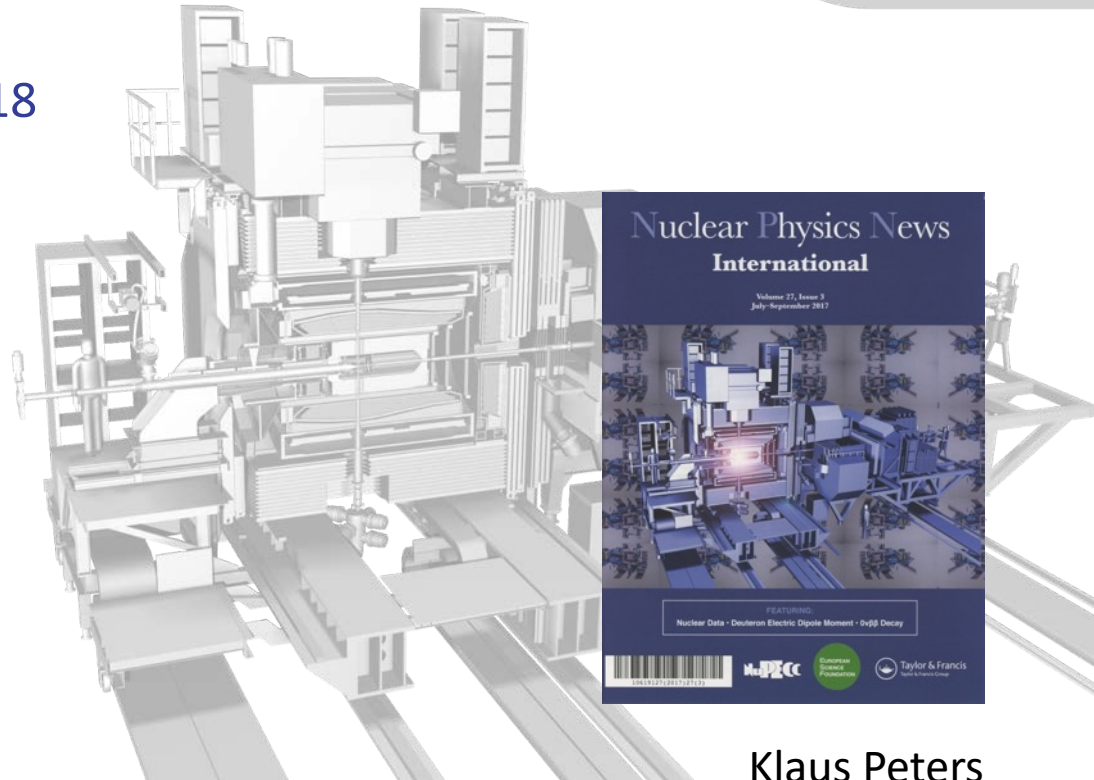


# PANDA COLLABORATION Status & Highlights

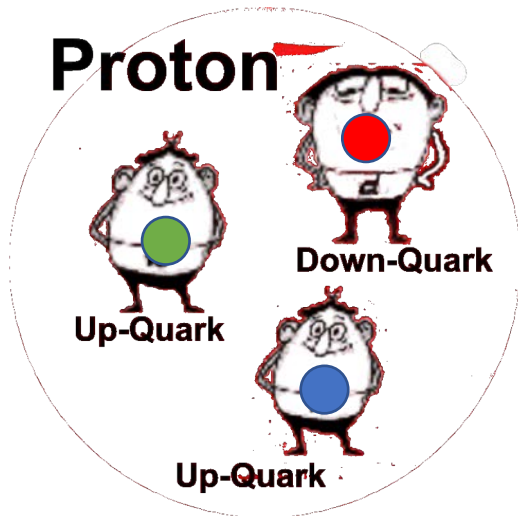
International School on High Energy Physics  
Salvador de Bahia, Sept 11, 2018



Klaus Peters  
GSI/U Frankfurt

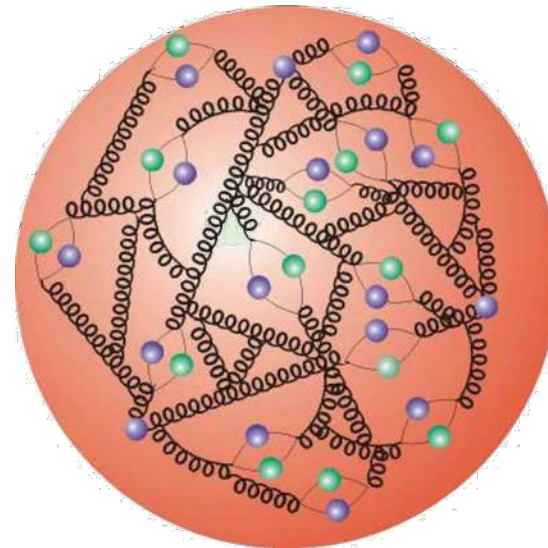
# The Proton – and its mass

the usual picture is, that the **Proton** consists of a **few Quarks**



a **Proton** is one configuration  
In general they are called **Hadron**  
(from old-gr. *ἄδρός hadrós* ,thick' ,strong')

if you look **more closely**,  
things appear to be more **complicated**

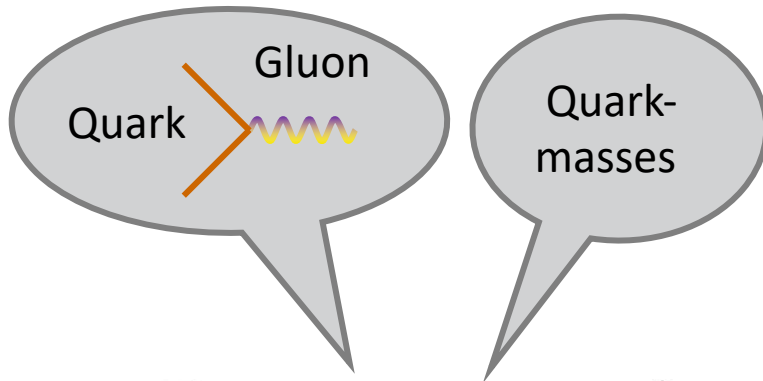


In addition there  
is glue → **Gluons**

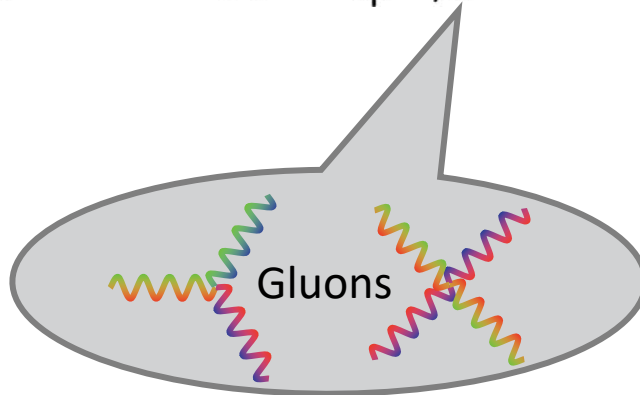
# QCD – Quantum Chromo Dynamics



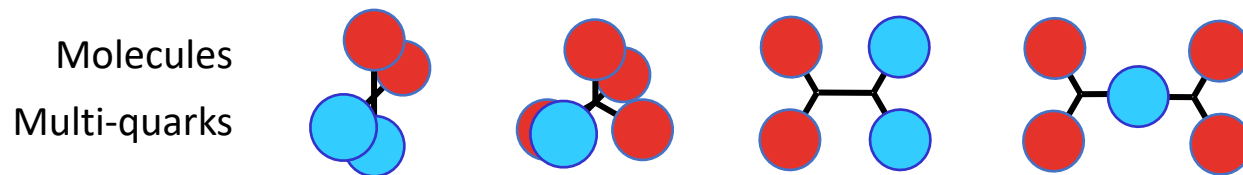
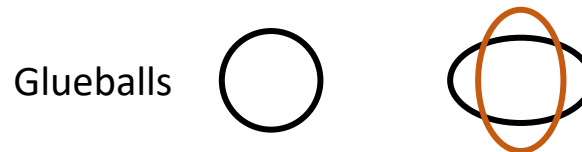
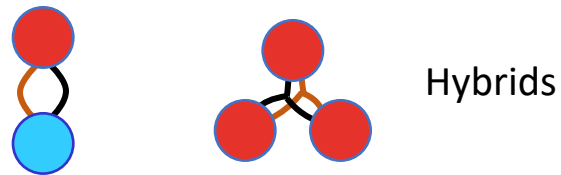
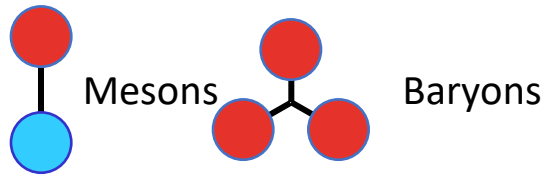
Fritzsch, Gell-Mann, Leutwyler 1973



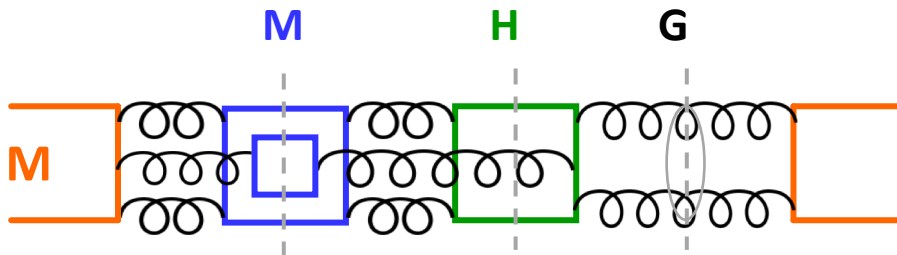
$$L_{QCD} = \bar{\psi}(i\gamma_{\mu}D^{\mu} - m)\psi - \frac{1}{4}G_{\mu\nu}G^{\mu\nu}$$



Quarks		spin=1/2	
Flavor		Approx. Mass GeV/c <sup>2</sup>	Charge
<b>u</b>	up	0.003	2/3
<b>d</b>	down	0.006	-1/3
<b>c</b>	charm	1.3	2/3
<b>s</b>	strange	0.1	-1/3
<b>t</b>	top	175	2/3
<b>b</b>	bottom	4.3	-1/3
Gauge Boson		spin=1	
Name		Mass GeV/c <sup>2</sup>	Charge
<b>g</b>	gluon	0	0



## Presence of mixing



non- $q\bar{q}$  states expected to contribute to the meson wave function

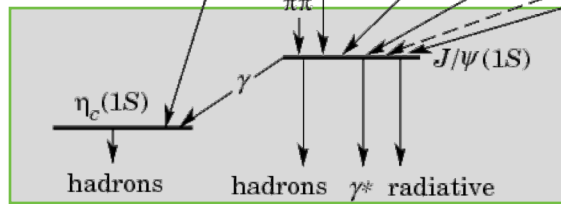
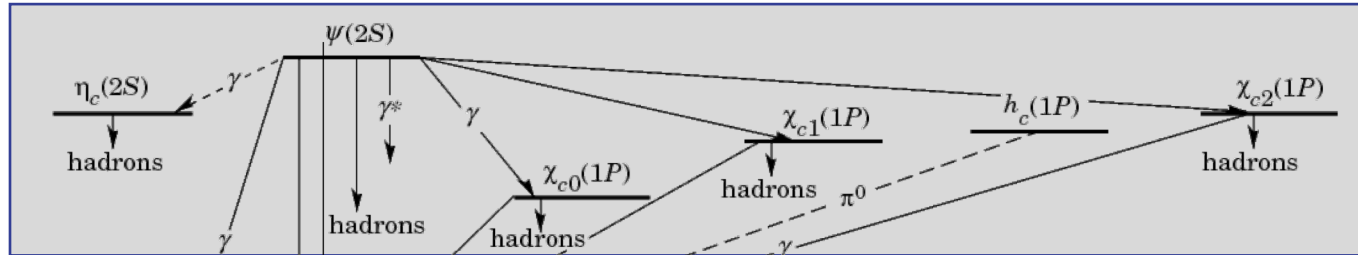
exotics can (and will) mix with conventional  $q\bar{q}$  states for identical quantum numbers

$$\begin{aligned}
 & q\bar{q} \quad + \quad \text{[diagram: two spheres connected by a straight line]} \\
 & + \\
 & (q\bar{q})(q\bar{q}) \quad + \quad \text{[diagram: two pairs of spheres connected by straight lines]} \\
 & + \\
 & (q\bar{q})g \quad + \quad \text{[diagram: two spheres connected by a wavy line]} \\
 & + \\
 & gg \quad + \quad \text{[diagram: a rectangular loop]} \\
 & + \dots
 \end{aligned}$$

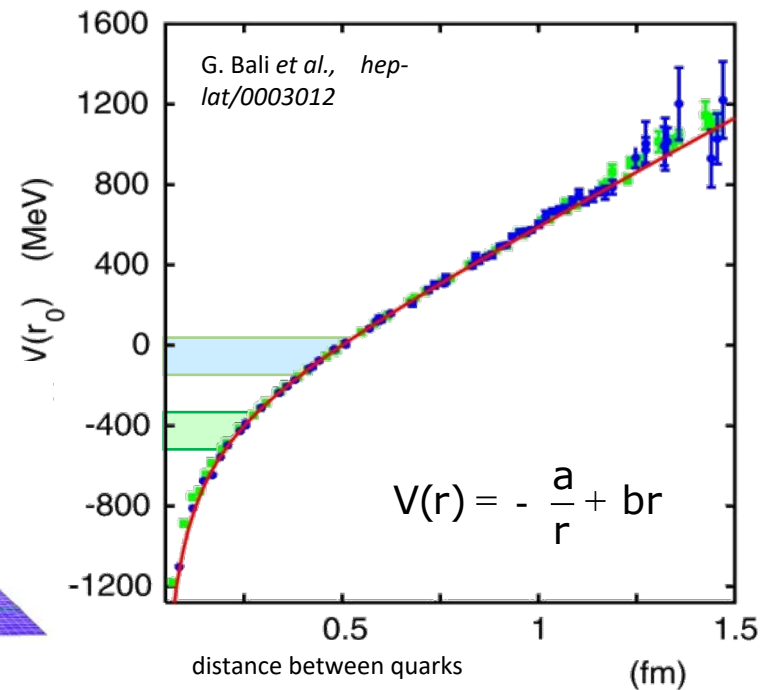
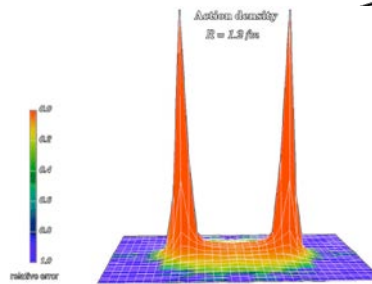
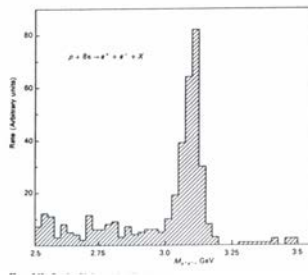
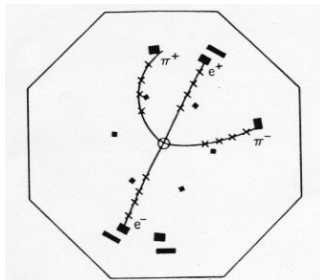

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$$\text{[diagram: two overlapping spheres]} = \sum_i (q\bar{q})_i \sum_j g_j$$

# Charmonium

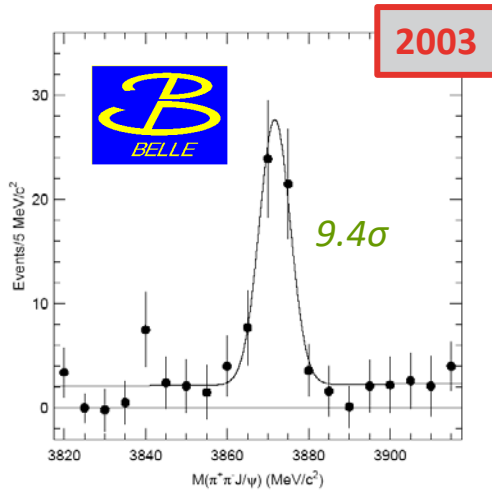


$J^{PC} = \quad 0^{-+} \quad \quad 1^{--} \quad \quad 0^{++} \quad \quad 1^{++}$

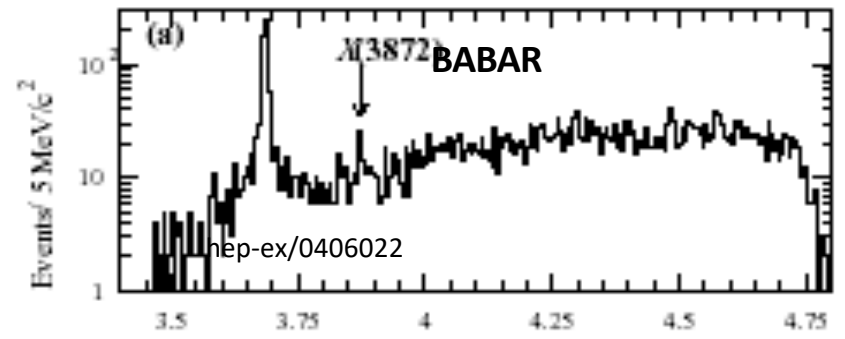
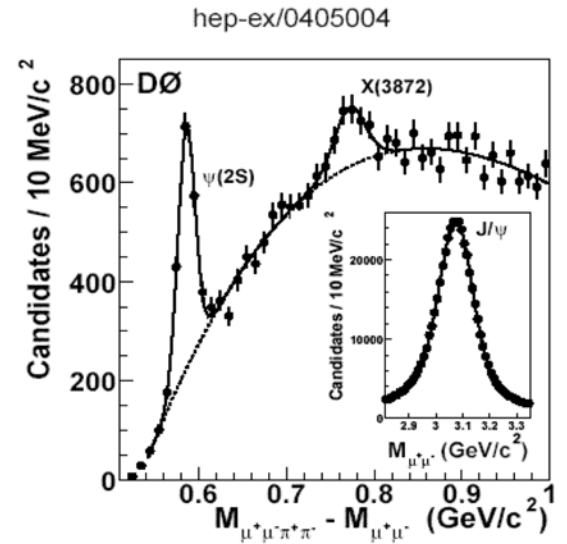
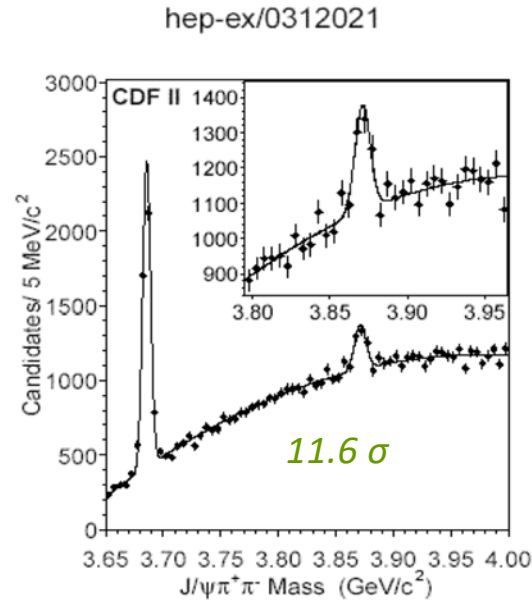


J.E. Augustin *et al.*, Mark I, Phys. Rev. Lett. 33, 1406–1408 ( $\psi$ )  
 J.J. Aubert *et al.*, BNL, Phys. Rev. Lett. 33, 1404–1406 ( $J$ )

# Discovery of the X(3872)

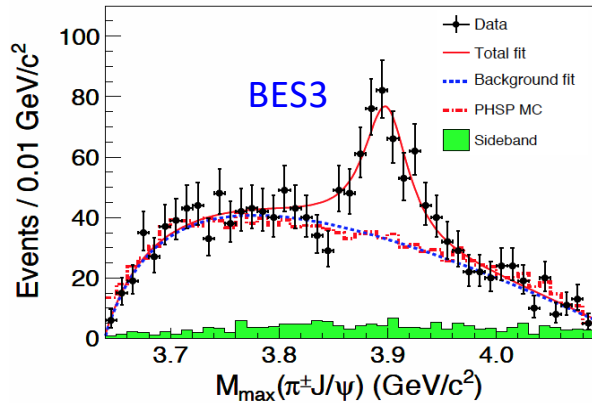


Phys. Rev. Lett. 91(2003)262001  
152 Mill. BB

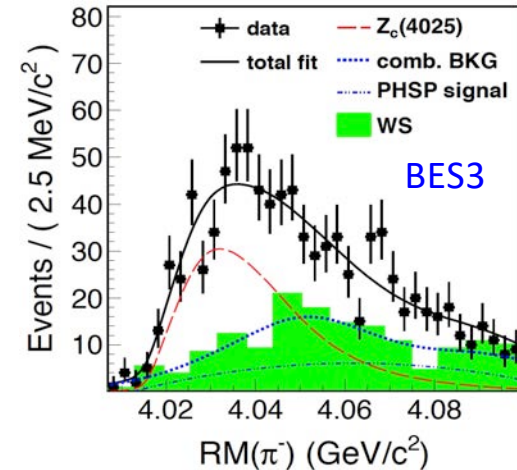
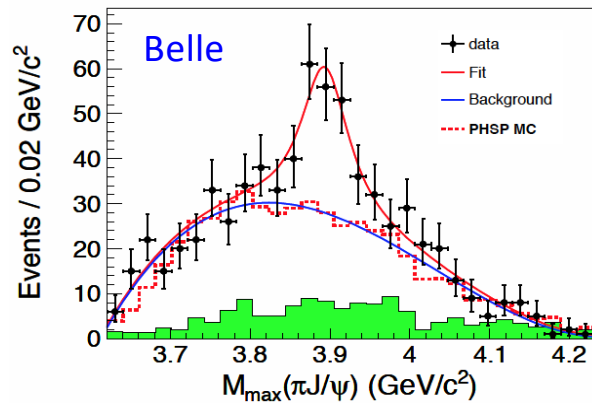


# Discovery of the $Z^+(3900)$

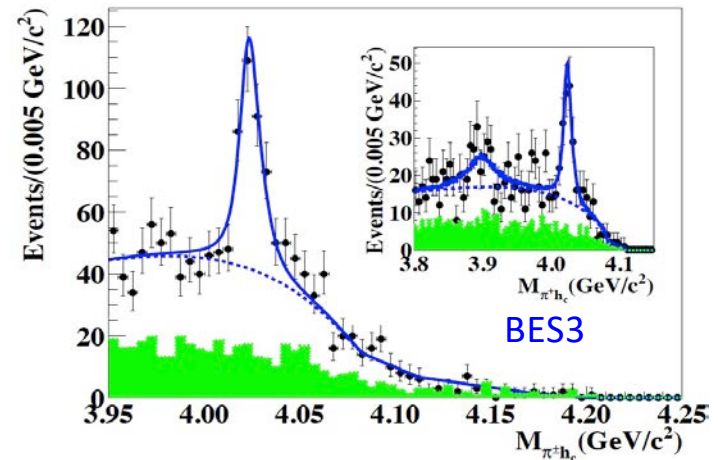
2013



Discovery of the  $Z_c^{+/-}$  (3900) in the  $J/\psi \pi^{+/-}$  invariant mass spectrum in the decay  $\Upsilon(4260) \rightarrow J/\psi \pi^+\pi^-$

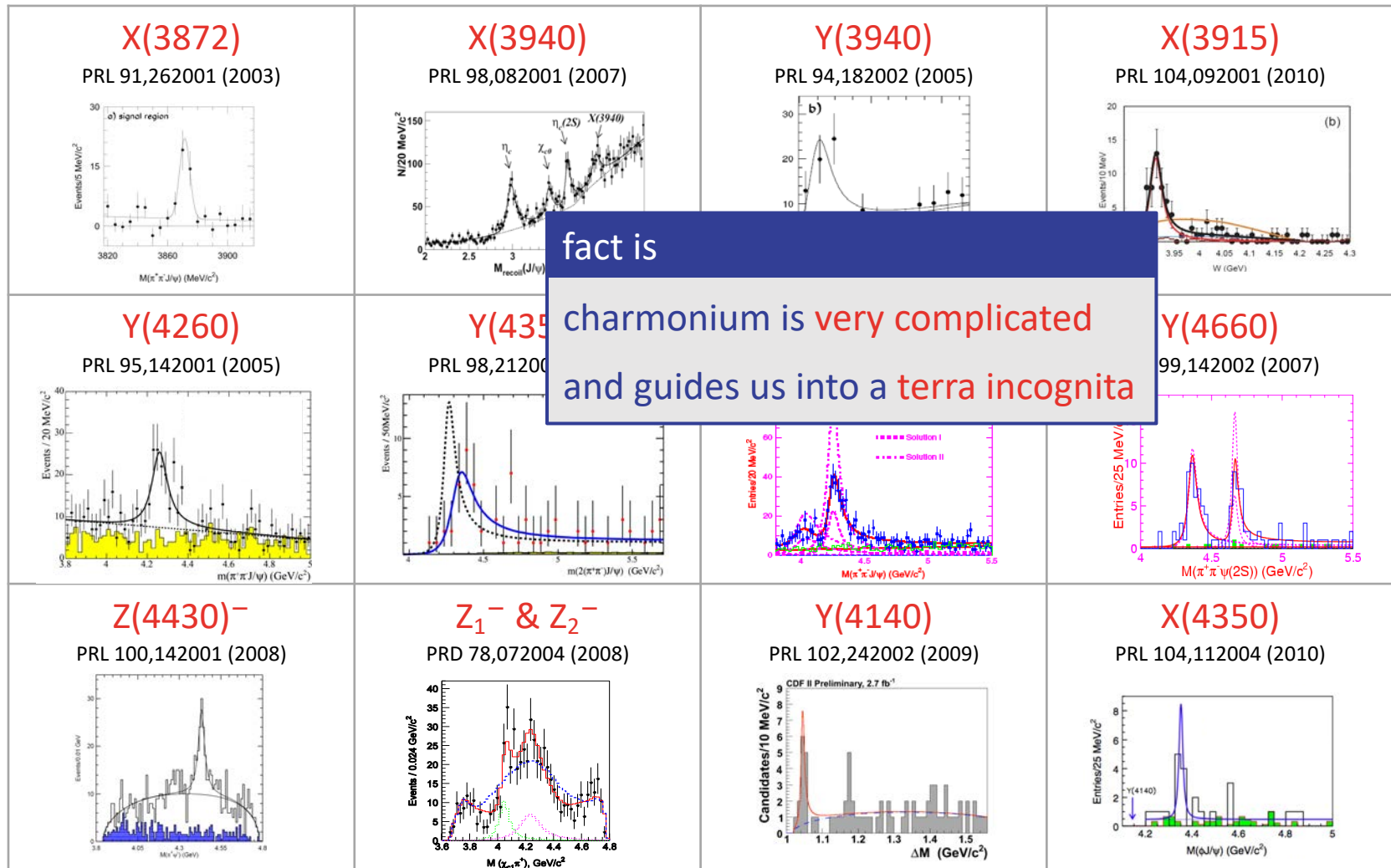


Observation of the  $Z_c^{+/-}(4025)$  in the  $h_c\pi^{+/-}$  and  $\bar{D}^*D^*$  invariant spectrum in  $\Upsilon(4260/4360)$  decays

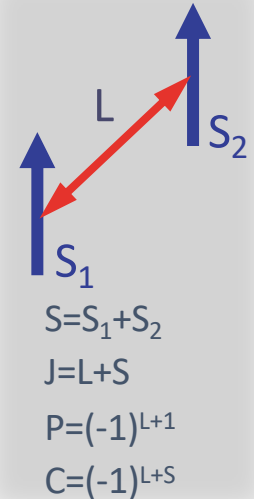
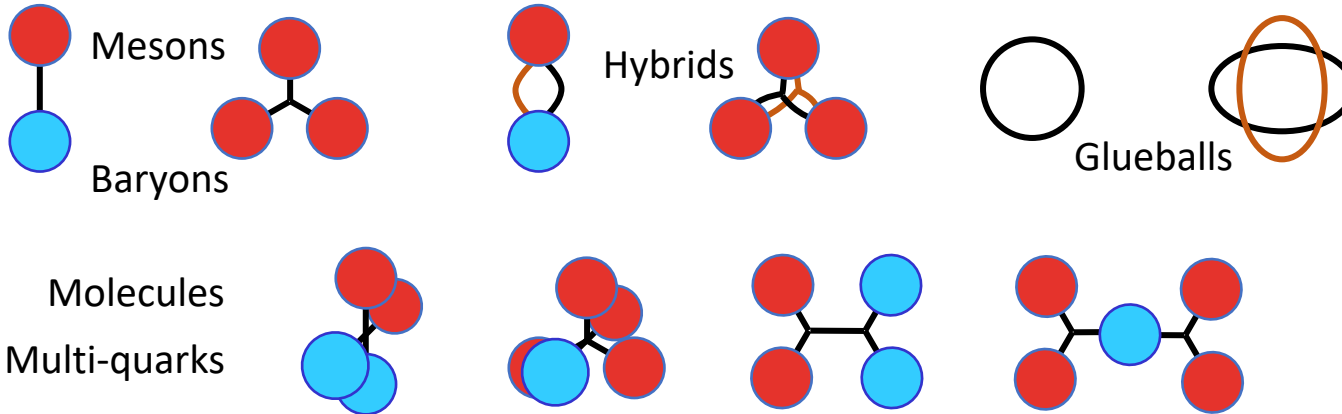




# New Charmonium-like Discoveries

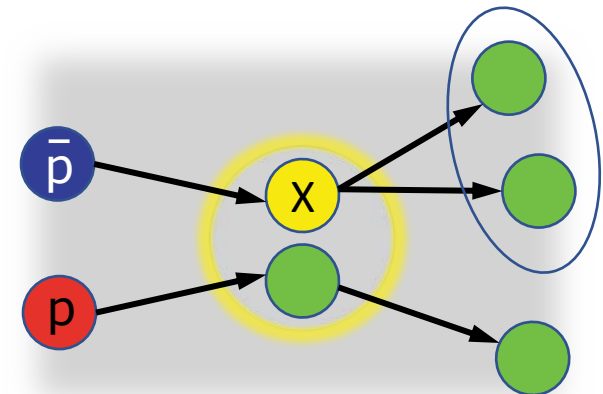


# Production of Hadronic States



**Production** all exotic and non-exotic quantum numbers accessible with a recoil

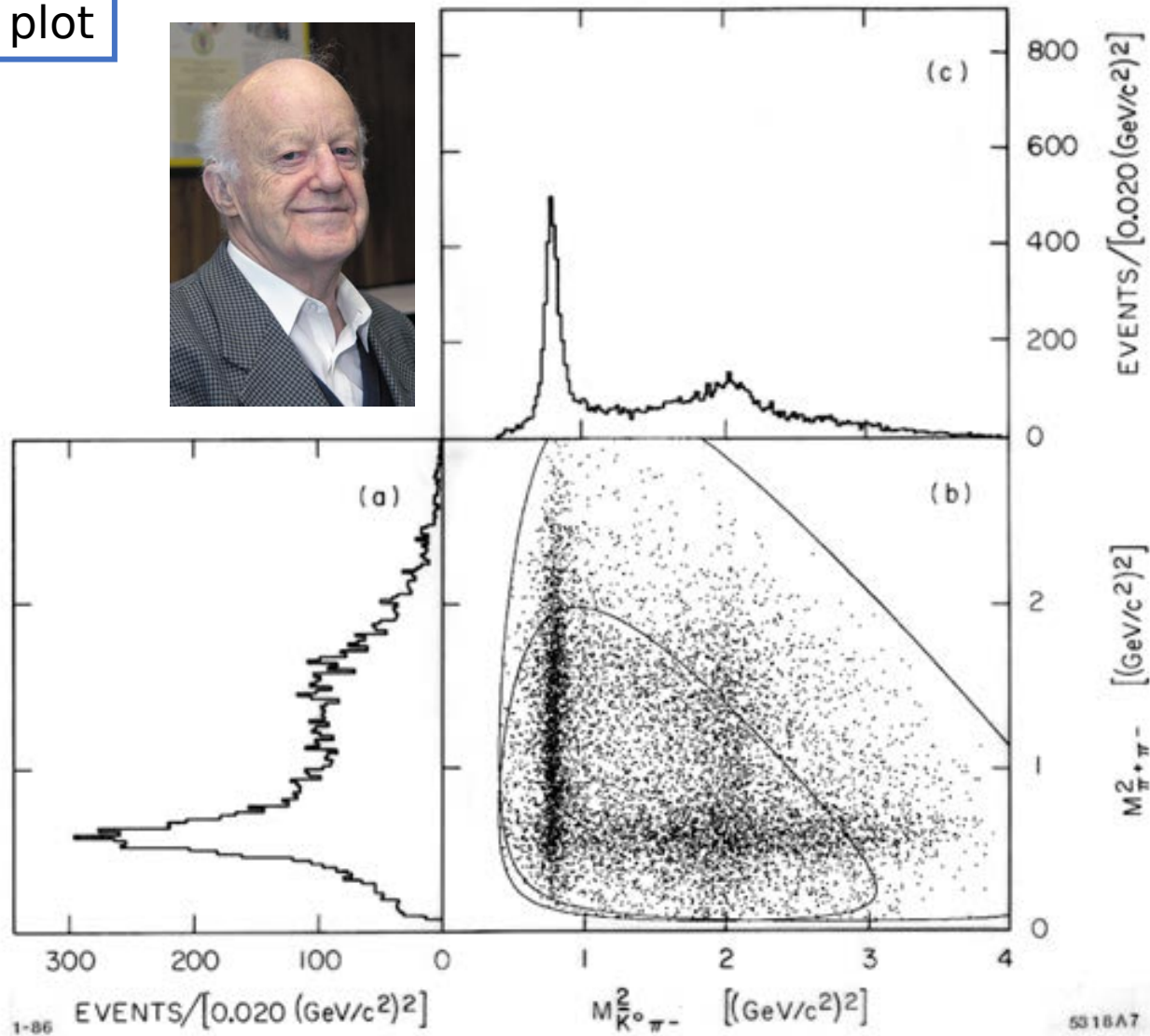
- high discovery potential
- associated, access to all quantum numbers (exotic)



all quantum numbers possible

# $n$ -Particle Phase space, $n=3$

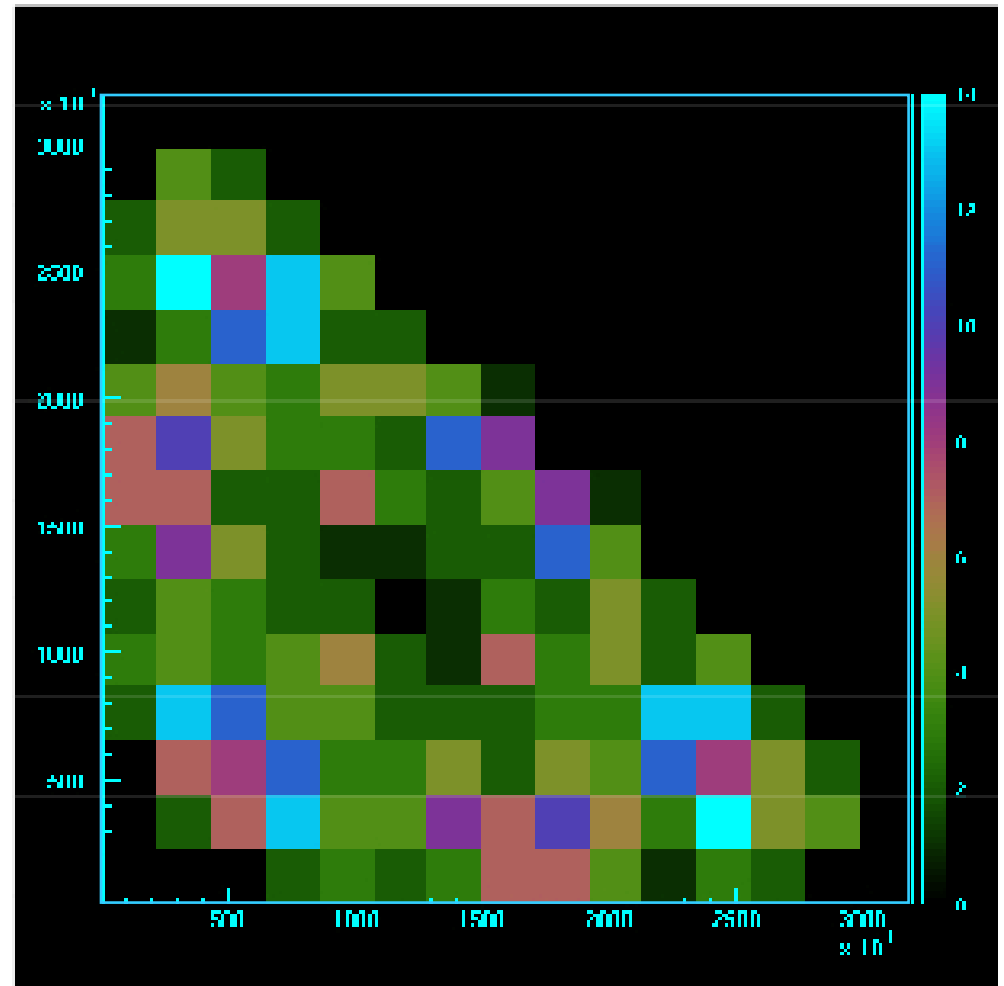
Dalitz plot



# It's All a Question of Statistics ...

$$p\bar{p} \rightarrow 3\pi^0$$

with  
100 events



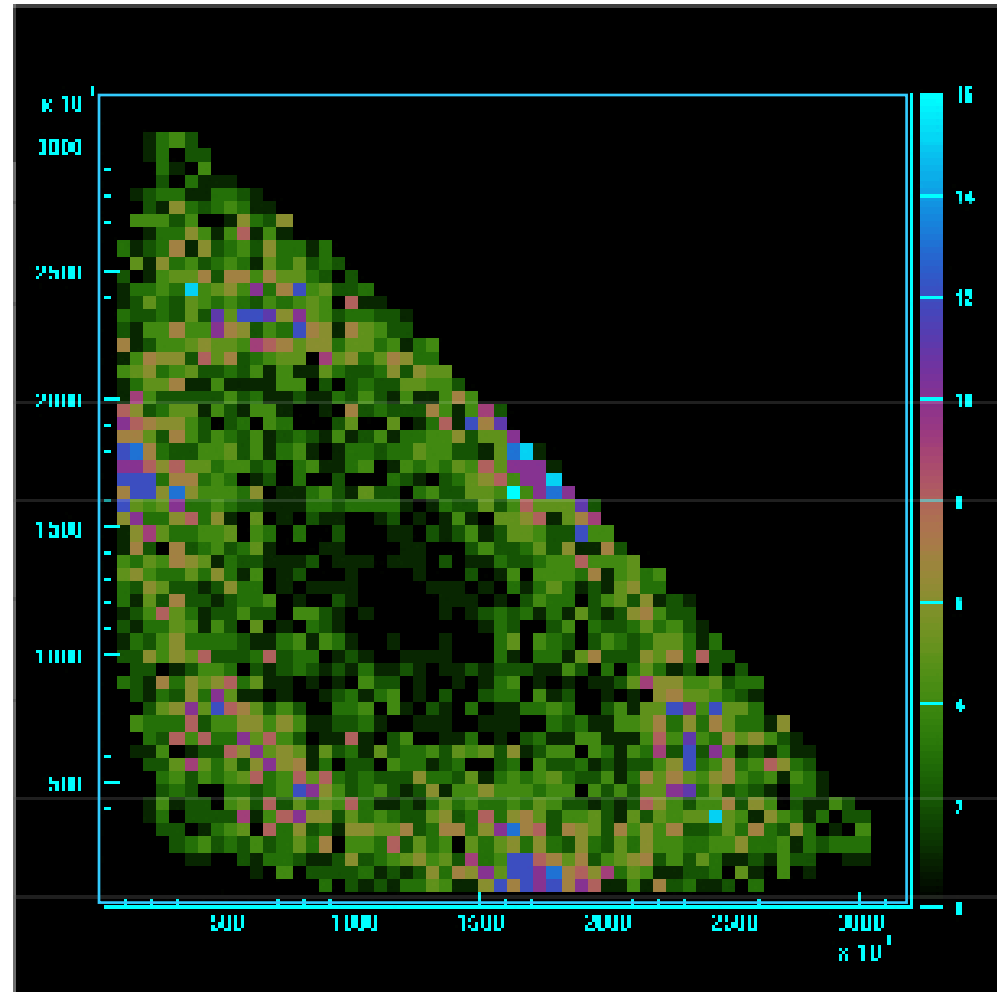
# It's All a Question of Statistics ... ..

$$p\bar{p} \rightarrow 3\pi^0$$

with

~~100 events~~

1000 events



# It's All a Question of Statistics ... ..

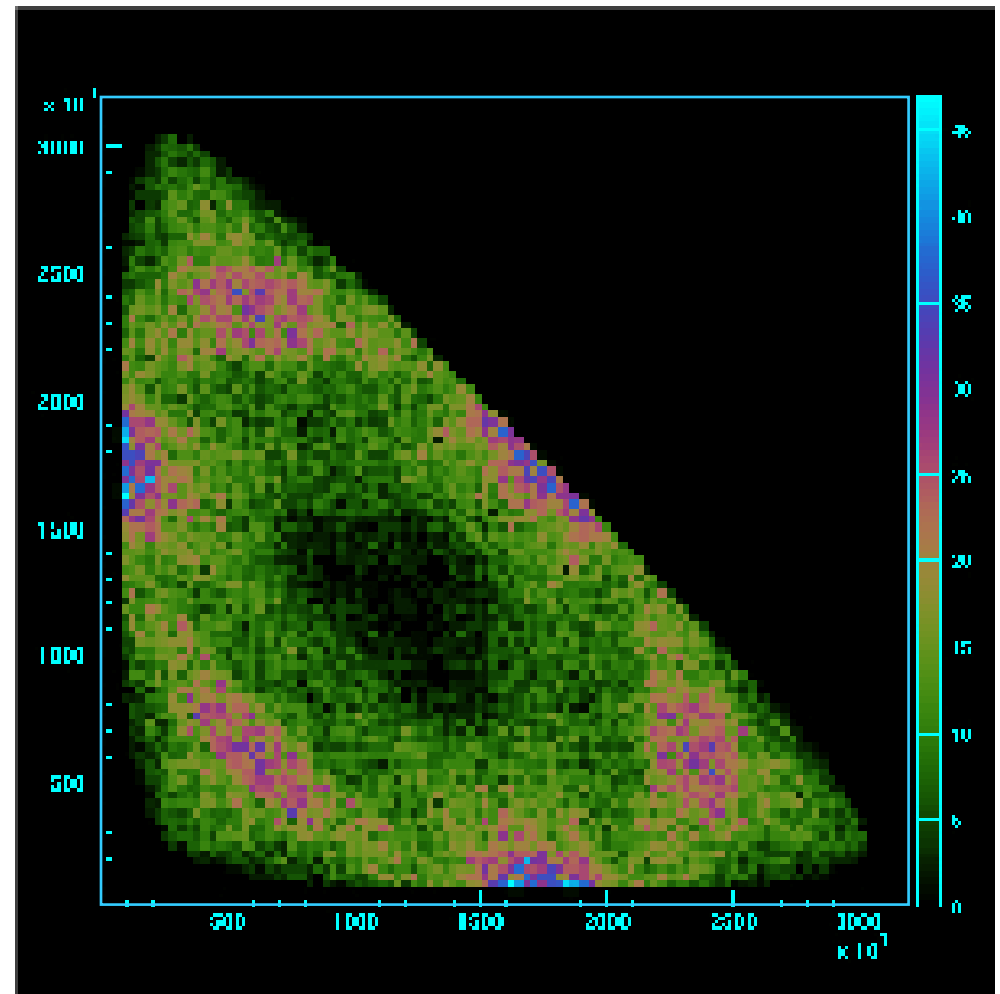
$$p\bar{p} \rightarrow 3\pi^0$$

with

~~100 events~~

~~1000 events~~

10000 events



# It's All a Question of Statistics ... ..

$$p\bar{p} \rightarrow 3\pi^0$$

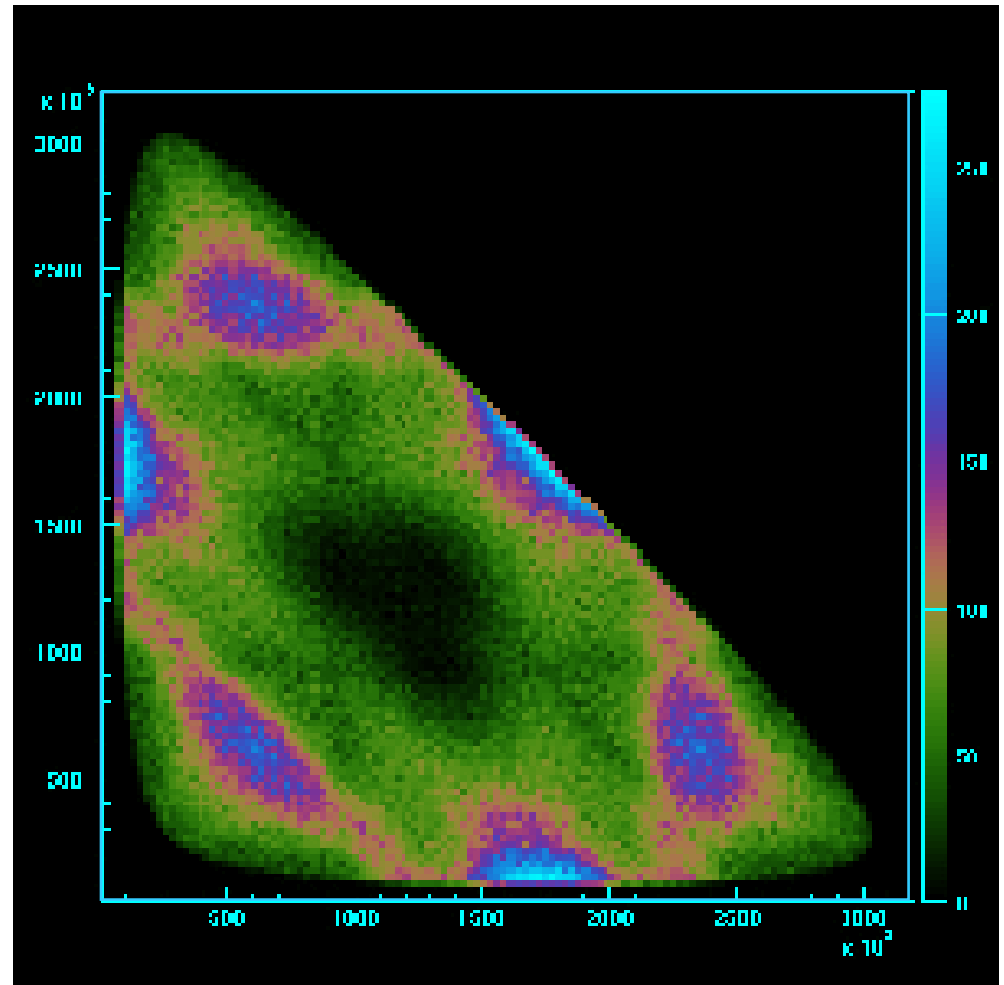
with

~~100 events~~

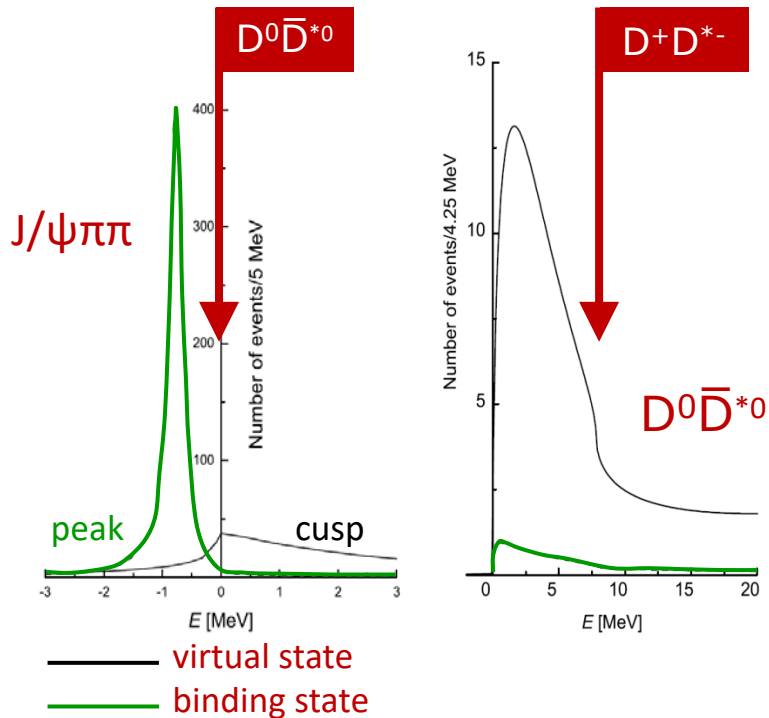
~~1000 events~~

~~10000 events~~

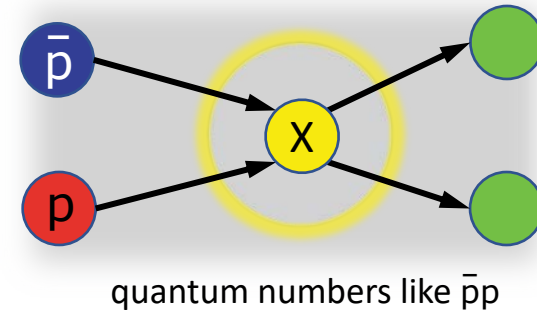
100000 events



# Formation: Line-shape Scans



needs a line-shape measurement



**Formation** all non-exotic quantum numbers accessible

- not only limited to  $J^{PC} = 1^{--}$  as  $e^+e^-$  precision physics of known states
- resonant, high statistics, extremely good precision in mass and width



## Nuclear Structure & Astrophysics

(rare isotope beams)

## Hadron Physics

(stored and cooled  
15 GeV/c anti-protons)

## QCD-Phase Diagram

(HI beams 2 to 45 GeV/u)

## Fundamental Symmetries & Ultra-High EM Fields

(anti-protons & highly stripped ions)

## Dense Bulk Plasmas

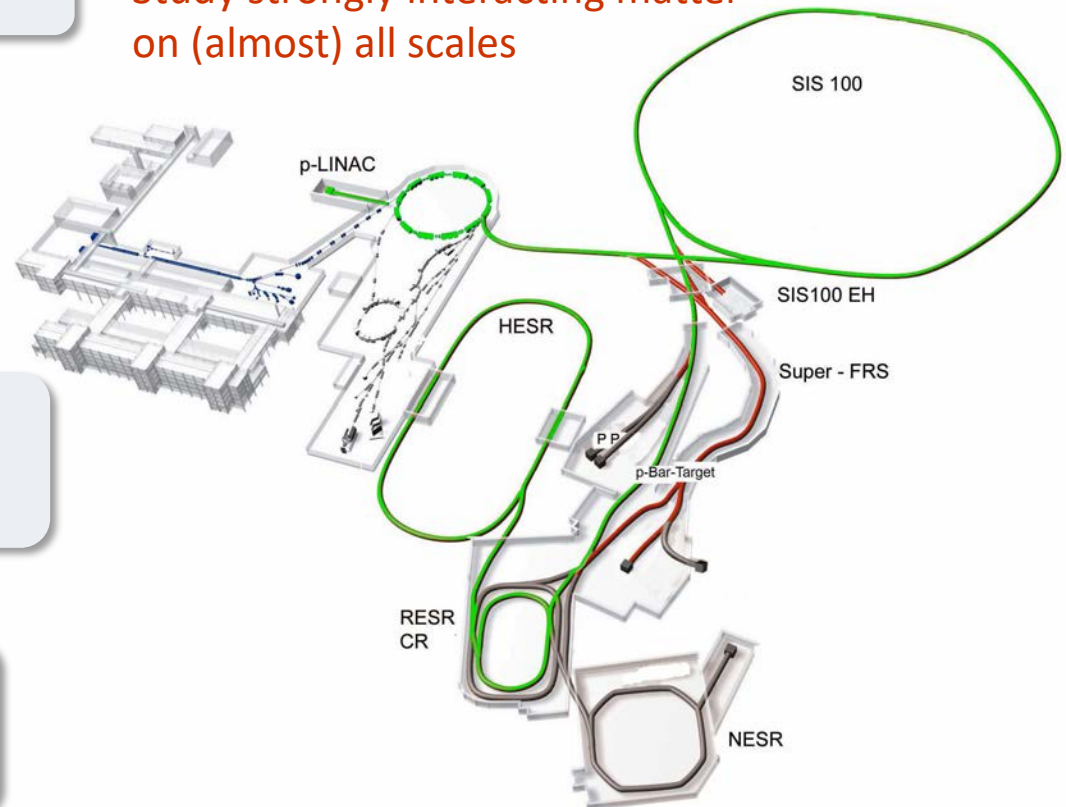
(ion beam bunch compression  
& petawatt-laser)

## Materials Science & Radiation Biology

(ion & anti-proton beams)

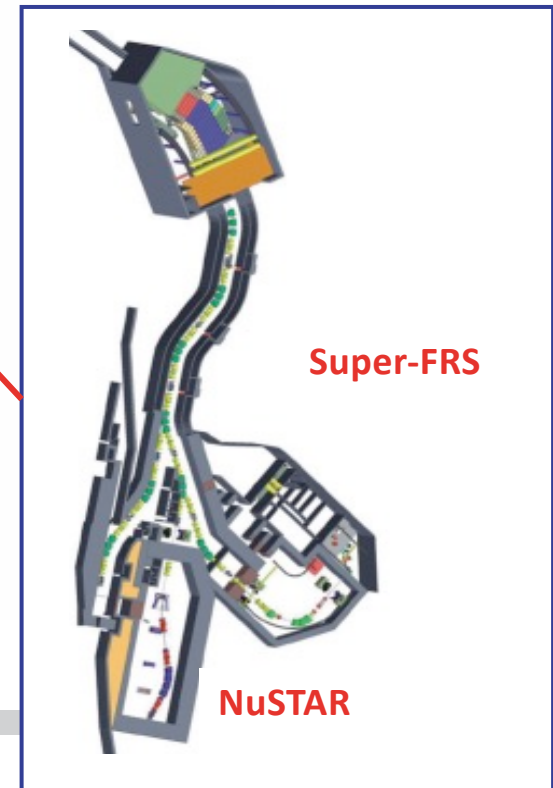
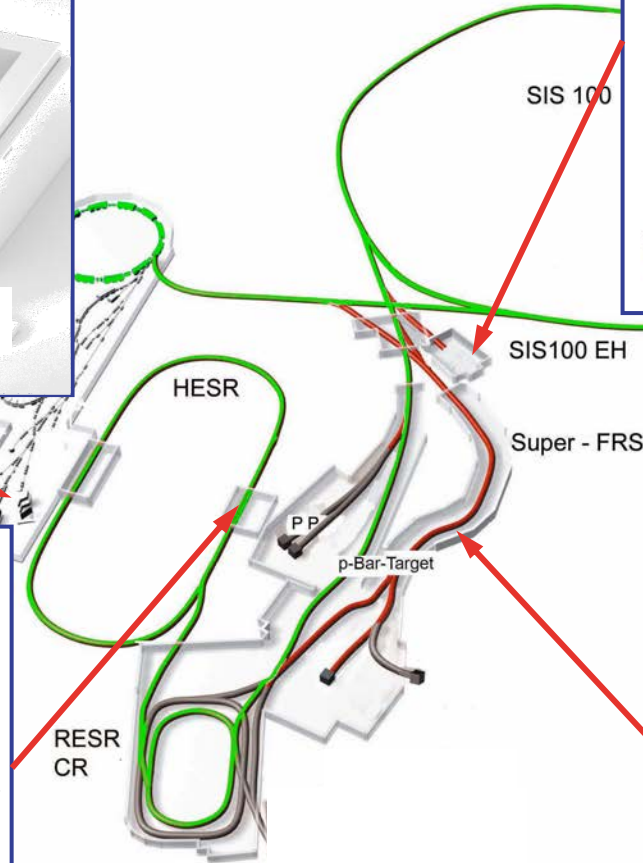
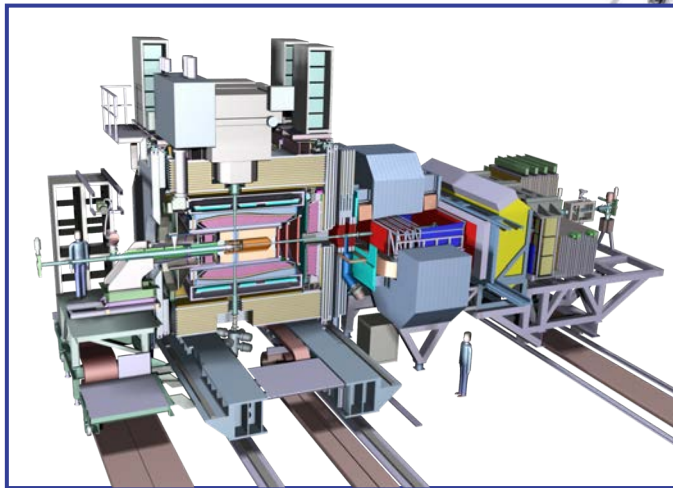
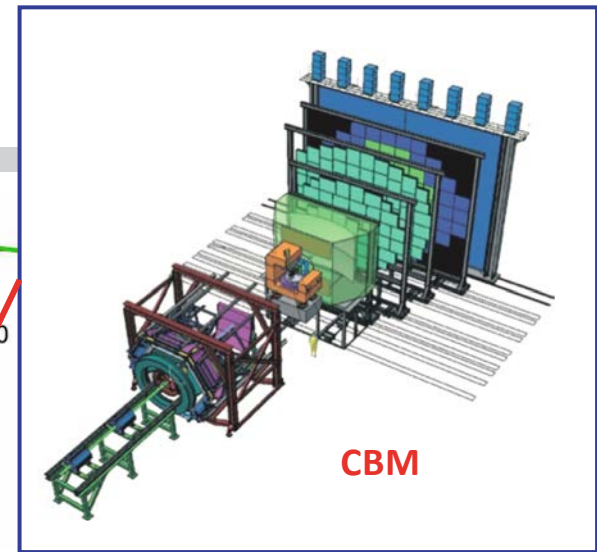
## Our Mission

Study strongly interacting matter  
on (almost) all scales

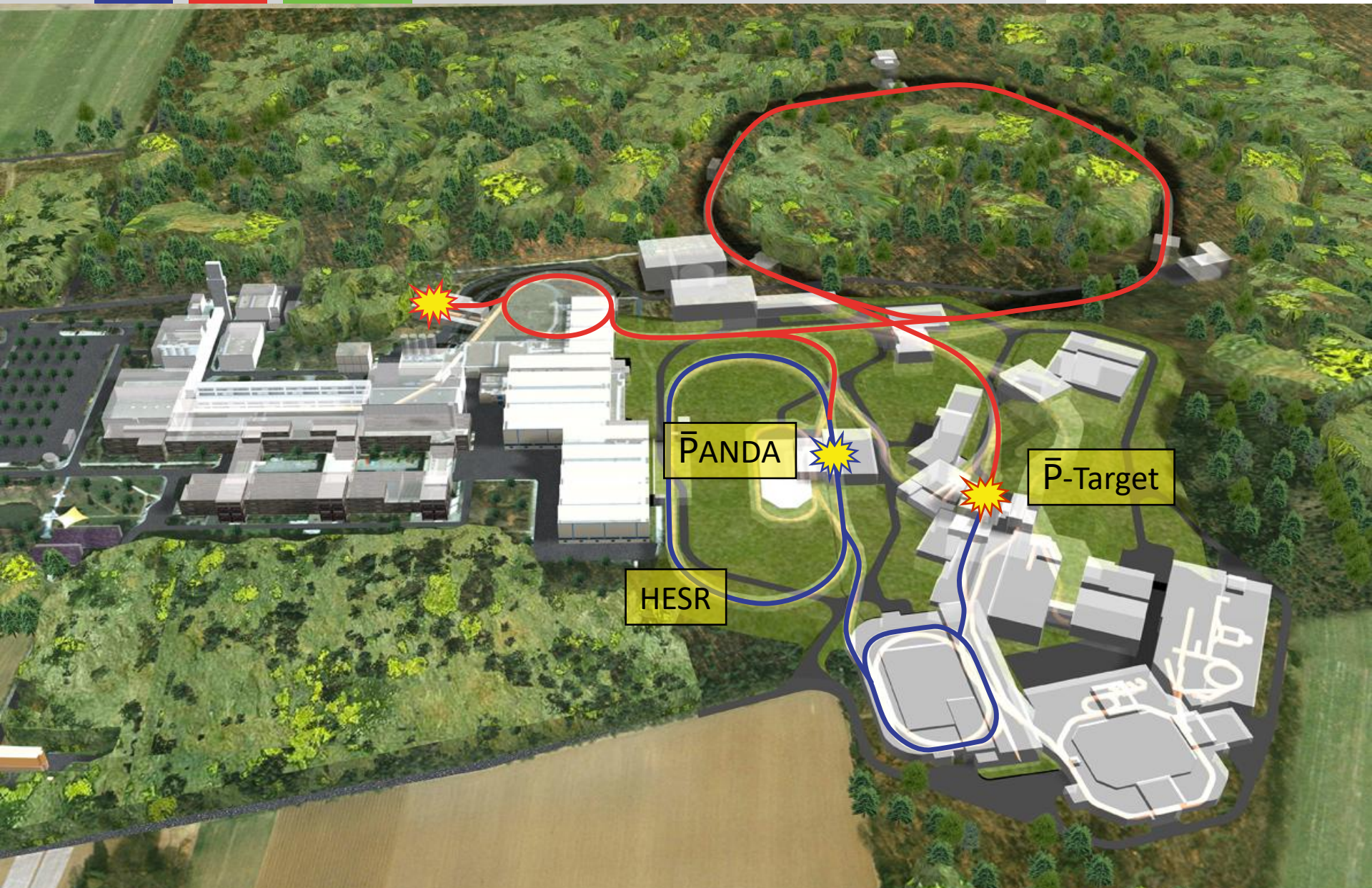


Accelerator Physics

# FAIR Experiments



# HESR, PANDA and FAIR

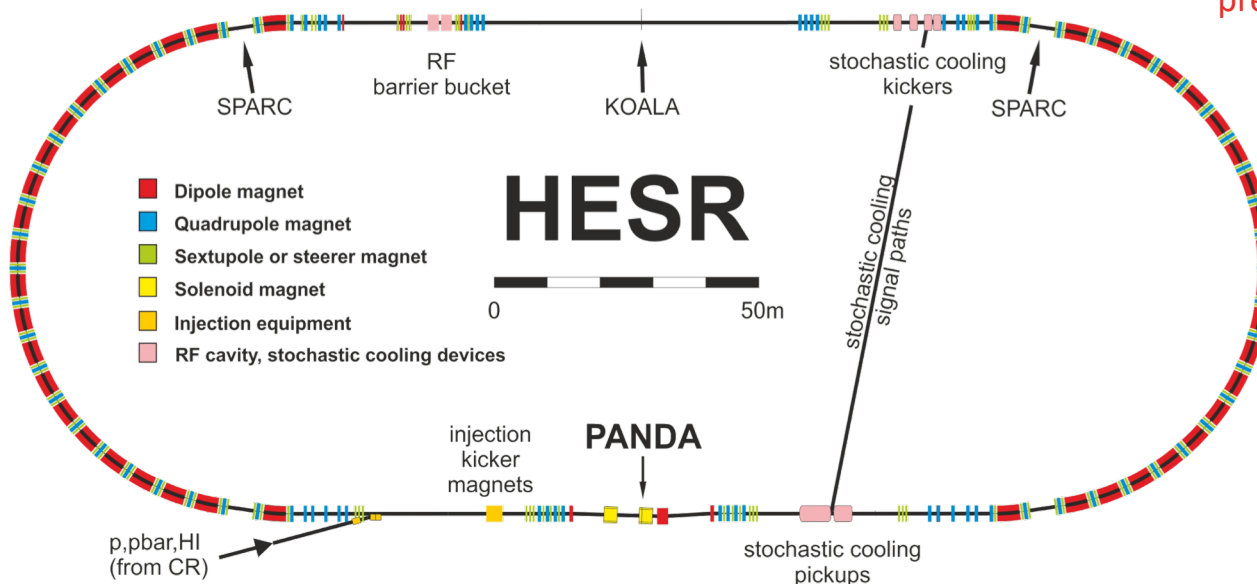
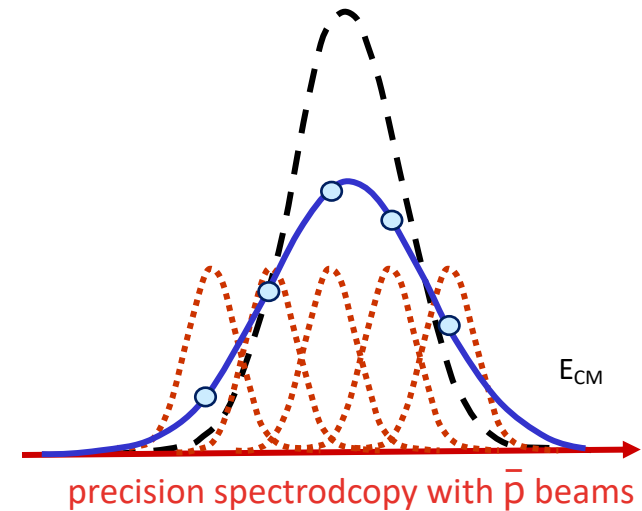


# HESR – Storage Ring for Antiprotons



## Parameters of HESR

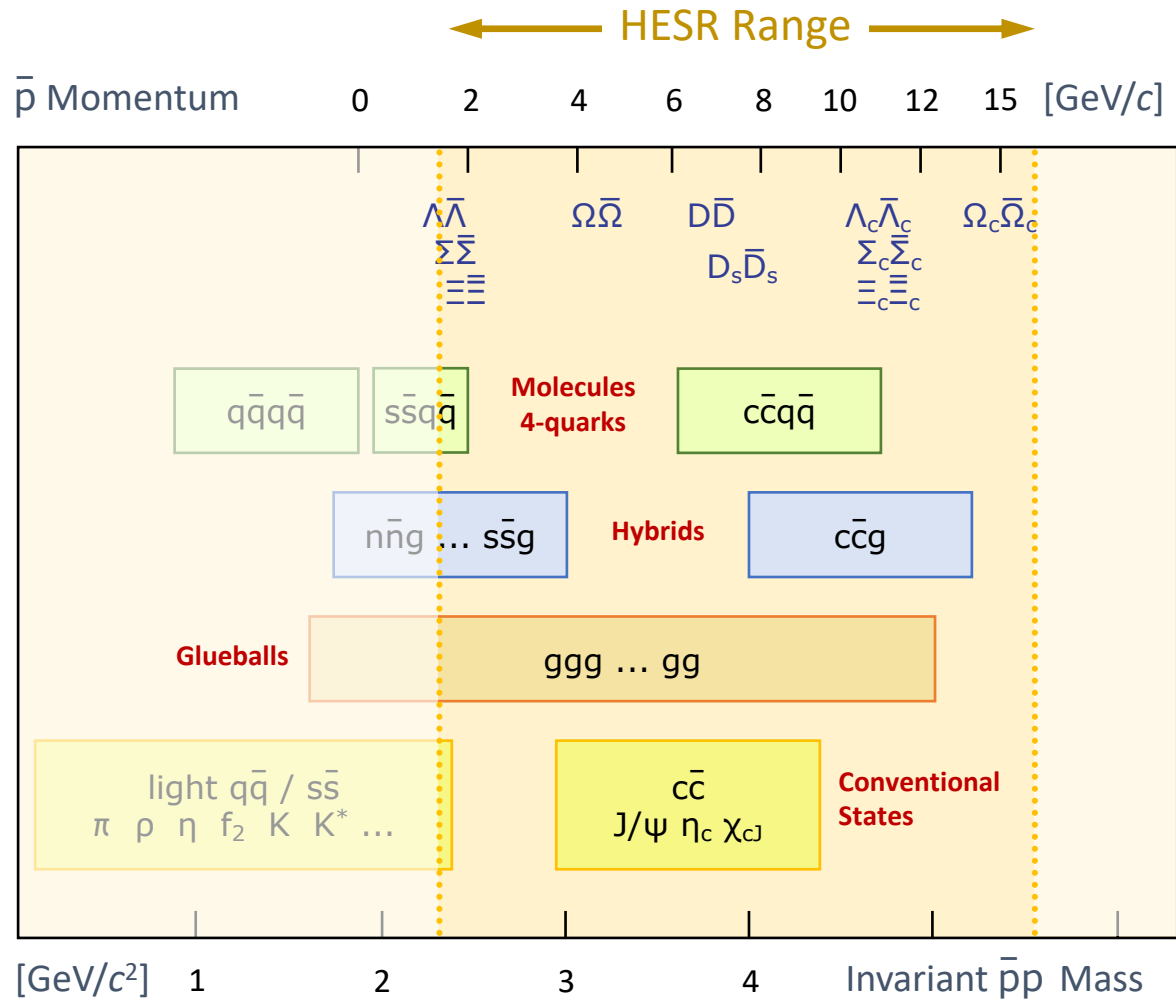
injection of  $\bar{p}$  at 3.7 GeV  
 slow synchrotron (1.5-14.5 GeV/c)  
 storage ring for internal target operation  
 luminosity up to  $L \sim 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$   
 beam cooling (stochastic & electron)



## Resonance scan

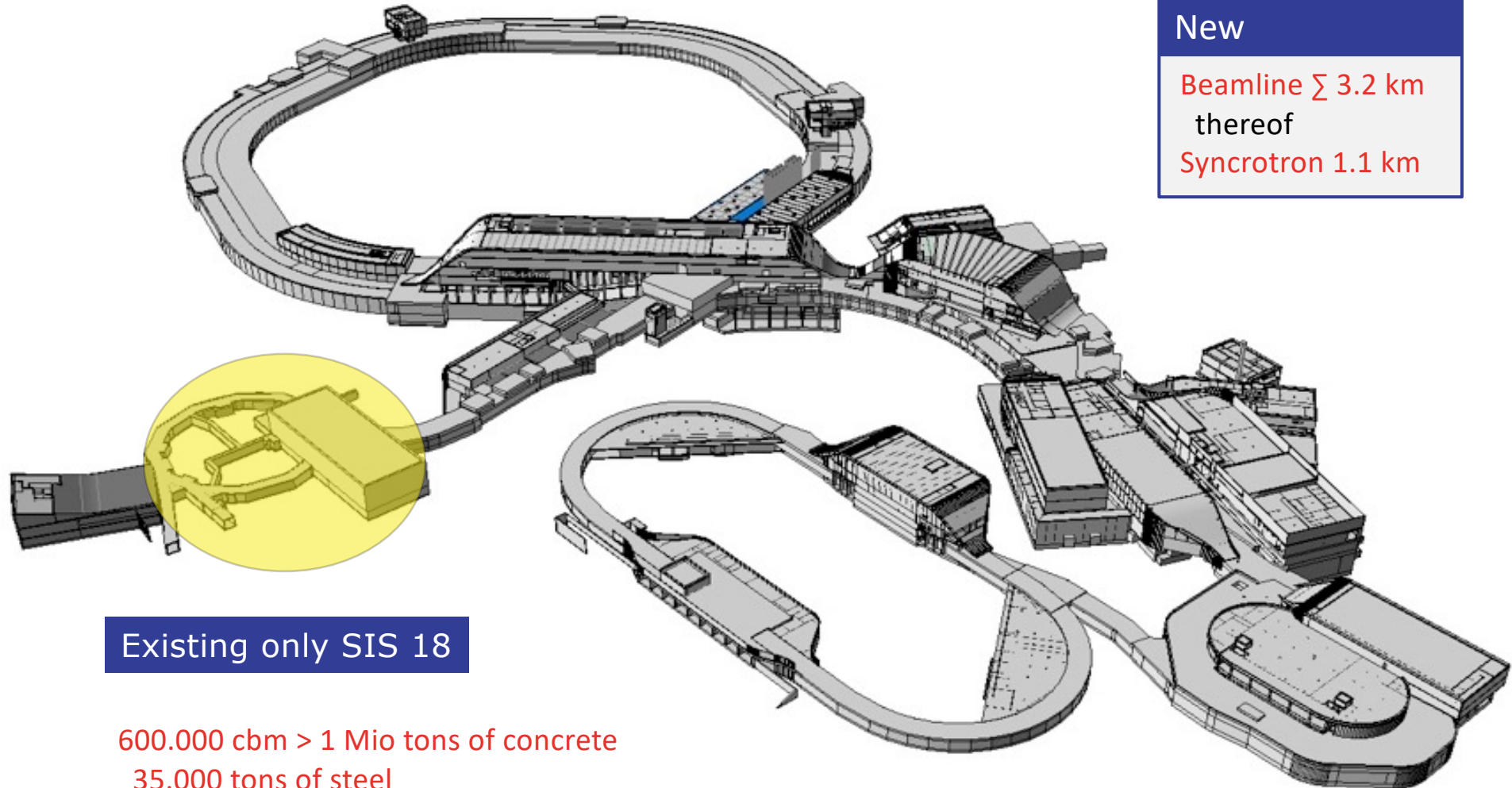
energy resolution  $\sim 50 \text{ keV}$   
 tune  $E_{\text{CM}}$  to probe resonance  
 get precise mass and width

# Accessible Hadrons at PANDA



New

Beamline  $\Sigma$  3.2 km  
thereof  
Synchrotron 1.1 km



Existing only SIS 18

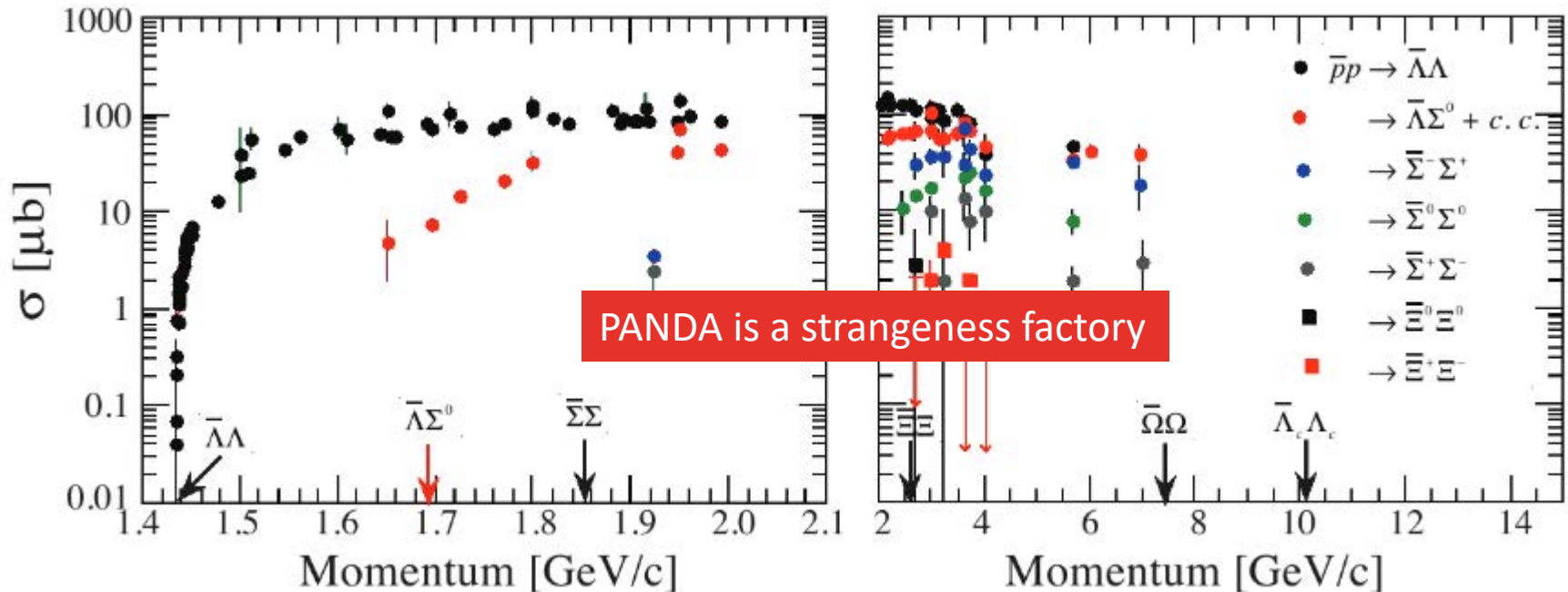
600.000 cbm > 1 Mio tons of concrete  
35.000 tons of steel



# Construction Site (Status June)



# Previous measurements of $\bar{p}p \rightarrow \bar{Y}Y$



A lot of data on  $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$  near threshold, mainly from PS185 at LEAR

Very scarce data bank above 4 GeV

Only a few bubble chamber events

No data on  $\bar{p}p \rightarrow \bar{\Omega}\Omega$  &  $\bar{p}p \rightarrow \bar{\Lambda}_c\Lambda_c$

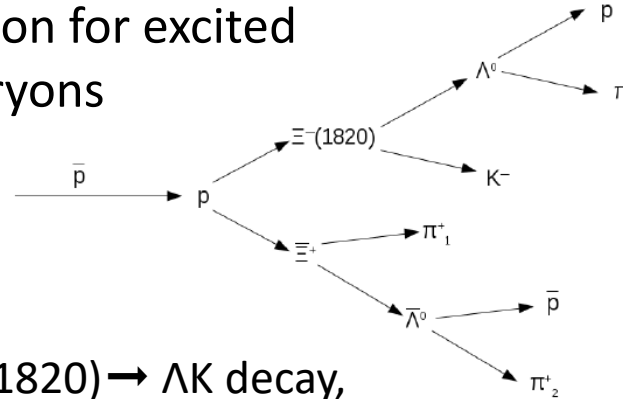
Octet  $\Xi$  states: no partner for most  $N^*$   
 Decuplet  $\Xi$  and  $\Omega$  states: no partner of  $\Delta^*$

PDG note on  $\Xi$  resonances:

“... nothing of significance on  $\Xi$  resonances has been added since our 1988 edition.”



High signal rates and high background rejection for excited double strange baryons



$$\bar{p}_{beam} = 4.6 \text{ GeV}/c$$

Consider the  $\Xi^*(1820) \rightarrow \Lambda K$  decay,

if  $BR = 100\%$  and  $\sigma = 1 \mu\text{b}$

(result scales with smaller BR accordingly)

Simplified MC framework

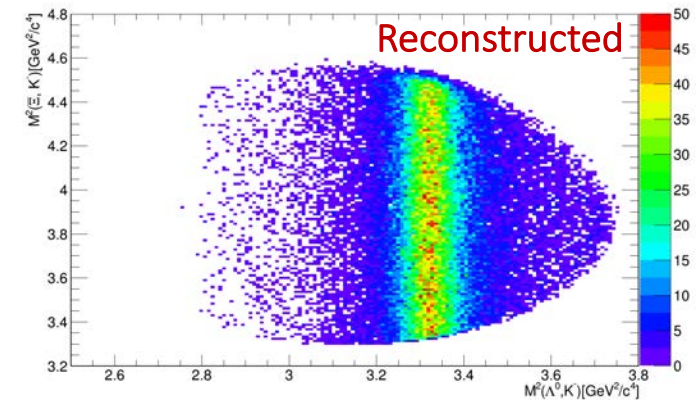
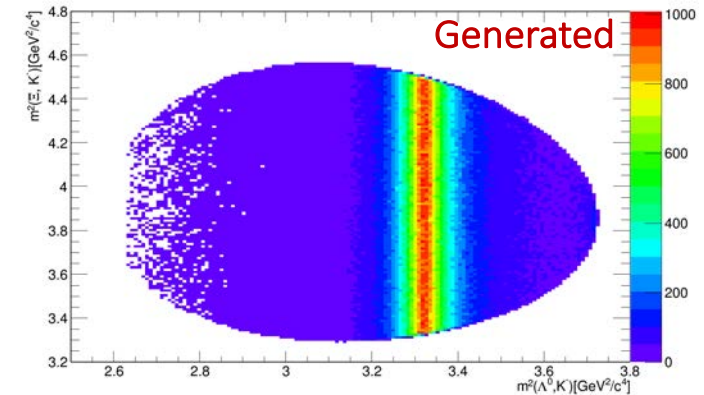
Day-1 luminosity:  $10^{31} \text{cm}^{-2} \text{s}^{-1}$

## Results

~30 % inclusive efficiency for  $\Xi^*(1820)$

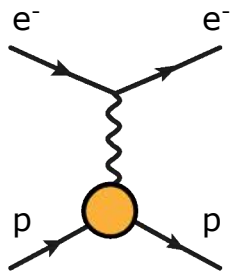
~5 % exclusive efficiency for  $\Xi^+ \Xi^*(1820)$

Low background level  $\rightarrow$  ~15000 exclusive events / day

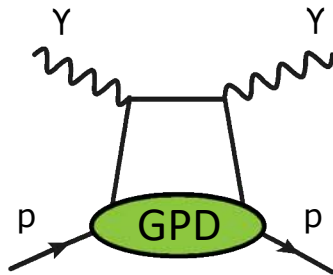


# Nucleon Electromagnetic Final States

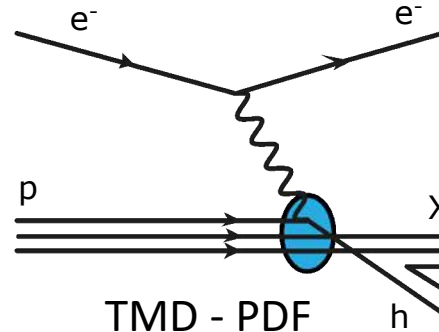
Background Suppression  $\sim 10^{-8}$



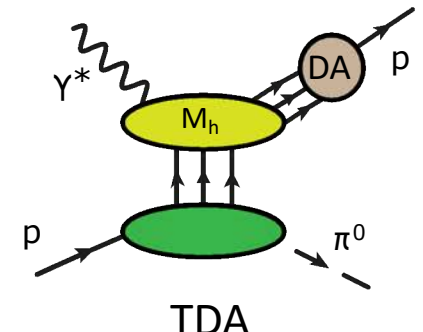
elm FF



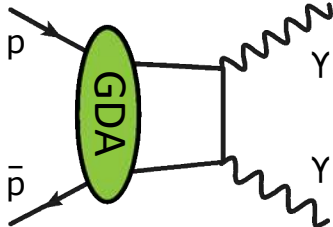
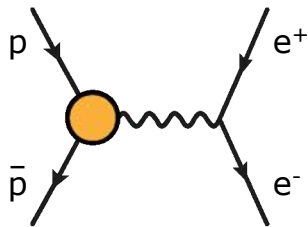
GPD



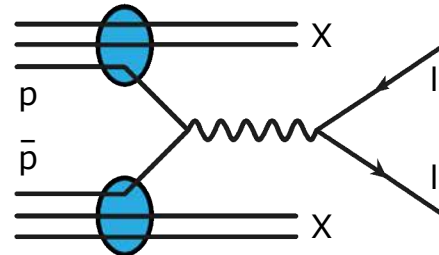
TMD - PDF



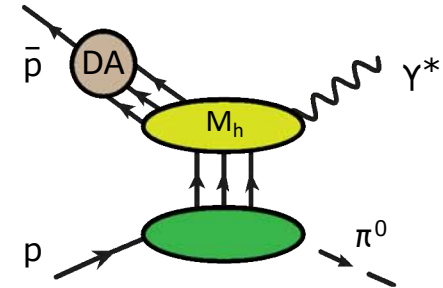
TDA



GDA



TMD - PDF



TDA

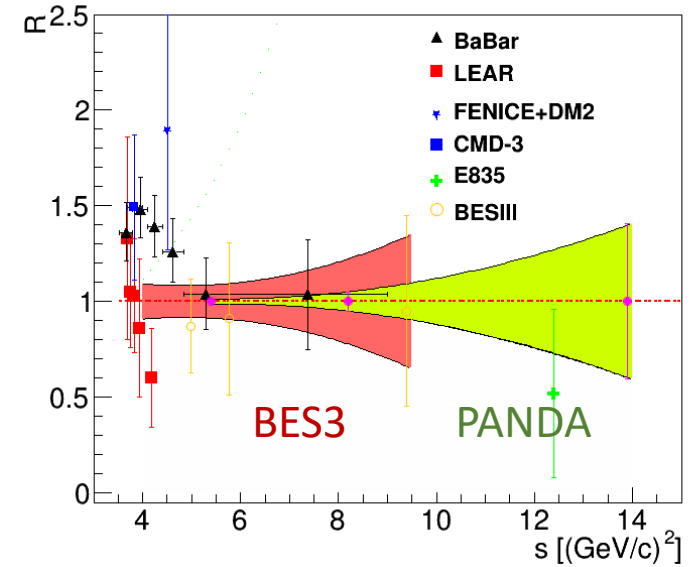
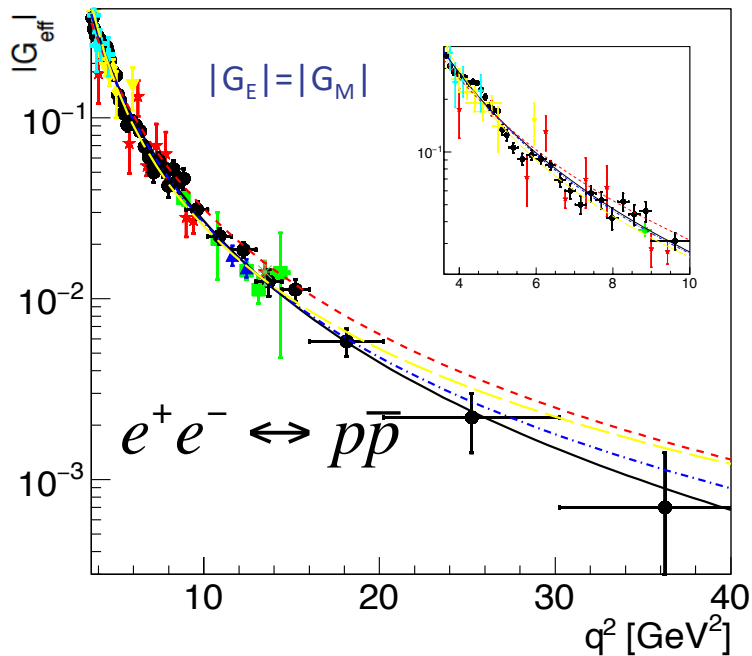
# Time-Like proton electromagnetic FFs



Eur.Phys.J. A52 (2016) no.10, 325

The **effective FF** can be measured  
up to  $q^2 \sim 30 \text{ GeV}^2$   
but no individual determination of  $G_E$  and  $G_M$  so far

PRL 114 (2015) 232301

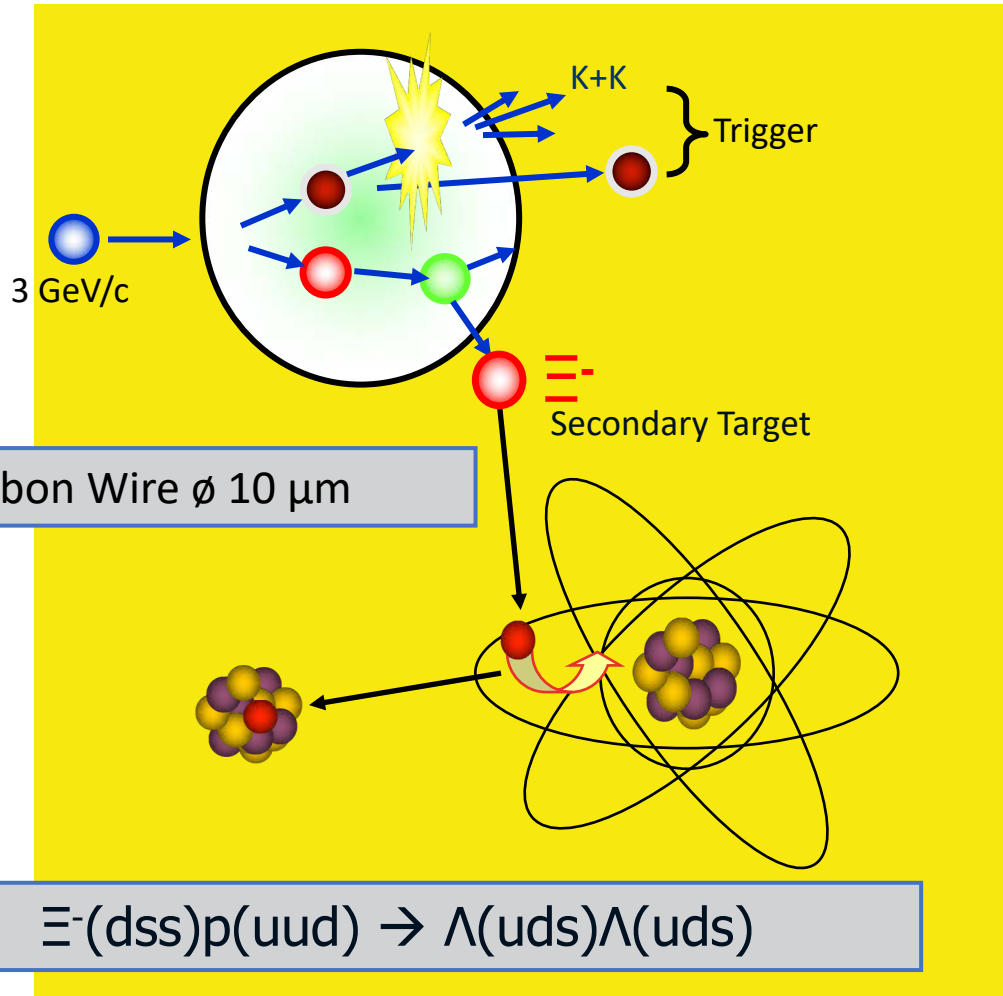


	BESIII	PANDA
$s \text{ [(GeV/c)}^2]$	4 - 9.5	5 - 14
$R =  G_E / G_M $	9 % - 35 %	1.4 % - 41 %
	21 scan points = 552 pb <sup>-1</sup> (2015)	L=2 fb <sup>-1</sup> 2.10 <sup>32</sup> cm <sup>-1</sup> s <sup>-1</sup>

with transverse polarized target

$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{1,y} \propto \sin 2\Theta \text{Im}(G_M G_E^*)$$

# Hypernuclear Physics @ PANDA



Minimum 8 months full running

Strange Baryons as constituents in Nuclei

9									
8					$^{16}_{\Lambda}\text{O}$			$^{18}_{\Lambda}\text{O}$	
7				$^{14}_{\Lambda}\text{N}$	$^{15}_{\Lambda}\text{N}$				
6			$^{12}_{\Lambda}\text{C}$	$^{13}_{\Lambda}\text{C}$	$^{14}_{\Lambda}\text{C}$				
5		$^{9}_{\Lambda}\text{B}$	$^{10}_{\Lambda}\text{B}$	$^{11}_{\Lambda}\text{B}$	$^{12}_{\Lambda}\text{B}$				
4	$^{7}_{\Lambda}\text{Be}$	$^{8}_{\Lambda}\text{Be}$	$^{9}_{\Lambda}\text{Be}$	$^{10}_{\Lambda}\text{Be}$					
3	$^{6}_{\Lambda}\text{Li}$	$^{7}_{\Lambda}\text{Li}$	$^{8}_{\Lambda}\text{Li}$	$^{9}_{\Lambda}\text{Li}$					
2	$^{4}_{\Lambda}\text{He}$	$^{5}_{\Lambda}\text{He}$	$^{6}_{\Lambda}\text{He}$	$^{7}_{\Lambda}\text{He}$	$^{8}_{\Lambda}\text{He}$				
1	$^{3}_{\Lambda}\text{H}$	$^{4}_{\Lambda}\text{H}$							# Neutrons
	1	2	3	4	5	6	7	8	9

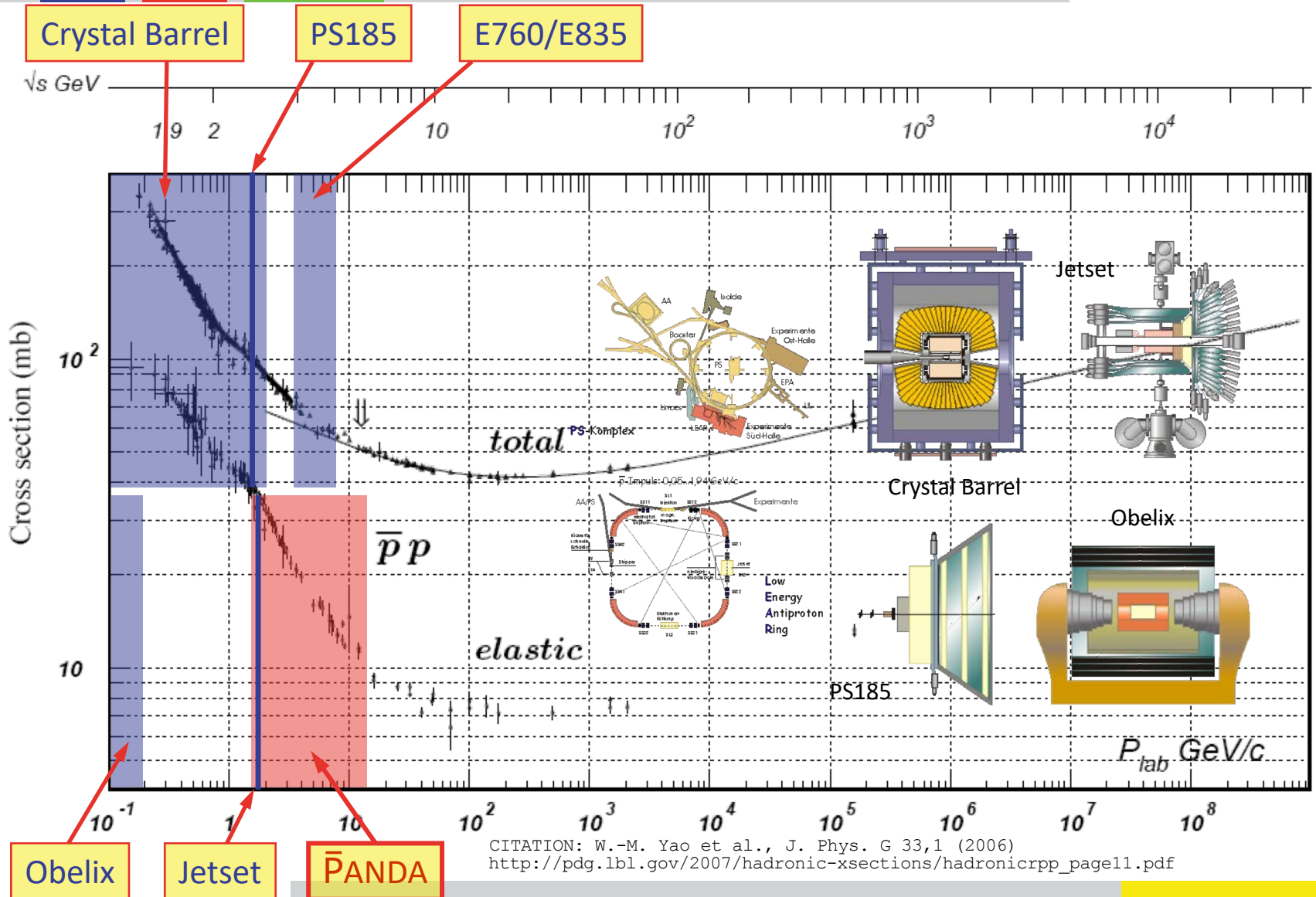
Limiting factor

charged particle load on central detector  $(0.6-1.0) \cdot 10^7$

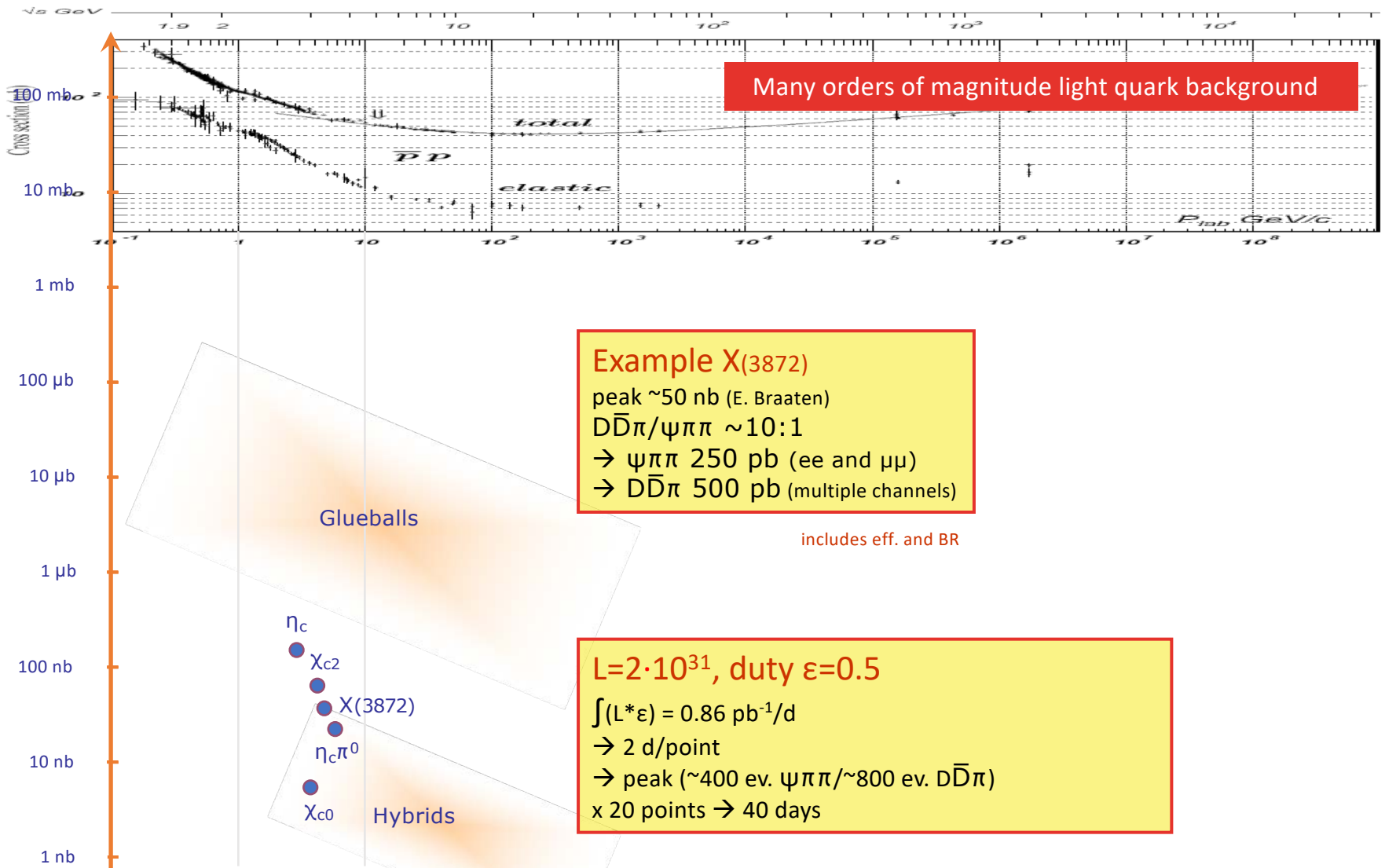
$L=(3-5) \cdot 10^{30} \text{ cm}^{-2}\text{s}^{-1}$

$\bar{p}$  re-storage  $< 6 \cdot 10^6$

# $\bar{p}p$ cross sections

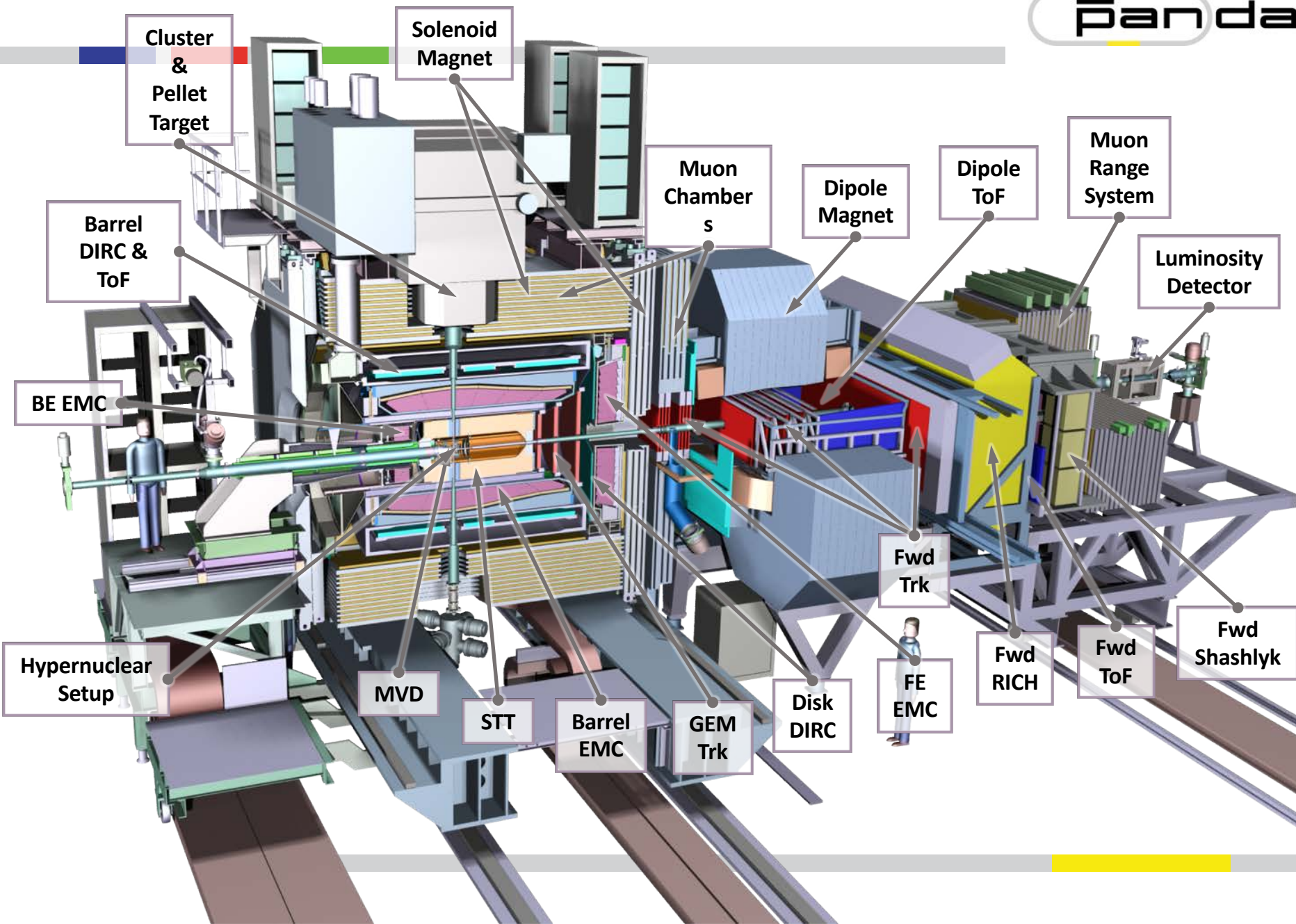


# $\bar{p}p$ cross sections – exclusive final states



## What we need







# Electromagnetic Calorimeter (TS)

## PANDA PWO Crystals

PWO is dense and fast  
Low  $\gamma$  threshold is a challenge  
Increase light yield

- improved PWO II (2xCMS)
- operation at  $-25^{\circ}\text{C}$  (4xCMS)

### Challenges

- temperature stable to  $0.1^{\circ}\text{C}$
- control radiation damage
- low noise electronics

Delivery of crystals 54 %

## Large Area APDs

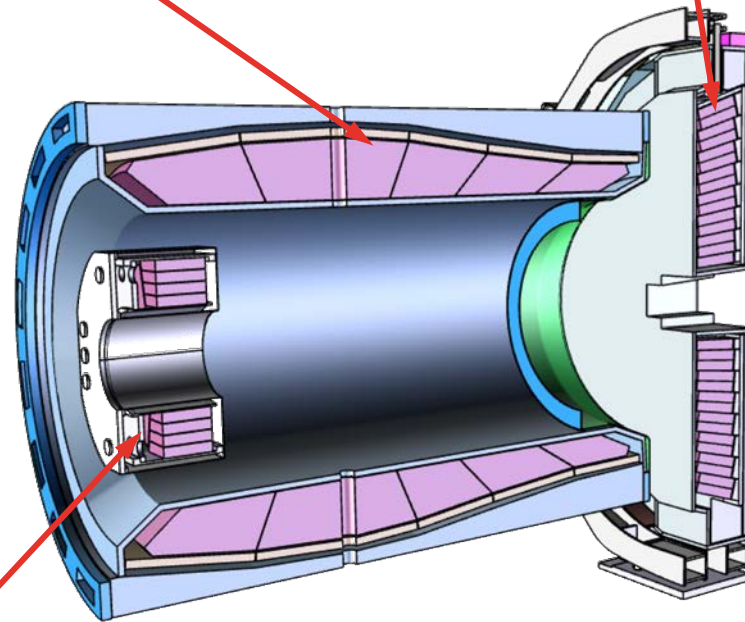


## Barrel Calorimeter

11000 PWO Crystals  
LAAPD readout,  $2 \times 1 \text{cm}^2$   
 $\sigma(E)/E \sim 1.5\%/ \sqrt{E} + \text{const.}$

## Forward Endcap

4000 PWO crystals  
High occupancy in center  
LA APD and VPTT



Backward Endcap for hermeticity, 530 PWO crystals

# Electromagnetic Calorimeter (TS)



## Crystals

1<sup>st</sup> lot of crystals delivered

New producer Crytur

Test production in 2016 (~100pc)

## APD/Preamp/VPTT

Screening of 30000 APDs ongoing

ASIC preamp design finalized

VPTT (Forward) characterized

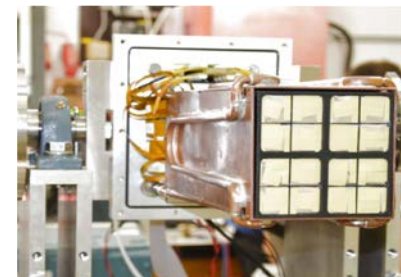
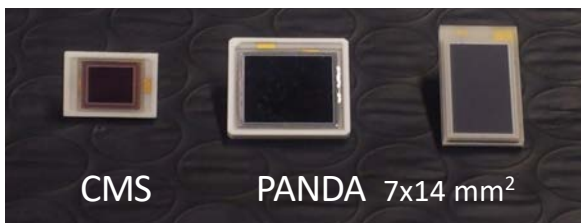
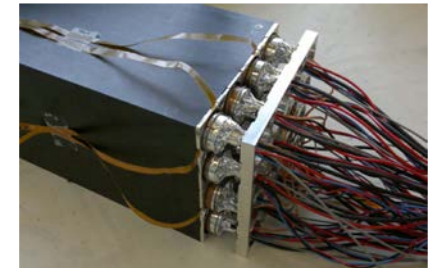
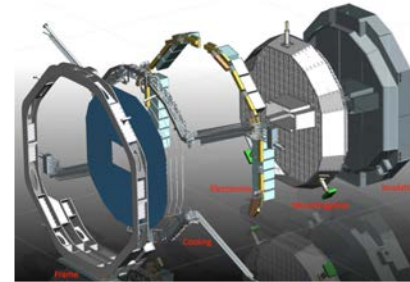
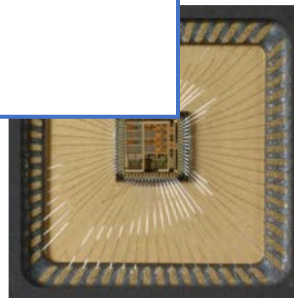
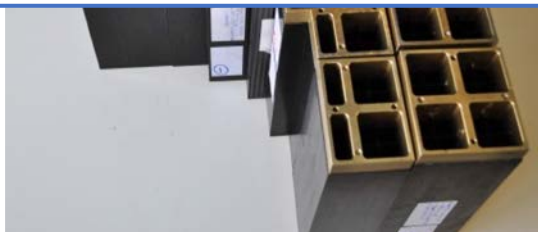
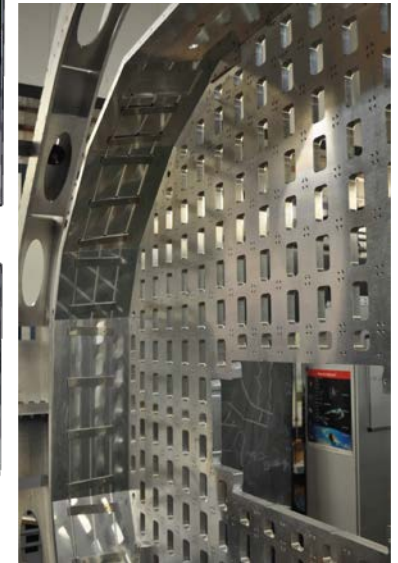
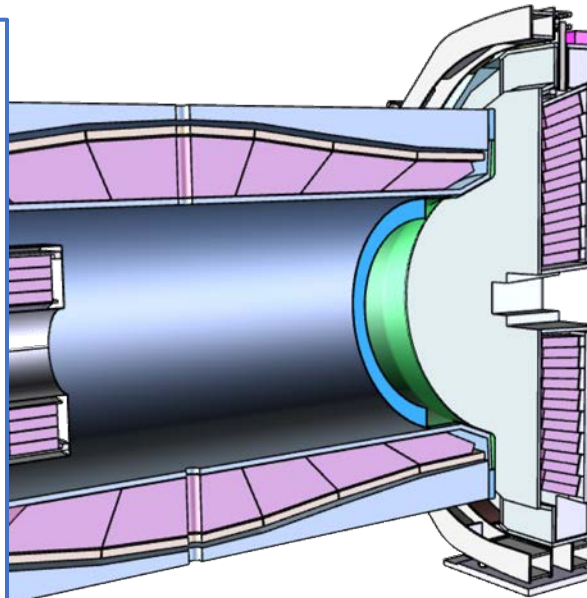
## Assembly

Forward-EMC full completion 'til 2018

Backward-EMC prototype-tests successful

Barrel-EMC: alveoles produced

1<sup>st</sup> slice in construction



# Straw Tube Tracker

## Detector Layout

4600 straws in 21-27 layers,  
of which 8 layers skewed at  $\sim 3^\circ$   
Tube made of 27  $\mu\text{m}$  thin Al-mylar,  $\phi=1\text{cm}$   
 $R_{\text{in}}=150\text{ mm}$ ,  $R_{\text{out}}=420\text{ mm}$ ,  $l=1500\text{ mm}$

**Self-supporting straw double layers**

at  $\sim 1\text{ bar}$  overpressure (Ar/CO<sub>2</sub>)

Readout with ASIC+TDC or FADC

## Material Budget

Max. 26 layers,

0.05 %  $X/X_0$  per layer

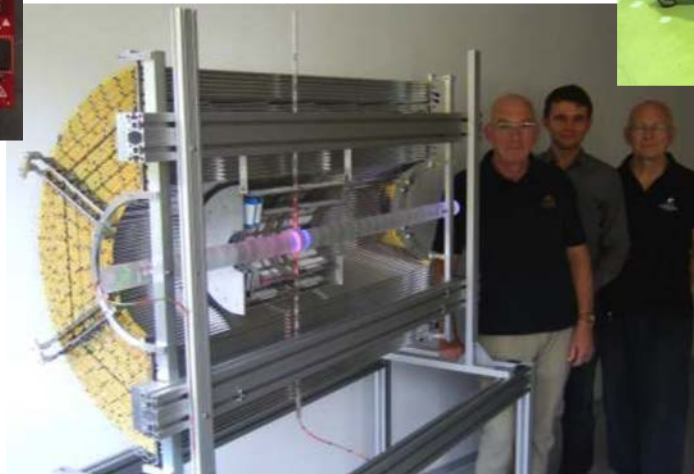
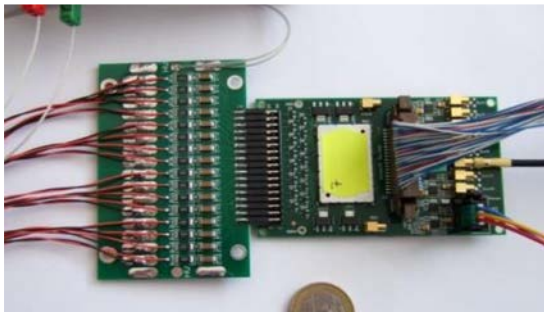
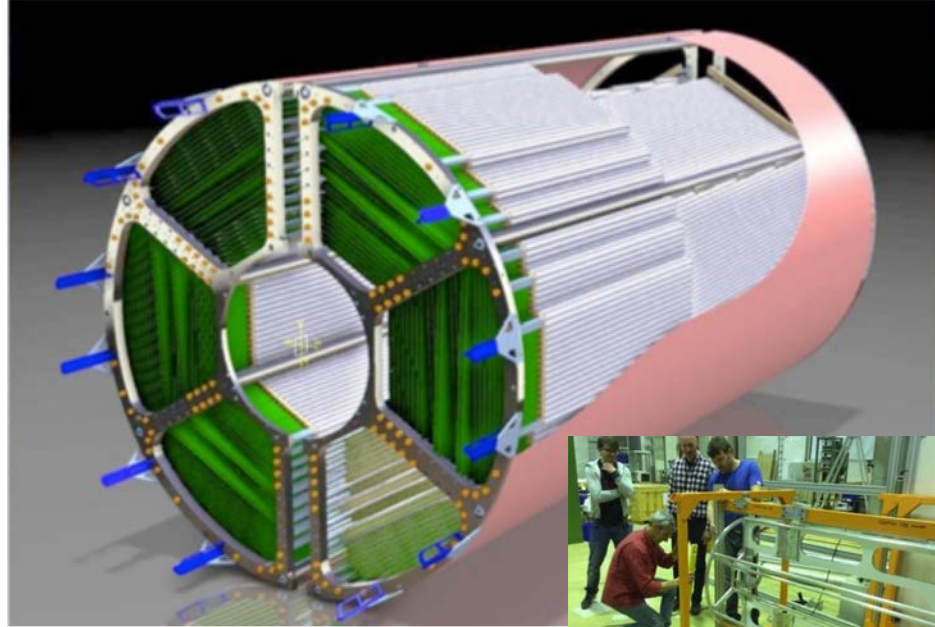
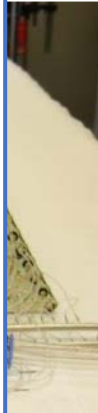
**Total 1.3%  $X/X_0$**

## Project Status

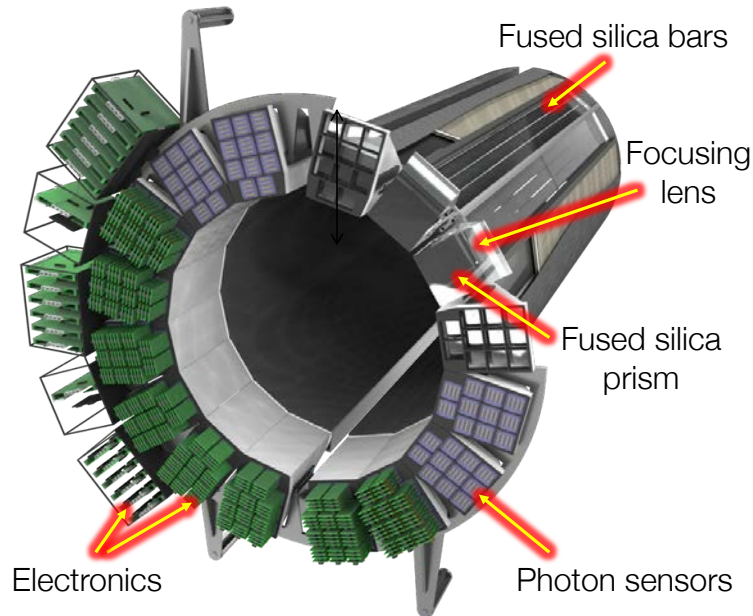
3000 Straws produced

Readout prototypes and beam tests

Ageing tests: up to 1.2 C/cm<sup>2</sup>



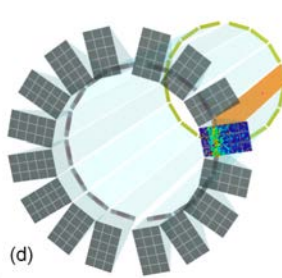
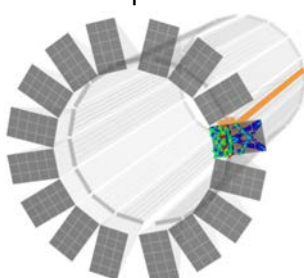
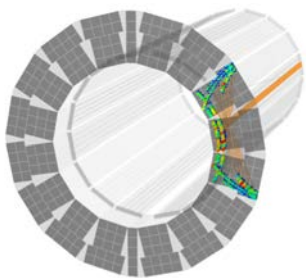
For more detail, see  
PANDA Barrel DIRC TDR, arXiv:1710.00684



Baseline

Bars & prism

Plates



## Geometry

48 radiator bars (16 sectors),  
synthetic fused silica:

17mm (T) x 53mm (W) x 2400mm (L).

## Optics

Focusing optics: 3-layer spherical lens

Compact expansion volume:

30 cm-deep solid fused silica prisms

~11k ch. of lifetime-enhanced MCP-PMTs

## Readout

Fast FPGA-based readout electronics.

~100ps per photon timing resolution

Expected performance

(simulation and particle beams):

better than 3 s.d.  $\pi/K$  separation

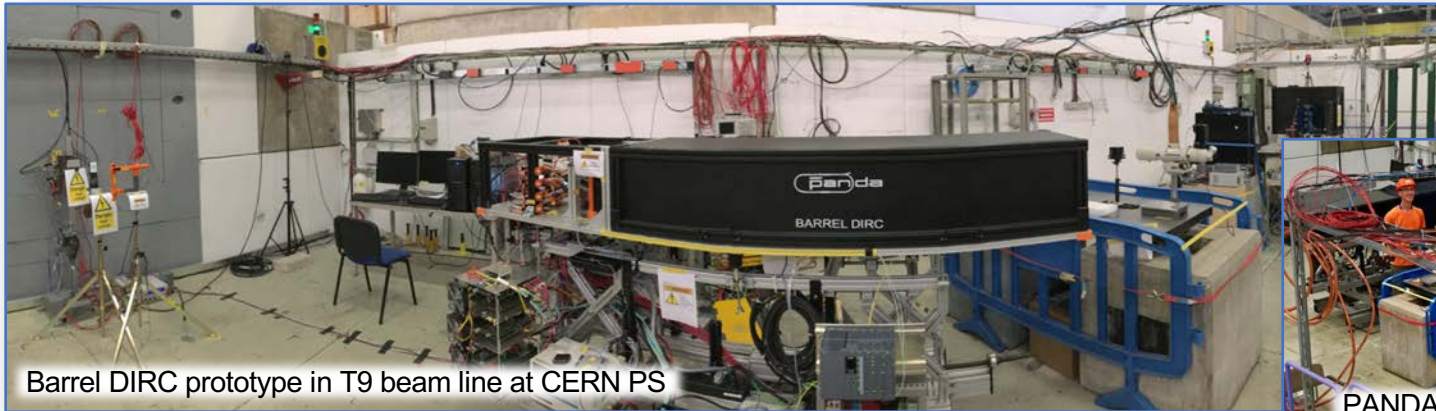
for entire acceptance.

Excellent performance, robust,  
little sensitivity to backgrounds  
and timing deterioration.

# Barrel DIRC (beam tests)



Increasingly complex prototypes with mixed hadron beams at GSI and CERN PS

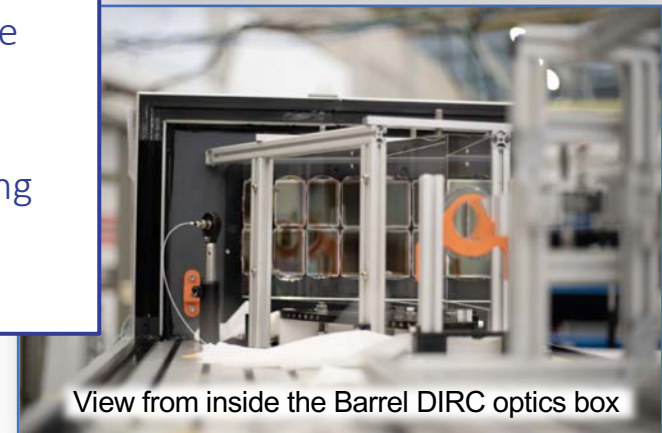


Barrel DIRC prototype in T9 beam line at CERN PS



PANDA DIRC team at CERN in 2018

- direct measurement of PID performance across PANDA phase space
- measured photon yield and Cherenkov angle resolution in excellent agreement with expectation and Geant simulation
- achieved  $\pi/K$  separation power of  $N_{\text{sep}} = 4.3$  s.d. for most challenging phase space region
- PID performance meets or exceeds PANDA PID requirements

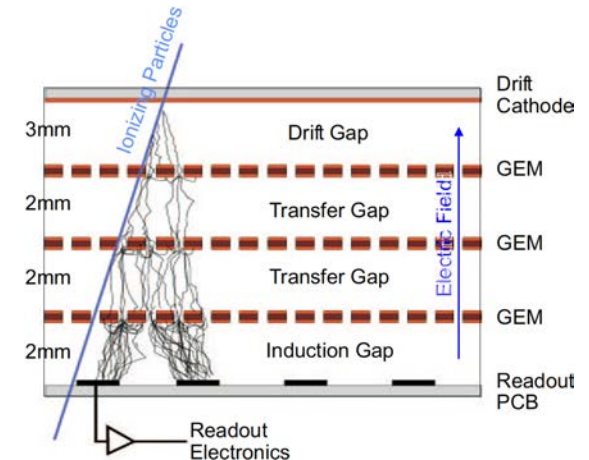
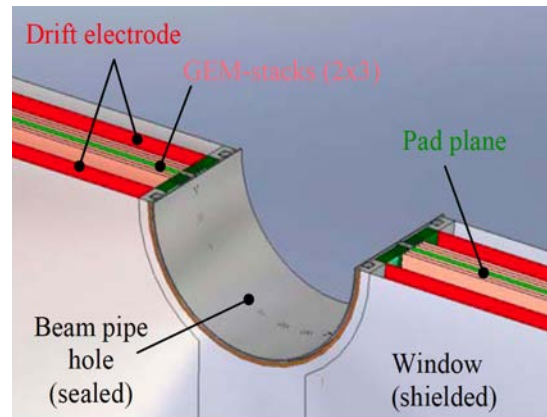
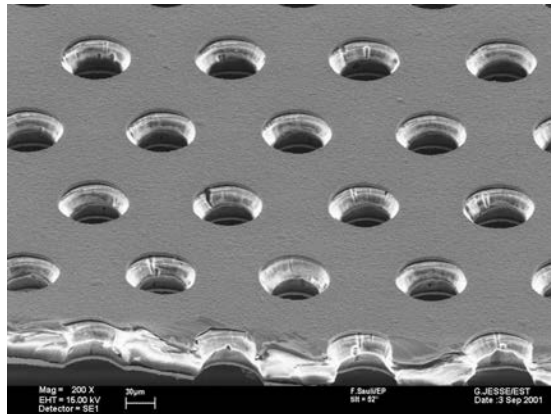
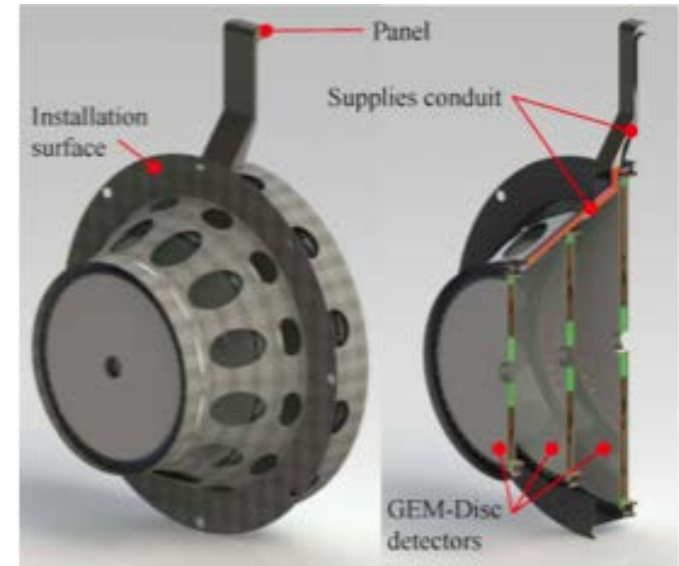


View from inside the Barrel DIRC optics box

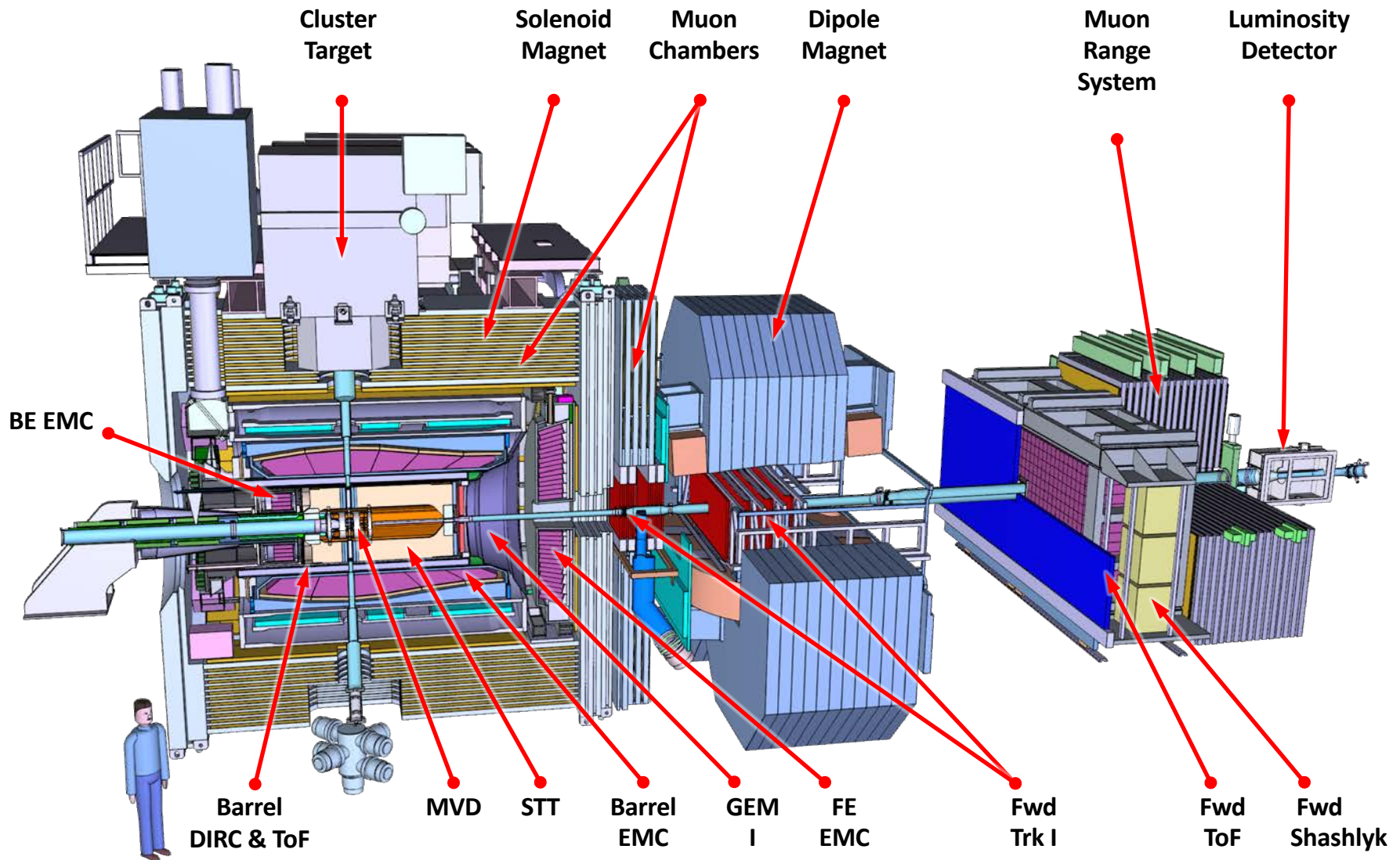
# Forward GEM Tracker

## Forward Tracking inside Solenoid

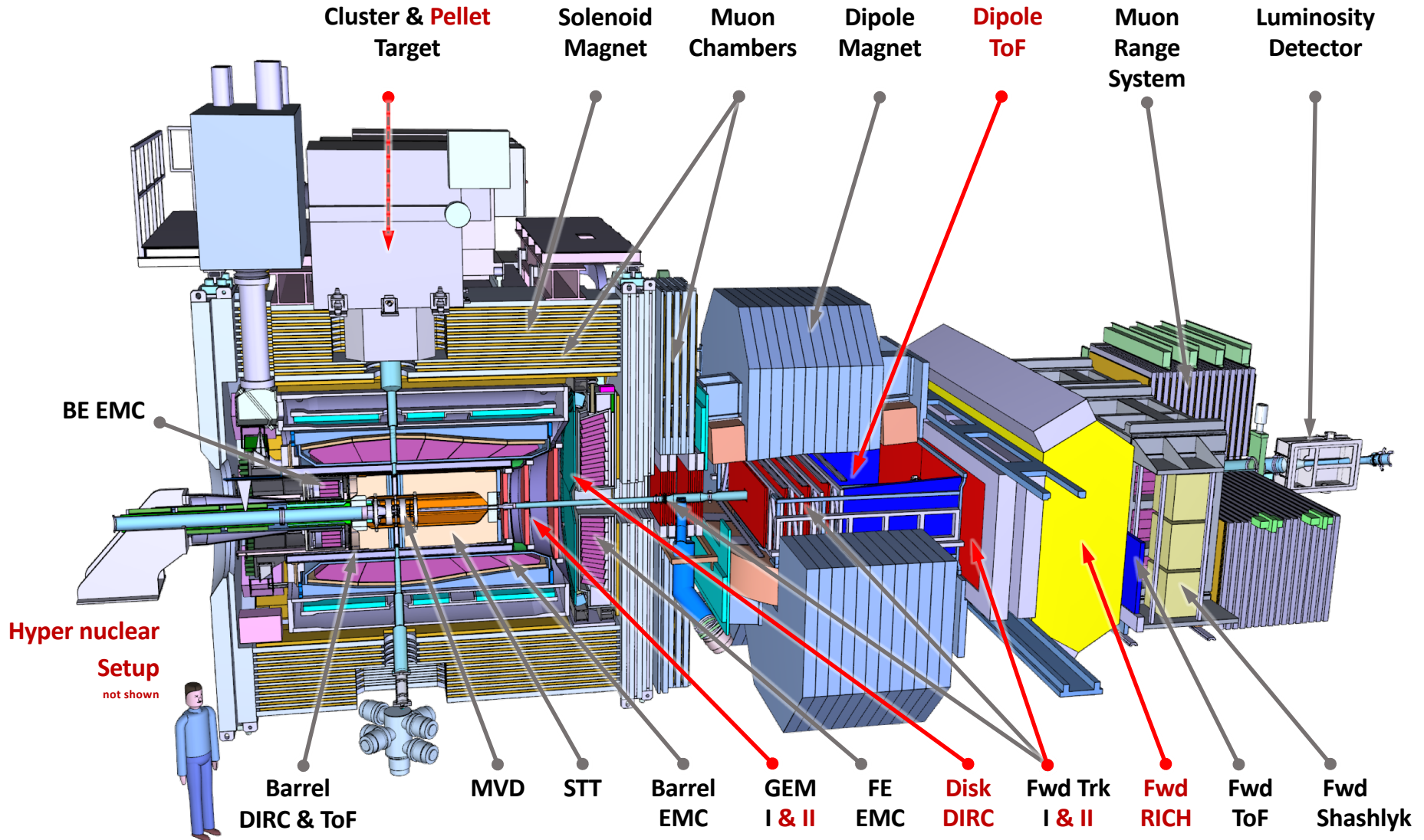
3-4 stations with 4 projections –rad., conc., x, y  
 Central readout plane for 2 GEM stacks  
 Large area GEM foils from CERN  
 (50 $\mu$ m Kapton, 2-5 $\mu$ m copper coating)  
 ADC readout for cluster centroids  
 Approx. 35000 channels total  
 Challenge to minimize material



# Start-Setup (Phase-1)



# Full Setup (Phase-2)





# Status of TDRs



**2008 approved**  
In production

**2009 approved**  
In production

**2013 approved**  
In production

**2013 approved**  
In production

**2013 approved**  
In production

**2013 approved**  
In production

**2014 approved**

**2016 approved**  
In production

**2017 approved**  
In production

**2017**  
→ in Review

**2017 approved**

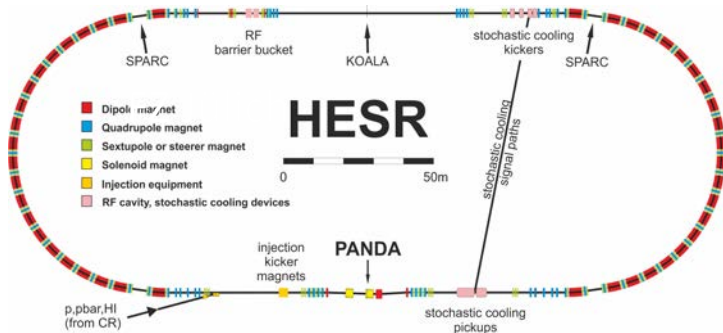
**2018**  
→ in Review

**2018**  
→ in Review

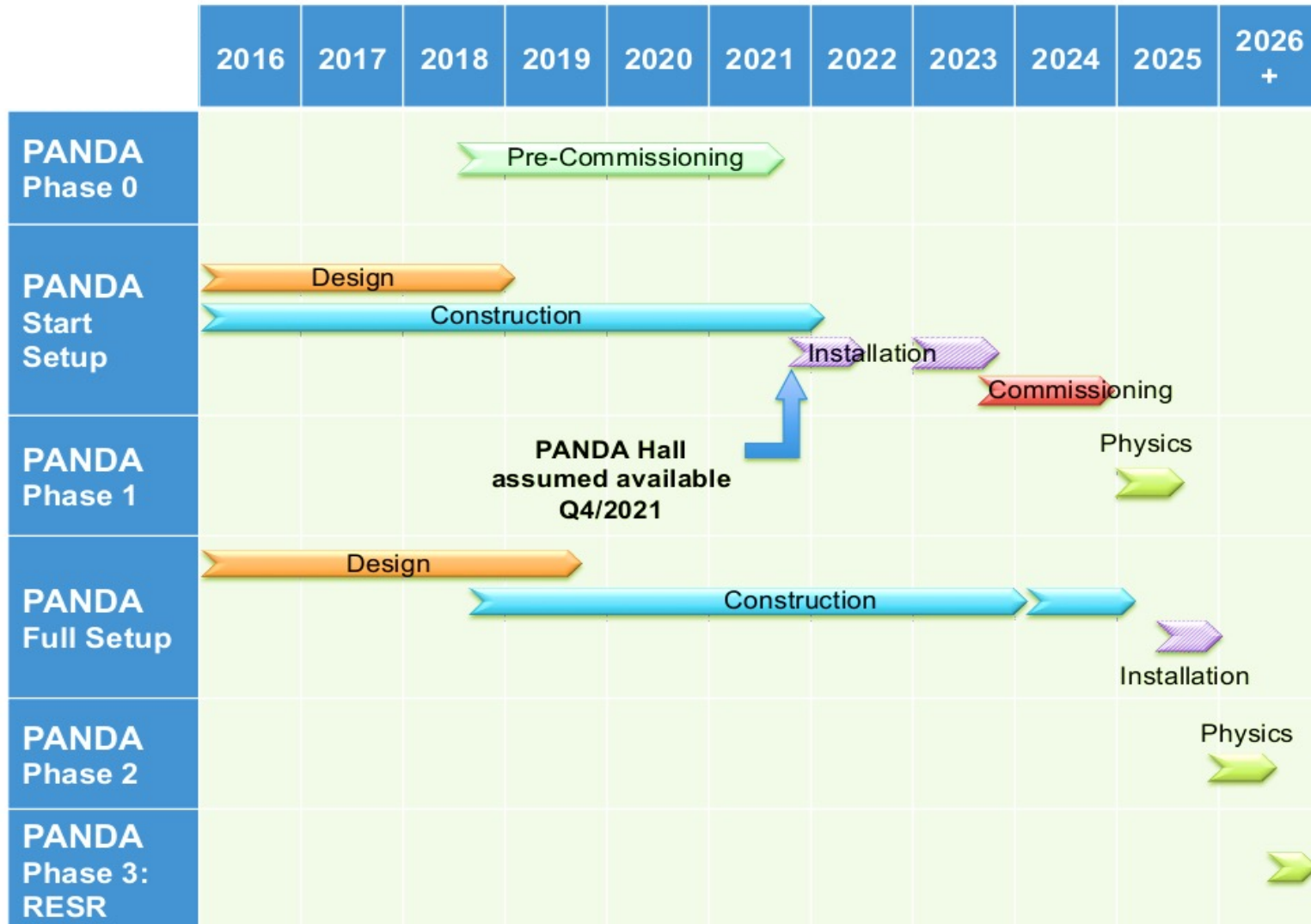
**2018 DCS and DAQ TDR**  
**2019 GEM TDR**  
Computing TDR after FAIR Computing CDR is accepted

# Status of HESR Dipoles and Quadrupoles complete

- 46 dipoles and 84 quadrupoles are waiting for installation
- Power converters delivered
- Sextupoles in production



# Schedule



# Collaboration



UniVPM 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  
U Cracow  
FAIR Darmstadt  
GSI Darmstadt  
JINR Dubna  
U Edinburgh  
U Erlangen  
NWU Evanston

U & INFN Ferrara  
FIAS Frankfurt  
U Frankfurt  
LNF-INFN Frascati  
U & INFN Genova  
U Gießen  
U Glasgow  
BITS Pilani KKBGC, Goa  
KVI Groningen  
Sadar Patel U, Gujart  
Gauhati U, Guwahati  
USTC Hefei  
URZ Heidelberg  
FH Iserlohn  
Doğuş U, Istanbul  
FZ Jülich  
IMP Lanzhou  
INFN Legnaro  
U Lund

HI Mainz  
U Mainz  
INP Minsk  
ITEP Moscow  
MPEI Moscow  
BARC Mumbai  
U Münster  
Nankai U, Tianjin  
BINP Novosibirsk  
Novosibirsk State U  
IPN Orsay  
U Wisconsin, Oshkosh  
U & INFN Pavia  
Charles U, Prague  
Czech TU, Prague  
IHEP Protvino  
Irfu Saclay

U of Sidney  
PNPI St. Petersburg  
West Bohemian U, Pilzen  
KTH Stockholm  
U Stockholm  
SUT, Nakhon Ratchasima  
SVNIT Surat-Gujarat  
S Gujarat U, Surat-Gujarat  
FSU Tallahassee  
U & INFN Torino  
Politecnico di Torino  
U & INFN Trieste  
U Uppsala  
U Valencia  
SMI Vienna  
U Visva-Bharati  
NCBJ Warsaw

more than 460 physicists from  
from more than 75 institutions in 20 countries

Concentration on unique and forefront physics topics

- Production of **multi-strangeness baryons**  
(unexplored, new territory, „Strangeness-Factory“)
- Precise measurement of the **line shape of narrow XYZ-states**,  
e.g. X(3872)  
(only possible in proton–antiproton, counting experiment,  
clarification of the nature of the states)
- Resonant formation of the  
**negative and uncharged partners of the Z-States**  
(only possible in proton–antiproton, goal is the nature of the states)
- Measurement of **the electromagnetic form factors of the proton** in  
the time-like domain with electrons and muons in the final state
- Production of **high-spin charmonia**  
(only possible in proton–antiproton)  
light mesons, baryons and production of hybrids und glueballs

XYZ-, Hyperon Factory

## Concentration on unique and forefront physics topics

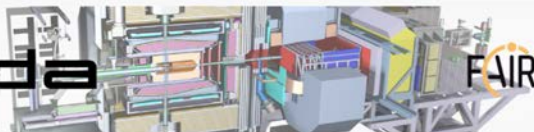
- Production of **multi-strangeness baryons**  
(unexplored, new territory, „Strangeness-Factory“)
- Precise measurement of the **line shape of narrow XYZ-states**,  
e.g. X(3872)  
(only possible clarification of XYZ-states)
- Resonant formation of **negative and positive parity states**  
(only possible clarification of XYZ-states)
- Measurement of **the electromagnetic form factors of the proton** in  
the time-like domain with electrons and muons in the final state
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light mesons, baryons and production of hybrids und glueballs

**Please stay tuned for start  
of proton beam 2024  
and anti-proton beam 2025**

**XYZ-, Hyperon Factory**



# panda.gsi.de



Search

## +++ RECENT NEWS +++



**PANDA: Strong Interaction Studies with Antiprotons**  
2017 Sep 27  
Article in Nuclear Physics News



**FAIR forges its future**  
2017 Sep 27  
Cerncourier article

## Welcome to the PANDA Experiment Website

The PANDA Experiment will be one of the key experiments at the Facility for Antiproton and Ion Research (FAIR) which is under construction and currently being built on the area of the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany. The central part of FAIR is a synchrotron complex providing intense pulsed ion beams (from p to U). Antiprotons produced by a primary proton beam will then be filled into the High Energy Storage Ring (HESR) which collide with the fixed target inside the PANDA Detector.

The PANDA Collaboration with more than 500 scientist from 17 countries intends to do basic physics research on various topics around the weak and strong forces, exotic states of matter and the structure of hadrons. In order to gather all the necessary information from the antiproton-proton collisions a versatile detector will be build being able to provide precise trajectory reconstruction, energy and momentum measurements and very efficient identification of charged particles.



# Thank you