Tel Aviv University

CEPC as a Cutting-Edge High-Luminosity Machine for Heavy Flavor QCD Spectroscopy

Marek Karliner
Tel Aviv University

arXiv:1503.07209, with Matthew Low, Jon Rosner and Lian-Tao Wang
and
arXiv:1506.06386, arXiv:1508.01496
PRD91 (2015) 1, 014014 & PRD90 (2014) 9, 094007 with J. Rosner
JHEP 7,153(2013) with Shmuel Nussinov

CEPC Workshop, IHEP Beijing, 10-12 Aug 2015

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Radiative Return Capabilities of a High-Energy High-Luminosity e^+e^- collider

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

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

OUTLINE

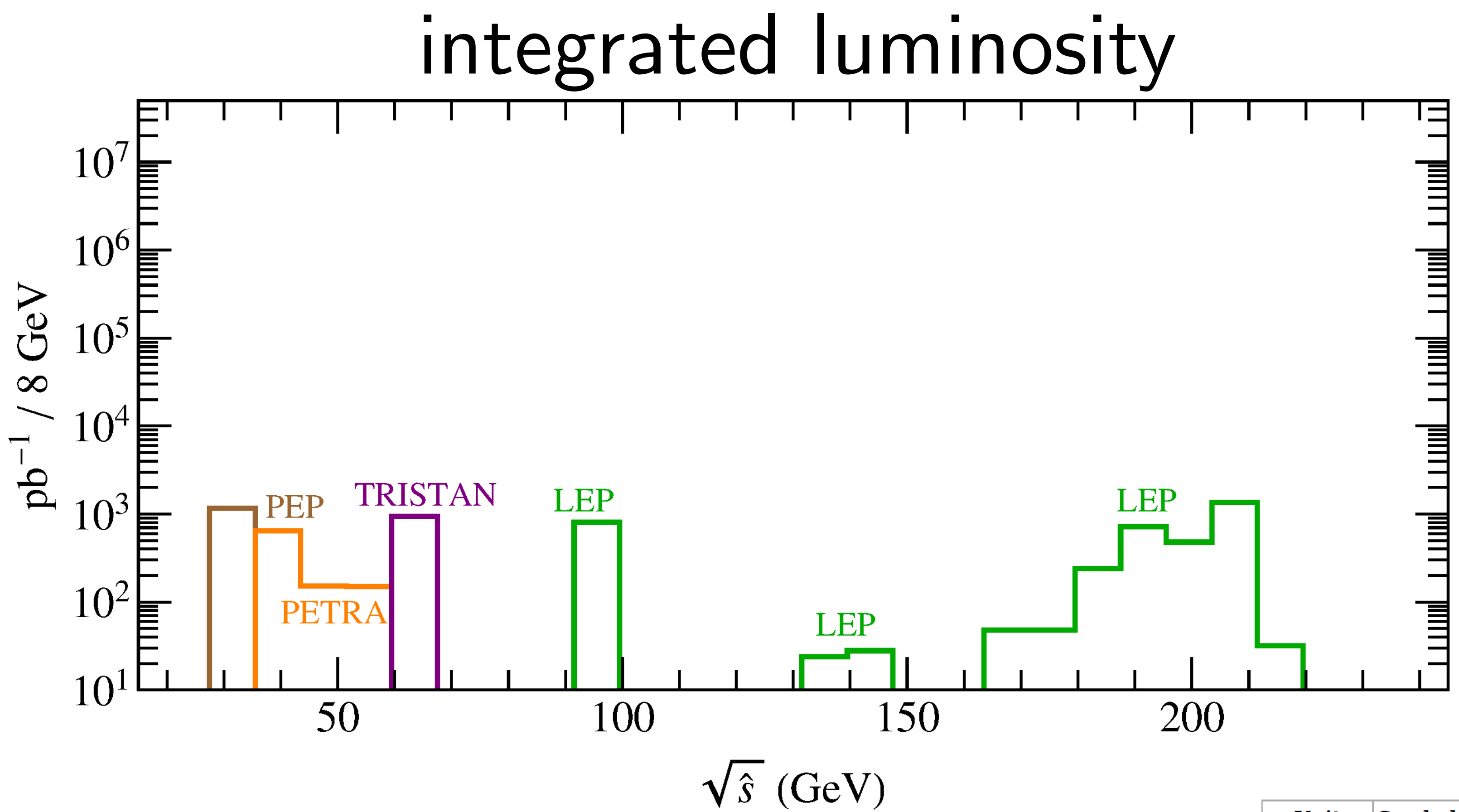
- e^+e^- collider designed for a certain E_{CM} can collect events at all lower energies through initial-state radiation (ISR or *radiative return*)
  "it's not a bug, it's a feature"

- 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

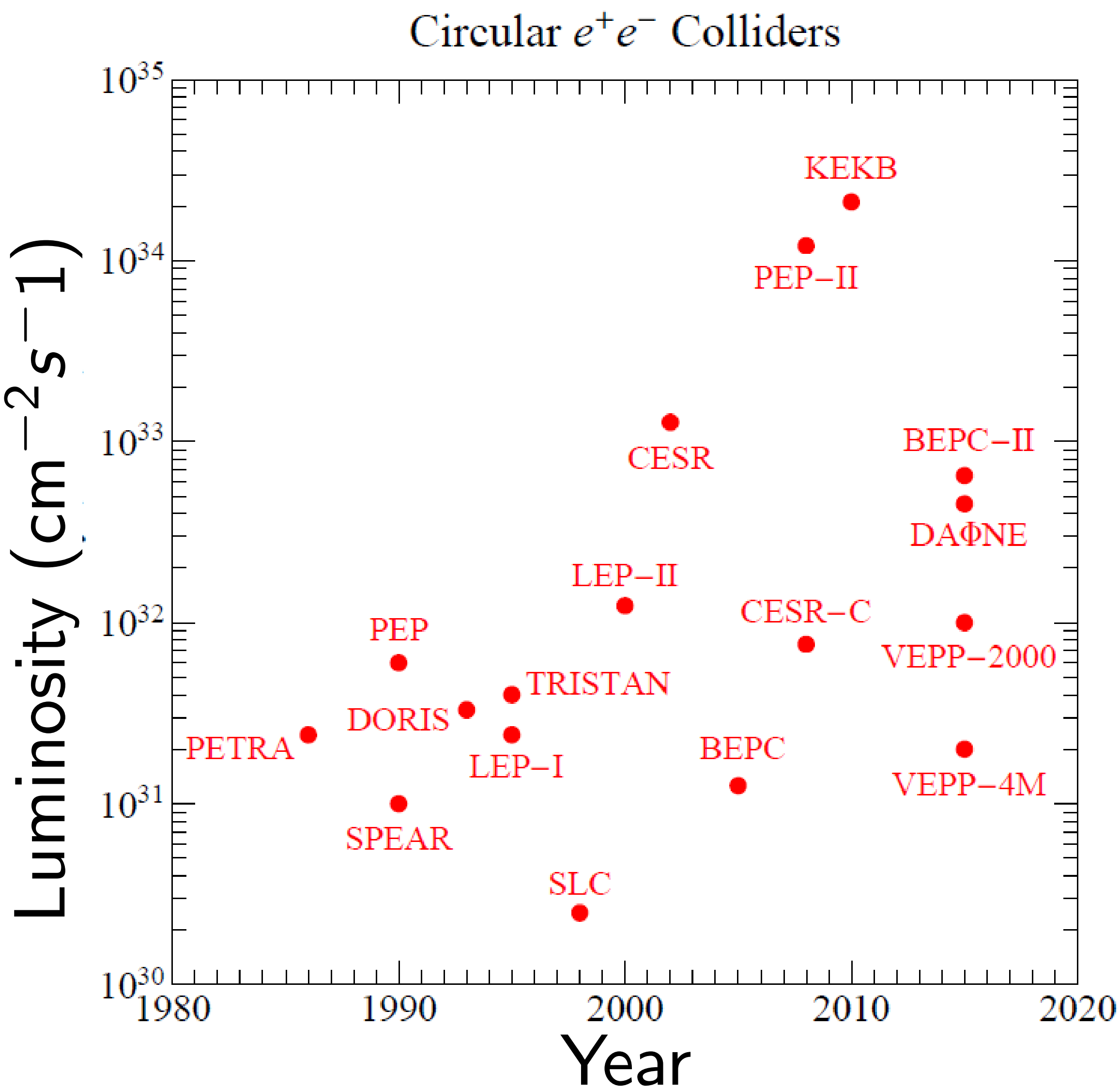
	$\sqrt{s} = 90$ GeV	$\sqrt{s} = 250$ GeV
CEPC	0.5 ab^{-1}	5 ab^{-1}
FCC-ee	50 ab^{-1}	10 ab^{-1}

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)

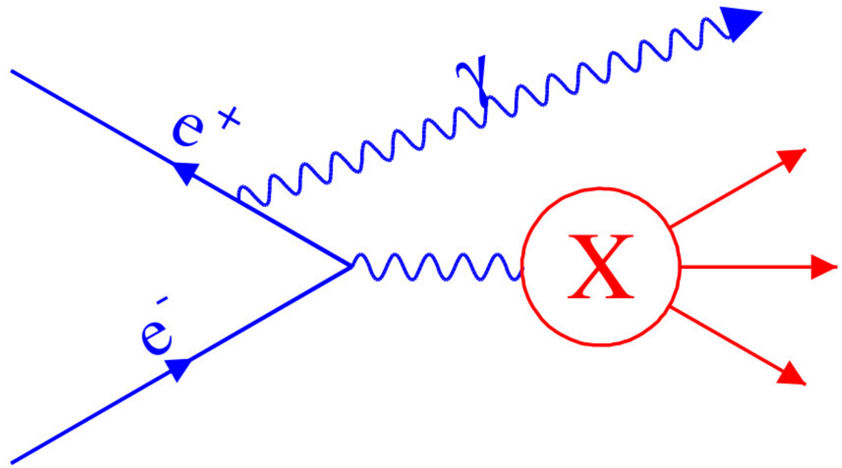
Instantaneous and/or integrated luminosities achieved at some e^+e^- colliders

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

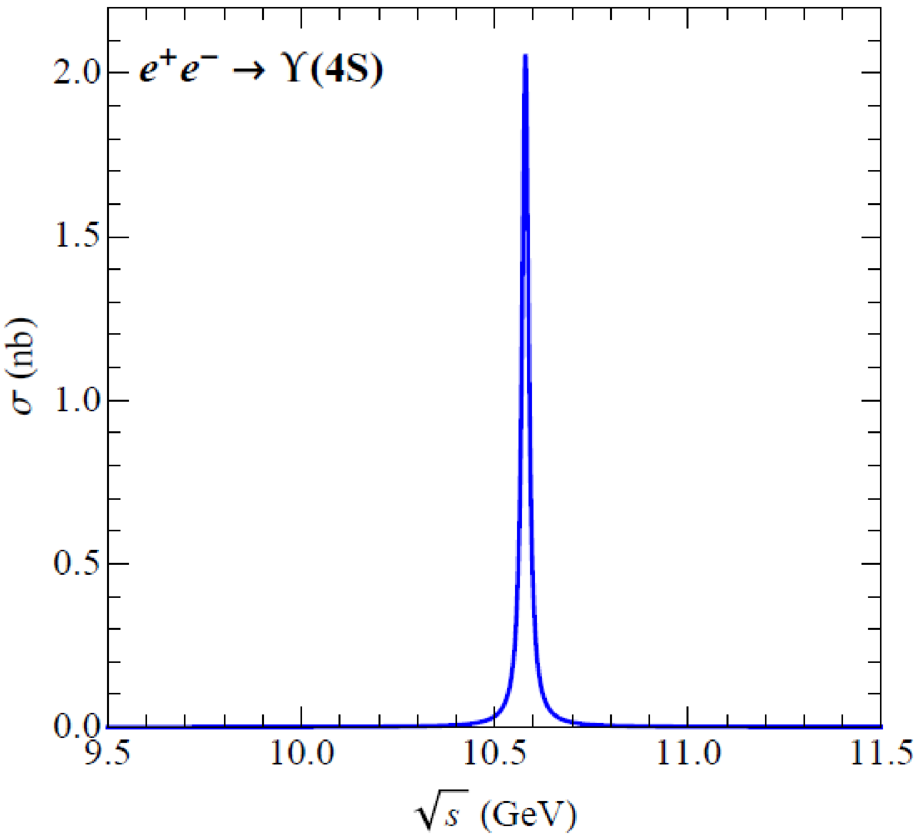
and ends up with energy xE with probability per unit x

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

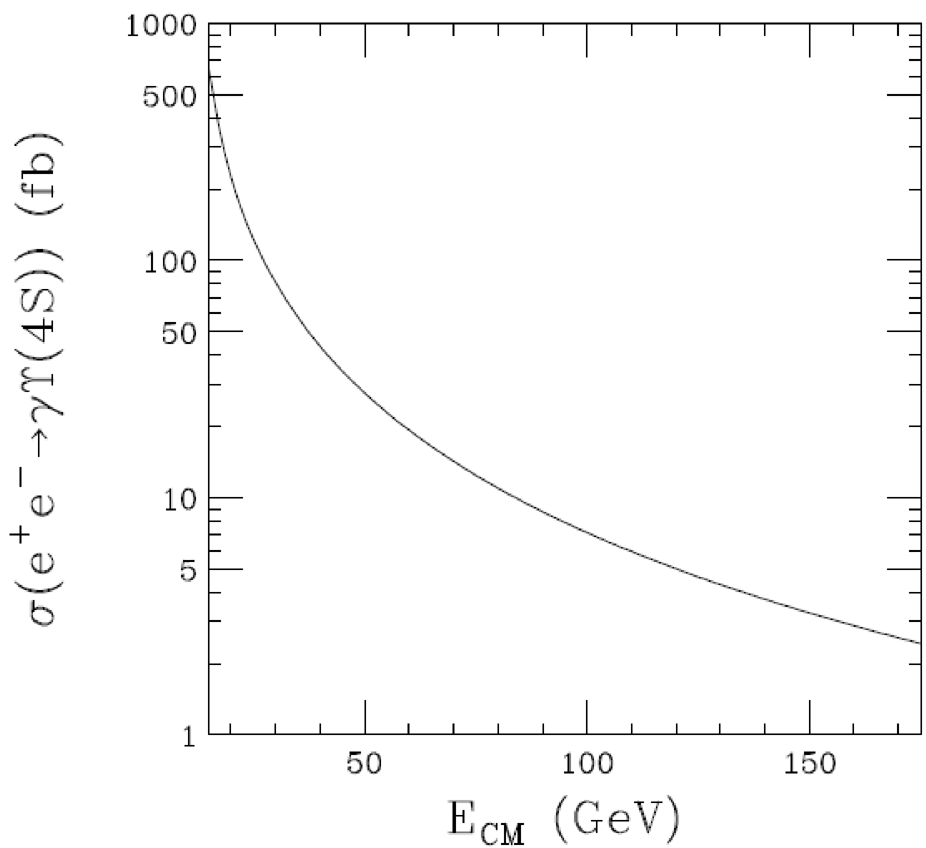
$\Rightarrow \sigma$ for production of R by rad. return

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

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

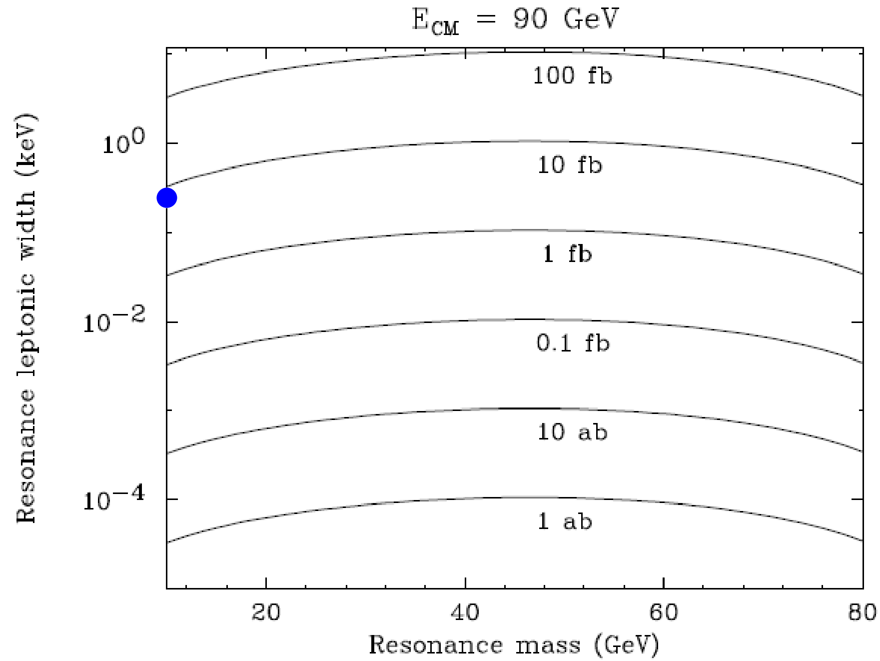


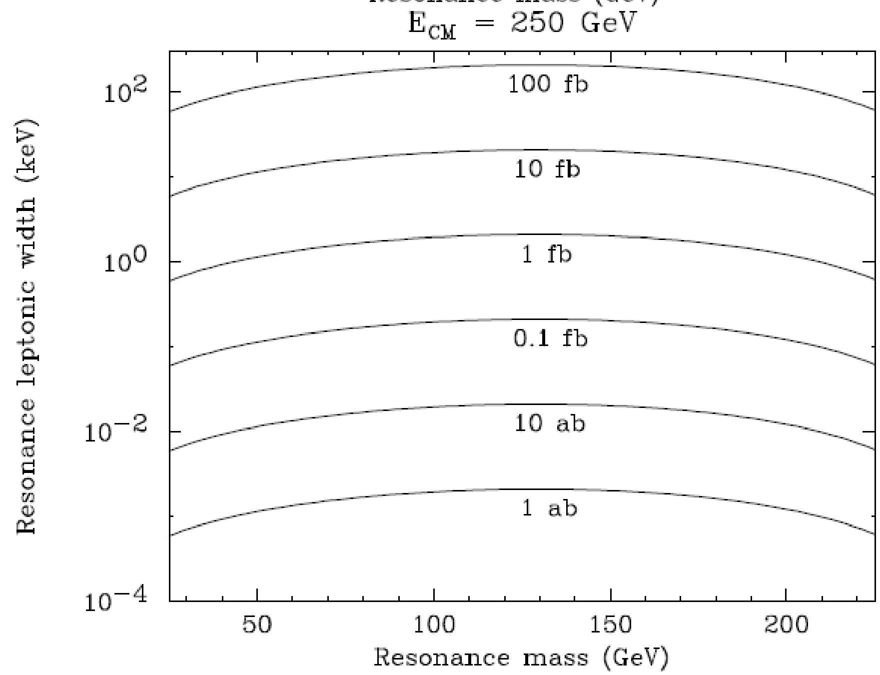
$\sigma(e^+e^- \to \gamma \Upsilon(4S))$ at collider of energy E_{CM}



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

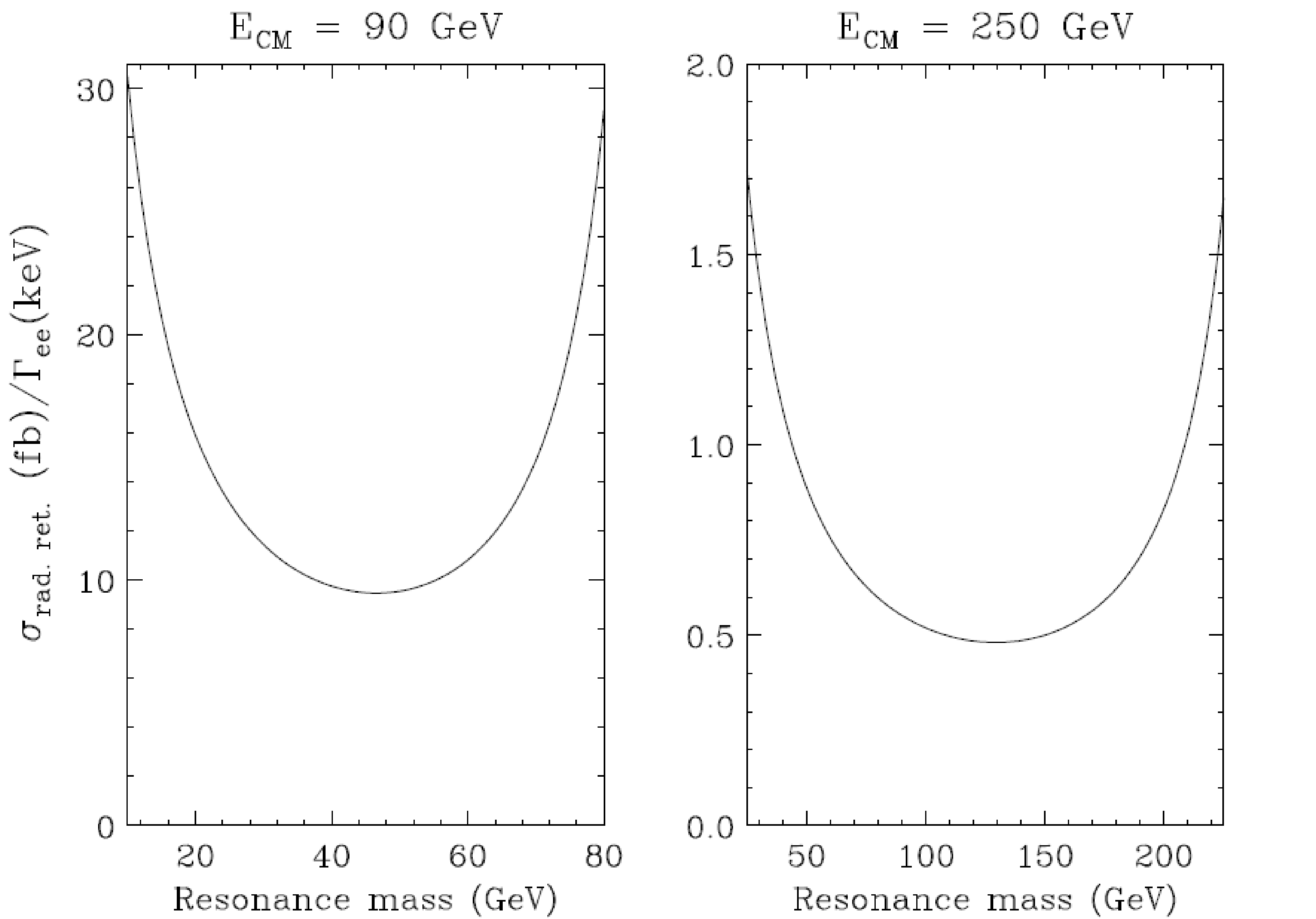
e.g. for $\Upsilon(4S)$:
m=$10.6 GeV, \Gamma_{ee} = 0.322$ keV
$\sigma = 9.17$ fb at $E_{CM} = 90$ GeV





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

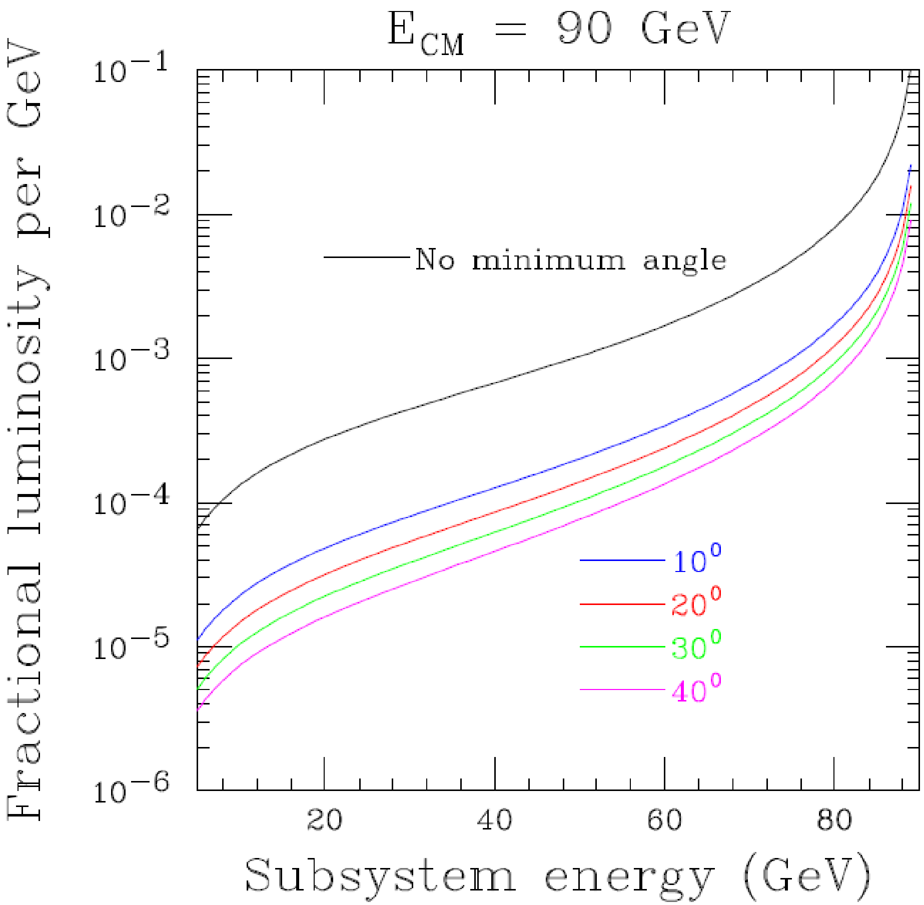
$$\frac{d\sigma(s)}{dx} = \frac{2\alpha}{\pi}\frac{1+x^2}{1-x}\ln\frac{E}{m_e}\hat{\sigma}(\hat{s})$$

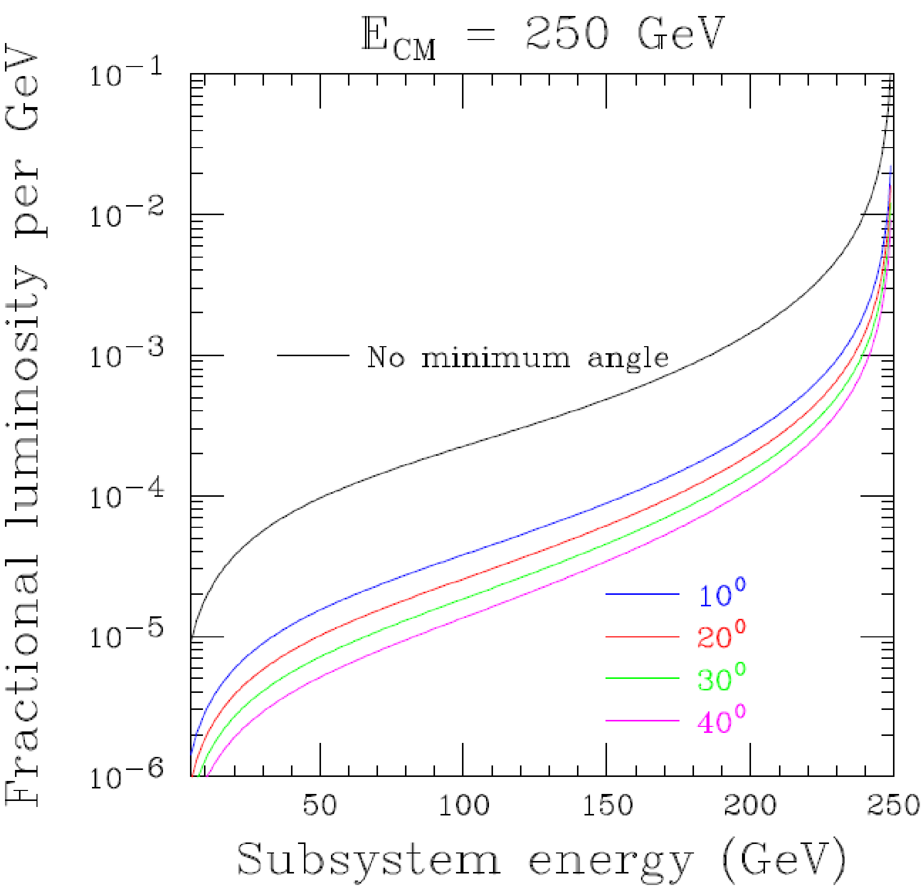
cross section per unit $\hat{E}_{CM}$ times an interval Δ of $\hat{E}_{CM}$

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

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

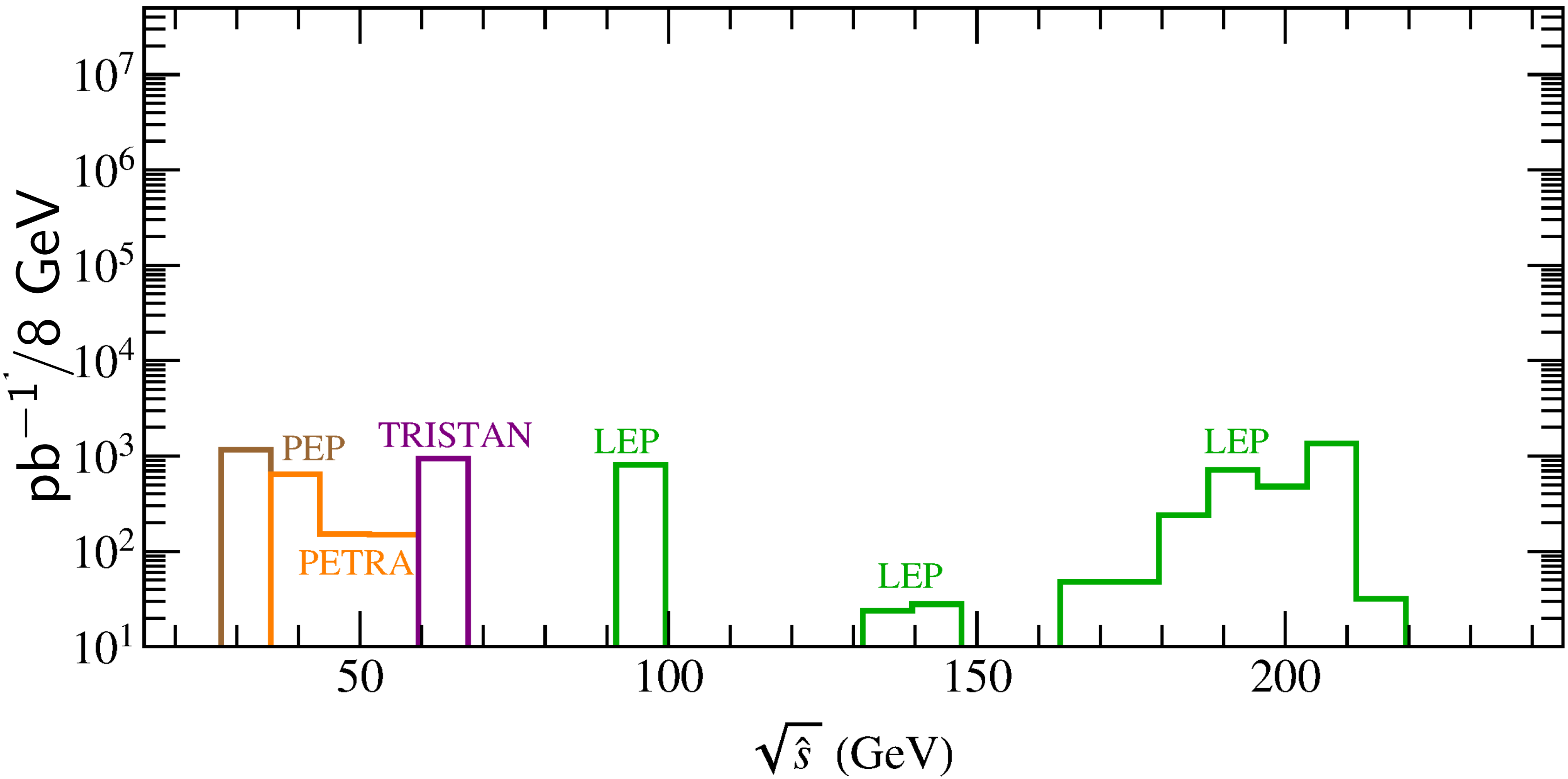
fractional luminosity L_f as function of subsystem energy





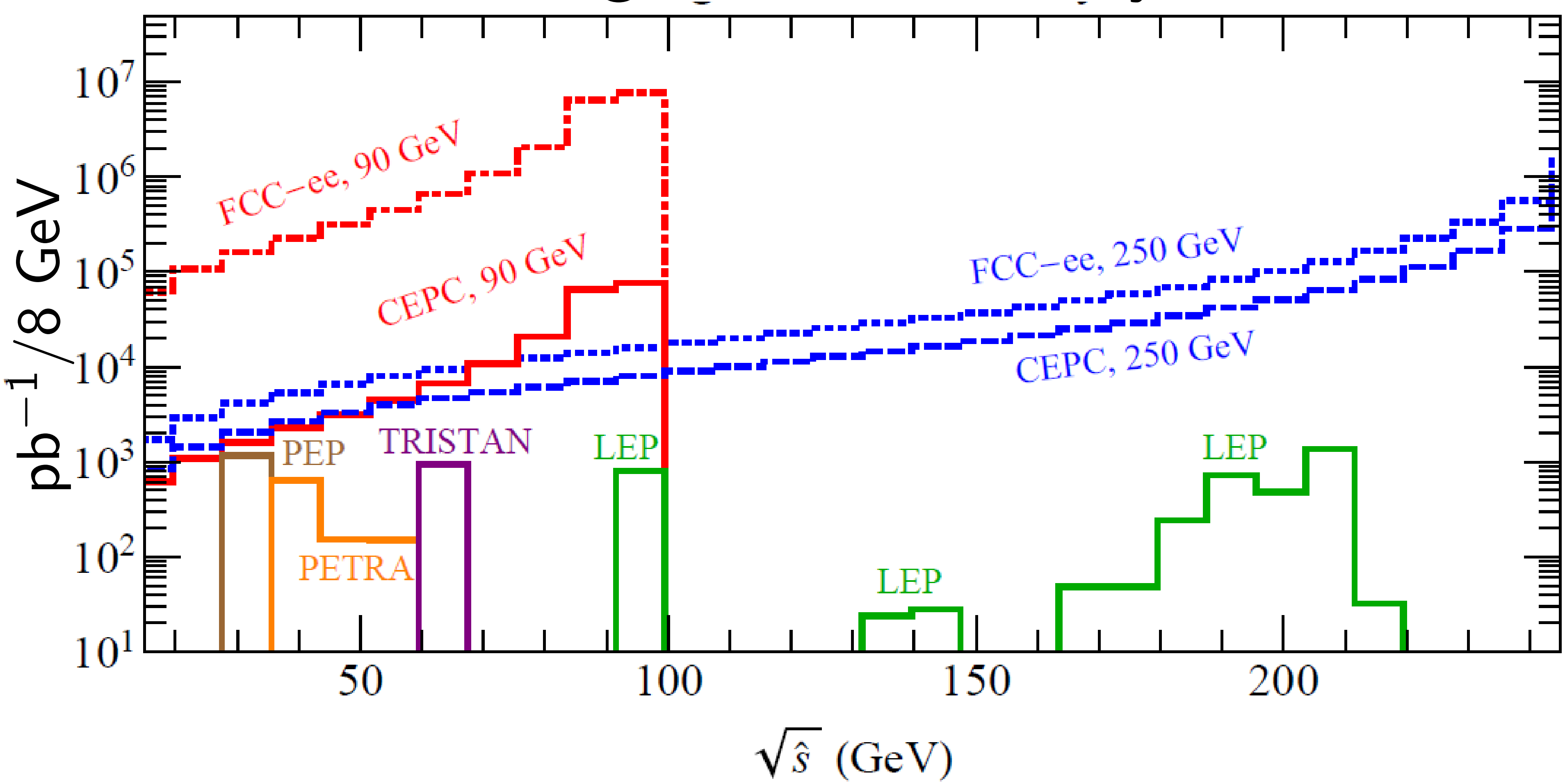
larger cut on photon angle → cleaner signal, but less σ

integrated luminosity



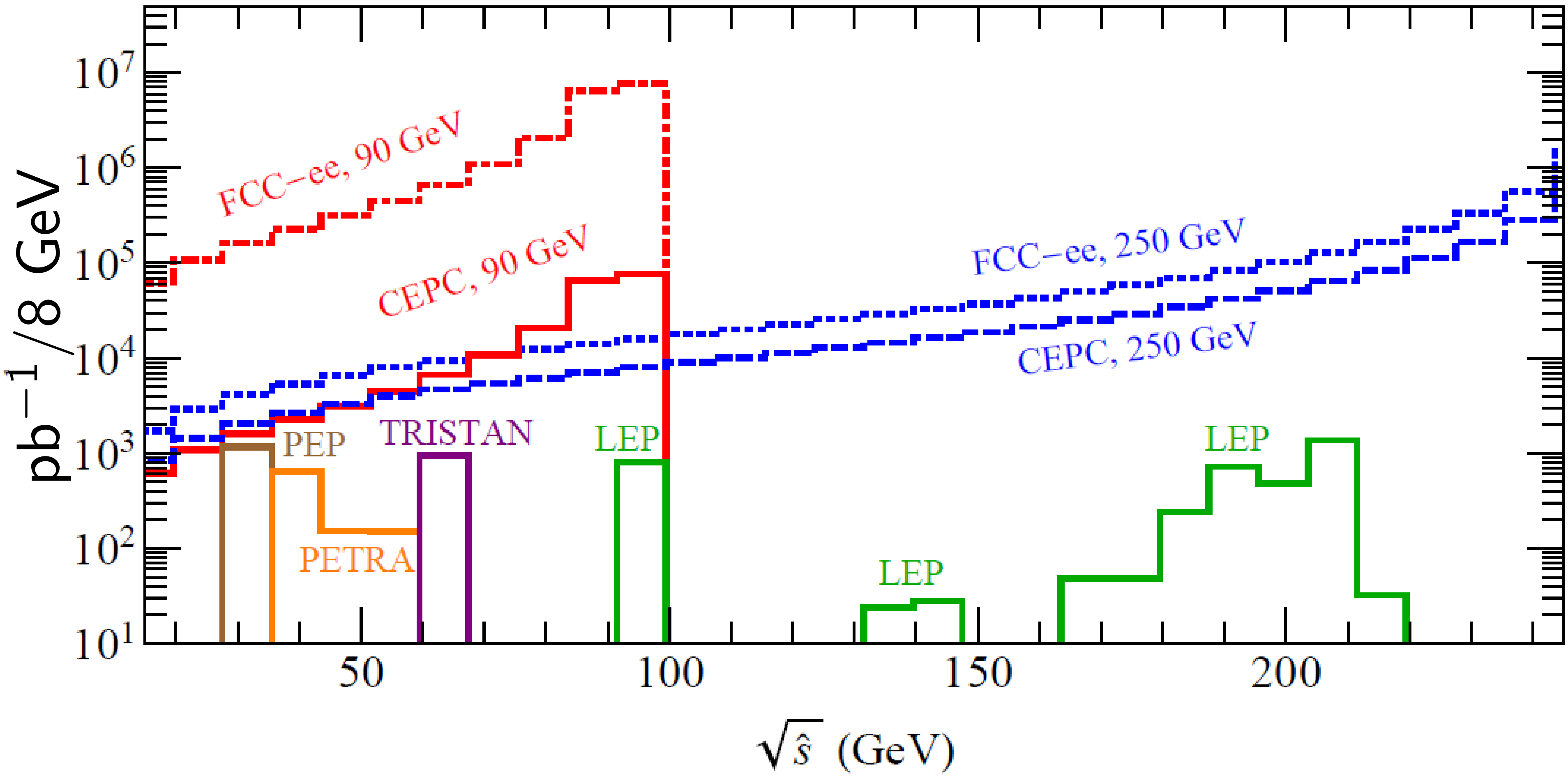
gaps left by PEP, PETRA, TRISTAN and LEP

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

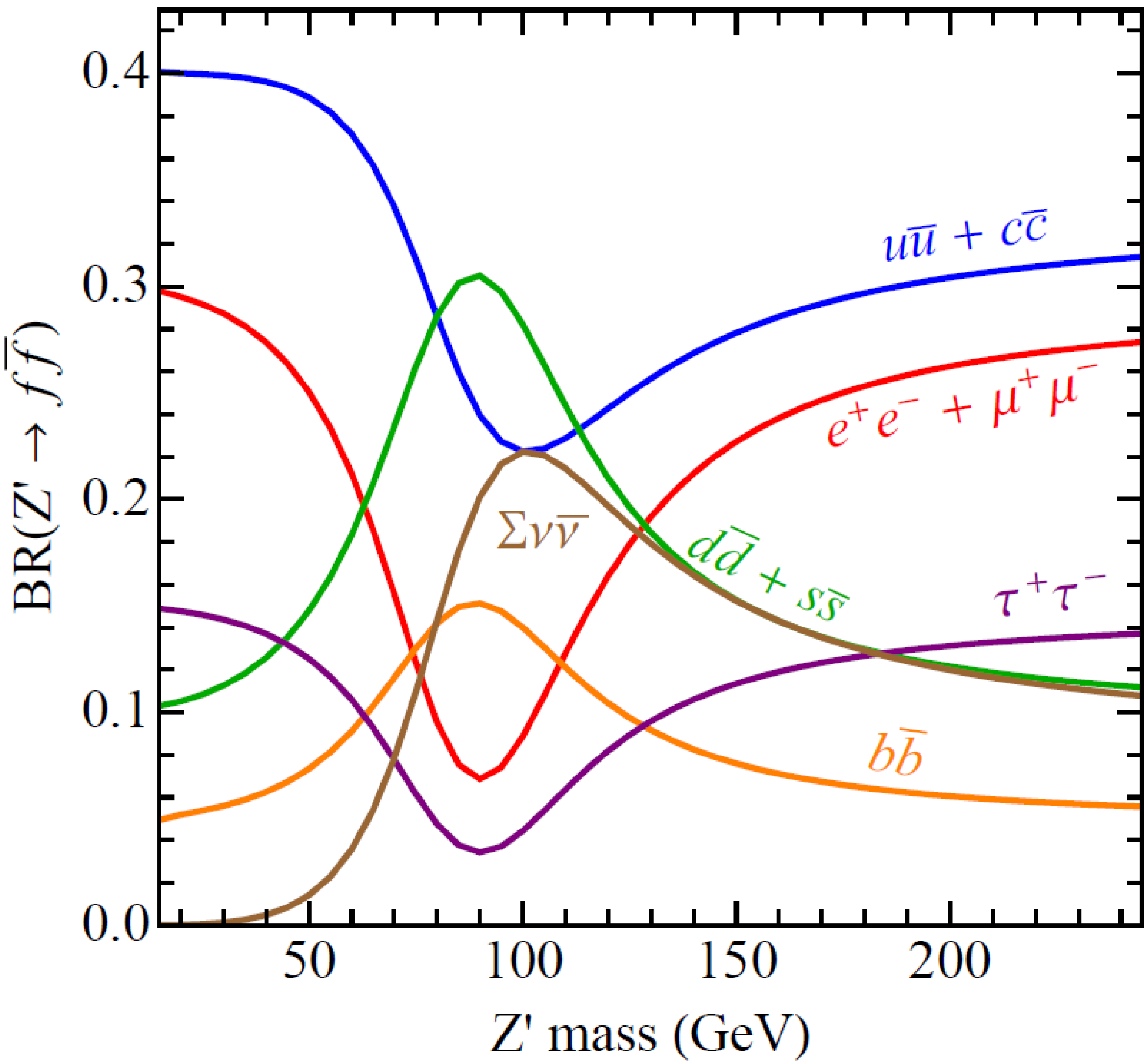
$$\mathcal{L} = -\frac{1}{4}\hat{B}^2_{\mu\nu} - \frac{1}{4}\hat{Z}'^2_{\mu\nu} + \epsilon\frac{1}{2c_w}\hat{Z}'_{\mu\nu}\hat{B}^{\mu\nu} + \frac{1}{2}M^2_{Z'}\hat{Z}'^2_{\mu}$$

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

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

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

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

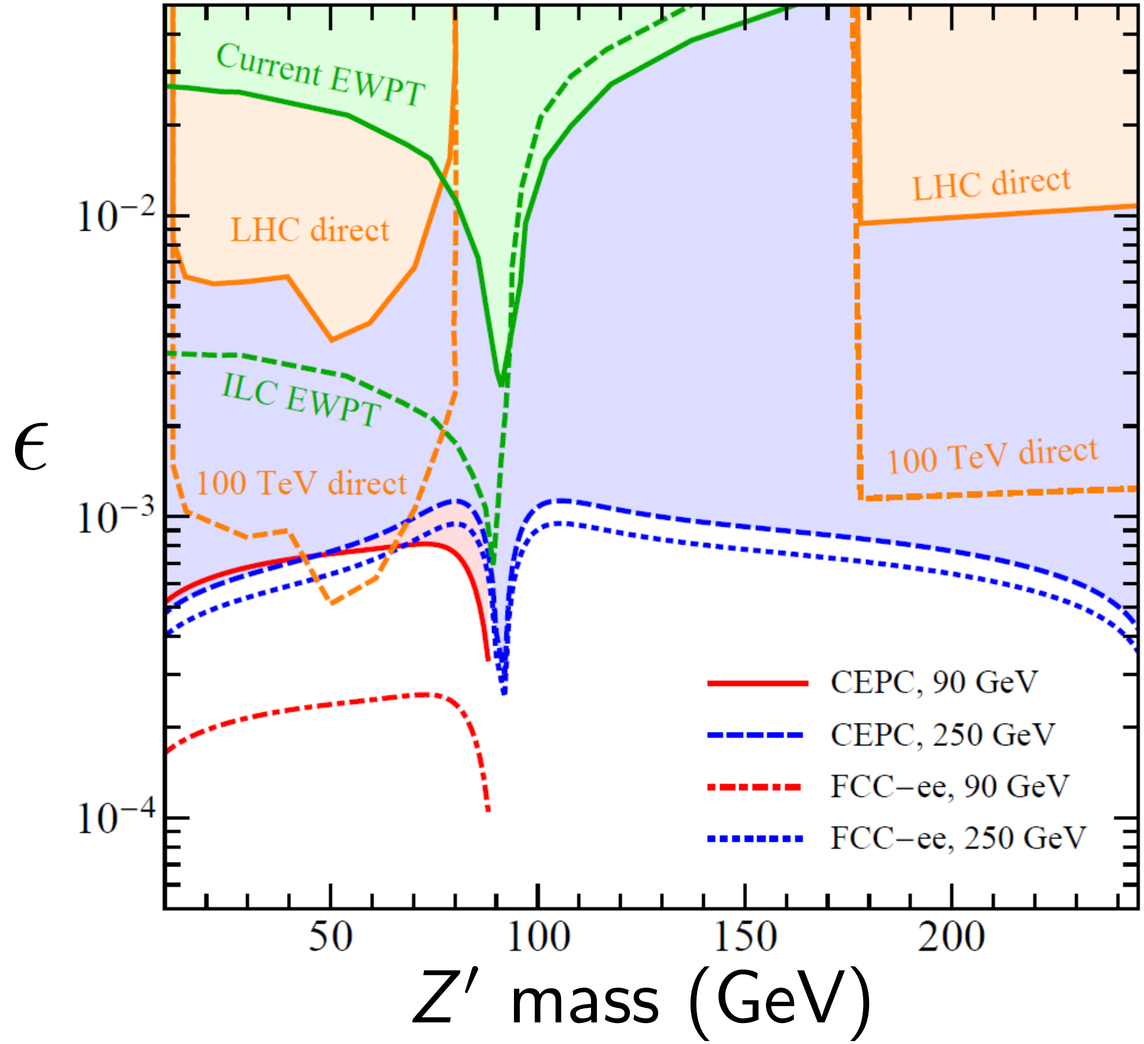


(for $\epsilon \ll 1$ BR-s become independent of ϵ)

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 $\int \mathcal{L} dt = 3000$ fb $^{-1}$

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

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

new rich heavy flavor QCD spectroscopy

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

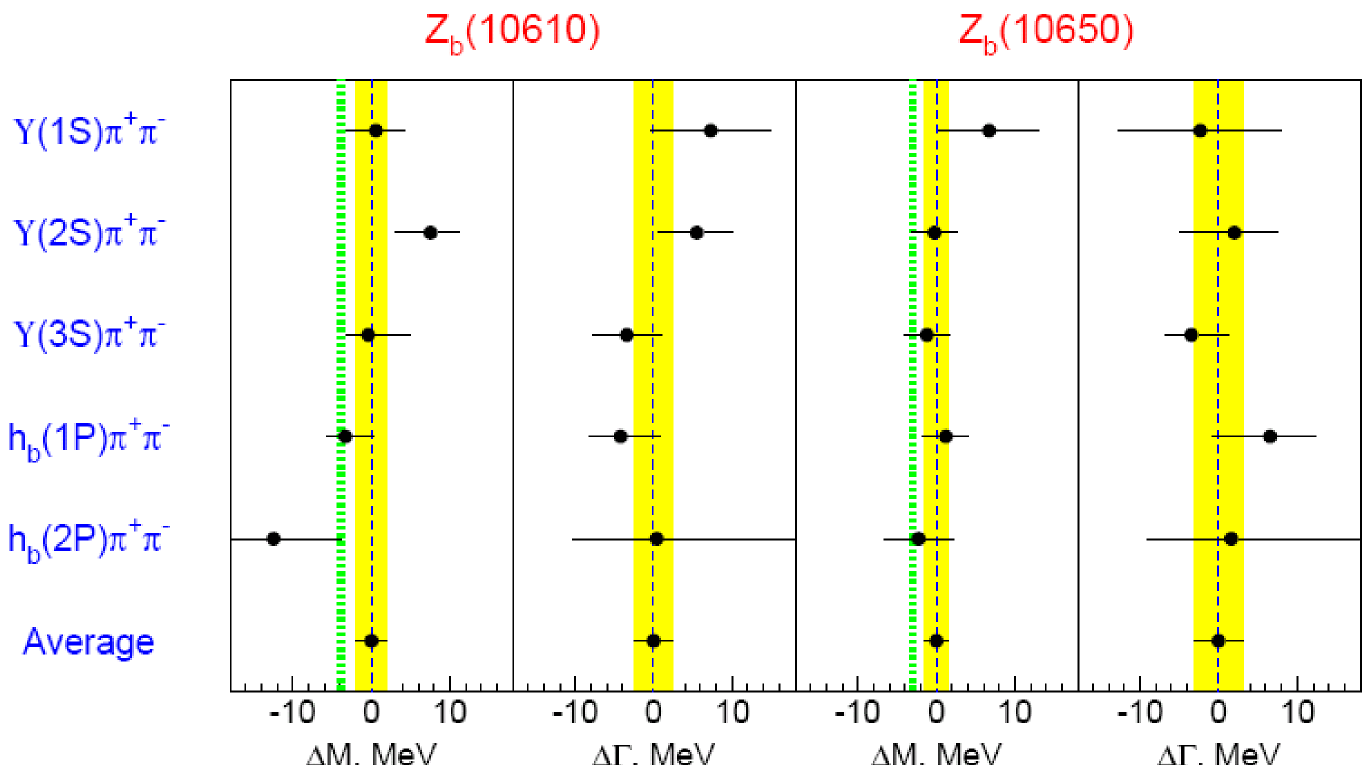
(b) new exotics – doubly-heavy hadronic molecules
meson-meson, baryon-meson, baryon-baryon
the lightest one:
LHCb "pentaquark" $= \Sigma_c \bar{D}^* \ (\bar{c}cuud)$

(c) doubly heavy QQq baryons

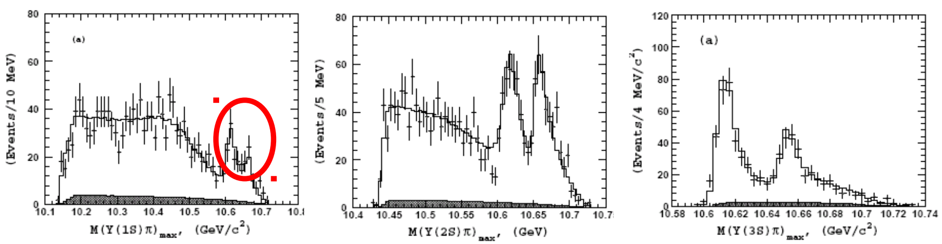
(d) b analogues of $D^*_{s0}(2317)$ and $D_{s1}(2460)$:
BK molecules or chiral partners of B_s, B_s

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

- extensive spectrum of exotic charmonia
- $\bar{c}c\bar{q}q$ or mixtures of $\bar{c}$ and $\bar{D}D^*$ "hadronic molecules", e.g. $X(3872)$
- Z_c: charged $\rightarrow$ manifestly exotic, $\sim \bar{c}cu\bar{d}$
- $m_b \gg m_c \rightarrow$ bottomonium analogues for all X, Y, Z; possibly additional yet heavier exotics
- Belle: beautiful data for two Z_b-s
- but X_b not seen yet, could camouflage as $\chi_{b1}(3P)$
- many states beyond reach of B-factories, accessible via radiative return in e^+e^- at high E_{CM}



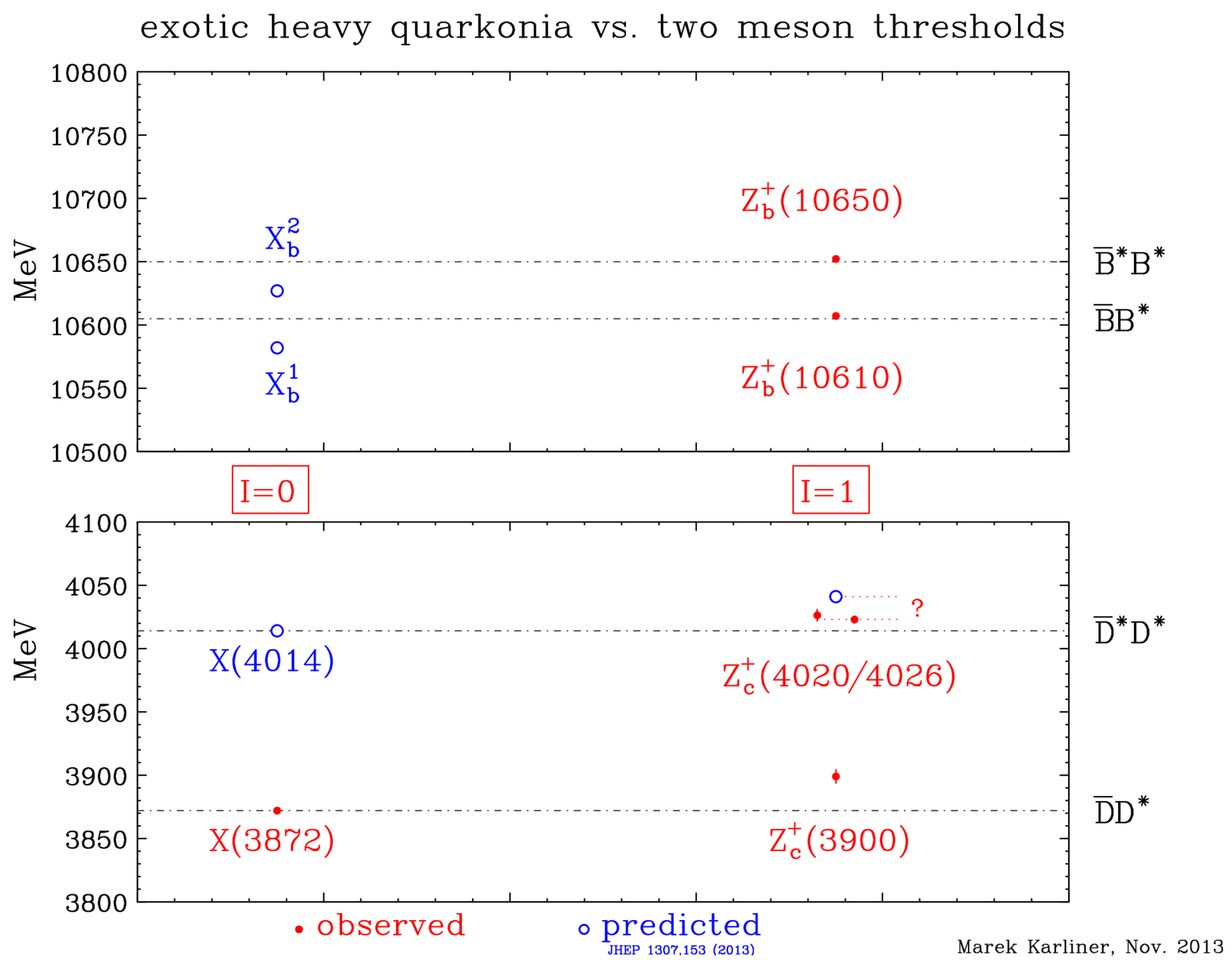
Comparison of $Z_b(10610)$ and $Z_b(10650)$ parameters obtained from different decays

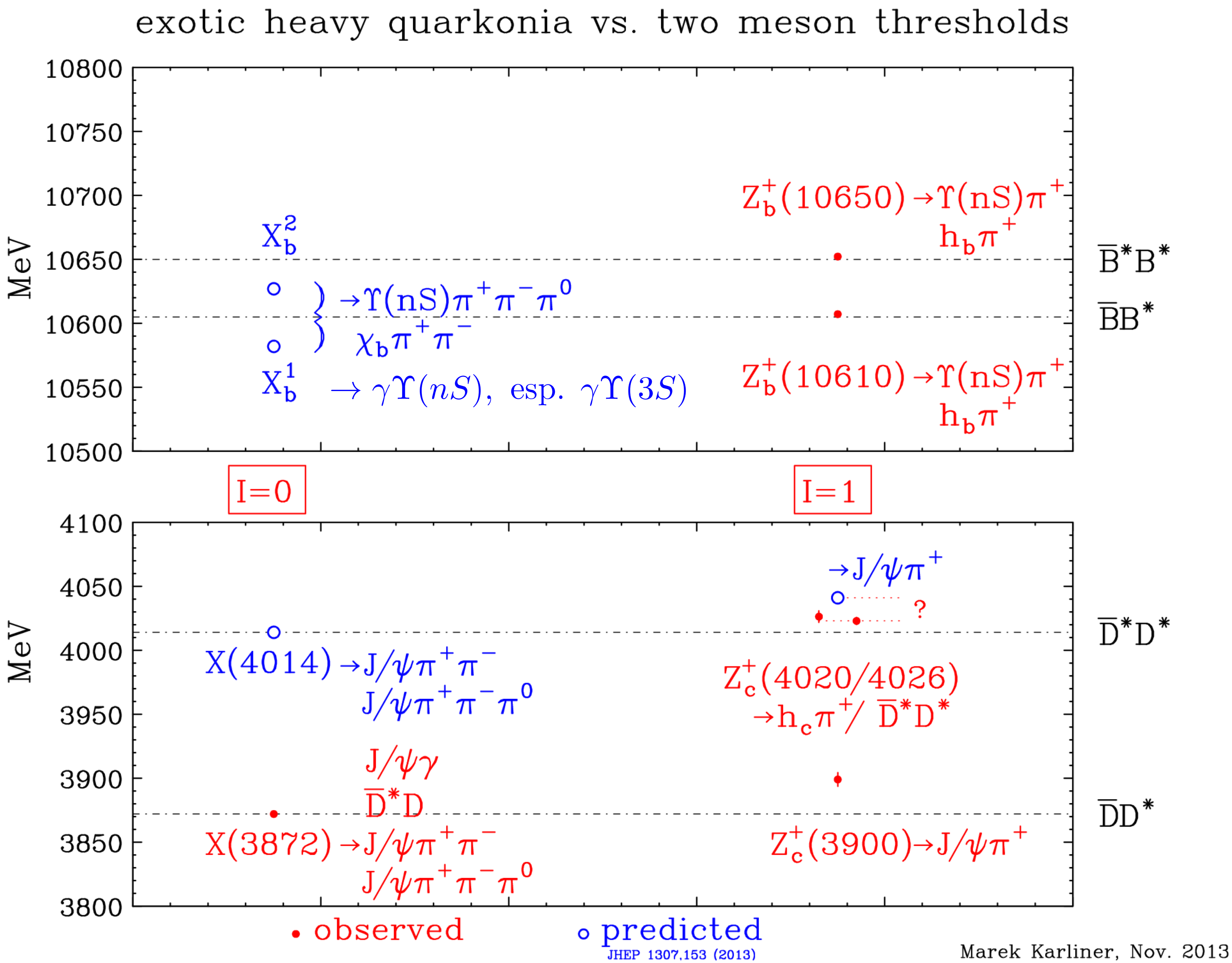


$\Upsilon(3S)\pi^+$ $\Upsilon(2S)\pi^+$ $\Upsilon(1S)\pi^+$

$\Gamma[Z_b(10610)] \approx \Gamma[(Z_b(10650)] \approx 15$ MeV

$J^P = 1^+$ for both $Z_b(10610)$ and $Z_b(10650)$


exotic heavy quarkonia vs. two meson thresholds
MeV
10800
10750
10700
10650
10600
10550
10500
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
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
MeV
10800
10750
10700
10650
10600
10550
10500
X_b^2
X_b^1
$\to \Upsilon(nS)\pi^+\pi^-\pi^0$
$\chi_b \pi^+\pi^-$
$\to \gamma\Upsilon(nS)$, esp. $\gamma\Upsilon(3S)$
$Z_b^+(10650) \to \Upsilon(nS)\pi^+$
$h_b\pi^+$
$Z_b^+(10610) \to \Upsilon(nS)\pi^+$
$h_b\pi^+$
$\bar{B}^*B^*$
$\bar{B}B^*$
I=0
I=1
4100
4050
4000
3950
3900
3850
3800
$\to J/\psi\pi^+$
?
$\bar{D}^*D^*$
$X(4014) \to J/\psi\pi^+\pi^-$
$J/\psi\pi^+\pi^-\pi^0$
$Z_c^+(4020/4026)$
$\to h_c\pi^+ / \bar{D}^*D^*$
$J/\psi\gamma$
$\bar{D}^*D$
$\bar{D}D^*$
$X(3872) \to J/\psi\pi^+\pi^-$
$J/\psi\pi^+\pi^-\pi^0$
$Z_c^+(3900) \to J/\psi\pi^+$
• observed
∘ predicted
JHEP 1307,153 (2013)
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(b) doubly-heavy hadronic molecules:
most likely candidates with $Q\bar{Q}'$, $Q = c, b$, $\bar{Q}' = \bar{c}, \bar{b}$:

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

$\Sigma_c\bar{D}^*$, $\Sigma_c B^*$, $\Sigma_b\bar{D}^*$, $\Sigma_b B^*$, 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)
$b\bar{c}$ 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 $\Sigma_b\Lambda_c$.

(b) doubly-heavy hadronic molecules:
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$\Sigma_c\bar{D}^*$, $\Sigma_c B^*$, $\Sigma_b\bar{D}^*$, $\Sigma_b B^*$, 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 $\Sigma_b\bar{\Lambda}_c$.

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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 $\Sigma_b\Lambda_c$.

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† successfully predicted; talk on Thursday 10AM @TH

prediction of doubly heavy baryon with hidden charm:

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

$\Sigma_c^{++}(cuu)\, D^{-*}(\bar{c}d)$, 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: $\bar{c}c\, uud$
a molecule, not a pentaquark

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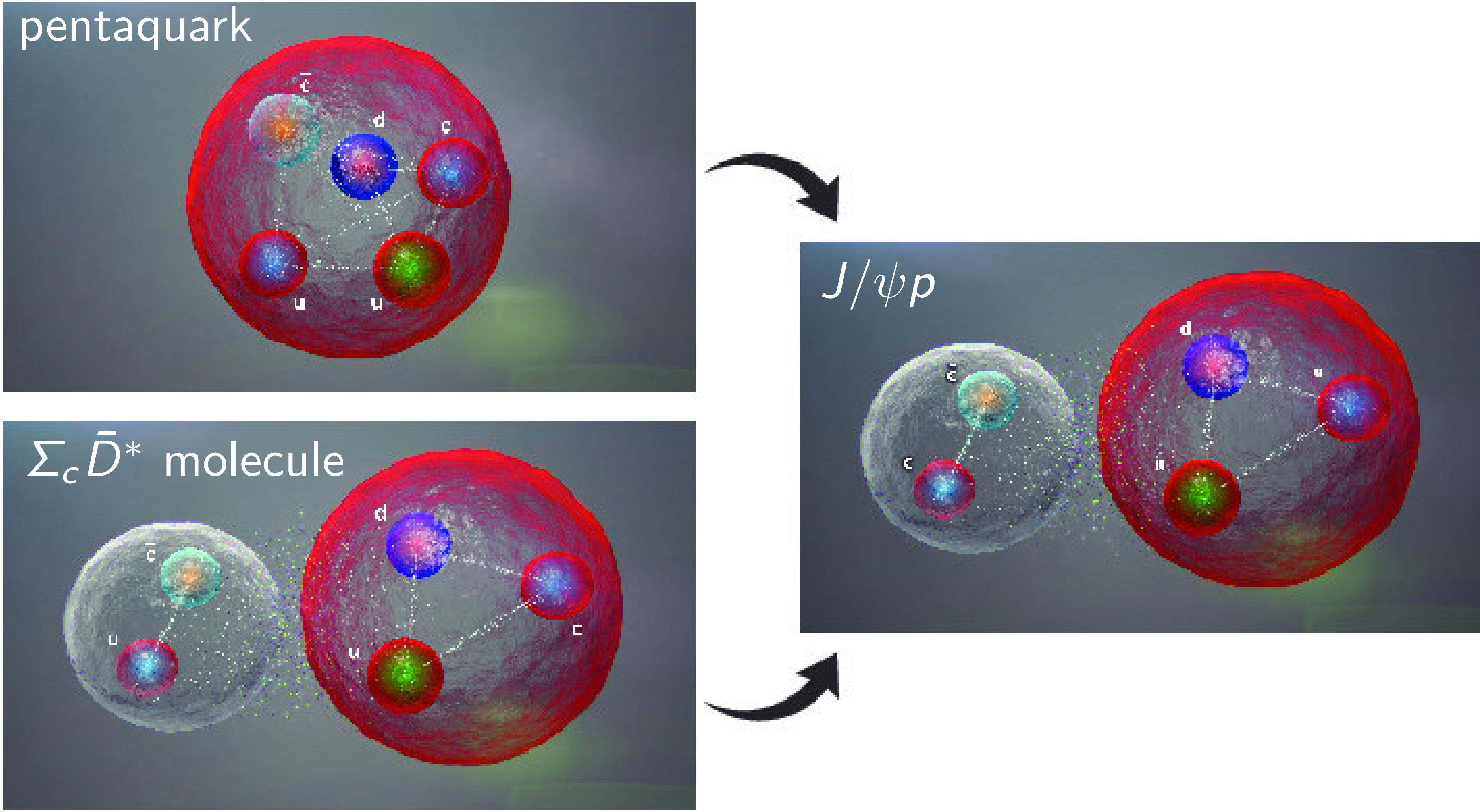
$\Theta_{\bar{c}c}$ minimal quark content: $\bar{c}c\, uud \equiv P_c(4450)$
a molecule, not a pentaquark

Decay of a pentaquark vs. hadronic molecule into $J/\psi p$



$$\left| \langle \Sigma_c \bar{D}^* | J\psi p \rangle \right| \ll \left| \langle \text{pentaquark} | \text{J}\psi\text{p} \rangle \right|$$

$\Sigma_b^+ \Sigma_b^-$ dibaryon ?

Σ_b heavier, with $I = 1 \rightarrow$ stronger binding via π

→ deuteron-like J=1, I=0 bound state: "beautron"

electric charges contribute extra ~3 MeV to binding energy

exp. signature:

$$(\Sigma_b^+ \Sigma_b^-) \rightarrow \Lambda_b \, \Lambda_b \, \pi^+ \, \pi^-$$

$$\Gamma(\Sigma_b^-) = 4.9 \pm 3 \text{ MeV}, \quad \Gamma(\Sigma_b^+) = 9.7 \pm 3 \text{ MeV}$$

so might be visible

should be seen in lattice QCD

$(\Sigma_c^0 \Sigma_c^+) \rightarrow \Lambda_c \, \Lambda_c \pi^- \pi^0$ as well?

(c) doubly heavy baryons QQq:

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

must exist, but have never been seen

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!

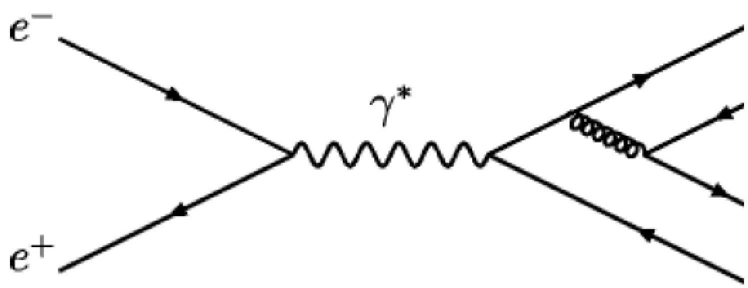
with sufficient E_{CM} may study double heavy flavor production

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

$\Rightarrow$ 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

(c) 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)

(d) 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

summary

- gaps in e^+e^- coverage of $12 < E_{CM} < 80$ GeV
- $e^+e^- \to \gamma_{ISR}\, e^+e^- \to \gamma_{ISR}\, f$

  at high-$\mathcal{L}$ 90/250 GeV collider

  can help fill the gaps
- exciting new physics to explore:
  - dark photon
  - X_b, Y_b, Z_b
  - doubly-heavy hadronic molecules – exotics
  - doubly heavy baryons
  - ?...
- detailed detector simulation needed

Additional transparencies