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Doubly heavy exotic mesons and baryons and how to look for them

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PRD91 (2015) 1, 014014 & PRD90 (2014) 9, 094007, with Jon Rosner
JHEP 7,153(2013) with Shmuel Nussinov
arXiv:1503.07209, with Matthew Low, Jon Rosner and Lian-Tao Wang
arXiv:1506.06386, with Jon Rosner

55 Cracow School of Theoretical Physics, Zakopane, June 2015

Outline

(1) new mesons and baryons with
two heavy quarks;
some manifestly exotic

(2) using radiative return in
future high-E high-$\mathcal{L}$
e^+e^- colliders to explore
this new spectroscopy of QCD

mesonic doubly-heavy exotics:

hadronic molecules
and/or
tetraquarks

it has been realized early on that quark models and QCD sustain a much richer pattern of different multi-quark and/or color network configurations, beyond the "non-exotic" standard $\bar{q}q$ mesons and qqq baryons. Still, production rates of such particles are often suppressed and the light pions will in most cases allow rapid decays of the exotics into final states with pion(s) – turning them into very broad resonances.

This explains why the vast majority of known hadrons are simple mesons and baryons.

The situation is different for exotics which contain a heavy quark-antiquark pair and a light quark-antiquark pair: $\bar{Q}Q\bar{q}q$

The heavy quarks hardly mix with the light quarks, so such exotics decay into quarkonium and pion(s) or into two heavy-light mesons, providing clear signature of their exotic nature:

$$\bar{Q}Q\bar{q}q \rightarrow \bar{Q}Q\ \pi$$
$$\bar{Q}Q\bar{q}q \rightarrow (\bar{Q}q)\ (Q\bar{q})$$

Hadrons containing heavy quarks are simpler

than hadrons containing light quarks only,

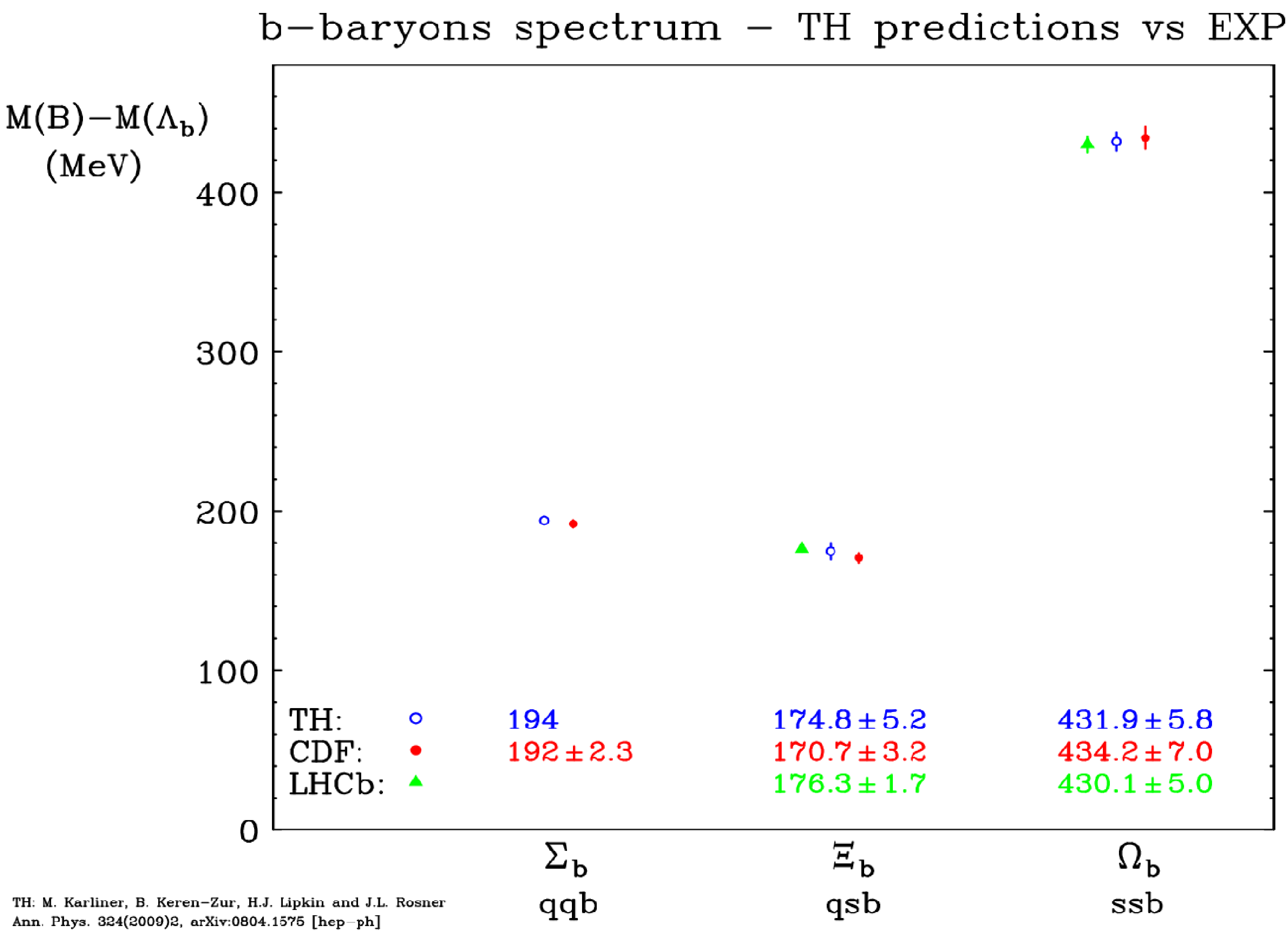
because the heavy quarks are almost static

and have a very small spin-dependent interaction

with other quarks.

This was the key to the accurate prediction of

baryons containing the b quark:


b–baryons spectrum – TH predictions vs EXP
M(B)–M(Λb) (MeV)
400
300
200
100
0
TH:
CDF:
LHCb:
194
192 ± 2.3
174.8 ± 5.2
170.7 ± 3.2
176.3 ± 1.7
431.9 ± 5.8
434.2 ± 7.0
430.1 ± 5.0
Σb
qqb
Ξb
qsb
Ωb
ssb
TH: M. Karliner, B. Keren–Zur, H.J. Lipkin and J.L. Rosner
Ann. Phys. 324(2009)2, arXiv:0804.1575 [hep–ph]

Possibility of Exotic States in the Upsilon system

Marek Karliner [a*]
and
Harry J. Lipkin [a,b†]

Abstract

Recent data from Belle show unusually large partial widths $\Upsilon(5S) \to \Upsilon(1S)\,\pi^+\pi^-$ and $\Upsilon(5S) \to \Upsilon(2S)\,\pi^+\pi^-$. The $Z(4430)$ narrow resonance also reported by Belle in $\psi'\pi^+$ spectrum has the properties expected of a $\bar{c}cu\bar{d}$ charged isovector tetraquark $T^{\pm}_{\bar{c}c}$. The analogous state $T^{\pm}_{\bar{b}b}$ in the bottom sector might mediate anomalously large cascade decays in the Upsilon system, $\Upsilon(mS) \to T^{\pm}_{\bar{b}b}\pi^{\mp} \to \Upsilon(nS)\,\pi^+\pi^-$, with a tetraquark-pion intermediate state. We suggest looking for the $\bar{b}bu\bar{d}$ tetraquark in these decays as peaks in the invariant mass of $\Upsilon(1S)\,\pi$ or $\Upsilon(2S)\,\pi$ systems. The $\bar{b}bu\bar{s}$ tetraquark can appear in the observed decays $\Upsilon(5S) \to \Upsilon(1S)\,K^+K^-$ as a peak in the invariant mass of $\Upsilon(1S)\,K$ system. We review the model showing that these tetraquarks are below the two heavy meson threshold, but respectively above the $\Upsilon\,\pi\pi$ and $\Upsilon\,K\bar{K}$ thresholds.

Observation of two charged bottomonium-like resonances

The Belle Collaboration

(Dated: May 24, 2011)

Abstract

We report the observation of two narrow structures at 10610 MeV/c^2 and 10650 MeV/c^2 in the $\pi^\pm\Upsilon(nS)$ $(n = 1, 2, 3)$ and $\pi^\pm h_b(mP)$ $(m = 1, 2)$ mass spectra that are produced in association with a single charged pion in $\Upsilon(5S)$ decays. The measured masses and widths of the two structures averaged over the five final states are $M_1 = 10608.4 \pm 2.0\,\mathrm{MeV}/c^2$, $\Gamma_1 = 15.6 \pm 2.5\,\mathrm{MeV}$ and $M_2 = 10653.2 \pm 1.5\,\mathrm{MeV}/c^2$, $\Gamma_2 = 14.4 \pm 3.2\,\mathrm{MeV}$. Analysis favors quantum numbers of $I^G(J^P)=1^+(1^+)$ for both states. The results are obtained with a $121.4\,\mathrm{fb}^{-1}$ data sample collected with the Belle detector near the $\Upsilon(5S)$ resonance at the KEKB asymmetric-energy e^+e^- collider.

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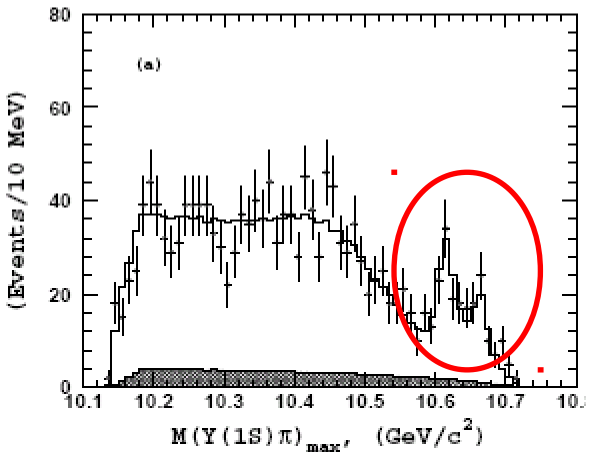
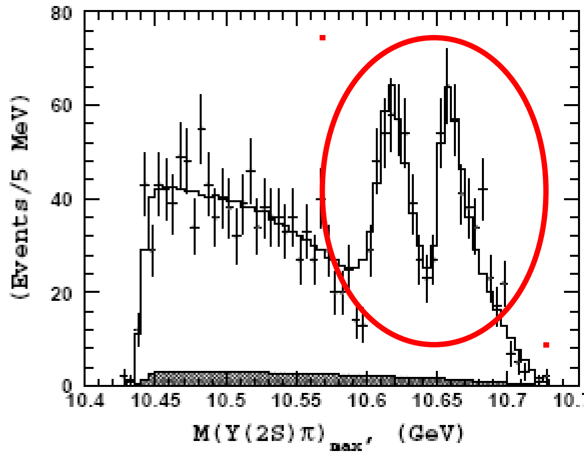
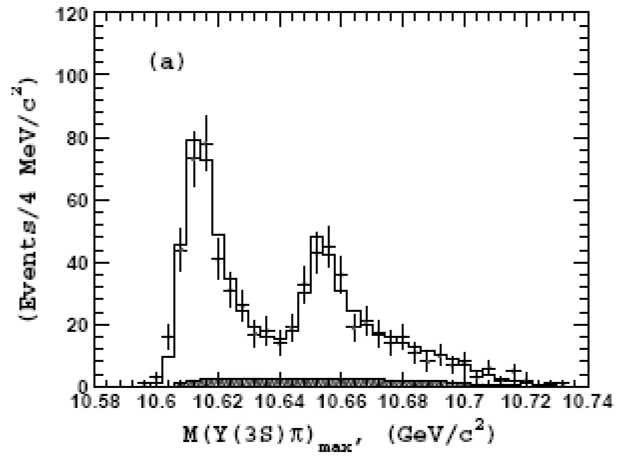
much more in lectures by S. Eidelman

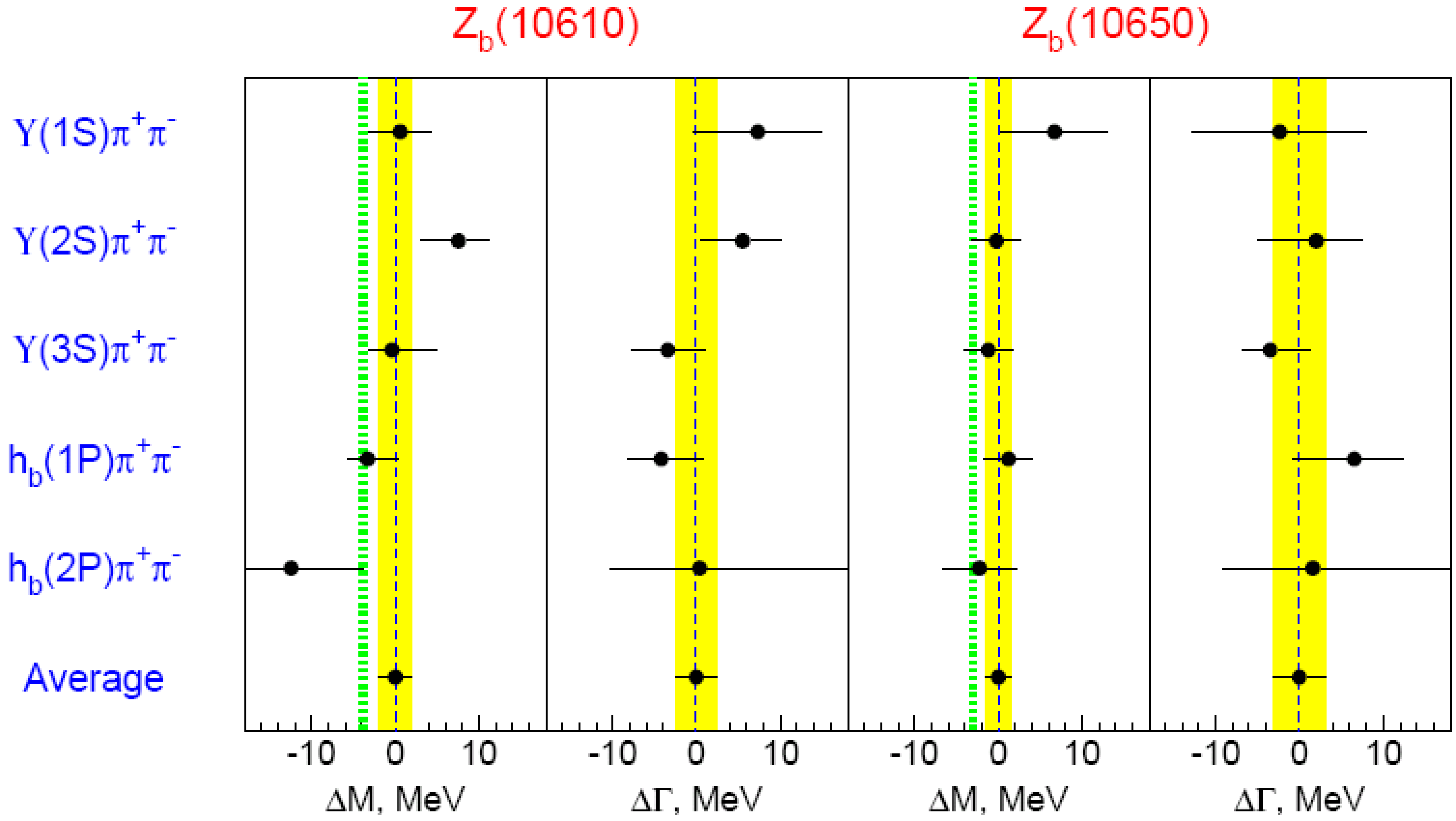






$\Upsilon(3S)\pi^+$ $\Upsilon(2S)\pi^+$ $\Upsilon(1S)\pi^+$

1



Comparison of $Z_b(10610)$ and $Z_b(10650)$ parameters obtained from different decay channels. The vertical dotted lines indicate $B^*\overline{B}$ and $B^*\overline{B}^*$ thresholds.

$$J^P = 1^+ \quad \text{for both } Z_b(10610) \text{ and } Z_b(10650)$$

Full Amplitude Analysis with Full Statistics

Parameter	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$
$f_{Z_b^{\mp}(10610)\pi^{\pm}}$, %	$4.8 \pm 1.2^{+1.5}_{-0.3}$	$18.1 \pm 3.1^{+4.2}_{-0.3}$	$30.0 \pm 6.3^{+5.4}_{-7.1}$
$M(Z_b(10610))$, MeV	$10608.5 \pm 3.4^{+3.7}_{-1.4}$	$10608.1 \pm 1.2^{+1.5}_{-0.2}$	$10607.4 \pm 1.5^{+0.8}_{-0.2}$
$\Gamma(Z_b(10610))$, MeV	$18.5 \pm 5.3^{+6.1}_{-2.3}$	$20.8 \pm 2.5^{+0.3}_{-2.1}$	$18.7 \pm 3.4^{+2.5}_{-1.3}$
$f_{Z_b^{\mp}(10650)\pi^{\pm}}$, %	$0.87 \pm 0.32^{+0.16}_{-0.12}$	$4.05 \pm 1.2^{+0.95}_{-0.15}$	$13.3 \pm 3.6^{+2.6}_{-1.4}$
$M(Z_b(10650))$, MeV	$10656.7 \pm 5.0^{+1.1}_{-3.1}$	$10650.7 \pm 1.5^{+0.5}_{-0.2}$	$10651.2 \pm 1.0^{+0.4}_{-0.3}$
$\Gamma(Z_b(10650))$, MeV	$12.1^{+11.3+2.7}_{-4.8-0.6}$	$14.2 \pm 3.7^{+0.9}_{-0.4}$	$9.3 \pm 2.2^{+0.3}_{-0.5}$

$J^P = 1^+$ for both Z_b is favored over 1^-, 2^- and 2^+ at more than 6σ

A. Garmash et al., Phys. Rev. D 91 (2015) 072003

$f_{Z_b(10610)}$ much bigger for $\Upsilon(3S)$, which has a large spatial extent.
$\Longrightarrow$ $Z_b(10610)$ is a large object.

The Z_b resonances decay into

$\Upsilon(nS)$ and a charged pion

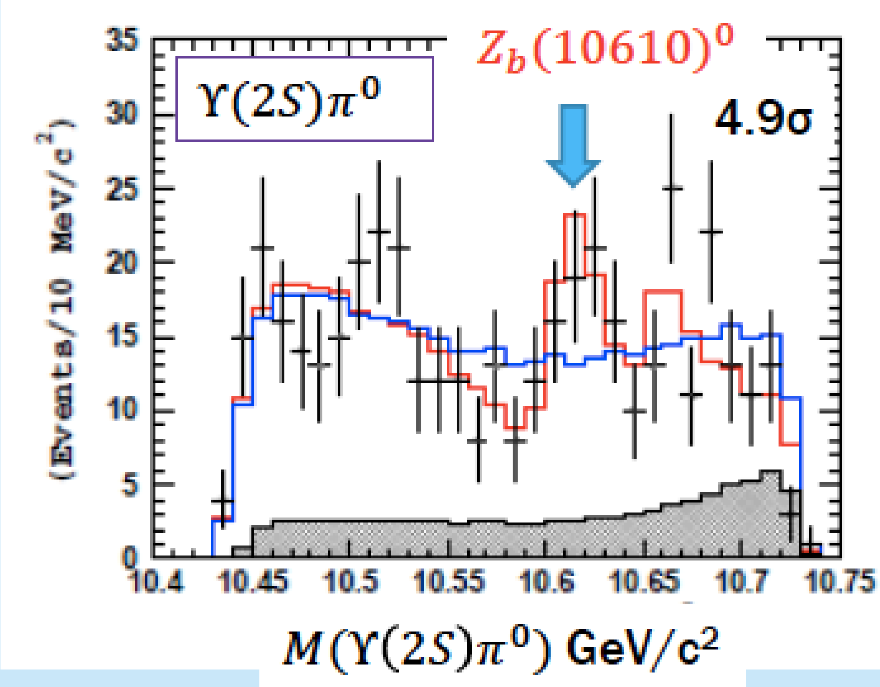
$\Longrightarrow$ must contain both $\bar{b}b$ and $\bar{d}u$

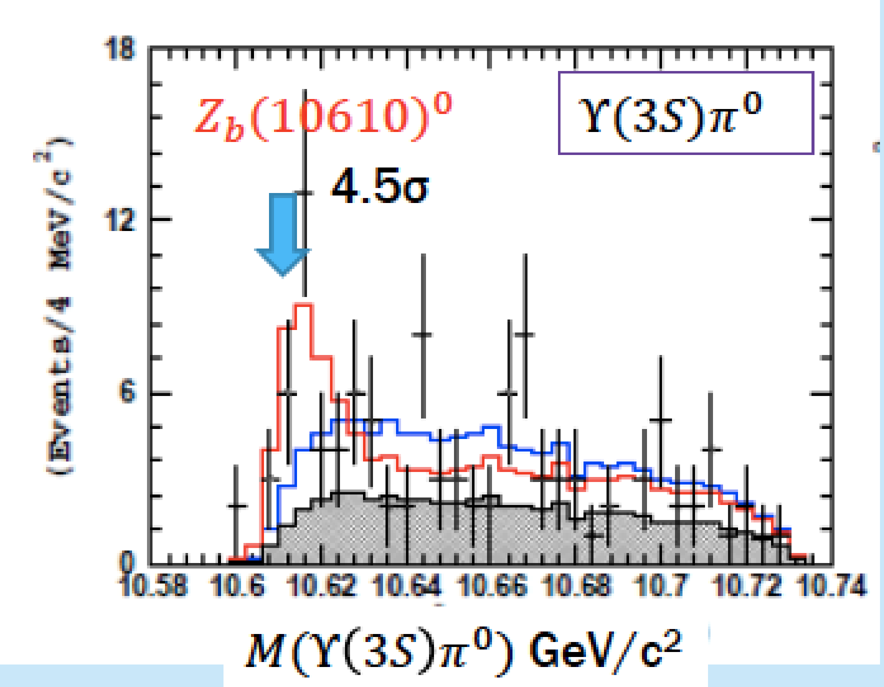
$\Longrightarrow$ manifestly exotic

Neutral member of the I=1 multiplet also observed by Belle in Dalitz plot analysis

$\Upsilon(5S) \to \Upsilon(nS)\pi^0\pi^0$ decay

In this fit mass and width are fixed from the charged Z_b result.





Simultaneous fit gives 6.3 σ for $Z_b(10610)^0$

arXiv:1207.4345

After the discovery of Z_b-s by Belle,
natural to expect analogous states
in the charm system

one caveat:

a priori unknown whether charmed quarks
are heavy enough to allow for binding

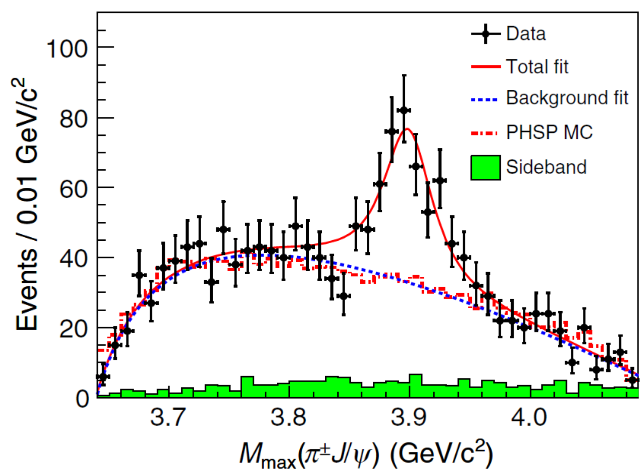
in March 2013 BES in Beijing,
followed by Belle in KEK provided
the answer for the question if charm is heavy enough:

BESIII Collaboration

Selected for a Viewpoint in *Physics*
PRL **110,** 252001 (2013) PHYSICAL REVIEW LETTERS week ending 21 JUNE 2013

Observation of a Charged Charmoniumlike Structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV

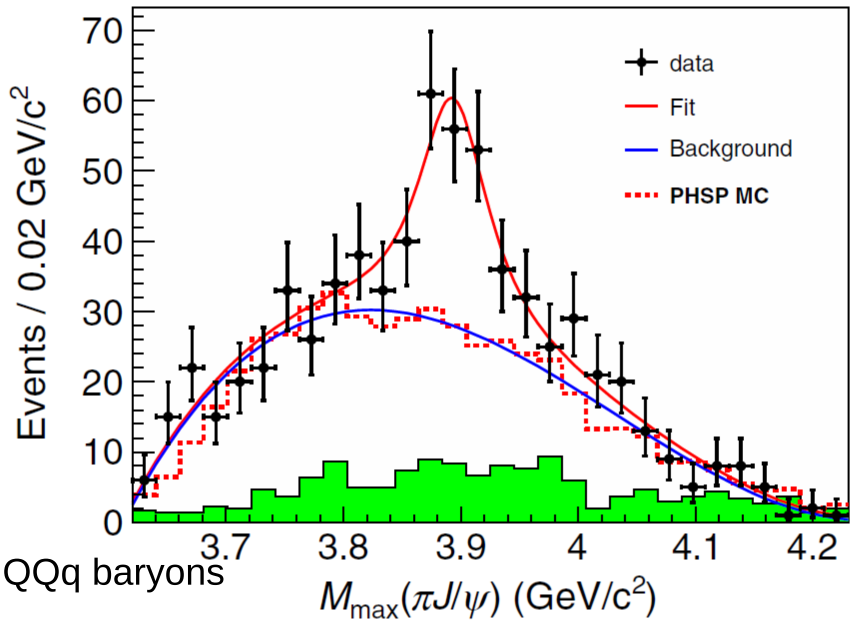
We study the process $e^+e^- \to \pi^+\pi^- J/\psi$ at a center-of-mass energy of 4.260 GeV using a 525 pb^{-1} data sample collected with the BESIII detector operating at the Beijing Electron Positron Collider. The Born cross section is measured to be $(62.9 \pm 1.9 \pm 3.7)$ pb, consistent with the production of the $Y(4260)$. We observe a structure at around 3.9 GeV/c^2 in the $\pi^\pm J/\psi$ mass spectrum, which we refer to as the $Z_c(3900)$. If interpreted as a new particle, it is unusual in that it carries an electric charge and couples to charmonium. A fit to the $\pi^\pm J/\psi$ invariant mass spectrum, neglecting interference, results in a mass of $(3899.0 \pm 3.6 \pm 4.9)$ MeV/c^2 and a width of $(46 \pm 10 \pm 20)$ MeV. Its production ratio is measured to be $R = (\sigma(e^+e^- \to \pi^\pm Z_c(3900)^\mp \to \pi^+\pi^- J/\psi)/\sigma(e^+e^- \to \pi^+\pi^- J/\psi)) = (21.5 \pm 3.3 \pm 7.5)\%$. In all measurements the first errors are statistical and the second are systematic.



Selected for a Viewpoint in *Physics*
PRL **110**, 252002 (2013) PHYSICAL REVIEW LETTERS week ending 21 JUNE 2013

Study of $e^+e^- \to \pi^+\pi^- J/\psi$ and Observation of a Charged Charmoniumlike State at Belle

The cross section for $e^+e^- \to \pi^+\pi^- J/\psi$ between 3.8 and 5.5 GeV is measured with a 967 fb^{-1} data sample collected by the Belle detector at or near the $\Upsilon(nS)$ ($n = 1, 2, \ldots, 5$) resonances. The $Y(4260)$ state is observed, and its resonance parameters are determined. In addition, an excess of $\pi^+\pi^- J/\psi$ production around 4 GeV is observed. This feature can be described by a Breit-Wigner parametrization with properties that are consistent with the $Y(4008)$ state that was previously reported by Belle. In a study of $Y(4260) \to \pi^+\pi^- J/\psi$ decays, a structure is observed in the $M(\pi^\pm J/\psi)$ mass spectrum with 5.2σ significance, with mass $M = (3894.5 \pm 6.6 \pm 4.5)$ MeV/c^2 and width $\Gamma = (63 \pm 24 \pm 26)$ MeV/c^2, where the errors are statistical and systematic, respectively. This structure can be interpreted as a new charged charmoniumlike state.

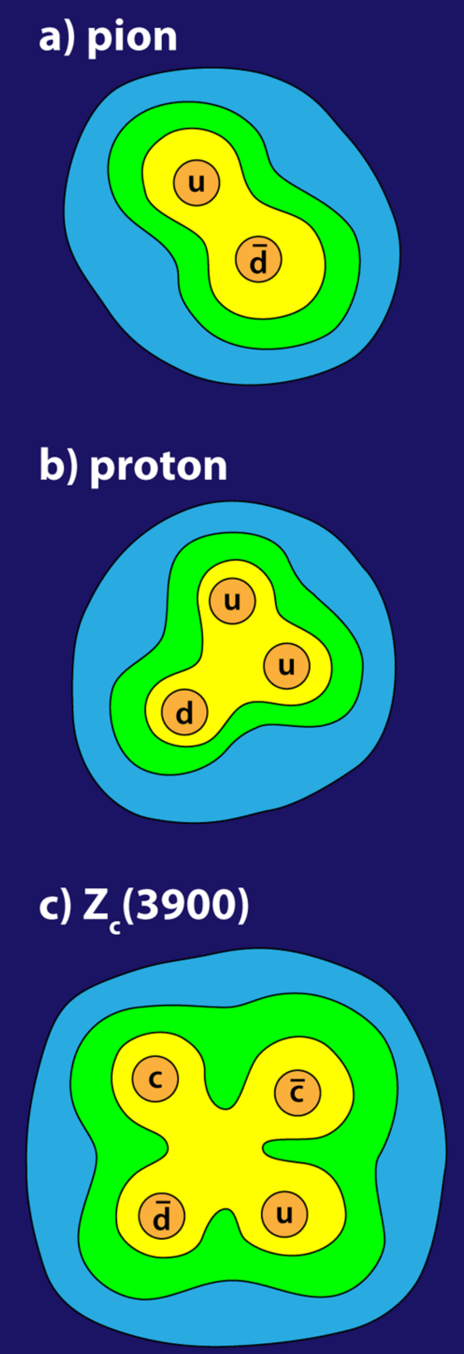


$$\frac{\Gamma(Z_c(3885) \to \bar{D} D^*)}{\Gamma(Z_c(3885) \to J/\psi\pi)} = 6.2 \pm 1.1 \pm 2.7$$

(BESIII/Yu-Ping Guo @EQCD, Jinan 6/2015)

overlap of Z_c wave function with $J/\psi\pi$ much smaller than with $\bar{D}D$

$\Rightarrow$ indicates an extended object



tetraquark or a "hadronic molecule" ?

The molecule idea has a long history:
Voloshin Okun (1976),
de Rujula, Georgi Glashow (1977)
Tornqvist, Z. Phys. C61,525 (1993)

Z_b-s: 3 MeV above the $\bar{B}B^*$ and $\bar{B}^*B^*$ thresholds
$X(3872)$: <u>at</u> $\bar{D}D^*$ threshold

despite large phase space (hundreds of MeV)
narrow widths in decays into $\bar{Q}Q\,\pi$
$\Longrightarrow$ very small overlap of wave functions: $|\langle i|f\rangle|^2 \ll 1$

<u>strong hint in favor of molecular interpretation</u>

what about $Z_c(3900)$?

Heavy-liqht $Q\bar{q}$ mesons have $I = 1$

$\Rightarrow$ they couple to pions; $m_{Q\bar{q}} \gg m_N$

$\Rightarrow$ deutron-like meson-meson bound states, "*deusons*"

pion exchange $\rightarrow$ no $\bar{D}D$, only $\bar{D}D^*$, $\bar{D}^*D^*$

$\bar{D}D^*$ $(I = 0)$ at threshold: $X(3872)$!

S-wave $\rightarrow$ $J^P = 1^+$, confirmed by BESIII

$I = 1$: $3\times$ weaker than $I = 0$

$\Rightarrow$ $I = 1$ well above threshold

What about $\bar{B}B^*$ analogue ?....

$\bar{B}B*$ vs. $\bar{D}D^*$:

- same attractive potential
- much heavier, so smaller kinetic energy

$\Rightarrow$ expect $\bar{B}B^*$ and $\bar{B}^*B^*$ states near threshold

$\Rightarrow$ $Z_b(10610)$ and $Z_b(10650)$ seen by Belle !

- $I = 0$ much stronger than $I = 1$

$\Rightarrow$ $I = 0$ states expected well <u>below</u> thresholds

EXP signature:

$X_b^{(*)}(I = 0) \to \Upsilon(nS)\,\omega, \quad \chi_b\pi^+\pi^-$

perhaps also

$X_b^*(I = 0) \to \bar{B}B^*\gamma$ via $\bar{B}^* \to \bar{B}\gamma$

$\Rightarrow$ LHCb !

in the $M_Q \longrightarrow \infty$ limit attractive potential between the two heavy mesons becomes universal, as kinetic energy vanishes:

$$\text{Kinetic } E \sim \frac{p^2}{M_Q} \longrightarrow 0 \quad \text{as } M_Q \to \infty$$

→ treat kinetic E as perturbation:

$$H = a \cdot p^2 + V(r) \qquad\qquad \text{where } a \equiv 1/2\mu_{\rm red}$$

convert the parameter $a \sim 1/M_Q$ into a dimensionless parameter $\tilde{a}$

"natural" unit of $\sim$ 0.8 Fermi $\sim$ 4.0 GeV^{-1}

With $m_D \sim 2\,\mathrm{GeV}$ and $m_B \sim 5.3\,\mathrm{GeV}$

$\tilde{a}(D) = 1/8$ $\qquad$ $\tilde{a}(B) = 1/21$

→ small: can use 1-st order P.T.

for I=1 potential have 2 data points:

$Z_c(3900)$ at $\tilde{a}(D)$ approximately $27\,\mathrm{MeV}$ above $\bar{D}D^*$ threshold

$Z_b(10610)$ at $\tilde{a}(B)$ approximately $3\,\mathrm{MeV}$ above $\bar{B}B^*$ threshold

Linear extrapolation to $\tilde{a} = 0$ yields

$$E_b^{I=1}(\tilde{a}{=}0) \approx -11.7\,\mathrm{MeV}$$

In view of the convexity, the actual binding energy likely to slightly exceed this linear extrapolation

→ use this result for the isovector channel to estimate the $\bar{B}B^*$ binding in the isoscalar channel

Assuming that the isoscalar binding energy in the $m_Q \to \infty$ limit is 3 times larger than for the isovector,

$$E_b^{I=0}(\tilde{a}{=}0) \approx 3 \cdot (-11.7) = -35\,\mathrm{MeV}$$

$X(3872)$ at $\bar{D}D^*$ threshold → $E_b^{I=0}(\tilde{a}(D)) \approx 0$

Linear extrapolation to $\tilde{a}(B)$ yields $\bar{B}B^*$ binding energy in the isoscalar channel $\approx -20\,\mathrm{MeV}$

Heavy Quark Nuclear Physics!

discovery of isovector $Z_c(3900)$

$\Rightarrow$ several quantitative predictions, arXiv:1304.0345:

- two narrow $X_b(I = 0)$ bottomonium-like resonances $\sim$ 23 MeV below $Z_b(10610)$ and $Z_b(10650)$, i.e. $\sim$ 20 MeV below $\bar{B}B^*$ and $\bar{B}^*B^*$ thresholds
- $I = 0$ narrow resonance very close to $\bar{D}^*D^*$ threshold
- $I = 1$ narrow resonance a bit above $\bar{D}^*D^*$ threshold

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did not have to wait long. . .

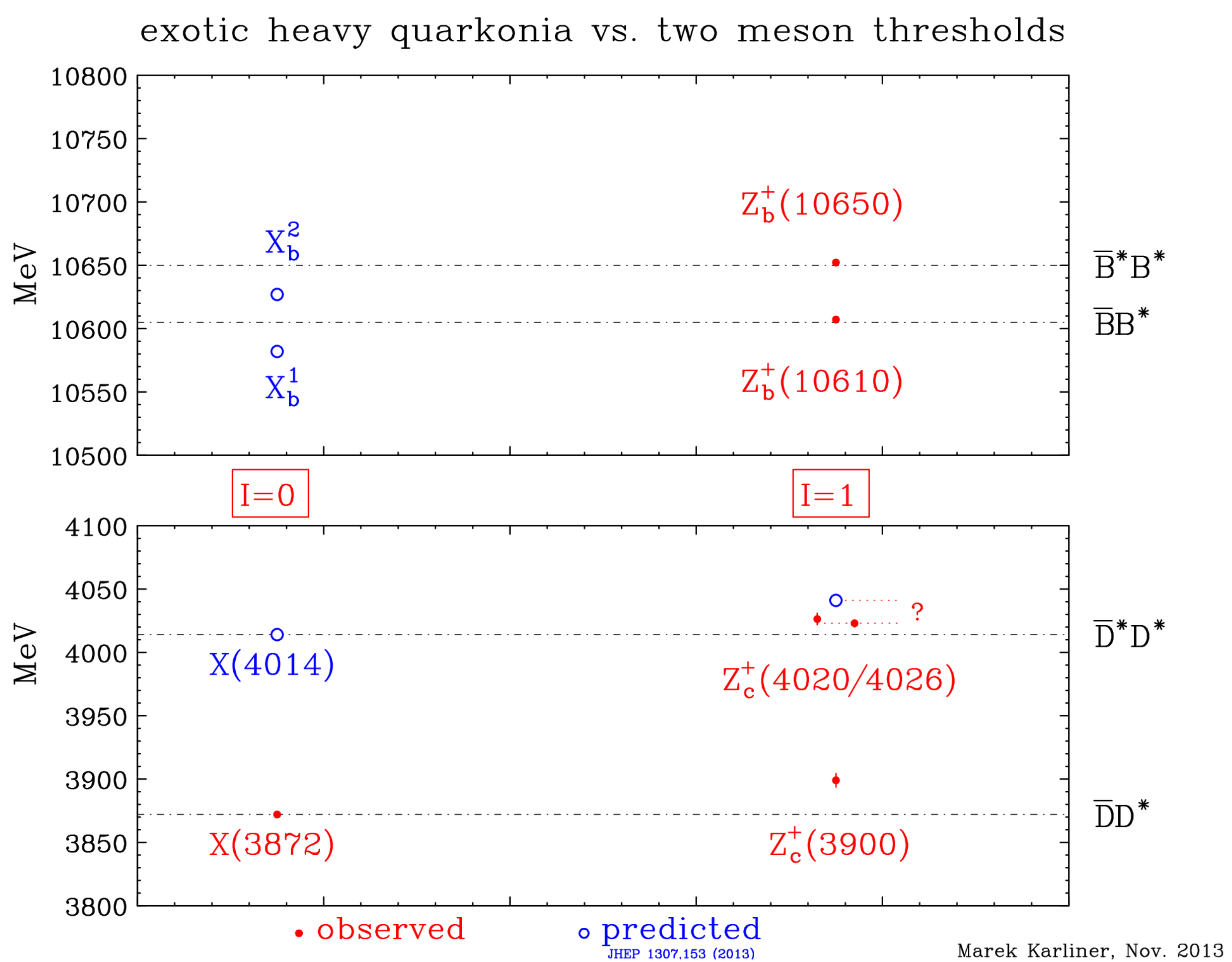
BESIII:

$Z_c^+(4025)$, arXiv:1308.2760, $\Gamma \approx 25$ MeV

$Z_c^+(4020)$, arXiv:1309.1896; $\Gamma \approx 8$ MeV same phenomena in charmonium

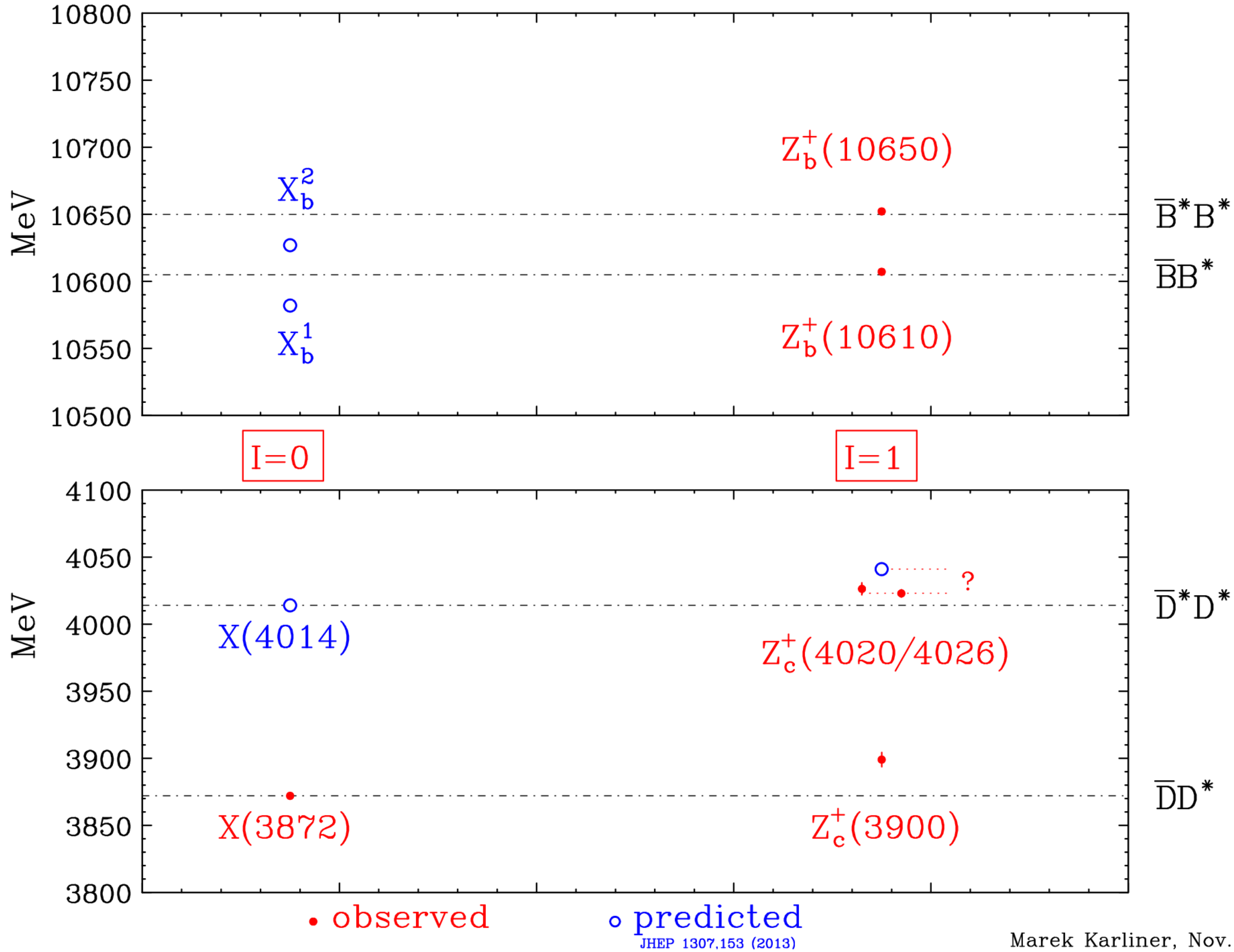
and bottomonium systems.

need a unified picture:



exotic heavy quarkonia vs. two meson thresholds
10800
10750
10700
10650
10600
10550
10500
MeV
X_b^2
X_b^1
$Z_b^+(10650)$
$Z_b^+(10610)$
$\bar{B}^*B^*$
$\bar{B}B^*$
I=0
I=1
4100
4050
4000
3950
3900
3850
3800
MeV
X(4014)
X(3872)
?
$Z_c^+(4020/4026)$
$Z_c^+(3900)$
$\bar{D}^*D^*$
$\bar{D}D^*$
observed
predicted
JHEP 1307,153 (2013)
Marek Karliner, Nov. 2013

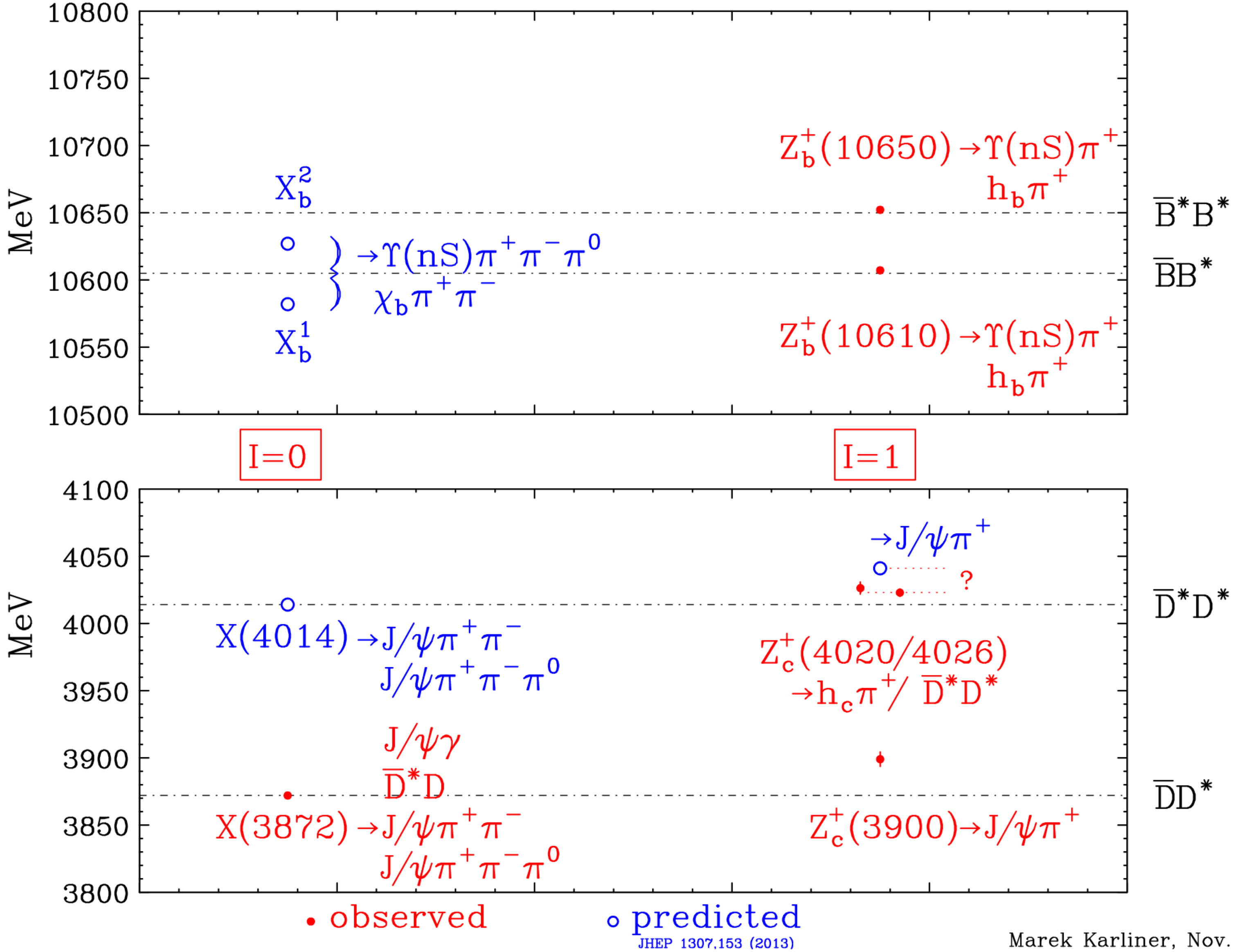
exotic heavy quarkonia vs. two meson thresholds



Marek Karliner, Nov. 2013

caveat: some masses = peak positions,
with interference $\neq$ pole mass

exotic heavy quarkonia vs. two meson thresholds



Marek Karliner, Nov. 2013

Caveat about mass predictions:

$m(D^*) - [m(D) + m(\pi)] \approx 0^{\pm}$,

depending on D^* and π charges;

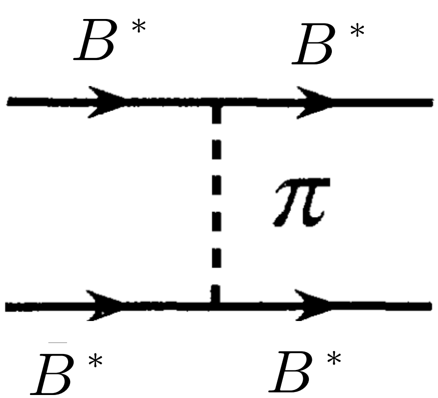
affects $D^* \to D\pi$ (strong decay)

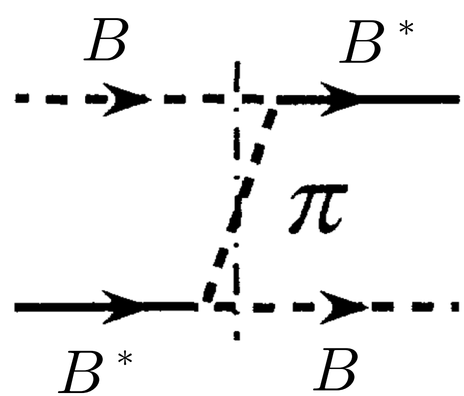
vs.

$B^* \to B\gamma$ (EM decay)

so $\bar{D}D^*$ and $\bar{D}^*D^*$ potential

might be slightly different from $\bar{B}B^*$ and $\bar{B}^*B^*$





Likely observable at LHC and Tevatron:

$\sim$ nb x-section for $Z_b(10610)$, $Z_b(10650)$ and X_b

for $Z_c(3900)$, $Z_c(4020)$ 20-30$\times$ larger

Guo, Meiner Wang, arXiv:1308.0193

Guo, Meiner, Wang Yang, arXiv:1402.6236

large enough to be observed

Null result from CMS:

CERN-PH-EP/2013-157
2013/09/03

CMS-BPH-11-016

Search for a new bottomonium state decaying to $\Upsilon(1S)\pi^+\pi^-$ in pp collisions at $\sqrt{s} = 8$ TeV

The CMS Collaboration*

Abstract

The results of a search for the bottomonium counterpart, denoted as X_b, of the exotic charmonium state X(3872) is presented. The analysis is based on a sample of pp collisions at $\sqrt{s} = 8$ TeV collected by the CMS experiment at the LHC, corresponding to an integrated luminosity of $20.7\,\mathrm{fb}^{-1}$. The search looks for the exclusive decay channel $X_b \to \Upsilon(1S)\pi^+\pi^-$ followed by $\Upsilon(1S) \to \mu^+\mu^-$. No evidence for an X_b signal is observed. Upper limits are set at the 95% confidence level on the ratio of the inclusive production cross sections times the branching fractions to $\Upsilon(1S)\pi^+\pi^-$ of the X_b and the $\Upsilon(2S)$. The upper limits on the ratio are in the range 0.9–5.4% for X_b masses between 10 and 11 GeV. These are the first upper limits on the production of a possible X_b at a hadron collider.

The null result from CMS in search for

$$X_b \to Y(1S)\pi^+\pi^-$$

is excellent news for the molecular picture,

since isoscalar X_b with $J^{PC} = 1^{++}$

cannot decay into $\Upsilon(1S)\pi^+\pi^-$

It can decay into $\Upsilon(1S)\,\omega$ or $\chi_b\,\pi^+\pi^-$

a propos CMS search for X_b:
their search was motivated by analogy between J/ψ and X_b

analogies are useful, but have to be used with care, otherwise they can lead to <u>unrealistic expectations</u>.

For example, extrapolating from the former First Lady of US

to the former First Lady of USSR…

could have lead Mrs Khrushchev

to think it was her, rather than

Jackie, that should have

married the Greek shipping

magnate Aristotle Onassis...

X_b as mixture of $\bar{B}B^*$ (1^{++}) and $\chi_b(3P)$

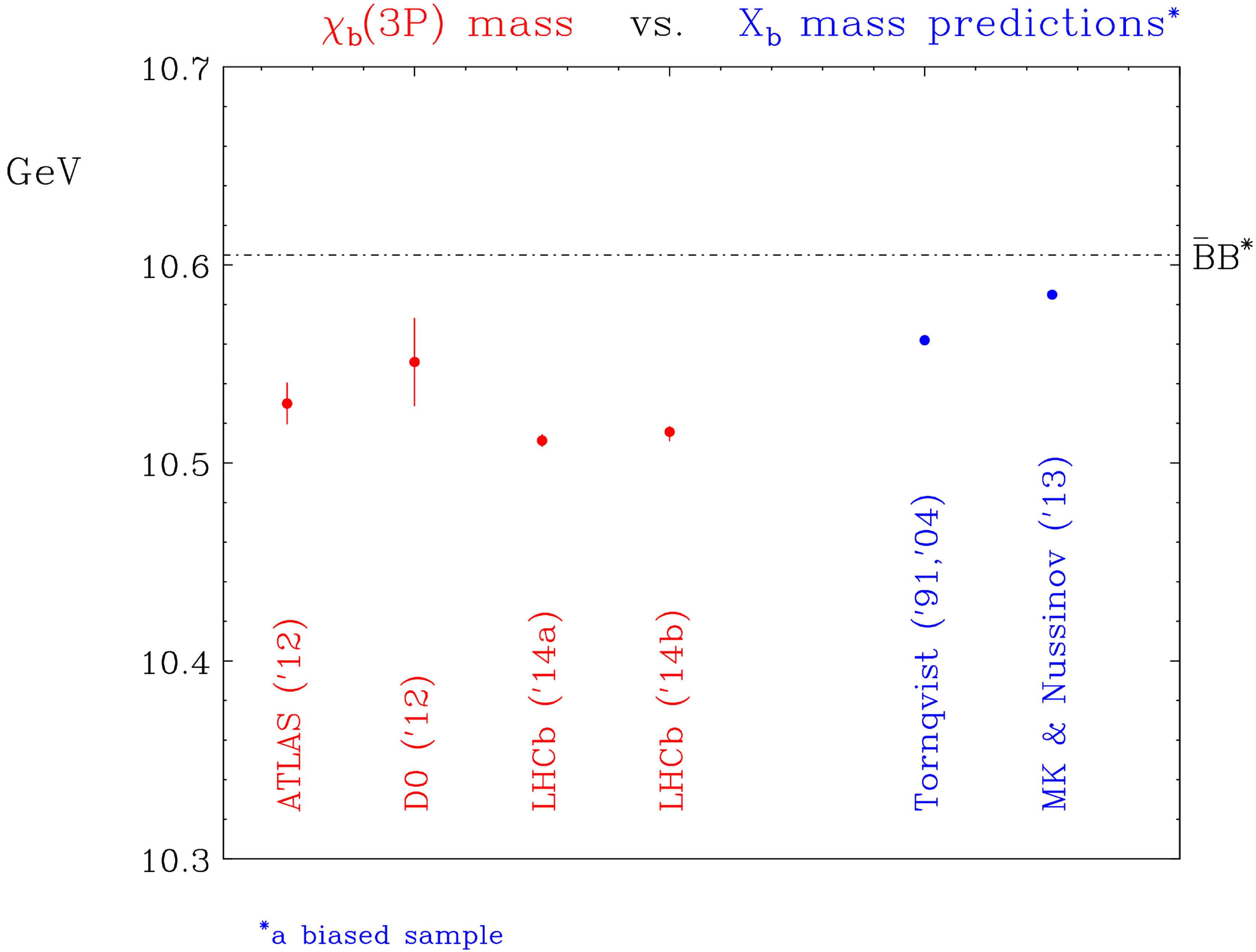
$$R_{\psi\gamma} \equiv \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29 \text{ [LHCb]}$$

suggests that $X(3872)$ is a mixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{*0}$

In the bottomonium system $\chi_{b1}(2P)$ is much too light, but $\chi_{b1}(3P)$ is near the expected X_b mass.
Seen in $\chi_{b1}(3P) \to \Upsilon(mS)\gamma$, $m = 1, 2, 3$

Values of $M(\chi_{b1}(3P))$ observed in various experiments.

Collaboration	Reference	Value (MeV/c^2)
ATLAS	[17]	$10530 \pm 5 \pm 9$
D0	[18]	$10551 \pm 14 \pm 17$
LHCb (a)	[19]	$10511.3 \pm 1.7 \pm 2.5$
LHCb (b)	[20]	$10515.7^{+2.2+1.5}_{-3.9-2.1}$



χ_b(3P) mass vs. X_b mass predictions*
GeV
10.7
10.6
10.5
10.4
10.3
$\bar{B}B^*$
ATLAS ('12)
D0 ('12)
LHCb ('14a)
LHCb ('14b)
Tornqvist ('91,'04)
MK & Nussinov ('13)
*a biased sample

- X_b and $\chi_{1b}(3P)$ have the same quantum numbers

- their masses are close

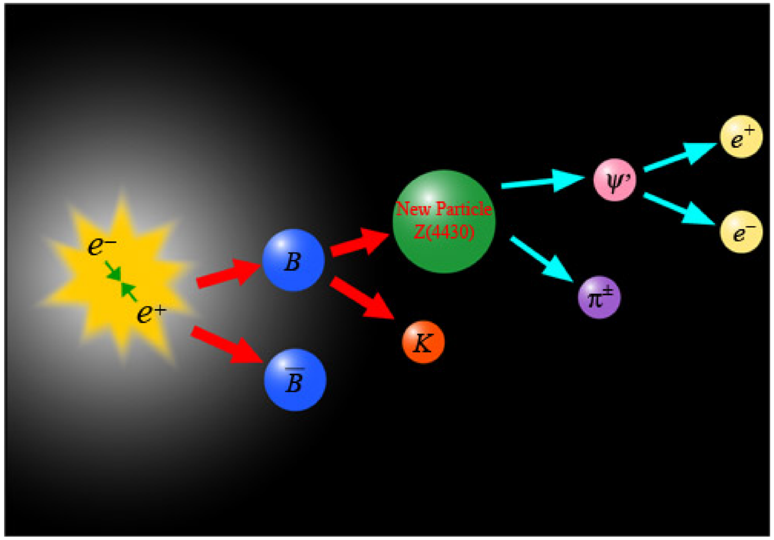
$\Rightarrow$ mixing is inevitable

$\Longrightarrow$ X_b might have been seen already,
by ATLAS, D0 and LHCb,
camouflaging as $\chi_{1b}(3P)$

Z(4430)

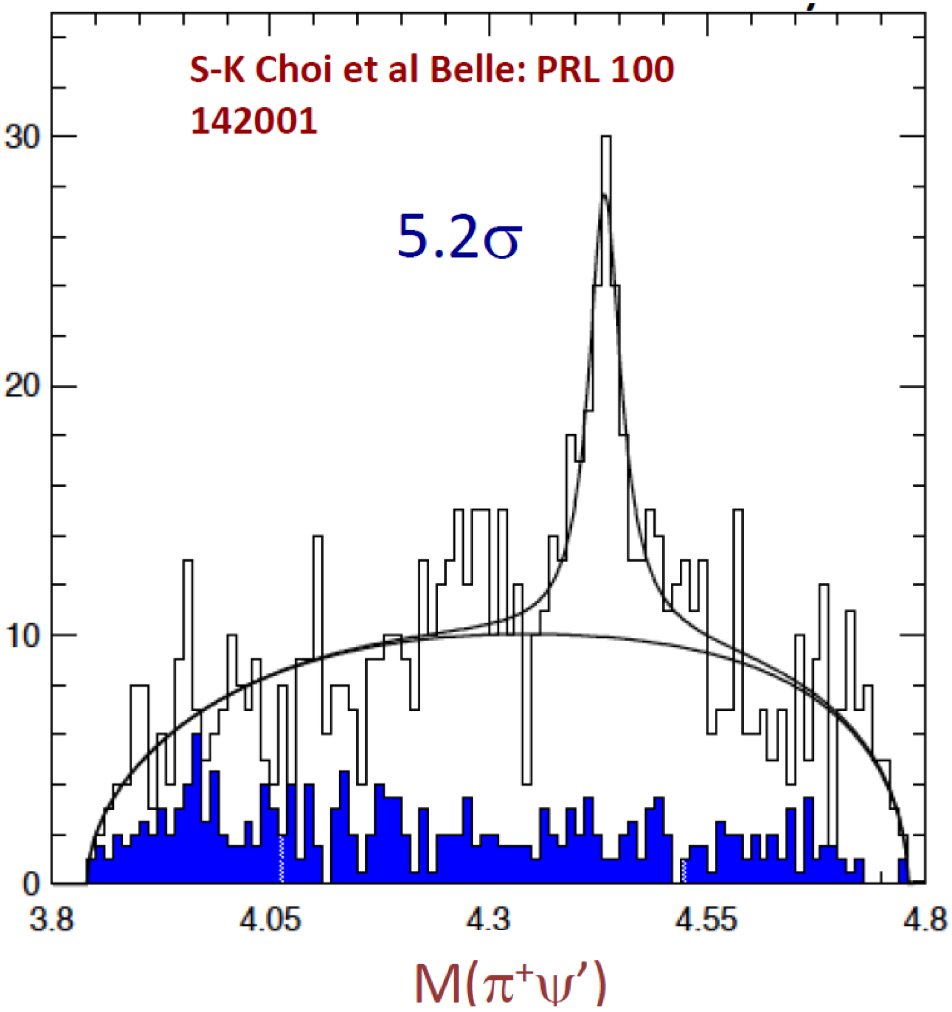
also manifestly exotic, but odd man out

Belle 2007:

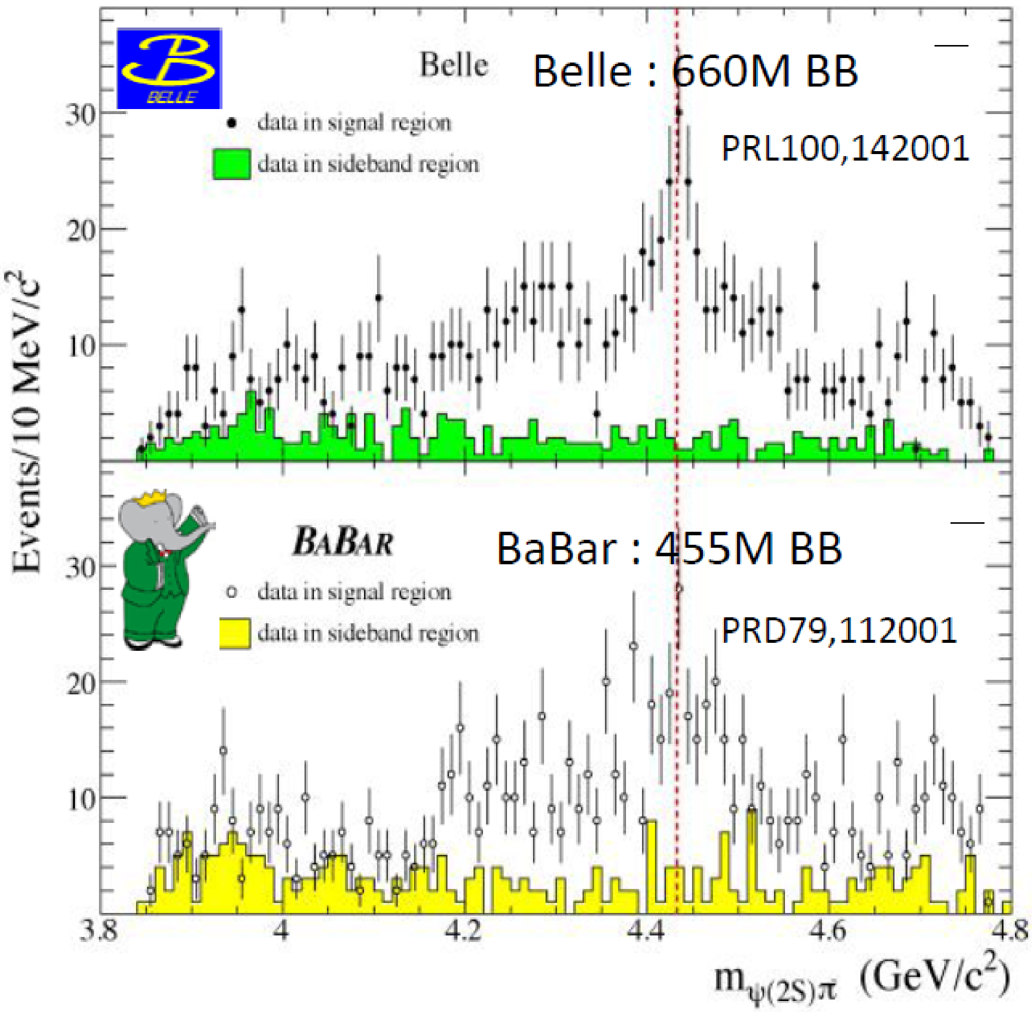


$$M = 4433 \pm 4 \pm 2 \text{ MeV}$$

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



Z(4430) not seen by BaBar



$Z(4430)^{\pm} \rightarrow \psi' \pi^{\pm}$

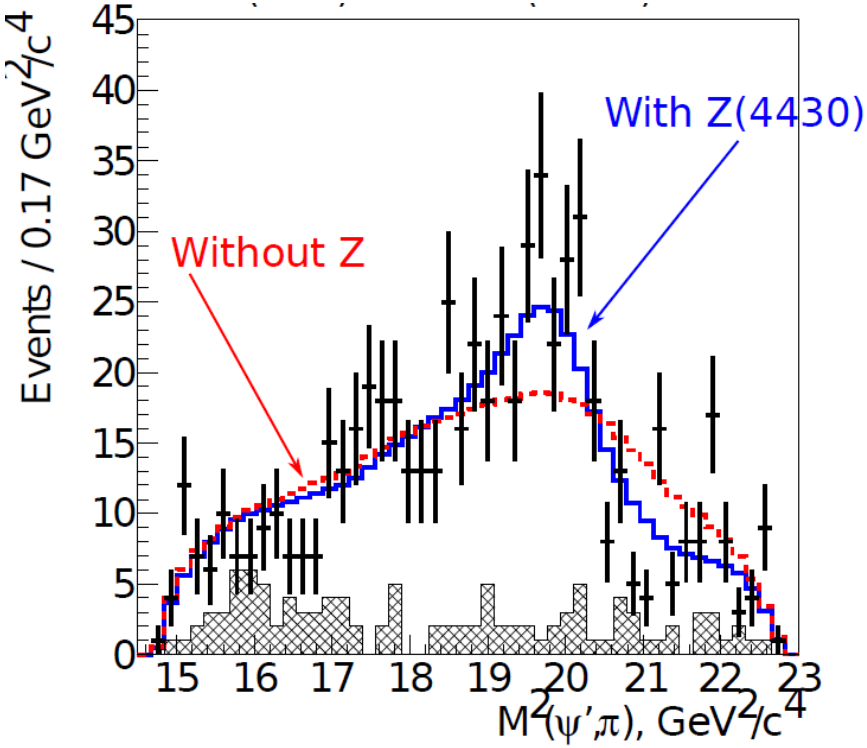
Significant signal at Belle

v.s.

Only hint with 1.9σ at BaBar

Statistically, both are not contradictory, answer requires higher statistics data.

2013: Belle 4-dim amplitude analysis -



$$M = 4485^{+22+28}_{-22-11}\ \mathrm{MeV}/c^2$$

$$\Gamma = 200^{+41+26}_{-46-35}\ \mathrm{MeV}.$$

6.4σ

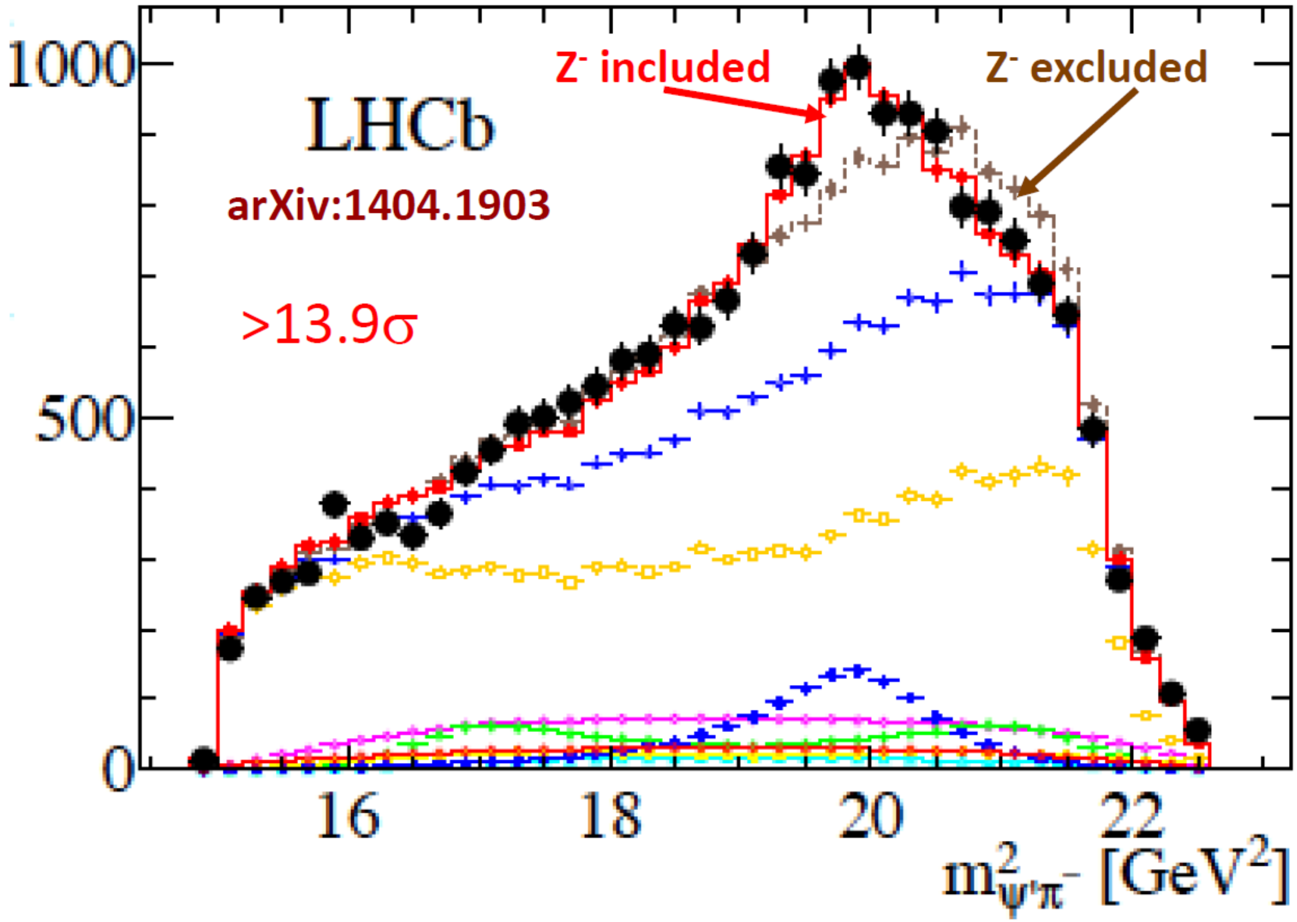
$J^P = 1^+$

Belle preliminary, K. Chilikin, Moriond QCD 2014:

$$\frac{BR(Z(4430)\to\psi'\pi)}{BR(Z(4430)\to J/\psi\,\pi)} \approx 10$$

natural if $Z(4430)$ radius is large, as then w.f. overlap with ψ' larger than with J/ψ

LHCb, 2014: very high stats analysis of $B \to \psi' \pi \;\; K^+$



$> 13.9\sigma$

$J^P = 1^+$

$M = 4475 \pm 7^{+15}_{-25}$ MeV

$\Gamma = 172 \pm 13^{+37}_{-34}$ MeV

large width: $\Gamma(Z(4430)) \gg \Gamma(Z_b),\ \Gamma(Z_c)$.

$\Longrightarrow$ unlikely to be a simple "hadronic molecule"

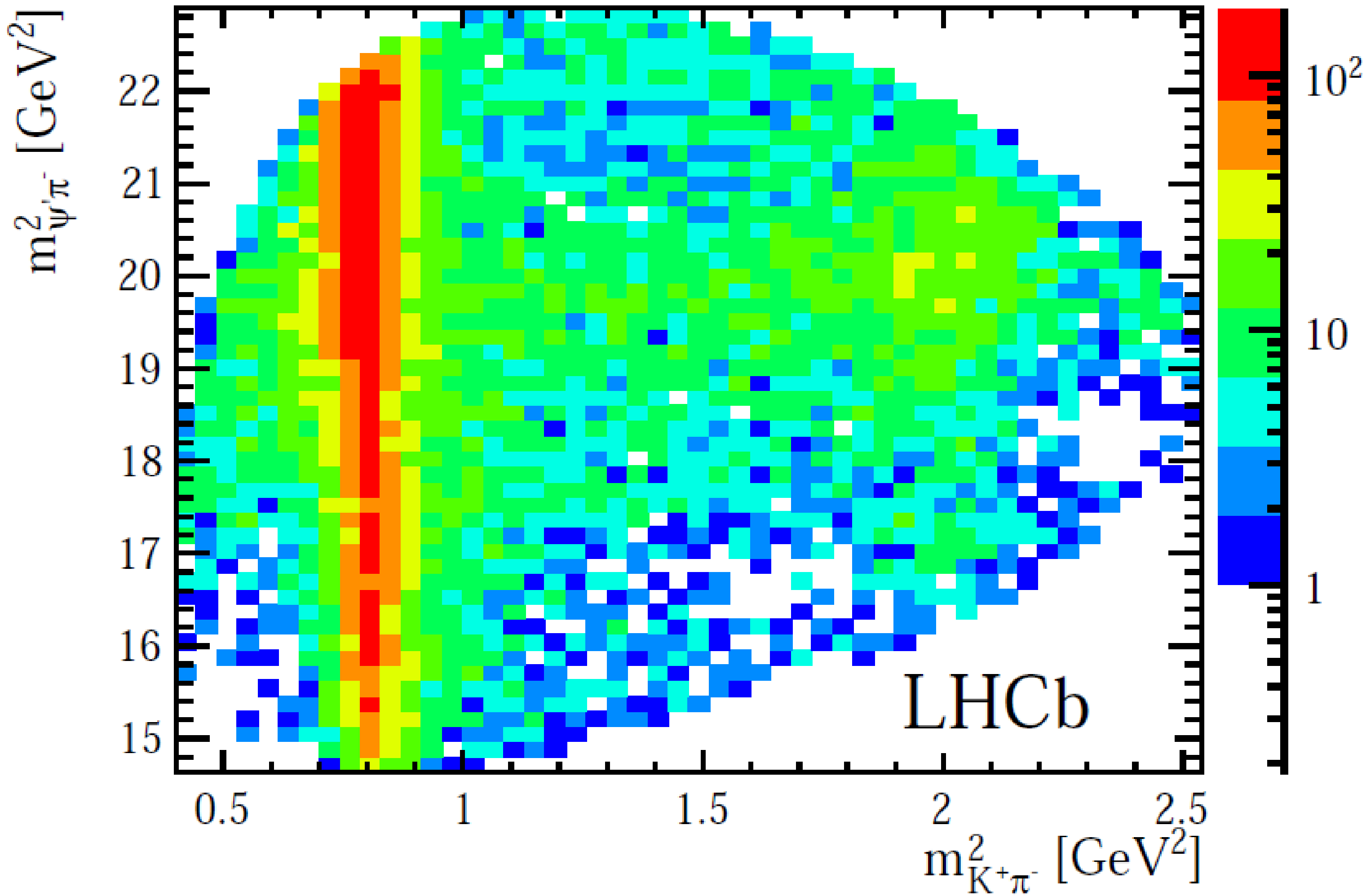


Figure 2: Dalitz plot for $B^0 \to \psi' K^+ \pi^-$ candidates. The background has been subtracted using sWeights determined by the fit shown in Fig, 1. The colors indicate number of signal events per bin. The dominant vertical band is due to the $K^*(892)$ resonance. A faint vertical band at $m^2_{K^+\pi^-}$ around 2 GeV^2 is due to the $K_2^*(1430)$ peak. A horizontal $Z(4430)^-$ band is also visible ($m^2_{\psi'\pi^-}$ around 20 GeV^2).

Argand plot

Breit-Wigner resonant behaviour:

counter-clockwise rotation of the amplitude as function of energy

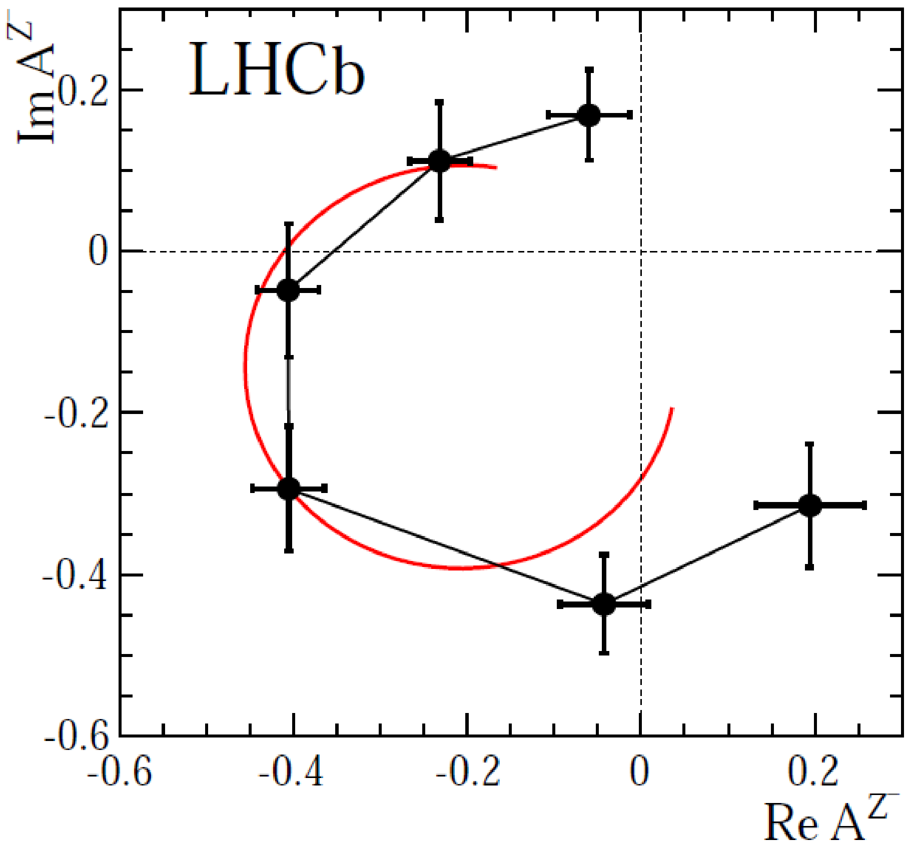


Figure 3: Fitted values of the Z_1^- amplitude in six $m^2_{\psi'\pi^-}$ bins, shown in an Argand diagram (connected points with the error bars, $m^2_{\psi'\pi^-}$ increases counterclockwise). The red curve is the prediction from the Breit-Wigner formula with a resonance mass (width) of 4475 (172) MeV and magnitude scaled to intersect the bin with the largest magnitude centered at $(4477\ \mathrm{MeV})^2$. Units are arbitrary. The phase convention assumes the helicity-zero $K^*(892)$ amplitude to be real.

Should see the neutral partner, $Z(4430)^0$.

For example in

$B^- \to \psi' \pi^0 K^-$

or

$e^+ e^- \to \psi' \pi^0 \pi^0$

two interesting coincidences related to $Z(4430)$ mass:

- $M(Z_c(4430)) - M(Z_c(3900)) \approx 575 \pm 25$ MeV
  $M(\psi') \quad - \quad M(J/\psi) \quad = 589 \qquad$ MeV

$\Rightarrow Z_c(4430)$ a radial excitation of $Z_c(3900)$?

if so, $|\langle Z_c(4430)|\psi'\rangle|^2 \gg |\langle Z_c(4430)|J/\psi\rangle|^2$
but why $\Gamma(Z_c(4430)) \gg \Gamma(Z_c(3900))$?

$\bar{b}b$ analogue: $M(Z_b(10610)) + 575 \approx 11185$ MeV

- $\psi'\rho$ threshold nearby, at 4456 MeV
  if so, analogue at $\Upsilon(2S)\rho$ threshold, at 10793 MeV

both possibilities testable, but E too high for Belle

binding two hadrons through π exchange:

explains conspicous absence of $\bar{D}D$ and $\bar{B}B$ resonances

e.g. $\bar{D}D$ resonance through π would require $DD\pi$ vertex. But 3-pseudoscalar vertex is forbidden in QCD by parity conservation.

another way to understand why no $D \to D\pi$:
$J^P = 0^-$, so parity demands $D \to D\pi$ in P-wave;
but D and π in P-wave give $J = 1$

On the other hand, $\bar{D}D^*$ OK:

$\bar{D} \to \bar{D}^* + \pi$
$D^* + \pi \to D$
so $\bar{D}D^* \to \bar{D}^*D$ and $\bar{D}^*D \to \bar{D}D^*$
physical state $= (\bar{D}D^* + \bar{D}^*D)/\sqrt{2}$
goes into itself under π exchange

$\bar{D} * D^*$ also OK:

$D^* \to D^* + \pi, \quad P$-wave
$L = 1$ can combine with $S = 1$ to give back $J = 1$;
same for D^*, so $\bar{D}^*D^* \to \bar{D}^*D^*$

necessary* conditions for existence of a resonance

(a) both hadrons heavy, as $E_{kin} \sim 1/\mu_{RED}$

(b) both couple to pions;
one of them can have $I = 0$, e.g.
$\Sigma_c \bar{\Lambda}_c \underset{\pi}{\longrightarrow} \Lambda_c \bar{\Sigma}_c$.

(c) spin & parity which allow the state
go into itself under one π exchange

(d) $\Gamma(h_1) + \Gamma(h_2) \ll \Gamma(\text{molecule})$

---

*may not be sufficient

the binding mechanism can in principle

apply to any two heavy hadrons

which couple to isospin

and satisfy these conditions,

be they mesons or baryons

π exchange between two states with I_1, I_2 and S_1, S_2:

$$V_{\rm eff} \sim \pm(I_1 \cdot I_2)(S_1 \cdot S_2) \qquad \text{for } (qq, q\bar{q}) \ ,$$

q or $\bar{q}$:
light quark(s) or antiquark(s) in hadrons 1 and 2,

- applies as long as the total spins S_i are correlated with the direction of the light-quark spins.

- true for D^*, B^*, Σ_c, and Σ_b

most likely candidates with $Q\bar{Q}'$, $Q = c, b$, $\bar{Q}' = \bar{c}, \bar{b}$:

$D\bar{D}^*$, $D^*\bar{D}^*$, D^*B^*, $\bar{B}B^*$, $\bar{B}^*B^*$,

$\Sigma_c\bar{D}^*$, Σ_cB^*, $\Sigma_b\bar{D}^*$, Σ_bB^*,

$\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Lambda}_b$, $\Sigma_b\bar{\Sigma}_b$, $\Sigma_b\bar{\Lambda}_b$, and $\Sigma_b\bar{\Lambda}_c$.

$c\bar{c}$ and $b\bar{b}$ states decay strongly to $\bar{c}c$ or $\bar{b}b$ and π-(s)
$b\bar{c}$ and $c\bar{b}$ states decay strongly to $B_c^{\pm}$ and π-(s)

QQ' candidates – dibaryons:

$\Sigma_c\Sigma_c$, $\Sigma_c\Lambda_c$, $\Sigma_c\Lambda_b$, $\Sigma_b\Sigma_b$, $\Sigma_b\Lambda_b$, and $\Sigma_b\Lambda_c$.

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$\Sigma_c\bar{D}^*$, Σ_cB^*, $\Sigma_b\bar{D}^*$, Σ_bB^*, the lightest of new kind

$\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Lambda}_b$, $\Sigma_b\bar{\Sigma}_b$, $\Sigma_b\bar{\Lambda}_b$, and $\Sigma_b\bar{\Lambda}_c$.

$c\bar{c}$ and $b\bar{b}$ states decay strongly to $\bar{c}c$ or $\bar{b}b$ and π-(s)
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$\Sigma_c\Sigma_c$, $\Sigma_c\Lambda_c$, $\Sigma_c\Lambda_b$, $\Sigma_b\Sigma_b$, $\Sigma_b\Lambda_b$, and $\Sigma_b\Lambda_c$.

doubly heavy baryon with hidden charm:

$\Sigma_c \bar{D}^* \equiv \Theta_{\bar{c}c}, \quad m_{\Theta_{\bar{c}c}} \approx 4460$ MeV

$\Sigma_c^{++}(cuu)\, D^{-*}(\bar{c}d)$, or

$\Sigma_c^{+}\ (cud)\, \bar{D}^0\, (\bar{c}u)$

possible decay mode: $\Theta_{cc} \to J/\psi\, p$

small overlap of molecular state with $J/\psi p$
$\Longrightarrow$ narrow width $\lesssim$ few tens of MeV
despite > 400 MeV phase space

$\Theta_{\bar{c}c}$ minimal quark content: $\bar{c}c\, uud$

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$\Theta_{\bar{c}c}$ minimal quark content: $\bar{c}c\, uud$
a molecule, not a pentaquark

Thresholds for $Q\bar{Q}'$ molecular states

Channel	Minimum isospin	Minimal quark content[a,b]	Threshold (MeV)[c]	Example of decay mode
$D\bar{D}^*$	0	$c\bar{c}q\bar{q}$	3875.8	$J/\psi\,\pi\pi$
$D^*\bar{D}^*$	0	$c\bar{c}q\bar{q}$	4017.2	$J/\psi\,\pi\pi$
D^*B^*	0	$c\bar{b}q\bar{q}$	7333.8	$B_c^+\pi\pi$
$\bar{B}B^*$	0	$b\bar{b}q\bar{q}$	10604.6	$\Upsilon(nS)\pi\pi$
$\bar{B}^*B^*$	0	$b\bar{b}q\bar{q}$	10650.4	$\Upsilon(nS)\pi\pi$
$\Sigma_c\bar{D}^*$	1/2	$c\bar{c}qqq'$	4462.4	$J/\psi\,p$
Σ_cB^*	1/2	$c\bar{b}qqq'$	7779.5	$B_c^+\,p$
$\Sigma_b\bar{D}^*$	1/2	$b\bar{c}qqq'$	7823.0	$B_c^-\,p$
Σ_bB^*	1/2	$b\bar{b}qqq'$	11139.6	$\Upsilon(nS)p$
$\Sigma_c\bar{\Lambda}_c$	1	$c\bar{c}qq'\bar{u}\bar{d}$	4740.3	$J/\psi\,\pi$
$\Sigma_c\bar{\Sigma}_c$	0	$c\bar{c}qq'\bar{q}\bar{q}'$	4907.6	$J/\psi\,\pi\pi$
$\Sigma_c\bar{\Lambda}_b$	1	$c\bar{b}qq'\bar{u}\bar{d}$	8073.3[d]	$B_c^+\pi$
$\Sigma_b\bar{\Lambda}_c$	1	$b\bar{c}qq'\bar{u}\bar{d}$	8100.9[d]	$B_c^-\pi$
$\Sigma_b\bar{\Lambda}_b$	1	$b\bar{b}qq'\bar{u}\bar{d}$	11433.9	$\Upsilon(nS)\pi$
$\Sigma_b\bar{\Sigma}_b$	0	$b\bar{b}qq'\bar{q}\bar{q}'$	11628.8	$\Upsilon(nS)\pi\pi$

[a]Ignoring annihilation of quarks. [b]Plus other charge states when $I \neq 0$.
[c]Based on isospin-averaged masses. [d]Thresholds differ by 27.6 MeV.

detailed analysis needed to determine

if π exchange suffices to bind two

hadrons in each of these channels,

and in corresponding QQ' channels.

but

- relevant π-hadron couplings yet unknown
- exchanges other than π, e.g. must have short-distance repulsion to stabilize the potential
- possible contributions beyond S-waves c.f. D-wave in deuteron

$\Longrightarrow$ too early to calculate the binding in most cases

$\Sigma_b^+ \Sigma_b^-$ dibaryon:

$\Sigma_b^+ \Sigma_b^-$ vs. $\bar{B} B^*$:

$m_{\Sigma_b} > m_B$, $I = 1$ vs. $I = \frac{1}{2}$ $\rightarrow$ stronger binding via π

$\Rightarrow$ deuteron-like $J = 1$, $I = 0$ bound state, "*beautron*"

extra ~ 3 MeV binding from EM interaction

EXP signature: $\rightarrow \Lambda_b \Lambda_b \pi^+ \pi^-$

$\Gamma(\Sigma_b) \sim 5 \div 10$ MeV, so might be visible

should be seen in lattice QCD

doubly heavy baryons QQq:

ccq, bcq, bbq, $\quad q = u, d$

must exist, but have never been seen

fascinating challenge for EXP & TH

LHCb sees thousands of B_c-s
$\Longrightarrow$ should see bcq, ccq, etc.

QQq baryons are <u>the simplest</u> baryons:

when $m_Q \to \infty$, QQ form a static $\overline{3}_c$ diquark

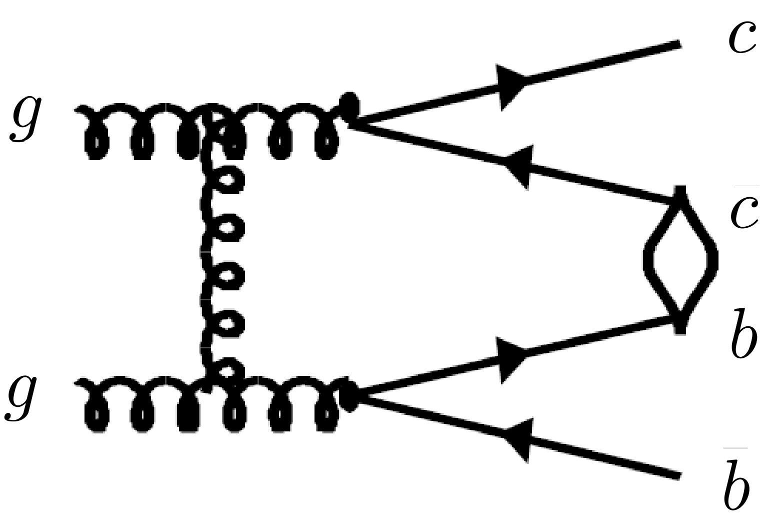
so QQq baryon $\sim \bar{Q}q$ meson

e.g. form factors: $F_{QQq}(q^2) = F_{\bar{Q}q}(q^2)$

corrections: $f\left(\frac{\Lambda_{QCD}}{m_Q}\right)$, calculable in QCD

hydrogen atom of baryon physics!

B_c production in LHCb: gg fusion



v. hard to compute reliably from first principles, but...

Ξ_{bc} production: same diagram,

but b needs to pick up c, instead of c: $\mathbf{3}_c\mathbf{3}_c$ vs. $\bar{\mathbf{3}}_c\mathbf{3}_c$

$$\Longrightarrow \quad \sigma(pp \to \Xi_{bc} + X) \sim \sigma(pp \to B_c + X)$$

LHCb is making a lot of B_c-s. $\sigma(pp \to B_c + X) = 0.4\mu b$

$\Longrightarrow$ LHCb is making a lot of (QQq) baryons !!!

Ξ_{cc} is the lightest doubly-heavy baryon

is it LHCb's best bet for (QQq) ?

$\sigma(\bar{c}c\,\bar{c}c) \gg \sigma(\bar{b}b\,\bar{c}c) \gg \sigma(\bar{b}b,\bar{b}b)$

but $\tau(b) \sim 7\tau(c)$ (Cabibbo),

e.g. $\tau(\Lambda_b) \approx 1.4 \times 10^{-12}$ sec.
vs. $\tau(\Lambda_c) \approx 0.2 \times 10^{-12}$ sec.

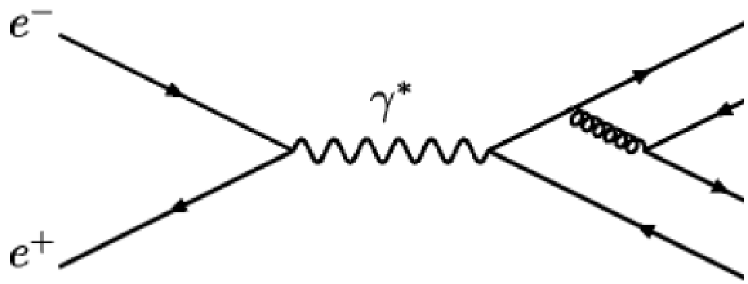
verified by detailed lifetime calculation with sufficient E_{CM} may study double heavy flavor production

$$e^+e^- \to b\bar{b}c\bar{c} + X \ ,$$
$$e^+e^- \to b\bar{b}b\bar{b} + X$$

$\Rightarrow$ a precondition for producing doubly heavy B_c, B_c^*, and doubly heavy $\Xi_{bc} = bcq$, and $\Xi_{bb} = bbq$, $q = u, d$.

must be able to see the (known) B_c state if one expects to be able to detect Ξ_{bc}

same diagram for B_c and Ξ_{bc}:



estimate $\sigma(e^+e^- \to \gamma B_c^+ B_c^- + X)$

$\sim$ 1.7 fb @90 GeV, 0.24 fb @250 GeV

masses of doubly-heavy baryons:

use same toolbox that predicted

b baryon masses.

doubly heavy baryons: masses and lifetimes

our mass predictions (in MeV) for lowest-lying baryons with two heavy quarks. States without a star have $J = 1/2$; states with a star are their $J = 3/2$ hyperfine partners. The quark q can be either u or d. The square or curved brackets around cq denote coupling to spin 0 or 1.

State	Quark content	$M(J = 1/2)$	$M(J = 3/2)$
$\Xi_{cc}^{(*)}$	ccq	3627 ± 12	3690 ± 12
$\Xi_{bc}^{(*)}$	$b[cq]$	6914 ± 13	6969 ± 14
Ξ_{bc}'	$b(cq)$	6933 ± 12	–
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

summary of lifetime predictions for baryons containing two heavy quarks. Values given are in fs.

Baryon	This work	[27]	[51]	[70]	[71]
$\Xi_{cc}^{++} = ccu$	185	430±100	460±50	500	~ 200
$\Xi_{cc}^{+} = ccd$	53	120±100	160±50	150	~ 100
$\Xi_{bc}^{+} = bcu$	244	330±80	300±30	200	–
$\Xi_{bc}^{0} = bcd$	93	280±70	270±30	150	–
$\Xi_{bb}^{0} = bbu$	370	–	790±20	–	–
$\Xi_{bb}^{-} = bbd$	370	–	800±20	–	–

interesting thresholds for heavy flavor production in e^+e^-

Final state	Threshold (MeV)
$B\bar{B}$	10559
$B\bar{B}^*$	10605
$B^*\bar{B}^*$	10650
$B_s\bar{B}_s$	10734
$B_s\bar{B}_s^*$	10782
$B_s^*\bar{B}_s^*$	10831
$B_{s0}\bar{B}_s^*$	11132–11193[a]
$\Lambda_b\bar{\Lambda}_b$	11239
$B_c\bar{B}_c$	12551
$B_c\bar{B}_c^*$	12619–12635[b]
$B_c^*\bar{B}_c^*$	12687–12719[b]
$\Xi_{bc}\,\bar{\Xi}_{bc}$	13842–13890[c]
$\Xi_{bb}\,\bar{\Xi}_{bb}$	20300–20348[c]

[a] analogue of the very narrow $D_{s0}(2317)$
[b] With estimated B_c^* B_c splitting 68 84 MeV
[c] estimate, MK&Rosner (2014)

Likely decay modes of QQq baryons

- $\Xi_{cc}^{++} = ccu$

$\Xi_{cc}^{++} \to (csu)\, W^+ \to (csu)\, (\pi^+, \rho^+, a_1^+)$
e.g.
$\Xi_{cc}^{++} \to 3\pi^+\, \Xi^-$ (missed by CDF trigger)
$\Xi_{cc}^{++} \to \Lambda_c K^- 2\pi^+$

lifetime: each c quark can decay independently

$\Gamma(\Xi_{cc}^{++}) = 3.56 \times 10^{-12}$ GeV
$\tau(\Xi_{cc}^{++}) = 185$ fs

- $\Xi_{cc}^{+} = ccd$

In addition to $c \to su\bar{d}$, have $cd \to su$

$\Longrightarrow \quad \tau(\Xi_{cc}^{+}) = 50 \div 100$ fs

- $\Xi_{bc}^{+} = bcu$

$b \to cdu$ and $c \to sud$

e.g. $\Xi_{bc} \to J/\psi\, \Xi_c$

$\tau(\Xi_{bc}^{+}) \approx 240$ fs

- $\Xi_{bc}^{0} = bcd$

$\tau(\Xi_c^{+}) = (4.42 \pm 0.26) \times 10^{\;\;13}$ s
$\tau(\Xi_c^{0}) = (1.12^{+0.13)}_{\;\;0.10}\,) \;\; \times 10^{\;\;13}$ s

the difference due to $cd \to su$

$\Longrightarrow \tau(\Xi_{bc}^{0}) = 93$ fs

e.g. $\Xi_{bc}^{0} \to j/\psi\, \Xi^{0}$ or $\Xi_{bc}^{0} \to J/\psi\, \Xi^{-}\pi^{+}$

- $\Xi_{bb} = bbq$

$bu \to cd$ possible for Ξ^0_{bb}, but
$\tau(\Xi^0_b)$ not much different from $\tau(\Xi^-_b)$
so treat Ξ^0_{bb} and Ξ^-_{bb} generically as Ξ_{bb}

$\Longrightarrow \quad \tau(\Xi_{bb}) \approx 376$ fs

rare but spectacular decay mode:

$$(bbq) \to (\bar{c}cs)\,(\bar{c}cs)q \to J/\psi\, J\psi\, \Xi$$

rough estimate of Ξ_{cc} production rate

assume suppression due to $s \to c$
indep. of spectators, i.e.

Ξ_{cc} suppressed vs. Ξ_c as Ξ_c vs. Ξ :

$$\sigma(pp \to \Xi_{cc} + X) \sim \sigma(pp \to \Xi_c + X) \cdot \frac{\sigma(pp \to \Xi_c + X)}{\sigma(pp \to \Xi + X)}$$

perhaps can generalize to Ξ_{bc} and Ξ_{bb} production rate

$$\sigma(pp \to \Xi_{bc} + X) \sim \sigma(pp \to \Xi_b + X) \cdot \frac{\sigma(pp \to \Xi_c + X)}{\sigma(pp \to \Xi + X)}$$

or

$$\sigma(pp \to \Xi_{bc} + X) \sim \sigma(pp \to \Xi_c + X) \cdot \frac{\sigma(pp \to \Xi_b + X)}{\sigma(pp \to \Xi + X)}$$

and

$$\sigma(pp \to \Xi_{bb} + X) \sim \sigma(pp \to \Xi_b + X) \cdot \frac{\sigma(pp \to \Xi_b + X)}{\sigma(pp \to \Xi + X)}$$

a possible way to check if Ξ_{bc} and B_c

production rates are comparable:

compare analogous prod. rates of Ξ_c and D_s

(or Ξ_b and B_s) in the same setup,

and large enough E_{CM}

be it e^+e^-, $\bar{p}p$ or pp

Several high-energy high-luminosity future e^+e^- colliders are currently under discussion.

We point out that with ISR it might be possible to use them to explore interesting physics *significantly below* their design E_{CM}.

such machines may turn out to be our best chance at exploring the rich new QCD spectroscopy of doubly-heavy hadrons

OUTLINE

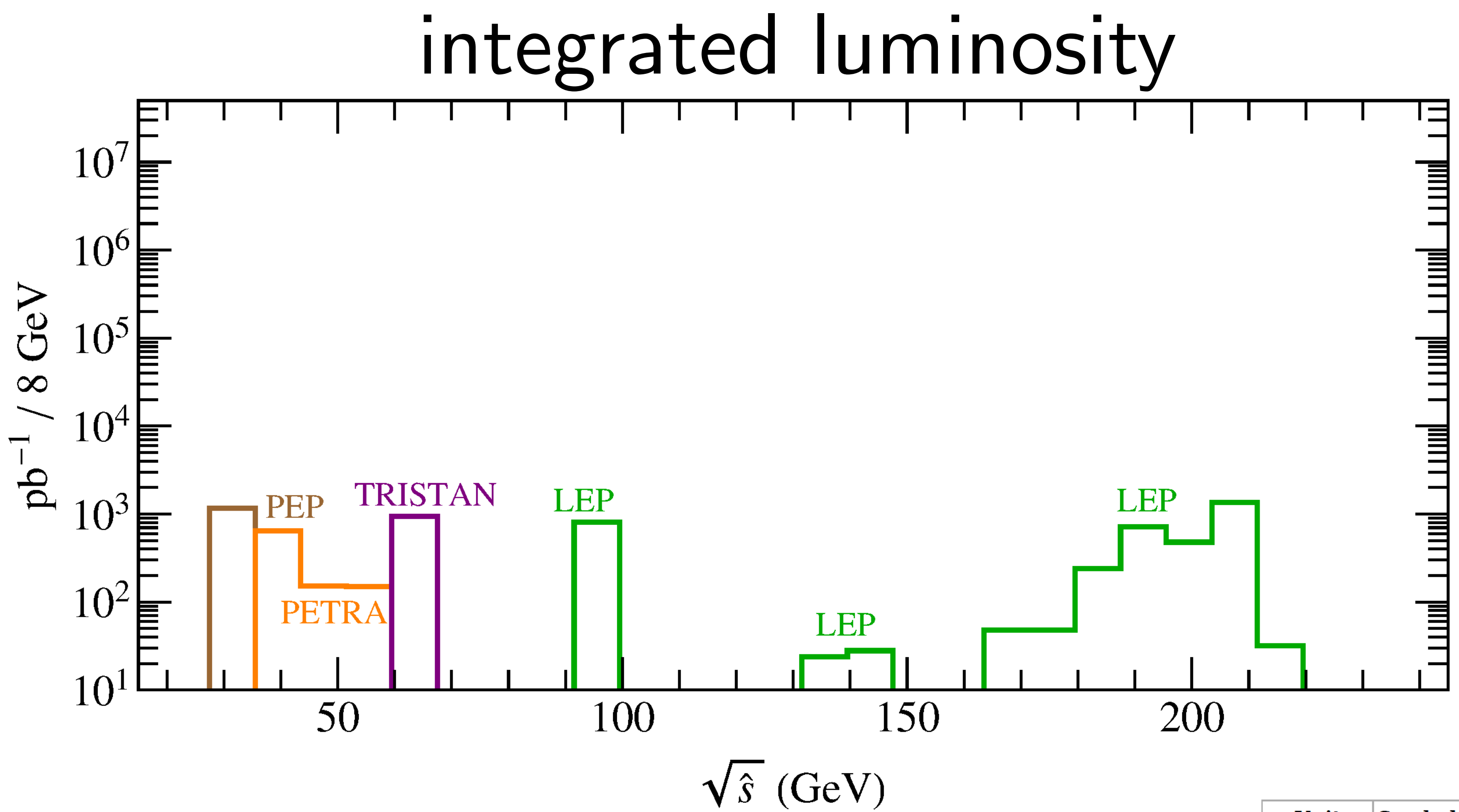
- e^+e^- collider designed for a certain E_{CM} can collect events at all lower energies through initial-state radiation (ISR or *radiative return*)
  "it's not a bug, it's a feature"

- explore the capabilities for radiative return studies by a proposed high-luminosity collider at $E_{CM} = 250$ or 90 GeV

- fill in the gaps left by PEP, PETRA, TRISTAN and LEP

- sample apps:
  – dark photon searches
  – heavy quark exotic spectroscopy

E_{CM} above B-factories: gaps left by PEP, PETRA, TRISTAN and LEP



Unit	Symbol	m^2	cm^2
millibarn	mb	10^{-31}	10^{-27}
microbarn	μb	10^{-34}	10^{-30}
nanobarn	nb	10^{-37}	10^{-33}
picobarn	pb	10^{-40}	10^{-36}
femtobarn	fb	10^{-43}	10^{-39}
attobarn	ab	10^{-46}	10^{-42}

Projected luminosities for CEPC and FCC-ee

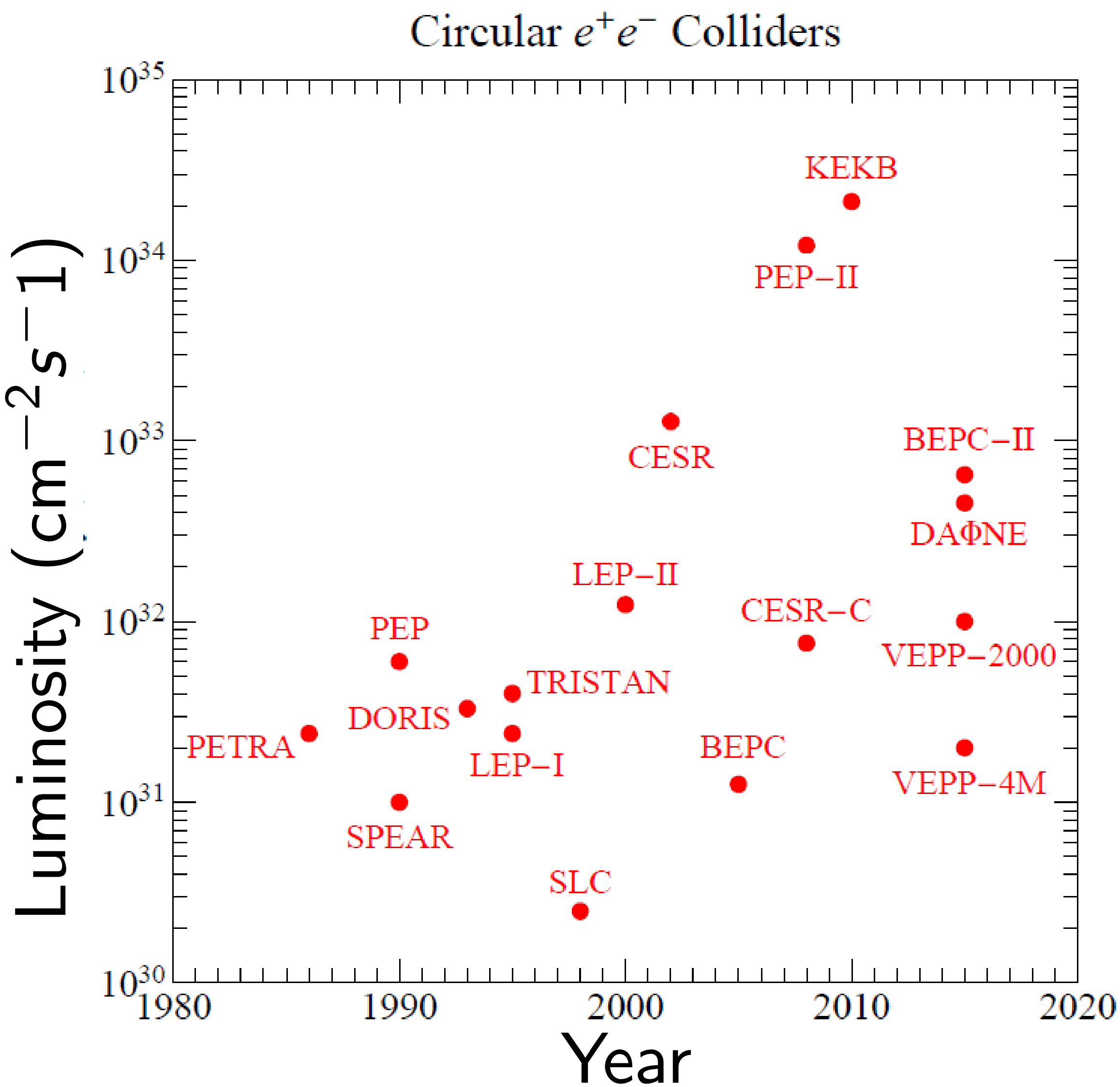
	$\sqrt{s} = 90$ GeV	$\sqrt{s} = 250$ GeV
CEPC	0.5 ab^{-1}	5 ab^{-1}
FCC-ee	50 ab^{-1}	10 ab^{-1}

e.g. observation of a new resonance with at least 10 events:

@ 90 GeV need $\sigma \geq$ 20 ab (CEPC) and 0.2 ab (FCC-ee)
@250 GeV need $\sigma \geq$ 2 ab (CEPC) and 1.0 ab (FCC-ee)

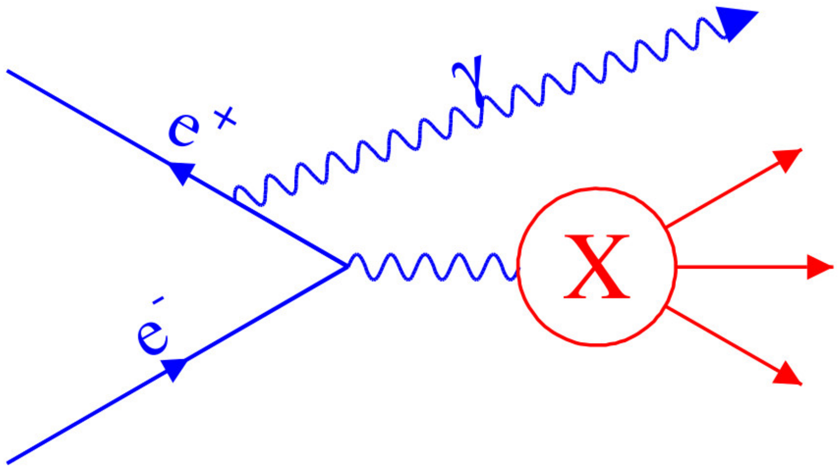
Instantaneous and/or integrated luminosities achieved at some e^+e^- colliders

Collider	Detector	CM energy (GeV)	Max. $\mathcal{L}$ (10^{30} cm^{-2}s^{-1})	$\int \mathcal{L}dt$ (fb^{-1})
DAΦNE	KLOE	1.02	453	2.5
		1.00	453	0.23
CESR	CLEO	9.46–11.30	1280 at 10.6 GeV	15.1
PEP-II	BaBar	10.58	12069	424.7
		10.18	...	43.9
KEK-B	Belle	9.46–10.89	21083	980
PEP		29	60	1.167[a]
PETRA		46.8[b]	24 at 35 GeV	0.817[c]
TRISTAN		64[b]	40	0.942[d]
LEP		M_Z	24	0.808[e]
		> 130	34–90	2.980[e]



Maximum instantantenous luminosities of circular e^+e^- colliders vs. time

Previous uses of radiative return



S. Eidelman

KLOE and DAΦNE
CLEO and CESR
BaBar and PEP-II
Belle at KEK-B
LEP: ALEPH, DELPHI, L3 & OPAL

Resonance production

$$\sigma(e^+e^- \to R \to f; s) = \frac{12\pi \Gamma_{ee}\Gamma_f}{(s - m_R^2)^2 + (m_R \Gamma_R)^2}$$

where $s = E_{CM}^2$, *and* m_R and Γ_R are the resonance mass and total width

R may be produced by the radiative return process $e^+e^- \to \gamma R$

e^- or e^+ of $E = E_{CM}/2$ radiates fraction $1 - x$ of its energy

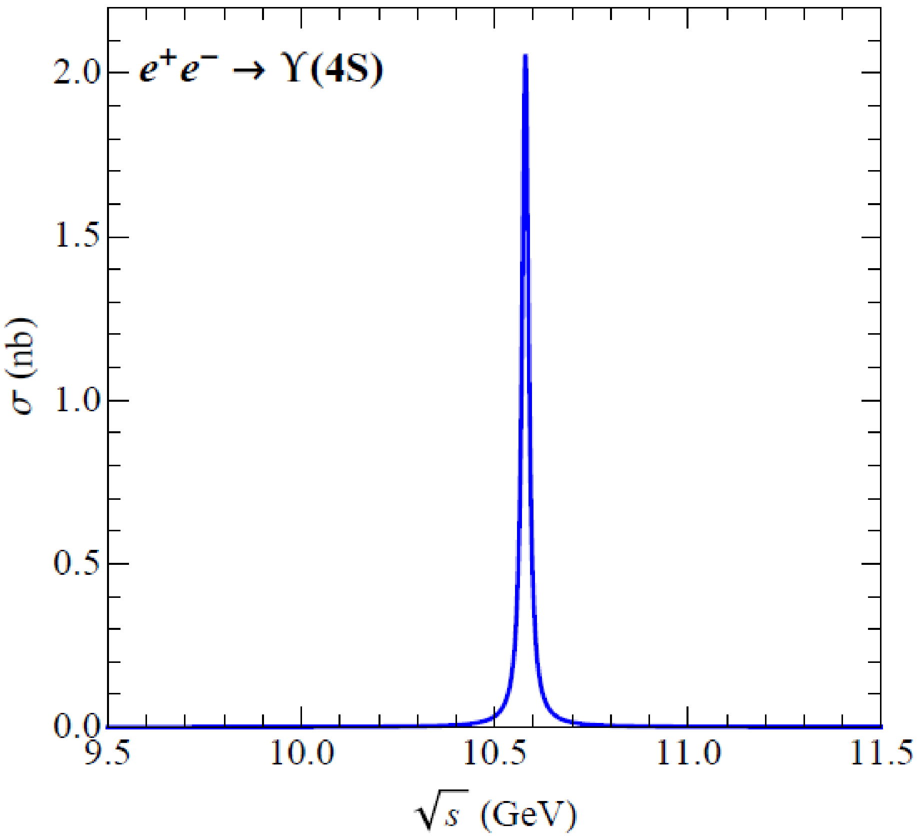
and ends up with energy xE with probability per unit x

$$f_e(x, \sqrt{s}, p_{T,cut}) = \frac{\alpha}{\pi} \frac{1 + x^2}{1 - x} \frac{E}{p_{T,cut}} \qquad p_{T,cut} = m_e$$

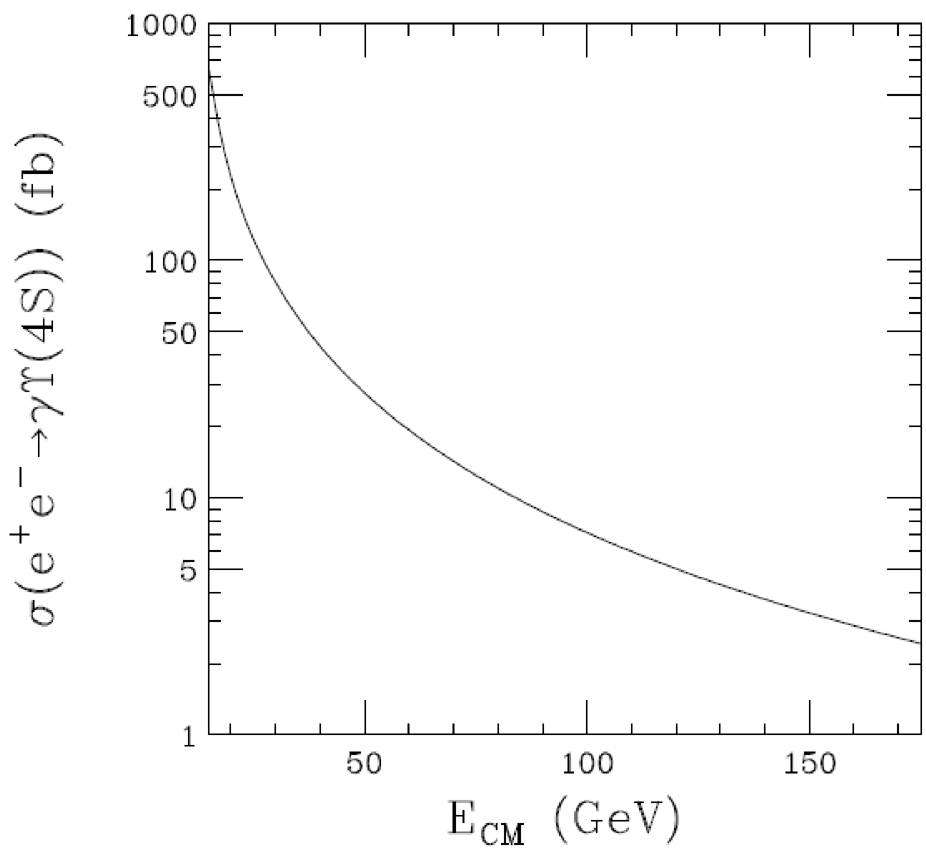
$\Rightarrow \sigma$ for production of R by rad. return

$$\sigma(e^+e^- \to \gamma R \to \gamma f) = \frac{2\alpha}{\pi} \ln \frac{E}{m_e} \int_0^1 dx \frac{1+x^2}{1-x} \sigma(e^+e^- \to R \to f; xs)$$

$\sigma(e^+e^- \to \Upsilon(4s))$

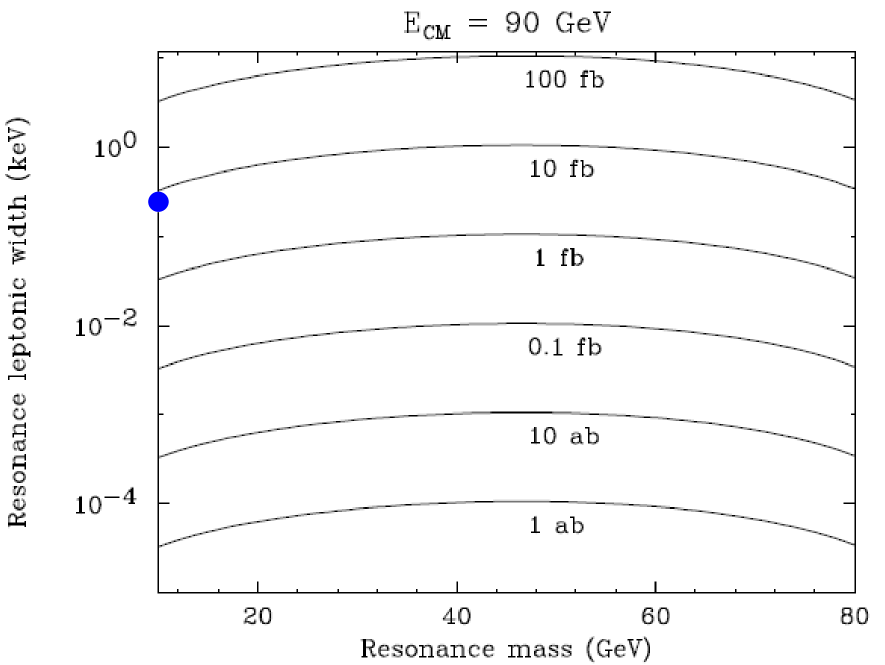


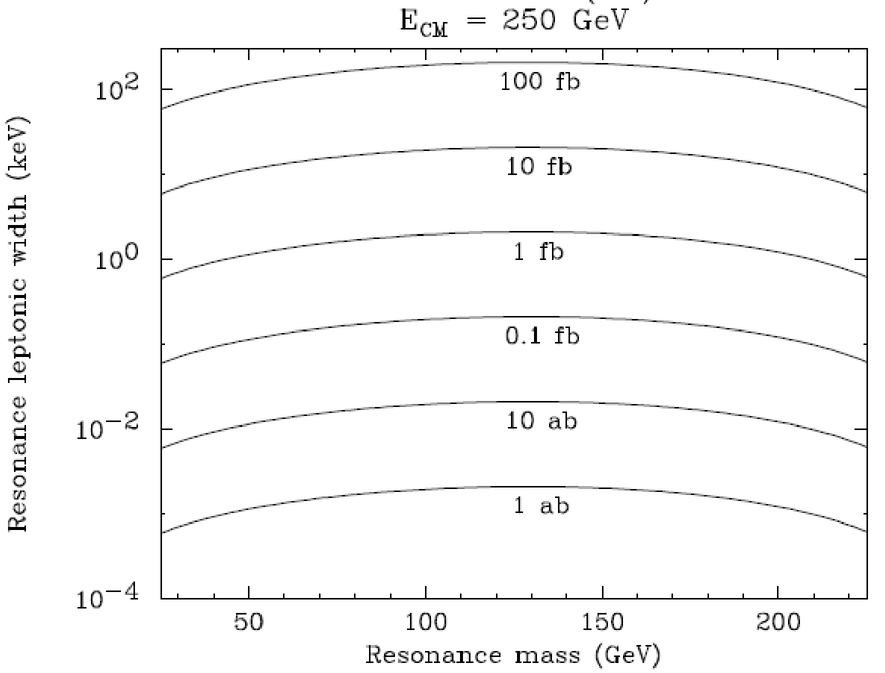
$\sigma(e^+e^- \to \gamma\Upsilon(4S))$ at collider of energy E_{CM}



equal σ contours in $M_R - \Gamma_R$ plane for rad. return production of R

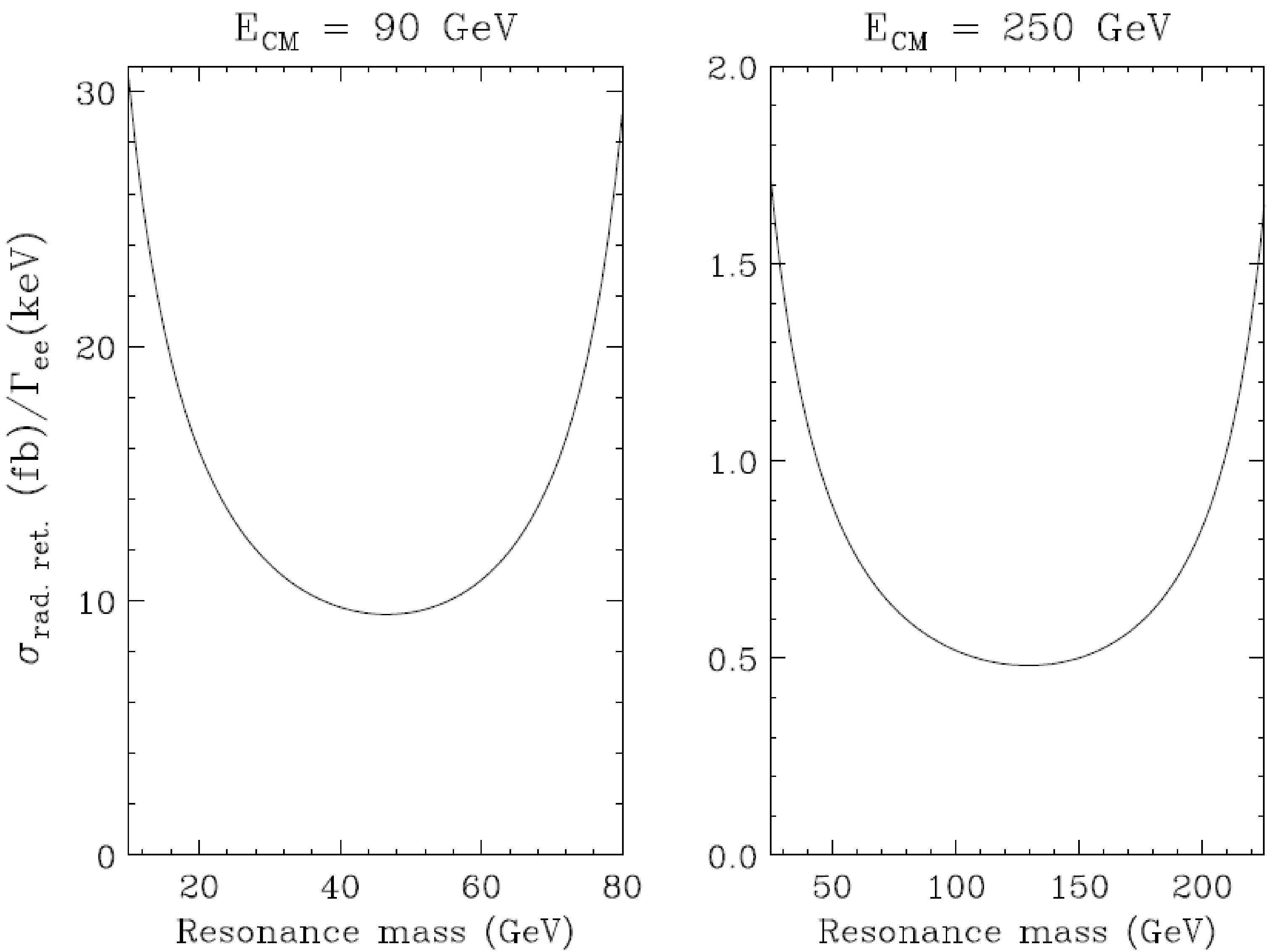
e.g. for $\Upsilon(4S)$:
m=10.6GeV,$\Gamma_{ee} = 0.322$ keV
$\sigma = 9.17$ fb at $E_{CM} = 90$ GeV





in narrow resonance approximation $\sigma_{\text{rad. ret.}} \sim \Gamma_{ee}\mathcal{B}_f$

so $\sigma(e^+e^- \to \gamma R \to \gamma f)/\Gamma_{ee}\mathcal{B}_f = f(m_R; E_{CM})$:



continuum production

effective luminosity
of a high-energy collider with beam energy E, $s = 4E^2$
for studying any given process at lower $\hat{E}_{CM}$, $\hat{s} = \hat{E}_{CM}^2$

$\sigma(s) \equiv \sigma(e^+e^- \to \gamma f; s)$,
$\hat{\sigma}(\hat{s}) \equiv \sigma(e^+e^- \to f; \hat{s})$
$x \equiv \hat{s}/s$

the relation between the two

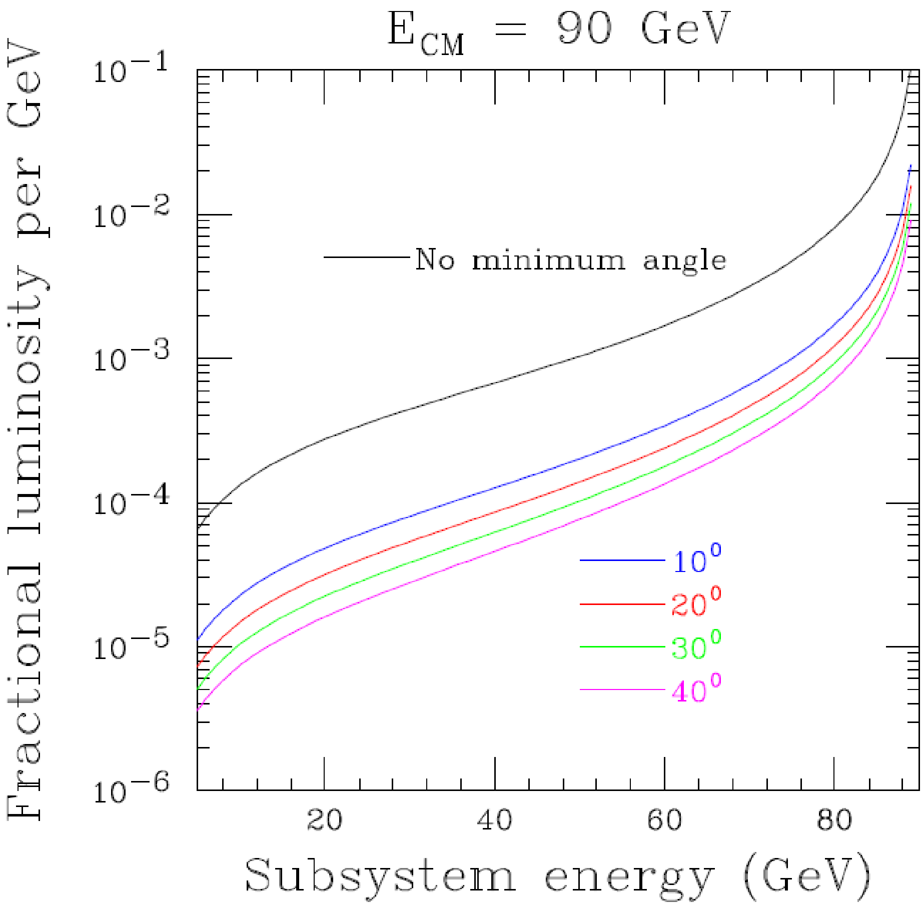
$$\frac{d\sigma(s)}{dx} = \frac{2\alpha}{\pi} \frac{1+x^2}{1-x} \ln \frac{E}{m_e} \hat{\sigma}(\hat{s})$$

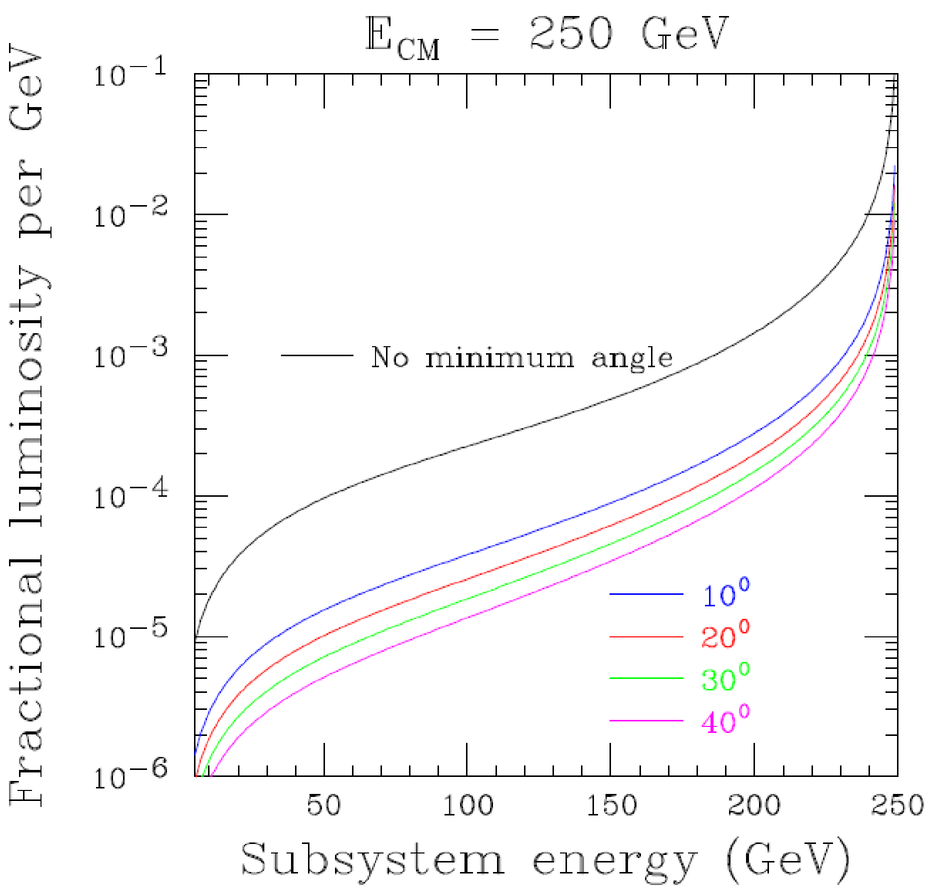
cross section per unit $\hat{E}_{CM}$ times an interval Δ of $\hat{E}_{CM}$

$$\frac{d\sigma(s)}{d\hat{E}_{CM}} \Delta = \frac{4\alpha \hat{E}_{CM}}{\pi s} \frac{1+x^2}{1-x} \Delta \ln \frac{E}{m_e} \hat{\sigma}(\hat{s}) \equiv L_f \hat{\sigma}(\hat{s})$$

$L_f \equiv$ *fractional luminosity* per $\hat{E}_{CM}$ bin of size Δ $\qquad$ (*dimensionless*)

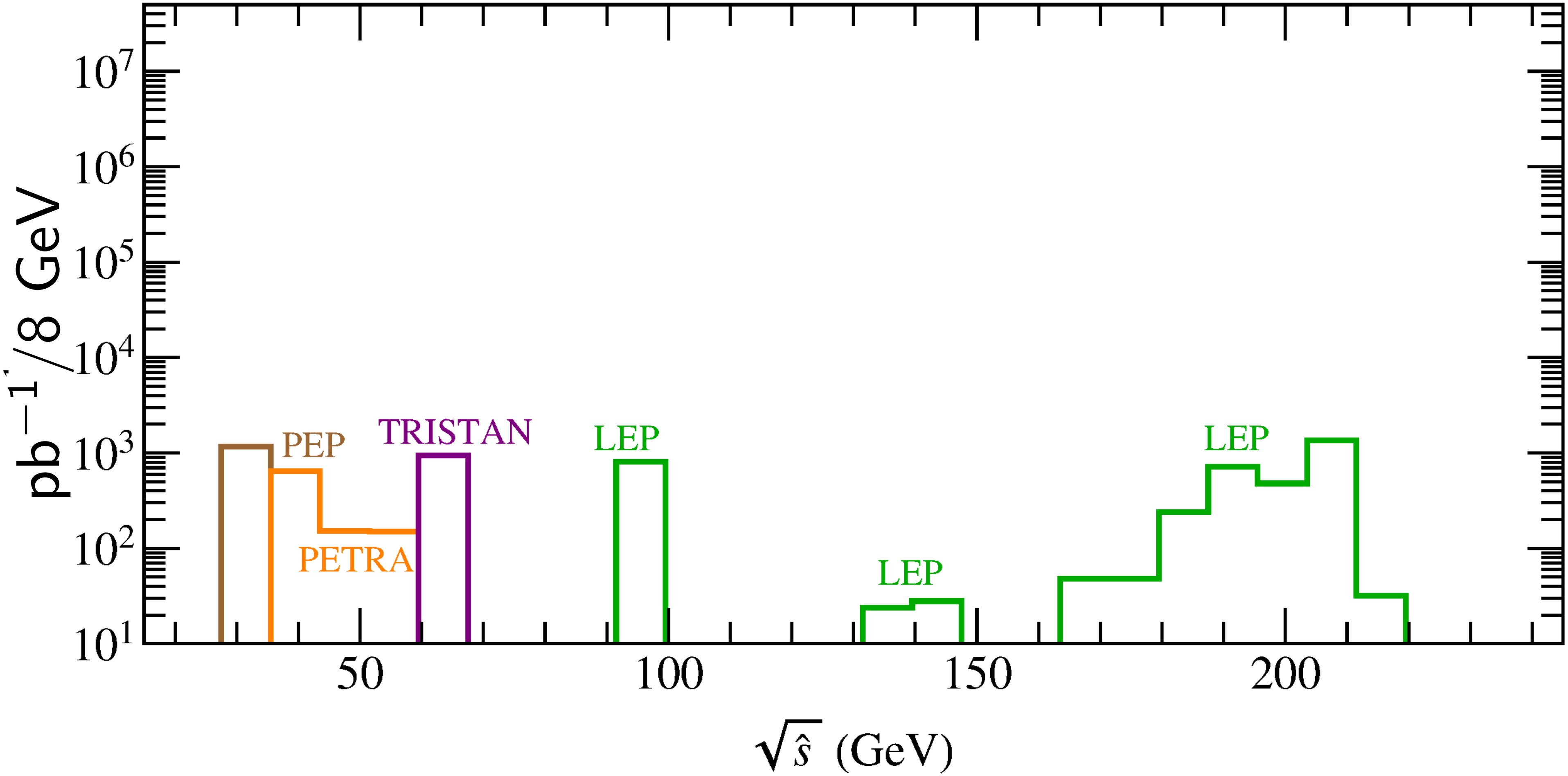
fractional luminosity L_f as function of subsystem energy





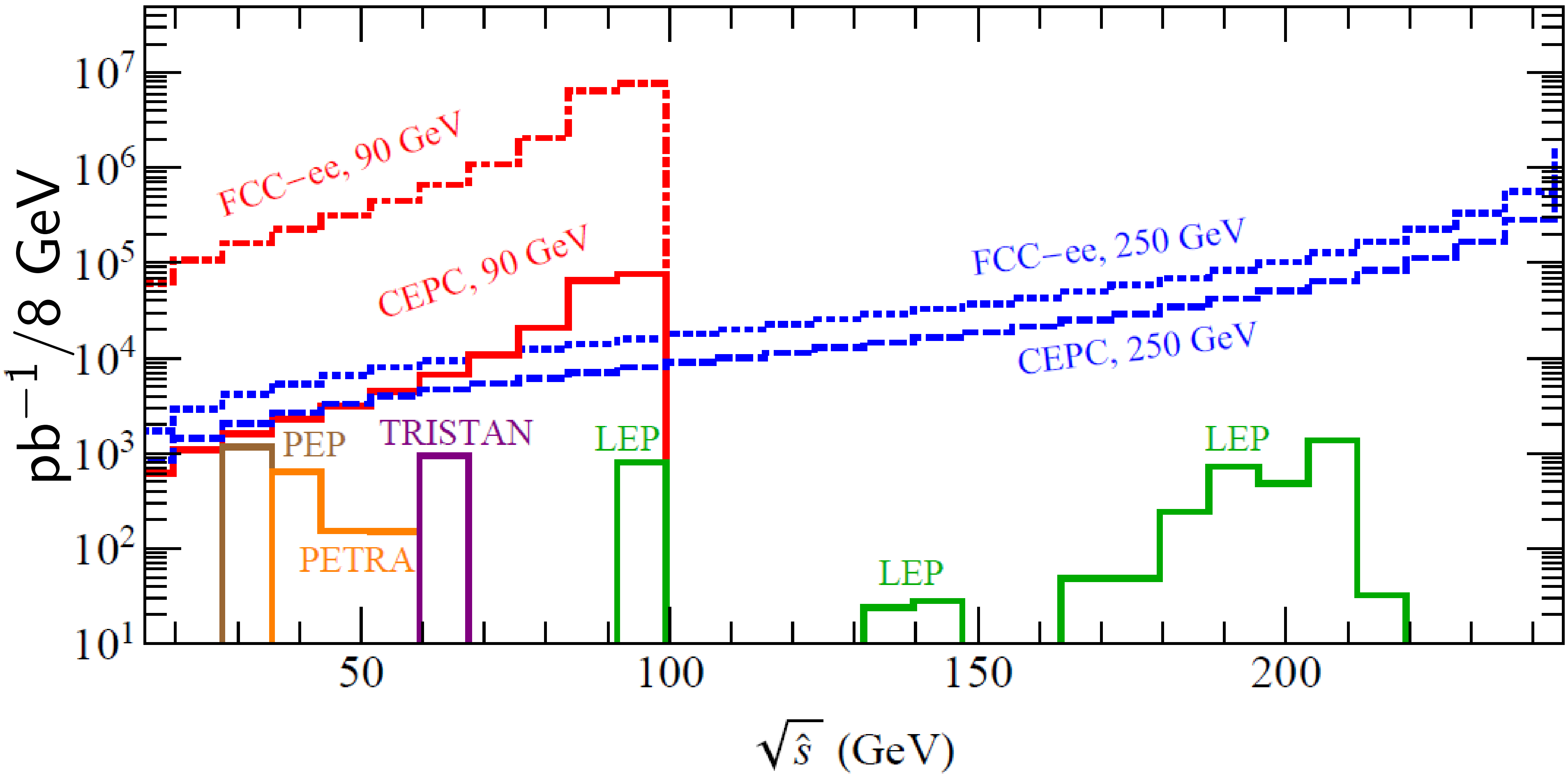
larger cut on photon angle → cleaner signal, but less σ

integrated luminosity



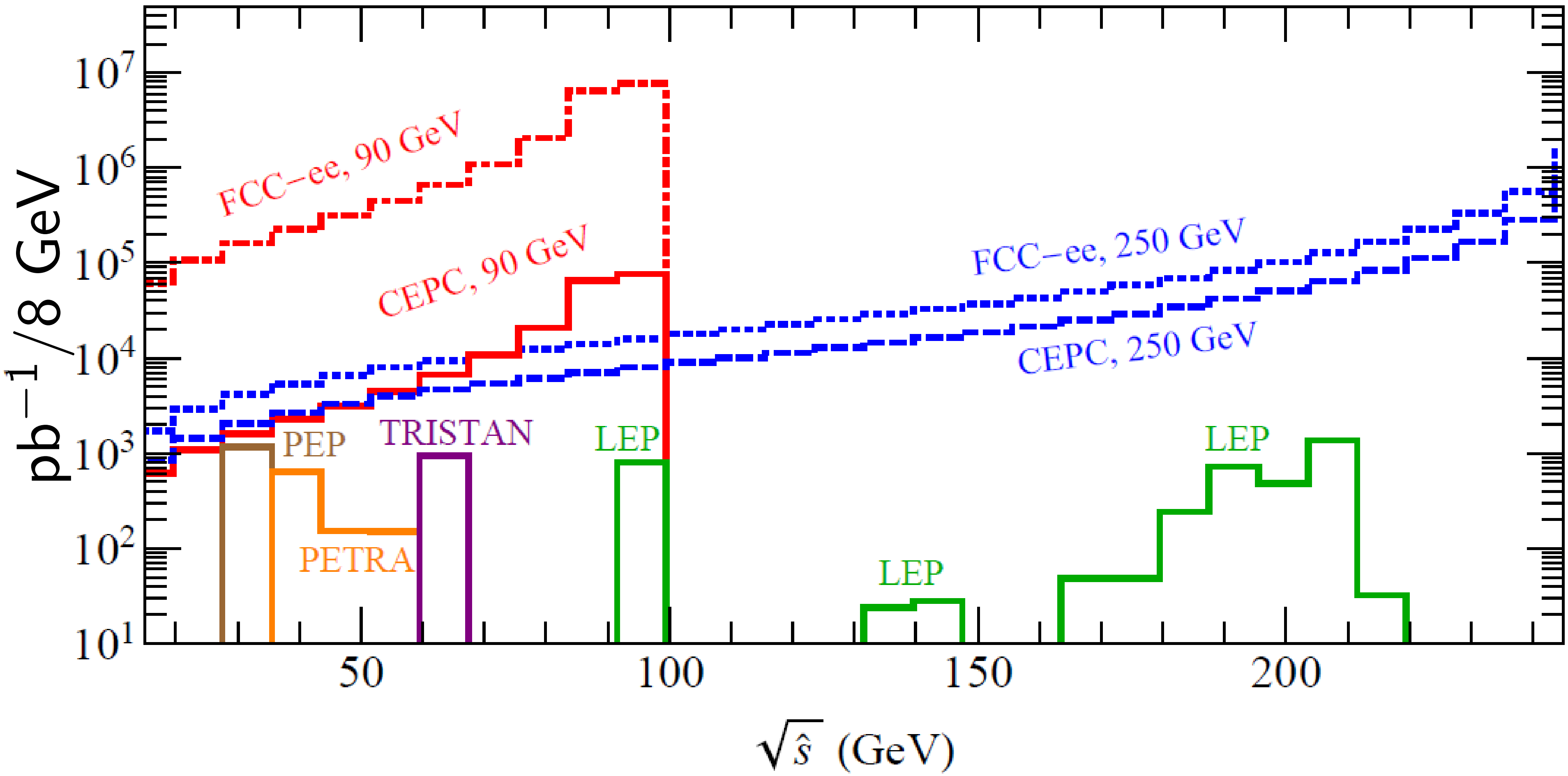
gaps left by PEP, PETRA, TRISTAN and LEP

integrated luminosity



Integrated luminosity from past low energy e^+e^- colliders at their nominal center-of-mass energies compared to the effective luminosity through radiative return from future e^+e^- colliders at $\sqrt{s} = 90$ or 250 GeV

integrated luminosity



Integrated luminosity from past low energy e^+e^- colliders at their nominal center-of-mass energies compared to the effective luminosity through radiative return from future e^+e^- colliders at $\sqrt{s} = 90$ or 250 GeV

gaps filled in and much more

Sensitivities of colliders for benchmark processes

Dark photon search:

assume small kinematic mixing ϵ of "dark photon" Z' with hypercharge gauge boson B

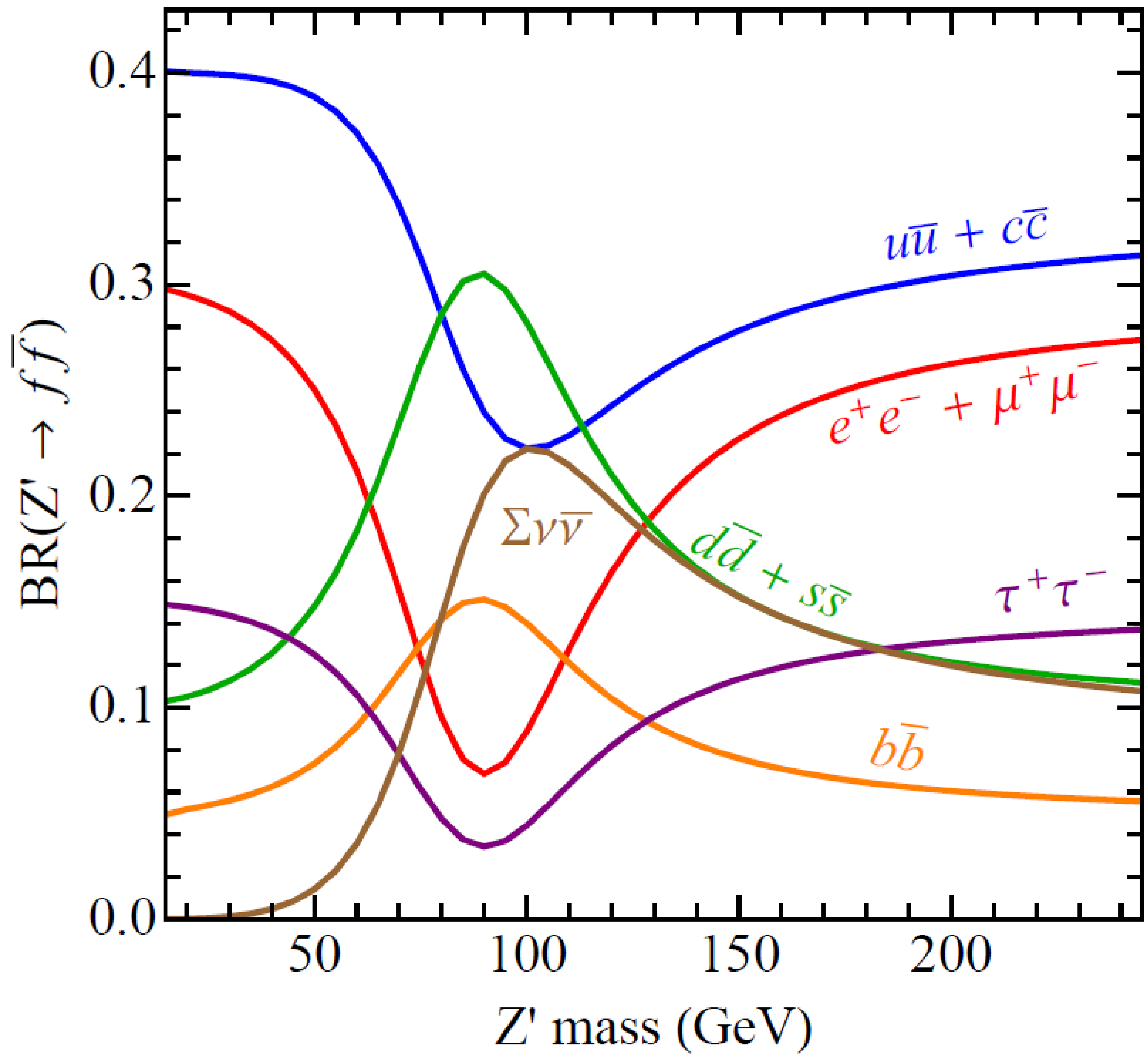
$$\mathcal{L} = -\frac{1}{4}\hat{B}^2_{\mu\nu} - \frac{1}{4}\hat{Z}'^2_{\mu\nu} + \epsilon \frac{1}{2c_w}\hat{Z}'_{\mu\nu}\hat{B}^{\mu\nu} + \frac{1}{2}M^2_{Z'}\hat{Z}'^2_{\mu}$$

for $\epsilon \ll 1$ and $M_{Z'} \ll M_Z$, Z' is photon-like:

$$\Gamma(Z' \to \bar{f}f) = \frac{\alpha M_{Z'}}{3} Q_f^2 N_c \beta_f \left(\frac{3-\beta_f^2}{2}\right)\epsilon^2 \,, \qquad \beta_f^2 \equiv 1 - \frac{4m_f^2}{M_{Z'}^2}$$

$M_{Z'} \approx M_Z$: $\to$ Z-like
$M_{Z'} \gg M_Z$: $\to$ B-like

Dark photon branching ratios for $\epsilon = 5 \times 10^{-3}$

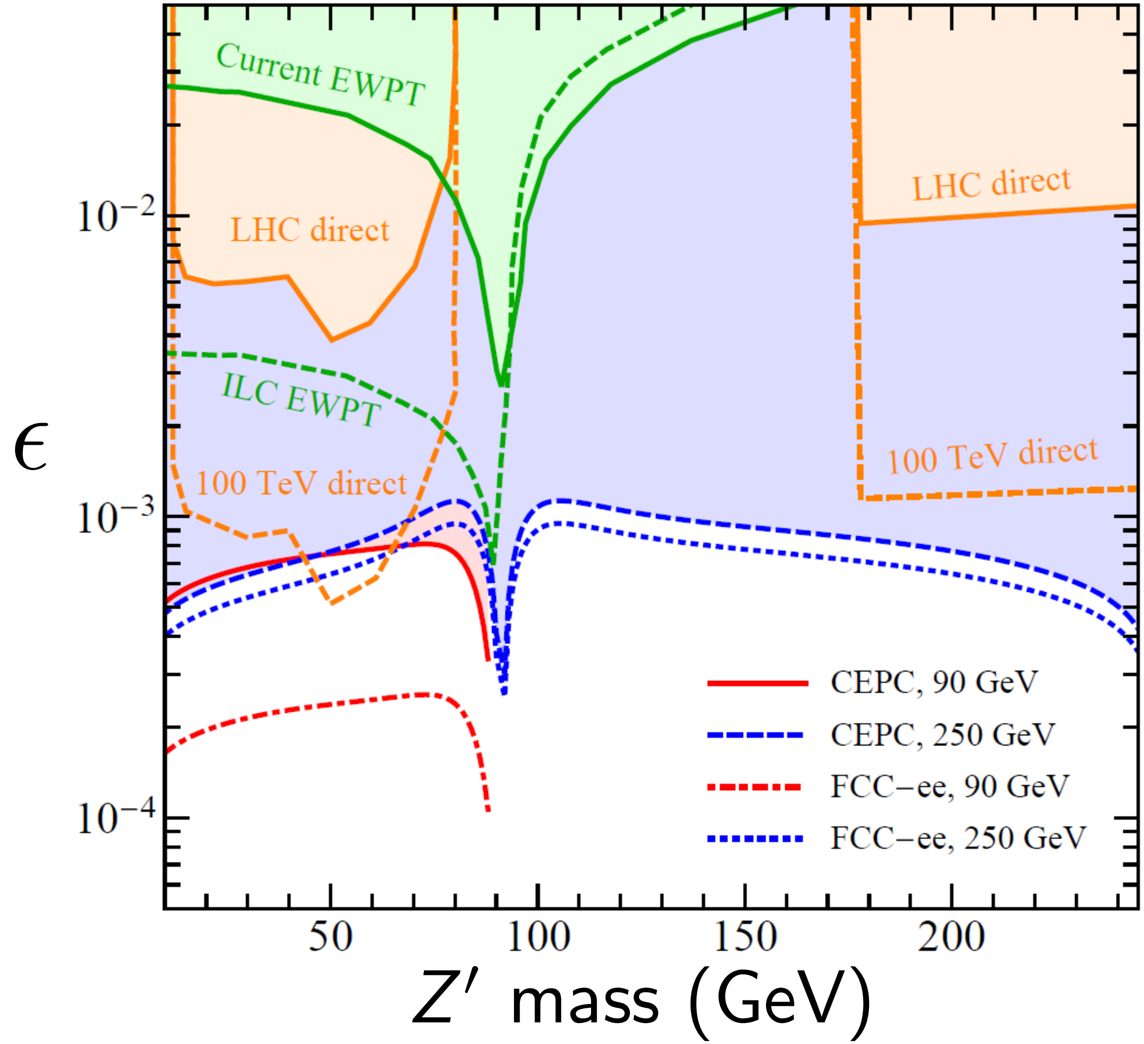


(for $\epsilon \ll 1$ BR-s become independent of ϵ)

BR-s from PT, w/o nonpert. corrections

dark photon limits on ϵ at 95% C.L.

including $e^+e^- \to \gamma Z' \to \gamma\mu^+\mu^-$



EWPT = electroweak precision constraints
100 TeV projection assumes $\int \mathcal{L} dt = 3000\ \mathrm{fb}^{-1}$

EWPT & direct searches from
J. Fan, M. Reece, and L. T. Wang,
arXiv:1411.1054

assume $\Delta m = m^2/(10^5\ \mathrm{GeV})$

apps to heavy flavor spectroscopy

(a) bottomonium analogues of charmonium X, Y, Z states

(b) bottom-charm exotics: $\bar{B}^* D^*$, etc.

(c) b analogues of $D^*_{s0}(2317)$ and $D_{s1}(2460)$:
BK molecules or chiral partners of B_s, B_s ?

(d) baryon-meson, baryon-baryon doubly heavy molecules

(e) doubly heavy QQq baryons

Pair production of narrow B_{sJ} states

$e^+e^- \to B_{sJ} + X$

may be used to look for b-quark
analogues of the very narrow D_{sJ} states
seen by BaBar, CLEO and Belle

e.g. $D_{s0}(2317)$, $J^P = 0^+$, likely chiral partner of D_s:

$m[D_{s0}(2317)] - m[D_s] = 345$ MeV $\approx m_q^{\text{const.}}$

below DK threshold $\Rightarrow$ very narrow, $\Gamma < 3.8$ MeV,

decay: $D_{s0}(2317) \to D_s^+ \pi^0$
through v. small isospin-violating η–π^0 mixing

detailed v. interesting predictions for b analogues
$\Rightarrow$ opportunity to test our understanding of χSB

the upshot:

while the new generation of high-E high-$\mathcal{L}$ e^+e^- colliders requires a *total commitment* of the BSM community,

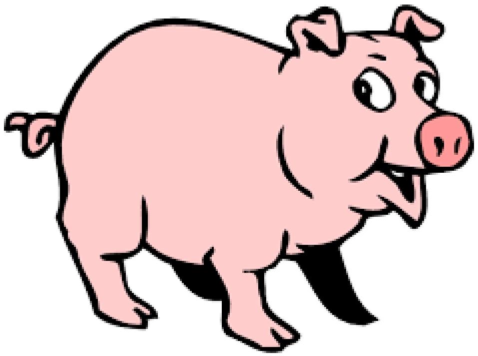
it provides an exiciting an opportunity for *active participation* of the QCD community.

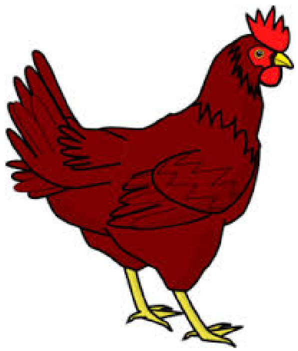
what is the difference between *total commitment* and *active participation* ?

the difference between the two is best explained by a statement a pig made to a hen:

take eggs and bacon as an example:

for you, it implies active participation,
from me, it requires a total commitment!





SUMMARY

- the new narrow exotic resonances are loosely bound $J^P = 1^+$ states of $\bar{D}D^*$, $\bar{D}^*D^*$, $\bar{B}B^*$ $\bar{B}^*B^*$

predictions:

– $\bar{D}^*D^*$ in $I = 0$ and $I = 1$ channels; $I = 1$ seen!

– new isosinglet $\bar{B}B^*$ and $\bar{B}^*B^*$ states below threshold; $\chi_1 b(3P)$?

– *heavy deuterons*: $\Sigma_c D^*$, $\Sigma_b B^*$, $\Sigma_b D^*$, $\Sigma_Q \bar{\Lambda}_{Q'}$, $\Sigma_Q^+ \Sigma_Q^-$ ...

– doubly heavy baryons QQq @pp & e^+e^-

- new spectroscopy in future e^+e^- high-$\mathcal{L}$ high-E colliders

Supplementary transparencies