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Future Physics with PANDA at FAIR

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Talk at the Workshop on Emergence of Hadron Mass
November 30th- December 4th 2020

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Outline

- Objective
- PANDA at FAIR
- PANDA Physics Pillars:
  - Nucleon Structure
  - Strangeness Physics
  - Charm and Exotics
  - Hadrons in Nuclei
- Summary

How is the visible mass of the Universe generated?

What is the inner structure of matter?

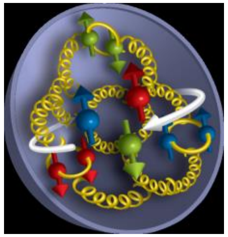
What kind of exotic hadrons are there?

Why more matter than antimatter in the Universe?

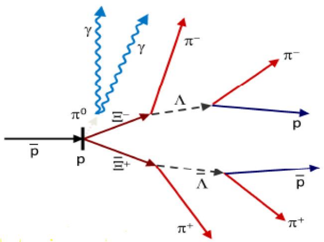
Equation of State of neutron stars?

$\bar{p}p$ and $\bar{p}A$ annihilations

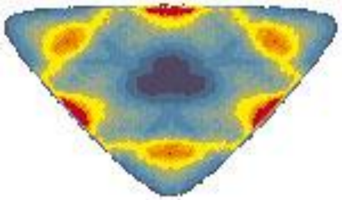
Nucleon structure



Strangeness physics



Charm and exotics



Hadrons in Nuclei

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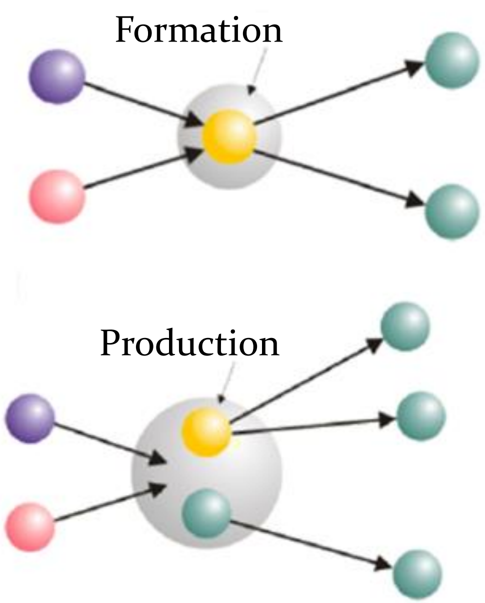
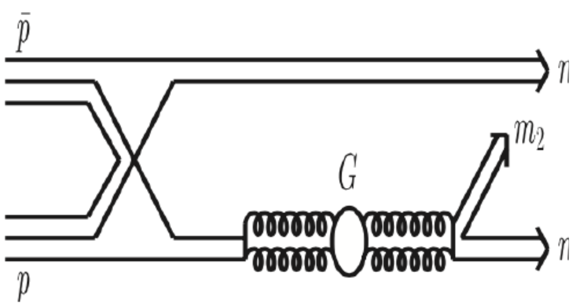
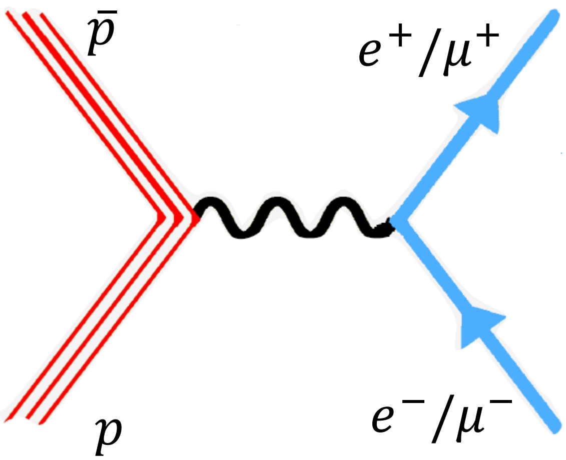
Virtues of low-energy antiprotons

- Annihilations provide a *gluon-rich* environment.
- All neutral, hidden-flavour, meson-like states accessible in *formation*.
- Multi-strange and charmed $\bar{Y}Y$ final states in *2-body production*.
- *Time-like* structure observables with electron and muon "probes".
- Provide secondary hyperons that can form *hypernuclei*.







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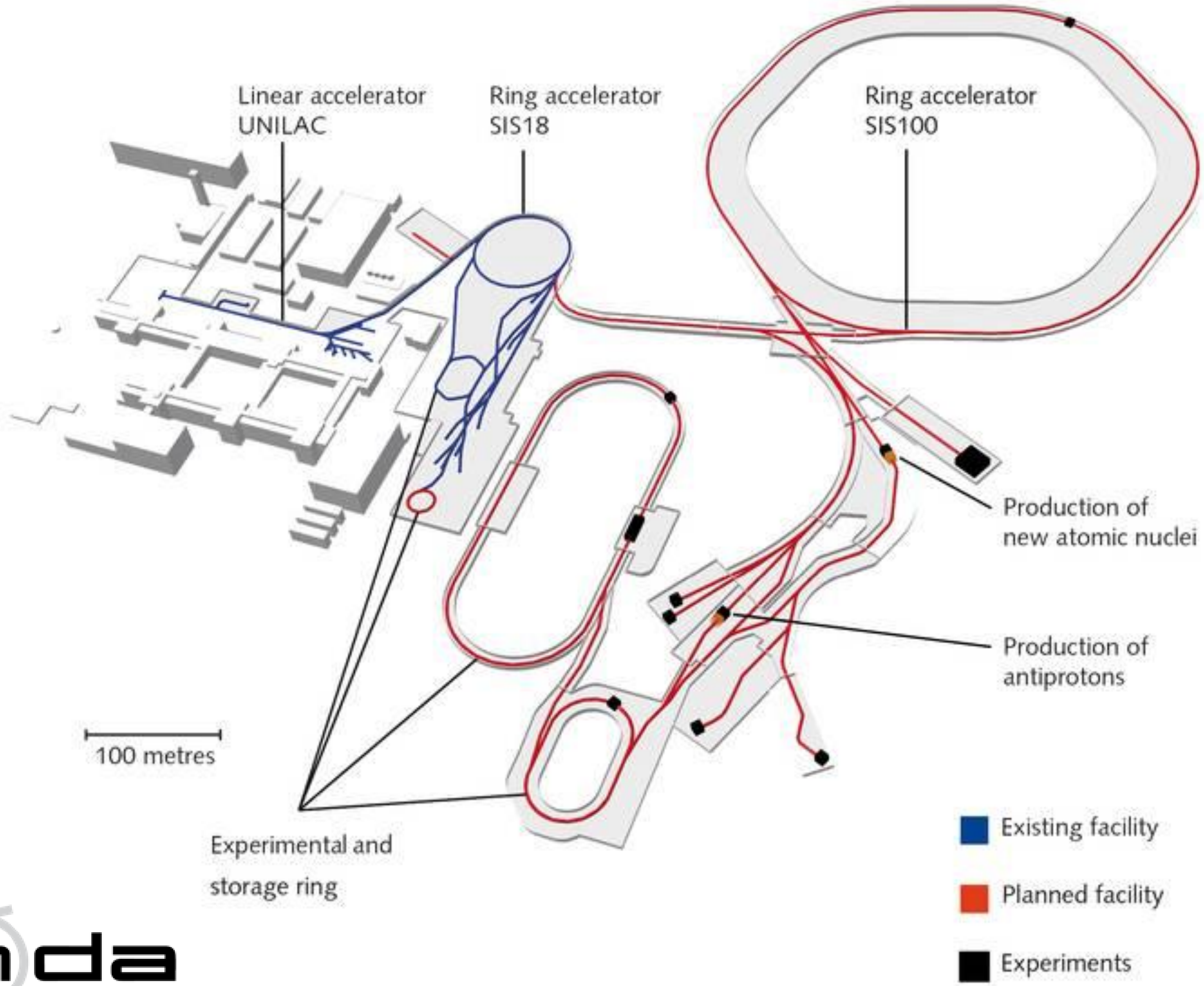
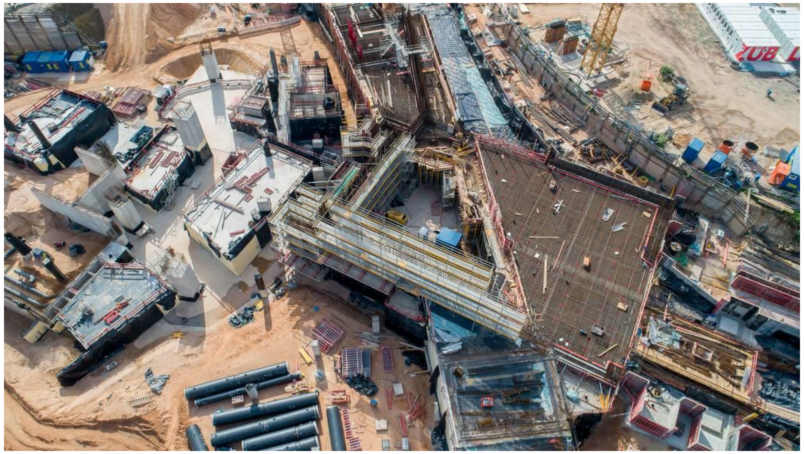
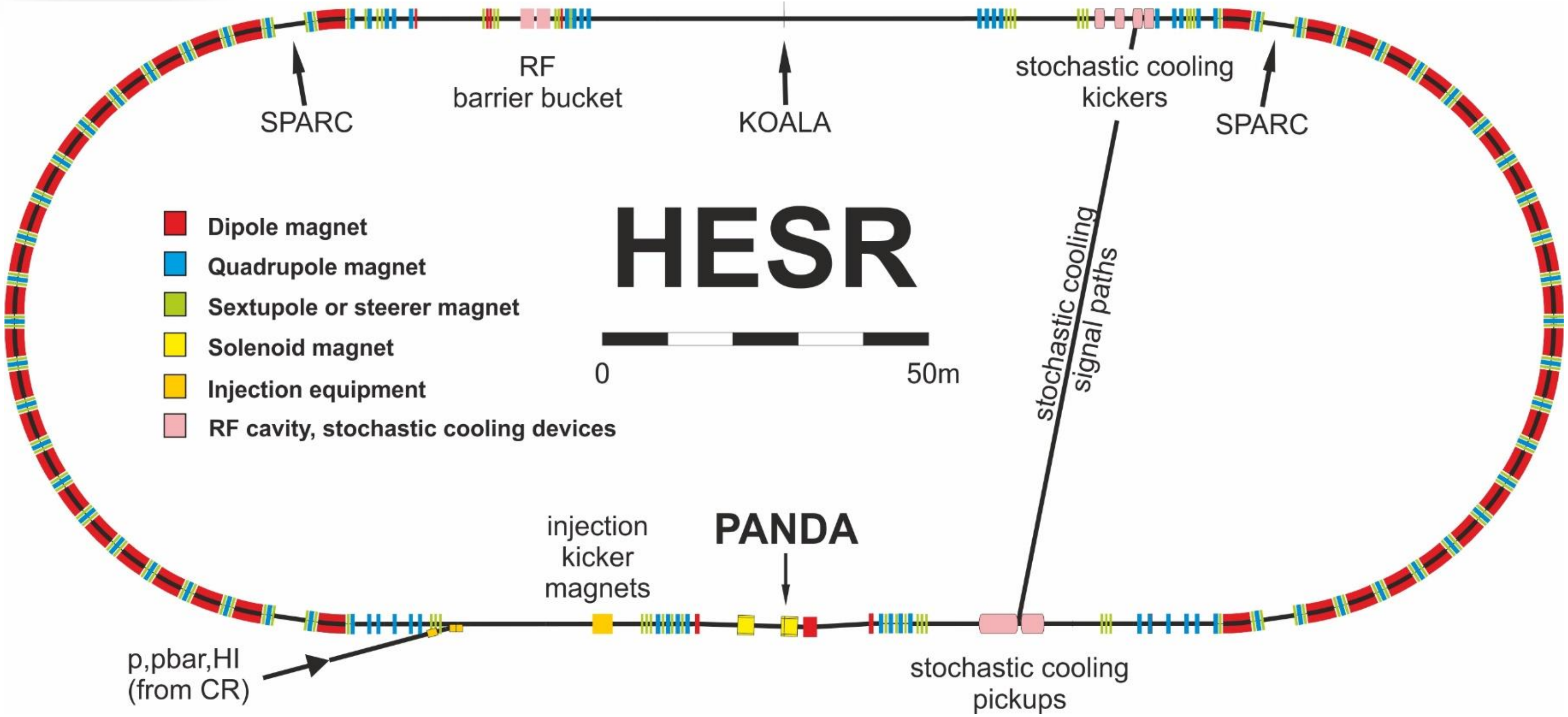
Facility for Antiproton and Ion Research (FAIR)



Construction of FAIR



The High Energy Storage Ring (HESR)



- Anti-protons within
  $1.5 < p_{beam} < 15$ GeV/c
- Internal targets
  - Cluster jet and pellet ($\bar{p}p$)
  - Foils ($\bar{p}A$)
- Luminosity:
  - Design ~$2{\cdot}10^{32}$ cm^{-2}s^{-1}
  - Phase One ~10^{31} cm^{-2}s^{-1}

AMBER *vs* PANDA

- **Time**:
  - AMBER 2022
  - PANDA ~2025.
- Antiproton **momentum** range:
  - AMBER p_{beam} = 12-20 GeV/c
  - PANDA p_{beam} = 1.5-15 GeV/c
- $\bar{p}p$ **luminosity**:
  - AMBER L = 10^{30}cm^{-1}s^{-1}
  - PANDA Phase One: L = 10^{31}cm^{-1}s^{-1}, Phase Three: L = $2\cdot 10^{32}$cm^{-1}s^{-1}
- Longitudinal **interaction** region:
  - AMBER 40 cm
  - PANDA Phase One: ~15 mm, Phase Two/Three:~2 mm

AMBER *vs* PANDA

AMBER and PANDA largely complementary in time, momentum, luminosity and interaction volume

- **Time**:
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  - PANDA ~2025.
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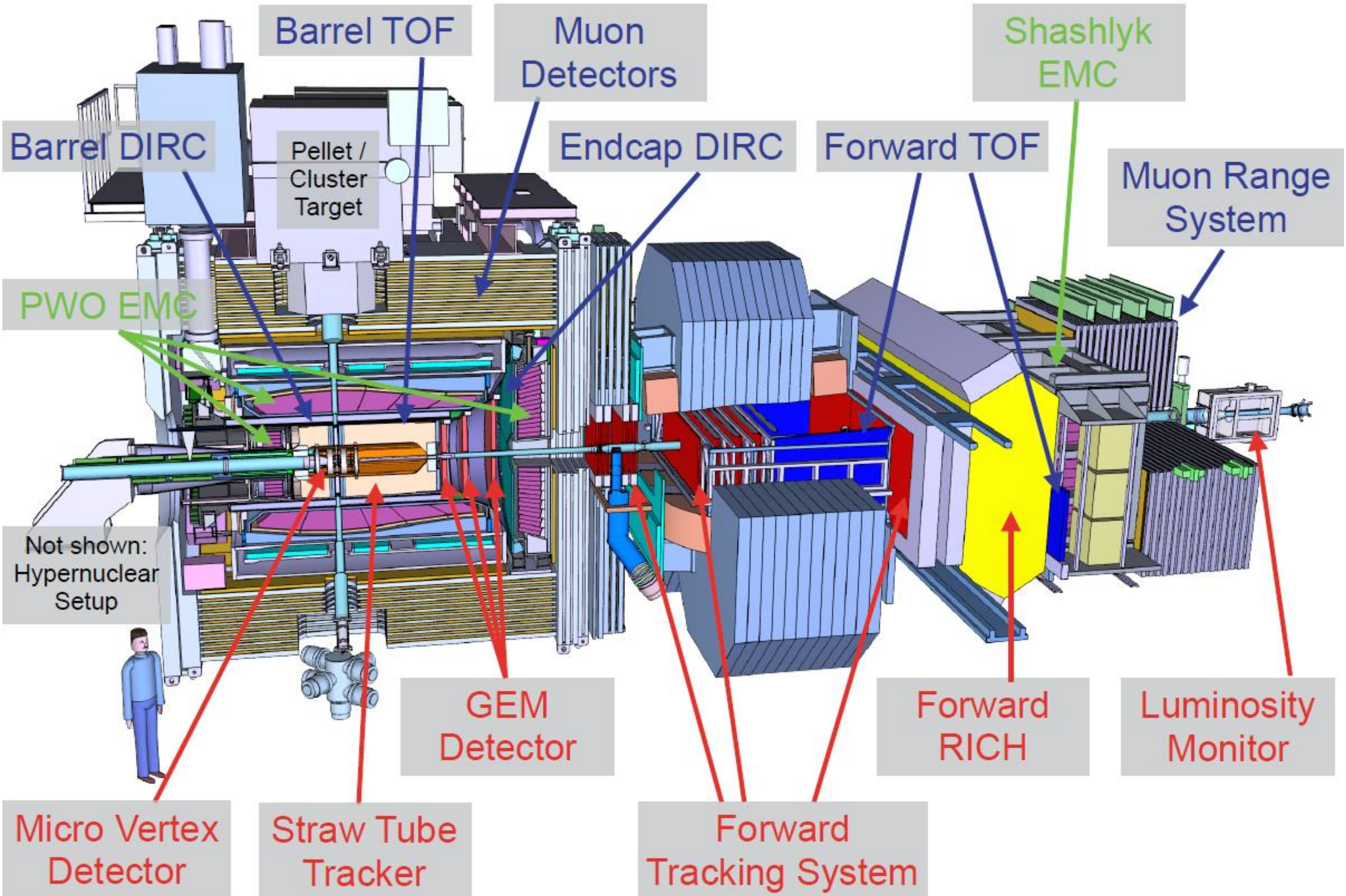
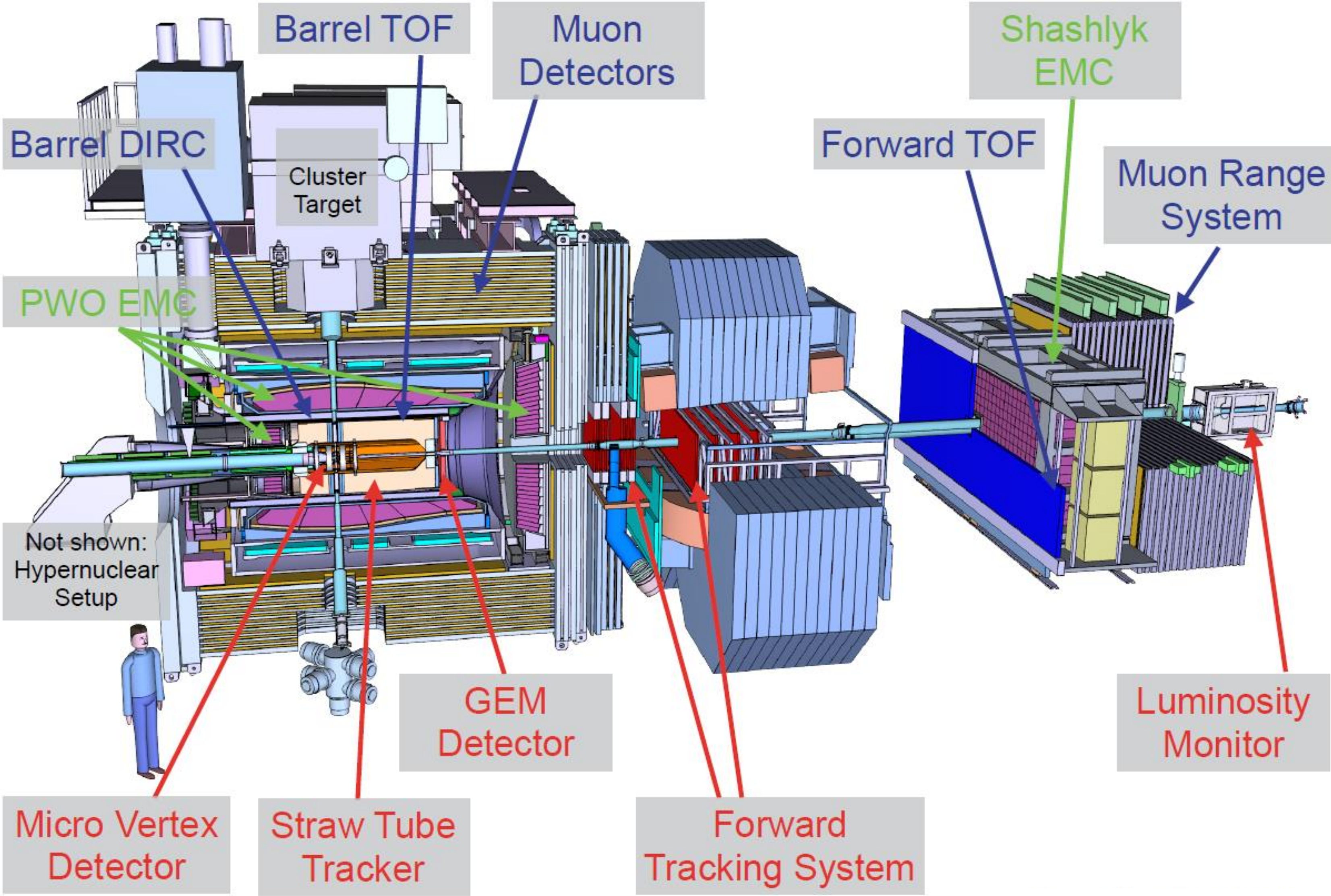
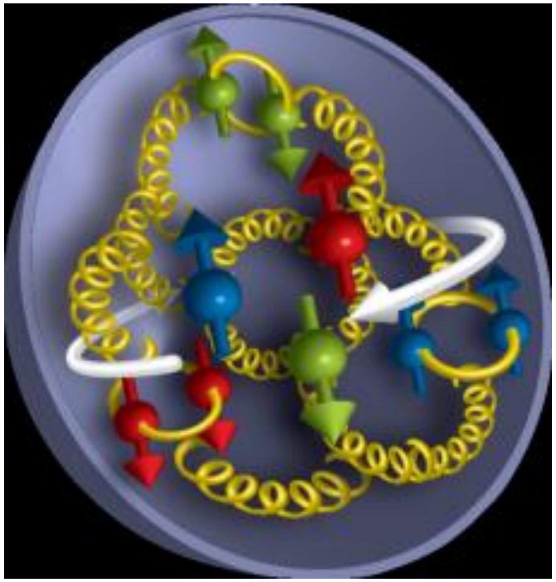
PANDA – full setup



PANDA – Phase One setup



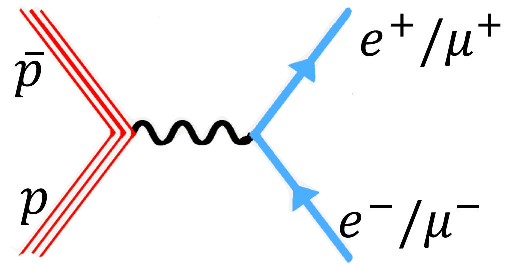


Physics Programme

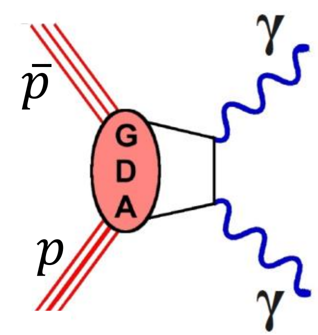
NUCLEON STRUCTURE

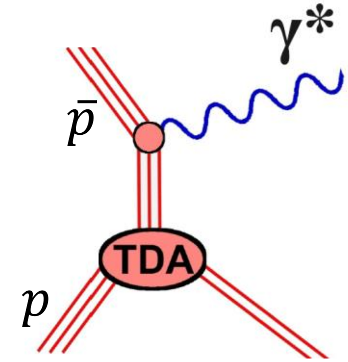
Nucleon Structure

Electromagnetic Form factors

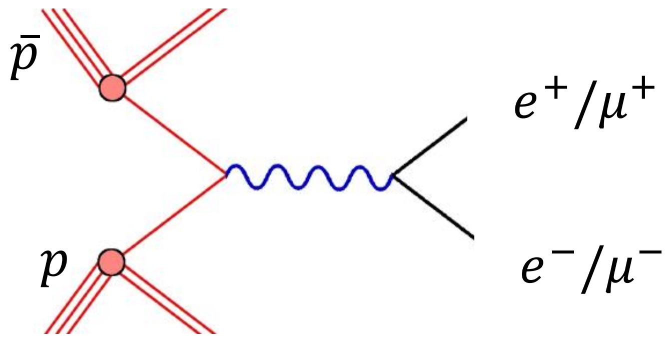


Generalized Distribution Amplitudes





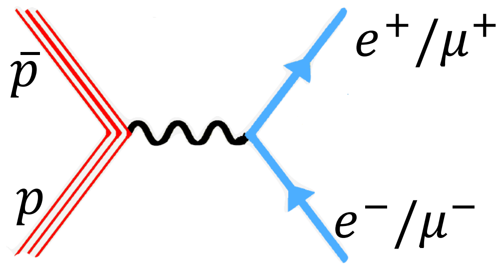
Transition Distributions Amplitides



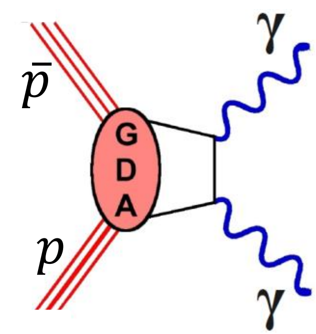
Parton Distribution Amplitudes

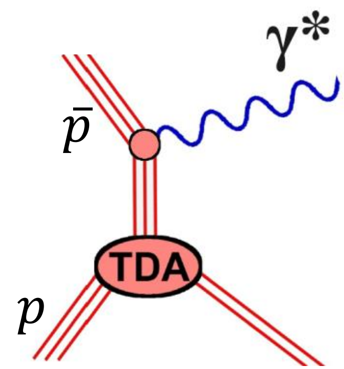
Nucleon Structure

Electromagnetic Form factors

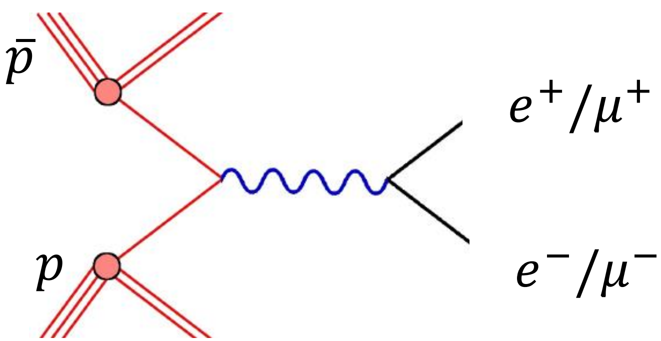


Generalized Distribution Amplitudes



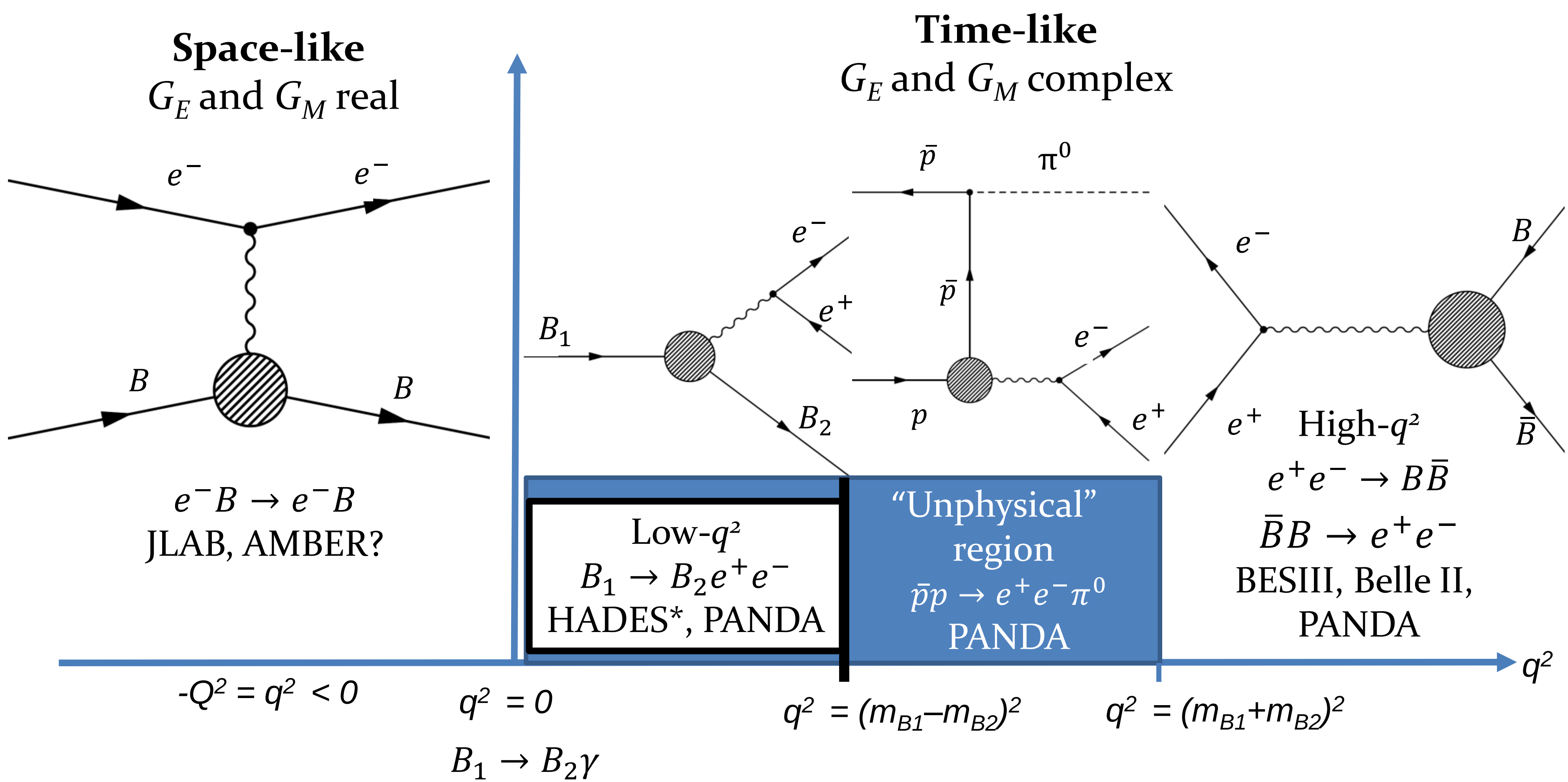


Transition Distributions Amplitides



Parton Distribution Amplitudes

Electromagnetic Form Factors



* arXiv [nucl-ex]: 2010.0696

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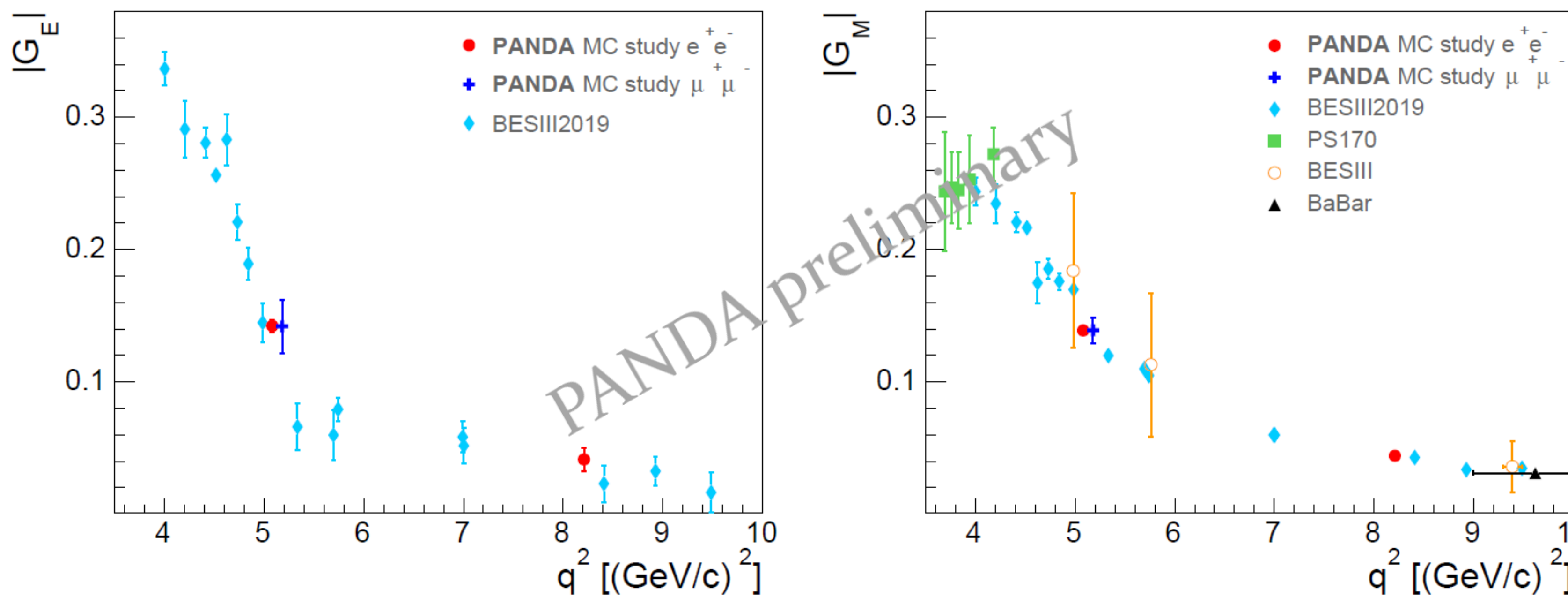
Electromagnetic Form Factors

Prospects for Phase One:

- Integrated luminosity of 0.1 fb^{-1}
- Separation of G_E and G_M possible with better precision than before.
- Independent e and μ measurement: test of lepton universality

$$\sigma\left(\frac{G^{e}_{eff}}{G^{\mu}_{eff}}\right) \approx 3.2\ \%$$



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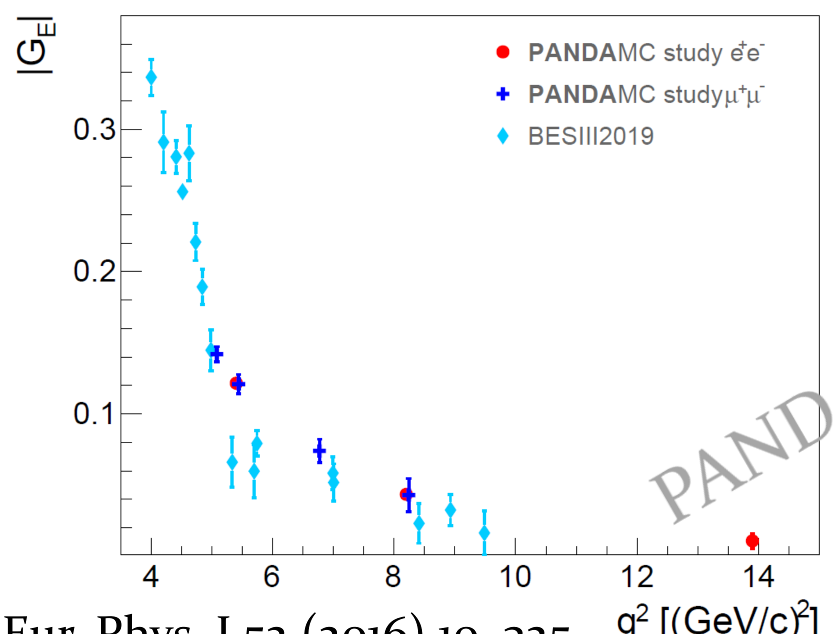
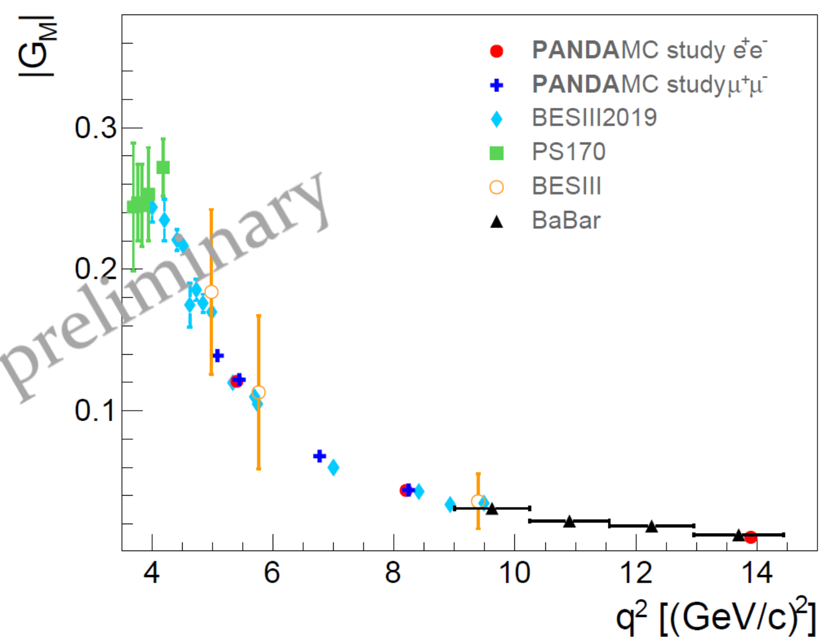
Electromagnetic Form Factors

Long-term prospects*,**:

- Improved statistical precision
- Measurements up to 28 (GeV/c)² – test onset of analyticity:

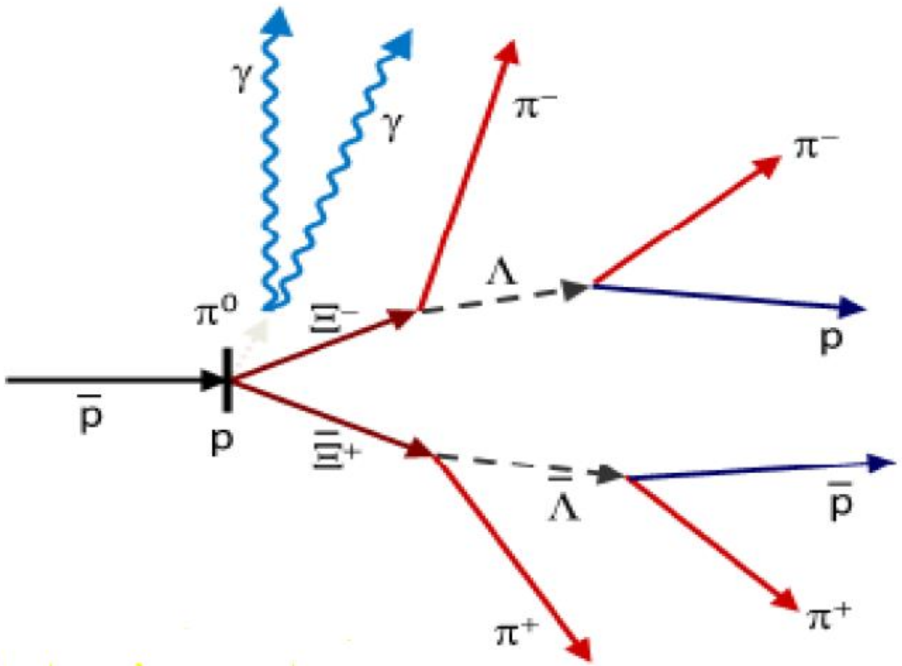
Space-like FF ≈ Time-like FF





*Eur. Phys. J 52 (2016) 10, 325

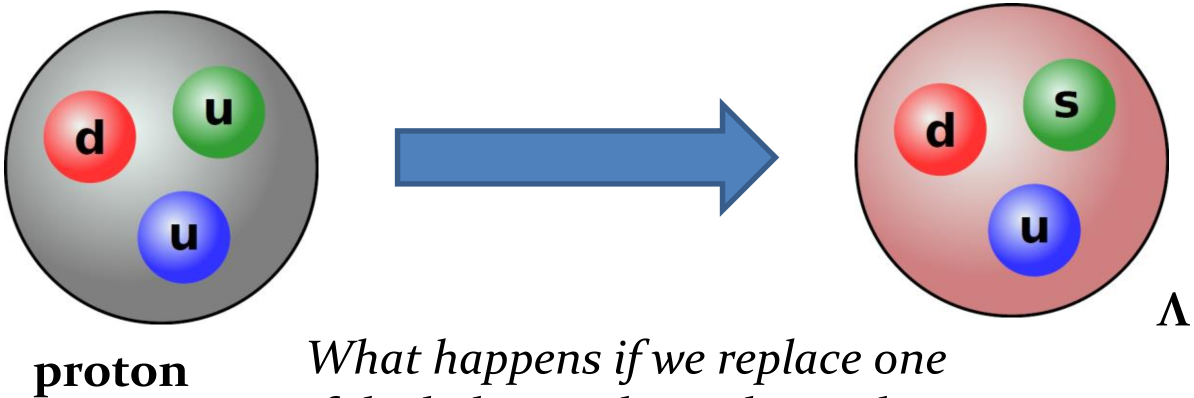
** arXiv[hep-ex]:2006.16363



Physics Programme

STRANGENESS PHYSICS

Strangeness with PANDA



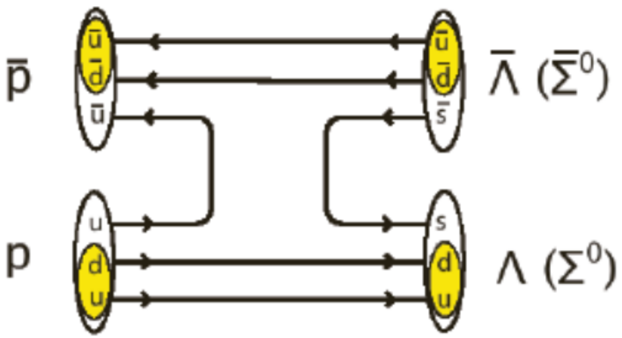
What happens if we replace one of the light quarks in the nucleon with a heavier one?

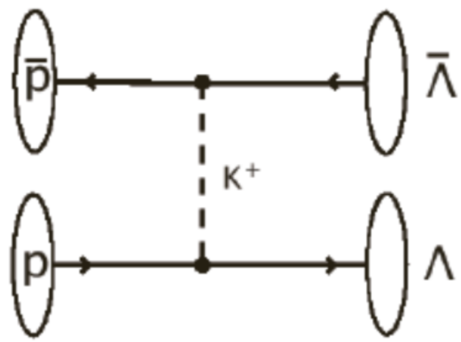
Main objectives:

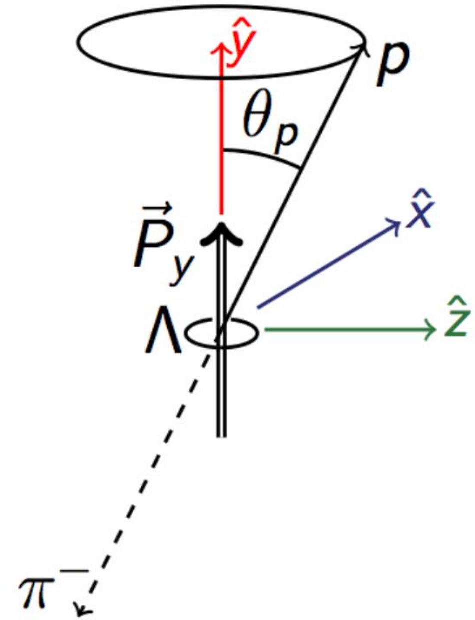
- Structure and production dynamics of established states.
- Search for hitherto unknown states.
- Search for CP violation on hyperon decays.

Hyperon Spin Properties

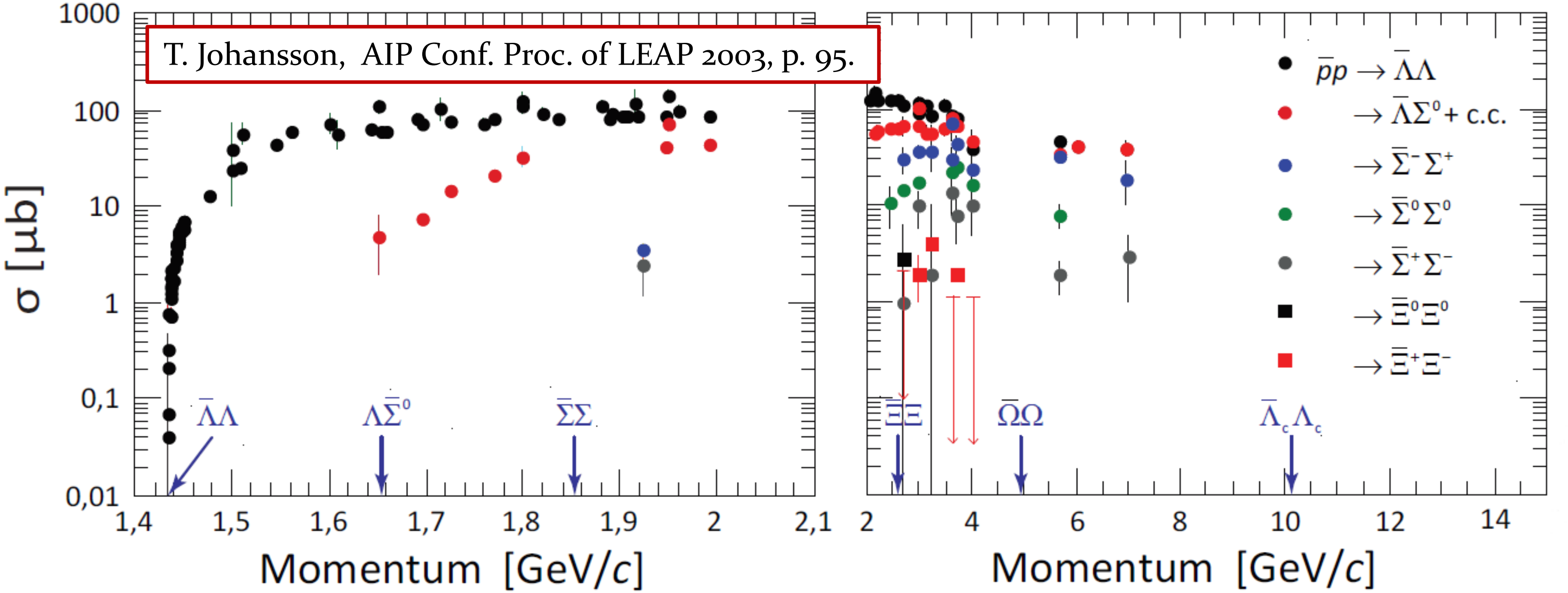
- Accessible *e.g.* through $I(\cos\theta_p) = N(1+\alpha P_\Lambda \cos\theta_p)$
  - α decay asymmetry → searches for CP violation
  - P_Λ production related.







Advantages of PANDA



- Measured cross sections of ground-state hyperons in $\bar{p}p \to \bar{Y}Y$ 1-100 μb*.
- Excited hyperon cross sections should to be similar to those of ground-states**.

→ Large expected production rates!

* E. Klempt *et al.*, Phys. Rept. 368 (2002) 119-316
**V. Flaminio *et al.*, CERN-HERA 84-01

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Hyperon prospects with PANDA

New simulation studies of single- and double-strange hyperons*:

- Exclusive measurements of
  - $\bar{p}p \to \bar{\Lambda}\Lambda, \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$.
  - $\bar{p}p \to \bar{\Sigma}^0\Lambda, \Lambda \to p\pi^-, \bar{\Sigma}^0 \to \bar{\Lambda}\gamma, \bar{\Lambda} \to \bar{p}\pi^+$.
  - $\bar{p}p \to \bar{\Xi}^+\Xi^-, \Xi^- \to \Lambda\pi^-, \Lambda \to p\pi^-, \bar{\Xi}^+ \to \bar{\Lambda}\pi^+, \bar{\Lambda} \to \bar{p}\pi^+$.
- Ideal pattern recognition and PID
- Background using Dual Parton Model

* By W. Ikegami-Andersson (PhD thesis, Uppsala 2020) and G. Perez Andrade (master thesis, Uppsala 2019)

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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Hyperon prospects with PANDA

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  - $\bar{p}p \to \bar{\Xi}^+\Xi^-, \Xi^- \to \Lambda\pi^-, \Lambda \to p\pi^-, \bar{\Xi}^+ \to \bar{\Lambda}\pi^+, \bar{\Lambda} \to \bar{p}\pi^+$.
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1.77						207 000
6.0						432 000
4.6						26000
7.0						8600

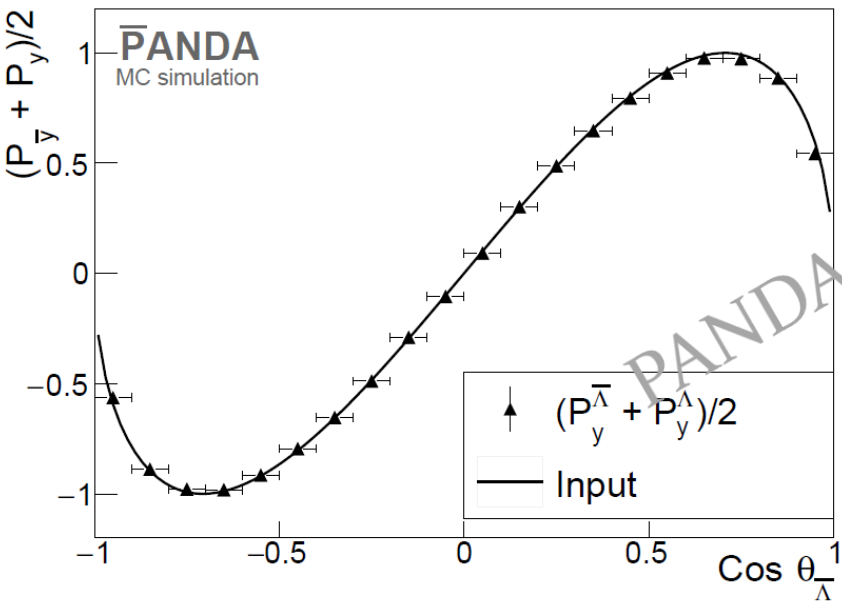
** 90% C.L.

PANDA will be a **hyperon factory** already during Phase One!

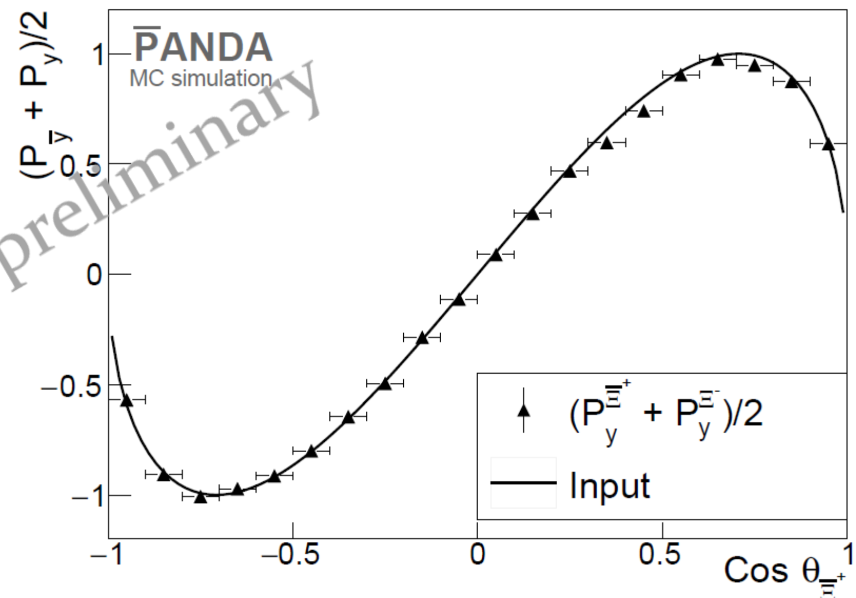
With full luminosity, the rate will be ~20 times larger!

Hyperon Prospects with PANDA

$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ at p_{beam} = 1.64 GeV/c



$\bar{p}p \rightarrow \bar{\Xi}^{+}\Xi^{-}$ at p_{beam} = 4.6 GeV/c



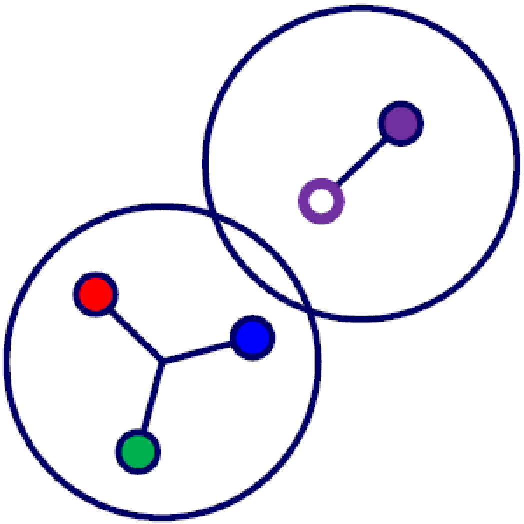
Spin observables in production of single- and multistrange hyperons*

* arXiv[hep-ex]:2009.11582

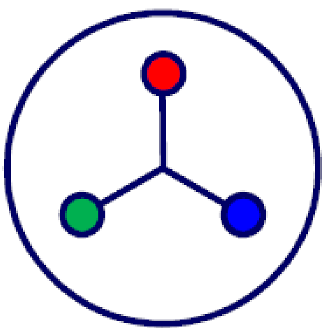
Hyperon Spectroscopy

How do quarks form baryons?

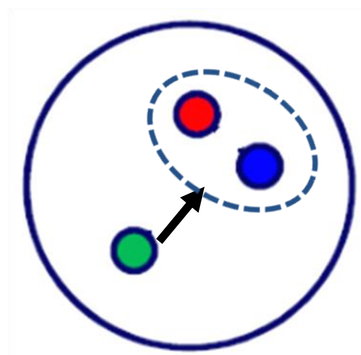
- Forces?
- Degrees of freedom?



Molecule / hadronic d.o.f.



Symmetric quark model



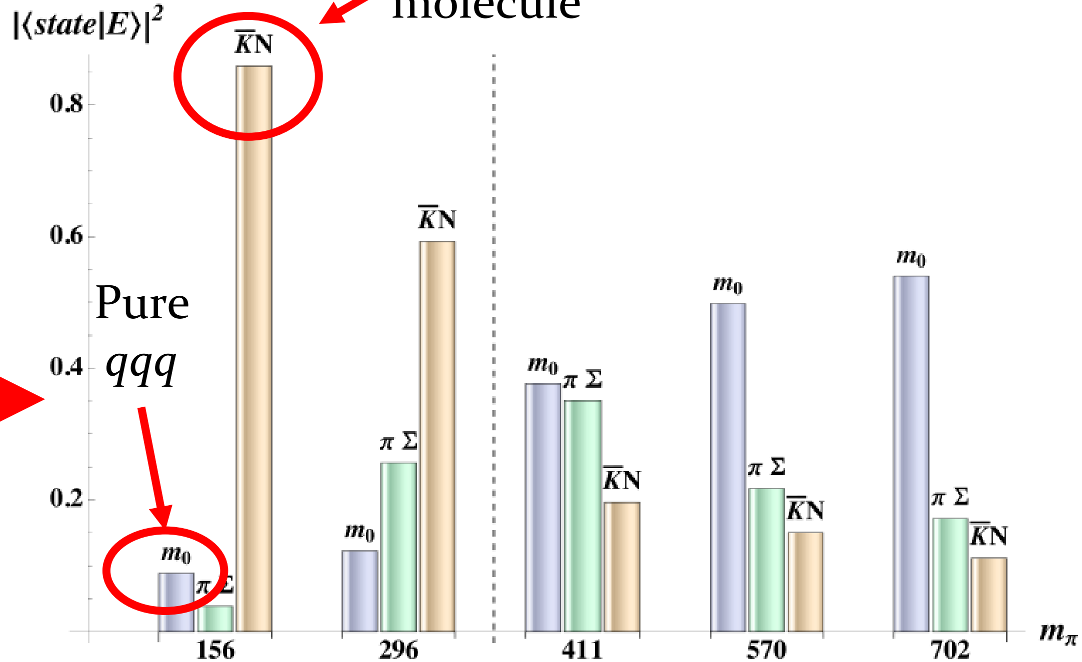
Quark - diquark

Hyperon spectroscopy

How do the features of the light- and single strange baryon spectrum carry over to the multi-strange sector?

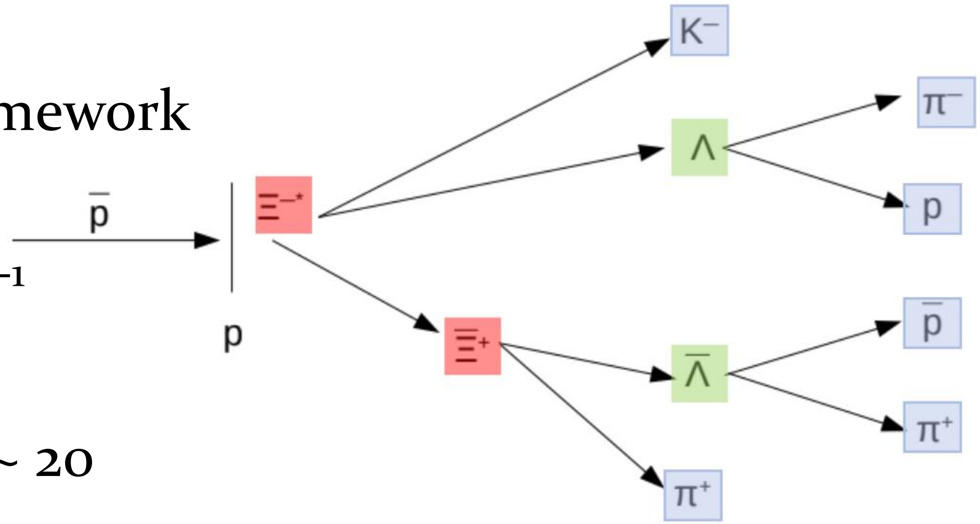
- Light baryon spectrum*:
  - ”Missing” states
  - Parity pattern
- Single strange spectrum:
  - ”Missing” states
  - Non-*qqq* features of *e.g.* $\Lambda(1405)$**
- Multi-strange spectrum:
  - Very scarce data bank

$\bar{K}N$ molecule

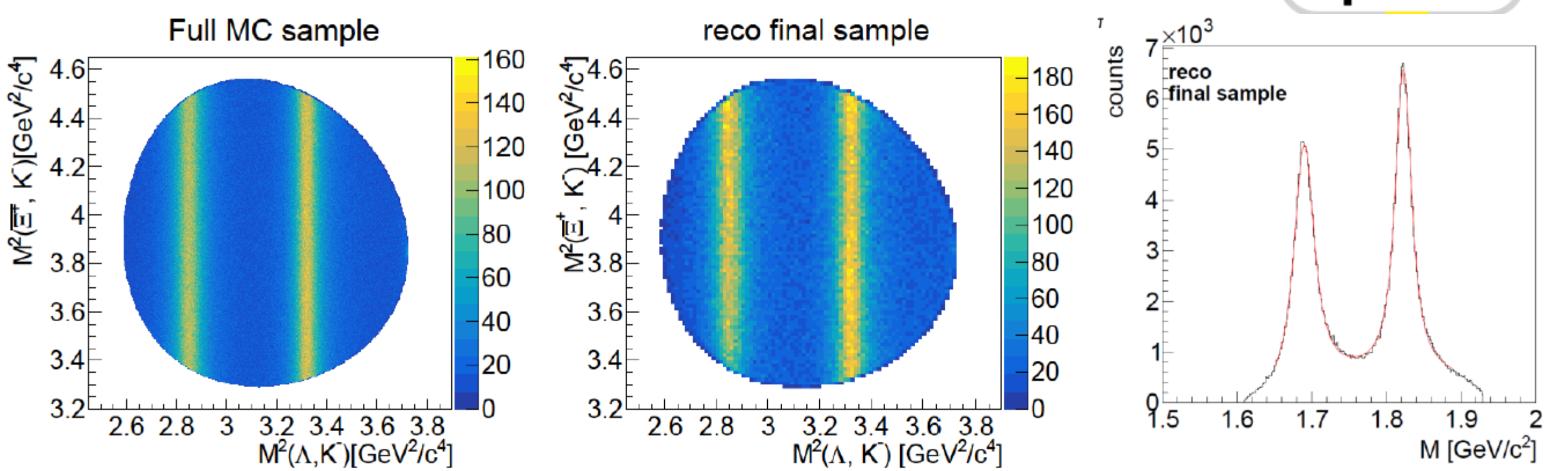


*EPJA 48 (2012) 127, EPJA 10 (2001) 395
** PRL 114 (2015) 132002

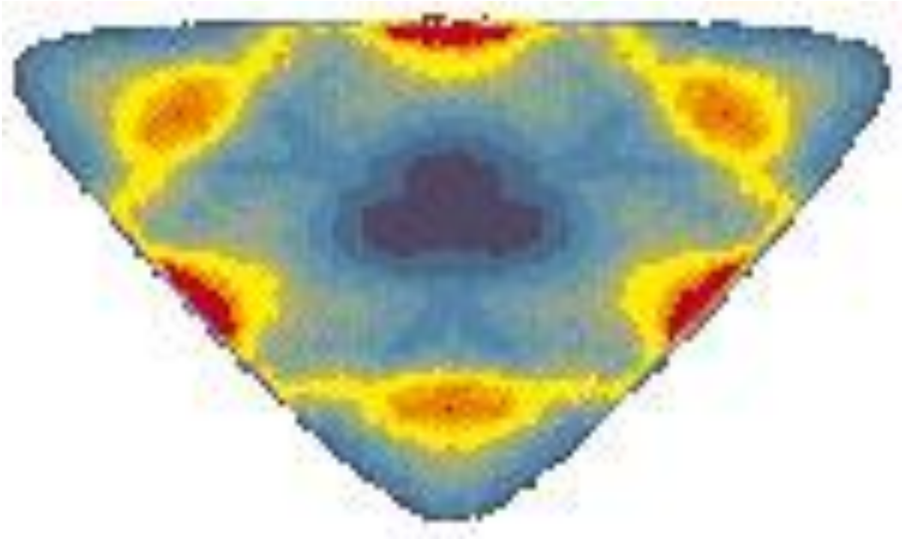
Feasibility study of $\bar{p}p \to \bar{\Xi}^{+}\Lambda K^{-} + c.c.$



- Simplified PANDA MC framework
- p_{beam} = 4.6 GeV/c
- σ = 1 μb and L = 10^{31} cm^{-2}s^{-1}
- Results:*
  - Efficiency ~5.5 % , S/B ~ 20
  - ~38000 exclusive $\bar{\Xi}^{+}\Lambda K^{-} + c.c.$ events / day



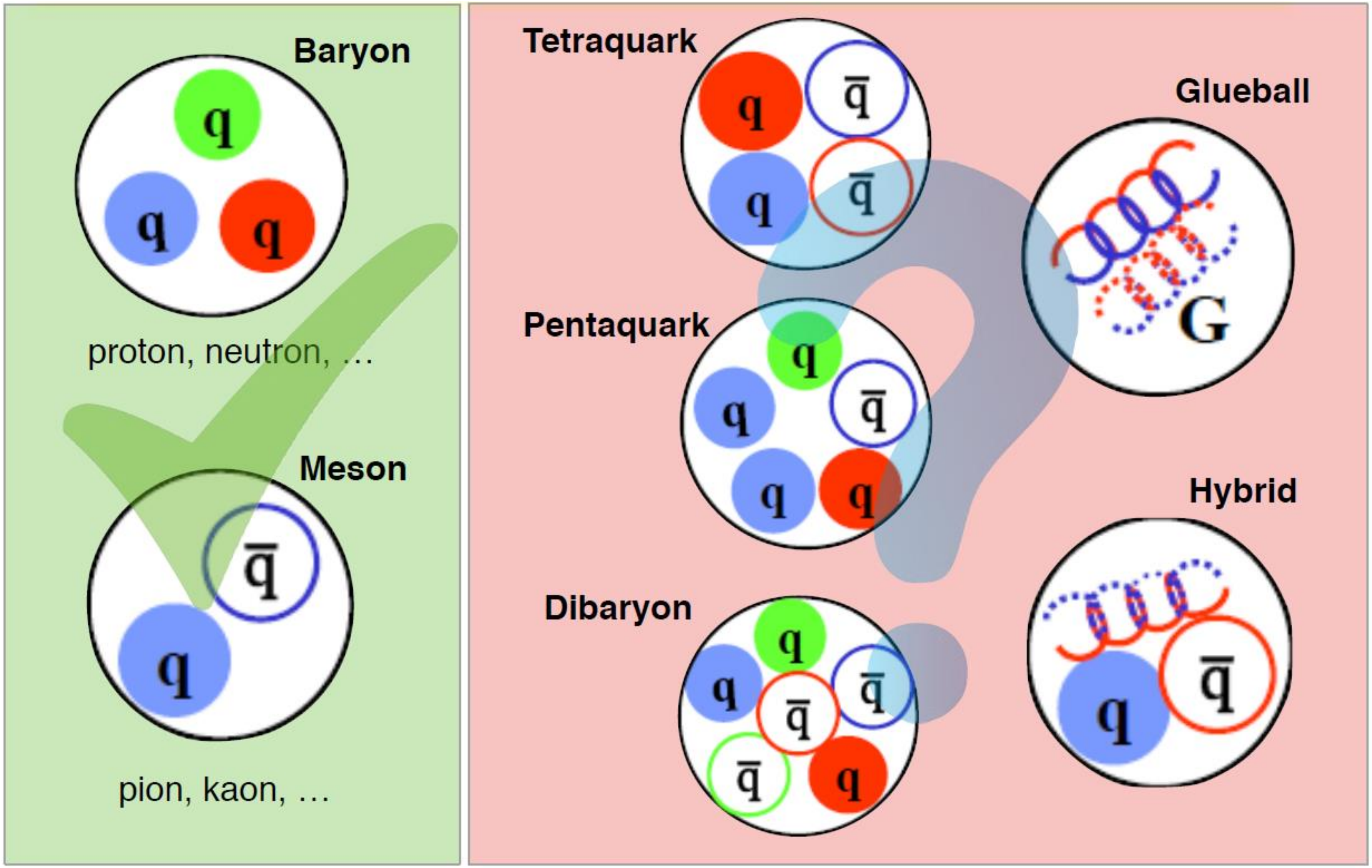
* J. Pütz, PhD Thesis, Bonn University (2020)



Physics Programme

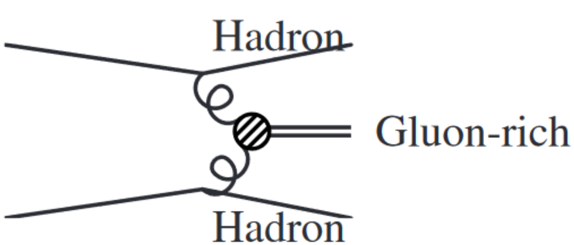
CHARM AND EXOTICS

Ordinary *versus* Exotic matter

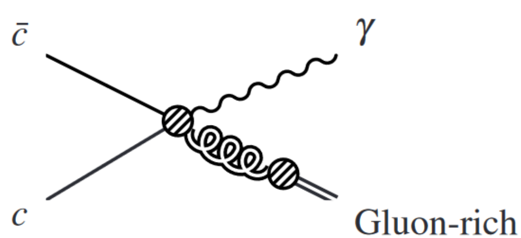


Charm and exotics

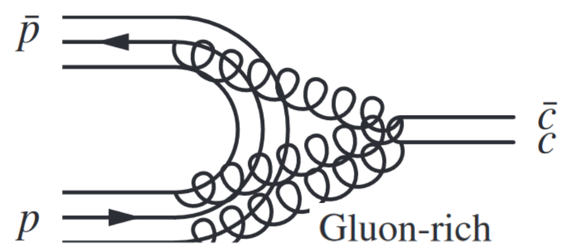
- Experimental classification:
  - Spin-exotic quantum numbers J^{PC}
  - Production mechanism
  - Precision measurement of properties



AMBER



BESIII, Belle II



PANDA, AMBER

Charm and exotics

- Experimental classification:
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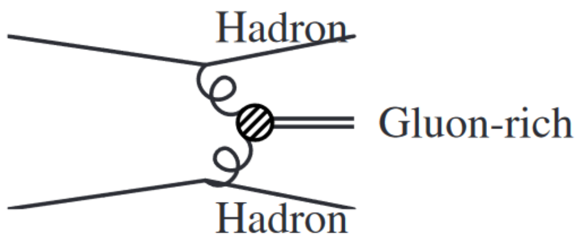
  - – Precision measurement of properties

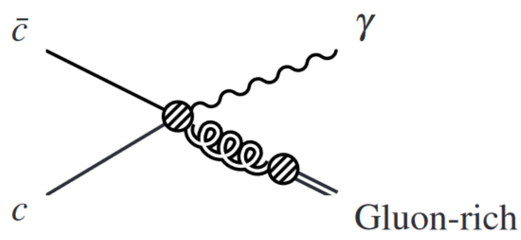
Spectroscopy with PANDA:

Light hadrons:
→ Large data samples for PWA

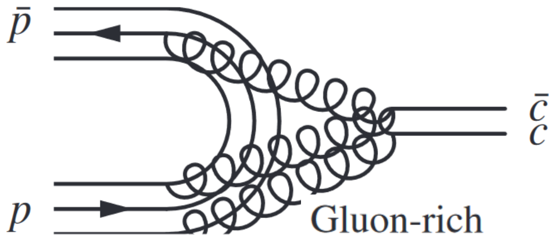
Open and hidden charm:
→ High spin states accessible



AMBER



BESIII, Belle II



PANDA, AMBER

Charm and exotics

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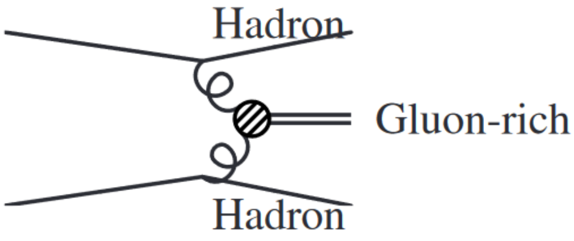
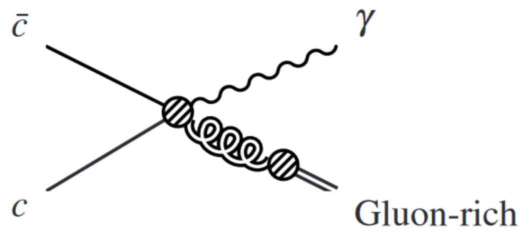
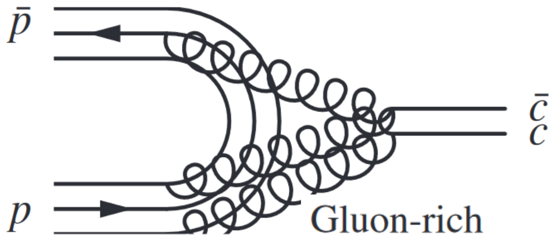
Gluon-rich environment



AMBER



BESIII, Belle II

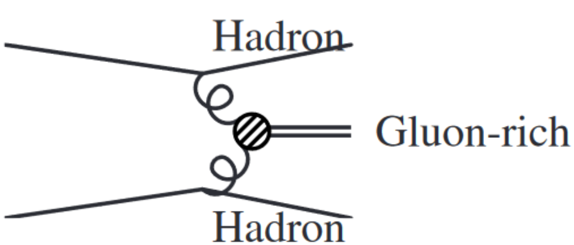


PANDA, AMBER

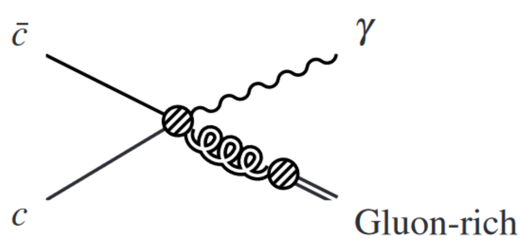
Charm and exotics

- Experimental classification:
  - Spin-exotic quantum numbers J^{PC}
  - Production mechanism
  - Precision measurement of properties

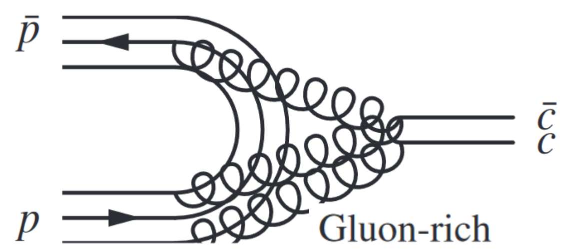
Let's have a closer look.



AMBER



BESIII, Belle II



PANDA, AMBER

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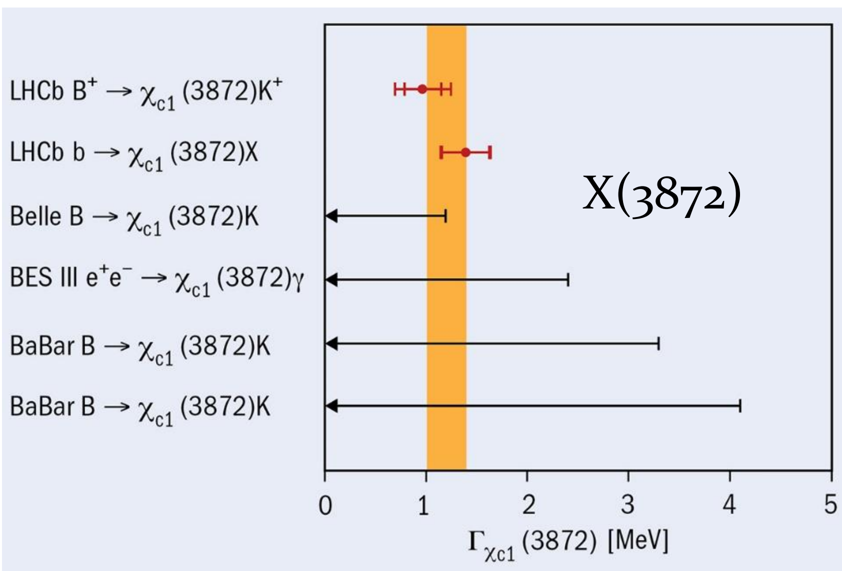
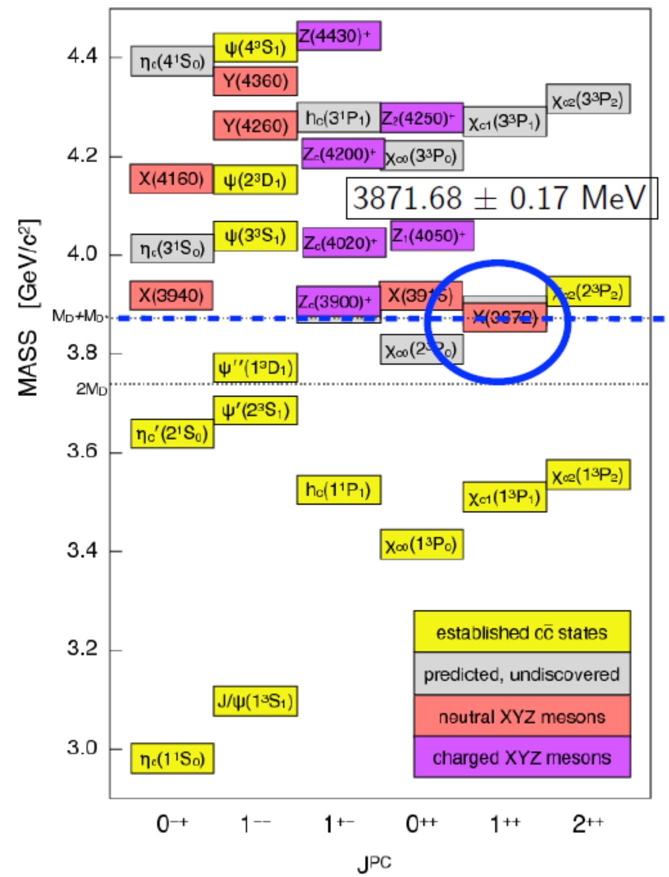
Charmonium precision studies

- Many narrow charmonium resonances above $D\bar{D}$ threshold
  - The discovery of the X(3872) started a new era*
  - Inconsistent with quark model predictions**

* PRL 91, 262001 (2003)
**PRD 17, 3090 (1978)

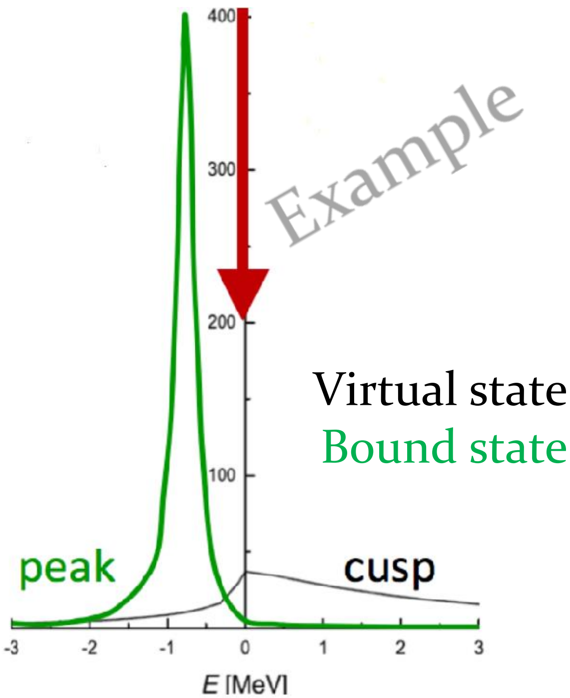


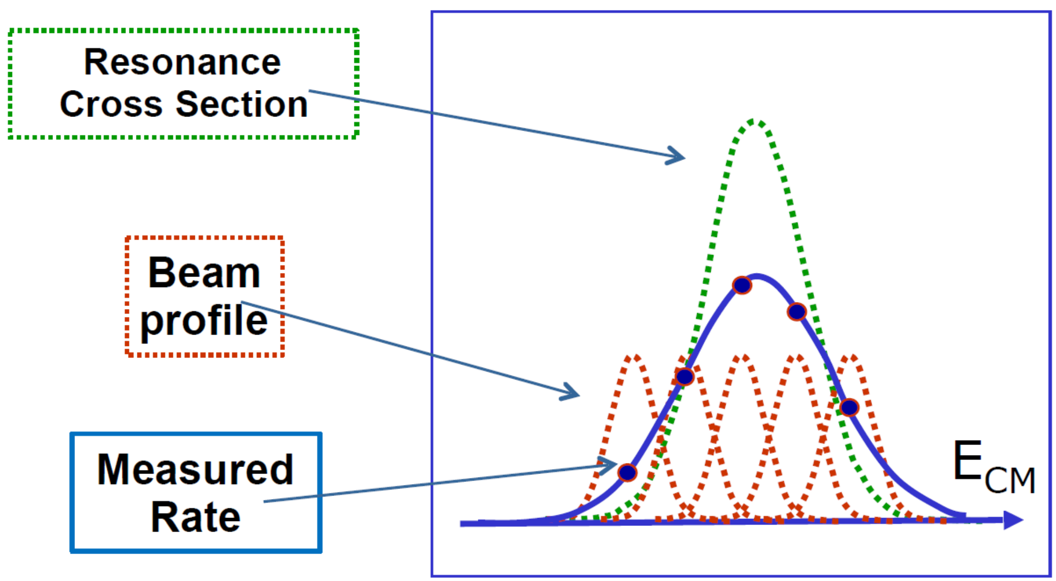


Credit: LHCb, Phys.Rev. D 102 (2020) 9, 092005

Charmonium precision studies

- Line-shape sensitive to underlying structure*.
  - Bound / virtual states distinguished through the Flatté parameter E_f.
- Can be precisely measured in formation.
  - e^+e^- annihilation: only states with $J^{PC} = 1^{--}$ accessible.
  - $\bar{p}p$ annihilation: all "$q\bar{q}$" – like J^{PC} accessible.

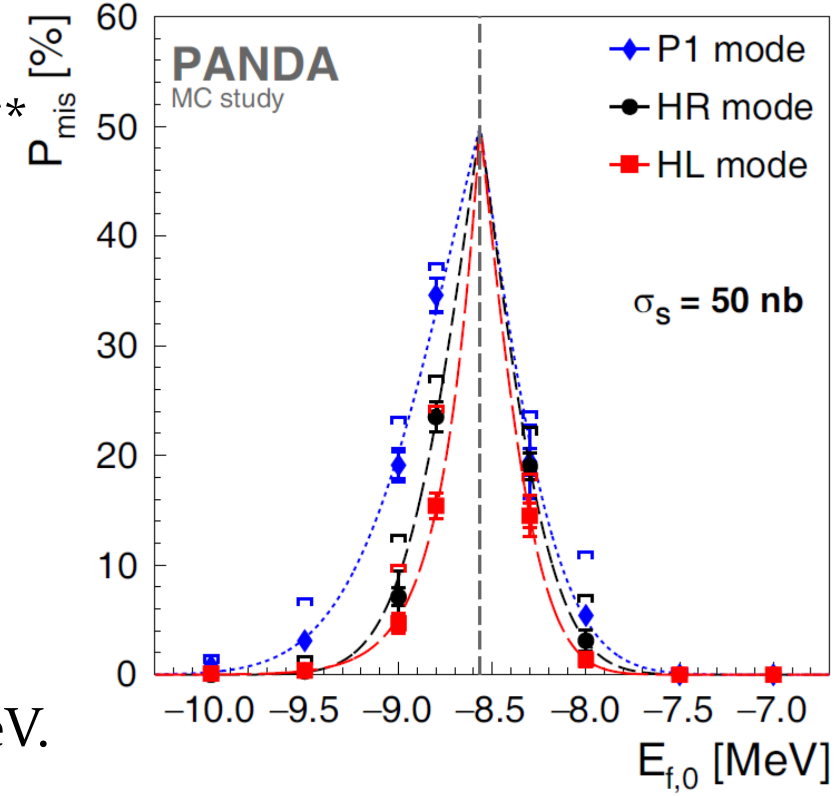




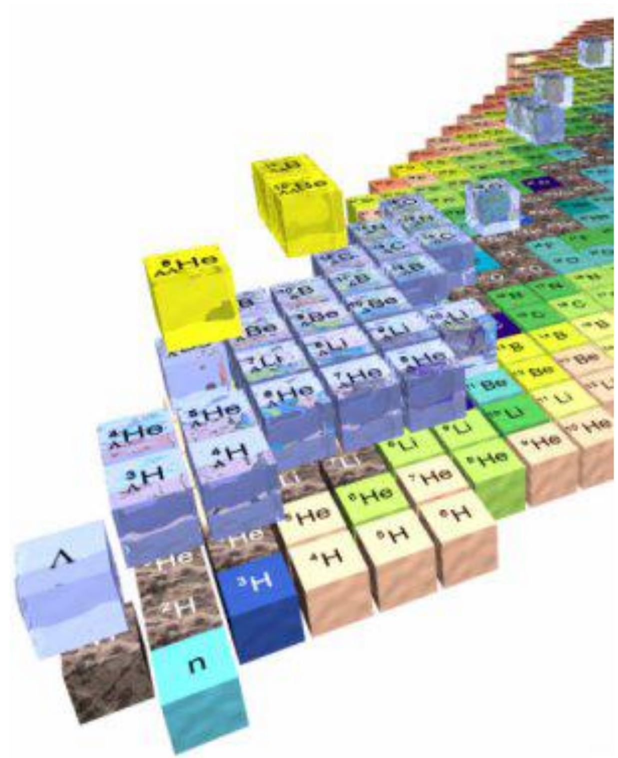
* Phys. Rev. D 76, 034007 (2007)

Example: X(3872)

- Recent LHCb measurement*: Breit-Wigner and Flatté line-shape equally probable.
- Recent PANDA simulation study**
  - $\bar{p}p \to X(3872) \to J/\Psi\pi^+\pi^-$.
  - 40 scan points á 2 days.
  - Different scenarios for
    - » cross section
    - » Luminosity
    - » B-W width
    - » Flatté parameter E_f
  - Sensitive to widths > 40-110 keV.
  - Possible to distinguish bound from virtual state through direct line-shape measurement.



* Phys. Rev. D 76, 034007 (2007)
**Eur. Phys. J A 55, 42 (2019).



Physics Programme

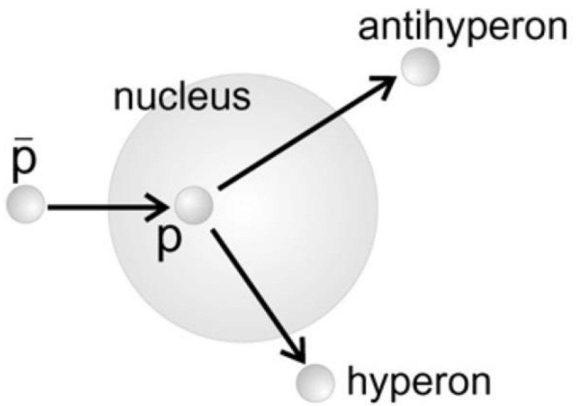
HADRONS IN NUCLEI

Hadrons in Nuclei

Multi-baryon interactions crucial to understand macroscopic systems such as neutron stars.

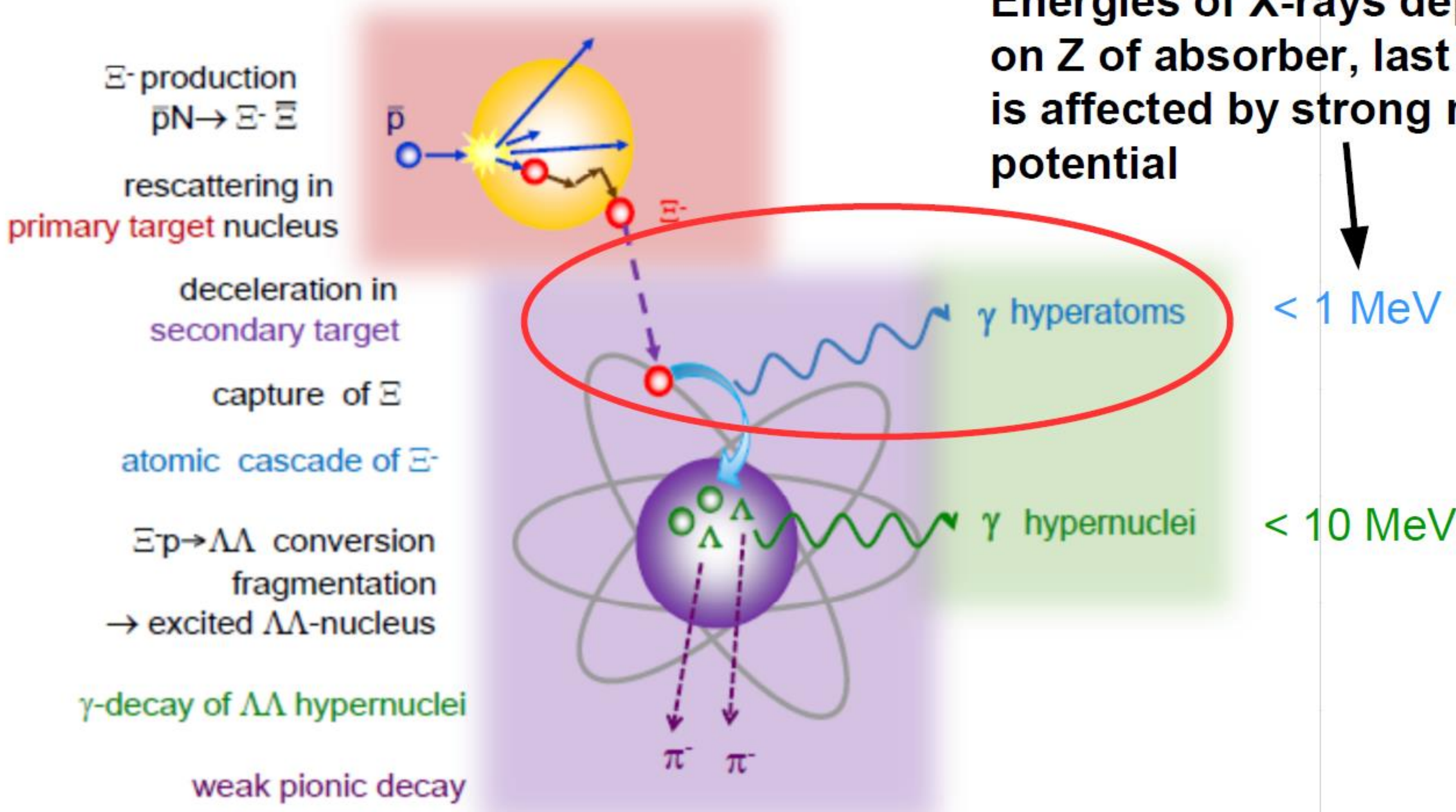
In PANDA, these interactions can be studied in*

- Antihyperons in nuclei
- Hyperatom spectroscopy
- Hypernuclear spectroscopy



Nucl. Phys. A 954, 323 (2016)

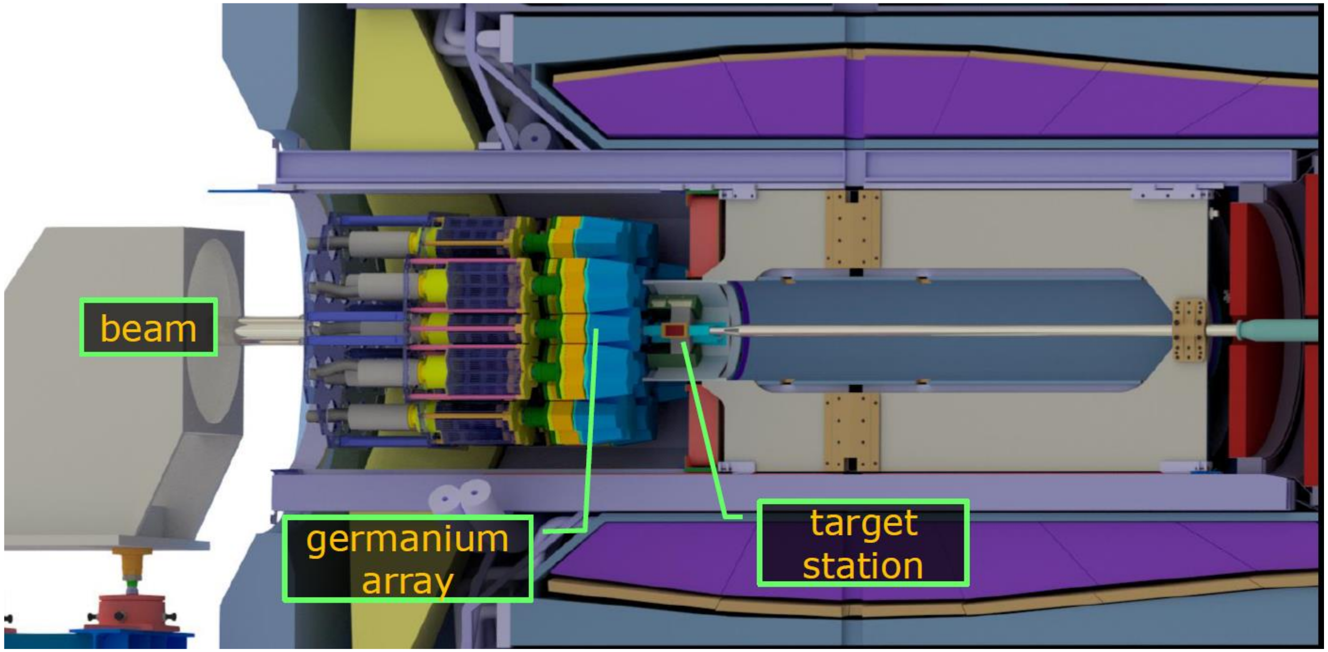
Hyperatoms and hypernuclei



Energies of X-rays depend on Z of absorber, last X-ray is affected by strong nuclear potential

Details in Nucl. Phys. A 954 (2018) 323.

Hyperatoms and hypernuclei



- Large $\bar{Y}Y$ production rates.
  - Opportunity for multi-strange physics.
- Secondary target.
- Germanium detector array for γ-spectroscopy.

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Summary

- PANDA is a next-generation antiproton facility for hadron and nuclear physics.
- The physics programme consists of four pillars:
  - Nucleon structure
  - Strangeness physics
  - Charm and exotics
  - Hadrons in nuclei
- PANDA and AMBER are complemenray in time, beam momentum, luminosity and interaction volume.

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Thanks to:

Alaa Dbeyssi, Jennifer Pütz, Tobias Stockmans,
Johan Messchendorp and Christoph Hanhart

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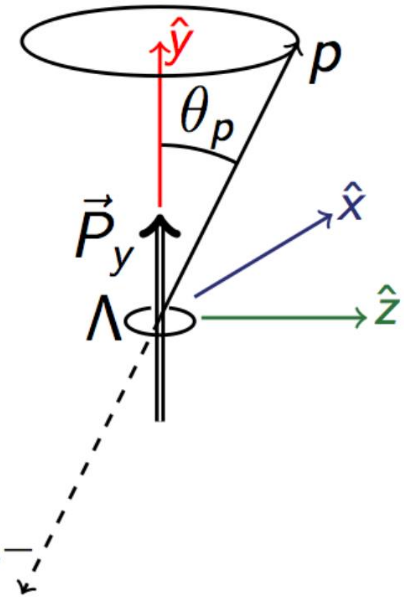
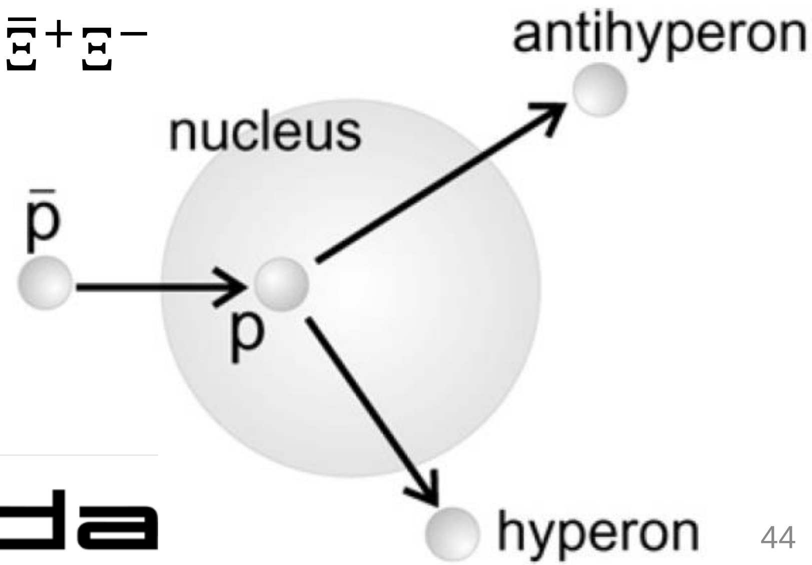
CP violation in hyperon decays

- CP violation in SM insufficient to explain matter-antimatter asymmetry.
- CP violation beyond SM never observed for baryons.
- The $\bar{p}p \to \bar{Y}Y$ process suitable for CP measurements:
  - Clean, no mixing.
  - Symmetric particle – antiparticle conditions.
- If CP valid, $\alpha = -\bar{\alpha}$ *i.e.* $A_{CP} = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} = 0.0000\ldots$



Anti-hyperons in nuclei

- Antibaryon potential in nuclei:
  - Discrepancy theory/data for antiprotons in nuclei.
  - (Anti-) strangeness sector experimentally unknown.*
- Advantage of PANDA:
  - Large production cross sections for $\bar{Y}Y$.
- Simulation studies of $\bar{\Lambda}\Lambda$ and $\bar{\Xi}^+\Xi^-$ show promising results.



*PLB 669 (2008) 306.
** PLB 749 (2015) 421.

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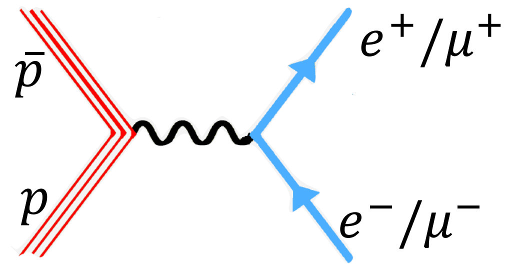
Nucleon Structure

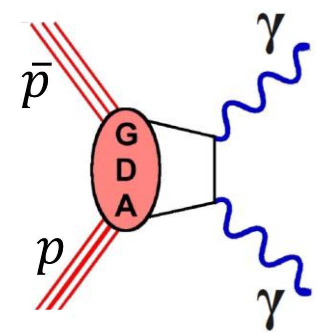
Electromagnetic Form factors

PANDA: time-like with e and μ
AMBER: space-like with μ

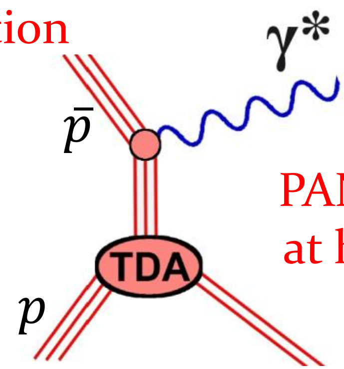


Generalized Distribution Amplitudes

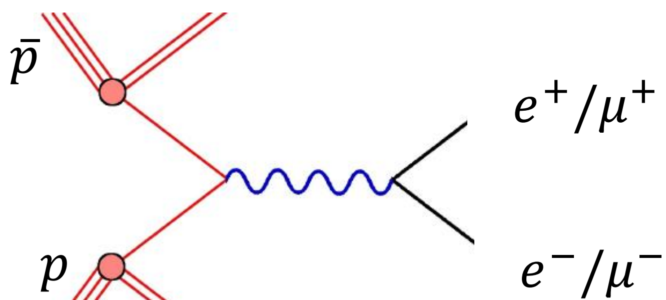
PANDA: GDA from Wide Angle Compton Scattering and Hard Exclusive Meson Production
AMBER: GPD from DVCS



Transition Distributions Amplitides



PANDA: e^+e^-M at high energies’



*Eur. Phys. J A 51, 107 (2015)

Parton Distribution Amplitudes

PANDA: low energy Drell-Yan
AMBER: high energy Drell-Yan