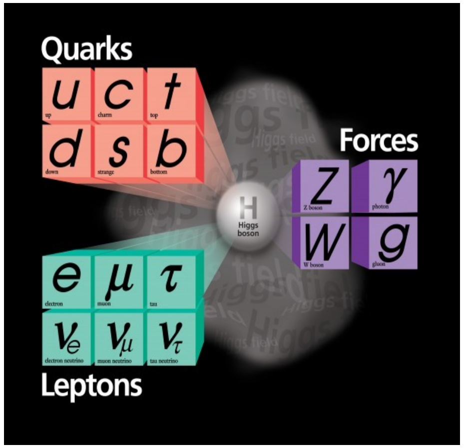
Perspectives of Open Charm Physics with the P̄ANDA experiment

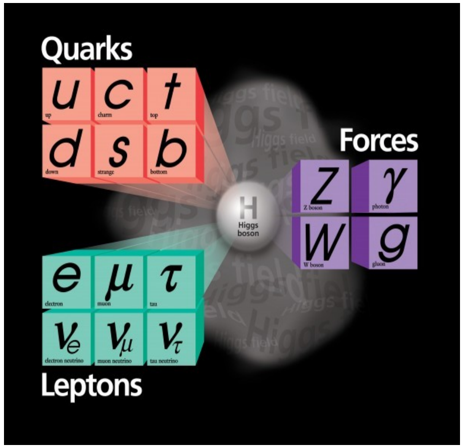
August 6th, 2014 | Elisabetta Prencipe, Forschungszentrum Jülich | ICNPF 2014, Kolymbari (Greece)

Outline



- Introduction
- The $\overline{P}ANDA$ experiment
- Why the interest in charm physics
  - ▶ Strong interactions
    - QCD
    - Intermediate case between heavy and light quarks
    - Spectroscopy
    - Strong decay modes
  - ▶ Weak interactions
    - CP violation
    - Mixing
    - Possible window to search for New Physics beyond the Standard Model
- Charm Physics with $\overline{P}ANDA$
- Summary

Outline



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- The experiment $\overline{P}ANDA$
- Why the interest in charm physics
  - Strong interactions
    - QCD
    - Intermediate case between heavy and light quarks
    - Spectroscopy
    - Strong decay modes

This talk is focused on strong interactions in Charm Physics

- Exotics in Open Charm Physics with $\overline{P}ANDA$
- Summary

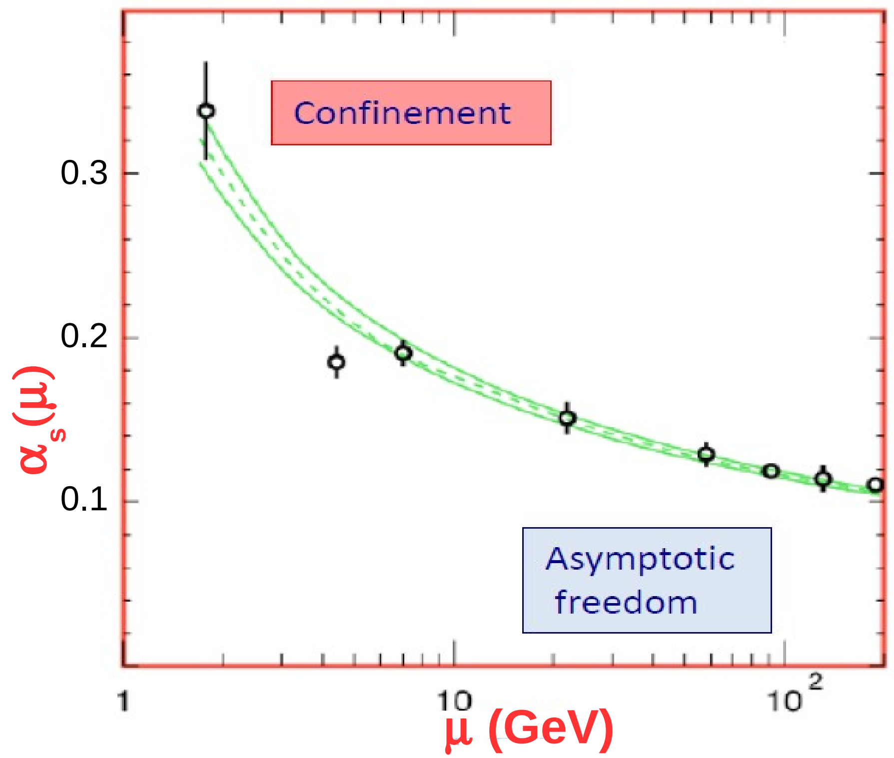
Introduction: QCD

- The modern theory of strong interactions is the Quantum Chromo Dynamics (QCD)
  - QCD is the quantum field theory of quarks and gluons
  - It is based on the non-abelian gauge group SU(3)
  - It is part of the Standard Model

- At high energy QCD is well tested
  - The coupling constant α_s becomes small at high energy
  - Perturbation theory applies

- At low energy, QCD is still to be understood
  - Several theoretical approaches:
    - Potential models
    - Lattice QCD (LQCD)
    - Effective field theory (EFT)
    - ....

- Input from experimental physics
  - Several experimental techniques



Theoretical approaches to non-perturbative QCD

- **Potential Models** Bound system of heavy quarks can be treated in the framework of non-relativistic potential model. Masses and widths are obtained solving the Schrödinger equation

- **LQCD** QCD equations of motion are discretized on a 4-dim. space-time lattice and solved by large-scale computer simulations
  - Enormous progress in recent years (quenched→unquenched lattice calculations)
  - Precision increasing, thanks also to synergies with EFT

- **EFT** Exploit the symmetries of QCD and the existence of hierarchies of scales to provide effective lagrangians that are equivalent to QCD with:
  - quark and gluon degrees of freedom (non-perturbative QCD approach: NPQCD)
  - hadronic degrees of freedom (Chiral Perturbation theory: ChPT)

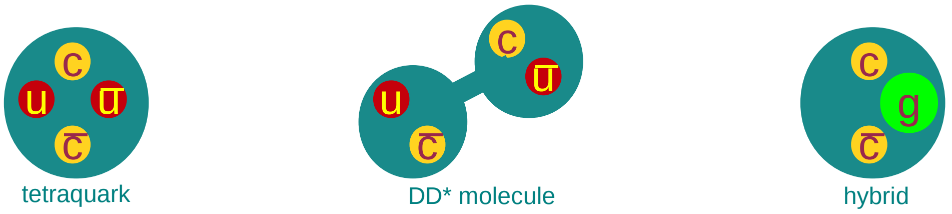
Experimental inputs

- **Spectroscopy of QCD bound states**. Precision measurement of particle spectra:
  - Mass
  - Width
  - Branching Ratios (BR) and cross sections

  Observables must be compared with the theoretical predictions
  Identification of relevant degrees of freedom
  - D mesons
  - Baryons

- **Search for new form of hadronic matter**
  - Hybrids
  - Glueballs
  - multiquark states

  ...



- **Hadron in nuclear matter**
  - Origin of the mass
  - Hypernuclei

- **Study of nucleon structure**
  - Form factors

- **Spin Physics**

Experimental techniques

e^+e^- colliders

- Direct formation
- Two photon production
- Initial state radiation (ISR)
- B meson decays

(BaBar, Belle(II), BES, Cleo(-c), CESR, LEP...)

Low hadronic background
High discovery potential

BUT

Direct formation limited to vector states
Limited mass and width resolution for non vector states

$\bar{p}p$ annihilation
(LEAR, Fermilab E760/E835, *$\overline{\text{P}}$ANDA*)

Hadron production
(CDF, D0, LHC)

Electro/photon production
(HERA, JLAB)

High hadronic background

BUT

High discovery potential
Direct formation for all (non exotic) states
Excellent mass and width resolution for all states

Charm spectrum

- The charm spectrum was predicted in 1985 [**S. Godfrey, N. Isgur, PRD32, 189 (1985)**] and updated in 2011 [**M. Di Pierro, N. Eitchen, PRD64, 114004 (2001)**]

- The theoretical predictions are generally in qualitative agreement with observations

- Still discrepancies are seen for some of those states (experimental limitation in the measurement of the width, small statistics, large level of background in inclusive measurements)

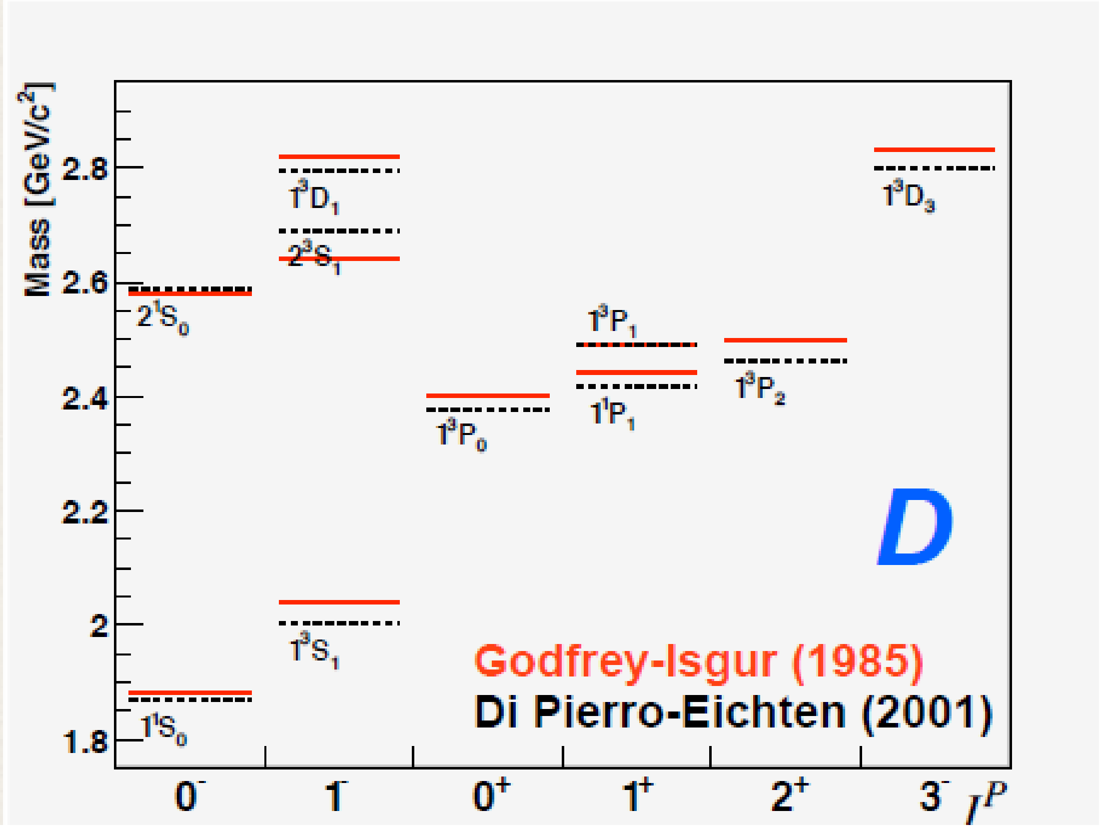
From PDG 2012:

D mesons: $|c\bar{u}\rangle$, $|c\bar{d}\rangle$

$\overline{M}_D = (1864.91 \pm 0.17)$ MeV/c^2

$M_\pm - M_0 = (4.74 \pm 0.28)$ MeV/c^2

$\bar{\tau} = (410.1 \pm 1.5) \times 10^{-15}$s



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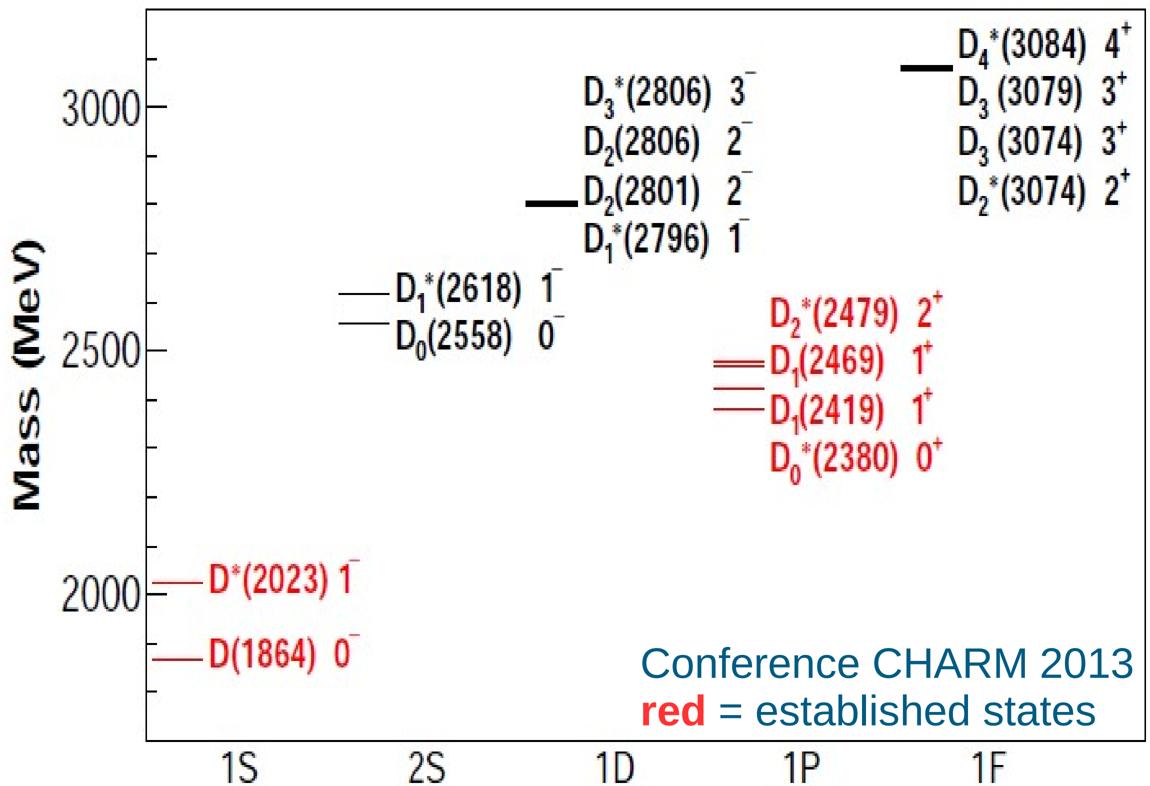
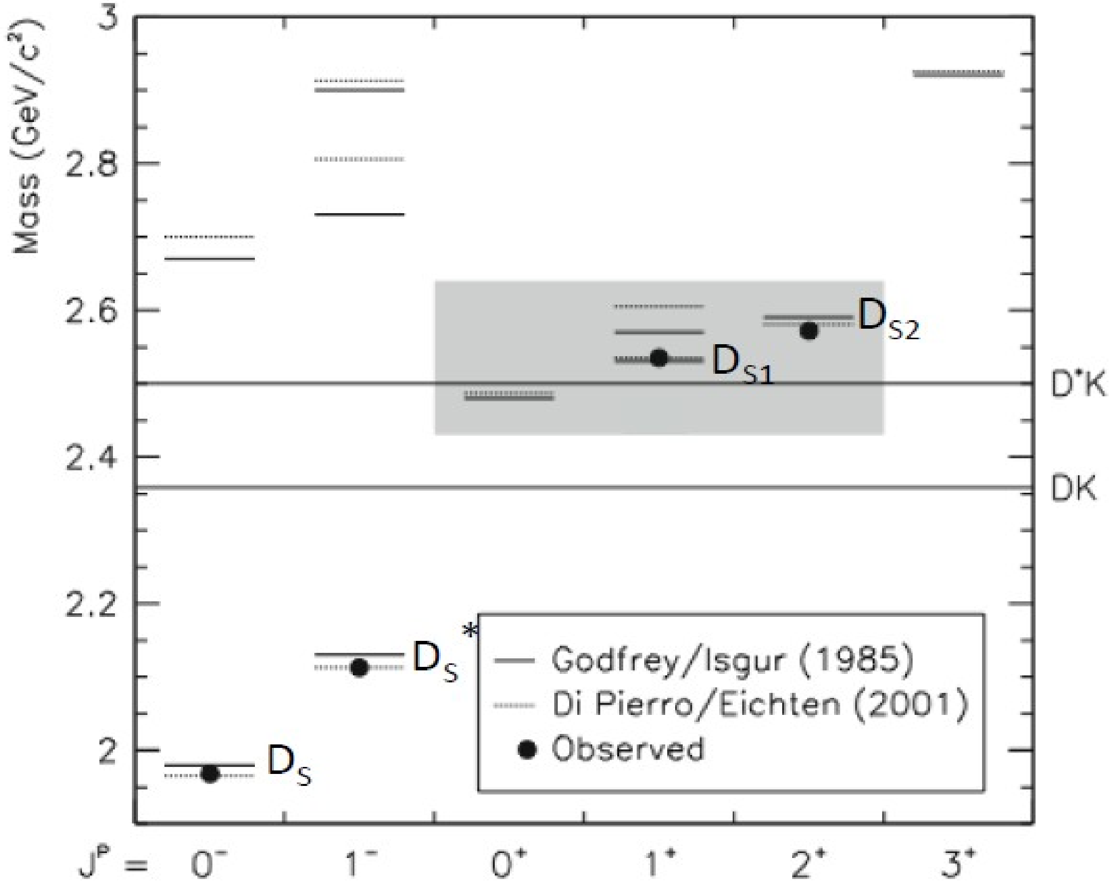


Excited D_s states

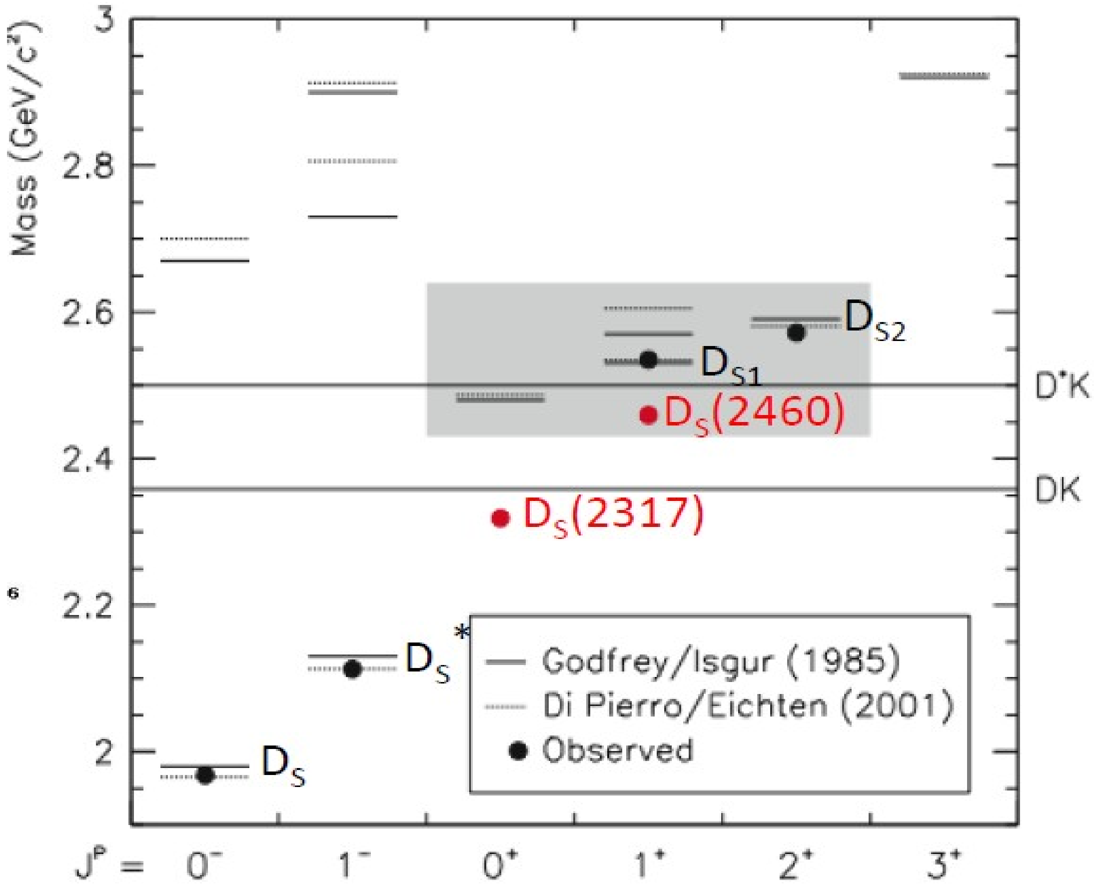


$|c\bar{u}\rangle$ $|c\bar{d}\rangle$ (D mesons): theory and experiments are in agreement

$|c\bar{s}\rangle$ (**D**$_{SJ}$ states): the quark model describes the spectrum of unobserved heavy-light systems, expected to be predicted with good accuracy

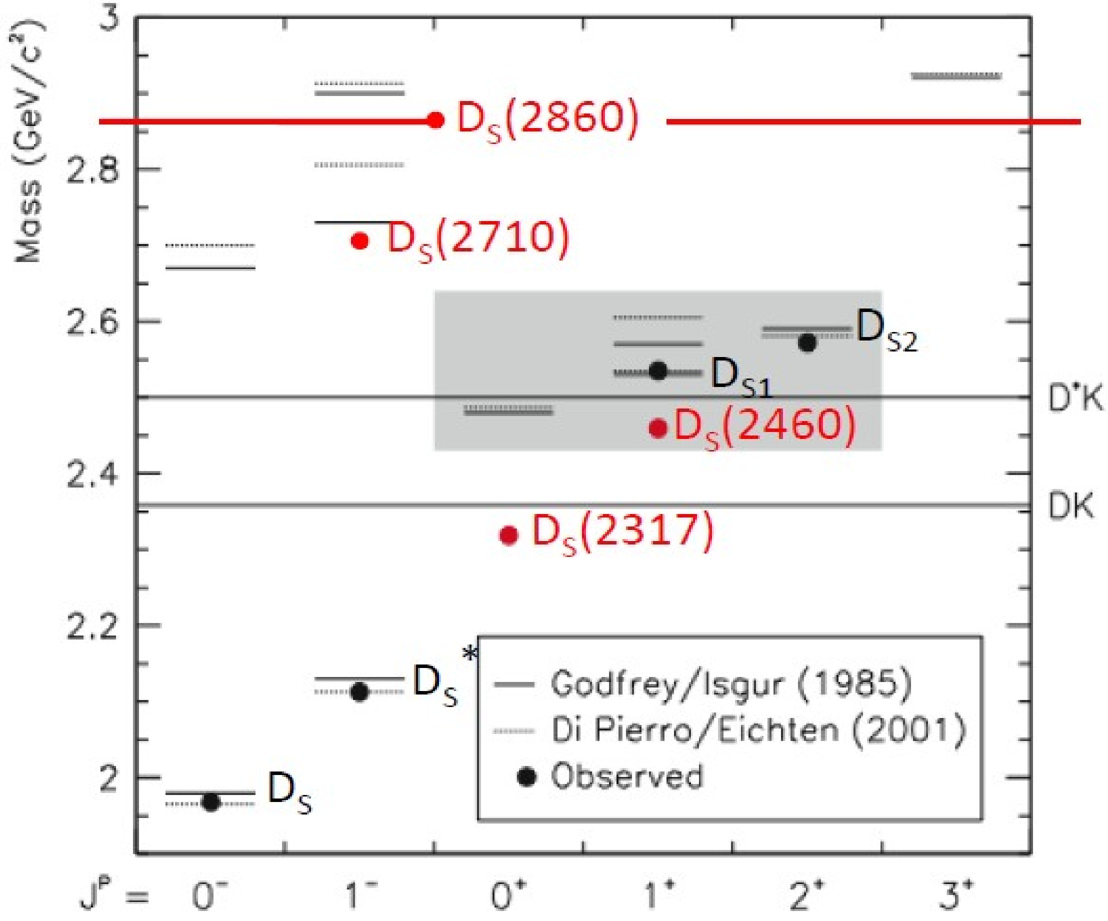
until 2003!

Excited D_s states



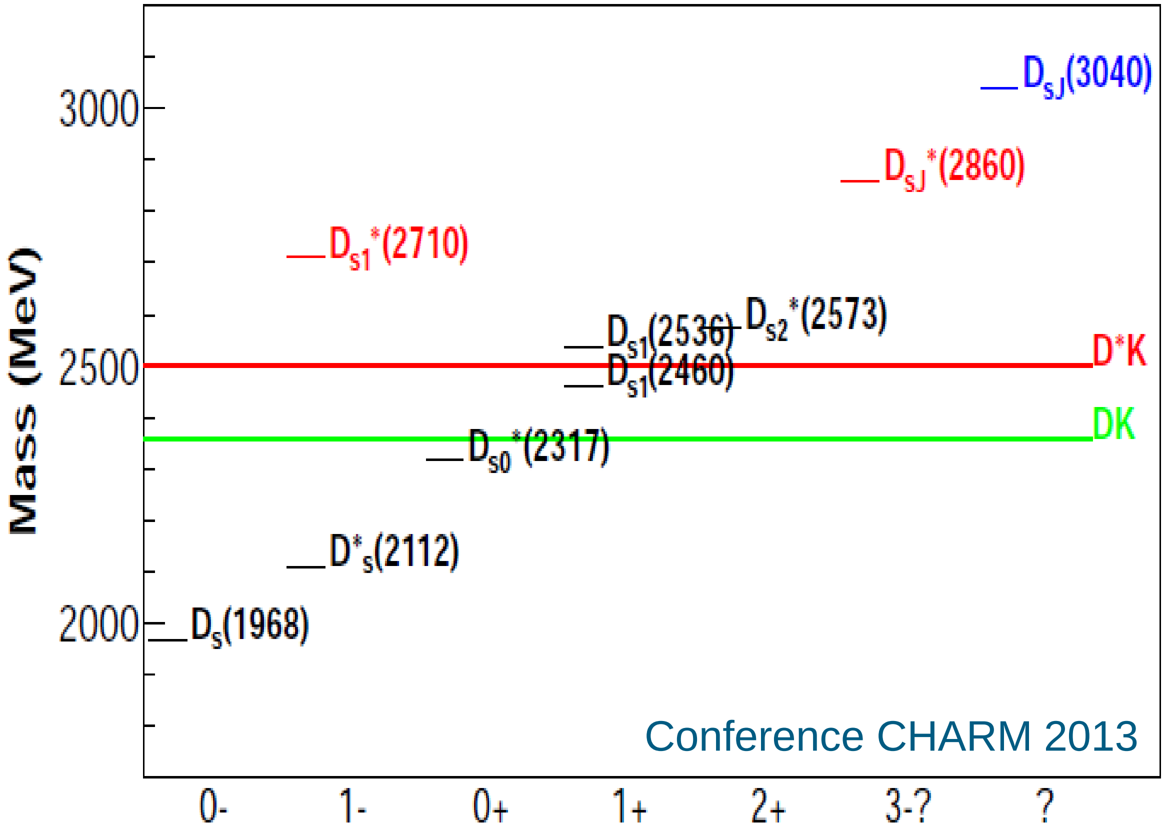
$D_s(2317)^+$ discovered in $e^+e^- \to c\bar{c}$, observed by BaBar [PRL 90 242001 (2003)], Belle [PRL 91 262002 (2003)], CLEO [PRB 340 (1994)]. Confirmed by LHCb

Excited D_s states



- Several others excited states have been found
- The identification of these states as 0^+ or 1^+ $c\bar{s}$ states is difficult in the potential model

Excited D_s states



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- The identification of these states as 0^+ or 1^+ $c\bar{s}$ states is difficult in the potential model

Experimental overview of D_{s0}*(2317) and D_{s1}(2460)

Decay Channel	$D_{sJ}^*(2317)^+$	$D_{sJ}(2460)^+$
$D_s^+\pi^0$	Seen	Forbidden
$D_s^+\gamma$	Forbidden	Seen
$D_s^+\pi^0\gamma$ (a)	Allowed	Allowed
$D_s^*(2112)^+\pi^0$	Forbidden	Seen
$D_{sJ}^*(2317)^+\gamma$	—	Allowed
$D_s^+\pi^0\pi^0$	Forbidden	Allowed
$D_s^+\gamma\gamma$ (a)	Allowed	Allowed
$D_s^*(2112)^+\gamma$	Allowed	Allowed
$D_s^+\pi^+\pi^-$	Forbidden	Seen

(a) Non-resonant only

- Most of theoretical works treat *$c\bar{s}$-systems* as the hydrogen atom (potential models, c=heavy quark):
- $D_{s1}(2326)^+$ and $D_{s2}(2573)^+$ are predicted, found with good accuracy

but:

m(D_{s0}*(2317)$^+$) found 180 MeV lower

m($D_{s1}(2460)^+$) found 70 MeV lower

than predicted

- $D_{s0}^*(2317)^+$ is found below the DK threshold:
- $D_{s0}^*(2317)^+$ can in principle decay
  - electromagnetically (no exp. evidence); or
  - through isospin-violation $D_s^+\pi^0$ strong decay

Is D_{s0}^* the missing 0^+ state of the *$c\bar{s}$-spectrum*?

- $D_{s1}(2460)^+$ is found in the inv. mass $D_s^+\gamma$
- Spin at least 1
- We can exclude the hypothesis 0^+, only, because $D_{s1}(2460)^+ \to D_s^+\gamma$

Is D_{s1} the missing 1^+ of the *$c\bar{s}$-spectrum*?

Do these 2 particles belong to the same family of exotics?

$D_{s0}^*(2317)^+$ theoretical overview

Different theoretical approaches, different interpretations	$\Gamma(D_{s0}^*(2317)^+ \to D_s \pi^0)$ (keV)
M. Nielsen, Phys. Lett. B 634, 35 (2006)	**6 ± 2**
P. Colangelo and F. De Fazio, Phys. Lett. B 570, 180 (2003)	**7 ± 1**
S. Godfrey, Phys. Lett. B 568, 254 (2003)	**10** Pure $c\bar{s}$ state
Fayyazuddin and Riazuddin, Phys. Rev. D 69, 114008 (2004)	**16**
W. A. Bardeen, E. J. Eichten and C. T. Hill, Phys. Rev. D 68, 054024 (2003)	**21.5**
J. Lu, X. L. Chen, W. Z. Deng and S. L. Zhu, Phys. Rev. D 73, 054012 (2006)	**32**
W. Wei, P. Z. Huang and S. L. Zhu, Phys. Rev. D 73, 034004 (2006)	**39 ± 5**
S. Ishida, M. Ishida, T. Komada, T. Maeda, M. Oda, K. Yamada and I. Yamauchi, AIP Conf. Proc. 717, 716 (2004)	**15 - 70**
H. Y. Cheng and W. S. Hou, Phys. Lett. B 566, 193 (2003)	**10 - 100** Tetraquark state
A. Faessler, T. Gutsche, V.E. Lyubovitskij, Y.L. Ma, Phys. Rev. D 76 (2007) 133	**79.3 ± 32.6** DK had. molecule
M.F.M. Lutz, M. Soyeaur, Nucl. Phys. A 813, 14 (2008)	**140** Dynamically gen. resonance
L. Liu, K. Orginos, F. K. Guo, C. Hanhart, Ulf-G. Meißner Phys. Rev. D 87, 014508 (2013)	**133 ± 22** DK had. molecule
M. Cleven, H. W. Giesshammer, F. K. Guo, C. Hanhart, Ulf-G. Meißner hep-ph: arXiV 1405.2242 (2014)	NEW! Strong and radiative decays of $D_{s0}^*(2317)$ and $D_{s1}(2460)$

$D_{S0}^{*}(2317)^{+}$ theoretical overview

JÜLICH FORSCHUNGSZENTRUM

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D_s^{0*} and D_{s1} theoretical overview: Hadronic width

M. Cleven, H. W. Griesshammer, F.-K. Guo, C. Hanhart, Ulf-G. Meissner, arXiV 1405.2242:[hep-ph]

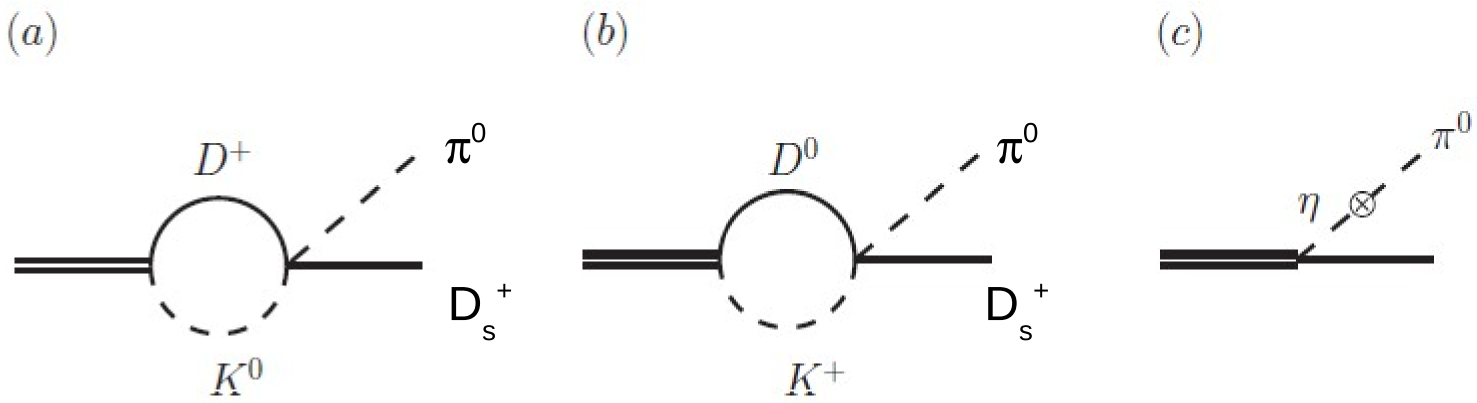


Figure 2: The two mechanisms that contribute to the hadronic width of the D_{s0}^*. (a) and (b) represent the nonvanishing difference for the loops with D^+K^0 and D^0K^+, respectively. (c) depicts the decay via π^0-η mixing.

- Contribution (a) – (b) non-zero for $m_{D+} \neq m_{D0}$, $m_{K+} \neq m_{K0}$; this applies to molecular states

Table 2: Hadronic decay widths from different mechanisms.

Decays	loops	π^0-η mixing	full result
$D_{s0}^* \to D_s\pi^0$	(26 ± 3) keV	(23 ± 3) keV	(96 ± 19) keV
$D_{s1} \to D_s^*\pi^0$	(20 ± 3) keV	(19 ± 3) keV	(78 ± 14) keV

D_s^{0*} and D_{s1} theoretical overview: Radiative width

M. Cleven, H. W. Griesshammer, F.-K. Guo, C. Hanhart, Ulf-G. Meissner, arXiV 1405.2242:[hep-ph]

Table 3: The decay widths (in keV) calculated only from the coupling to the electric charge (EC), from the magnetic moments (MM) and from the contact term (CT), respectively, compared to the total (including interference). The CT strength for the transitions to odd parity mesons is fixed to data, while that to even parity states, marked as '?', is undetermined and part of the uncertainty.

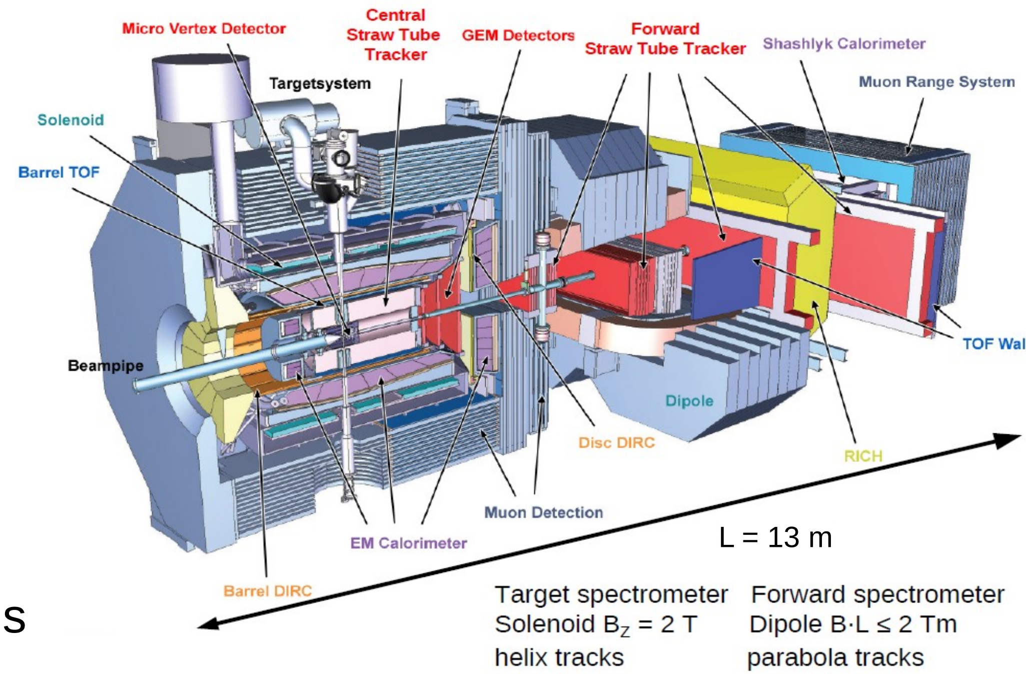
Decay Channel	EC	MM	CT	Sum	[1]	[2]	[3,4,5]
$D_{s0}^* \to D_s^* \gamma$	2.0	0.03	3.3	9.4	$4-6$	1.94(6.47)	0.55-1.41
$D_{s1} \to D_s \gamma$	4.2	0.2	11.3	24.2	$19-29$	44.50(45.14)	2.37-3.73
$D_{s1} \to D_s^* \gamma$	9.4	0.5	10.3	25.2	$0.6-1.1$	21.8(12.47)	–
$D_{s1} \to D_{s0}^* \gamma$	–	1.3	?	1.3	$0.5-0.8$	0.13(0.59)	–

[1] P. Colangelo, F. De Fazio, A. Ozpineci. PRD 72, 074004 (2005);
[2] M. F. M. Lutz, M. Soyeur, Nucl. Phys. A 813, 14 (2008);
[3] A. Faessler, T. Gutsche, V. E. Lyubovitskij and Y. L. Ma, PRD 76, 014005 (2007);
[4] A. Faessler, T. Gutsche, V. E. Lyubovitskij and Y. L. Ma, PRD 76, 114008 (2007);
[5] A. Faessler, T. Gutsche, V. E. Lyubovitskij and Y. L. Ma, PRD 77, 114013 (2008).

- **Only hadronic decays are sensitive to a possible molecular component of D_{s0}^* and D_{s1}**
- **Hadronic width of ≥ 100 KeV: unique feature for molecular state**
- **Demand for a new generation machine: Δm ~100 keV, 20 times better than attained at B factories**

The detector $\bar{P}$ANDA @ FAIR

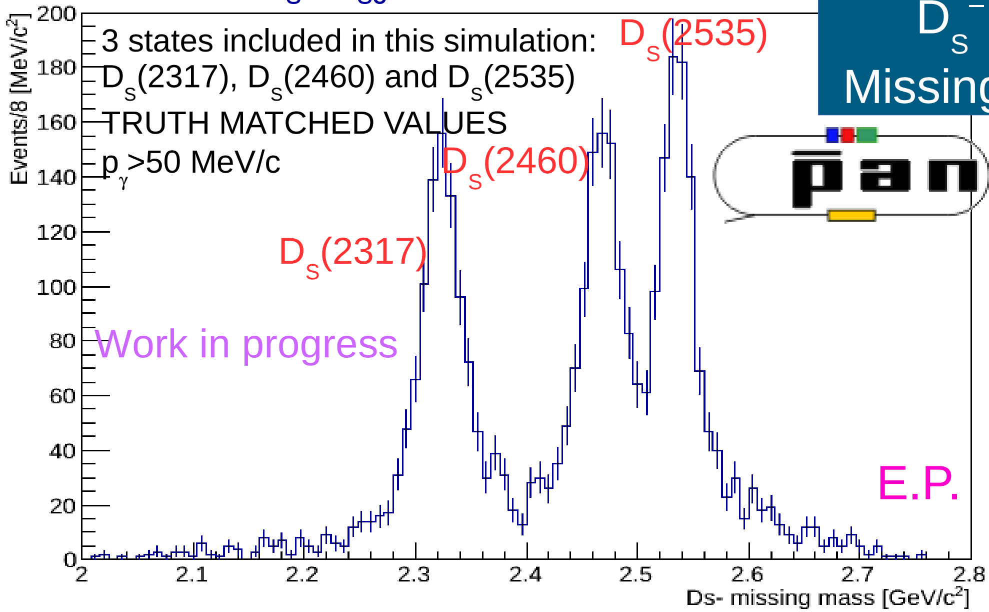
- $\bar{P}$ANDA is a fixed target detector, with antiproton beam up to p = 15 GeV/c
  - Why antiprotons?
    access to all quantum numbers!
  - Particles in formation:
    mass resolution ~ 100 KeV
  - $\Delta p/p \sim 10^{-4}; 10^{-5}$
  - High boost $\beta_{cms} \geq 0.8$
  - Many tracks and photons in fwd acceptance ($\theta \leq 30°$), high p_z, E_γ



- High background from hadronic reactions
  - Expected S/B ~ 10^{-6}
  - S (signal) and B (background) have same signature
  - Hardware trigger not possible
  - Self-triggered electronics
  - Free streaming data
  - 20 MHz interaction rate
  - Complete real-time event reconstruction

Challenges in D_s meson spectroscopy

- $\bar{p}p \rightarrow D_s^- D_{sJ}^+$

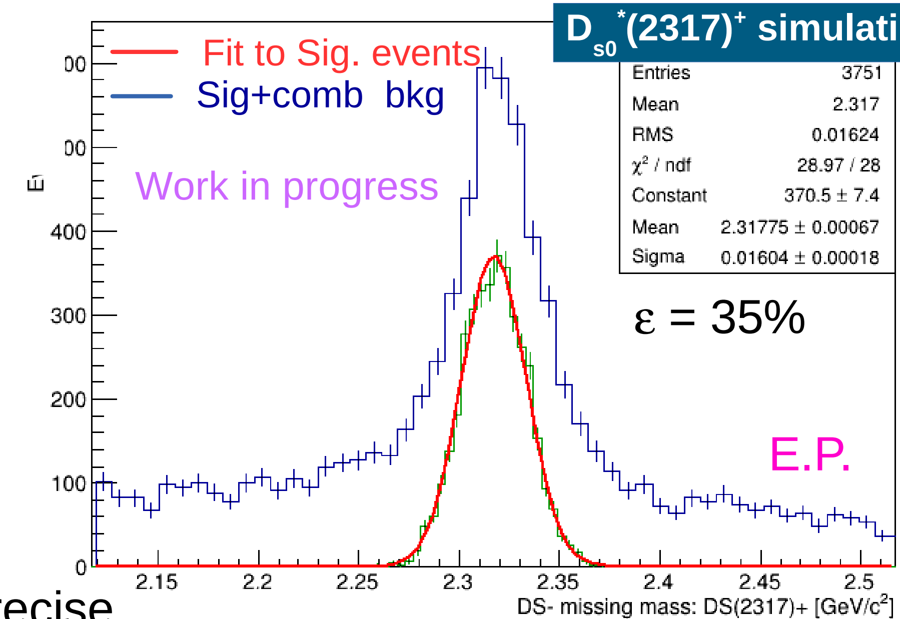


D_s^-
Missing M

- Missing mass of D_s^-: improve mass resolution and efficiency
- D_{SJ} reconstructed exclusively to evaluate the width
- Bkg cross section > thousand times than expected on signal
- Expected ~$(10^3\text{-}10^5) \cdot \varepsilon$ events/day

high res. mode

$D_{s0}^*(2317)^+$ simulation



$\varepsilon = 35\%$

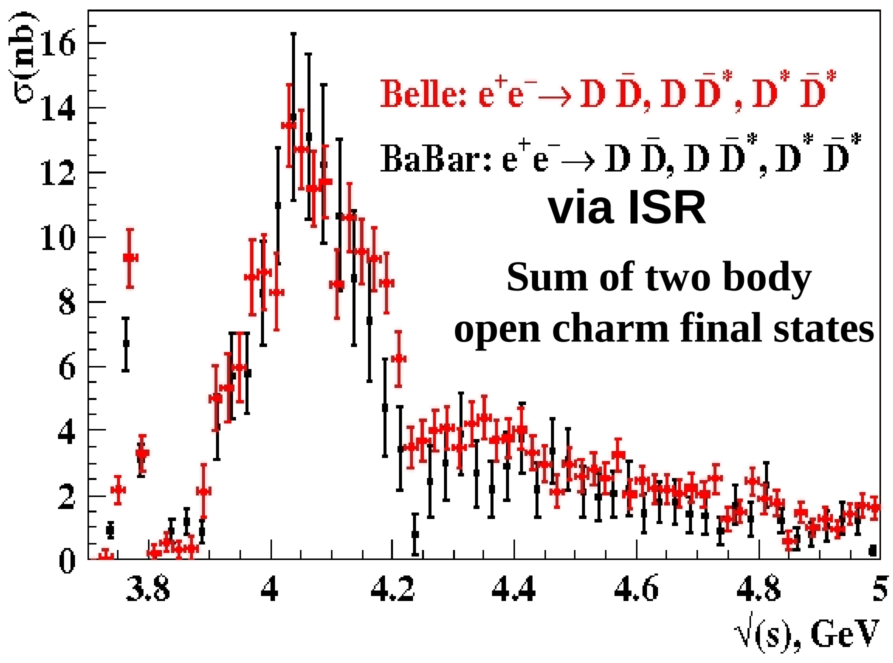
- Goals:

1. Cross section measurement in $\bar{p}p$ (unknown, difficult predictions: 1-100 nb)
2. Measurement of the width with mass scan and the excitation function of cross section
3. Mixing between D states with same spin, e.g. $D_{S1}(2460)$ and $D_{S1}(2535)$
4. Chiral symmetry breaking, involving very precise mass measurement: $D_{S0}(2317)$ and $D_{S1}(2460)$ can be interpreted as chiral partners of the same heavy-light system

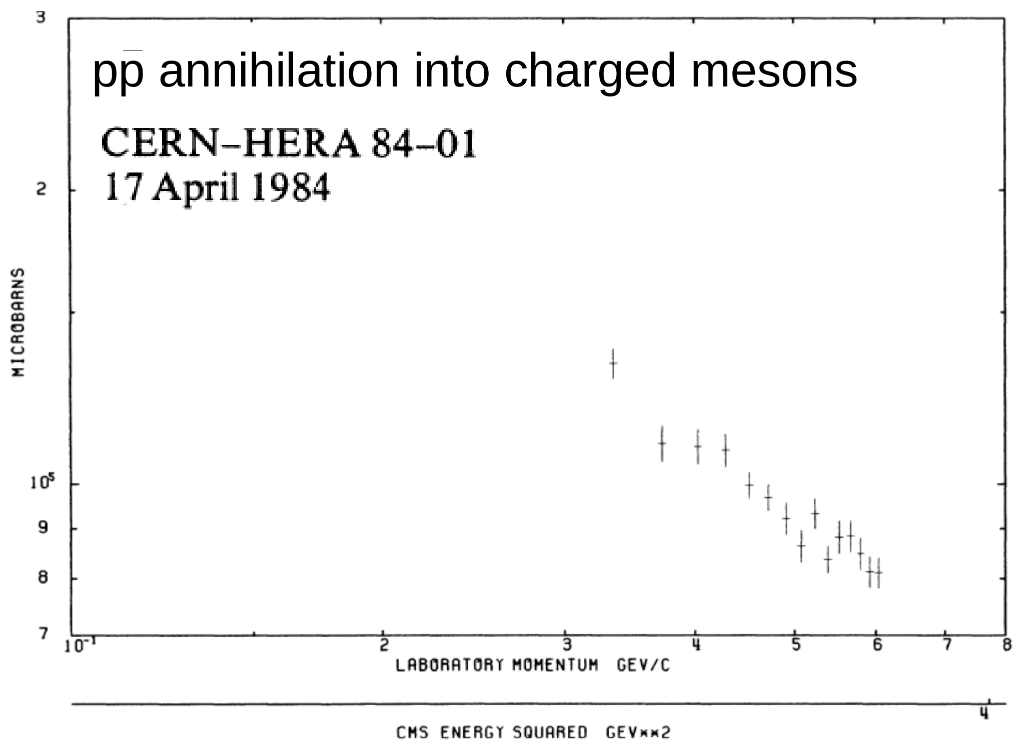
1. Cross section

- Predictions are complicated due to the s-quark for D_{sJ} mesons: expected <100nb
- Inclusive search: better for cross section measurement, but higher background. Challenge!
- Exclusive cross section measurement: feasible, but theoretical predictions are difficult

Phys. Rev. Lett. 98, 092001 (2007)
Phys.Rev. D79, 092001(2009)



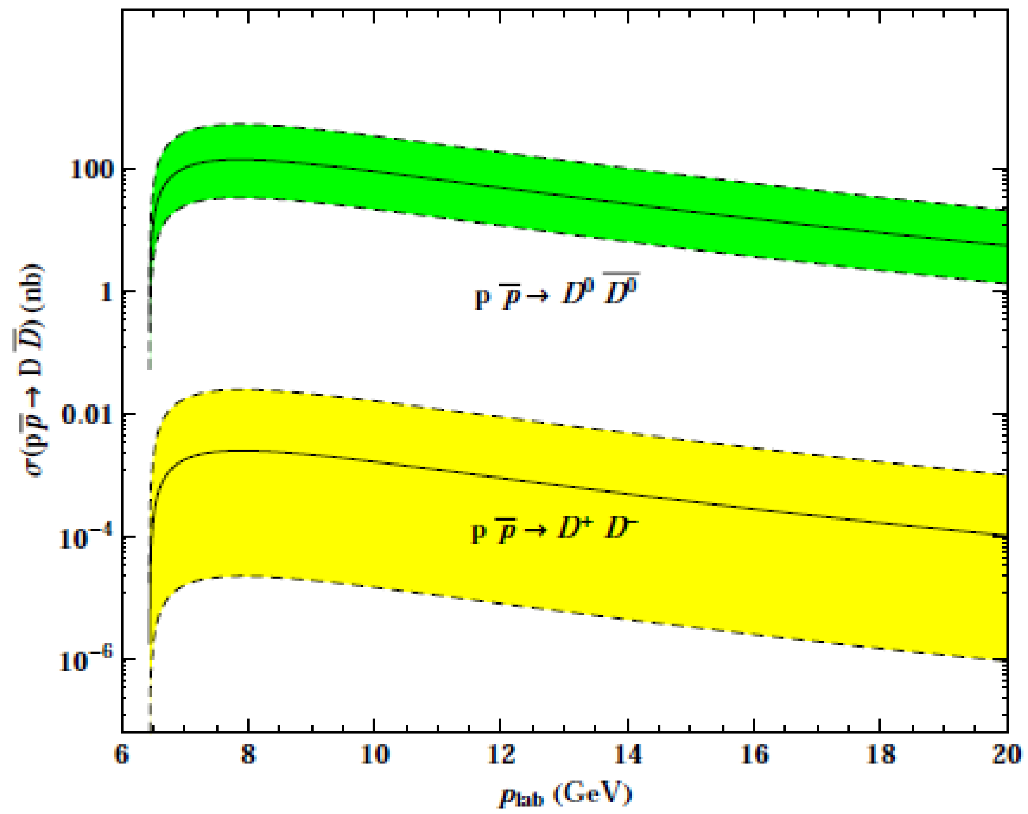
V. Flaminio, W.G. Moorhead, D.R.O. Morrison, N. Rivoire



- Our simulations in $\bar{P}ANDA$ for the D_{s0}* and D_{s1} cross section: p > 8.8 GeV/c

1. Cross section

- Better theoretical predictions exist for the charmed ground states (D^+, D^0)
- Even in the D_J sector (no s-quark), for excited states calculations are difficult
- Calculation in perturbative regime can under-estimate the real cross section



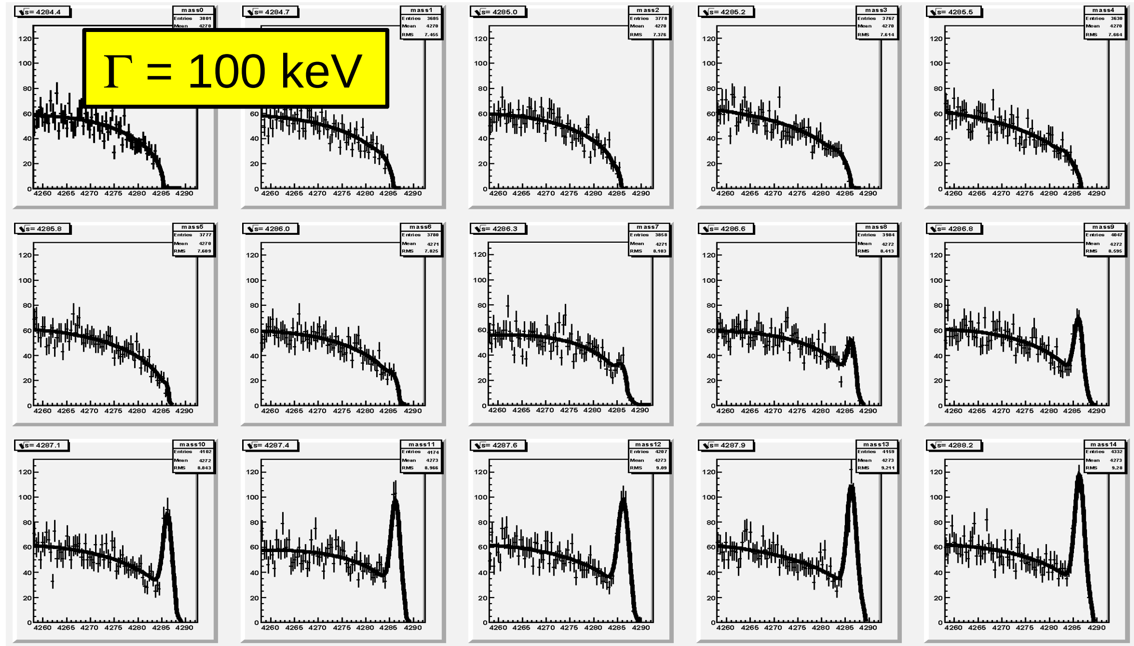
http://arxiv.org/abs/1111.3798

A. Khodjamirian, Ch. Klein, Th. Mannel, Y.M. Wang

2. Scan of $D_{s0}^{*}(2317)^{+}$

- $D_{s0}^{*}(2317)^{+} \rightarrow D_s^{+}\,\pi^0$

M. Mertens

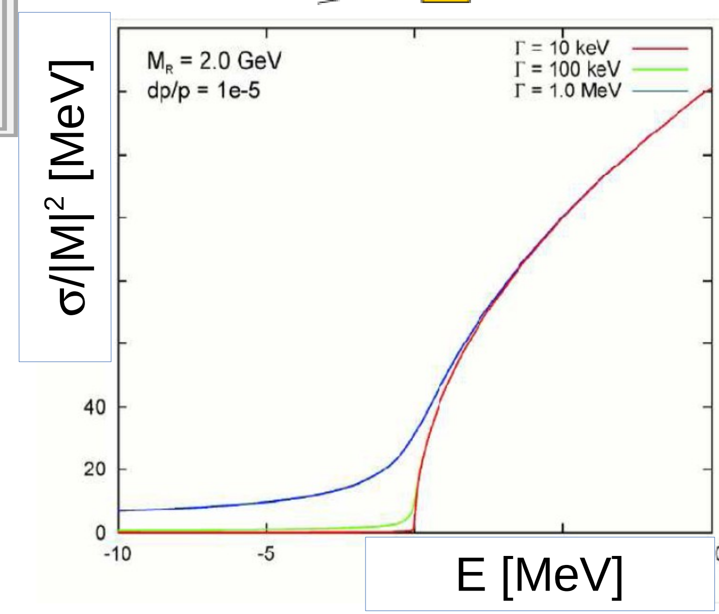


- PDG: Γ <4.6 MeV at 90% c.l.
- Excitation function of the cross section:

$$\sigma(\lambda) = \sqrt{m_R \Gamma}\,|M^2|\,\frac{1}{\pi}\int_{-\infty}^{\lambda} \mathrm{d}x,\ \frac{\sqrt{\lambda - x}}{x^2+1}$$

$$\sigma(0) = \sqrt{\frac{m_R \Gamma}{2}}\,|M^2|$$

$$\lambda = (\sqrt{s} - 2M_R)/\Gamma$$



3. Mixing

- System of heavy-light quark (*c* = heavy; *s* = light)

  The angular momentum j = l+s (light quark) is conserved
  P wave states ⇨ j = 3/2 or j = 1/2

- Total angular momentum of the system with light quark + heavy quark: J=2 or 1
  States with $J=2^+$ or 1^+ are expected to have a small width ($D_{sJ}(2573)^+$, $D_{s1}(2536)^+$)

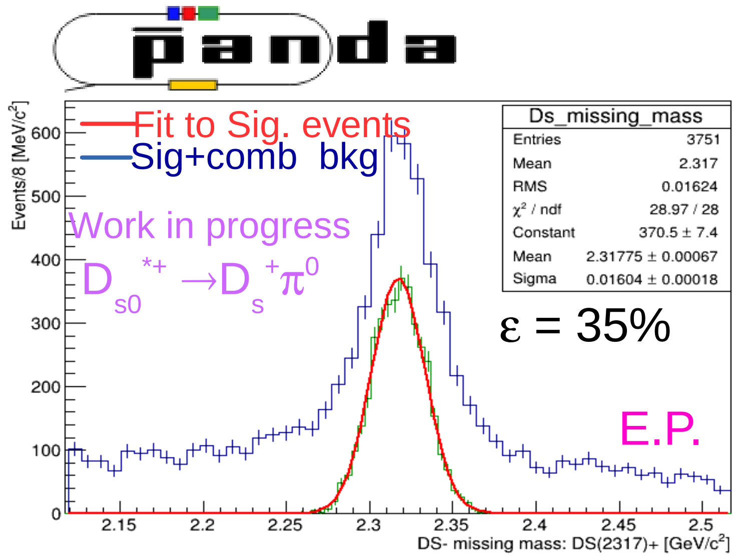
- $D_{s1}(2536)^+$ can include a small mixing of the j=1/2, $J^P=1^+$ state

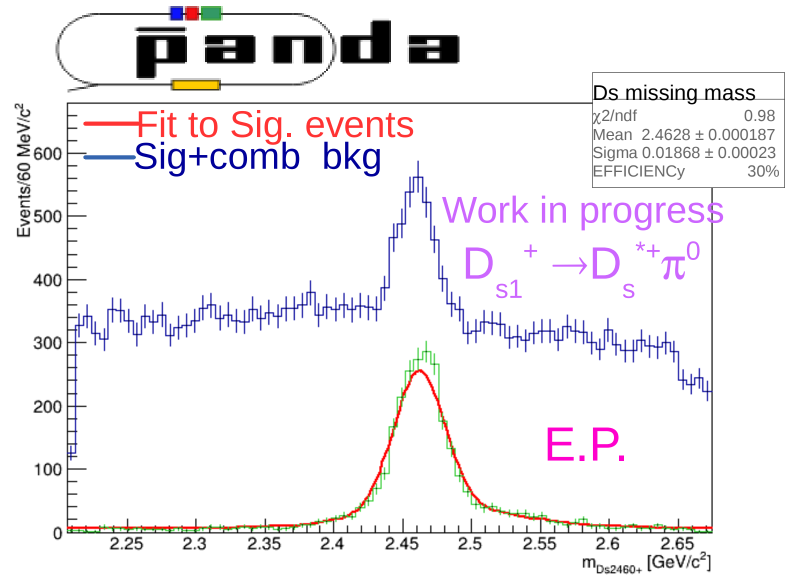
  $D_{s1}(2460)^+$ j=1/2 (supposed to be pure S-wave)
  $D_{s1}(2536)^+$ j=3/2 (supposed to be pure D-wave)

- Experiments showed an overlap between S- and D- waves
  $\Delta m = 78\ MeV/c^2$, $\Gamma < 2.3$ MeV. **Why do they mix?**

PANDA could help solving this puzzle

4. Chiral limit



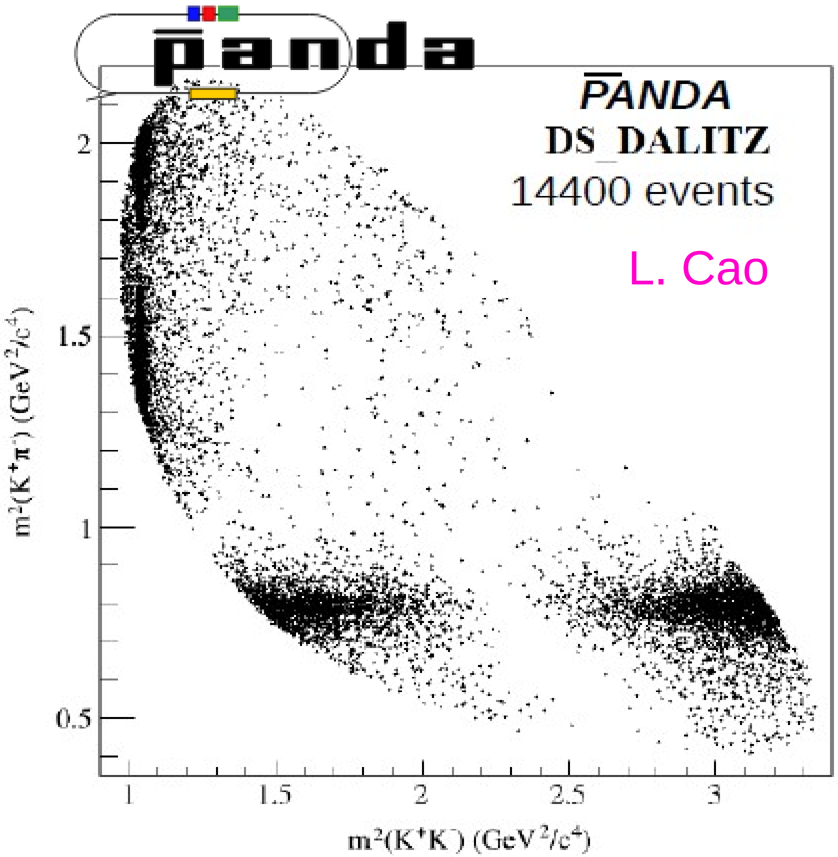


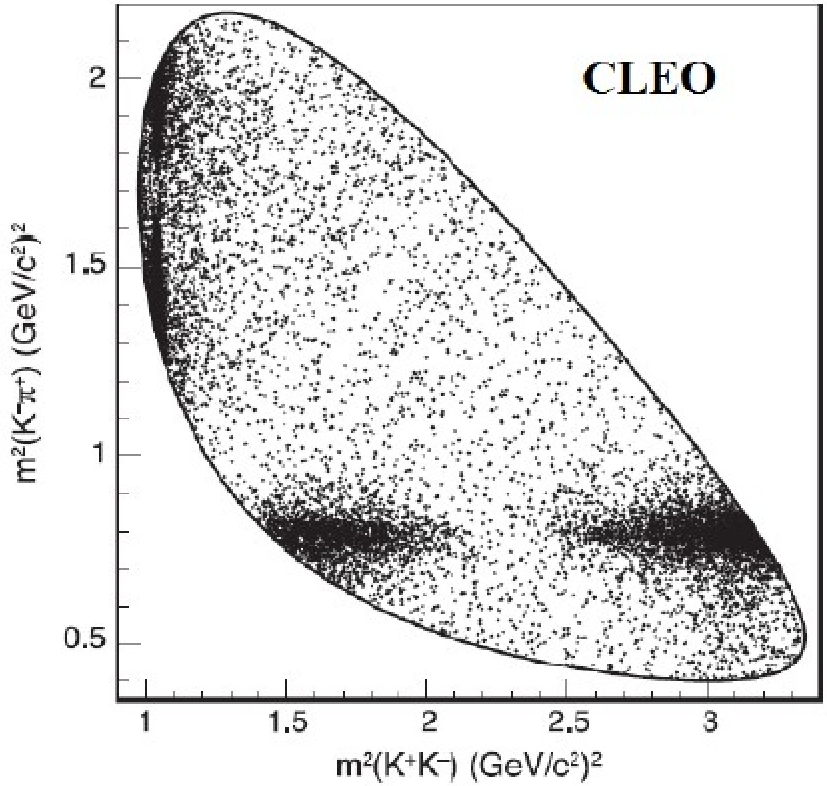
- The 2 states $D_s(2317)^+$ and $D_s(2460)^+$ could be interpreted as first chiral partners of hadrons built with heavy+light quarks.

- The sector of light quark mass is characterized by spontaneous breaking of chiral symmetry. The sector of heavy quark mass features symmetry

- The spontaneous chiral symmetry breaking leads to a mass splitting for chiral doublets, expected to be ~ 345 MeV/c^2. Experiments quote:
$m(D_s^+\pi^0) - m(D_s) = (350.0\pm1.2\pm1.0)$ MeV/c^2 ($D_{sJ}(2317)^+$ was observed in $D_s^+\pi^0$)
$m(D_s^{*+}\pi^0) - m(D^*_s) = (351.2\pm1.7\pm1.0)$ MeV/c^2 ($D_s(2460)^+$ was observed in $D_s^{*+}\pi^0$)
However, it was never observed in B_s systems...

Realistic amplitude model in our simulations





- Full detector simulation
- PID: likelihood method

PandaRoot = Root-based framework developed inside the FairRoot project, for FAIR experiments and PANDA

- D. Bertini, M. A-Turany, I. Koenig and F. Uhlig , Journal of Physics: Conference Series 119 (2008) 032011
- S. Spataro, Journal of Physics: Conference Series 396 (2012) 022048

Summary

- Several open questions in Charm Physics
- Need precise measurements to better understand the $c\bar{s}$*-spectrum*
- $\overline{P}$*ANDA* offers the opportunity to perform very precise measurements
- Expected mass resolution 100 keV: 20 times better than B factories
- Need very high mass resolution to discriminate among theoretical models
- Simulations at advanced stage in our project
- Wide and ambitious physic program from $\overline{P}$*ANDA* @ FAIR, not only in the sector of charm physics
- Important and original contributions expected from $\overline{P}$*ANDA* measurements

$\overline{\text{P}}$ANDA Collaboration, >500 physicists, 18 Countries (2014)

THANKS!

"The greatest danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieve our mark." (Michelangelo, 1475 - 1564)

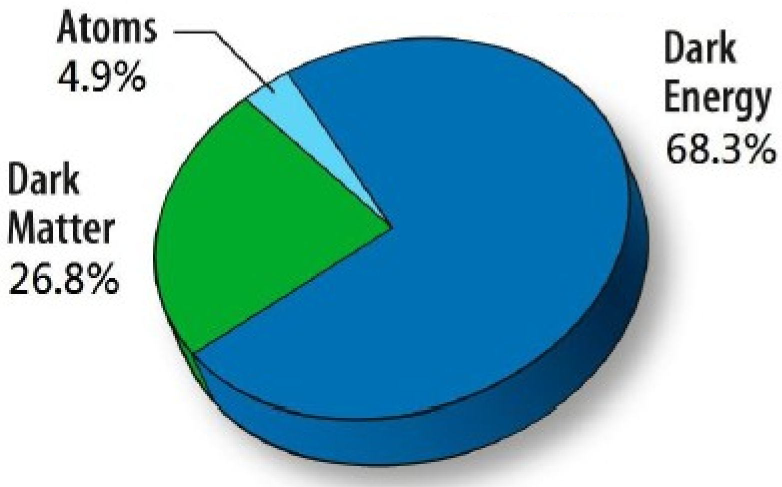
Back up slides

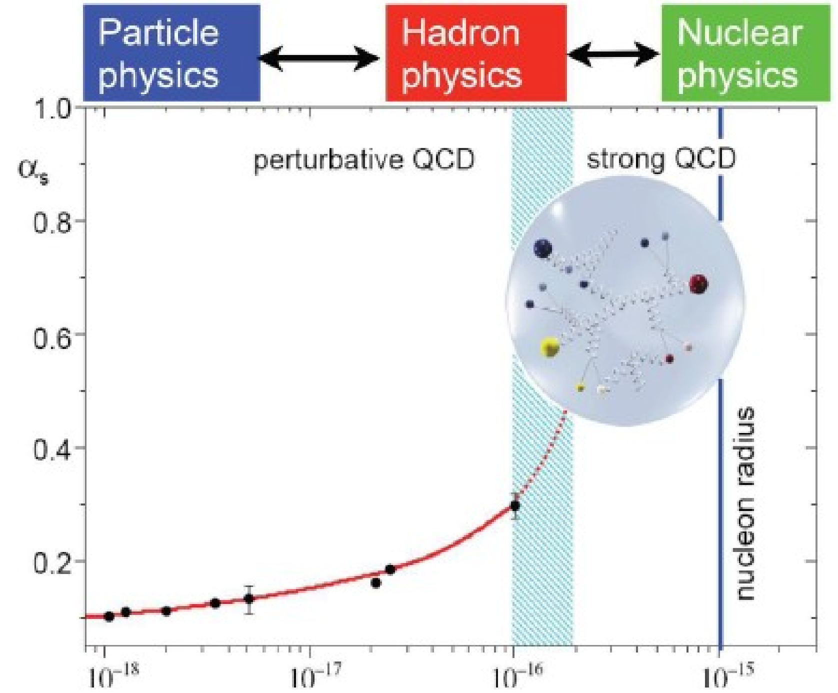
Motivation: the physics case

Understanding confinement
Origin of hadron masses

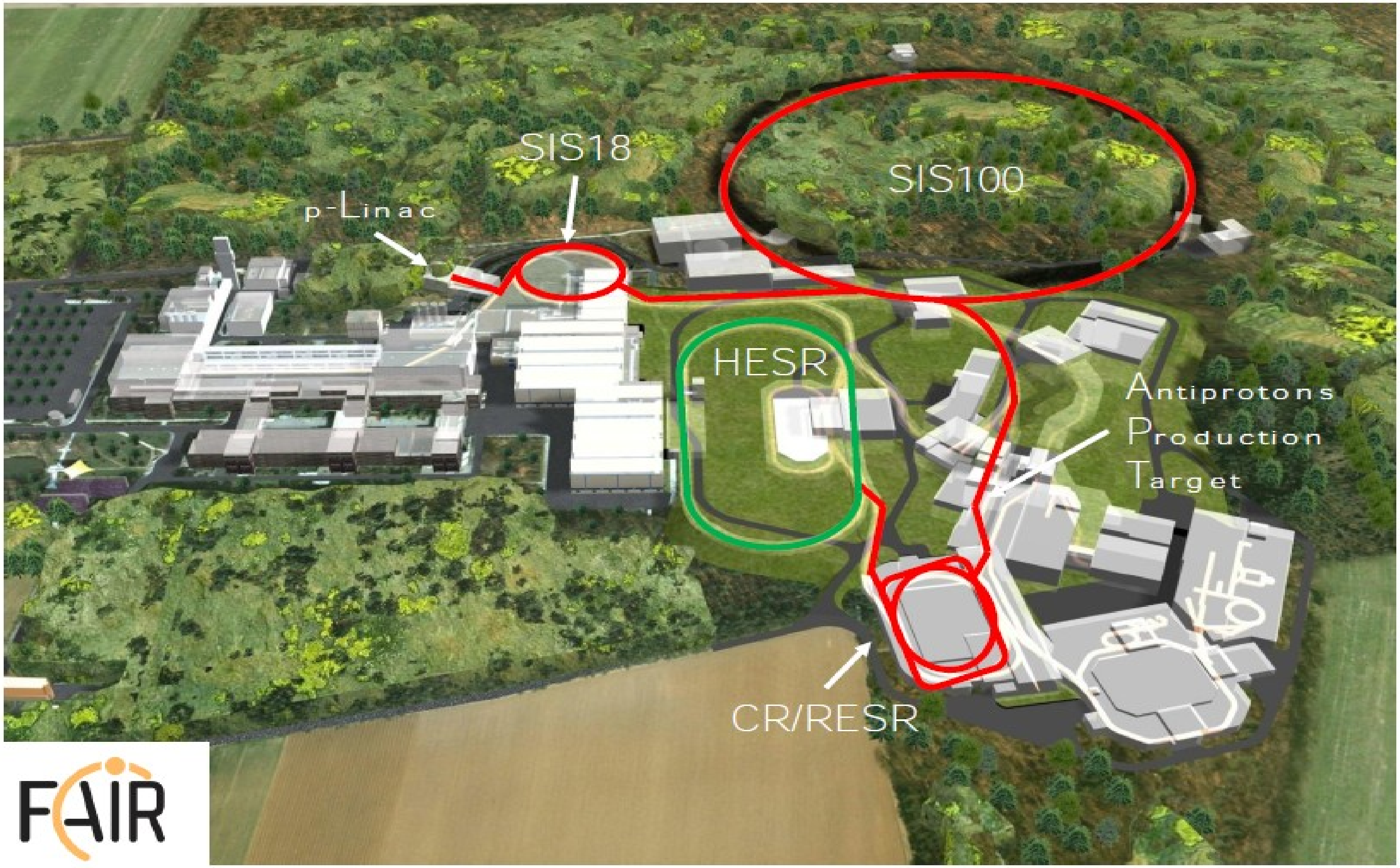
through the study of

- Hadron spectroscopy
  - Search for gluonic excitations
  - Charmonium spectroscopy
  - D meson spectroscopy
  - Baryon spectroscopy
  - QDC dynamics
- Nucleon structure
  - Parton distributions
  - Time-like form factors of the proton
  - Transition distribution amplitudes
  - Generalized distribution amplitudes
- Hadrons in matter
- Hypernuclei





Facility for Antiproton and Ion Research



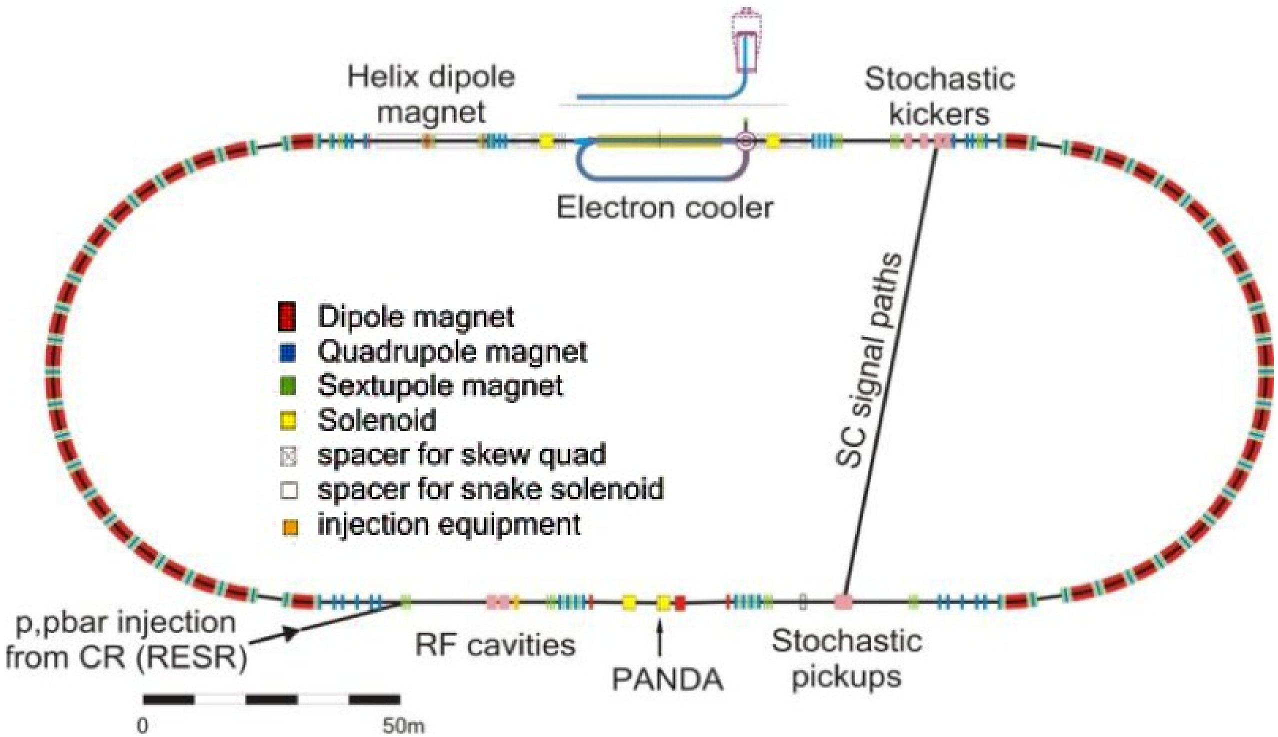
Scientific pillars of FAIR:

1. **A**tomic, **Pl**asma **P**hysics and **A**pplications – *APPA*
2. **C**ompressed **B**aryonic **M**atter – *CBM*
3. **NU**clear **ST**ructure, **A**strophysics and **R**eactors – *NUSTAR*
4. anti**P**rotons **AN**nihilation at **DA**rmstadt - *PANDA*

A bird view of the site

Total area > 200 000 m^2
Area buildings = 98 000 m^2
Usable area = 135 000 m^2

HESR with $\overline{P}$ANDA



HESR	
575 m	Circumference
1.5 – 15 GeV/c	Momentum
up to 9 GeV/c	Electron Cooling
Full range	Stochastic Cooling

- Thick target: $4 \cdot 10^{15}$ cm^{-2}
- Beam life time >30 min

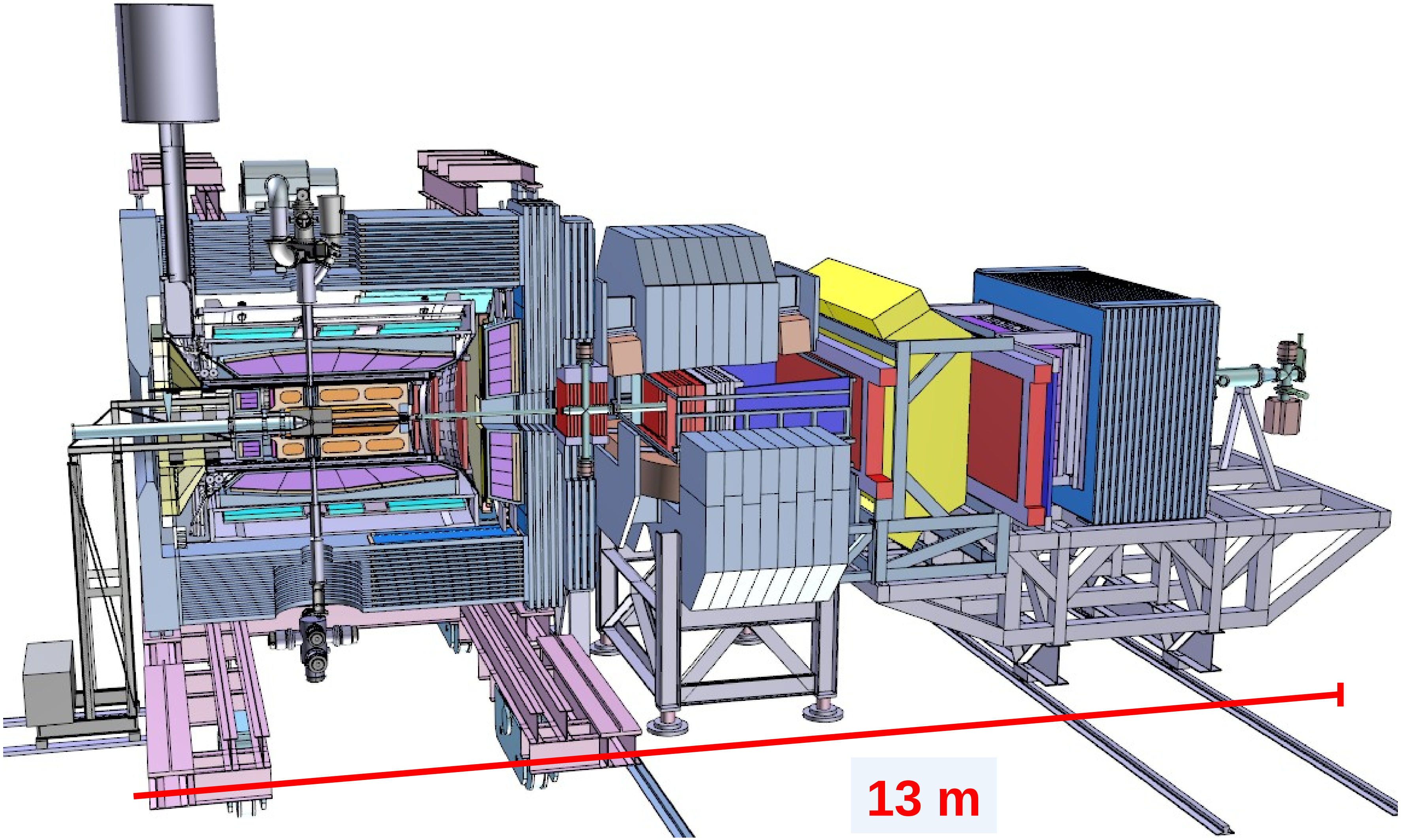
High resolution mode

- e^- cooling, $1.5 \leq p \leq 8.9$ GeV/c
- 10^{10} antiprotons stored
- Luminosity up to $2 \cdot 10^{31}$ cm^{-2} s^{-1}
- $\Delta p/p = 4 \cdot 10^{-5}$

High intensity mode

- Stochastic cooling, $p \geq 3.8$ GeV/c
- 10^{11} antiprotons stored
- Luminosity up to $2 \cdot 10^{32}$ cm^{-2} s^{-1}
- $\Delta p/p = 2 \cdot 10^{-4}$

The detector $\bar{P}$ANDA @ FAIR



- Pre-assembling at COSY, Jülich

PANDAROOT status

Progress in MC Simulation

PANDA Physics Performance Report arXiv:0903.3905[hep-ex]	NEW FRAMEWORK PandaRoot D Bertini, M A-Turany, I Koenig and F Uhlig Journal of Physics 119 (2008) 032011 S. Spataro Journal of Physics 331 (2011) 032031
homogenous B_Z field	B field maps (precision ≤1 cm)
MC truth track finder	pattern recognition track finder
	materials (pipes, cables) → used for track reconstruction (Kalman filter)
phasespace decays	Dalitz models (sub-resonances) for D and D_S decays
	new physics topics not covered before, e.g. X(3872)

Courtesy of S. Lange, Charm2013