Colored and Colorless Correlations in Hadrons

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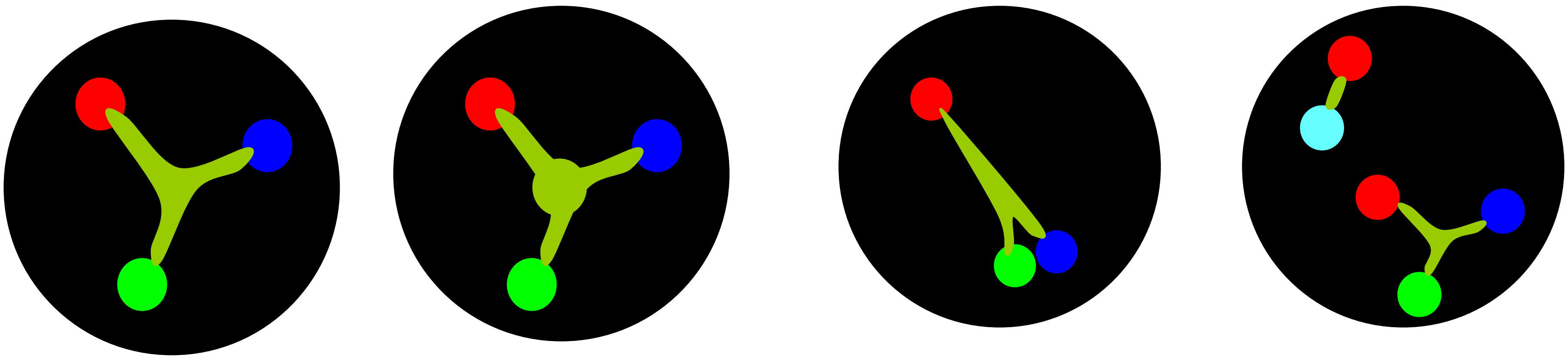
What are effective degrees of freedom ?



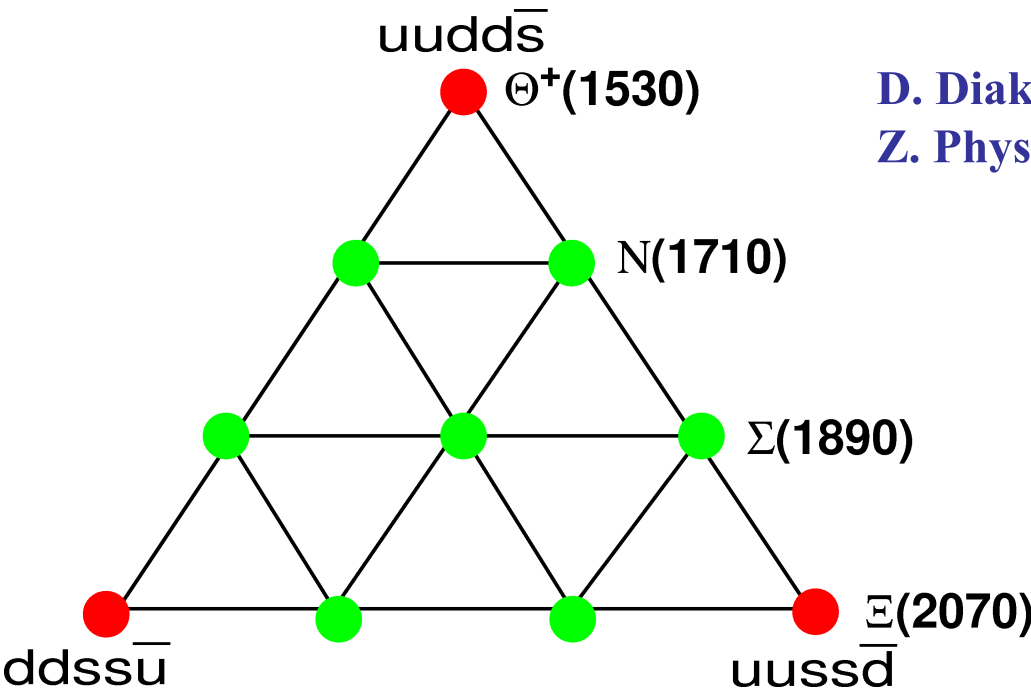
3q hybrid diquark meson-cloud

$$|B = 1 > = a_0|3q > + a_1|(qq)(qq)\bar{q} > + a_2|MB > + \cdots$$

- **How can we learn about the structure of the hadrons from their production and decay?**

Pentaquark

The antiquark has a different flavor than the other 4 quarks.



D. Diakonov, V. Petrov, and M. Polyakov, Z. Phys. A 359 (1997) 305.

- **Exotic: S=+1**
- **Low mass: 1530 MeV**
- **Narrow width: ~ 15 MeV**
- **$J^p=1/2^+$**

M = [1890-180*Y] MeV

Baryon masses in constituent quark model

$m_u \sim m_d$ = 300 ~ 350 MeV, $m_s = m_{u(d)}$+130~180 MeV

- Mainly 3 quark baryons:

  M ~ 3Mq + (strangeness)+(symmetry)

- π, K, and η are light:

  Nambu-Goldstone bosons of spontaneously broken chiral symmetry.

- 5-quark baryons, naively:

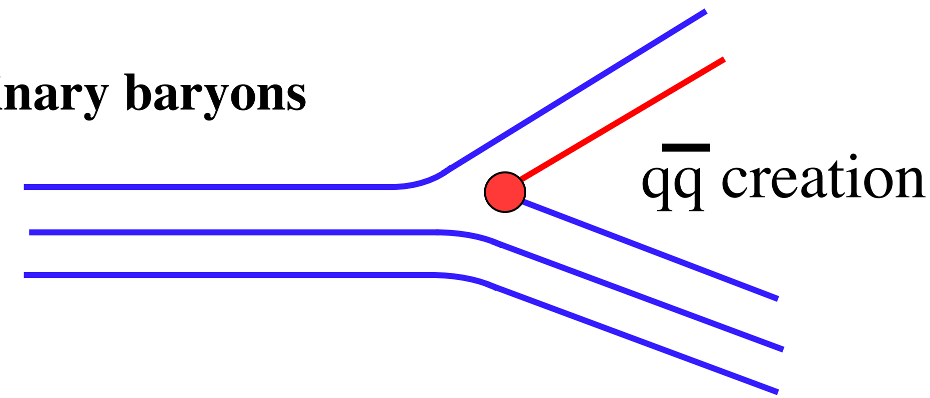
  M ~ 5Mq + (strangeness) +(symmetry)

  1700~1900 MeV for Θ^+

Fall-apart decay problem

- **DPP predicted the Θ^+ with M=1530MeV, Γ<15MeV, and $J^p=1/2^+$.**
- **Naïve QM (and many Lattice calc.) gives M=1700~1900MeV with $J^p=1/2^-$.**
- **But the negative parity state must have very wide width (~1 GeV) due to "fall apart" decay.**

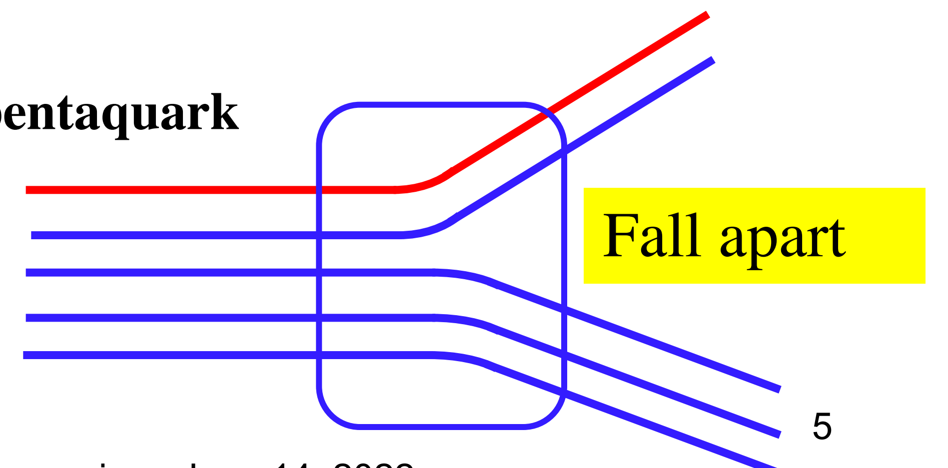
Ordinary baryons



Positive Parity?

- **Positive parity requires P-state excitation.**
- **Expect state to get heavier.**
- **Need counter mechanism.**

For pentaquark

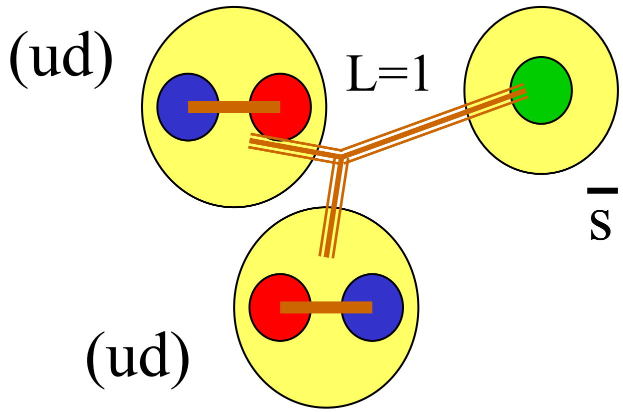


A di-quark model for pentaquarks

$$[ud][ud]\bar{s}$$

JW hep-ph/0307341

JM hep-ph/0308286

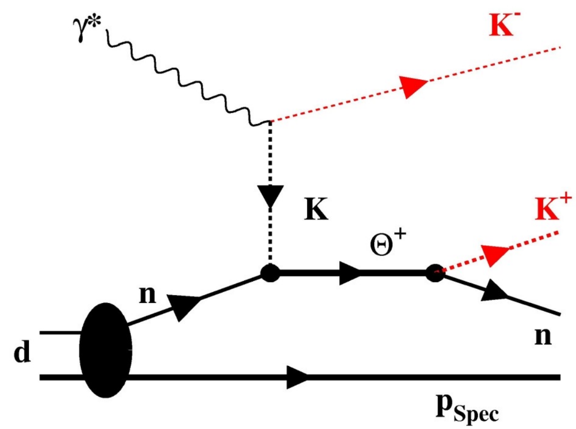


L=1, one unit of orbital angular momentum needed to get $J^P=1/2^+$

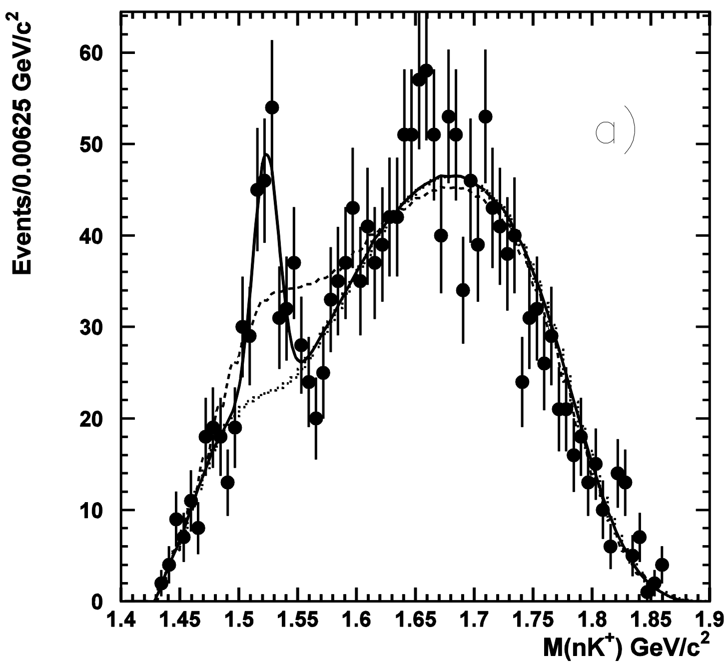
Uncorrelated quarks: $J^P = 1/2^-$

Decay Width: $\langle [ud][ud]\bar{s} \,|\, [uud][u\bar{s}] \rangle = \frac{1}{2\sqrt{6}} \quad \Gamma \approx \frac{200\ MeV}{\left(2\sqrt{6}\right)^2} \approx 8\ MeV$

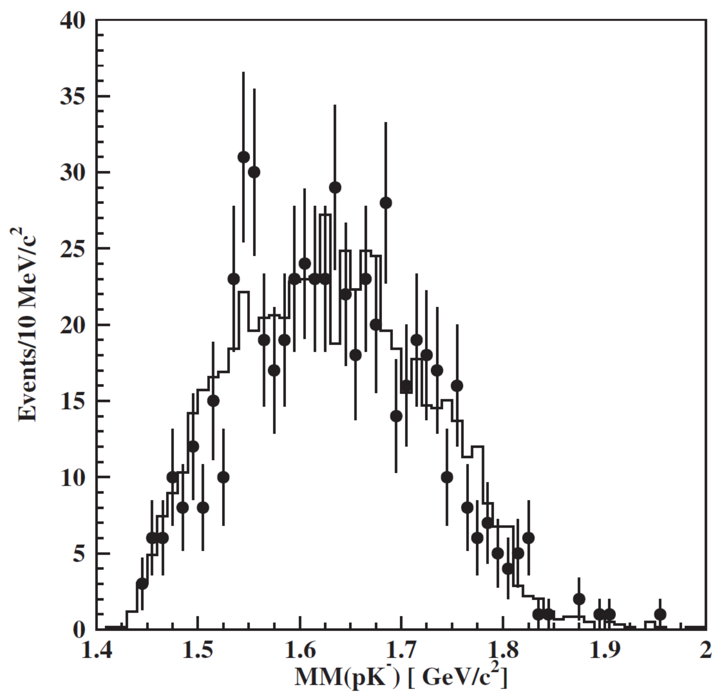
Pentaquark Θ^+ search in photo-production



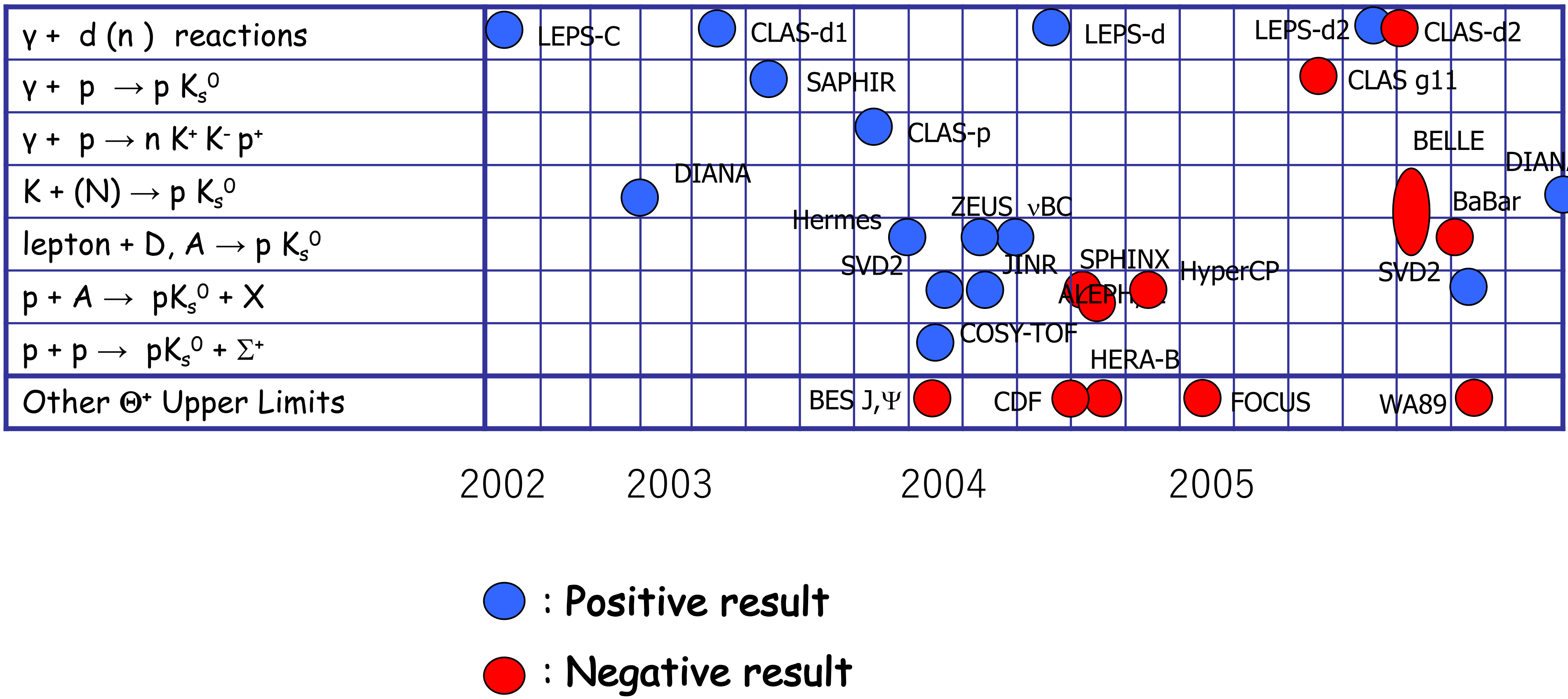
LEPS
positive



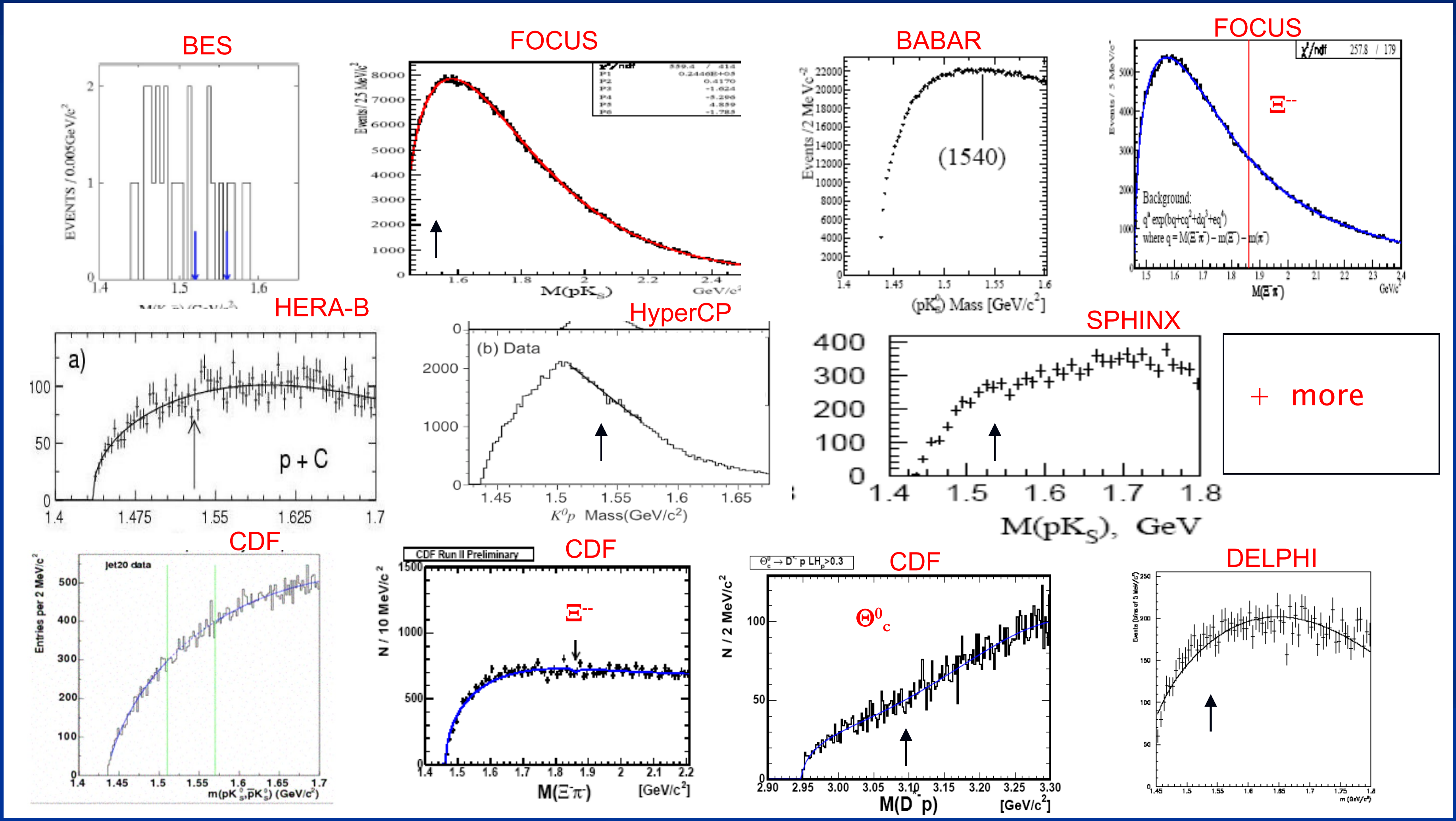
CLAS
negative



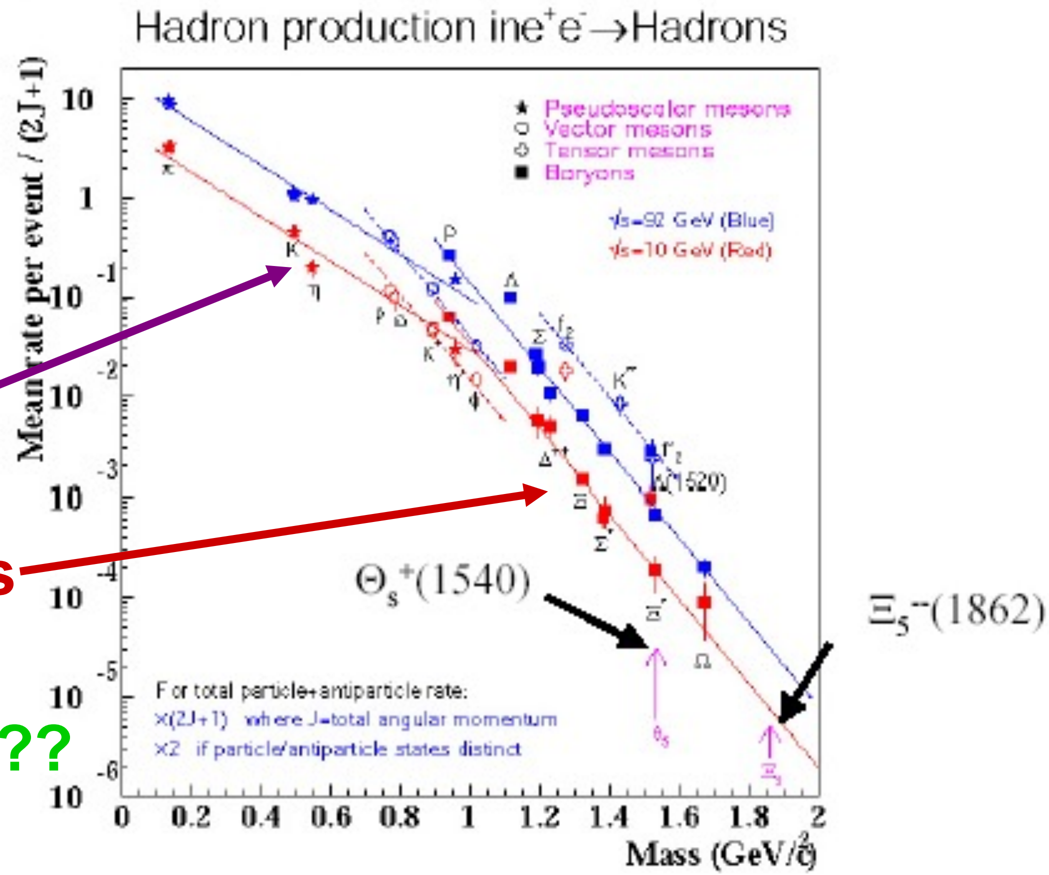
Time dependent experimental status of Θ^+



Null results for Pentaquarks in High energy experiments



Hadron Rate in e⁺e⁻ → Hadron



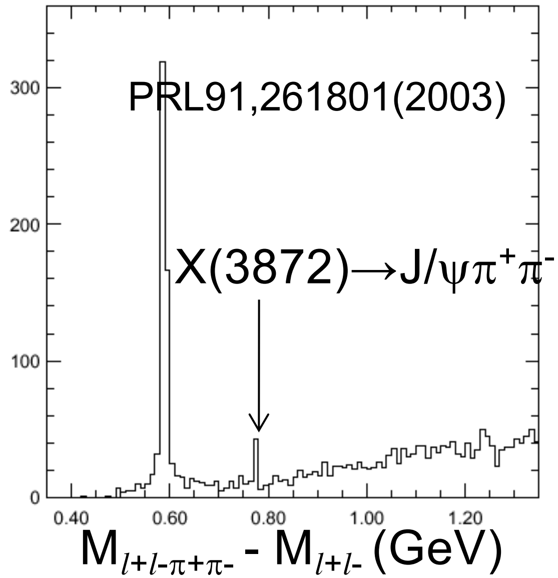
Slope for mesons

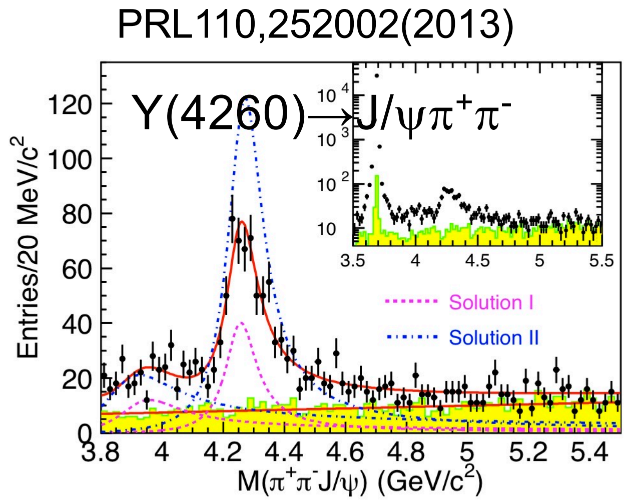
Slope for baryons

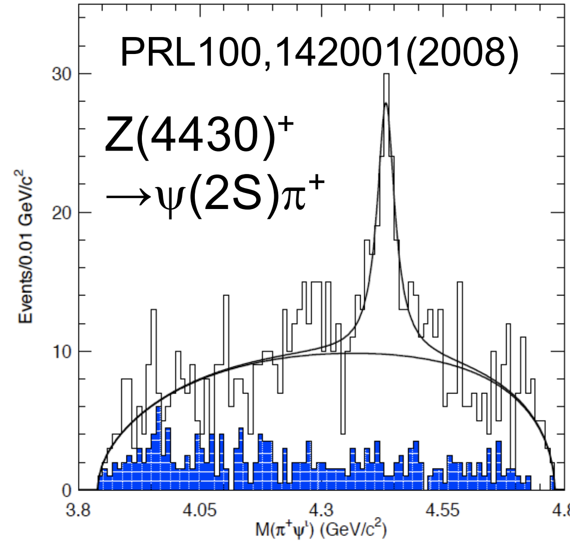
Slope for pentaquarks??

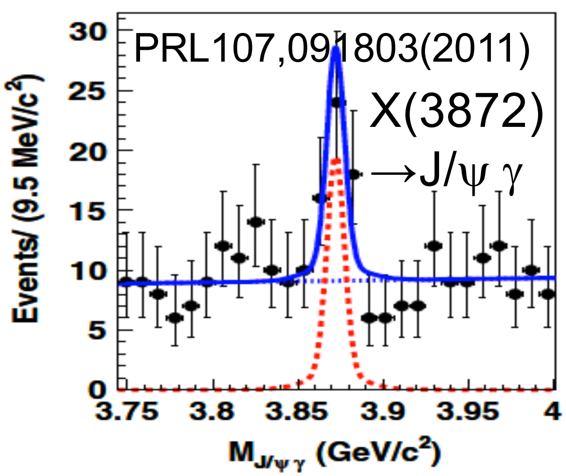
Assuming the Pentaquark production is the same as baryon production we expect the total production of Θ_s^+, Ξ_5^{--} per event continuum to be $\Theta_s^+ = 7 \times 10^{-4}$, $\Xi_5^{--} = 3. \times 10^{-5}$

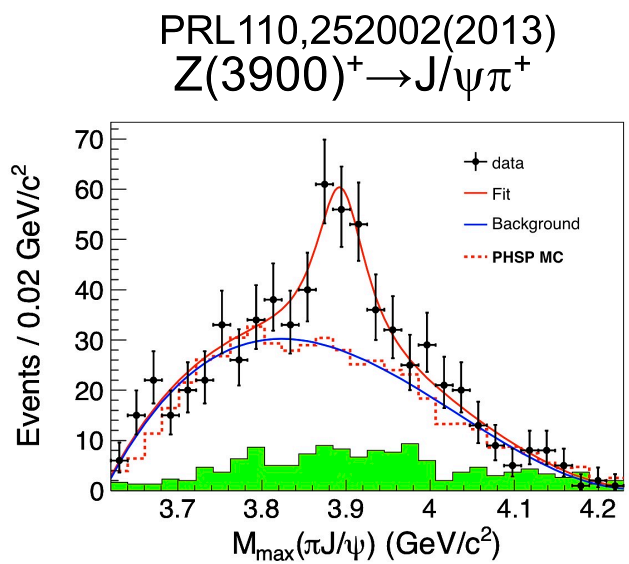
“XYZ” sensations at Belle

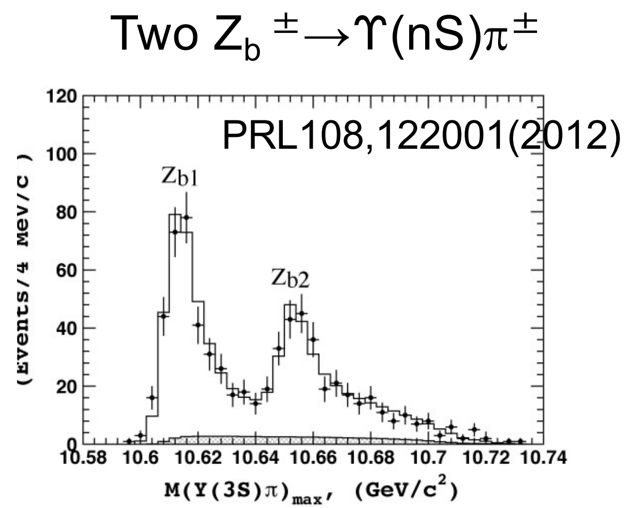








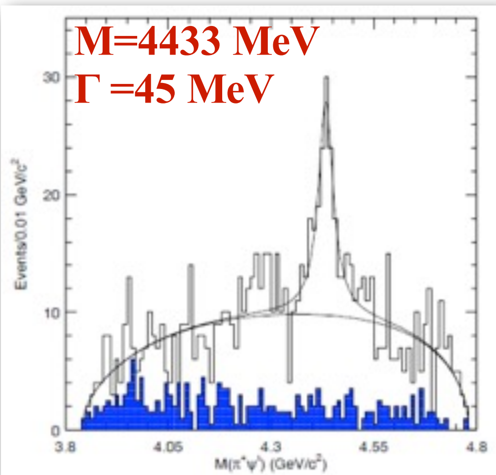




Explicitly Exotic Hadrons

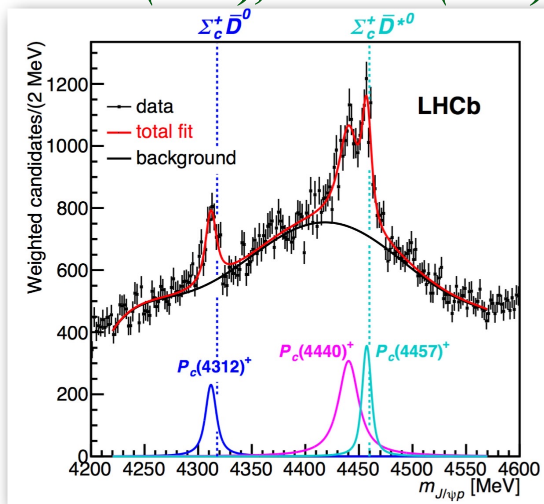
$Z_c^+(4430)$ Belle

PRL 100 (2008) 142001



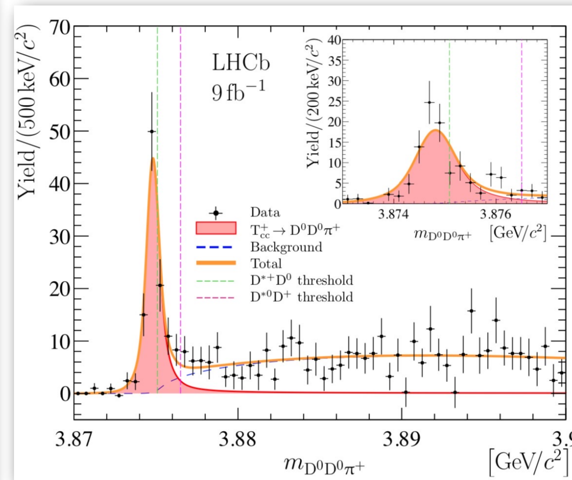
P_c (4312) (4440) (4457) LHCb

PRL 115 (2015), PRL 122 (2019)



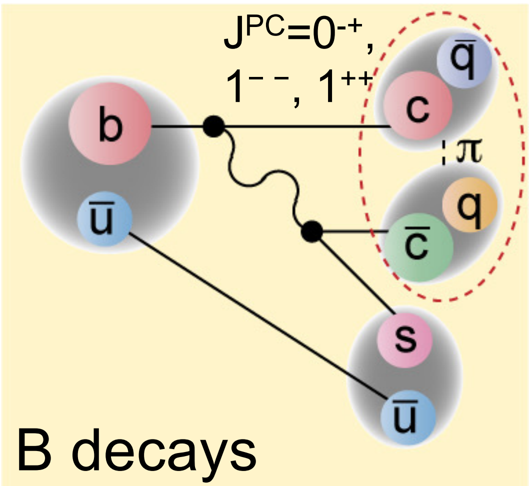
T_{cc} LHCb

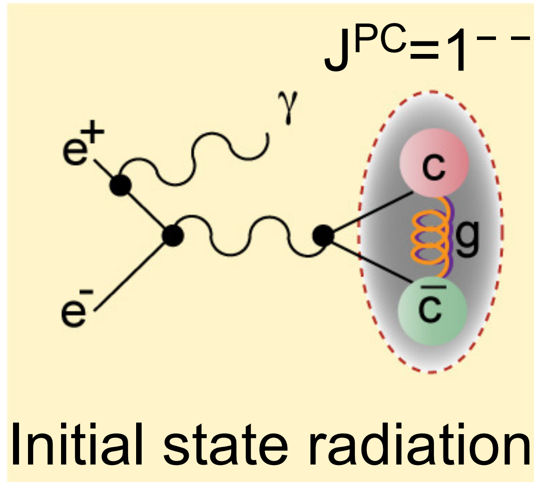
arXiv:2109.01038, 2109.01056

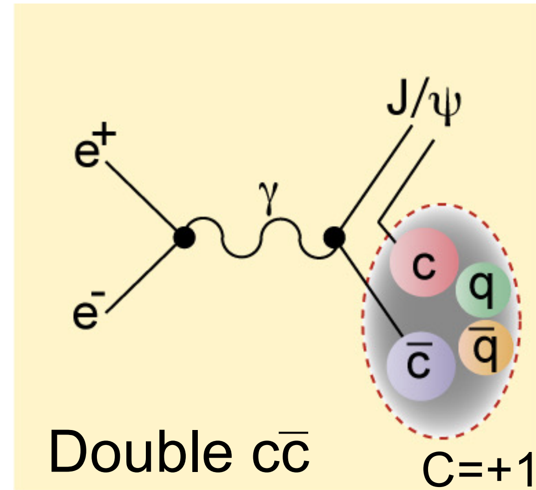


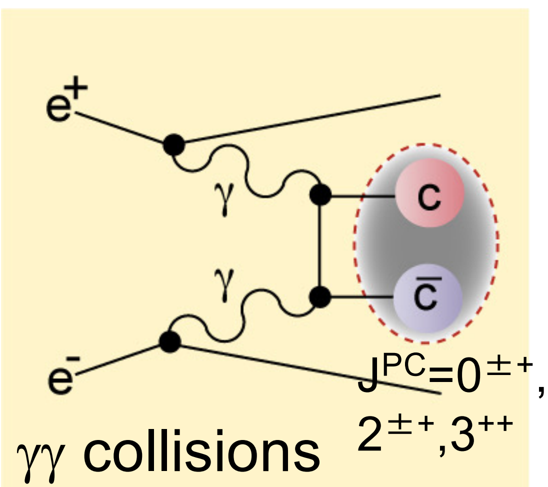
These hadrons require *new components* beyond the minimum constituent quarks, *ex.* colorless meson $\bar{q}q$ or colored diquark qq.

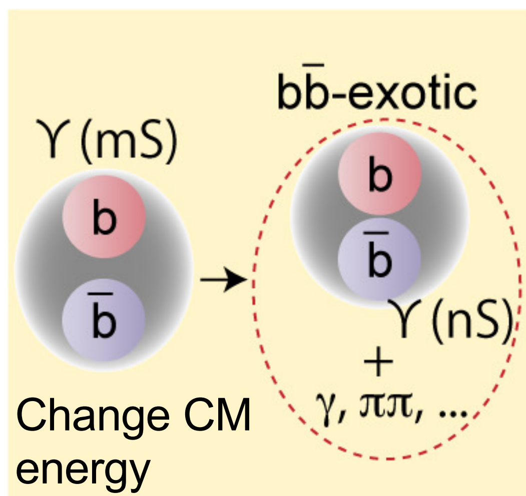
Variety of recorded reactions







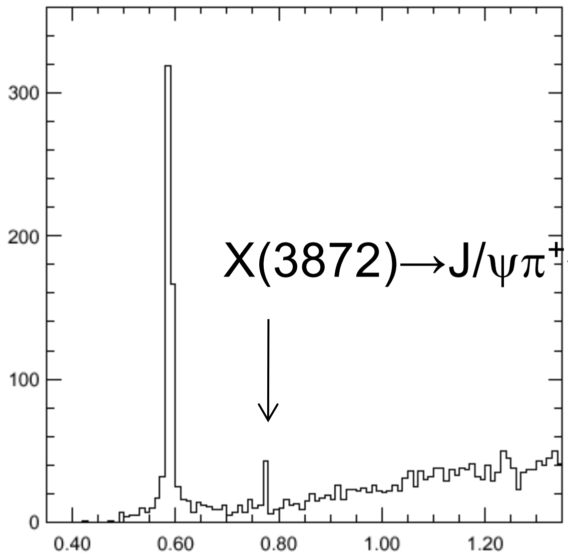




Allowed/favored production process depends on quantum numbers of a hadron.

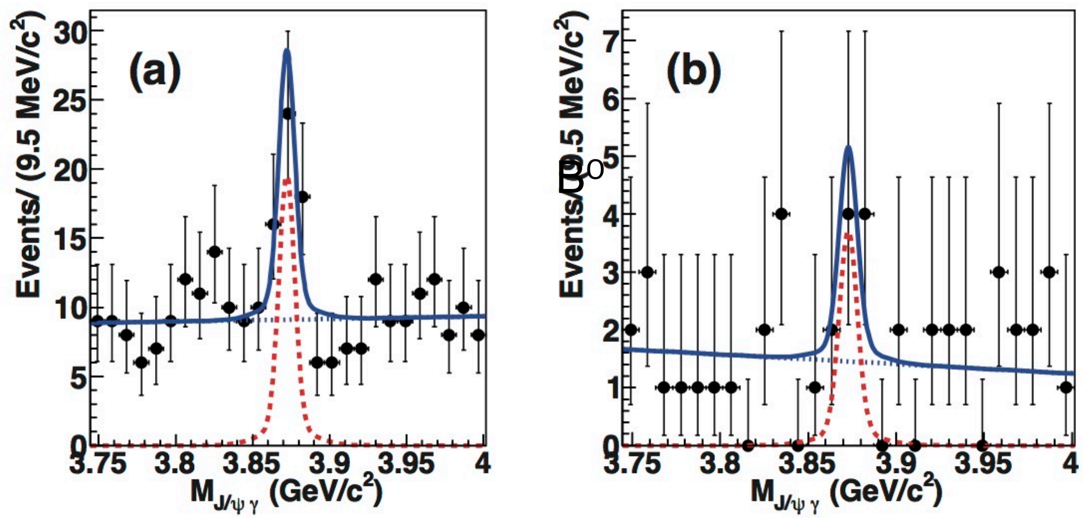
Spin-Parity of X(3872)

Belle PRL91,261801(2003)



$M_{l+l-\pi+\pi-}$ - M_{l+l-} (GeV)

X(3872)→J/ψ γ; C=+1



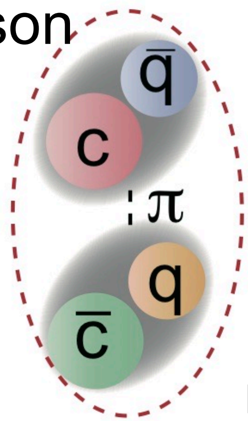
Belle PRL07,091803(2011)

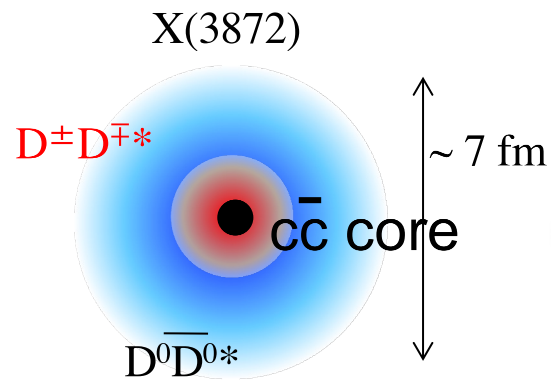
$J^{PC}=1^{++}$ (Belle, BaBar, CDF, LHCb) from J/ψ $\pi^+\pi^-$ angular distribution.
(PRL110, 222001(2013) and cited papers)

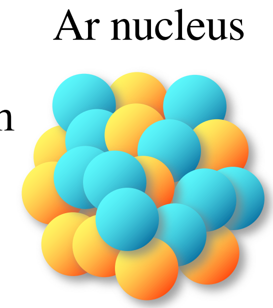
Br(X(3872)→$D^0\overline{D}^{*0}$) is about Br(X(3872)→J/ψ $\pi^+\pi^-$) × 10.

Admixture : Plausible interpretation for X(3872)

Meson-meson molecule







E. J. Eichiten et al. Phys. Rev. D 73, 014014 (2006);
A. M. Badalin et al. Phys. Rev.D 85, 031103 (2012);
S. Takeuchi, K. Shimizu and M.Takizawa PTEP2014, 123D01(2014).

$D\overline{D}^*$ component is coupled with the same J^{PC} $c\bar{c}$, $\chi_{c1}(2P)$ (unseen).

→can explain $Br(X \to D^0\overline{D}^{*0})/Br(X \to J/\psi\ \pi^+\pi^-)$ is about 10.

→pure molecule; too fragile to have prompt produced in Tevatron/LHC.

→another $\chi_{c1}(2P)$ dominant state would become broad.

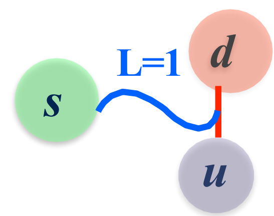
A Puzzle in Baryon Spectroscopy

Λ(1405) (1/2⁻) is the lowest negative parity baryon, even below **N***.

2 competing pictures:

1. *P-wave excitation*

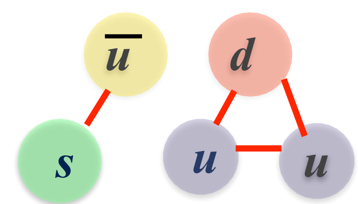
uds with S=1/2, L=1 orbital excitation ⇒ $J^\pi=1/2^-$ and $3/2^-$



spin-orbit partner Λ(1520) $3/2^-$ is too high?

2. *Additional qqbar pair*

qqq(qqbar) L= 0 state (NO orbital excitation)
S=1/2, L=0 => $J^\pi=1/2^-$
likely to be N($1/2^+$) + $K^{bar}(0^-)$ bound state

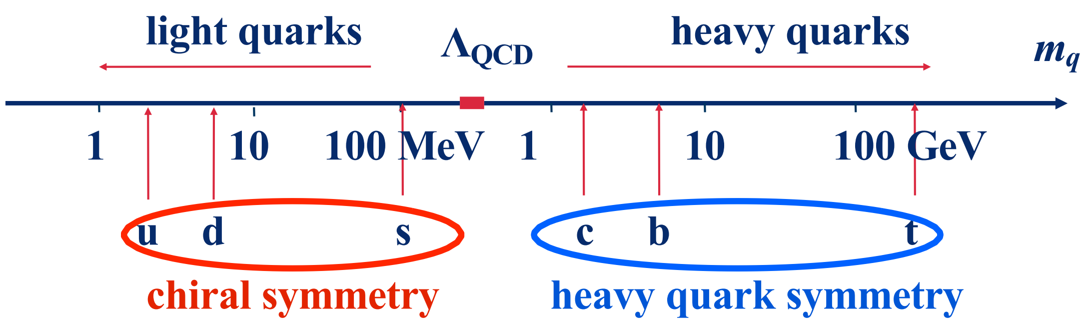


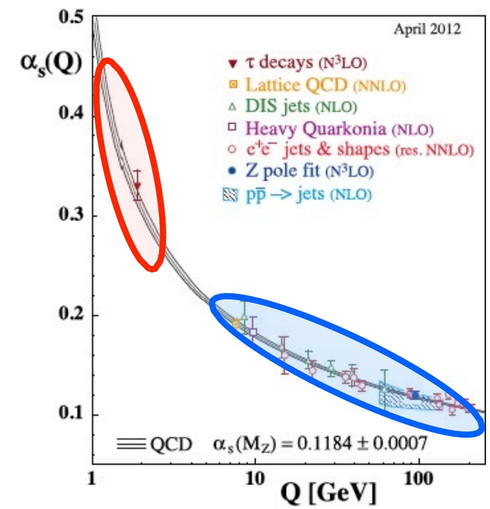
Similar competition in

X(3872) (1^+) ~ cc^{bar} ($^3P_1$)+ DD^{*bar}(S-wave)

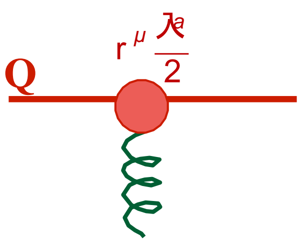
Heavy Quark Dynamics

Dynamics of heavy quarks (c, b) is perturbative and nonrelativistic. It decouples from light quarks.





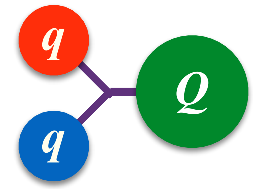
Magnetic gluon coupling is suppressed.



$$\propto \frac{1}{m_Q}$$

$\Rightarrow$ ***Heavy quark symmetry*** **: Light quarks do not feel the mass and spin of the heavy quark (in the limit $m_Q \to \infty$).**

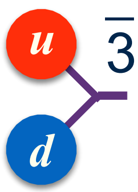
Diquarks in Heavy Baryons

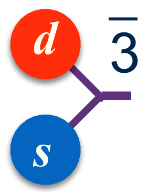


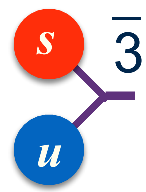
- **Scalar diquark** $S(0^+)$

  L=0, S=0, color 3^{bar} → flavor $SU(3)_f$ 3^{bar}(antisym) :

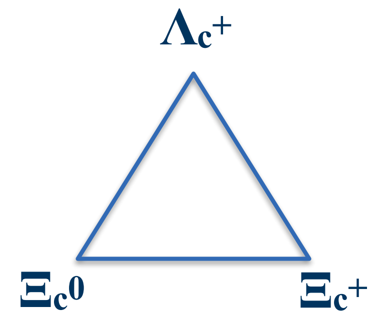
  [ud]=(ud-du), [ds]=(ds-sd), [su]=(su-us)







⇒ flavor 3^{bar} HQ baryons: Λ_Q, Ξ_Q

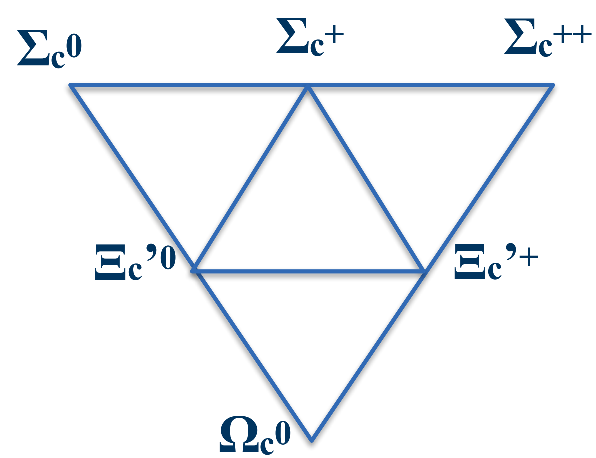


- **Axial vector diquark** $A(1^+)$

  L=0, S=1, color 3^{bar} → $SU(3)_f$ 6 (sym)

  uu, {ud}, dd, {us}, {ds}, ss

⇒ flavor 6 HQ baryons: Σ_Q, Ξ_Q', Ω_Q

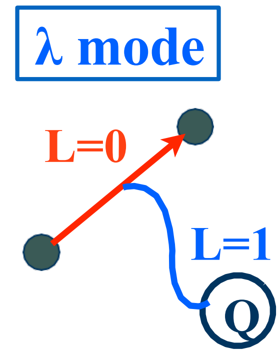


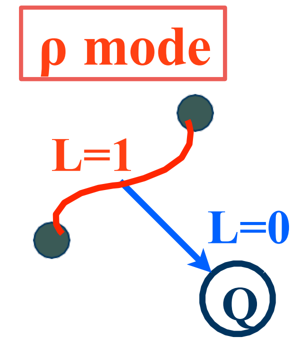
Diquarks in Excited Heavy Baryons

P-wave excited states of heavy baryons, Λ_Q, Σ_Q, . . Two distinctive modes: λ and ρ modes

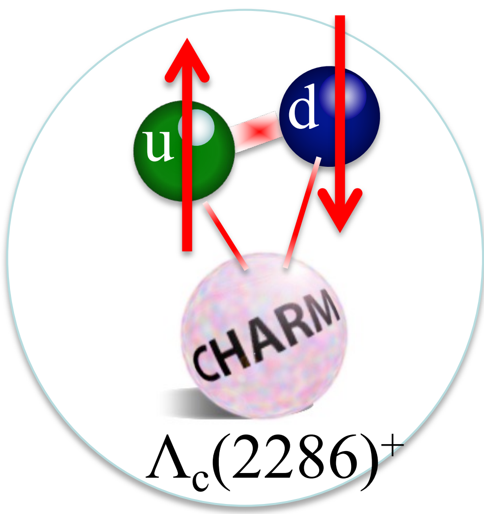
***E* (λ-mode) < *E* (ρ-mode)**

generally in the quark model

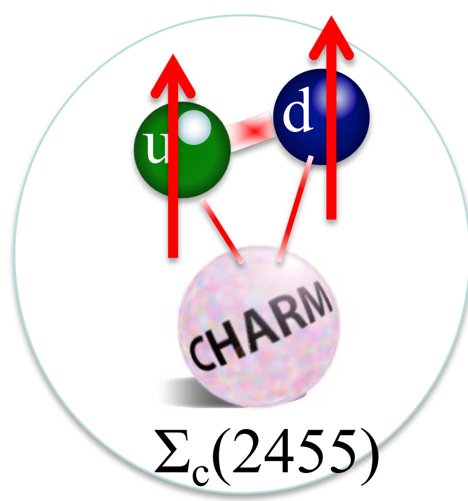




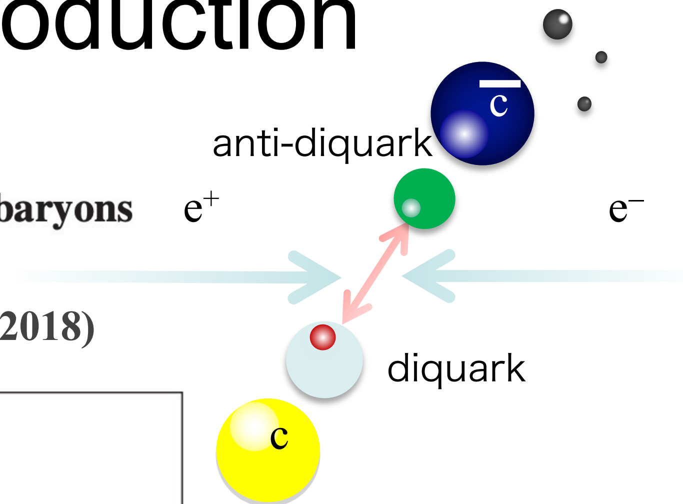
Scaler diquark
“good diquark”



Axial vector diquark
“bad diquark”

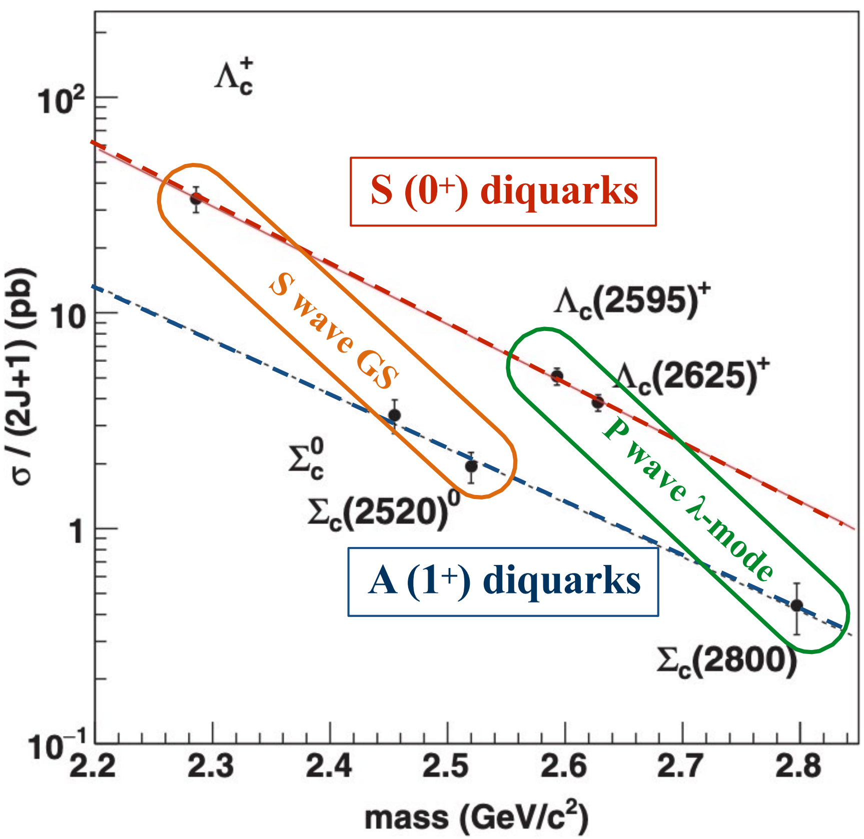


Charm Baryon Production



Production cross sections of hyperons and charmed baryons from e^+e^- annihilation near $\sqrt{s}=10.52$ GeV

Belle Collaboration, Phys. Rev. D97, 072005 (2018)



Diquark in Lattice QCD

M(1⁺) - M(0⁺) for Lattice QCD

Alexandrou, de Forcrand, Lucini, PRL 97 (2006) 222002

Quench QCD, from gauge-invariant Qqq system

M(1⁺) - M(0⁺) ~ 200-220 MeV

Babich, et al., PR D76 (2007) 074021

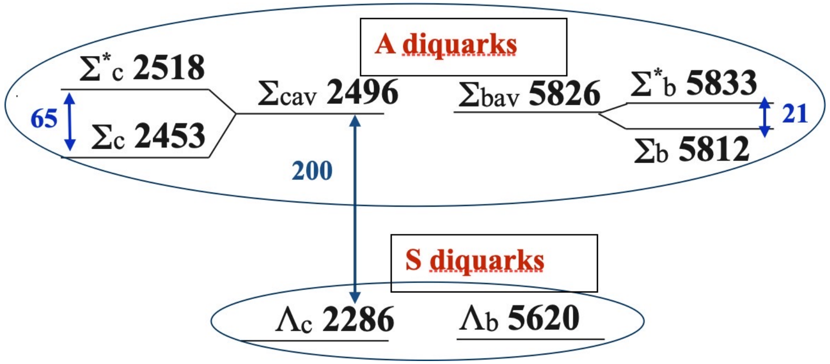
Quench QCD, Landau gauge

M(1⁺) - M(0⁺) ~162 MeV

Y. Bi, et al., Chinese Physics C40 (2016)

Full QCD, Landau gauge

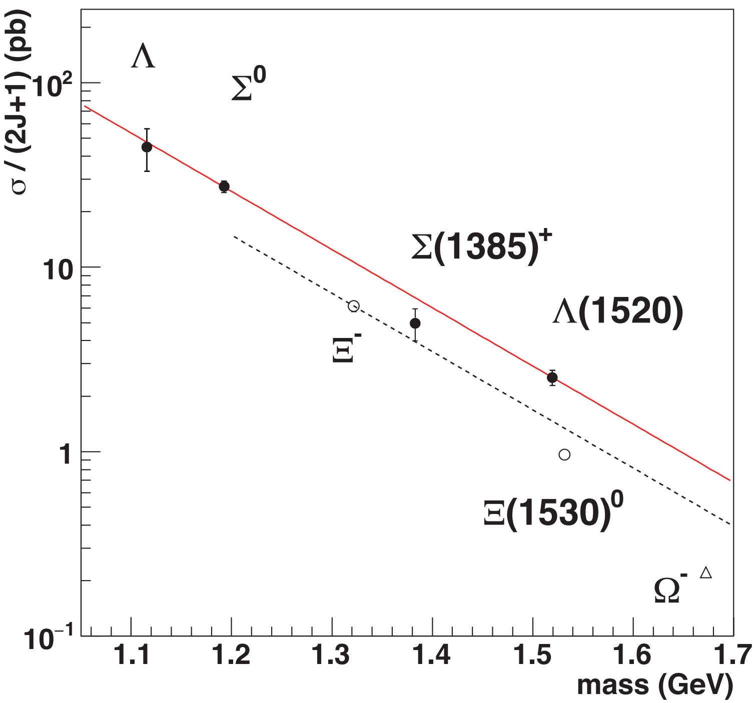
M(1⁺) - M(0⁺) ~290 MeV



Hyperon Production

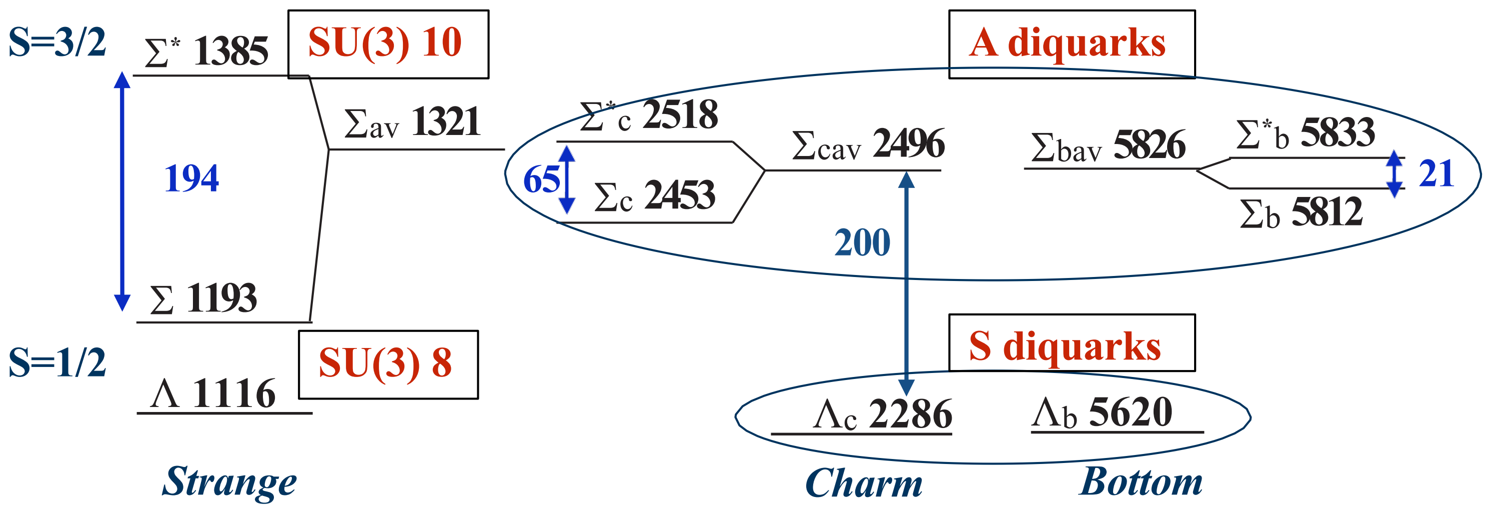
Production cross sections of hyperons and charmed baryons from e^+e^- annihilation near $\sqrt{s} = 10.52$ GeV

Belle Collaboration, Phys. Rev. D97, 072005 (2018)



- Λ's and Σ's are on a line with possible suppression of Σ(1385)$^+$
- Spin-spin interaction may compete with diquark correlation
- Measurement of Λ(1405) will be interesting

Diquarks in Strange and Charm



In the strange sector, the spin-spin force splits SU(3) 8 and 10.

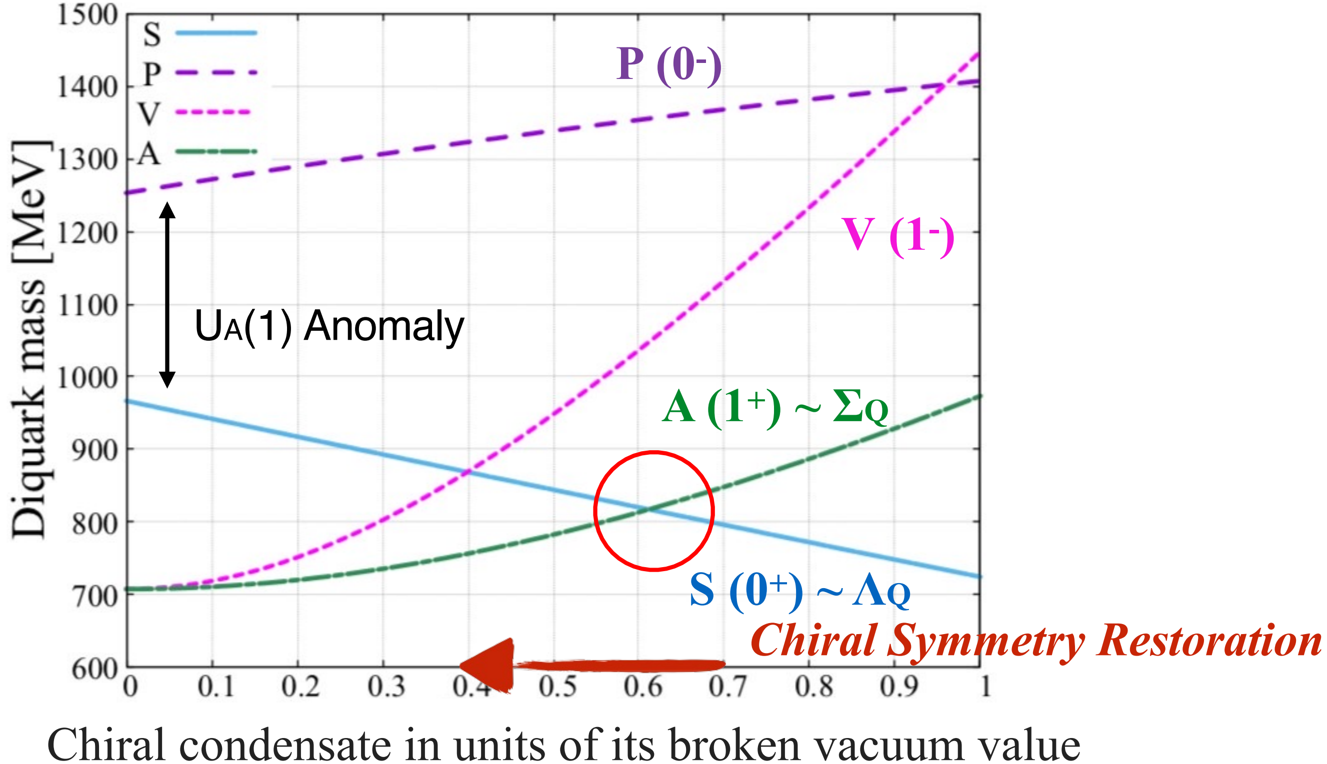
In the heavier sectors, the heavy-quark spin symmetry suppresses $\Sigma_Q(1/2)$ - $\Sigma_Q(3/2)$ splitting.

Diquark structure appear clearly in charm and bottom

Diquark masses and chiral symmetry

Mass changes of the 0^+ and 1^+ diquarks under chiral restoration

Y. Kim, Y.R. Liu, M.Oka, K. Suzuki, Phys. Rev. D 104, 054012 (2021)



Possible inversion of the scalar and axial-vector diquarks
→ may be significant for the behaviors of heavy baryons and diquark condensates in dense matter.

Doubly Heavy Tetraquarks

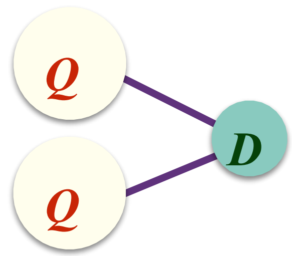
- The same model is applied to DHTQ

Y. Kim, M. Oka, K. Suzuki, Phys. Rev. D 105, 074021 (2022)

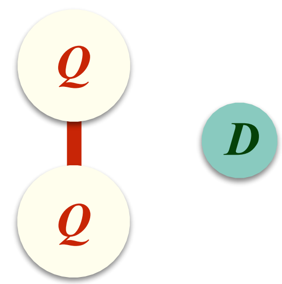
- Potential between a heavy quark and a diquark

$$V_0(r) = -\frac{\alpha}{r} + \lambda r + C$$

$$V_{ss}(r) = (\boldsymbol{s}_i \cdot \boldsymbol{s}_j)\frac{\kappa}{M_i M_j}\frac{\Lambda^2}{r}\exp(-\Lambda r)$$



- Potential between heavy quarks
  (a la Semay-Silvestra Brac)



$$V(r) = -\frac{\alpha}{r} + \lambda r^p + C + (\boldsymbol{s}_i \cdot \boldsymbol{s}_j)\frac{8\kappa}{3m_i m_j\sqrt{\pi}}\frac{e^{-r^2/r_0^2}}{r_0^3}$$

- *Predictions*

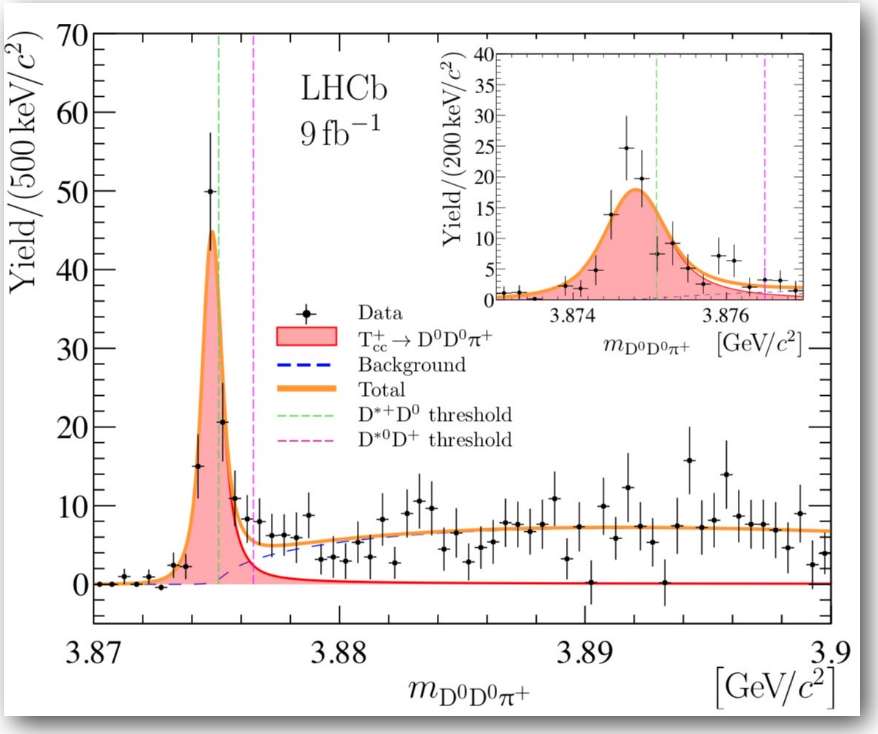
$M(T_{bb})$=10489 MeV below BB^* threshold

$M(T_{cc})$=3961 MeV above DD^* threshold

Observation of T_{cc}

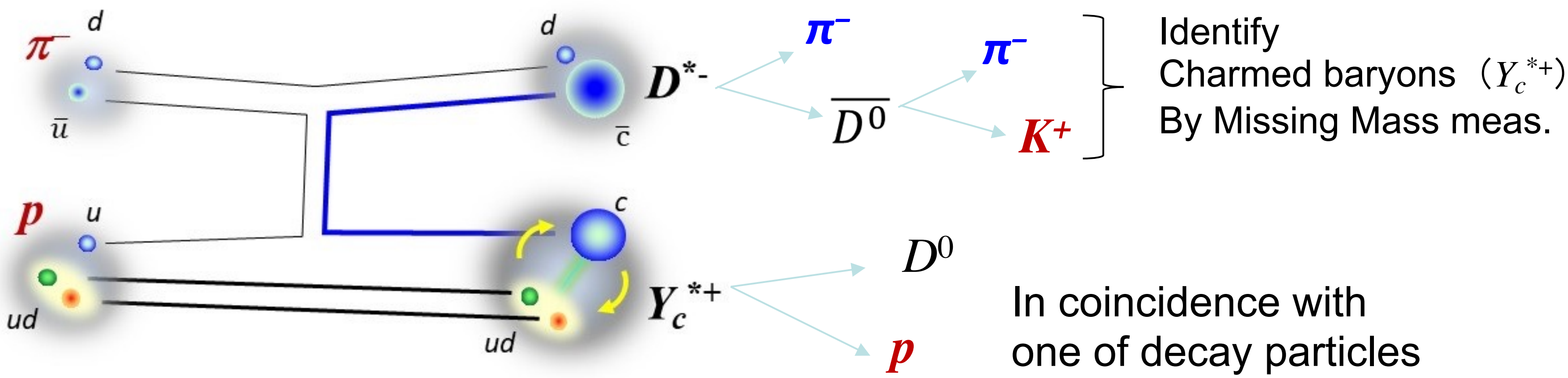
T_{cc} LHCb

arXiv:2109.01038, 2109.01056



- Very close to $D^{*+}D^0$ threshold
- Likely to be D^*D^0 molecule
- May require 4q core for the production at LHCb

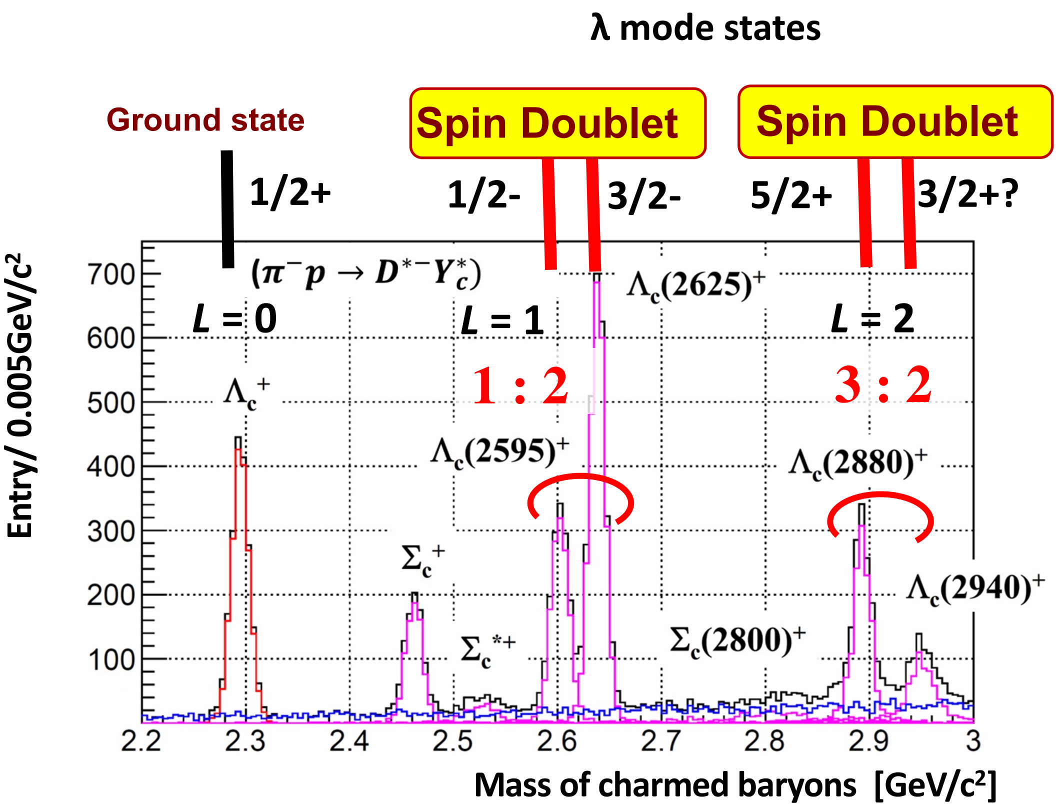
Measurment of charmed baryons (Y_c^{*+}) formations and decays

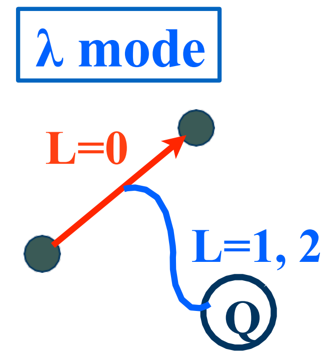


Missing Mass Meas. @J-PARC E50 Experiment

- Inclusive/systematic measurement of Y_c^{*+}
- Decay branching ratios (independent meas. of decay particles)

Expected spectrum





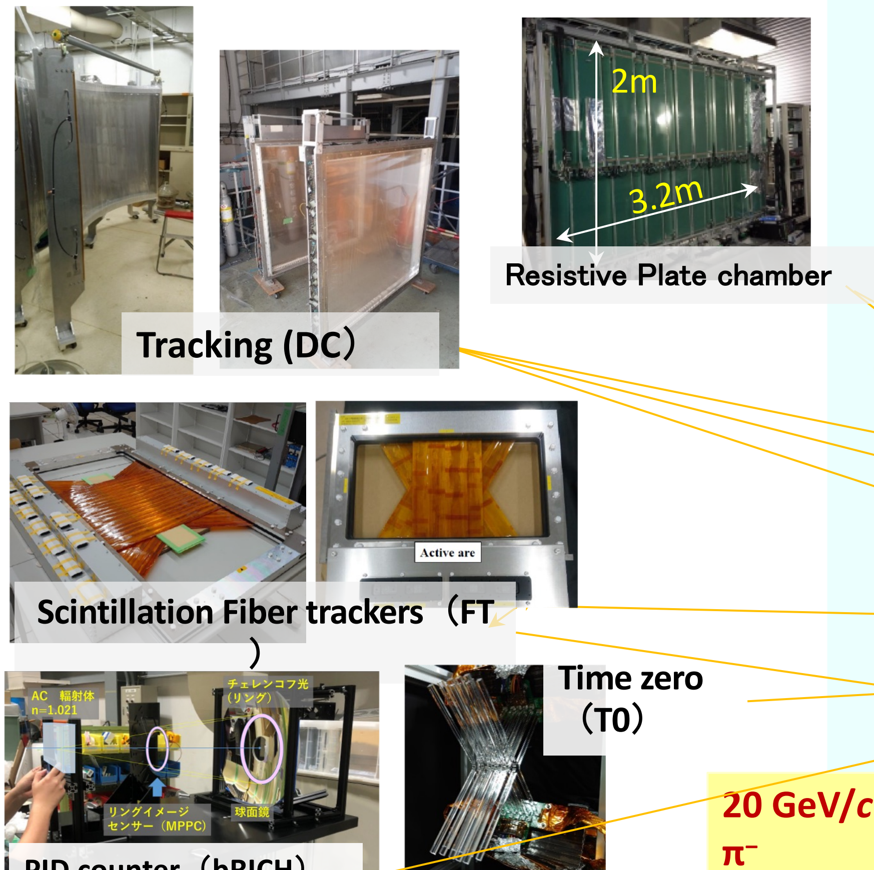
Production rate to be L:L+1

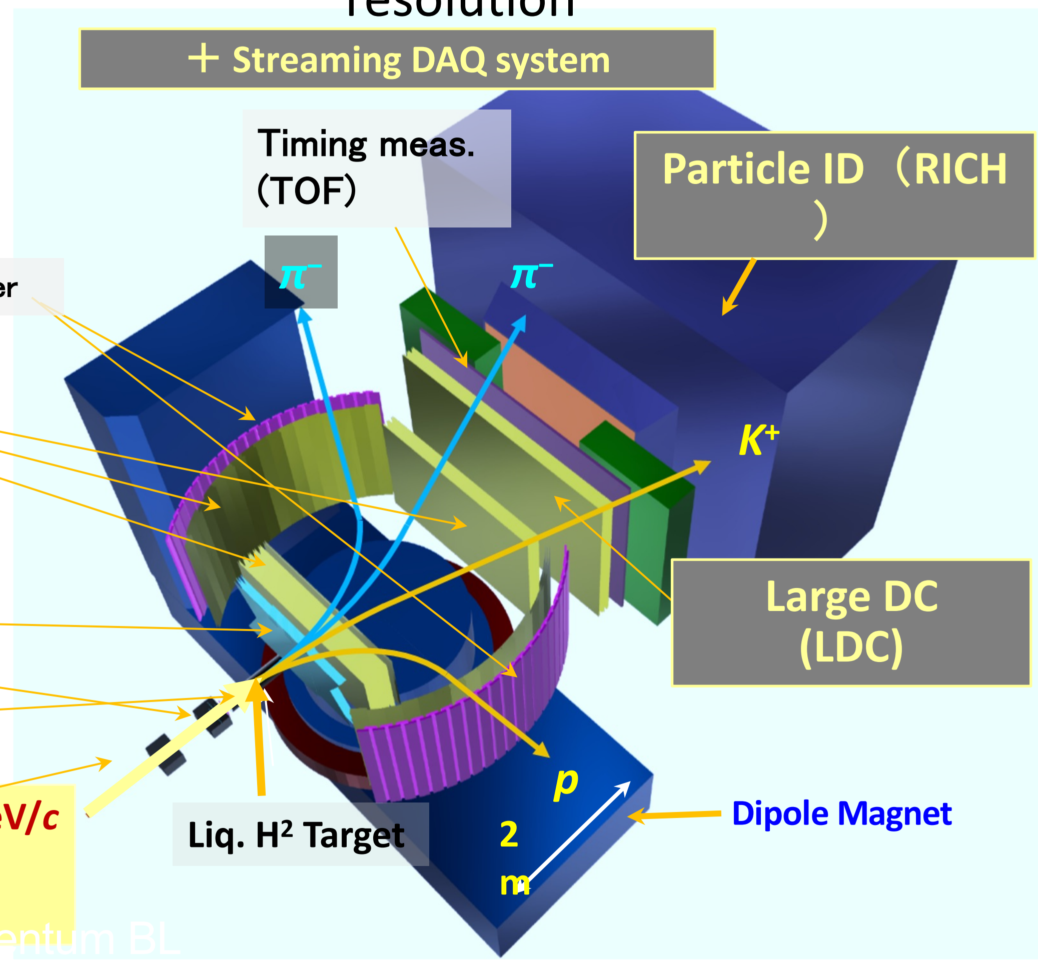
→determine spin-parities

Requires high resolution and good PID at *very* high rate

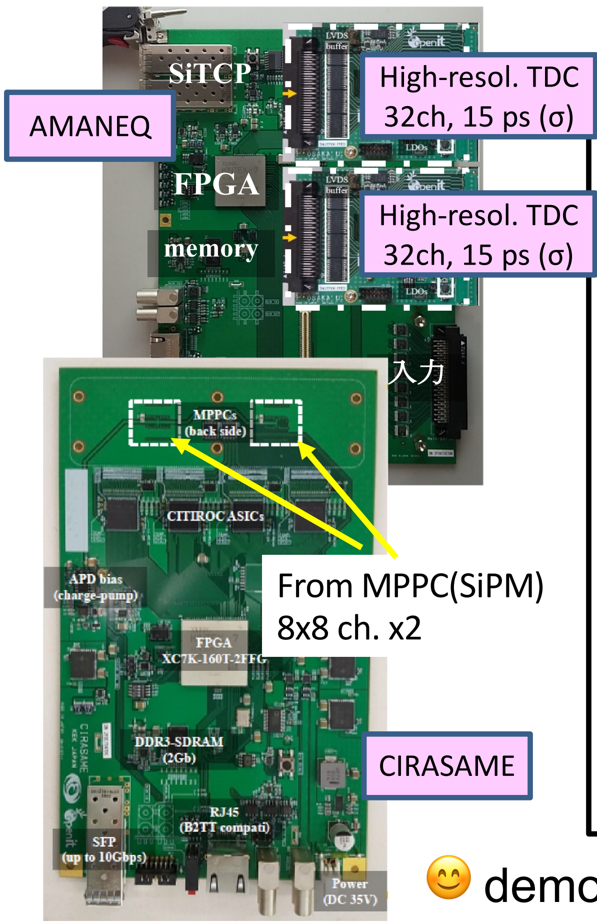
E50 Spectrometer

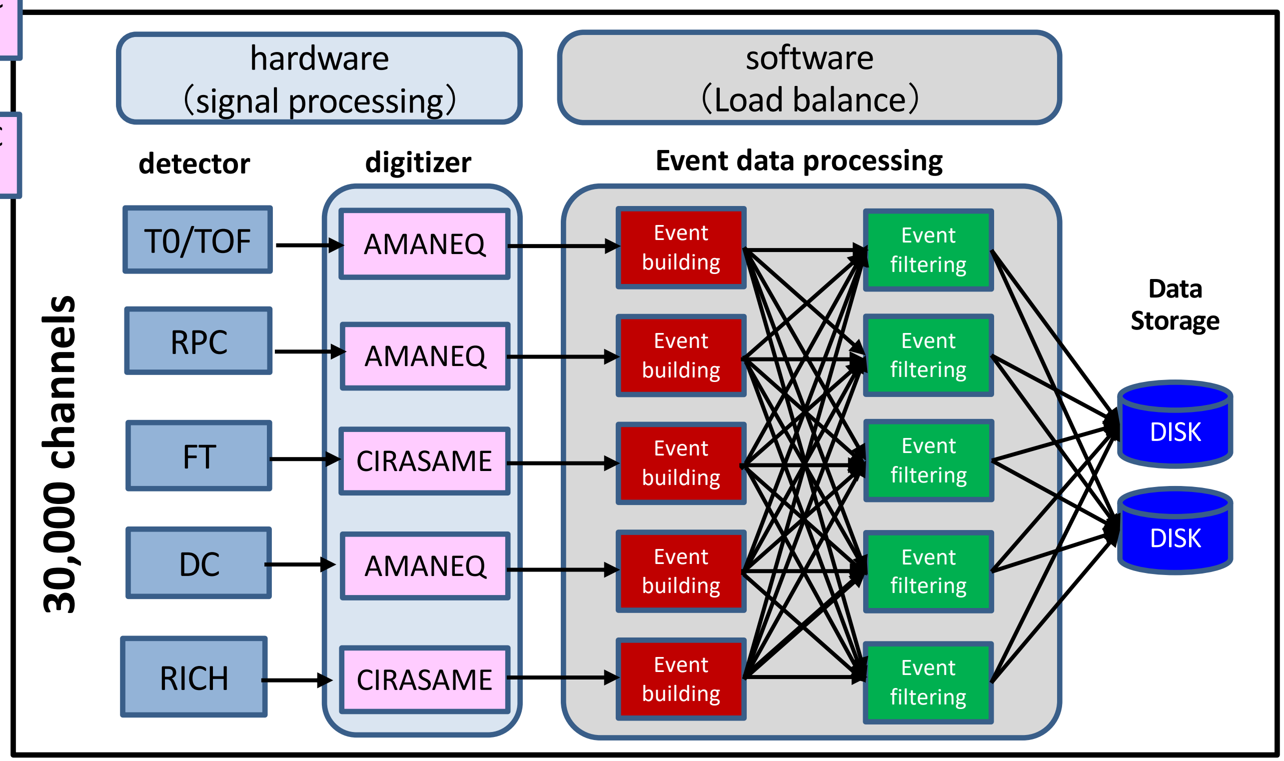
Large Solid Angle、PID system、high-resolution





Streaming DAQ system

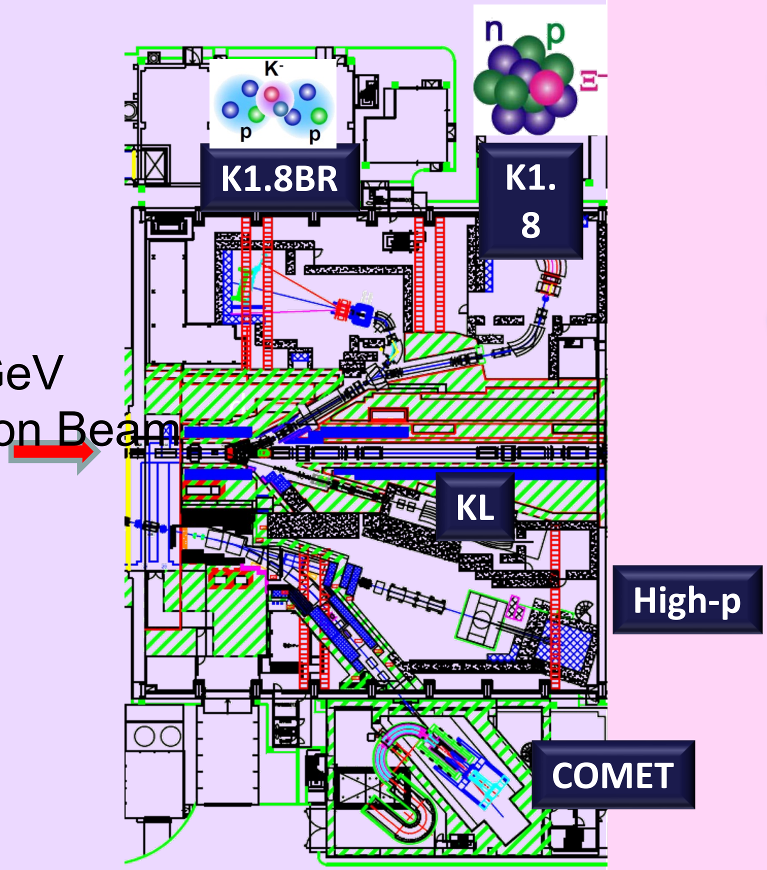




😊 demonstrated in test experiments: R. Honda, PTEP 2021, 123H01)

Current Hadron Experimental Facility

30 GeV
Proton Beam



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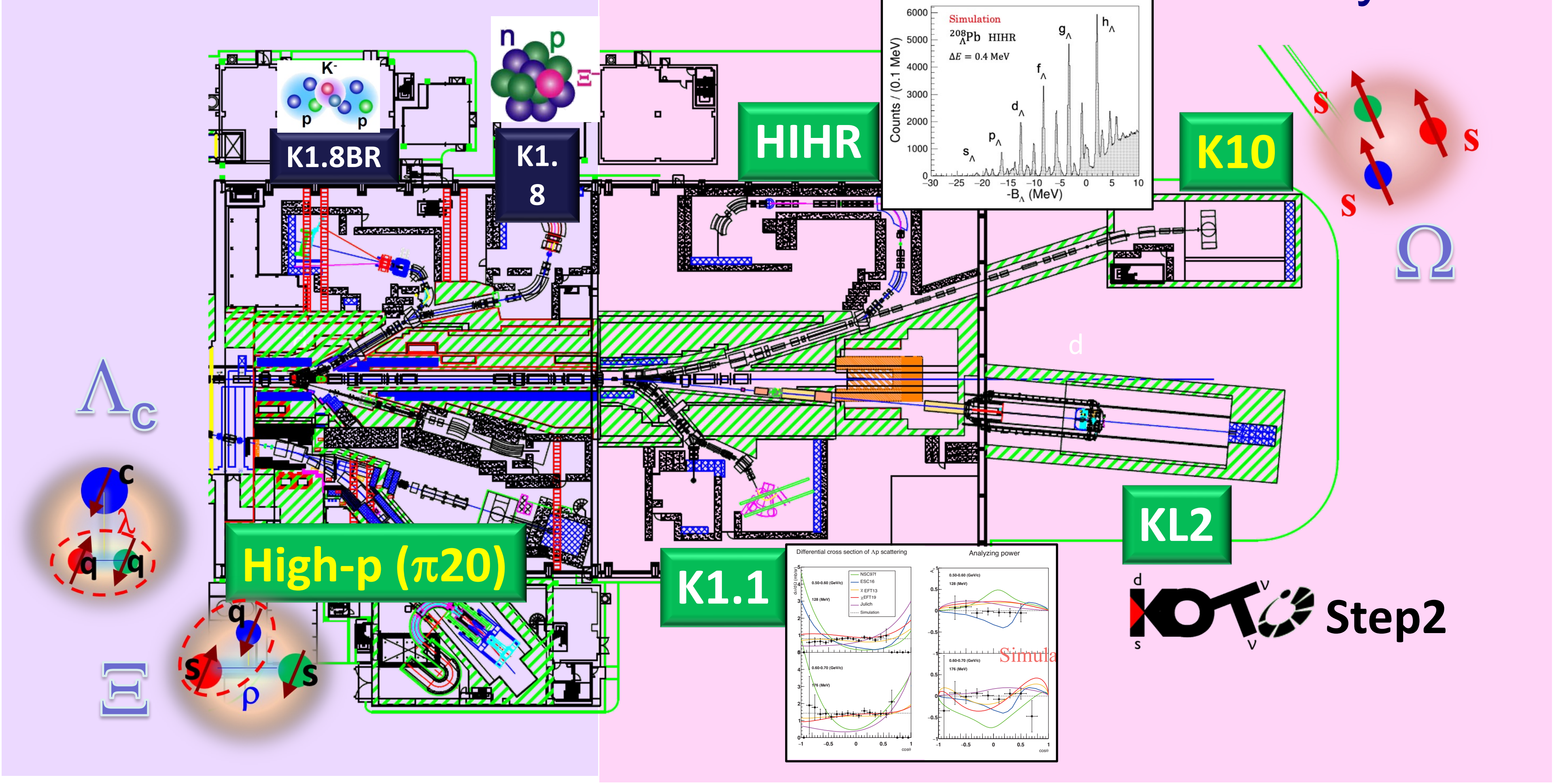
Extended Hadron Experimental Facility



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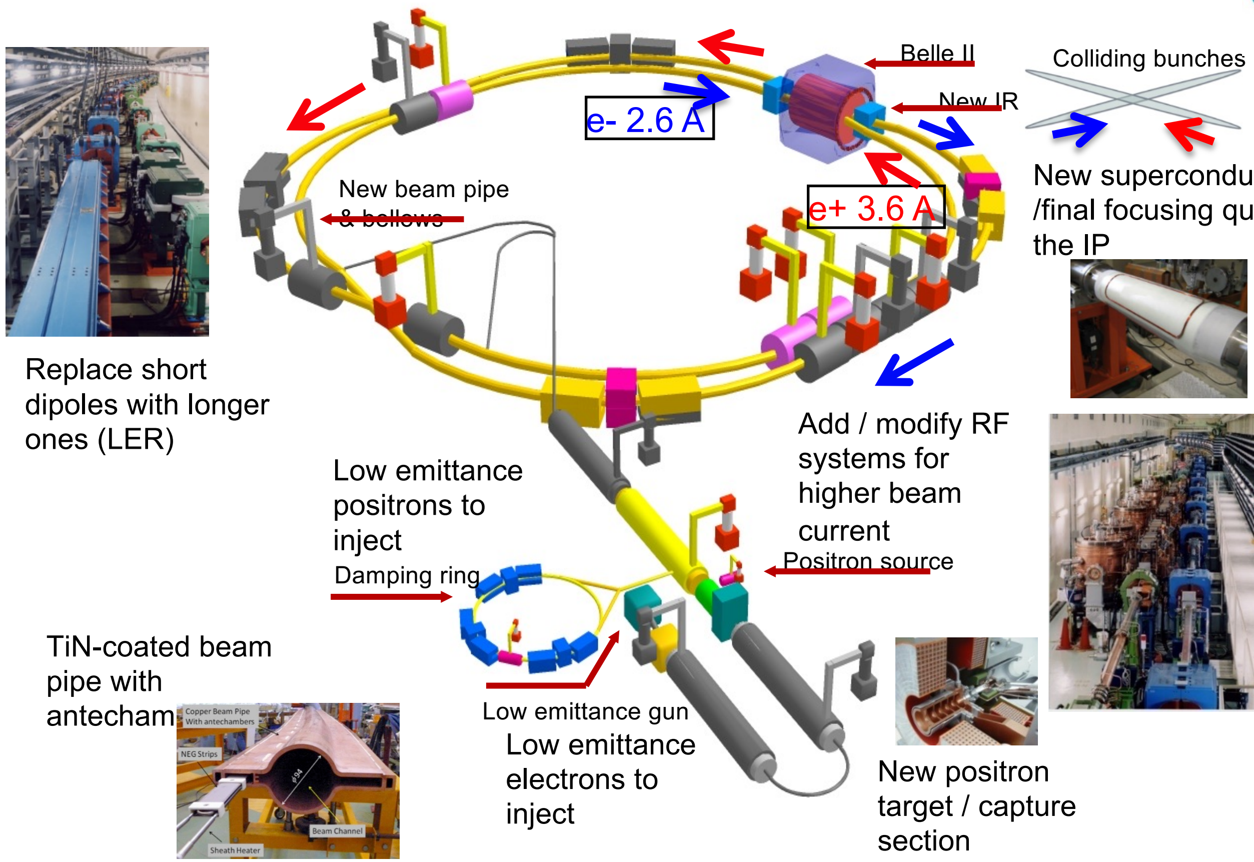
SuperKEKB collider



KEKB
×40

- Nano-beam
- Increase currents

➡ Peak luminosity : $2.1\text{x}10^{34}$ $cm^{-2}s^{-1}$ => **$8.0\text{x}10^{35}$ $cm^{-2}s^{-1}$**

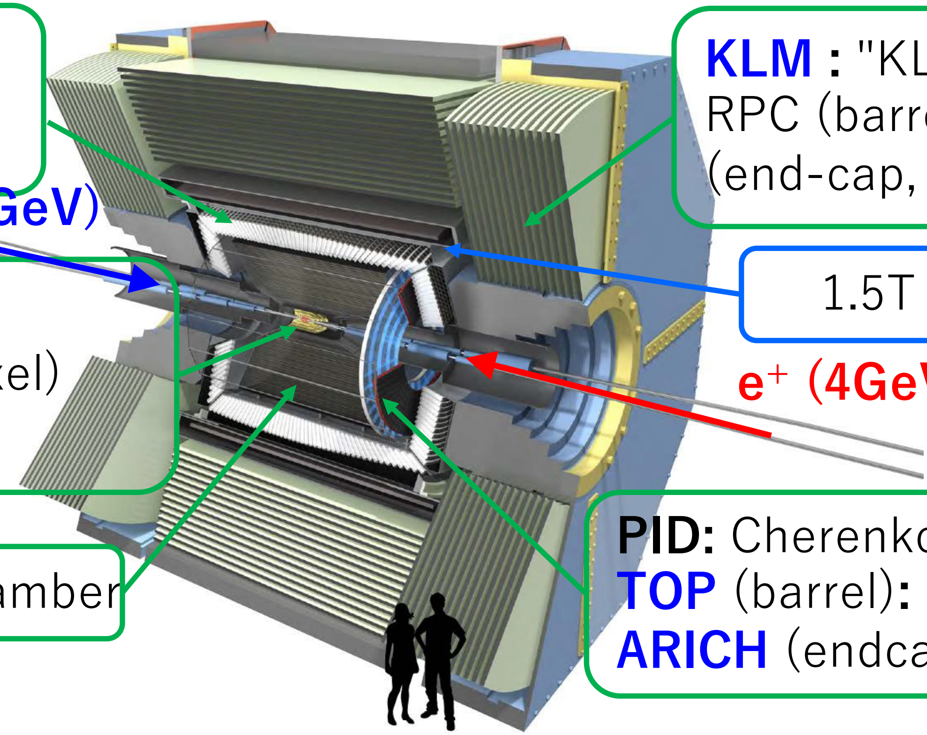
Beam energy : 3.5 / 8.0 GeV => **4.0 / 7.0 GeV**

Boost factor ~2/3

Belle II detector

ECL : CsI (TI), waveform sampling

KLM : "KL and muon" RPC (barrel) + SiPM (end-cap, inner barrel)



VXD :
PXD : DEPFET (pixel)
SVD : Silicon strip

1.5T solenoid coil

CDC : drift chamber

PID: Cherenkov ring image
TOP (barrel): Quarts
ARICH (endcap): Aerogel

Issues to overcome

- Beam background
- High rate capability
- Boost ~ 2/3

Technical choice

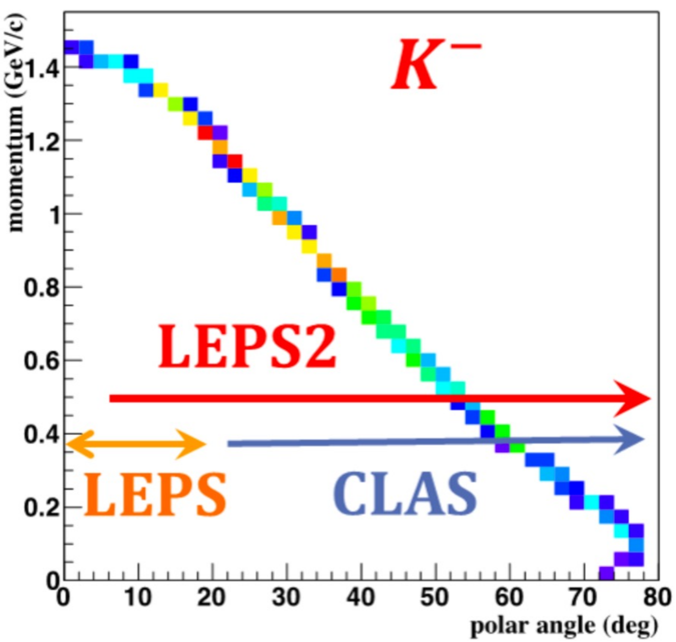
- Finer segmentation, waveform sampling.
- Material change
- Larger angular coverage (CDC, SVD)
- Closer to the IP (PXD) 3 -> 2cm
- Particle ID improve (K/π)(TOP, ARICH)

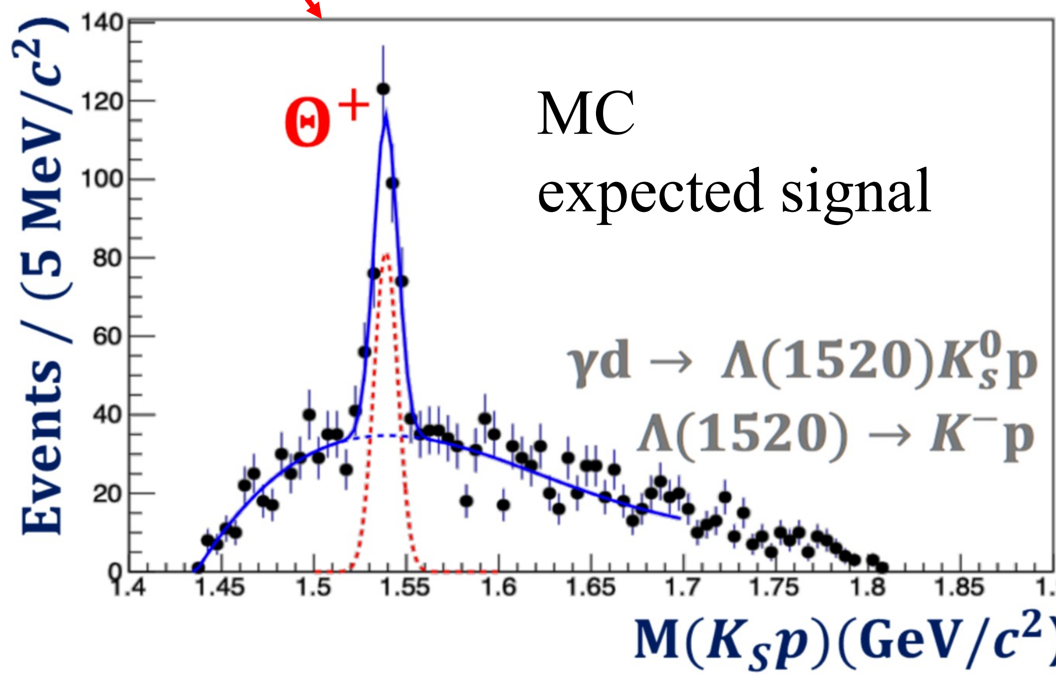
Pentaquark Θ^+ search @ LEPS2

$\gamma d \to \Theta^+ K^- p$ Strangeness tagging

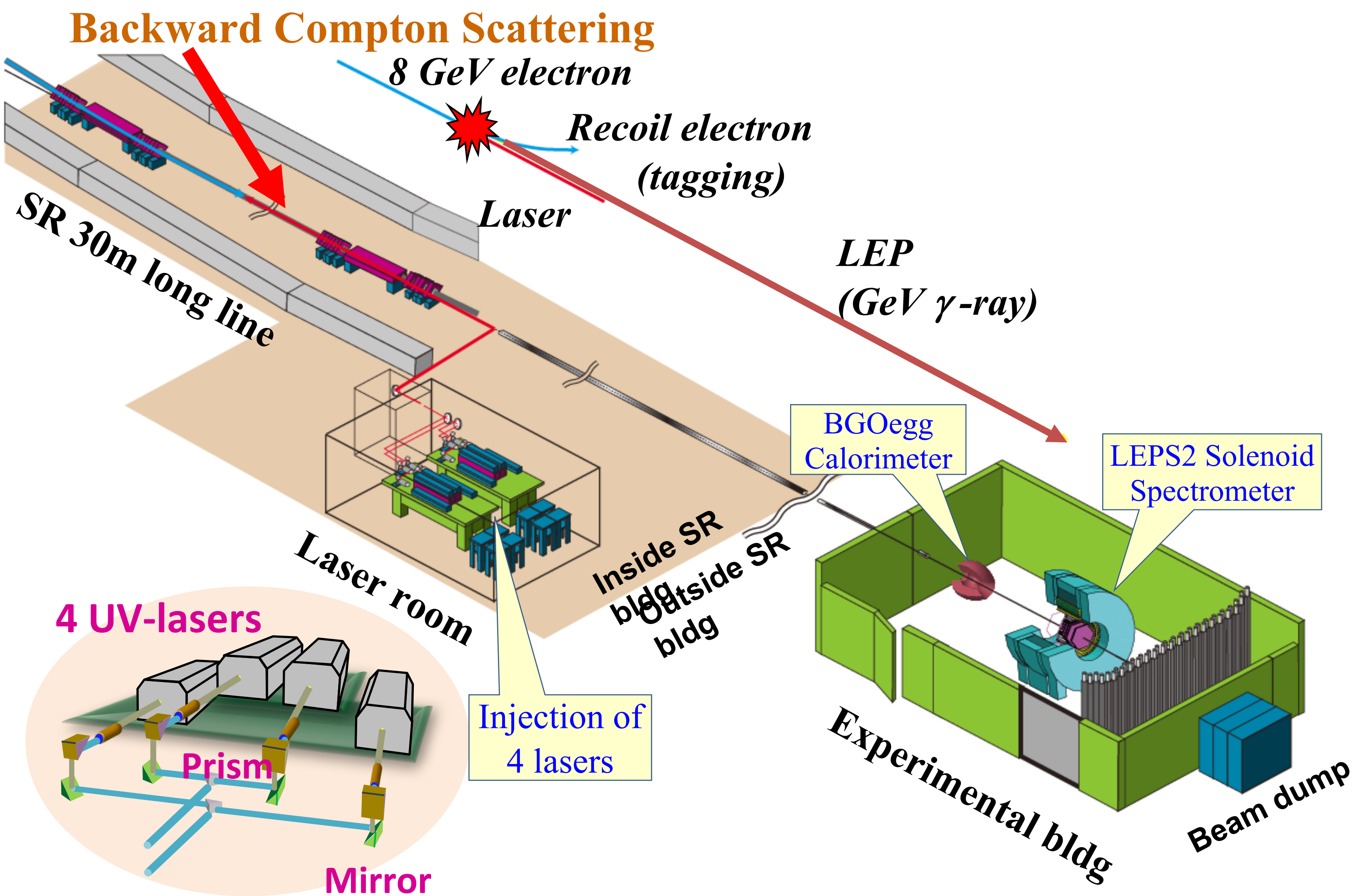
$\Theta^+ \to K_s^0 p \to \pi^+ \pi^- p$ Invariant mass measurement

Wide angle coverage



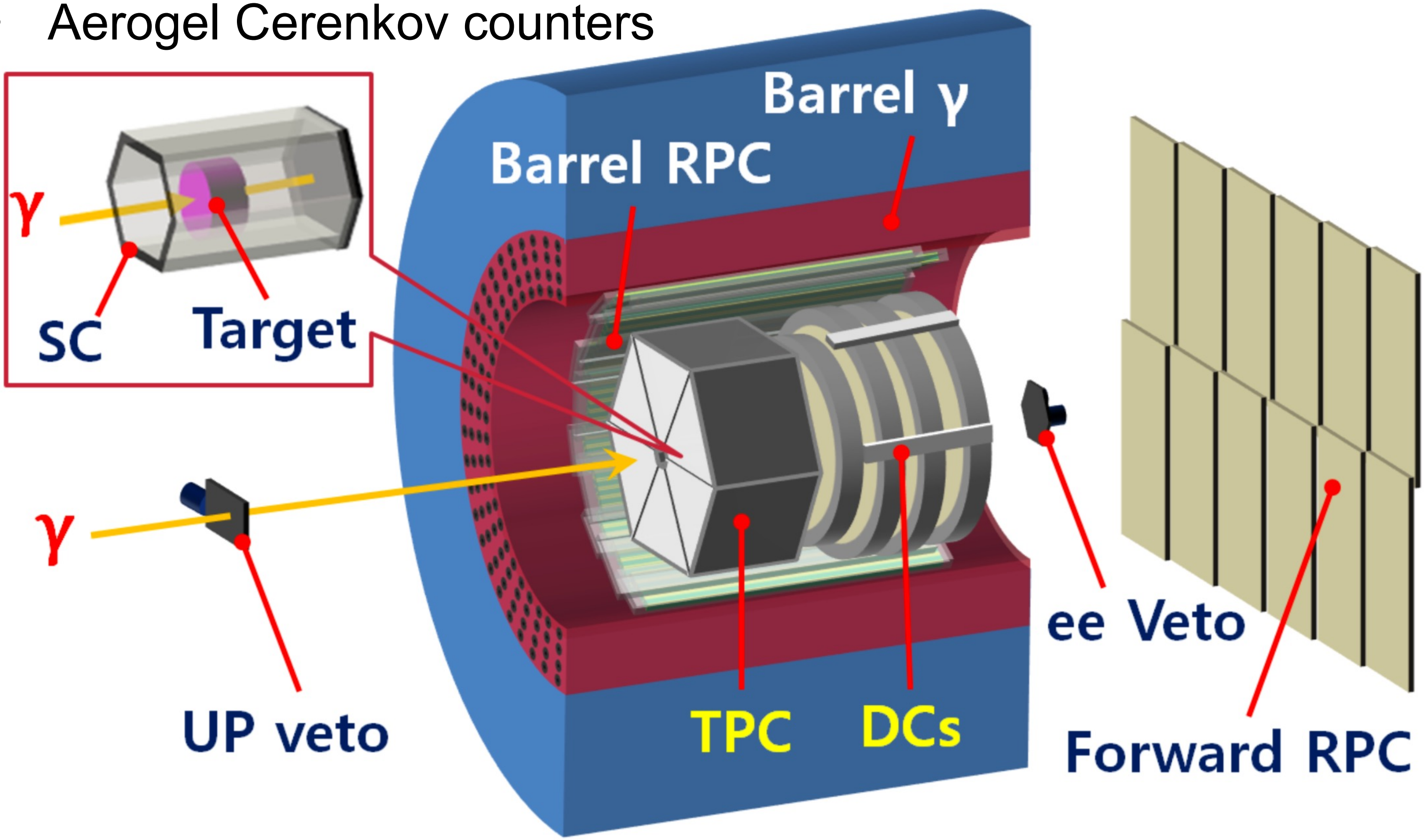


LEPS2 Beamline

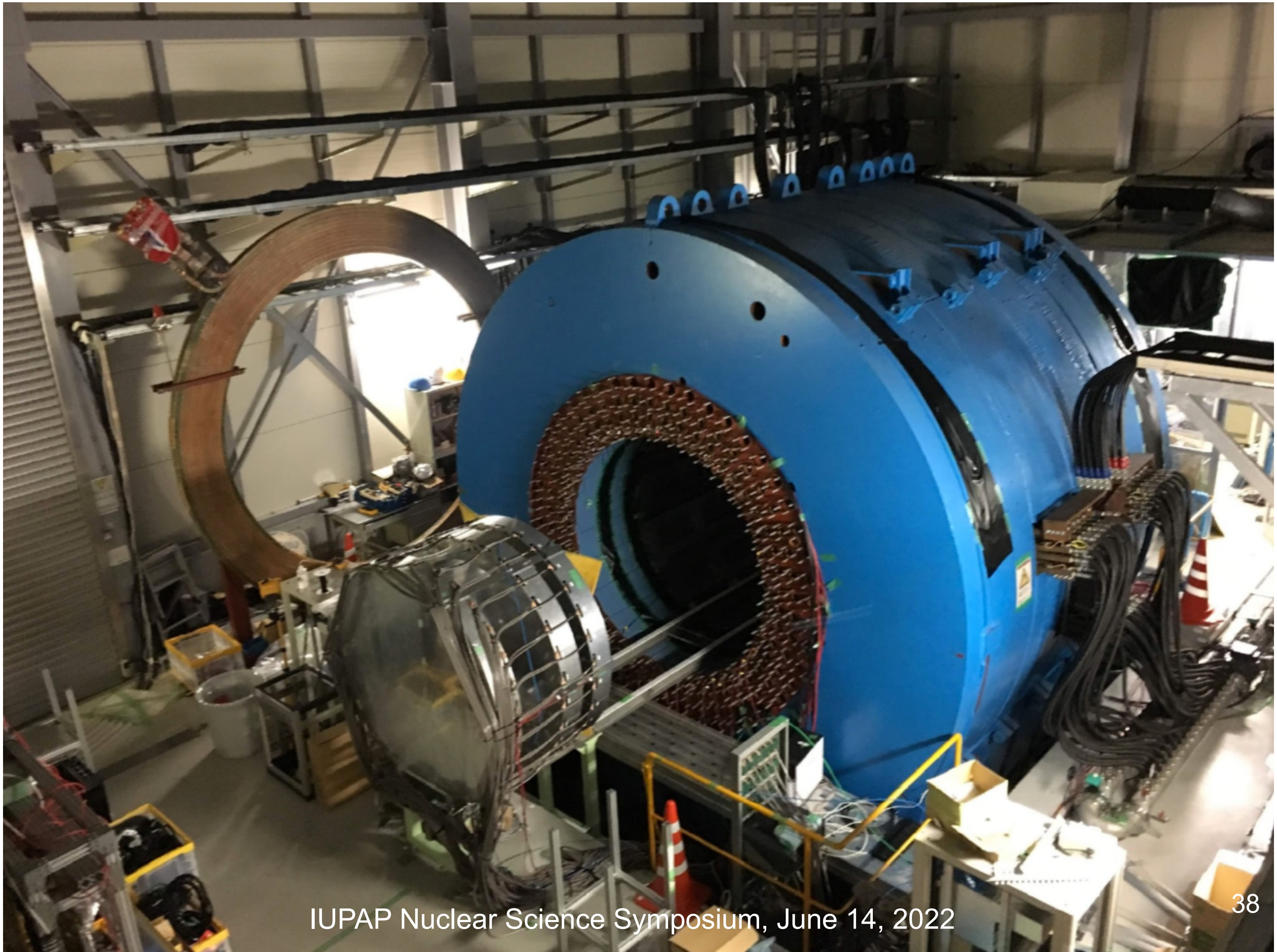


Solenoid spectrometer

- Timing counter: SC, Forward and Barrel RPCs
- Tracker: TPC, DCs
- EM calorimeter: Barrel γ
- Aerogel Cerenkov counters



Solenoid spectrometer



Summary

- Hadron spectroscopy including exotic hadrons is shedding lights on “effective” degrees of freedom for hadron structure and excitation, *ex. molecular states, diquarks, collective motions.*
- Production and decay of heavy hadrons is promising to reveal the dynamics and roles of diquarks.
- High-intensity and wide-acceptance facilities such as J-PARC (with Hadron Hall Extension in near future), Belle II@Super KEKB, and LEPS2@SPring-8 will provide us with opportunities to explore the colored and colorless correlations further.

Acknowledgement

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