Spectroscopy of exotic states
(Experimental aspects)

Jens Sören Lange
Justus-Liebig-Universität Gießen

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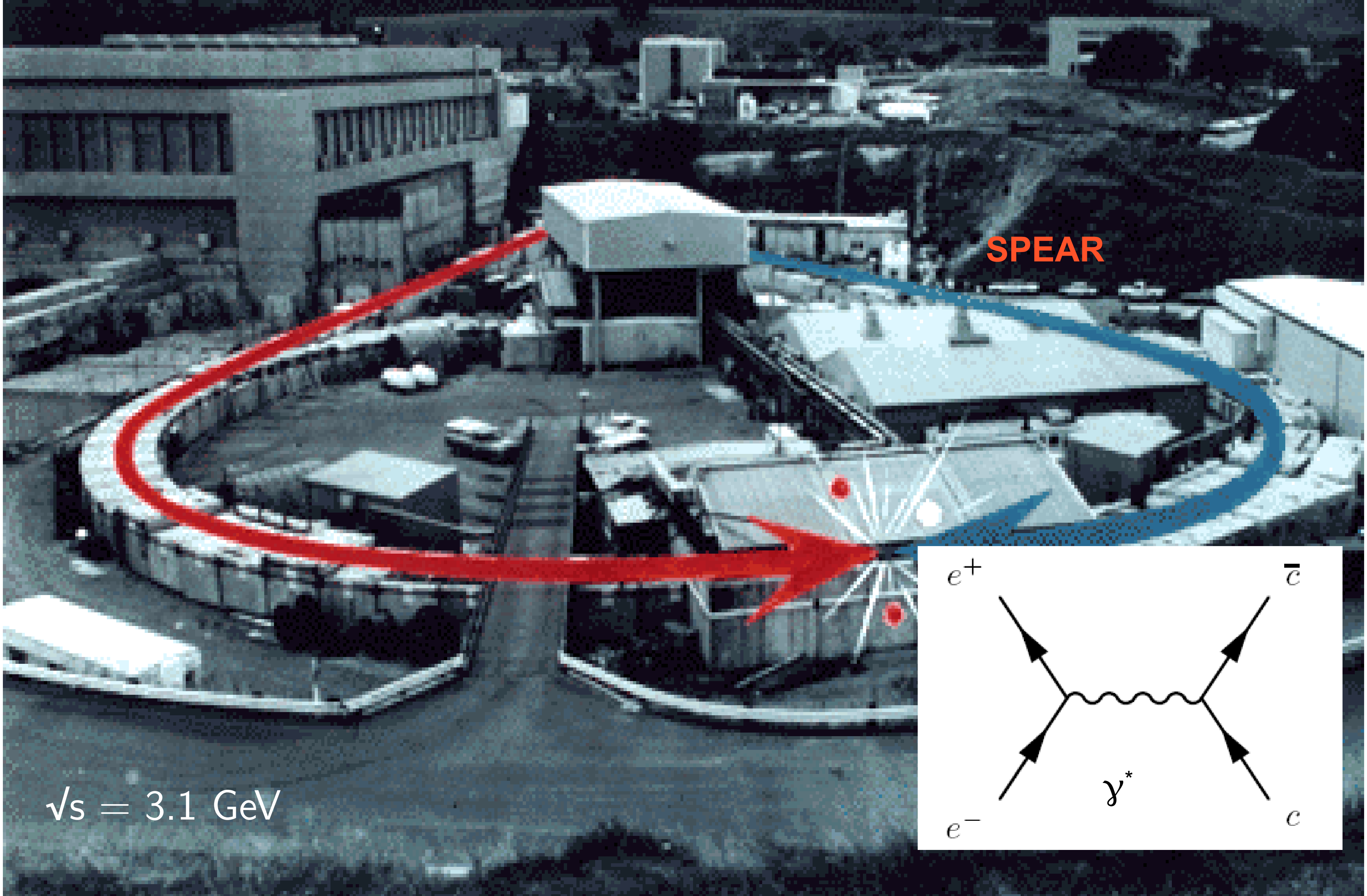
OUTLINE

- Lecture 1: The Past and Present
  - How it all began (on a parking lot)
  - The X, the Y and the Z
  - What is „beam constraint“?
- Lecture 2: The Future
  - Dalitz formalism: how to „see“ quantum numbers
  - (Bottomonium: recoil mass, kinematic reflections $\rightarrow$ BACKUP)
  - Belle II (ready to take data ?)
  - Panda, an X factory! („detailed balance“)

e+ e− Collisions at SLAC (1973)



$\sqrt{s} = 3.1$ GeV

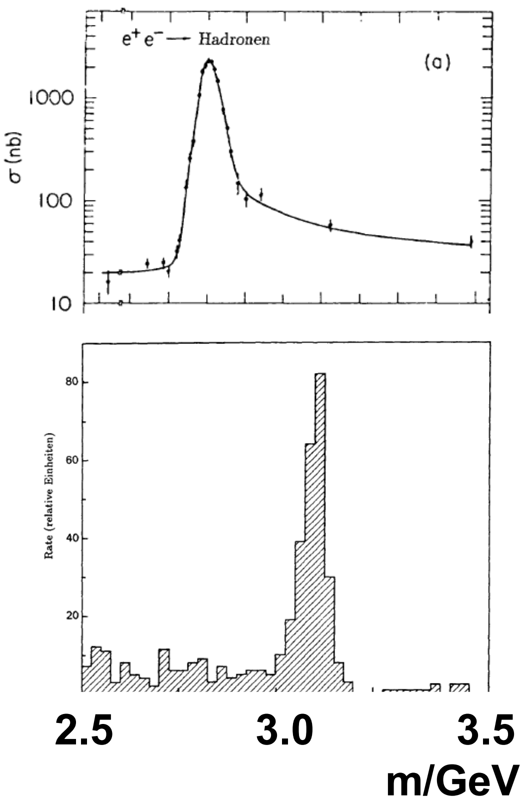
Discovery of Charmonium (J/ψ)

- 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
  (decay to light mesons blocked by OZI)
  width $\sim$100 keV

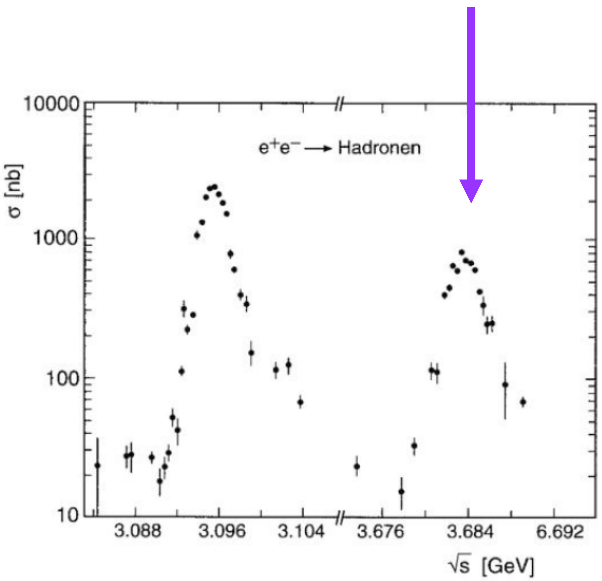
- experimental proof for existance of 4th quark

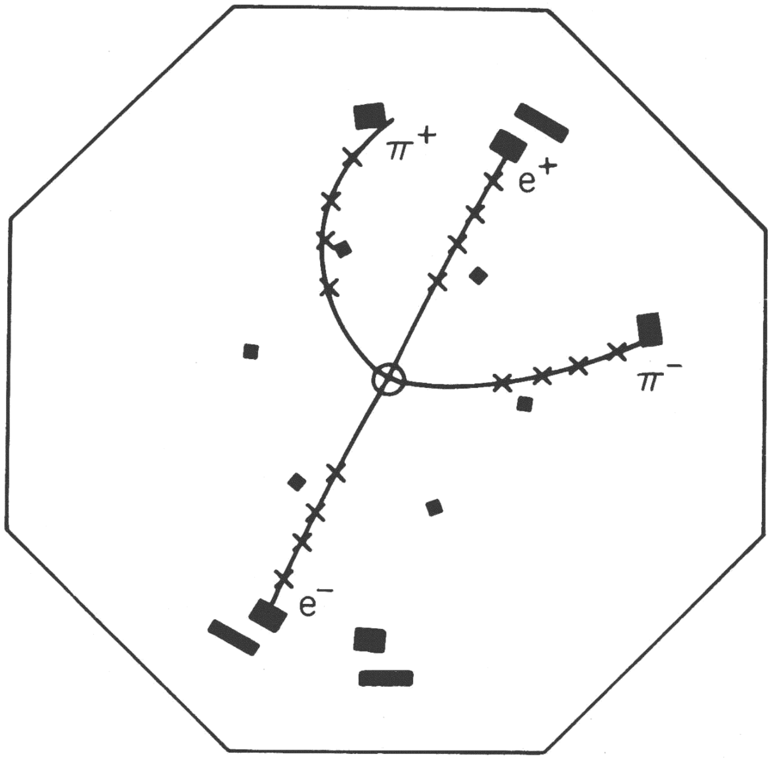


MARK I group reacted quickly
$\rightarrow$ it was feasible to modify the accelerator, so that the beam energies could be changed to $\leq$1 MeV every minute.

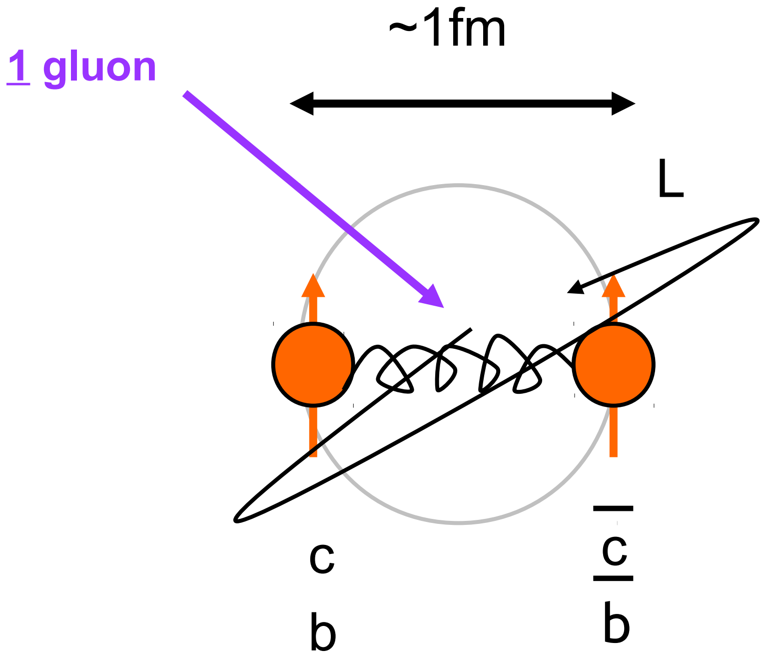
Discovery of ψ'

- **first exited (n=2) state of *J/ψ***
- **only 3 weeks after *J/ψ***
- **beginning of charmonium <u>spectroscopy</u>**
- **Decay:**
  Ψ´→J/Ψ π+ π-



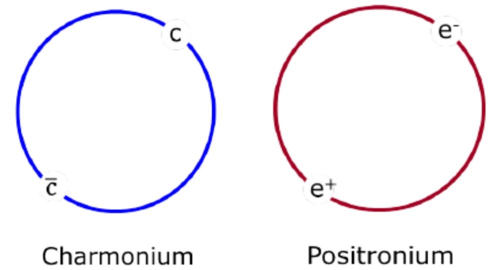


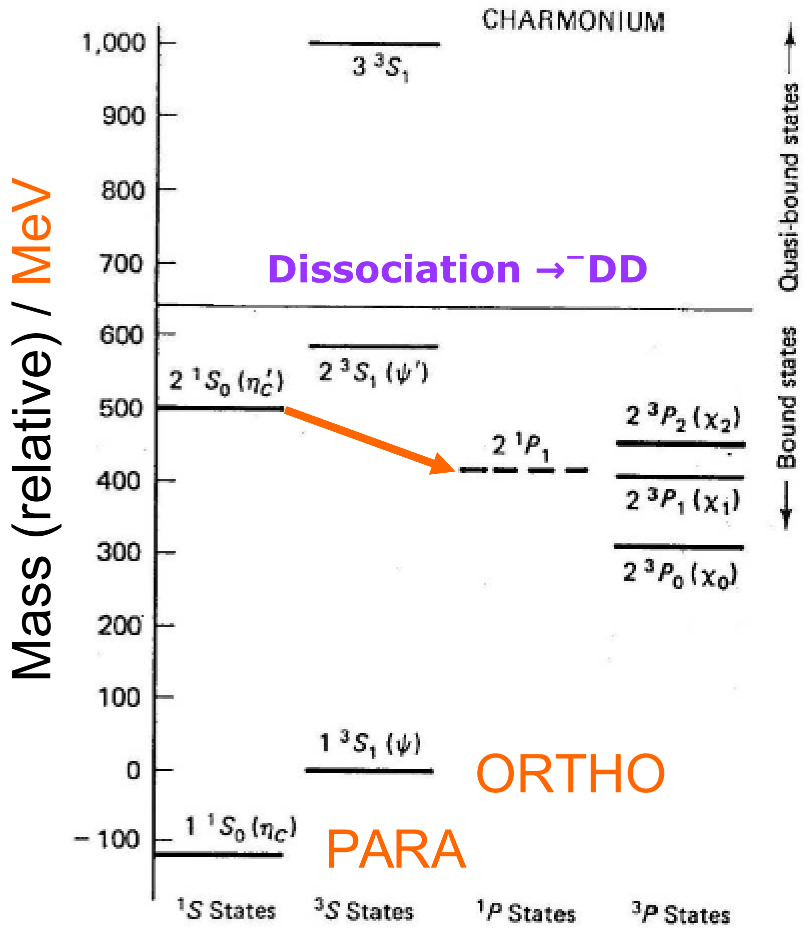
Heavy Quarkonium

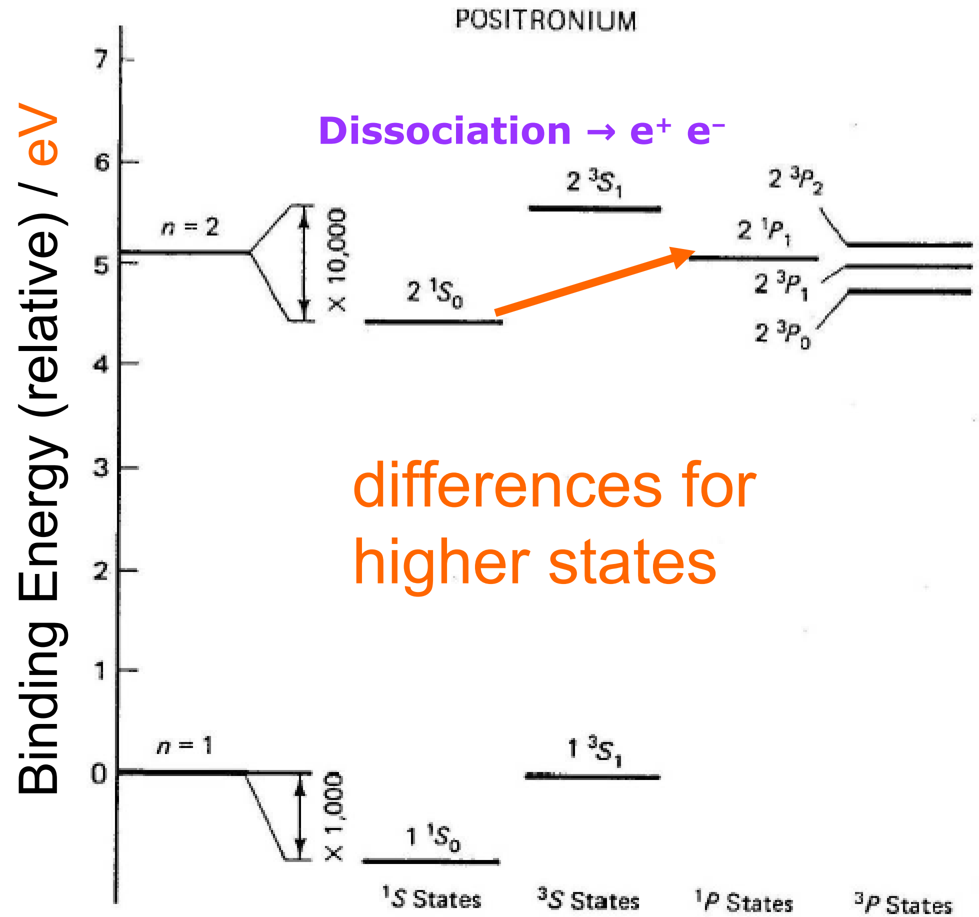


Charmonium vs. Positronium

Decays to light quarks suppressed
$\rightarrow$ narrow widths







Cornell–Potential

Eichten, Gottfried, et al. PRD 17(1978)3090
Barnes, Godfrey, Swanson, PRD 72(2005)054026

- Coulomb-Potential
  + Confinement-Term

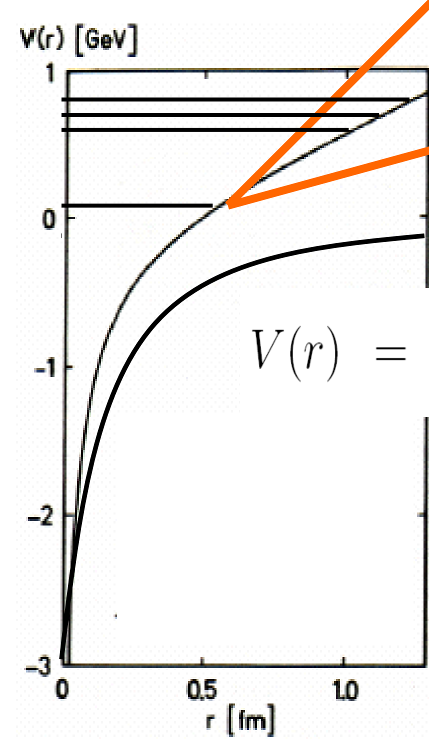
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \boxed{kr}$$

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

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

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

k=0.5 GeV/fm



k=1.5 GeV/fm

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

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

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

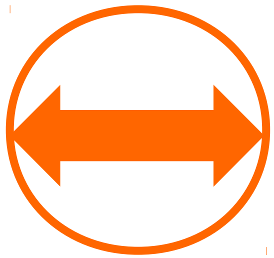
$$\left[-\frac{1}{m_q}\left(\frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r} + \frac{l(l+1)}{m_q r^2} + V(r)\right)\right]R_{nl}(r) = E_{nl}R_{nl}(r)$$

Notation
$n^{2S+1}L_J$
J^{PC}

Quarkonium Excited States

radial

n

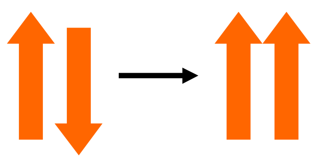


orbital

L

spin

S



spectroscopic
notations

$n^{2S+1} L_J$

J^{PC}

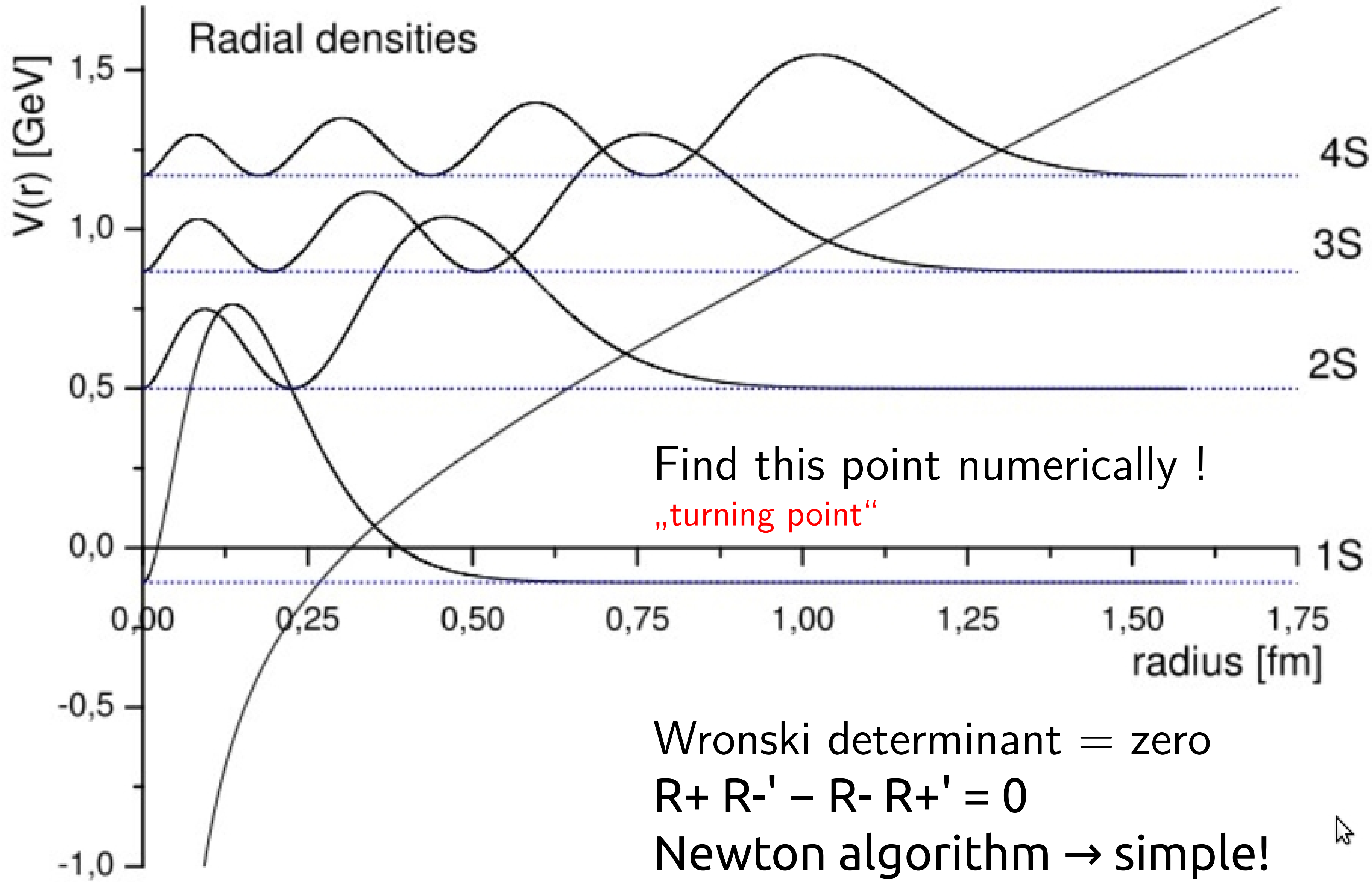
L=S,P,D,...

$$\vec{J} = \vec{L} + \vec{S}$$
$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$

parity

charge conjugation

exponential tail



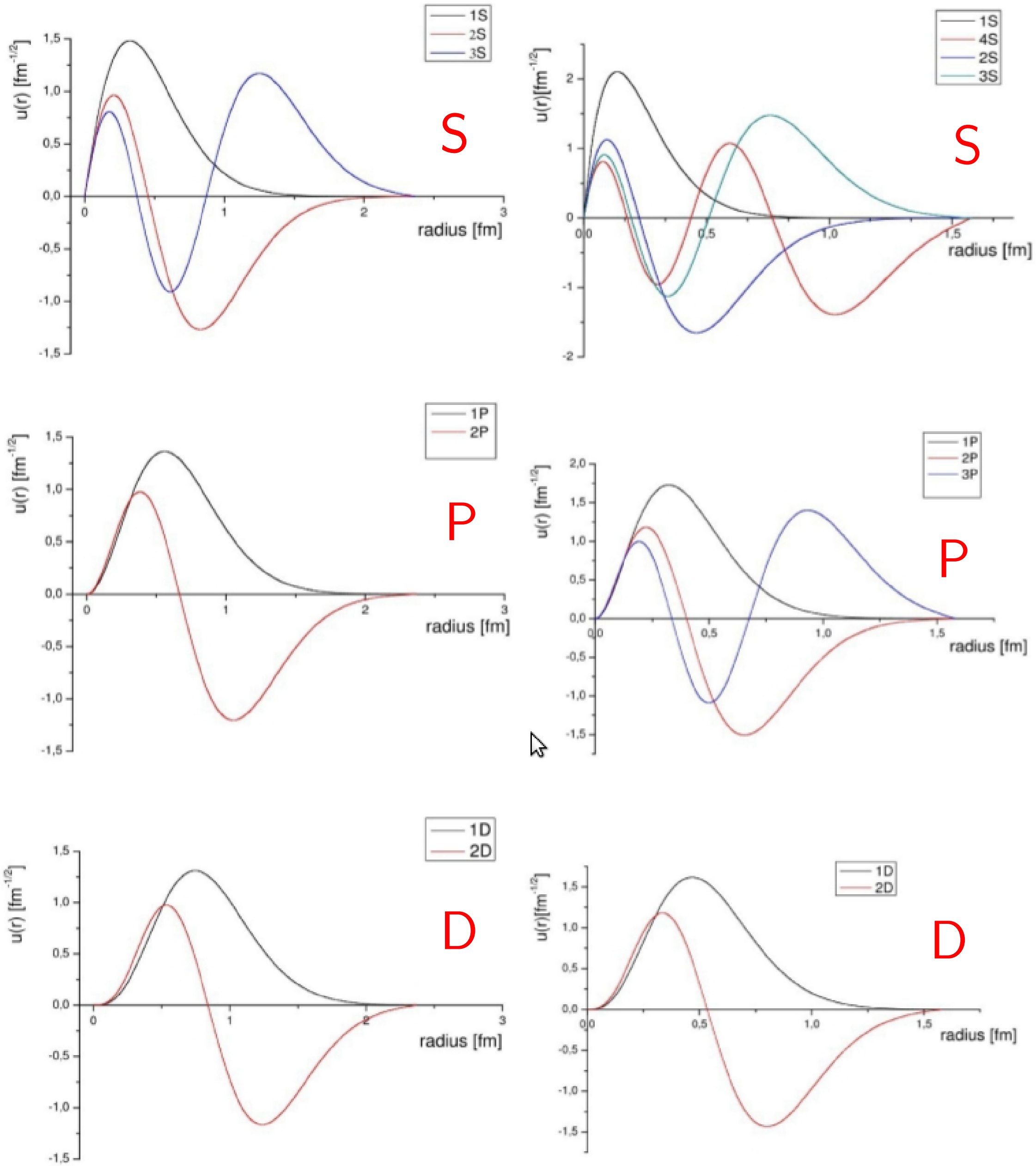
Find this point numerically !

„turning point“

Wronski determinant = zero

R+ R-' – R- R+' = 0

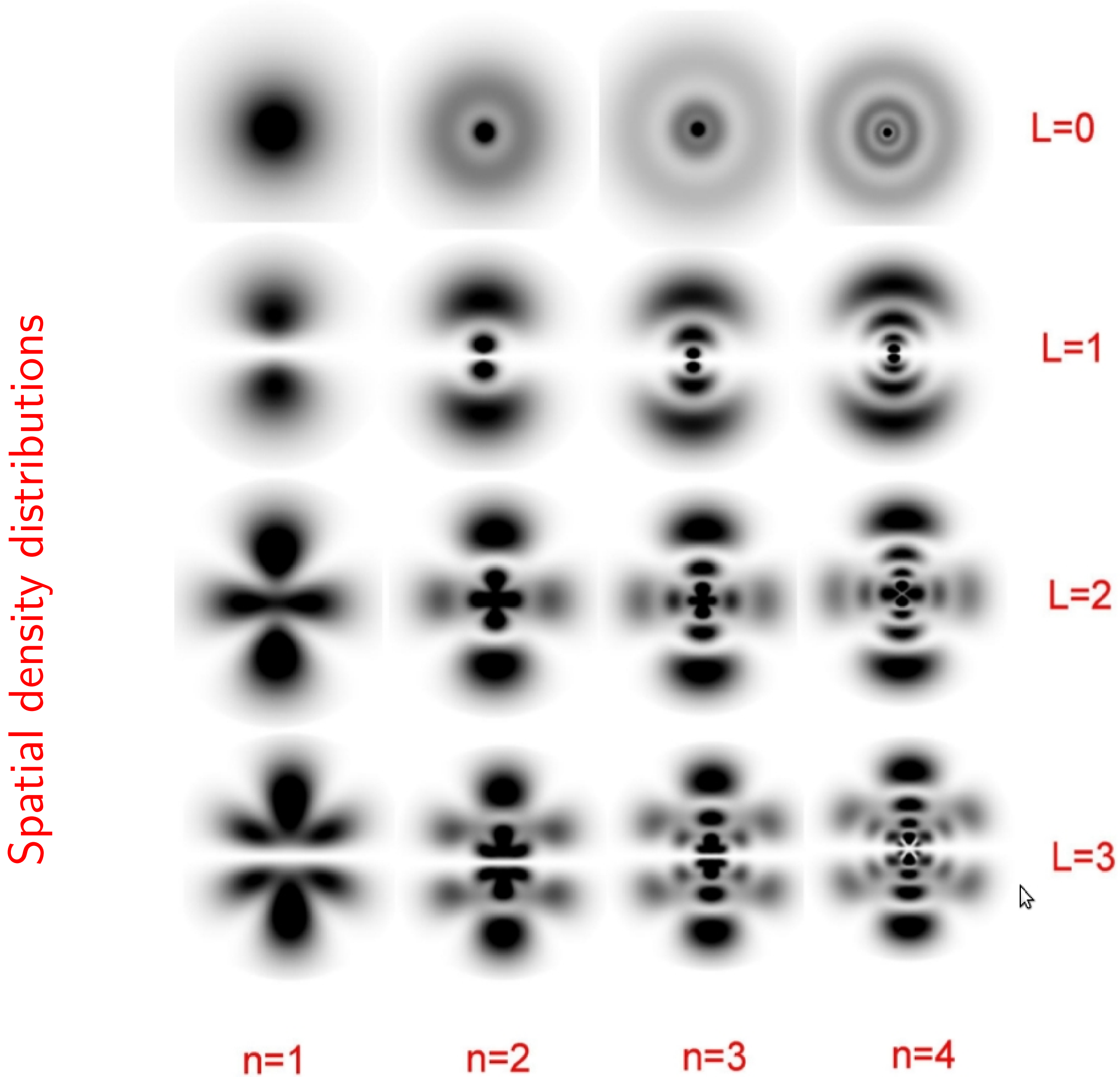
Newton algorithm → simple!

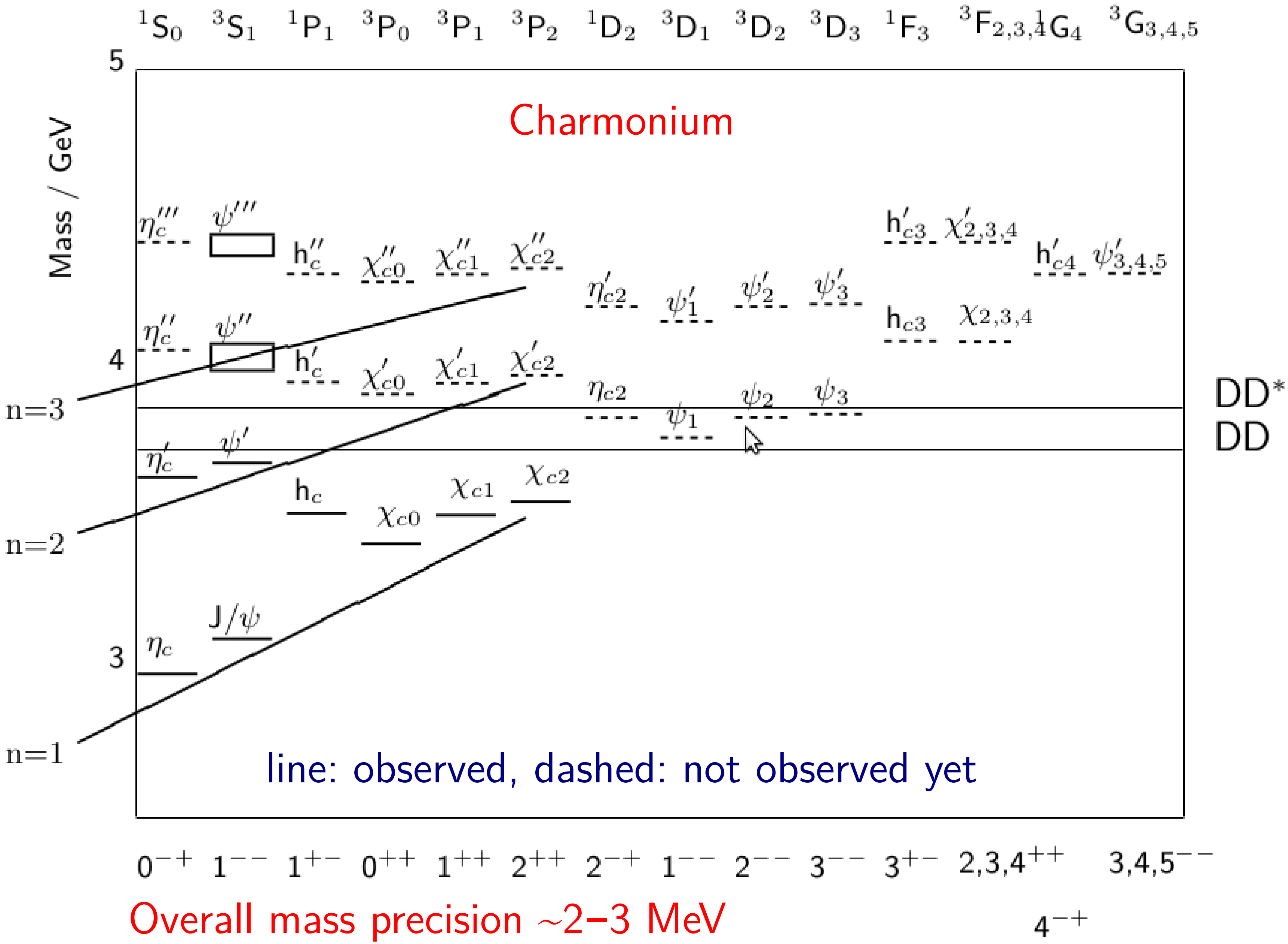


Charmonium

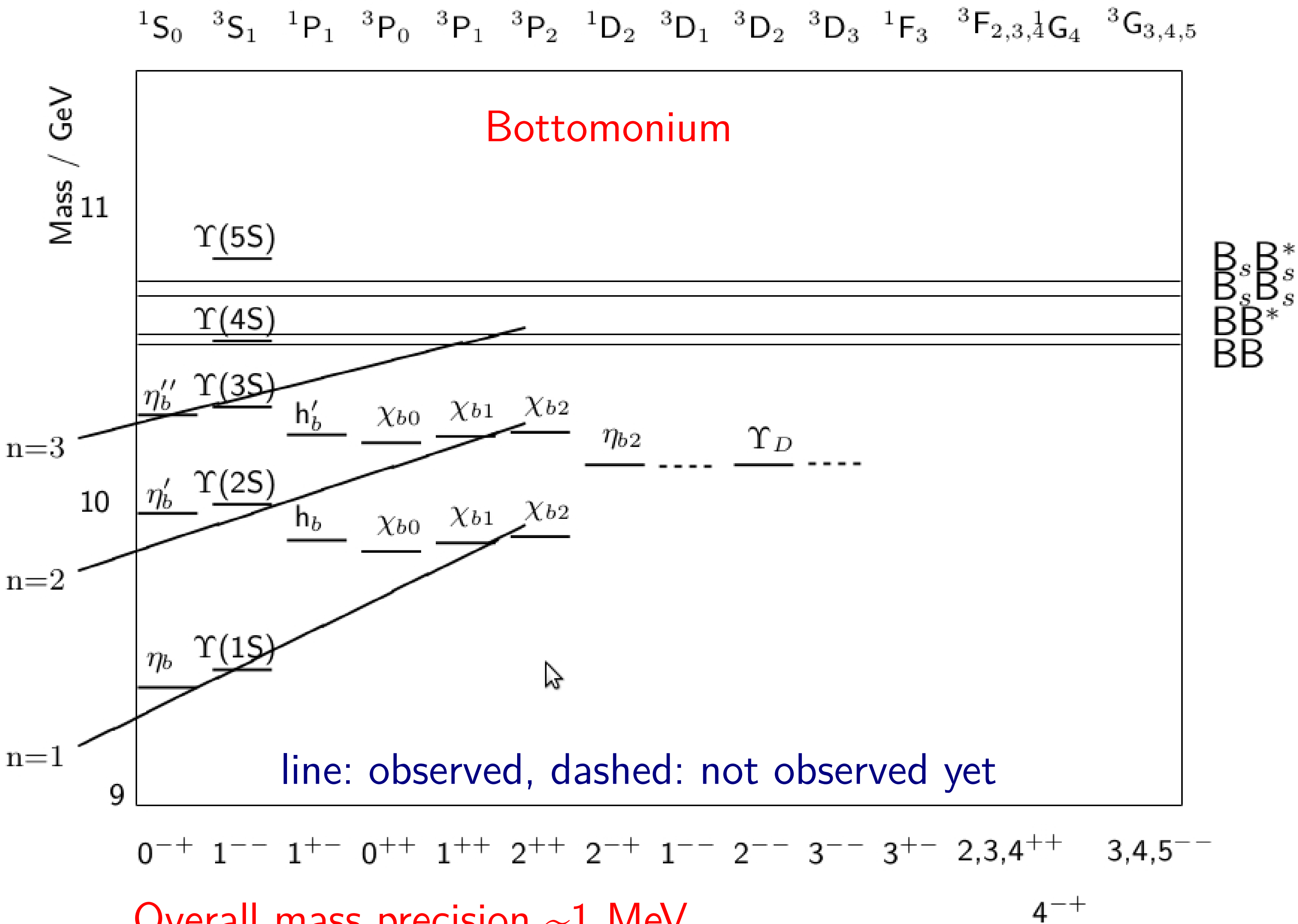
Bottomonium

Radial Wavefunctions


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



Overall mass precision ~2–3 MeV

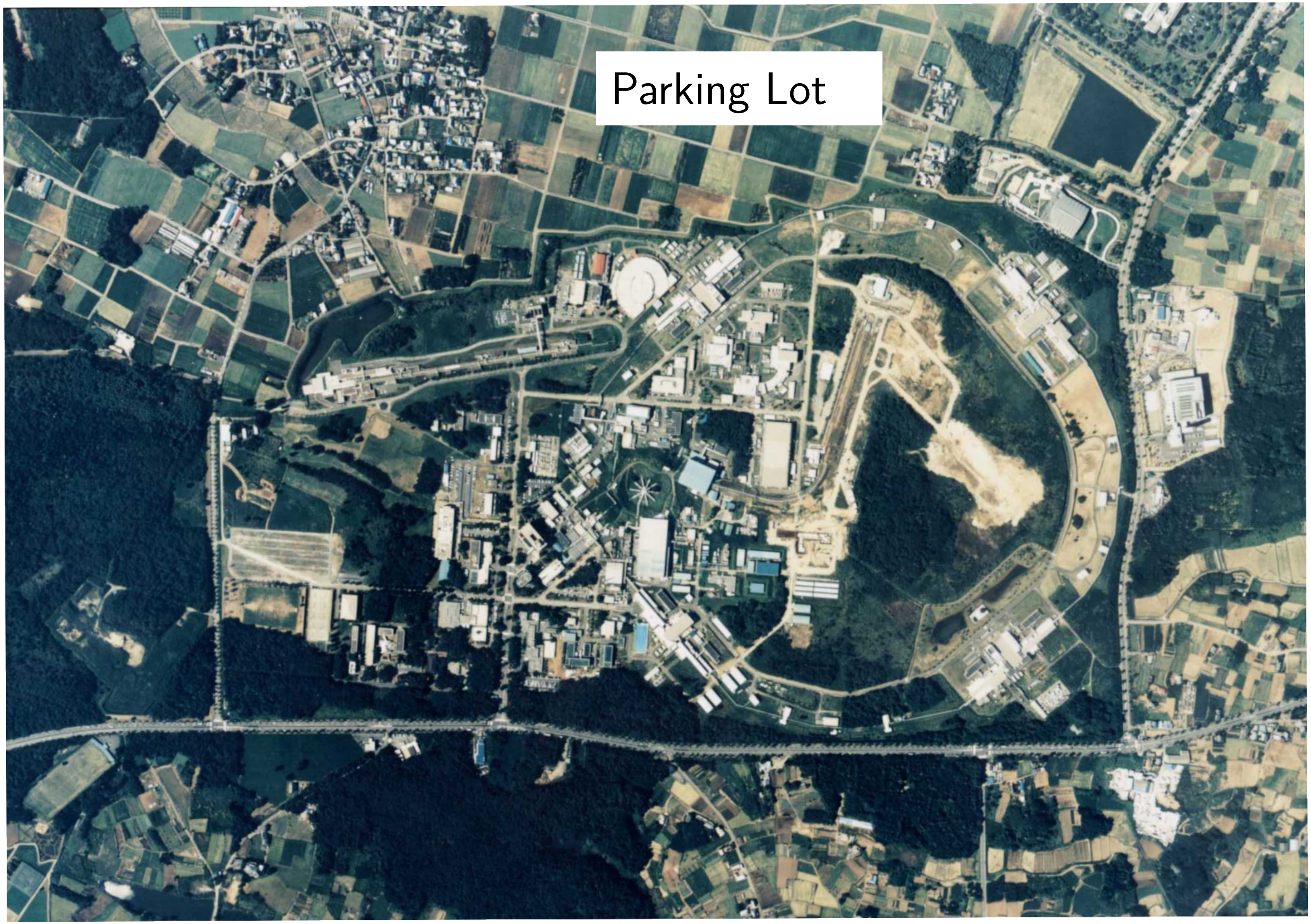


Overall mass precision ~1 MeV

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

About 30 years passed.

Belle and KEKB, Japan

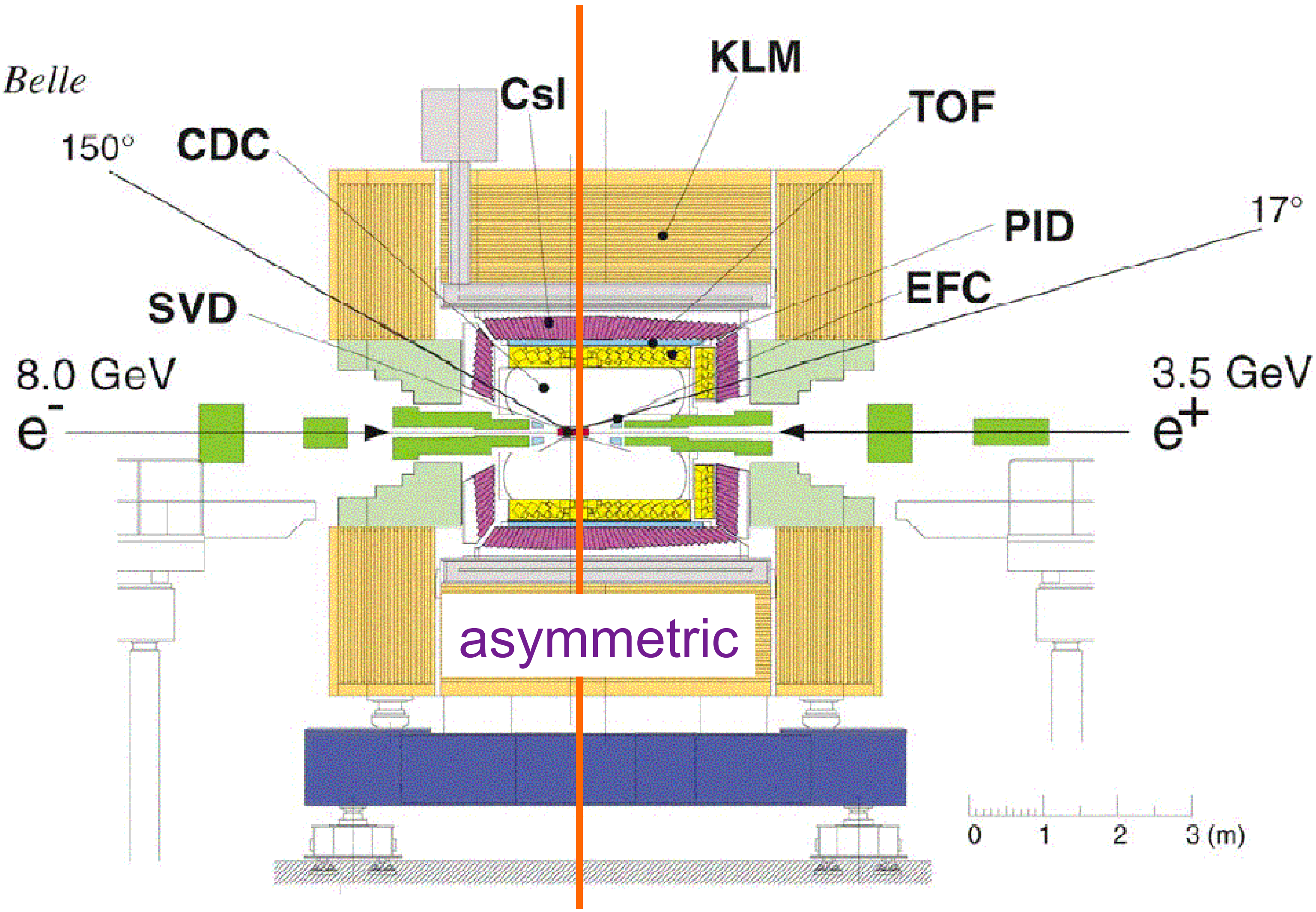


asymm.
$\rightarrow$ extend decay length of B mesons

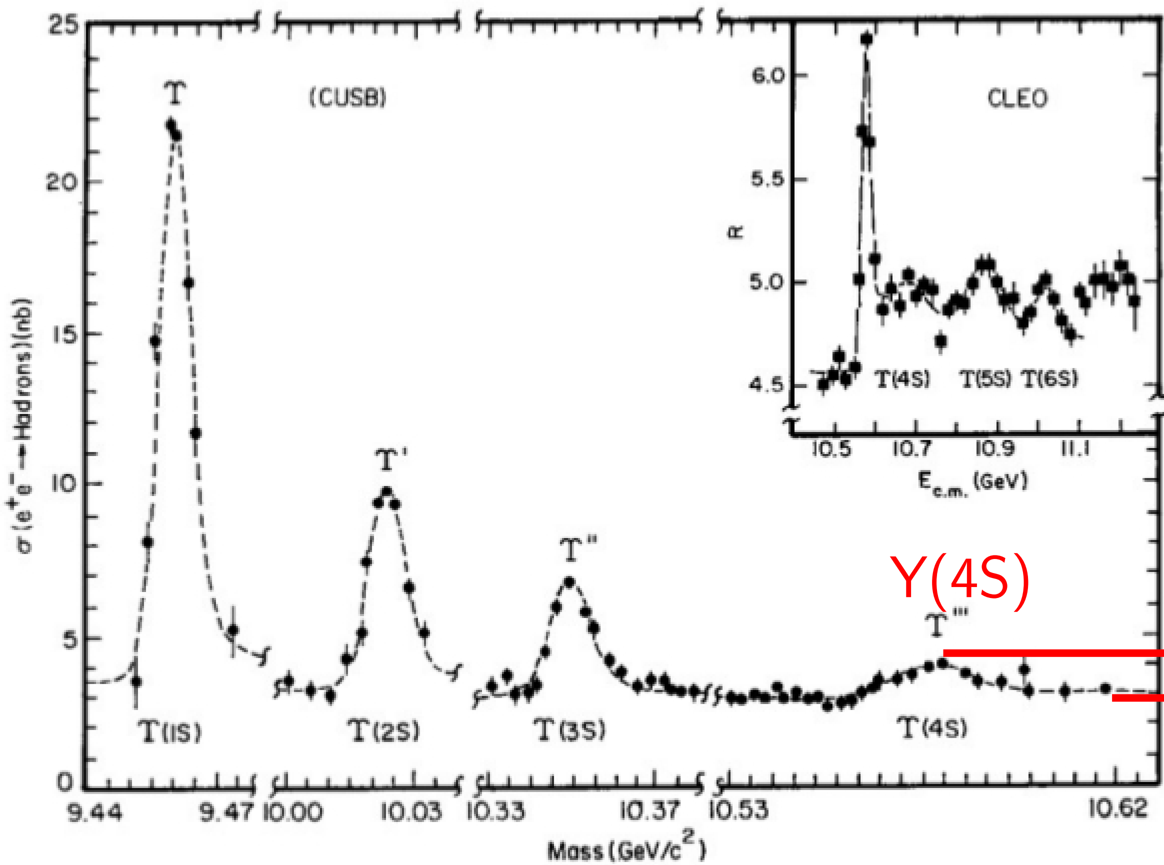
symm.

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 ($10^{33}/\mathrm{cm}^2\mathrm{s}$)	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



A. The $\Upsilon(nS)$ states



„on-resonance“

4.2 nb

3.0 nb

„continuum“

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
```

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

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

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

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

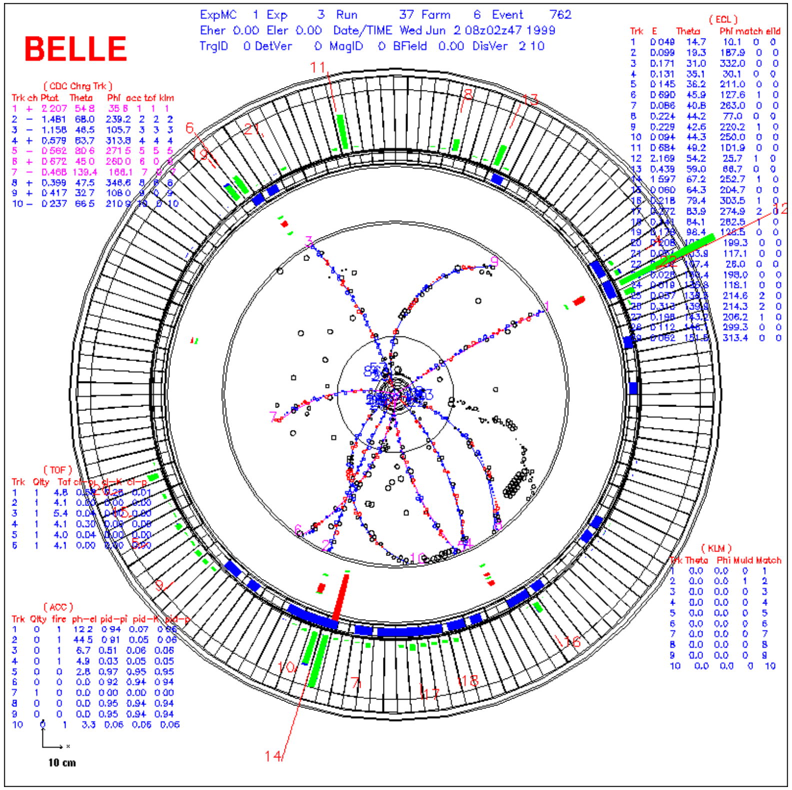
1 nb cross section
x 1.000.000 nb^{-1} per 1 day
$=$ 1.000.000 Y(4S) per 1 day !

Almost every Y(4S) decays into a B anti-B meson pair.

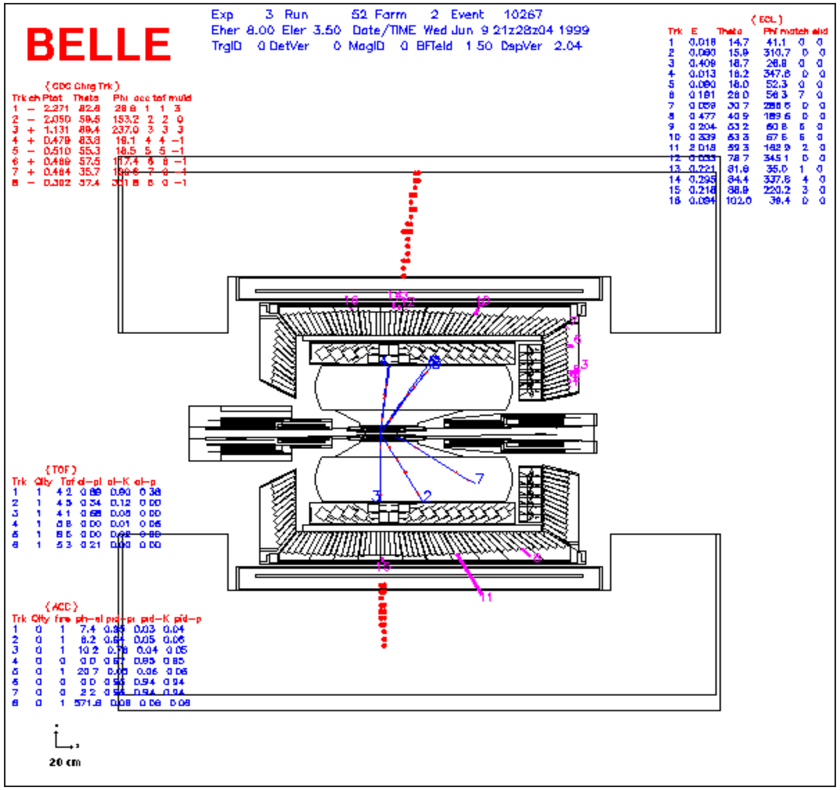
$\rightarrow$ we call it a „B meson factory“

Example Events with Charmonium

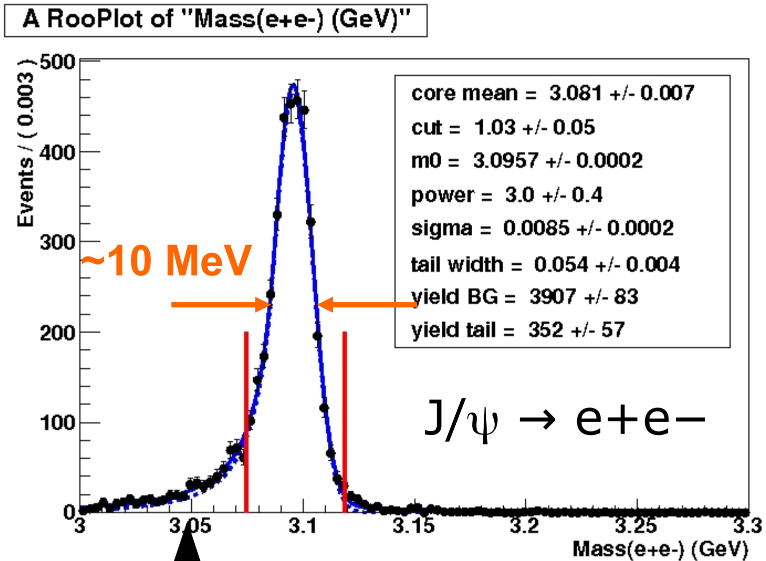
$J/\psi \to e^+e^-$

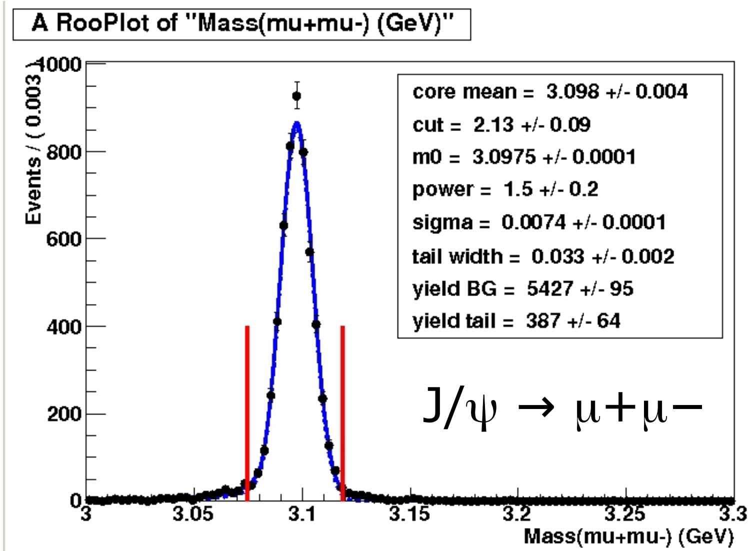


$J/\psi \to \mu^+\mu^-$



J/ψ→e+e–, μ+μ– Invariant Mass

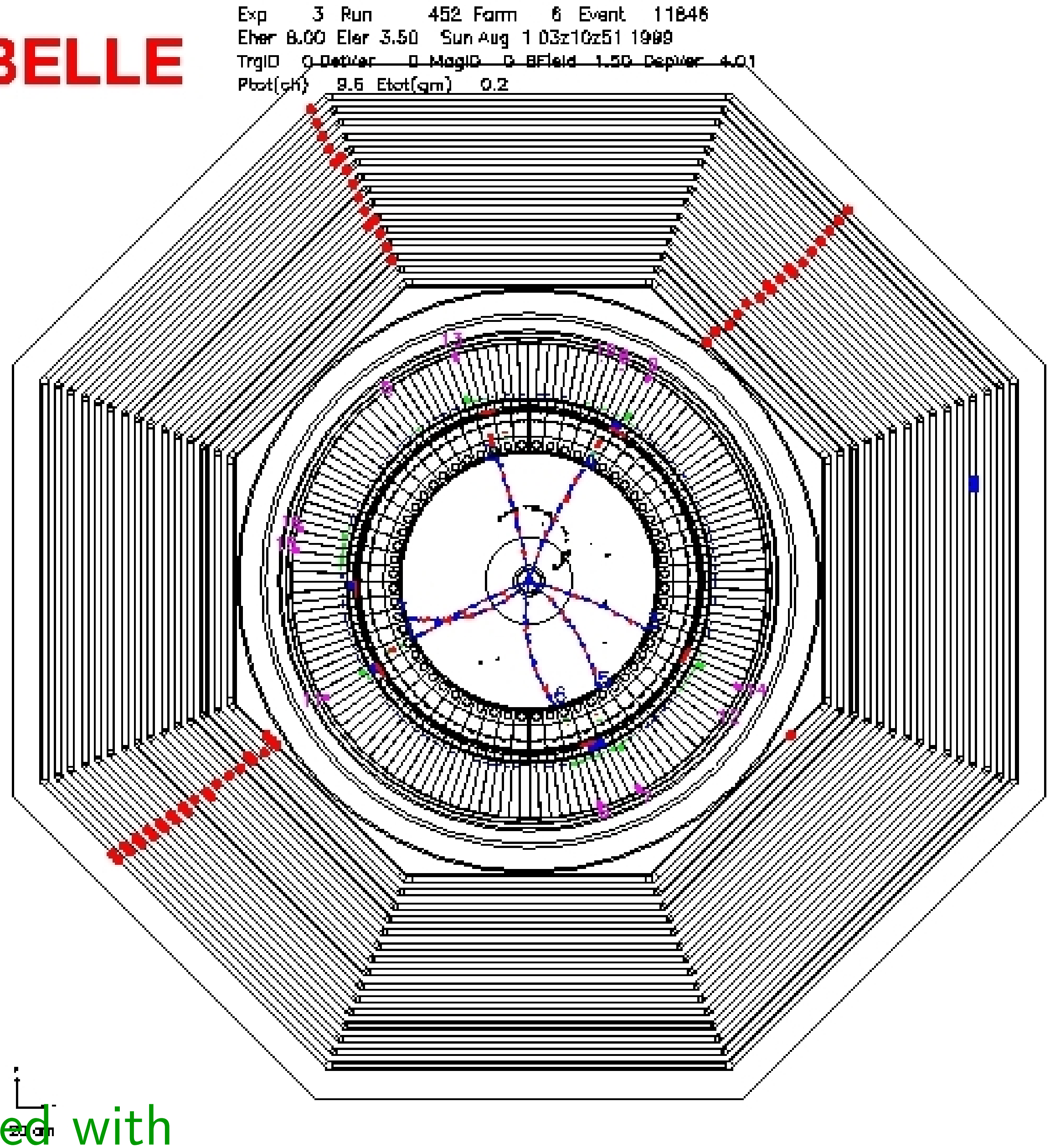




radiative tail (Bremsstrahlung)

BELLE

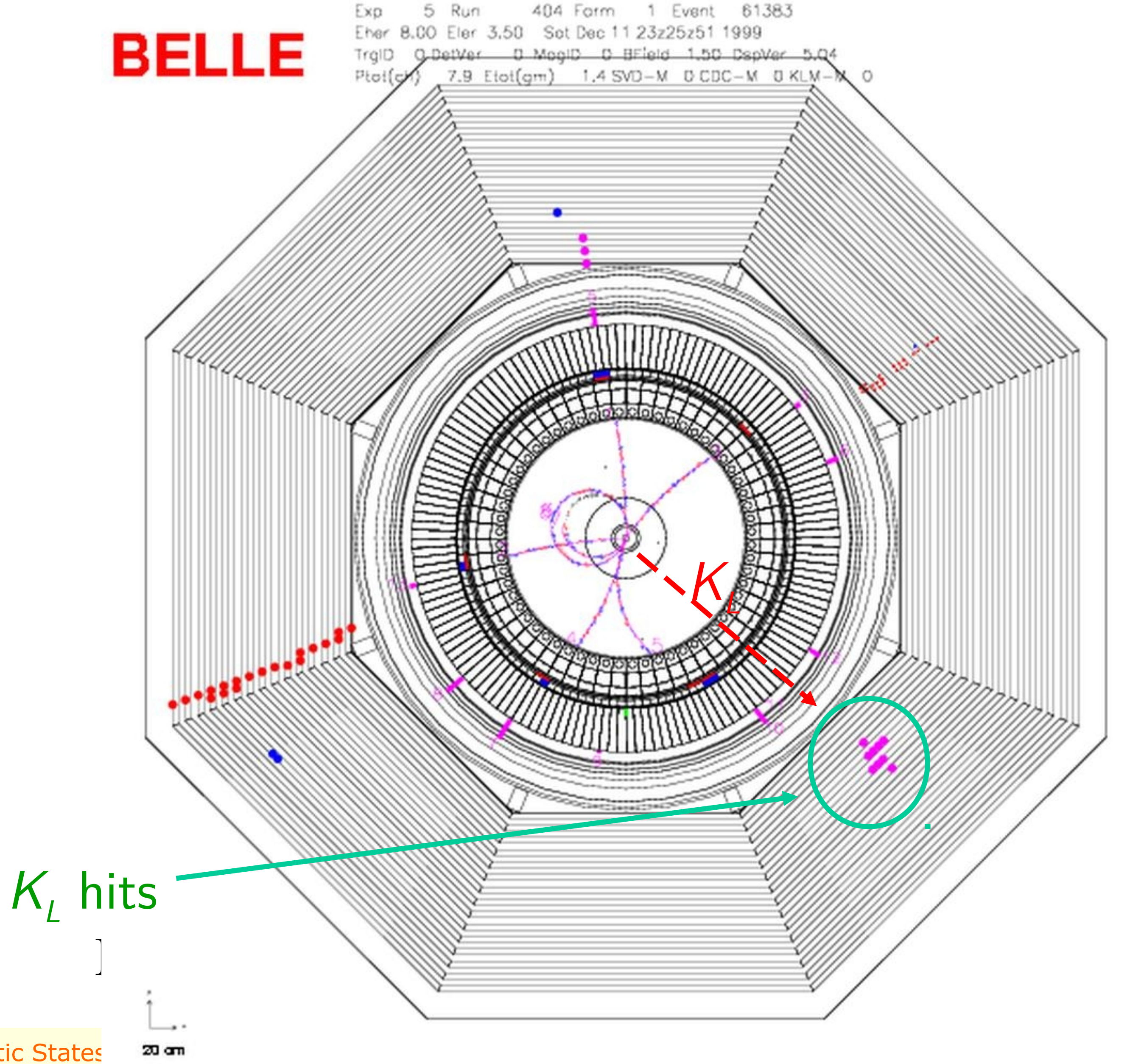
Muon Identification



The gaps are instrumented with RPCs (Resistive Plate Chambers)

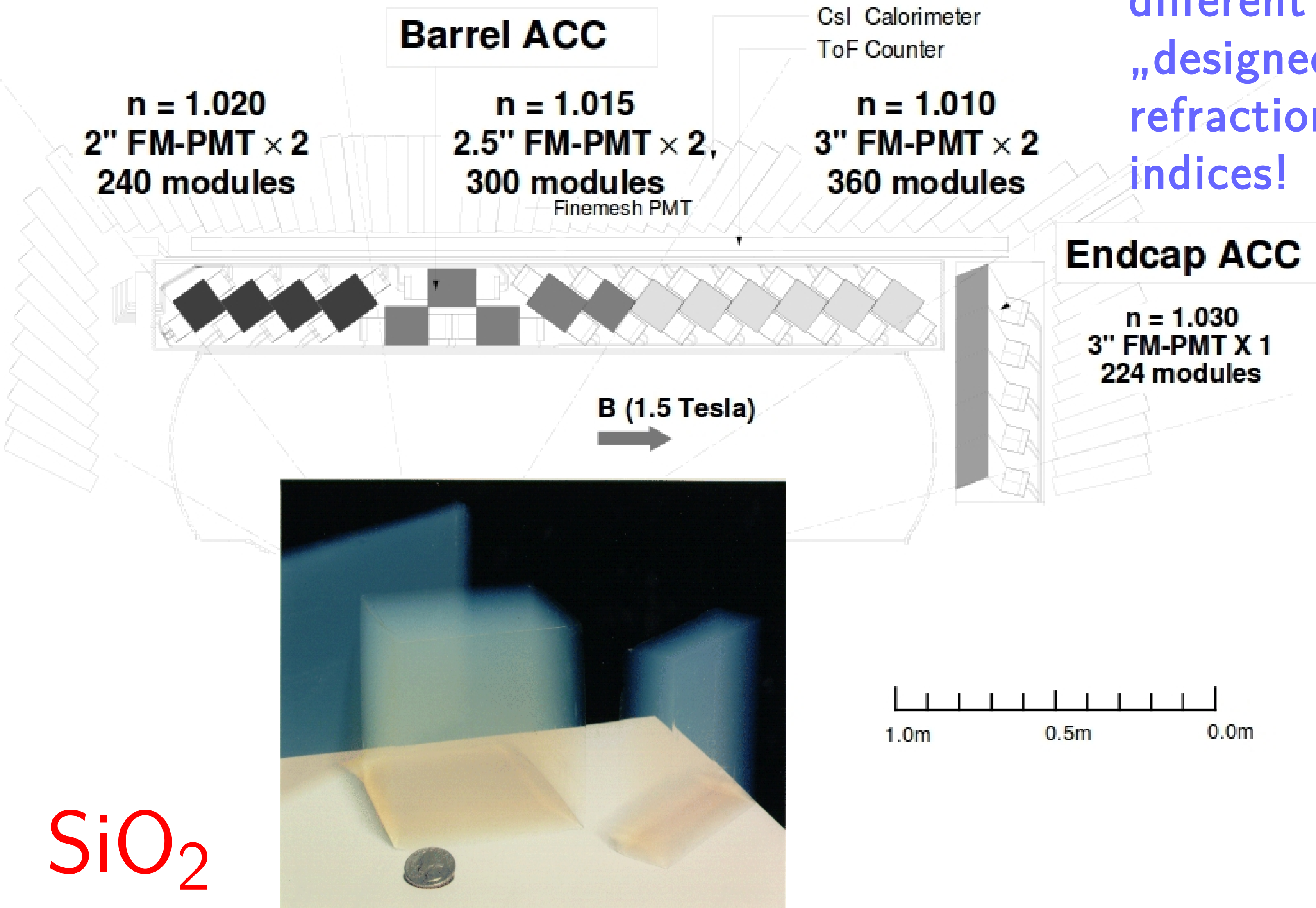
K_{long} Detection, also with the muon detector

$$B^0 \to J/\Psi K_L$$



A difference between BaBar and Belle: the Cerenkov detectors

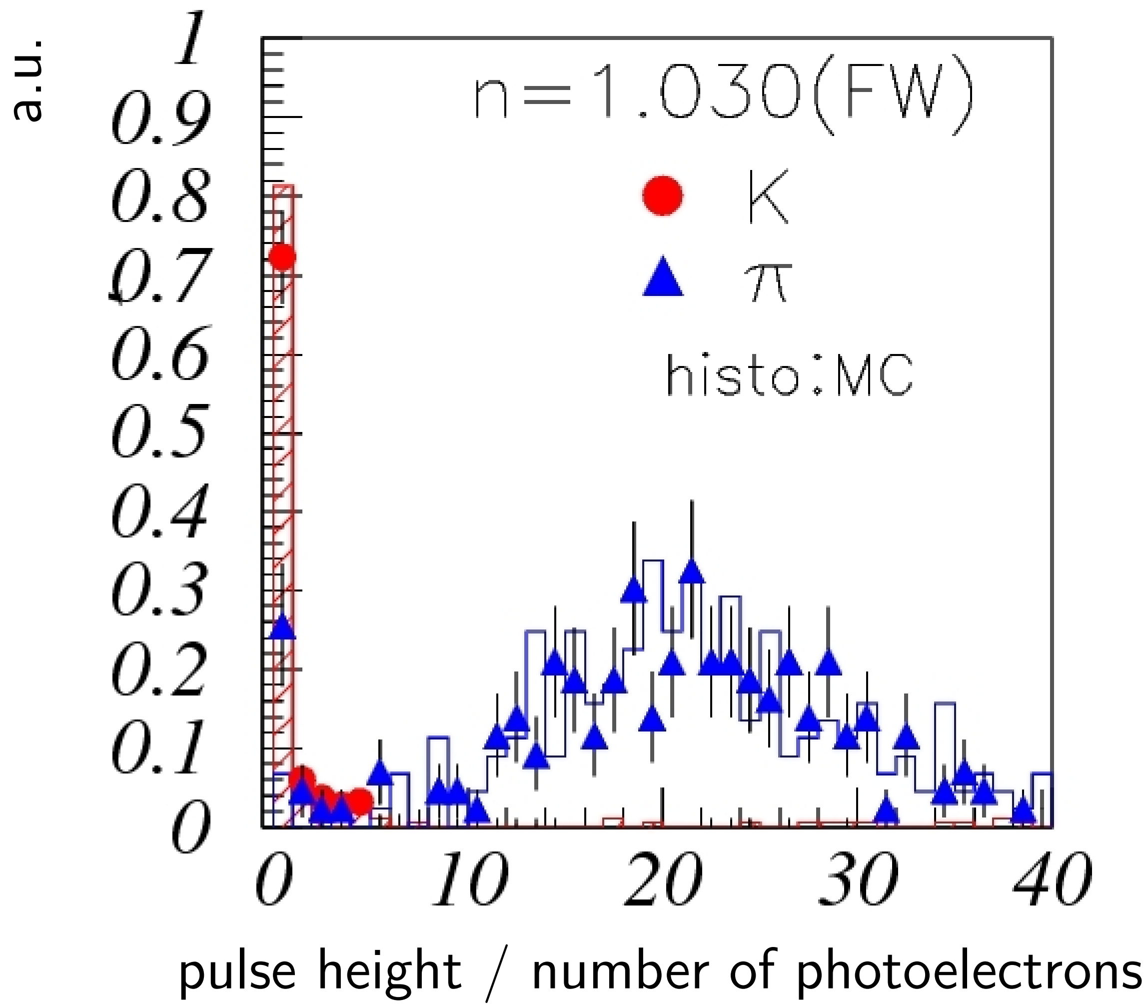
Belle: Aerogel Cerenkov Detector



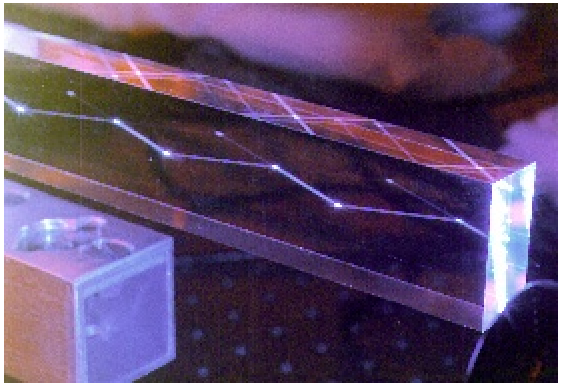
different „designed" refraction indices!

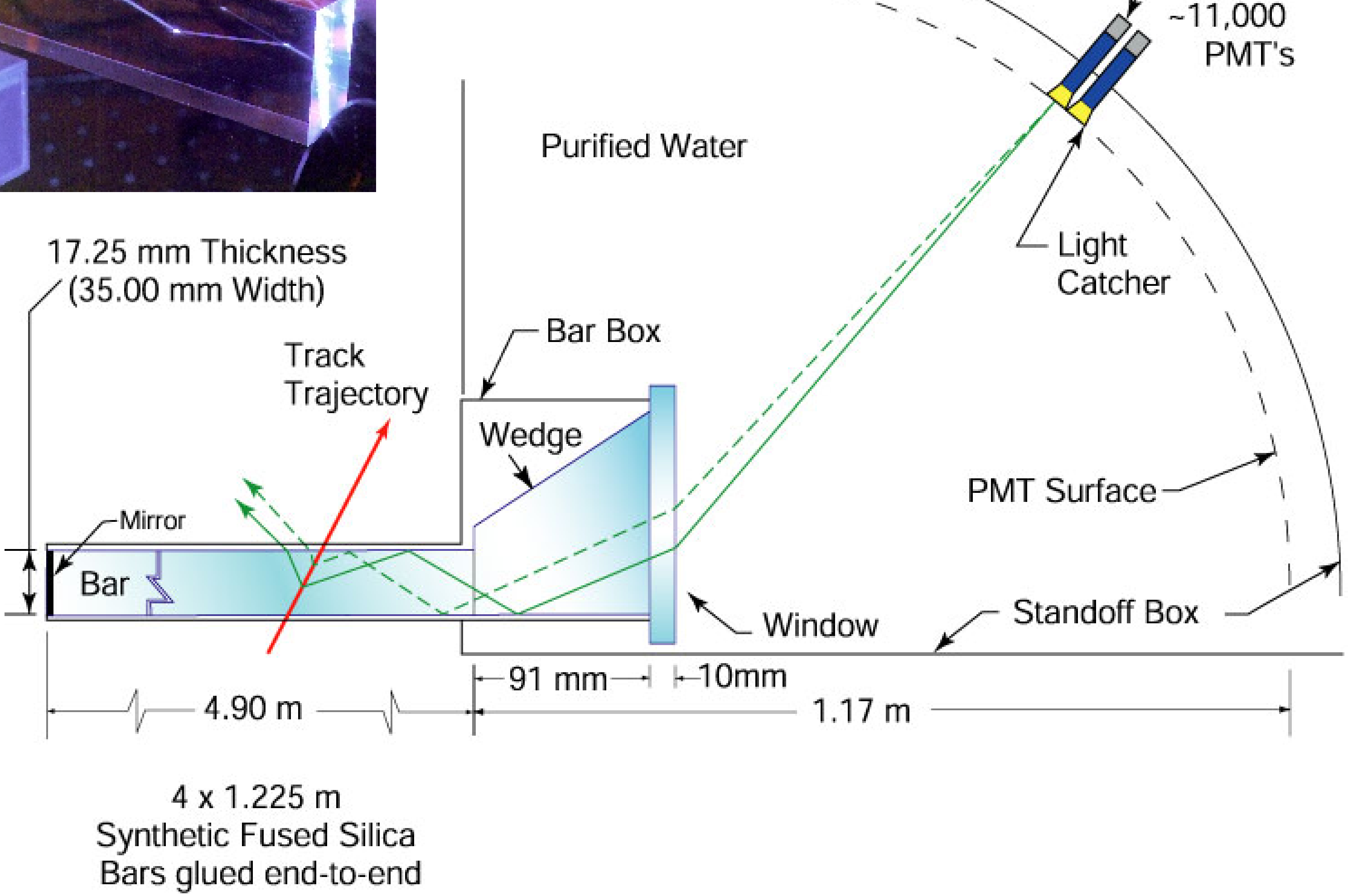
SiO_2

Particle Indentification with Aerogel „threshold mode“ (Belle)



BaBar DIRC (Detection of internally reflected Cerenkov light)





Belle Silicon Vertex Detector

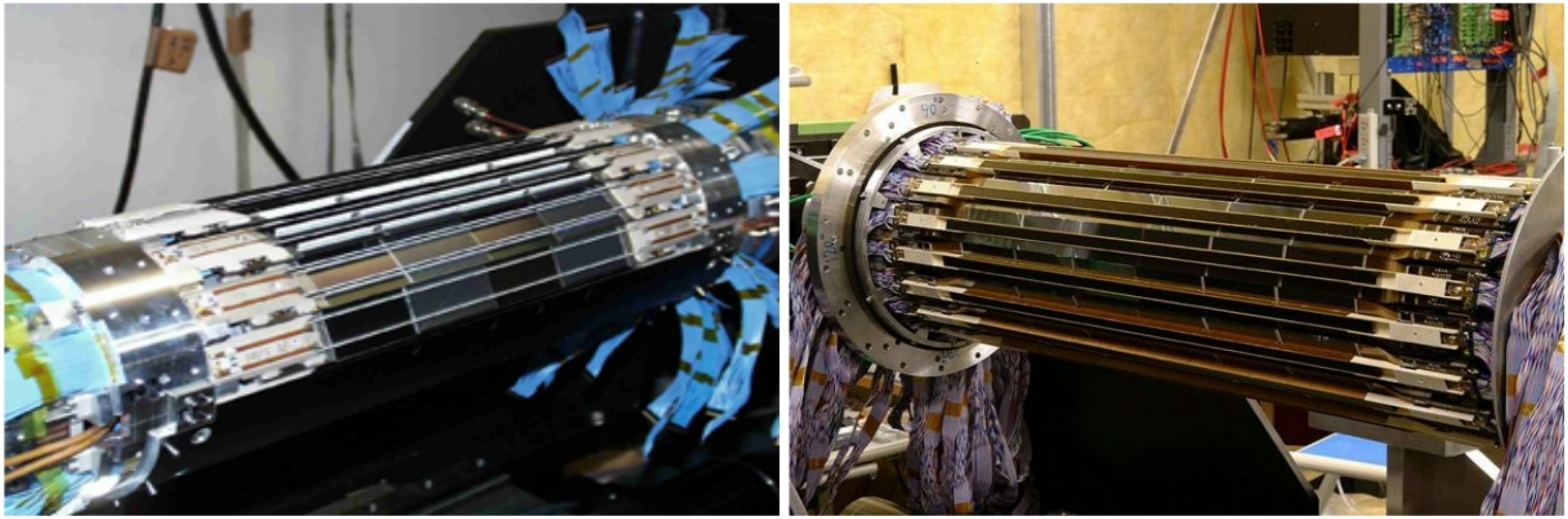


FIG. 28. Belle SVD 1.4 (left) and SVD 2.0 (right).

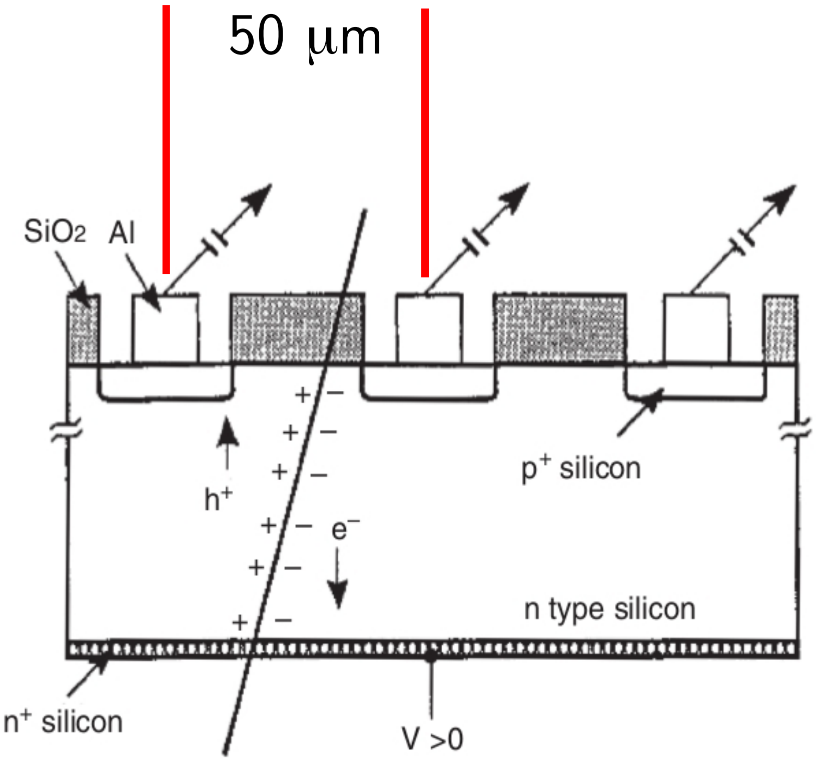
about 10^5 readout channels

vertex resolution in beam direction $\Delta z \sim 50\ \mu m$

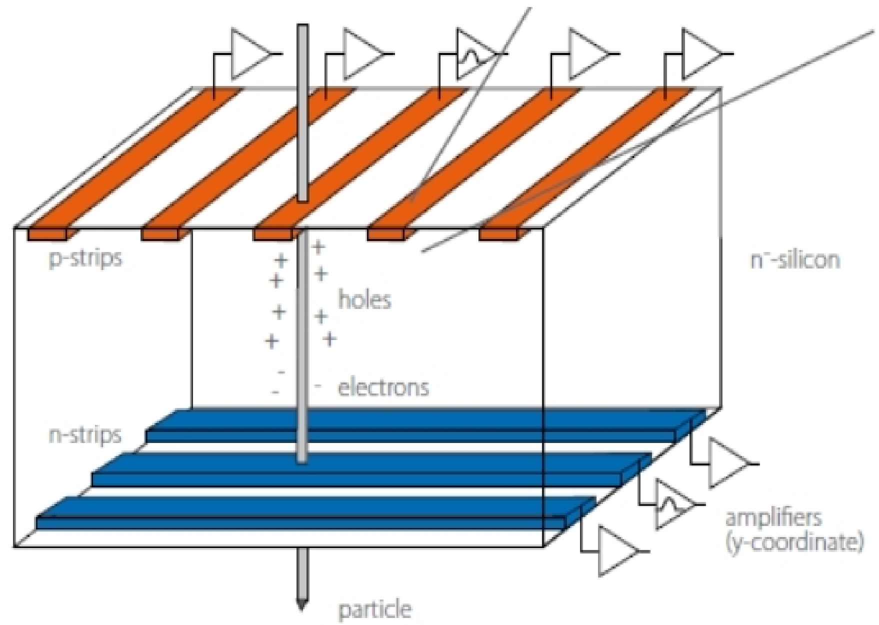
Particle Detection with Silicon Vertex Detectors

single sided

double sided



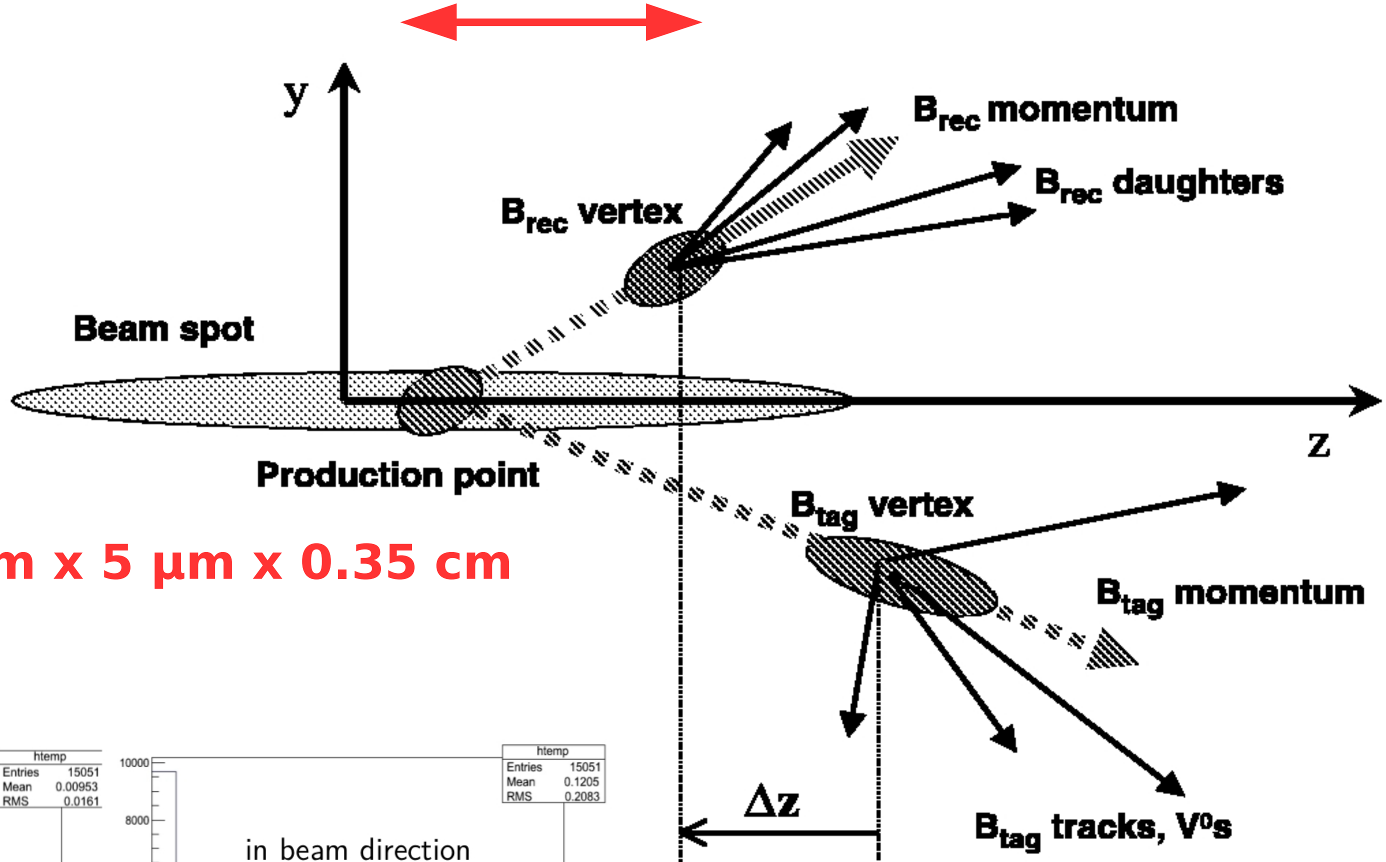
Schematic of a single-sided silicon-strip detector



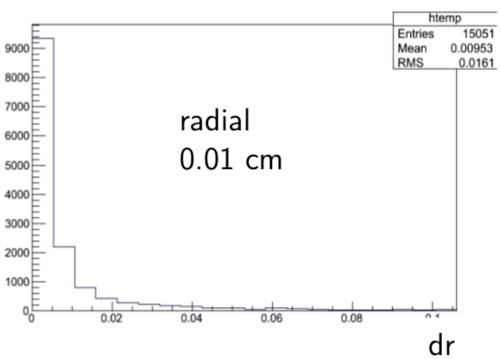
G.J.Barker, b Quark Physics at LEP

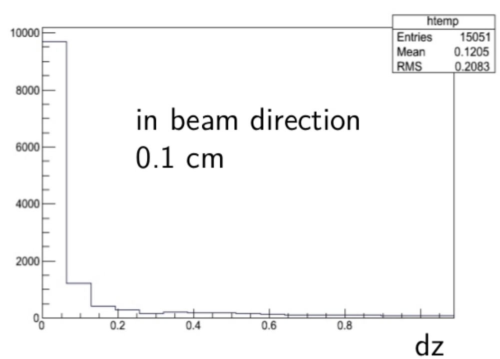
~200 μm

resolution ~50 μm



110 µm x 5 µm x 0.35 cm

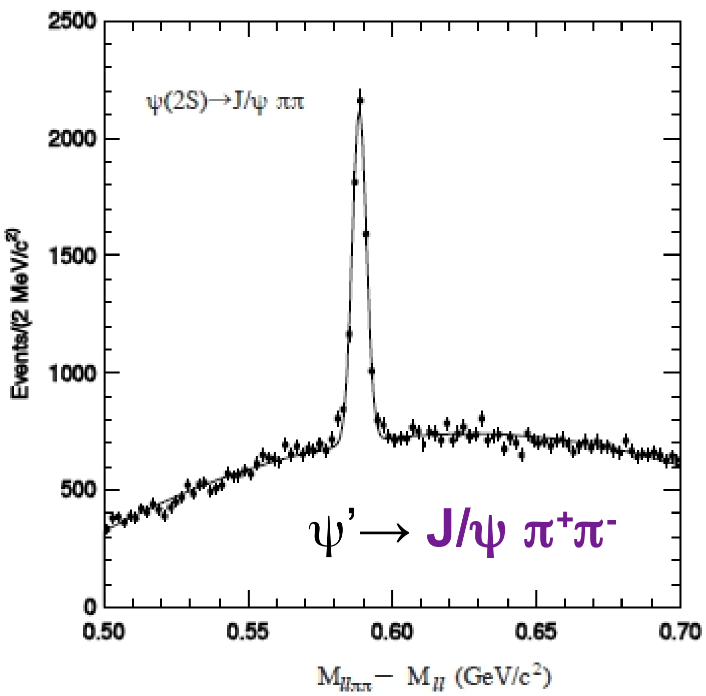


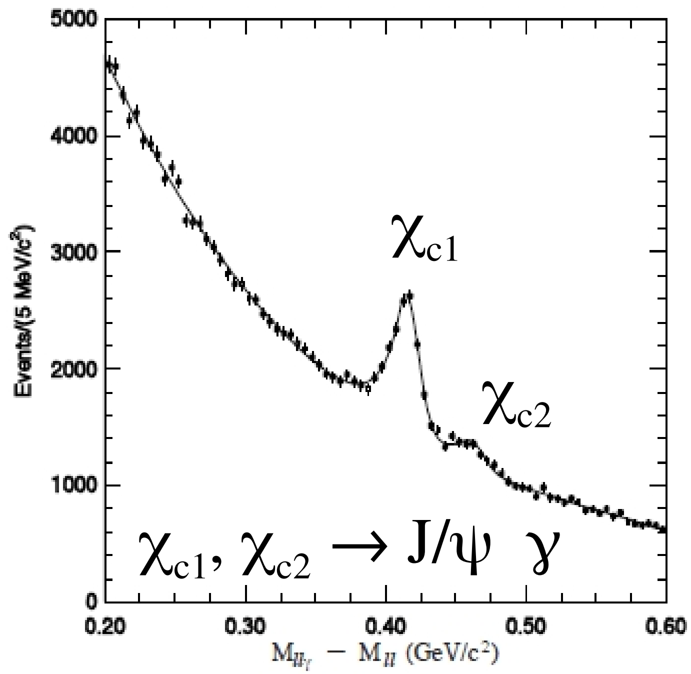


Reconstruction of higher charmonium states by invariant mass

$$m = \sqrt{\left(\sum_i E_i^2\right) - \left(\sum_i \vec{p_i}^{\,2}\right)}$$

often DOUBLE GAUSSIAN





Why we often use double Gaussian to fit a signal:

a.) for real data

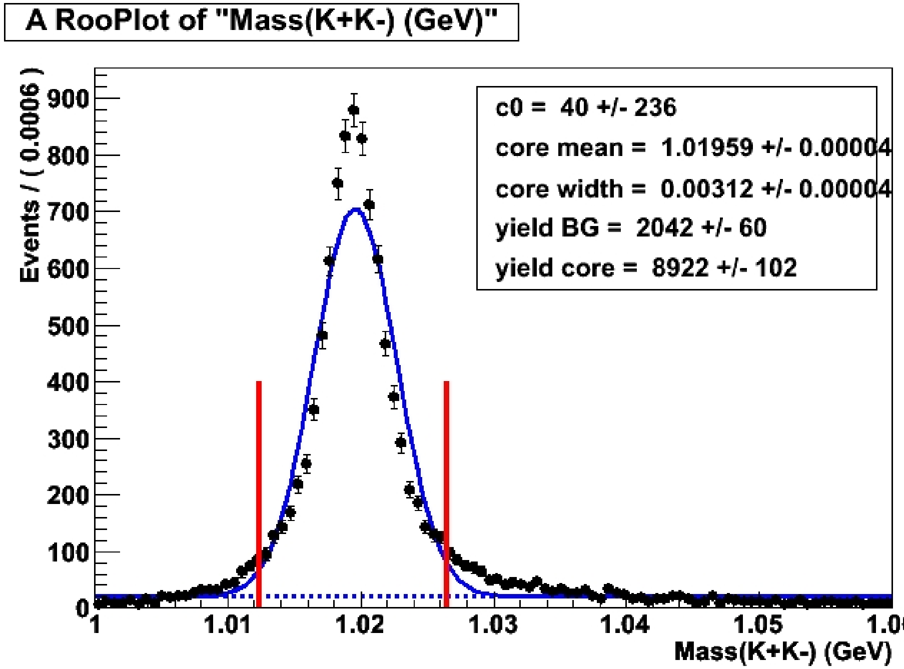
any effect, which is not in MC,
is parametrized as an additional Gaussian

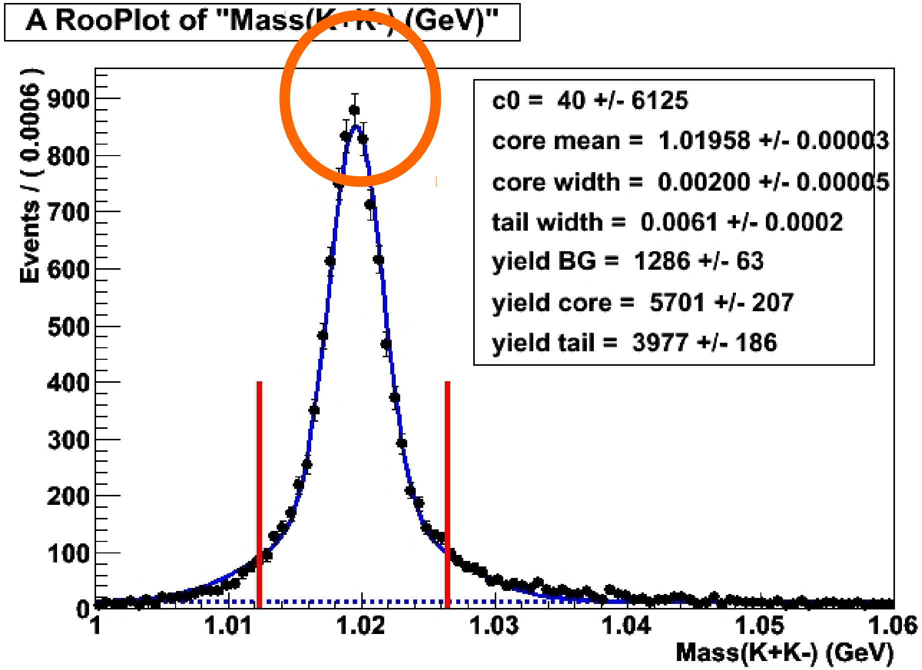
b.) if a peak is constructed from two (or more) daughter particles

each daughter particle contributes as a Gaussian
(in particular, when combining a neutral and a charged particle)

Example: $\phi \rightarrow K+ K-$

Signal MC





Single Gaussian
sigma 3.12 MeV

double Gaussian
sigma 2.00 MeV

input value in generator: width 4.26 MeV

Note: narrow and wide Gaussian are forced to same mean.

Breit Wigner Shape

in particular for particles with a natural width comparable to detector resolution

$$p(m) = \frac{1}{(m^2 - m_0^2)^2 + m_0^2 \Gamma^2(m)}$$

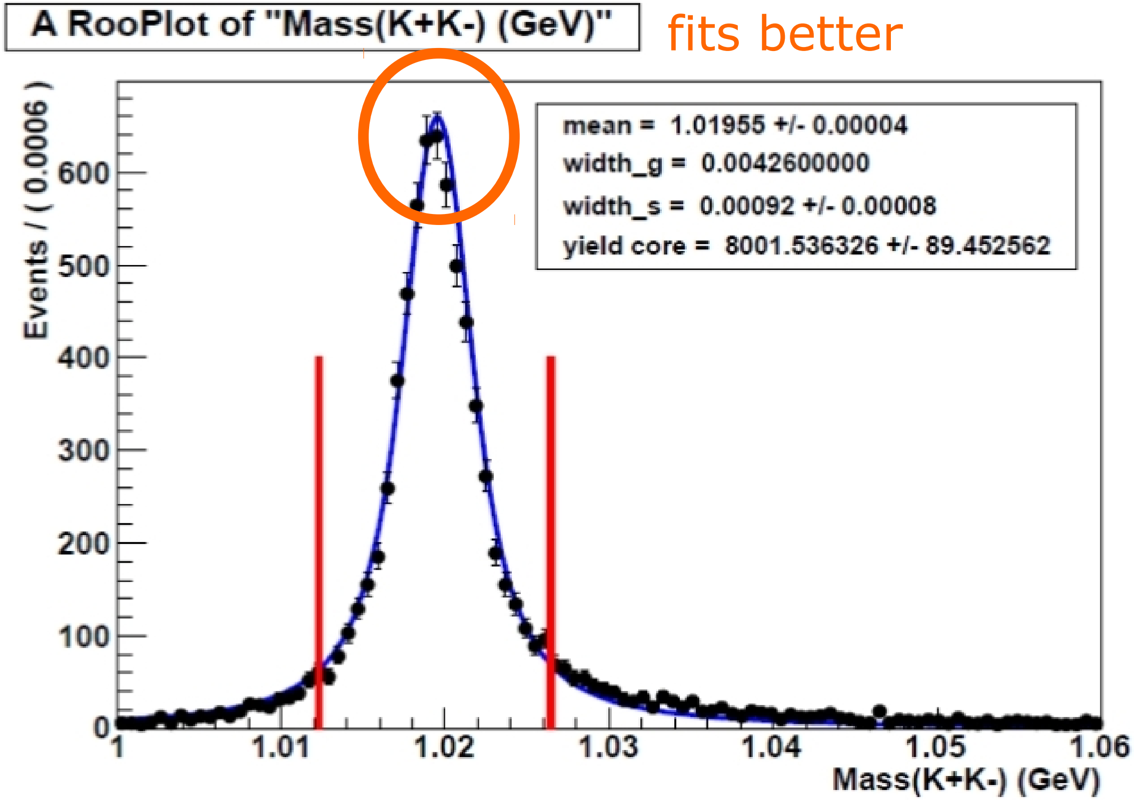
width may change with m !!!

from resonance theory („T matrix“):
the pole of a resonance is a complex number:
a real part (m) and an imaginary part (Γ)

Voigtian shape
Breit-Wigner and Gauss, folded

- Width of BW fixed to 4.26 MeV (input width in EvtGen)
- Result: Gaussian adds 0.9 MeV (= resolution)

fits better



Attention!
never forget the factor 2
when you compare
width of Breit-Wigner
and width of Gaussian!

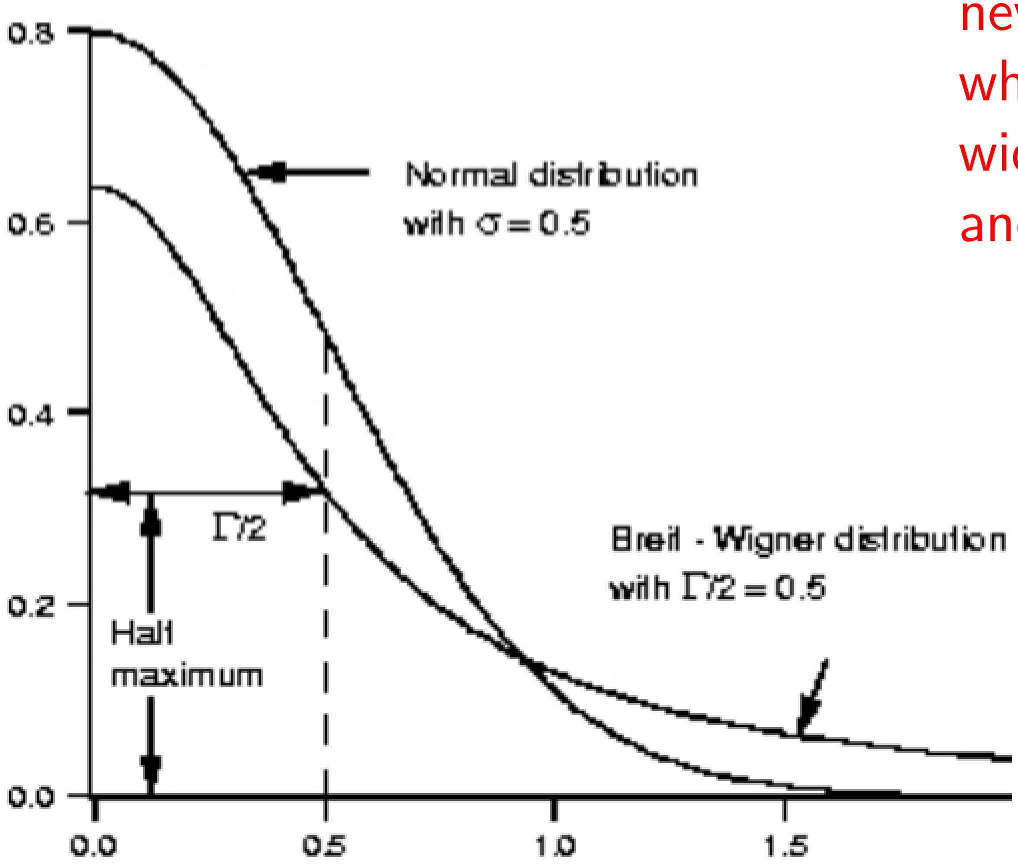


FIG. 109. Difference of the line shape of a Breit-Wigner probability distribution and a Gaussian probability distribution

R. K. Bock, W. Krischer, The Data Analysis BriefBook

Beam Constrained Mass m_{BC}
or
energy substituted mass m_{ES}

$$m_{bc} = \sqrt{\frac{(E_{beam}^{cms})^2}{4} - (p_B^{cms})^2}$$

$$= \sqrt{\frac{E_{BC}^2}{4} - \left(\left[\sum_i p_{ix}\right]^2 + \left[\sum_i p_{iy}\right]^2 + \left[\sum_i p_{iz}\right]^2\right)}$$

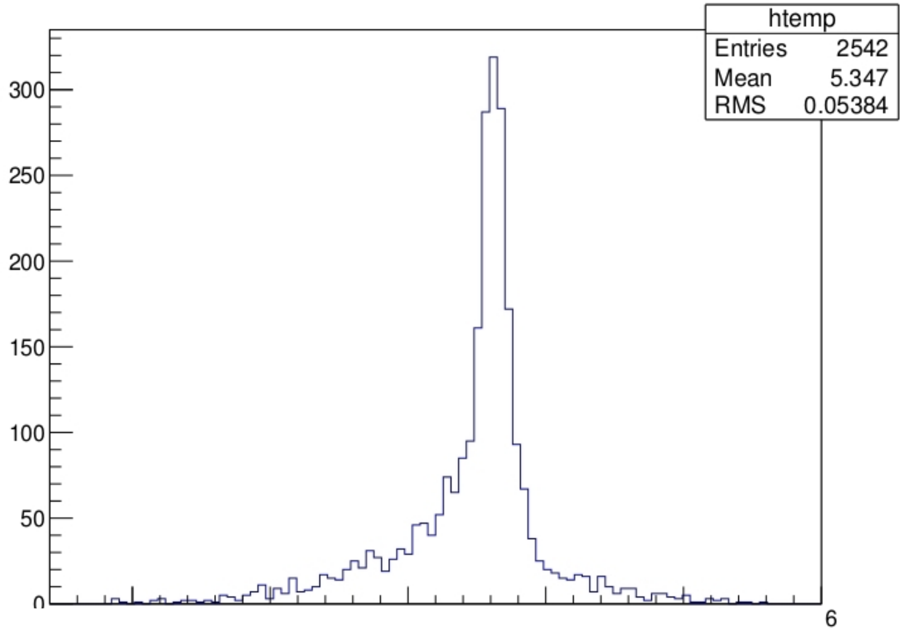
$$B \rightarrow K \, [\, J/\psi \;\; \pi_1 \;\; \pi_2 \,]$$

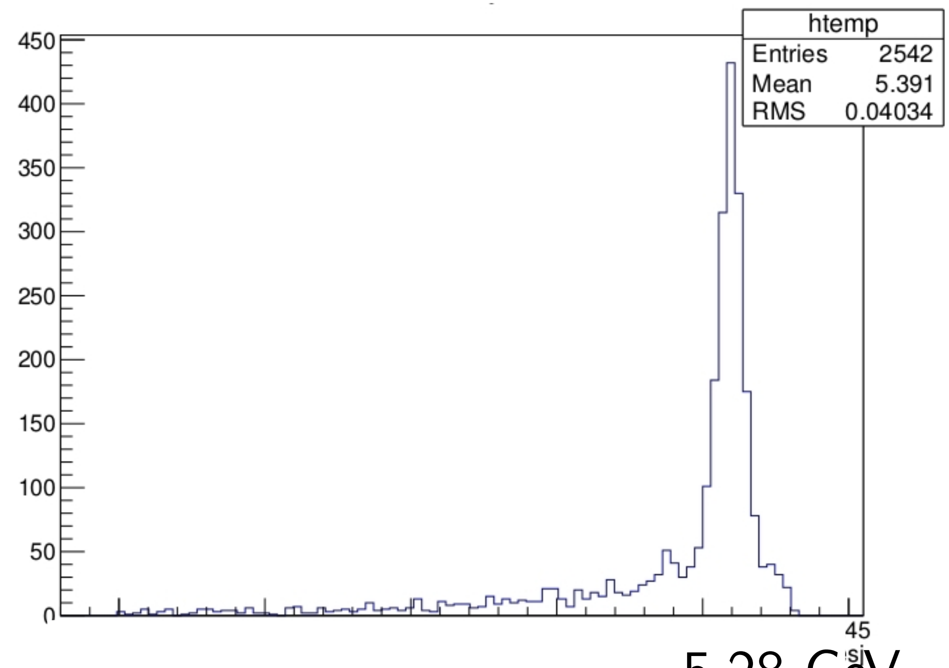
```
px_Bc= jpsi_vector.x() + pcms[kaon].x() + pcms[pion1].x() + pcms[pion2].x();
py_B = jpsi_vector.y() + pcms[kaon].y() + pcms[pion1].y() + pcms[pion2].y();
pz_B = jpsi_vector.z() + pcms[kaon].z() + pcms[pion1].z() + pcms[pion2].z();

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

deltaE = ECM/2 – esum_B;

mass_B = sqrt( esum_B*esum_B – (px_B*px_B + py_B*py_B + pz_B*pz_B) );

mass_BC = sqrt( ECM*ECM/4. - (px_B*px_B + py_B*py_B + pz_B*pz_B) );
```

ECM comes from accelerator measurement.

B meson
invariant mass

Beam constrained mass
m_{BC}
or
energy substituted mass
m_{ES}

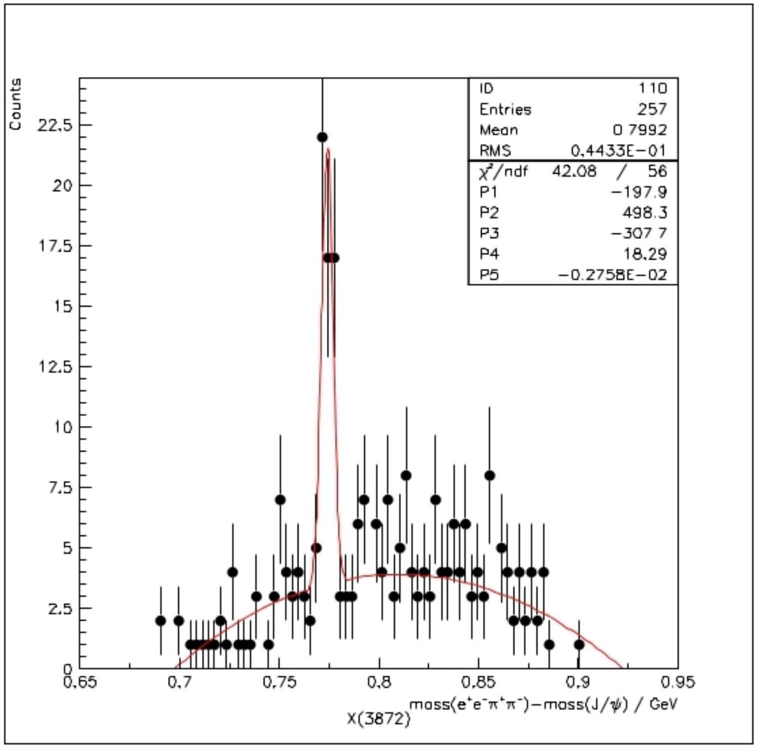


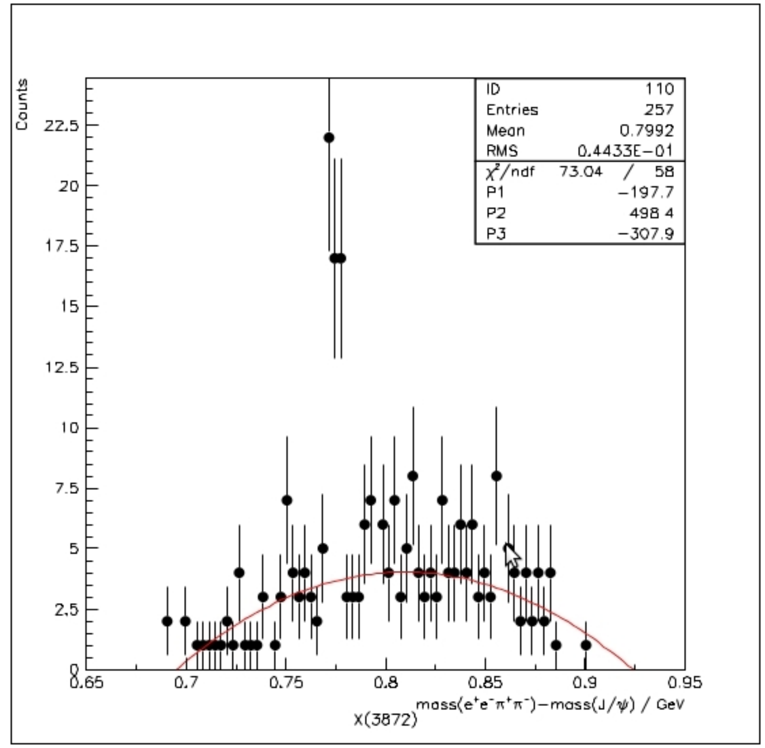


5.28 GeV

5.28 GeV

Statistical Significance





Fit S+BG

χ^2=42.08

Fit only BG

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 ($>5\sigma$)

χ^2 fit vs. log likelihood fit

S = √(χ^2(B) – χ^2(S+B))

$$P_\lambda(k) = \frac{\lambda^k}{k!}\,\mathrm{e}^{-\lambda},$$

If number of events is small → Poisson statistics
→ exp() Term → log likelihood is better than χ^2
(in other words, removing the shape of exp() and make it flat,
when searching for the global minimum)

$\chi^2 = -2 \ln L + \text{constant}$
(don't forget the minus sign!
minimum χ^2, but maximum log likelihood)

S = √(2 (– ln L(B) – – ln L(S+B)))

HOWTO scale the significance

- for a known resonance (control channel)
  mass and width are known from PDG
  only yield is floating $\rightarrow$ ndof=1
- for a new resonance (maybe exotic)
  nothing is known
  mass, width, and yield are floating $\rightarrow$ ndof=3

rule: we must scale the significance

chi2=52.58 for a fit with ndof=3

```
root [4] TMath::Prob(42.08,3)
(Double_t)3.85831510574144829e-09
```

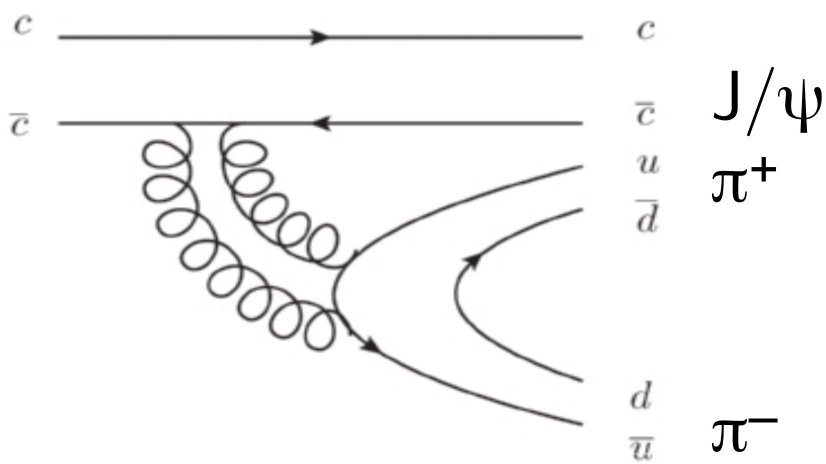
search for new chi2 with same p-value, but ndof=1

```
root [68] TMath::Prob(34.694,1) // corrected chi2
(Double_t)3.85818878297546610e-09
```

X(3872)

A molecular state?

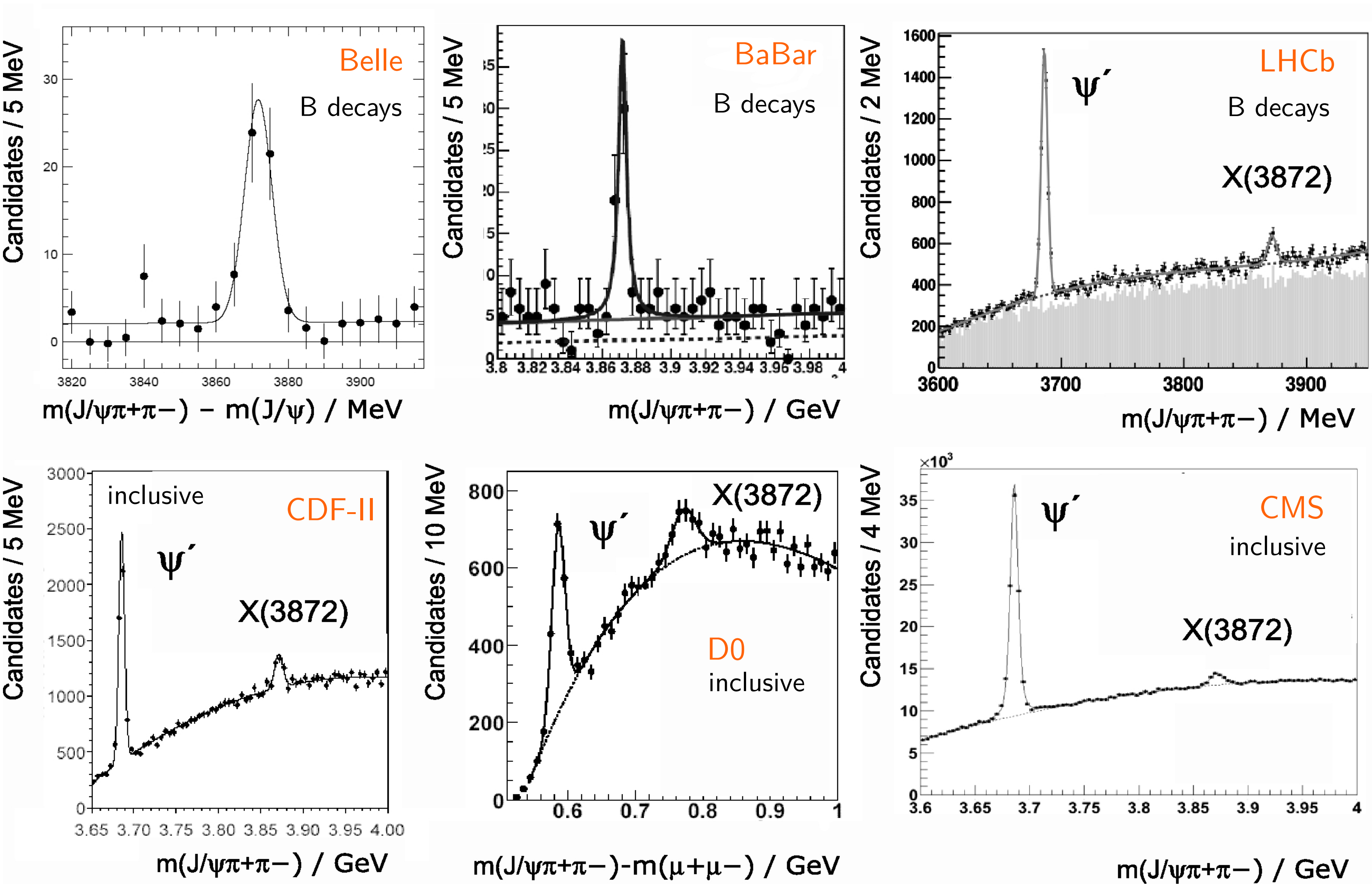
$$B^{\pm} \to K^{\pm} \underbrace{J/\psi\pi^{+}\pi^{-}}_{\text{resonant state?}}$$



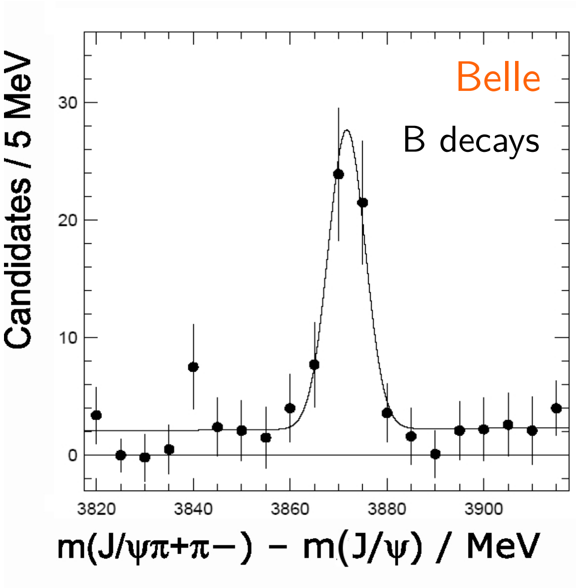
Product branching fraction small

B(B decay) $\times$ B(X decay) $\simeq$ 10^{-5}

X(3872)


Belle
B decays
Candidates / 5 MeV
m(J/ψπ+π−) – m(J/ψ) / MeV
BaBar
B decays
Candidates / 5 MeV
m(J/ψπ+π−) / GeV
LHCb
B decays
ψ´
X(3872)
Candidates / 2 MeV
m(J/ψπ+π−) / MeV
CDF-II
inclusive
ψ´
X(3872)
Candidates / 5 MeV
m(J/ψπ+π−) / GeV
D0
inclusive
ψ´
X(3872)
Candidates / 10 MeV
m(J/ψπ+π−)-m(μ+μ−) / GeV
CMS
inclusive
ψ´
X(3872)
Candidates / 4 MeV
m(J/ψπ+π−) / GeV

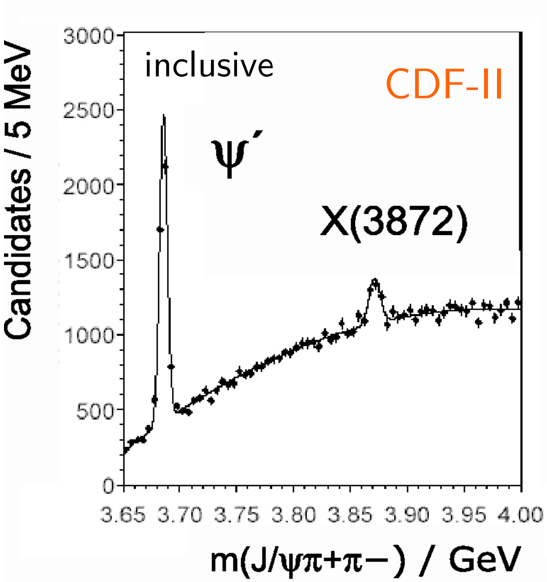
X(3872)



This is B meson decays

This is not simply invariant mass,
but fitted m_{BC} yield (for a given mass bin)
many fits!

Trick: subtract the J/ψ mass
(so the experimental resolution of the J/ψ
is „taken out“)

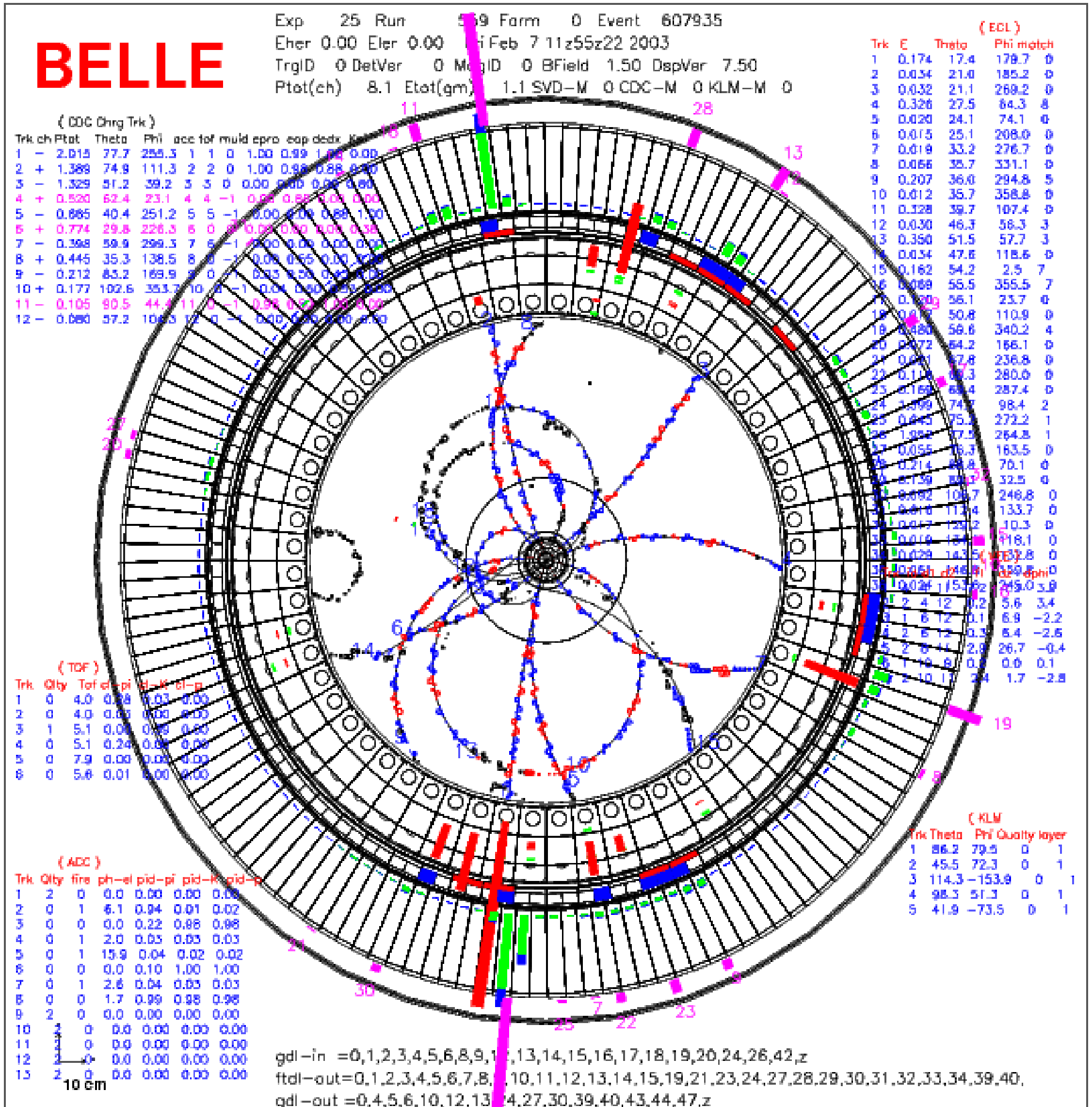


This is „inclusive“ production (not B decays)

This is invariant mass.

J/ψ mass is not subtracted.

X(3872→J/ψππ event - can you „see" the ψ shape ?



What do we know about the X(3872) ?

- Observed by 7 experiments
- Observed in 5 decay channels

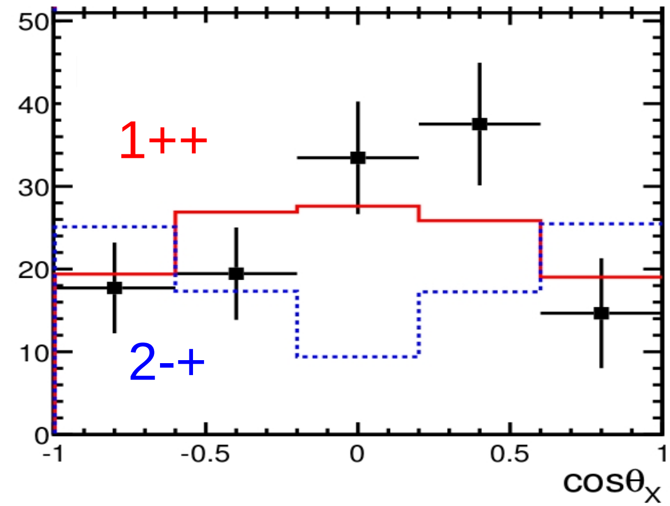
- very near to $D\bar{D}^*$ threshold
  E_B=0.01±0.18 MeV
  but $D\bar{D}^*$ decays dominant
  (factor ~10)

- Γ ≤1.2 MeV → very narrow
  (Belle, by 3-dim overconstrained fit)

- $J^{PC}=1^{++}$
  Cornell-potential: χ_{c1}'
  Barnes et al., Phys. Rev. D72(2005)054026
  → predicted mass ≥50 MeV higher
  → predicted width factor ≥100 larger

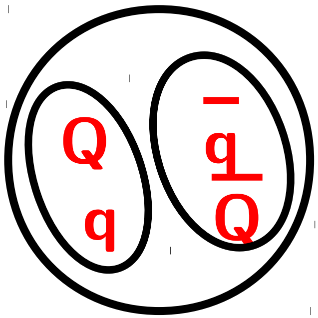
- isospin violating decays

LHCb, Phys. Rev. Lett. 110(2013)222001



Is the X(3872) exotic ?

TETRAQUARK

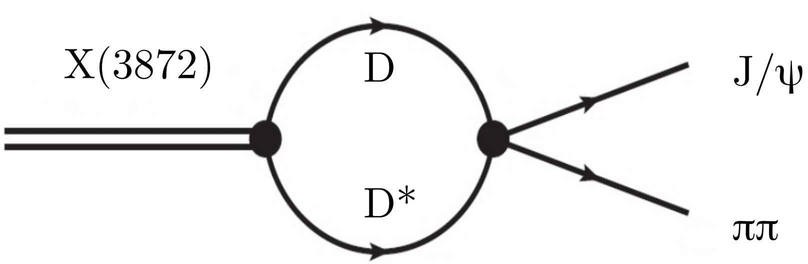


$[qQ]_8[\overline{qQ}]_8$

Diquarks are colored

Maiani, Riquer, Piccinini, Polosa, Burns;
Ebert, Faustov, Galkin; Chiu, Hsieh;
Ali, Hambrock, Wang

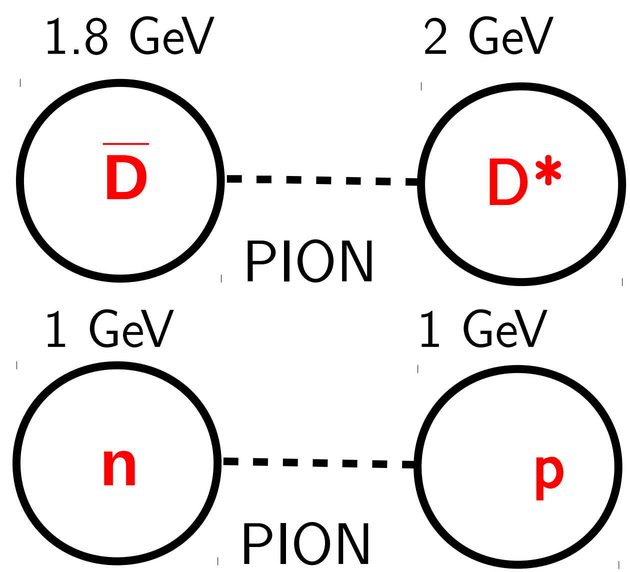
THRESHOLD CUSP



Bugg; Swanson

MOLECULE

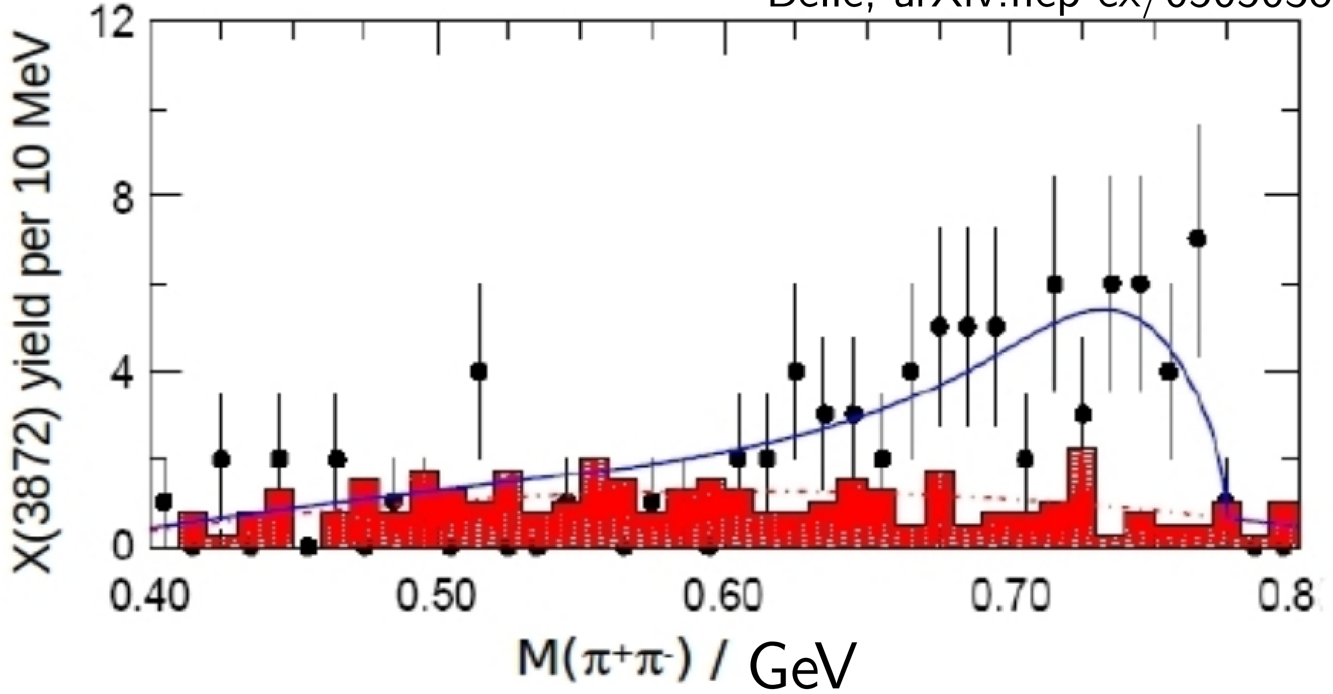
Intriguing Analogon



Tornqvist; Swanson; Braaten, Kusonoki,
Wong; Voloshin; Close, Page
Guo, Hanhart, Meissner

Subresonant structure of X(3872) → $J/\psi[\pi^+\pi^-]$

Belle, arXiv:hep-ex/0505038



almost no non-resonant phasespace component !

dominated by ρ^0 (~100%) ! ISOSPIN VIOLATING

2 particle decay (back-to-back), not a 3-particle decay !

Isospin violating charmonium transistions

Only 2 decays for charmonium measured in PDG

$\psi(2S)$

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

$J/\psi(1S)$anything	(61.0 ± 0.6) %
$J/\psi(1S)$neutrals	(25.11 ± 0.33) %
$J/\psi(1S)\pi^+\pi^-$	(34.46 ± 0.30) %
$J/\psi(1S)\pi^0\pi^0$	(18.14 ± 0.31) %
$J/\psi(1S)\eta$	(3.36 ± 0.05) %
$J/\psi(1S)\pi^0$	$(1.268 \pm 0.032) \times 10^{-3}$

Hadronic decays

$\pi^0 h_c(1P)$	$(8.6 \pm 1.3) \times 10^{-4}$

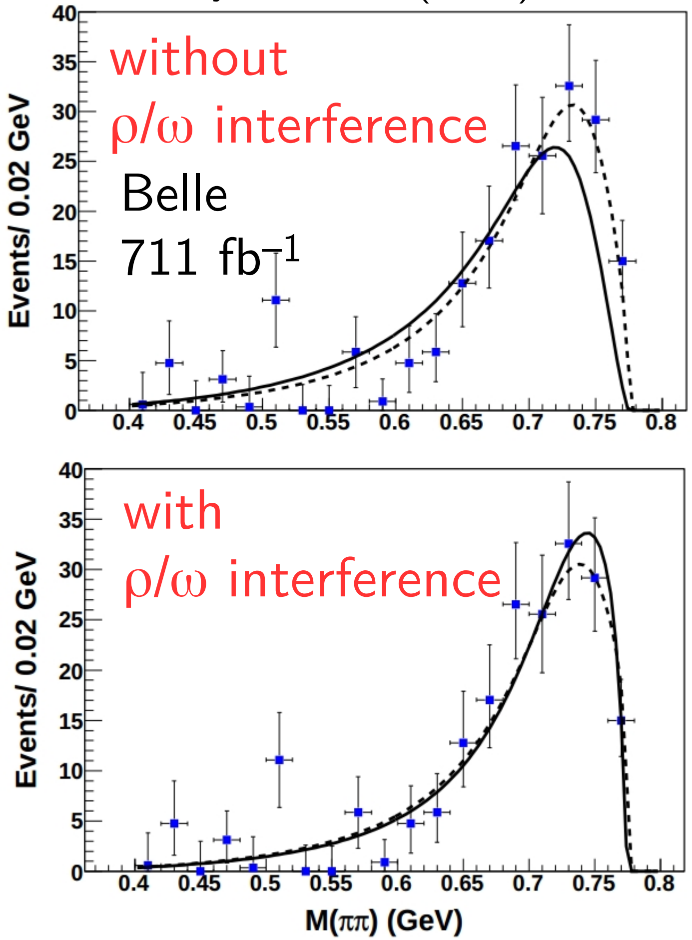
but branching fraction of

$\mathcal{B}(X(3872) \to J/\psi\rho)$ is order of ~5–10%

factor ~10^2 too large

Is there isospin <u>inside</u> the X(3872) ?

Phys Rev D84(2011)052004



No evidence. Significant ρ/ω interference can explain lineshape.

(proposed by Terasaki, Prog. Theor. Phys. 122(2010)1285)

What important knowledge is missing? $\rightarrow$ Width of X(3872)

upper limit on width (Belle I),
$\Gamma < 1.2$ MeV

for pure χ_{c1}' charmonium state,
prediction $\Gamma = 40$ keV
G. Y. Chen, J. P. Ma, arXiv:0802.2982[hep-ph], Phys. Rev. D77(2008]097501.

if molecule
- must be larger than width of D*
  Γ > $82.3 \pm 1.2 \pm 1.4$ keV
  E. Braaten, arXiv:0711.1854 [hep-ph], Phys. Rev. D77(2008)034019.
- long-range molecular components in the wavefunction?

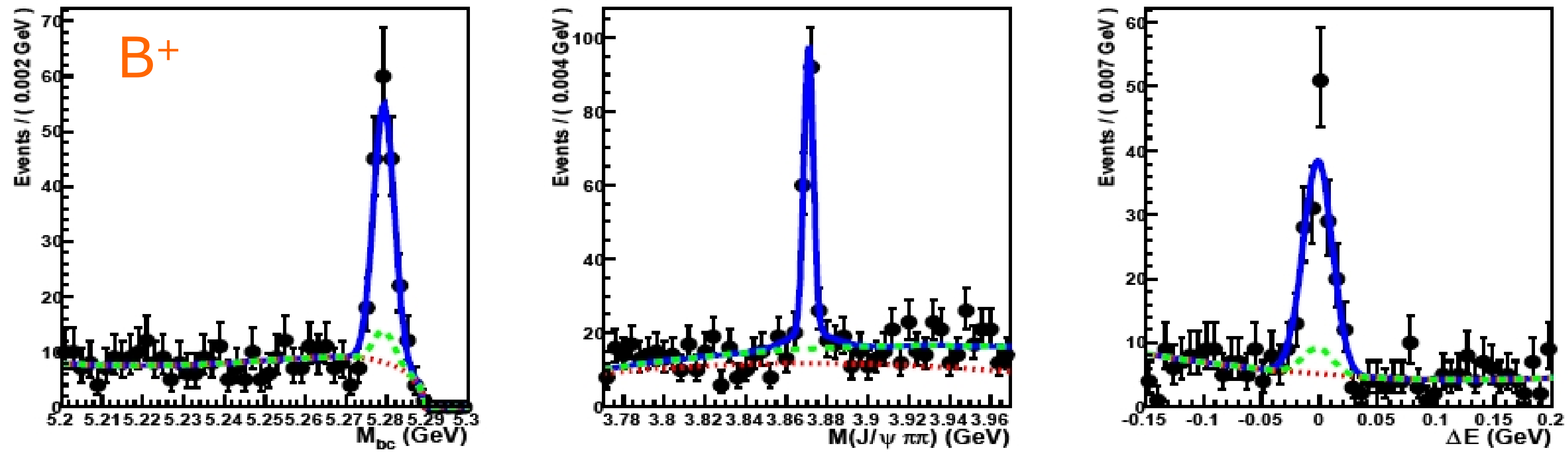
$\rightarrow$ measure the width of the X(3872)
in the sub-MeV regime

X(3872) Width Measurement at Belle I

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

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

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



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

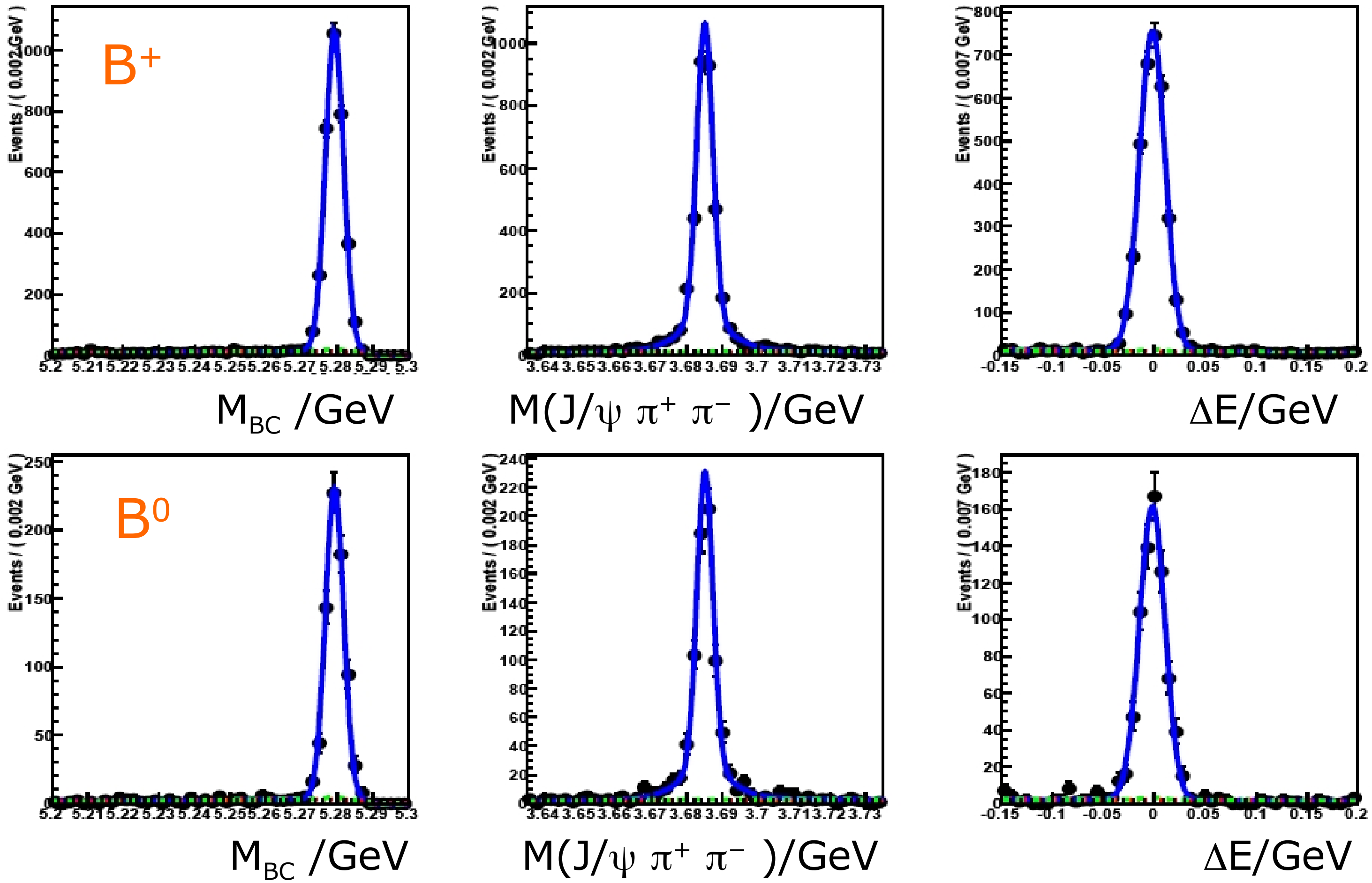
3-dim fit →kinematical over-constraint provides access to observables smaller than detector resolution

Belle, Phys. Rev. D84(2011)052004

Reference Analysis: B→Kψ´, ψ´ → J/ψ π⁺π⁻

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

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



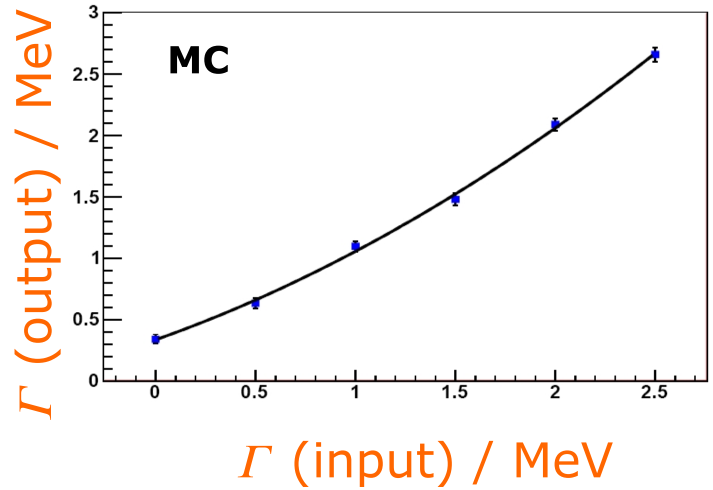
factor ~10 more statistics than X(3872) → use as reference signal

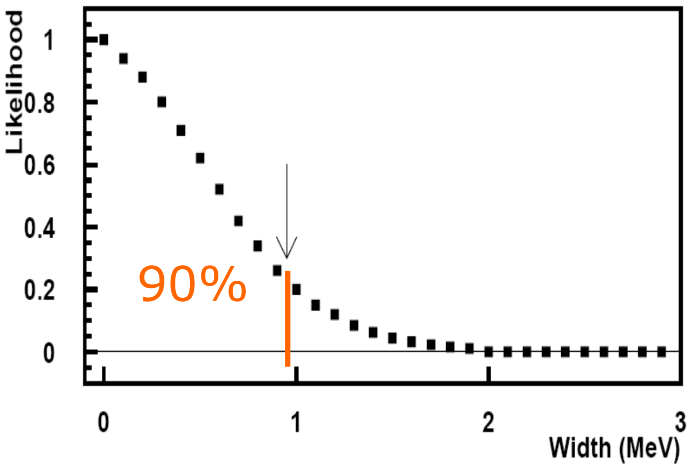
→ fix resolution parameters

→ fix absolute mass scale (MC/data shift +0.92±0.06 MeV)

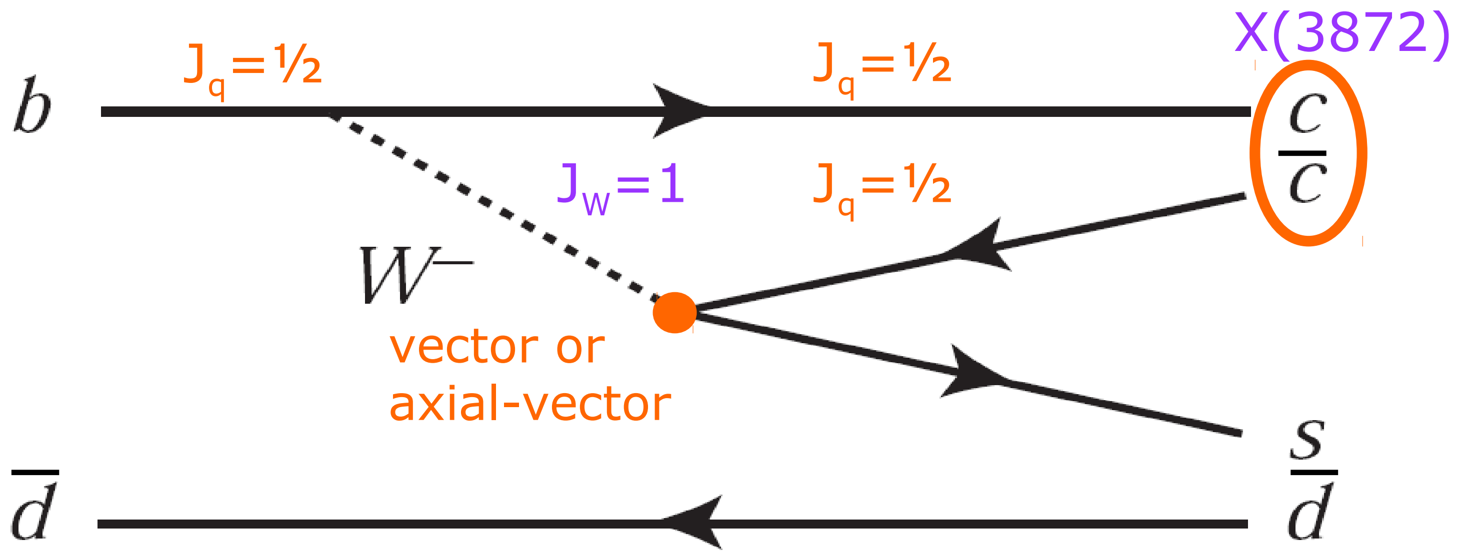
Measurement of width of X(3872)

- Correlation function from MC
  Γ (output) $=$ f(Γ (input))
- 3-dim fits 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_{BG} floating
  → calculate likelihood
- $\Gamma_{X(3872)} \underbrace{< 0.95 \text{ MeV} + \text{bias}}_{1.2 \text{ MeV}}$
- implication: width of X(3872)
  can be measured at Belle II
  with syst, error ±110 keV
  (PANDA, expected fit error ±15–20 keV)





X(3872) in B decays



Exercise:

$$B \rightarrow K\ X(3872)$$
$$0- \rightarrow 0-\ 1+$$
$$\text{parity } (-1) \rightarrow \text{parity } (-1) \times (+1) \times (-1)^{L}$$

Exercise:

$B \rightarrow K\ X(3872)$

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

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

We need L=1 to create J=1,
but this violates parity.
The X(3872) is created in a parity violating weak decay.

Y(4260)

a gluonic 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)

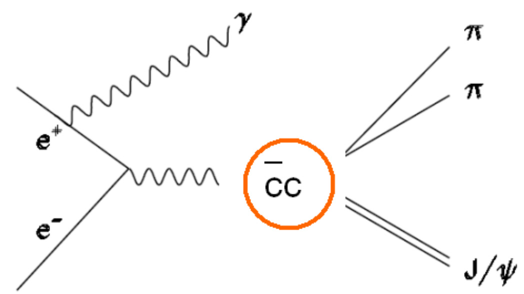
- mass >4 GeV
  far above D(*)D(*) thresholds
  decay to $J/\psi\pi^+\pi^-$
  should be suppressed

- width < 100 MeV
  quite narrow
  for such a high state

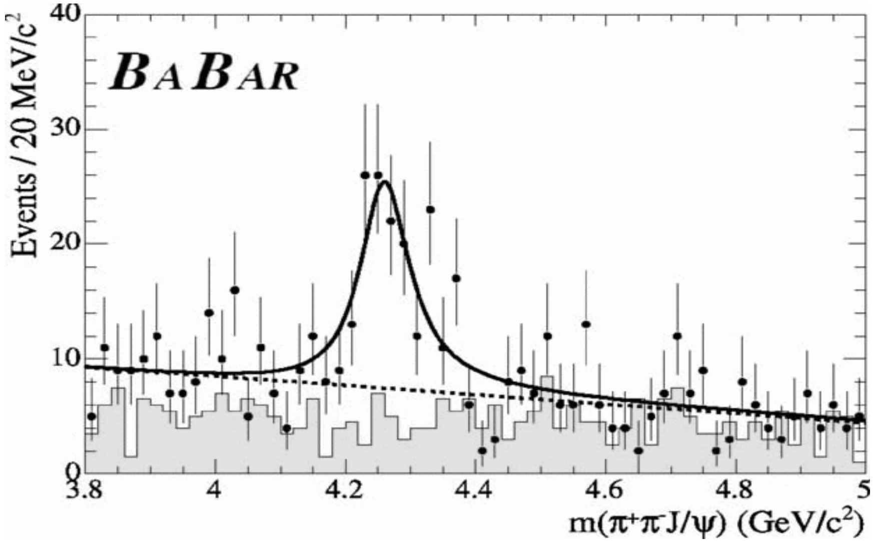
- quantum numbers must be
  (based upon production
  mechanism)

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

initial state radiation



Phys. Rev. Lett. 95(2005)142001

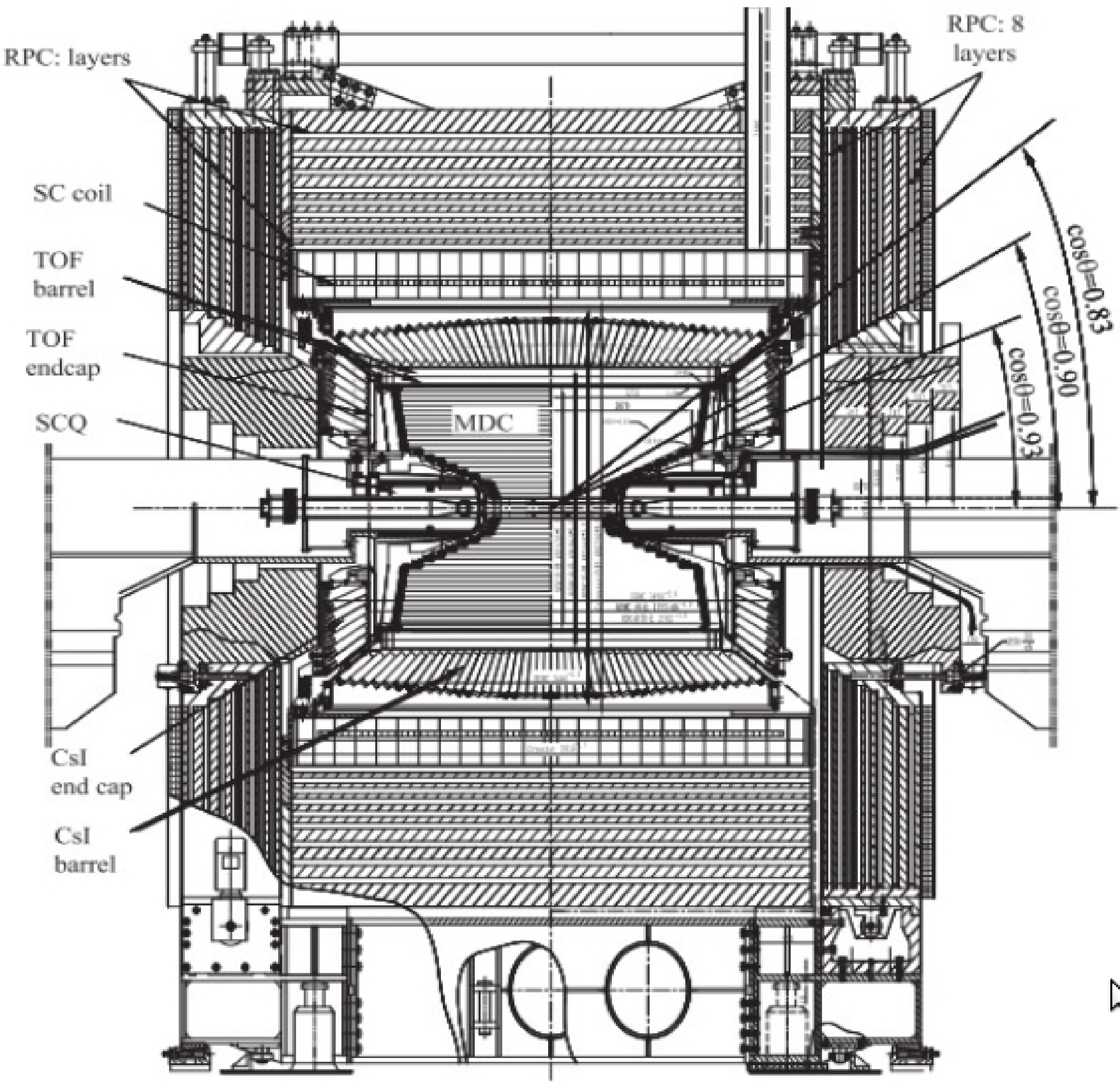


Y(4260) Parameters

	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.

BESIII Experiment at BEPC II (symmetric !)



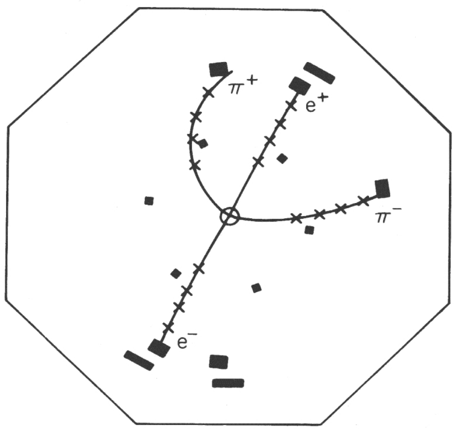
Superconducting solenoid
B=1 T

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

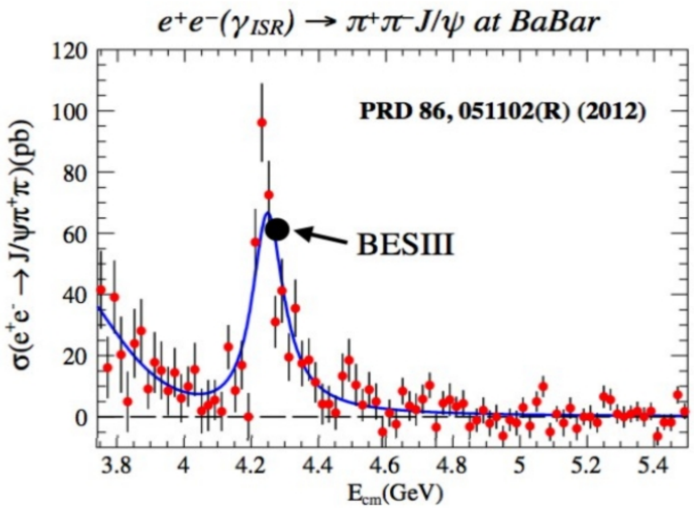
no Cerenkov detector (time-of-flight sufficient for K/π separation, low momentum)

$e^+e^- \rightarrow Y(4260) \rightarrow J/\psi\ \pi^+\ \pi^-$ at BESIII

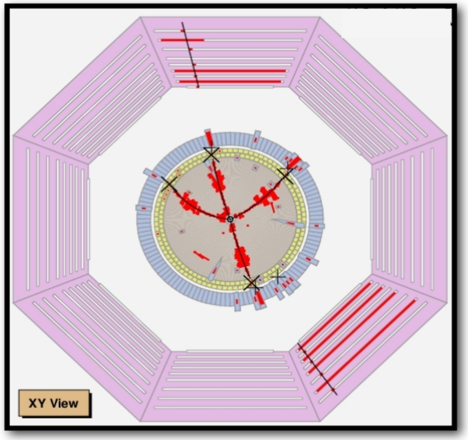
MARK I, 1977
$e^+e^- \rightarrow \psi'$
$\rightarrow J/\psi\ \pi^+\ \pi^-$
$\sqrt{s}$=3868 MeV

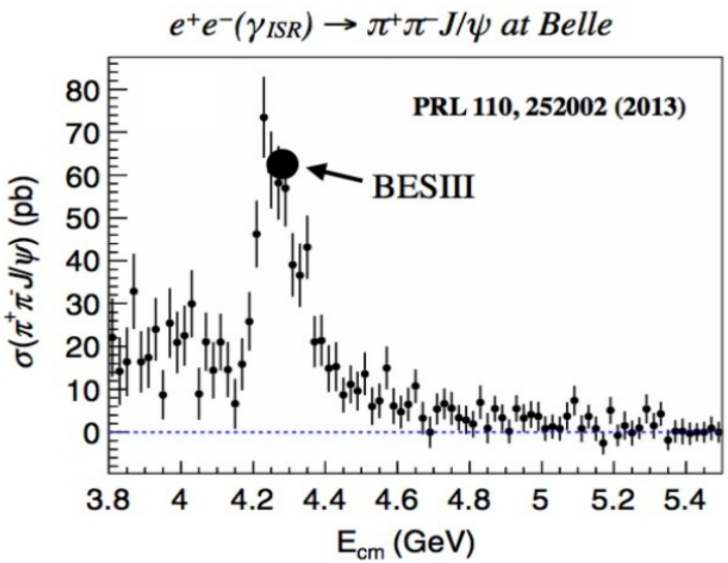


BESIII, PRL110(2013)252001



BESIII, 2013
$e^+e^- \rightarrow Y(4260)$
$\rightarrow J/\psi\ \pi^+\ \pi^-$
$\sqrt{s}$=4260 MeV

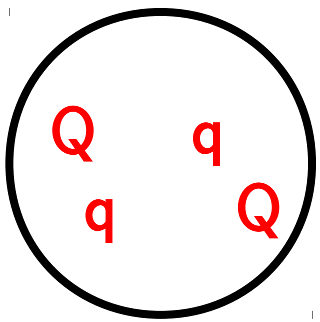




Is the Y(4260) exotic ?

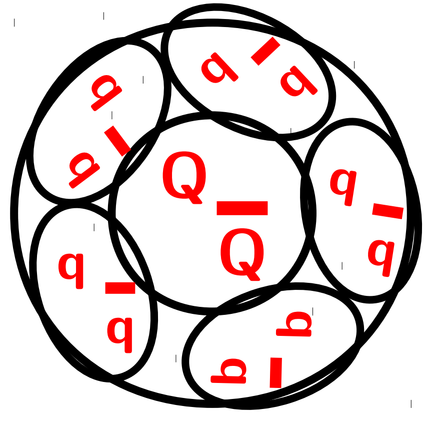
TETRAQUARK

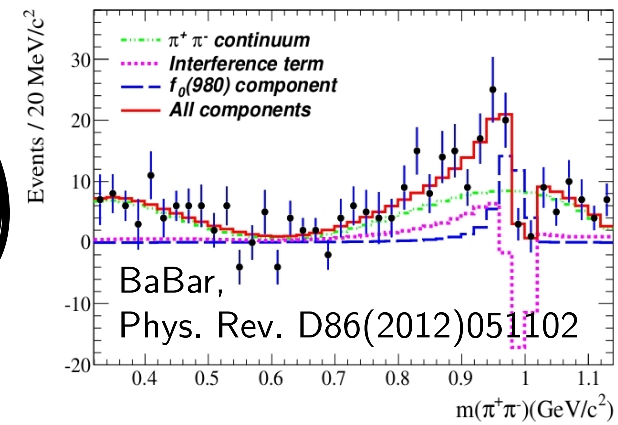
higher excitation ?



Maiani, Riquer, Piccinini, Polosa, Burns

HADRO-CHARMONIUM $[J/\psi\ f_0(980)]$

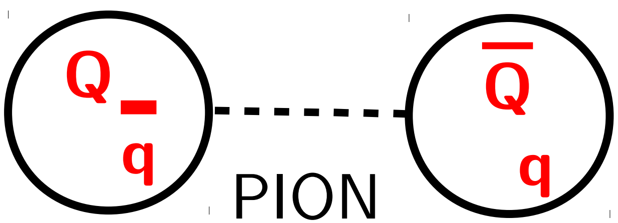




Voloshin, Li
(Guo, Hanhart, Meissner)

MOLECULE

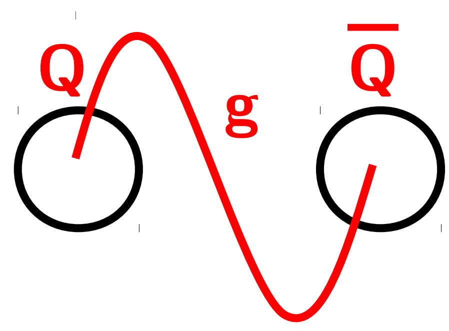
heavier mesons ($\bar{D}D_1(2460)$) ?



[Swanson, Rosner, Close
Guo, Hanhart, Meissner

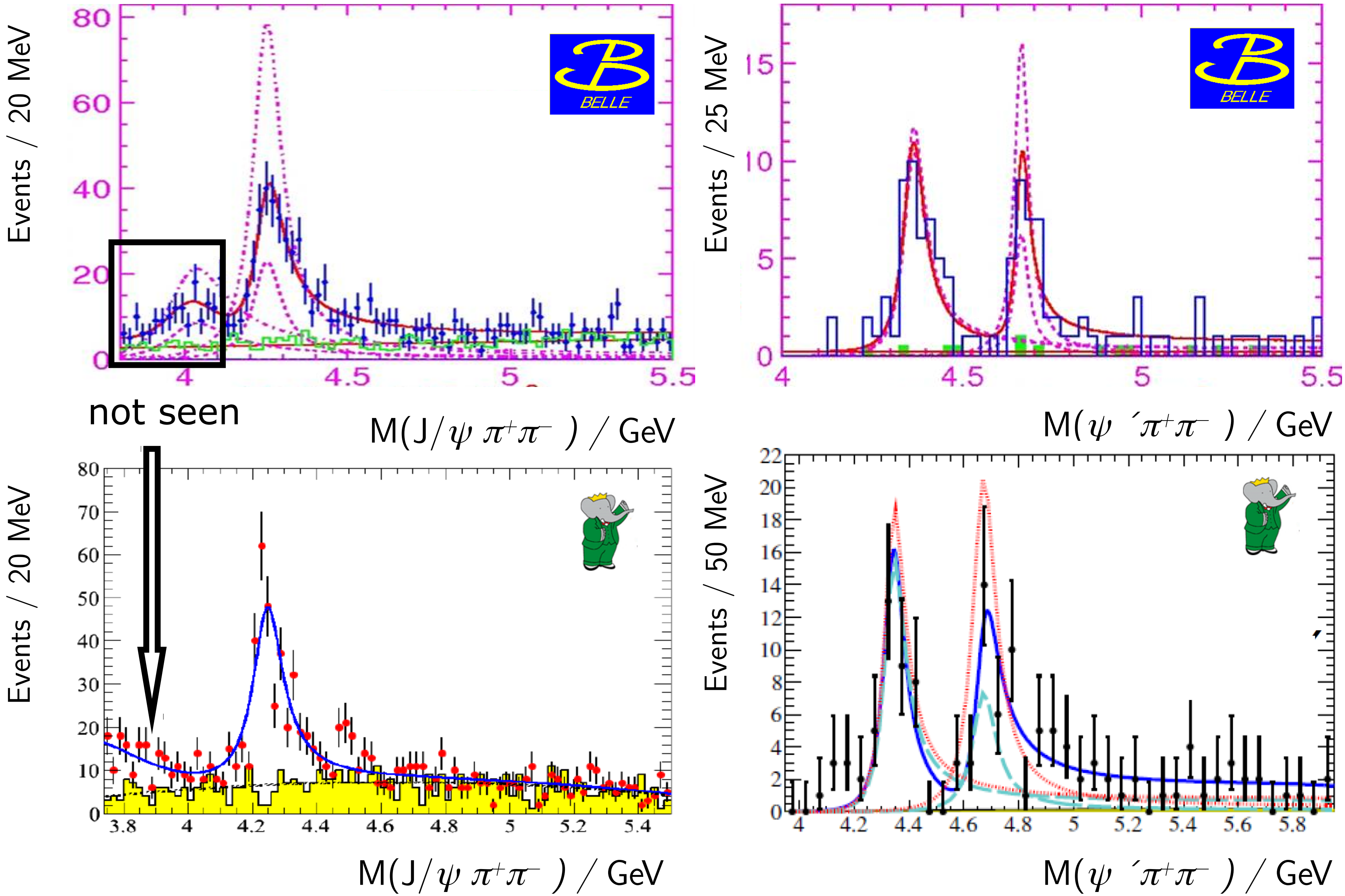
HYBRID

$[Q\bar{Q}]_8 g$



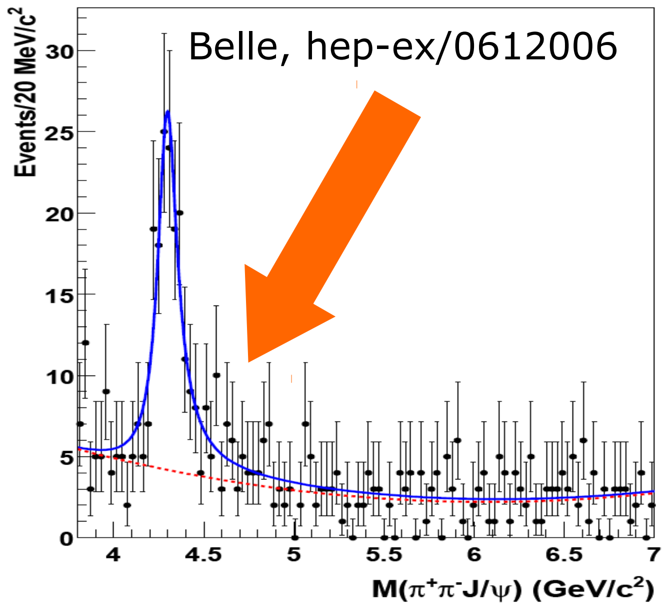
Zhu; Kou, Pene; Close, Page;
Lattice QCD, Bernard et al.; Mei, Luo

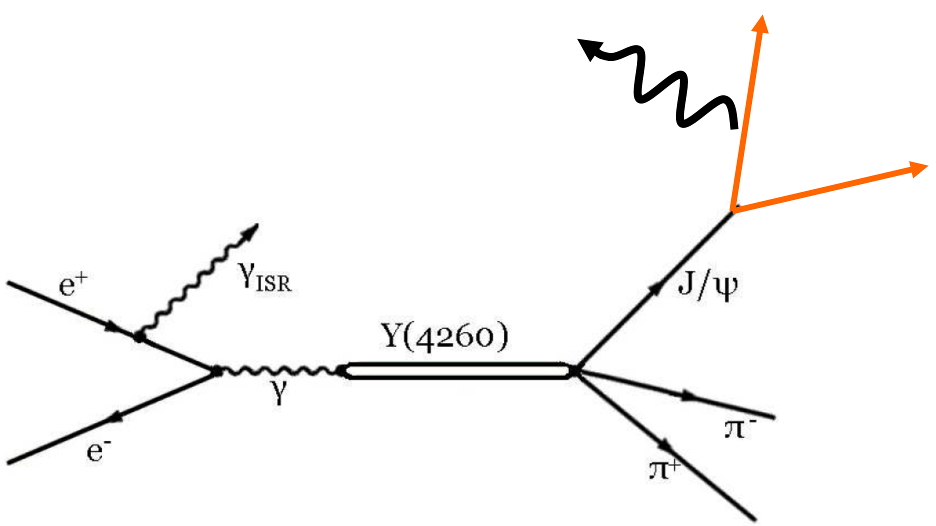
$e^+e^- \to \gamma_{ISR}\, J/\psi\ (\psi')\ \pi^+\pi^-$: Y(4008,4260,4350,4660)



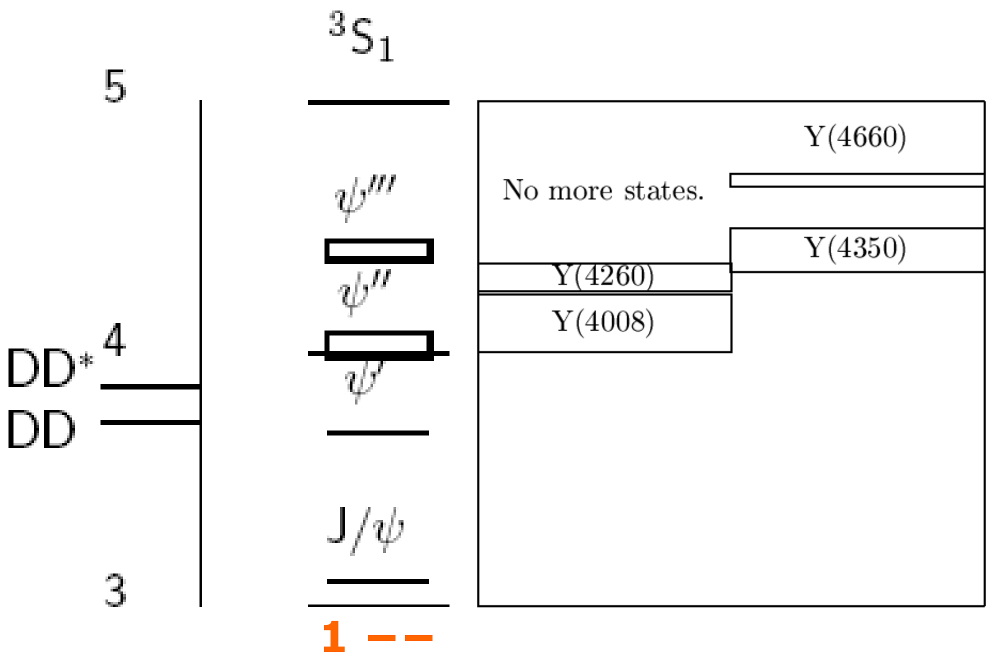
What is the tail around 4.7 GeV?

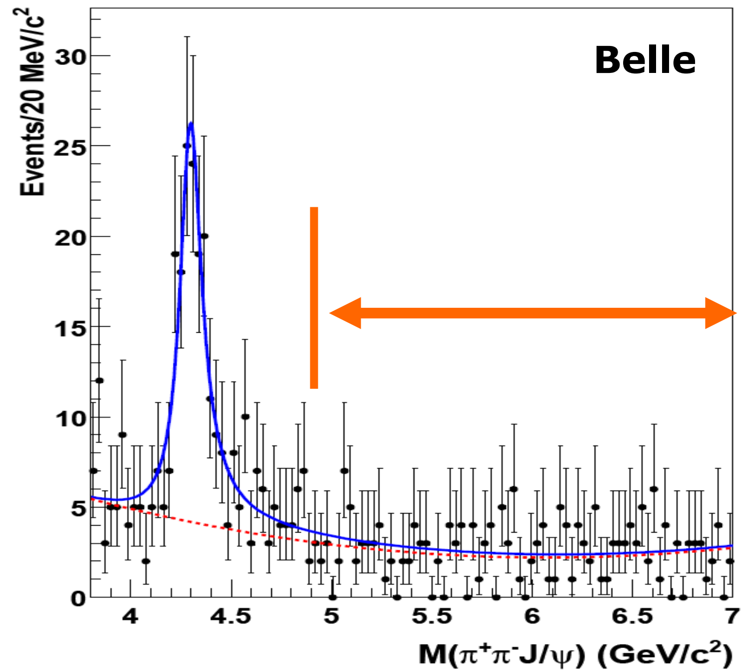
- Threshold m(D)+m(D**) = 4326 MeV
  Lineshape distorted? No.
- Non-corrected radiative effects? No.
  Radiative lower mass tail in $J/\psi \to e^+ e^-$
  might generate higher mass tail in m(J/ψ-with-wrong-mass $\pi^+\pi^-$).
- Fit funtion: Breit Wigner x Phasespace x Efficiency
  Efficiency $a(m-m_0)+b$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





Overpopulation of 1^{--} States





No more [$J/\psi\ \pi^+\ \pi^-$] state up to 7 GeV

All same quantum number

but apparently

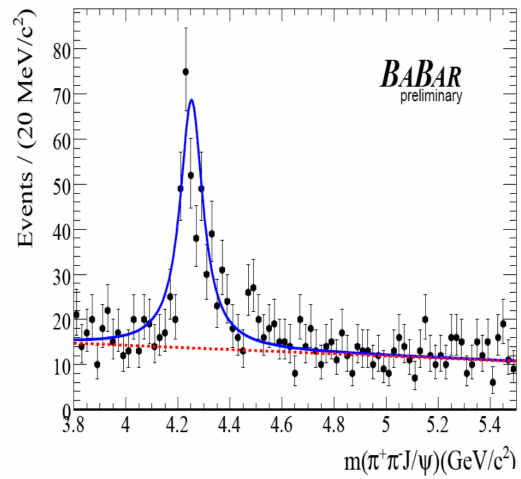
- no mixing with other ψ states
- no mixing among them
  Y(4260) seems not decay to $\psi'\ \pi^+\ \pi^-$
  Y(4350) seems not decay to $J/\psi\ \pi^+\ \pi^-$

Note: radiative transitions between the states forbidden by parity

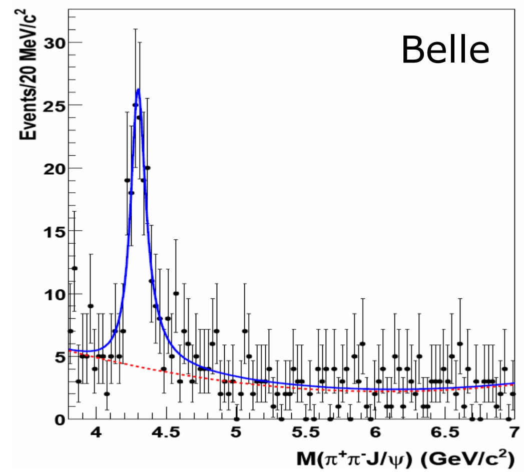
Y(4260): Comparison Belle and BaBar

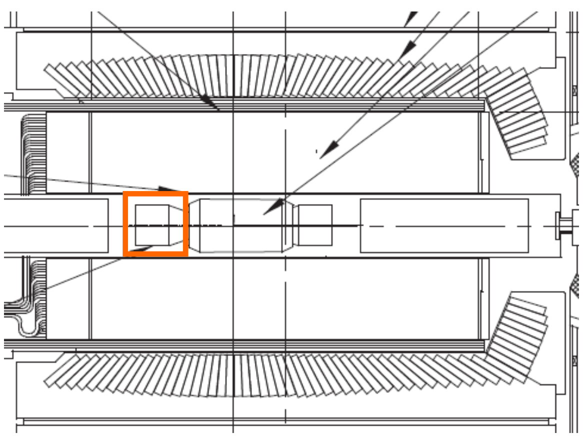
- BaBar collisions head-on, dipole magnet close to IR
- Belle: ±11 mrad
- slightly higher background at BaBar (also seen as MRad SVD radiation dose)
- backward acceptance for $\theta \sim 180^\circ$ limited

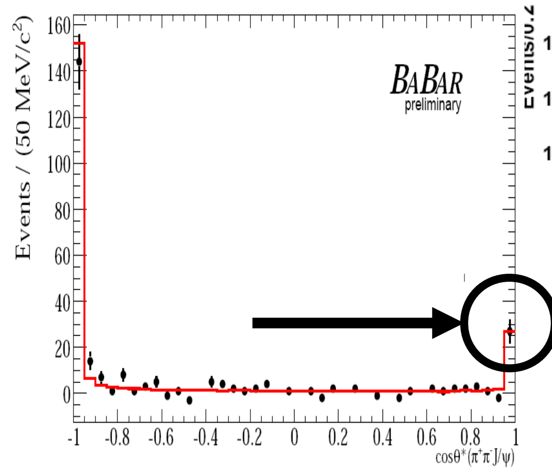
arXiv:0808.1543, 454/fb

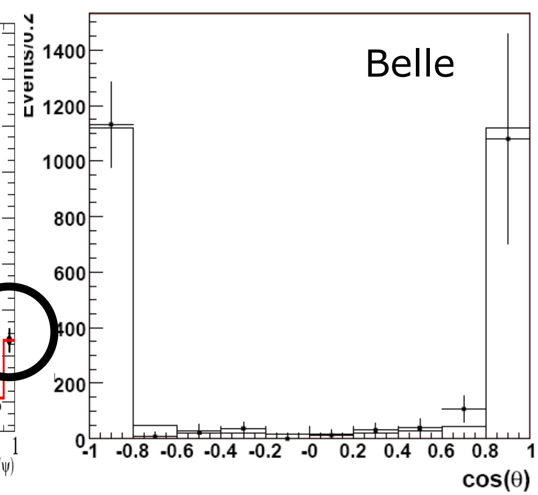


hep-ex/0612006, 553/fb









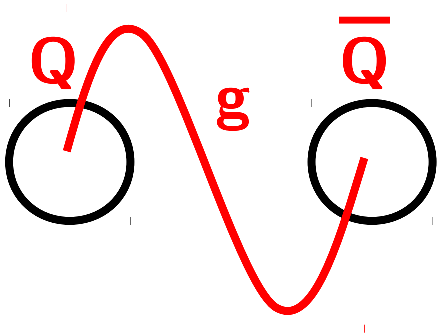
CMS polar angle of Y(4260) to e− beam

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 Γ(e^+ e^-) =
  (7.5±0.9±0.8) eV
  BaBar, arXiv:0808.1543

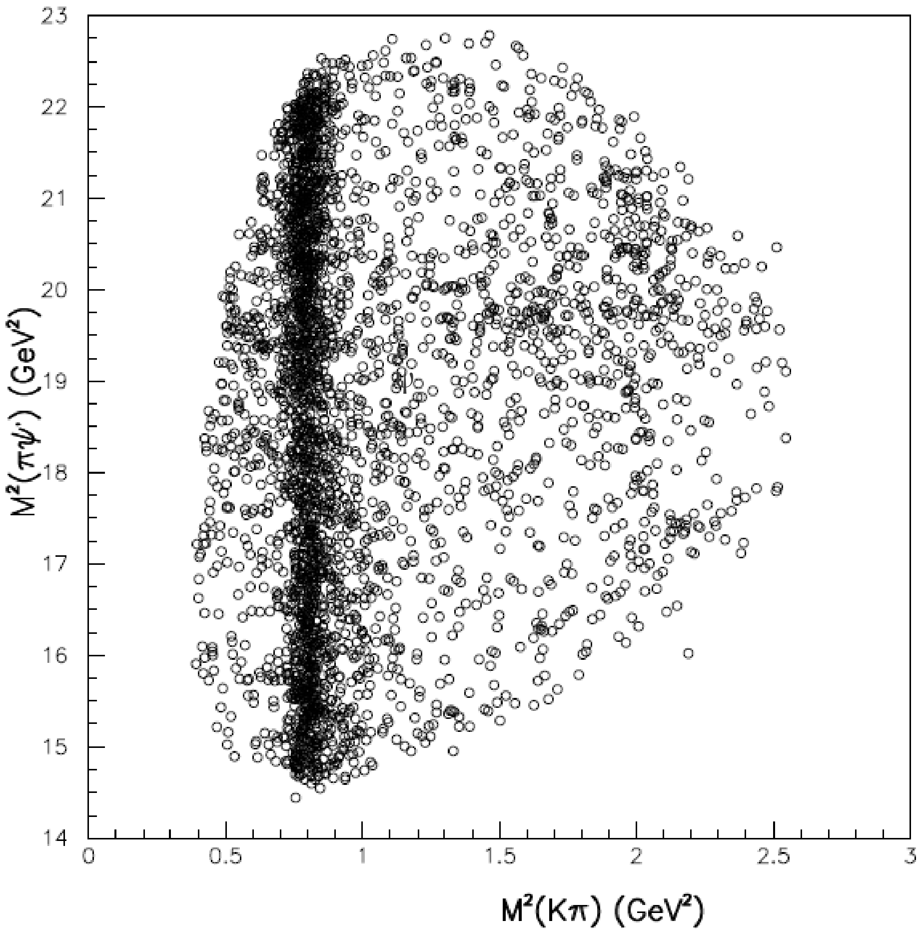


- This is a partial width of the order „eV“
  of a state which is ~100 MeV total width !
  $\rightarrow$ factor 10^8 suppressed

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

$Z(4430)^+$

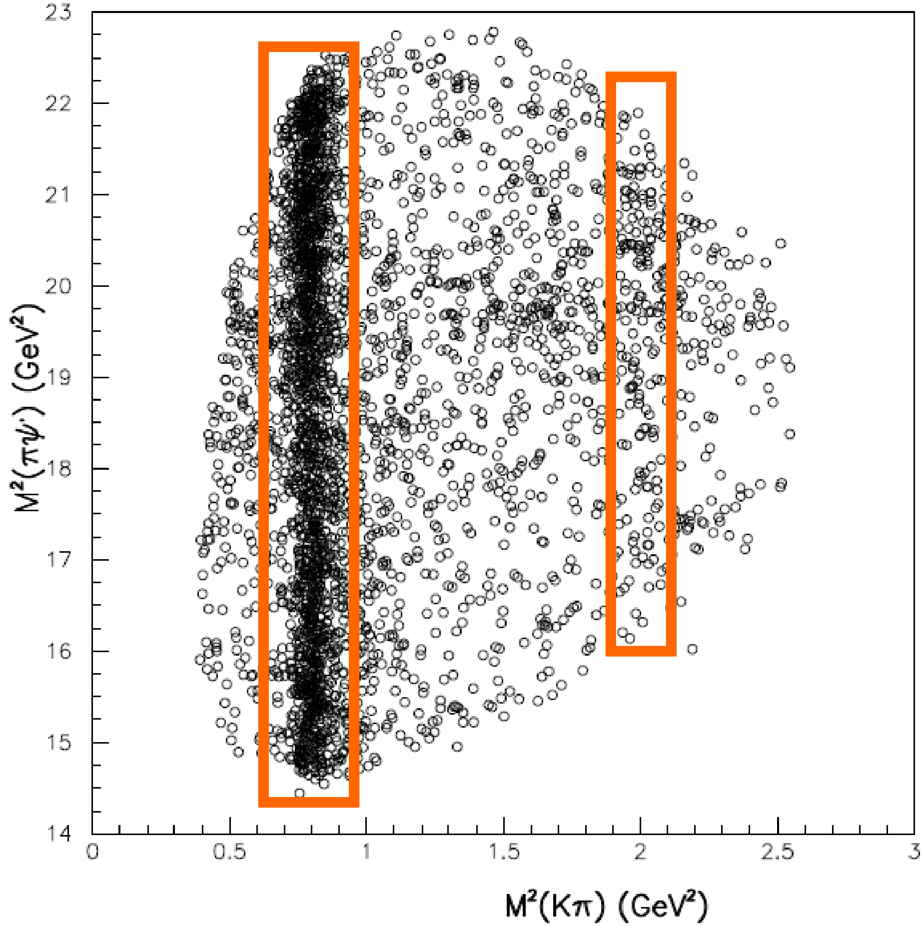
$B^0 \rightarrow K^+ \psi' \pi^-$
$\psi' \rightarrow J/\psi \; \pi^+ \pi^-$



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

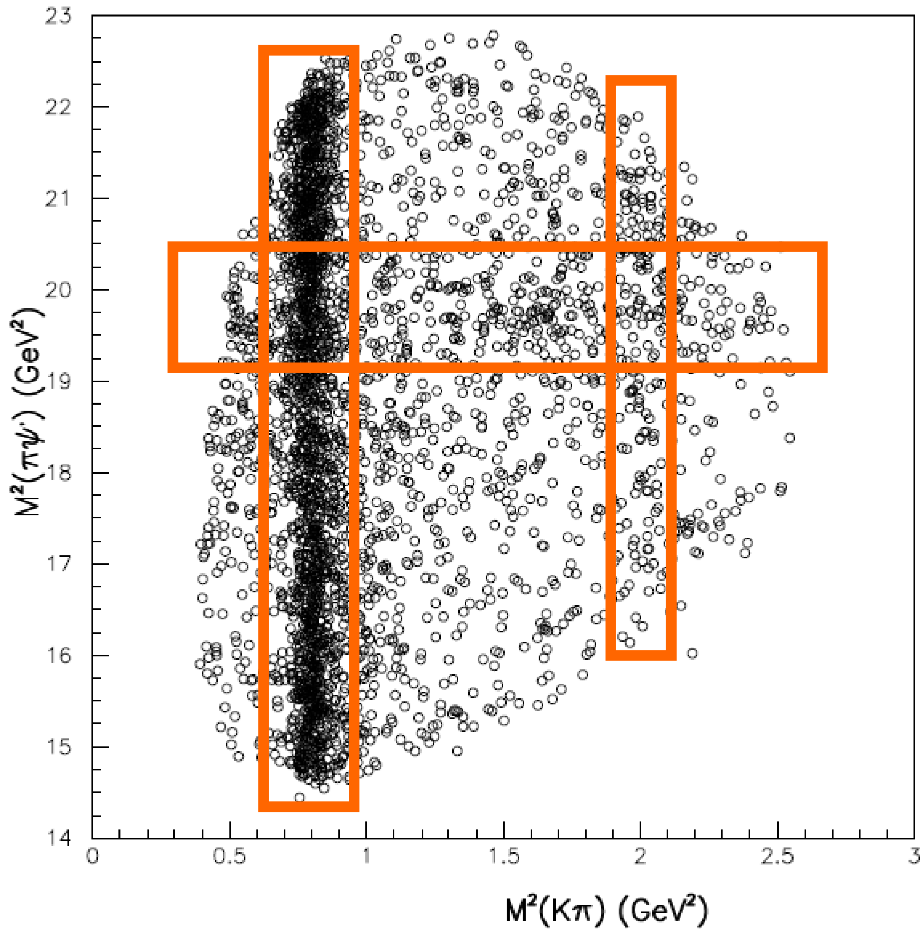
$\psi' \rightarrow J/\psi \; \pi^+ \pi^-$

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



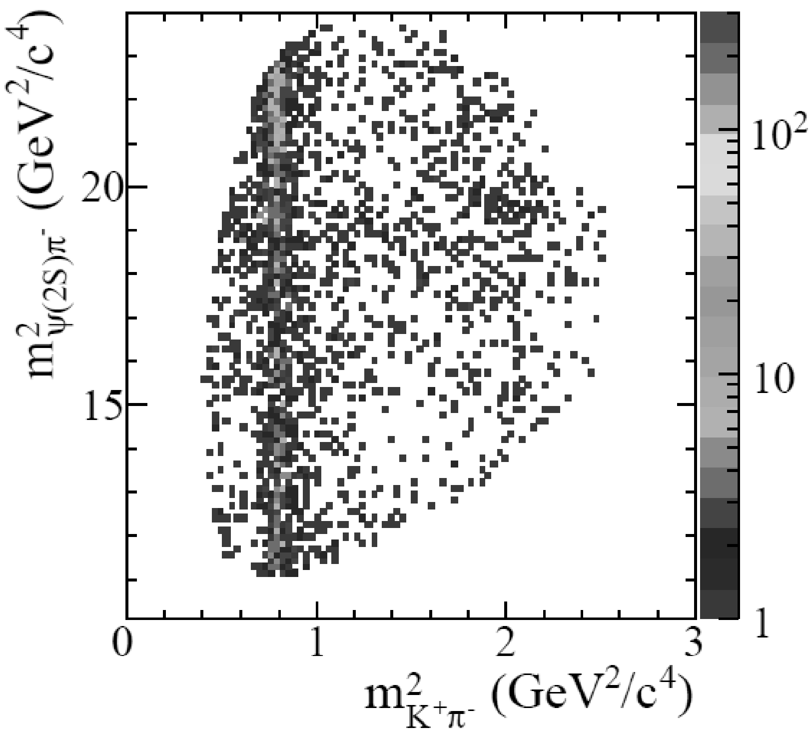
$B^0 \rightarrow K^+ \psi' \pi^-$
$\psi' \rightarrow J/\psi\ \pi^+ \pi^-$

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

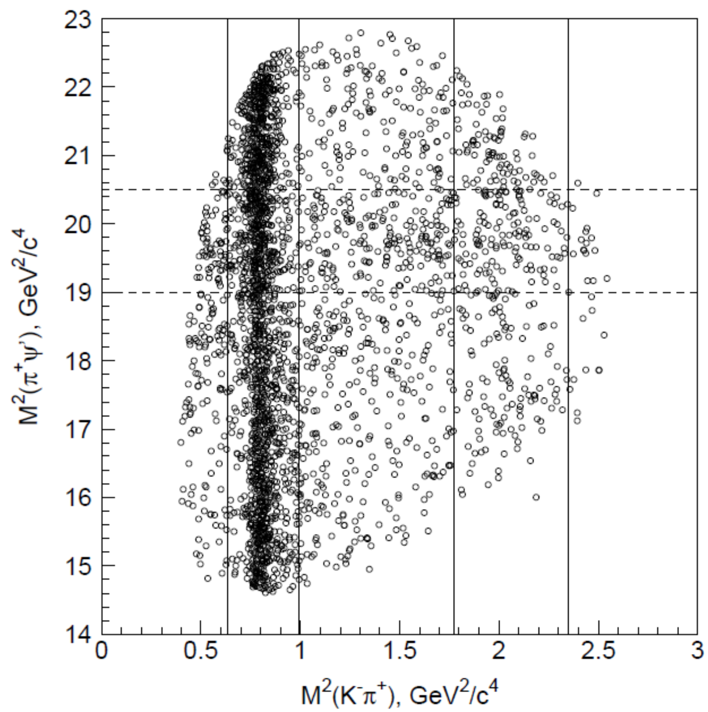


A charged state can never be a charmonium state.

Z(4430)$^+$



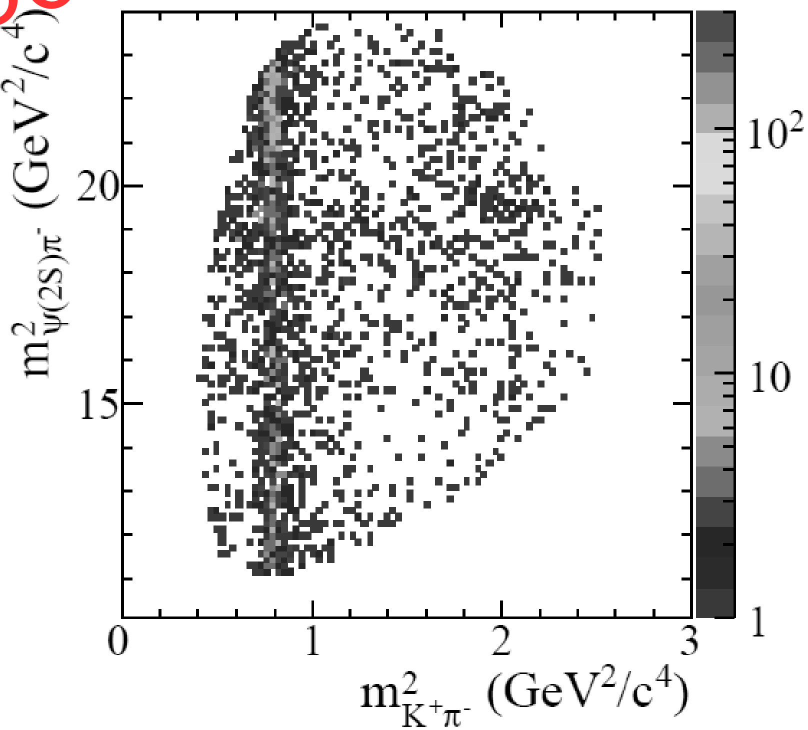
BaBar
Phys. Rev. D79(2008)112001
413/fb



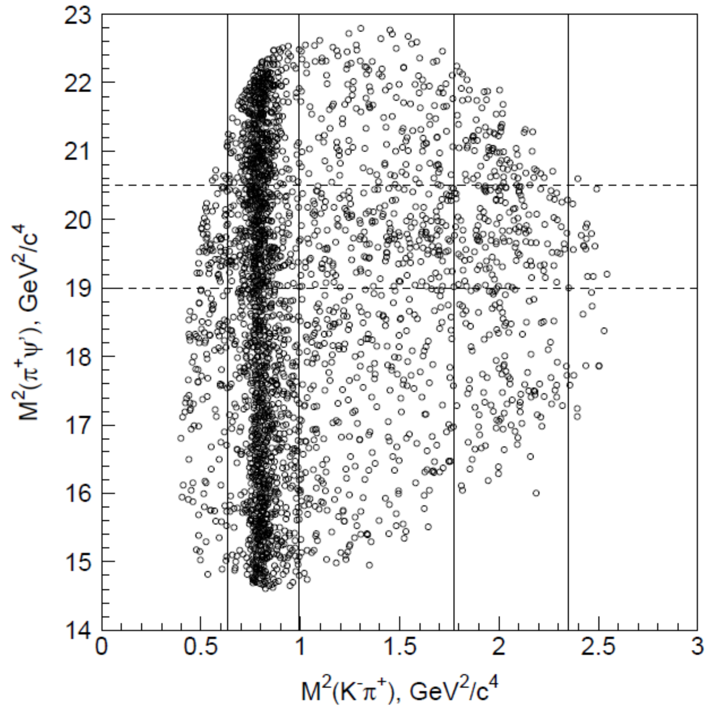
Belle
Phys. Rev. D80(2009)031104
605/fb

Look closer!

Z(4430)$^+$

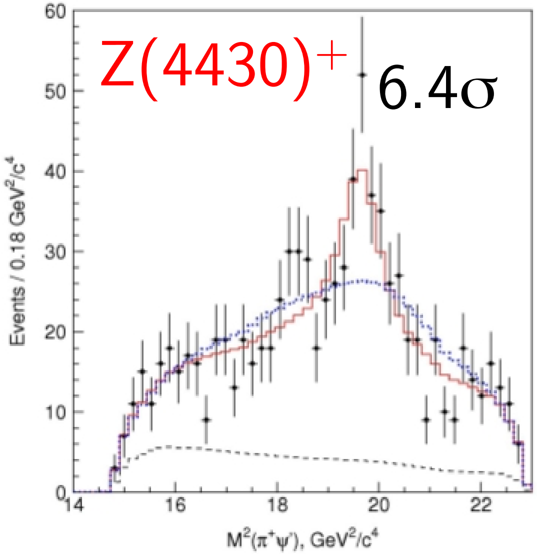


BaBar
Phys. Rev. D79(2008)112001
413/fb



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

Can you see something maybe wrong?

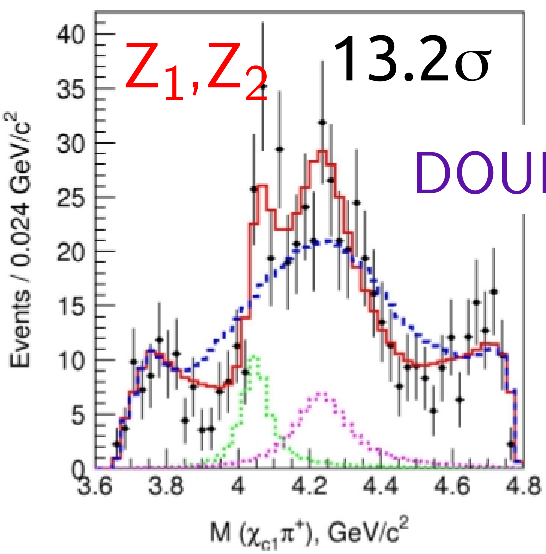


$$B^0 \to K^\pm \underbrace{\psi' \pi^\mp}_{\text{resonant state?}}$$

not confirmed by BaBar

$$m = 4433 \pm 4 \pm 2 \text{ MeV}, \; \Gamma = 45^{+18+30}_{-13-13} \text{ MeV}$$

Belle, Phys. Rev D80(2009)031104



DOUBLET

$$B^0 \to K^\pm \underbrace{\chi_{c1} \pi^\mp}_{\text{resonant state?}}$$

not confirmed by BaBar

$$m(\mathrm{Z}_1) = 4051 \pm 14^{+20}_{-41} \text{ MeV}, \; \Gamma(\mathrm{Z}_1) = 82^{+21+47}_{-17-22} \text{ MeV}$$

$$m(\mathrm{Z}_2) = 4248^{+44+180}_{-29-35} \text{ MeV}, \; \Gamma(\mathrm{Z}_2) = 177^{+54+316}_{-39-61} \text{ MeV}$$

Belle, Phys. Rev D78(2008)072004

Long discussion between Belle and BaBar (2007–2014)

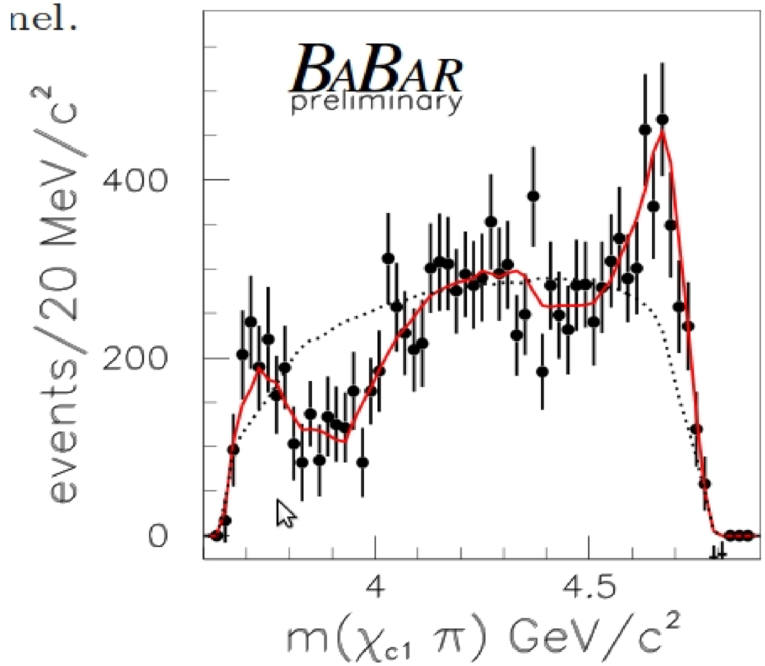
Is the Z+(4430) a kinematical effect ?

- $\cos\theta_K$, 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 !



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