Paola Gianotti

The $\overline{\text{P}}$ANDA Physics Program


International Workshop on Antiproton Physics and Technology at FAIR

16-19 November 2015
Budker Institute of Nuclear Physics SB RAS
Novosibirsk, Russia
http://fair15.inp.nsk.su/

International Workshop on Antiproton Physics and Technology for FAIR
Budker Institute of Nuclear Physics, Novosibirk, Russia
16-19 November 2015

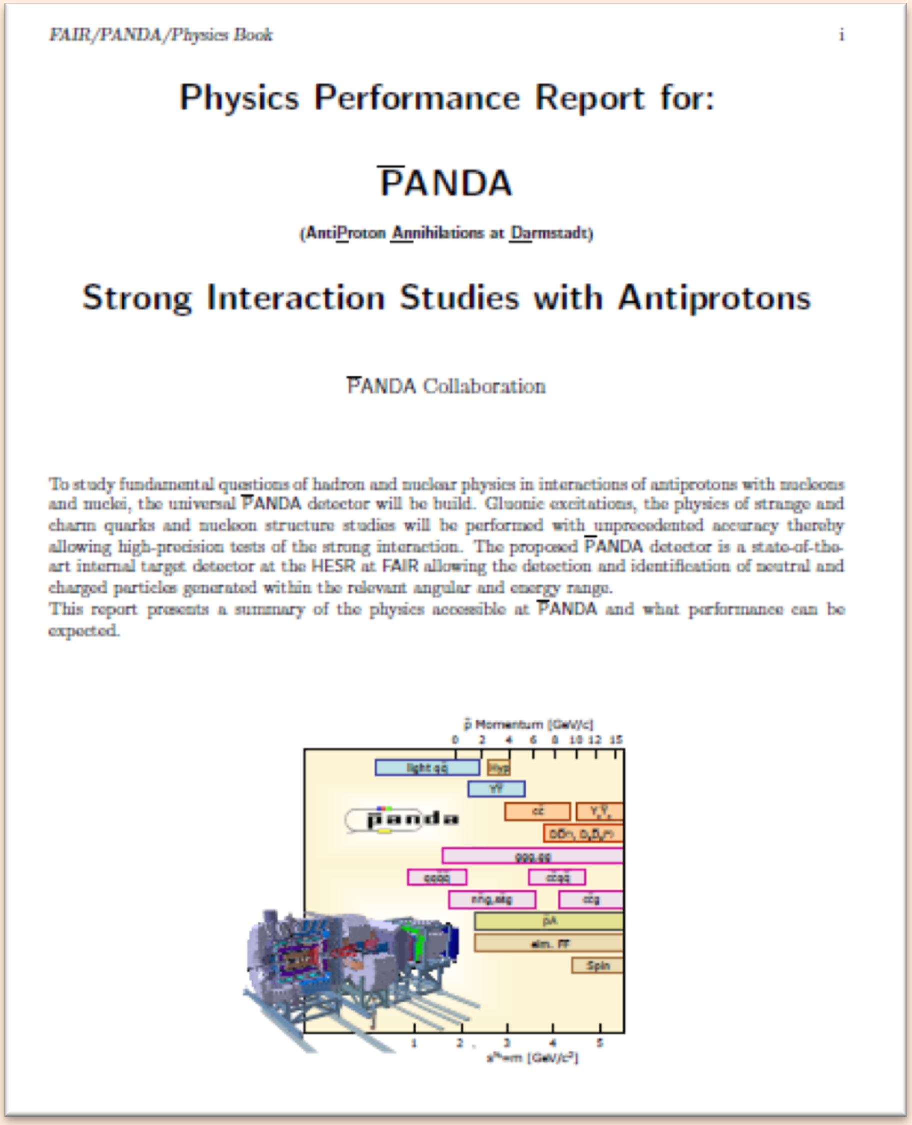
Outline

- Hadron spectroscopy with antiprotons;
- Low energy sector;
- Open-Charm and Charmonium spectroscopy;
- Exotic states;
- e.m. reactions.

$\overline{\text{P}}$ANDA Physics Program

- HADRON SPECTROSCOPY
  - CHARMONIUM
  - GLUONIC EXCITATIONS
  - OPEN CHARM
  - (MULTI)STRANGE BARYONS
- NUCLEON STRUCTURE
  - ELECTROMAGNETIC FORM FACTORS
  - TMDs
  - GPDs, TDAs
- HYPERNUCLEAR PHYSICS
- HADRONS IN THE NUCLEAR MEDIUM

$$\sqrt{s} = 2 \div 5.5\ GeV$$



FAIR/PANDA/Physics Book i

Physics Performance Report for:

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

(AntiProton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

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

To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal $\overline{\text{P}}$ANDA detector will be build. Gluonic excitations, the physics of strange and charm quarks and nucleon structure studies will be performed with unprecedented accuracy thereby allowing high-precision tests of the strong interaction. The proposed $\overline{\text{P}}$ANDA detector is a state-of-the-art internal target detector at the HESR at FAIR allowing the detection and identification of neutral and charged particles generated within the relevant angular and energy range.
This report presents a summary of the physics accessible at $\overline{\text{P}}$ANDA and what performance can be expected.

ArXiV:0903.3905

Physics scope

One of the open problems in the Standard Model is a full understanding of Quantum Chromodynamics (QCD).

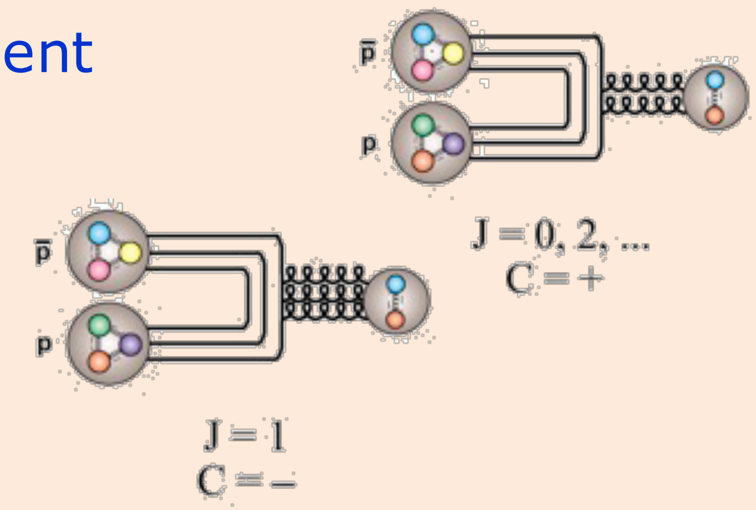
QCD describe well phenomena at high energies (perturbative regime).

At low energies, QCD becomes a strongly coupled theory, many aspects of which are not understood.

$\bar{\text{P}}$ANDA will study $\bar{p}p$ and $\bar{p}A$ annihilations, providing unique and decisive measurements on a wide range of QCD aspects

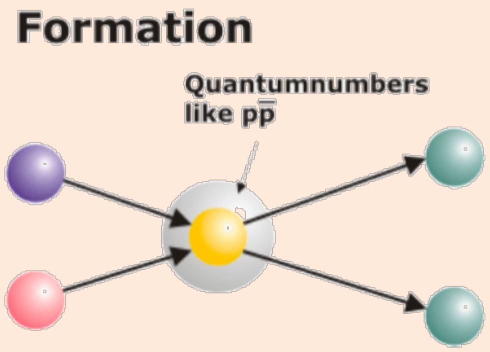
$\bar{p}p$ Anihilation

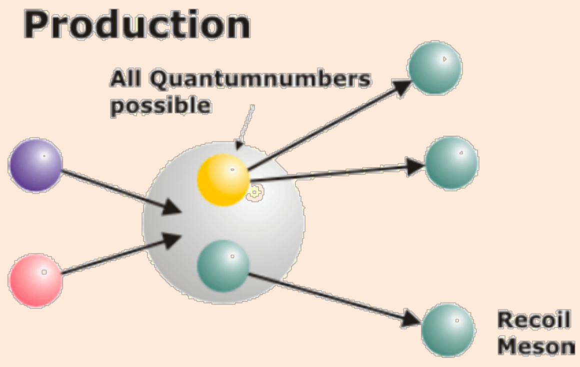
$\bar{p}p$ annihilation is a Gluon-Rich environment



Direct resonant formation of states with all non-exotic quantum numbers.
⇒ excellent precision in mass and width measurement

Access to both exotic and non-exotic quantum numbers via production and formation reactions





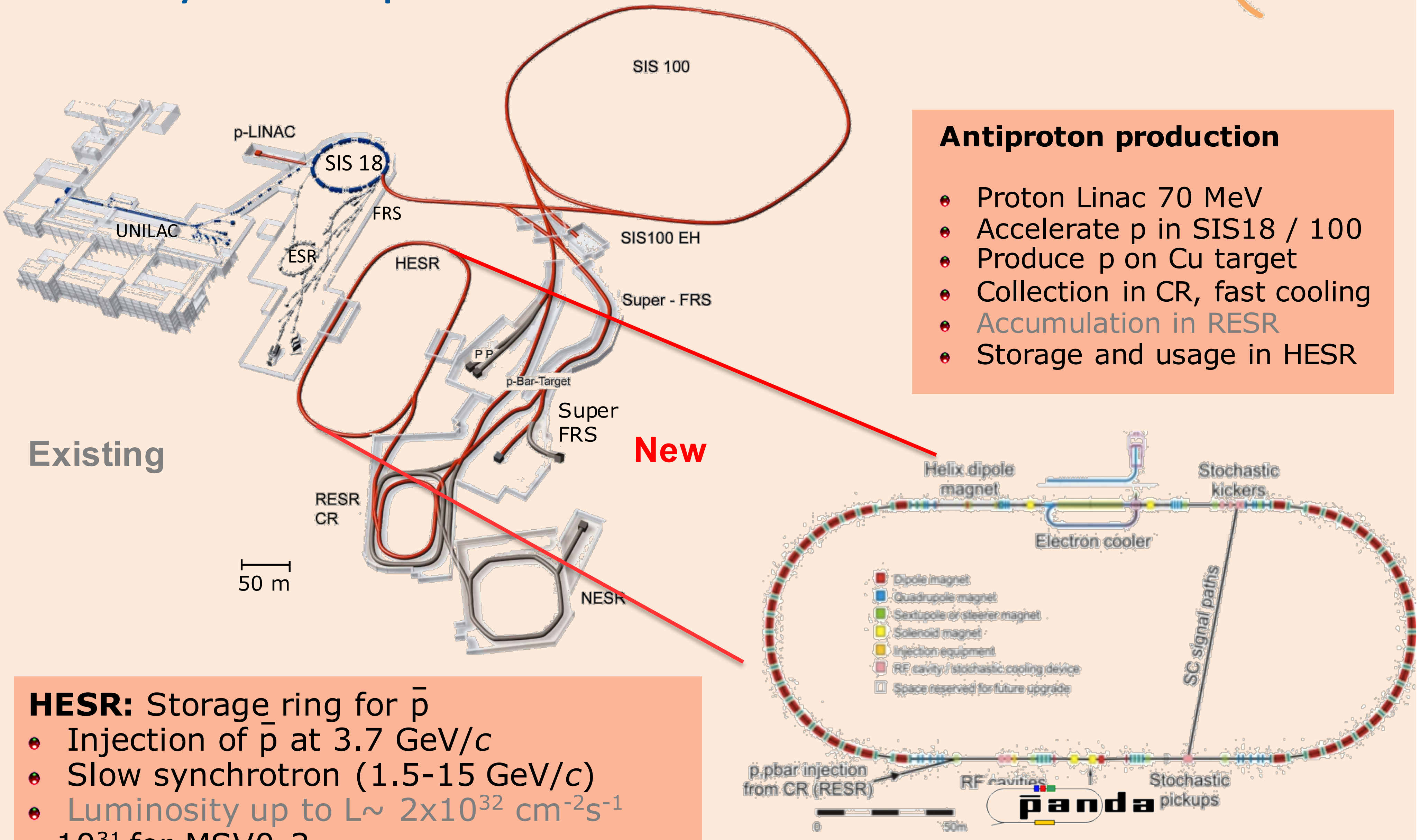
Versatility of physics program
if coupled to universal detector

Uniqueness of $\bar{p}$ probe
no other $\bar{p}$ facility in this energy range in the world

Facility for Antiproton and Ion Research

Antiproton production

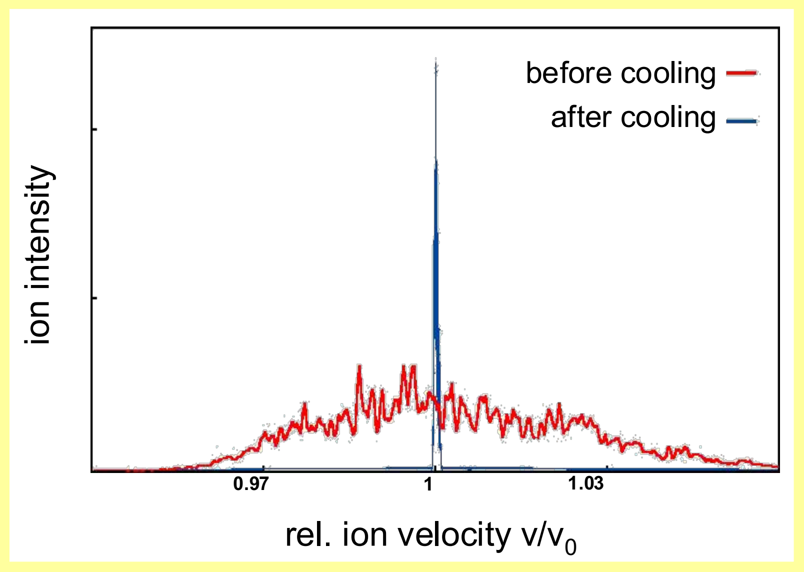
- Proton Linac 70 MeV
- Accelerate p in SIS18 / 100
- Produce p on Cu target
- Collection in CR, fast cooling
- Accumulation in RESR
- Storage and usage in HESR



HESR: Storage ring for $\bar{p}$
- Injection of $\bar{p}$ at 3.7 GeV/*c*
- Slow synchrotron (1.5-15 GeV/*c*)
- Luminosity up to L~ $2x10^{32}$ $cm^{-2}s^{-1}$
  10^{31} for MSV0-3
- Beam cooling (stochastic & electron)

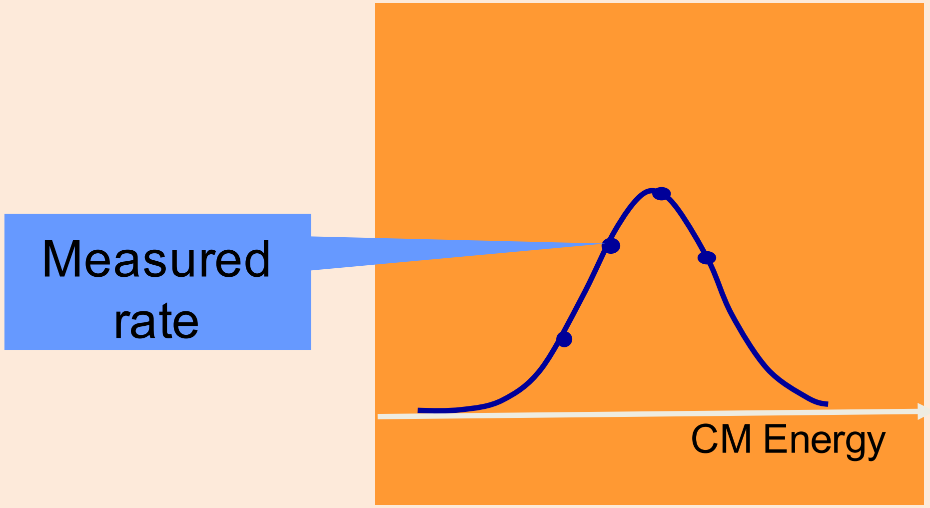
Antiproton power

$\bar{p}$-beams can be cooled → Excellent resonance resolution



Antiproton power

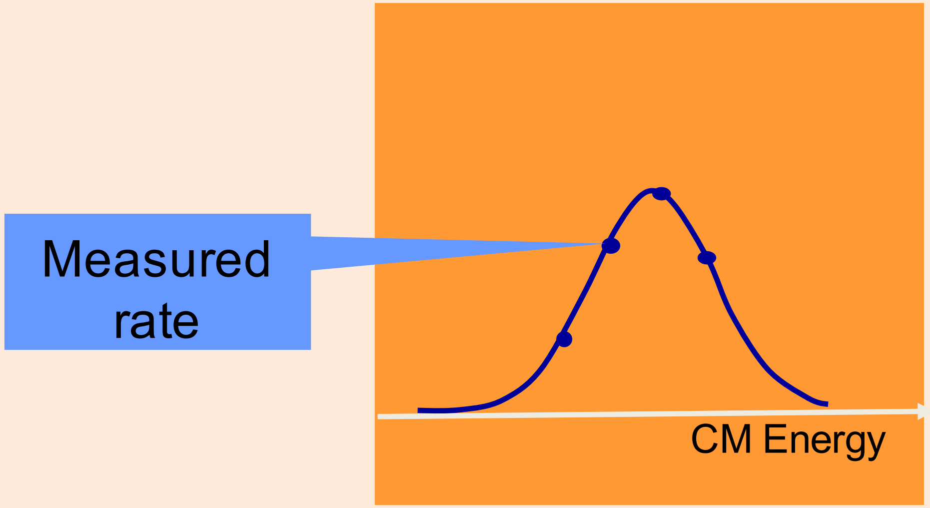
$\bar{p}$-beams can be cooled → Excellent resonance resolution



The production rate of a certain final state ν

Antiproton power

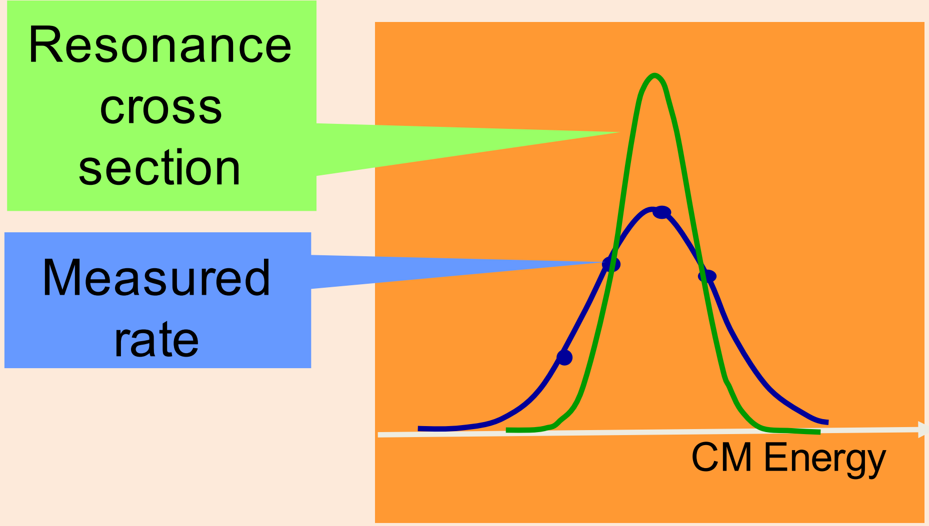
$\bar{p}$-beams can be cooled → Excellent resonance resolution



The production rate of a certain final state ν is a convolution of the

Antiproton power

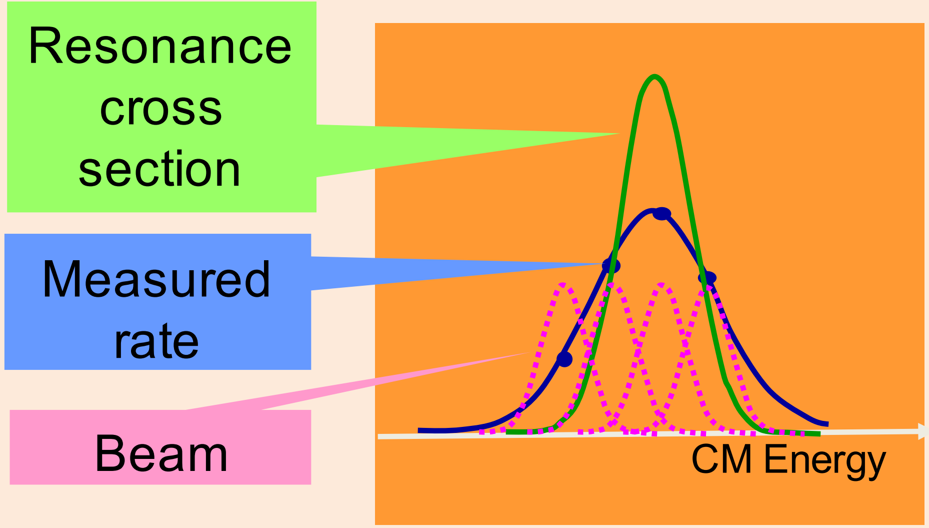
$\bar{p}$-beams can be cooled → Excellent resonance resolution



The production rate of a certain final state ν is a convolution of the BW cross section

Antiproton power

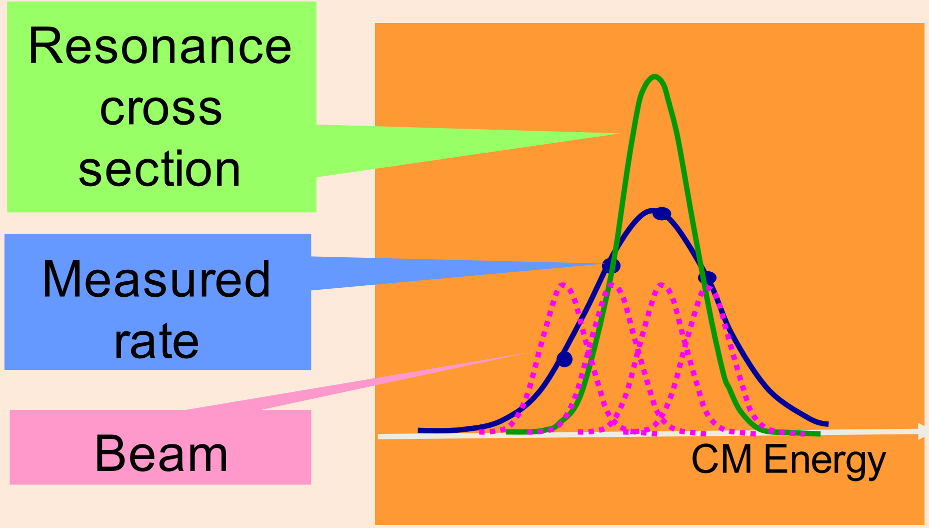
$\bar{p}$-beams can be cooled → Excellent resonance resolution



The production rate of a certain final state ν is a convolution of the BW cross section and the beam energy distribution function $f(E,\Delta E)$:

Antiproton power

$\bar{p}$-beams can be cooled → Excellent resonance resolution



Resonance cross section

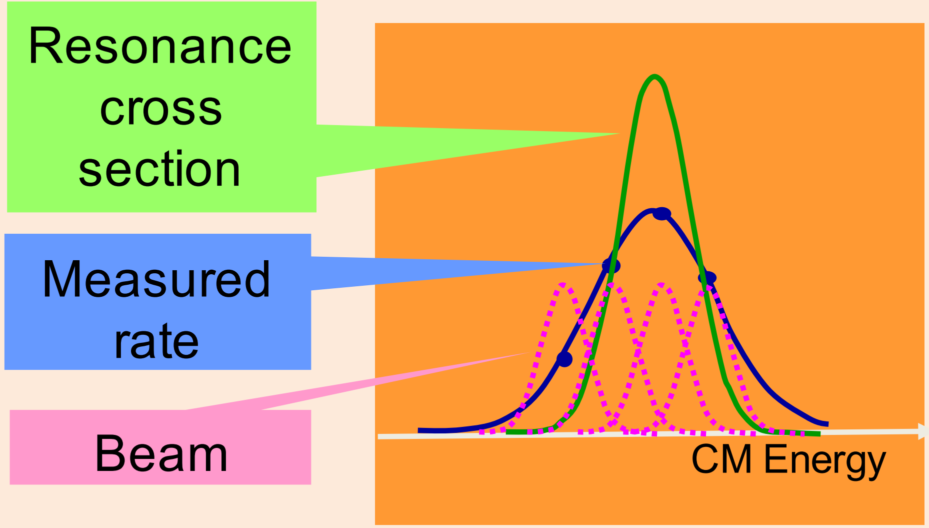
Measured rate

Beam

The production rate of a certain final state ν is a convolution of the BW cross section and the beam energy distribution function *f(E,ΔE):*

$$\nu = L_0\left\{\varepsilon\int dEf(E,\Delta E)\sigma_{BW}(E)+\sigma_b\right\}$$

Antiproton power

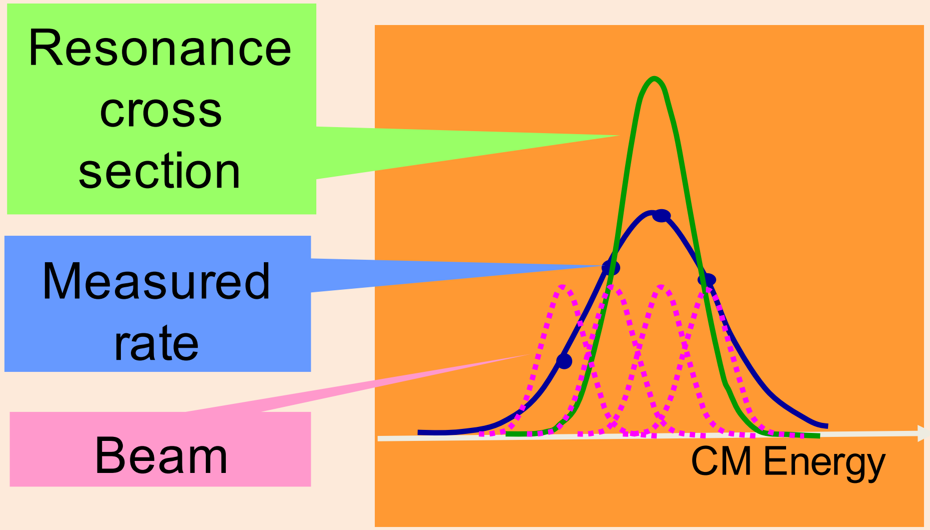


The production rate of a certain final state ν is a convolution of the BW cross section and the beam energy distribution function *f(E,ΔE)*:

$$\nu = L_0 \left\{ \varepsilon \int dE f(E,\Delta E) \sigma_{BW}(E) + \sigma_b \right\}$$

The resonance mass M_R, total width Γ_R and product of branching ratios into the initial and final state $B_{in}B_{out}$ can be extracted by measuring the formation rate for that resonance as a function of the cm energy E.

Antiproton power



Typical mass resolution

- e^+e^-: ~ MeV
- Fermilab: 240 KeV
- HESR: down to 50 KeV

The production rate of a certain final state ν is a convolution of the BW cross section and the beam energy distribution function *f(E,ΔE)*:

$$\nu = L_0\left\{\varepsilon\int dE f(E,\Delta E)\sigma_{BW}(E)+\sigma_b\right\}$$

The resonance mass M_R, total width Γ_R and product of branching ratios into the initial and final state $B_{in}B_{out}$ can be extracted by measuring the formation rate for that resonance as a function of the cm energy *E*.

Comparison with other techniques

- e^+e^-
  - direct formation limited to $J^{PC} = 1^{--}$
  - limited mass and width resolution for non vector states
  - sub-MeV widths very difficult or impossible
  - high L not accessible
- high-energy (several TeV) hadroproduction
  - high combinatorial background makes discovery of new states very difficult
  - width measurements limited by detector resolution
- B decays (both for e^+e^- and hadroproduction)
  - limited J^{PC}
  - C cannot be determined since not conserved in weak decay

Antiproton power

- e^+e^- interactions:

- $p\bar{p}$ reactions:

Antiproton power

- e^+e^- interactions:

  - Only 1^{--} states are formed
  - Other states only by secondary decays (sub-MeV widths very difficult or impossible)
  - high L not accessible

- $p\bar{p}$ reactions:

Antiproton power

- e^+e^- interactions:

  - Only 1^{--} states are formed
  - Other states only by secondary decays (sub-MeV widths very difficult or impossible)
  - high L not accessible

- $p\bar{p}$ reactions:

  - all $q\bar{q}$ states directly formed (very good mass resolution; $\bar{p}$-beam can be efficiently cooled $\Delta p/p \sim 10^{-5}$)

Antiproton power

$e^+e^- \to \psi(2S)$
$\to \boxed{\gamma\chi_{1,2}}$
$\to \gamma\gamma J/\psi$
$\to \gamma\gamma e^+e^-$

$\bar{p}\,p \to \boxed{\chi_{1,2}}$
$\to \gamma J/\psi$
$\to \gamma e^+e^-$

- e^+e^- interactions:

  - Only 1^{--} states are formed
  - Other states only by secondary decays (sub-MeV widths very difficult or impossible)
  - high L not accessible

- $p\bar{p}$ reactions:

  - all $q\bar{q}$ states directly formed (very good mass resolution; $\bar{p}$-beam can be efficiently cooled $\Delta p/p \sim 10^{-5}$)

Antiproton power

$e^+e^- \to \psi(2S)$
$\to \boxed{\gamma\chi_{1,2}}$
$\to \gamma\gamma J/\psi$
$\to \gamma\gamma e^+e^-$

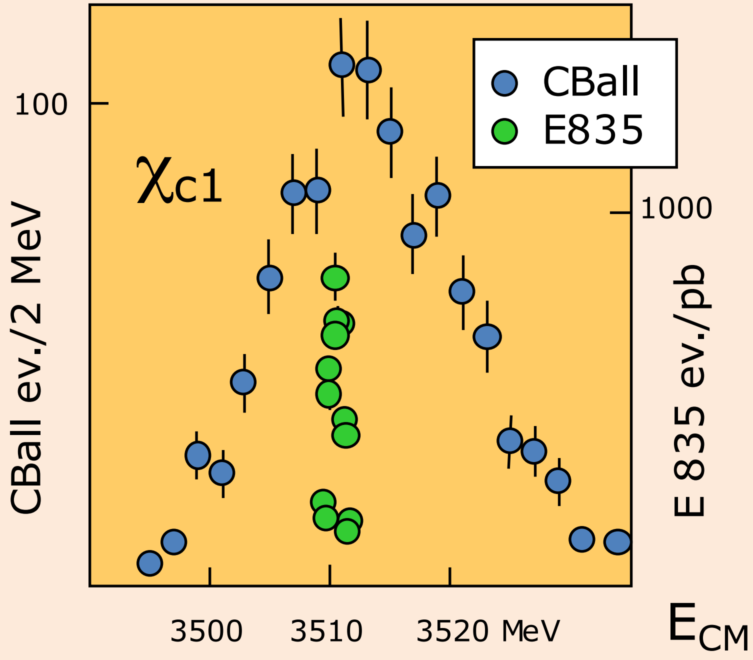
$\bar{p}\,p \to \boxed{\chi_{1,2}}$
$\to \gamma J/\psi$
$\to \gamma e^+e^-$

- e^+e^- interactions:

  - Only 1^{--} states are formed
  - Other states only by secondary decays (sub-MeV widths very difficult or impossible)
  - high L not accessible

- $p\bar{p}$ reactions:

  - all $q\bar{q}$ states directly formed (very good mass resolution; $\bar{p}$-beam can be efficiently cooled $\Delta p/p \sim 10^{-5}$)



Antiproton power

$e^+e^- \to \psi(2S)$
$\to \boxed{\gamma\chi_{1,2}}$
$\to \gamma\gamma J/\psi$
$\to \gamma\gamma e^+e^-$

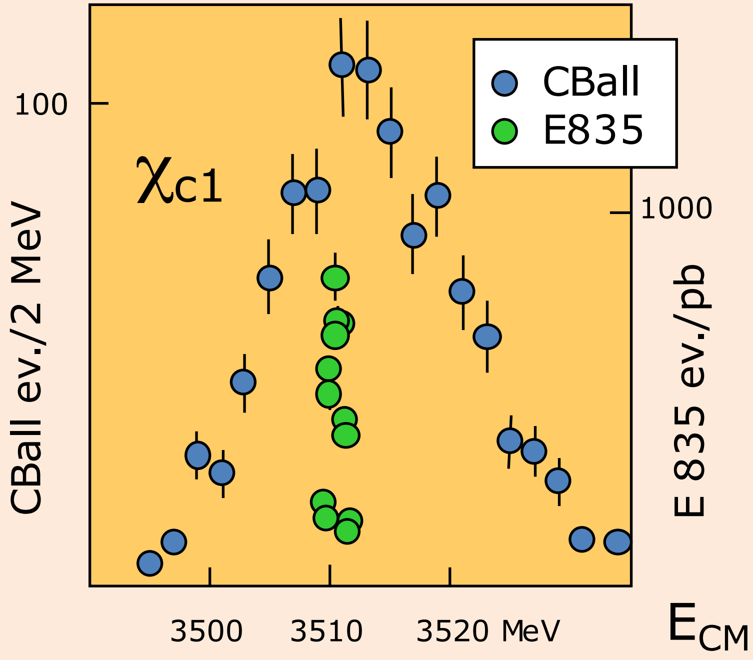
$\bar{p}\,p \to \boxed{\chi_{1,2}}$
$\to \gamma J/\psi$
$\to \gamma e^+e^-$

- e^+e^- interactions:

  - Only 1^{--} states are formed
  - Other states only by secondary decays (sub-MeV widths very difficult or impossible)
  - high L not accessible

- $p\bar{p}$ reactions:

  - all $q\bar{q}$ states directly formed (very good mass resolution; $\bar{p}$-beam can be efficiently cooled $\Delta p/p \sim 10^{-5}$)

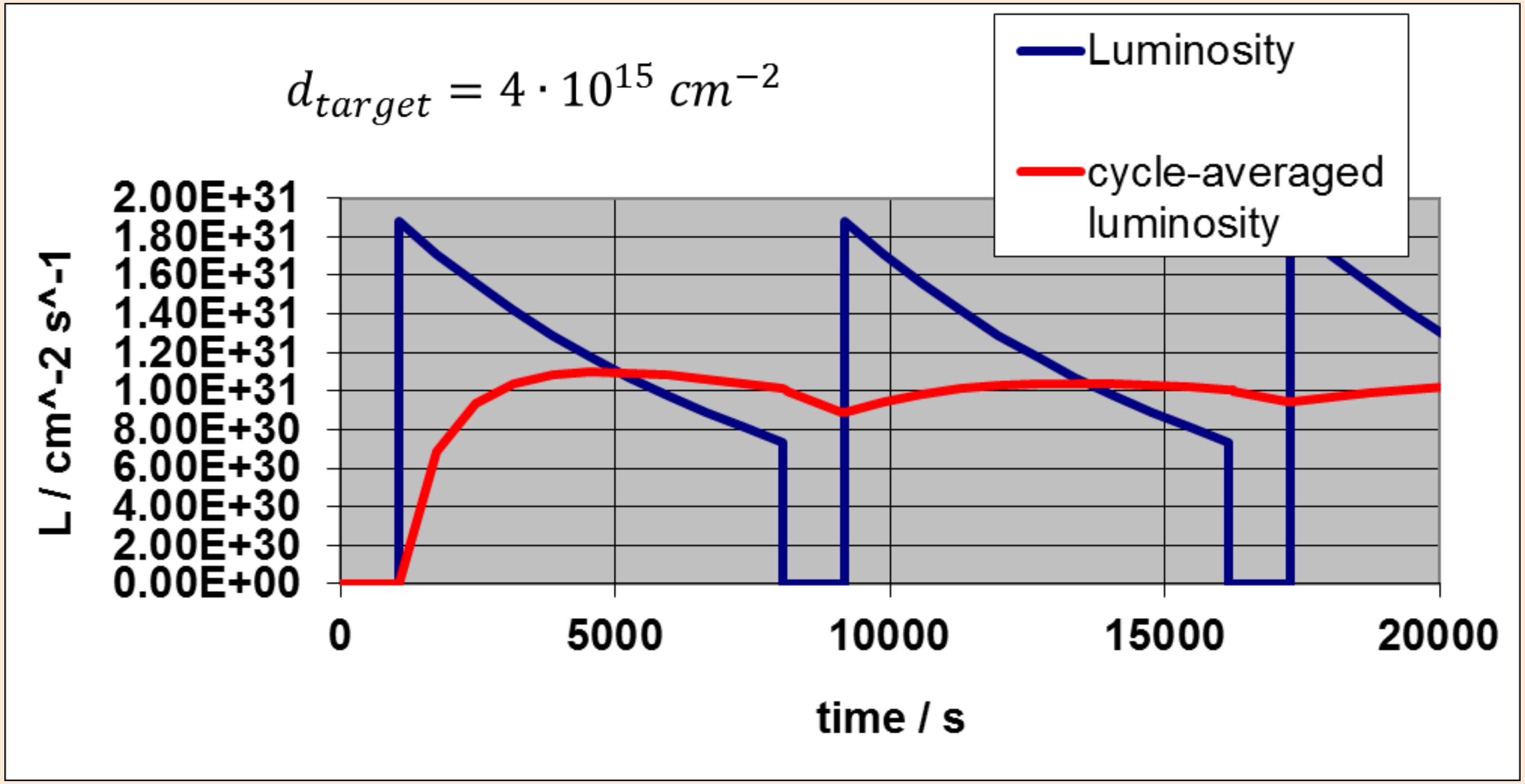


$\text{Br}(\bar{p}p \to \eta_c) = 1.2\ 10^{-3}$

$\text{Br}(e^+e^- \to \psi') \cdot \text{Br}(\psi' \to \gamma\eta_c) = 2.5\ 10^{-5}$

HESR in the MSV

- The intensity in the HESR in the MSV0-3 is limited to 10^{10} p-bars due to the cooling and injection efficiencies (RESR will not be present and its work will be done in the HESR).
- This means for PANDA:
  1. Lower intensity
  2. Lower duty cycle



The low energy range

In the last 20 years many steps forward in the field were possible thanks to the variety of facilities available all over the world.

Main non-$q\bar{q}$ candidates	
$f_0(980)$	4q state, molecule
$f_0(1500)$	0^{++} glueball candidate
$f_0(1370)$	0^{++} glueball candidate
$f_0(1710)$	0^{++} glueball candidate
$\eta(1410)$; $\eta(1460)$	0^{-+} glueball candidate
$f_1(1420)$	hybrid, 4q state
$\pi_1(1400)$	hybrid candidate 1^{-+}
$\pi_1(1600)$	hybrid candidate 1^{-+}
π (1800)	hybrid candidate 0^{-+}
$\pi_2(1900)$	hybrid candidate 2^{-+}
$\pi_1(2000)$	hybrid candidate 1^{-+}
$a_2'(2100)$	hybrid candidate 1^{++}
$\phi(2170)$	hybrid candidate 1^{--}, 4q state

Nowadays confirmation of predictions, together with unexpected results, are still coming out mainly from $e^+ e^-$ collider.

$Y_S(2175)$

The Y_S [X](2175) [or ϕ(2170) on PDG] was first observed by BABAR in the process $e^+e^- \to \phi(1020) f_0(980)$ and identified as a 1^{--} state

M = (2.175±0.010±0.015) GeV, Γ = (58±16±20) MeV.

Then was confirmed by BES in the decay $J/\Psi \to \eta\phi f_0(980)$

with M = (2.186±0.010±0.006) GeV and Γ = (65±25±17) MeV.

We performed a preliminary study for this channel looking to the following reaction: $\bar{p}p \to Y_S(2175) + X$ with X being a π^0 or $\pi^+\pi^-$

$$\hookrightarrow \phi\pi^+\pi^-, \phi\pi^0\pi^0$$

assuming different hypotheses for the signal cross-section and the decay B.R.

This is an example of "meson production" for which we can investigate different decay channels.

Light meson spectroscopy

Assuming cross sections of about 10 nb for glueball/hybrid candidates important topics of the P̄ANDA light hadron spectroscopy program can be addressed:

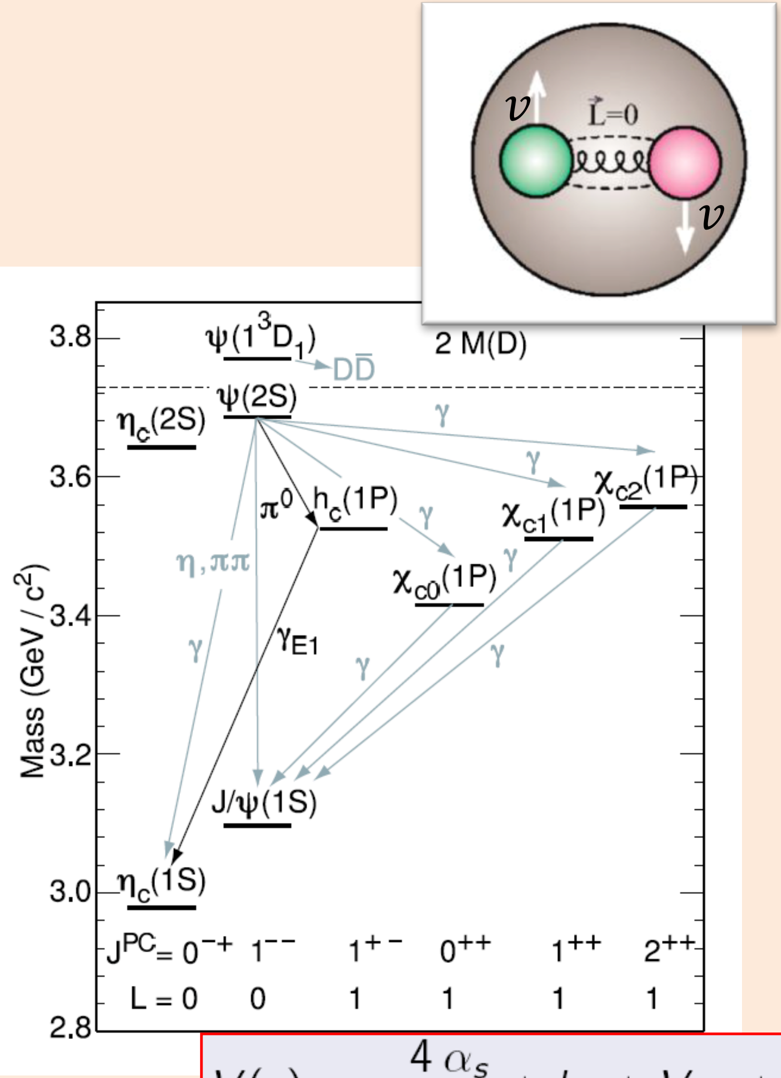
- with an integrated luminosity of about 2 pb^{-1} /channel;
- for new resonances, which do not require a Partial Wave Analysis, results can be obtained with data samples of 0.1 pb^{-1}.

Data samples of 2 pb^{-1} recorded in the low and high energy region, will allow to start first spin-parity analyses for spectroscopy.
These corresponds to 5 days with a Luminosity of 10^{31} cm^{-2} s^{-1} that is foreseen for the PANDA Day-1.

P̄ANDA will collect high statistics on many channels in the low energy sector

Charmonium States

Study of charmonium states plays a crucial role in understanding QCD.

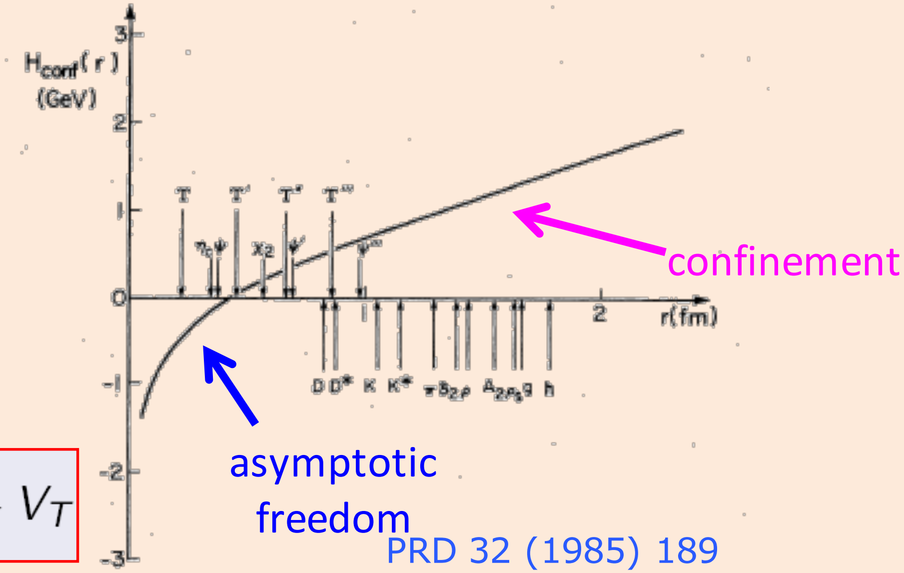


The system is non relativistic: $v_c^2 \approx 0.3$

The mass scale is perturbative: $m_c \approx 1.5 GeV$

The structure of separated energy scales makes charmonium an ideal probe of (de)confinement.
Charmonium probe the perturbative, non perturbative transition regime.

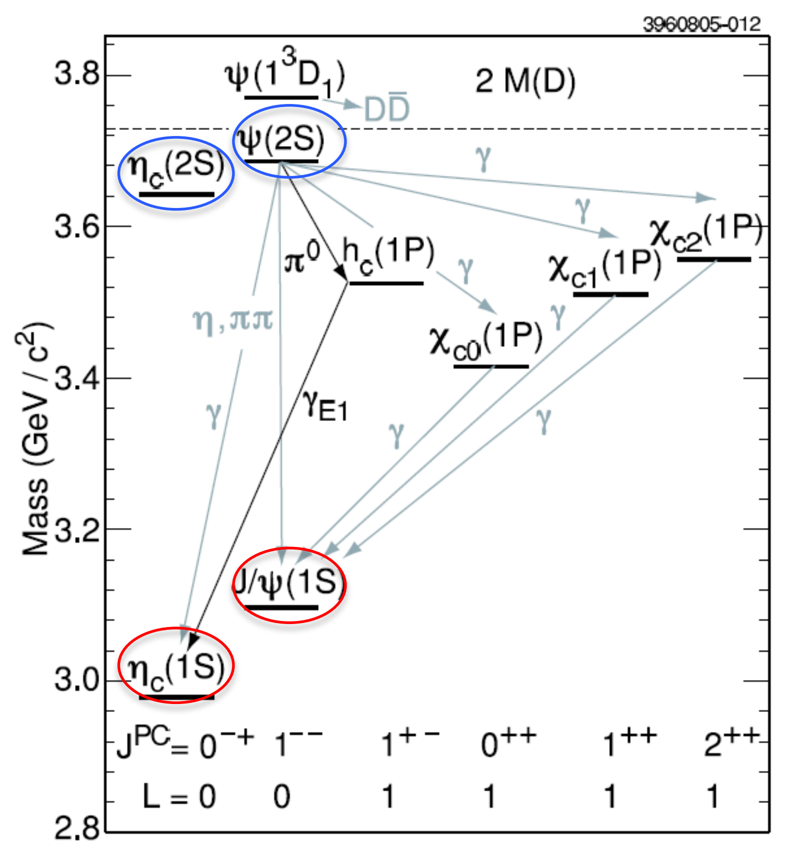
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr + V_{LS} + V_{SS} + V_T$$



PRD 32 (1985) 189

Charmonium states

The spin dependence of the c$\bar{c}$ potential give access to V_{SS} component of quark potential model.



The only well-measured hyperfine splitting was that for the 1S states of charmonium.

$$\Delta M_{hf}(1S)_{c\bar{c}} \equiv M(J/\psi) - M(\eta_c) = 116.6 \pm 1.0 \text{ MeV}$$

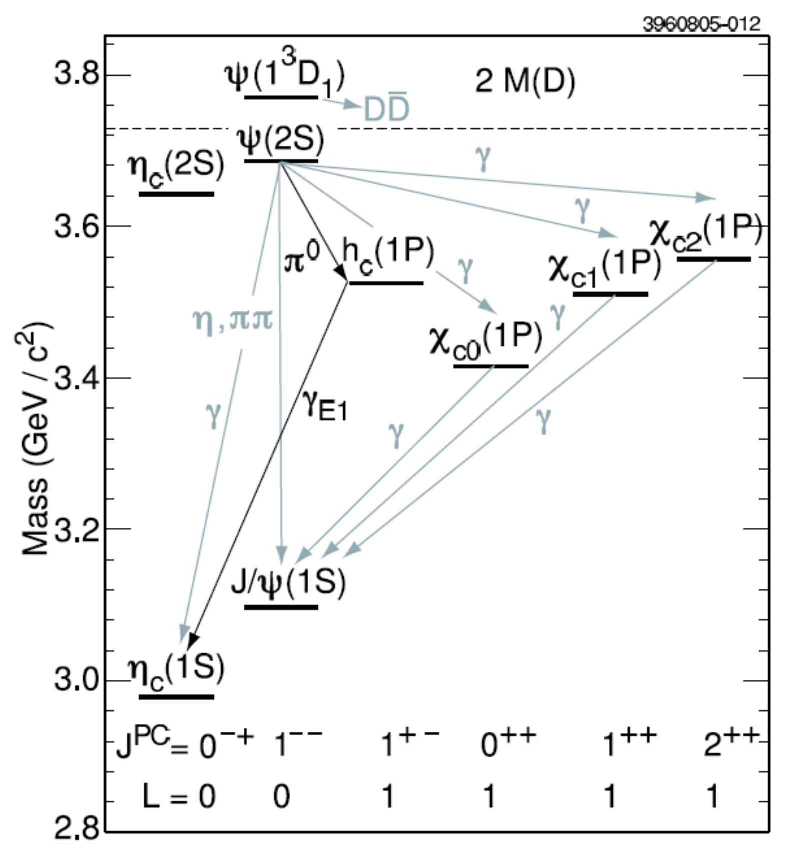
Recently $\eta'_C(2^1S_0)$ has been identified by Belle [PRL89(2002)102001] and the mass measured also by CLEO and BaBar in two photon fusion.

$$\Delta M_{hf}(2S)_{c\bar{c}} \equiv M(\psi'(2^3S_1)) - M(\eta'_c(2^1S_0)) = 49 \pm 4 \text{ MeV}$$

To complete the picture the P states hyperfine splitting was missing.

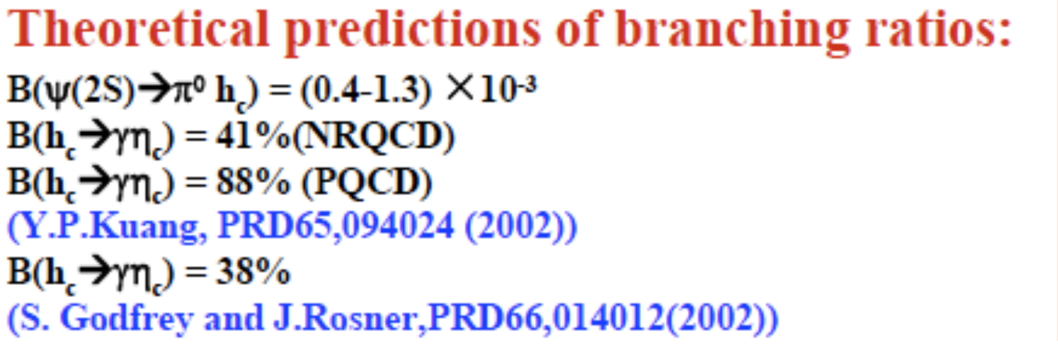
$h_c(^1P_1)$ charmonium state

The process $\psi' \to \pi^0 h_c$ is the only way to produce h_c from ψ' decay ➔ Limited phase space



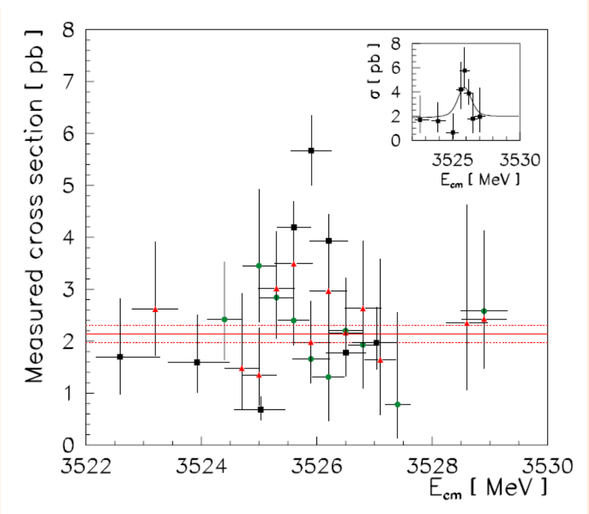
From the assumption of a small V_{SS} interaction it was expected

$$\boxed{\Delta M_{hf}(1P) \equiv M(^3P) - M(^1P) = 0}$$



Theoretical predictions of branching ratios:

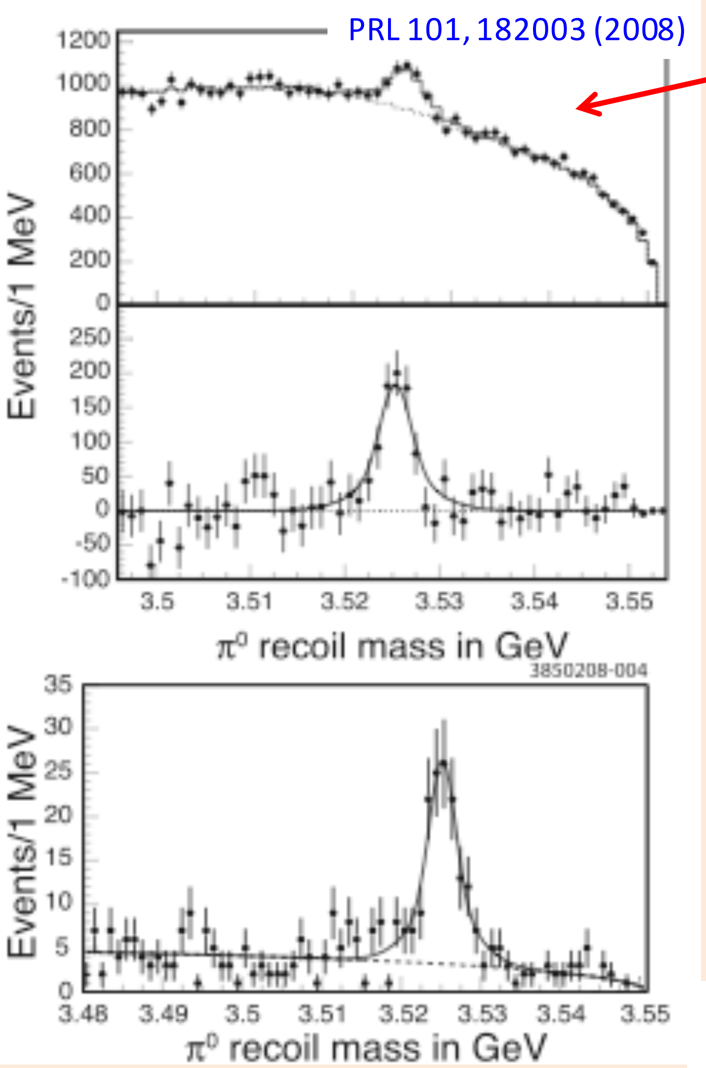
B(ψ(2S)→π⁰ h_c) = (0.4-1.3) ×10⁻³
B(h_c→γη_c) = 41%(NRQCD)
B(h_c→γη_c) = 88% (PQCD)
(Y.P.Kuang, PRD65,094024 (2002))
B(h_c→γη_c) = 38%
(S. Godfrey and J.Rosner,PRD66,014012(2002))



There were attempts to produce h_c in $p\bar{p}$ annhilitation at Fermilab (E760,E835) but the statistic was very poor.

$h_C(^1P_1)$ charmonium state

$e^+e^- \rightarrow \psi' \rightarrow \pi^0 h_c \rightarrow (\gamma\gamma)(\gamma\eta_c)$ The ψ' decay mode is isospin violating

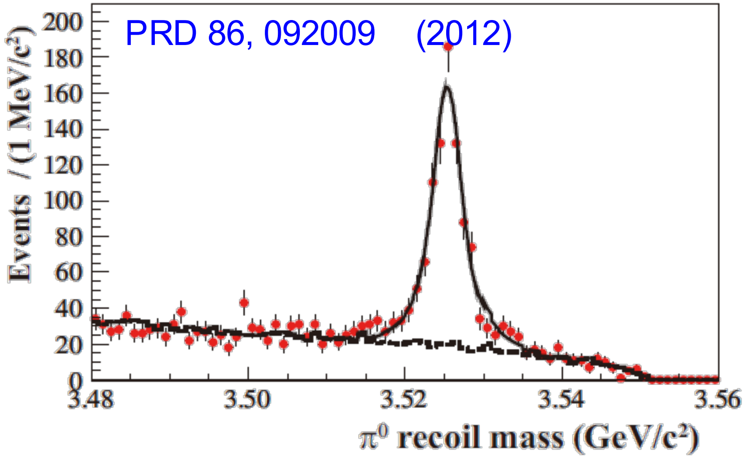


PRL 101, 182003 (2008)

The CLEO experiment was able to find it with a significance of 13 σ in ψ' decay by means of an exclusive analysis.

The width and the BF $\psi' \rightarrow \pi^0 h_c$ were not measured.

A similar analysis, with higher statistic, was also done by BES. Here 16 final states of η_C were studied



PRD 86, 092009 (2012)

h_c

$M(h_c) = 3525.31\pm0.11\pm0.14$ MeV/c^2

$(h_c) = 0.70\pm0.28\pm0.22$ MeV

$$\Delta M_{hf}(1P) \equiv M(^3P) - M(^1P) = -0.01 \pm 0.11(stat) \pm 0.15(sys) MeV/c^2$$

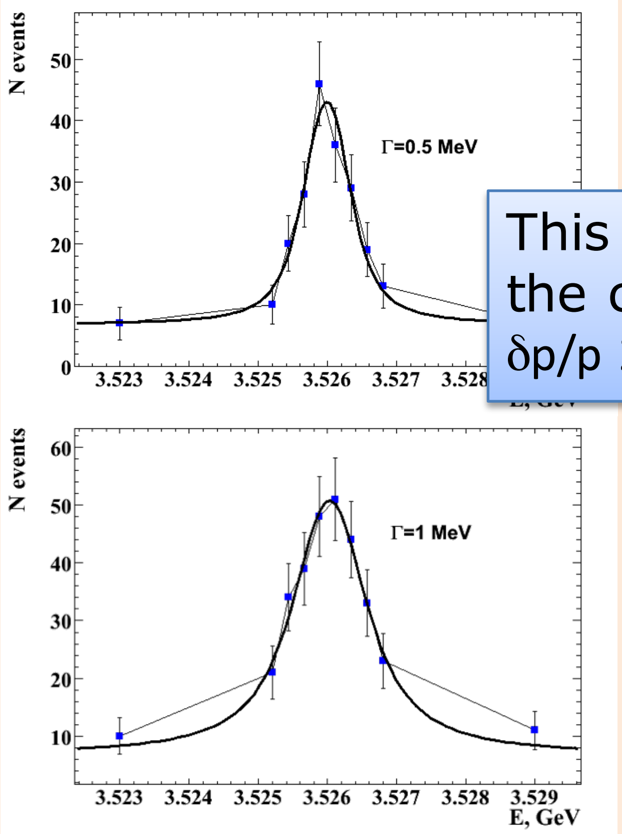
Center of gravity of P-states

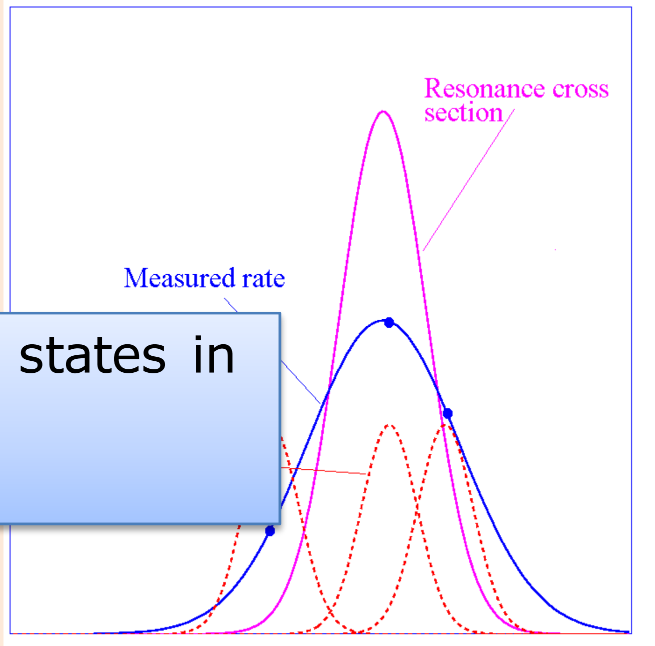
$h_c(^1P_1)$ @ $\bar{\text{p}}$anda

Thanks to the precise HESR momentum definition, widths of known states can be precisely measured with an energy scan.

Energy scan of 10 values around the h_c mass; each point represents a 5 day data taking in high luminosity mode, for the channel: $h_c \rightarrow \eta_c\gamma \rightarrow \phi\phi\gamma \rightarrow 4KK\gamma$ with a S/B 8:1.

Cross section $\sigma_{\bar{p}p\rightarrow h_c\rightarrow\eta_c+\gamma} = 40nb$





This holds for all known states in the charmonium region

$\delta p/p$ $2\times10^{-5} \longrightarrow$ Γ 50 KeV

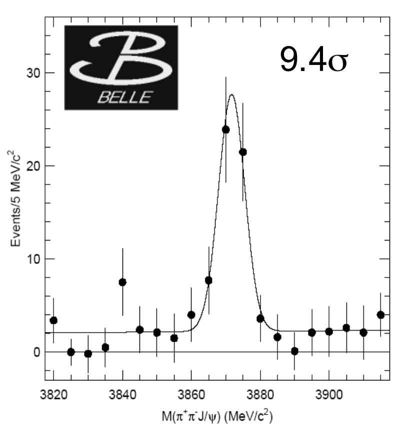
Sensitivity

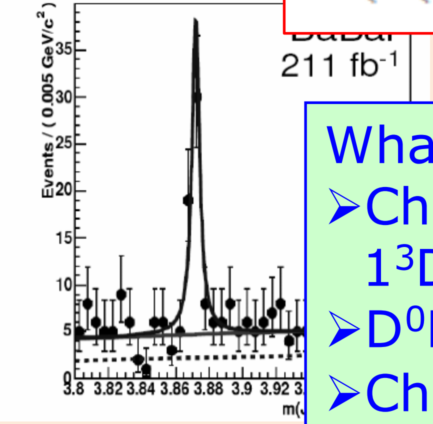
$\Gamma_{R,MC}$[MeV]	$\Gamma_{R,reco}$[MeV]	$\Delta\Gamma_R$[MeV]
1	0.92	0.24
0.75	0.72	0.18
0.5	0.52	0.14

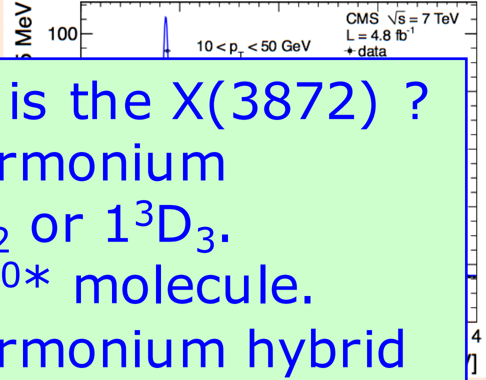
X(3872)

Discovered in 2003 by Belle (+ CDF, D0, BaBar, LHC …) in $B^+ \rightarrow X\ K^+$ $X \rightarrow J/\psi\pi^+\pi^-$ is the big brother of the new "charmonium like" states. The mass is currently known with < 1.0 MeV/c^2 precision. For the width we have only an upper limit.

$$M(X(3872)) = 3871.95 \pm 0.48(\text{stat}) \pm 0.12(\text{syst})\ \text{MeV}/c^2$$







What is the X(3872) ?

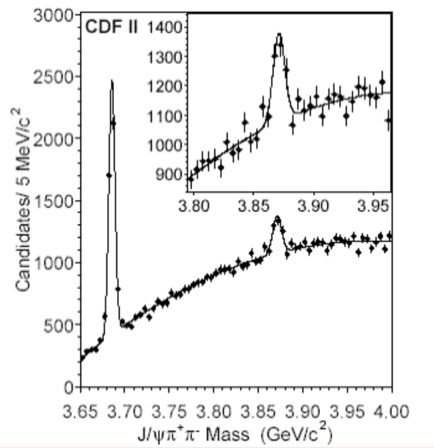
- Charmonium 1^3D_2 or 1^3D_3.
- D^0D^{0*} molecule.
- Charmonium hybrid ($c\bar{c}g$).

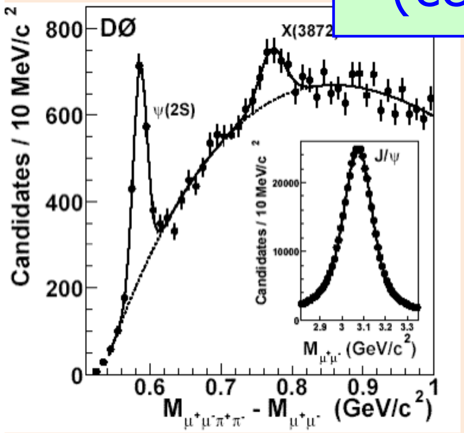
X(3872) has been observed in several decay channels

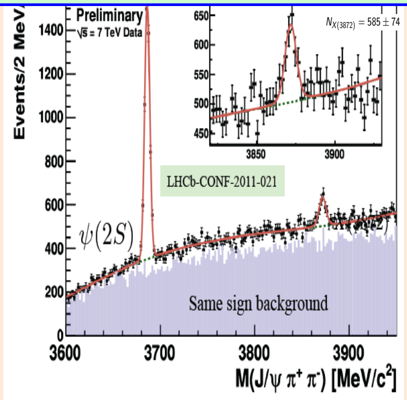
$J/\psi\pi^+\pi^-$, D^*D^0, $\gamma J/\psi$, $\omega J/\psi$

Interpretations oscillate:

- charmonium state;
- D^*D^0 molecule;
- tetra-quark state.







The mass of X(3872) is 0.42 MeV below $D^{*0}\bar{D}^0$ threshold. Γ is < 1.2 MeV/c^2 @ 90% C.L.

X(3872) @ p̄anda

Thanks to the precise HESR momentum definition, widths of known states can be precisely measured with an energy scan.

Martin Galuska
(Giessen)

Input parameters:

$m = 3.872$ GeV/c^2

$\Gamma = 1$ MeV/c^2

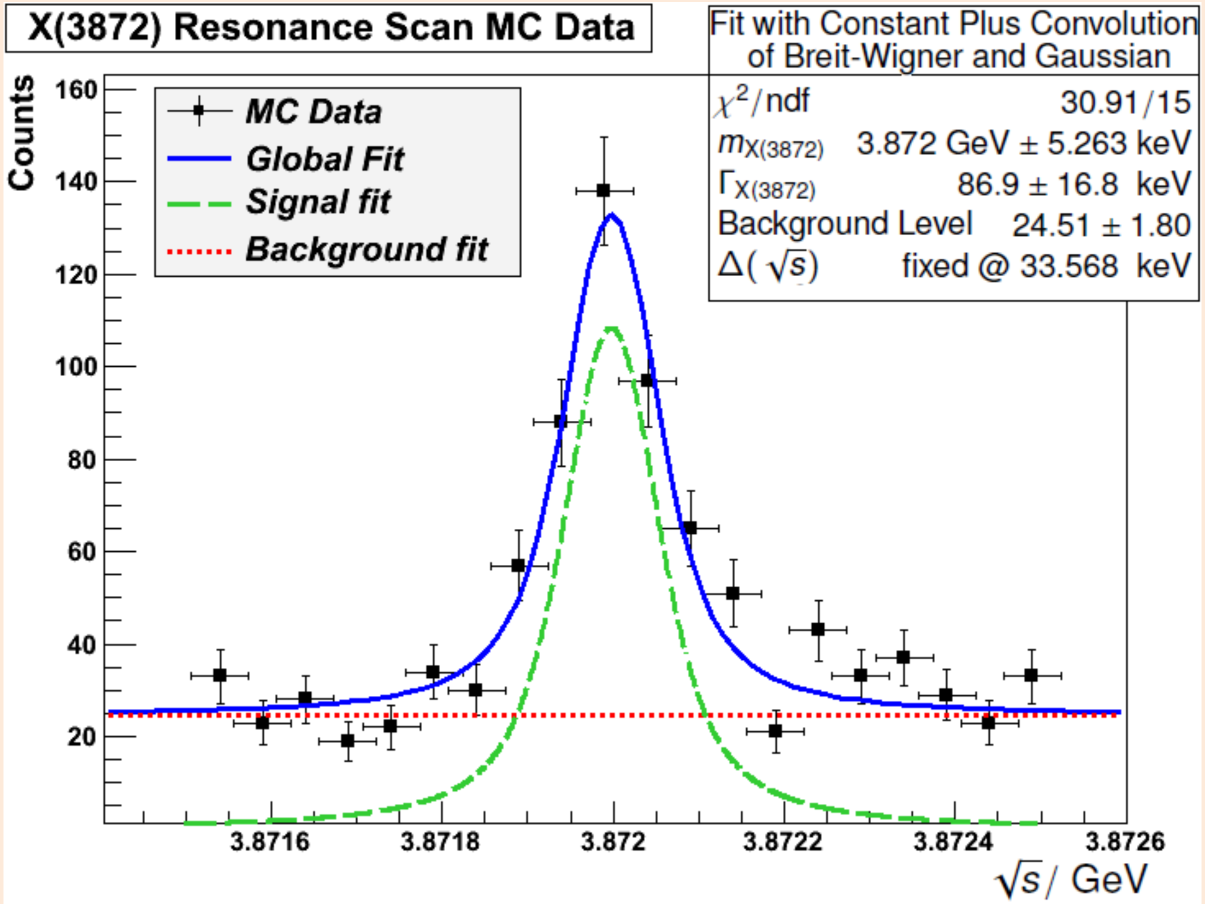
$\bar{p}p \rightarrow X(3872)$ (σ_{BW}= 50 nb)

$\bar{p}p \rightarrow J/\psi\, \pi^+\pi^-$ (σ= 1.2 nb)

Background from $\pi^+\pi^-\pi^+\pi^-$ reduction factor >10^6achieved by PID

Mass resolution~ 5 keV/c^2

Width precision~ 10-20%

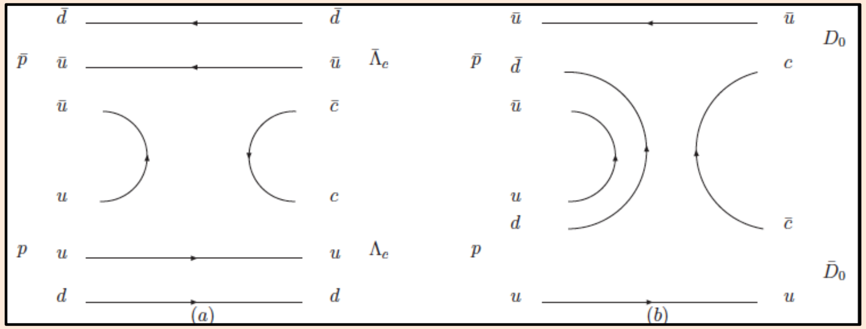


Production rate will be higher than any present or future experiment: 350 X(3872)/day

OpenCharm states

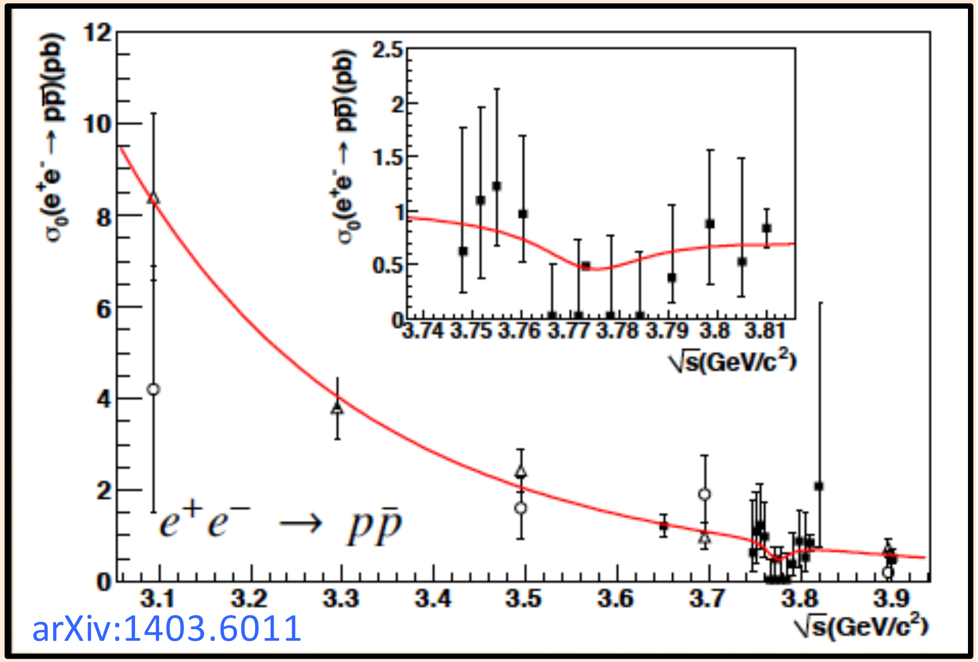
The study of charmed hadrons give access to interesting aspects of strong and weak interactions. Predicted cross sections vary from nano to micro barns

Interesting physics in production mechanisms.



Two solutions for the cross section σ(p$\bar{p}$)→ψ(3770) are obtained by BESIII:

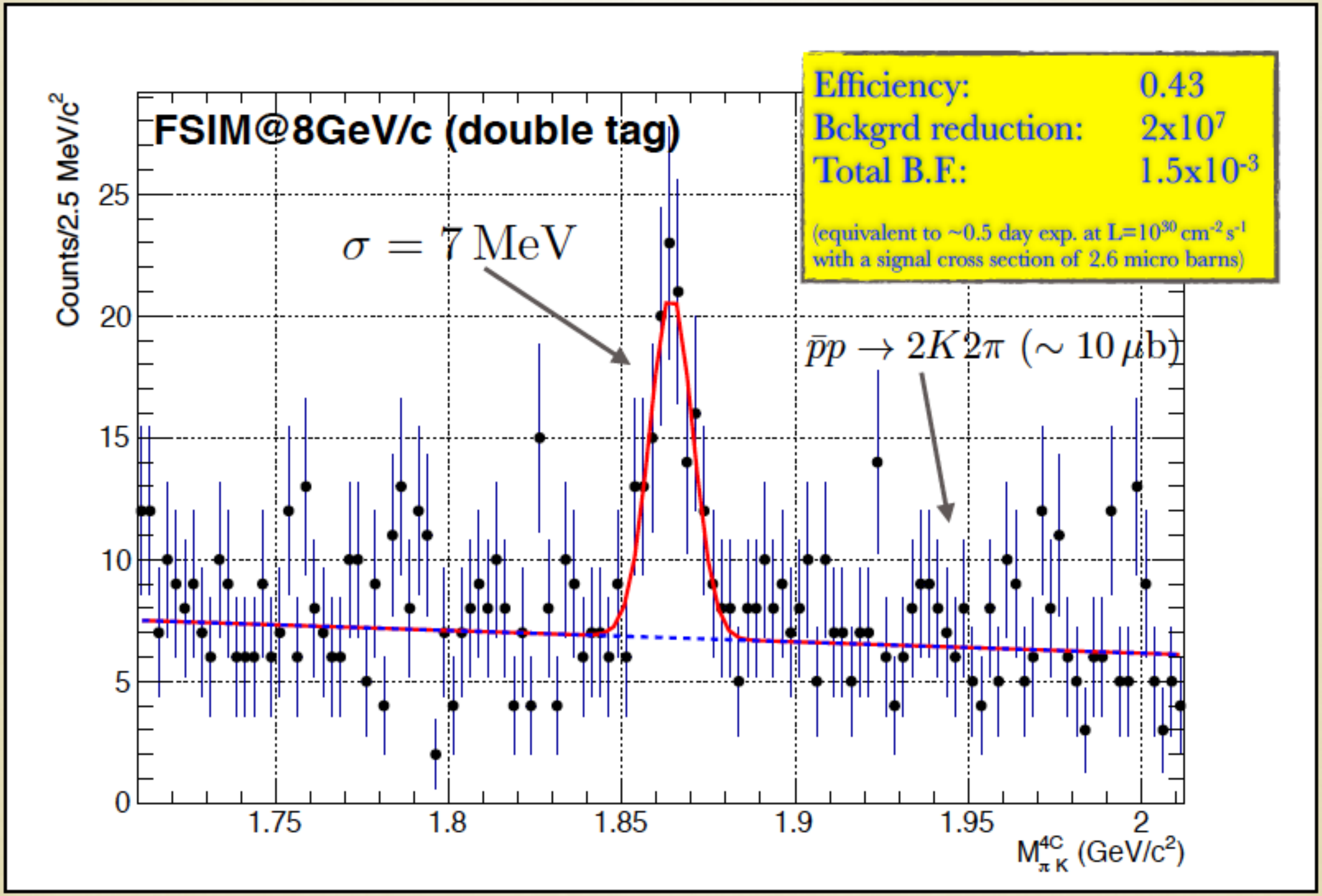
- (9.8+11.8−3.9) nb, is compatible with a simple scaling from J/ψ
- (425.6+42.9−43.7) nb, is two order of magnitudes larger.



arXiv:1403.6011

Exclusive: $p\bar{p} \to D^0\bar{D}^0 \to (K^-\pi^+)(K^+\pi^-)$

Alexandros Apostolou, J.M. (KVI-CART)



$\sigma = 7\,\mathrm{MeV}$

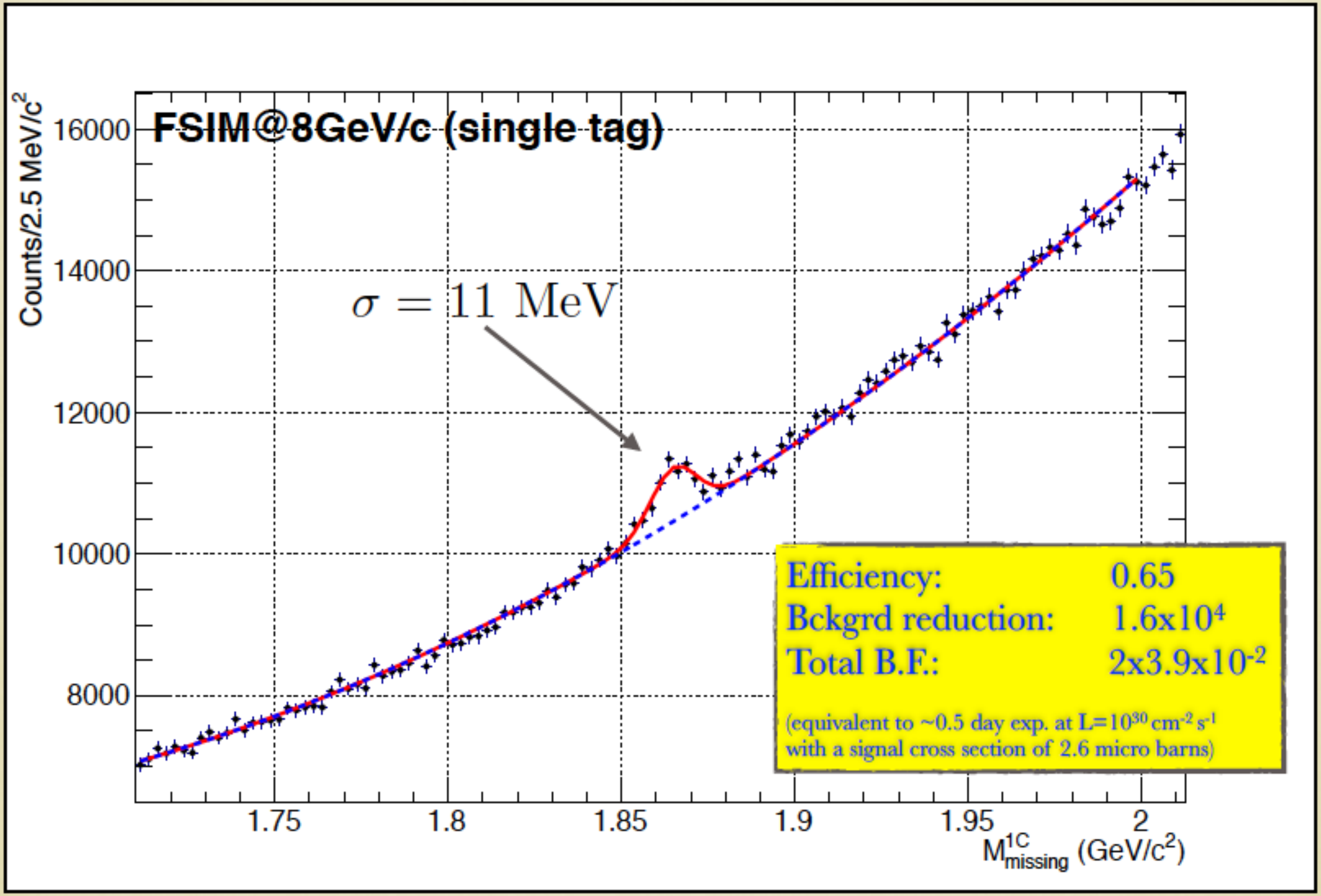
$\bar{p}p \to 2K2\pi$ ($\sim 10\,\mu$b)

Efficiency:	0.43
Bckgrd reduction:	2x10^7
Total B.F.:	1.5x10^{-3}

(equivalent to ~0.5 day exp. at L=10^{30} cm^{-2} s^{-1} with a signal cross section of 2.6 micro barns)

Only cuts on kinematics: 4C kin.fit, mass window on opposite Kpi pair

Inclusive: $p\bar{p} \rightarrow D^0\bar{D}^0 \rightarrow (K\pi) + X$ *Alexandros Apostolou, J.M. (KVI-CART)*



Efficiency:	0.65
Bckgrd reduction:	1.6×10^4
Total B.F.:	$2 \times 3.9 \times 10^{-2}$

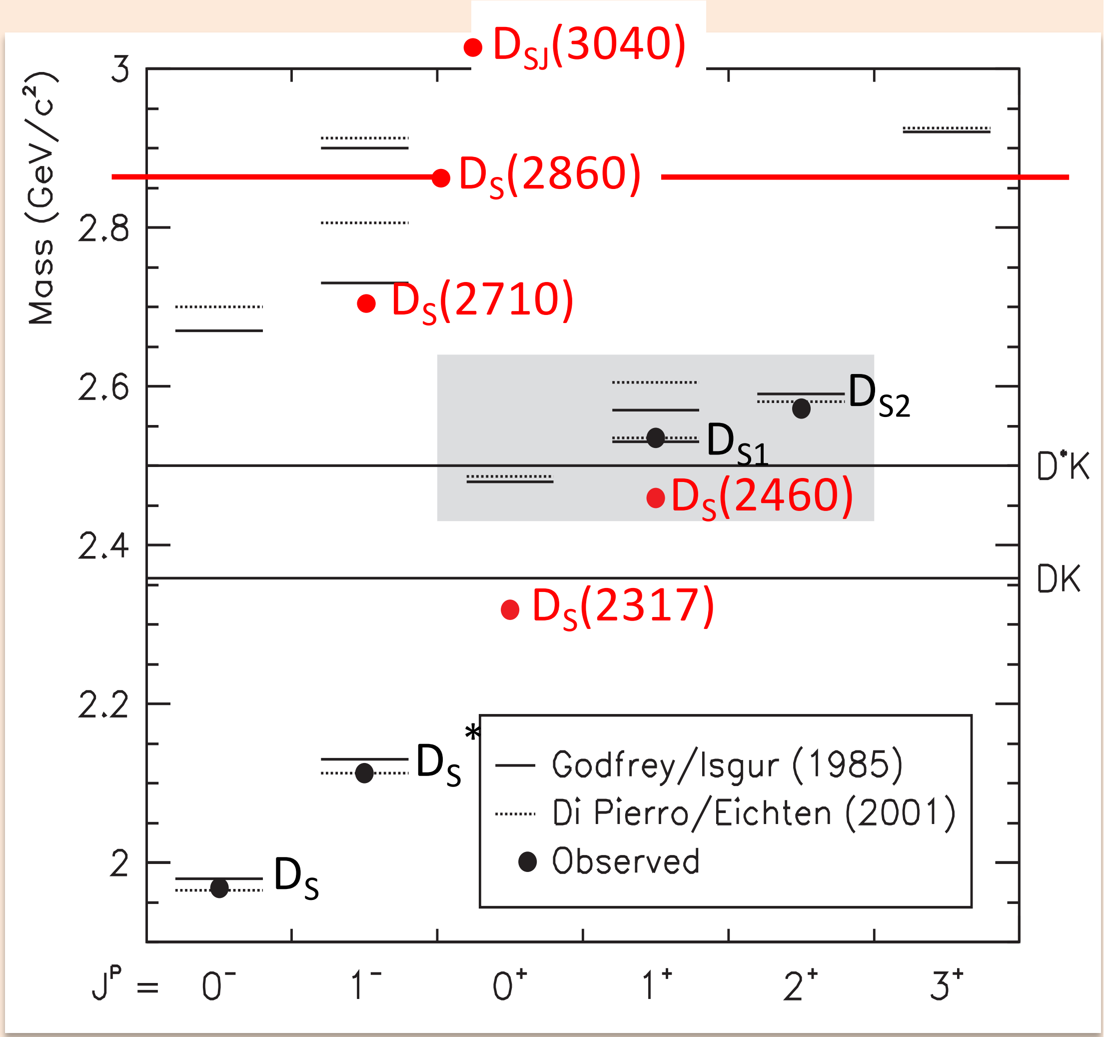
(equivalent to ~0.5 day exp. at $L=10^{30}$ cm^{-2} s^{-1} with a signal cross section of 2.6 micro barns)

Only cuts on kinematics: 1C kin.fit, mass window on tagged Kpi pair

D_S states

For the c($\bar{u}$/$\bar{d}$)states, theory and experiment were in agreement, but the discovery of new D_{SJ} states has brought into question theoretical models.

The quantum numbers of D_{s0}(2317) and D_{s1}(2460) are not yet really established, and in order to answer important questions related to their interpretation, we need to measure their widths.



B. Aubert et al., PRD74, 032007 (2006).

opportunity *D_s* meson spectroscopy

D$_{s0}$*(2317) world average (PDG)

- *Mass: 2317.8 **±0.6** MeV/c^2*
- *Width: **< 3.8** MeV/c^2*

D$_{s0}$*(2317) Energy Scan

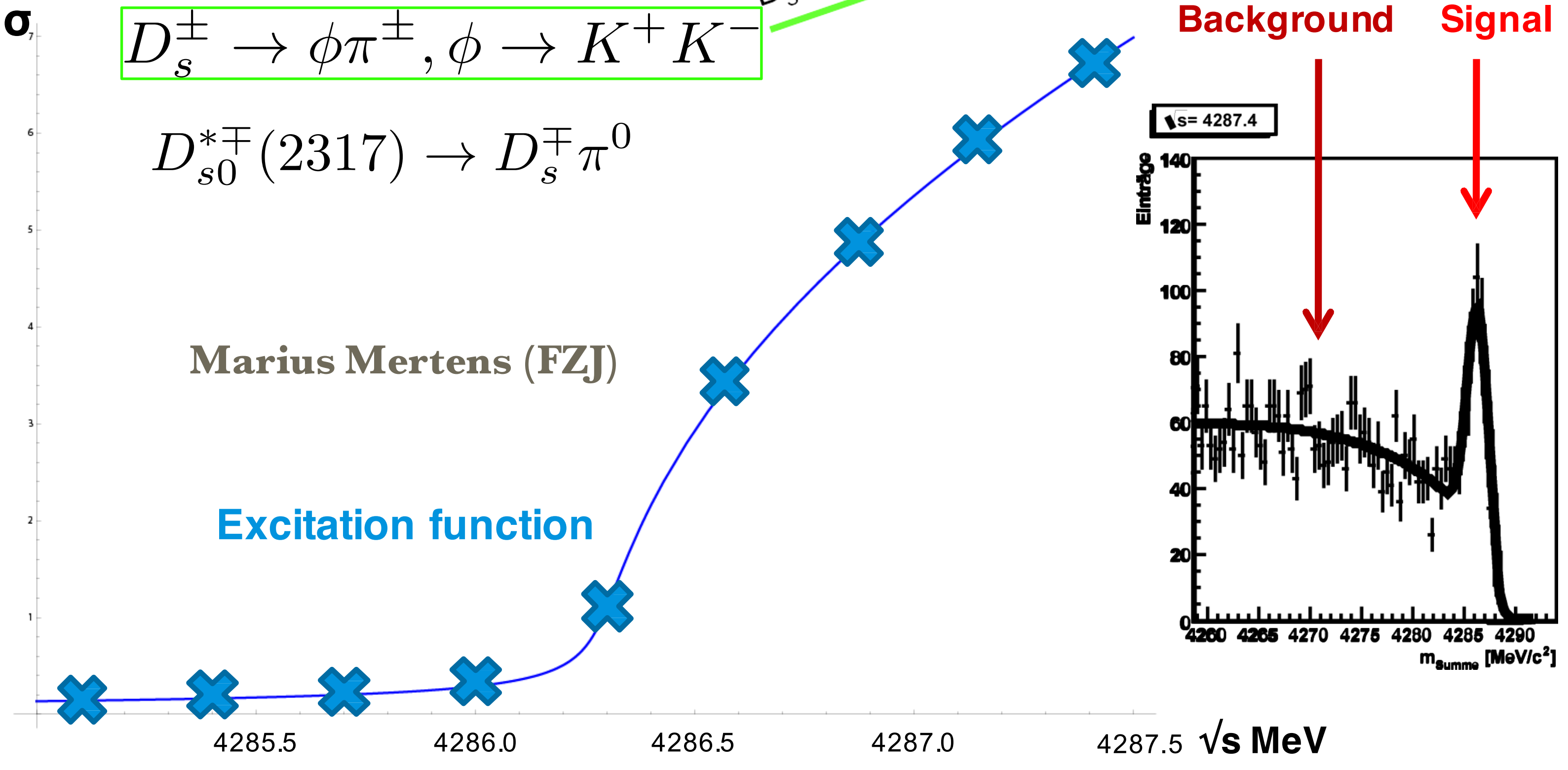
$$\bar{p}p \rightarrow D_s^{\pm} D_{s0}^{*\mp}(2317)$$

$$\boxed{D_s^{\pm} \rightarrow \phi\pi^{\pm}, \phi \rightarrow K^+K^-}$$

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

Inclusive reconstruction
D$_s$ + missing mass

Simulated sum mass spectrum



Marius Mertens (FZJ)

Excitation function

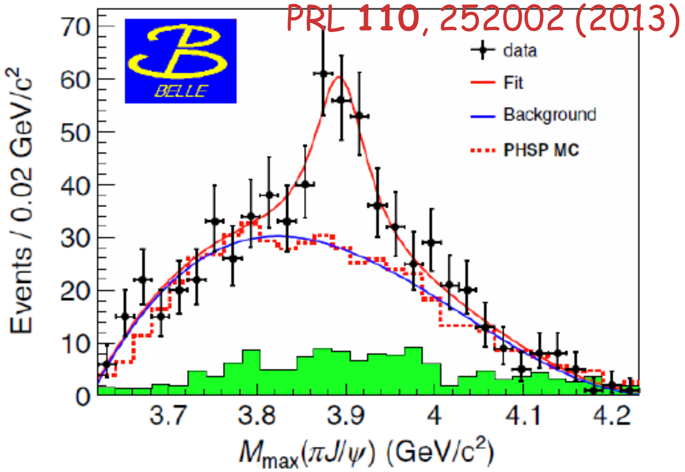
Multi-quark states

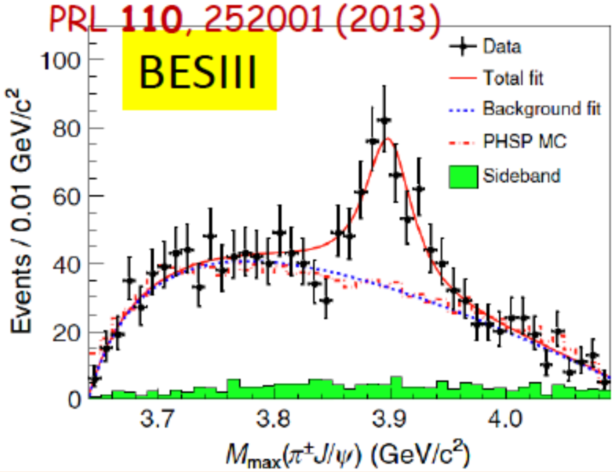
The first has been the $Z^+(4430)$ observed in the invariant mass $\Psi'\pi^\pm$ by Belle, followed by other states in the bottomomium energy range.

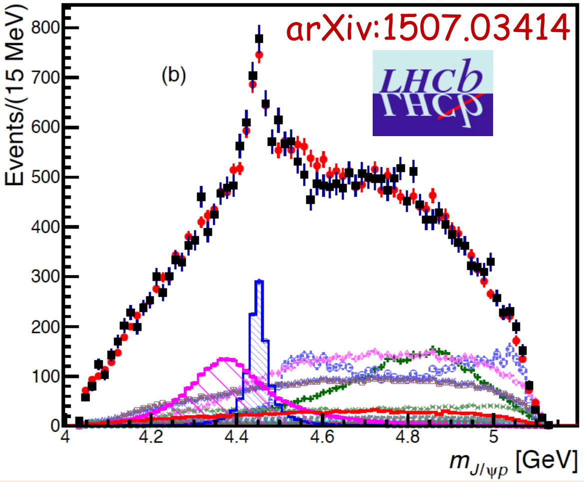
Recently, BESIII collaboration discovered an other charged charmonium-like axial meson $Z^+_c \rightarrow J/\Psi\pi^\pm$ ($M = 3899\pm6$ MeV, $\Gamma = 46\pm22$ MeV), confirmed by Belle and CLEO. The simplest quantum numbers $J^P = 1^+$, with positive G-parity.

More Recently LHCb has observed 2 five-quarks state in the $J/\Psi p$ invariant mass. Quantum numbers are still open.

particle	decay	collaboration
$Z^+(4430)$	$\psi(2S)\,\pi^+$	Belle, LHCb
$Z^+(4050)$ $Z^+(4250)$	$\chi_{c1}\ \pi^+$	Belle, unconfirmed
$Z_c^+(3900)$	$J/\psi\ \pi^+$	BESIII, Belle, CLEOc
$Z_c^+(4020)$	$h_c(1P)\,\pi^+$	BESIII preliminary
$Z_c^+(4025)$	$(D^*\ D^*)^+$	BES III preliminary
$P_C^+(4450)$ $P_C^+(4380)$	$J/\psi\ p$	LHCb


PRL 110, 252002 (2013)


PRL 110, 252001 (2013)


arXiv:1507.03414

$Z^{\pm}$ states @ $\bar{\text{p}}$anda

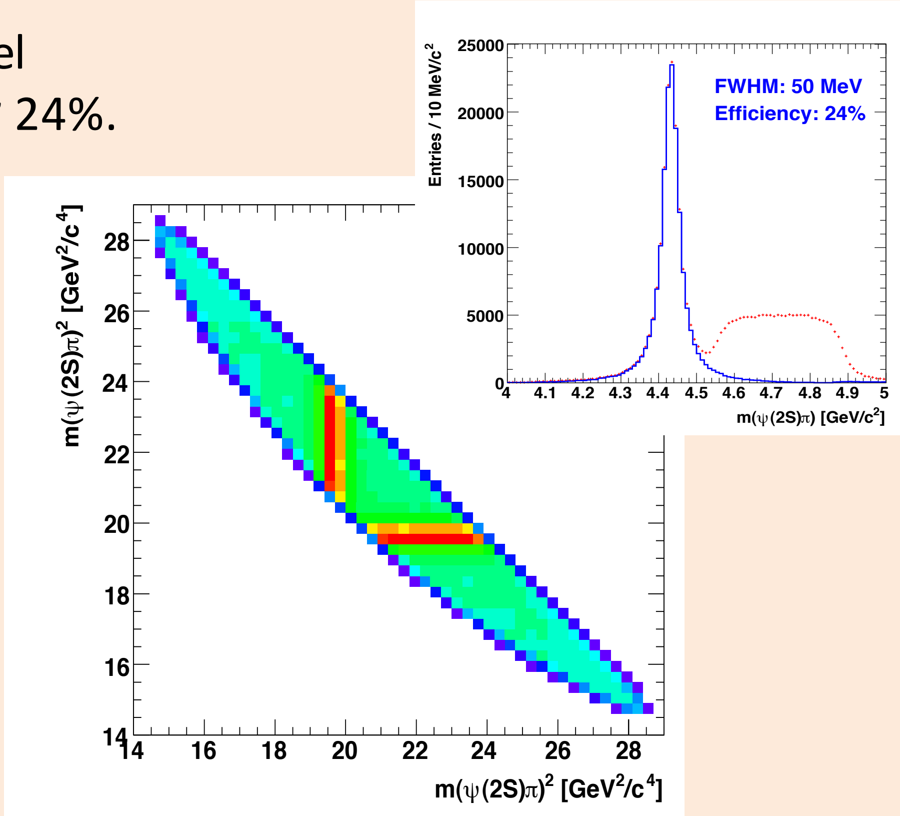
P̄ANDA can study the $Z^{\pm}$ states in both production and formation experiments.

In the production experiment, the $Z^{\pm}$ would be produced, e.g., in the reaction

$$\bar{p}p \rightarrow Z^{\pm}\pi^{\mp}$$

The subsequent decay chain could then be: $Z^{+}(4430) \rightarrow \psi(2S)\pi^{+} \rightarrow J/\psi\pi^{+}\pi^{-}\pi^{+} \rightarrow e^{+}e^{-}\pi^{+}\pi^{-}\pi^{+}$

The reconstruction efficiency for the $Z^{+}(4430)$ channel has been studied in Monte Carlo calculations and is ~ 24%.



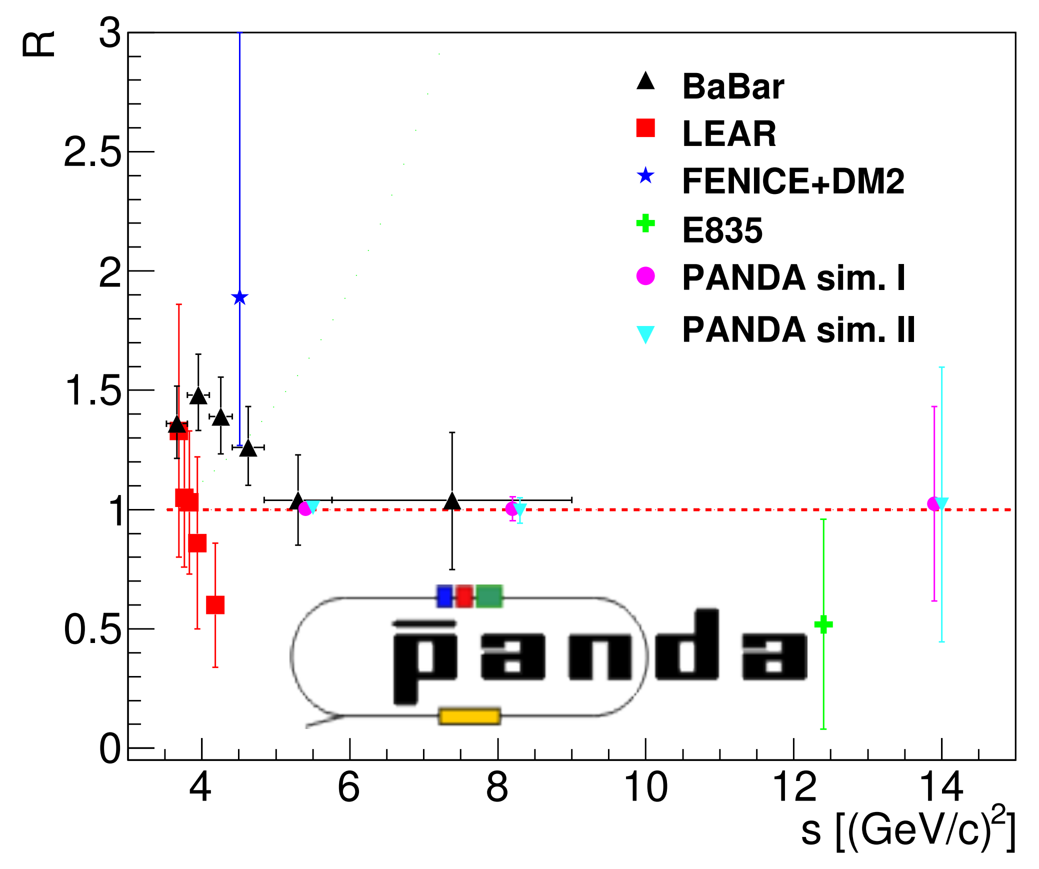
In formation mode $Z^{\pm}$ states can be produced by using a deuterium target:

$$\bar{p}d \rightarrow Z^{-}p_{spectator}$$

The reconstruction efficiency for this channel studied in Monte Carlo reactions is ~ 35%.

Proton Electromagnetic Form Factors in the Timelike Region

$\overline{p}p \rightarrow e^+e^-$ $\overline{p}p \rightarrow \mu^+\mu^-$



Measurement of effective form factor over wide q^2 range (30 GeV^2)

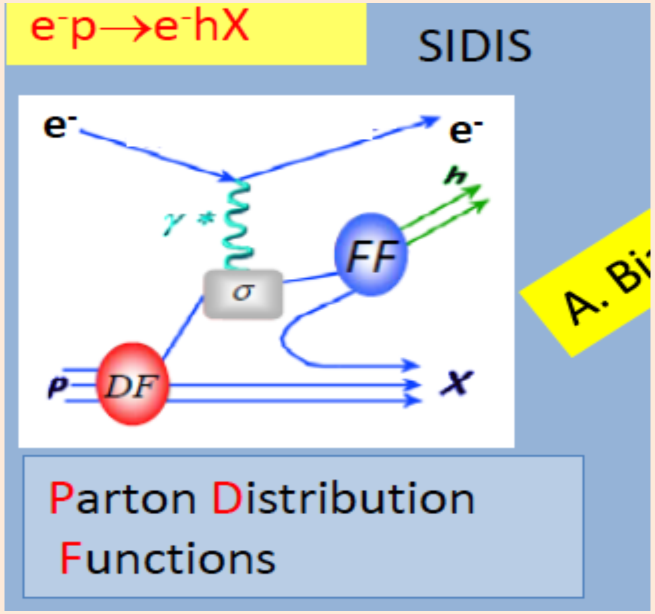
Individual measurement of $|G_E|$ and $|G_M|$ and their ratio R

First measurement of form factors with muons.

Measurement of form factors in unphysical region

Longer range goal: measurement of phase of $|G_E|$ and $|G_M|$ via polarisation observables.

Drell-Yan Processes


$e^-p\rightarrow e^-hX$

SIDIS

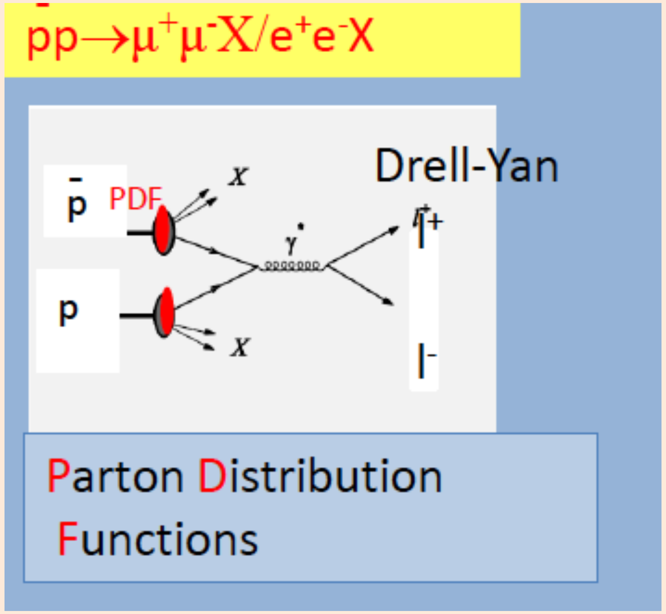
Parton Distribution Functions

PDFs are convoluted with
the fragmentation functions

@ FAIR unique energy range
up to s~30 GeV^2 with PANDA
up to s~200 GeV^2 with PAX

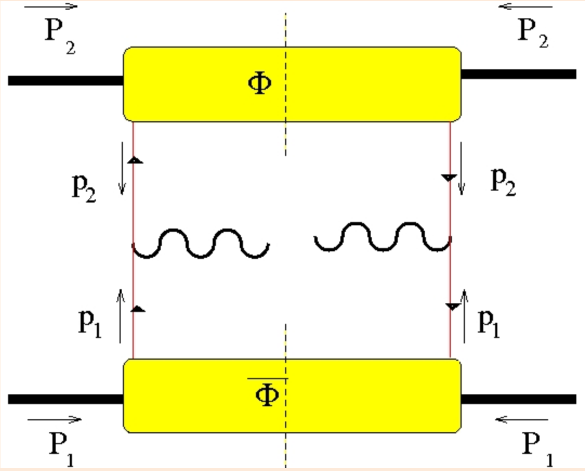
@ much higher energies
→ big contribution from sea-quarks

@ppbar annihilation each valence quark
contribute to the diagram


$p\bar{p}\rightarrow\mu^+\mu^-X/e^+e^-X$

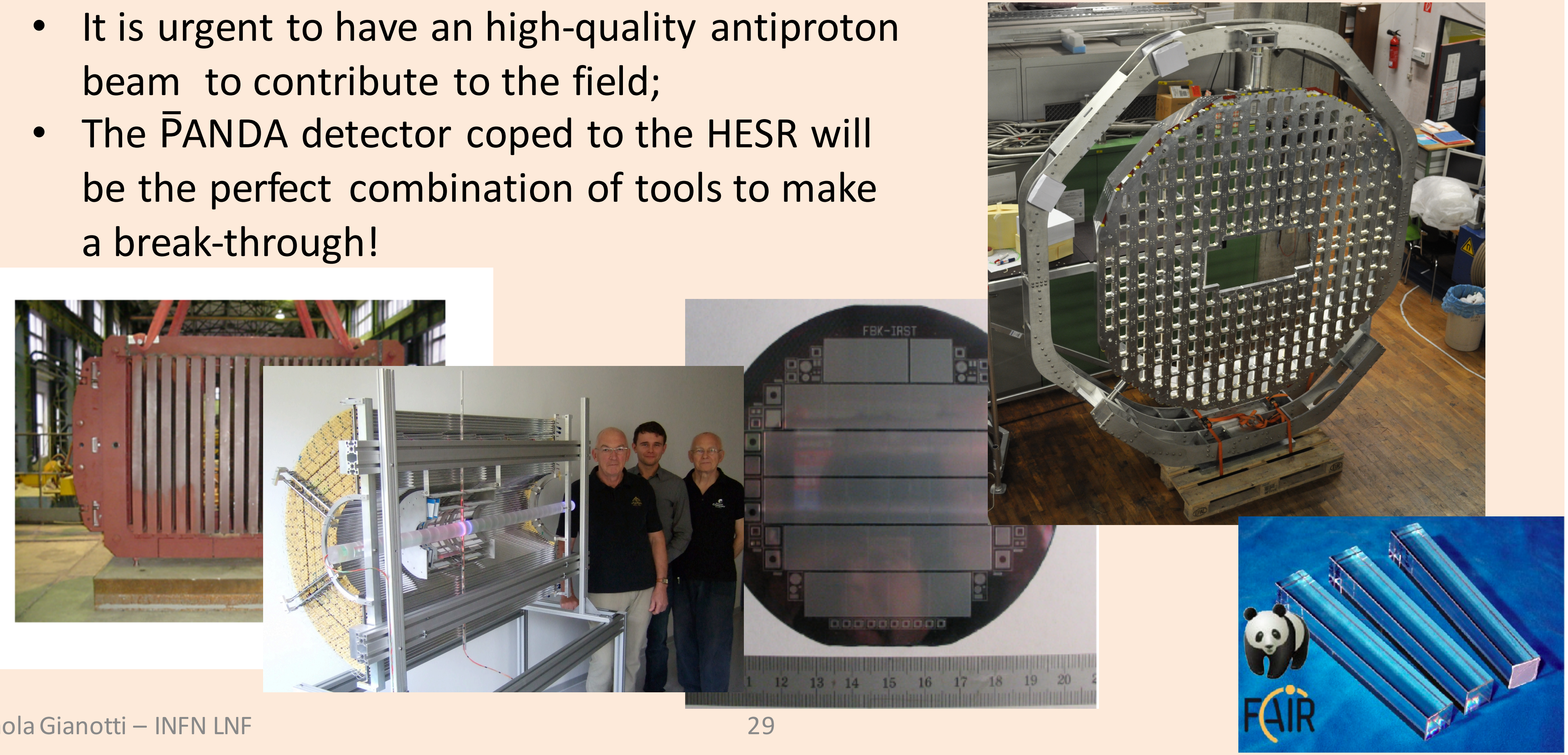
Parton Distribution Functions

Handbag diagram: $s>>M_h^2$



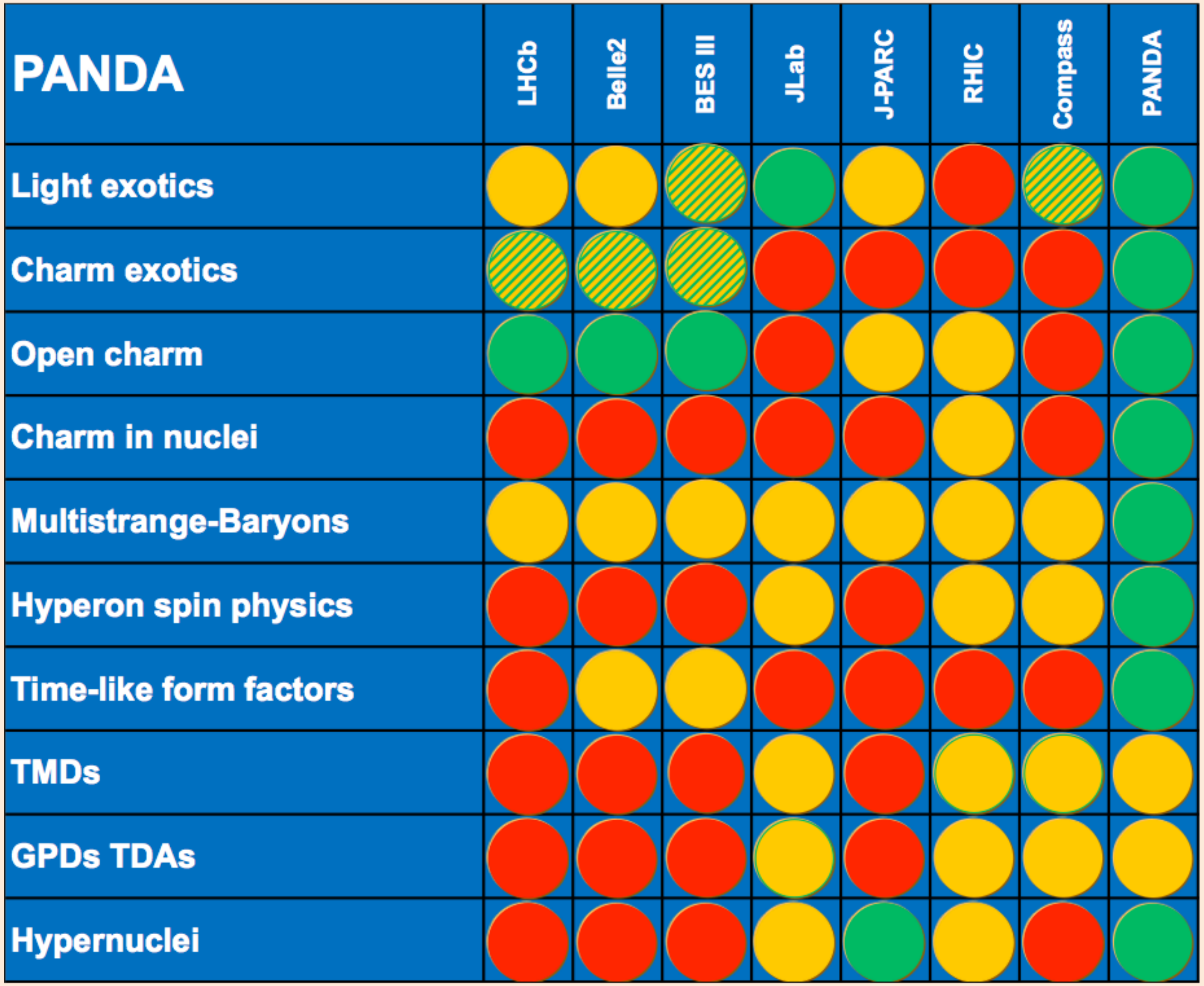
Conclusions

- Hadron spectroscopy is experiencing a new renascence;
- New high quality measurements are coming from e^+-e^- colliders and LHC experiments reveling unexpected properties of hadrons;
- All over the world there is lack of antiproton beams that have been shown in the past unique capabilities in the field;
- It is urgent to have an high-quality antiproton beam to contribute to the field;
- The P̄ANDA detector coped to the HESR will be the perfect combination of tools to make a break-through!



$\bar{\text{P}}$ANDA Physics Competitiveness

🟢 **excellent** 🟡 **limited (e.g. accept., resol., quantum numbers, …)** 🔴 **impossible**

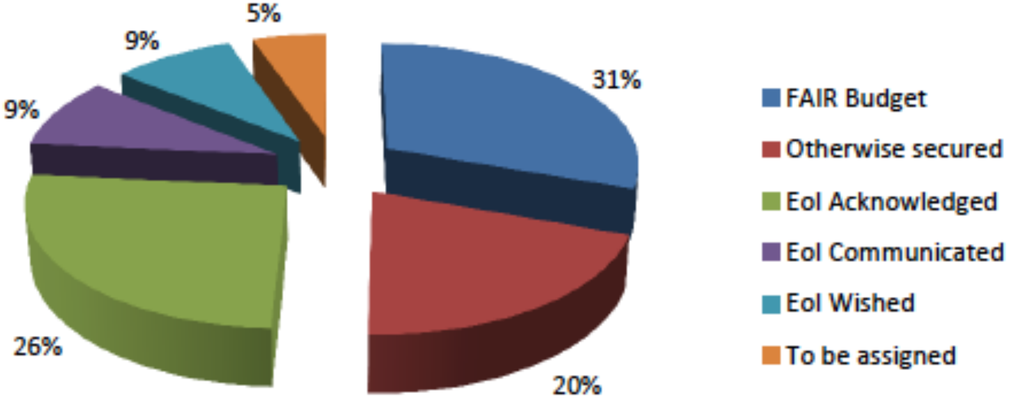


PANDA	LHCb	Belle2	BES III	JLab	J-PARC	RHIC	Compass	PANDA
Light exotics	🟡	🟡	▨	🟢	🟡	🔴	▨	🟢
Charm exotics	▨	▨	▨	🔴	🔴	🔴	🔴	🟢
Open charm	🟢	🟢	🟢	🔴	🟡	🟡	🔴	🟢
Charm in nuclei	🔴	🔴	🔴	🔴	🔴	🟡	🔴	🟢
Multistrange-Baryons	🟡	🟡	🟡	🟡	🟡	🟡	🟡	🟢
Hyperon spin physics	🔴	🔴	🔴	🟡	🔴	🟡	🟡	🟢
Time-like form factors	🔴	🟡	🟡	🔴	🔴	🔴	🔴	🟢
TMDs	🔴	🔴	🔴	🟡	🔴	🟡	🟡	🟡
GPDs TDAs	🔴	🔴	🔴	🟡	🔴	🟡	🟡	🟡
Hypernuclei	🔴	🔴	🔴	🟡	🟢	🟡	🔴	🟢

An EoI needed to accomplish a system or a part of a system without response from the funding agency is classified as **"Wished"**.

"Communicated" describes the EoIs that are made known to the FA and are within the funding frame of the FAs.

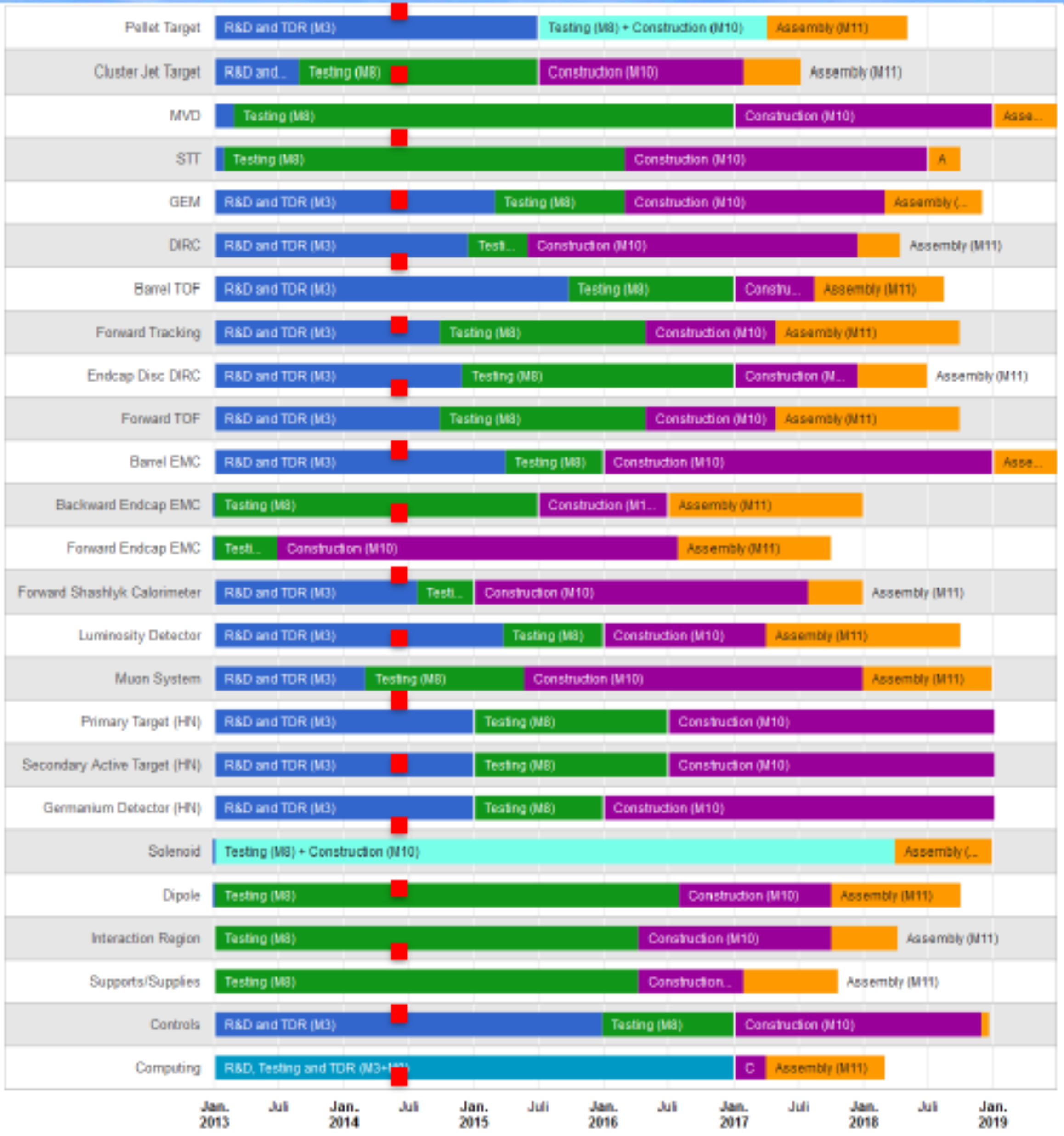
"Acknowledged" are EoIs to which the corresponding FA has responded positively prior to an official approval.



TDR status

System	Submission Expected	M3 (Approval) Expected
Target Spectrometer EMC		08/08/2008
Solenoid		05/21/2009
Dipole		05/21/2009
Micro Vertex Detector (MVD)		02/26/2013
Straw Tube Tracker (STT)		01/29/2013
Cluster Jet Target		08/28/2013
Muon System		09/22/2014
Forward Shashlyk Calorimeter	17/6/2015	*1/2016*
Luminosity Detector	*3/2016*	*9/2016*
Forward TOF	*3/2016*	*9/2016*
Forward Tracking	*3/2016*	*9/2016*
Barrel DIRC	*6/2016*	*12/2016*
Hypernuclear Setup	*6/2016*	*12/2016*
Pellet Target	*6/2016*	*12/2016*
Planar GEM Trackers	*9/2016*	*3/2017*
Barrel Time of Flight (TOF)	*9/2016*	*3/2017*
Controls	*6/2017*	*12/2017*
DAQ	*6/2017*	*12/2017*
Endcap Disc DIRC	*6/2017*	*12/2017*
Computing	*9/2017*	*3/2018*
Silicon Lambda Disks	tba	tba
Forward RICH	tba	tba
tba: to be announced		Status 3/11/2015
For the items “Interaction Region”, “Supports” and “Supplies” no TDRs are planned, only specification documents.		

Timeline of the PANDA Systems



🟦 R&D and TDR

🟩 Testing

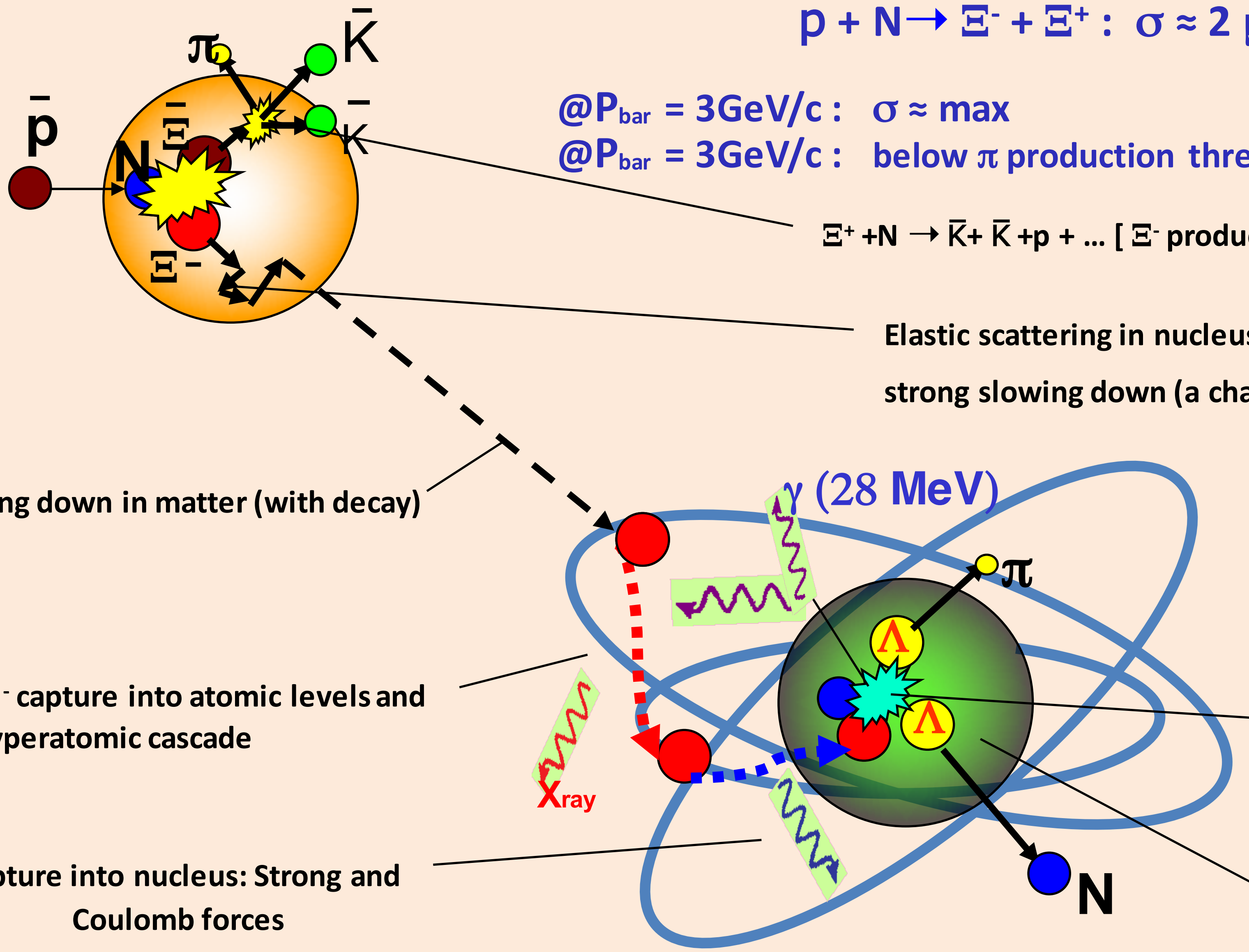
🟪 Construction

🟧 Assembly

Jim Ritman

Doubly strange systems @ $\bar{\text{p}}$anda

I Target



$\bar{p} + N \rightarrow \Xi^- + \Xi^+$: σ ≈ 2 μb;

@P_{bar} = 3GeV/c : σ ≈ max

@P_{bar} = 3GeV/c : below π production threshold

$\Xi^+ + N \rightarrow \bar{K} + \bar{K} + p + \ldots$ [Ξ^- production tag]

Elastic scattering in nucleus:

strong slowing down (a challenge)

slowing down in matter (with decay)

II Target

$^-$ capture into atomic levels and hyperatomic cascade

Capture into nucleus: Strong and Coulomb forces

$\Xi^- N \rightarrow \Lambda\Lambda$ conversion + ΛΛ sticking

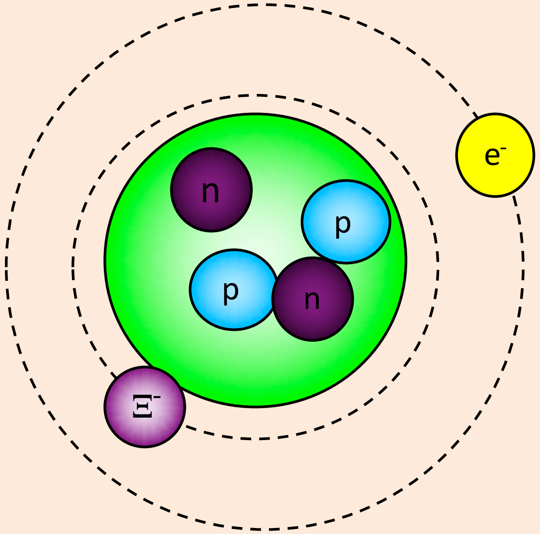
ΛΛ decay (MWD,NMWD…)

Doubly strange systems

(S=±2) hyperon –antihyperon systems are fully accessible at $\overline{\text{P}}$ANDA

Exotic hyperatom:

Ξ^- occupies an atomic level

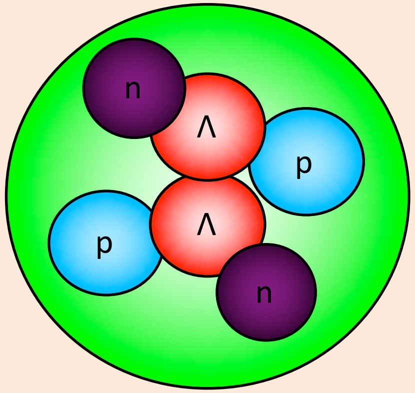


Ξ^- -nucleus interaction

- Atomic orbits overlap nucleus
- Strong interaction and Coulomb force interplay
- Lowest atomic levels are shifted and broadened
- Potential: Coulomb + optical

Double Λ Hypernucleus:

2 Λ 's replace 2 nucleons in a nucle



ΛΛ strong interaction

- only possible in double hypernuclei
- YY potential: attractive/repulsive?
- hyperfragments probability dependence on YY potential

One Boson Exchange features

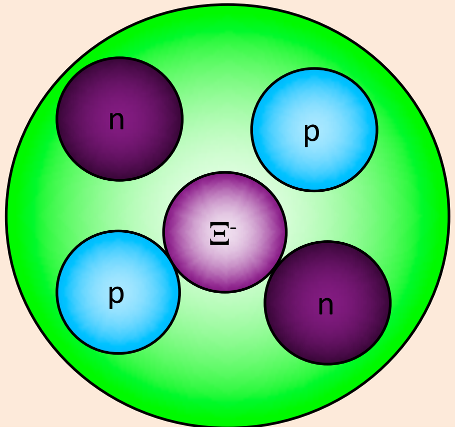
ΛΛ → ΛΛ: only *non strange, I =0 meson* exchange (ω,η…)

ΛΛ weak interaction: hyperon induced decay:

- ΛΛ →Λ n: $\Gamma_{\Lambda n}$ << Γ_{free} (expected)
- ΛΛ → Σ^-p:$\Gamma_{\Sigma p}$ << Γ_{free} (expected)

Doubly Strange Hypernucleus:

Ξ^- occupies a nuclear level



Ξ -N interaction:

- short range interaction
- long range interaction
- …..

ΛΛ Hypernuclei

Status of the art:

Nucleus	$B_{\Lambda\Lambda}({}_{\Lambda\Lambda}{}^{A}Z)$ [MeV]	$\Delta B_{\Lambda\Lambda}({}_{\Lambda\Lambda}{}^{A}Z)$ [MeV]	Reference	Reaction
${}_{\Lambda\Lambda}{}^{10}$Be	17.7± 0.4	4.3±0.4	M.Danysz et al., PRL.11(1963) 29	$K^- + A \rightarrow K^+ + \Xi^-$
${}_{\Lambda\Lambda}{}^{6}$He	10.9±0.5	4.6±0.5	D.J.Prowse, PRL.17(1966) 782	$K^- + A \rightarrow K^+ + \Xi^-$
${}_{\Lambda\Lambda}{}^{10}$Be	8.5±0.7	-4.9±0.7	KEK-E176	$K^- + p \rightarrow K^+ + \Xi^-$ (q.f)
${}_{\Lambda\Lambda}{}^{13}$B	$27.6\pm0.7^{+0.18}_{-0.11}$	$4.9\pm0.7^{+0.18}_{-0.11}$	S.Aoki et al., PTP.85(1991) 1287	$K^- + p \rightarrow K^+ + \Xi^-$ (q.f)
${}_{\Lambda\Lambda}{}^{12}$B		4.5±0.5	P.Khaustov et al., PRC.61(2000)027601	$({}^{12}C)_{atom}\Xi^- \rightarrow {}^{12}B_{\Lambda\Lambda} + n$
${}_{\Lambda\Lambda}{}^{6}$He	$7.25\pm0.19^{+0.18}_{-0.11}$	1.01±0.2	KEK-E373,NAGARA H.Takahashi et al., PRL.87(2001)212502-1	$K^- + p \rightarrow K^+ + \Xi^-$ (q.f)
${}_{\Lambda\Lambda}{}^{12}$B		$\sigma\ (\theta<8^0) \approx$ 6-10nb	K.Yamamoto et al., PLB.478(2000) 401	$K^- + {}^{12}C \rightarrow K^+ + {}^{12}B_{\Lambda\Lambda}$

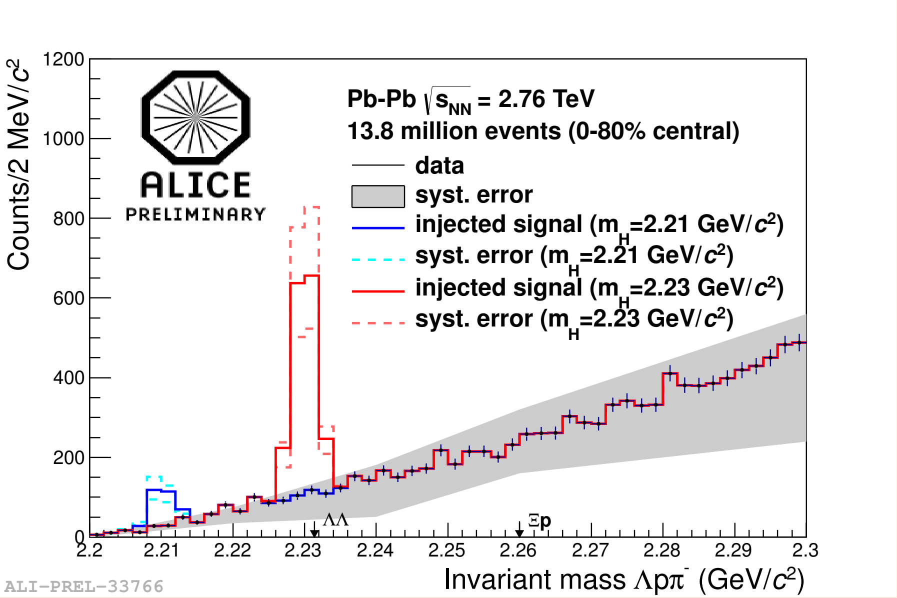
Features:

$$-V_{\Lambda\Lambda} = \Delta B_{\Lambda\Lambda}\left({}^{A}_{\Lambda\Lambda}Z\right) \equiv B_{\Lambda\Lambda}\left({}^{A}_{\Lambda\Lambda}Z\right) - 2B_{\Lambda}\left({}^{A-1}_{\Lambda}Z\right)$$

- **Binding energy →** parameters in potential models
- **Core of the ΛΛ interaction ($V_{\Lambda\Lambda}$) :** needs of several A-hypernuclei
- ΛΛ interaction: only I=0 ***non***-*strange mesons* contributes (only ω,η)
- **Weak Decay presents some peculiarities**

H-Dibarion

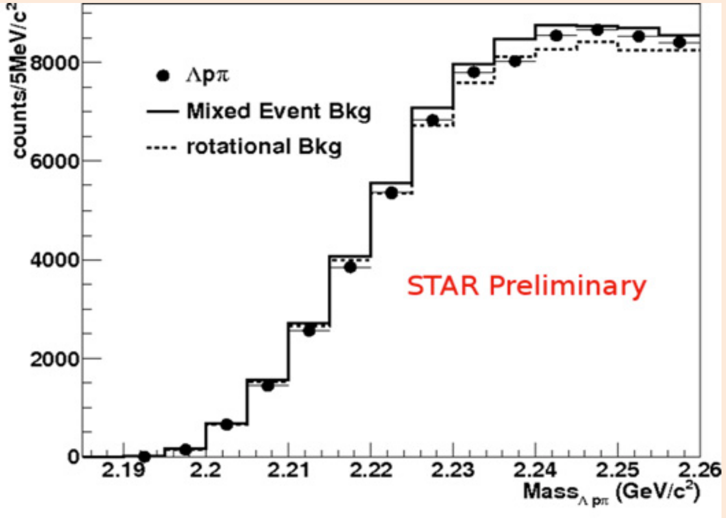
The measurement of the $_{\Lambda\Lambda}{}^{6}$He binding energy has triggered new speculations on the H-dibarion existence [PRL106 (2011)162001]. The original prediction of a 6-quark state with a binding ≃ 81 MeV has been ruled out.



Nowadays, the only possibility is for a baryon-baryon molecule.

HI collision experiments searched in the Λ p invariant mass system for a possible signal.

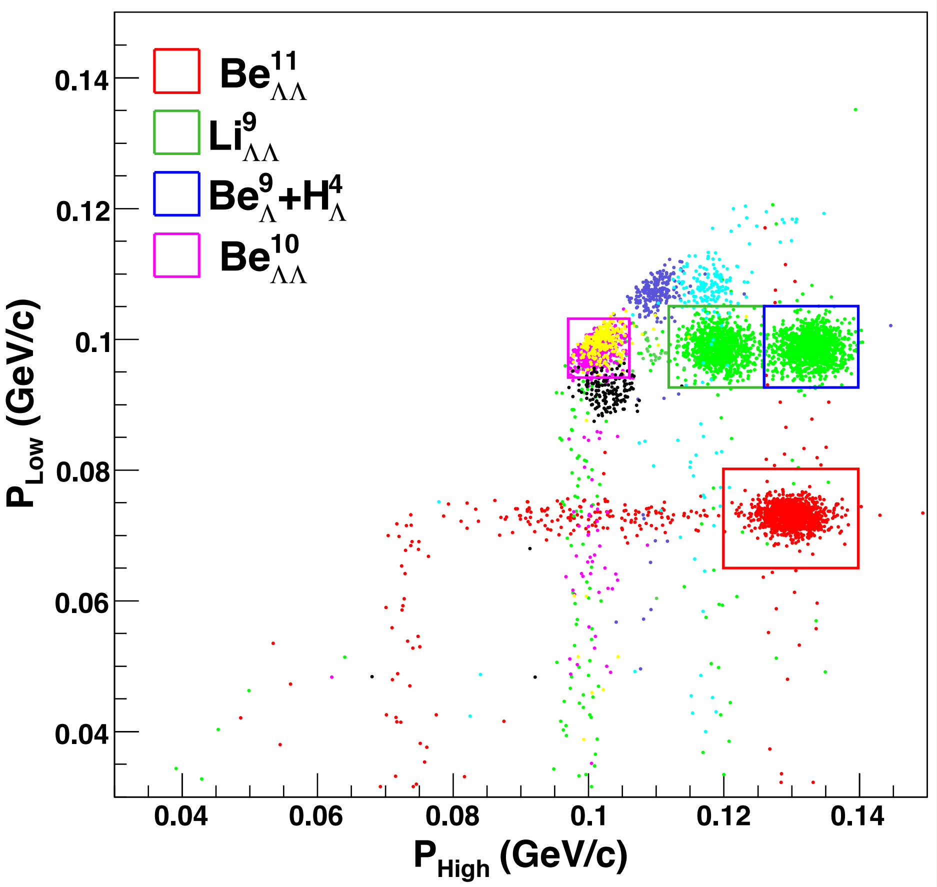
A deeper knowledge of S=−2 sector would help to extend models that have been successful in describing the S=0 and −1 sectors to account for SU(3) symmetry.

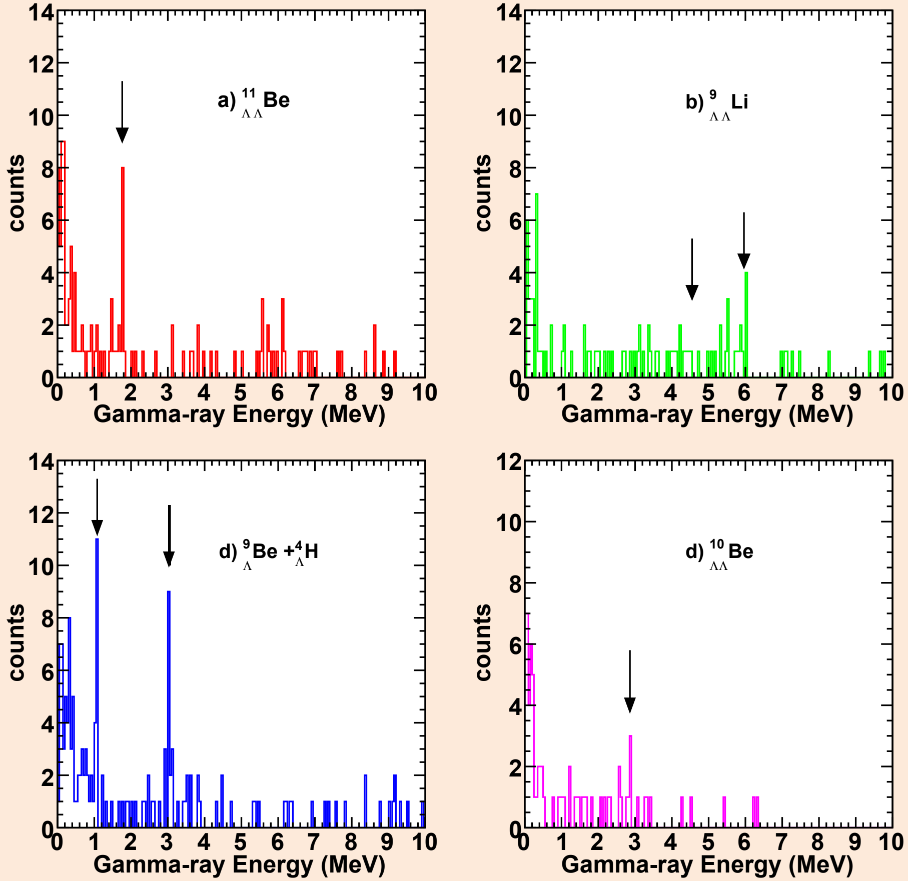


ΛΛ hypernuclei

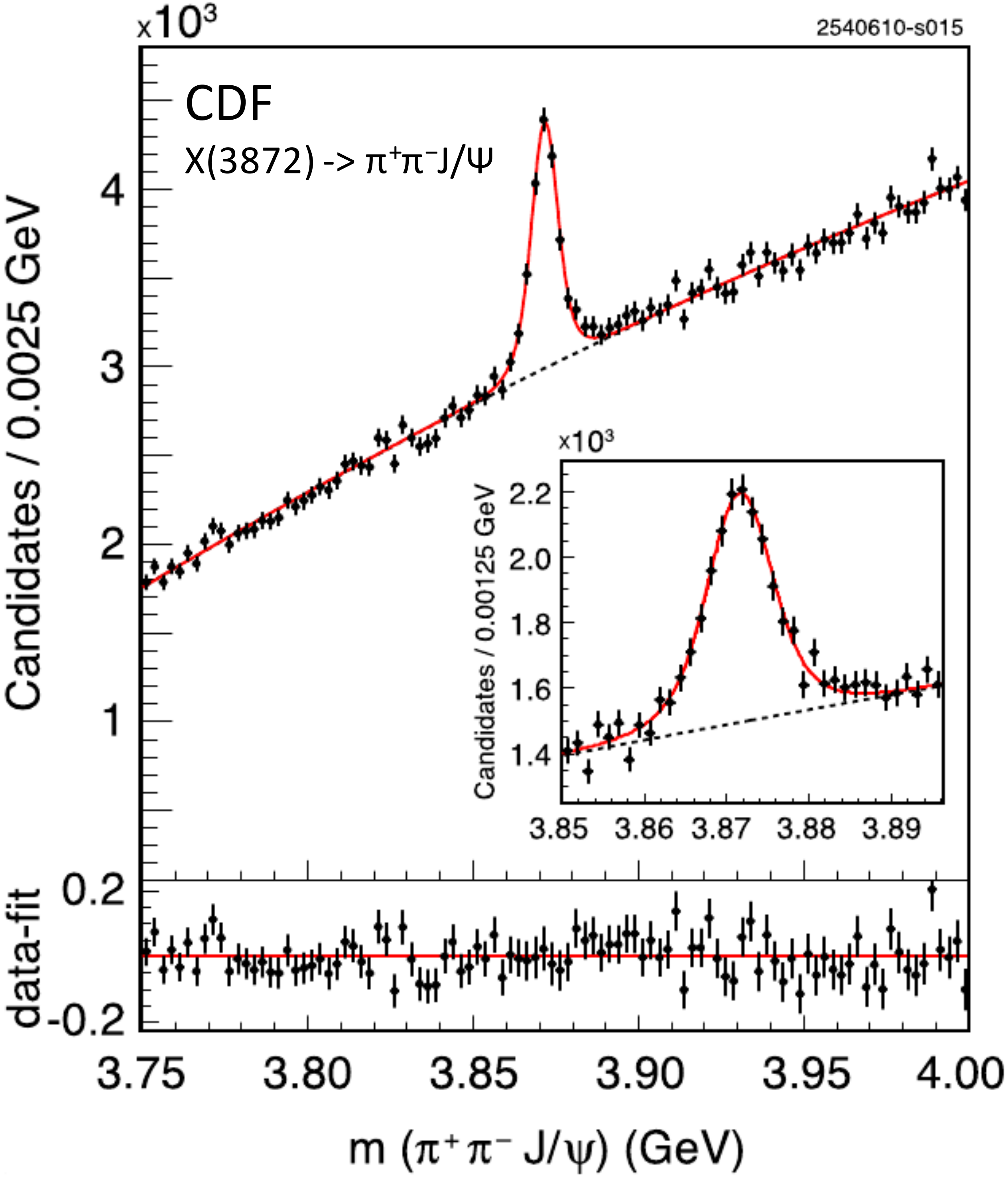
We assumed a Ξ^{-}+p → ΛΛ conversion probability of 5%.

The identication of the double hypernuclei relys on the unique assignment of the detected γ-transitions.





To determine the binding energies we will perform γ-rays spectroscopy detecting in coincidence the pions coming out from the Λ decays.


CDF
X(3872) -> π⁺π⁻J/Ψ
x10³
2540610-s015
Candidates / 0.0025 GeV
4
3
2
1
data-fit
0.2
-0.2
3.75
3.80
3.85
3.90
3.95
4.00
m (π⁺π⁻ J/ψ) (GeV)
x10³
Candidates / 0.00125 GeV
2.2
2.0
1.8
1.6
1.4
3.85
3.86
3.87
3.88
3.89