Perspectives of the X(3872) line shape measurement at PANDA

Frank Nerling
HFHF, Campus Frankfurt,
GSI Darmstadt & GU Frankfurt
on behalf of the PANDA collaboration

”Hadron Spectroscopy: The Next Big Steps”
2022, March 14th - 25th

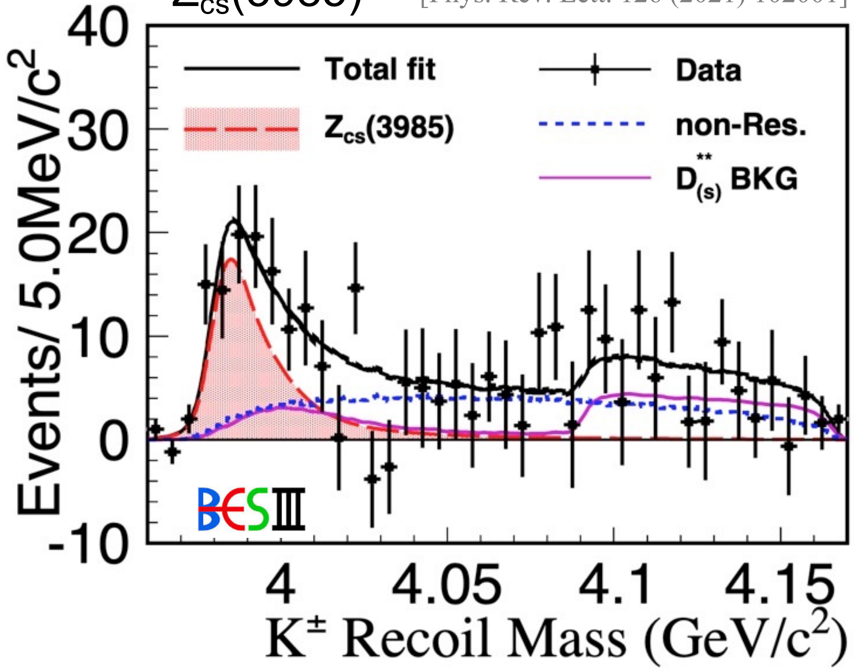
Outline

- **Introduction & Motivation**
  - PANDA physics programme
  - Advantage of anti-protons
- **Energy scans of very narrow resonances**
  - The X(3872) experimentally, line shape
  - Comprehensive performance study
- **Summary & outlook**

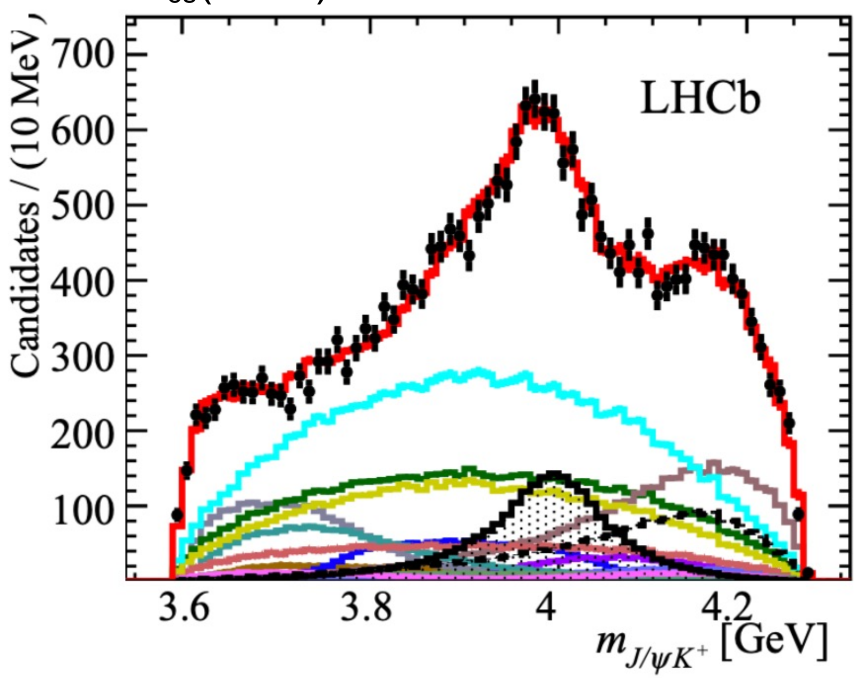
Recent hot topics

Hadron Spectroscopy

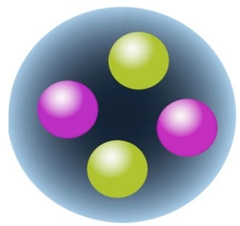
$Z_{cs}(3985)$ [Phys. Rev. Lett. 126 (2021) 102001]



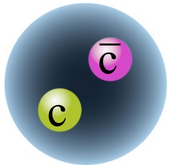
$Z_{cs}(4000)$ [LHCb, arXiv:2103.01803]



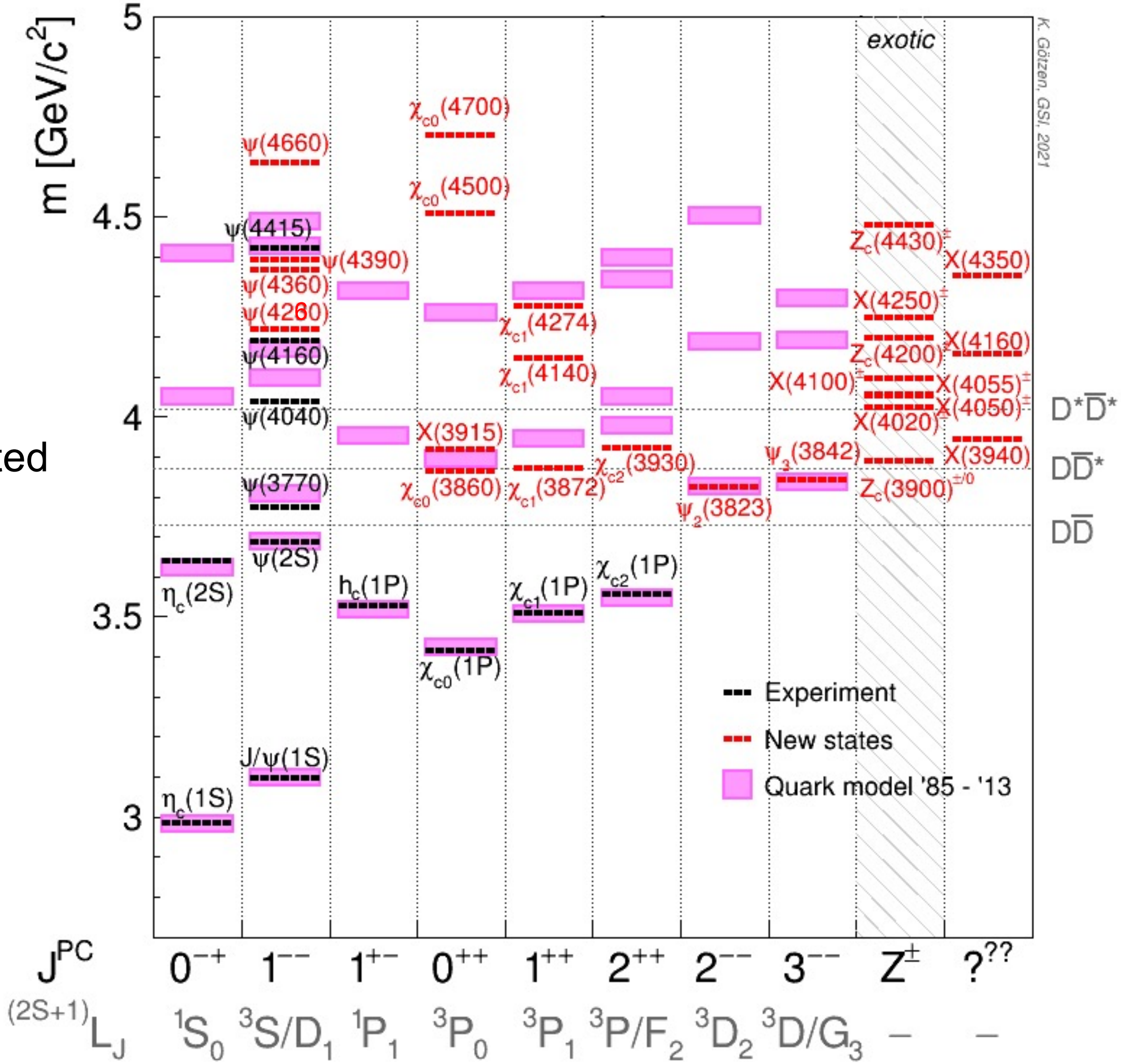
Strange partner of the famous, unexpected, manifestly exotic $Z_c(3900)$?



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:

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

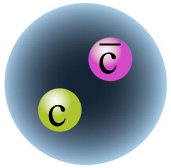
$$V_{\text{spin-dep.}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

+ relativistic corrections!

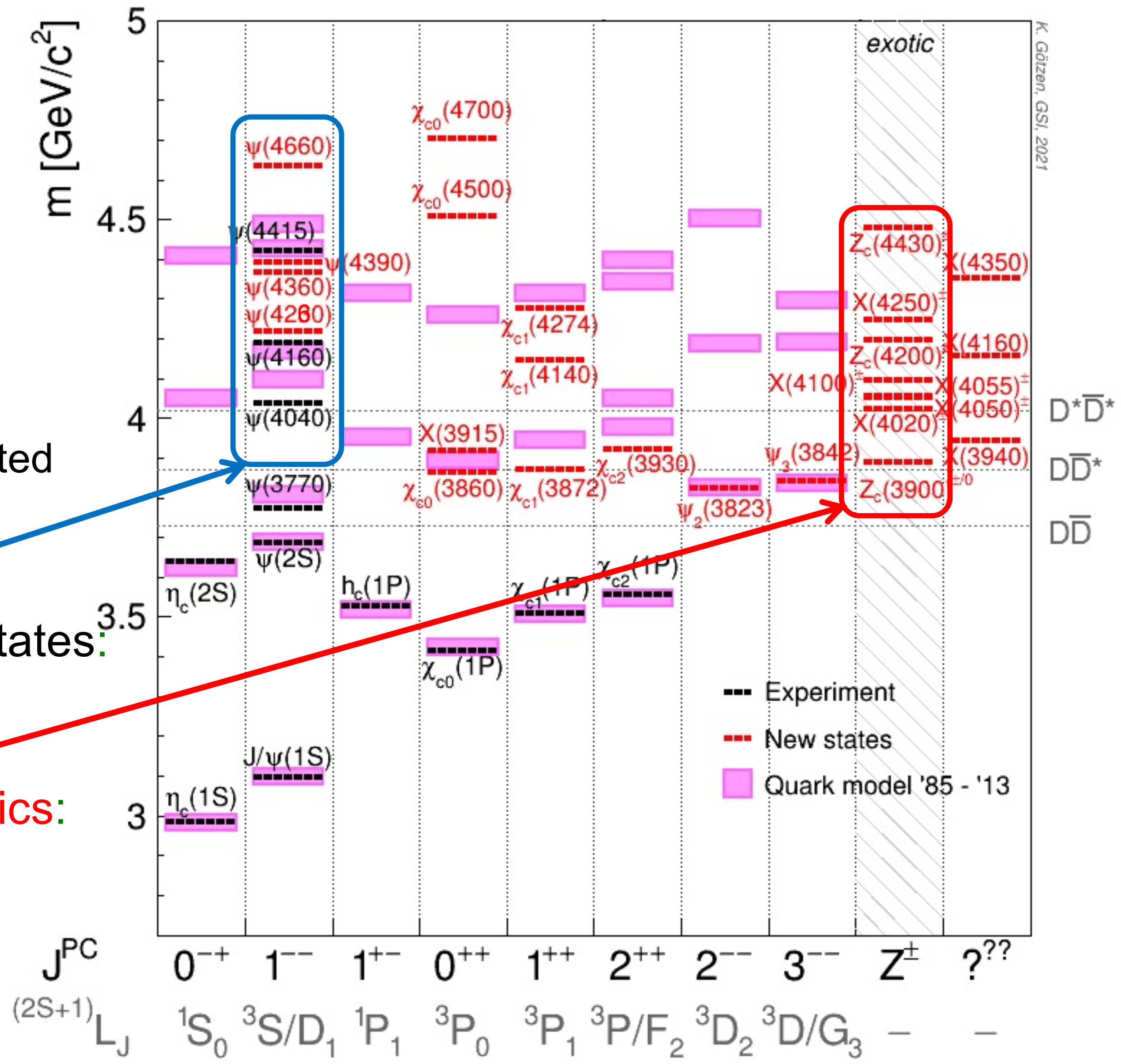
[Godfrey & Isgur, PRD 32 (1985) 189]

[Barnes, Godfrey & Swanson, PRD 72 (2005) 054026]

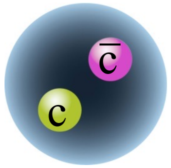
Charmonium spectrum ($c\bar{c}$)



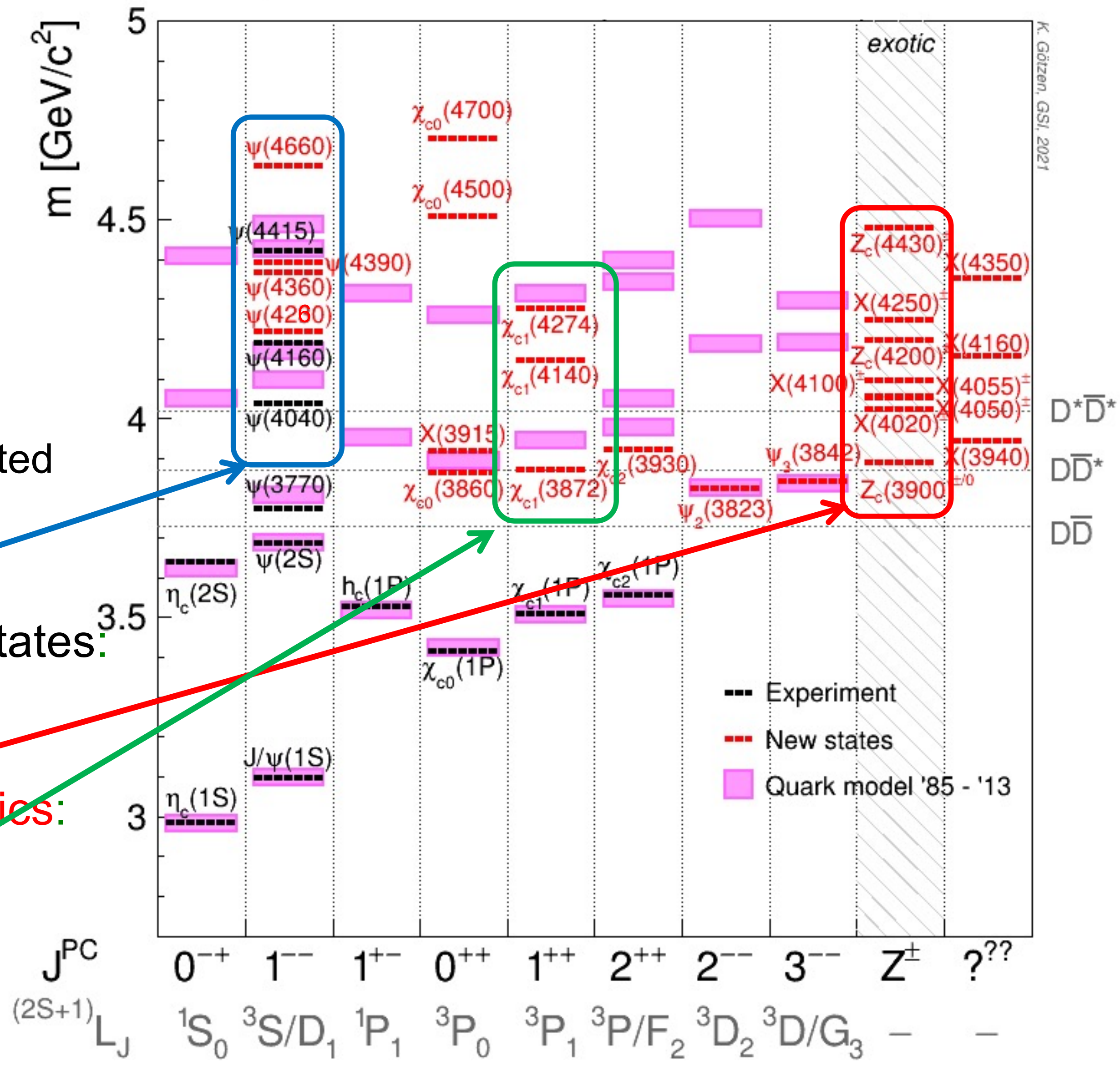
- Before 2003:
  - Good agreement between theory and experiment, particularly beneath open charm thresholds
- After 2003:
  - Severe mismatch between predicted and observed spectrum
- Several supernumerary vector states: Y(4260), ..., Y(4660)
- Several charged manifestly exotics: $Z_c(3900)^{+/-}$, ...,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



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

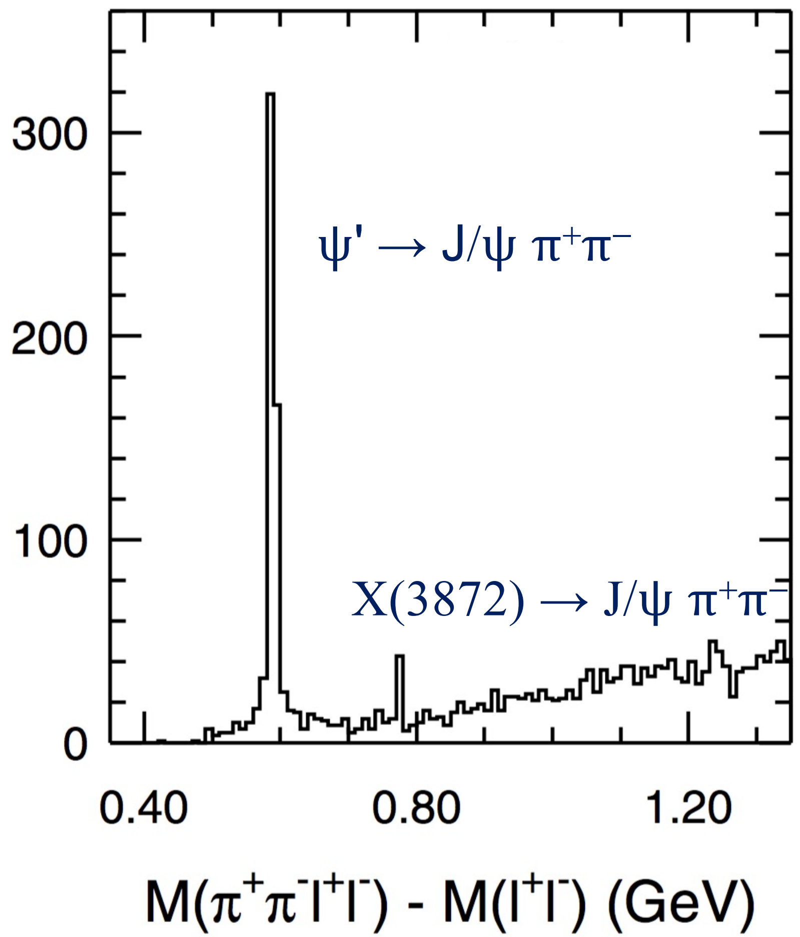


- Before 2003:
  - ➢ Good agreement between theory and experiment, particularly beneath open charm thresholds
- After 2003:
  - ➢ Severe mismatch between predicted and observed spectrum
- Several supernumerary vector states: Y(4260), ..., Y(4660)
- Several charged manifestly exotics: $Z_c(3900)^{+/-}$, ..., $Z_c(4430)^{+/-}$
- The X states – the $\chi_{c1}(3872)$ was the first observed in 2003



Experimental review of the X(3872)

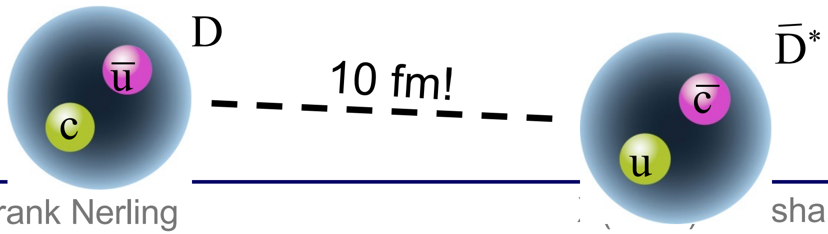
[Belle Collab., PRL 91 (2003) 262001]



- 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 $m[X(3872)] - m[D^{*0}] - m[D^0]$

  $= (-0.07 \pm 0.12)$ MeV/c^2 (LHCb 2020)
- Width measurement:
  - $\Gamma_{X(3872)} < 1.2$ MeV (2011, Belle)
  - $\Gamma_{X(3872)} = 1.39$ MeV (2020, LHCb)

Analogy to deuteron:

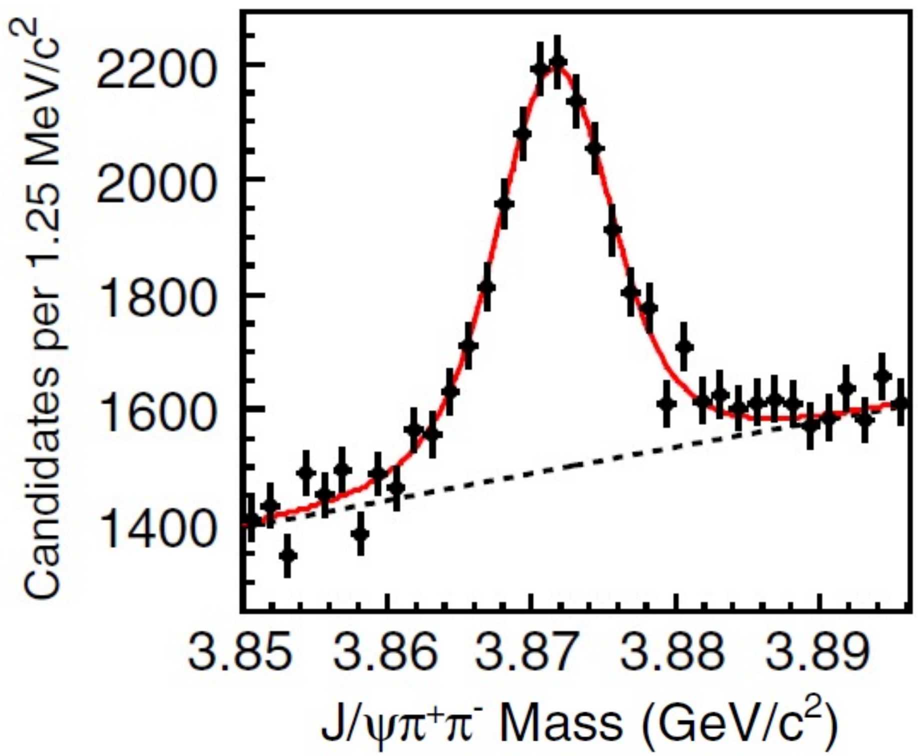


For clarification:

=> Precision measurement with sub-MeV resolution needed!

Experimental review of the X(3872)

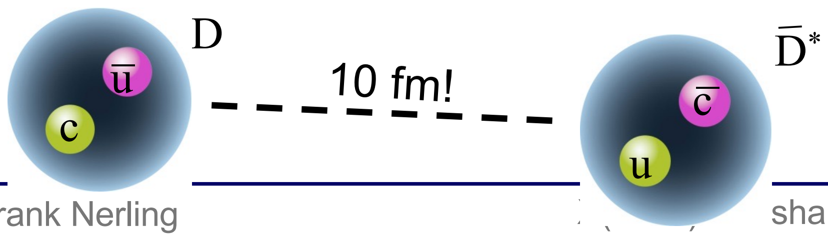
[CDF, Phys. Rev. Lett., 103 (2009) 152001]



- First observed by Belle in 2003
  - $X(3872) \rightarrow J/\psi\pi^+\pi^-$
  - very narrow state with $J^{PC} = 1^{++}$
- Belle & BaBar report signal in
  - $X(3872) \rightarrow D^0\bar{D}^{*0}$
- Mass $m[X(3872)] - m[D^{*0}] - m[D^0]$

  $= (-0.07 \pm 0.12)$ MeV/c^2 (LHCb 2020)
- Width measurement:
  - $\Gamma_{X(3872)} < 1.2$ MeV (2011, Belle)
  - $\Gamma_{X(3872)} = 1.39$ MeV (2020, LHCb)

Analogy to deuteron:

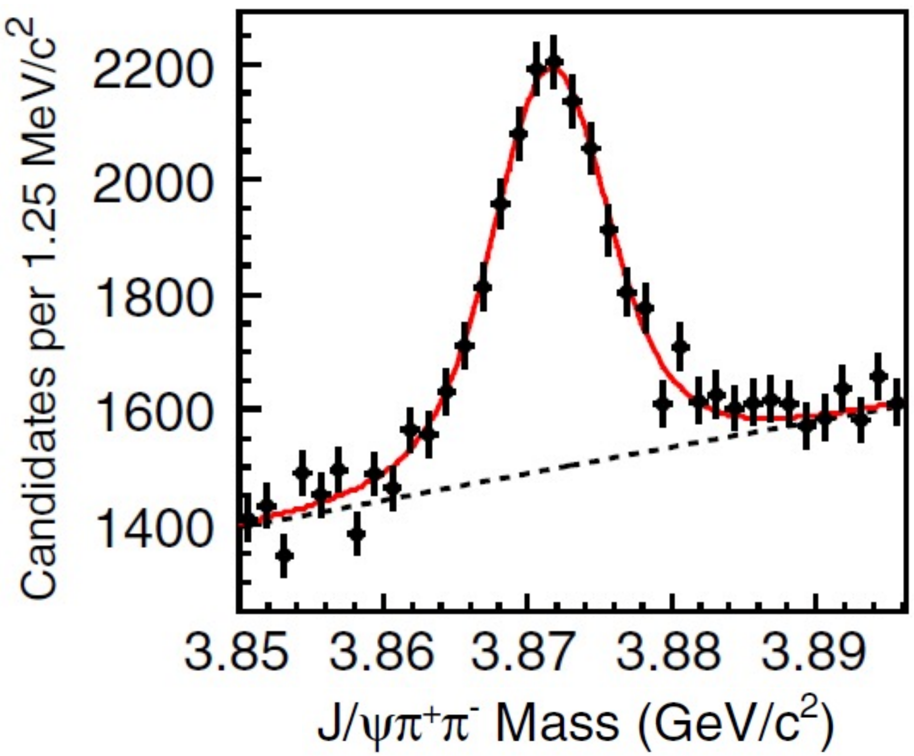


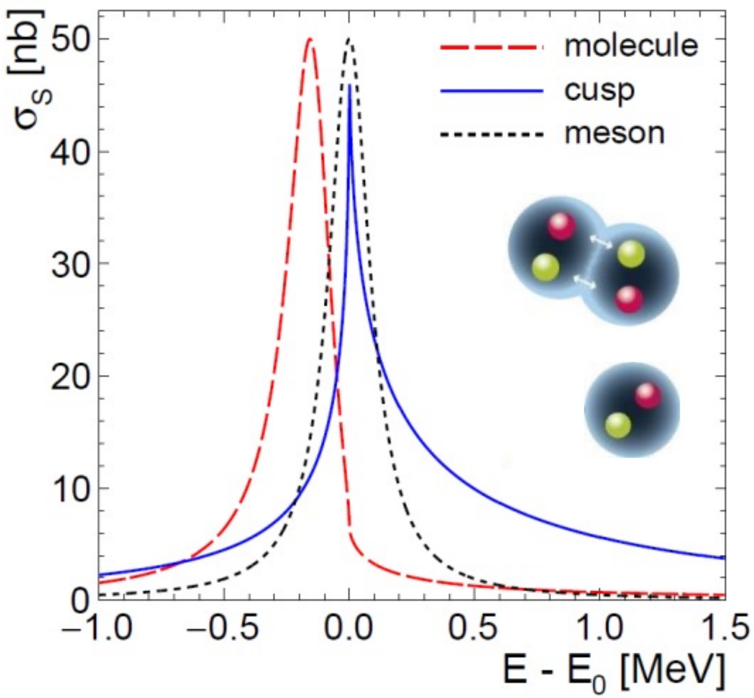
For clarification:

=> Precision measurement with sub-MeV resolution needed!

Experimental review of the X(3872)

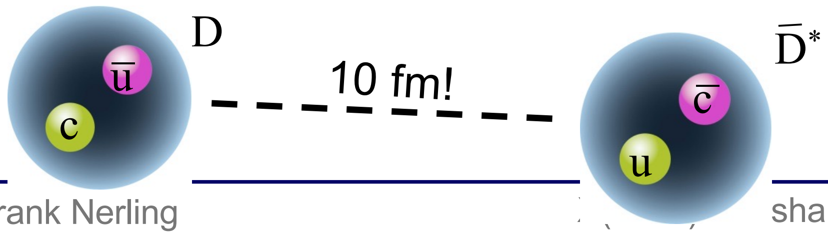
[CDF, Phys. Rev. Lett., 103 (2009) 152001]





- Width measurement:
  - $\Gamma_{X(3872)} <$ 1.2 MeV (2011, Belle)
  - $\Gamma_{X(3872)} =$ 1.39 MeV (2020, LHCb)

Analogy to deuteron:

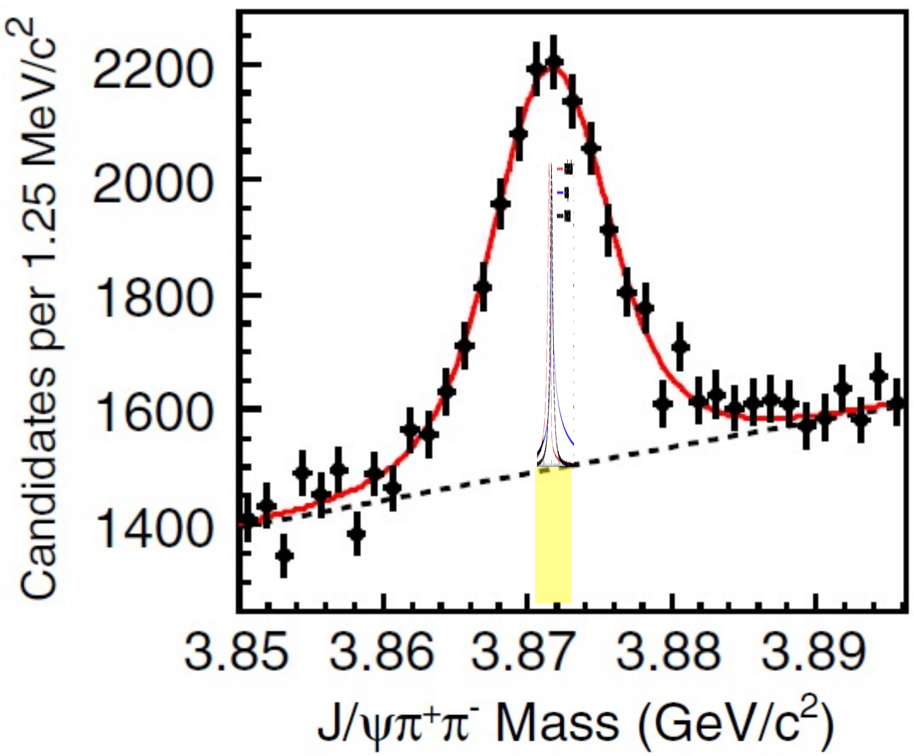


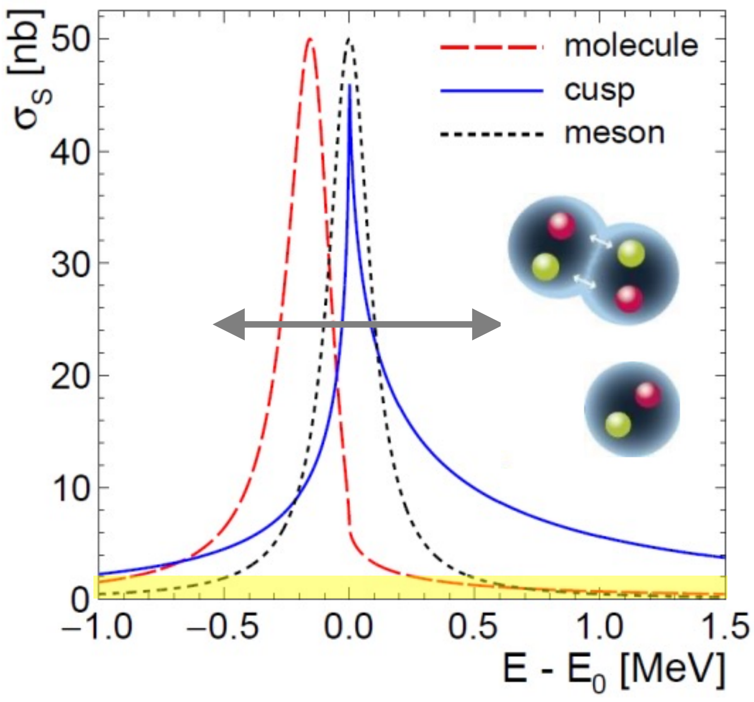
For clarification:

=> Precision measurement with sub-MeV resolution needed!

Experimental review of the X(3872)

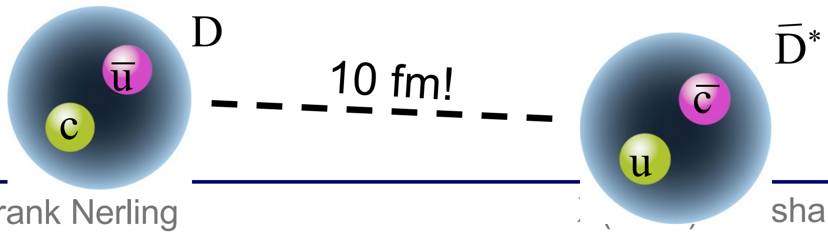
[CDF, Phys. Rev. Lett., 103 (2009) 152001]





- Width measurement:
  - $\Gamma_{X(3872)} < 1.2$ MeV (2011, Belle)
  - $\Gamma_{X(3872)} = 1.39$ MeV (2020, LHCb)

Analogy to deuteron:



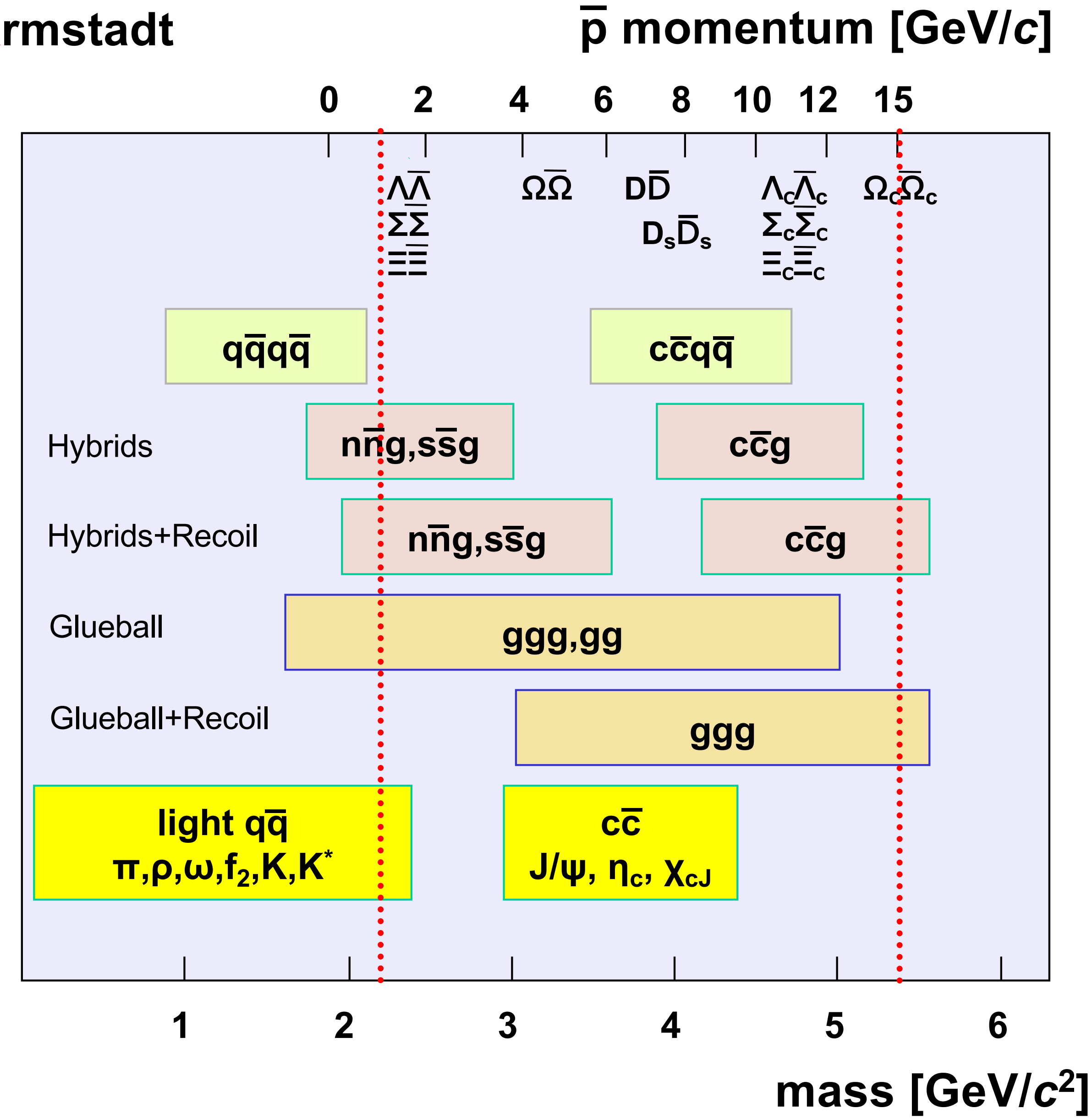
For clarification:

=> Precision measurement with sub-MeV resolution needed!

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



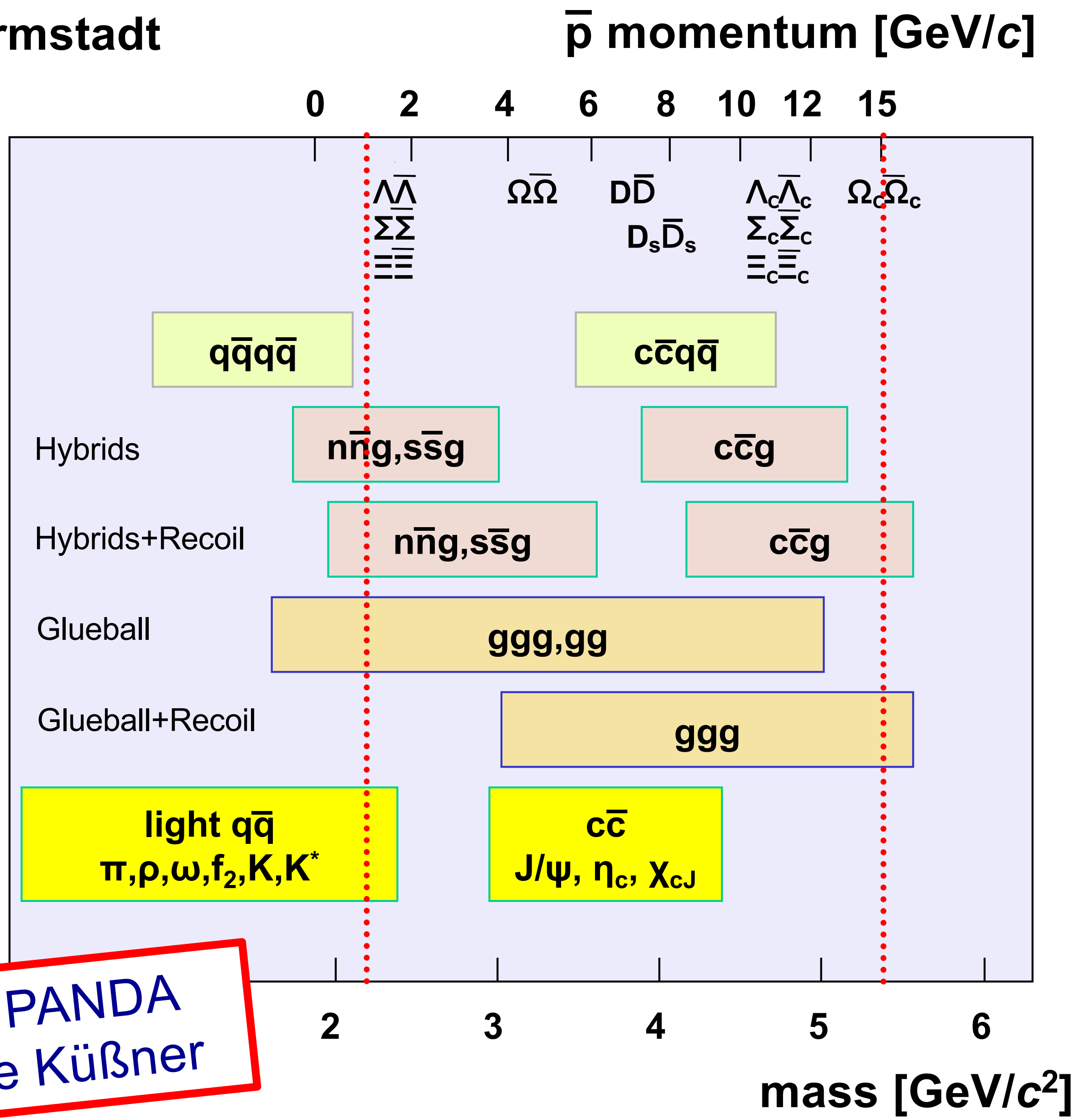
PANDA Physics Programme

Anti-Proton ANnihilation in DArmstadt

- **Meson spectroscopy**
  - Light mesons
  - Open charm
  - Charmonium
  - Exotic states:

    glue-balls, hybrids,

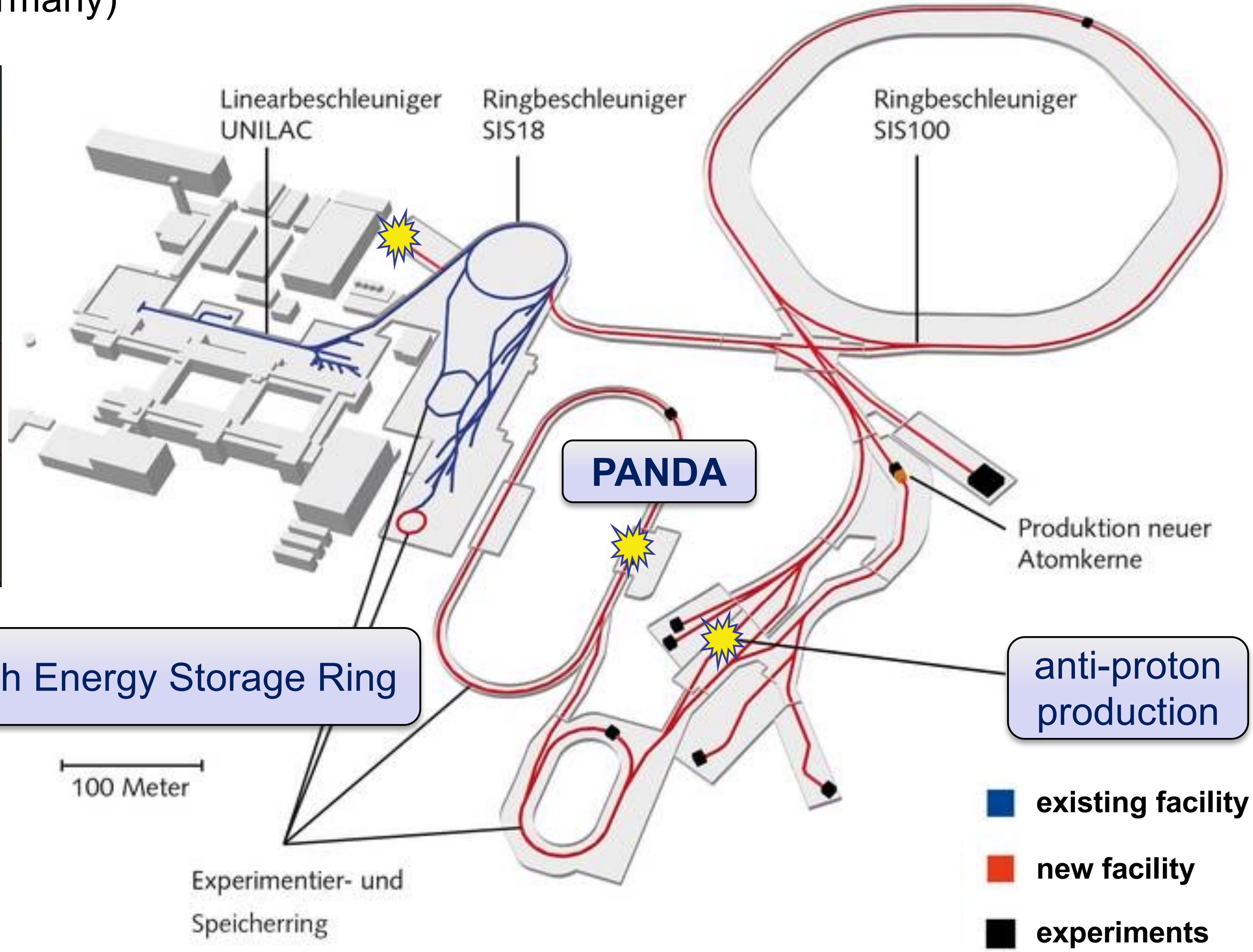
    molecules / multi-quarks
- **(Anti-) Baryon production**
- **Nucleon structure**
- **Charm in nuclei**
- **Strangeness physics**
  - Hypernuclei,
  - S = -2 nuclear system



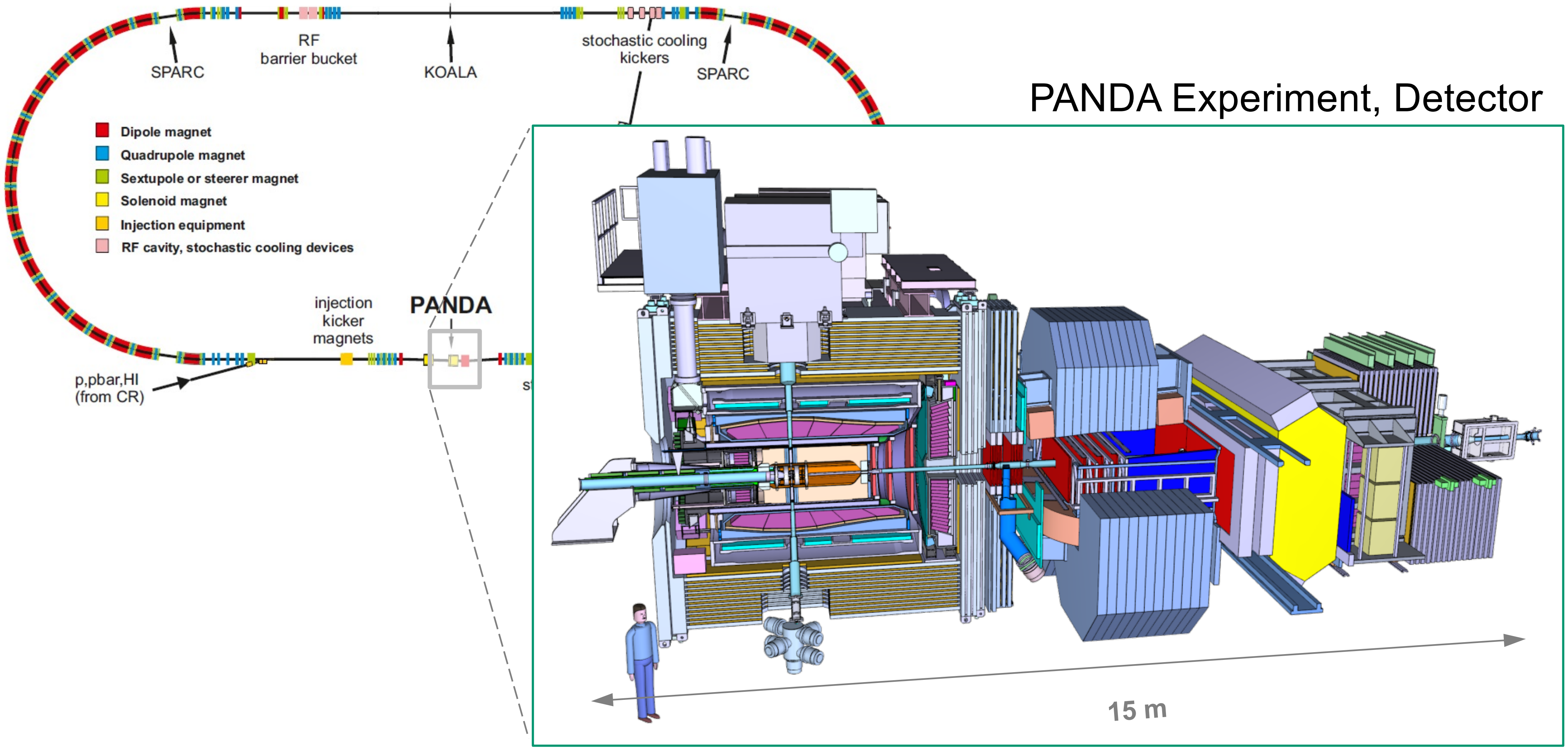
See the more general PANDA overview talk by Meike Küßner

Facility for Antiproton and Ion Research

PANDA at FAIR
(GSI, Darmstadt, Germany)



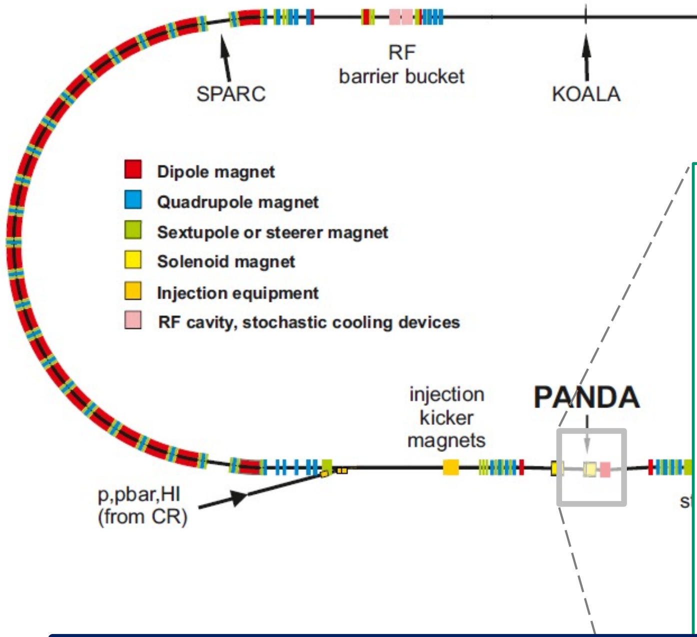
High Energy Storage Ring -- HESR



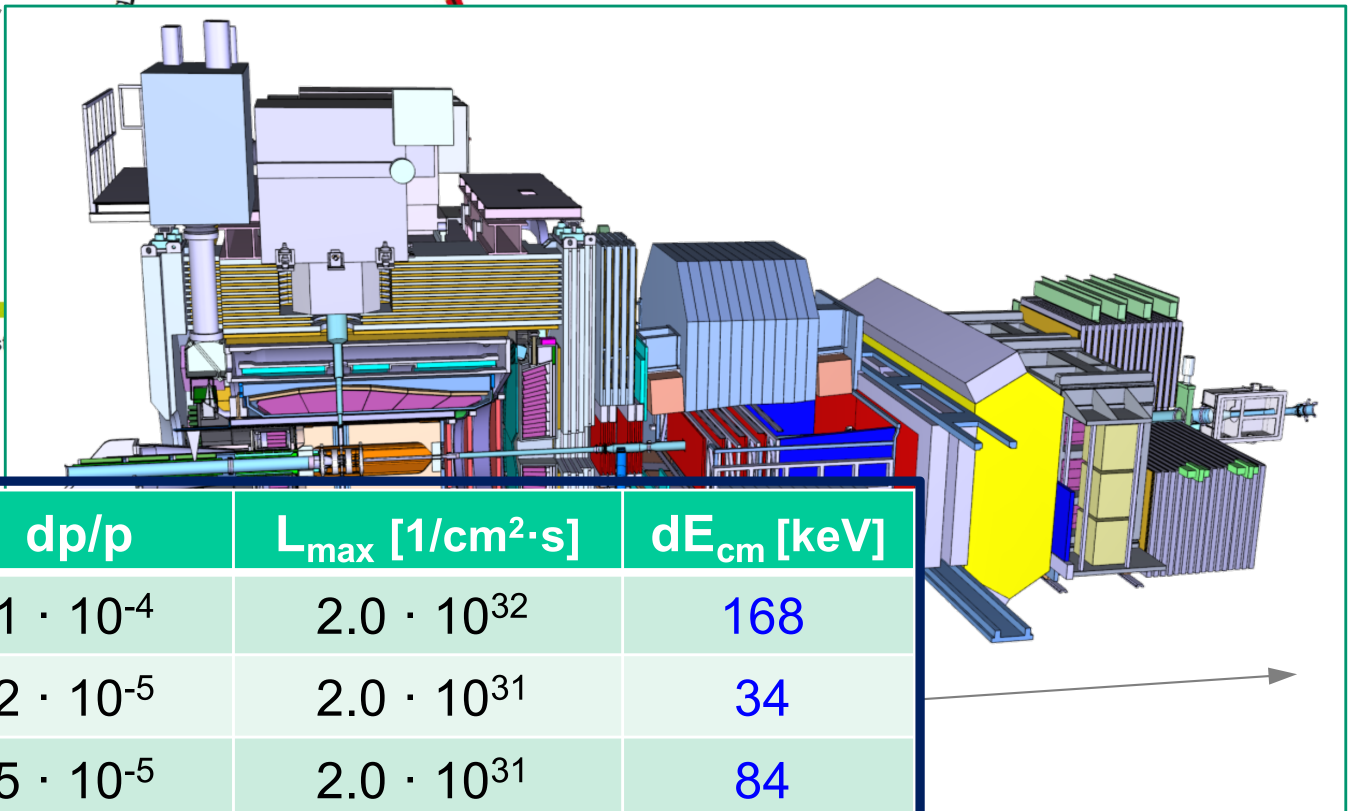
High Resolution (HR) mode:
- Luminosity up to 2 x 10^{31} cm^{-2} s^{-1}
- $\Delta p/p$ = 2 x 10^{-5}

High Luminosity (HL) mode:
- Luminosity up to 2 x 10^{32} cm^{-2} s^{-1}
- $\Delta p/p$ = 1 x 10^{-4}

High Energy Storage Ring -- HESR



PANDA Experiment, Detector



HESR mode	dp/p	L_{max} [1/cm²·s]	dE_{cm} [keV]
High Luminosity (HL)	$1 \cdot 10^{-4}$	$2.0 \cdot 10^{32}$	168
High Resolution (HR)	$2 \cdot 10^{-5}$	$2.0 \cdot 10^{31}$	34
Phase 1 Mode (P1)	$5 \cdot 10^{-5}$	$2.0 \cdot 10^{31}$	84

High Resolution (HR) mode:
- Luminosity up to 2 x 10^{31} cm^{-2} s^{-1}
- $\Delta p/p$ = 2 x 10^{-5}

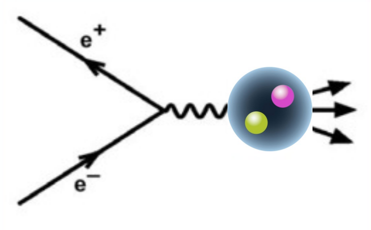
High Luminosity (HL) mode:
- Luminosity up to 2 x 10^{32} cm^{-2} s^{-1}
- $\Delta p/p$ = 1 x 10^{-4}

Some Advantages of Anti-Protons

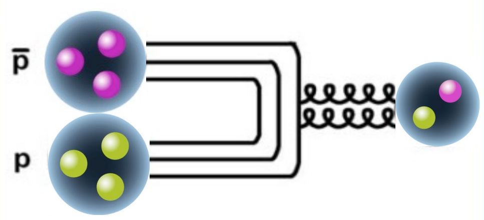
- Access to all fermion-antifermion quantum numbers *(not in e^+e^-)*

- Access to states of high spin J

Formation:



only $J^{PC} = 1^{--}$



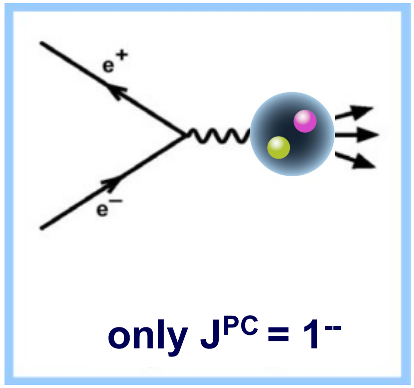
all $q\bar{q}$ J^{PC}

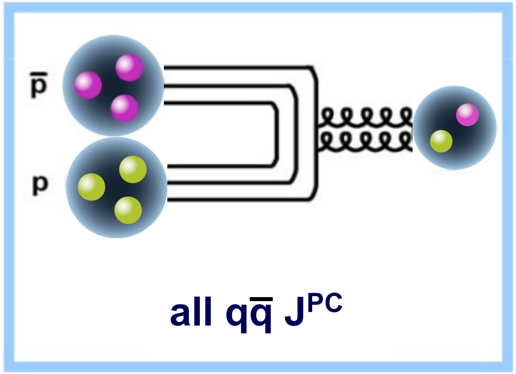
Some Advantages of Anti-Protons

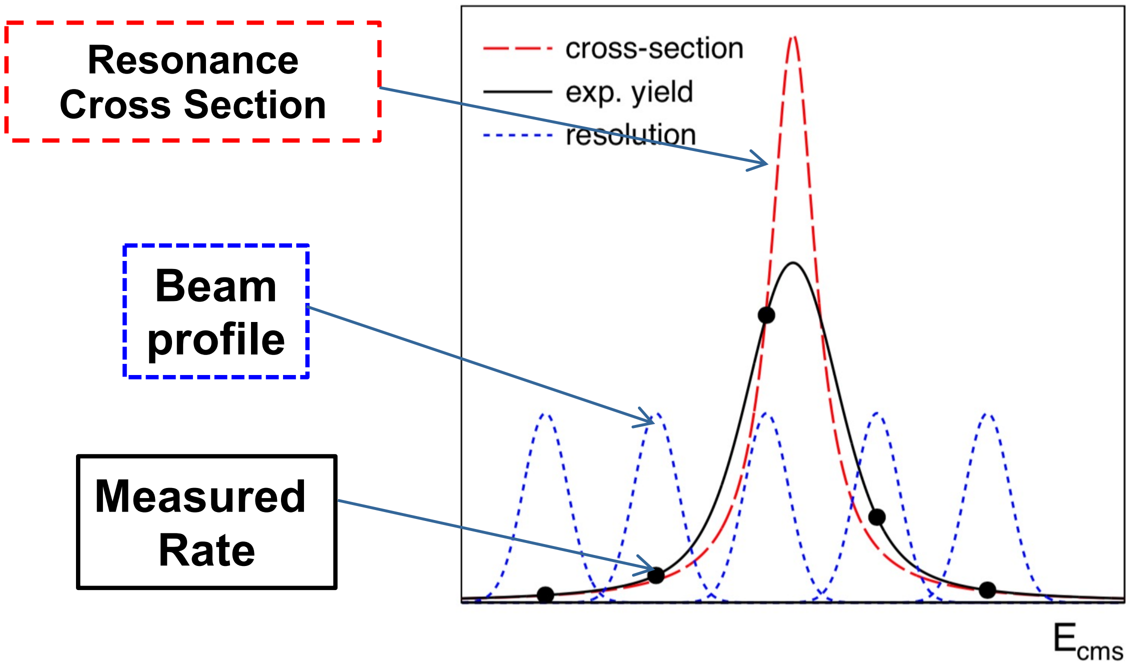
- Access to all fermion-antifermion quantum numbers *(not in e^+e^-)*
- Access to states of high spin J
- Precise mass resolution in formation reactions

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

Formation:

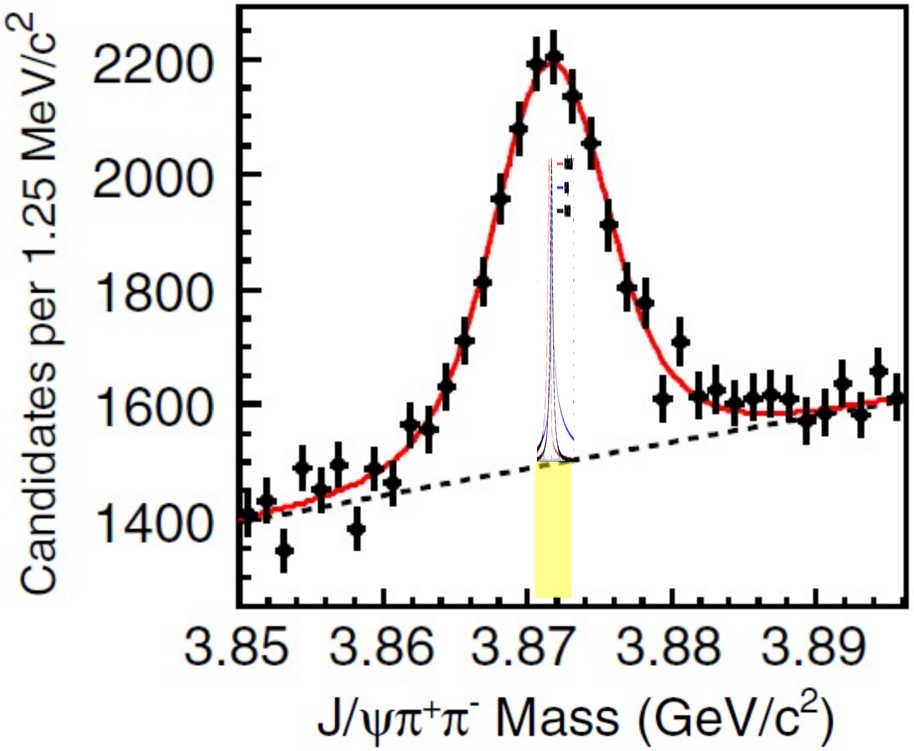


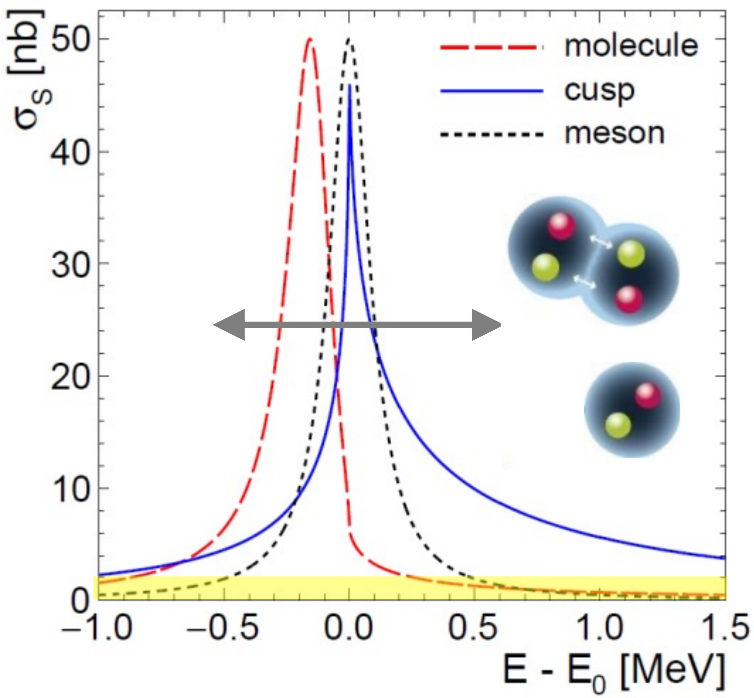




Experimental review of the X(3872)

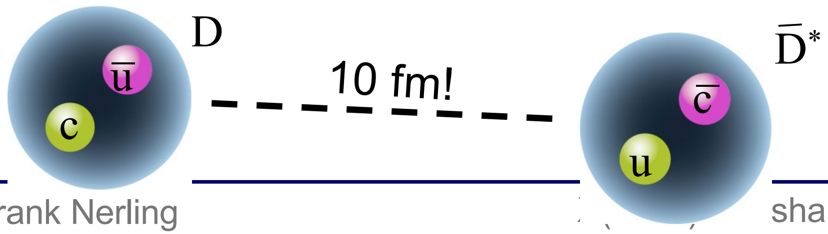
[CDF, Phys. Rev. Lett., 103 (2009) 152001]





- Width measurement:
  - ➢ $\Gamma_{X(3872)} <$ 1.2 MeV (2011, Belle)
  - ➢ $\Gamma_{X(3872)}$ = 1.39 MeV (2020, LHCb)

Analogy to deuteron:



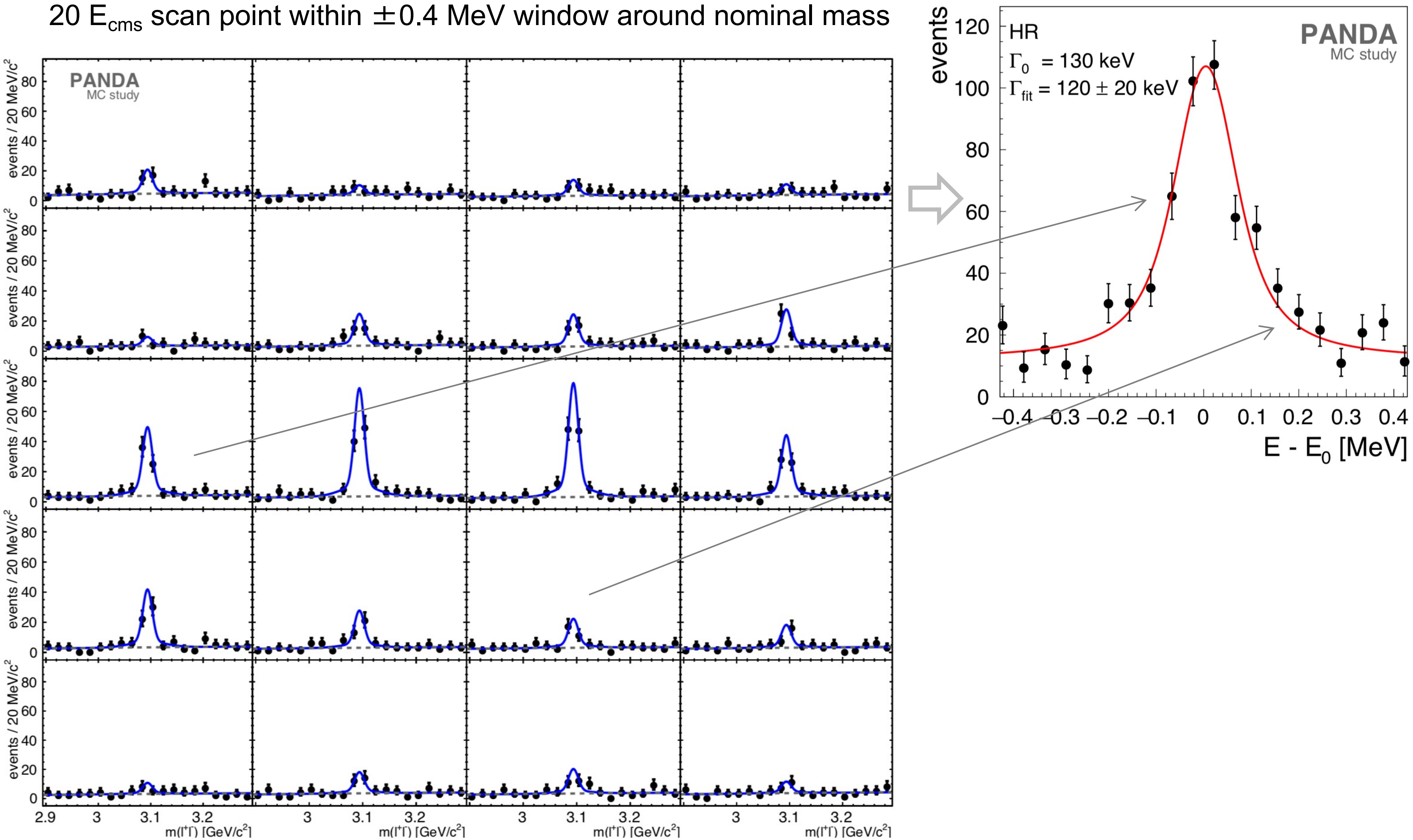
For clarification:
=> Precision measurement with sub-MeV resolution needed!

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

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

Scan Procedure Principle (Example)

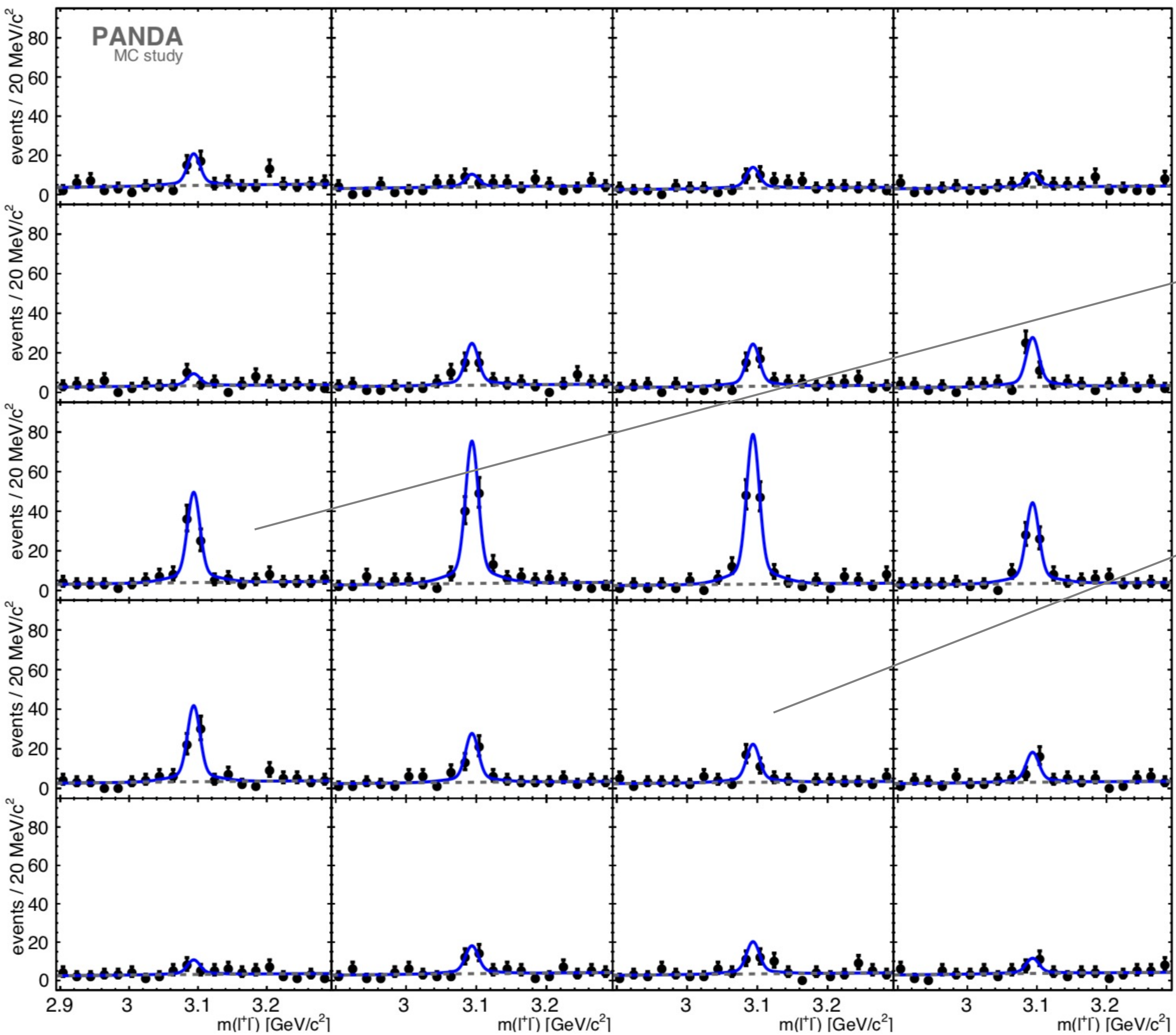
20 E_{cms} scan point within ±0.4 MeV window around nominal mass

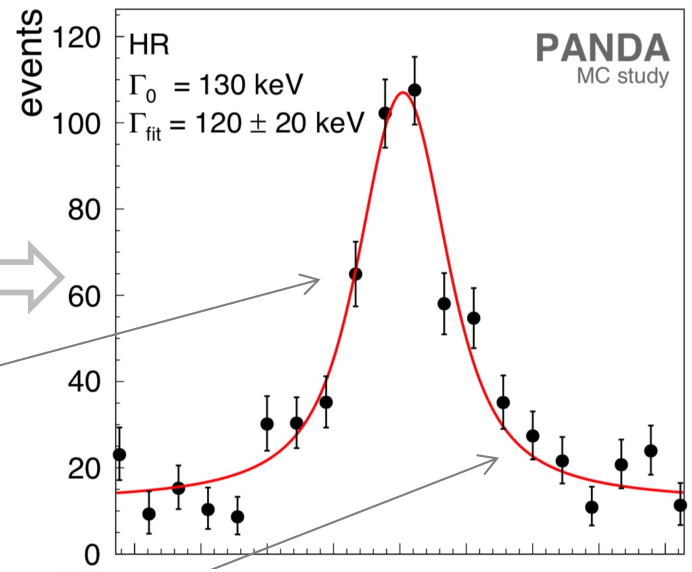


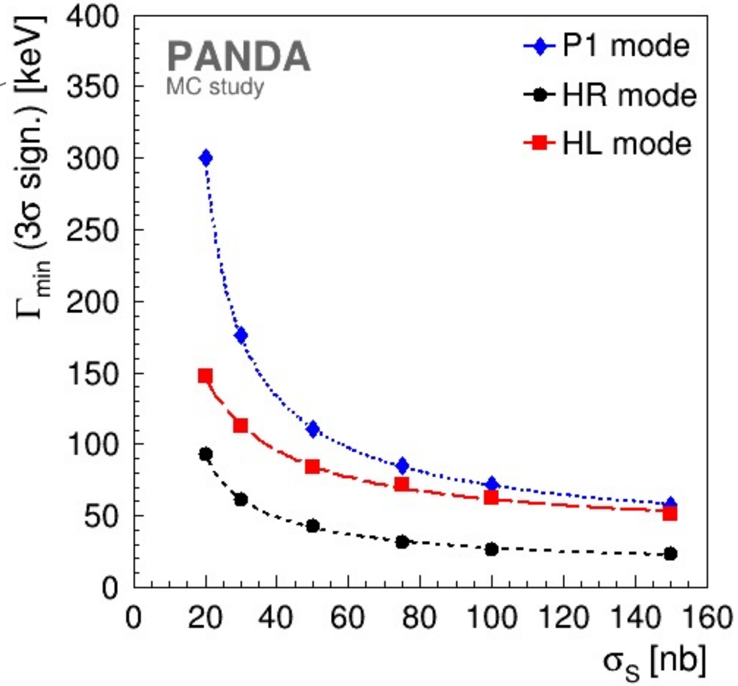
[PANDA, Eur. Phys. J. A 55 (2019) 42]

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]

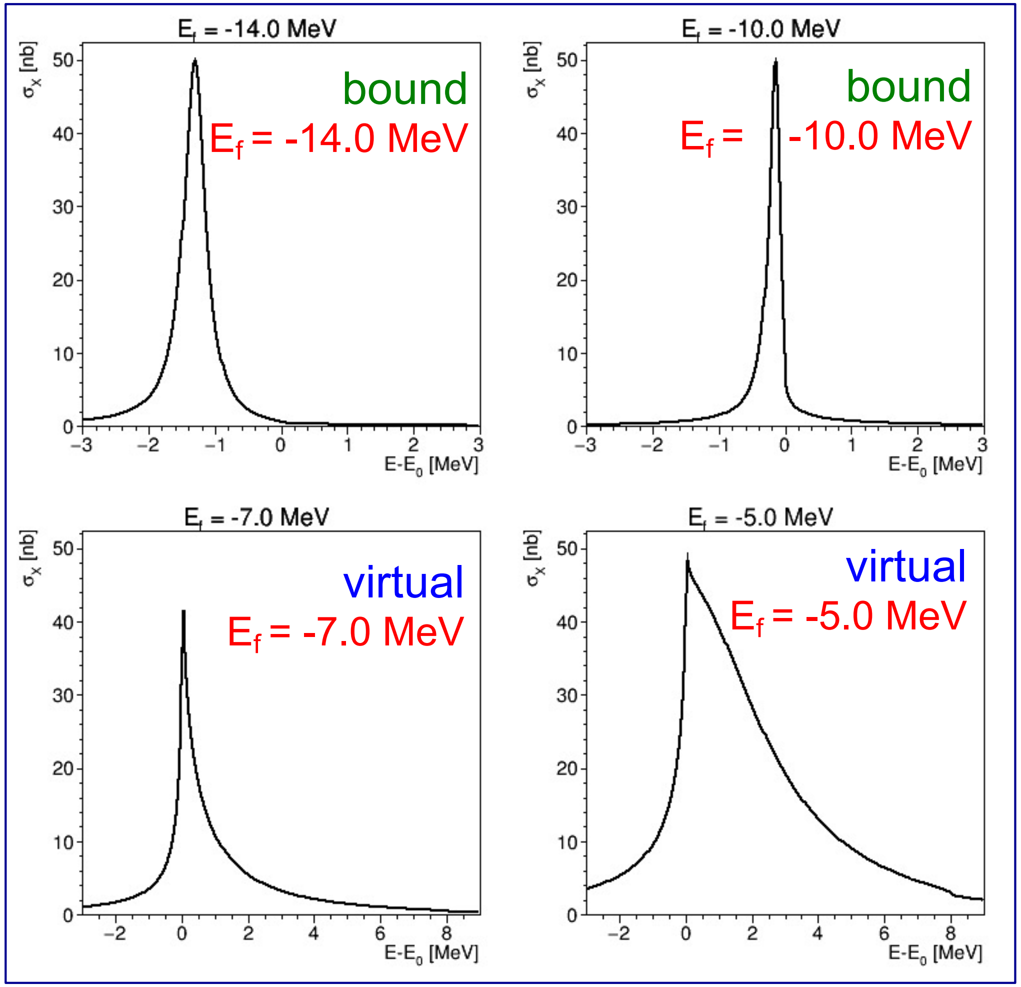
Distinction of Lineshapes (40 x 2d)

- How well can virtual vs bound state be distinguished?

[Phys. Atom. Nucl. 73 (2010) 1592]

$$\sigma(E;E_f) \sim \frac{\Gamma_{\pi^+\pi^- J/\psi}(E)}{|D(E;E_f)|^2}$$

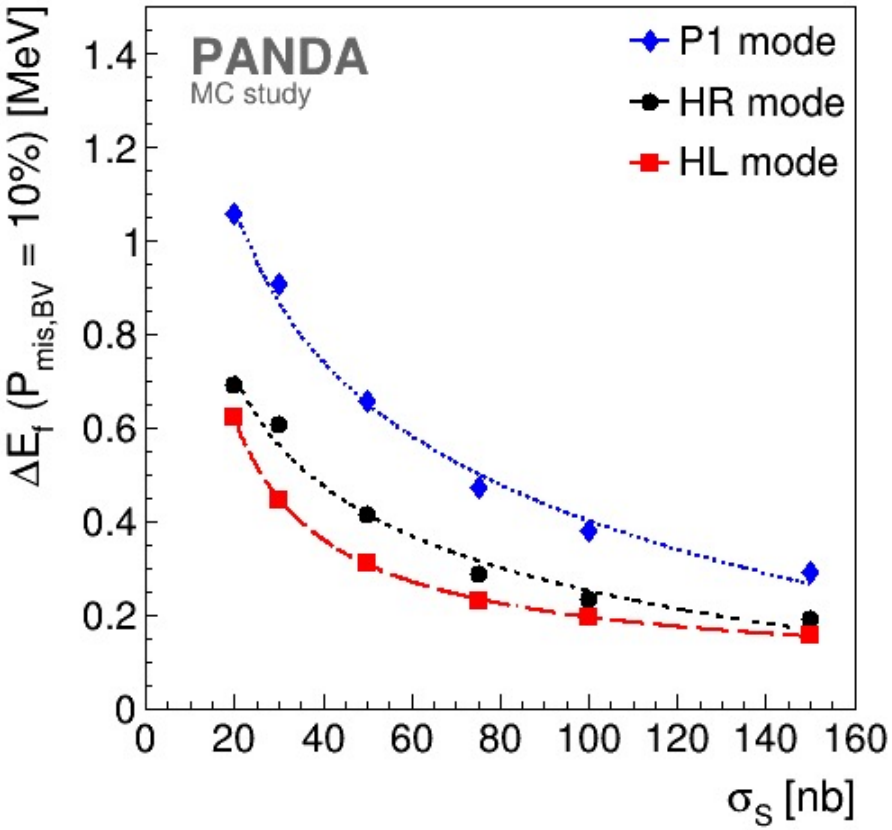
Flatté line shape depends on E_f



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

Sensitivity

10% P_{mis} , bound as virtual state



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

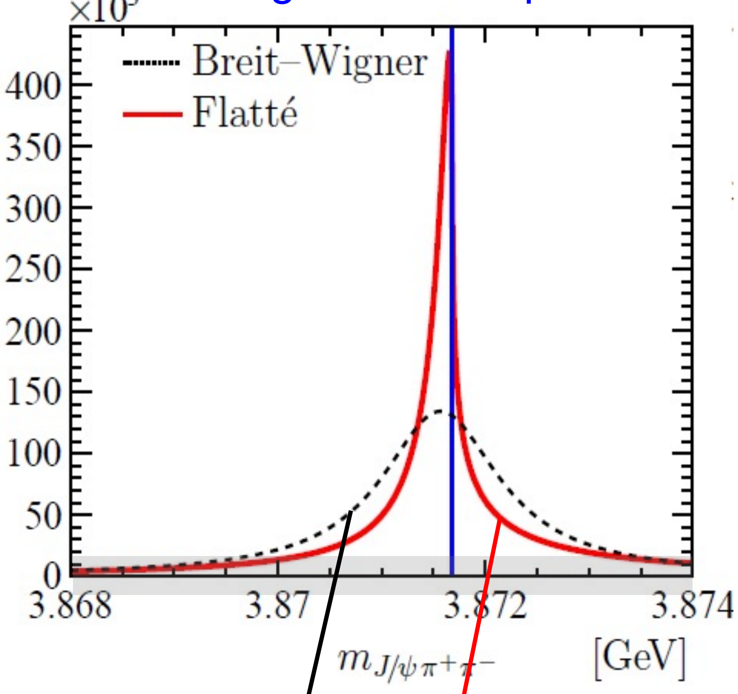
A study of the lineshape of the $\chi_{c1}(3872)$ state is made using a data sample corresponding to an integrated luminosity of $3\,\text{fb}^{-1}$ collected in pp collisions at centre-of-mass energies of 7 and 8 TeV with the LHCb detector. Candidate $\chi_{c1}(3872)$ mesons from b-hadron decays are 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

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

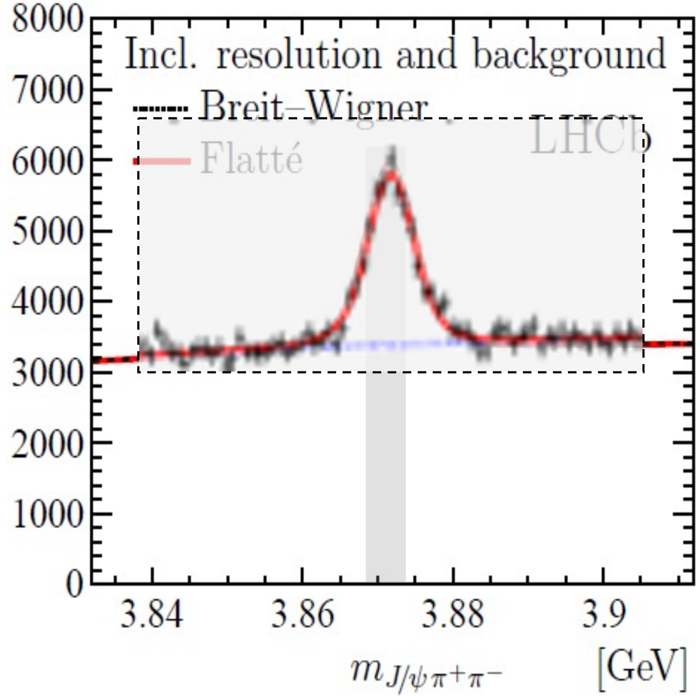
where the first uncertainty is statistical and the second systematic. Using a Flatté-inspired lineshape, two poles for the $\chi_{c1}(3872)$ state in the complex energy plane are found. The dominant pole is compatible with a quasi-bound $D^0\bar{D}^{*0}$ state but a quasi-virtual state is still allowed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

LHCb lineshapes (incl. resolution)

Original lineshapes



Lineshapes with resolution



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

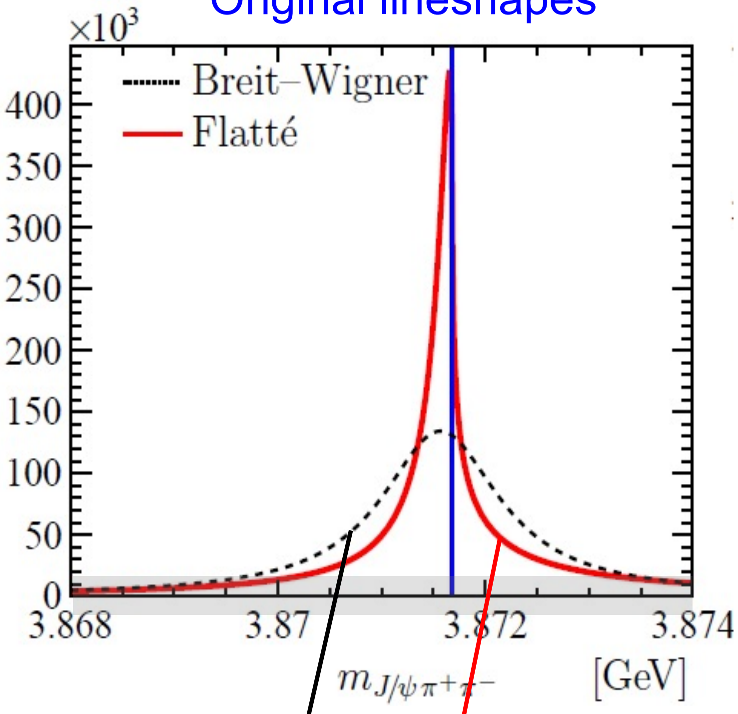
Mode [MeV]	Mean [MeV]	FWHM [MeV]
$3871.69^{+0.00}_{-0.04}{}^{+0.05}_{-0.13}$	$3871.66^{+0.07}_{-0.06}{}^{+0.11}_{-0.13}$	$0.22^{+0.06}_{-0.08}{}^{+0.25}_{-0.17}$

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.

LHCb lineshapes (incl. resolution)

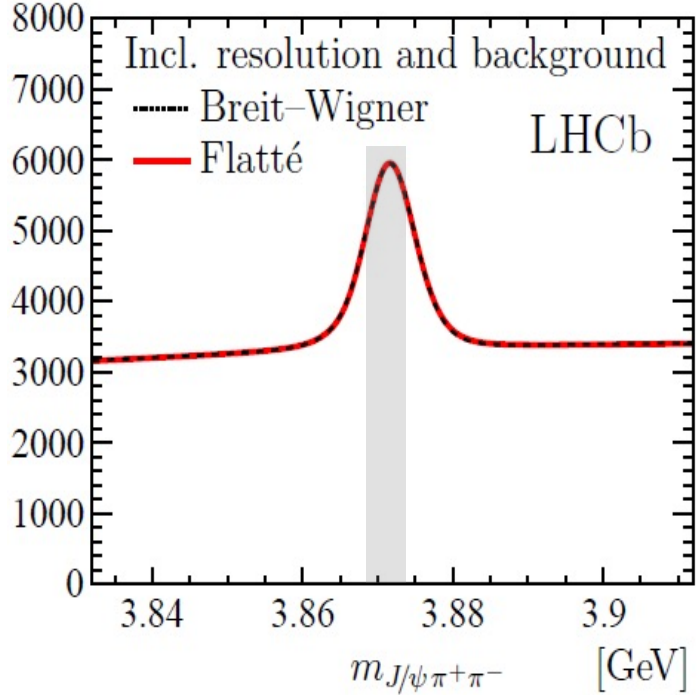
Original lineshapes



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

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

Lineshapes with resolution



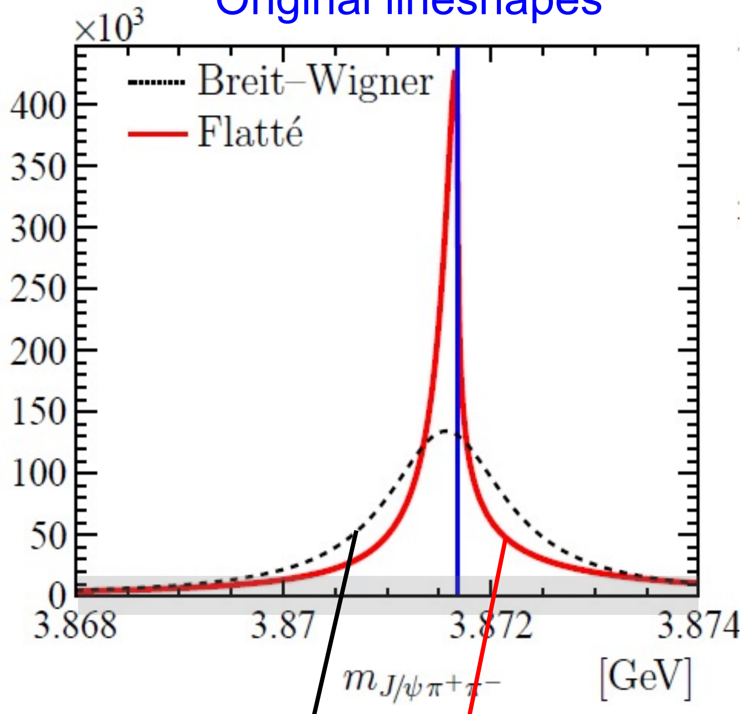
7.3 Comparison between Breit–Wigner and Flatté lineshapes

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 at LHCb
  - 1.39 MeV (BW) vs. 0.22 MeV (Flatté) => factor of ~5

LHCb lineshapes (incl. resolution)

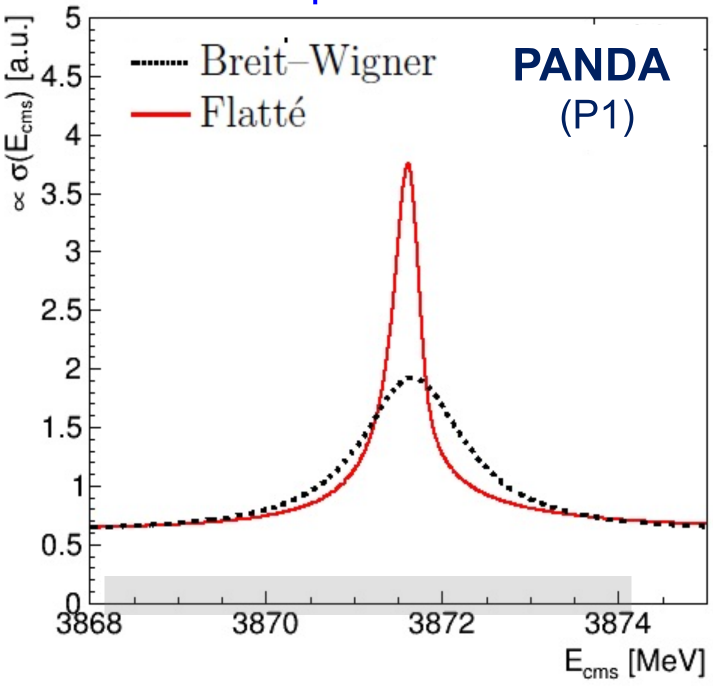
Original lineshapes



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

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

Lineshapes with resolution



- Due to the excellent beam resolution O(50-100 keV) at PANDA
  - ➢ Models are well distinguishable => Let's quantify

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

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)

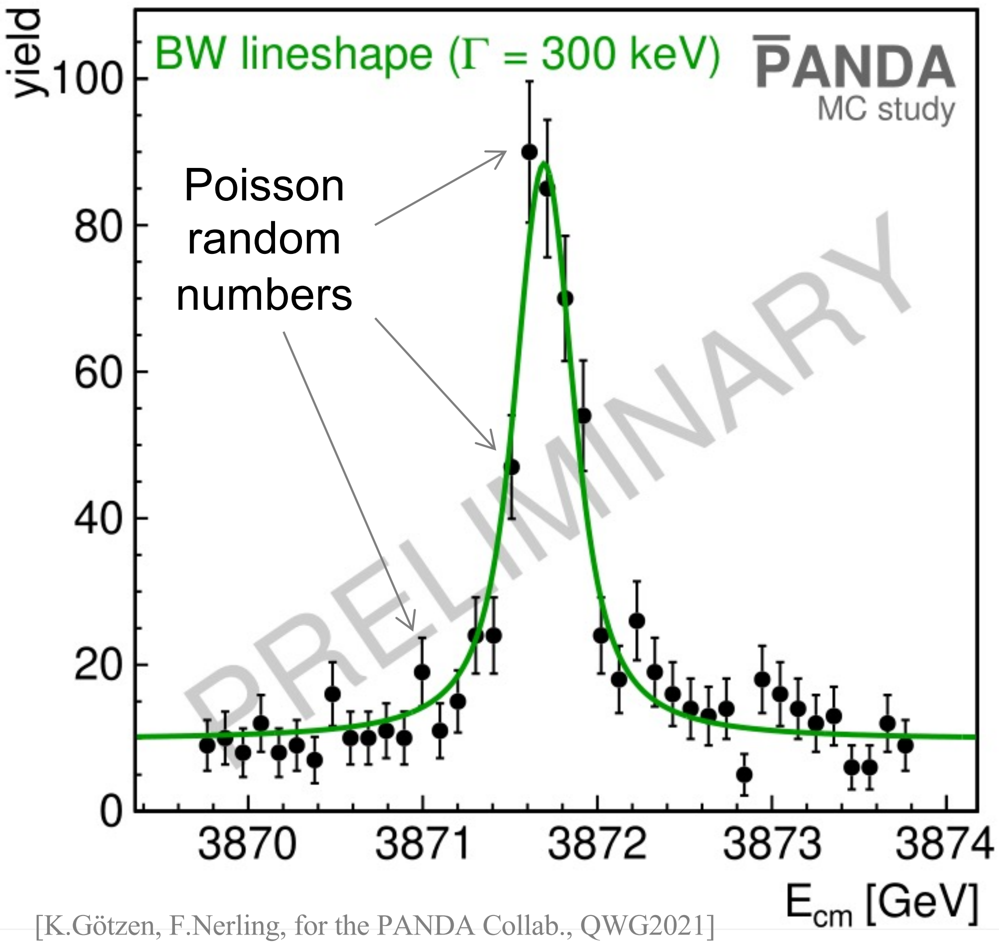
- <u>Addendum:</u>
  Investigate separation power
  → E_f (Flatté) vs. Γ (BW)
- Key parameters from
  → EPJ A 55 (2019) 42
- Total beam time
  → 40 × 2d = 80 d
- Generate many (toy) spectra for Flatté & BW model
- Fit both line shapes to each generated distribution
- Determine fit probabilities P_F &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

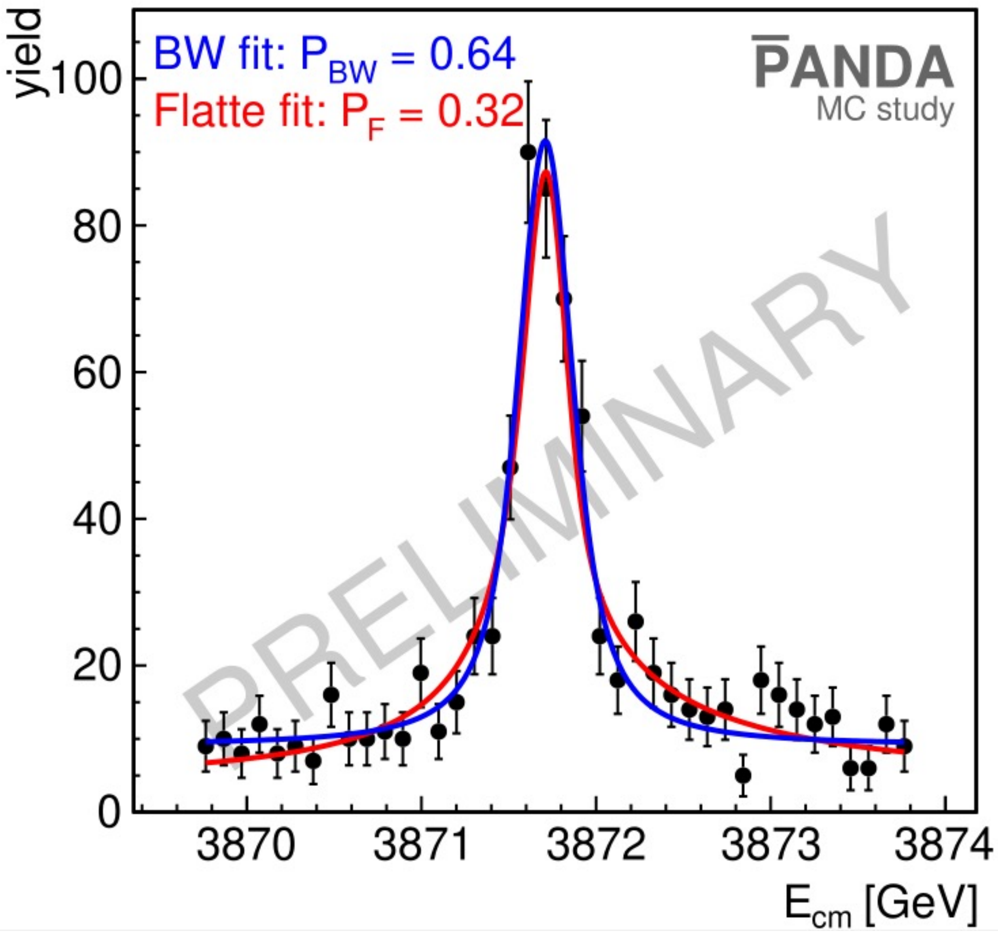
	Parameter	Value
Branching Fractions	$BR(J/\psi \to e^+ e^-)$	5.97 %
	$BR(J/\psi \to \mu^+ \mu^-)$	5.96 %
	$BR(\rho^0 \to \pi^+ \pi^-)$	100%
	$BR(X \to J/\psi\ \rho^0)$	5 % (UL: 6.6%)
Cross sections	$\sigma_{peak}(p\bar{p} \to X)$	[20,30,50,75,100,150] nb
	$\sigma(p\bar{p} \to J/\psi\ \pi^+\pi^-$ non-res)	1.2 nb [theory]
	$\sigma(p\bar{p} \to$ 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 ($dp/p = 5\cdot10^{-5}$)

Scan Procedure Principle (Example)

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

- Compute true line shape (BW or Flatté)
- Generate poisson random number $N_{poisson}$ for each E_{cm} and fill into graph
- Fit line shapes to extract fit probabilities P_{BW} and P_F

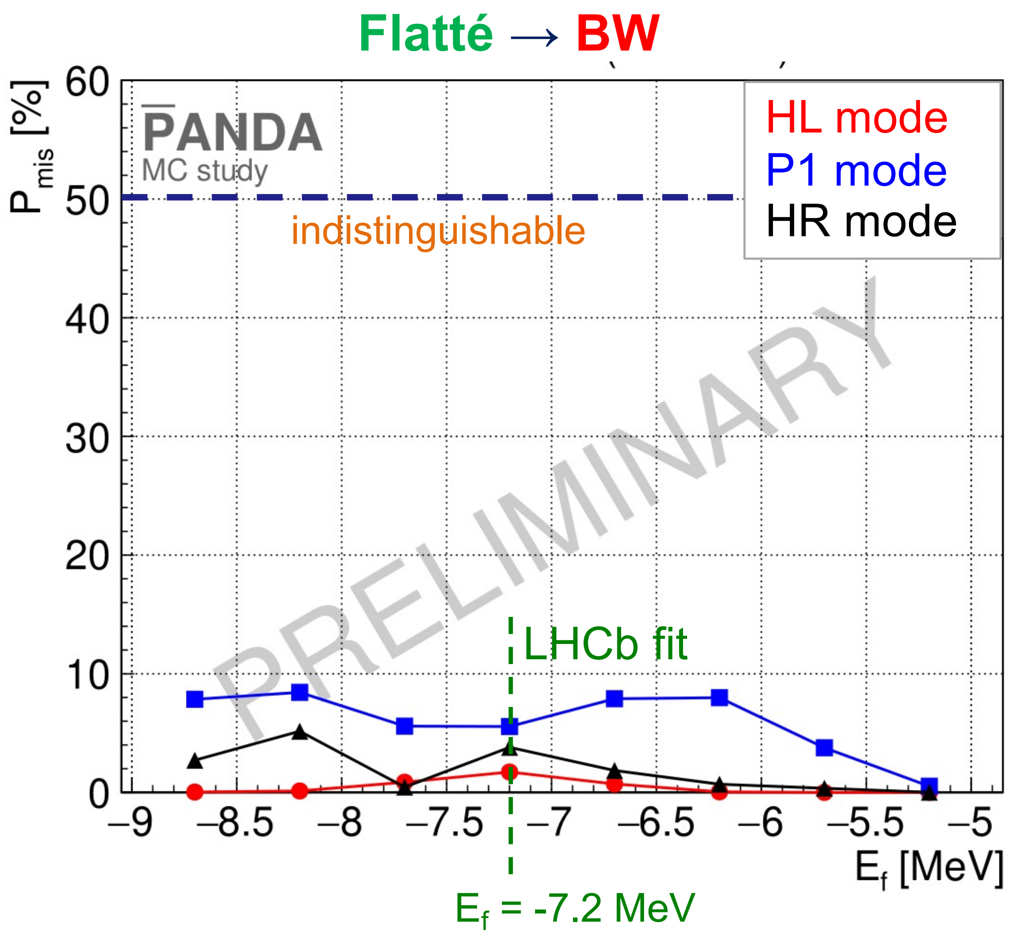




[K.Götzen, F.Nerling, for the PANDA Collab., QWG2021]

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"

Distinguish between models:
HL Mode : ≳ 98% correct
HR Mode : ≳ 95% correct
P1 Mode : ≳ 90% correct

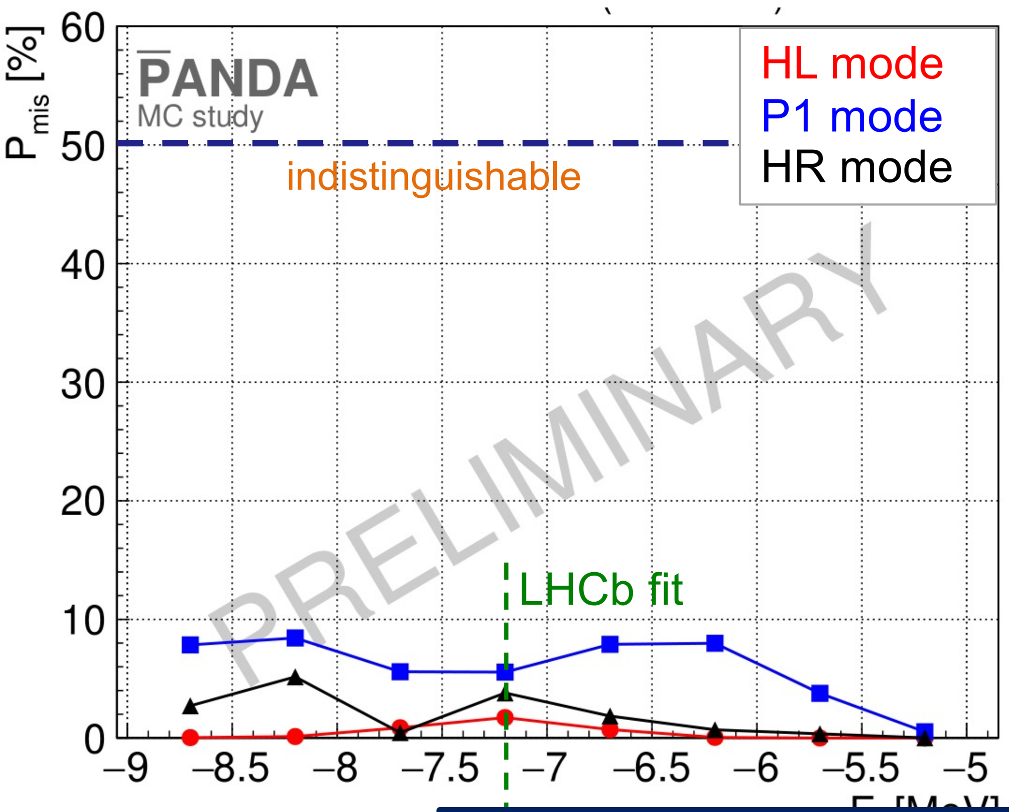
[K.Götzen & F.Nerling for PANDA Collab., QWG2021; also PoS CHARM2020 (2021) 004]

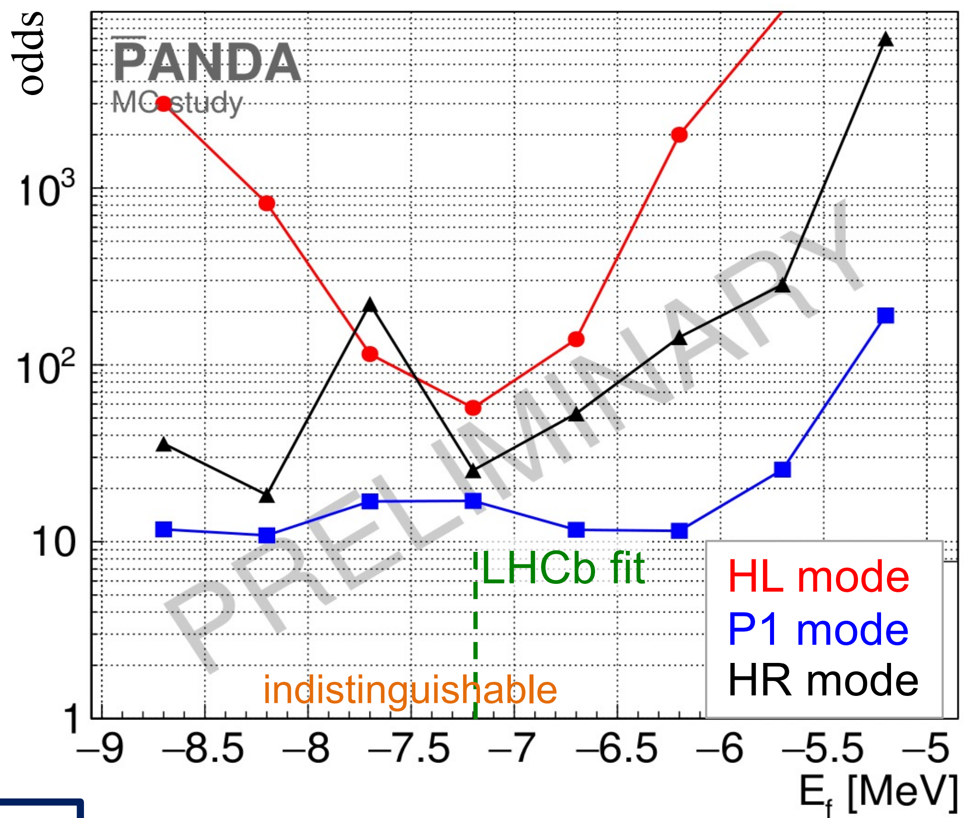
Parameter dependent performance

How much better are we than than "indistinguishable“?

Idea: Consider so-called odds := correct identifications per wrong one

Flatté → BW





At least ~10x better than indistinguishable *(full range)*

$$\text{odds} = (1 - P_{mis}) / P_{mis}$$

[K.Götzen & F.Nerling for PANDA Collab., QWG2021; also PoS CHARM2020 (2021) 004]

Summary & Conclusions

- Feasibility study for resonance energy scans at PANDA
  - Lineshape and width measurements for X(3872)
  - Achievable performance quantified
- Determined sensitivity for BW width measurement
  - Sensitivity $\Gamma/\Delta\Gamma > 5$ at $\Gamma \gtrsim 50 \ldots 120$ keV
  - HR mode performs better for smaller widths
- Determined sensitivity for molecular line-shape measurement
  - Possible to distinguish bound/virtual state
  - $P_{HR,HL} > 90\%$ for $|E_f - E_{f,th}| \gtrsim 700$ keV
  - Sub-MeV resolution on $|E_f - E_{f,th}|$ already for Phase-1 (P1)
  - HL mode performs better over investigated

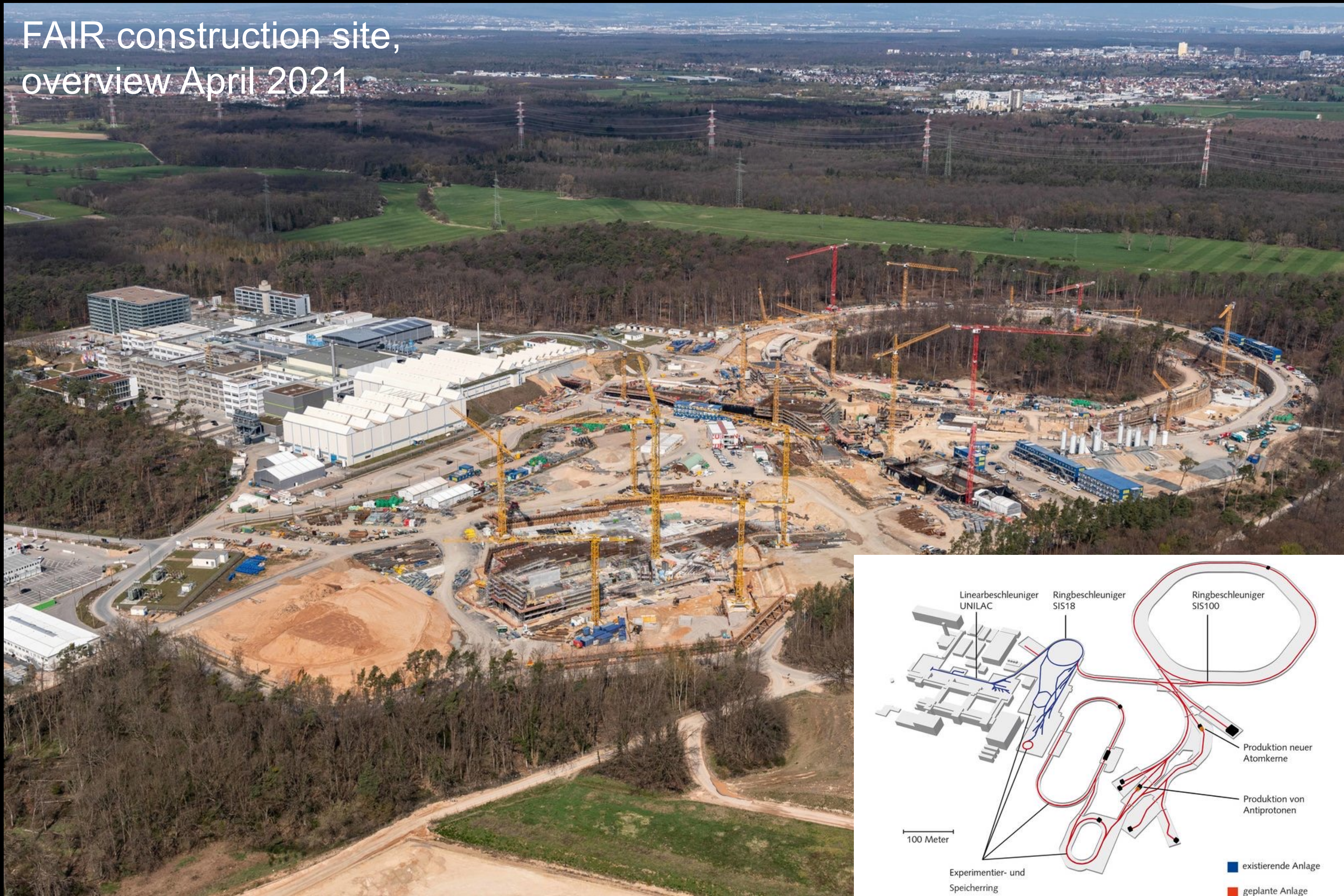
[PANDA, Eur. Phys. J. A 55 (2019) 42]

Summary & Conclusions

- Feasibility study for resonance energy scans at PANDA
  - Lineshape and width measurements for X(3872)
  - Achievable performance quantified
- Determined sensitivity for BW width measurement
  - Sensitivity $\Gamma/\Delta\Gamma > 5$ at $\Gamma \gtrsim 50 \ldots 120$ keV
  - HR mode performs better for smaller widths
- Determined sensitivity for molecular line-shape measurement
  - Possible to distinguish bound/virtual state
  - $P_{HR,HL} > 90\%$ for $|E_f - E_{f,th}| \gtrsim 700$ keV
  - Sub-MeV resolution on $|E_f - E_{f,th}|$ already for Phase-1 (P1)
  - HL mode performs better over investigated
- Comparison to recent LHCb result
  - Simulation of X(3872) line shape measurement at PANDA extended
    => Different models can be well distinguished
  - Correct assignment of fit model over full range between $\gtrsim$90% (P1) and $\gtrsim$98% (HL) depending on beam mode
  - At least ~10x higher odds to identify correct model than LHCb

[PANDA, Eur. Phys. J. A 55 (2019) 42] [K.Götzen & F.Nerling for PANDA Collab., QWG2021; also PoS CHARM2020 (2021) 004]

Facility for Antiproton and Ion Research



Facility for Antiproton and Ion Research

FAIR construction site,
overview Feb 2022

Facility for Antiproton and Ion Research

FAIR construction site,
overview Feb 2022

Facility for Antiproton and Ion Research

FAIR construction site,
overview Feb 2022

Facility for Antiproton and Ion Research

FAIR construction site,
overview Feb 2022