Strangeness Studies with PANDA at Phase One

Johan Messchendorp (RuG), THEIA/JAEA REIMEI Web-seminar, March 31, 2021

What to expect from this presentation?

Features of PANDA

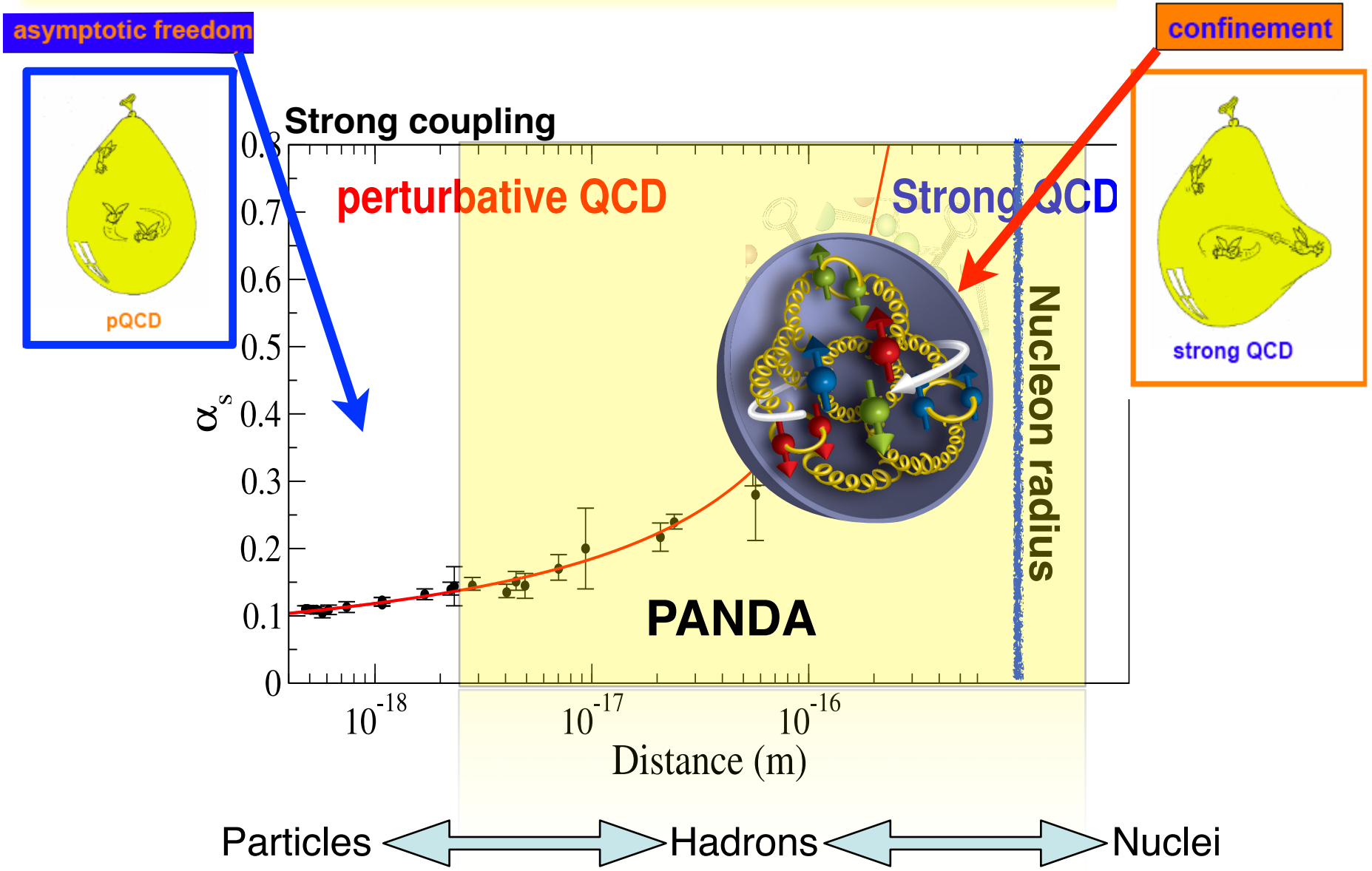
Overall physics ambitions

Focus: baryon studies from |S|=0-3

Focus: “Phase One”

Touch the “beyond” Phase One

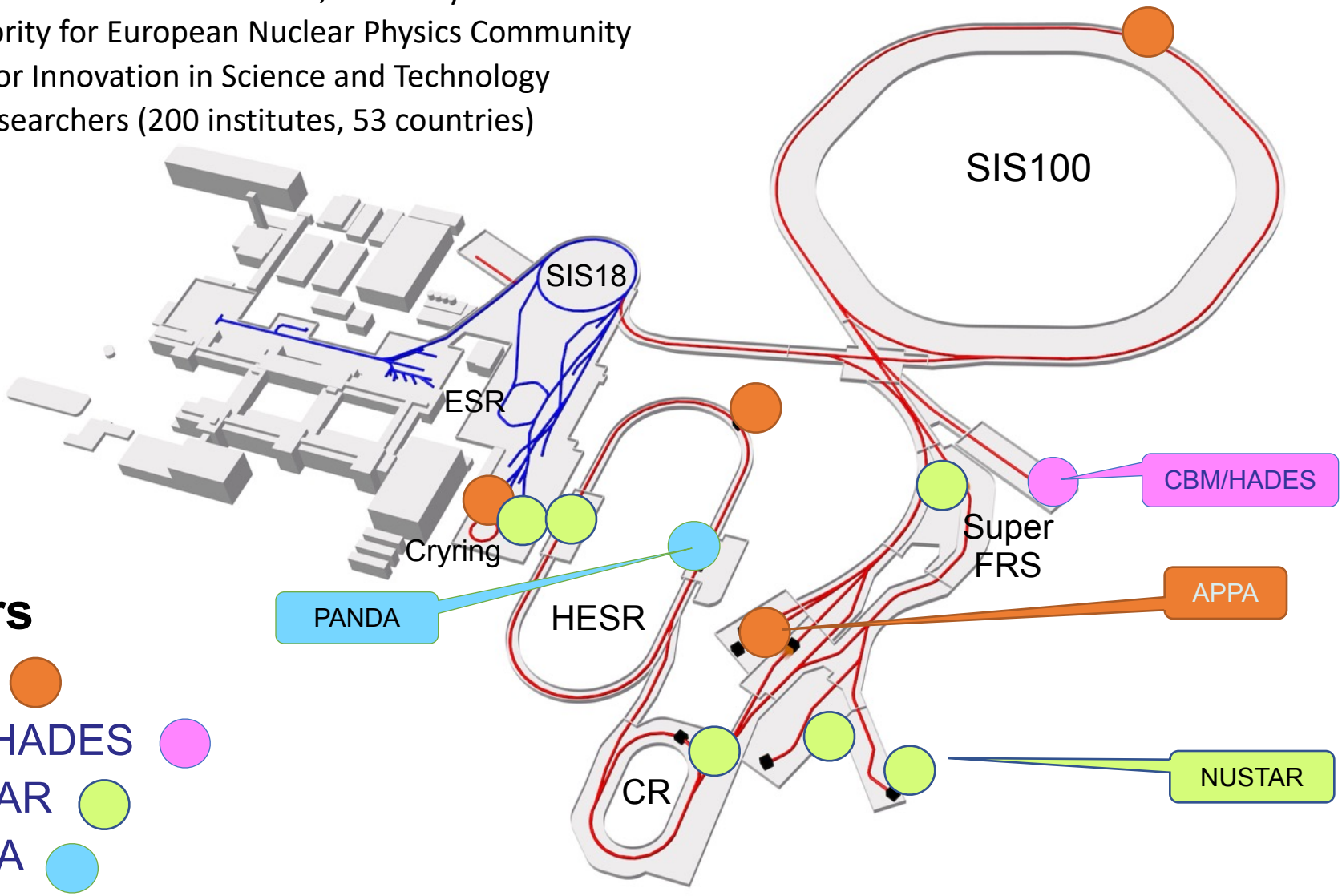
The dynamics of QCD!



Facility for **A**ntiproton and **I**on **R**esearch

Facility for **A**ntiproton and **I**on **R**esearch

- ESFRI Landmark near Frankfurt, Germany
- Top priority for European Nuclear Physics Community
- Driver for Innovation in Science and Technology
- 3000 researchers (200 institutes, 53 countries)



Pillars

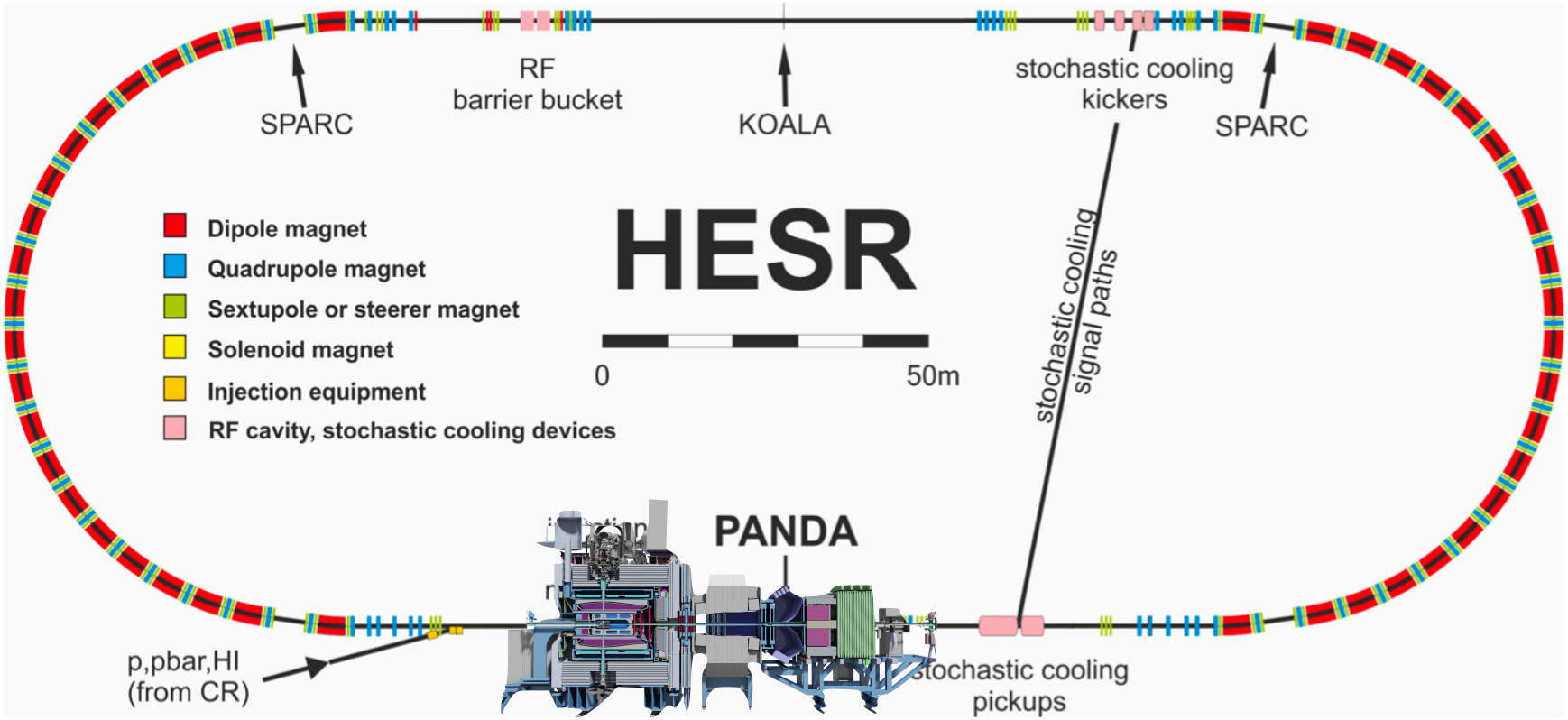
APPA

CBM/HADES

NUSTAR

PANDA

High Energy Storage Ring - *precision* antiprotons



MSV-HESR mode (Phase-1+2)

- Momentum range: 1.5 -15 GeV/c
- Stochastic cooling: $dp/p<5\times10^{-5}$
- Accumulation: 10^{10} antiprotons in 1000 s → 10^{11} antiprotons
- Luminosity up to 2×10^{31} $cm^{-2}s^{-1}$ → 2×10^{32} $cm^{-2}s^{-1}$

+RESR (Phase-3)

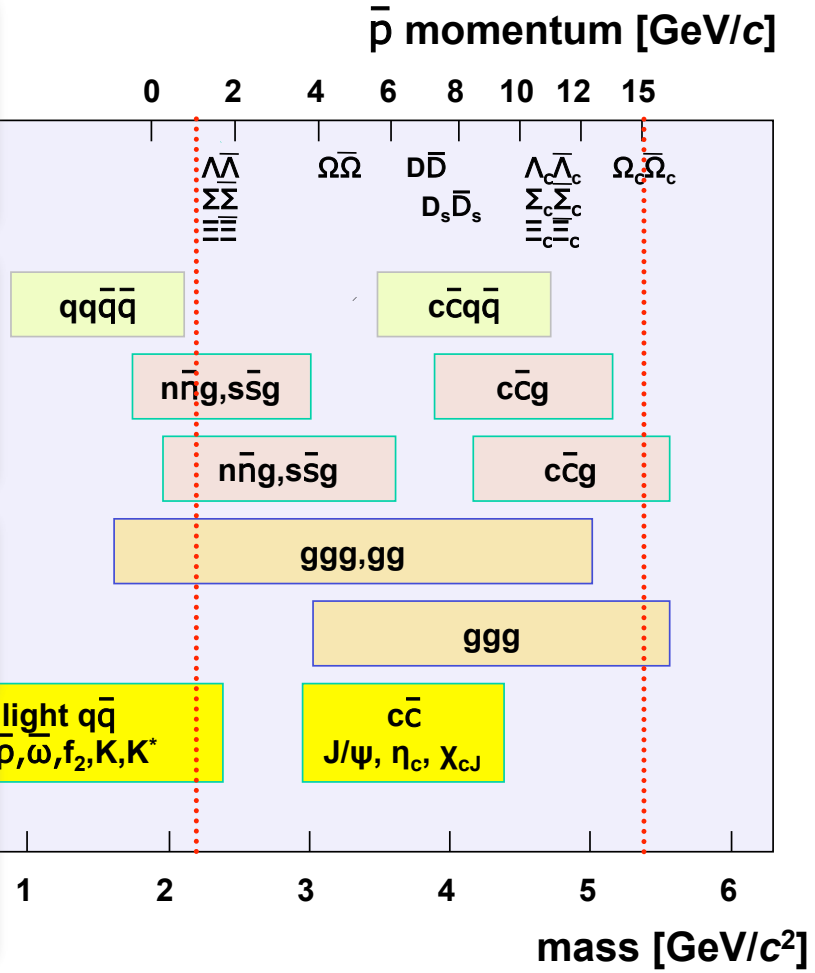
Versatility of antiprotons

Large mass-scale coverage
- center-of-mass energies from 2 to 5.5 GeV
- from light, strange, to charm-rich hadrons
- from quark/gluons to hadronic degrees of freedom

High hadronic production rates
- charm+strange factory -> discovery by statistics!
- gluon-rich production -> potential for new exotics
- good perspectives already at “Day-One"!

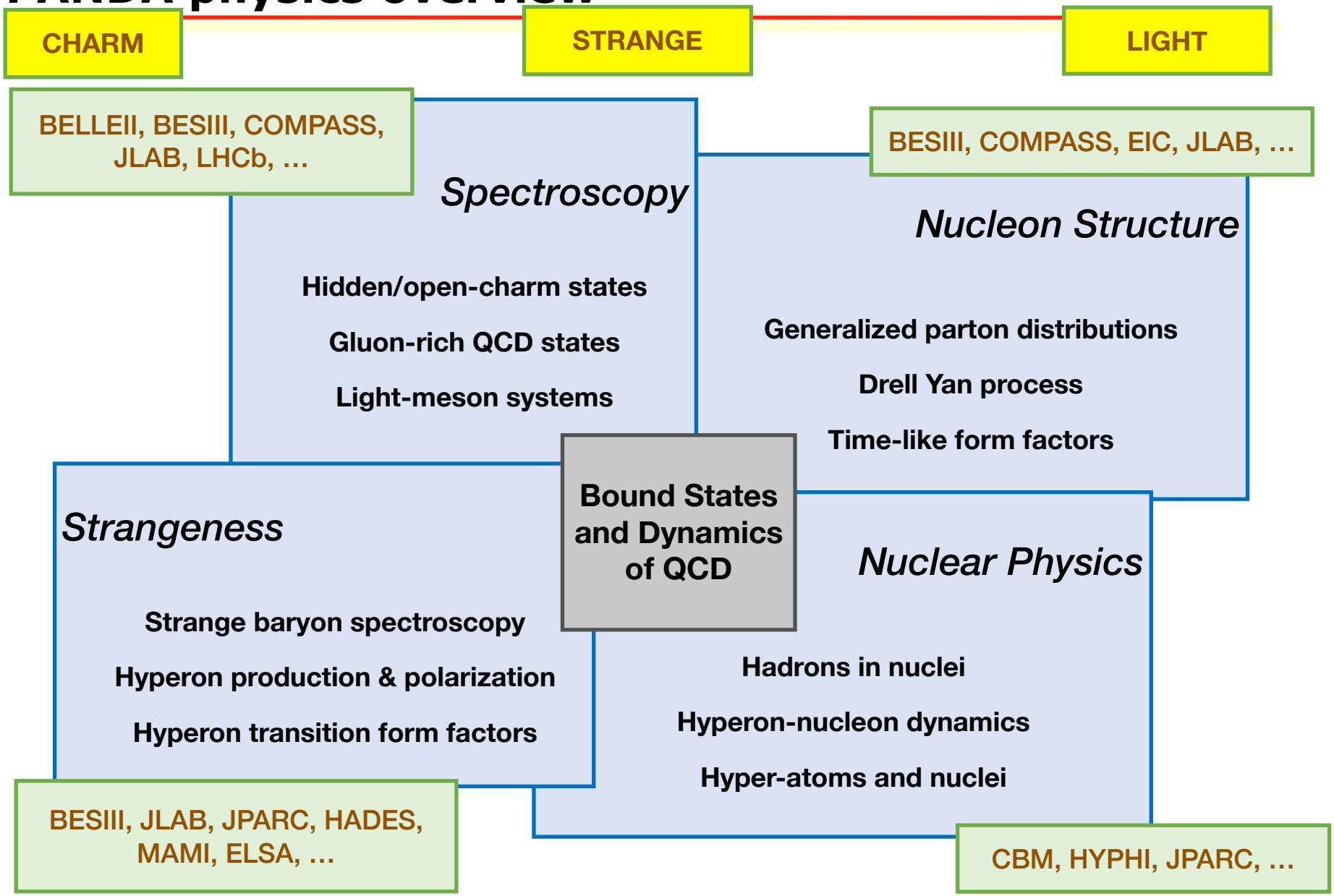
Access to large spectrum of J^{PC} states
- direct formation of *all* conventional J^{PC} states
- large sensitivity to high spin states

Associated hadron-pair production
- access to hidden-strange/charm hadrons
- tagging possibilities
- near thresh.: good resolution and low background

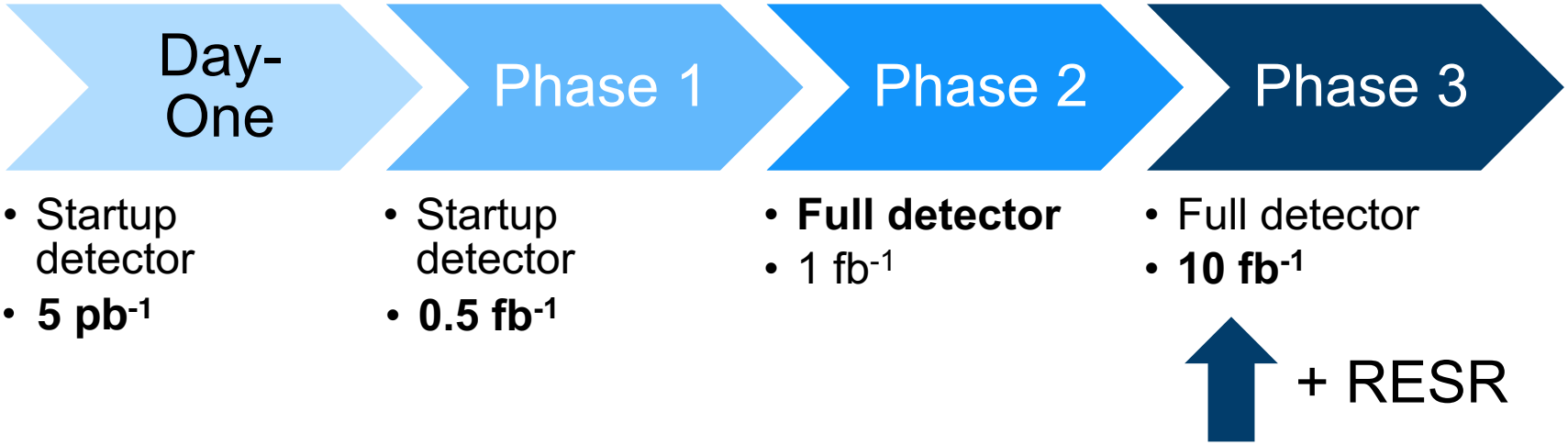


Systematic and precise tool to rigorously study the dynamics of QCD

PANDA physics overview

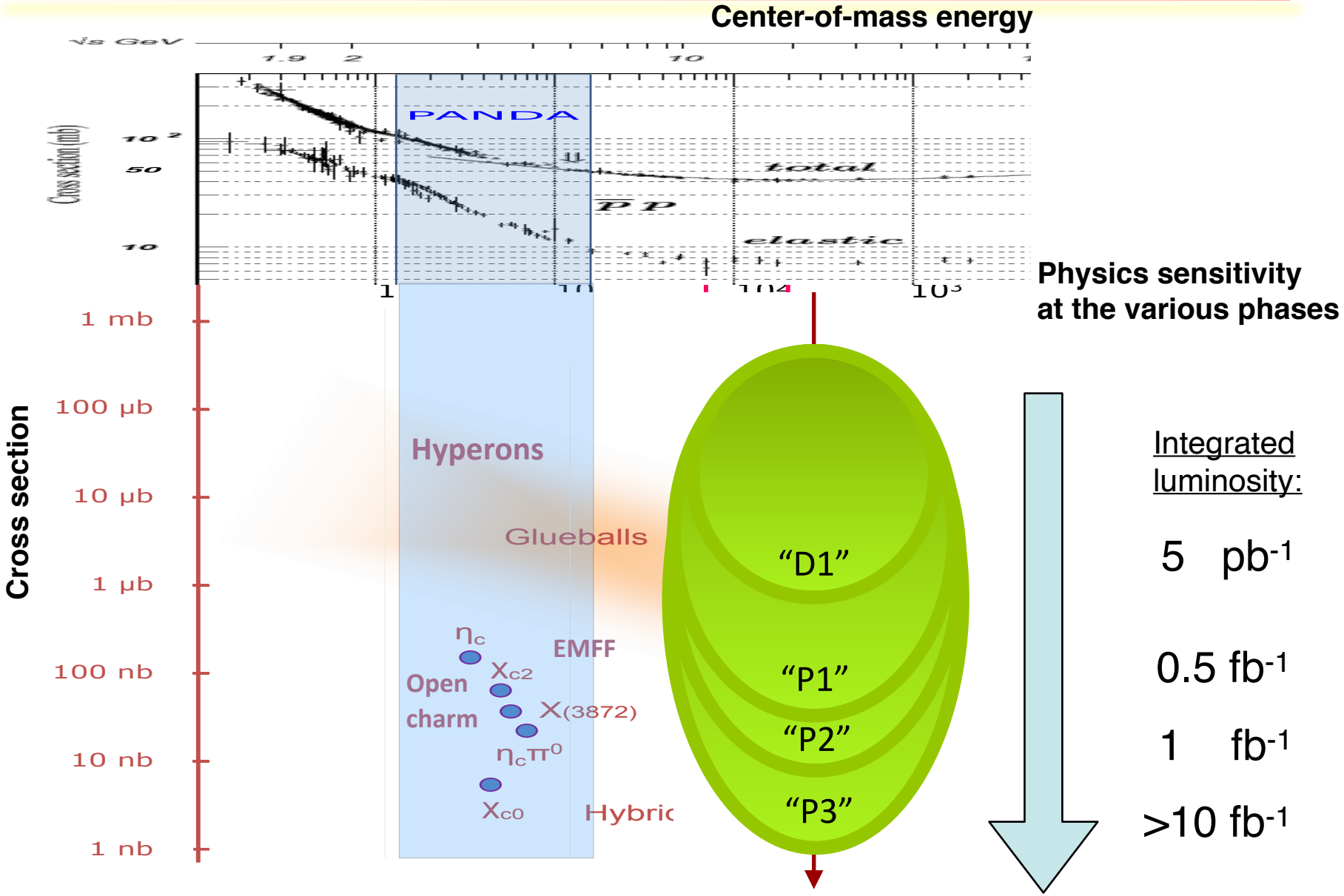


Staging of PANDA



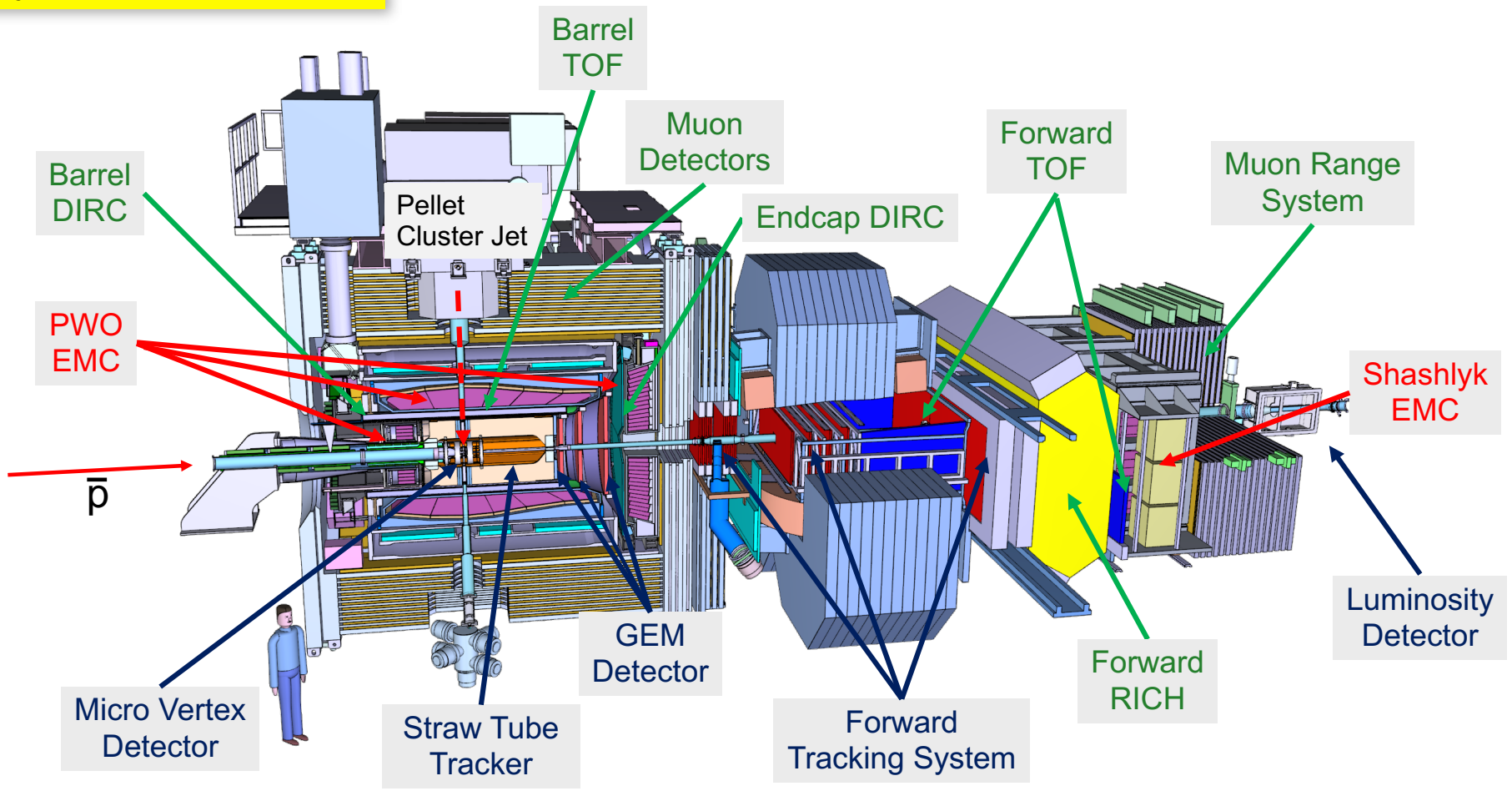
Today: Phase 0

Physics staging at PANDA



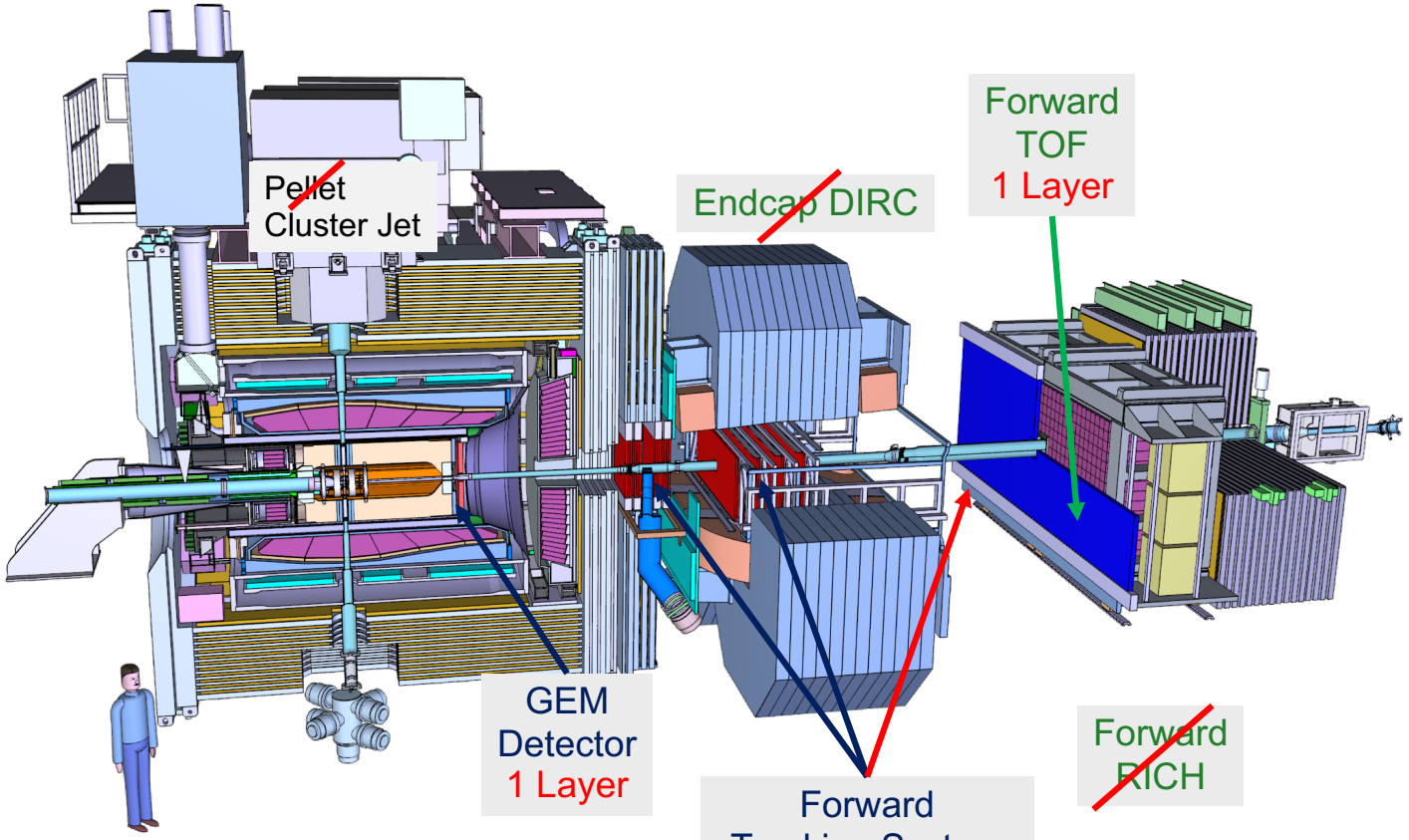
PANDA "full" setup

Not shown: modular hypernuclei detector

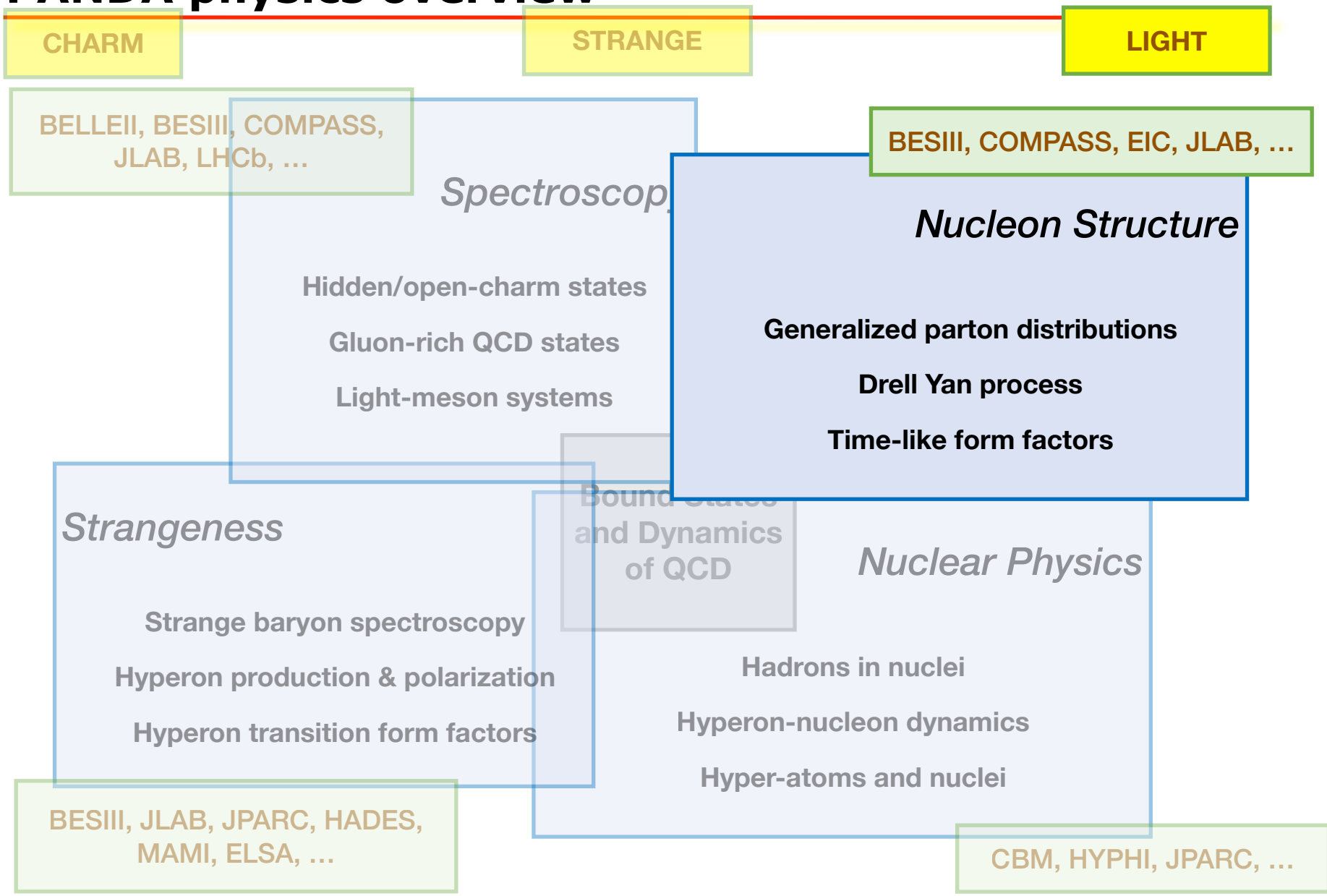


PANDA "startup" setup

Not shown: modular hypernuclei detector



PANDA physics overview



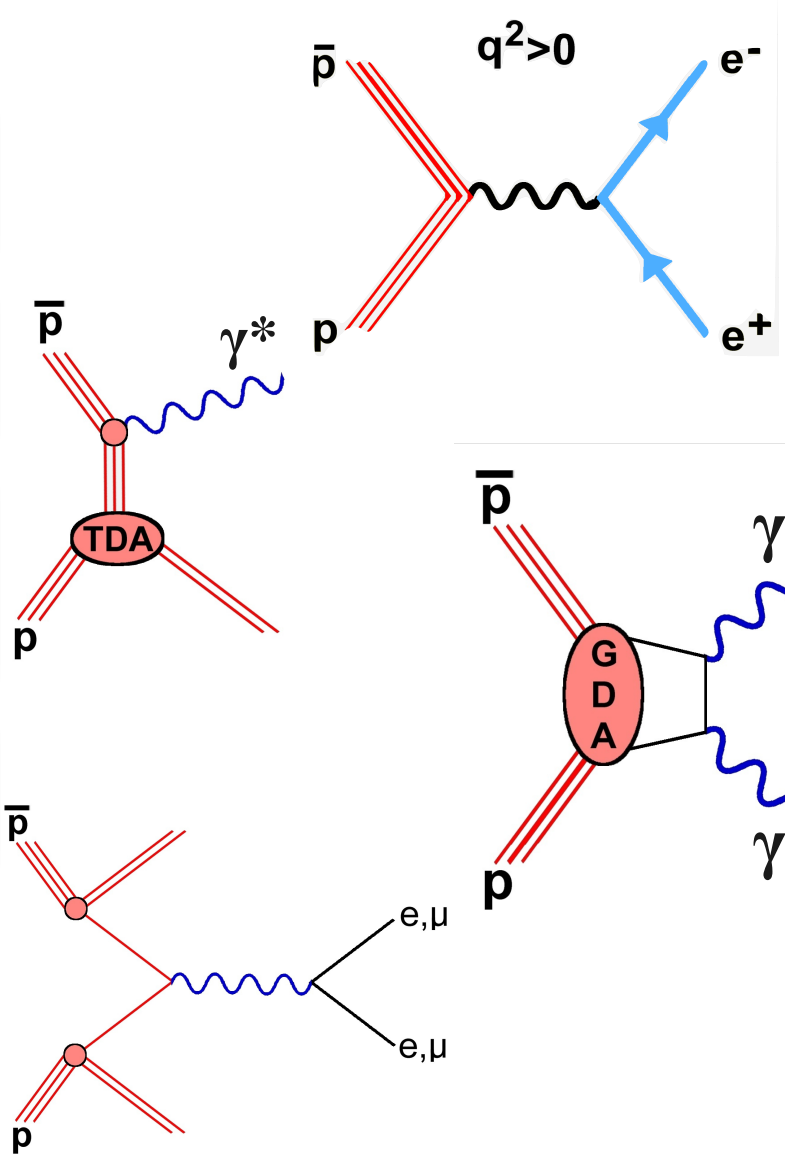
PANDA- the structure of the proton

Time-like Electromagnetic Form Factors
(lepton pair production) arXiv:1606.01118

Transition Distribution Amplitudes
(meson production) arXiv:1409.0865

Generalised Distribution Amplitudes
(time-like Compton, hard exclusive processes)

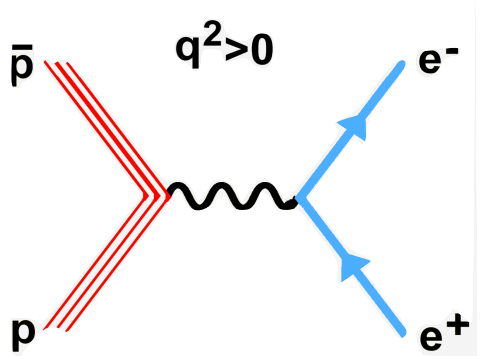
Transverse Parton Distribution Functions
(Drell-Yan production)



Analytical nature of form factors

EPJA 52 325 (2016)

Time-like Electromagnetic Form Factors
(lepton pair production) arXiv:1606.01118



$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2\beta s}\left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}\sin^2\theta|G_E|^2\right]$$

Analytical nature of form factors

EPJA 52 325 (2016)

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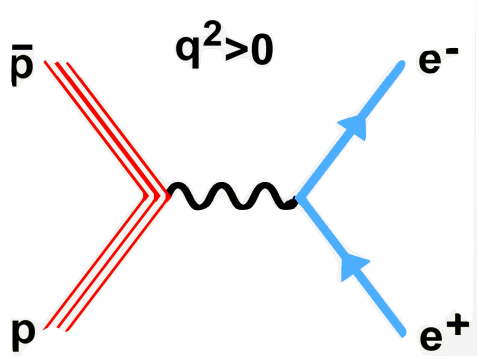
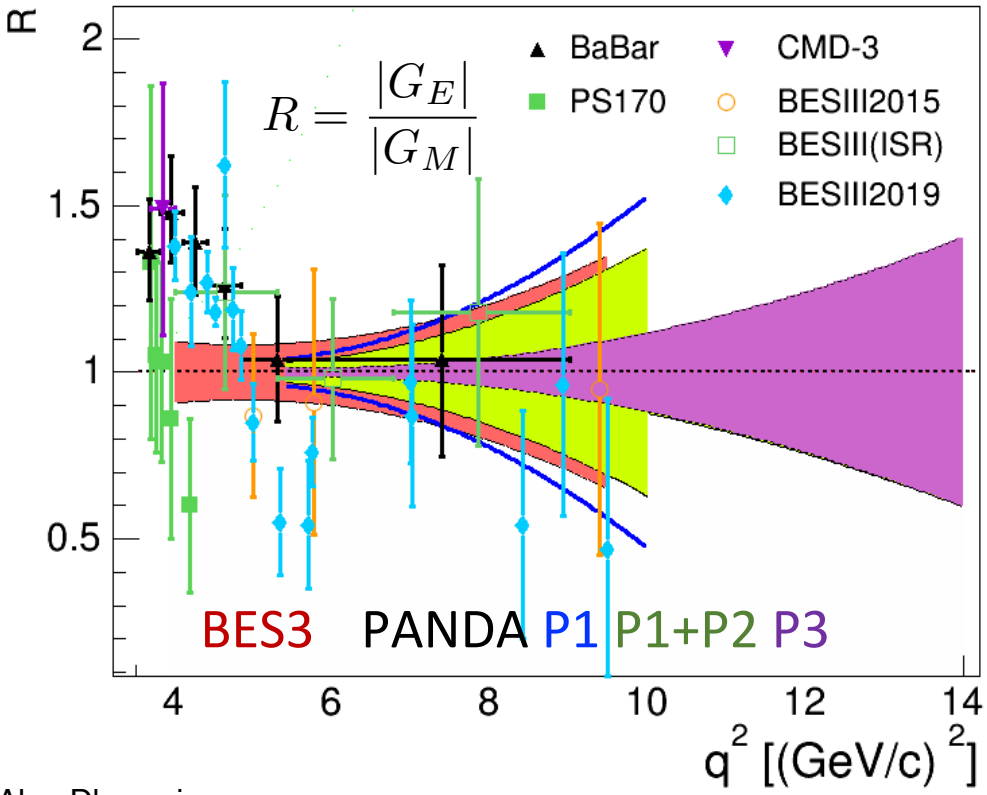
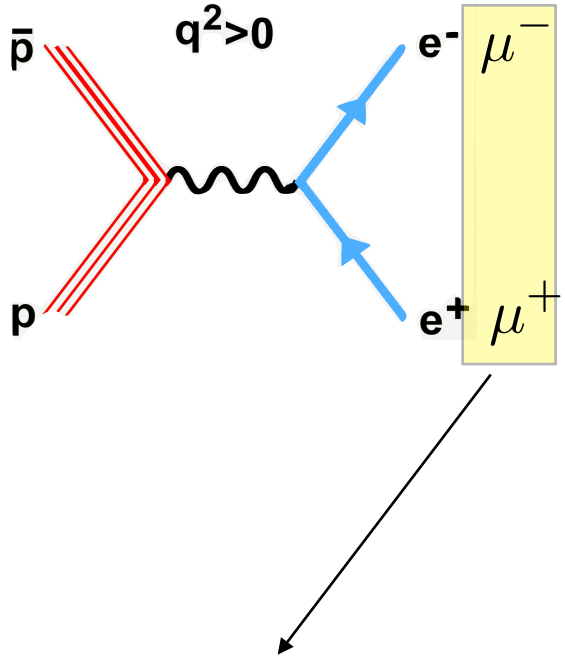




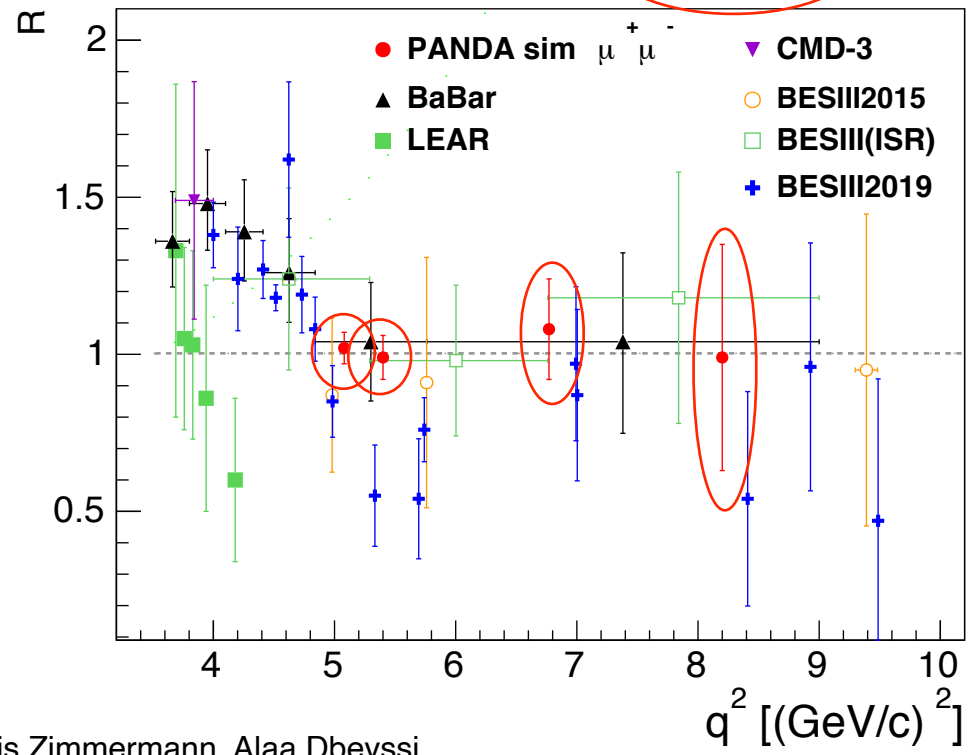
Phase-1
pp → e^+e^- @1.5 GeV/c ~ 220/day
pp → e^+e^- @3.3 GeV/c ~ 10/day

Analytical nature of form factors

Time-like Electromagnetic Form Factors
(lepton pair production)



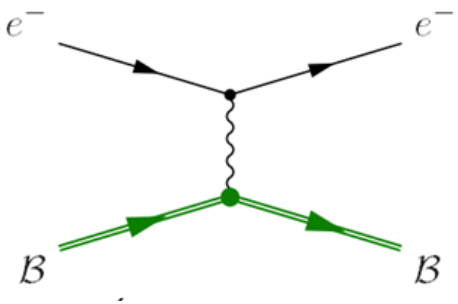
Results for Phase-3 (L=2 fb^{-1})



Features:
- Lepton universality
- Radiative corrections

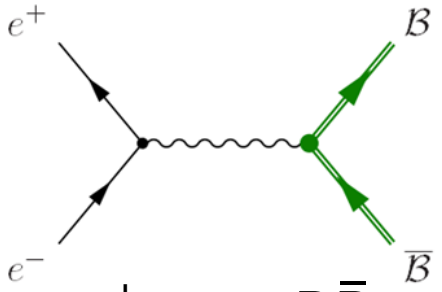
EPJA 57, 30 (2021); arXiv:2006.16363

Form factors from space to time-like region



$e^- B \to e^- B$

e.g. JLAB



$e^+e^- \to B\bar{B}$

$\bar{B}B \to \ell^+\ell^-$

BES III

BELLE II

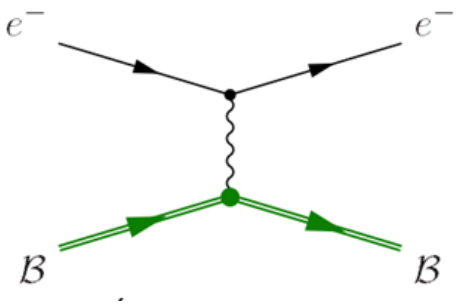
PANDA

$-Q^2 = q^2 < 0$ $\quad q^2 = 0$ $\quad q^2 = (m_{B_1} - m_{B_2})^2$ $\quad q^2 = (m_{B_1} + m_{B_2})^2$ $\quad q^2$

Space-like and time-like are related by dispersion theory!

Form factors from space to time-like region

Day-1
pp → $e^+e^-\pi^0$ @1.5 GeV/c ~ 3'500/day



$e^-B \to e^-B$
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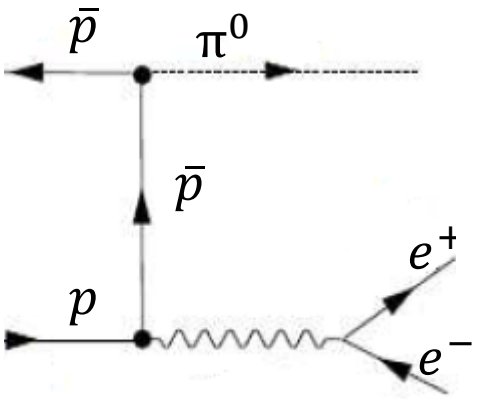

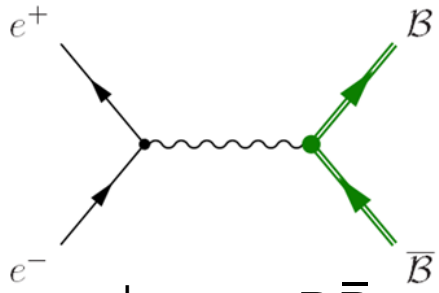

$e^+e^- \to B\bar{B}$
$\bar{B}B \to \ell^+\ell^-$
BES III
BELLE II
PANDA

"unphysical" region
PANDA

$-Q^2 = q^2 < 0$ $q^2 = 0$ $q^2 = (m_{B_1}-m_{B_2})^2$ $q^2 = (m_{B_1}+m_{B_2})^2$ q^2

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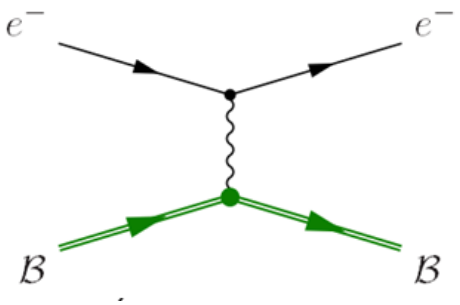
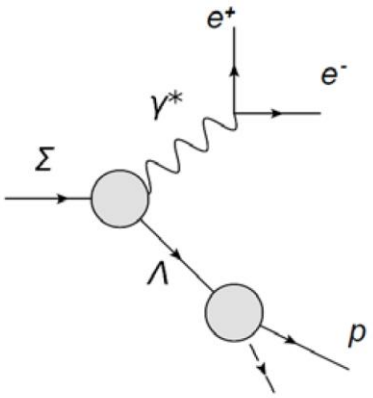
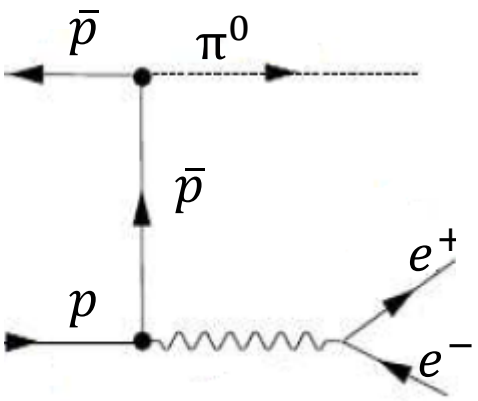
Form factors from space to time-like region



$e^-B \to e^-B$

e.g. JLAB





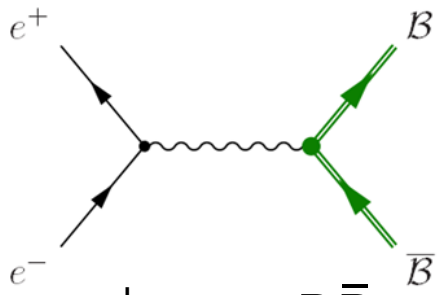
$B_1 \to B_2 e^+ e^-$

HADES/PANDA

BES III

"unphysical" region

PANDA



$e^+e^- \to B\bar{B}$

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BES III

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Space-like and time-like are related by dispersion theory!

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

Drell Yan process

Time-like form factors

Strangeness

Strange baryon spectroscopy

Hyperon production & polarization

Hyperon transition form factors

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

Bound States and Dynamics of QCD

Nuclear Physics

Hadrons in nuclei

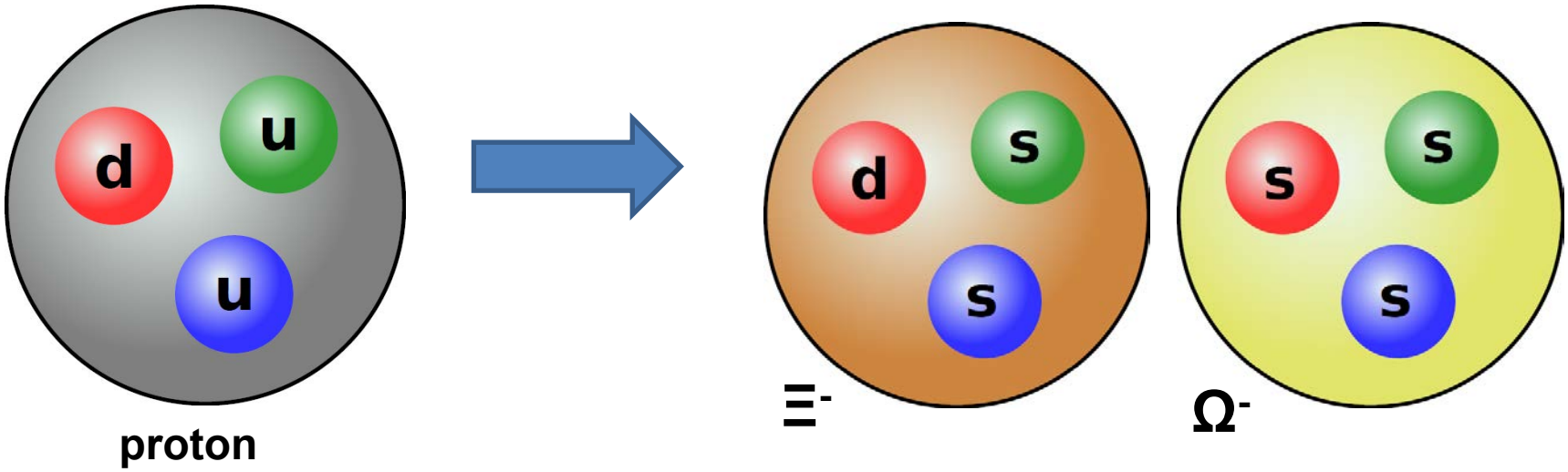
Hyperon-nucleon dynamics

Hyper-atoms and nuclei

CBM, HYPHI, JPARC, …

Exploring the hyperon sector

What happens if we replace one of the light quarks in the proton with one - or many - heavier quark(s)?

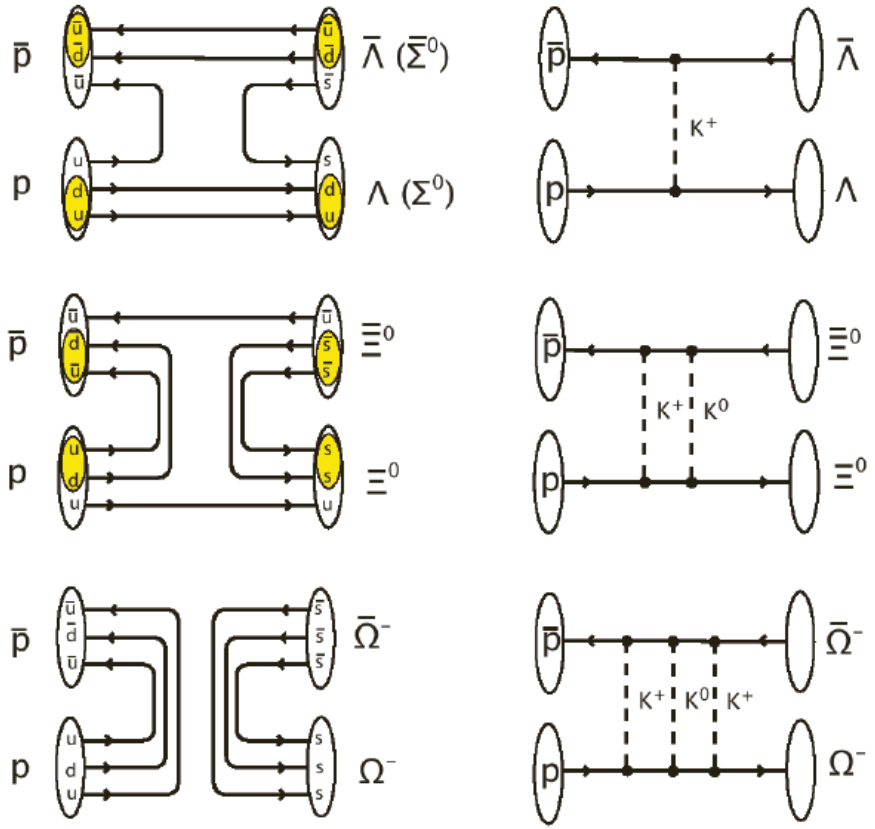


Courtesy: Karin Schoenning

Hyperon *dynamics*

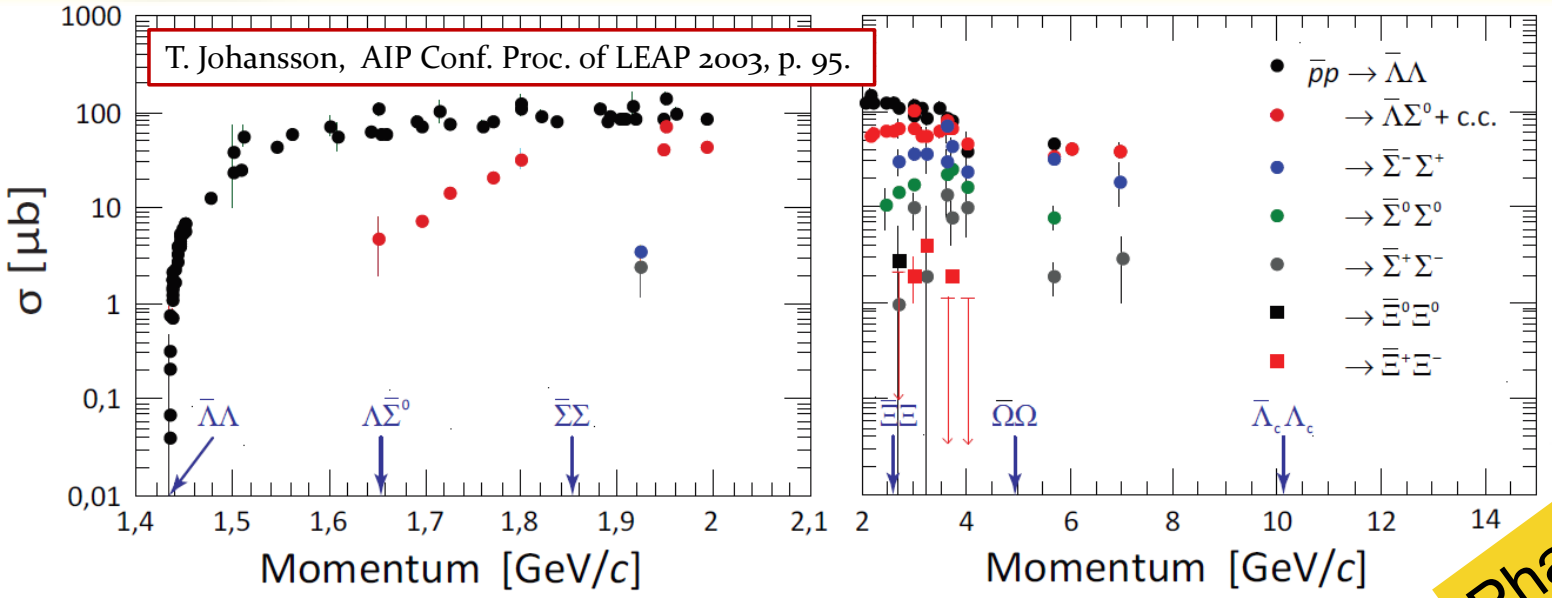
Strong production dynamics

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



Courtesy: Karin Schoenning

PANDA is a hyperon factory!



Phase-1

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

Courtesy: Karin Schoenning

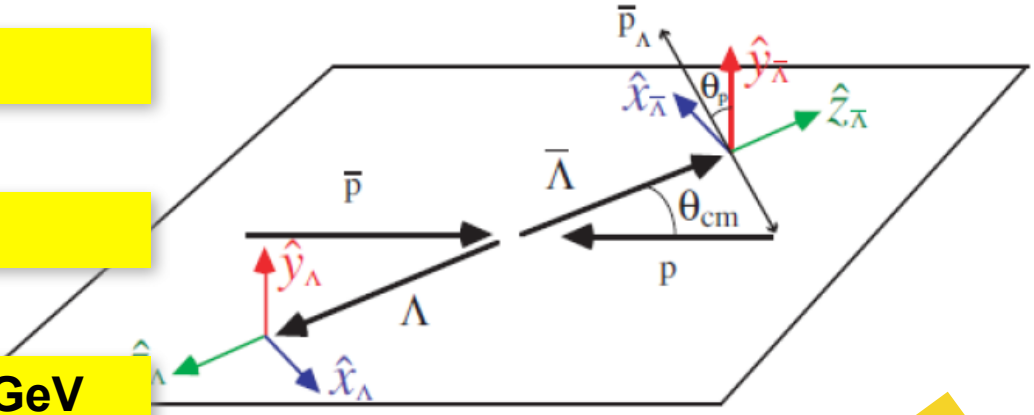
** 90% C.L.

PANDA is a hyperon factory!

Rich set of polarisation observables

(double) strange and charm baryons

Explore hyperon dynamics above 4 GeV



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

BESIII, Nature Physics 15, 631 (2019)

Phase-1

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EPJA in print, arXiv:2009.11582

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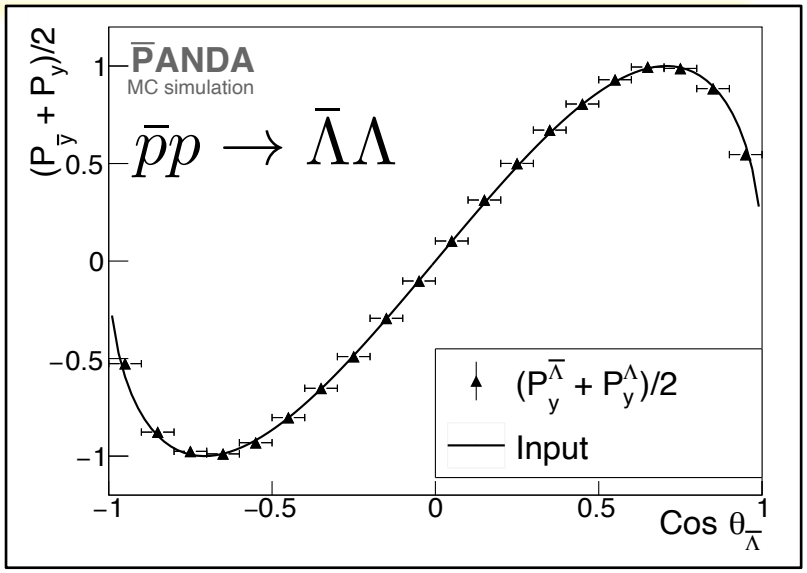


Day-1:

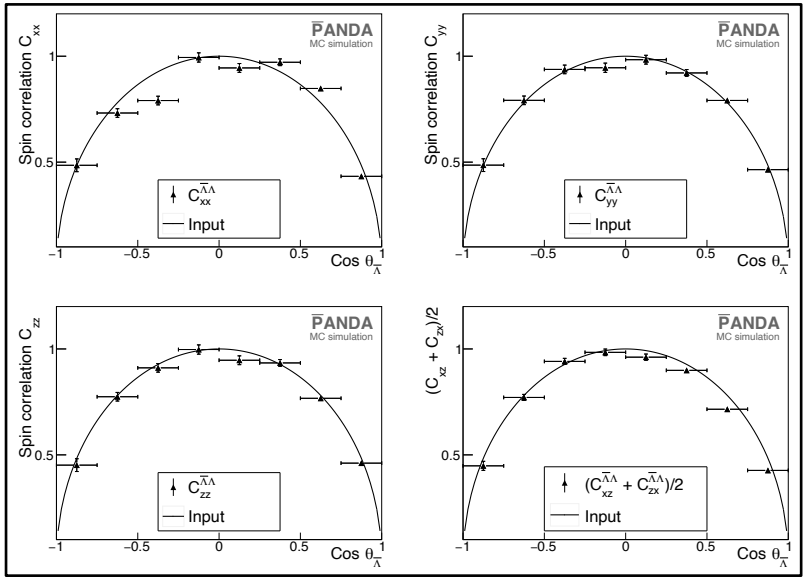
Reproduce LEAR studies @1.64 GeV/c

Extend at 4 GeV/c and for |S|=2 hyperons

Phase-1:

Spin correlations in |S|=1,2

Extend to |S|=3 and charm hyperons

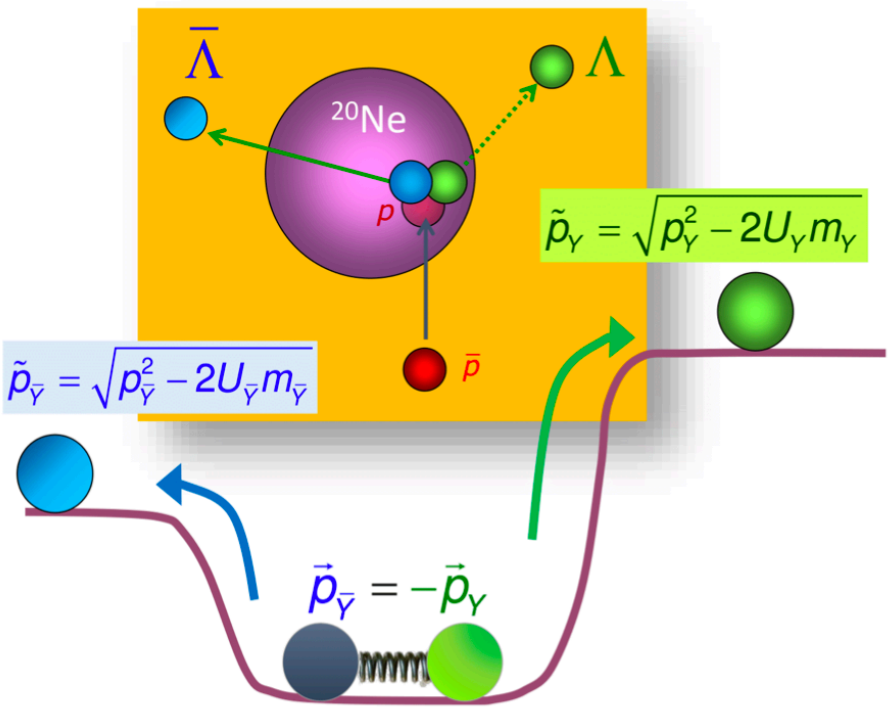


Antihyperons in nuclei @ Phase-1

Josef Pochodzalla

Phase-1: antihyperon optical potential

Exploit abundantly produced hyperon-antihyperon pairs near threshold



Momentum asymmetry measurements:

$$\alpha_T = \frac{p_T(Y) - p_T(\overline{Y})}{p_T(Y) + p_T(\overline{Y})}, \qquad \alpha_L = \frac{p_L(Y) - p_L(\overline{Y})}{p_L(Y) + p_L(\overline{Y})}.$$

Antihyperons in nuclei @ Phase-1

Josef Pochodzalla

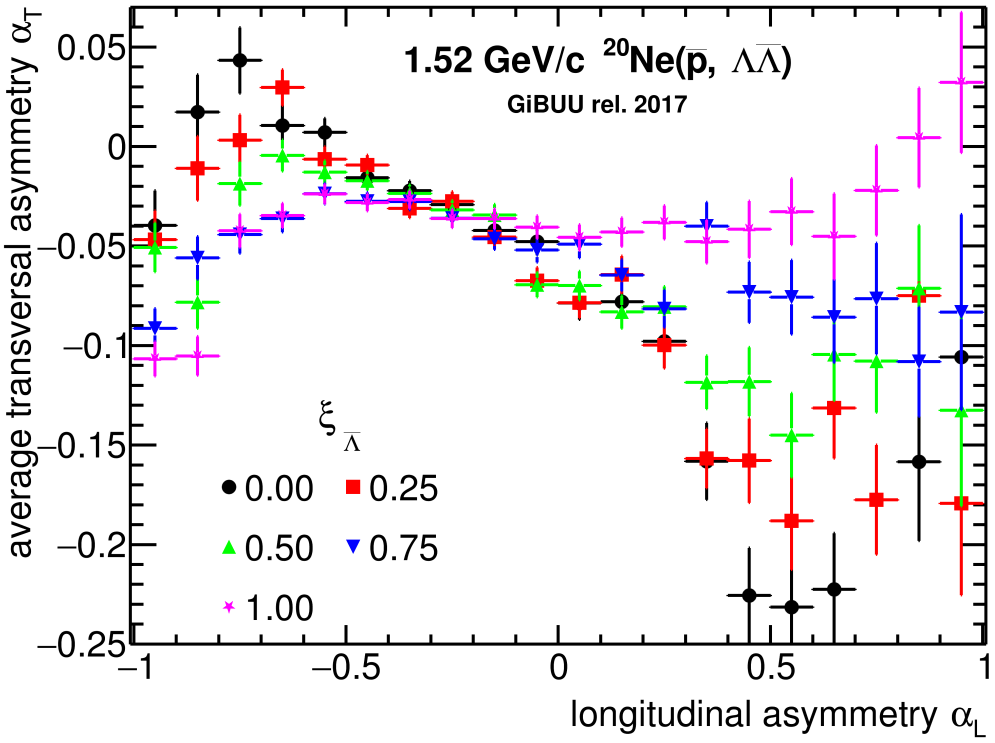
Phase-1: antihyperon optical potential

Exploit abundantly produced hyperon-antihyperon pairs near threshold

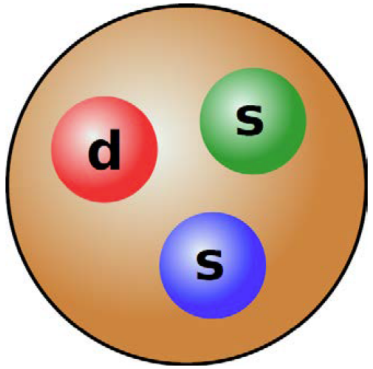
Spectrum: ~12 hours of beam time at interaction rates 10^6 s^{-1}

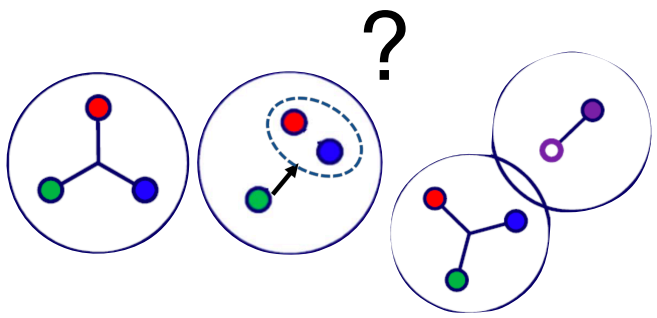
Striking sensitivity to potential

First step towards hyperatom and hypernuclei program



Hyperon *spectroscopy*





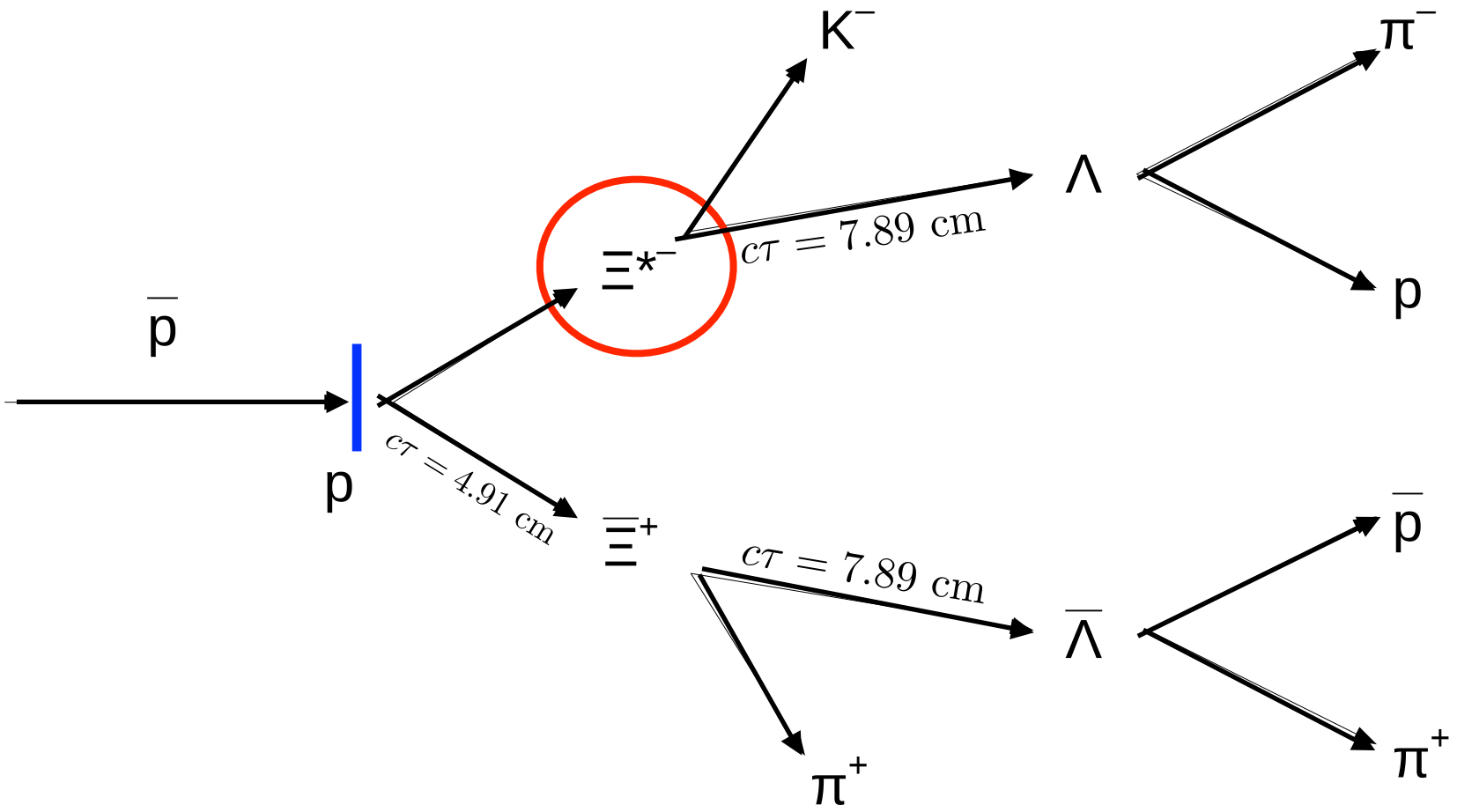
- PDG: “[…] nothing of significance on Ξ resonances has been added since our 1988 edition“*
- Phase-1: 20 events/s produced
- Good background suppression through tracking

Particle	J^P	Overall status
Ξ(1318)	1/2+	****
Ξ(1530)	3/2+	****
Ξ(1620)		*
Ξ(1690)		***
Ξ(1820)	3/2−	***
Ξ(1950)		***
Ξ(2030)		***
Ξ(2120)		*
Ξ(2250)		**
Ξ(2370)		**
Ξ(2500)		*

M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

Hyperon *spectroscopy*

Map out the |S|=2 excited baryon spectrum

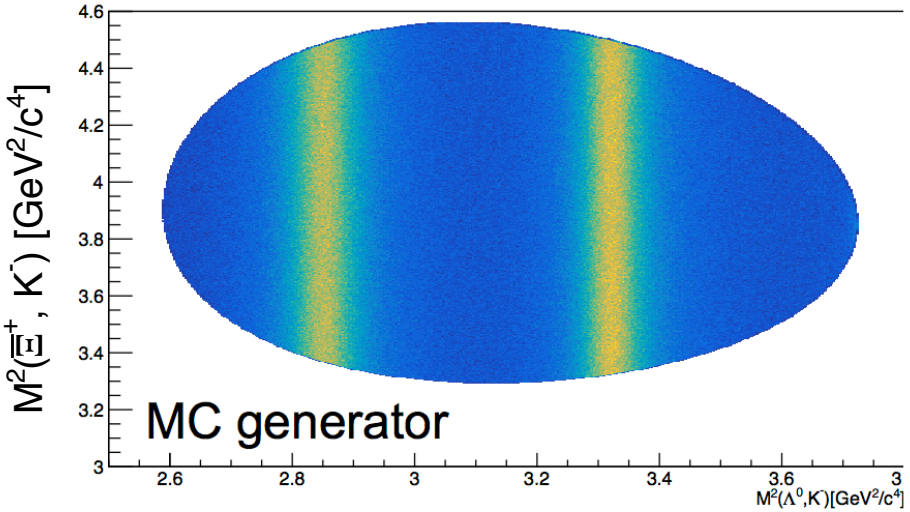


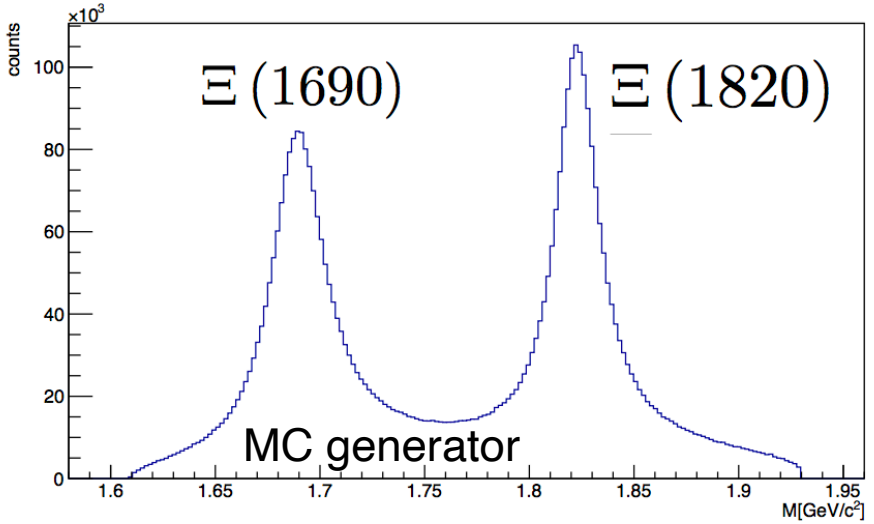
Hyperon *spectroscopy*

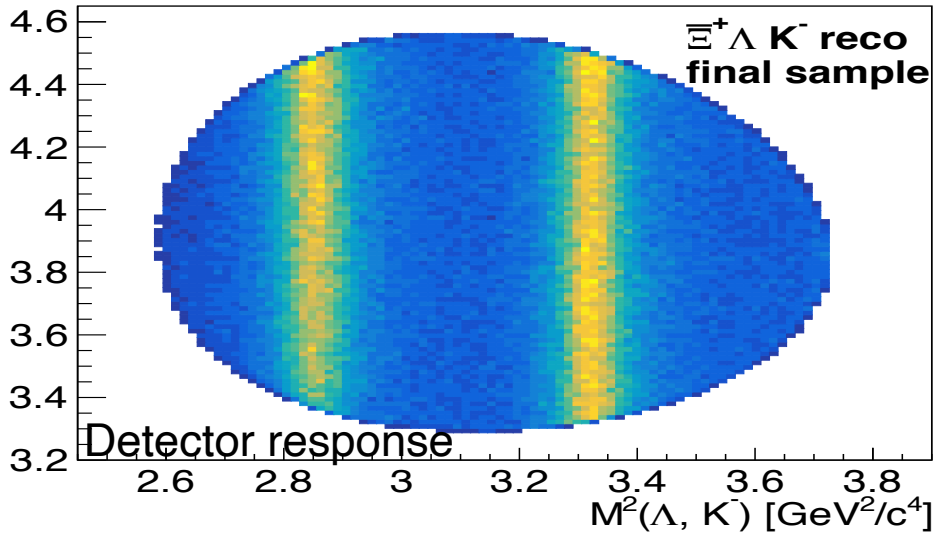
EPJA in print, arXiv:2012.01776

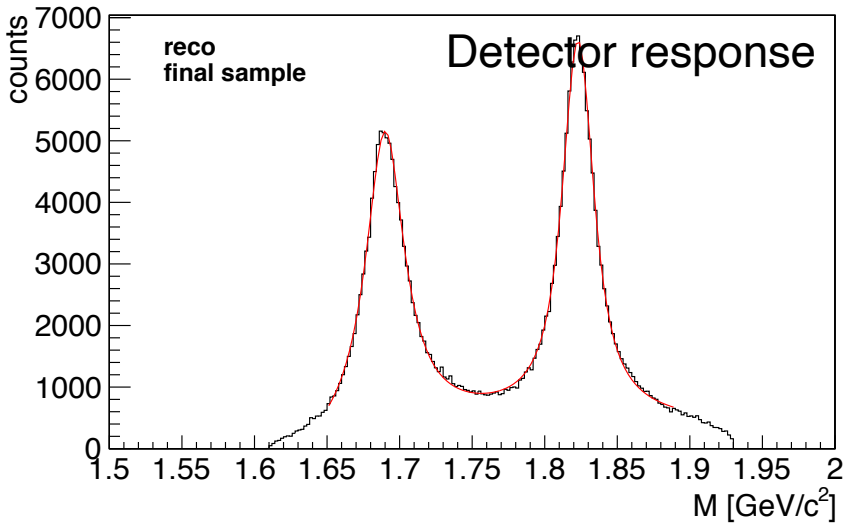
Jennifer Puetz, Albrecht Gillitzer

Map out the |S|=2 excited baryon spectrum



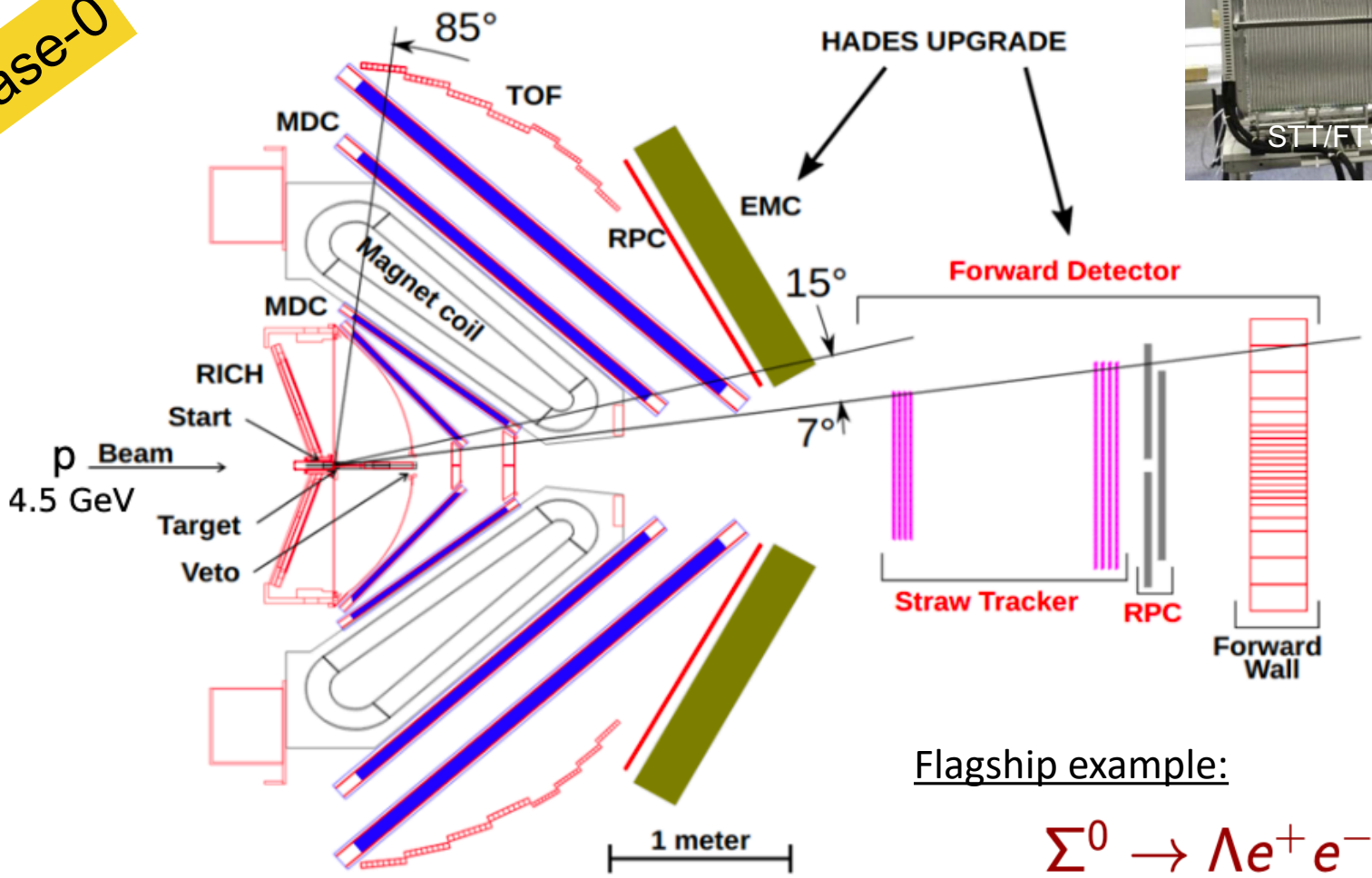






Hyperon *structure* with PANDA@HADES

Phase-0

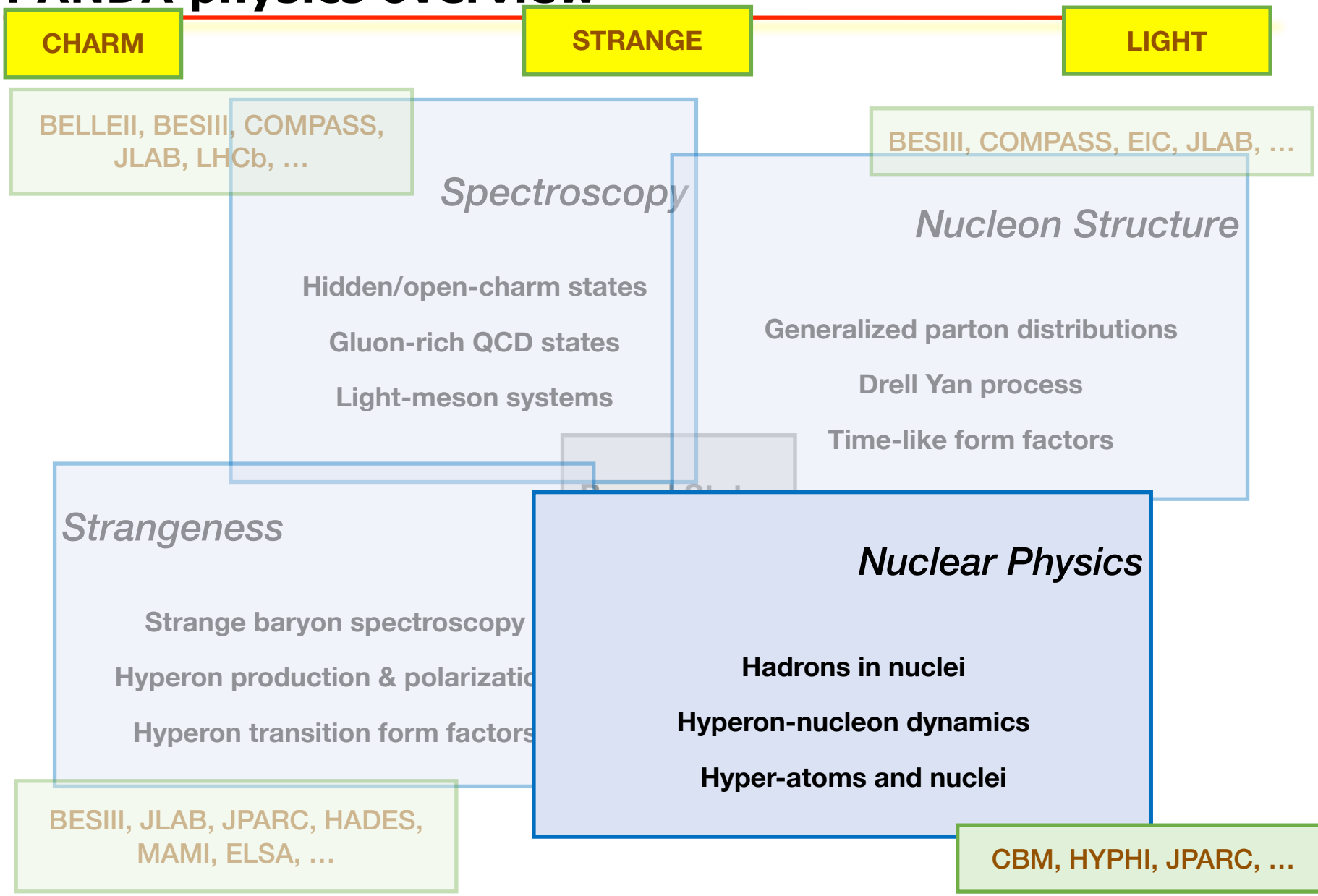


Flagship example:

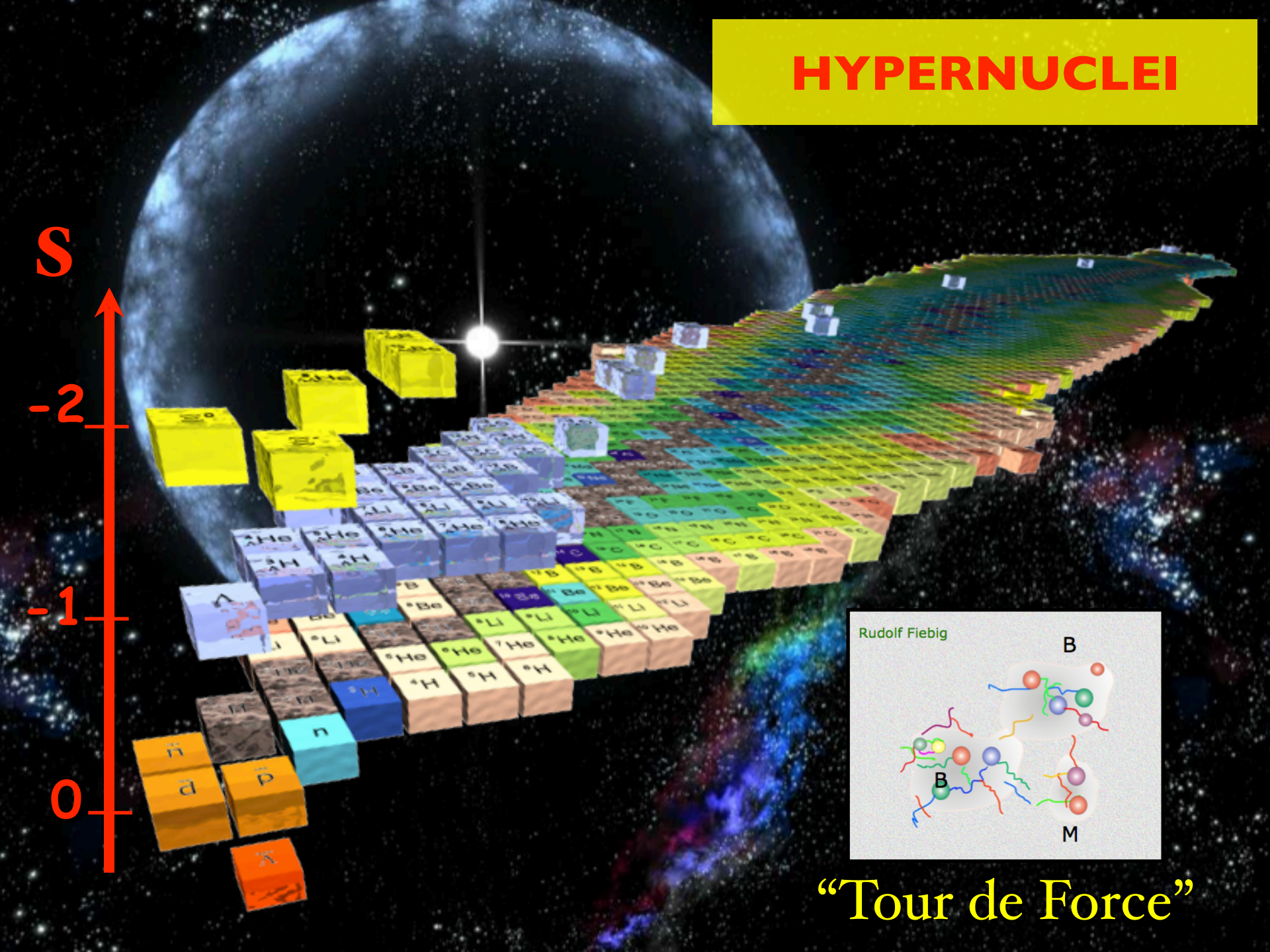
$$\Sigma^0 \rightarrow \Lambda e^+ e^-$$

HADES with PANDA@HADES Collaboration, EPJA in print, arXiv:2010.06961 (2020)

PANDA physics overview



HYPERNUCLEI



"Tour de Force"

Ξ^- production

$\bar{p}N \rightarrow \Xi^- \bar{\Xi}$

rescattering in primary target nucleus

deceleration in secondary target

capture of Ξ

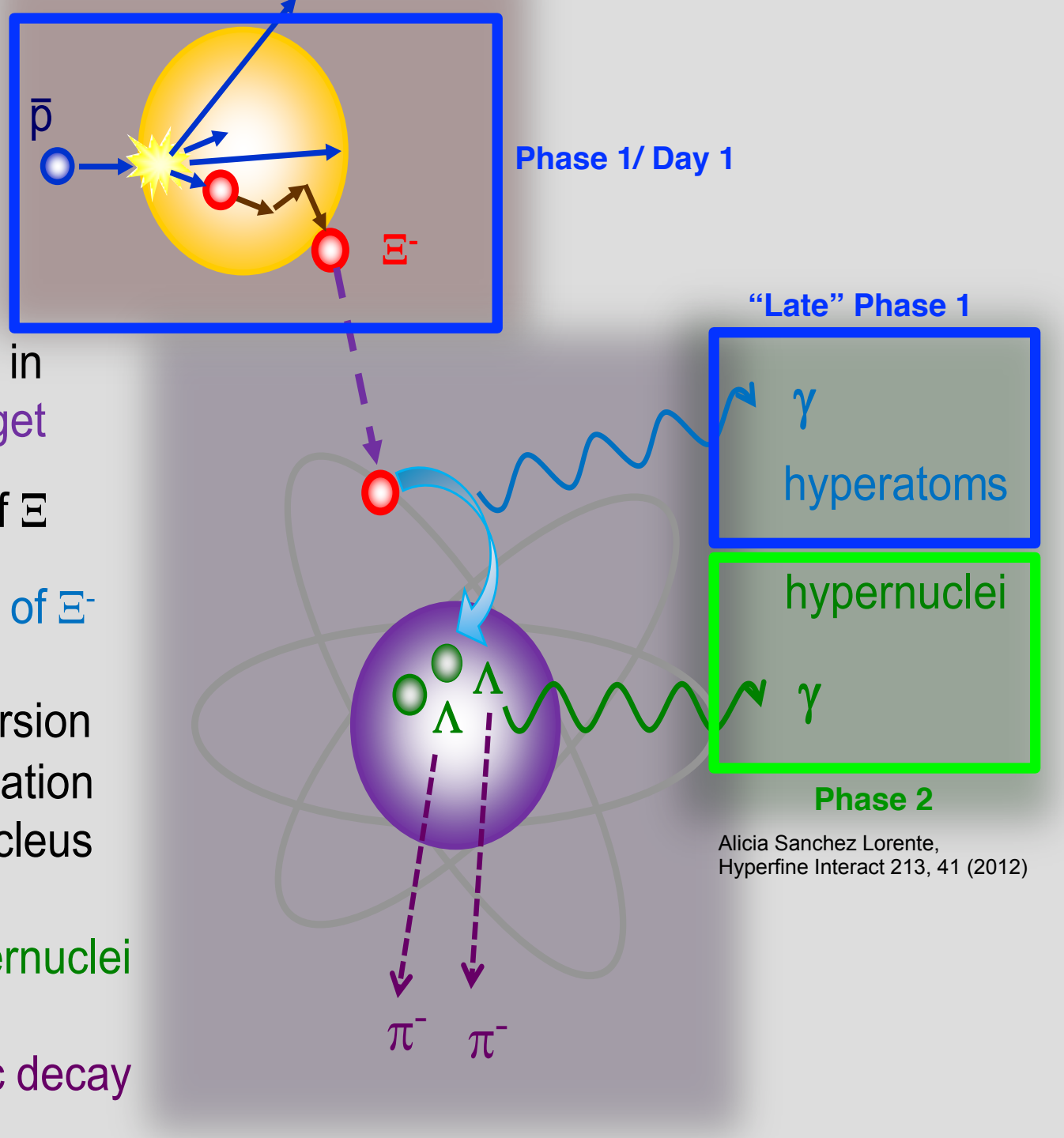
atomic cascade of Ξ^-

$\Xi^- p \rightarrow \Lambda\Lambda$ conversion fragmentation

$\rightarrow$ excited $\Lambda\Lambda$-nucleus

γ-decay of $\Lambda\Lambda$ hypernuclei

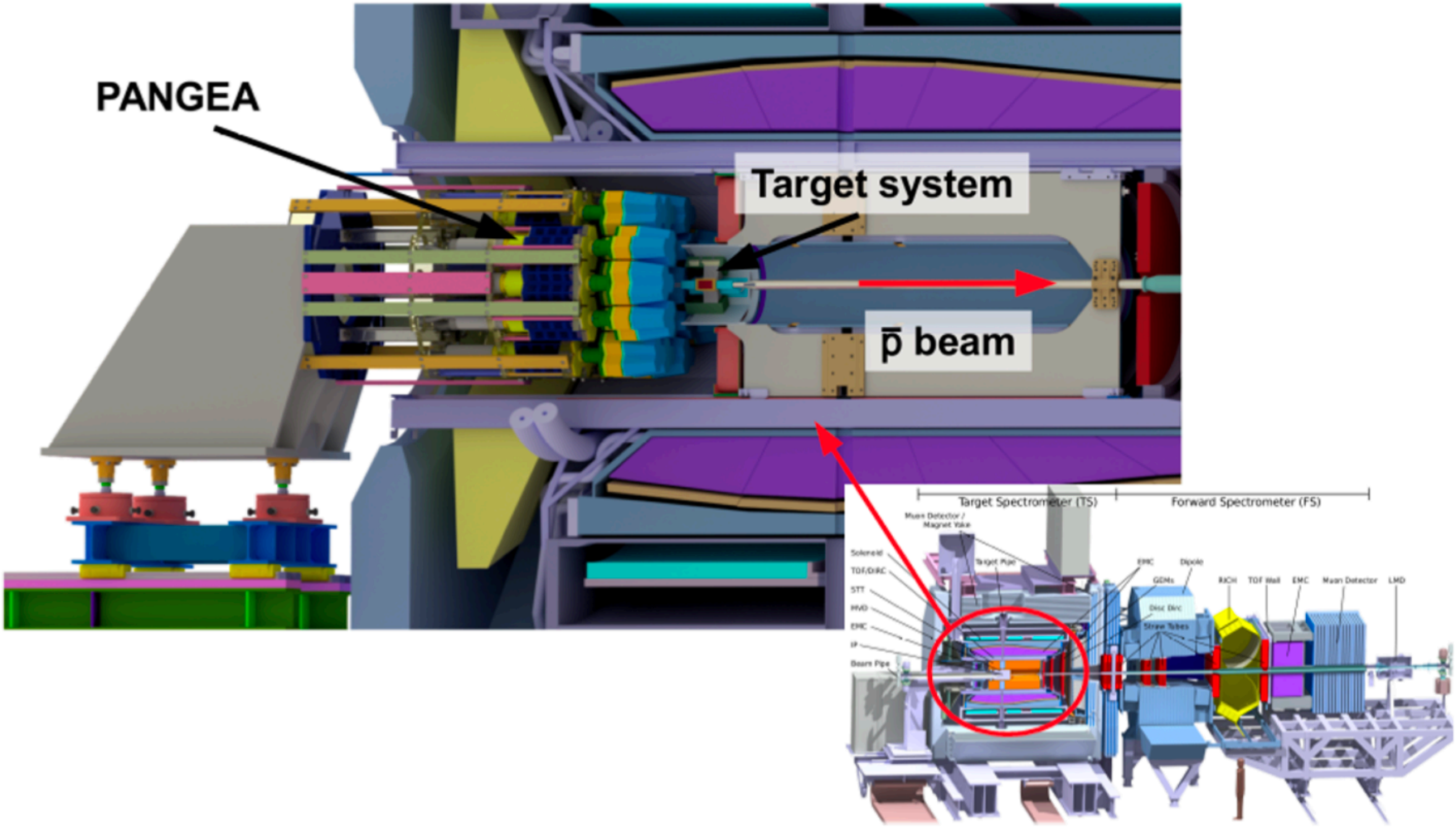
weak pionic decay



Alicia Sanchez Lorente,
Hyperfine Interact 213, 41 (2012)

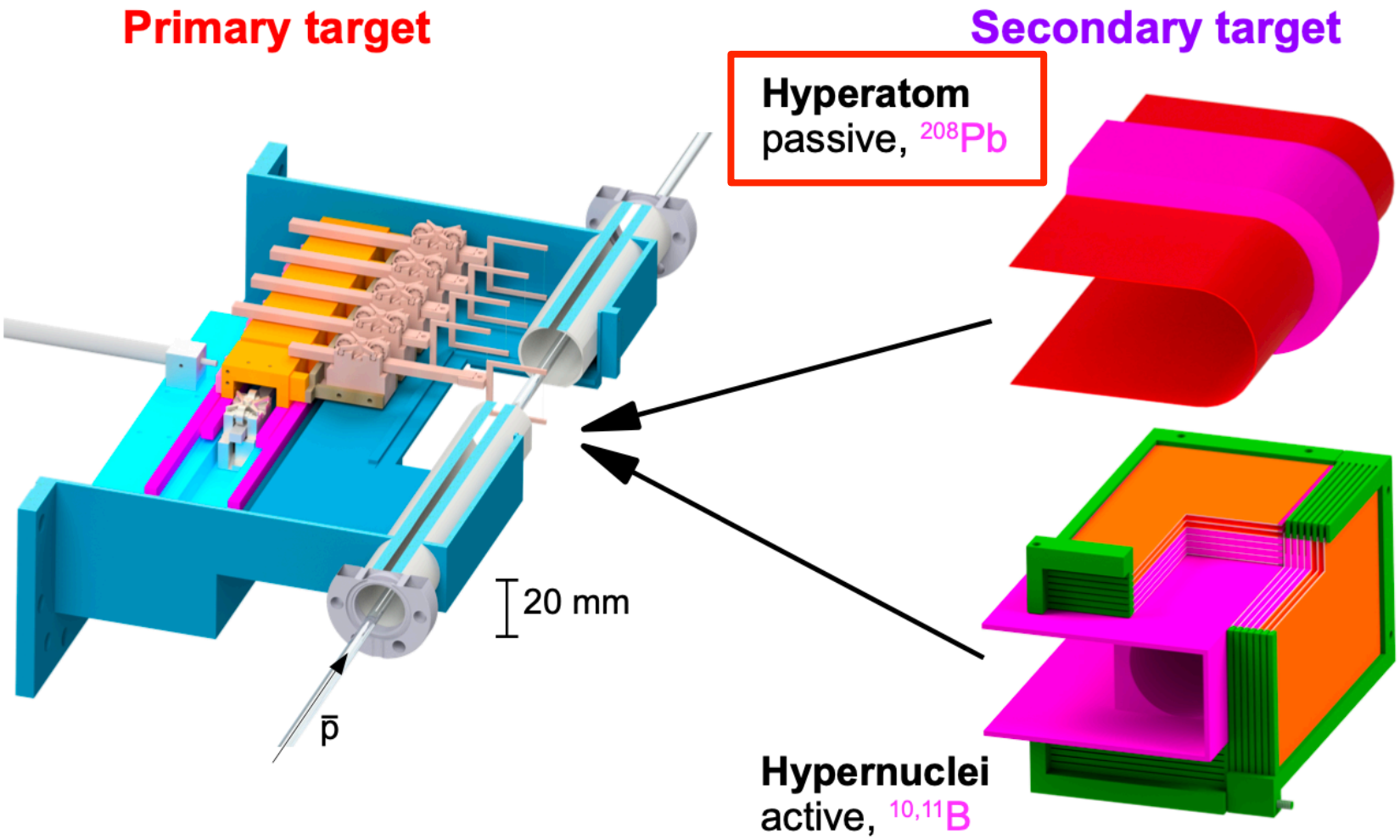
Hyperatom/nucleus setup

Marcell Steinen, PhD dissertation



Hyperatom/nucleus setup

Marcell Steinen, PhD dissertation



Hyperatoms - the basic concepts

Marcell Steinen, PhD dissertation

- Hyperon puzzle in neutron stars

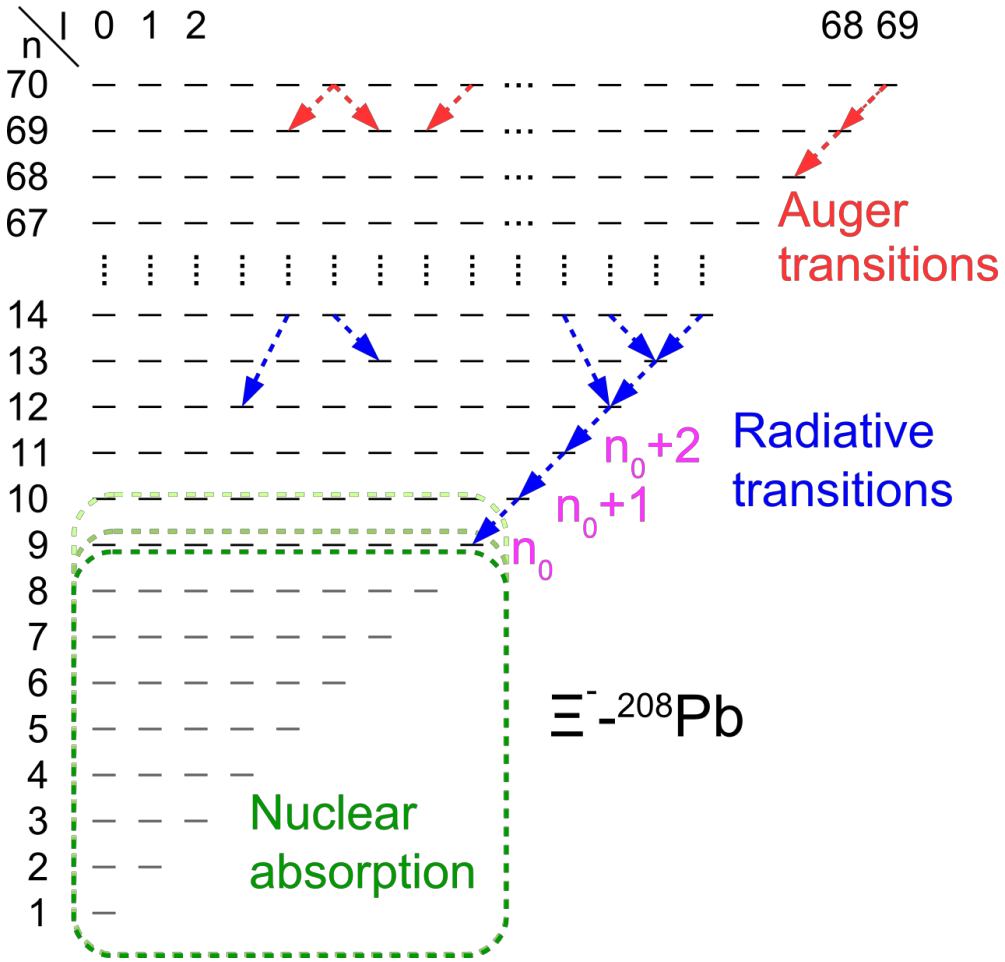
- $m_{red,\Xi} \approx 2570\, m_{red,e}$
- High initial (n,l) states
- X-ray energy to keV-MeV

  → Germanium detectors

- Radius of states: $r \propto \frac{n^2}{m_{red}}$

  → Nuclear interaction in neutron rich periphery

  → Measurement of V_Ξ



Adaptation from T. Aramaki et al Astroparticle Physics 49 (2013), pp. 52-62

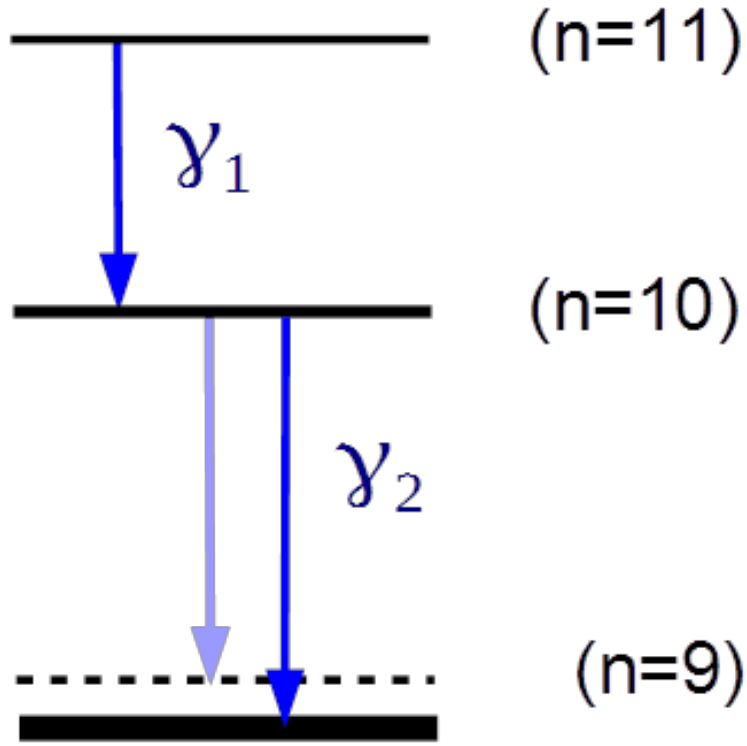
Hyperatoms - the observables

Marcell Steinen, PhD dissertation

$\Gamma^{abs}_{n_0+1} \rightarrow Y_{\gamma_2}$ Nuclear absorption

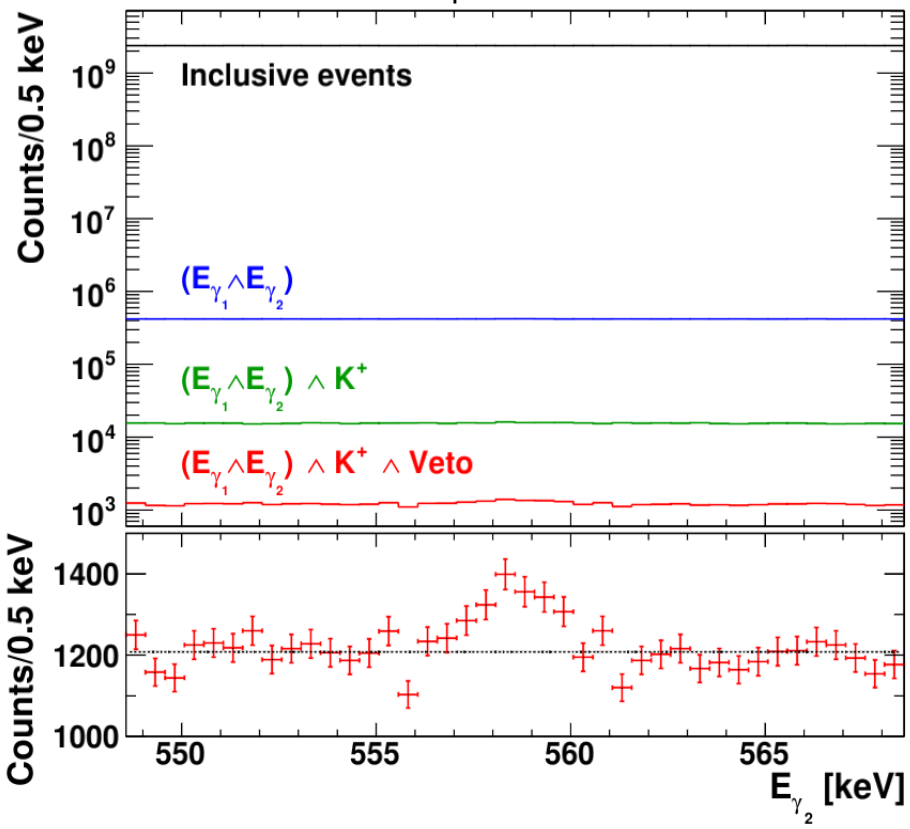
$\Delta E^{nuc}_{n_0}$ Strong shift

$\Gamma^{abs}_{n_0}$ and width

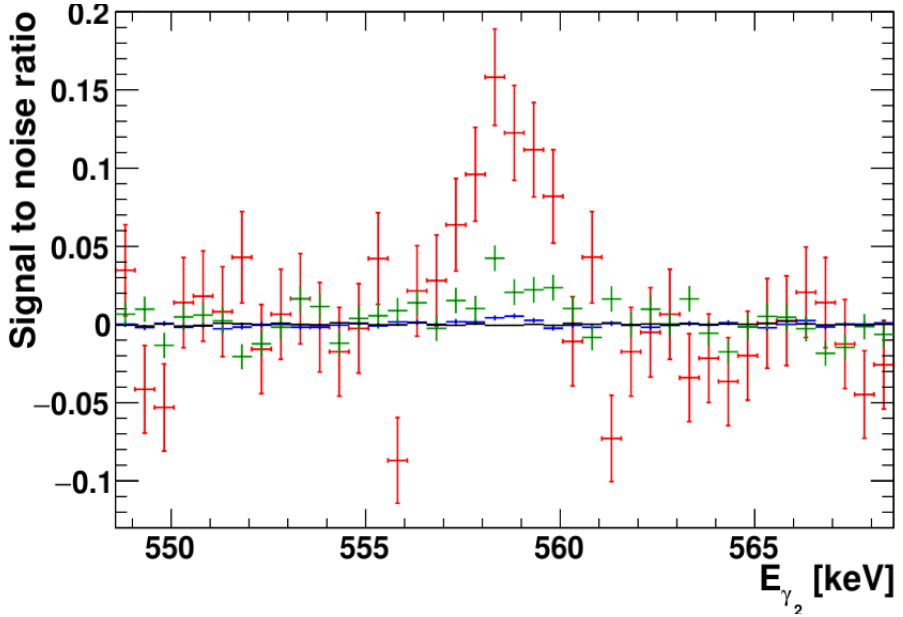


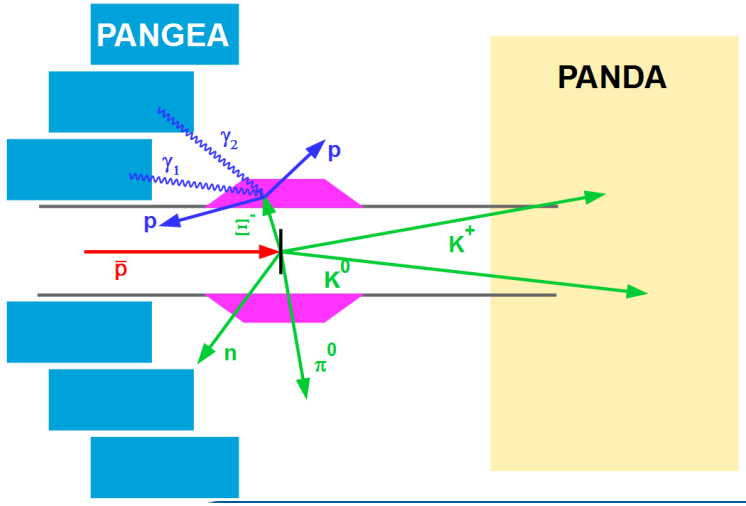
Hyperatoms - the expected signal

Based on GiBUU transport model!



Marcell Steinen, PhD dissertation



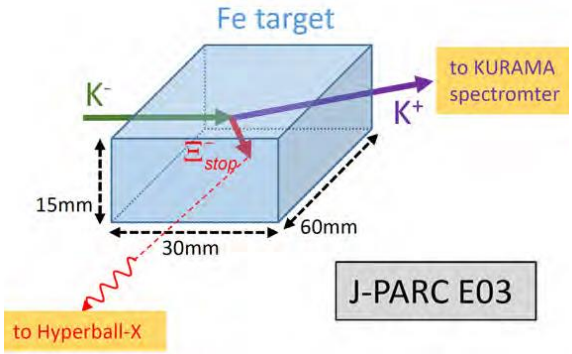


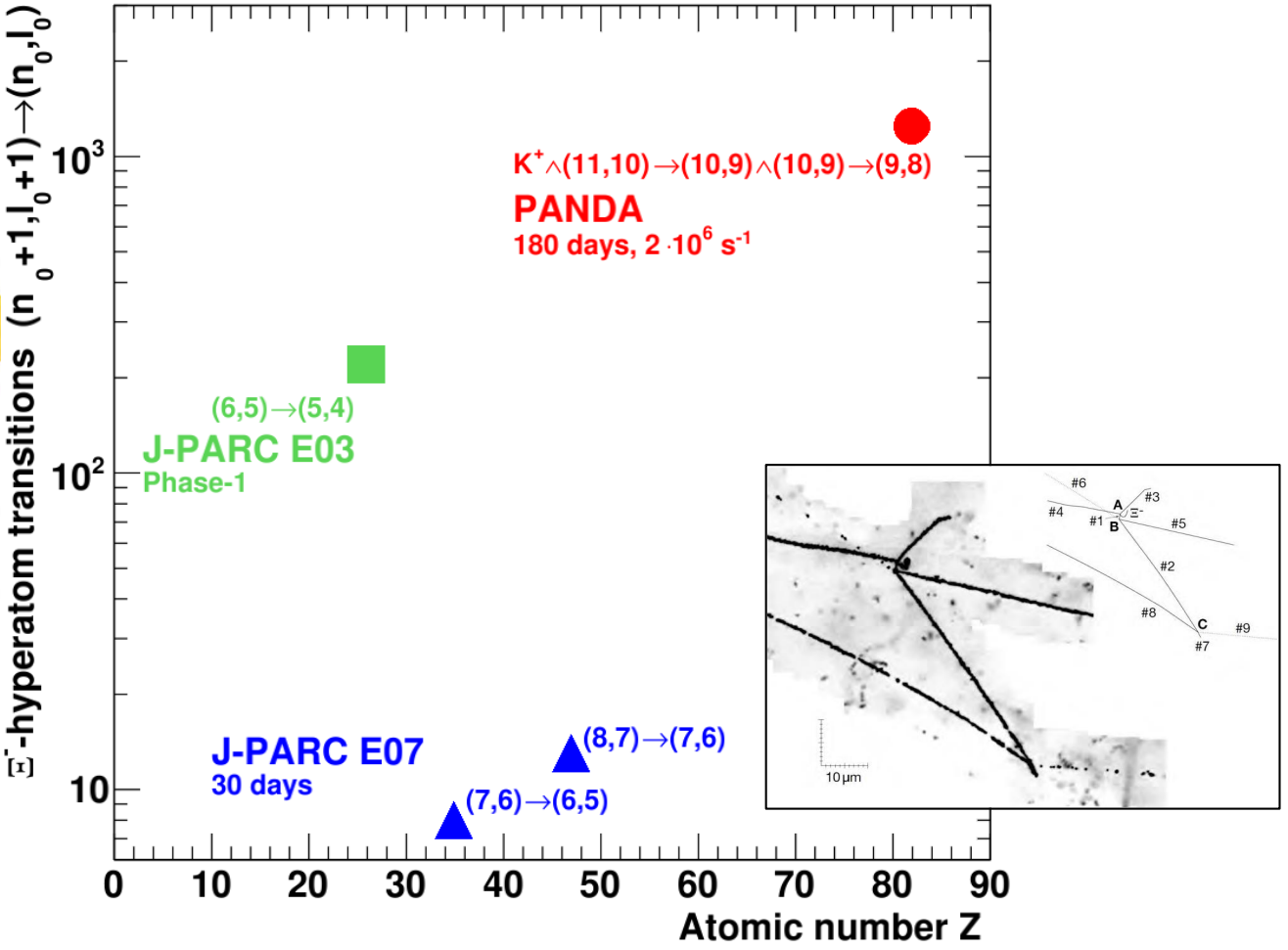
- Signals after cuts (180 days): 1237
- Signal efficiency: 0.9 %
- Background suppression : $2 \cdot 10^6$

Hyperatoms - complementary experiments

Marcell Steinen, PhD dissertation

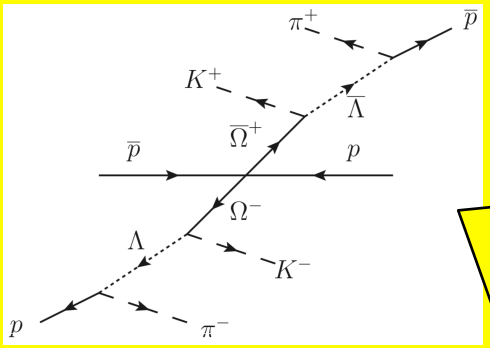
Expected number of observed transitions





We have follow-up ambitions!

Spin dynamics



Spectroscopy

Ω^*

$\Omega^- - \mathrm{Pb}$

Quadrupole moment!

Stay tuned ….

Strangeness Studies with PANDA at Phase One

PANDA covers particle, hadron, and nuclear aspects

- quark d.o.f.: from light to heavy
- gluon d.o.f.: glueballs, hybrids, etc.
- meson-baryon d.o.f.: B-B interaction in SU(3)

… is complementary and competitive

- *unique* antiproton facility
- versatile detector

Review "PANDA Phase One": see arXiv:2101.11877

… follows a staged approach

- driven by step-wise luminosity/detector upgrades
- with a broad program at each phase

… with a rich "strangeness" program @ Phase One