

Hadron Physics using Antimatter Probes at J-PARC HEF

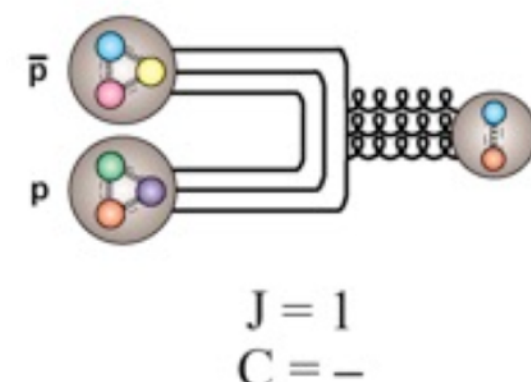
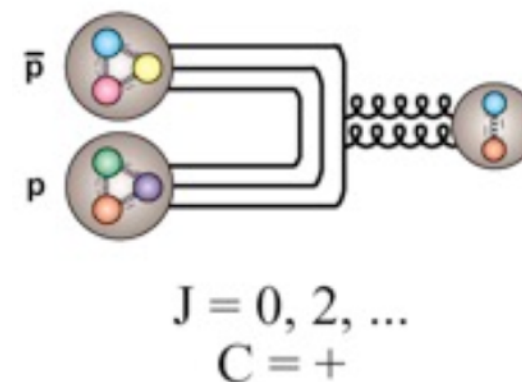
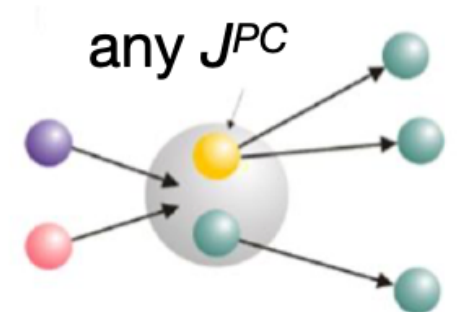
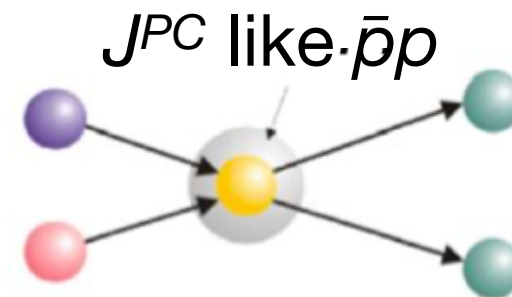
New Perspective on Exotic and Heavy Hadrons

Outline

- Introduction: Antiproton for Hadron Physics
- Physics Reach, Antiproton Facilities, Statistical Reach
- |S| scan of symmetric Hyperon-Antihyperon production: $\bar{p}p \rightarrow \bar{Y}Y$

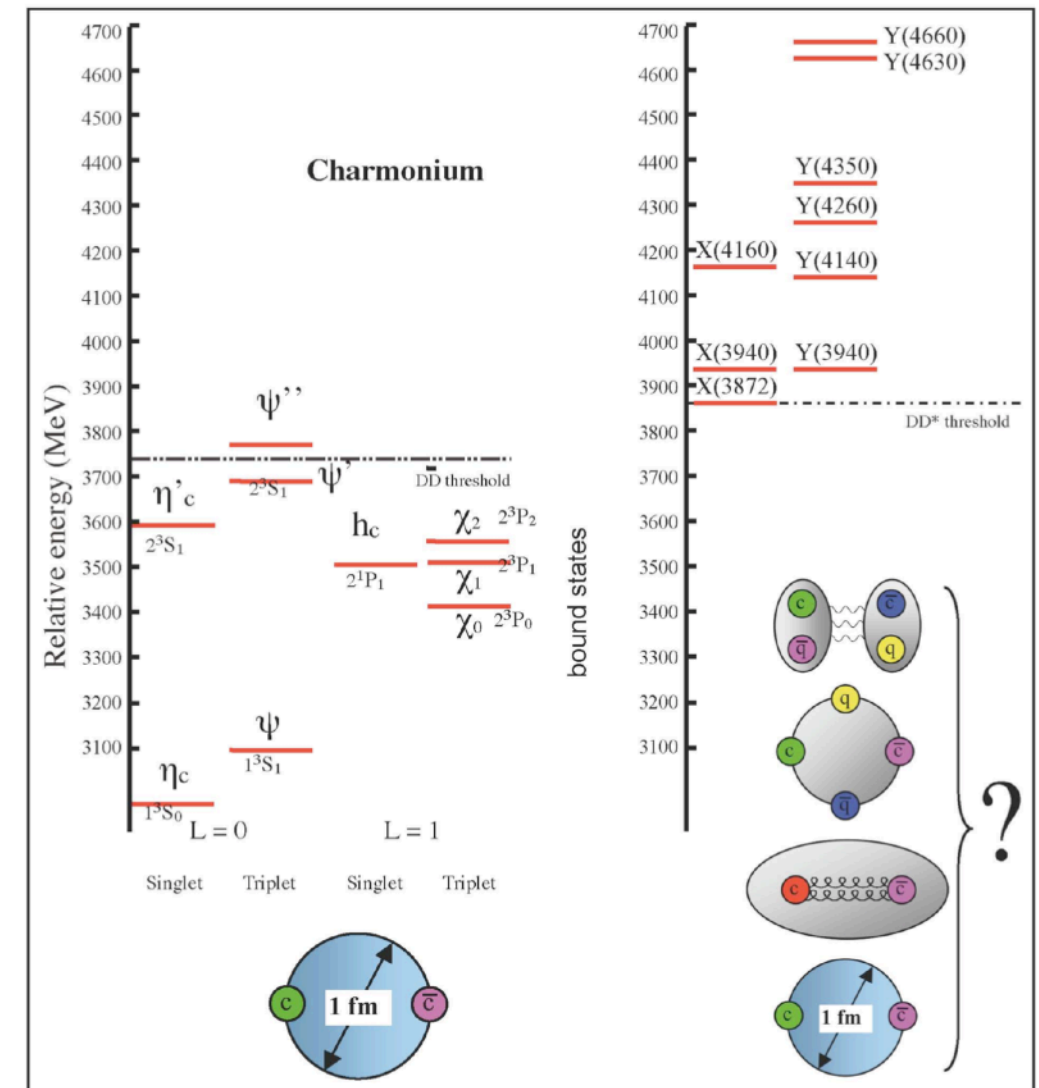
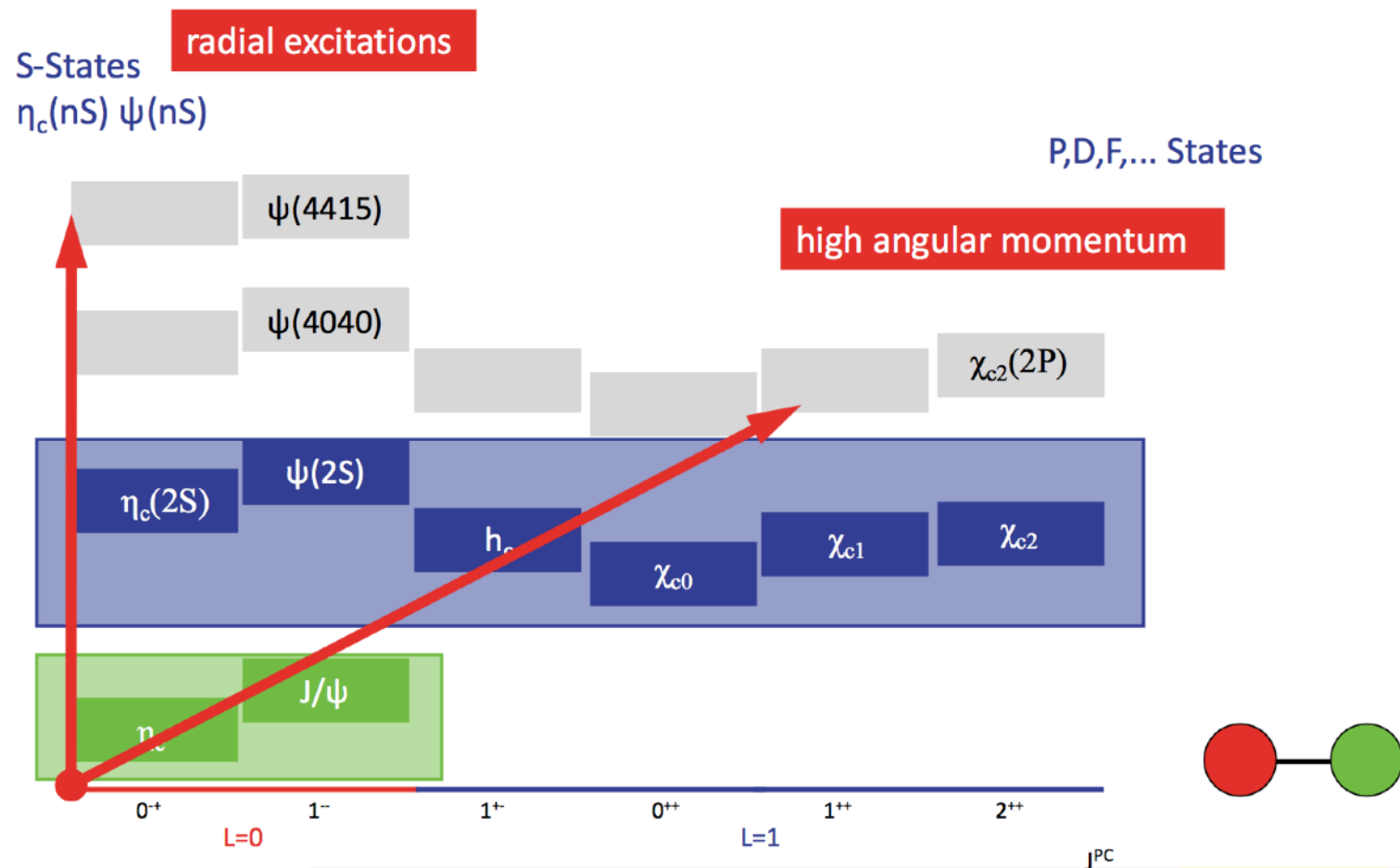
Why Antiproton? A Unique Probe

- Formation of any J^{PC}
 - $\bar{p}p$ annihilation forms resonances of "any" J^{PC} . Fix $\sqrt{s}$ by tuning beam momentum and scan a resonance directly, with none of the missing-mass ambiguity of production experiments.
- A glue-rich process
 - Each annihilation dumps ~ 2 GeV into a flavour-singlet, gluon-rich final state – one of the most efficient known mechanisms for populating glueballs and hybrids.



Charmonium(-like) Spectroscopy

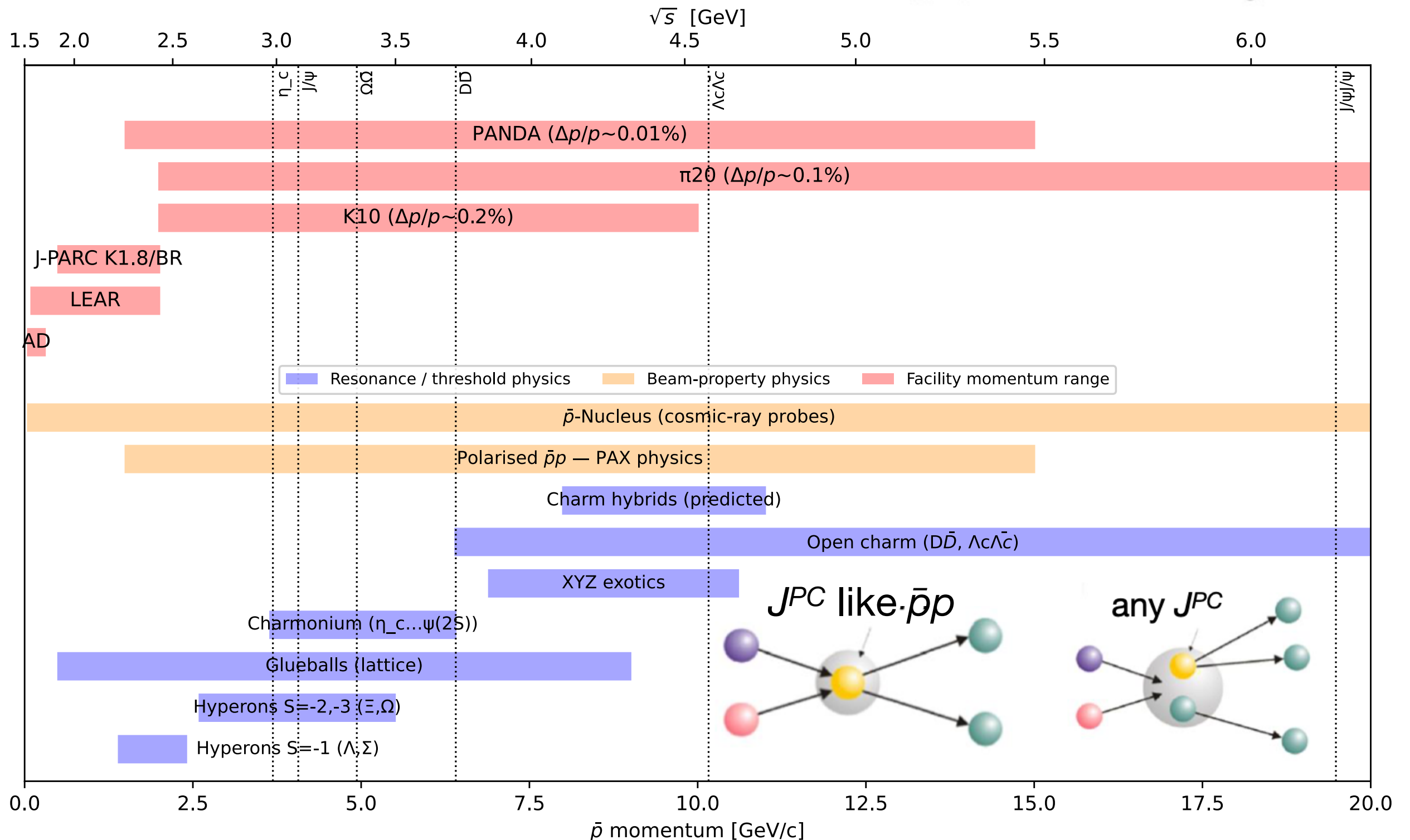
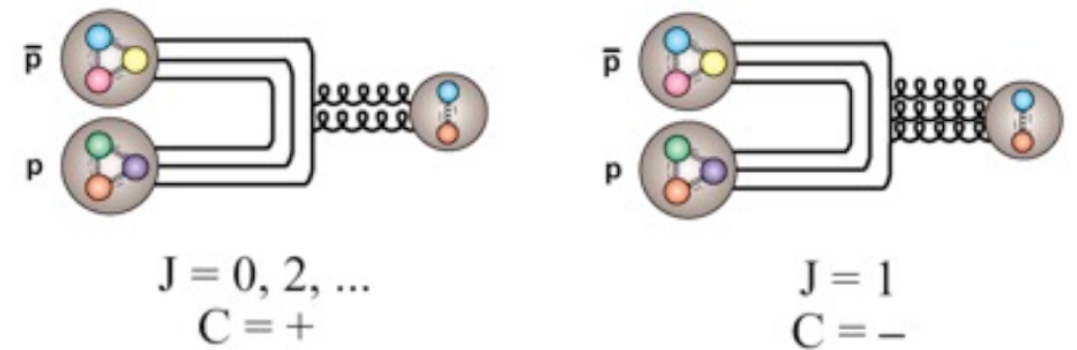
glueballs and exotics



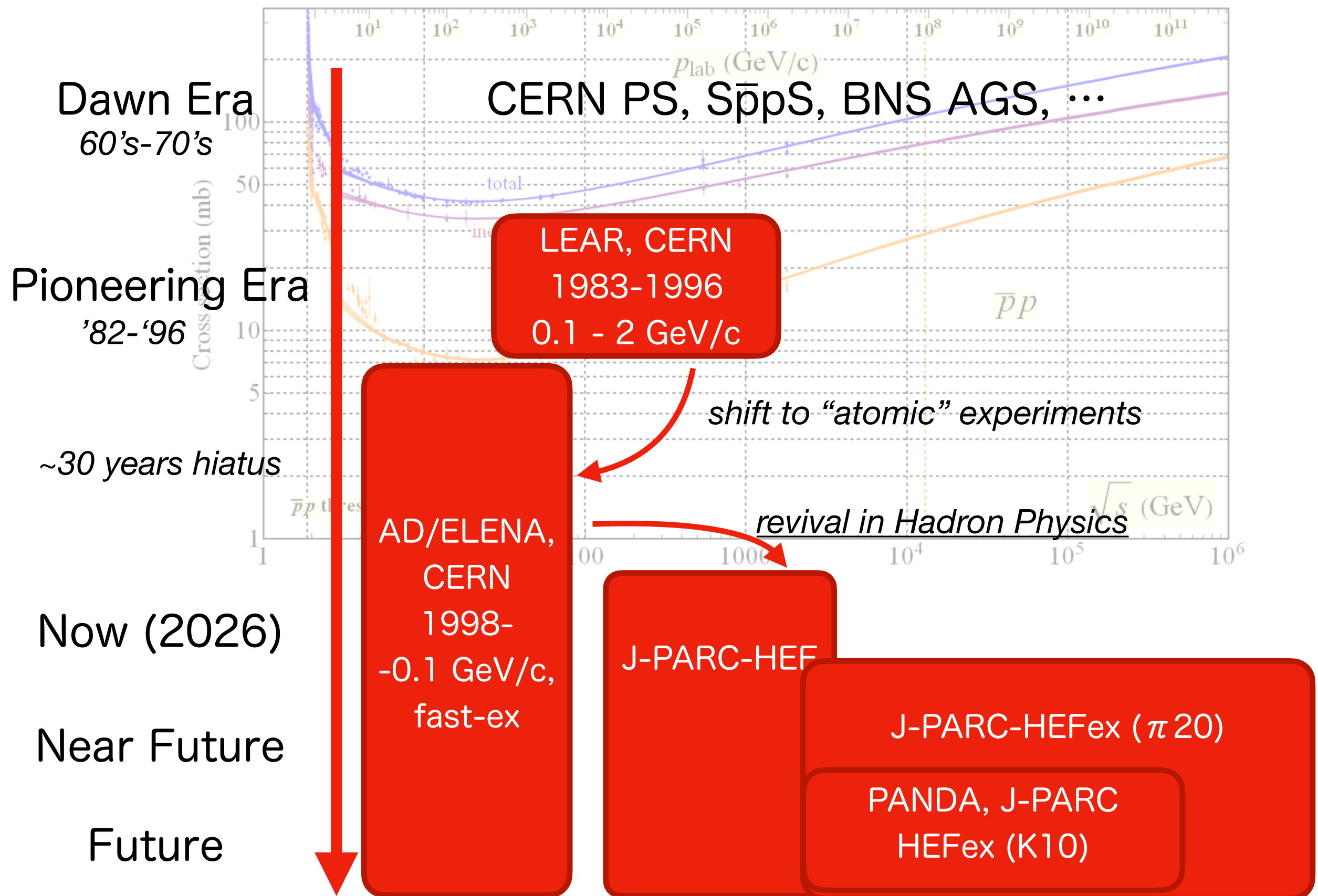
“Mainstream” QCD physics, which LHCb, Belle, PANDA and Lattice QCD are chasing

Physics Reach

$\bar{p}p$ reactions

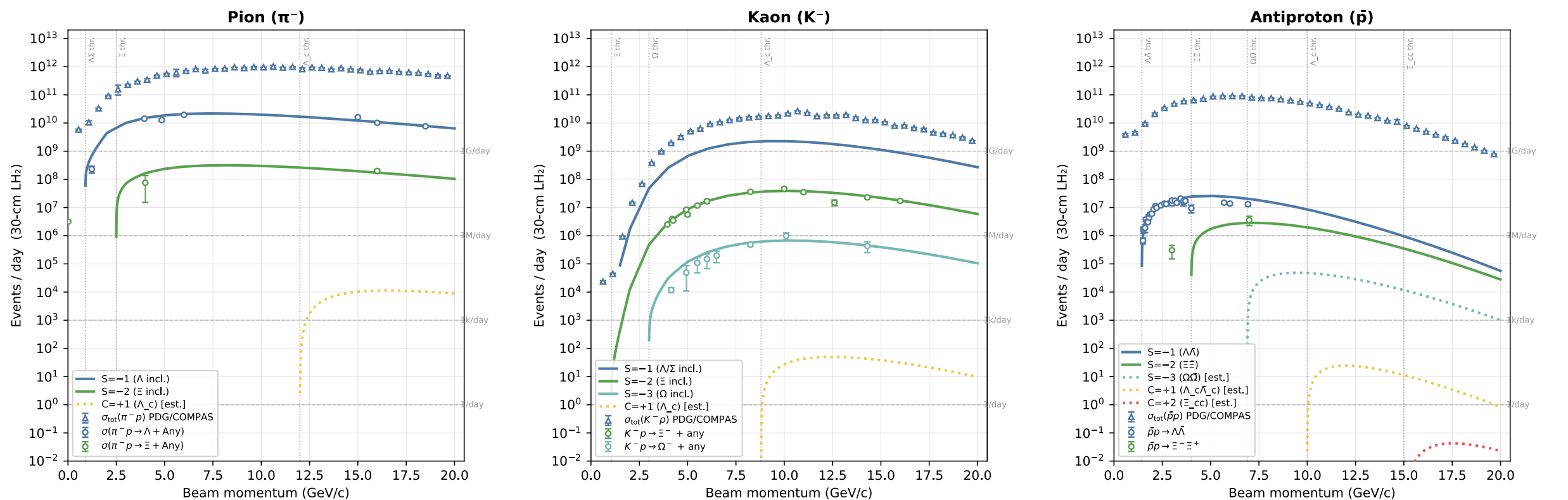
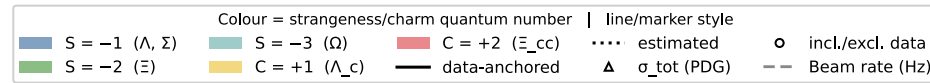
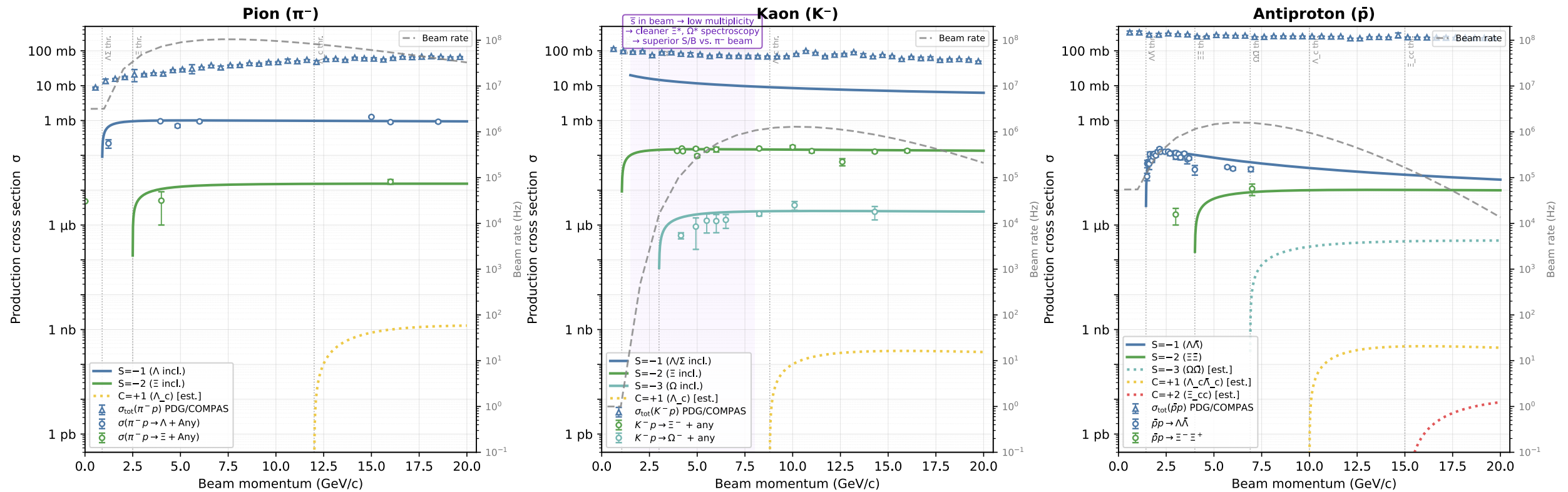


Why now? Why J-PARC? -Antiproton Facilities-



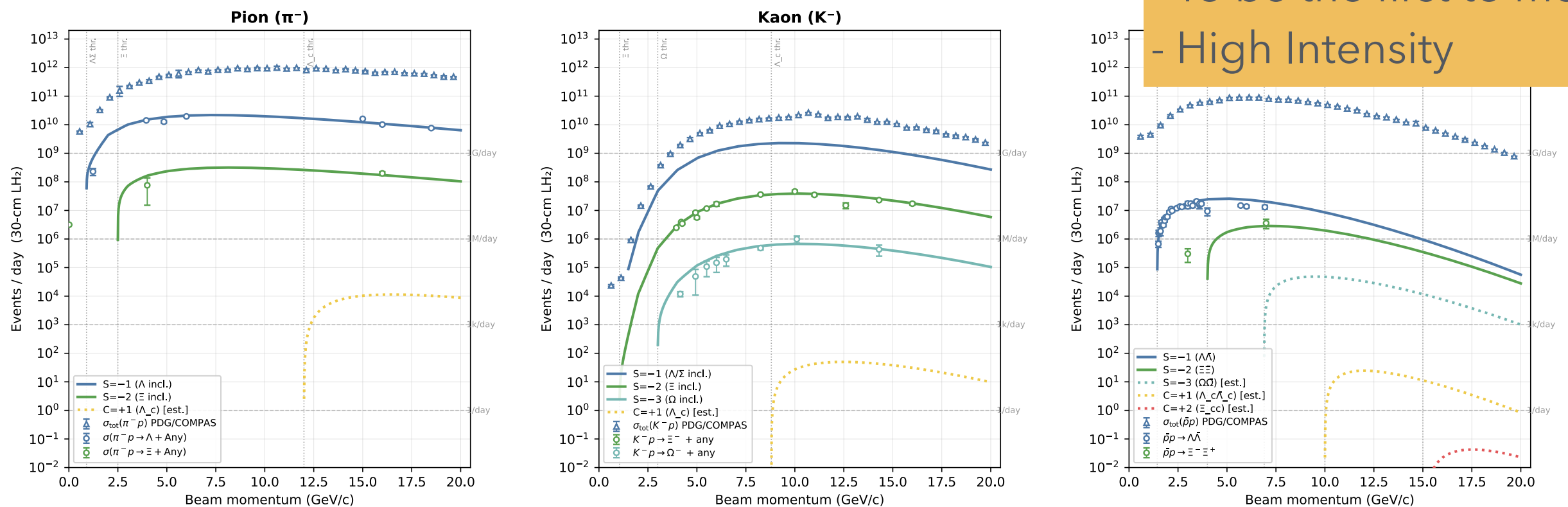
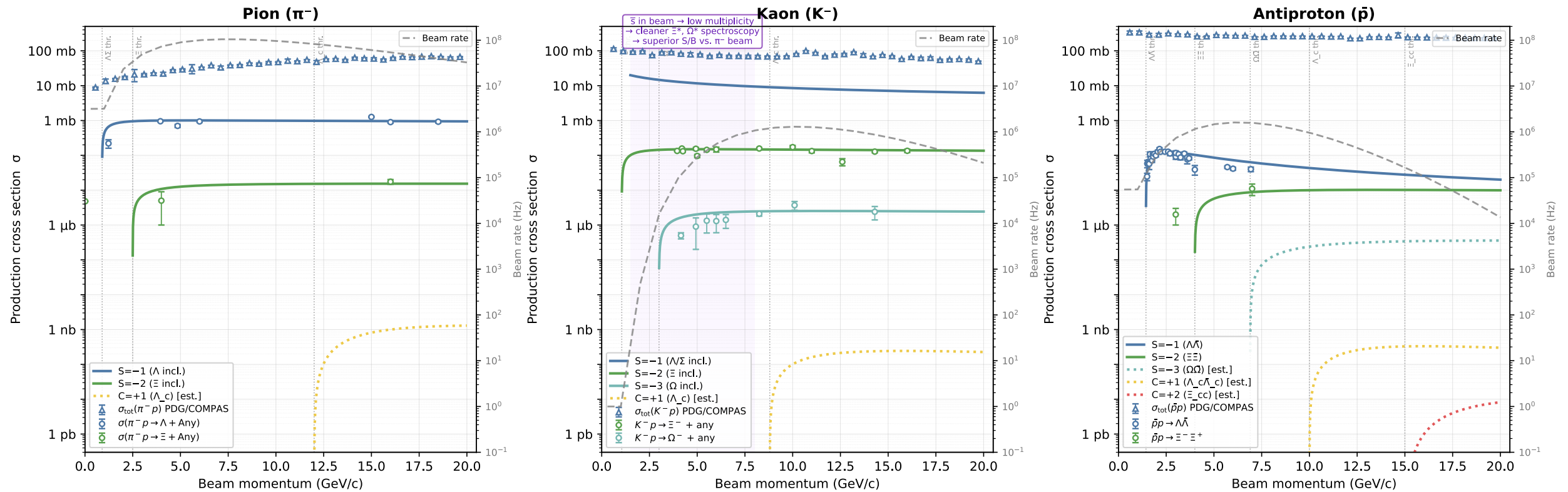
Statistical Reach $\bar{p}$, Ideally coupled with a **storage ring**

J-PARC Hadron Facility — Physics Reach with Realistic Beam Intensities
Cross section vs. beam momentum (right axis: realistic beam rate)



Statistical Reach $\bar{p}$, Ideally coupled with a **storage ring**

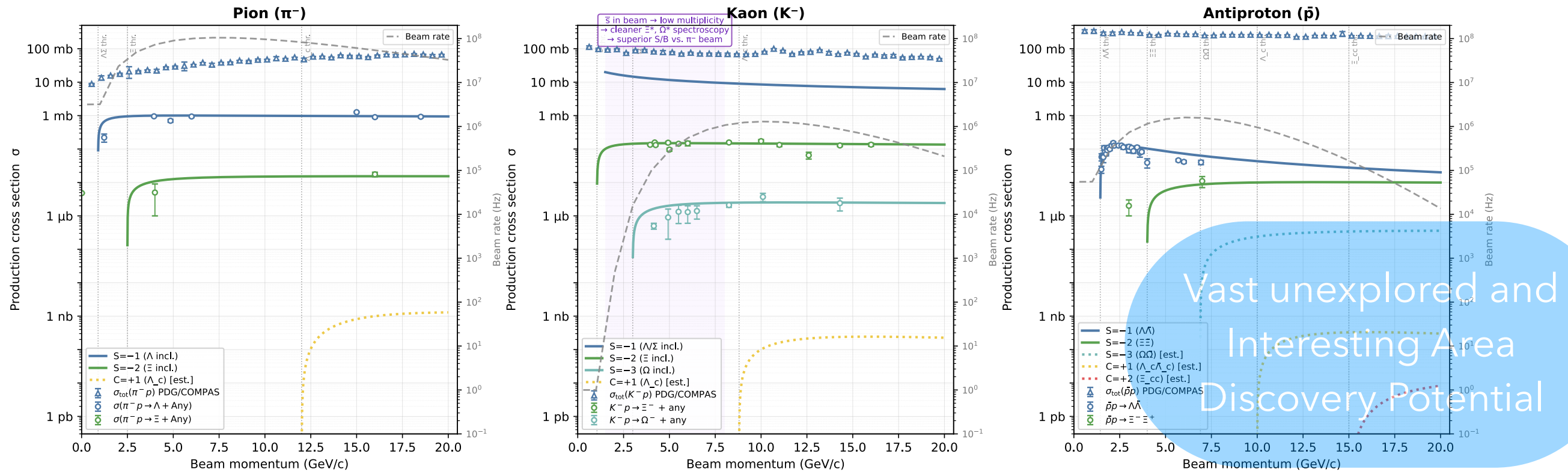
J-PARC Hadron Facility — Physics Reach with Realistic Beam Intensities
Cross section vs. beam momentum (right axis: realistic beam rate)



- To be the first to measure
- High Intensity

Statistical Reach $\bar{p}$, Ideally coupled with a **storage ring**

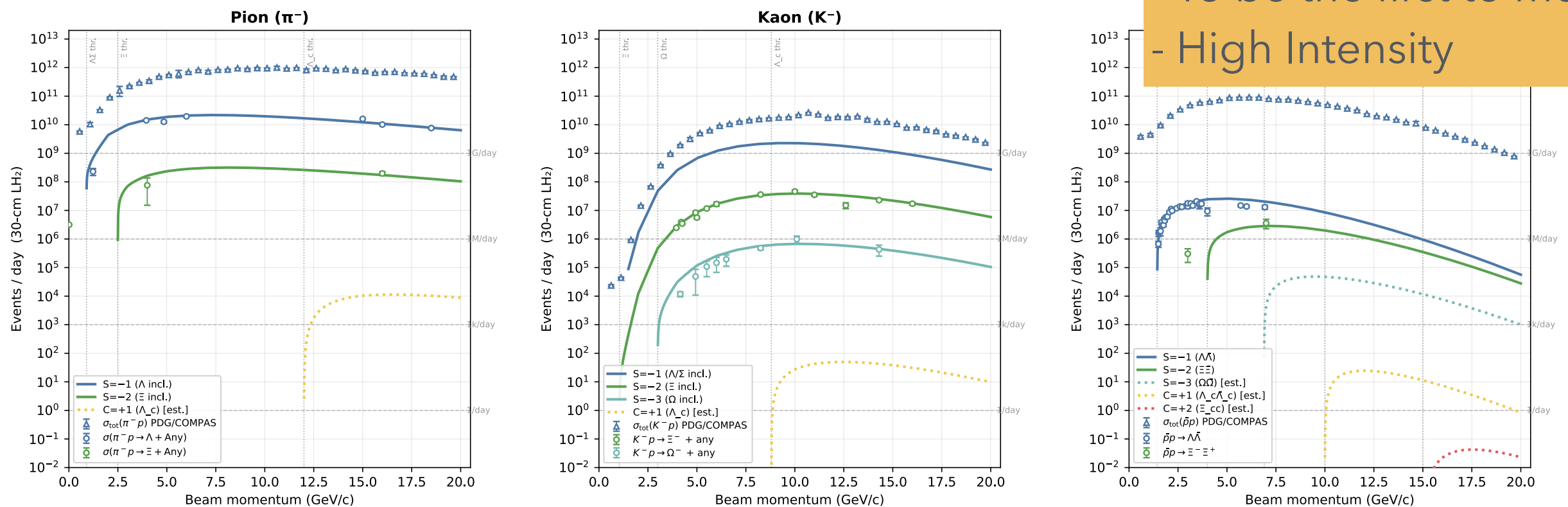
J-PARC Hadron Facility — Physics Reach with Realistic Beam Intensities
Cross section vs. beam momentum (right axis: realistic beam rate)



Colour = strangeness/charm quantum number | line/marker style

$S = -1$ (Λ, Σ) $S = -3$ (Ω) $C = +2$ (Ξ_{cc}) estimated Δ σ_{tot} (PDG) --- Beam rate (Hz)

$S = -2$ (Ξ) $C = +1$ (Λ_c) — data-anchored $\circ$ incl./excl. data



- To be the first to measure

- High Intensity

$\bar{p}$ beam parameter comparison

- $\pi 20$
 - unseparated beam, dominated by π , can limit the overall beam intensity
 - MPD: Multi Purpose/Physics Detector/Data-taking
- K10
 - separated beam, potentially higher intensity

		$\bar{p}$ momentum range	corresponding $\sqrt{s}$ ($\bar{p}+p$ reaction)	momentum precision	intensity	Available from	
FAIR	$\bar{P}$ ANDA High Luminosity Mode	1.5-15 GeV/c	2.3-5.3 GeV	1×10^{-4}	< 20 MHz*	20??	Precision study
	$\bar{P}$ ANDA High Resolution Mode	1.5-15 GeV/c	2.3-5.3 GeV	5×10^{-5}	< 2 MHz*		
J-PARC	K1.8(BR)	-2 GeV/c	~ 2.5 GeV		2M/spill (90%)@1.8GeV/c	✓	Discovery
	$\pi 20$ @J-PARC	~ 2 -20 GeV/c	2.5-6.4 GeV	1×10^{-3}	7M/spill @7GeV/c	202?	
	K10@J-PARC	~ 2 -10 GeV/c	2.5-4.3 GeV	2×10^{-3}	6.5M/spill @7GeV/c	203?	

* Interaction rate

$$\bar{p}p \rightarrow \bar{Y}Y \text{ |s| scan}$$

Symmetric Hyperon-Antihyperon production

S=-1

LEAR

S=-2

LEAR not accessible

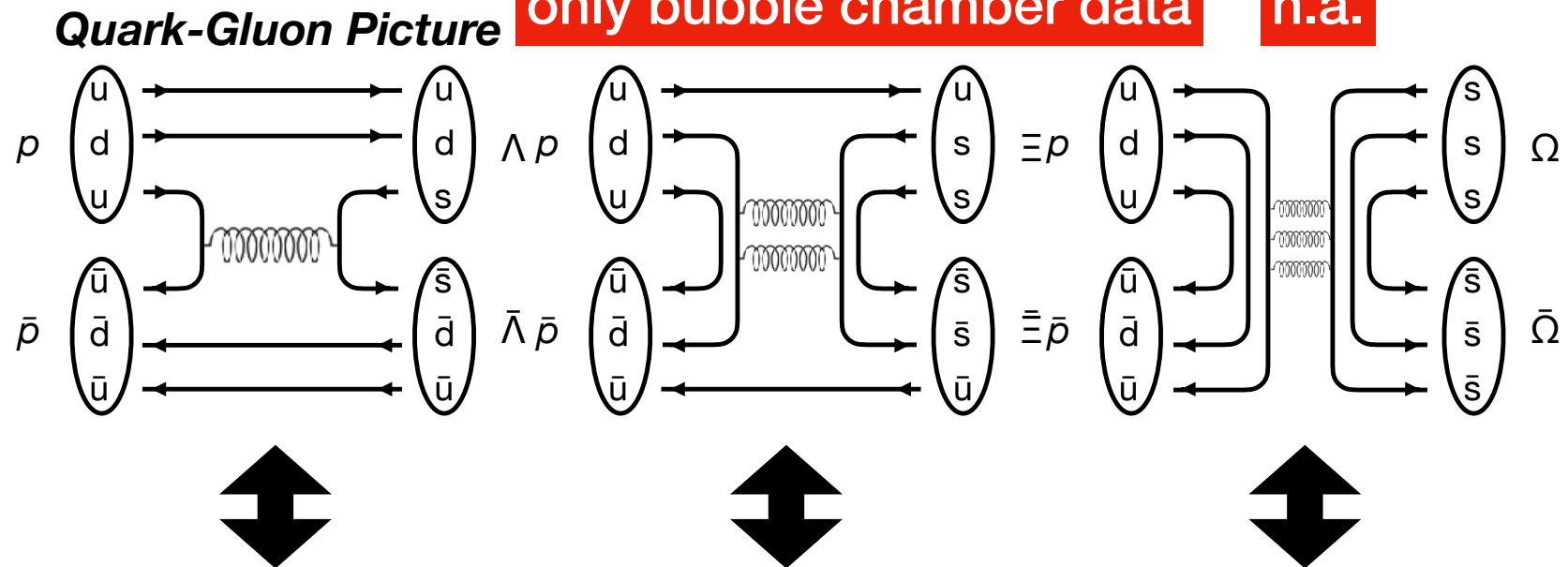
S=-3

n.a.

Total inelastic ~50 mb

Quark-Gluon Picture

s-channel interaction of $\bar{q}q$ turning to $\bar{s}s$.



Meson-Exchange Picture

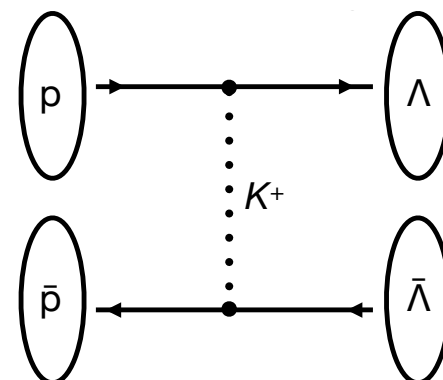
strong t-channel tensor interaction to spin-flip

- $\bar{p}p \rightarrow \bar{\Xi}^+ \Xi^-$ (dss)

- ~1 μb (bubble chamber data)

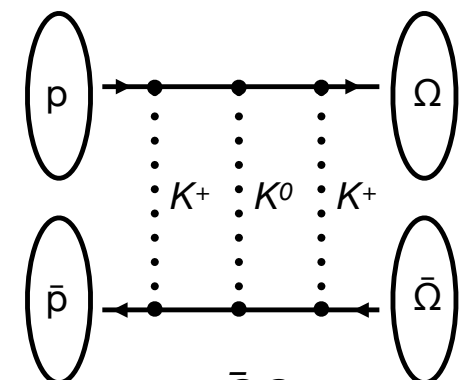
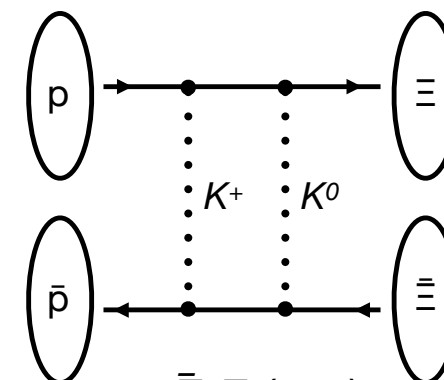
- $\Xi^- \rightarrow \Lambda \pi^-$ (100%)

- comparison to $\bar{p}p \rightarrow \bar{\Lambda} \Lambda$: I_0 , OZI rule



- $\bar{p}p \rightarrow \bar{\Xi}^0 \Xi^0$ (uss)

- π^0 in the final state



- $\bar{p}p \rightarrow \bar{\Omega} \Omega$

- ~50 nb?

- vs $\bar{p}p \rightarrow \phi \phi \phi$

Additional Motivations

- Near-threshold systematics may give more than cross sections. The energy dependence and the $\bar{Y}Y$ invariant-mass distribution carry the $\bar{Y}Y$ scattering length, and s-t crossing turns this into a constraint on the pY interaction.
- HAL QCD predicts a shallow (~ 1.6 MeV) bound state in $\Omega\Omega$ (1S_0) and a bound $N\Omega$ (5S_2). ALICE femtoscopy tests this only indirectly, through final-state interactions. **An independent method is decisively missing.**
- The hyperon puzzle in neutron stars. For $|S|\geq 2$, the scarcity of ΞN and ΩN data remains one of the largest uncertainties in the equation of state of dense matter. (c.f. gravitational-wave)
- **$\bar{\Lambda}\Lambda$ bound states.** The near-threshold behaviour seen by PS185 has never been settled. A $|S|$ scan revisits it with modern statistics.

$e^+e^- \rightarrow \bar{Y}Y$ at BESIII

Phys. Rev. Lett. 126, 092002 (2021)

- $e^+ + e^- \rightarrow \psi(3686) \rightarrow \Omega^-\bar{\Omega}^+$.
- $4.48 \times 10^8 \psi(3686)$
- Fit Joint angular distribution $\Omega^- \rightarrow K^-\Lambda$, $\Lambda \rightarrow p\pi^-$, Helicity amplitudes and $\Omega^- \rightarrow K^-\Lambda$ decay parameter.
- Model-independent determination of Ω^- spin=3/2 ($>14\sigma$)
- Almost no additional cost for going S=1 to 3
- $\Gamma(\psi \rightarrow \bar{\Omega}\Omega)/\Gamma(\psi \rightarrow \bar{\Lambda}\Lambda) \sim 0.5$

“Self-Analysing” Quirk of Hyperon

- Hyperon decays with a parity-violating weak interaction

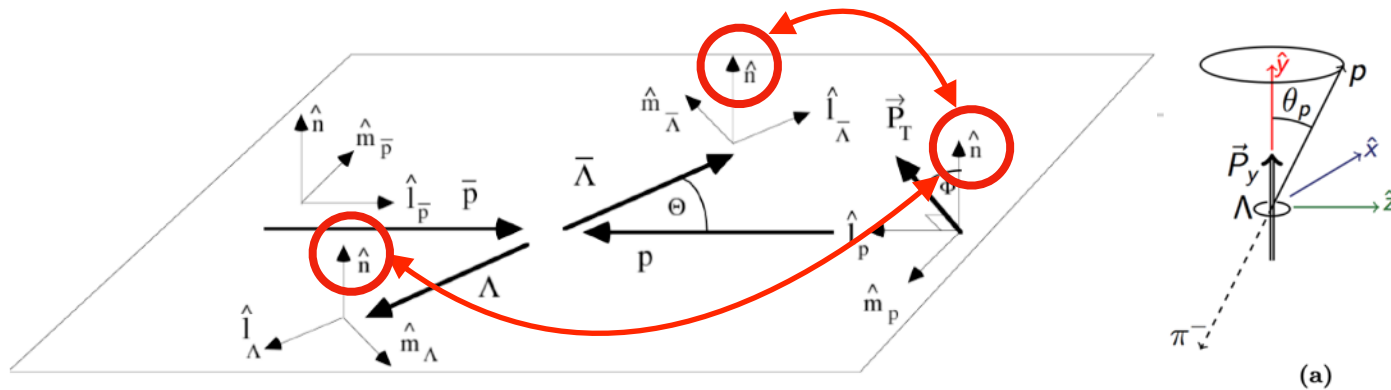
In the $\Lambda \rightarrow p\pi^-$ decay, proton emission direction asymmetric to Λ spin direction

- decay angular distribution: $\frac{dN}{d\Omega} \propto 1 + \alpha_{\Lambda} \vec{P}_{\Lambda} \cdot \hat{n}_p$

α : decay asym. parameter, P : polarisation, $\hat{n}$: daughter particle direc.

- hyperon becomes a polarimeter (Self-analysing)
- Unique feature unlike other hadrons. Parity is conserved in resonances that decay with strong-int. (e.g. Δ)
- Spin-dissolved reaction mechanism

Accessing Full Spin Obs. via $\bar{p}p \rightarrow \bar{Y}Y$



Polarised Particle	None	Beam	Target	Both
None	I_{0000}	A_{i000}	A_{0j00}	A_{ij00}
Scattered	$P_{00\mu 0}$	$D_{i0\mu 0}$	$K_{0j\mu 0}$	$M_{ij\mu 0}$
Recoil	$P_{000\nu}$	$K_{i00\nu}$	$D_{0j0\nu}$	$N_{ij0\nu}$
Both	$C_{00\mu\nu}$	$C_{i0\mu\nu}$	$C_{0j\mu\nu}$	$C_{ij\mu\nu}$

Conventional Naming Scheme

Erik Thomé, Thesis (Uppsala-U 2012)

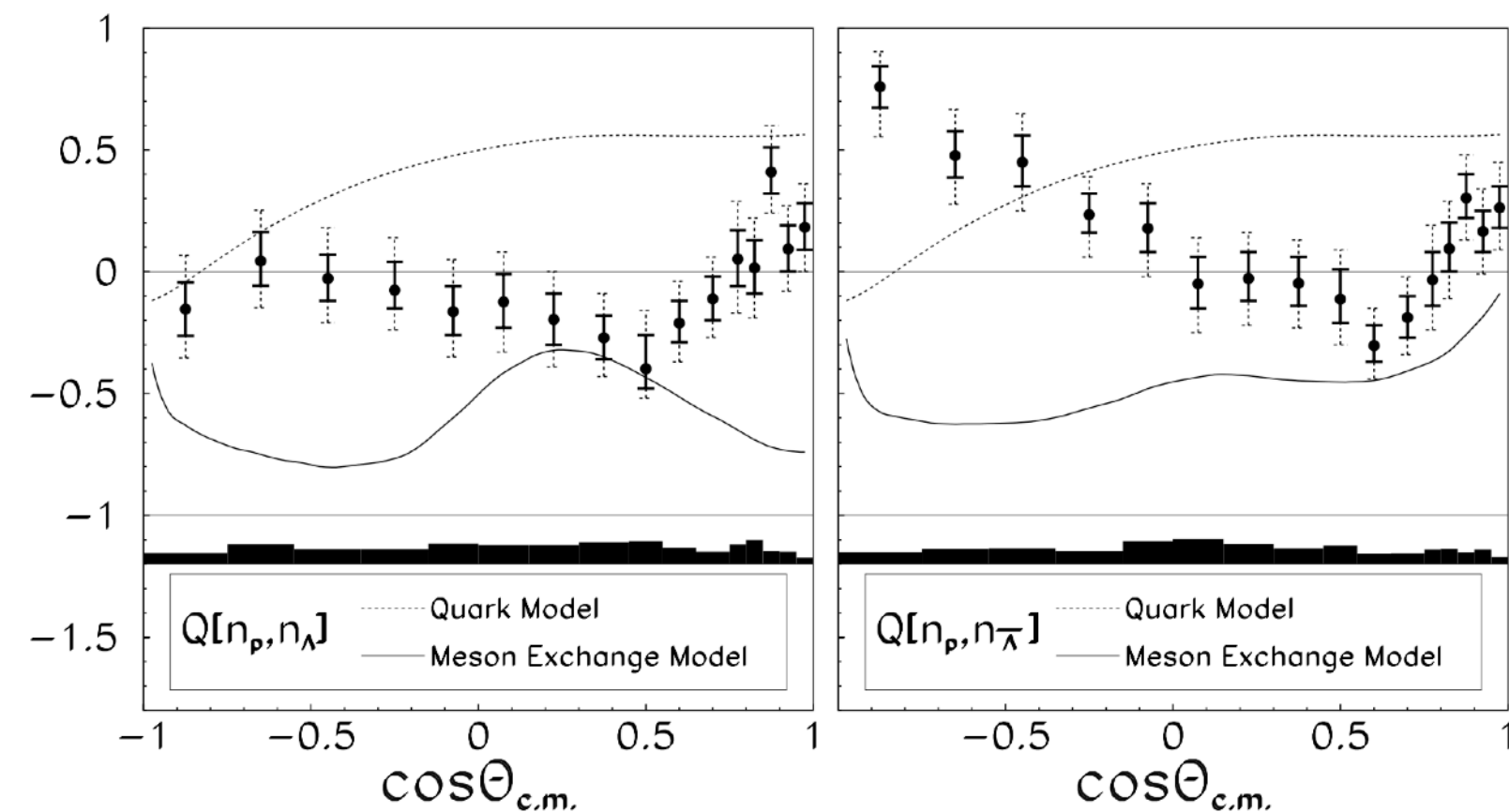


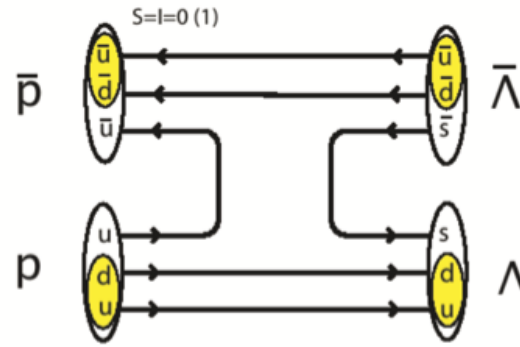
FIG. 12: Results for spin transfer observables $Q[n_p, n_\Lambda]$ (often called depolarization, D_{nn}) and $Q[n_p, n_{\bar{\Lambda}}]$ (often called spin-transfer, K_{nn}) at 1.637 GeV/c, compared to MEX model prediction [7] (solid) and QG model prediction [9] (dashed) at 1.642 GeV/c. Statistical error bars are shown on each data point, with 2σ error bars superimposed (dashed). The estimated systematic error width of the measurement is shown at the bottom of each plot (dark shaded region).

For two to three decades it has been theory's turn to catch up with experiment – for $\bar{\Lambda}\Lambda$. Experiment should now move on to $|S|=2,3$

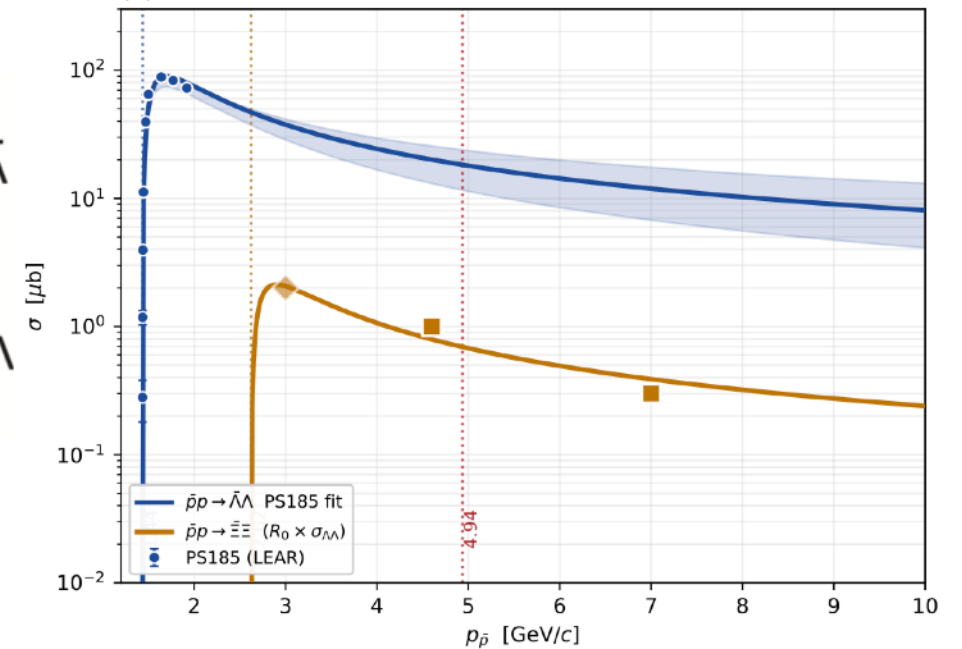
$$e^+e^- \rightarrow \bar{Y}Y \text{ vs } \bar{p}p \rightarrow \bar{Y}Y$$

Same final states, different production process

- It's not "photon vs gluon", $\psi \rightarrow \bar{Y}Y$ involves also 3 gluons.
- The difference is 3S_1 (gluon) vs 3P_0 (vacuum) vs meson-exchange
- What's behind the huge difference in suppression factor in |S| scan?
 - $\Gamma(\psi \rightarrow \bar{\Omega}\Omega)/\Gamma(\psi \rightarrow \bar{\Lambda}\Lambda) \sim 0.5$
 - $\sigma(\bar{p}p \rightarrow \bar{\Omega}\Omega)/\sigma(\bar{p}p \rightarrow \bar{\Lambda}\Lambda) \sim (1/40)^2$
- Does each additional $\bar{s}s$ pair cost the same? $R \equiv \sigma(|S|)/\sigma(|S| - 1)$
 - "Measured": $R(1 \rightarrow 2) = 0.024 \pm 0.005$, and it looks flat over a factor 10 in excess energy
 - **Unknown:** $R(2 \rightarrow 3)$
 - constant $\rightarrow$ independent pair creation · larger $\rightarrow$ glue-rich, shared gluon field · smaller $\rightarrow$ meson exchange, extra K, larger |t|
- One caveat: Λ and Ξ are octet, spin-1/2, but Ω is **decuplet, spin-3/2**. The last rung changes multiplet as well as strangeness. The clean alternatives are the octet ladder $n \rightarrow \Lambda \rightarrow \Xi$, and the decuplet ladder $\Delta \rightarrow \Sigma^* \rightarrow \Xi^* \rightarrow \Omega$, whose mass spacing is uniform. $\bar{p}p \rightarrow \bar{\Xi}^*\Xi^*$ sits just below $\bar{\Omega}\Omega$ in threshold and is only two pions away from $\bar{\Xi}\Xi$ in the final state – we should measure it. Both data should be simultaneously collected.



- $\Lambda = ud_{\{S=0\}}s$. Λ spin is that of s quark. $\Lambda\bar{\Lambda}$ spin state is a reflection of the $\bar{s}s$ spin state.



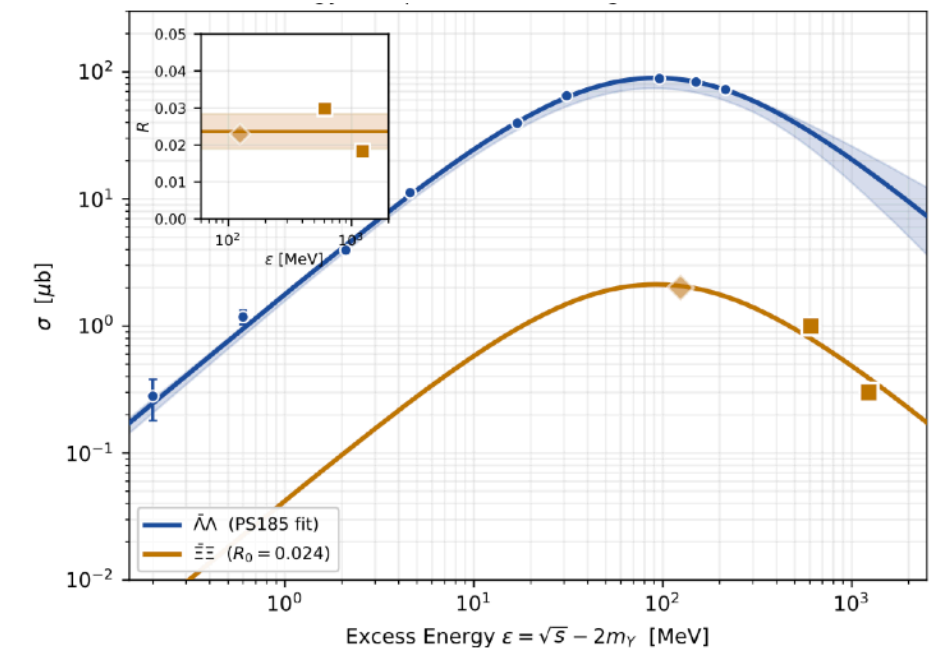
- Singlet Fraction S_F : the fraction of $\bar{\Lambda}\Lambda$ pairs which are produced in a spin-singlet state
- PS185 shows "often-accepted empirical rule, $S_F=0$ " is "broken" at back angles.

$$S_F = \frac{1}{4}(1 - Q[n_\Lambda, n_{\bar{\Lambda}}] + m_\Lambda, m_{\bar{\Lambda}} + l_\Lambda, l_{\bar{\Lambda}}) = \frac{|b - c|^2}{4I_0}$$

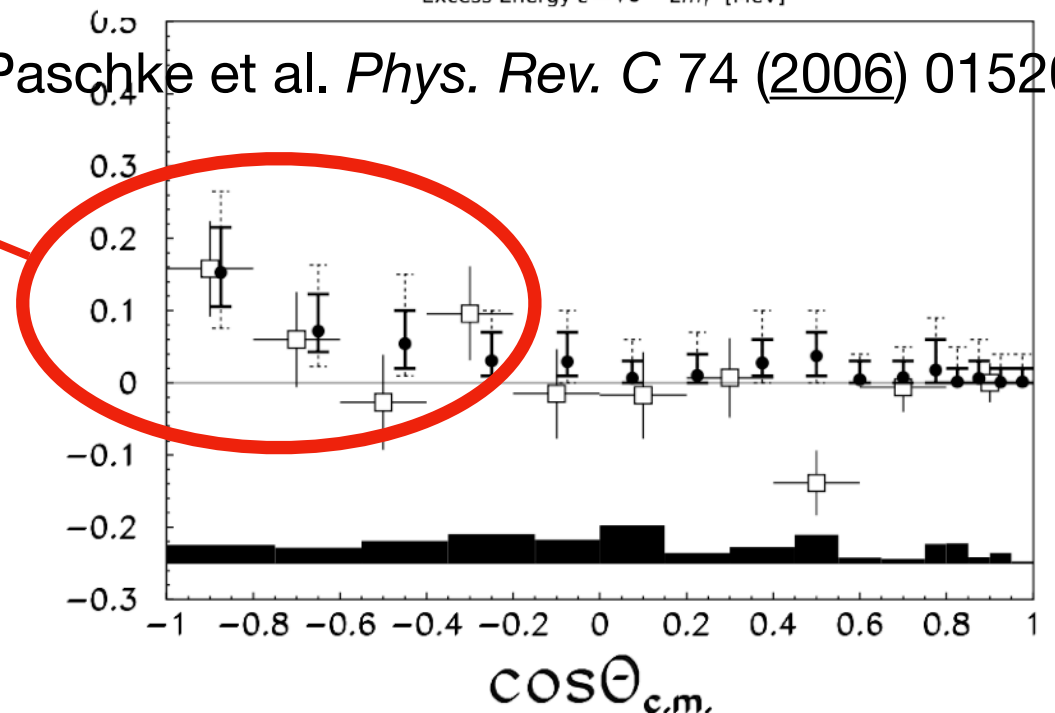
- rise of p-wave contribution

- $\Xi (ss_{\{S=1\}})$, $\Omega (S=3/2)$. Relation to s -quark spin is not as trivial as Λ case. Unexplored and interesting.

- $R(\epsilon) \sim \text{flat?}$

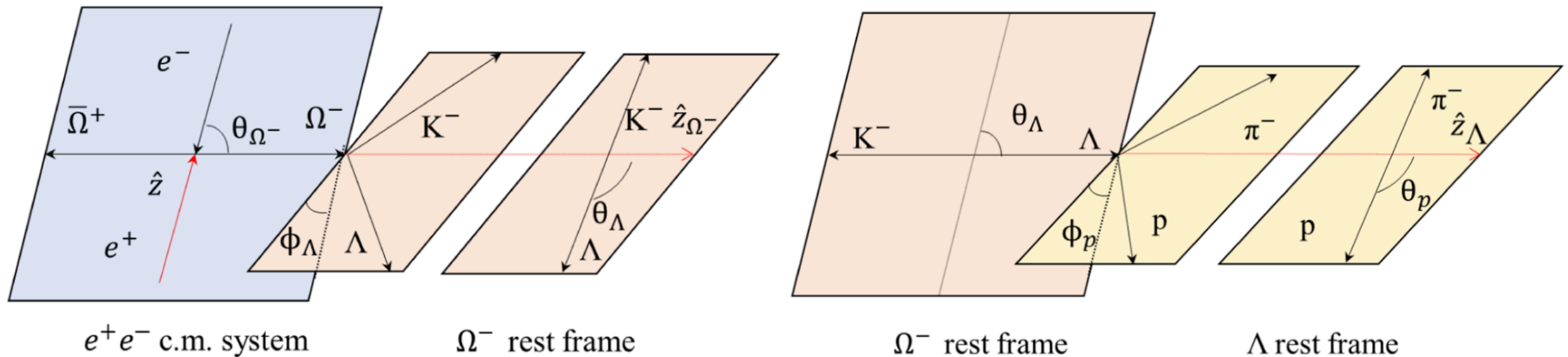
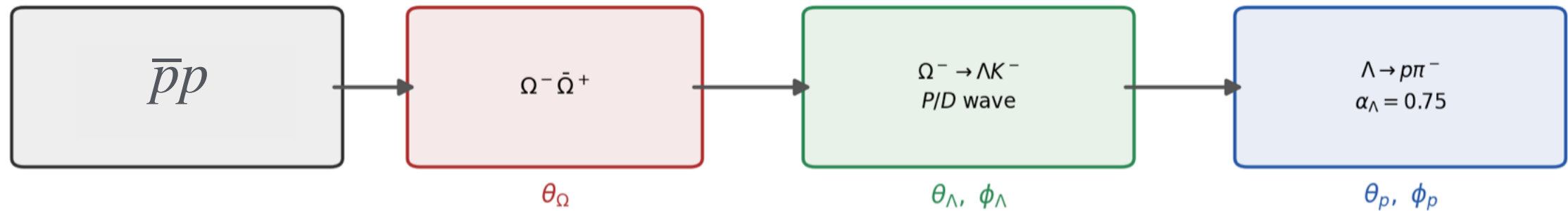


K.D. Paschke et al. *Phys. Rev. C* 74 (2006) 015206



Measurement

Full decay chain of $\bar{p}p \rightarrow \bar{\Omega}\Omega$



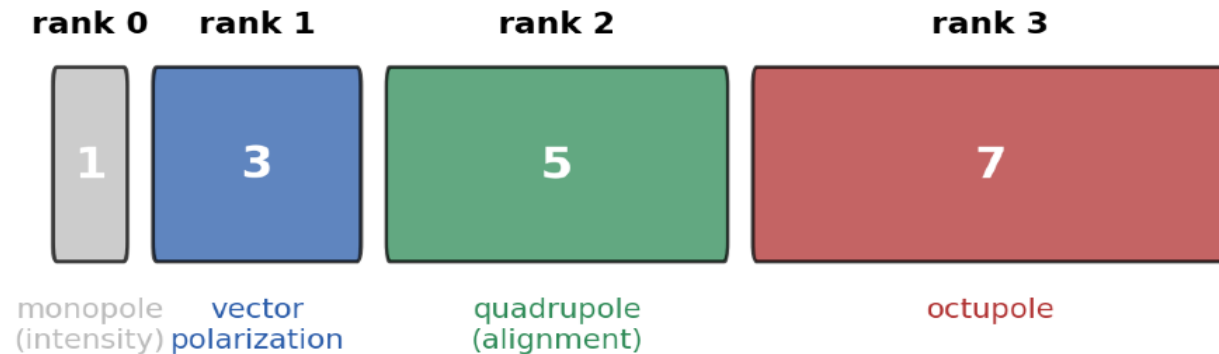
- 5 helicity angles $\rightarrow$ Joint angular distribution $\rightarrow$ Simultaneous fit

Spin 3/2 case

(a) What a spin-3/2 hyperon can carry

spin-3/2 density matrix : $4 \times 4 = 16$ independent components

$$16 = 1 + 3 + 5 + 7$$

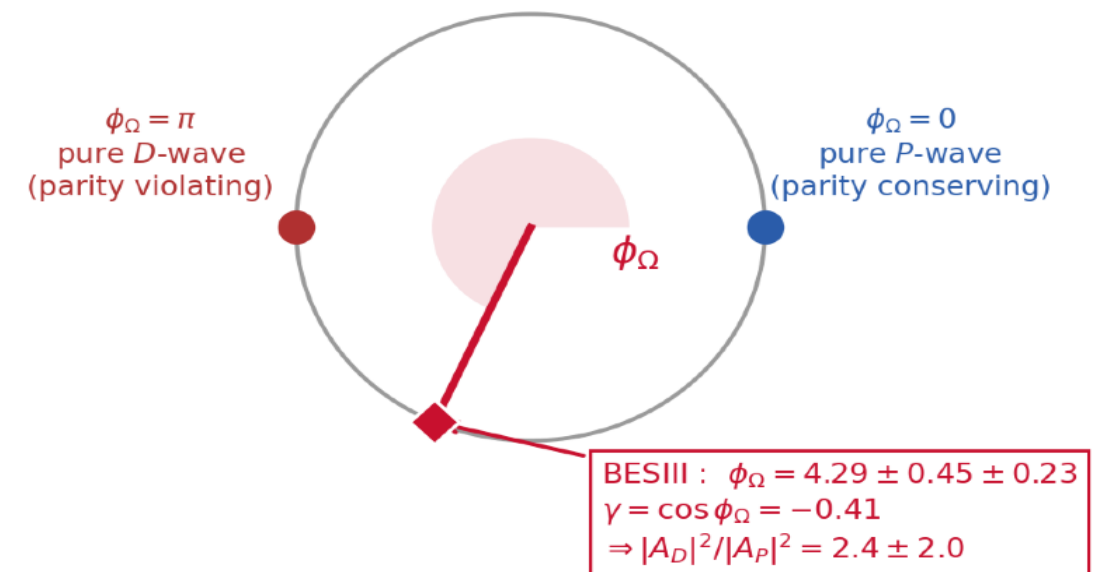


exists for spin 1/2 as well **NEW observables that appear only for spin 3/2**

(b) The phase tells you which partial wave wins

$$\Omega^- \rightarrow \Lambda K^- : \gamma = \sqrt{1 - \alpha^2} \cos \phi_\Omega$$

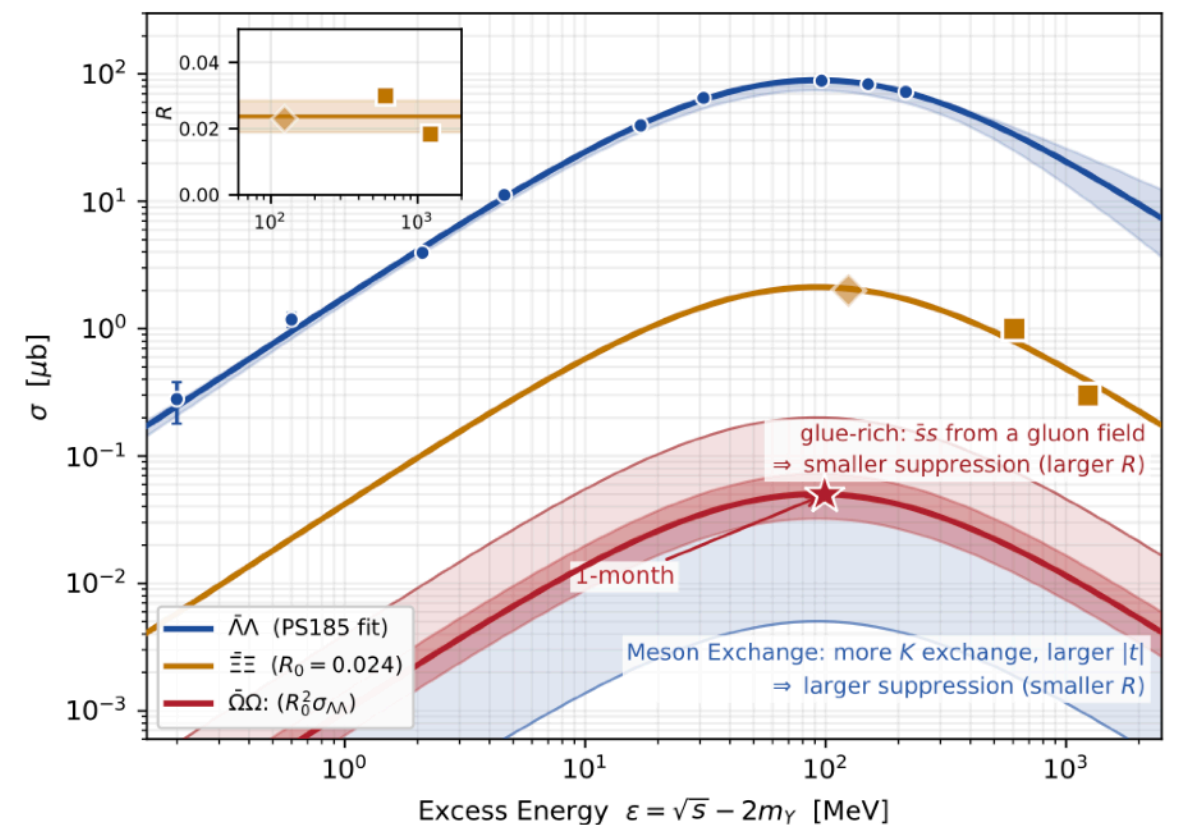
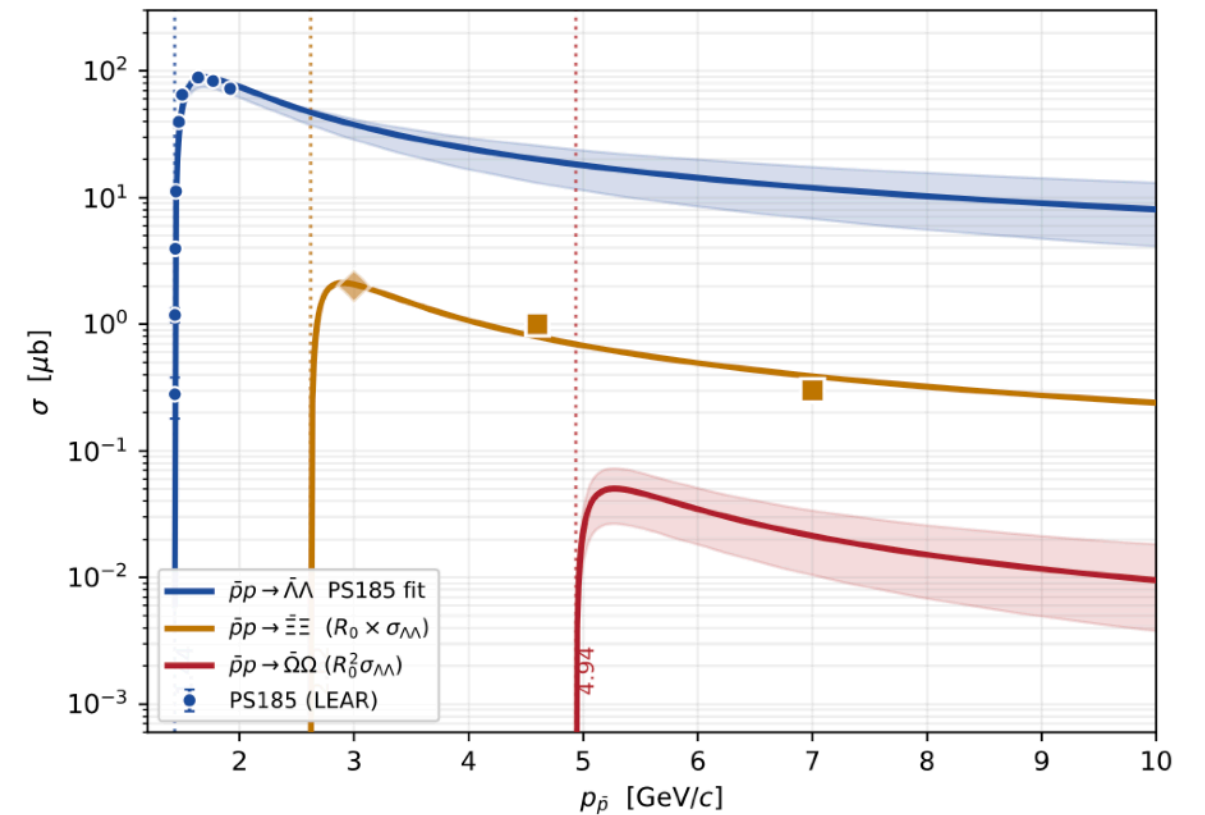
$$\gamma = (|A_P|^2 - |A_D|^2) / (|A_P|^2 + |A_D|^2)$$



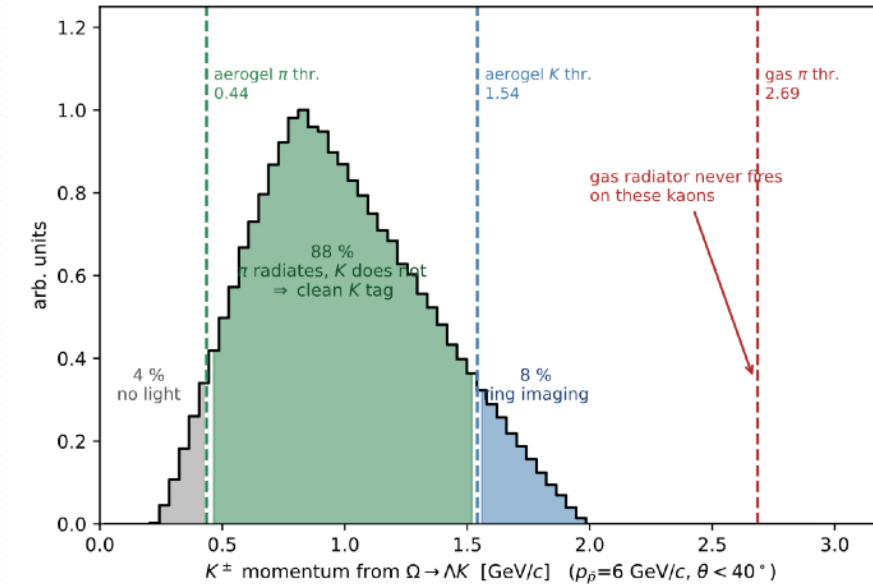
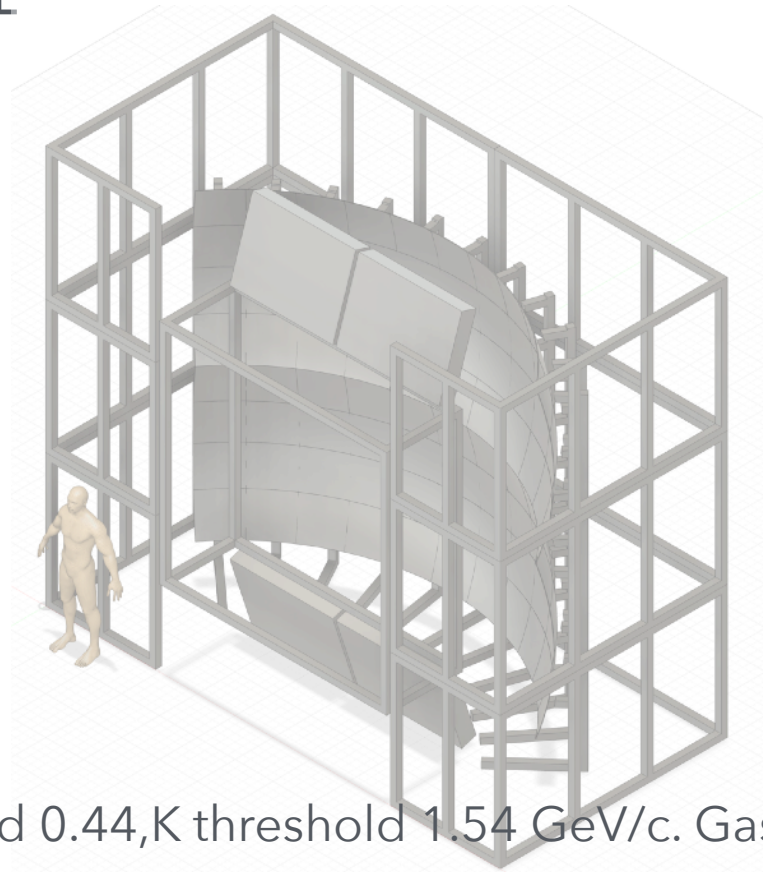
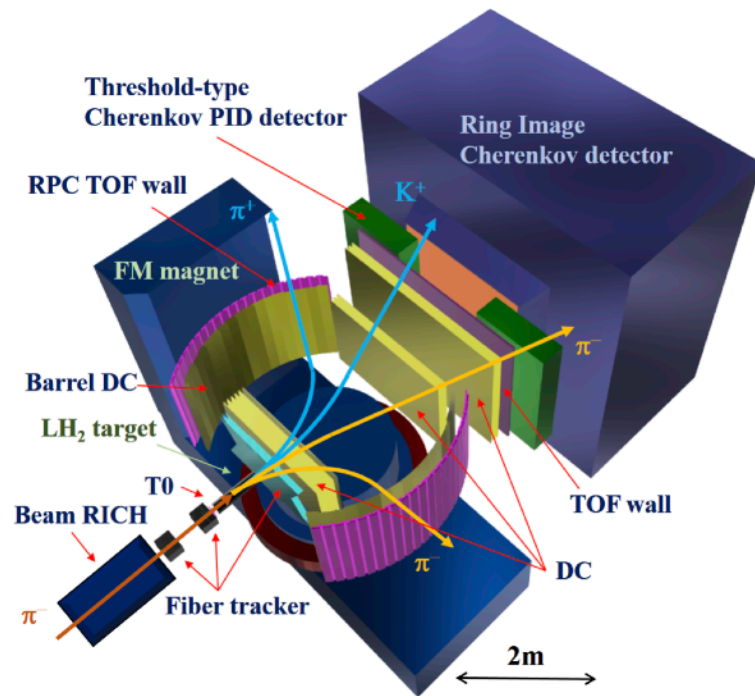
- **Production:** $2 \rightarrow 4$ complex form factors. Four independent helicity amplitudes survive: $|\lambda_1 - \lambda_2| \leq 1$ (10) $\rightarrow$ parity (5) $\rightarrow$ particle-antiparticle exchange (**4**).
- Spin state: $4 \times 4 = 16 = 1 + 3 + 5 + 7$. Rank 2 (quadrupole / alignment) and rank 3 (octupole) exist only for spin 3/2. Decay $\Omega^- \rightarrow \Lambda K$, $\Lambda^0 \rightarrow \Lambda K^-$: $L=1$ (P, parity conserving) or $L=2$ (D, parity violating). Two parameters: α_Ω (interference) and ϕ_Ω (which partial wave wins).
- BESIII: $\phi_\Omega = 4.29 \pm 0.45 \pm 0.23 \rightarrow |A_D|^2 / |A_P|^2 = 2.4 \pm 2.0 \rightarrow$ **D-wave dominant**, opposite to pole-model expectations.

$$\bar{p}p \rightarrow \bar{\Omega}\Omega$$

- Identical final states as the BESIII Phys. Rev. Lett. 126, 092002 (2021)
 - 4000 events (!)
- much larger background
- π/K separation by RICH is the key
- $\sigma(\bar{\Omega}\Omega)/\sigma(\bar{\Xi}\Xi)$ vs $\sigma(\bar{\Xi}\Xi)/\sigma(\bar{\Lambda}\Lambda)$
 - Assuming the same R , 1-month full $\pi 20/\text{MARQ}$ can reach
 - $\delta R(\Xi\Xi/\Lambda\Lambda) \sim 0.4\%$ and $\delta R(\Omega\Omega/\Xi\Xi) \sim 1.3\%$



MARQ-RICH



- Dual radiator. Aerogel ($n=1.05$): π threshold 0.44, K threshold 1.54 GeV/c. Gas (R-1233zd): π threshold 2.69 GeV/c.
- K from $\Omega \rightarrow \Lambda K$ sits at **0.5-2.5 GeV/c** $\rightarrow$ 96 % inside the aerogel acceptance; the gas radiator never fires on these kaons.
- **88 %** fall in the " π radiates, K does not" veto window $\rightarrow$ K identification reduces to **not missing the π ring**.
- $\epsilon_\pi \gtrsim e^{-N_{pe}}$, and K^+K^- coincidence makes background scale as ϵ_π^2 . With $\sigma(\bar{\Omega}\Omega)/\sigma_{\text{tot}} \sim 3 \times 10^{-6}$ this requires $N_{pe} \gtrsim 12$
- **Light concentrator:** hexagonal Winston cone, $24 \rightarrow 12$ mm, $C=4 \Leftrightarrow \theta_{\text{max}}=30^\circ$ by étendue; $\theta_c(n=1.05)=17.8^\circ \rightarrow \pm 12^\circ$ of track-angle margin.
- SiPM S13360-6050VE, 2×2 hybrid; photon counting needs $-20 \dots -30^\circ\text{C}$.

Summary

- Antiproton-Physics for Hadron Studies,
 - glue-rich environment through annihilation. largely unexplored area.
- J-PARC HEF is a unique facility capable of providing high-quality antiproton beams for hadron physics experiments and beyond.
- Antiproton programme is re-gaining momentum lead by a J-PARC-based community.
- |S| scan of symmetric Hyperon-Antihyperon production: $\bar{p}p \rightarrow \bar{Y}Y$ is a very attractive programme. Falsifiable R measurement for QG vs MEX effective dof. question.

Backup

Hadron Physics using Antimatter Probes (HAMP2025)

6–9 Oct 2025
KEK Tokai-Campus
Asia/Tokyo timezone

<https://indico.rcnp.osaka-u.ac.jp/event/2649/>

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Overview

Timetable

Contribution List

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First Circular

Second Circular

For Participants

Description

Hadron physics, guided by quantum chromodynamics (QCD), remains a dynamic field with significant unexplored territory despite progress since the 1970s. Antimatter probes—antiprotons ($\bar{p}$), antideuterons ($\bar{d}$), and antineutrons ($\bar{n}$)—offer distinctive approaches to decipher complex hadronic phenomena, have yet to be fully explored. Pioneering efforts at CERN's LEAR through the 1990s laid the groundwork, but today, only a few facilities experiments with anti-baryons. Key players include the Hadron Experimental Facility (HEF) at J-PARC and the Antiproton Decelerator (AD) at CERN, with emerging prospects like GSI/FAIR.

A major initiative, designed around a stored, high-quality antiproton beam coupled with a versatile 4π detector, has long been anticipated to open new horizons in hadron physics. While its scientific potential remains compelling, ongoing delays have prompted renewed interest in what can be achieved at currently operational facilities such as J-PARC's Hadron Experimental Facility. Notably, the emerging $\pi 20$ beamline offers extracted antiprotons in the momentum of 2–20 GeV/c at intensities reaching up to 10^6 $\bar{p}$ /spill. Though still in its early stages, this capability is drawing increased attention, with a growing user base exemplified by the J-PARC Antimatter Consortium. This workshop seeks to harness and strengthen this momentum.

Contact

✉ hamp2025-contact@rcn...

HAMP2026 (23-24 June 2025, Cracow)

<https://indico.rcnp.osaka-u.ac.jp/event/2848/>