# Baryon Spectroscopy in ($\pi$, 2$\pi$) Reactions at J-PARC

Ken Hicks (Ohio University)
for J-PARC E45 Collaboration

JLab Workshop: Exploring hadrons with electromagnetic probes
3 November 2017, Newport News

1. Introduction
2. Experimental design
3. Detector status
4. Summary and outlook

# J-PARC E45 Collaboration


| | |
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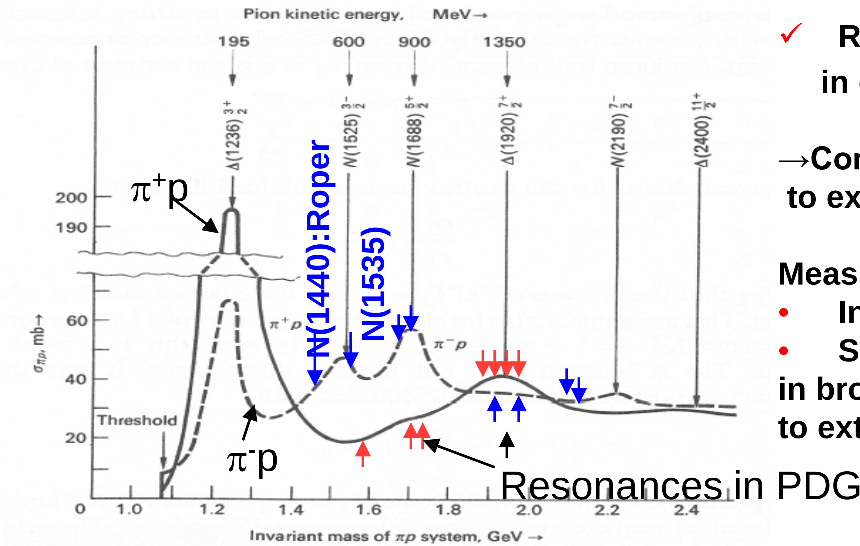
# Baryon spectroscopy :
## Physics of broad and overlapping resonances




D.H.Perkins, Introduction to High Energy Physics

- ✓ **Width: a few hundred MeV.**
- ✓ **Resonances are highly overlapped in energy except Δ(1232).**

**→Complicated Partial Wave Analysis to extract hidden resonances**

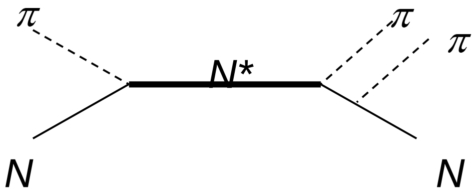
**Measure cross sections as a function of**
- **Incident pion energy**
- **Scattering angle**

**in broad range (with fine bins) to extract resonance poles**

# J-PARC E45

Proposed to study baryon resonances in $(\pi, 2\pi)$ reactions.

- Precise measurements of baryon resonance properties
- Deeper understanding of non-perturbative QCD
- Search for new baryon states
  - *e.g.* hybrid baryons (*qqqg*)



# Why now?

- For almost 40 years, there have been no new measurements on ($\pi$,2$\pi$) in the nucleon resonance region.
  - For many years, elastic $\pi$N was good enough
  - With precise new data on $\gamma N \rightarrow \pi N$, $\pi\pi N$ at Jefferson Lab, Bonn and elsewhere, along with theory advances, it becomes clear that hadronic-beam data is also needed to properly interpret the photoproduction data.

# Dynamical Coupled-Channels model (ANL-Osaka)

Matsuyama, Sato, Lee, Phys. Rep. 439 193 (2007)

Physical *N**s will be a "mixture" of the two pictures:


$|N^*\rangle = |MB\rangle$

$|N^*\rangle = |qqq\rangle + |\mathrm{m.c.}\rangle$

$$V_{a,b} = v_{a,b} + \sum_{N^*} \frac{\Gamma^{\dagger}_{N^*,a}\Gamma_{N^*,b}}{E - M_{N^*}}$$

✓ Transition potentials:

exchange potentials of ground state mesons and baryons

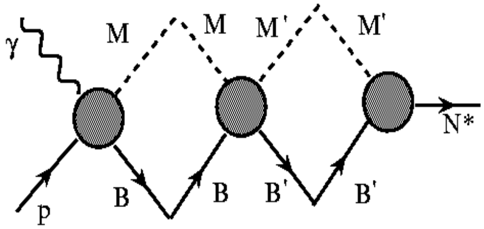
bare *N** states

H. Kamano, JAEA seminar

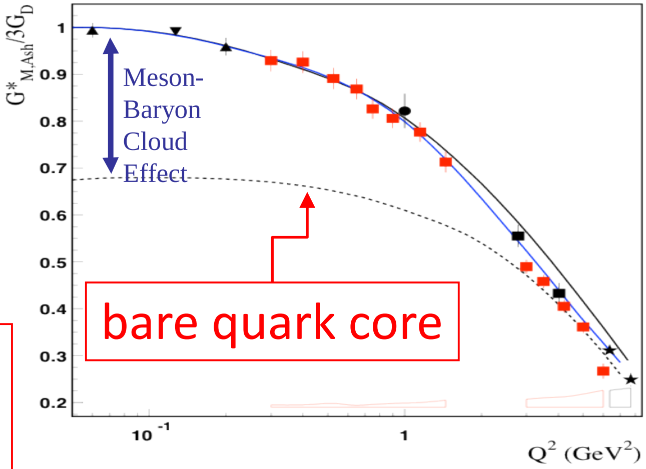
# NΔ Transition Form Factor (GM) from EBAC

**The range of $Q^2$<7.0 GeV2 is far from pQCD domain**

- One third of G*M at low $Q^2$ is due to contributions from meson–baryon (MB) dressing:

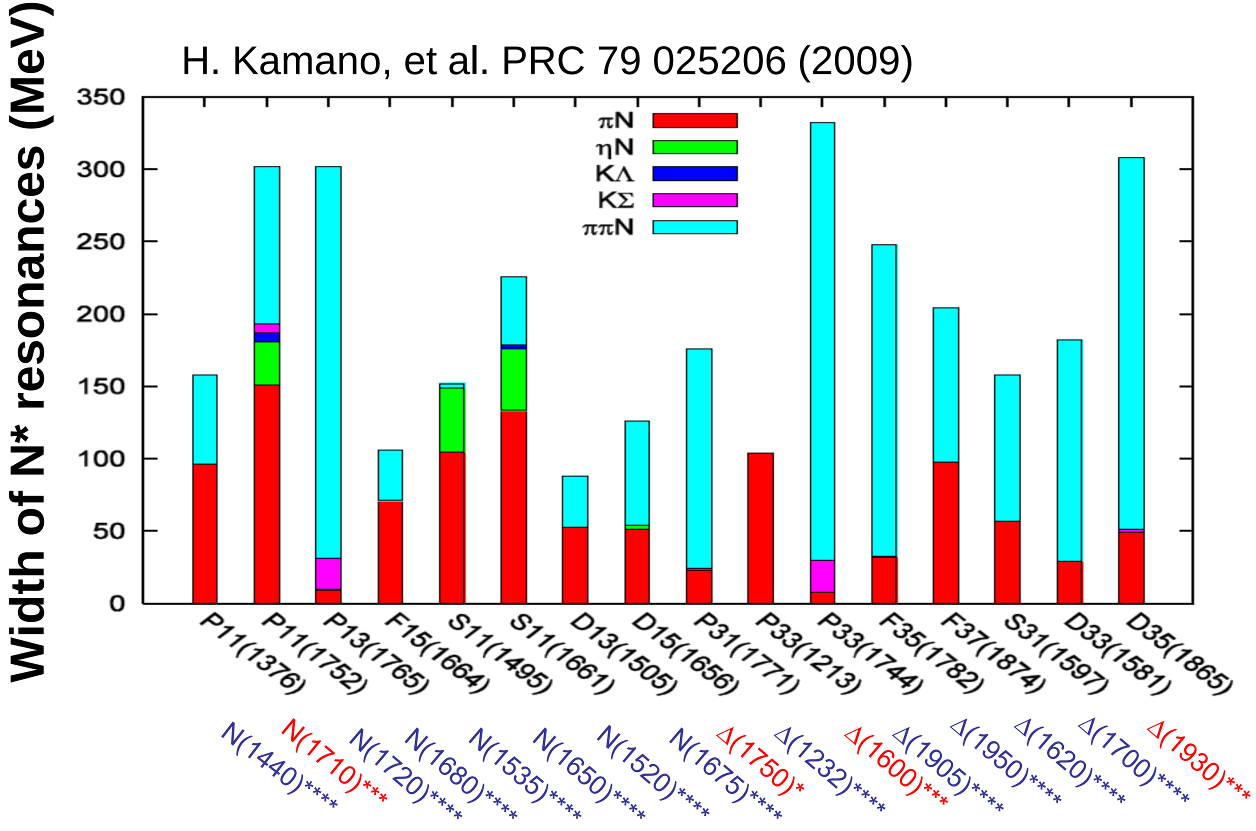



In the relativistic QM framework, the bare-core contribution is well described by the three-quark component of the wavefunction at high $Q^2$.




B.Julia-Diaz *et al.*, PRC 69, 035212 (2004)

# Importance of $N\pi\pi$ Decay



# The Primary Source of $(\pi,2\pi)$

Nuclear Physics B78 (1974) 233–250. North-Holland Publishing Company

**EXPERIMENTAL RESULTS ON $\pi^-$p INTERACTIONS IN THE CM ENERGY RANGE 1.50 – 1.74 GeV**

J. DOLBEAU, M. NEVEU, F.A. TRIANTIS * and C. COUTURES

*Departement de Physique des Particules Elementaires, CEN, Saclay*

Received 21 March 1974

Abstract: Channel cross sections, elastic differential cross sections and single pion production mass spectra and angular distributions are presented for $\pi^-$p interactions, based on 139 000 events observed at six energies in the center of mass region 1.50 – 1.74 GeV.

# Complete (π,2π) Database

M. Manley, Phys. Rev. D 30, 904 (1984).

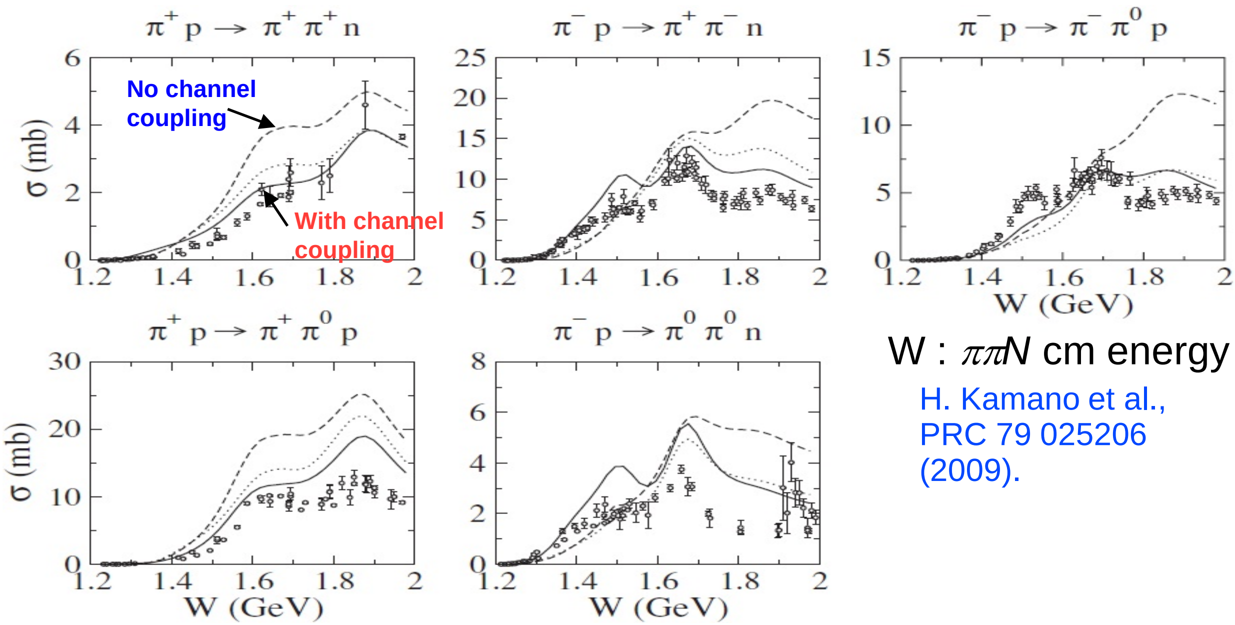
TABLE I. Summary of the number of events analyzed at each energy.

| $W$ (MeV) | $\pi^+\pi^-n$ | $\pi^0\pi^-p$ | $\pi^0\pi^+p$ | $\pi^+\pi^+n$ | Total |
|---|---|---|---|---|---|
| 1340±20 | 1664 | 11 | 0 | 0 | 1675 |
| 1375±15 | 3893 | 145 | 15 | 2 | 4055 |
| 1400±10 | 3646 | 826 | 63 | 15 | 4550 |
| 1440±10 | 3790 | 1339 | 207 | 48 | 5384 |
| 1460±10 | 2074 | 971 | 152 | 36 | 3233 |
| 1480±10 | 7246 | 3776 | 537 | 128 | 11 687 |
| 1500±10 | 6224 | 4055 | 1160 | 250 | 11 689 |
| 1520±10 | 5650 | 4671 | 795 | 143 | 11 259 |
| 1540±10 | 6230 | 5320 | 1115 | 183 | 12 848 |
| 1565±15 | 2237 | 1598 | 2704 | 481 | 7020 |
| 1595±15 | 3065 | 1962 | 2864 | 483 | 8374 |
| 1620±10 | 0 | 0 | 4203 | 621 | 4824 |
| 1640±10 | 7437 | 4177 | 7939 | 1013 | 20 566 |
| 1660±10 | 7411 | 4273 | 4071 | 752 | 16 507 |
| 1680±10 | 8784 | 5340 | 4999 | 847 | 19 970 |
| 1700±10 | 8377 | 5394 | 5375 | 1007 | 20 153 |
| 1725±15 | 6265 | 4594 | 5679 | 524 | 17 062 |
| 1755±15 | 5442 | 4200 | 1316 | 18 | 10 976 |
| 1790±20 | 1966 | 1352 | 4715 | 228 | 8261 |
| 1830±20 | 3543 | 2223 | 2322 | 0 | 8088 |
| 1870±20 | 4342 | 3382 | 8190 | 557 | 16 471 |
| 1910±20 | 6036 | 4081 | 6445 | 0 | 16 562 |
| Total | 105 322 | 63 690 | 64 866 | 7336 | 241 214 |

Total number of events!

# World's $\pi N \to \pi\pi N$ data

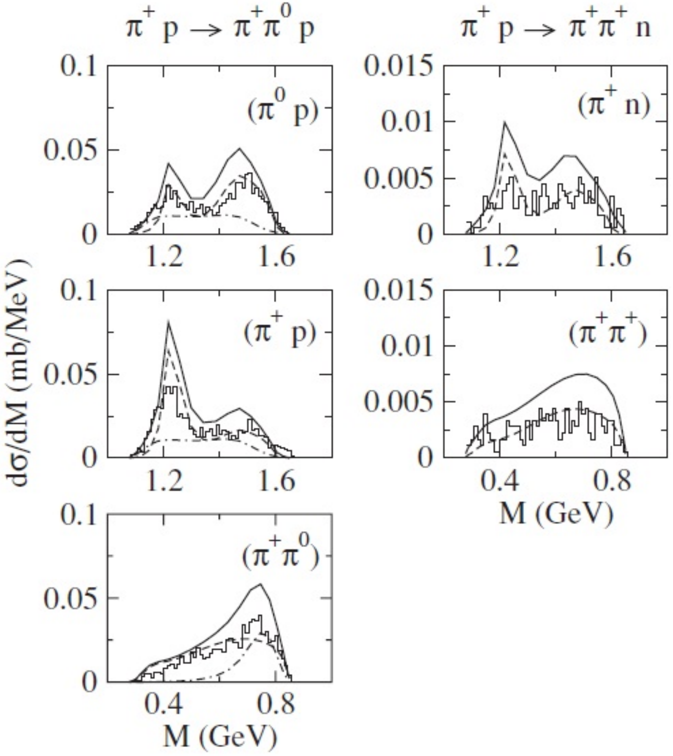
## Only 240K events measured in 1970's




W : $\pi\pi N$ cm energy

H. Kamano et al., PRC 79 025206 (2009).

# Mass Projections

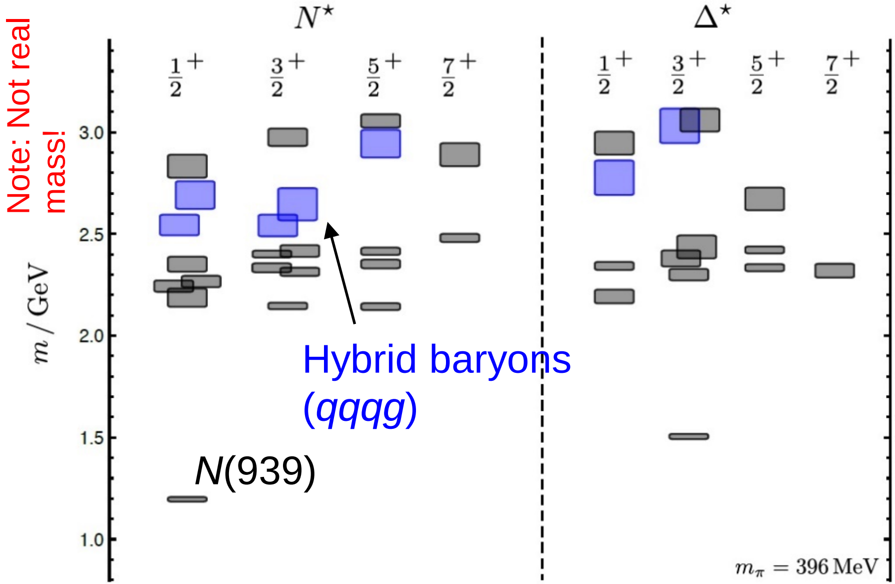



Note: the normalization of these data is not known. The total cross sections were used to set the vertical scale.

The solid curves are the full calculation using only $\pi$N elastic data. The other curves do not include some coupled-channels effects.

# Hybrid baryons from Lattice QCD

J. Dudek et al., PRD85 (2012) 054016



# Additional final state: KY data

- Data for $K\Lambda$ and $K\Sigma$ come for free
  - Cross sections are smaller, but the final state is two-body, so less data are needed.
  - These final states have two charged particles and hence will be part of the trigger.
- Data on $\pi^+ p \rightarrow K^+ \Sigma^+$ are especially useful
  - Only isospin 3/2 contributes: $\Delta$ resonances.
  - Is the $\Delta(1600)$ the I=3/2 partner of the Roper?

# J-PARC E45 spectrometer

Measuring ($\pi$,2$\pi$) in large acceptance TPC (HypTPC)

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

$\pi^+ p \rightarrow \pi^0 \pi^+ p,\ \pi^+ \pi^+ n$ Trigger with hodoscope *missing mass*

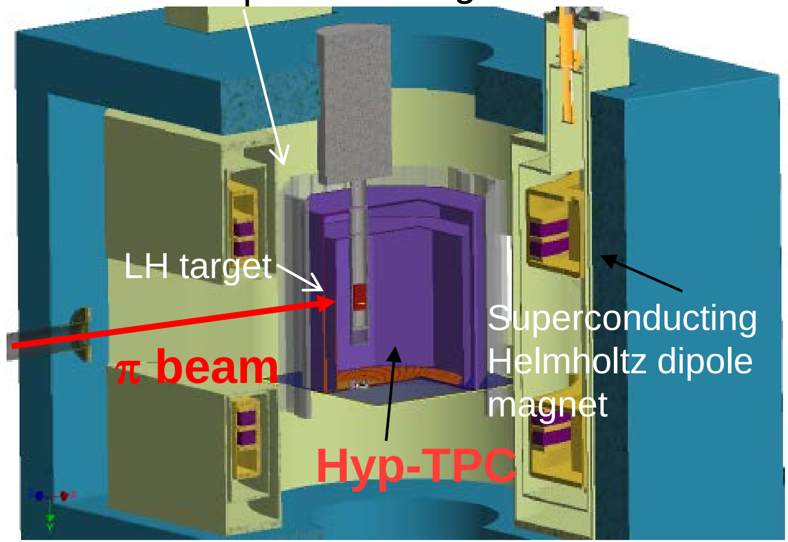
*$\pi N \rightarrow KY$ (2-body reaction)*

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

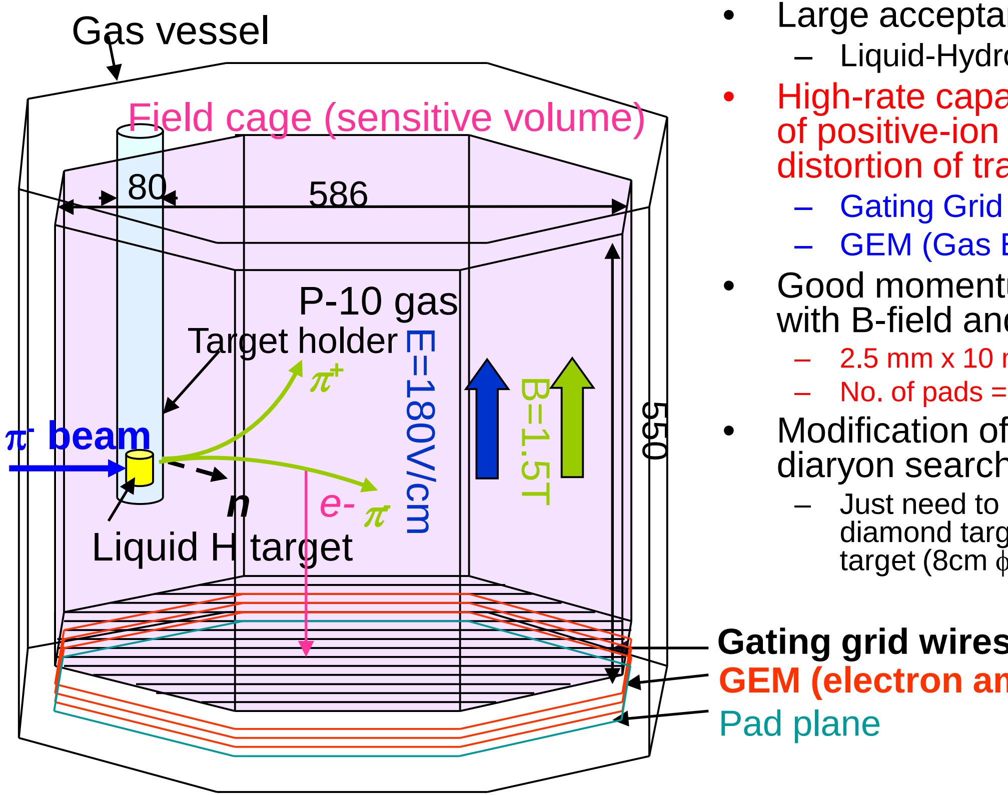
$\pi^+ p \rightarrow K^+ \Sigma^+$ ($I=3/2$, $\Delta^*$)

$\pi^{+-}$ beam on liquid-H target

p= 0.73 – 2.0 GeV/c



# HypTPC

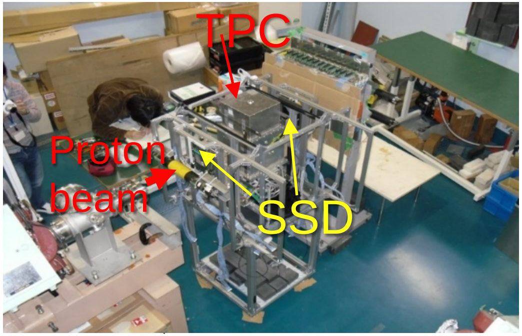



- Large acceptance
  - Liquid-Hydrogen target inside
- High-rate capability with suppression of positive-ion backflow causing distortion of trajectories
  - Gating Grid
  - GEM (Gas Electron Multiplier)
- Good momentum resolution (1-3%) with B-field and fine-segmented pads
  - 2.5 mm x 10 mm pad
  - No. of pads = 5800
- Modification of HypTPC from E42 (H-diaryon search) to E45
  - Just need to replace the target holder for diamond target (2x3cm) to that for liquid-H target (8cm ϕ)

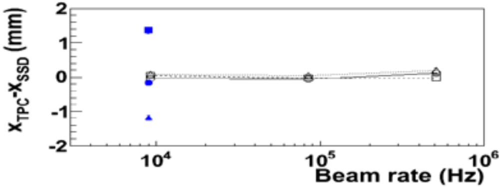
# Prototype TPC test

NIMA763(2014)65-81

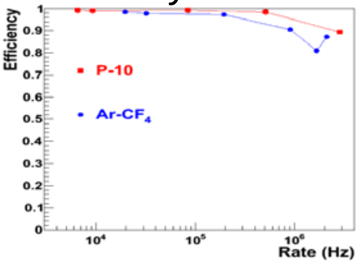
- Beam test at RCNP (Osaka Univ.)
  - Proton beam at 400 MeV
  - Beam rate up to $10^6$ Hz/cm$^2$




Hit position distortion <0.1mm

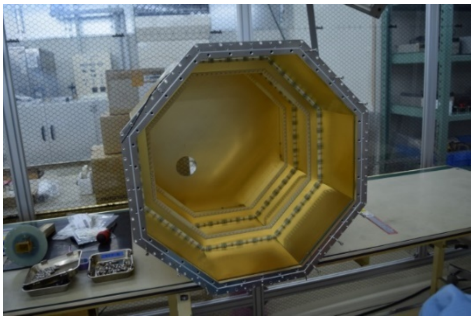


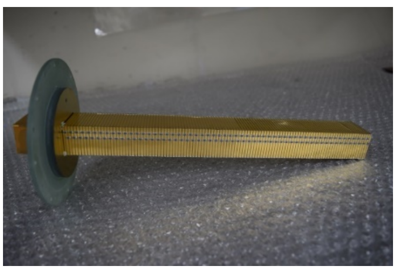

Efficiency>95% at $10^6$Hz



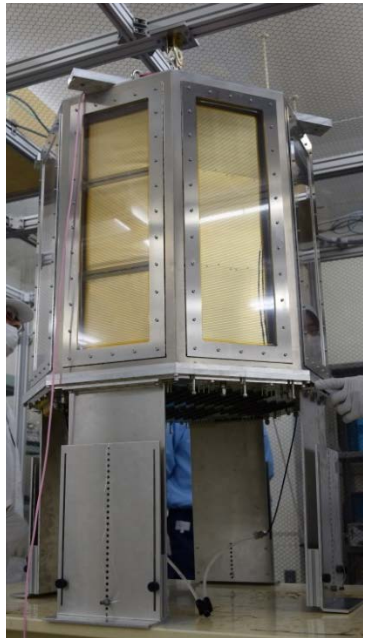
# HypTPC

Field cage

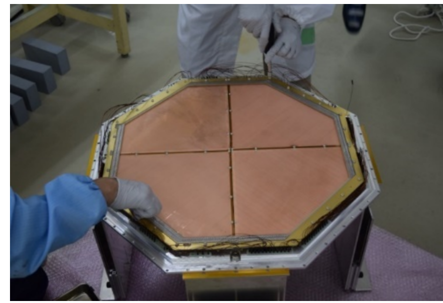


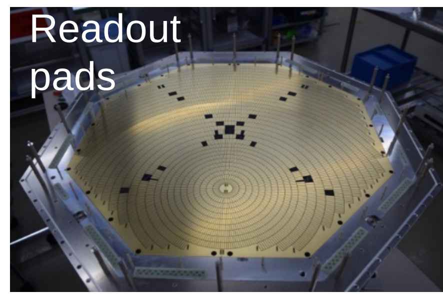


Completed in 2016



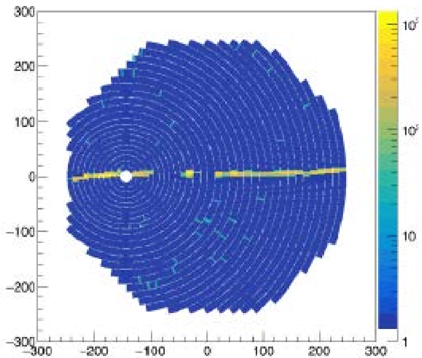
GEM

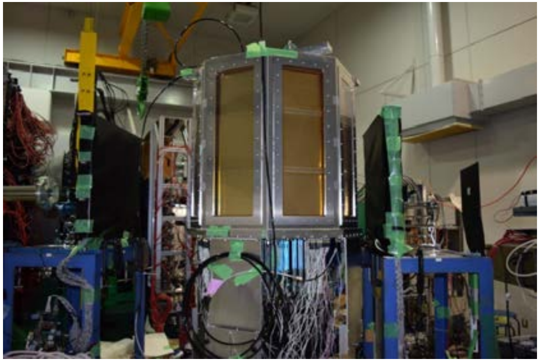


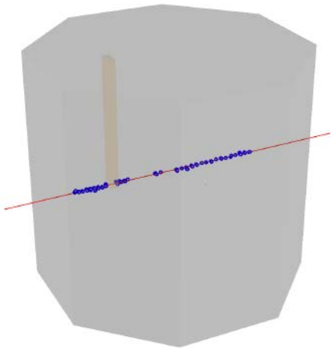


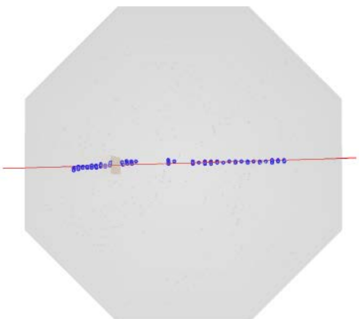
# Beam test at ELPH (Tohoku U.) Nov. 2016

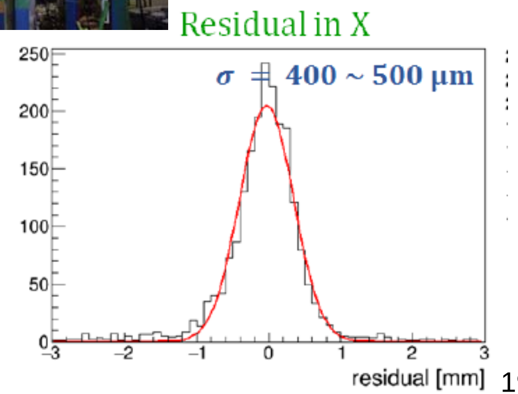
- TPC efficiency and position resolution similar to the designed values



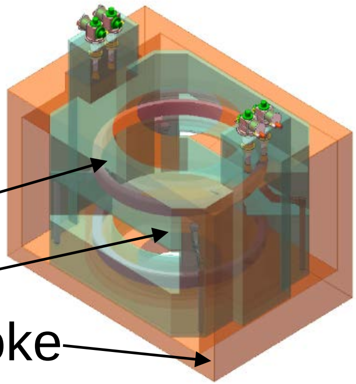




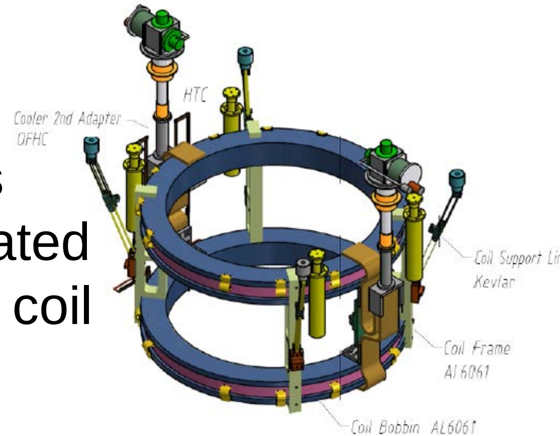


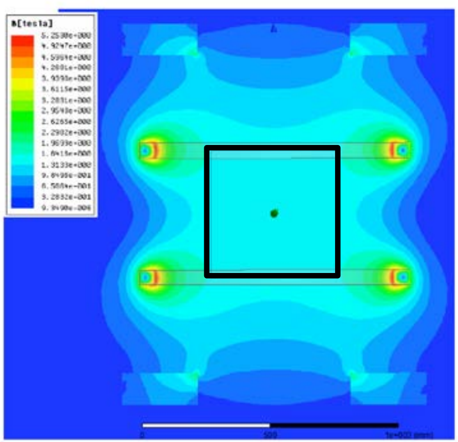
# Superconducting Helmholtz magnet

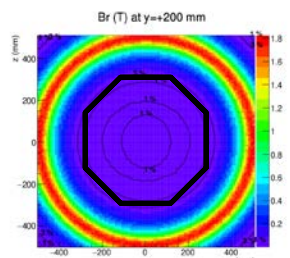
Coils
Cryostat
Return yoke



2 coils separated by the coil radius



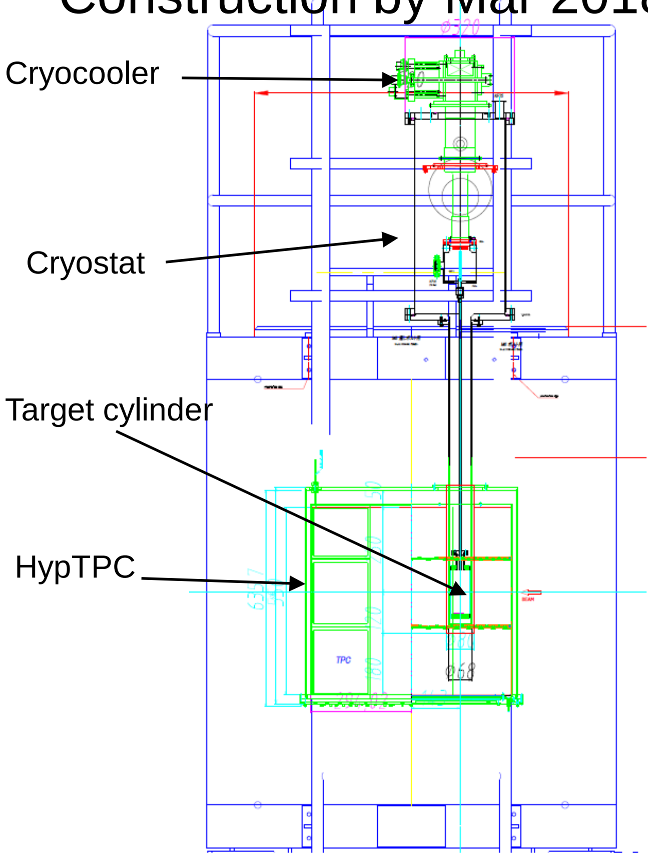


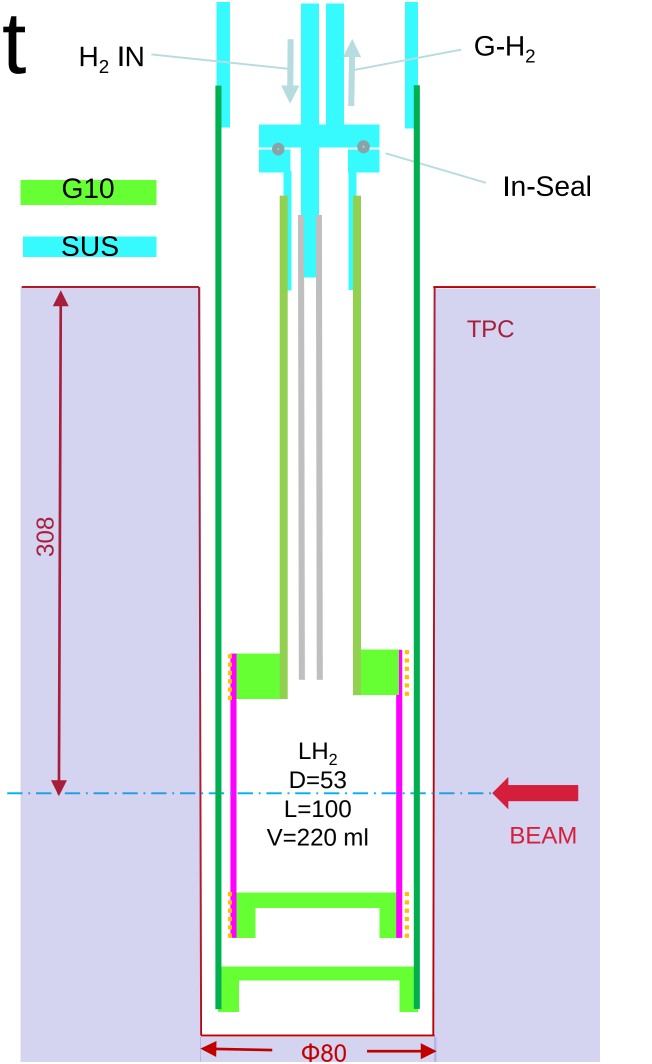

Br in TPC field cage <1%

# L-$H_2$ target

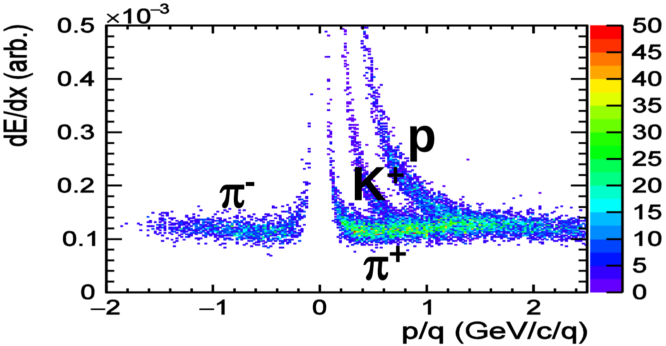
Design underway

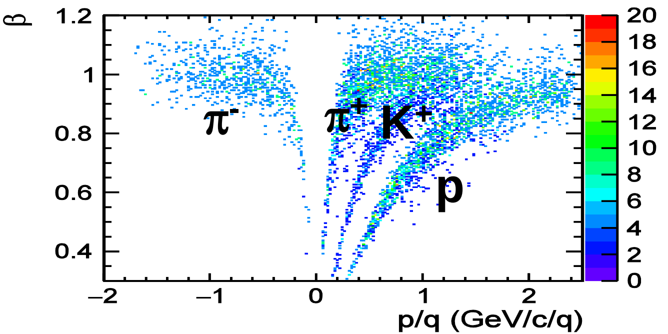
Construction by Mar 2018



# Particle identification (GEANT)




TPC dE/dx

$\pi$/K : p<=0.5 GeV/c

$\pi$/p : p<=1.1 GeV/c

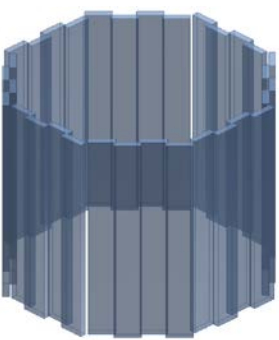
Hodoscope TOF

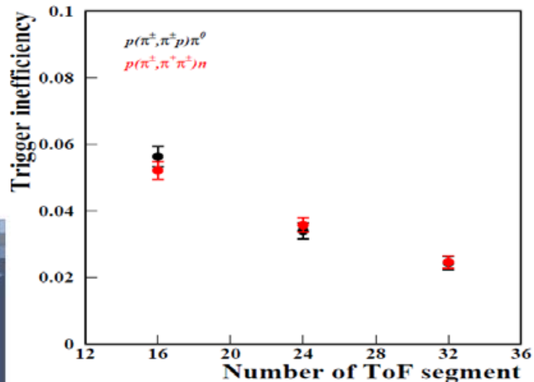
$\sigma_T$ = 100ps

# Trigger efficiency and acceptance

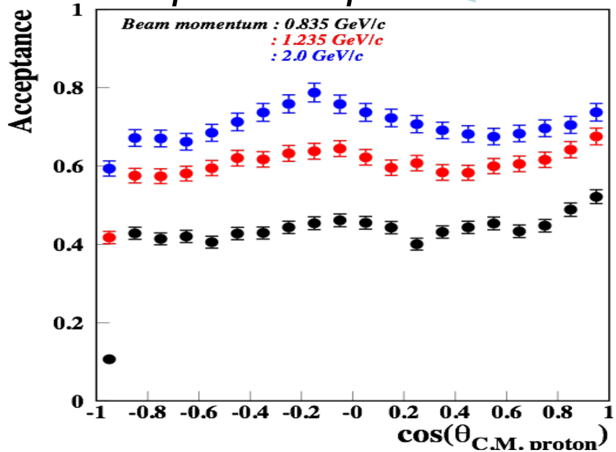
2-charged particle trigger
(inefficiency due to double hit)

hodoscope



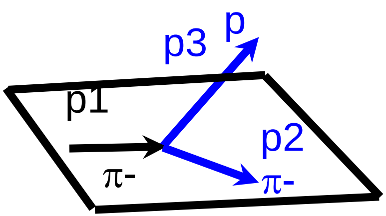



$\pi^+p \to \pi^+\pi^0p$ reaction



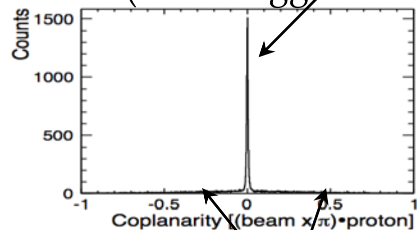

Proton momentum > 300 MeV/c

# Rejection of elastic scattering



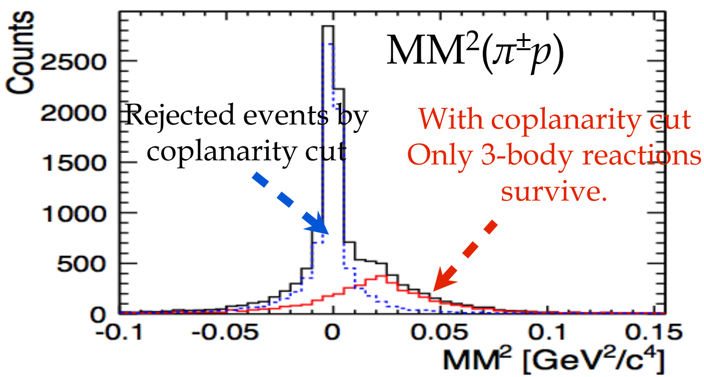

Coplanarity
=cosine of angle
between p1 and
(p2xp3)

Elastic scattering
(Same trigger condition)




3-body reaction

$\pi^- p \rightarrow \pi^- \pi^0 p$ reaction



# Expected statistics at E45

- $\pi$ beam rate : ~$10^6$ / cycle (6s)
- Liquid H target : 5 cm thickness
- TPC acceptance : 40%
- ($\pi$,2$\pi$) cross section : ~2 mb
- ⇨ 160 events / cycle (6 s)
- Background : elastic scattering
  3200 events / cycle

- $\pi$p CM energy : 1.50 – 2.15 GeV
- No. of bins : $\pi^-$ beam : 24 (energy) x 20 (angle)
  $\pi^+$ beam : 23 (energy) x 20 (angle)
- No. of events / bin : 32 K

⇨ 30M events in 15 days

Increase world's $\pi\pi N$ data (240K) by a factor of 130

# Other physics possibilities with HypTPC

- *H*-dibaryon (E42) : $K^{-}C \rightarrow K^{+}H X$, $H \rightarrow \Lambda\Lambda, \Lambda\pi^{-}p, \Xi^{-}p$
- $\Lambda(1405)$ : $\pi^{-}p \rightarrow K^{0}\Lambda(1405)$

  $\Lambda(1405) \rightarrow \Lambda\gamma$ ($\bar{K}$N compositeness, T. Sekihara, *PR*C89 (2014) 025202)
- $K^{-}pp$ : $\pi^{+}d \rightarrow K^{+}K^{-}pp$

  $K^{-}pp \rightarrow \Lambda p, \Sigma^{0}p, \Lambda\pi^{0}p, \Sigma^{0}\pi^{0}p$
- $\Xi$ excited states:

  $K^{-}p \rightarrow K^{+}\Xi^{-*}$, $\Xi^{-*} \rightarrow \Lambda K^{-}, \Sigma^{0}K^{-}, \Sigma^{-}K^{0}, \Xi^{-}\pi^{0}, \Xi^{0}\pi^{-}, \Xi^{-}\gamma$

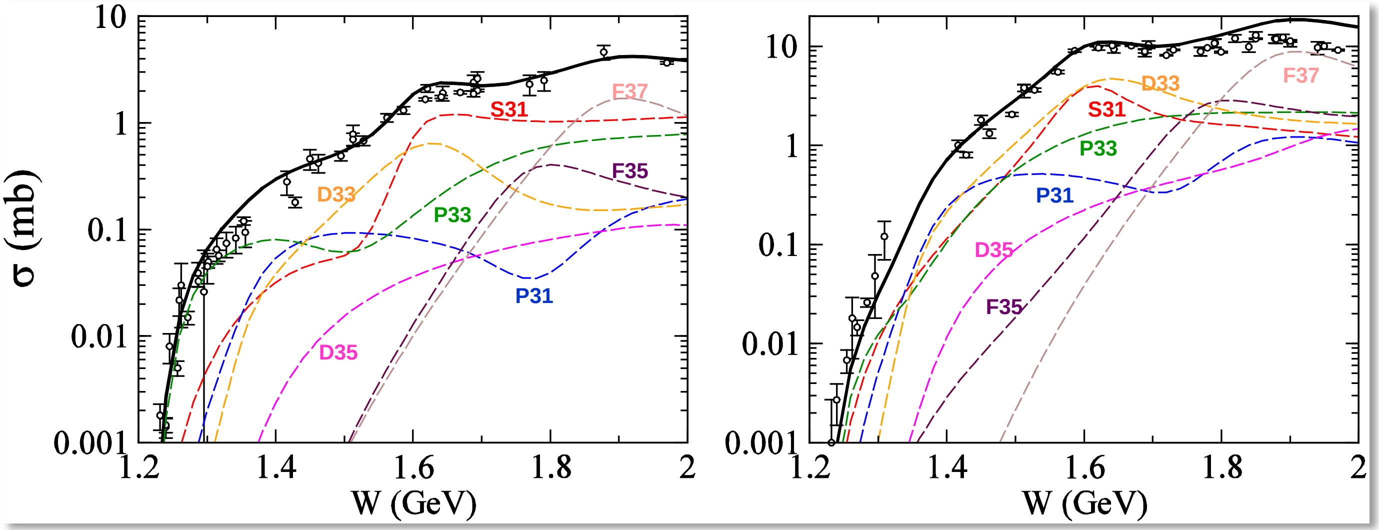
  $K^{-}p \rightarrow K^{0}\Xi^{0*}$, $\Xi^{0*} \rightarrow \Lambda K^{0}, \Sigma^{0}K^{0}, \Sigma^{+}K^{-}, \Xi^{-}\pi^{+}$

# Summary and outlook

- J-PARC E45 was proposed to establish baryon excited states up to 2 GeV/$c^2$ in ($\pi$,2$\pi$) reactions, which will increase previous data statistics by two-orders of magnitude.
- Large acceptance spectrometer was designed based on HypTPC, Helmholtz magnet with $10^6$Hz pion beams.
- The spectrometer will be ready in Mar 2018.
- Application of Stage-II to J-PARC PAC in Jan 2018.
- Stage-II approval in Jul 2018?→Ready for the experiment.

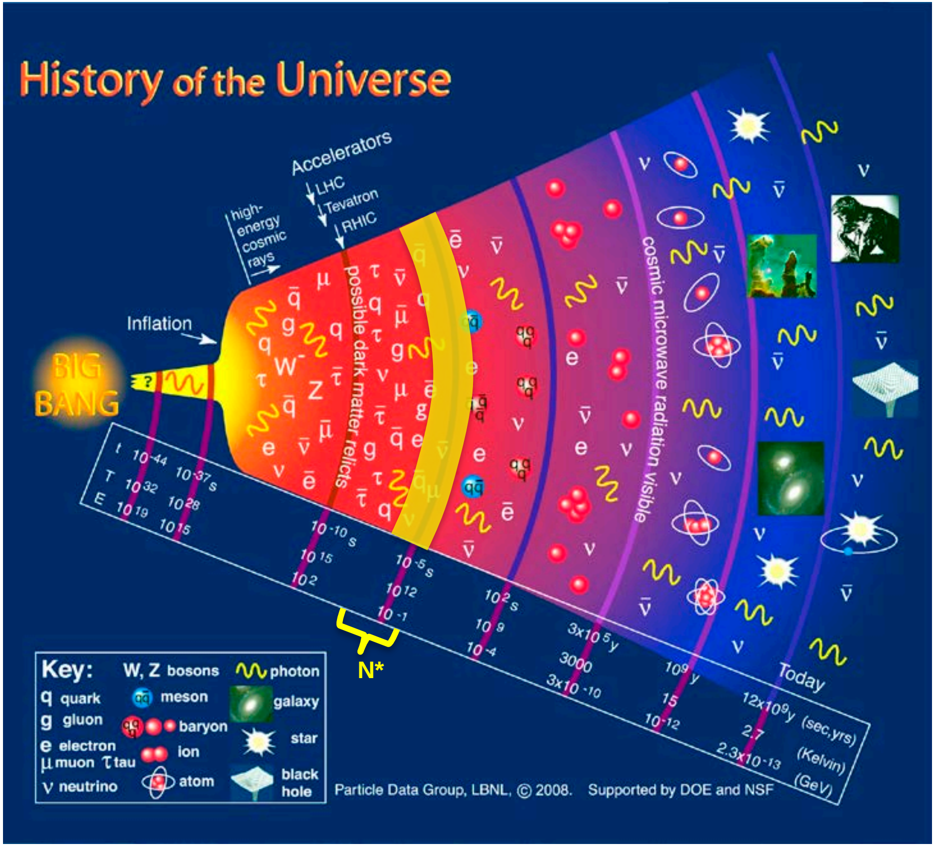
# Contribution of each partial wave

$\pi^+ p \to \pi^+ \pi^+ n$ $\pi^+ p \to \pi^+ \pi^0 p$




**F37, S31, D33, (F35), (P33) have dominant contributions.**

# Excited Baryons in the history of the Universe

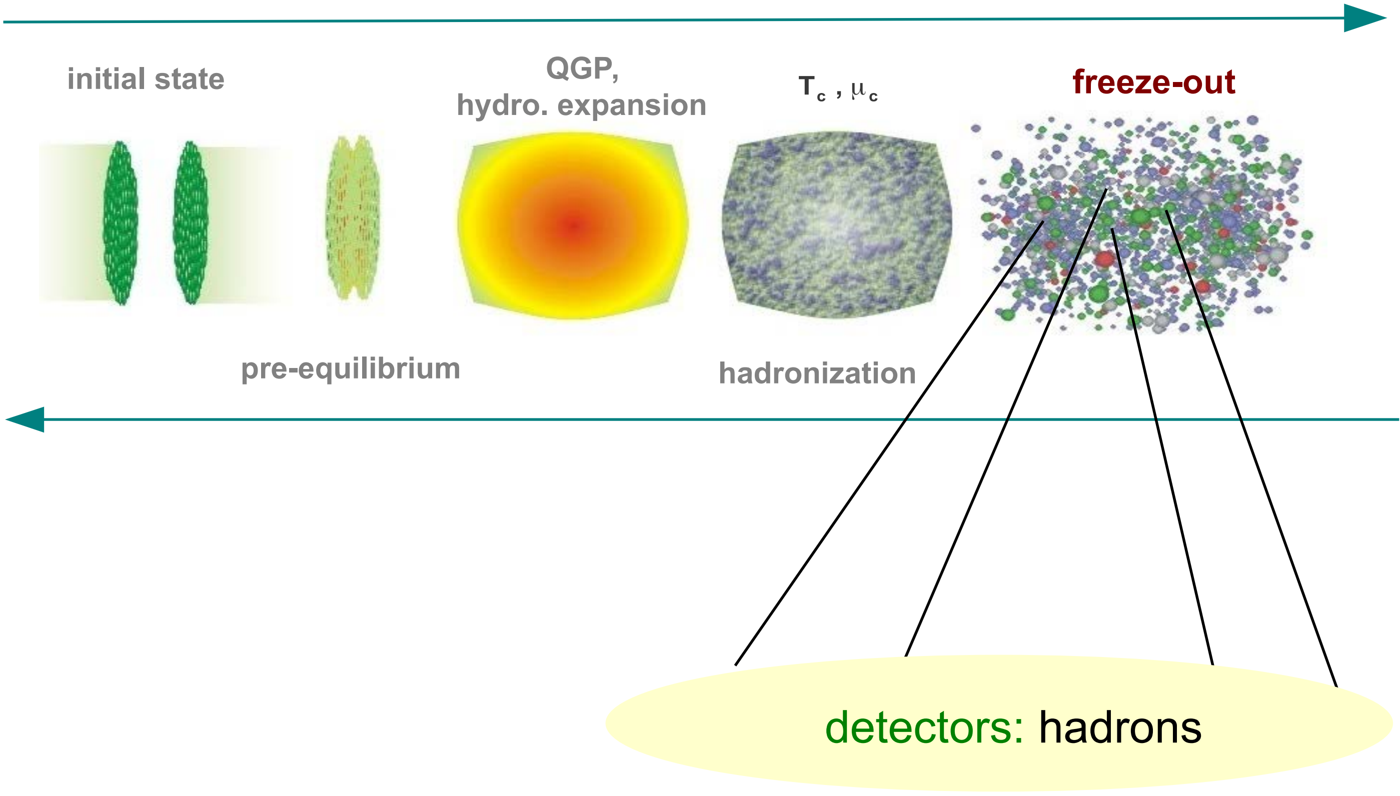



Excited baryons are at the transition between the quark-gluon liquid, described in **hot QCD**, and the confinement of quarks and gluons in nucleons, described in **strong QCD**. This period lasted ~ $10^{-6}$ seconds.

**Do we understand this transition?**

Slide borrowed from V. Burkert.

# Heavy-ion collisions: a sketch




freeze-out stage

' in HIC

Slide borrowed from S. Mukherjee.