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Charm (-onium) physics at PANDA

Frank Nerling
HFHF, GSI Darmstadt
on behalf of the PANDA Collaboration

10th Intern. Workshop on Charm Physics
May 31st - June4th 2021

Outline

- **Introduction**
  - Motivation, PANDA physics programme
  - Advantage of anti-protons
  - Exotic mesons
- **Charmonium(-like) spectroscopy**
  - Charmonium-like exotics
  - Charmed hybrids
  - Open charm
- **Summary & outlook**

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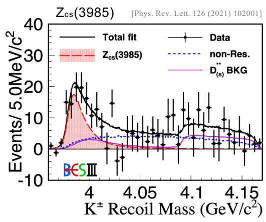
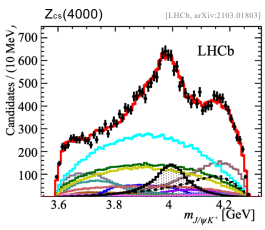
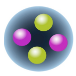
Recent Hot Topics

Hadron Spectroscopy





Strange partner of the famous, unexpected, manifestly exotic $Z_c(3900)$?



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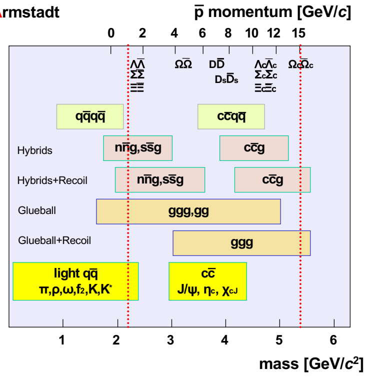
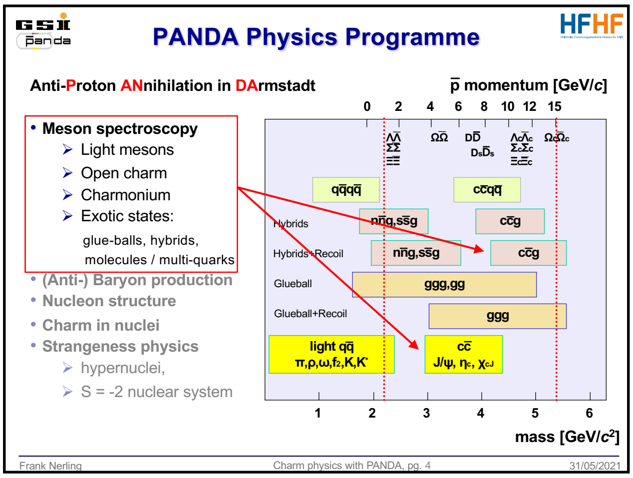
PANDA Physics Programme

Anti-Proton ANnihilation in DArmstadt

- **Meson spectroscopy**
  - Light mesons
  - Open charm
  - Charmonium
  - Exotic states:
    glue-balls, hybrids, molecules / multi-quarks
- **(Anti-) Baryon production**
- **Nucleon structure**
- **Charm in nuclei**
- **Strangeness physics**
  - hypernuclei,
  - S = -2 nuclear system



3


PANDA Physics Programme
Anti-Proton ANnihilation in DArmstadt
p̄ momentum [GeV/c]
• Meson spectroscopy
Light mesons
Open charm
Charmonium
Exotic states:
glue-balls, hybrids,
molecules / multi-quarks
• (Anti-) Baryon production
• Nucleon structure
• Charm in nuclei
• Strangeness physics
hypernuclei,
S = -2 nuclear system
Hybrids
Hybrids+Recoil
Glueball
Glueball+Recoil
light qq̄
π,ρ,ω,f₂,K,K*
cc̄
J/ψ, η_c, χ_cJ
mass [GeV/c²]
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Charm physics with PANDA, pg. 4
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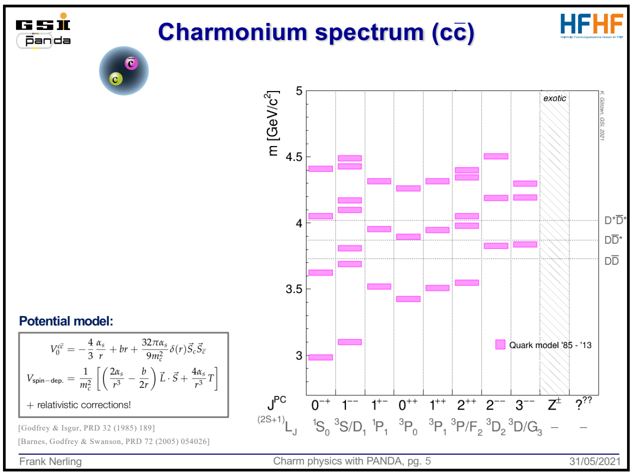
Charmonium spectrum (cc̄)
m [GeV/c²]
exotic
D*D̄*
DD̄*
DD̄
Quark model '85 - '13
Potential model:
+ relativistic corrections!
[Godfrey & Isgur, PRD 32 (1985) 189]
[Barnes, Godfrey & Swanson, PRD 72 (2005) 054026]
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Charm physics with PANDA, pg. 5
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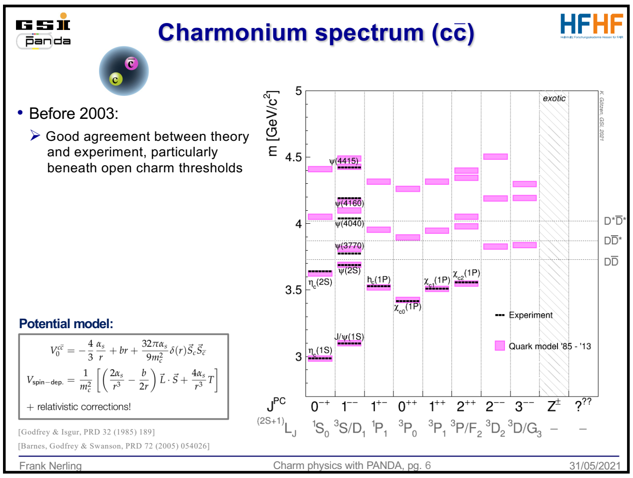
Charmonium spectrum (cc̄)
• Before 2003:
Good agreement between theory and experiment, particularly beneath open charm thresholds
m [GeV/c²]
exotic
ψ(4415)
ψ(4160)
ψ(4040)
ψ(3770)
ψ(2S)
J/ψ(1S)
D*D̄*
DD̄*
DD̄
Experiment
Quark model '85 - '13
Potential model:
+ relativistic corrections!
[Godfrey & Isgur, PRD 32 (1985) 189]
[Barnes, Godfrey & Swanson, PRD 72 (2005) 054026]
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Charmonium spectrum ($c\bar{c}$)

- Before 2003:
  - Good agreement between theory and experiment, particularly beneath open charm thresholds
- After 2003:
  - Severe mismatch between predicted and observed spectrum

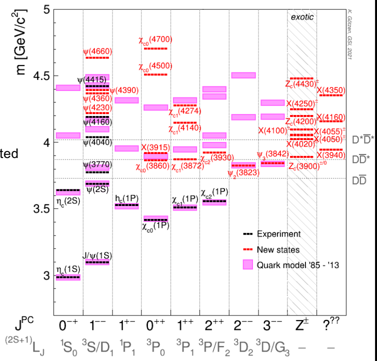
Potential model:

$$V_0^{c\bar{c}} = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\delta(r)\vec{S}_c\vec{S}_{\bar{c}}$$

$$V_{\text{spin-dep.}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

+ relativistic corrections!

[Godfrey & Isgur, PRD 32 (1985) 189]
[Barnes, Godfrey & Swanson, PRD 72 (2005) 054026]



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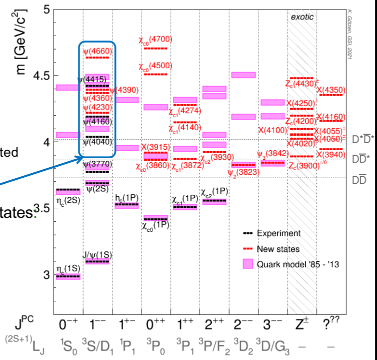
Charmonium spectrum ($c\bar{c}$)

- Before 2003:
  - Good agreement between theory and experiment, particularly beneath open charm thresholds
- After 2003:
  - Severe mismatch between predicted and observed spectrum
- Several supernumerary vector states: Y(4260), ..., Y(4660)



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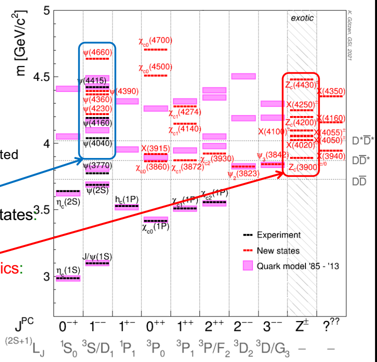
Charmonium spectrum ($c\bar{c}$)

- Before 2003:
  - Good agreement between theory and experiment, particularly beneath open charm thresholds
- After 2003:
  - Severe mismatch between predicted and observed spectrum
- Several supernumerary vector states: Y(4260), ..., Y(4660)
- Several charged manifestly exotics: $Z_c(3900)^{+/-}$, ..., $Z_c(4430)^{+/-}$



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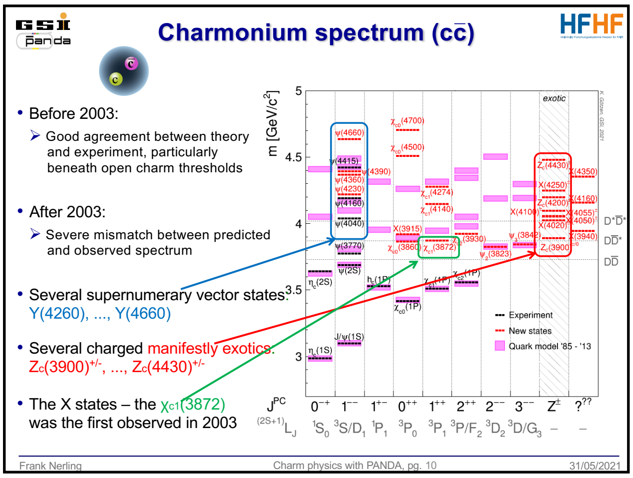
Charmonium spectrum (cc̄)
• Before 2003:
➢ Good agreement between theory and experiment, particularly beneath open charm thresholds
• After 2003:
➢ Severe mismatch between predicted and observed spectrum
• Several supernumerary vector states Y(4260), ..., Y(4660)
• Several charged manifestly exotics: Zc(3900)+/-, ..., Zc(4430)+/-
• The X states – the χc1(3872) was the first observed in 2003
m [GeV/c²]
exotic
Experiment
New states
Quark model '85 - '13
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Charm physics with PANDA, pg. 10
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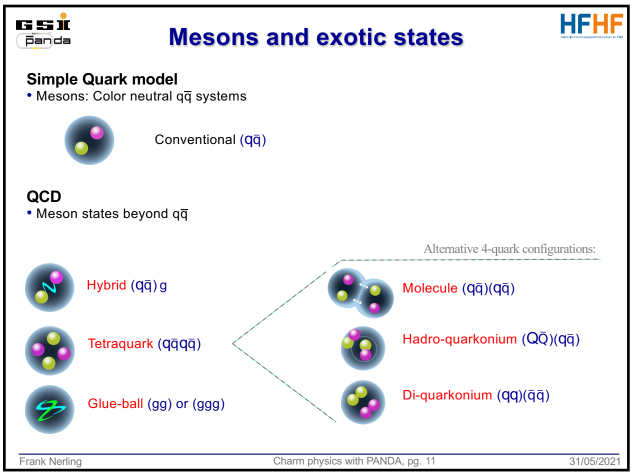
Mesons and exotic states
Simple Quark model
• Mesons: Color neutral qq̄ systems
Conventional (qq̄)
QCD
• Meson states beyond qq̄
Alternative 4-quark configurations:
Hybrid (qq̄) g
Tetraquark (qq̄qq̄)
Glue-ball (gg) or (ggg)
Molecule (qq̄)(qq̄)
Hadro-quarkonium (QQ̄)(qq̄)
Di-quarkonium (qq)(q̄q̄)
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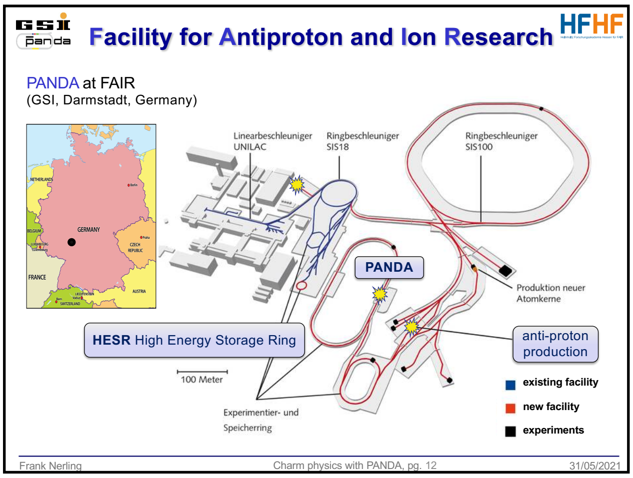
Facility for Antiproton and Ion Research
PANDA at FAIR
(GSI, Darmstadt, Germany)
Linearbeschleuniger UNILAC
Ringbeschleuniger SIS18
Ringbeschleuniger SIS100
PANDA
Produktion neuer Atomkerne
anti-proton production
HESR High Energy Storage Ring
100 Meter
Experimentier- und Speicherring
existing facility
new facility
experiments
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Charm physics with PANDA, pg. 12
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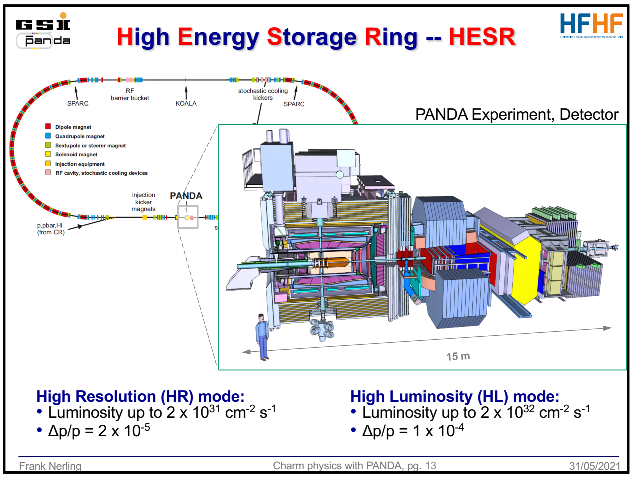
High Energy Storage Ring -- HESR
HFHF
SPARC
RF barrier bucket
KOALA
stochastic cooling kickers
SPARC
PANDA Experiment, Detector
PANDA
15 m
High Resolution (HR) mode:
• Luminosity up to 2 x 10^31 cm^-2 s^-1
• Δp/p = 2 x 10^-5
High Luminosity (HL) mode:
• Luminosity up to 2 x 10^32 cm^-2 s^-1
• Δp/p = 1 x 10^-4
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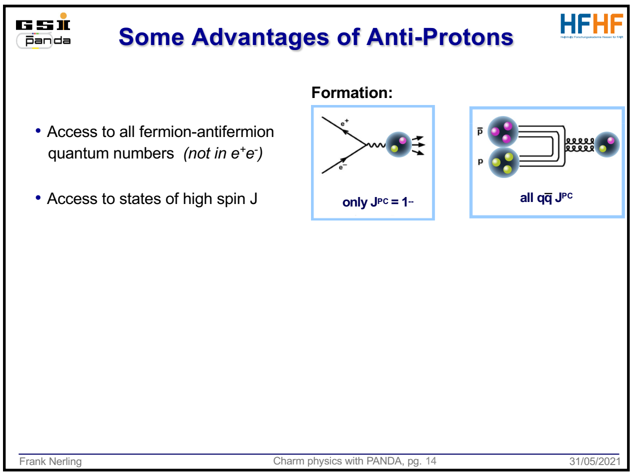
Some Advantages of Anti-Protons
HFHF
Formation:
• Access to all fermion-antifermion quantum numbers (not in e+e-)
• Access to states of high spin J
only JPC = 1--
all qq̄ JPC
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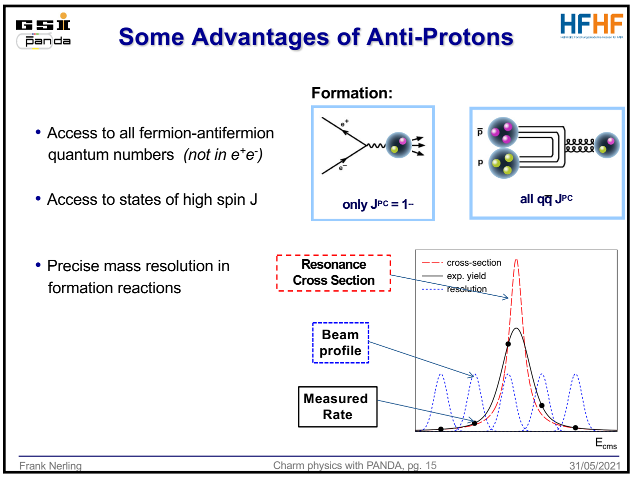
Some Advantages of Anti-Protons
HFHF
Formation:
• Access to all fermion-antifermion quantum numbers (not in e+e-)
• Access to states of high spin J
only JPC = 1--
all qq̄ JPC
• Precise mass resolution in formation reactions
Resonance Cross Section
cross-section
exp. yield
resolution
Beam profile
Measured Rate
Ecms
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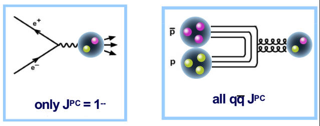
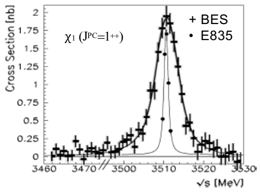
Some Advantages of Anti-Protons

Formation:



- Access to all fermion-antifermion quantum numbers *(not in e^+e^-)*
- Access to states of high spin J
- Precise mass resolution in formation reactions



E760/835@Fermilab ≈ 240 keV
PANDA@FAIR ≈ 50 keV

Ablikim et al., Phys. Rev. D71 (2005) 092002: BES (IHEP): 3510.3 ± 0.2 MeV/c²
Andreotti et al., Nucl. Phys. B717 (2005) 34: E835 (Fermilab): 3510.641 ± 0.074 MeV/c²

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Charmonium-like Exotics -- XYZ states

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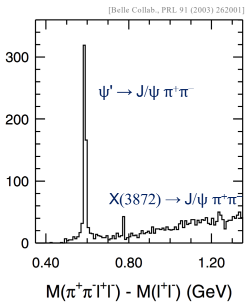
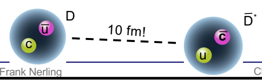
Experimental review of the X(3872)

[Belle Collab., PRL 91 (2003) 262001]



- First observed by Belle in 2003
  - $X(3872) \to J/\psi \pi^+\pi^-$
  - very narrow state with $J^{PC} = 1^{++}$
- Belle & BaBar report signal in
  - $X(3872) \to D^0 \bar{D}^{*0}$
- Mass $m[X(3872)] - m[D^{*0}] - m[D^0]$ = (-0.07 ± 0.12) MeV/c² (LHCb 2020)
- Width measurement:
  - $\Gamma_{X(3872)} <$ 1.2 MeV (2011, Belle)
  - $\Gamma_{X(3872)}$ = 1.39 MeV (2020, LHCb)

Analogy to deuteron:



For clarification:
=> Precision measurement with sub-MeV resolution needed!

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Perfomance Study for energy resonance scans of narrow resonances, like the X(3872)

Reminder:
Sub-MeV resolution needed to clarify nature => panda

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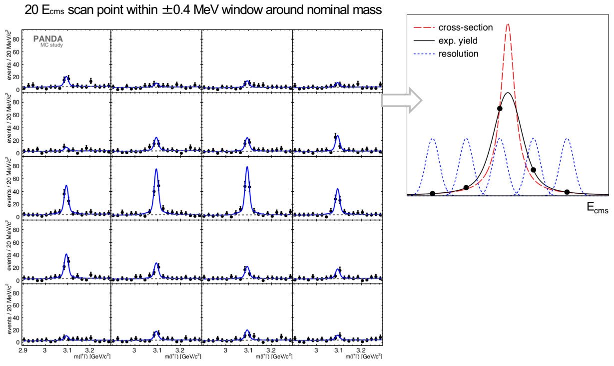
Scan Procedure Principle (Example)

20 E_{cms} scan point within ±0.4 MeV window around nominal mass



[PANDA, Eur. Phys. J. A 55 (2019) 42]

20

Scan Procedure Principle (Example)

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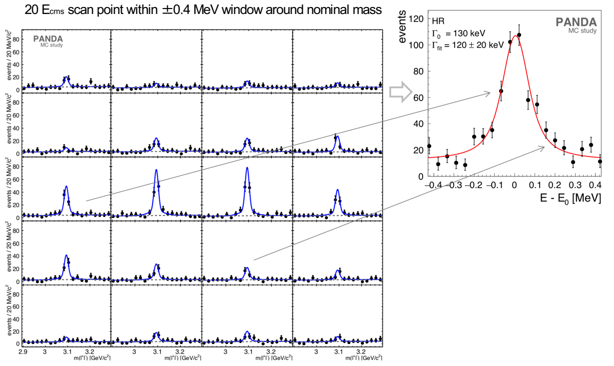
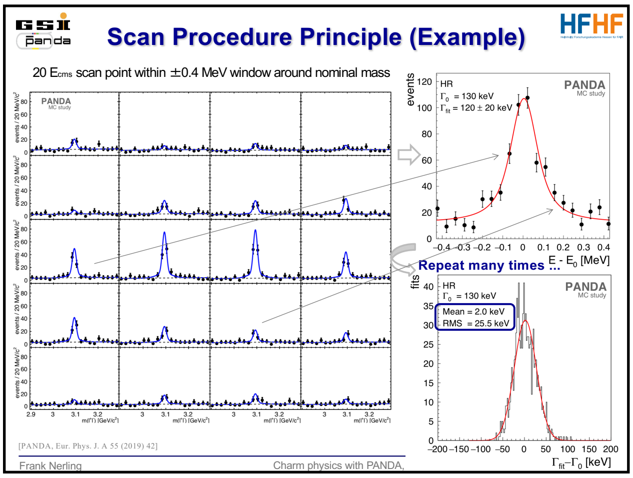


[PANDA, Eur. Phys. J. A 55 (2019) 42]

21


Scan Procedure Principle (Example)
20 Ecms scan point within ±0.4 MeV window around nominal mass
HR
Γ0 = 130 keV
Γfit = 120 ± 20 keV
PANDA
MC study
events
E - E0 [MeV]
Repeat many times ...
fits
Mean = 2.0 keV
RMS = 25.5 keV
Γfit−Γ0 [keV]
[PANDA, Eur. Phys. J. A 55 (2019) 42]
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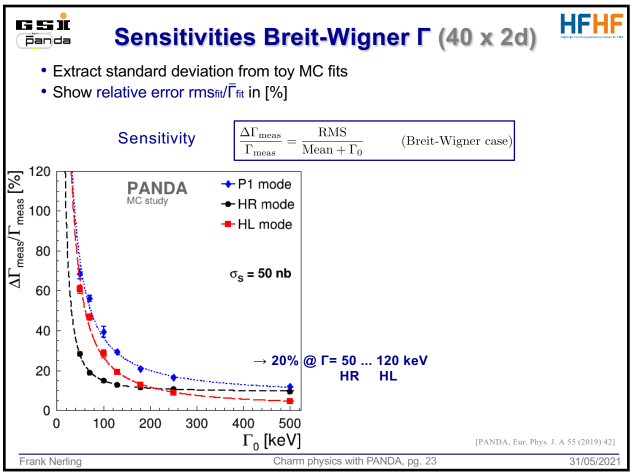
Sensitivities Breit-Wigner Γ (40 x 2d)
• Extract standard deviation from toy MC fits
• Show relative error rmsfit/Γfit in [%]
Sensitivity
ΔΓmeas / Γmeas = RMS / (Mean + Γ0) (Breit-Wigner case)
PANDA
MC study
P1 mode
HR mode
HL mode
σS = 50 nb
→ 20% @ Γ= 50 ... 120 keV
HR HL
ΔΓmeas/Γmeas [%]
Γ0 [keV]
[PANDA, Eur. Phys. J. A 55 (2019) 42]
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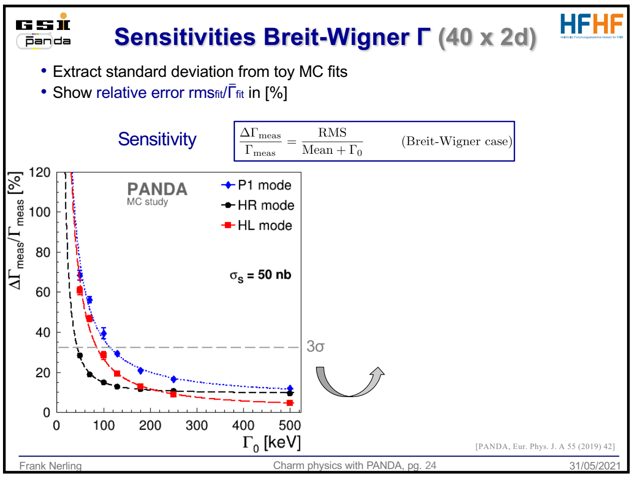
Sensitivities Breit-Wigner Γ (40 x 2d)
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Sensitivity
ΔΓmeas / Γmeas = RMS / (Mean + Γ0) (Breit-Wigner case)
PANDA
MC study
P1 mode
HR mode
HL mode
σS = 50 nb
3σ
ΔΓmeas/Γmeas [%]
Γ0 [keV]
[PANDA, Eur. Phys. J. A 55 (2019) 42]
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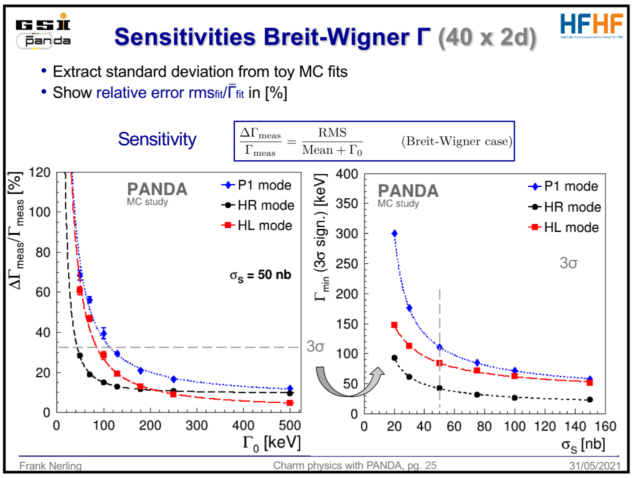
Sensitivities Breit-Wigner Γ (40 x 2d)
• Extract standard deviation from toy MC fits
• Show relative error rmsfit/Γfit in [%]
Sensitivity
(Breit-Wigner case)
PANDA
MC study
P1 mode
HR mode
HL mode
σS = 50 nb
3σ
Γ0 [keV]
σS [nb]
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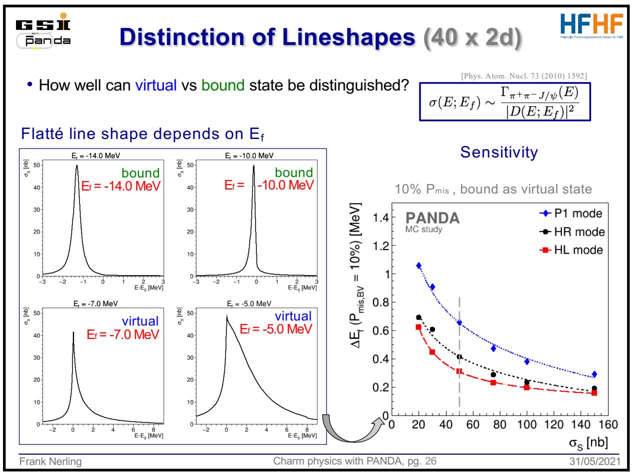
Distinction of Lineshapes (40 x 2d)
• How well can virtual vs bound state be distinguished?
[Phys. Atom. Nucl. 73 (2010) 1592]
Flatté line shape depends on Ef
bound
Ef = -14.0 MeV
bound
Ef = -10.0 MeV
virtual
Ef = -7.0 MeV
virtual
Ef = -5.0 MeV
Sensitivity
10% Pmis , bound as virtual state
PANDA
MC study
P1 mode
HR mode
HL mode
σS [nb]
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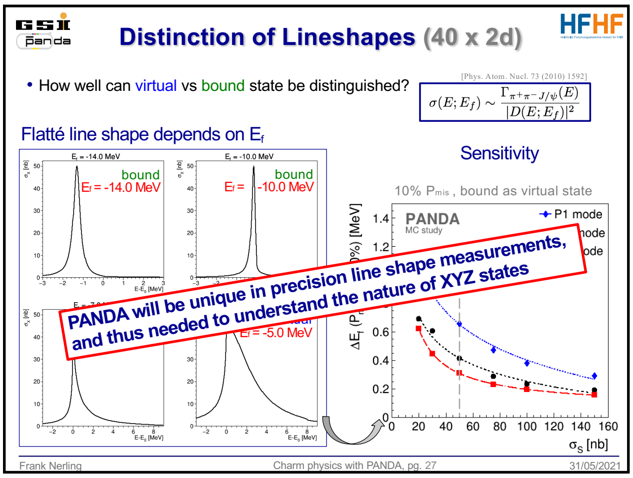
Distinction of Lineshapes (40 x 2d)
• How well can virtual vs bound state be distinguished?
[Phys. Atom. Nucl. 73 (2010) 1592]
Flatté line shape depends on Ef
Sensitivity
10% Pmis , bound as virtual state
PANDA will be unique in precision line shape measurements,
and thus needed to understand the nature of XYZ states
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LHCb measurement of $\chi_1(3872)$

[Phys.Rev.D 102 (2020) 9, 092005]
[https://arxiv.org/abs/2005.13419]

CERN-EP-2020-086
LHCb-PAPER-2020-008
May 27, 2020

Study of the lineshape of the $\chi_{c1}(3872)$ state

Abstract

A study of the lineshape of the $\chi_{c1}(3872)$ state is made using a data sample corresponding to an integrated luminosity of $3\,\text{fb}^{-1}$ collected in pp collisions at centre-of-mass energies of 7 and 8 TeV with the LHCb detector. Candidate $\chi_{c1}(3872)$ mesons from b-hadron decays are selected in the $J/\psi\pi^+\pi^-$ decay mode. Describing the lineshape with a Breit–Wigner function, the mass splitting between the $\chi_{c1}(3872)$ and $\psi(2S)$ states, Δm, and the width of the $\chi_{c1}(3872)$ state, Γ_{BW}, are determined to be

$$\Delta m = 185.588 \pm 0.067 \pm 0.068\,\text{MeV},$$
$$\Gamma_{BW} = 1.39 \pm 0.24 \pm 0.10\,\text{MeV},$$

where the first uncertainty is statistical and the second systematic. Using a Flatté-inspired lineshape, two poles for the $\chi_{c1}(3872)$ state in the complex energy plane are found. The dominant pole is compatible with a quasi-bound $D^0\bar{D}^{*0}$ state but a quasi-virtual state is still allowed at the level of 2 standard deviations.

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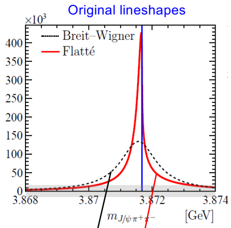
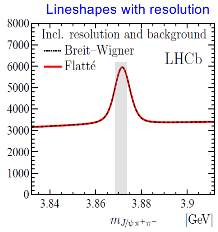
LHCb lineshapes (incl. resolution)

Original lineshapes



Lineshapes with resolution



$$m_{\chi_{c1}(3872)} = 3871.695 \pm 0.067 \pm 0.068 \pm 0.010\,\text{MeV}$$
$$\Gamma_{BW} = 1.39 \pm 0.24 \pm 0.10\,\text{MeV}$$

Mode [MeV]	Mean [MeV]	FWHM [MeV]
$3871.69^{+0.00+0.05}_{-0.04-0.13}$	$3871.66^{+0.07+0.11}_{-0.06-0.13}$	$0.22^{+0.06+0.25}_{-0.08-0.17}$

7.3 Comparison between Breit–Wigner and Flatté lineshapes

Figure 4 shows the comparison between the Breit–Wigner and the Flatté lineshapes. While in both cases the signal peaks at the same mass, the Flatté model results in a signifcantly narrower lineshape. However, after folding with the resolution function and adding the background, the observable distributions are indistinguishable.

- Due to detector resolution both models cannot be distinguished
  - 1.39 MeV (BW) vs. 0.22 MeV (Flatté) => factor of ~5

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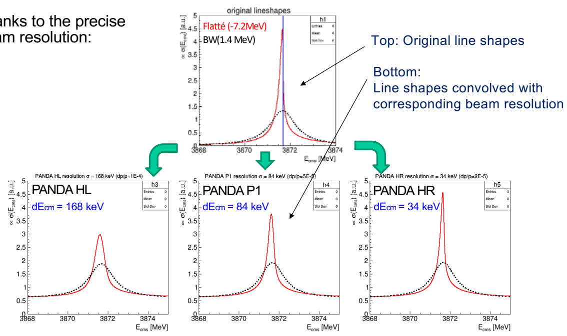
What can we do with PANDA?

Thanks to the precise beam resolution:



=> Breit-Wigner and Flatté models are distinguishable at PANDA

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Eur. Phys. J. A (2019) 55: 42
DOI 10.1140/epja/i2019-12718-2

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

Precision resonance energy scans with the PANDA experiment at FAIR Sensitivity study for width and line shape measurements of the X(3872)

- Addendum: Investigate separation power → E_f (Flatté) vs. Γ (BW)
- Key parameters from → EPJ A 55 (2019) 42
- Total beam time → 40 × 2d = 80 d
- Generate many (toy) spectra for Flatté & BW model
- Fit both line shapes to each generated distribution
- Determine fit probabilities P_F & P_{BW} and fractions of incorrect assignments → P_{mis}

	Parameter	Value
Branching Fractions	BR($J/\psi \rightarrow e^+ e^-$)	5.97 %
	BR($J/\psi \rightarrow \mu^+ \mu^-$)	5.96 %
	BR($\rho^0 \rightarrow \pi^+ \pi^-$)	100%
	BR($X \rightarrow J/\psi\ \rho^0$)	5 % (UL: 6.6%)
Cross sections	$\sigma_{peak}(p\bar{p} \rightarrow X)$	[20,30,50,75,100,150] nb
	$\sigma(p\bar{p} \rightarrow J/\psi\ \pi^+\pi^-$ non-res)	1.2 nb [theory]
	$\sigma(p\bar{p} \rightarrow$ inelastic) @ 3.872 GeV	46 mb [CERN-HERA-84-01 (1984)]
Luminosities	L_{HL} (3.872 GeV)	13683 $(nb\cdot d)^{-1}$
	L_{HR} (3.872 GeV)	1368 $(nb\cdot d)^{-1}$
	L_{P1} (3.872 GeV)	1170 $(nb\cdot d)^{-1}$
Resolutions	ΔE_{abs} *(energy prec. w/ calibration)*	168 keV ($dp/p = 10^{-4}$)
	ΔE_{rel} *(relative energy positioning)*	1.7 keV ($dp/p = 10^{-6}$)
	ΔE_{mom} (HL)	168 keV ($dp/p = 10^{-4}$)
	ΔE_{mom} (HR)	34 keV ($dp/p = 2\cdot10^{-5}$)
	ΔE_{mom} (P1)	84 keV ($dp/p = 5\cdot10^{-5}$)

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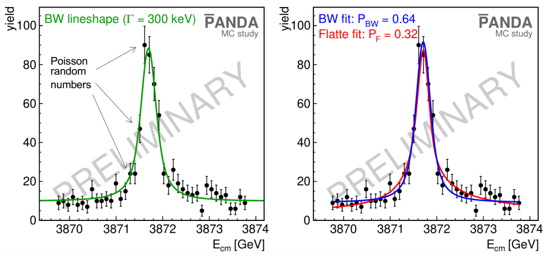
Scan Procedure Principle (Example)

Example: Breit-Wigner, Γ = 300 keV (P1 mode)



- Compute true lineshape (BW or Flatté)
- Generate poisson random number for each E_{cm} and fill graph
- Fit lineshapes to extract fit probabilities P_{BW} and P_F

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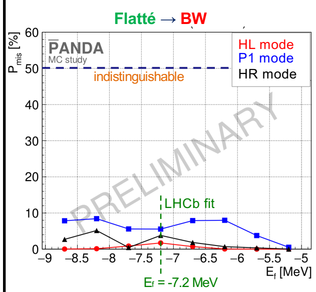
Parameter dependent performance

Performance across Flatté energy E_f range *(LHCb: E_f = -7.2 MeV)*,



Performance as Mis-ID of Flatté as BW
- Mis-identification probability P_{mis} vs. E_f
- For three beam modes (HL, HR, P1)
- P_{mis} = 50% => "indistinguishable"

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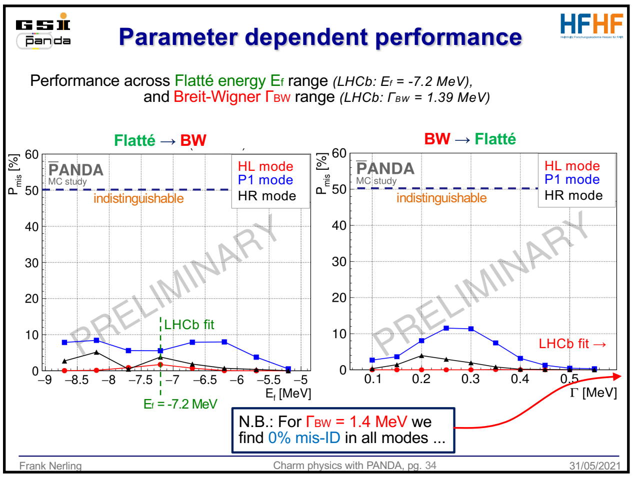
Parameter dependent performance
Performance across Flatté energy E_f range (LHCb: E_f = -7.2 MeV),
and Breit-Wigner Γ_{BW} range (LHCb: Γ_{BW} = 1.39 MeV)
Flatté → BW
BW → Flatté
PANDA
MC study
HL mode
P1 mode
HR mode
indistinguishable
PRELIMINARY
LHCb fit
E_f = -7.2 MeV
E_f [MeV]
LHCb fit →
Γ [MeV]
P_{mis} [%]
N.B.: For Γ_{BW} = 1.4 MeV we find 0% mis-ID in all modes ...
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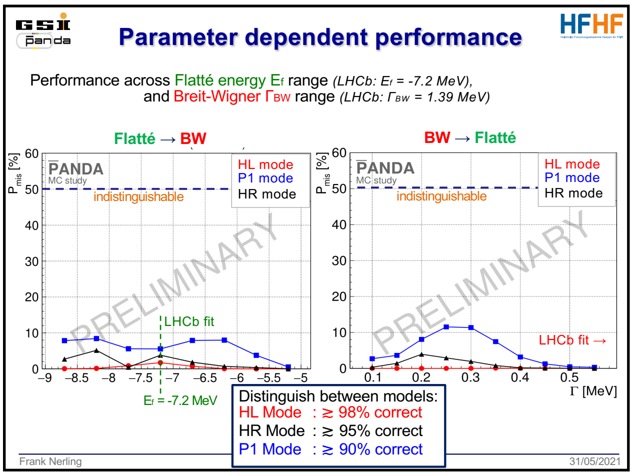
Parameter dependent performance
Performance across Flatté energy E_f range (LHCb: E_f = -7.2 MeV),
and Breit-Wigner Γ_{BW} range (LHCb: Γ_{BW} = 1.39 MeV)
Flatté → BW
BW → Flatté
PANDA
MC study
HL mode
P1 mode
HR mode
indistinguishable
PRELIMINARY
LHCb fit
E_f = -7.2 MeV
LHCb fit →
Γ [MeV]
P_{mis} [%]
Distinguish between models:
HL Mode : ≳ 98% correct
HR Mode : ≳ 95% correct
P1 Mode : ≳ 90% correct
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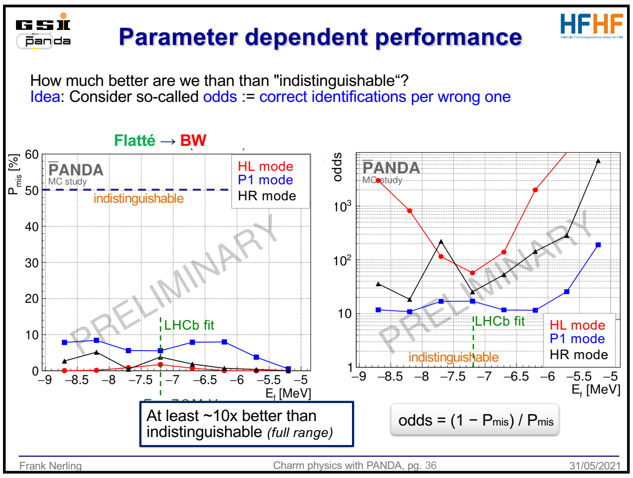
Parameter dependent performance
How much better are we than than "indistinguishable"?
Idea: Consider so-called odds := correct identifications per wrong one
Flatté → BW
PANDA
MC study
HL mode
P1 mode
HR mode
indistinguishable
PRELIMINARY
LHCb fit
E_f [MeV]
P_{mis} [%]
odds
At least ~10x better than indistinguishable (full range)
odds = (1 − P_{mis}) / P_{mis}
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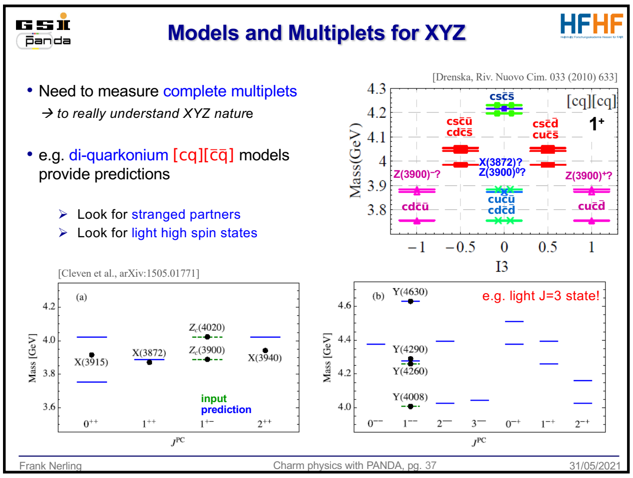
Models and Multiplets for XYZ
• Need to measure complete multiplets
→ to really understand XYZ nature
• e.g. di-quarkonium [cq][c̄q̄] models provide predictions
➢ Look for stranged partners
➢ Look for light high spin states
[Drenska, Riv. Nuovo Cim. 033 (2010) 633]
[cq][cq]
1+
X(3872)?
Z(3900)⁰?
Z(3900)⁻?
Z(3900)⁺?
I3
Mass(GeV)
[Cleven et al., arXiv:1505.01771]
input
prediction
e.g. light J=3 state!
Y(4630)
Y(4290)
Y(4260)
Y(4008)
X(3915)
X(3872)
X(3940)
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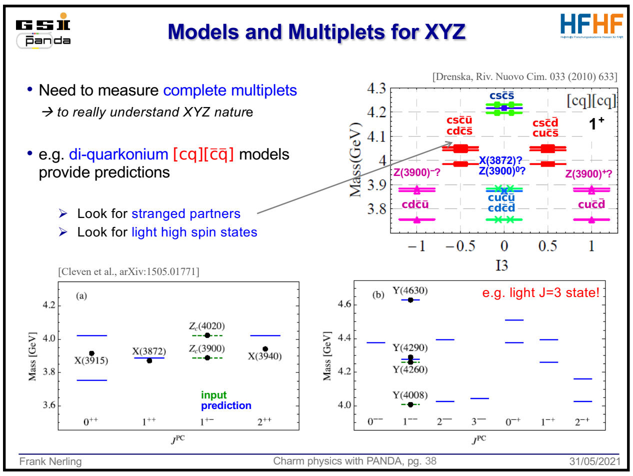
Models and Multiplets for XYZ
• Need to measure complete multiplets
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• e.g. di-quarkonium [cq][c̄q̄] models provide predictions
➢ Look for stranged partners
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[Drenska, Riv. Nuovo Cim. 033 (2010) 633]
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input
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e.g. light J=3 state!
Y(4630)
Y(4290)
Y(4260)
Y(4008)
X(3915)
X(3872)
X(3940)
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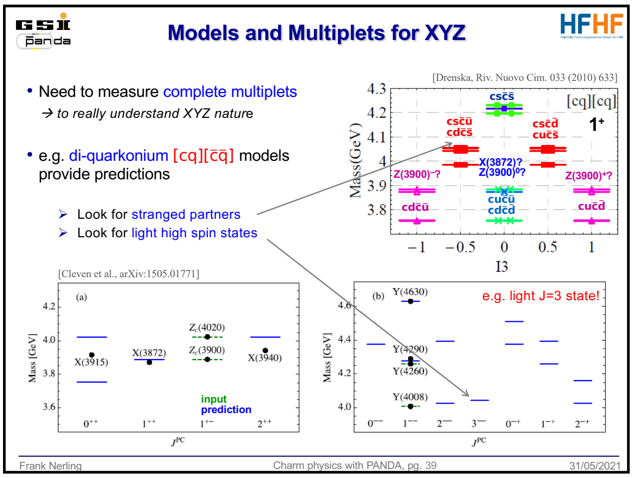
Models and Multiplets for XYZ
• Need to measure complete multiplets
→ to really understand XYZ nature
• e.g. di-quarkonium [cq][c̄q̄] models provide predictions
➢ Look for stranged partners
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[Drenska, Riv. Nuovo Cim. 033 (2010) 633]
[cq][cq]
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Z(3900)⁰?
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Z(3900)⁺?
I3
Mass(GeV)
[Cleven et al., arXiv:1505.01771]
input
prediction
e.g. light J=3 state!
Y(4630)
Y(4290)
Y(4260)
Y(4008)
X(3915)
X(3872)
X(3940)
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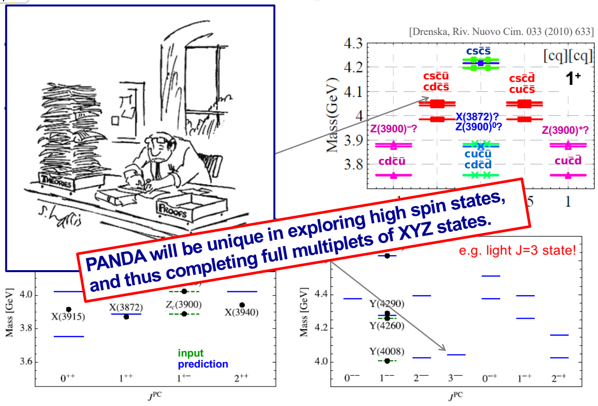
Models and Multiplets for XYZ



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Charmonium-like Exotics
-- Charmed Hybrids

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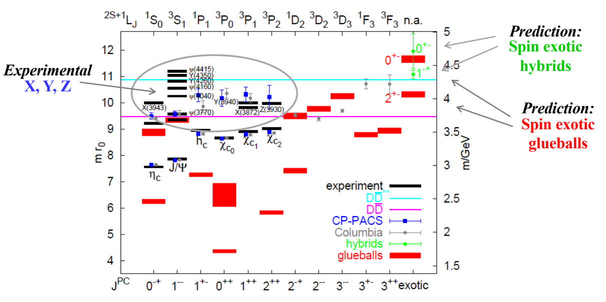
Lattice Predictions

- Lattice QCD → Predictions for masses/properties
- Current predictions for mesons, glueballs, hybrids



[G. S. Bali, Int.J.Mod.Phys. A21 (2006) 5610]

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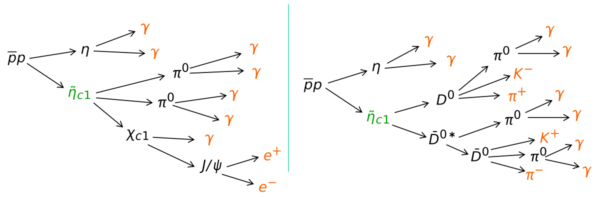
Charmonium Hybrid Candidate $\tilde{\eta}_{c1}$

- From LQCD calculations:
  Spin-exotic hybrid candidate $\tilde{\eta}_{c1}$ with $m \approx 4.3\,\mathrm{GeV}/c^2$, $J^{PC} = 1^{-+}$
- Exclusive reconstruction in two favoured channels:

$\bar{p}p \to \tilde{\eta}_{c1}\,\eta \to \chi_{c1}\pi^0\pi^0\eta$ $\qquad$ $\bar{p}p \to \tilde{\eta}_{c1}\,\eta \to D^0\bar{D}^{0*}\eta$



- Production X-section assumed similar to $\bar{p}p \to \psi(2S)\,\eta$ (33pb)
  → *Need good calorimetry + good particle identification*

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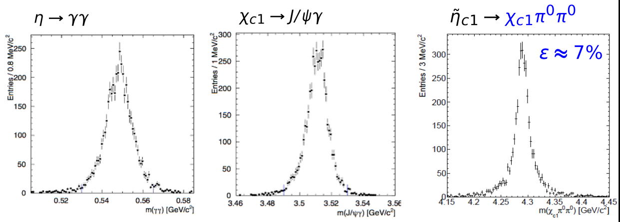
$\bar{p}p \to \tilde{\eta}_{c1}\,\eta \to \chi_{c1}\pi^0\pi^0\eta$

- Simulation @ 15 GeV/c
  - 80k signals + 80k each background, e.g.
    $\bar{p}p \to J/\psi\,\pi^0\pi^0\pi^0\,\eta,\ \bar{p}p \to \chi_{c1}\pi^0\eta\eta$
  - 9C kinematic fit (mass constraints, 4C energy momentum)

$\eta \to \gamma\gamma$ $\qquad$ $\chi_{c1} \to J/\psi\gamma$ $\qquad$ $\tilde{\eta}_{c1} \to \chi_{c1}\pi^0\pi^0$



- Signal to noise: $\frac{S}{N} > 250 \cdot \frac{\sigma_S}{\sigma_B}$ => well feasible for σ_B ≈< 10 σ_S !

[arXiv:0903.3905, hep-ex]

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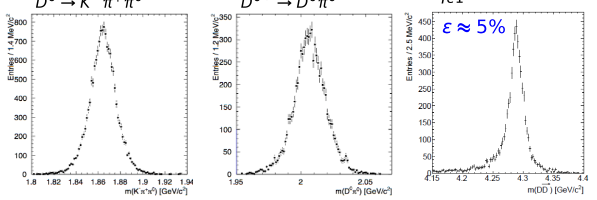
$\bar{p}p \to \tilde{\eta}_{c1}\,\eta \to D^0\bar{D}^{0*}\eta$

- Simulation @ 15 GeV/c
  - 200k signals + background, e.g. $\bar{p}p \to D^0\bar{D}^{0*}\pi^0$
  - 11C kinematic fit (mass constraints, 4C energy momentum)

$D^0 \to K^-\pi^+\pi^0$ $\qquad$ $D^{0*} \to D^0\pi^0$ $\qquad$ $\tilde{\eta}_{c1} \to D^0\bar{D}^{0*}$



- Signal to noise:
  $\frac{S}{N} > 2900 \cdot \mathcal{B}(\tilde{\eta}_{c1} \to D^0\bar{D}^{0*})$ => feasible for non-vanishing BR

[arXiv:0903.3905, hep-ex]

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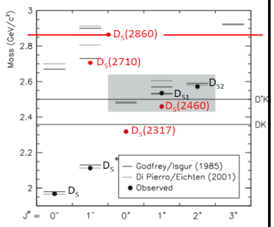
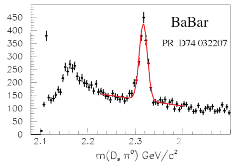
Open charm: The D_s spectrum

- Qualitative agreement theory vs. experiment on D states – details however still open
- Many new D_J mesons *(LHCb)*
- Narrow states *(2003)*: D_{s0}*(2317) and D_{s1}*(2460) still under discussion *(and other broad states recently)*
- Masses: Significantly lower than expected *(quark potential model)*, and just below DK and D*K threshold
- Widths: Only upper limits
- Interpretation unclear: DK / D*K molecules, tetraquarks, chiral doublers, ...? Sensitive to width





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Interpretation ←→ Width of D_{s0}*(2317)

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. Soyeur, 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)	Strong and radiative decays of $D_{s0}^*(2317)$ and $D_{s1}(2460)$	

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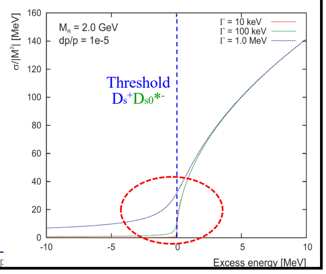
Width of D_{s0}*(2317)

- Theoretical interpretations very sensitive for $\Gamma(D_{s0}^*(2317))$
- Formation reaction not possible: $\bar{p}p \not\to D^*_{s0}(2317)$
  → *Energy scan with recoil at threshold:* $\bar{p}p \to D_s^+ D^*_{s0}(2317)^-$

$$\frac{\sigma(s)}{|M^2|} = \frac{\Gamma}{4\pi\sqrt{s}} \int_{-\infty}^{\sqrt{s}-m_{D_s}} \mathrm{d}m \frac{\sqrt{\left(s-(m+m_{D_s})^2\right)\left(s-(m-m_{D_s})^2\right)}}{\left(m-m_{D(2317)}\right)^2+(\Gamma/2)^2}$$ [C. Hanhart]

→ Lineshape at threshold depends on $\Gamma(D_{s0}(2317)^*)$



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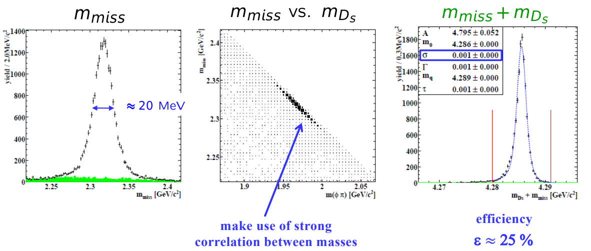
Reconstruction of $p\bar{p} \rightarrow D_s^+ D_{s0}^*(2317)^-$

- Simulation @ 8.8 GeV/c
  - 40k signals, 40k each background, e.g. $\bar{p}p \rightarrow D_s^+ D_s^- \pi^0$
  - 10M generic background events
  - Inclusive reconstruction of $D_s^{\pm}$, missing mass technique



[arXiv:0903.3905, hep-ex]

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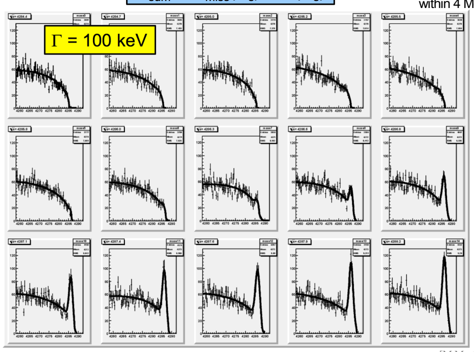
Energy scan simulation around threshold

$\bar{p}p \rightarrow D_s^{\pm} D_{s0}^*(2317)^{\mp}$

$M_{sum} = M_{miss}(D_s) + M(D_s)$

15 measured points within 4 MeV window



[M.Mertens, PhD thesis]

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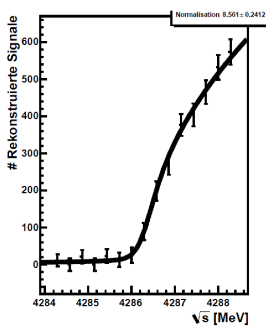
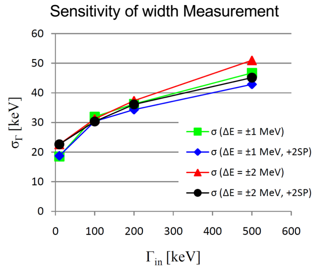
Energy scan simulation around threshold

Extracted excitation function



Sensitivity of width Measurement



=> Relative accuracy
σ_Γ/Γ < 1/3 for Γ > 100 keV

[M.Mertens, PhD thesis]

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Summary and prospectives

- Broad & fascinating physics programme at PANDA
  - Hadron spectroscopy, in particular exotics
  - Selected examples discussed:
    Charmonium (-like) states, Charmed Hybrids, Open Charm
- Many new, unexpected (exotic) states observed during last decade
  - Interpretation still unclear
  - Precise measurements and confirmations needed
- Anti-protons provide experimental key technique
- Upcoming PANDA experiment at FAIR
  - Complementary production mechanisms and measurements
  - Precise knowledge of decay width and line shape essential
  - Complete the exotic multiplets
    → *Unique: High statistics + precision resonance scans + high spin states*

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Summary and prospectives

- Broad & fascinating physics programme at PANDA
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- Anti-protons prov... ...technique
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  - Complete the exotic multiplets
    → *Unique: High statistics + precision resonance scans + high spin states*

PANDA unique in combining potential for discovery and precision measurements!

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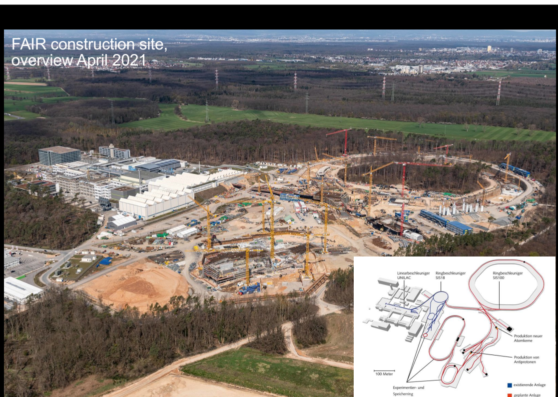
Facility for Antiproton and Ion Research



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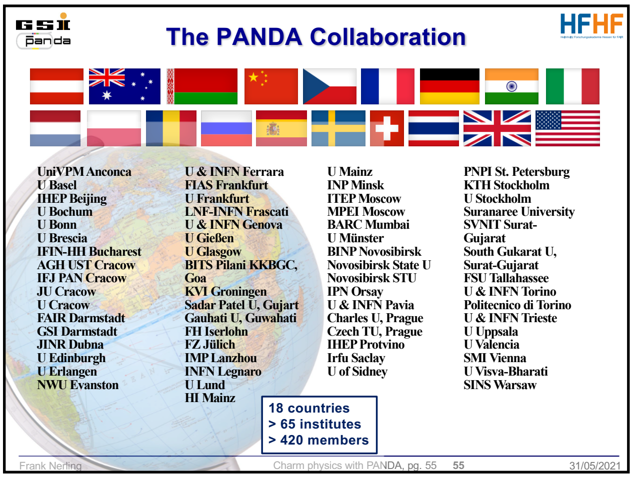
The PANDA Collaboration
UniVPM Anconca
U Basel
IHEP Beijing
U Bochum
U Bonn
U Brescia
IFIN-HH Bucharest
AGH UST Cracow
IFJ PAN Cracow
JU Cracow
U Cracow
FAIR Darmstadt
GSI Darmstadt
JINR Dubna
U Edinburgh
U Erlangen
NWU Evanston
U & INFN Ferrara
FIAS Frankfurt
U Frankfurt
LNF-INFN Frascati
U & INFN Genova
U Gießen
U Glasgow
BITS Pilani KKBGC, Goa
KVI Groningen
Sadar Patel U, Gujart
Gauhati U, Guwahati
FH Iserlohn
FZ Jülich
IMP Lanzhou
INFN Legnaro
U Lund
HI Mainz
U Mainz
INP Minsk
ITEP Moscow
MPEI Moscow
BARC Mumbai
U Münster
BINP Novosibirsk
Novosibirsk State U
Novosibirsk STU
IPN Orsay
U & INFN Pavia
Charles U, Prague
Czech TU, Prague
IHEP Protvino
Irfu Saclay
U of Sidney
PNPI St. Petersburg
KTH Stockholm
U Stockholm
Suranaree University
SVNIT Surat-Gujarat
South Gukarat U, Surat-Gujarat
FSU Tallahassee
U & INFN Torino
Politecnico di Torino
U & INFN Trieste
U Uppsala
U Valencia
SMI Vienna
U Visva-Bharati
SINS Warsaw
18 countries
> 65 institutes
> 420 members
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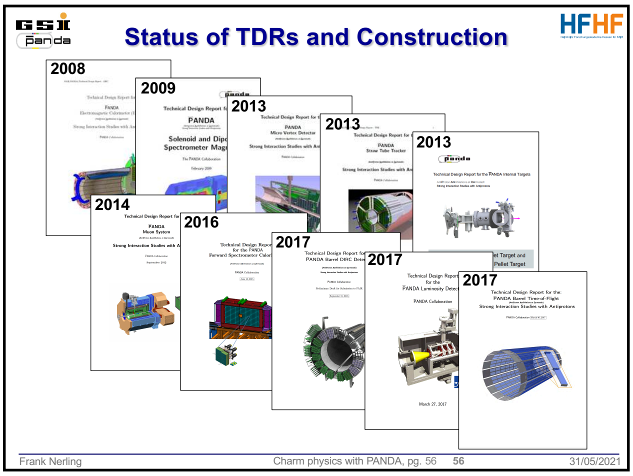
Status of TDRs and Construction
2008
2009
2013
2013
2013
2014
2016
2017
2017
2017
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Charm physics with PANDA, pg. 56 56
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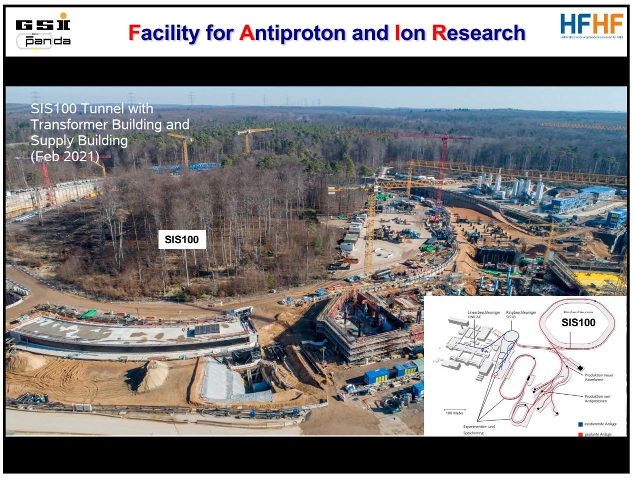
Facility for Antiproton and Ion Research
SIS100 Tunnel with
Transformer Building and
Supply Building
(Feb 2021)
SIS100
SIS100

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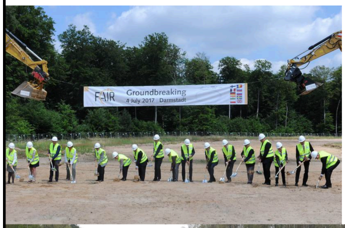
Facility for Antiproton and Ion Research



Official ground breaking in summer 2017

Same area in July 2018

[Courtesy: I.Lehmann, FAIR]

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Facility for Antiproton and Ion Research

Construction of the tunnel for SIS100 -- Feb 2019

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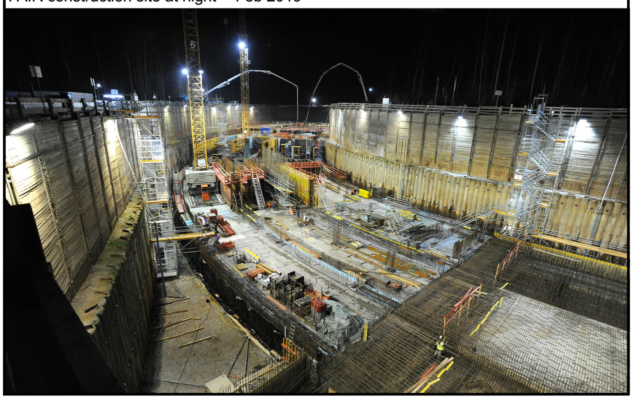
Facility for Antiproton and Ion Research

FAIR construction site at night -- Feb 2019



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Concrete ceiling of the first tunnel segment is poured at night -- Feb 2019

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Ceiling of the first tunnel segment -- Feb 2019

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