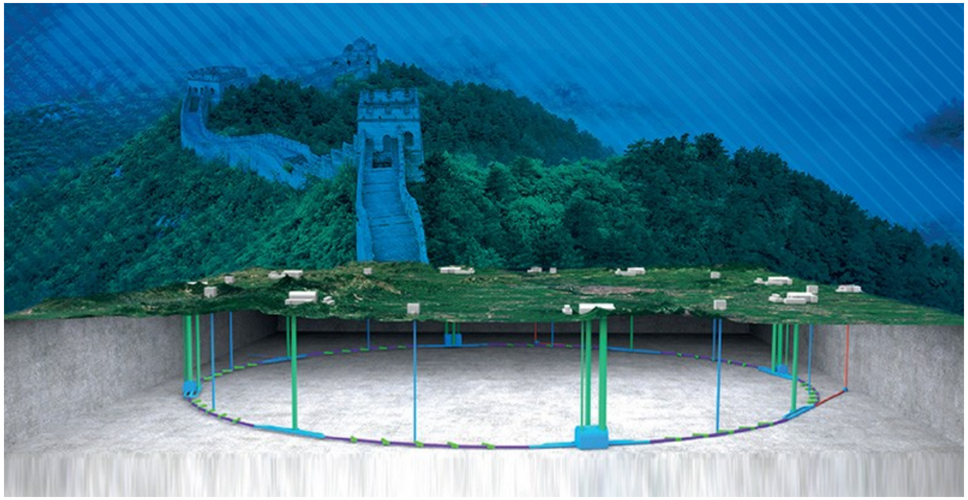

Heavy flavor opportunities at Z^0

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with

Hai-Yang Cheng, Academia Sinica, Taipei
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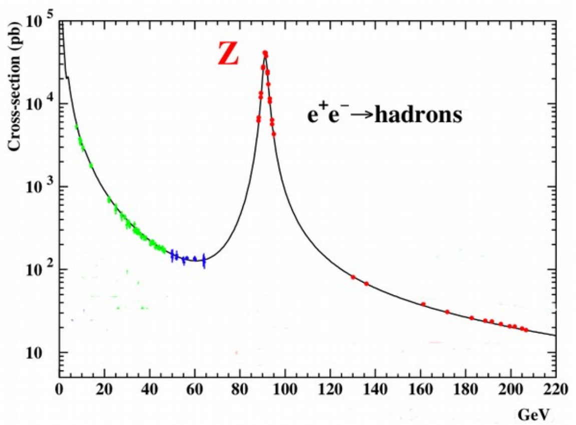
CEPC Workshop, PKU, Beijing, July 2 2019

heavy flavor at tera-Z factory

- huge number of charmed hadrons
- cleanliness of the production mechanism
- novel observables in CPV
- QCD: heavy-Q exotics; new spectroscopy



$$BR(Z^0 \to \bar{c}c) = 12.03 \pm 0.21\%$$

CEPC: $\sim 10^{12}$ Z^0

expect $\sim$

58×10^9 D^+ ,

146×10^9 D^0 vs. 4.7×10^9 @LHCb

19×10^9 D_s,

15×10^9 Λ_c ,

1×10^9 Ξ_c^+ and Ξ_c^0 each

60×10^6 Ω_c

early goal: incl. yields of charmed hyperons

e.g. $\gamma(\Lambda_c) \simeq (20) \to \gamma\tau(\Lambda_c) \cdot c = 1.2$ mm

CPV in charm: beyond LHCb tour de force

mixing and time-dep. CPV in $D^0 \to K^0_S \pi^+ \pi^-$:

$D^0 - \bar{D}^0$ mixing with unprecedented accuracy.

$146 \times 10^9\ D^0 \times \mathcal{B}(D^0 \to K^0_S \pi^+ \pi^-) \simeq 4 \times 10^9$

vs. 3.5×10^9 in runs 1-5 of LHCb with 300 fb^{-1}

SM: opposite signs of CP asymm. in

$D^0 \to K^+ K^-$ (negative) vs. $D^0 \to \pi^+ \pi^-$ (positive)

& $D^+ \to K^+ \bar{K}^0$, $D^0 \to \pi^0 \pi^0$, $D_s \to \pi^0 K^0$, $D_s \to \pi^0 K^+$

$\Rightarrow$ π^0 detection @CEPC

CPV in charmed baryons

$\Lambda_c: \ \Delta A_{CP} = A_{CP}(\Lambda \to pK^+K^-) - A_{CP}(\Lambda \to p\pi^+\pi^-)$

LHCb: $\Delta A_{CP} = (0.30 \pm 0.91 \pm 0.61)\%$, cons. with

SM: $\Delta A_{CP} \lesssim \ 0.1\%$

to probe SM need $\gtrsim \mathcal{O}(100)$ stats

LHCb sample: 24×10^6 Λ_c-s, vs.

CEPC sample: 15×10^9 Λ_c-s

$\gtrsim$ 600 times more

ideally suited for NP search in charmed baryon decay

Hai-Yang Cheng and Jon Rosner

: Comparison of ultimate HL/HE-LHC reach and tera-Z reach in measuring the parameter q/p describing D^0–$\bar{D}^0$ mixing, assuming 146 billion D^0 produced at a tera-Z

Decay mode	$\mathcal{B}(D^0 \to f)$	$\sigma(q/p)$ (LHC)	$N(D^0)$ LHC	$N(D^0)$ Tera-Z	Ratio Tera-Z/LHC	
$D^{*+} \to D^0(\to K^+\pi^-)\pi^+$ [a,b]	3.89%	0.01	42.5×10^9	5.7×10^9	0.134	?
$D^0 \to K_S\pi^+\pi^-$ [b]	2.75%	0.004	3.5×10^9	4.0×10^9	1.14	recheck LHC numbers
$D^0 \to K^+\pi^-\pi^-\pi^+$	2.61×10^{-4}	0.002	22.5×10^6	38.1×10^6	1.69	

[a]Including time-dependent CP violation. [b]A smaller additional sample (about 14%) is available from charm produced in b decays.

: Comparison of ultimate HL/HE-LHC reach and tera-Z reach in measuring some SCS and DCS decays of D^+, assuming 58 billion D^+ produced at a tera-Z

Decay mode	$\mathcal{B}(D^+ \to f)$	$N(D^+)$ LHC	$N(D^+)$ Tera-Z	Ratio, Tera-Z/LHC	
$D^+ \to K^-K^+\pi^+$	0.951%	17.42×10^9	0.55×10^9	0.032	
$D^+ \to \pi^-\pi^+\pi^+$	0.313%	8.71×10^9	0.18×10^9	0.021	
$D^+ \to K^-K^+K^+$	8.5×10^{-5}	1.219×10^9	4.93×10^6	0.004	?
$D^+ \to \pi^-K^+\pi^+$	5.19×10^{-4}	697×10^6	30.1×10^6	0.043	

SCS = singly Cabibbo suppressed
DCS = doubly Cabibbo suppressed

new rich heavy flavor QCD spectroscopy

(a) doubly heavy $QQ'q$ baryons

$\Xi_{cc}^{++} = (ccu)$ observed by LHCb

(b) doubly heavy QQ' tetraquarks

stable $bb\bar{u}\bar{d}$ and $bc\bar{u}\bar{d}$; $LHCb\,\surd$

(c) new $Q\bar{Q}'$ exotics – doubly-heavy hadronic molecules
meson-meson, baryon-meson, baryon-baryon; open flavor
LHCb pentaquarks $= \Sigma_c \bar{D}^{(*)}$ $(\bar{c}cuud)$

(d) b analogues of charmonium X, Y, Z states

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

(f) Five very narrow Ω_c-s

$bb\bar{u}\bar{d}$ tetraquark production in Z factory

A. Ali et al.

Phys.Lett. B782 (2018) 412

$$Z \to b\bar{b}\, b\bar{b}$$

in high-L Z factory, like CEPC,

$\exists$ huge number of bb pairs.

Might be enough for penalty

due to required proximity in phase space

$\Rightarrow$ produce bbq baryons and $bb\bar{u}\bar{d}$ Tq-s

the challenge: reliable estimate of σ

$\Gamma(Z \to B_c + X)$: useful upper bound (MK)

$$\mathcal{B}(Z \to T^{\{bb\}}_{[\bar{u}\bar{d}]} + \bar{b}\bar{b}) = (1.4^{+1.1}_{-0.5}) \times 10^{-6},$$

(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}

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)

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Radiative return capabilities of a high-energy, high-luminosity e^+e^- collider

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An electron-positron collider operating at a center-of-mass energy E_{CM} can collect events at all lower energies through initial-state radiation (ISR or *radiative return*). We explore the capabilities for radiative return studies by a proposed high-luminosity collider at $E_{\mathrm{CM}} = 250$ or 90 GeV, to fill in gaps left by lower-energy colliders such as PEP, PETRA, TRISTAN, and LEP. These capabilities are compared with those of the lower-energy e^+e^- colliders as well as hadron colliders such as the Tevatron and the CERN Large Hadron Collider (LHC). Some examples of accessible questions in dark photon searches and heavy flavor spectroscopy are given.

CEPC: $\mathcal{L} \sim 10^{34}$ cm^{-2} s^{-1}

with rad. ret. can explore

interesting physics

significantly *below* design E_{CM}.

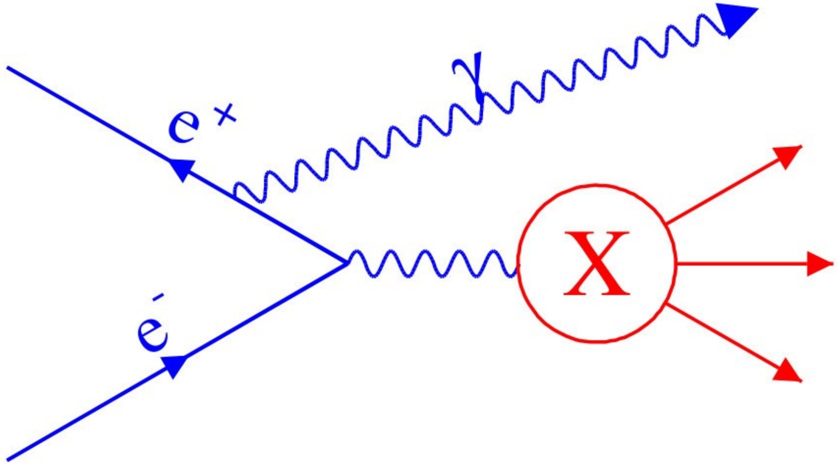
- e^+e^- collider designed for a certain E_{CM} can collect events at all lower energies through initial-state radiation (ISR or *radiative return*)
  "it's not a bug, it's a feature"

- 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

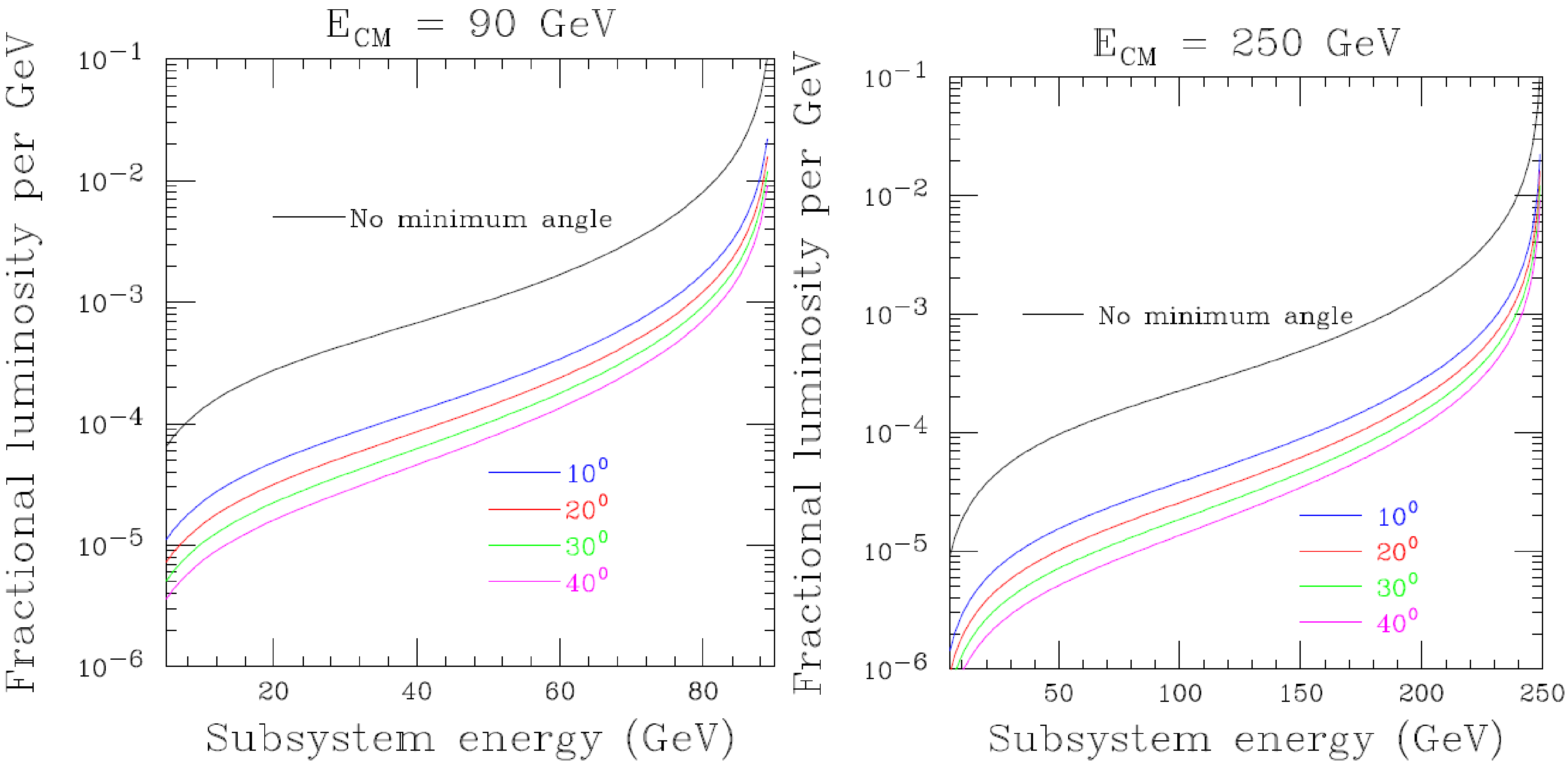
Previous uses of radiative return



S. Eidelman

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

fractional luminosity L_f as function of subsystem energy



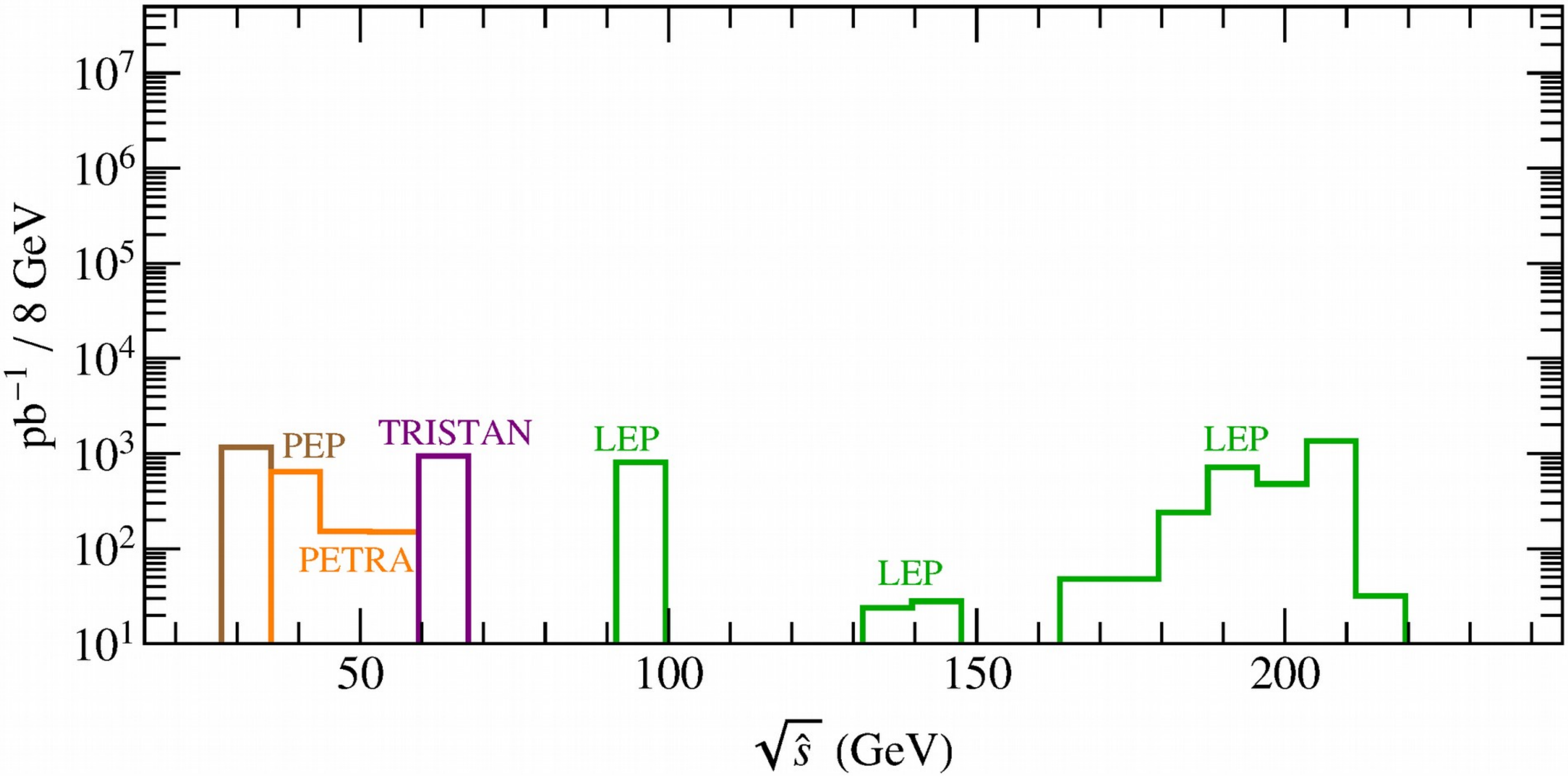
larger cut on photon angle → cleaner signal, but less σ

loose 3-5 orders of magnitude in $\mathcal{L}$,

but since original $\mathcal{L}$ is huge ,

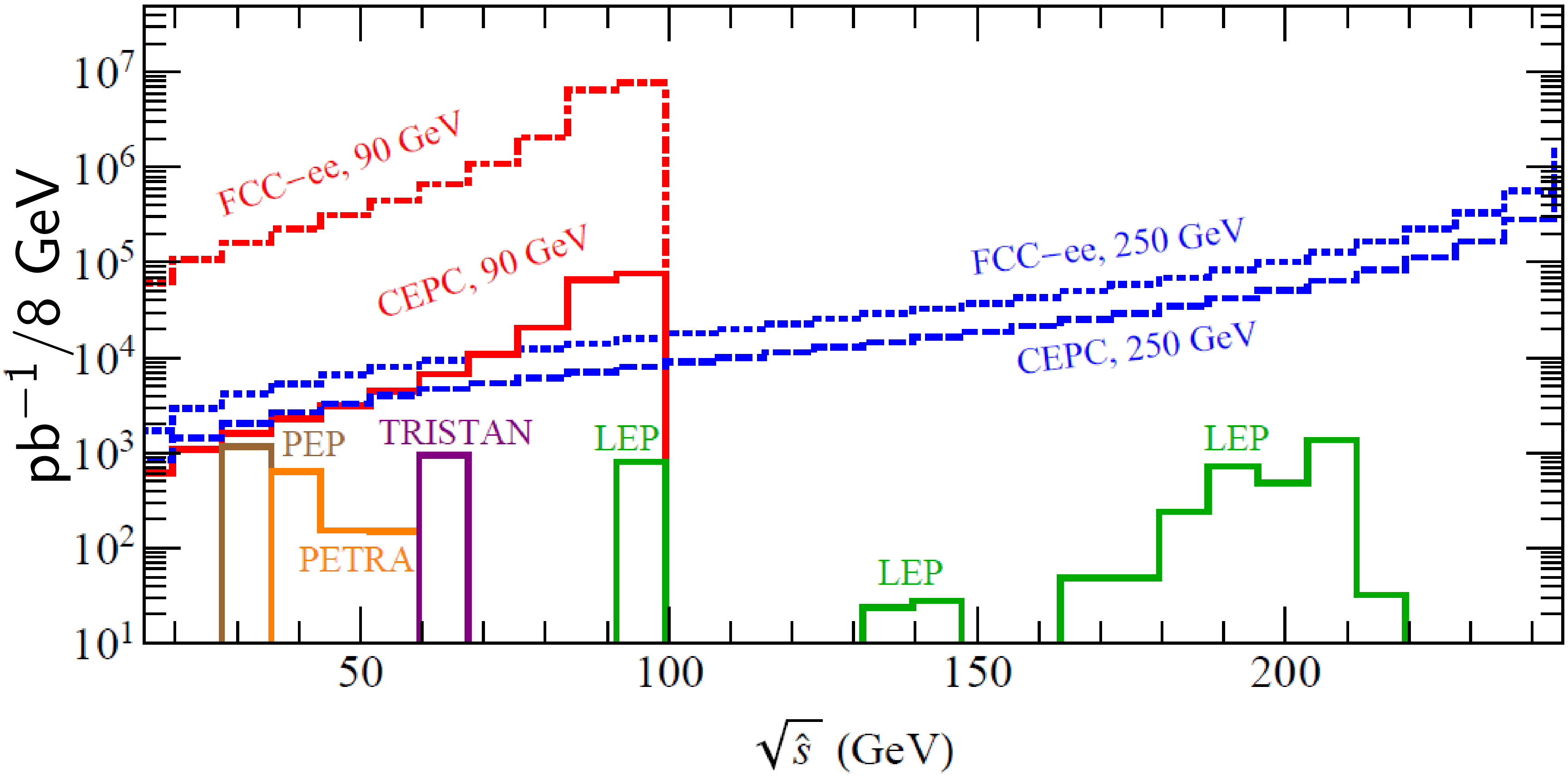
what remains is still very large.

integrated luminosity



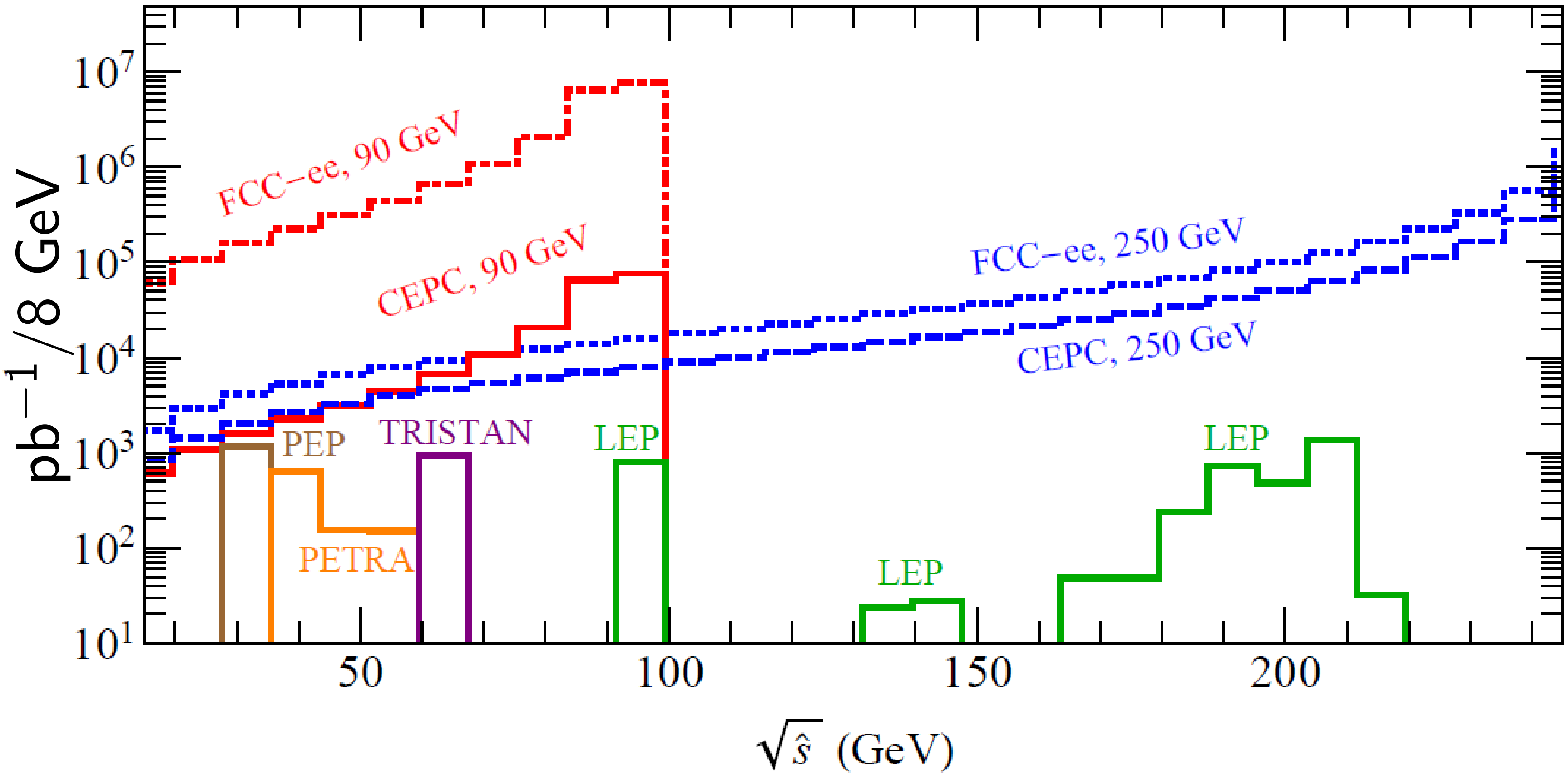
gaps left by PEP, PETRA, TRISTAN and LEP

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



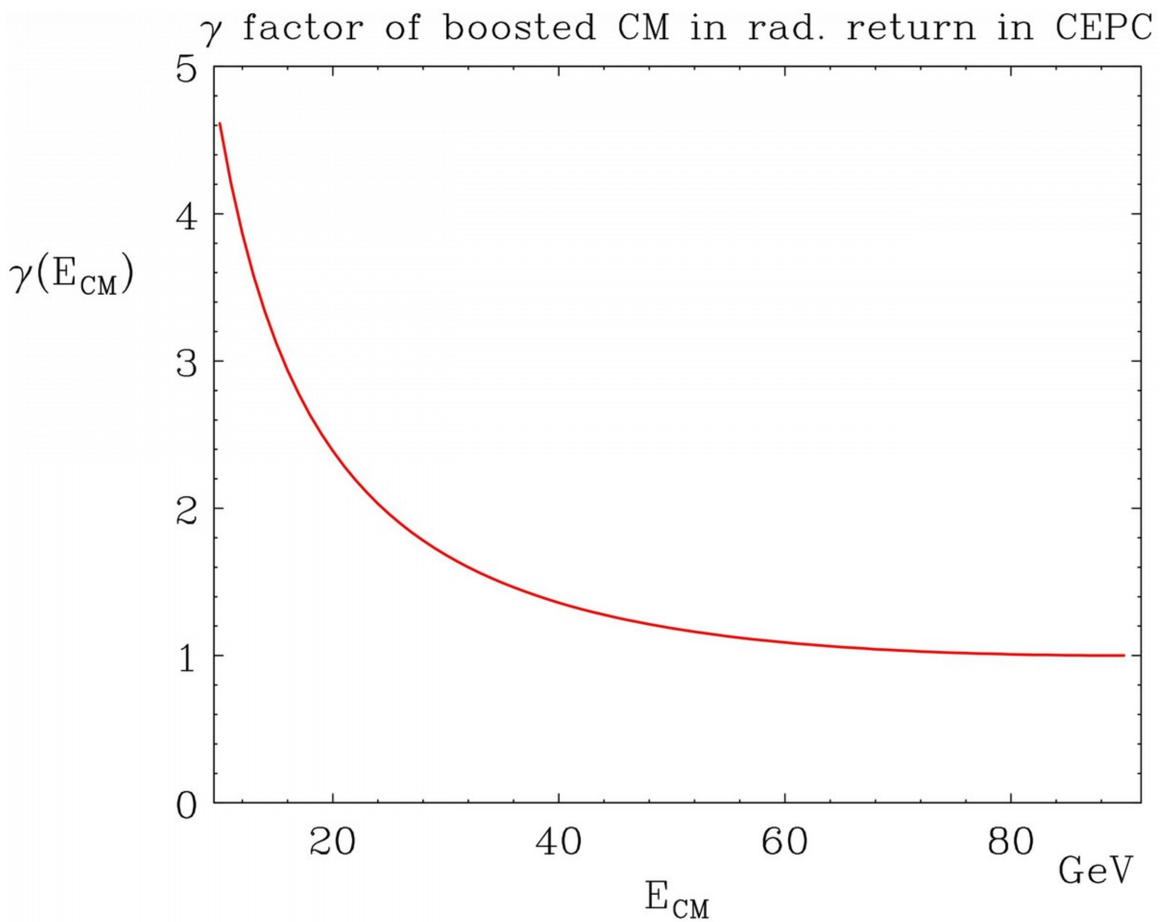
Integrated luminosity from past low energy e^+e^- colliders at their nominal center-of-mass energies compared to the effective luminosity through radiative return from future e^+e^- colliders at $\sqrt{s} = 90$ or 250 GeV

gaps filled in and much more

extra bonus: CM only moderately boosted -
for $E_{CM} \approx 20\%$ of the original E_{CM}, $\gamma \approx 2.5$
for CEPC at Z^0,

$$\gamma(E_{CM}) = \frac{1}{2}\left(\frac{E_{CM}}{M_Z} + \frac{M_Z}{E_{CM}}\right)$$

does not require
dedicated detectors !



Derivation of the $\gamma = E_{lab}/E_{CM}$ factor of the boosted e^+e^- system after e^+ or e^- emits a hard photon.

For sake of definitness we start from two charged leptons with equal energy, $E_1 = E_2 = M_Z/2$. Without loss of generality we assume that it is lepton No. 2 that has lost energy.

$$E_{CM}^2 = E_{lab}^2 - p_{lab}^2 = (E_1 + E_2)^2 - (E_1 - E_2)^2 = 4E_1E_2.$$

where we treat the leptons as effectively massless, $|p_i| = E_i$,
since $E_1, E_2 \gg m_e$.

$$E_1 = \frac{M_Z}{2}; \qquad E_2 = \frac{E_{CM}^2}{4E_1} = \frac{M_{CM}^2}{2M_Z}$$

$$E_{lab} = E_1 + E_2 = \frac{M_Z}{2} + E_2 = \frac{M_Z}{2} + \frac{E_{CM}^2}{2M_Z}$$

$$\gamma = \frac{E_{lab}}{E_{CM}} = \frac{1}{2}\left(\frac{M_Z}{E_{CM}} + \frac{E_{CM}}{M_Z}\right)$$

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 $\approx m_q^{\rm const.}$

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

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

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

heavy flavor at tera-Z: conclusions

- unprecedented heavy Q stats
- cleaniness of production
- charm CPV: high sensitivity & baryons
- Q spectroscopy bonanza,

  $\Rightarrow$ stable $bb\bar{u}\bar{d}$, $bc\bar{u}\bar{d}$ teraquarks

  $\Rightarrow$ new $Q\bar{Q}'qqq$ and $Q\bar{Q}'q\bar{q}$ hadronic molecules
- Z/h factory in radiative return mode:

  huge $\mathcal{L}$ for QCD, DM; $\Upsilon(4S) < E_{CM} < Z^0$