Hadron Physics from $\bar{p}p$ Annihilation using the $\bar{\text{p}}$anda detector (FAIR):

Time-Like Electromagnetic Form Factors of the nucleon

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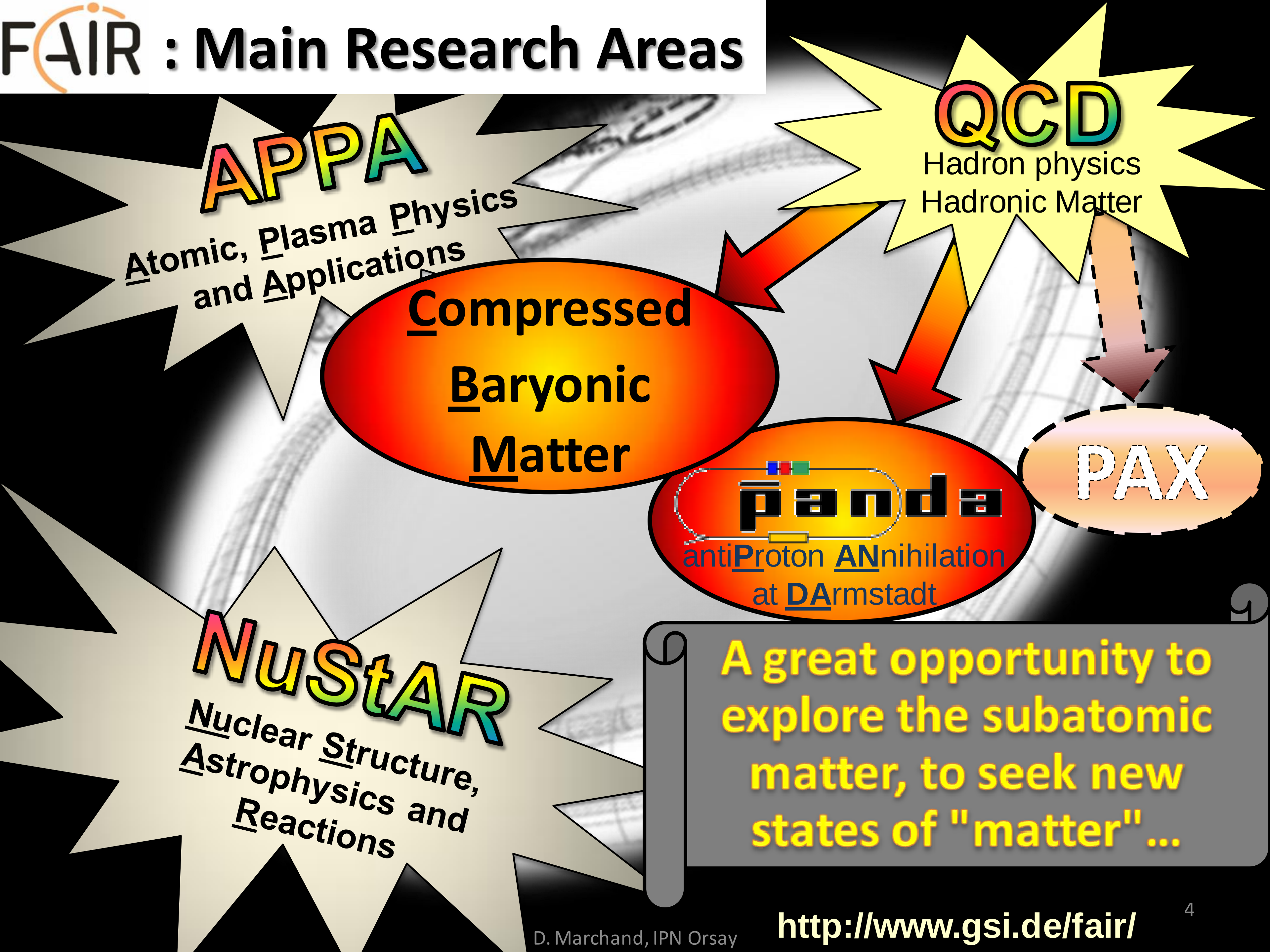
Outline

- FAIR @ Darmstadt
- PANDA Physics Program
- The PANDA detector
- Time-Like EM Form Factors of the Nucleon:
  - Motivation
  - Analysis of simulated events
  - Preliminary results from simulation
- Conclusion

FAIR: Facility for Antiprotons and Ions Research


FAIR : Main Research Areas
APPA
Atomic, Plasma Physics and Applications
QCD
Hadron physics
Hadronic Matter
Compressed
Baryonic
Matter
panda
antiProton ANnihilation at DArmstadt
PAX
NuStAR
Nuclear Structure, Astrophysics and Reactions
A great opportunity to explore the subatomic matter, to seek new states of "matter"...
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http://www.gsi.de/fair/
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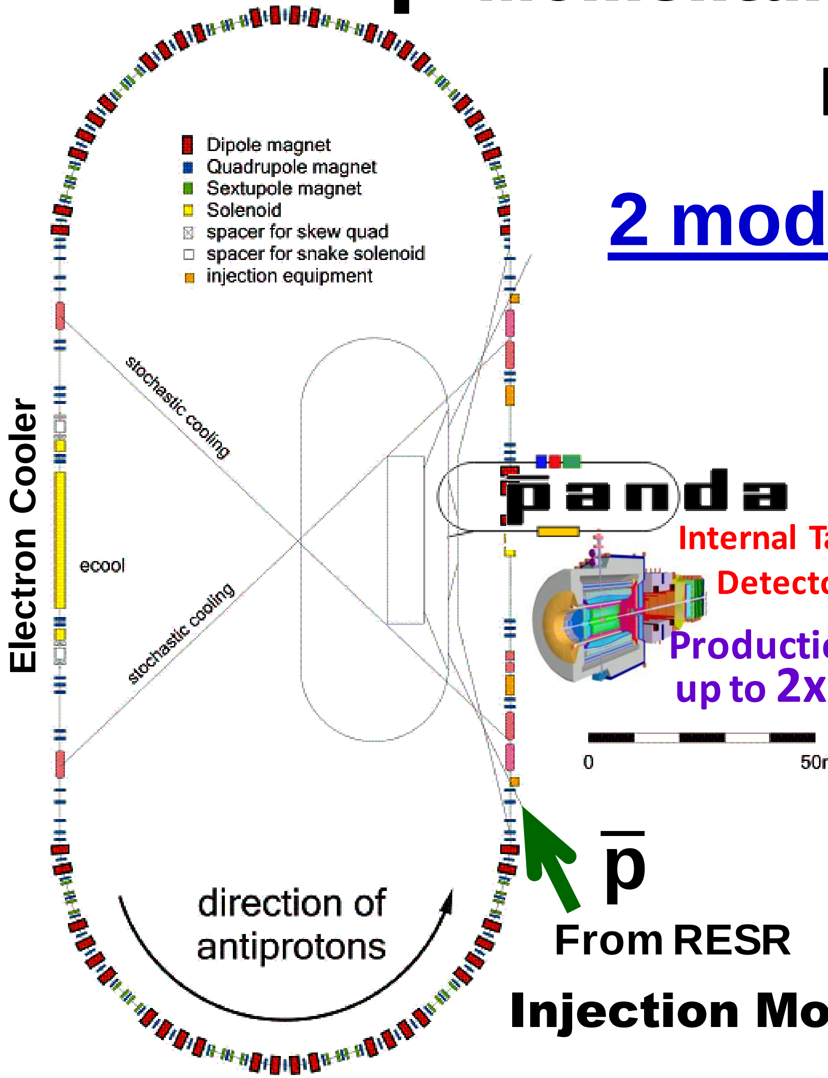
Parameters of the High Energy Storage Ring (HESR)

$\bar{p}$ Momentum : 1.5 – 15 GeV/c (E_{kin} : 0.8 – 14 GeV)
($2.3 \leq \sqrt{s} \leq 5.5$ GeV)

$N_{stored} \sim 10^{11}\ \bar{p}$



Internal Target

Detector

Production rate up to $2x10^7$/s

$\bar{p}$

From RESR

Injection Momentum : 3.8 GeV/c

2 modes of operation:

- **High *Luminosity* Mode:**
  - $\mathscr{L} = 2 \cdot 10^{32}\ cm^{-2}\ s^{-1}$
  - $\delta p/p \sim 10^{-4}$ (stochastic cooling)

- **High *Resolution* Mode:**
  - $\delta p/p \sim 10^{-5}$ (electron cooling)
  - $\mathscr{L} = 10^{31}\ cm^{-2}\ s^{-1}$

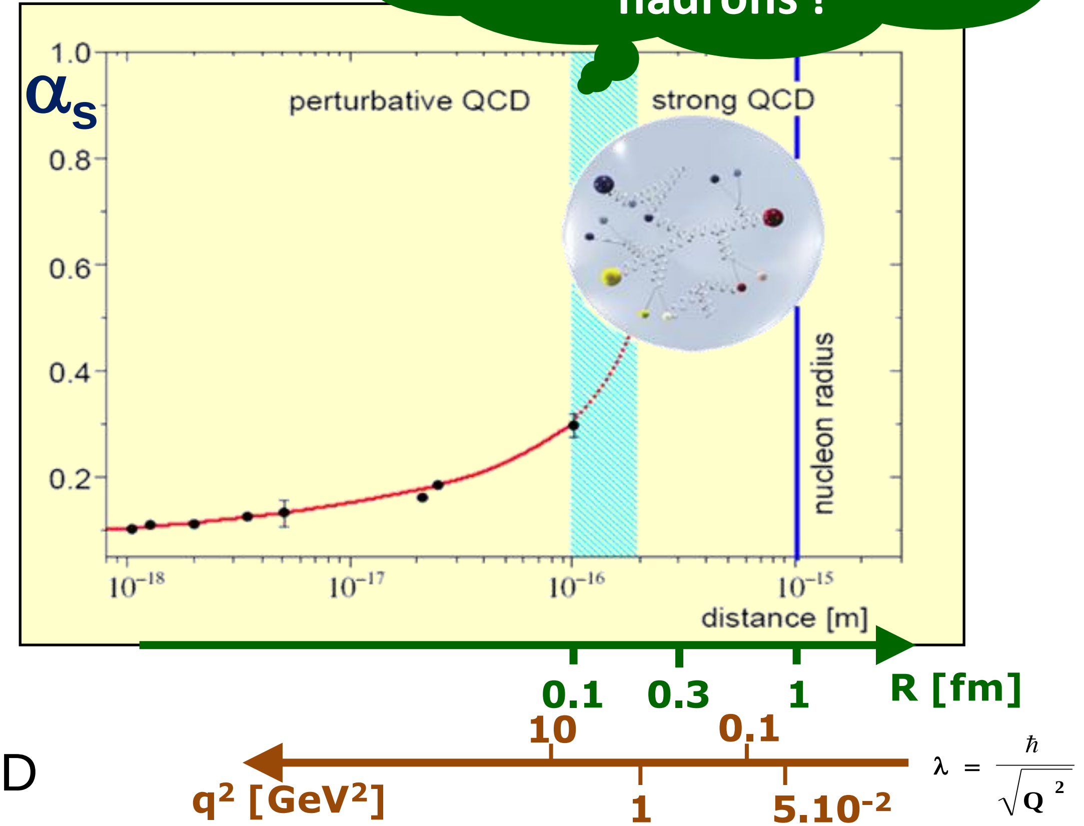
The panda Physics Program

« Charm, Exotic, Hyper Physics, … »

$1.5 \le p_{\bar{p}} \le 15$ (GeV/c)
$2.3 \le \sqrt{s} \le 5.5$ GeV

Studies of the Strong Interaction in the domain from non-perturbative to perturbative QCD

Dynamics of quark confinement within hadrons ?



Transition region:

- Phenomenoligical models
- Region where the models are tuned
- Experimental data essential !
  * Constraints
  * Evaluation

♦ ***$c\bar{c}$ energy range :***

Charmonium states predicted (heavy quark potential)

→ Confinement potential in QCD

Charmonium ($c\bar{c}$ mesons) Spectroscopy

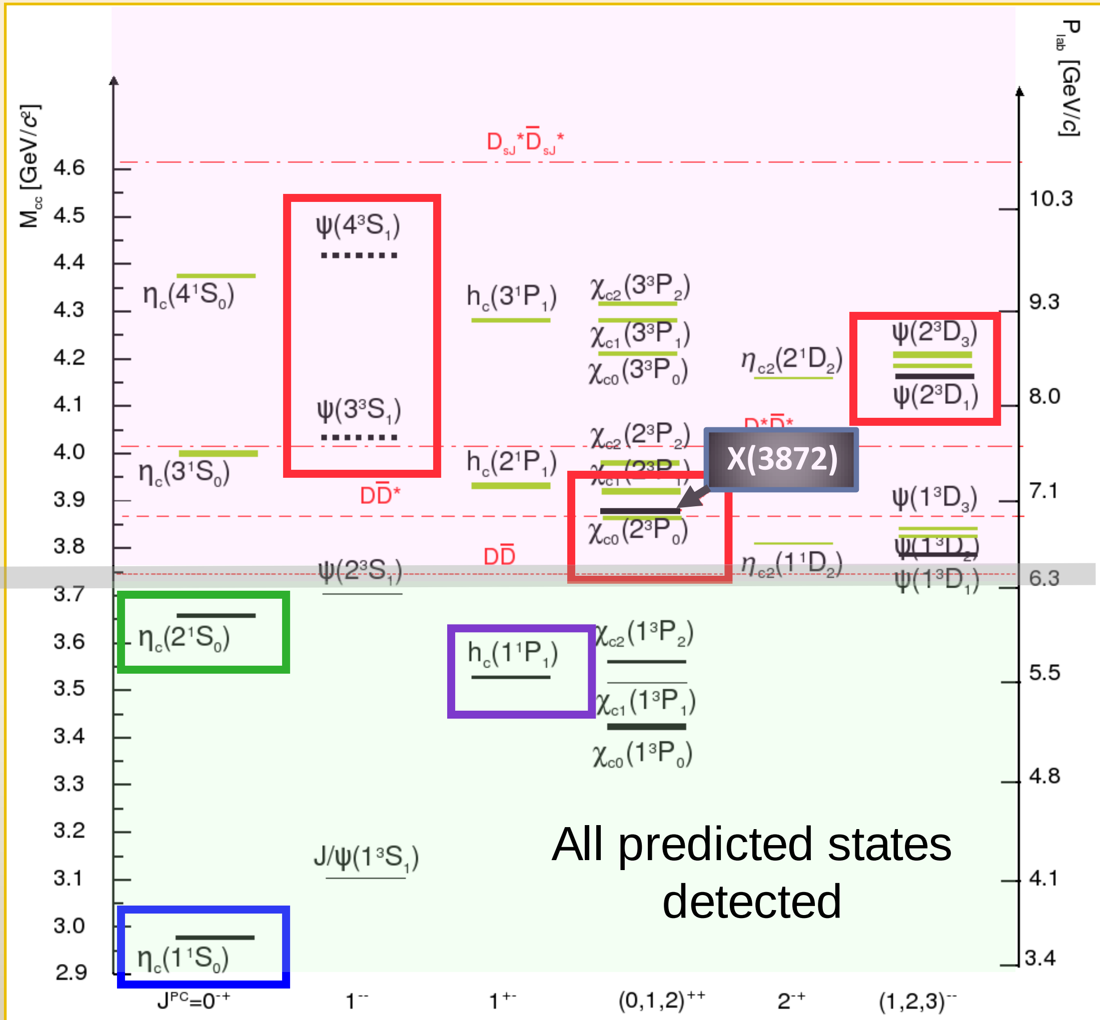
Characterization of all accessible charmonium states (mass, width, branching ratios)

⇨ **Below $D\bar{D}$ threshold** (3.73 GeV/c^2)

- 5 exp. : Inconsistency in η_c mass and width…
- η'_c unambiguously seen, although discrepancy with 1st measurement…
- h_c seen with poor statistics…

⇨ **Above $D\bar{D}$ threshold** states are not well established

- **XYZ** states studies : X(3872), Y(4361), Y(4664), Z(4430), … J^{PC} not well established.
- New resonances…



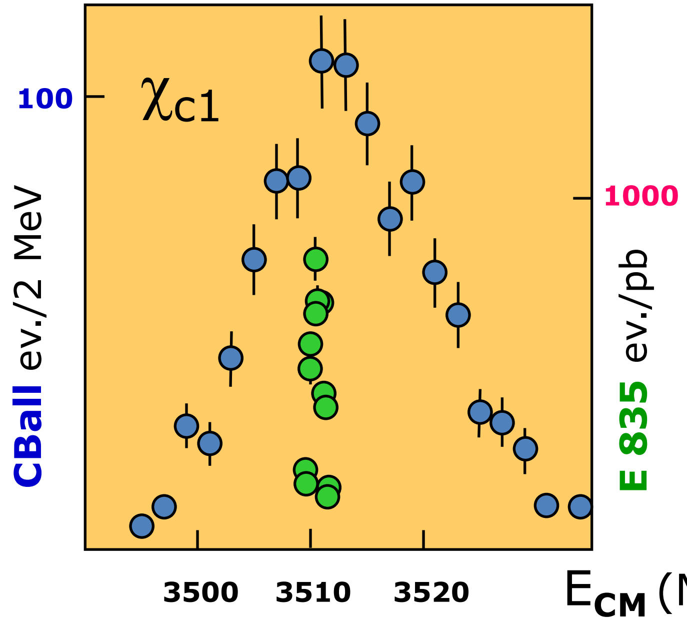
Antiproton's power

- **e^+e^- interactions:**
  - Only $J^{PC} = 1^{--}$ states are formed
  - Other states only by secondary decays (moderate mass resolution)

$e^+e^- \rightarrow \Psi'$
$\rightarrow \gamma\, \chi_{c1,2}$
$\rightarrow \gamma\, \gamma\, J/\psi$
$\rightarrow \gamma\, \gamma\, e^+e^-$

- **$\bar{p}p$ annihilation:**
  - All $q\bar{q}$ states directly produced (very good mass resolution)

$\bar{p}\, p \rightarrow \chi_{c1,2}$
$\rightarrow \gamma\, J/\psi$
$\rightarrow \gamma\, e^+e^-$



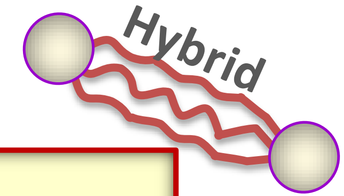
- Crystal ball (SLAC, e^+e^-) Edwards et al. PRL 48 (1982) 70
- E835 (Fermi Lab, $\bar{p}p$) Ambrogiani et al, PRD 62 (2000) 52002

PDG

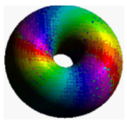
$M_{\chi_{c1}} = 3510.66 \pm 0.07$ MeV
$\Gamma = 0.89 \pm 0.05$ MeV

$\bar{P}$ANDA
$\delta p/p \sim 10^{-5}$
$\Delta M < 20$ keV

The P̄ANDA Physics Program



Charmonium ($c\bar{c}$ mesons) Spectroscopy

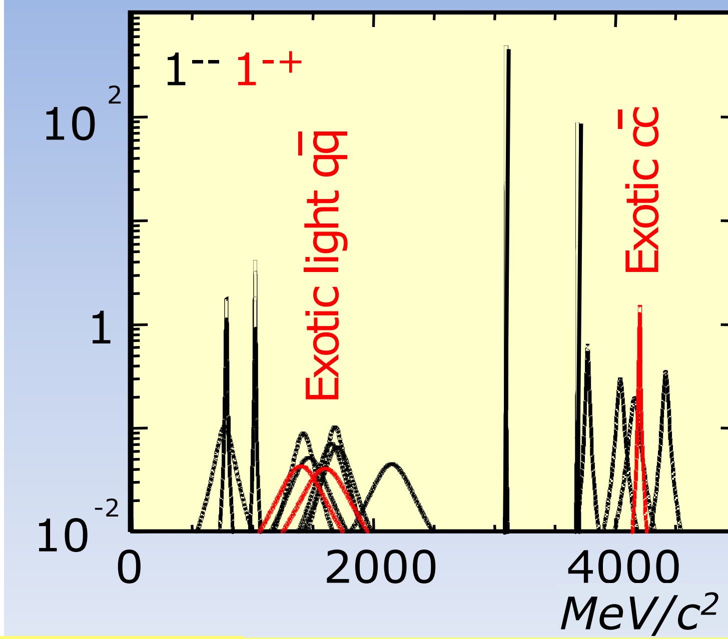


Search for Exotic Hadron States :

Hybrids ($q\bar{q}g$), GlueBalls (gg,ggg), multi-quark systems

QCD allows for **richer** spectrum

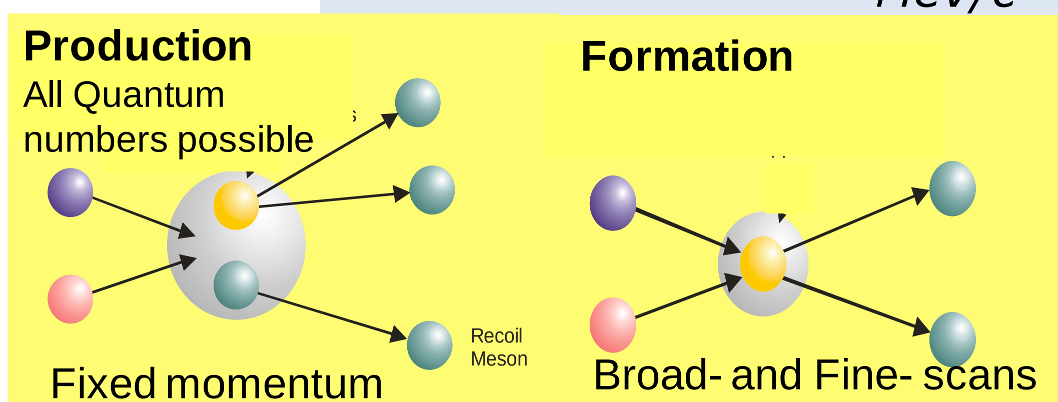
- ➢ Gluons may act as hadron components



✸ Spin-exotic quantum numbers J^{PC}:
powerful signature for hybrids

✸ $c\bar{c}$ meson spectrum: density of states is lower ↔ less overlap of exotics and $c\bar{c}$ mesons

✸ 2 complementary techniques:



✸ $\bar{p}p$ at CB-LEAR: candidates for 1^{-+} hybrids and 0^{++} glueball...

The PANDA Physics Program

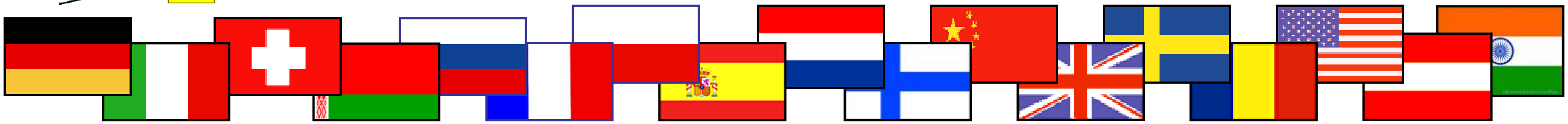
- Charmonium ($c\bar{c}$ mesons) Spectroscopy
- Search for Exotic Hadron States :
  Hybrids ($q\bar{q}g$), GlueBalls (gg,ggg), multi-quarks systems
- Mesons in Nuclear matter:
  medium effects on open (D mesons) and hidden charm (J/Ψ)
  In-medium modification of D meson production (lower threshold?)
- Hypernuclear Physics: ΛΛ-Hypernuclei production via Ξ^- capture
  ⇨ 3rd dimension in the nuclear chart: strangeness
  Study of ΛΛ interaction
- Open Charm (D_{sJ} mesons) Spectroscopy
  Precise measurement of the D_{SJ} widths (threshold scans)

⇨ Nucleon Structure:
GPDs (Wide Angle Compton Scattering, Hard exclusive meson production),
Unpolarized Drell-Yan Processes: quark distribution functions
Time-Like Electromagnetic Form Factors (CNRS/IN2P3, IKP-Mainz, GSI)

- *Other topics …*

More details on http://www-panda.gsi.de/

panda Collaboration



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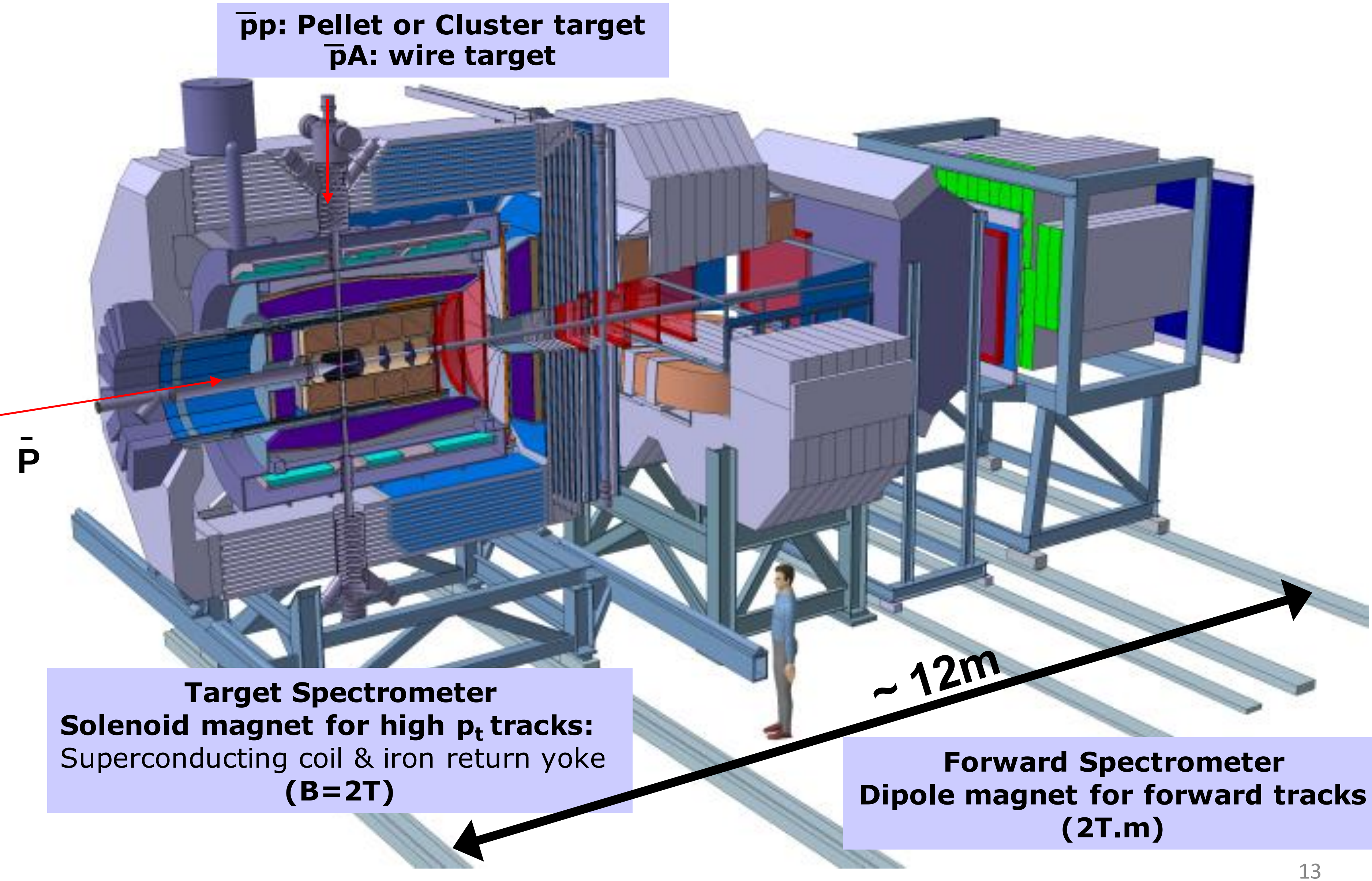
Basel, Beijing, Bochum, IIT Bombay, Bonn, Brescia, IFIN Bucharest, Catania, Cracow, IFJ PAN Cracow, Cracow UT, Dresden, Edinburgh, Erlangen, Ferrara, Frankfurt, Genova, Giessen, Glasgow, GSI, Inst. of Physics Helsinki, FZ Jülich, JINR Dubna, Katowice, KVI Groningen, Lanzhou, LNF, Lund, Mainz, Minsk, ITEP Moscow, MPEI Moscow, TU München, Münster, Northwestern, BINP Novosibirsk, IPN Orsay, Pavia, Piemonte Orientale, IHEP Protvino, PNPI St.Petersburg, KTH Stockholm, Stockholm, INFN Torino, Torino, Torino Politecnico, Trieste, TSL Uppsala, Tübingen, Uppsala, Valencia, SINS Warsaw, TU Warsaw, SMI Wien

http://www.gsi.de/panda

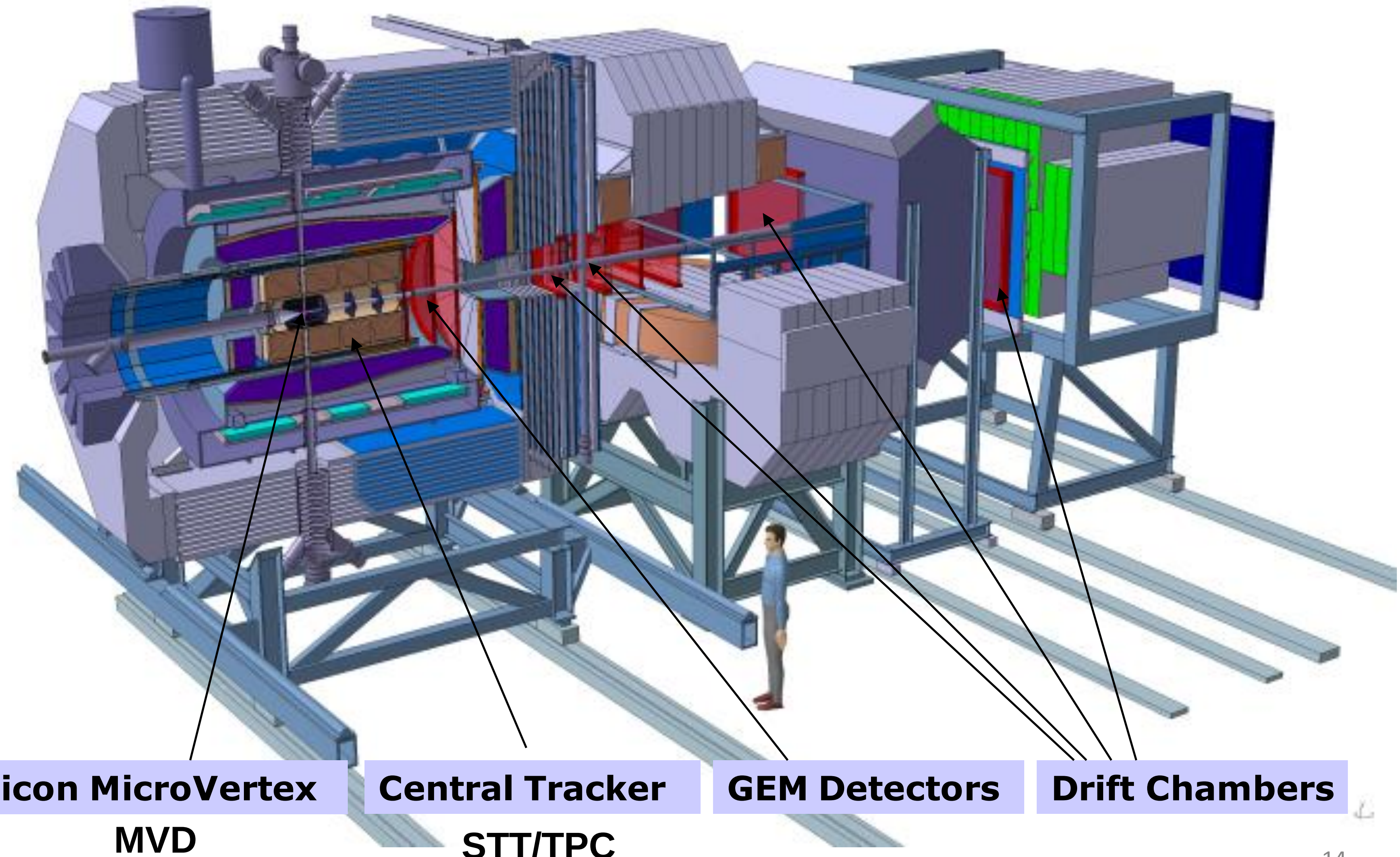
The $\bar{p}$anda detector

Detector requirements:

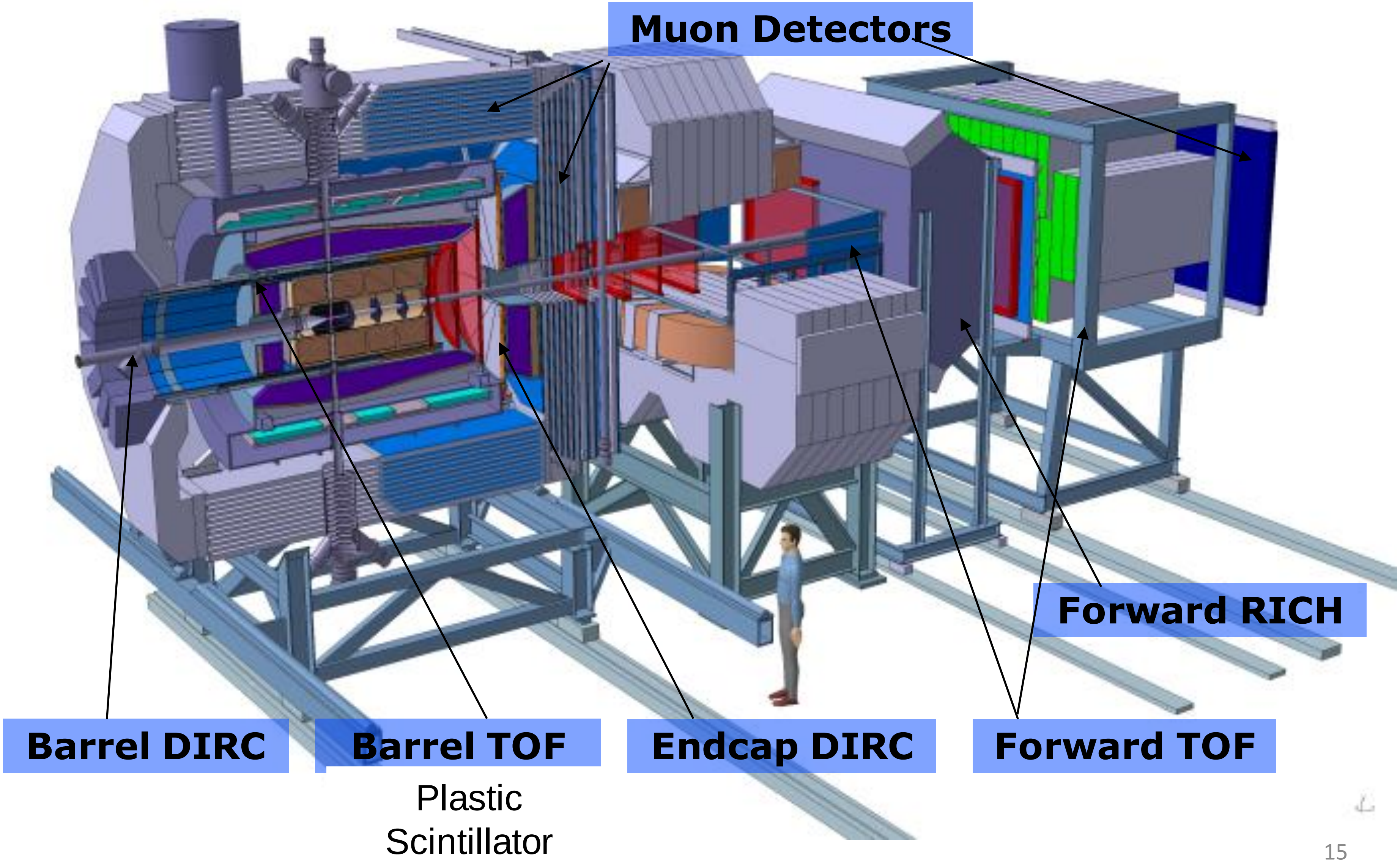
- nearly 4π solid angle for PWA
- high rate capability: 2×10^7 interactions/s
- good momentum resolution $\Delta p/p \approx 1\%$
- vertex resolution > 100 μm
  for K^0, Σ, Λ, D ($c\tau \approx 317$ μm)
- good PID (γ, e, μ, π, K, p)
- γ detection: 10MeV < E_γ < 10 GeV
- efficient event selection

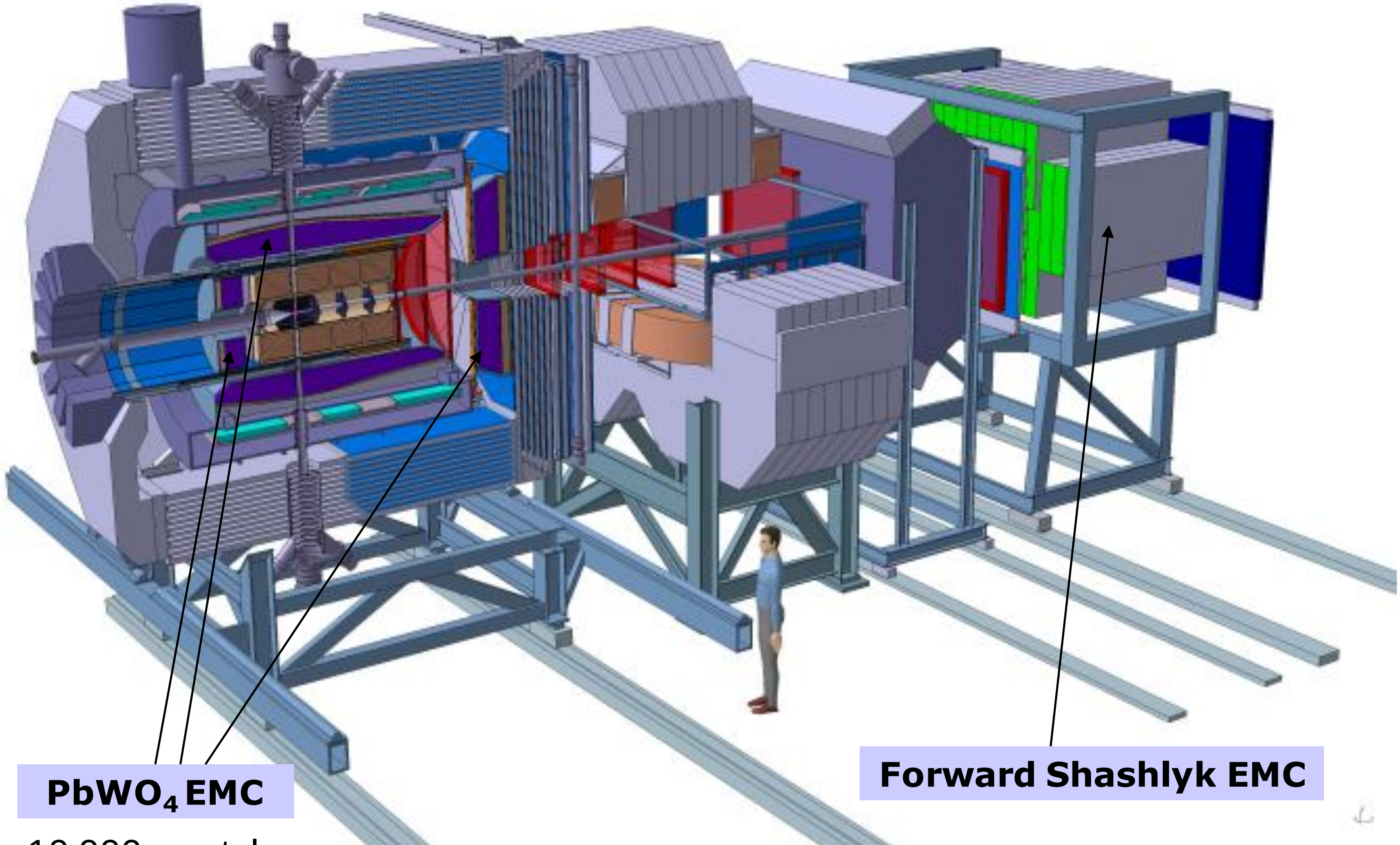

$\bar{p}p$: Pellet or Cluster target
$\bar{p}A$: wire target
$\bar{P}$
Target Spectrometer
Solenoid magnet for high p_t tracks:
Superconducting coil & iron return yoke
(B=2T)
~ 12m
Forward Spectrometer
Dipole magnet for forward tracks
(2T.m)

Tracking


Silicon MicroVertex
MVD
Central Tracker
STT/TPC
GEM Detectors
Drift Chambers

Particle IDentification





10 000 crystals

Nucleon Electromagnetic Form Factors

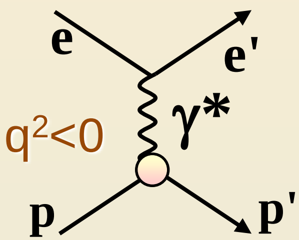
- ► Characterize the internal EM structure of non point-like particles
- ► (2S+1) FF for a particle of spin S

Proton, Neutron ⇨ 2 FF : F_1^p, F_1^n (Dirac), F_2^p, F_2^n (Pauli)

Proton current

$$J_\mu = F_1(q^2)\,\gamma_\mu + i(\kappa_p/2M_p)\,F_2(q^2)\,\sigma_{\mu\upsilon}q^\upsilon$$

Space Like (SL)



$Q^2 = -q^2 = 4E_eE_{e'}\,sin^2(\theta_{ee'}/2)>0$

Sachs FF

$$G_E^p(Q^2) = F_1(Q^2) - \tau\,F_2(Q^2)$$
$$G_M^p(Q^2) = F_1(Q^2) + F_2(Q^2)$$

$\tau = Q^2/(4M_p^2)$

Normalization

$$G_E^p(Q^2=0) = 1$$
$$G_M^p(Q^2=0) = \mu_p \quad (\mu_p = 1 + \kappa_p = 2.79)$$

Non-relativistic limit : G_E, G_M Fourier Transform of charge and magnetization densities

Elastic ***ep*** cross section (1-γ exchange)

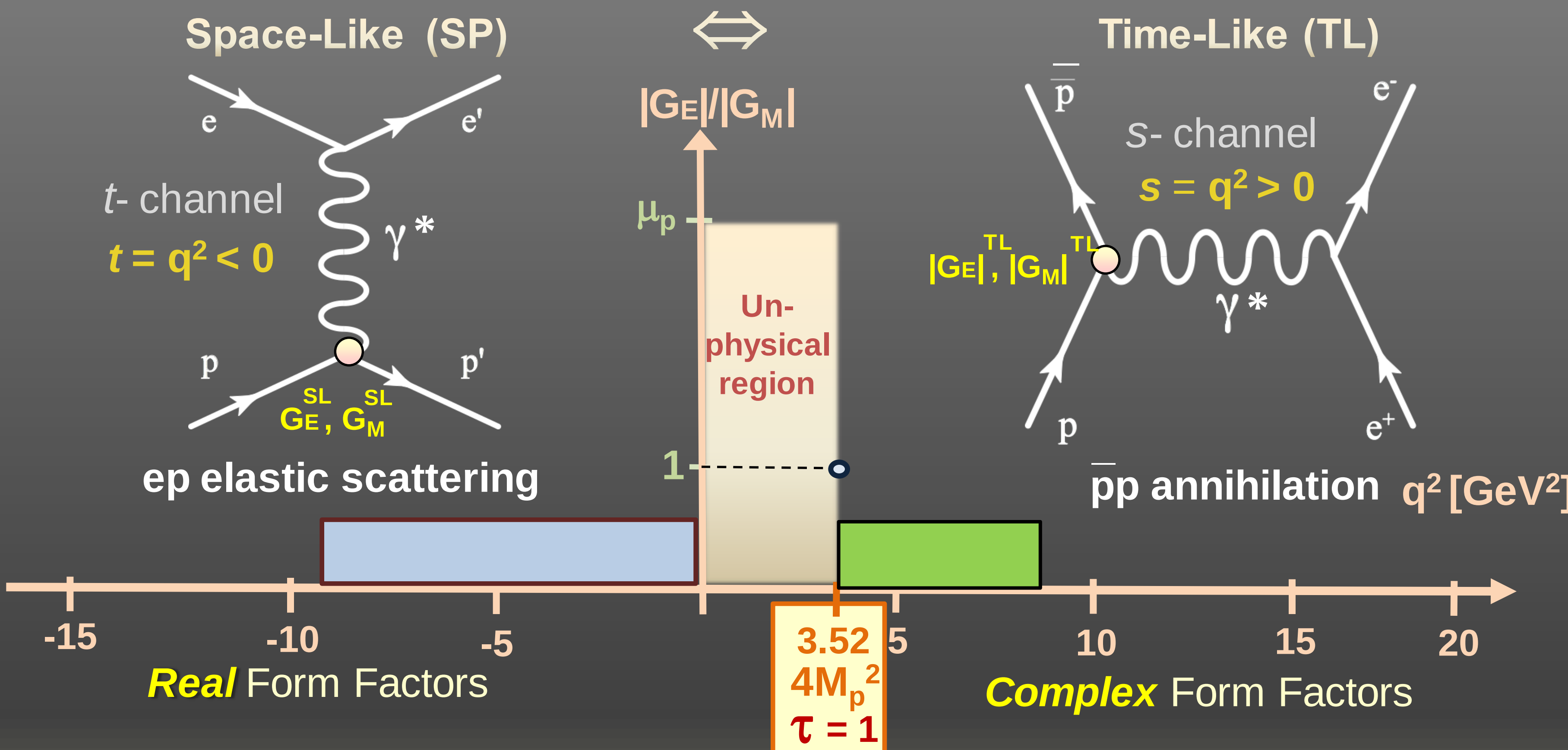
$$\frac{d\sigma}{d\Omega_e} = \sigma_{Mott}\left[2\tau G_M^2 \tan^2\frac{\theta_e}{2} + \frac{G_E^2 + \tau G_M^2}{1+\tau}\right]$$

SL FF : extensively measured up to $Q^2 \sim 6$ GeV^2 [9 GeV^2]

Rosenbluth // Polarization transfer (recent data)

$\mu_P G_E = G_M$ // $\mu_P G_E \neq G_M$

Nucleon Electromagnetic Form Factors



Analyticity : $\lim_{|q^2| \to \infty}$ ⇨

$G_E^{TL} = G_E^{SL}$

$G_M^{TL} = G_M^{SL}$

(Phragmén-Lindelöf principle)

At Threshold :

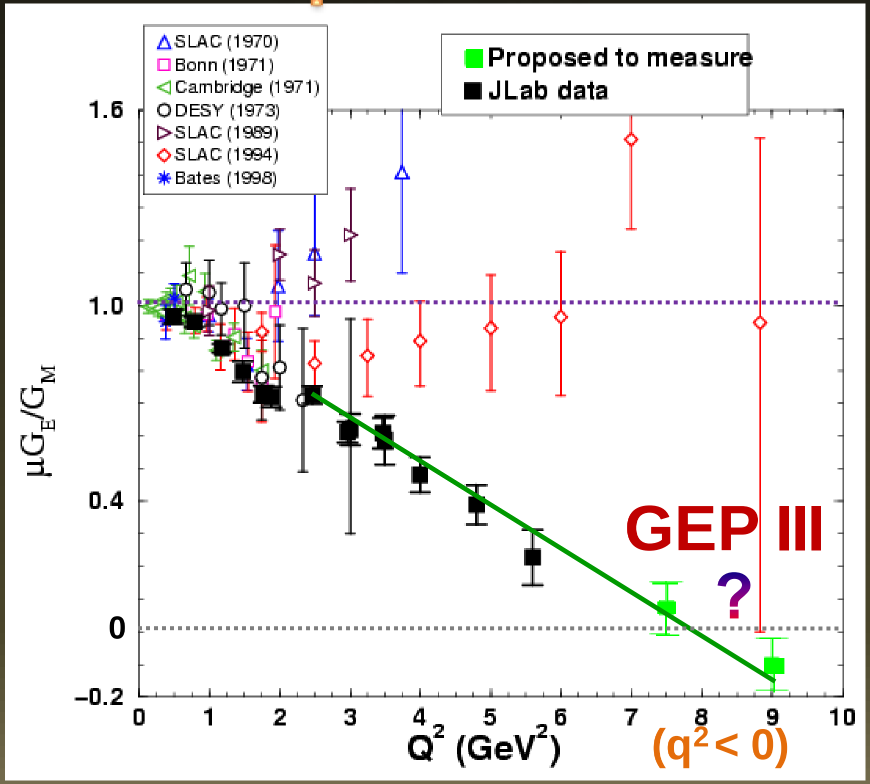
$\tau = 1$

$|G_E|^{TL} = |G_M|^{TL}$

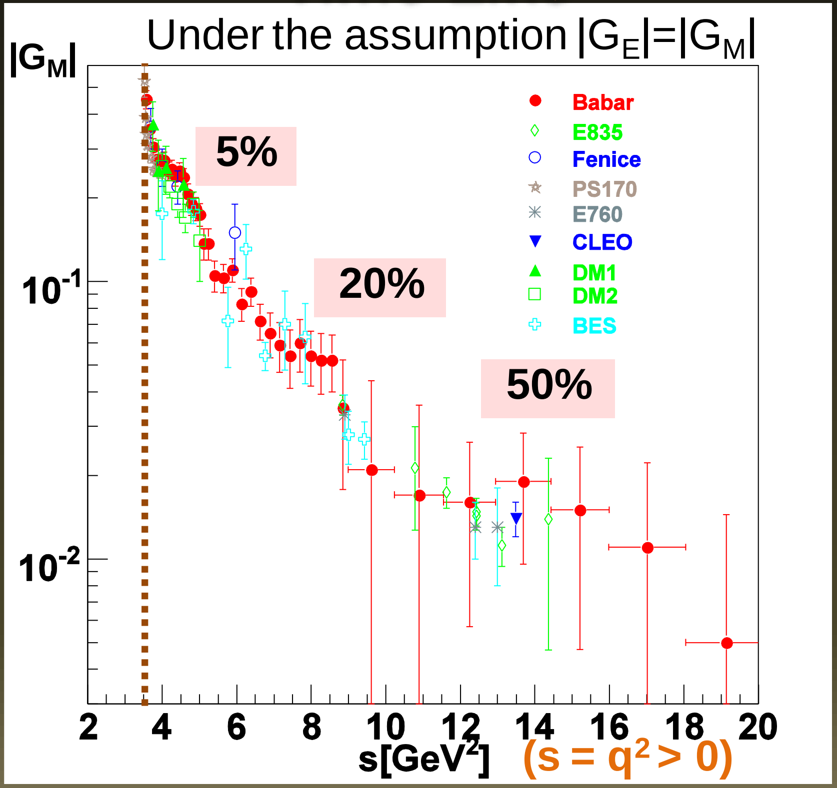
SL and TL FF intimately connected by dispersion relations

Existing Results on the Proton Form Factors

Space Like



Time Like



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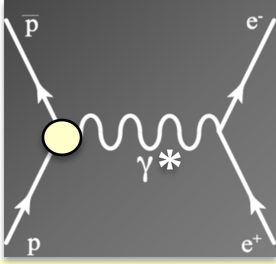
Time Like Form Factors of the proton from $\bar{p}p$ annihilation



$\bar{p}\,p \rightarrow e^{+}e^{-}$ Differential Cross Section

$$\frac{d\sigma}{d(\cos\theta_{CM})} = \frac{\pi\alpha^2}{8M^2\sqrt{\tau(\tau-1)}}\left[\tau\left|G_M^{TL}\right|^2(1+\cos^2\theta_{CM}) + \left|G_E^{TL}\right|^2\sin^2\theta_{CM}\right]$$

with M : proton mass ; θ_{CM} : $(\widehat{e,\bar{p}})$ in the center of mass frame

$$\tau = \frac{q^2}{4M^2} = \frac{s}{4M^2}$$ [Physical domain : $s \geq 4M^2$ ($4M^2 = 3.52\ GeV^2$) $\leftrightarrow \tau \geq 1$]

$$\frac{d\sigma}{d(\cos\theta_{CM})} = K(q^2)\left\{\tau(1+\cos^2\theta_{CM}) + \left[R(q^2)\right]^2\sin^2\theta_{CM}\right\} \quad \text{with } R(q^2) = \frac{\left|G_E^{TL}\right|}{\left|G_M^{TL}\right|}$$

***R* Determination from a 2-parameter fit of the angular distribution**

Total cross section (Ntot) α $|G_M^{TL}|^2$

⇨ Separation of $|G_E^{TL}|$ and $|G_M^{TL}|$

Background channels:

- 3 body reactions
- 2 charged body reactions ($\pi^+\pi^-$, $\mu^+\mu^-$, K^+K^-)

Background

Background reactions:

➔ **3 body reactions:** "easy" to eliminate

➔ kinematical constraints

➔ PID

➔ **2 charged body reactions** ($\pi^+\pi^-$, $\mu^+\mu^-$, K^+K^-)

➔ Most important background is $\pi^+\pi^-$: $\frac{\sigma_{\pi^+\pi^-}}{\sigma_{e^+e^-}} \sim 10^6$

➔ Kinematical constraints

➔ PID very important

Are we able to discriminate e^+e^- from $\pi^+\pi^-$?

High statistics GEANT4 simulations → **YES !**

Worse case : few $^0/_{00}$ pion pollution / $\cos\theta_{CM}$ bin

→ Pion polllution < 1% on the total cross section up to 16 GeV^2

$p\bar{p} \rightarrow e^+e^-$ Angular Distributions

➔ Full GEANT4 simulation of the $p\bar{p} \rightarrow e^+e^-$ reaction for several q^2 values [5.4 - 16.7 GeV^2]

➔ 3 assumptions: $G_E=0$, $G_E=G_M$, $G_E=3G_M$

Analysis: selection of “good” events (e^+e^- pairs):

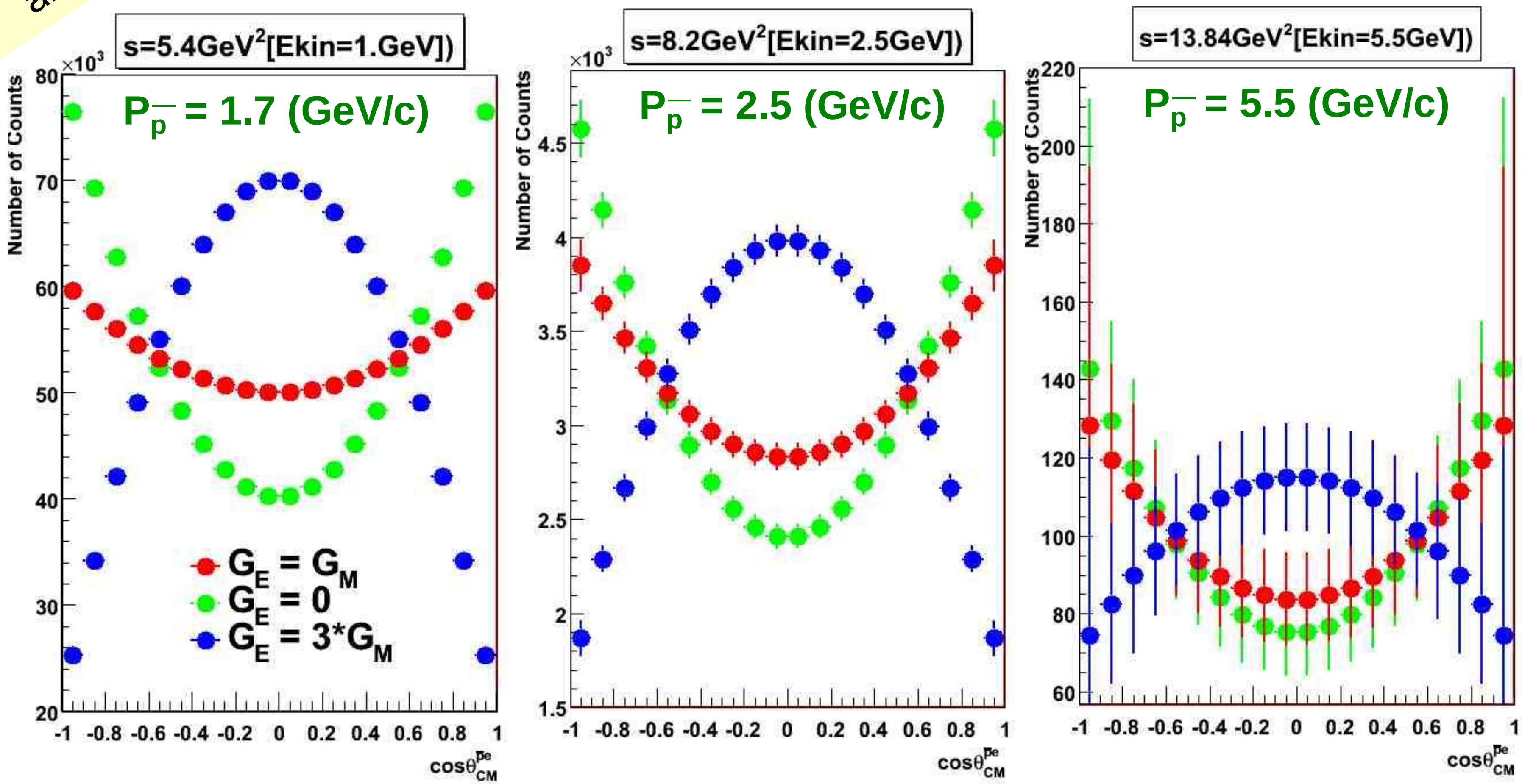
combined probability of 99.8% to be e+/e-

$\bar{p}p \rightarrow e^+e^-$ Angular Distributions

Corrected for efficiency and acceptance

Simulation

$\mathscr{L} = 2x10^{32}\ cm^{-2}.s^{-1}$, 10^7 s (~100 days)



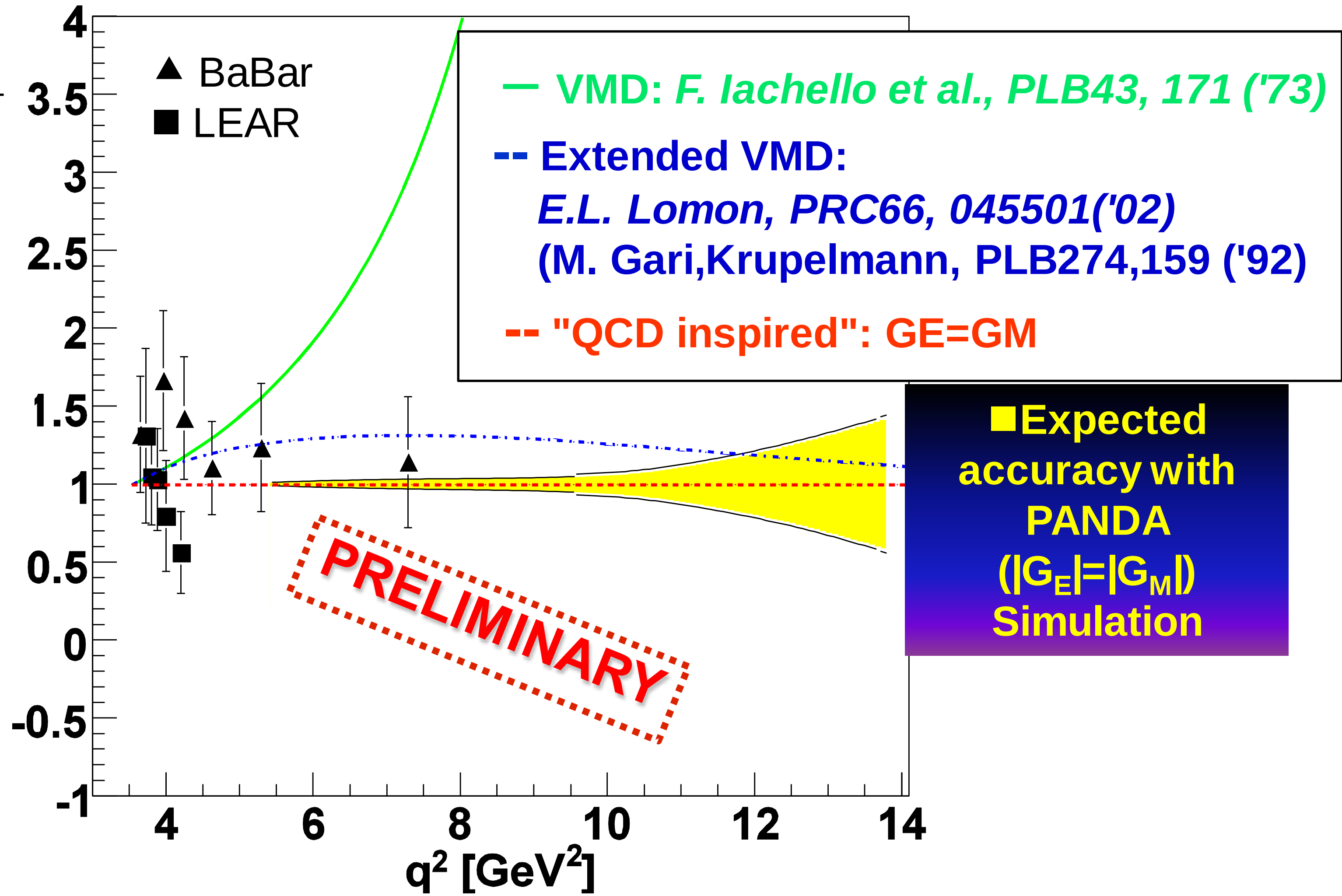
Expected number of counts:

$|\cos\ \theta_{CM}| \leq 1$

$N_{tot}=10^6$ $\quad$ $N_{tot}=64000$ $\quad$ $N_{tot}=2000$

Time Like Form Factors of the proton: Comparison with BaBar, LEAR results and models

$$R(q^2) = \frac{|G_E^{TL}|}{|G_M^{TL}|}$$



Measurement of the $|G_E|/|G_M|$ ratio at PANDA can be done with unprecedent precision compared to BaBar and LEAR

Time Like Magnetic Form Factor of the proton: Comparison with present data

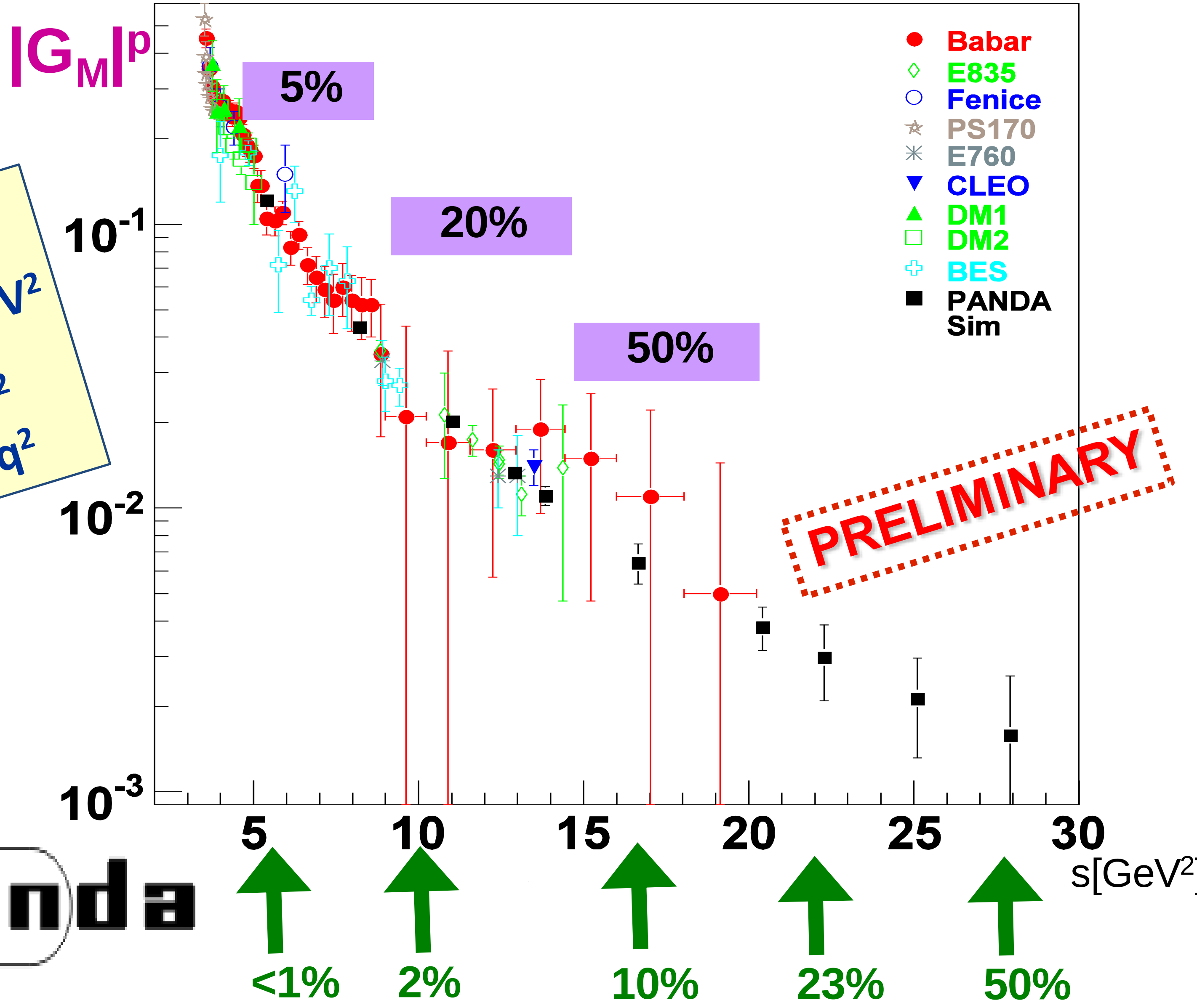
$(|G_E|=|G_M|)$

PANDA range :

$5.4 \leq q^2 \leq 30$ GeV^2

$\mathcal{L} = 2 \times 10^{32}$

~100 days/q^2



Time Like EM Form Factors of the proton with PANDA
Summary/Outlook

- Feasibility study (simulation) : discrimination of $\bar{p}p \rightarrow e^+e^-$ from $\bar{p}p \rightarrow \pi^+\pi^-$

- Determination of $R=|G_E|/|G_M|$ from angular distributions ($\bar{p}p \rightarrow e^+e^-$) up to at least $q^2=14(GeV^2)$ with unprecedent precision.

- Precise measurement of the total $\bar{p}p \rightarrow e^+e^-$ cross section up to $q^2=30GeV^2$ $\rightarrow |G_M|$

- Feasibility study of $\bar{p}p \rightarrow \mu^+\mu^-$ underway

- Feasibility study of $\bar{p}p \rightarrow e^+e^-\pi^0$ $\rightarrow |G_E|$ and $|G_M|$ in the unphysical domain.

- ../…Tranversely polarized target: access to the relative phase of G_E^{TL} and G_M^{TL}

Issue: Unified View of Nucleon EM Form Factors in SL and in the TL

Conclusion

✷ **High statistics simulations of the major processes have been performed. Results from these analysis are gathered in the PANDA Physics book which is being finalized.**

✷**By 2015, the PANDA experiment, together with the new antiproton facility HESR@FAIR will start to provide significant answers and clues to many open questions on the strong interaction in the transition region.**

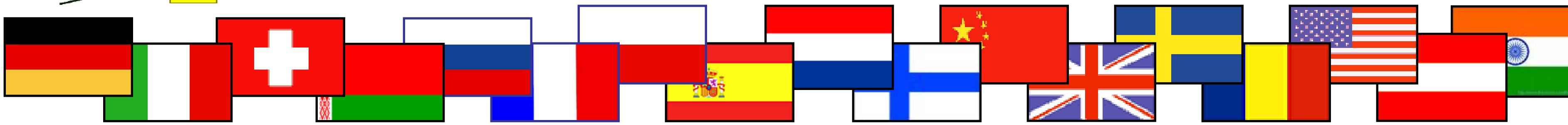
✷**$\bar{p}p$, e^+e^- and ep reactions bring complementary information in hadron physics.**

✷ **$\bar{p}p$ annihilation in the $c\bar{c}$ energy range is a key process to reveal unobserved $c\bar{c}$ states, to sign exotic states and many more...**

Thank you for your attention

СПАСИБО

panda Collaboration



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