XYZ States
Results from Experiments

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Physics of Heavy Quarks and Hadrons
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JINR, Dubna, Russia

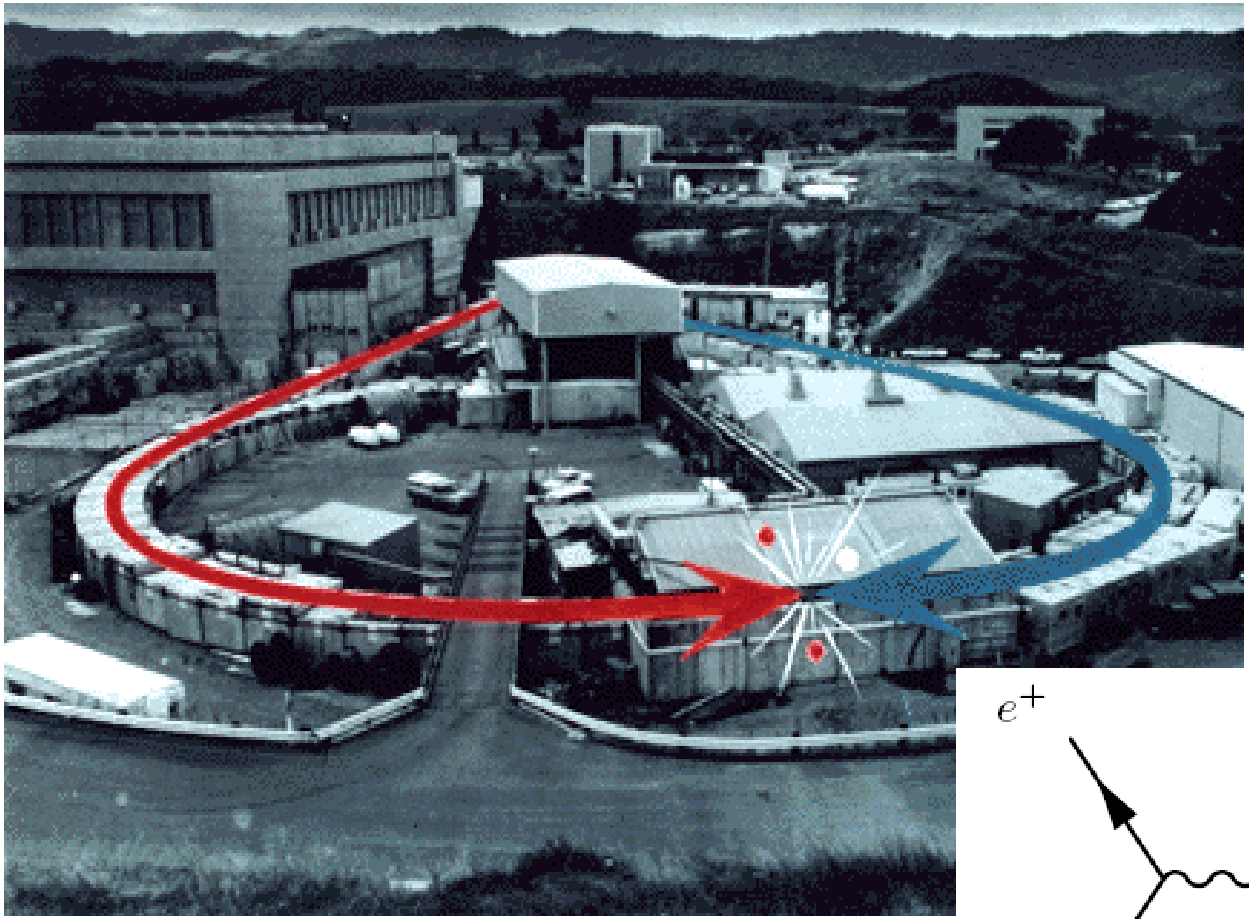
arXiv:1208.6128[hep-ex]
arXiv:1109.1699[hep-ex]
arXiv:1010.2350[hep-ex]
arXiv:1010.2331[hep-ex]

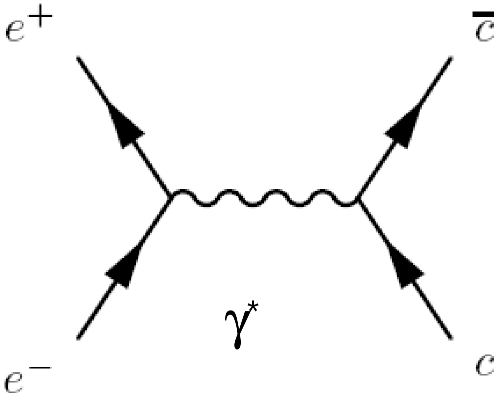
Outline

- Past and Present Experiments
  - How it all began, on a parking lot
  - B factories (Belle, BaBar)
  - BESIII
- Charmonium-like states
  - X(3872)
  - Y(4260) and family
  - Z+(4430) and family
  - D-wave state
- Bottomonium-like states
  - Yb(1088)
  - Zb
- Future experiments
  Panda, Belle-II

e+ e– Collisions at SLAC (1973)

SPEAR





$\sqrt{s} = 3.1$ GeV

Discovery of Charmonium (J/ψ)

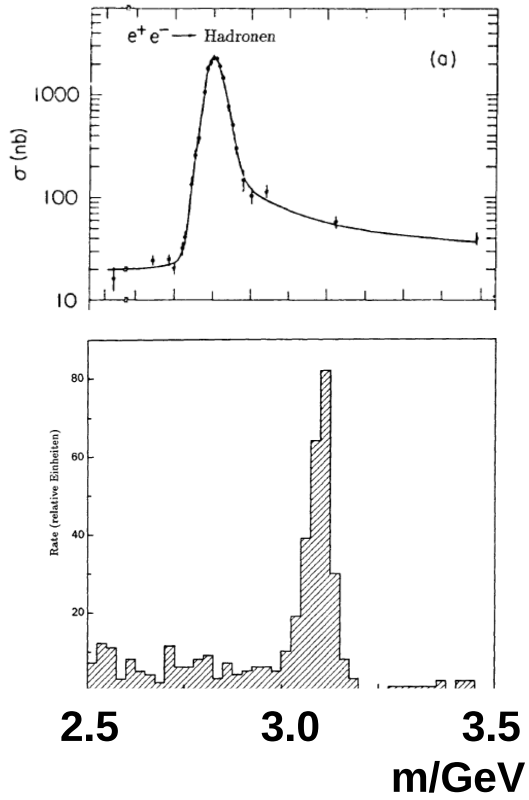
- SLAC (Stanford)
  Mark I, Richter et al.
  $e^+ e^- \rightarrow$ hadrons, $e^+ e^-$, $\mu^+ \mu^-$

- BNL (Brookhaven)
  E598, Ting et al.
  $p + A \rightarrow [e^+ \; e^-] X$

- new, very narrow state: J/ψ
  m=3.1 GeV, $\Gamma \sim 100$ keV,
  interpreted as [$\bar{c}c$]
  spin=1 (↑↑) ground state

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

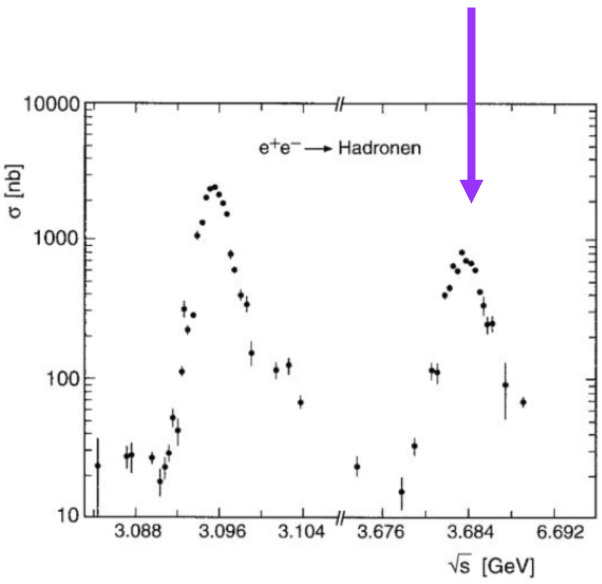
- (experimental proof for existance of 4th quark)

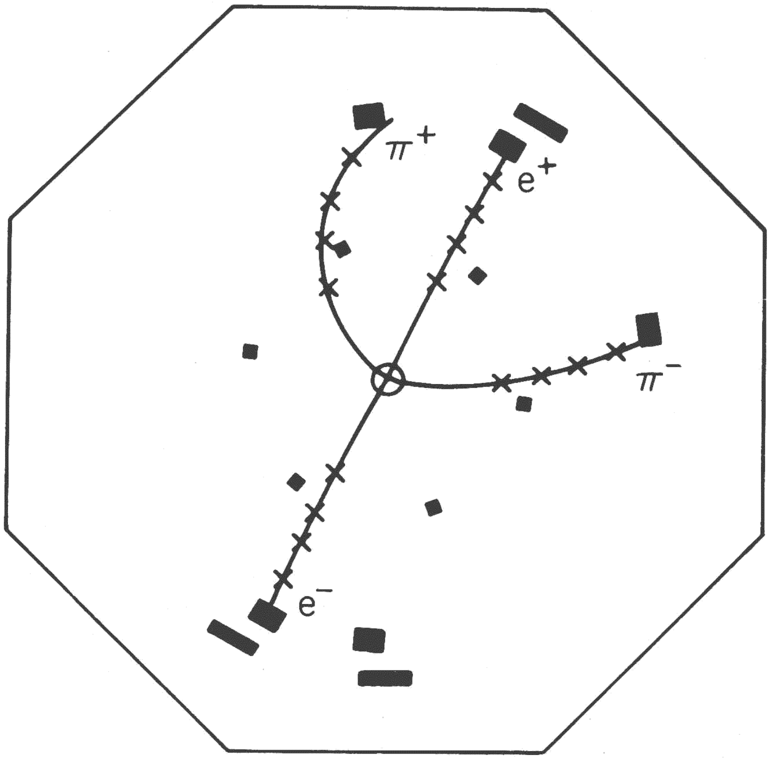


MARK I group reacted quickly
→ it was feasible to modify the accelerator, so that the beam energies could be changed to ≤1 MeV every minute.

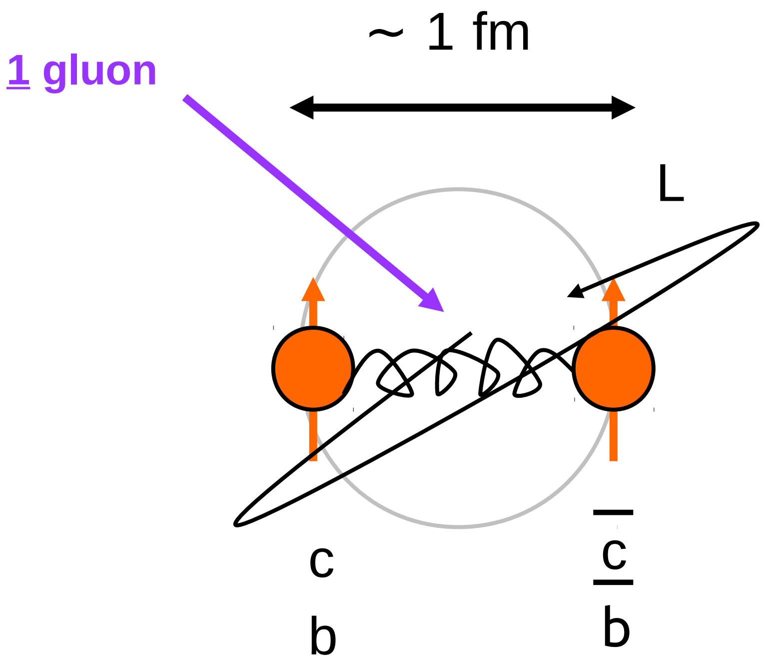
Discovery of ψ'

- **first exited (n=2) state of *J/ψ***
- **only 3 weeks after *J/ψ***
- **beginning of charmonium spectroscopy**
- **Decay:**
  $\Psi' \to J/\Psi\ \pi^+\ \pi^-$





Heavy Quarkonium



Static Quark-Antiquark Potential for Charmonium

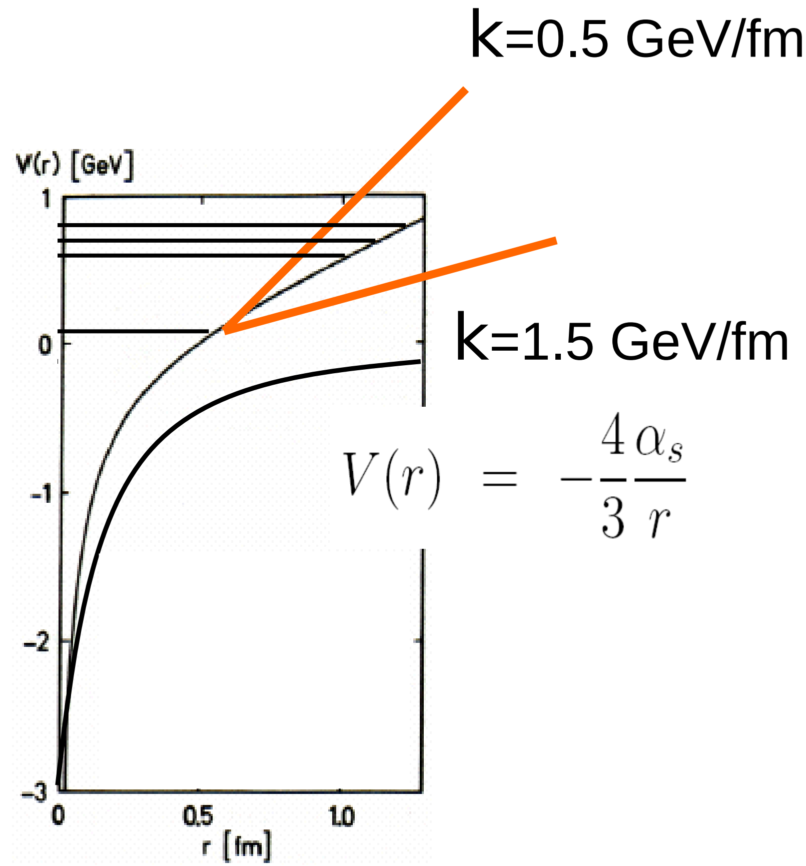
- Coulomb-Potential
  + Confinement-Term

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \boxed{kr}$$

spin-spin $\quad + \frac{32\pi\alpha_s}{9m_c^2}\delta_r \vec{S}_c\vec{S}_{\overline{c}}$

spin-orbit $\quad + \frac{1}{m_c^2}\left(\frac{2\alpha_s}{r^3} - \frac{k}{2r}\right)\vec{L}\vec{S}$

tensor $\quad + \frac{1}{m_c^2}\frac{4\alpha_s}{r^3}\left(\frac{3\vec{S}_c\vec{r}\cdot\vec{S}_{\overline{c}}\vec{r}}{r^2} - \vec{S}_c\vec{S}_{\overline{c}}\right)$



- solve Schrödinger equation
  (quark mass heavy → non-relativistic)
  → states

$$\Psi(r,\theta,\phi) = R_{nl}(r)Y_{lm}(\theta,\phi)$$

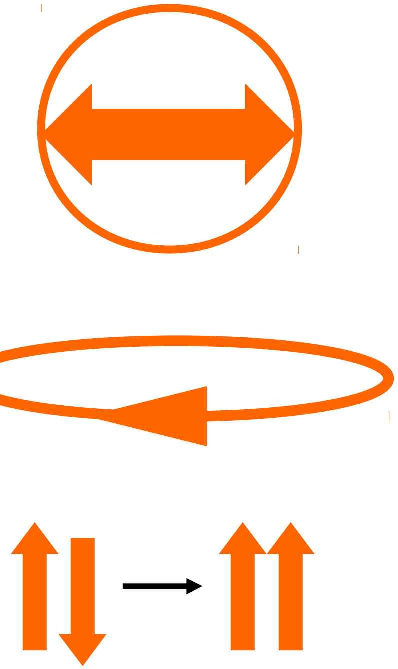
$$\left[-\frac{1}{m_q}\left(\frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r} + \frac{l(l+1)}{m_q r^2} + V(r)\right)\right] R_{nl}(r) = E_{nl}R_{nl}(r)$$

Quarkonium Excited States

radial
n

orbital
L

spin
S



spectroscopic
notations

$n^{2S+1} L_J$

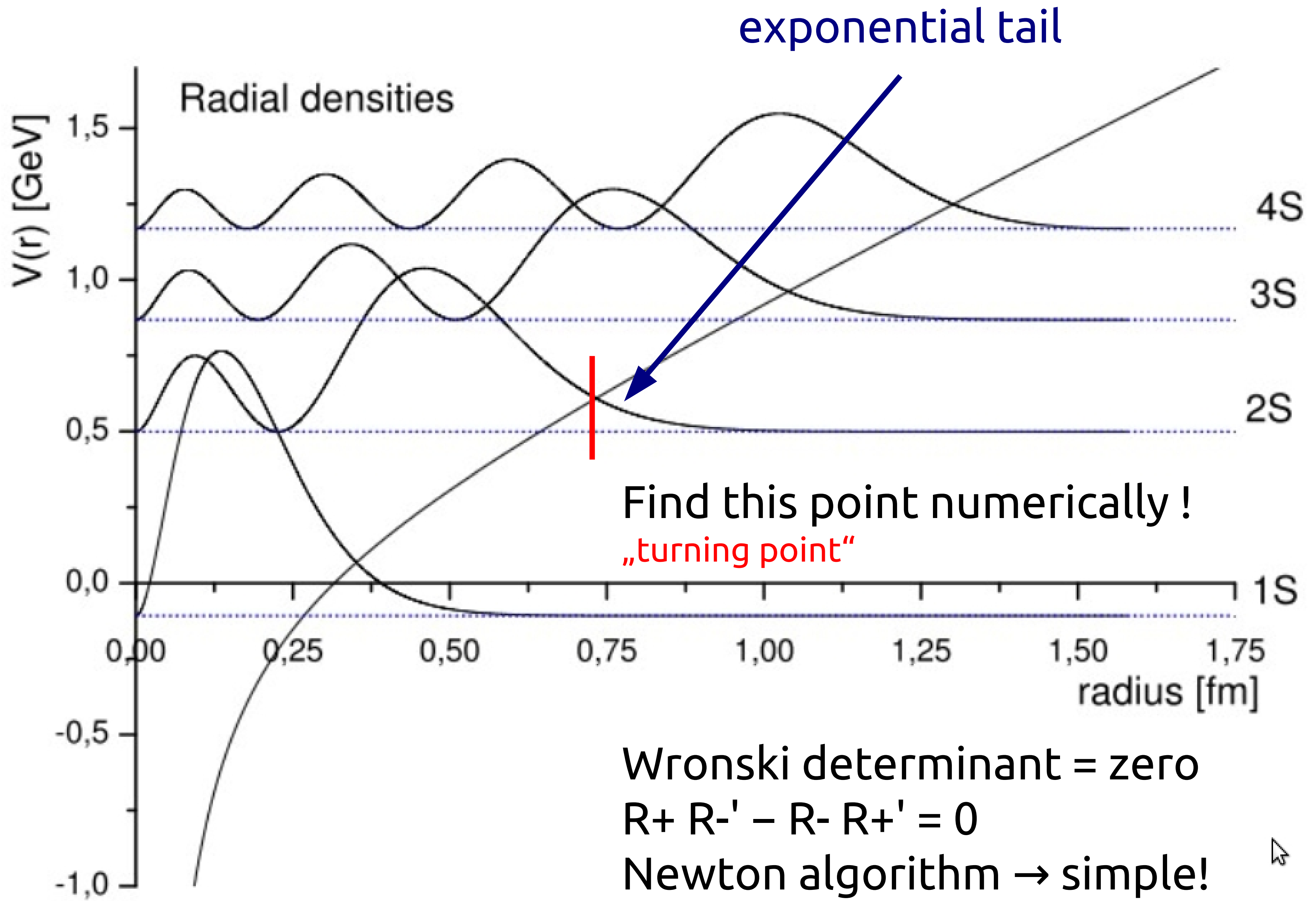
L=S,P,D,...

J^{PC}

$$\vec{J} = \vec{L} + \vec{S}$$

$$P = (-1)^{L+1}$$ parity

$$C = (-1)^{L+S}$$ charge conjugation



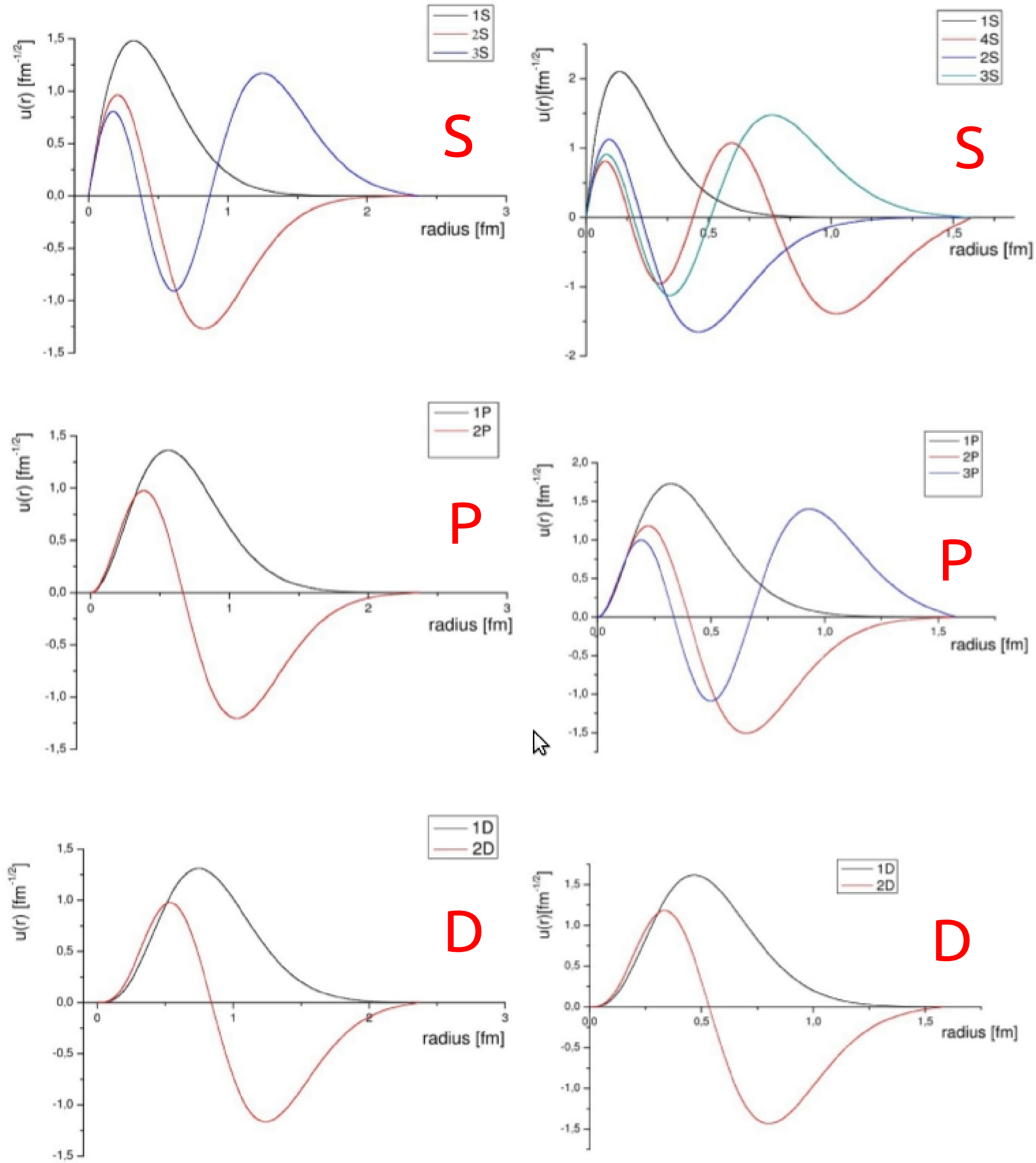
Find this point numerically !

Wronski determinant = zero

R+ R-' – R- R+' = 0

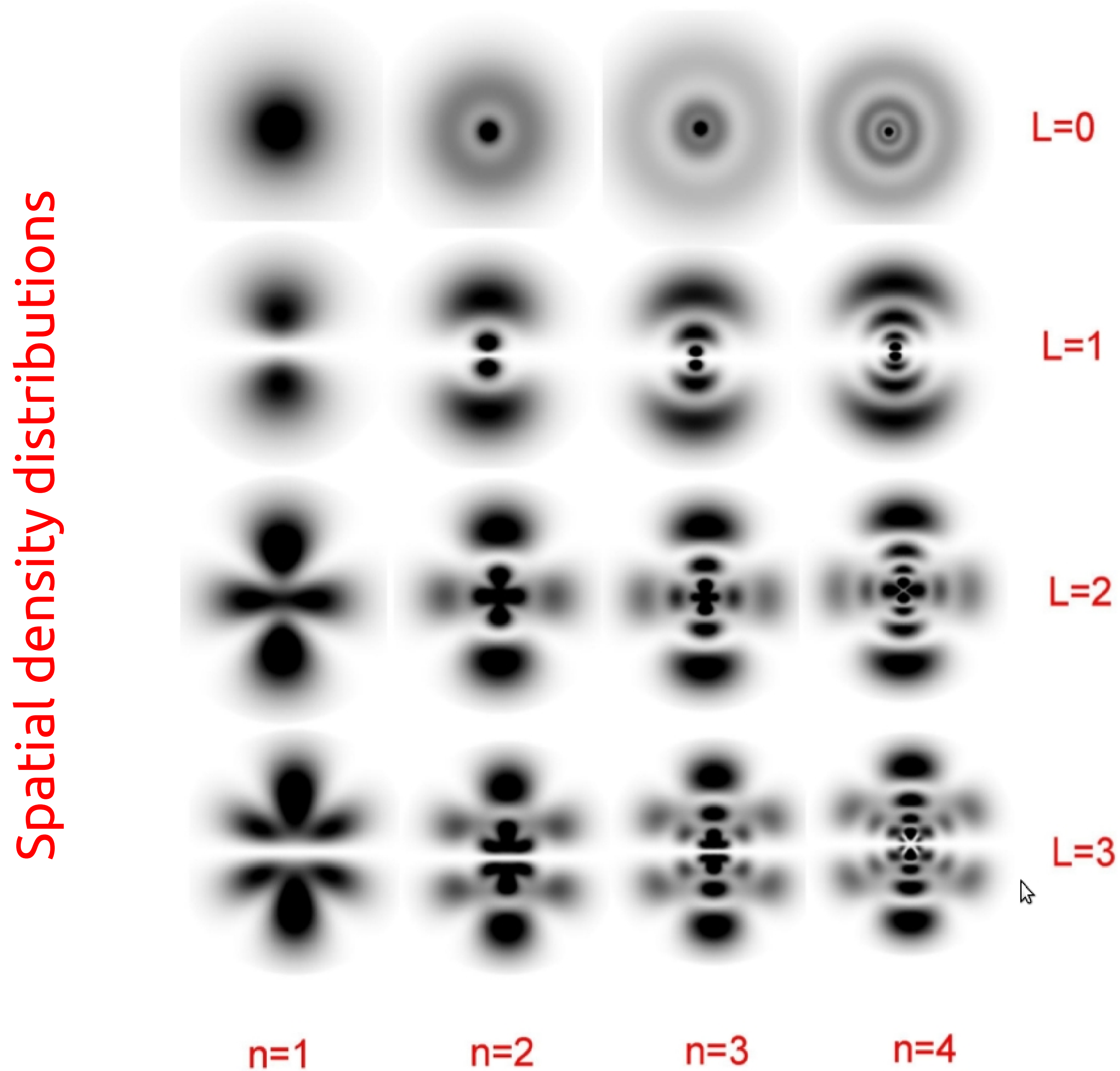
Newton algorithm → simple!

Charmonium



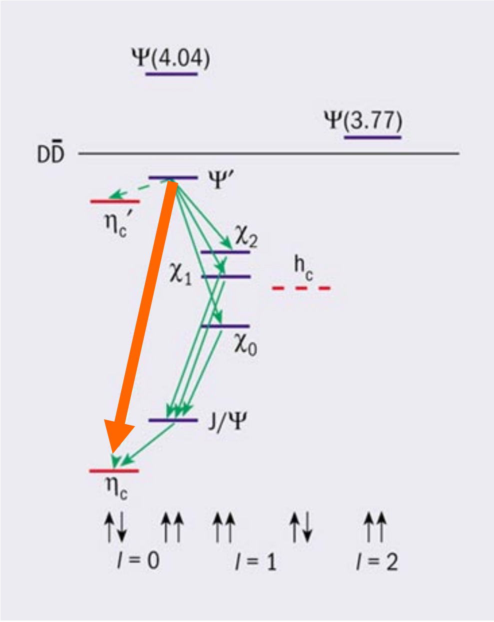
Bottomonium

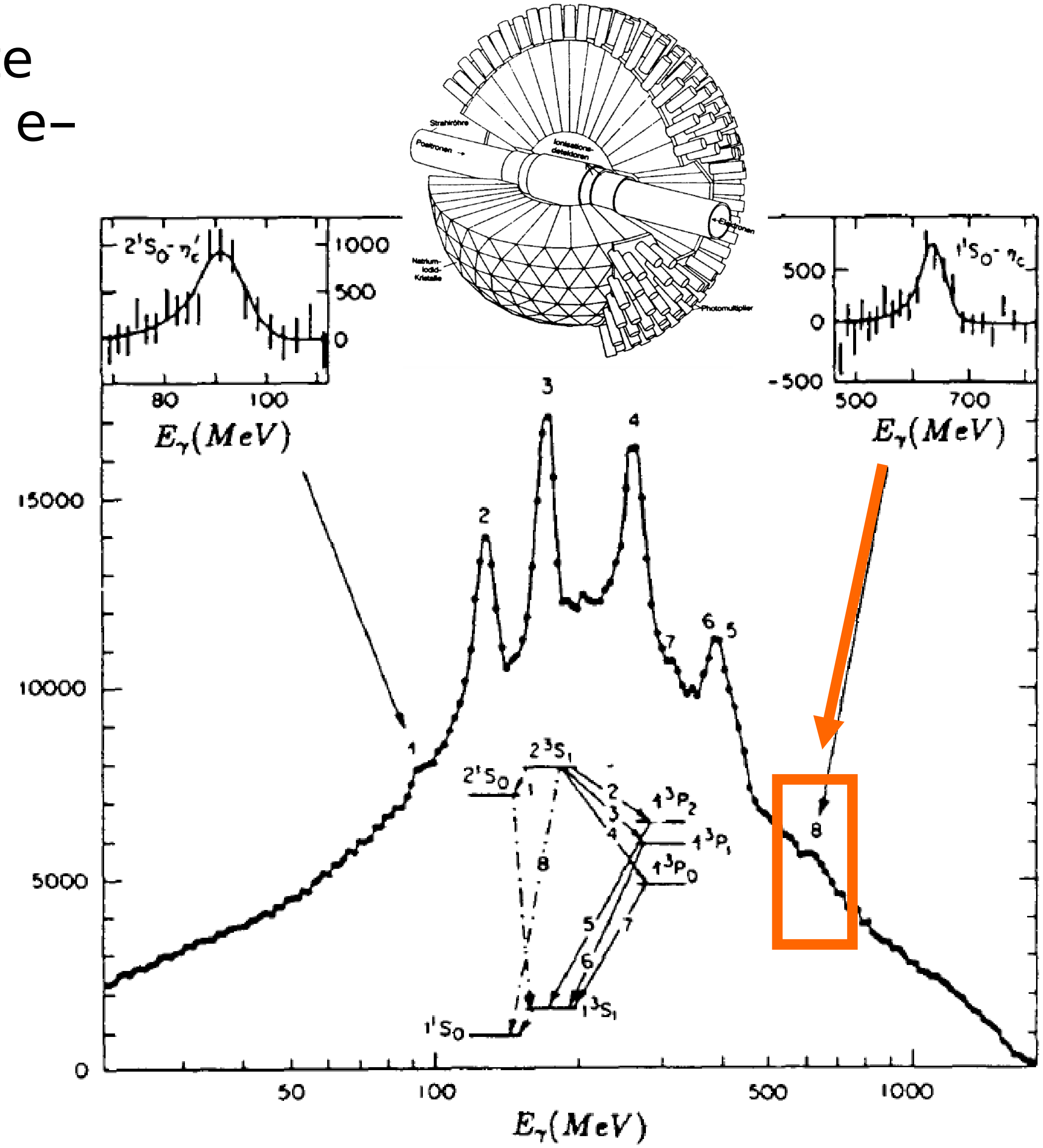
Radial Wavefunctions

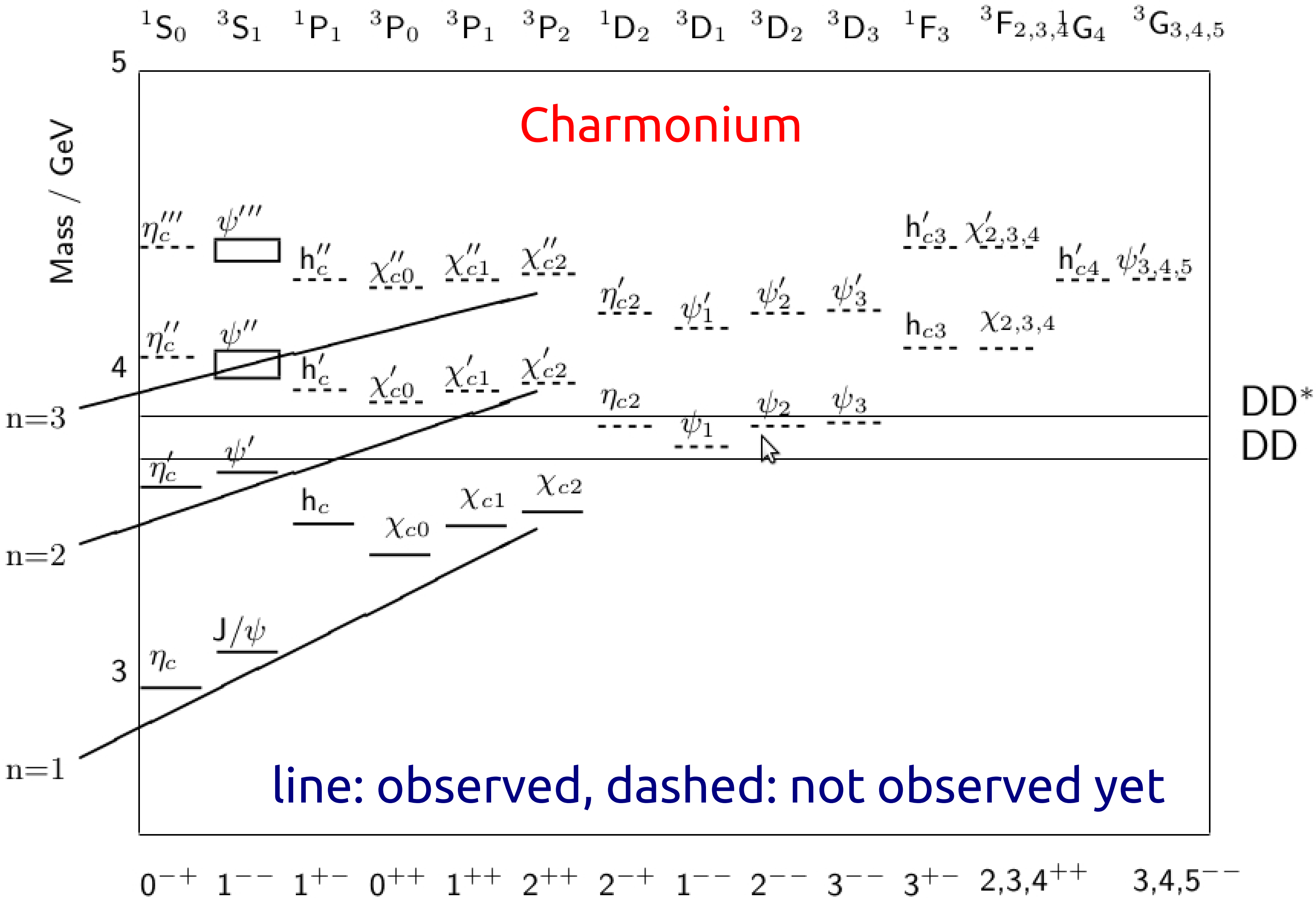

Spatial density distributions
L=0
L=1
L=2
L=3
n=1
n=2
n=3
n=4

Discovery of η_c

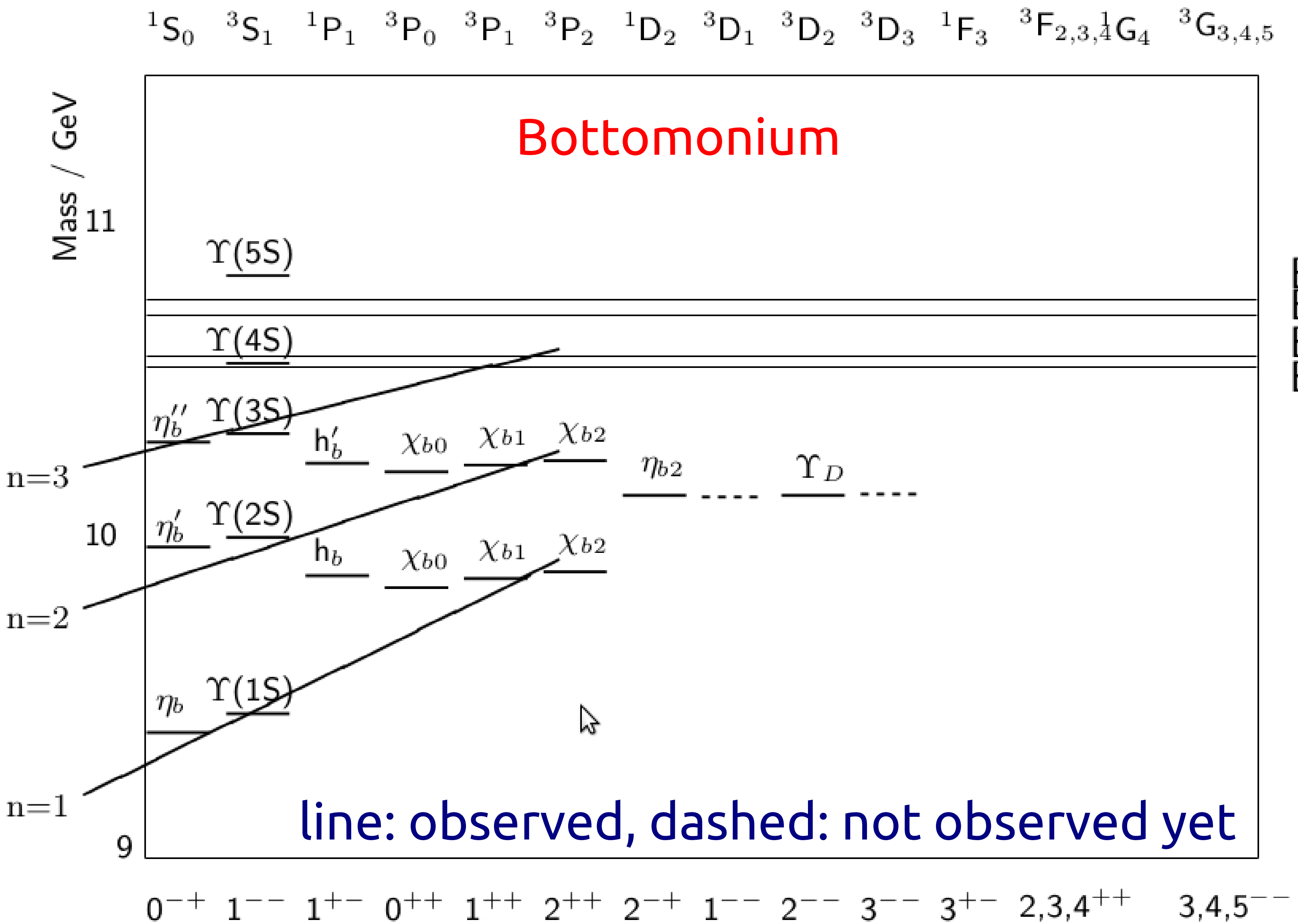
- spin=0 (↑↓) ground state can not decay → γ → e+ e–
- SLAC (1979) Crystal Ball Detector
- radiative transistions, detect photon only







Overall mass precision ~2–3 MeV



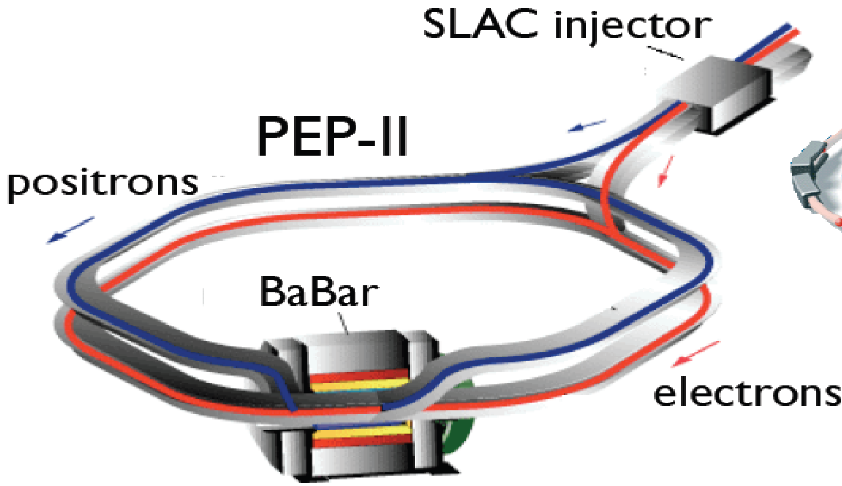
Overall mass precision ~1 MeV

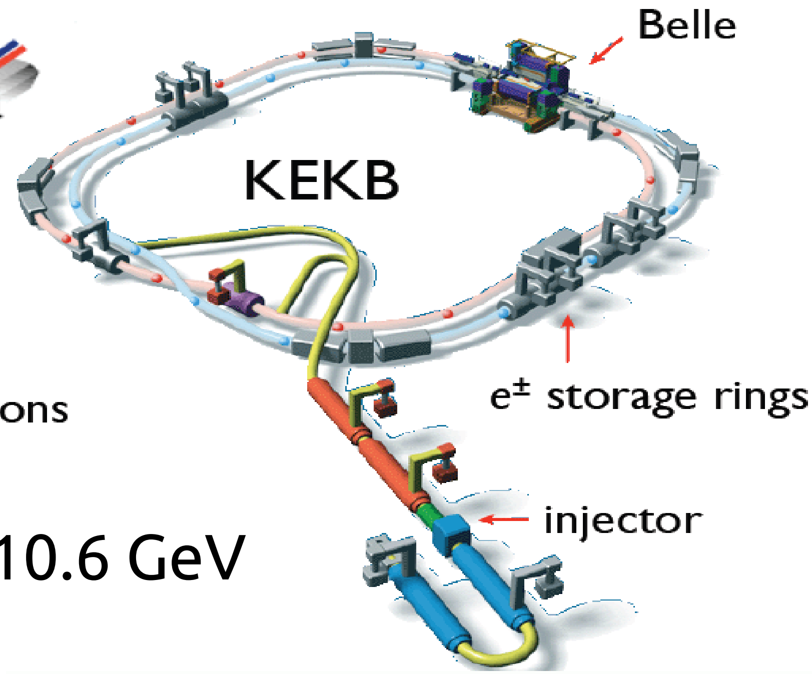
The agreement between prediction by the potential model and experimental observation is and was encouraging (level ~10^{-3}, 2–3 MeV compared to mass of 3-10 GeV) and hadron physicists were living happily.

About 30 years passed.

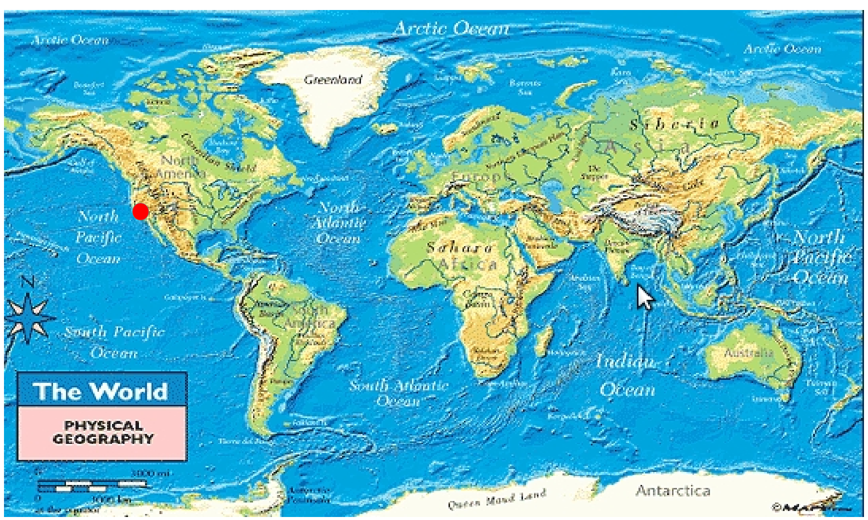
And then the following things happened ...

B Factories

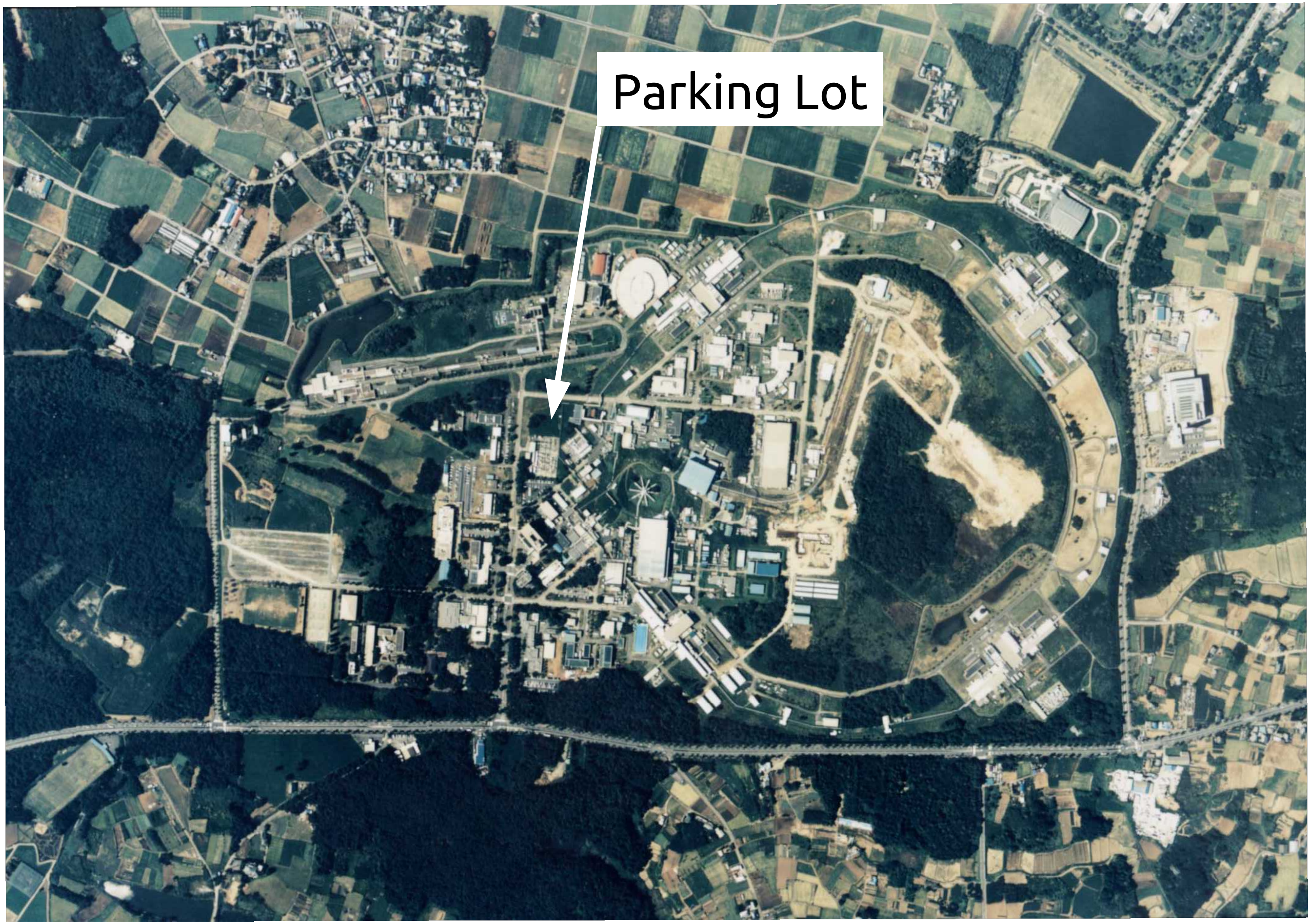




$\sqrt{s}$=9.4-10.6 GeV



Belle and KEKB, Japan

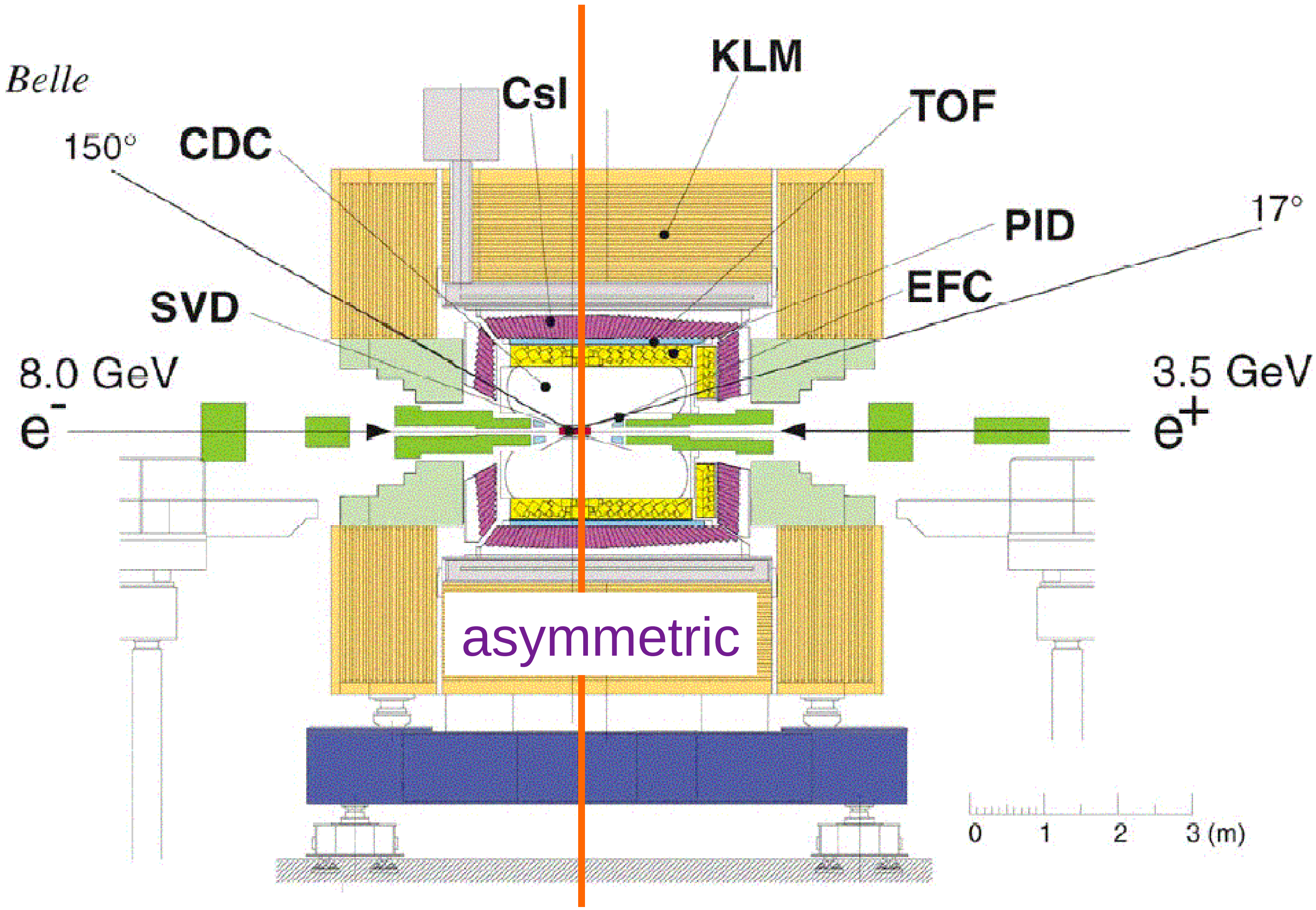


symm.

asymm.
→ extend decay length
of B mesons

Accelerator Laboratory	CESR Cornell	KEKB KEK	PEP-II SLAC	SuperKEKB KEK
Detector	CLEO III	Belle	BaBar	Belle II
	(achieved)	(achieved)	(achieved)	(planned)
Circumference (km)	0.768	3.0	2.2	3.0
Energy e^-/e^+ (GeV)	5.3/5.3	8.0/3.5	9.0/3.1	7.0/4.0
Lorentz boost $\beta\gamma$	0	0.43	0.56	0.28
Beam current e^-/e^+ (A)	0.5/0.5	$1.6/1.2^\dagger$	3.2/2.1	3.6/2.6
Number of bunches	45	5120	1732	2500
Crossing angle (mrad)	±2.3	±11	0	83
Luminosity ($10^{33}/\text{cm}^2\text{s}$)	1.55	21.08	12.07	800
σ_x (μm)	n.a.	103-116	120	7.2-8.9
σ_y (μm)	n.a.	0.94	4	36×10^{-3}
σ_z (mm)	n.a.	6	11	5

The BELLE Detector



Luminosity

```
-----------------------------------------------
Belle Run Summary(v1.84) - Exp    47  Run   529
-----------------------------------------------

Start Time: 2005 Dec  7, 22:58:37 took   78 sec to start
Stop  Time: 2005 Dec  7, 23:14:01 took  924 sec
Stop Reason: FATAL from [EFARM1] E1TRK CDC timeout (1 sec rx0 stat=28 len=64/0/11448 ev=193658,


Expert shift:   S. Lange
Non-Expert:     K. Kinoshita
BCG shift:      Ishikawa (4862)

Run Mode:       Luminosity Run

Accelerator:     at start      at stop    Fill-number=16364  Status=Physics Run
   HER current   1337.4 mA    1321.5 mA   7.9947 GeV  Physics Run
   LER current   1719.2 mA    1732.6 mA   3.4977 GeV  Physics Run
                              (CM-energy 10.5759 GeV)
   HER beamsiz 239.5/  4.2  242.3/  3.9 um (x/y)  life 229 min
   LER beamsiz 186.3/  3.6  187.5/  3.8 um (x/y)  life -243 min
   HER vacuum    5.0/  3.0    5.1/  3.0 x1e-8 Pa (average/upstream)
   LER vacuum    6.6/  4.6    6.6/  4.6 x1e-8 Pa (average/upstream)
   LER cont. inj. ON  (8.6 Hz  7934 times)   inj.veto ON (0)

Luminosity:       ECL         EFC        KEKB
   at start    155.80e32  140.07e32  108.39e32
   at stop     156.55e32  139.11e32  109.06e32
   peak/fill   157.78e32
```

$L > 1 \times 10^{34}\ s^{-1}\ cm^{-2}$

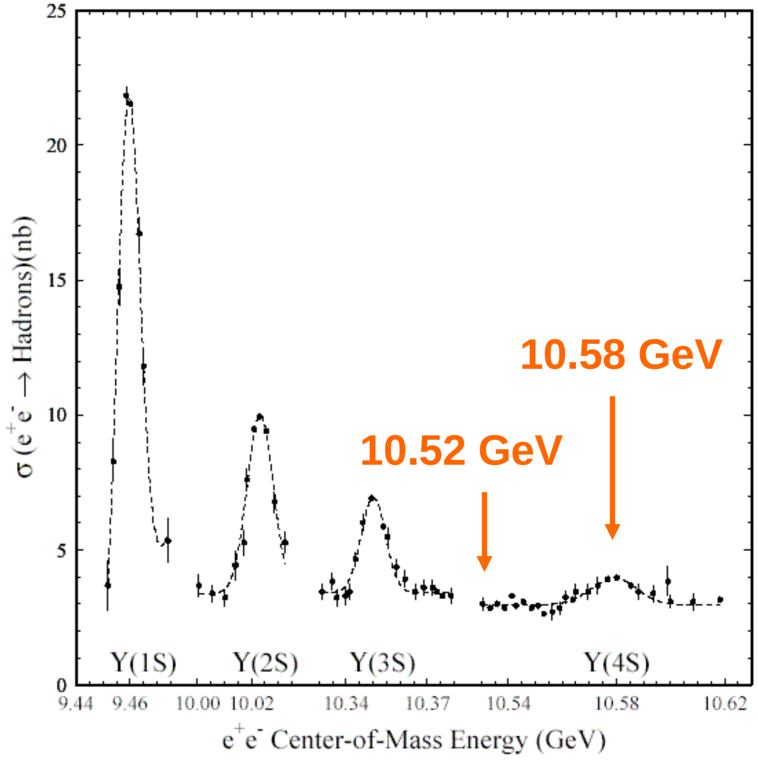
$1 \times 10^{34}\ s^{-1}\ cm^{-2}$

$1\ barn = 10^{-24}\ cm^2$

$24\ hours \times 60\ min \times 60\ seconds \times 10^{10}\ barn^{-1}$
$= 86.400 \times 10^{10}\ barn^{-1}$
$\sim 10^{15}\ barn^{-1}$
= 1 inverse femtobarn per 1 day

Beam Energy

- adjusted to the Upsilon(4S) resonance (decays ~99% to $\bar{B}B$ mesons)
- ~10% of time $\sqrt{s}$=10.52 GeV in non-resonant continuum

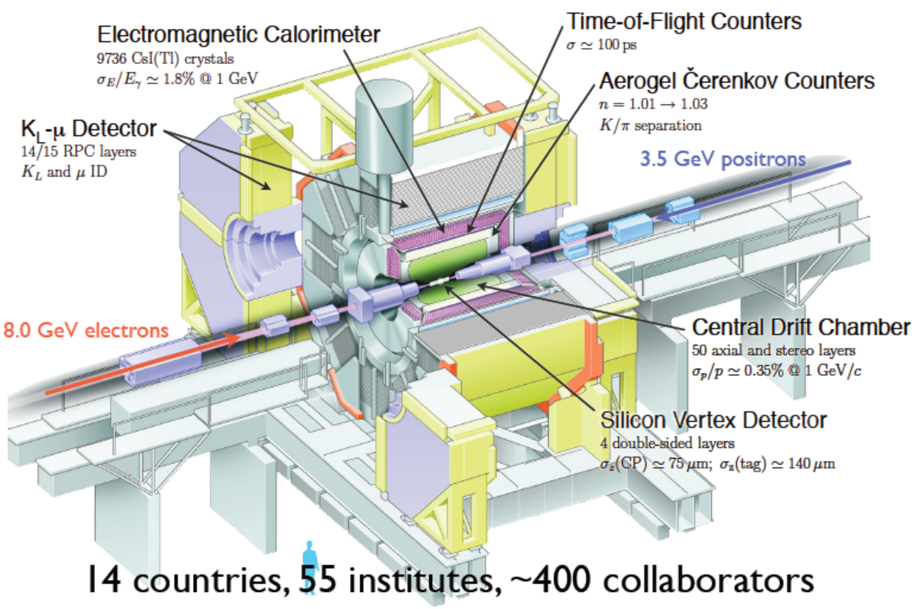


Cross section
$\sigma(e^+ e^- \rightarrow \Upsilon(4S))$
~1 nb

1 fb^{-1} per 1 day

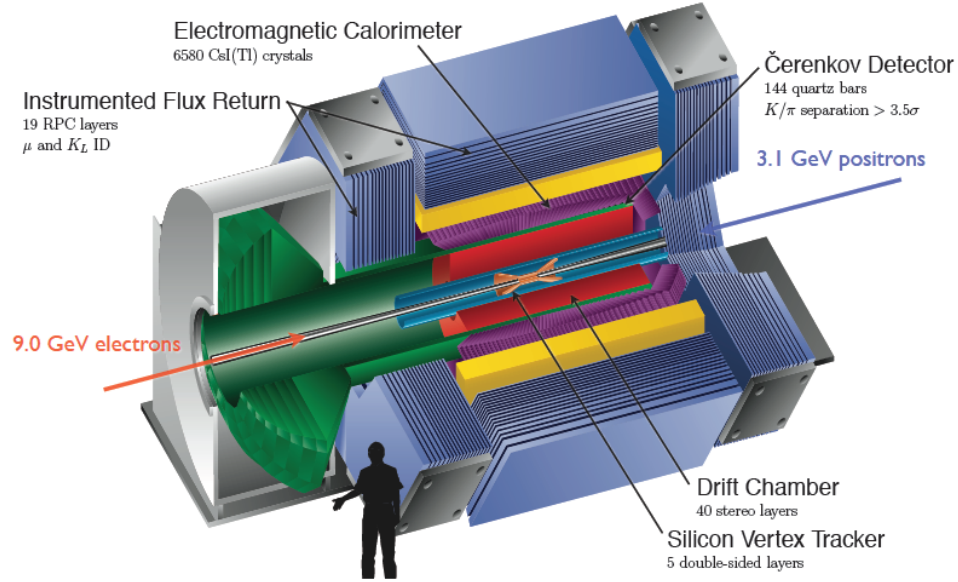
This means:
~1 Million *B* Meson pairs per 1 day

Belle at KEKB



14 countries, 55 institutes, ~400 collaborators

BaBar at PEP-II



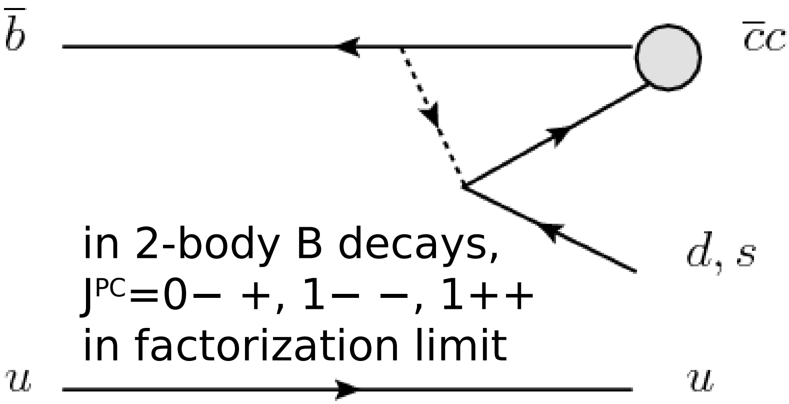
11 countries, 80 institutes, ~600 collaborators

~1000 /fb
On-resonance samples:
Υ(4S): 711 /fb
Υ(5S): 121 /fb
Υ(3S): 3.0 /fb
Υ(2S): 24 /fb
Υ(1S): 5.7 /fb
Off-resonance: 87 /fb

~553 /fb
On-resonance samples:
Υ(4S): 433 /fb
Υ(3S): 30 /fb
Υ(2S): 14 /fb
Off-resonance: 54 /fb

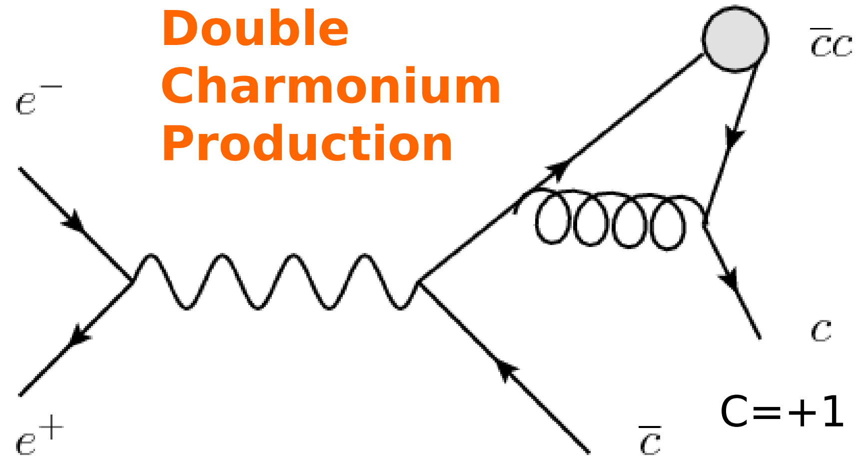
Production of Charmonium

B Decays



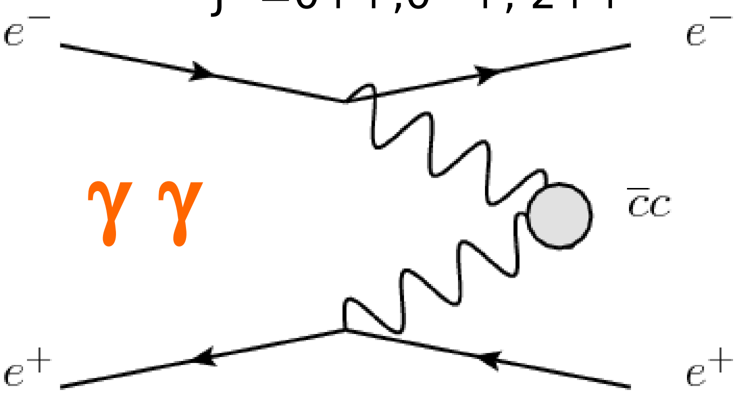
in 2-body B decays,
J^{PC}=0− +, 1− −, 1++
in factorization limit

Double Charmonium Production



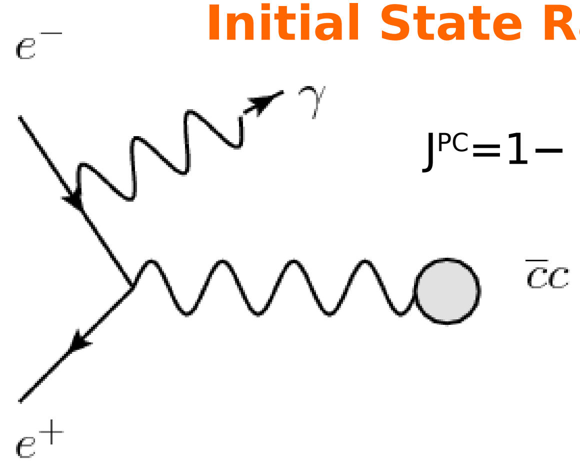
C=+1

J^{PC}=0++,0−+, 2++



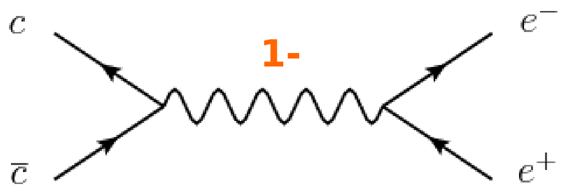
γ γ

Initial State Radiation



J^{PC}=1− −

Decays of Charmonium States



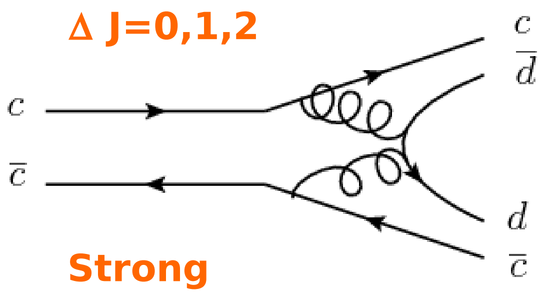
1-

EM

Annihilation

e.g. $J/\psi \rightarrow \pi^+ \pi^- \pi^0$
OZI suppressed

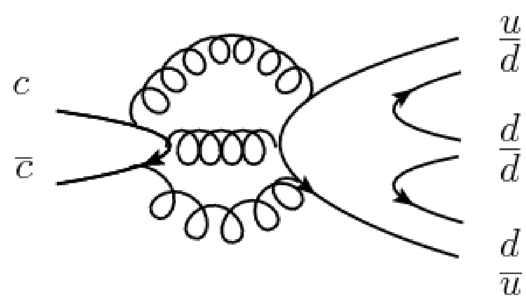
Δ J=0,1,2



$D^{o(*)}$

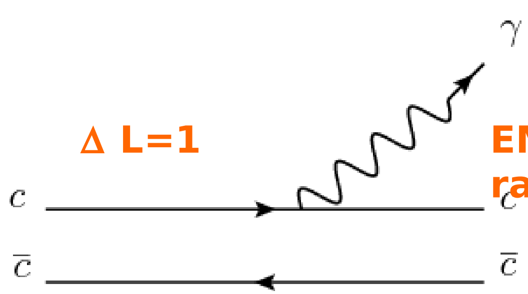
$\bar{D}^{o(*)}$

Strong



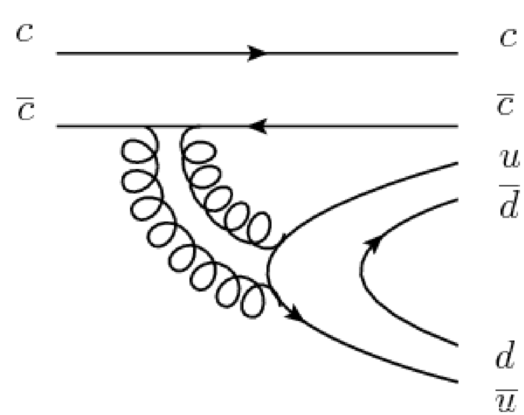
Strong
$\sim 1/\alpha_s^3$

Δ L=1



EM
radiative

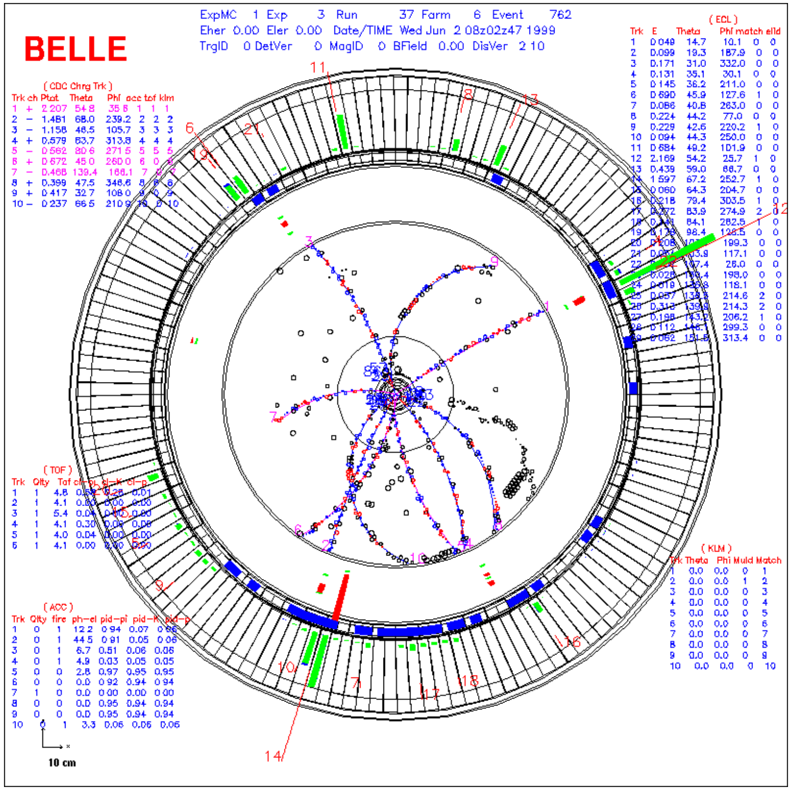
e.g. $\psi' \rightarrow \chi_{cJ}\, \gamma$



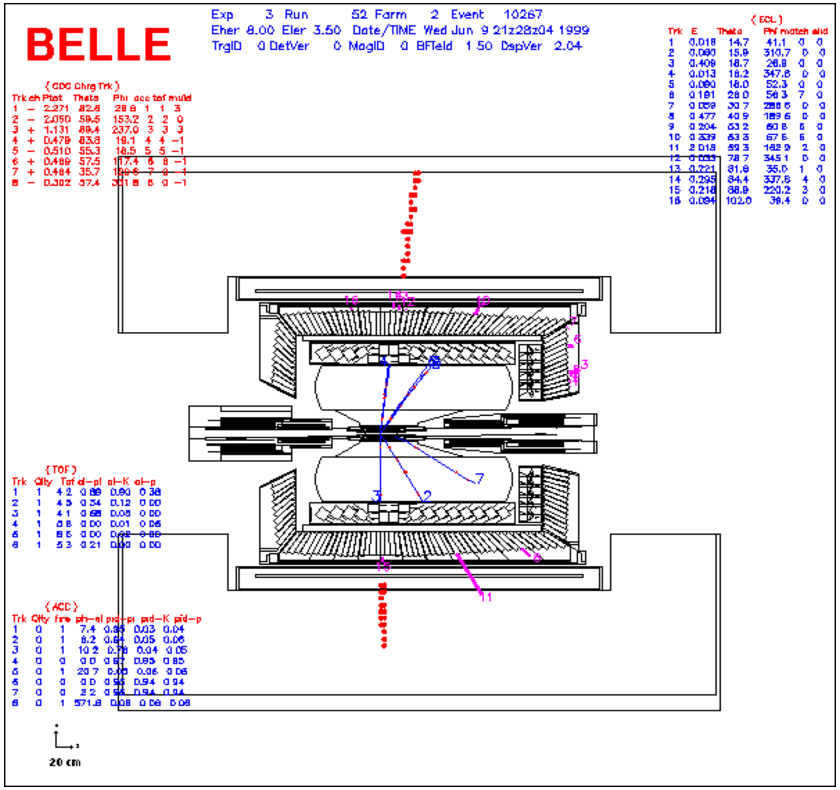
Strong
spectator
isospin
transition ?
(if $(\pi\pi)=\rho$)
$\sim 1/\alpha_s^2$
e.g. $\psi' \rightarrow J/\psi\, \pi^+ \pi^-$

Example Events with Charmonium

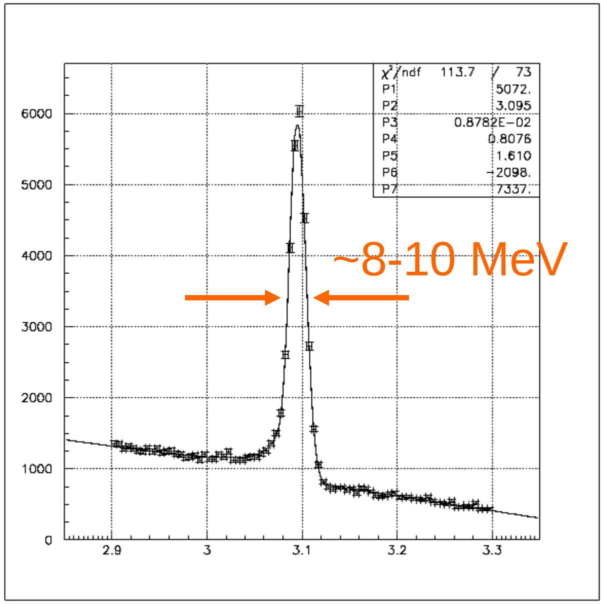
$J/\psi \to e^+e^-$

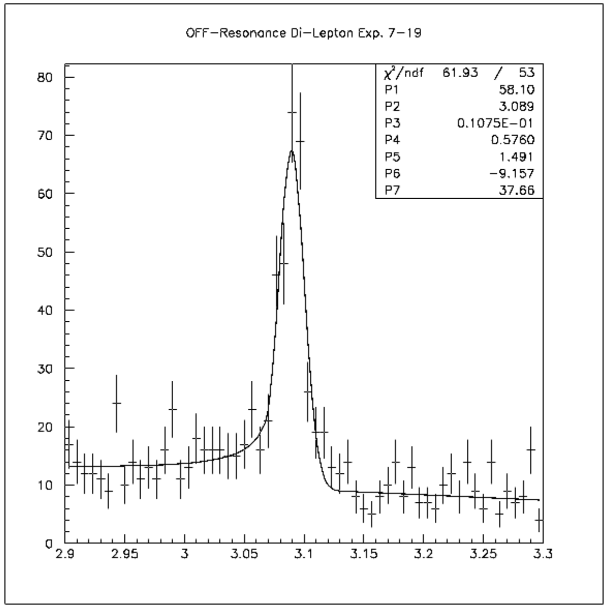


$J/\psi \to \mu^+\mu^-$



J/ψ Invariant Mass

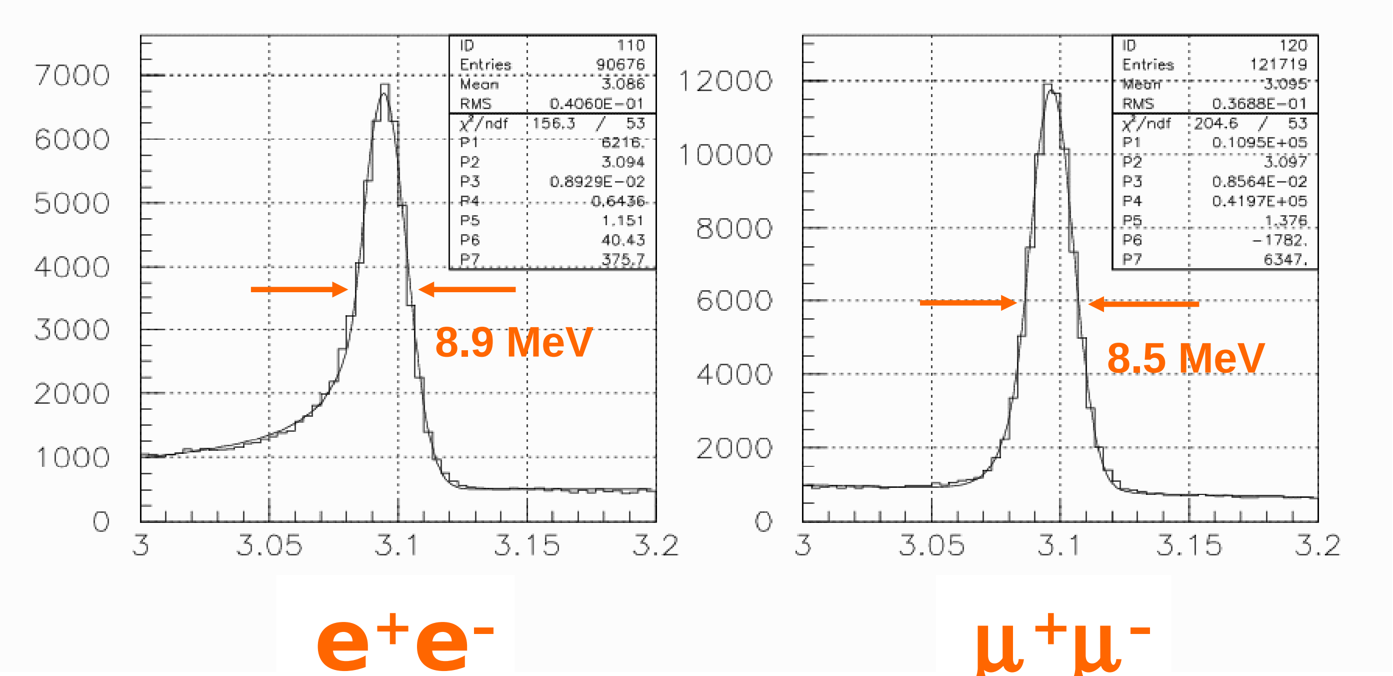




√s=10.58 GeV
on-resonance
J/ψ from B decays

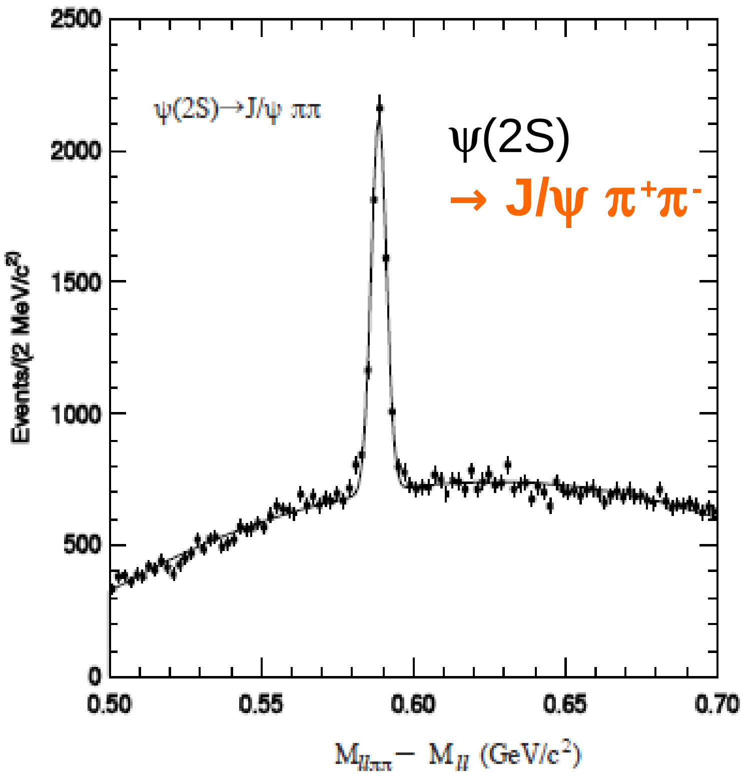
√s=10.52 GeV
off-resonance
direct J/ψ production

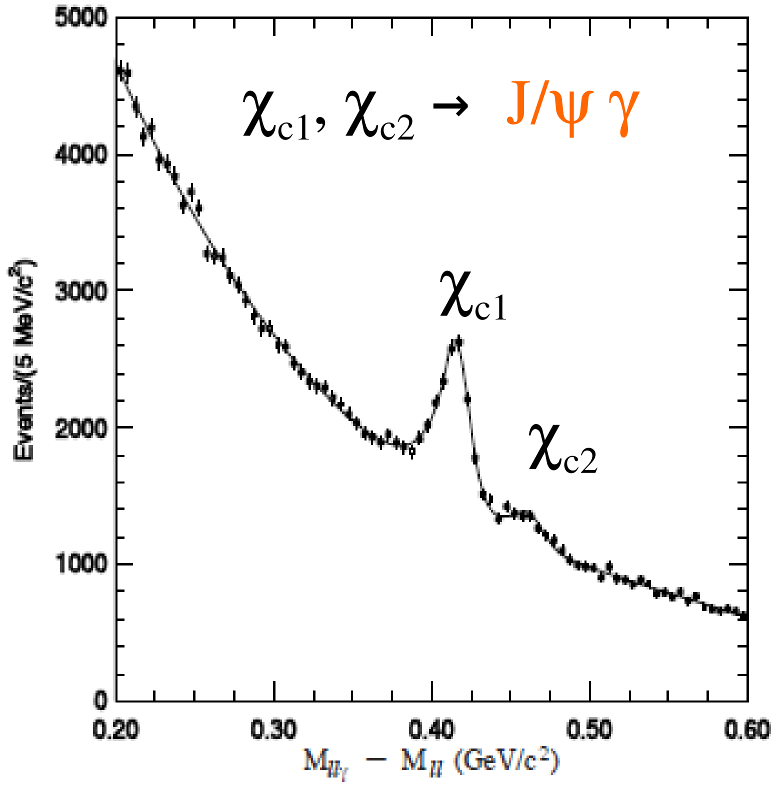
J/ψ Invariant Mass



Radiative Tail !

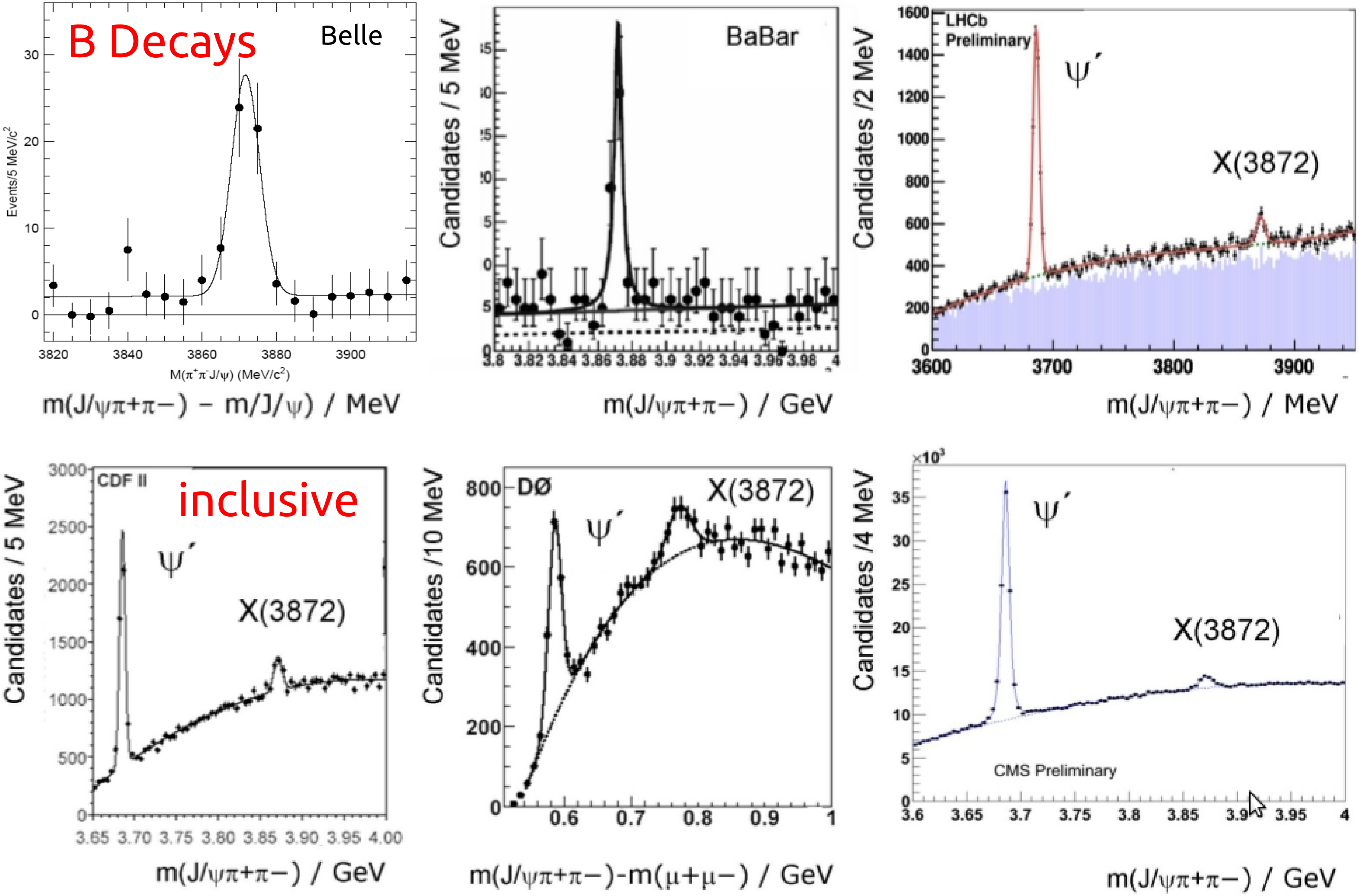
Reconstruction of higher Charmonium States





X(3872)

A molecular state?

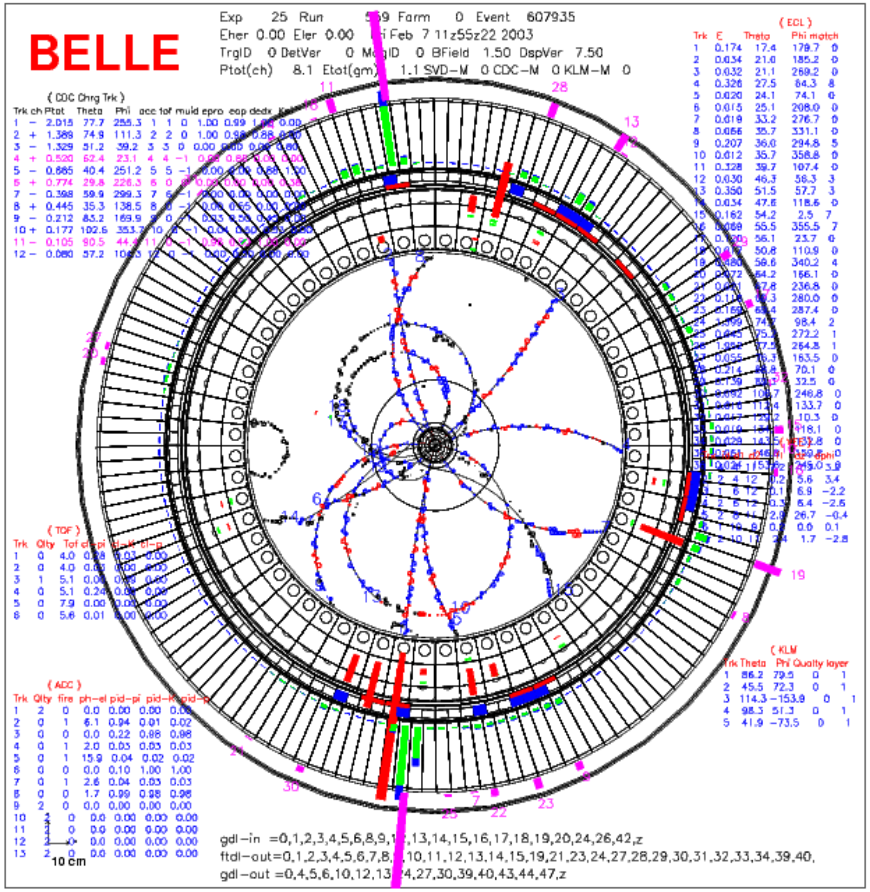

B Decays
Belle
Events/5 MeV/c^2
M(π+π-J/ψ) (MeV/c^2)
m(J/ψπ+π−) − m/J/ψ) / MeV
BaBar
Candidates / 5 MeV
m(J/ψπ+π−) / GeV
LHCb Preliminary
ψ´
X(3872)
Candidates /2 MeV
m(J/ψπ+π−) / MeV
inclusive
CDF II
ψ´
X(3872)
Candidates / 5 MeV
m(J/ψπ+π−) / GeV
DØ
ψ´
X(3872)
Candidates /10 MeV
m(J/ψπ+π−)-m(μ+μ−) / GeV
ψ´
X(3872)
CMS Preliminary
Candidates /4 MeV
m(J/ψπ+π−) / GeV

X(3872)

- observed
  in more than one
  decay channel

$$X(3872) \rightarrow J/\psi\pi^+\pi^-$$
$$X(3872) \rightarrow J/\psi\gamma$$
$$X(3872) \rightarrow J/\psi\pi^+\pi^-\pi^0$$
$$X(3872) \rightarrow D^0\overline{D}^0\pi^0$$
$$X(3872) \rightarrow D^0\overline{D}^0\gamma$$
$$X(3872) \rightarrow \psi'\gamma$$

- very narrow width
  Γ<1.2 MeV (90% CL)
- mass very close
  to $\overline{D}D^*$ threshold

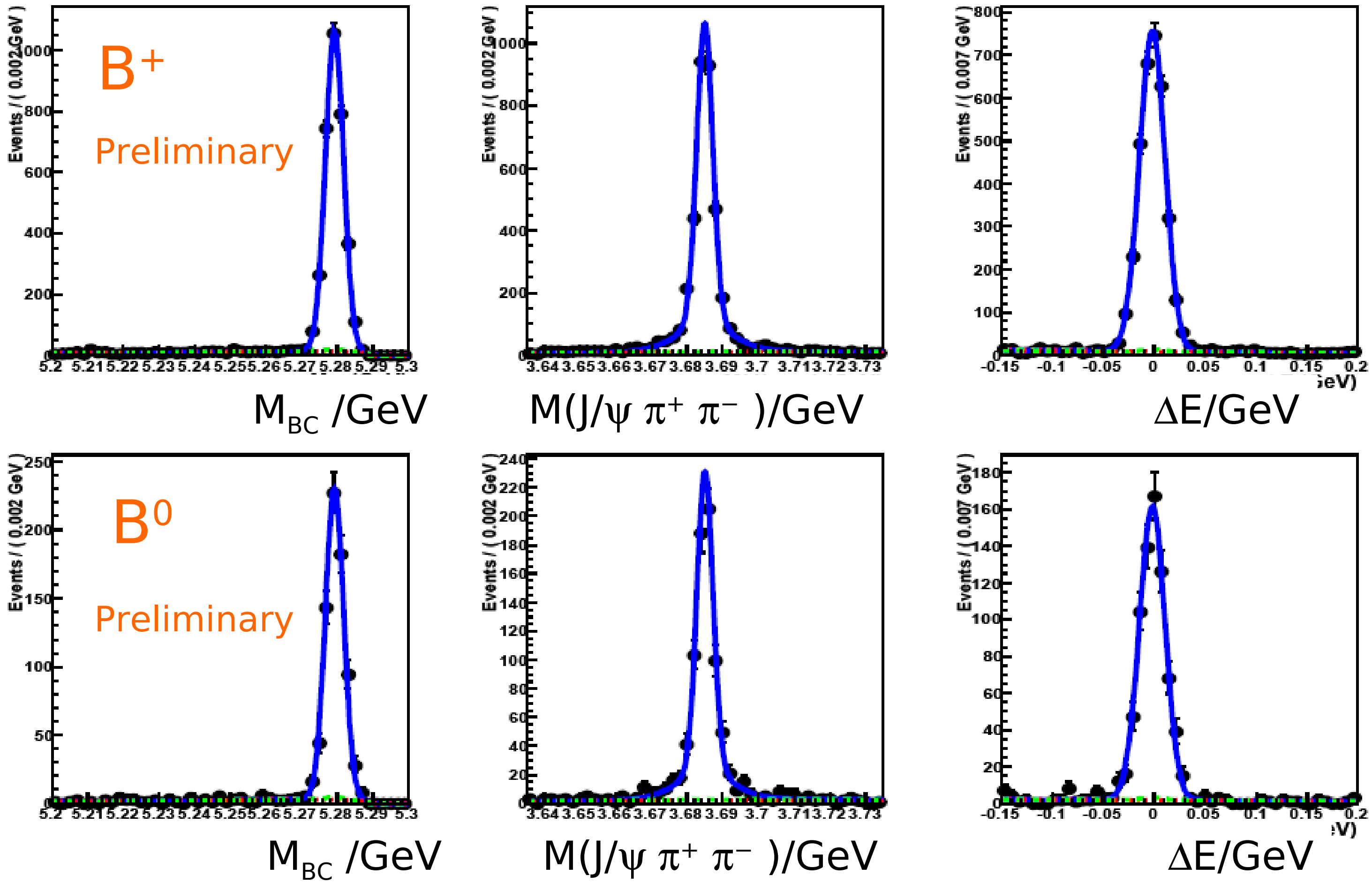


Belle, Phys. Rev. Lett.91(2003)262001
CDF-II, Phys. Rev. Lett.93(2004)072001
D0, Phys. Rev. Lett.93(2004)162002
BaBar, Phys. Rev. D71(2005)071103
LHCb, Eur. Phys. J. C72(2012)1972
CMS, arXiv:1302.3968[hep-ex]

Reference Analysis: $B \to K\psi'$, $\psi' \to J/\psi\, \pi^+\pi^-$

$M_{bc} \equiv \sqrt{(E_{beam}^{cms})^2 - (p_B^{cms})^2}$

$\Delta E \equiv E_B^{cms} - E_{beam}^{cms}$



3-dim fit in beam constrained mass, $J/\psi\, \pi^+ \pi^-$ mass and ΔE
at first, fit reference signal ψ'
$\to$ fix core Gaussian and tail Gaussian for resolution parameters

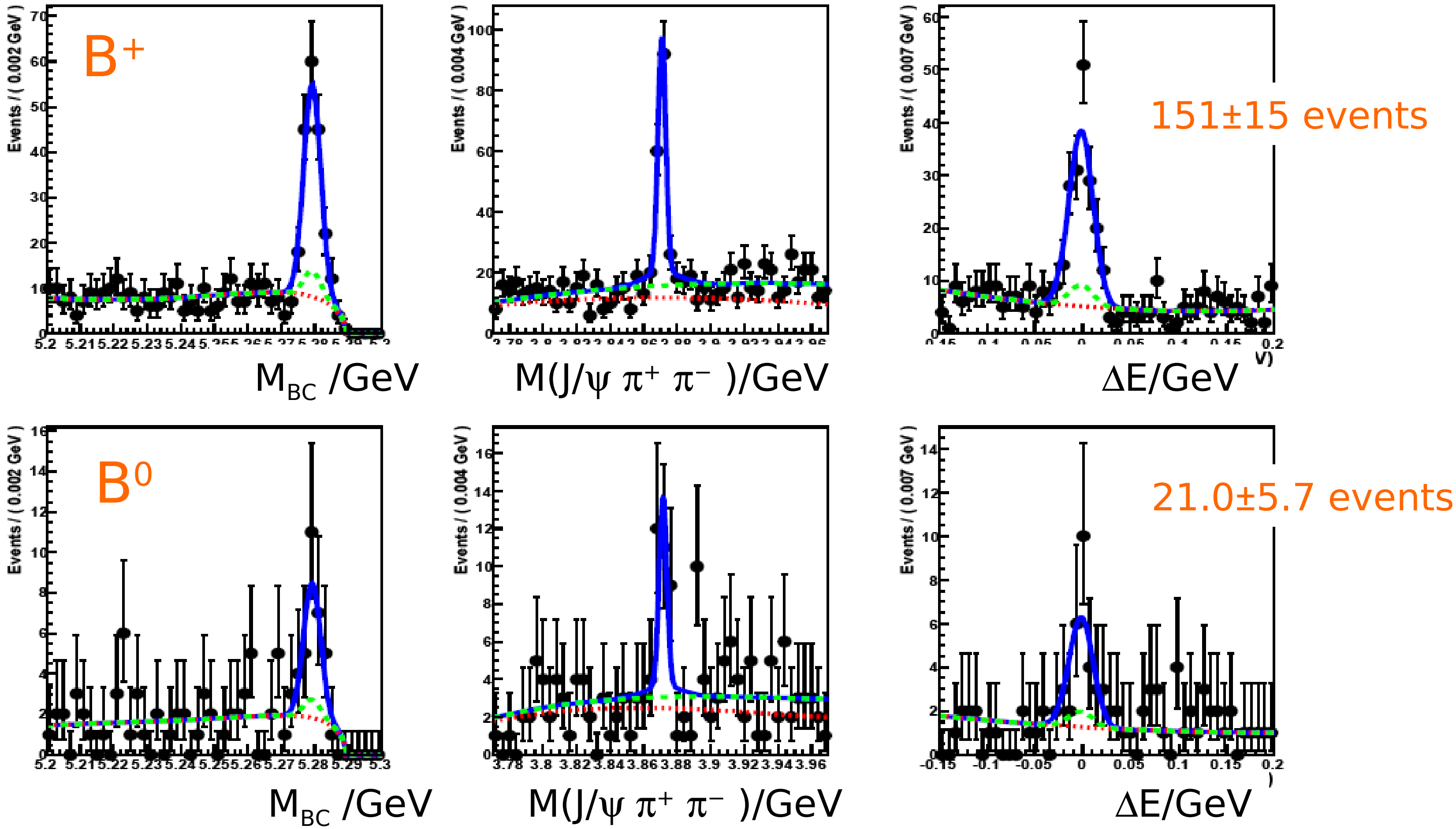
$$B \to K\,[\,J/\psi\,\pi_1\,\pi_2\,]$$

```
px_Bc = jpsi_vector.x() + pcms[kaon].x() + pcms[pion1].x() + pcms[pion2].x();
py_Bc = jpsi_vector.y() + pcms[kaon].y() + pcms[pion1].y() + pcms[pion2].y();
pz_Bc = jpsi_vector.z() + pcms[kaon].z() + pcms[pion1].z() + pcms[pion2].z();

esum_Bc = jpsi_vector.e() + pcms[kaon].e() + pcms[pion1].e() + pcms[pion2].e();

deltaE = ECM/2 – esum_Bc;

mass_BC = sqrt( ECM*ECM/4. - (px_Bc*px_Bc + py_Bc*py_Bc + pz_Bc*pz_Bc) );
```

ECM comes from accelerator measurement.

Analysis of X(3872) → J/ψ π+π−

Preliminary



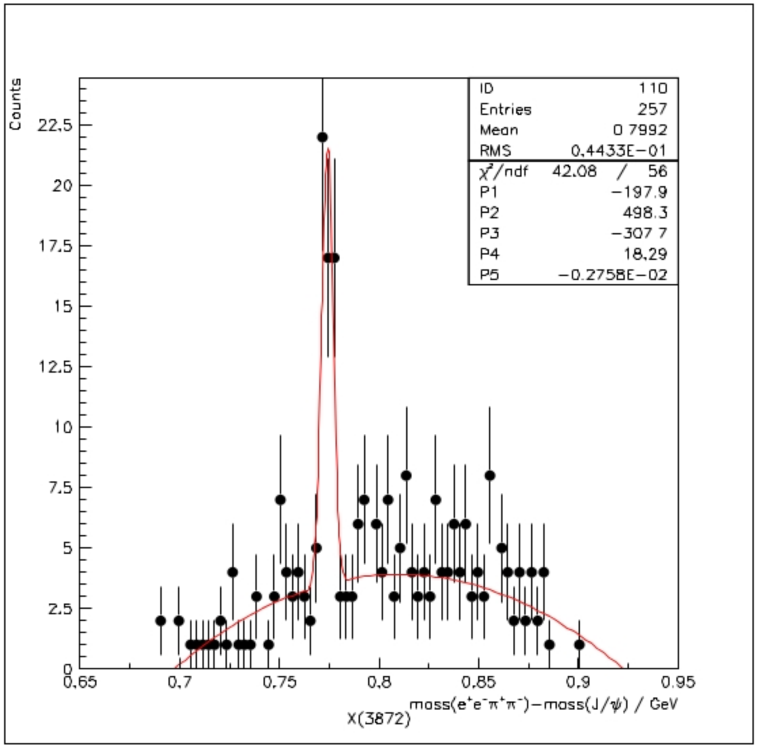
3-dim fit
with fixed resolution parameters from ψ´
Mass MC/data shift +0.92±0.06 MeV, measured and fixed from ψ´ mass

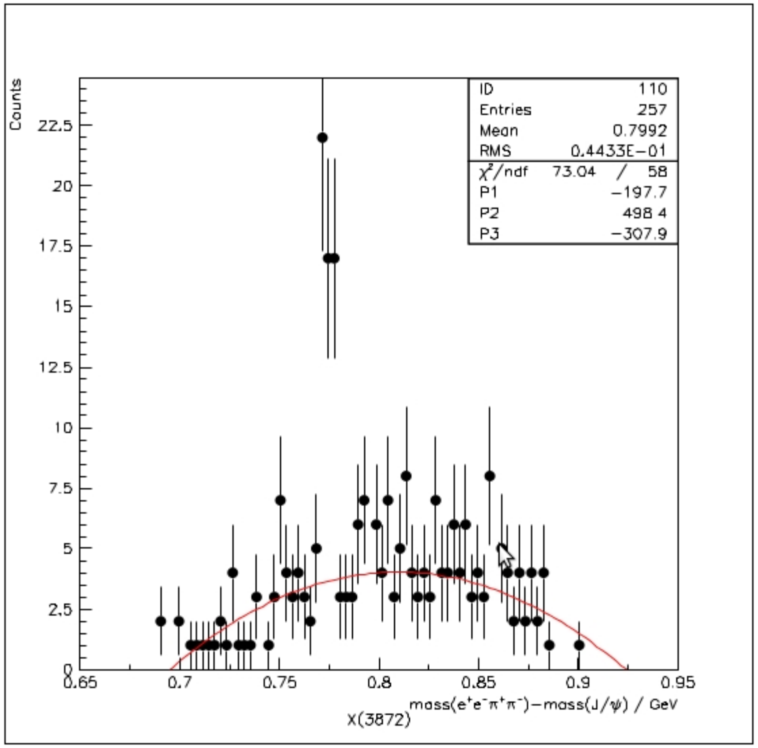
Experiment	Mass of X(3872)
CDF2	3871.61±0.16±0.19 MeV
BaBar (B^+)	3871.4±0.6±0.1 MeV
BaBar (B^0)	3868.7±1.5±0.4 MeV
D0	3871.8±3.1±3.0 MeV
Belle	3871.84±0.27±0.19 MeV
LHCb	3871.95±0.48±0.12 MeV
World Average	3871.68±0.17 MeV

$m(D^0)+m(D^{*0})=3871.84\pm0.28$ MeV
„binding energy“ −0.16±0.33 MeV

reminder: binding energy of deuteron 2.2 MeV

Statistical Significance





Fit S+BG — Fit only BG

χ^2=42.08 — χ^2=73.04

Significance = $\sqrt{(-42.08 + 73.08)}$ = 5.6 „sigma“

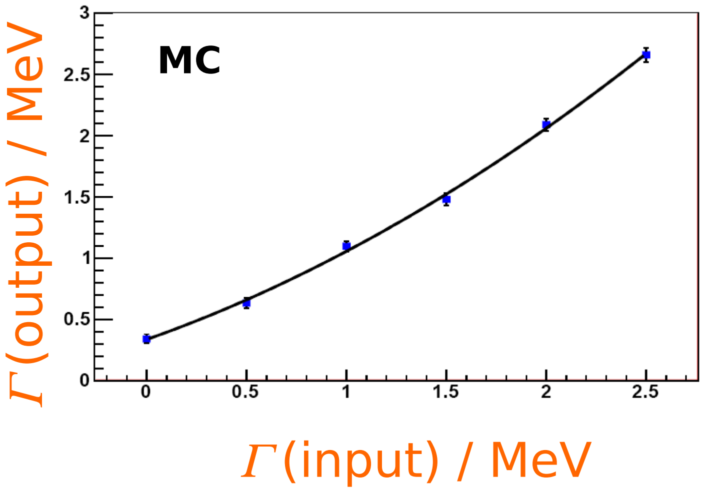
if „likelihood fit“, then $\chi^2 \rightarrow$ 2ln(likelihood)

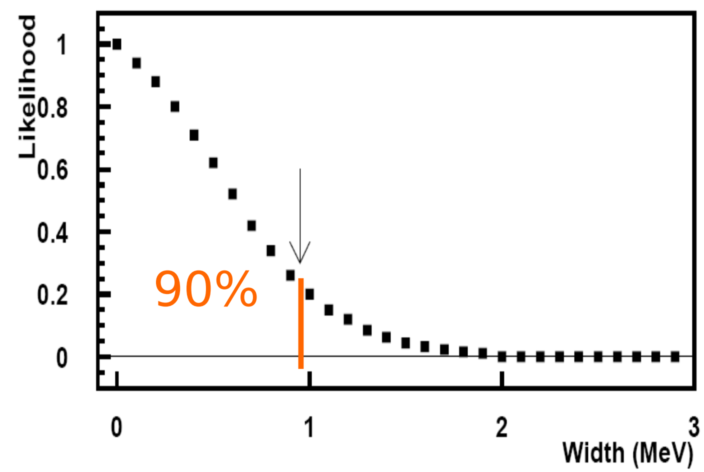
Upper limit ($<3\sigma$), evidence ($>3\sigma$), observation ($>5\sigma$)

Measurement of width of X(3872)

- Previous best limit
  $\Gamma_{X(3872)}$ < 2.3 MeV (90% CL)
- 3-dim fits are sensitive
  to natural widths narrower
  than resolution <σ>~4 MeV
  because of constraints (m_{BC}, ΔE)
- Method validated with ψ´width
  $\Gamma_{\psi'}$=0.52±0.11 MeV
  (PDG 0.304±0.009 MeV)
  → bias 0.23±0.11 MeV
- procedure for upper limit:
  width in 3-dim fit fixed
  n_{signal} and $n_{peaking\ BG}$ floating
  → calculate likelihood
- $\Gamma_{X(3872)}$ < 0.95 MeV + bias

  1.2 MeV





One X or two XX ?

X(3872) and x(3875)

Tetraquark interpretation, Maiani et al., hep-ph/0707.3354, Phys. Rev. Lett.99(2007)182003

[cu][cu]→ $\bar{D}^0 D^0 \pi^0$ = X(3875) , [cd][cd] → $J/\psi\, \pi^+ \pi^-$ = X(3872)

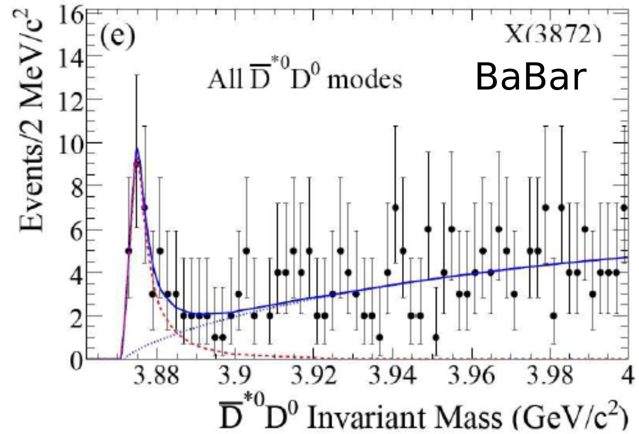
background

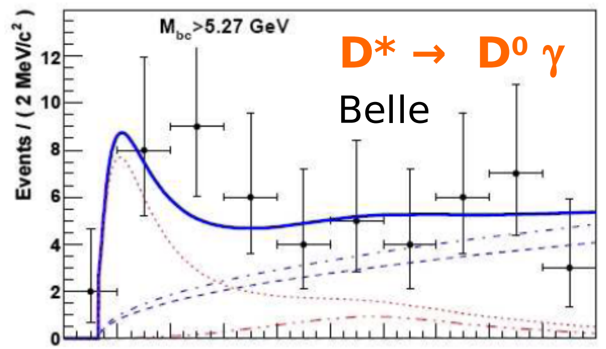
X(3872) $\to \bar{D}D^*$

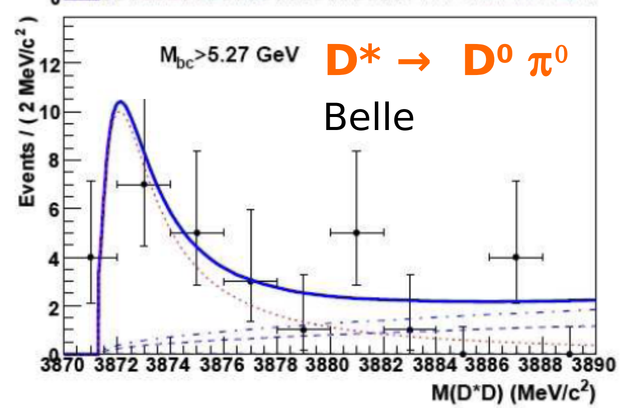
- Decay into $\bar{D}D^*$ is dominant
  BR is factor ~10
  higher than for $J/\psi\, \pi^+ \pi^-$
  BR(B decay) x BR(X decay) ~10^−4

- BaBar, Phys. Rev. D77(2008)011102(R)
  m=$3875.1^{+0.7}_{-0.5} \pm 0.5$ MeV
  - binned maximum likelihood fit
  - 1-dim fit, M(D*D)
  - signal pdf from MC
  - exponential function background

- Belle, Phys. Rev. D81(2010)031103
  m=$3872.9^{+0.6}_{-0.4}{}^{+0.4}_{-0.5}$ MeV
  - <u>un</u>binned maximum likelihood fit
  - 2-dim fit
    - beam constraint mass
      Gaussian signal
      Argus function for background
    - M($\bar{D}D^*$)
      Breit-Wigner signal
      square root for background

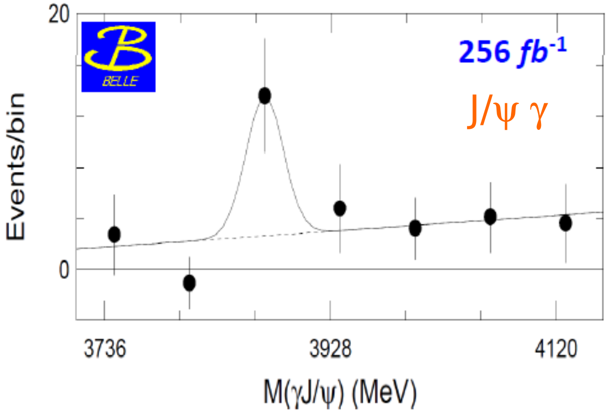


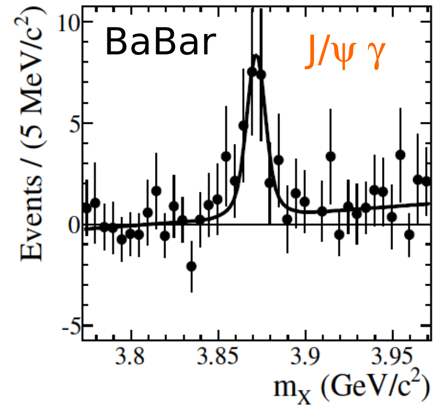


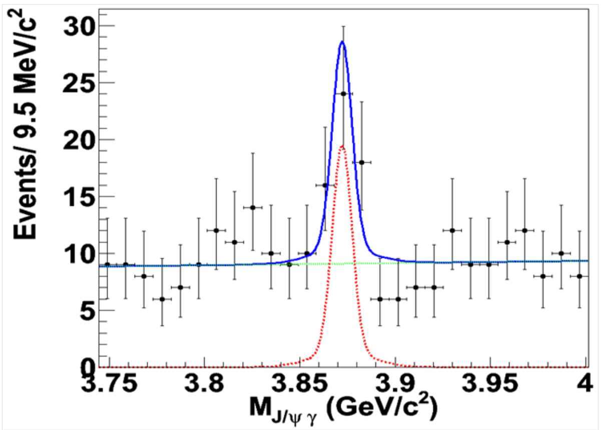


Radiative Decay
X(3872) → J/ψ γ

- Rare Decay
  BR is factor ~6
  smaller than BR(X → J/ψ $\pi^+ \pi^-$)
  BR(B decay) x BR(X decay) ~10^-6
- Evidence for X(3872) → J/ψ γ by Belle
  256/fb
  13.6±4.4 events
  arXiv:hep-ex/0505037
- Confirmed by BaBar
  424/fb
  23.0±6.4 events
  Phys. Rev. D 74(2006)071101
- Re-analysed
  Belle 711 fb^{-1}
  PRL 107(2011)091803 (2011)
- **Proof for C=+1 (positive C parity)**







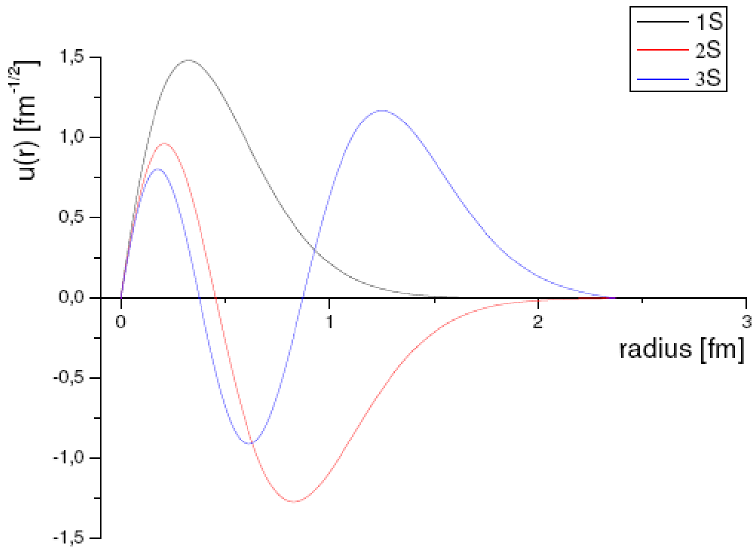
C=+ states

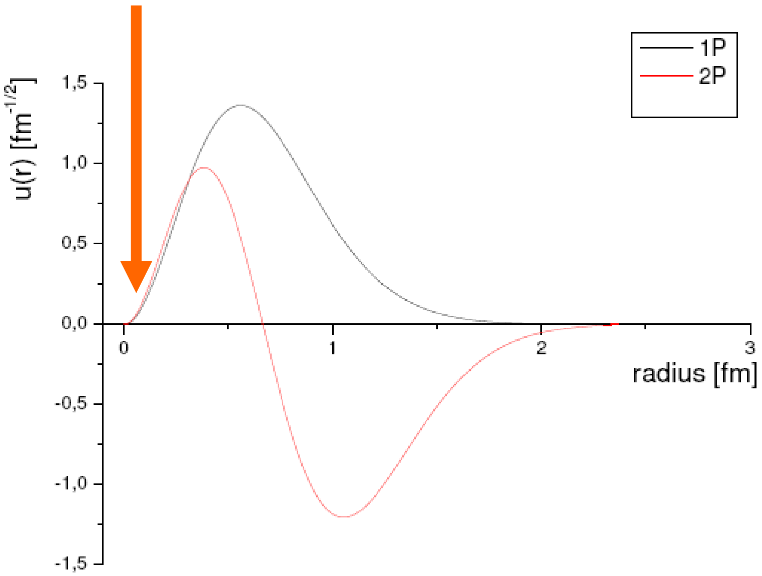
- Cannot decay to γ ($\rightarrow e^+ e^-$)
- only decay to $\gamma\gamma$ or gluon gluon

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

$$\Gamma(^3P_0 \to \gamma\gamma) = \frac{256}{3}\frac{\alpha_{em}^2}{m_c^4}|\frac{\partial\psi}{\partial r}(r=0)|^2$$

sensitive to derivative of wavefunction

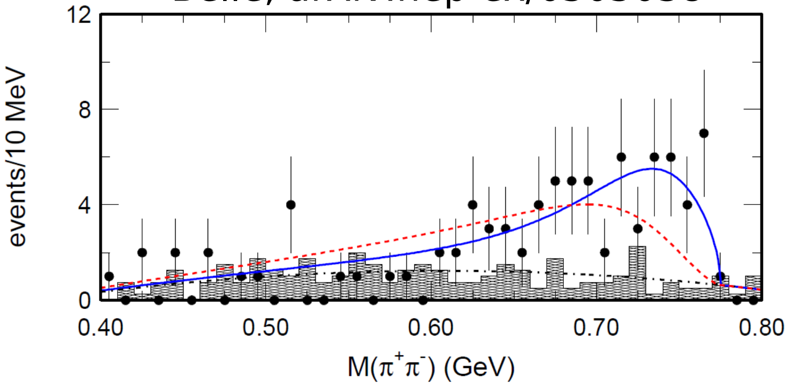


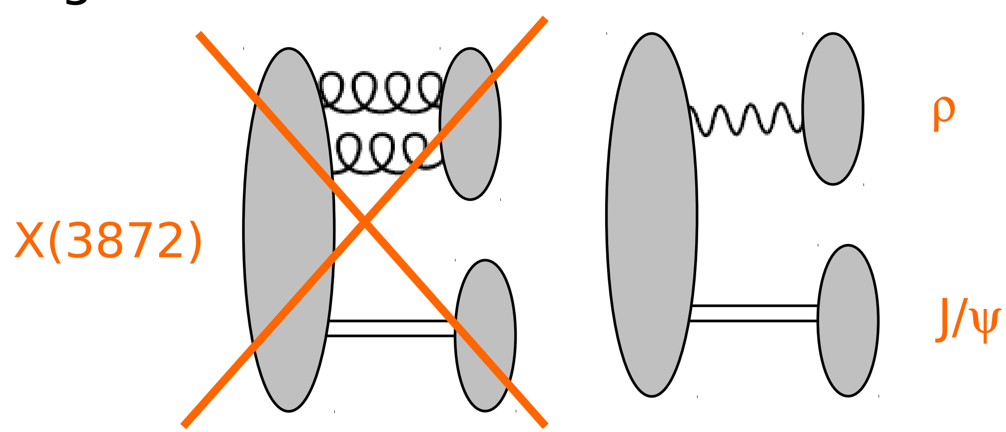


Isospin Violation

- X(3872) → J/ψ $\pi^+ \pi^-$
  observation: $\pi^+\pi^-$ invariant mass peaks at ρ^0
- X(3872) → J/ψρ*(I=1)* violates isospin
- Reason?
  - u-d mass difference (in strong interactions)
  - u-d charge difference (in EM interactions)
- X(3872) can only decay into $\bar{D}^{0}$*D^0, [cu]
  not in D^+*D^-, [cd]
  (threshold is 8 MeV higher)
- or this decay is EM, not strong

Belle, arXiv:hep-ex/0505038





Isospin violating Charmonium Transistions

Only two decays for charmonium measured in PDG.

ψ'

Decays into $J/\psi(1S)$ and anything

$J/\psi(1S)$anything	(59.5 ± 0.8) %		–
$J/\psi(1S)$neutrals	(24.5 ± 0.4) %		–
$J/\psi(1S)\pi^+\pi^-$	(33.6 ± 0.4) %		477
$J/\psi(1S)\pi^0\pi^0$	(17.73 ± 0.34) %		481
$J/\psi(1S)\eta$	(3.28 ± 0.07) %		199
$J/\psi(1S)\pi^0$	$(1.30 \pm 0.10) \times 10^{-3}$	S=1.4	528

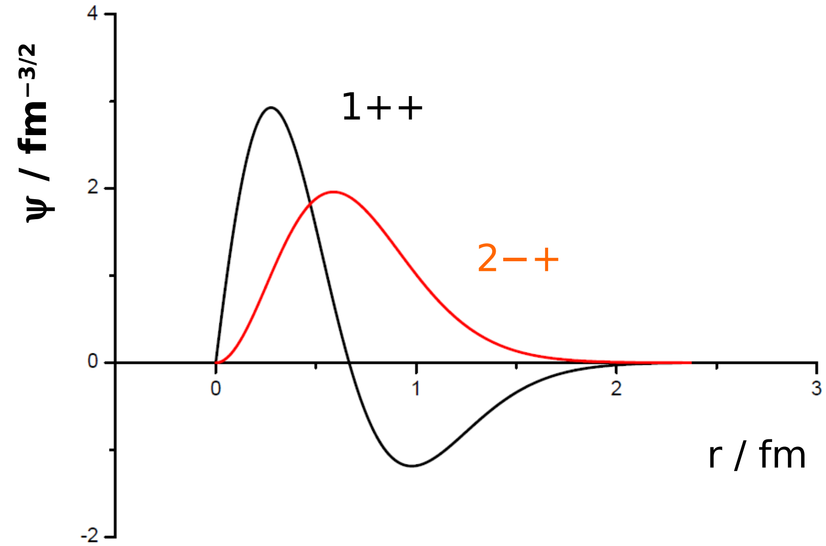
But branching fraction of
$X(3872) \rightarrow J/\psi\rho$
is order of ~10%

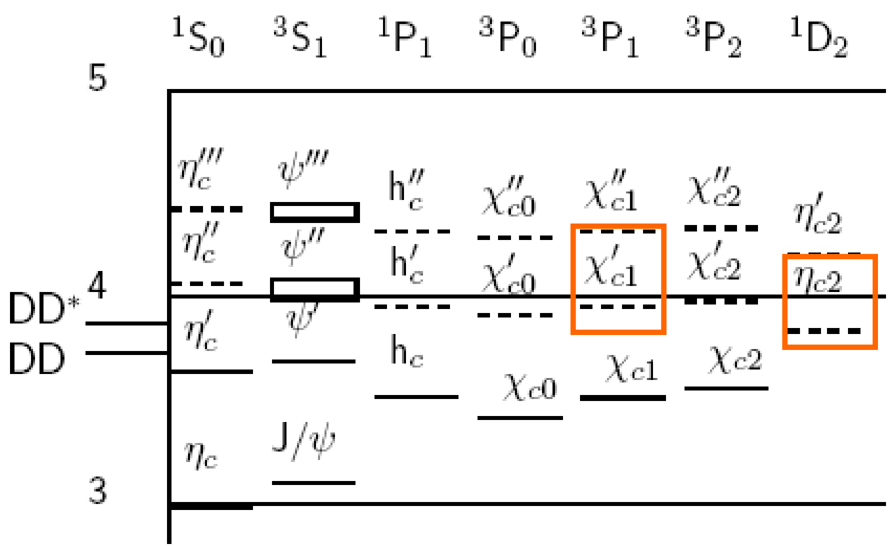
2nd decay is
$\psi' \rightarrow h_c \pi^0$

Possible Charmonium Assignment of X(3872)

- Case 2π → P=+
  1++
  χ_{c1}' $^3P_1$
  predicted mass 70 MeV higher
  n=2

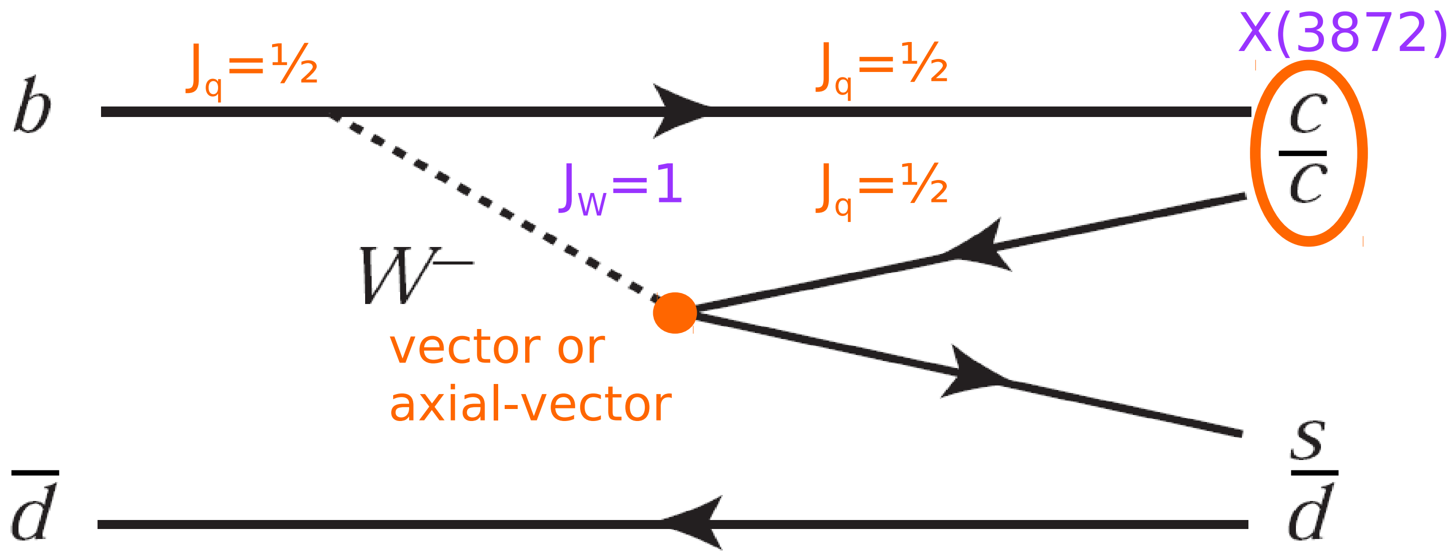
- Case 3π → P=−
  2−+
  η_{c2} $^1D_2$
  predicted mass 35 MeV lower
  n=1
  (would be a L=2 meson)





Mass predictions by
Barnes, Godfrey, Swanson
Phys. Rev. D72(2005)054026

J=2 in B decays ?

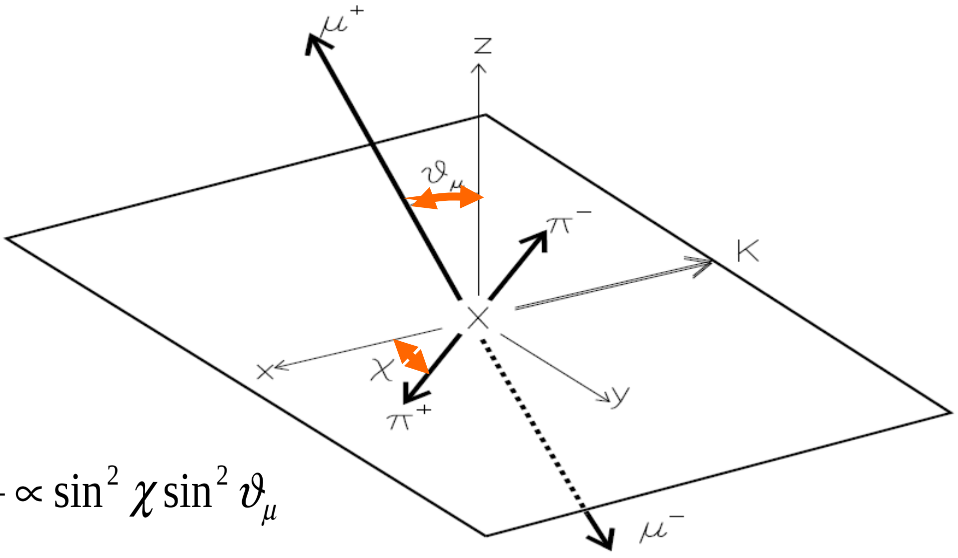


J=0 or J=1 preferred
Parity + or parity − allowed
$J^P=1^+$ no problem (e.g. $B^+ \rightarrow K^+\chi_{c1}$ seen with BR 4.6±0.4 x 10^{-4})

but J=2 very hard to be generated

Angular Analysis of X(3872)

- Assume
  X(3872) → J/ψ ρ
  in kinematic limit:
  both particles at rest
  in X(3872) rest frame
  $m_\chi = m_\rho + m_{J/\psi}$
  → higher partial waves
  can be neglected



$$\frac{d\Gamma(1^{++})}{d\cos\chi \, d\cos\vartheta_\mu} \propto \sin^2\chi \sin^2\vartheta_\mu$$

J. Rosner
PRD 70(2004)092023

- 1++
  1 amplitude
  L=0, S=1

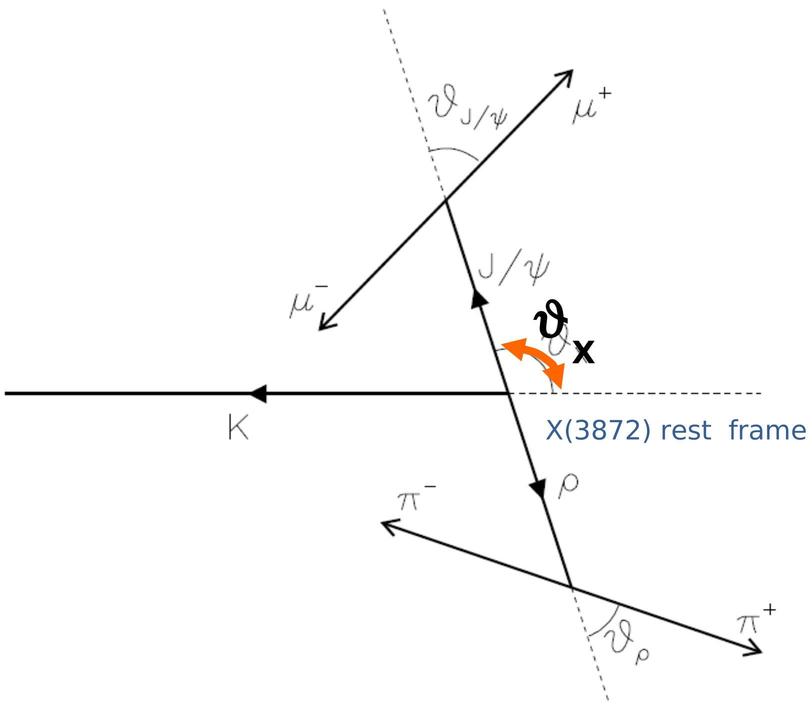
  only normalization
  floating in fit

- 2−+
  2 amplitudes
  L=1, S=1 or S=2

  normalization and α (complex)
  floating in the fit

$$\alpha = \frac{B_{11}}{B_{11} + B_{12}} = \frac{1}{1 + \frac{B_{12}}{B_{11}}}$$

Angular Variables

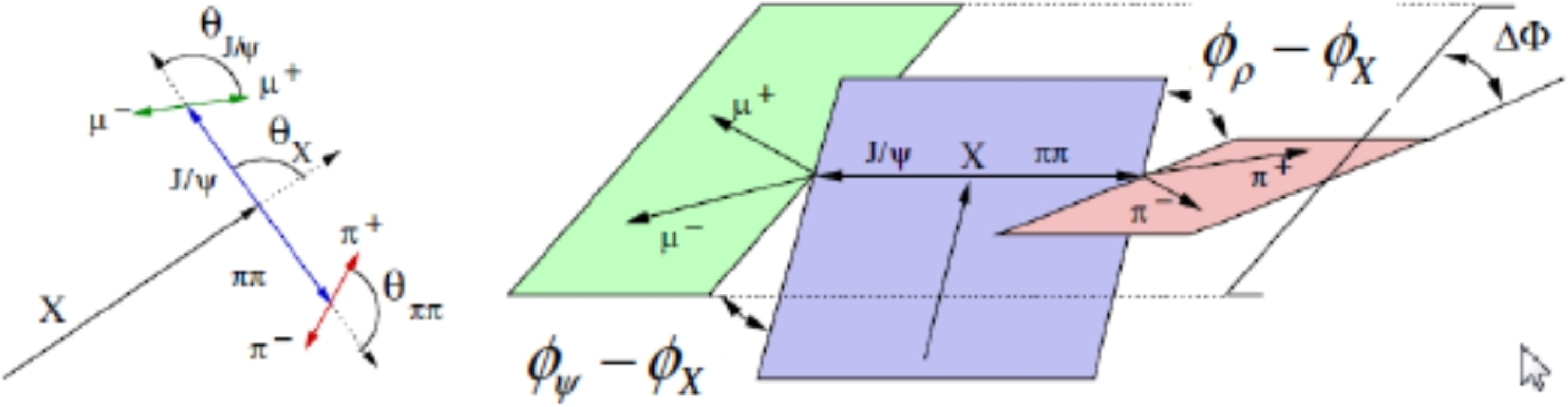


$$1^{++}: \frac{d\Gamma}{d\cos\vartheta_X} \propto \textit{flat}$$

2^{-+}

$$\alpha = 1: \frac{d\Gamma}{d\cos\vartheta_X} \propto 1 + 3\cos^2\vartheta_X$$

$$\alpha = 0: \frac{d\Gamma}{d\cos\vartheta_X} \propto \sin^2\vartheta_X$$



LHCb
5-dim analysis (3 helicity angles, 2 angles of decay planes)

→ quantum numbers of X(3872) are 1++
(2−+ excluded by 8.2 sigma)

arXiv: 1302.6269, Phys. Rev. Lett. 110(2013)222001, 1.0/fb

Exercise:

$B \rightarrow K\ X(3872)$

$0^- \rightarrow 0^-\ 1^+$

parity $(-1) \rightarrow$ parity $(-1) \times (+1) \times (-1)^L$

Exercise:

$B \to K\, X(3872)$

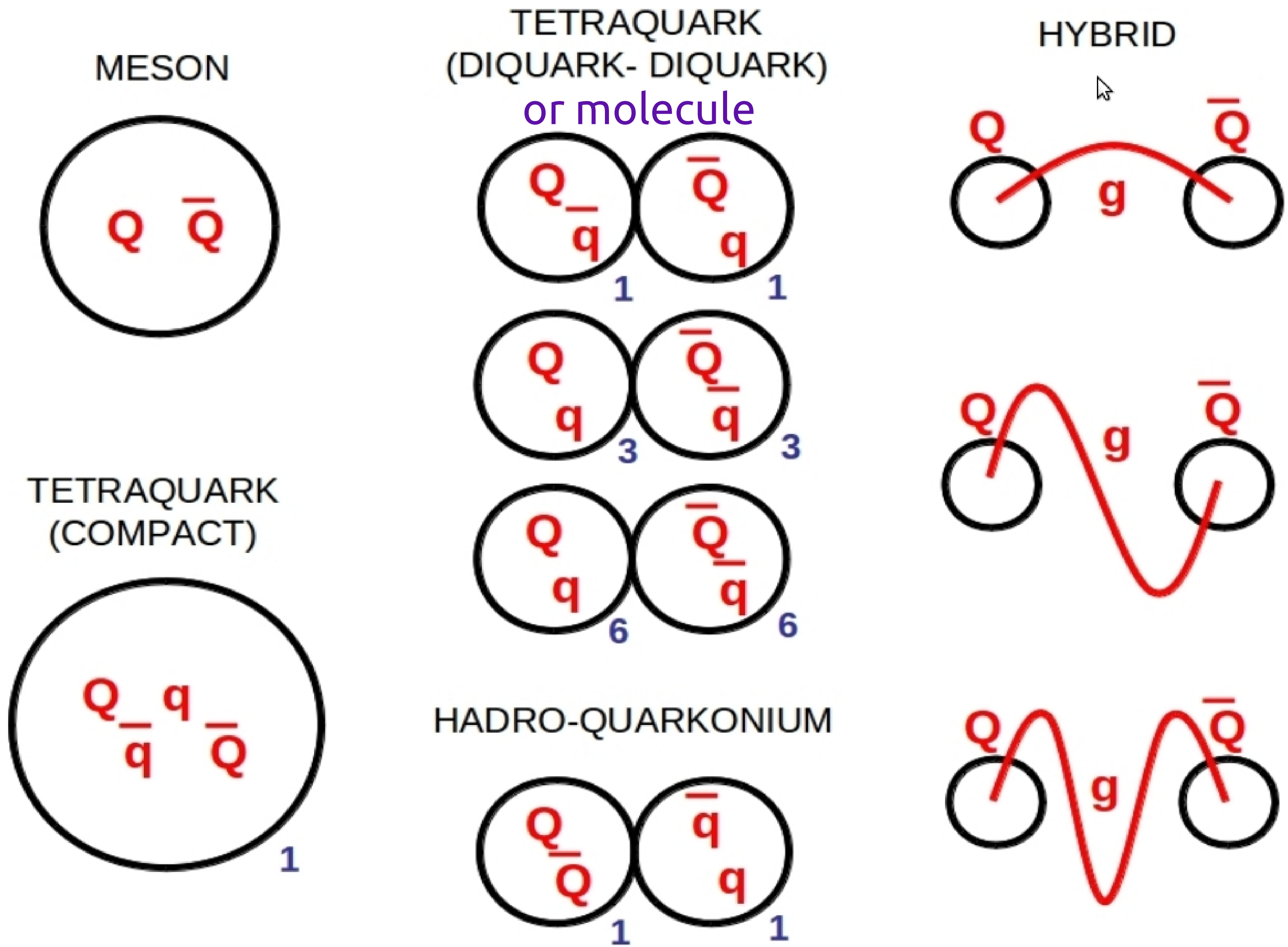
$0^- \to 0^-\ 1^+$

parity $(-1) \to$ parity $(-1) \times (+1) \times (-1)^L$

We need L=1 to create J=1,
but this violates parity.

What is the X(3872) ?

After 10 years we are still not sure.



Classification following E. Braaten, QWG'09

Y(4260)

$J^P=1^-$, but coupling to e^+e^- small.

(a hybrid state?)

Note: recent notation by PDG as X(4260)

Y(4260)

- initial state radiation events
  $e^+e^- \to \gamma\, J/\psi\pi^+\pi^-$
  (undetected γ parallel to beam axis)

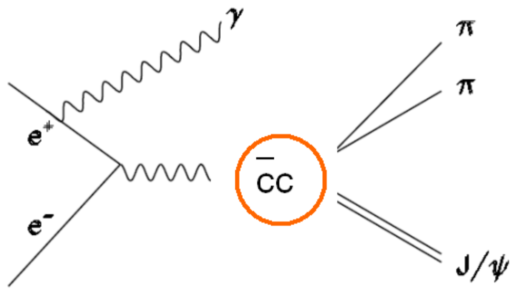
- mass >4 GeV
  far above DD(*) threshold

- width < 100 MeV
  quite narrow

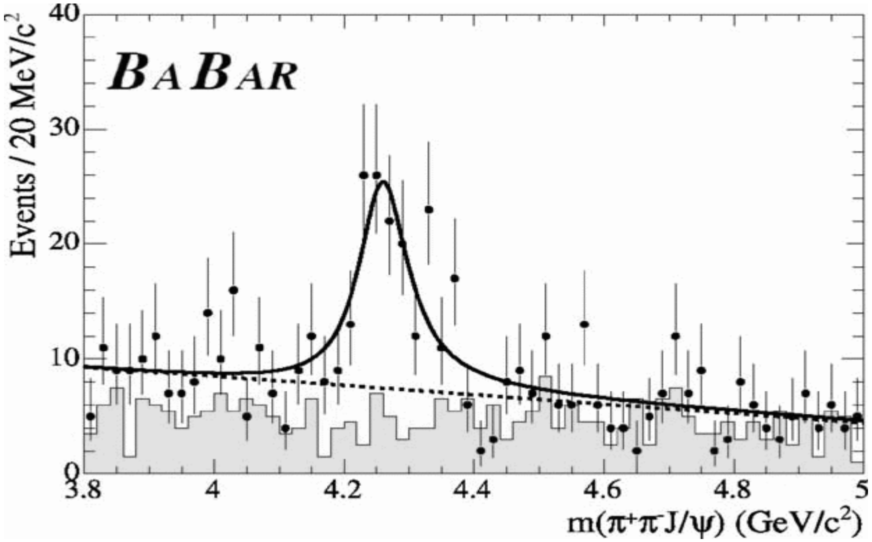
- significance $>10\sigma$

- quantum numbers must be
  (based upon production
  mechanism)
  $J^{PC}=1^{--}$

initial state radiation



Phys. Rev. Lett. 95(2005)142001

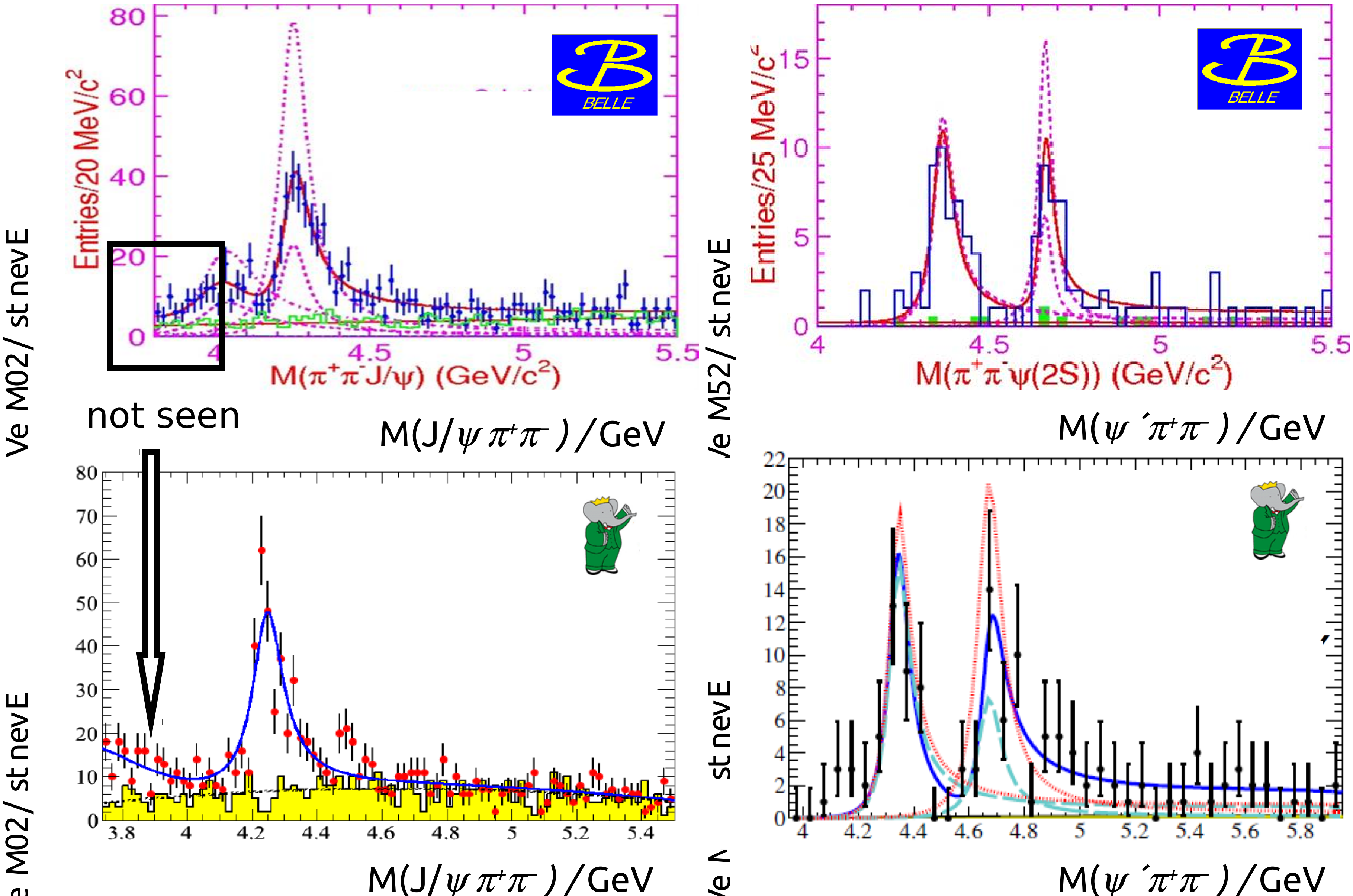


Y(4260) Parameters

	BaBar [1]	CLEO-c [2]	Belle [3]	Belle [4]	BaBar [5]	BaBar [6]
$\mathcal{L}$	211 fb^{-1}	13.3 fb^{-1}	553 fb^{-1}	548 fb^{-1}	454 fb^{-1}	454 fb^{-1}
N	125 ± 23	$14.1^{+5.2}_{-4.2}$	165 ± 24	324 ± 21	344 ± 39	–
Significance	$\simeq 8\sigma$	$\simeq 4.9\sigma$	$\geq 7\sigma$	$\geq 15\sigma$	–	–
m / MeV	$4259\pm8^{+2}_{-6}$	$4283^{+17}_{-16}\pm4$	$4295\pm10^{+10}_{-3}$	$4247\pm12^{+17}_{-32}$	$4252\pm6^{+2}_{-3}$	$4244\pm5\pm4$
Γ / MeV	$88\pm23^{+6}_{-4}$	70^{+40}_{-25}	$133\pm26^{+13}_{-6}$	$108\pm19\pm10$	$105\pm18^{+4}_{-6}$	$114^{+16}_{-15}\pm7$

[1] BaBar Collaboration, arXiv:hep-ex/0506081, Phys. Rev. Lett. 95(2005)142001.
[2] CLEO-c Collaboration, arXiv:hep-ex/0611021, Phys. Rev. D74(2006)091104.
[3] Belle Collaboration, arXiv:hep-ex/0612006.
[4] Belle Collaboration, arXiv:0707.2541[hep-ex], Phys. Rev. Lett. 99(2007)182004.
[5] BaBar Collaboration, arXiv:0808.1543[hep-ex].
[6] BaBar Collaboration, arXiv:1204.2158[hep-ex], Phys. Rev. D86(2012)051102.

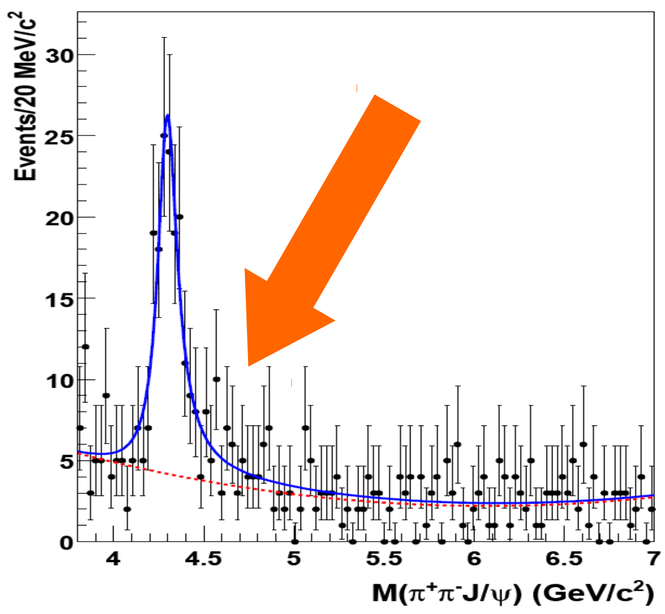
$e^+e^- \to \gamma_{ISR}\, J/\psi\ (\psi')\ \pi^+\pi^-$: Y(4008,4260,4350,4660)

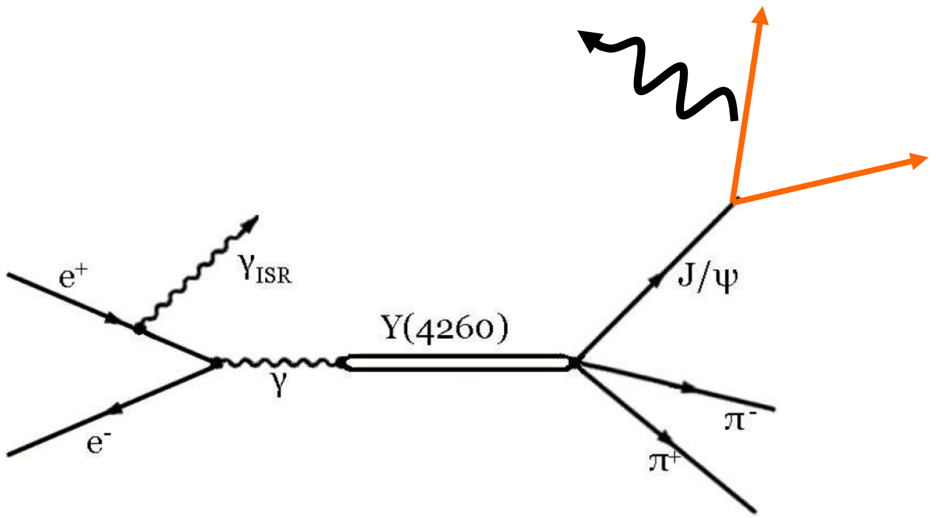


What is the tail around 4.7 GeV?

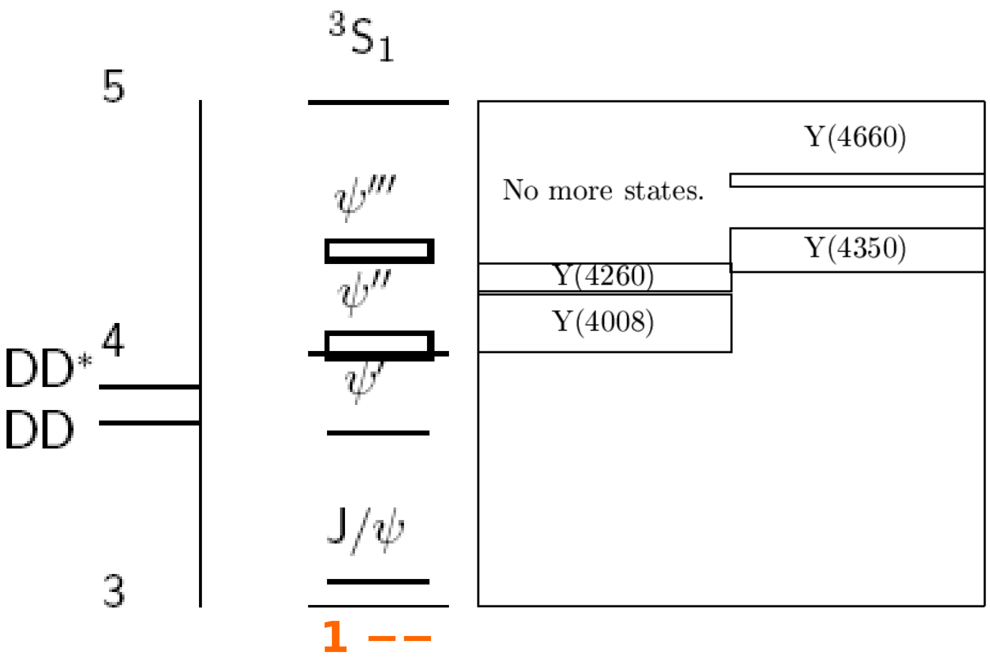
- Threshold m(D)+m(D**) = 4326 MeV
  Lineshape distorted? No.
- Non-corrected radiative effects? No.
  Radiative lower mass tail in $J/\psi \rightarrow e^+ e^-$
  might generate higher mass tail in m(J/ψ-with-wrong-mass $\pi^+\pi^-$).
- Fit funtion: Breit Wigner x Phasespace x Efficiency
  Efficiency $a(m-m_0)+b$ with $a=7.4\pm1.3$ GeV^{-1}, b=9.31 § 0.07 (Belle)
  changes factor ~2 over peak

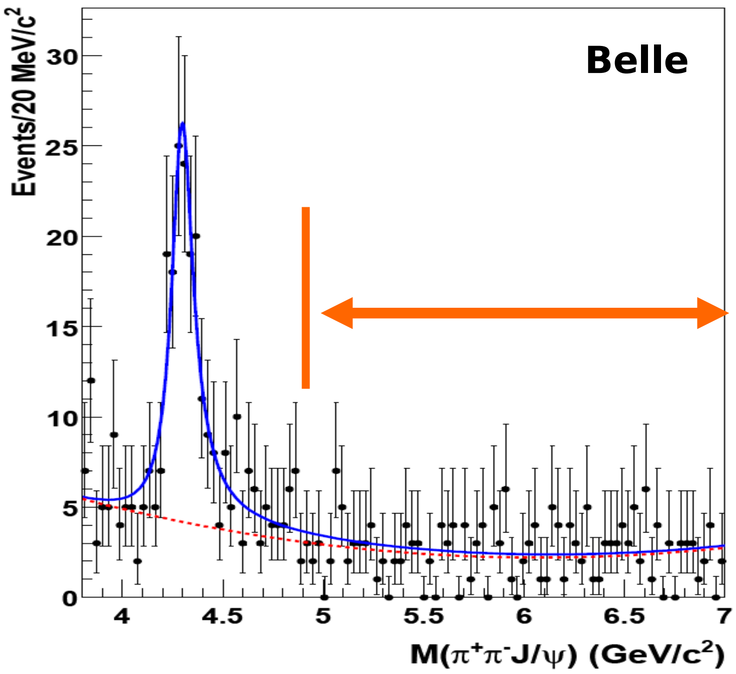
Belle, hep-ex/0612006





Overpopulation of 1^{--} States





No more [J/ψ π^+ π^-] state up to 7 GeV

All same quantum number

but apparently

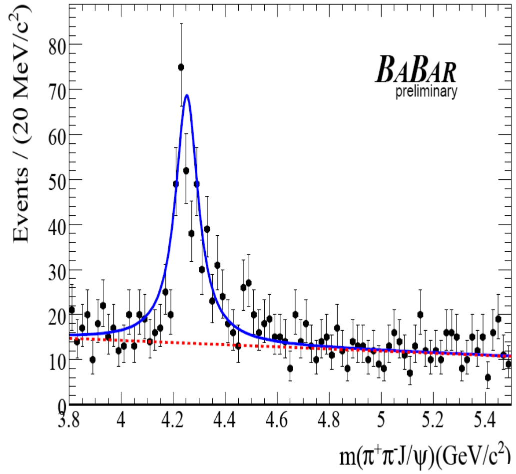
- no mixing with other ψ states
- no mixing among them
  Y(4260) seems not decay to ψ´ π^+ π^-
  Y(4350) seems not decay to J/ψ π^+ π^-

Note: radiative transistions between the states forbidden by parity

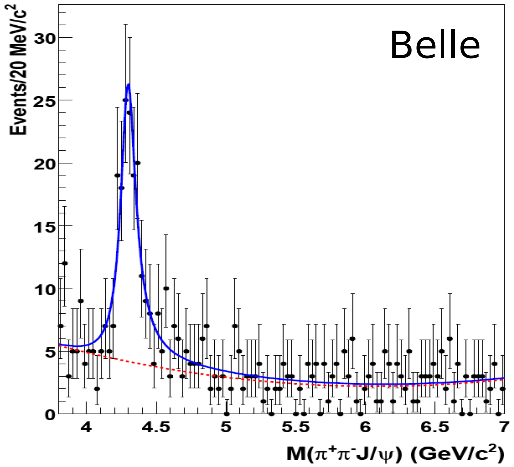
Y(4260): Comparison Belle and BaBar

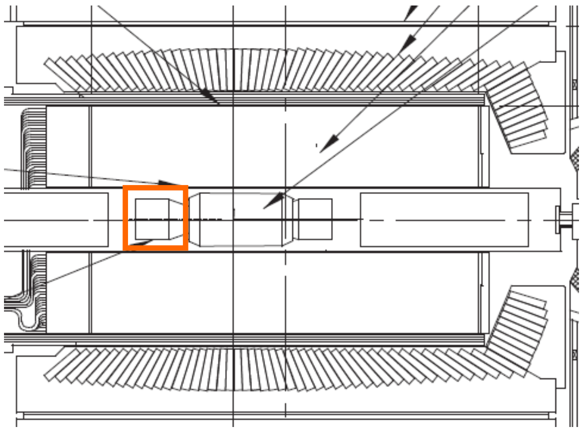
- BaBar collisions head-on, dipole magnet close to IR
- Belle: ±11 mrad
- slightly higher background at BaBar (also seen as MRad SVD radiation dose)
- backward acceptance for $\theta=180^0$ limited

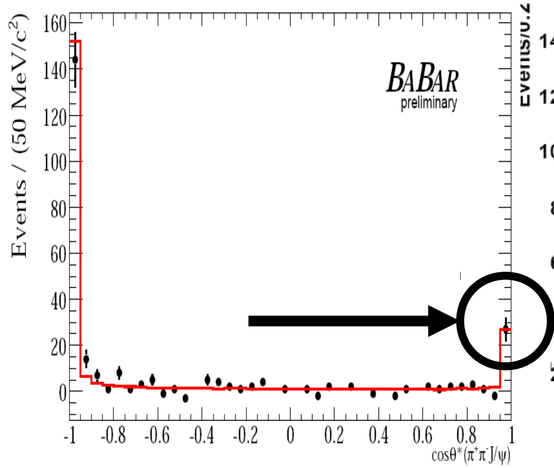
arXiv:0808.1543, 454/fb

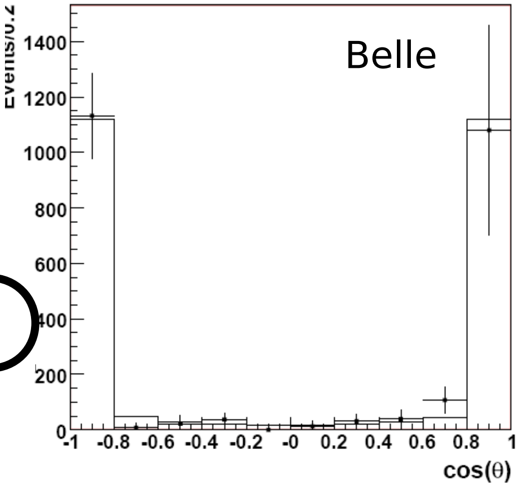


hep-ex/0612006, 553/fb









CMS polar angle of Y(4260) to e− beam

What is the Y(4260) ?

A hybrid ? $[QQ]_8 g$

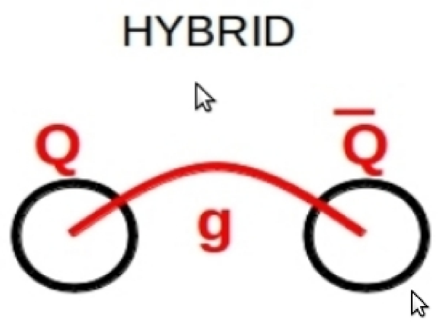
Does the Y(4260) decay to e+e– ?

- very small coupling to e+ e–
  (although J^P=1--)
  BR(J/ψ π^+ π^-) x $\Gamma(e^+ e^-)$ =
  (7.5±0.9±0.8) eV
  BaBar, arXiv:0808.1543

- This is a partial width of the order „eV“
  of a state which is ~100 MeV total width !

  → factor 10^8 suppressed

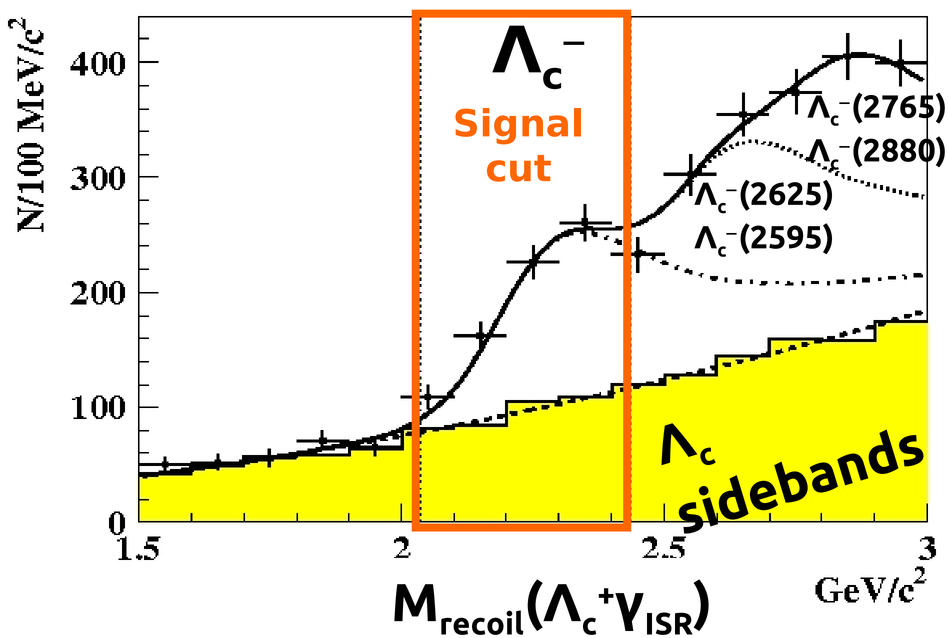
  What is blocking these decays?
  (maybe the gluonic string ?)



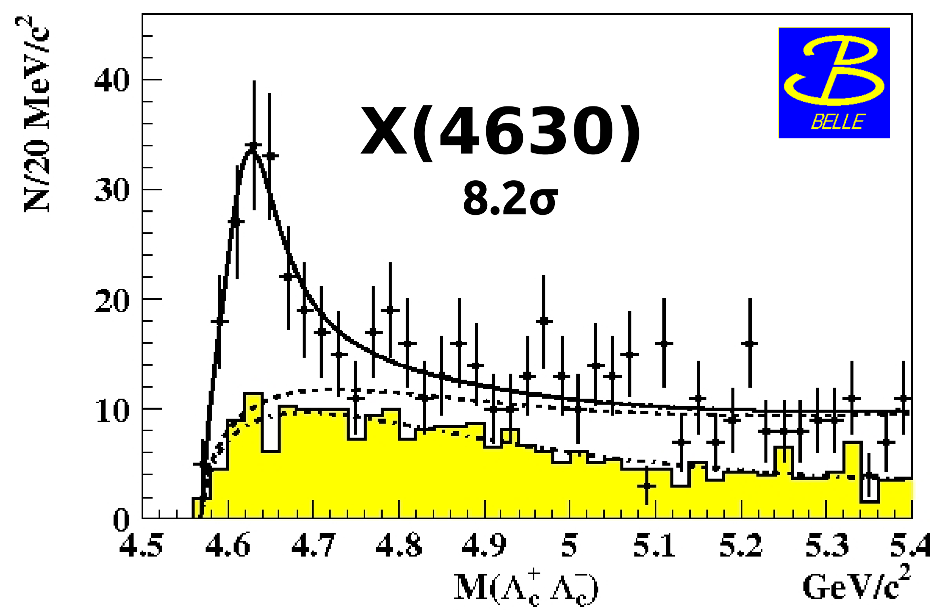
X(4630)

$e^+e^- \to \Lambda_c^+ \Lambda_c^- \gamma_{ISR}$

$\Lambda_c \to pK_s^0$, $pK^-\pi^+$, $\Lambda\pi^+$
Λ_c^- is tagged by anti-proton,
(partial reconstruction)



Phys. Rev. Lett. 101(2008)172001, 670/fb



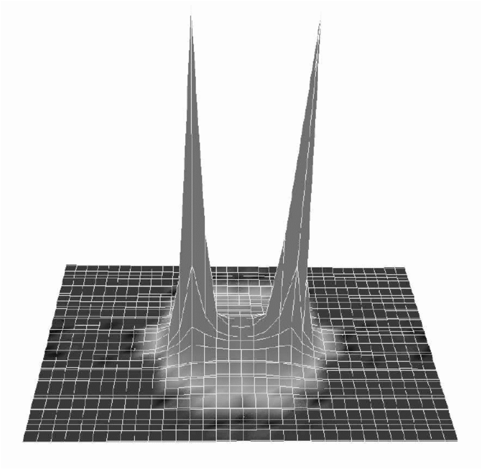
The X(4630) is the first observed XYZ state which decays into BARYONS !

The X(4630) and the Y(4660) are both seen in ISR.

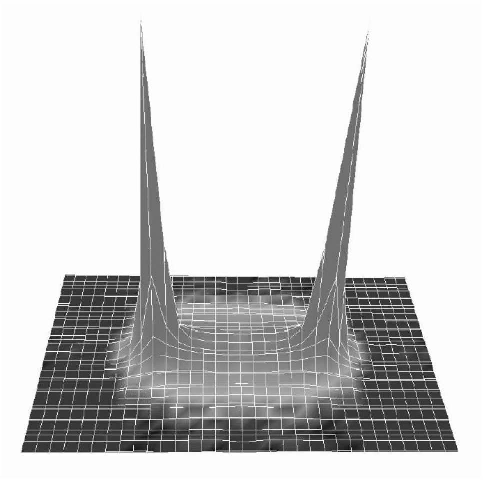
→ they are both 1^{--}

→ they could be the identical state (because it would be very very strange to have so many 1^{--} states so nearby)

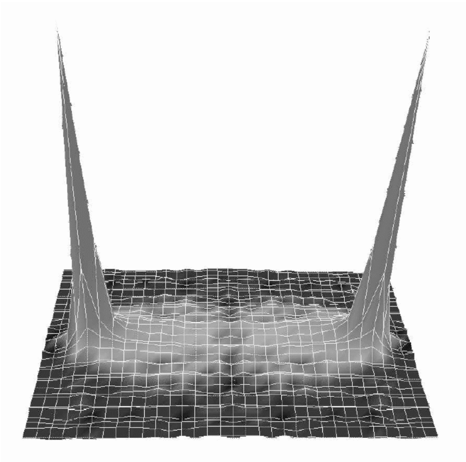
Reminder:
the QCD string is supposed to break at r>1.35 fm
(according to Lattice QCD)



r=0.7 fm



r=1.0 fm

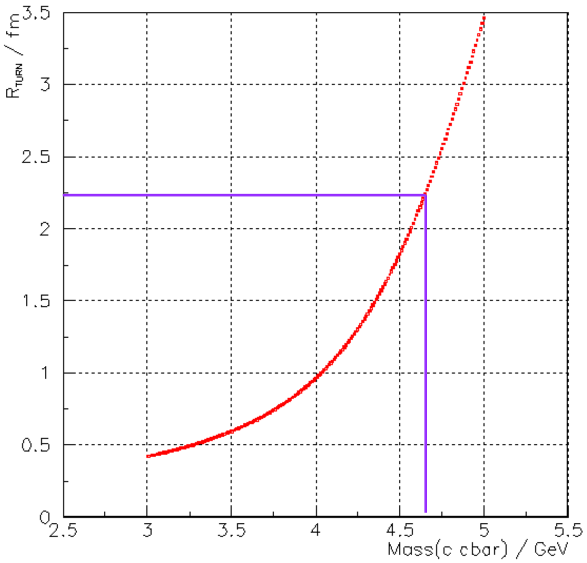


r=1.35 fm

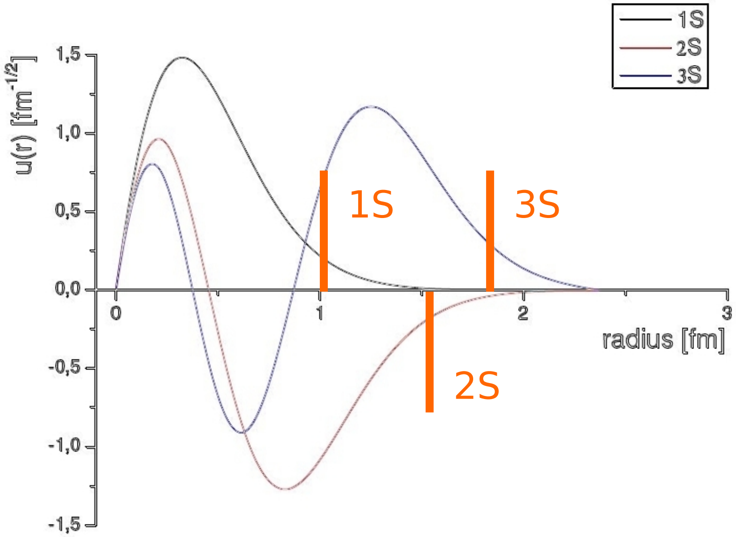
G. Bali, hep-lat/9409005

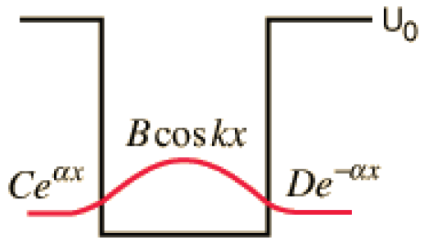
Potential Model:
Wronski-Determinant must be =0 at turning point

$$r_{\text{turning point}} = \frac{E-2m}{2\sigma} + \sqrt{\frac{4m^2-4mE+E^2}{4\sigma^2} + \frac{4\alpha_s}{3\sigma}}$$



- at m=4.660 GeV, the turning point of the wave function is at r>2 fm!
- large fraction of wave function is in string breaking regime r>1.35 fm



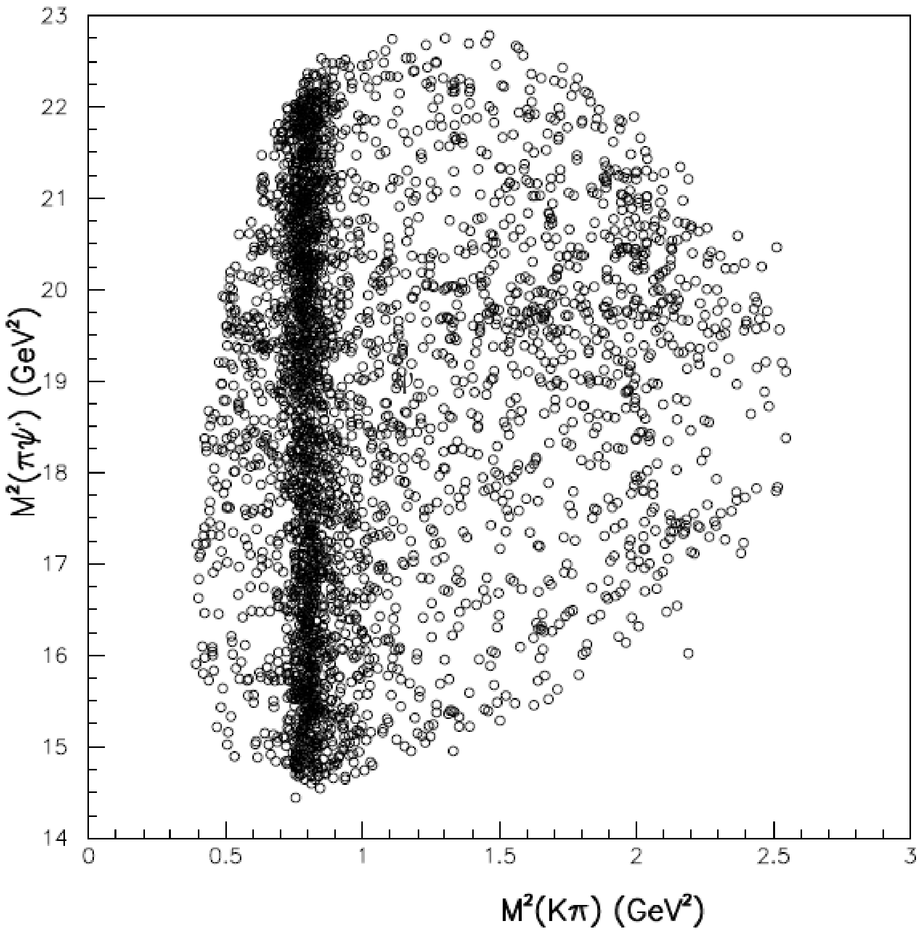


$Z(4430)^{+}$

A charged charmonium(-like) state.

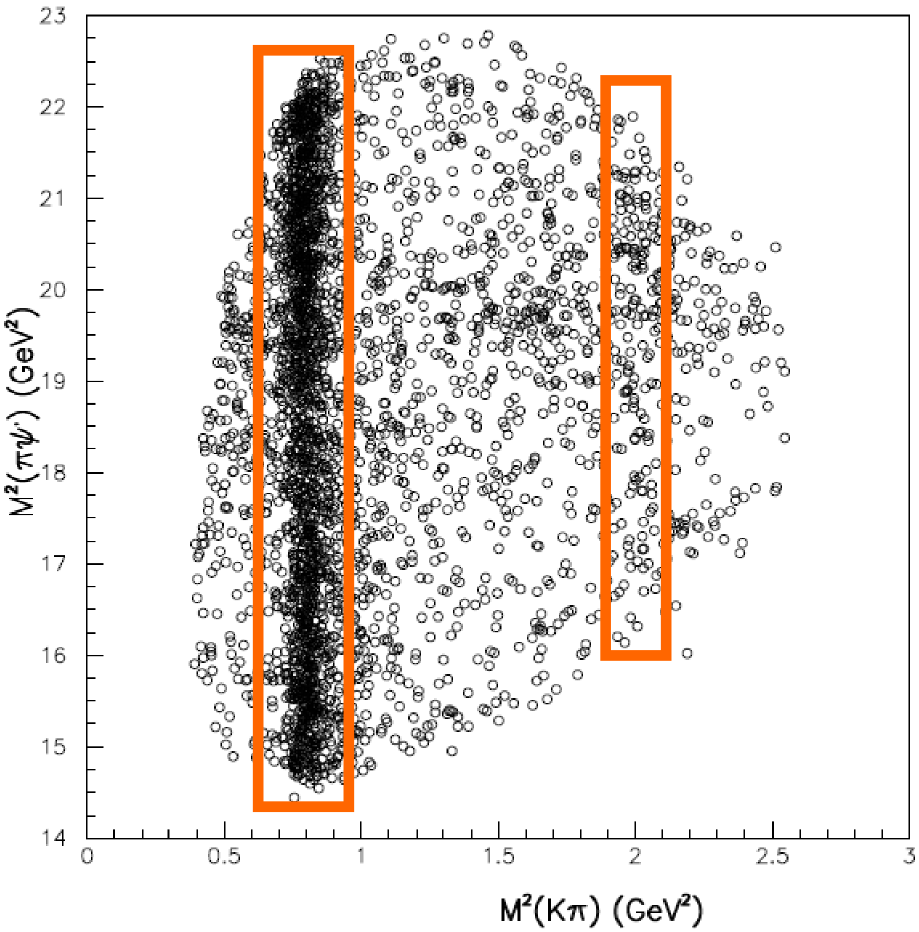
Belle, arXiv:0708.1790[hep-ex], Phys. Rev. Lett. 100(2008)142001
Belle, arXiv:0806.4098[hep-ex], Phys. Rev. D78(2008)072004
Belle, arXiv:0905.2869[hep-ex], Phys. Rev. D80(2009)031104
BaBar, arXiv:0811.0564[hep-ex], Phys. Rev. D79(2009)112001

$B^0 \rightarrow K^+ \psi' \pi^-$
$\psi' \rightarrow J/\psi \, \pi^+ \pi^-$



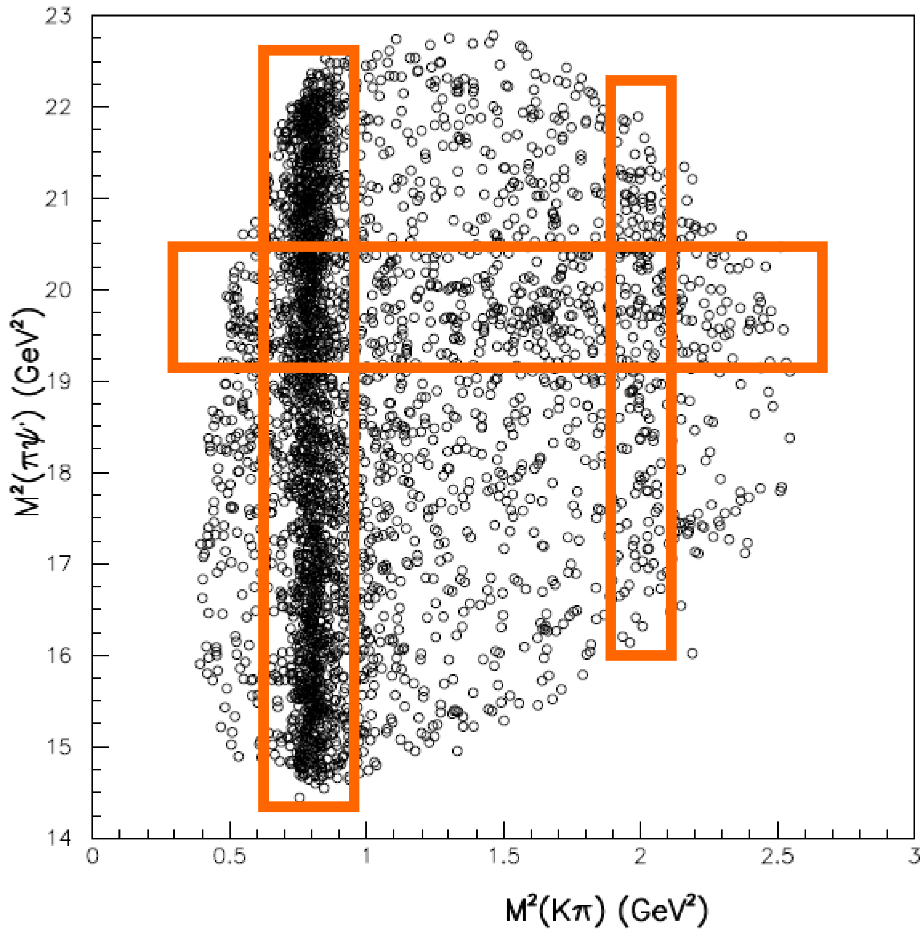
$B^0 \to K^+ \psi' \pi^-$
$\psi' \to J/\psi\, \pi^+ \pi^-$

K*(892) **K*(1430)**



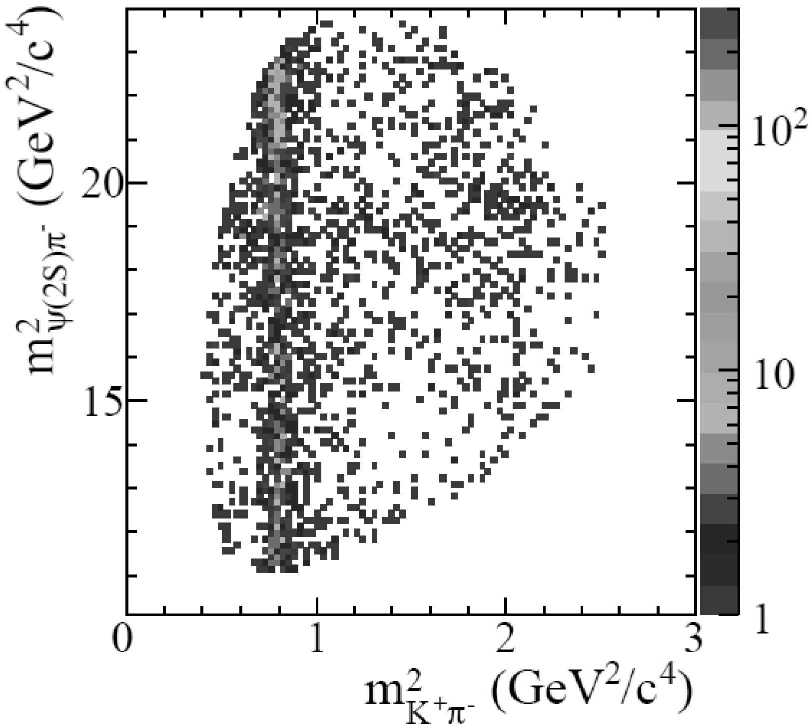
$B^0 \rightarrow K^+ \psi' \pi^-$
$\psi' \rightarrow J/\psi\ \pi^+ \pi^-$

K*(892) **K*(1430)**

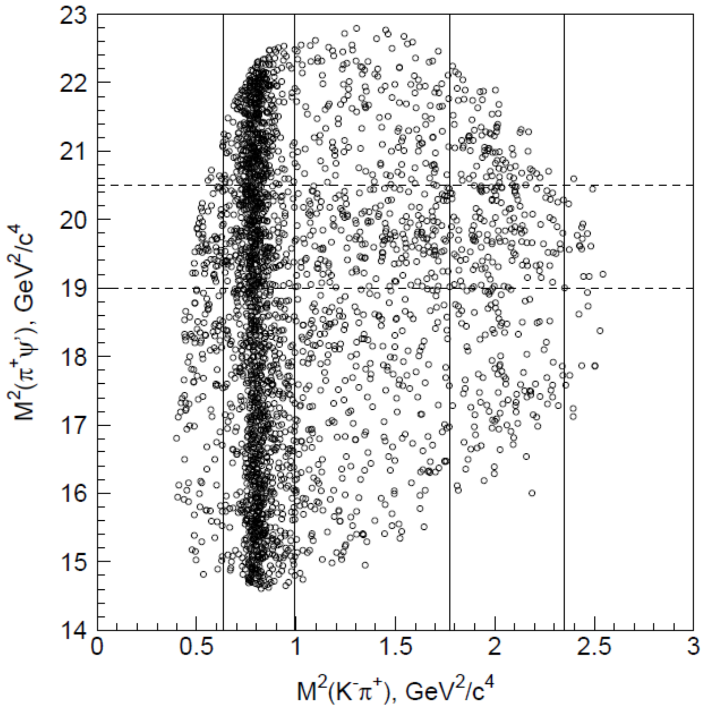


A charged state can never be a charmonium state.

$Z(4430)^+$



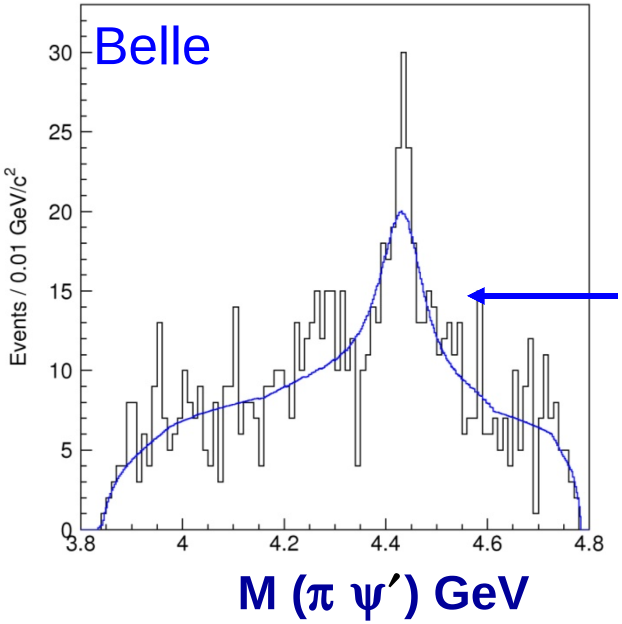
BaBar
Phys. Rev. D79(2008)112001
413/fb



Belle
Phys. Rev. D80(2009)031104
605/fb

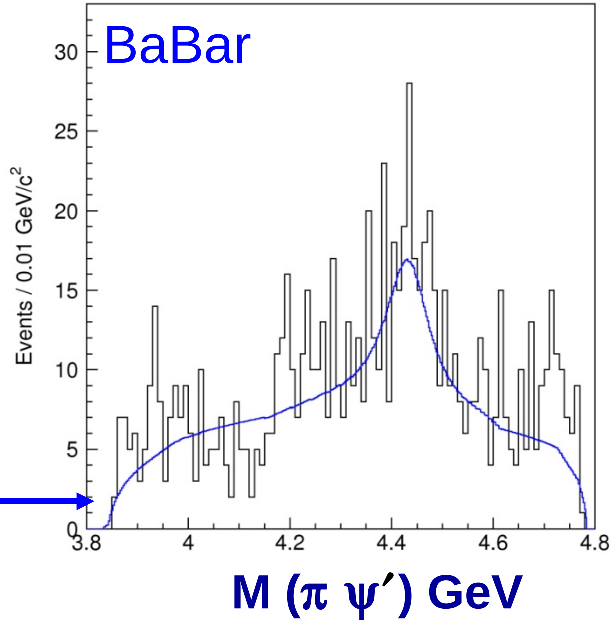
Belle and BaBar data look similar.

with K* veto

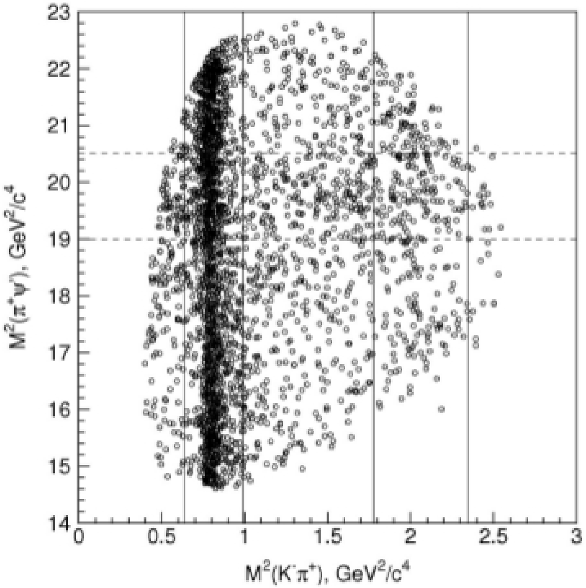


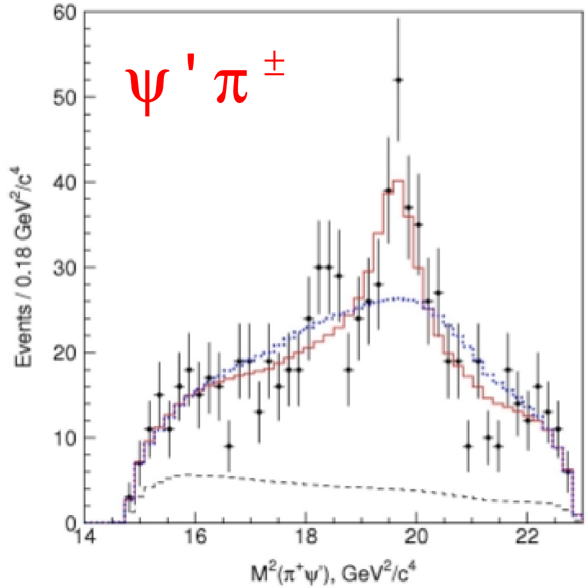
Result of Belle Dalitz fit analysis.

The same curve divided by 1.18 (scaled with Integrated luminosity)



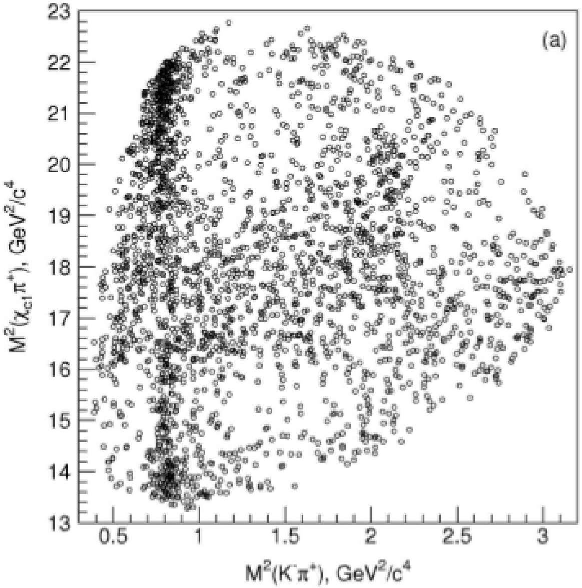
Enhancement in **Mass(πψ′)** is seen in both data samples, only interpretation is different.

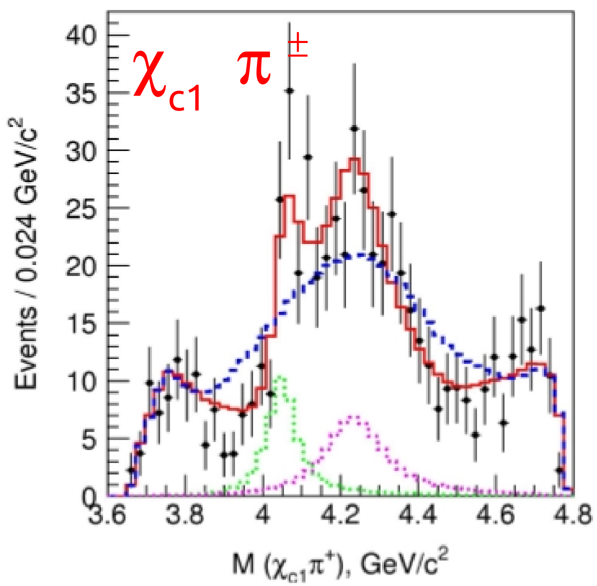




$$m=4433\pm4\pm2\ \text{MeV}$$

$$\Gamma=45^{+18+30}_{13\ \ 13}\ \text{MeV}$$





$$m(Z_1)=(4051\pm14^{+20}_{-41})\ \text{MeV}$$

$$\Gamma(Z_1)=(82^{+21+47}_{-17-22})\ \text{MeV}$$

$$M(Z_2)=(4248^{+44+180}_{-29-35})\ \text{MeV}$$

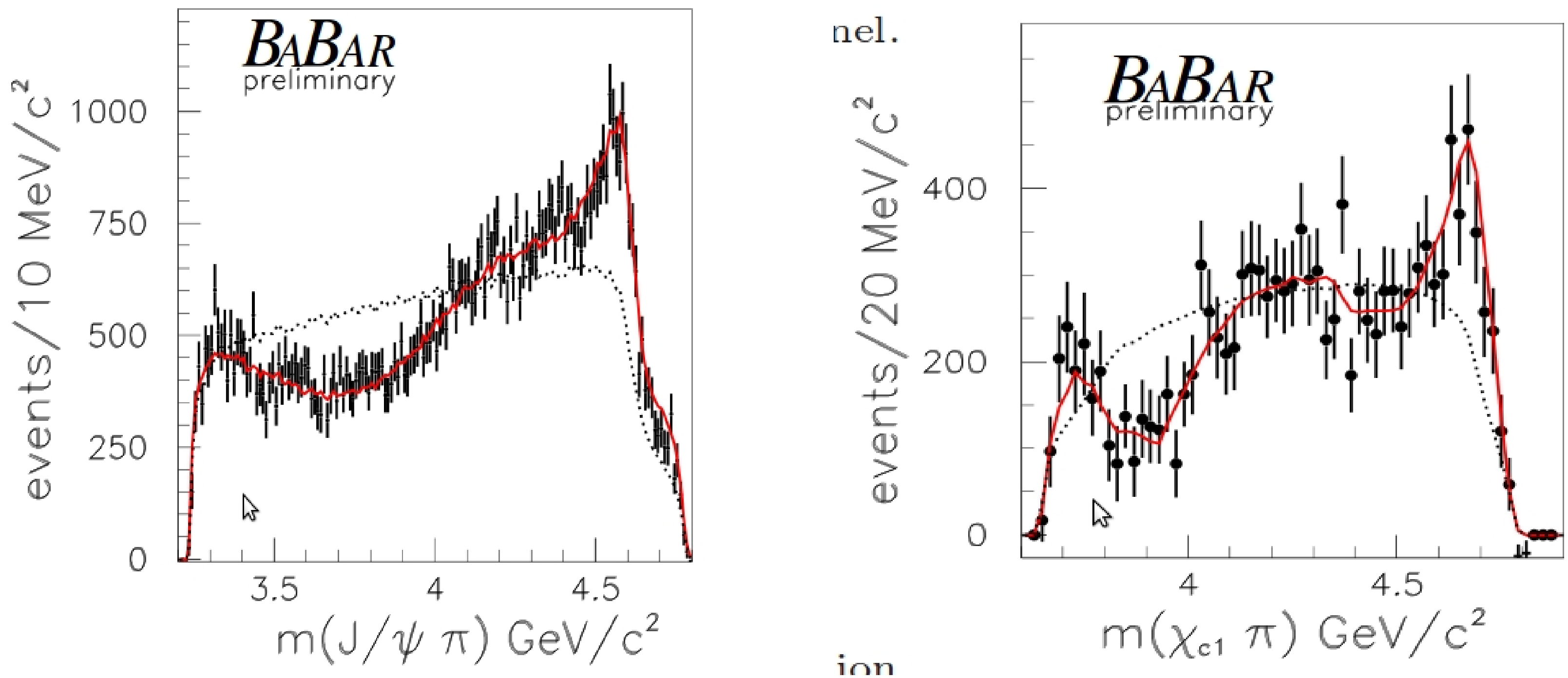
$$\Gamma(Z_2)=(177^{+54+316}_{-39-61})\ \text{MeV}$$

Is the Z+(4430) a kinematical effect ?

- $\cos\theta_K$, the normalized dot-product between the $K\pi$ three-momentum vector in the parent-B rest frame and the kaon three-momentum vector after a Lorentz transformation from the B meson rest frame to the $K\pi$ rest frame
- $\cos\theta_\psi$, the normalized dot-product of the $\psi'\pi^\mp$ three-momentum vector in the parent B meson rest frame and the ψ' three-momentum vector in the $\psi'\pi^\mp$ rest frame.

$\cos\theta_K$ is correlated with $m(K^\pm\pi^\mp)$, $\cos\theta_\psi$ is correlated with $m(\psi\pi^\mp)$, $\cos\theta_K$ is correlated with $\cos\theta_\psi$

TRUE !



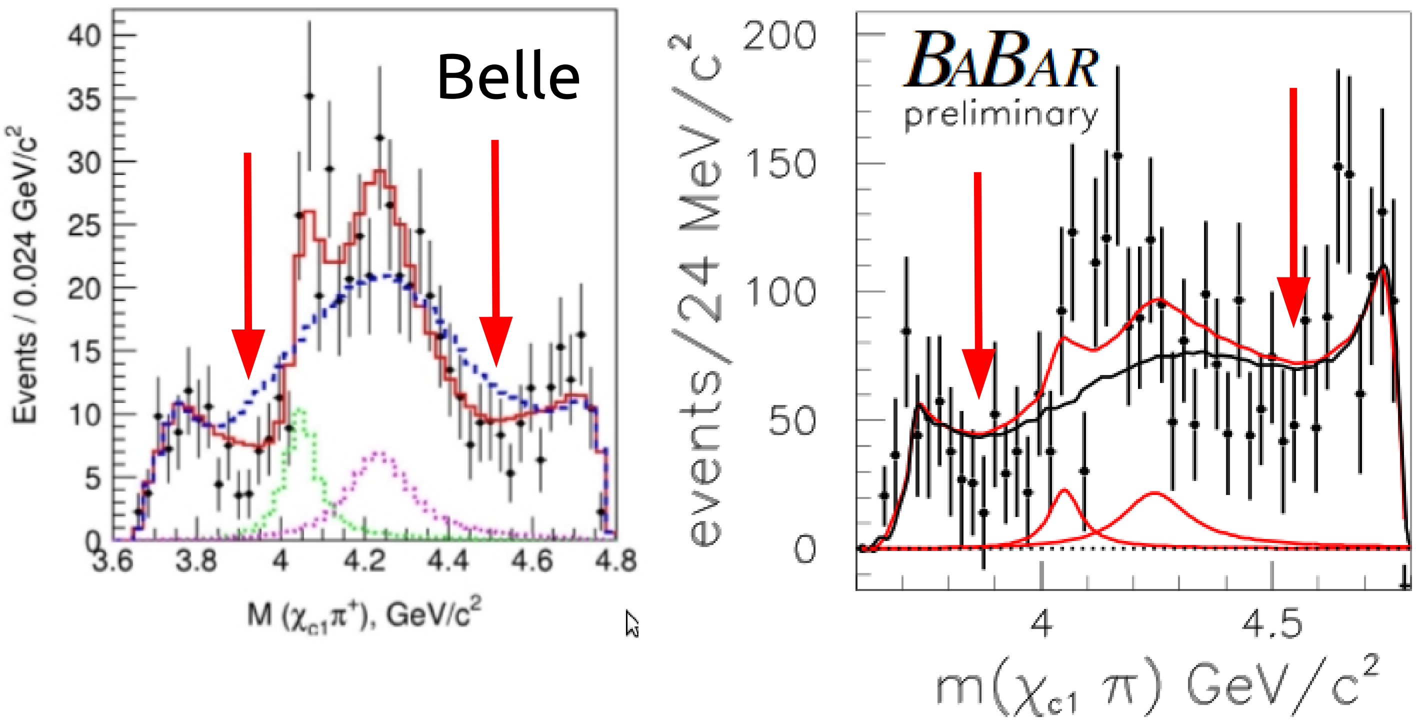
Argument #1:

MC with angular correlations can describe data well.

No Z+ states in red line (MC) required !

BaBar, arXiv:1111.5919, Phys.Rev. D85(2012)052003

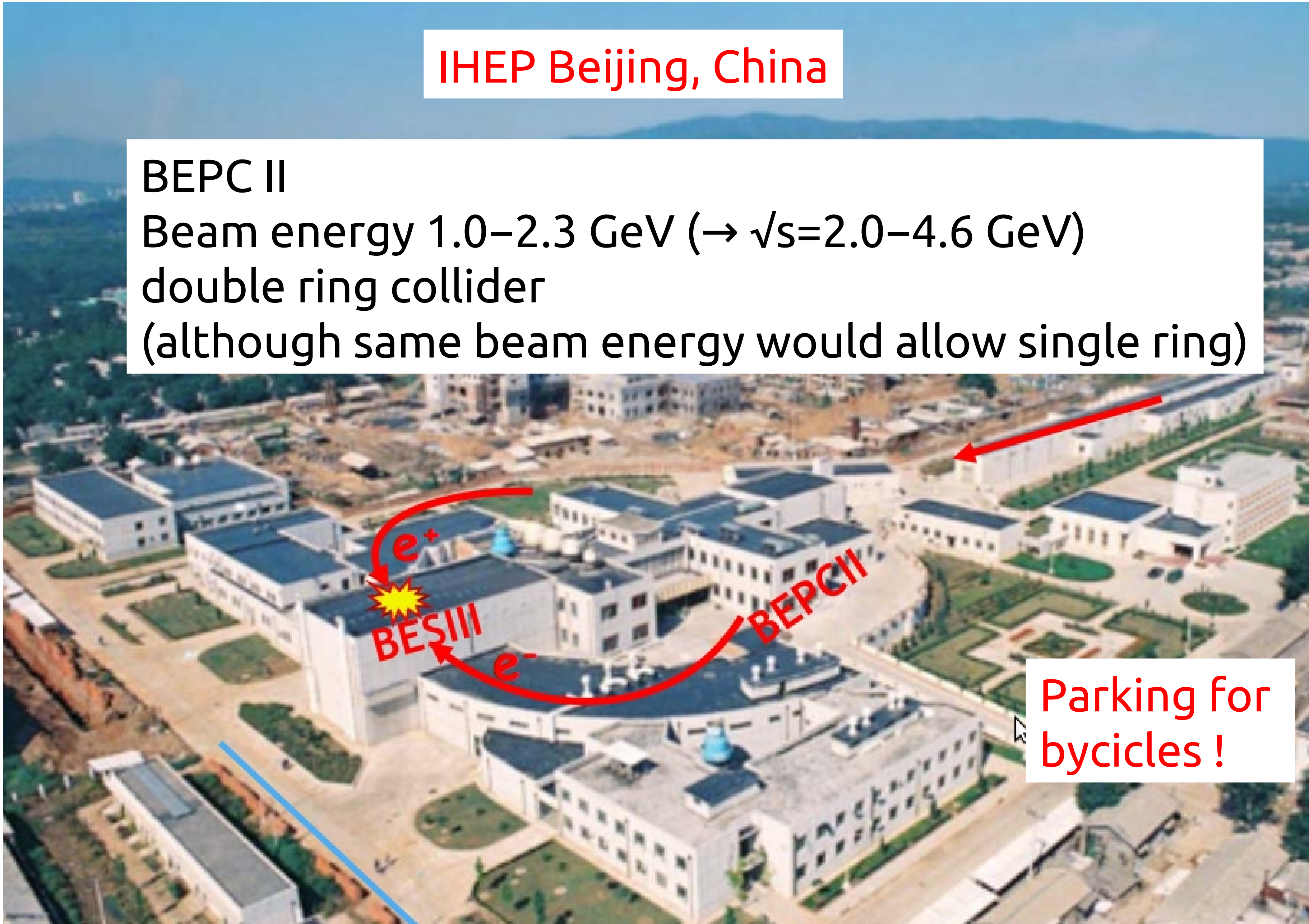
$\chi_{c1}\ \pi^{\pm}$



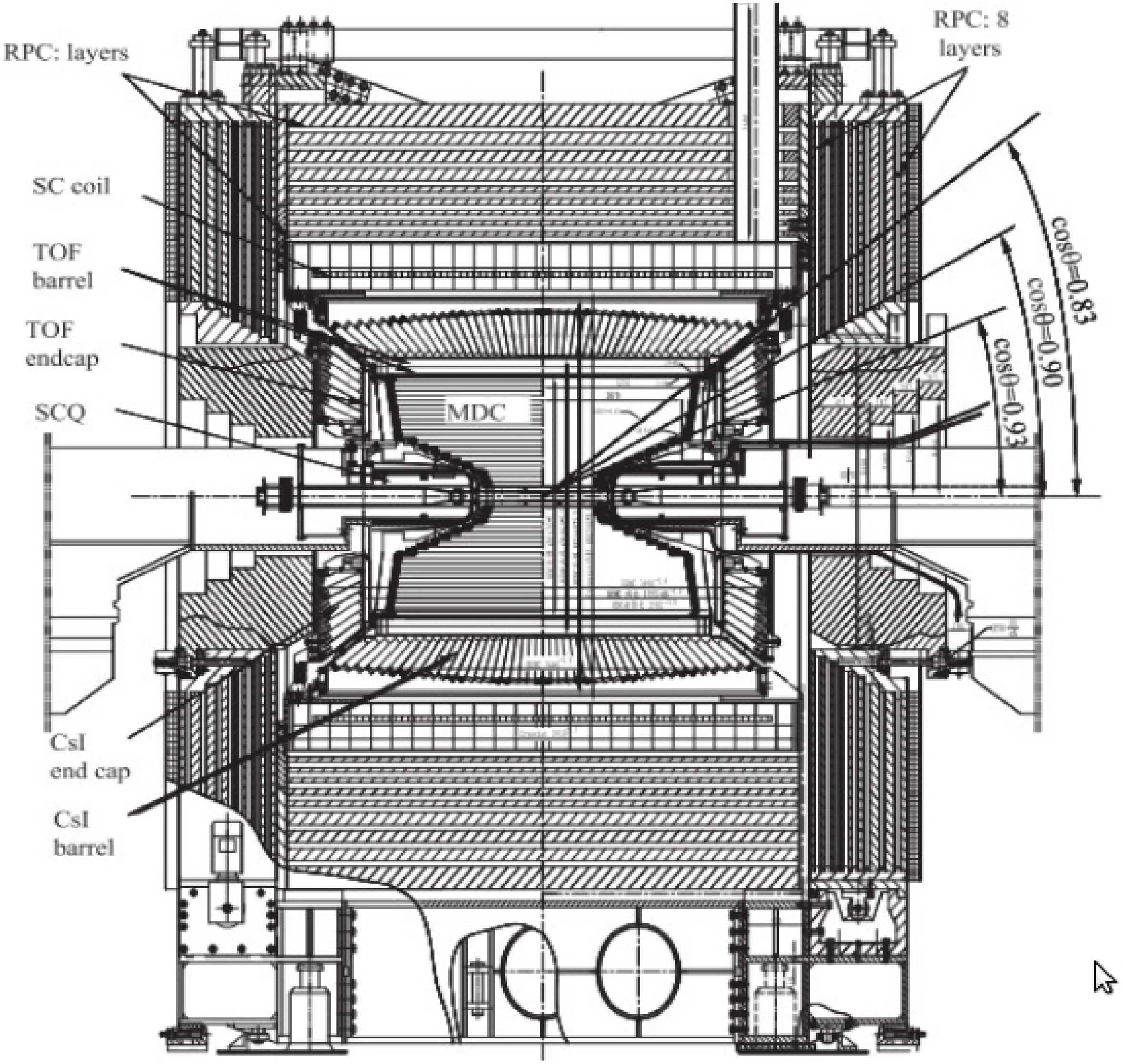
Argument #2:
significance is higher, if destructive interference is allowed in the fit (if not → ≤2σ)

IHEP Beijing, China

BEPC II
Beam energy 1.0–2.3 GeV (→ $\sqrt{s}$=2.0–4.6 GeV)
double ring collider
(although same beam energy would allow single ring)



BESIII Experiment at BEPC II (symmetric !)



Superconducting solenoid
B=1 T

no vertex detector, because only D mesons
(no separation of B mesons and D mesons required)

40.000 readout channels

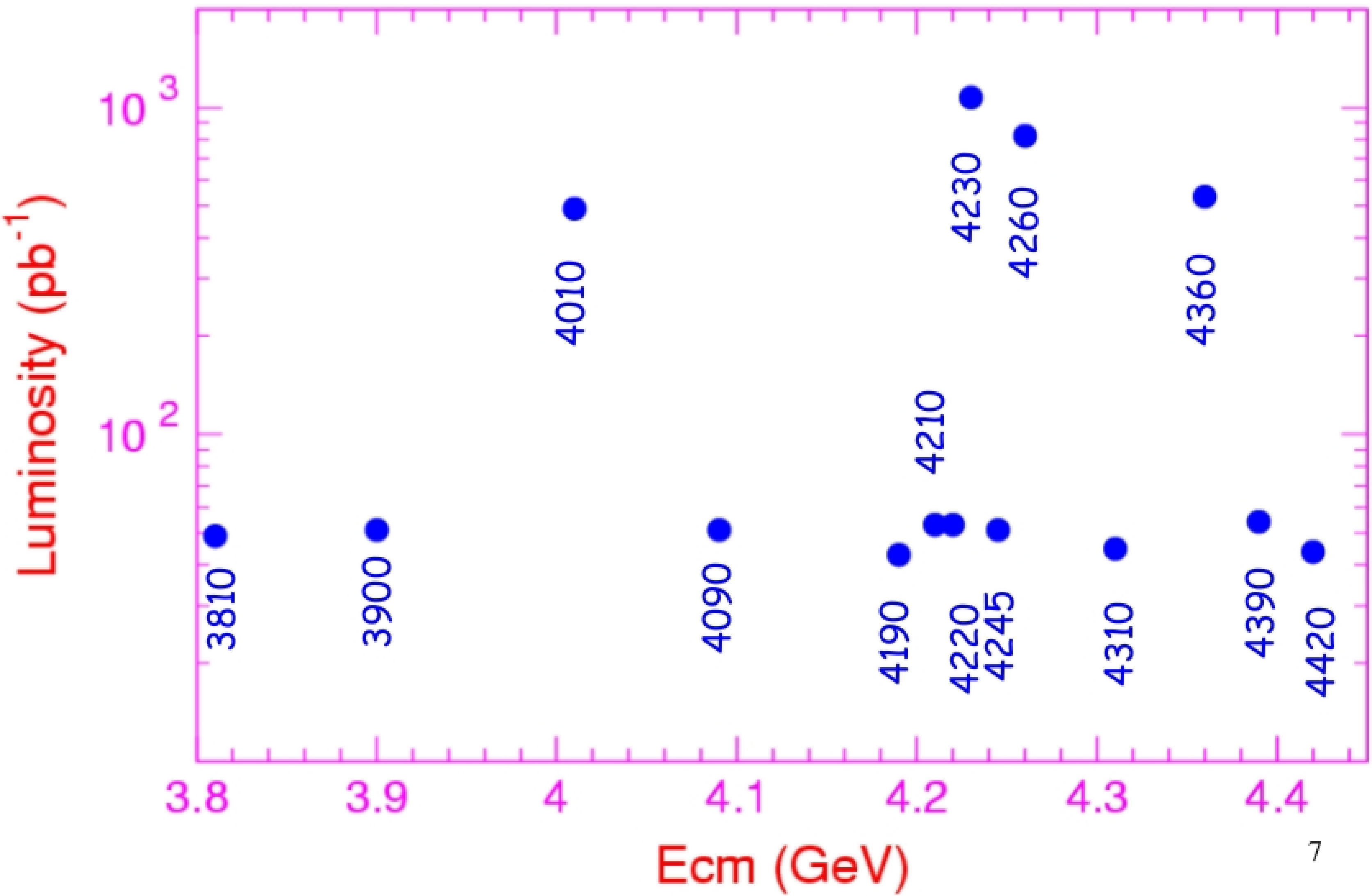
6 kHz trigger rate

design luminosity
1.0 x 10^{33} cm^{-2} s^{-1}
(@ 1.89 GeV beam energy)

→ 10 billion J/psi per 1 year

	CLEO-c	BESIII
J/ψ	n.a.	$\geq 1.3\times10^7$ decays
ψ'	27×10^6 decays	$\simeq 106\times10^6$ decays
$\psi(3770)$	572 pb^{-1}	$\simeq$2900 pb^{-1}
$\psi(4040)$	n.a.	$\simeq$470 pb^{-1}
$\psi(4140)$	314 pb^{-1}	–
Y(4260)	13 pb^{-1}	$\geq$500 pb^{-1}
Y(4350)	–	$\geq$500 pb^{-1}

Bes3 data taking **on** the Y(4260)
e+ e− → Y(4260)



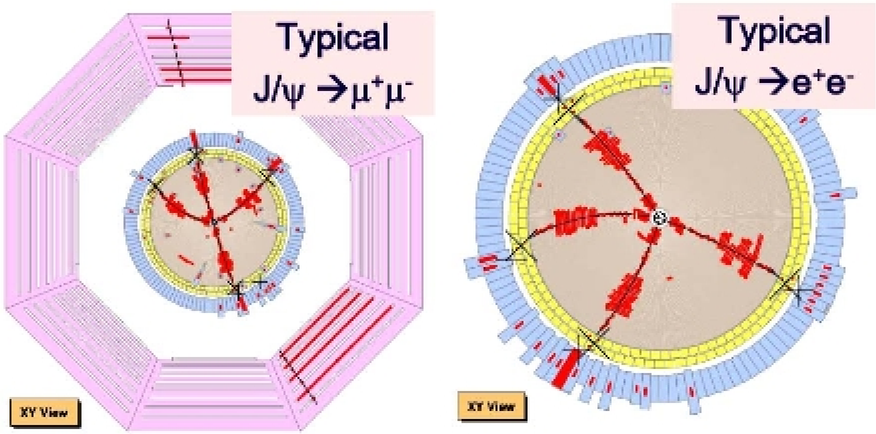
Y(4260)

BESIII

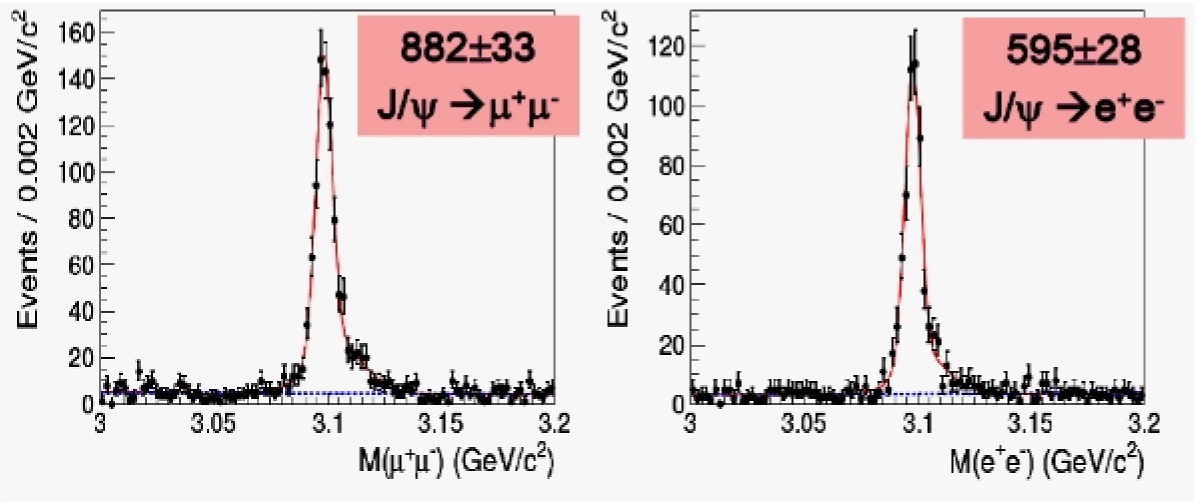
Select $e^+e^- \rightarrow \pi^+\pi^- J/\Psi$, $J/\Psi \rightarrow l^+l^-$ events.

1477 events found.

Born cross section, (62.9 ± 1.9 ± 3.7) pb, consistent with production of Y(4260).

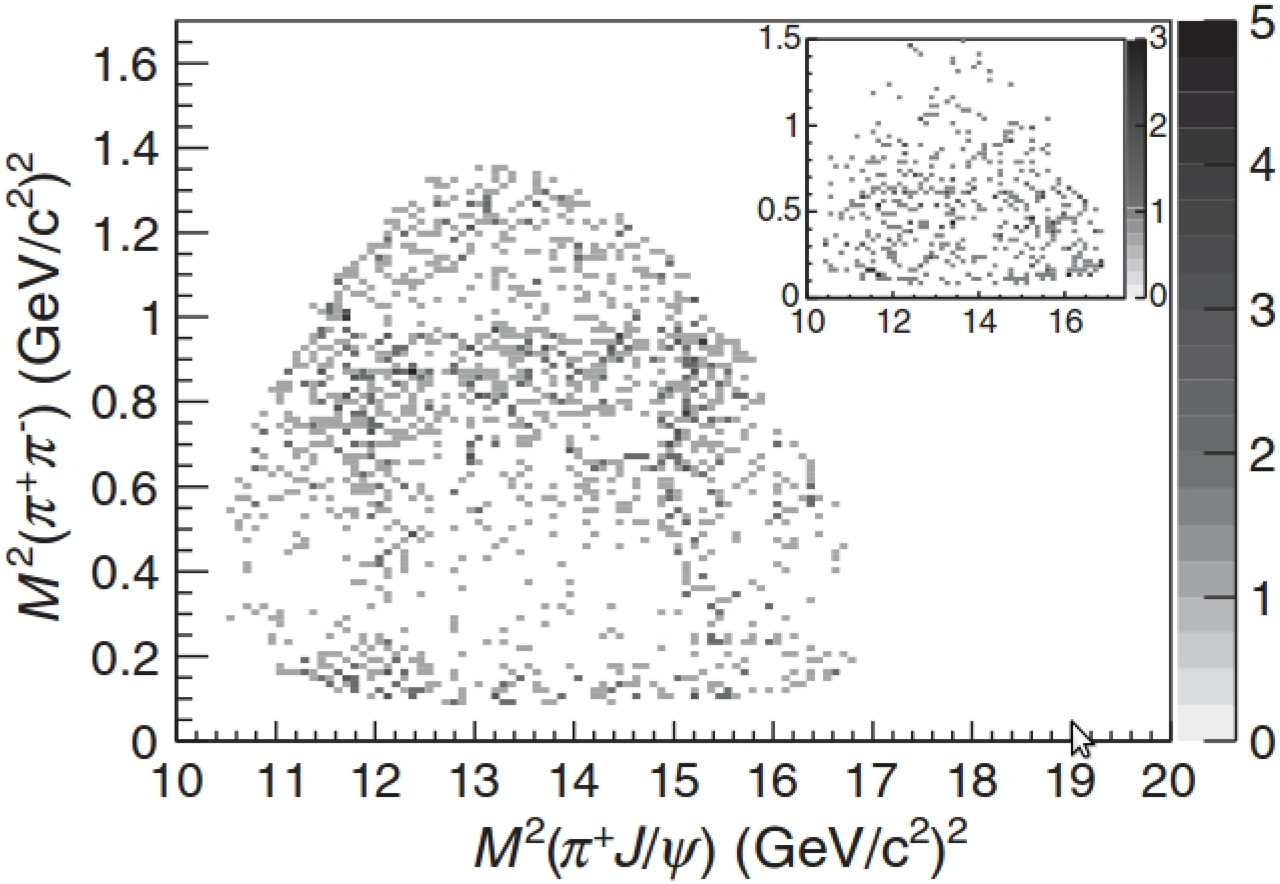


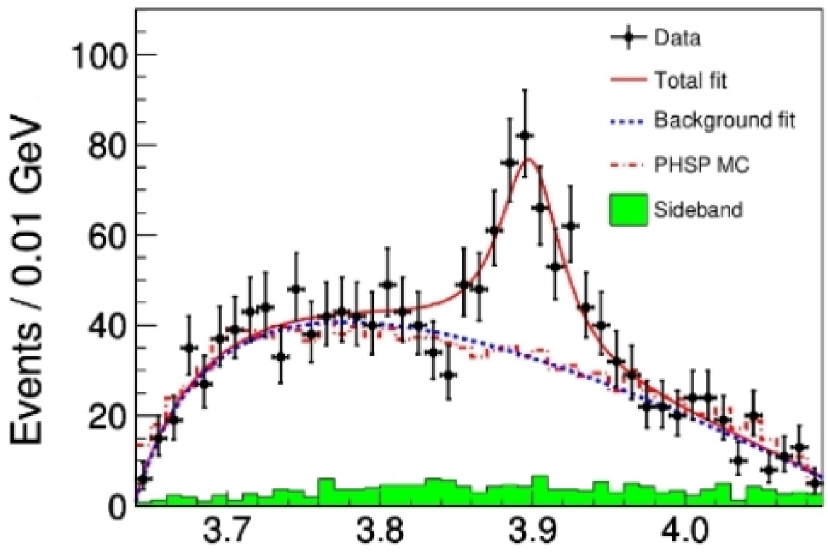
This is the Y(4260), not the ψ' !



$Y(4260) \to [J/\psi\pi+]\ \pi-$

BesIII, Phys. Rev. Lett. 110 (2013)252001
Belle, Phys. Rev. Lett. 110(2013)252002





Bes3

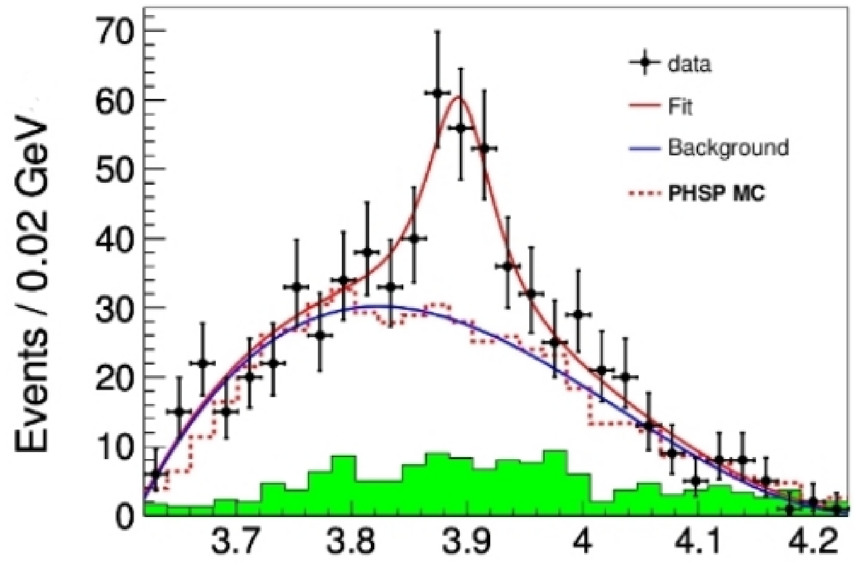
m = 3899.0±3.6±4.9 MeV

Γ = 46±10±20 MeV

307±48 events

>8 sigma

arXiv:1303.5949, PRL 110(2013)252001



Belle

m = 3894.5±6.6±4.5 MeV

Γ = 63±24±26 MeV

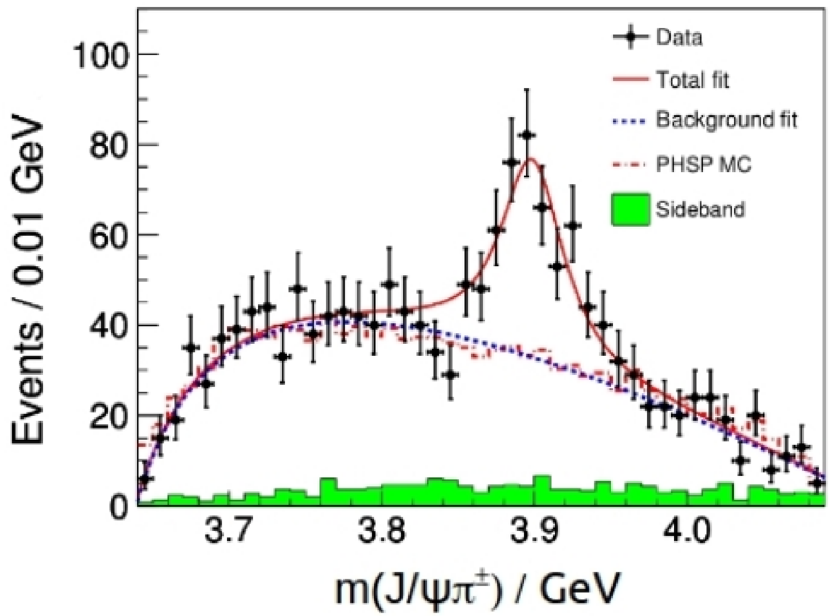
159±49 events

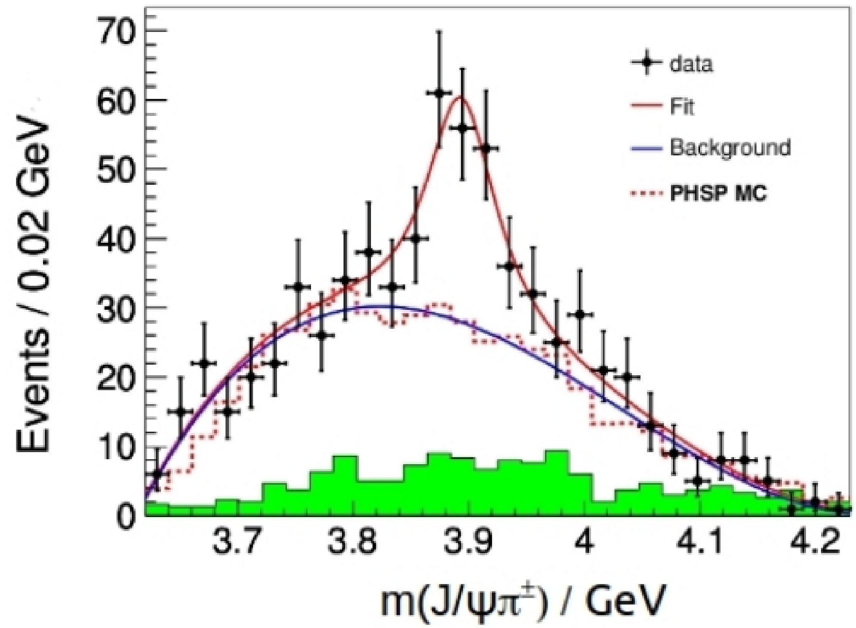
>5.2 sigma

arXiv:1304.0121, PRL 110(2013)252002

Y(4260) → [J/ψπ+] π−

- is charged (cannot be charmonium!)
- must have isospin 1 (as the pion has isospin 1)
- 1− 0− and assume L=0 → J^P=1+, similar to X(3872)





Zc+(3900)

- no C parity ! (only for neutral states)

G parity (-1)^(L+S+I)

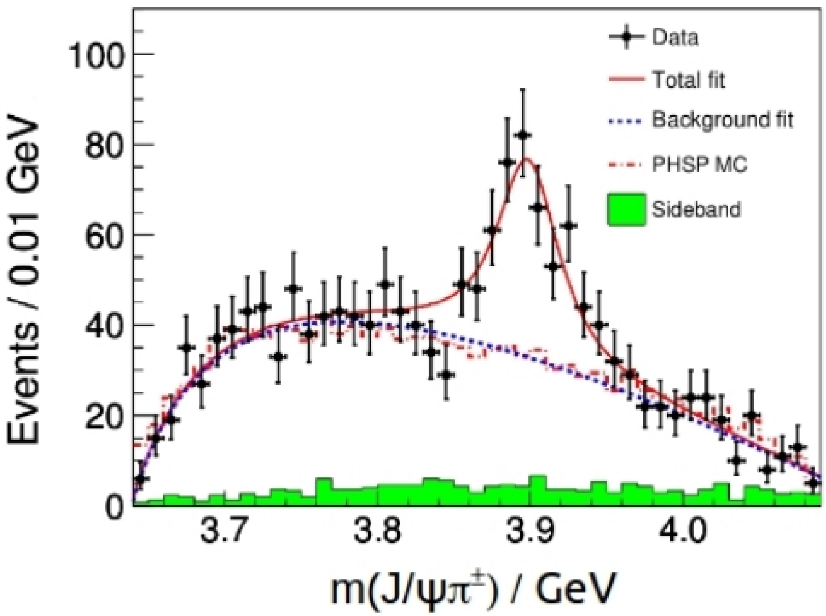
L=0, S=1, I=1 → G=+1

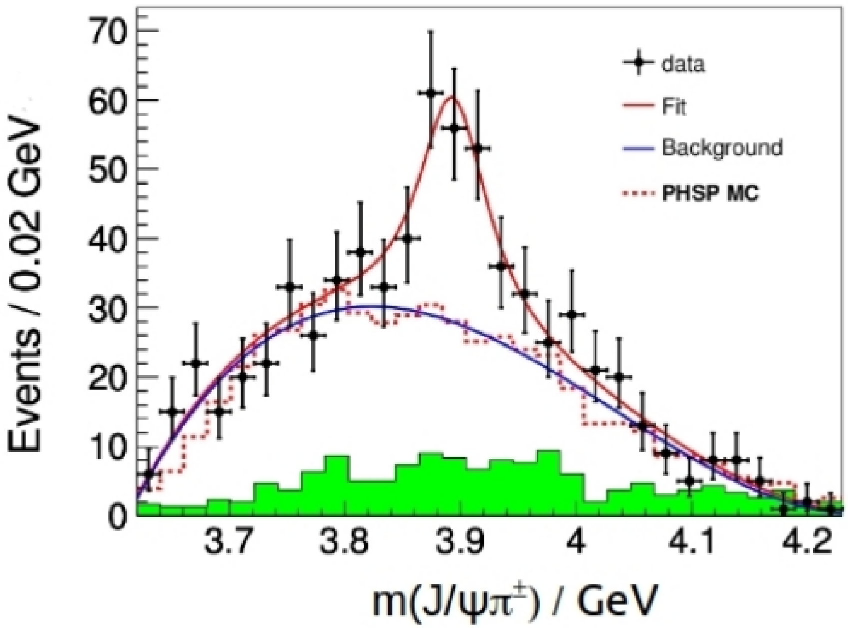
as G parity is conserved in strong decays, and G(π+)=−1

→ G parity of Y(4260) must be G=−1

this means: isospin of Y(4260) should be zero

this means: there should not be a charged partner of the Y(4260)





Molecule ?

D^+ has mass 1869,62 MeV

D^{*0} has mass 2010,28 MeV

Sum is 3879,90 MeV.

Measured BES3 3899 MeV, Belle 3894 MeV

→ higher mass !

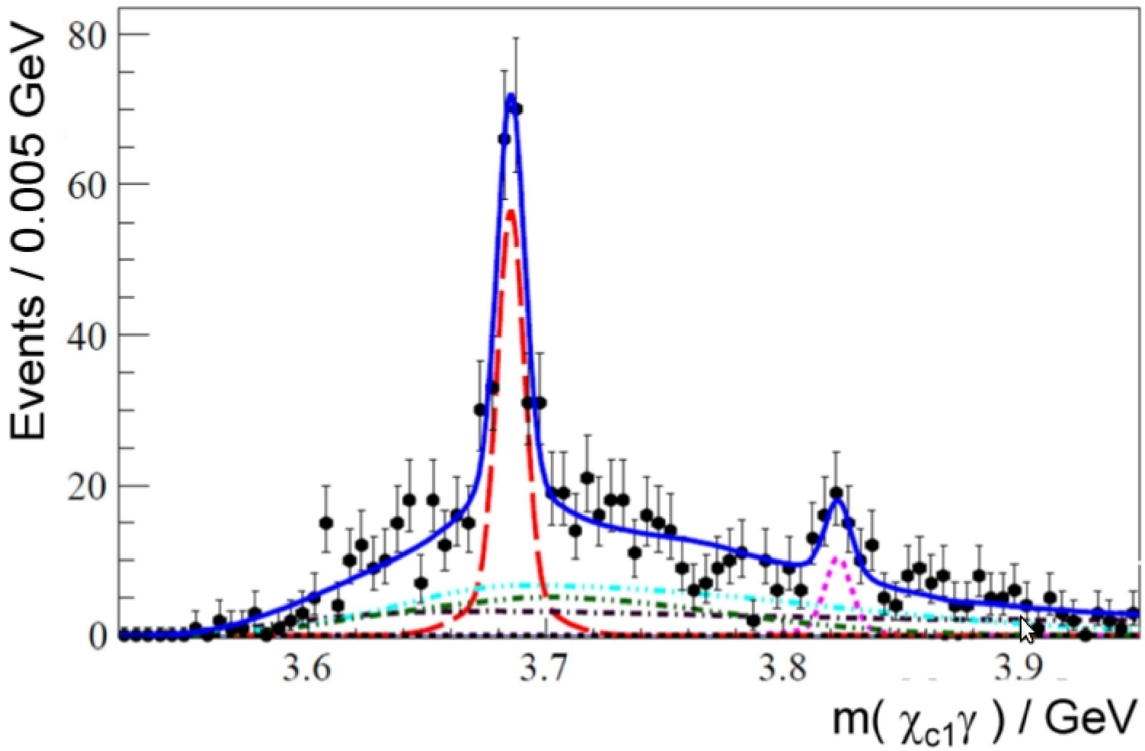
→ no binding energy („virtual state“)

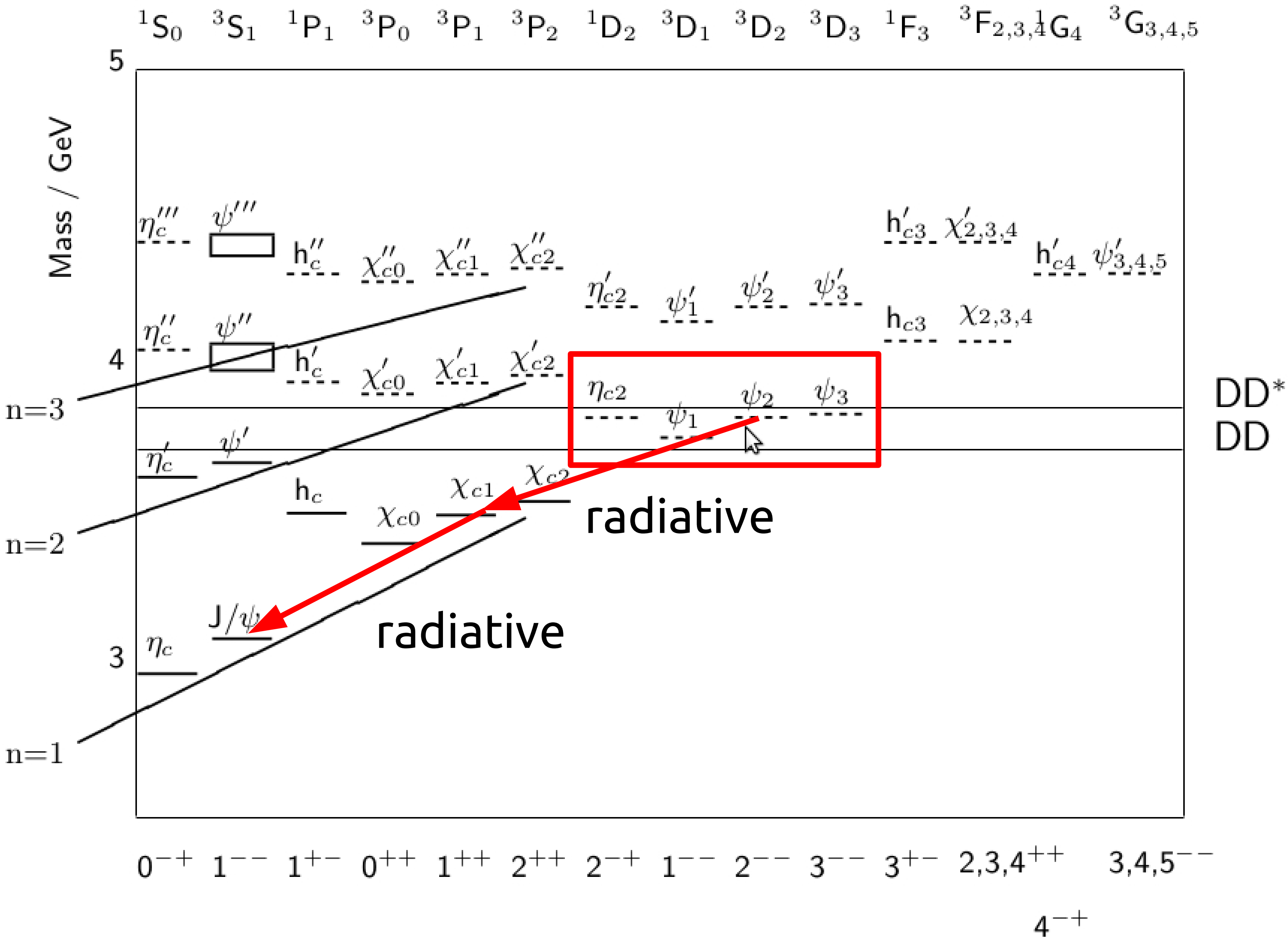
X(3820)

An L=2 Charmonium State ?

D-wave (L=2) state ?

Belle, arXiv:1304.3975, complete Y(4S) data set
mass 3823.1 ± 1.8 ± 0.7 MeV
significance 3.8σ
$B\pm \rightarrow K\pm X_{cc}$, $X_{cc} \rightarrow \chi_{c1}\gamma$, $\chi_{c1} \rightarrow J/\psi\,\gamma$





$^1S_0$ $^3S_1$ $^1P_1$ $^3P_0$ $^3P_1$ $^3P_2$ $^1D_2$ $^3D_1$ $^3D_2$ $^3D_3$ $^1F_3$ $^3F_{2,3,4}$ $^1G_4$ $^3G_{3,4,5}$
Mass / GeV
5
4
3
n=3
n=2
n=1
DD*
DD
radiative
radiative
0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++} 2^{-+} 1^{--} 2^{--} 3^{--} 3^{+-} $2,3,4^{++}$ $3,4,5^{--}$
4^{-+}

$^3D_1$ is predicted much lower
3.7699 GeV, admixture in $\psi(3770)$

$^1D_2$ would require a spin-flip in the transition
(suppressed)

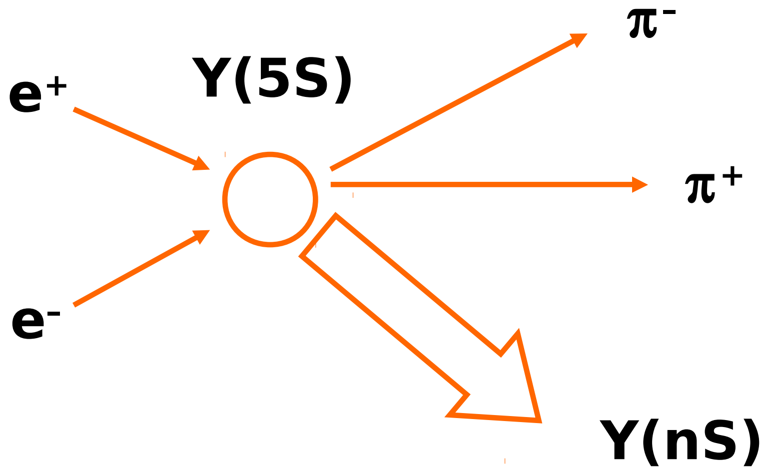
$^3D_3$ (3 - -) can not decay radiatively to χ_{c1} (1++)
would be $\Delta J = 2$

only candidate:
$^3D_2$
is predicted narrow (300-400 keV),
consistent with measured narrow width 4±7 MeV
(above DD threshold, but 2-- → 0-+ 0-+ is forbidden by parity
DD* and D*D* kinematically forbidden)

Bottomonium-like States

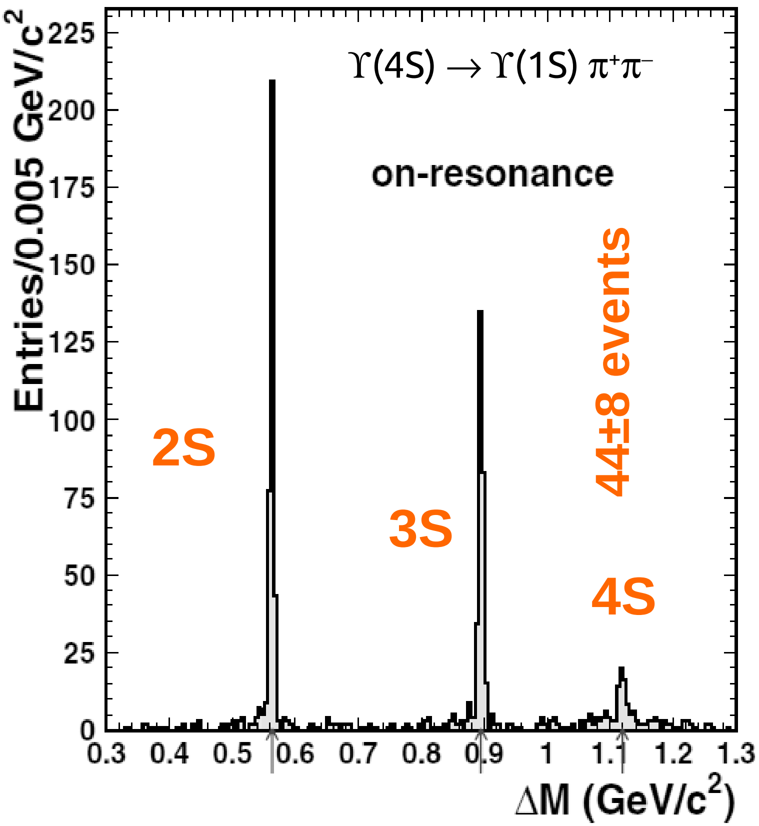
Υ(5S) data taking

- 9.06.-30.06.2007
  KEK-B and Belle changed beam energy to Υ(5S)
- 21.7 fb^{-1} recorded
- investigate [vector → vector π π]
  as an analogy to Y(4260) → J/ψ π π



Γ[Y(5S)→ππY(nS)] is huge

Y(4S)→ππY(1S)
477 fb^{-1}

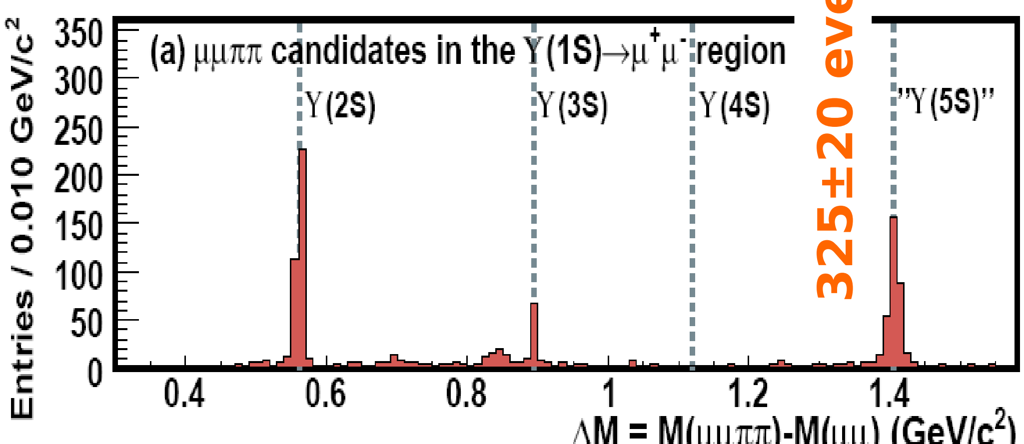


Phys. Rev. D75(2007)071103

8 times as many events integrated for Y(nS)

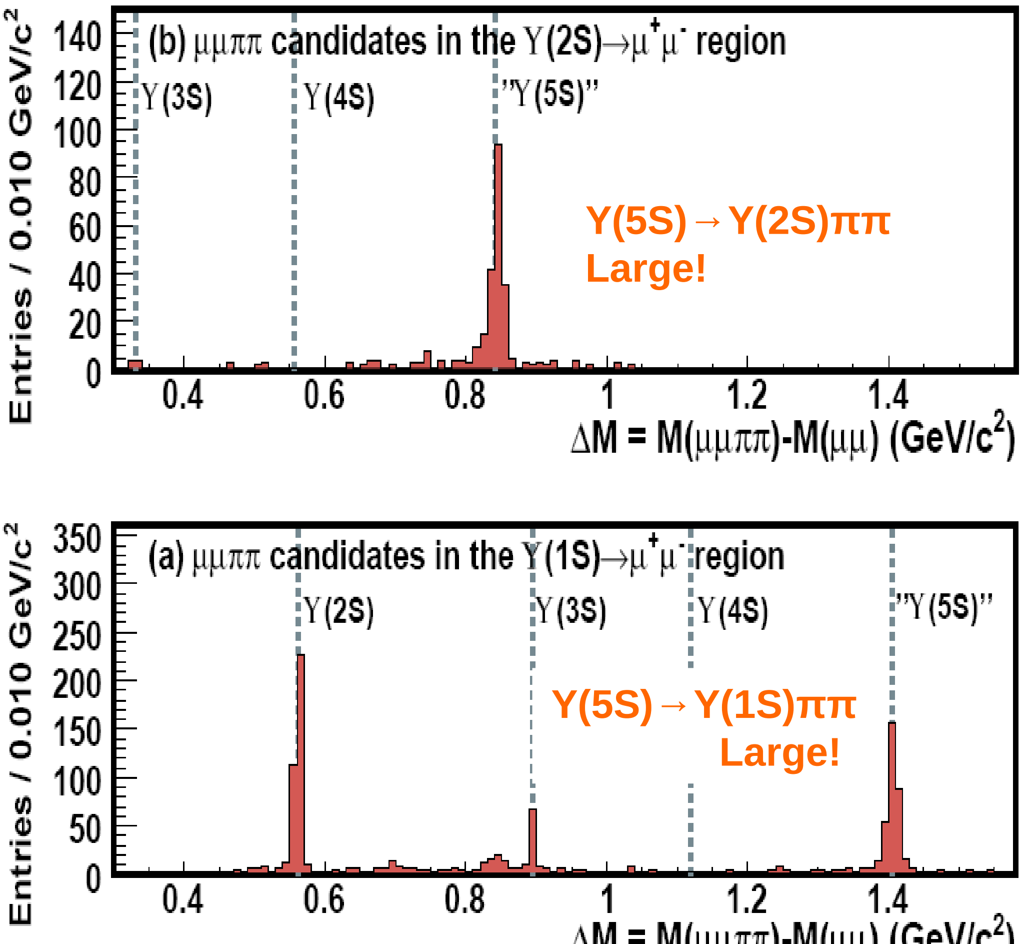
1/20 times the data & ~1/10th the crosssection

Y(5S)→ππY(1S)
21.7 fb^{-1}



Belle Phys. Rev. Lett. 100, 112001 (2008)

Not only Υ(5S) → Υ(1S)ππ is large, but also Υ(5S) → Υ(2S)ππ



Is there a non-expected state near the $\Upsilon(5S)$ contributing to $\Upsilon(nS)\pi\pi$?

→ beam energy scan!

Beam Energy Scan, Dec 2007

Target Ecm [relative to 5S]	KEKB Ecm*	$\mathcal{L}$ (RunInfo)
10800[−69] MeV	10798.5 MeV	30.71/pb
10824[−45] MeV	10824.0 MeV	
10829[−40] MeV	10827.5 MeV	1615.22/pb
10844[−25] MeV	10844.0 MeV	
10854[−15] MeV	10852.5 MeV	30.70/pb
10844[−5] MeV	10864.0 MeV	
10869 MeV	10869.0 MeV	
10869 MeV	10871.0 MeV†	
10884[+15] MeV	10882.5 MeV	1745.28/pb
10884[+15] MeV	10884.0 MeV	
10891.5[+22.5] MeV	10889.5 MeV	30.76/pb
10899[+30] MeV	10897.5 MeV	1339.23/pb
10904[+35] MeV	10904.0 MeV	
10929[+60] MeV	10927.5 MeV	1074.67/pb
10959[+90] MeV	10957.5 MeV	945.84/pb
10989[+120] MeV	10987.5 MeV	30.53/pb
11019[+150] MeV	11017.5 MeV	792.04/pb

	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$

$\sqrt{s}$=10.8275 GeV

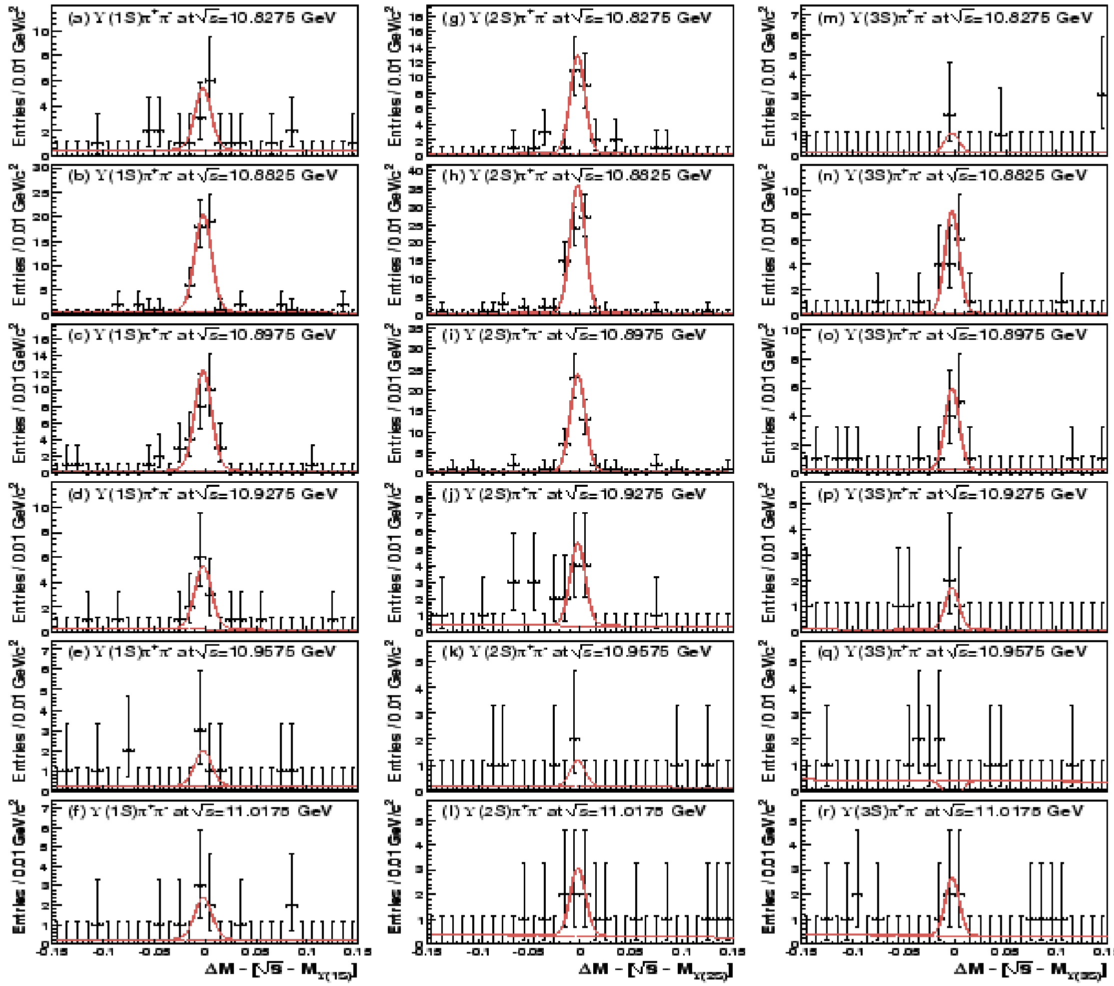
$\sqrt{s}$=10.8825 GeV

$\sqrt{s}$=10.8975 GeV

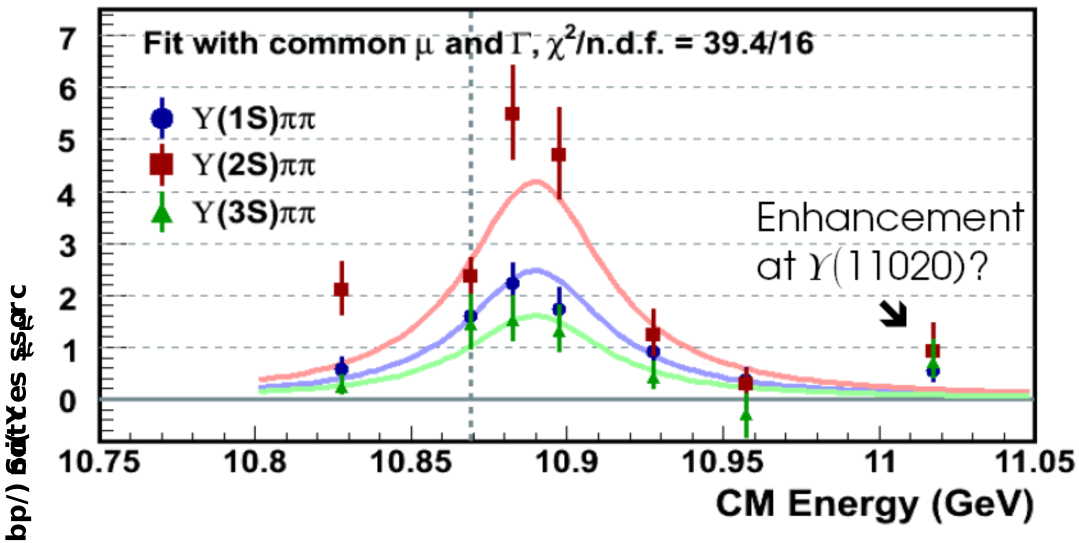
$\sqrt{s}$=10.9275 GeV

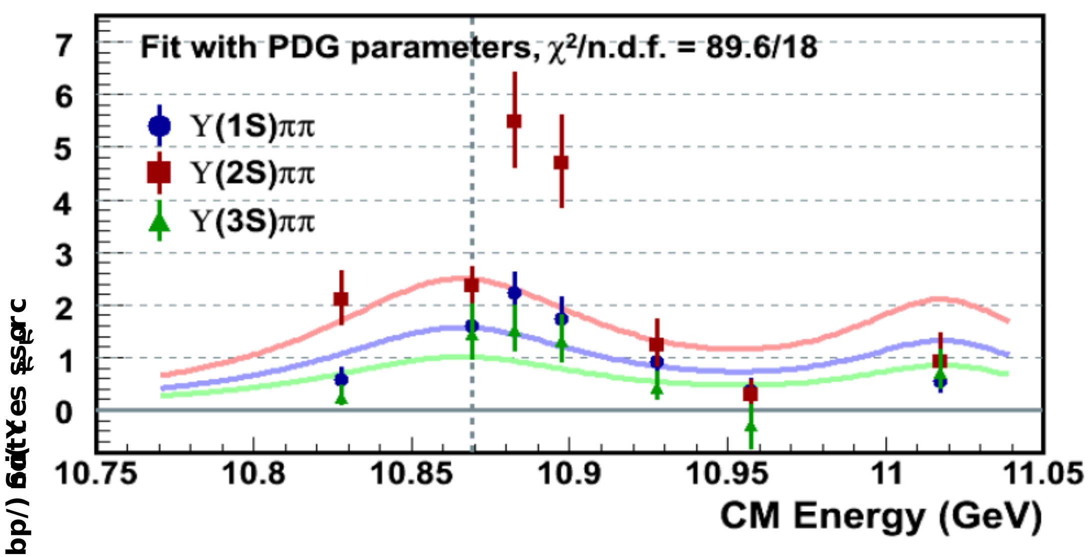
$\sqrt{s}$=10.9575 GeV

$\sqrt{s}$=11.0175 GeV



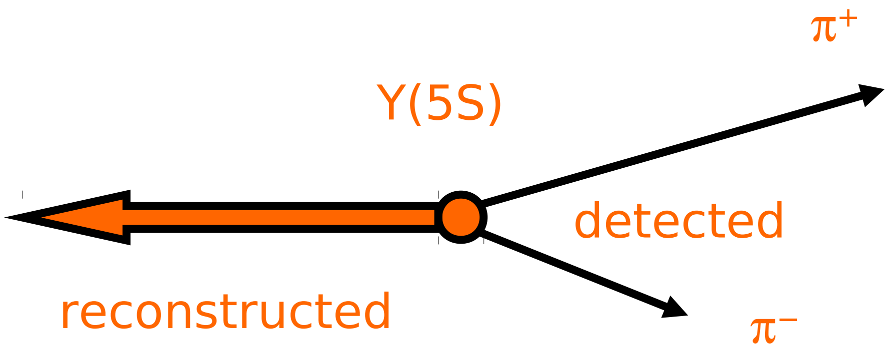
Υ_b(10889)

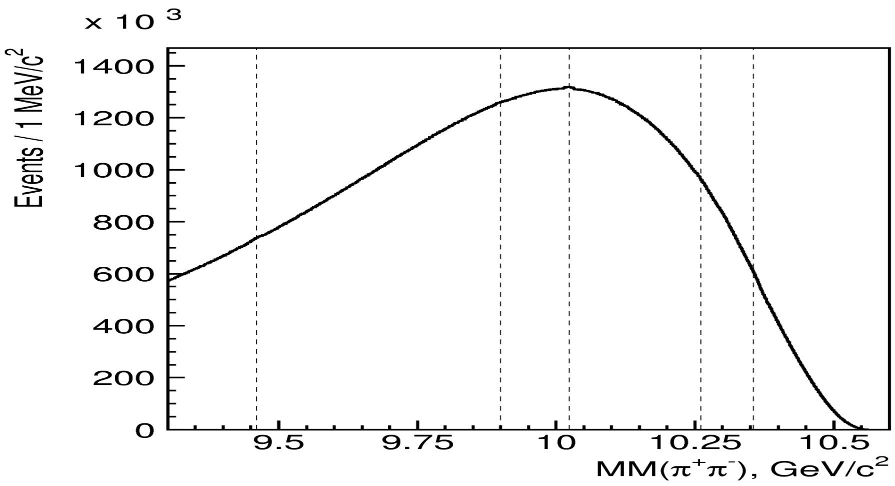


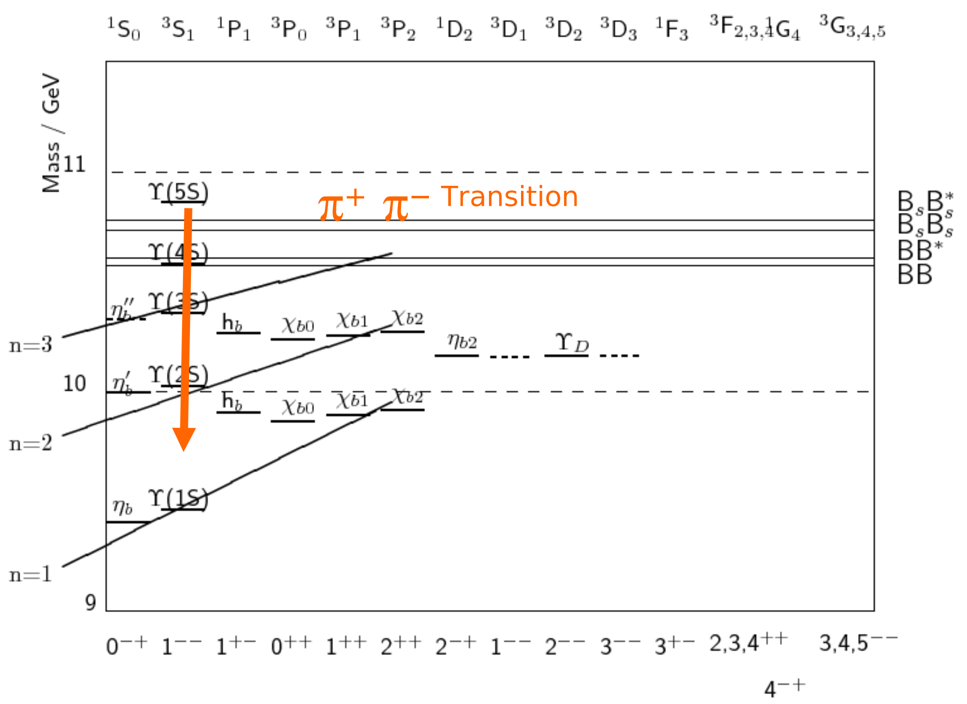


- Fit with 1 Breit-Wigner (floated mean and width) with 3 floated normalizations (for 1S, 2S and 3S)
- Comparison Υ_b vs. Υ(5S): mean ~20 MeV higher width around ½
- Fit with 2 Breit-Wigners fixed to Υ(10860) = Υ(5S) Υ(11020) = Υ(6S) PDG parameters
- 2 states ?

$\Upsilon(5S) \to X\,\pi^+\pi^-$ reconstruction







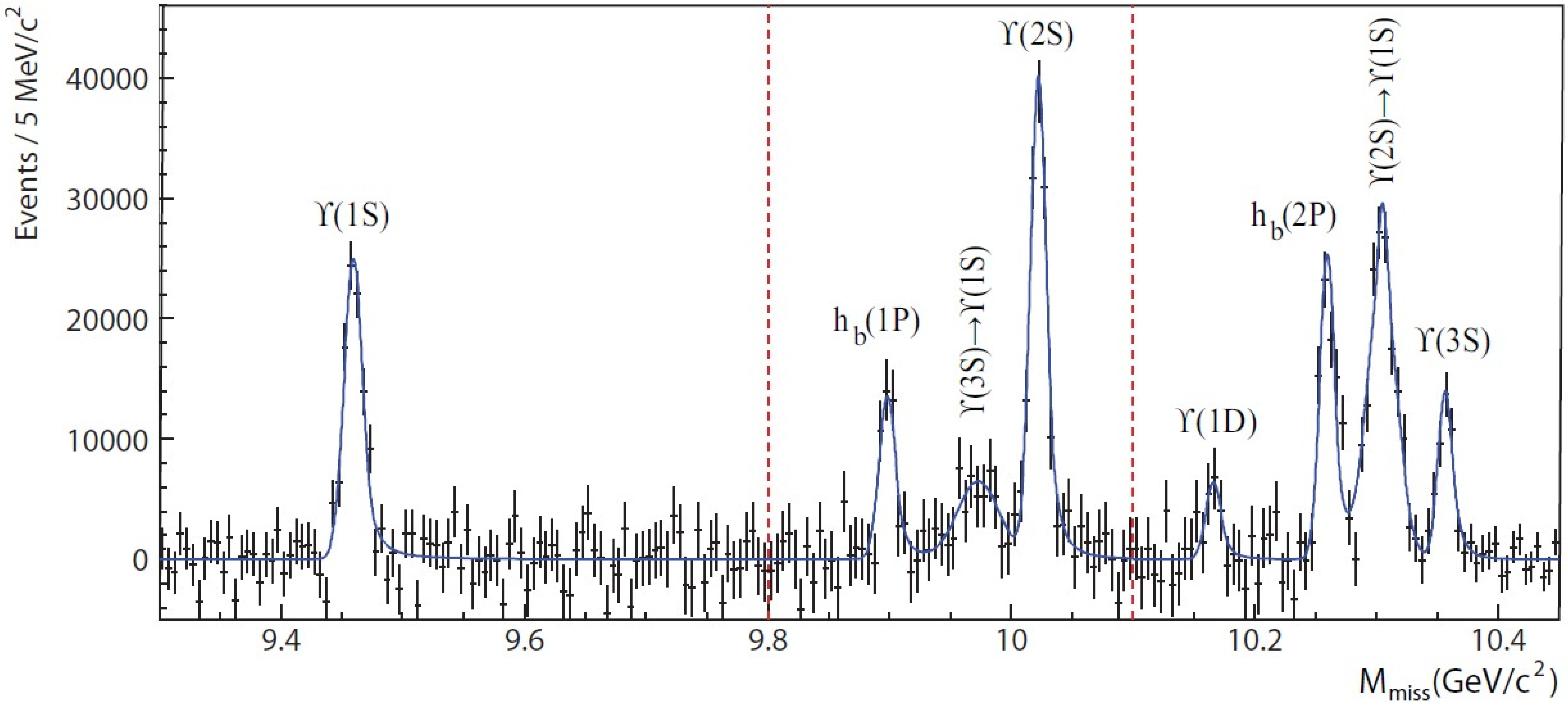
$$M_{\rm miss}(X) = \sqrt{(E_{\rm c.m.} - E^*_X)^2 - p^{*2}_X}$$

Υ(5S) Decays

$\pi^+ \pi^-$ missing mass

First observation of
$h_b(1P)$ and $h_b(2P)$

Belle, 121.4 fb^{-1}
Phys. Rev. Lett 108(2011)032001
arXiv:1103.3419



Prediction from potential model
D. Ebert,
R.N. Faustov,
V.O. Galkin,
arXiv:hep-ph/0210381, Phys. Rev. D67(2003)014027

	Yield, 10^3	Mass, MeV/c^2	Significance	
$\Upsilon(1S)$	$105.0 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	$18.1\,\sigma$	
$h_b(1P)$	$50.0 \pm 7.8^{+4.5}_{-9.1}$	$9898.2^{+1.1+1.0}_{-1.0-1.1}$	$6.1\,\sigma$	9901 MeV
$3S \to 1S$	55 ± 19	9973.01	$2.9\,\sigma$	
$\Upsilon(2S)$	$143.8 \pm 8.7 \pm 6.8$	$10022.2 \pm 0.4 \pm 1.0$	$17.1\,\sigma$	
$\Upsilon(1D)$	22.4 ± 7.8	10166.1 ± 2.6	$2.4\,\sigma$	
$h_b(2P)$	$84.0 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	$12.3\,\sigma$	10261 MeV
$2S \to 1S$	$151.3 \pm 9.7^{+9.0}_{-20.}$	$10304.6 \pm 0.6 \pm 1.0$	$15.7\,\sigma$	
$\Upsilon(3S)$	$45.5 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	$8.5\,\sigma$	

Newly observed h_b(1P) and h_b(2)
are nicely consistent with
predictions by potential model.

Precision Test of Tensor Term in $\bar{q}q$ Potential

$$m(h_c) \stackrel{?}{=} \frac{m(\chi_{c0}) + 3 \cdot m(\chi_{c1}) + 5 \cdot m(\chi_{c2})}{9}$$

and analogue for h_b

- Test of hyperfine splitting
  $\Delta m_{HF} = \langle m(n^3P_J) \rangle_{\text{spin-averaged}} - m(n^1P_1)$
- For the 1st time possible in the bottomonium system
- For the 1st time possible for n=1 and n=2
  as $h_c(2P)$ not observed yet

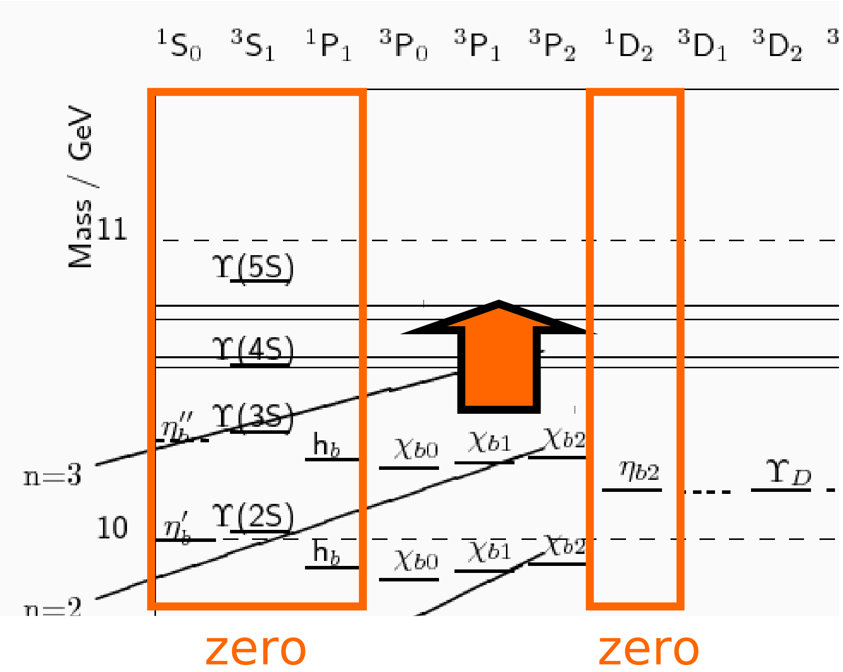
$\bar{q}q$ Potential
with fine structure and hyperfine structure

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr + \frac{32\pi\alpha_s}{9m_c^2}\delta_r \vec{S}_c\vec{S}_{\bar{c}} + \frac{1}{m_c^2}\left(\frac{2\alpha_s}{r^3} - \frac{k}{2r}\right)\vec{L}\vec{S} + \frac{1}{m_c^2}\frac{4\alpha_s}{r^3}\left(\frac{3\vec{S}_c\vec{r}\cdot\vec{S}_{\bar{c}}\vec{r}}{r^2} - \vec{S}_c\vec{S}_{\bar{c}}\right)$$

tensor term

Precision Test: Tensor Term in $q\bar{q}$ Potential

- treated as perturbation
- vanishes for
  S=0 (η_b, Υ, ...)
  L=0 ($^1D_2$,...)
- sign of potential term is positive
  → masses should be shifted up
- Simplified view:
  wavefunction of h_c (h_b) at r=0 is not vanishing



Result:

State	$h_b(1P)$	$h_b(2P)$
ΔM_{HF}, MeV	1.7 ± 1.5	$+0.5^{+1.6}_{-1.2}$

compared to 0.00 ± 0.15 MeV for the $h_c(1P)$

One step further:

$$h_b \to \eta_b \gamma$$

- With 50k events of $h_b(1P)$ and 84k of $h_b(2P)$
- Reminder: $\eta_b(1S)$ only known for 3 years
  First observations by BaBar (2008, 2009) and CLEO (2010)
- In addition, search for $\eta_b(2S)$

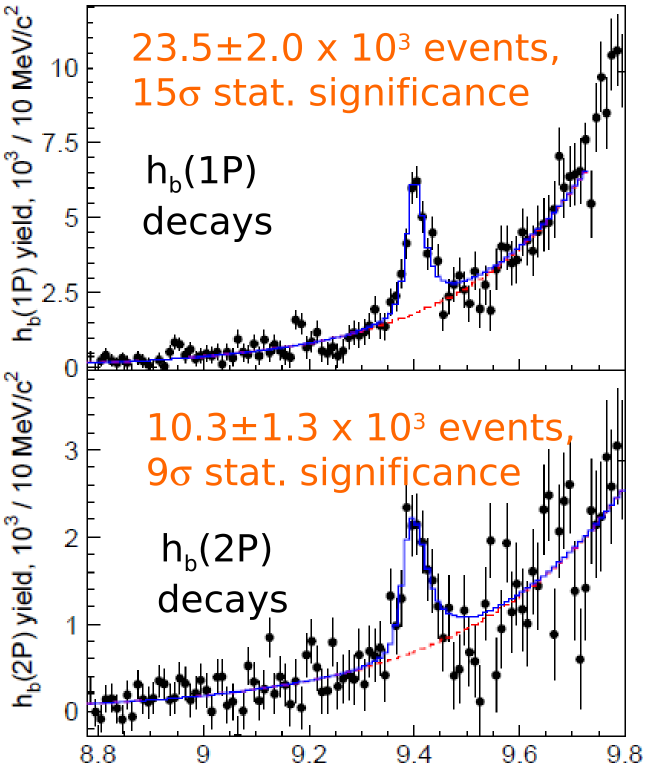
η_b(1S) and evidence for η_b(2S)

State	Mass, MeV	Width, MeV
$\eta_b(1S)$	$9402.4 \pm 1.5 \pm 1.8$	$10.8^{+4.0+4.5}_{-3.7-2.0}$
$\eta_b(2S)$	$9999.0 \pm 3.5^{+2.8}_{-1.9}$	< 24

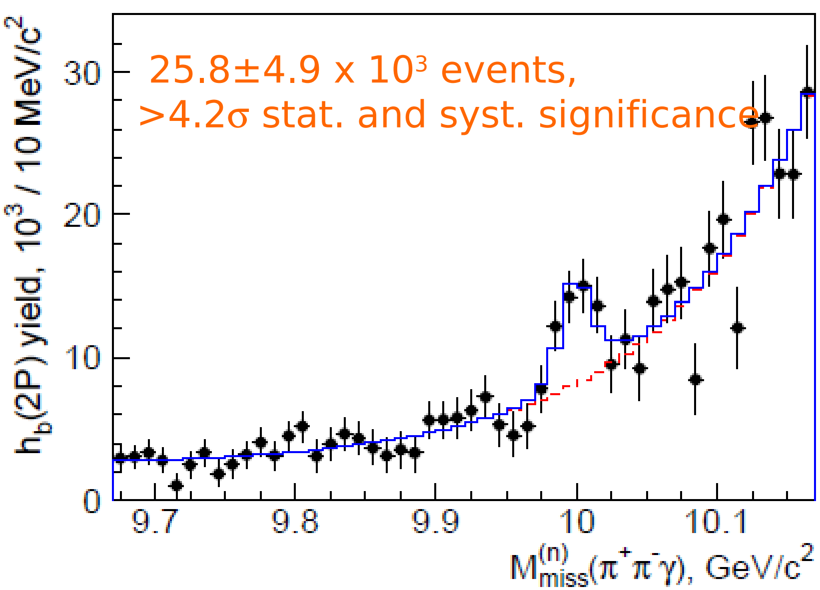
Ebert, Faustov, Galkin,
arXiv:hep-ph/0210381
Phys. Rev. D67(2003)014027

9400 MeV

9993 MeV

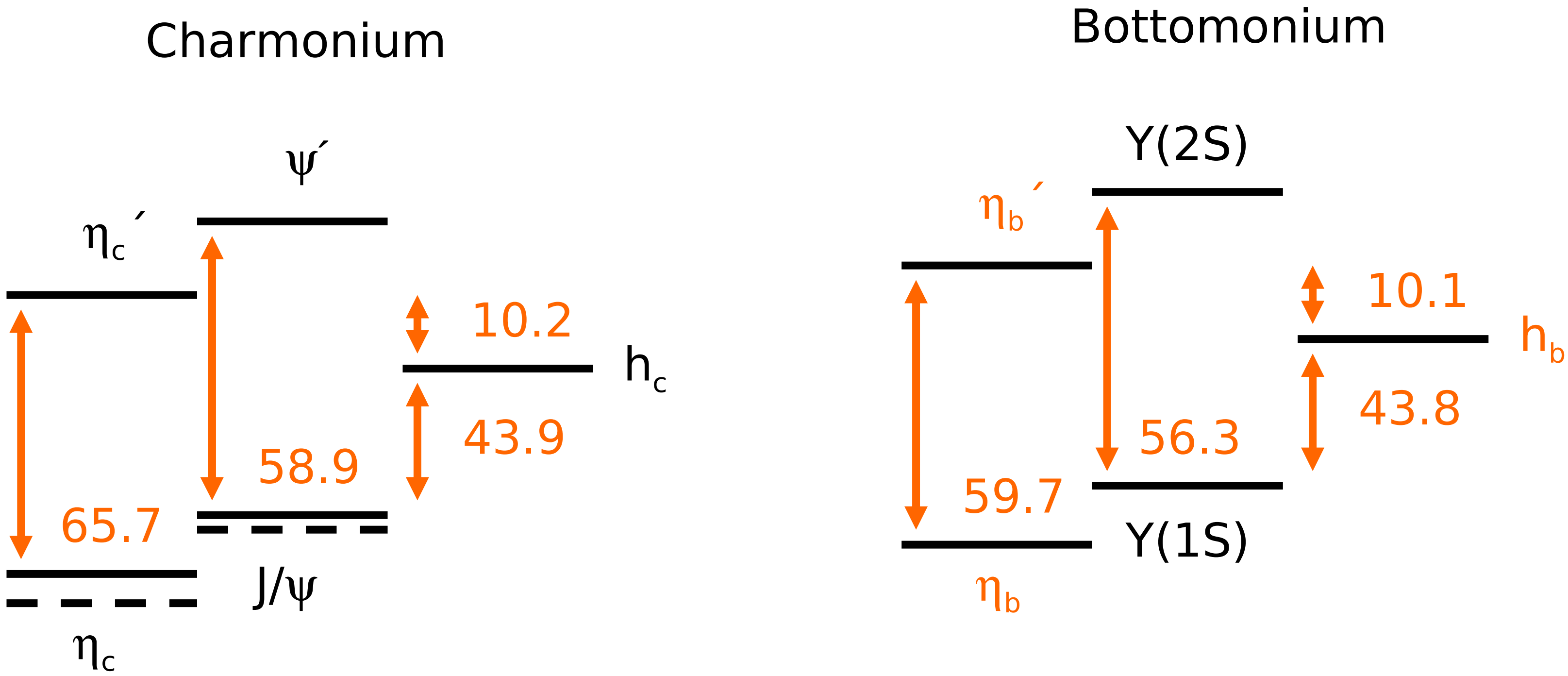


Belle, arXiv:1205.6351
Phys.Rev.Lett. 109 (2012) 232002
133.4 fb^{-1}

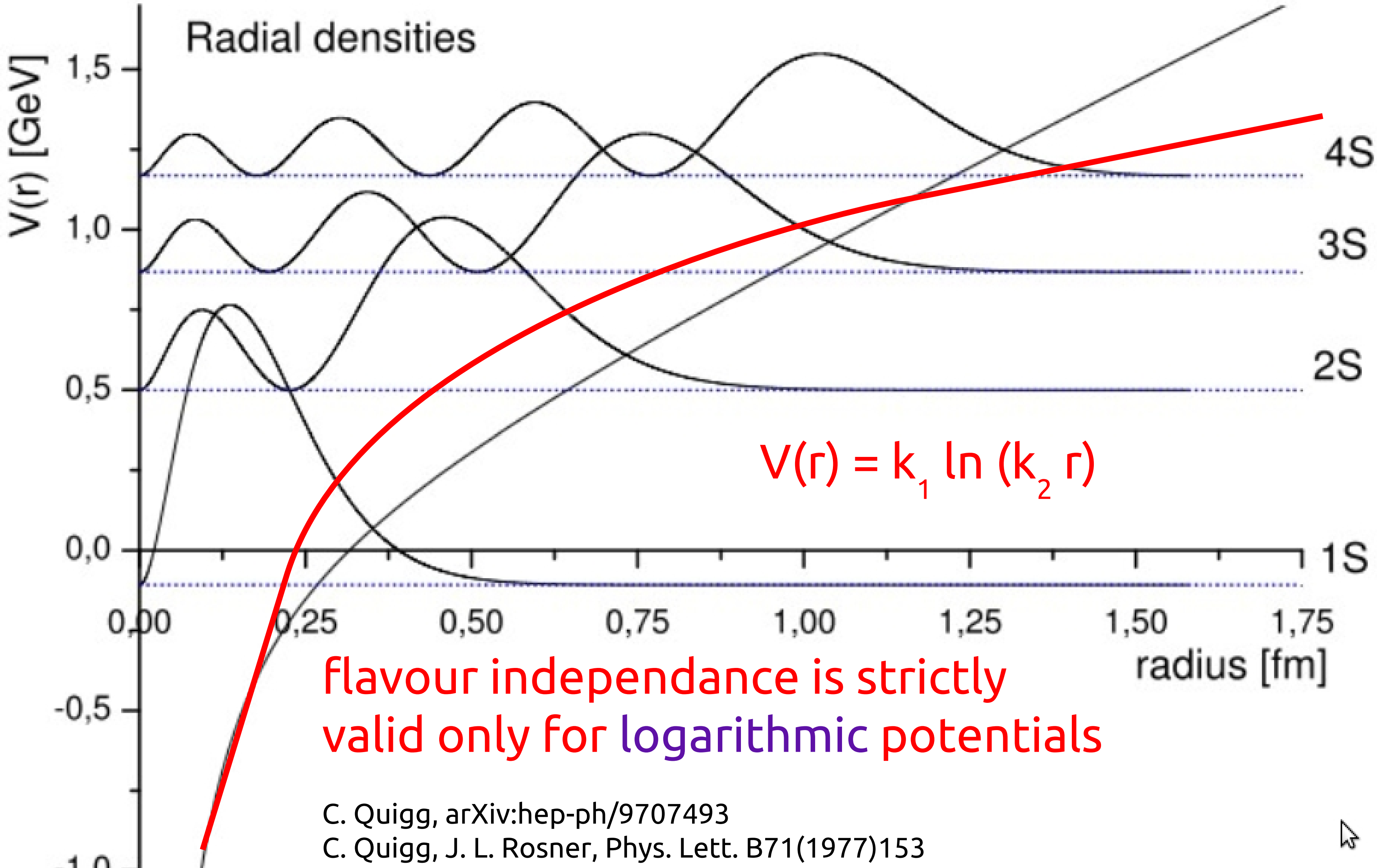


What does it have to do with Confinement ?

Precision Test:
Flavour Independance of $\bar{q}q$ Potential
Are the level spacings the same?



Excellent agreement for h states (S=0,L=1)
Poor agreement for the ground states (S=0, L=0)
Mixing η, η', η_c ? Gluonic component?



flavour independance is strictly valid only for logarithmic potentials

C. Quigg, arXiv:hep-ph/9707493
C. Quigg, J. L. Rosner, Phys. Lett. B71(1977)153
C. Quigg, J. L. Rosner, H. B. Thacker, Phys. Rev. D21(1980) 234
C. Quigg, J. L. Rosner, Phys. Rev. D23(1981)2625

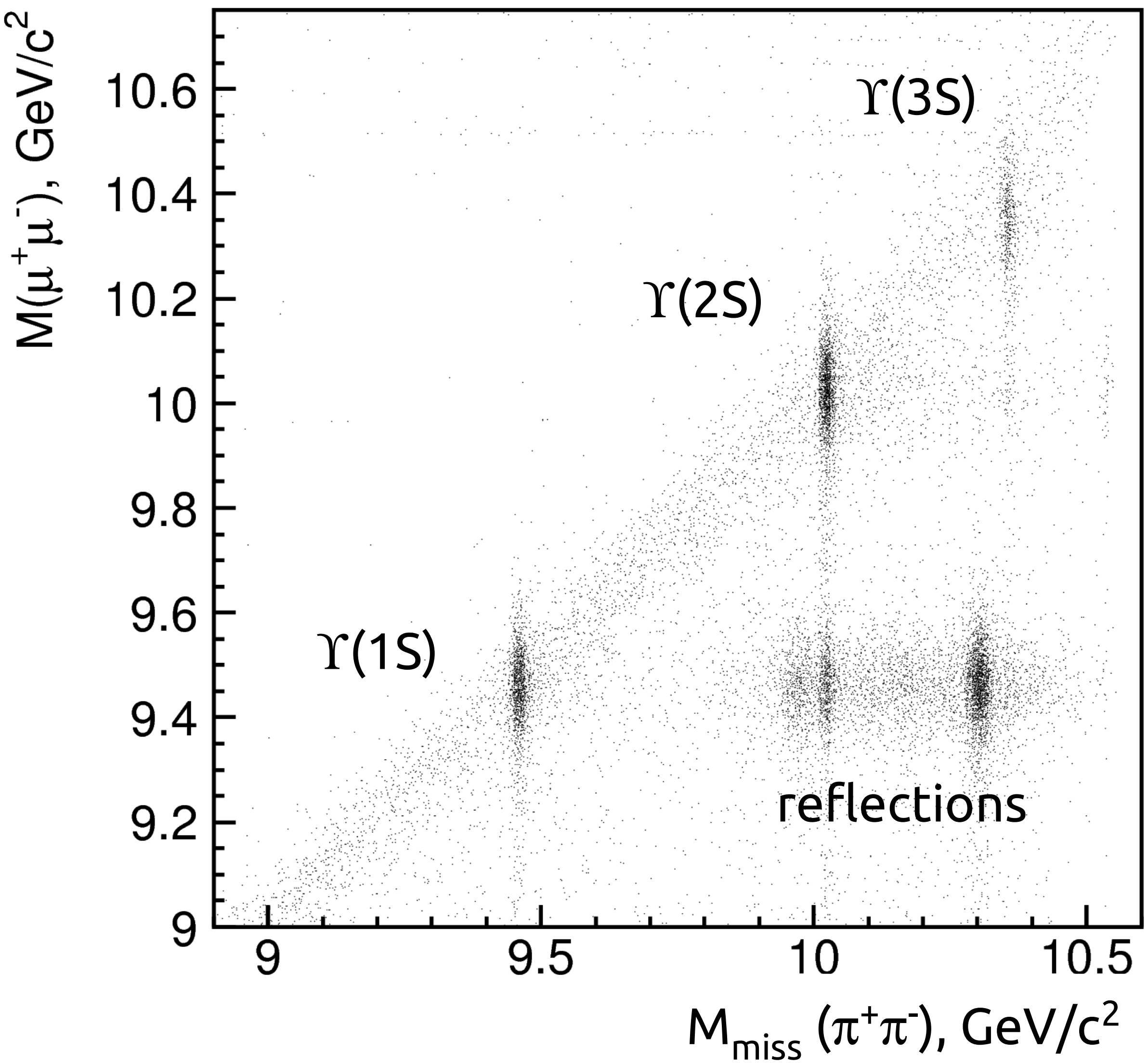
Resonant structure of

$\Upsilon(5S) \to \Upsilon(nS)\,\pi^+\pi^-$

(n=1,2,3)

$\Upsilon(5S) \rightarrow \Upsilon(nS)\ \pi^+\pi^-$ (n = 1,2,3)

$\quad\quad\quad\quad\quad\quad \hookrightarrow \mu^+\mu^-$

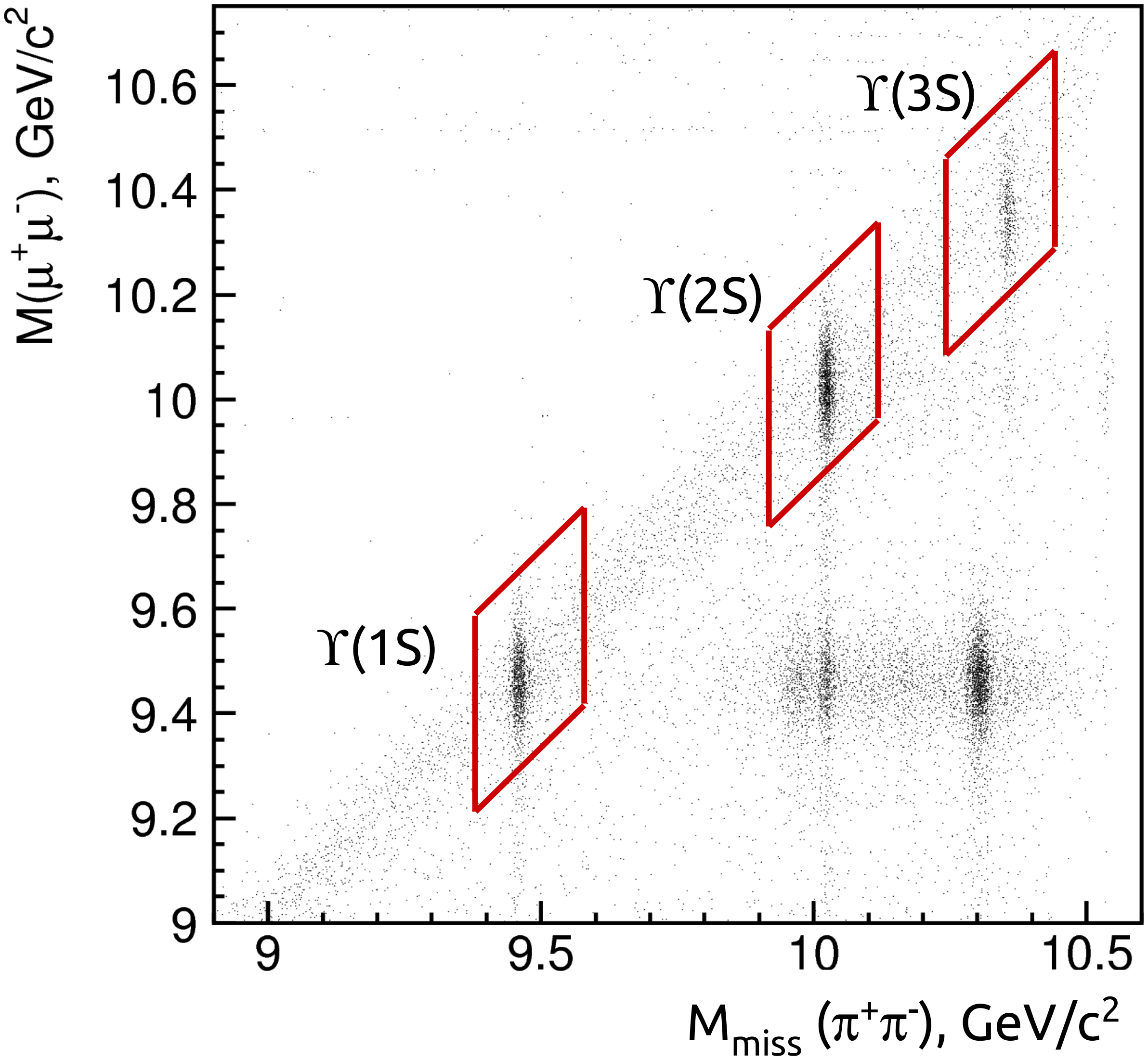


$\Upsilon(5S) \to \Upsilon(nS)\ \pi^+\pi^-$

$\hookrightarrow \mu^+\mu^-$

(n = 1,2,3)

purity 92 – 94%



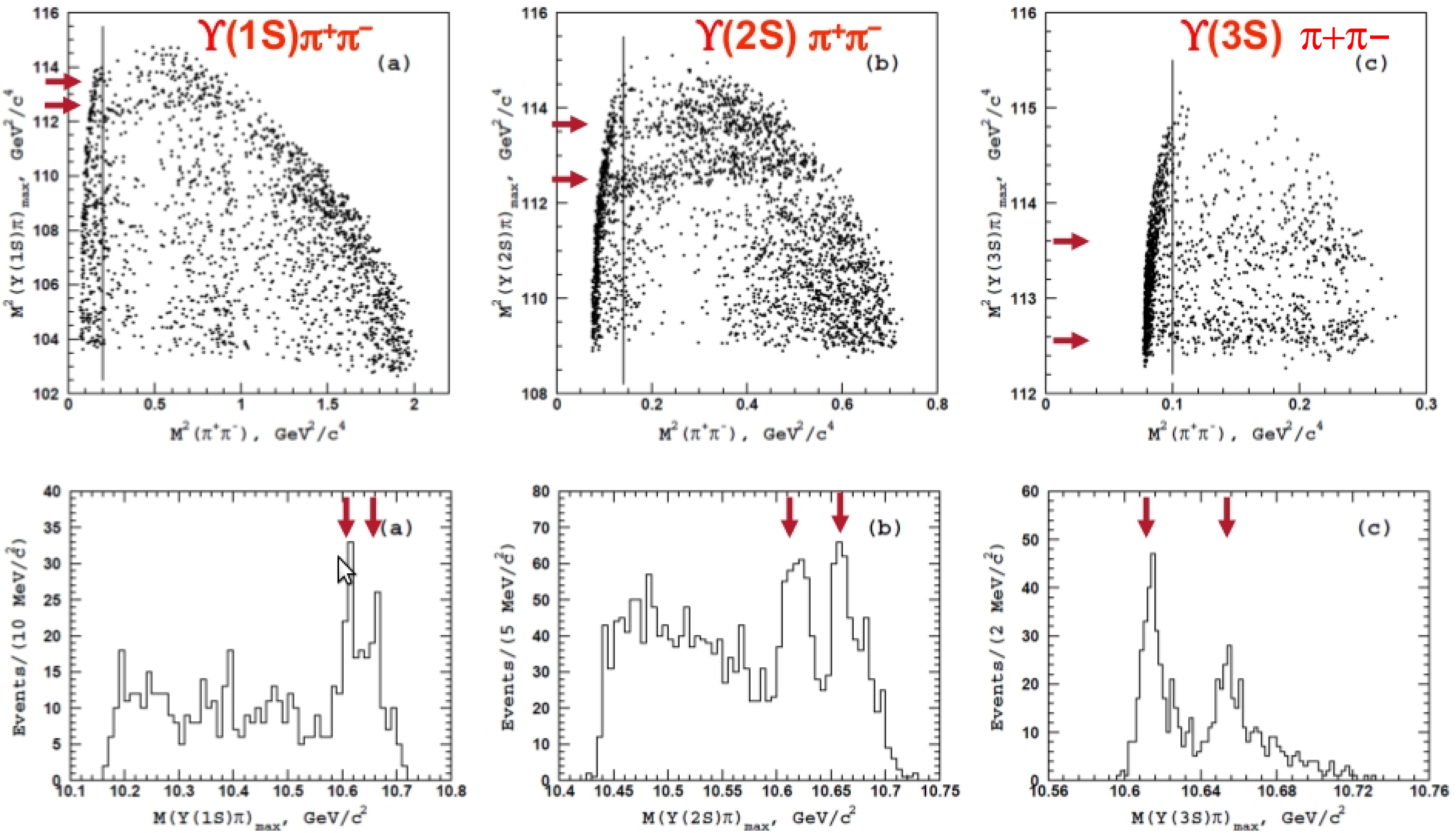
Reflections

Y(5S)

→ Y(2S,3S)ππ

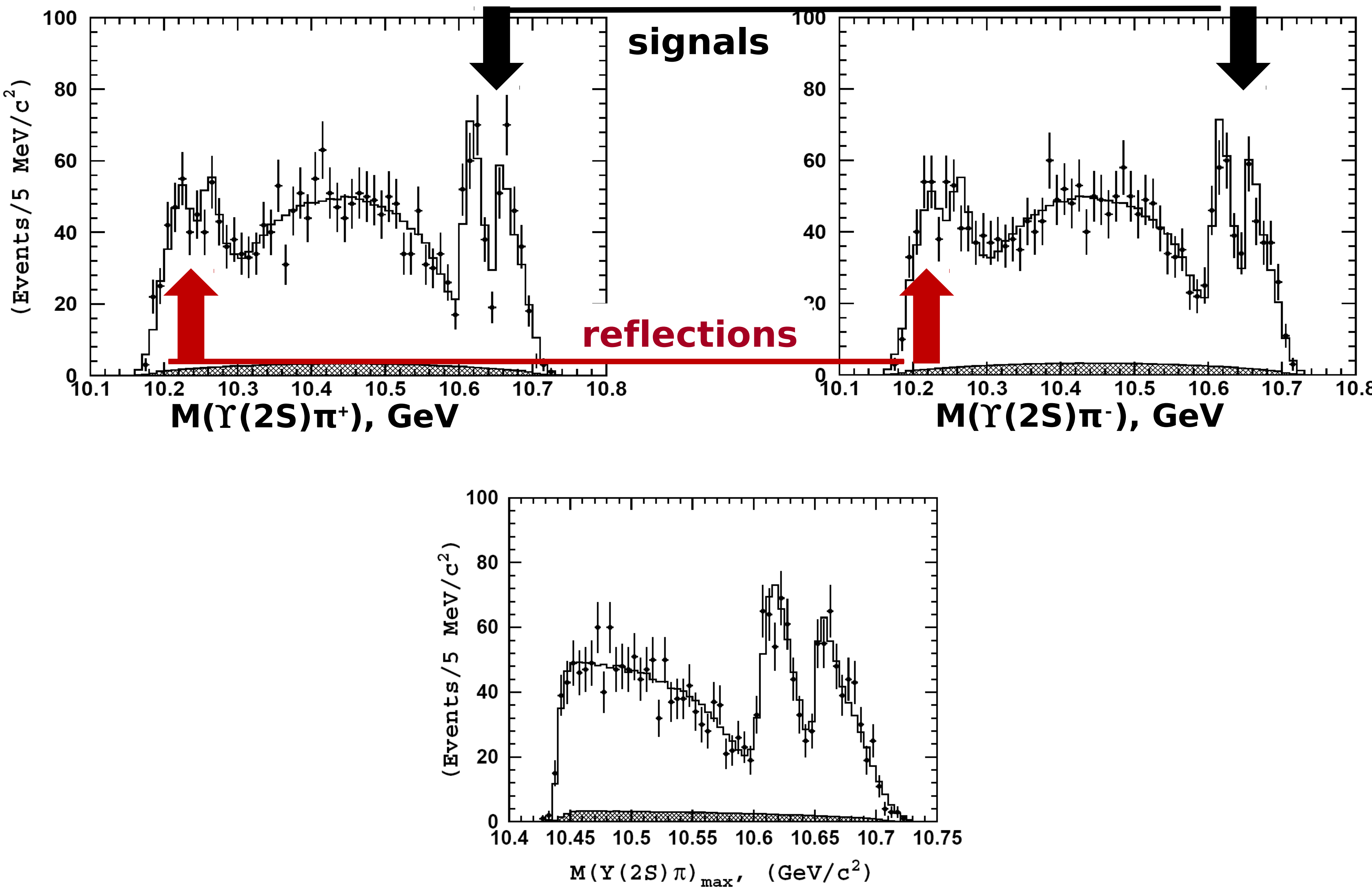
→ Y(1S)ππππ

$\Upsilon(5S) \to \Upsilon(nS)\,\pi^+\pi^-$ Dalitz plots



→ Signals of $Z_b(10610)$ and $Z_b(10650)$

Results: $\Upsilon(2S)\pi^+\pi^-$



Charged states decaying to
$\Upsilon(nS)\ \pi^{\pm}$
can never be bottomonium.

Summary of Z_b parameters

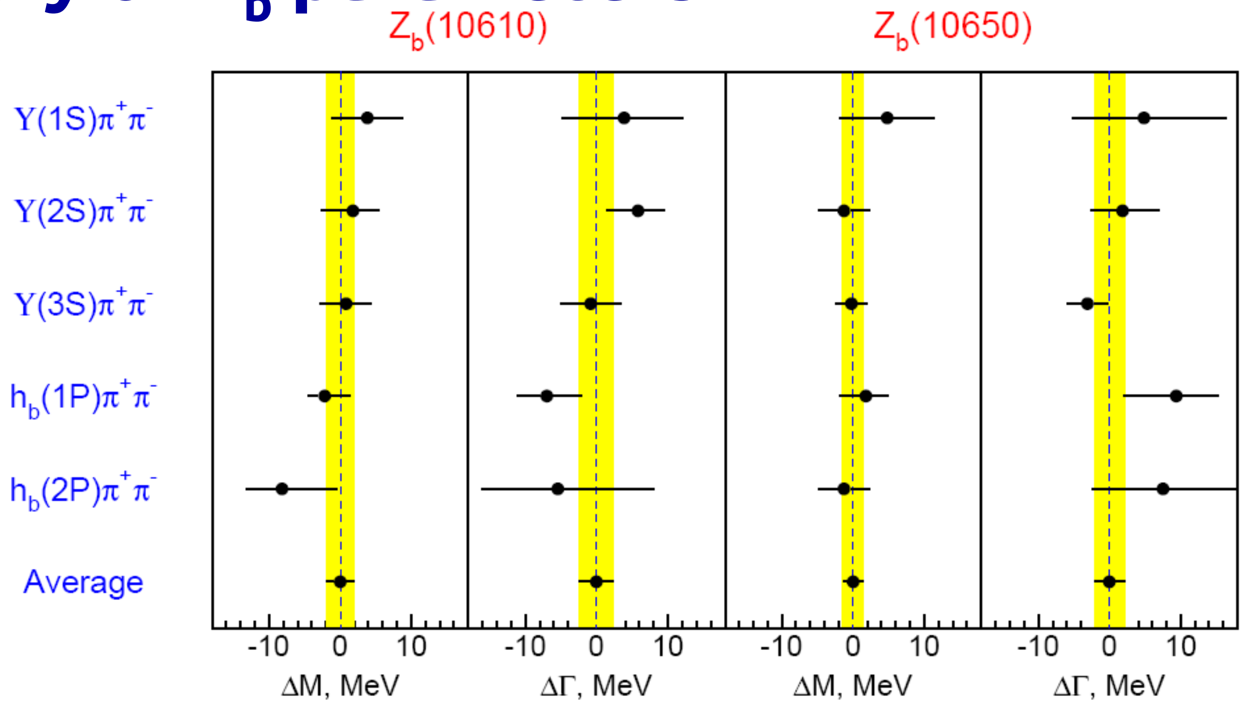
Average over 5 channels

$\langle M_1 \rangle$ = 10607.2±2.0 MeV

$\langle \Gamma_1 \rangle$ = 18.4±2.4 MeV

$\langle M_2 \rangle$ = 10652.2±1.5 MeV

$\langle \Gamma_2 \rangle$ = 11.5 ± 2.2 MeV



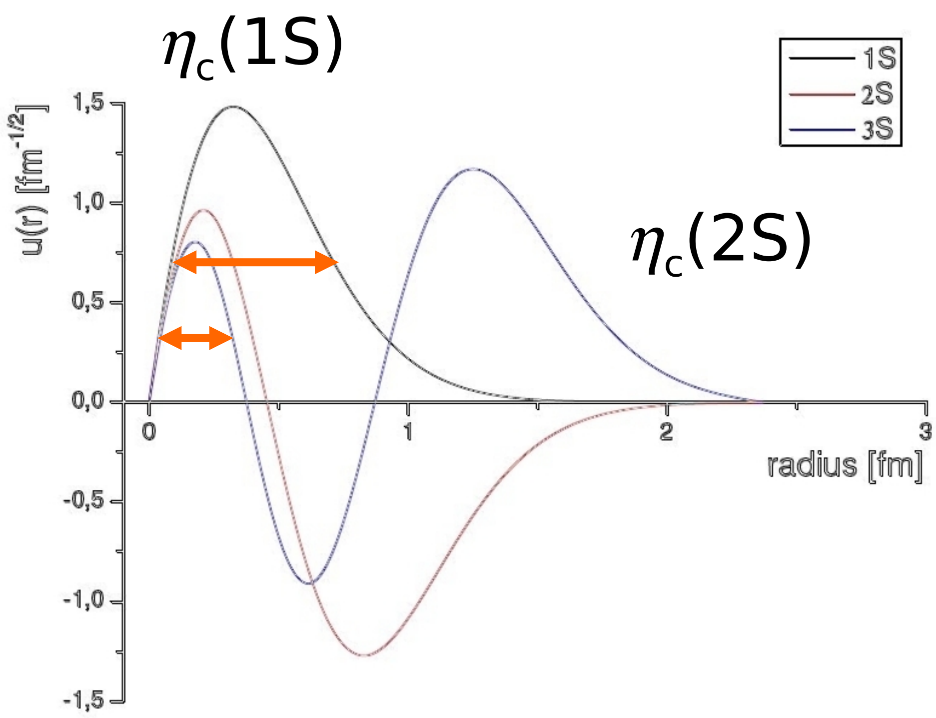
Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)]$, MeV/c^2	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)]$, MeV	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4\ ^{+4.5+2.1}_{-3.9-1.2}$	$13\ ^{+10+9}_{-8-7}$
$M[Z_b(10650)]$, MeV/c^2	$10657 \pm 6 \pm 3$	$10651 \pm 2 \pm 3$	$10652 \pm 1 \pm 2$	$10654 \pm 3\ ^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma[Z_b(10650)]$, MeV	$16.3 \pm 9.8^{+6.0}_{-2.0}$	$13.3 \pm 3.3^{+4.0}_{-3.0}$	$8.4 \pm 2.0 \pm 2.0$	$20.9\ ^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7\ ^{+11}_{-7}$
Rel. normalization	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Rel. phase, degrees	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$

The two charged states are observed in 5 decays channels.

Future Experiments

measure the WIDTHS of new states
in the sub-MeV regime

Widths provide knowledge about wave function



Width of $\eta_c(1S)$
32.0 ± 0.9 MeV (PDG)

Width of $\eta_c(2S)$
11.3+3.2-2.9 MeV (PDG)

$$\Gamma(^1S_0 \to gg) = \frac{32\pi}{3}\frac{\alpha_S^2}{m_c^2}|\psi(r=0)|^2$$

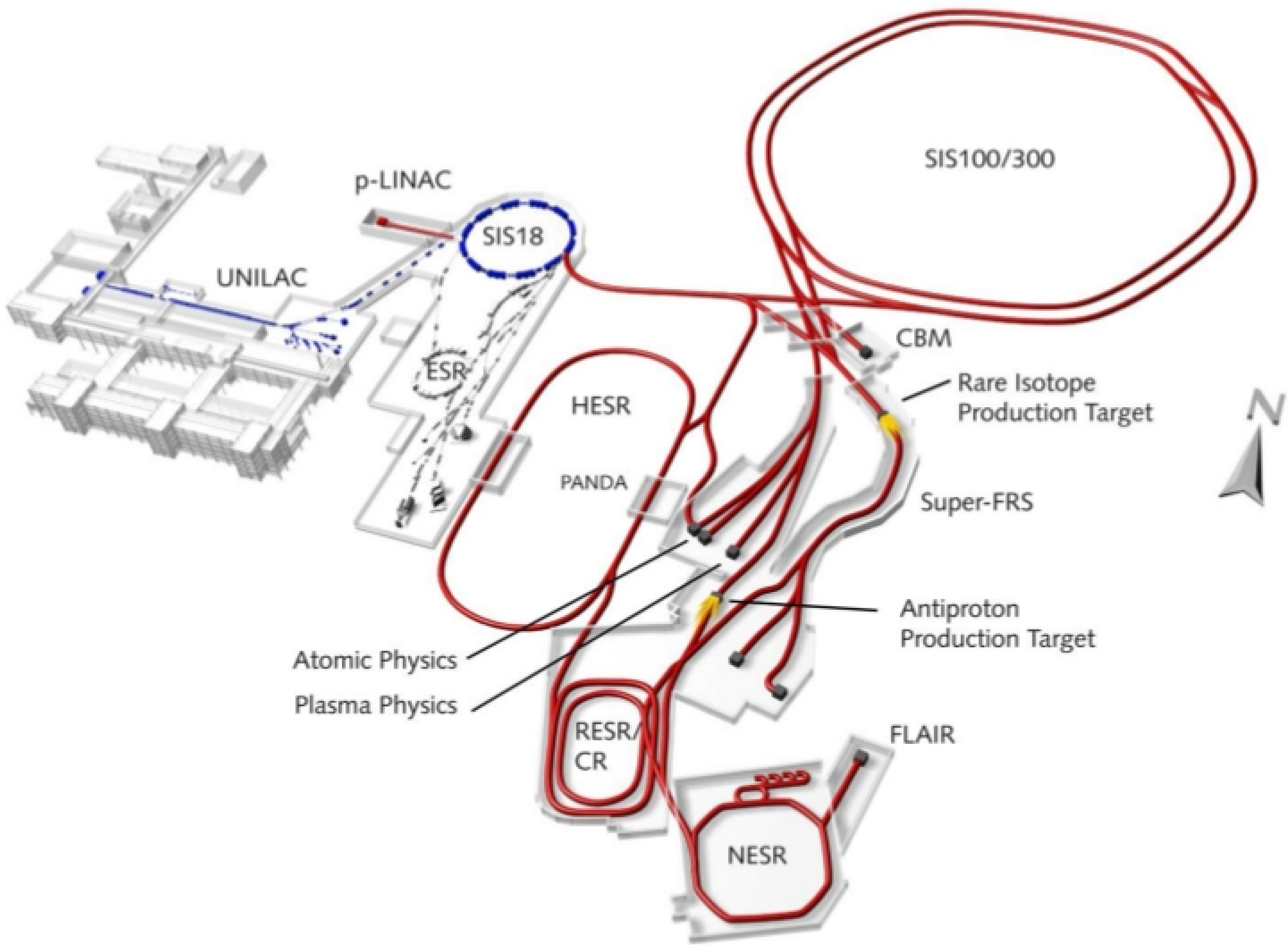
$\overline{\text{P}}$ANDA

determine the width of the X(3872)

with a cooled anti-proton beam

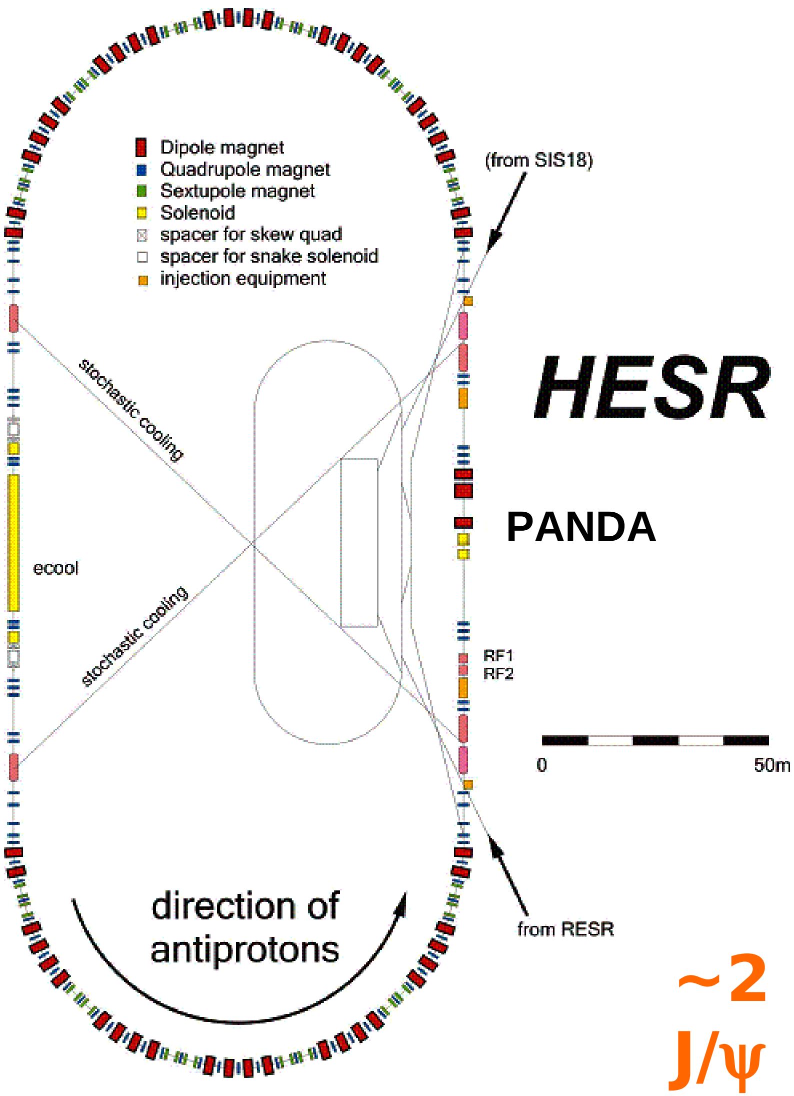
by a resonance scan technique

FAIR (**F**acility for **A**nti-Proton and **I**on **R**esearch) Helmholtz Center GSI Darmstadt (Germany)



(no parking lot !)

HESR (High Energy Storage Ring)



For Anti-Protons

High intensity mode

- $10^{11}\ \bar{p}$
- $\delta p/p \approx 10^{-4}$ (stochastic cooling)

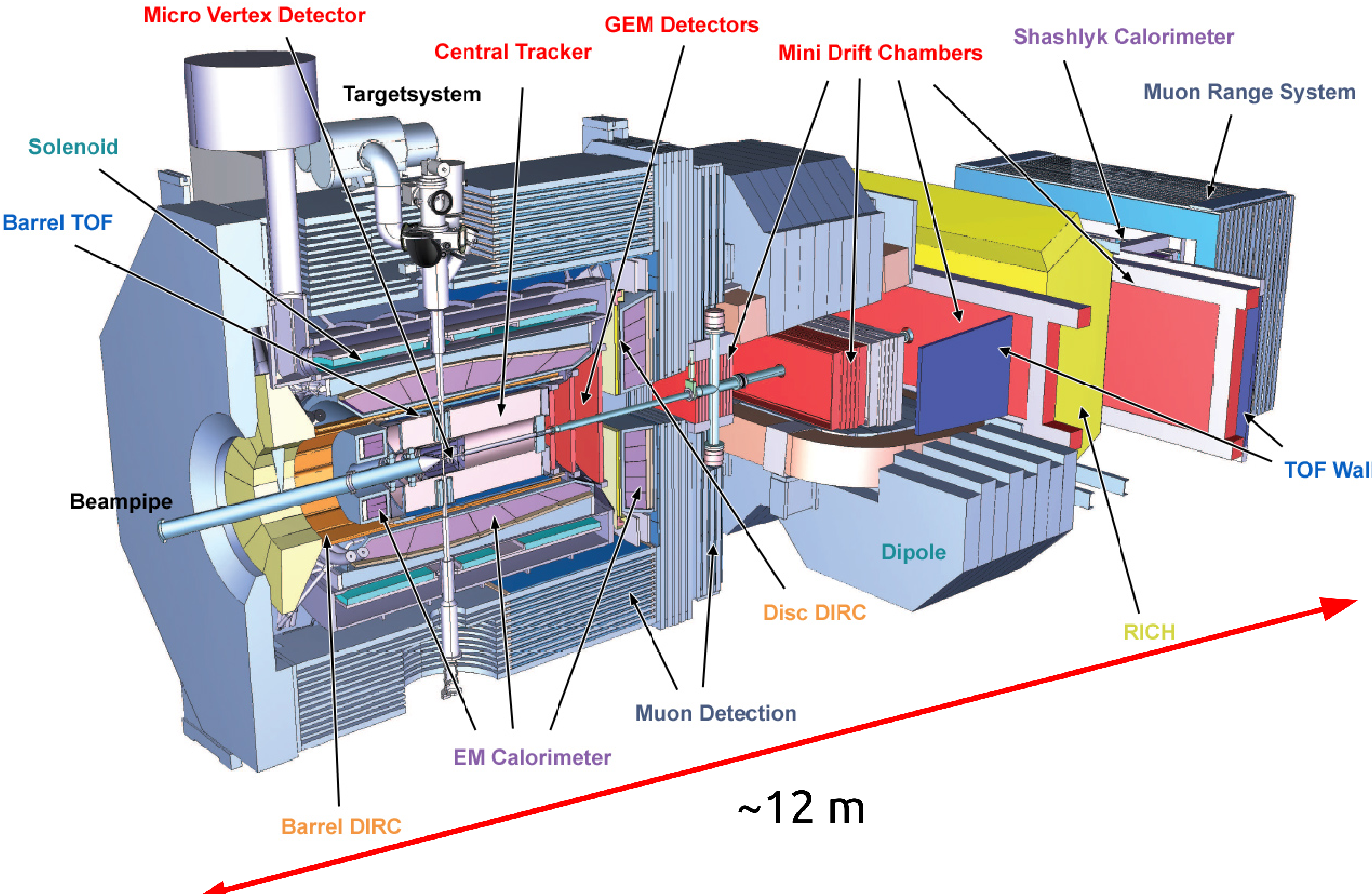
High resolution mode

- $10^{10}\ \bar{p}$
- $\delta p/p \approx 10^{-5}$ (e^- cooling)

Internal targets

- $\mathcal{L} = 2 \times 10^{32}\ cm^{-2}\ s^{-1}$
- H_2 Pellets
- Cluster jet
- Nuclei: Be, C, Si, Al

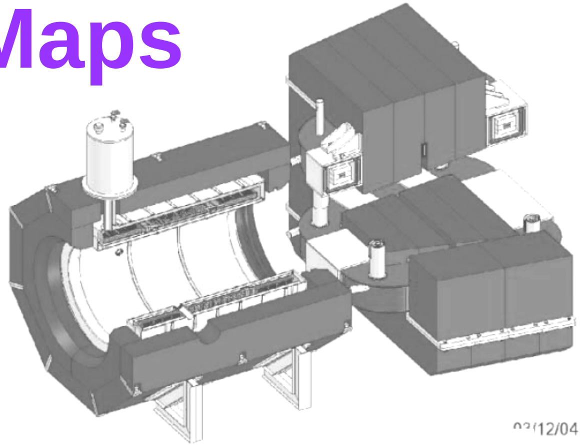
~2 x 10^9 J/ψ per year



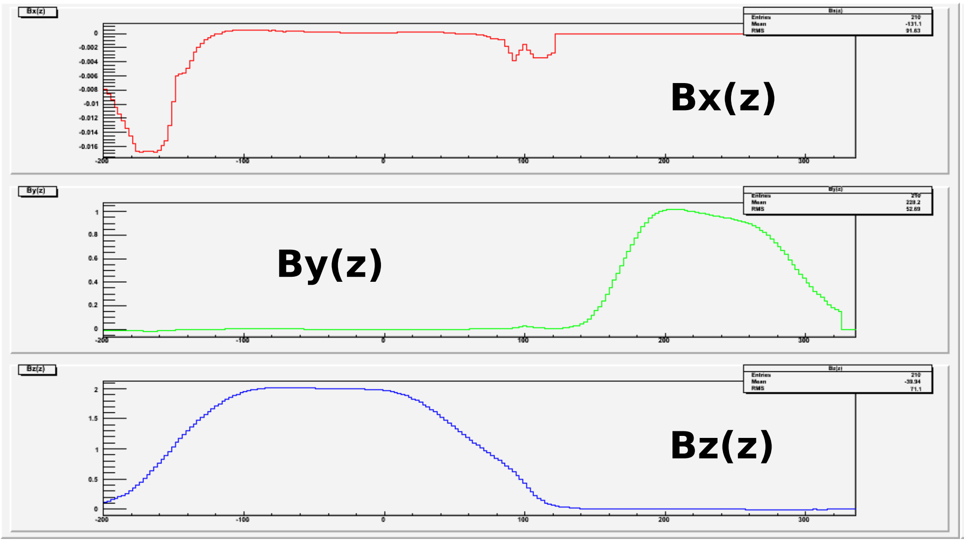
Target spectrometer
Bz = 2 T

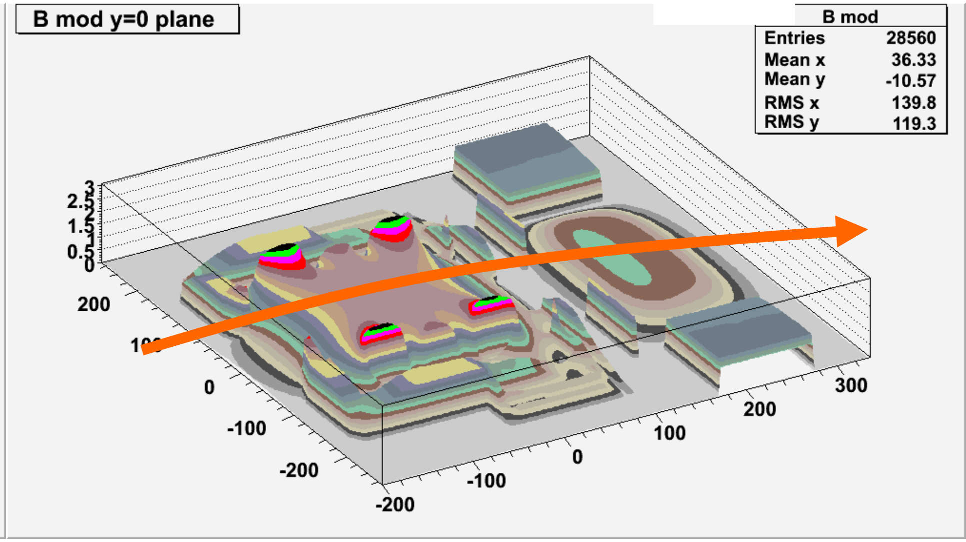
Forward spectrometer
Dipole B·L = 2 Tm

Panda B Field Maps



B field in kG

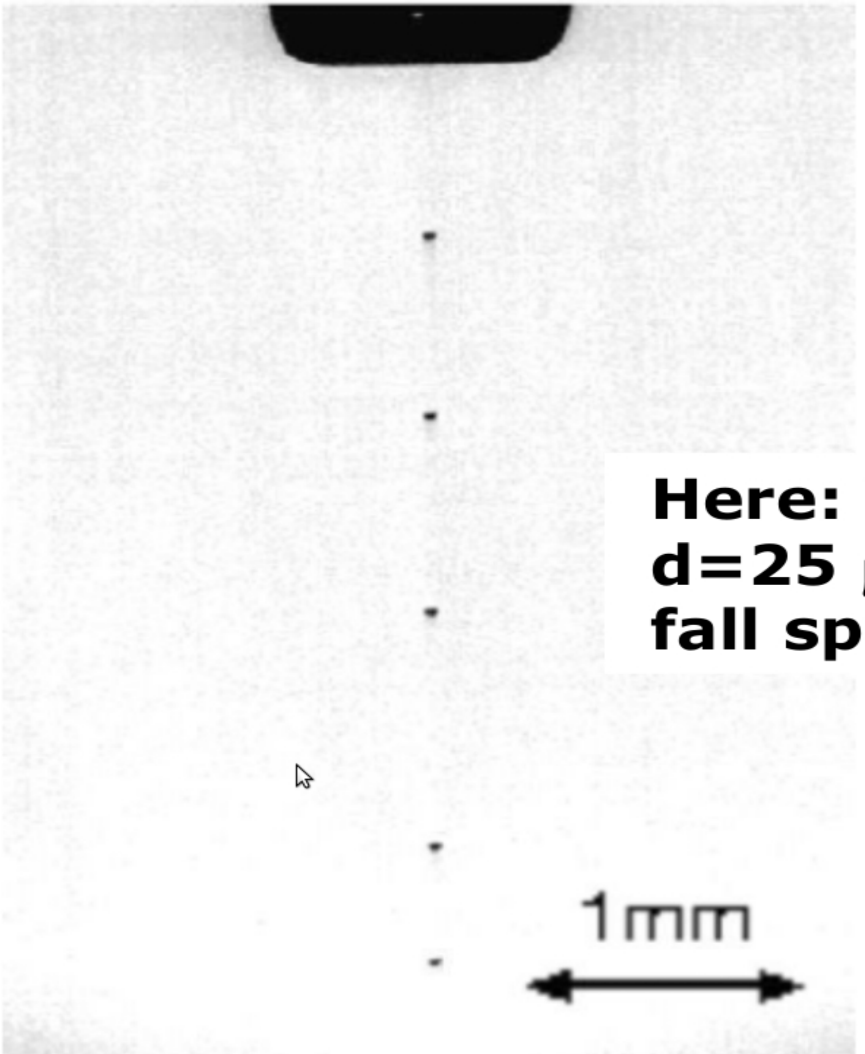




-200 0 +300
z/cm

→ beam deflection for p_{beam}=15 GeV/c
4.2 cm @ z=6m (end of dipole)

The Panda Pellet Target



Here: WASA Target
d=25 μm
fall speed $\geq$ 60 m/s

Anti-proton beam momentum $p \leq 15$ GeV/c
→ $\sqrt{s} \leq 5.5$ GeV
access to states higher than 5 GeV !
not available in Belle II (B decays) neither at BesIII

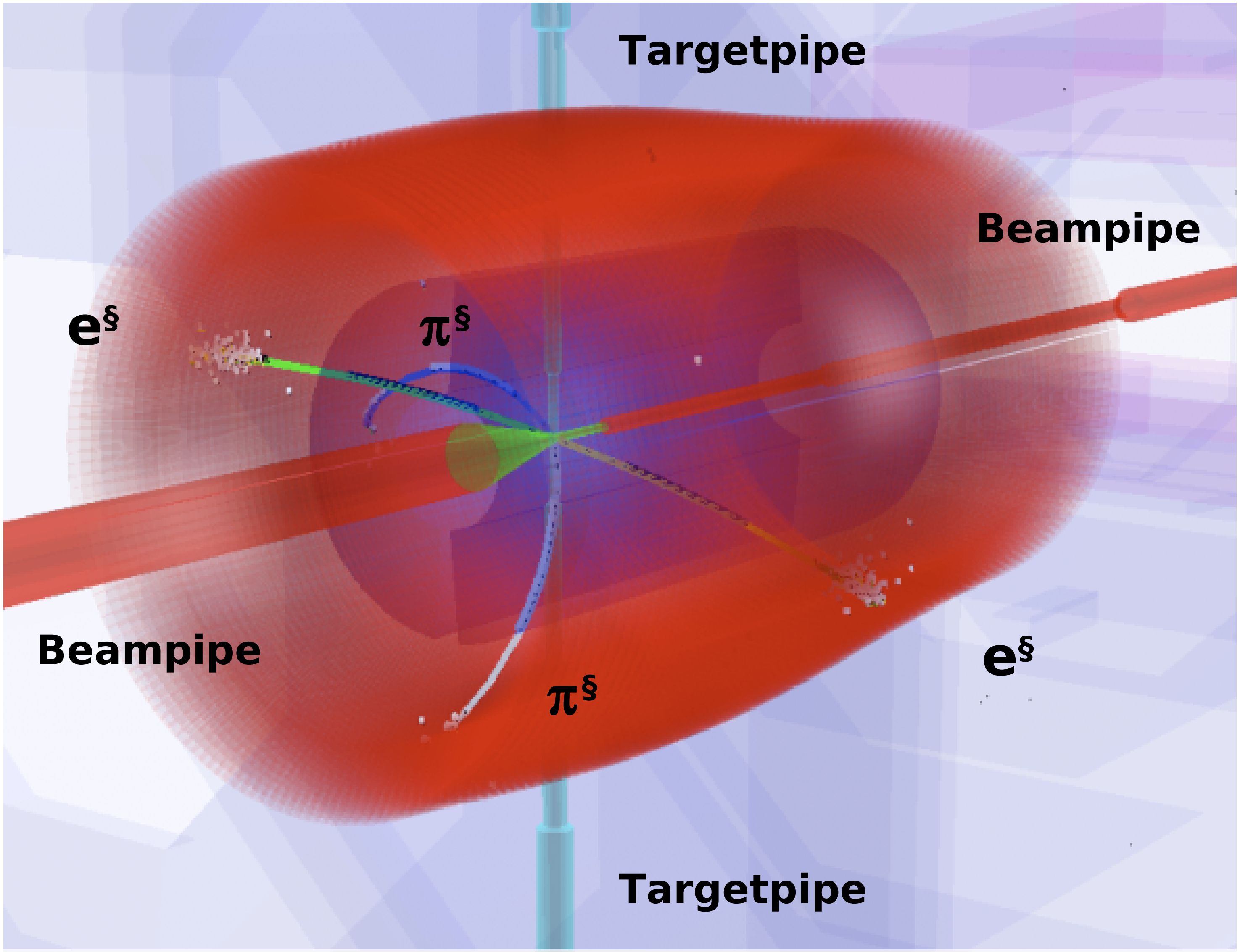
$p\bar{p} \rightarrow 1^{++}$ direct formation possible !
($e^+ e^- \rightarrow X(3872)$ not possible)

B=2 T (high!)

fixed target
→ high p_z of tracks (boosted)

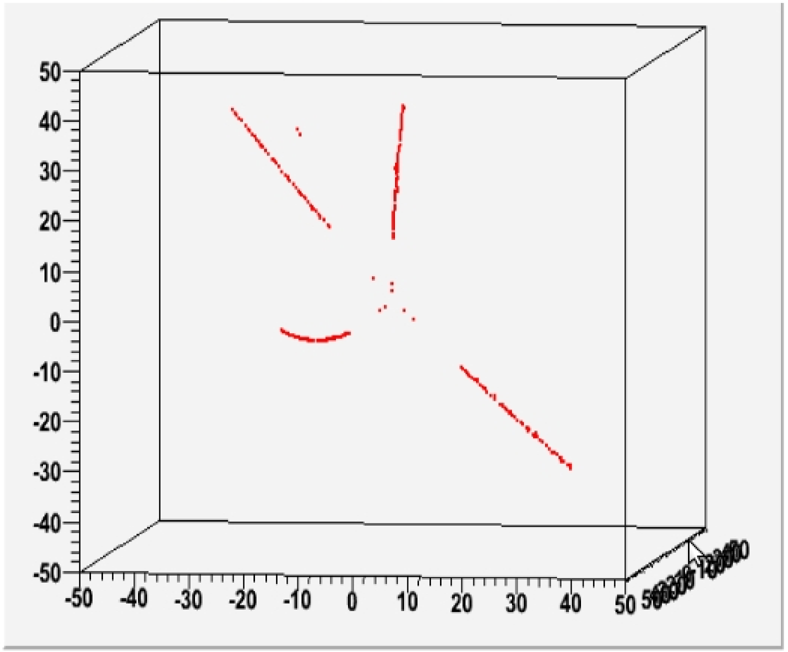
NO TRIGGER
full reconstruction online
with interaction rate 2×10^7 /s

X(3872) → J/ψ π⁺ π⁻ Event, PandaRoot Simulation

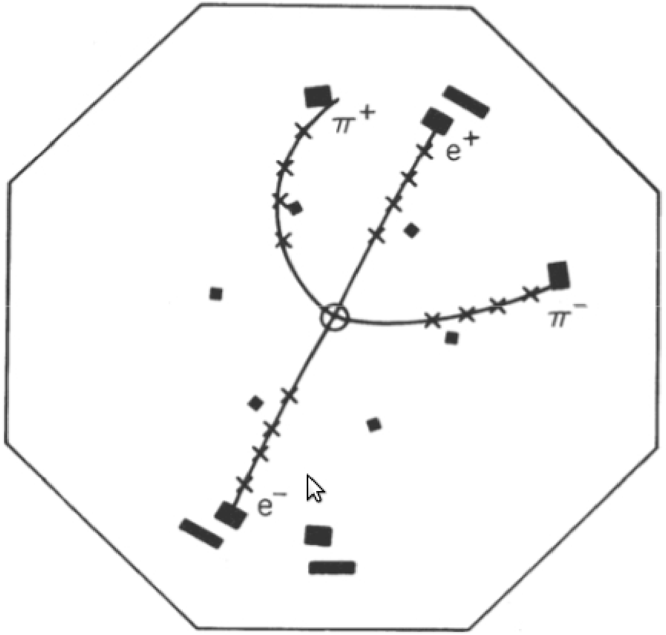


PandaRoot Framework Simulation
$X(3872) \to J/\psi\ \pi^+\ \pi^-$
TPC digitization,
MVD Silicon Tracker digitization

XYZ coordinates / cm



$\psi' \to J/\psi\ \pi^+\ \pi^-$
Mark II, 1973



How do we know cross sections @ $\overline{\text{P}}$ANDA ?
→ Detailed Balance

Production
@ Panda

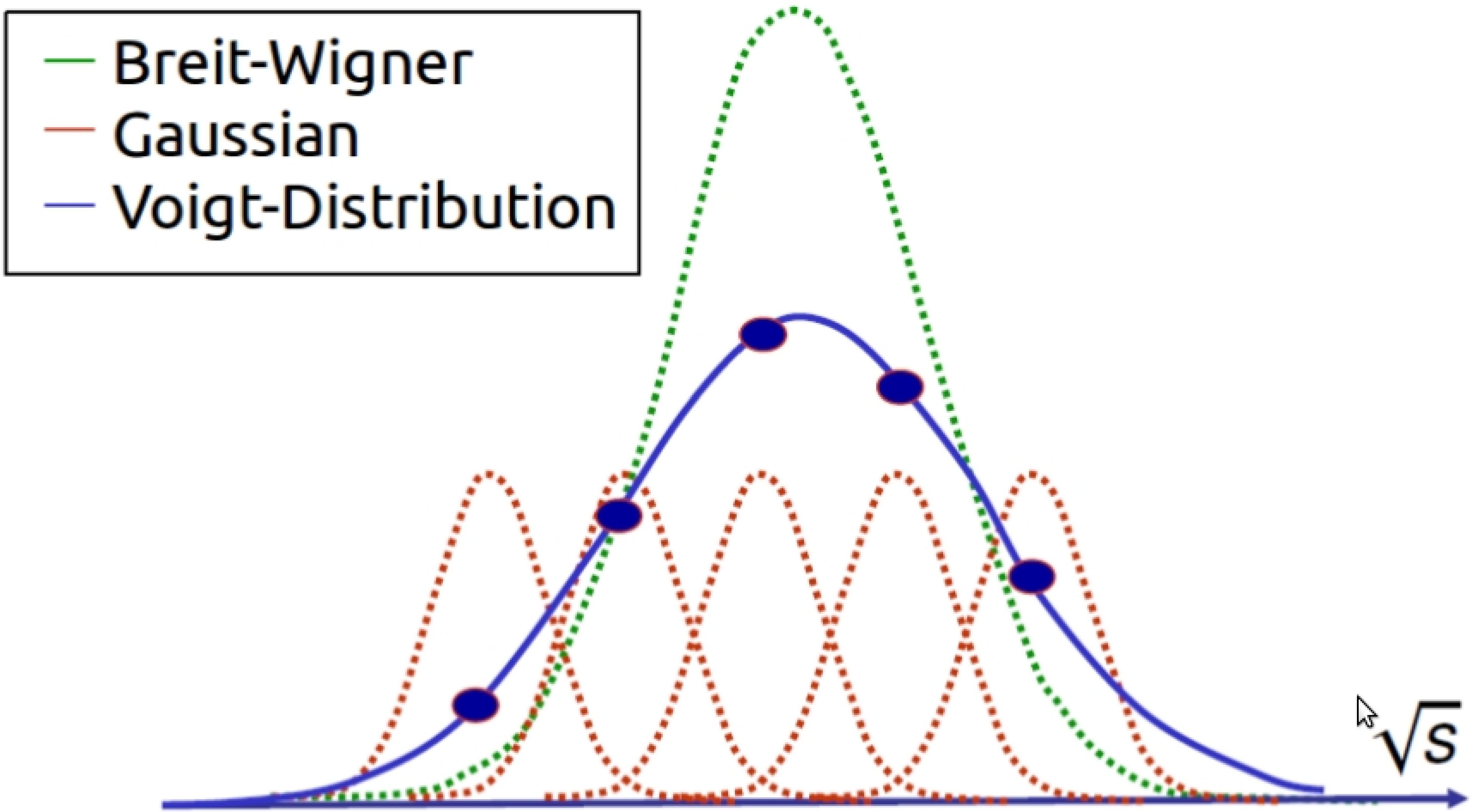
$$\sigma[p\bar{p} \to X(3872)] = \sigma_{BW}[p\bar{p} \to X \to \text{all}](m_{X(3872)})$$

$$= \frac{(2J+1)\cdot 4\pi}{m^2_{X(3872)} - 4m_p^2} \cdot \frac{\mathcal{B}(X(3872) \to p\bar{p}) \cdot \overbrace{\mathcal{B}(X(3872) \to f)}^{=1} \cdot \Gamma^2_{X(3872)}}{\underbrace{4(m_{X(3872)} - m_{X(3872)})^2}_{=0} + \Gamma^2_{X(3872)}}$$

$$\overset{(J=1)}{=} \frac{3 \cdot 4\pi}{m^2_{X(3872)} - 4m_p^2} \cdot \mathcal{B}(X(3872) \to p\bar{p})$$

Decay
@ Belle, BaBar, Bes3, LHCb

X(3872) Resonance Scan



Resonance scan of X(3872) @ $\overline{\text{P}}$ANDA

Assumptions

50 nb signal cross section ($p\bar{p} \rightarrow X(3872) \rightarrow J/\psi\pi^+\pi^-$)

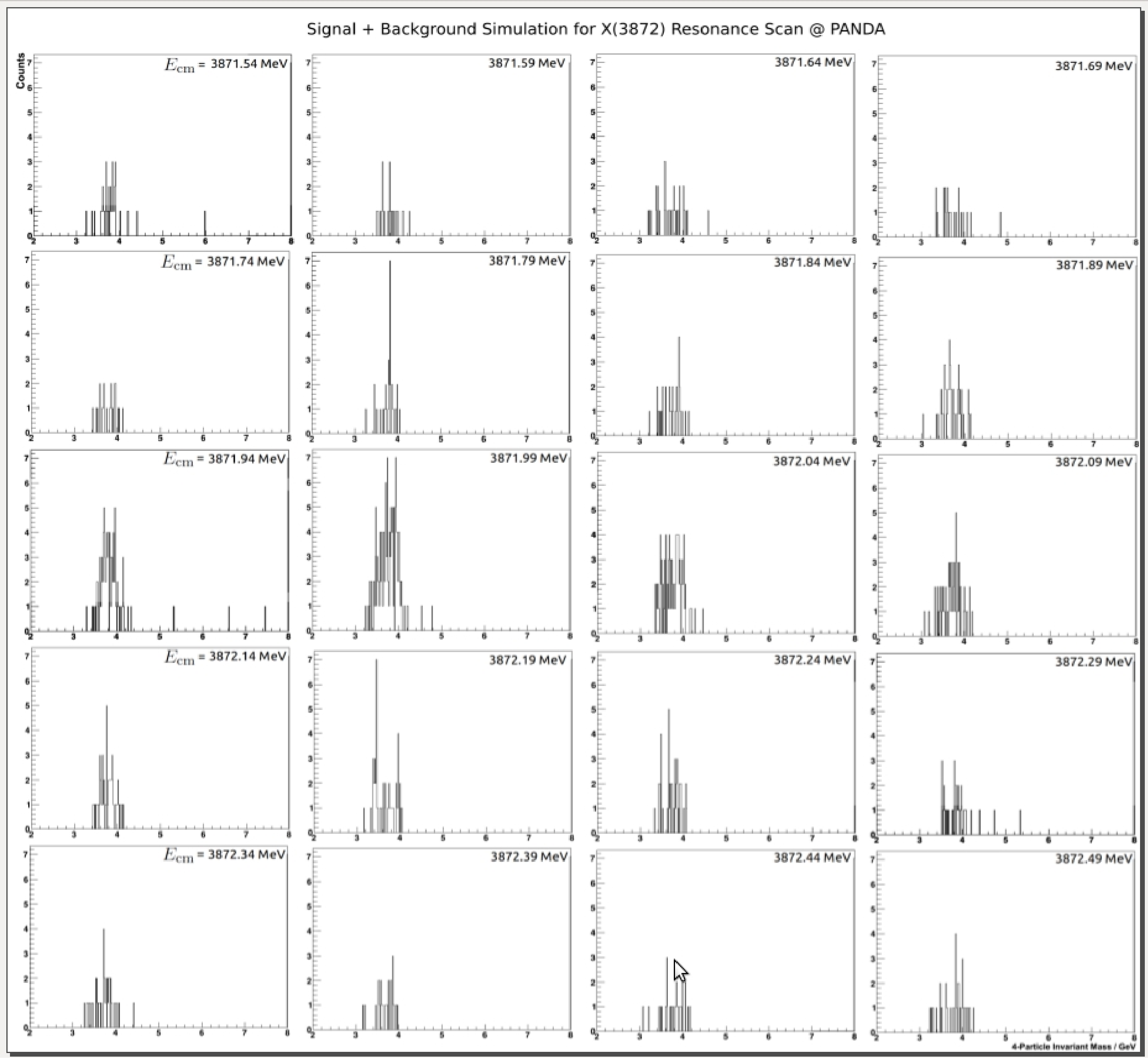
Width of X(3872) Γ=100 keV

HESR high resolution mode
p = 6.992 GeV/c
 = 2×10^{-5}
$\rightarrow$ E_{cm} resolution 33.568 keV

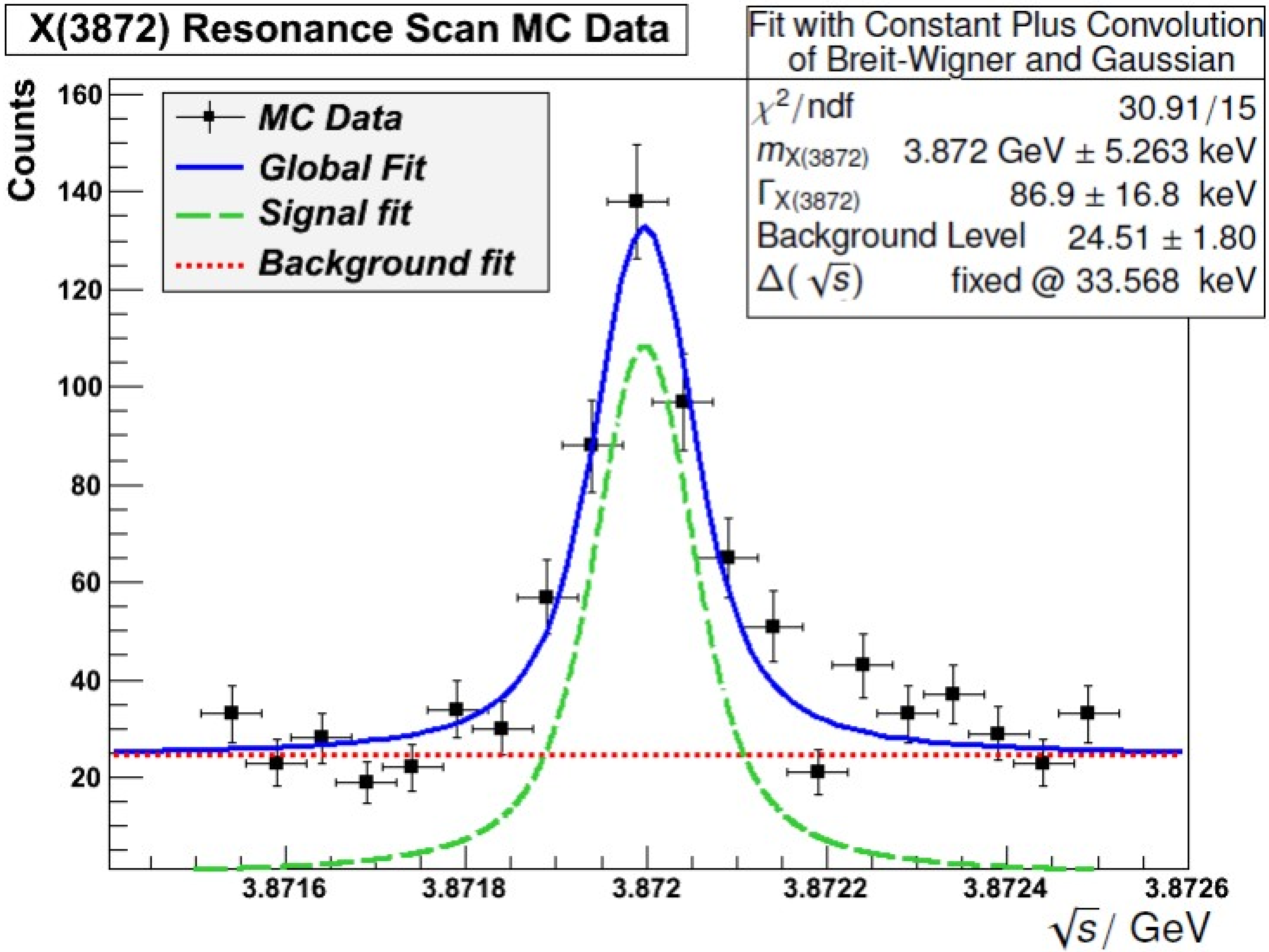
0.864 pb^{-1} / day

20 scan points, 2 days per 1 scan point

Background Dual Parton Model (DPM)
see V. V. Uzhinsky, A. S. Galoyan, hep-ph/0212369
for cross sections



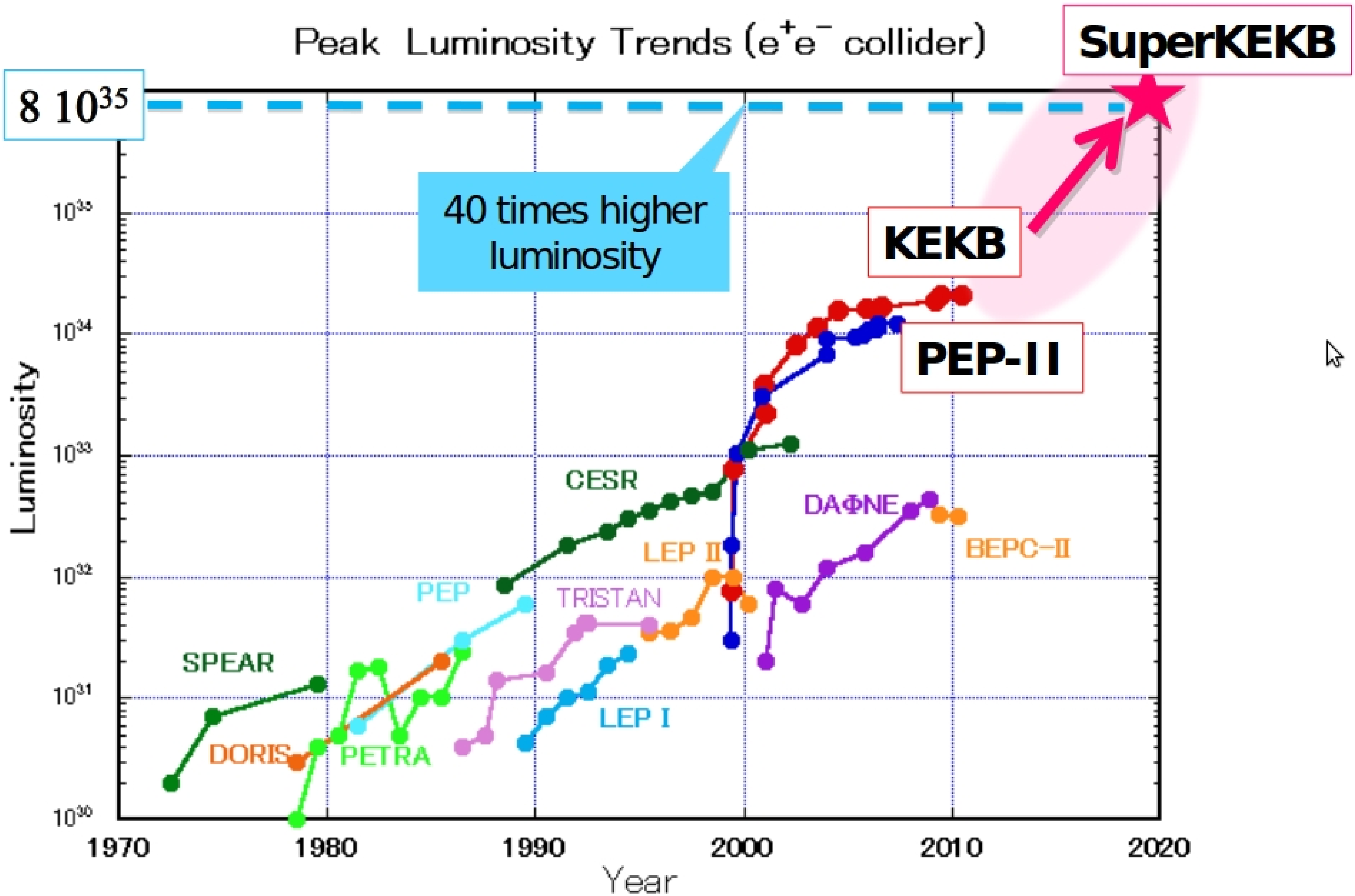
Signal + Background Simulation for X(3872) Resonance Scan @ PANDA
Counts
E_{cm} = 3871.54 MeV
3871.59 MeV
3871.64 MeV
3871.69 MeV
E_{cm} = 3871.74 MeV
3871.79 MeV
3871.84 MeV
3871.89 MeV
E_{cm} = 3871.94 MeV
3871.99 MeV
3872.04 MeV
3872.09 MeV
E_{cm} = 3872.14 MeV
3872.19 MeV
3872.24 MeV
3872.29 MeV
E_{cm} = 3872.34 MeV
3872.39 MeV
3872.44 MeV
3872.49 MeV
4-Particle Invariant Mass / GeV



Natural width of 100 keV can be reproduced!
(within the error bars)

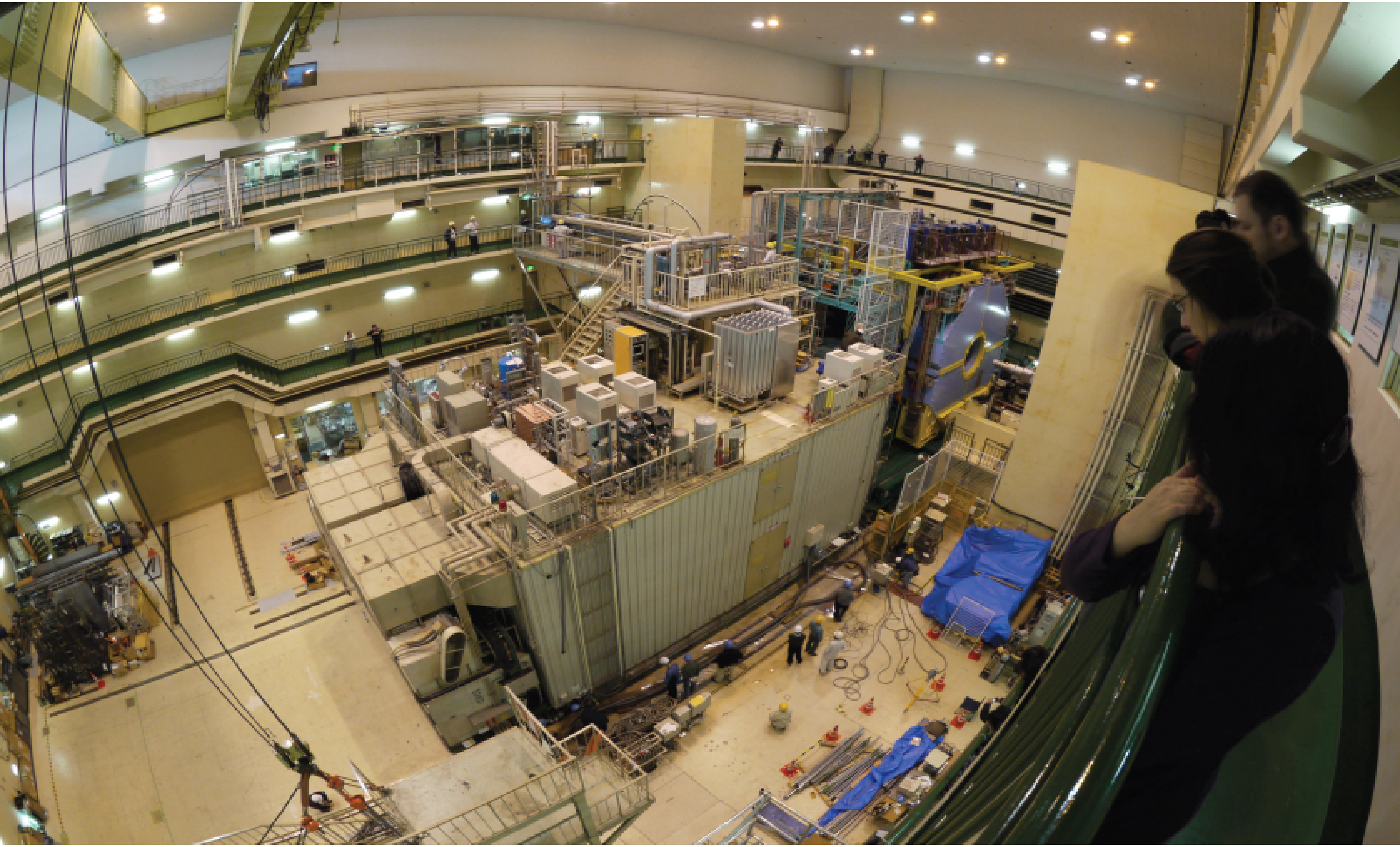
Belle II

≥2016 at KEK, Tsukuba, Japan

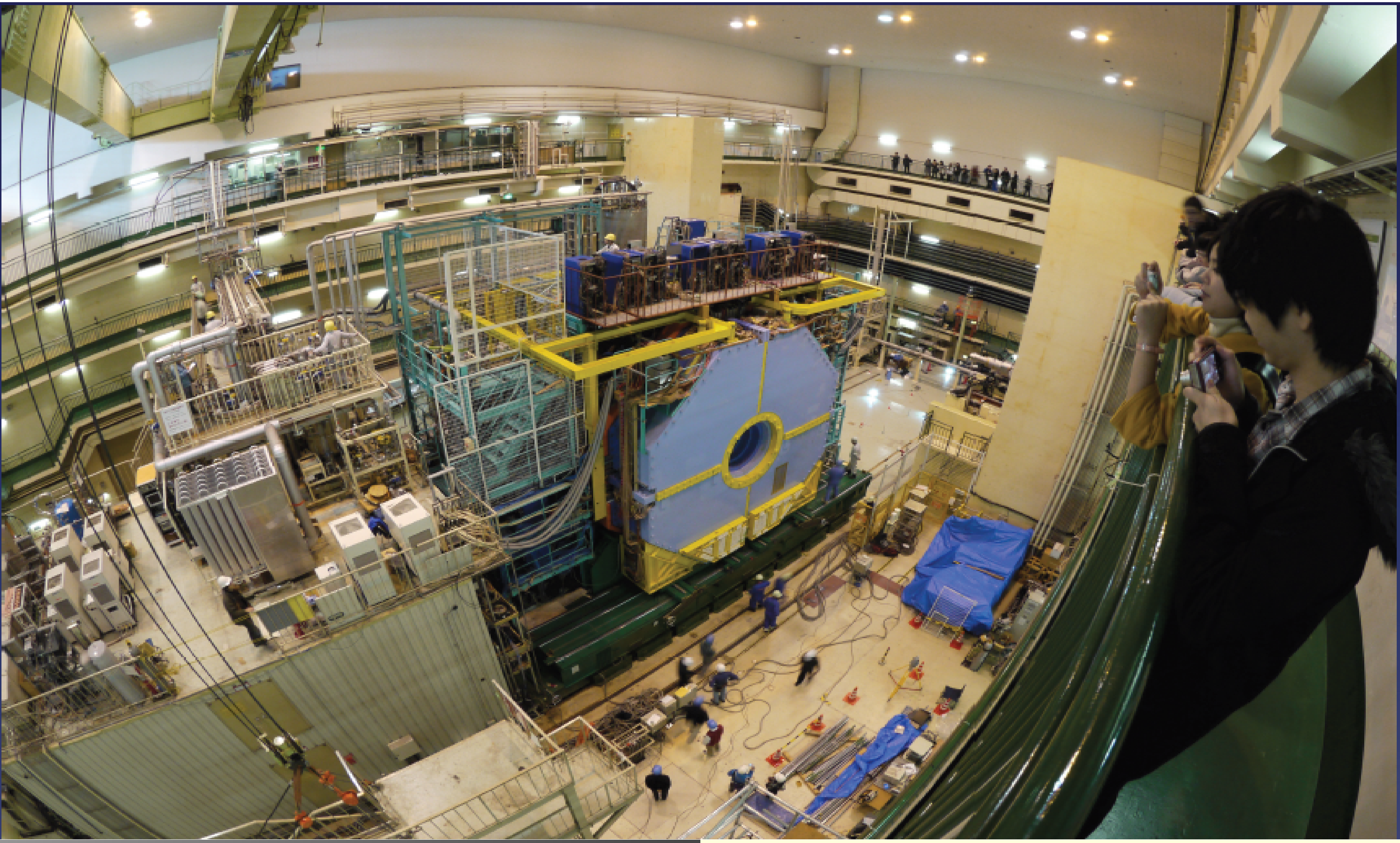


Peak Luminosity Trends (e+e− collider)
SuperKEKB
8 10^35
40 times higher luminosity
KEKB
PEP-II
CESR
DAΦNE
LEP II
BEPC−II
PEP
TRISTAN
SPEAR
DORIS
PETRA
LEP I
Luminosity
Year
1970
1980
1990
2000
2010
2020

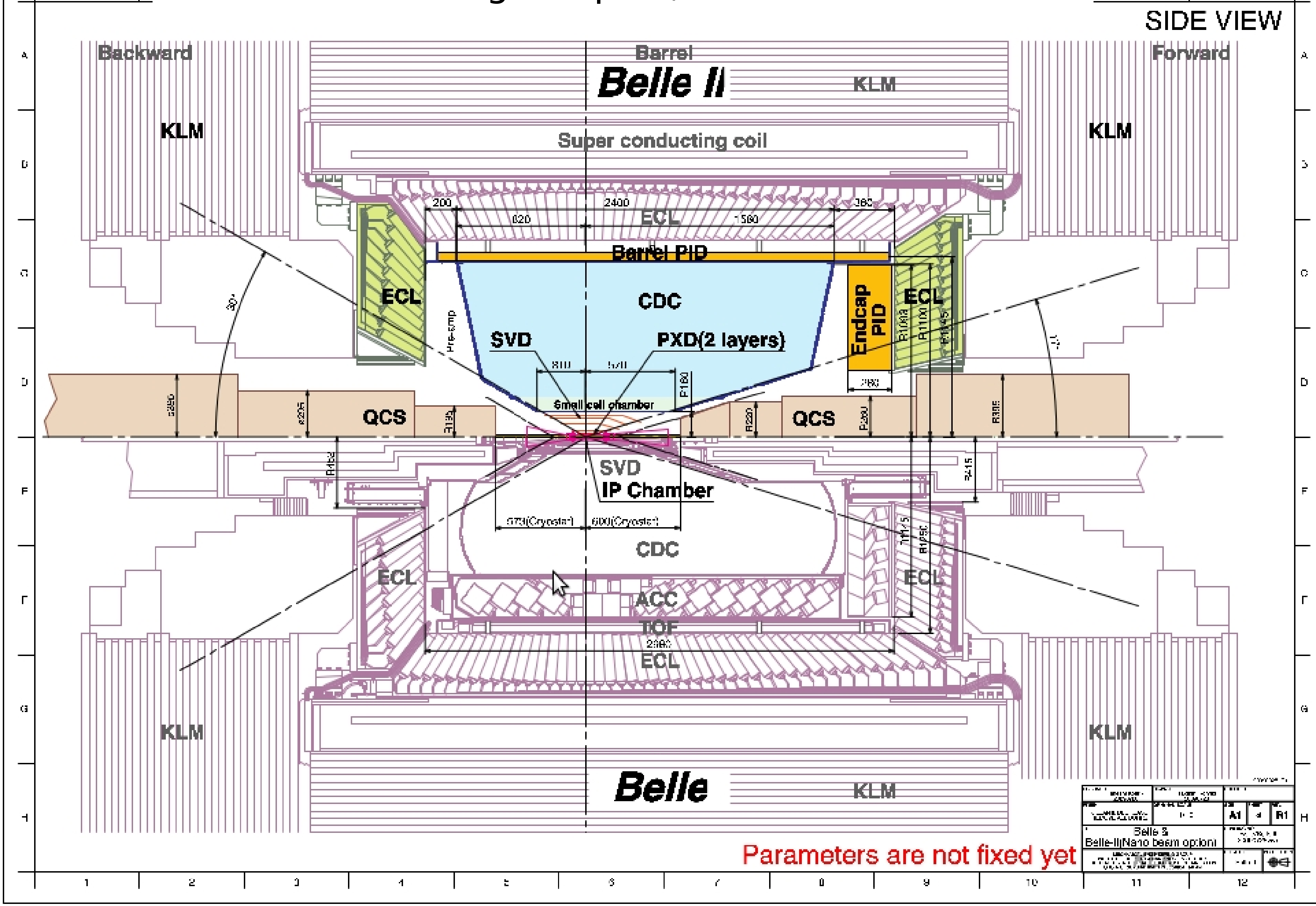
Belle Rollout, 09.12.2010



Belle Rollout, 09.12.2010

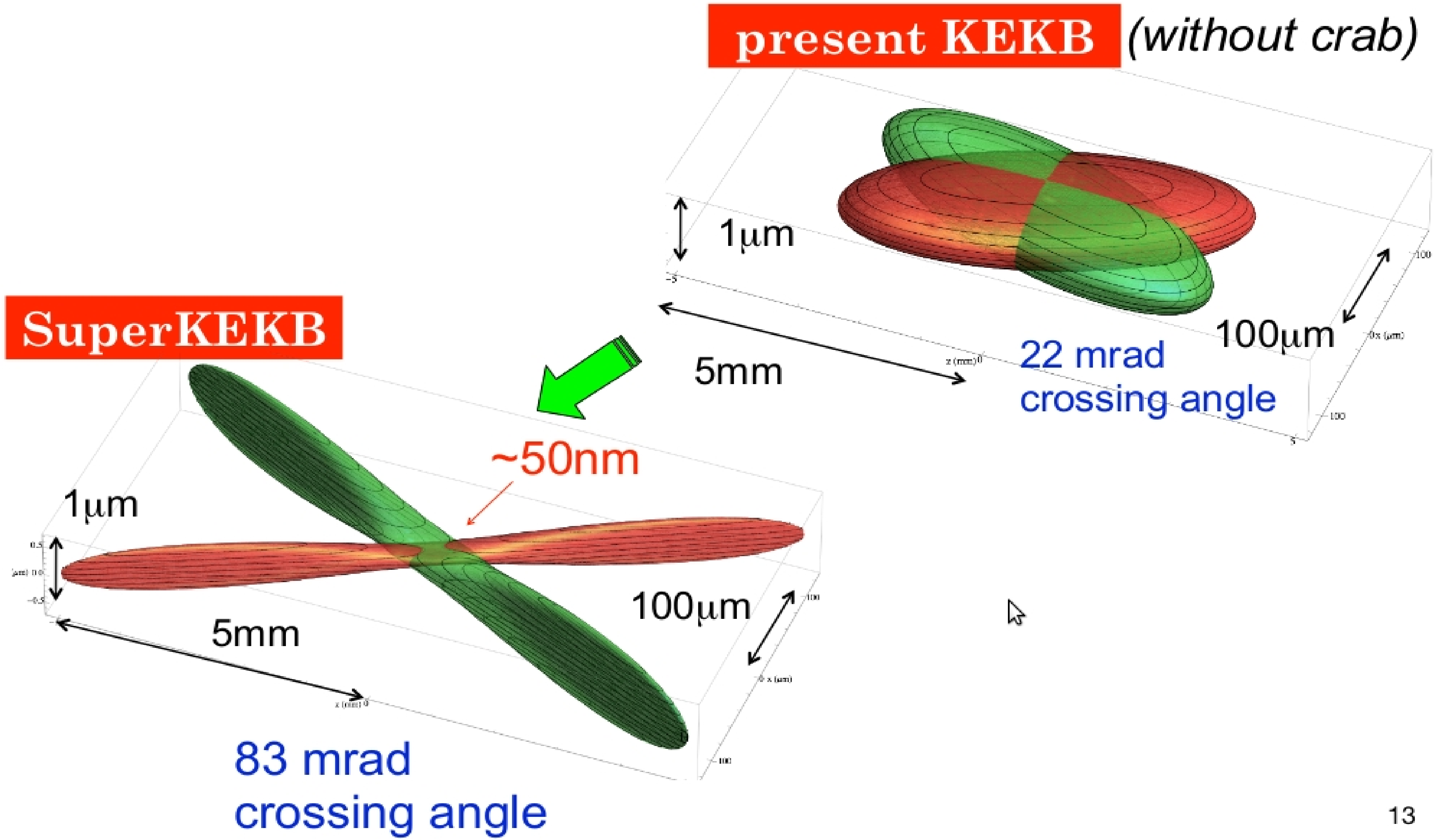


Technical Design Report, arXiv:1011.0352



Planned improvement of B meson z vertex resolution by factor ~2 ($\Delta z \geq 25$ um for p=1 GeV/c)

Nano-Beam Scheme



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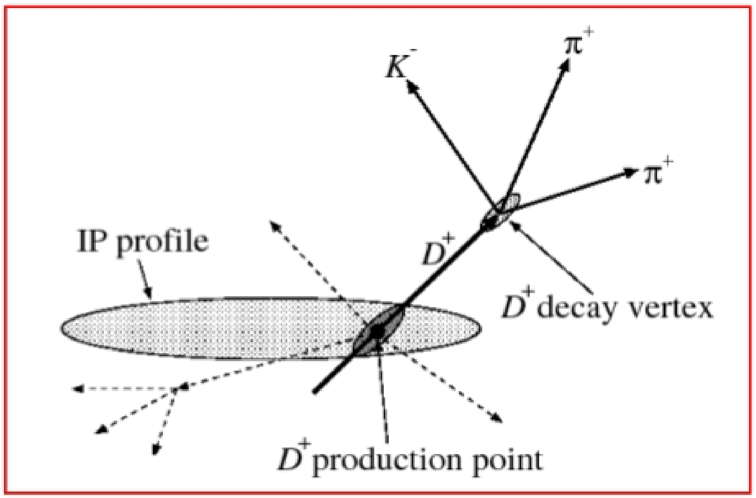
IP Profile for Belle and Belle II („nanobeam“)

100μm(H) x 2μm(V) → 10μm(H) x 59nm(V)



Magnet installation

field measurement

move into tunnel

Installation of 100 new LER bending magnets done

carry on an air-pallet

carry over existing HER dipole

19

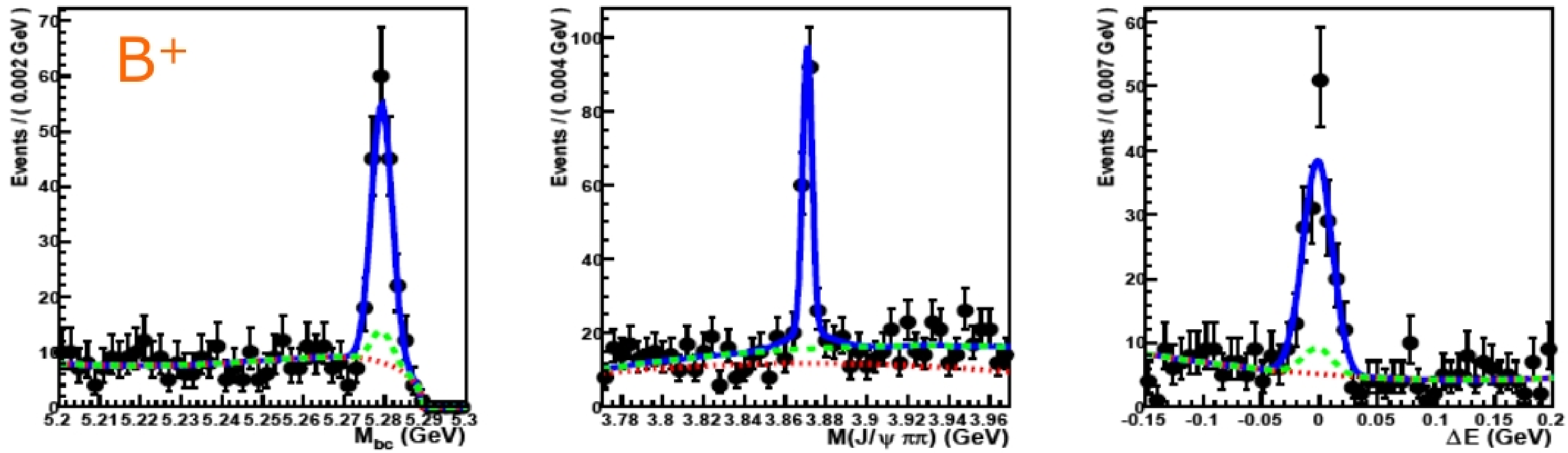
SuperKEKB Status, 7th BPAC, Mar. 11, 2013, K. Akai

X(3872) Width Measurement at Belle

$M_{\rm bc} \equiv \sqrt{(E_{\rm beam}^{\rm cms})^2 - (p_B^{\rm cms})^2}$

$X(3872) \to J/\psi\, \pi^+ \pi^-$

$\Delta E \equiv E_B^{\rm cms} - E_{\rm beam}^{\rm cms}$



M_{BC} /GeV $M(J/\psi\, \pi^+ \pi^-)$/GeV ΔE/GeV

3-dim fit → kinematical over-constraint provides access to observables smaller than detector resolution

upper limit on width $\Gamma_{X(3872)} < 1.2$ MeV (90% C.L.)

Belle II: width measurement in $X(3872) \to J/\psi\gamma$
expected yield $N \simeq 1750$
monoenergetic photon provides additional constraint
$\Gamma < 1$ MeV might be feasible

Summary

State	Production	J^{PC}	Width (MeV)	Decay	Experiment	Interpretation
X(3872)	B decays, $p\overline{p}$	1^{++}	<2.3	$J/\psi\rho$, $J/\psi\omega$, $J/\psi\gamma$, $D^0\overline{D}^{0*}$	Belle, BaBar, CDF D0, LHCb, CMS	$D^0\overline{D}^{*0}$ molecule?
X(3940)	$e^+e^-\to c\overline{c}c\overline{c}$	$0^{?+}$	$\simeq$37	DD^* (not DD, $J/\psi\omega$)	Belle	shifted η_c''?
Y(3940)	B decays	$?^{?+}$	$\simeq$30	$J/\psi\omega$ (not DD^*)	Belle, BaBar	?
Y(3990)	Y(4260) decays	1^+	$\geq$10	$J/\psi\pi^\pm$	BESIII, Belle	4-quark ? $D^+\overline{D}^{*0}$ molecule ?
Y(4140)	B decays	$?^{?+}$	$\simeq$11	$J/\psi\phi$	CDF	$c\overline{c}s\overline{s}$
X(4160)	$e^+e^-\to c\overline{c}c\overline{c}$	$0^{?+}$	$\simeq$140	D^*D^* (not DD, DD^*)	Belle	η_c''?
Y(4008)	ISR	1^{--}	$\simeq$220	$J/\psi\pi^+\pi^-$	Belle (not BaBar)	$c\overline{c}g$ hybrid?
Y(4260)	ISR	1^{--}	$\simeq$80	$J/\psi\pi^+\pi^-$, $J/\psi\pi^0\pi^0$, $J/\psi K^+K^-$	BaBar, CLEO, Belle	$c\overline{c}g$ hybrid?
X(4350)	$\gamma\gamma$	$?^{?+}$	$\simeq$13	$J/\psi\phi$	Belle	$c\overline{c}s\overline{s}$
Y(4350)	ISR	1^{--}	$\simeq$75	$\psi'\pi^+\pi^-$	BaBar, Belle	$c\overline{c}g$ hybrid?
Y(4660)	ISR	1^{--}	$\simeq$50	$\psi'\pi^+\pi^-$	Belle	$c\overline{c}g$ hybrid?
X(4630)	ISR	1^{--}	$\simeq$90	$\Lambda_c\overline{\Lambda_c}$	Belle	$\Lambda_c\overline{\Lambda_c}$ molecule?
$Z^\pm$(4430)	B decays	$?^?$	$\simeq$100	$\psi'\pi^\pm$	Belle (not BaBar)	4-quark?
$Z^\pm$(4050)	B decays	$?^?$	$\simeq$80	$\chi_{c1}\pi^\pm$	Belle	4-quark?
$Z^\pm$(4250)	B decays	$?^?$	$\simeq$180	$\chi_{c1}\pi^\pm$	Belle	4-quark?
$Z_b^\pm$(10610)	Υ(5S) decays	1^+	8–25	$\Upsilon(1S)\pi^\pm$ $\Upsilon(2S)\pi^\pm$ $\Upsilon(3S)\pi^\pm$ $h_b(1P)\pi^\pm$ $h_b(2P)\pi^\pm$	Belle	4-quark? B^+B^* molecule?
$Z_b^\pm$(10650)	Υ(5S) decays	1^+	8–25	$\Upsilon(1S)$ $\Upsilon(2S)\pi^\pm$ $\Upsilon(3S)\pi^\pm$ $h_b(1P)\pi^\pm$ $h_b(2P)\pi^\pm$	Belle	4-quark? $B^{+*}B^*$ molecule?
Y_b(10889)	e^+e^-	1^{--}	30	$\Upsilon(1S)\pi^+\pi^-$ $\Upsilon(2S)\pi^+\pi^-$ $\Upsilon(3S)\pi^+\pi^-$	Belle	$b\overline{b}g$ hybrid?

большое спасибо

for my 3rd summer trip to Dubna
and beautiful evening walks at the Wolga beach ...

Backup Slides

Mass of a Charmonium State

(Potential Model)

n dependant term

$$M(n^{2S+1}l_j) = E_{nl} + 2m_q + \frac{2\alpha_s}{3m_q^2}\int d^3r\Psi^*(\vec{r})\left(\frac{1}{r}\vec{\nabla}^2 + \frac{1}{r}\frac{\partial^2}{\partial r^2}\right)\Psi(\vec{r})$$

$$+ \frac{4\pi\alpha_s}{3m_q^2}|\Psi(0)|^2 + \frac{32\pi\alpha_s}{9m_q^2}\left(\frac{1}{2}S(S+1) - \frac{3}{4}\right)|\Psi(0)|^2$$

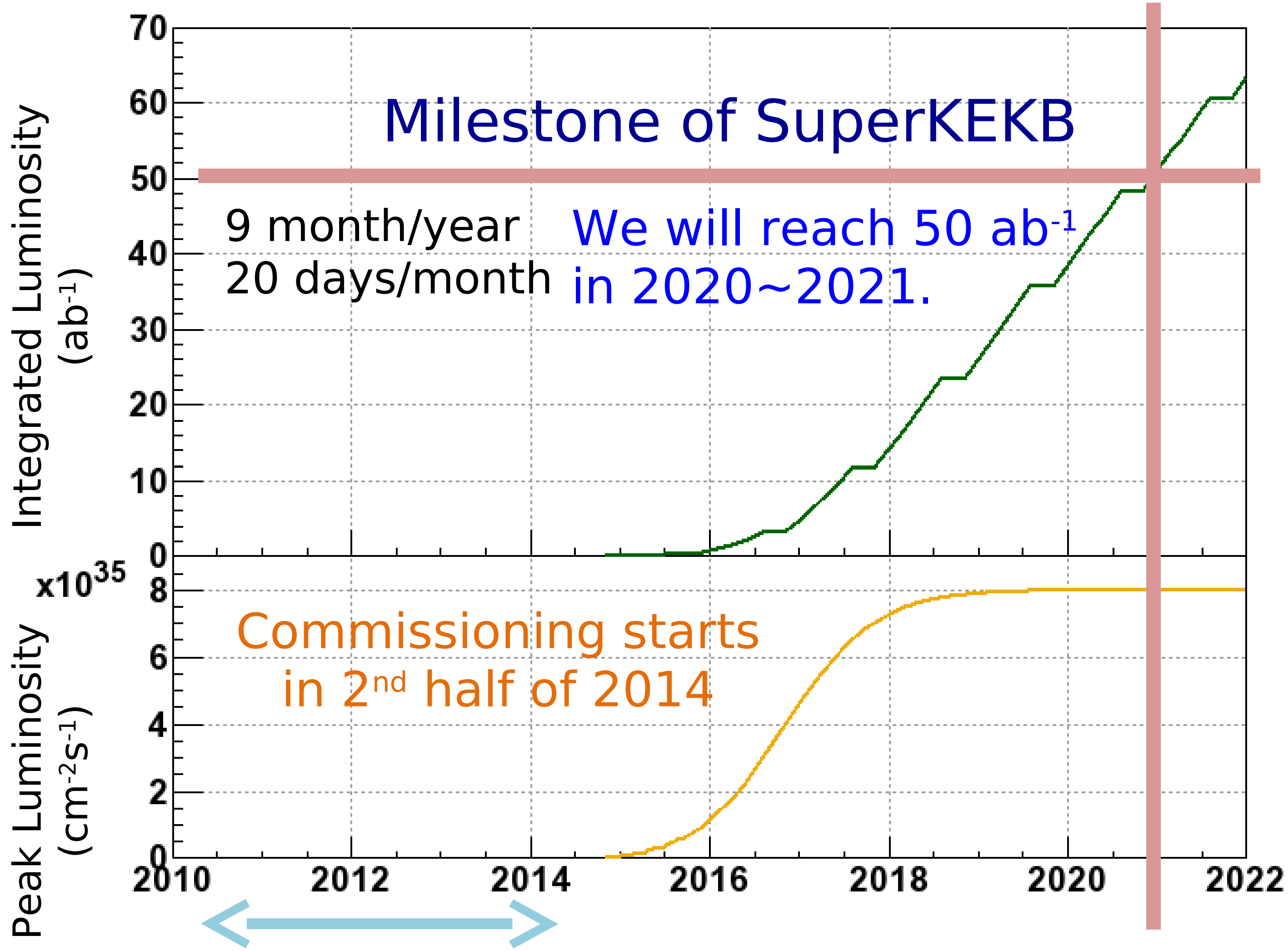
spin-spin

$$+ \alpha_s\frac{j(j+1) - l(l+1) - S(S+1)}{m_q^2}\left\langle\frac{1}{r^3}\right\rangle + \alpha_s\frac{S_{12}}{3m_q^2}\left\langle\frac{1}{r^3}\right\rangle$$

spin-orbit

tensor

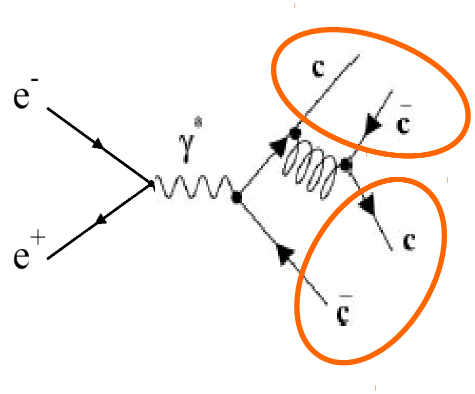
Luminosity prospect



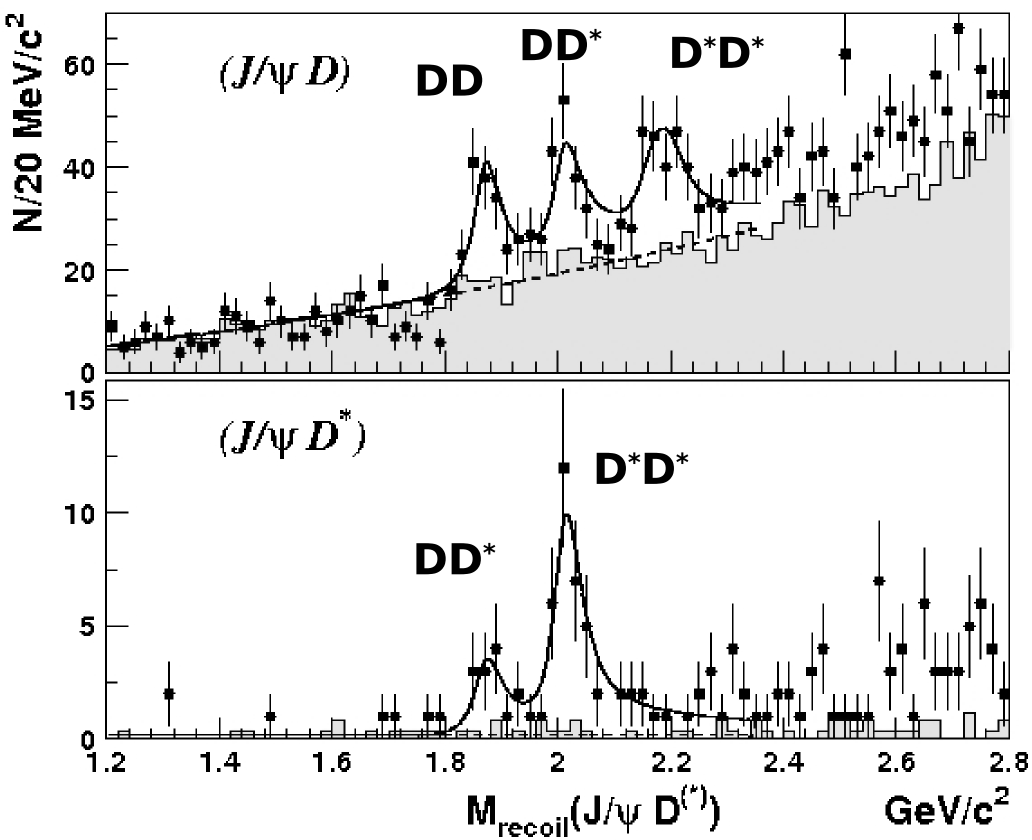
Shutdown
for upgrade

150

Double charmonium production
Recoil mass
(direct production in continuum)



Belle, 693/fb, arXiv:0708.3812

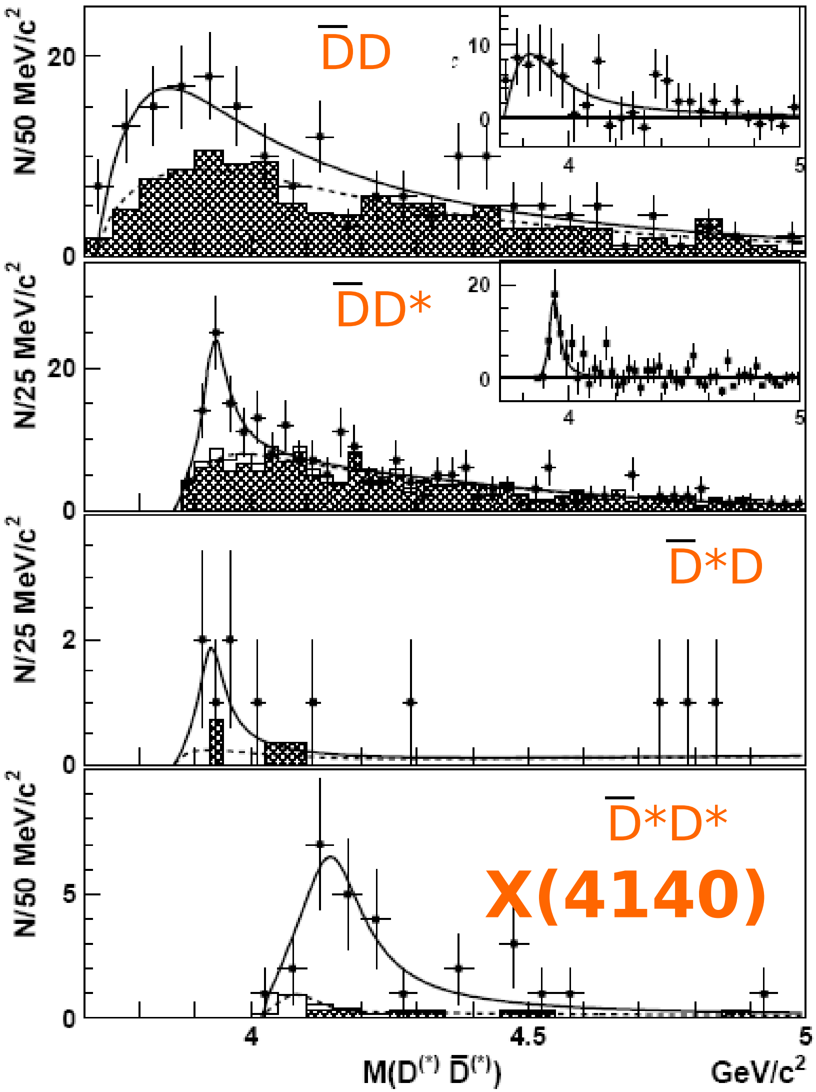


recoil = $D^{(*)}D^{(*)}$

C=+ preferred

High branching fraction
for this process unexplained
(probably non-pertubative QCD)

Any of the $D^{(*)}D^{(*)}$ seems to indicate S-wave enhancement



Too high
for molecular
Hypothesis.

Constituents	J^{PC}	Mass [MeV]
$D\bar{D}^*$	0^{-+}	≈ 3870
$D\bar{D}^*$	1^{++}	≈ 3870
$D^*\bar{D}^*$	0^{++}	≈ 4015
$D^*\bar{D}^*$	0^{-+}	≈ 4015
$D^*\bar{D}^*$	1^{+-}	≈ 4015
$D^*\bar{D}^*$	2^{++}	≈ 4015

Predictions of molecular states
one-pion exchange model
Törnqvist
Phys. Lett. B590(2004)209
Phys. Rev. Lett. 67(1991)556

missing mass^2 =
(Sum E_initial - Sum E_final)^2 - (Sum p_initial - Sum p_final)^2

recoil mass =
(Sum E_initial - Sum E_final)^2 - (Sum p_final)^2