XYZ States and Confinement

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Outline

- QCD color confinement

  Focus: long–range, linear potential

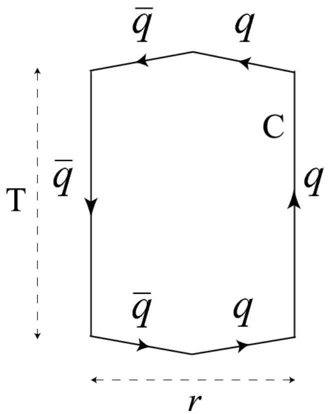
- Test of confinement with (conventional) charmonium

- Exotic states

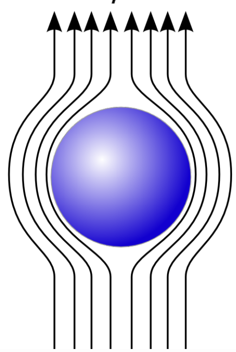
  - X(3872)
  - Y(4260)
  - Z(3900)

- Belle II experiment

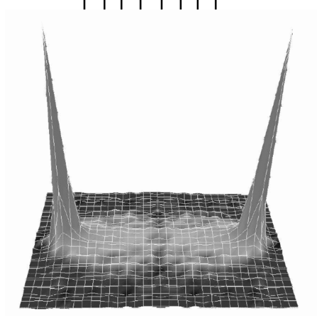
QCD color confinement (simplified view)



Wilson 1974
loop (e.g. qq pair, propagating in time)
energy cost ~ area ~ linear in r
see also talk by Daniel Mohler (Monday)
Kondo, arXiv:1412.8008 [hep-th]



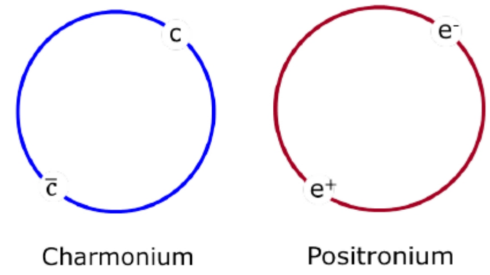
Analogy: Meissner effect in
type II superconductor (B field very strong)
→ B field lines are expelled, form „flux tubes“
QCD: duality (Nambu 1974), B → E
chromo-electric field lines



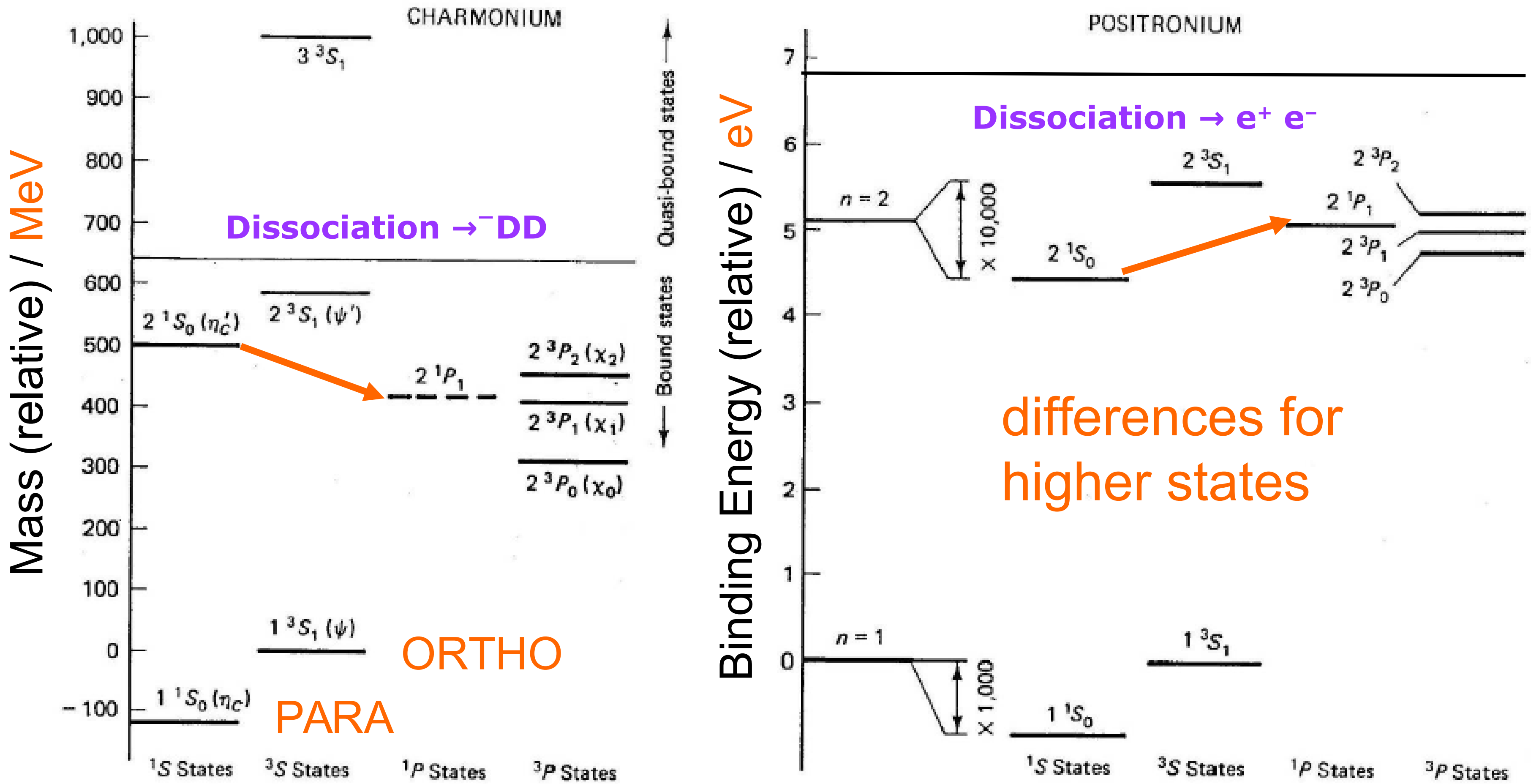
Lattice QCD (quenched):
Flux tube breaks at r≥1.0–1.5 fm
Bali, hep-lat/9409005

Dynamical origin, quark–„cloud“ feedback–loop (Gribov, Dyson-Schwinger)
Non–perturbative

Charmonium vs. Positronium



Decays to light quarks suppressed
→ narrow widths



Cornell–Potential

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

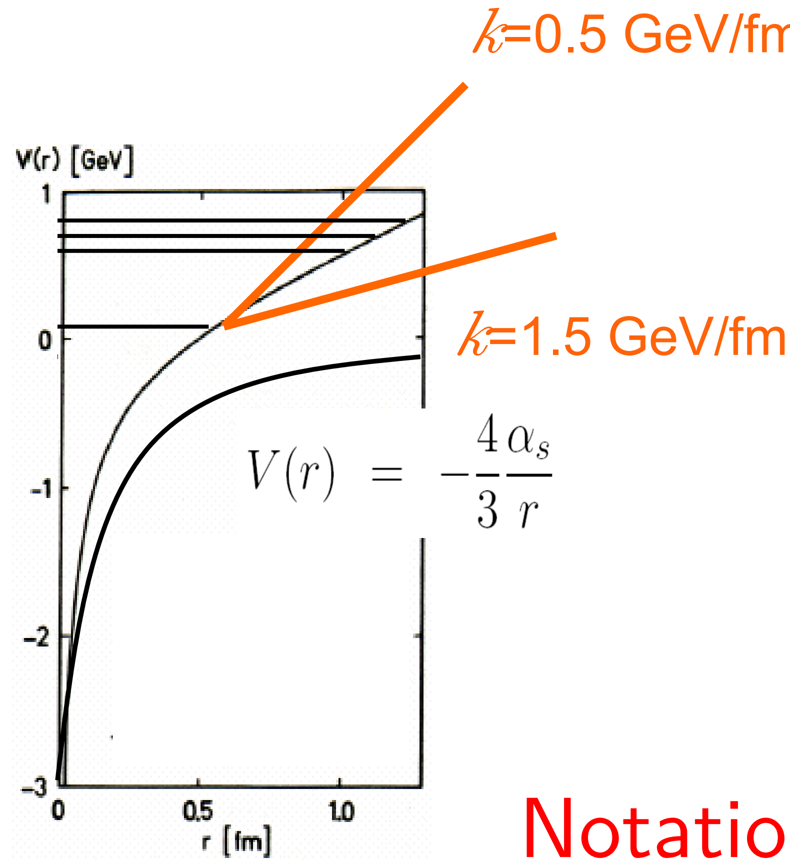
- Coulomb-Potential
  + Confinement-Term

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

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

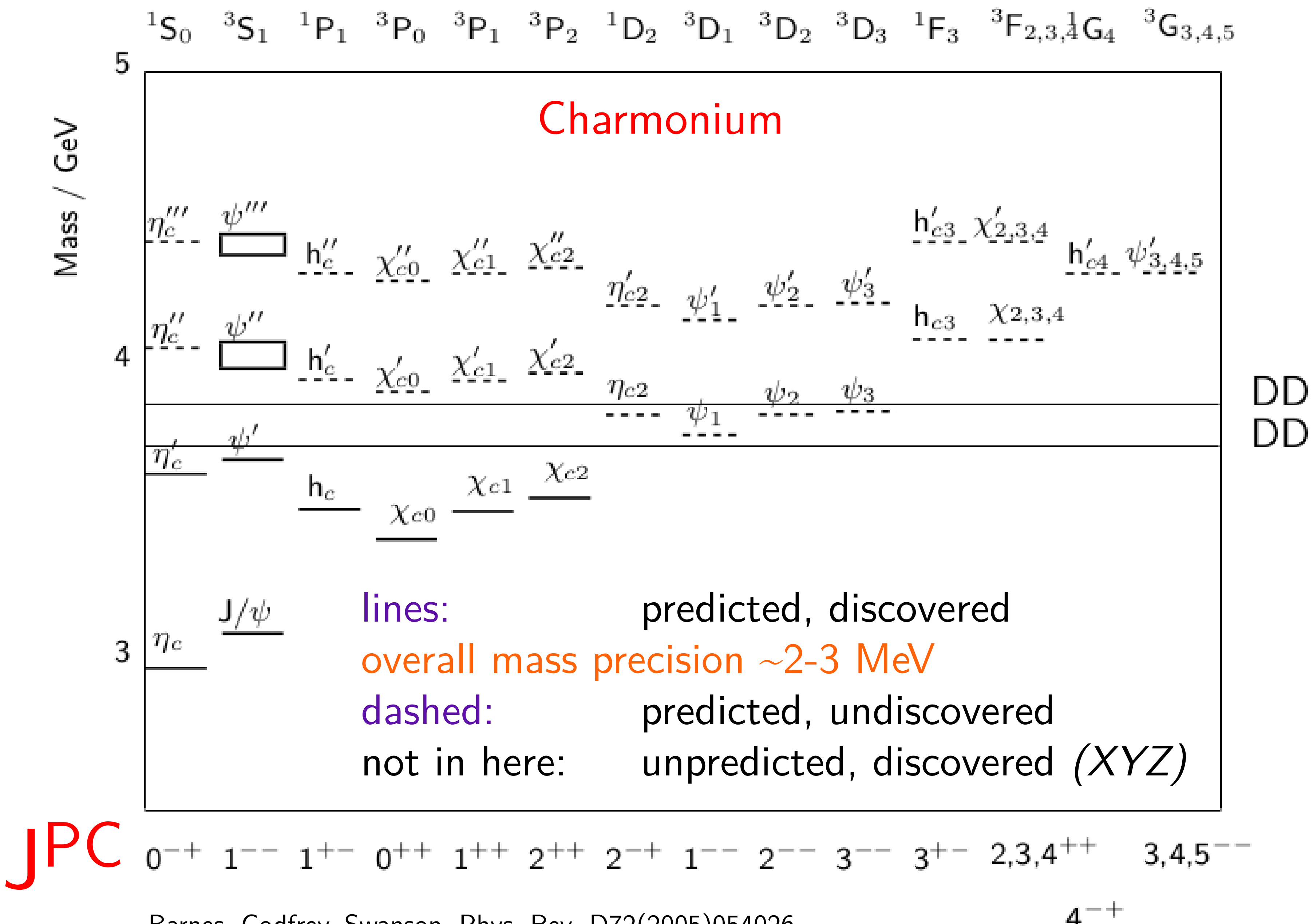


- solve Schrödinger equation
  (quark mass heavy →\on-relativistic)
  →states

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

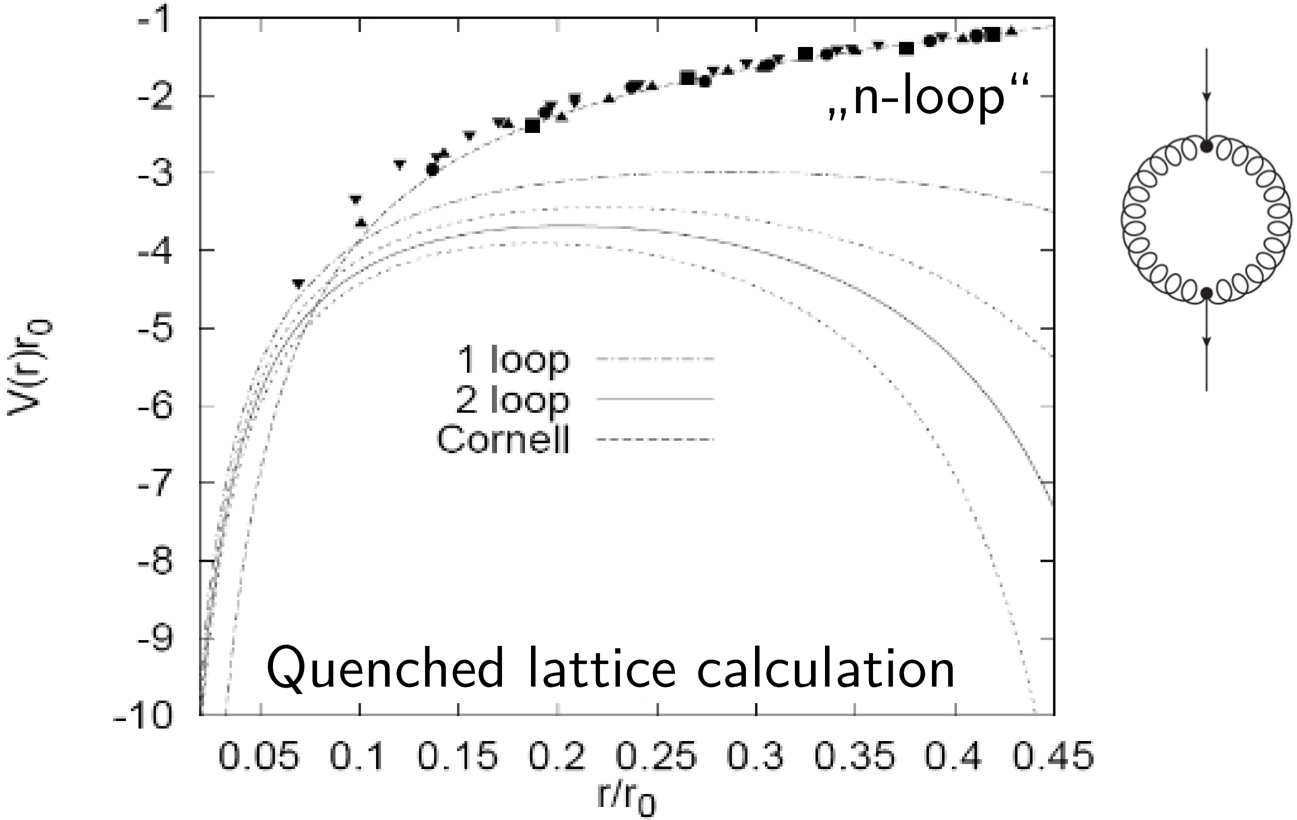
$$\left[-\frac{1}{m_q}\left(\frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r} + \frac{l(l+1)}{m_q r^2} + V(r)\right)\right]R_{nl}(r) = E_{nl}R_{nl}(r)$$

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



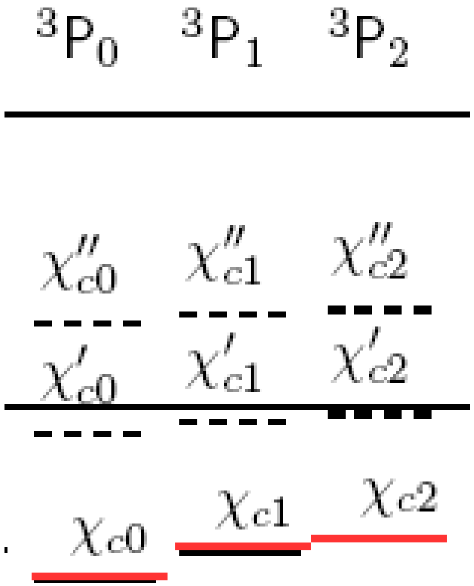
Barnes, Godfrey, Swanson, Phys. Rev. D72(2005)054026

Why is the confinement term linear ?
→ Consequence of higher order



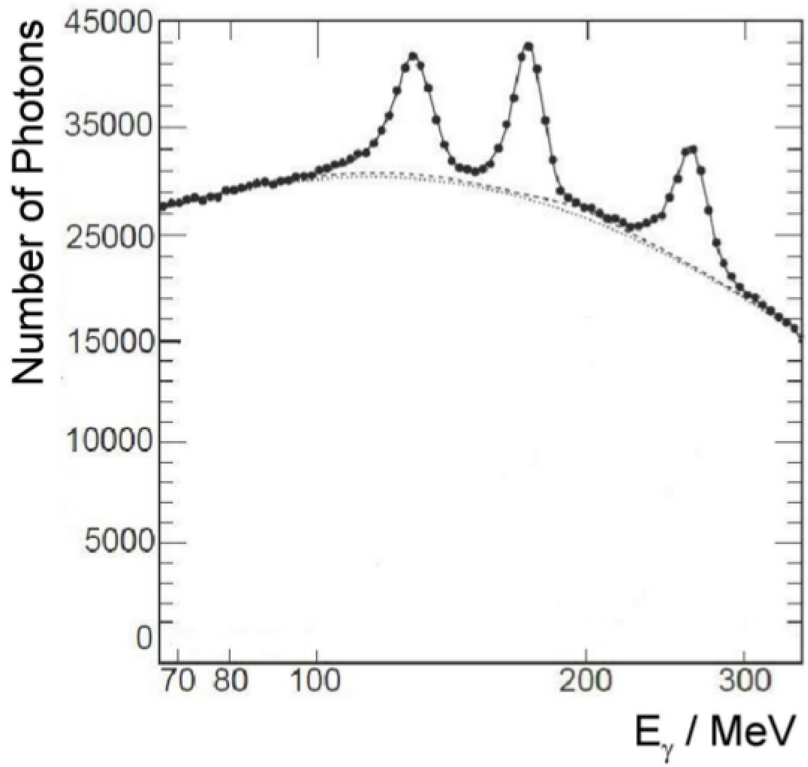
G. S. Bali, Phys. Lett. B460(1999)170
G. S. Bali, Eur. Phys. J. A19(2004)1

Test of confinement with χ_{cJ} states

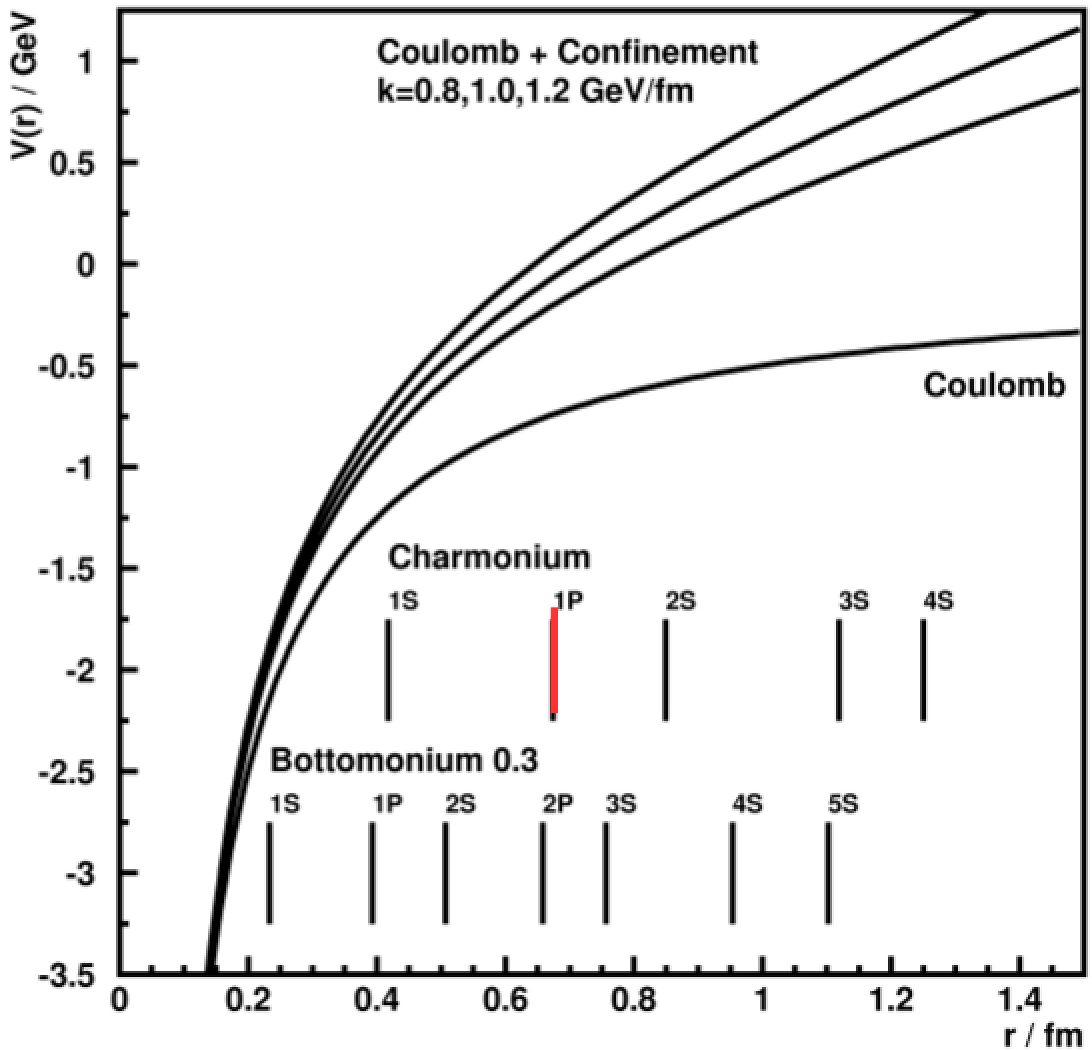


J^{PC}=$(0,1,2)^{++}$

CLEOIII, Phys. Rev. D70(2004)112002



$$R = \frac{m(^3P_2) - m(^3P_1)}{m(^3P_1) - m(^3P_0)}$$


Coulomb + Confinement
k=0.8,1.0,1.2 GeV/fm
Coulomb
Charmonium
1S
1P
2S
3S
4S
Bottomonium 0.3
1S
1P
2S
2P
3S
4S
5S
V(r) / GeV
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
r / fm

Long-range forces: testing confinement

- Testing mass splitting of P-wave states, $< r > \simeq$0.7 fm
- Lorentz vector
  - addditive to momentum 4-vector
    $p_\mu \rightarrow p_\mu + A_\mu$ (gauge invariance)
  - examples: A_μ in QED, Coulomb potential
  - $R \geq$0.8
- Lorentz scalar
  - not well defined, generallly accepted opinion:
    additive to mass $m(r) = m_0 + V_s(r)$
  - examples: bag-like confinement, linear potential
- Experimental result R=0.48±0.01 $\rightarrow$ scalar (at least partially)

Reminder: Schrödinger Equation

beware: this should be relativistic (as we are probing the behaviour under Lorentz transformation)

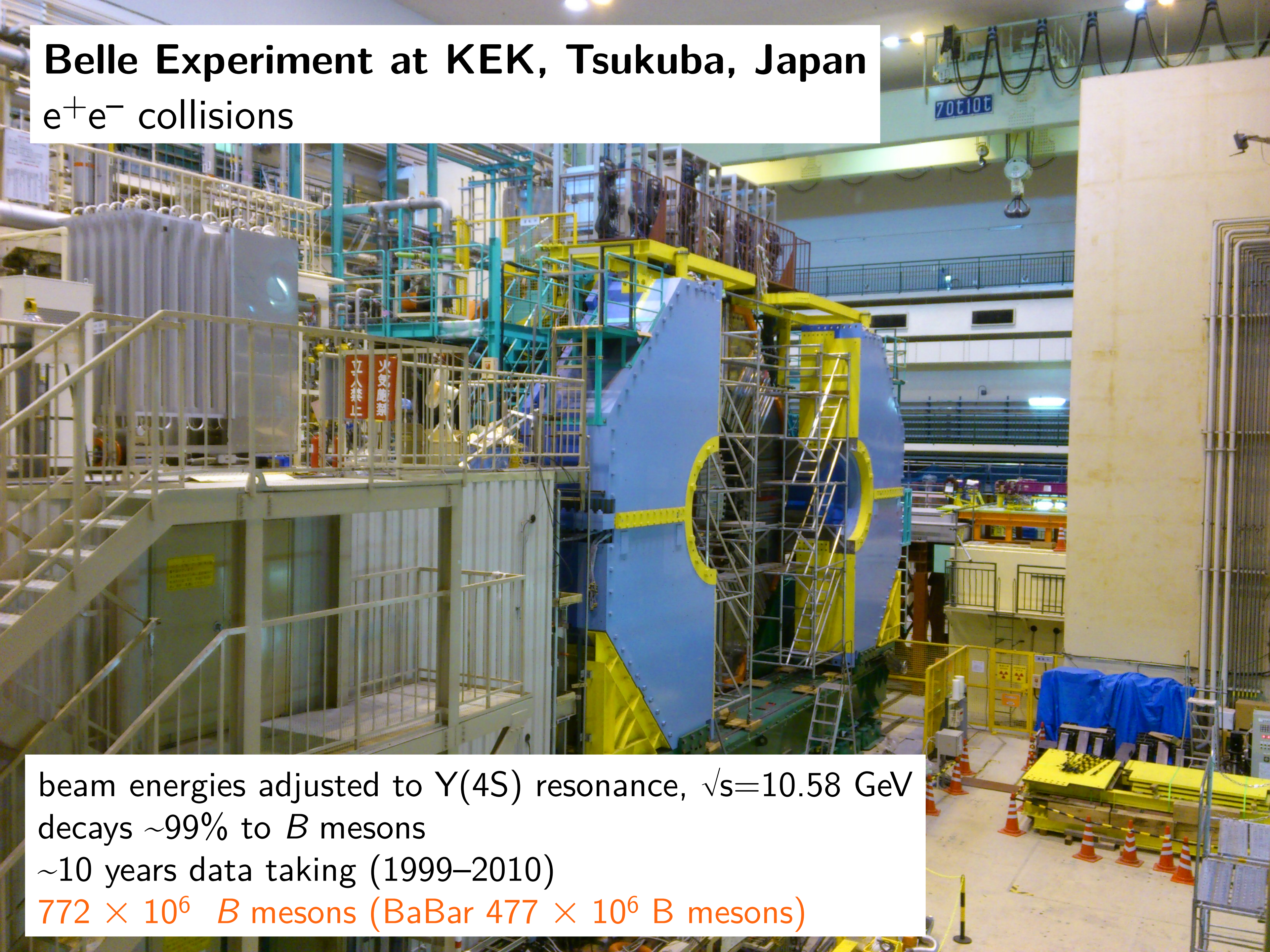
quadratic

$$i\hbar \frac{\partial}{\partial t}\psi(\vec{r},t) = \left[\frac{1}{2m}\left(\frac{\hbar}{i}\nabla - \frac{q}{c}\vec{A}(\vec{r},t)\right)^2 + qV(\vec{r},t)\right]\psi(\vec{r},t)$$

vector potential　　scalar potential

Belle Experiment at KEK, Tsukuba, Japan

e^+e^- collisions



beam energies adjusted to $\Upsilon(4S)$ resonance, $\sqrt{s}$=10.58 GeV

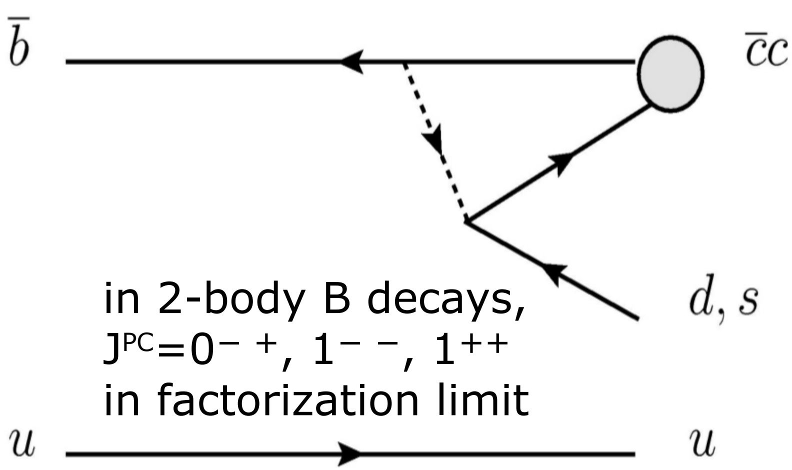
decays ~99% to B mesons

~10 years data taking (1999–2010)

772×10^6 B mesons (BaBar 477×10^6 B mesons)

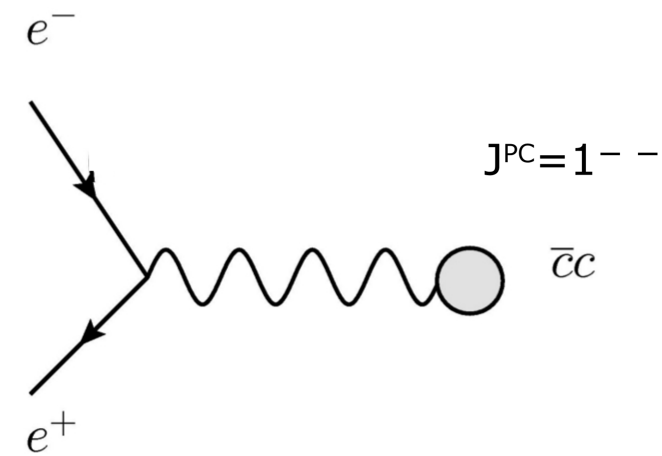
Charmonium Production

B Meson Decays

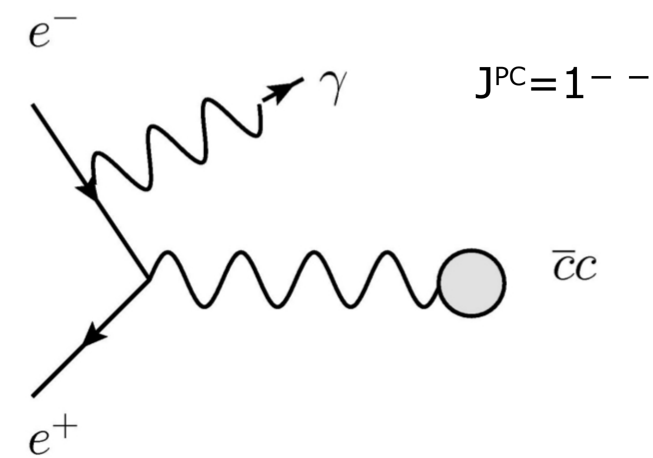


in 2-body B decays,
$J^{PC}=0^{-+}, 1^{--}, 1^{++}$
in factorization limit

Direct Production



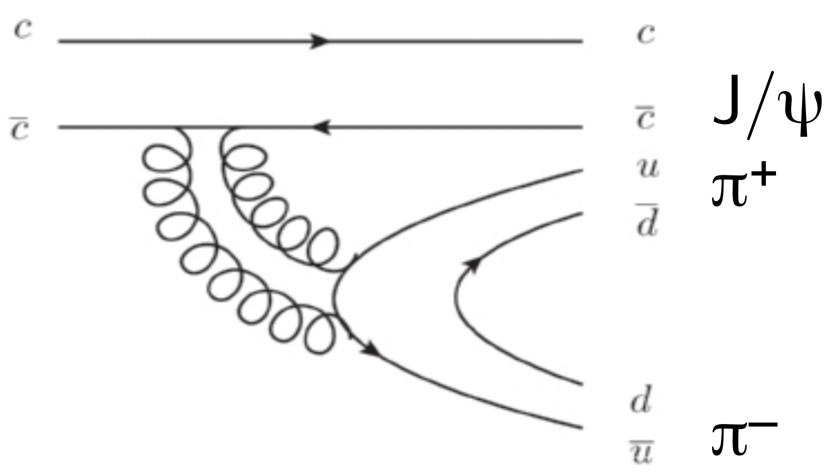
Initial State Radiation



Not discussed today:
production in e^+e^- continuum
see talk of Elisabetta Prencipe (Tuesday)

X

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

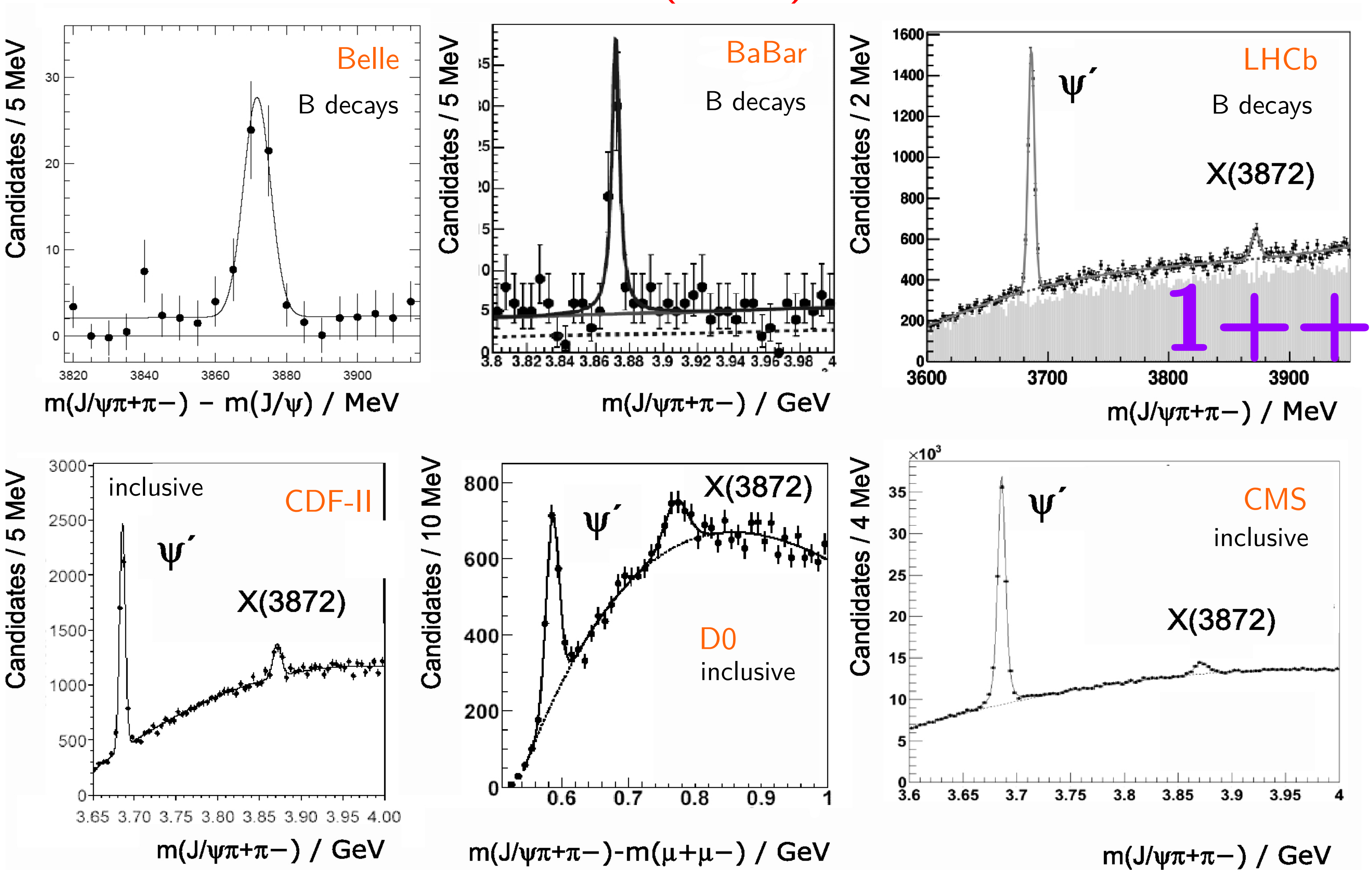


Product branching fraction small

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

requires a *B* meson factory

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)
1++
Candidates / 2 MeV
m(J/ψπ+π−) / MeV
inclusive
CDF-II
ψ´
X(3872)
Candidates / 5 MeV
m(J/ψπ+π−) / GeV
ψ´
X(3872)
D0
inclusive
Candidates / 10 MeV
m(J/ψπ+π−)-m(μ+μ−) / GeV
ψ´
CMS
inclusive
X(3872)
Candidates / 4 MeV
m(J/ψπ+π−) / GeV

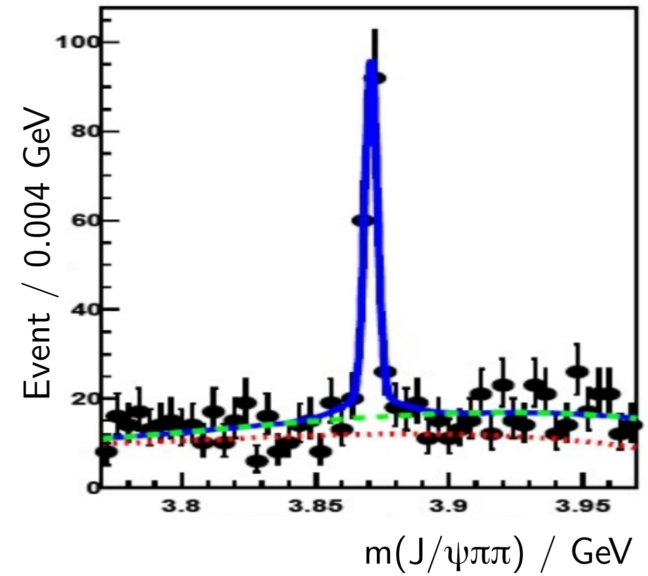
X(3872)

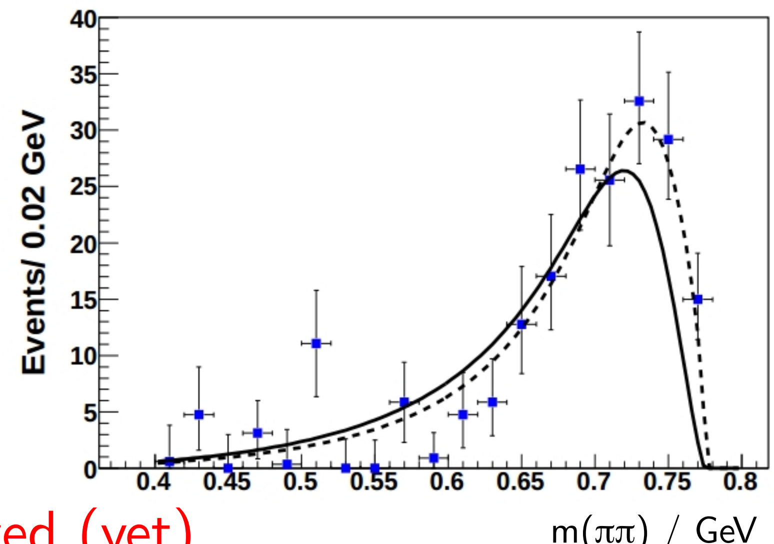
- at $D\bar{D}^*$ threshold
  $E_B = 160 \pm 330$ keV
  but no threshold effect
  $\Gamma \leq 1.2$ MeV $\rightarrow$ too narrow ($\sim$10 MeV)
  Bugg, J. Phys. G35(2008)075005
- but $D\bar{D}^*$ decays dominant
  (factor $\sim$10 larger than other decays)
  $\rightarrow$ molecule ?
- violates isospin
  $\mathcal{B}(X(3872) \rightarrow J/\psi\rho)$
  factor $\sim 10^2$ too large
- $J^{PC} = 1^{++}$, predicted nearby χ_{c1}'
  Barnes et al., Phys. Rev. D72(2005)054026
  $\rightarrow$ mass $\geq$50 MeV higher
  $\rightarrow$ width factor $\geq$100 larger

recent hot topic: no admixture observed (yet)

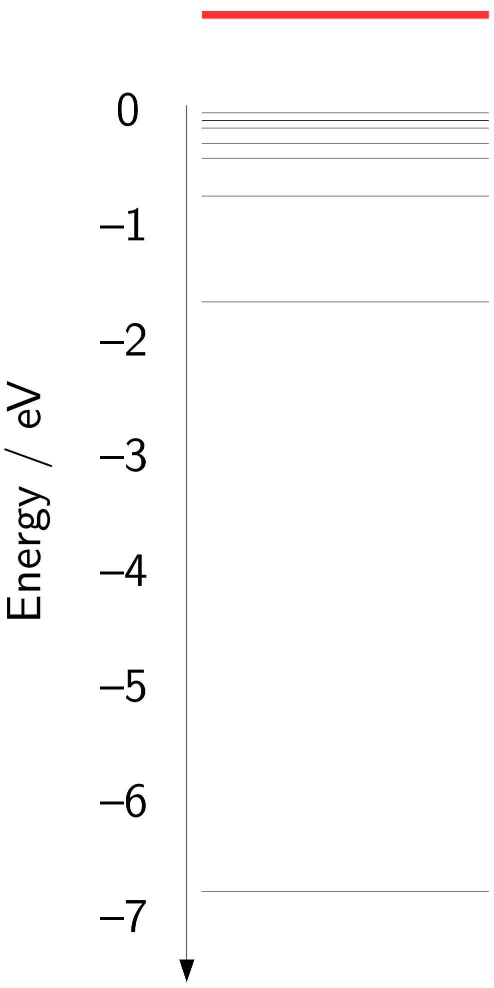
$\sim$150 events in 10 years

Belle, Phys Rev D84(2011)052004



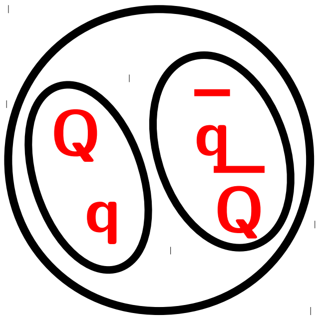


X(3872), analogy in atomic physics (positronium)
narrow state (<0.001 eV) in the continuum
~1 eV above the dissociation energy (~7 eV)
decay blocked by quantum numbers



Is the X(3872) exotic ?

TETRAQUARK



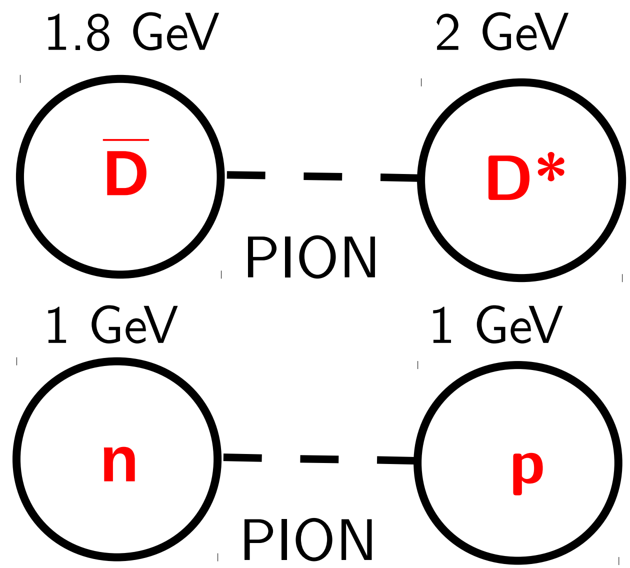
$[qQ]_8[\overline{qQ}]_8$

Diquarks
are colored

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

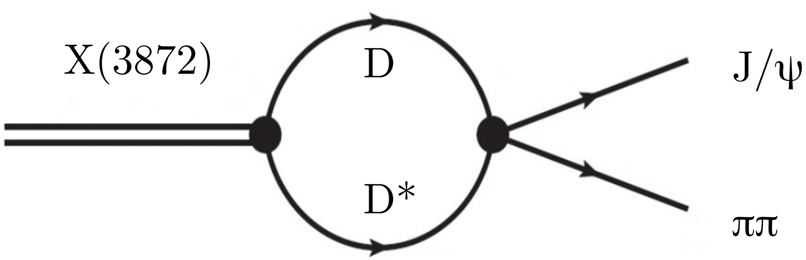
MOLECULE

Intriguing Analogon



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

THRESHOLD CUSP



Bugg; Swanson

For an S-wave near-threshold resonance with an assumed positive scattering length, E_b is inversely proportional to the squared scattering length a according

$$E_b = \hbar^2 / 2\mu a^2$$

$$<r> = a / \sqrt{2}$$

$$<r> \geq 31.7^{+\infty}_{-24.5} \text{ fm}$$

E_b=0.010.18 MeV (PDG)

At these distances, QCD confinement is not possible (QCD string breaks at r=1.0–1.5 fm)

Braaten, Kusunoki, 2004
Braaten, Lu, 2007, 2008

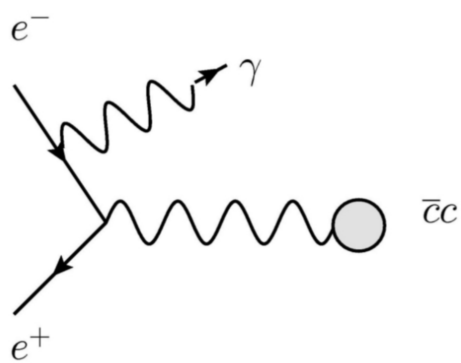
Y

Y(4260)

- Initial state radiation events

$$e^+e^- \to \gamma_{ISR} \underbrace{J/\psi\pi^+\pi^-}_{\text{resonant state?}}$$

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

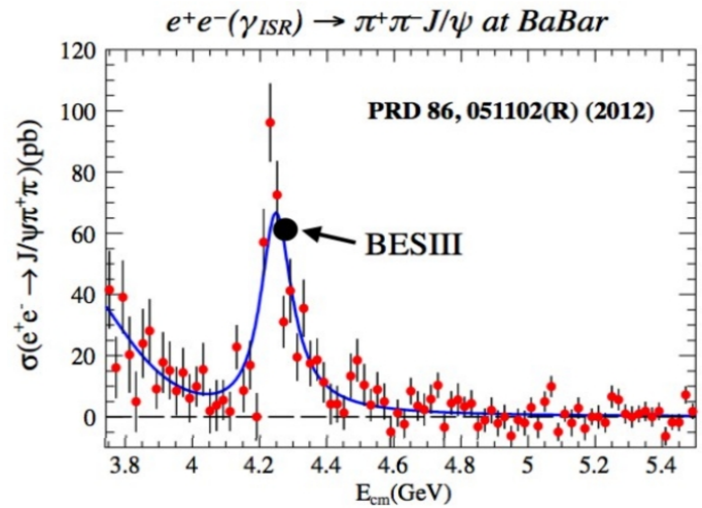


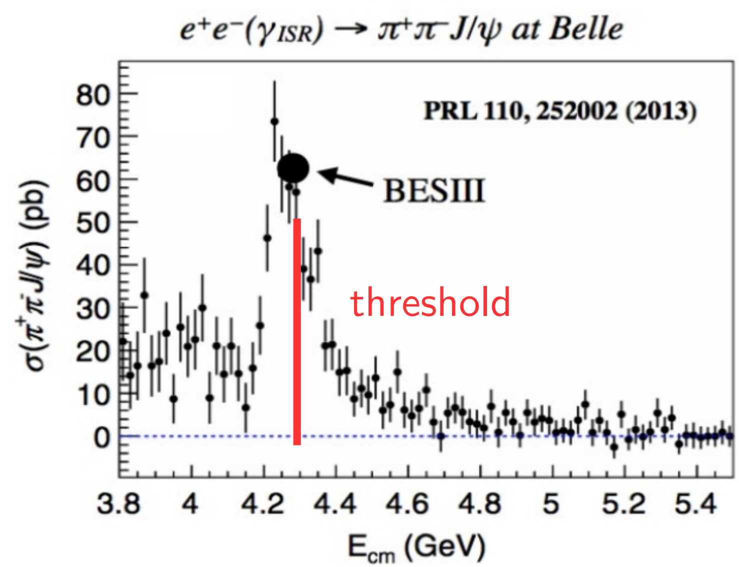
(based upon production r

- decay to e^+e^- not seen (although 1– –)
- decay to $D^{(*)}D^{(*)}$ not seen (although phasespace huge)
- recent hot topic: lineshape distortion at DD_1(2460) threshold ?

BESIII, Phys. Rev. Lett. 118 (9) (2017) 092001

BESIII, PRL110(2013)252001





Y(4260) parameters

	BABAR	CLEO-c	Belle	Belle	BABAR	BABAR	BESIII
$\mathcal{L}$	211 fb^{-1}	13.3 fb^{-1}	553 fb^{-1}	548 fb^{-1}	454 fb^{-1}	454 fb^{-1}	9 fb^{-1}
N	125±23	$14.1^{+5.2}_{-4.2}$	165±24	324±21	344±39	–	3853±68
$\mathcal{S}$	$\simeq 8\sigma$	$\simeq 4.9\sigma$	$\geq 7\sigma$	$\geq 15\sigma$	–	–	7.6σ
m	$4259\pm 8^{+2}_{-6}$	$4283^{+17}_{-16}\pm 4$	$4295\pm 10^{+10}_{-3}$	$4247\pm 12^{+17}_{-32}$	$4252\pm 6^{+2}_{-3}$	4244±5±4	4222.0±3.1±1.4
Γ	$88\pm 23^{+6}_{-4}$	70^{+40}_{-25}	$133\pm 26^{+13}_{-6}$	108±19±10	$105\pm 18^{+4}_{-6}$	$114^{+16}_{-15}\pm 7$	44.1±4.3±2.0

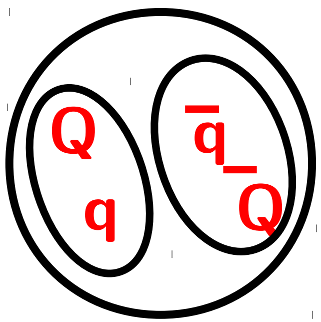
BaBar, Phys. Rev. Lett. 95(2005)142001
CLEO-c, Phys. Rev. D74(2006)091104
Belle, arXiv:hep-ex/0612006
Belle, Phys. Rev. Lett. 99(2007)182004
BaBar, arXiv:08081543[hep-ex]
BaBar, Phys. Rev. D86(2012)051102
BESIII, Phys. Rev. Lett. 118(2017)092001

Recent hot topic:
mass in direct e+e–
seems lower than in ISR

Is the Y(4260) exotic ?

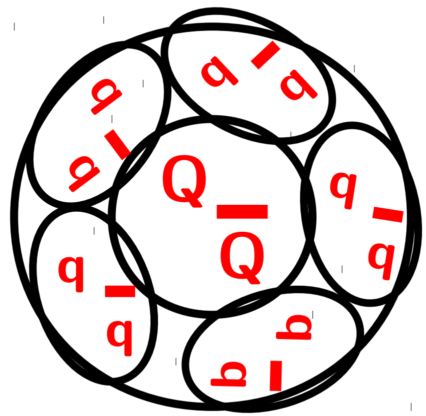
TETRAQUARK

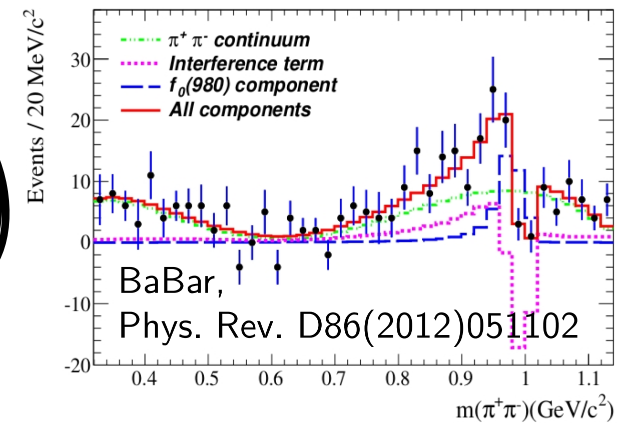
higher excitation ?



Maiani, Riquer, Piccinini, Polosa, Burns

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

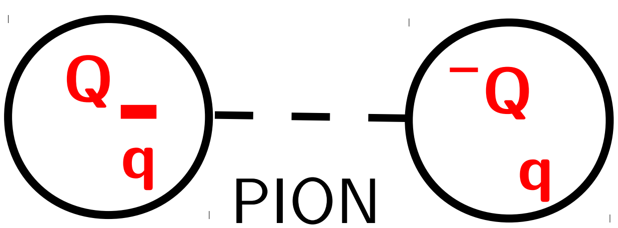




Voloshin, Li
(Guo, Hanhart, Meissner)

MOLECULE

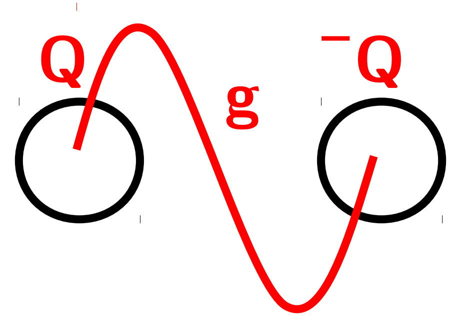
heavier mesons ($\bar{D}D_1(2460)$) ?



[Swanson, Rosner, Close
Guo, Hanhart, Meissner

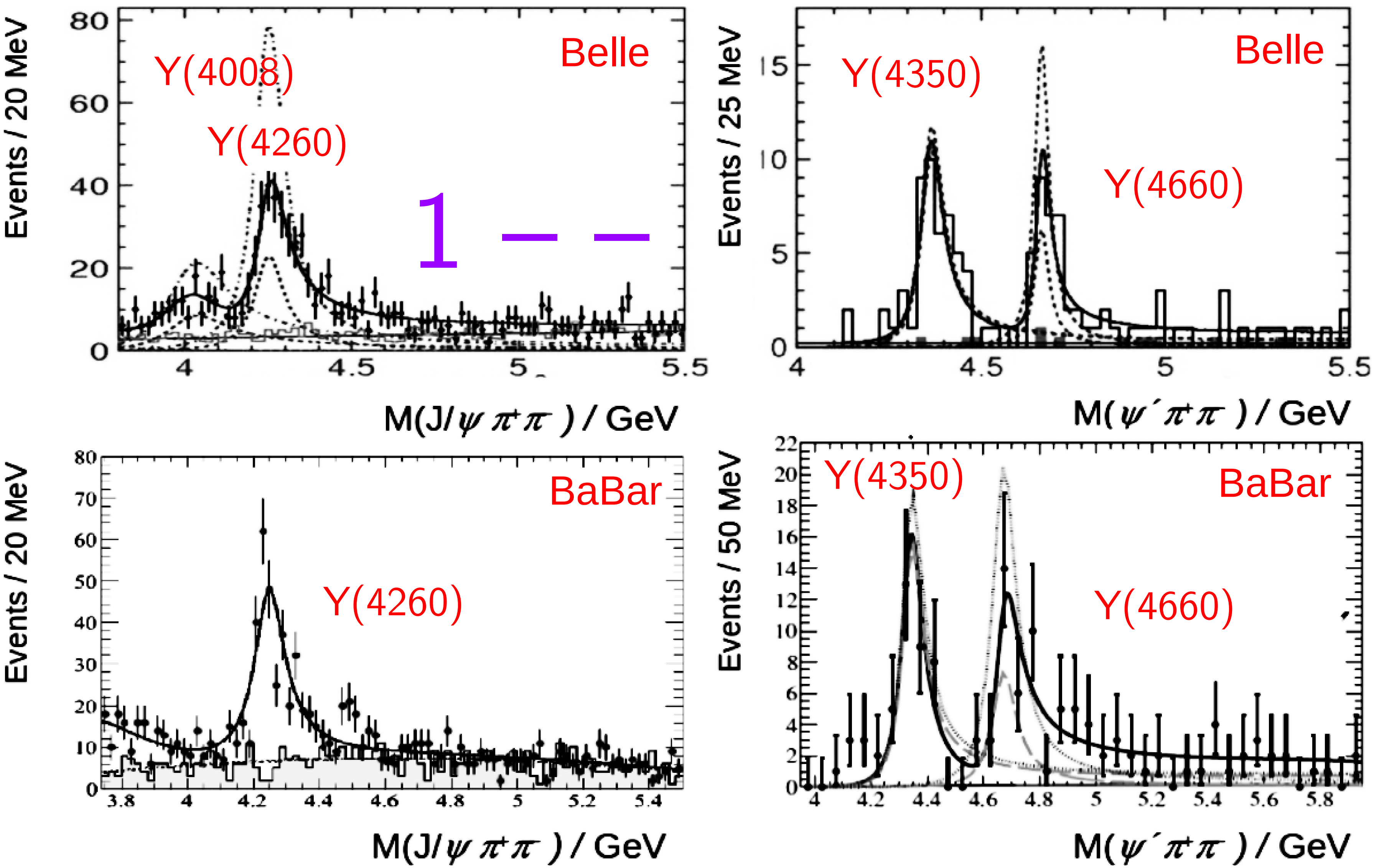
HYBRID

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

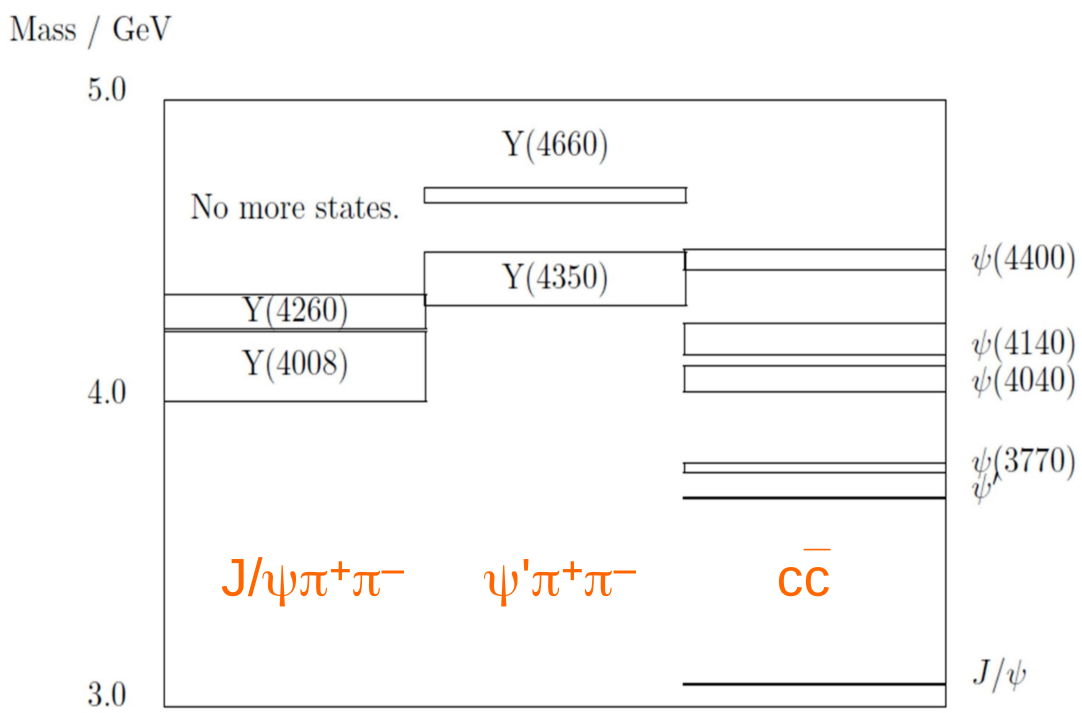


Zhu; Kou, Pene; Close, Page;
Lattice QCD, Bernard et al.; Mei, Luo

Y STATES

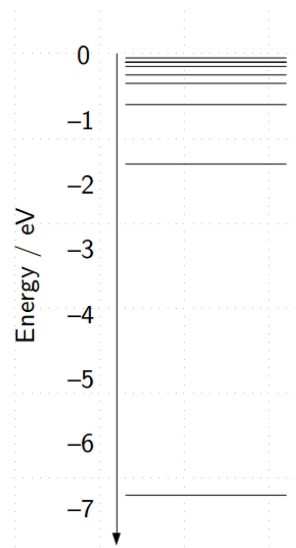

Belle
Y(4008)
Y(4260)
1 − −
Events / 20 MeV
M(J/ψ π⁺π⁻) / GeV
Belle
Y(4350)
Y(4660)
Events / 25 MeV
M(ψ′ π⁺π⁻) / GeV
BaBar
Y(4260)
Events / 20 MeV
M(J/ψ π⁺π⁻) / GeV
BaBar
Y(4350)
Y(4660)
Events / 50 MeV
M(ψ′ π⁺π⁻) / GeV

OVERPOPULATION OF $J^{PC}=1^{--}$ STATES



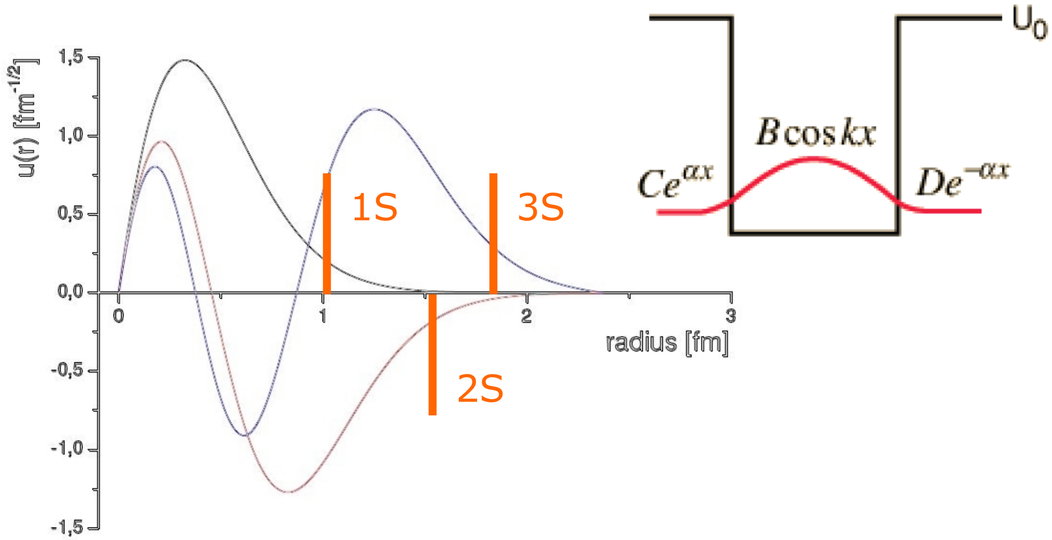
Non-trivial <u>two-doublet</u> pattern
No mixing with conventional states

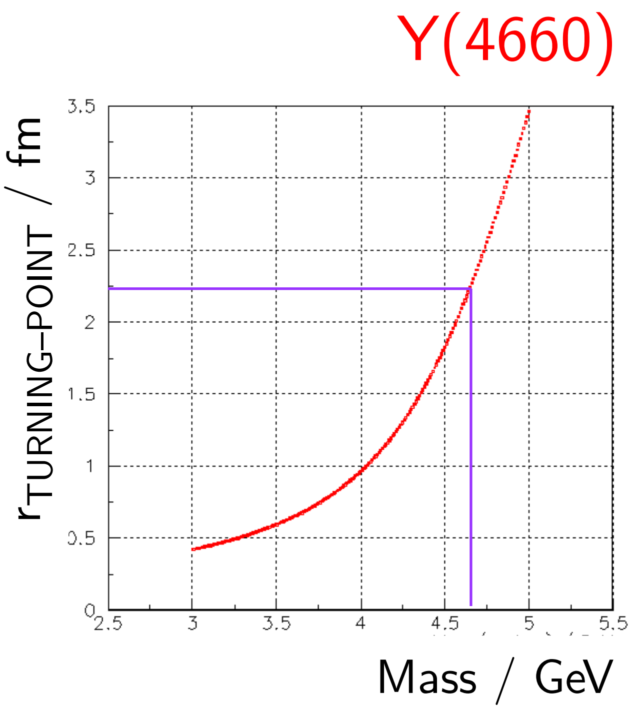
Y(4660), analogy in atomic physics (positronium)
quite narrow state (1 eV) in the continuum
∼10 eV above the dissociation energy (∼7 eV)
decay blocked by unknown mechanism



Cornell potential:
Wronski-Determinant must be zero at turning point

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





- m=4.660 GeV → turning point of wave function is 2.2 fm!
- large fraction of wave function in string breaking regime r>1.4 fm

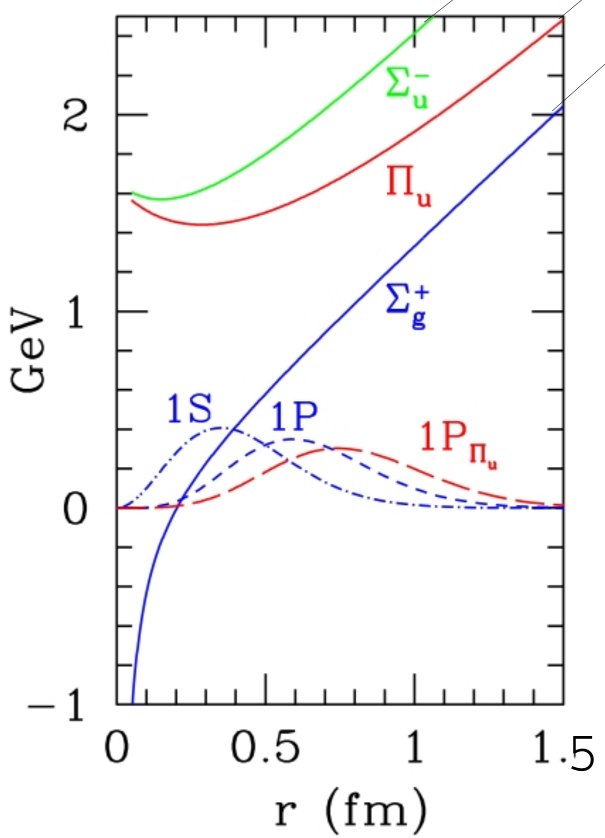
Juge, Kuti, Morningstar,
Phys. Rev. Lett. 82(1999)4400
AIP Conf. Proc. 688(2004)193

Howto „restore“ confinement for Y(4660) ?

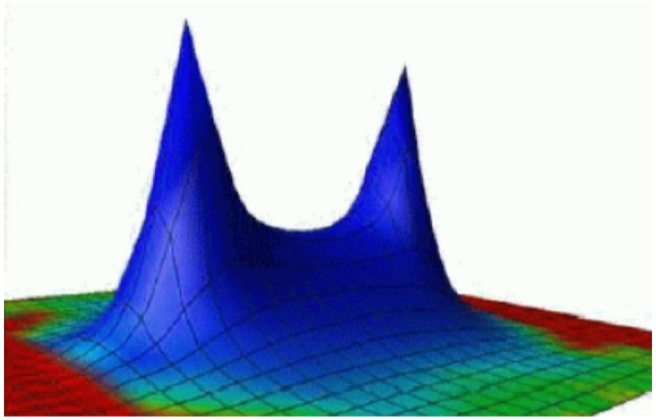
Hybrid potential
1.4 fm

Y(4660)

Charmonium



Cornell potential
2.2 fm



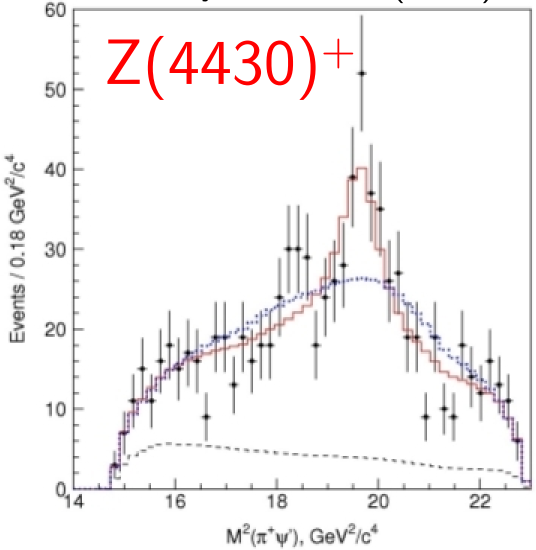
G. Bali, Phys. Rev. D51(1995)5165

Molecule ?
No bound state.
≥80 MeV above threshold

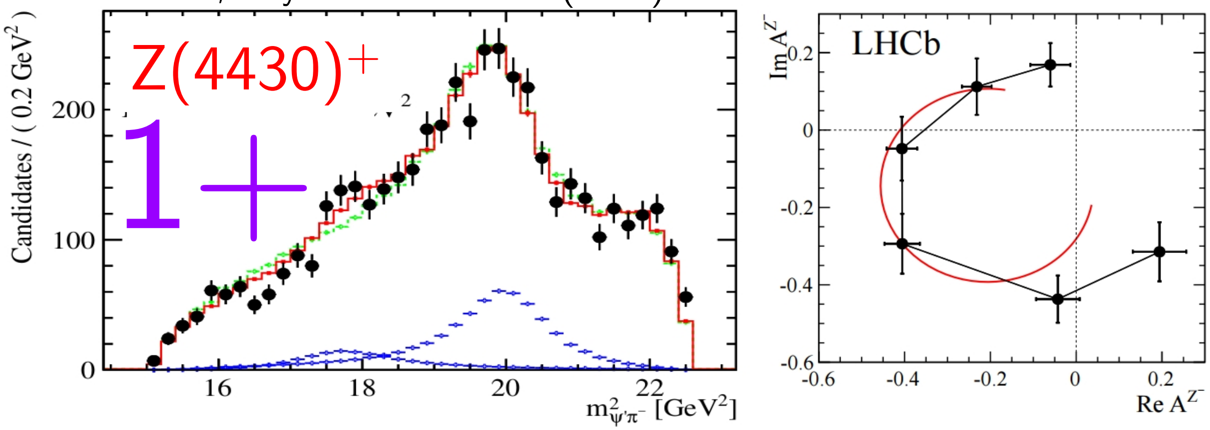
Z

Z STATES

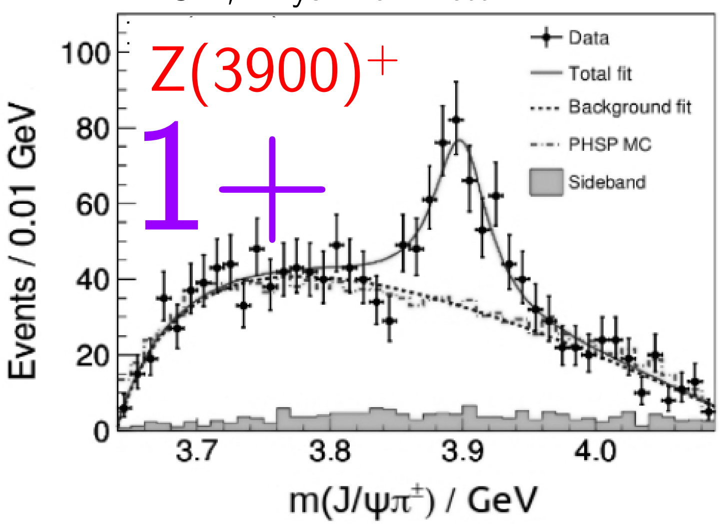
Belle, Phys. Rev D80(2009)031104



LHCb, Phys. Rev. Lett. 112(2014)222002



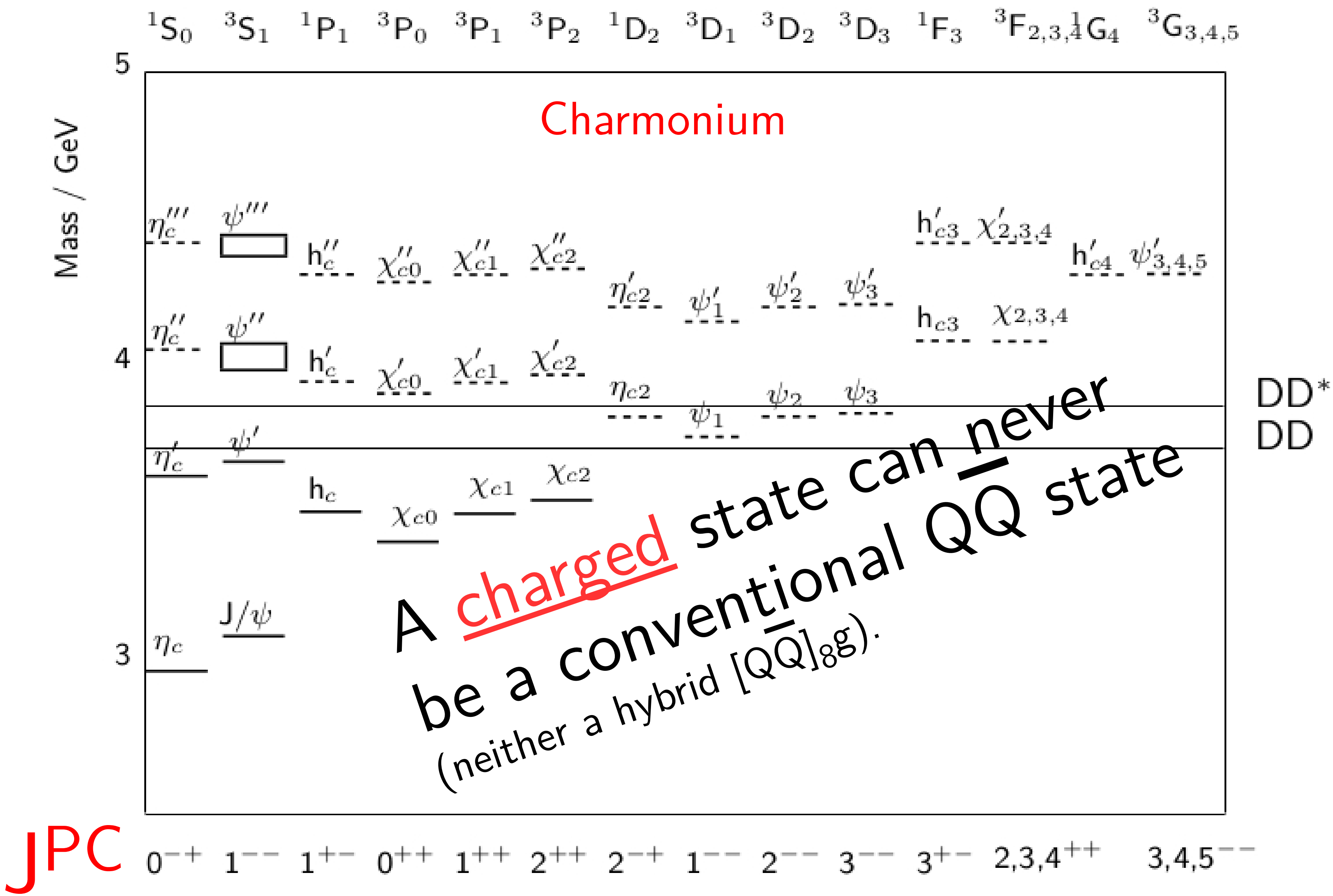
BESIII, Phys. Rev. Lett.



CHARGED

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

$$e^+e^- \to (\ Y(4260)\ ) \to \underbrace{J/\psi \pi^\pm}_{\text{resonant state?}} \quad \pi^\mp$$



A **charged** state can **never** be a conventional $Q\bar{Q}$ state

(neither a hybrid $[Q\bar{Q}]_8 g$).

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

Why „charged“ here means „exotic“ ? (what about charged mesons?)

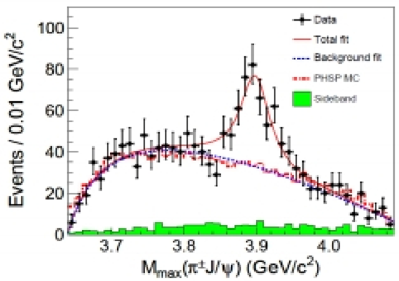
u,c,t	charge +2/3
d,s,b	charge –1/3

Quark content	Mass / GeV
$u\bar{d}$	0.139
$s\bar{u}$	0.493
$c\bar{d}$	1.8
?	3.9
$b\bar{u}$	5.3

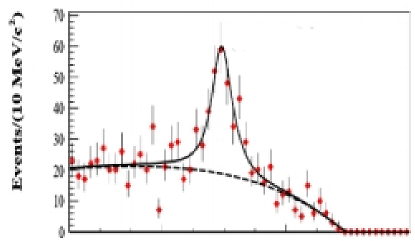
→ requires minimum configuration 4-quark
example $[c\bar{c}u\bar{d}]$
molecule or tetraquark

Z STATES AT BESIII

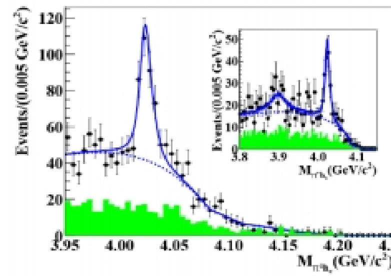
$D\bar{D}^*$ threshold | $D^*\bar{D}^*$ threshold



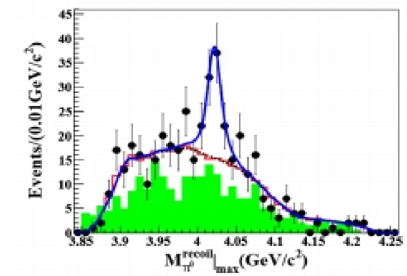
$e^+e^- \to \pi^+ \pi^- J/\Psi$



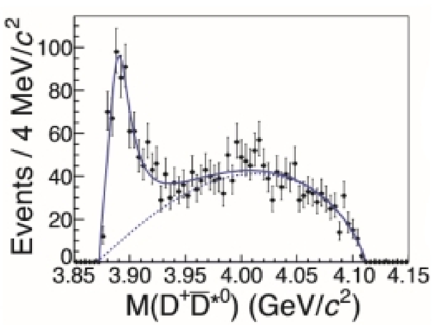
$e^+e^- \to \pi^0 \pi^0 J/\Psi$



$e^+e^- \to \pi^+ \pi^- h_c$

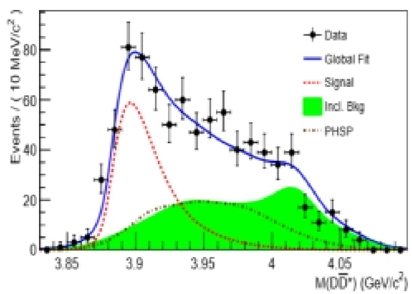


$e^+e^- \to \pi^0 \pi^0 h_c$



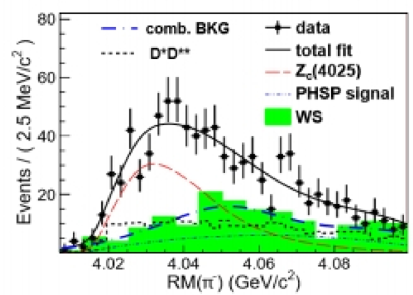
$e^+e^- \to \pi^+ (D\bar{D}^*)^-$

charged



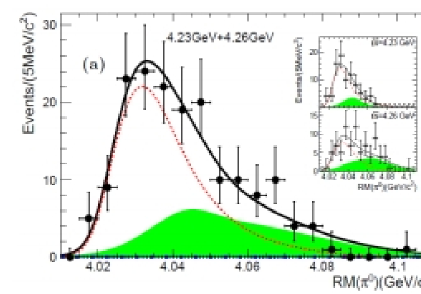
$e^+e^- \to \pi^0 (D\bar{D}^*)^0$

neutral



$e^+e^- \to \pi^+ (D^*\bar{D}^*)^-$

charged



$e^+e^- \to \pi^0 (D^*\bar{D}^*)^0$

neutral

Recent hot topic: neutral partners $\to$ isospin triplets
All of them 1+, whereever tested.

Z states and „confinement“ ?

All measured Z_c^+ masses are above $D^{(*)}\overline{D}^{(*)}$ thresholds

State	m (MeV)	Threshold	Δm (MeV)
$Z_c(3900)$	$3899.0\pm3.6\pm4.9$	$D^+\overline{D}^{0*}$	$+22.4$
$Z_c(3900)$	$3899.0\pm3.6\pm4.9$	$D^0\overline{D}^{+*}$	$+23.9$
$Z_c(3900)$	$3894.5\pm6.6\pm4.5$	$D^+\overline{D}^{0*}$	$+17.9$
$Z_c(3900)$	$3894.5\pm6.6\pm4.5$	$D^0\overline{D}^{+*}$	$+19.4$
$Z_c(3900)$	$3885\pm5\pm1$	$D^+\overline{D}^{0*}$	$+8.4$
$Z_c(3900)$	$3885\pm5\pm1$ MeV	$D^0\overline{D}^{+*}$	$+9.9$
$Z_c(3885)$	$3883.9\pm1.5\pm4.2$	$D^+\overline{D}^{0*}$	$+7.4$
$Z_c(3885)$	$3883.9\pm1.5\pm4.2$	$D^0\overline{D}^{+*}$	$+8.8$
$Z_c(4020)$	$4022.9\pm0.8\pm2.7$	$D^{0*}\overline{D}^{\pm*}$	$+5.6$
$Z_c(4025)$	$4026.3\pm2.6\pm3.7$	$D^{0*}\overline{D}^{\pm*}$	$+9.0$
$Z_c(4032)^+$	$\simeq 4032.1\pm2.4$	$D^{0*}\overline{D}^{\pm*}$	$+15.0$

	possible?
threshold CUSP	no (must be @ threshold)
tetraquark	yes (spin–spin forces)
molecules	no, if bound state (pole below threshold, E_B>0)

Belle II (Upgrade of Belle)

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
JENNIFER
Belle II
Bundesministerium für Bildung und Forschung
An MSCA-RISE project funded by European Union under grant n.644294


Mt. Tsukuba
SuperKEKB asymmetric B meson factory, e+ e– → B$\bar{B}$
adjusted to Y(4S) resonance, √s=10.6 GeV
different beam energies
8 GeV → 7 GeV (improved emittance)
3.5 GeV → 4 GeV (Touschek lifetime)
Upgrade: peak luminosity x40, integrated luminosity x50
Belle II Detector
Linac

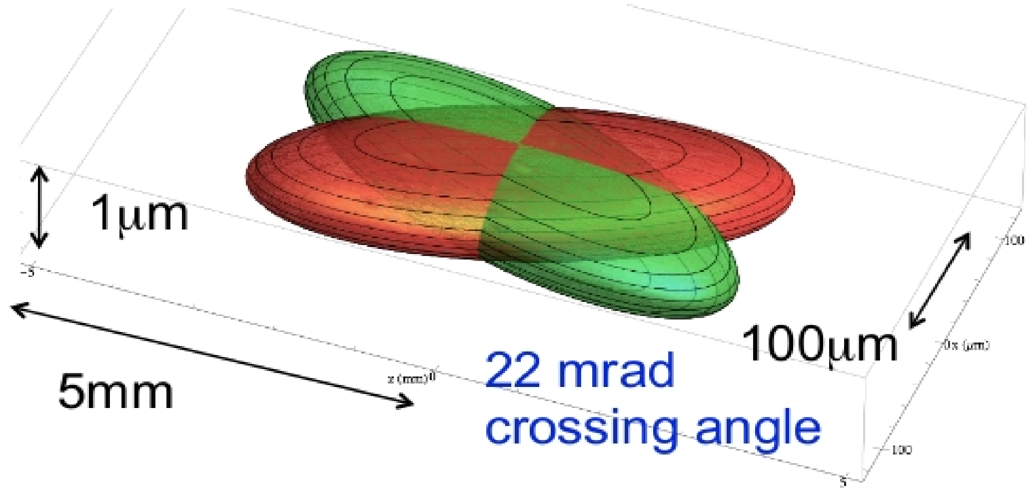
Nano-Beam Scheme

Belle → Belle II

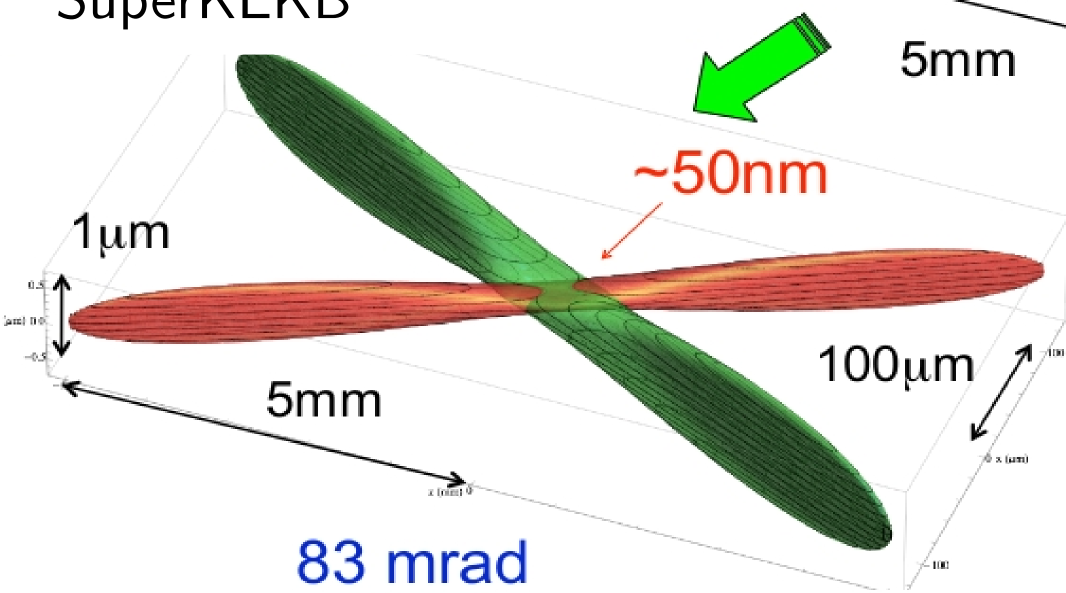
Luminosity x 40

$L \leq 0.8 \times 10^{36}\ cm^{-2}\ s^{-1}$

KEKB *(without crab)*



SuperKEKB



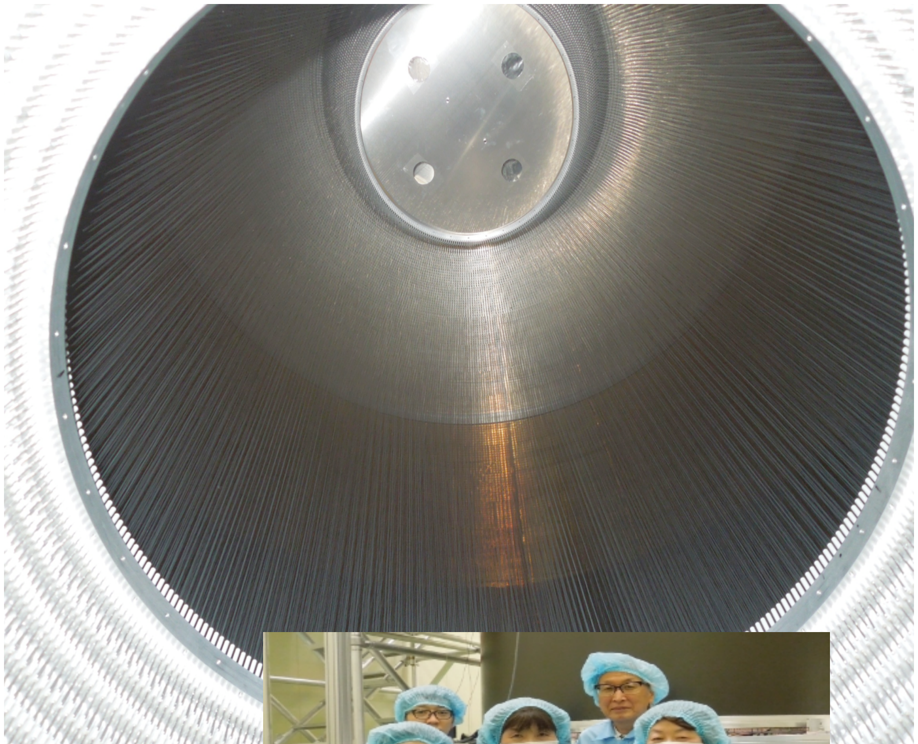
originally proposed for SuperB
by P. Raimondi (INFN)

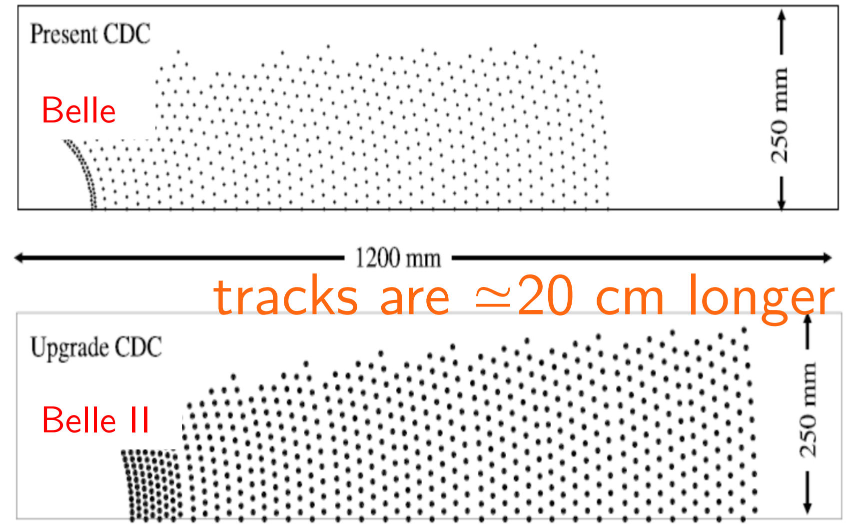
graphics E. Paoloni (Pisa)


Interaction Region

CDC (Charged Drift Chamber)

wire stringing finished (01/2014), 51456 wires





Improved resolution:

$\sigma(p_T)/p_T =$

$0.19\ p_T \oplus 0.30/\beta$ (Belle)

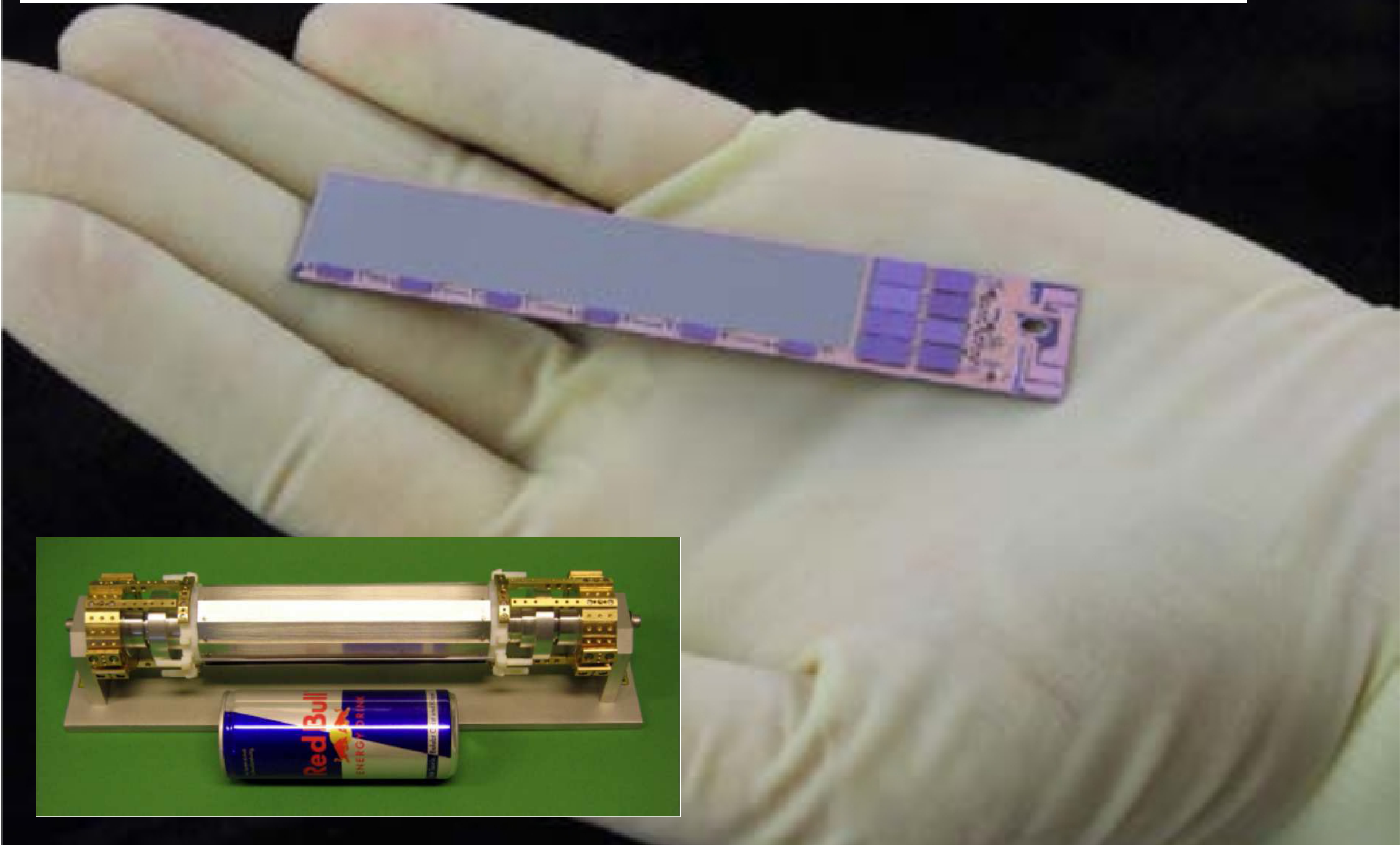
$0.11\ p_T \oplus\ 0.30/\beta$ (Belle II)

dE/dx 6.8% $\rightarrow$ 4.8%

Belle II CDC transport from Fuji Hall to Tsukuba Hall (01/2015)

Belle II DEPFET Pixel Detector

Univ. Bonn, DESY, Univ. Giessen, Univ. Göttingen, Univ. Hamburg, Univ. Heidelberg, KIT Karlsruhe, Univ. Mainz, HLL München, MPI München, LMU München, TU München

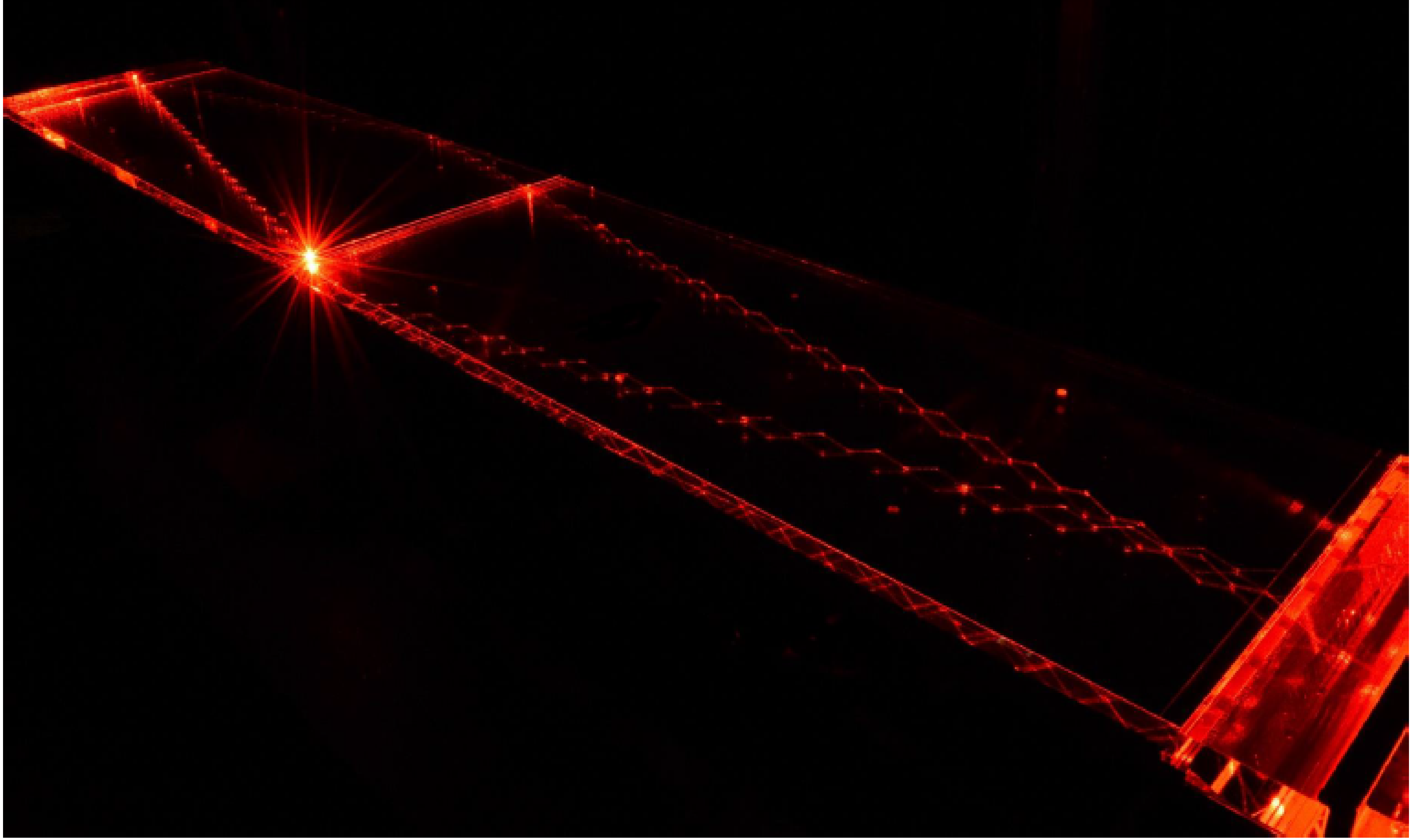


Final PXD readout hardware, mass production (IHEP, Giessen)

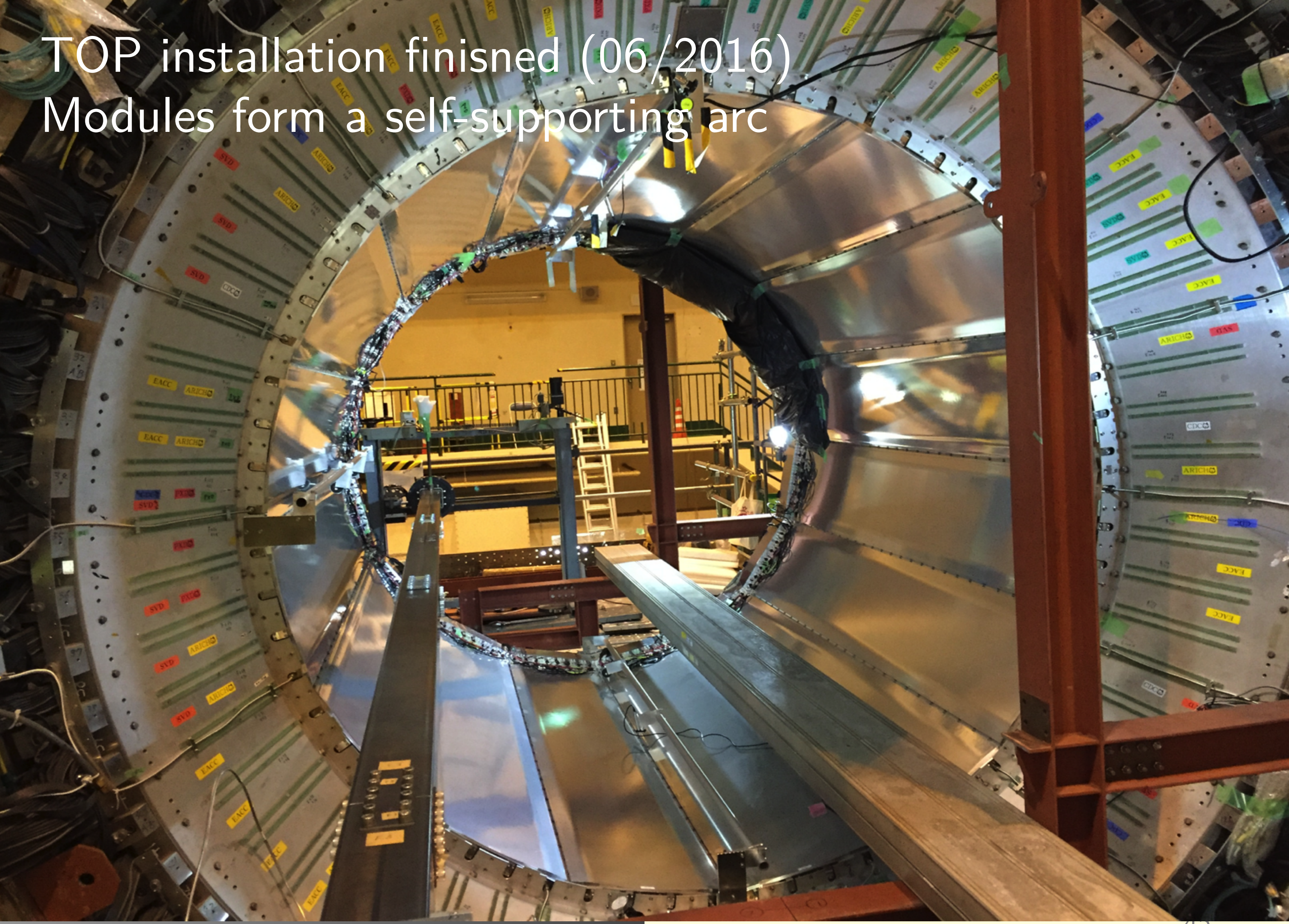
Pixel detector generates 10x more data than rest of Belle II

Cerenkov detector, laser in TOP module (Time–of-propagation, $t \leq 50$ ps)

Photo: K. Inami (Nagoya)



TOP installation finisned (06/2016)
Modules form a self-supporting arc



KEK
Inter-University Research Institute Corporation
High Energy Accelerator Research Organization

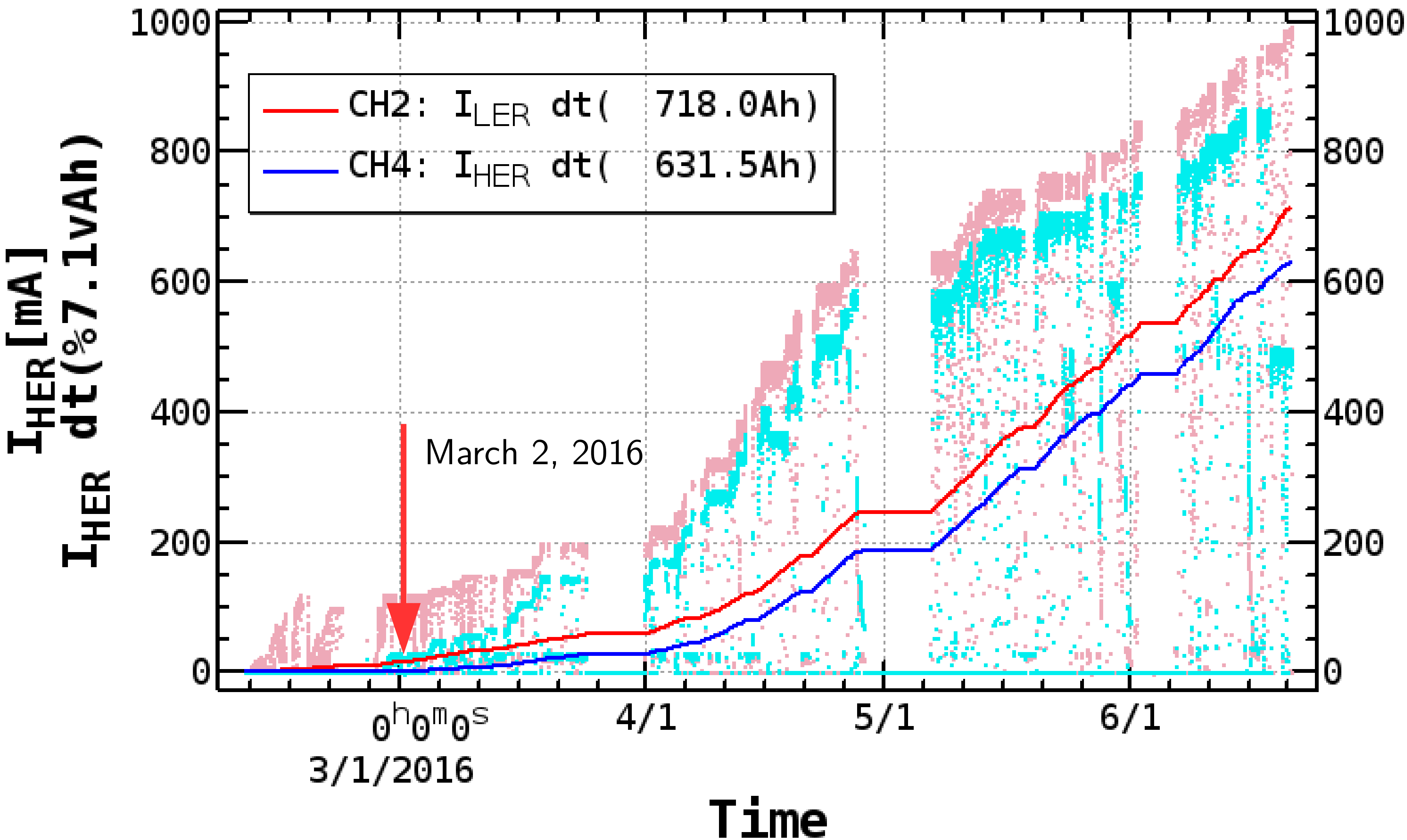
Press Release

First turns and successful storage of beams in the SuperKEKB electron and positron rings

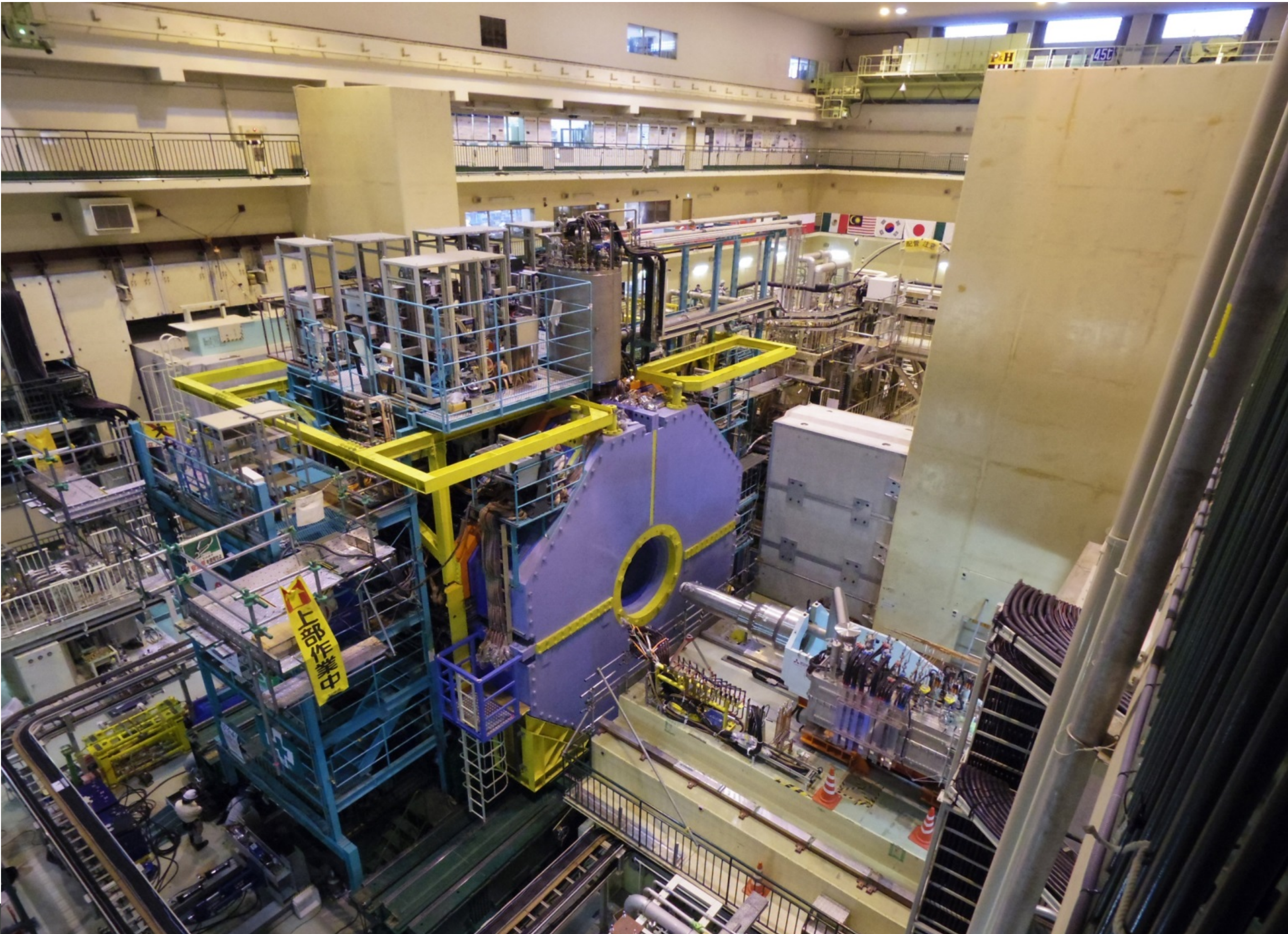
March 2nd, 2016

High Energy Accelerator Research Organization (KEK)

June 21, 2016: LER beam current exceeded 1 Ampere



ROLL-IN, 11.04.2017


上部作業中

Start of phase 2 data taking: February 15, 2018 (in ∼4 weeks)

Belle II XYZ reach

assume 50 ab^{-1} ($\geq$2024)

State	Production and Decay	N
X(3872)	$B \to K\mathrm{X}(3872)$, $\mathrm{X}(3872) \to J/\psi\pi^+\pi^-$	$\simeq$14400
Y(4260)	ISR, $\mathrm{Y}(4260) \to J/\psi\pi^+\pi^-$	$\simeq$29600
Z(4430)	$B \to K^\mp \mathrm{Z}(4430)$, $\mathrm{Z}(4430) \to J/\psi\pi^\pm$	$\simeq$10200

$\to$ search for rare decays feasible

same number of X(3872):

- BESIII $\simeq$60 years (Y(4260) radiative decays)
- LHCb (upgrade) with $\geq$40 fb^{-1} (2026?) (assume no change in trigger efficiency)
- PANDA $\simeq$20 days (pp $\to$ X(3872))

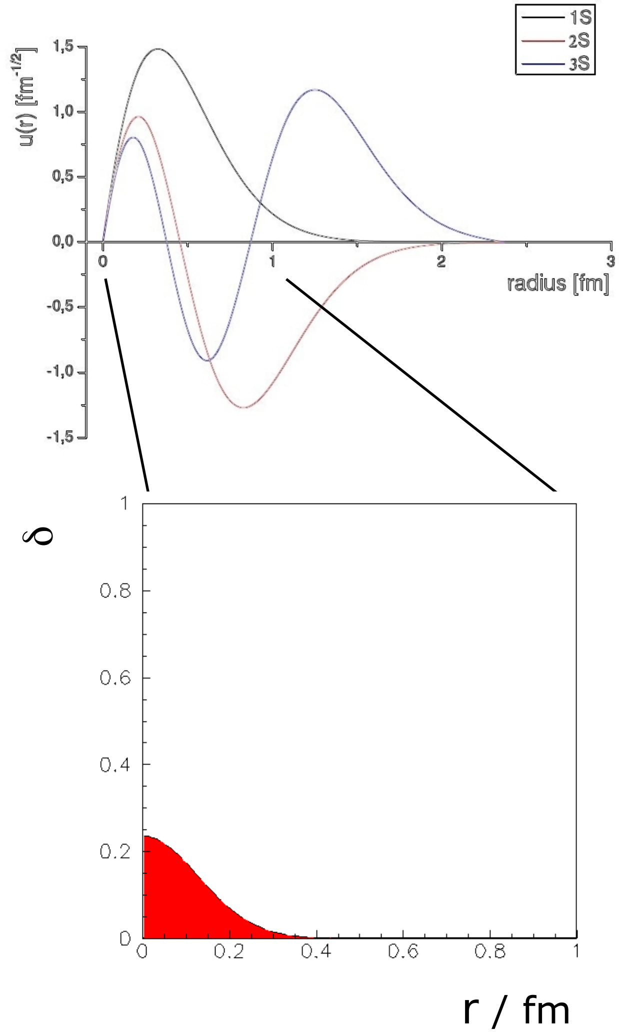
Summary

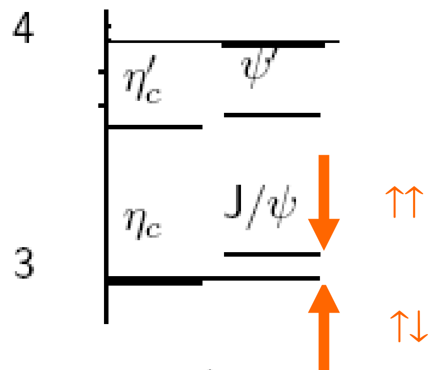
- $\geq$10 years of unexpected, narrow states with heavy quarks, still many open questions
  - evidence for fine–tuning to thresholds (sub–MeV)
  - evidence for long-range binding ($>$10 fm)
  - evidence that isospin plays an important role (isospin breaking, isospin triplets)
- Reminder: rare signals (branching fractions 10^{-5} or less)
- Belle II: start data taking in $\sim$4 weeks
  more experiments ongoing (BESIII, LHCb) or future ($\overline{\text{P}}$ANDA)
  next 10 years $\rightarrow$ statistics $\times$ 10^2–10^3

BACKUP

Short-range Forces: Spin-Spin Term

- consequence of one-gluon exchange
- spin-spin term is put into the potential, i.e. not treated as a mass shift
- radial only
- „contact term", Gaussian
- fit to experimental data gives $\sigma \simeq 1$ GeV

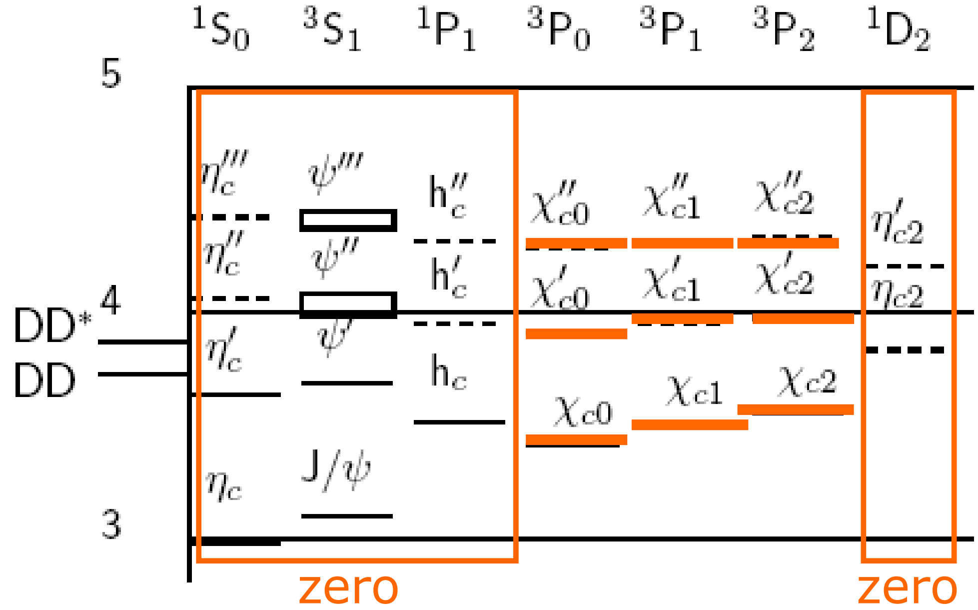




$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\,\tilde{\delta}_\sigma(r)\,\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

$$\tilde{\delta}_\sigma(r) = (\sigma/\sqrt{\pi})^3\, e^{-\sigma^2 r^2}$$

Tensor Term



- treated as perturbation
- has diagonal and non-diagonal elements
- vanishes for S=0
- vanishes for L=0
- same order of magnitude and same range as LS term

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

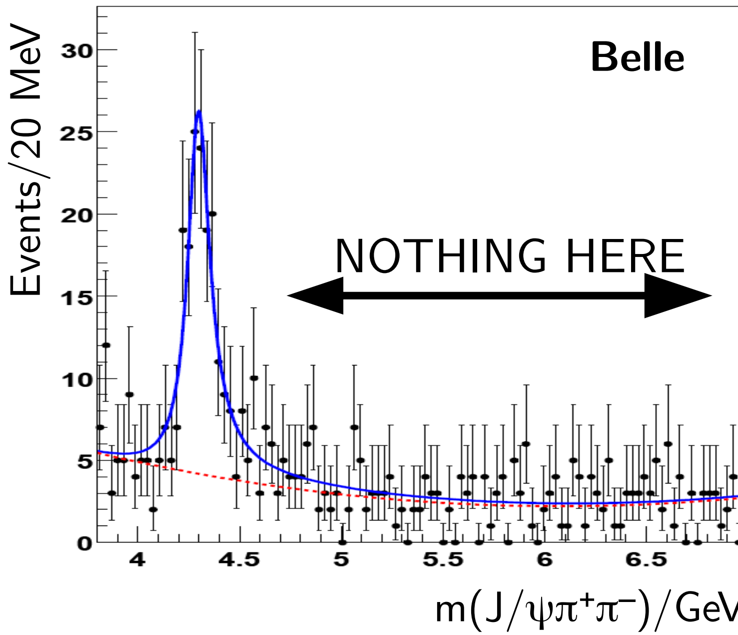
Among all the states used as input for potential model fit, only χ_{cJ} are shifted by tensor term.

j	l-1	l	l+1
S_{12}	$-\frac{2l+2}{2l-1}$	2	$-\frac{2l}{2l+3}$

No higher $J/\psi\pi^+\pi^-$ states with $J^{PC}=1^{--}$ up to 7.0 GeV

remarkable!

for charmonium,
radial excitations
n=2 vs. n=1
(ψ' vs. J/ψ)
mass gap ~0.5 GeV



mass gap 2.5 GeV hard to explain,
for any potential
(charmonium, molecule, tetraquark, hybrid)

$1^{+(+)}$

a „magic" quantum number ?
for many Z states and X(3872)

Molecule

for axial PV states, tensor potential is attractive and significant (but short range, $1/r^2$, $1/r^3$ terms)

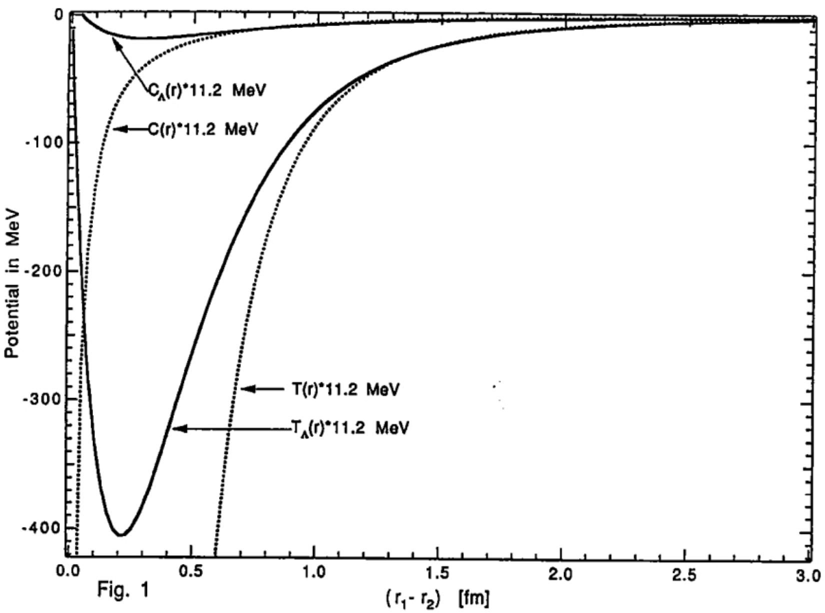
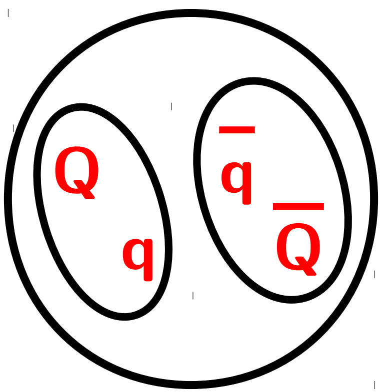


Fig. 1

Törnqvist, Phys. Lett. B590(2004)209
Törnqvist, Phys. Rev. Lett. 67(1991)556

TETRAQUARK
DIQUARK ANTI–DIQUARK MODEL



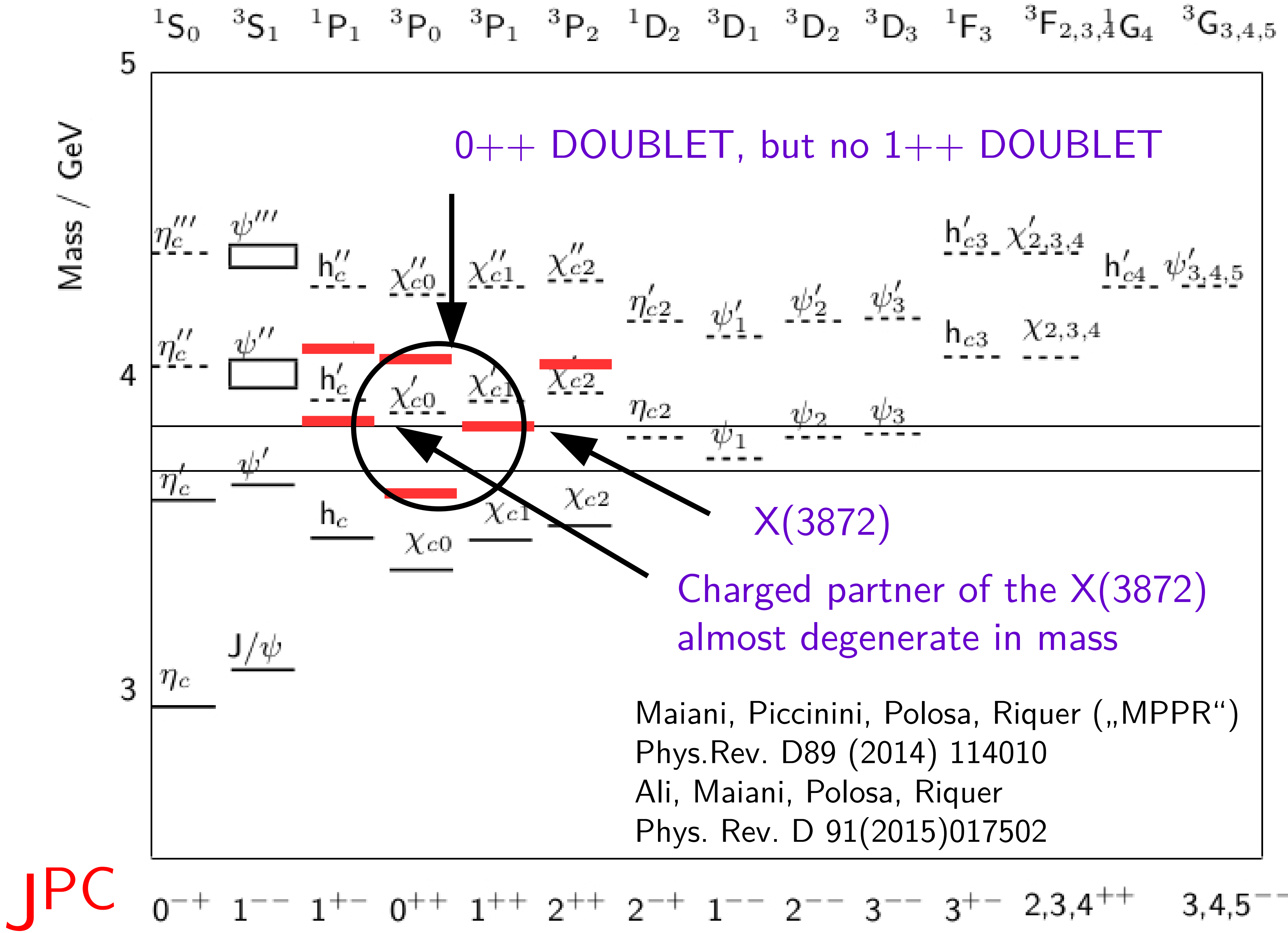
$[qQ]_8[\overline{qQ}]_8$

diquarks
are colored

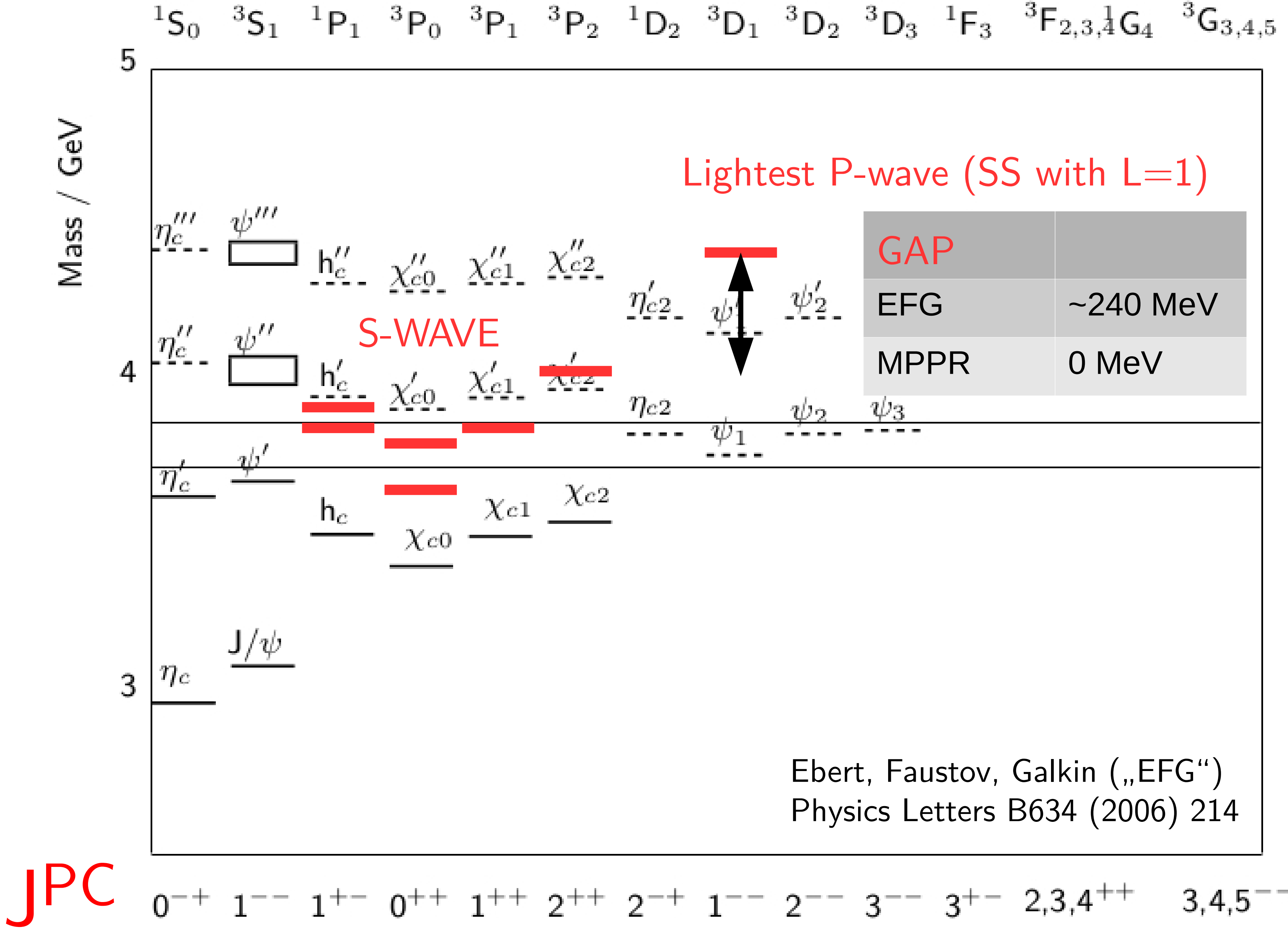
State J^{PC}	Diquark content
$1S$	
0^{++}	$S\bar{S}$
$1^{+\pm}$	$(S\bar{A} \pm \bar{S}A)/\sqrt{2}$
0^{++}	$A\bar{A}$
1^{+-}	$A\bar{A}$
2^{++}	$A\bar{A}$
$1P$	
1^{--}	$S\bar{S}$

S scalar
A axial–vector

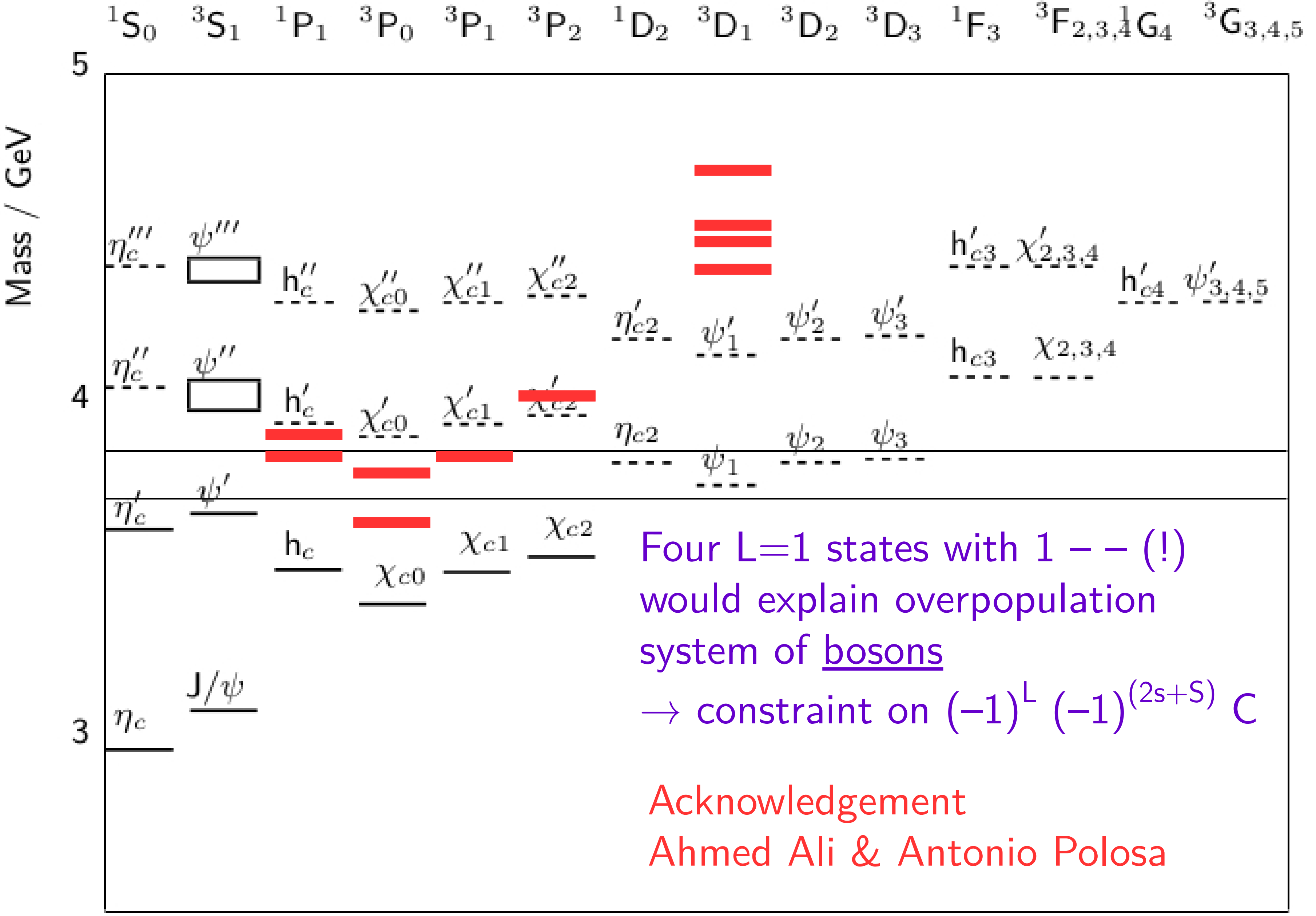
Ebert, Faustov, Galkin
Physics Letters B 634 (2006) 214–219



0++ DOUBLET, but no 1++ DOUBLET
X(3872)
Charged partner of the X(3872)
almost degenerate in mass
Maiani, Piccinini, Polosa, Riquer („MPPR“)
Phys.Rev. D89 (2014) 114010
Ali, Maiani, Polosa, Riquer
Phys. Rev. D 91(2015)017502
Mass / GeV
JPC



GAP	
EFG	~240 MeV
MPPR	0 MeV

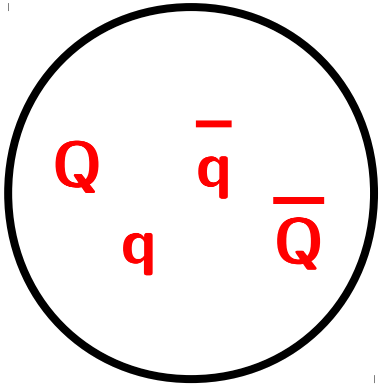


Four L=1 states with 1 – – (!)
would explain overpopulation
system of <u>bosons</u>
$\rightarrow$ constraint on $(-1)^L\ (-1)^{(2s+S)}\ C$

Acknowledgement
Ahmed Ali & Antonio Polosa

JPC 0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++} 2^{-+} 1^{--} 2^{--} 3^{--} 3^{+-} $2,3,4^{++}$ $3,4,5^{--}$

4–QUARK MODEL



4 quarks
(not diquark anti–diquark)

Color-spin basis
(singlet-singlet, octet-octet)

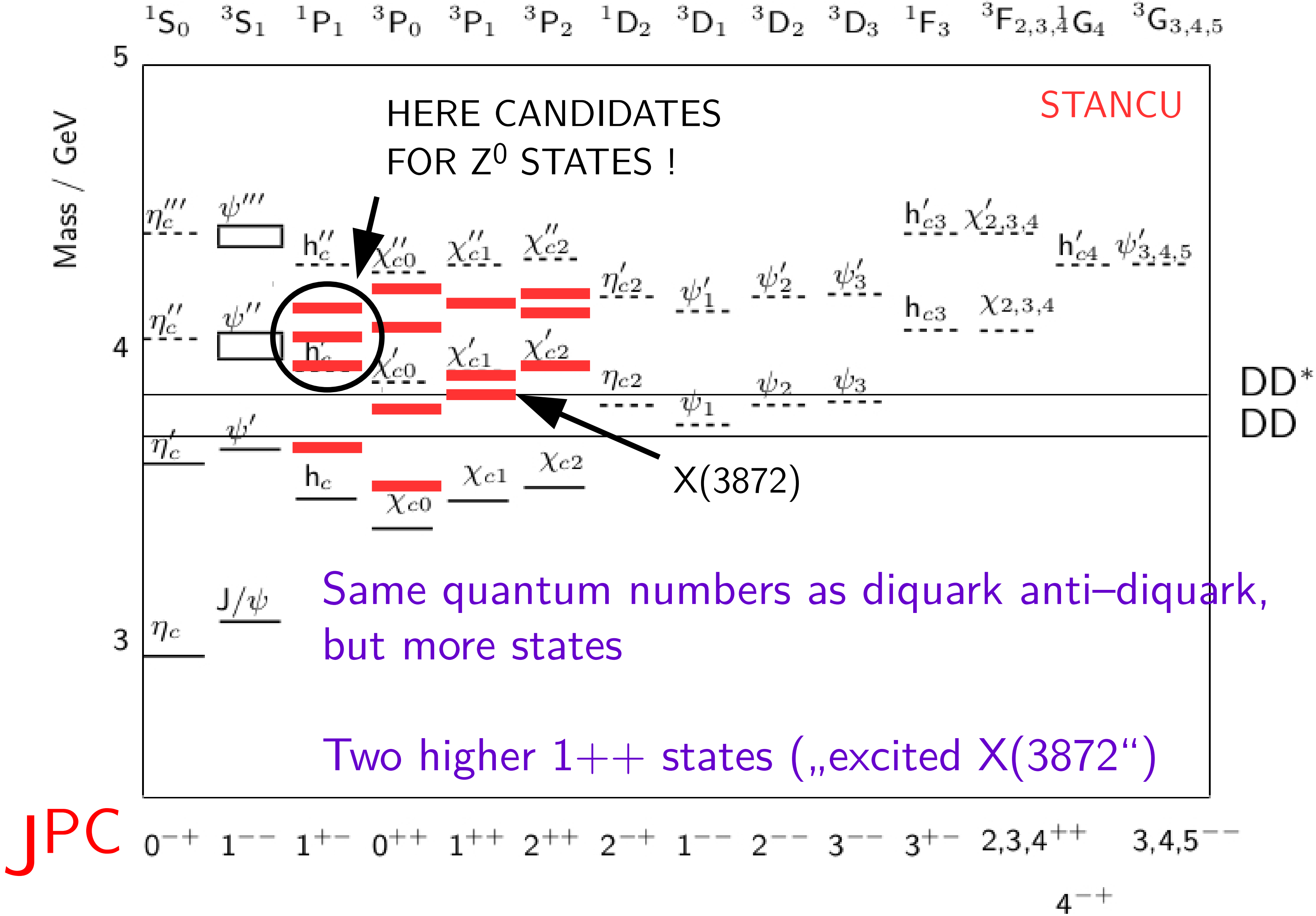
F. Stancu
Phys. Rev. D 57(1998)6778
F. Stancu, D. Brink
arXiv:hep-ph/0607077

$$H = \sum_i m_i + H_{\rm CM},$$

$$H_{\rm CM} = -\sum_{i,j} C_{ij}\, \lambda_i^c \cdot \lambda_j^c\, \vec{\sigma}_i \cdot \vec{\sigma}_j.$$

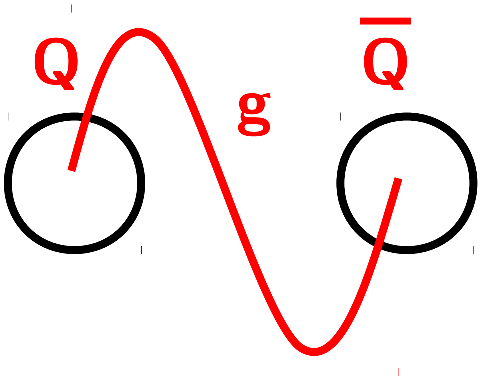
$$C_{cs} = 5.0\ \text{MeV}, \qquad C_{c\bar{c}} = 5.5\ \text{MeV},$$

$$C_{c\bar{s}} = 6.7\ \text{MeV}, \qquad C_{s\bar{s}} = 8.6\ \text{MeV}.$$



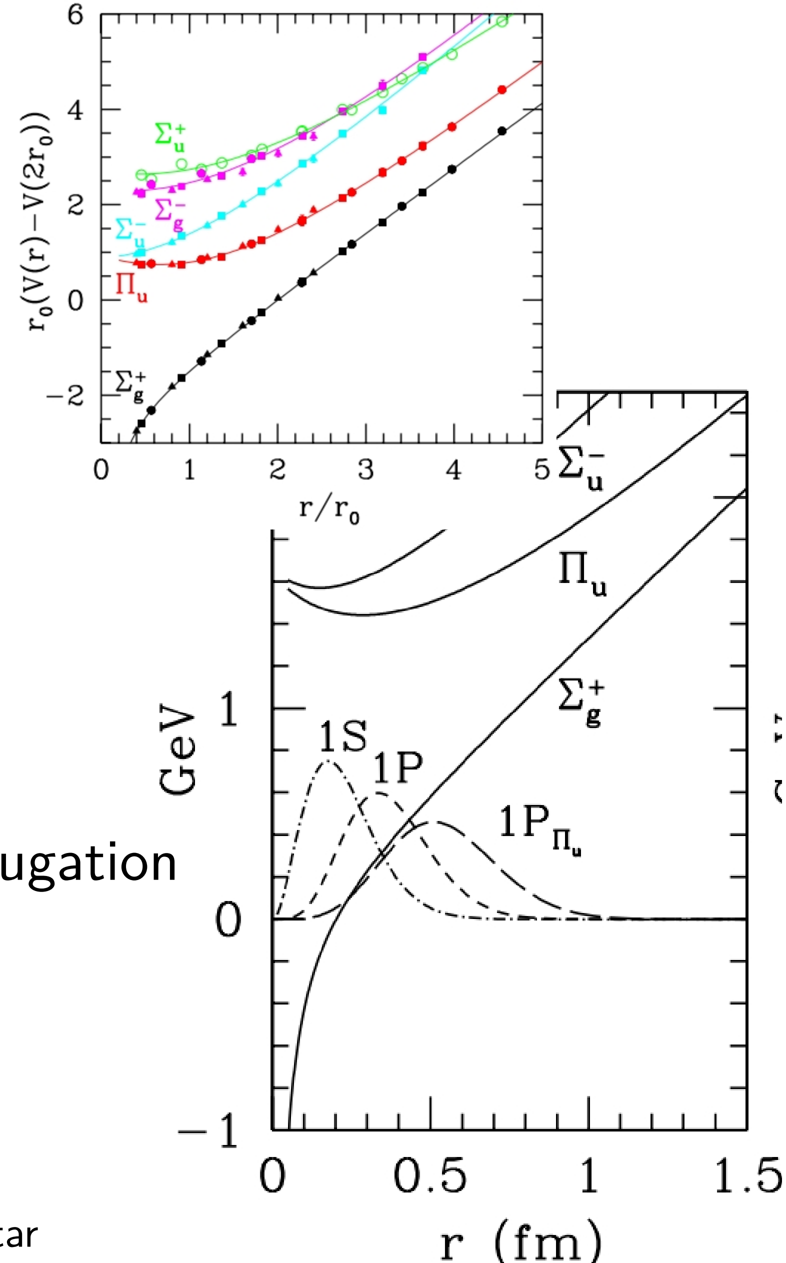
Same quantum numbers as diquark anti–diquark, but more states

Two higher 1++ states („excited X(3872“)



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

HYBRID POTENTIALS



projection of gluon angular momentum
onto QQ axis
0,1,2,... $\rightarrow \Sigma, \ \Pi, \ \Delta, \ \ldots$

product of gluonic parity and charge conjugation
$(PC)_g$
„u“ (negative), „d“ (positive)

reflection of system through plane
containing QQ axis
Superscript „+“ or „–„

Juge, Kuti, Morningstar
Phys. Rev. Lett. 82(199)4400
Nucl. Phys. Proc. Suppl. 63(1998)3261

	S	L	J^{PC}
η_c	0	0	0^{-+}
J/ψ	1	0	1^{--}
h_c	0	1	1^{+-}
χ_c	1	1	$(0,1,2)^{++}$

CORNELL POTENTIAL

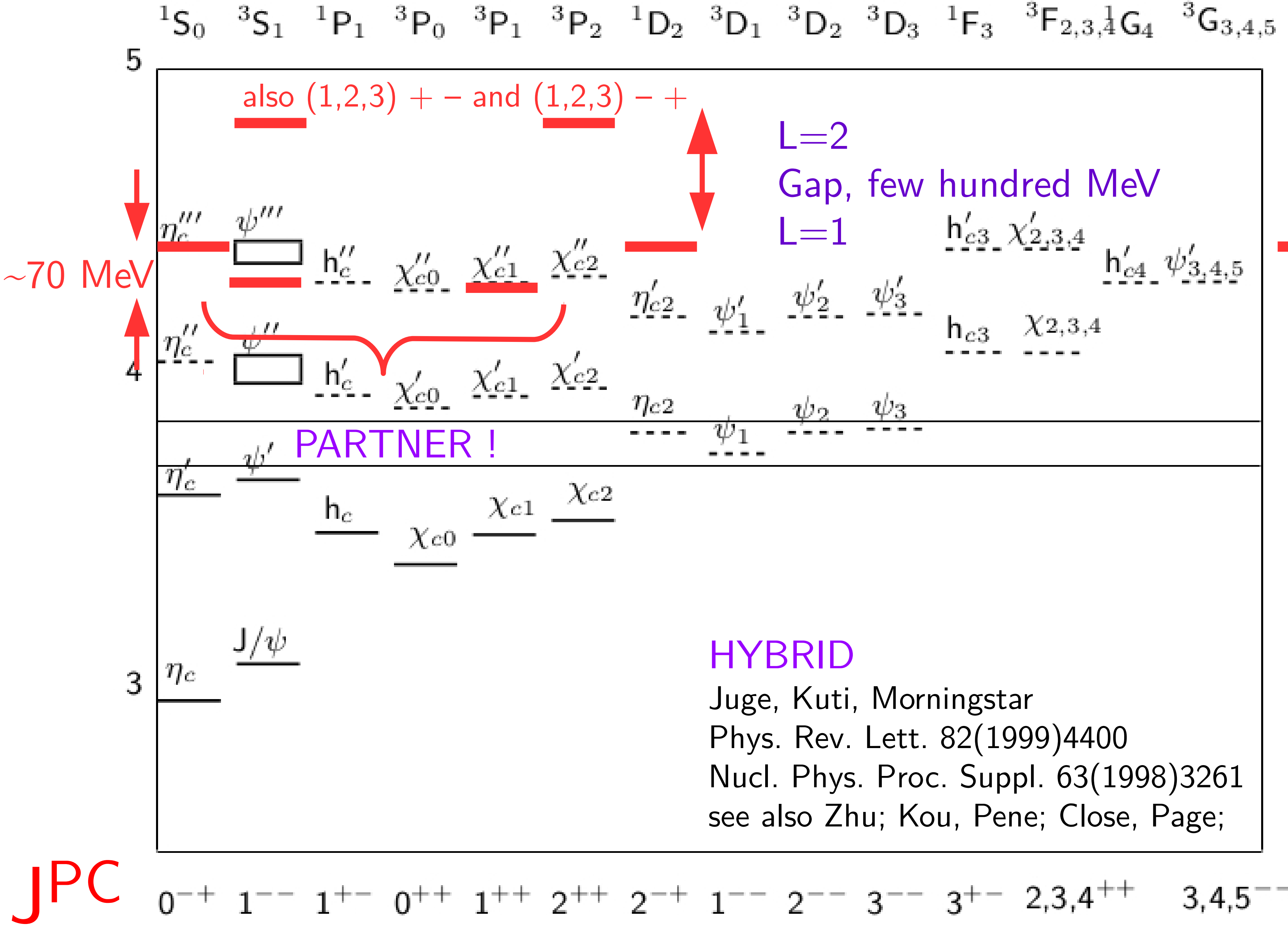
Table 3: Σ_g^+ Meson Quantum Numbers.

MASS

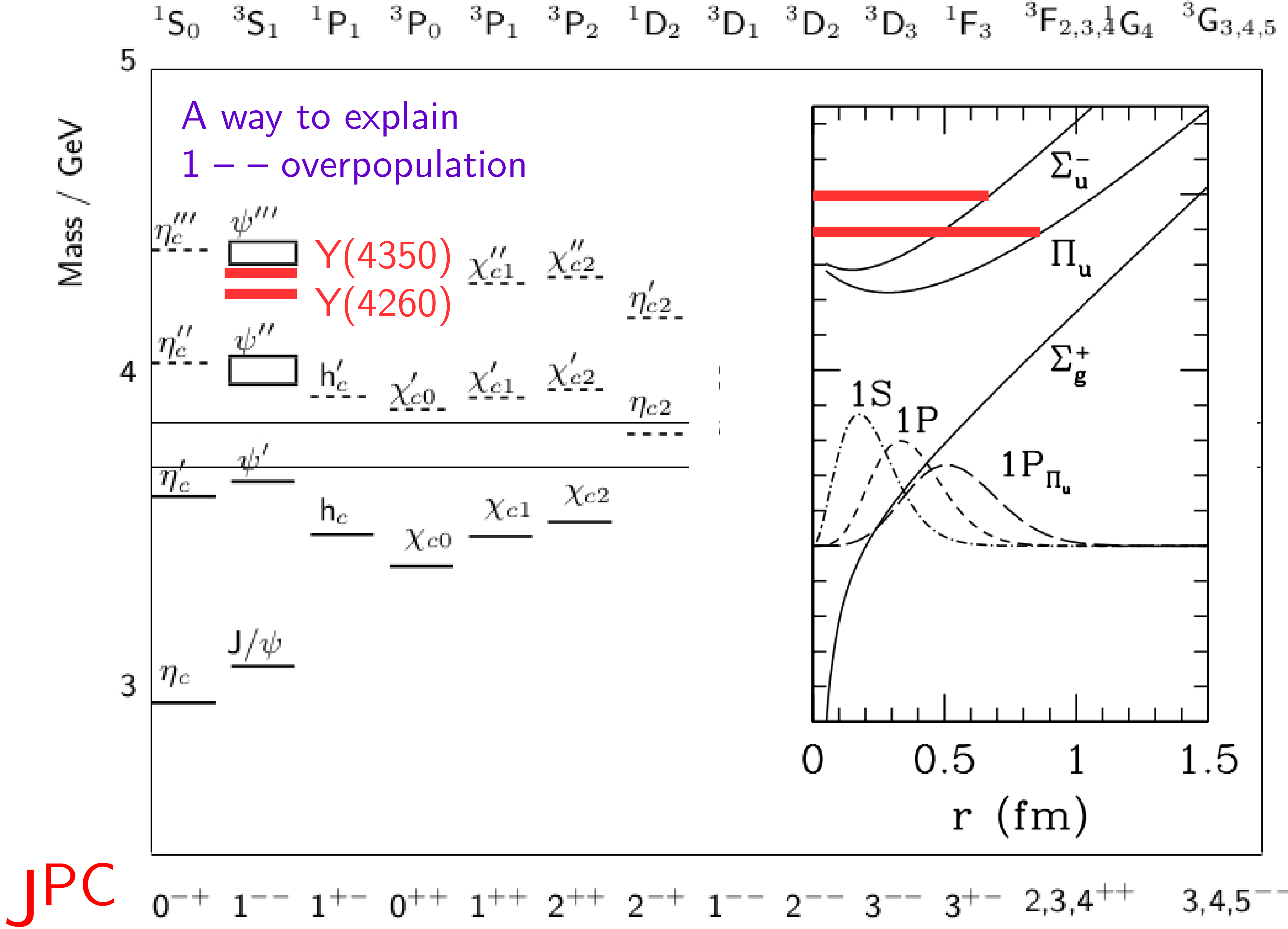
S	L	J^{PC}
0	1	1^{--}, 1^{++}
1	1	$(0,1,2)^{-+}$, $(0,1,2)^{+-}$
0	2	2^{++}, $2{--}$
1	2	$(1,2,3)^{+-}$, $(1,2,3)^{-+}$

A GLUONIC POTENTIAL: HERE Π_u

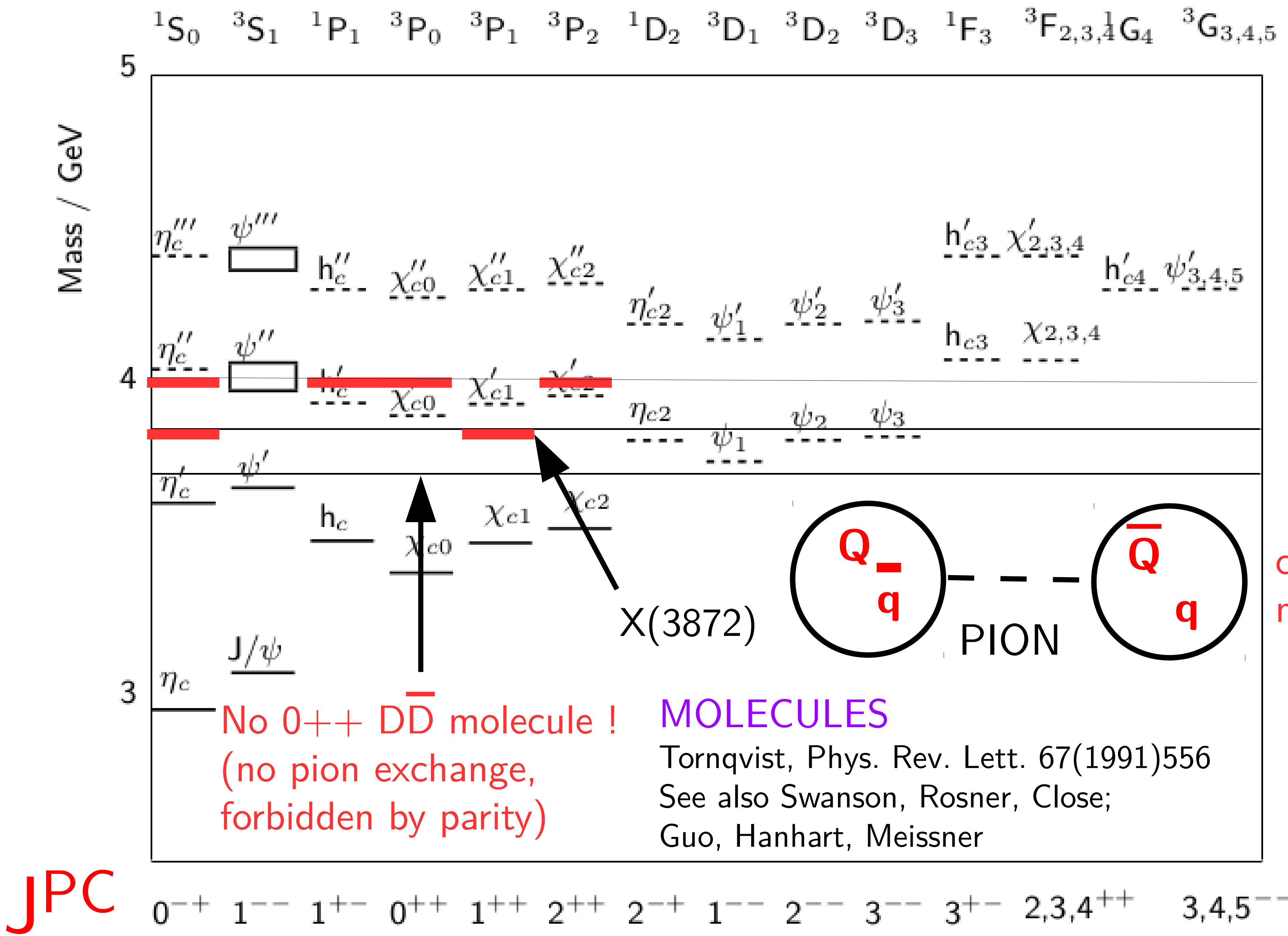
Table 4: Π_u Meson Quantum Numbers.



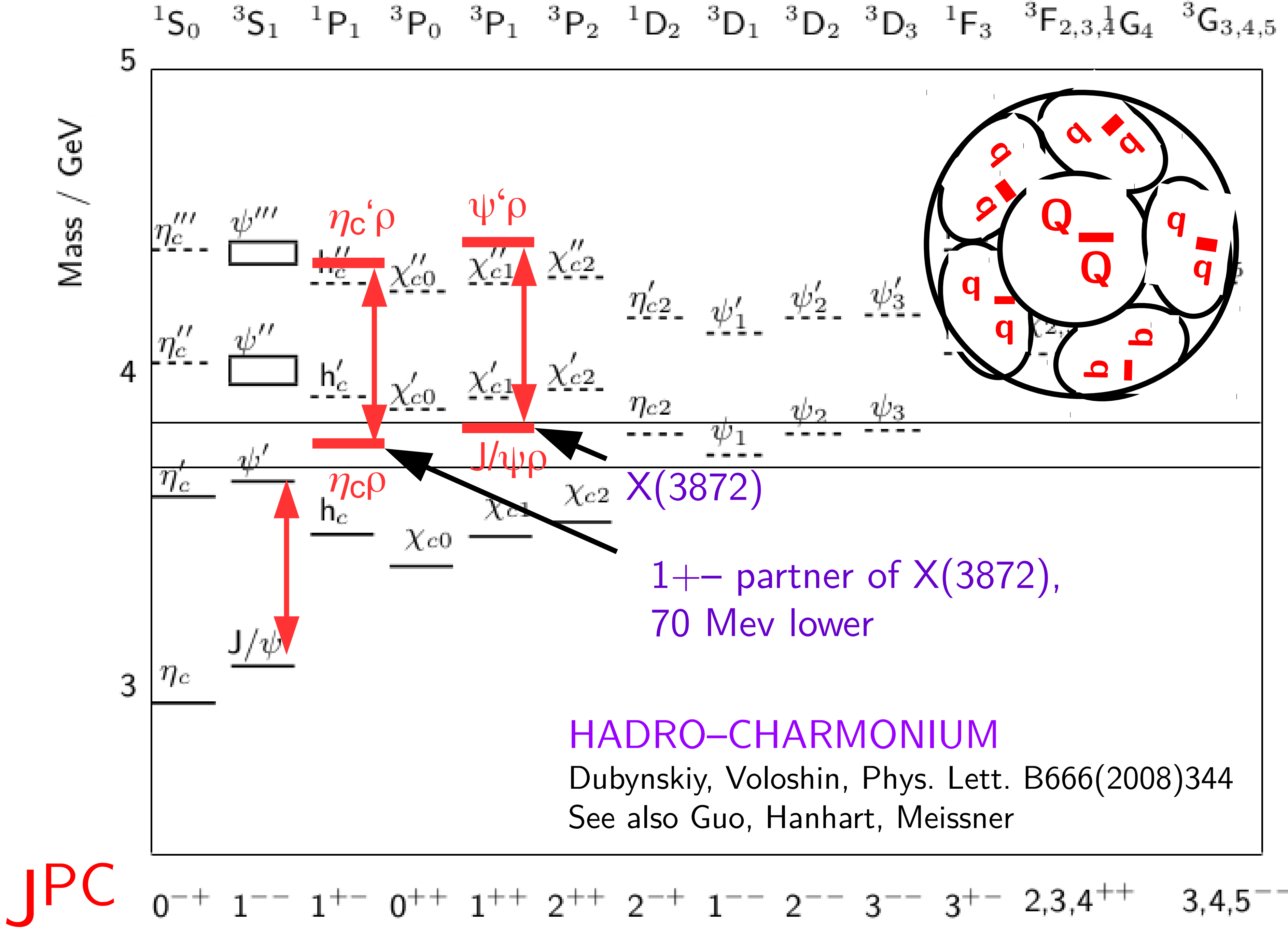
$^1S_0$ $^3S_1$ $^1P_1$ $^3P_0$ $^3P_1$ $^3P_2$ $^1D_2$ $^3D_1$ $^3D_2$ $^3D_3$ $^1F_3$ $^3F_{2,3,4}$ $^1G_4$ $^3G_{3,4,5}$
also (1,2,3) + − and (1,2,3) − +
L=2
Gap, few hundred MeV
L=1
~70 MeV
PARTNER !
η_c''' ψ''' h_c'' χ_{c0}'' χ_{c1}'' χ_{c2}'' h_{c3}' $\chi_{2,3,4}'$ h_{c4}' $\psi_{3,4,5}'$
η_{c2}' ψ_1' ψ_2' ψ_3' h_{c3} $\chi_{2,3,4}$
η_c'' ψ'' h_c' χ_{c0}' χ_{c1}' χ_{c2}' η_{c2} ψ_1 ψ_2 ψ_3
η_c' ψ' h_c χ_{c0} χ_{c1} χ_{c2}
η_c J/ψ
5
4
3
HYBRID
Juge, Kuti, Morningstar
Phys. Rev. Lett. 82(1999)4400
Nucl. Phys. Proc. Suppl. 63(1998)3261
see also Zhu; Kou, Pene; Close, Page;
JPC
0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++} 2^{-+} 1^{--} 2^{--} 3^{--} 3^{+-} $2,3,4^{++}$ $3,4,5^{--}$



A way to explain
1 − − overpopulation
Y(4350)
Y(4260)
Mass / GeV
JPC
r (fm)
1S
1P
$1P_{\Pi_u}$
Σ_u^-
Π_u
Σ_g^+



$^1S_0$ $^3S_1$ $^1P_1$ $^3P_0$ $^3P_1$ $^3P_2$ $^1D_2$ $^3D_1$ $^3D_2$ $^3D_3$ $^1F_3$ $^3F_{2,3,4}$ $^1G_4$ $^3G_{3,4,5}$
Mass / GeV
5
4
3
η_c''' ψ''' h_c'' χ_{c0}'' χ_{c1}'' χ_{c2}'' η_{c2}' ψ_1' ψ_2' ψ_3' h_{c3}' $\chi_{2,3,4}'$ h_{c4}' $\psi_{3,4,5}'$
h_{c3} $\chi_{2,3,4}$
η_c'' ψ'' h_c' χ_{c0}' χ_{c1}' χ_{c2}' η_{c2} ψ_1 ψ_2 ψ_3
η_c' ψ' h_c χ_{c0} χ_{c1} χ_{c2}
η_c J/ψ
X(3872)
Q q̄ PION Q̄ q
No 0++ $D\bar{D}$ molecule !
(no pion exchange,
forbidden by parity)
MOLECULES
Tornqvist, Phys. Rev. Lett. 67(1991)556
See also Swanson, Rosner, Close;
Guo, Hanhart, Meissner
JPC
0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++} 2^{-+} 1^{--} 2^{--} 3^{--} 3^{+-} $2,3,4^{++}$ $3,4,5^{--}$



1S0 3S1 1P1 3P0 3P1 3P2 1D2 3D1 3D2 3D3 1F3 3F2,3,4 1G4 3G3,4,5
Mass / GeV
5
4
3
ηc'ρ
ψ'ρ
J/ψρ
ηcρ
X(3872)
1+− partner of X(3872),
70 Mev lower
Q
Q
q
HADRO–CHARMONIUM
Dubynskiy, Voloshin, Phys. Lett. B666(2008)344
See also Guo, Hanhart, Meissner
JPC
0−+ 1−− 1+− 0++ 1++ 2++ 2−+ 1−− 2−− 3−− 3+− 2,3,4++ 3,4,5−−

Installation of 100 new LER Dipole Magnets

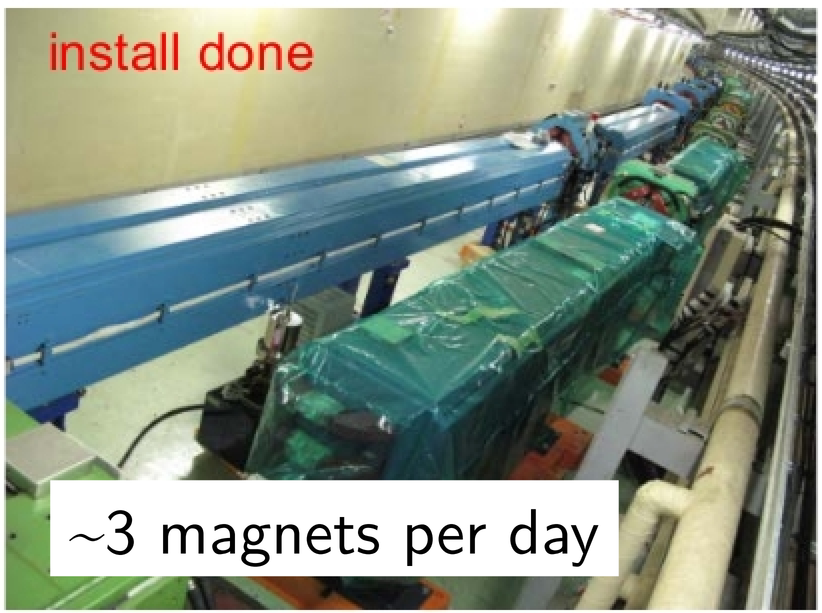
field measurement

move into tunnel

Installation of 100 new LER bending magnets done

carry on an air-pallet

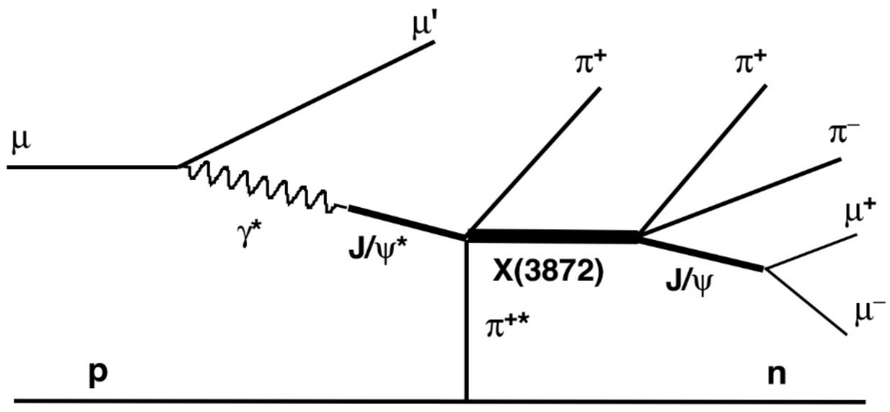
Install over HER magnets



19

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

Photoproduction of X(3872)

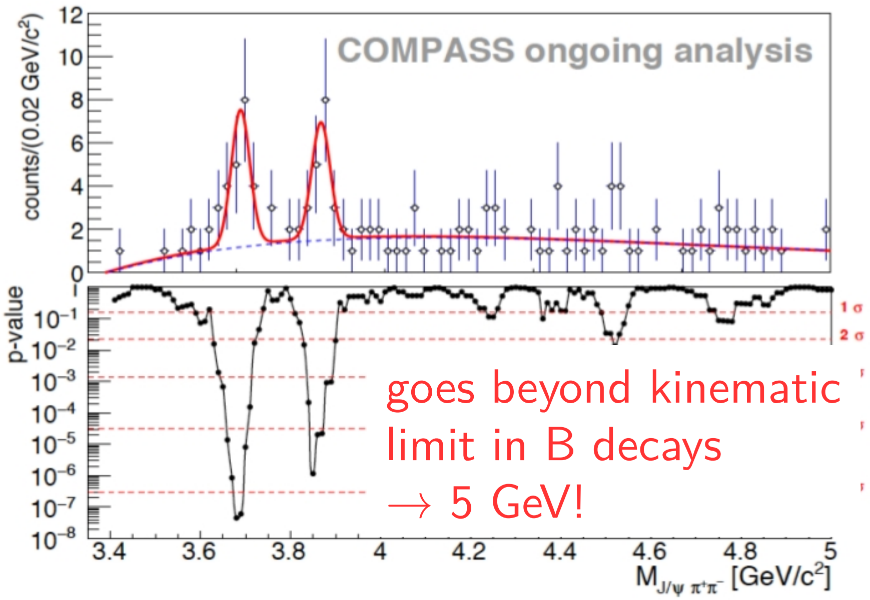


Muon data 2003-2010

$N_{\psi(2S)} = 16.1 \pm 5.2$

$N_{X(3872)} = 13.9 \pm 4.9$

$\sigma_M = 20.6 \pm 6.1$ MeV



goes beyond kinematic limit in B decays
→ 5 GeV!

COMPASS, arXiv:1707.01796 [hep-ex]