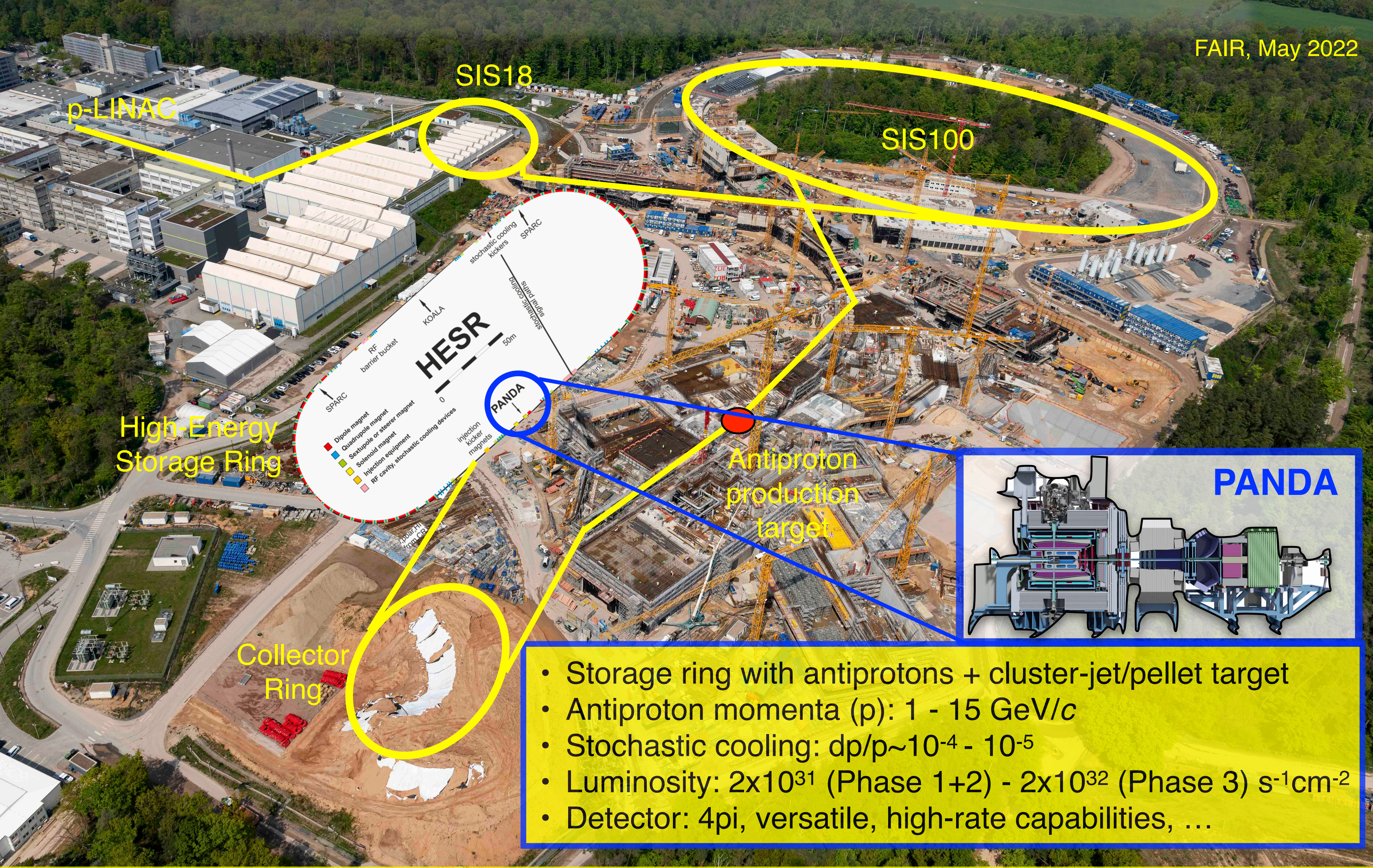
Physics prospects at PANDA

FAIR, May 2022

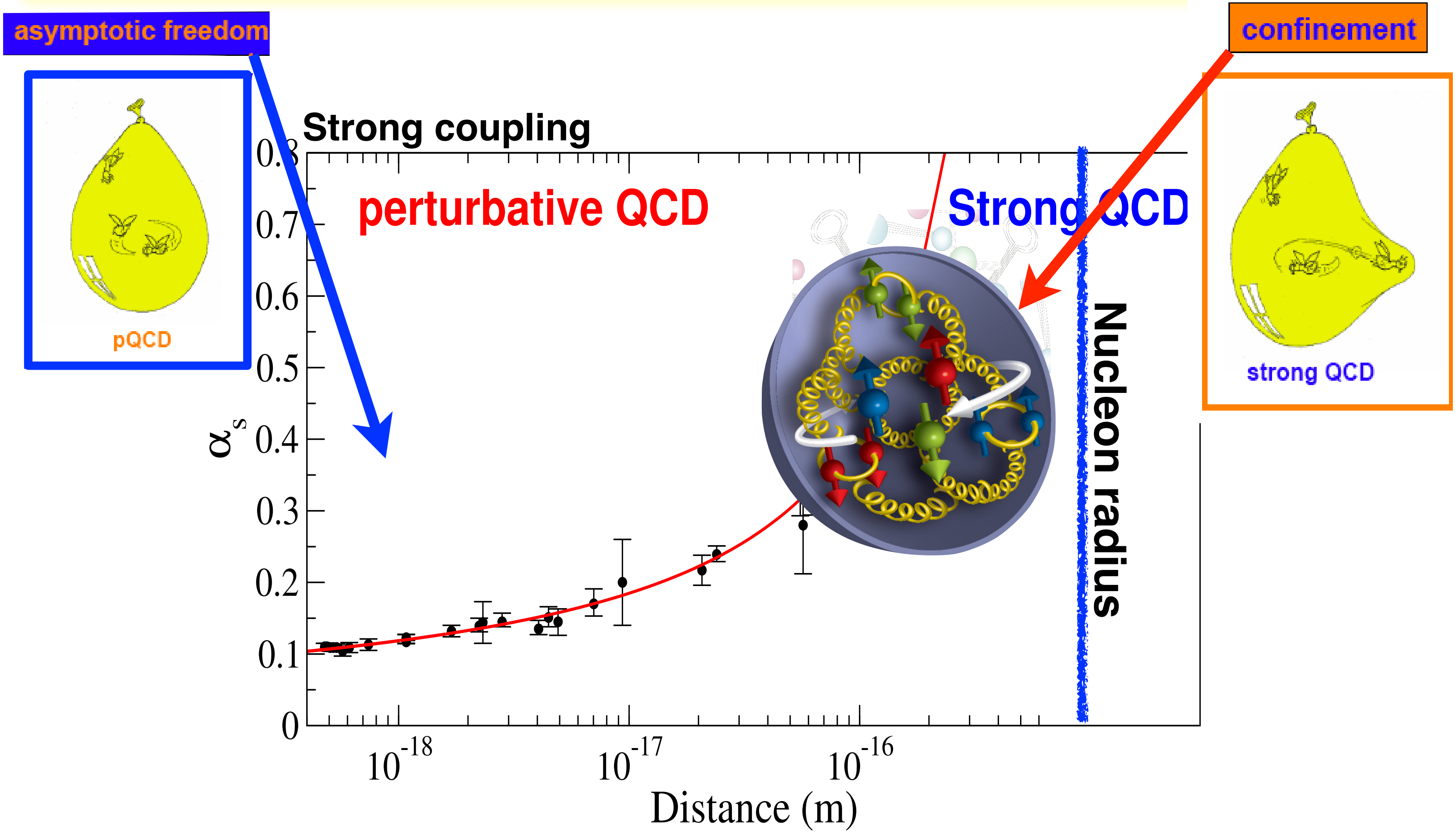
Johan Messchendorp (GSI, Darmstadt) on behalf of PANDA, IPA2022, September 6, 2022

Physics prospects at PANDA



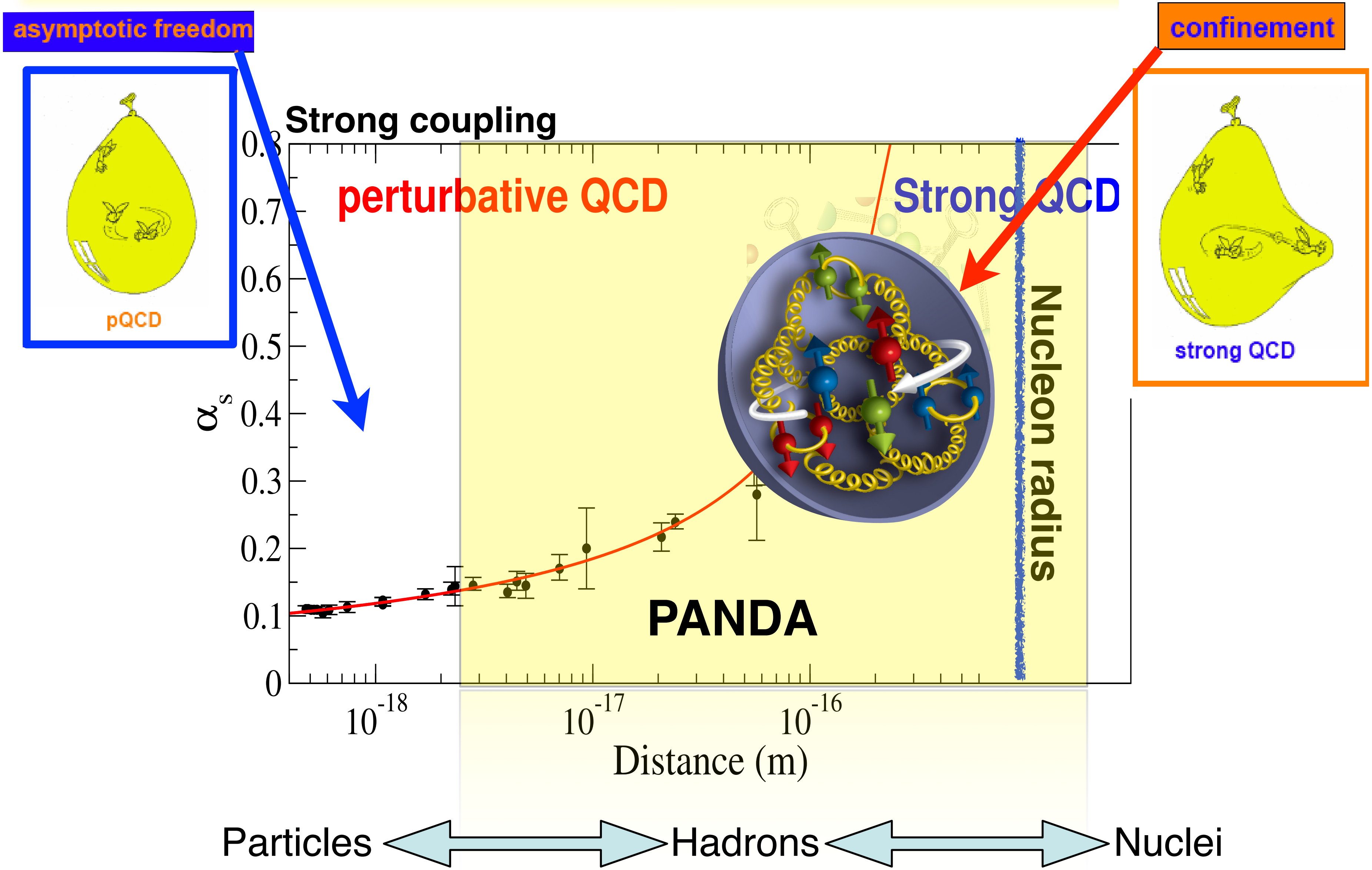
- Storage ring with antiprotons + cluster-jet/pellet target
- Antiproton momenta (p): 1 - 15 GeV/*c*
- Stochastic cooling: $dp/p \sim 10^{-4} - 10^{-5}$
- Luminosity: 2×10^{31} (Phase 1+2) - 2×10^{32} (Phase 3) $s^{-1}cm^{-2}$
- Detector: 4pi, versatile, high-rate capabilities, …

The dynamics of QCD!



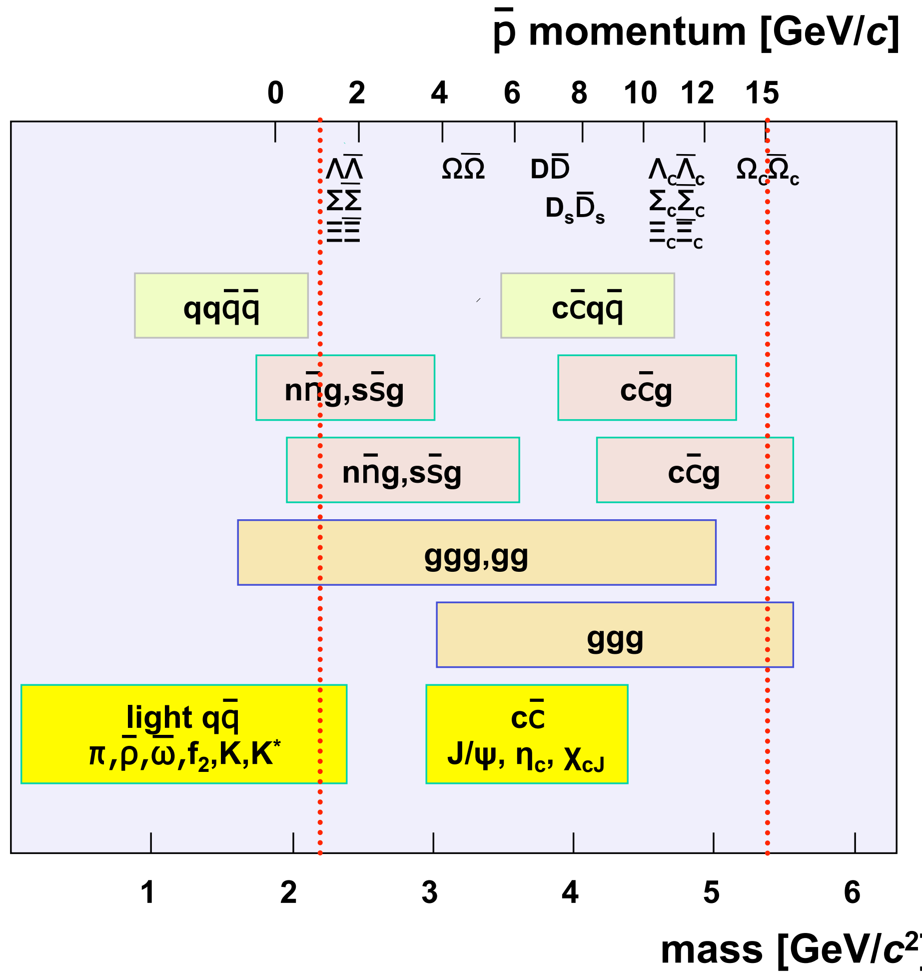
Particles ⟷ Hadrons ⟷ Nuclei

The dynamics of QCD!



Why antiprotons?

PANDA Phase One, EPJA57, 44 (2021)



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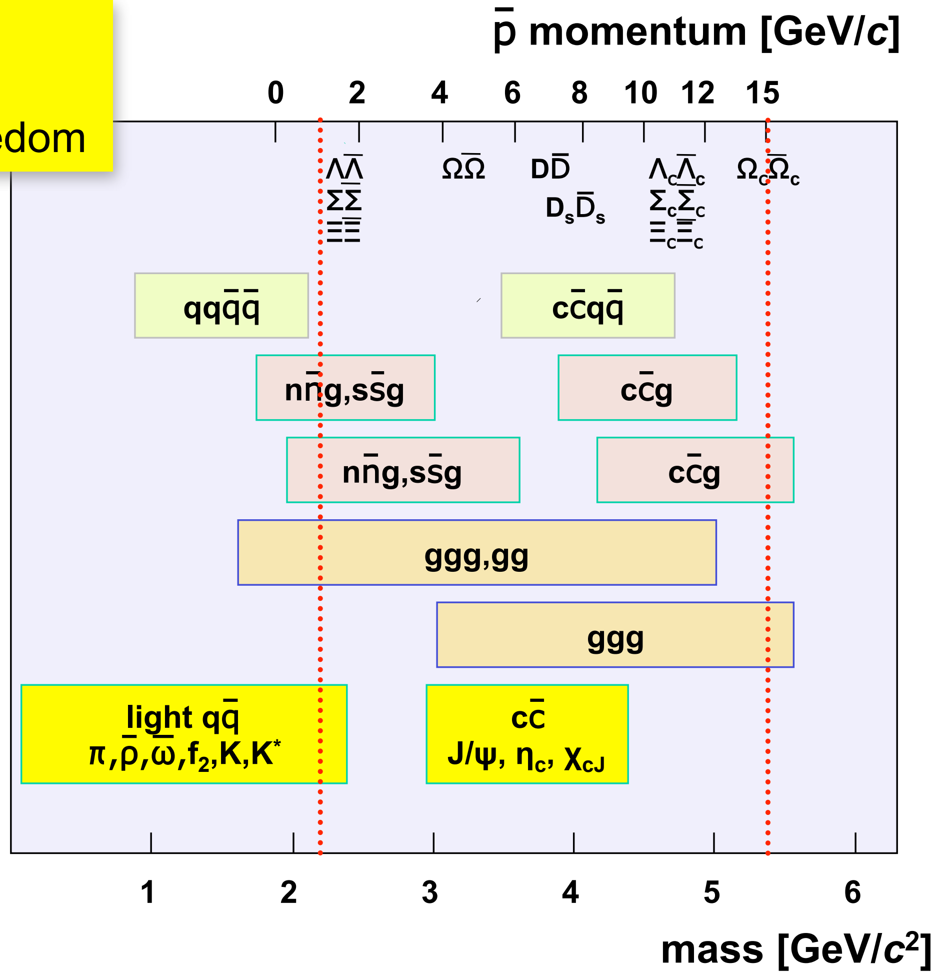
Large mass-scale coverage
- from light, strange, to charm-rich hadrons
- from quark/gluons to hadronic degrees of freedom



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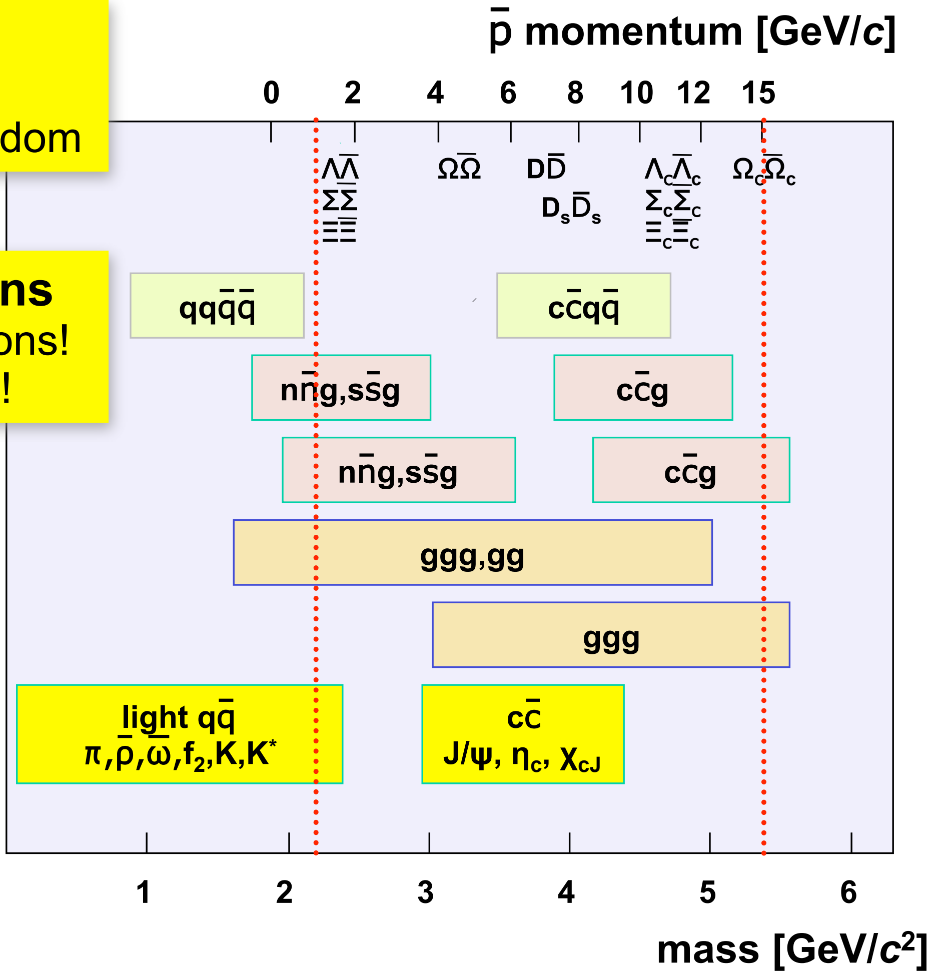
Large production rates of (exotic) hadrons
- charm+strange factory -> charmonium, hyperons!
- gluon-rich production -> potential for glueballs!



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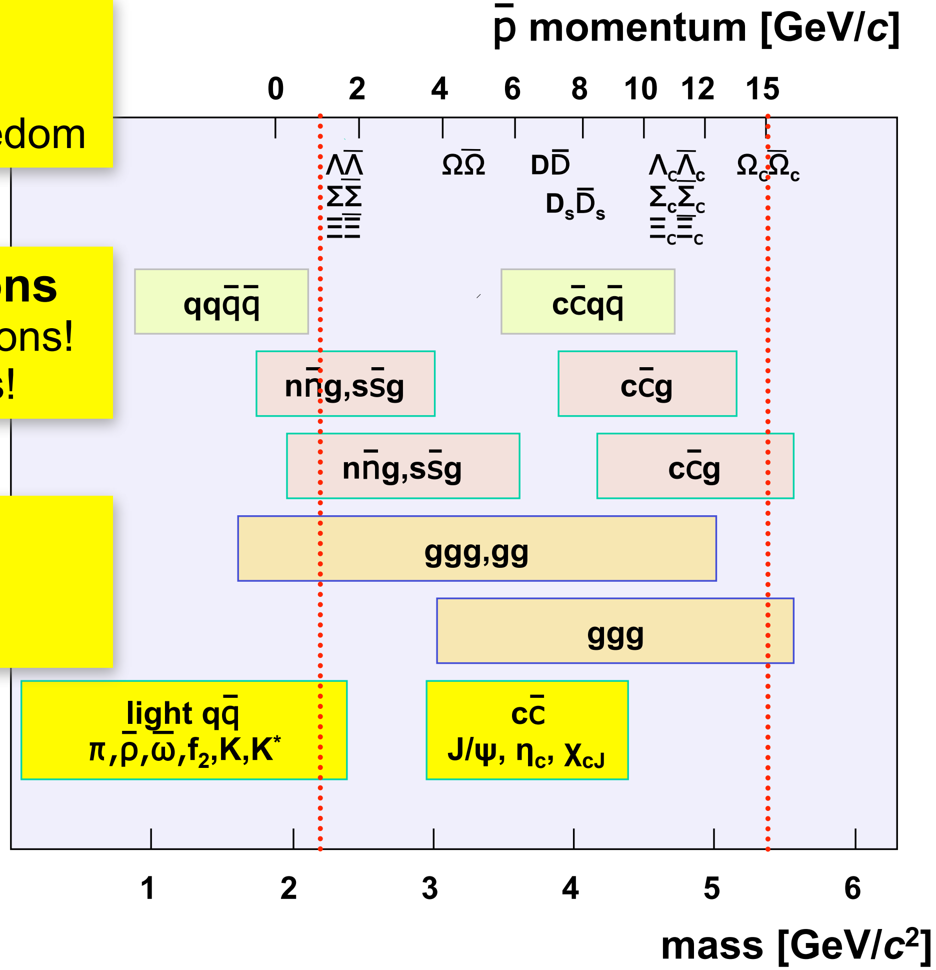
Access huge spectrum of hadrons
- direct formation of *all* conventional J^{PC} states
- large sensitivity to high spin states



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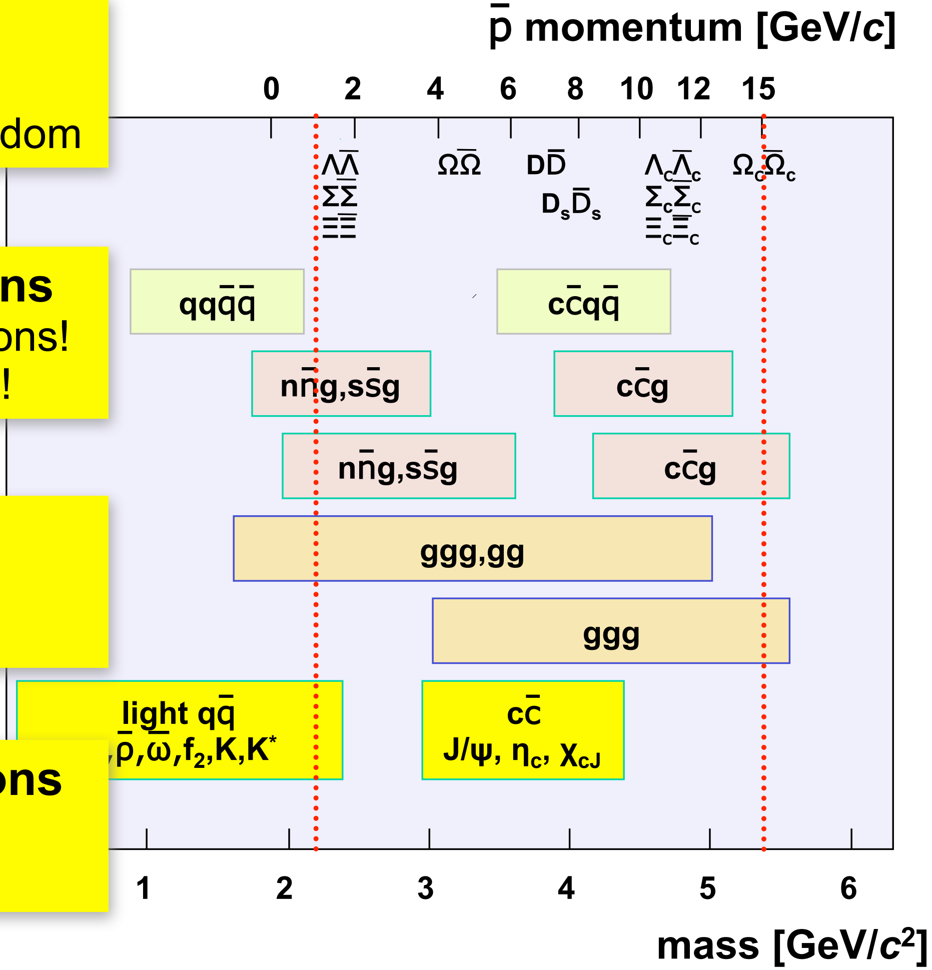
Production of pairs of hadron+antihadrons
- matter-antimatter asymmetry studies
- excellent experimental conditions



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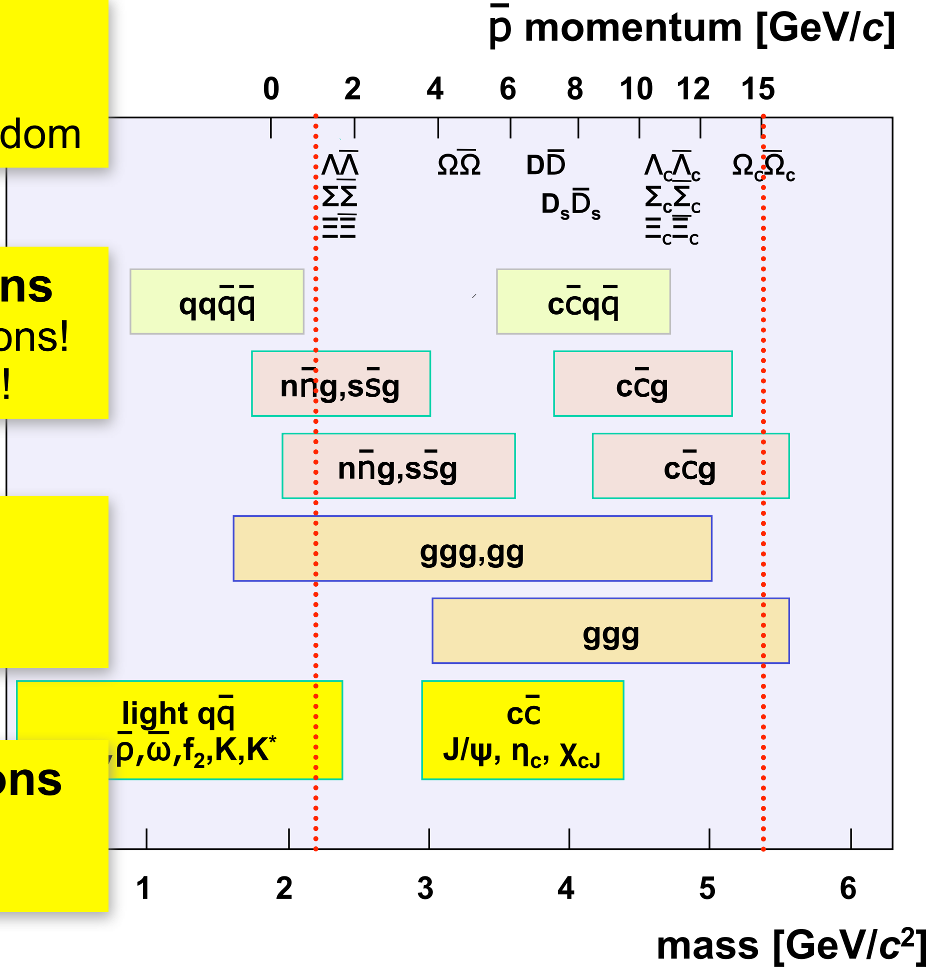

Unprecedented tool to rigorously study non-perturbative QCD!

PANDA physics overview

PANDA Phase One, EPJA57, 44 (2021)

Bound States and Dynamics of QCD

PANDA physics overview

PANDA Phase One, EPJA57, 44 (2021)

CHARM

STRANGE

LIGHT

Bound States and Dynamics of QCD

PANDA physics overview

PANDA Phase One, EPJA57, 44 (2021)

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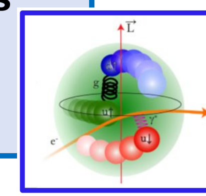
BESIII, COMPASS, EIC, JLAB, ...

Nucleon Structure

Generalized Parton Distributions

Transition Distribution Amplitudes

Time-like Form Factors



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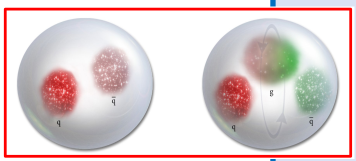

Spectroscopy

- Hidden/open-charm states
- Gluon-rich QCD states
- Light-meson systems

BESIII, COMPASS, EIC, JLAB, …

Nucleon Structure

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- Transition Distribution Amplitudes
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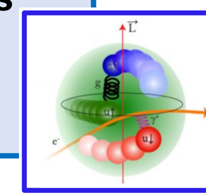

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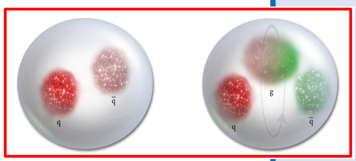

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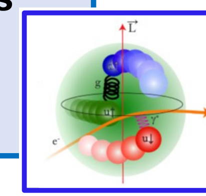
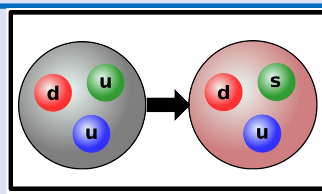


Bound States and Dynamics of QCD

Strangeness



Strange baryon spectroscopy

Hyperon production & polarization

Hyperon transition form factors

BESIII, JLAB, JPARC, HADES, MAMI, ELSA, …

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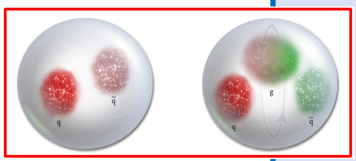

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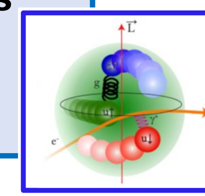

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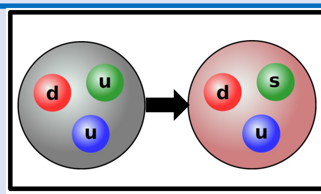

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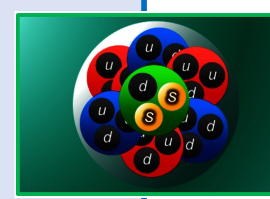

CBM, HYPHI, JPARC, …

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CHARM — STRANGE — LIGHT

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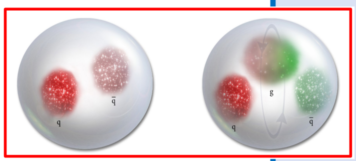

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Charmonium-like particles - terra incognita

- Narrow states
- Heavy charm quarks

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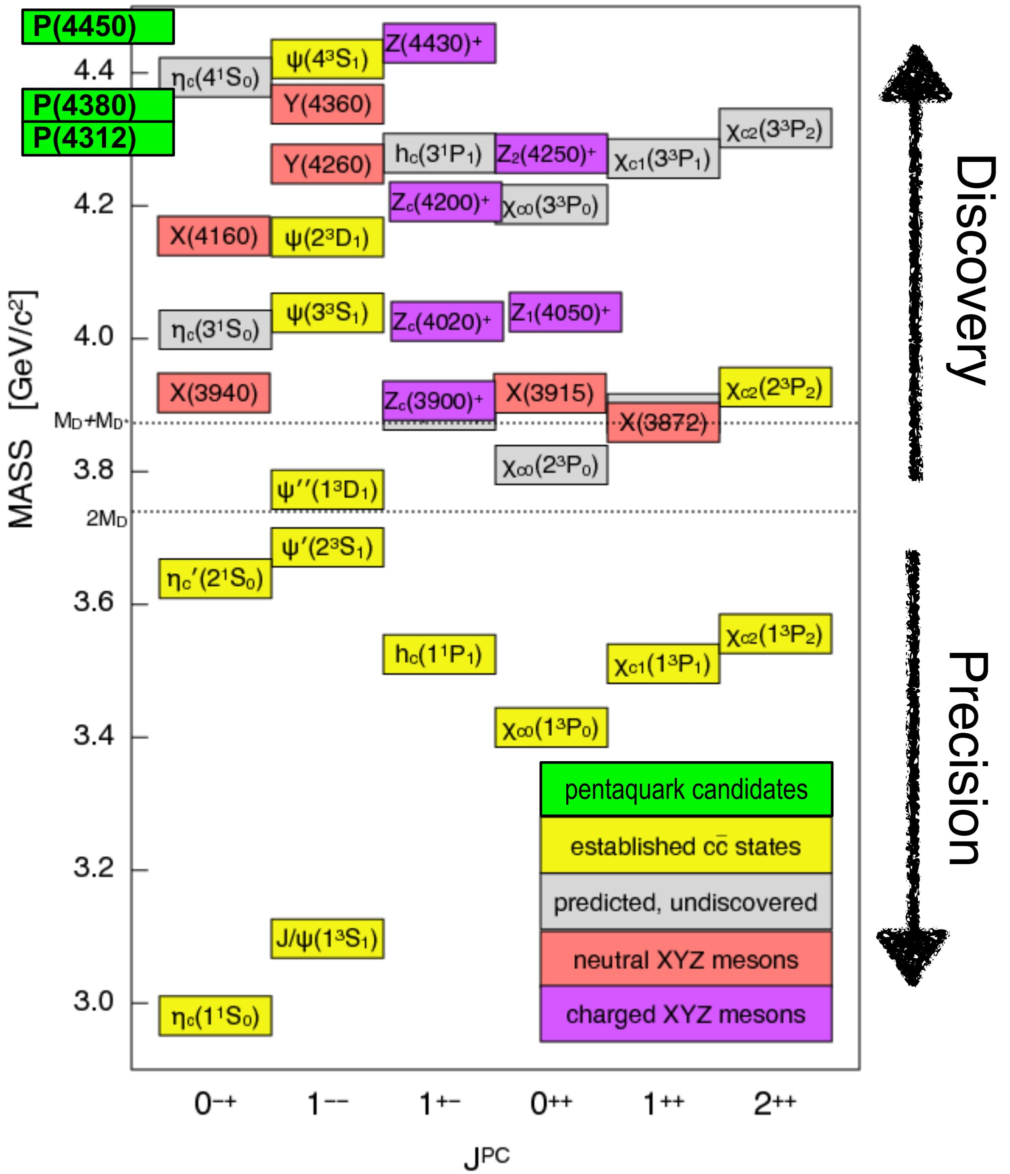

- **Narrow states**
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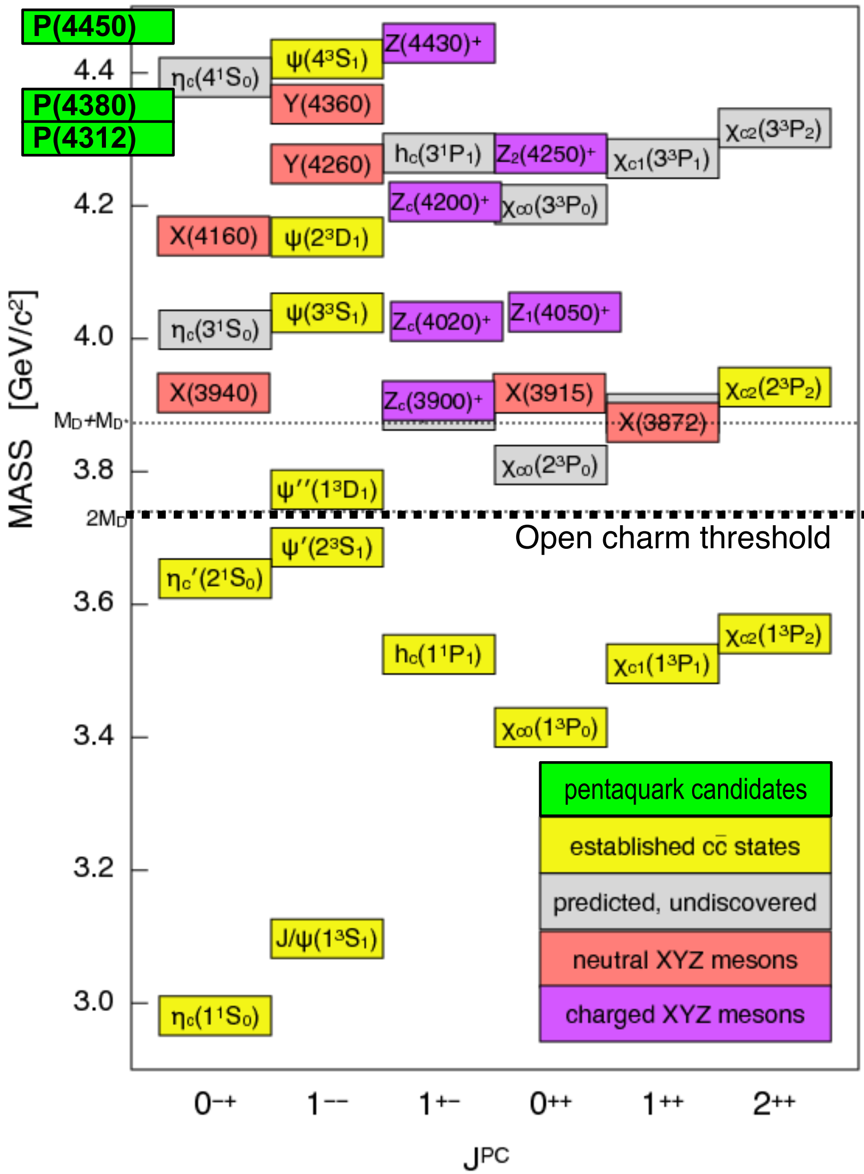

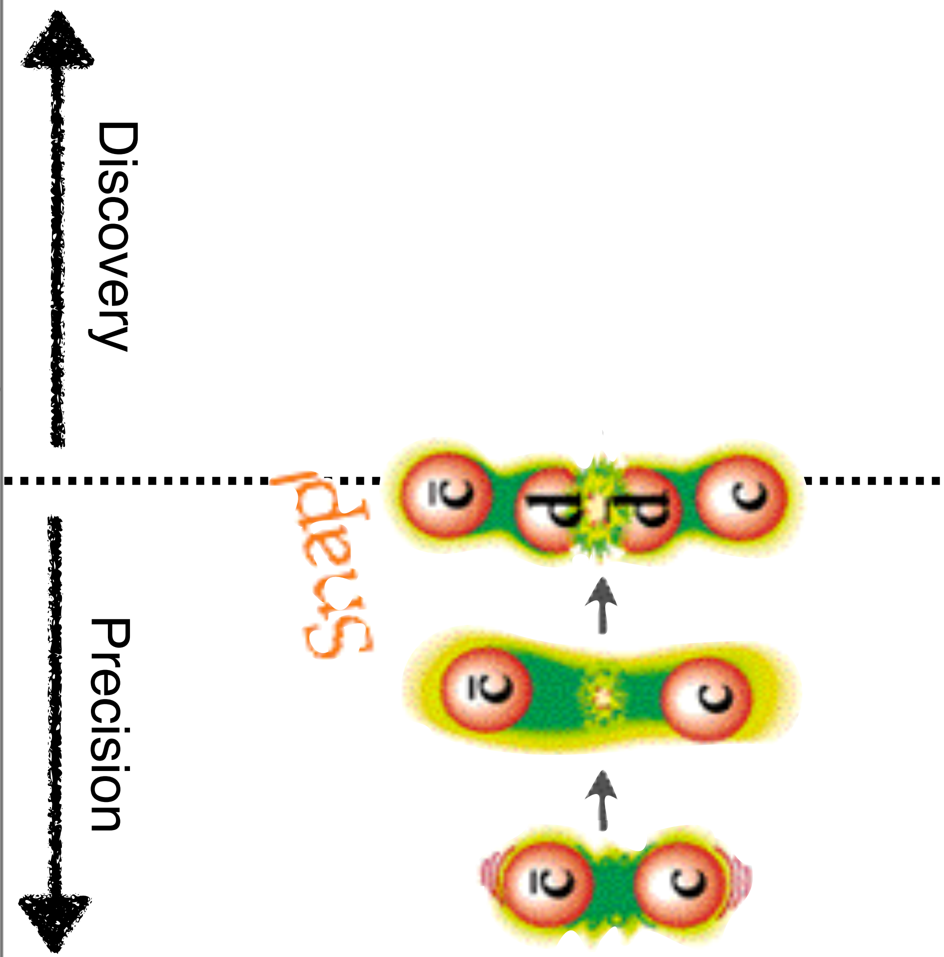

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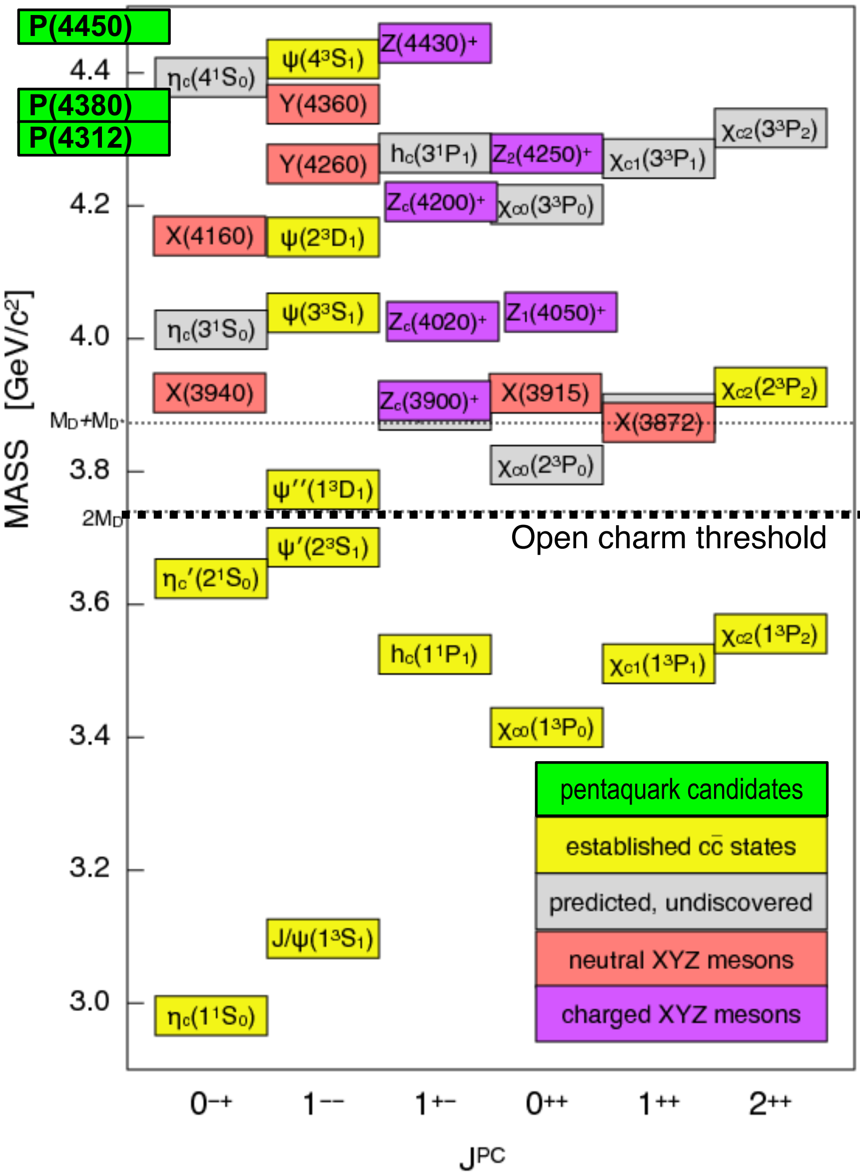

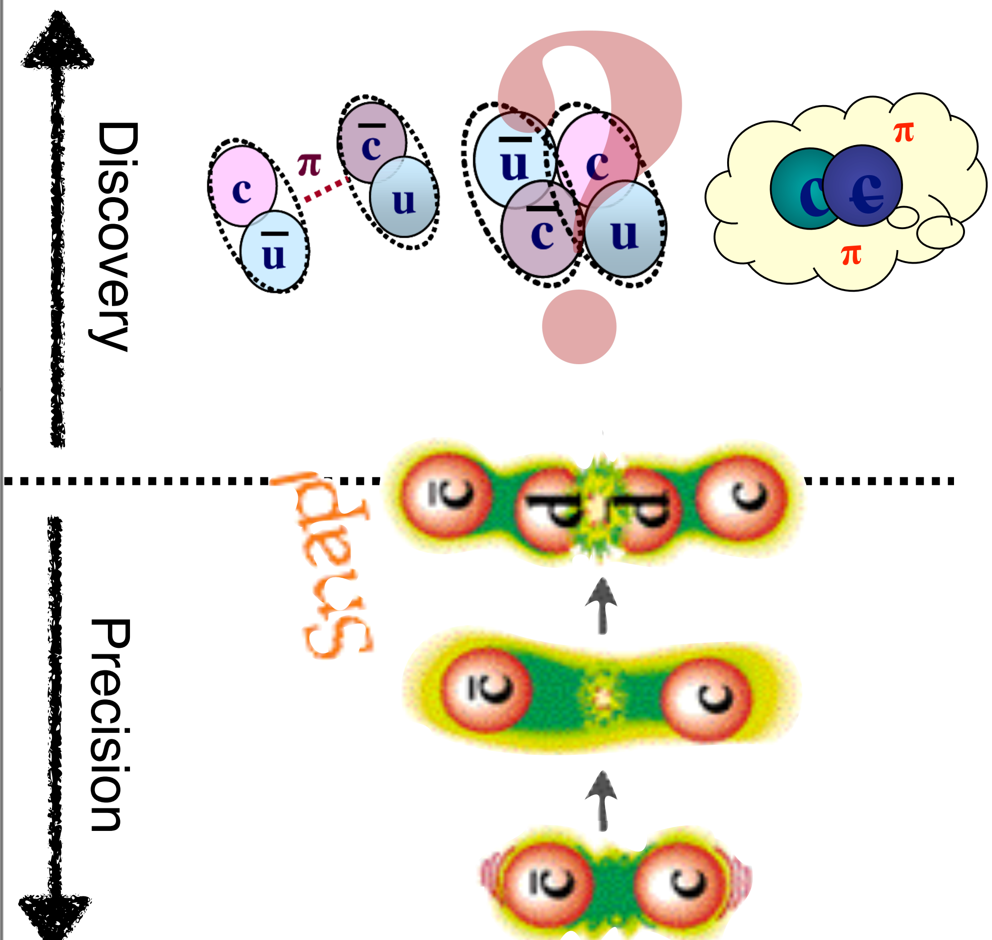

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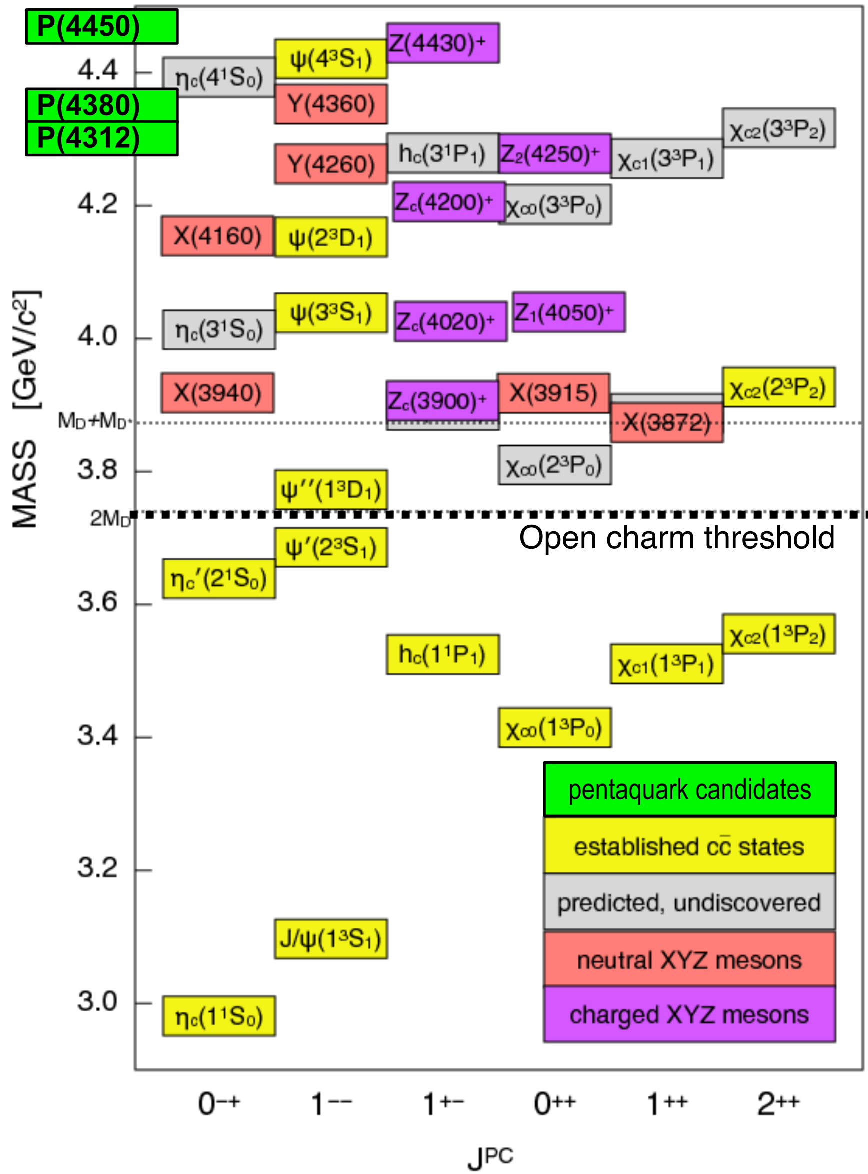
Charmonium-like particles - PANDA opportunities



- line shape of, f.e., X(3872)
- neutral+charged Z-states
- X,Y,Z decays
- search for h_c', $^3F_4$, …
- spin-parity/mass&width of $^3D_2$
- Search for glueballs/hybrids

- line shape/width of the eta_c, h_c
- radiative transitions
- hadronic transitions
- light-quark spectroscopy

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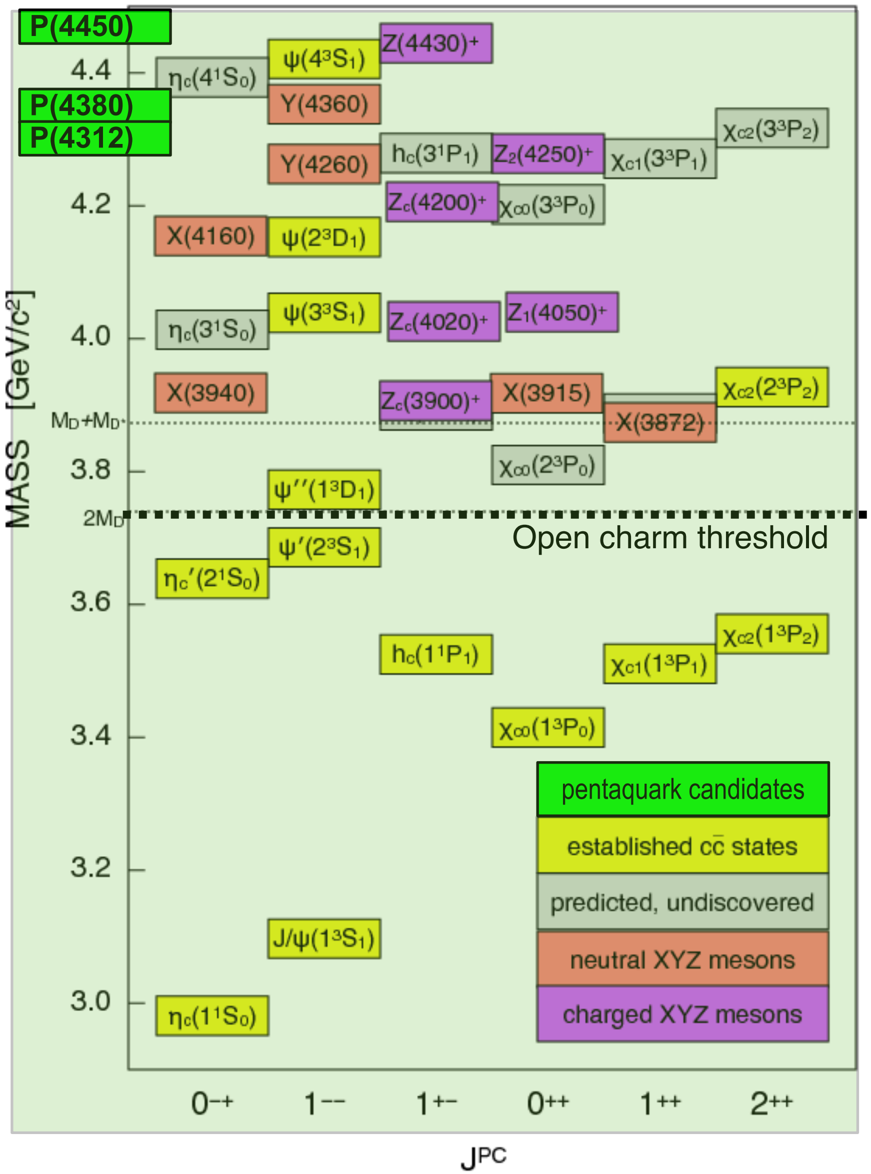

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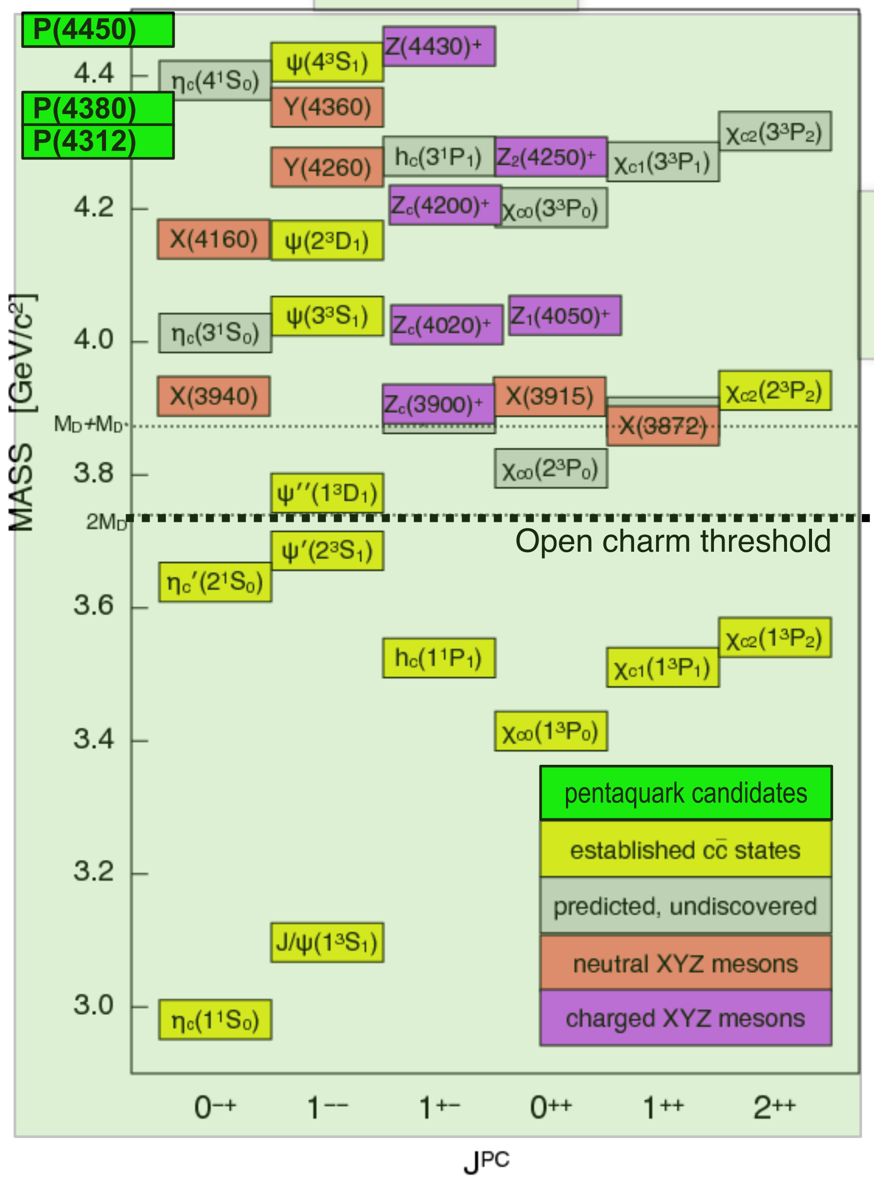

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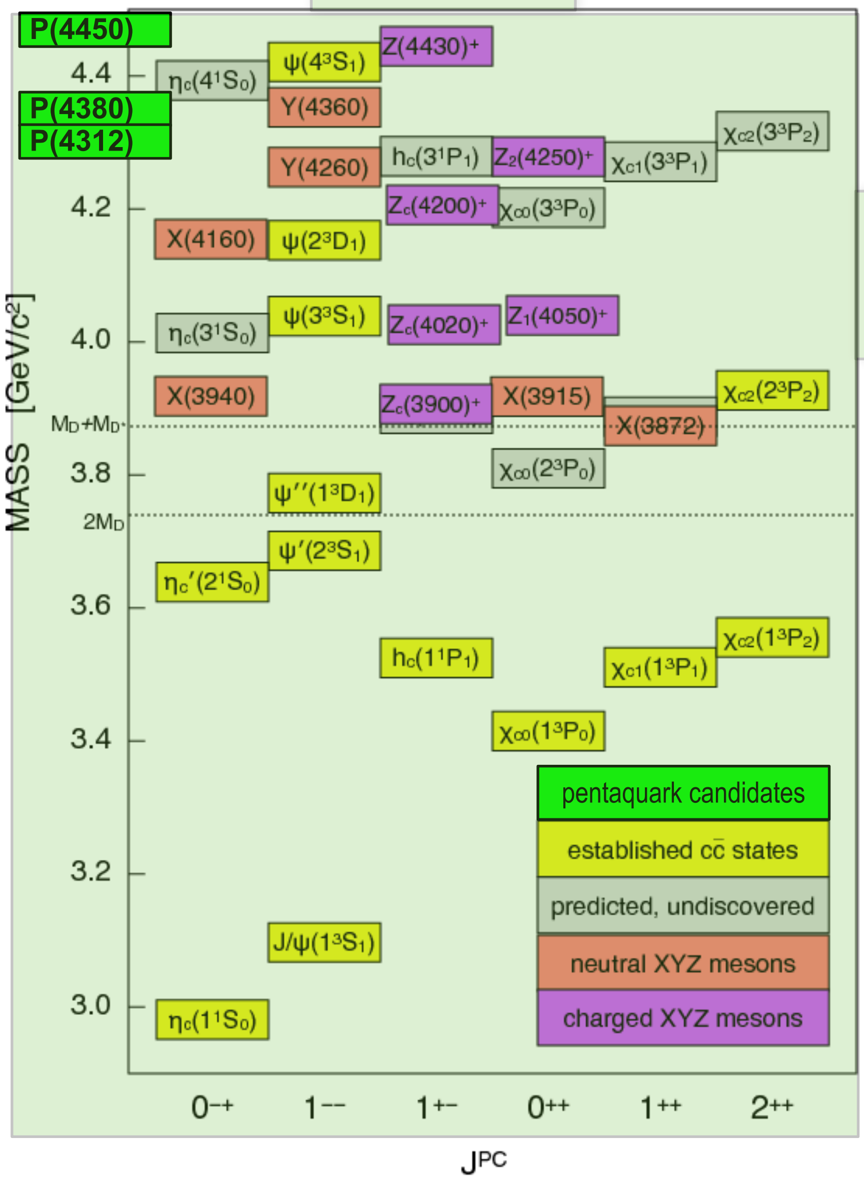
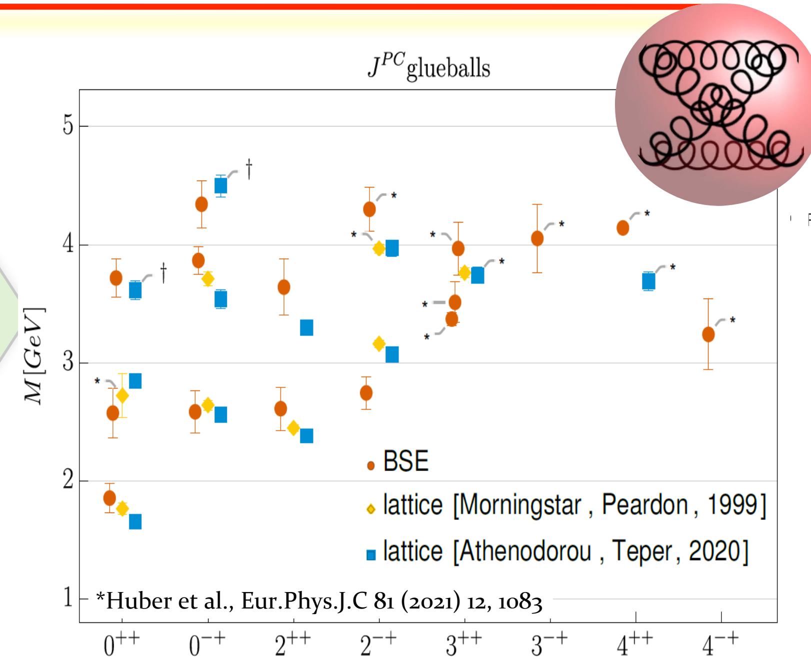
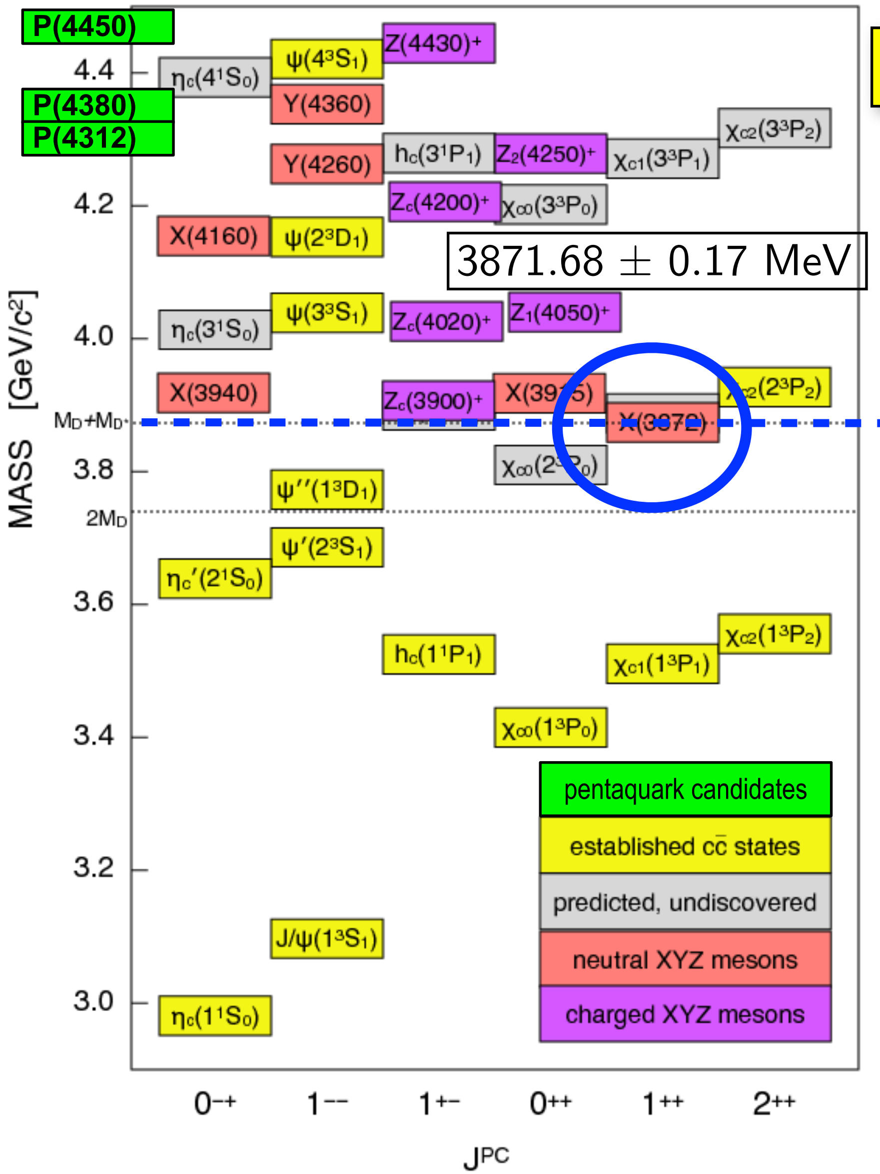




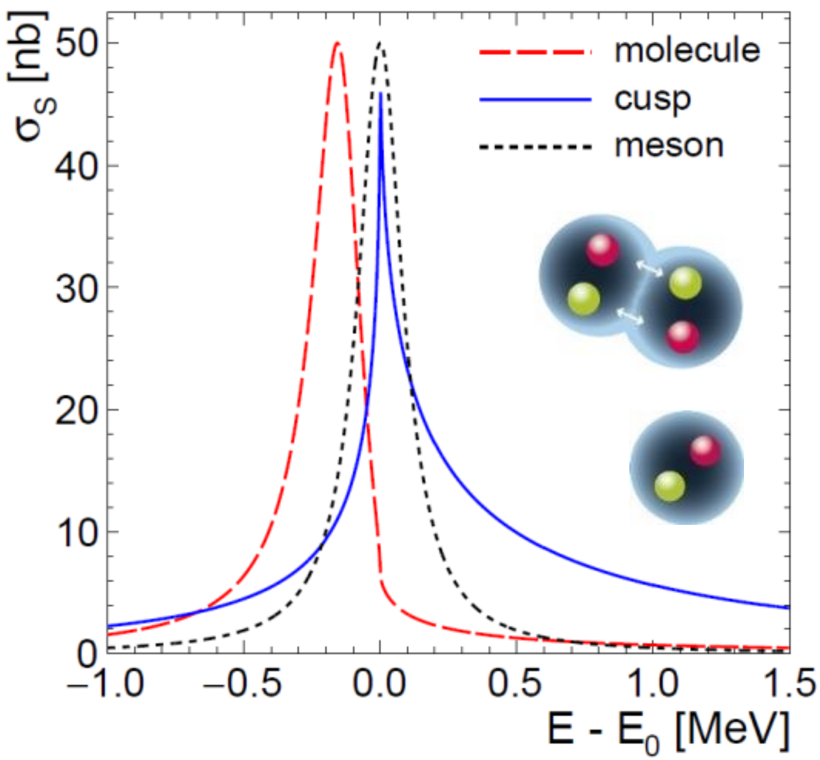
Line-shape study of the X(3872)



Strikingly narrow:

$$\Gamma < 1.2\,\mathrm{MeV}$$

*recent LHCb observation:
width=1.4 MeV *assuming* Breit-Wigner resonance



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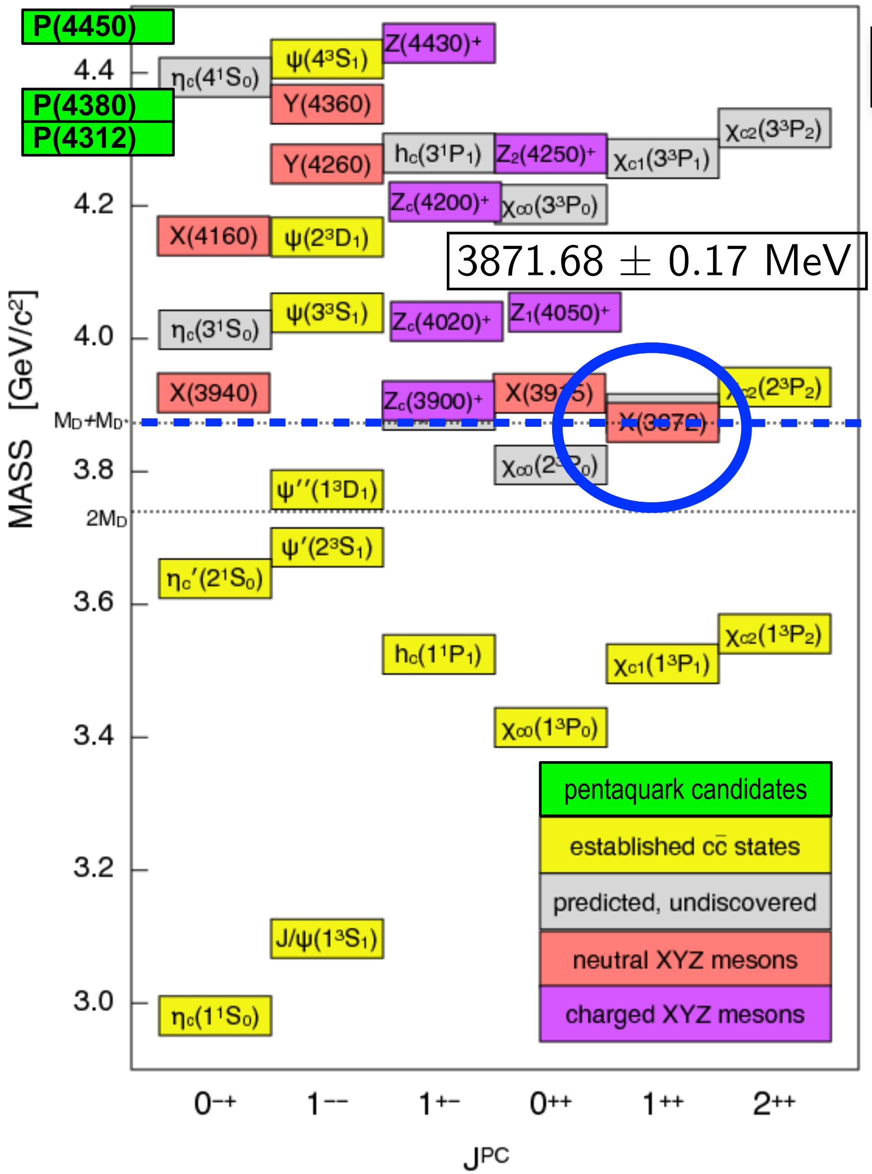

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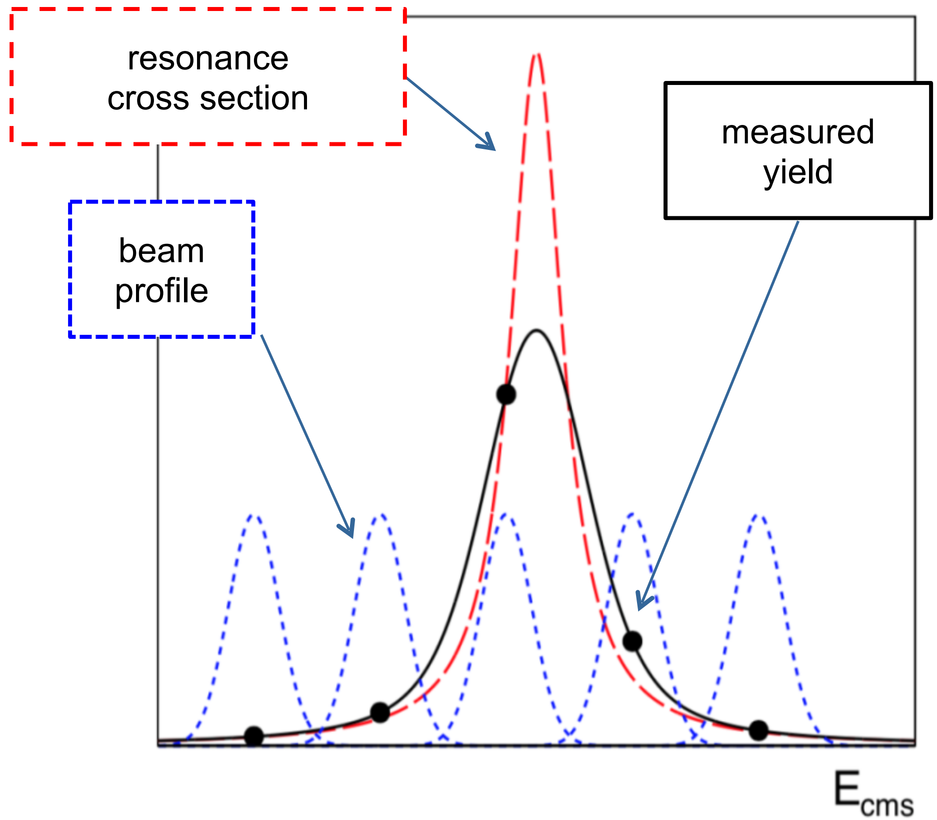

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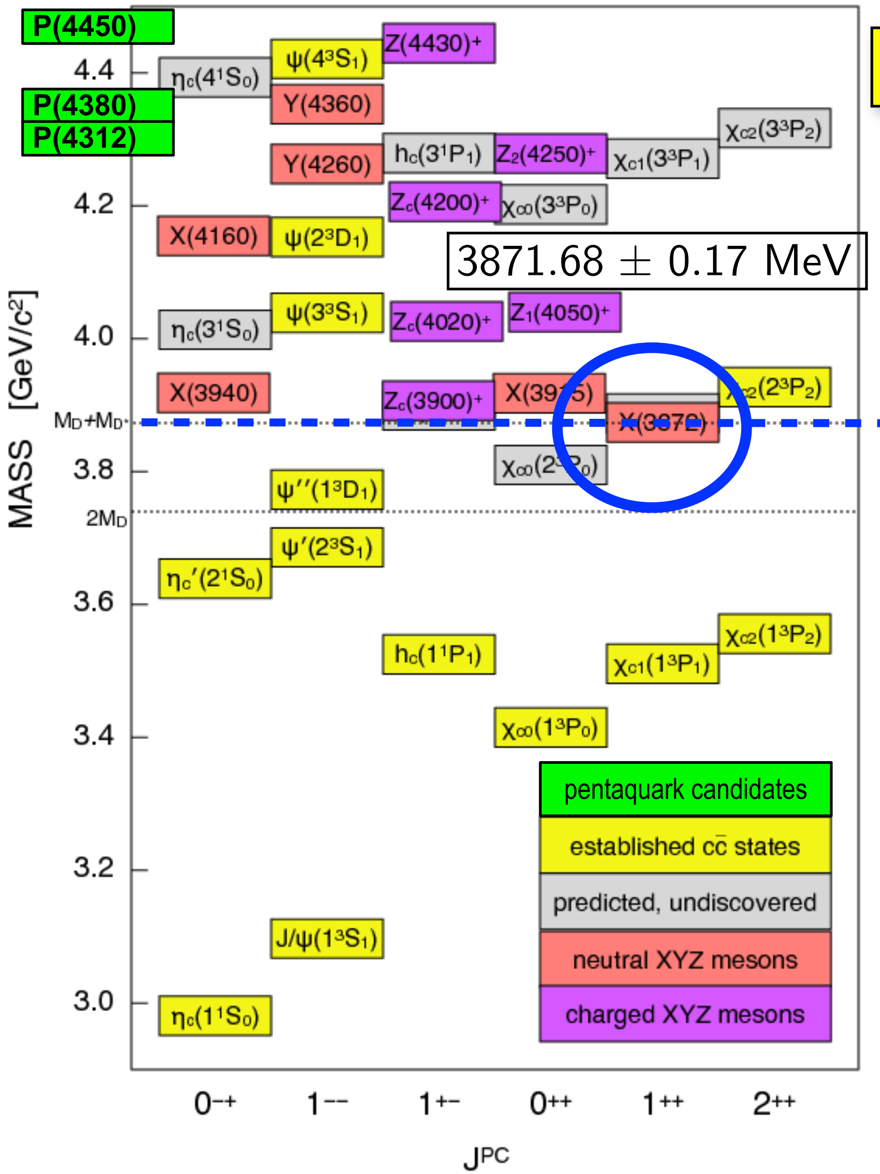

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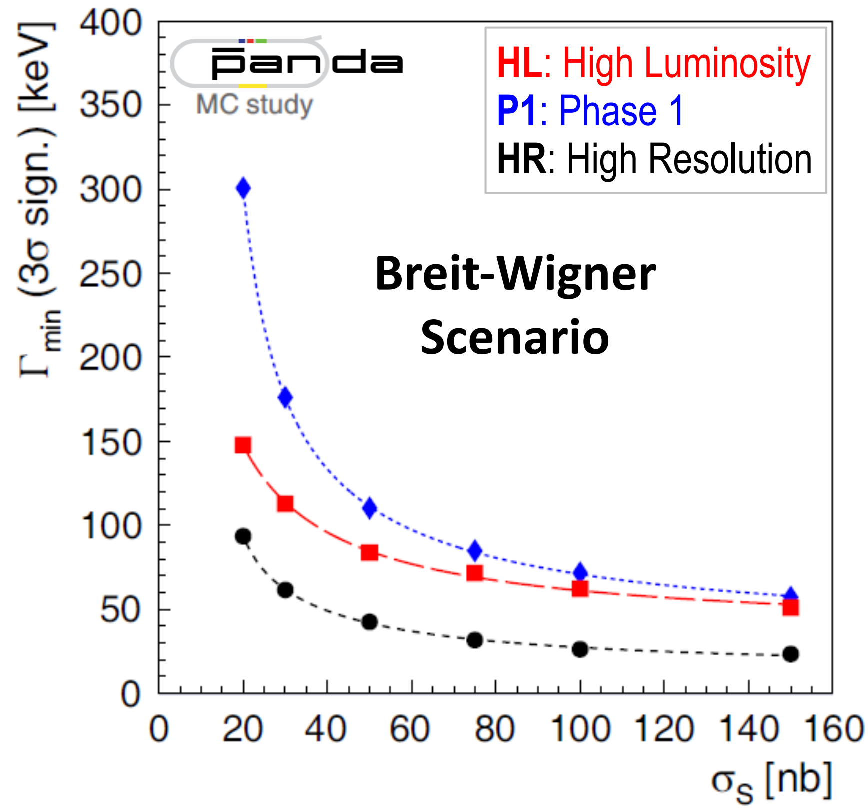

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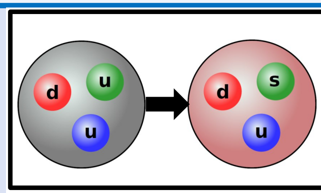

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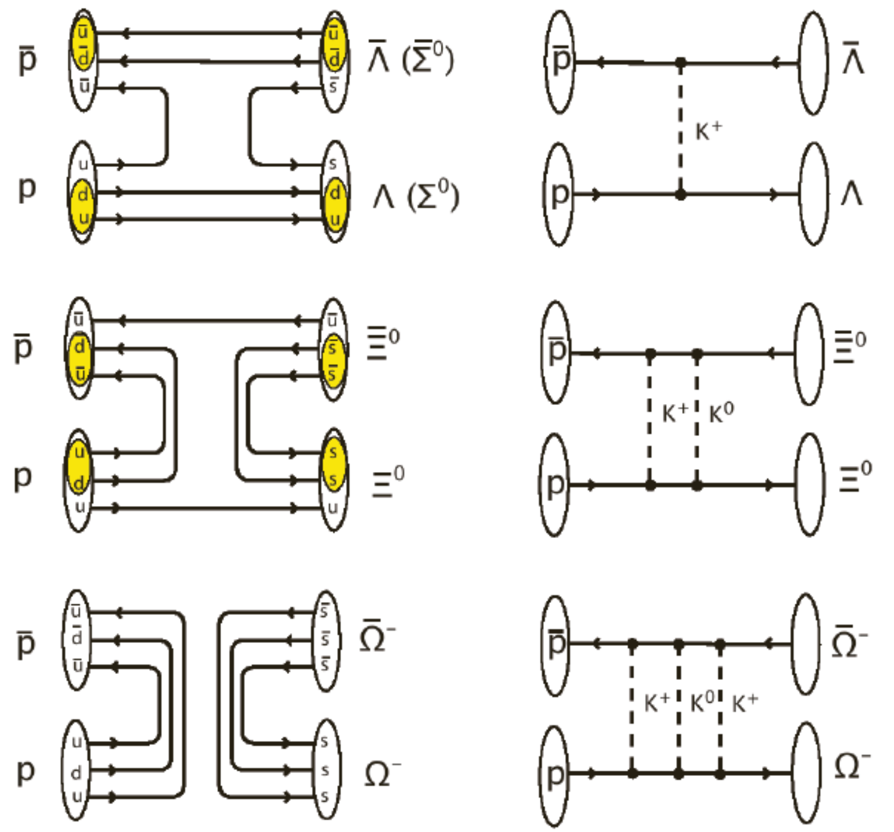
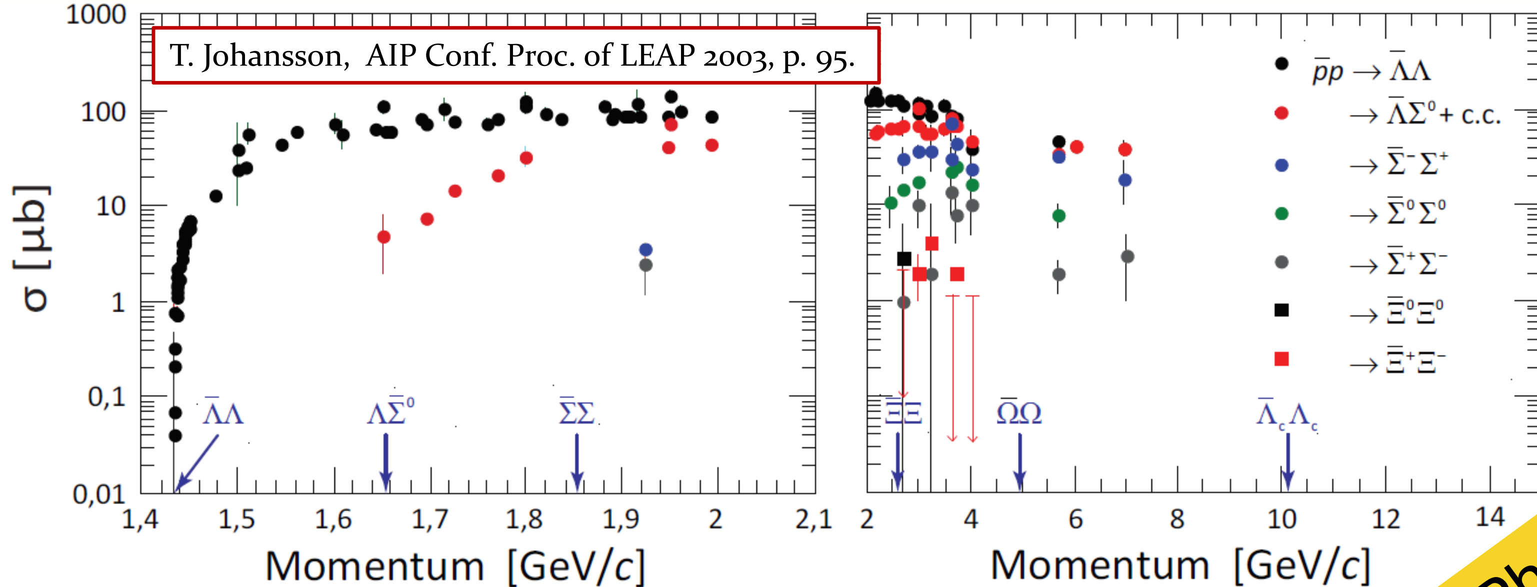
Hyperon *dynamics*

Strong production dynamics

- Relevant degrees of freedom?
- Strange *versus* charm sector?
- Role of spin?



PANDA is a hyperon factory!



p_{beam} (GeV/c)	Reaction	σ (μb)	ε (%)	Rate @ 10^{31} cm^{-2}s^{-1}	S/B	Events /day
1.64	$\bar{p}p \to \bar{\Lambda}\Lambda$	64.0	16.0	44 s^{-1}	114	$3.8 \cdot 10^6$
1.77	$\bar{p}p \to \bar{\Sigma}^0\Lambda$	10.9	5.3	2.4 s^{-1}	>11**	207 000
6.0	$\bar{p}p \to \bar{\Sigma}^0\Lambda$	20	6.1	5.0 s^{-1}	21	432 000
4.6	$\bar{p}p \to \bar{\Xi}^+\Xi^-$	~1	8.2	0.3^{-1}	274	26000
7.0	$\bar{p}p \to \bar{\Xi}^+\Xi^-$	~0.3	7.9	0.1^{-1}	65	8600

** 90% C.L.

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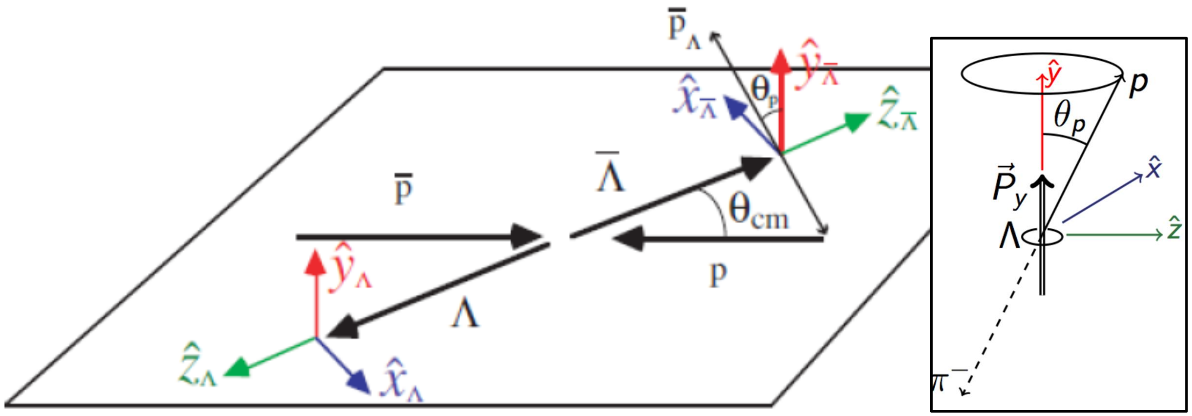
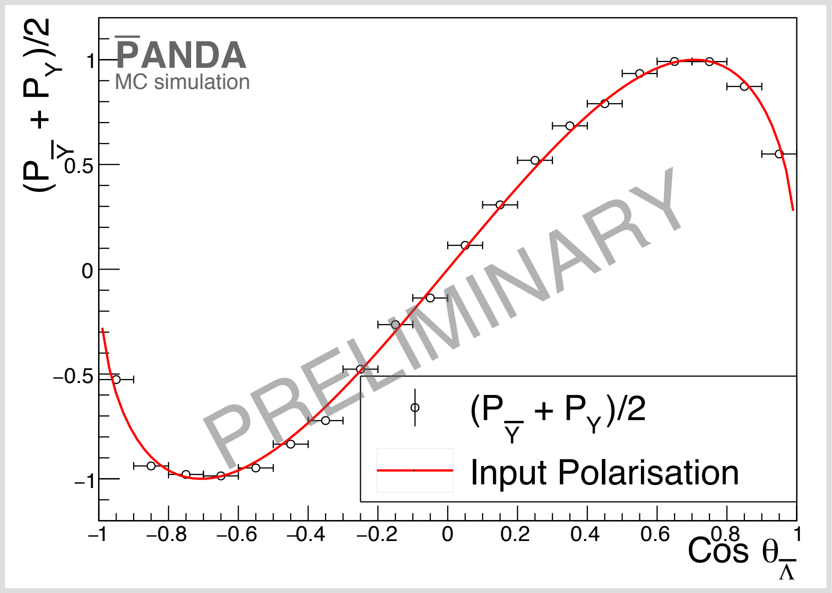


$$I(\cos\theta_B) = \frac{1}{4\pi}(1 + \alpha_Y P_y \cos\theta_B)$$

Weak decay: interference between parity-conserving P-wave and parity-violation S-wave amplitudes -> f.e. decay parameter α_Y

"Self-analyzing" hyperon decays: angular distribution related to polarization.

Provides a **rich set of polarisation & spin correlation** observables!



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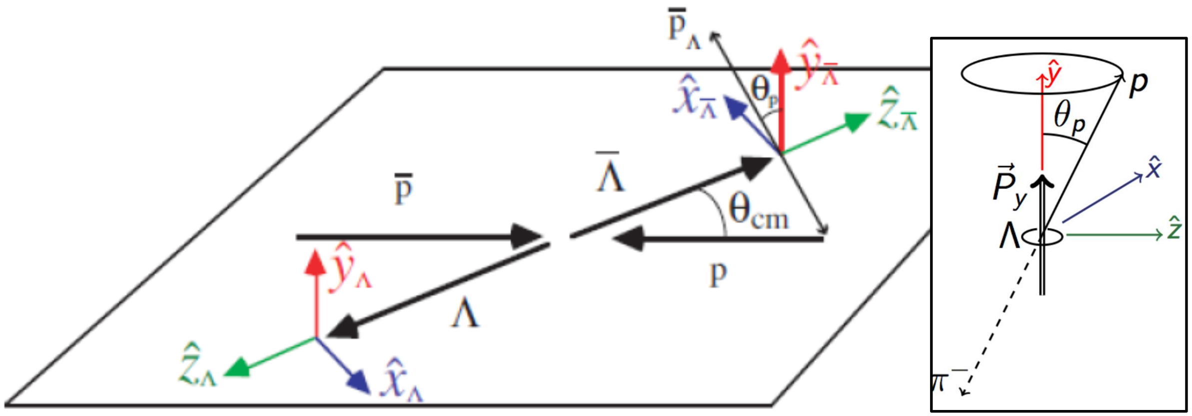

Particle physics!

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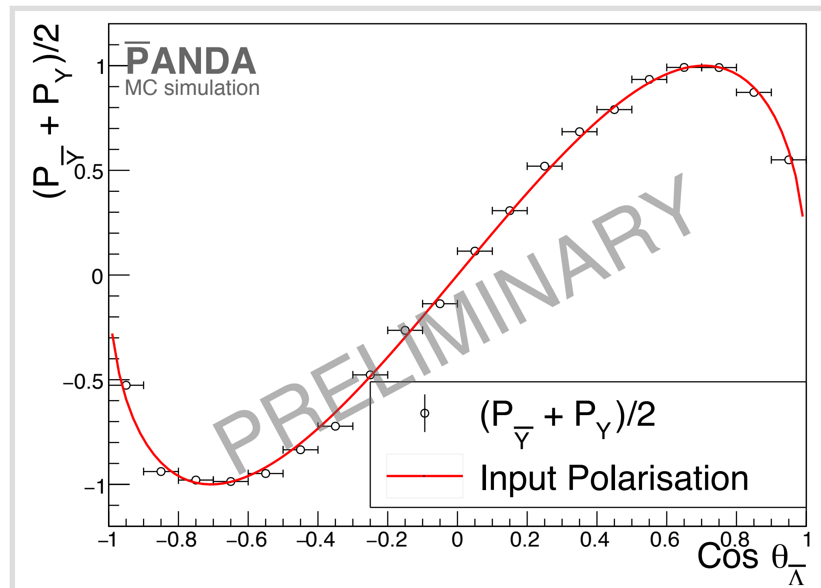
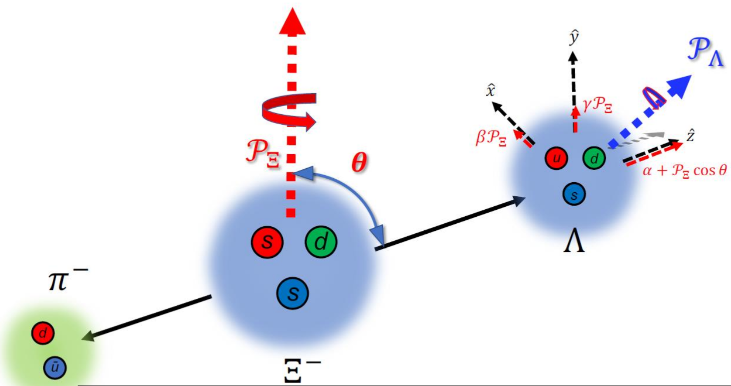
Test of **matter-antimatter asymmetry!**



CP symmetry studies in baryon sector



nature $e^+e^- \to J/\Psi \to \Xi\bar{\Xi} \to \Lambda\bar{\Lambda}\pi\pi$

Article | Open Access | Published: 01 June 2022

Probing CP symmetry and weak phases with entangled double-strange baryons

The BESIII Collaboration

606, 64–69 (2022) | Cite this article

*BESIII, Nature 606, 64-69 (2022)
**Tandean *et. al*, Phys. Rev. D 67, 056001 (2003)

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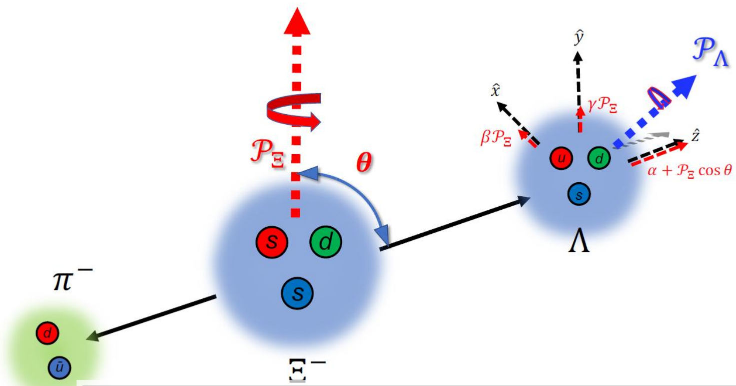


$$A_{\mathrm{CP}}^{Y} = \frac{\alpha_Y + \bar{\alpha}_Y}{\alpha_Y - \bar{\alpha}_Y}$$

$$\approx -\tan(\delta_p - \delta_s)\tan(\xi_p - \xi_s)$$

CPV effects suppressed by small **strong**-phase differences

nature $e^+e^- \to J/\Psi \to \Xi\bar{\Xi} \to \Lambda\bar{\Lambda}\pi\pi$

Article | Open Access | Published: 01 June 2022

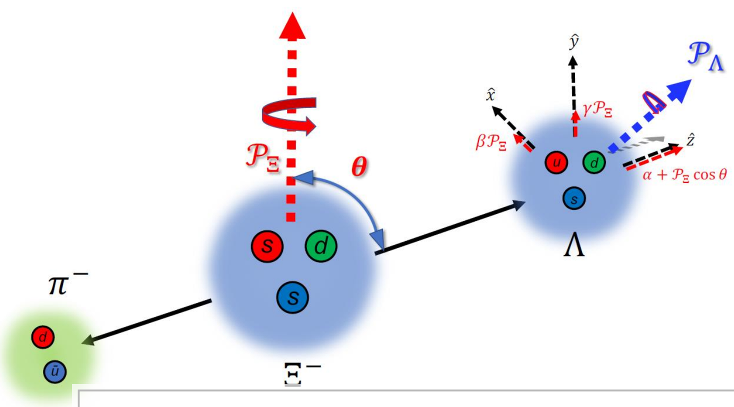
Probing CP symmetry and weak phases with entangled double-strange baryons

The BESIII Collaboration

606, 64–69 (2022) | Cite this article

*BESIII, Nature 606, 64-69 (2022)
**Tandean *et. al*, Phys. Rev. D 67, 056001 (2003)

CP symmetry studies in baryon sector



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$$\approx \frac{\alpha}{\sqrt{1-\alpha^2}}(\xi_p - \xi_s)_{LO}{}^{*}$$

Decouples **strong** and **weak** phases
—> very sensitive to CPV!

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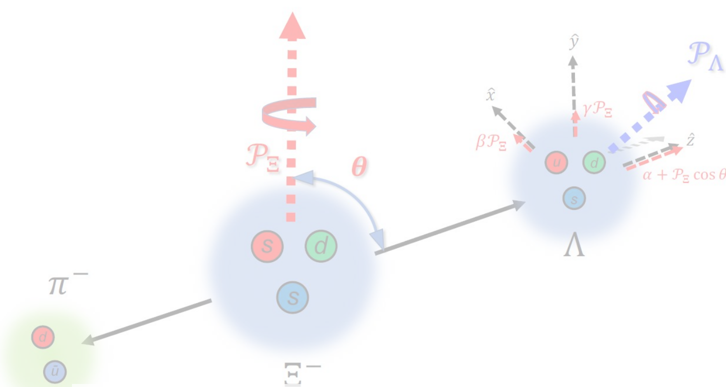

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$\mathcal{O}(\xi_p - \xi_s)$: 0.01*

SM: $\xi_p - \xi_s$ ~10^{-4}**

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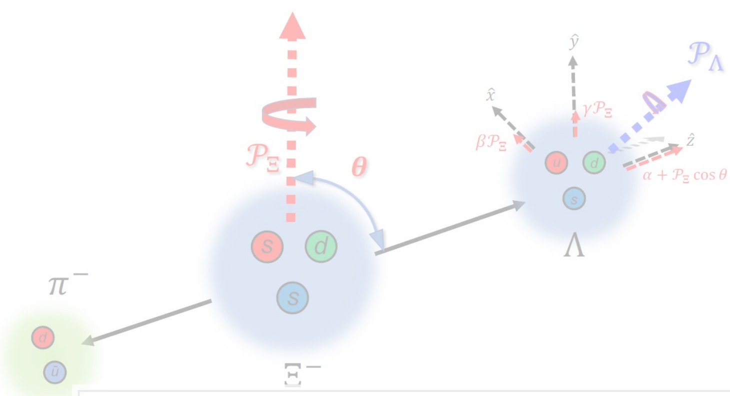

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PANDA: $\mathcal{O}(\xi_p - \xi_s)$ ~ 0.01 in < 3 days

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PANDA physics overview

CHARM — **STRANGE** — **LIGHT**

BELLEII, BESIII, COMPASS, JLAB, LHCb, ...

Spectroscopy

Hidden/open-charm states

Gluon-rich QCD states

Light-meson systems

BESIII, COMPASS, EIC, JLAB, ...

Nucleon Structure

Generalized Parton Distributions

Transition Distribution Amplitudes

Time-like Form Factors

Strangeness

Strange baryon spectroscopy

Hyperon production & polarizatio

Hyperon transition form factors

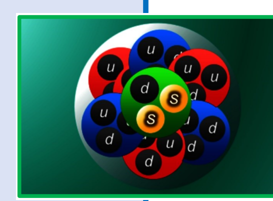
BESIII, JLAB, JPARC, HADES, MAMI, ELSA, ...

Nuclear Physics

Hadrons in nuclei

Hyperon-nucleon dynamics

Hyper-atoms and nuclei



CBM, HYPHI, JPARC, ...

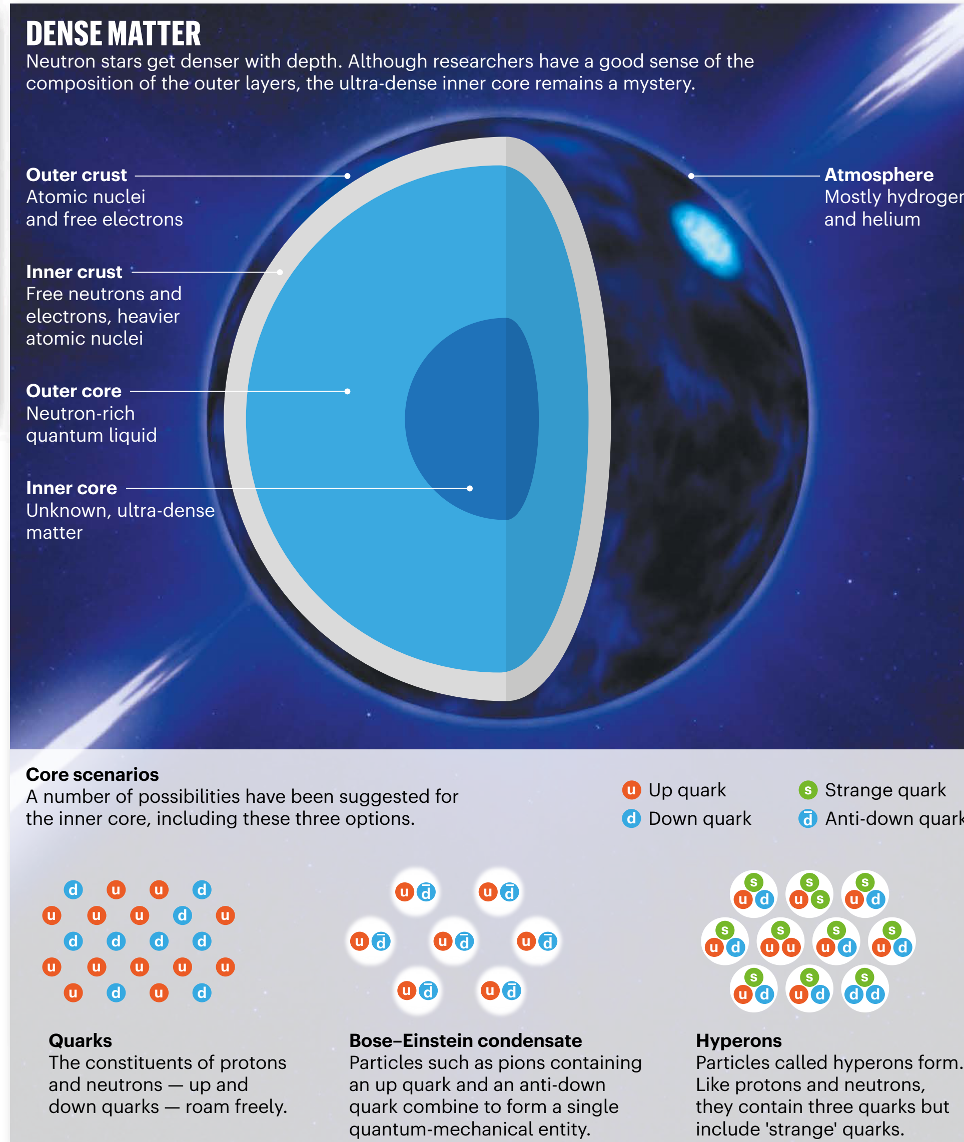
From matter of ~10^{-15} m to ~10^{4} m

nature

NEWS FEATURE | 04 March 2020

The golden age of neutron-star physics has arrived

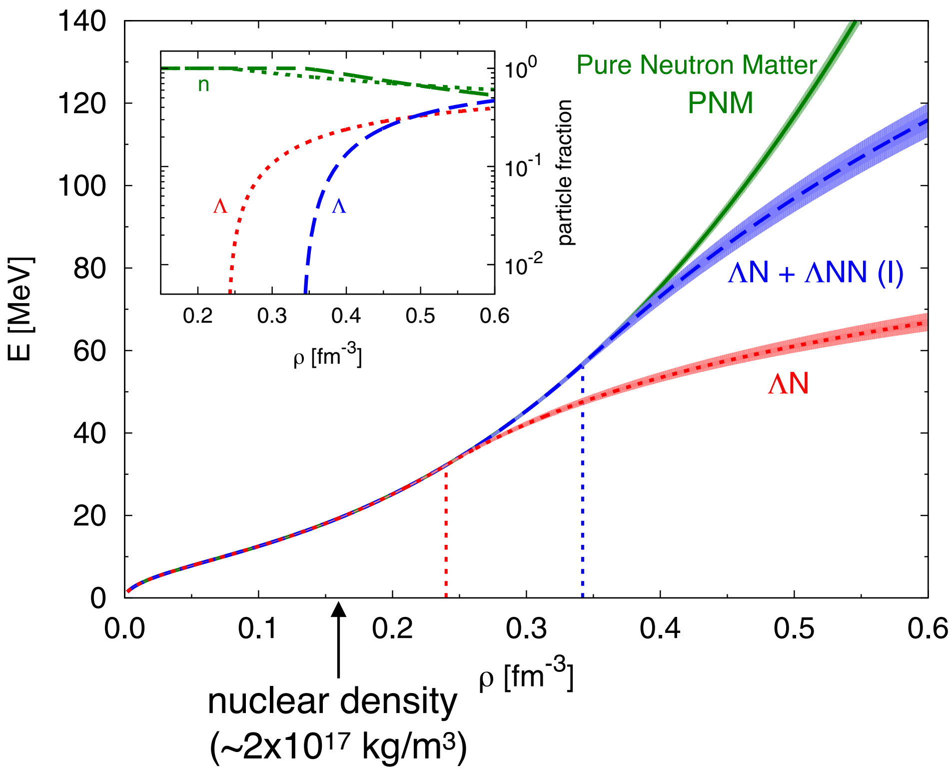
These stellar remnants are some of the Universe's most enigmatic objects – and they are finally starting to give up their secrets.



Hyperon puzzle in neutron stars?

D. Lonardoni et al., PRL114, 092301 (2015)

Quantum MC calculations including realistic NN, NNN potentials (Argonne-Illinois)



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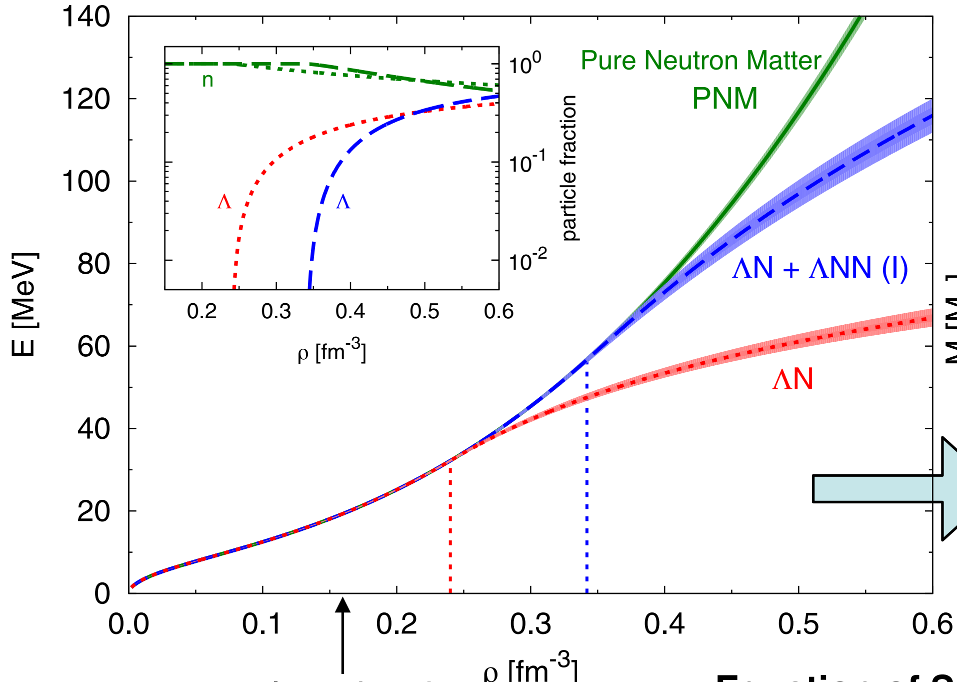
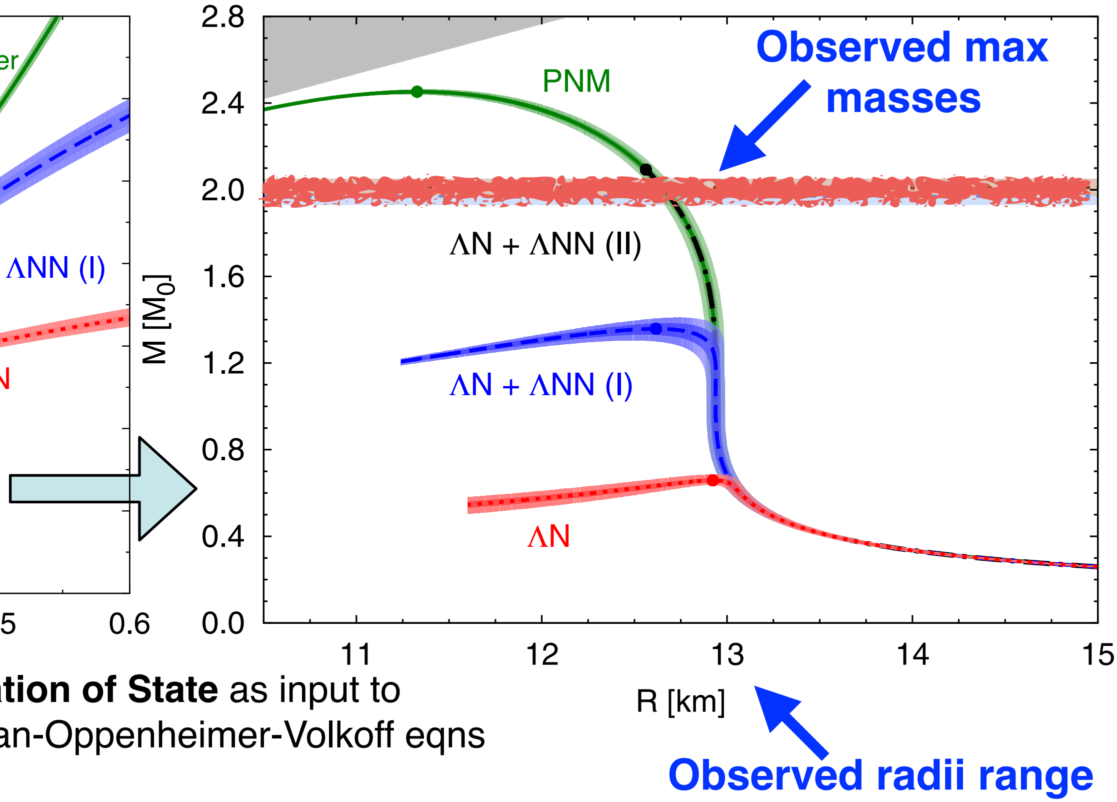


nuclear density
(~2x10^17 kg/m^3)

Equation of State as input to
Tolman-Oppenheimer-Volkoff eqns



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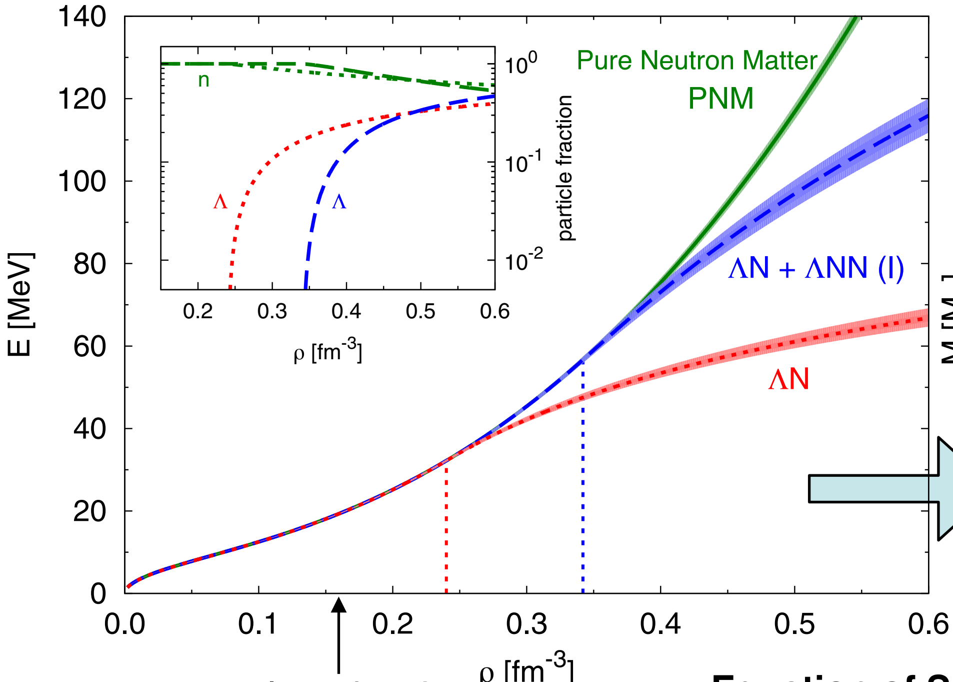

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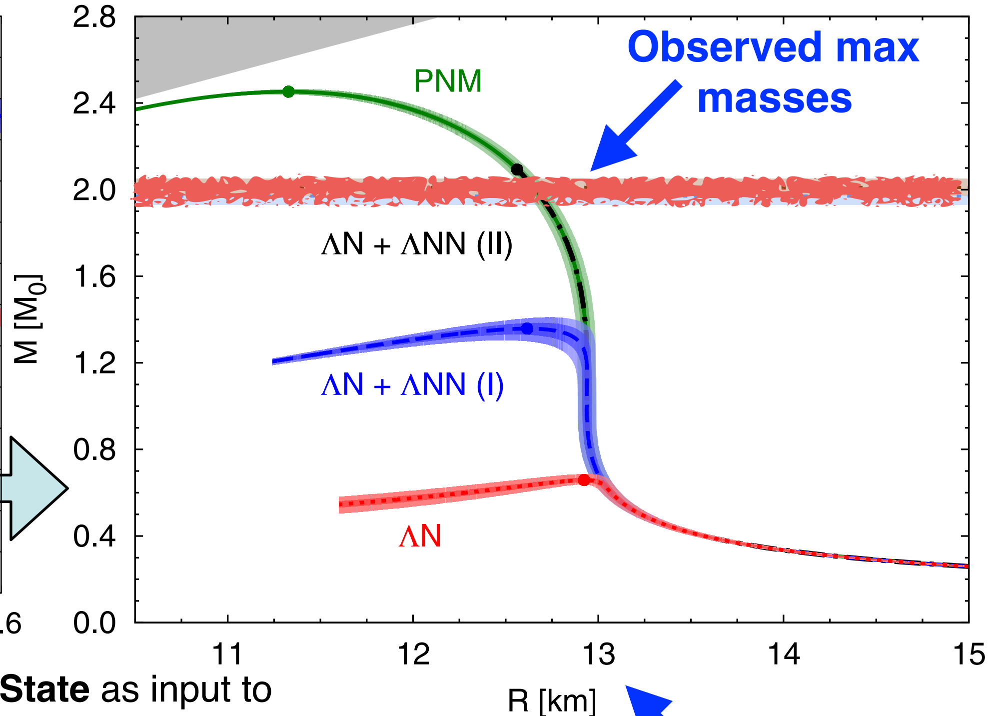


Equation of State as input to Tolman-Oppenheimer-Volkoff eqns

Observed radii range

Equation of State too soft with lightest hyperon (Y)

Strong repulsion in YN or YNN forces could resolve puzzle?

Precision measurements in the lab. of YN/YNN/YY forces needed!

Hyperon interaction studies @PANDA

Production of Ξ^-

Rescattering in
primary target

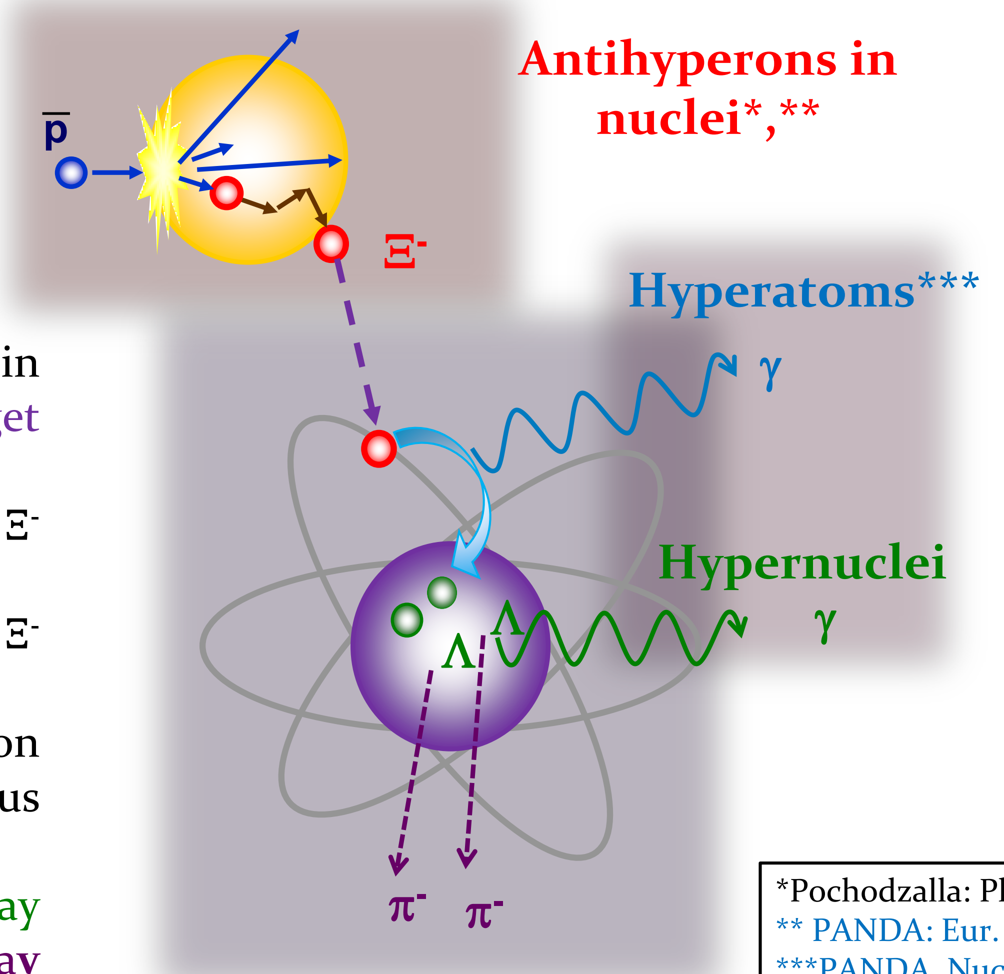
Deceleration in
secondary target

Capture of Ξ^-

Atomic cascade of Ξ^-

$\Xi^- p \rightarrow \Lambda\Lambda$ conversion
$\rightarrow$ Excited $\Lambda\Lambda$-nucleus

γ-decay
Weak pionic decay



*Pochodzalla: Phys. Lett. B 669, 306 (2008)
** PANDA: Eur. Phys. J A 57, 184 (2021)
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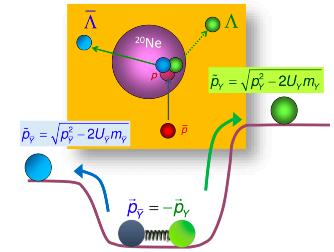

Production of Ξ⁻

Rescattering in primary target

Deceleration in secondary target

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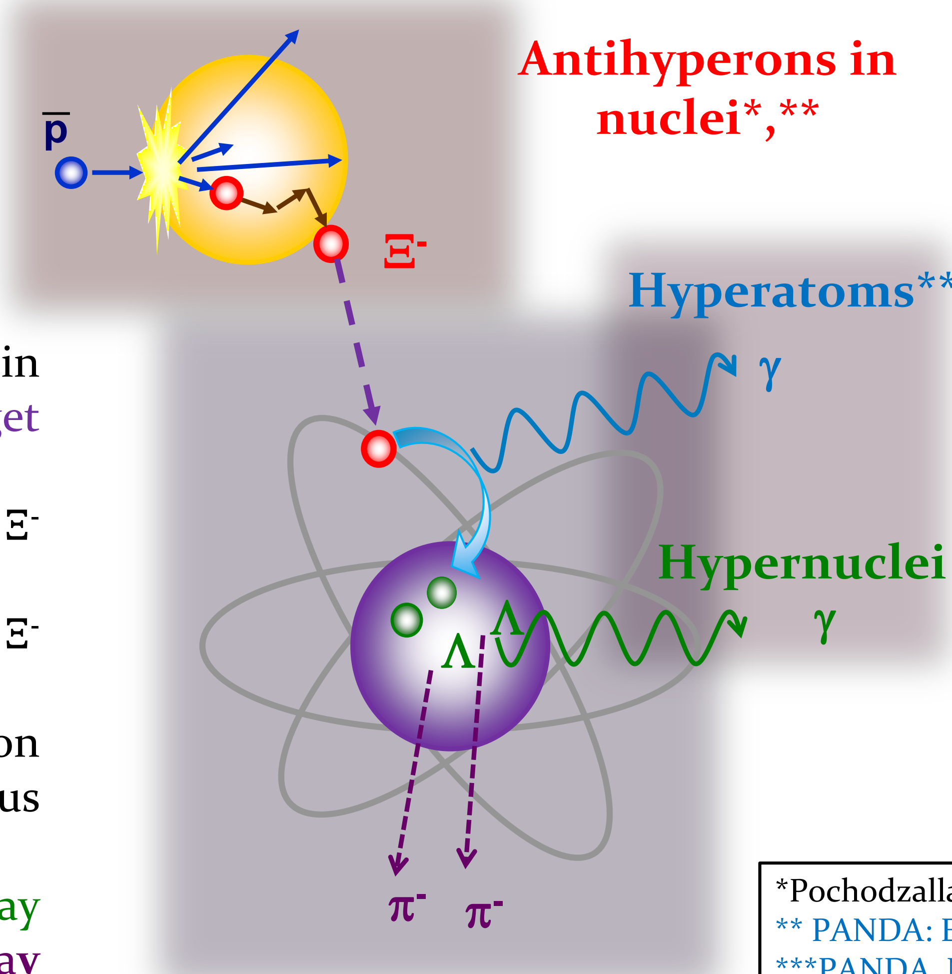

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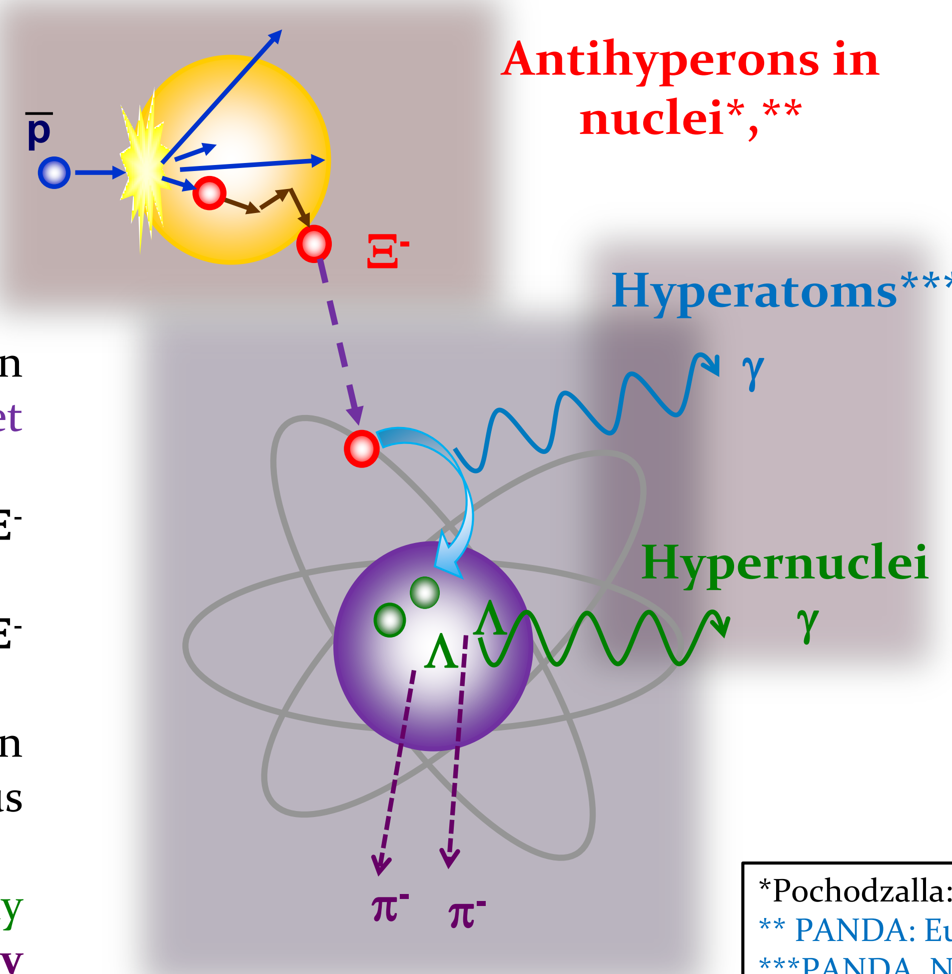

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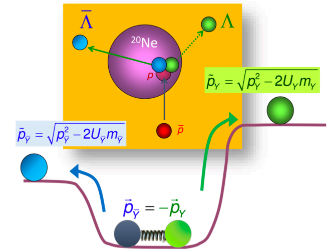

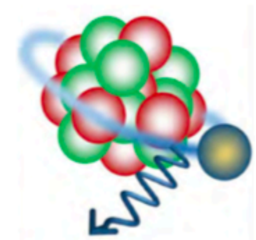

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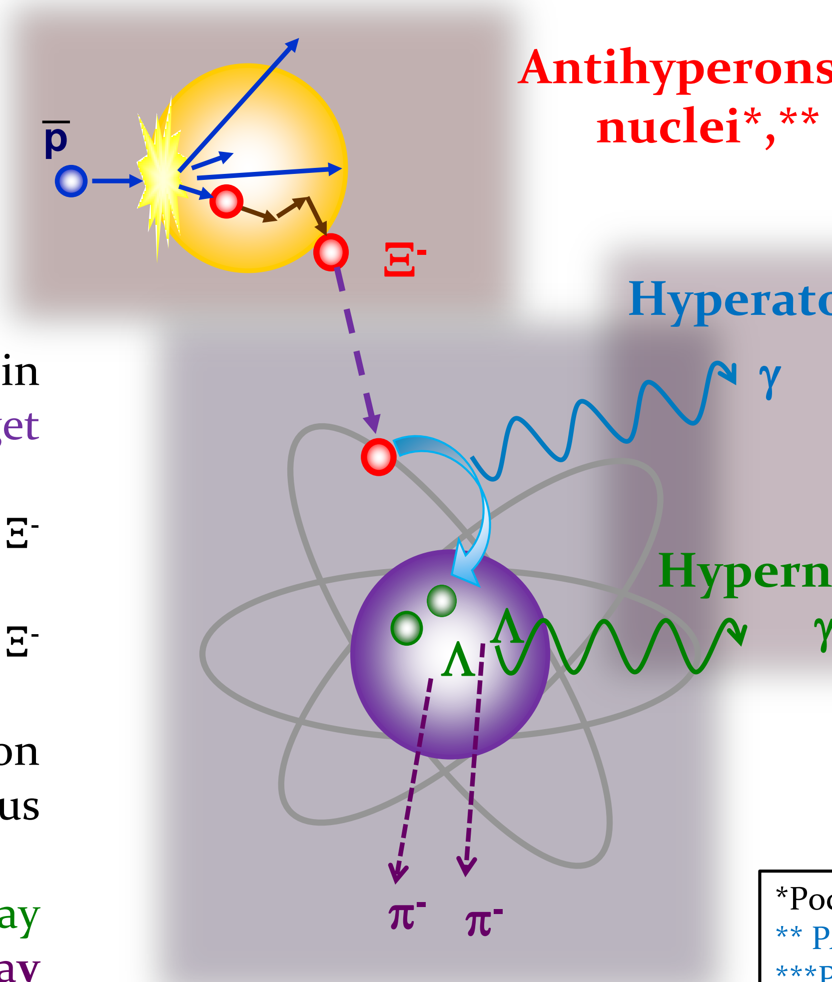

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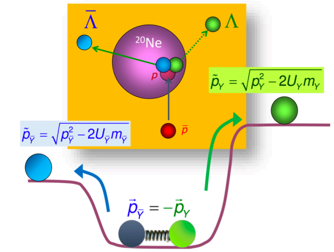
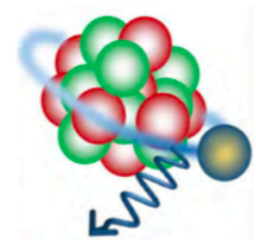
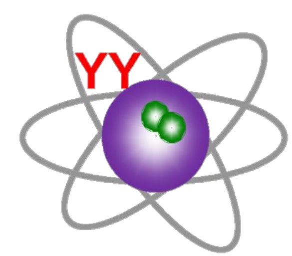


Hyperatoms***



Hypernuclei



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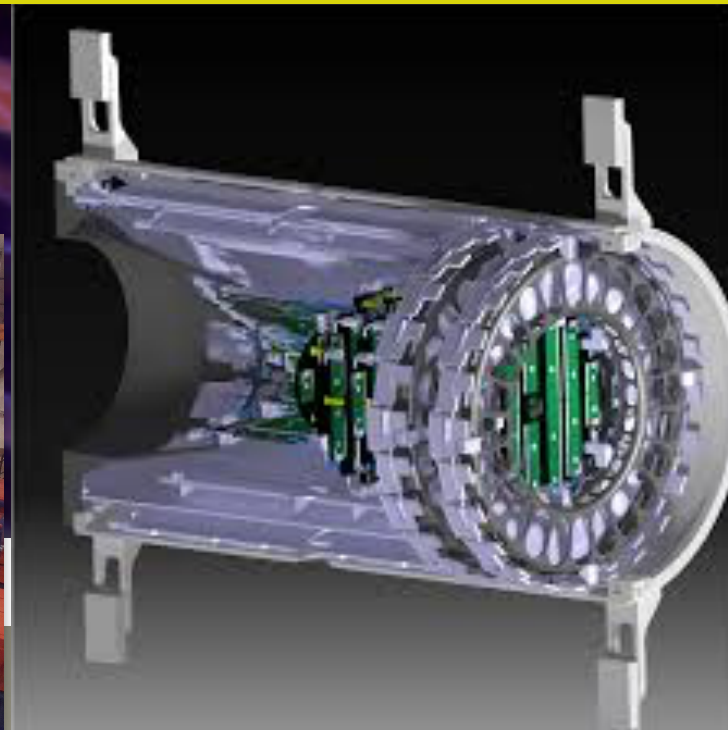
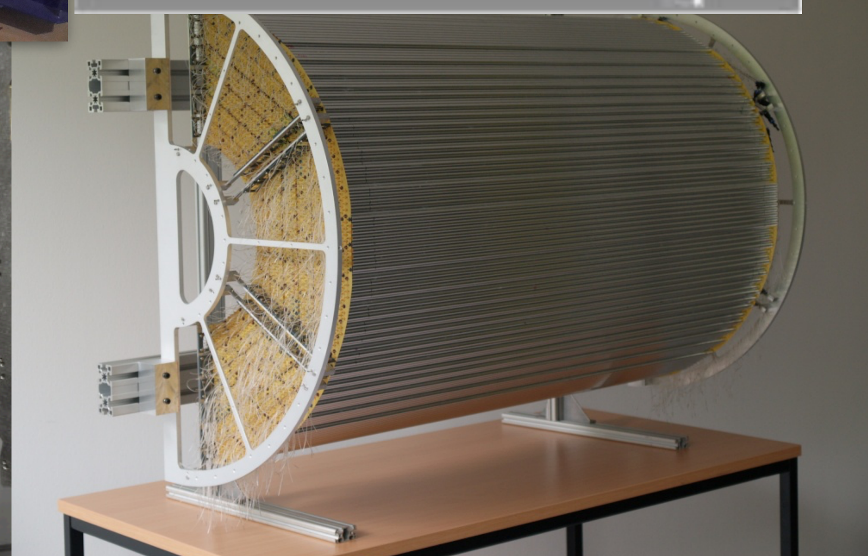
Physics prospects at PANDA



j.messchendorp@gsi.de

Physics prospects at PANDA

… important pillar at FAIR
- ESFRI landmark near Frankfurt, top priority NuPECC
- civil construction of FAIR well underway
- presently under ‘scientific' review

… covers particle, hadron, and nuclear aspects
- quark & gluon d.o.f.: quarkonium exotics, glueballs, etc.
- meson & baryon d.o.f.: B-B interaction in SU(3)

… is complementary and competitive
- *unique* antiproton facility

… remains vigilant (and patient)

j.messchendorp@gsi.de

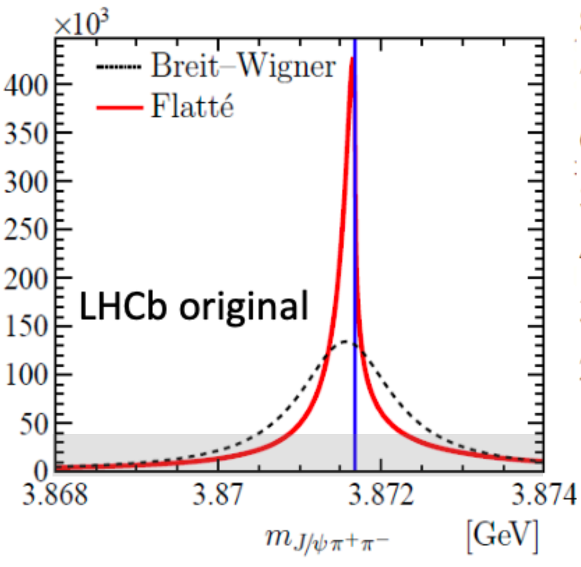
Backup

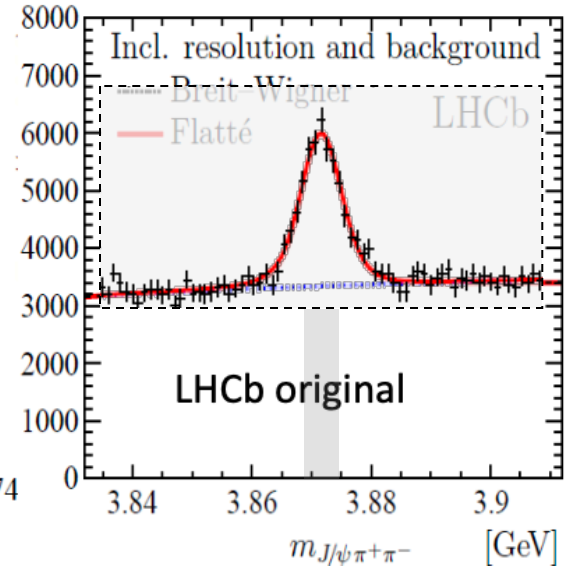
BESIII Result $e^+e^- \rightarrow J/\Psi \rightarrow \Xi\bar{\Xi} \rightarrow \Lambda\bar{\Lambda}\pi\pi$

Parameter	This work	Previous result	Reference
α_ψ	0.586±0.012±0.010	0.58±0.04±0.08	Ref. [49]
$\Delta\Phi$	1.213±0.046±0.016 rad	–	
α_Ξ	−0.376±0.007±0.003	−0.401±0.010	Ref. [26]
ϕ_Ξ	0.011±0.019±0.009 rad	−0.037±0.014 rad	Ref. [26]
$\bar{\alpha}_\Xi$	0.371±0.007±0.002	–	
$\bar{\phi}_\Xi$	−0.021±0.019±0.007 rad	–	
α_Λ	0.757±0.011±0.008	0.750±0.009±0.004	Ref. [4]
$\bar{\alpha}_\Lambda$	−0.763±0.011±0.007	−0.758±0.010±0.007	Ref. [4]
$\xi_P-\xi_S$	$(1.2\pm3.4\pm0.8)\times10^{-2}$ rad	–	
$\delta_P-\delta_S$	$(-4.0\pm3.3\pm1.7)\times10^{-2}$ rad	$(10.2\pm3.9)\times10^{-2}$ rad	Ref. [3]
A_{CP}^{Ξ}	$(6\pm13\pm6)\times10^{-3}$	–	
$\Delta\phi_{CP}^{\Xi}$	$(-5\pm14\pm3)\times10^{-3}$ rad	–	
A_{CP}^{Λ}	$(-4\pm12\pm9)\times10^{-3}$	$(-6\pm12\pm7)\times10^{-3}$	Ref. [4]
$\langle\phi_\Xi\rangle$	0.016±0.014±0.007 rad		

The $J/\psi \rightarrow \Xi^-\bar{\Xi}^+$ angular distribution parameter α_ψ, the hadronic form factor phase $\Delta\Phi$, the decay parameters for $\Xi^- \rightarrow \Lambda\pi^-$ (α_Ξ, ϕ_Ξ), $\bar{\Xi}^+ \rightarrow \bar{\Lambda}\pi^+$ $(\bar{\alpha}_\Xi, \bar{\phi}_\Xi)$ $\Lambda \rightarrow p\pi^-$ (α_Λ) and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ $(\bar{\alpha}_\Lambda)$; the CP asymmetries A_{CP}^{Ξ}, $\Delta\phi_{CP}^{\Xi}$ and A_{CP}^{Λ}, and the average $\langle\phi_\Xi\rangle$. The first and second uncertainties are statistical and systematic, respectively.

Resonance scanning, a case study





- Width assuming **B-W**:
  $\Gamma = 1.39 \mp 0.24 \mp 0.10$ MeV (LHCb 2020*)
- Width assuming **Flatté** model:
  FWHM = $0.22^{+0.06+0.25}_{-0.08-0.17}$ MeV (LHCb 2020*))

→ Not possible to distinguish by LHCb

* LHCb: Phys. Rev. D 102, 9, 092005 (2020)

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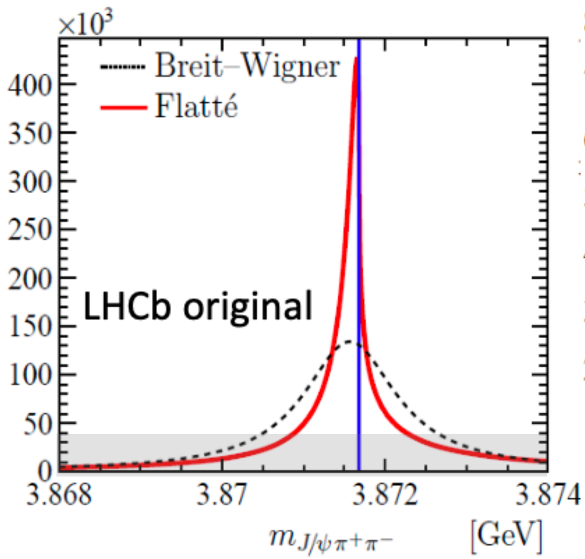

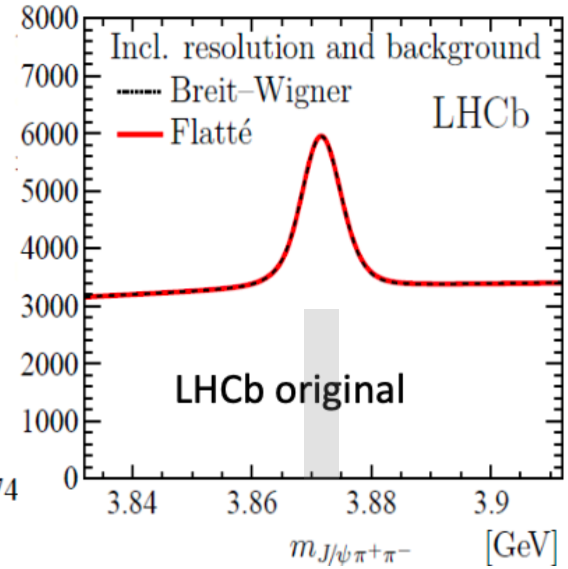

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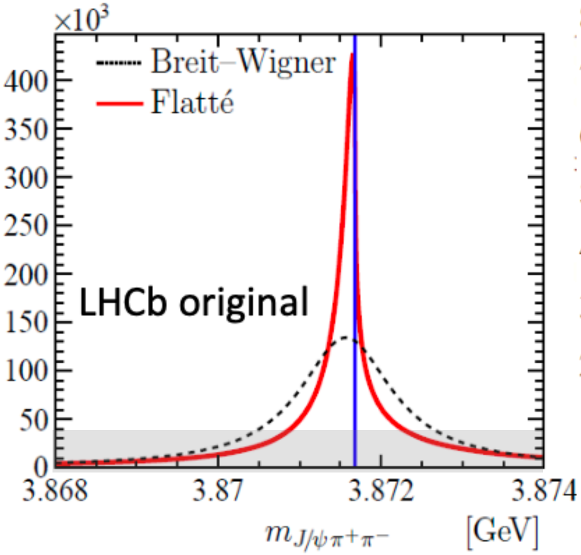

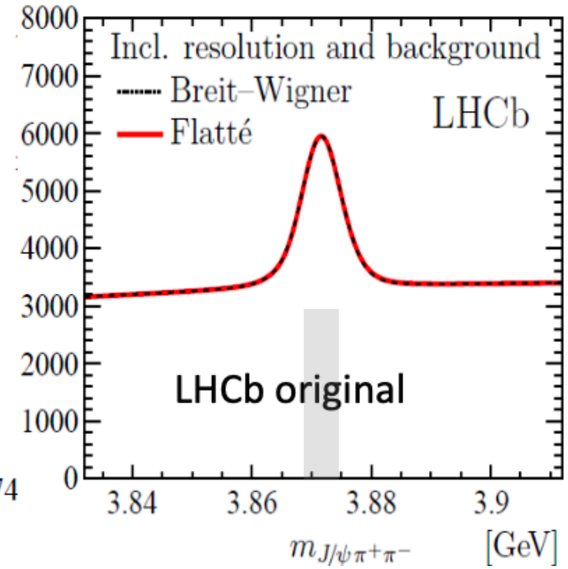

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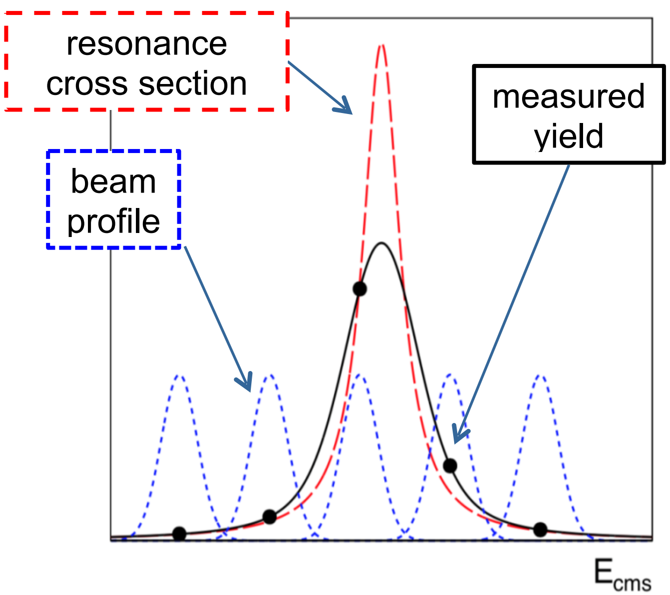

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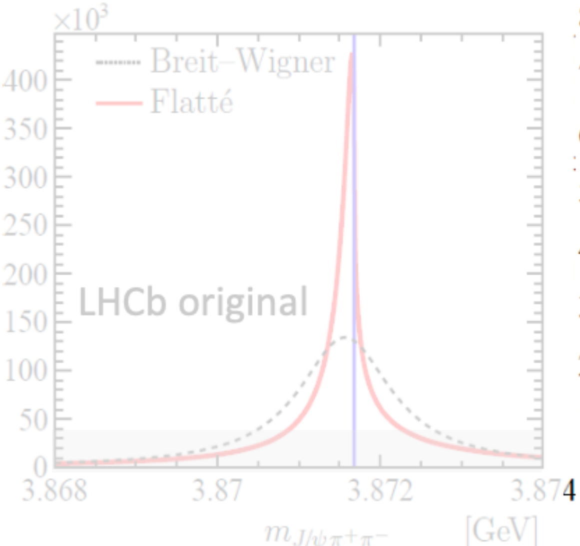

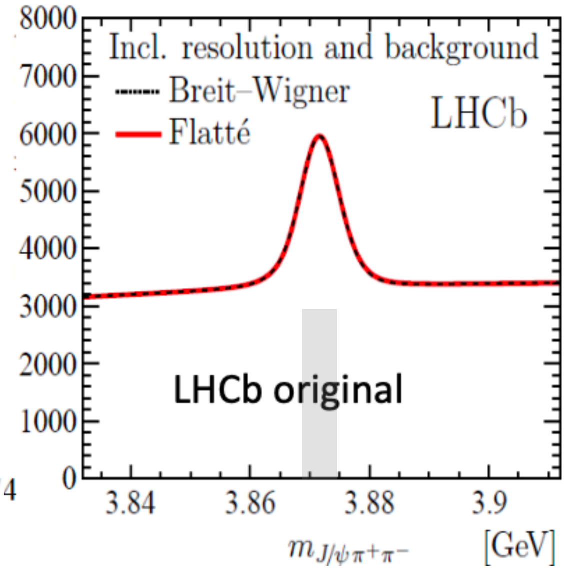

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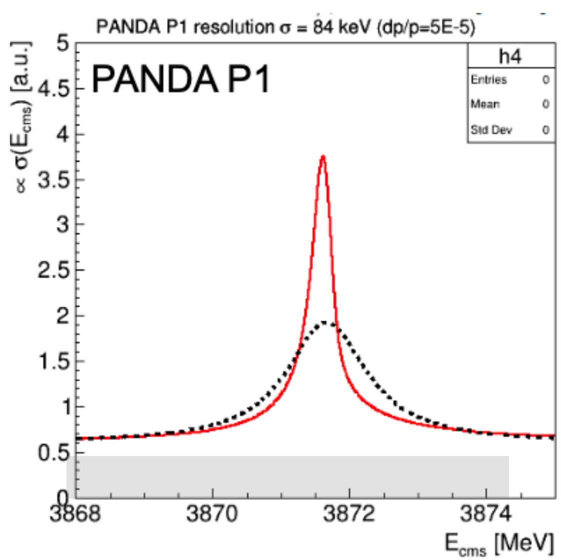
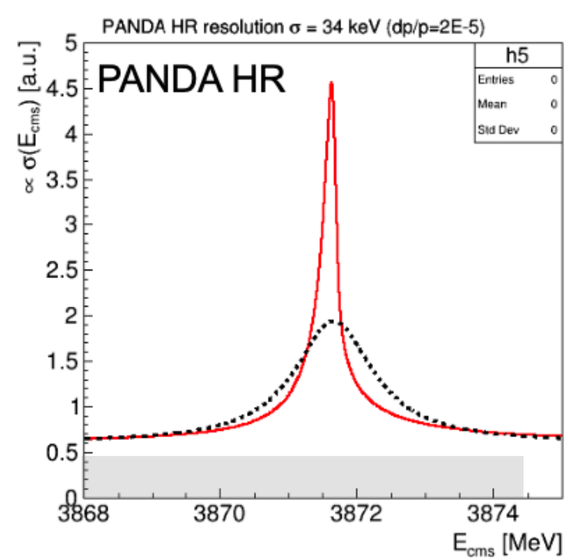




Antihyperons in nuclei @ Day-1

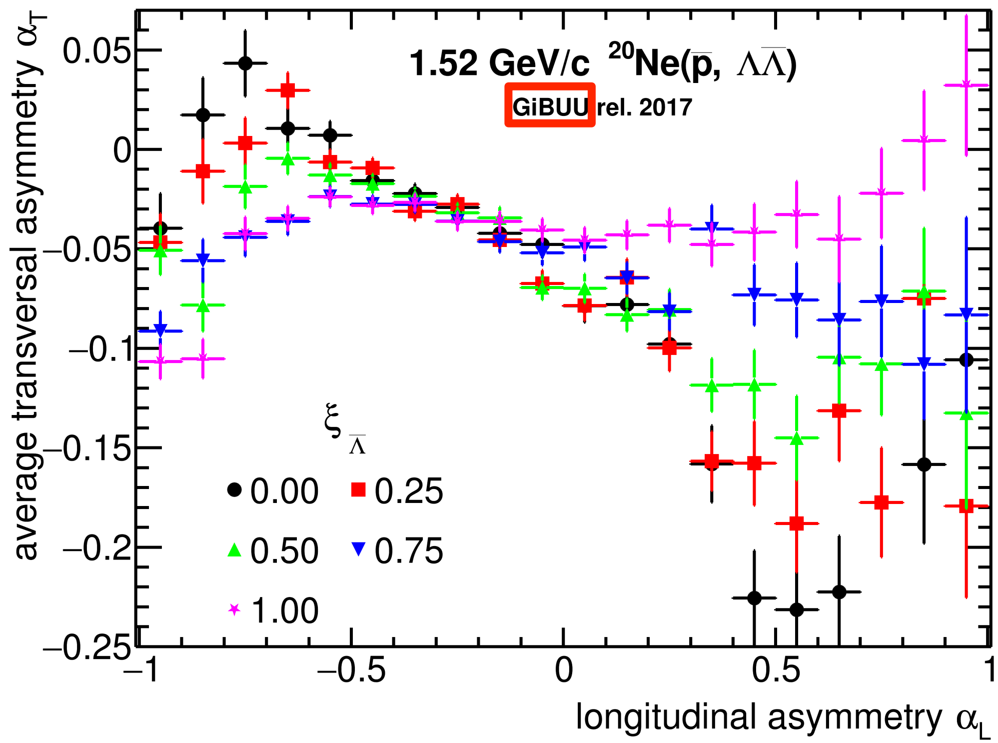
Josef Pochodzalla

Day-1: antihyperon optical potential

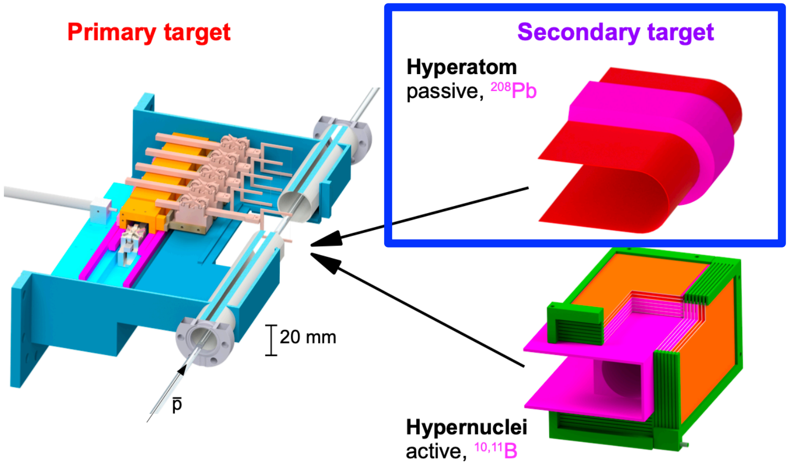
Exploit abundantly produced hyperon-antihyperon pairs near threshold

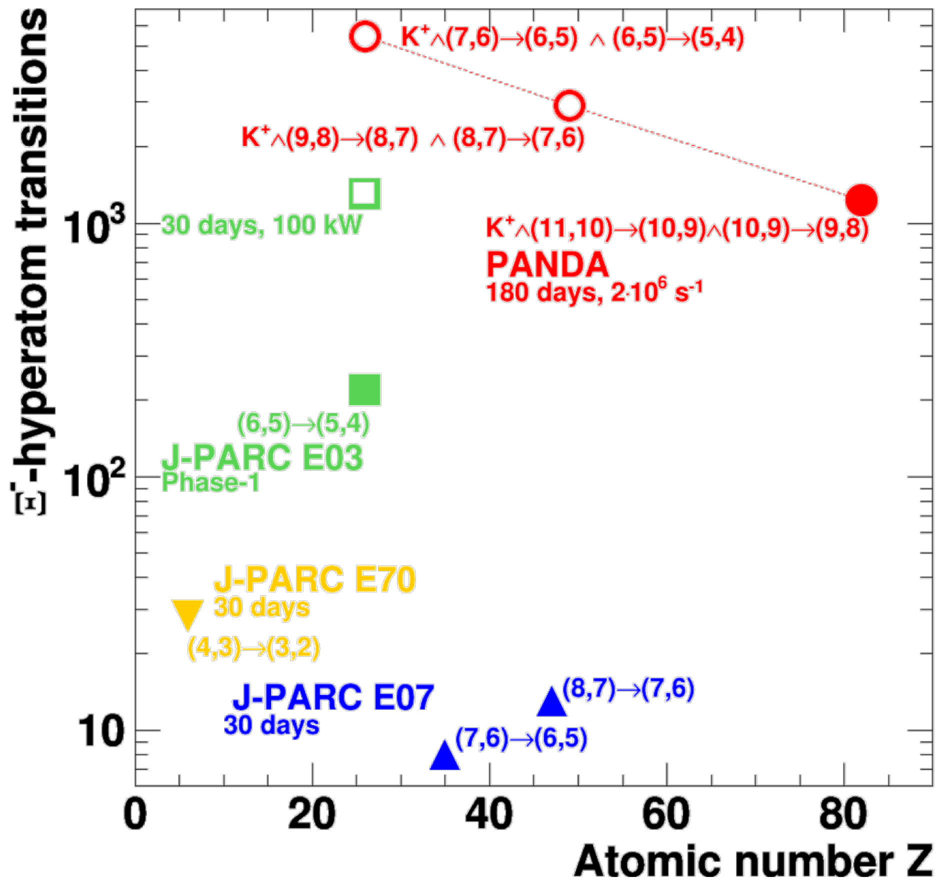
Spectrum: less than 1 hour of beam time at Day-1 luminosities!

First step towards hyperatom and hypernuclei program



Ξ^- Hyperatoms at Phase One





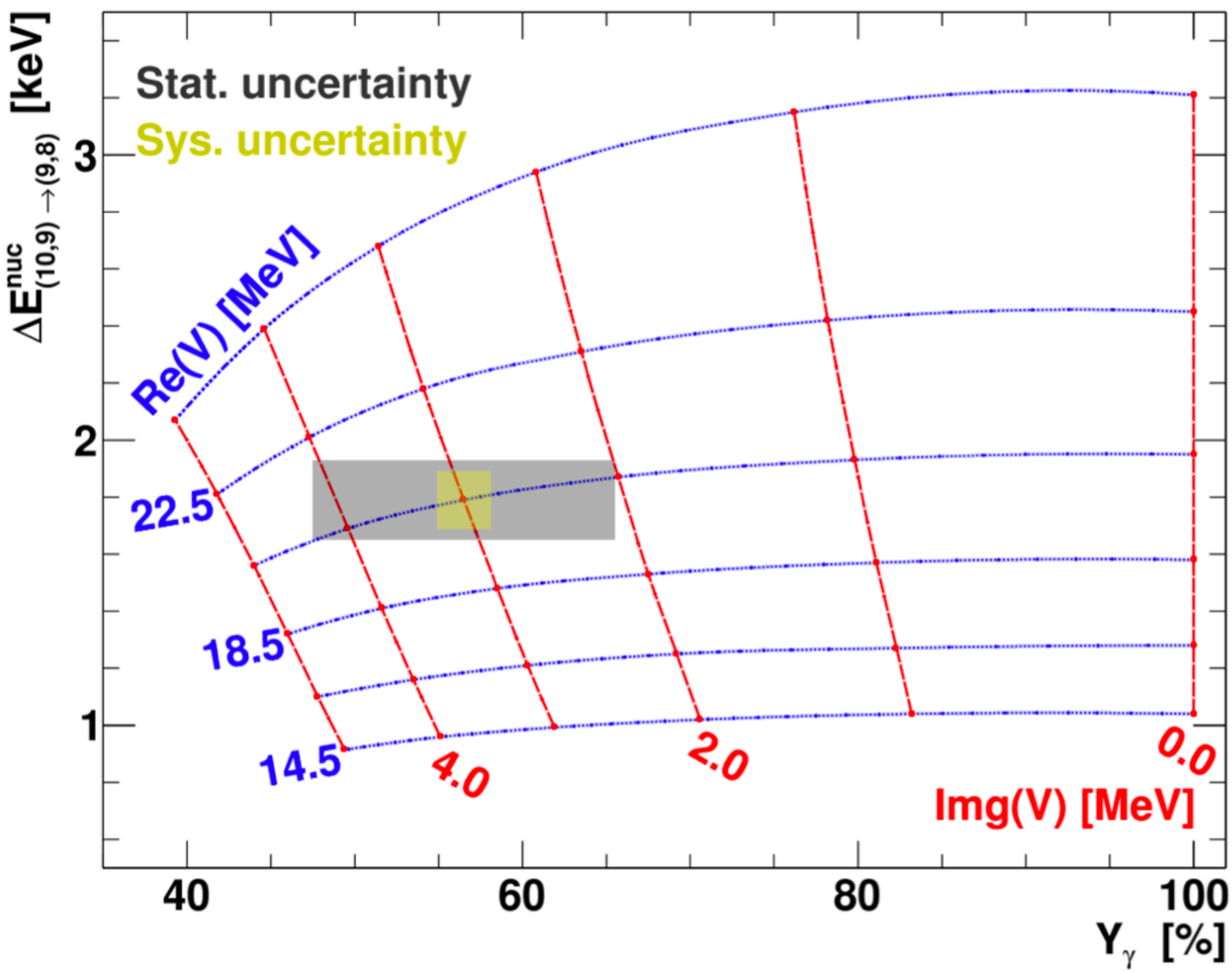
Measure strong interaction shift and width at periphery of nucleus

X-ray spectroscopy of transition prior to capture

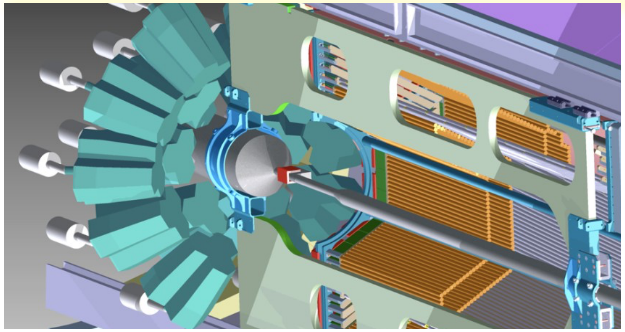
PANDA unique: high neutron density probed using Pb target

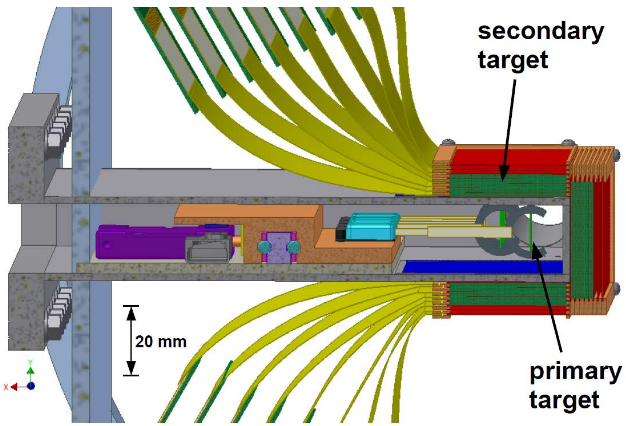
Hyperatoms - potential sensitivity

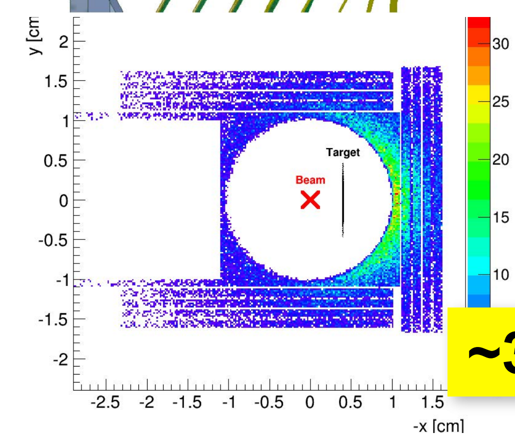
Marcell Steinen, PhD dissertation

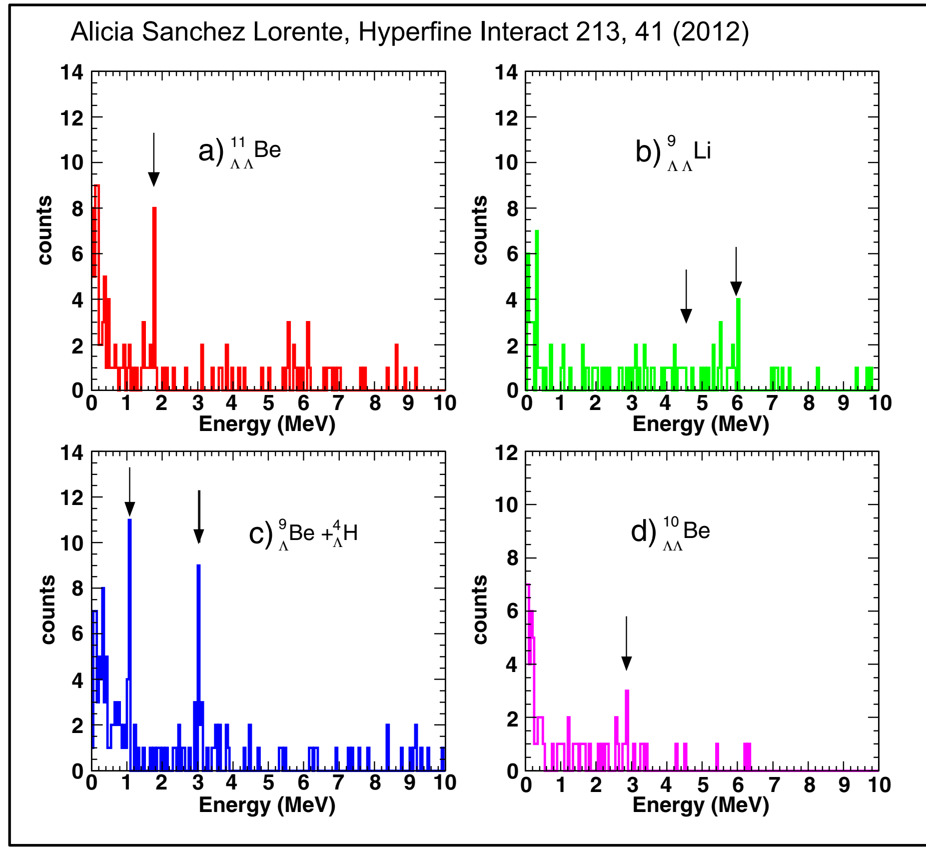


Double hypernuclear spectroscopy



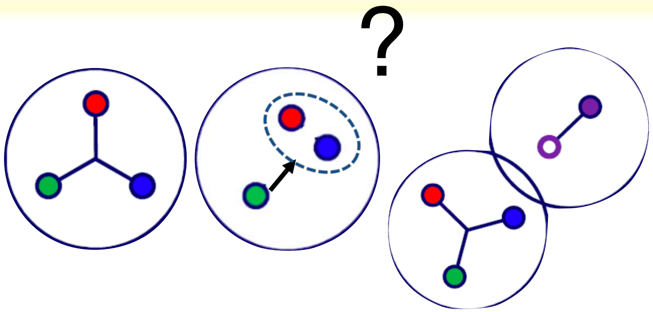




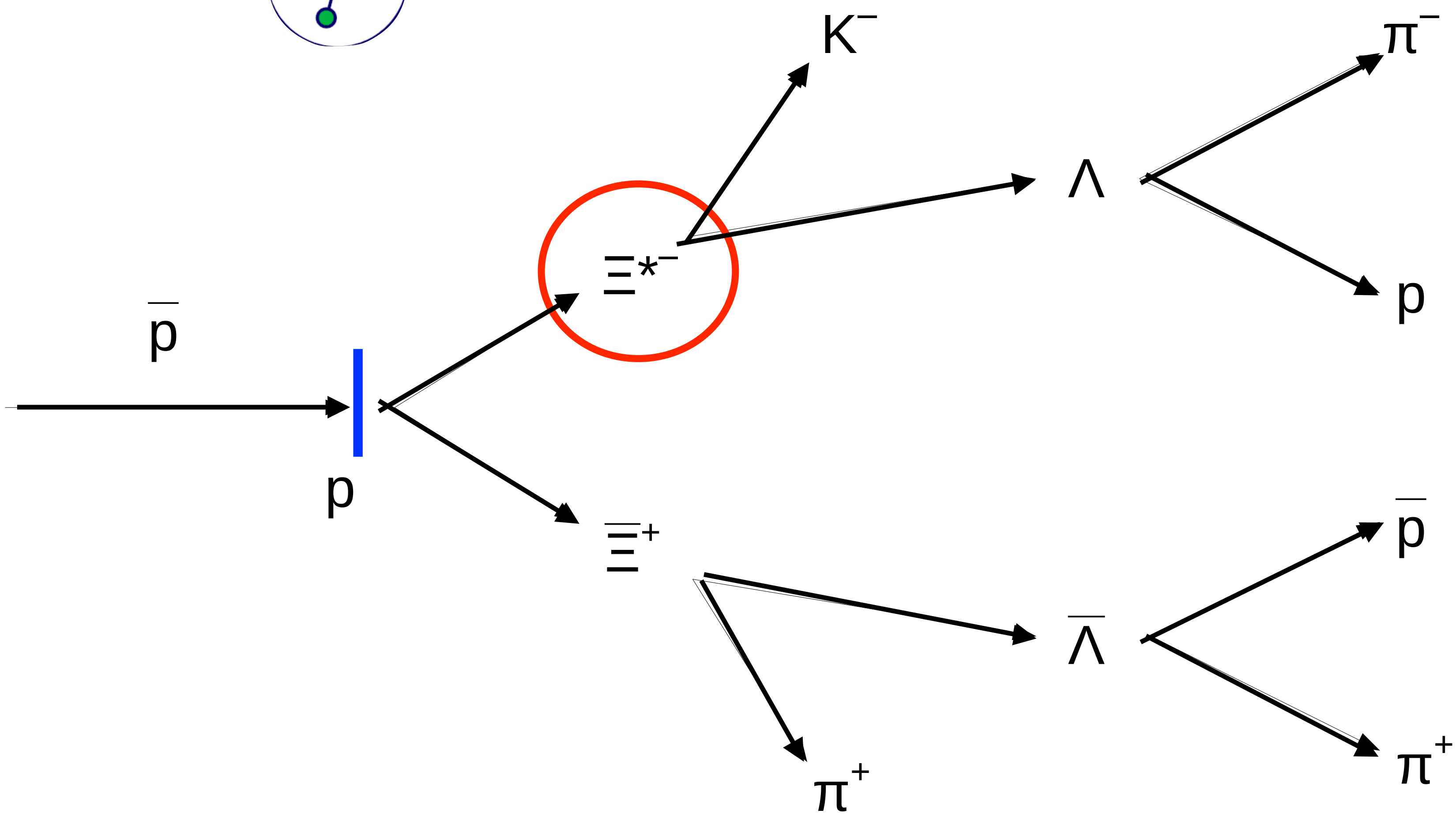


~30.000 stopped Ξ^-'s per day

Hyperon *spectroscopy*



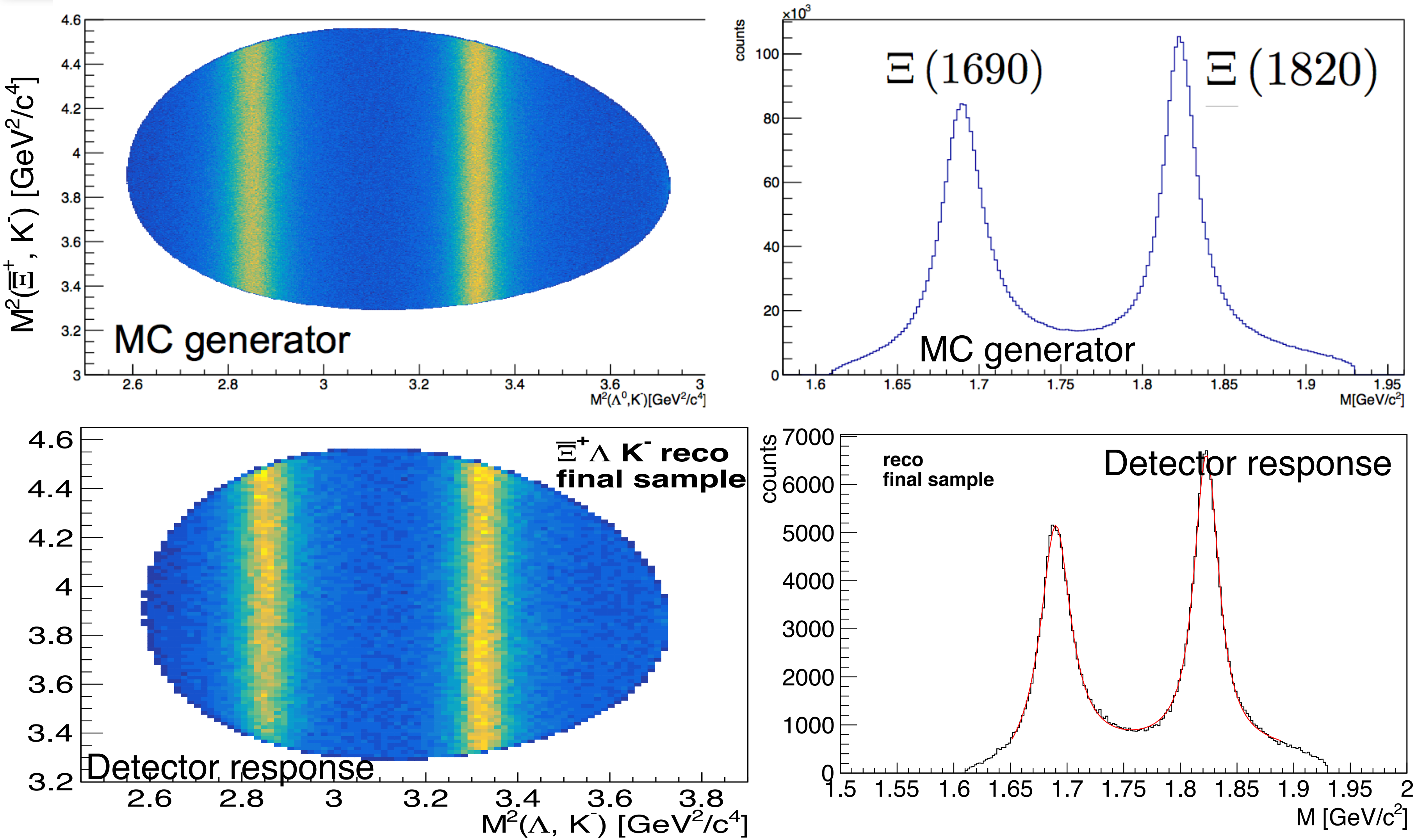
Map out the |S|=2 excited baryon spectrum



Hyperon spectroscopy

Jennifer Puetz, Albrecht Gillitzer

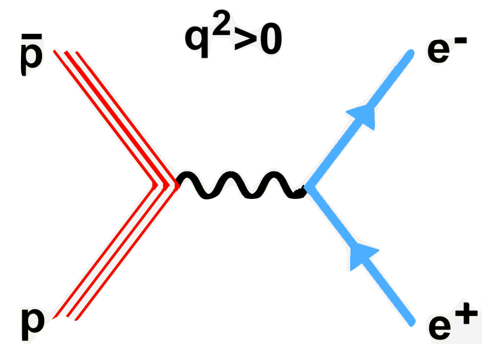
Map out the |S|=2 excited baryon spectrum

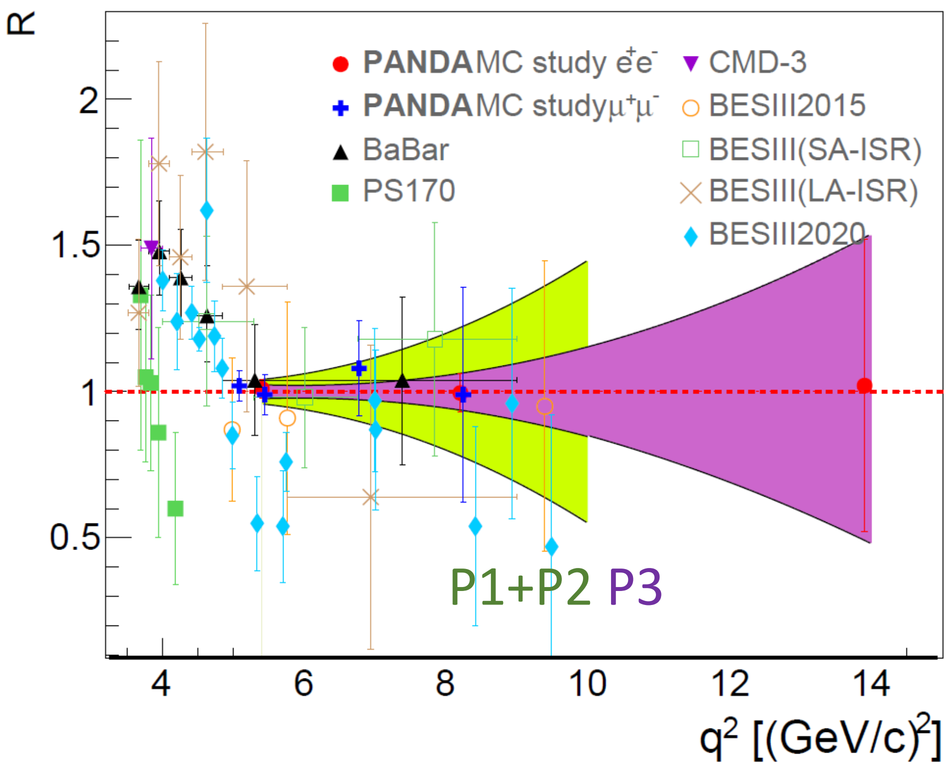


Analytical nature of form factors

* EPJA 52 325 (2016)

Time-like Electromagnetic Form Factors *
(lepton pair production)





$$R = \frac{|G_E|}{|G_M|}$$

Phase-1

pp → e^+e^- @1.5 GeV/c ~ 220/day

pp → e^+e^- @3.3 GeV/c ~ 10/day

Analytical nature of form factors

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Time-like Electromagnetic Form Factors *
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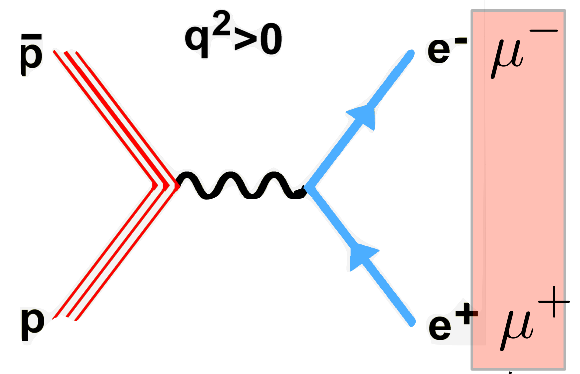
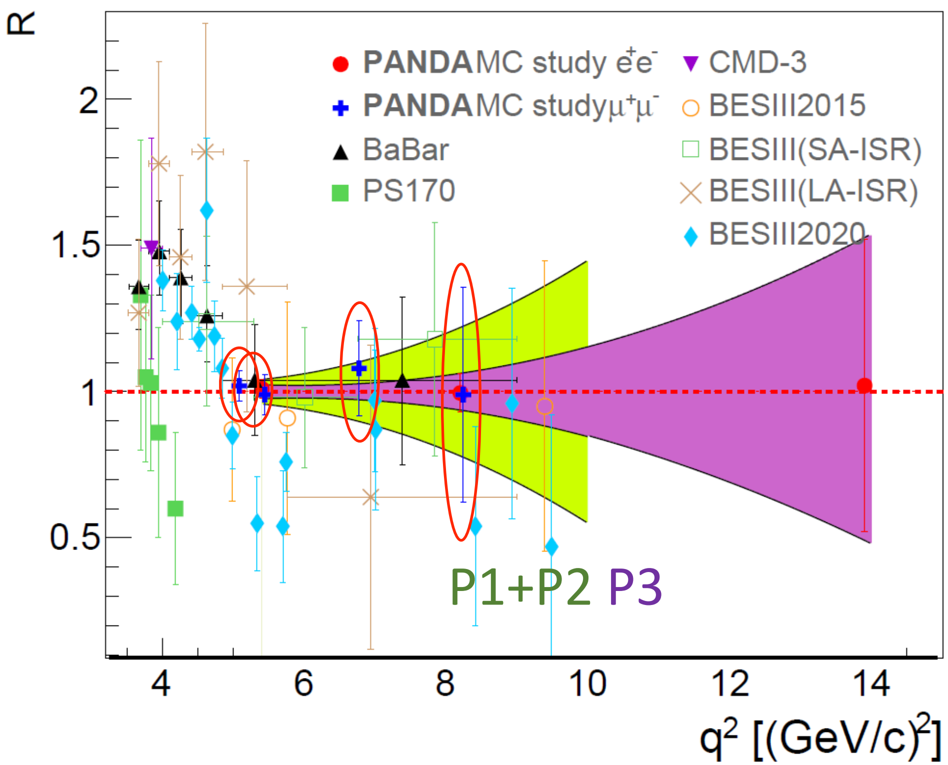


Unique for PANDA



$$R = \frac{|G_E|}{|G_M|}$$

Phase-1

pp → e^+e^-	@1.5 GeV/c	~ 220/day
pp → e^+e^-	@3.3 GeV/c	~ 10/day
pp → $\mu^+\mu^-$	@1.5 GeV/c	~ 170/day