Physics Prospects of $\overline{\text{P}}$ANDA at FAIR

9th International Conference on New Frontiers in Physics
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Creta

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Ruhr-Universität Bochum (Germany)
On Behalf of the $\overline{\text{P}}$ANDA Collaboration

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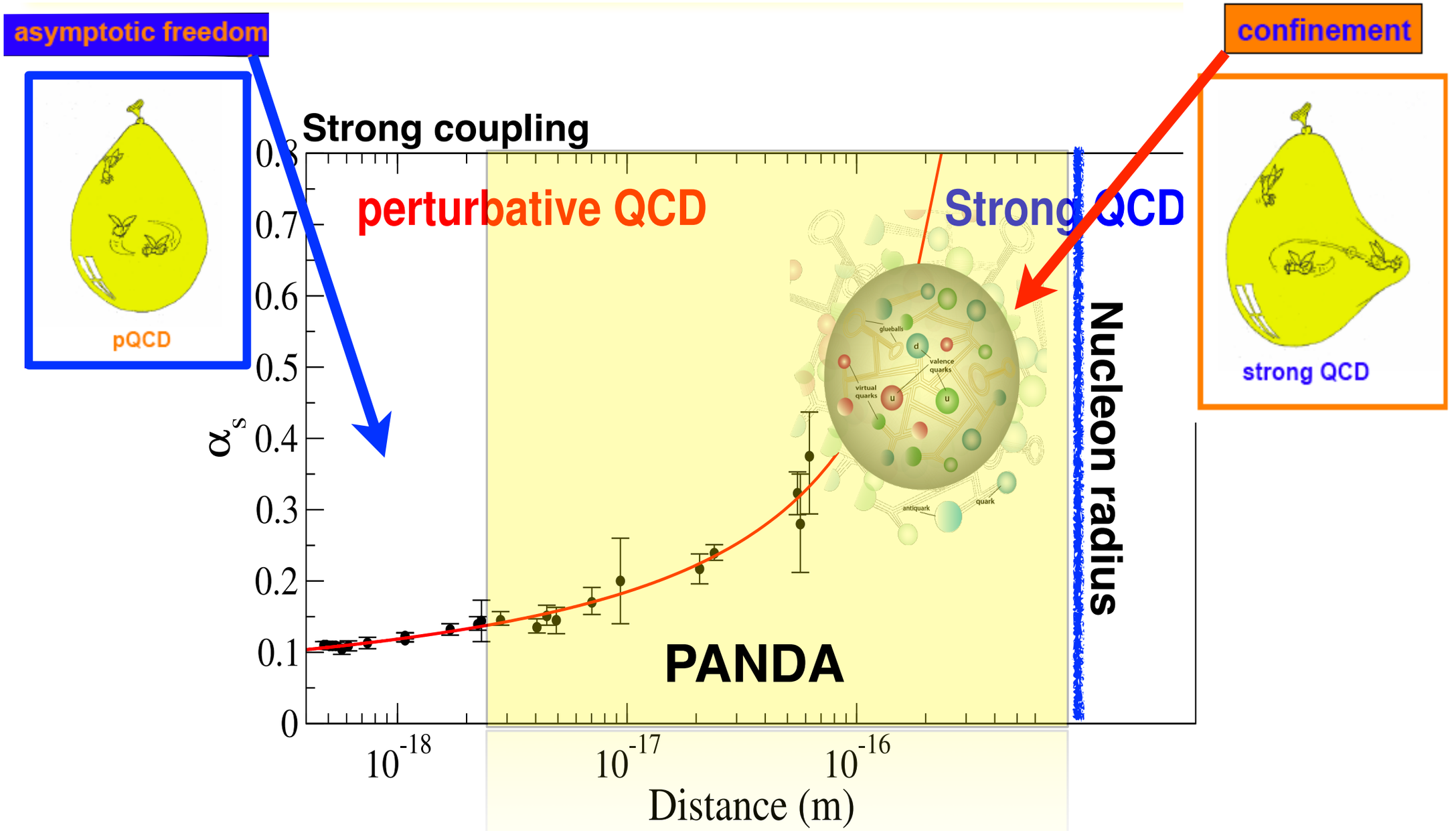
Bundesministerium für Bildung und Forschung

Strong Interaction



Particles ↔ Hadrons ↔ Nuclei

Questions PANDA will address

Why are quarks confined in hadrons?

How is the mass of matter generated?

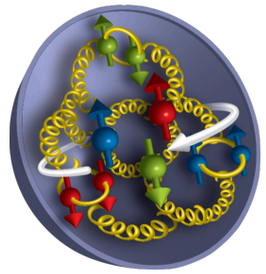
What is the inner structure of matter?

Do exotic hadrons exist?

What causes the matter-antimatter asymmetry?

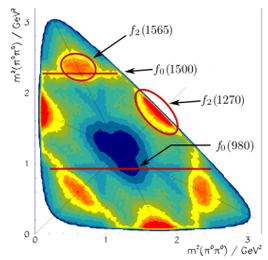
$\bar{p}p$ and $\bar{p}A$ interactions

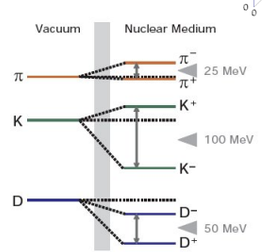
Nucleon Structure



Strangeness Physics

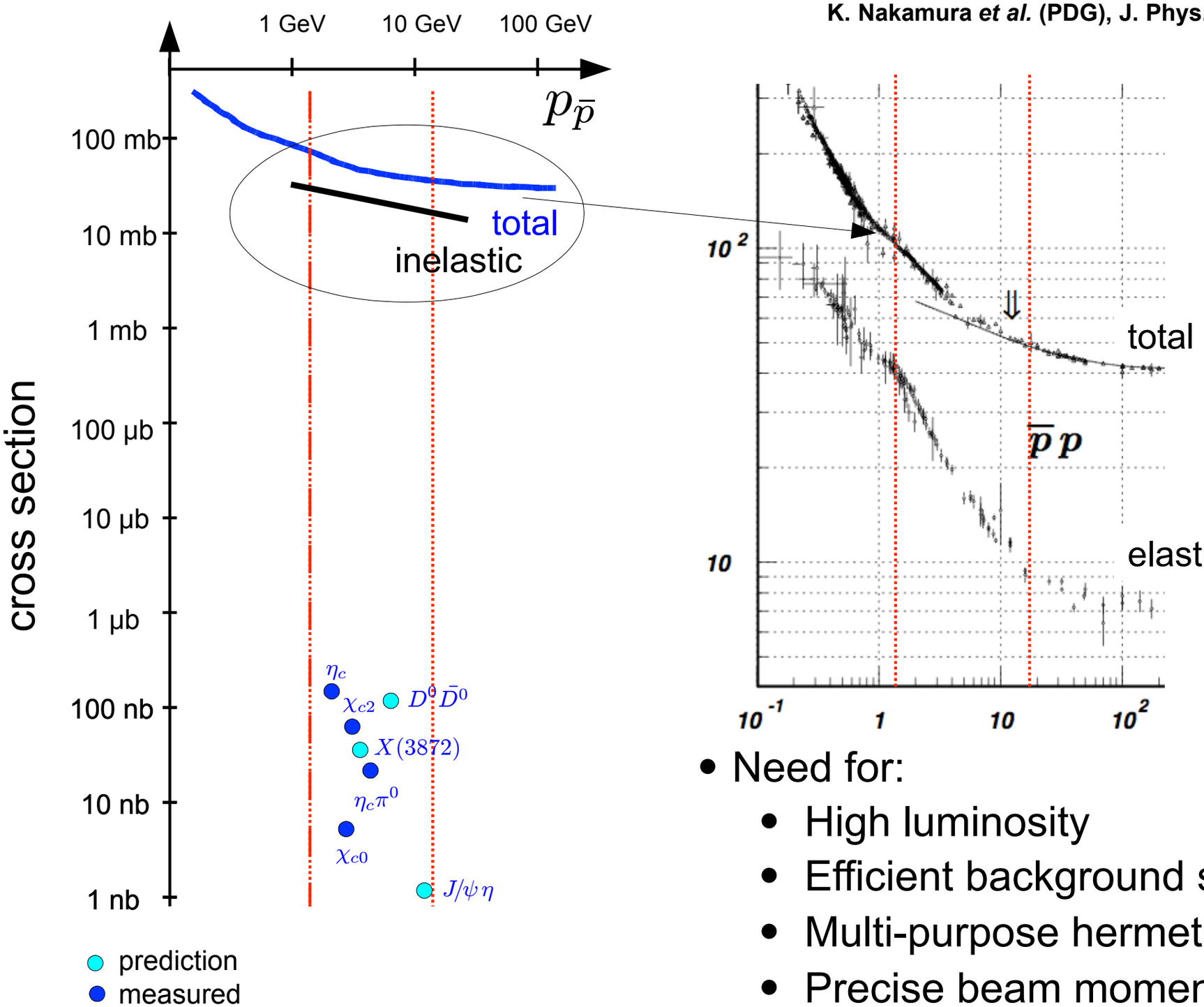
Charmed and Exotic Hadrons





Hadrons in Nuclei

Cross Section

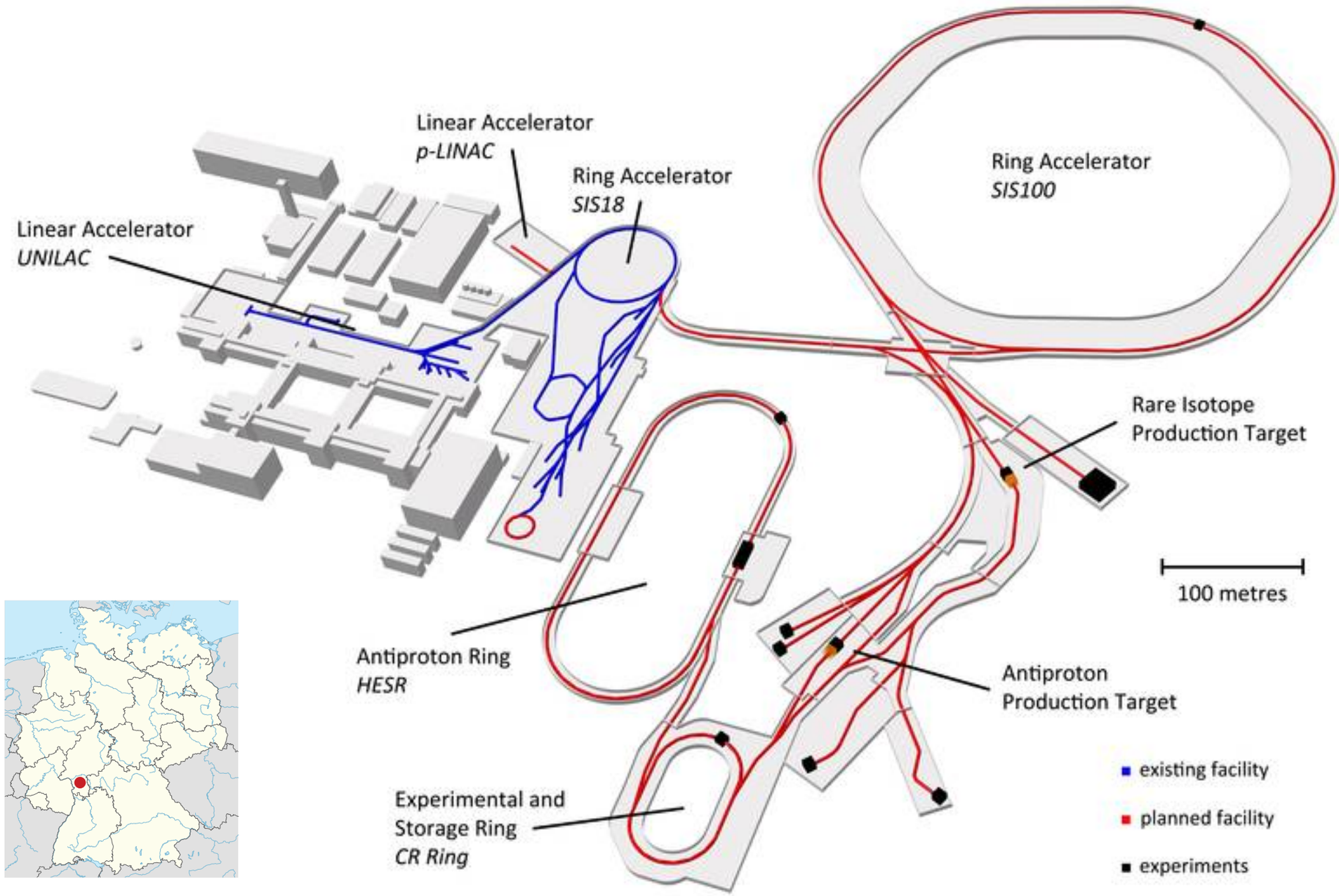


K. Nakamura *et al.* (PDG), J. Phys. G 37, 075021 (2010)

- Need for:
  - High luminosity
  - Efficient background suppression
  - Multi-purpose hermetic 4π detector
  - Precise beam momentum

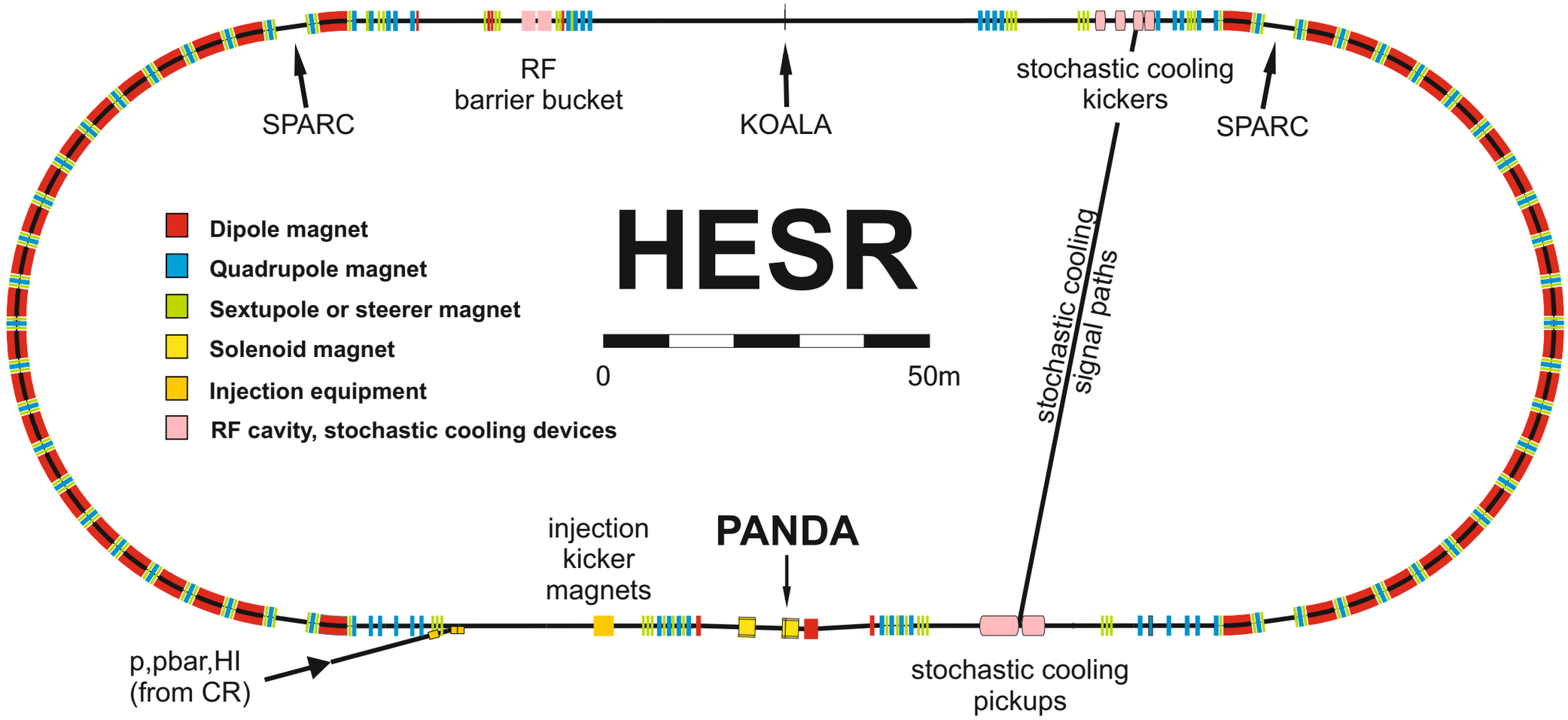
Location of the PANDA experiment

- Extension of the heavy ion research center GSI in Darmstadt (Germany) to the Facility for Antiproton and Ion Research (FAIR)



Construction of FAIR

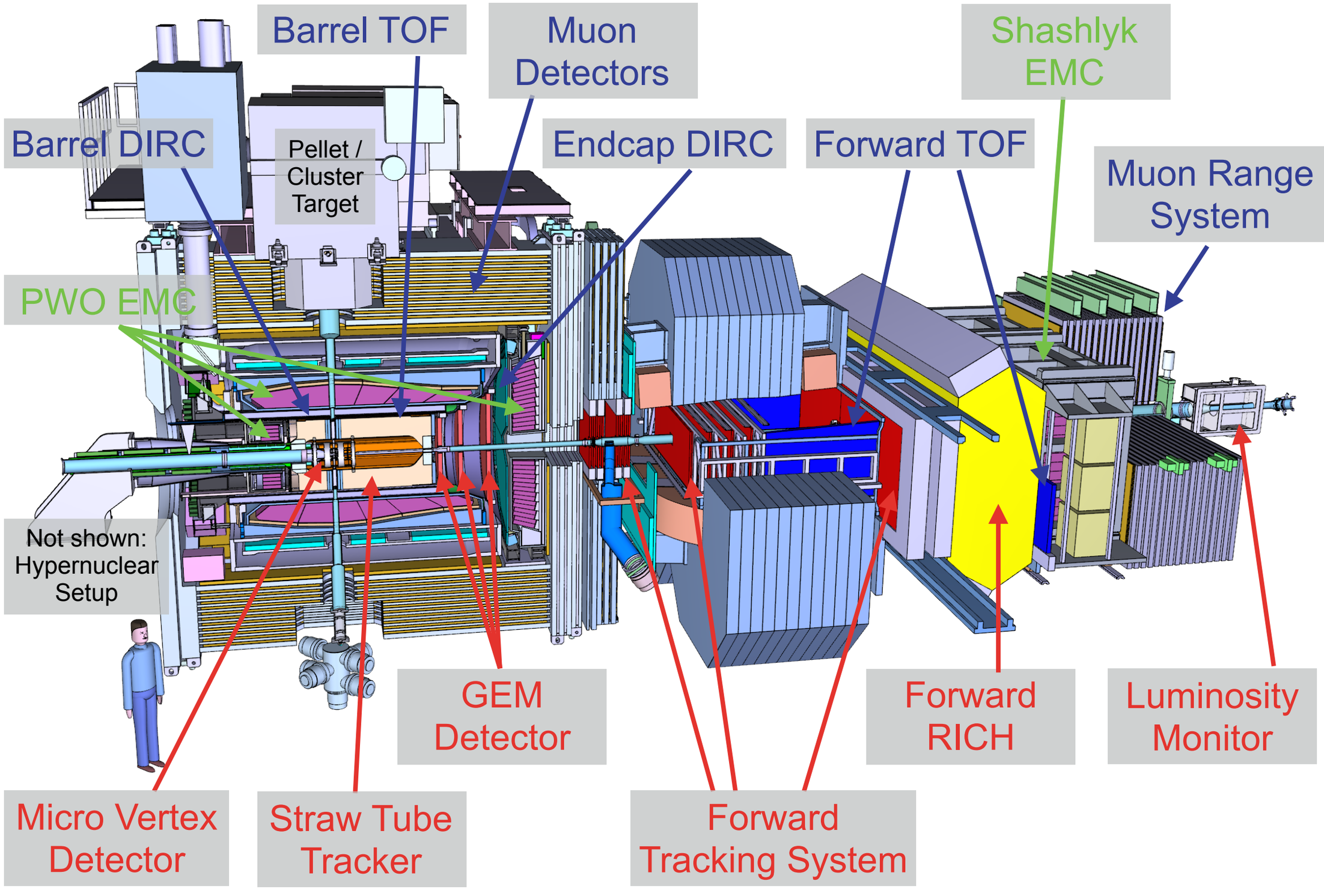
High Energy Storage Ring



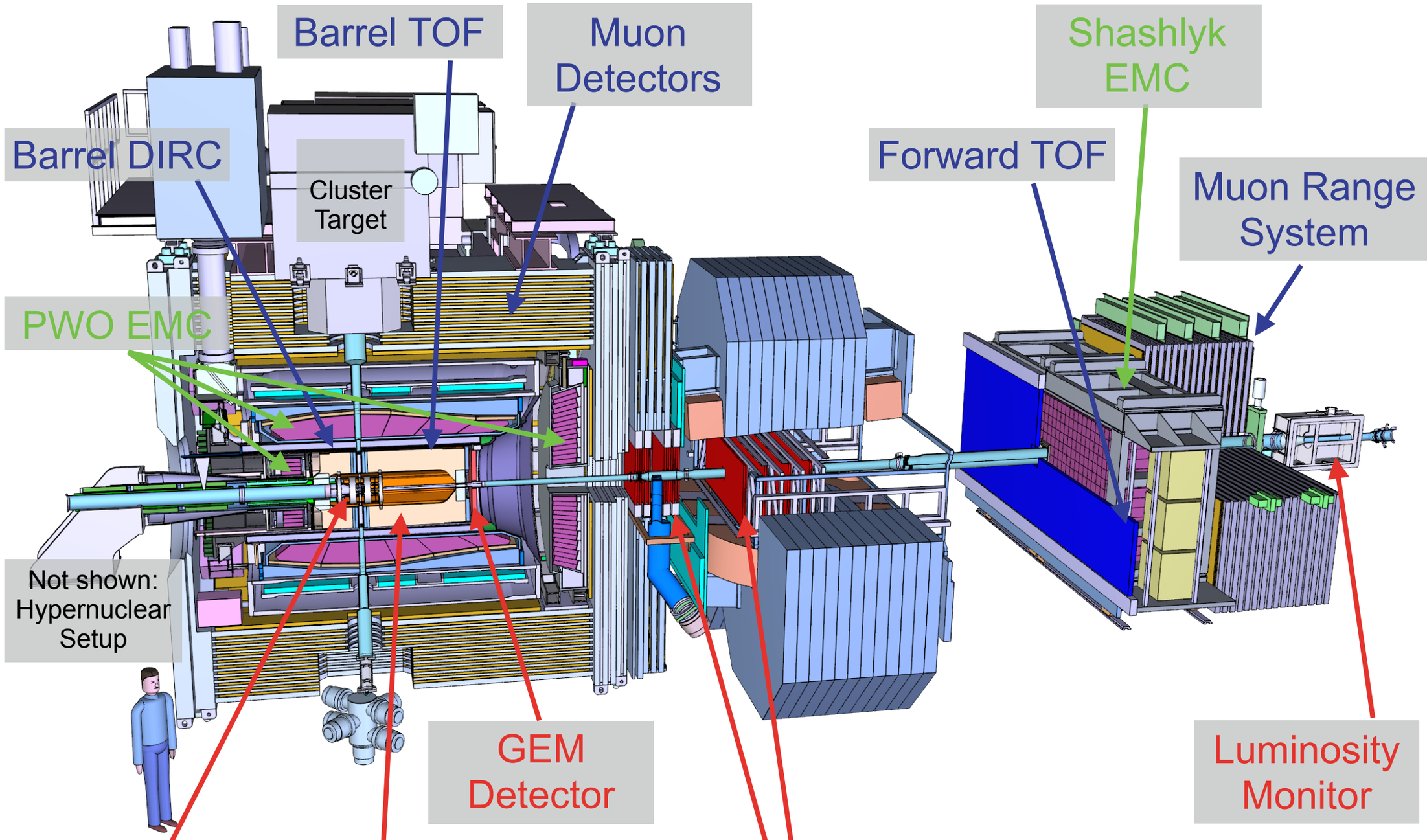
- Circumference: 574 m
- Momentum range: 1.5 - 15 GeV/c
- Stochastic cooling
- Quasi continuous beam

Mode	High Luminosity	High Resolution	Phase 1
$\Delta p/p$	$1 \cdot 10^{-4}$	$2 \cdot 10^{-5}$	$5 \cdot 10^{-5}$
Stored $\bar{p}$	10^{11}	10^{10}	10^{10}
$\mathcal{L}$ [cm^{-2}s^{-1}]	$2 \cdot 10^{32}$	$2 \cdot 10^{31}$	$2 \cdot 10^{31}$

PANDA detector - Full Setup

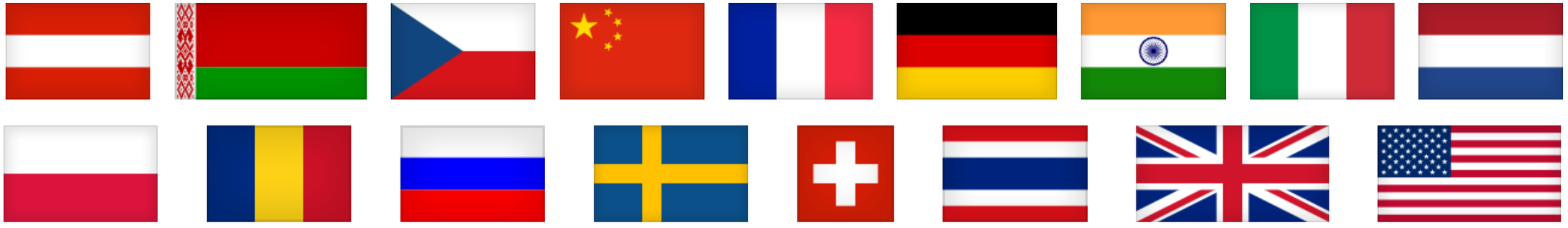


PANDA detector - Day-1 Setup



more information:
talk by A. Belias

Members of the PANDA collaboration



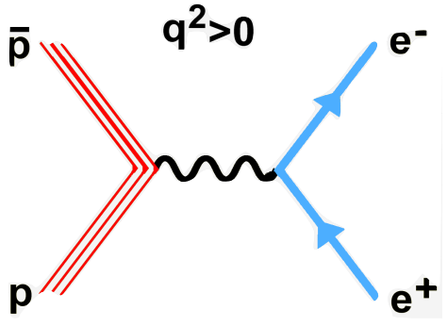
UP Marche Ancona
U Basel
IHEP Beijing
U Bochum
Abant Izzet Baysal
U Golkoy, Bolu
U Bonn
U Brescia
IFIN-HH Bucharest
AGH UST Cracow
IFJ PAN Cracow
JU Cracow
Cracow UT
FAIR Darmstadt
GSI Darmstadt
JINR Dubna
U Erlangen
NWU Evanston
U Frankfurt
LNF-INFN Frascati
U & INFN Genova

U Gießen
Giresun U
U Glasgow
KVI Groningen
Gauhati U, Guwahati
USTC Hefei
URZ Heidelberg
Doğuş U, Istanbul
Okan U, Istanbul
FZ Jülich
IMP Lanzhou
INFN Legnaro
Lund U
HI Mainz
U Mainz
RINP Minsk
ITEP Moscow
MPEI Moscow
U Münster
BINP Novosibirsk
Novosibirsk State U

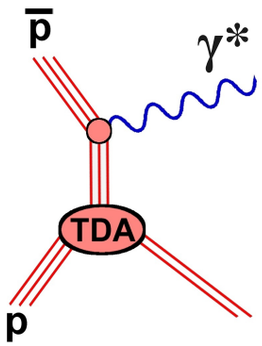
IPN Orsay
U Wisconsin, Oshkosh
U & INFN Pavia
PNPI St. Petersburg
Wet Boh. U, Pilzen
Charles U, Prague
Czech TU, Prague
IHEP Protvino
Irfu Saclay
KTH Stockholm
Stockholm U
SUT, Nakhon Ratchasima
SVNIT Surat-Gujarat
S Gujarat U, Surat-Gujarat
FSU Tallahassee
U & INFN Torino
Politecnico di Torino
U Uppsala
SMI Vienna
NCBJ Warsaw
U York

Proton Structure

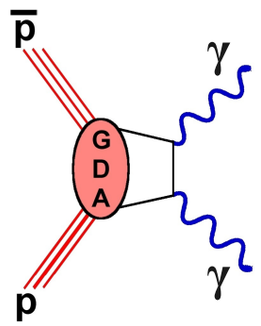
- Accessible at PANDA:
  - Time-like Electromagnetic Form Factors (lepton pair production) arXiv:1606.01118



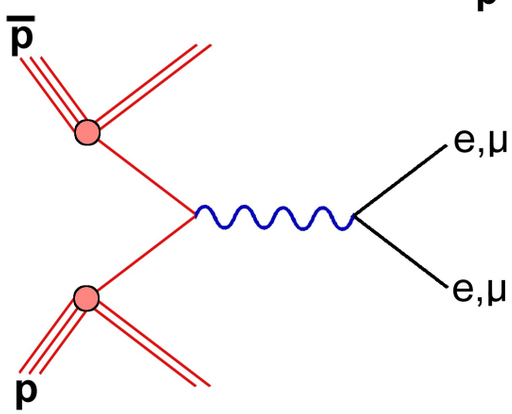
  - Transition Distribution Amplitudes (meson production) arXiv:1409.0865



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



  - Transverse Parton Distribution Functions (Drell-Yan production)



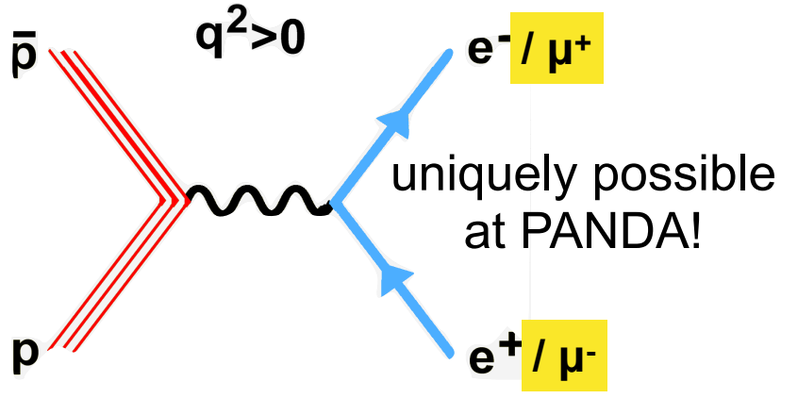
Proton Structure

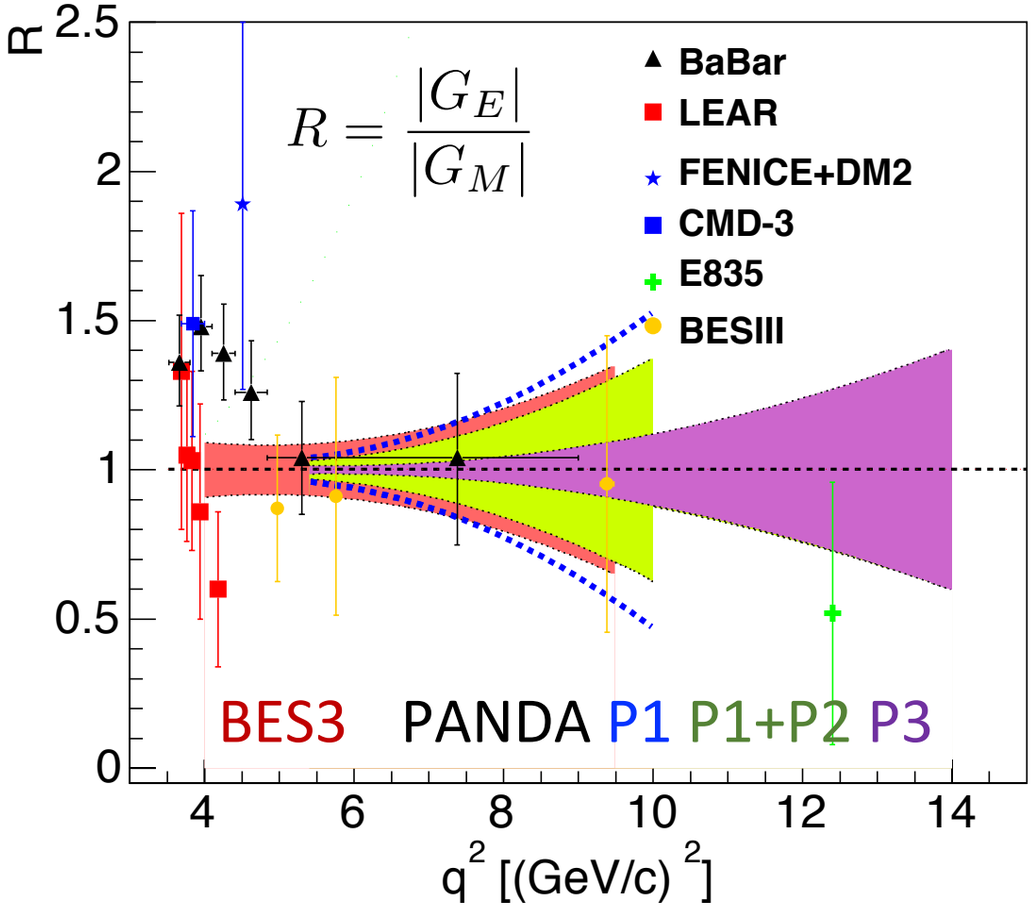
- Time-like Electromagnetic Form Factors (lepton pair production)
- Phase-1:

  $\bar{p}p \rightarrow e^+e^-$ @ 1.5 GeV/c: ~220/day

  $\bar{p}p \rightarrow e^+e^-$ @ 3.3 GeV/c: ~10/day

  $\bar{p}p \rightarrow \mu^+\mu^-$ @ 1.5 GeV/c: ~170/day

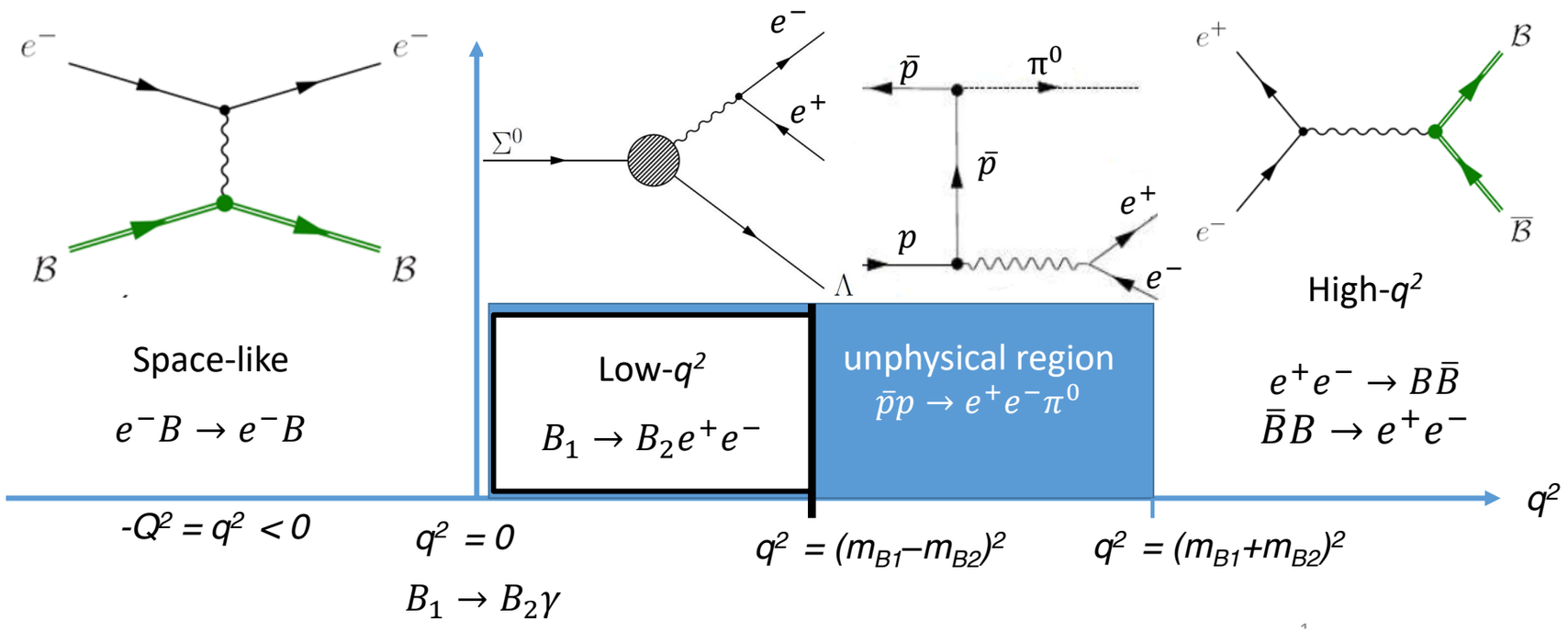




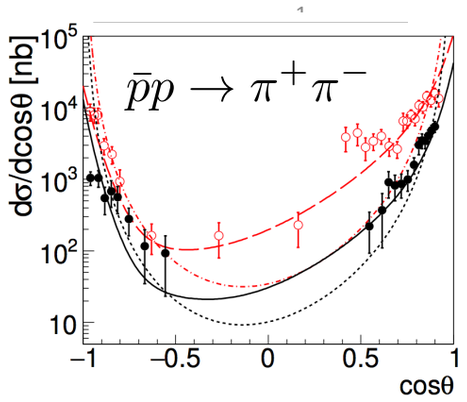
$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2\beta s}\left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}\sin^2\theta|G_E|^2\right]$$

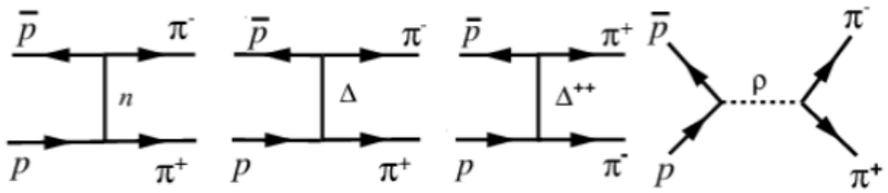
Proton Structure

- Even unphysical region of form factors accessible at PANDA via $\bar{p}p \rightarrow e^+e^-\pi^0$

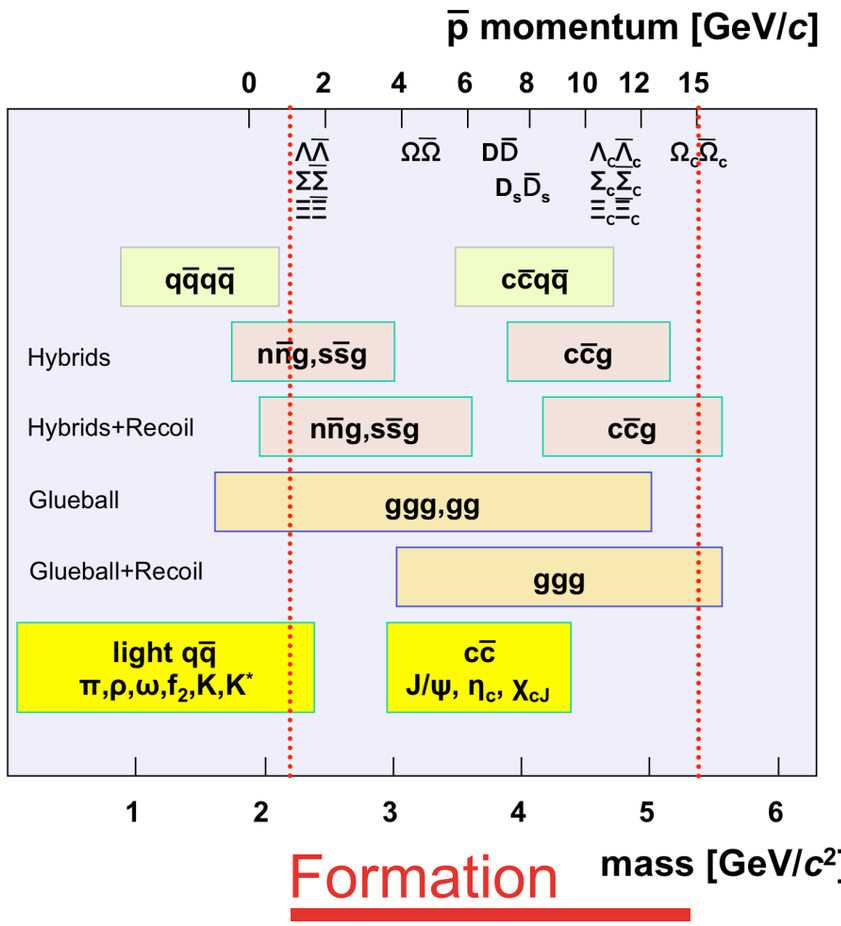


- Day-1:
  - Demonstrate feasibility to identify di-lepton (+π^0) events
  - Build database on multi-pion production in $\bar{p}p$ as input for QCD calculations

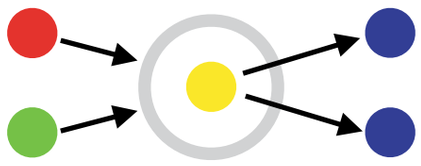




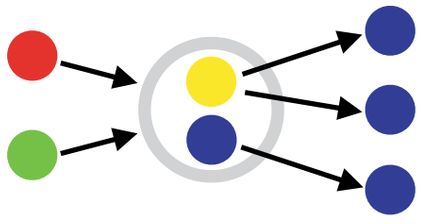
Hadron Spectroscopy @ PANDA



Formation



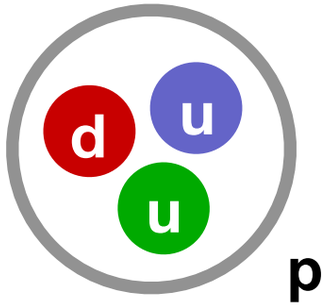
Production



- Large mass coverage: E_{CM} = (2 - 5.5) GeV
  - Light, strange and charm-rich hadrons
  - From quark/gluon to hadronic degrees of freedom
- High hadronic production rates
  - Strange and charm factory: Discovery by statistics
  - Gluon-rich production: Potential for new exotics
- Access to large spectrum of J^{PC} states
  - Formation of *all* conventional J^{PC} states
  - Large sensitivity for high spin states
- Associated hadron-pair production
  - Access to open-strange/charm hadrons
  - Tagging possibilities
  - Near threshold: Good resolution and low background

Exploring Hyperons

- What happens when replacing one or two light quarks with a strange quark?
- What are the relevant degrees of freedom?
  - Constituent quark model vs. meson exchange model
- Which role plays the spin?



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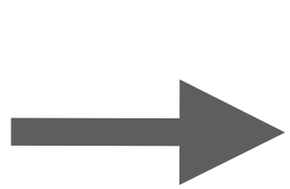
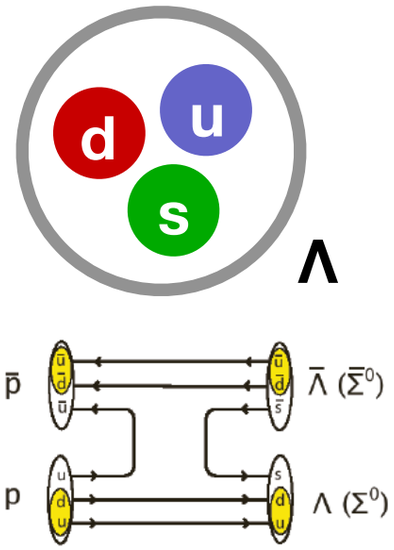
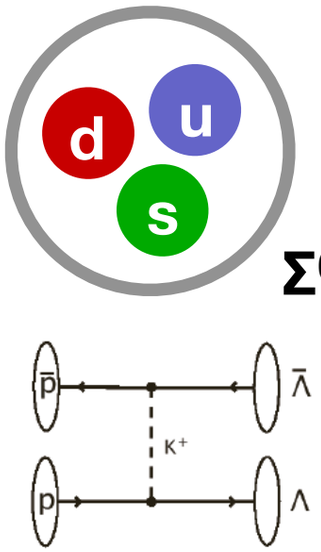
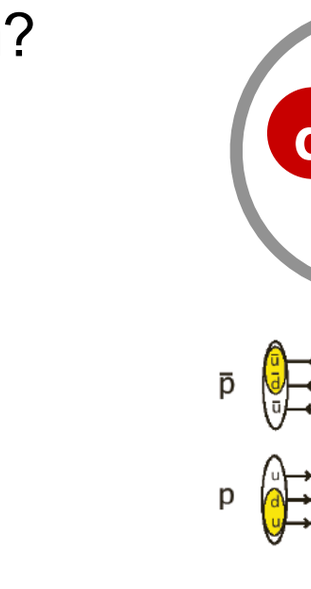
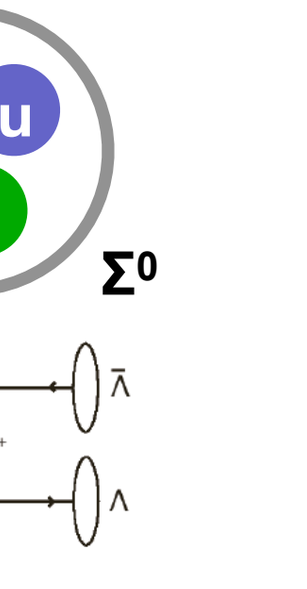




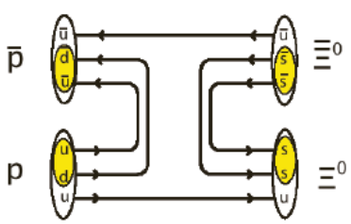


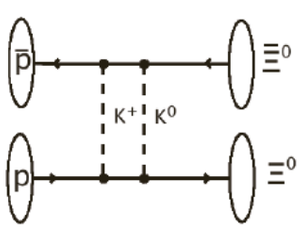


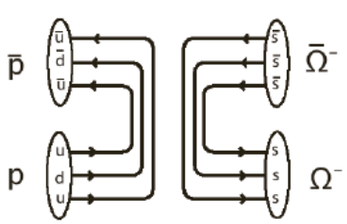
Ξ⁻

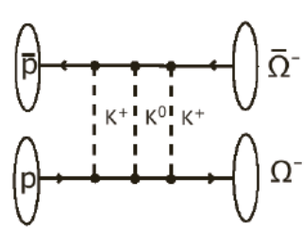


Ω⁻

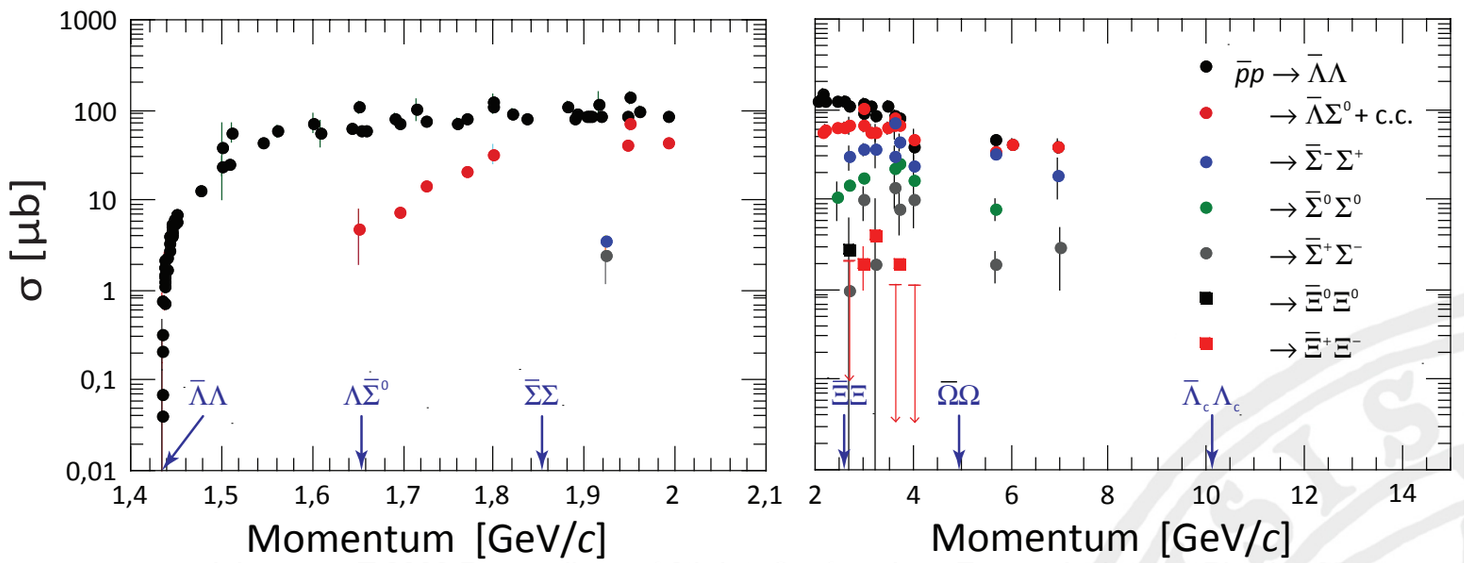








PANDA is a hyperon factory



Johansson T 2003 Proceedings of 8th Int. Conf. on Low Energy Antiproton Physics 95

- Lot of data on $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ near threshold recorded mainly by PS185 at LEAR
- No data on $\bar{p}p \rightarrow \bar{\Omega}\Omega$ or , $\bar{p}p \rightarrow \bar{\Lambda}_c \Lambda_c$
- Only scarce data above 4 GeV/*c*

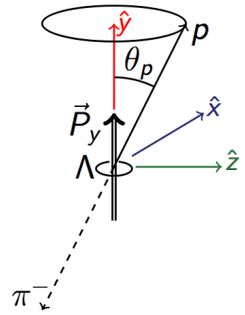
Phase-1

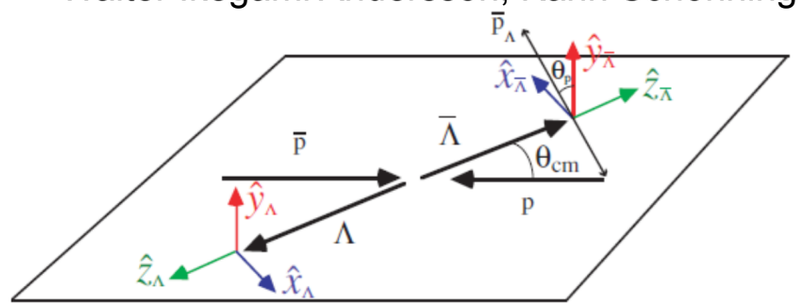
$p_{\bar{p}}$ (GeV/c)	Reaction	σ (μb)	Eff (%)	Decay	S/B	Rate (s^{-1}) at $10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
1.64	$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$	64.0 [94]	15.7	$\Lambda \rightarrow p\pi^-$	114	44
1.77	$\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$	10.9 [94]	5.3	$\Sigma^0 \rightarrow \Lambda\gamma$	> 11 (90% C.L.)	2.4
6.0	$\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$	20.0 [104]	6.1	$\Sigma^0 \rightarrow \Lambda\gamma$	21	5.0
4.6	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	1.0 [92]	8.2	$\Xi^- \rightarrow \Lambda\pi^-$	274	0.3
7.0	$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$	0.3 [92]	7.9	$\Xi^- \rightarrow \Lambda\pi^-$	165	0.1
4.6	$\bar{p}p \rightarrow \bar{\Lambda}K^+\Xi^- + c.c$	1	5.4	$\Xi^- \rightarrow \Lambda\pi^-$ $\Lambda \rightarrow p\pi^-$	> 19 (90% C.L.)	0.2

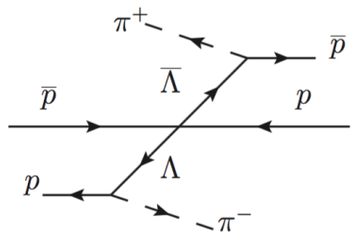
Hyperon Production and Spectroscopy

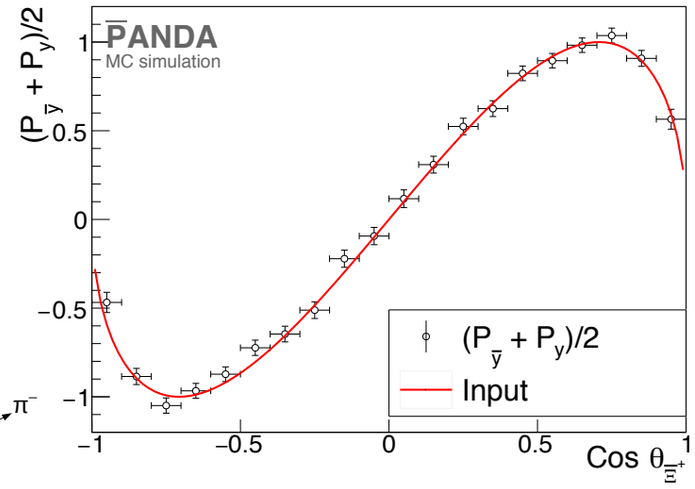
- Rich set of polarisation variables
- Double strange and charm baryons
- Explore hyperon dynamics above 4 GeV
- Day-1:
  - Reproduce LEAR studies at 1.64 GeV/*c*
  - Extend at 4 GeV and for |S| = 2 hyperons
- Phase-1:
  - Spin correlations in |S| = 1, 2
  - Extend to |S| = 3 and charmed hyperons

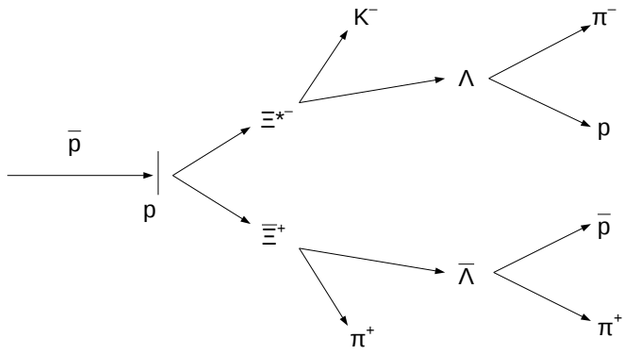
Walter Ikegami Andersson, Karin Schönning



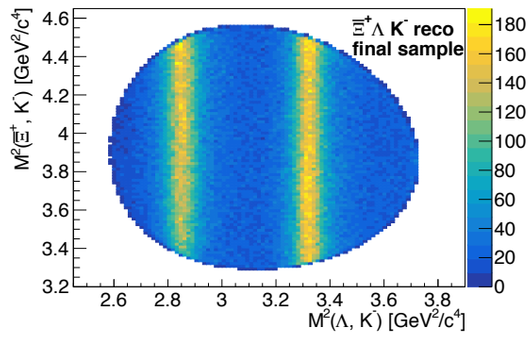


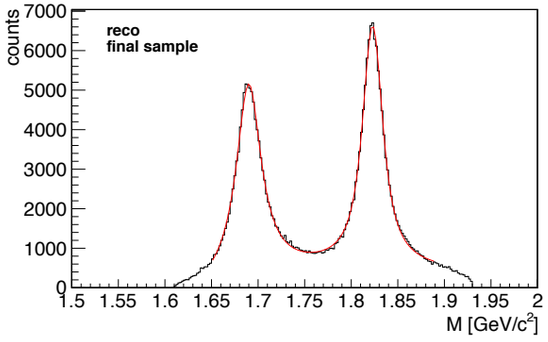






Jenny Pütz, Albrecht Gillitzer





Hypernuclei

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

rescattering in
primary target nucleus

deceleration in
secondary target

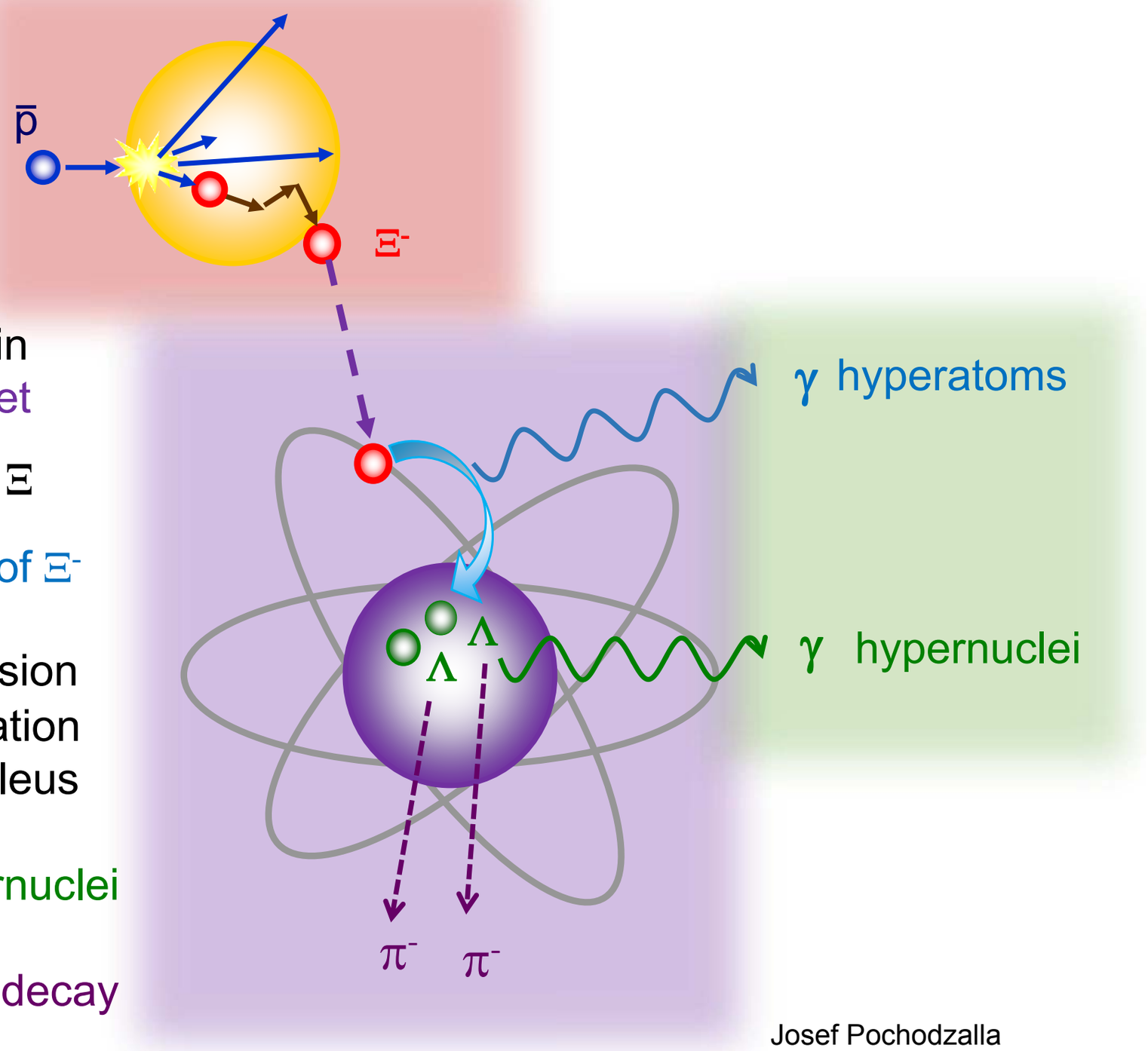
capture of Ξ

atomic cascade of Ξ^-

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

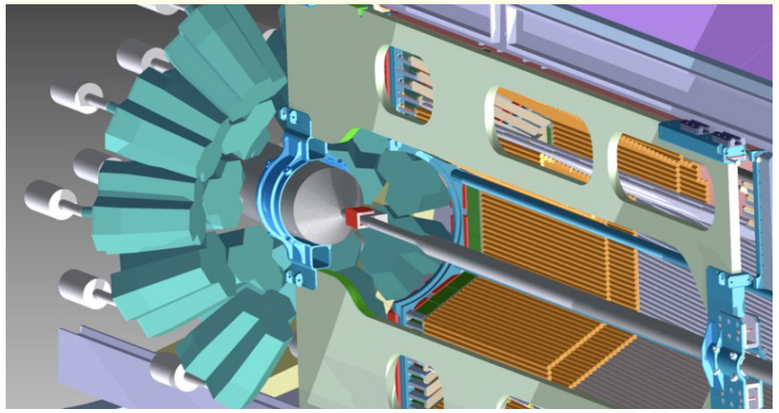
γ-decay of $\Lambda\Lambda$ hypernuclei

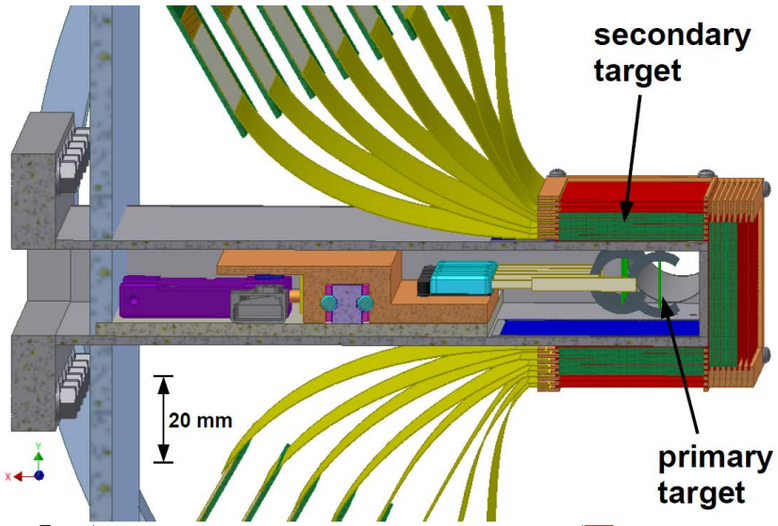
weak pionic decay

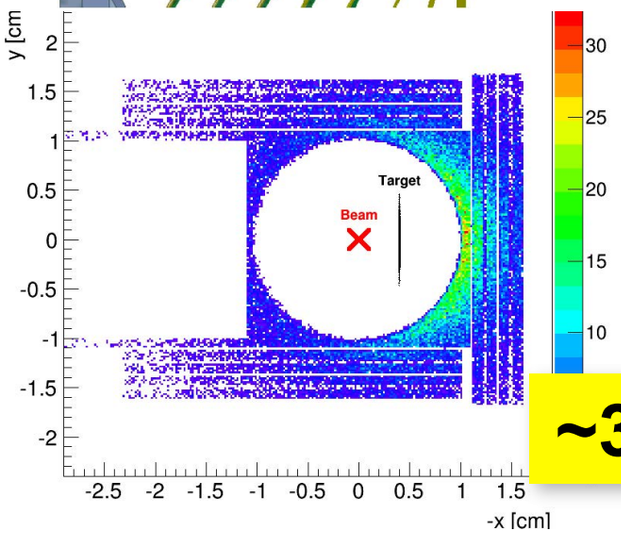


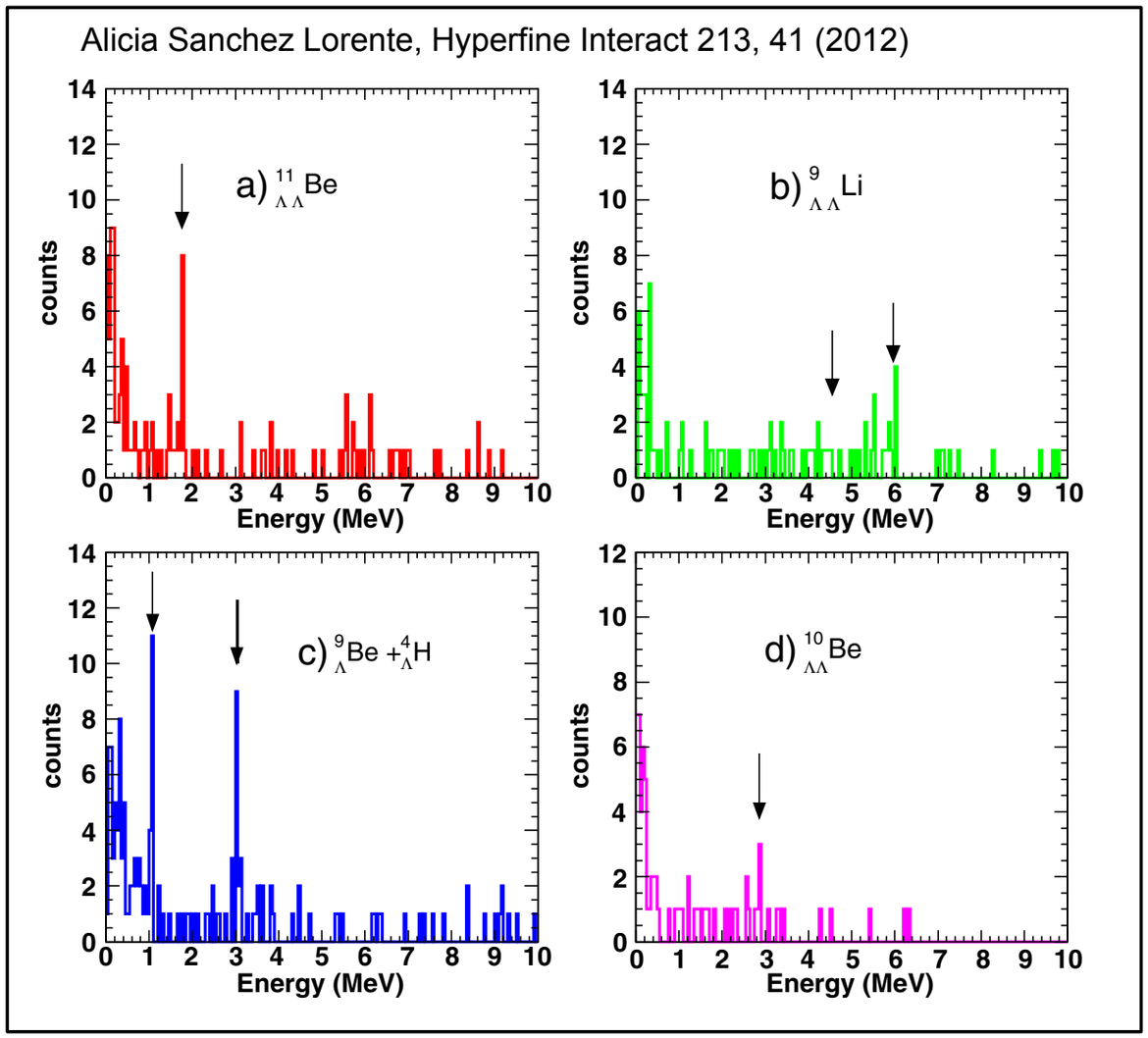
Josef Pochodzalla

Double Hypernuclear Spectroscopy







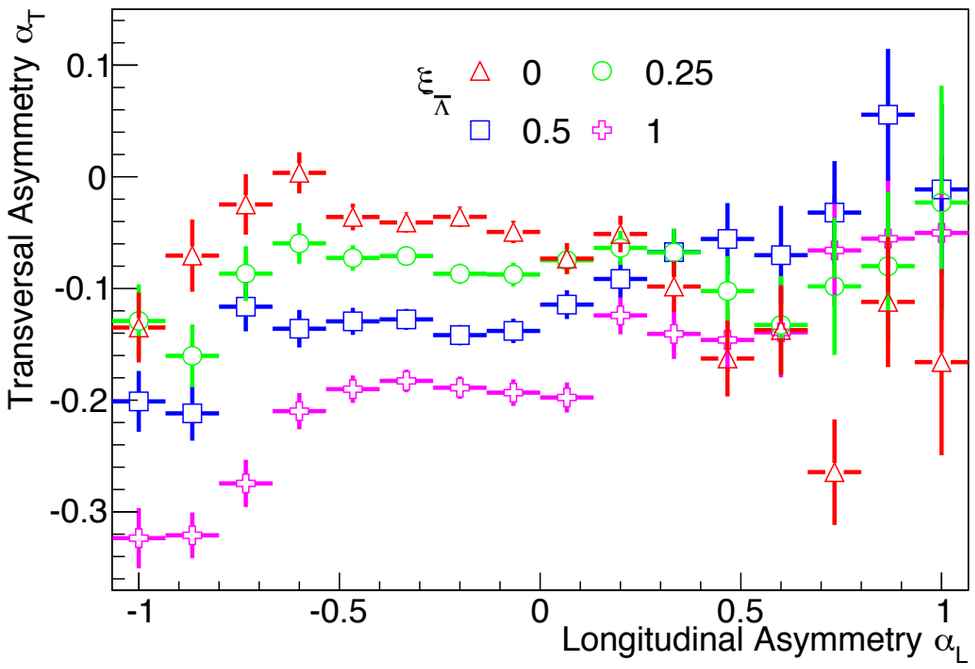


~33.000 stopped Ξ^-'s per day

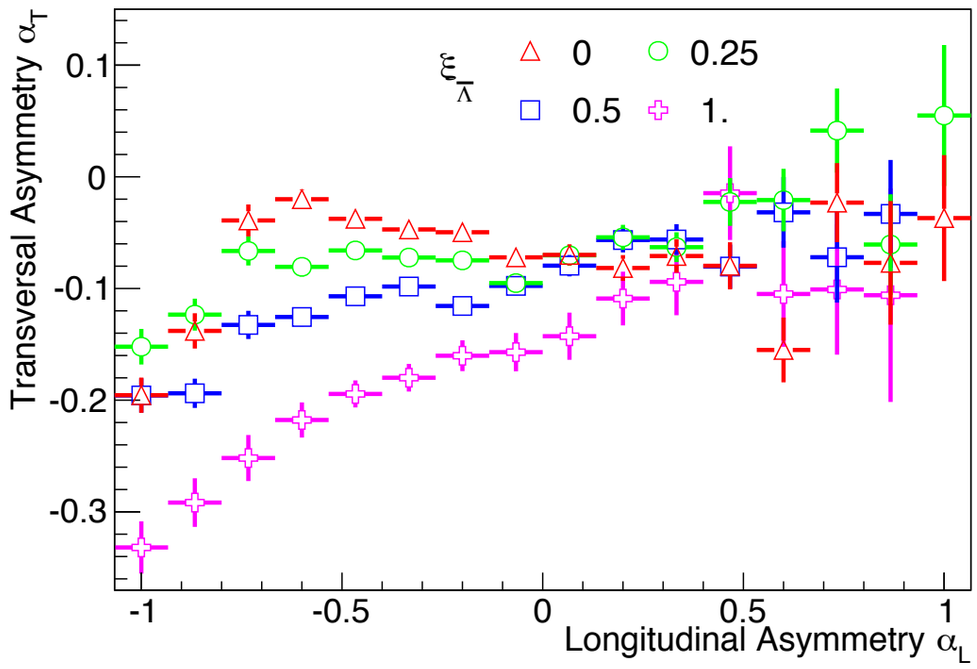
Josef Pochodzalla

Antihyperons in Nuclei

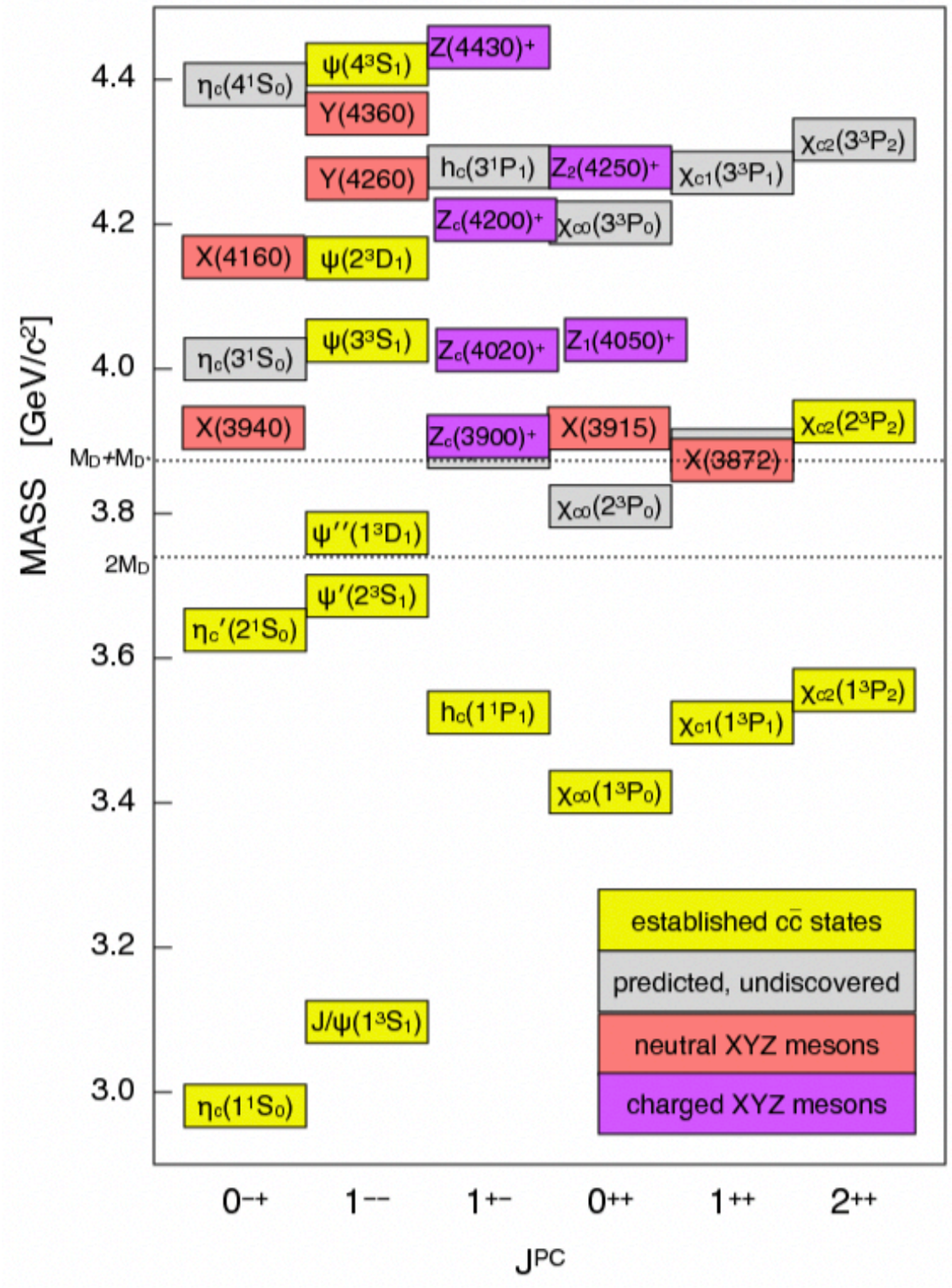
- Antiprotons sensitive to study antihyperon potential in nuclei
- Exploit abundantly produced hyperon-antihyperon pairs near threshold
- Benchmark data to test theoretical concepts to describe dynamics of (anti)hyperons in heavy-ion collisions
- Important first step of the |S| = 2 program of PANDA



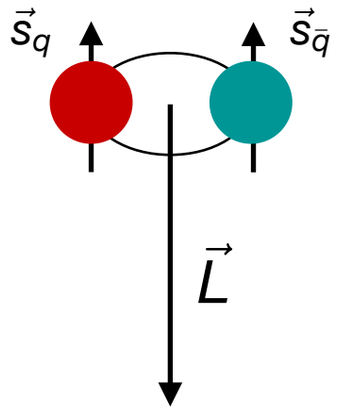
Josef Pochodzalla



Charmonium Spectroscopy



- Below the open charm threshold
  - Potential model description matches observations
- Above the open charm threshold
  - Predicted states not found but multiple unexpected discovered!



$$\vec{S} = \vec{s}_q + \vec{s}_{\bar{q}}$$

$$\vec{J} = \vec{L} + \vec{S}$$

$$P = (-1)^{L+1}$$

$$C = (-1)^{L+S}$$

Example from Barnes, Godfrey, Swanson:

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

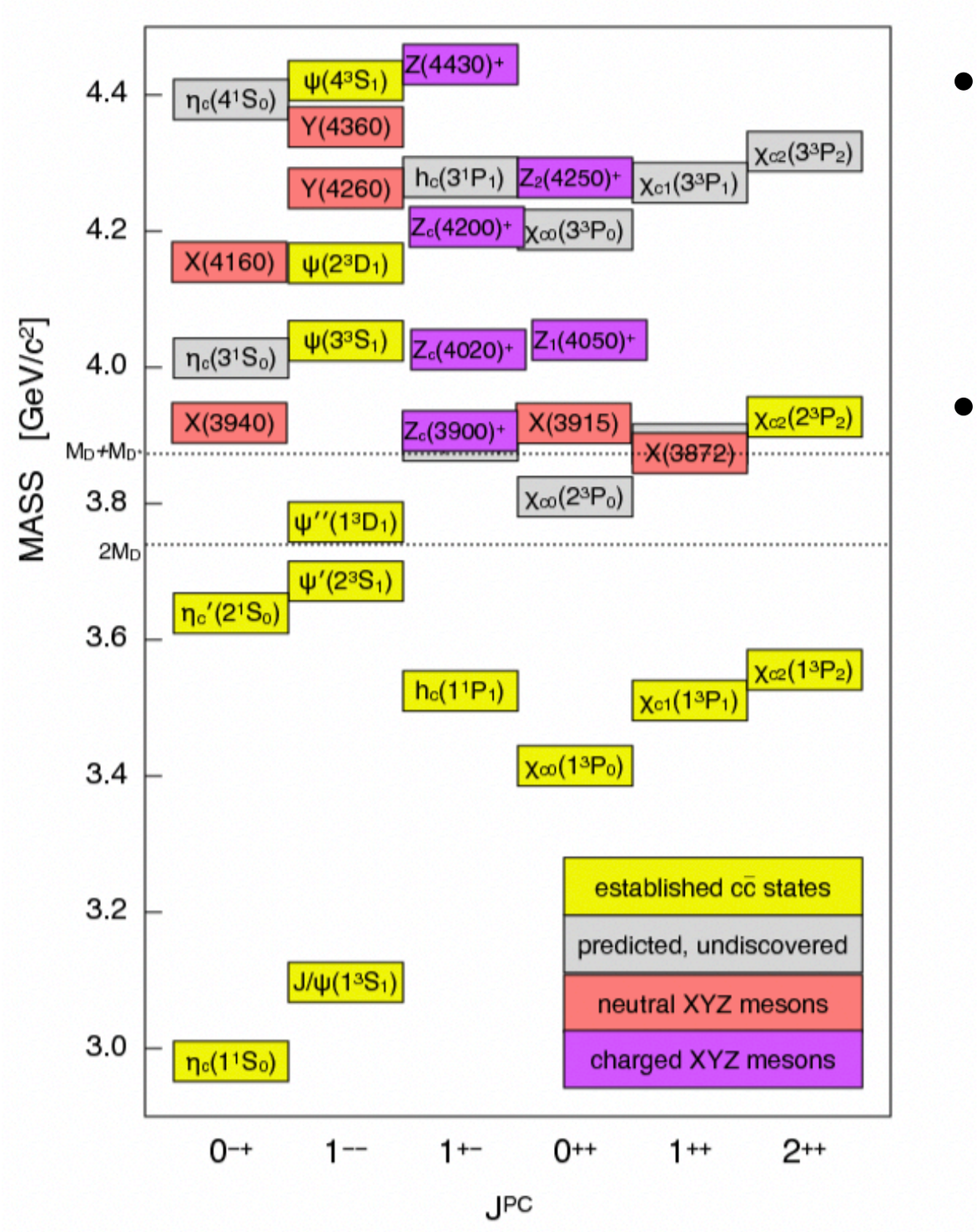
(Coulomb + Confinement + Contact)

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

(Spin-Orbit + Tensor)

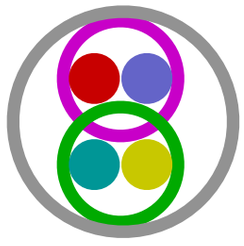
PRD72, 054026 (2005)

Charmonium Spectroscopy

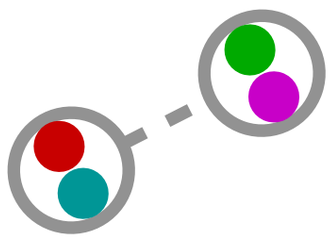


- Day-1:
  - Exploration of new Z states using direct formation
  - Line-scan proof of principle with narrow conventional charmonia
- Phase-1:
  - Search for high-spin states with hidden charm
  - Line-scan of exotic candidates such as X(3872)

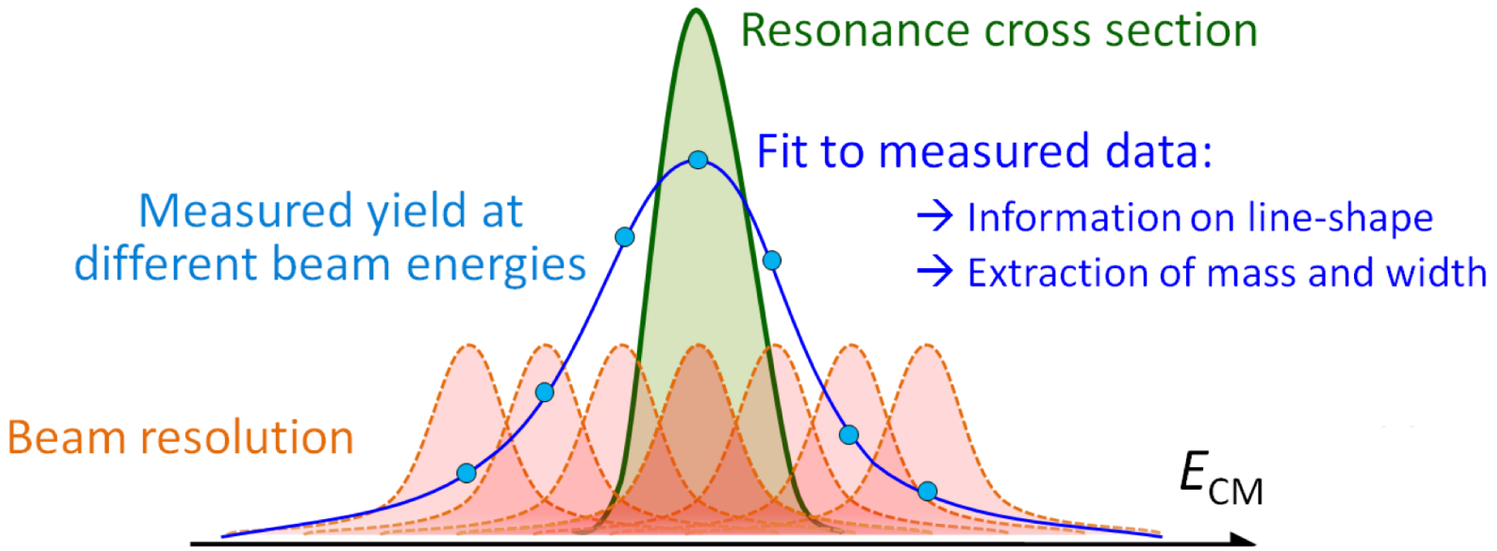
Tetraquark

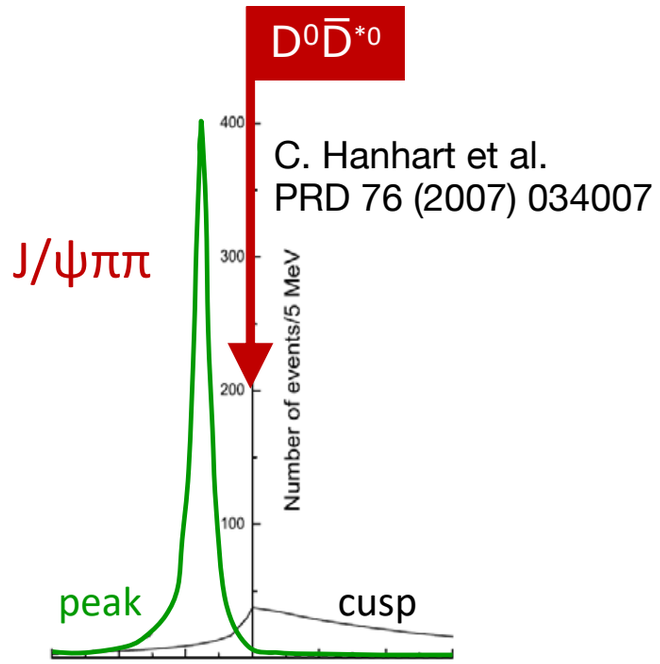


Molecule



Line-Scan of X(3872)



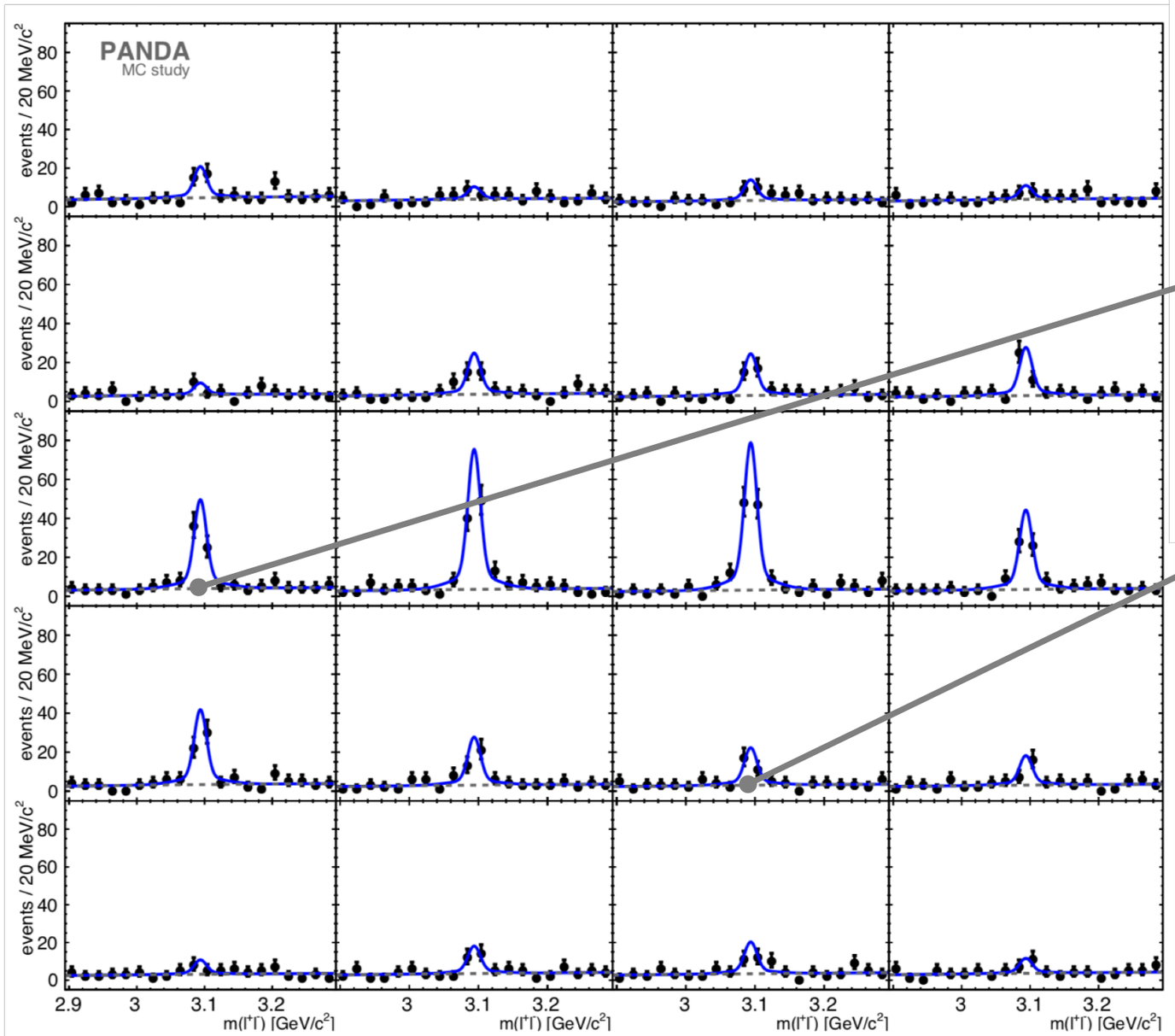


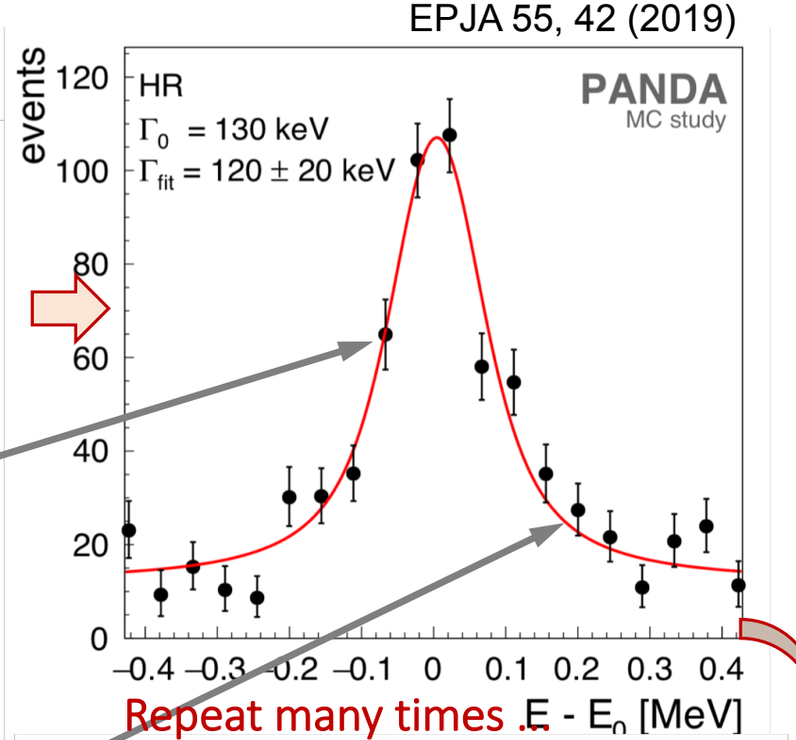
- Resolution with e^+e^-: 1 - 2 MeV ($J^{PC} = 1^{--}$)
- Resolution with $\bar{p}p$ at E760/835@FermiLab: 250 keV
- Resolution with $\bar{p}p$ at $\bar{P}$ANDA@FAIR: ~50 keV
- Exact line shape reveal the nature of this strikingly narrow state (Γ<1.2 GeV): Is it a virtual or bound state?
- Simulation study for line scan of the “mysterious” X(3872) has been performed
- Analysis performed for $\bar{p}p \rightarrow X(3872) \rightarrow J/\psi\pi^+\pi^-$
  - Generated data samples for each scan point
  - Extracted X(3872) signal and reconstruct input line shape

Line-Scan Procedure

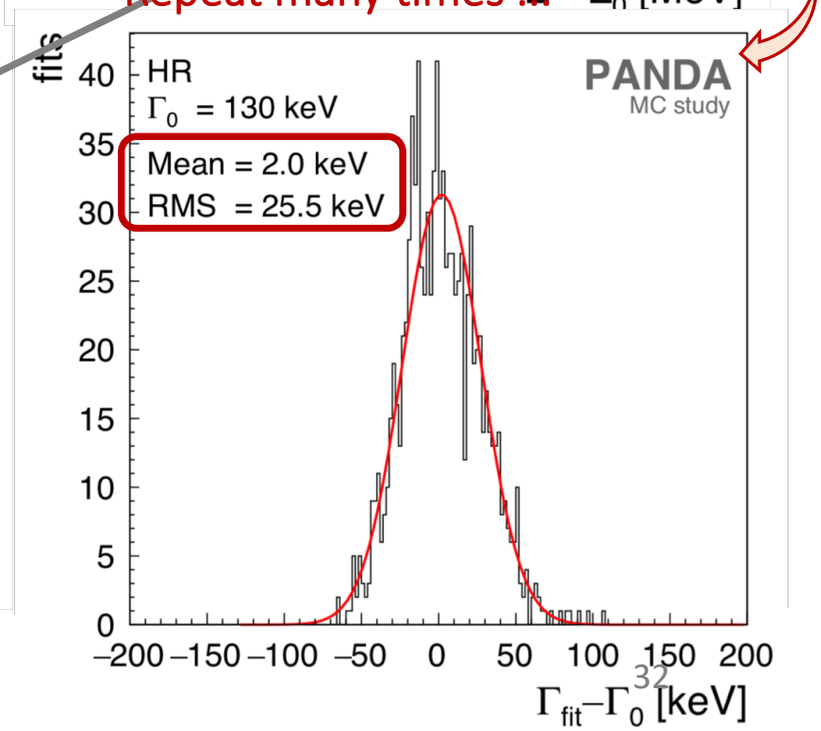
EPJA 55, 42 (2019)

20 E_{cms} scan point within ±0.4 MeV window around nominal mass



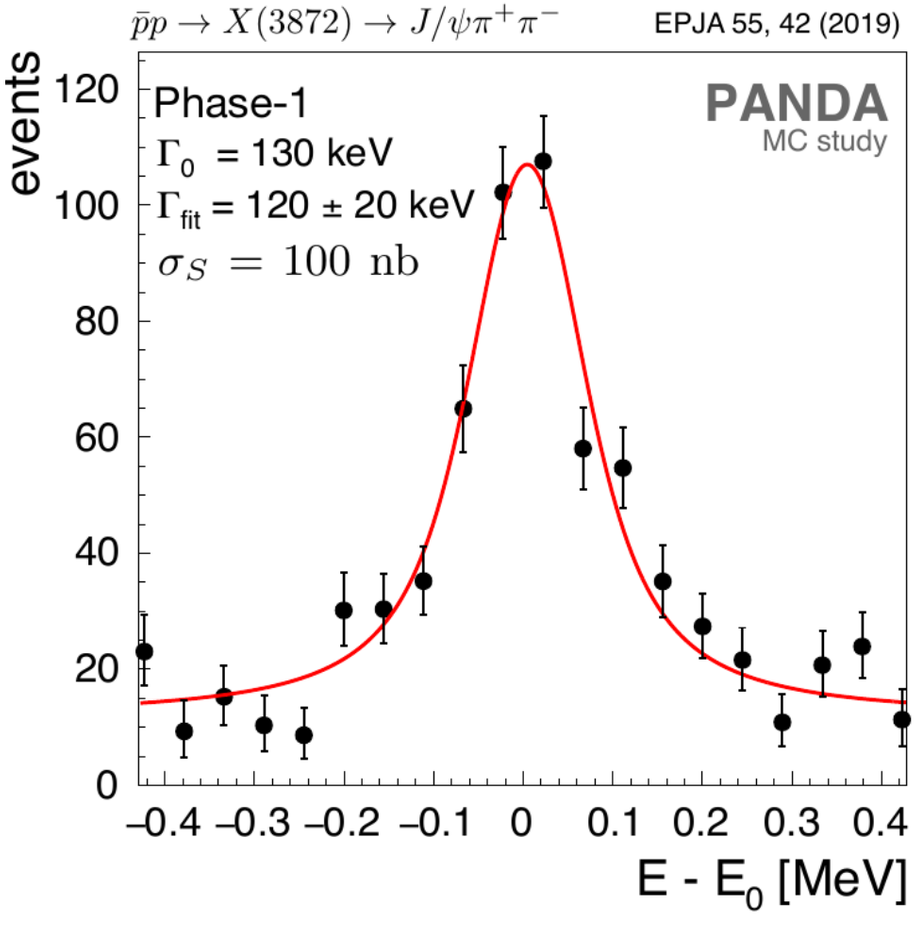


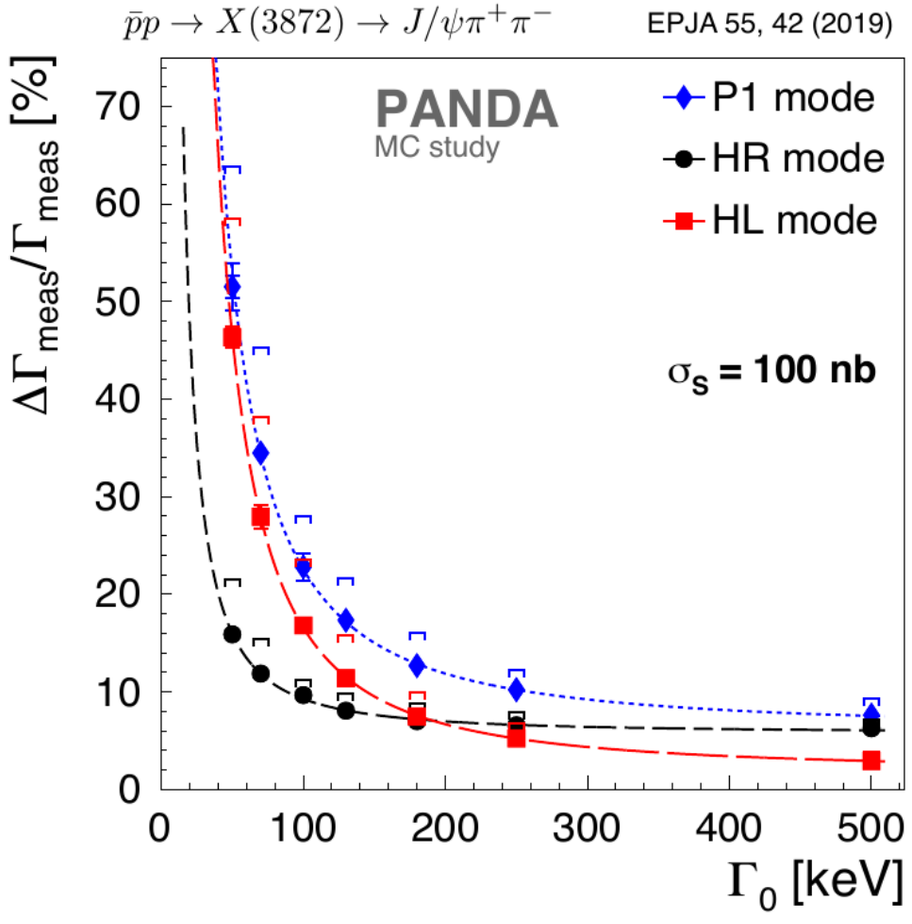
Repeat many times ...



Line-Scan Performance

- Extract width Γ from fit to energy dependent yield
- Study was performed for various assumptions (cross section, beam resolution, …)
- Outcome: Depending on operating mode, 3σ significance can be achieved down to Γ = 40 - 80 keV

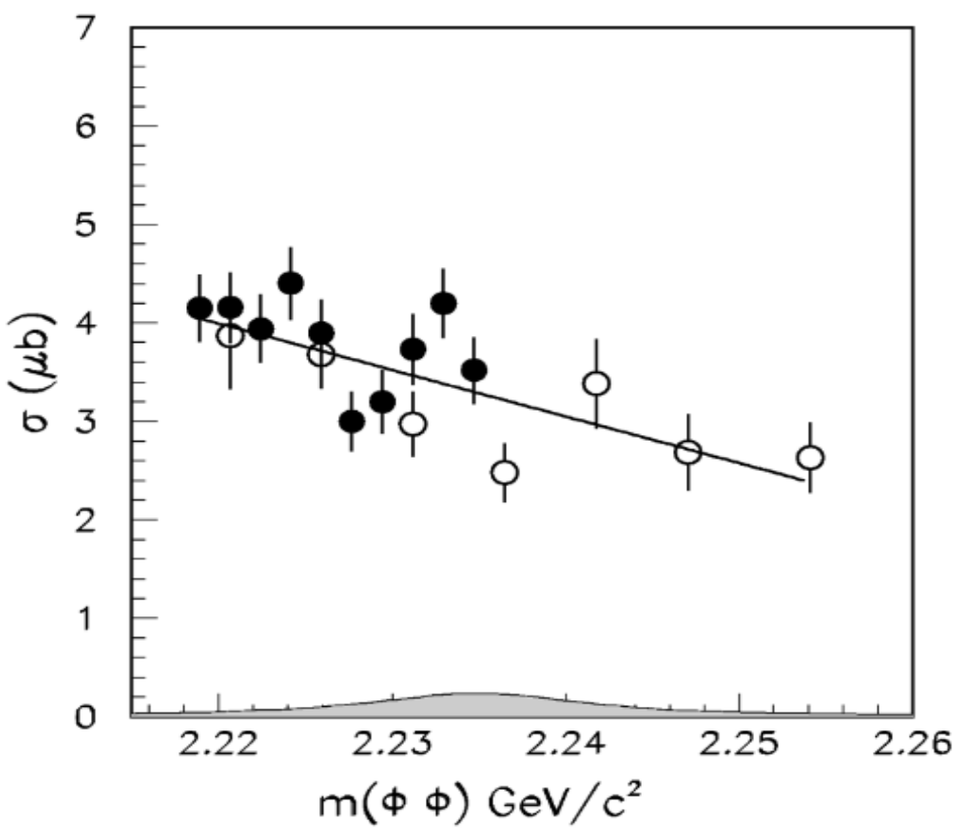




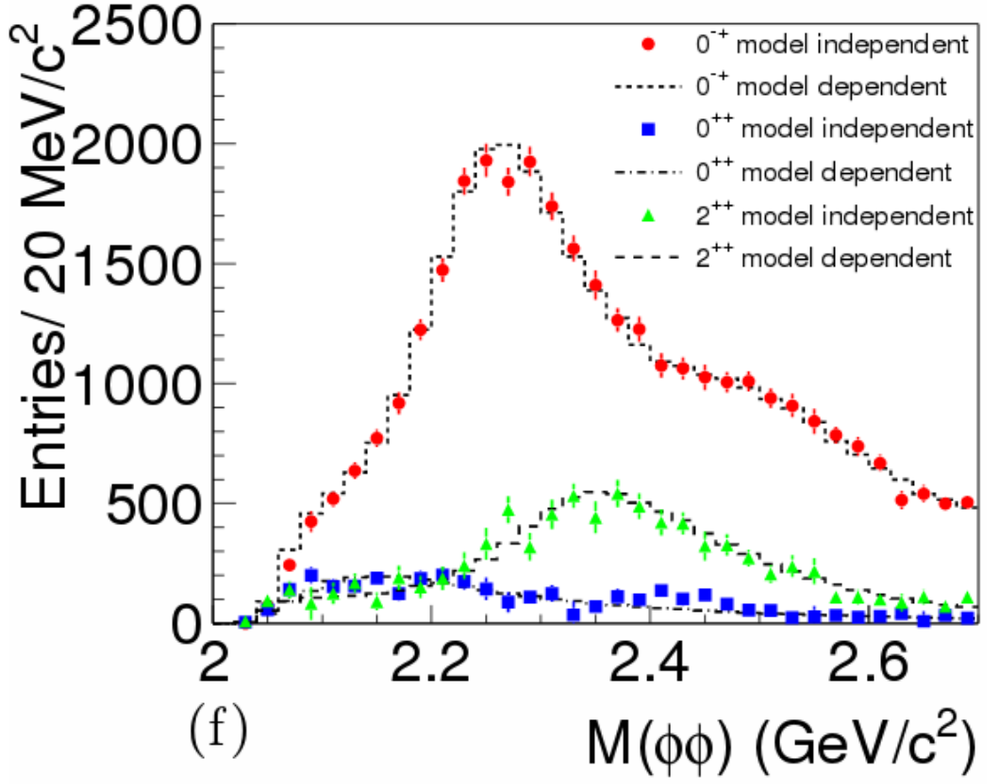
Glueball Search in $\bar{p}p \rightarrow \varphi\varphi$

- $\bar{p}p \rightarrow \varphi\varphi$ cross section exceeds expectation by two orders of magnitude
- Observation of multiple f_2 states with M > 2 GeV in $\pi p \rightarrow \varphi\varphi n$ and $J/\psi \rightarrow \gamma\varphi\varphi$
- Possible sign of intermediate glueball state?
- LQCD predicts tensor glueball state around ~2.4 GeV!

JETSET, Phys.Rev.D57,5370

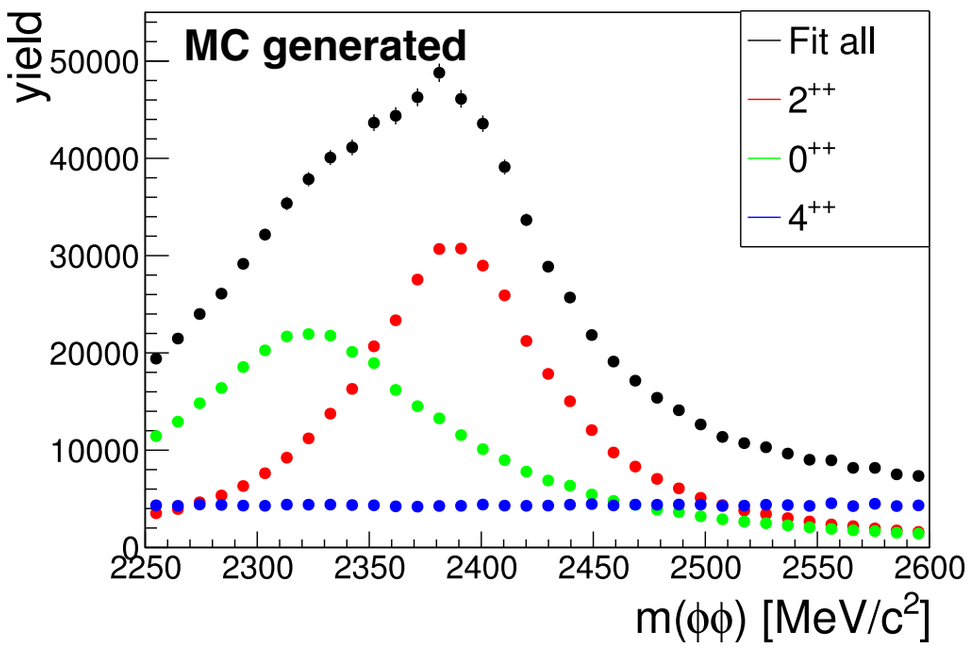


BESIII, Phys.Rev.D93,112011

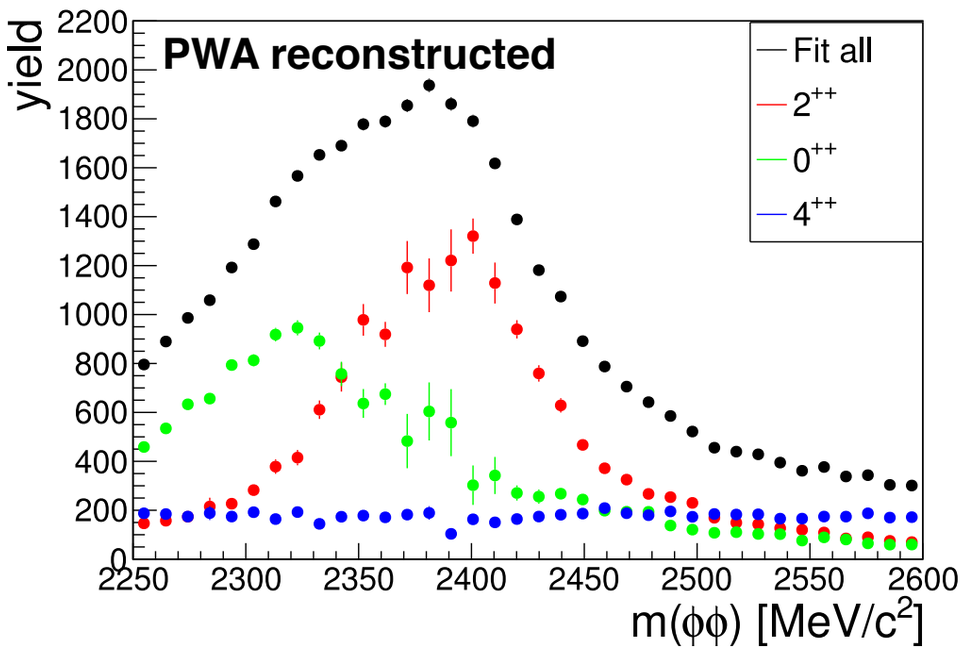


Glueball Search in $\bar{p}p \rightarrow \varphi\varphi$

- Scan above 2.25 GeV: terra incognita
- 0^{++}, 2^{++} and 4^{++} accessible
- Conventional mesons suppressed due to OZI
- Partial wave analysis to distinguish resonant from non-resonant contributions
- 5×10^4 reconstructed events/day at $L=10^{31}$ $cm^{-2}s^{-1}$
- physics studies at reduced luminosities feasible



Iman Keshk



Physics Prospects of PANDA at FAIR

- Cover particle, hadron and nuclear aspects
  - ✦ Quark degrees of freedom: from light to charm
  - ✦ Gluon degrees of freedom: glueballs, hybrids etc.
  - ✦ Meson/baryon degrees of freedom: B-B interaction
- Complementary and competitive
  - ✦ Unique antiproton facility
  - ✦ Versatile detector
- Follow a staged approach
  - ✦ Driven by stepwise luminosity/detector upgrades
  - ✦ With a broad program at each phase
- Open for collaboration and new ideas!