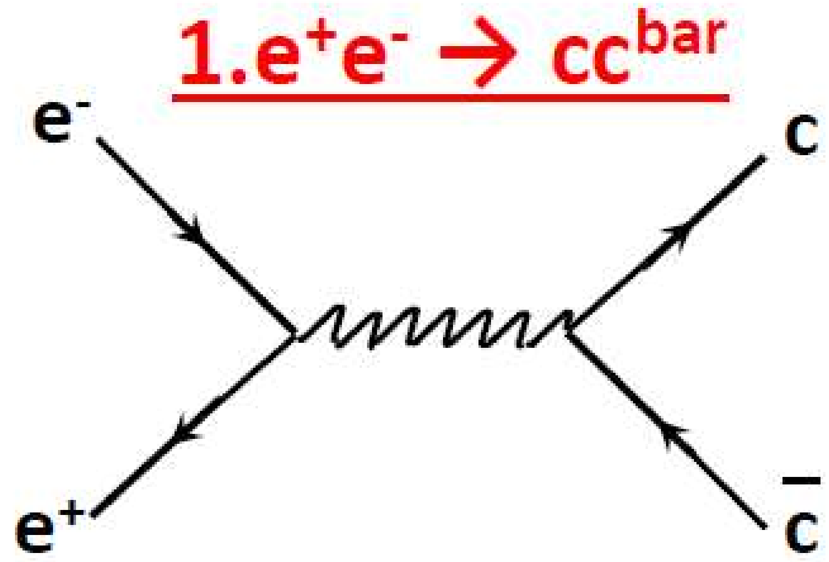
Belle experiment

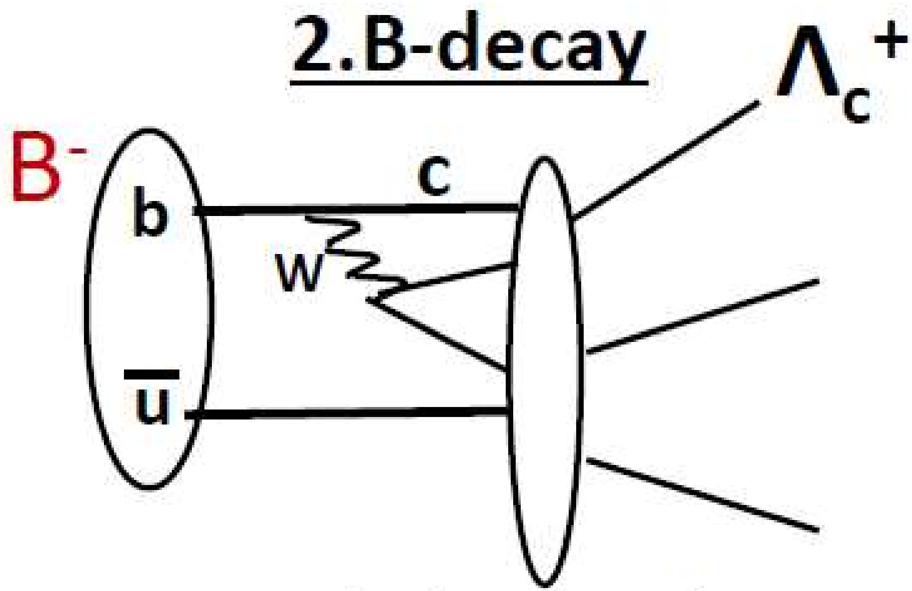


- √s~10.6 GeV
- Integrated Luminosity > 1 ab^{-1}

Almost 4π, good momentum resolution (Δp/p～0.1%), EM calorimeter, PID & Si Vertex detector

Baryon production in B factory





Baryons produced via fragmentation

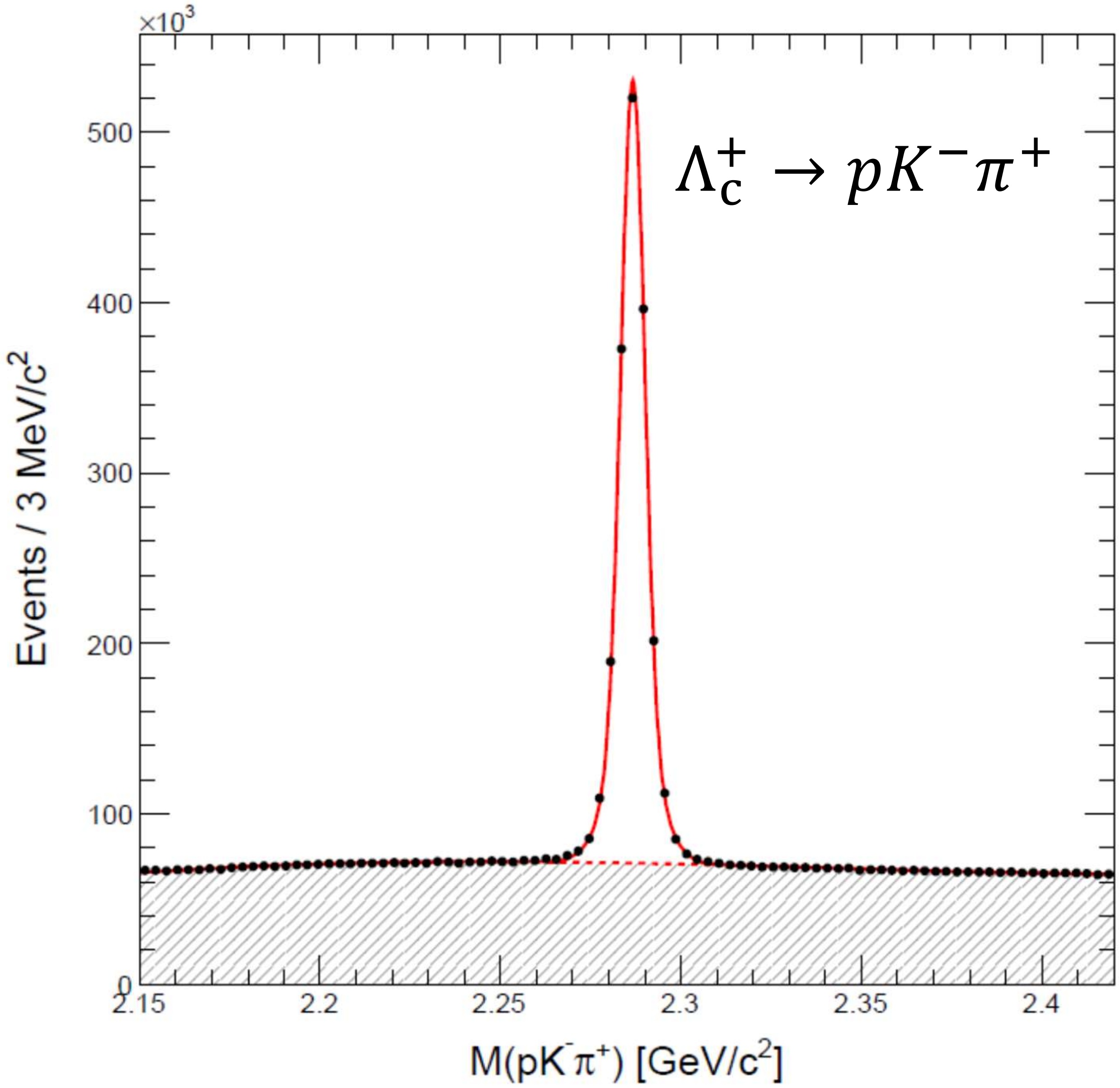
- Charmed baryons – rather direct
- Hyperons – later stage of fragmentation

Huge statistics

B is efficiently produced via Υ(4s)

Once bottom is produced, it favorably decays into charm.

Huge statistics, good quality



> 1 M events reconstructed

Resolution:
< 10 MeV FWHM

S/N ~ 10

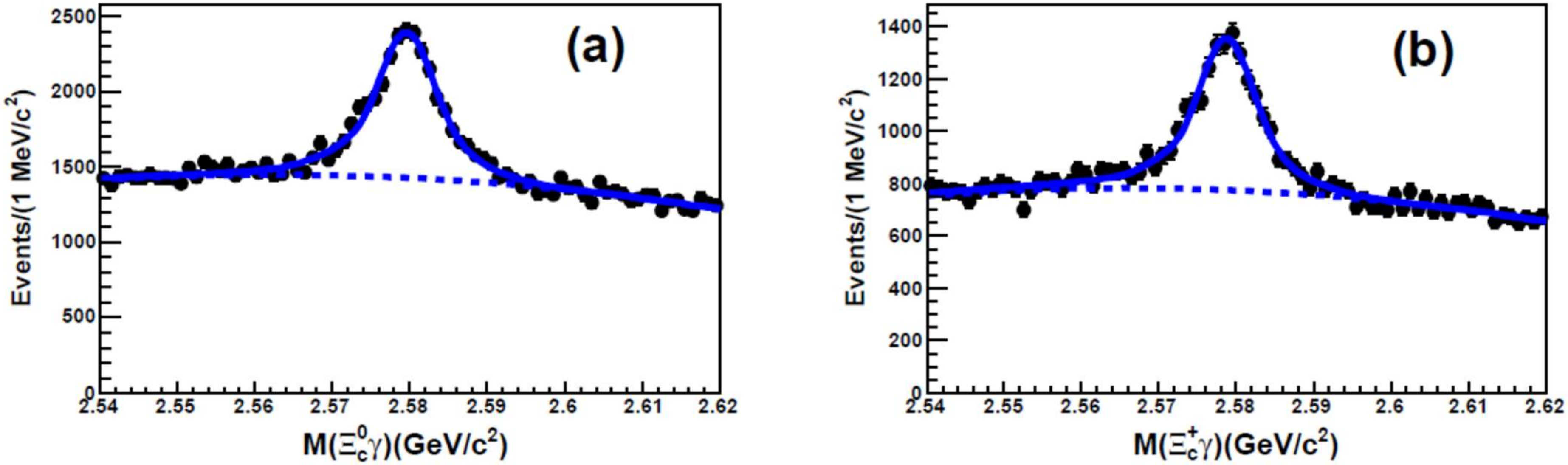
1.1 Spectroscopy of Ξ_c

Measurements

- Various Ξ_c resonances are observed in $\Xi_c\pi$, $\Xi_c\pi\pi$, $\Lambda_c K\pi$, and ΛD.
- Masses & widths are precisely determined for 7 states: $\Xi'_c(2580)$, $\Xi_c(2645)$, $\Xi_c(2790)$, $\Xi_c(2815)$, $\Xi_c(2980)$, $\Xi_c(3055)$, and $\Xi_c(3080)$
  - Fundamental information to identify the nature of these states.
  - Significant mass difference in isodoublets observed.

$\Xi'_c(2580)$

$\Sigma_c(2455)$ analog, $J^P=1/2^+$



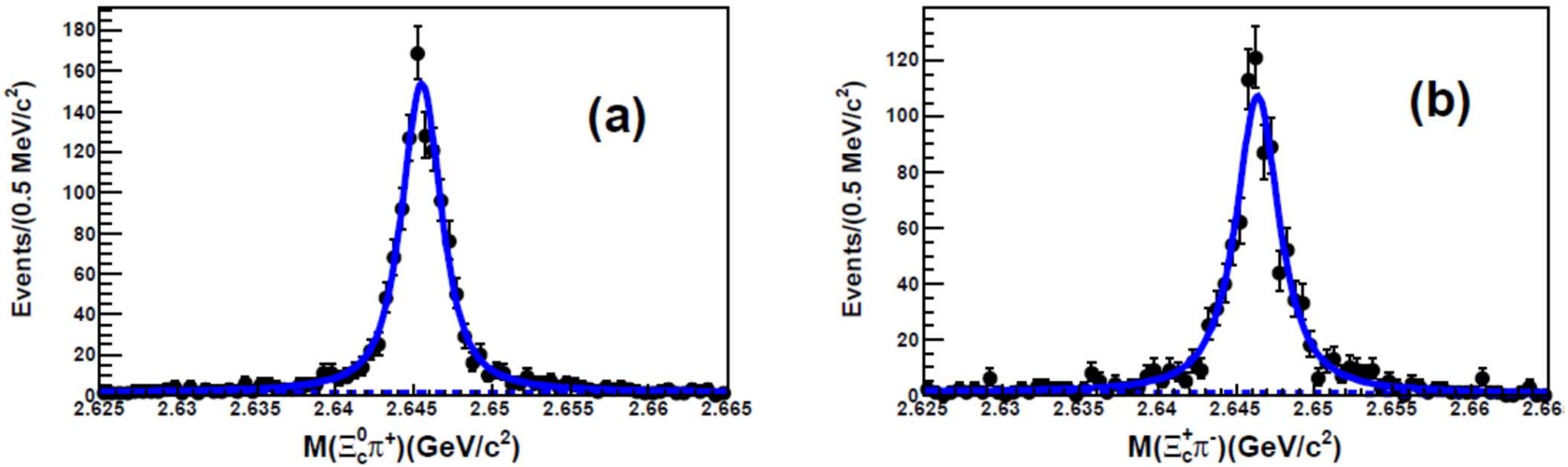
- Mass: Ξ'^+_c: $2578.4 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$
  [MeV] Ξ'^0_c: $2579.2 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$

$\Delta M = 0.8\ MeV$

PRD**94**, 052011

$\Xi_c(2645)$

$\Sigma^*_c(2520)$ analog, $J^P=3/2^+$



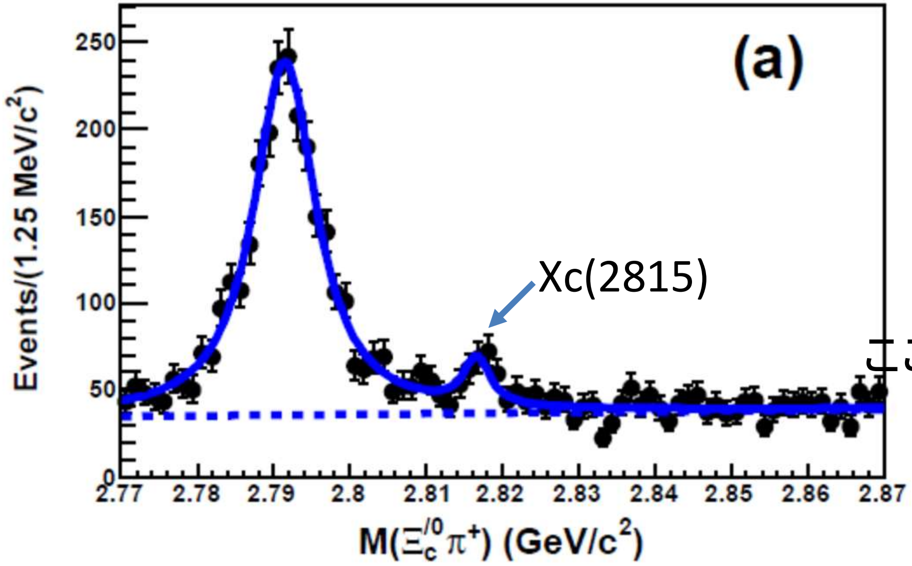
$\Delta M = 0.8\ MeV$

- Mass: $\Xi_c(2645)^+$: $2645.58 \pm 0.06 \pm 0.07^{+0.28}_{-0.40}$
  $\Xi_c(2645)^0$: $2646.43 \pm 0.07 \pm 0.07^{+0.28}_{-0.40}$
- Width: $\Xi_c(2645)^+$: $2.06 \pm 0.13 \pm 0.13$
  $\Xi_c(2645)^0$: $2.35 \pm 0.18 \pm 0.13$

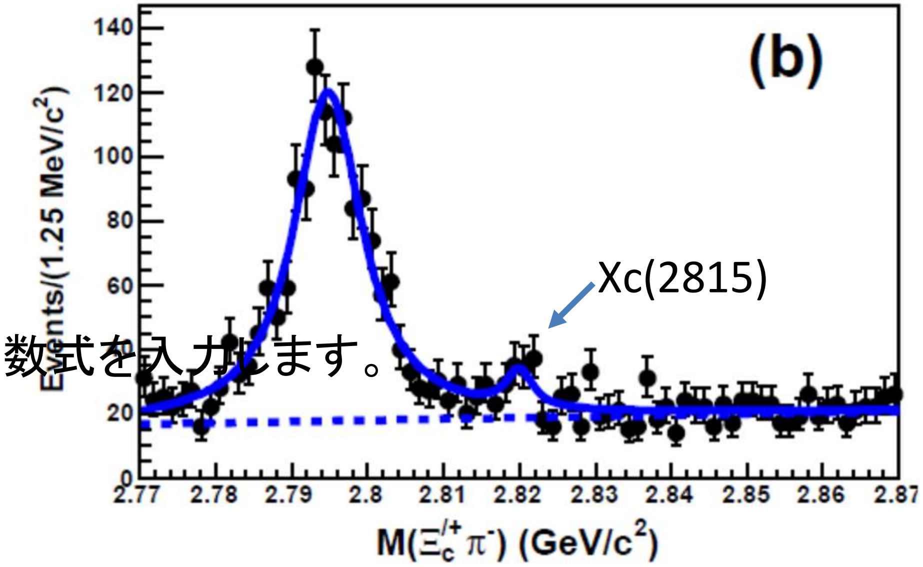
PRD**94**, 052011

$\Xi_c(2790)$

$\Lambda_c(2593)$ analog, $J^P=1/2^-$



ここに数式を入力します。



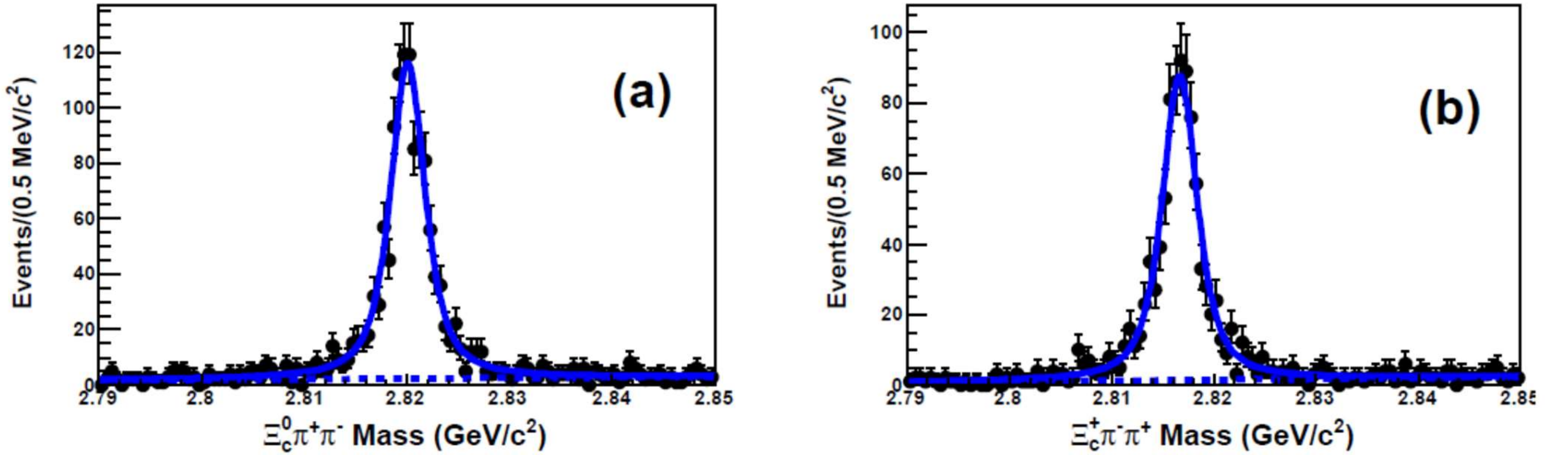
$\Delta M = 3.3\ MeV$

- Mass: $\Xi_c(2790)^+$: $2791.6 \pm 0.2 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$
  $\Xi_c(2790)^0$: $2794.9 \pm 0.3 \pm 0.1 \pm 0.4^{+0.3}_{-0.4}$
- Width: $\Xi_c(2790)^+$: $8.9 \pm 0.6 \pm 0.8$
  $\Xi_c(2790)^0$: $10.0 \pm 0.7 \pm 0.8$

PRD**94**, 052011

$\Xi_c(2815)$

$\Lambda_c(2620)$ analog, $J^P=3/2^-$



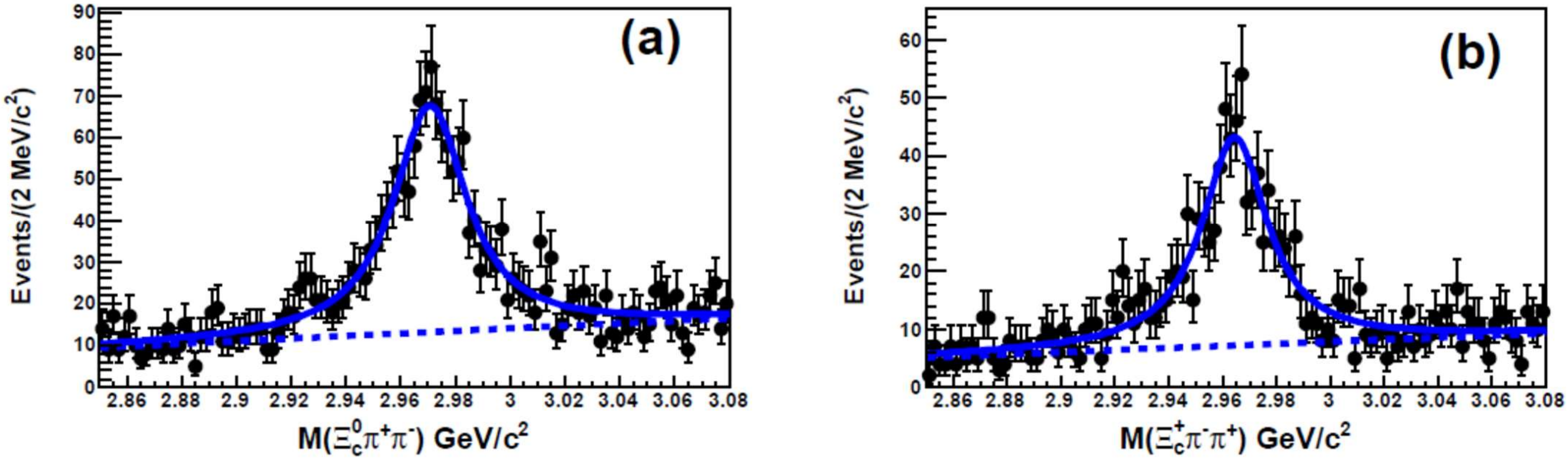
$\Delta M = 3.5\ MeV$

- Mass: $\Xi_c(2815)^+$: $2816.73 \pm 0.08 \pm 0.06^{+0.28}_{-0.40}$
  $\Xi_c(2815)^0$: $2820.20 \pm 0.08 \pm 0.07^{+0.28}_{-0.40}$
- Width: $\Xi_c(2815)^+$: $2.43 \pm 0.20 \pm 0.17$
  $\Xi_c(2815)^0$: $2.54 \pm 0.18 \pm 0.17$
  - First observation of finite width

PRD**94**, 052011

$\Xi_c(2980)$

$\Lambda_c(2765)$ analog??



- Mass: $\Xi_c(2980)^+$: $2966.0 \pm 0.8 \pm 0.2^{+0.3}_{-0.4}$
  $\Xi_c(2980)^0$: $2670.8 \pm 0.7 \pm 0.2^{+0.3}_{-0.4}$
- Width: $\Xi_c(2980)^+$: $28.1 \pm 2.4^{+1.0}_{-5.0}$
  $\Xi_c(2980)^0$: $30.3 \pm 2.3^{+1.0}_{-1.8}$

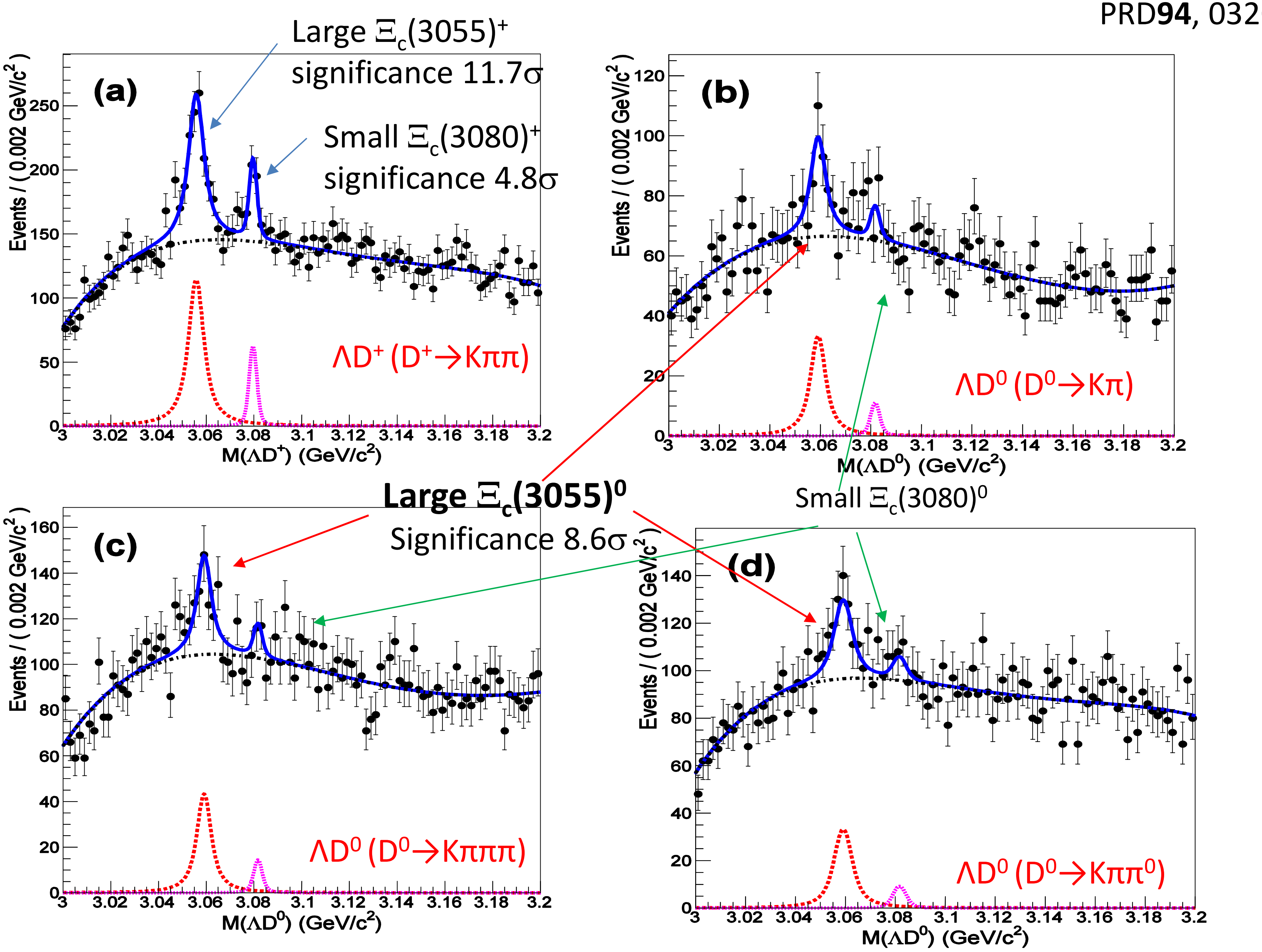
$\Delta M = 4.8\ MeV$

PRD**94**, 052011

Measurements

- Various Ξ_c resonances are observed in $\Xi_c\pi$, $\Xi_c\pi\pi$, $\Lambda_c K\pi$, and ΛD.
- Masses & widths are precisely determined for 7 states: $\Xi'_c(2580)$, $\Xi_c(2645)$, $\Xi_c(2790)$, $\Xi_c(2815)$, $\Xi_c(2980)$, $\Xi_c(3055)$, and $\Xi_c(3080)$
- New observations in ΛD mode:
  – $\Xi_c(3055)^0$ is newly discovered
    ΛD modes are firstly observed for $\Xi_c(3055)^+$ and $\Xi_c(3080)^+$

PRD**94**, 032002



Mass difference in isodoublets

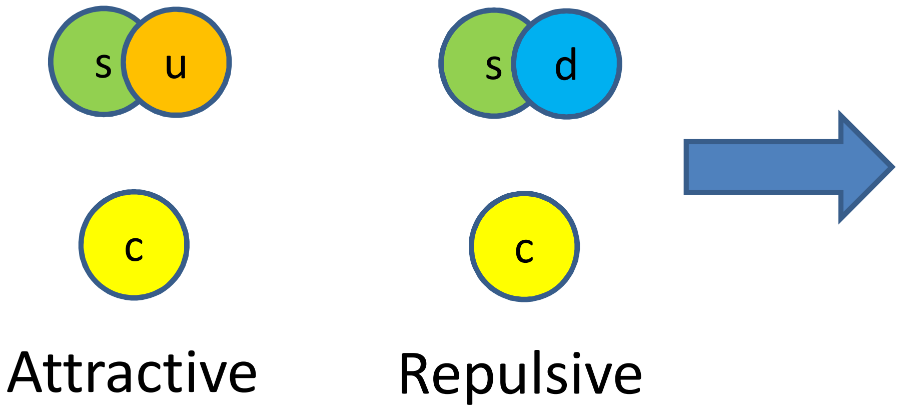
	Analog state/J^P	$M(\Xi_c^0)$-$M(\Xi_c^+)$ (MeV)
Ξ_c(g.s.)	Λ_c $1/2^+$	2.93±0.24
Ξ'_c(2580)	Σ_c(2455), $1/2^+$	0.8±0.5
Ξ^*_c(2645)	Σ_c(2520), $3/2^+$	0.9±0.5
Ξ_c(2790)	Λ_c(2593), $1/2^-$	3.3±0.7
Ξ_c(2815)	Λ_c(2625), $3/2^-$	3.5±0.5
Ξ_c(2980)	?	4.8±0.6
Ξ_c(3055)	?	3.2±0.9

Small mass difference ($\lesssim$1 MeV) for Σ_c analog states

Larger mass difference (~3 MeV) for the others

Interpretation in diquark picture

- When us/ds is a "good diquark" → Coulomb effect is large



Ξ_c^+ is more stable
Large mass splitting

- "Bad diquark" → Small mass splitting
  - Case for $\Xi'_c(2580)$ & $\Xi^*_c(2645)$
- Supportive for diquark picture
- Should be different for λ/ρ excitation, too.
  - Gives hint for structure
- $\Xi_c(2980)$, $\Xi_c(3050)$ –Λ_c analog with good diquark & λ mode excitation?

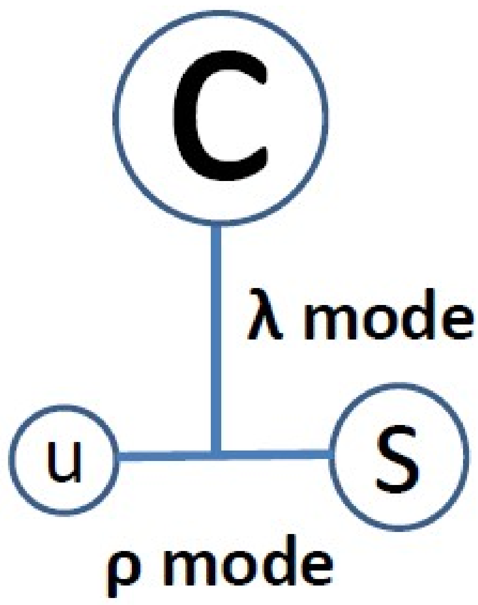
Measurements

- Various Ξ_c resonances are observed in $\Xi_c\pi$, $\Xi_c\pi\pi$, $\Lambda_c K\pi$, and ΛD.
- Masses & widths are precisely determined for 7 states: $\Xi'_c(2580)$, $\Xi_c(2645)$, $\Xi_c(2790)$, $\Xi_c(2815)$, $\Xi_c(2980)$, $\Xi_c(3055)$, and $\Xi_c(3080)$
- New observations in ΛD mode:
  - $\Xi_c(3055)^0$ is newly discovered
    ΛD modes are firstly observed for $\Xi_c(3055)^+$ and $\Xi_c(3080)^+$
  - Branching ratios of $\Xi_c(3055)^+$ and $\Xi_c(3080)^+$ to $\Lambda D^+/\Sigma_c K$ mode are measured
    → Sensitive to structure of these states under heavy quark symmetry.

Branching ratios

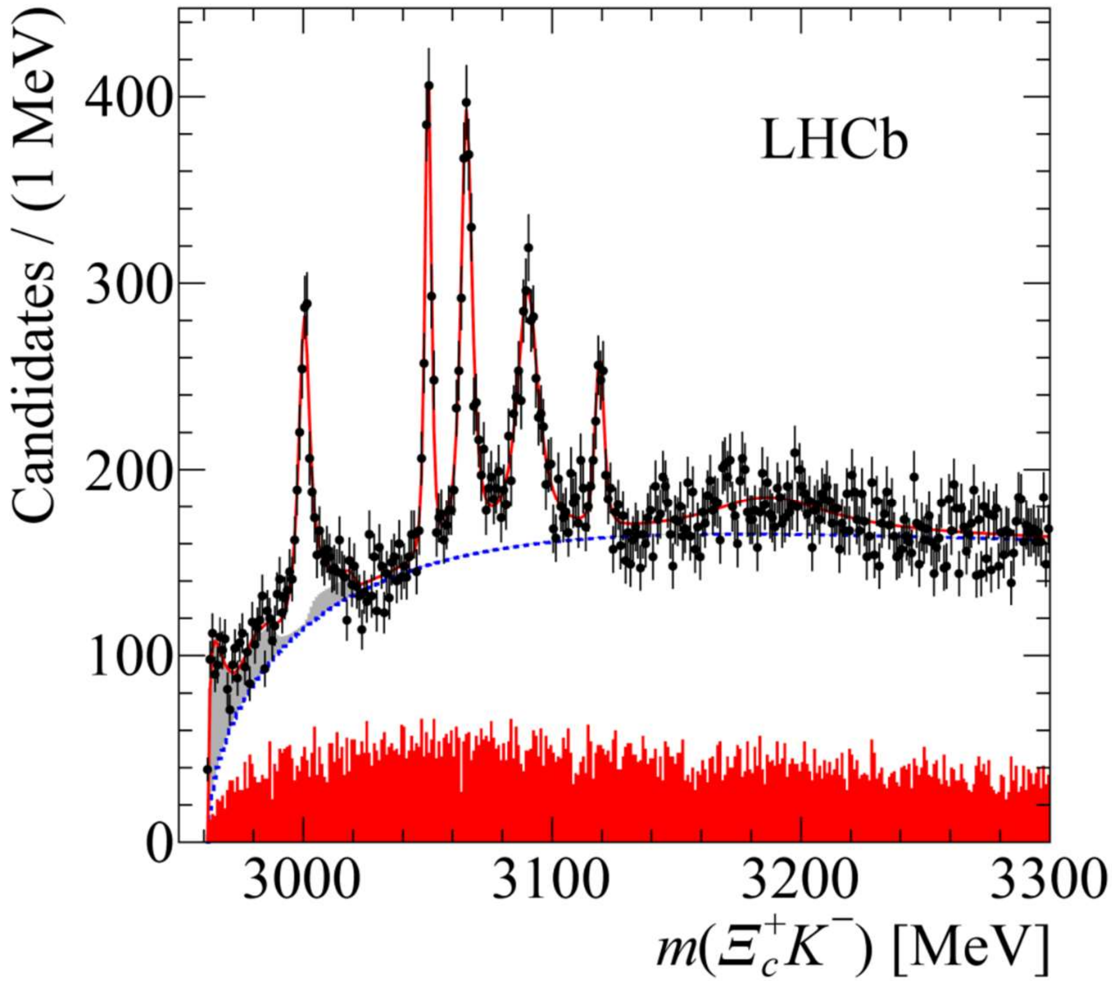
PRD**94**, 032002

- $B(\Xi_c(3055)^+ \to \Lambda D^+)/B(\Sigma_c^{++}K^-) = 5.09 \pm 1.01 \pm 0.76$
  $B(\Xi_c(3080)^+ \to \Lambda D^+)/B(\Sigma_c^{++}K^-) = 1.29 \pm 0.30 \pm 0.15$
  $B(\Xi_c(3080)^+ \to \Sigma_c^{*++}K^-)/B(\Sigma_c^{++}K^-) = 1.27 \pm 0.27 \pm 0.01$
- BR Reflects the structure of each resonance.
  - Naively, Large ΛD branching ratio suggests the excitation is in between c and us (λ mode), not in between s and u (ρ mode).
  - BR for heavy-quark spin doublet partner (e.g., from/to Σ_c^* and Σ_c) are related by heavy quark symmetry.
  - A challenge to theorists, together with mass & width

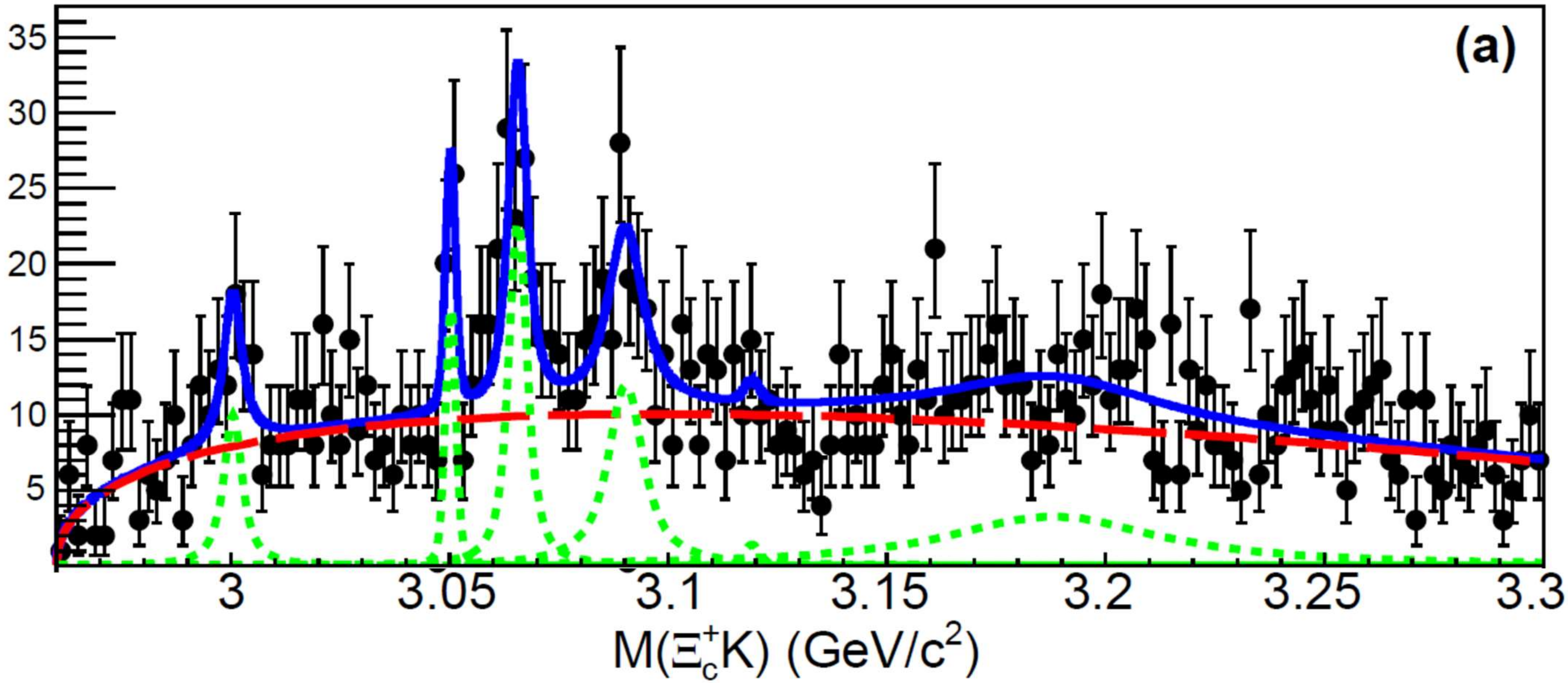


Excited Ω_c search

- 5 Narrow Ω_c^* resonances (+ possibly one wide one) are found by LHCb in the decay mode of $\Omega_c^* \rightarrow \Xi_c K^-$
- Of course, Belle can look at the same final states



Belle preliminary result

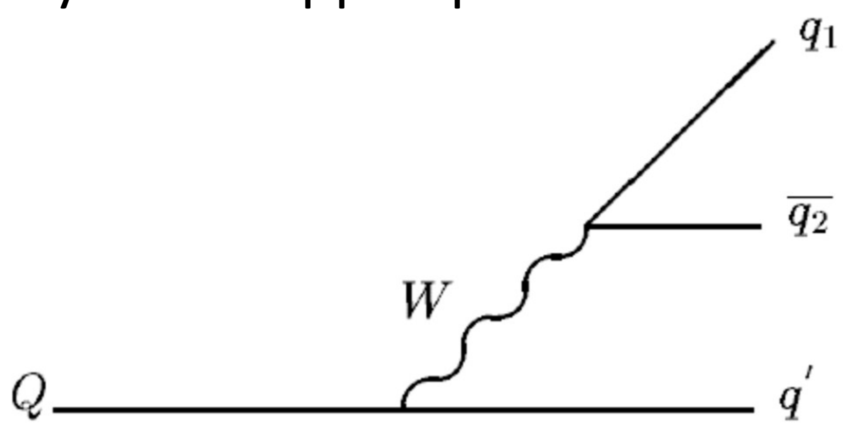


- Masses and widths are FIXED to the LHCb results
- Significant signals for the Ω_c (3066) & Ω_c(3090). Less significant for Ω_c(3000) and Ω_c(3050).
- No signal for the Ω_c(3119)

1.2 Double-Cabibbo suppressed decay of Λ_c: $\Lambda_c^+ \rightarrow pK^+\pi^-$

Doubly Cabibbo-suppressed decay

- Weak decay amplitude of a charm quark
  - c → s: $\cos\theta_c$ ~ 1
    d: $\sin\theta_c$ ~ 0.23 ← Cabibbo suppression
  - At the same time, emitted W decays into a qqbar pair
    $u\bar{d}$: $\cos\theta_c$
    $u\bar{s}$: $\sin\theta_c$
- So, the decay $c \to d(u\bar{s})$ is twice suppressed
  → Doubly Cabibbo-suppressed decay
  - Naively, decay branch is O($\tan^4\theta_c$) ~ 0.28% smaller compared to counterpart ($c \to s(\bar{d}u)$)



Analysis strategy

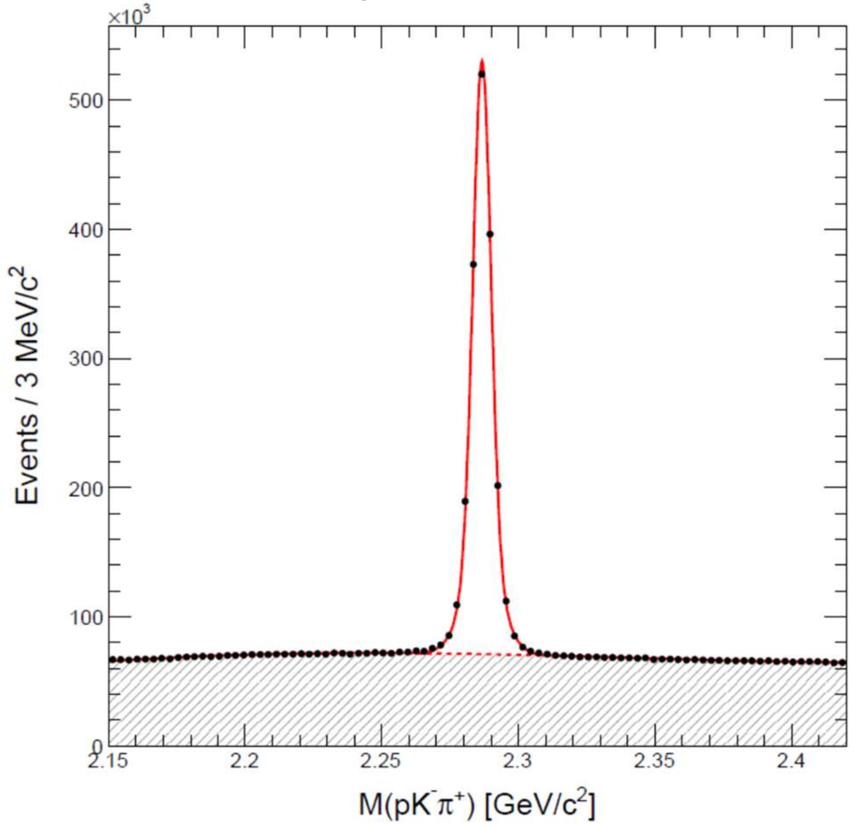
- Get the branching ratio wrt the CF counterpart, $\Lambda_c^+ \to pK^-\pi^+$

$$\frac{BR(\Lambda_c^+ \to pK^+\pi^-)}{BR(\Lambda_c^+ \to pK^-\pi^+)} \cong \frac{N(\Lambda_c^+ \to pK^+\pi^-) + CC}{N(\Lambda_c^+ \to pK^-\pi^+) + CC}$$

- Strong cancelation in acceptance & efficiencies
  → Small systematic error
  - Each single particle (p, pbar, K^+, K^-, π^+, π^-) appears once both in denominator and numerator
    → Single particle efficiencies cancel exactly
- Phase space is also the same

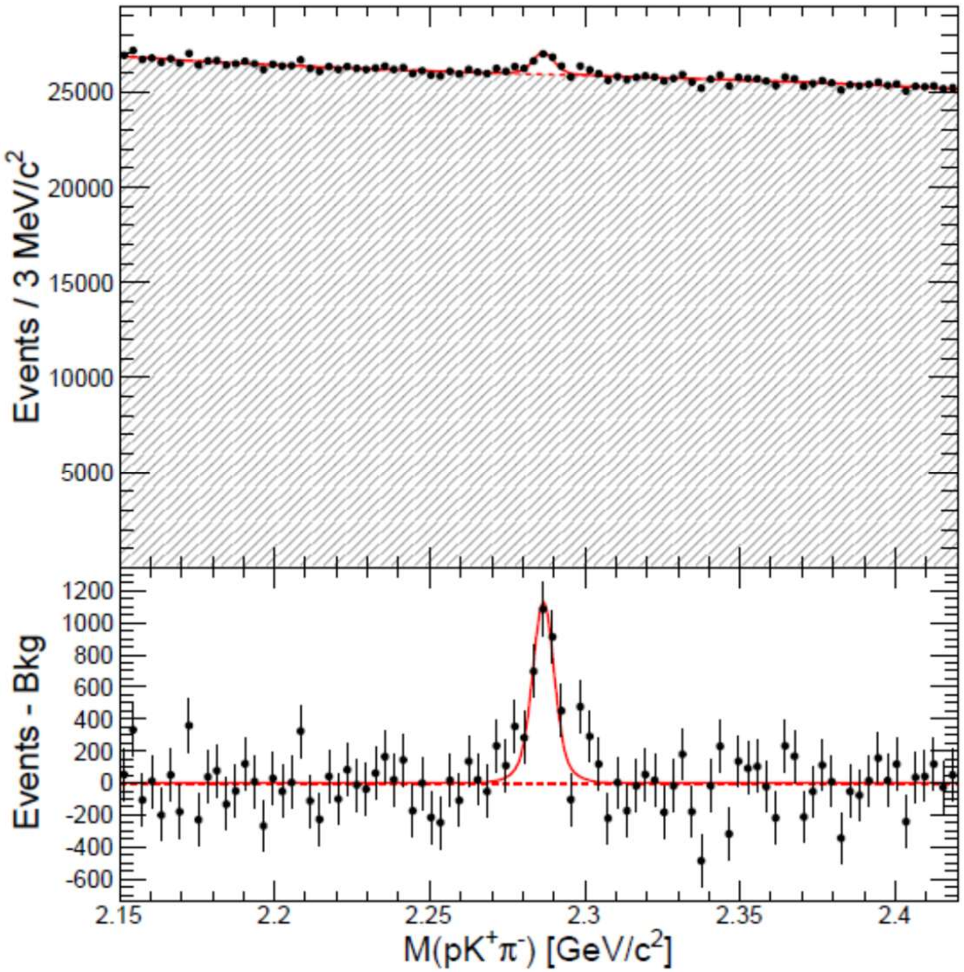
Spectra

CF: $\Lambda_c^+ \to pK^-\pi^+$



$(1.452 \pm 0.015) \times 10^6$ events

DCS: $\Lambda_c^+ \to pK^+\pi^-$



3587±380 events

Significant signal observed!

(significance 9.4σ)

[PRL117, 011801]

Result

$$\frac{BR(\Lambda_c^+ \to pK^+\pi^-)}{BR(\Lambda_c^+ \to pK^-\pi^+)} = (2.35 \pm 0.27 \pm 0.21) \times 10^{-3}$$

- Statistical significance: 9.4σ
- Together with $BR(\Lambda_c^+ \to pK^-\pi^+) = (6.84 \pm 0.24^{+0.21}_{-0.27})\%$,

$$BR(\Lambda_c^+ \to pK^+\pi^-) = (1.61 \pm 0.23^{+0.07}_{-0.08}) \times 10^{-4}$$

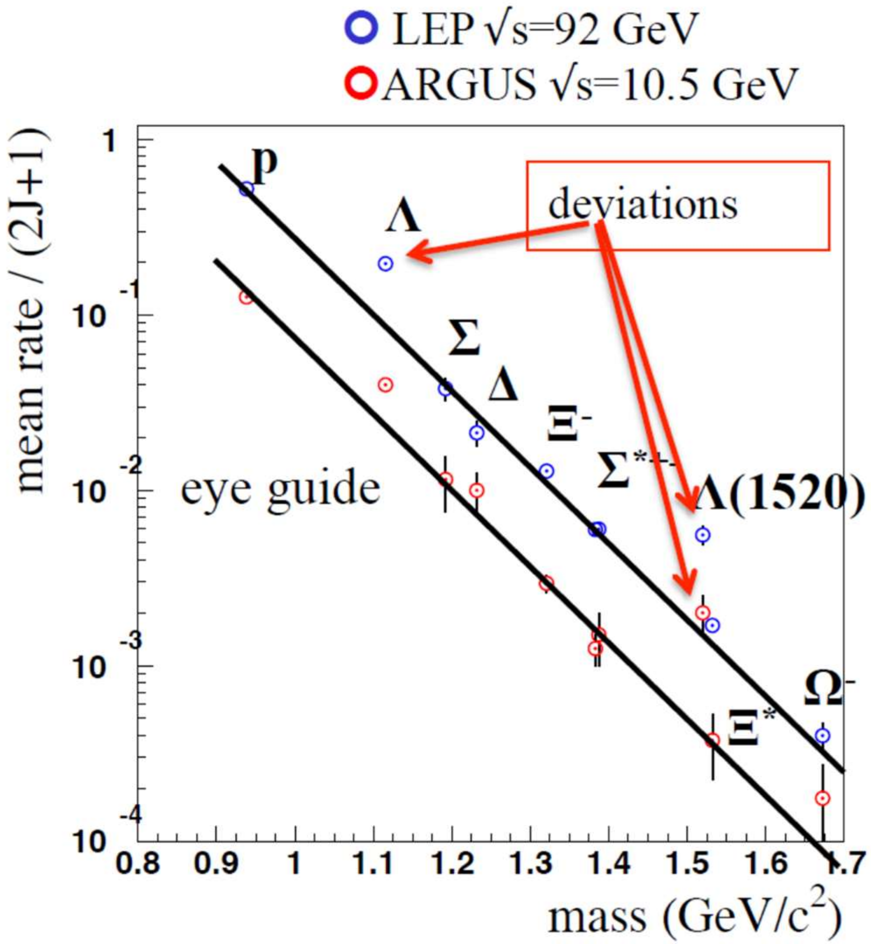
- The first observation of DCS decay in Baryon

[PRL117, 011801]

1.3 Production rates of charm baryons and hyperons

Baryon production rates

- Inclusive $e^+e^- \rightarrow h\ (+X)$ cross section
  $\sigma \propto (2J+1)\exp(-\alpha m)$
- Deviation for Λ and Λ(1520) in previous measurements
  - J=0, light (ud) di-quark in Λ?
- Need correction for feed-down
- How about charmed baryons?

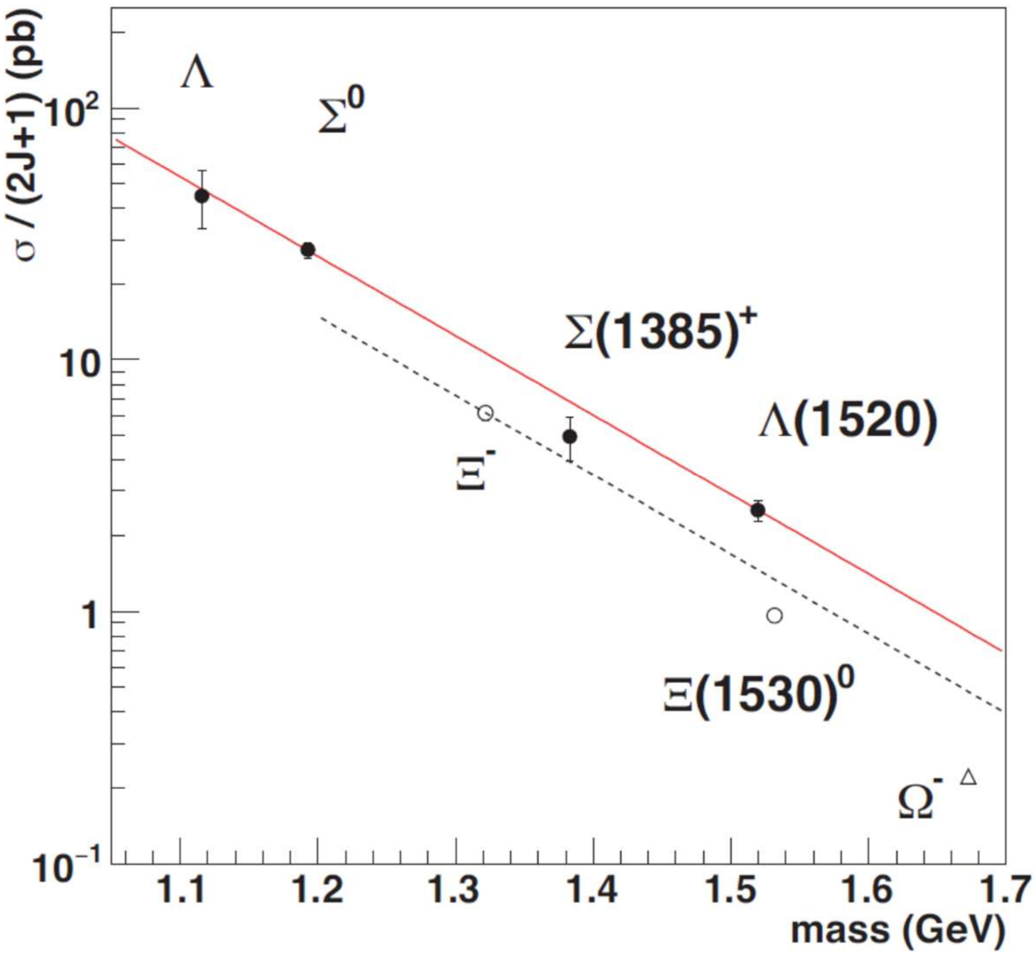


- New measurement in Belle

Result1 -- hyperons

[arXiv:1706.06791]

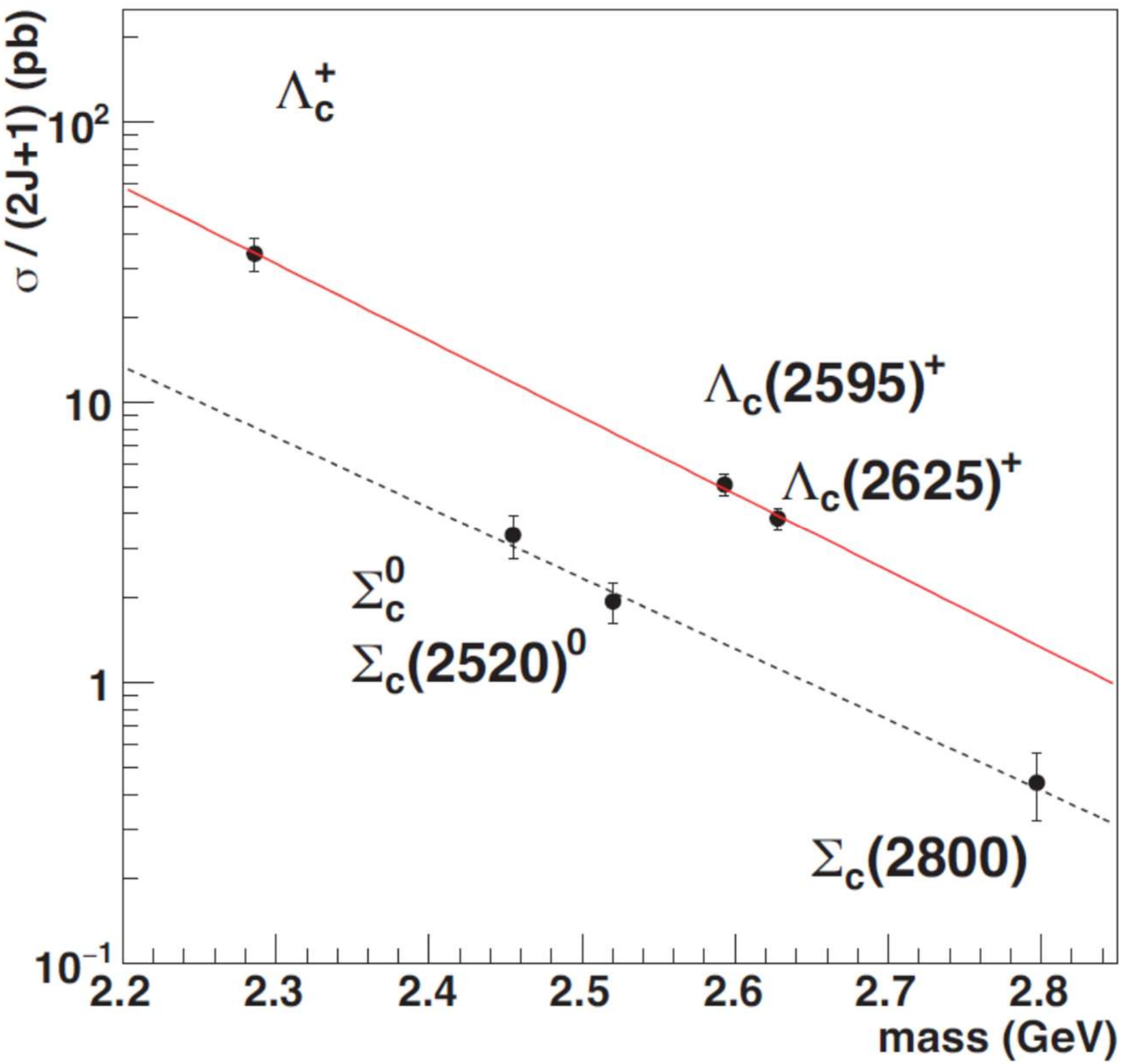
- Slope parameter
  $\alpha = -7.3 \pm 0.3$ GeV^{-1}
- Enhancement of Λ and Λ(1520) is not observed
- Suppression for "bad diquark"?
- Suppression of multi-strangeness baryons
  - g → ss suppress



Result2 – charm baryons

[arXiv:1706.06791]

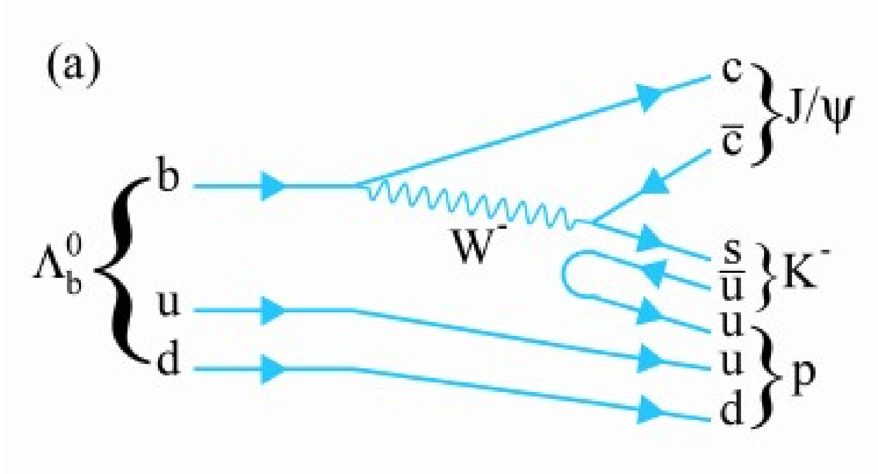
- Λ_c line is siginificantly above the Σ_c line
  - By factor ~4
- Slope
  $\alpha = -6.3 \pm 0.5$ GeV^{-1} for Λ_c
  $\alpha = -5.8 \pm 1.0$ GeV^{-1} for Σ_c
- “Good diquarks” are preferably produced

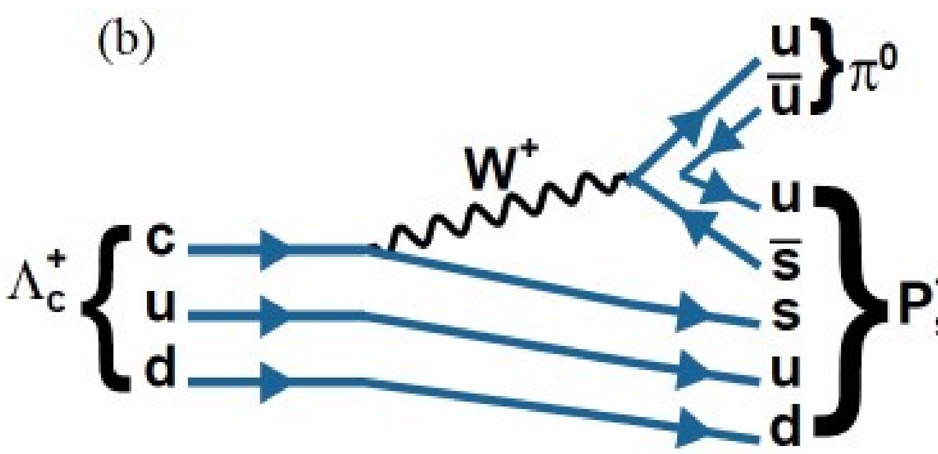


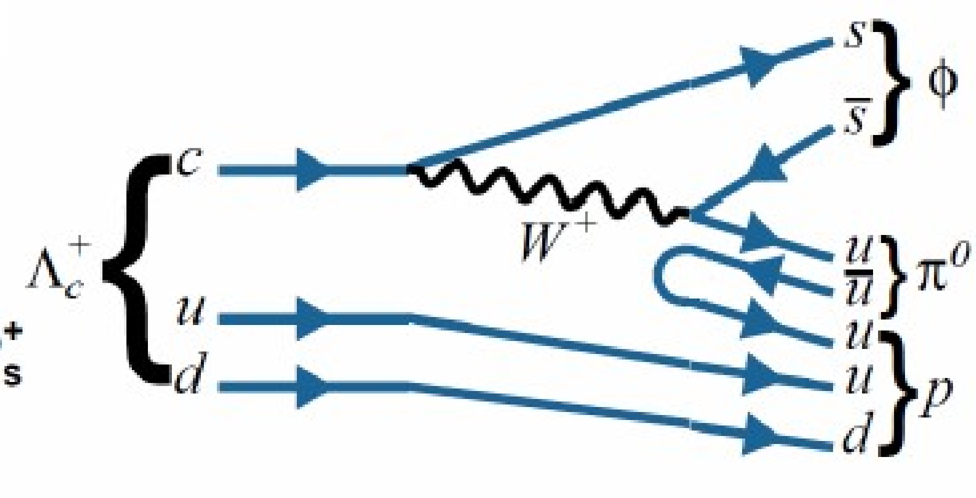
1.4 $\Lambda_c^+ \rightarrow p\phi\pi^0$ and search for pentaquark

Search for a pentaquark in $\Lambda_c^+ \to p\phi\pi^0$

- LHCb discovered hidden-charm pentaquark (P_c^+) in $J/\psi\, p$ of $\Lambda_b^0 \to J/\psi\, pK^-$
- Strange analog state (P_s^+) may appear in ϕp of $\Lambda_c^+ \to \phi p \pi^0$
  [V. Kopeliovich, PRD93 074012],
  [R. F. Lebed, PRD92 114030]



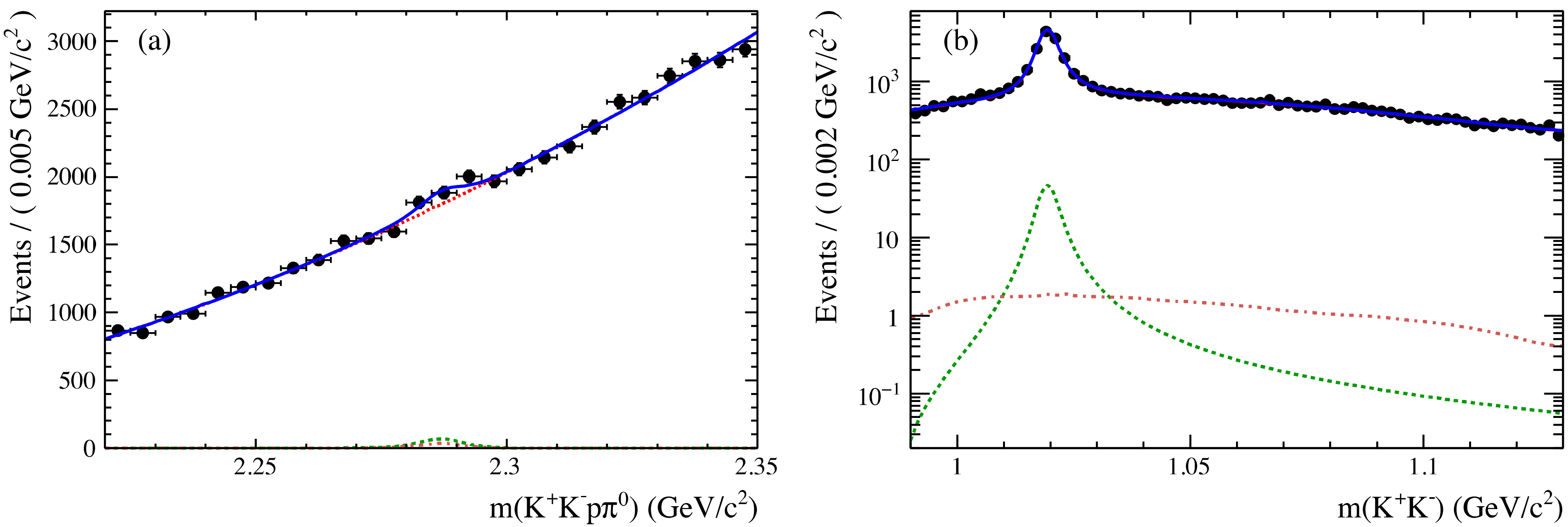




Analysis of $\Lambda_c^+ \to p\phi\pi^0$

- Exclude events of $M(p\pi^0)$ within 10 MeV of mass of Σ^+
- Two dimensional fit for $pK^+K^-\pi^0$ and K^+K^- invariant masses

[arXiv:1707.00089, accepted by PRD]

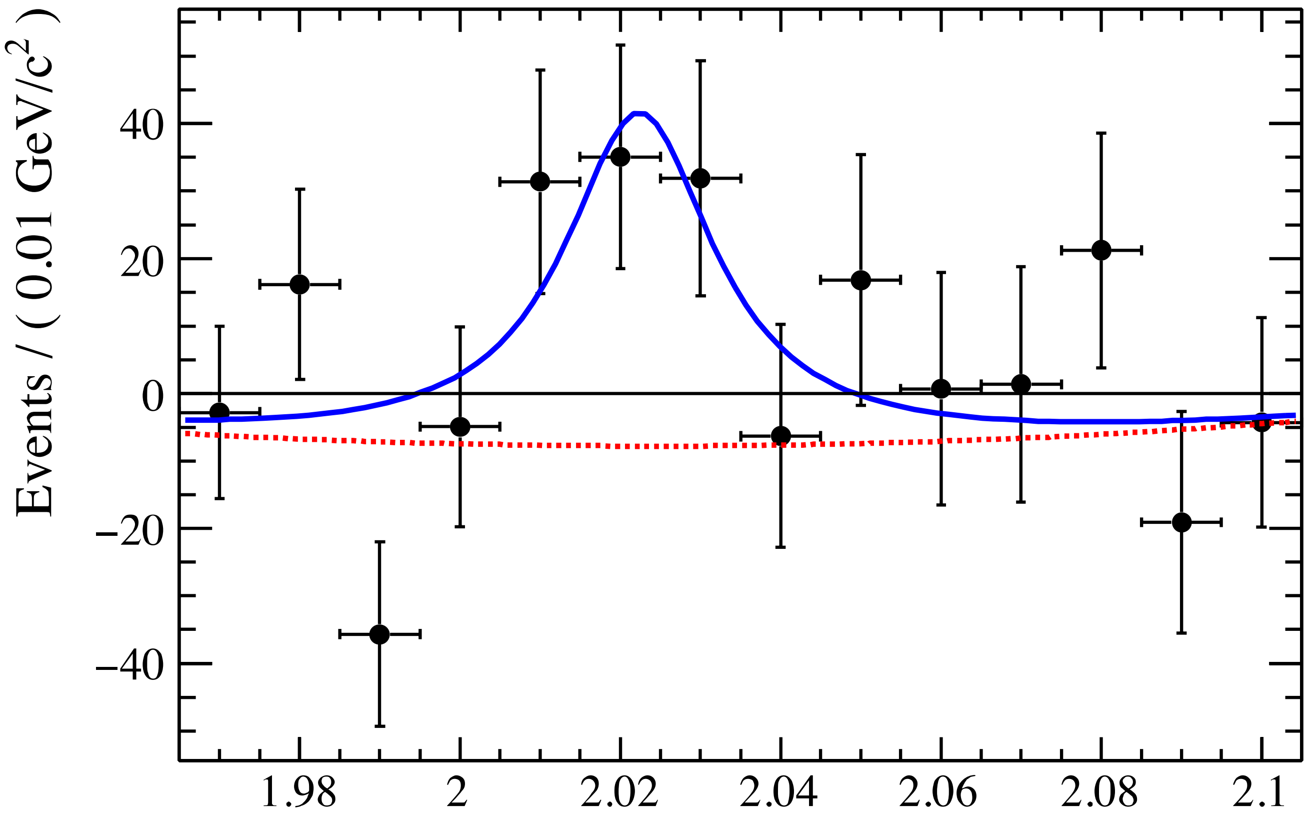


$$\mathcal{B}(\Lambda_c^+ \to \phi p \pi^0) \ < \ 15.3 \times 10^{-5},$$

$$\mathcal{B}(\Lambda_c^+ \to K^+ K^- p \pi^0)_{\mathrm{NR}} \ < \ 6.3 \times 10^{-5},$$

Search for P_s

- Select $\Lambda_c^+ \to pK^+K^-\pi^0$ candidates with $M(K^+K^-)$ being within 20 MeV of ϕ mass



NOT significant: 77.6±28.1 events

$$\mathcal{B}(\Lambda_c^+ \to P_s^+\pi^0) \times \mathcal{B}(P_s^+ \to \phi p) \ < \ 8.3 \times 10^{-5}$$

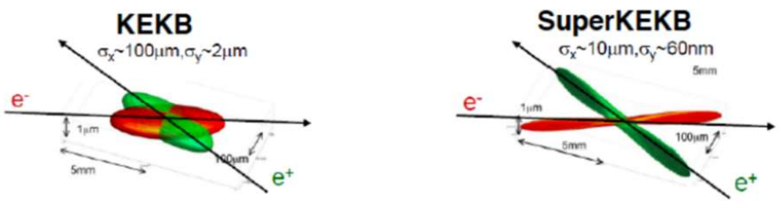
Part II.
(My personal points of view)
Future prospects for Belle II and J-PARC

SuperKEKB and Belle II

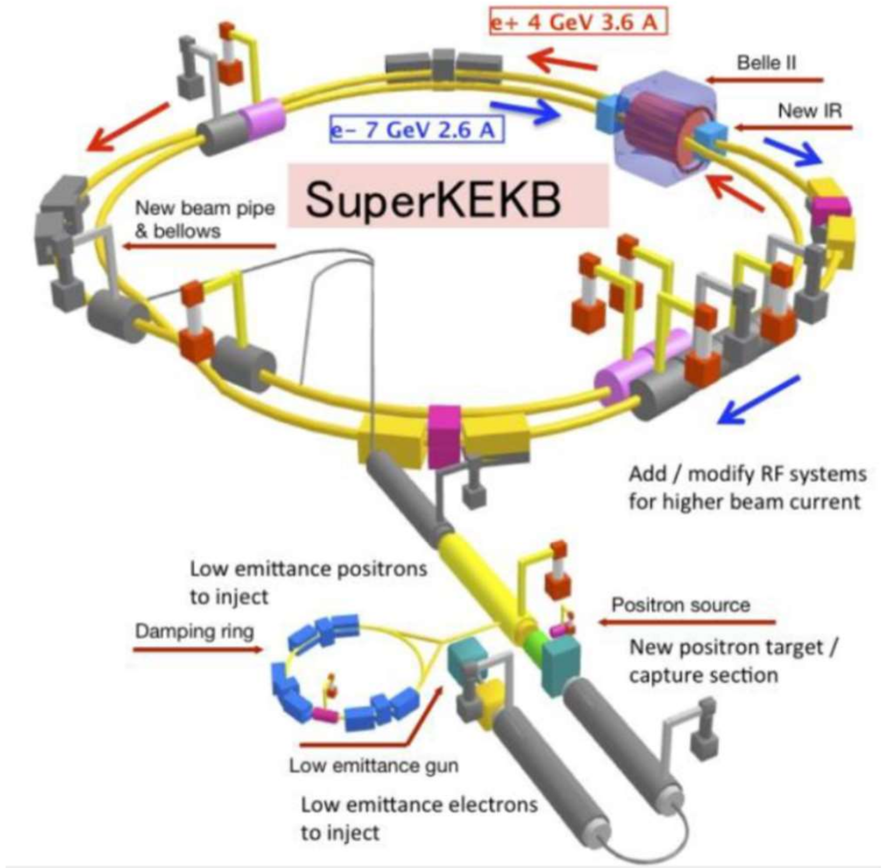
Upgrade for SuperKEKB and Belle II to achieve 40x peak $\mathcal{L}$ under 20x bkgd

- Reduction in the beam size by 1/20 at the IP.
- Doubling the beam currents.

$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

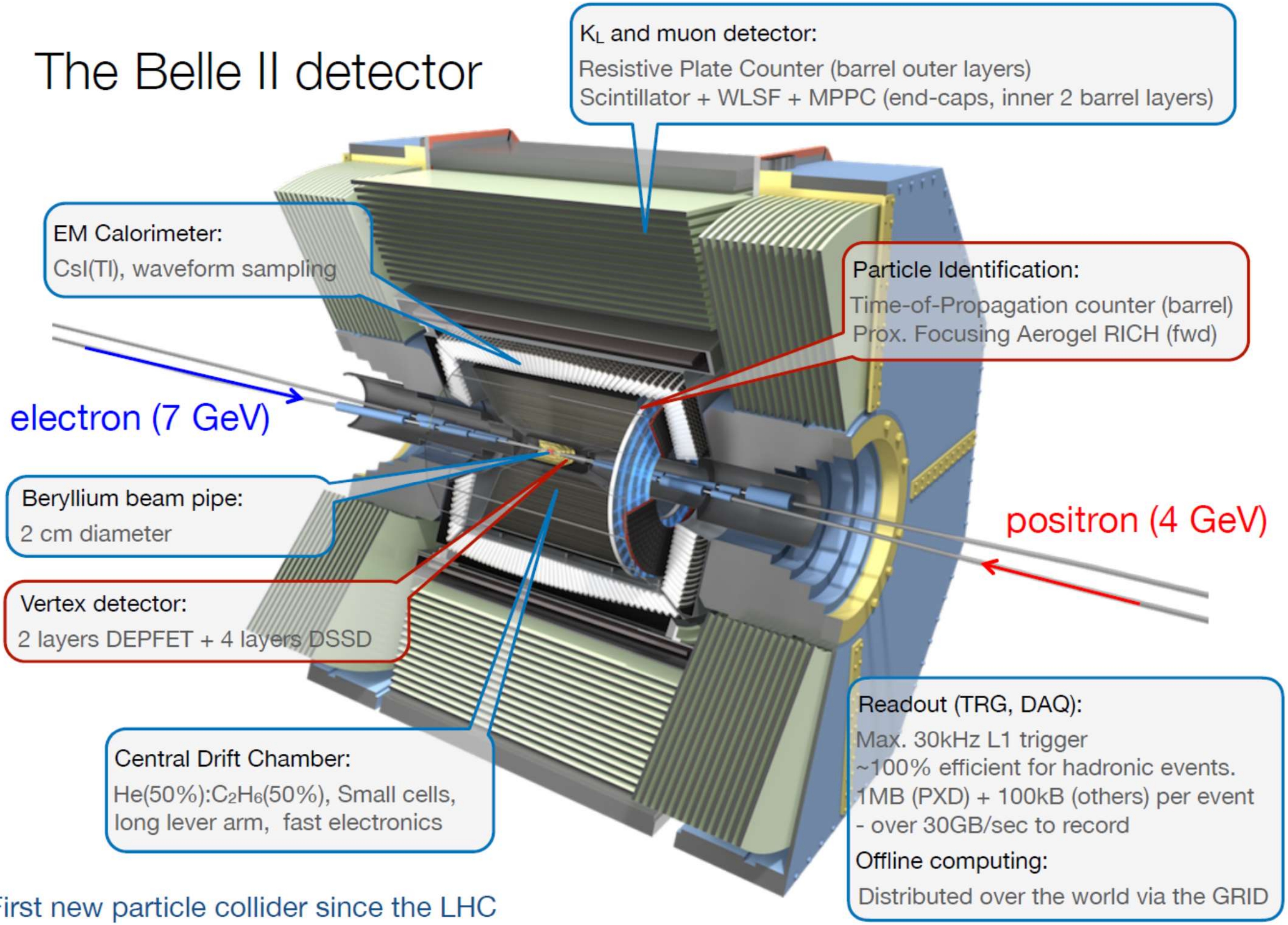


- ▶ *First turns achieved Feb. 2016*
- ▶ *Beam-background studies ongoing*



Goal: x50 more statistics than Belle

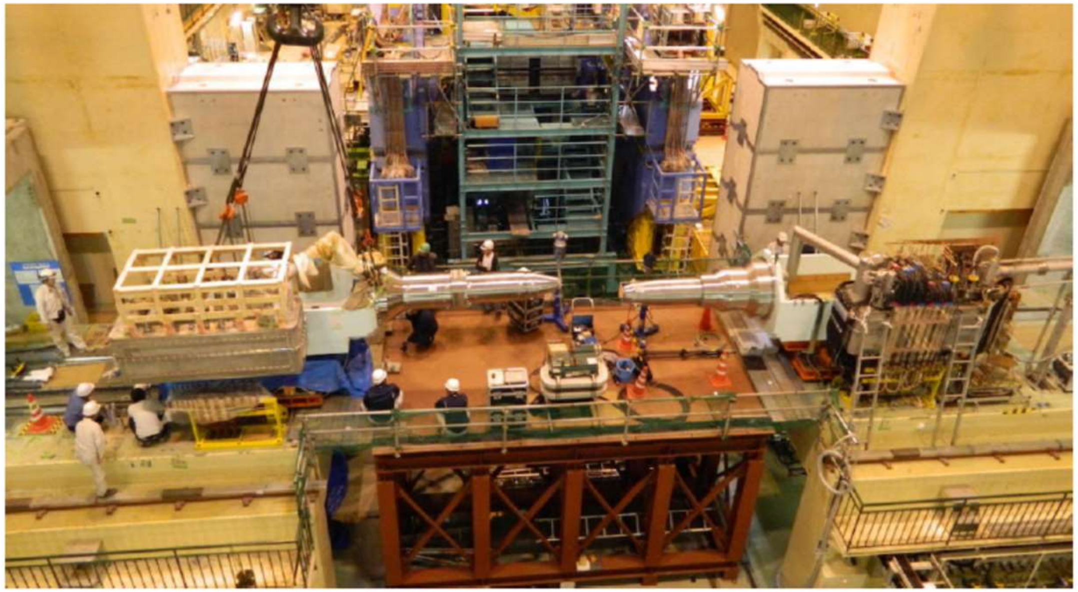
The Belle II detector

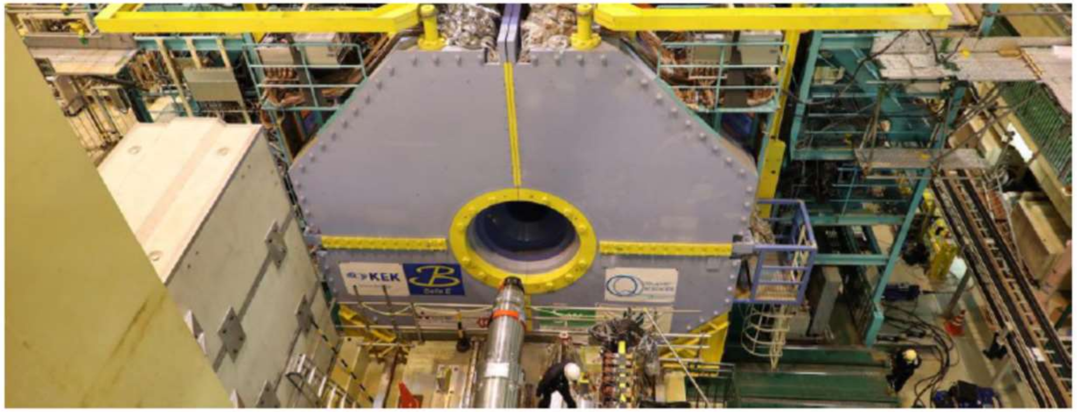


First new particle collider since the LHC
(intensity rather than energy frontier; e^+e^- rather than pp)

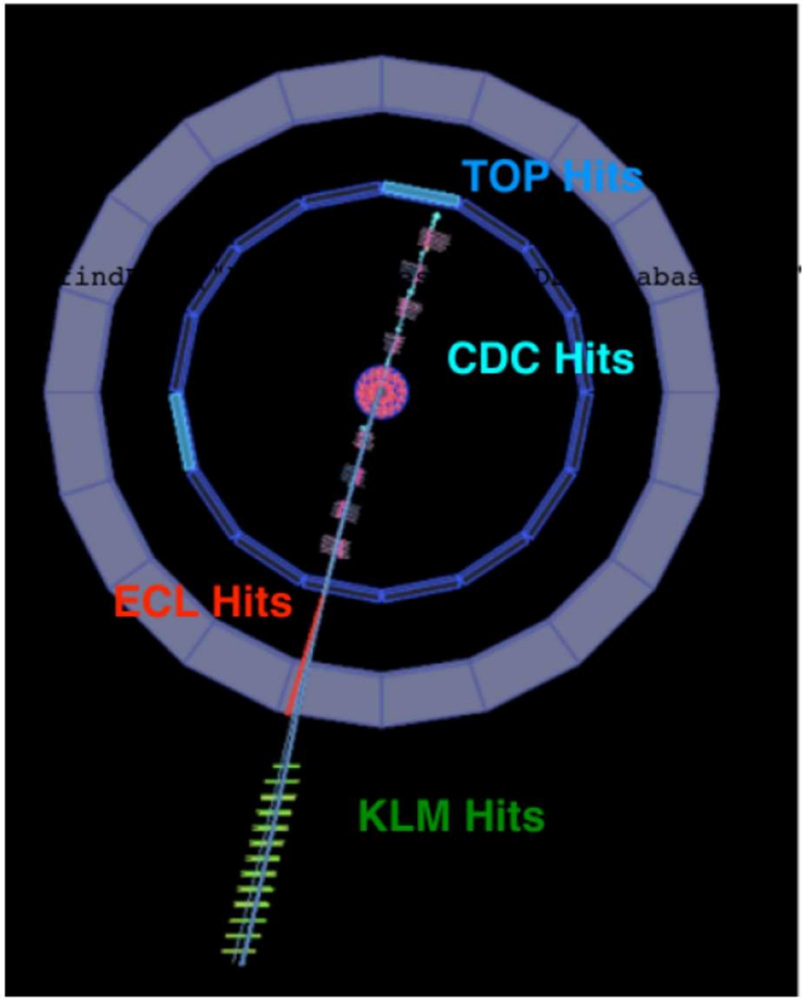
arXiv:1011.0352 [physics.ins-det]

Belle II today



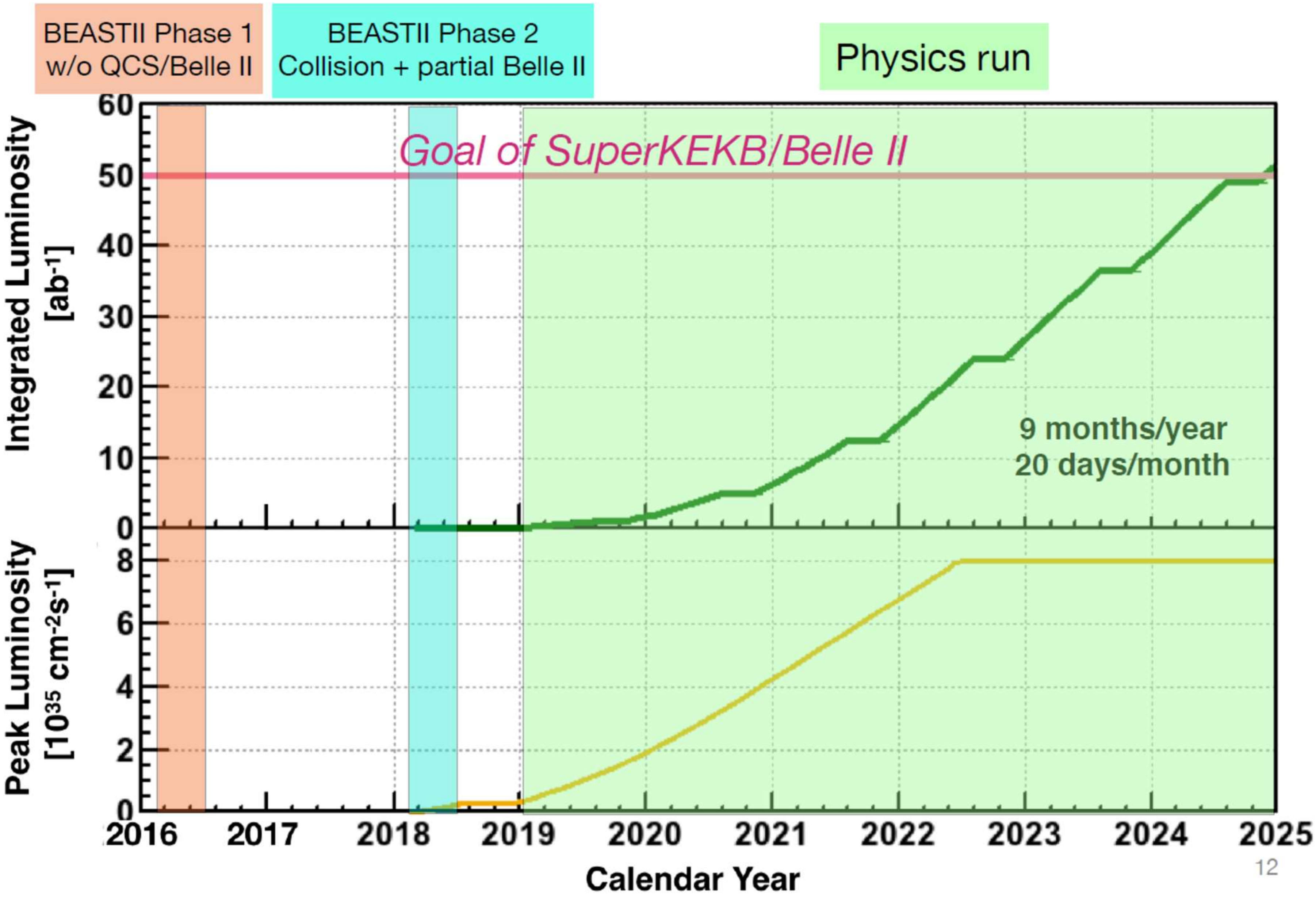


Belle II roll-in (April 11)



Global cosmic run (August)

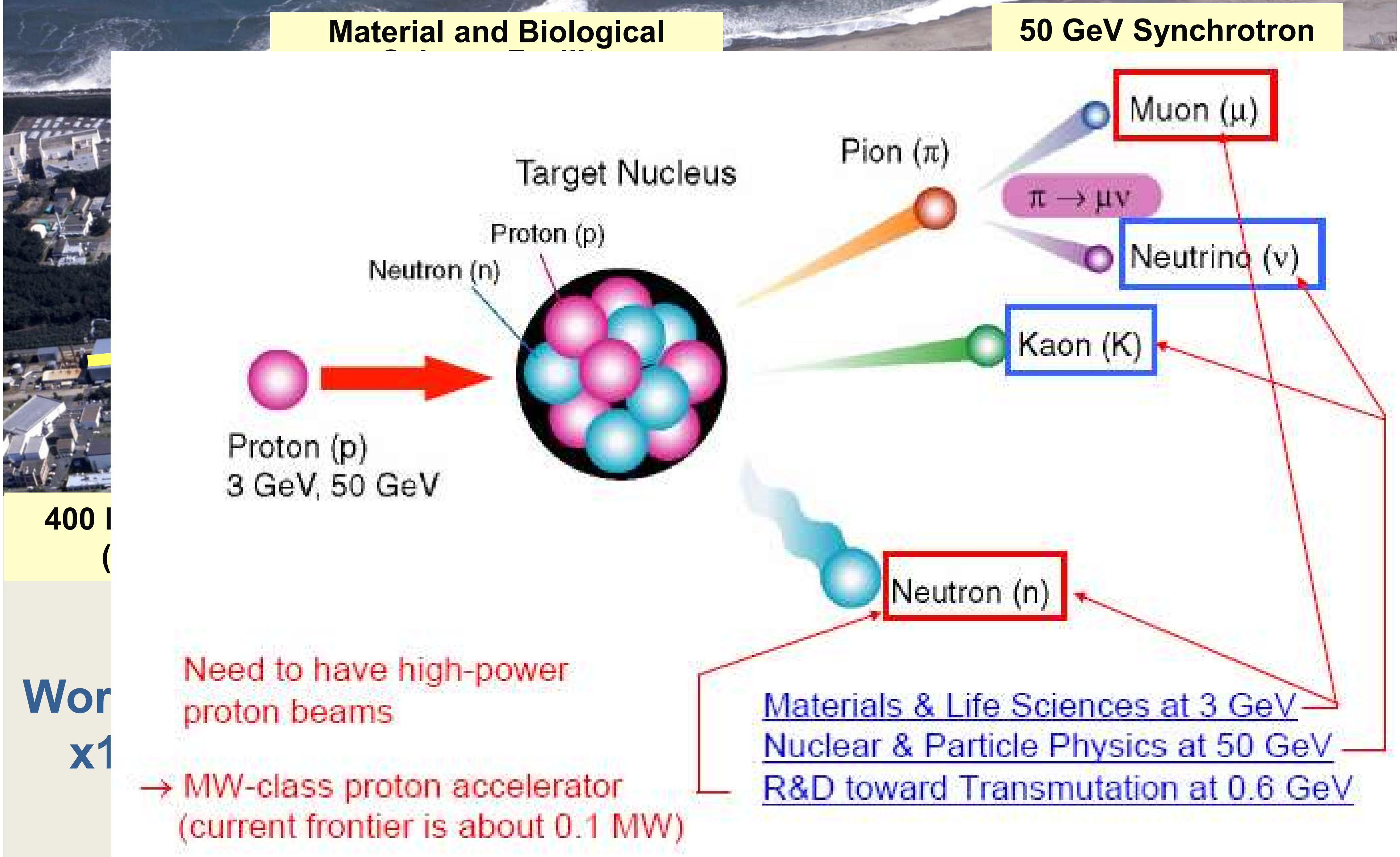
Luminosity projection



J-PARC

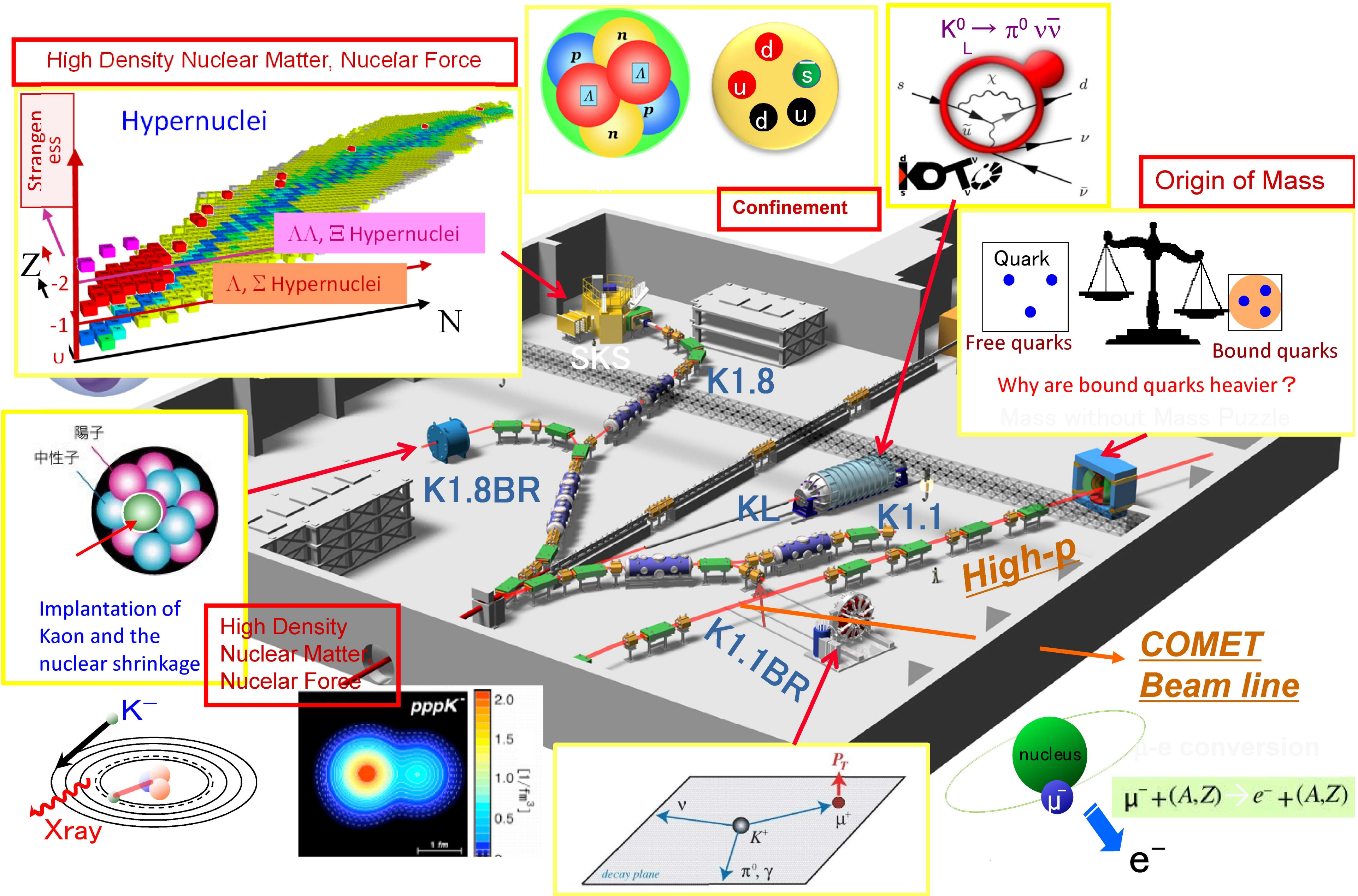
Tokai, Japan

(Japan Proton Accelerator Research Complex)



Nuclear & Hadron Physics in J-PARC

Experiments at a glance (not all)



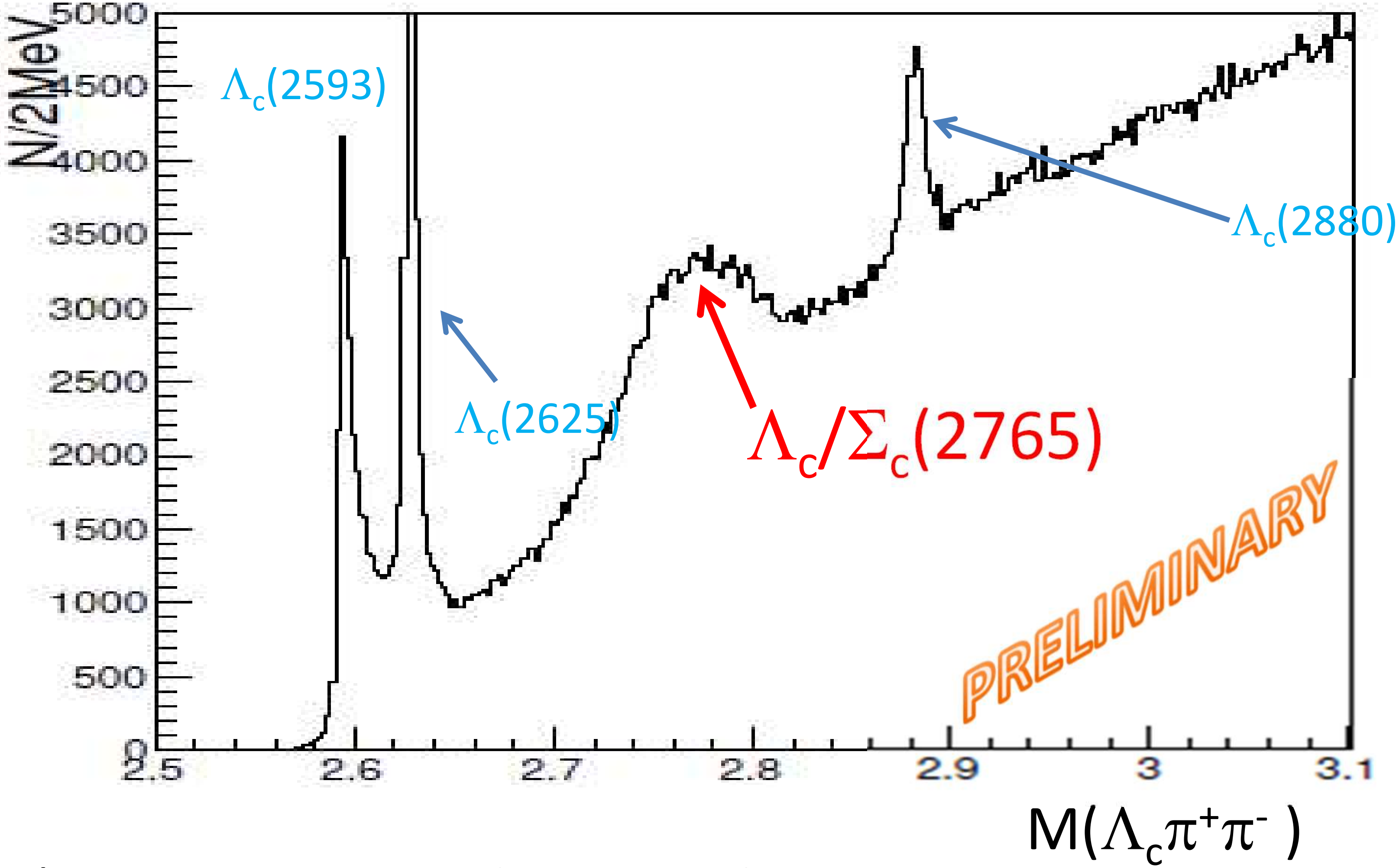
2.1 Charmed baryon spectroscopy

Belle II possibilities

- Many things, but some of them can be done in Belle, too
  - We have not used the full potential of Belle data
- Examples include:
  - Search for more Y_c resonances in unsearched modes; e.g., $\Lambda_c\eta$
  - J^P measurements for Λ_c*, Ξ_c*, Ω_c* …; Partial wave analysis.
    → We can determine J^P of most of presently known states
    → Comprehensive list of charmed baryons
  - Search for $\Xi*$ and $\Omega*$ resonances in the decay of Λ_c and Ξ_c.
  - Weak decay branches and decay asymmetry parameters
  - Exotic search: pentaquarks, dibaryons, …
    e.g., ND, $N\overline{D}$(or Θ_c), H, H_c, $\Lambda_c N$, …

……

$\Lambda_c/\Sigma_c(2765)\rightarrow\Lambda_c\pi^+\pi^-$



1* resonance in PDG, but certainly exists

I(J^P) not known yet → We will determine soon, together with mass, width, and branching ratios

What is the nature?

- Roper resonance analog?
  - Predict $J^P=1/2^+$
- Bound state of DN?
  - Binding energy: 45 MeV
  - S-wave → $J^P=1/2^-$, analogous to $\Lambda(1405)$
    $\Sigma_c(2800)$ may be regarded as I=1 counterpart
- Quark model interpretation may be possible ($J^P=1/2^-,3/2^+,...$)
- Other possibilities

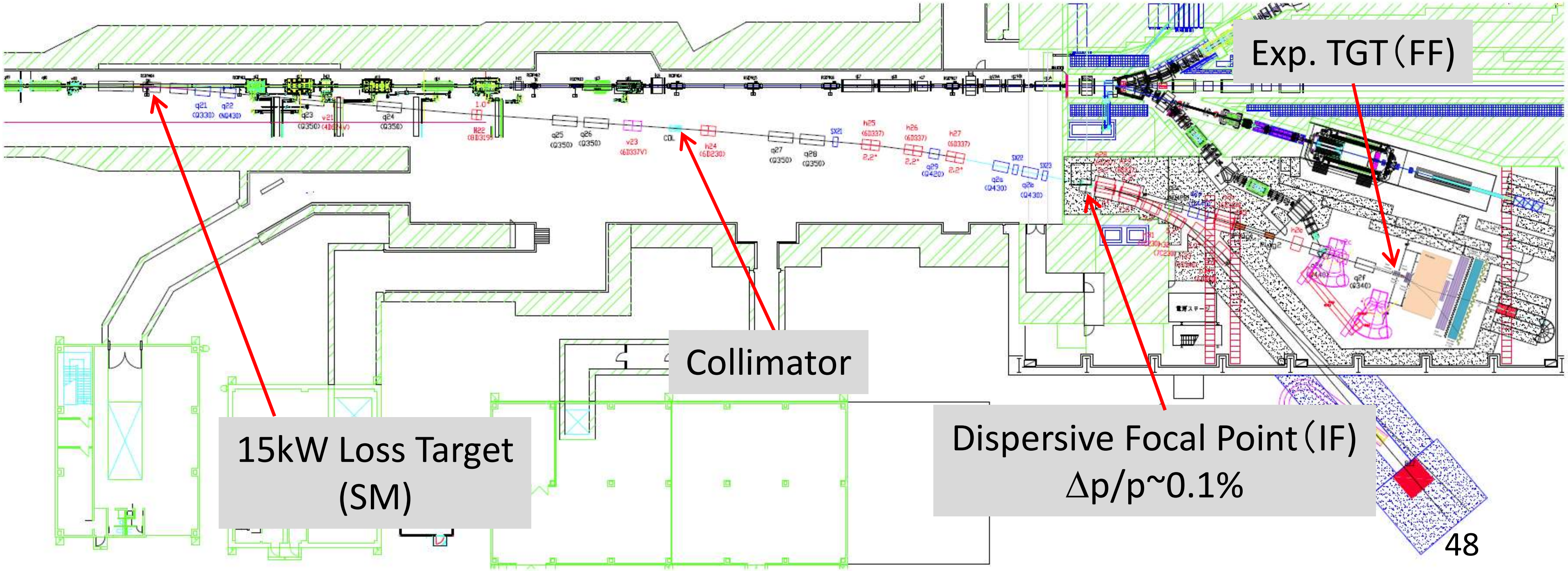
- In Belle II, we can determine whether there are analog states in Ξ_c and Ω_c

J-PARC E50: Missing mass spectroscopy by $p(\pi^-, D^{*-})$

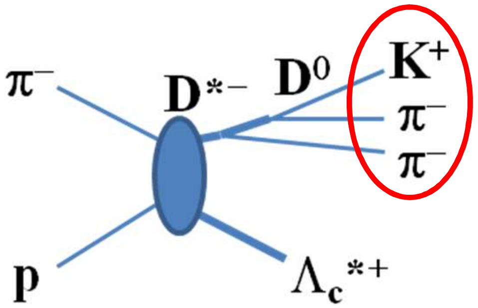
- Analogous to p(π,K)Y reaction
- Direct reaction
  - possibility to produce resonances not made in fragmentation
  - Production cross section gives valuable information
  - No bias on decays
    → Absolute branching ratio can be measured
- Cross Section: $\sigma \sim 1$ nb
  - Intense Beam at J-PARC is indispensable.
    $> 10^7$ Hz at 15 GeV/c pions

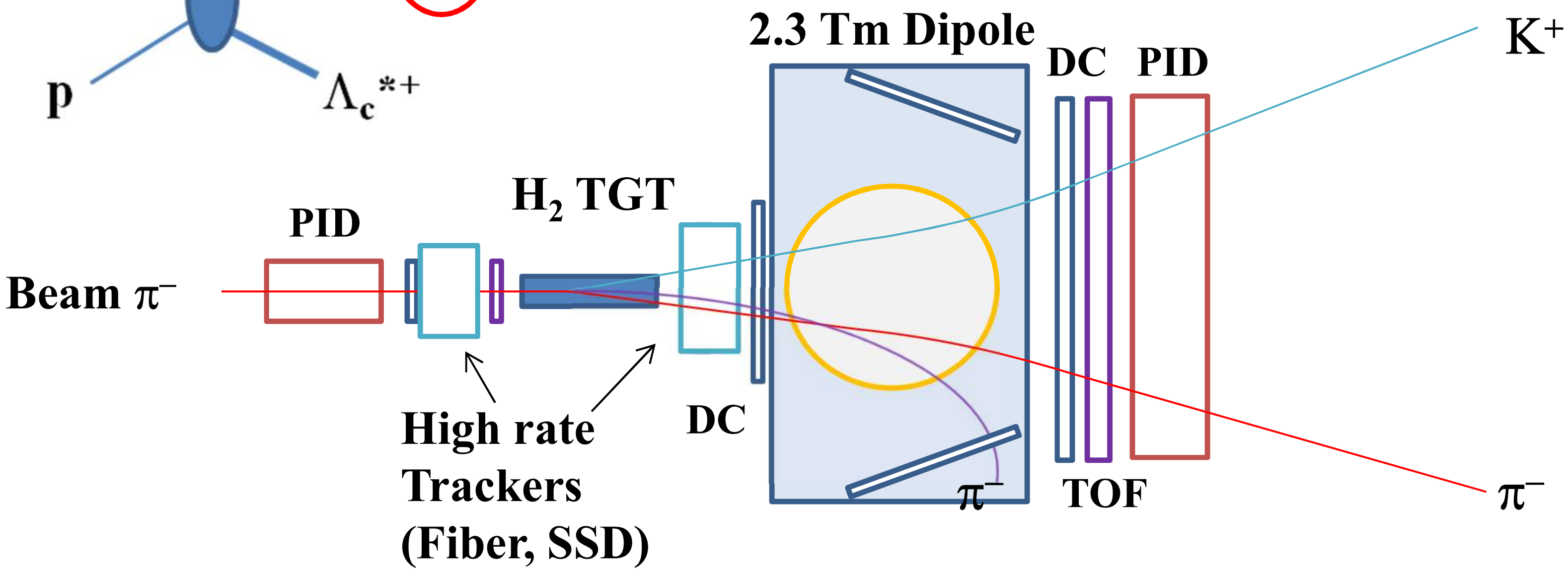
High momentum beam line

- High-intensity secondary beam（unseparated）
  - 2 msr・%、1.0 x 10^7 Hz @ 15GeV/c π
- High-resolution beam: $\Delta p/p$~0.1%
  - Momentum dispersion and eliminate 2^{nd} order aberrations

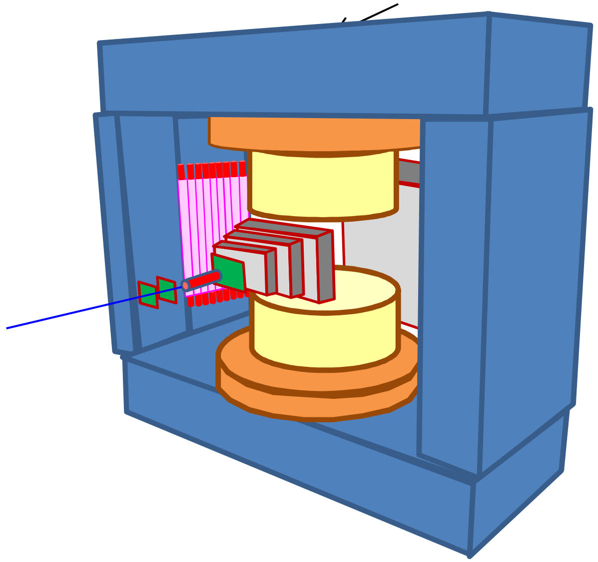


Concept

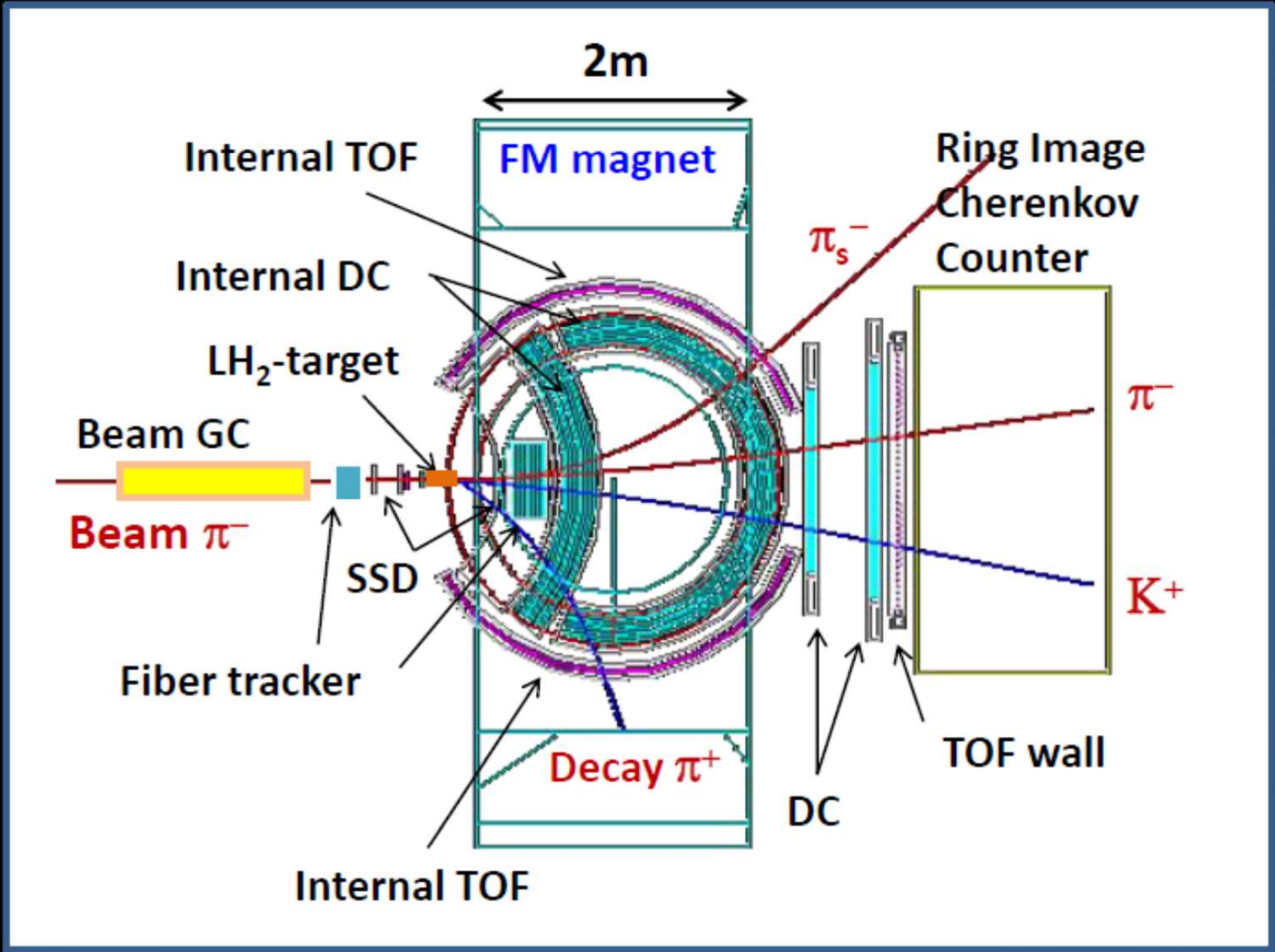




- Large Acceptance, Multi-Particle
  - *K*, *π* from D^0 decays
  - Soft π from D^{*-} decays
  - (Decay products from Y_c^*)
- High Resolution
- High Rate
  - SFT/SSD: >10M/spill at K1.8



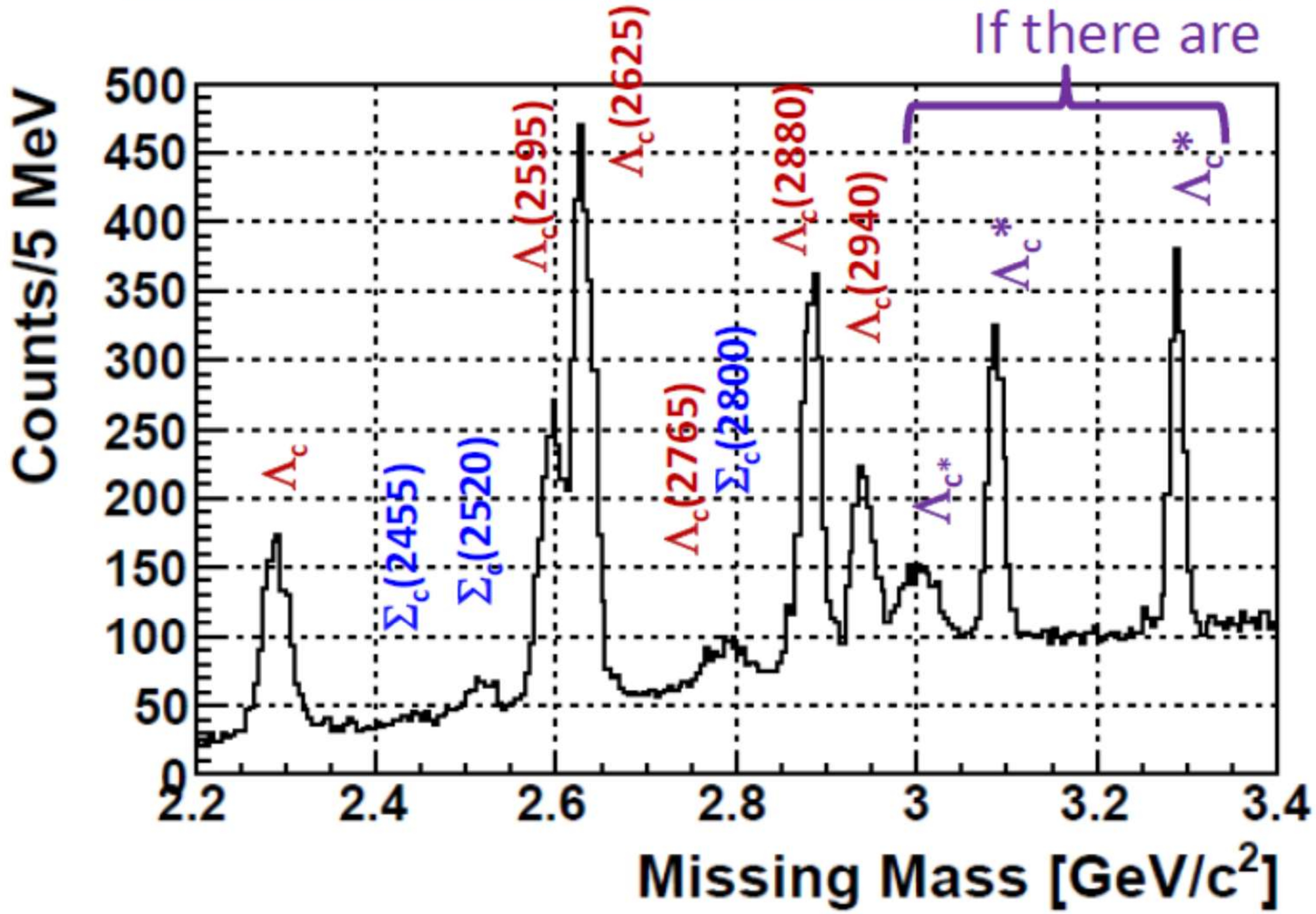
Charmed Baryon Spectrometer



Large acceptance ~ 60% (for *D), $\Delta p/p$~0.2% at ~5 GeV/*c***

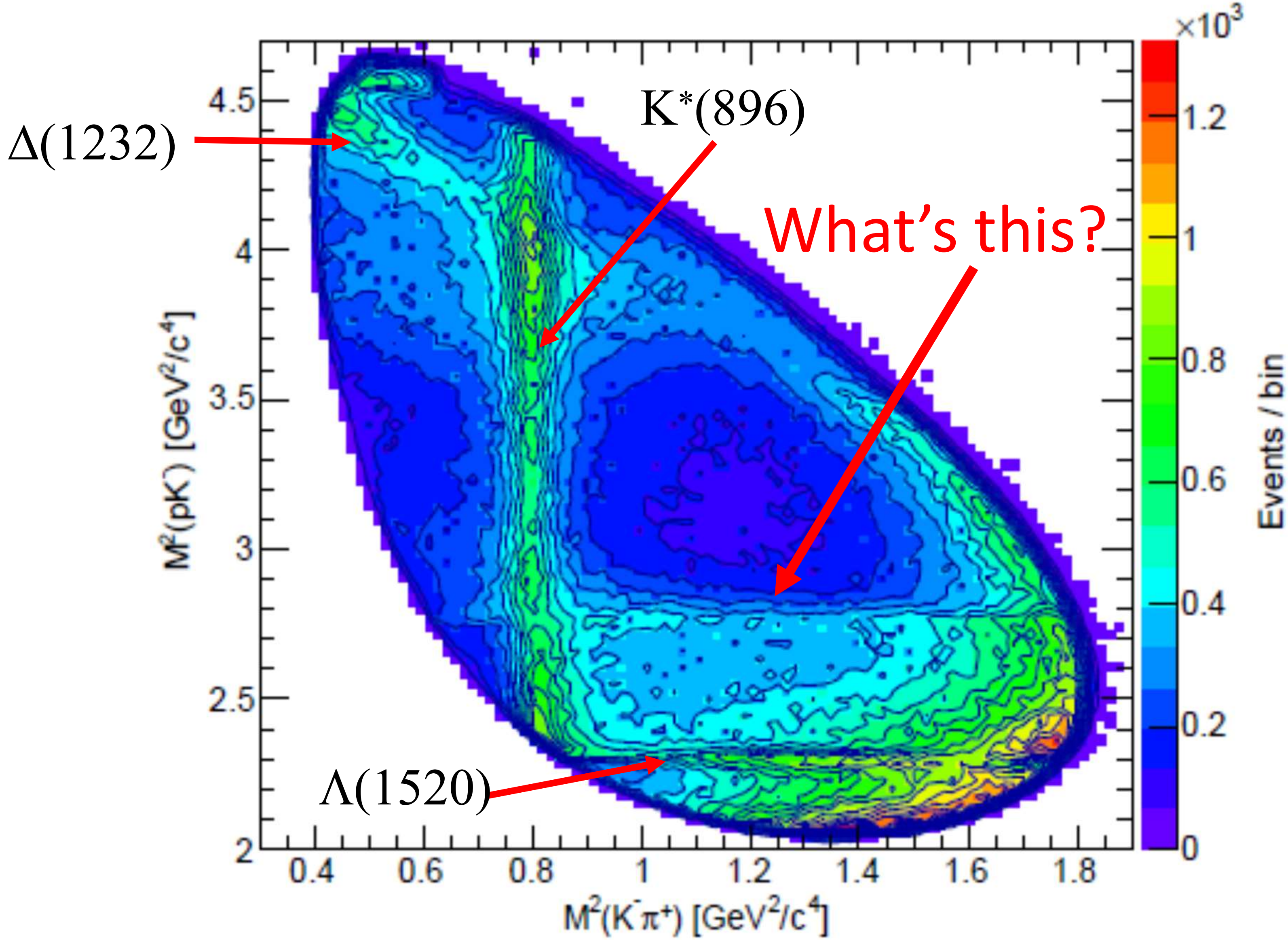
Expected spectrum: σ_{GS} = 1 nb

N(Yc*)~1000 events/1nb/100 days
Better mass resolution: ~10 MeV/c^2
Sensitivity: ~0.1 nb (3σ, Γ~100 MeV)

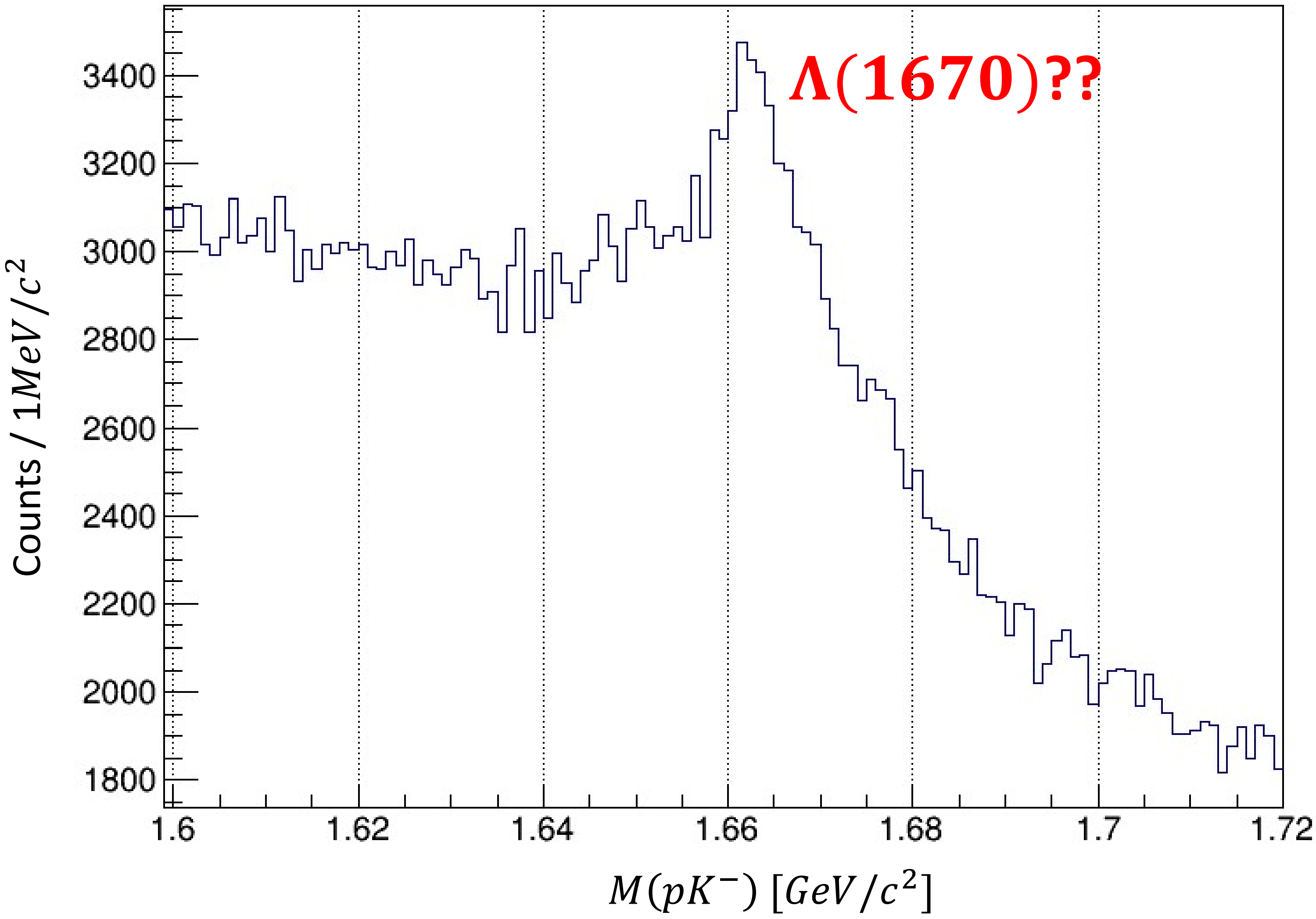


2.2 Search for new hyperon resonance around the $\Lambda\eta$ threshold

Dalitz plot: $\Lambda_c^+ \to pK^-\pi^+$ [PRL117.011801]



■ 1D projection -- $M(pK^-)$



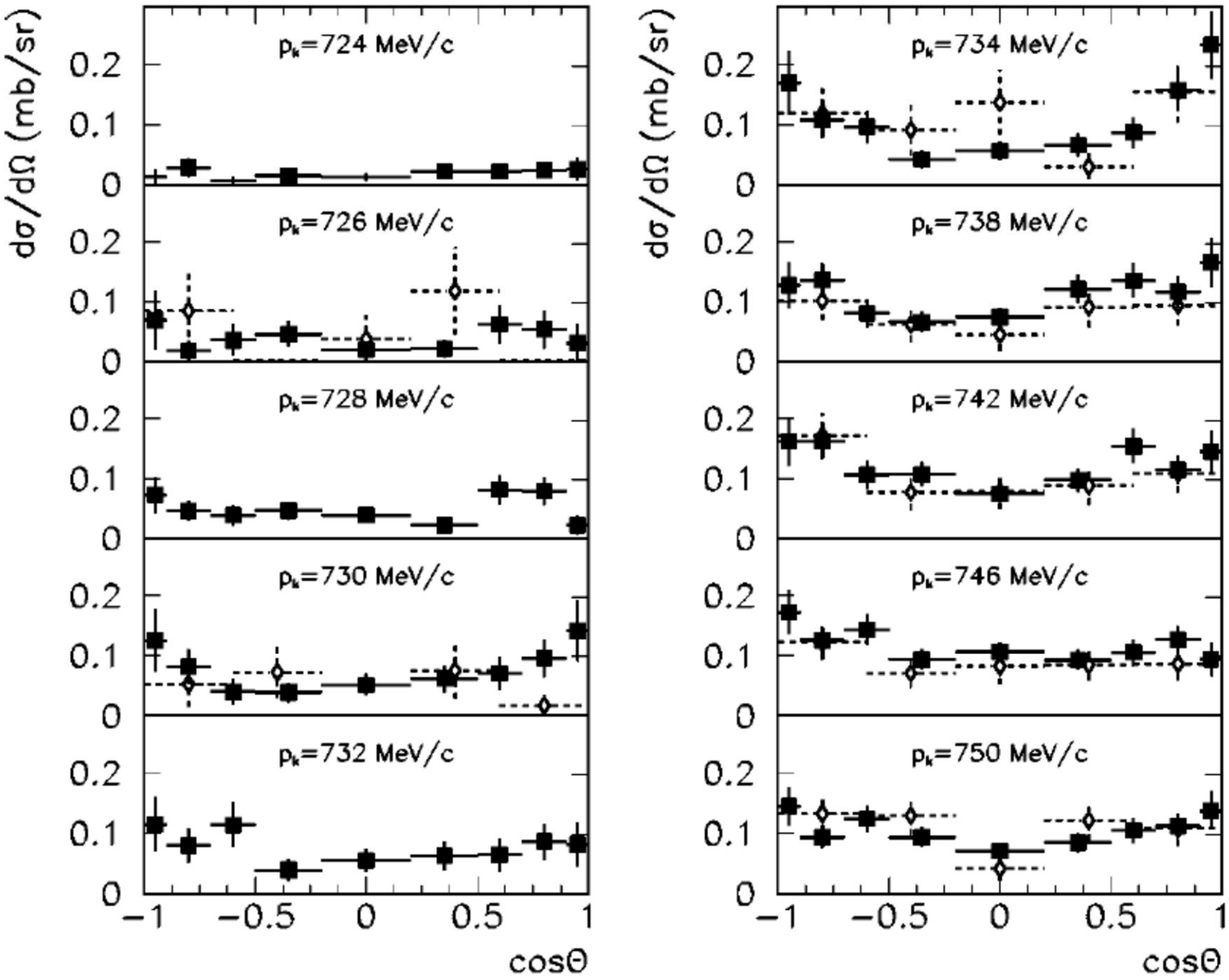
Then, what's that?

- The peak position is ~1663 MeV, near the $\Lambda\eta$ threshold (1663.5 MeV)
- Width is ~10 MeV, significantly narrower than Λ, Σ resonances in this region
  - $\Lambda(1670)$: 25-50 MeV
  - $\Sigma(1660)$: 40-200 MeV
  - $\Sigma(1670)$: 40-80 MeV
  - $\Lambda(1690)$: ~60 MeV

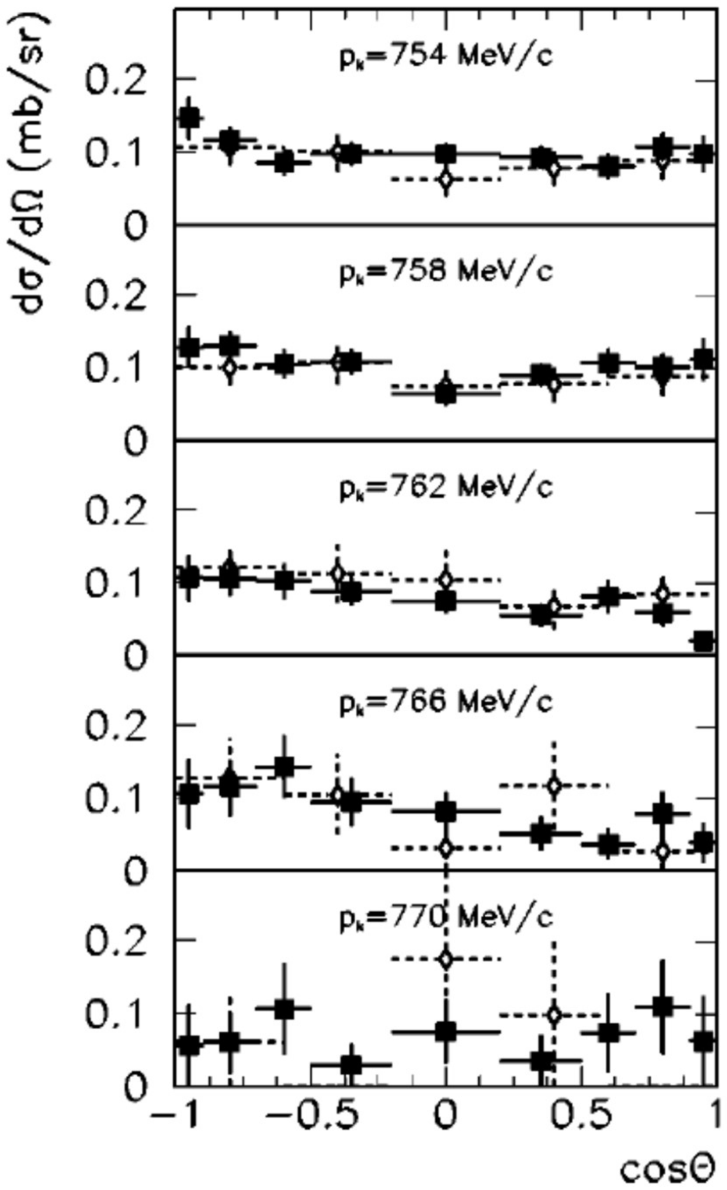
A new idea

- 2 independent groups claim there is a new narrow Λ^* resonance at this energy with J=3/2
  - Kamano et al. [PRC90.065204, PRC92.025205]
    $J^P=3/2^+$ (P_{03}), M=1671+2-8 MeV, Γ=10+22-4 MeV
  - Liu & Xie [PRC85.038201, PRC86.055202]
    $J^P=3/2^-$ (D_{03}), M=1668.5$\pm$0.5 MeV, Γ=1.5$\pm$0.5 MeV
- The reason is the same
  - From $K^-p \rightarrow \Lambda\eta$ measurement near the threshold by Crystal Ball collaboration at BNL [PRC64.055205]
  - Especially the angular distribution → Model independent
- There is no state in quark models
  - It must be an exotic
  - $uds s\bar{s}$ pentaquark??

Differential cross sections (1)



Differential cross sections (2)



- Flat near the threshold
  - Expected for J=1/2 (S-wave)
- Concave-up around p_K=734 MeV/c (√s=1669 MeV)
- Flat again for p_K > 750 MeV/c (√s=1677 MeV)

- Concave shape requires J=3/2 amplitude → reason for a narrow resonance; model independent

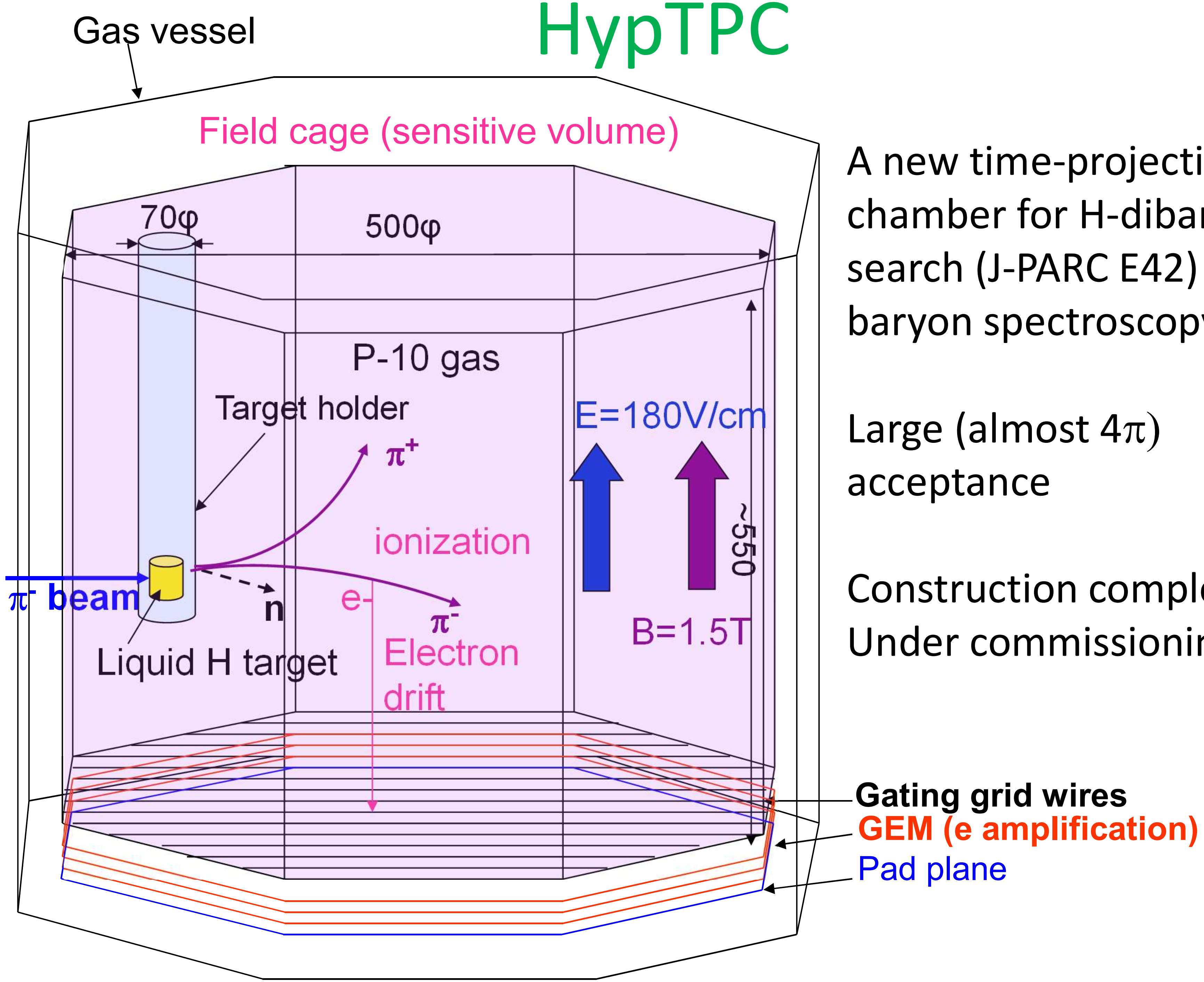
Measurement@Belle (II)

- The peak in the M(pK$^-$) spectrum in $\Lambda_c \to pK^-\pi^+$ decay is due to the new Λ^* resonance?
- If yes, key measurements are
  - J=3/2 – angular distribution (correlation) between π^+ and K$^-$
    $1+3\cos^2\theta$ for pure J=3/2 amplitude
    flat for pure J=1/2 amplitude
  - I=0, strongly couples to $\Lambda\eta$ channel
    → Important to see $\Lambda\eta$ channel
  - Width
- Parity is also important, but…
  - Needs measurement of polarization of Λ in the $\Lambda\eta$ channel.
  - In principle possible, but needs very high statistics
  - Impossible @Belle, difficult even at Belle2

New experiment at J-PARC

- Repeat the Kp → $\Lambda\eta$ experiment again with a large acceptance detector, i.e., TPC (HypTPC)
- Principle
  - K beam momentum: 720-770 MeV/c
    2 settings: 735 MeV/c & 755 MeV/c (±3%)
    → K1.8BR or K1.1 beamline
  - Momentum resolution: 1 MeV/c or better
    → Can identify narrow resonance of Γ=1.5 MeV
  - Detect Λ → $p\pi^-$, identify η by missing mass
  - Both Λ and η go to forward direction

HypTPC



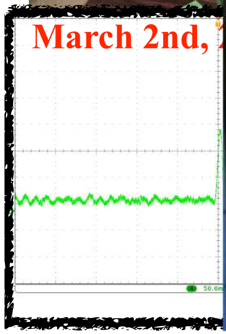
A new time-projection chamber for H-dibaryon search (J-PARC E42) & baryon spectroscopy (E45)

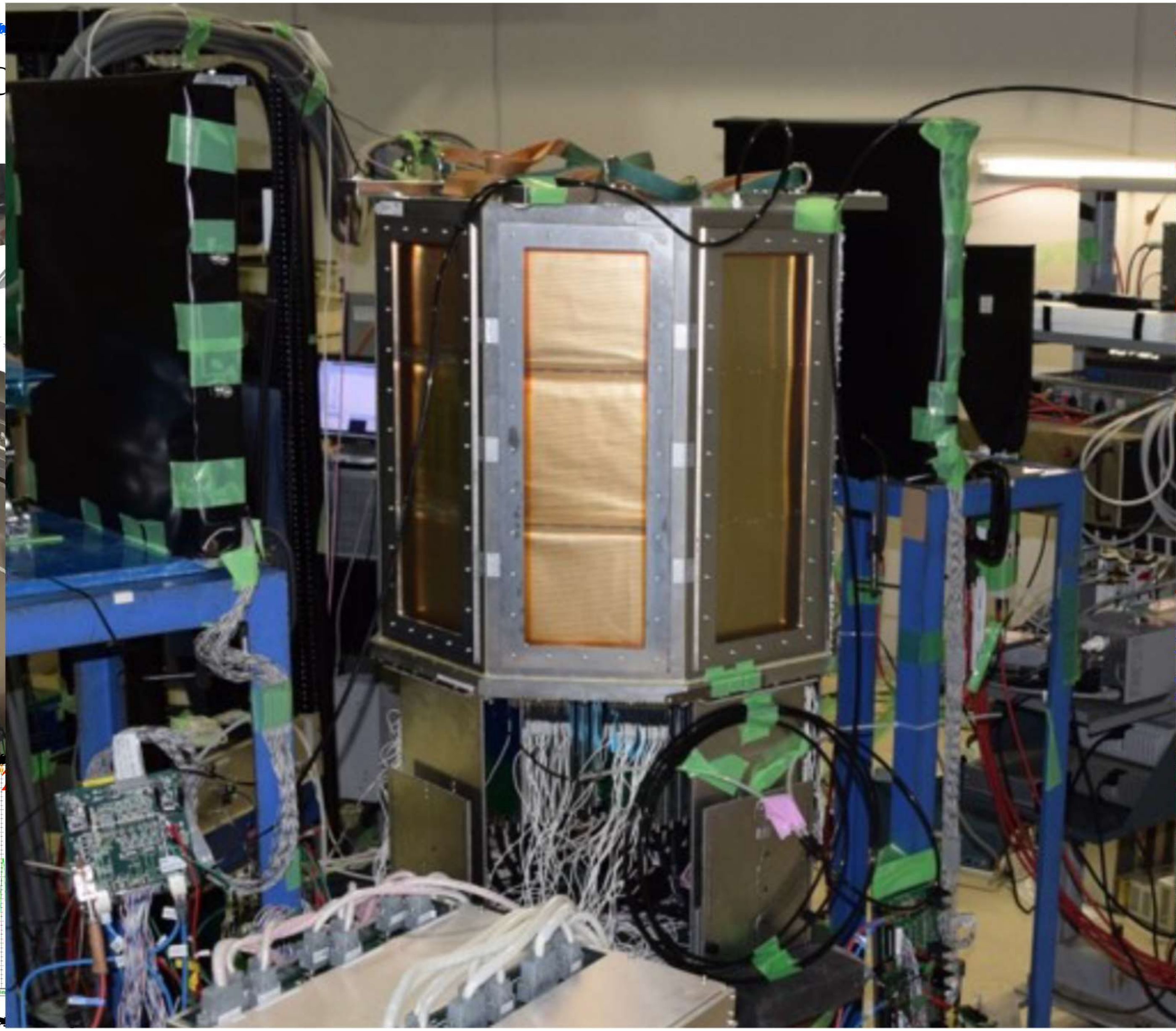
Large (almost 4π) acceptance

Construction complete.
Under commissioning

Construction of the HypTPC

•HypTPC



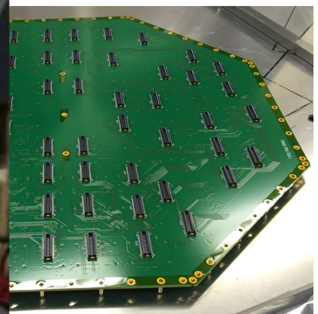


-coated Cathode

ld-wire plane

ting grid
nm pitch)

layers) &
-out PAD
50um + 100um
4



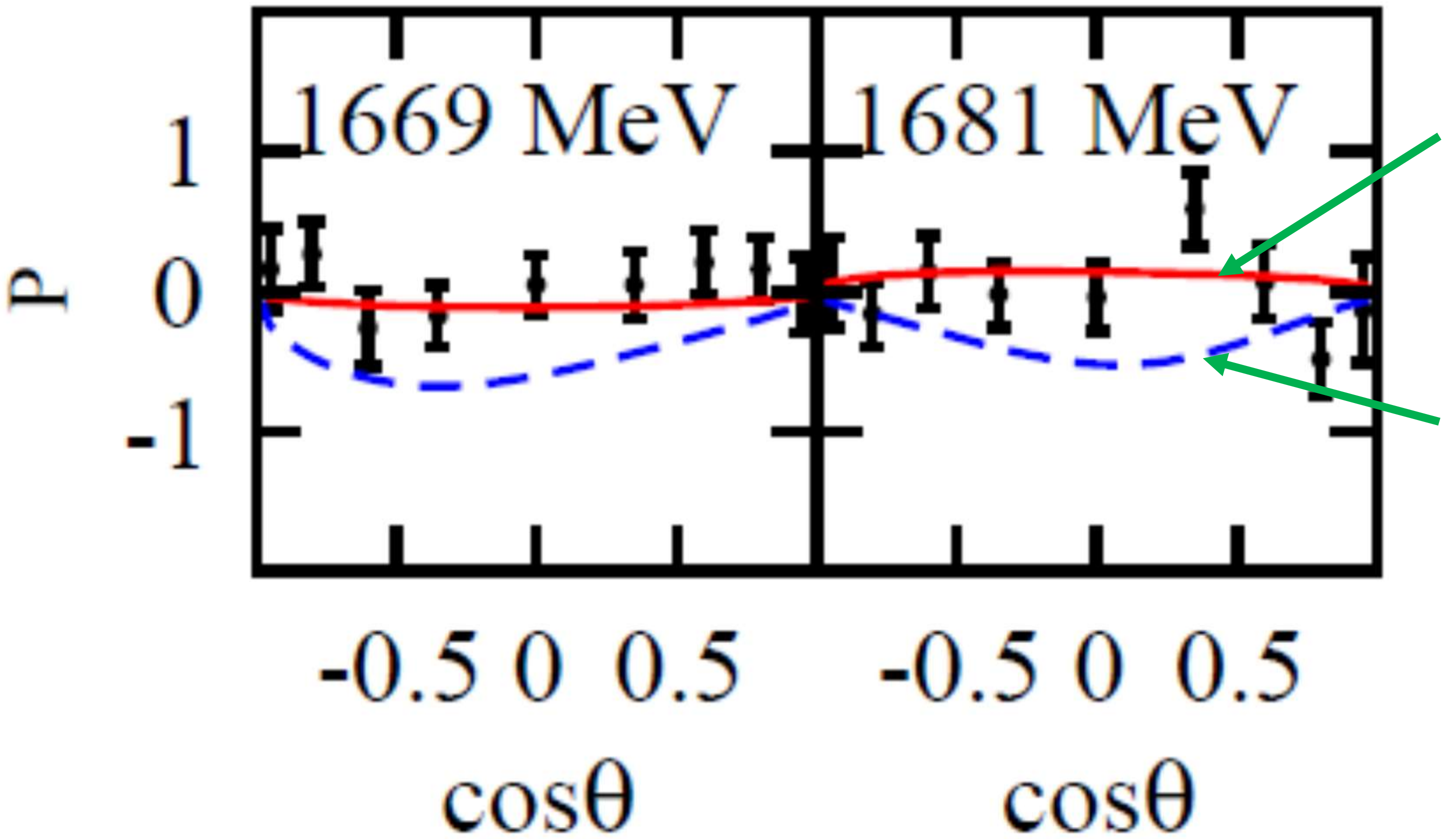
Yield estimation

- Beam intensity: 30 k/spill
- Target: Liq. H_2 5 cm (0.35 g/cm^2 or 2.1x10^{23}/cm^2)
- Reaction rate: 6.3/spill for 1 mb
- Acceptance & efficiency: 0.3?
  ← need a simulation
- Event rate: 1200/h
  → 200k events in a week.
  Cf. Crystal Ball: 2700 events in total

Identify parity

- Angular distribution is the same for $3/2^+$ (P wave) and $3/2^-$ (D wave)
  - Again, we need polarization of the final Λ
- Crystal-Ball data is very poor for polarization
  - Support for new resonance is not obtained

Polarization – Parity in CB data



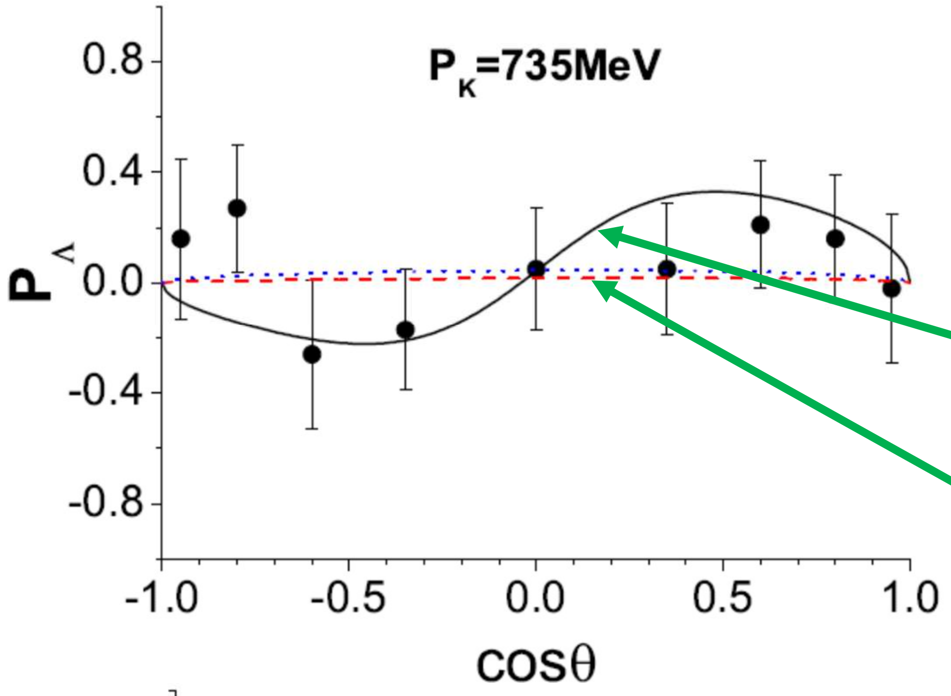
No new resonance

New resonance in $3/2^{+}$ (P_{03})

Model calc. by Kamano et al. [PRC92.025205]

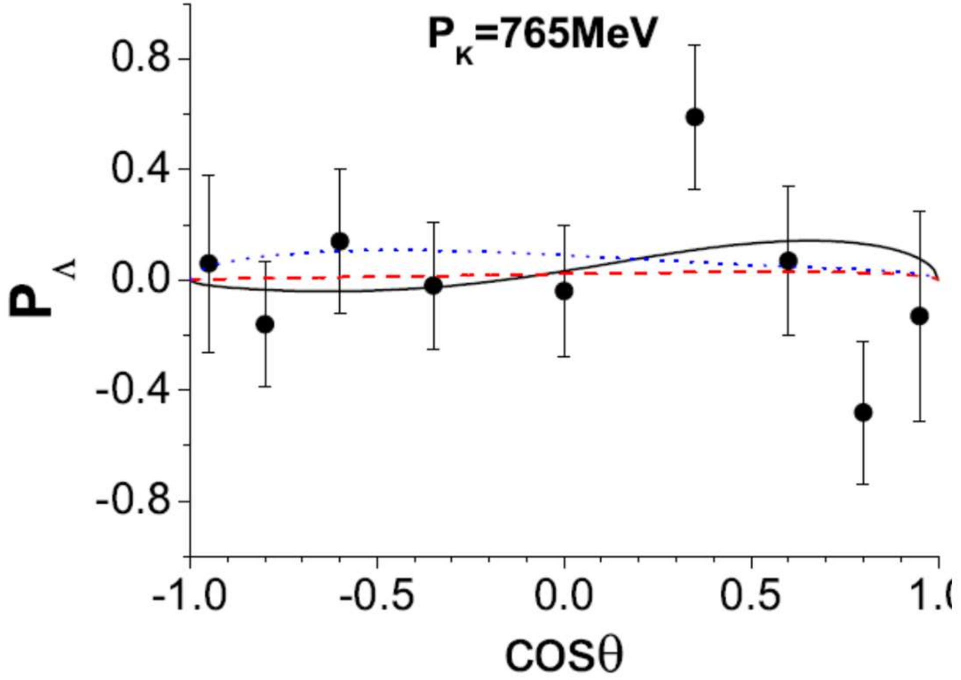
- Crystal ball data is average of 722-750 MeV/c & 750-770 MeV/c, not for each momentum.
  ⇔ Meanwhile, calculations are done on the points.

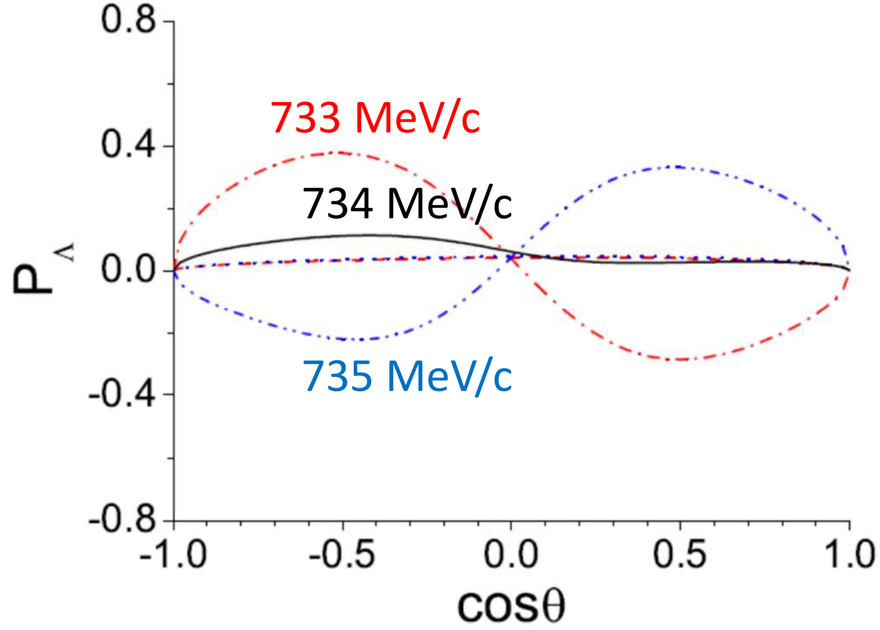
Calculation by Liu & Xie [PRC86.055202]



New resonance in $3/2^-$ (D_{03})

No new resonance





Identify parity

- Angular distribution is the same for $3/2^+$ (P wave) and $3/2^-$ (D wave)
  - Again, we need polarization of the final Λ
- Crystal-Ball data is very poor for polarization
  - Support for new resonance is not obtained
- How we can distinguish P&D?
  - P wave – no node, D wave – node
- We need δp~0.05 for each momentum/angle bin
  → Large statistics needed
  x16: δP 0.2 → 0.05
  x10: binning 2 → 20
  → Need ~2 weeks of beamtime. Looks feasible

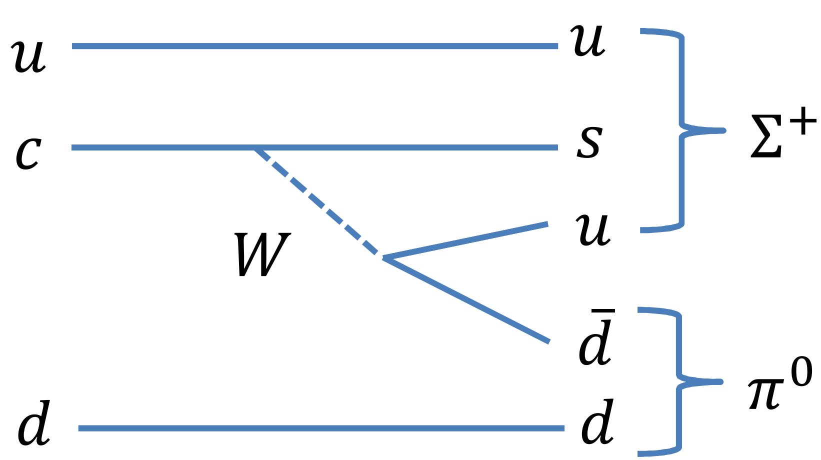
2.3 Hyperon spin structure study using Λ_c^+ decay

Idea

- To measure hyperon polarization in Λ_c decay
  - Semileptonic: $\Lambda_c \rightarrow Y + e(\mu) + \nu$
  - Non-leptonic: $\Lambda_c \rightarrow Y + \pi$
  - Main target is $Y=\Lambda(1405)$
- Why it is interesting?
  - s quark from charm decay is polarized
  - Naively, polarization transfer from quark to hyperon = How much fraction of spin of hyperon is carried out by the quark. E.g., quark model predicts $P(\Lambda)=P(s)\sim-0.9$
  - We can discuss hyperon spin structure.
  - For $\Lambda(1405)$, 3 quark state should have P~+0.3, while 5 quark state (or KN bound state) should have P~0.

Existing data (from PDG)

- $\Lambda_c \rightarrow \Lambda + e(\mu) + \nu$: P = α = −0.86±0.04 OK
- $\Lambda_c \rightarrow \Lambda + \pi^+$: P = −0.91±0.15 OK
- $\Lambda_c \rightarrow \Sigma^+ + \pi^0$: P = −0.45±0.32 OK?
  - Contribution of strange quark should give P~+0.3, but there is a contribution of up quark P~-0.6, giving P~-0.3 in total



Seemingly, the naïve model can explain the existing data

Semileptonic vs nonleptonic modes

- Theoretical cleanness vs experimental easiness
- Semileptonic: no peak in invariant mass because of missing ν.
  - BG may be severe, very complicated analysis
  - Tagging Λ_c in missing mass?
    Up to 100 counts in the present Belle, a few thousands expected in Belle II.
    → Detection may be possible with Belle data,
    polarization needs Belle II statistics
- Non-leptonic:
  - Study possible with Belle data, but interpretation is the issue
  - Measure mass dependence → identify 2-pole structure??
  - $\Lambda(1520)$ as a control sample

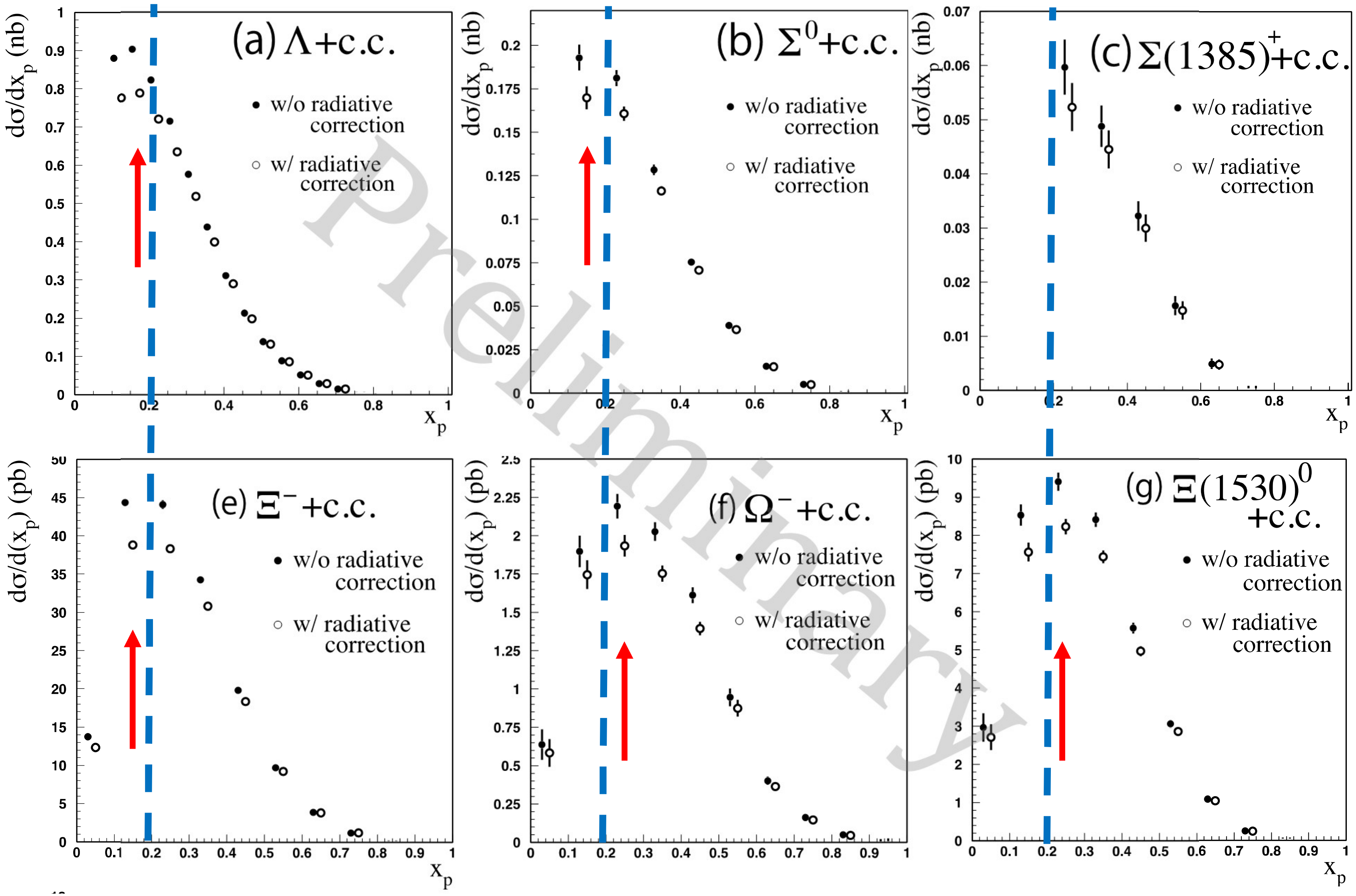
Summary

- Belle data taking is over, but still actively publishing results. Many interesting results coming on baryon spectroscopy.
  - Spectroscopy of Ξ_c and Ω_c
  - The first observation of doubly Cabibbo-suppressed decay in charmed baryon, $\Lambda_c^+ \to pK^+\pi^-$
  - Measurement of baryon production rates
  - Search for Ps in $\Lambda_c^+ \to p\phi\pi^0$
- Interesting results are expected in Belle II, where 50 times more statistics than Belle. And J-PARC, too.
  - Spin-parity determination of most known charmed baryons
  - New hyperon resonance(s), hyperon spin structure study to identify exotics
  - And more

Backup

Inclusive differential cross sections, hyperons

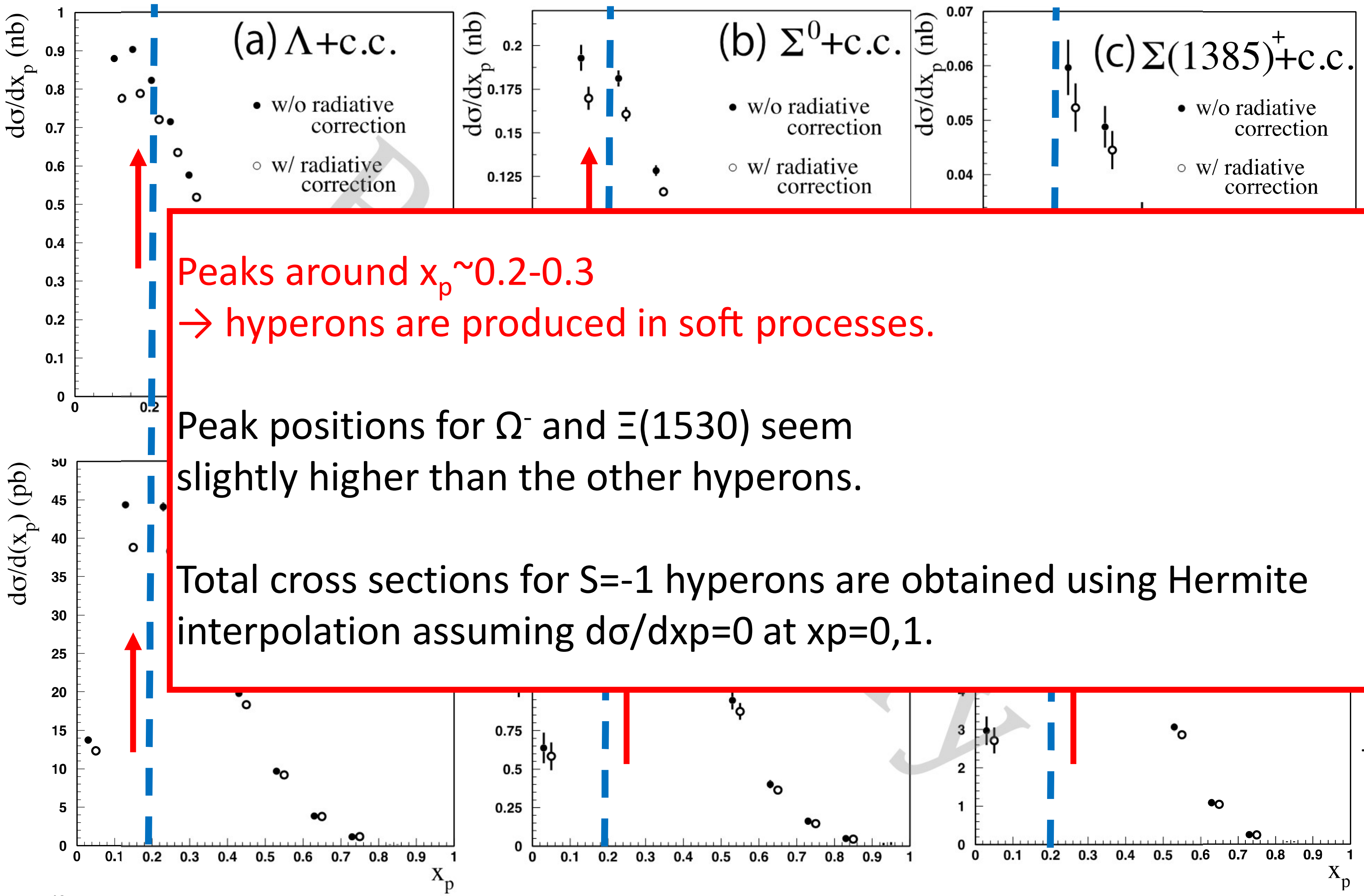
"Inclusive" cross sections (including feed-down) are obtained as a function of hadron scaled momentum (x_p). $x_p = p/\sqrt{s/4 - M^2}$ (M, p : mass and CM momentum)



Error bar represent statistical fluctuation.

Inclusive differential cross sections, hyperons

"Inclusive" cross sections (including feed-down) are obtained as a function of hadron scaled momentum (x_p). $x_p = p/\sqrt{s/4 - M^2}$ (M, p : mass and CM momentum)



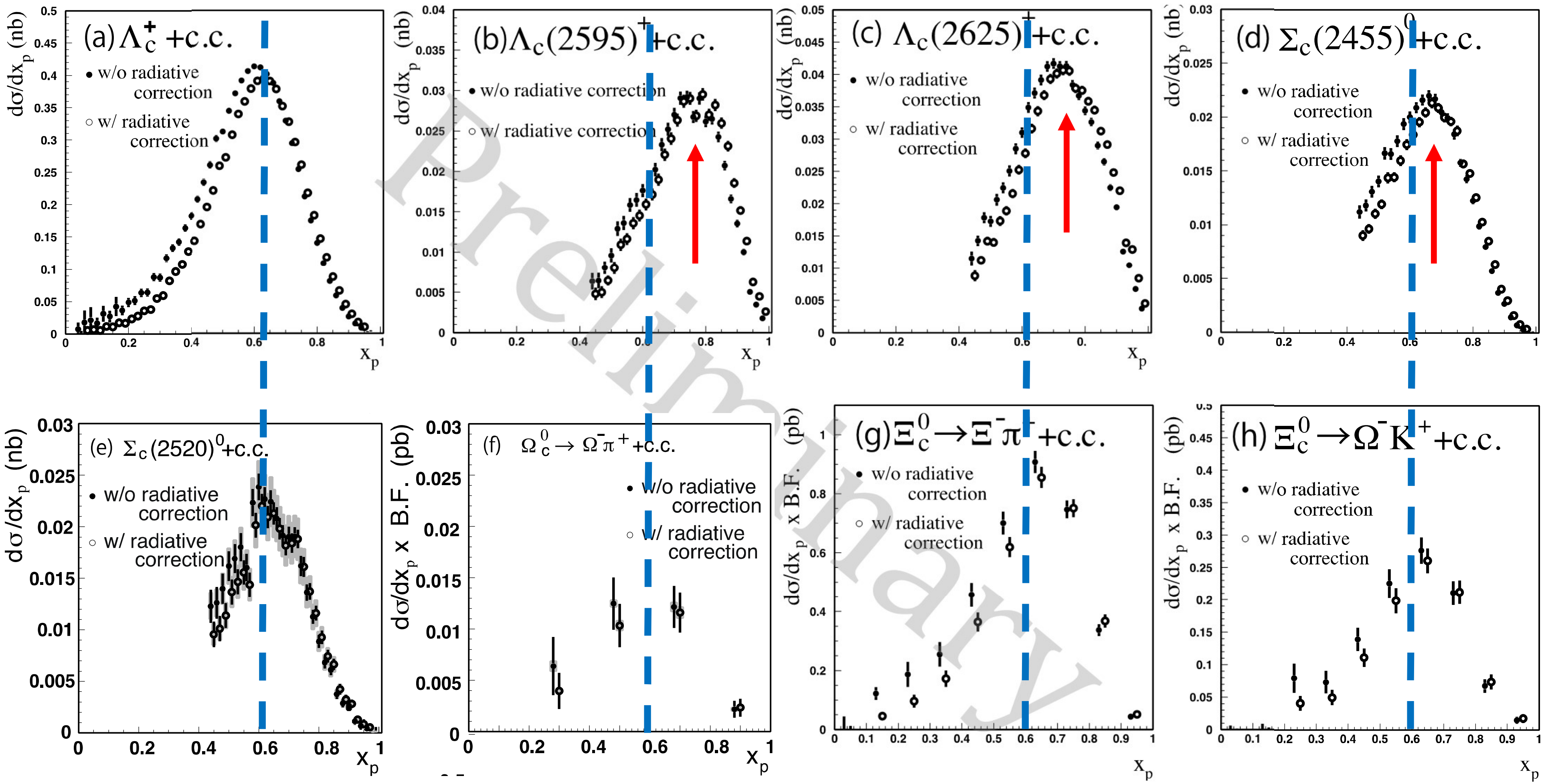
Peaks around x_p~0.2-0.3
→ hyperons are produced in soft processes.

Peak positions for Ω^- and Ξ(1530) seem slightly higher than the other hyperons.

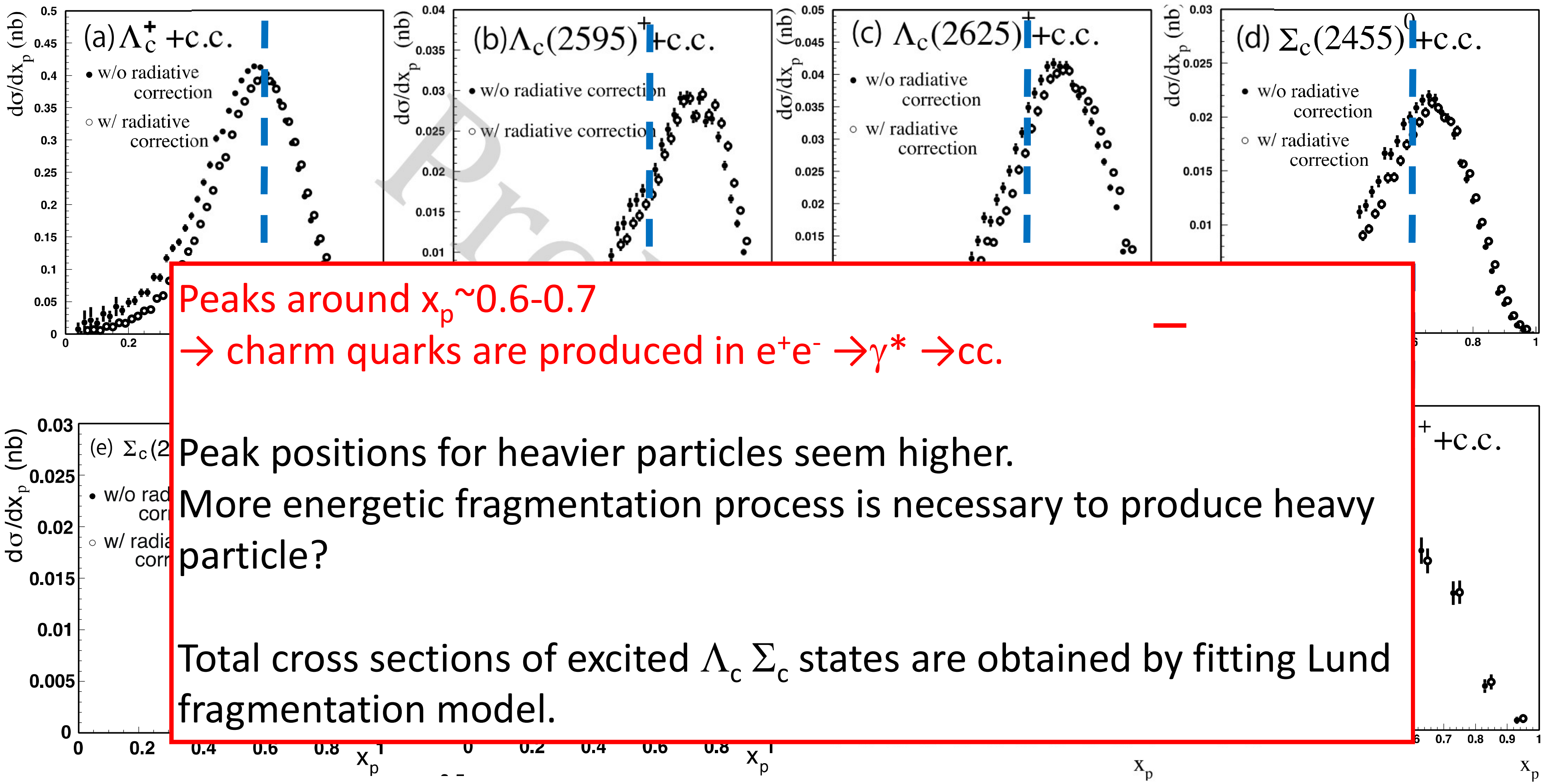
Total cross sections for S=-1 hyperons are obtained using Hermite interpolation assuming dσ/dxp=0 at xp=0,1.

Error bar represent statistical fluctuation.

Inclusive differential cross sections, charmed baryons



Inclusive differential cross sections, charmed baryons



Peaks around x_p~0.6-0.7

→ charm quarks are produced in $e^+e^- \rightarrow \gamma^* \rightarrow c\bar{c}$.

Peak positions for heavier particles seem higher.

More energetic fragmentation process is necessary to produce heavy particle?

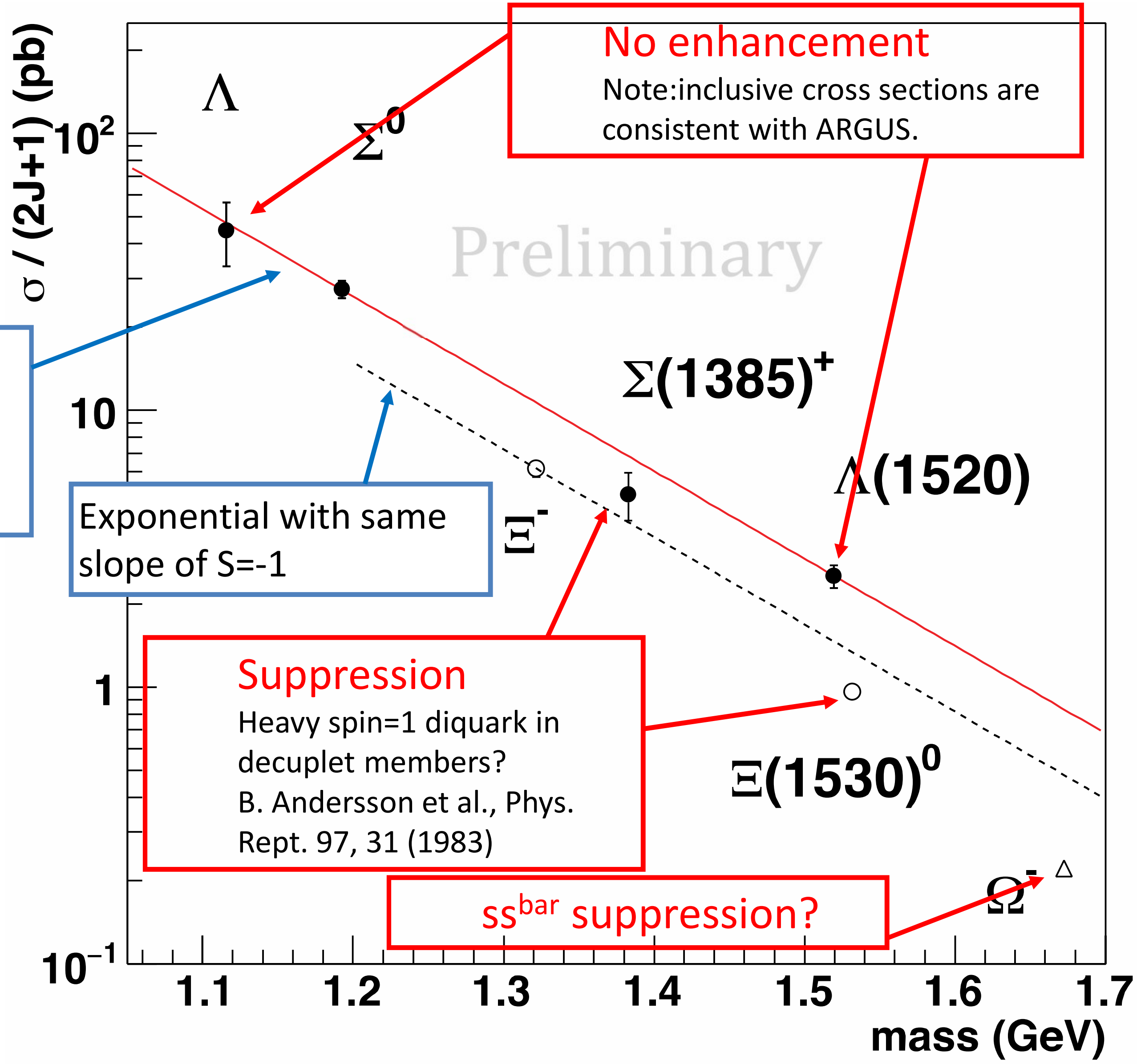
Total cross sections of excited Λ_c Σ_c states are obtained by fitting Lund fragmentation model.

Results for hyperons

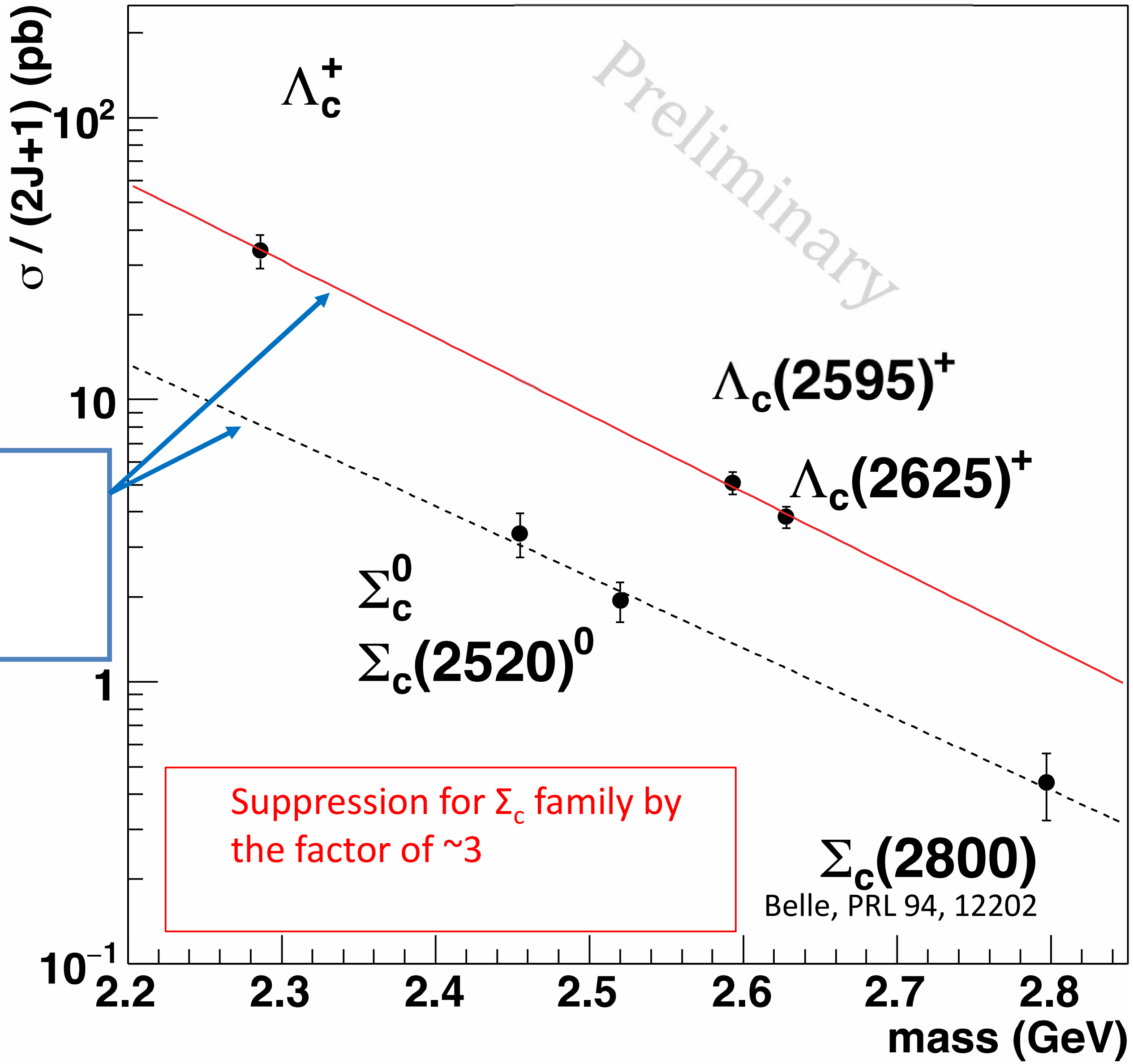
Feed-down subtracted

Fit with $a_0 exp(a_1 m)$,
Slope parameter
-7.3± 0.3 $(GeV/c^2)^{-1}$

- Suppression
- Σ(1385) : 33% with 2.3σ
- Ξ(1530) : 22% with 4.6σ



Results of charmed baryons



Slope parameters
Λ_c : -6.3± 0.5 (GeV/c²)⁻¹
Σ_c : -5.8± 1.0 (GeV/c²)⁻¹
consistent

Discussion

- Assuming that a c-quark picks up a diquark from vacuum,
  - Schwinger-like "tunnel effect" of diquark and anti-diquark

$$\sigma \propto \exp(-\pi\mu^2/\kappa)$$

μ: diquark mass
κ: gluonic string tension

B. Andersson et al., Phys. Scripta. 32, 574 (1985)

- $\sigma(\Sigma_c)/\sigma(\Lambda_c) = 0.27 \pm 0.07$
  - Λ_c: spin-0 diquark, Σ_c: spin-1 diquark,
  - mass difference of spin-1 and 0 diquarks

$$m(ud_1)^2 - m(ud_0)^2$$
$$= (8.2 \pm 0.8) \times 10^4 \ (\mathrm{MeV}/c^2)^2$$

ref. $$490^2 - 420^2 = 6.4 \times 10^4 \ (\mathrm{MeV}/c^2)^2$$

B. Andersson et al., Phys. Rept. 97, 31 (1983)

- Slightly higher than reference but consistent with the spin-1/0 diquark mass difference!