Open-charm Physics: from e^+e^- to $\bar{p}p$ machines

29th May, 2017 | Elisabetta Prencipe, Forschungszentrum Jülich (DE)| FAIRNESS 2017, Sitges (ES)
on behalf of the $\bar{\text{P}}$ANDA Collaboration

Outline

- Motivation
- Theoretical overview
- Experimental observations
- The role of the $\overline{\text{P}}$ANDA experiment @ FAIR
- Future perspectives
- Conclusion

Introduction

Since 2003

- Unexpected observations posed the potential models into questions
- Charm (cq) and Charmonium ($c\bar{c} + q\bar{q}$) sectors populated by several new states
- Strangeness in Charm and Charmonium physics still to be exploited
- Great contribution from past and still presently running experiments [BaBar, Belle, CLEO2, BES III, CDF, CMS, D0, LHCb]:
  - ▸ spectrum still to be understood
  - ▸ different interpretations
- Charm sector: D mesons interesting for *weak*- and *strong*- interactions:
  D and D_s mesons predicted;
  D_s mesons below DK threshold still of unclear interpretation [BaBar, Belle, CLEO2]:
  - ▸ limitations due to the past experiments to measure the D_s line shape;
  - ▸ limitation at LHCb to detect D_s states below the DK threshold.
    → low momentum photons

Introduction

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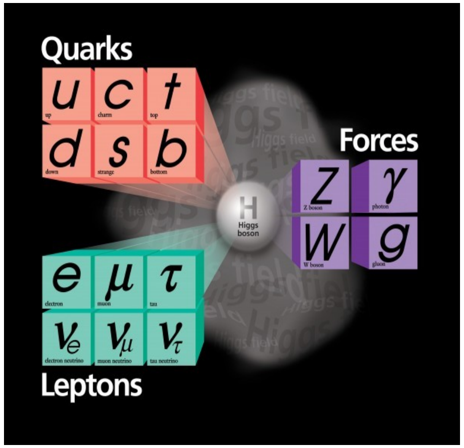
  - ▸

This talk is mainly devoted to D_s spectroscopy
STRONG INTERACTIONS

Charm physics



$D^0 = |c\bar{u}\rangle$, $D^+ = |c\bar{d}\rangle$;

Charged and neutral D mesons

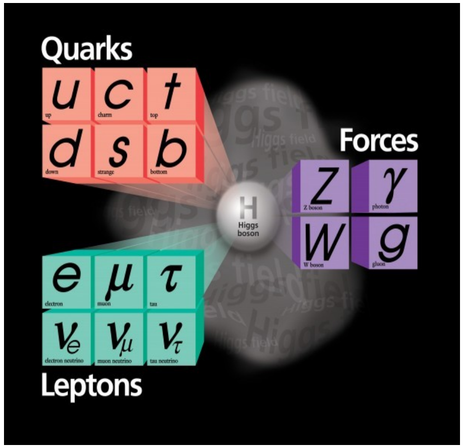
$D_s^+ = |c\bar{s}\rangle$

Charged D_s mesons

Why is that interesting?

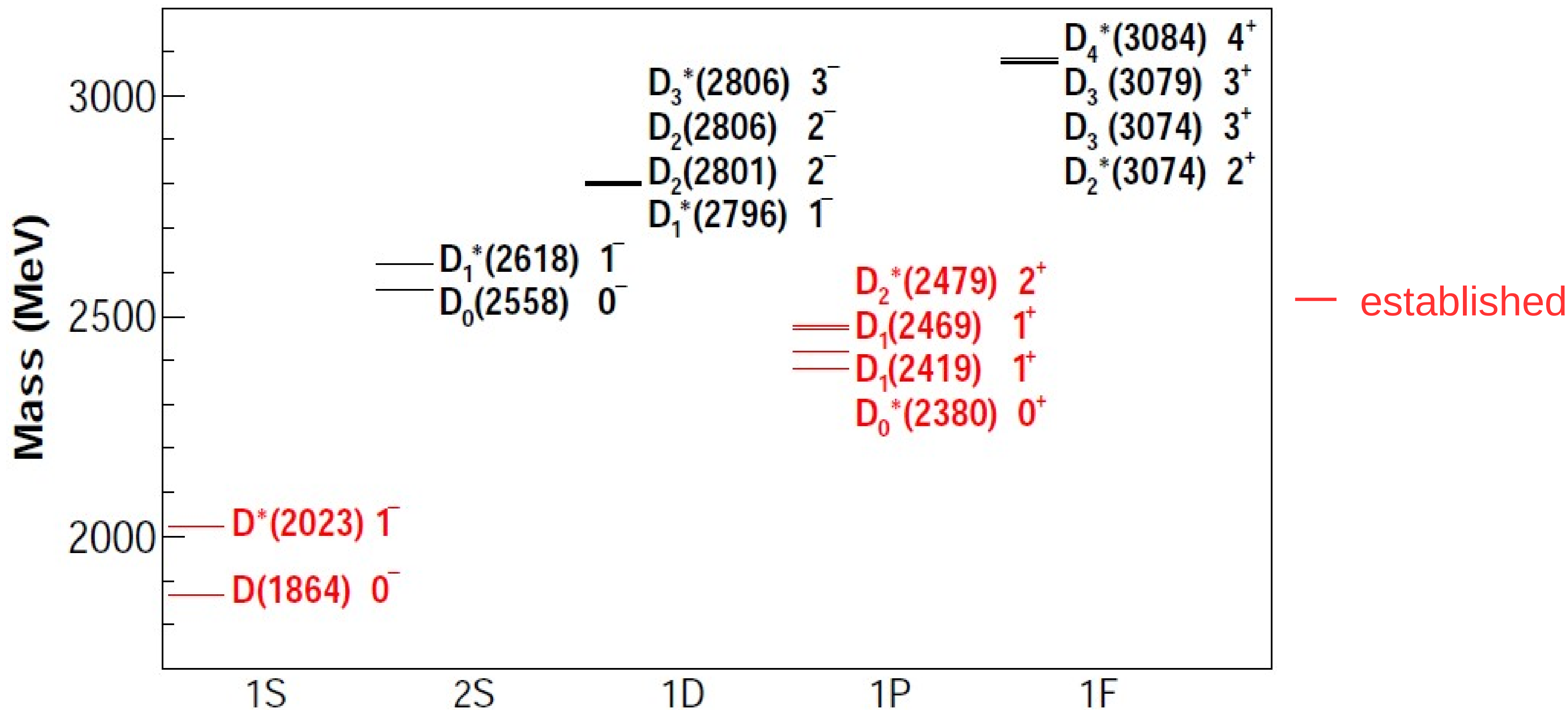
Charm physics

$D^0 = |c\bar{u}\rangle$, $D^+ = |c\bar{d}\rangle$;
$D_s^+ = |c\bar{s}\rangle$



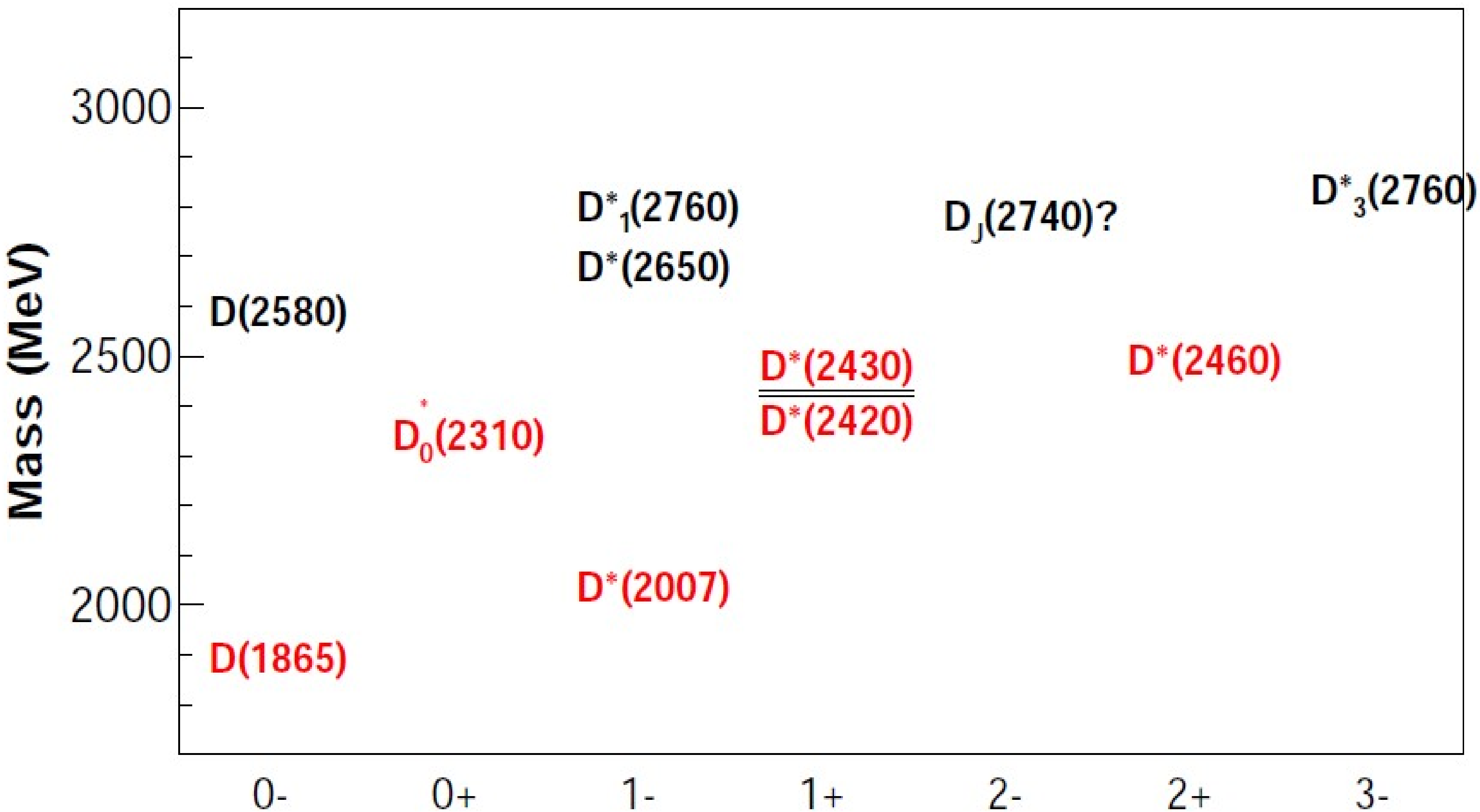
- Why the interest in charm physics
  - Strong interactions
    - QCD
    - Intermediate case between heavy and light quarks
    - Spectroscopy
    - Strong decay modes
  - Weak interactions
    - CP violation
    - Mixing
    - Possible window to search for New Physics beyond the Standard Model

Charm spectrum

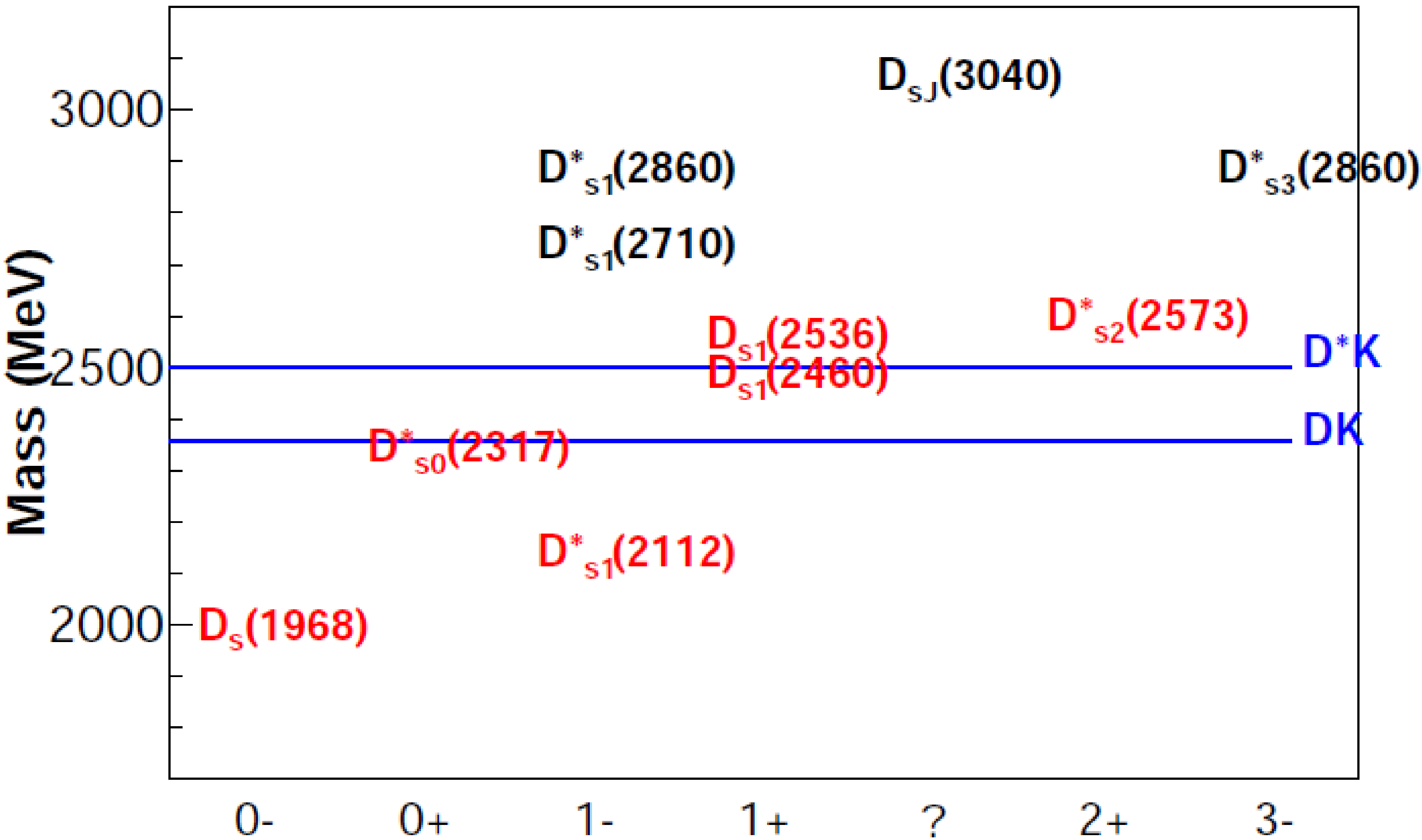


- States having $J^P = 0^+, 1^-, 2^+, 3^-, \ldots$ are defined as having "Natural Parity"
- States having $J^P = 0^-, 1^+, 2^-, \ldots$ are defined as having "Unnatural Parity"
- A resonance decaying to $D\pi$ has "Natural Parity" (labeled D^*)
- The $D^*\pi$ system can access to both "Natural Parity" and "Unnatural Parity", except for $J^P = 0^+$ (forbidden)
- Access via inclusive $e^+e^- \to D_J X$ (BaBar, Belle) and $pp \to D_J X$ (LHCb)

Charm spectrum, today

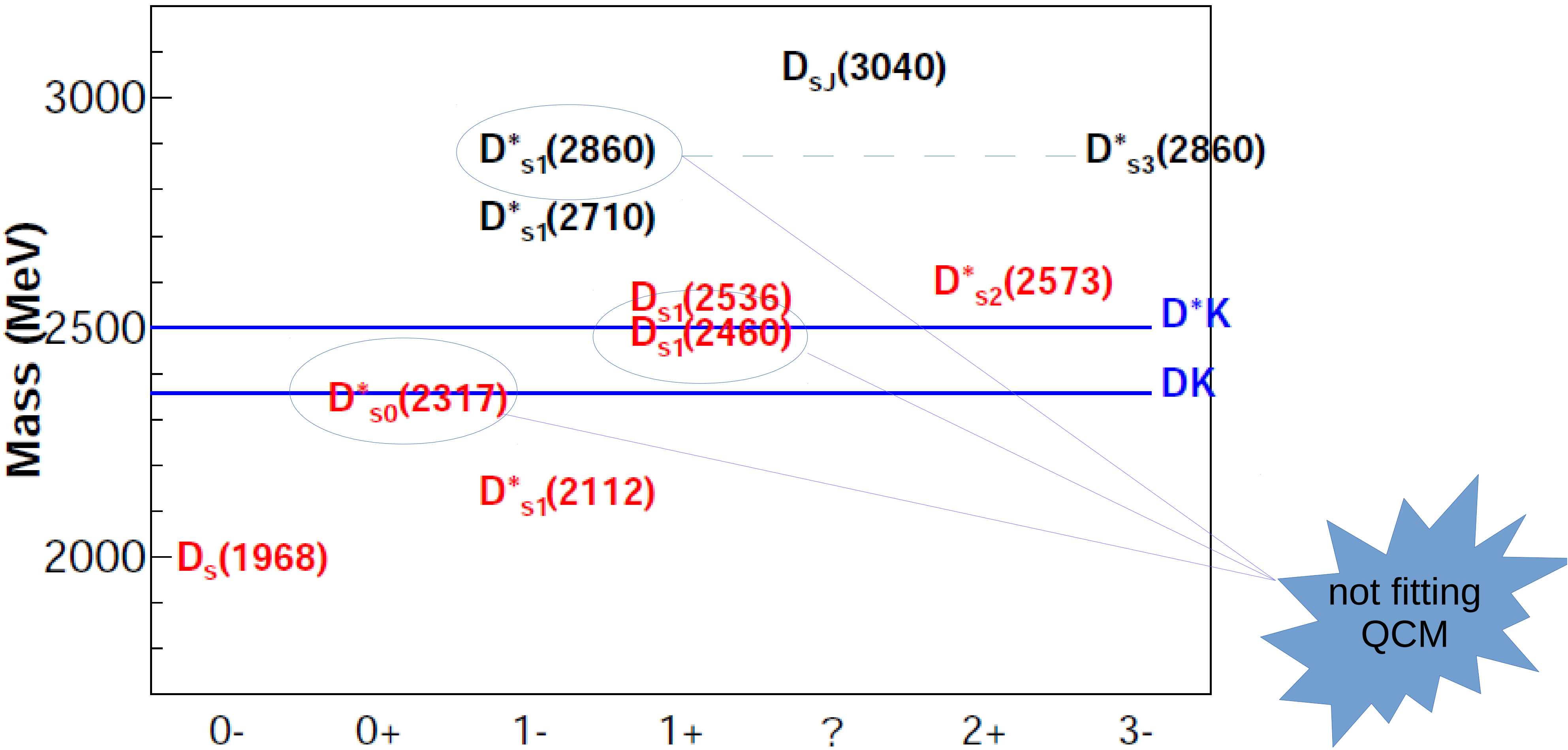


Charm-strange spectrum, today



courtesy of A. Palano

Charm-strange spectrum, today



QCM = quark conventional model

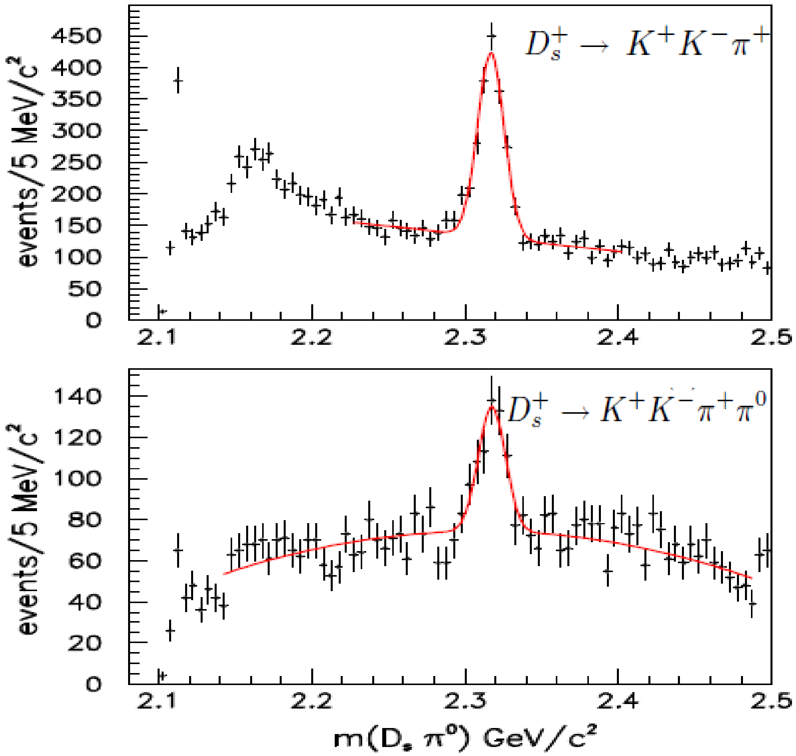
courtesy of A. Palano

How did the D_s-*story* begin?

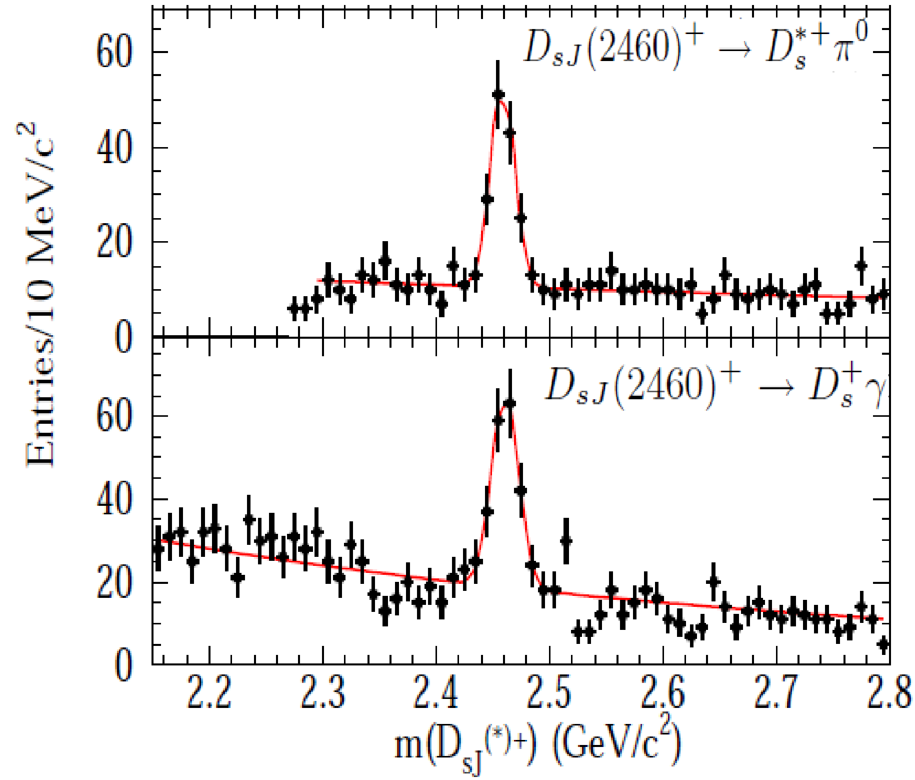
Observation of $D_{s0}^{*}(2317)$ and $D_{s1}(2460)$

JÜLICH FORSCHUNGSZENTRUM

BABAR, PRL 90 (2003) 242001



BABAR, PRL 93 (2004) 181801



$m(D_{s0}^{*}(2317)^{+}) = (2317.7\pm0.6)$ MeV/c^2

$m(D_{s0}^{*}(2317)^{+} - m(Ds^{+})) = (349.4\pm0.6)$ MeV/c^2

$\Gamma < 3.8$ MeV CL=95.0%

$m(D_{s1}(2460)^{+}) = (2459.5\pm0.6)$ MeV/c^2

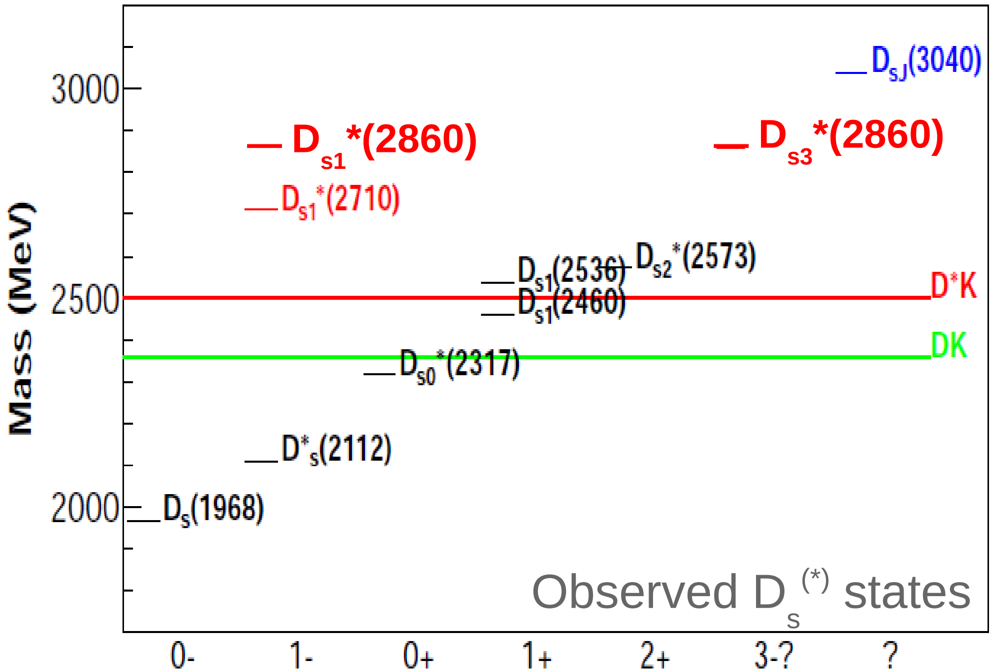
$m(D_{s1}(2460)^{+} - m(D_s^{*+})) = (347.3\pm0.7)$ MeV/c^2

$m(D_{s1}(2460)^{+} - m(D_s^{+})) = (491.2\pm0.6)$ MeV/c^2

$\Gamma < 3.5$ MeV CL=95.0%

- What did we learn after 14 years?

D_s spectroscopy, today: remarks



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

D_s mesons: $|c\bar{s}\rangle$

Predicted from Godfrey-Isgur (1985);
Update: Di Pierro- Eichten (2001)

- Many excited D_s states have been found:
  some of these not in agreement with potential models (→below the DK threshold);
  the identification of D_{s0}*(2317) and D_{s1}(2460) states as 0^+ or 1^+ *cs* states is difficult to accommodate in the potential models.

- LHCb recently performed amplitude analyses:
  D_{s2}(2573) confirmed with J=2;
  D_{s1-3}*(2860): for the first time a heavy flavored J=3 state is observed.

Highlighted paper: $D_{s0}^{*}(2317)^{+}$

- BaBar experiment optimized for CP violation study, measurement of angles and sides of the CKM matrix. For comparison:

"Observation of CP violation in the B^0 meson system"

Phys.Rev.Lett. 87 (2001) 091801

e-Print: hep-ex/0107013

Experiment: SLAC-PEP2-BABAR

824 citations

"Observation of a narrow meson decaying to $D^{+}_{s}\pi^{0}$ at a mass of 2.32-GeV/c^2"

Phys.Rev.Lett. 90 (2003) 242001

e-Print: hep-ex/0304021

Experiment: SLAC-PEP2-BABAR

786 citations

HIGH INTEREST IN HADRON PHYSICS!

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
$D_{sJ}^*(2317)^+\gamma$	—	Seen
$D_s^+\pi^0\pi^0$	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 *cs-systems* as the hydrogen atom (potential models, *c* = heavy quark):
- $D_{s1}(2317)^+$ and $D_{s2}(2460)^+$ are predicted, found with good accuracy <u>but</u>:

m(D_{s0}*(2317)$^+$) found 160 MeV/c^2 lower

m(D_{s1}(2460)$^+$) found 120 MeV/c^2 lower

than predicted by potential models

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

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

Is D_{s0}^* the missing 0^+ state of the *cs-spectrum*?

Is D_{s1} the missing 1^+ of the *cs-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 Eur. Phys. J A (2014) 50 -149	NEW! Strong and radiative decays of $D_{s0}^{*}(2317)$ and $D_{s1}(2460)$	

- The measurement of the **narrow width** plays a leading role in the interpretation of D_s^{*}

D_{S0}^* and D_{s1} theoretical overview: Hadronic width

M. Cleven, H. W. Griesshammer, F.-K. Guo, C. Hanhart, Ulf-G. Meissner, Eur. Phys. J. A(2014) 50, 149

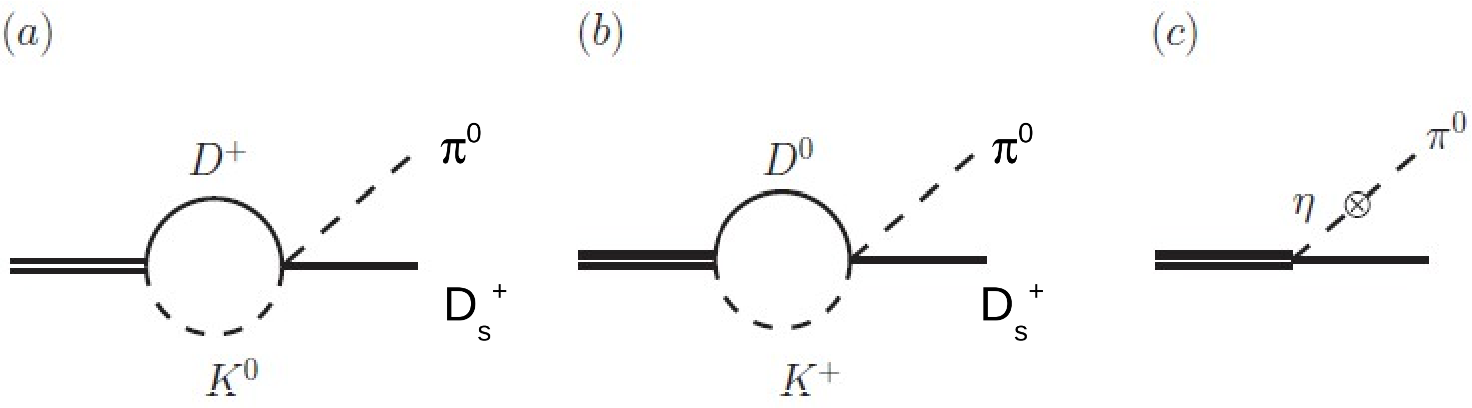


Figure 2: The two mechanisms that contribute to the hadronic width of the D^*_{s0}. (a) and (b) represent the nonvanishing difference for the loops with D^+K^0 and D^0K^+, respectively. (c) depicts the decay via π^0-η mixing.

- 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_{s0}^* and D_{s1} theoretical overview: Radiative width

M. Cleven, H. W. Griesshammer, F.-K. Guo, C. Hanhart, Ulf-G. Meissner, Eur. Phys. J. A(2014) 50, 149

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).

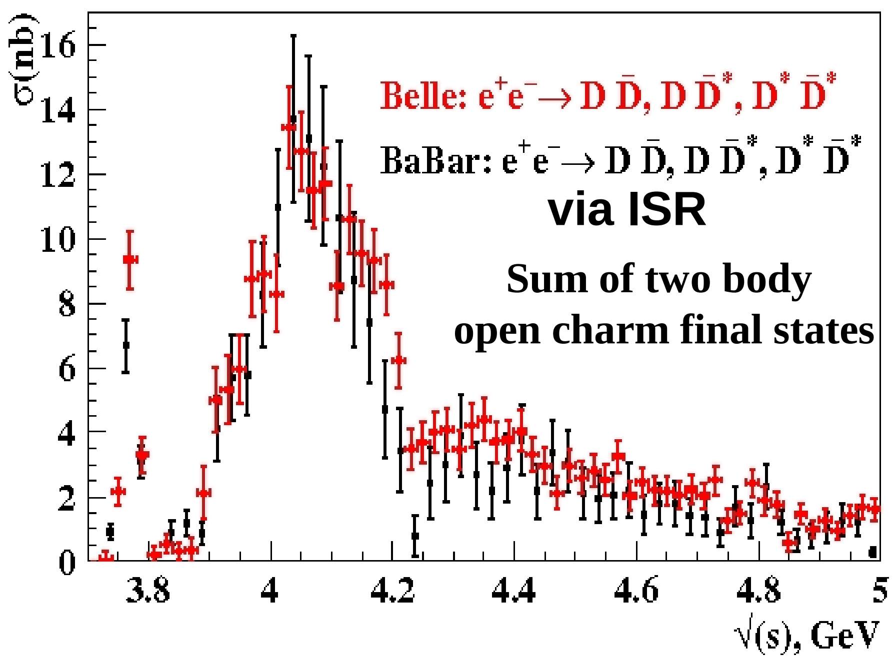
- **Only hadronic decays are sensitive to a possible molecular component of D_{s0}^* and D_{s1}**
- **Hadronic width of ≥ 100 keV: unique feature for molecular state**
- **Demand for a new generation machine: Δm ~100 keV, 20 times better than attained at B factories**

What do we know about the Open-charm Cross Section?

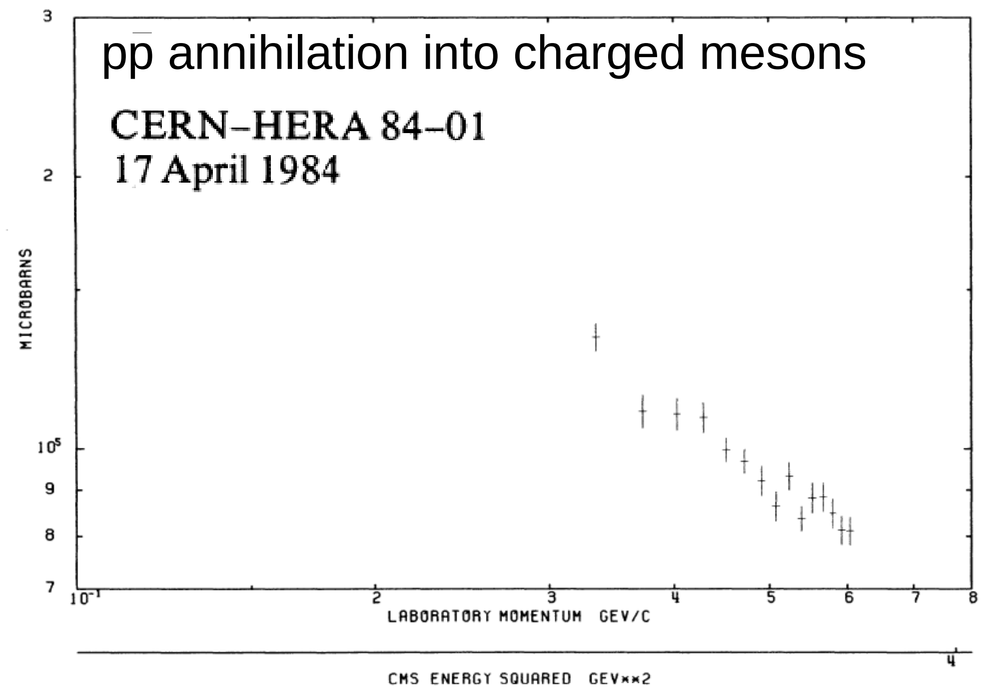
Cross section

- Predictions are difficult due to the presence of *s*-quark in D_{sJ} mesons:
  $\sigma(\bar{p}p \to \bar{D}D)$ expected <100nb
- Inclusive search: better for cross section measurement, but higher background. Challenge!
- Exclusive cross section measurement: theoretical predictions are difficult

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

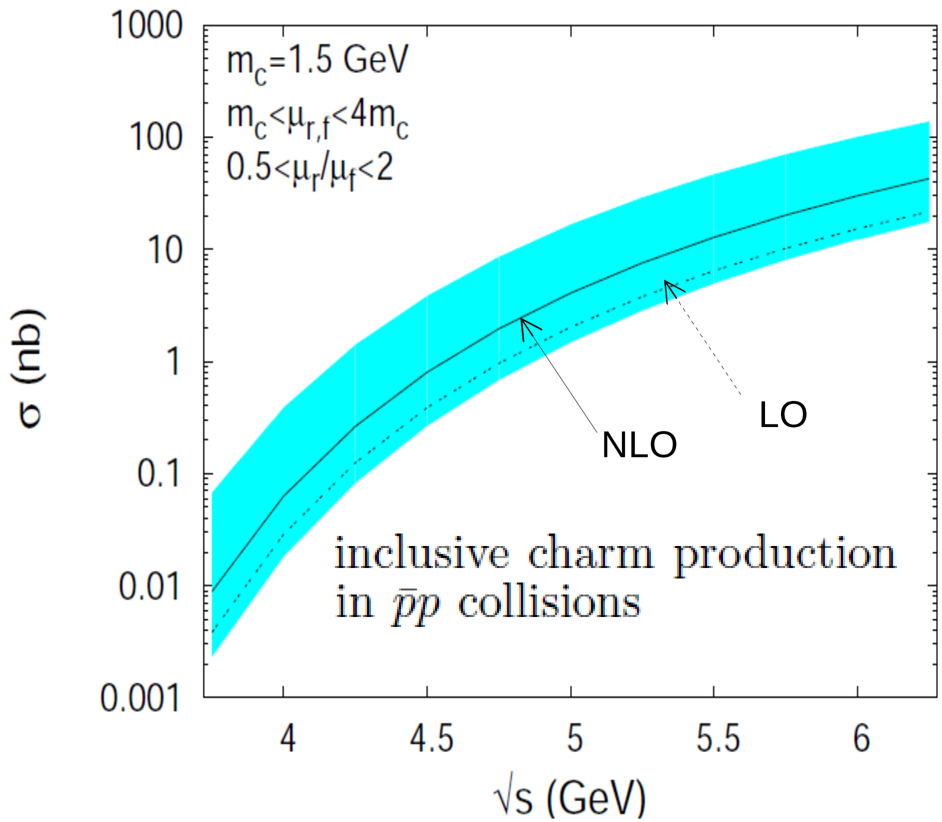


V. Flaminio, W.G. Moorhead, D.R.O. Morrison, N. Rivoire



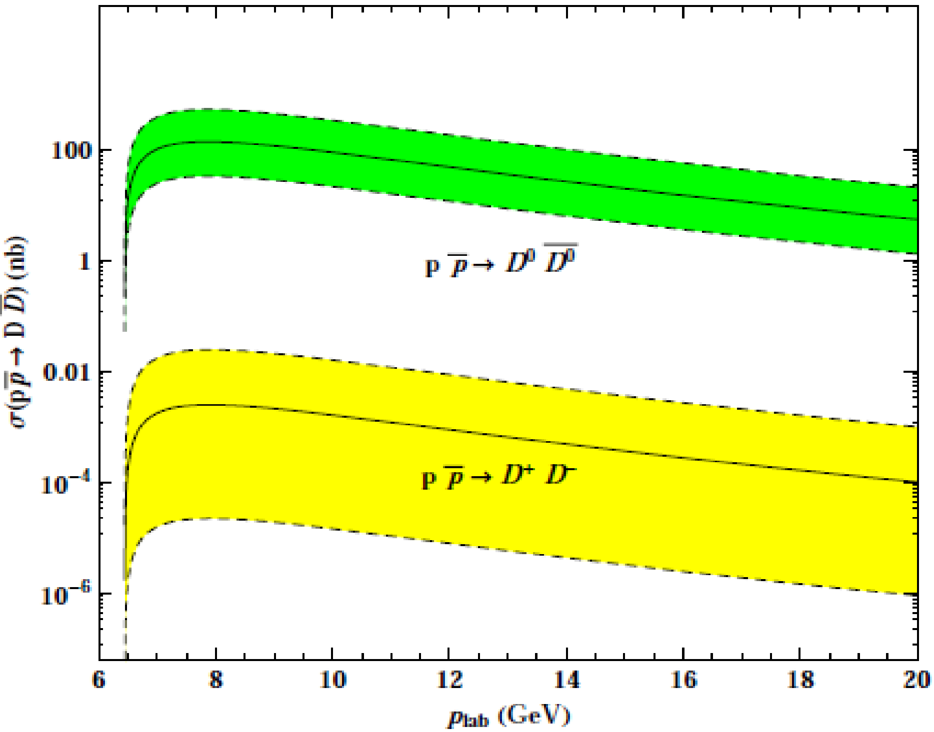
Cross section

- Theoretical predictions for the charmed ground states (D^+, D^0).
- Calculations for excited D states (no *s*-quark) are difficult:
  calculations in perturbative regime can under-estimate the real cross section



Phys. Rev. D 79 (2009) 114005

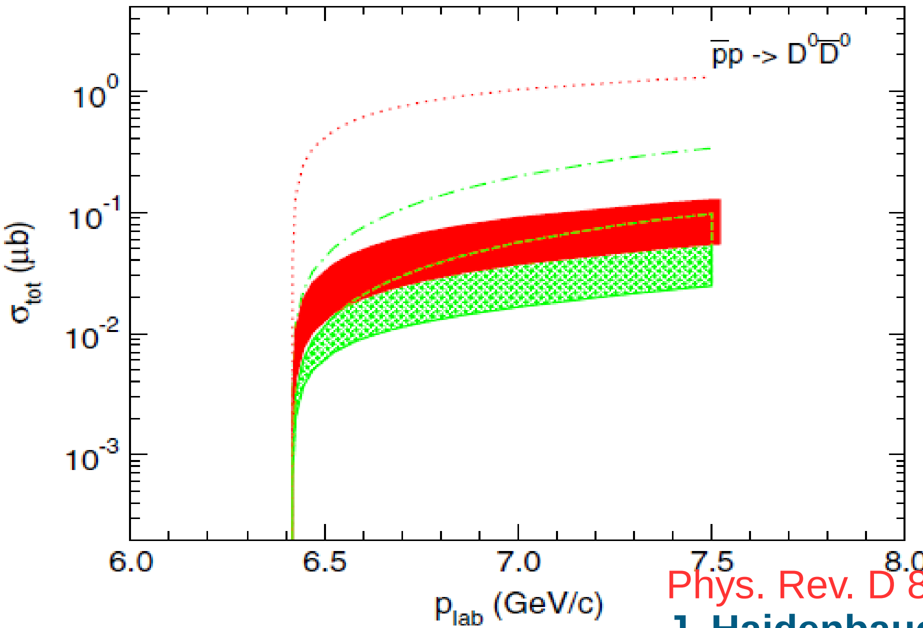
E. Braaten, P. Artoisenet

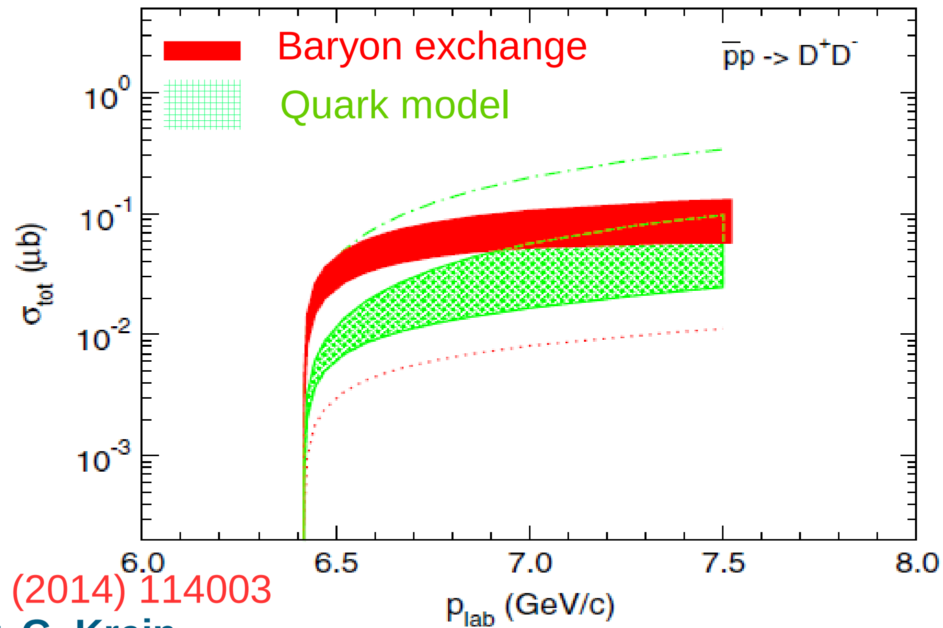


Eur. Phys. J. A 48 (2012) 31

A. Khodjamirian, C. Klein, T. Mannel, Y.M. Wang

Cross section

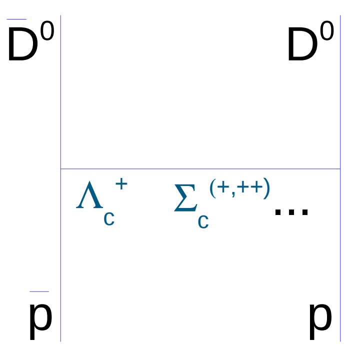




Phys. Rev. D 89 (2014) 114003

J. Haidenbauer, G. Krein

- Cross section predictions described in the PRD 89 (2014) 114003 are higher than in the paper cited as EPJ A 48 (2012) 31
  → different assumption: here (PRD paper) they rely in SU(4); coupling constant is fixed



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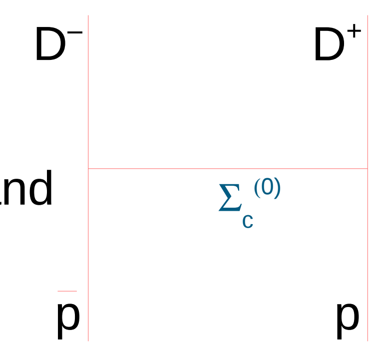
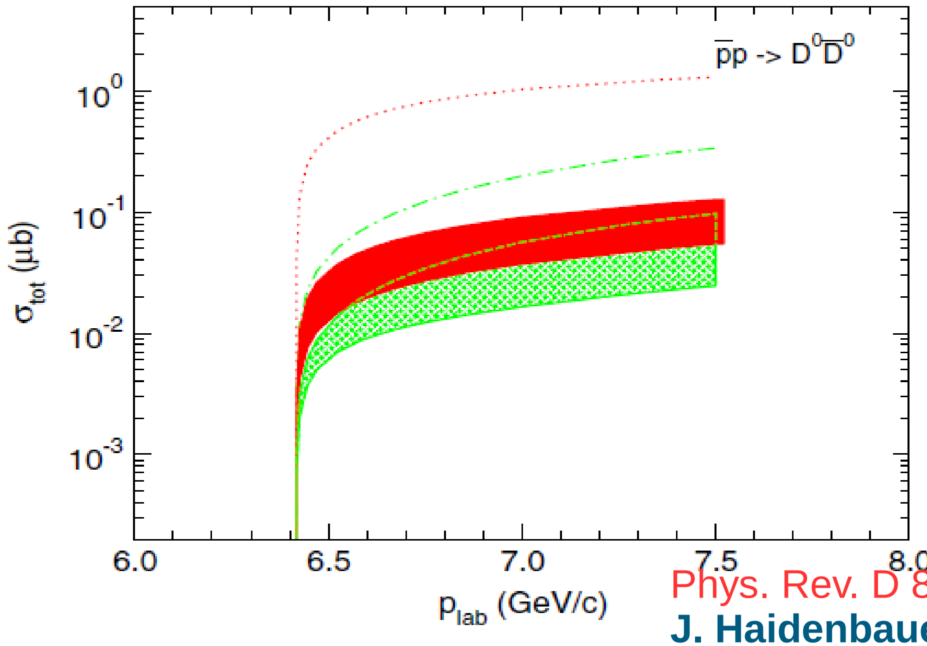
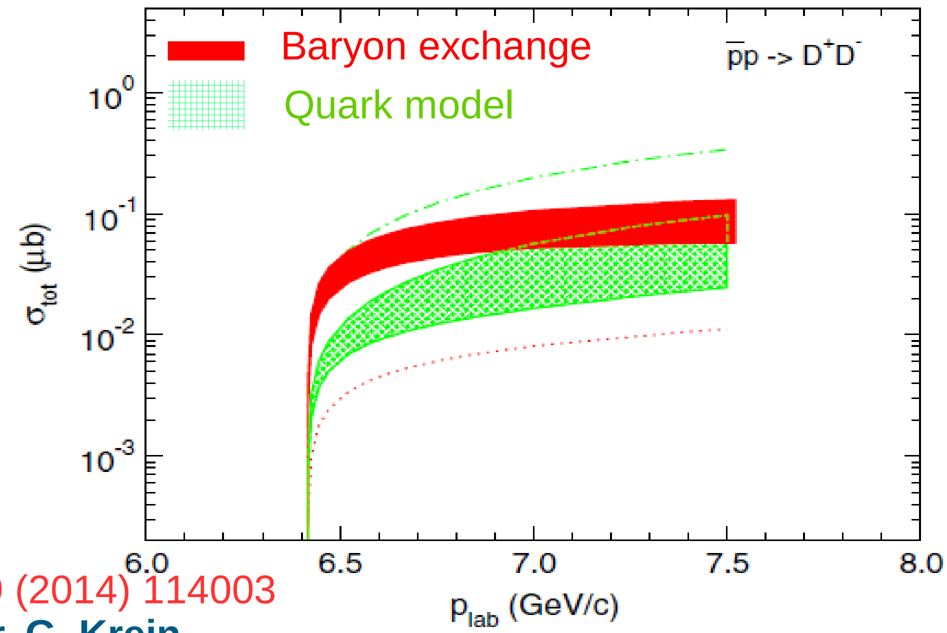


this contribution　　　　this contribution

Cross section





Phys. Rev. D 89 (2014) 114003
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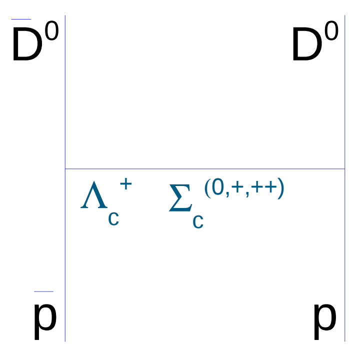

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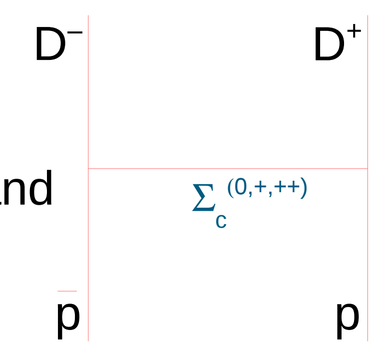
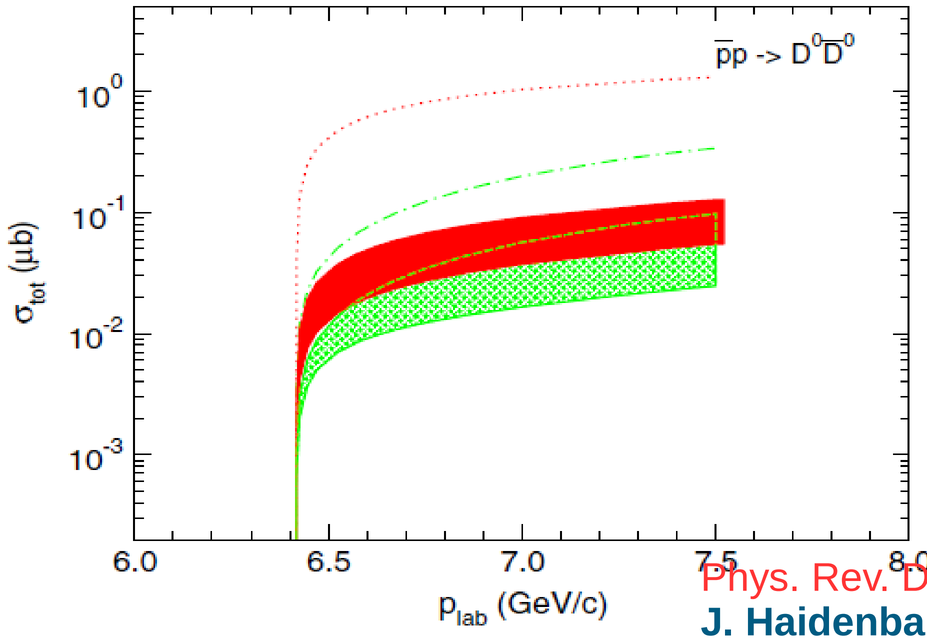
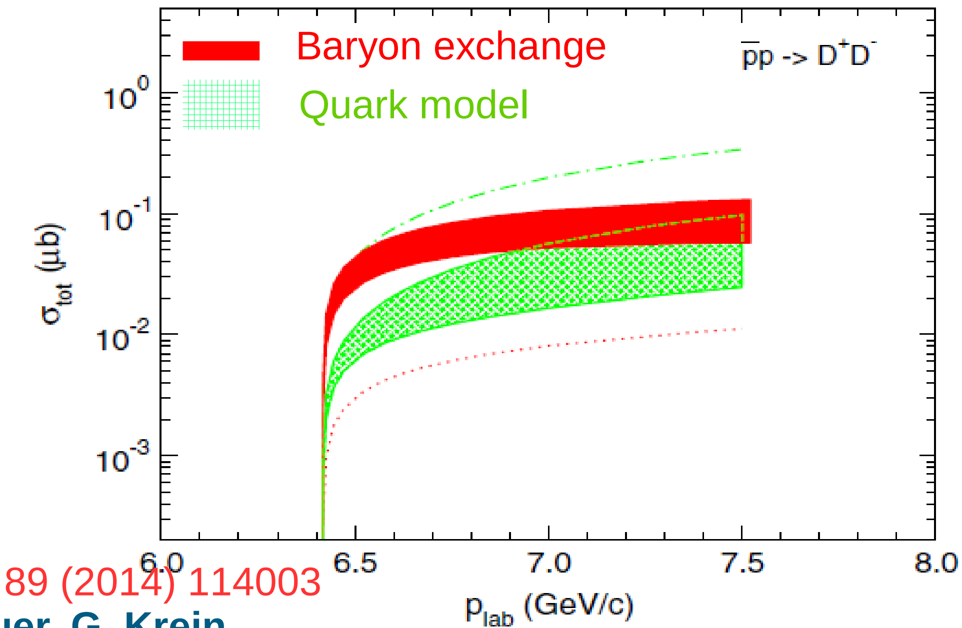


this contribution is $\gg$10 larger than this contribution

Cross section



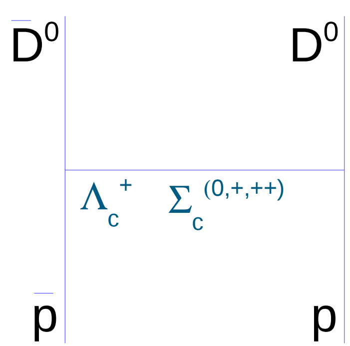


Phys. Rev. D 89 (2014) 114003

J. Haidenbauer, G. Krein

- Cross section prediction in the PRD 89 (2014) 114003 are higher than in EPJ A 48 (2012) 31 → different assumption: here (PRD paper) they rely in SU(4); coupling constant is fixed

Can we rely in SU(4)?



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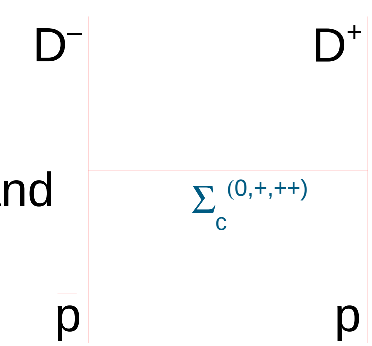
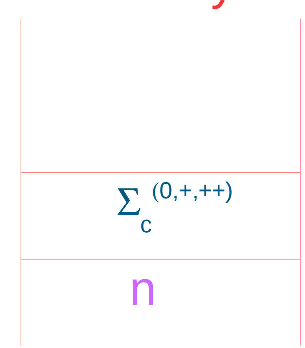


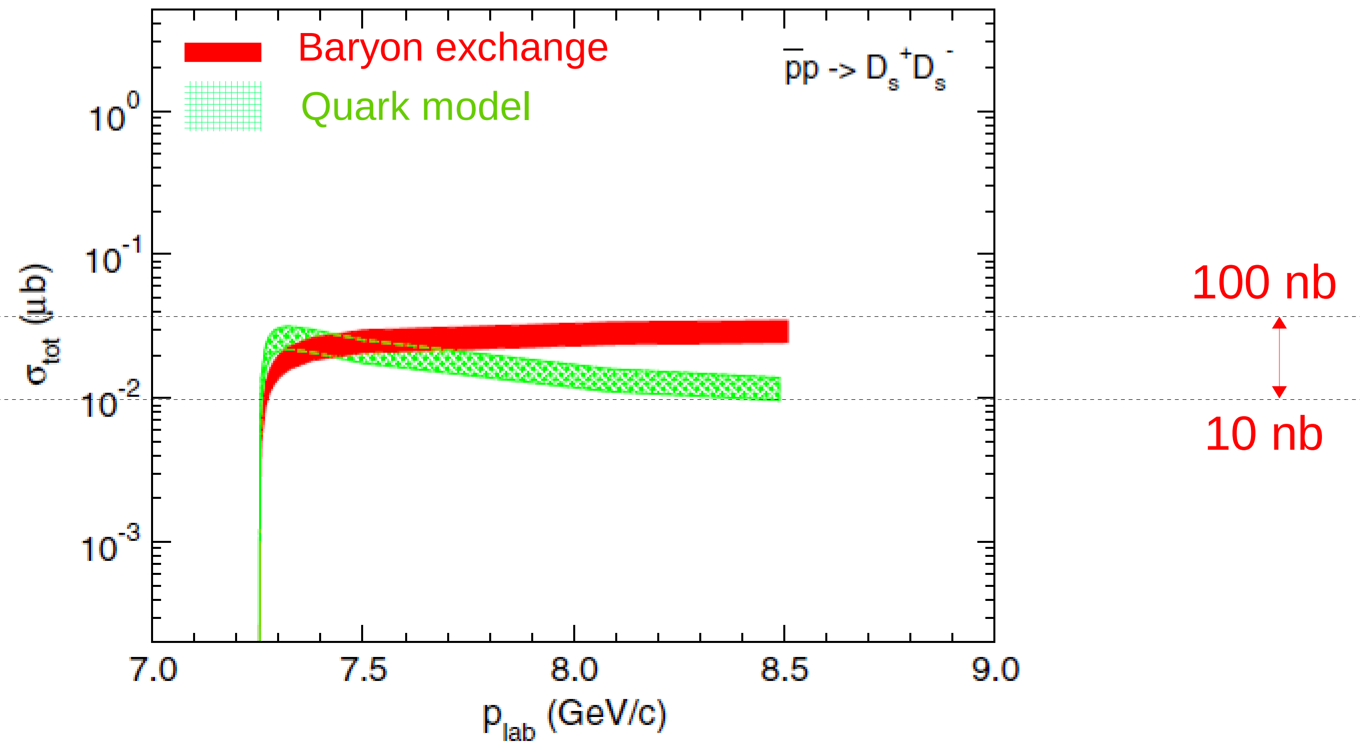
; but:



This contribution is >10 larger than this contribution; but a neutron in the loop as intermediate state can rise up the $\sigma(\bar{p}p \to D^+D^-)$ at same level as $\sigma(\bar{p}p \to \bar{D}^0D^0)$

Cross section

Phys. Rev. D 89 (2014) 114003
J. Haidenbauer, G. Krein



- With the approach described in slide 24, $\sigma(\bar{p}p \to D_s^+ D_s^-)$ should be feasible

What about the cross section of $\bar{p}p$ to excited **D_s** state?

It is more complicated!

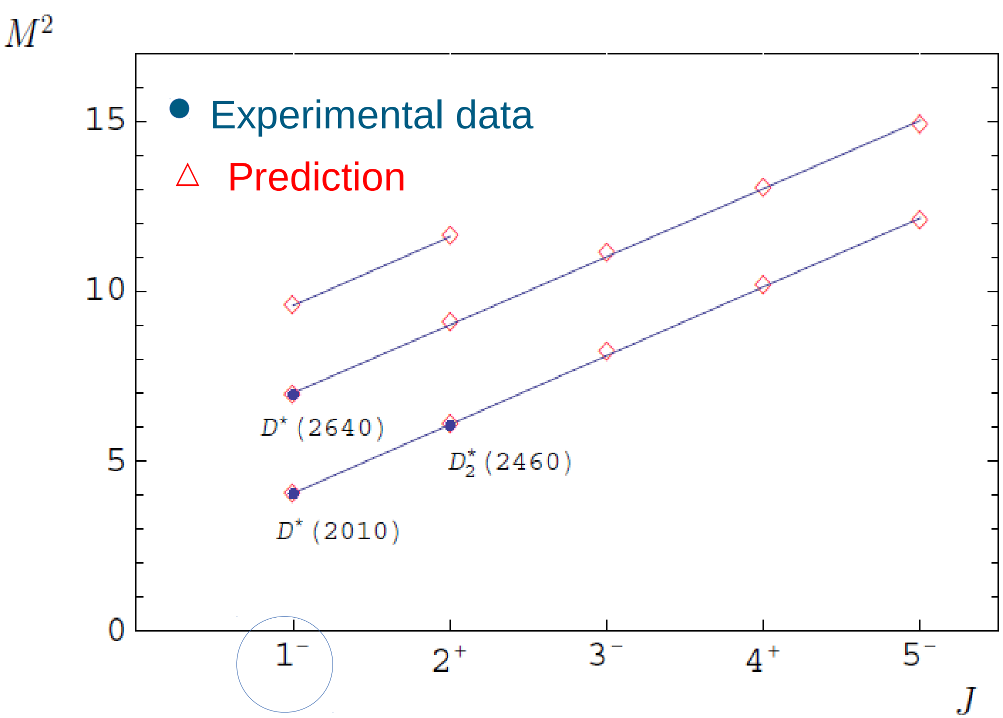
- We do not know anything about the coupling constant for D_s^*

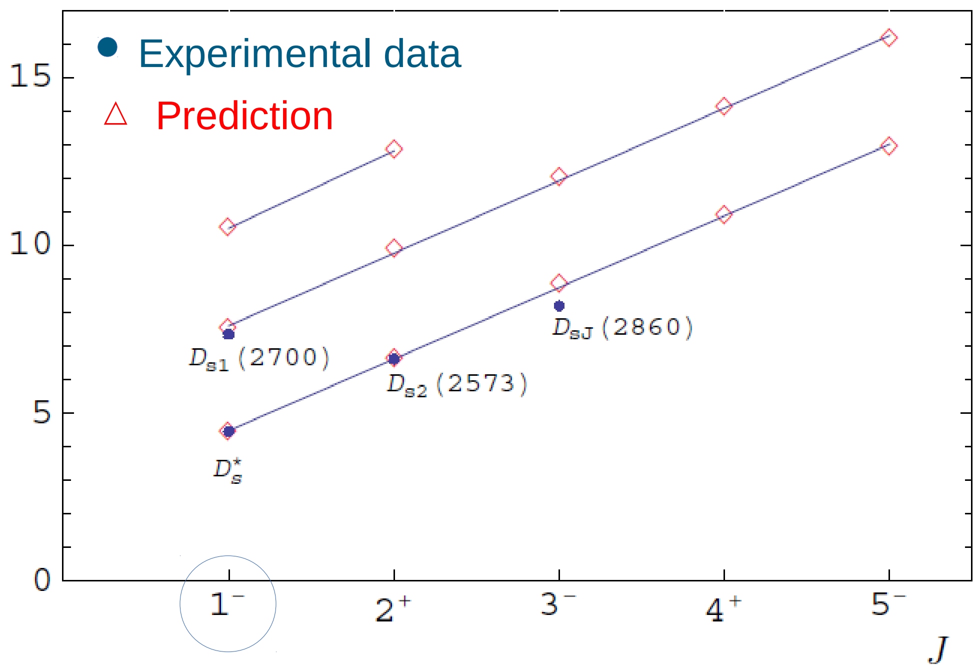
⇨ **we need REAL data**!

Cross section

- In the theoretical calculation for the cross section of $\bar{p}p \rightarrow \bar{D}D$ states, vector states could be involved in the loop, but technical problems occur.
- There are divergences difficult to cure.
- *Regge trajectories* are introduced for this purpose (α).

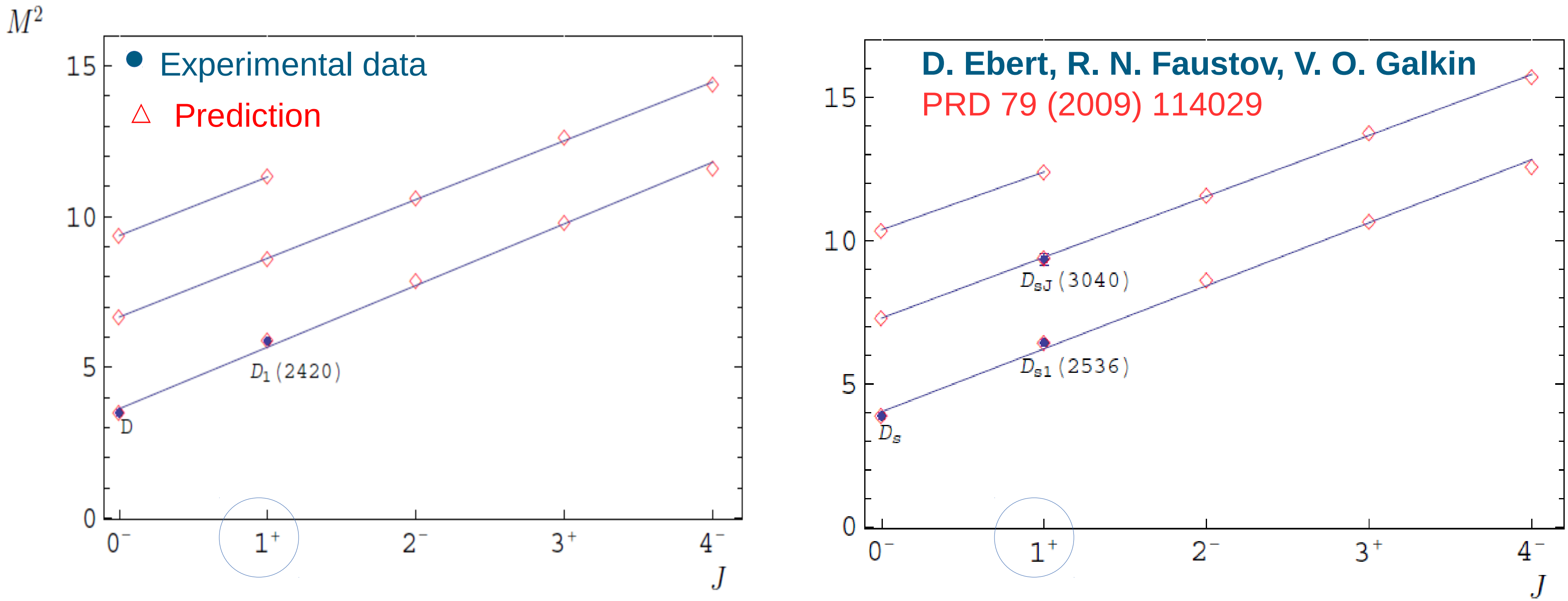
D. Ebert, R. N. Faustov, V. O. Galkin
PRD 79 (2009) 114029





- Regge trajectories for D(s) mesons with Natural Parity
- Both light (*q* = *u*,*d*,*s*) and heavy (*Q* = *c*,*b*) quarks are treated fully relativistically without application of the heavy quark $1/m_Q$ expansion.

Cross section



- Regge trajectories for D(s) mesons with Unnatural Parity

We calculated the masses of ground, orbitally and radially excited heavy-light mesons up to rather high excitations. This allowed us to construct the Regge trajectories both in (J, M^2) and (n_r, M^2) planes. It was found that they are almost linear, parallel and equidistant. Most of the available experimental data nicely fit to them. Exceptions are the anomalously light $D^*_{s0}(2317)$, $D_{s1}(2460)$ and $D^*_{sJ}(2860)$ mesons, which masses are 100-200 MeV lower than various model predictions. The masses of the charmed-strange $D^*_{s0}(2317)$, $D_{s1}(2460)$ mesons almost coincide or are even lower than the masses of the partner charmed $D^*_0(2400)$ and $D_1(2427)$ mesons. These states thus could have an exotic origin. It will be very important to find the bottom counterparts of these states in order to reveal their nature.

Is that feasible to perform the measurement of the Open-charm Cross Section in $\bar{p}p$?

Is that feasible to perform the measurement of the $D_s^*(2317)^+$ width in $\bar{p}p$?

Is that feasible to perform the measurement of the Open-charm Cross Section in $\bar{p}p$?

Is that feasible to perform the measurement of the $D_s^*(2317)^+$ width in $\bar{p}p$?

YES!

Is that feasible to perform the measurement of the Open-charm Cross Section in $\bar{p}p$?

Is that feasible to perform the measurement of the $D_s^*(2317)^+$ width in $\bar{p}p$?

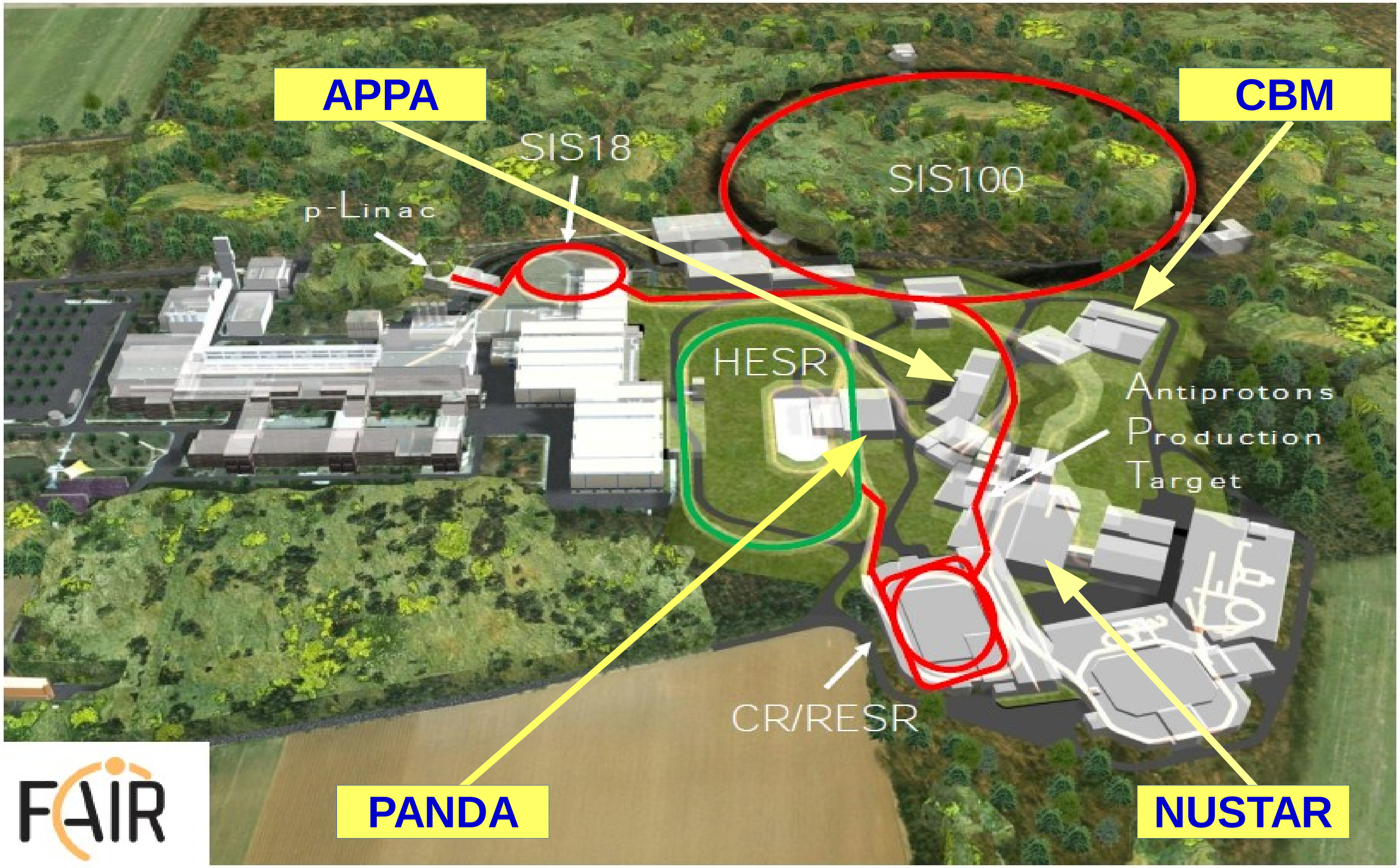
But...

Is that feasible to perform the measurement of the Open-charm Cross Section in $\bar{p}p$?

Is that feas ble to per surement

...we need the proper detector!

Facility for Antiproton and Ion Research

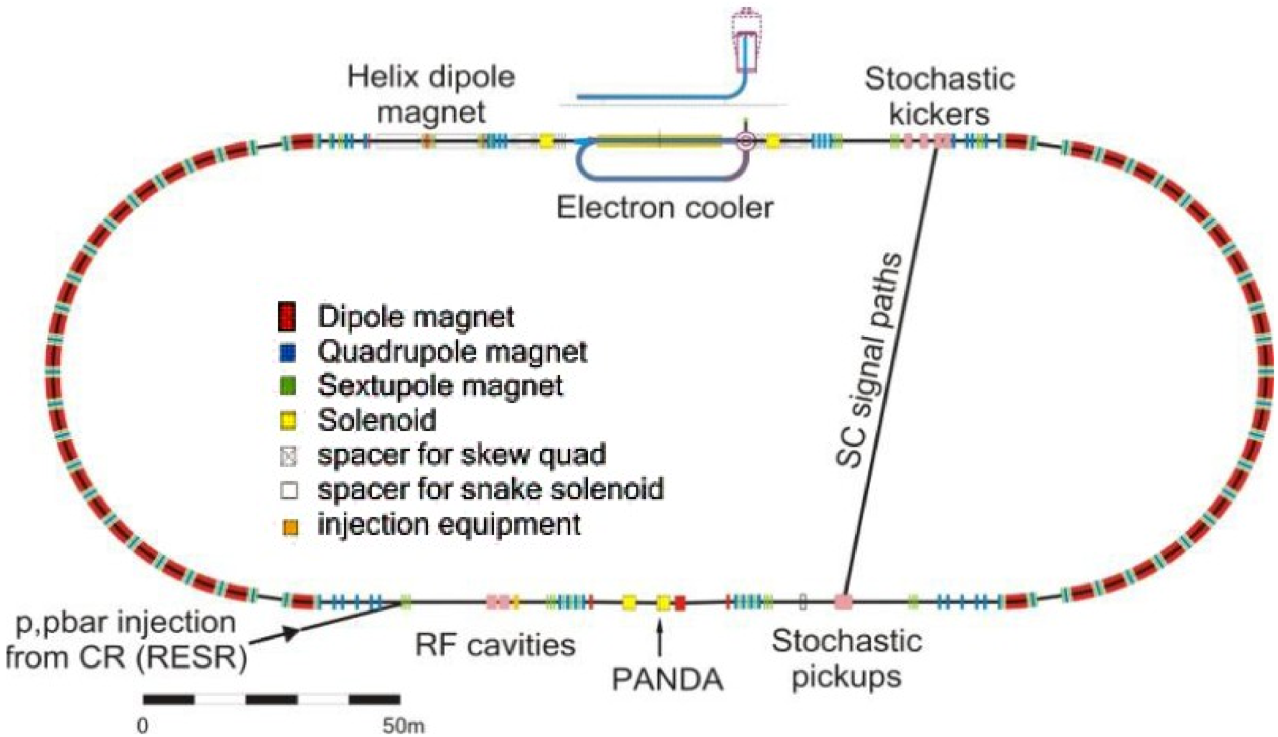


3000 Physicists
50 Countries

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 - *$\bar{P}$ANDA*

HESR with $\overline{\text{P}}$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

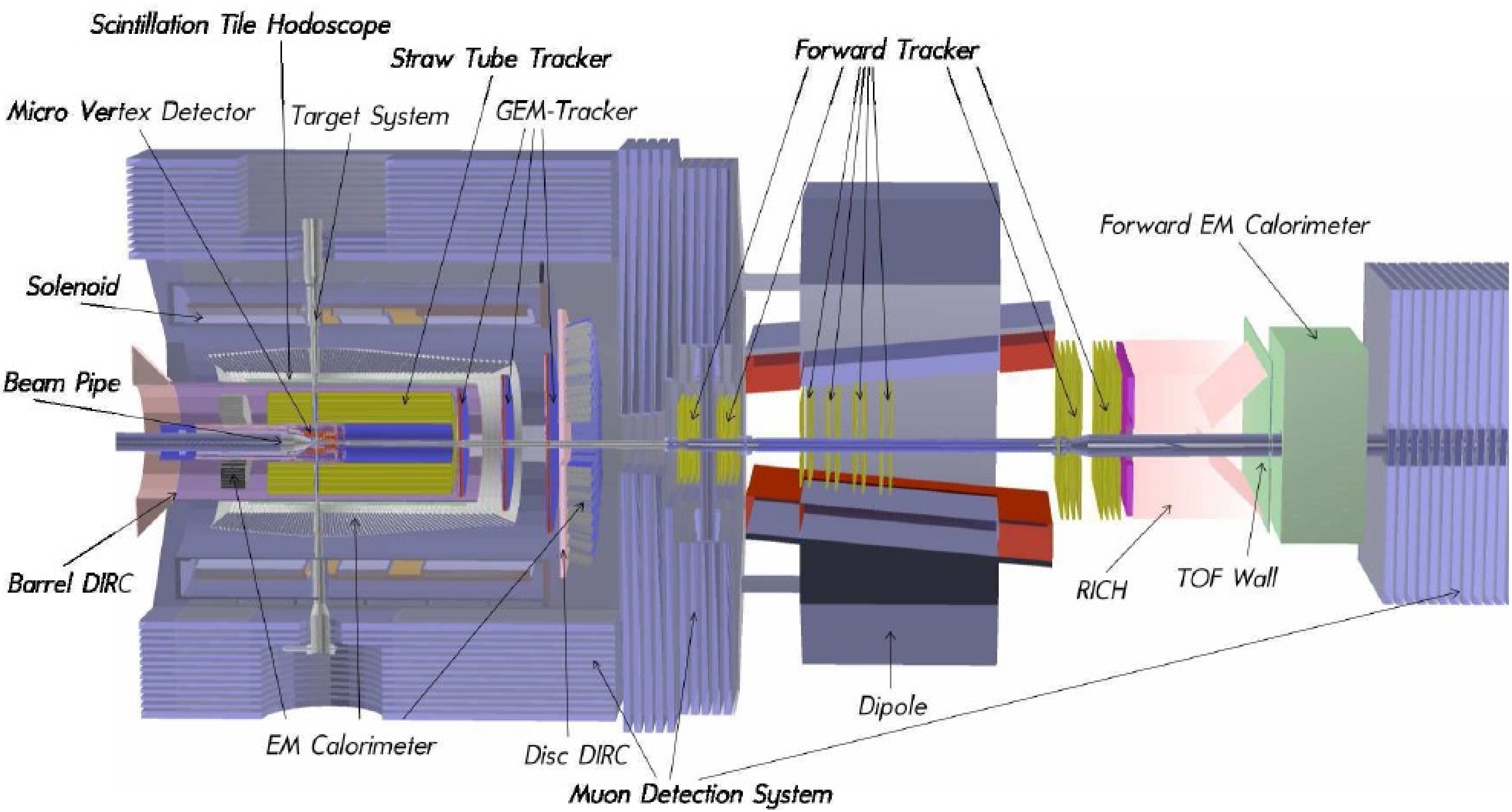
High resolution mode

- 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

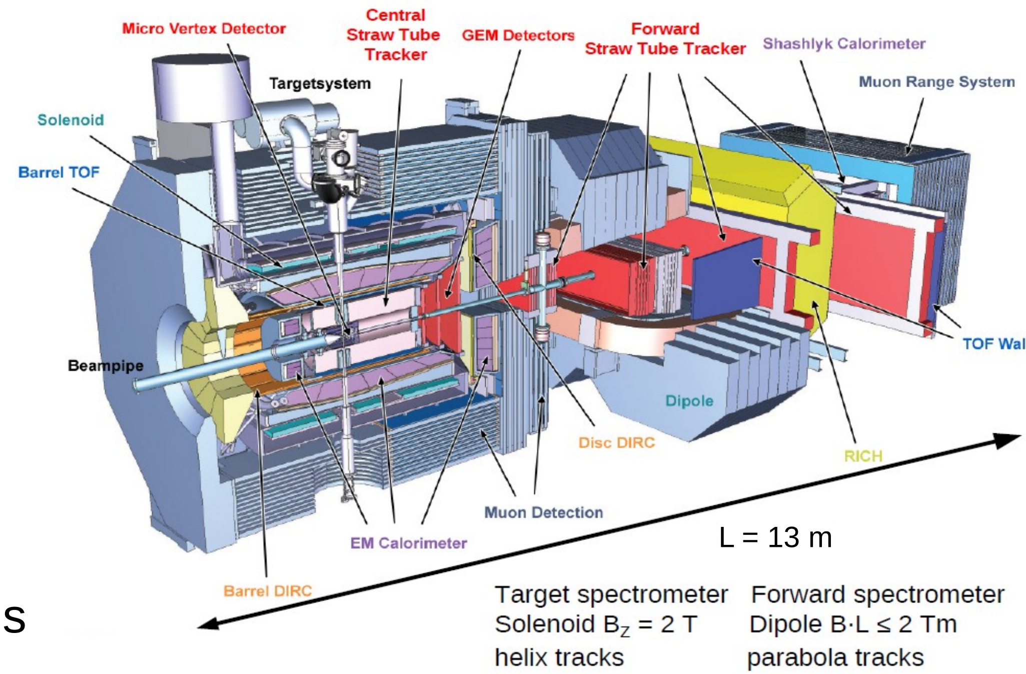
- Stochastic cooling, $p \geq 3.8$ GeV/c
- 10^{11} antiprotons stored
- Luminosity up to $2 \cdot 10^{32}$ cm^{-2} s^{-1}
- $\Delta p/p = 2 \cdot 10^{-4}$

$\overline{P}$ANDA



The detector $\overline{\text{P}}$ANDA @ FAIR

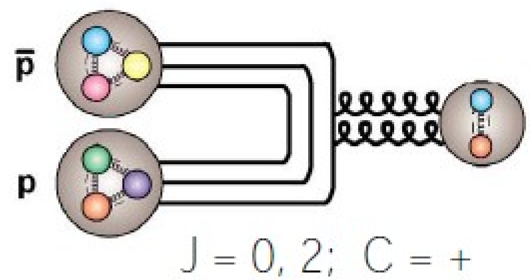
- PANDA is a fixed target detector
  - Antiproton beam up to p = 15 GeV/*c*
  - Particles in formation and production
  - Mass resolution ~ 100 KeV
  - $\Delta p/p$: $[10^{-4} - 10^{-5}]$
  - High boost $\beta_{cms} \geq 0.8$
  - Many tracks and photons in fwd acceptance ($\theta \leq 30°$), high p_z, 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
  - up to 20 MHz interaction rate
  - Complete real-time event reconstruction

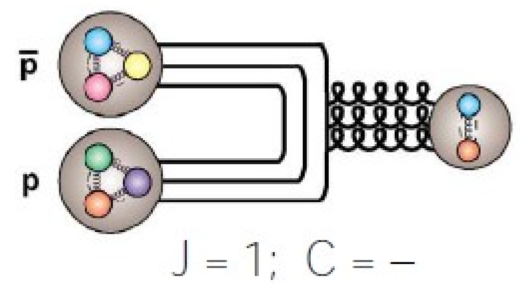
Why antiprotons in $\overline{P}ANDA$?

- Annihilation is a gluon rich process



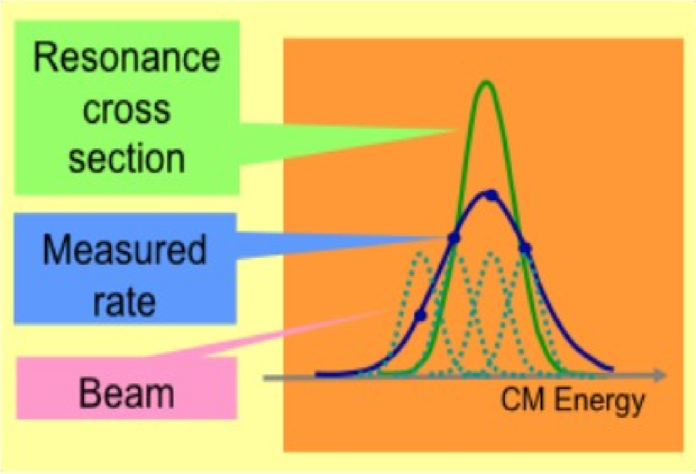
- In production:
all quantum numbers accessible in $\overline{p}p$ reactions

- High mass / width resolution in formation



- High angular momentum accessible

- Resonance scan technique:
invariant mass resolution depends on the beam resolution



- $\overline{P}ANDA$ is in an unique position to perform such a study!
Charm and Charmonium resonance mass scan

Mitglied in der Helmholtz-Gemeinschaft

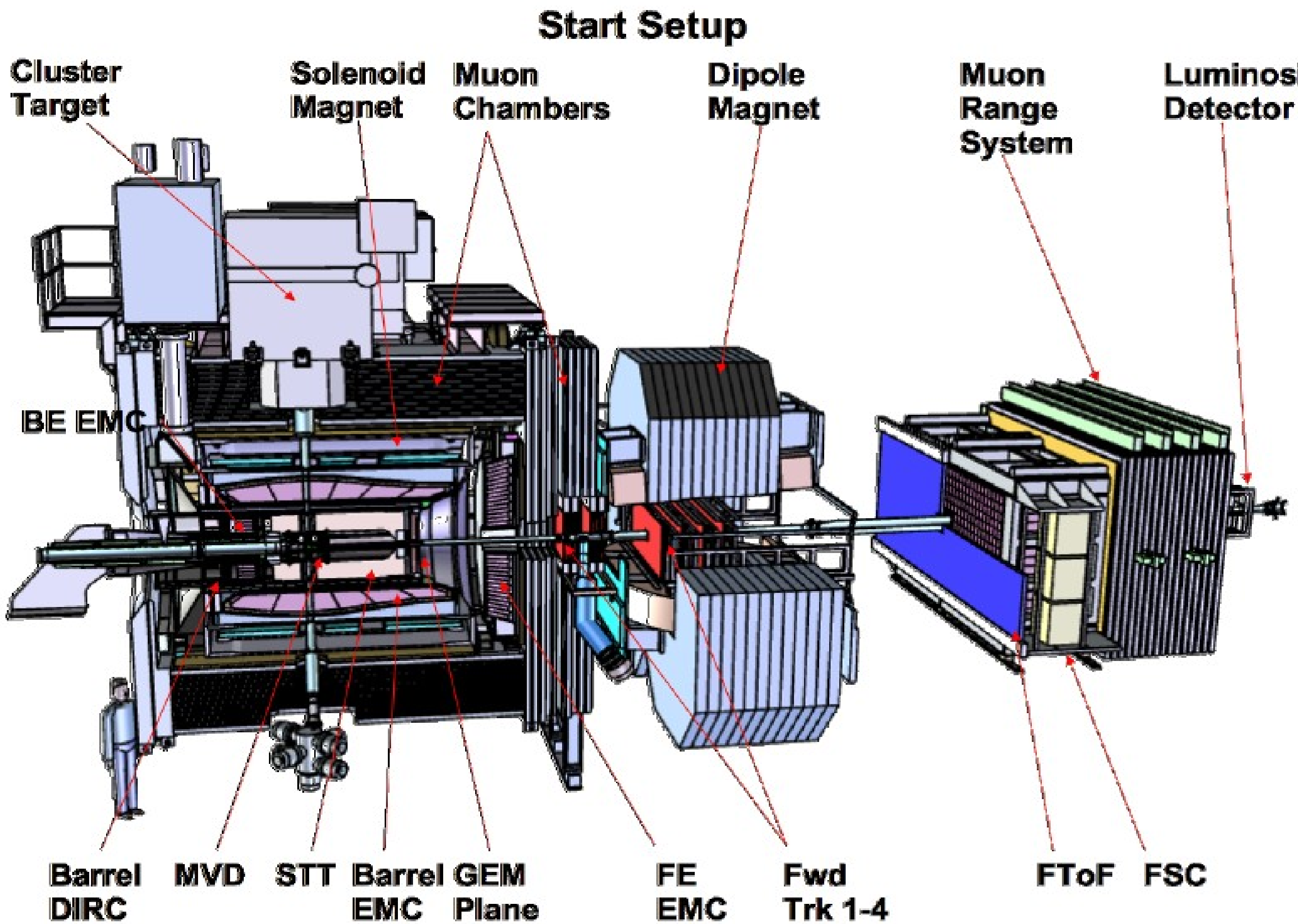
$\overline{\text{P}}$ANDA construction

- $\overline{\text{P}}$ANDA will be realized in different phases:

  Phase 0: pre-commissioning
  Phase I : start-up mode
  Phase II: complete setup (low luminosity)
  Phase III:complete setup (high luminosity)

P̄ANDA construction

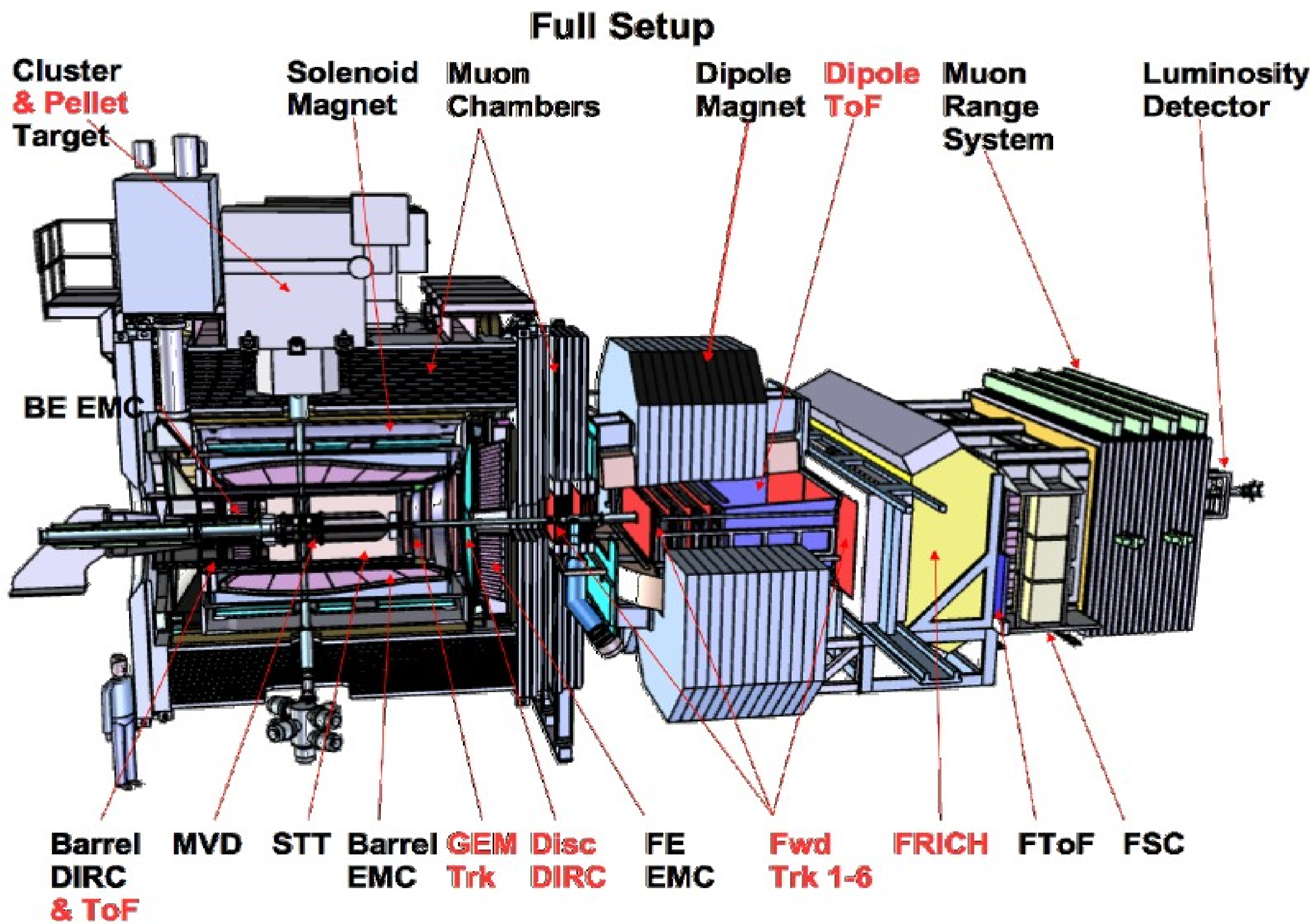
- P̄ANDA will be realized in different phases:



Start-up:
Phase I design

P̅ANDA construction

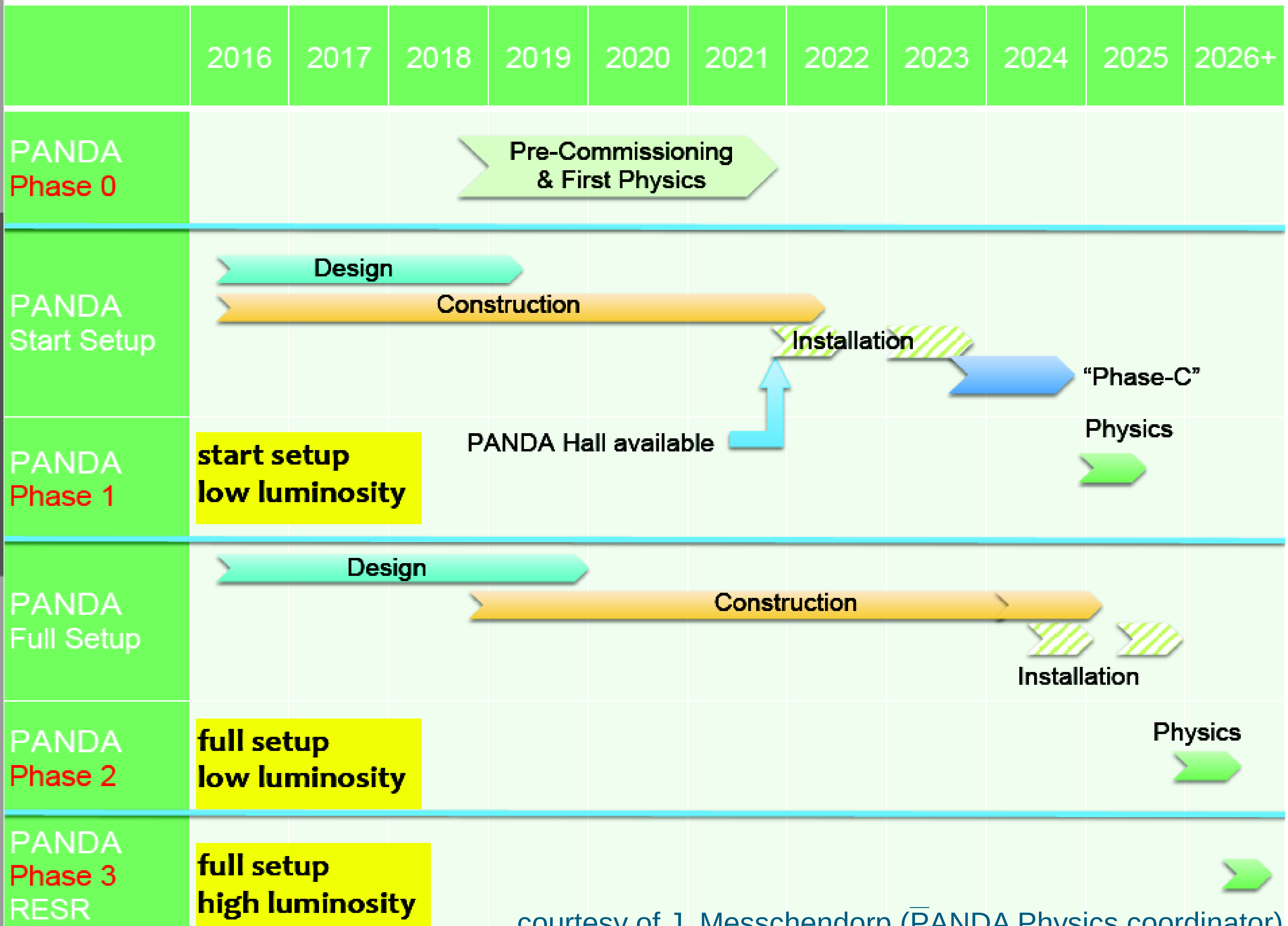
- P̅ANDA will be realized in different phases:



Complete setup:
Phase II design

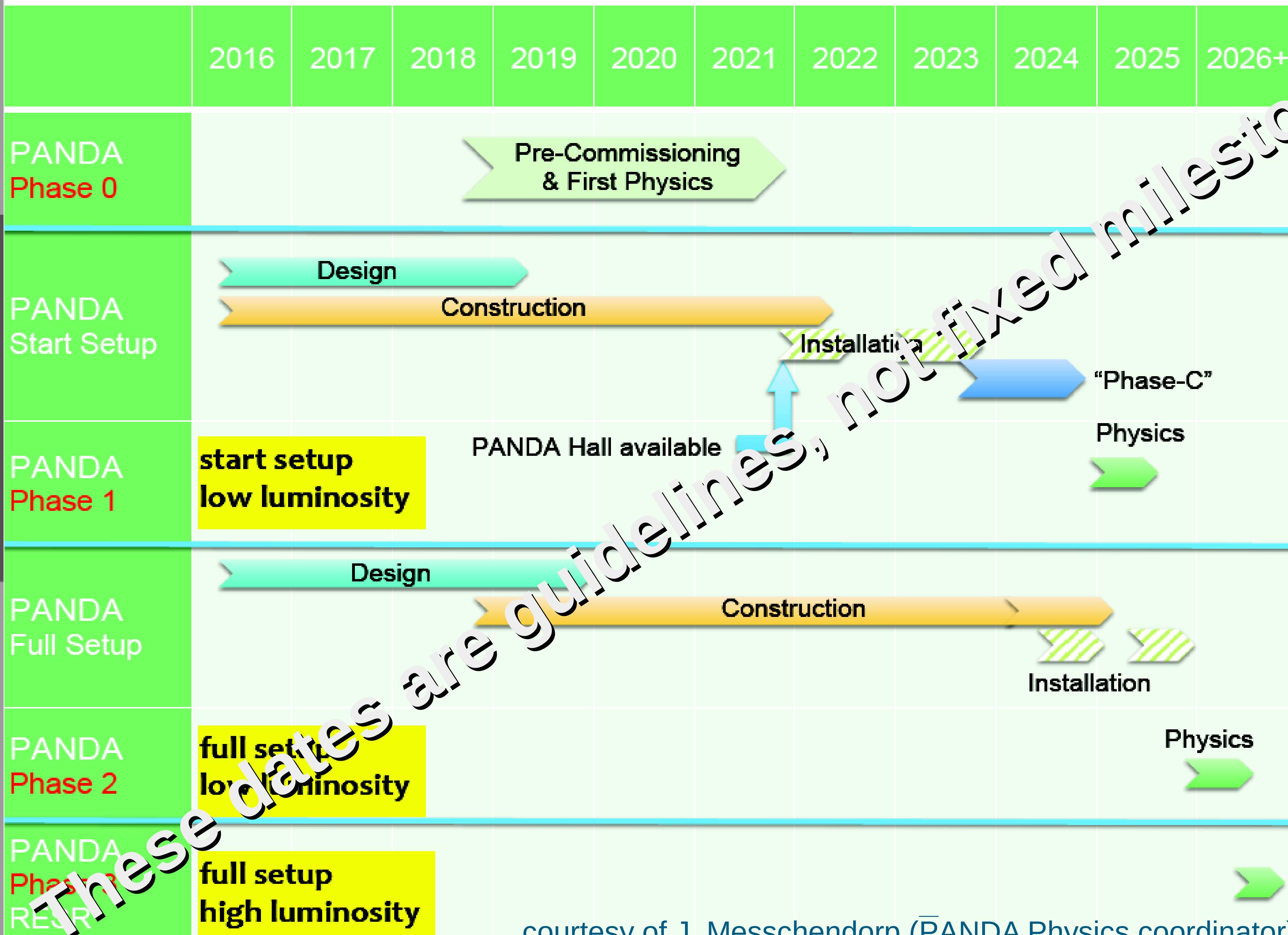
Charm physics

Perspectives for the first period of data taking at $\overline{\text{P}}$ANDA



courtesy of J. Messchendorp ($\overline{\text{P}}$ANDA Physics coordinator)

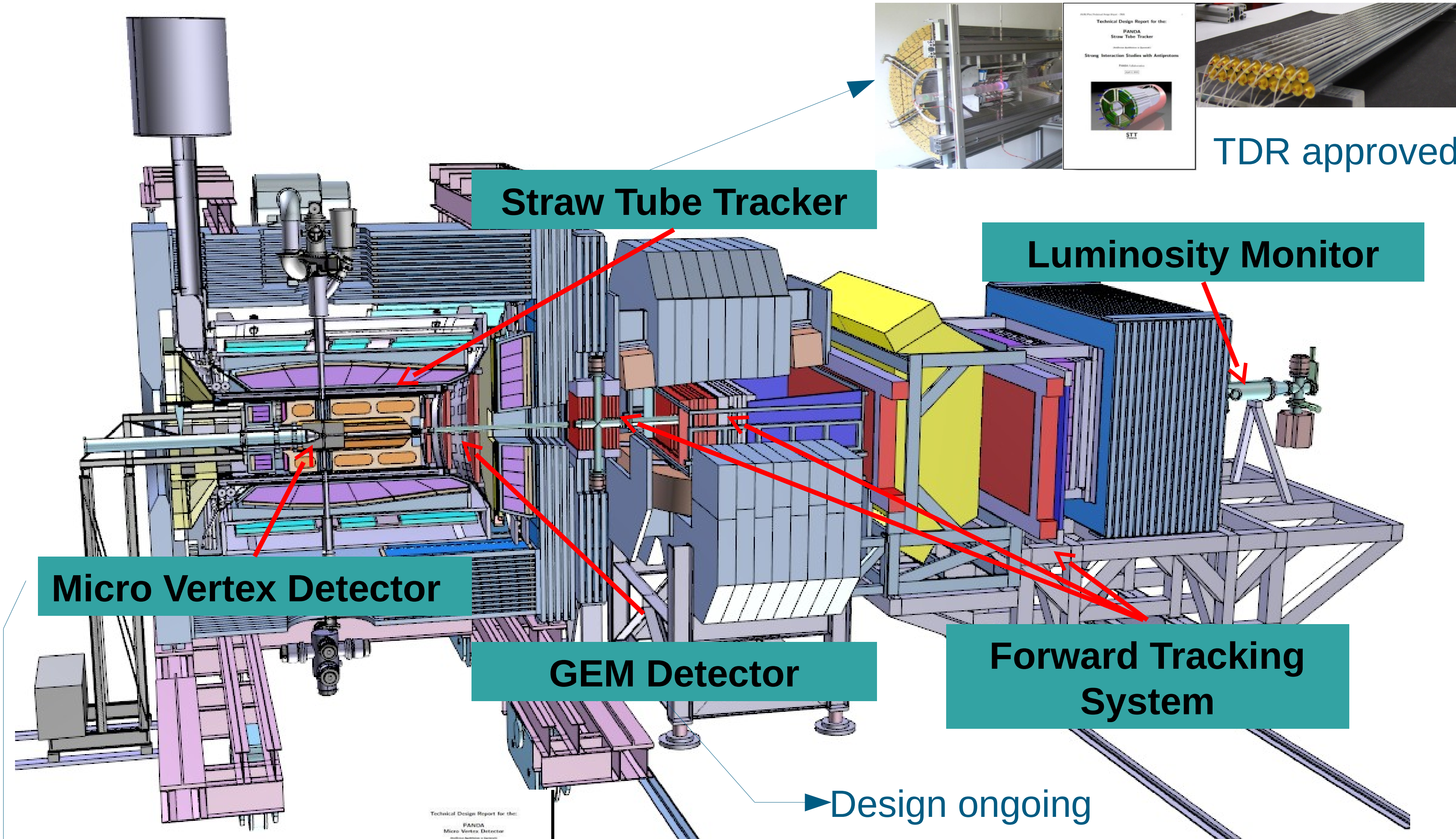
Perspectives for the first period of data taking at PANDA



courtesy of J. Messchendorp (P̄ANDA Physics coordinator)

What do we need to investigate Open-charm Physics in $\bar{p}p$?

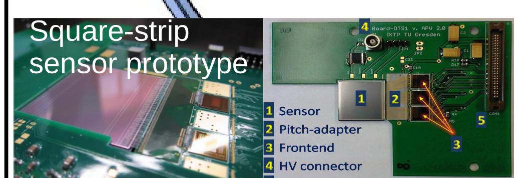
1. Good tracking system



TDR approved

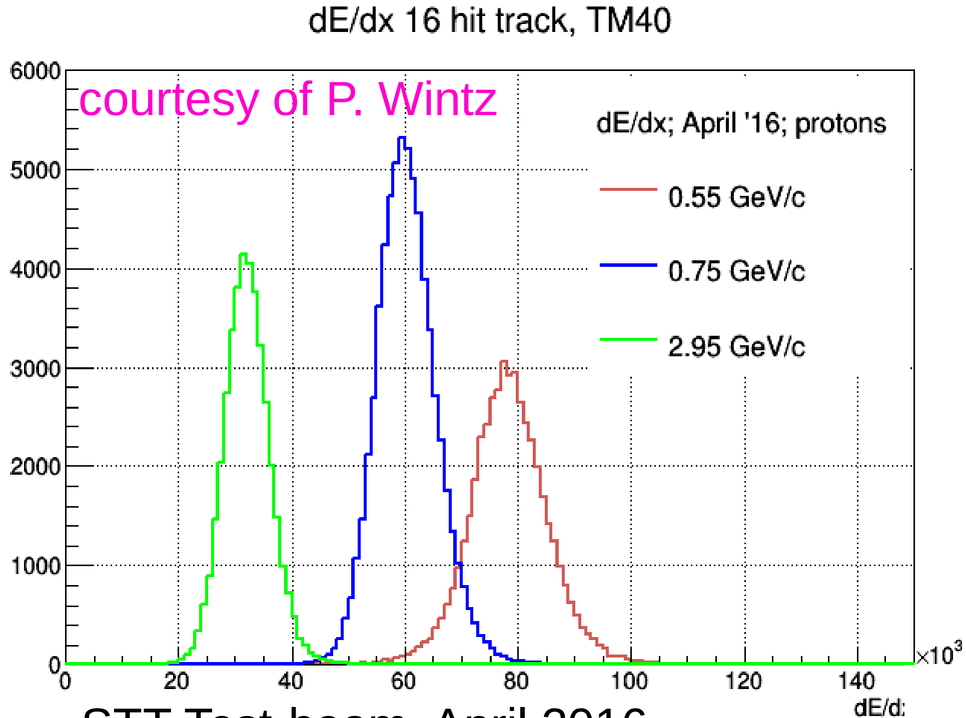
Design ongoing

TDR approved



Tracking system

$\overline{P}$ANDA tracking performance



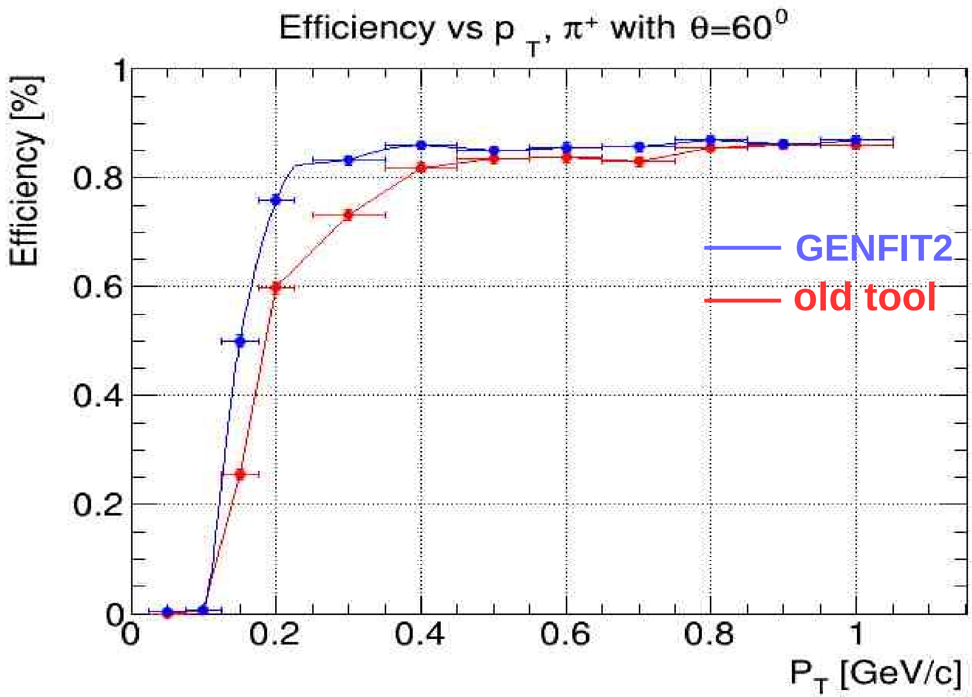
STT Test-beam, April 2016

Hardware

Software

E.P., EPJ C. 127 (2016) 00013

Good reconstruction for low momentum tracks with the GENFIT2 toolkit in PandaRoot

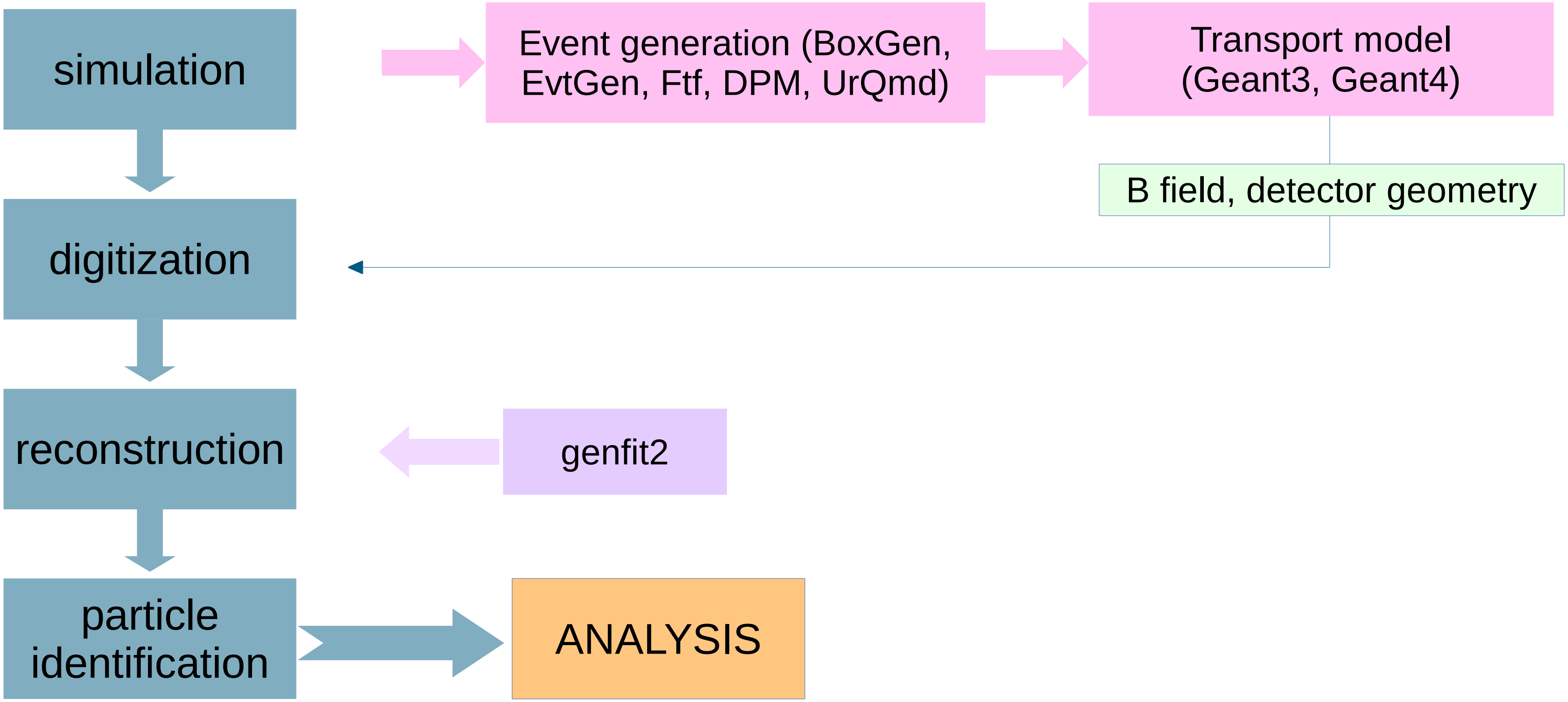


PandaRoot: official $\overline{\text{P}}$ANDA framework

- **PandaRoot**: code inside the FAIRRoot project, based on Root;
  code for simulation and analysis;
  working on many Linux distributions, and OS X.

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

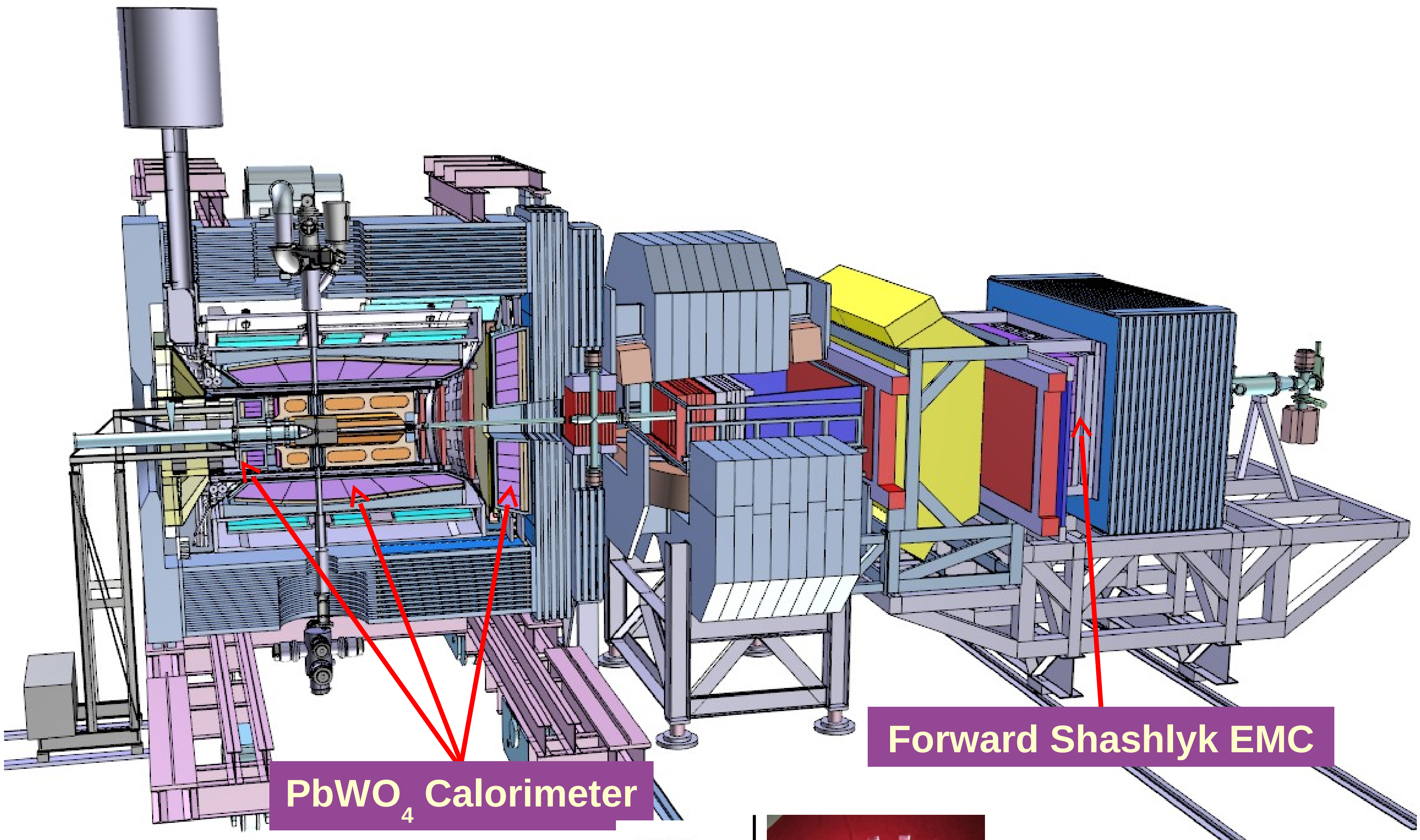
E.P., EPJ C. 127 (2016) 00013



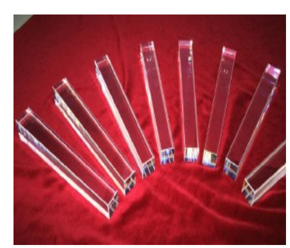
2. Excellent photon reconstruction

energy resolution below 2% at 1 GeV
photon energy detection ⩽ 30 MeV

$\overline{\text{P}}$ANDA Coll., EPJ A51 (2015), 107
$\overline{\text{P}}$ANDA Coll., EPJ A52 (2016), 325



Calorimeters:
All endcap crystals produced
TDR approved

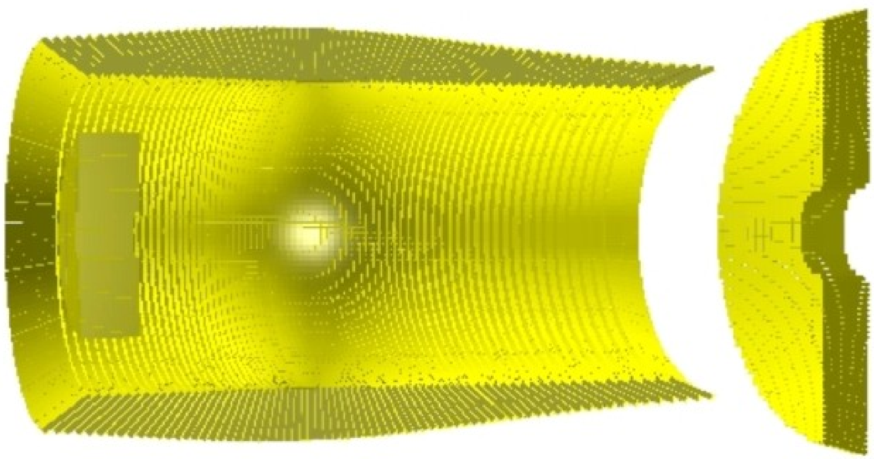


$\overline{P}$ANDA calorimeter

JÜLICH FORSCHUNGSZENTRUM

$\overline{P}$ANDA EMC (Electromagnetic Calorimeter)

17,200 crystals
$PbWO_4$ (radiation hard, fast τ_{Decay}~6 ns)
28 X_0
dE/dx=13.0 MeV/cm



operated at −25° C

- Crystal length: 20 cm = $22X_0$
- Increase of light yield:
  - PbWO II~x2 CMS $PbWO_4$ Crystals
  - Operation with 2 APDs (1 cm^2 each) increase effic. ~ x4 compared to CMS
  - Operation at -25 °C increases light yield compared to +18 °C ~x4 times

⇩

big improvement compared to CMS

Barrel Calorimeter
- 11360 $PbWO_4$ Crystals
- LAAPD readout, 2x1 cm^2
- σ(E)/E ~ `.5% E = const

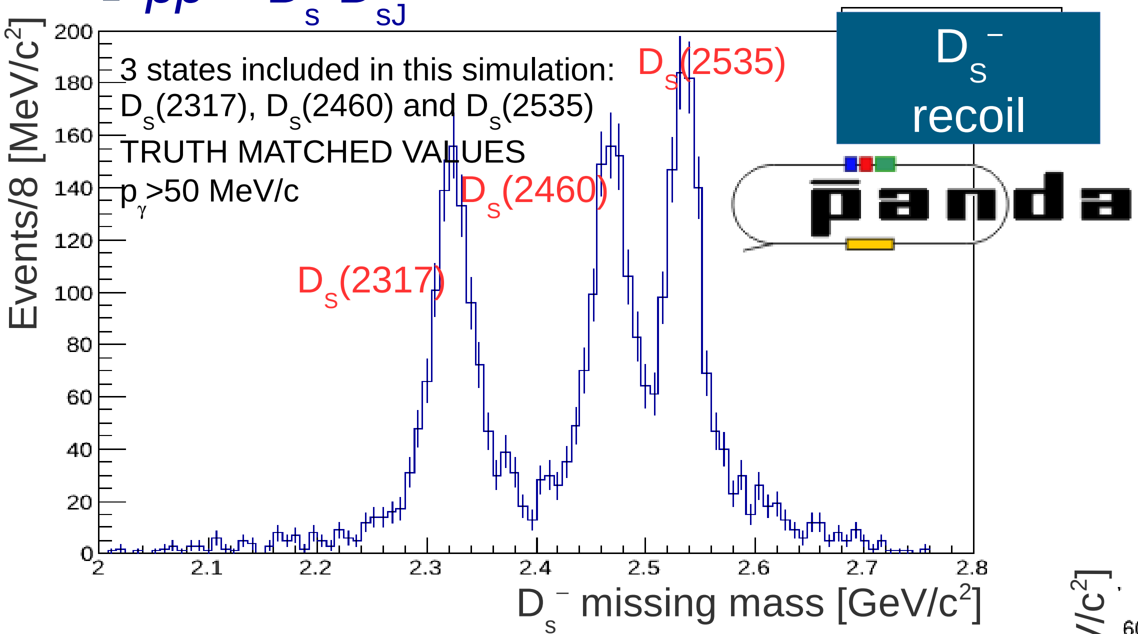
Forward Calorimeter
- 3600 $PbWO_4$ Crystals
- High occupancy in center
- LAAPD or VPT

Backward endcap
- 524 $PbWO_4$ Crystals

Challenges in D_s meson spectroscopy

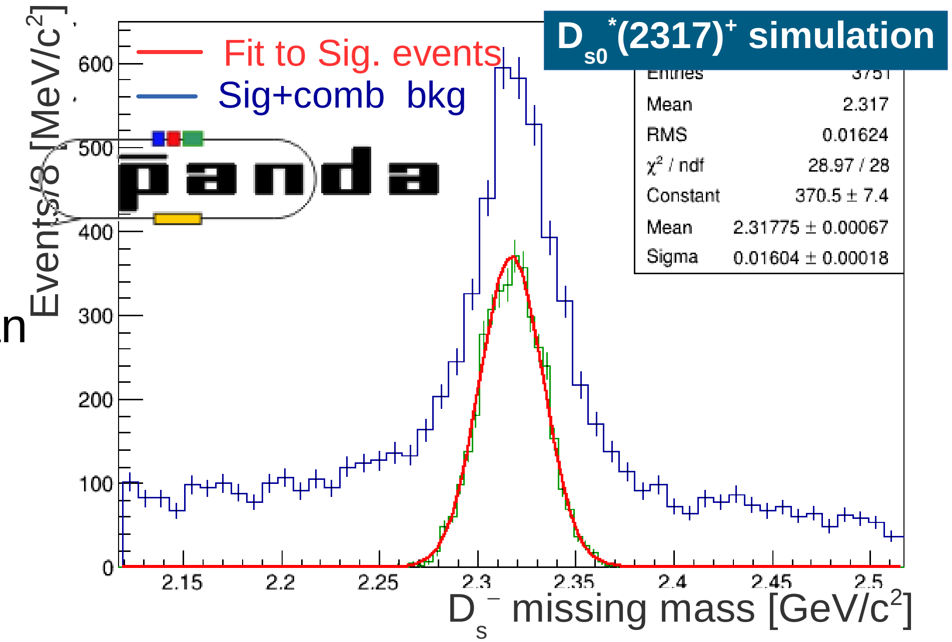
ICHEP2014 – E.P., Nucl. Part. Phys. Proc. 273 (2016) 231

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



- Missing mass of D_s^-:
- D_s reconstructed exclusively
- Bkg cross section > thousand times than expected on signal

- Goals:
  1. Cross section measurement in $\bar{p}p$
  2. Measurement of the width with mass scan
  3. Mixing between D states with same J^P,
  4. Chiral symmetry breaking



Cross section

- Excitation function of the cross section for $\bar{p}p \rightarrow D_s^- D_{s0}^*(2317)^+$:

$$\sigma(s) = \frac{|\mathcal{M}|^2}{64 \cdot \pi \cdot p_1^* \cdot s} \, \Phi(E)$$

$$\Phi(E) = \frac{1}{\pi} \sqrt{\frac{MM^*\Gamma^*}{M + M^*}} \int_{-\infty}^{\tilde{E}} d\delta \sqrt{\tilde{E} - \delta} \, \frac{1}{\delta^2 + 1}$$

$M = M(D_s^-)$
$M^* = M(D_s^*(2317)^+)$
$\Gamma^* = \Gamma(D_s^*(2317)^+)$
s = square energy in the center-of-mass system
p_1^* = momentum of the antiproton beam
$E = \sqrt{s} - M - M^*$
$\tilde{E} = 2\,E/\Gamma^*$
$\mu = MM^*/(M+M^*)$

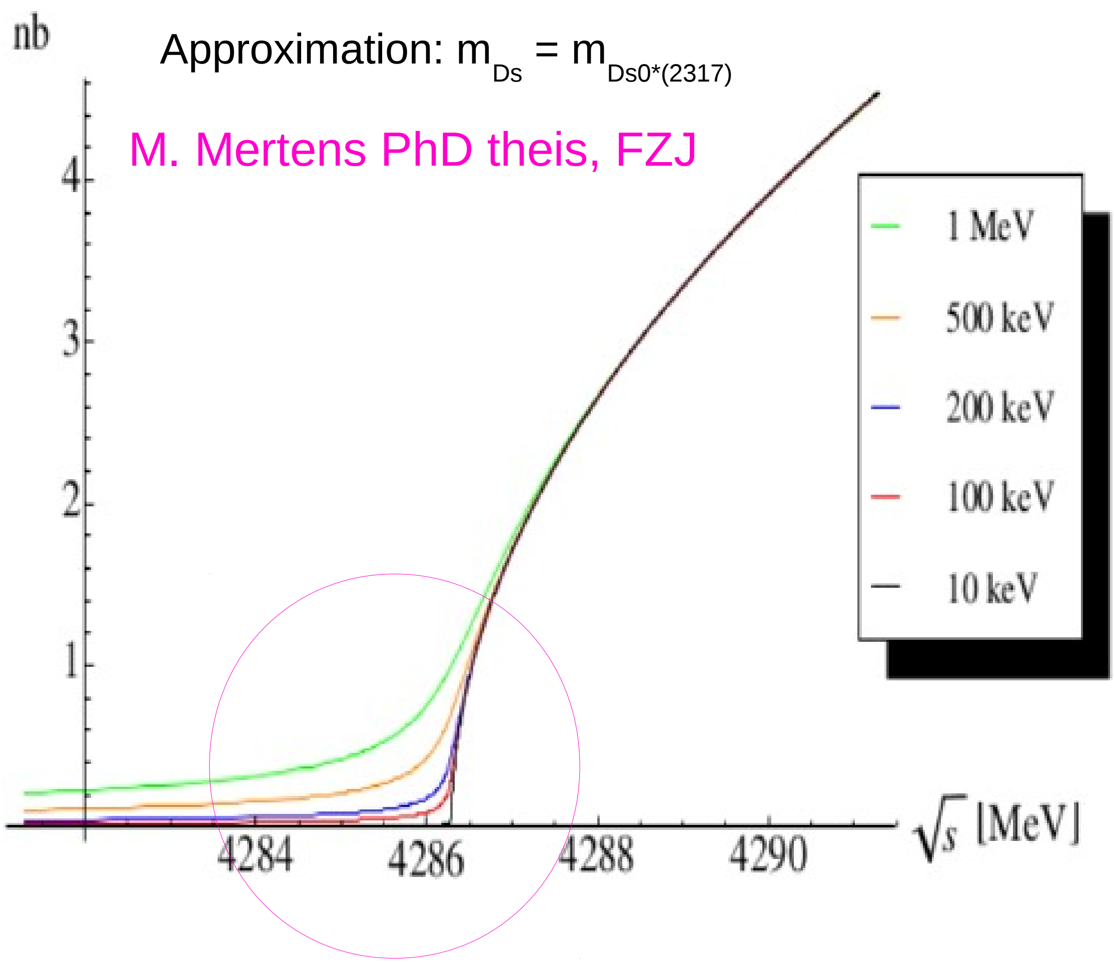
Many thanks to Christoph Hanhart for his extremely useful help!

$$\sqrt{\tilde{E}} \cdot \int d\delta / (\delta^2+1) = \pi$$

$$\Phi(E) \rightarrow \sqrt{2\tilde{E}/\Gamma^*} \cdot p^{cm}_{Ds2317}, \quad \text{for } \tilde{E}>>1$$

E.P, PoS Bormio2015 (2015) 044

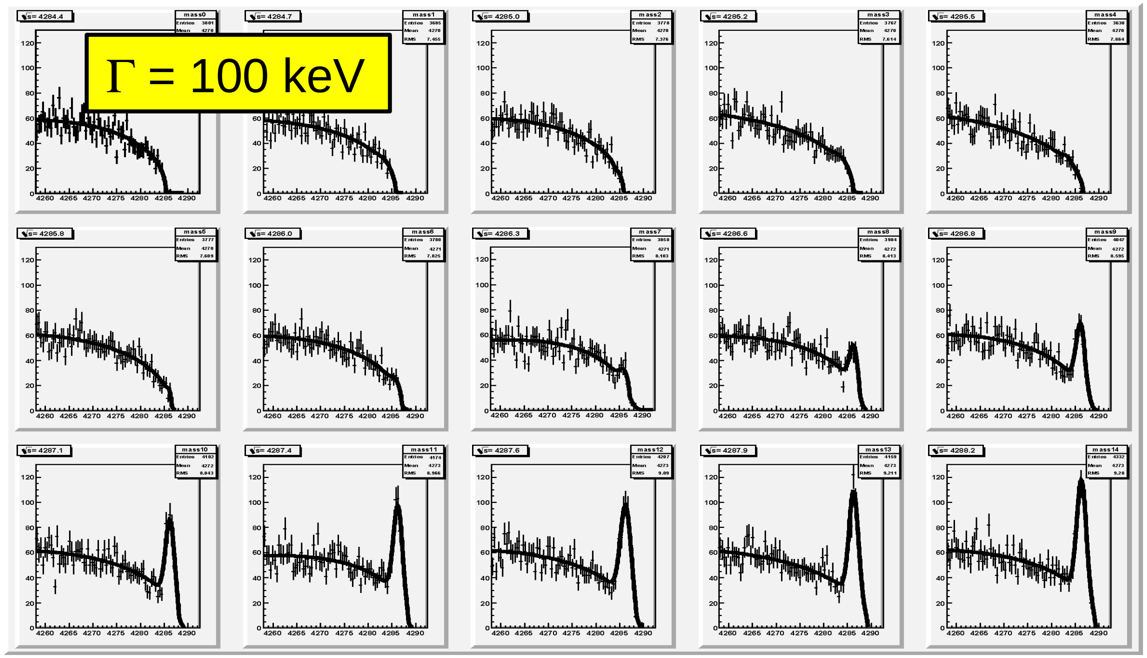
E.P., Nucl.Phys. A948 (2016) 93



Mitglied in der Helmholtz-Gemeinschaft

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

M. Mertens



What do we want to measure?

- PDG: Γ <3.8 MeV at 95% c.l.
- Excitation function of the cross section:

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

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

$\lambda = \sqrt{s} - m[D_s^-] - m[D_s(2317)^+]$

Summary: expected produced events

Input σ (nb)	Produced events per day (Start up) $\bar{L} = 10^{31}\ cm^{-2}\ s^{-1}$	Produced events per day (Full lumi) $\bar{L} = 10^{32}\ cm^{-2}\ s^{-1}$
20	17280	172800
10	8640	86400
5	4320	43200
2	1728	17280
1	864	8640

$\bar{p}p \rightarrow D_s^- D_s^*(2317)^+$

- Conservative range: σ [1 – 100] nb
- With **L = 10^{31} cm^{-2} s^{-1}** (average), **864** produced events/day (hyp: **σ = 1nb**)
- B factories:

  S/B ~ 5/1, ε = 8.2% in $e^+e^- \rightarrow D_s D_{s0}^*(2317)$;

  S/B ~ 2/1, $\varepsilon \in [0.42\text{-}2.75] \cdot 10^{-4}$ through B decays.

  Belle, Phys. Rev. Lett. 92, 012002 (2004) Phys. Rev. Lett. 91, 262002 (2003)

  Belle II will collect 43750 $D_{s0}^*(2317)$ in 10 years ($\mathscr{L}$ = 50 ab^{-1})

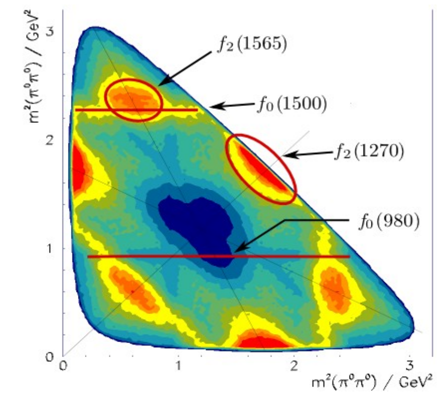
$\overline{P}$*ANDA* is suitable not only for Open-charm Physics studies.

.

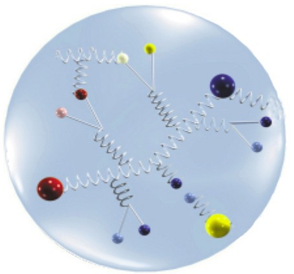
It is MUCH more...

$\overline{P}$ANDA physics program

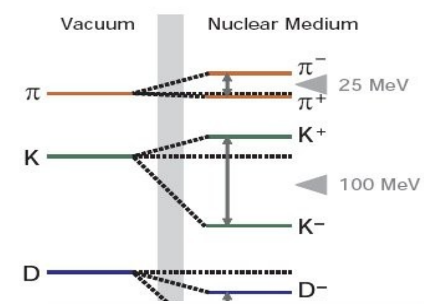
- **Hadron spectroscopy**:
  search for particles and measurement of hadron properties



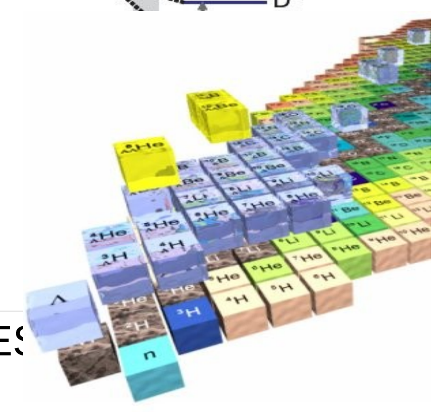
- **Nucleon structure**:
  generalized parton distribution, Drell-Yan processes and time-like form factor of the proton



- **Hadrons in matter**:
  study in medium effects of hadronic particles



- **Hypernuclei**:
  measurement of nuclear properties with an additional strangeness degree of freedom



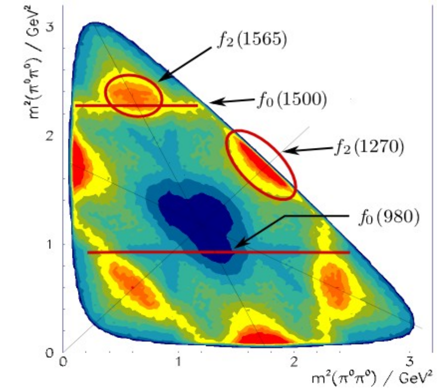
$\overline{\text{P}}$ANDA physics program

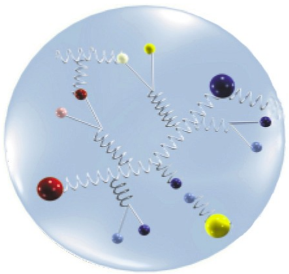
Hadron spectroscopy:
- Charmonium-like spectroscopy
- X(3872) line shape and decays (precision and uniqueness)
- Charged Z spectroscopy (uniqueness)
- High-spin states (uniqueness)

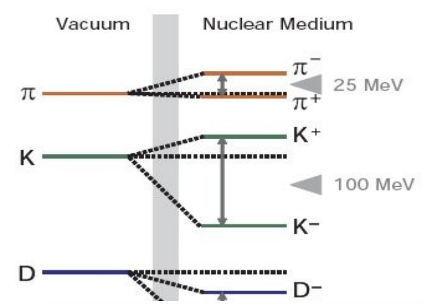
- **Nucleon structure**:
  generalized parton distribution, Drell-Yan processes and time-like form factor of the proton

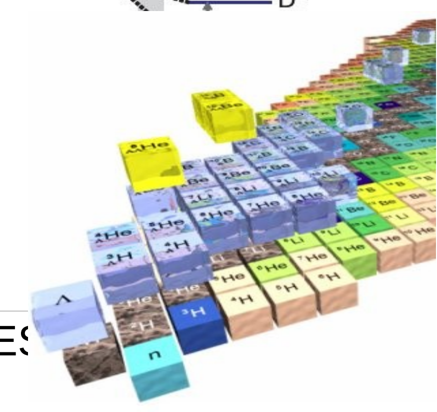
- **Hadrons in matter**:
  study in medium effects of hadronic particles

- **Hypernuclei**:
  measurement of nuclear properties with an additional strangeness degree of freedom









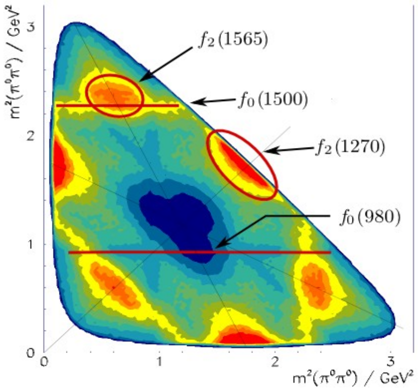
$\overline{\text{P}}$ANDA physics program

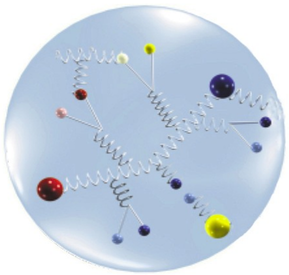
- **Hadron spectroscopy**:
  search for particles and measurement of hadron properties

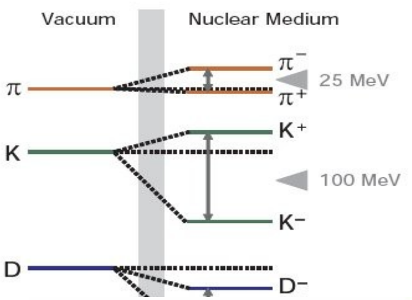
- Nucleon structure: EMFF in time-like regime
- Form factors via π^0 production (uniqueness)
- Light meson spectroscopy: glueballs, ,,, (precision)

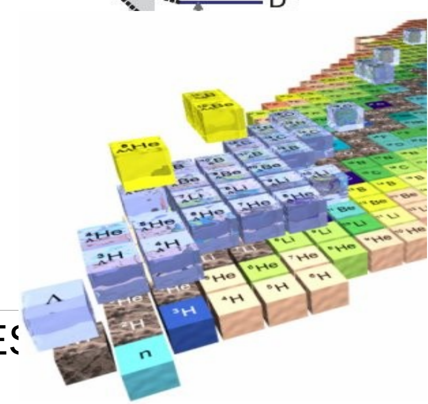
- **Hadrons in matter**:
  study in medium effects of hadronic particles

- **Hypernuclei**:
  measurement of nuclear properties with an additional strangeness degree of freedom





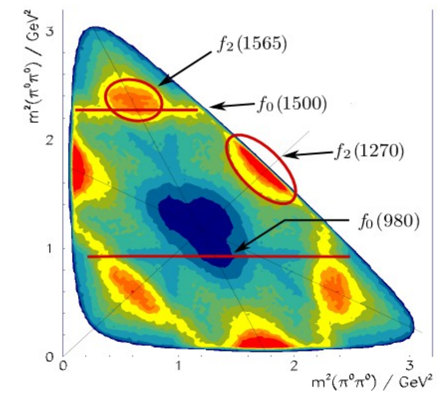


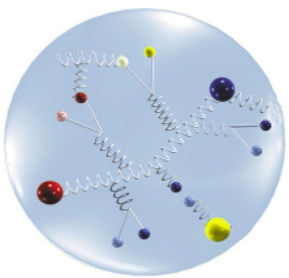


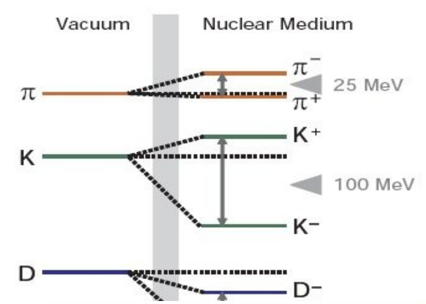
$\bar{P}$ANDA physics program

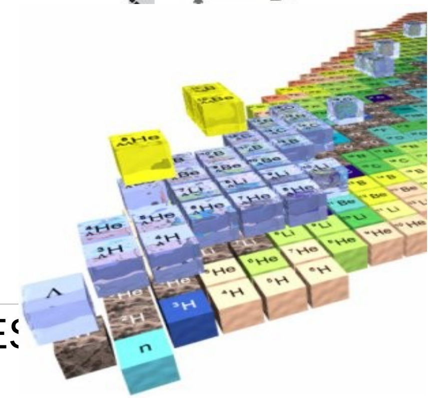
- **Hadron spectroscopy**:
  search for particles and measurement of hadron properties
- **Nucleon structure**:
  generalized parton distribution, Drell-Yan processes and time-like form factor of the proton
- **Hadrons in matter**:
  study in medium effects of hadronic particles

- Hyperon structure: spectroscopy (uniqueness)
- Hyperon production: cross sections, CP, ... (precision and unique)
- $\bar{p}$-A interaction (uniqueness)







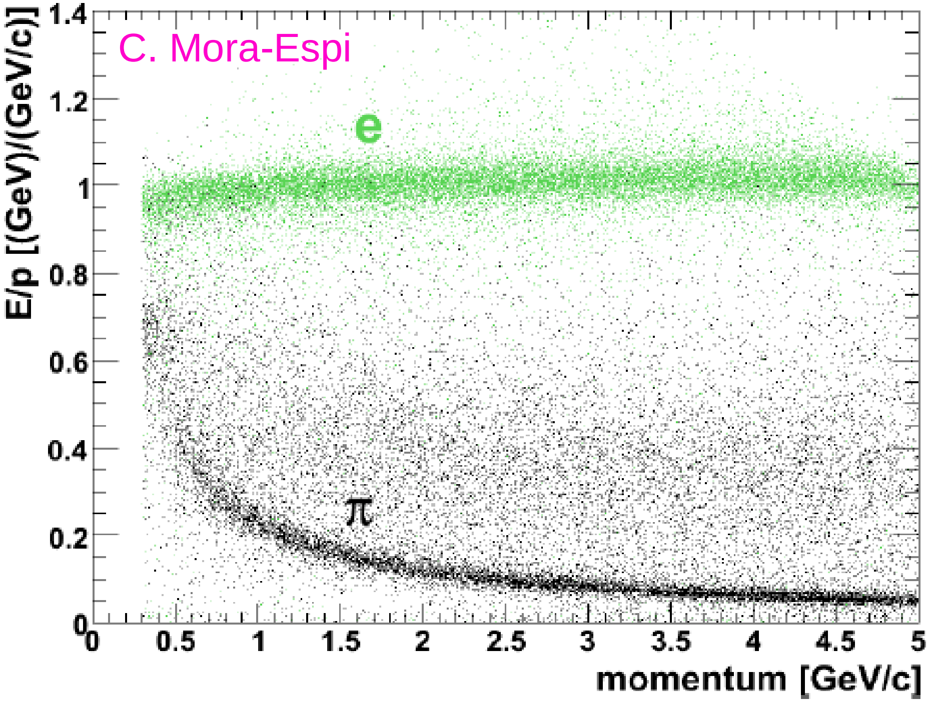


Some examples from $\overline{P}ANDA$ recent publications on highlight topics of the physics program:

EXAMPLE:

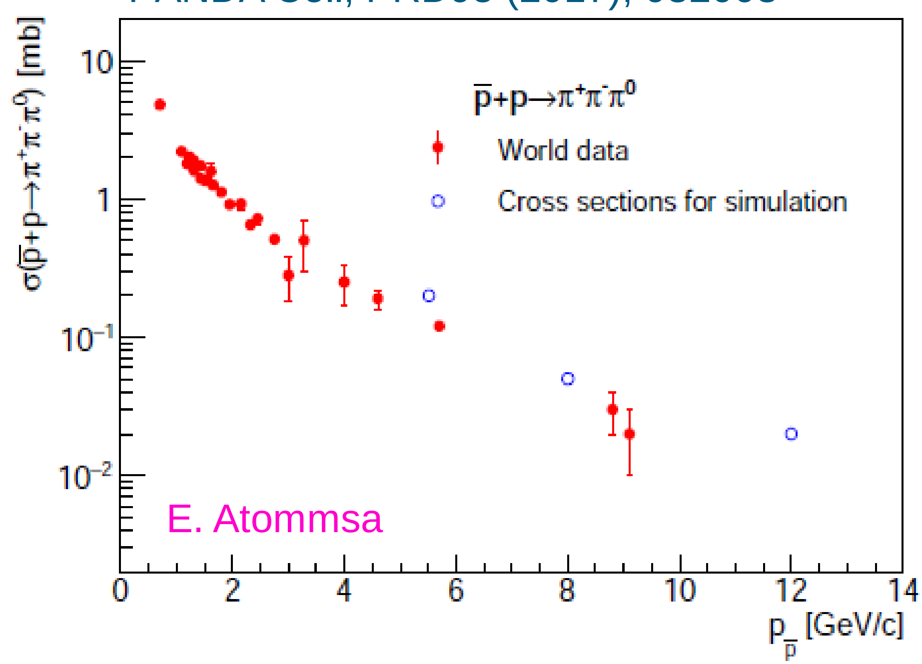
Investigating the structure of the proton

$\overline{\text{P}}$ANDA Coll, EPJ, A51 (2015), 107



- Good particle identification!
  Background power suppression:
  - up to $5 \cdot 10^7$ at low q^2;
  - $1 \cdot 10^7$ for larger q^2.

$\overline{\text{P}}$ANDA Coll, PRD95 (2017), 032003



- Feasibility studies (MC) on time-like proton electromagnetic form factor and transition distribution amplitudes (TDAs)

EXAMPLE:

Investigating the structure of the proton

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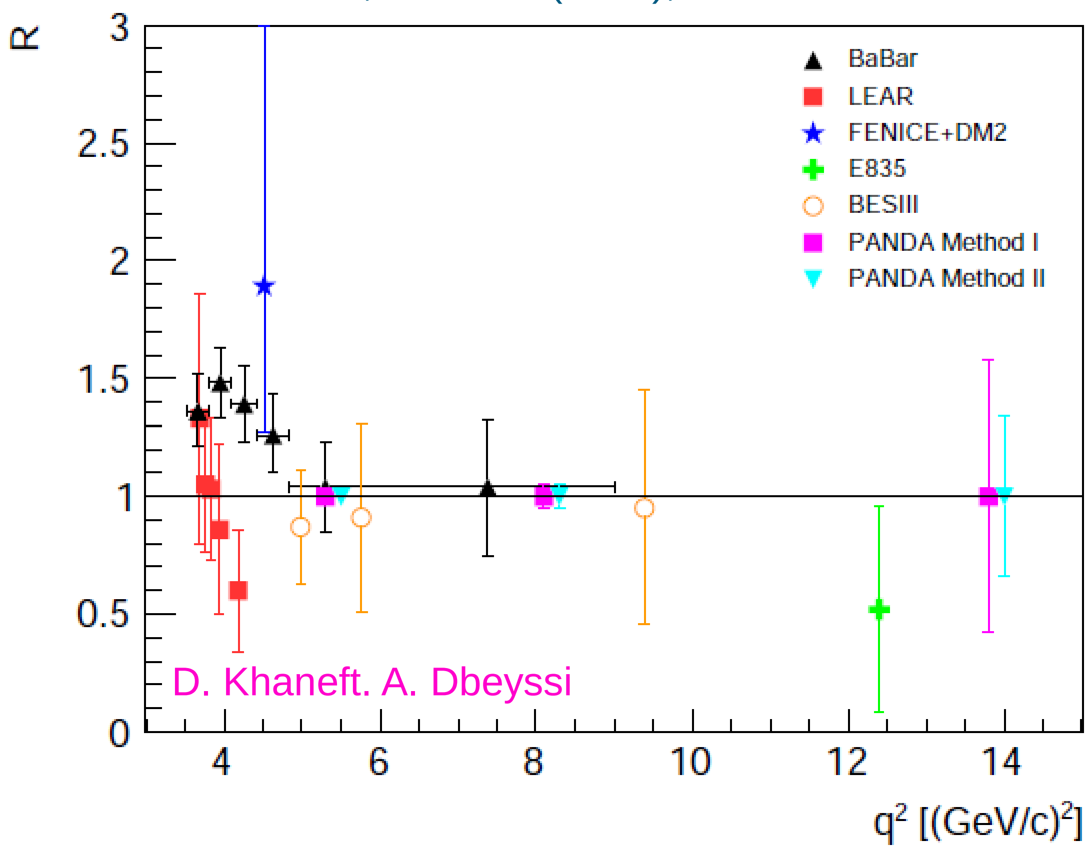
$\overline{\mathrm{P}}$ANDA Coll, EPJ A52 (2016), 325



$R = |G_E|/|G_M|$

EXAMPLE: X, Y, Z cross sections at $\overline{\text{P}}$ANDA

E.P., HADRON2015 - AIP Conf.Proc. 1735 (2016) 060011

- Detailed balance method:

$$\sigma[p\bar{p} \to R] \cdot \mathcal{B}(R \to f) = \frac{(2J+1)\cdot 4\pi}{s - 4m_p^2} \cdot \frac{\mathcal{B}(R \to p\bar{p}) \cdot \mathcal{B}(R \to f) \cdot \Gamma_R^2}{4(\sqrt{s} - m_R)^2 + \Gamma_R^2}$$

for non polarized incident beam.

- If BR(R →$p\bar{p}$) is known (from PDG), σ(X, Y, Z →$p\bar{p}$) → use the detailed balance method

- If BR(R →$p\bar{p}$) is **un**known (from PDG), σ(X, Y, Z →$p\bar{p}$) → evaluate BR(R →$p\bar{p}$) by scaling widths, then use detailed balance method

$$BR(R_1 \to p\bar{p}) = BR(R_2 \to p\bar{p}) \cdot \frac{\Gamma_{total}(R_2)}{\Gamma_{total}(R_1)}$$

- Reference resonance for our calculation: **ψ(3770)**

- Assumption: <u>partial width of charmonium states are identical</u>

How do we know that this method works?

EXAMPLE:

Detailed balance method

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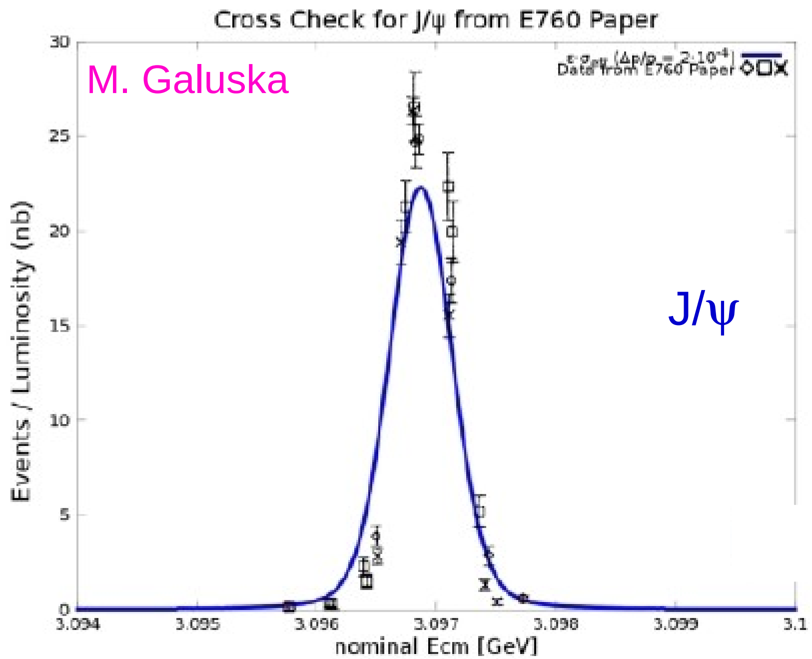

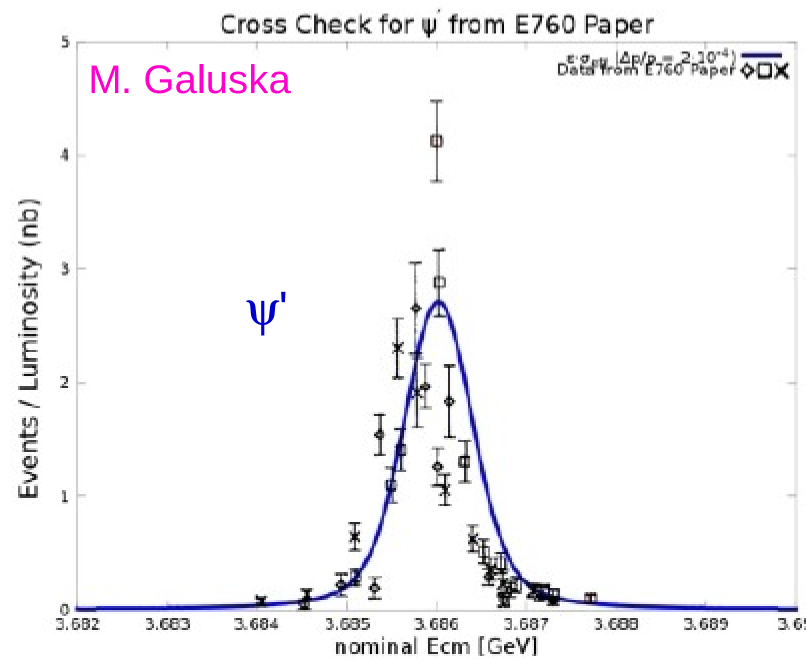

- Detailed balance method: check on E760 data

EXAMPLE:

X, Y, Z rates at $\overline{P}$ANDA

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Resonance	Cross section (nb)
X(3872) Y(4260) Z(3900)$^+$	<50 [0.077 – 2.2] [0.017 – 0.473]

How many X(3872), Y(4260), Z(3900)$^+$ can $\overline{P}$*ANDA* produce?

Upper limit — Start-up — Full lumi

Resonance	$\mathcal{L} = 8.64$	$\mathcal{L} = 0.864$
$X(3872)$	432000	43200
$Y(4260)$	19000	1900
$Z(3900)^+$	4050	405

pb^{-1}/**day**

Lower limit

Resonance	$\mathcal{L} = 8.64$	$\mathcal{L} = 0.864$
$X(3872)$	-	-
$Y(4260)$	665	67
$Z(3900)^+$	140	14

pb^{-1}/**day**

EXAMPLE:

Challenge: search for new exotic Z states

E.P., Z workshop 2015, Giessen; HADRON2015 - AIP Conf.Proc. 1735 (2016) 060011

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Resonance	Mass [MeV/c²]	Width [MeV]	Decay	J^P	
$Z(4430)^+$	$4433\pm4(stat)\pm2(syst)$	$45^{+18}_{-13}(stat)^{+30}_{-13}(syst)$	$\psi(2S)\pi^+$		[1]
$Z_c(3900)^+$	$3899.0\pm3.6(stat)\pm4.9(syst)$	$46\pm10(stat)\pm20(syst)$	$J/\psi\pi^+$, D^0D^{*-}		[2]
$Z_c(3900)^0$	$3894.8\pm2.3(stat)$	$29.6\pm8.2(stat)$	$J/\psi\pi^0$		[3]
$Z_c(4020)^+$	$4022.9\pm0.8(stat)\pm2.7(syst)$	$7.9\pm2.7(stat)\pm2.6(syst)$	$h_c\pi^+$		[4]
$Z_c(4020)^0$	$4023.6\pm2.2(stat)\pm3.9(syst)$	-	$h_c\pi^0$		[5]
$Z_c(3885)^+$	$3883.9\pm1.5(stat)\pm4.2(syst)$	$24.8\pm3.3(stat)\pm11.0(syst)$	$D^+\bar{D}^{*0}$	1^+	[6]
$Z_c(4025)^+$	$4026.3\pm2.6(stat)\pm3.7(syst)$	$24.8\pm5.6(stat)\pm7.7(syst)$	$D^{*+}\bar{D}^*$		[7]

[1] PRL 100(2008)142001; [2] PRL 110(2013)252001; [3] PLB 727(2013)366; [4] arXiV:1309.1806; [5] ICHEP2014; [6] PRL 112(2014)022001; [7] PRL 112(2014)132001.

- Expected Z states near $D\bar{D}$ threshold, never observed ($m_Z \sim$ 3730 MeV/c²)
- Production forbidden by parity conservation at e^+e^- colliders
- X(3872)→Z(3730) π transition kinematically allowed
  (but maybe rare decay and X(3872) statistics limited at e^+e^- colliders)
- Proposal @ $\bar{P}$ANDA:

$\bar{p}p \rightarrow Z(3730)^0\pi^0$, $Z(3730)^0 \rightarrow J/\psi\gamma$

$\bar{p}p \rightarrow Z(3730)^0\pi^0$, $Z(3730)^0 \rightarrow \chi_{c1}\,\pi^0$

$\bar{p}p \rightarrow Z(3730)^+\pi^-$, $Z(3730)^+ \rightarrow \chi_{c1}\pi^+$, $\chi_{c1} \rightarrow J/\psi\gamma$

....and more and more....

Summary

- Still many open questions in hadron physics:

a $\bar{p}p$ machine is needed

- Open-charm physics is still of very high interest
- $\overline{\text{P}}$ANDA is in a unique position to perform such measurements
- Original measurements are expected during the *Phase-1* of data taking
- Big hardware effort: test beam started, TDRs ongoing

$\overline{\text{P}}$ANDA has lots of high profile and unique physics cases

Important contributions expected from *$\overline{\text{P}}$ANDA* physics program.

"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)

THANK YOU!

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