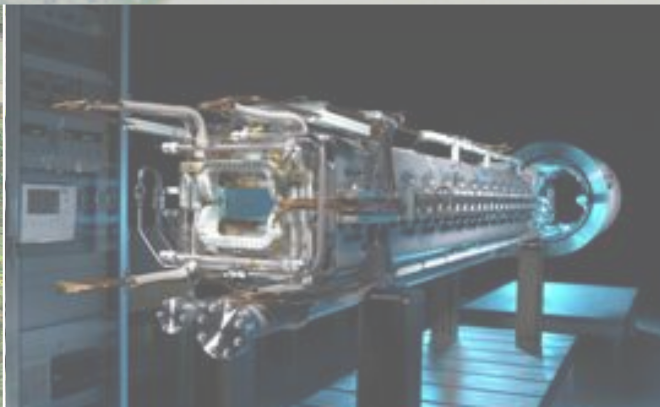
Proton-Antiproton Annihilations at FAIR - The PANDA Experiment

Inti Lehmann
Facility for Antiproton and Ion Research - FAIR

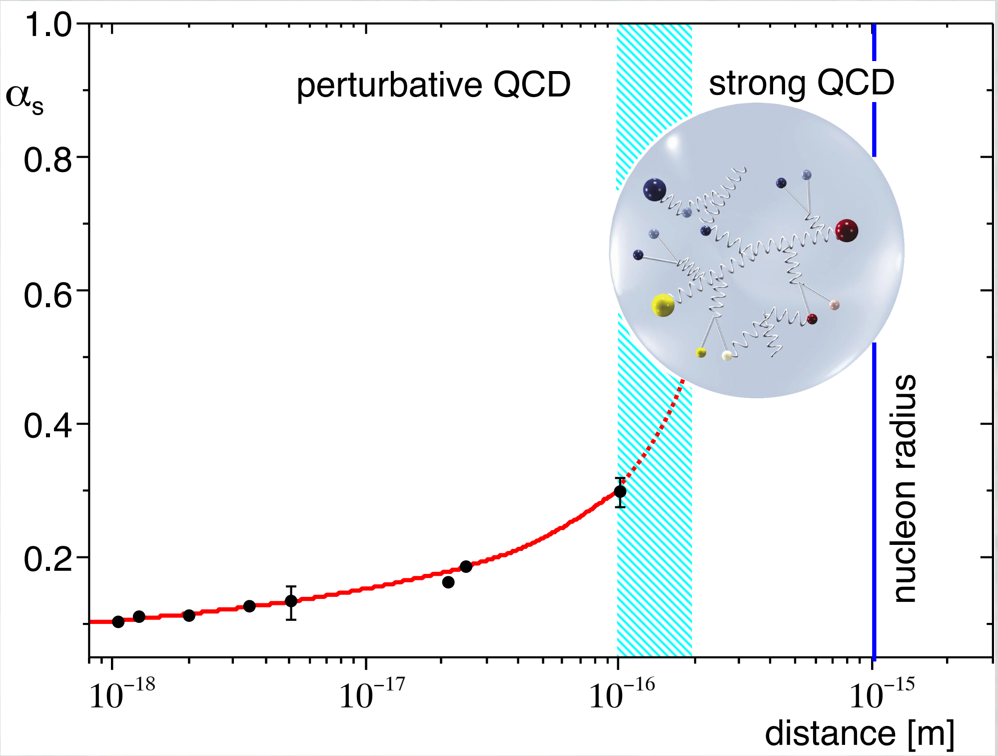
Spin Praha, July 2012





Overview

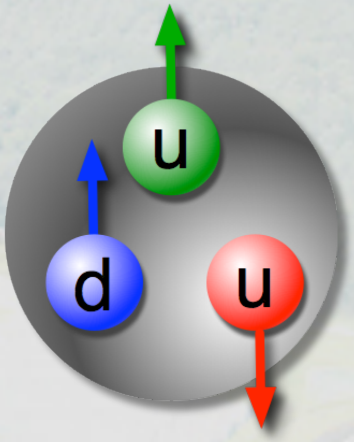
- **Some puzzles in hadron physics**
- **Experimental approach**
- **PANDA detector set-up**
- **Physics highlights at PANDA**

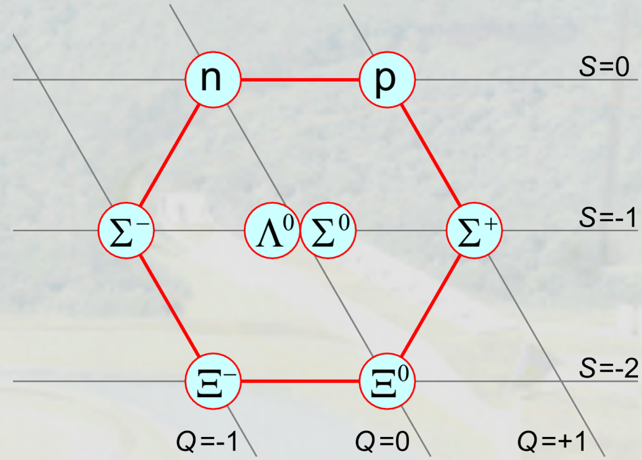


Some puzzles in hadron physics

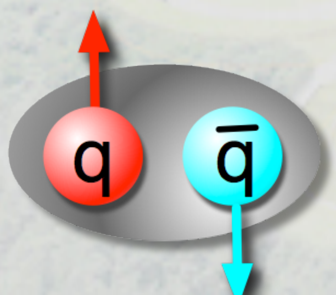
Naive Picture of the Hadron

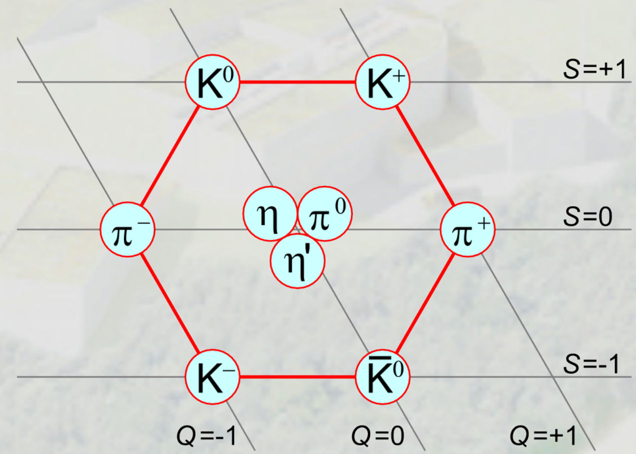
- **Baryons**
  - e.g. proton, neutron
  - 3 quarks
  - half integer spin





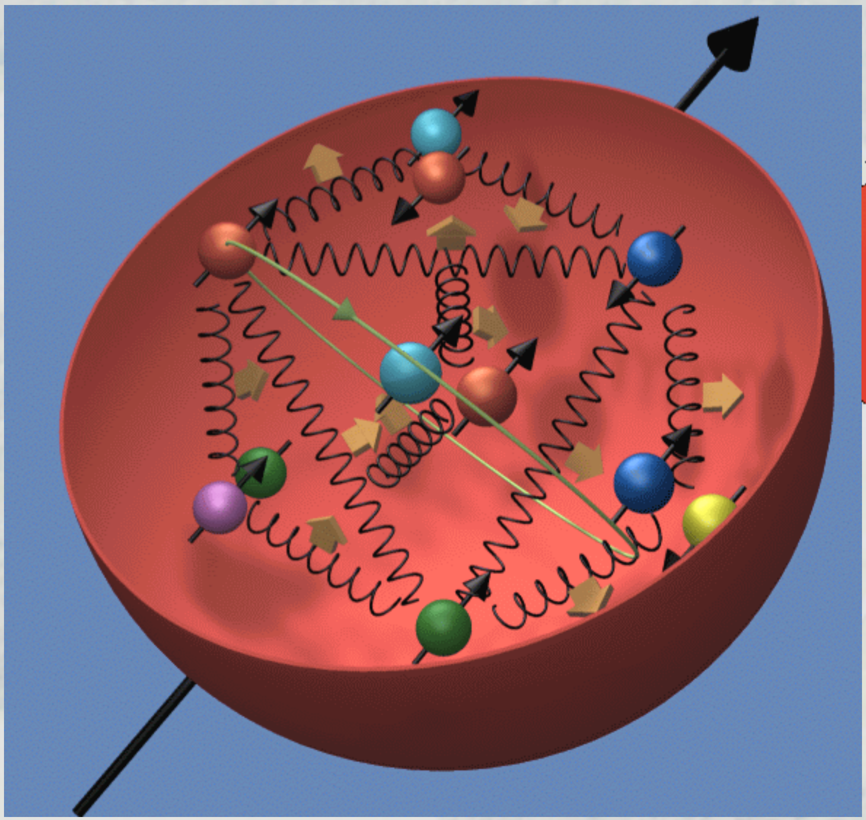
- **Mesons**
  - e.g. pion
  - quark-antiquark
  - integer spin

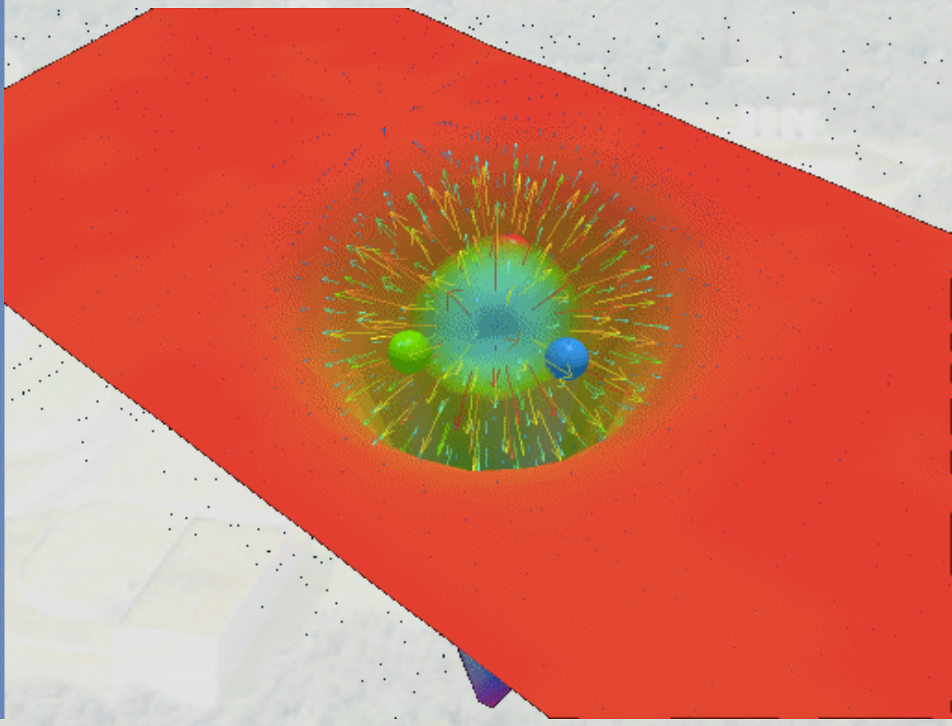




Closer Look

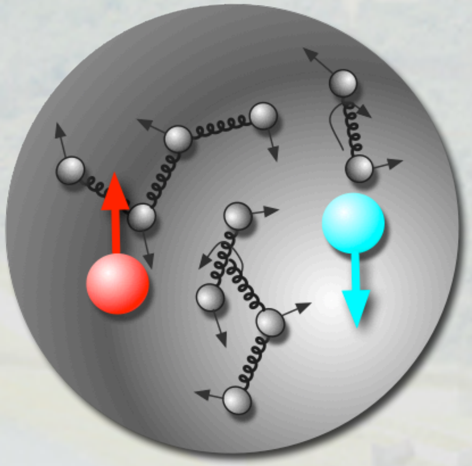
- **Reality is more complicated**





Semi-Naive Picture of the Hadron

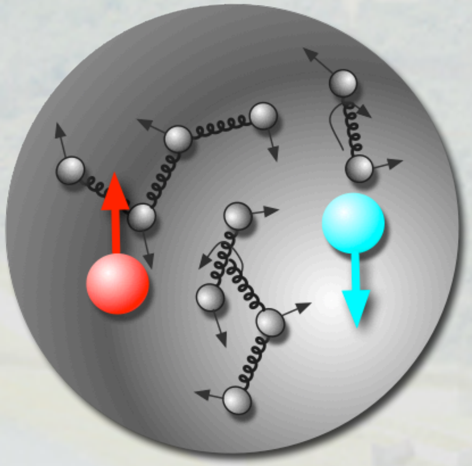
- Hadrons
  - contain quark-gluon sea
  - quantum numbers carried by “dressed” valence quarks

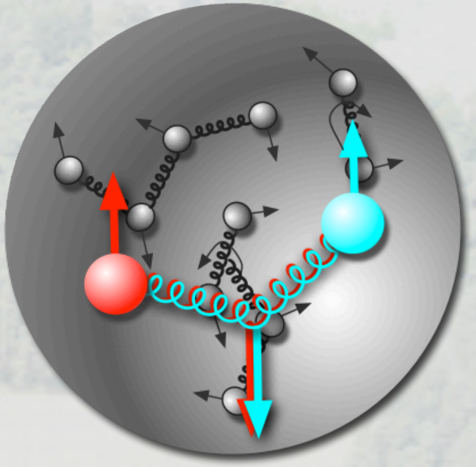


Does this only allow baryons and mesons?

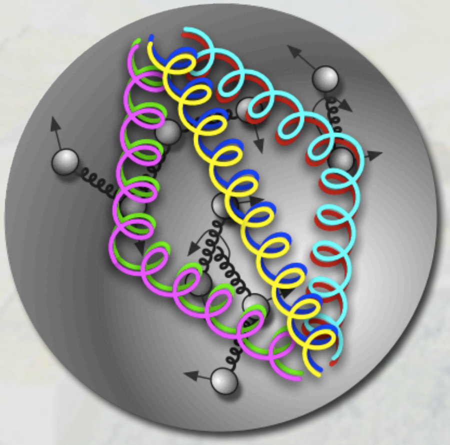
Puzzle 1: Exotic Hadrons

- Known hadrons
  - contain quark-gluon sea
  - quantum numbers carried by “dressed” valence quarks
- Exotic hadrons
  - gluons contribute to quantum numbers
  - no principle to forbid or suppress these





hybrid



glueball

Why not observed, are they?

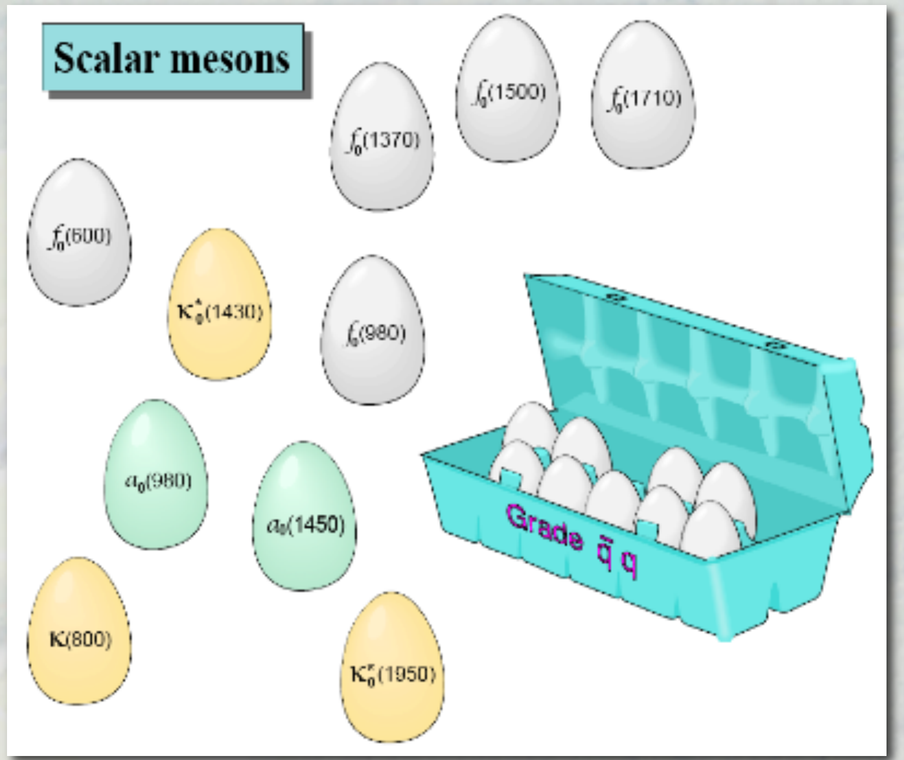
Indication: Overpopulation

- **7 candidates for 4 states with 0^{++}**

  (Light quark sector)

2^{++}	a_2 1320	f_2 1270	f'_2 1525	K^*_2 1430
1^{++}	a_1 1260	f_1 1285	f'_1 1510	K_{1A}
1^{+-}	b_1 1235	h_1 1170	h'_1 1380	K_{1B}
0^{++}	a_0	f_0	f_0	K^*_0 1430
	$a_0(980)$ $a_0(1450)$	$f_0(1370)$ $f_0(1500)$	$f_0(980)$ $f_0(1710)$	

L = 1

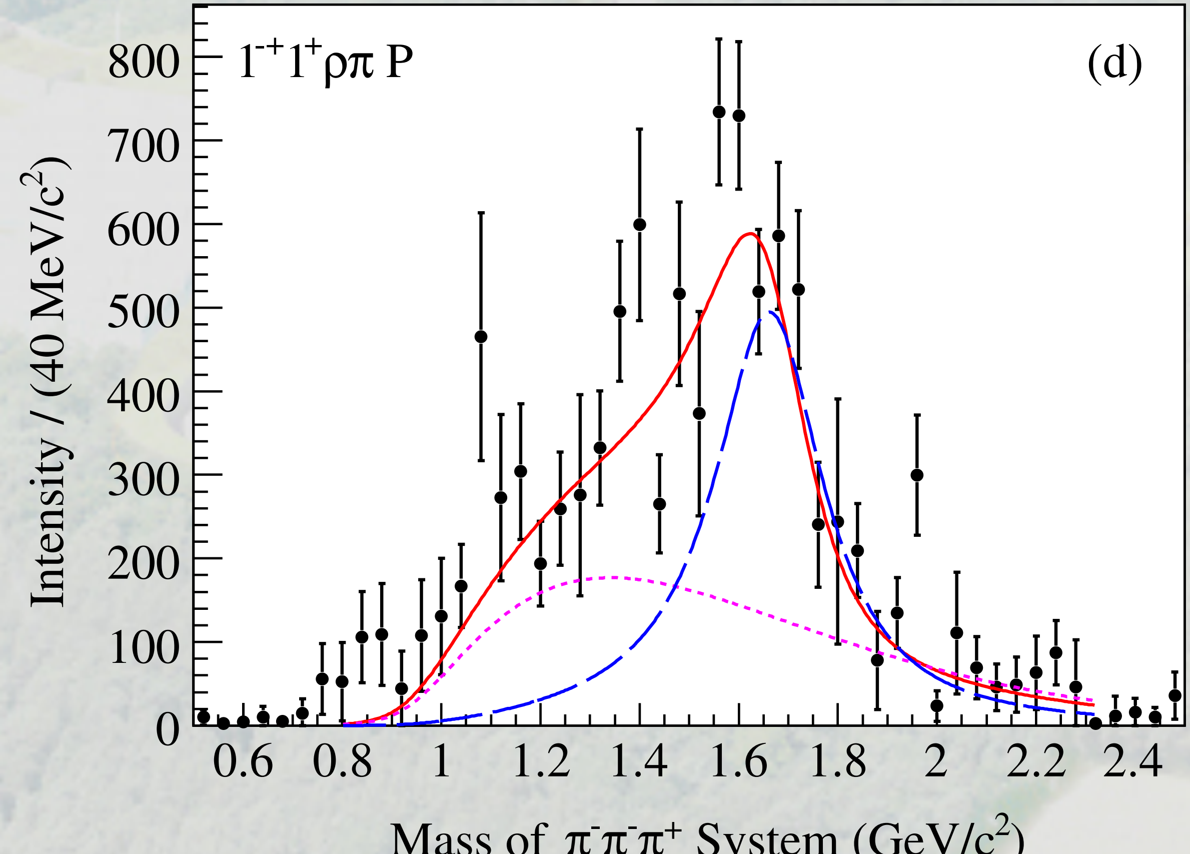


- **States mix: nature difficult to determine**

Example: Recent Finding

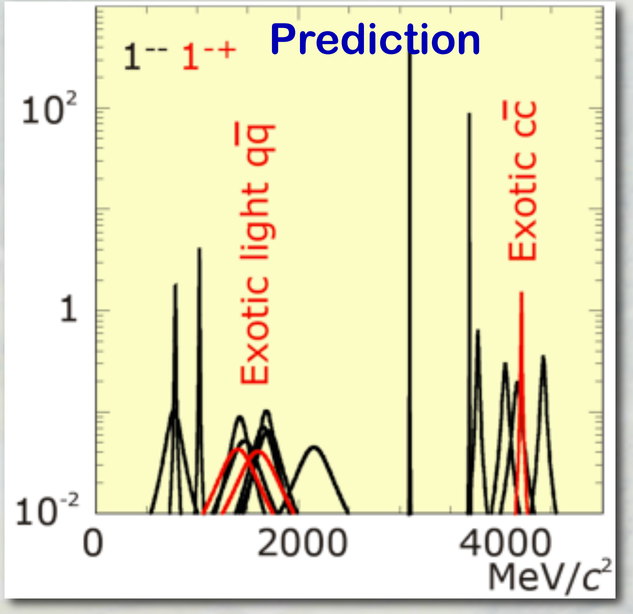
- **COMPASS partial wave analysis**
  - **Exotic $J^{PC} = 1^{-+}$ wave found at 1.66 GeV**

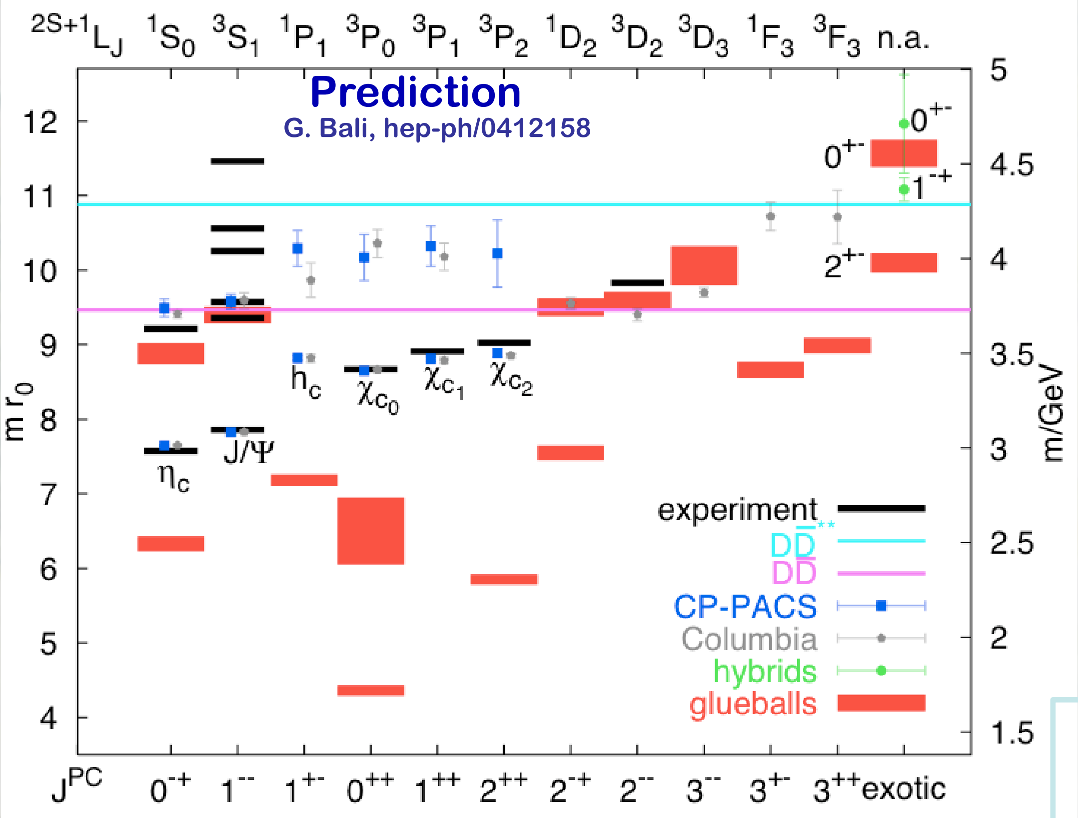
Phys. Rev. Lett. 104, 241803 (2010)



Charm Quark Sector

- More promising than light quark sector
  - Narrower states
  - Fewer states
  - Less mixing





- Exotic heavy glueballs
  - $m(0^{+-}) = 4560(70)$ MeV
  - $m(2^{+-}) = 3980(50)$ MeV
- Width unknown, but!
  - Nature invests more likely in mass than in momentum

No data!

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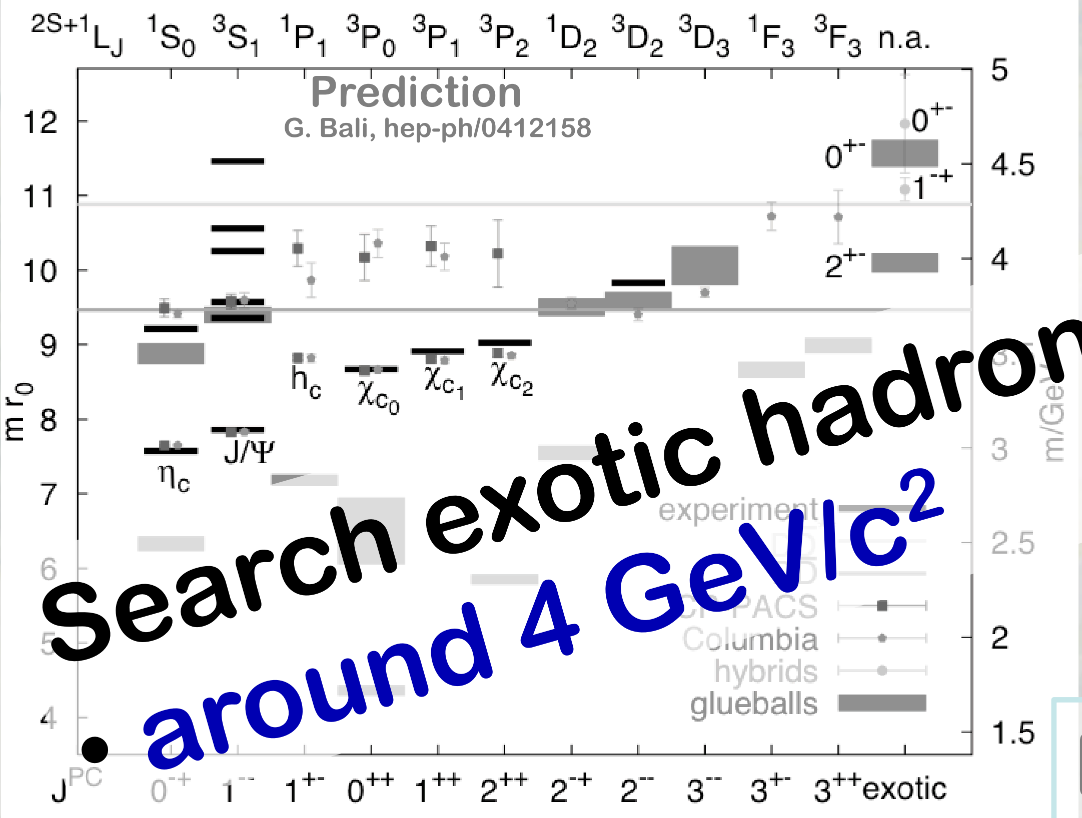
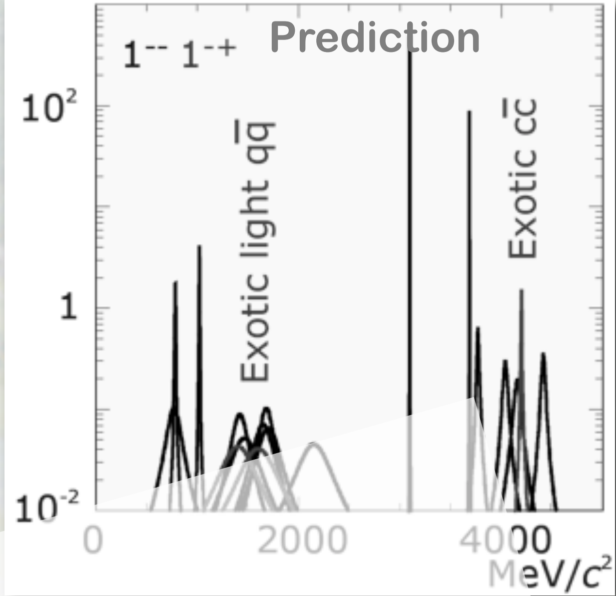




Search exotic hadrons

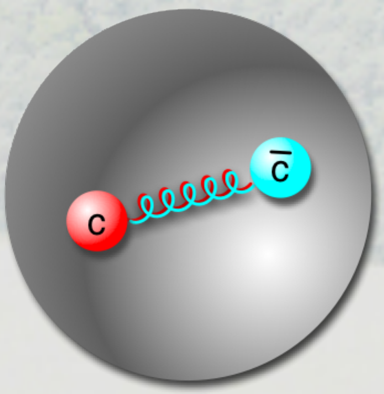
- **around 4 GeV/c^2**

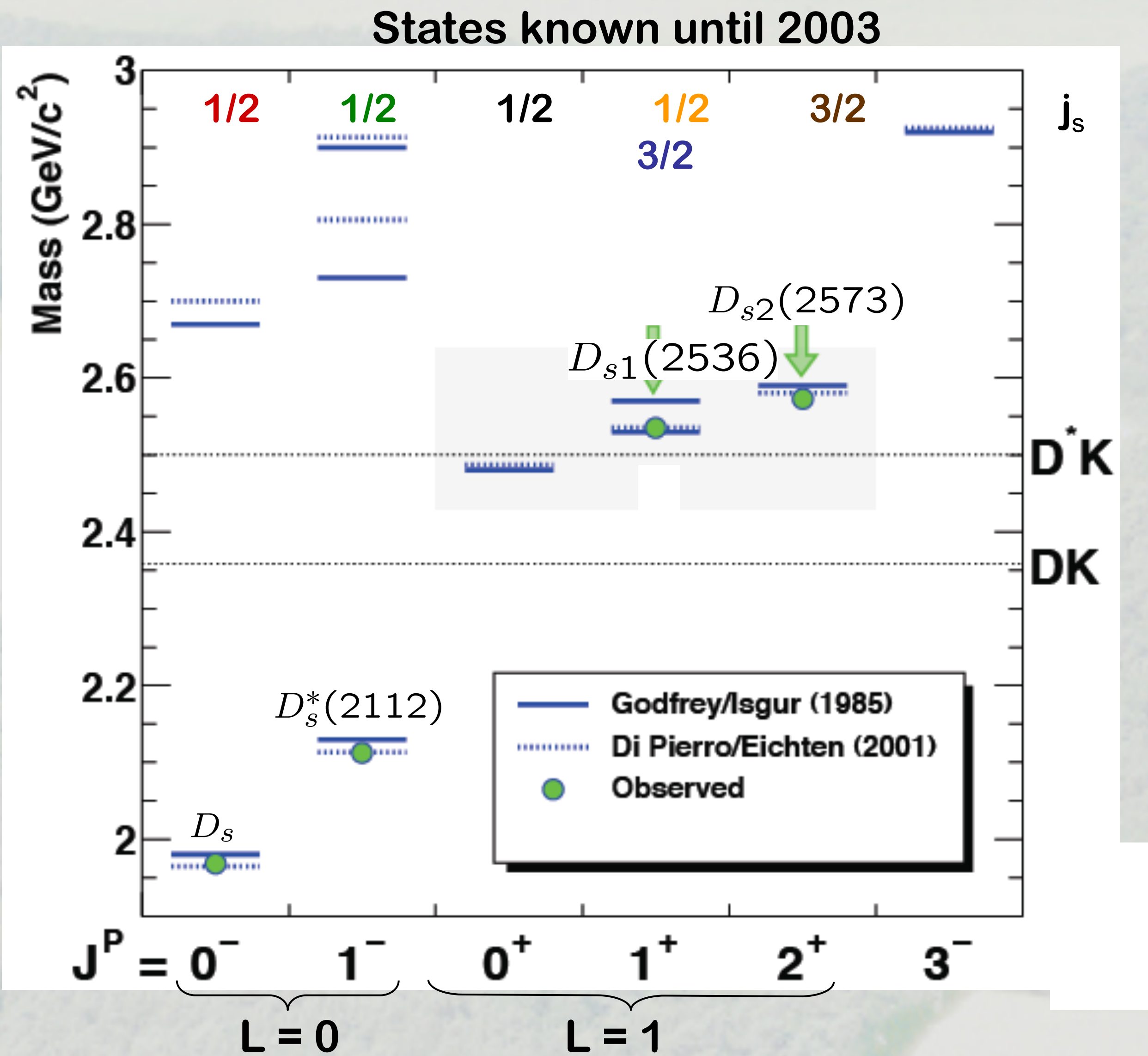
- Exotic heavy glueballs
  - $m(0^{+-}) = 4560(70)$ MeV
  - $m(2^{+-}) = 3980(50)$ MeV
- Width unknown, but!
  - Nature invests more likely in mass than in momentum

No data!

Puzzle 2: Charmonium Spectrum

- Positronium of QCD
- Until 2003
  - no surprises
  - well understood
- Example
  - D_s spectrum





Puzzle 2: Charmonium Spectrum

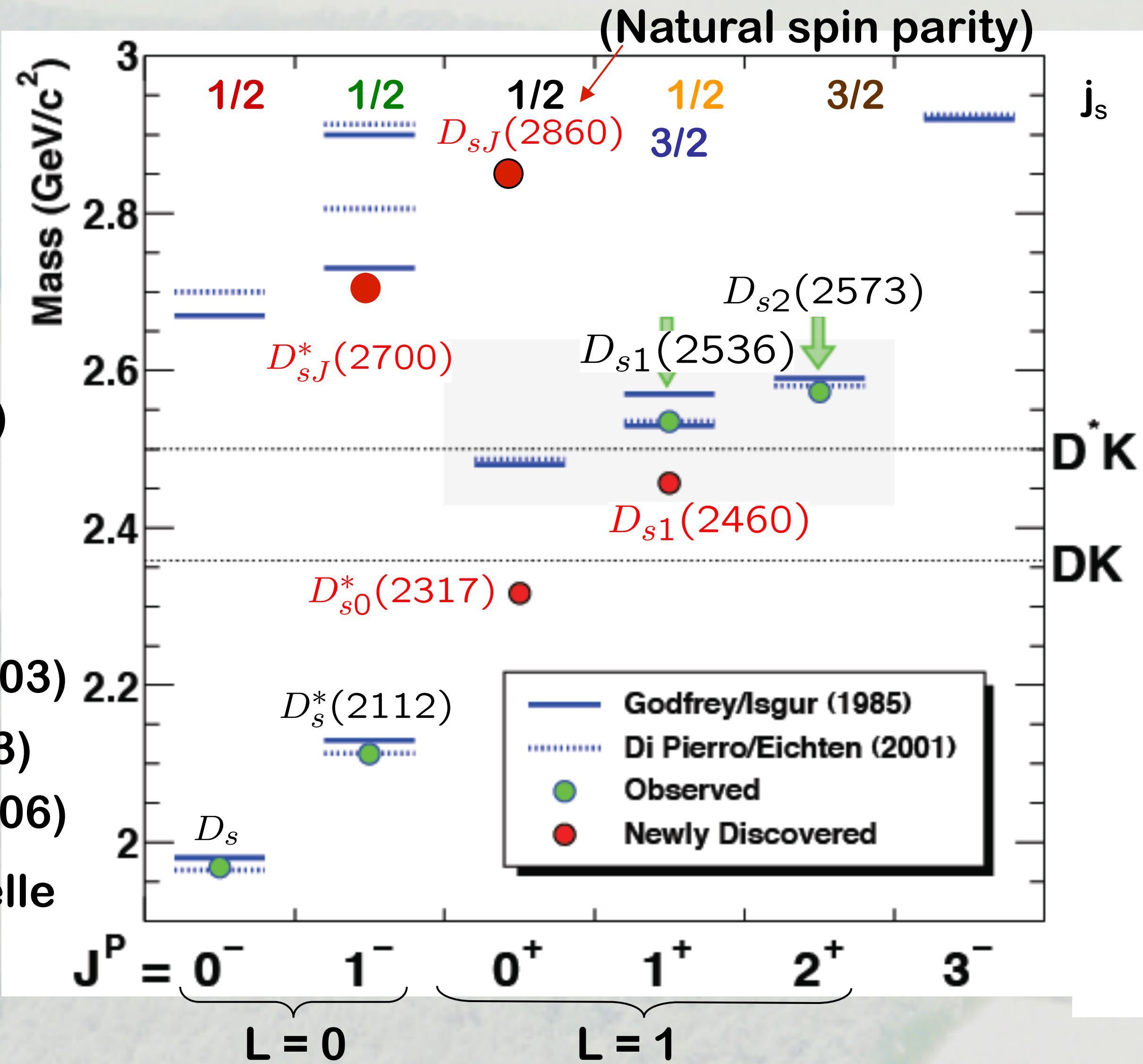
- Example
  - D_s spectrum

States known until 2003

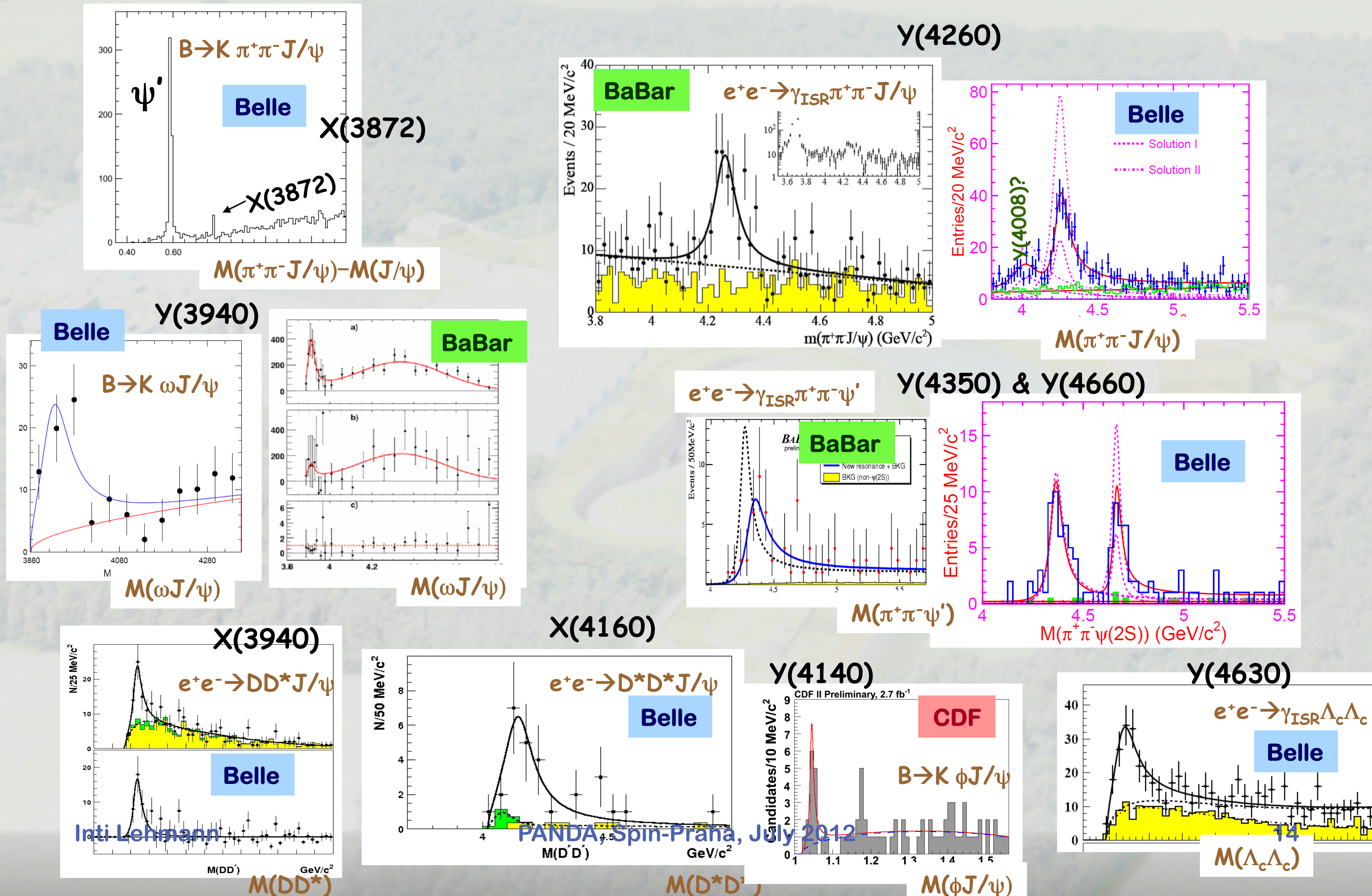
D_s	(Cleo, 1983)
$D_s^*(2112)$	(Slac, 1984)
$D_{s1}(2536)$	(Argus, 1989)
$D_{s2}(2573)$	(Cleo, 1994)

Discovered after 2003

cs?	$D_{s0}^*(2317)$	(BaBar, 2003)
	$D_{s1}(2460)$	(Cleo, 2003)
	$D_{sJ}(2860)$	(BaBar, 2006)
	$D_{sJ}^*(2700)$	(BaBar/Belle 2006)



Findings at B Factories



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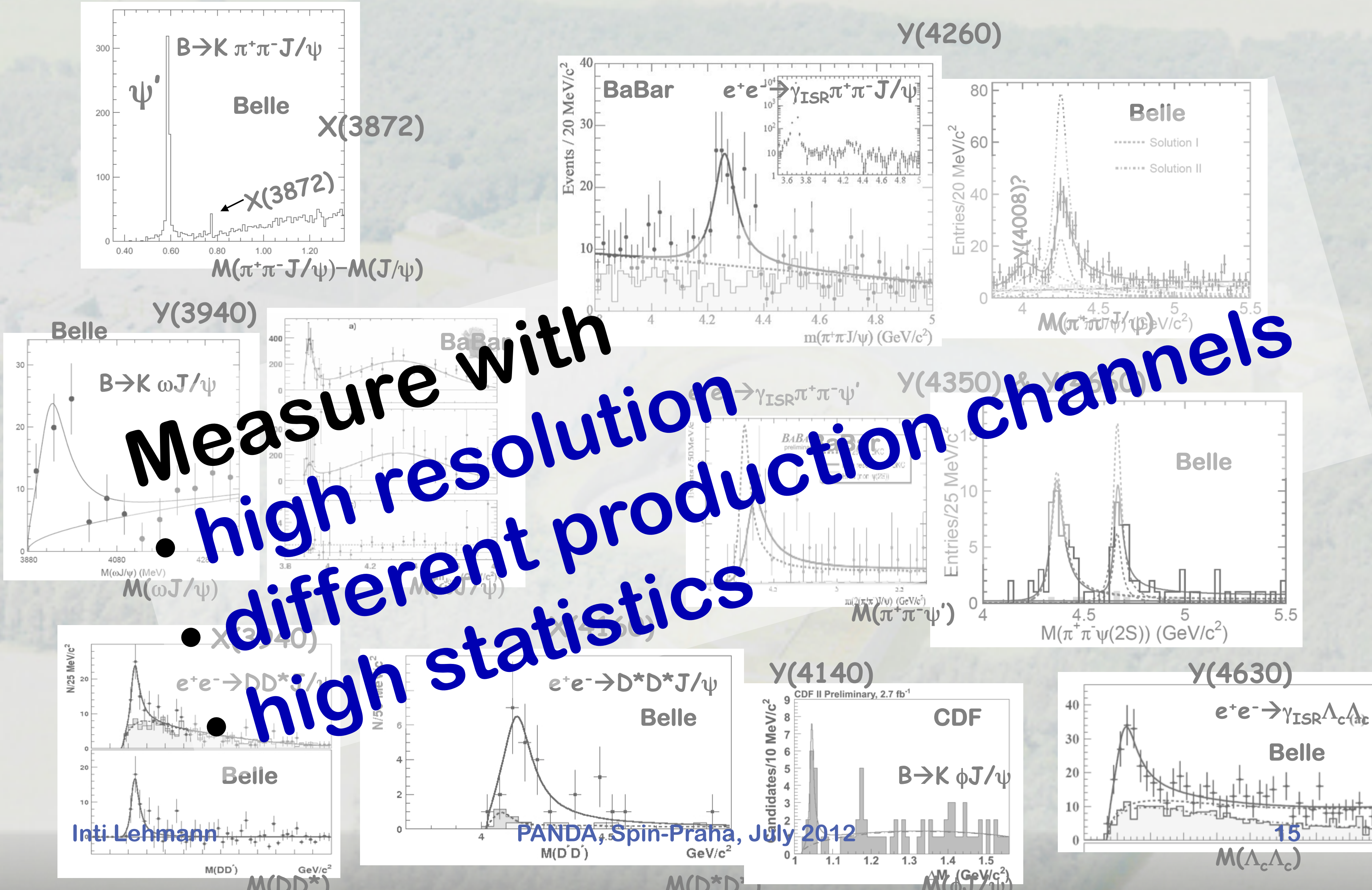
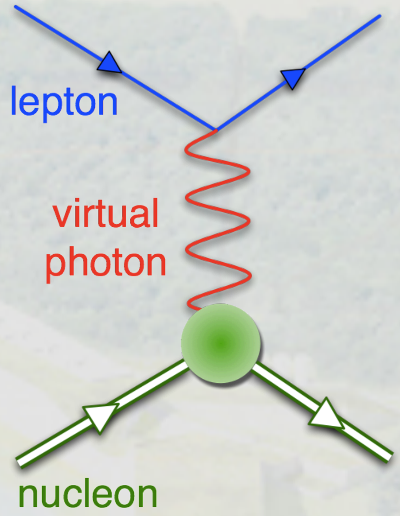


Measure with

- **high resolution**
- **different production channels**
- **high statistics**

Puzzle 3: Nucleon Structure

- Form factors - well understood?
- Successful approach for decades
  - **Rosenbluth separation**
    - assuming single photon exchange



$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Rosenbluth}} = \left[\frac{|G_E|^2 + \tau|G_M|^2}{1+\tau} + 2\tau|G_M|^2 \tan^2\frac{\theta}{2}\right]\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}$$

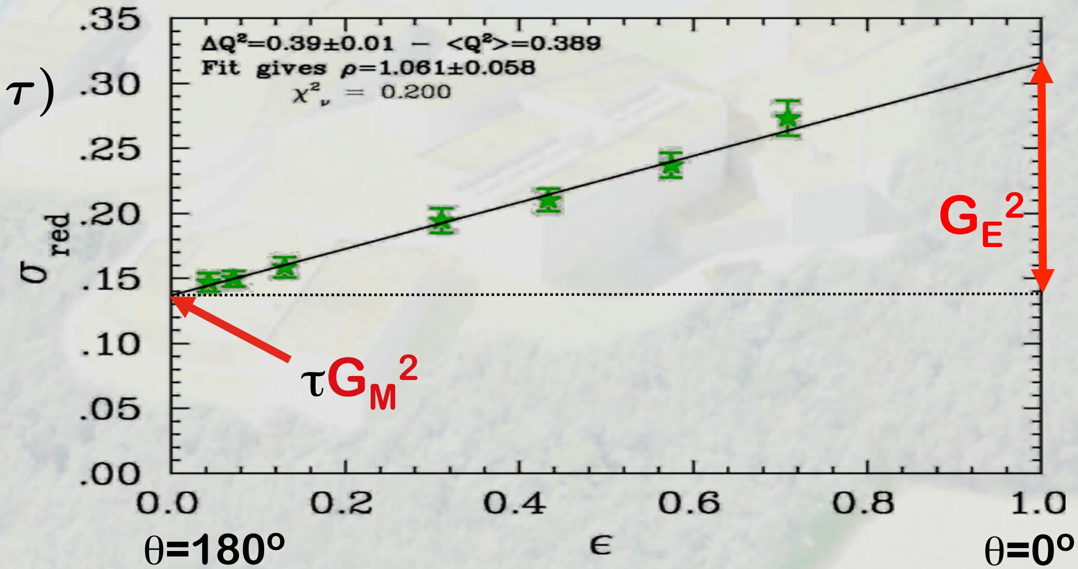
  - **Extract G_E and G_M**

$$\sigma_{\text{red}} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{\text{Rosenbluth}}}{\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}}\epsilon\,(1+\tau)$$

$$= \epsilon|G_E|^2 + \tau|G_M|^2$$

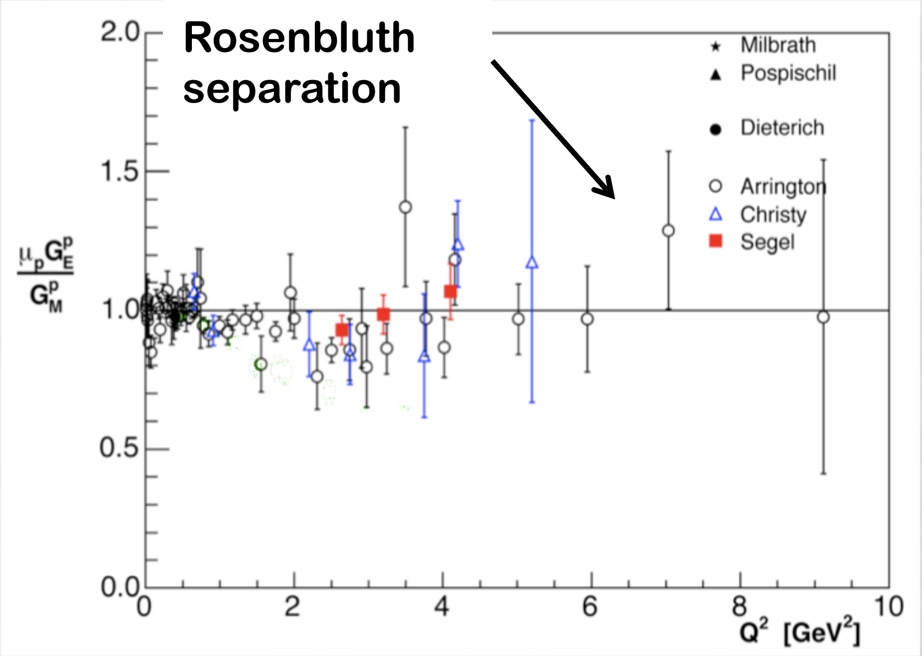
with $$\tau = \frac{Q^2}{4M_p^2}$$

$$\epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$



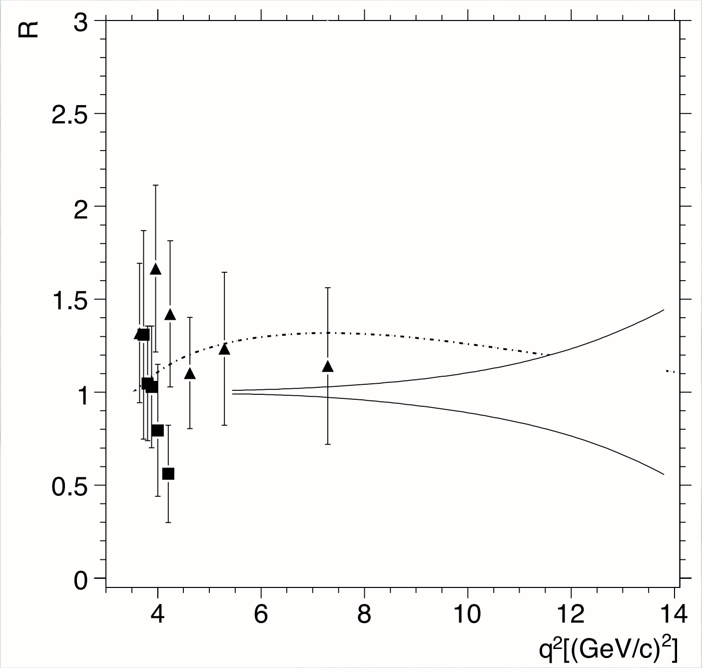
Puzzle 3: Nucleon Structure

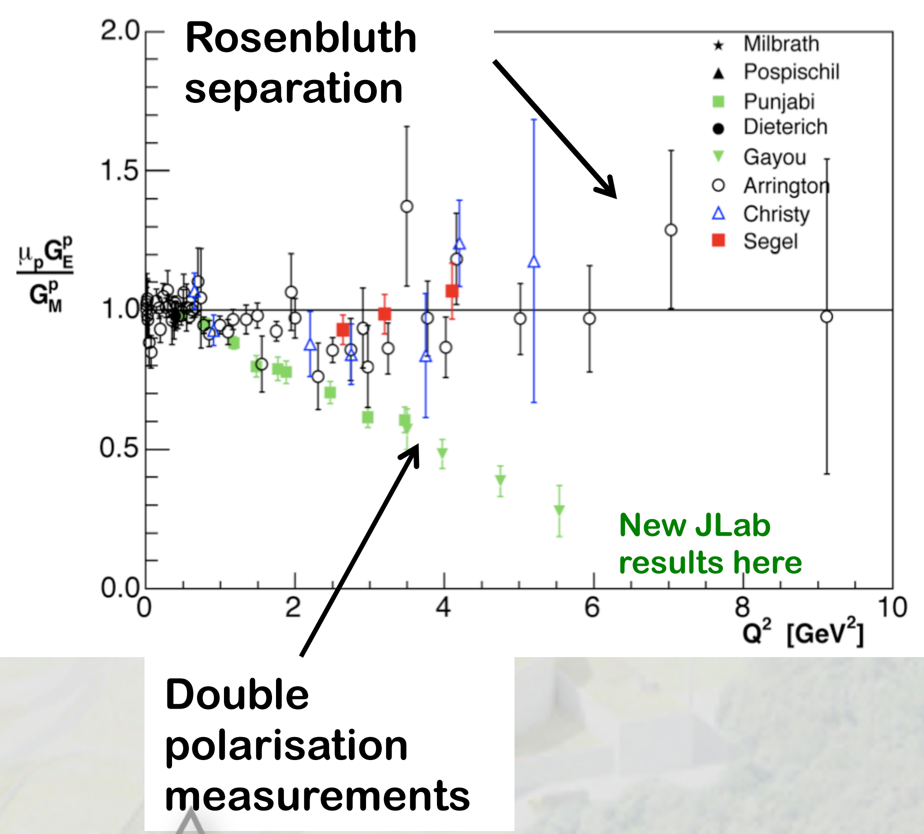
- Form factor ratio $R = \mu_p G_E/G_M$
- Space like form factor



Puzzle 3: Nucleon Structure

- Form factor ratio $R = \mu_p G_E / G_M$
- Space like form factor
  - unresolved discrepancy
- Time like form factor
  - basically uncharted territory

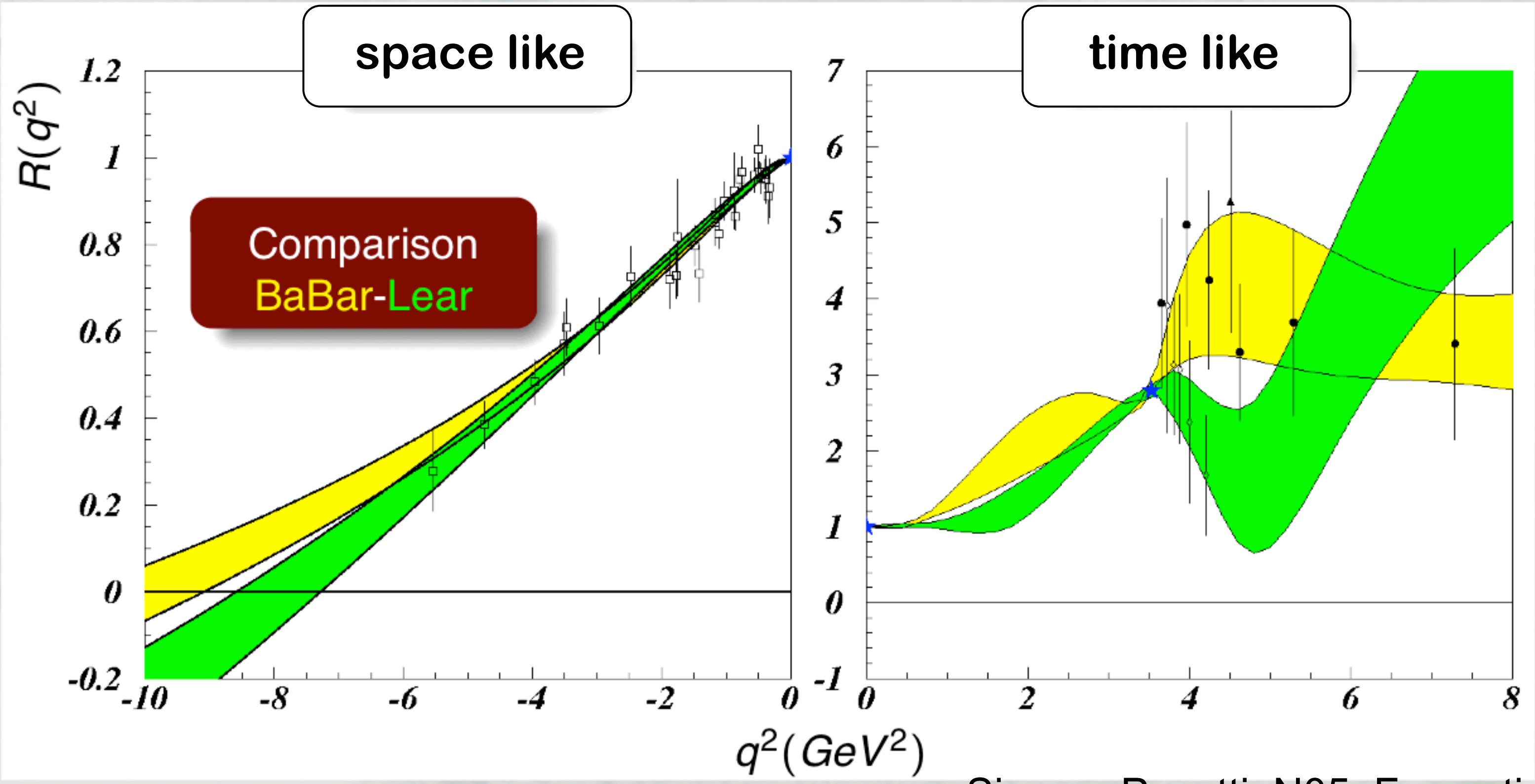




OLYMPUS experiment

Time and Space-Like Regions

- Closely related using dispersion relation
  - fit to double polarisation measurements in space like region
  - weak constraint: scarce data in time like region

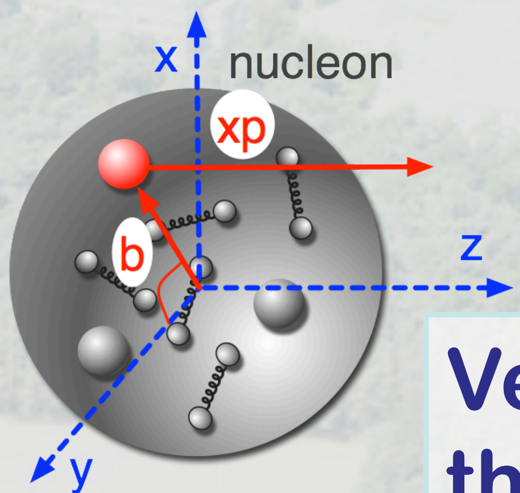


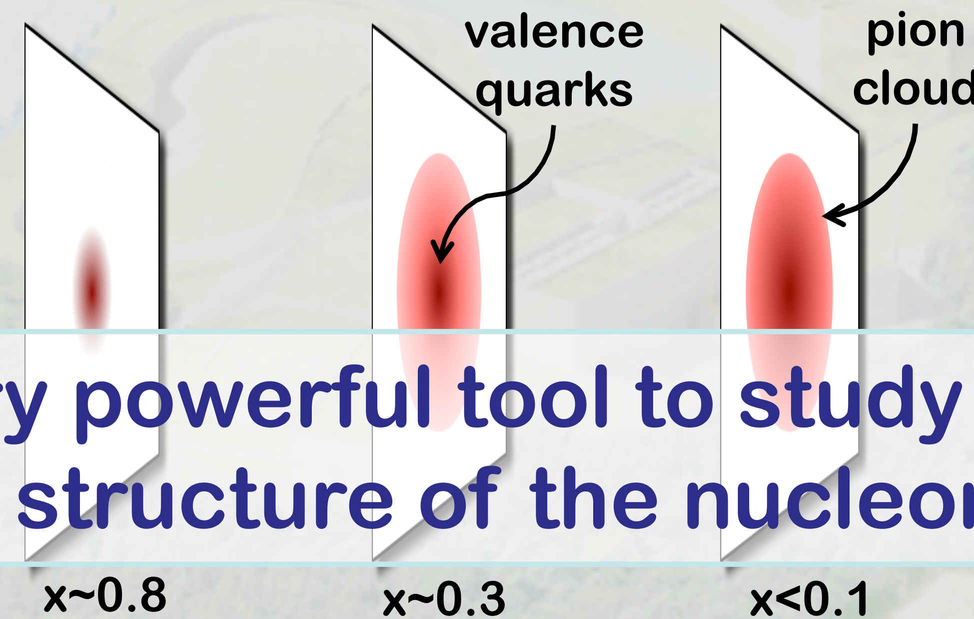
Simone Pacetti, N05, Frascati

Other Structure Functions

- Generalised Parton Distributions (GPDs)
- 2+1 dimensional picture of the nucleons
  - Fourier transformations of GPDs

$$q(x, b_\perp) = \int \frac{d^2\Delta_\perp^2}{(2\pi)^2} H(x, 0, -\Delta_\perp^2) e^{-i\Delta_\perp \cdot b_\perp}$$

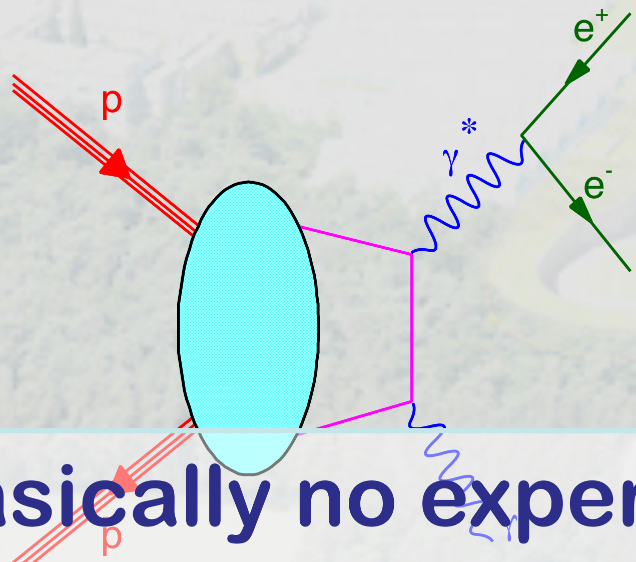


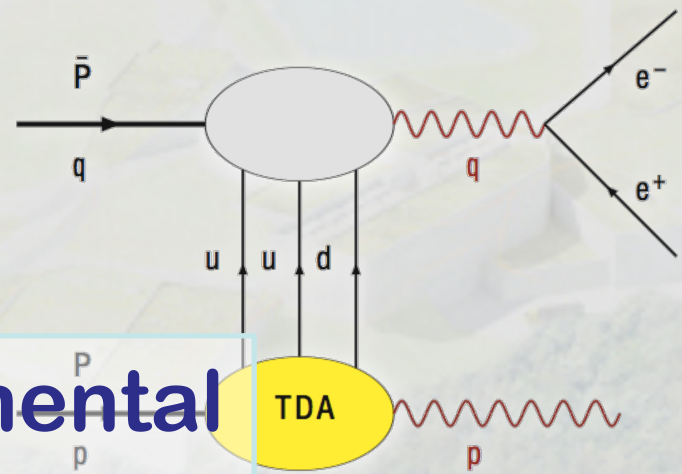


Very powerful tool to study the structure of the nucleon!

- **Analoge models**
  - **Time Like GPDs**
  - **Generalised Distribution Amplitudes (GDAs)**
  - **Transition Distribution Amplitudes (TDAs)**

•A. Afanasev, et al., arXiv:0903.4188
•M. Diehl, et al., Phys. Rev. Lett. 81 (1998)1782
•B. Pire, L. Szymanowski, Phys. Lett. B622:83-92,2005





Basically no experimental data available!

Time-Like Domain

- Available models
  - Time Like GPDs
  - Generalised Distribution Amplitudes (GDAs)
  - Transition Distribution Amplitudes (TDAs)

•A. Afanasev, et al., arXiv:0903.4188
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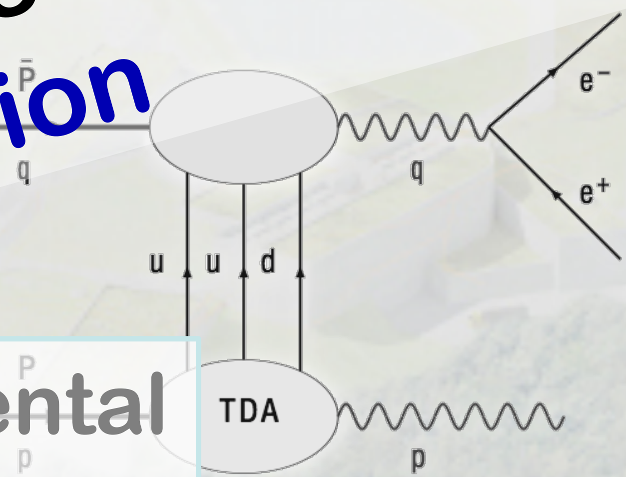
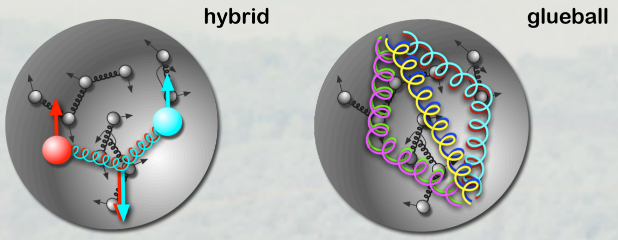


Explore structure functions
- **in time-like region**

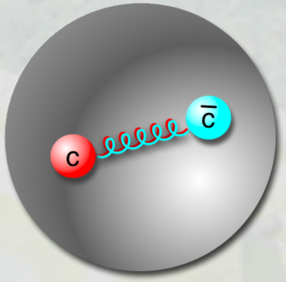
Basically no experimental data available!

Puzzle Reminder

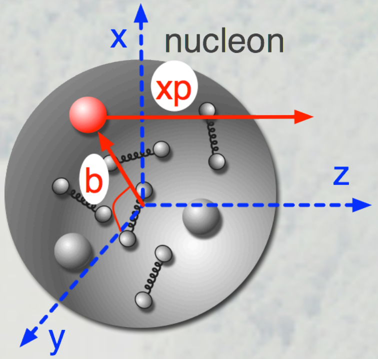
- 1) Exotic hadrons – observed or not?
  - Search around 4 GeV/c^2

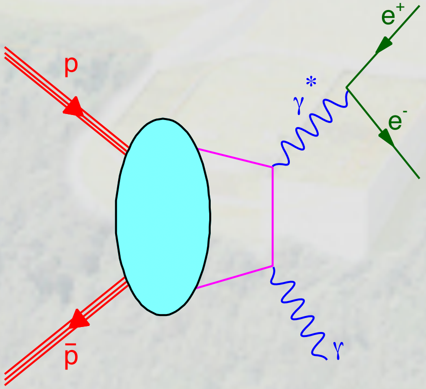


- 2) Charmonium spectrum – unpredicted states!
  - Check different production channels
  - Scan with high resolution
  - Measure with high statistics



- 3) Nucleon structure – form factor surprises
  - Explore time-like region

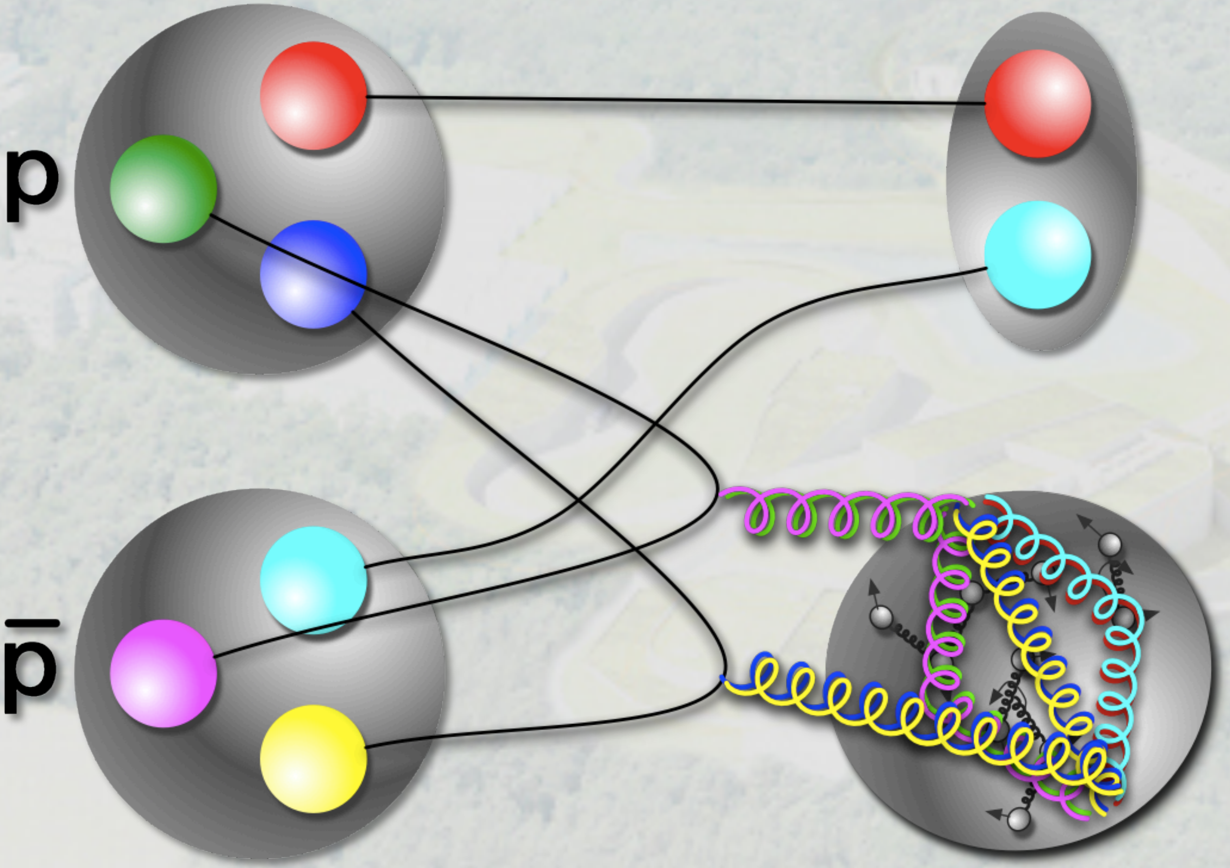




Experimental Approach

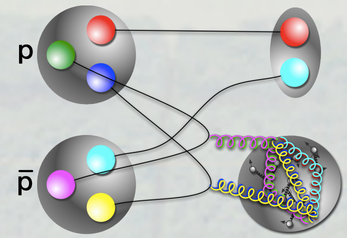
Experimental Approach

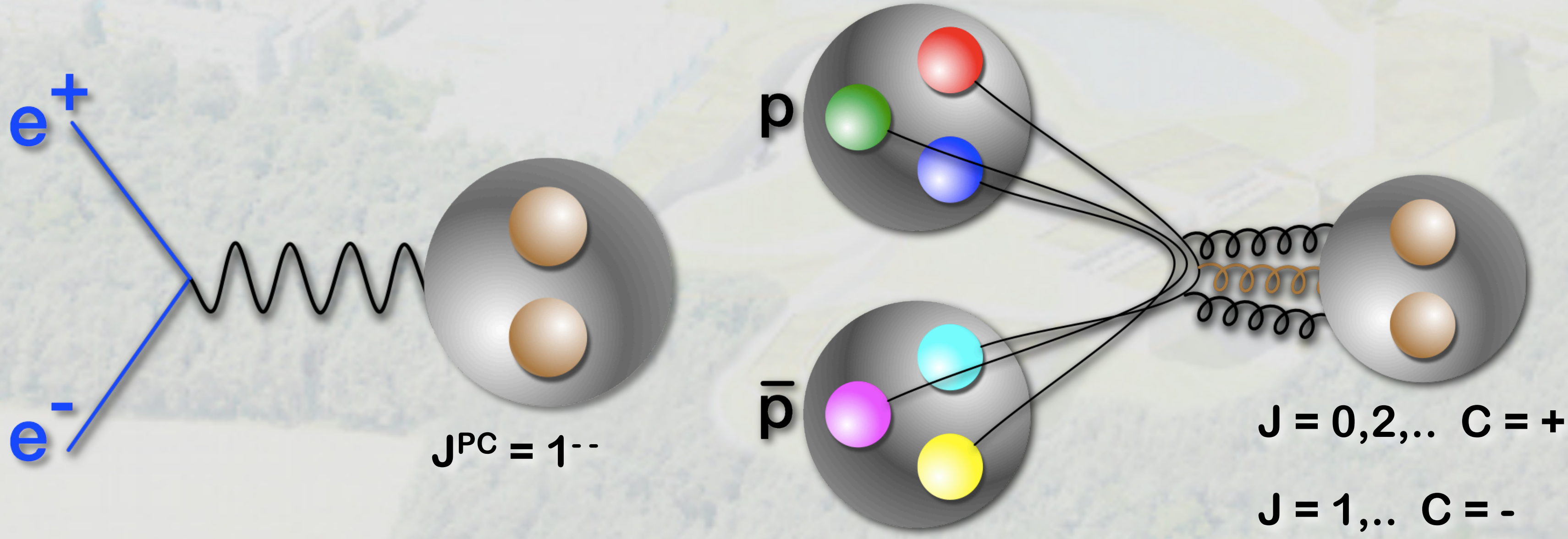
- **Gluon-rich environment**
  ⇒ Proton-antiproton annihilations



Experimental Approach

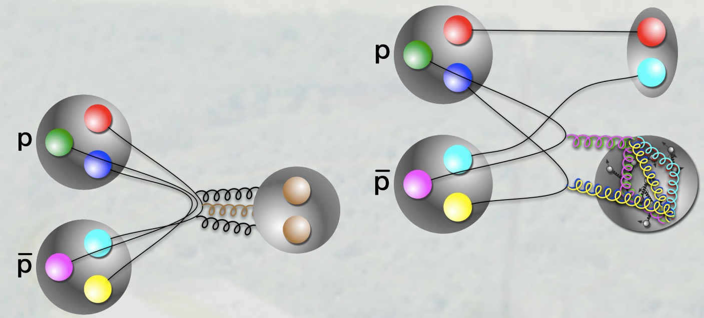
- **Gluon-rich environment**
  - ⇒ Proton-antiproton annihilations
- **Formation of various states**
  - ⇒ All (non-exotic) quantum numbers
  - ⇒ Large acceptance detector
  - ⇒ Fixed target exp. with zero degree acceptance

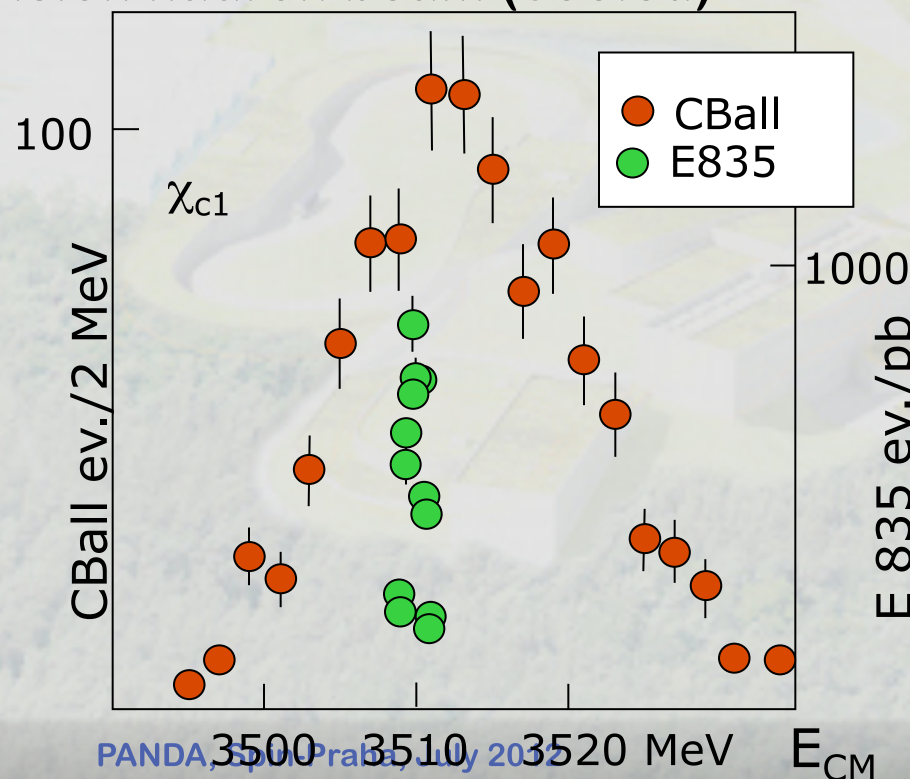




Experimental Approach

- **Gluon-rich environment**
  ⇒ Proton-antiproton annihilations
- **Formation of various states**
  ⇒ All QM, 4π (forward)
- **Precise resonance scan**
  ⇒ High precision hadron beam (cooled)





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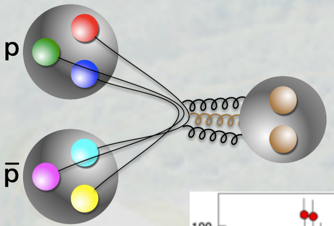
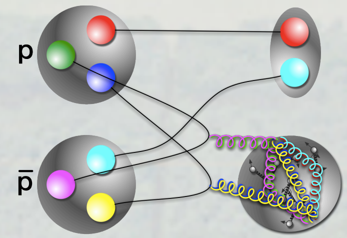
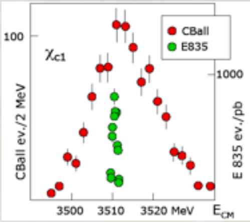
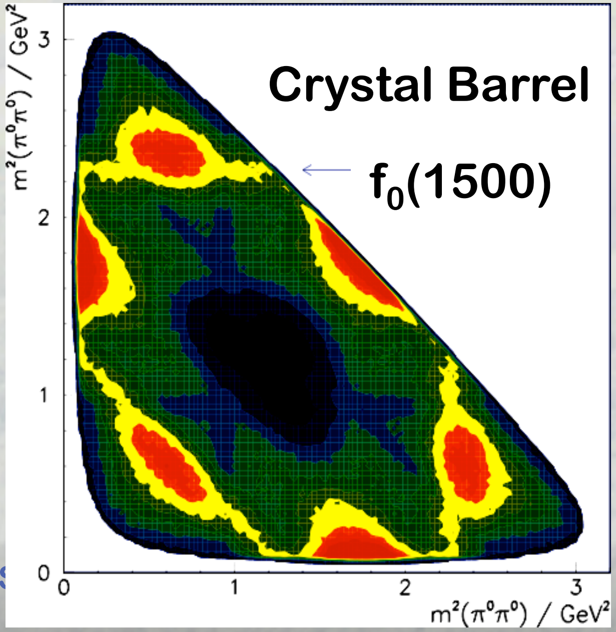
  ⇒ High precision hadron beam (cooled)
- **High statistics samples**
  ⇒ High luminosity and production cross section



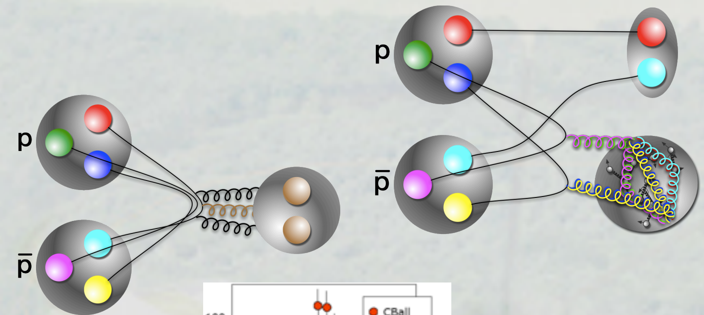


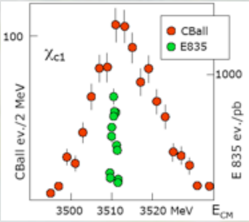


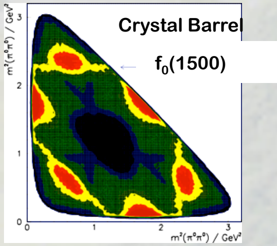


Experimental Approach

- Gluon-rich environment
  - ⇒ Proton-antiproton annihilations
- Formation of various states
  - ⇒ All QM, 4π (forward)
- Precise resonance scan
  - ⇒ High precision hadron beam (cooled)
- High statistics samples
  - ⇒ High luminosity and production cross section
- Physics topics
  - ⇒ Energy range $\sqrt{s}$ = 2 - 5.5 GeV







s-hyperon, c-meson, c-hyperon …

Hybrids | c-Hybrids

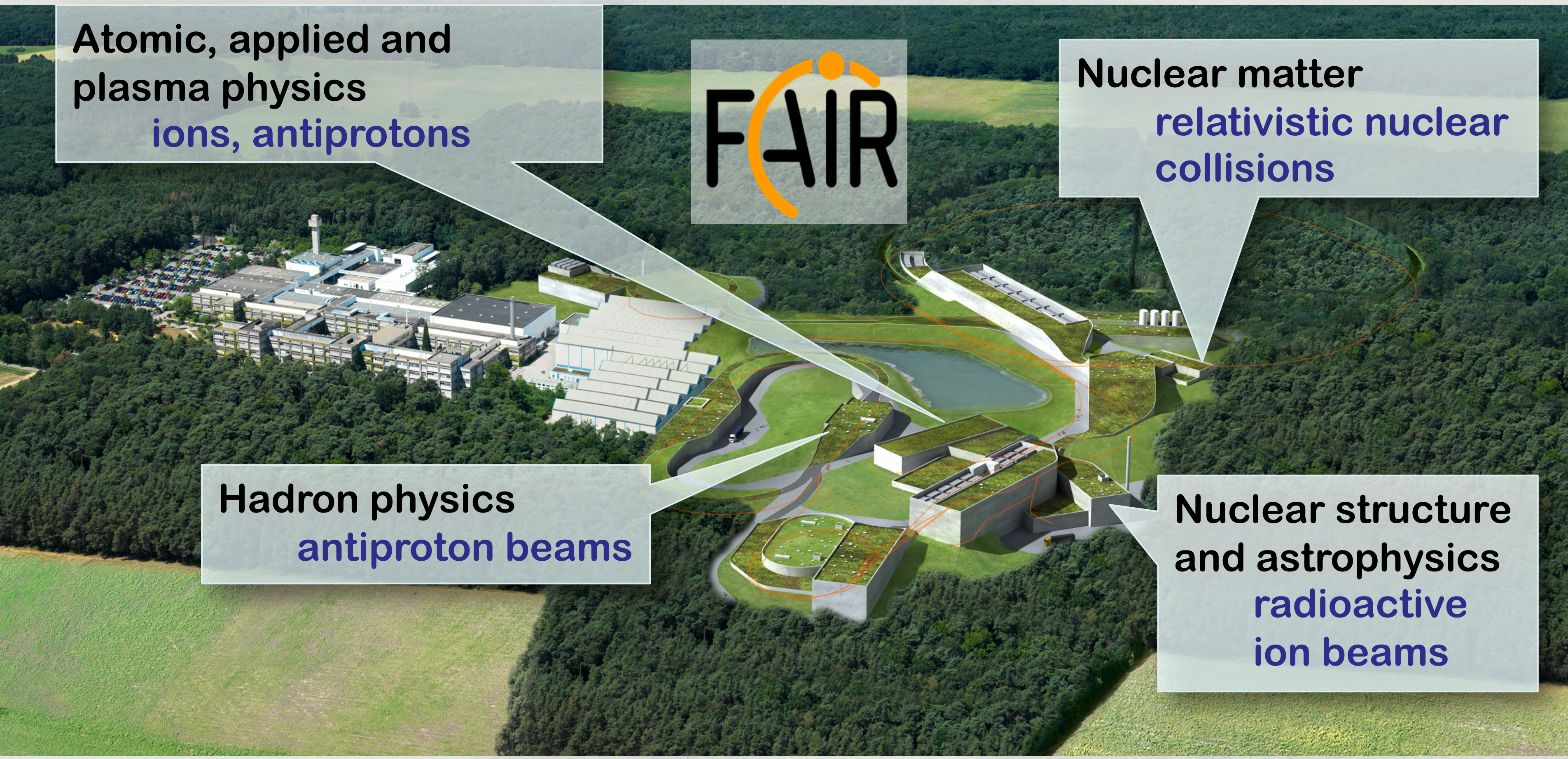
Glueballs

Charmonium

1 2 3 4 5 6 M [GeV/c²]

PANDA Detector Set-Up

Facility for Antiproton and Ion Research



See Diana Nicmorus' talk on Tuesday

Facility for Antiproton and Ion Research

A... tomic, applied and p... lasma phys... ions, ant...

Nuclear matter ... istic nuclear ... ons

Hadr... a...

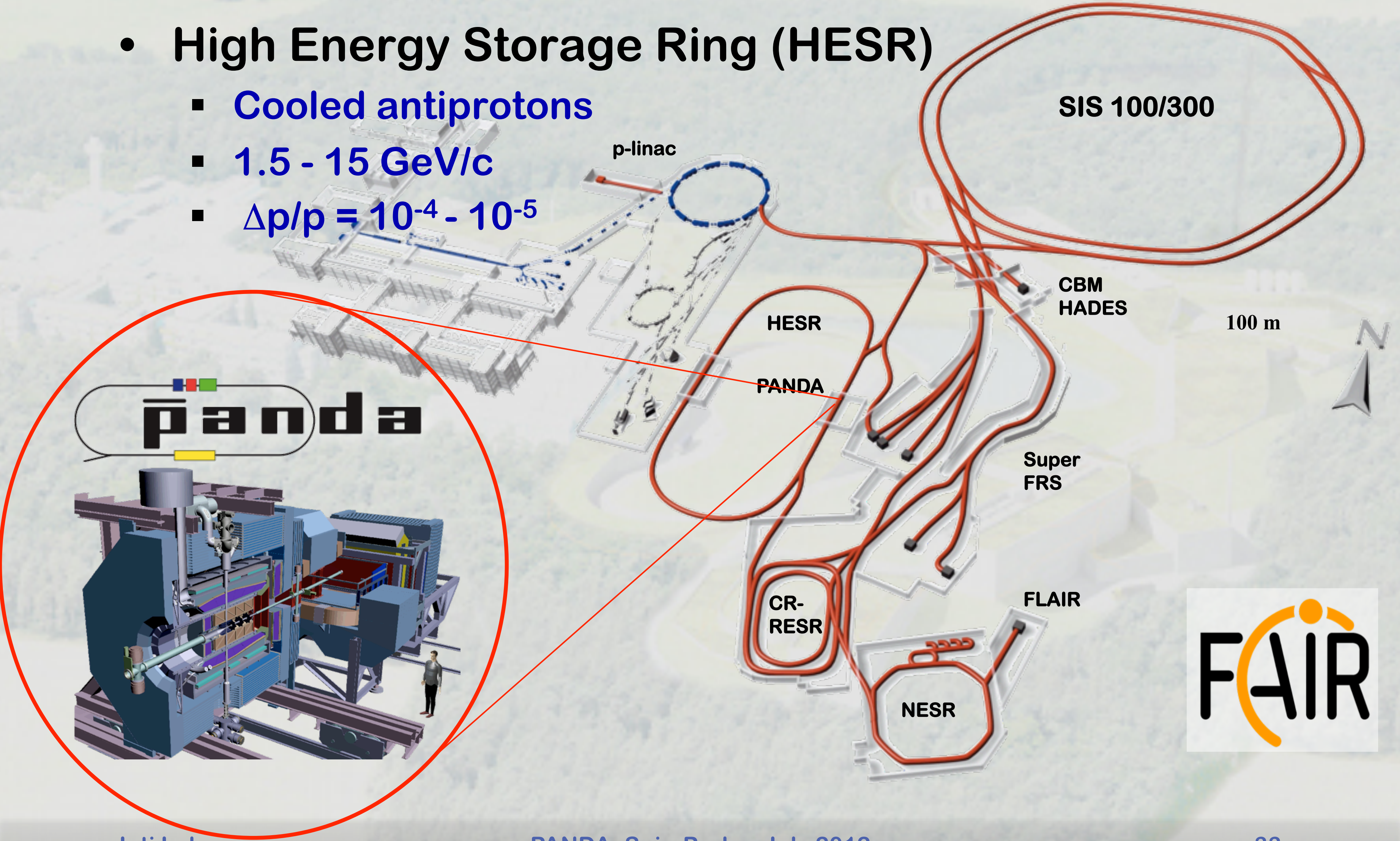
...ear structure ... strophysics ... adioactive ... on beams

Today 11am: €526M cheque

See Diana Nicmorus' talk on Tuesday

PANDA at FAIR

- High Energy Storage Ring (HESR)
  - Cooled antiprotons
  - 1.5 - 15 GeV/c
  - $\Delta p/p = 10^{-4} - 10^{-5}$



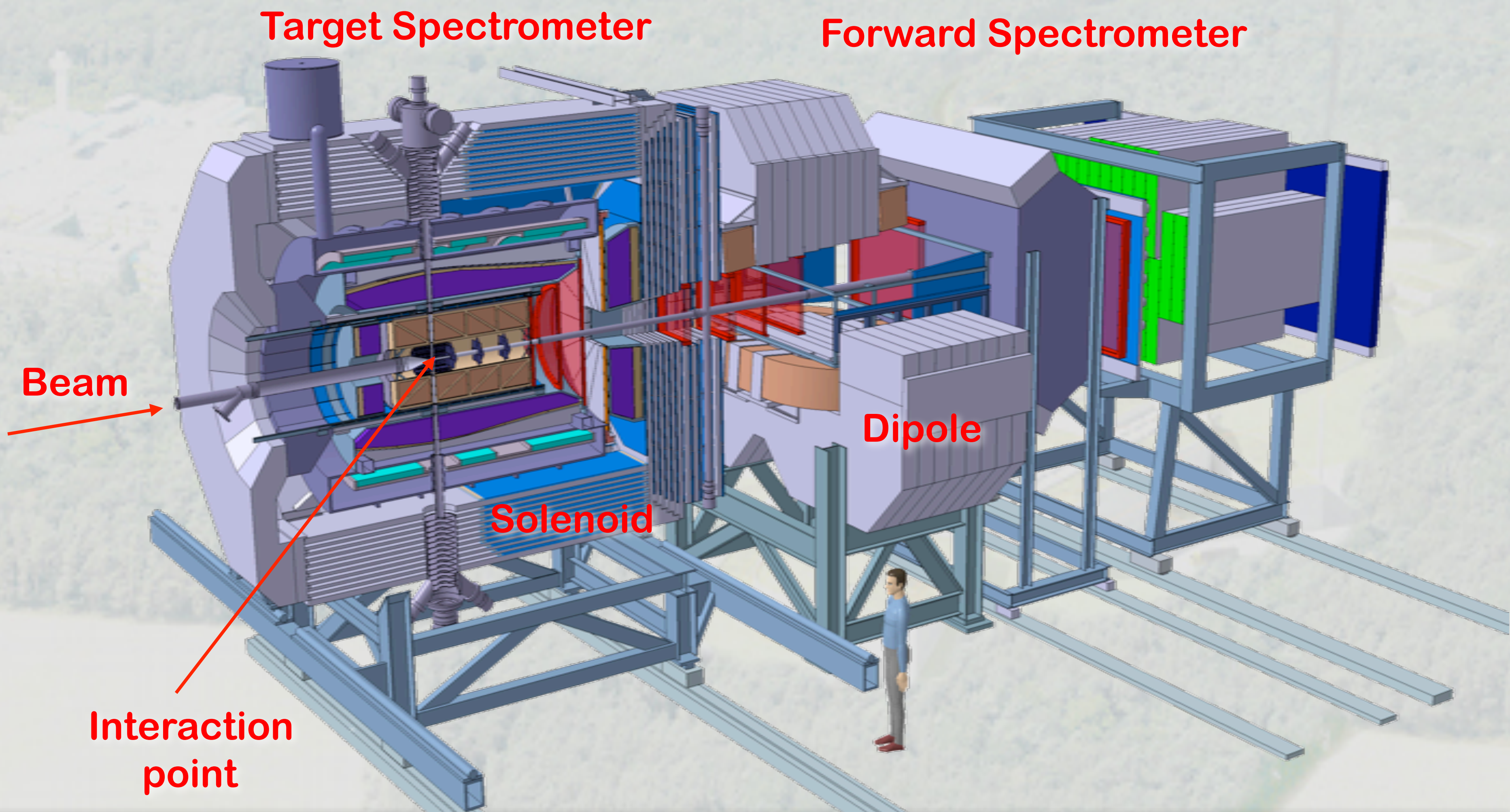
PANDA Collaboration

About 420 physicists from 53 institutions in 16 countries

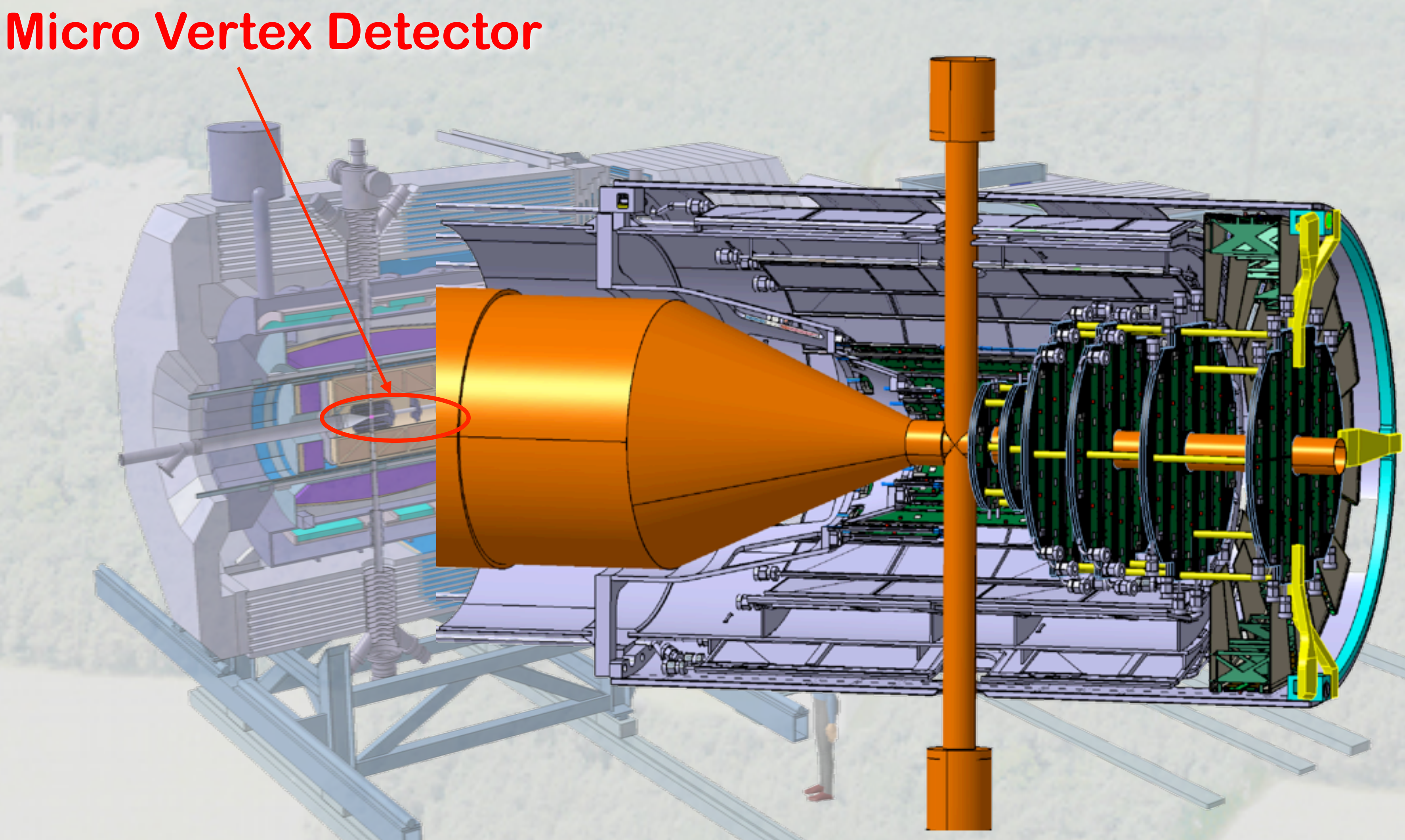
U Basel
IHEP Beijing
U Bochum
IIT Bombay
U Bonn
IFIN-HH Bucharest
U & INFN Brescia
U & INFN Catania
JU Cracow
TU Cracow
IFJ PAN Cracow
GSI Darmstadt
TU Dresden
JINR Dubna (LIT,LPP,VBLHE)
U Edinburgh
U Erlangen
NWU Evanston
U & INFN Ferrara
U Frankfurt
LNF-INFN Frascati
U & INFN Genova
U Glasgow
U Gießen
KVI Groningen
IKP Jülich I + II
U Katowice
IMP Lanzhou
U Lund
U Mainz
U Minsk
ITEP Moscow
MPEI Moscow
TU München
U Münster
BINP Novosibirsk
IPN Orsay
U & INFN Pavia
IHEP Protvino
PNPI Gatchina
U of Silesia
U Stockholm
KTH Stockholm
U & INFN Torino
Politecnico di Torino
U Piemonte Orientale, Torino
U & INFN Trieste
U Tübingen
TSL Uppsala
U Uppsala
U Valencia
SMI Vienna
SINS Warsaw
TU Warsaw

PANDA Experimental Set-Up

- **Fixed target magnetic spectrometer experiment**

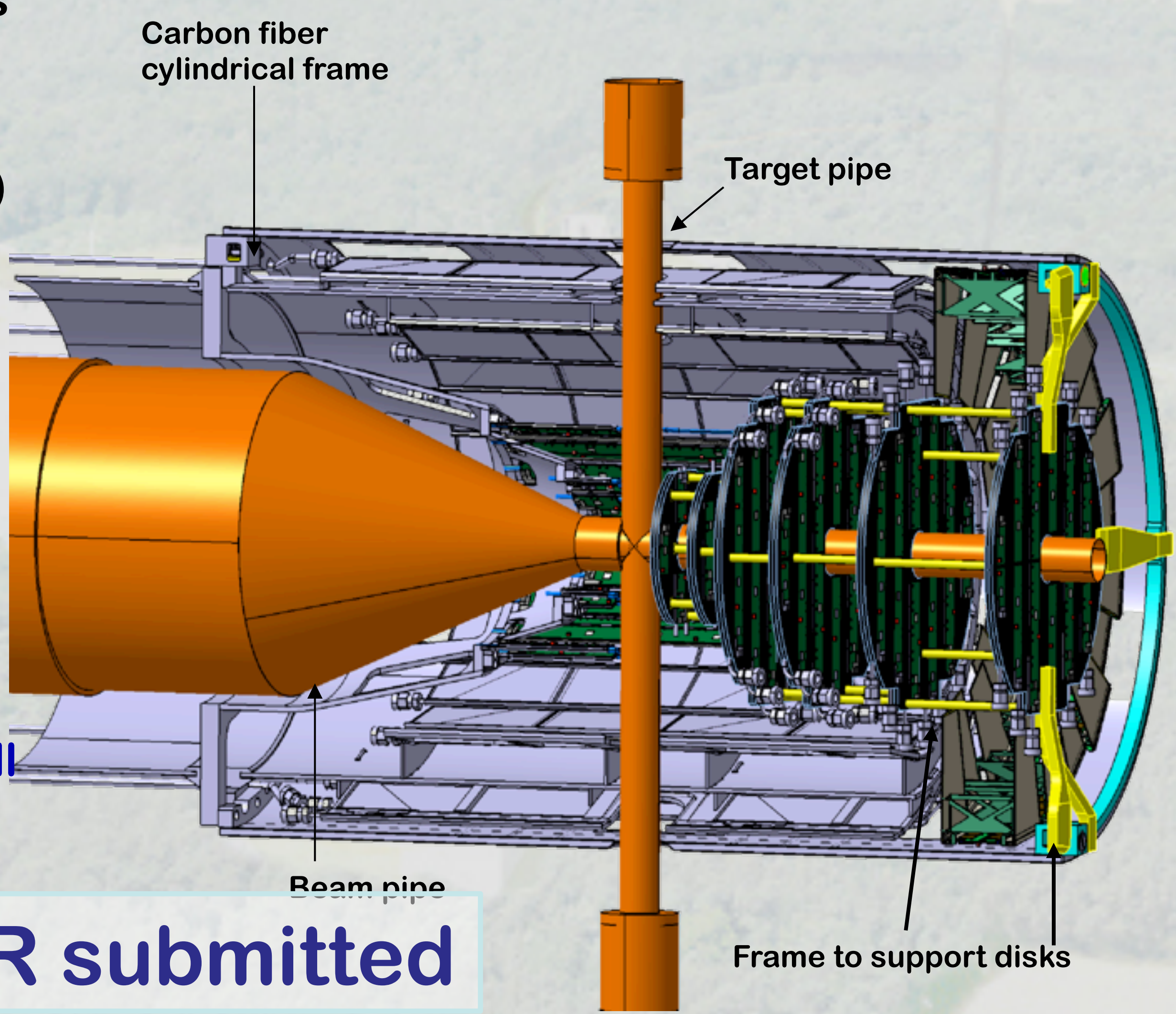


PANDA Experimental Set-Up



Micro Vertex Detector

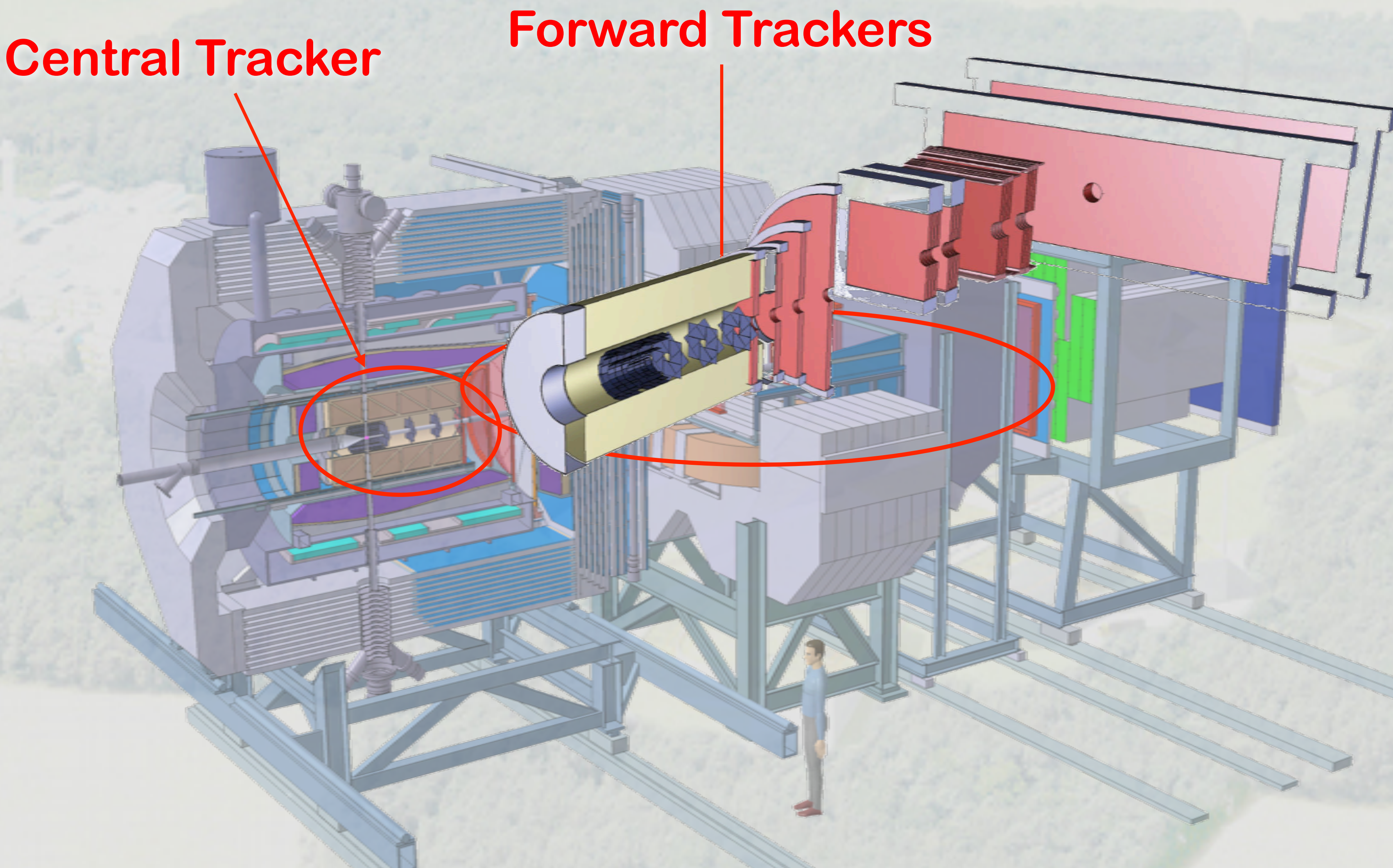
- 4 barrels and 6 disks
- Continuous readout
- Inner layers: hybrid pixels (100x100 μm²)
- Outer layers: double sided strips



- Challenges
  - Low mass supports
  - Cooling in a small volume
  - Radiation tolerance

TDR submitted

PANDA Experimental Set-Up

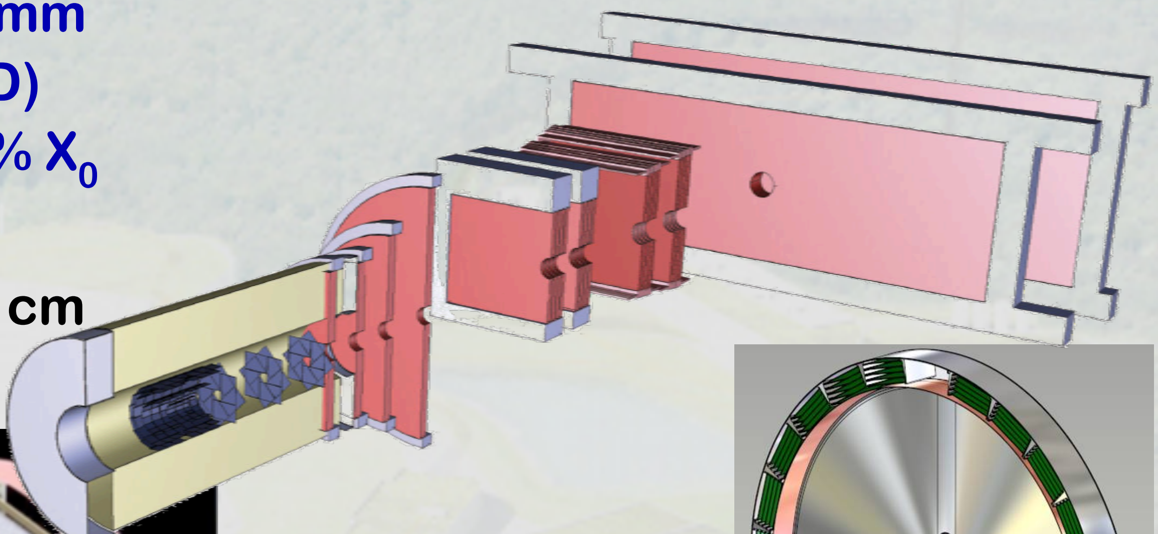


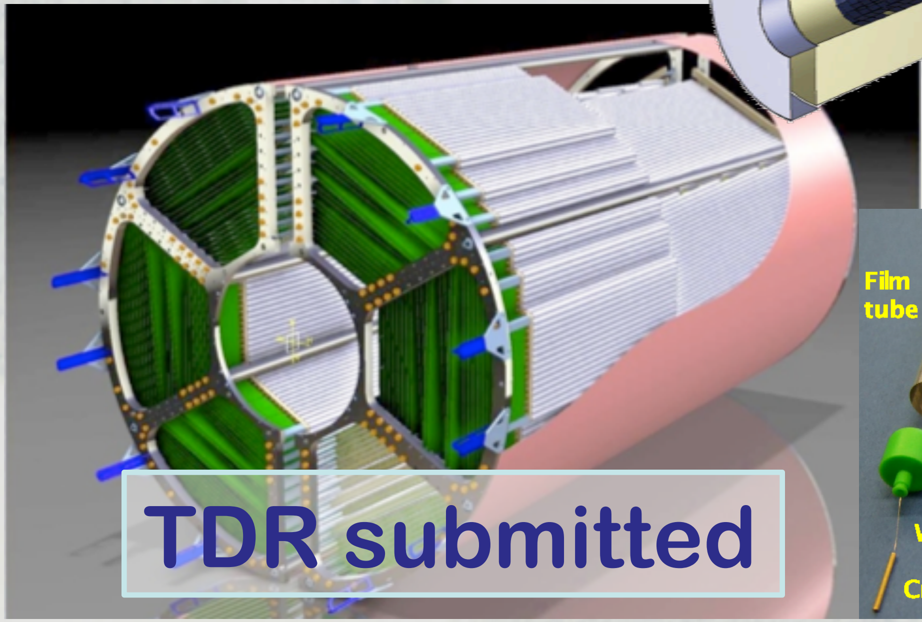
Tracking Detectors

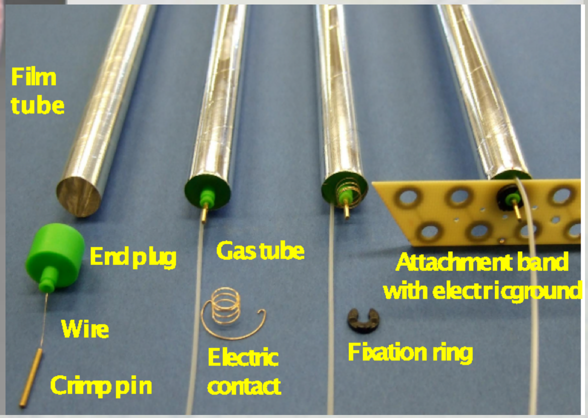
Central tracker (Straw Tubes)

- $\sigma_{r\phi}$~150µm , σ_z~1mm
- δ p/p~1% (with MVD)
- Material budget ~1% X_0

- 5000 Straws
- 27 µm, 1 cm Ø, 150 cm
- 1 bar overpressure







TDR submitted

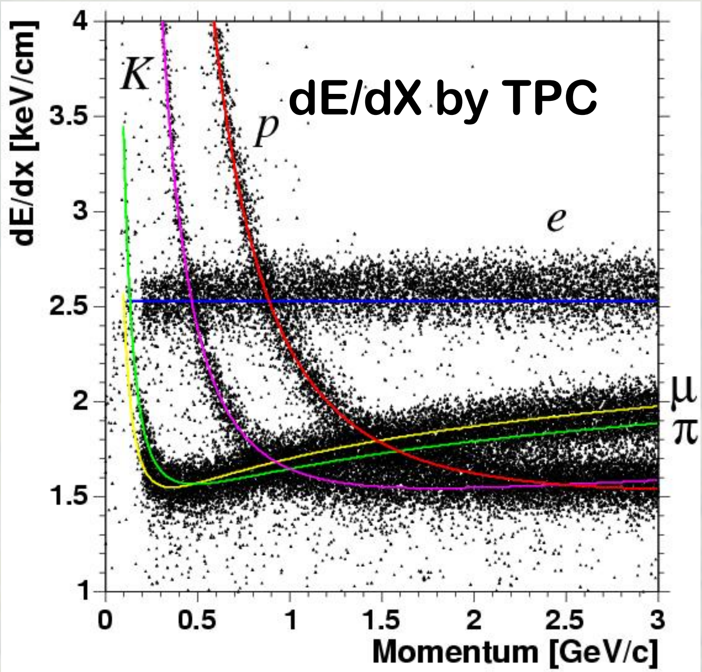
Particle Identification

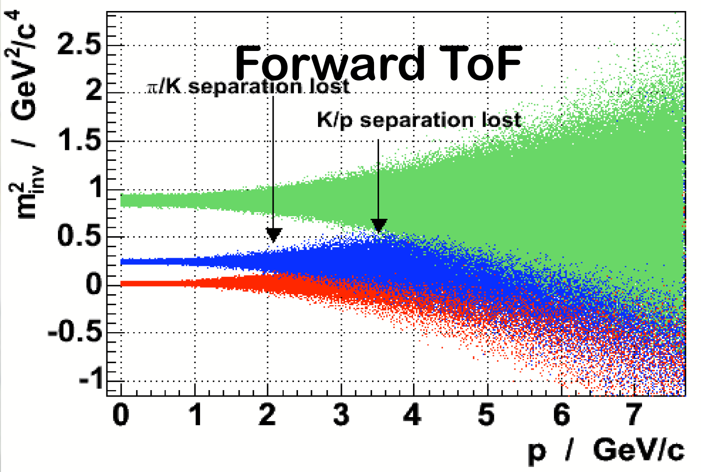
PANDA PID Requirements:

- separate charged π, K, p, e, μ
- momentum range 200MeV/c – 10GeV/c

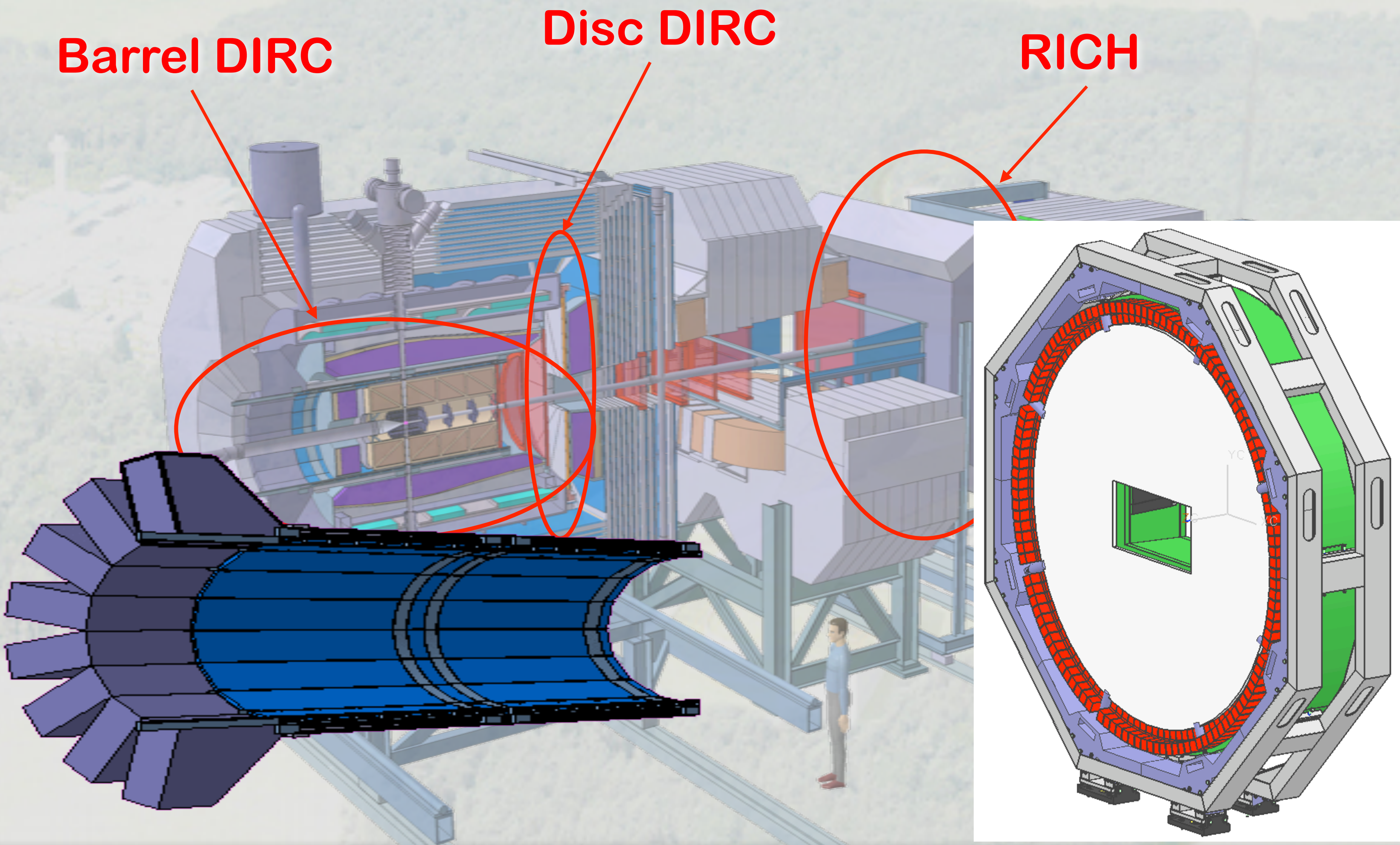
PID Processes:

- π, K, p below 1GeV: energy loss
  - micro vertex detector, trackers
- π, K, p above 1GeV: Cherenkov
  - barrel DIRC, disc DIRC, RICH
- π, K, p up to 4GeV: time of flight
  - TOF detectors
- e and γ: electromagnetic showers
  - electromagnetic calorimeter
- μ: showers
  - muon range system (magnet yoke)



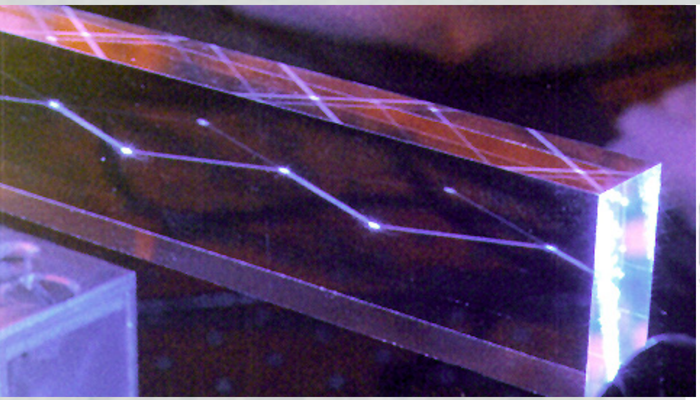


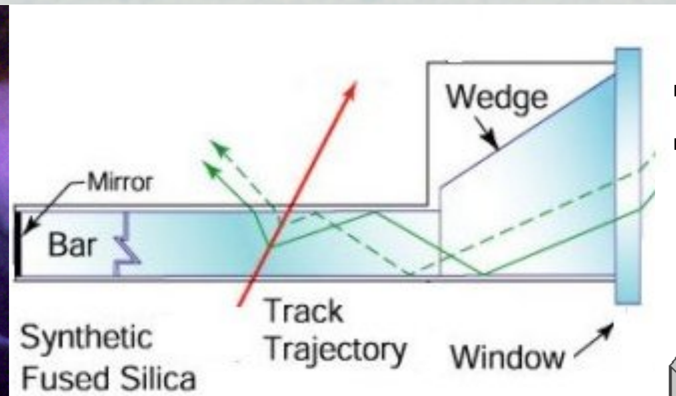
PANDA Experimental Set-Up



PANDA Cerenkov Detectors

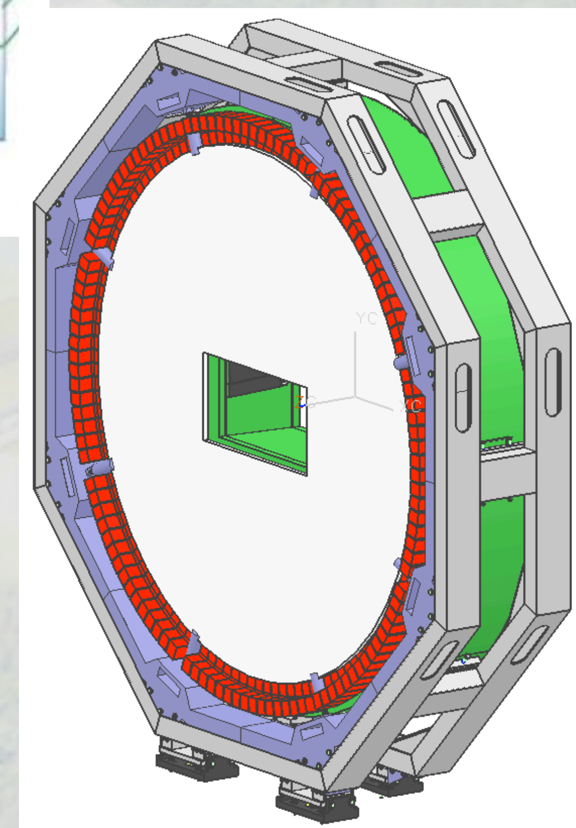
DIRC: Detection of Internally Reflected Cherenkov light



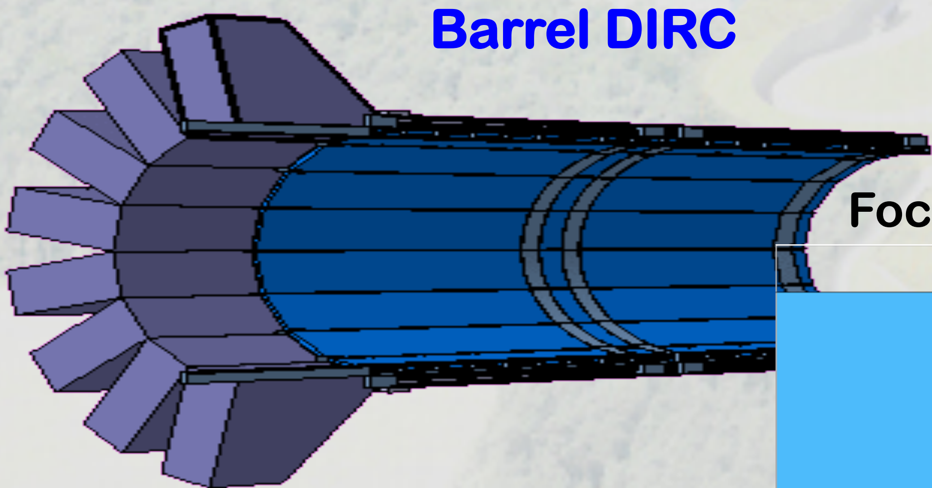


Disc DIRC

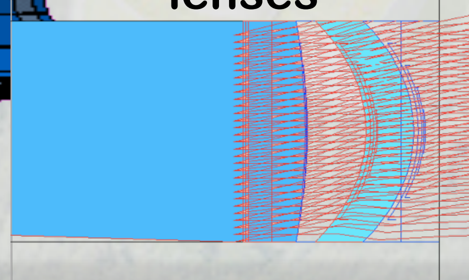
- Disc shaped radiator
- Readout at rim



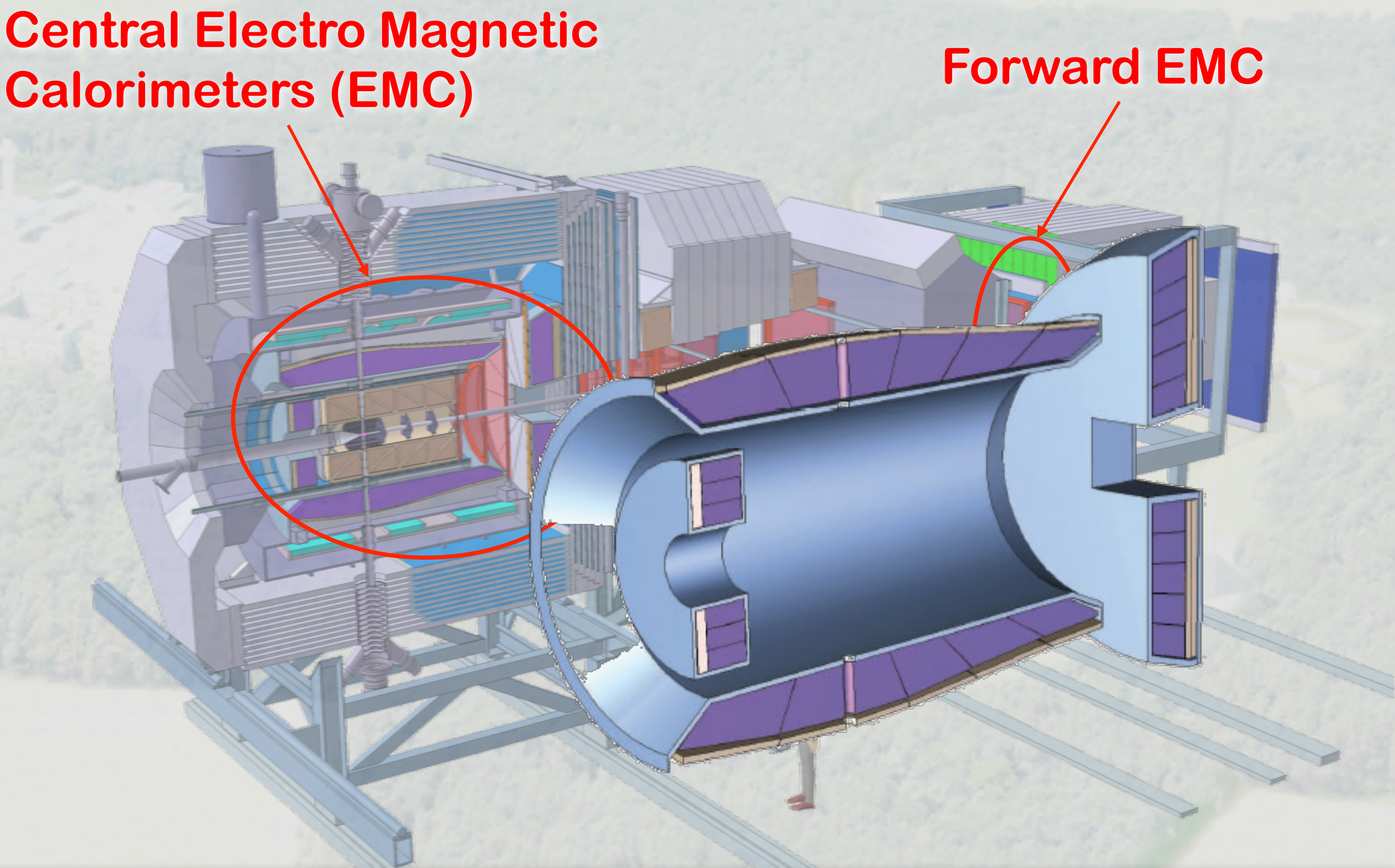
Barrel DIRC



Focusing with lenses



PANDA Experimental Set-Up



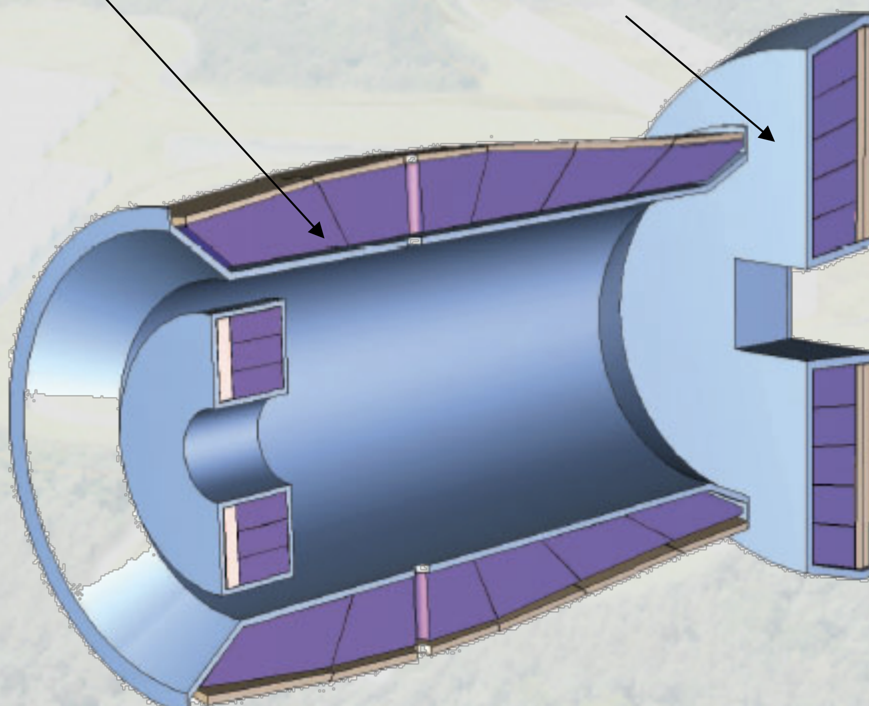
Electromagnetic Calorimeters

PANDA PWO Crystals
- PWO is dense and fast
- Low γ threshold

- Challenges:
  - temperature stablilisation to 0.1°C
  - radiation damage
  - low noise electronics
- Delivery of crystals started

Barrel Calorimeter
- 11000 PWO Crystals
- LAAPD readout, 2x1cm²
- $\sigma(E)/E \sim 1.5\%/\sqrt{E}$ + const.

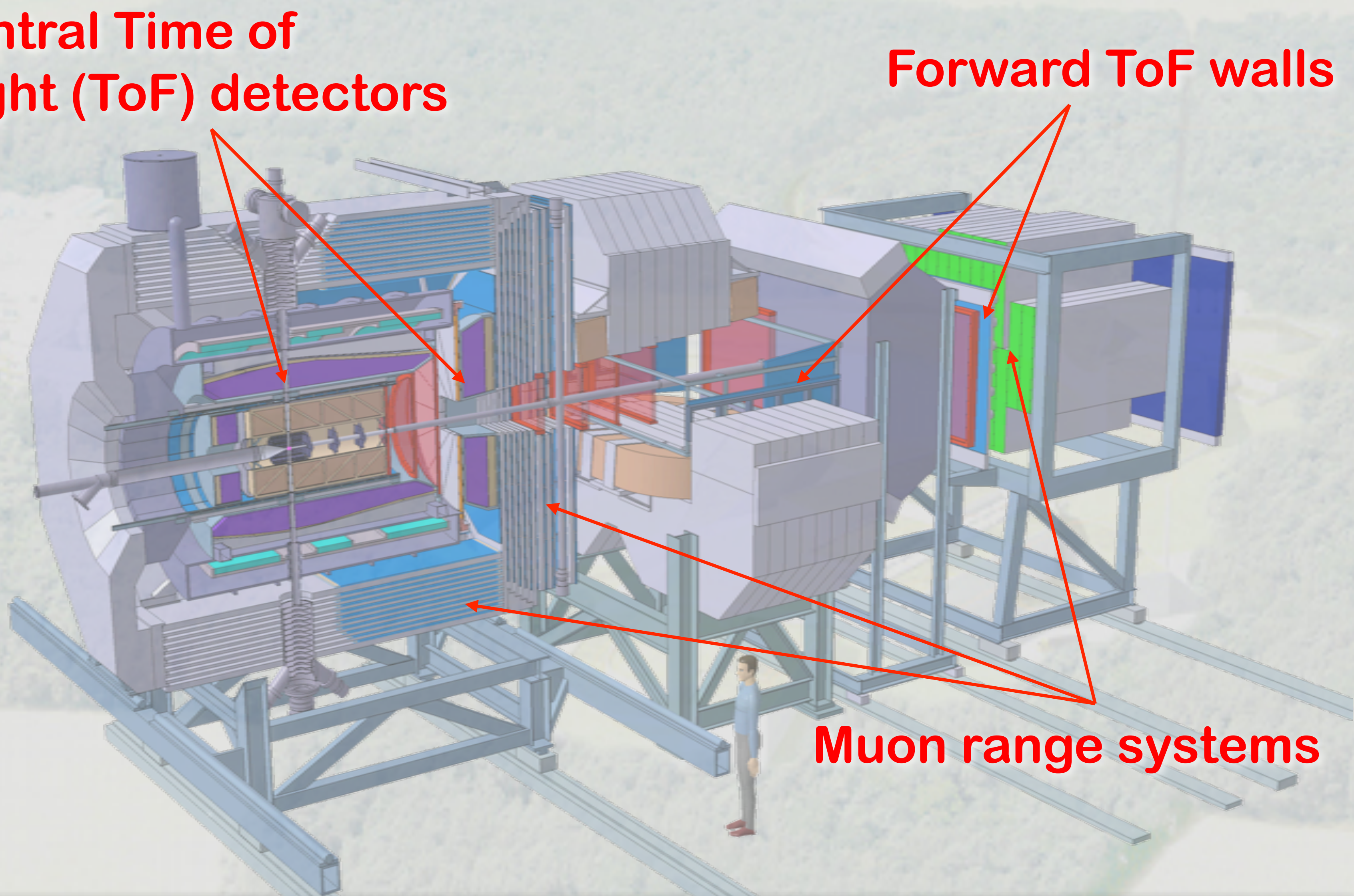
Forward Endcap
- 4000 PWO crystals
- High occupancy in center
- LA APD or VPT



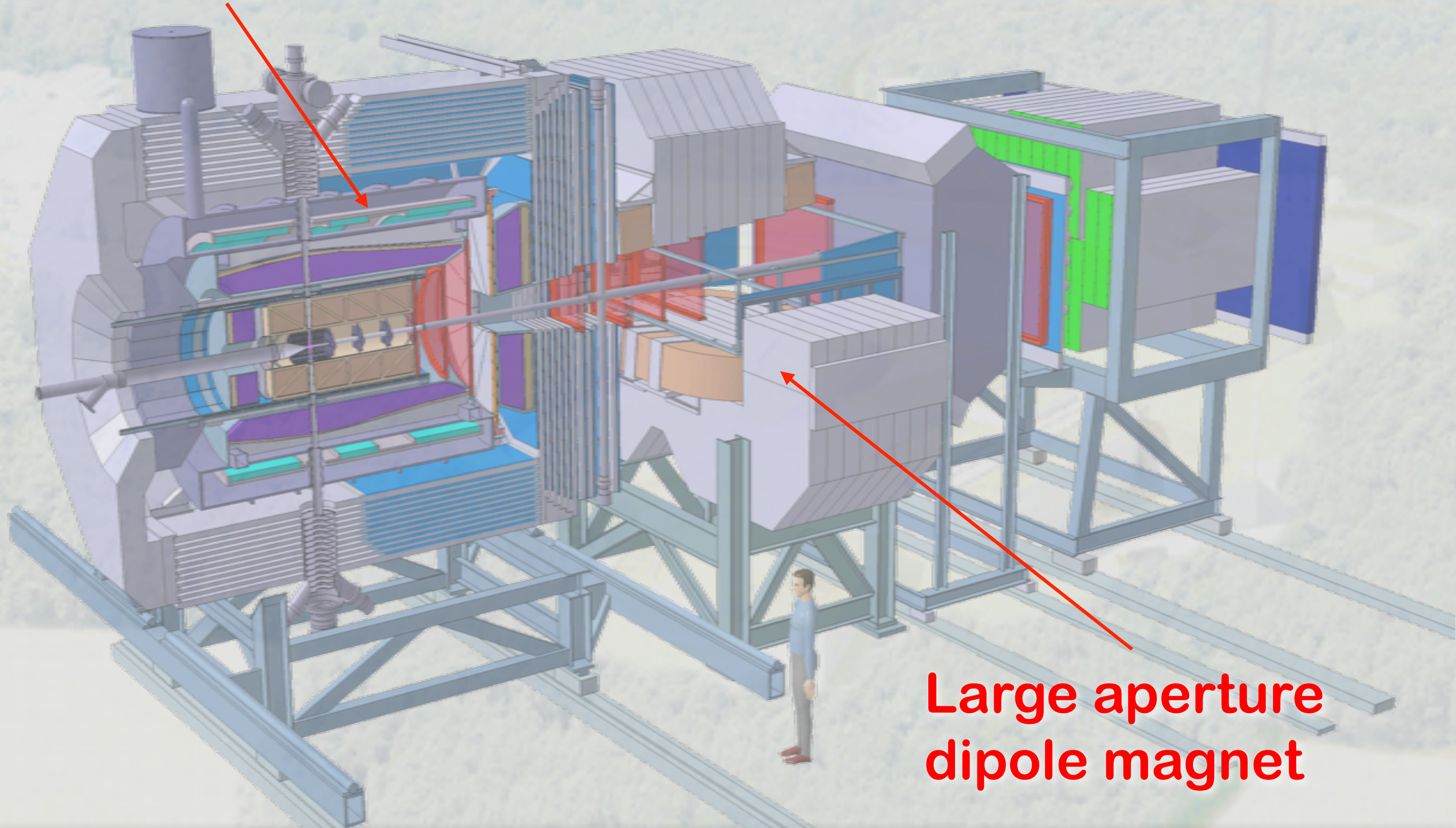
Approved TDR

Backward Endcap,
560 PWO crystals

PANDA Experimental Set-Up

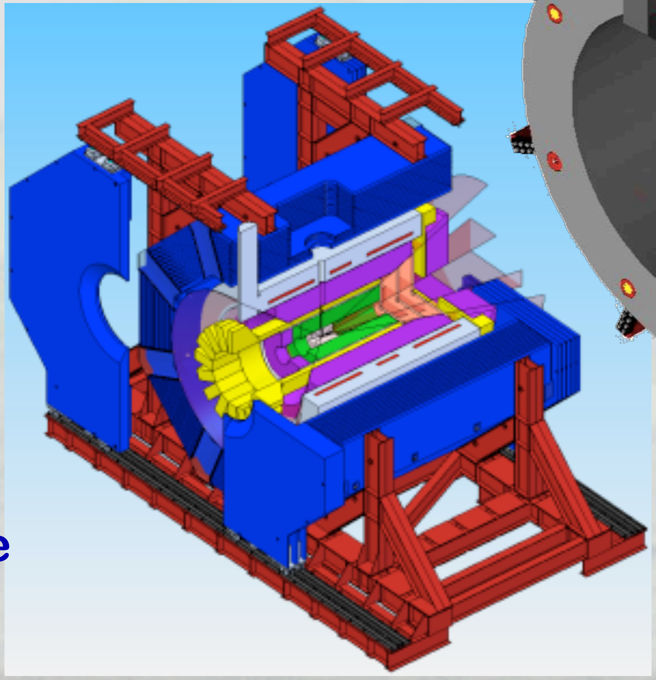


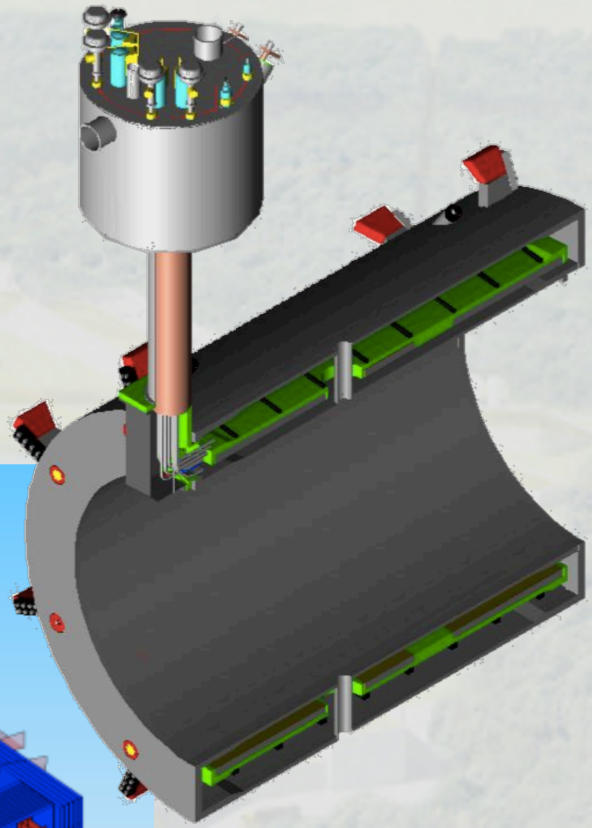
PANDA Experimental Set-Up



Superconducting Solenoid

- Features
  - 2T field
  - 4m x 1.9m free space
  - High field homogeneity
  - Target pipe intersection
  - Access on both sides
  - Movement by 20m
  - Muon range system
- Design
  - Asymmetric split coil
  - Internally wound
  - Indirect cooling
  - Opening doors
  - Retractable platform
  - Laminated return yoke

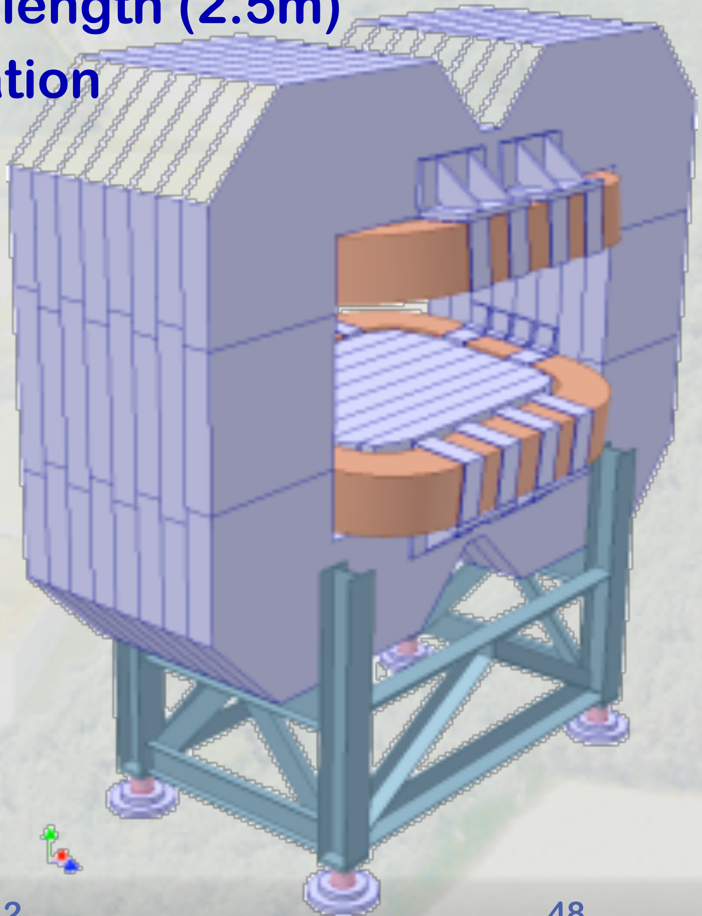




Large Aperture Dipole

- Features
  - 2Tm for particles scattered in 0 – 10^o (5^o vertical)
  - Allows momentum resolution <1%
  - Large aperture (1x3m) and short length (2.5m)
  - Ramping capability due to lamination

Field integral	2 Tm
Bending variation	≤ ±15%
Vertical Acceptance	±5°
Horizontal Acceptance	±10°
Ramp speed	1.25%/s
Total dissipated power	360 kW
Total Inductance	0.87 H
Stored energy	2.03 MJ
Weight	220 t
Dimensions (H × W × L)	3.88 × 5.3 × 2.5 m^3
Gap opening (H × W)	0.80 – 1.01 × 3.10 m^2

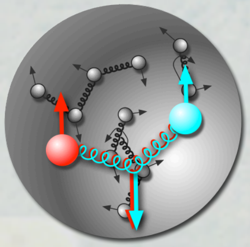


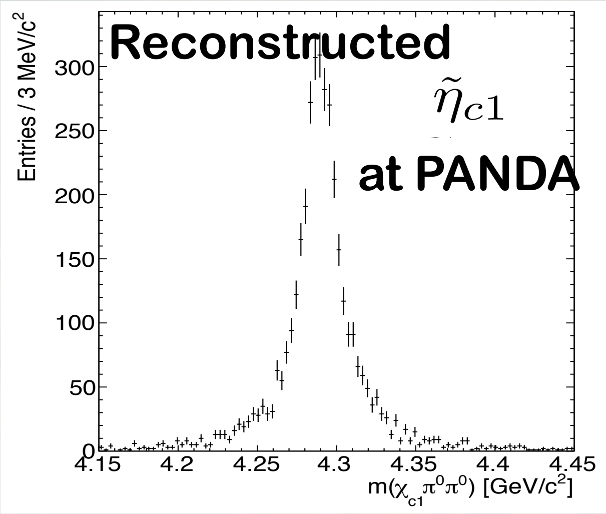
Approved TDR

Physics highlights at PANDA

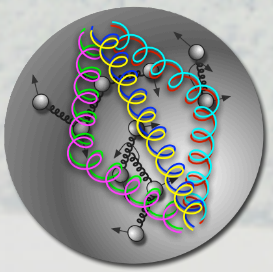
Expected Highlights: 1) Exotics

- Charmed hybrids
  - Feasible to detect at PANDA

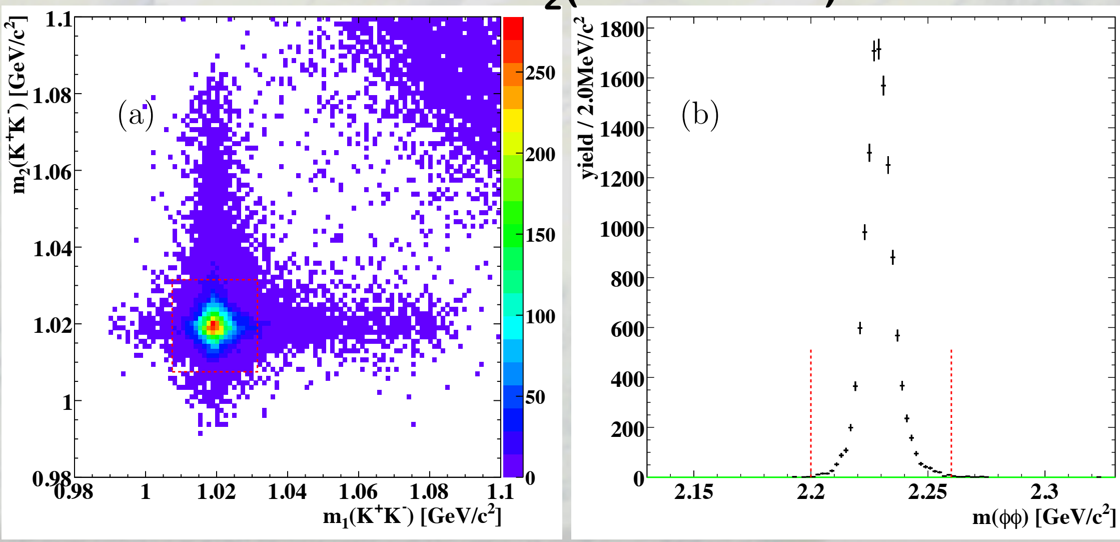




- Glueballs below 3 GeV/c^2
  - Feasible to detect at PANDA

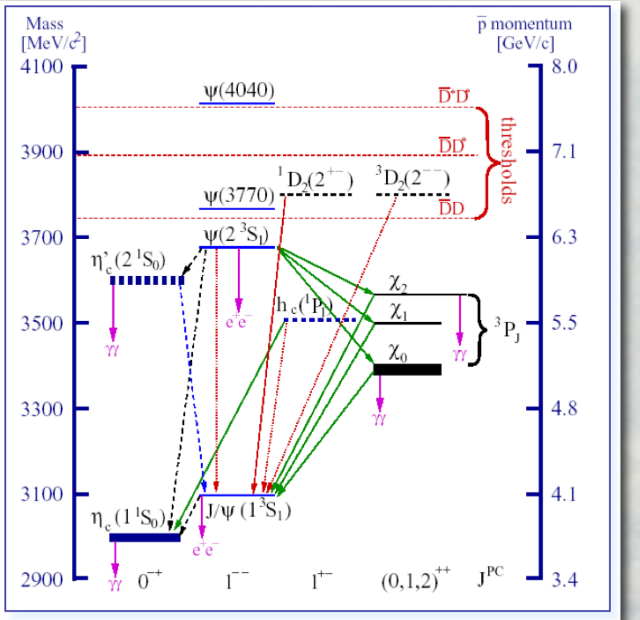


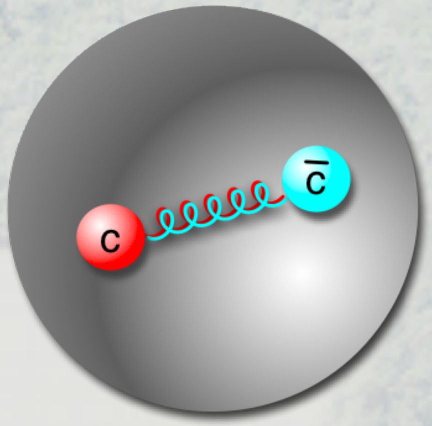
Reconstructed f_2(2000-2500) at PANDA

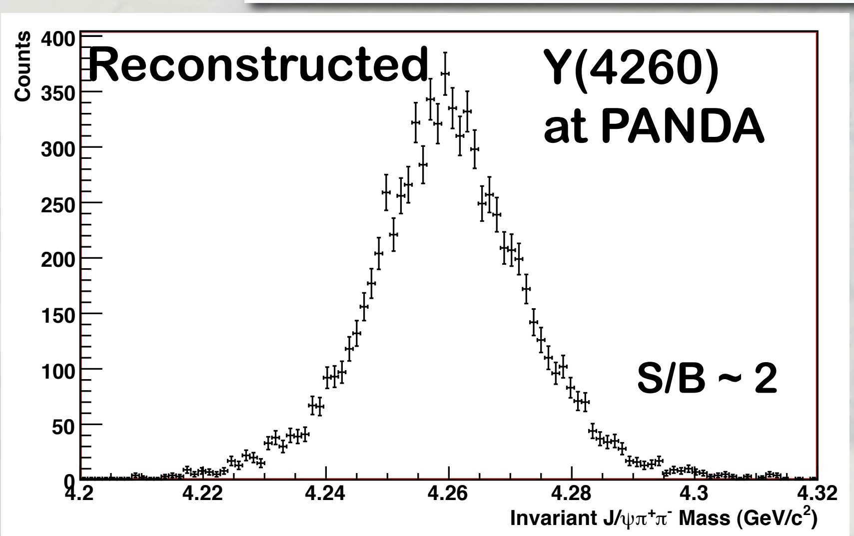


Expected Highlights: 2) Charmonium

- Charmonium States
  - **PANDA**
    - high statistics data
    - direct production
    - precise resonance scans (10^{-5})
    - channels not coupling to J/ψ and ψ'

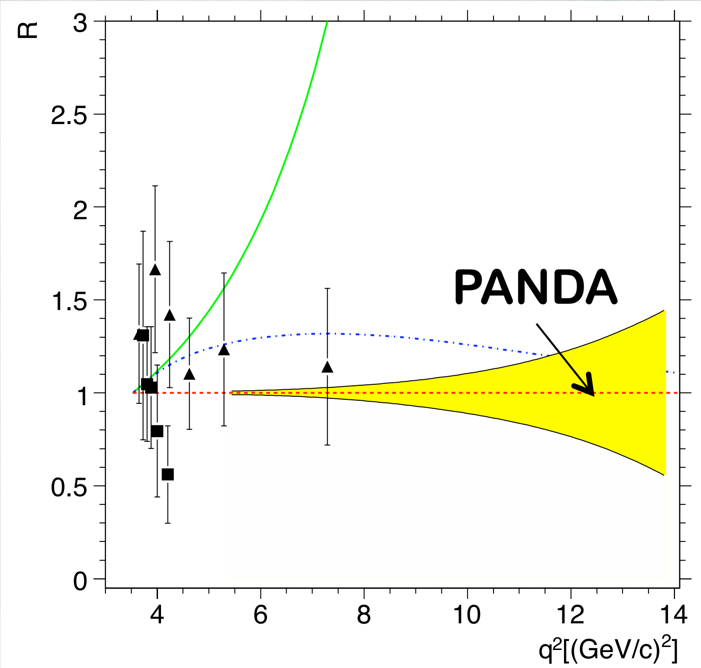


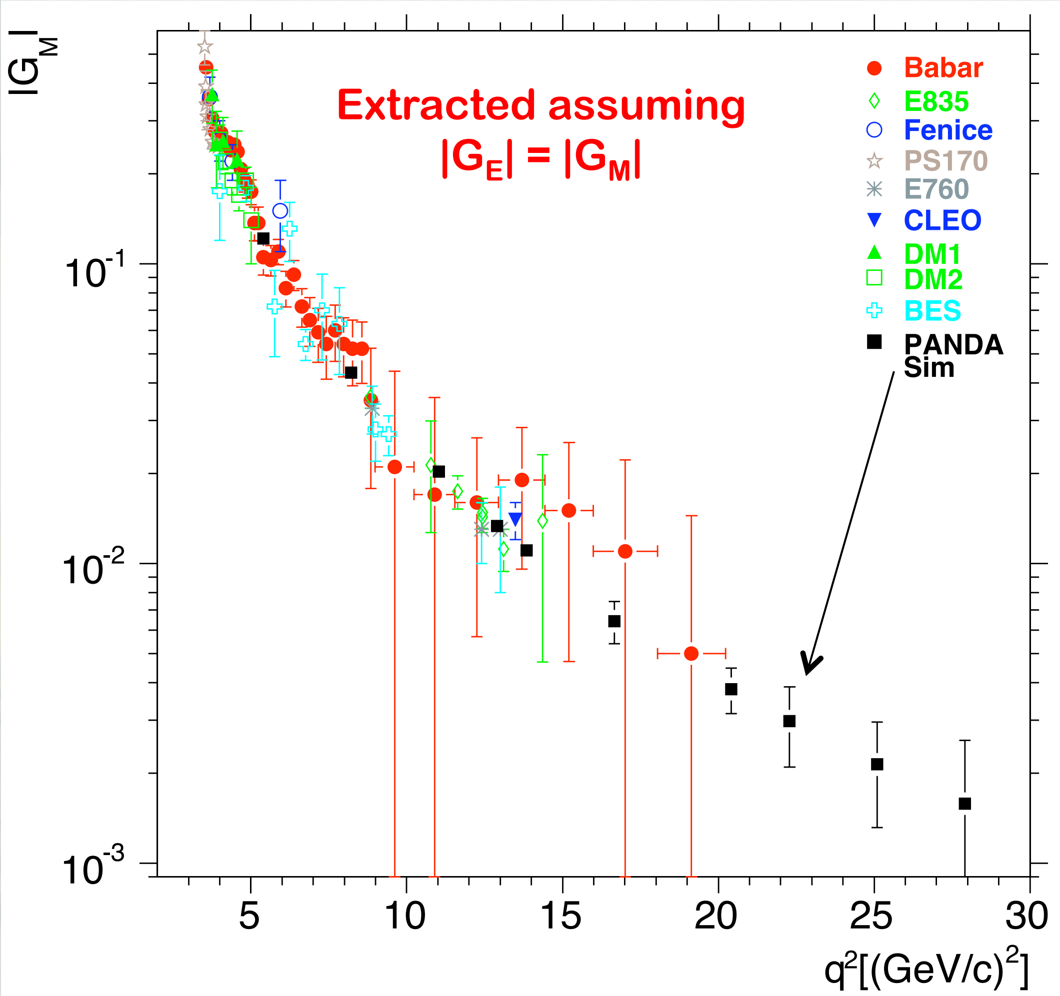




Expected Highlights: 3) Form factors

- Time like form factors
  - $R = \mu_p G_E/G_M$ with unprecedented precision

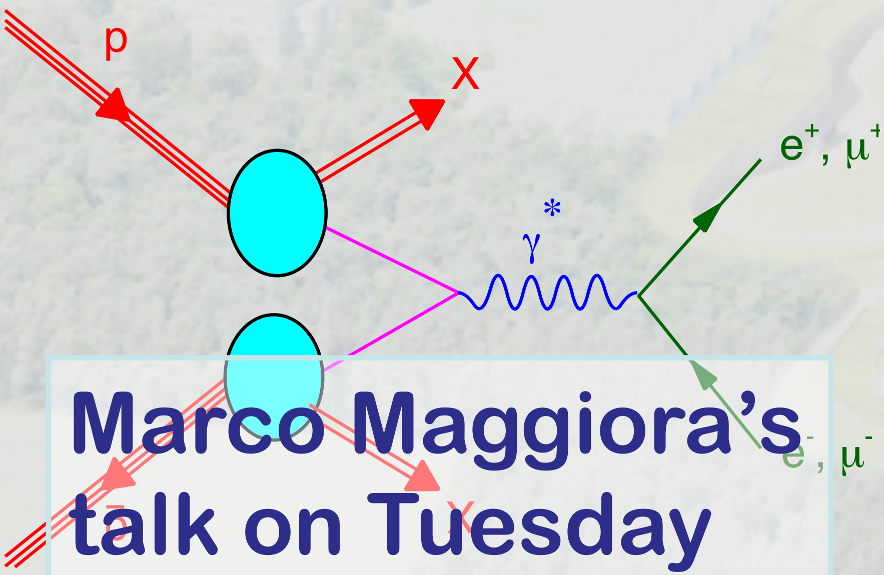




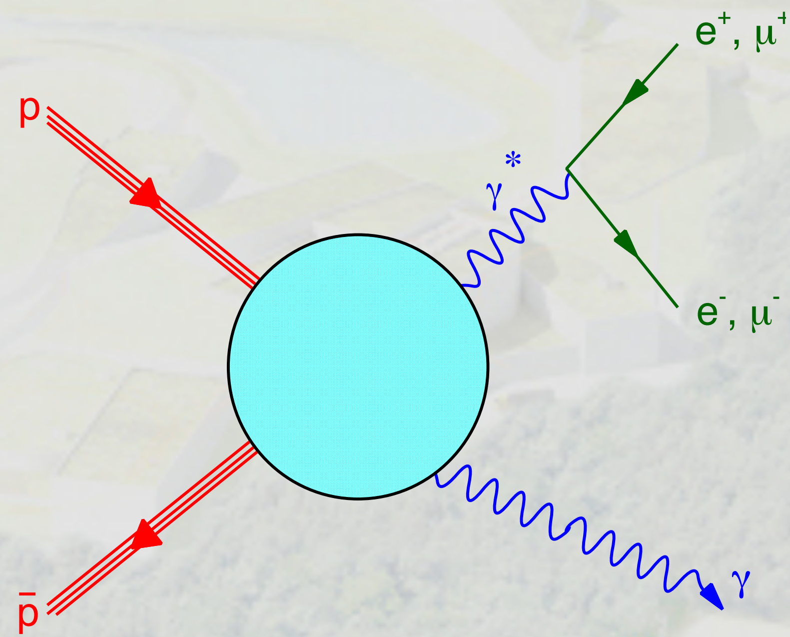
  - absolute value of $|G_M|$ up to $30 (GeV/c)^2$

PANDA Physics Performance Report: arXiv:0903.3905

- **Nucleon Structure**
  - Drell-Yan Processes
- Time like equivalents of Generalised Parton Distributions (GPDs)

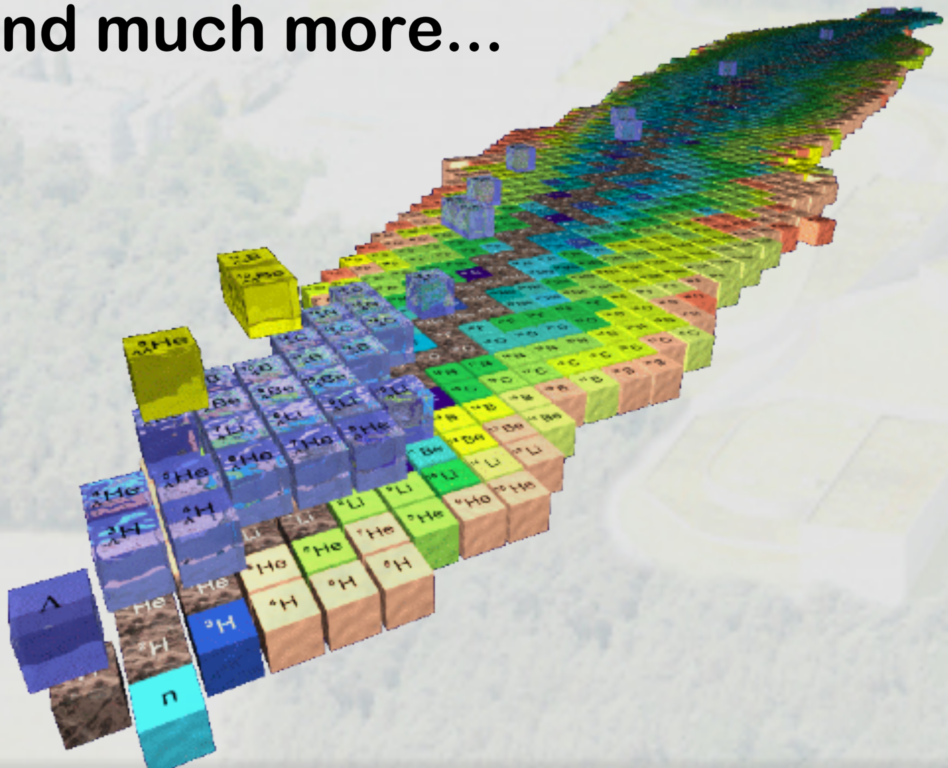


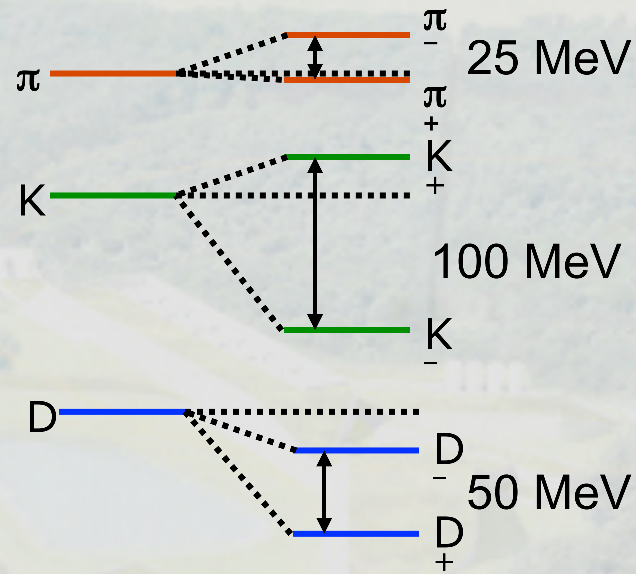
Marco Maggiora's talk on Tuesday



Expected Highlights: 5), 6), ...

- In medium mass modifications
  - extension to the charm sector
- Extension of nuclear chart
  - double hypernuclei
- And much more...





A. Hayashigaki, PLB 487 (2000) 96

Conclusions

- Open issues in
  - Exotic hadrons
  - Charmonium spectrum
  - Nucleon structure
- Best addressed by
  - Proton-antiproton annihilations
  - Fixed target experiment
  - Energy √s = 2 - 5.5 GeV
  - Versatile detector set up
- PANDA is the solution!
  - Design and constr. on track

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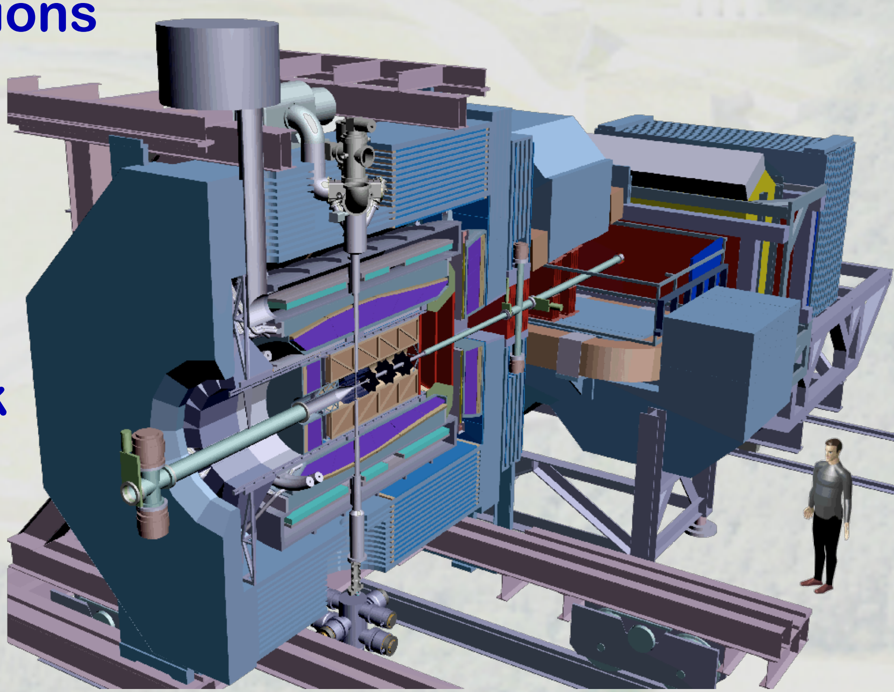

Conclusions

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  - Exotic hadrons
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  - Proton-antiproton annihilations
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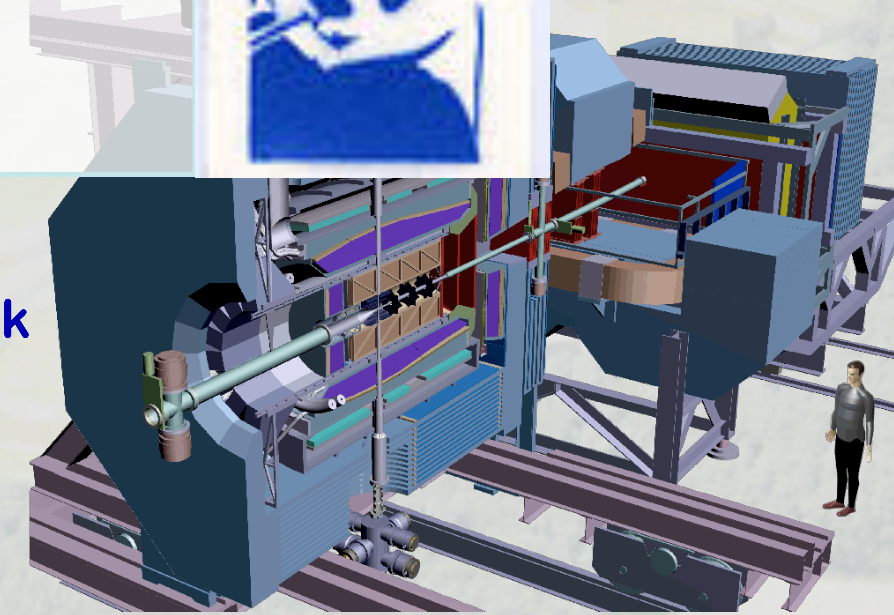
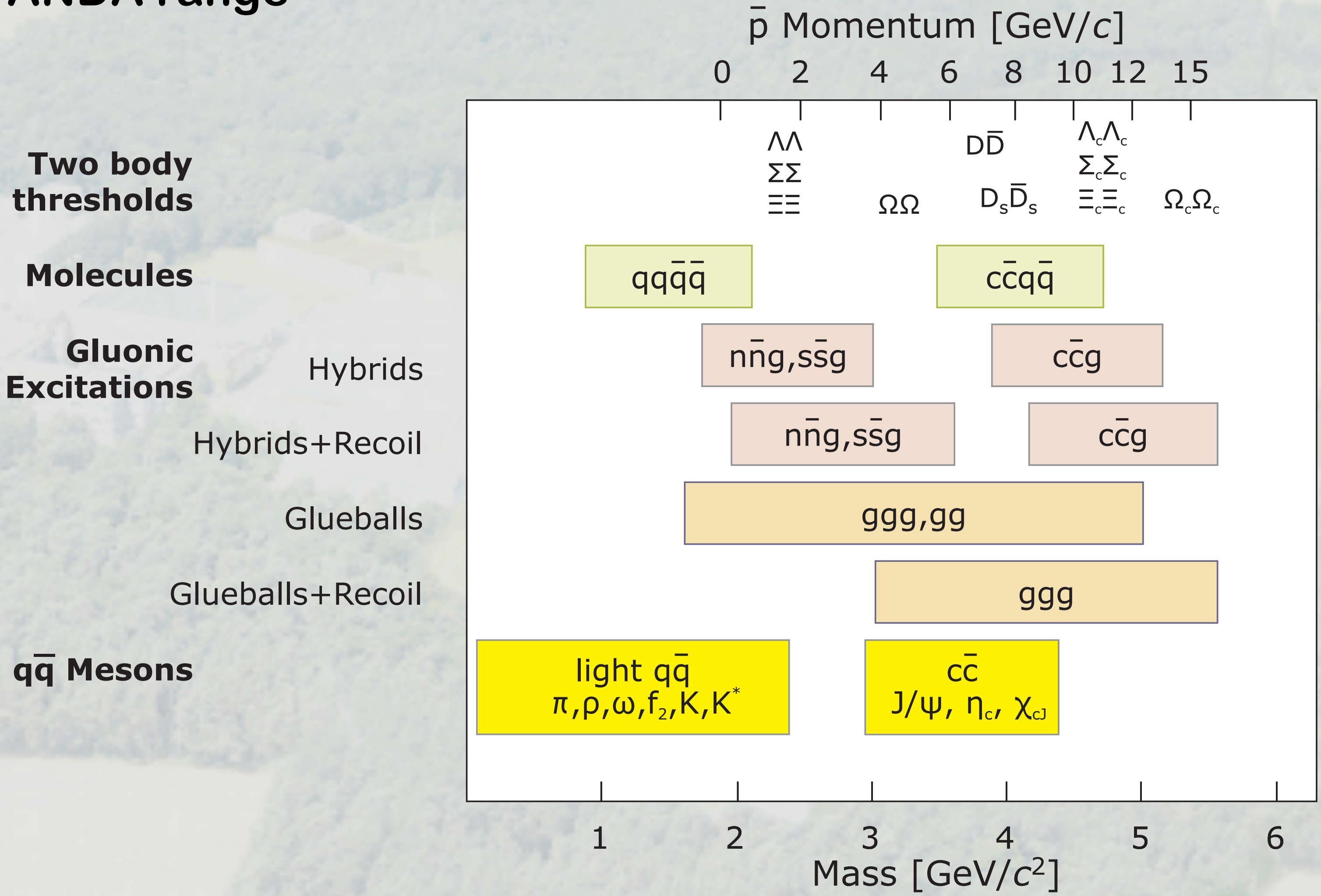
Cannot wait for 2018



Backup

Backup

- **PANDA range**

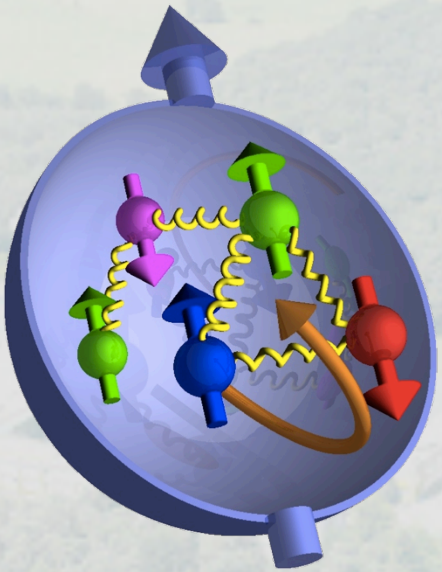


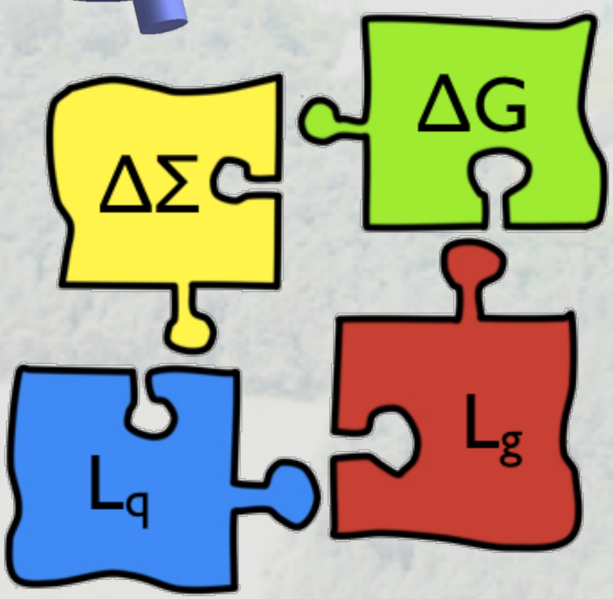
Spin Exotic Summary (Light Quarks)

thanks to G. Adams, RPI

	Experiment	Mass	Width	Decay	Citation
π_1(1400)	E852	1359 (+16-14) (+10-24)	314 (+31-29) (+9-66)	$\eta\pi$	PR D60, 092001
	Crystal Barrel	1400 (+20-20) (+20-20)	310 (+50-50) (+50-30)	$\eta\pi$	PL B423,175
	Crystal Barrel	1360 (+25-25)	220 (+90-90)	$\eta\pi$	PL B446,349
	Obelix	1384 (+28-28)	378 (+58-58)	$\rho\pi$	EPJ C35, 21
π_1(1600)	E852	1593 (+8-8) (+29-47)	168 (+20-20) (+150-12)	$\rho\pi$	PR D65, 072001
	E852	1597 (+10-10) (+45-10)	340 (+40-40) (+50-50)	$\eta'\pi$	PRL 86, 3977
	Crystal Barrel	1590 (+50-50)	280 (+75-75)	$b_1\pi$	PL B563,140
	E852	1709 (+24-24) (+41-41)	403 (+80-80) (+115-115)	$f_1\pi$	PL B595,109
	E852	1664±8±10	185±25±28	$(b_1\pi)^-$	submitted to PRL
	E852	≅ 1700		$(b_1\pi)^0$	preliminary
π_1(2000)	E852	2001±30±92	333±52±49	$f_1\pi$	PL B595,109
	E852	2014±20±16	230±32±73	$(b_1\pi)^-$	submitted to PRL
h_2(1950)	E852	1954±8 (stat.)	138±3 (stat.)	$(b_1\pi)^0$	preliminary

Puzzle 4: Spin Structure





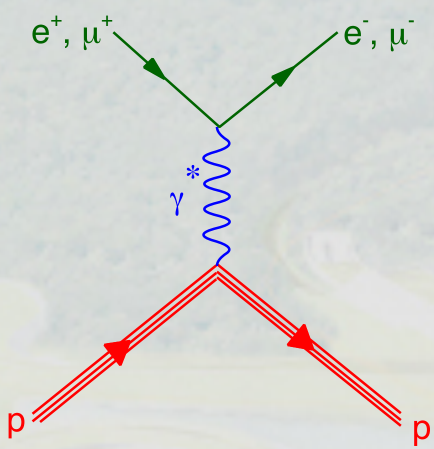
- **Proton spin**

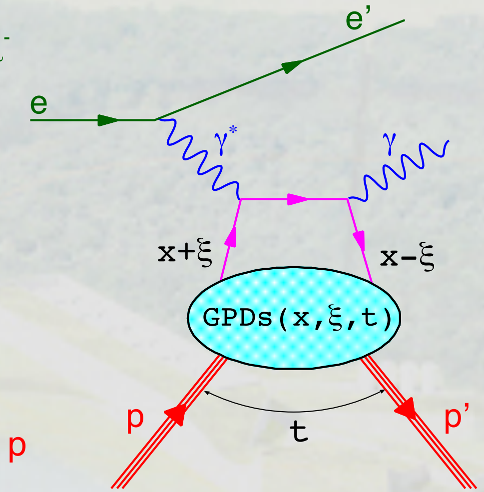
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

- **Studied in space-like reactions**
- **ΔΣ : quark spin**
  - **fraction about 1/3**
- **ΔG : gluon spin**
  - **first results**
- **L_q : quark angular momentum**
  - **unknown**
- **L_g : gluon angular momentum**
  - **unknown**

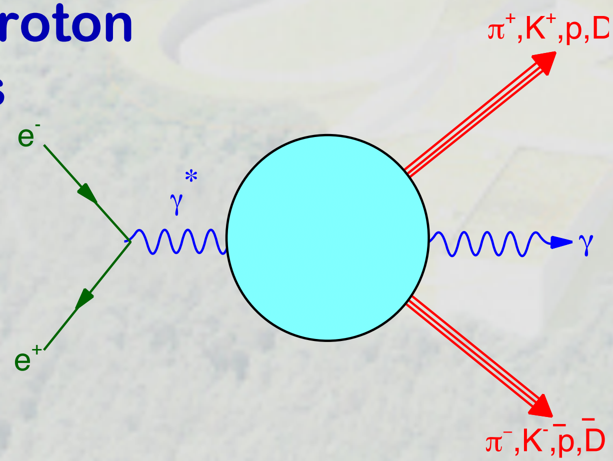
Space and Time Like Processes

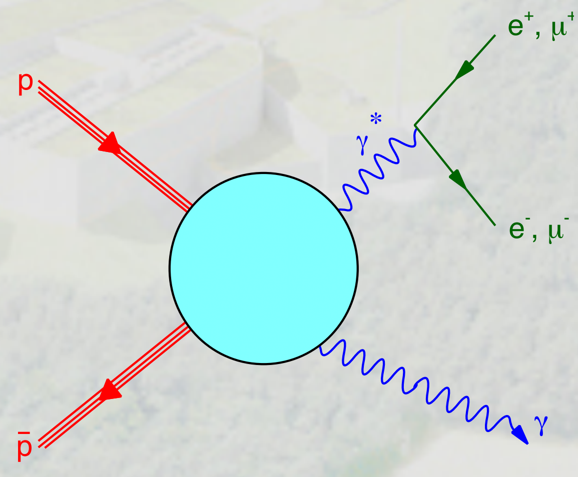
- Space like
  - elastic lepton scattering
  - deep virtual Compton scattering





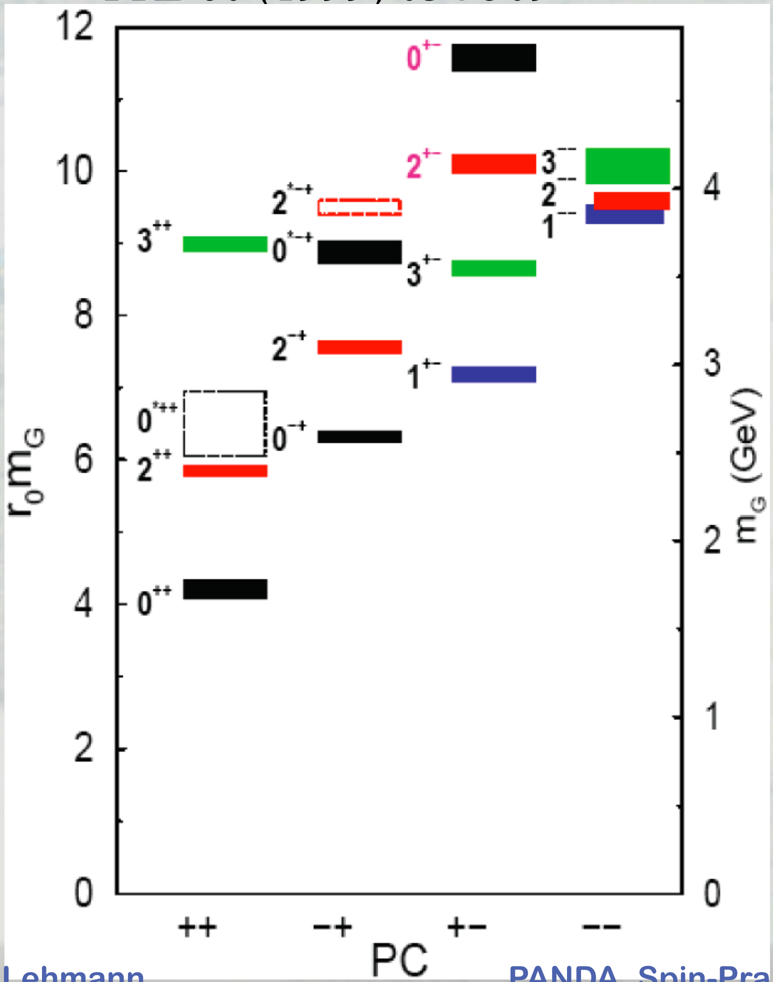
- Time like
  - electron-positron collisions
  - proton-antiproton annihilations



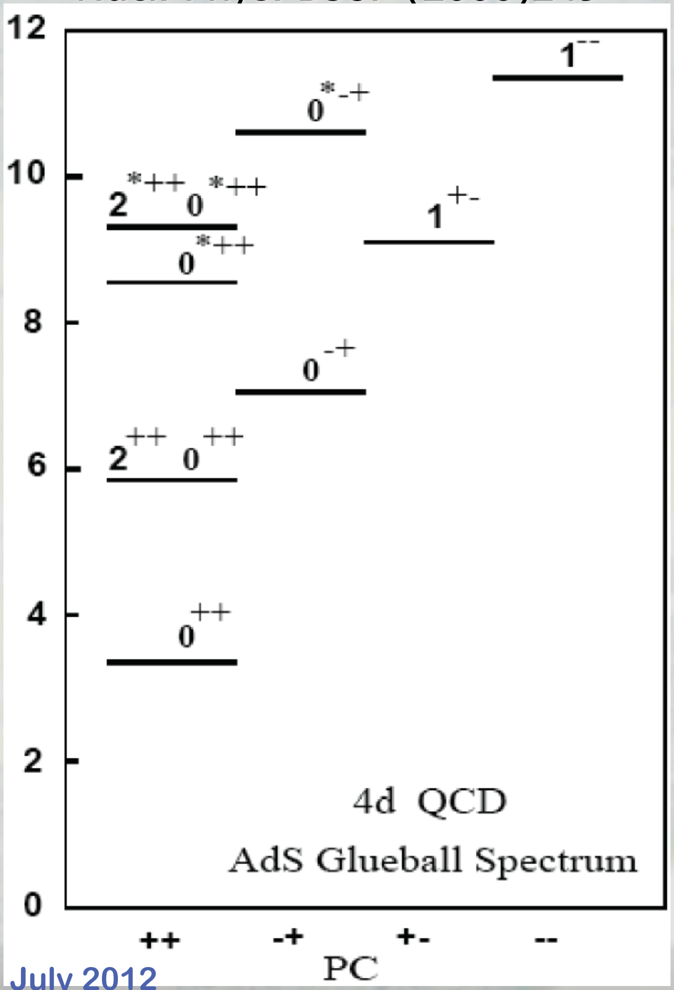


Glueball Predictions

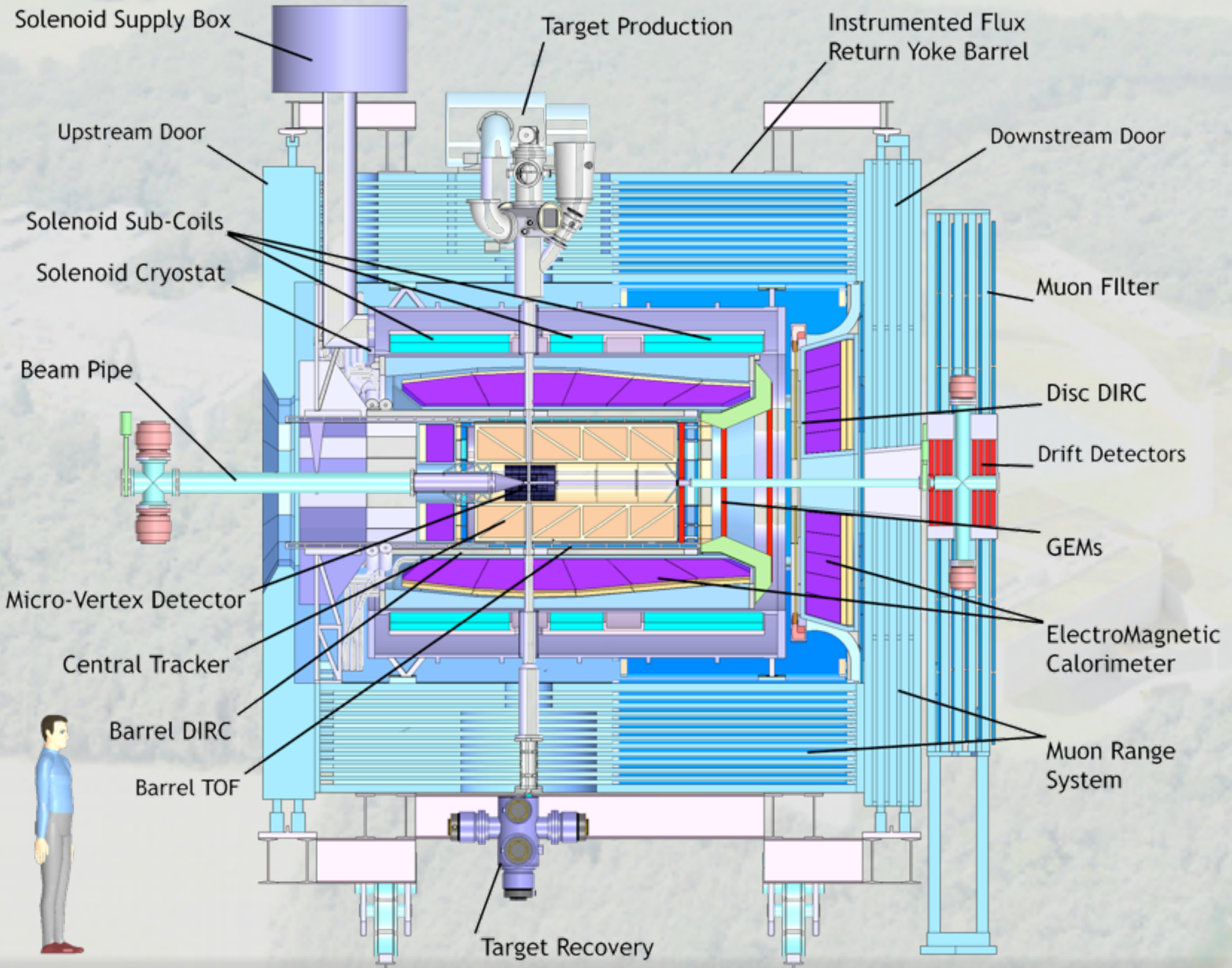
Lattice QCD calculations by Morningstar and Peardon;
PRD60 (1999) 034 509



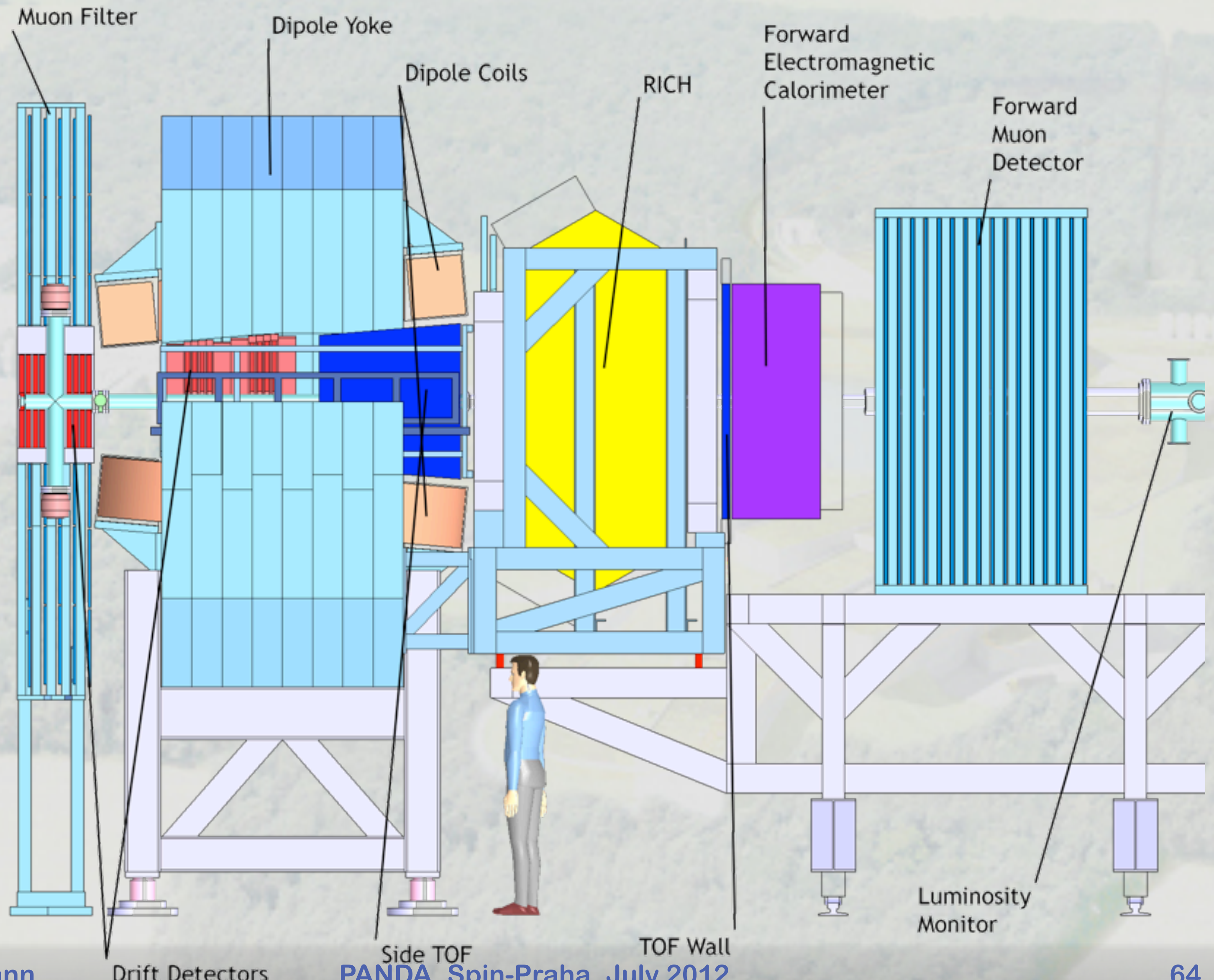
Flux tube calc. by Brower, Mathur and Tan.
Nucl. Phys. B587 (2000)249



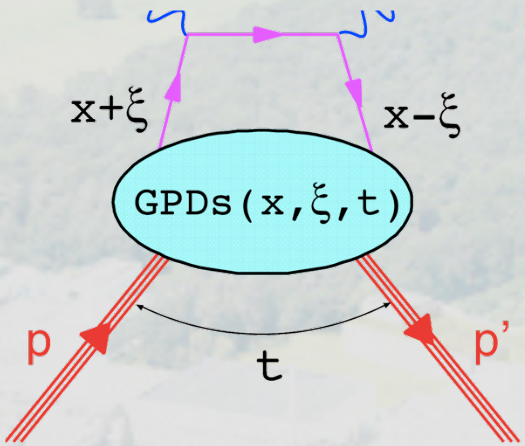
Target Spectrometer

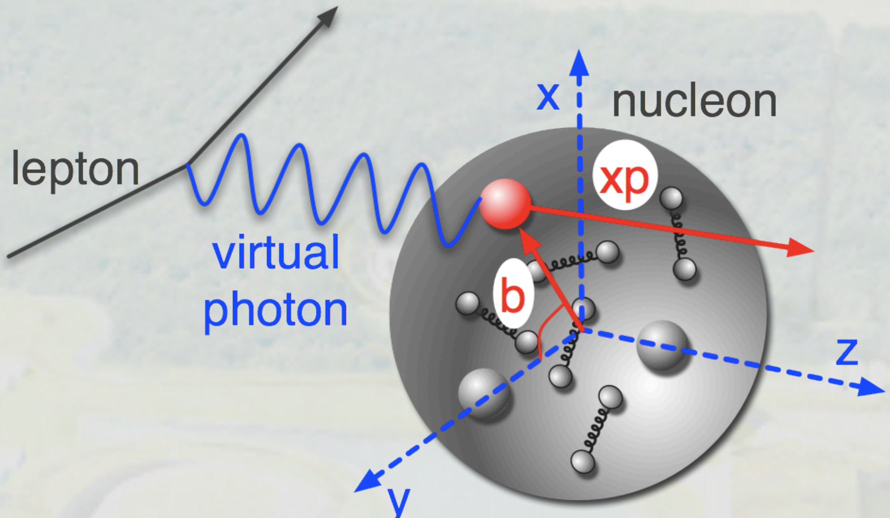


Forward Spectrometer



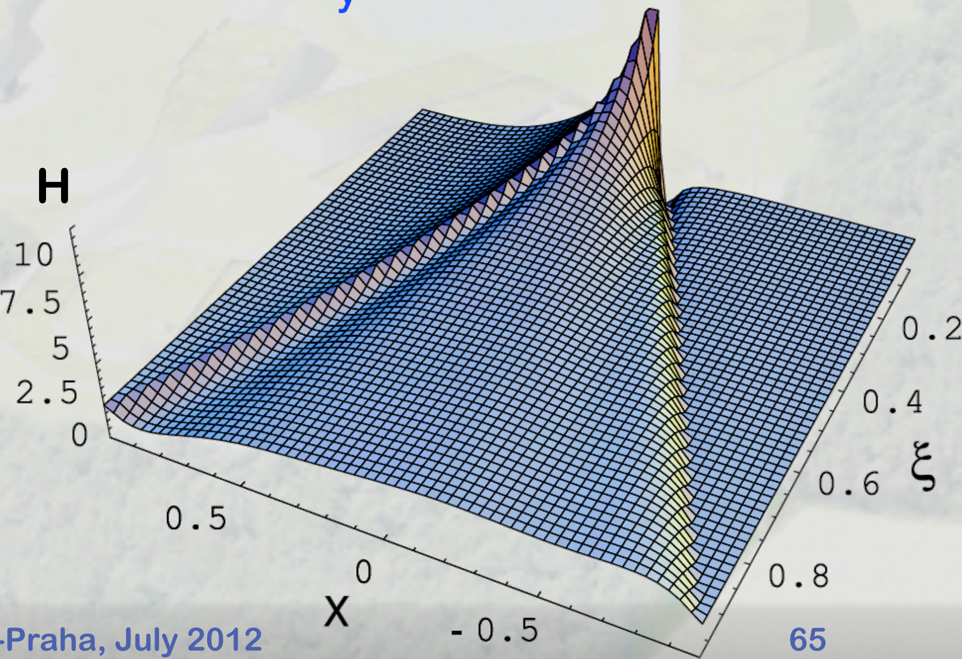
Generalised Parton Distributions





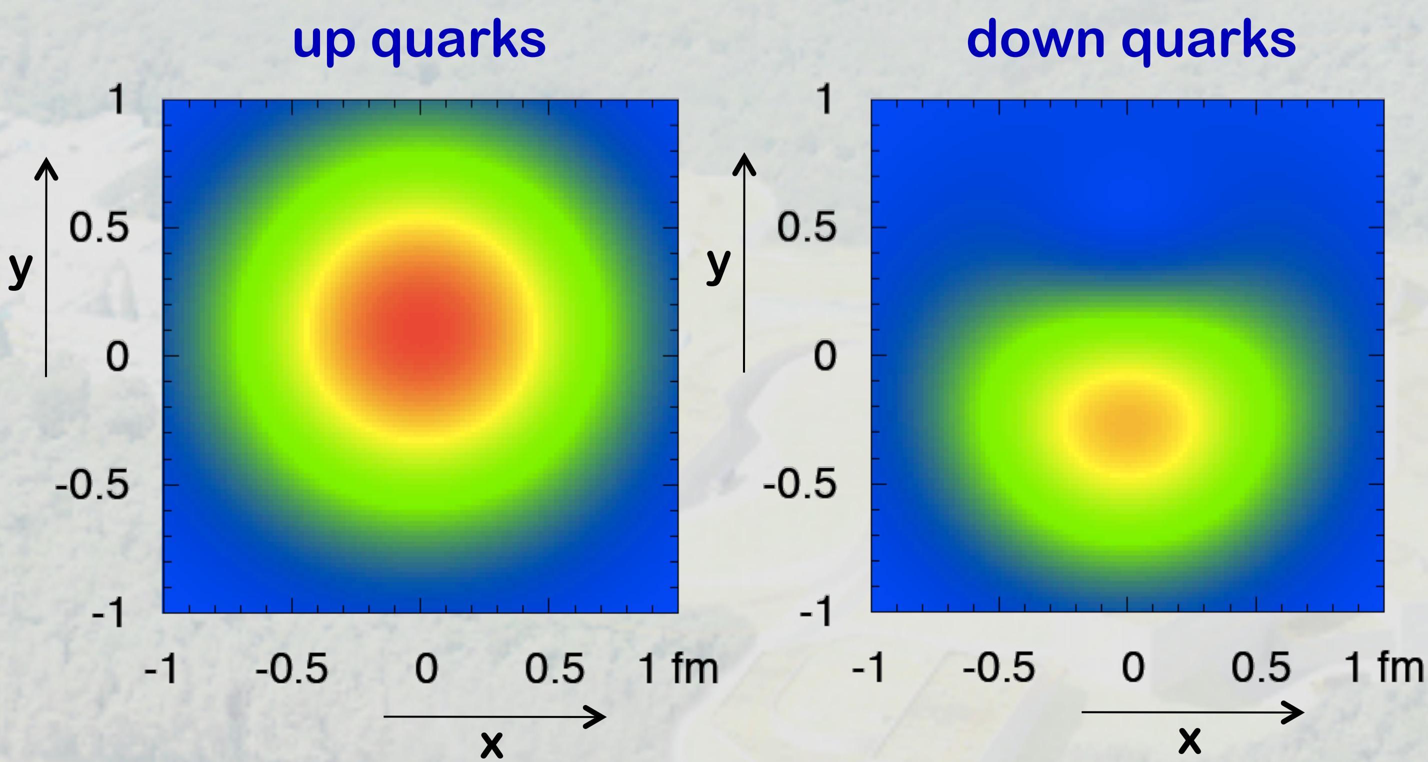
- Functions of 3 variables
  - parton momentum fraction x
  - skewedness ξ
  - p momentum transfer t
- 4 (chirality conserving) quark GPDs

$$H(x,\xi,t), E(x,\xi,t),$$
$$\widetilde{H}(x,\xi,t), \widetilde{E}(x,\xi,t)$$



Model Calculation

- GPD model, constrained by experimental form-factor data



- Density distribution in impact parameter plane for quarks. Proton transv. polarised along x axis.

[P.Kroll, AIP Conf.Proc.904:76-86,2007]

Facility for Antiproton and Ion Research

Primary Beams

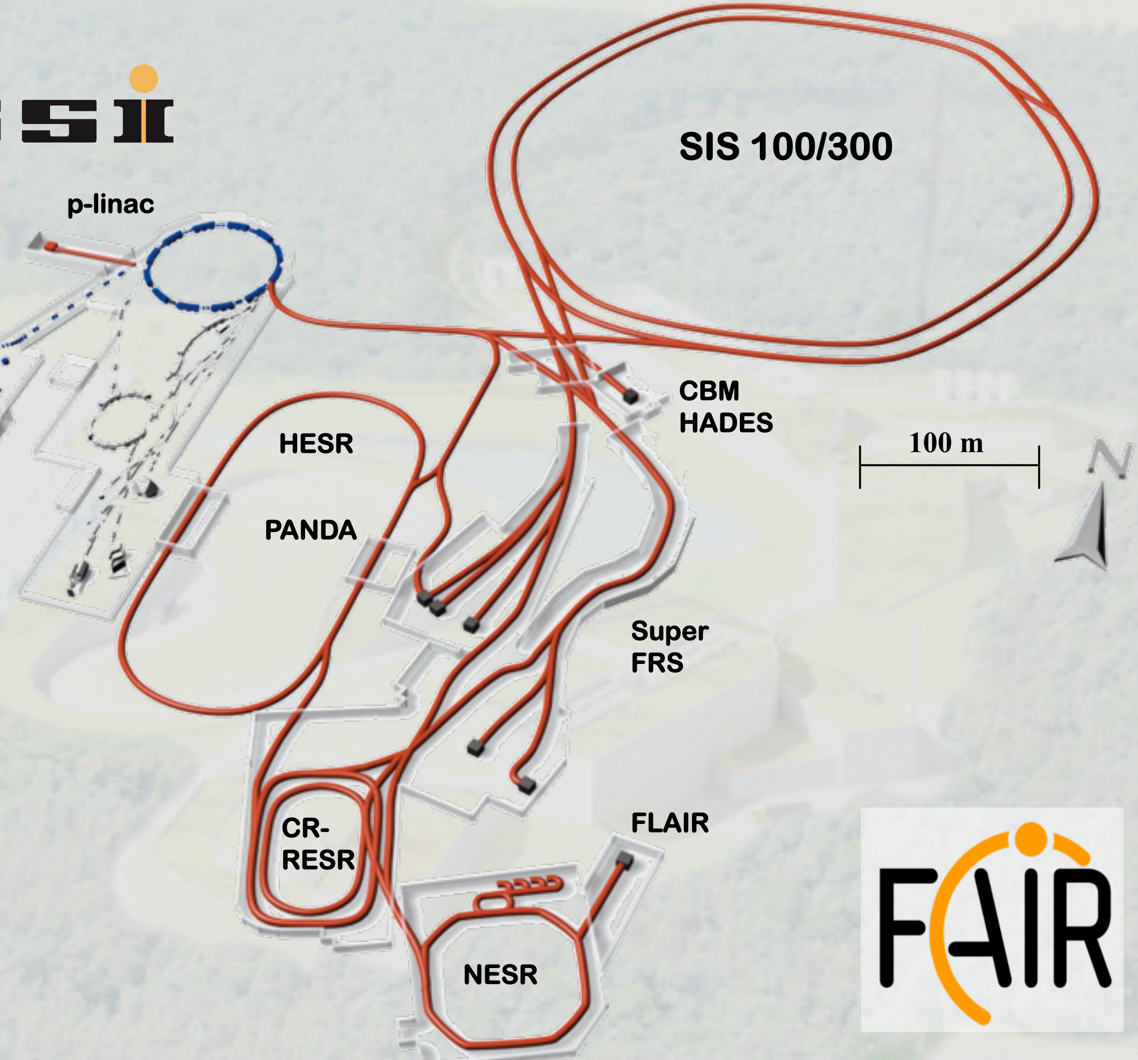
- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u
- 3×10^{13}/s 30 GeV protons

Secondary Beams

- range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 higher in intensity than presently
- antiprotons 3 - 30 GeV

Storage and Cooler Rings

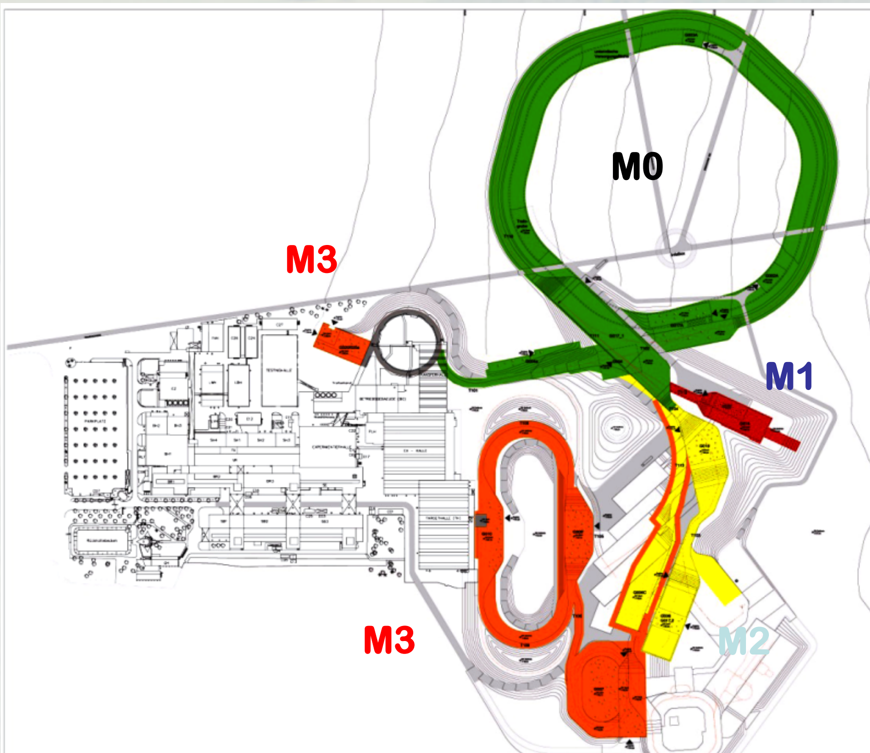
- radioactive beams
- 10^{11} antiprotons 1 - 15 GeV/c, stored and cooled

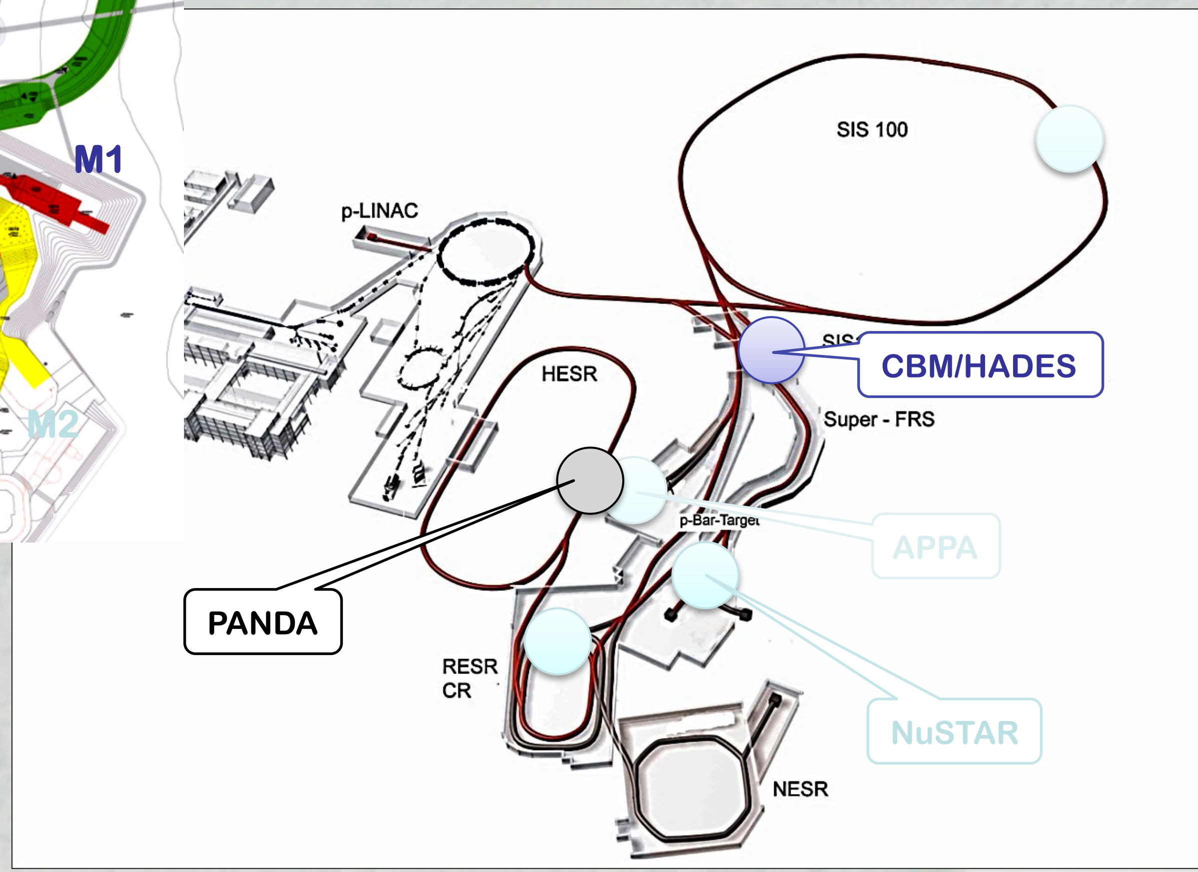


Technical Challenges

- cooled beams, rapid cycling superconducting magnets

Modularised Start Version





Experiments

M1: APPA
M1: CBM/HADES
M2: NuSTAR
M3: PANDA

Costs MSV

Accelerators and personnel (including Super-FRS)	502 M€
Civil construction (excluding site related costs)	400 M€
FAIR contribution to experimental end stations *	78 M€
FAIR GmbH personnel & running until 2018 (>8 years)	47 M€
Grand Total MSV, Modules 0 - 3	1027 M€

in 2005 €
(inflation escalation until 2018: ca. +50%)

* Total experimental end stations (excluding Super-FRS): ca. 210 M€ (2005) = 315 M€ (2018)

Funding Modules 0-3

Contracting Party	Contribution (in 2005 M€)
Finland	5.00
France	27.00
Germany	705.00
India	36.00
Poland	23.74
Romania	11.87
Russia	178.05
Slovenia	12.00
Sweden	10.00
Total	**1.008,66**

- **All numbers in 2005 € (escalation until 2018 ca. +50%)**
- **Spain expected to join soon (with 11.87 M€)**
- **China and the UK are potential Associate FAIR Members and will contribute to the experiments (6.6 M€)**

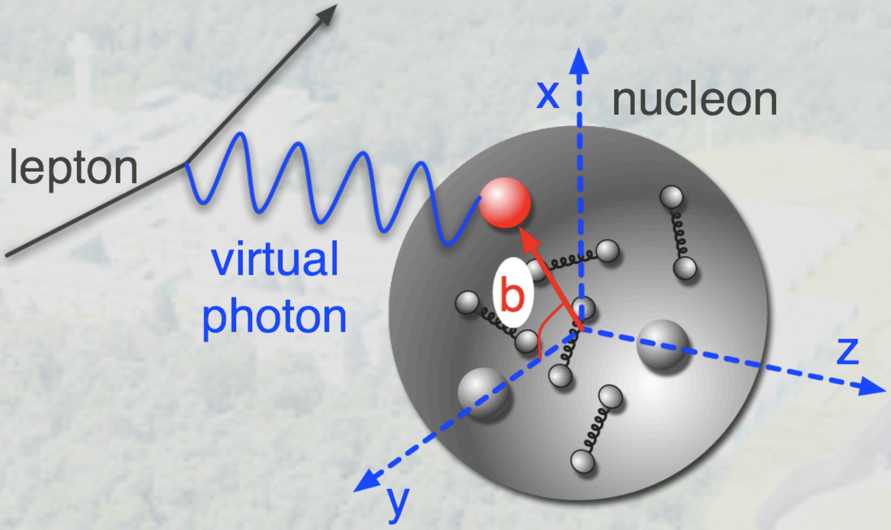
Timelines

- 6 Submission building permits
- 7 Site preparation
- 8 Civil construction contracts
- 9 Building of accelerator & detector components
- 10 Completion of civil construction work
- 11 Installation & commissioning of accelerators and detectors
- 12 Data taking

FAIR Open Space Planning

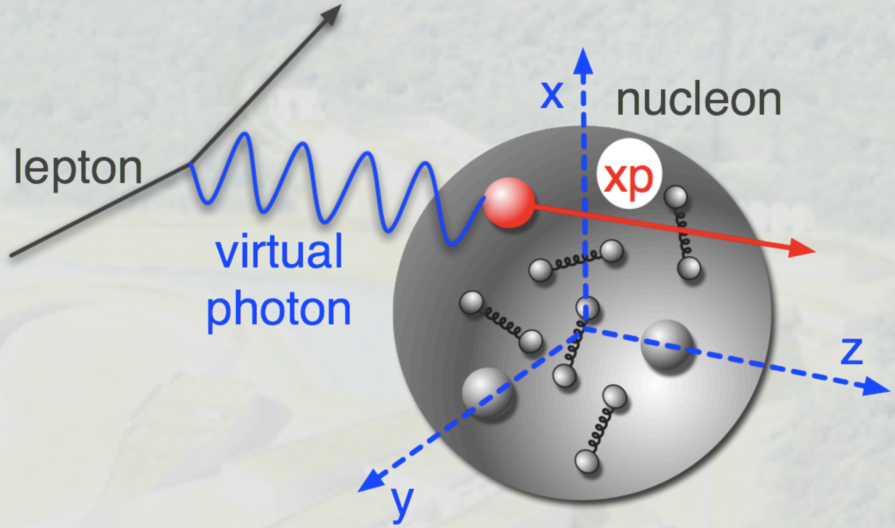
Other Structure Functions

Form Factors



Density in transverse impact parameter space

Parton Distribution Functions



Momentum fraction in longitudinal space

- Combined approach...