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

A. Blinov [(1)], M. Galuska [(2)], S. Lange [(2)], E. Prencipe [(3)], J. Ritman [(3)]

(1) Budker Institute and Novosibirsk State University;
(2) Justus-Liebig Univ. of Giessen;
(3) Forschungszentrum Jülich

September 9th, 2015 | Elisabetta Prencipe, Forschungszentrum Jülich | Charmonium session – C.M. 2015

Outline

- Evaluation of X, Y, Z rates in $\bar{p}p$ annihilation
- Detailed balance method
- Scaling approach
- X, Y, Z production at $\overline{P}ANDA$
- Summary

Open questions

- Lots of progress in charmonium spectroscopy in the past 12 years
- Can $\overline{\text{P}}$ANDA be competitive, in >2020, with running/future experiments, in this field?
- What can be the original contribution of $\overline{\text{P}}$ANDA in spectroscopy?
- Striking advantage of $\overline{\text{P}}$ANDA detector:
  high cross section in $\bar{p}p$ annihilation, proportional to $\alpha^2(\alpha^3)$, in 2(3) gluons
  $\rightarrow$ in e+e- machines: proportional to $\alpha_{e.m.}$ (1/137, much lower value than α_s (s))
- In $\overline{\text{P}}$ANDA c.m. energy in [1.5;5.5] GeV
- How many X, Y, Z can $\overline{\text{P}}$ANDA produce per day?
  $\rightarrow$ try to evaluate the cross section of X(3872), Y(4260), Z(3900)

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

- Detailed balance method:

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

for non polarized incident beam.

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

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

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

- Assumption: partial width of charmonium states are identical

Why?

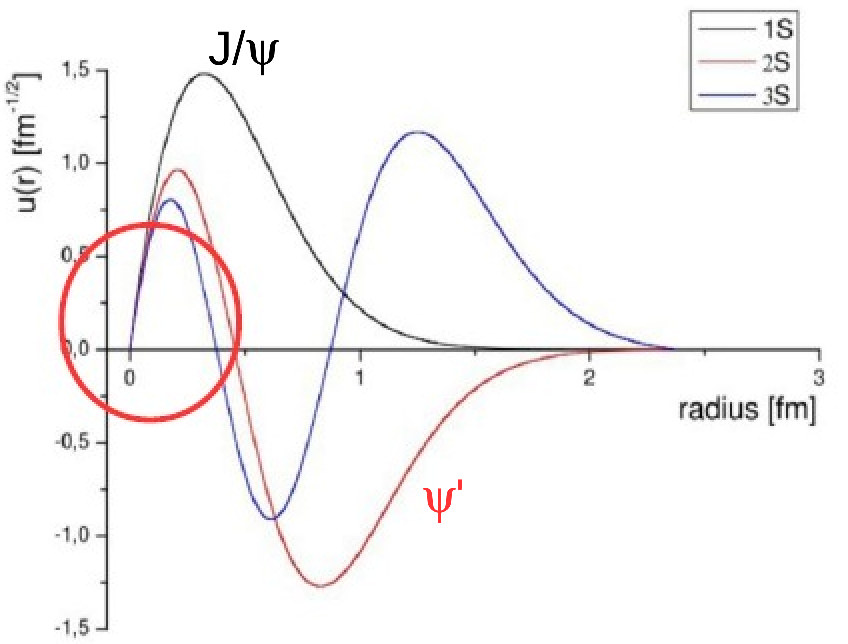
Physics reason for scaling

e.m. process:

$$\Gamma(^3S_1 \to \gamma) = \frac{65\pi}{9}\frac{\alpha_{em}}{m_c^2}|\psi(r=0)|^2$$

hadronic process:

$$\Gamma(^3S_1 \to ggg) = \frac{40}{81\pi}(\pi^2-9)\frac{\alpha_S^3}{M_0^2}|\psi(r=0)|^2$$



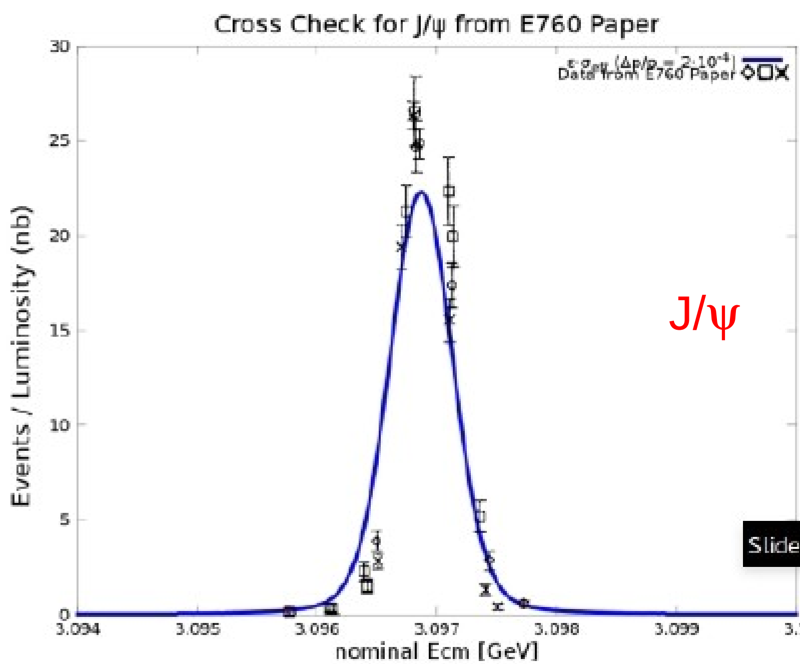
- Wave functions: solution of the Schrödinger equation for pure charmonium states
- Partial width for annihilation scales with $|\psi(r=0)|^2$

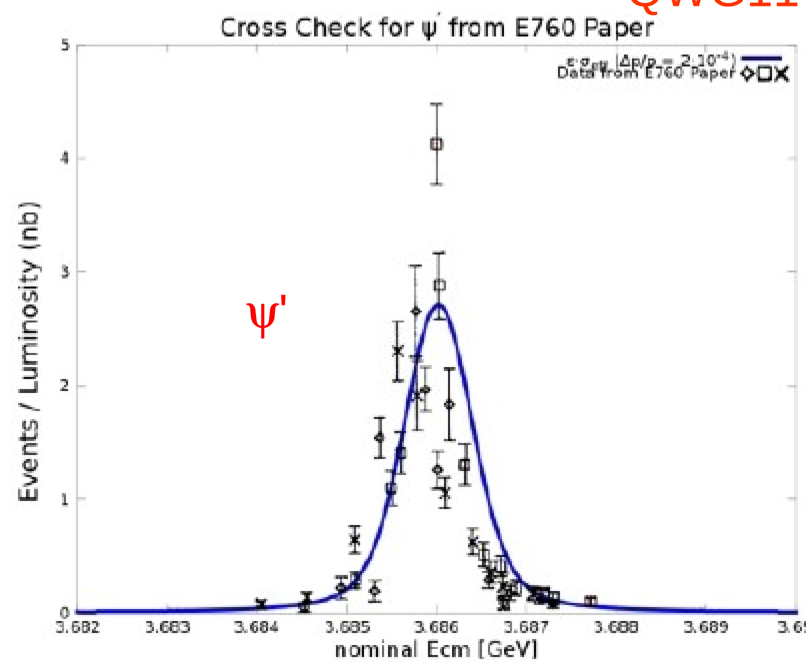
→ <u>assumption</u>: same partial width for charmonium states in our calculation

Checking detailed balance method

How do we know that the method works?

QWG11





- Detailed balance method: check on E760 data
- Formula overlapped to the data point: it looks good!

→ see also M. Galuska plenary talk, Coll. Meeting June 2013

X(3872) cross setion at $\overline{P}$ANDA

X(3872) cross section

$$\sigma[\bar{p}p \to X(3872)] \cdot BR(X(3872) \to f) =$$

$$= \frac{(2J+1)\cdot 4\pi}{s - 4m_p^2} \cdot \frac{BR(X(3872) \to \bar{p}p) \cdot BR(X(3872) \to f) \cdot \Gamma^2_{X(3872)}}{4(\sqrt{s} - m_{X(3872)})^2 + \Gamma^2_{X(3872)}}$$

$$= \frac{3 \cdot 4\pi}{m^2_{X(3872)} - 4m_p^2} \cdot BR(X(3872) \to \bar{p}p) \cdot BR(X(3872) \to f)$$

X(3872) cross section at $\overline{P}$ANDA

X(3872) cross section → Use detailed balance and PDG measured BRs

5% [PRL 112 (2014) 092001]

$$\sigma[\bar{p}p \to X(3872)] \cdot BR(X(3872) \to f) =$$

$$= \frac{(2J+1)\cdot 4\pi}{s - 4m_p^2} \cdot \frac{BR(X(3872) \to \bar{p}p) \cdot BR(X(3872) \to f) \cdot \Gamma^2_{X(3872)}}{4(\sqrt{s} - m_{X(3872)})^2 + \Gamma^2_{X(3872)}}$$

$$= \frac{3 \cdot 4\pi}{m^2_{X(3872)} - 4m_p^2} \cdot BR(X(3872) \to \bar{p}p) \cdot BR(X(3872) \to f)$$

from LHCb

arXiv:1303.7133 [hep-ex]

Eur. Phys.J. C73 (2013) 2462

An upper limit is calculated <68 nb
Reasonable value: 50 nb

Y(4260) cross section

FORSCHUNGSZENTRUM JÜLICH

- Partial width already used from other experiments

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

- arXiV 0808.1543:

  scaling of partial width of 1^{--} "charmonium" state [Y(4260)] to ψ(2S)
  first time applied by BaBar"

$$\frac{\Gamma_{ee}(Y)\mathcal{B}(Y \to \pi^+\pi^- J/\psi)}{\Gamma_{ee}(\psi(2S))\mathcal{B}(\psi(2S) \to \pi^+\pi^- J/\psi)} = \left(\frac{N(\gamma Y)}{N(\gamma\, \psi(2S))}\right) \cdot \left(\frac{m(Y)}{m(\psi(2S))}\right) \cdot \left(\frac{\varepsilon(\psi(2S))}{\varepsilon(Y)}\right) \cdot \left(\frac{W(\psi(2S))}{W(Y)}\right)$$

- In this BaBar paper: $\Gamma(Y(460))_{ee}$; in $\overline{\text{P}}$ANDA: $\Gamma(Y(4260))_{p\bar{p}}$

Y(4260) cross section

- Partial width already used from other experiments

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

- arXiV 0808.1543:

  scaling of partial width of 1^{--} "charmonium" state [Y(4260)] to ψ(2S) first time applied by BaBar"

$$\frac{\Gamma_{ee}(Y)\mathcal{B}(Y \to \pi^+\pi^- J/\psi)}{\Gamma_{ee}(\psi(2S))\mathcal{B}(\psi(2S) \to \pi^+\pi^- J/\psi)} = \left(\frac{N(\gamma\, Y)}{N(\gamma\, \psi(2S))}\right) \cdot \left(\frac{m(Y)}{m(\psi(2S))}\right) \cdot \left(\frac{\varepsilon(\psi(2S))}{\varepsilon(Y)}\right) \cdot \left(\frac{W(\psi(2S))}{W(Y)}\right)$$

- In this BaBar paper: $\Gamma(Y(460))_{ee}$; in $\overline{\text{P}}$ANDA: $\Gamma(Y(4260))_{p\bar{p}}$

Y(4260) branching fraction

- BR(Y(4260)) not quoted in the PDG. Only "seen".

All analyzed decay modes: BR normalized to BR($Y(4260) \to J/\psi\pi^+\pi^-$)

$\Gamma(J/\psi\pi\pi)$ is even called here Γ_{total}

$X(4260) \to J/\psi\pi^+\pi^-$	= seen		
$\Gamma(X(4260) \to J/\psi\pi^0\pi^0)$	= seen		No number, no reference
$\Gamma(X(4260) \to J/\psi K^+K^-)$	= seen	<1.2 eV	
$\Gamma(X(4260) \to X(3872)\gamma) / \Gamma(J/\psi\pi^+\pi^-)$	= seen		No number
$\Gamma(X(4260) \to Z_c(3900)^-\pi^+) / \Gamma(J/\psi\pi^+\pi^-)$	= seen	0.215 ±0.033 ±0.075	
$\Gamma(X(4260) \to J/\psi\, f0) / \Gamma(J/\psi\pi^+\pi^-)$	= seen	0.17 ±0.13	
$\Gamma(X(4260) \to \bar{p}p) / \Gamma(J/\psi\pi^+\pi^-)$	= seen	<0.13	No evidence
$\Gamma(X(4260) \to D\bar{D}) / \Gamma(J/\psi\pi^+\pi^-)$	= seen	<1.0	No evidence
$\Gamma(X(4260) \to D_s^{*+}D_s^{*-}) / \Gamma(J/\psi\pi^+\pi^-)$	= seen	<0.8	No evidence
$\Gamma(X(4260) \to D_s^+D_s^-) / \Gamma(J/\psi\pi^+\pi^-)$	= seen	<0.7	No evidence
$\Gamma(X(4260) \to D^*\bar{D}^*\pi) / \Gamma(J/\psi\pi^+\pi^-)$	= seen	<8.2	No evidence
$\Gamma(X(4260) \to \bar{D}D^*) / \Gamma(J/\psi\pi^+\pi^-)$	= seen	<34	No evidence
$\Gamma(X(4260) \to D^0D^{*+}\pi^-) / \Gamma(J/\psi\pi^+\pi^-)$	= seen	<9	No evidence

Y(4260) branching fraction

- BR(Y(4260)) not quoted in the PDG. Only "seen".

All analyzed decay modes: BR normalized to BR(Y(4260)→ $J/\psi\pi^+\pi^-$)

- Assumption: $BR(Y(4260) \to J/\psi\pi^+\pi^-) = 100\%$
  - The decay $Y(4260) \to J/\psi\pi^+\pi^-)$ was the discovery mode
  - For all known Y(4260) decay channels, the PDG quotes "seen"
  - All searches for decays to open charm lead to upper limits only
    all normalized to the $\mathrm{BR}(Y(4260) \to J/\psi\pi^+\pi^-)$
  - Recently, BESIII published $Y(4260) \to \gamma X(3872)$
    contributes in negligible way to the total $BR(Y(4260))$, i.e. $\leq 0.5\%$ only.

$BR(Y(4260) \to \bar{p}p)/BR(Y(4260) \to J/\psi\pi^+\pi^-) < 0.13$ at 90% c.l.

unrealistically cross section estimate of 4370 nb

Detailed balance

Y(4260) cross section at $\overline{\text{P}}$ANDA

JÜLICH FORSCHUNGSZENTRUM

Y(4260) cross section → Use scaling method and PDG values

$$BR(\psi(3770) \to \bar{p}p) = (7.1^{+8.6}_{-2.9}) \cdot 10^{-6}$$

$$\sigma(\bar{p}p \to \psi(3770)) = (9.8^{+11.8}_{-3.9})\ nb$$

Reference resonance: ψ(3770)
Values taken from PDG 2014

$$BR(Y(4260) \to p\bar{p}) = BR(\psi(3770) \to p\bar{p}) \cdot \frac{\Gamma_{total}(\psi(3770))}{\Gamma_{total}(Y(4260))}$$

$$\sigma(p\bar{p} \to Y(4260)) = \sigma(p\bar{p} \to \psi(3770)) \cdot \frac{\Gamma_{total}(\psi(3770))}{\Gamma_{total}(Y(4260))}$$

$$= 9.8\ nb \cdot \frac{27.2\ MeV}{102\ MeV} = 2.2\ nb$$

Upper limit

$$\sigma(p\bar{p} \to Y(4260)) = 2.2\ nb \cdot \frac{\Gamma_{ee}(Y(4260))}{\Gamma_{ee}(\psi(3770))}$$

$$= 2.2\ nb \cdot \frac{\Gamma_{ee}(Y(4260))}{BR(\psi(3770) \to e^+e^-) \cdot \Gamma_{total}(\psi(3770))} = 0.077\ nb$$

Lower limit

Y(4260) is treated as a charmonium state: no model for exotics

Y(4260) cross section at $\overline{\text{P}}$ANDA

- If the reference resonant state for this estimate is J/ψ, then the upper limit is: 1.9 nb

- Preference: ψ(3770), because:

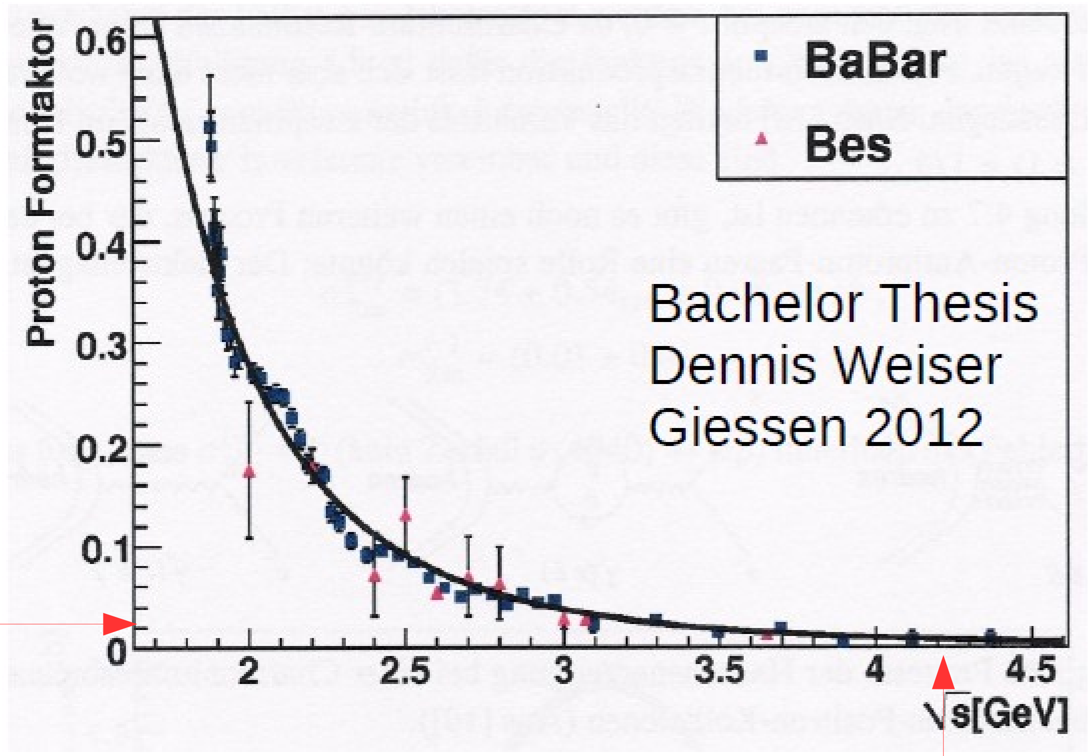
  - the J/ψ total width of $\simeq$93 keV << $Y(4260)$ $\simeq$120 MeV

  - $\mathrm{BR}(J/\psi \to e^+e^-, \mu^+\mu^- \simeq 12\%)$; for other charmonium states ~ 10^{-6}

Y(4260) cross section

- Why scaling for $\bar{p}p$ may not work perfectly?

Electrons are point-like particles; protons are composite object → formfactor!



proton formfactor G has an energy dependence $G(\sqrt{s})$

$Z(3900)^+$ cross section at $\overline{P}$ANDA

Z(3900) cross section

$$R = \frac{\sigma(e^+e^- \to Z_c(3900)^+\pi^- \to J/\psi\pi^+\pi^-)}{\sigma(e^+e^- \to J/\psi\pi^+\pi^-)} = 21.5\%$$

PRL 112 (2014) 092001

BES III @ 4.26 GeV

$$\sigma(\bar{p}p \to Z_c(3900)) = \sigma(\bar{p}p \to Y(4260)) \cdot 21.5\% = 0.473\ nb$$

Upper limit, using our upper limit on σ(Y(4260))

$$\sigma(\bar{p}p \to Z_c(3900)) = \sigma(\bar{p}p \to Y(4260)) \cdot 21.5\% = 0.017\ nb$$

Lower limit, using our lower limit on σ(Y(4260))

- Assumptions:

- Non-resonant Y(4260)→ $J/\psi\pi^+\pi^-$ contribution negligible;

- BR(Y(4260)→ $J/\psi\pi^+\pi^-$) = 100%

(no significant evidence of other channels reported in the PDG, except Y →Xγ)

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

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

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

Upper limit

Resonance	$\mathcal{L} = 8.64$	$\mathcal{L} = 0.864$	$\mathcal{L} = 0.432$
$X(3872)$	432000	43200	21600
$Y(4260)$	19000	1900	950
$Z(3900)^+$	4050	405	202

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

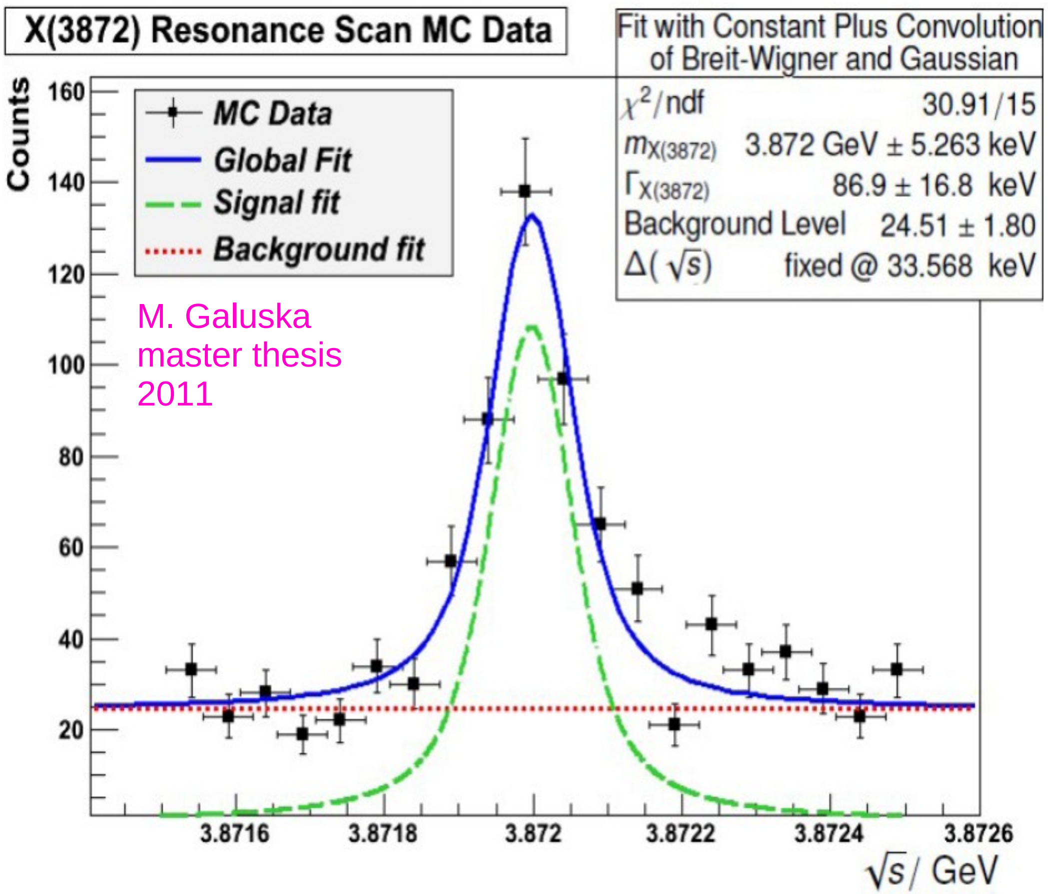
Lower limit

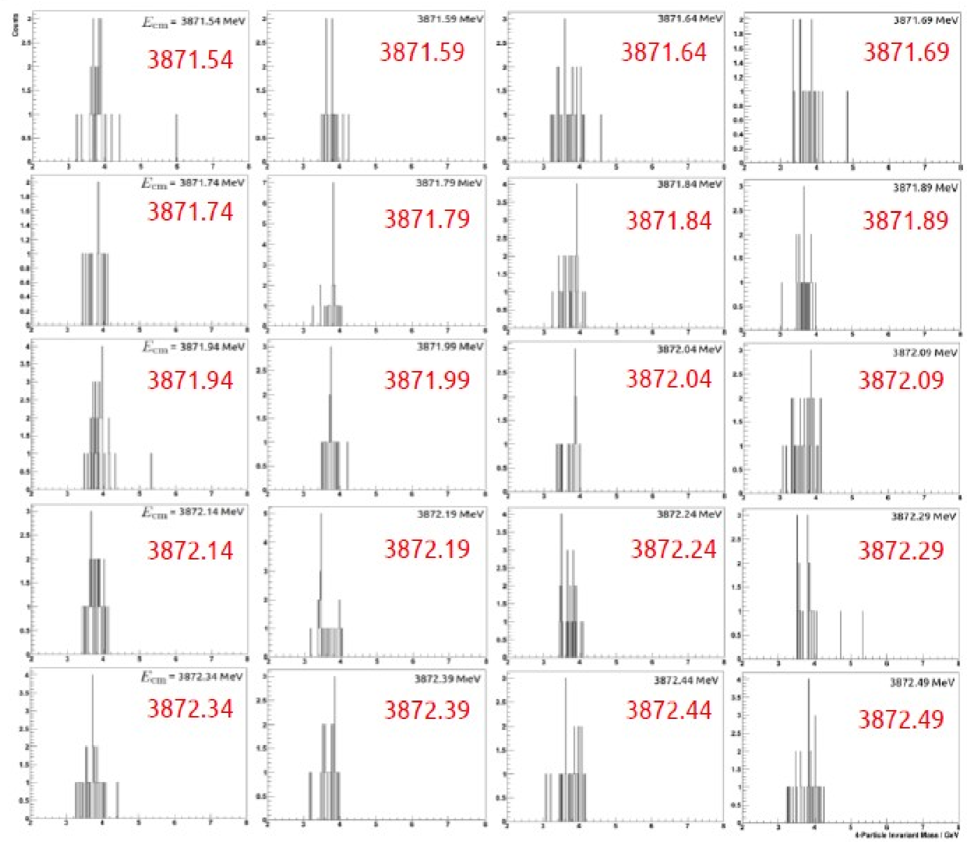
Resonance	$\mathcal{L} = 8.64$	$\mathcal{L} = 0.864$	$\mathcal{L} = 0.432$
$X(3872)$	-	-	-
$Y(4260)$	665	67	34
$Z(3900)^+$	140	14	7

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

Challenge: measurement of X(3872) width

Pos (Bormio 2012) 18



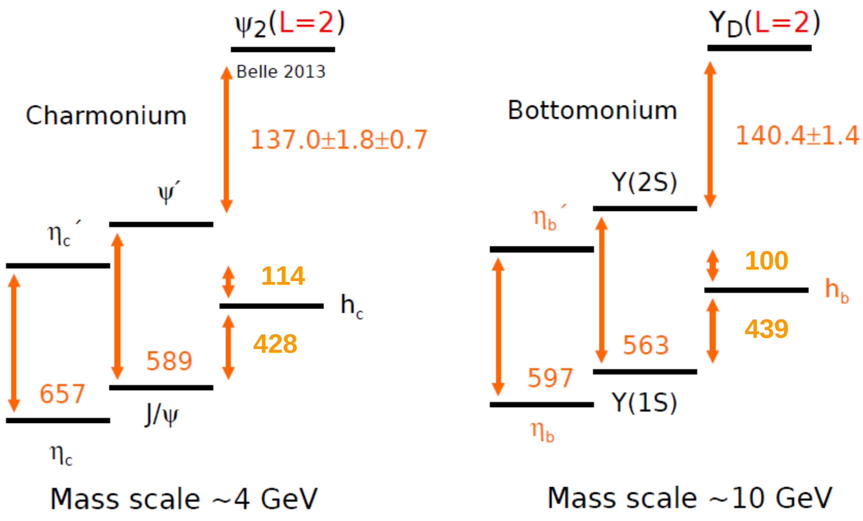


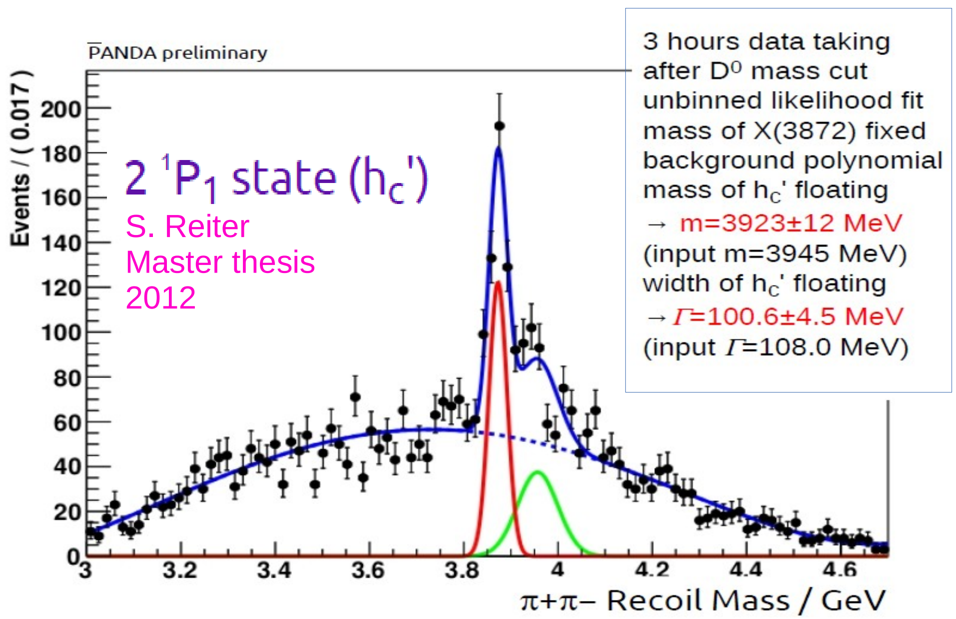
- Goal: measure the width of X(3872), for better understanding of its nature
- In PANDA: mass resolution x20 times better than B factories (challenge: 50-100 keV) [PDG upper limit: Γ<1.2 MeV @ 90% c.l.]

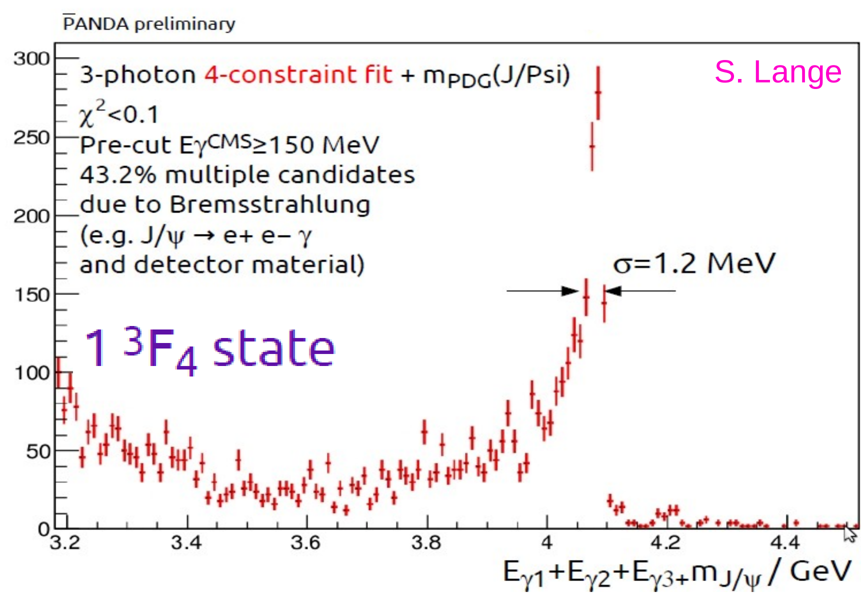
Challenge: high angular momentum states

arXiV:1311.7597 [hep-ex], CHARM2013

- Search for additional states as test of flavour independence
  - $^3F_4$ state predicted, never seen
  - Suppressed search in BES III, Belle II
  - $\overline{\text{P}}$ANDA can do this search



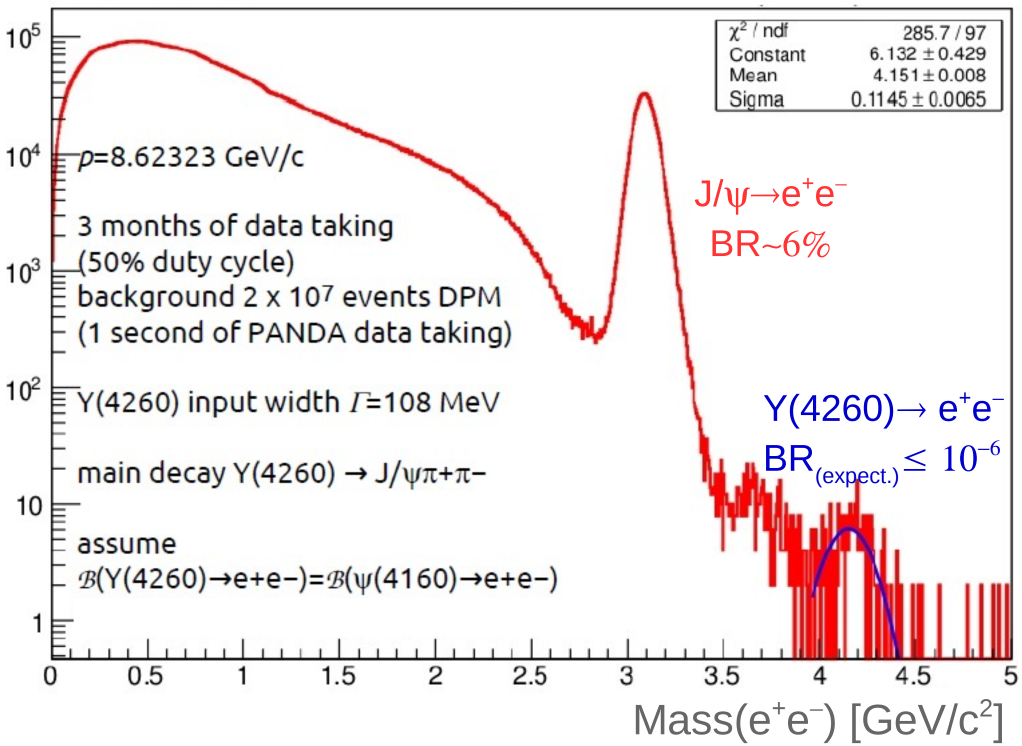




Challenge: interference effect in rare decays

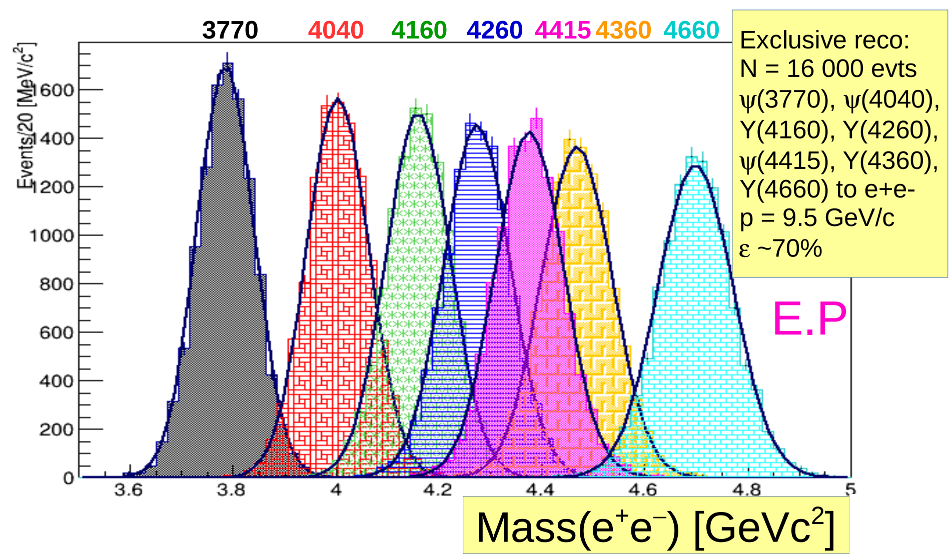
arXiV:1410.5201 [hep-ex], ICHEP2014

- $\bar{p}p \rightarrow$ Y(vector state), Y$\rightarrow e^+e^-$



Resonance	$BR(\psi \rightarrow e^+e^-)$	Γ/MeV
ψ(3770)	$(9.6\pm 0.7)\times10^{-6}$	27.2±1.0
ψ(4040)	$(1.07\pm 0.16)\times10^{-5}$	80±10
ψ(4160)	$(8.1\pm 0.9)\times10^{-6}$	103±8
ψ(4415)	$(9.4\pm 3.2)\times10^{-6}$	62±20

- PANDA: *mini*-Y(4260) factory.
- Y(4260) $\rightarrow e^+e^-$ not observed, yet: limit from coupling to initial state $\mathcal{B}(J/\psi\pi^+\pi^-) \times \mathcal{B}(e^+e^-) = (9.2\pm0.8)$ eV
  BaBar, PRD 86 (2012) 051102
- Overpopulated 1^{--} Charmonium spectrum
- In PANDA possibility to study very rare decays: Y(4260) $\rightarrow e^+e^-$ would be an absolute measurement
- 1^{--} states are large: they can interfere



Challenge: search for new exotic Z states

Z workshop 2015, Giessen (DE)

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

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

- Reasonably expected Z states near $D\bar{D}$ threshold, never observed ($m_Z \sim 3730$ MeV/c^2)

  X(3872)→ Z(3730)π transition kinematically allowed

  → forbidden by parity conservation at e^+e^- colliders

- Proposal @ $\bar{\text{P}}$ANDA:

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

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

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

Summary

PANDA RN-004

A proposal for Z state search with $\overline{\text{P}}$ANDA at FAIR.

Alexander Blinov, Budker Institute of Nuclear Physics and Novosibirsk State University, Novosibirsk (Russia);
Martin Galuska, Justus-Liebig-Universität, Giessen (Germany);
Jens Sören Lange, Justus-Liebig-Universität, Giessen (Germany);
Elisabetta Prencipe, Forschungszentrum Jülich (Germany);
James Ritman, Forschungszentrum Jülich (Germany);

on behalf of the $\overline{\text{P}}$ANDA charmonium-light exotics group.

Acknowledgment:
thanks to Frank and Klaus
who were present at every stage of this
internal note, since our first seevogh-meeting in June 2015,
for the interesting questions and careful reading of this draft.