University of Glasgow

Physics Programme of the PANDA Experiment at FAIR

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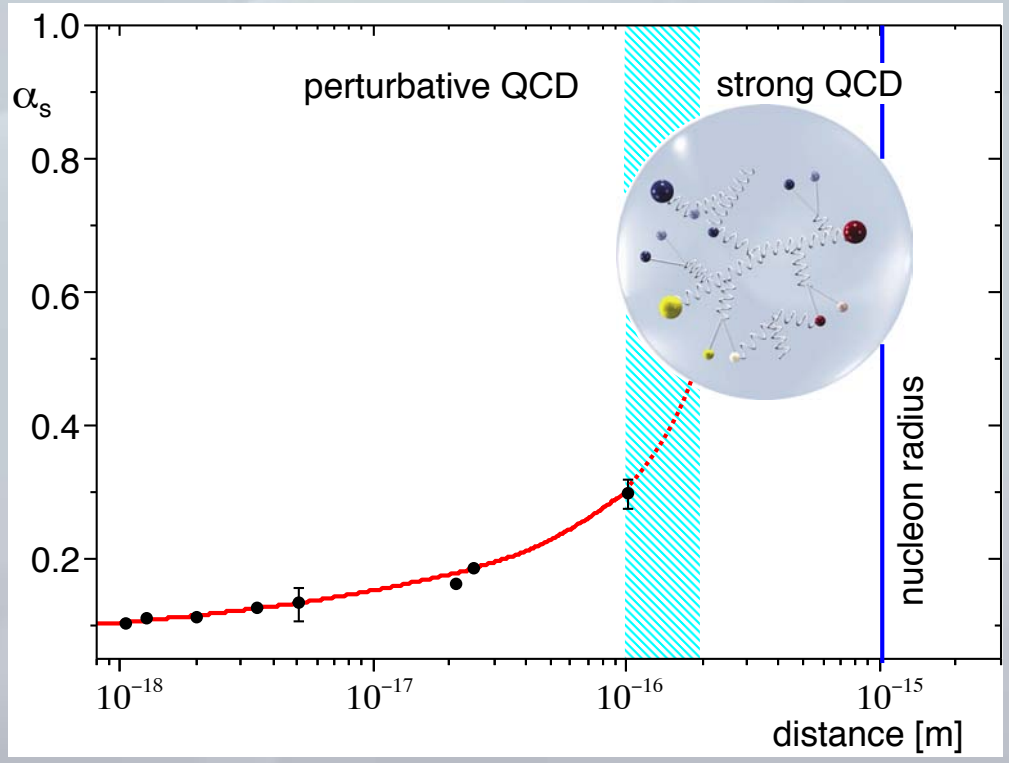
University of Glasgow
for the PANDA Collaboration

Spin Praha, 19-23 July 2010

Overview

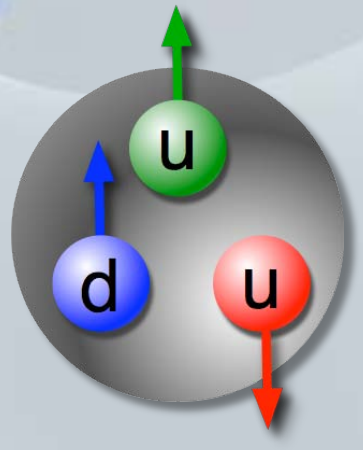
- Puzzles in strong QCD
- Experimental approach
- PANDA detector set-up
- Highlights at PANDA

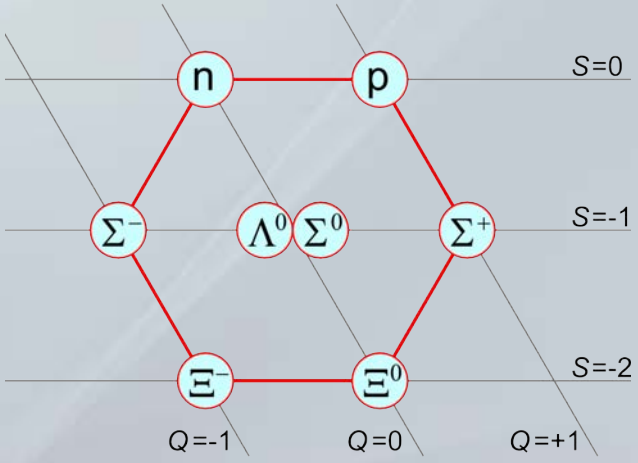


Puzzles in Strong QCD

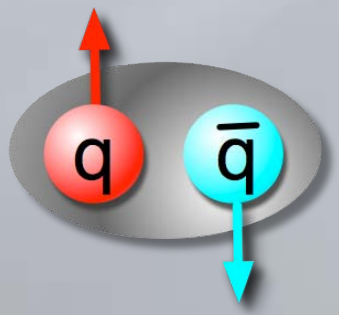
Naive Picture of the Hadron

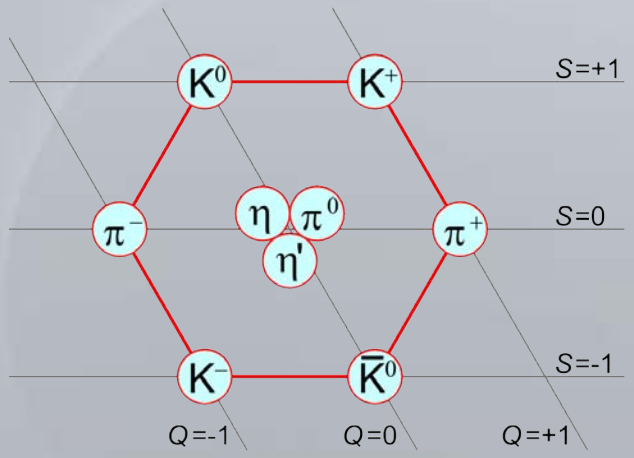
- **Baryons**
  - e.g. proton, neutron
  - 3 quarks
  - half integer spin





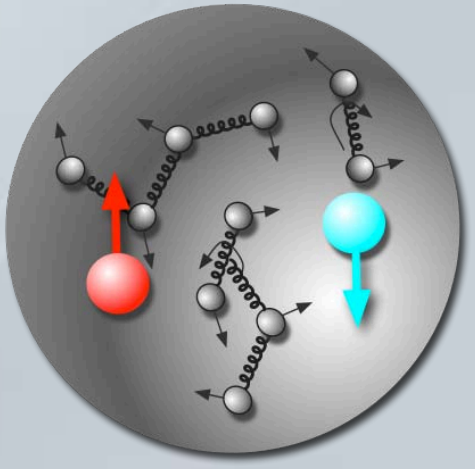
- **Mesons**
  - e.g. pion
  - quark-antiquark
  - integer spin





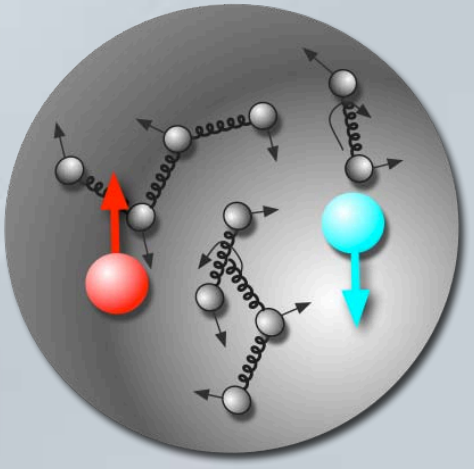
Semi-Naive Picture of the Hadron

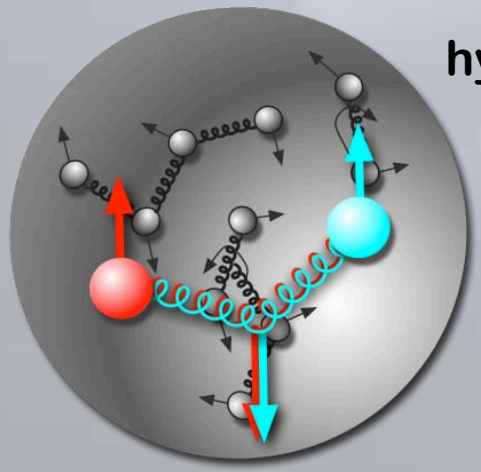
- Known hadrons
  - contain quark-gluon sea
  - quantum numbers carried by “dressed” valence quarks



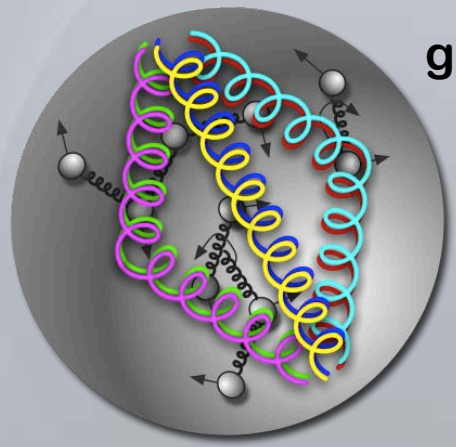
Puzzle 1: Exotic Hadrons

- 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
  - why not observed, or are they?





hybrid



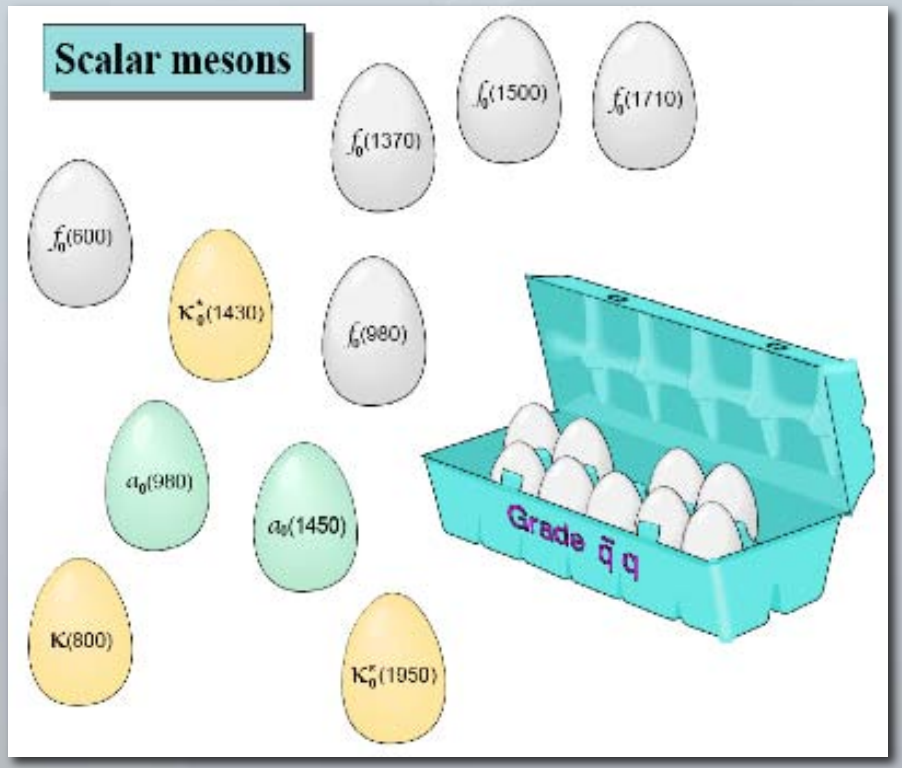
glueball

Indication: Overpopulation

- Light quark sector
  - 7 candidates for 4 states with 0^{++}

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

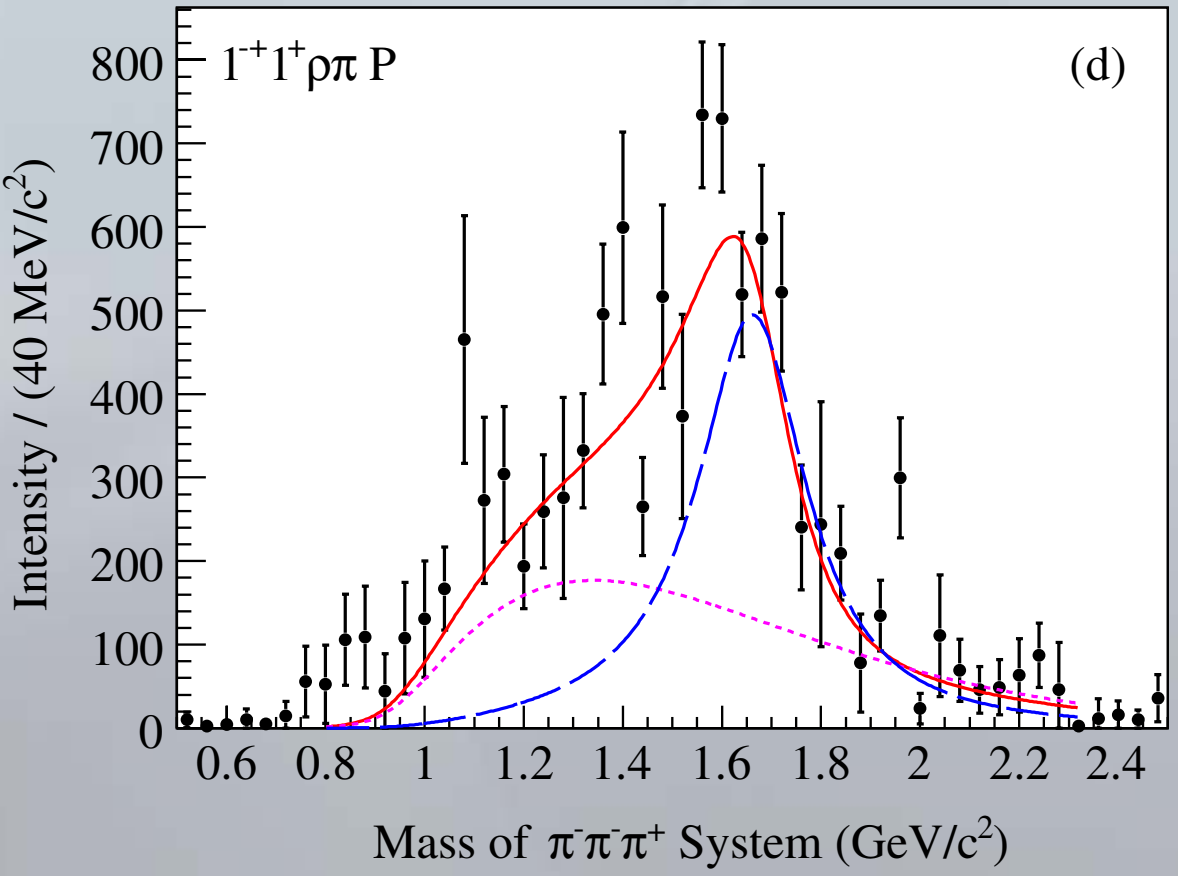


  - States mix: nature difficult to determine

Most Recent Finding

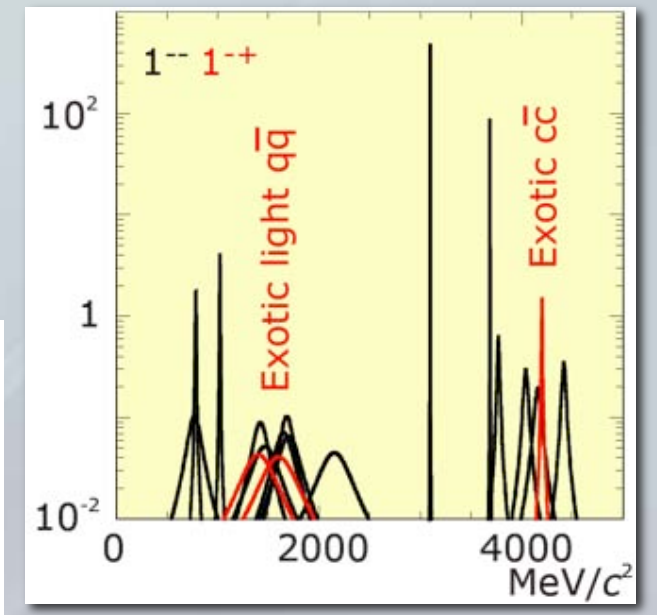
- COMPASS partial wave analysis
  - exotic $J^{PC} = 1^{-+}$ wave found at 1.66 GeV
  - consistent with $\pi_1(1600)$

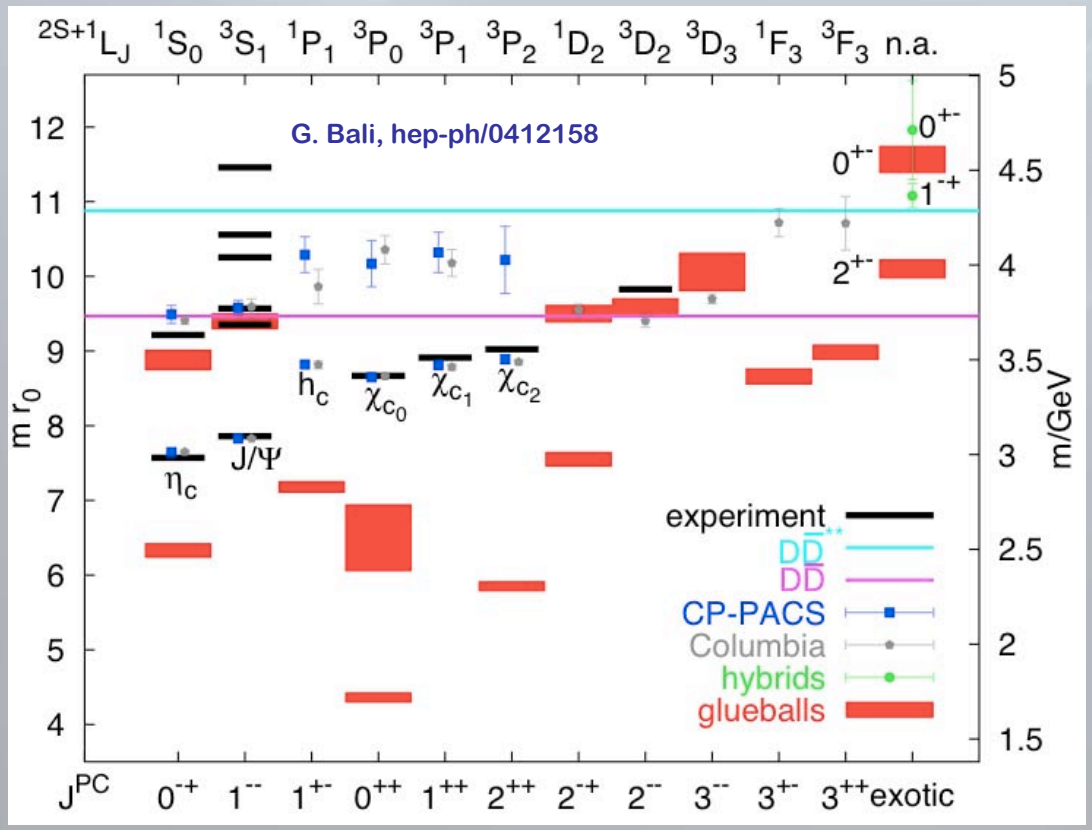
Phys. Rev. Lett. 104, 241803 (2010)



Charm Quark Sector

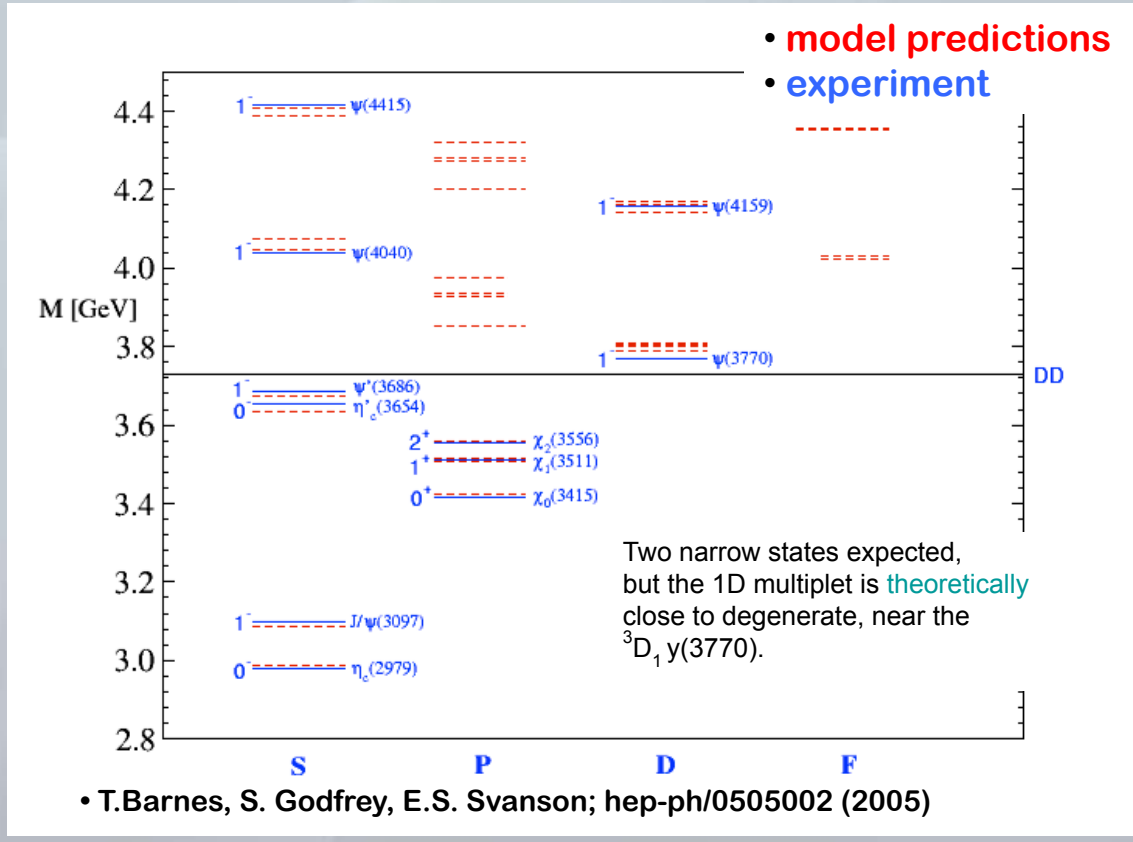
- Most promising
  - narrower states
  - fewer states
  - less mixing





Puzzle 2: Charmonium Spectrum

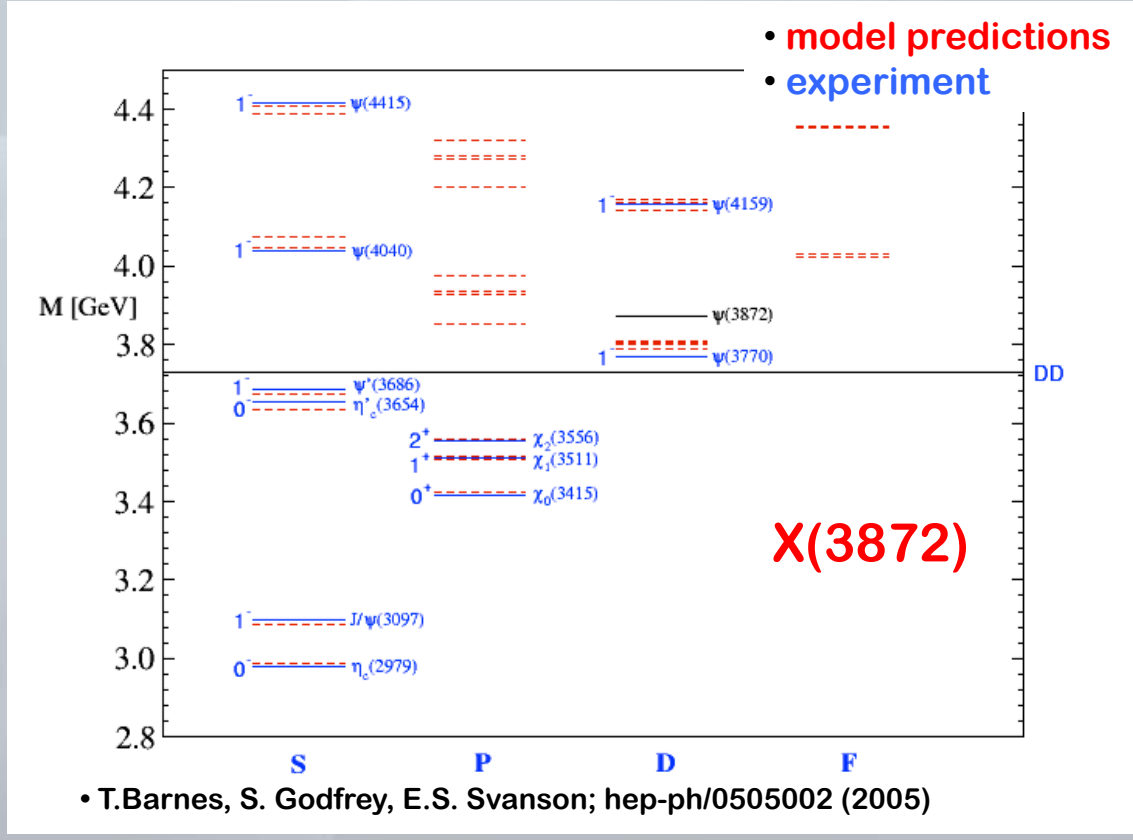
- Positronium of QCD
- Until 2005
  - no surprises
  - well understood



• T.Barnes, S. Godfrey, E.S. Svanson; hep-ph/0505002 (2005)

Puzzle 2: Charmonium Spectrum

- Positronium of QCD
- Until 2005
  - no surprises
  - well understood
- Recently
  - many new states
  - far off predictions



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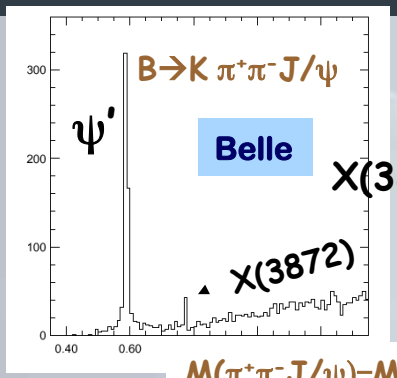
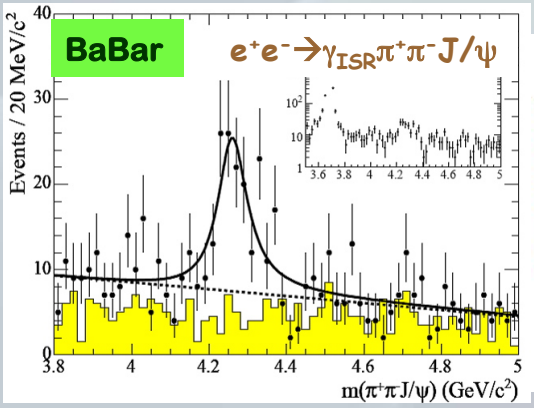
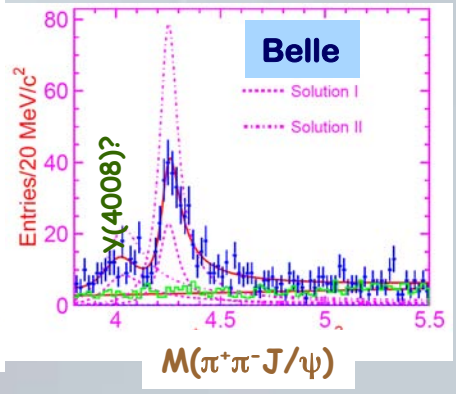
Findings at B Factories



Y(4260)





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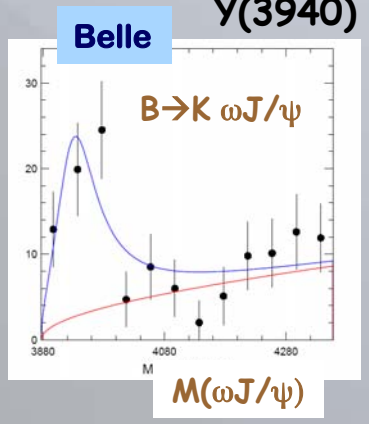
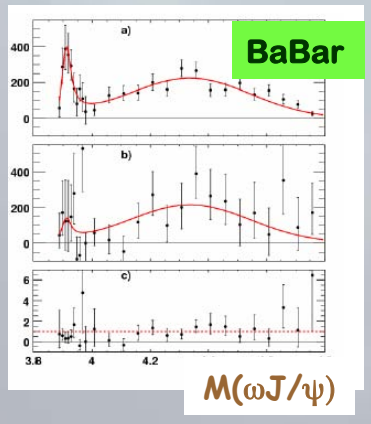
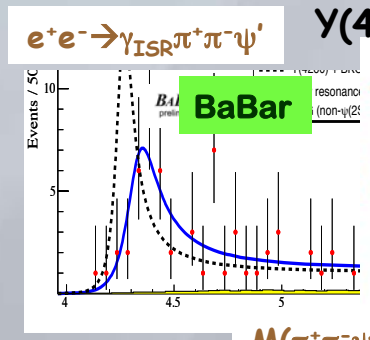
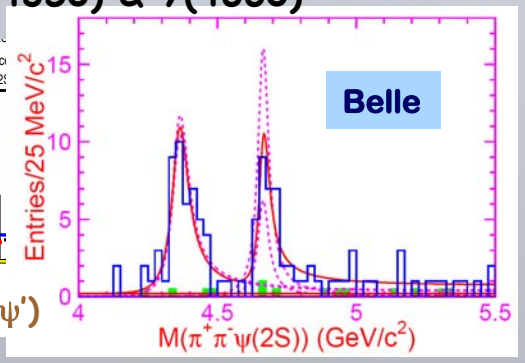






Y(4350) & Y(4660)



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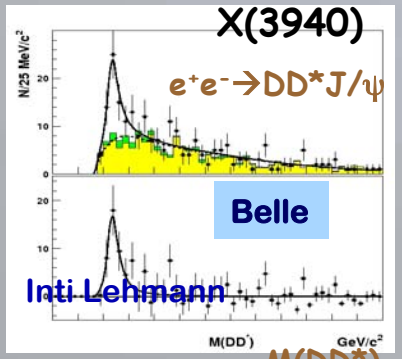
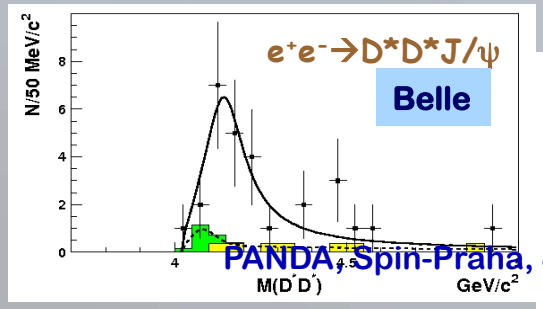
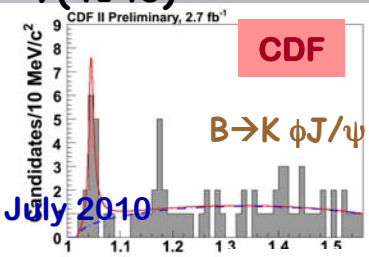


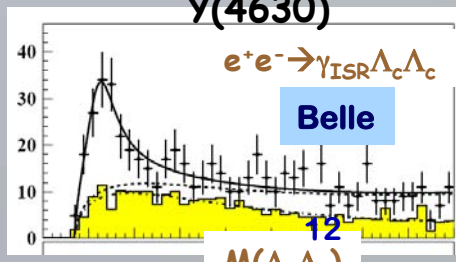
X(4160)



Y(4140)



Y(4630)



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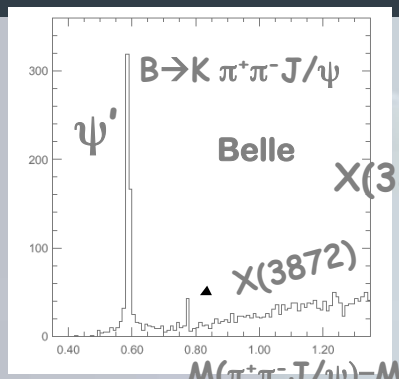
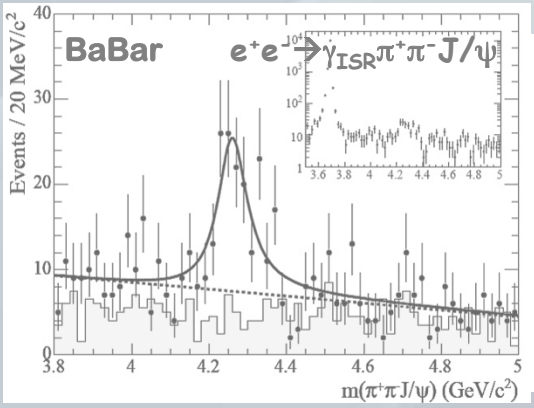
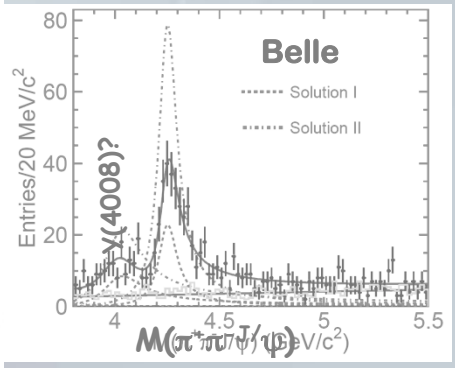
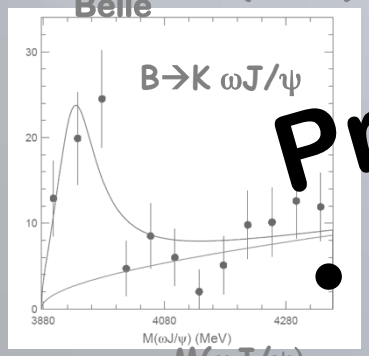


Y(4260)





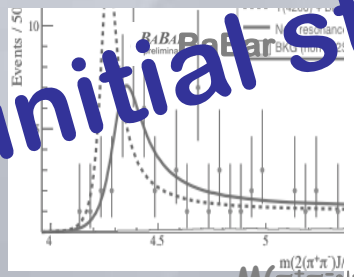
Y(3940)

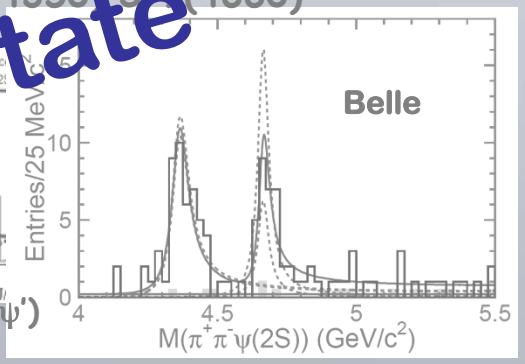


Problems

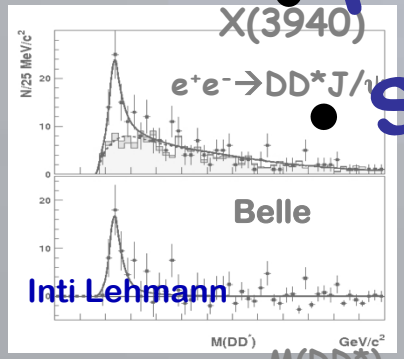
- resolution
- restricted initial state
- statistics

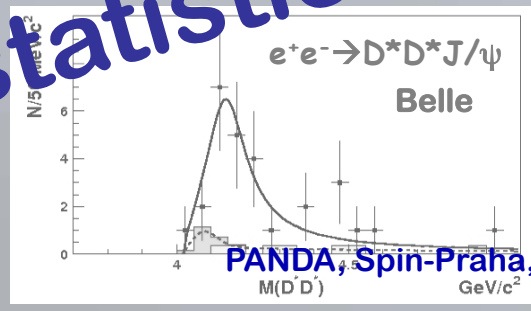
Y(4350) & Y(4660)





X(3940)





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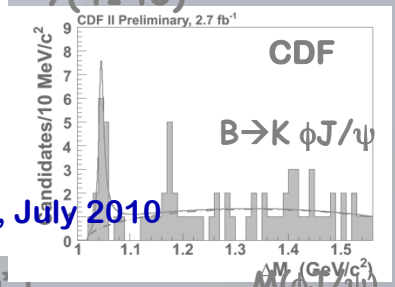
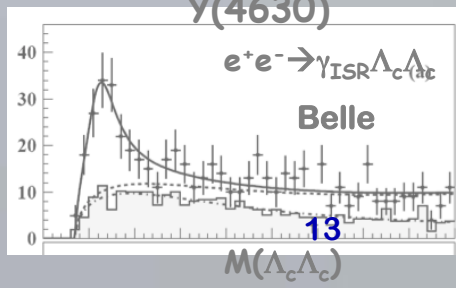
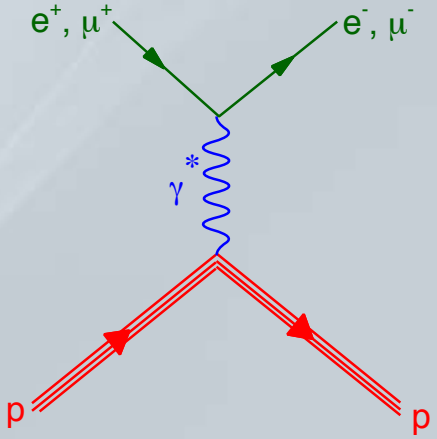


Y(4630)



Puzzle 3: Nucleon Structure

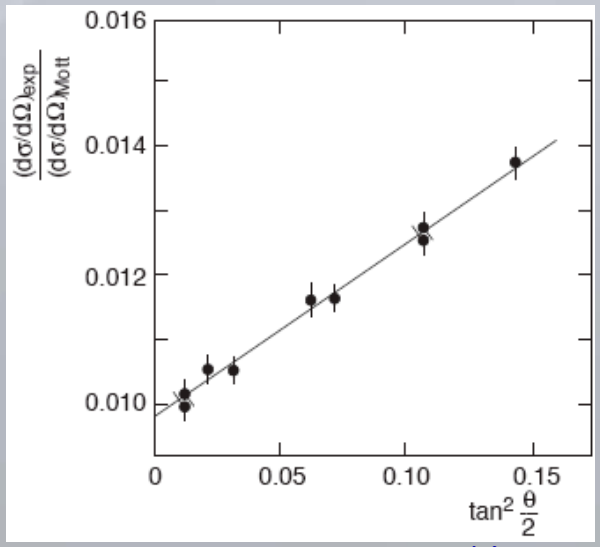
- Aside: proton charge radius 0.88 or 0.84fm?
  - *Nature* 466, 213-216 (8 July 2010)
- Form factors believed to be well understood
- Successful approach for decades
  - Rosenbluth cross section
    - assuming single photon exchange



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

$$\tau = \frac{Q^2}{4M_p^2} \qquad \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2}{4E^2}\frac{\cos^2\frac{\theta}{2}}{\sin^4\frac{\theta}{2}}\frac{E'}{E}$$

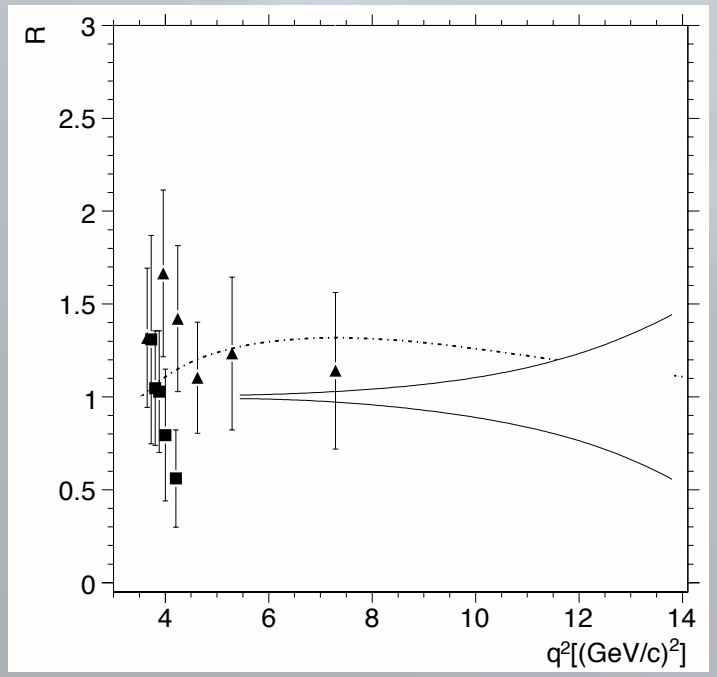
  - Extract G_E and G_M
    - slope determines G_M
    - offset allows to access G_E

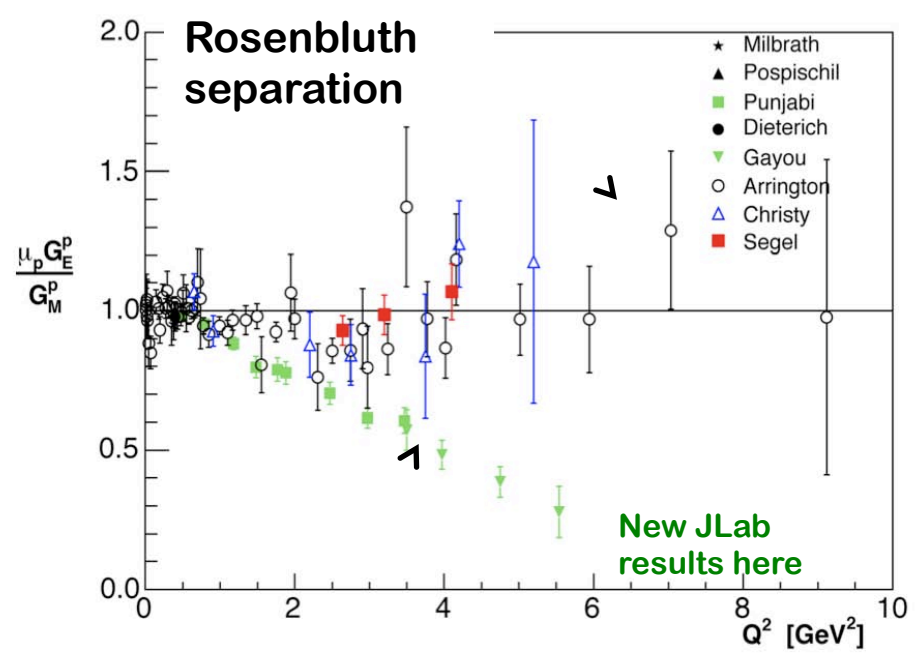


Puzzle 3: Nucleon Structure

- Space like form factor
  - unresolved discrepancy

  -> OLYMPUS
- Time like form factor
  - basically uncharted territory

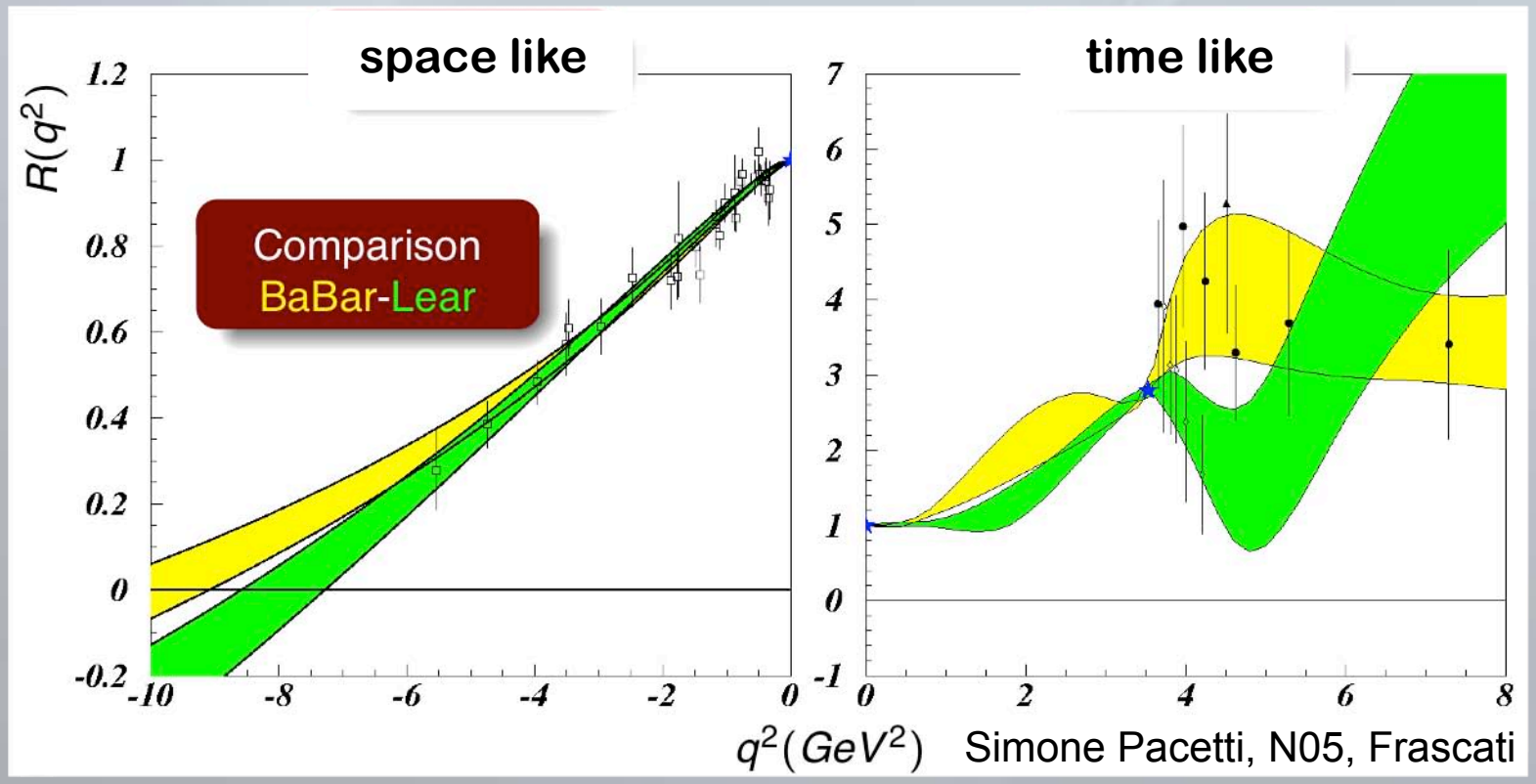




Double polarisation measurements

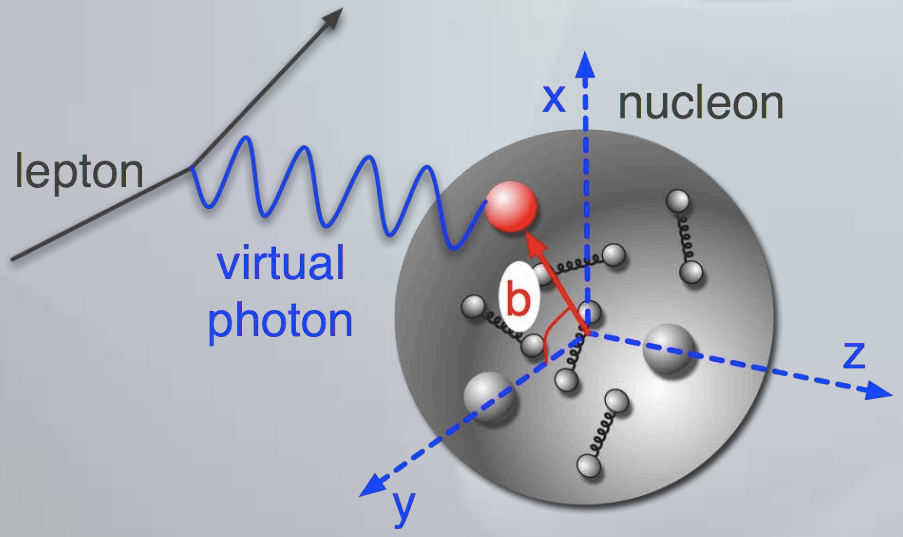
Time and Space-Like Regions

- Closely related using dispersion relation
- Form factor ratio $R = \mu_p G_E / G_M$
  - fit to double polarisation measurements in space like region
  - weak constraint: scarce data in time like region



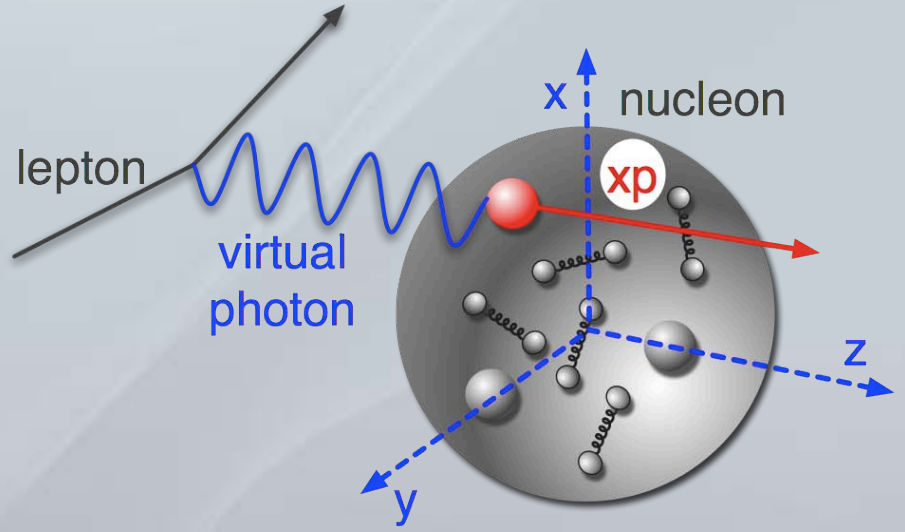
Other Structure Functions

Form Factors



Density in transverse impact parameter space

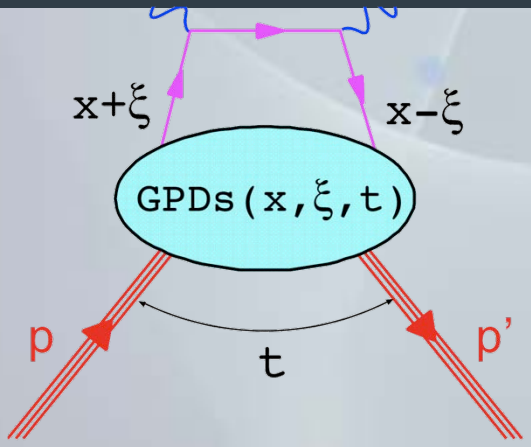
Parton Distribution Functions

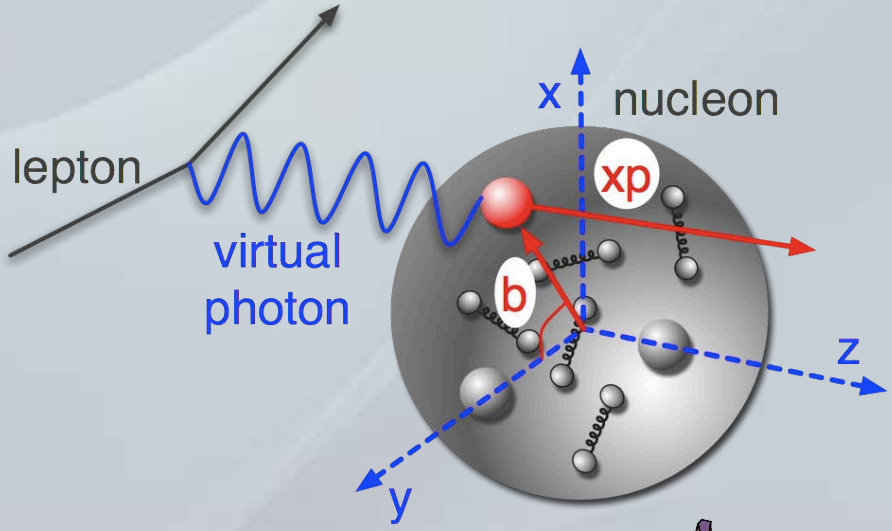


Momentum fraction in longitudinal space

- Combined approach…

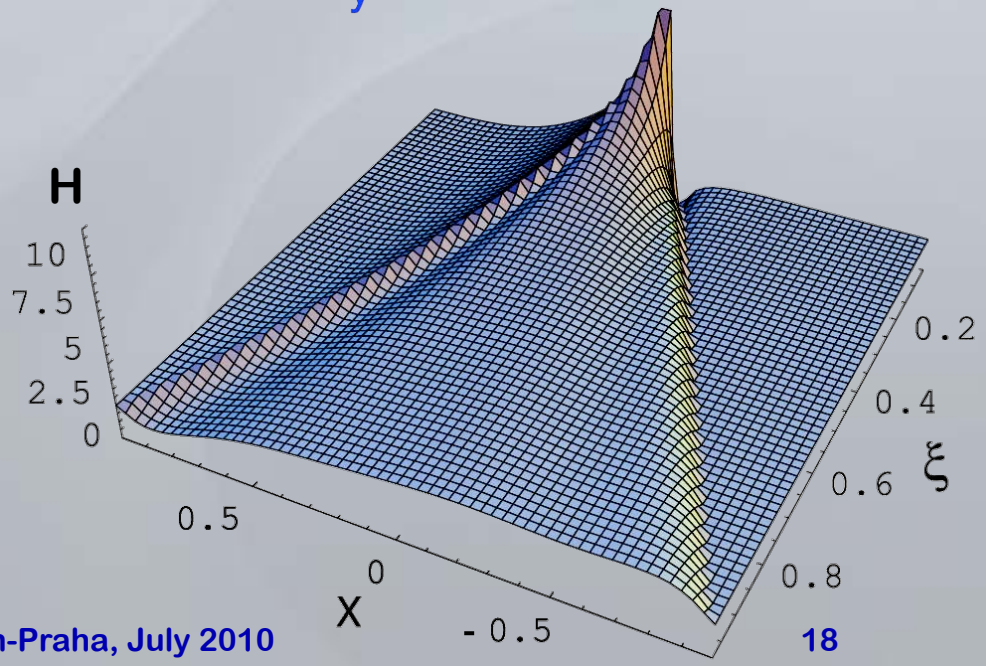
Generalised Parton Distributions





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

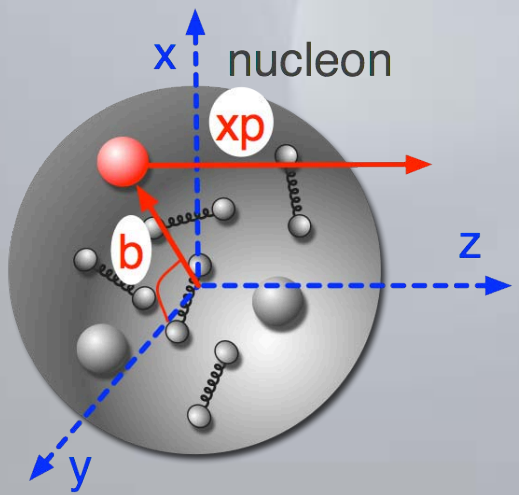
$$H(x,\xi,t), E(x,\xi,t),$$
$$\widetilde{H}(x,\xi,t), \widetilde{E}(x,\xi,t)$$

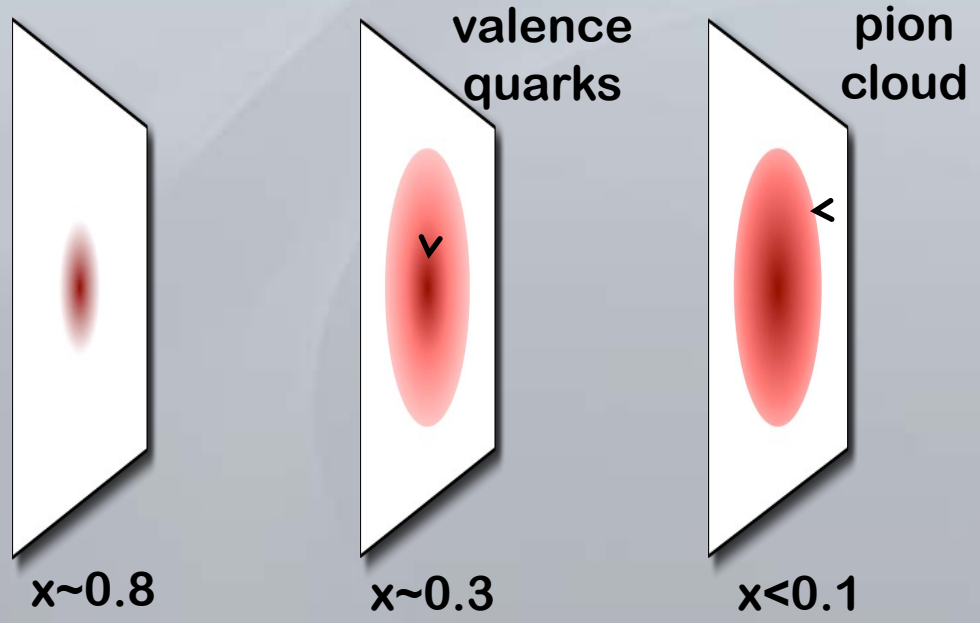


Interpretation of GPDs

- Fourier transformation of GPDs at $\xi=0$ yields 2+1 dimensional picture of the nucleons
  - i.e. longitudinal in momentum fraction and transversal in impact parameter space

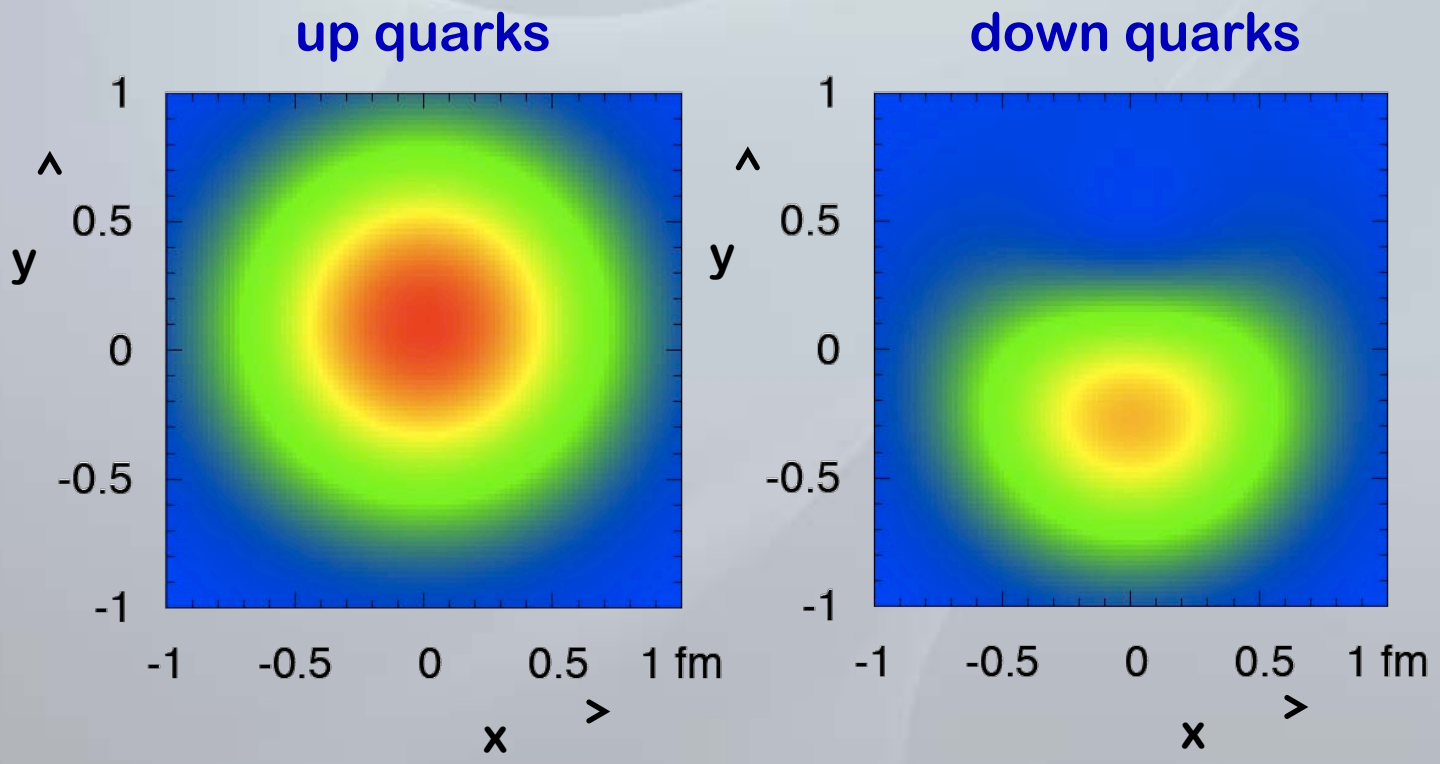
$$q(x, b_\perp) = \int \frac{d^2\Delta_\perp^2}{(2\pi)^2} H(x, 0, -\Delta_\perp^2) e^{-i\Delta_\perp \cdot b_\perp}$$





Model Calculation

- GPD model, constrained by experimental form-factor data



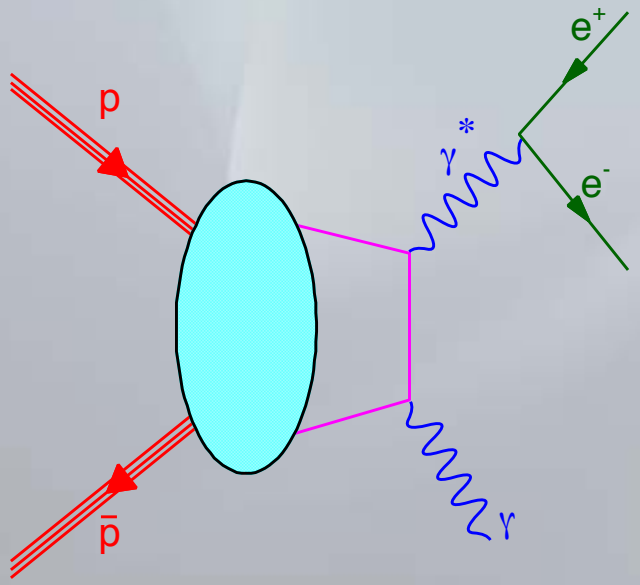
- Density distribution in impact parameter plane for quarks. Proton transv. polarised along x axis.

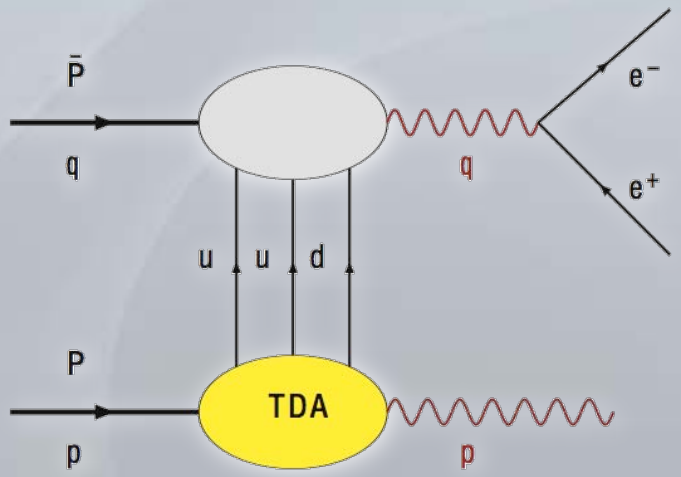
[P.Kroll, AIP Conf.Proc.904:76-86,2007]

Time-Like Domain

- Available 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



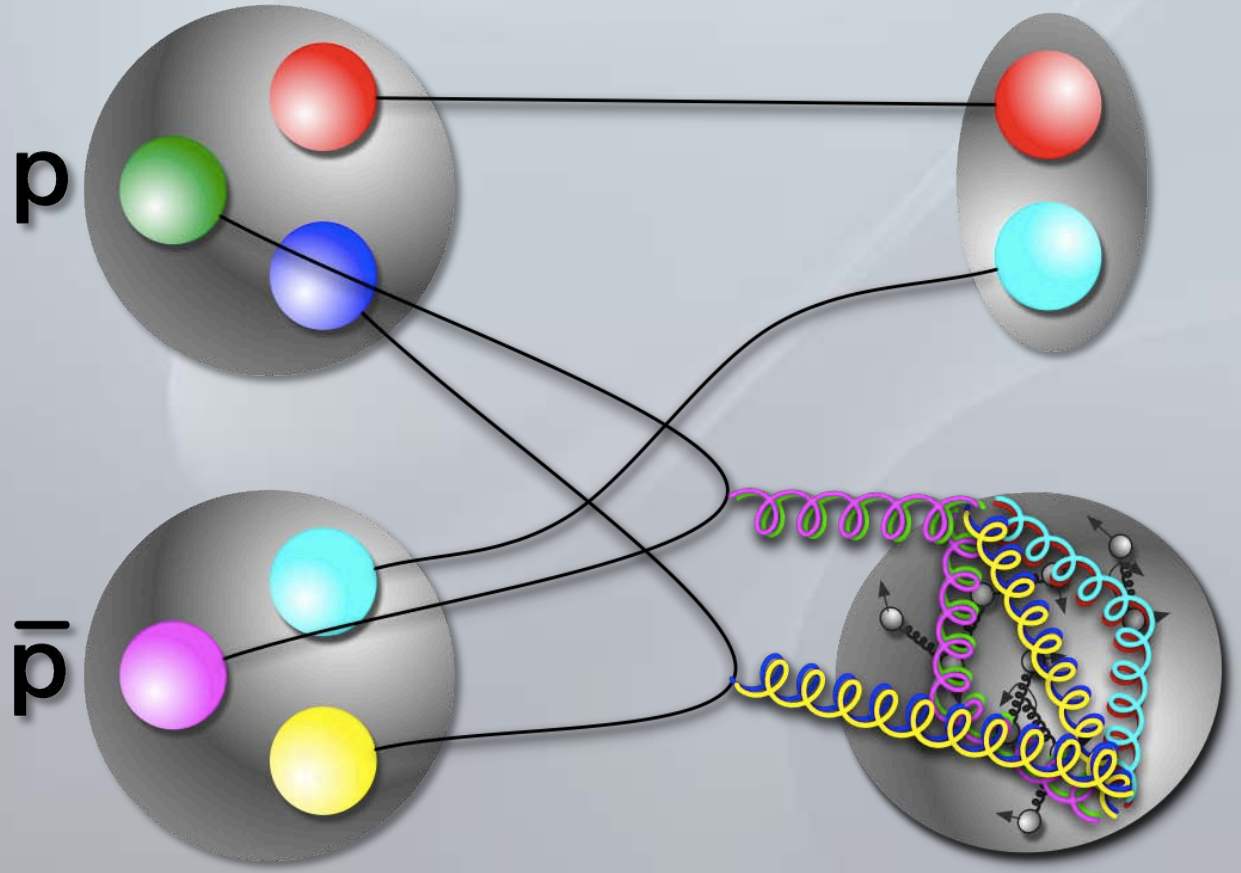


- Basically no experimental data available

Experimental Approach

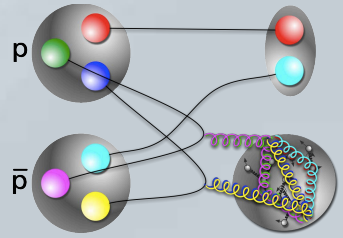
Experimental Requirements

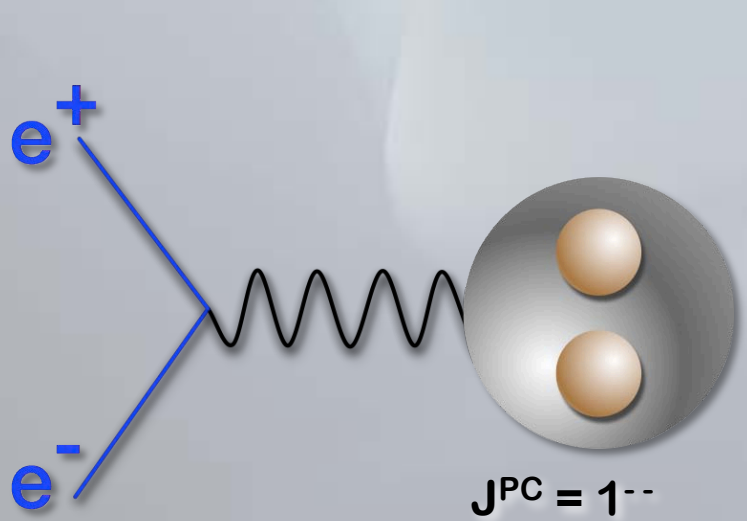
- **Gluon-rich environment**
  ⇒ Proton-antiproton annihilations

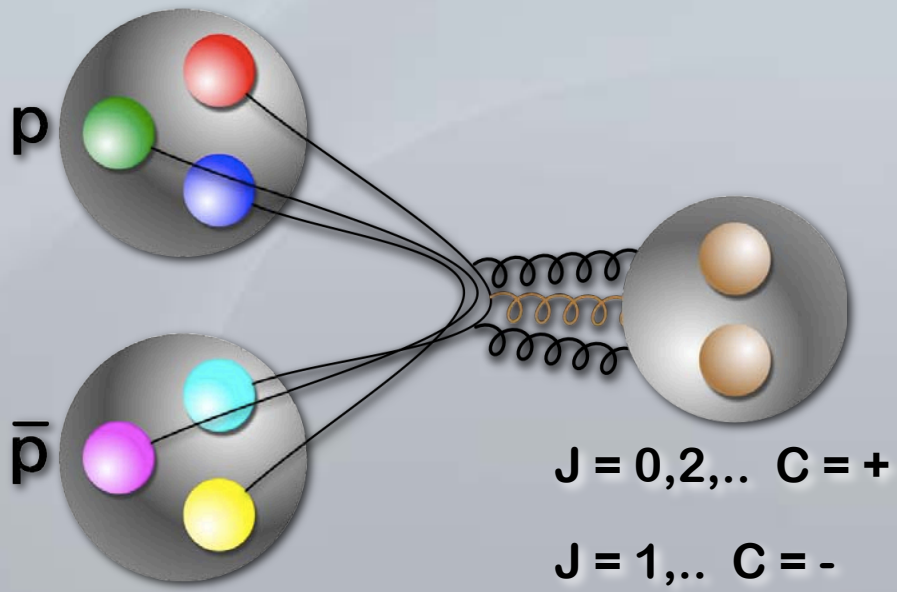


Experimental Requirements

- **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

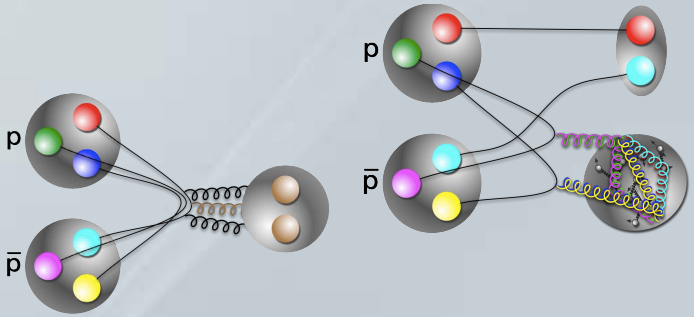


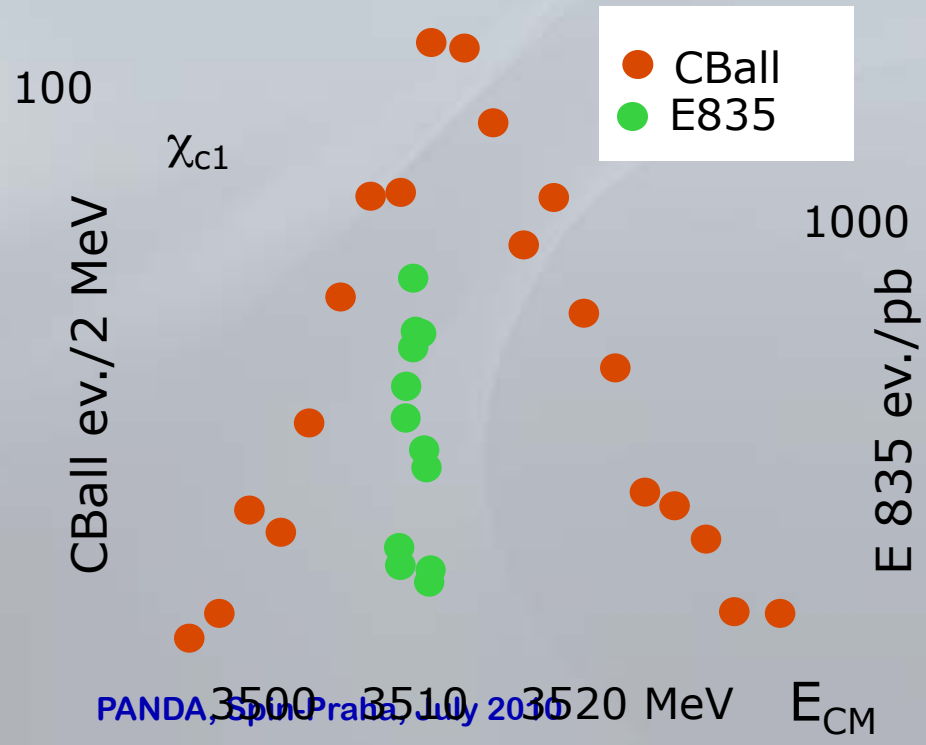




Experimental Requirements

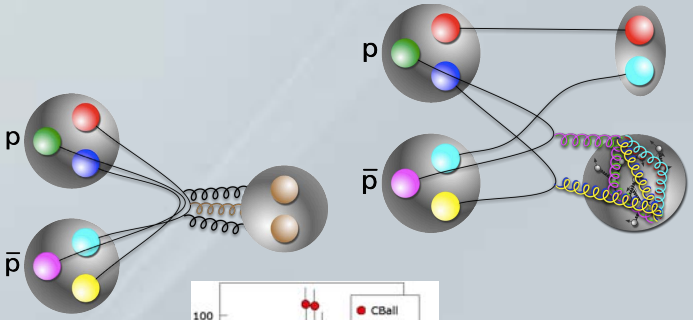
- **Gluon-rich environment**
  ⇒ Proton-antiproton annihilations
- **Formation of various states**
  ⇒ All QM, 4π (forward)
- **Precise resonance scan**
  ⇒ High precision hadron beam (cooled)

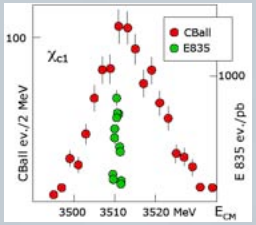


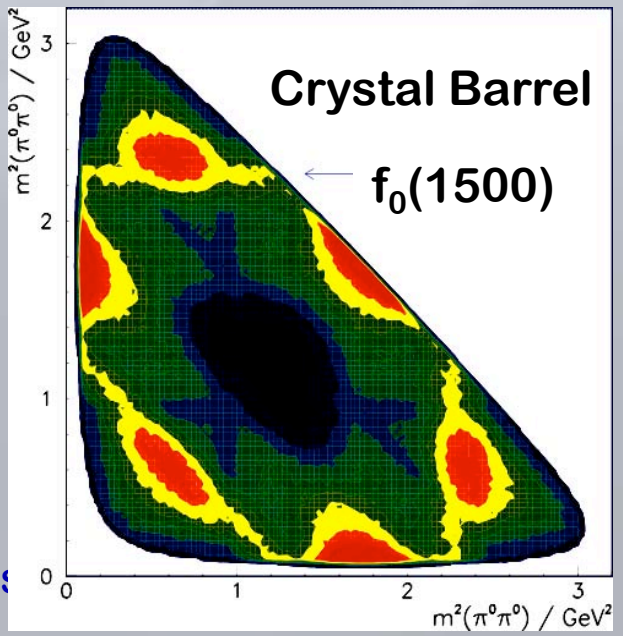


Experimental Requirements

- **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

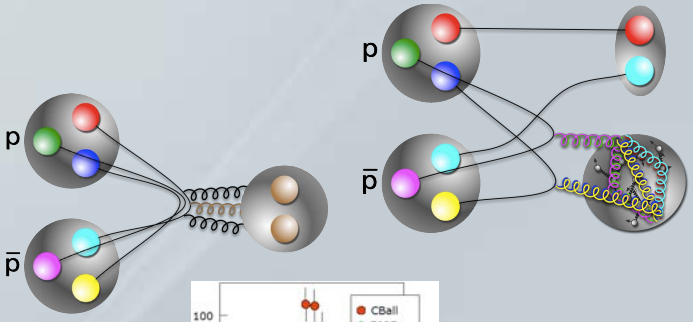


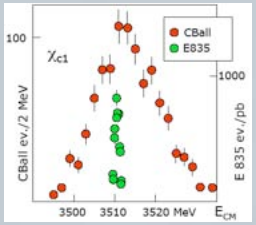


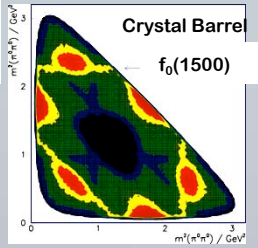


Experimental Requirements

- **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 p_p = 1.5 - 15 GeV/c







s-hyperon, c-meson, c-hyperon pairs

Hybrids | c-Hybrids

Glueballs

Charmonium

1 2 3 4 5 6 M [GeV/c²]

PANDA Detector Set-Up

Facility for Antiproton and Ion Research

- Nuclear structure and astrophysics
  - radioactive ion beams
- Hadron physics
  - antiproton beams
- Nuclear matter
  - relativistic nuclear collisions
- Atomic and applied physics
  - highly charged ions
  - low energy antiprotons
- Plasma physics
  - highly bunched beams

Facility for Antiproton and Ion Research

Primary Beams

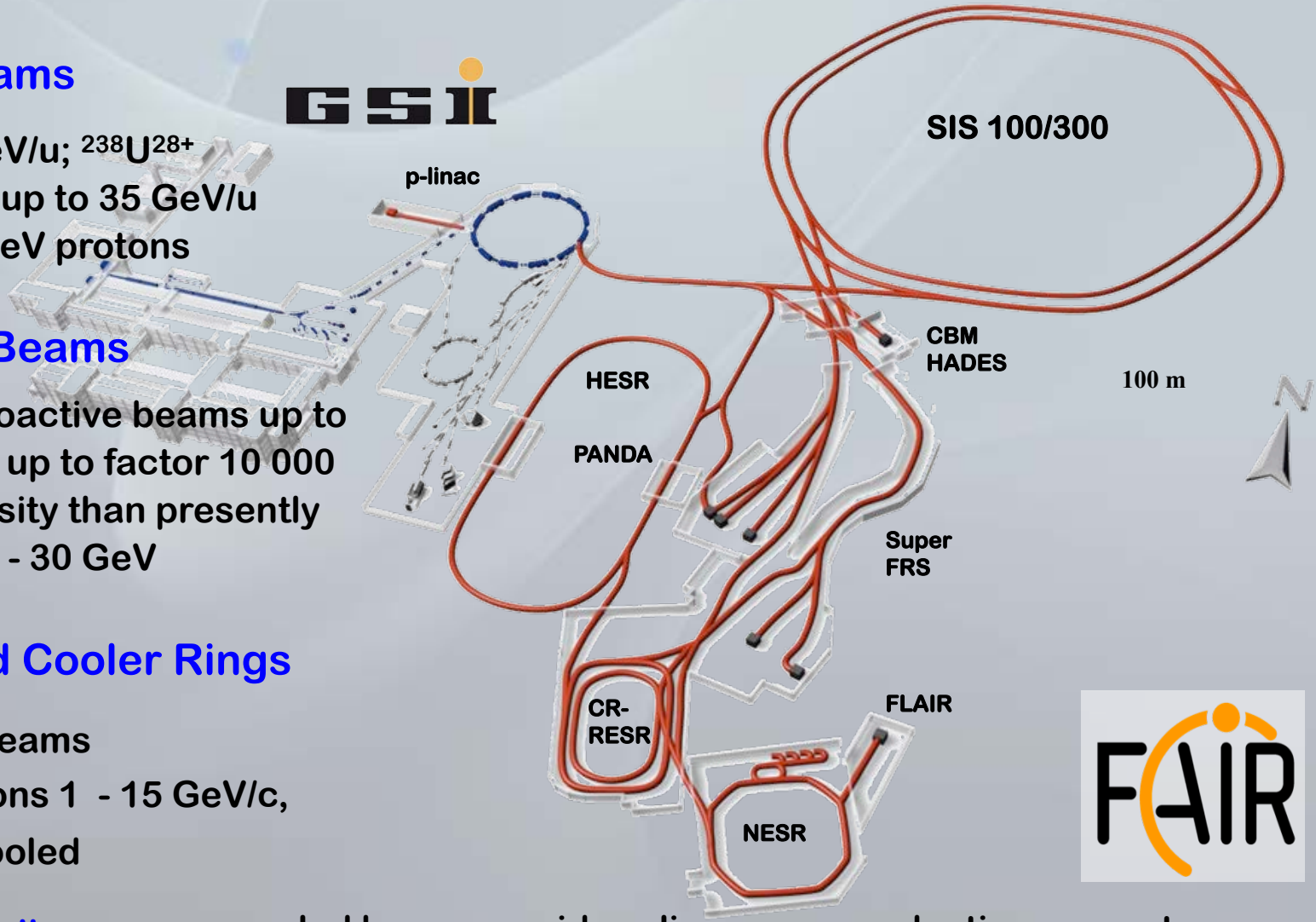
- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u
- 3x10^{13}/s 30 GeV protons

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

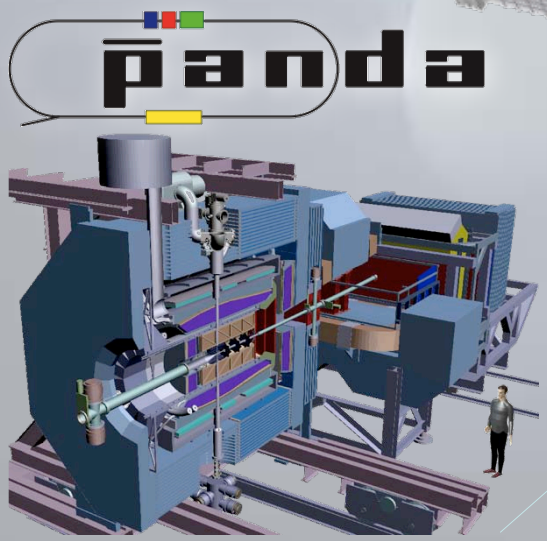


Technical Challenges

- cooled beams, rapid cycling superconducting magnets

PANDA at FAIR

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



PANDA Collaboration

More than 400 scientists of 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
Politechnico di Torino
U Piemonte Orientale,
Torino
U & INFN Trieste
U Tübingen
TSL Uppsala
U Uppsala
U Valencia
SMI Vienna
SINS Warsaw
TU Warsaw

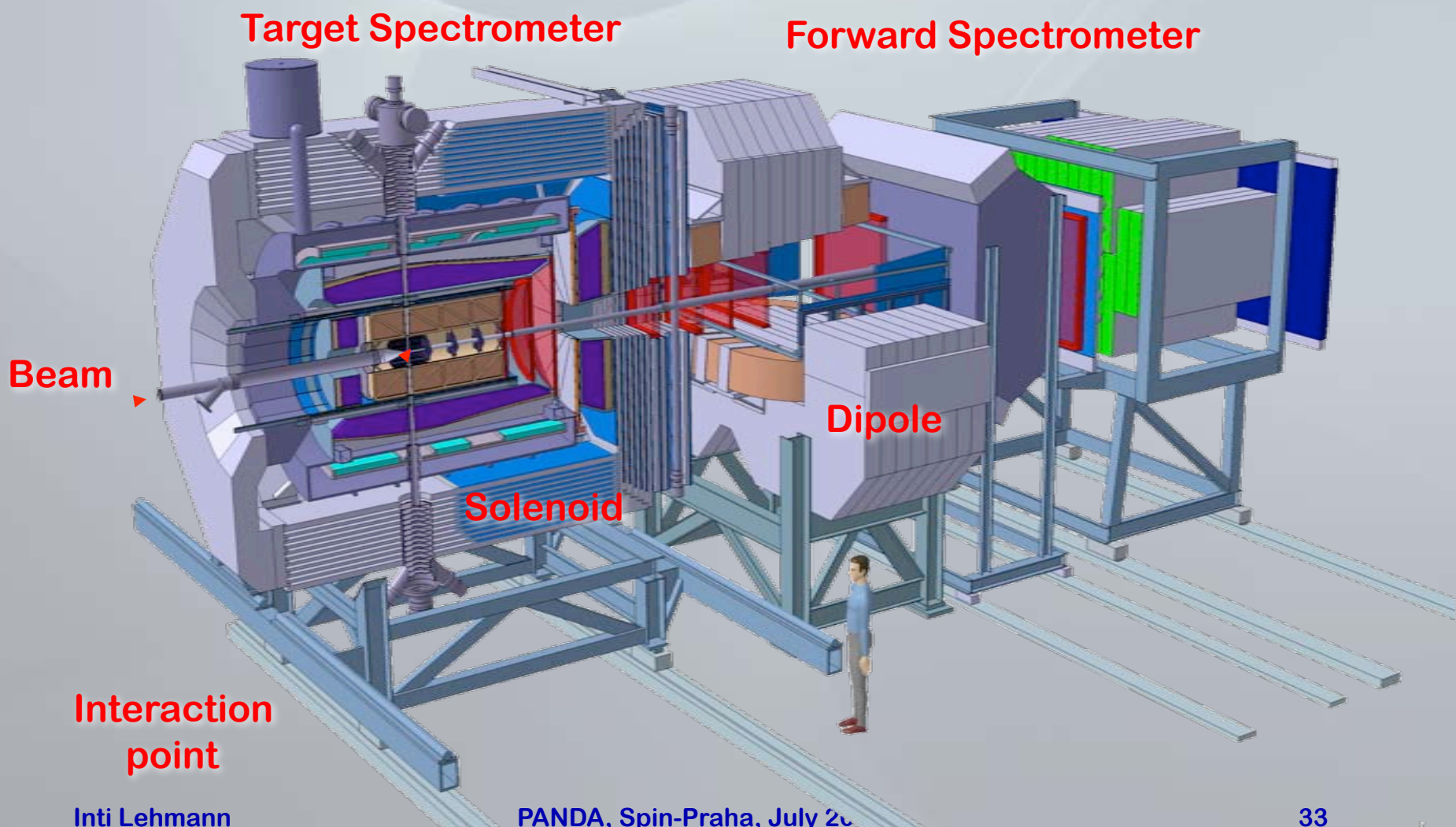






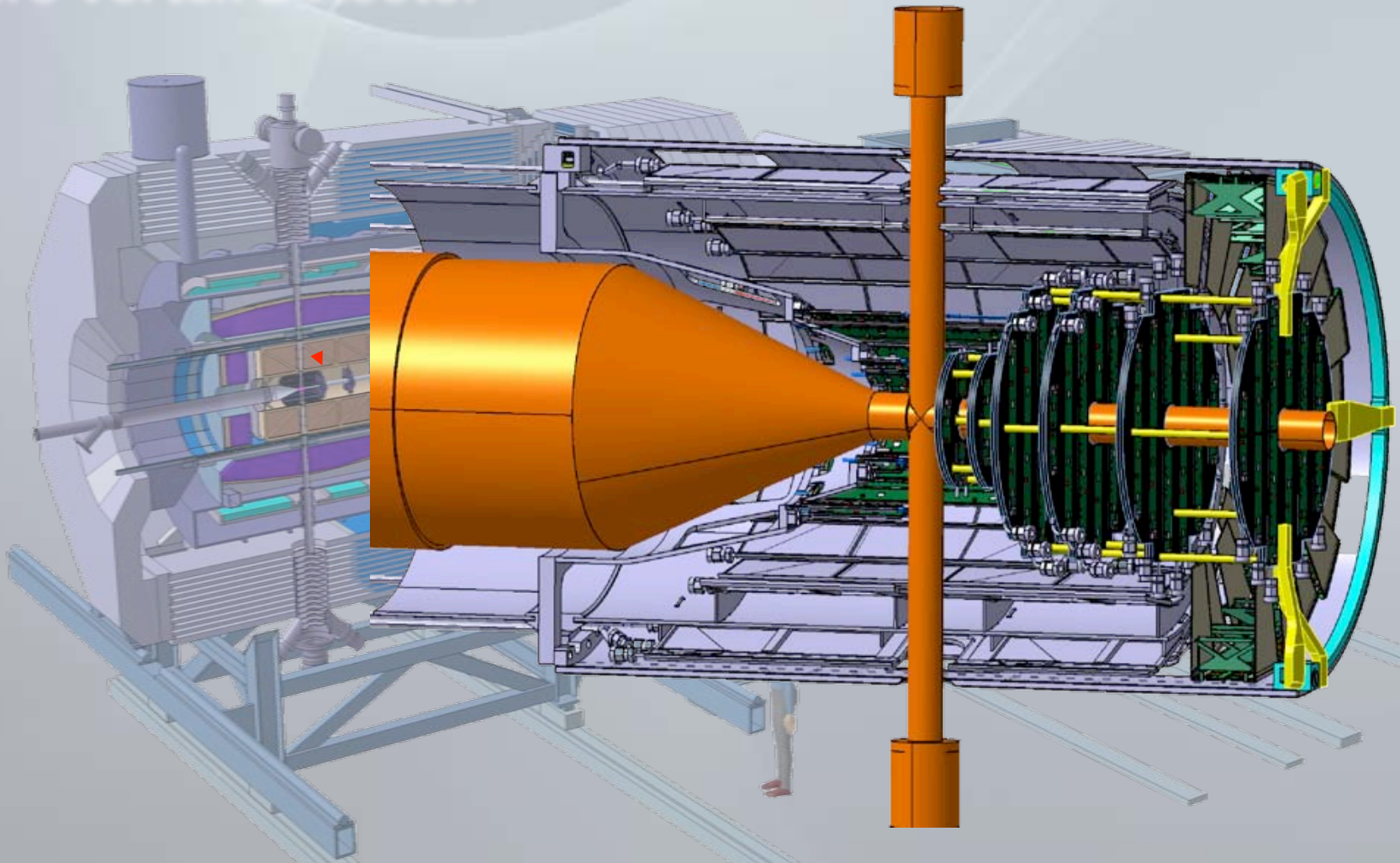

PANDA Experimental Set-Up

- Fixed target magnetic spectrometer experiment



PANDA Experimental Set-Up

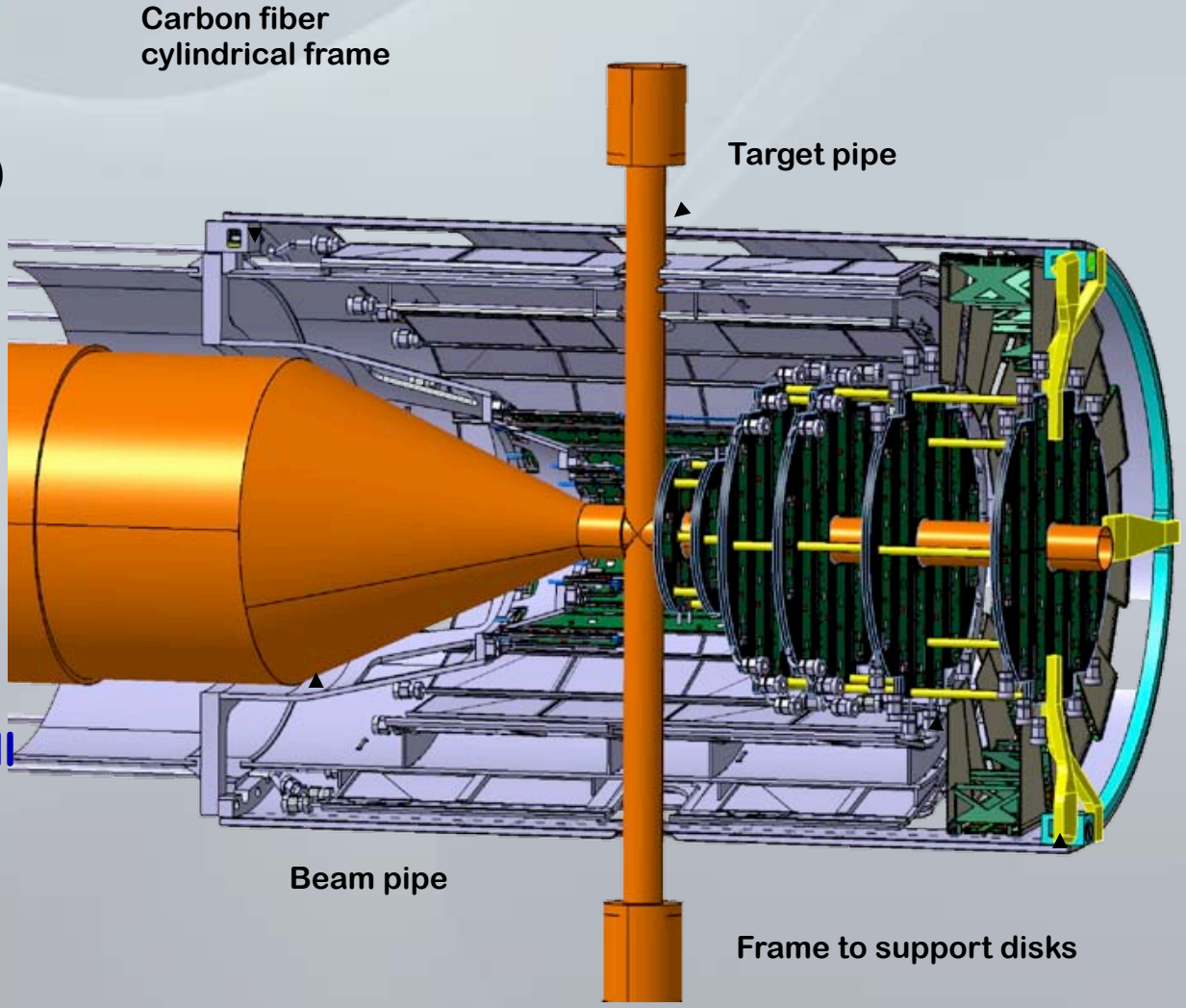
Micro Vertex Detector



Micro Vertex Detector

- 4 barrels and 6 disks
- Continuous readout
- Inner layers: hybrid pixels (100x100 μm^2)
- Outer layers: double sided strips

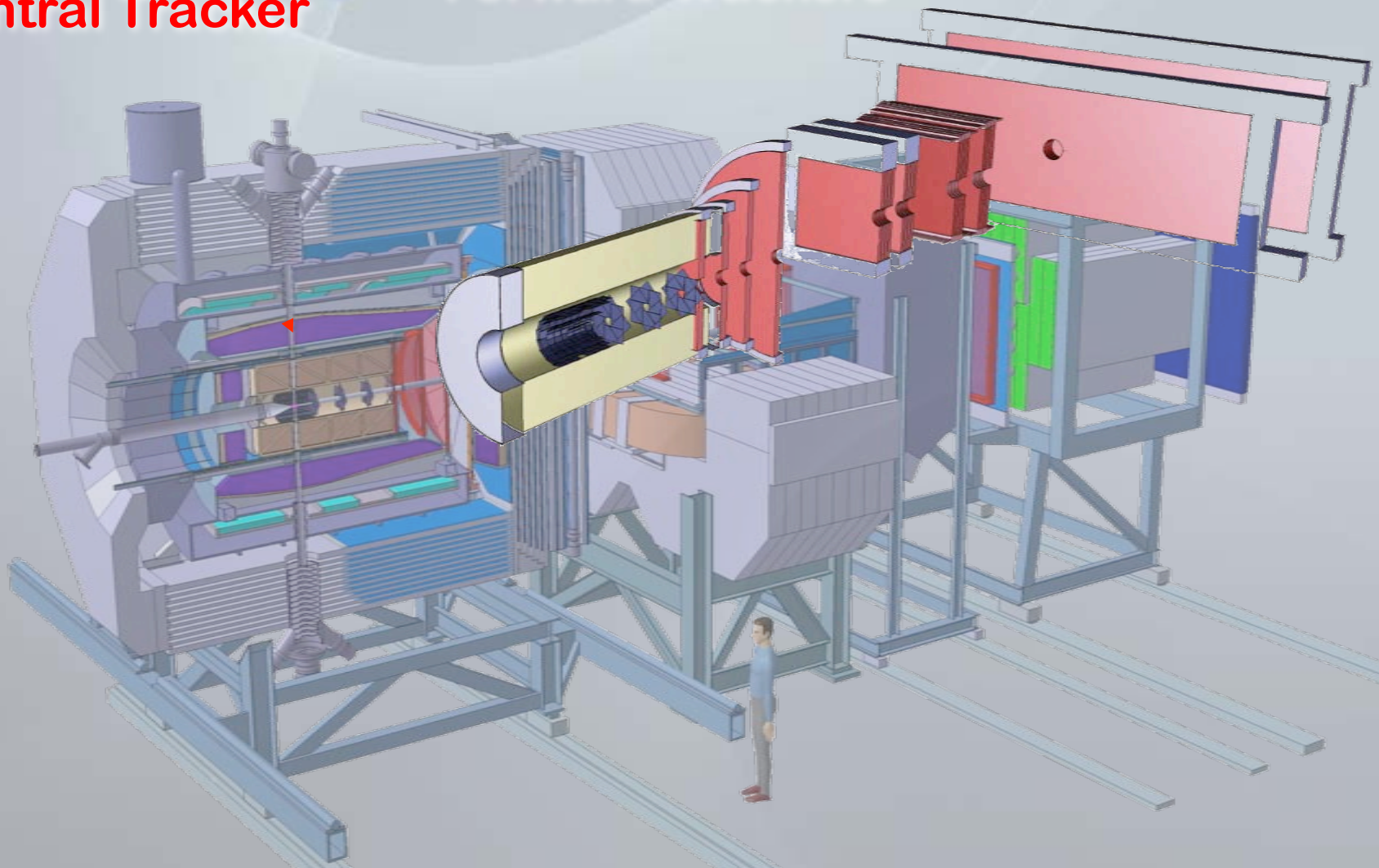
- Challenges
  - Low mass supports
  - Cooling in a small volume
  - Radiation tolerance



PANDA Experimental Set-Up

Central Tracker

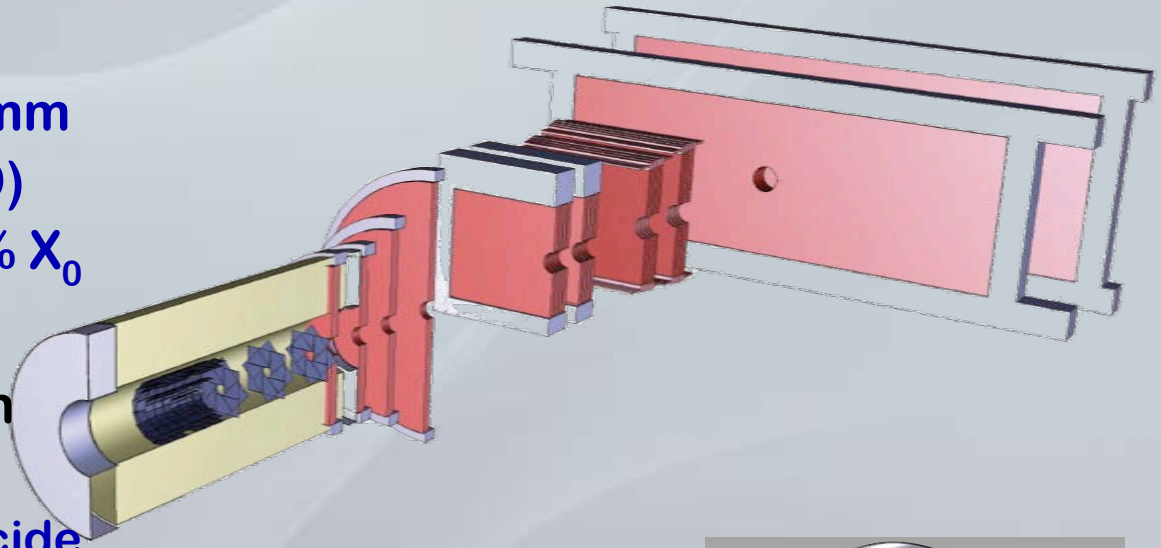
Forward Trackers



Tracking Detectors

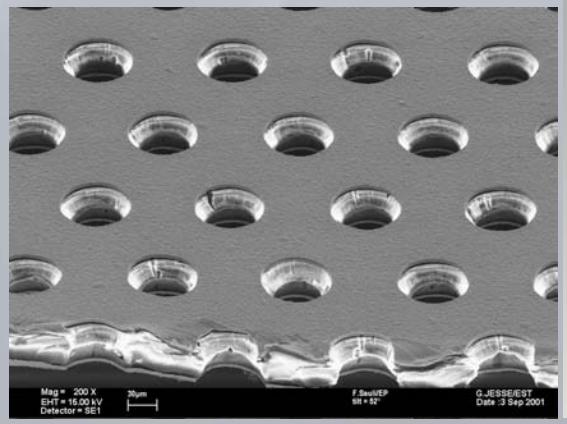
Central tracker

- Features:
  - $\sigma_{r\phi}$~150µm , σ_z~1mm
  - δ p/p~1% (with MVD)
  - Material budget ~1% X_0
- Straw Tube Tracker
- GEM Time Projection Chamber
  - ➔ Prototype tests decide the choice



Forward GEM Tracker

- Large area GEM foils
- Ultra thin coating



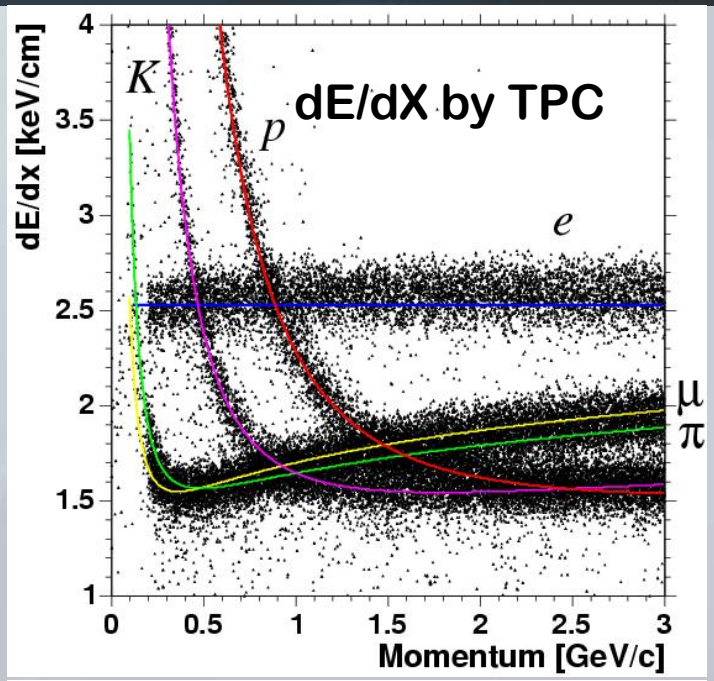
Particle Identification

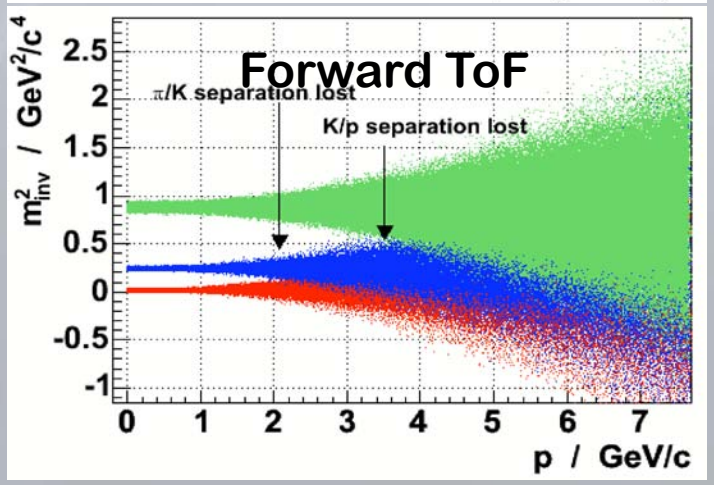
PANDA PID Requirements:

- 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)



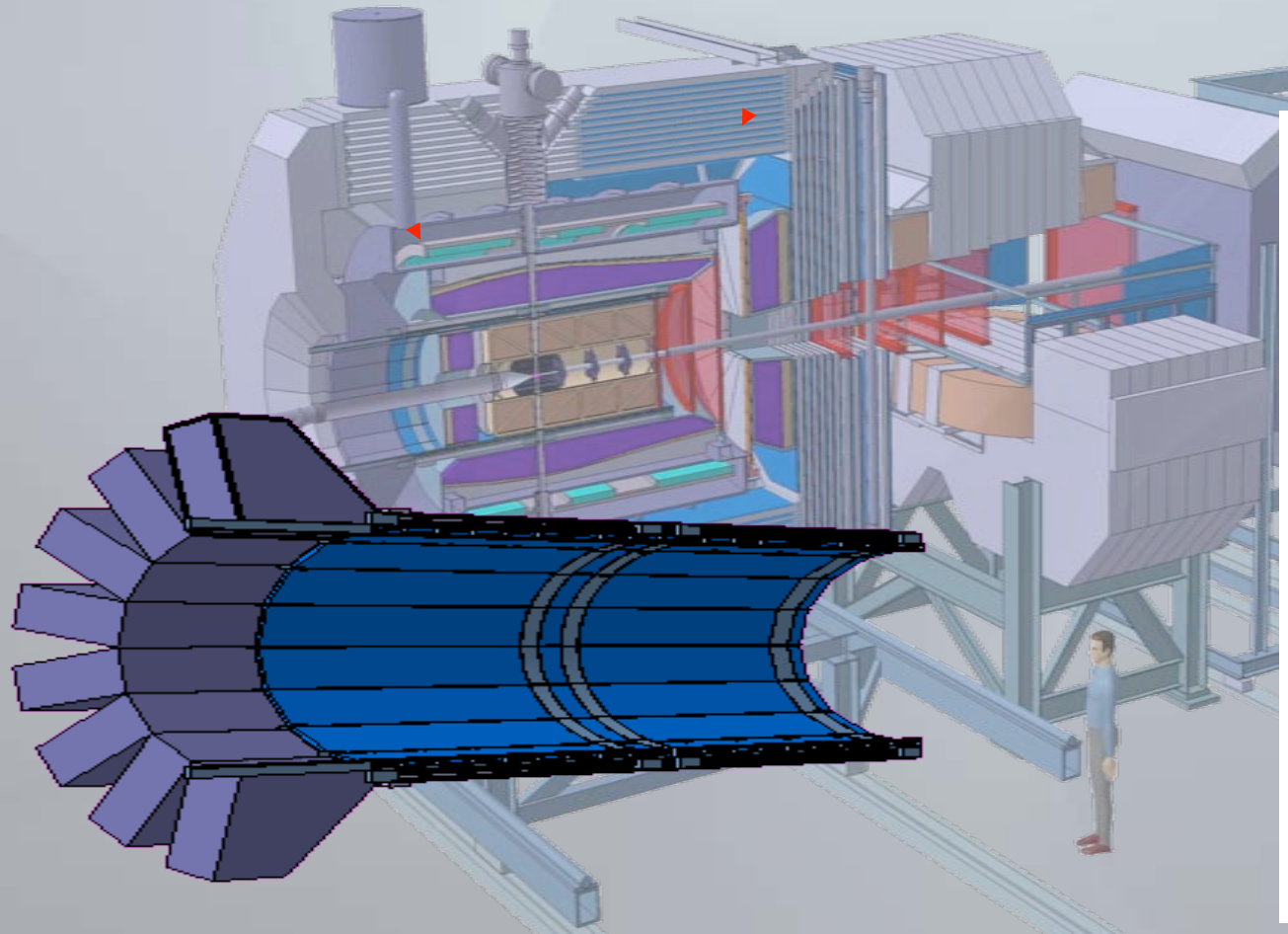


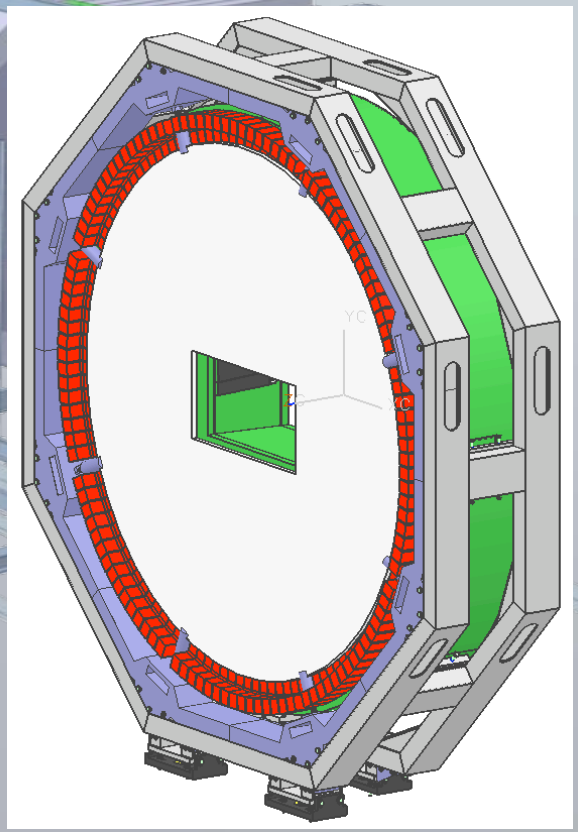
PANDA Experimental Set-Up

Barrel DIRC

Disc DIRC

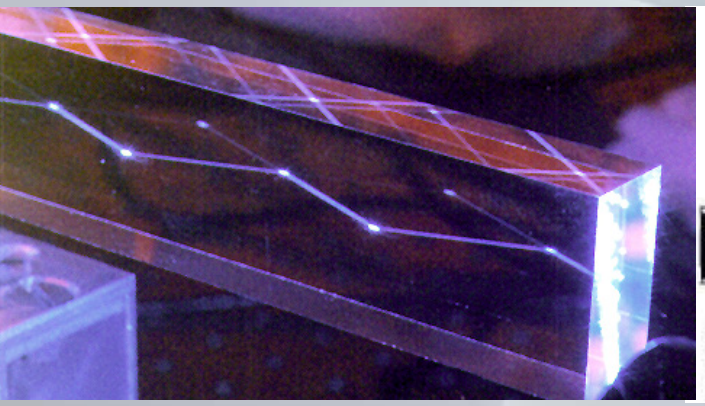
RICH

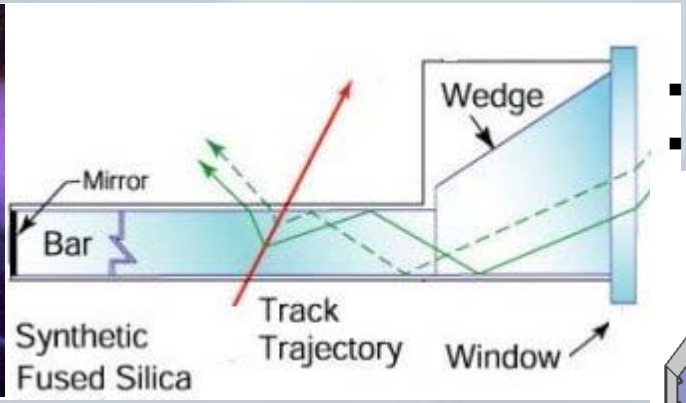




PANDA Cerenkov Detectors

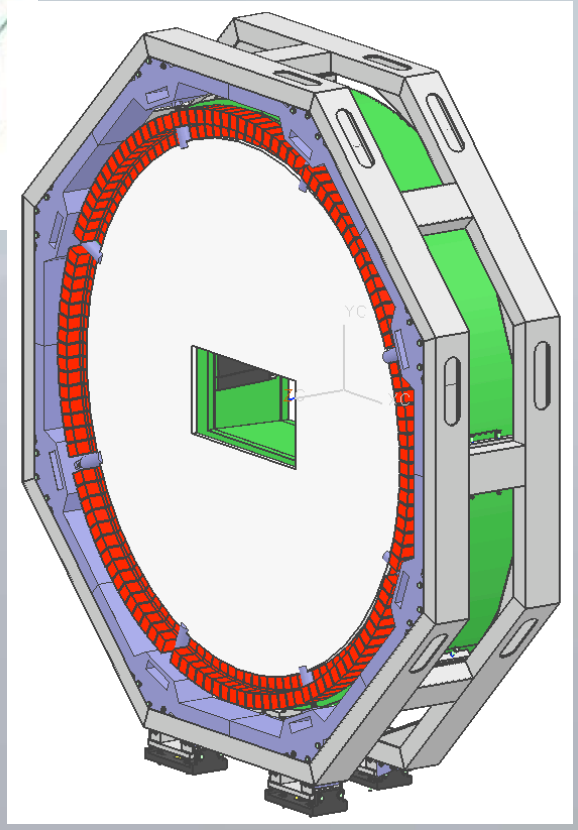
DIRC: Detection of Internally Reflected Cherenkov light



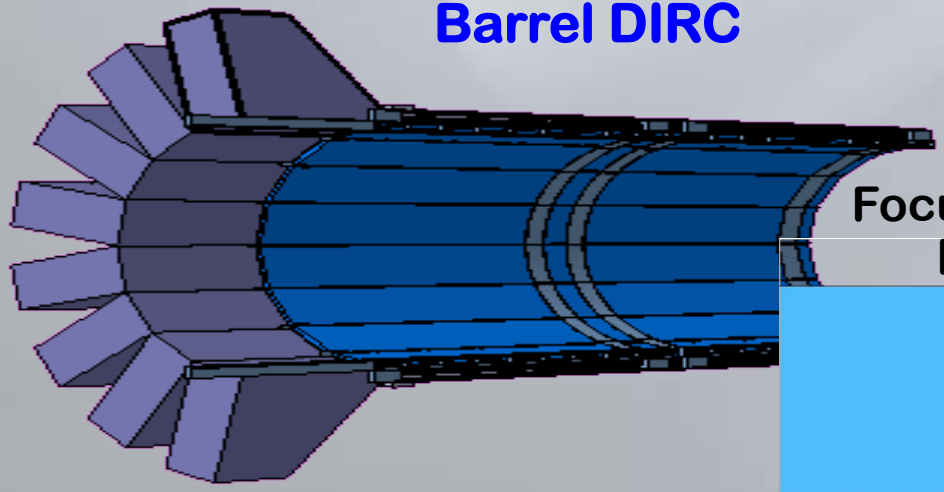


Disc DIRC

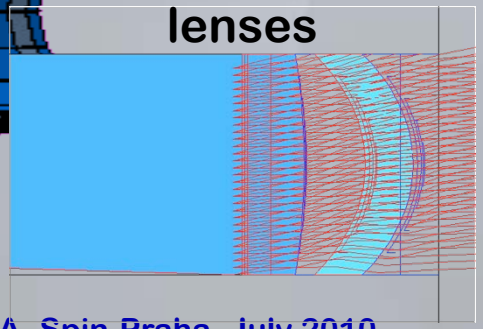
- Disc shaped radiator
- Readout at rim



Barrel DIRC



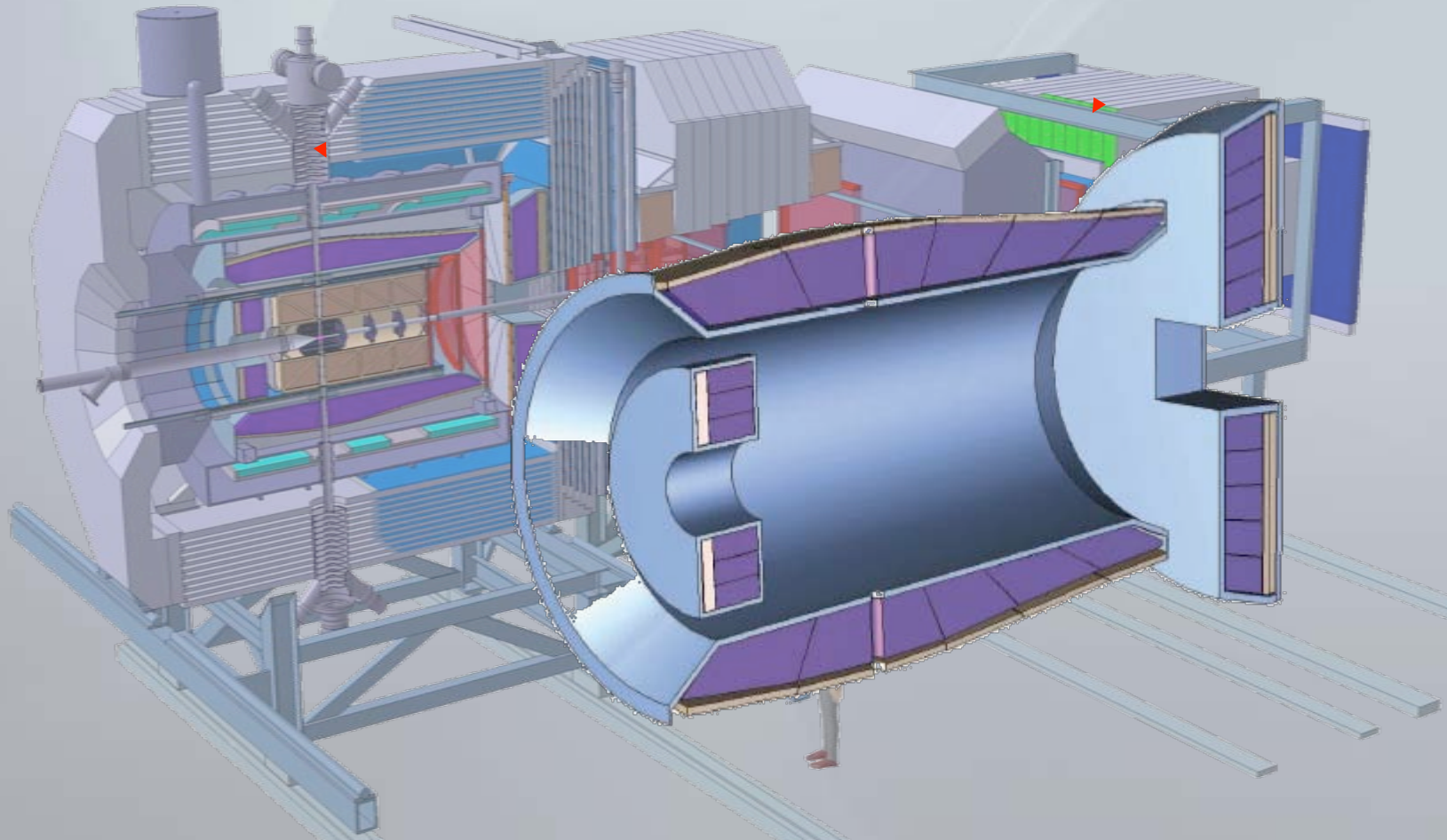
Focusing with lenses



PANDA Experimental Set-Up

Central Electro Magnetic Calorimeters (EMC)

Forward EMC



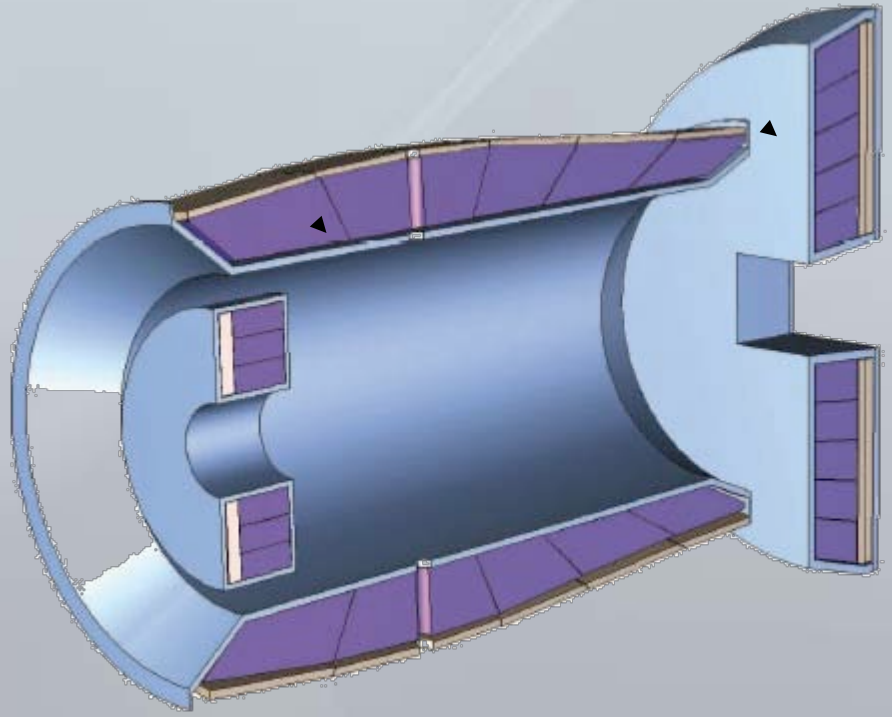
Electromagnetic Calorimeters

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, 2x1cm^2
- $\sigma(E)/E \sim 1.5\%/\sqrt{E}$ + const.

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

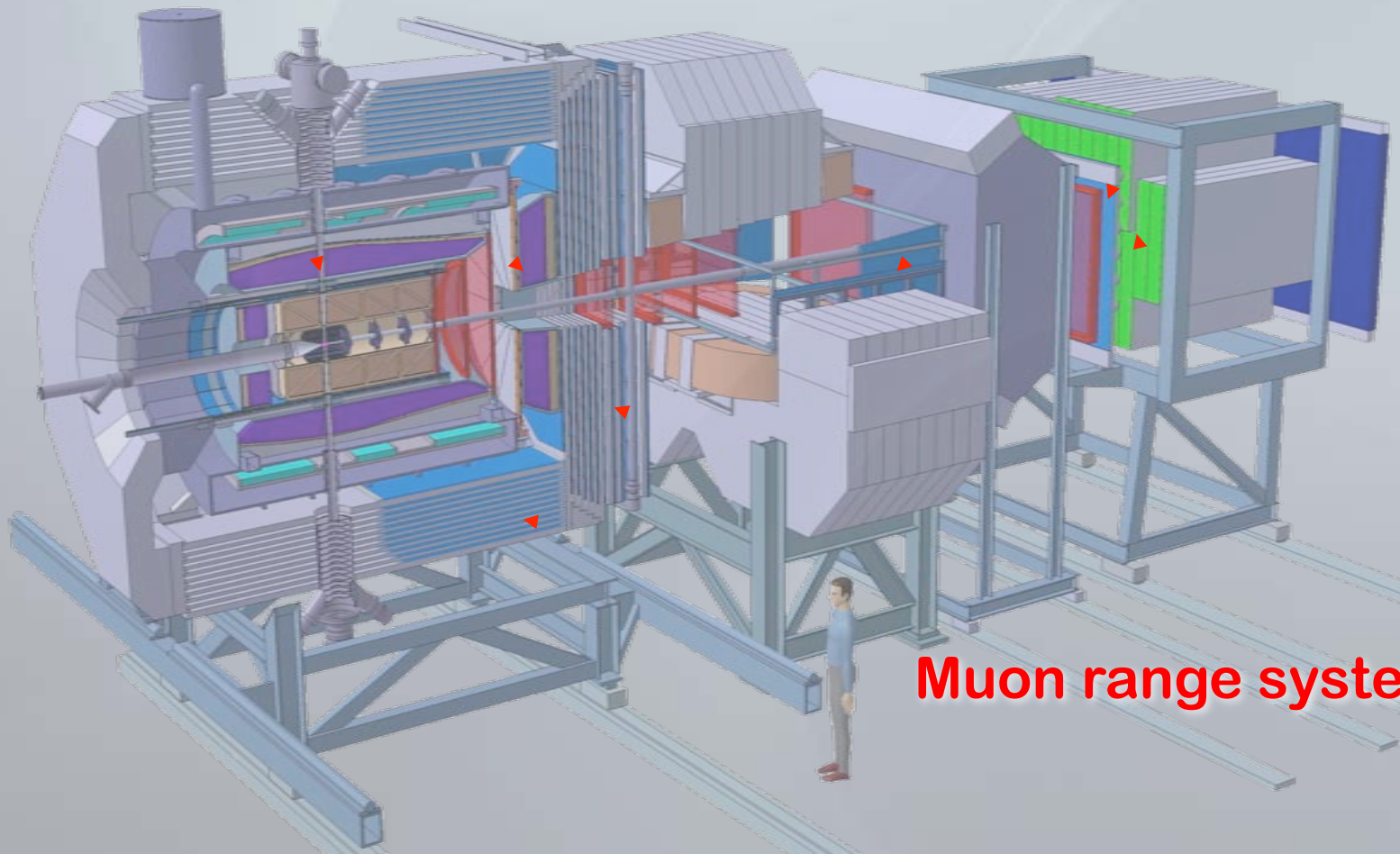


Backward Endcap,
560 PWO crystals

PANDA Experimental Set-Up

Central Time of Flight (ToF) detectors

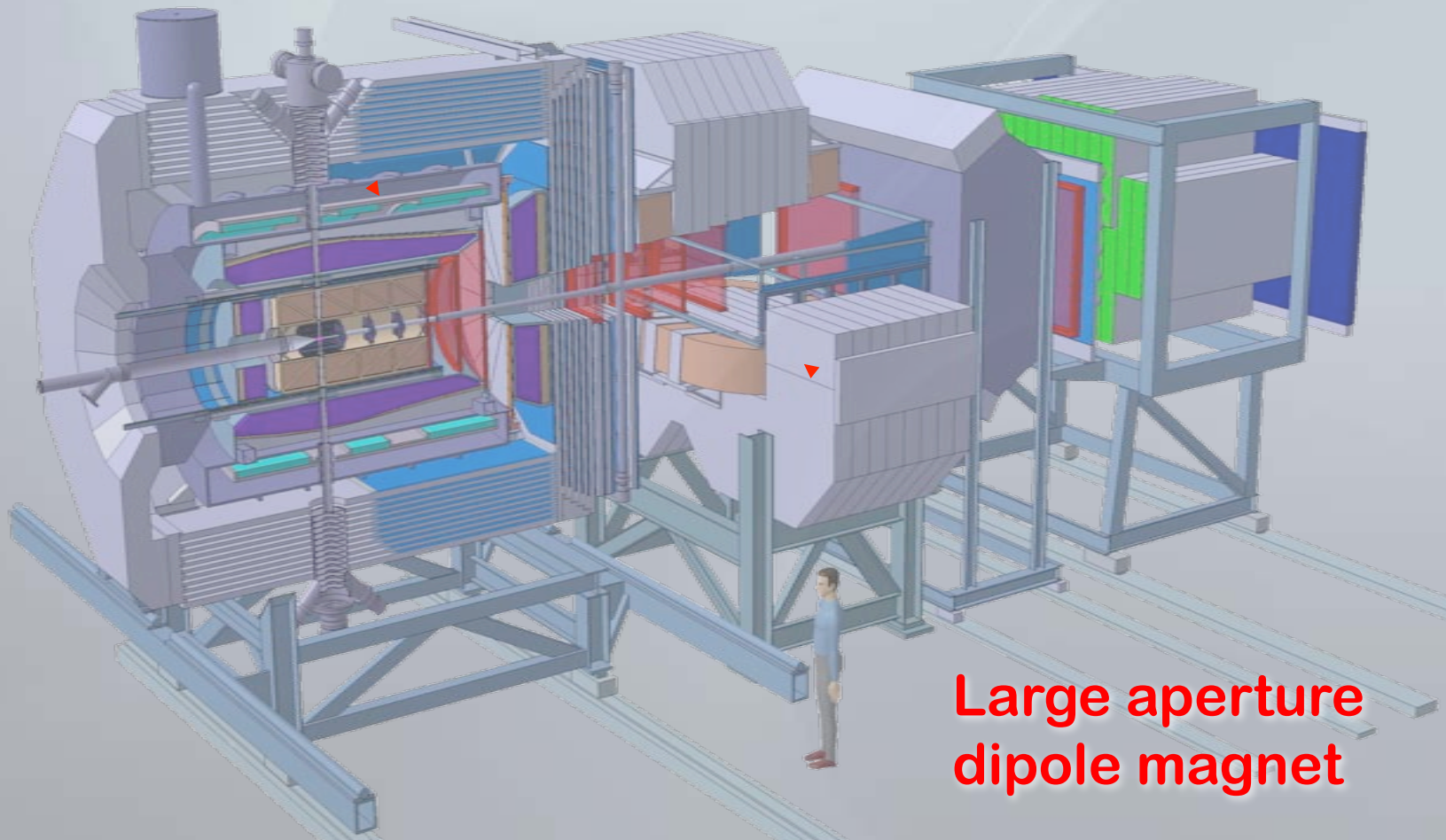
Forward ToF walls



Muon range systems

PANDA Experimental Set-Up

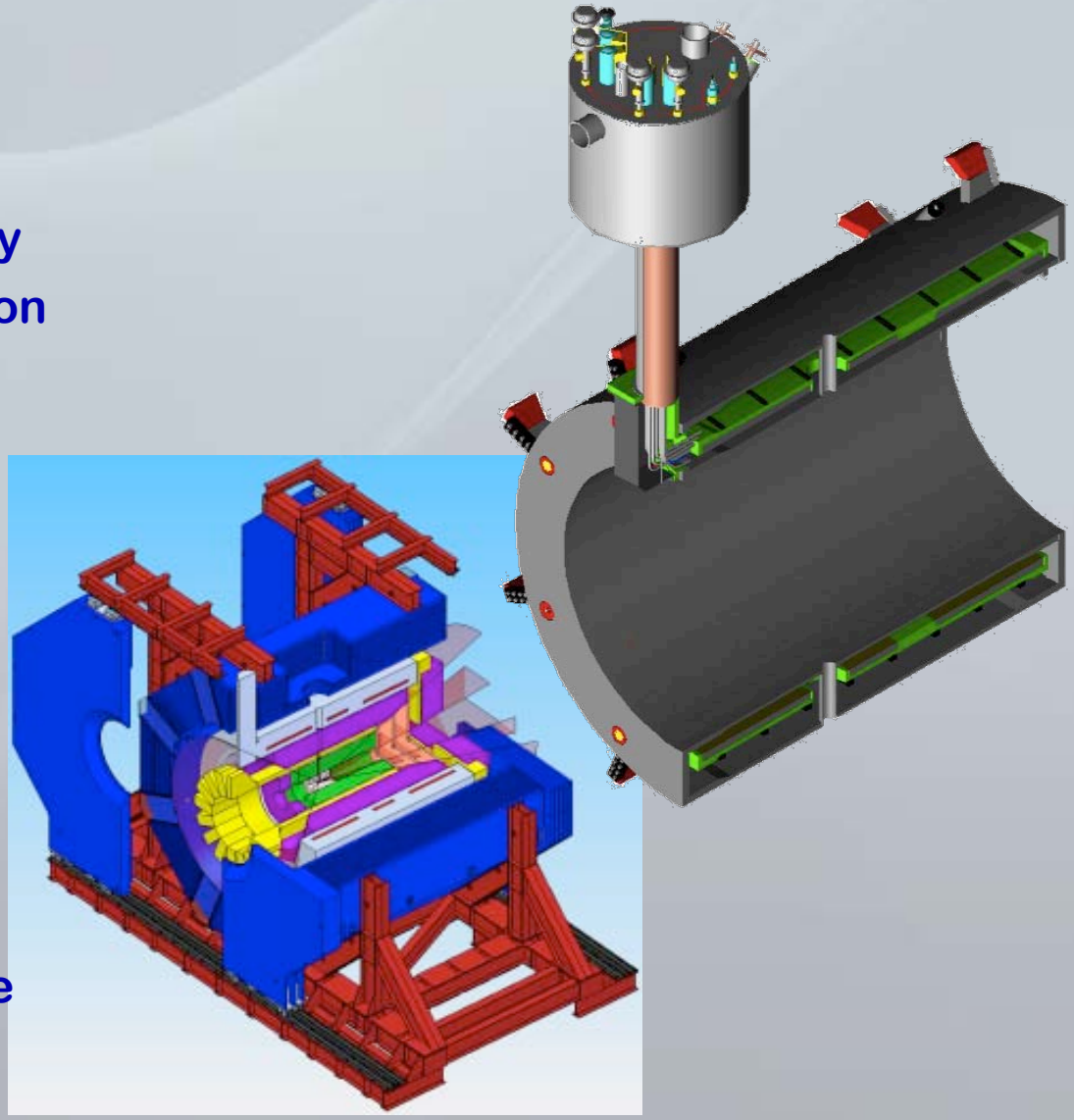
Superconducting solenoid magnet



Large aperture dipole magnet

Superconducting Solenoid

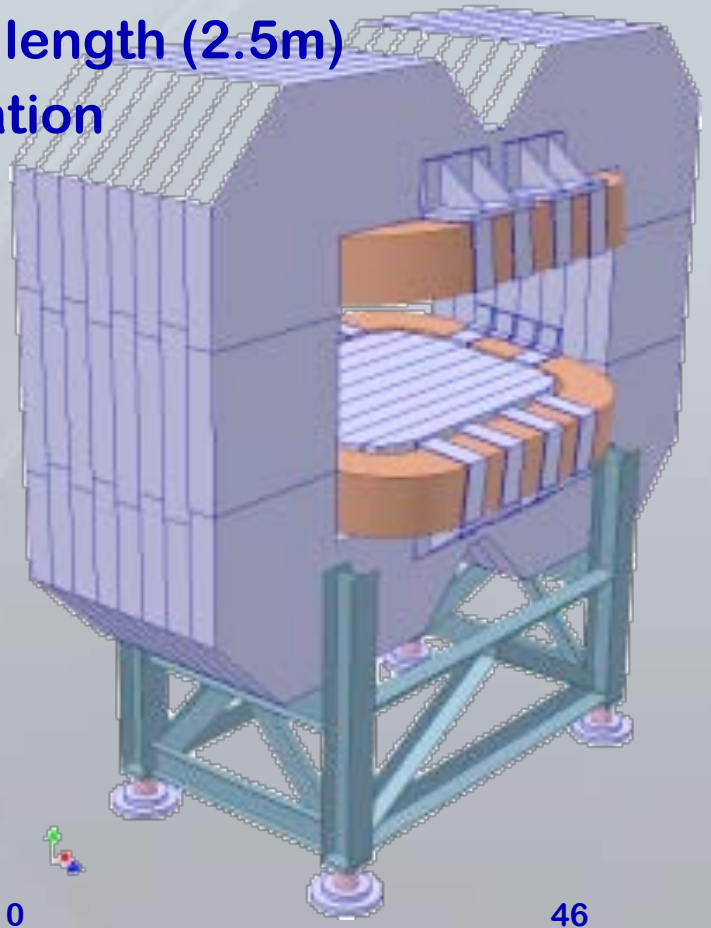
- Features
  - 2T field
  - 4m x 1.9m free space
  - High field homogeneity
  - Target pipe intersection
  - Access on both sides
  - Movement by 20m
  - Muon range system
- Design
  - Asymmetric split coil
  - Internally wound
  - Indirect cooling
  - Opening doors
  - Retractable platform
  - Laminated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



Large Aperture Dipole

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

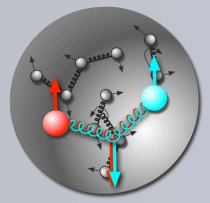
Field integral	2 Tm
Bending variation	≤ ±15%
Vertical Acceptance	±5°
Horizontal Acceptance	±10°
Ramp speed	1.25%/s
Total dissipated power	360 kW
Total Inductance	0.87 H
Stored energy	2.03 MJ
Weight	220 t
Dimensions (H × W × L)	3.88 × 5.3 × 2.5 m^3
Gap opening (H × W)	0.80 – 1.01 × 3.10 m^2



Highlights at PANDA

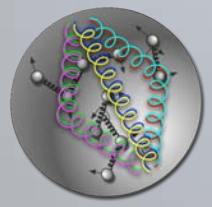
Expected Highlights

- Charmed hybrids

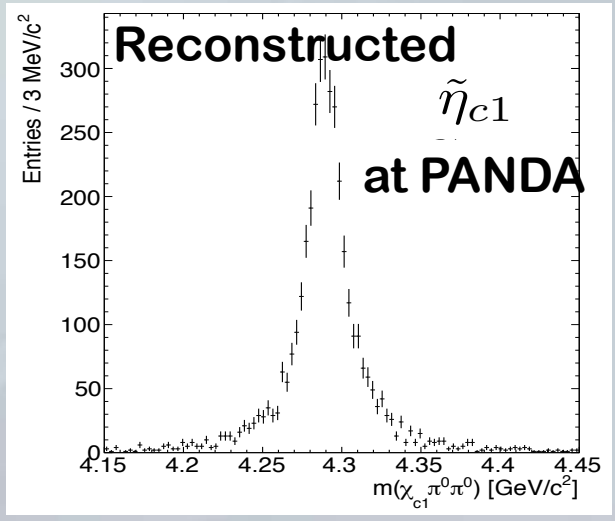


  - Narrow states expected
  - Exotic quantum numbers - no mixing
  - Around 4 GeV/c^2

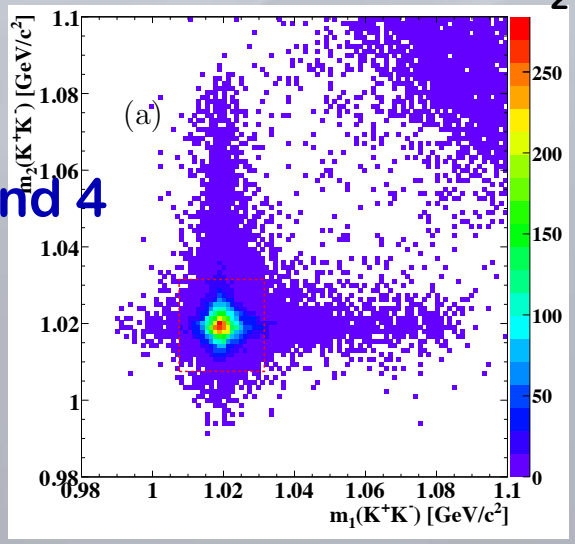
- Glueballs above 3 GeV/c^2

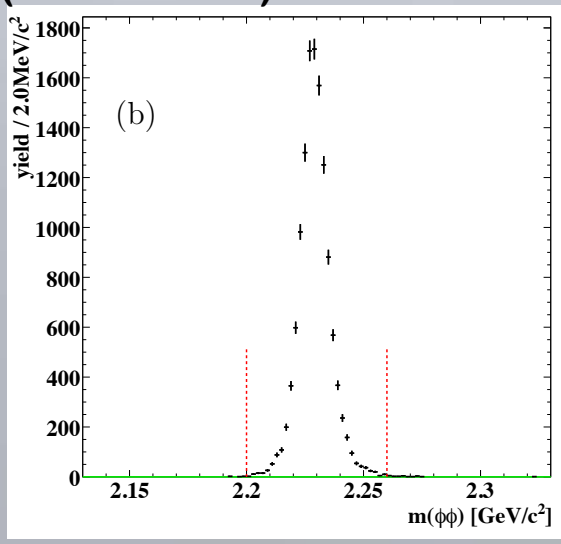


  - Few mesonic states
  - Smaller width than low states
  - Less mixing
  - Exotic states around 4 GeV/c^2



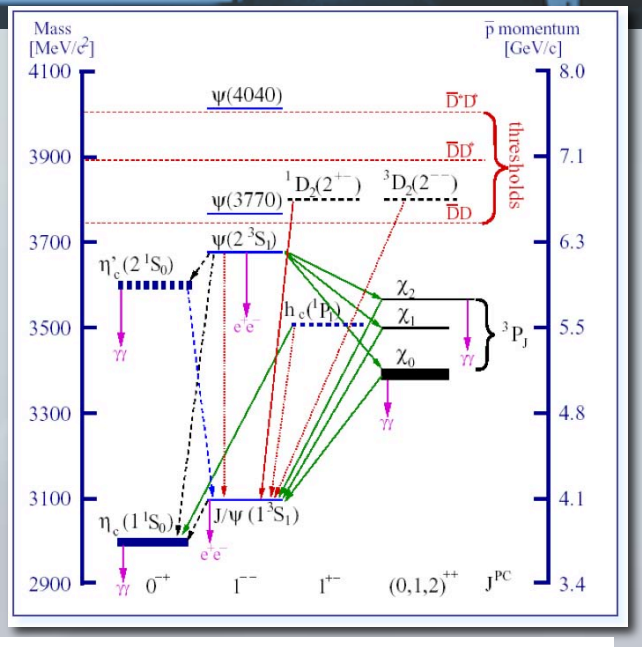
Reconstructed $f_2(2000\text{-}2500)$ at PANDA

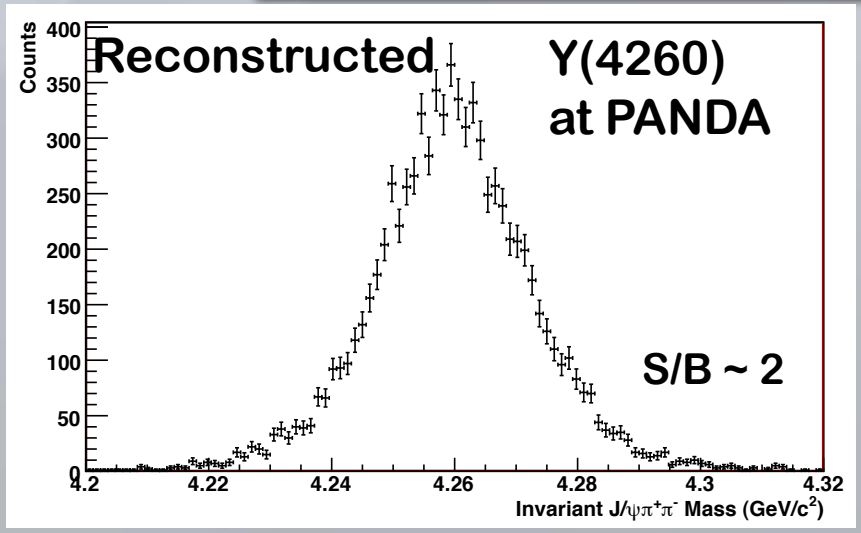




Expected Highlights

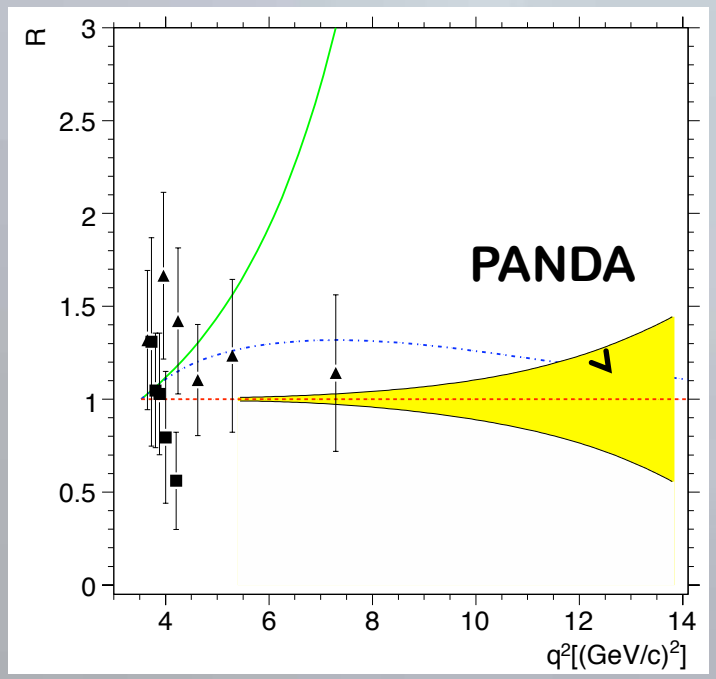
- Charmonium States
  - Positronium of QCD
  - Narrow states
  - Transition region
    - light - heavy quark
  - PANDA
    - high statistics data
    - direct production
    - precise resonance scans (10^{-5})
    - channels not coupling to J/ψ and ψ'



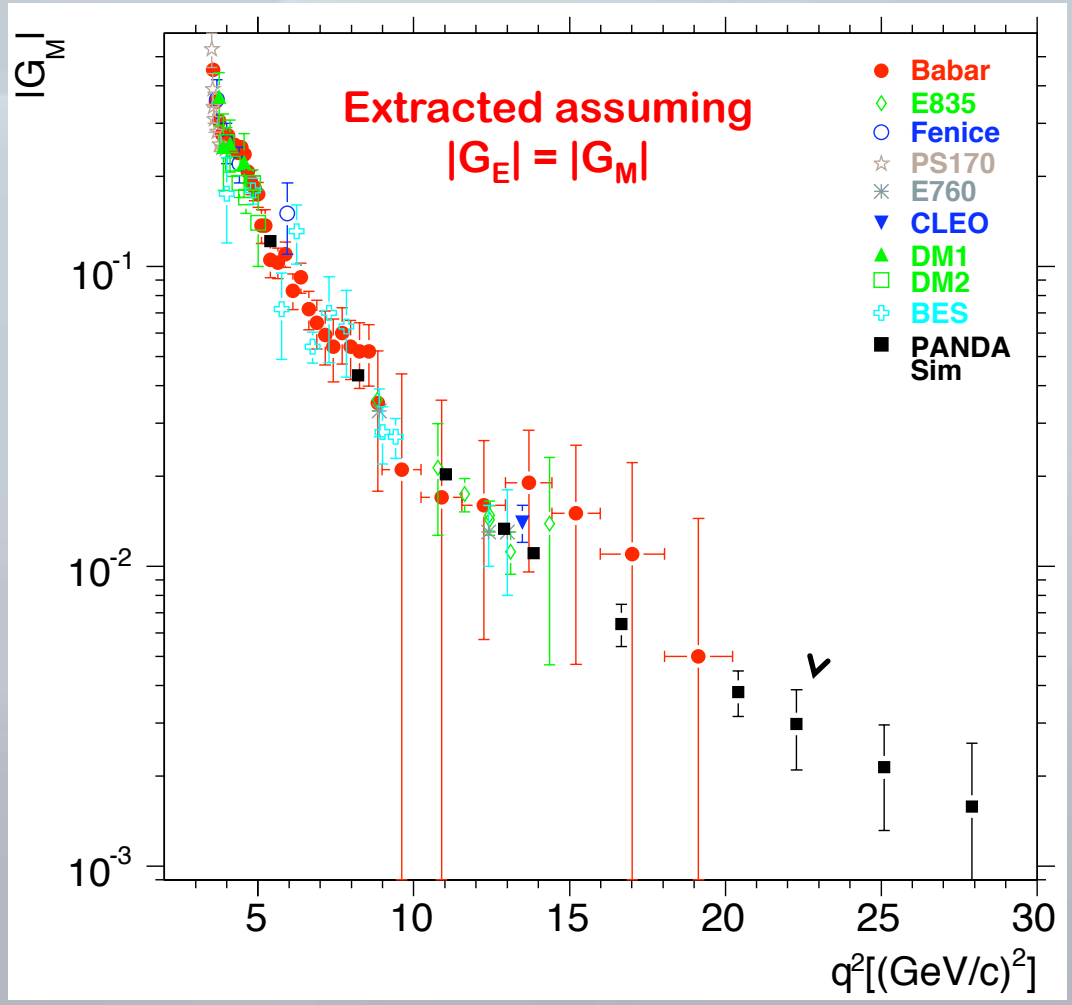


Expected Highlights

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



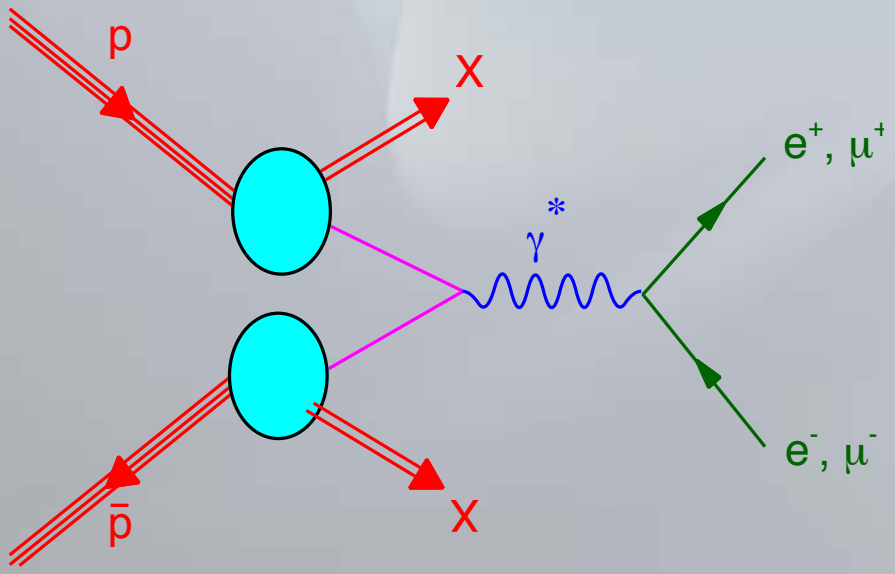
  - absolute value of $|G_M|$ up to 30(GeV/c)^2

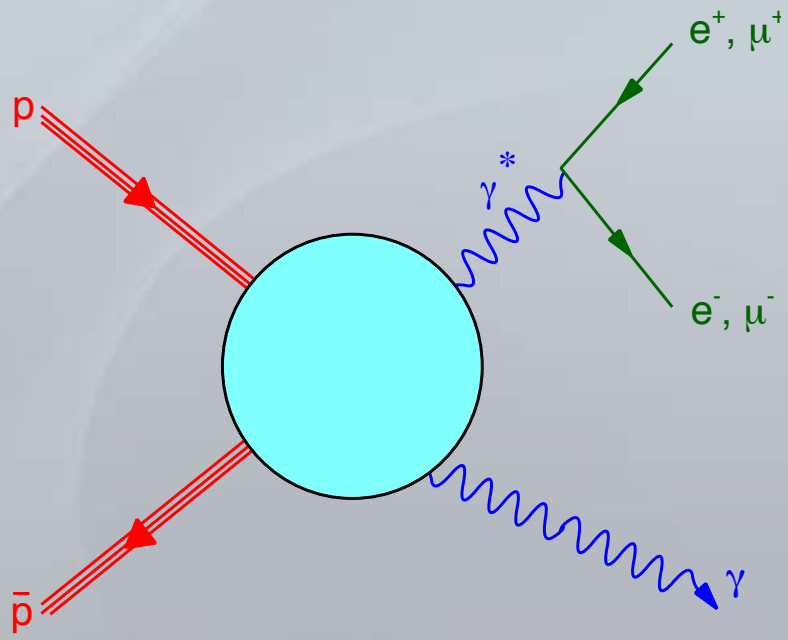


PANDA Physics Performance Report: arXiv:0903.3905

Expected Highlights

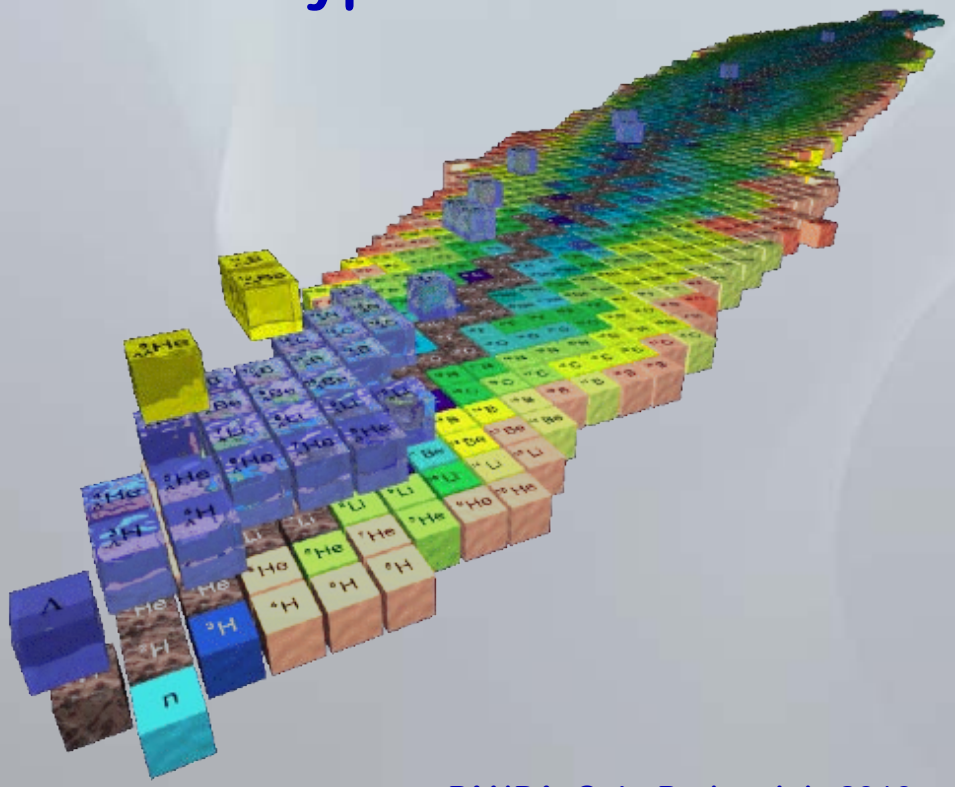
- Nucleon Structure
  - Drell-Yan Processes
- Time like equivalents of Generalised Parton Distributions (GPDs)





Expected Highlights

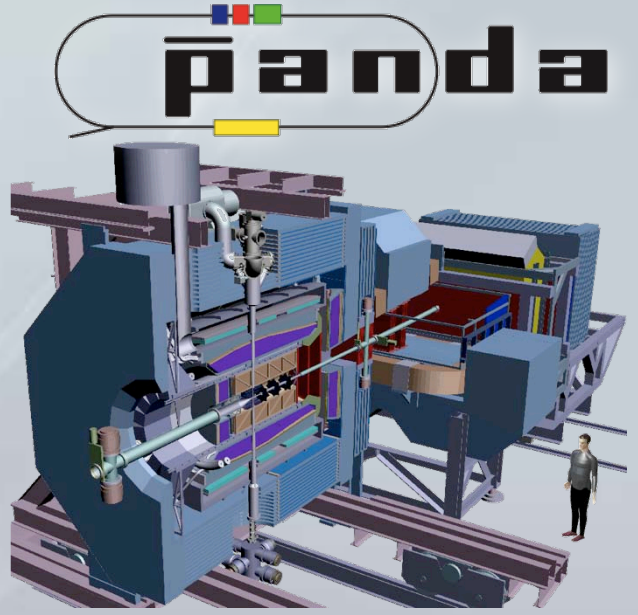
- In medium mass modifications
  - extension to the charm sector
- Extension of nuclear chart
  - double hypernuclei



A. Hayashigaki, PLB 487 (2000) 96

Conclusions

- Strong QCD is far from understood
  - Existence of exotic hadrons
  - Surprises in charmonium spectrum
  - Nucleon structure
- Experimentally ideal: PANDA
  - proton-antiproton annihilations
  - fixed target experiment $\sqrt{s}$ = 2-5GeV
  - 4π + forward magn. spectrometers
- Highlights at PANDA
  - High potential to clarify (non-)existence of exotics
  - Details and nature of (additional) charmonium states
  - Time-like nucleon structure (form factors, GPDs..)
  - Nucleon-nucleon interaction (in-medium, hypernuclei..)
  - And much more... ...www-panda.gsi.de



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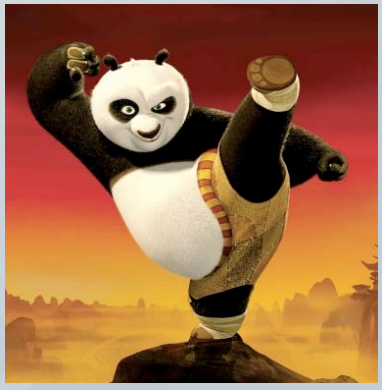
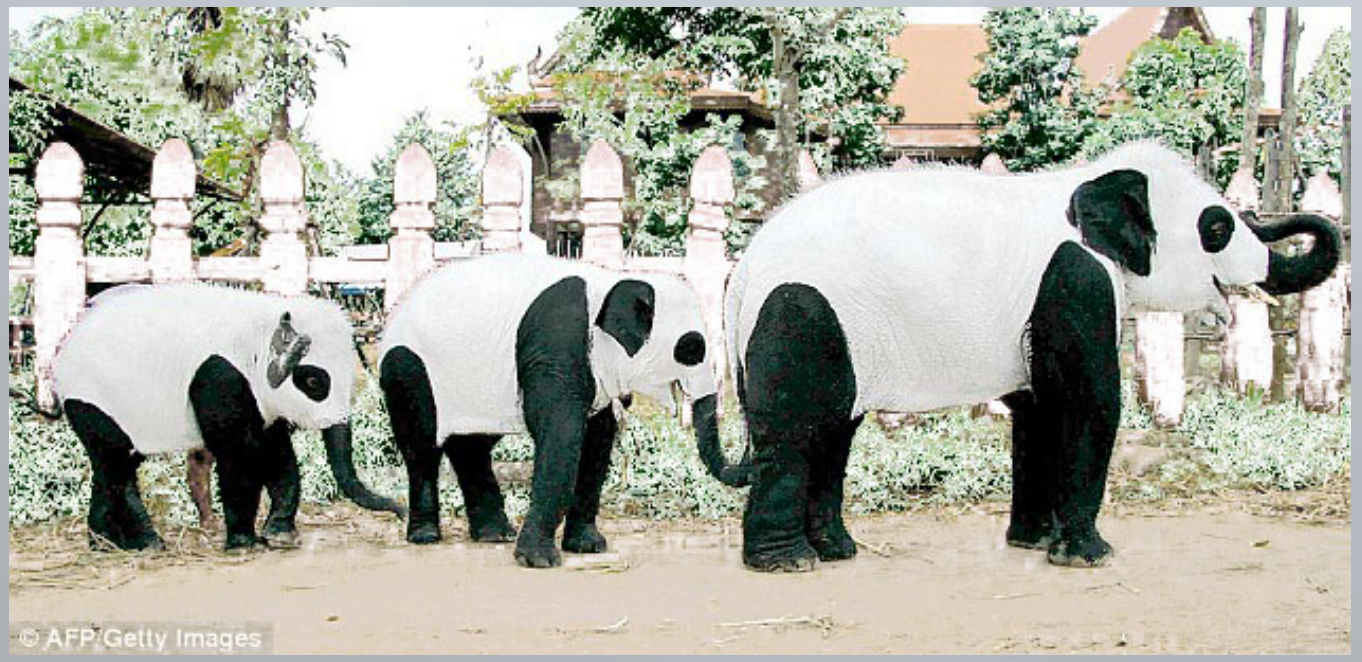


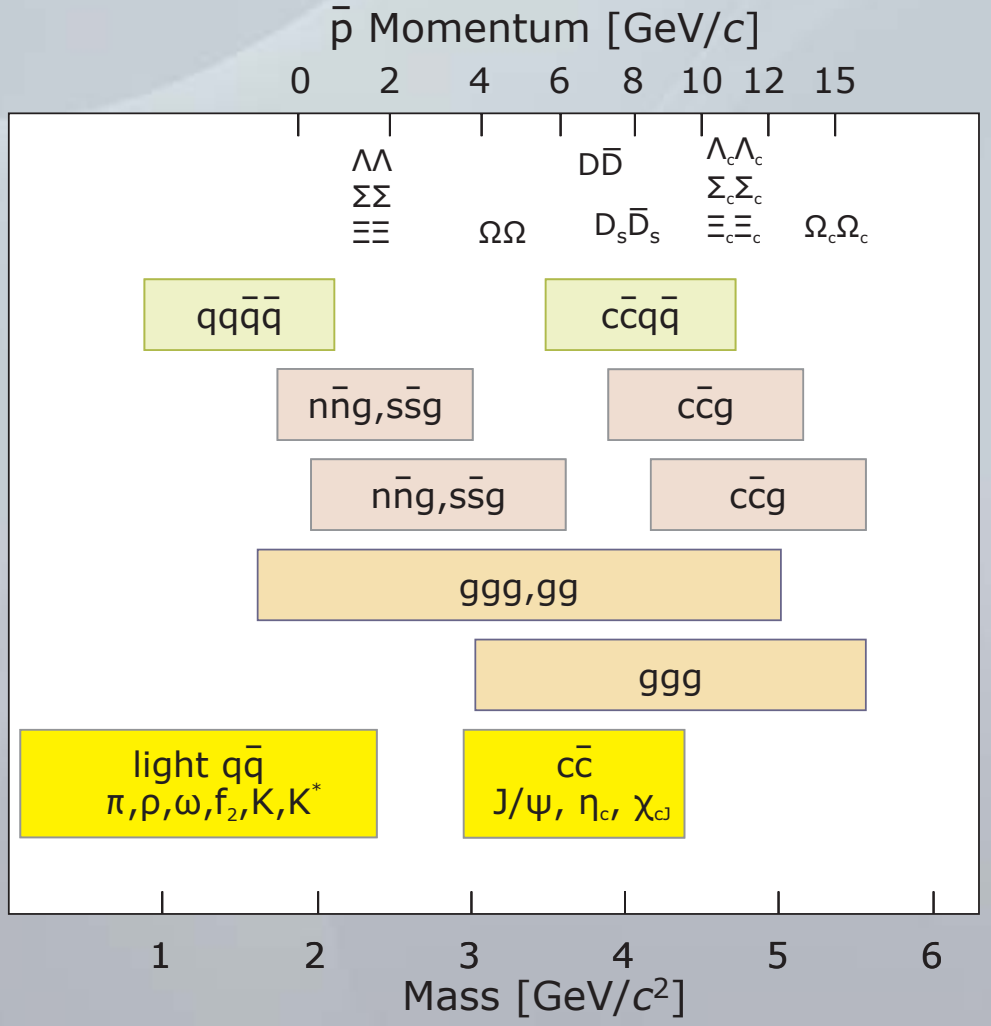


Cannot wait...

Backup

Backup

- **PANDA range**



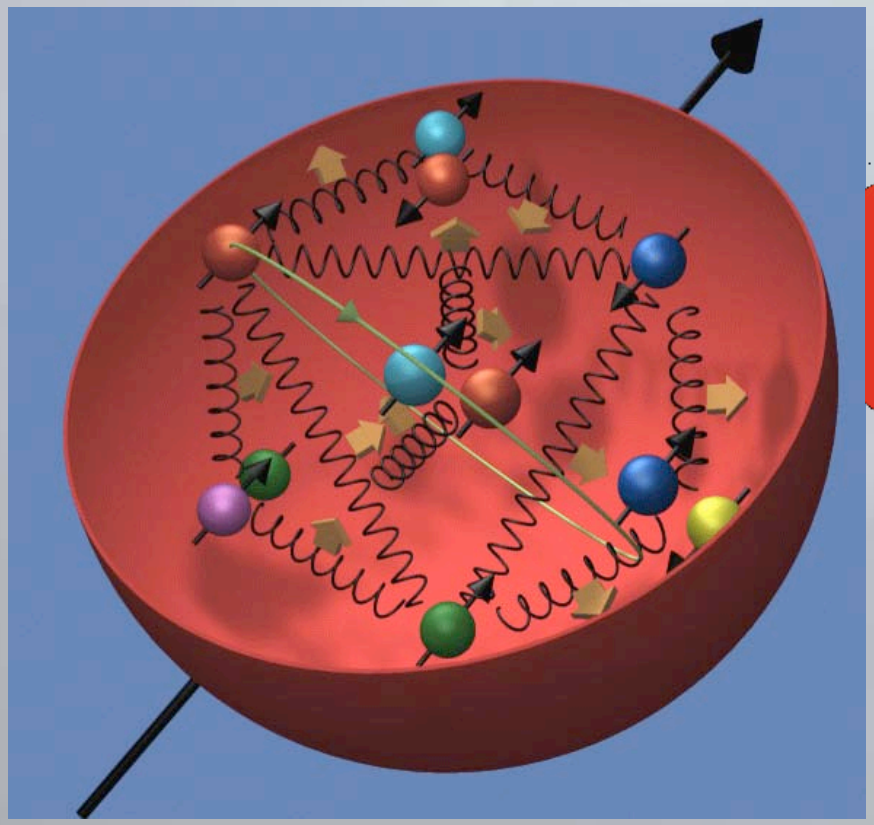
Spin-exotic Summary (Light Quarks)

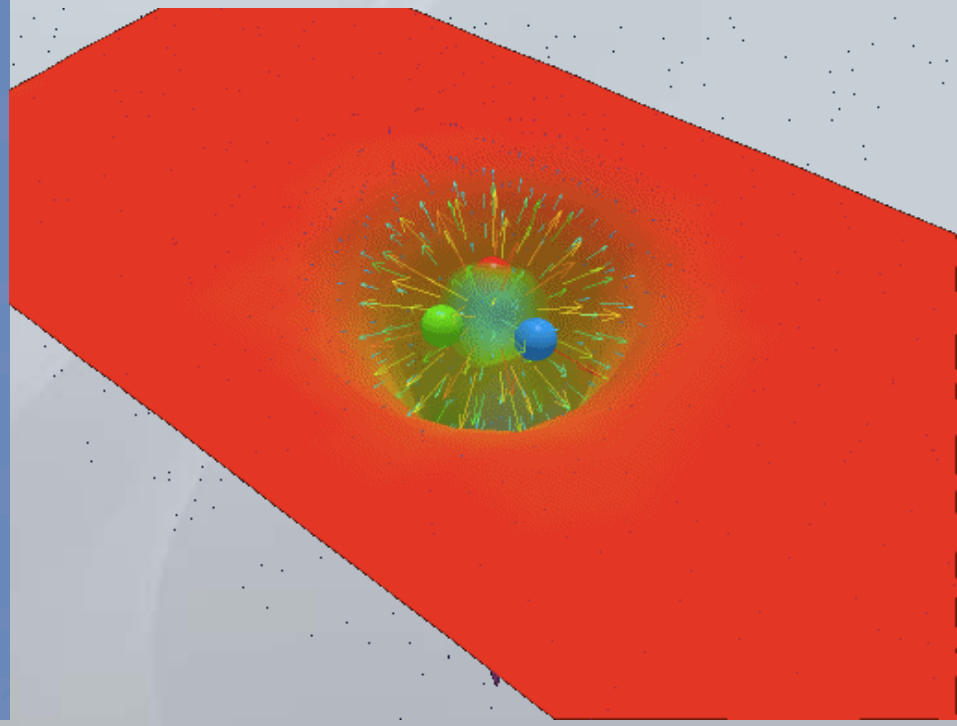
thanks to G. Adams, RPI

	Experiment	Mass	Width	Decay	Citation
$\pi_1(1400)$	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
$\pi_1(1600)$	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
$\pi_1(2000)$	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

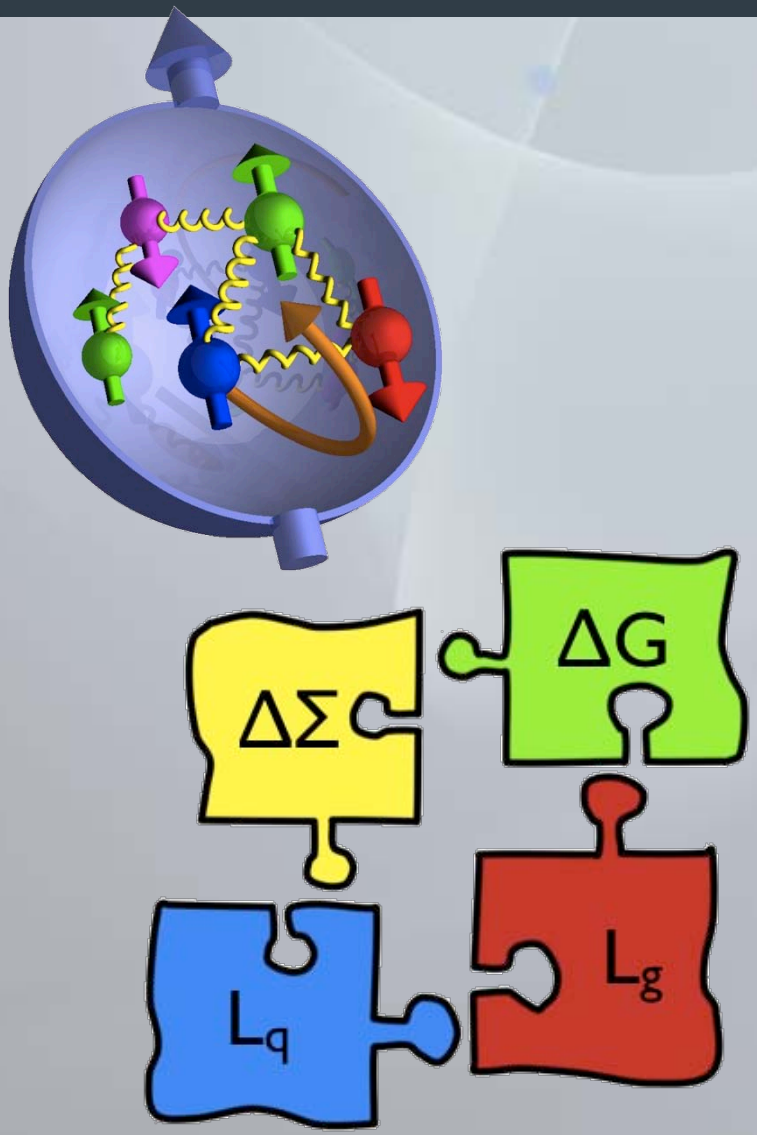
Closer Look

- Reality is more complicated





Puzzle 4: Spin Structure



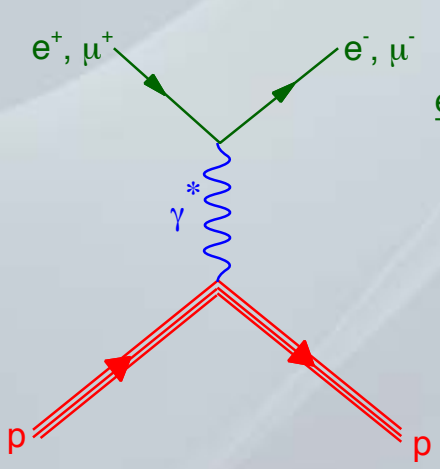
- Proton spin

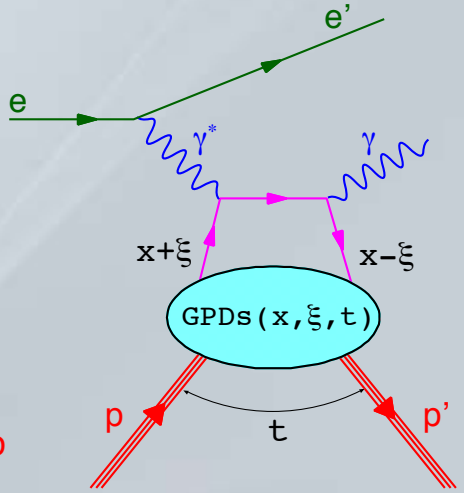
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

- Studied in space-like reactions
- $\Delta\Sigma$: quark spin
  - fraction about 1/3
- ΔG : gluon spin
  - first results
- L_q : quark angular momentum
  - unknown
- L_g : gluon angular momentum
  - unknown

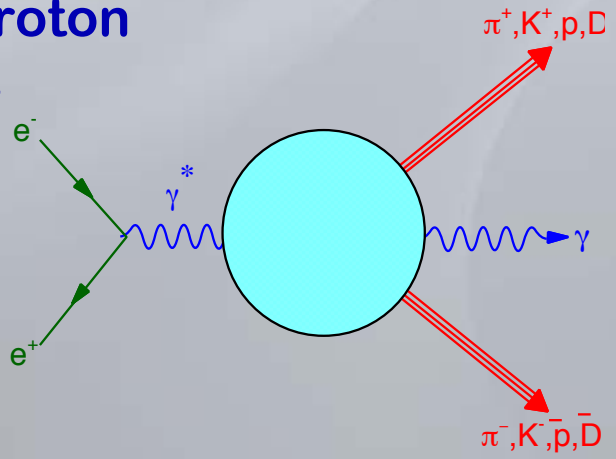
Space and Time Like Processes

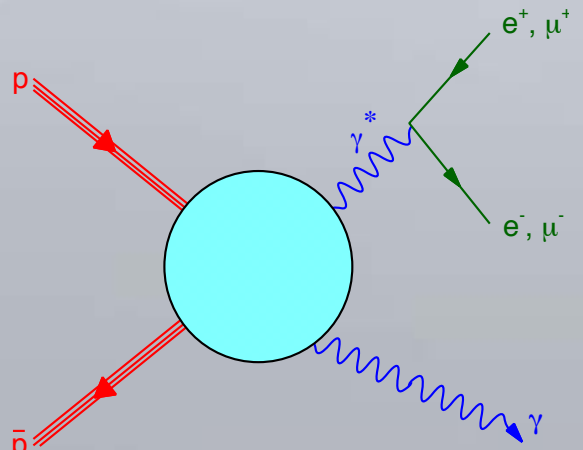
- Space like
  - elastic lepton scattering
  - deep virtual Compton scattering





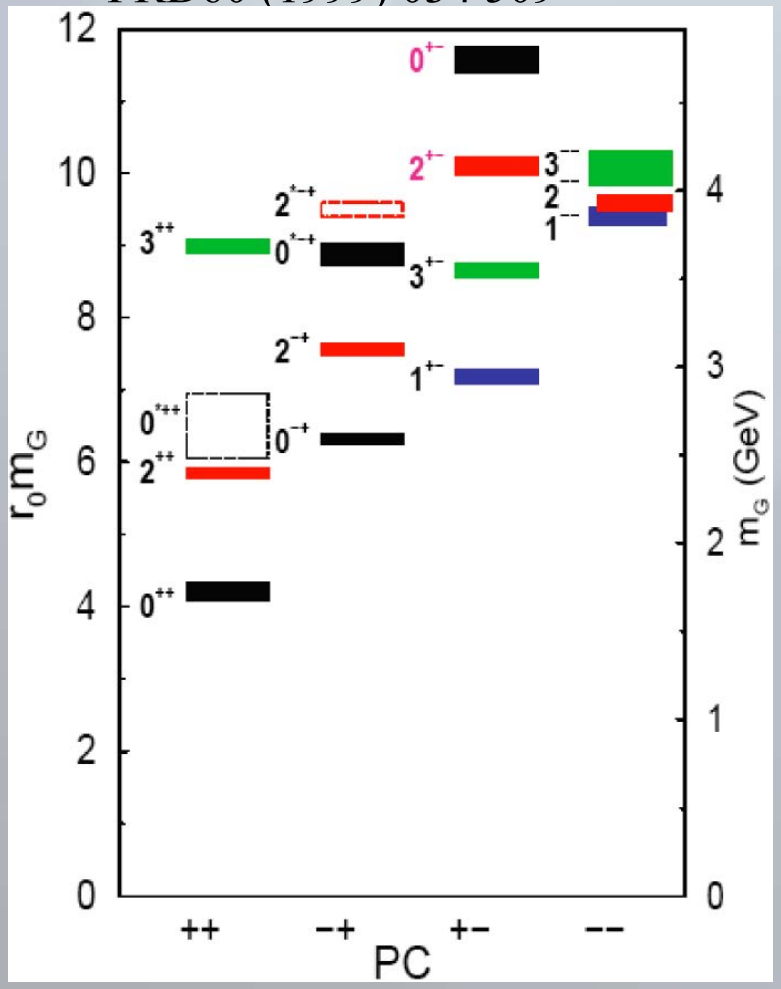
- Time like
  - electron-positron collisions
  - proton-antiproton annihilations



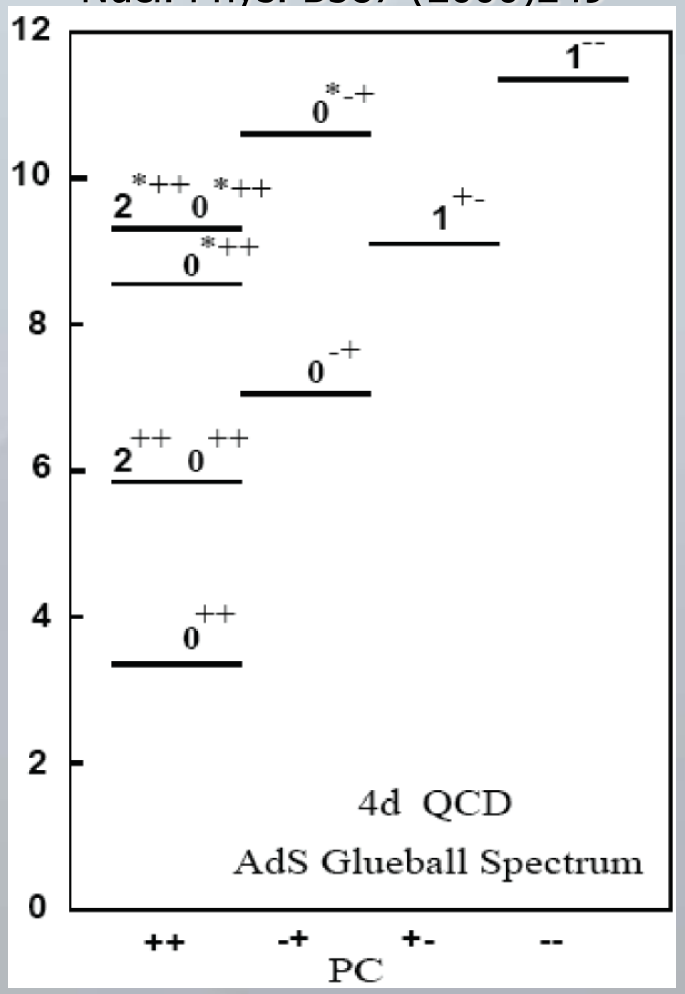


Glueball Predictions

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



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

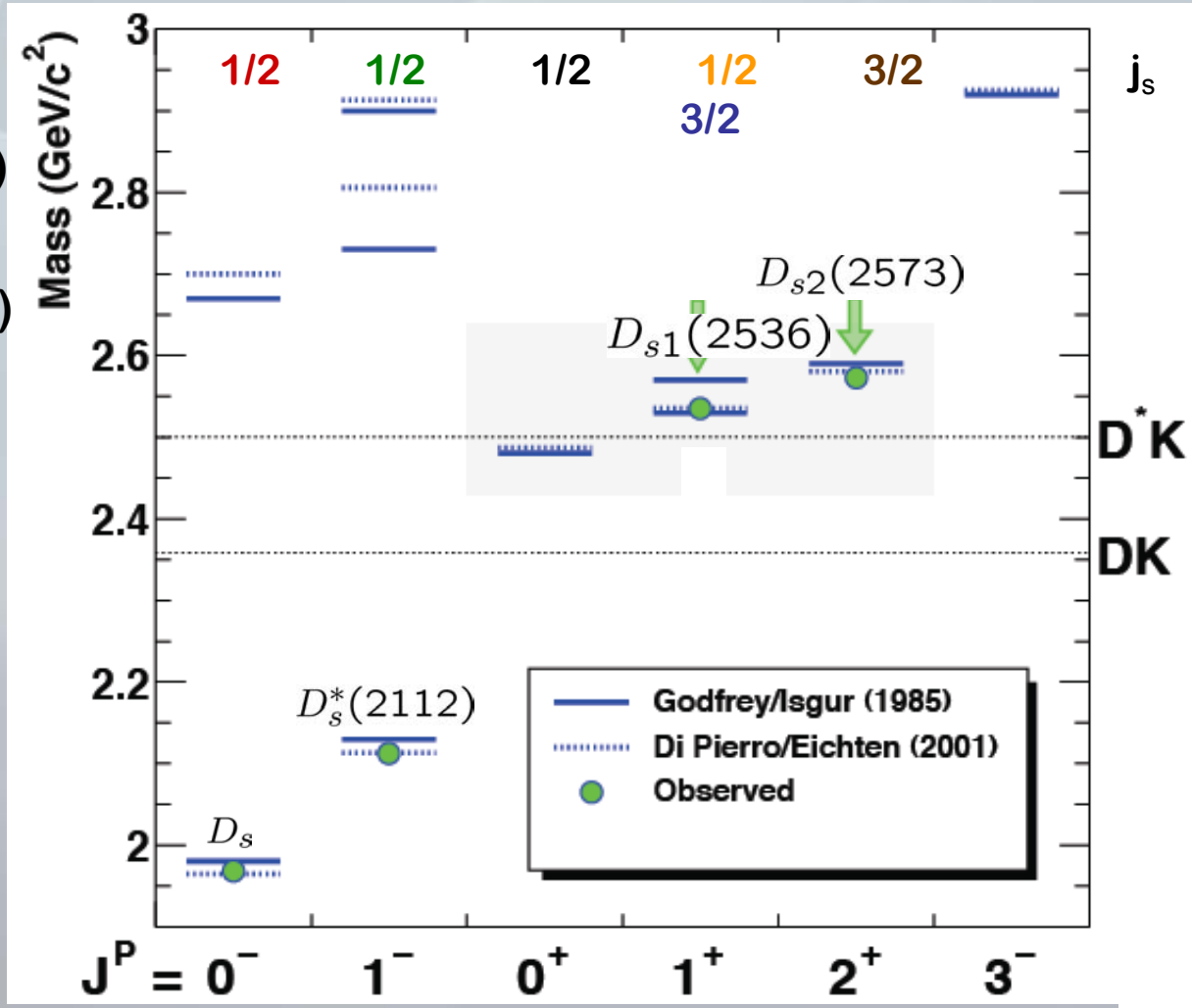


D_s Meson Spectrum

cs and c.c.

States known until 2003

D_s	(CLEO, 1983)
$D_s^*(2112)$	(PEP4, 1984)
$D_{s1}(2536)$	(Argus, 1989)
$D_{s2}(2573)$	(Cleo, 1994)



D_s Meson Spectrum

cs and c.c.

States known until 2003

D_s (Cleo, 1983)

$D_s^*(2112)$ (Slac, 1984)

$D_{s1}(2536)$ (Argus, 1989)

$D_{s2}(2573)$ (Cleo, 1994)

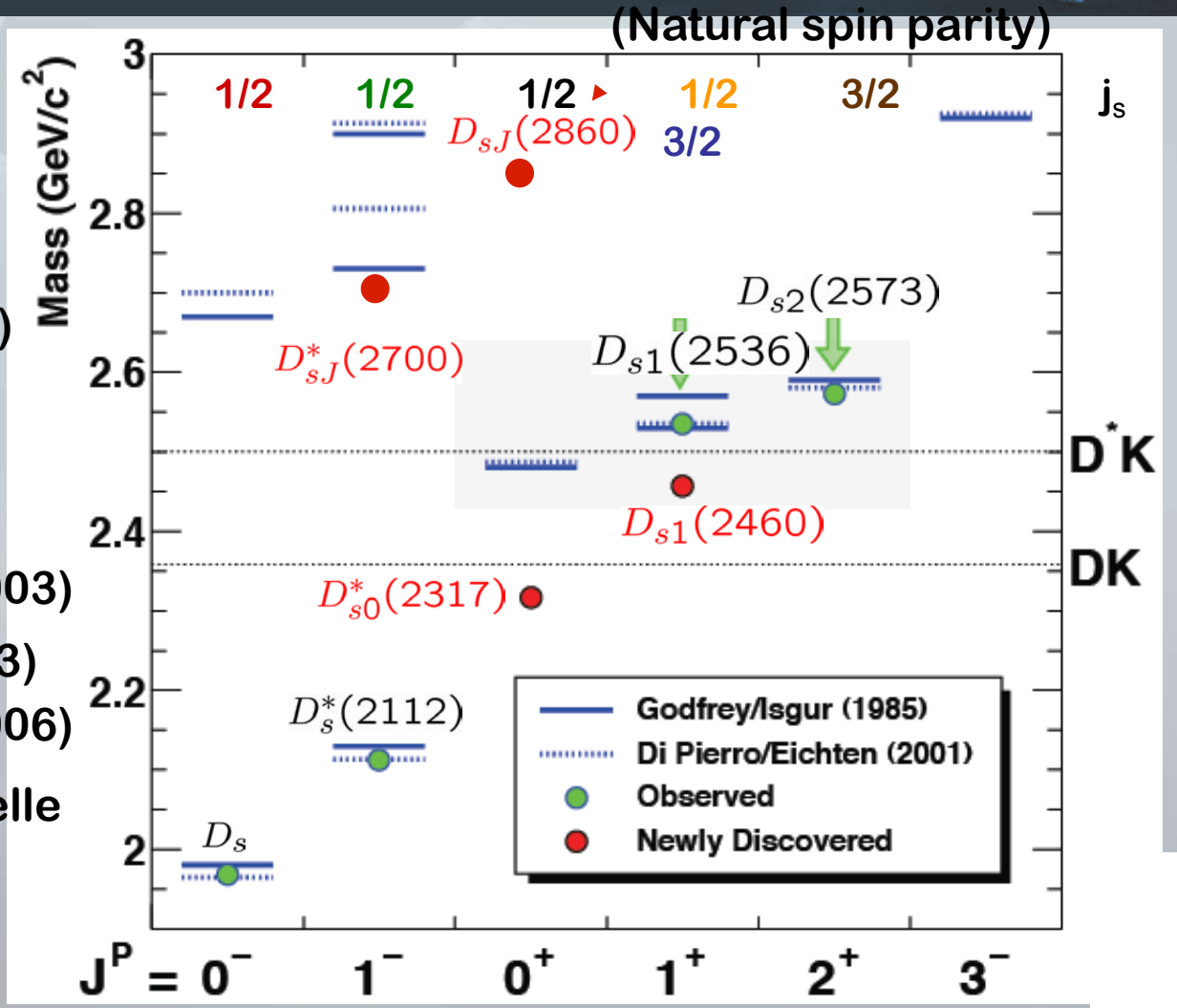
Discovered after 2003

cs? $D_{s0}^*(2317)$ (BaBar, 2003)

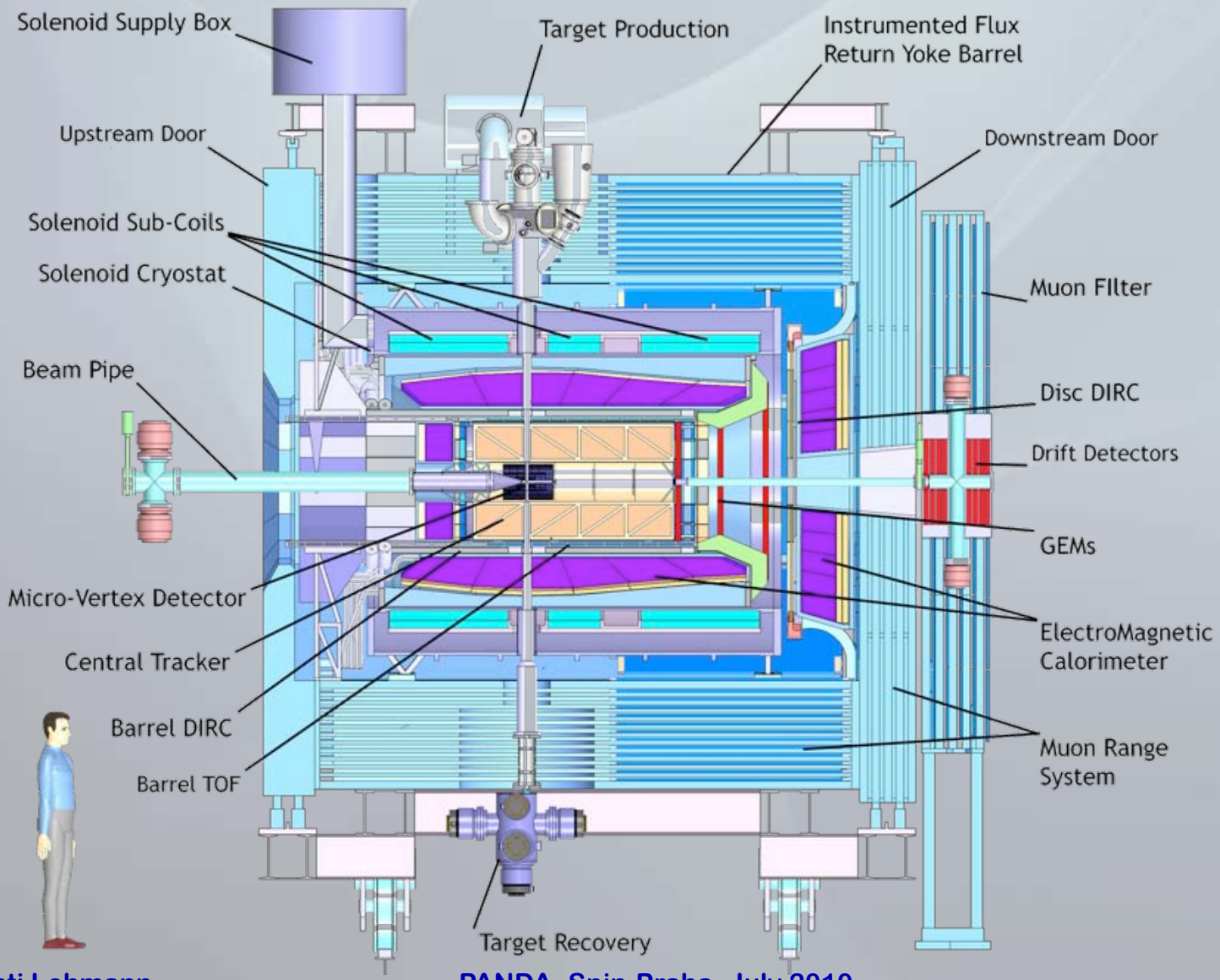
$D_{s1}(2460)$ (Cleo, 2003)

$D_{sJ}(2860)$ (BaBar, 2006)

$D_{sJ}^*(2700)$ (BaBar/Belle 2006)



Target Spectrometer



Forward Spectrometer