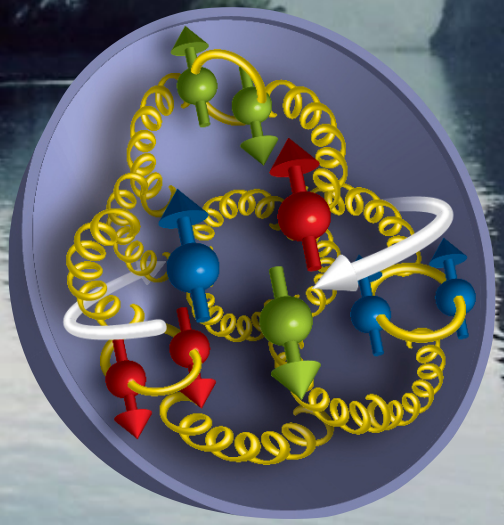
Few-Body Physics with PANDA



Johan Messchendorp (KVI-CART/University of Groningen, physics coordinator PANDA)

APFB2017, Guilin, China, 25-29 August 2017


AIRFRANCE KLM
Xing Ya 星雅 Wu Wen 武雯

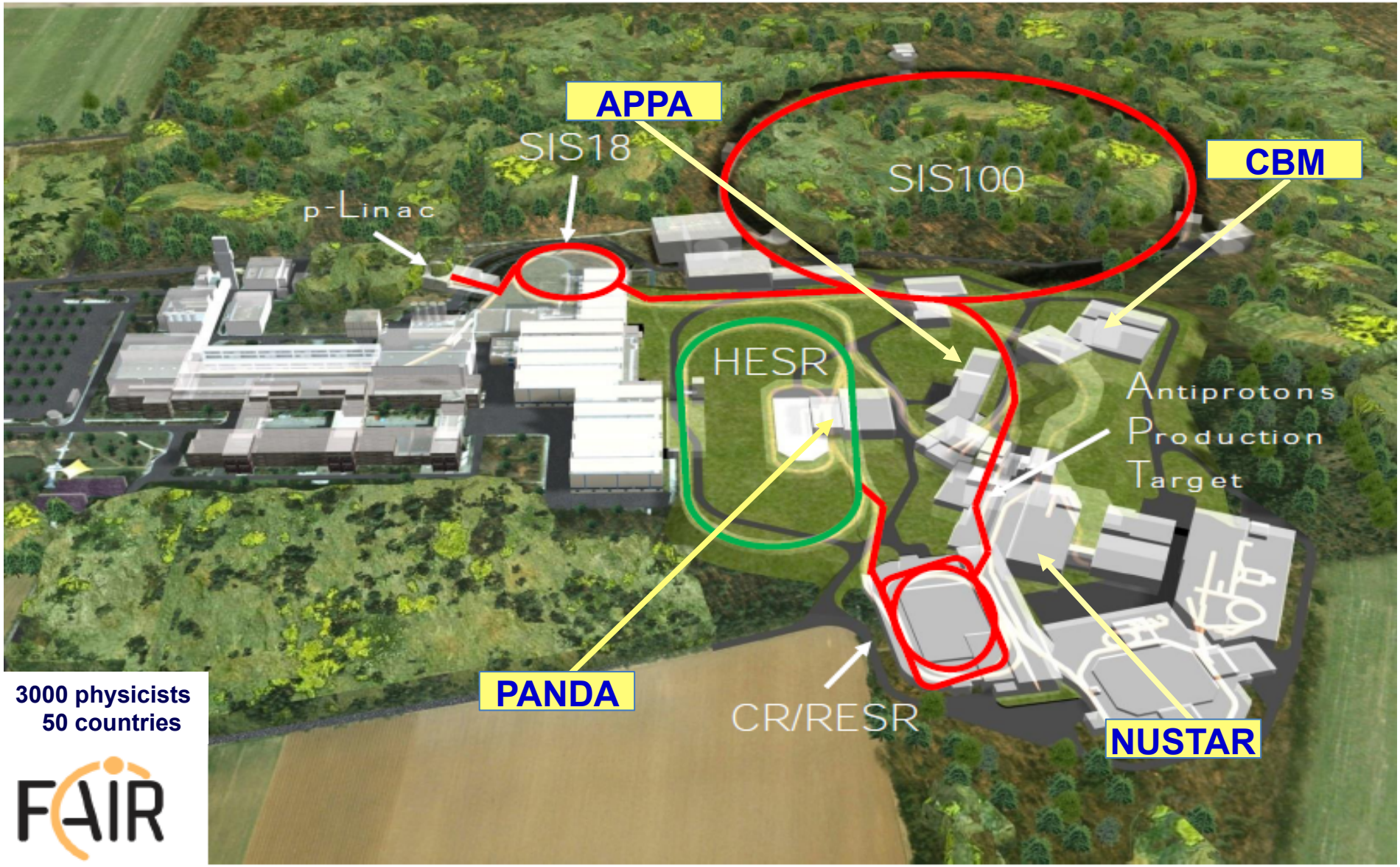
Why I joined PANDA!

Community
- interdisciplinair: nuclear, hadron & particle physics
- international: 450 scientists from 19 countries
- strong network in other collaborations

Uniqueness
- usage of antiprotons: precision & exploration
- strange, charm, and gluon “factory”

Technology
- data complexity & detector developments
- versatile instrument

Facility for Antiproton and Ion Research



3000 physicists
50 countries

Facility for Antiproton and Ion Research

Facility for Antiproton and Ion Research

Facility for Antiproton and Ion Research

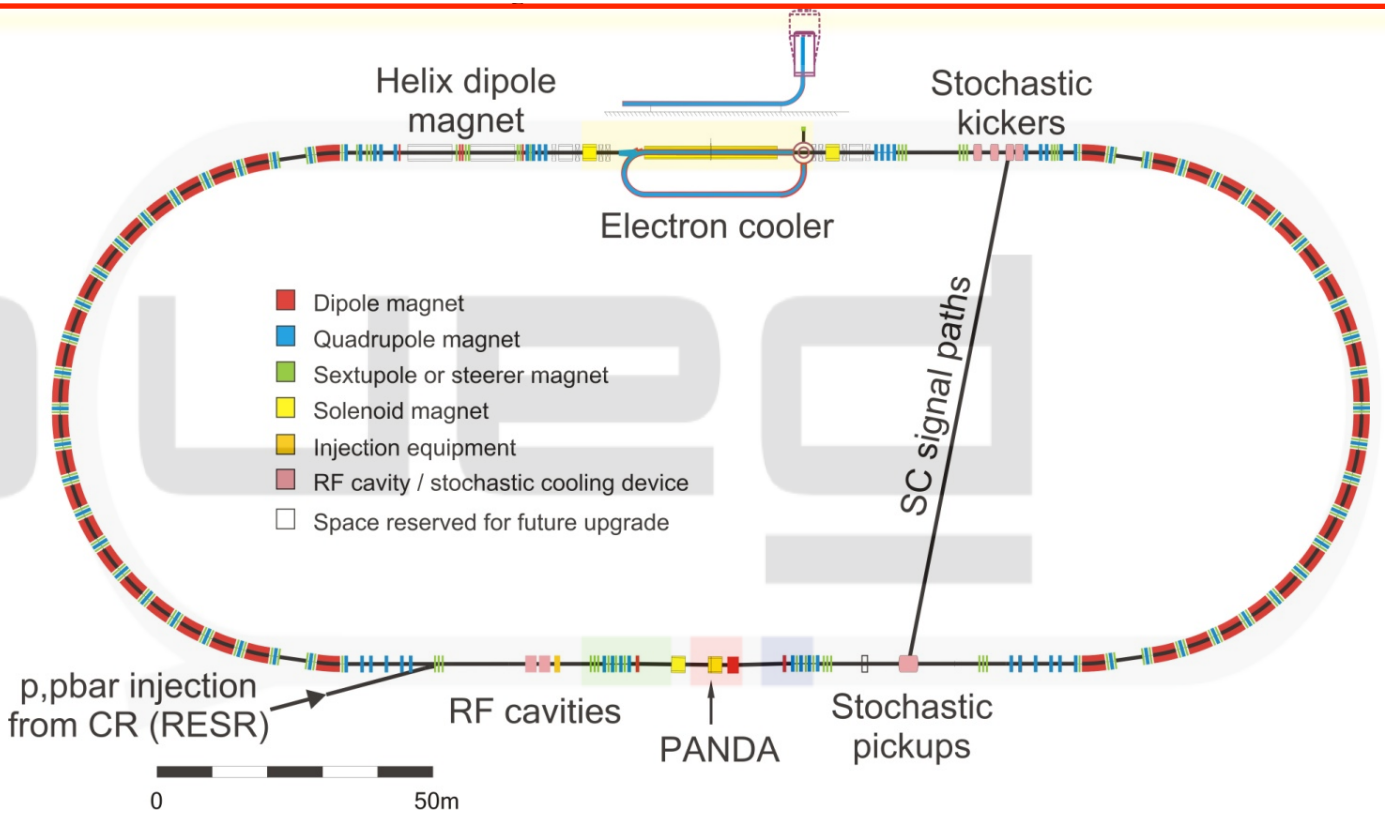
Phase 0 - experimental program using FAIR instruments before FAIR becomes available **~2018**

Phase 1- experimental program with SIS100 and secondary beams with “start setups”, “day 1” **~2024**

Phase 2 - experimental program at full potential of Modularised Start Version (MSV) **~2026**

Phase 3 - beyond MSV operation

High Energy Storage Ring - *precision* antiprotons



High resolution mode:

- e^- cooling : p<8.9 GeV/c
- 10^{10} antiprotons stored
- Luminosity up to $2x10^{31}$ $cm^{-2}s^{-1}$
- $dp/p = 4x10^{-5}$

High intensity mode:

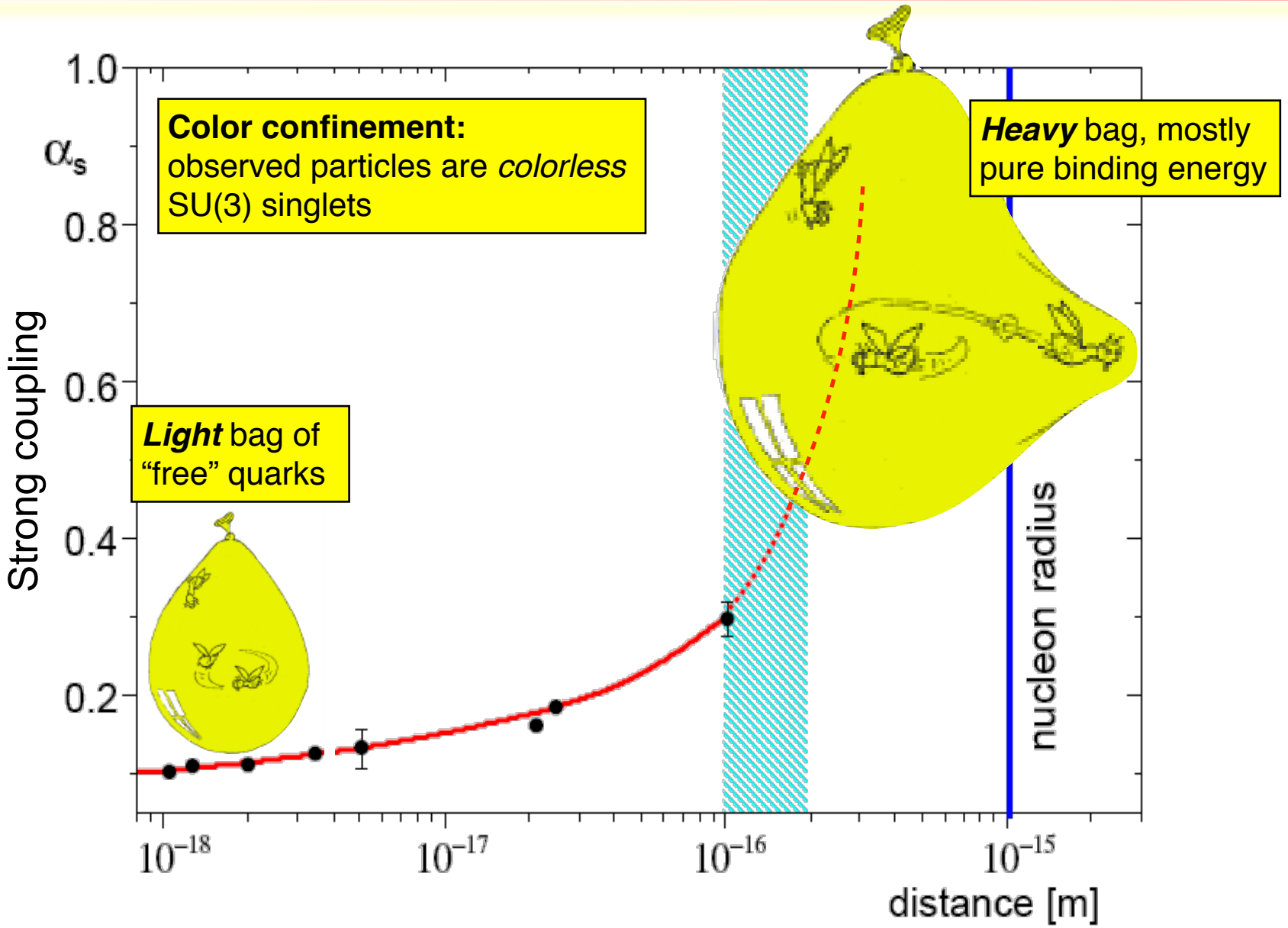
- Stochastic cooling
- 10^{11} antiprotons stored
- Luminosity up to $2x10^{32}$ $cm^{-2}s^{-1}$
- $dp/p = 2x10^{-4}$

Phase 1+2: max. 10^{10} antiprotons stored

The “magic” of antiprotons

I. Versatile

Probing QCD at various distance scales

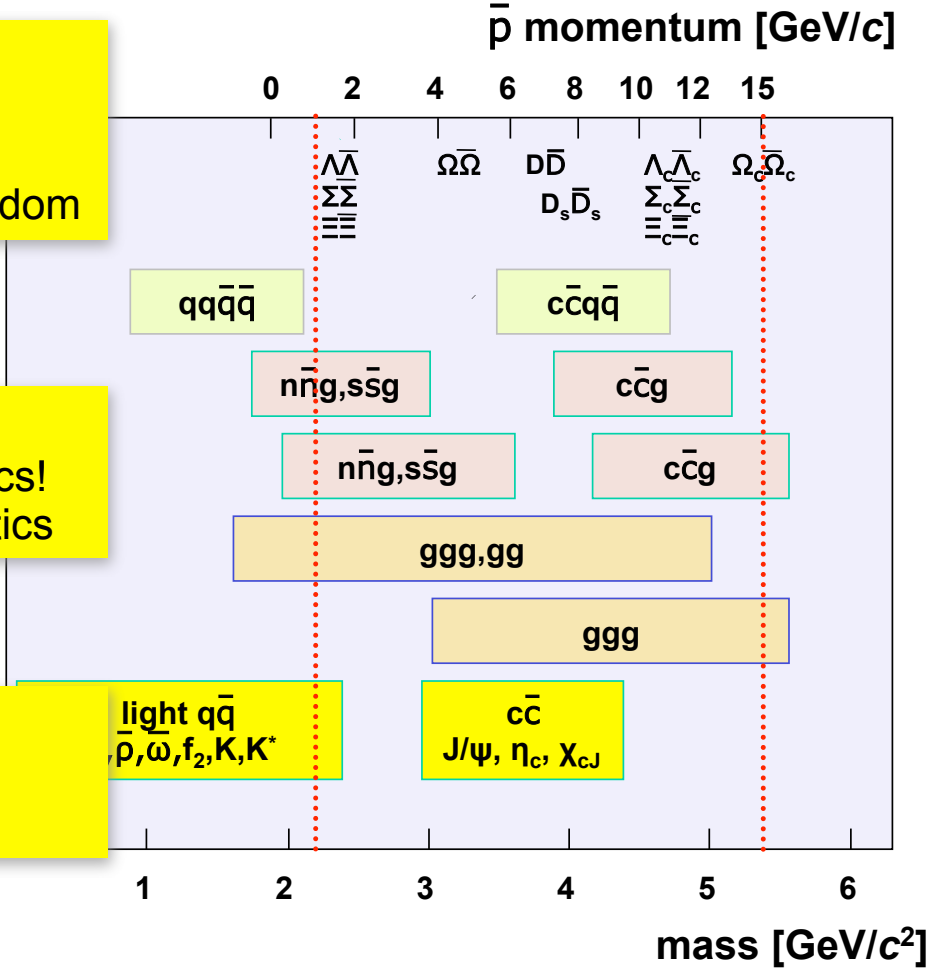


Versatility of antiprotons at PANDA

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

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



Systematic and precise tool to rigorously study the dynamics of QCD

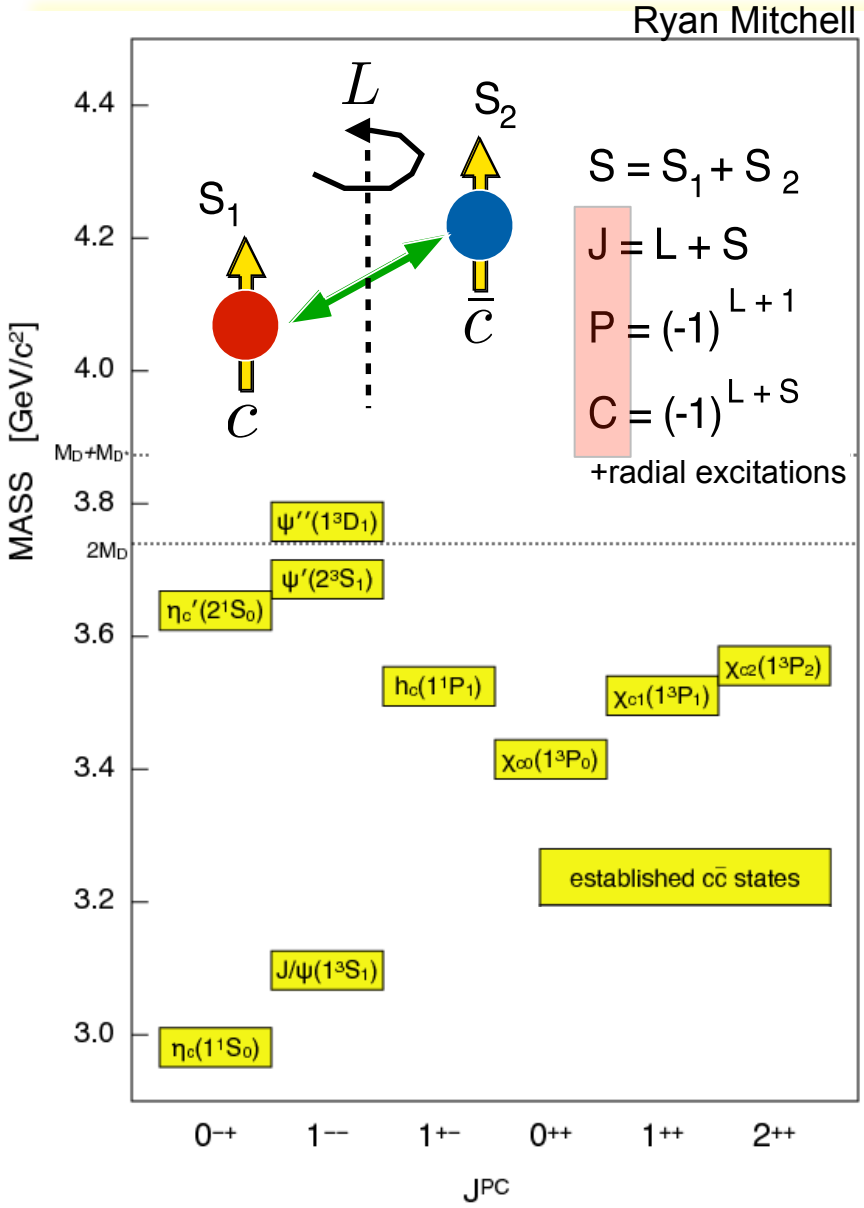
The “magic” of antiprotons

II. Discovery by precision and exploration

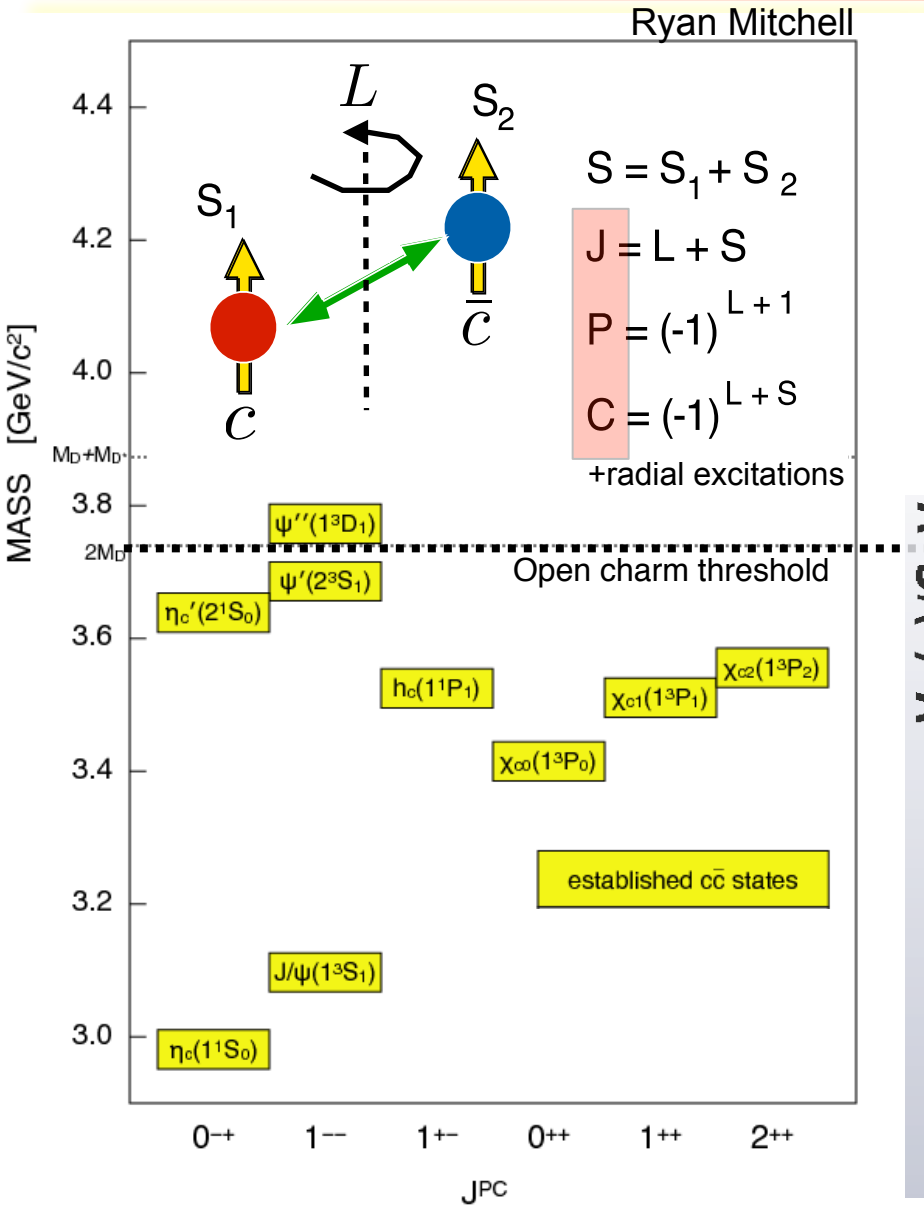
- a few examples

Charmonium - the "positronium" of QCD

Ryan Mitchell



Charmonium - the "positronium" of QCD



Example from Barnes, Godfrey, Swanson:

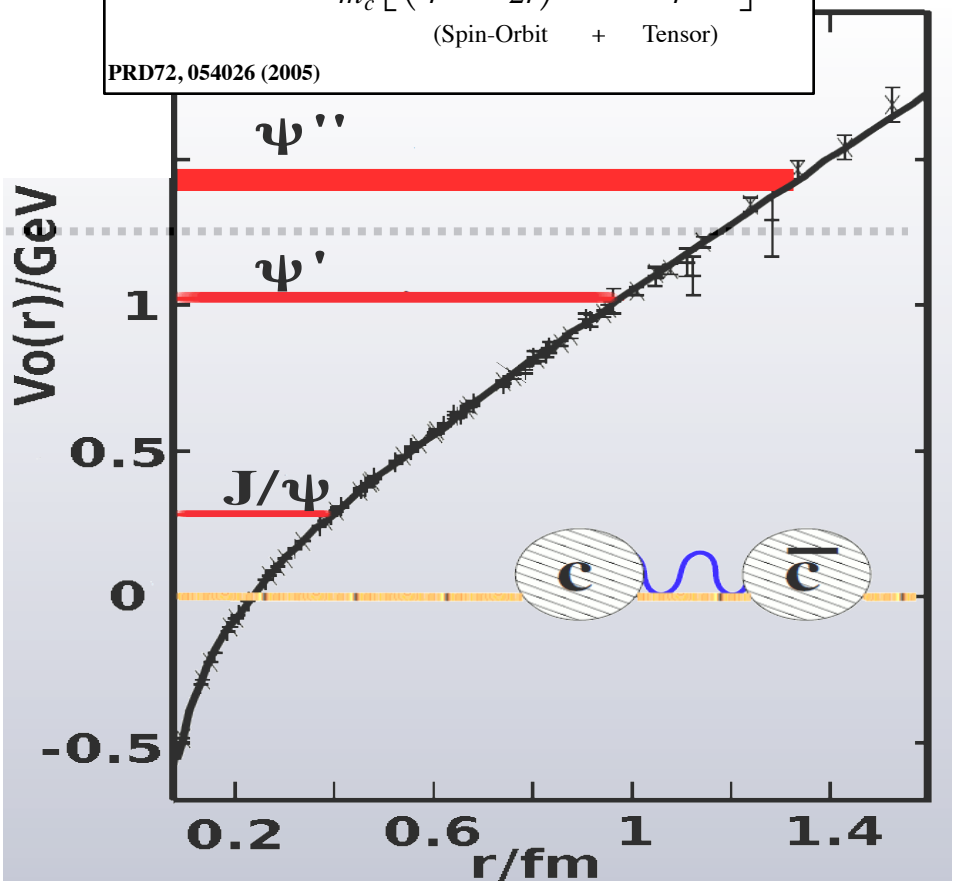
$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

(Coulomb + Confinement + Contact)

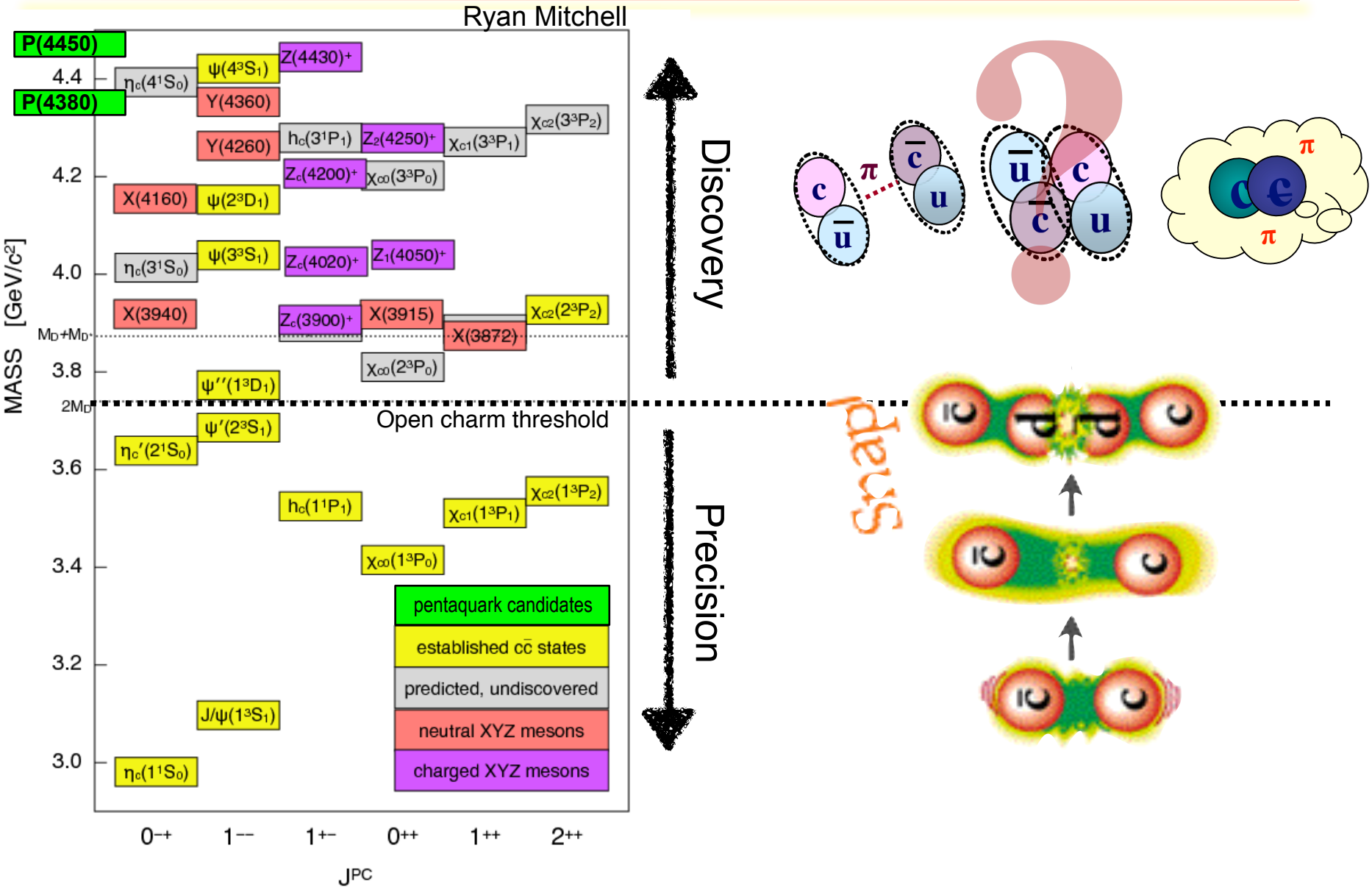
$$V_{\text{spin-dep}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

(Spin-Orbit + Tensor)

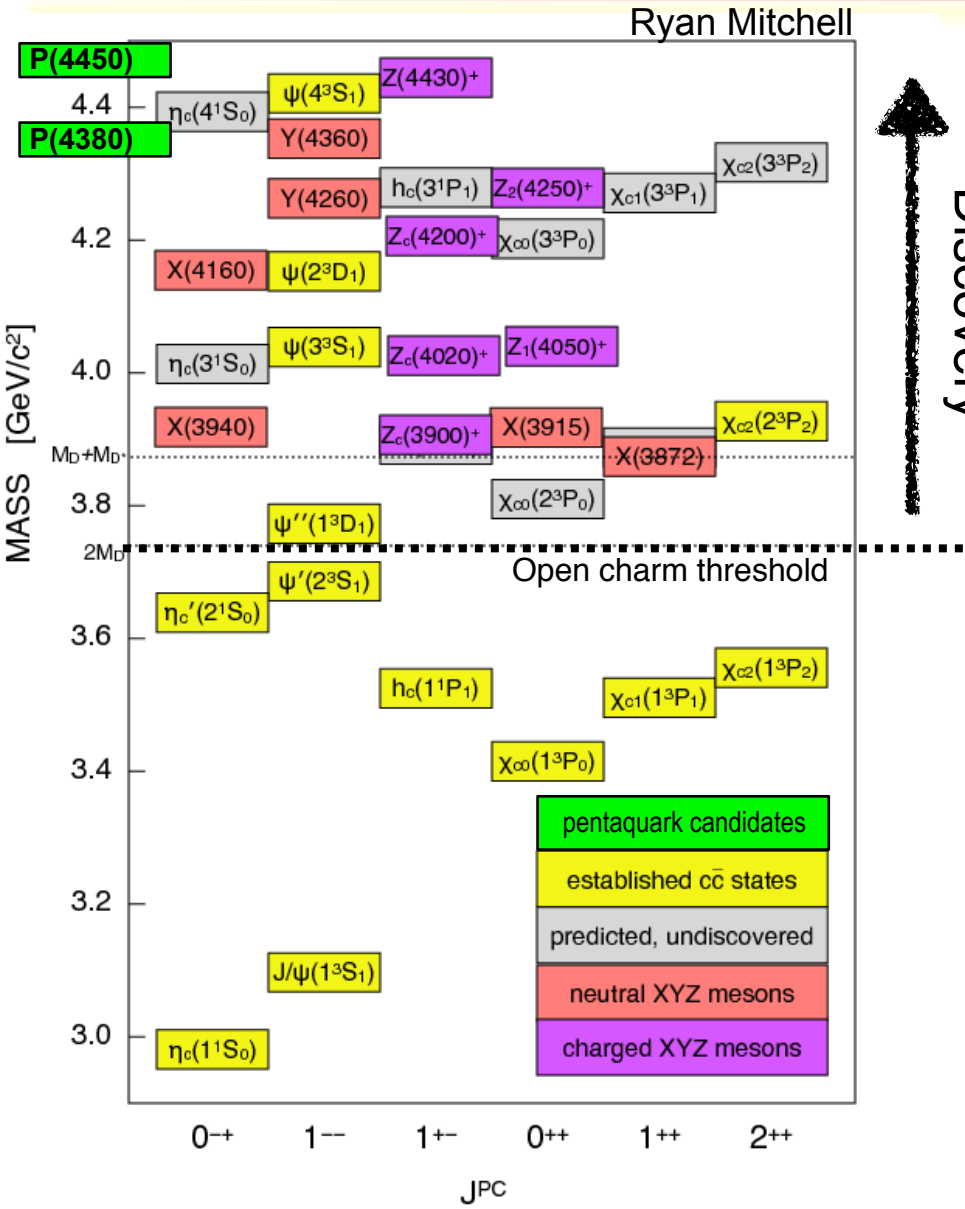
PRD72, 054026 (2005)



Charmonium-like particles - terra incognita



Charmonium-like particles - terra incognita



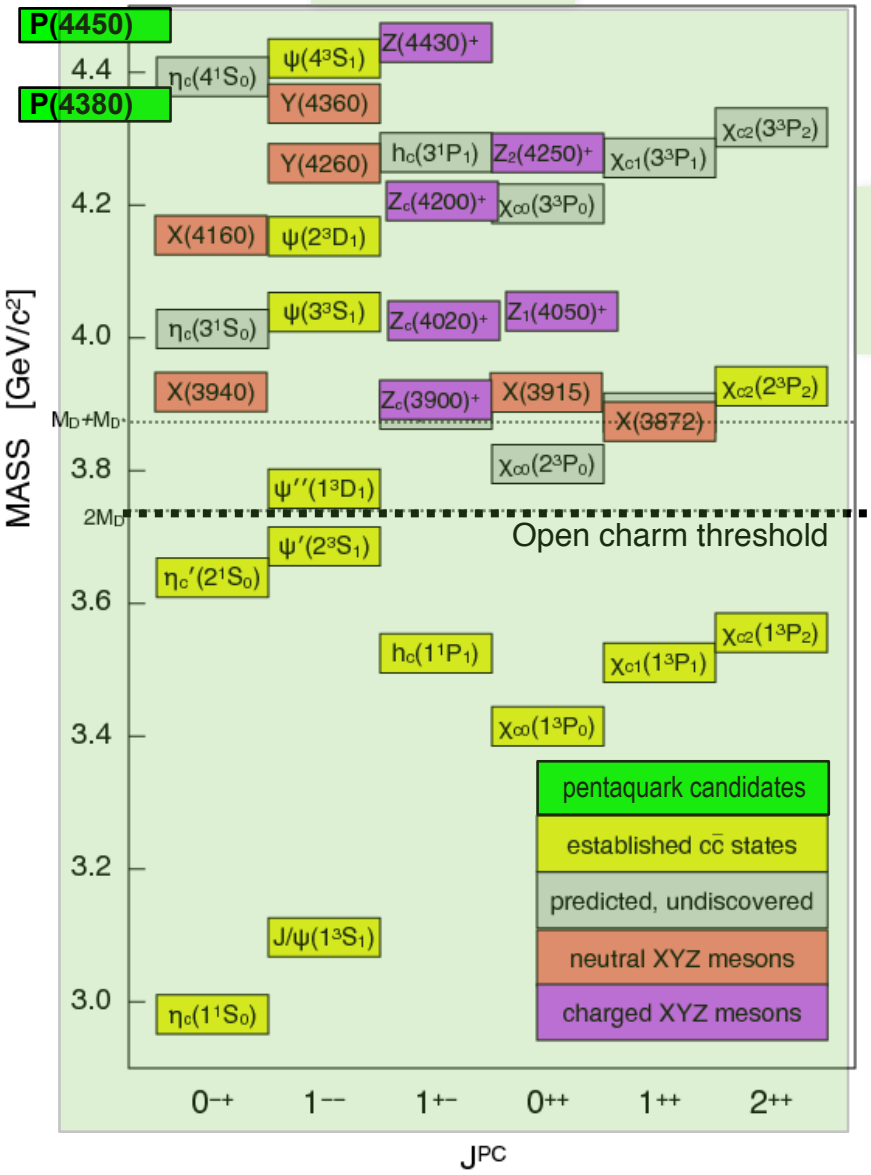
Discovery

APS highlights

2013: "QCD *excitement*"

Physics 6, 138 (2013), 8, 126 (2015)

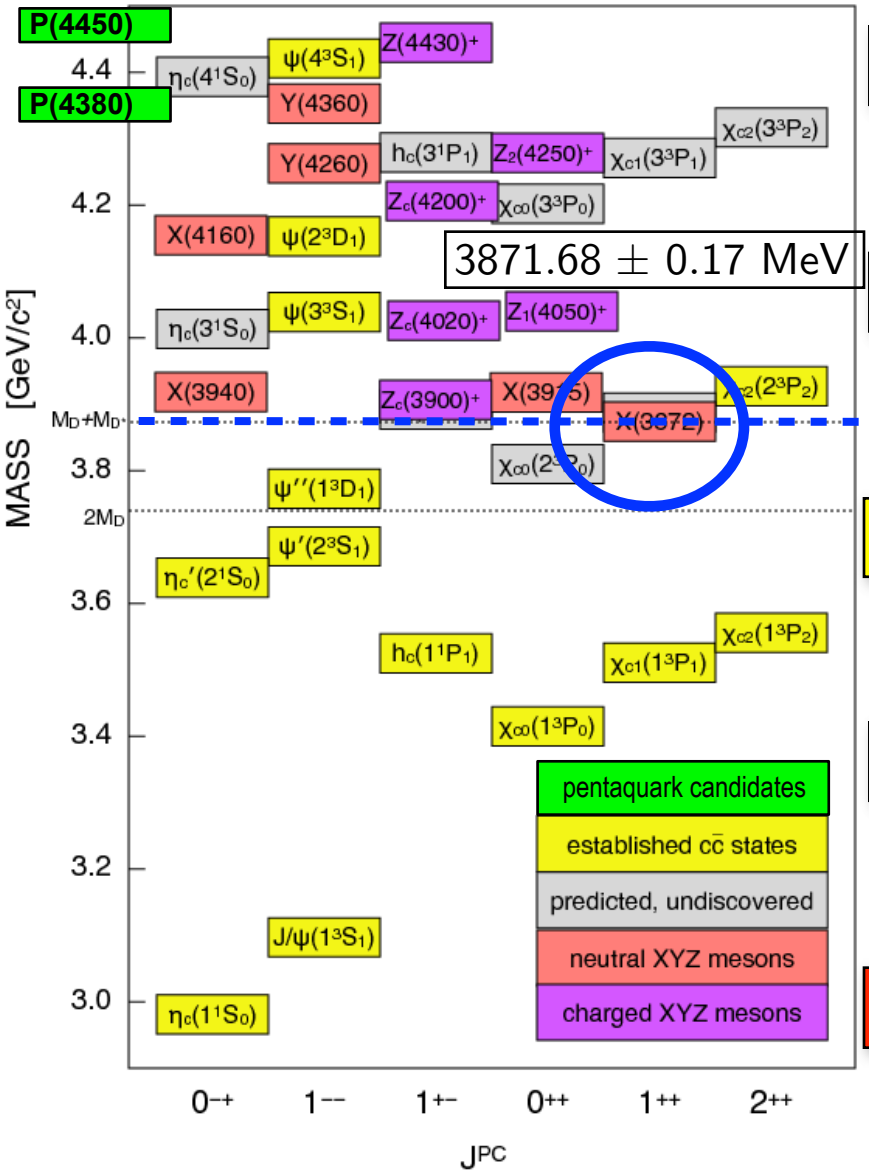
Charmonium-like particles - PANDA opportunities



- line shape of X(3872)
- neutral+charged Z-states
- hidden-charm pentaquark
- X,Y,Z decays
- search for h_c', $^3F_4$, …
- spin-parity/mass&width of $^3D_2$

- line shape/width of the h_c
- radiative decays (multipole)
- light-quark spectroscopy

Case study: the nature of the X(3872)



Strikingly narrow:

$$\Gamma < 1.2\,\mathrm{MeV} \quad (\Gamma(\psi'') = 27\,\mathrm{MeV})$$

Suspiciously close to DD* threshold:

$$\Delta E = -0.13 \pm 0.40\,\mathrm{MeV}$$

Large isospin breaking:

$$B(X \to \rho J/\Psi) \approx B(X \to \omega J/\Psi)$$

Spin-parity:

$$J^{PC} = 1^{++}$$

PRL110, 222001 (2013)

What is its nature?

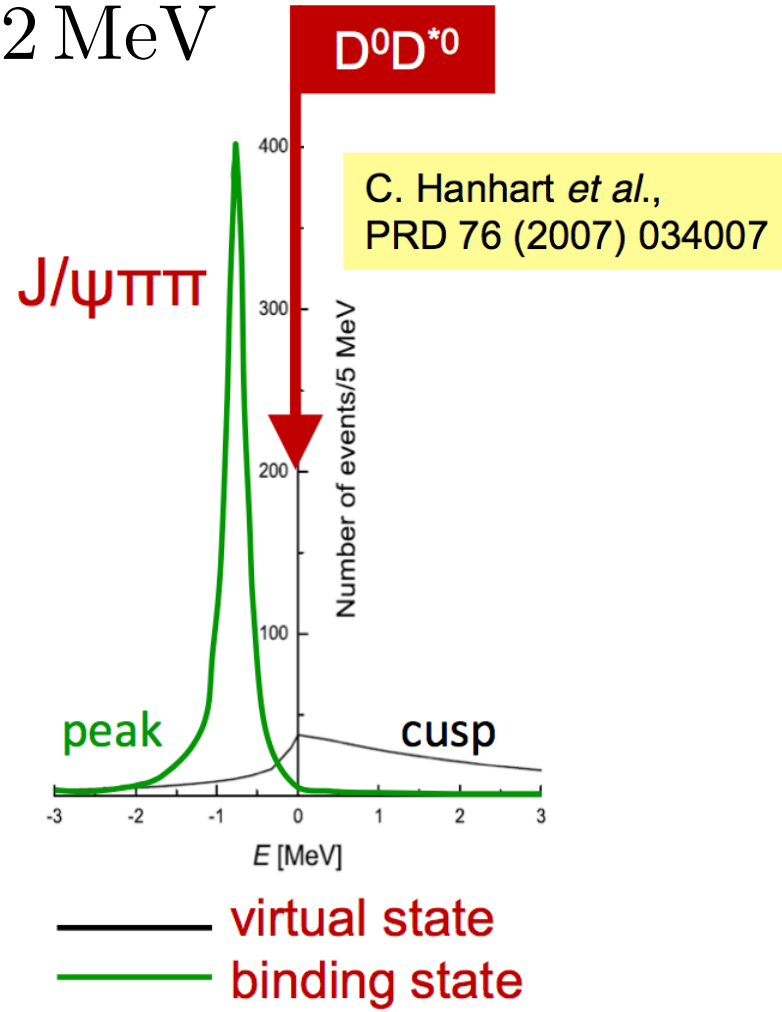
Case study: the nature of the X(3872)

Strikingly narrow:

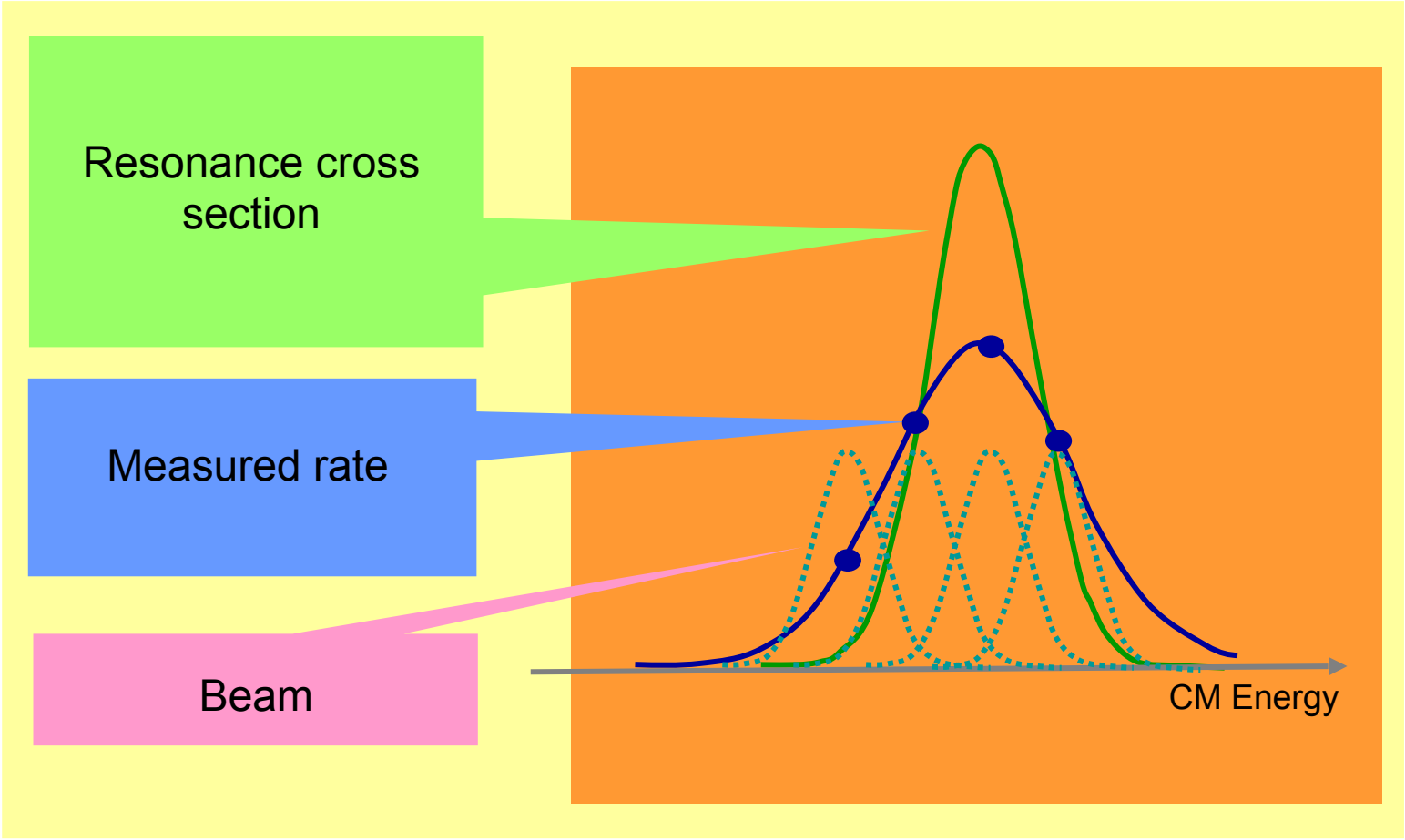
$$\Gamma < 1.2\,\mathrm{MeV}$$

Theoretical line-shape:
- depends on final state …
- … and nature of particle
-> sensitive observable!

PANDA:
- direct formation of X(3872)
- tagging of various final states (neutral&charged)
- access to line-shape parameters



Resonance scanning



Line shape measurement using HESR's superb mass resolution

Resonance scanning

$\bar{p}p \to X(3872) \to J/\psi\pi^+\pi^-$

Klaus Goetzen et al.

Luminosity:

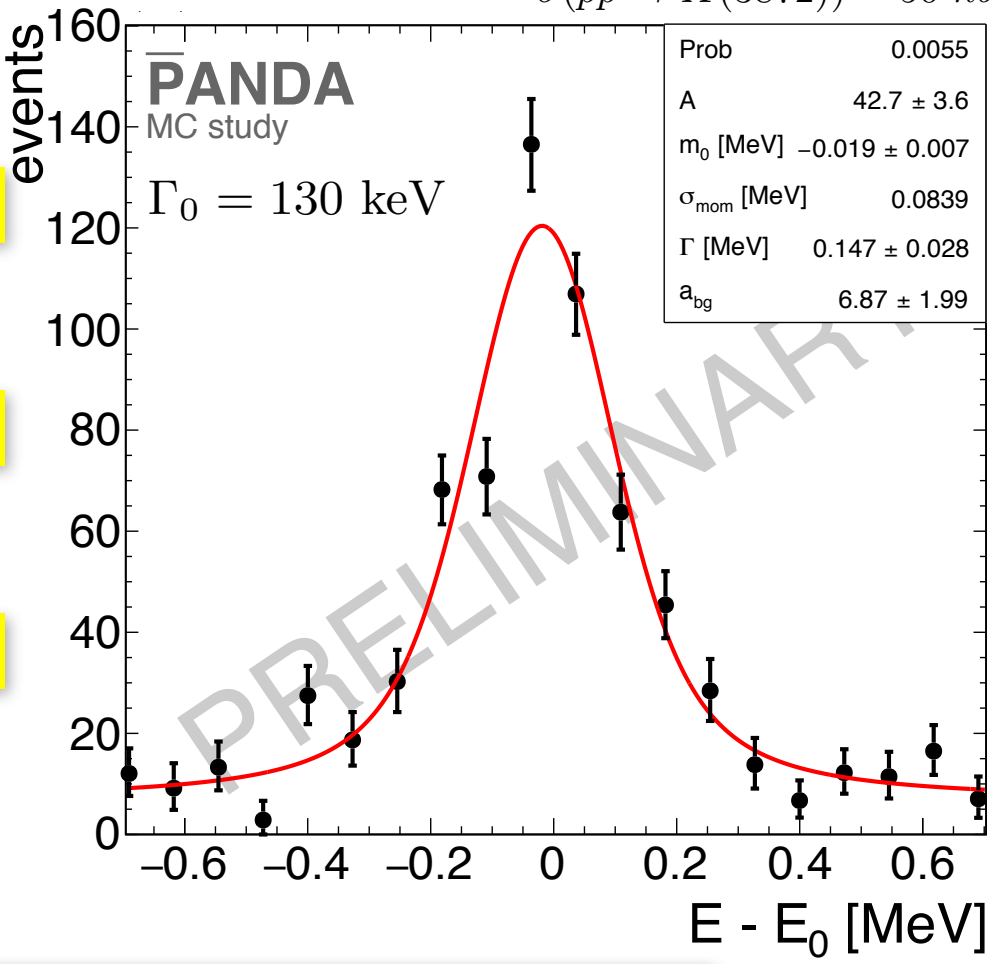
$1170\ (\mathrm{nb}\cdot\mathrm{day})^{-1}$

Energy resolution:

$\Delta E = 84\ \mathrm{keV}$

20 points each 2 days data taking!

$\sigma(\bar{p}p \to X(3872)) = 50\ nb$



Width sensitivity down to 100 keV achievable at day-one

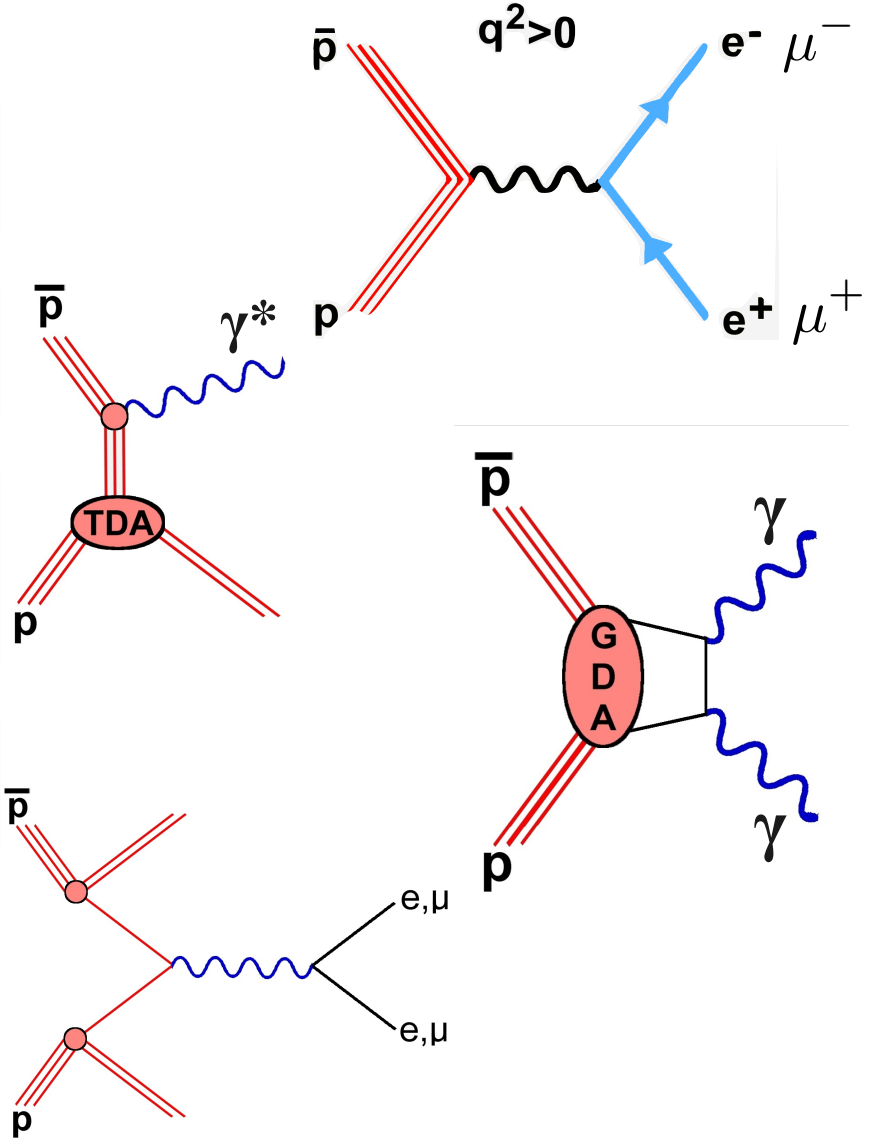
The structure of the proton

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

Transition Distribution Amplitudes
(meson production) arXiv:1409.0865

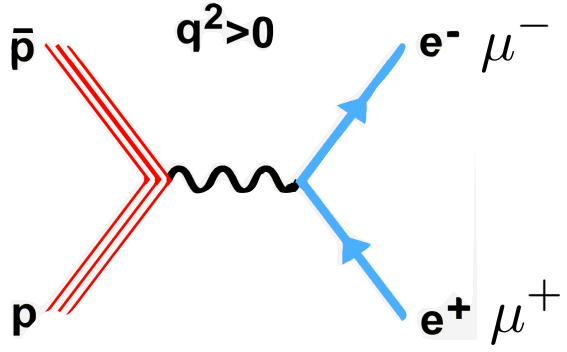
Generalised Distribution Amplitudes
(time-like Compton, hard exclusive processes)

Transverse Parton Distribution Functions
(Drell-Yan production)



Analytical nature of form factors

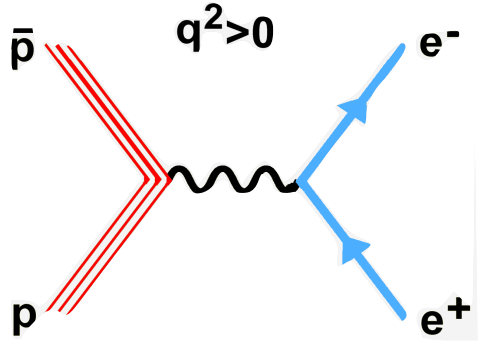
Time-like Electromagnetic Form Factors
(lepton pair production) arXiv:1606.01118



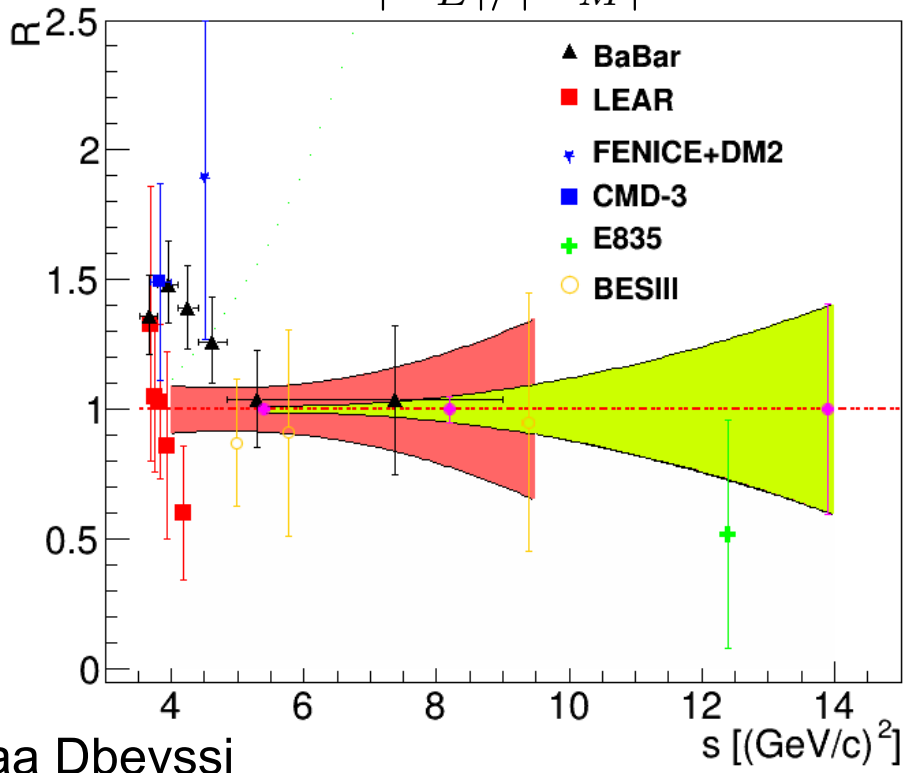
$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2\beta s}\left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}\sin^2\theta|G_E|^2\right]$$

Analytical nature of form factors

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



$$R = |G_E|/|G_M|$$



BESIII

21 scan points 2015 (552 pb^{-1})

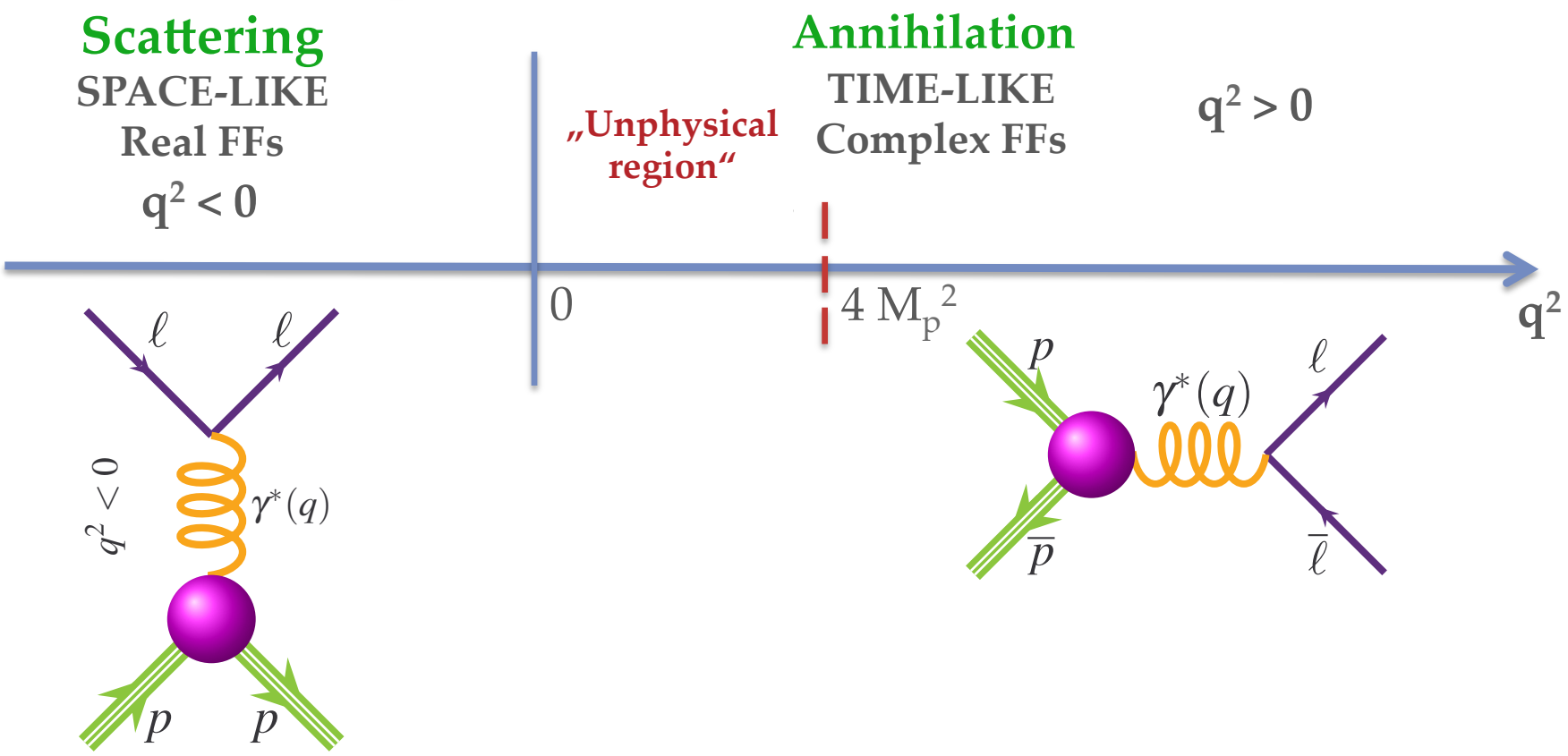
Monte Carlo Sim., R=1 (C. Morales)

PANDA

L=2 fb^{-1}
2.10^{32} cm^{-2}s^{-1}

~5 months data taking /point

Proton form factors in the *unphysical* region



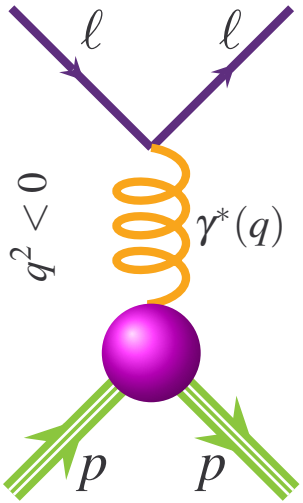
Proton form factors in the *unphysical* region

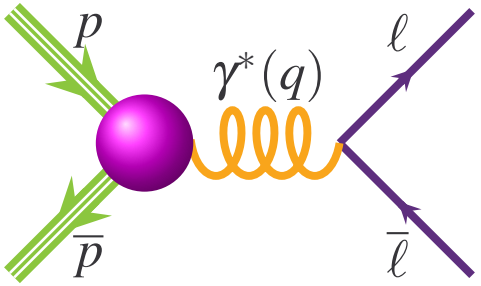
Scattering
SPACE-LIKE
Real FFs
$q^2 < 0$

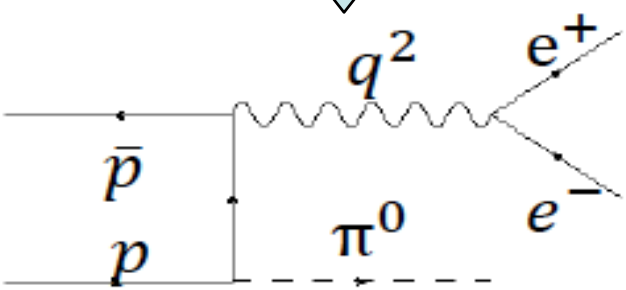
„Unphysical region“

Annihilation
TIME-LIKE
Complex FFs
$q^2 > 0$

0 $4 M_p^2$ q^2





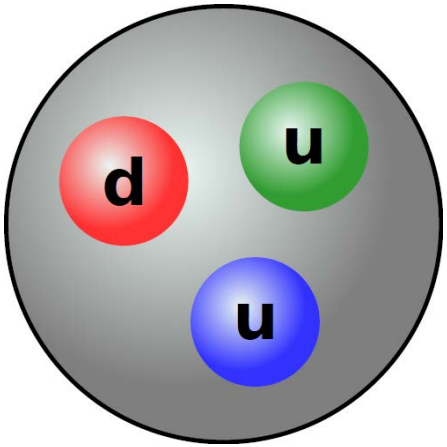


P [GeV/c]	ΔR/R ($2fb^{-1}$)	ΔR/R (4 months-Day1)
1.7	1.4 %	~7%

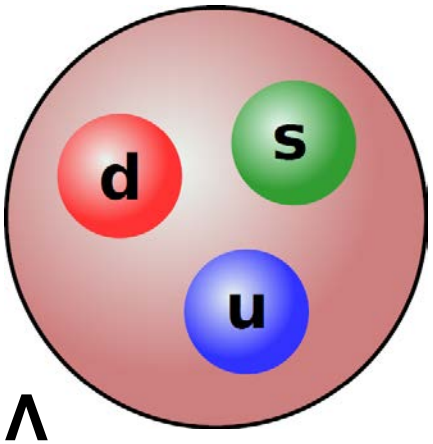
I. Zimmermann, J. Boucher

Exploring the hyperon sector

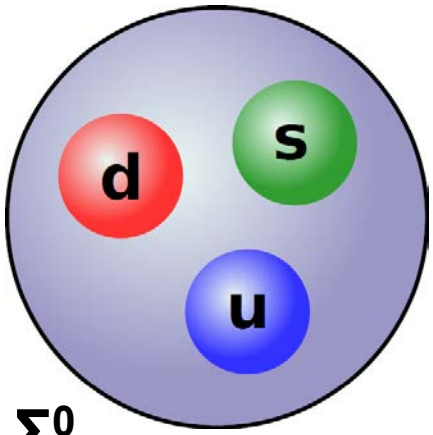
What happens if we replace one of the light quarks in the proton with one - or many - heavier quark(s)?



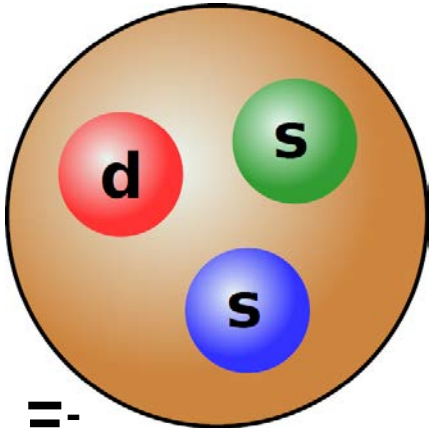
proton



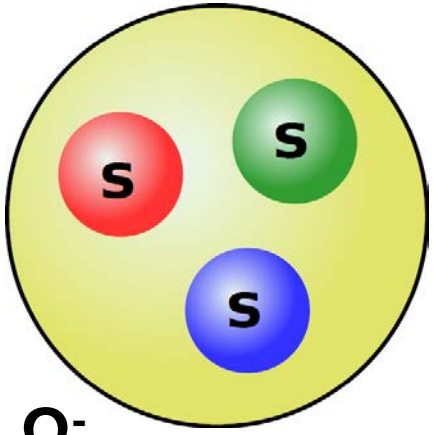
Λ



Σ^0

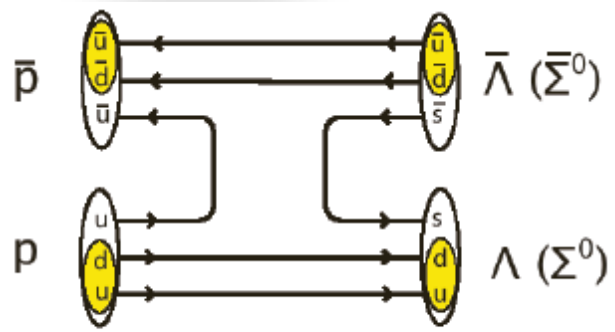


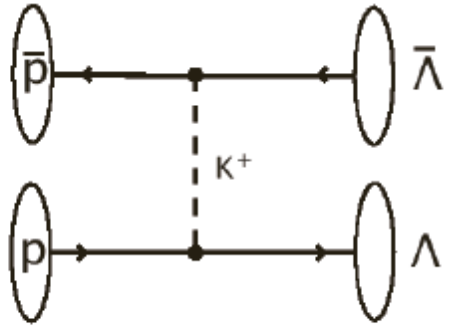
Ξ^-

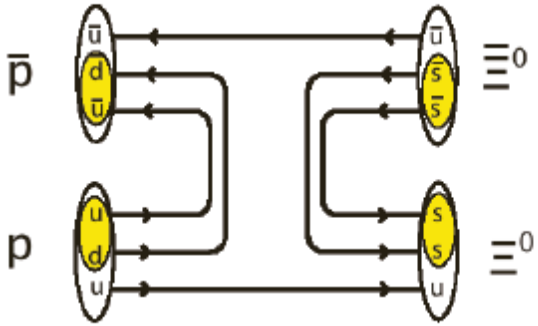


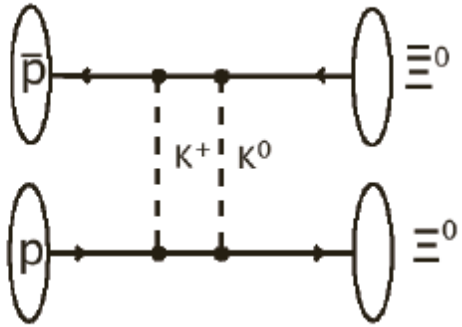
Ω^-

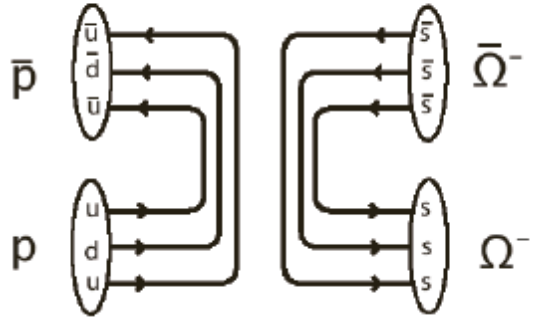
Exploring the hyperon sector

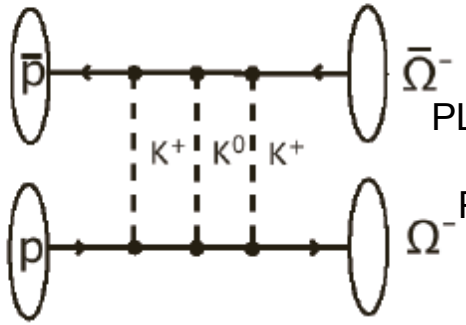












Models based on

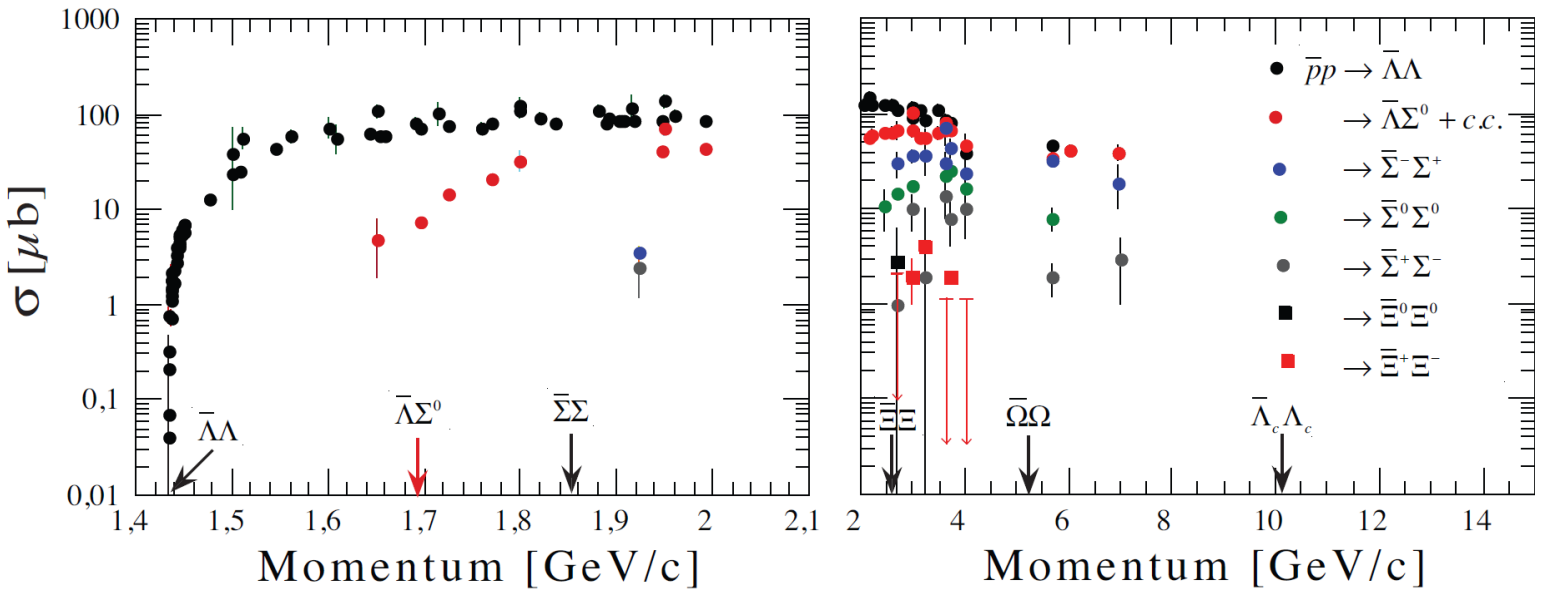
1) quark-gluon picture*

2) the hadron picture**

3) a combination of 1) and 2) ***

PL**B** 179 (1986) 15; PLB 165 (1985) 187; NPA 468 (1985) 669; **PRC** 31(1985) 1857; PLB179 (1986) 15; PLB 214 (1988) 317; *** PLB 696 (2011) 352.

PANDA is a hyperon factory!



- A lot of data on $\bar{p}p \to \bar{\Lambda}\Lambda$ near threshold, mainly from PS185 at LEAR*
- Very scarce data bank above 4 GeV
- Only a few bubble chamber events on $\bar{p}p \to \bar{\Xi}\Xi$
- No data on $\bar{p}p \to \bar{\Omega}\Omega$ nor $\bar{p}p \to \bar{\Lambda}_c\Lambda_c$

* See e.g. T. Johansson, AIP Conf. Proc. of LEAP 2003, p. 95

PANDA is a hyperon factory!

$$\bar{p}p \to \bar{\Lambda}\Lambda,\ \bar{\Sigma}^{-}\Sigma^{+},\ \bar{\Sigma}^{0}\Sigma^{0},\ \bar{\Sigma}^{-}\Sigma^{+},\ \bar{\Xi}^{0}\Xi^{0},\ \bar{\Xi}^{+}\Xi^{-},\ \bar{\Omega}^{+}\Omega^{-},\ \bar{\Lambda}_{c}^{-}\Lambda_{c}^{+}$$

$$\downarrow \qquad \downarrow \qquad \downarrow \qquad \downarrow \qquad \downarrow \qquad \downarrow \qquad \downarrow \qquad \downarrow$$

$$p\pi^{-} \quad p\pi^{0} \quad \Lambda\gamma \quad n\pi \quad \Lambda\pi^{0} \quad \Lambda\pi \quad \Lambda K \quad \Lambda\pi$$

$$64\% \quad 52\% \quad \approx 100\% \quad \approx 100\% \quad \approx 100\% \quad \approx 100\% \quad 68\% \quad \approx 1\%$$

Momentum (GeV/c)	Reaction	σ (μb)	Efficiency (%)	Rate (with 10^{31} $cm^{-2}s^{-1}$)
1.64	$\bar{p}p \to \bar{\Lambda}\Lambda$	64	11	29 s^{-1}
4	$\bar{p}p \to \bar{\Lambda}\Sigma^{o}$	~40	~30	50 s^{-1}
4	$\bar{p}p \to \bar{\Xi}^{+}\Xi^{-}$	~2	~20	1.5 s^{-1}
12	$\bar{p}p \to \bar{\Omega}^{+}\Omega^{-}$	~0.002	~30	~4 h^{-1}
12	$\bar{p}p \to \bar{\Lambda}_{c}^{-}\Lambda_{c}^{+}$	~0.1	~35	~2 day^{-1}

Day 1

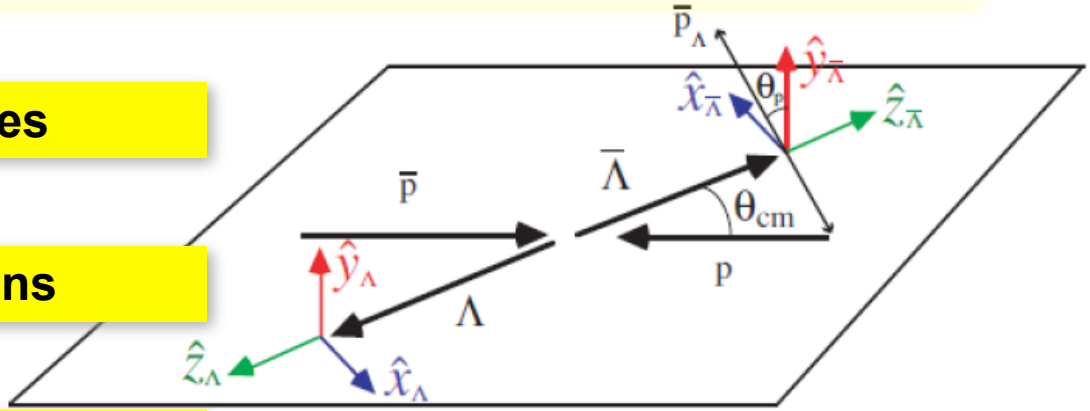
Karin Schoenning

PANDA is a hyperon factory!

Rich set of polarisation observables

(double) strange and charm baryons

Explore hyperon dynamics above 4 GeV



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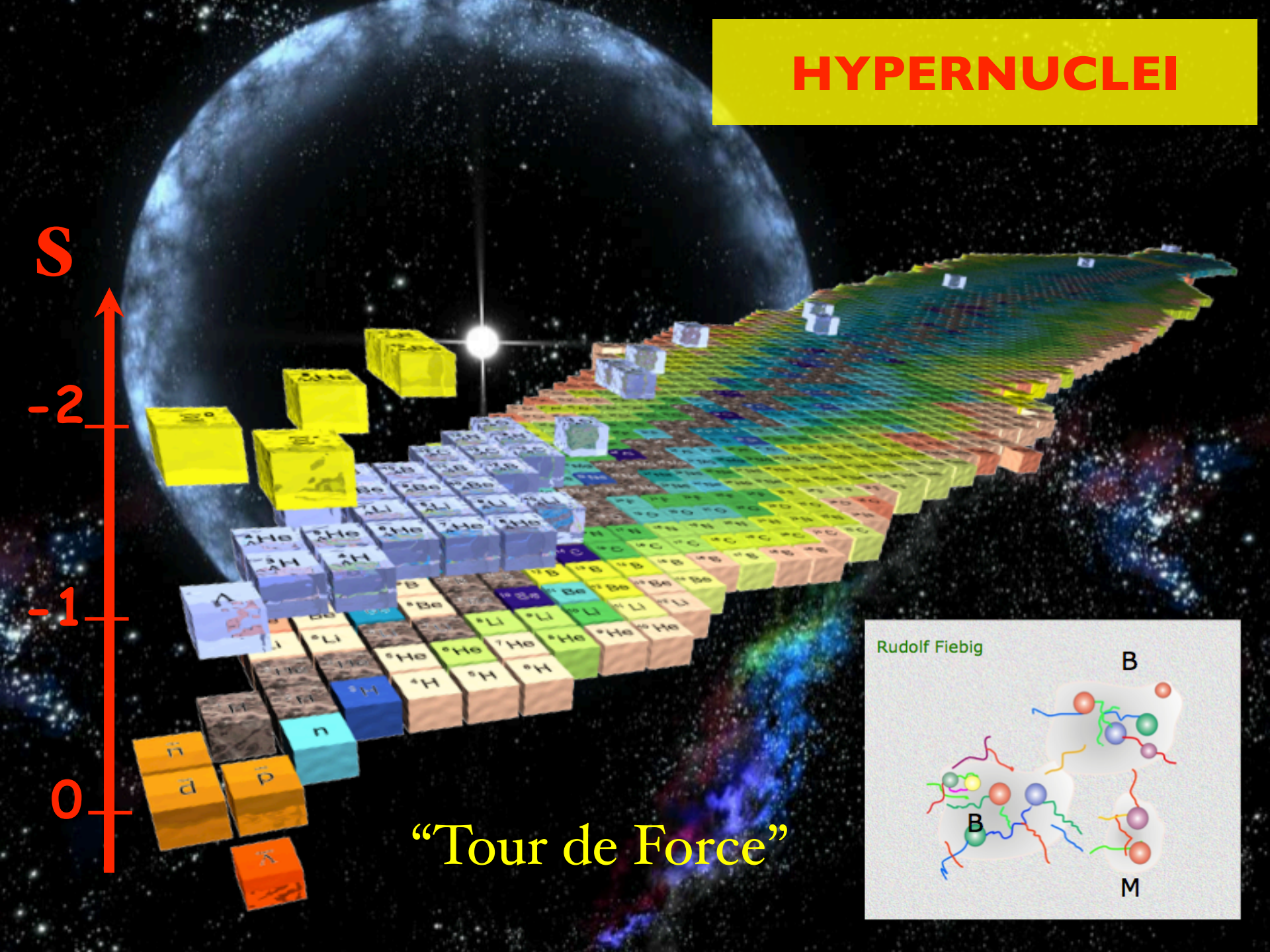
Day 1

Karin Schoenning

HYPERNUCLEI



HYPERNUCLEI

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

rescattering in
primary target nucleus

deceleration in
secondary target

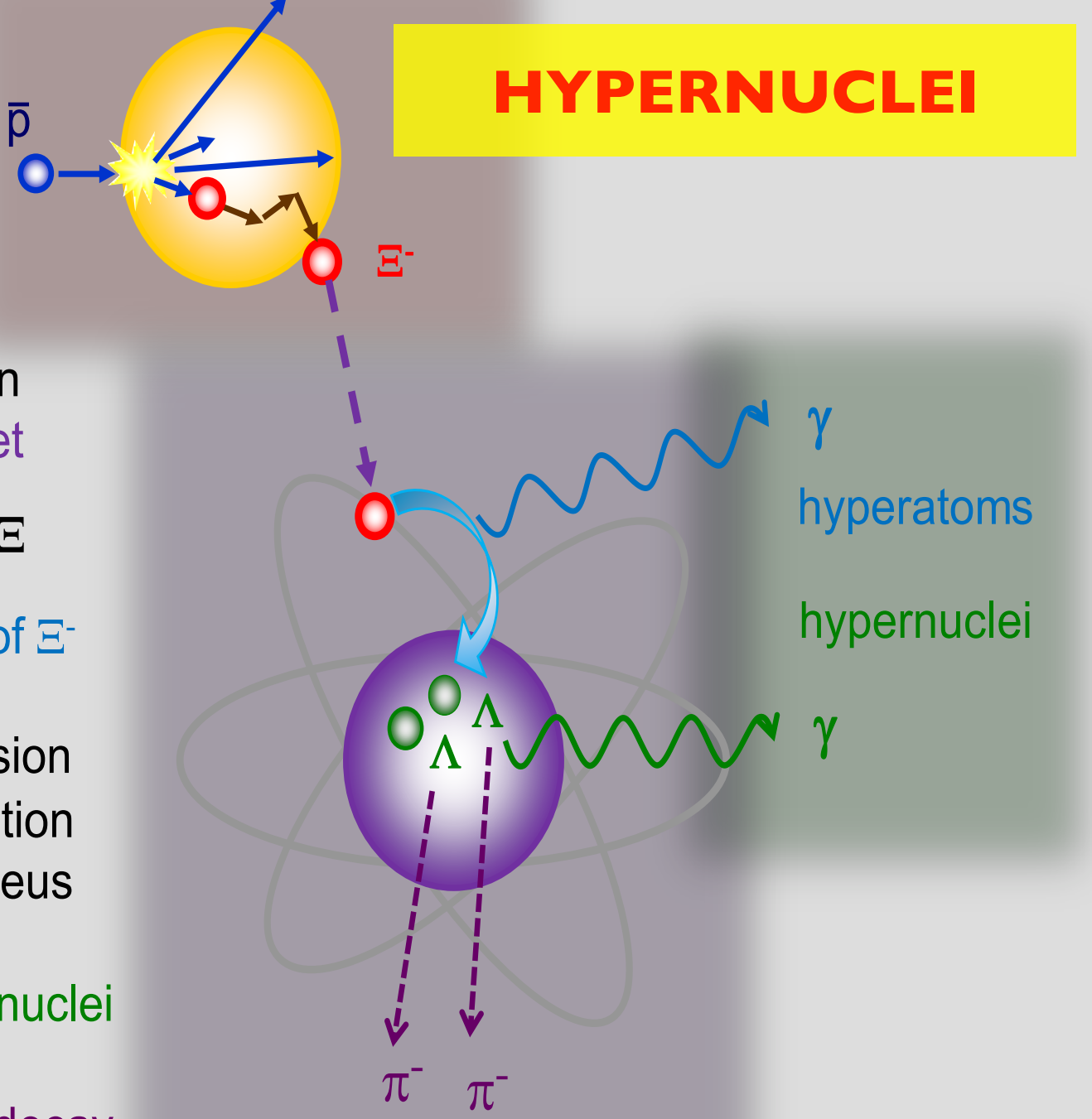
capture of Ξ

atomic cascade of Ξ^-

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

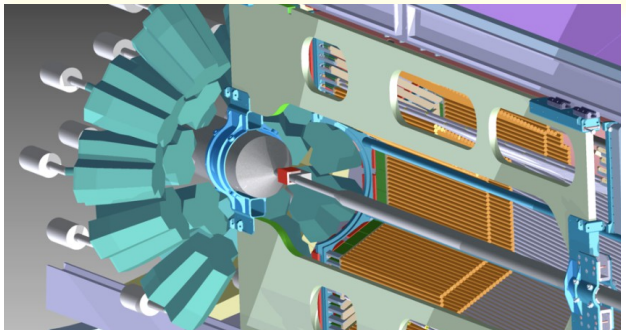
γ-decay of $\Lambda\Lambda$ hypernuclei

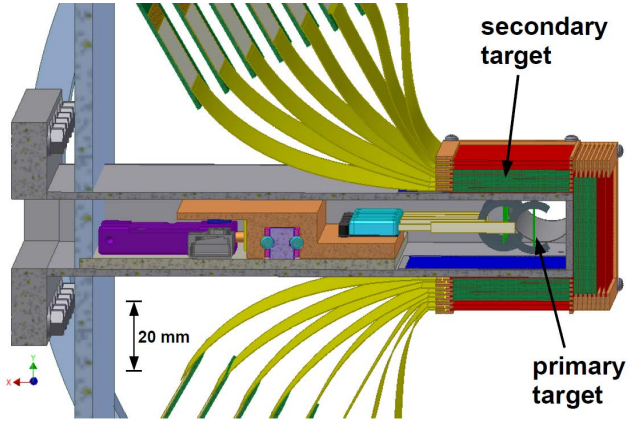
weak pionic decay

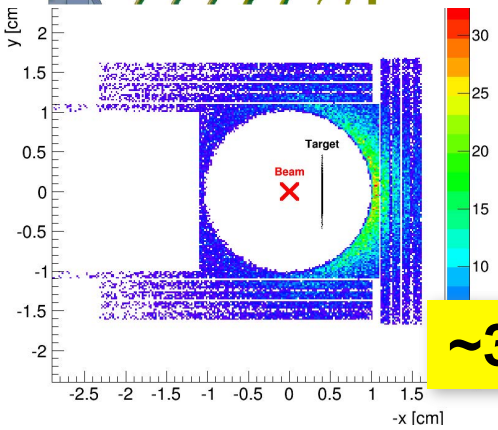


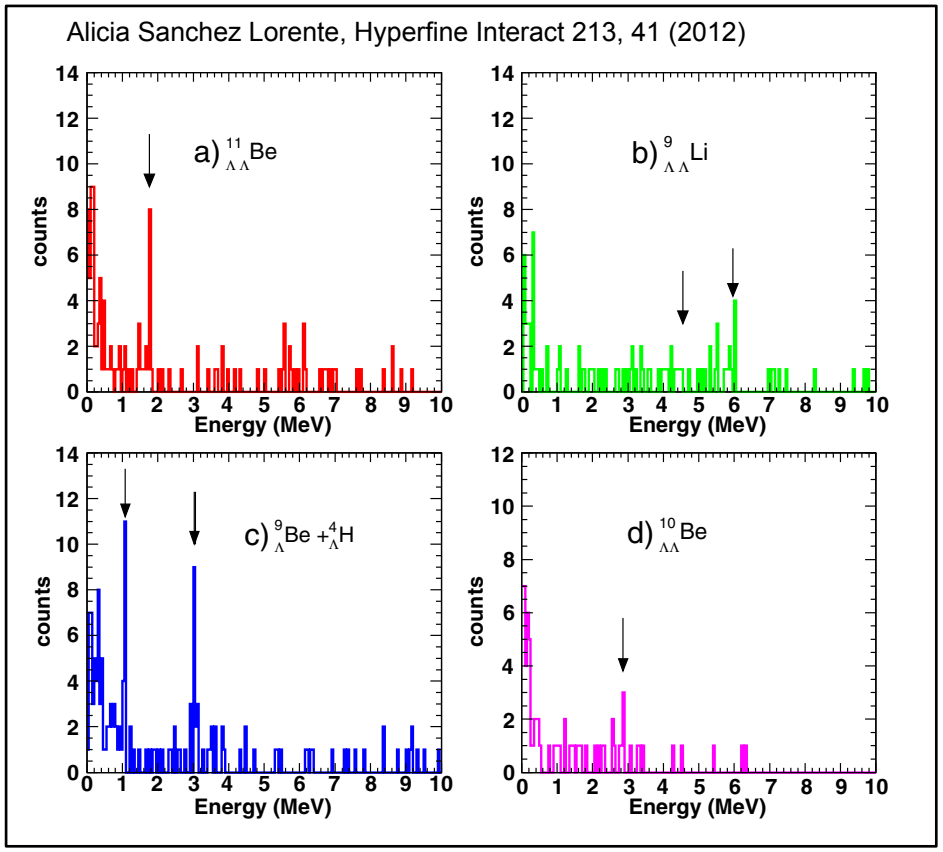
Josef Pochodzalla

Double hypernuclear spectroscopy







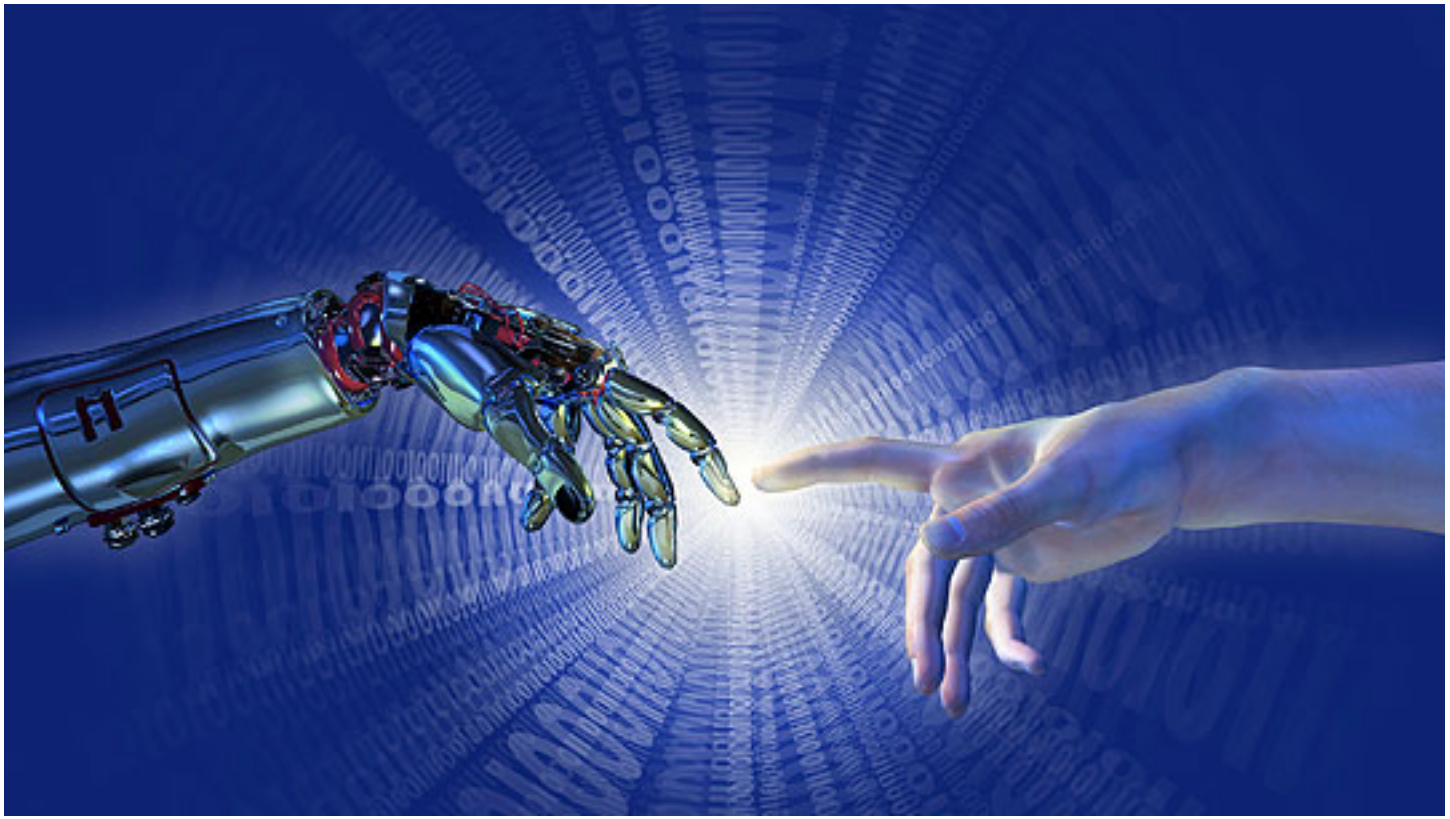


~33.000 stopped Ξ^-'s per day

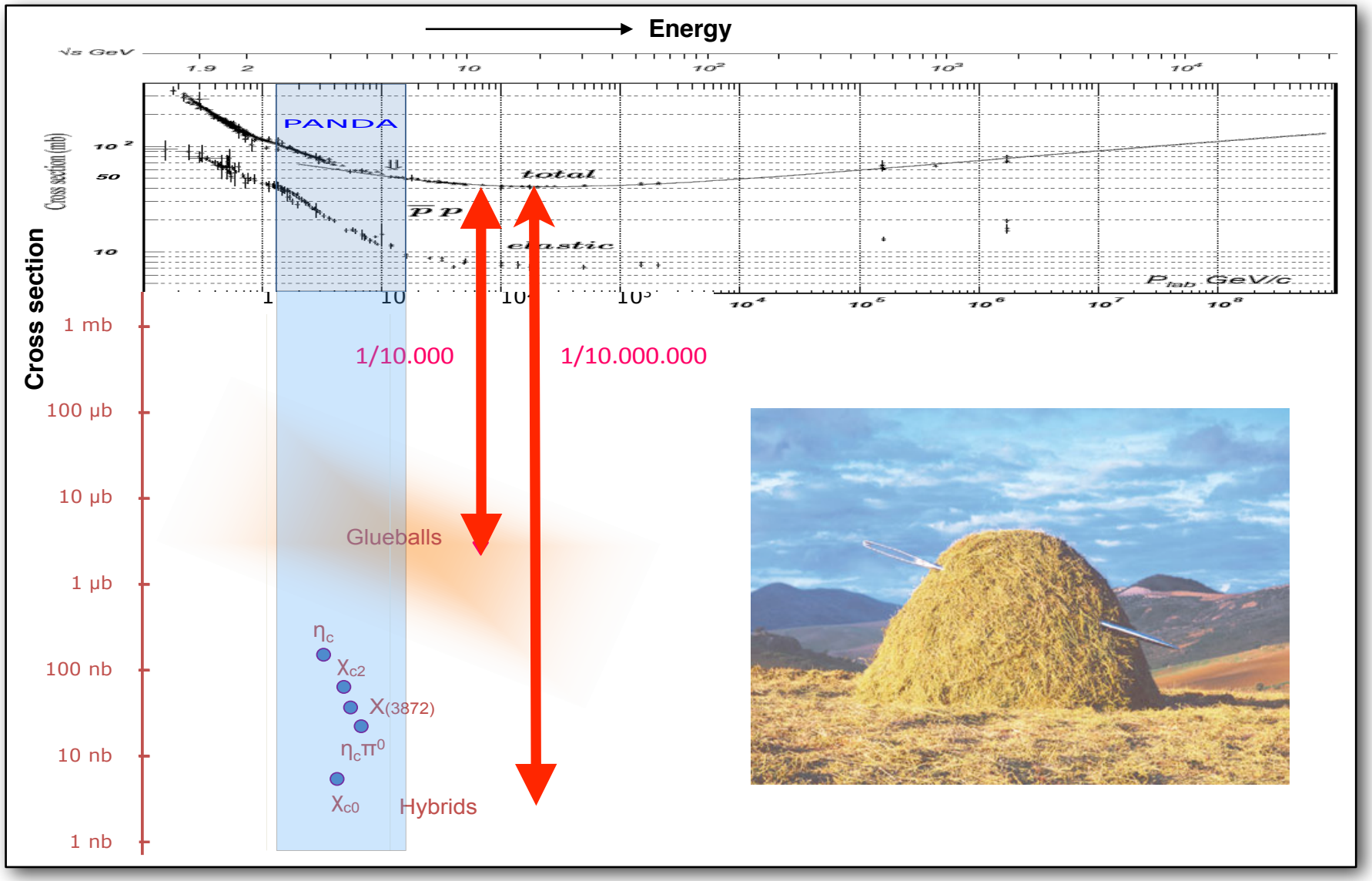
Josef Pochodzalla

The “magic” of antiprotons

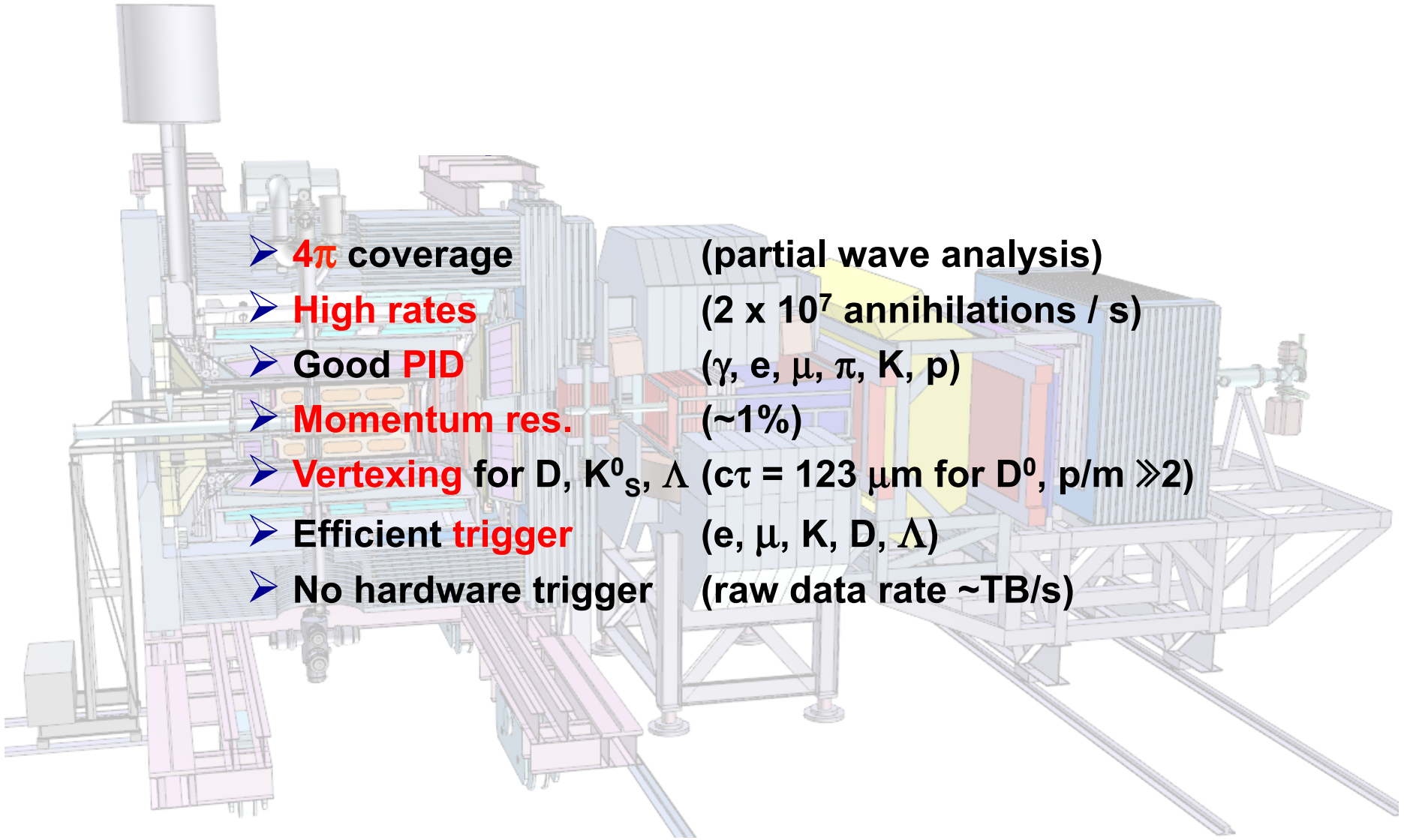
III. Technological innovation



Needle-in-a-haystack

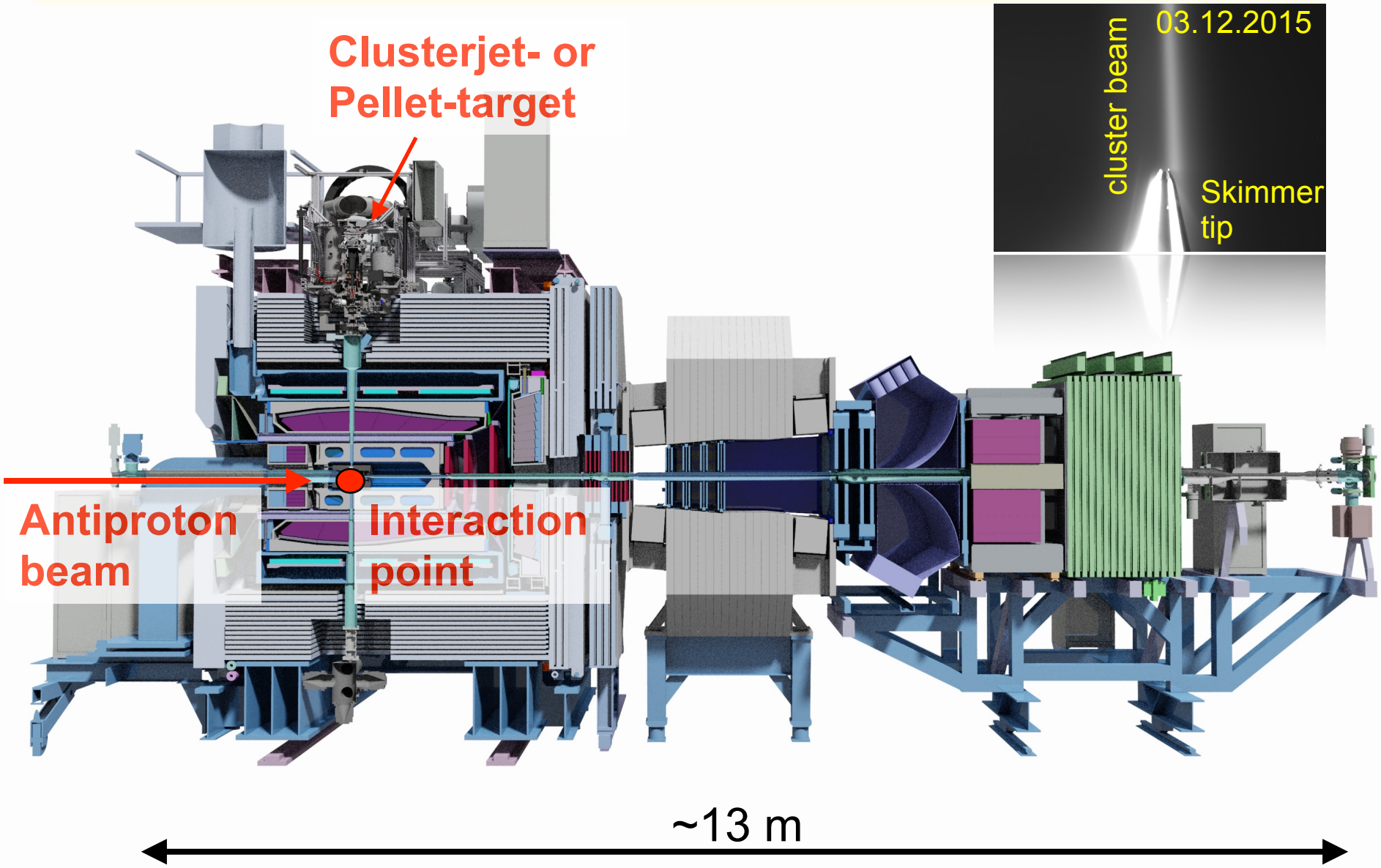


Detector capabilities

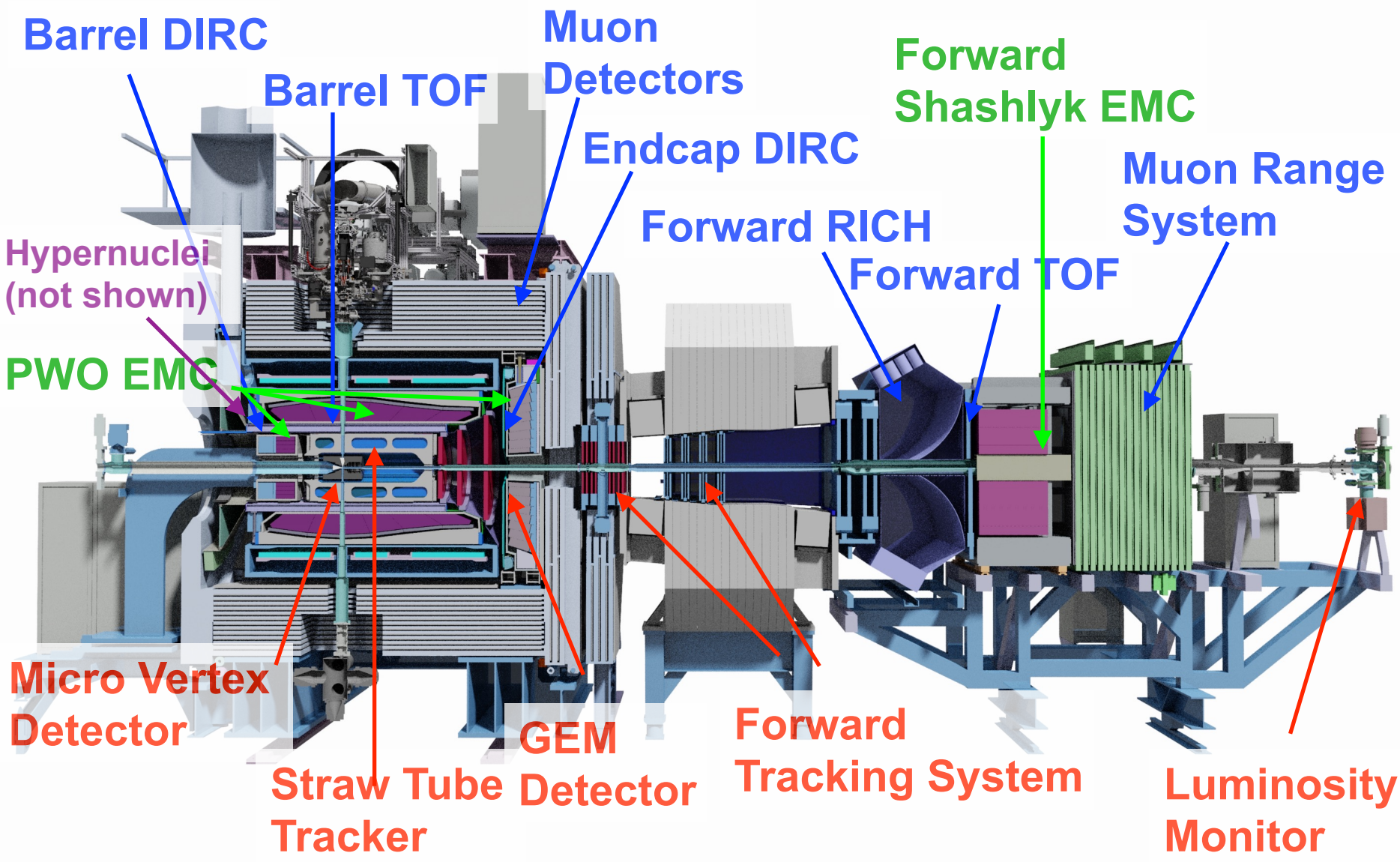


- 4π coverage (partial wave analysis)
- High rates (2×10^7 annihilations / s)
- Good PID (γ, e, μ, π, K, p)
- Momentum res. (~1%)
- Vertexing for D, K^0_S, Λ ($c\tau$ = 123 μm for D^0, p/m $\gg$2)
- Efficient trigger (e, μ, K, D, Λ)
- No hardware trigger (raw data rate ~TB/s)

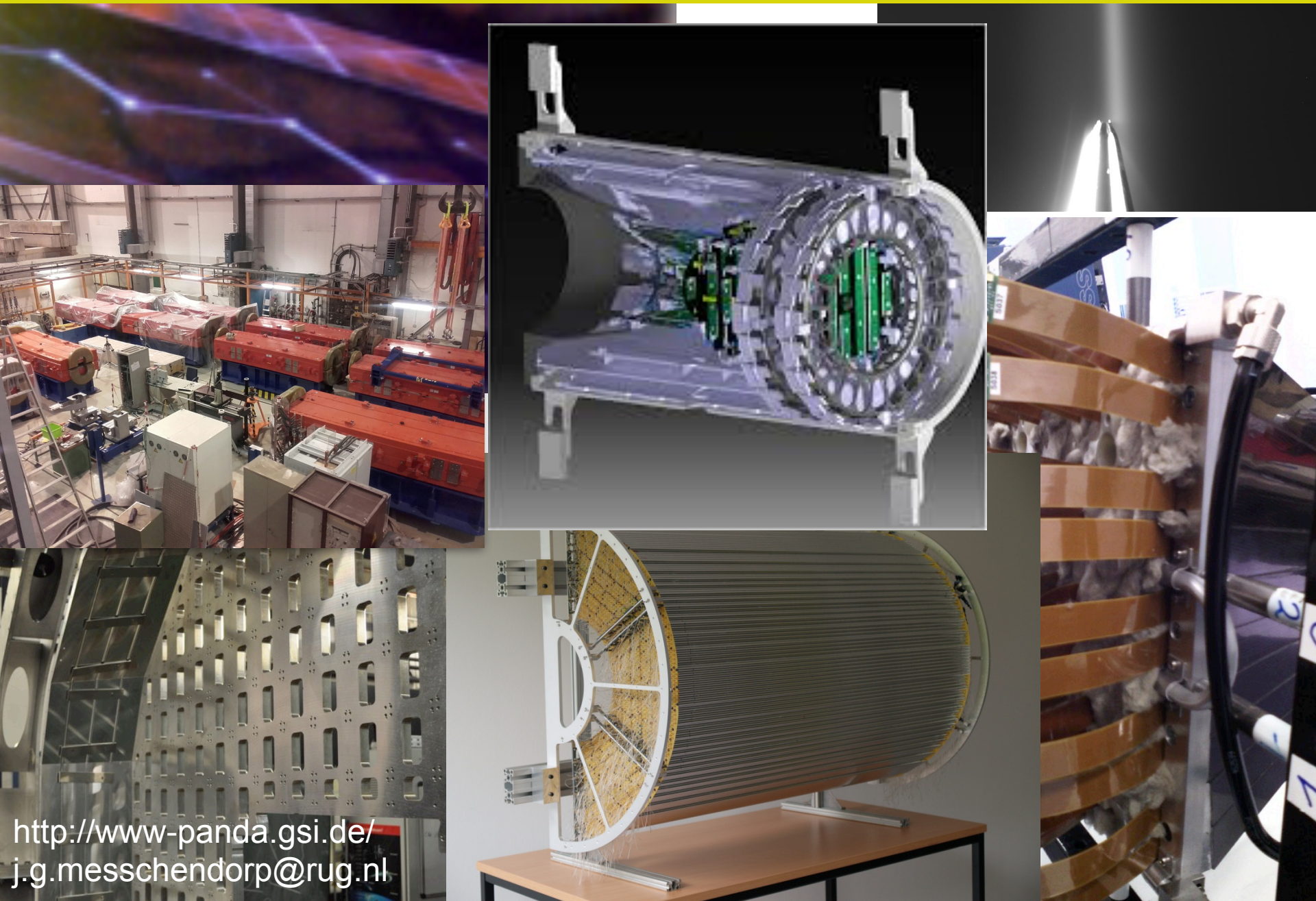
The PANDA detector



The PANDA detector



Few-Body Physics with PANDA at FAIR



http://www-panda.gsi.de/
j.g.messchendorp@rug.nl

Few-Body Physics with PANDA at FAIR

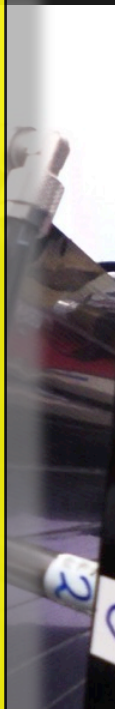
PANDA offers a *physics-driven* environment to …

… study the dynamics of Quantum Chromodynamics.

… bring together the experts in nuclear/hadron/particle physics.

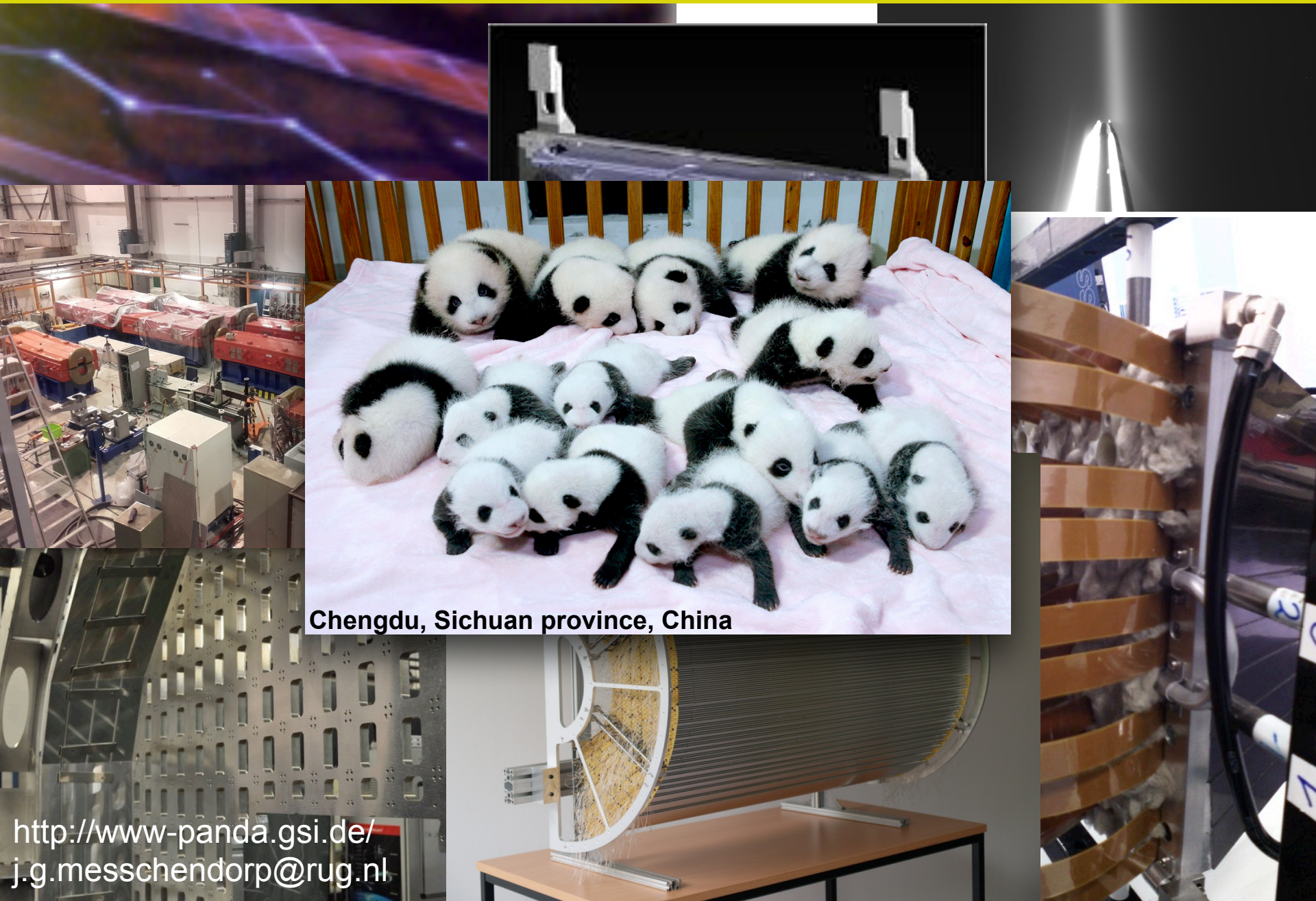
… build on the next generation instruments and techniques.

Physics Performance Book: arXiv:0903.305



http://www-panda.gsi.de/
j.g.messchendorp@rug.nl

Thanks for your attention and support!



Chengdu, Sichuan province, China

http://www-panda.gsi.de/
j.g.messchendorp@rug.nl

Backup

Quadrupole moment of hyperatoms

- reaching for the unthinkable!

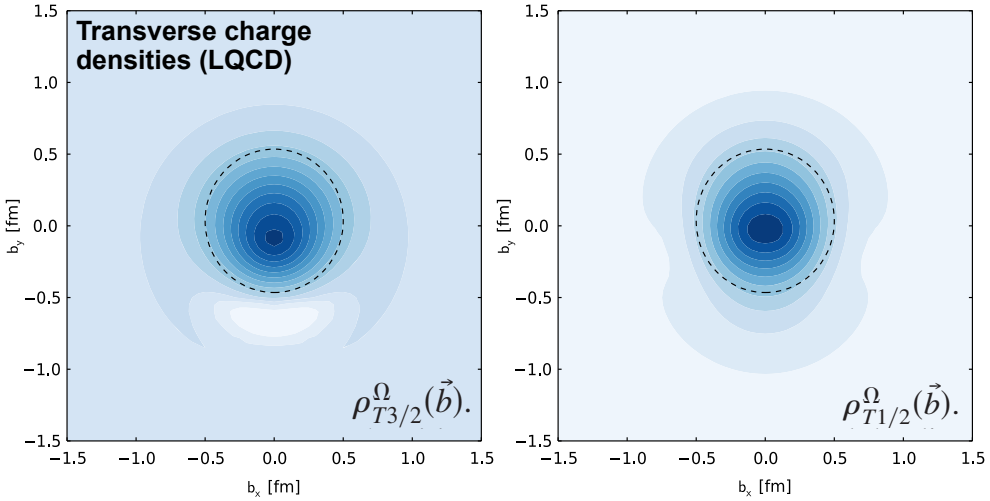
NPA 954, 323 (2016)

"The precision measurements of X-rays from Ω^--Pb atoms will certainly require a future generation of accelerators and probably also physicists." - C.J. Batty (1995)

Study "shape" of spin 3/2, |S|=3 Ω^-

Complementary to nucleon structure

Meson cloud correction expected small



Alexandro et al., PRD82, 034504 (2010)

Model	Q_Ω [e·fm^2]	Reference
NRQM	0.02	NP33,772 (1981)
NRQM	0.004	ZPC12,369 (1982)
NRQM	0.031	PRD25,2395 (1982)
SU(3) Bag model	0.052	NP45,109 (1987)
NRQM with mesons	0.0057	PRD41,924 (1990)
NQM	0.028	PRD43,3763 (1991)
Lattice QCD	0.0.005	PRD46,3067 (1992)
HBχPT	0.009	PRD49,3459 (1994)
Skyrme	0.024	PLB334,287 (1994)
Skyrme	0.0	PLA10, 1027 (1995)
QM	0.022	ZN52a, 877 (1997)
χQM	0.026	JPG26,267 (2000)
GP QCD	0.024	PRD65,073017 (2002)
QCD-SR	0.1	EPJC61,311 (2009)
χPT+qlQCD	0.0086	PRD80,034027 (2009)
Lattice QCD	0.0096±0.0002	PRD83,054011 (2011)

Josef Pochodzalla

PANDA physics ambitions

Study of the strong force using antiprotons

Hadron spectroscopy & dynamics
- charmonium
- gluons excitations (glueballs, hybrids, ..)
- open charm
- light meson systems

Nucleon structure
- electr. magn. form factors
- TMDs, GPDs, TDAs

Hyperons & Hypernuclei
- $\Lambda\Lambda$ - hypernuclei
- hyperfine splitting in Ω atom
- (multi) strange baryons

Hadrons in nuclear medium
- antiproton-A collisions
- nuclear potentials of antibaryons
- charmonium-nucleon interactions

Physics Performance Report for:

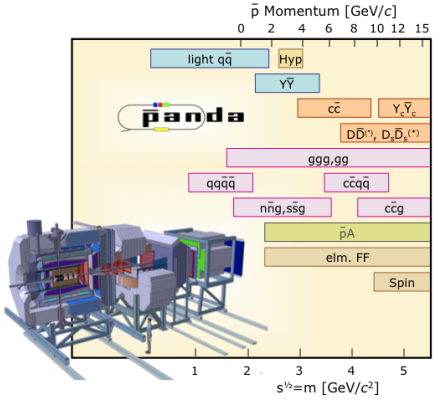
$\overline{\text{P}}$ANDA

(AntiProton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

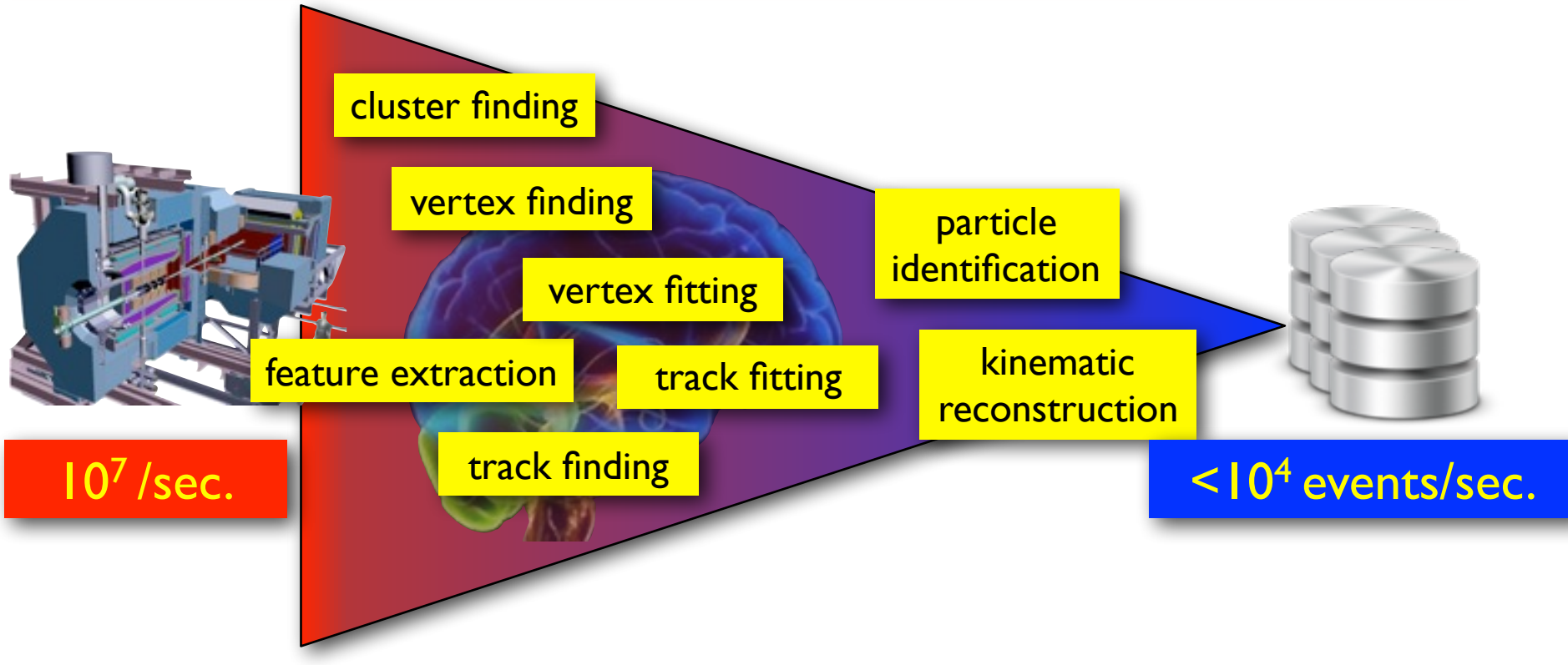
$\overline{\text{P}}$ANDA Collaboration

To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal $\overline{\text{P}}$ANDA detector will be build. Gluonic excitations, the physics of strange and charm quarks and nucleon structure studies will be performed with unprecedented accuracy thereby allowing high-precision tests of the strong interaction. The proposed $\overline{\text{P}}$ANDA detector is a state-of-the-art internal target detector at the HESR at FAIR allowing the detection and identification of neutral and charged particles generated within the relevant angular and energy range.
This report presents a summary of the physics accessible at $\overline{\text{P}}$ANDA and what performance can be expected.

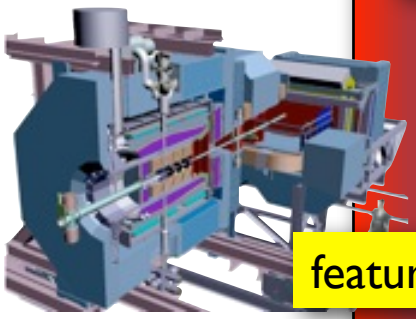


arXiv:0903.305

Intelligent *in-situ* data processing



Intelligent *in-situ* data processing



cluster finding

vertex finding

vertex fitting

feature extraction

track fitting

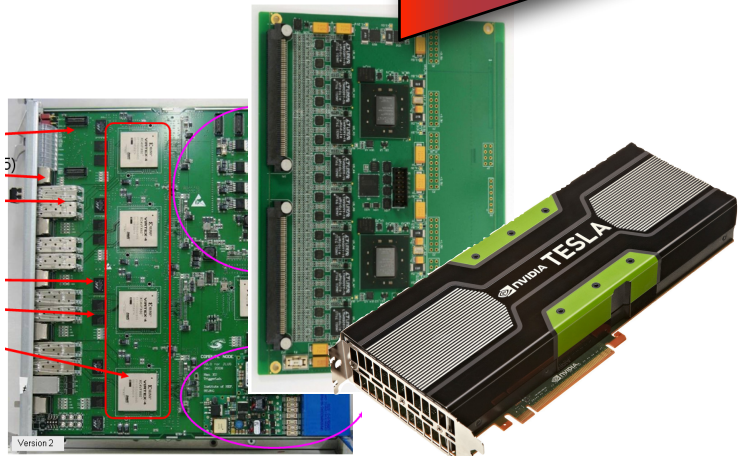
track finding

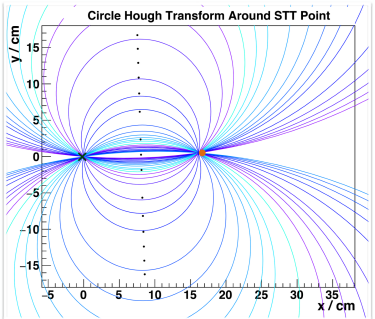
particle identification

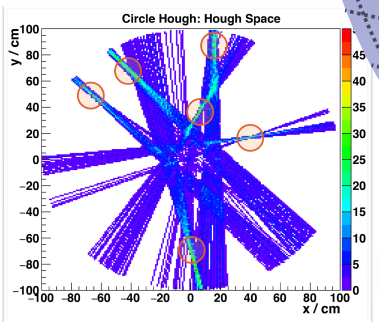
kinematic reconstruction

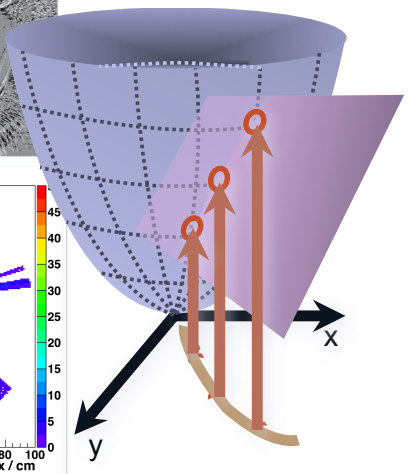
10^7 /sec.

$< 10^4$ events/sec.

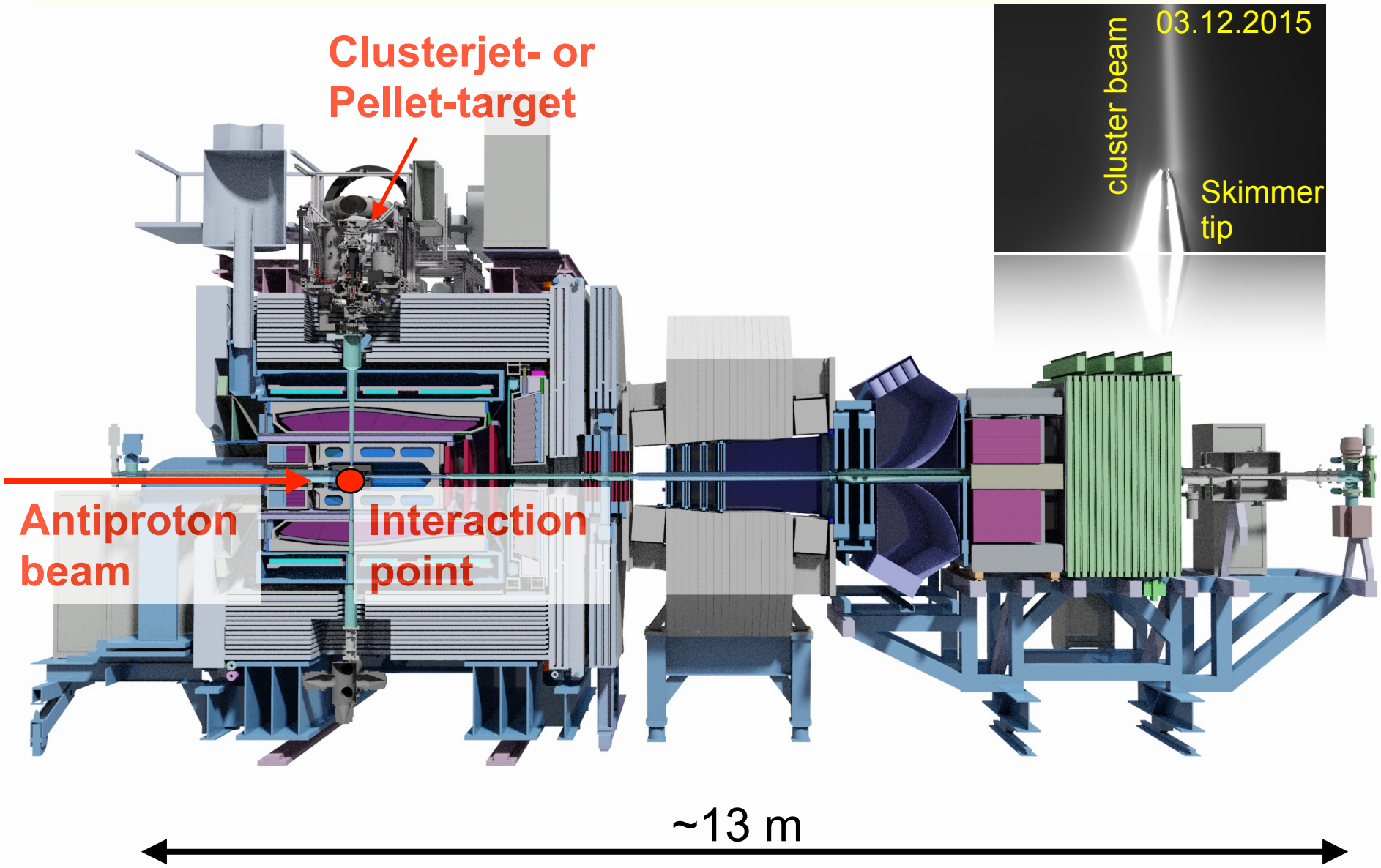




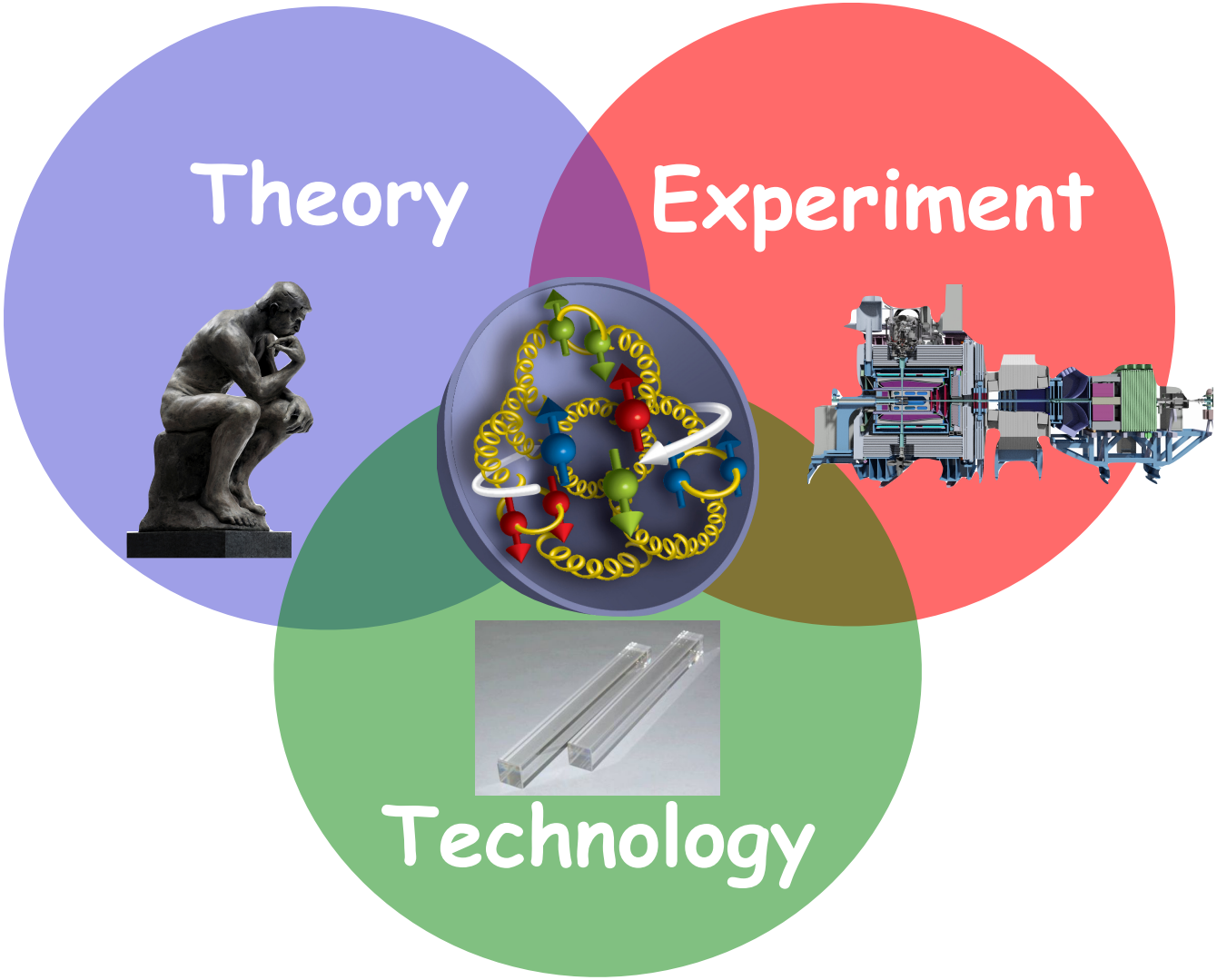




The PANDA detector



Be part of the endeavour!



Be part of the endeavour!

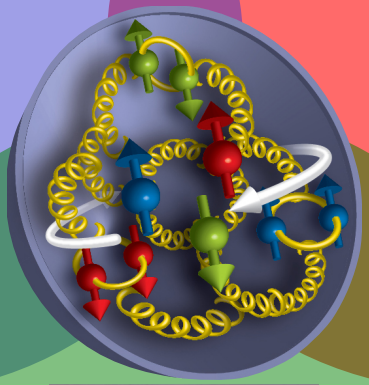
Connect experiment & theory
(partial-wave analysis, …)

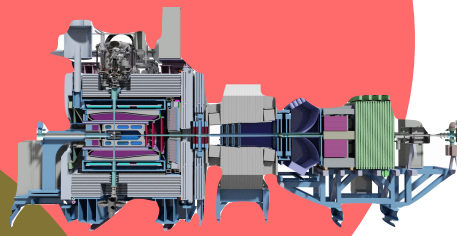
Develop key experiments to
find sensitive observables
(PANDA, BESIII, Belle2, GlueX, LHC+…)

Theoretical tools to give
insights and predictions
(Lattice QCD, EFT, FM, …)

Theory

Experiment





Data analysis at extremes;
needle-in-the-haystack tools
(smart algorithms & hardware)

Computational challenges
(ab-initio and “full” Lattice QCD)

Technology

State-of-the-art sensor developments
(resolution, radiation-hard, fast & compact, …)

S=-2 systems

- missing mass (K^-,K^+) reactions ⇒ Ξ bound state J-PARC
- Ξ capture ⇒ Ξ atoms J-PARC, FAIR
- Ξ capture and $\Xi^- p \rightarrow \Lambda\Lambda$ ⇒ ΛΛ hypernuclei J-PARC, FAIR,HI