Amplitude analysis in baryon spectroscopy at Belle and J-PARC

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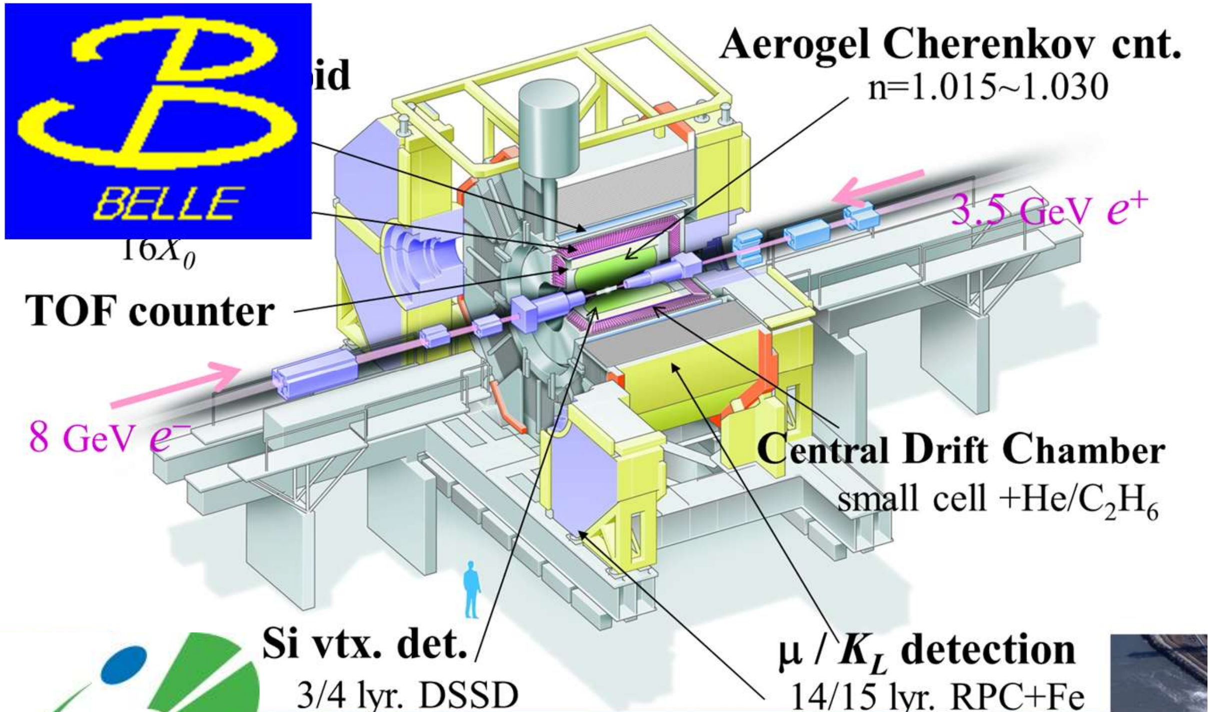
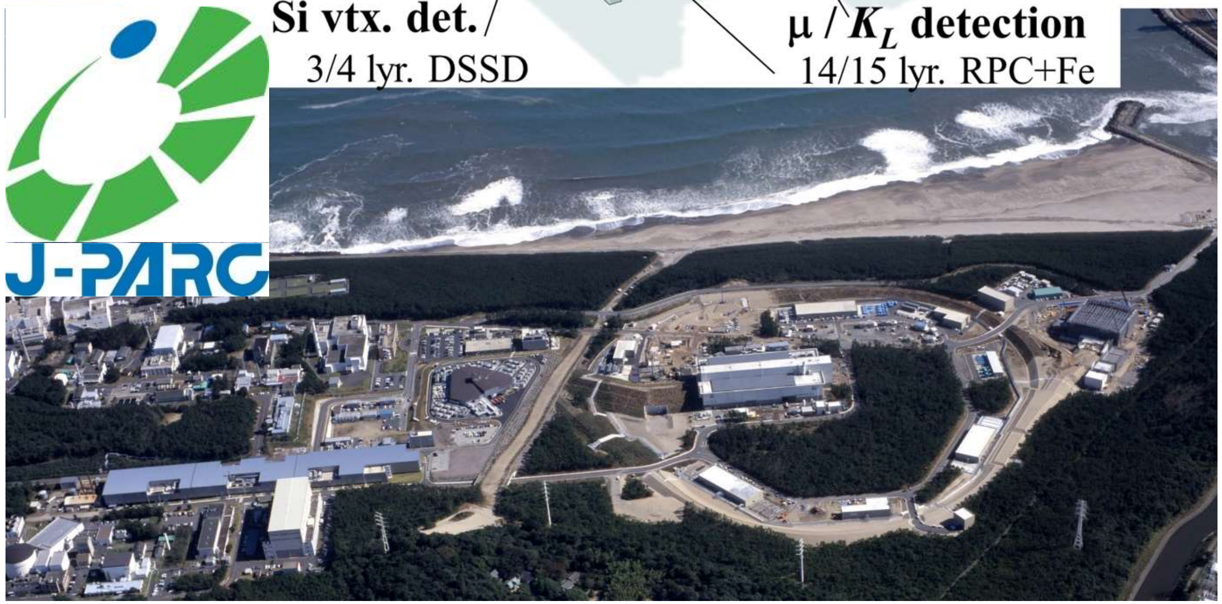
The two major facilities in Japan

- KEKB/Belle & J-PARC
- Complementary: e^+e^- collider vs proton + fixed-target
- High-intensity (luminosity) frontier





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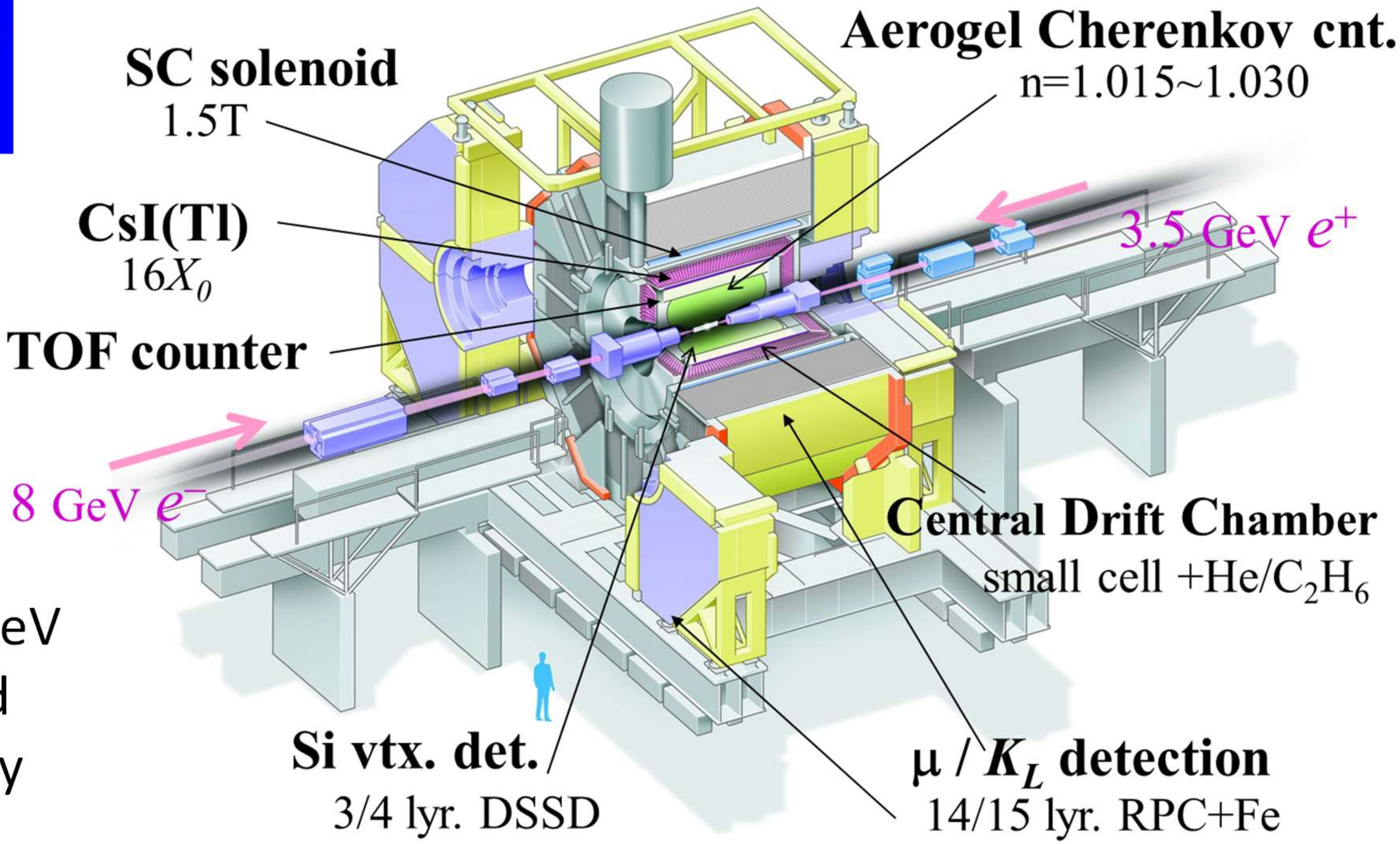
Part I.
Baryon spectroscopy
at Belle

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

PWA for baryons?

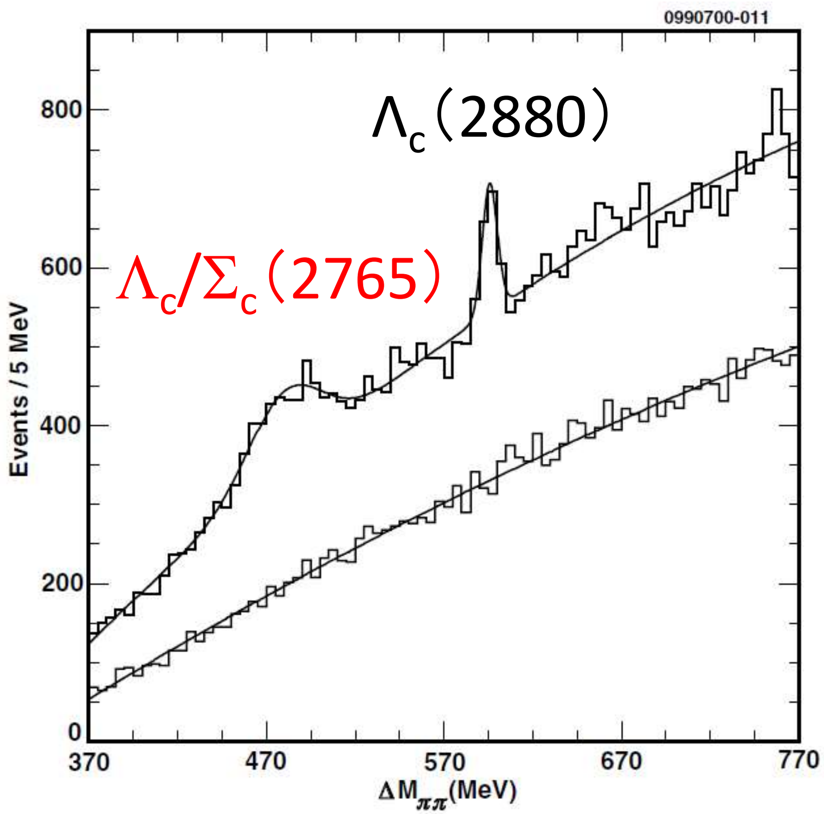
- Not very active in Belle
  ⇔c.f. for meson see presentation by D. Greenwald on Thursday.
- PWA more complicated – spin degree of freedom.
- Yet, PWA is eventually necessary to determine J^P, and to identify the nature
- A trial on $\Lambda_c/\Sigma_c(2765)$, possibility to apply for other baryons.

$\Lambda_c/\Sigma_c(2765)$

First observation by CLEO

$\Lambda_c(2765)^+$
or $\Sigma_c(2765)$

$I(J^P) = ?(?^?)$ Status: $*$



CLEO[PRL86（2001）4479]

- B decay → Λ_c^* → $\Lambda_c\pi\pi$ （$\Sigma_c\pi$、$\Sigma_c^*\pi$ included）
- Width～50 MeV (no uncertainty given)

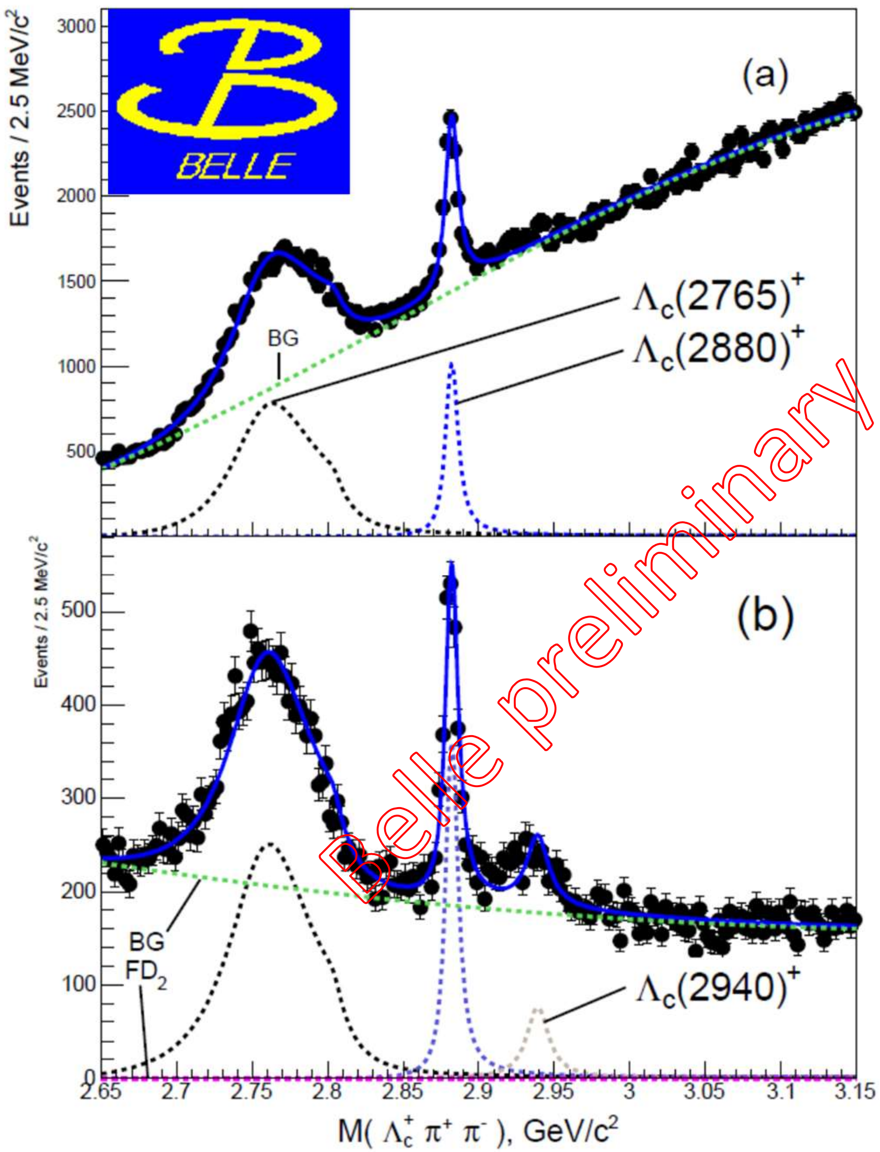
Known things

- Experimentally – very poor
  - $I(J^P)$ not determined yet
  - No uncertainty on width from CLEO
- Theoretically – so many
  - Quark models: six (or more) states in this mass region $I(J^P)$= $0(1/2^-)$, $0(3/2^+)$, $1(1/2^-)$, $1(1/2^-)$, $1(3/2^-)$, $1(3/2^-)$, …
  - Including other models, any combination of I=0 or 1, J=1/2 or 3/2, and P=+ or – seems possible
- Experimental determination of $I(J^P)$ is necessary to identify the nature of $\Lambda_c/\Sigma_c(2765)$

How to determine $I(J^P)$?

- Isospin (I): Search for possible isospin partners ($\Sigma_c(2765)^{++/0}$) by
  $\Sigma_c(2765)^{++/0} \rightarrow \Sigma_c^{++/0}\pi^0 \rightarrow \Lambda_c(2765)^+\pi^{\pm}\pi^0$

Reference mode: $\Lambda_c/\Sigma_c(2765)^+ \rightarrow \Sigma_c\pi$



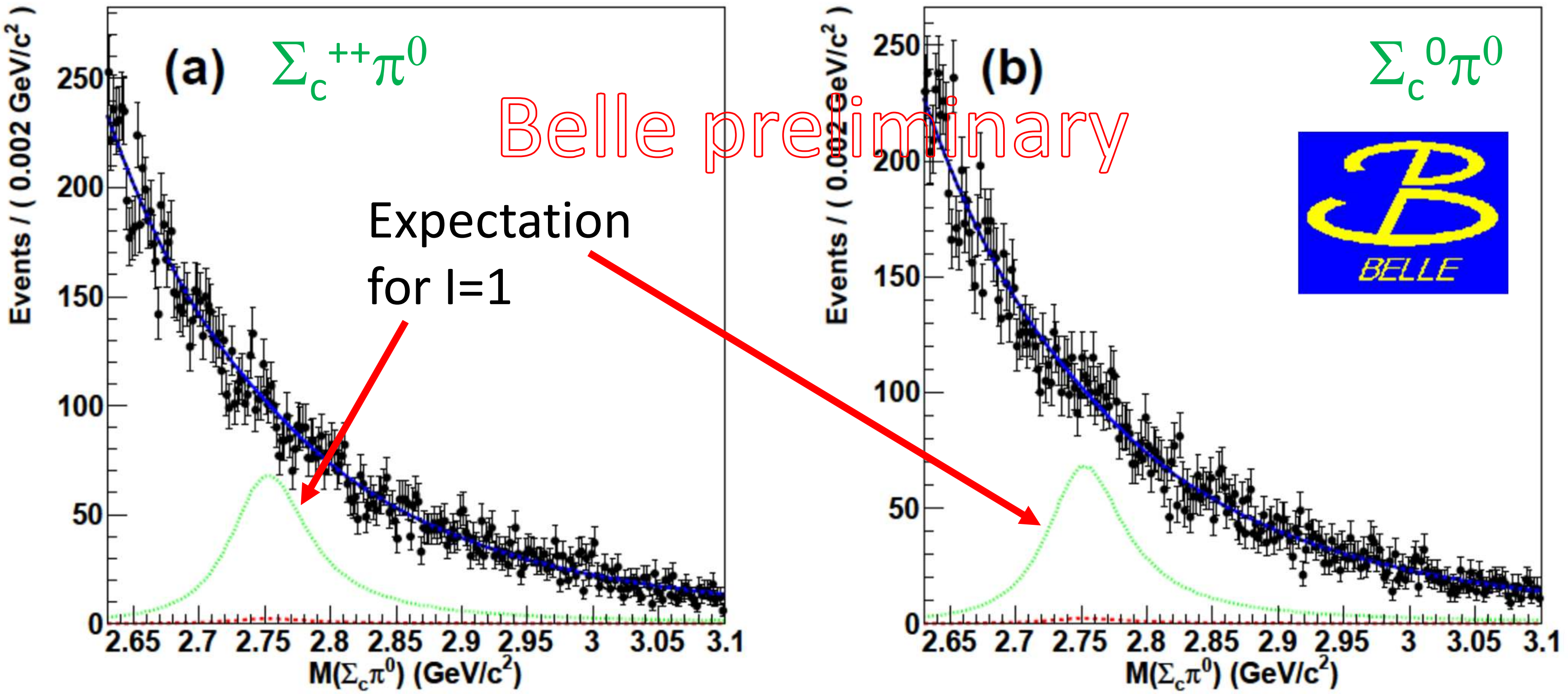
(a) Inclusive $\Lambda_c\pi^+\pi^-$

(b) With Σ_c selection

- Analyzed with full data of Belle (980 fb^{-1})
- Clear peaks are observed
- Fit with Breit-Wigner functions to extract yield.

$\Sigma_c(2765)^{++/0} \rightarrow \Sigma_c^{++/0}\pi^0$

[Belle-Conf-1905, ArXiv:1908.06235]



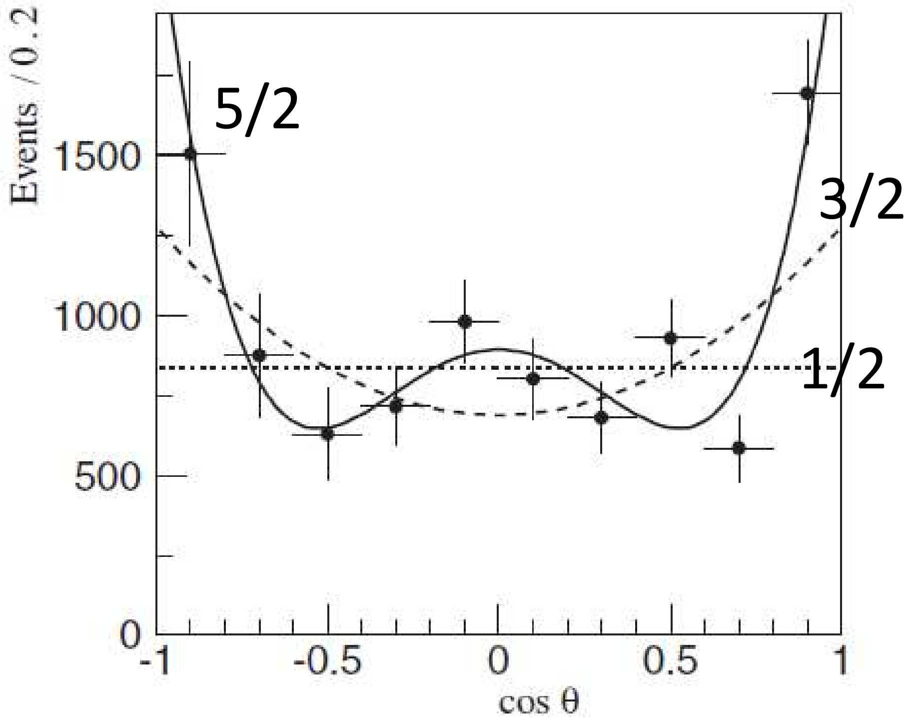
- No peak seen → Isospin is not 1, but 0.
  The name is indeed $\Lambda_c(2765)$

How to determine $I(J^P)$?

- Spin (J): angular distribution of the decay $\Lambda_c/\Sigma_c(2765) \to \Sigma_c^{(*)}\pi$ & angular correlation of two pions in $\Lambda_c/\Sigma_c(2765) \to \Sigma_c^{*}\pi_1 \to \Lambda_c\pi_1\pi_2$
- Parity (P): Use branching ratio (used for $\Lambda_c(2880)$)
$$R = \frac{\Gamma(\Lambda_c^* \to \Sigma_c^* \pi)}{\Gamma(\Lambda_c^* \to \Sigma_c \pi)}$$
- Isospin (I): Search for possible isospin partners ($\Sigma_c(2765)^{++/0}$) by $\Sigma_c(2765)^{++/0} \to \Sigma_c^{++/0}\pi^0 \to \Lambda_c(2765)^{+}\pi^{\pm}\pi^0$

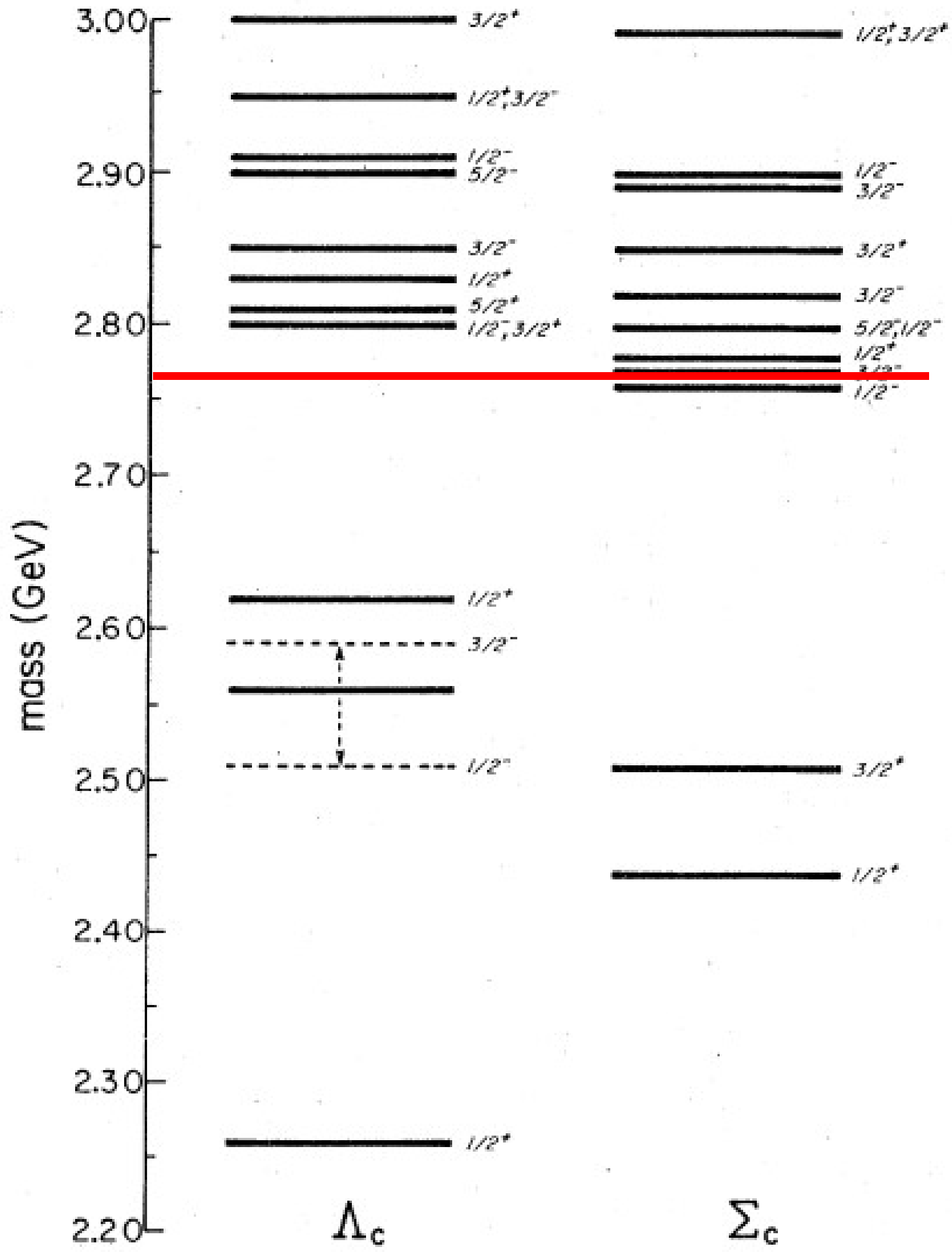
Angular distributions and PWA

- $\Lambda_c/\Sigma_c(2765) \rightarrow \Sigma_c^{(*)}\pi$: The same method used to determine $\Lambda_c(2880)$ spin.
- $\Sigma_c^{*} \rightarrow \Lambda_c\pi$: expected angular distribution:
  - $1 - \cos^2\theta$ for $|j_z|=1/2$
  - $1 + 3\cos^2\theta$ for $|j_z|=3/2$
  - We see an evidence that other partial waves than $P_{3/2}$ interfere → PWA ongoing



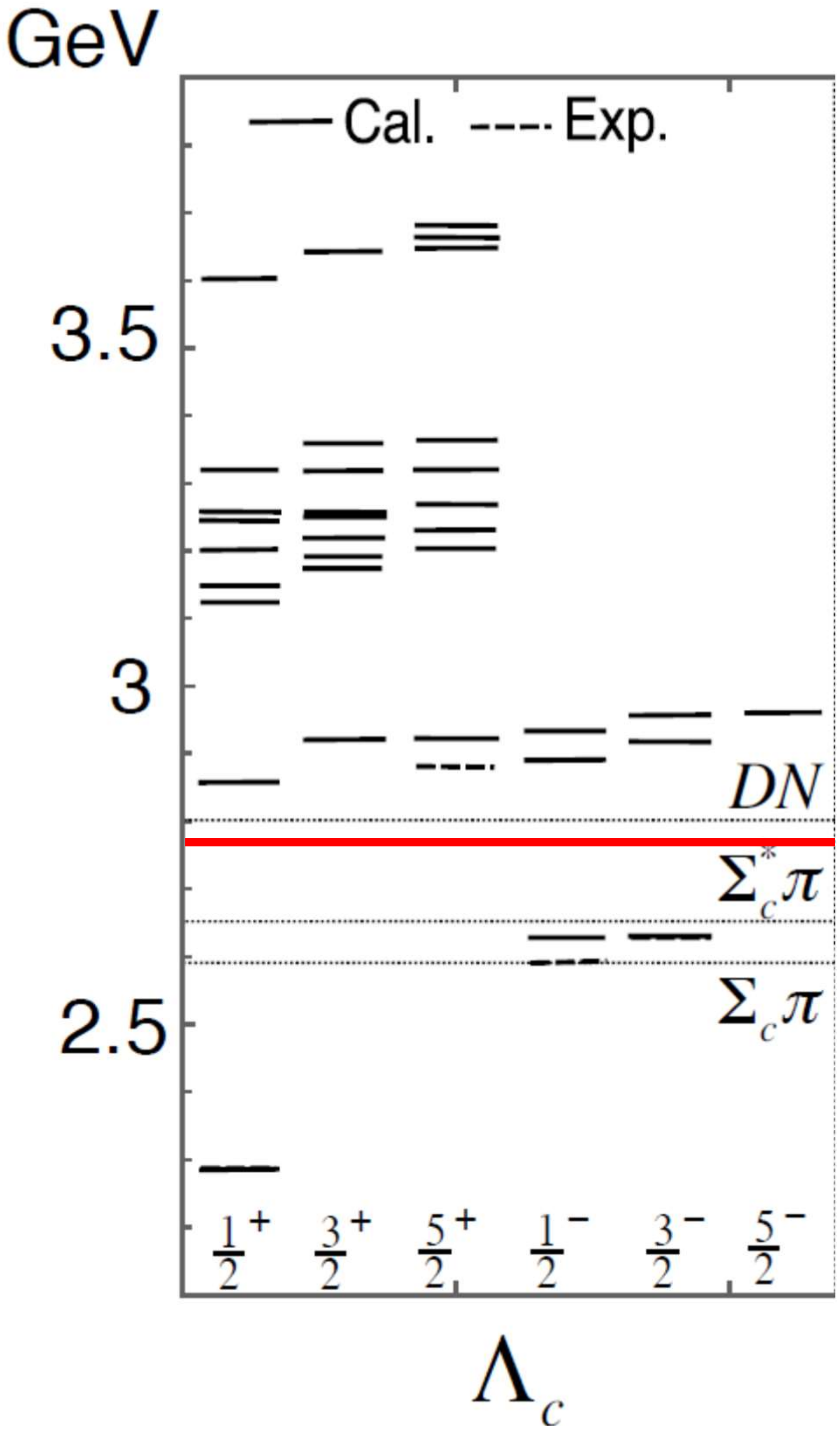
- Details & result coming soon.

Old QM calc.



- Old QM calc. by Copley et. Al. [PRD20 (1979) 768]
- A few states ($1/2^-$, $3/2^+$, ...) are within 50 MeV.
- Still, more states were predicted for I=1 – ruled out.

Recent QM calc.



- Latest QM calc. by Yoshida et al. [PRD92 114029]
- No I=0 state within 50 MeV.
- Limitation of QM?

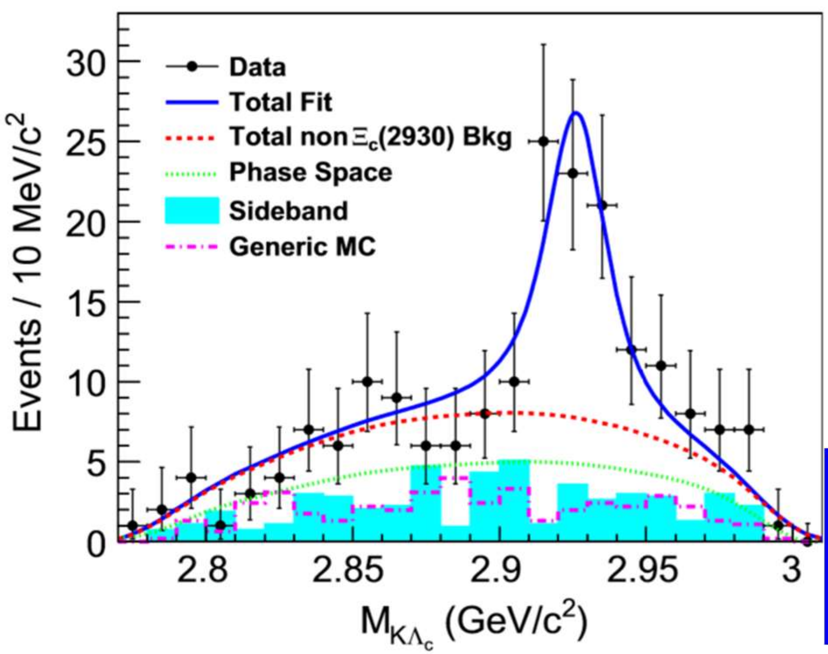
Recent results on other baryons & perspective for PWA

$\Xi_c(2930)^0$ and $\Xi_c(2930)^+$

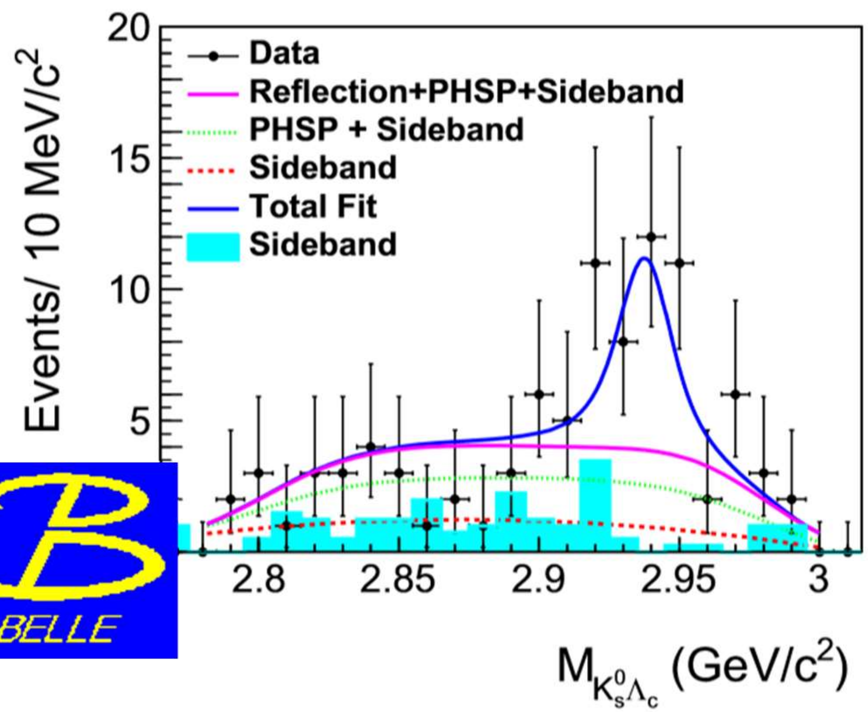
Babar observation is now confirmed by Belle

[EPJC 78, 928 and 78, 252]

$\Xi_c(2930)^0 \rightarrow K^- \Lambda_c^+$ in $B^- \rightarrow K^- \Lambda_c^+ \bar{\Lambda}_c^-$



$\Xi_c(2930)^+ \rightarrow K_S^0 \Lambda_c^+$ in $B^0 \rightarrow K_S^0 \Lambda_c^+ \bar{\Lambda}_c^-$

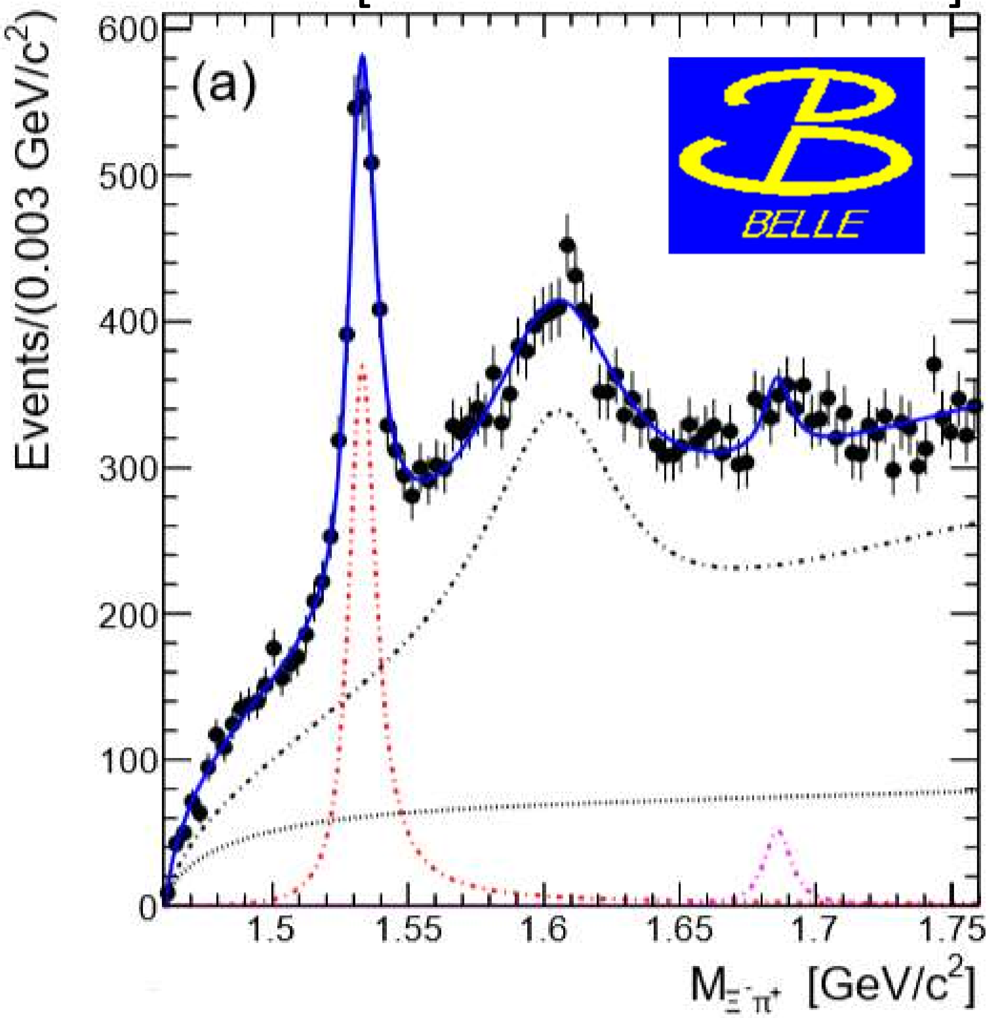


- $\Xi_c(2930)^0$: 5.1σ significance, $M = 2928.9 \pm 3.0\ ^{+0.9}_{-12.0}$ MeV
- $\Xi_c(2930)^+$: > 3.5σ significance, $M\ = 2942.3 \pm 4.4$ MeV

Ξ(1620) and Ξ(1690)

- Search for $\Xi^{*0} \to \Xi^-\pi^+$ in $\Xi_c^+ \to \Xi^-\pi^+\pi^+$

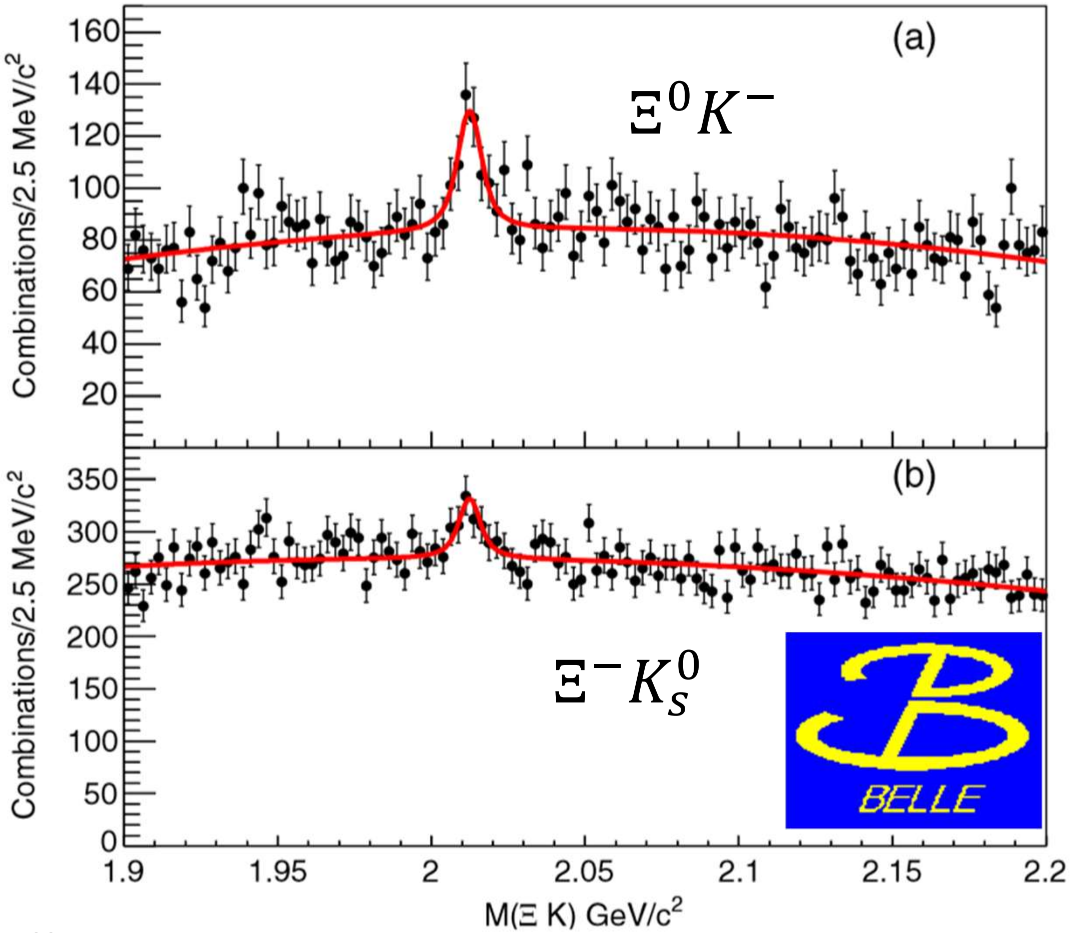
[Belle: PRL **122** 072501]



- Siginificance:
  25σ for Ξ(1620)
  4.5σ for Ξ(1690)
- M=1610.4±6.0 MeV,
  Γ=60.0±4.8 MeV
  near the ΛK threshold
- Not expected in quark models. Exotic?
- Analog of Λ(1405)?
  Two poles in J^P=1/2$^-$?

$\Omega^{*}(2012)$

- Very few Ω^* was discovered so far
- Search Ω^{*-} by ΞK decay in inclusive $\Upsilon(nS)$ decays



M=2012.4$\pm$0.7$\pm$0.6 MeV

Γ=$6.4^{+2.5}_{-2.0} \pm 1.6$ MeV

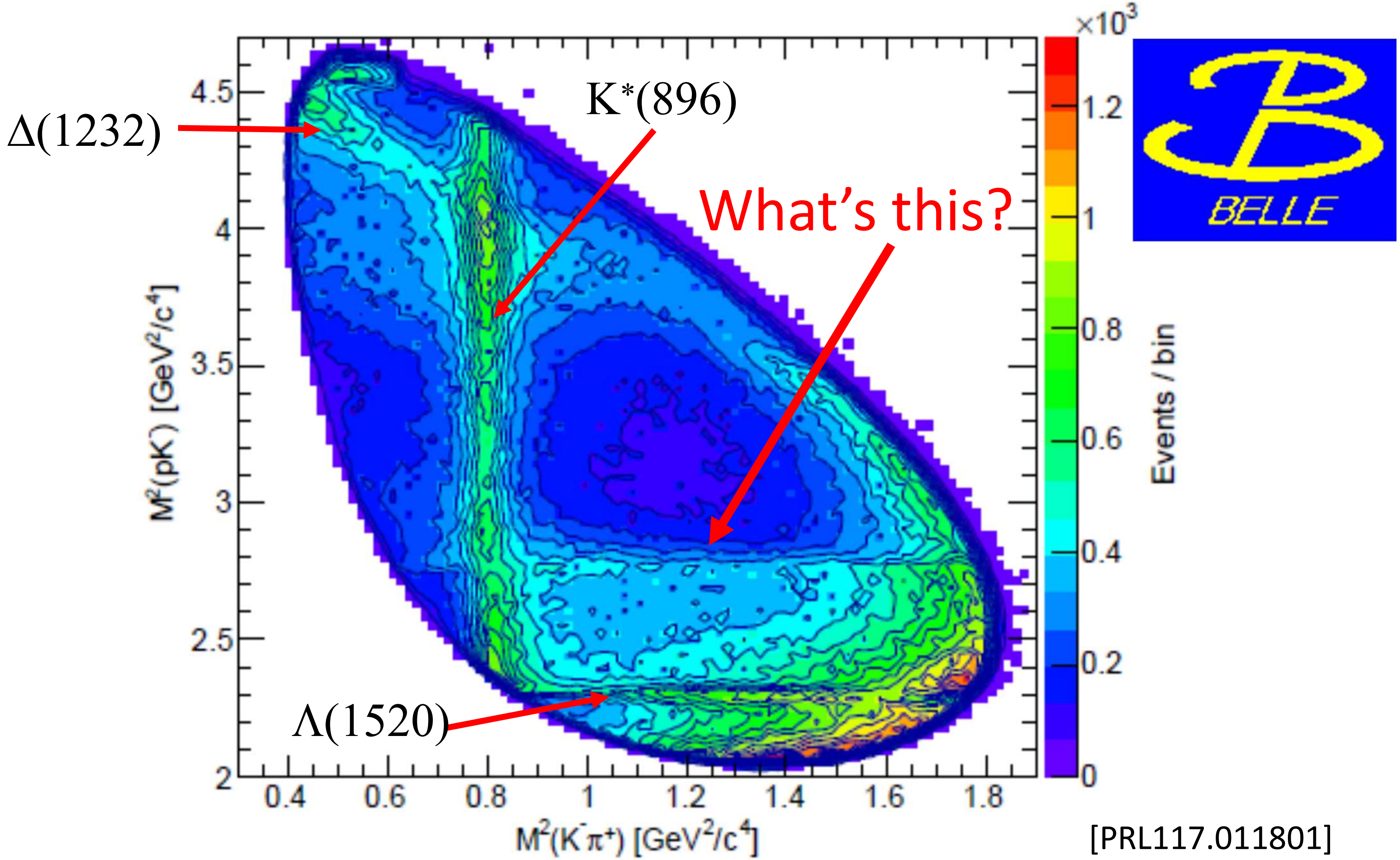
Significance: 7.2σ

* A J^P=3/2$^-$ state, as QM predicts?

* $\Xi(1530)K$ molecule? But not observed in KΞπ mode [PRD**100**, 032006]

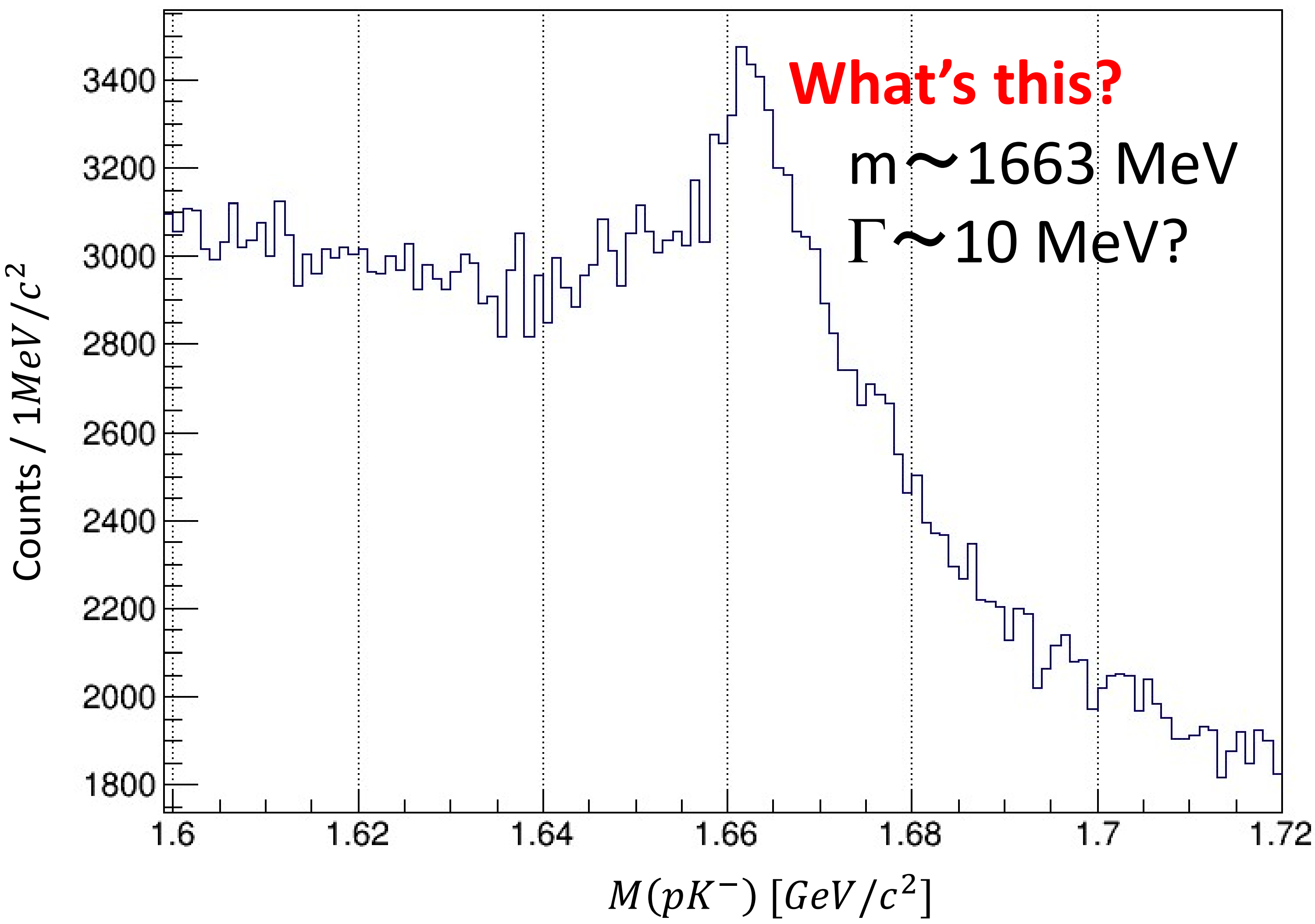
Belle:PRL **121** 052003

A new Λ^* in $\Lambda_c^+ \to pK^-\pi^+$?



[PRL117.011801]

■ **1D projection --** $M(pK^-)$



Spin-parity — PWA?

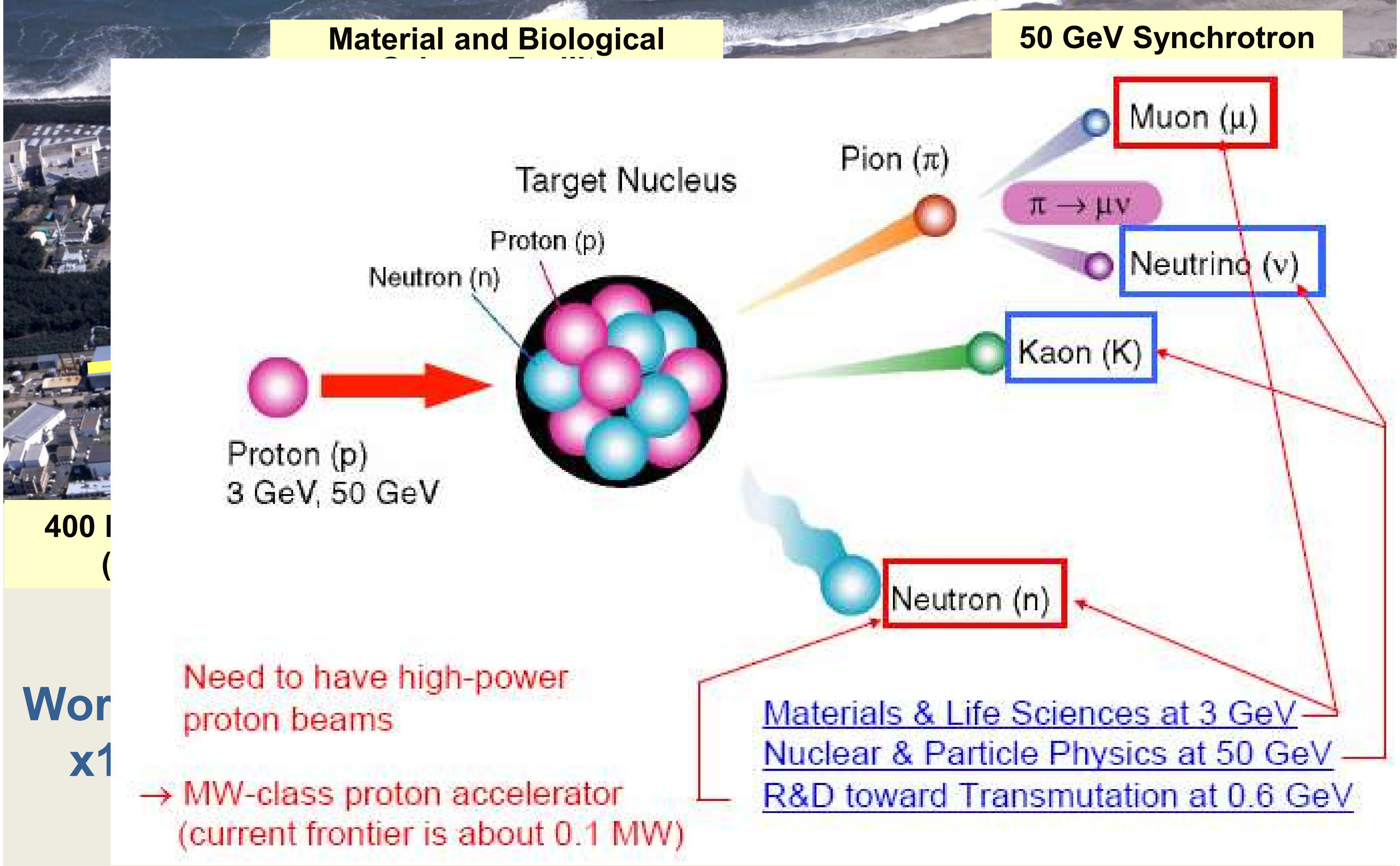
- Spin could be determined from angular distribution, if we have enough statistics…
  → We have to wait for Belle II data
- Parity needs even more (polarization, …)
- PWA would be necessary to take interference with background into account.
- If a peak is found in S-wave, we also have to consider possibility of a threshold cusp
  - Especially for $\Xi(1620)$ (on ΛK threshold) and $\Lambda(1665)$ (on $\Lambda\eta$ threshold)
  - We are trying fits with Flatte amplitude.

Part II.
Baryon spectroscopy at J-PARC

J-PARC

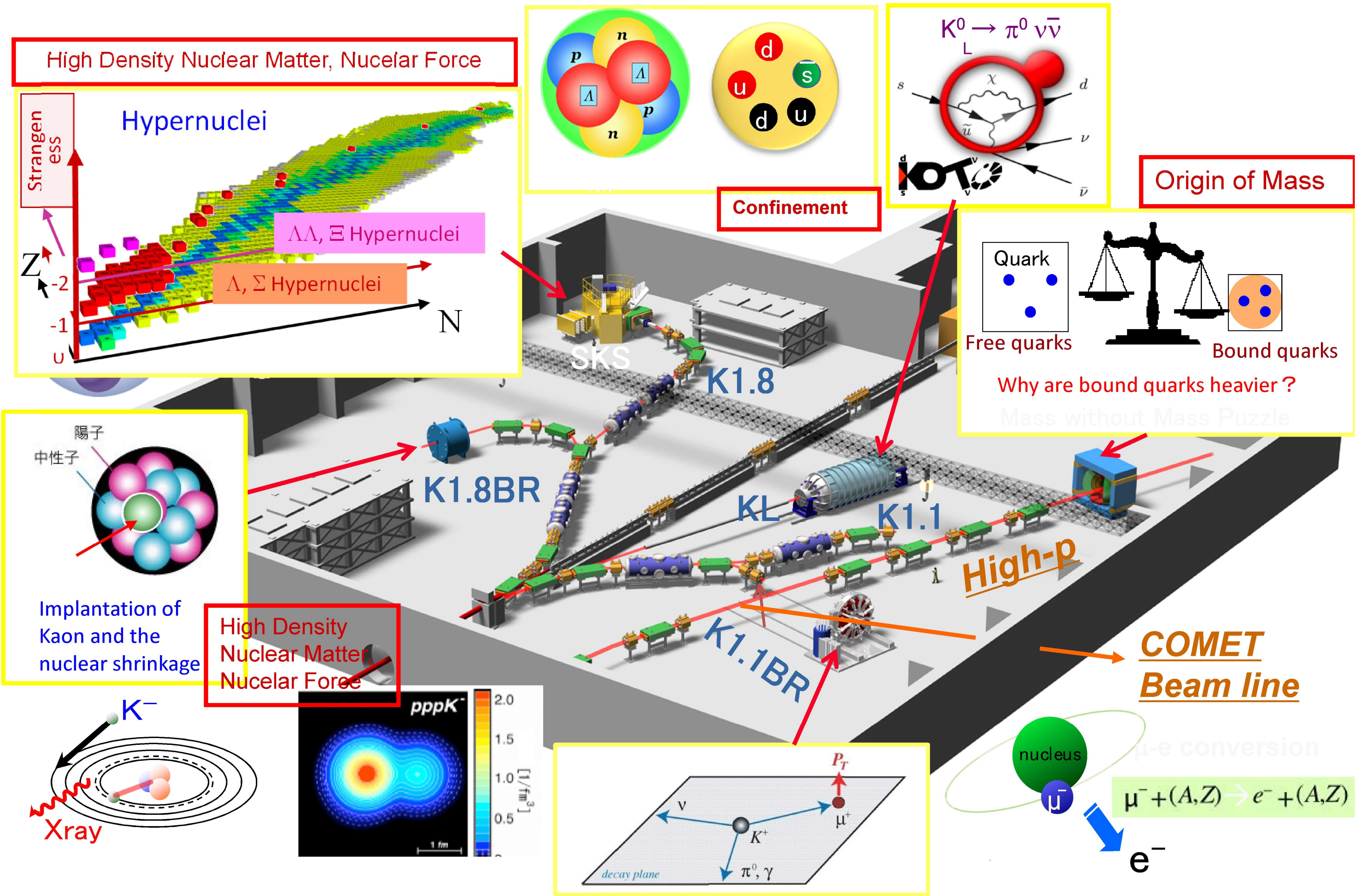
Tokai, Japan

(Japan Proton Accelerator Research Complex)



Nuclear & Hadron Physics in J-PARC

Experiments at a glance (not all)



Baryon Spectroscopy at J-PARC

- Past
  - E19 (Search for pentaquark Θ^+)
- In analysis
  - E31 (Hyperon Resonances Below $\bar{K}N$ Threshold)
- Near future
  - E42 (H-dibaryon Search)
  - E45 ($N\pi \rightarrow N\pi\pi$)
  - E50 (Charmed Baryon)
  - E72 (Search for new narrow Λ^*)

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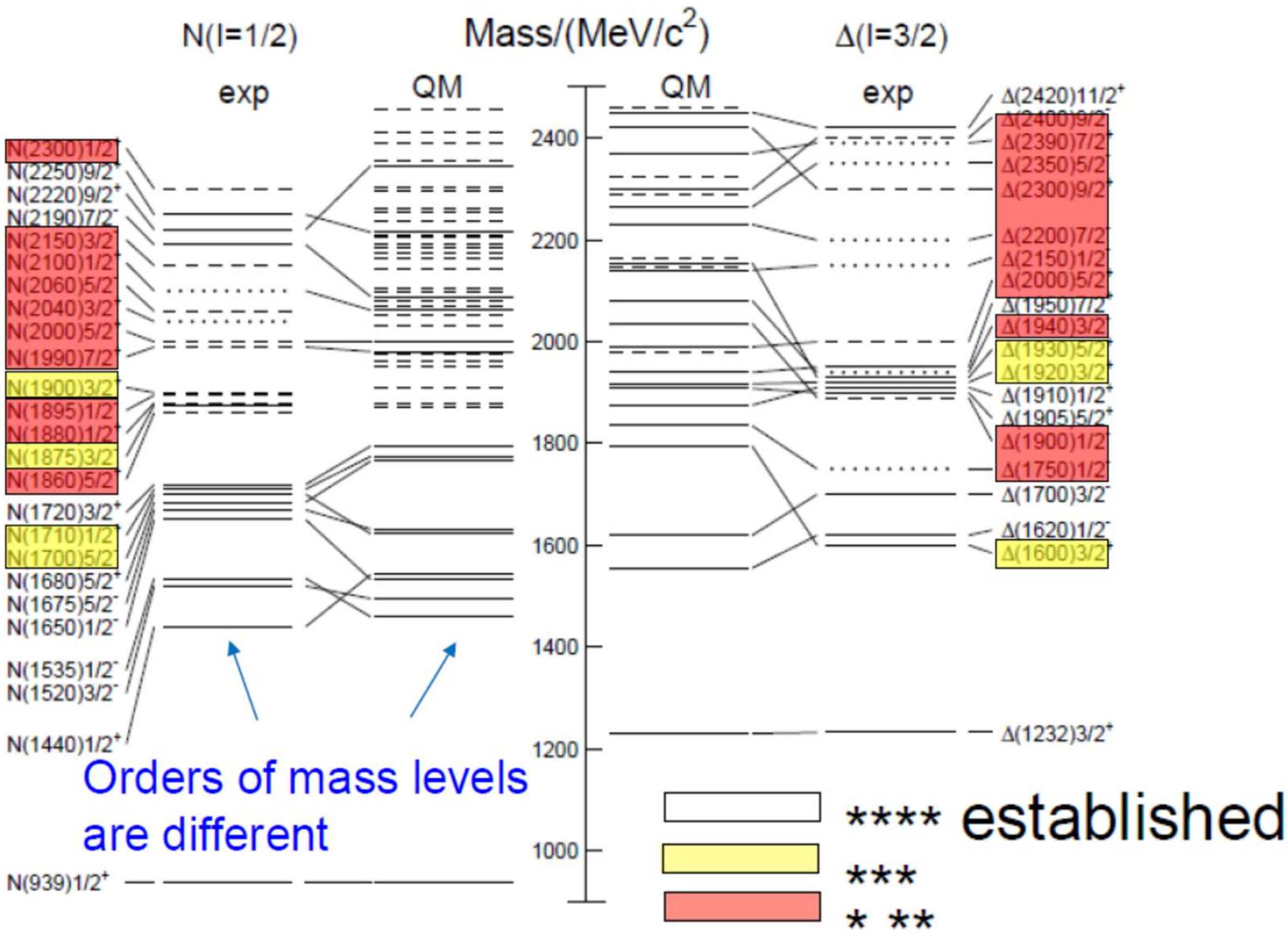
J-PARC E45 experiment

~Baryon spectroscopy by using p(π, 2π) reaction~

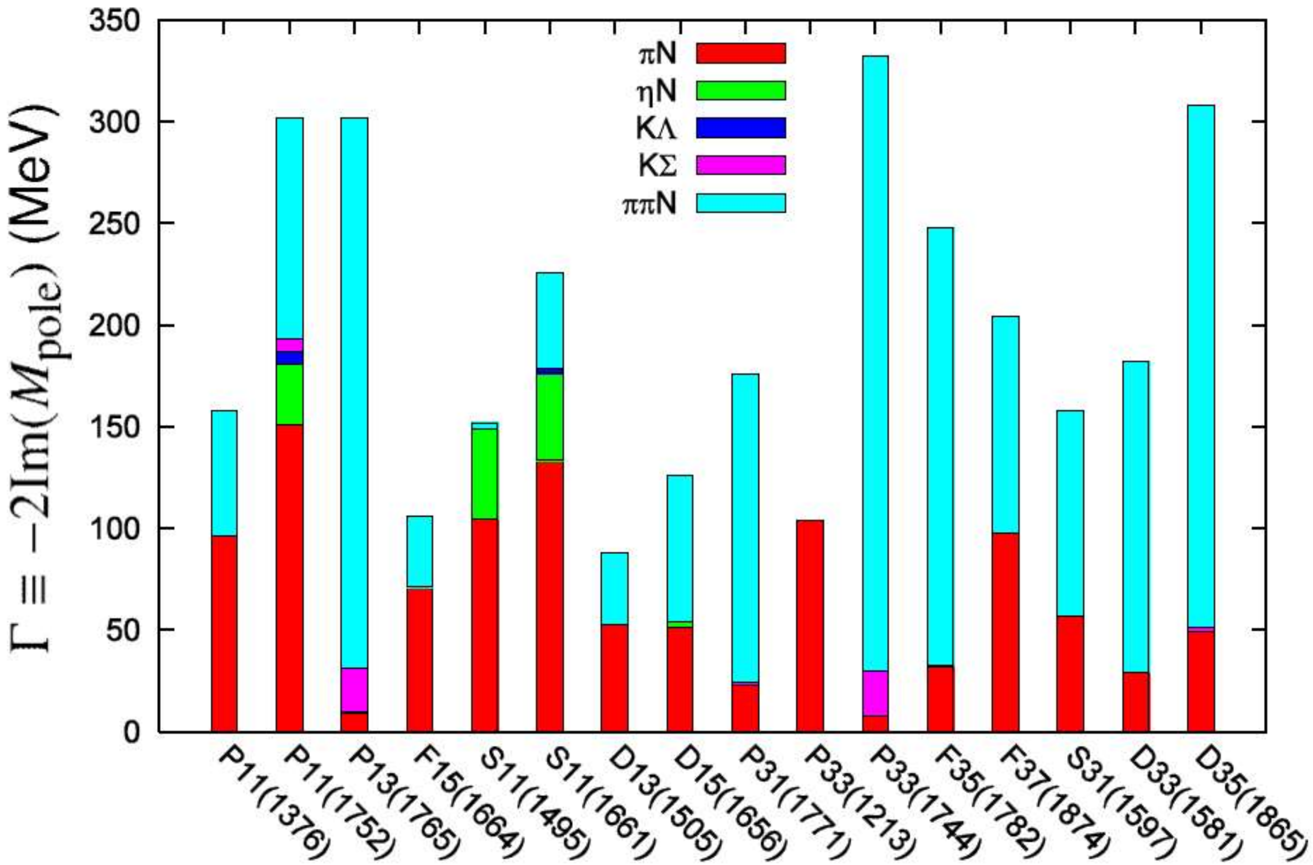
Missing resonances

- A lot of states are predicted by QM, but not observed
- Measured by using mainly πN → πN, γN → πN reactions



Importance of ππN (Width of N^* resonances)

Over half of the decay branchig fraction goes into 2π channel.



Kamano, Nakamura, Lee, Sato, 2012

E45 setup

Measure $(\pi,2\pi)$ in large acceptance TPC in dipole magnetic field

$\pi^- p \rightarrow \pi^+ \pi^- n,\ \pi^0 \pi^- p$ 2 charged particles + 1 neutral particle

$\pi^+ p \rightarrow \pi^0 \pi^+ p,\ \pi^+ \pi^+ n$ →missing mass technique

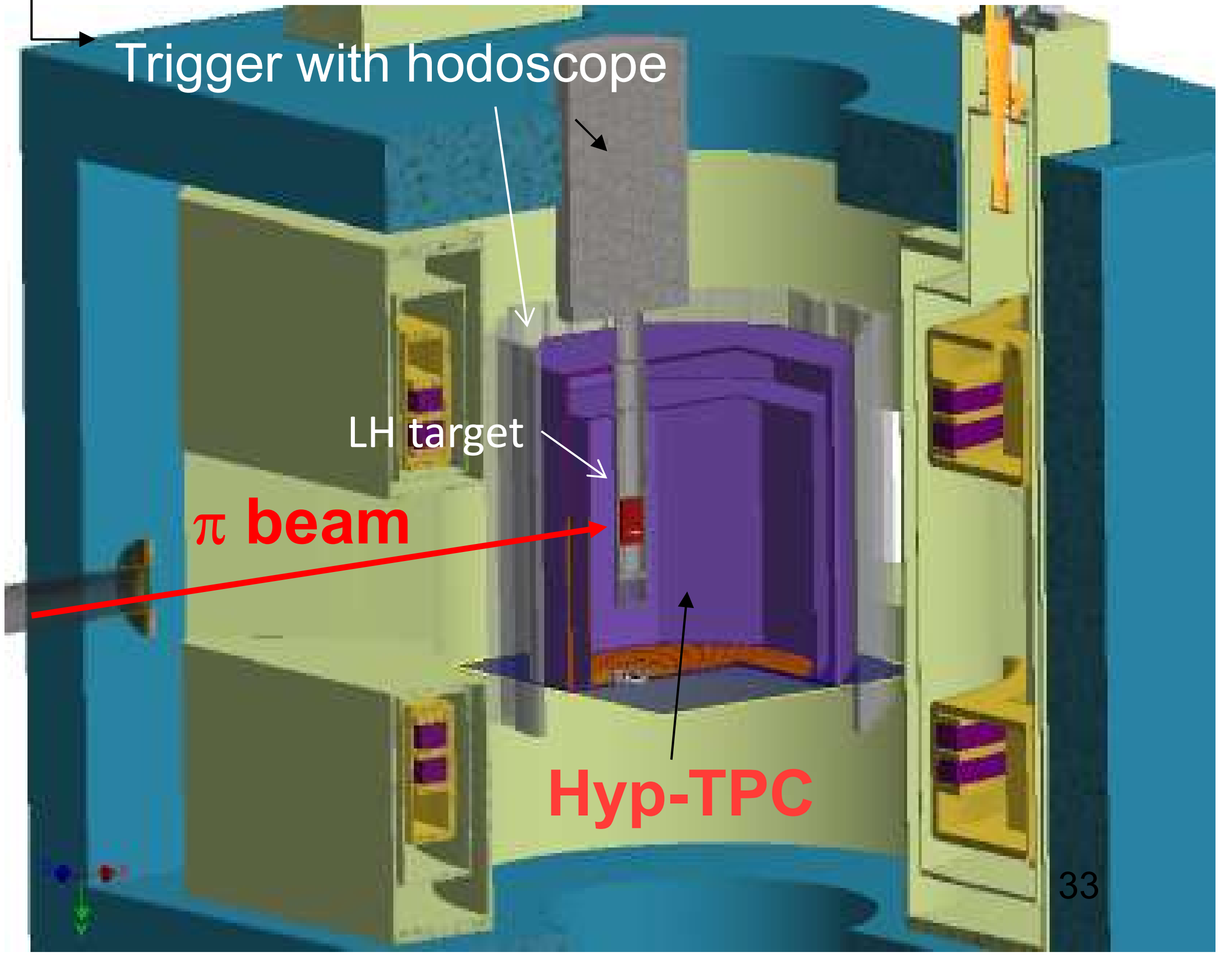
$\pi N \rightarrow KY$ (2-body reaction)

$\pi^- p \rightarrow K^0 \Lambda$,

$\pi^+ p \rightarrow K^+ \Sigma^+$ ($I=3/2$, Δ^*)

π^{+-} beam on liquid-H target
(p= 0.73 – 2.0 GeV/c
W=1.5-2.15 GeV)

x100 more statistics than ever



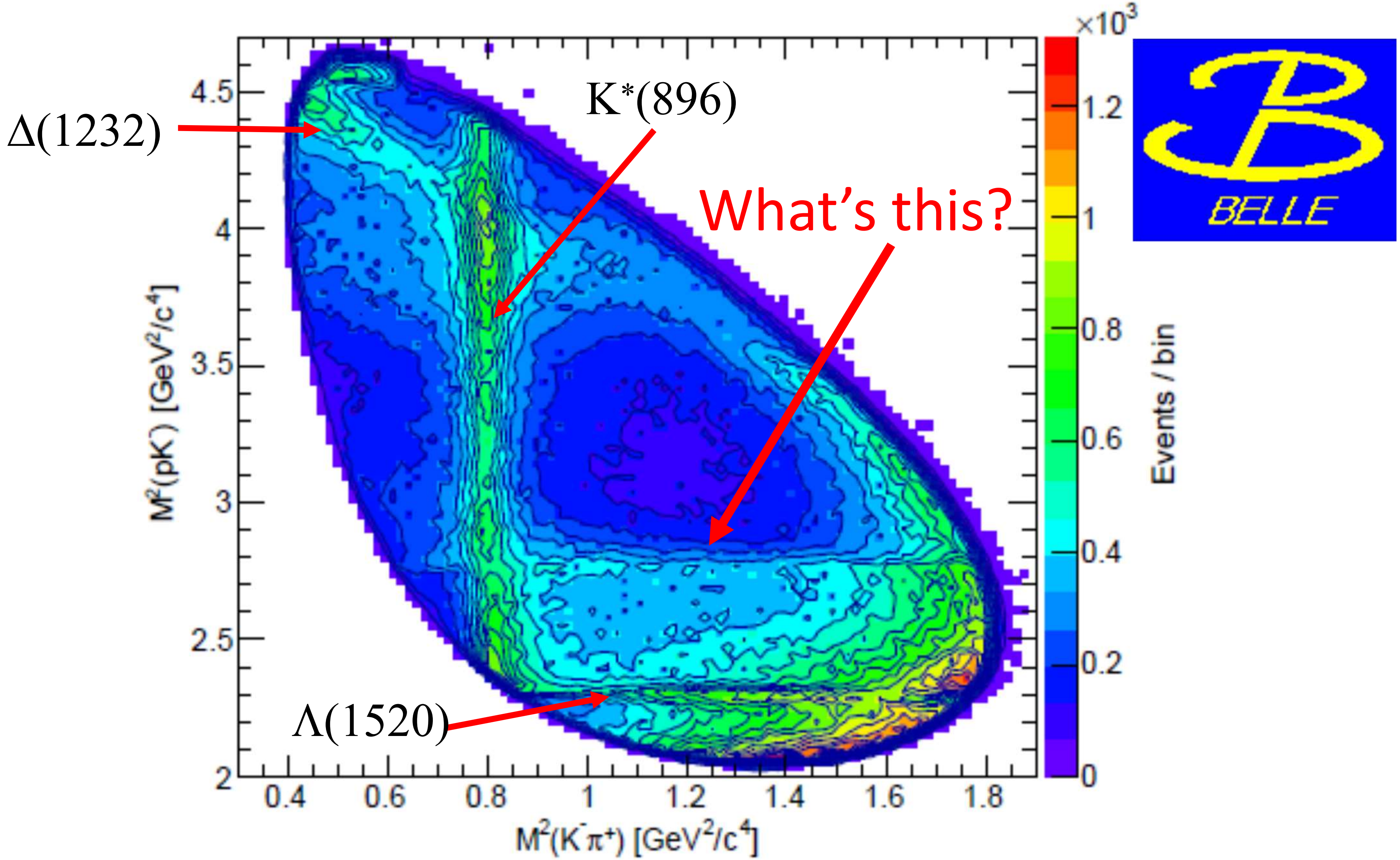
PWA on $(\pi,2\pi)$ reaction

- Model independent PWA – impossible
  - Spin observables are not measured
  - Double partial-wave expansion is necessary
- Need theory help for model dependent analysis
  - Model used for $(\gamma,2\pi)$ analysis@JLAB may be interesting
  - Global analysis with one-pion and two-pion reactions

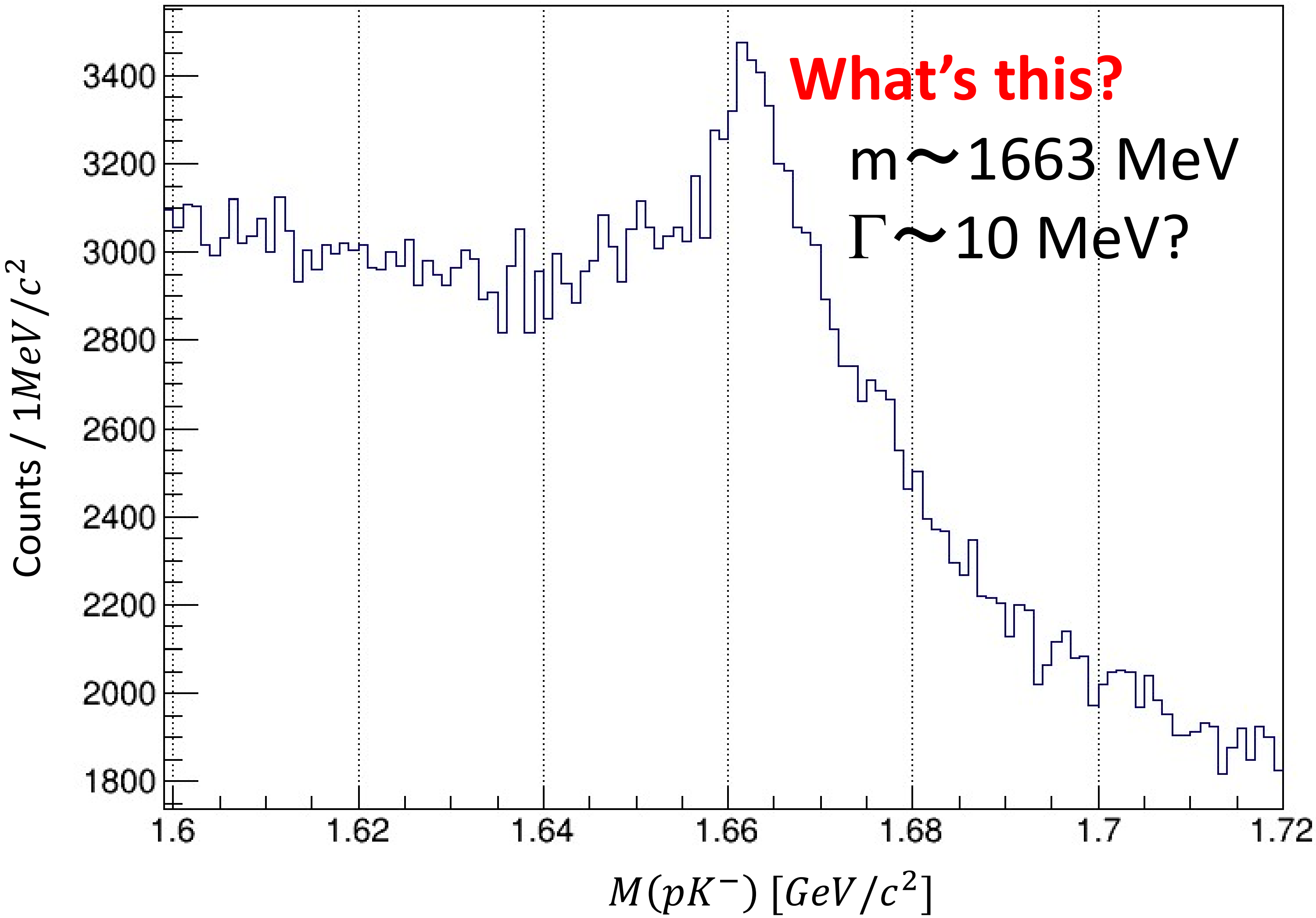
J-PARC E72 experiment

~Search for new Λ by using $K^{-}p \rightarrow \Lambda\eta$ reaction~*

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



■ 1D projection -- $M(pK^-)$



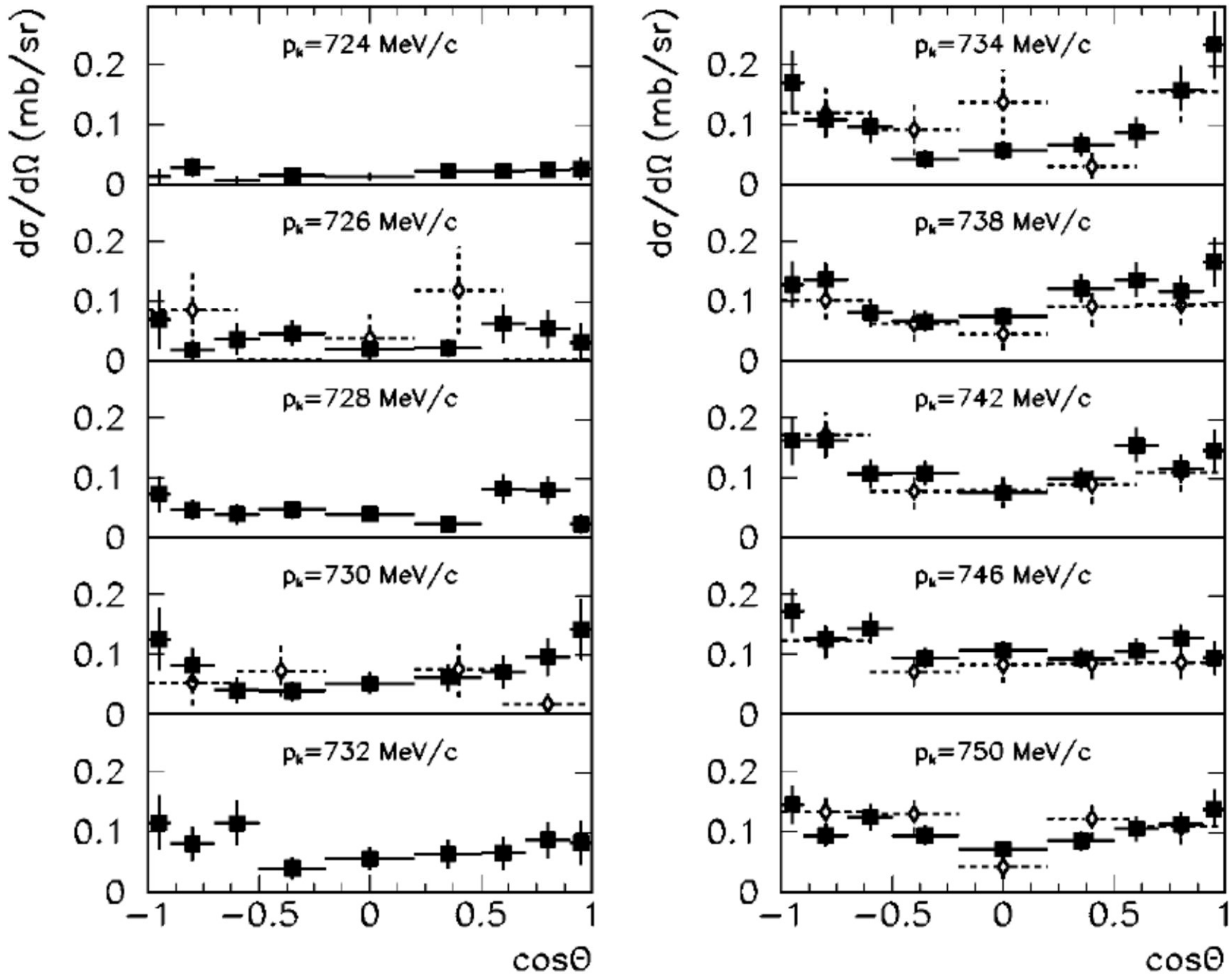
What's this?

- 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
  - Λ(1670): 25-50 MeV
  - Σ(1660): 40-200 MeV
  - Σ(1670): 40-80 MeV
  - Λ(1690): ~60 MeV
- No such narrow states are theoretically predicted in this region – exotic?

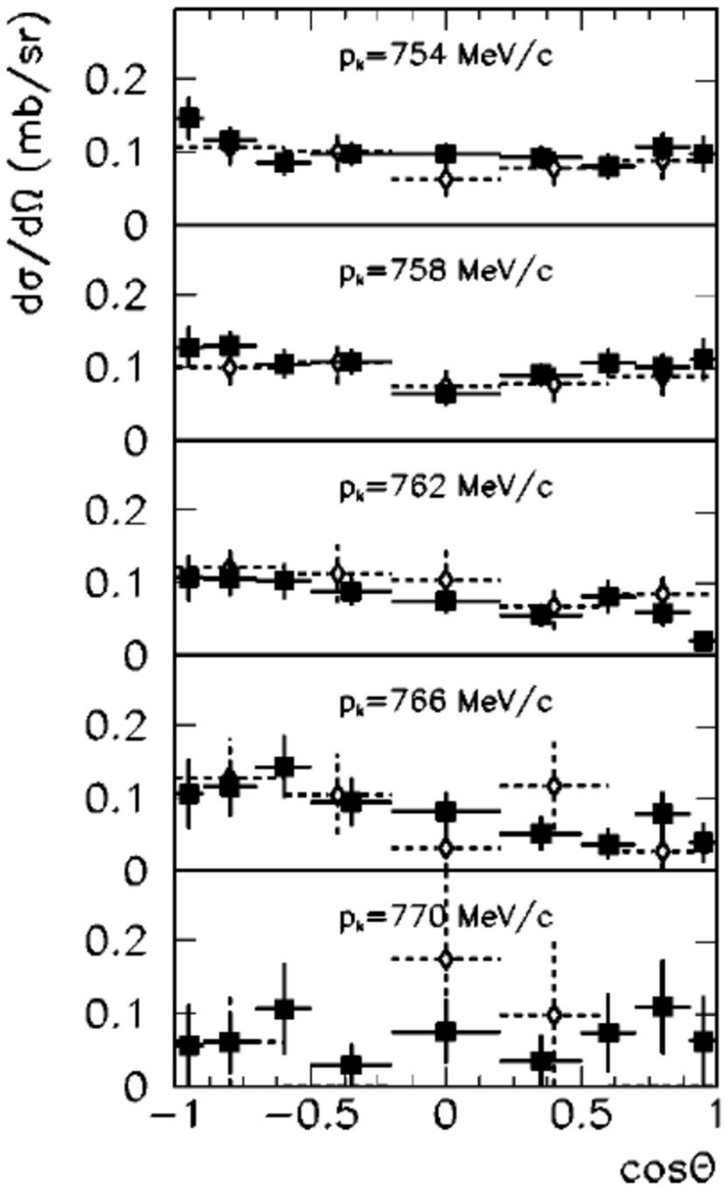
An idea

- 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±0.5 MeV, Γ=1.5±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]
  - Model independent

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

What can it be?

- The experimental data suggest the existence of a new Λ^* resonance with spin 3/2 (P_{03} or D_{03}), $\Lambda(1665)$:

  Q: What is the nature of $\Lambda(1665)$, if it really exists?

  A: We have few ideas at the moment, aside from that it must be exotic, and thus very interesting.

- It is near the $\Lambda\eta$ threshold, but threshold cusp is unlikely.
  - Visible cusp appears only in S wave
- A molecular state in P or D? Then, where is the S state?
  - Cf. X(3872) & $\Lambda(1405)$ are in S wave.

→ **It may be a new type of exotic state!**
  - Mixture of a molecular state and a 3-quark state???
  - $udss\bar{s}$ pentaquark???

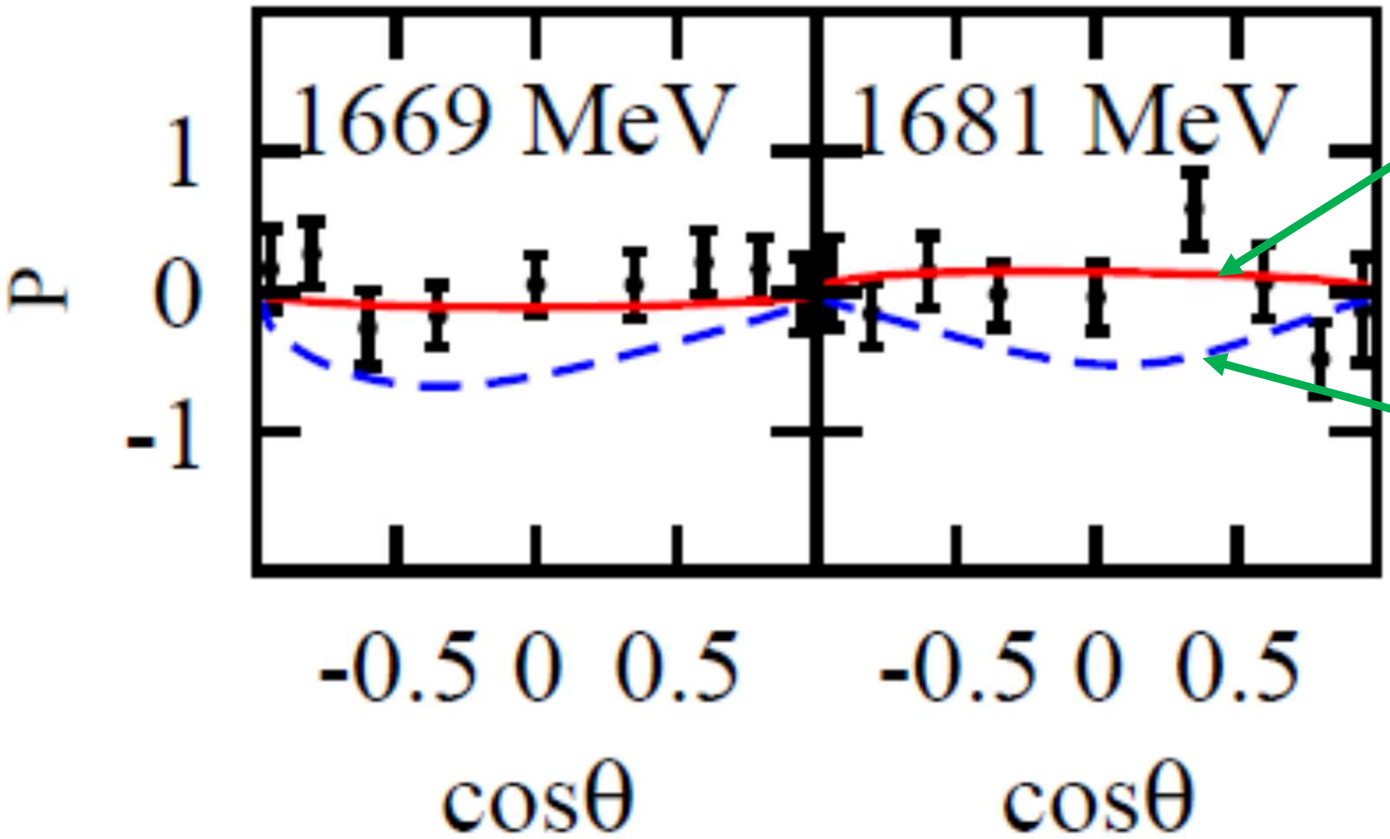
J-PARC E72

- Repeat the Kp → $\Lambda\eta$ experiment again with a large acceptance detector, i.e., TPC (HypTPC)
  - Confirm angular distribution & the new resonance
  - Determine parity by Λ polarization measurement
- Principle
  - K beam momentum: 720-770 MeV/c
  - Momentum resolution: 1 MeV/c or better
    → Can identify narrow resonance of Γ=1.5 MeV or cusp
  - Detect Λ → $p\pi^-$, identify η by missing mass
- Also take other reactions as well – PWA.
  - K^-p → K^-p, K^0n, $\pi^\pm\Sigma^\mp$, $\Lambda\pi\pi$, …

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



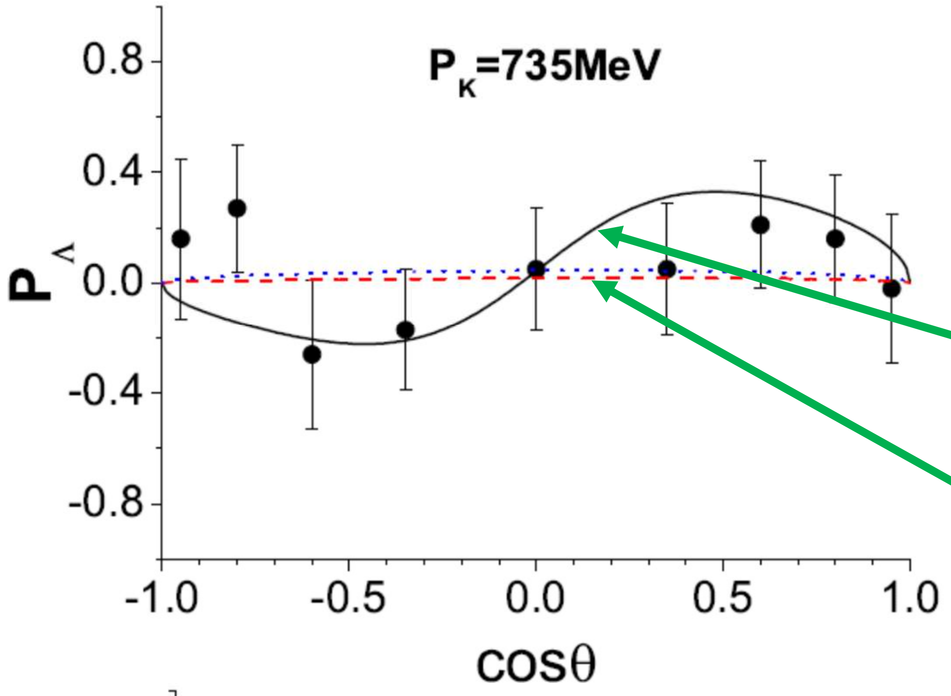
No new resonance

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

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

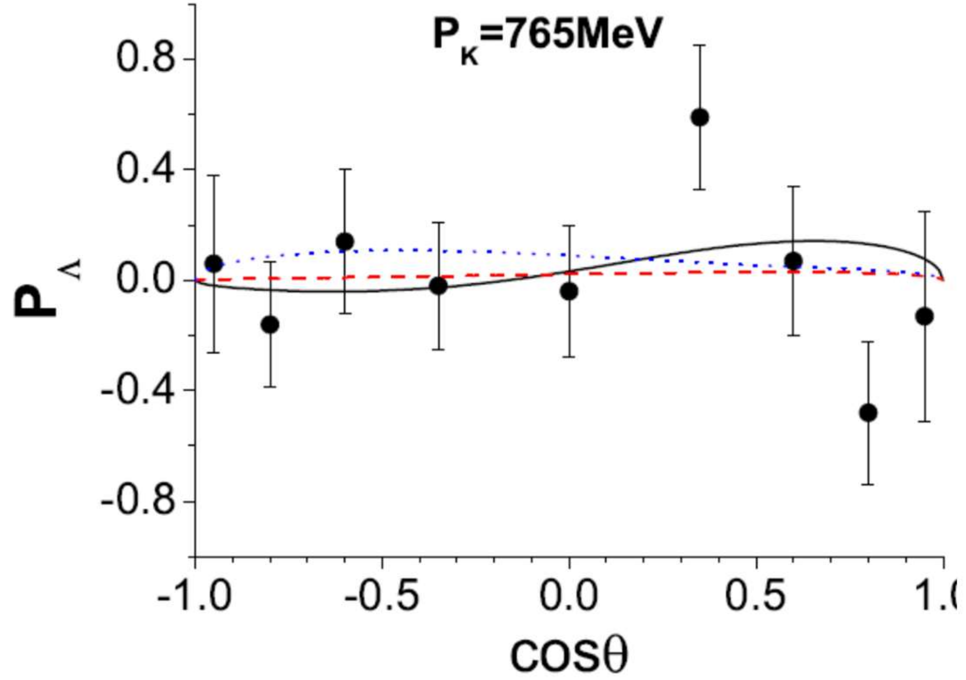
- Crystal ball data is average of 722-750 MeV/c & 750-770 MeV/c, not for each momentum.
⇔ Meanwhile, calculations are done on the points.

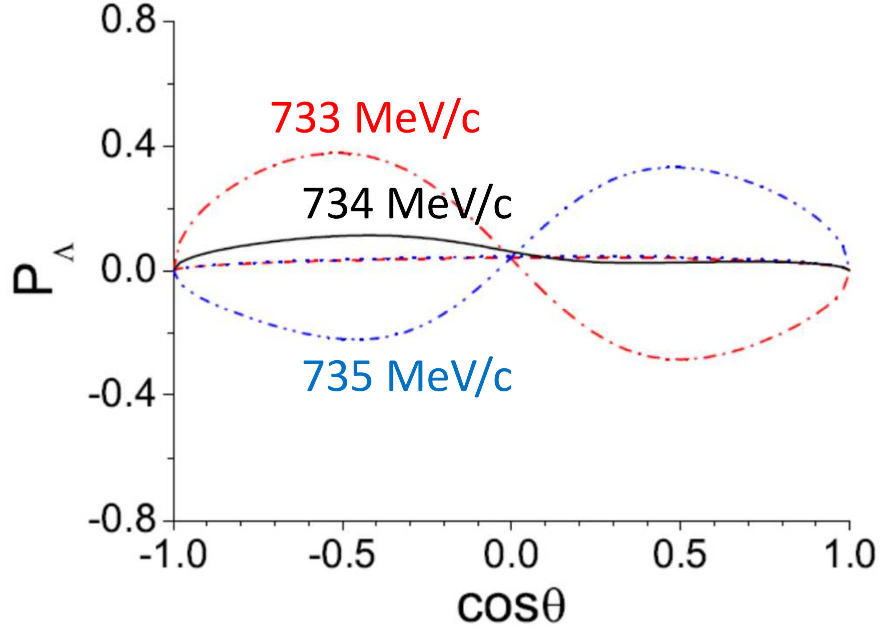
Calculation by Liu & Xie [PRC86.055202]



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

No new resonance





Identify parity

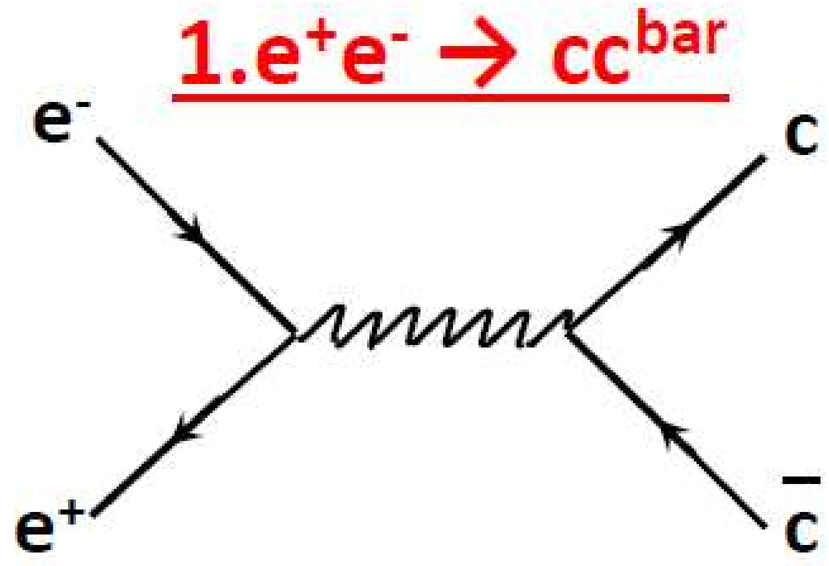
- Angular distribution is the same for $3/2^+$ (P wave) and $3/2^-$ (D wave)
  - Again, we need polarization of the final Λ
- Crystal-Ball data is very poor for polarization
  - Support for new resonance is not obtained
- How we can distinguish P&D?
  - P wave – no node, D wave – node
- We need δp~0.05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

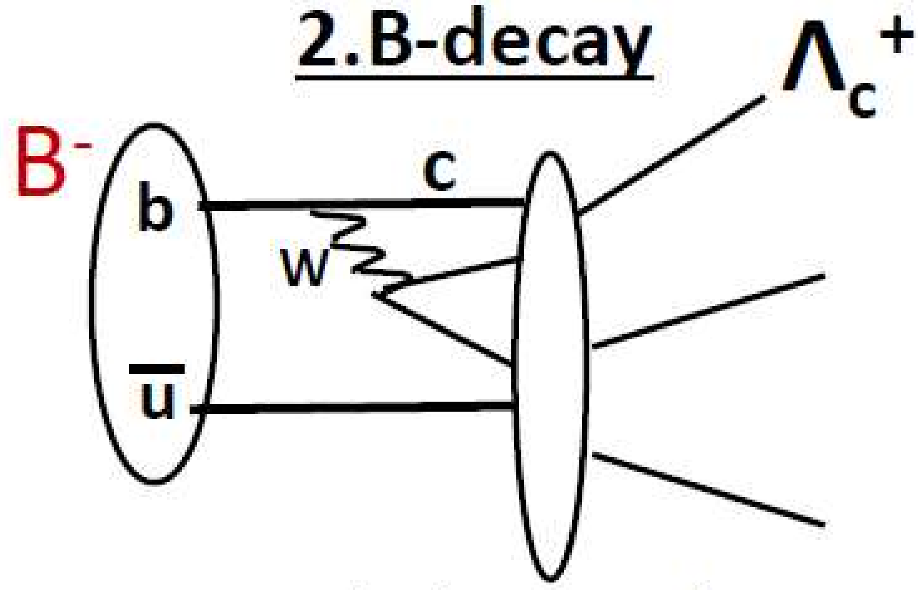
Summary

- Baryon spectroscopy with PWA
  - Spin-parity determination
- Belle
  - Λ_c(2765) isospin is determined to be 0
    PWA result for spin-parity coming soon
  - Many others found: J^P? Resonance or cusp?
    → Need amplitude analysis
- J-PARC
  - E45: N^*/Δ^* spectroscopy with p(π,2π) reaction
  - E72: New Λ^* search by p(K^-,Λ)η reaction

Backup

Baryon production in B factory





Baryons produced via fragmentation

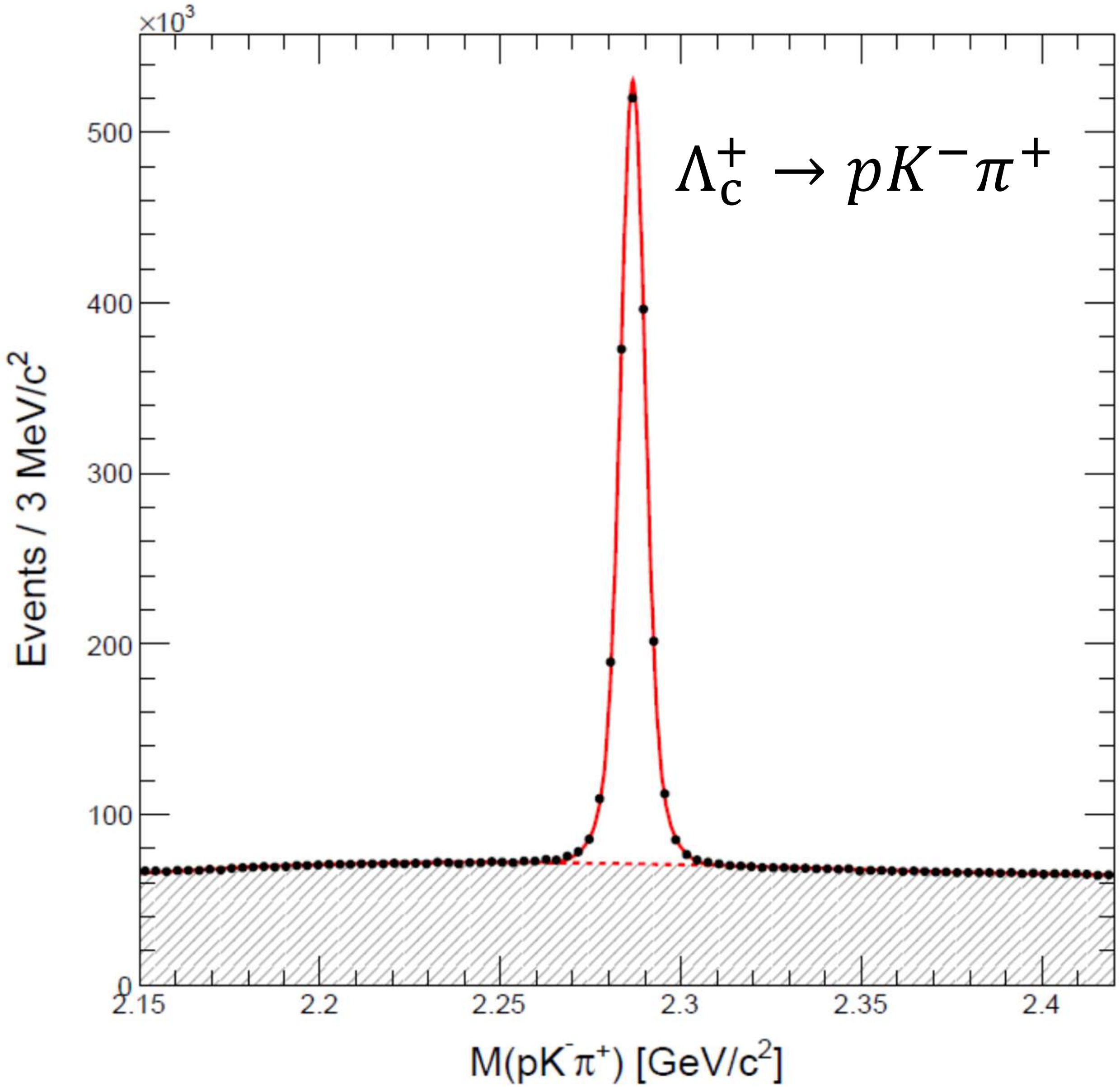
- Charmed baryons – rather direct
- Hyperons – later stage of fragmentation

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

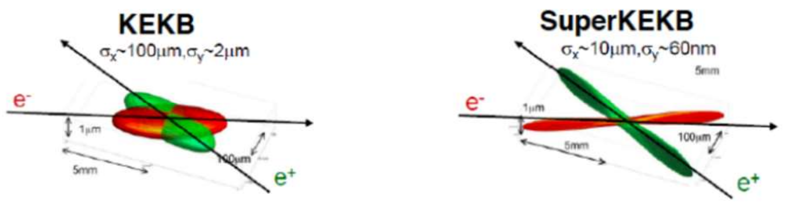
S/N ~ 10

SuperKEKB and Belle II

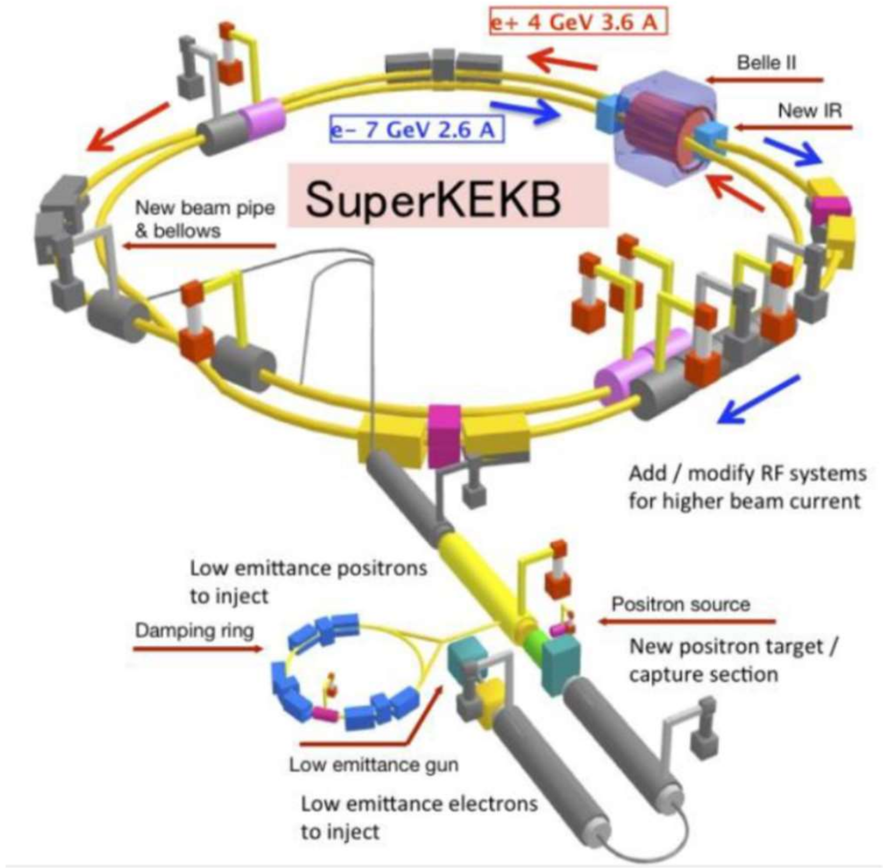
Upgrade for SuperKEKB and Belle II to achieve 40x peak $\mathcal{L}$ under 20x bkgd

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

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

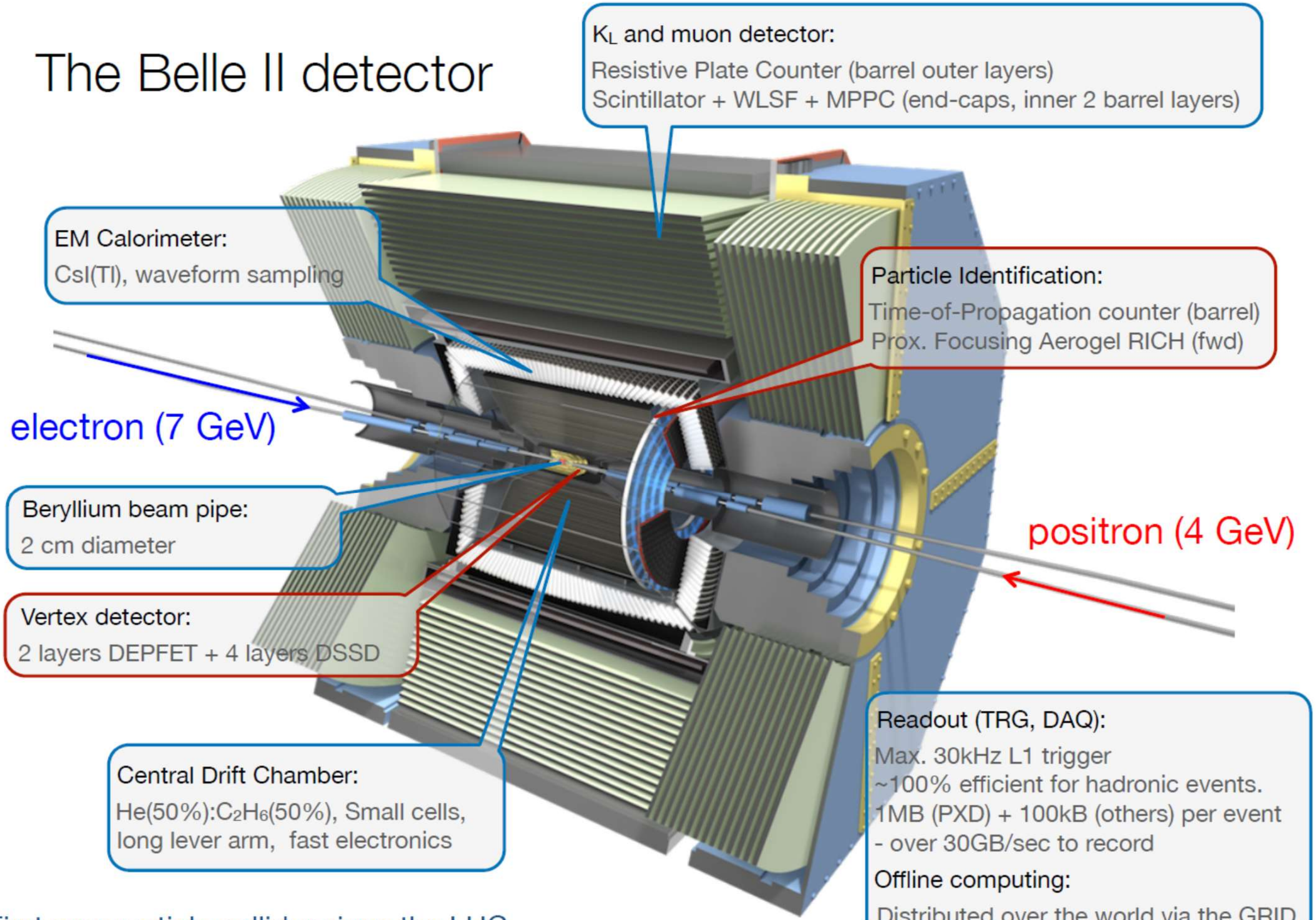


- ▶ *First turns achieved Feb. 2016*
- ▶ *Beam-background studies ongoing*



Goal: x50 more statistics than Belle

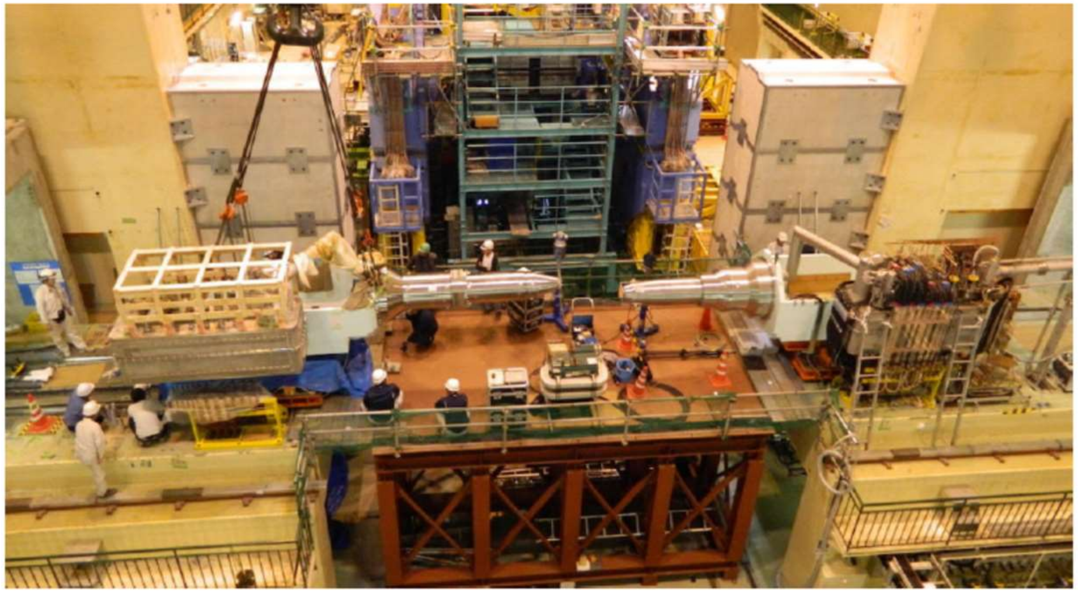
The Belle II detector

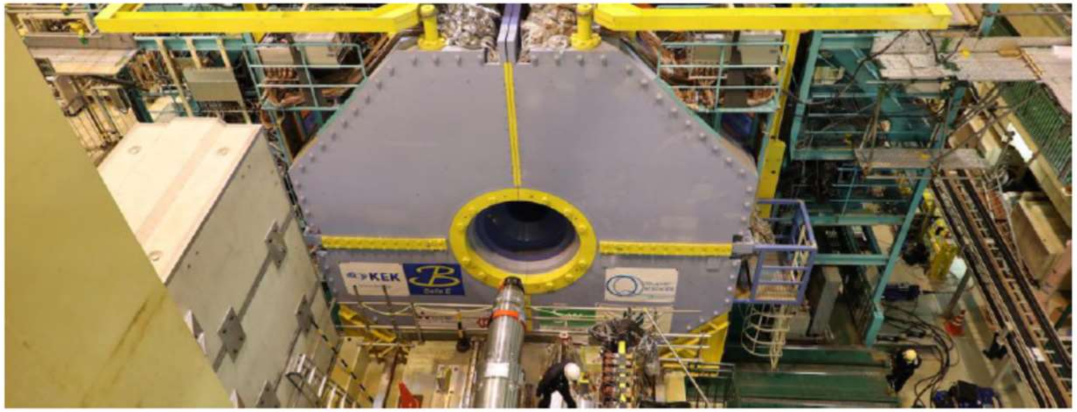


First new particle collider since the LHC
(intensity rather than energy frontier; e^+e^- rather than pp)

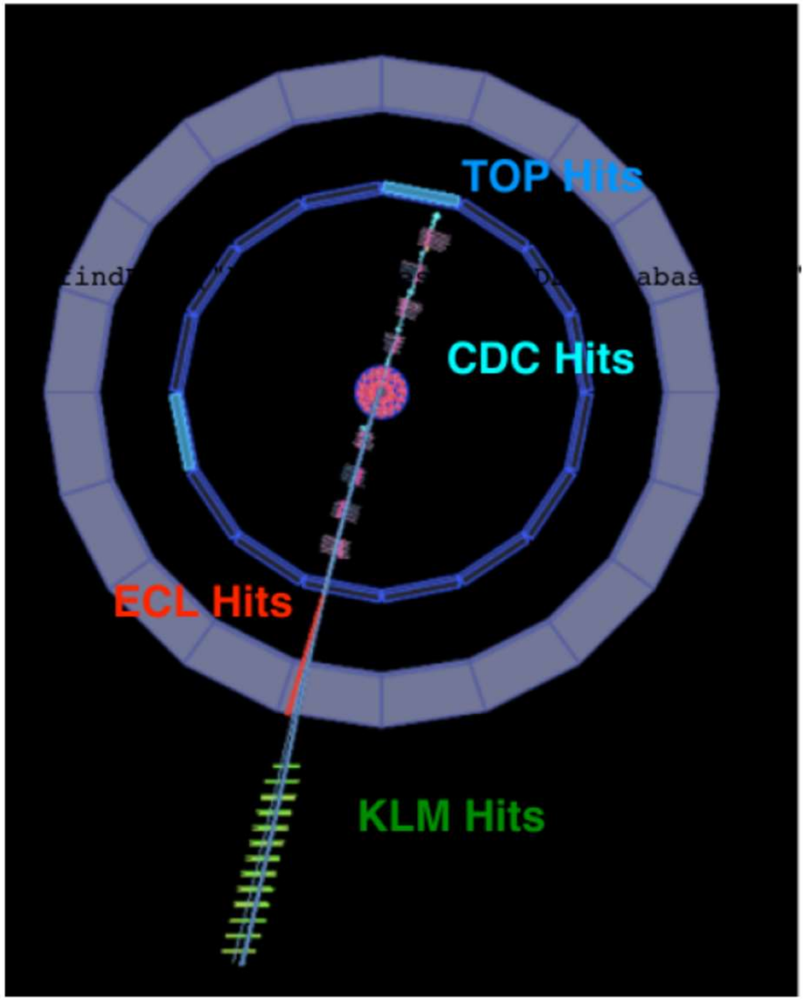
arXiv:1011.0352 [physics.ins-det]

Belle II today



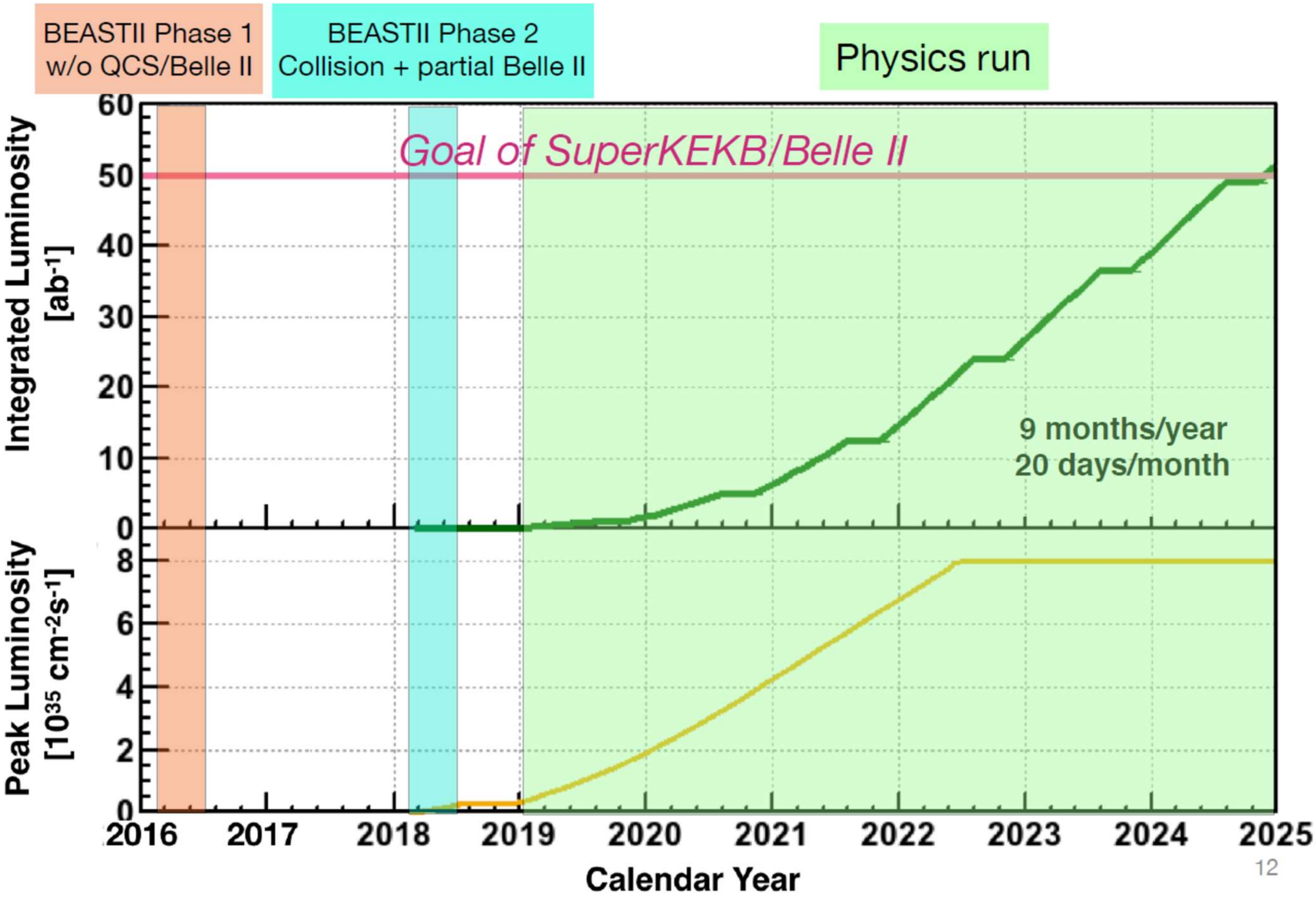


Belle II roll-in (April 11)



Global cosmic run (August)

Luminosity projection

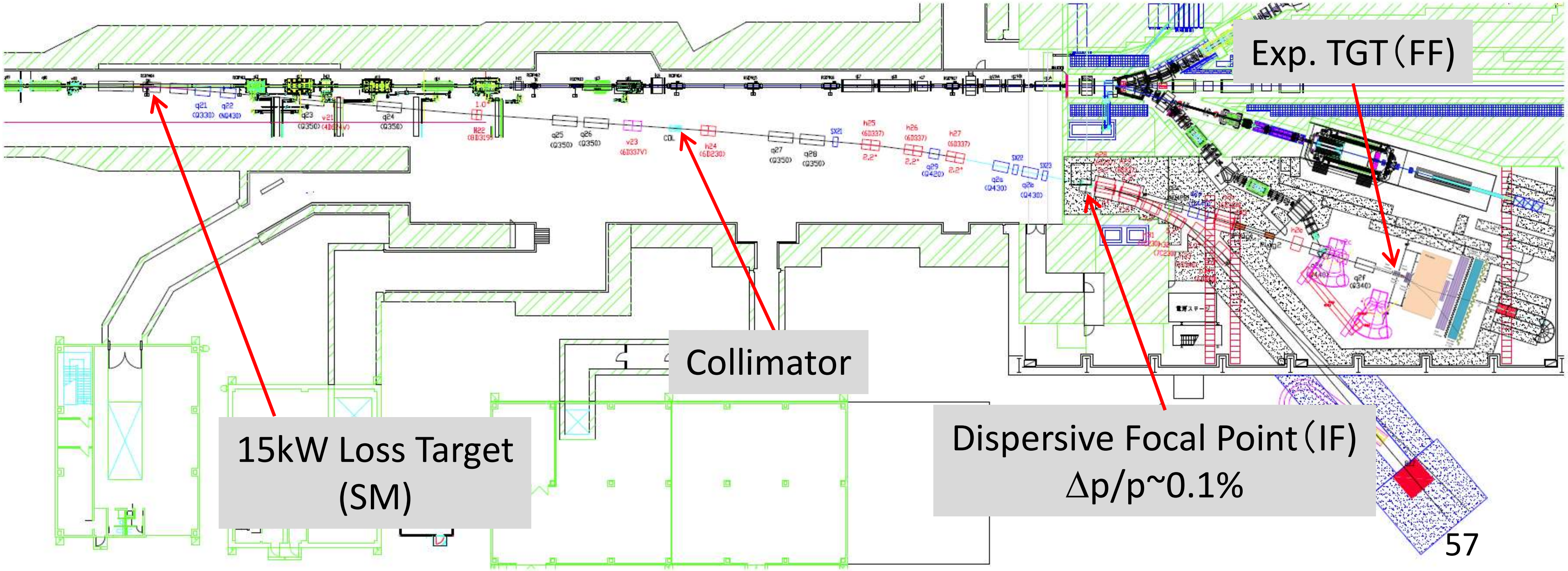


J-PARC E50: Missing mass spectroscopy by $p(\pi^-,D^{*-})$

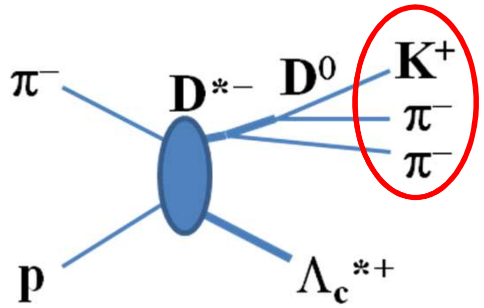
- Analogous to p(π,K)Y reaction
- Direct reaction
  - possibility to produce resonances not made in fragmentation
  - Production cross section gives valuable information
  - No bias on decays
    → Absolute branching ratio can be measured
- Cross Section: $\sigma \sim 1$ nb
  - Intense Beam at J-PARC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

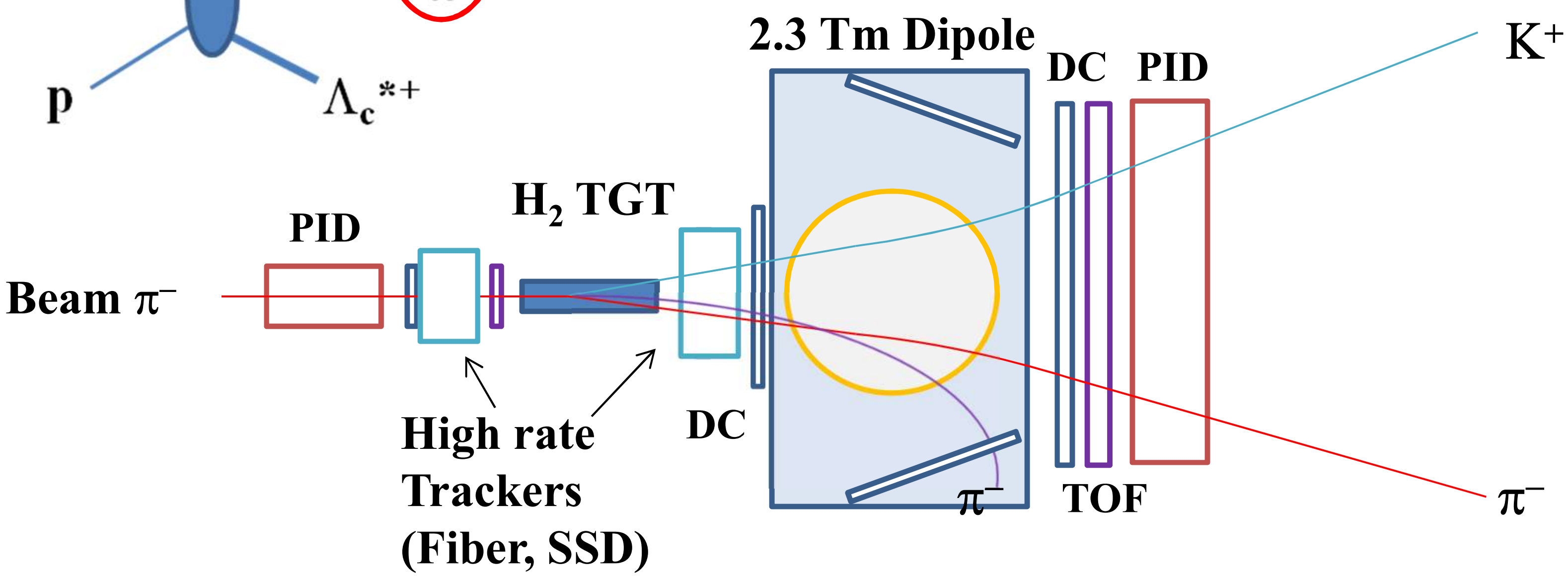
High momentum beam line

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

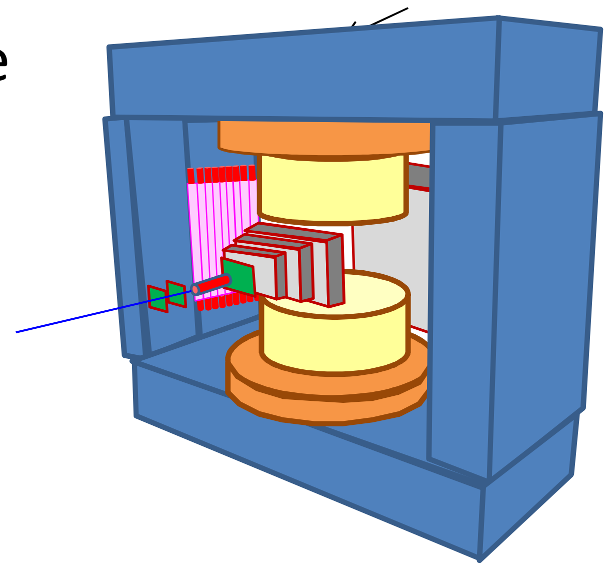


Concept

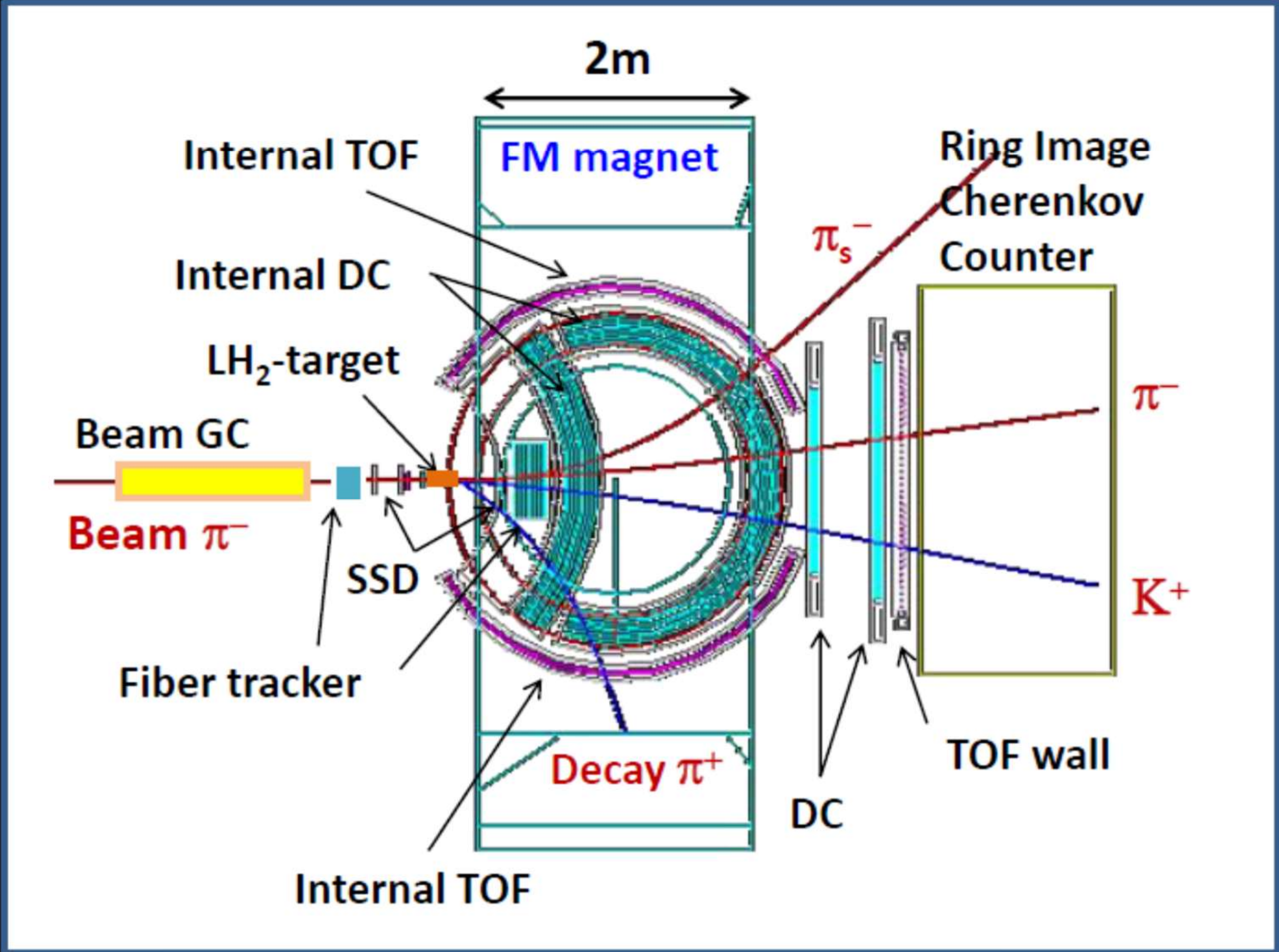




- Large Acceptance, Multi-Particle
  - *K*, π from D^0 decays
  - Soft π from D^{*-} decays
  - (Decay products from Y_c^*)
- High Resolution
- High Rate
  - SFT/SSD: >10M/spill at K1.8



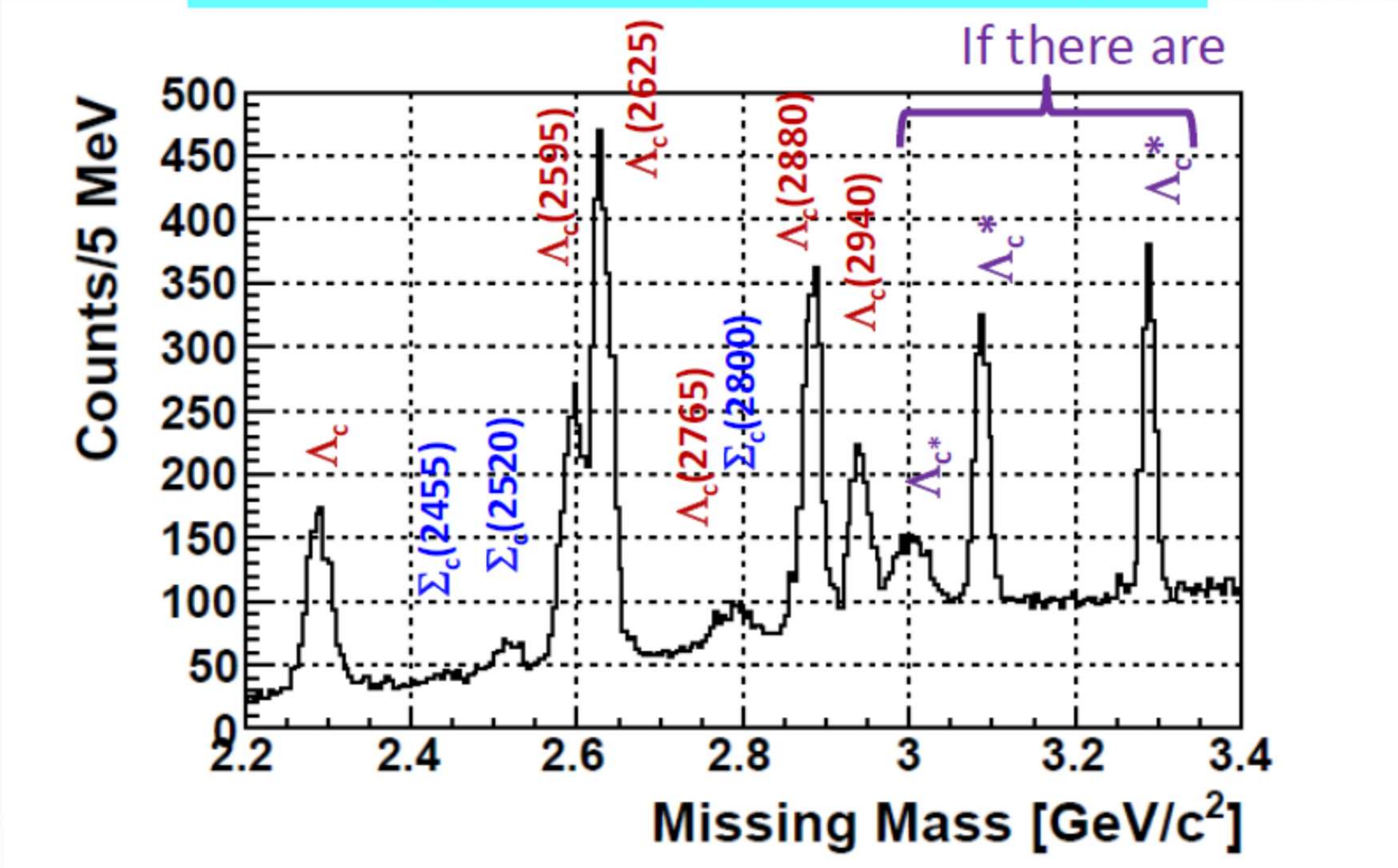
Charmed Baryon Spectrometer



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)



Measurement@Belle (II)

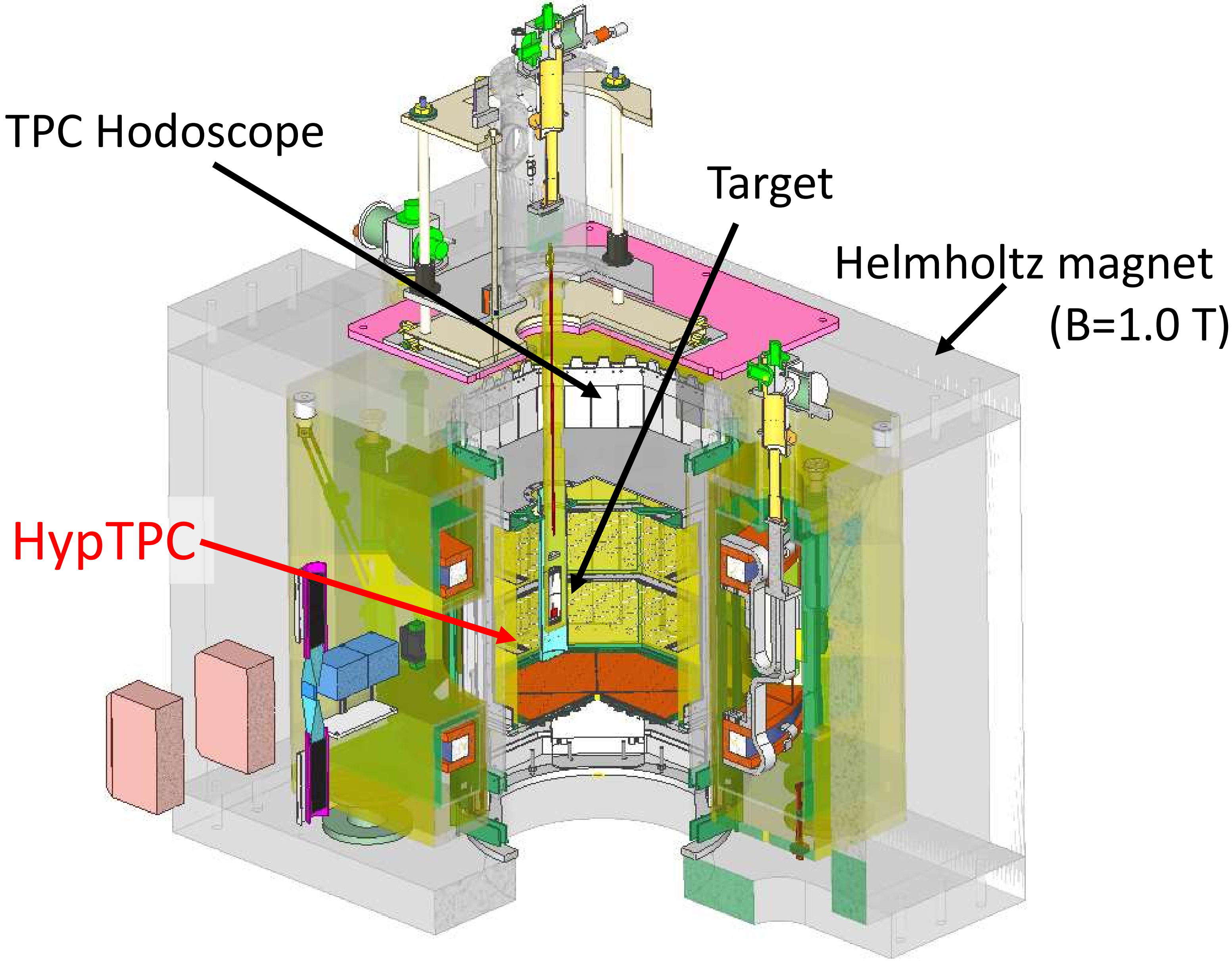
- The peak in the M(pK$^-$) spectrum in Λ_c → pK$^-\pi^+$ decay is due to the new Λ^* resonance?
- If yes, key measurements are
  - J=3/2 – angular distribution (correlation) between π^+ and K$^-$
    1+3cos$^2\theta$ for pure J=3/2 amplitude
    flat for pure J=1/2 amplitude
  - I=0, strongly couples 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

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

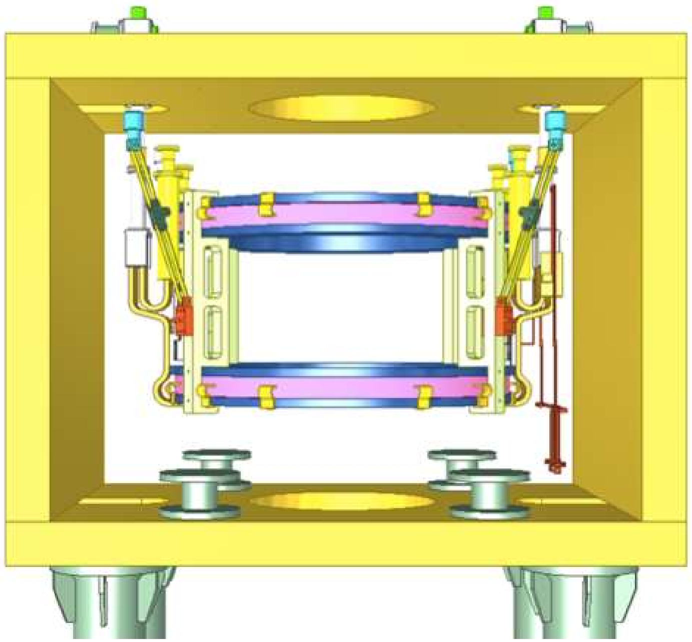
HypTPC
The common detector
for E45 & E72

Schematic view

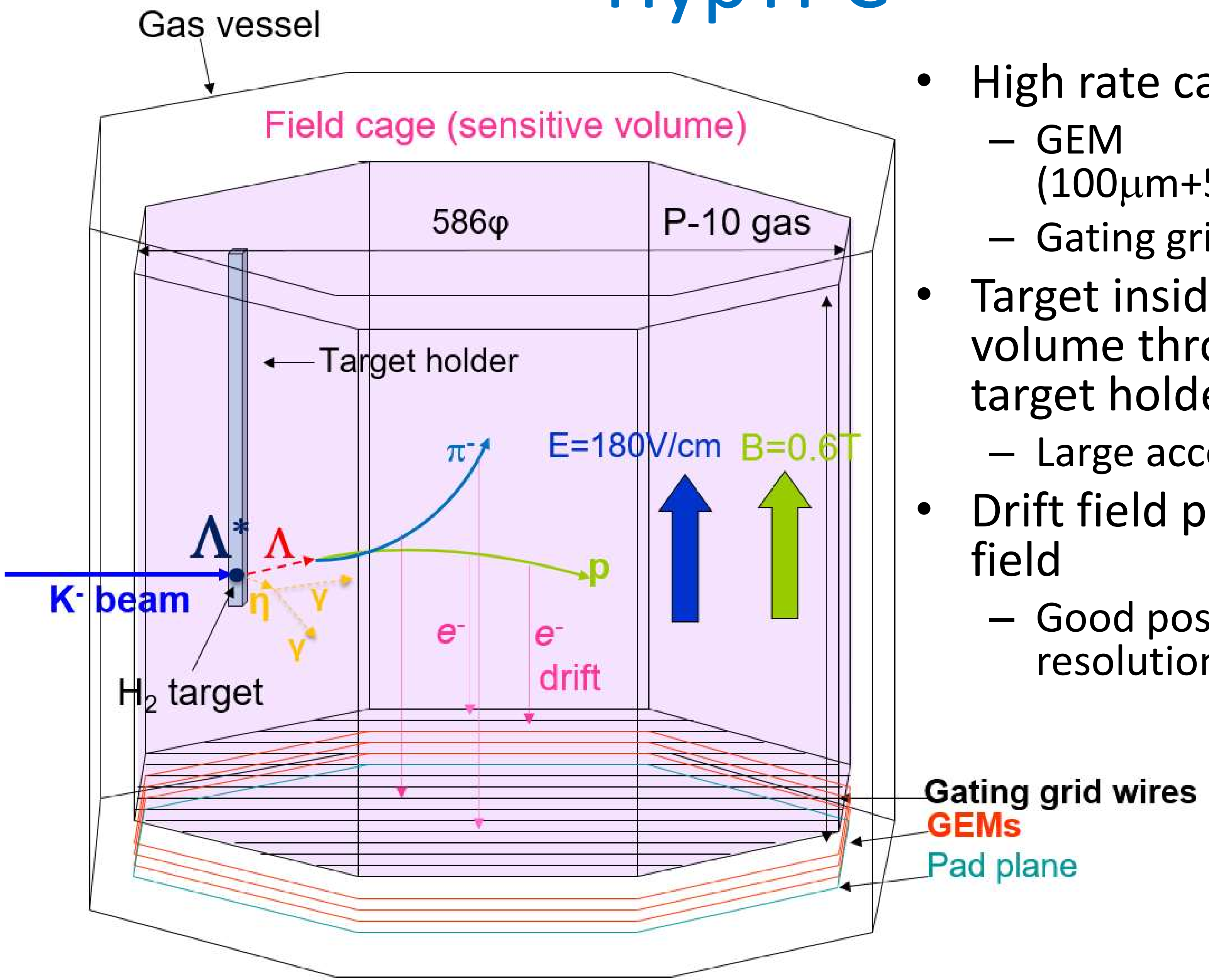


The Superconducting magnet

- Helmholz type, design maximum field : 1.5 T
- Conduction cooling with 2 GM cryocoolers
- Coil diameter : 1.0m
- Field uniformity : Br/By<1% in the TPC volume to achieve the good momentum resolution



HypTPC



- High rate capability
  - GEM (100μm+50μm+50μm)
  - Gating grid
- Target inside the drift volume through the target holder
  - Large acceptance
- Drift field parallel to B-field
  - Good position resolution

More info on HypTPC

- ○Octagonal prism field cage
- ○5768 readout pads
  - Inner(10 rows): 2.1-2.7 × 9 mm^2
  - Outer(22 rows): 2.3-2.4 × 12.5 mm^2
- ○ Gating grid: ϕ50 μm, 1mm space
- ○ Gas: P-10 (v_{max} ~ 5.3 cm /s)
- ○ Gain ~ 10^4
- ○ Position resolution < 300 μm
- ○ Δp/p = 1-3% for π and p