Very Asymmetric Collider for Dark Matter Search below 1 GeV

B. Wojtsekhowski, V.S. Morozov, and Y.S. Derbenev
Jefferson Lab, Newport News, VA 23606

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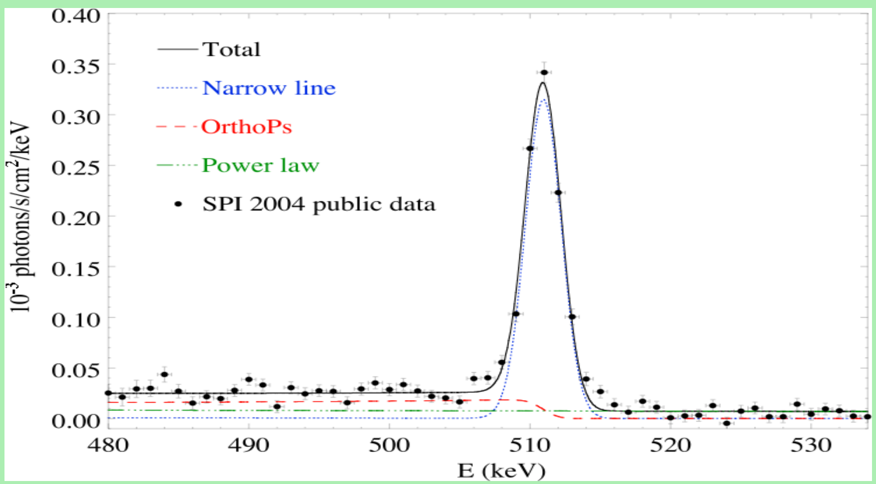
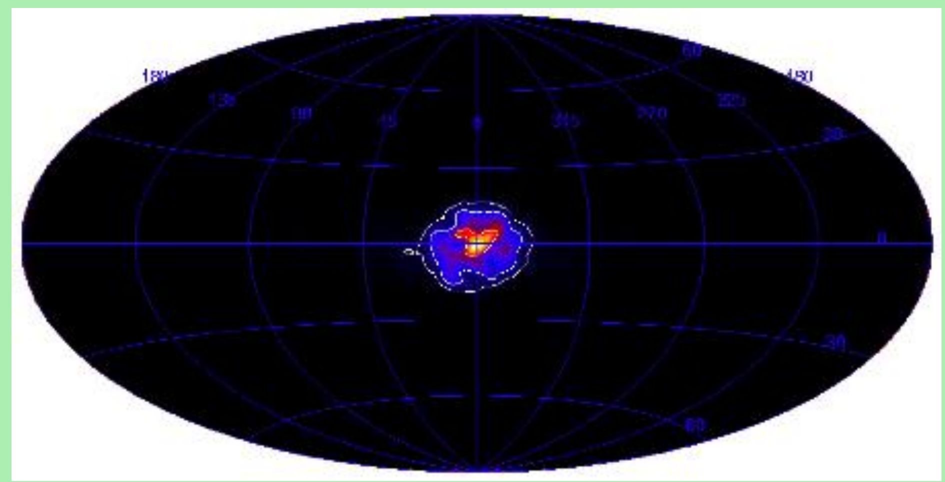
Evidence for Light Dark Matter

- P. Jean et al., Astron. Astrophys. 445, 579 (2006)
- 511 keV line in the photon spectrum

Photon energy spectrum

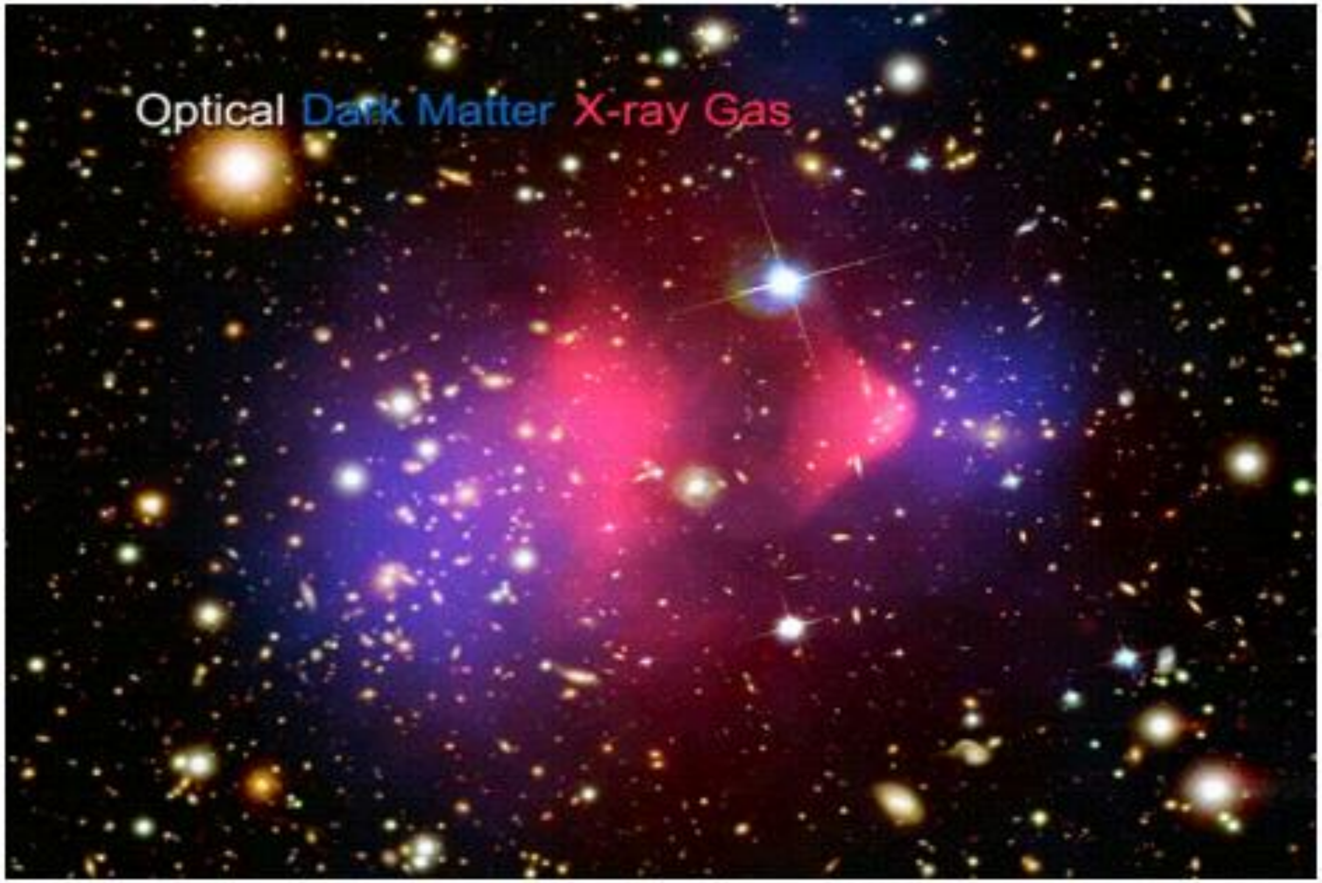


Location of the source



Direct Observation

- NASA/SLAC, September 2006
- Collision of two large clusters of galaxies



Search for New Particle

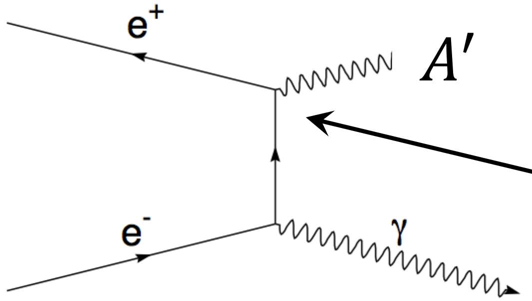
- Search for single-photon events

$$e^+e^- \to \gamma A'$$

- Seek a narrow peak in the distribution of

$$M_X^2 = s - 2E_\gamma^* \sqrt{s}$$

- Lowest-order Feynman diagram of $e^+e^- \to \gamma + A'$



A'

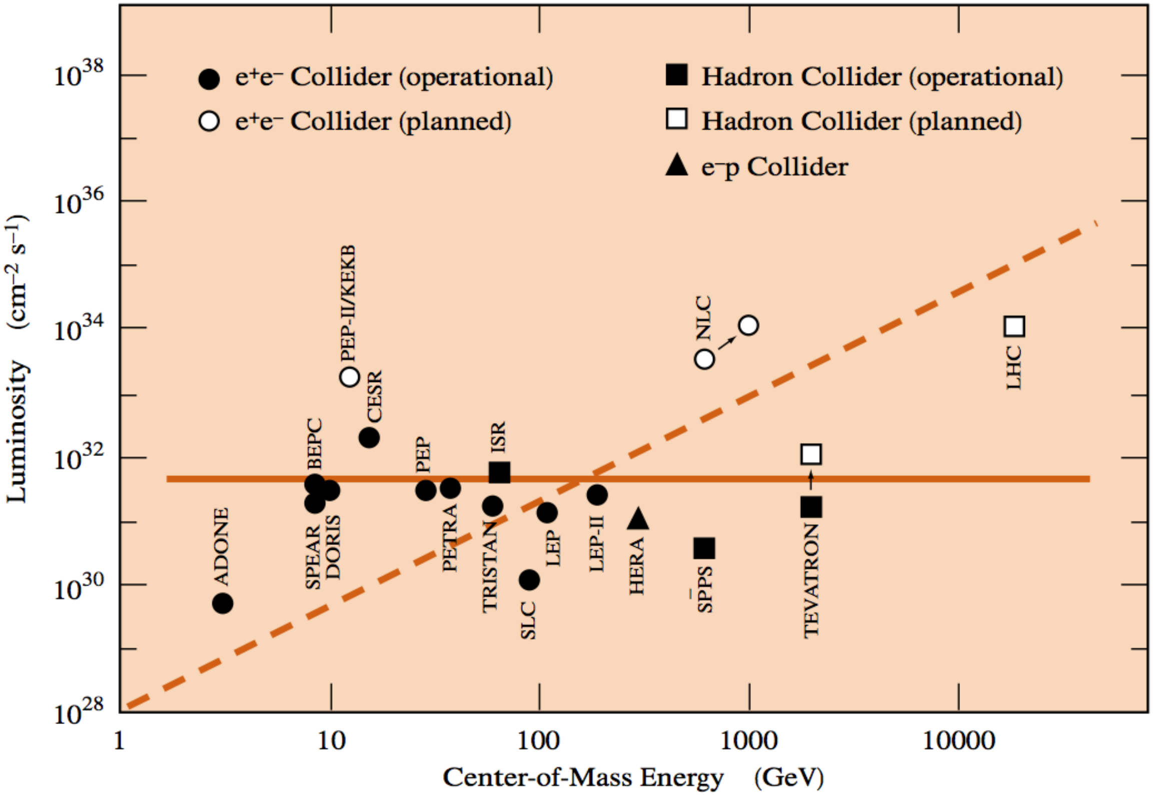
$s \sim 4E_+ \cdot (E_- - E_\gamma)$

$$\Delta\mathcal{L} \sim \mathcal{L} \times \frac{\Delta s}{s_{max}}; \quad \sqrt{s_{max}} = 10\ GeV, \sqrt{\Delta s} \sim 100\ MeV \ \Rightarrow \Delta\mathcal{L} \sim 10^{-4}\mathcal{L}$$

- Need a low-energy high-luminosity electron-positron collider

Collider Luminosity

- Collider luminosity generally drops off with energy
  - Geometric emittances/ beam sizes are larger at lower energies
  - Beams are less rigid and cannot interact strongly at lower energies
  - Collective effects are stronger at lower energies
- W. Panovsky's article in BEAM LINE



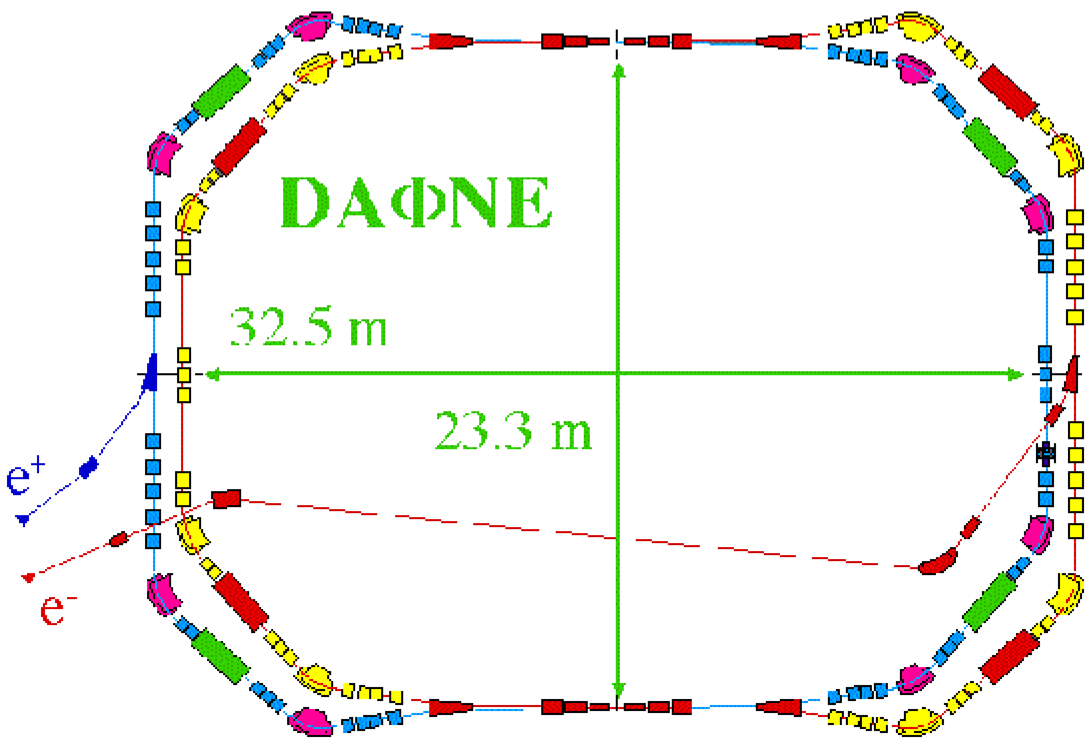
Dashed line:
$\mathcal{L} \sim E_{CM}^2$

$E_{CM} = 100$ MeV:
$\mathcal{L} \sim 10^{26} - 10^{29}$ cm^{-2}s^{-1}

DAΦNE

- A low-energy electron-positron ring-ring collider

$$E_{+/-} = 0.51\ \text{GeV}$$
$$L = 5.3 \cdot 10^{32}\ \text{cm}^{-2}\text{s}^{-1}$$

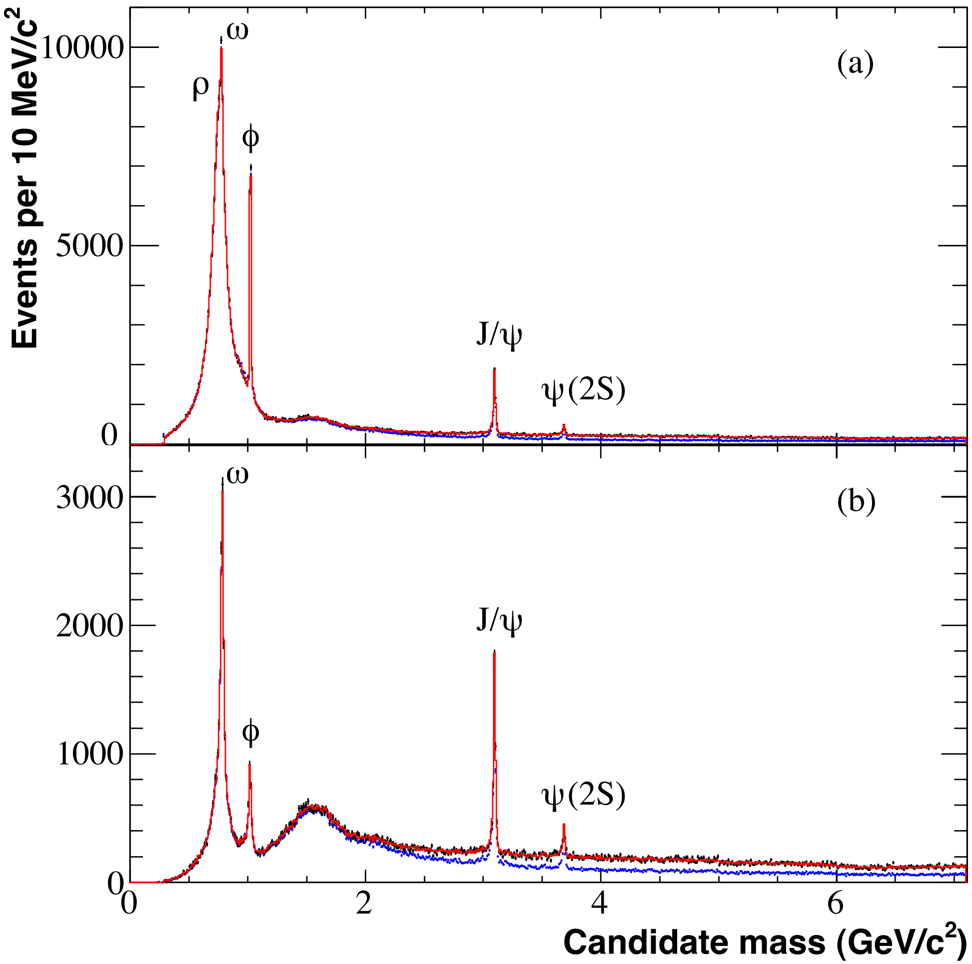


DAFNE BEAM-BEAM DESIGN PARAMETERS

Single beam energy	0.51 GeV
Number of particles per bunch	$8.9\text{x}10^{10}$
Number of bunches per ring	up to 120
Crossing frequency	up to 368.25 MHz
Horizontal emittance	1.0 mm.mrad
Vertical emittance	0.01 mm.mrad
Coupling factor	0.01
Horizontal beta function at crossing	4.5 m
Vertical beta function at crossing	0.045 m
Total crossing angle in the horizontal plane	20 to 30 mrad
Horizontal beam-beam tune shift per crossing	0.04
Vertical beam-beam tune shift per crossing	0.04
Bunch length	30 mm r.m.s.
Horizontal beam size at crossing	2.0 mm r.m.s.
Vertical beam size at crossing	0.02 mm r.m.s.
Synchrotron radiation loss per turn	9.3 KeV
Horizontal betatron damping time	36 msec
Vertical betatron damping time	36 msec
Longitudinal damping time	17.8 msec
Maximum stored current per ring	5.2 A
Maximum luminosity	$5.3\text{x}10^{32}\ \text{cm}^{-2}\ \text{s}^{-1}$

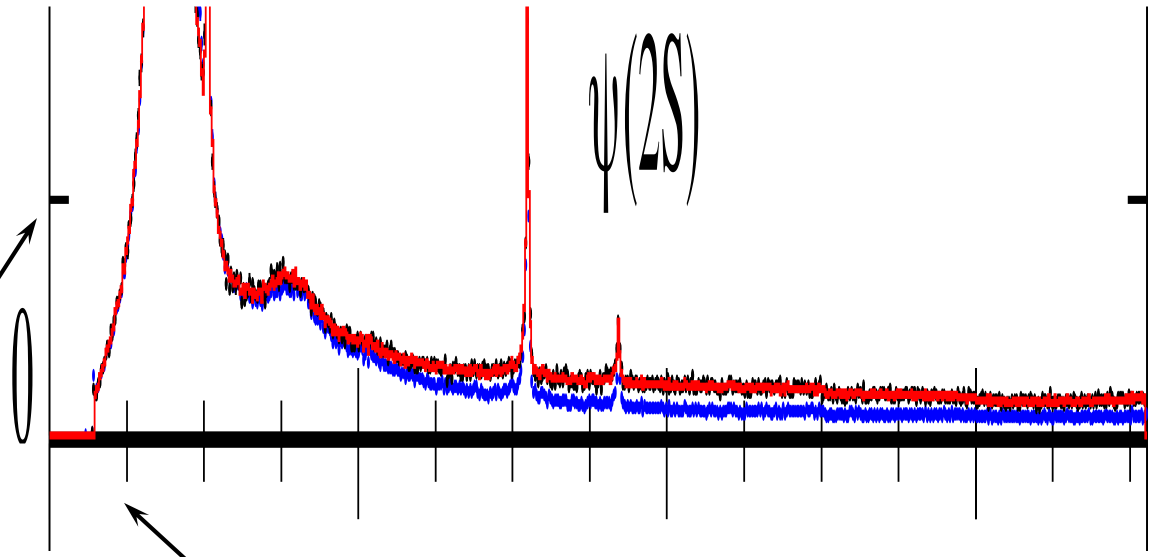
BABAR Search

- "Search for hadronic decays of a light Higgs boson in the radiative decay", PRL 107, 221803 (2011)



BABAR Search

- Low statistics at low energies

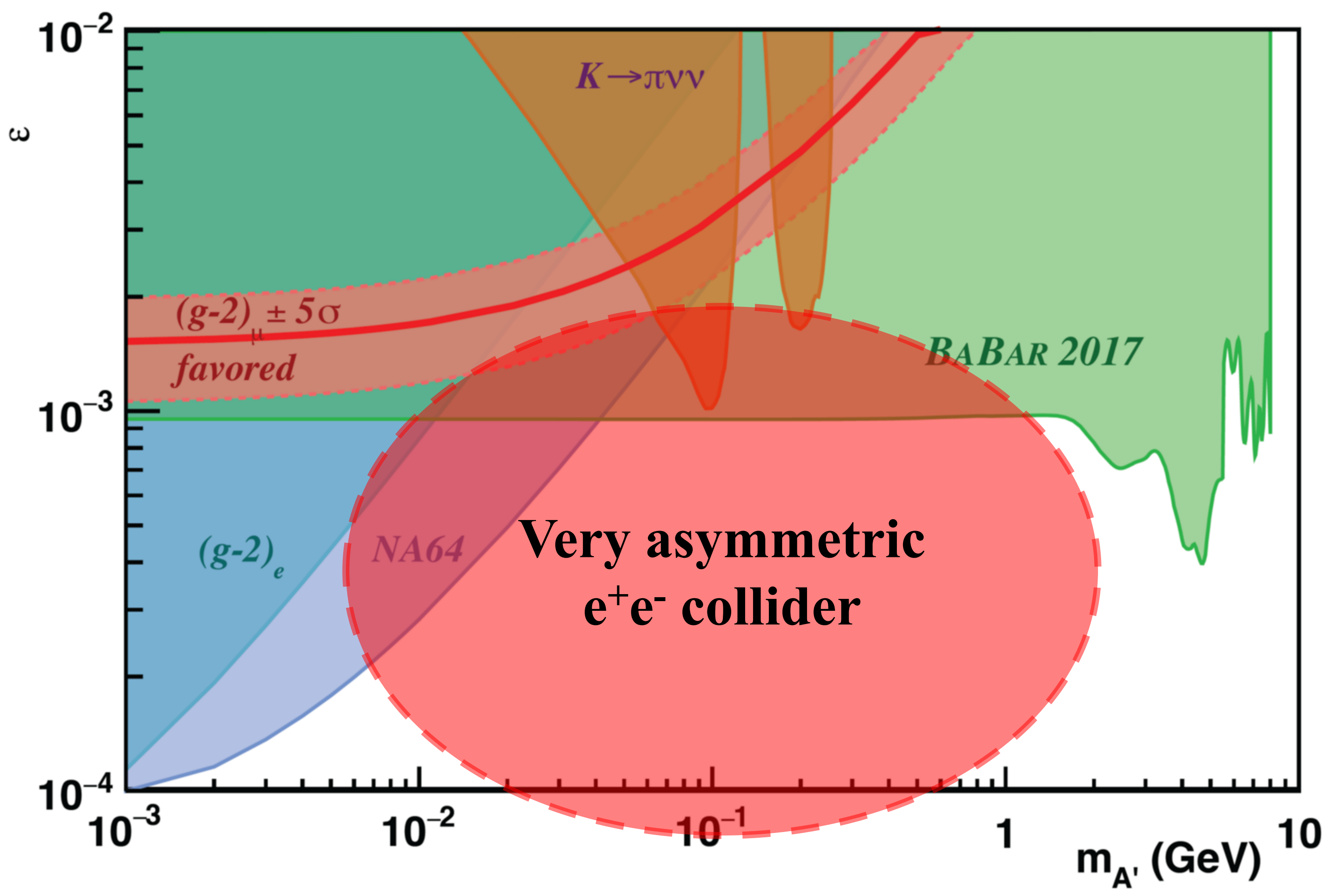


10k events/10 MeV

M = 500 MeV

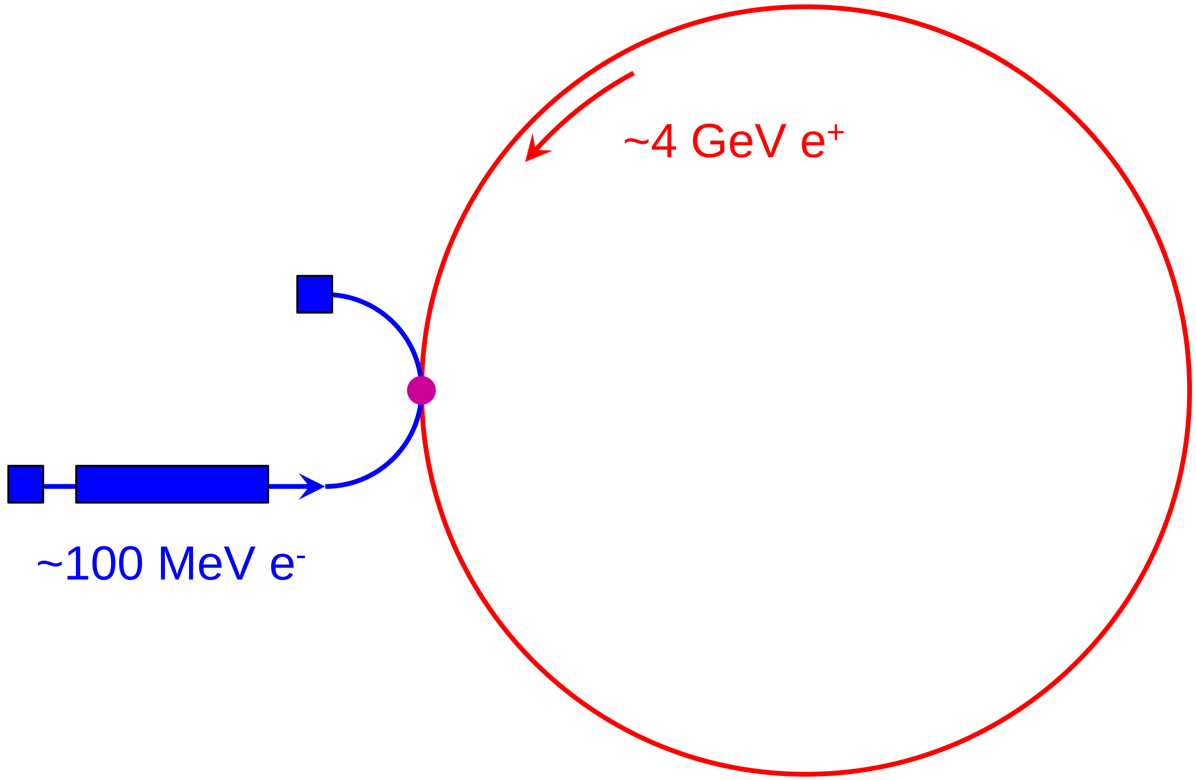
Mass Range of Current Interest

- Need low-energy high-luminosity e^+e^- collider to cover range of interest



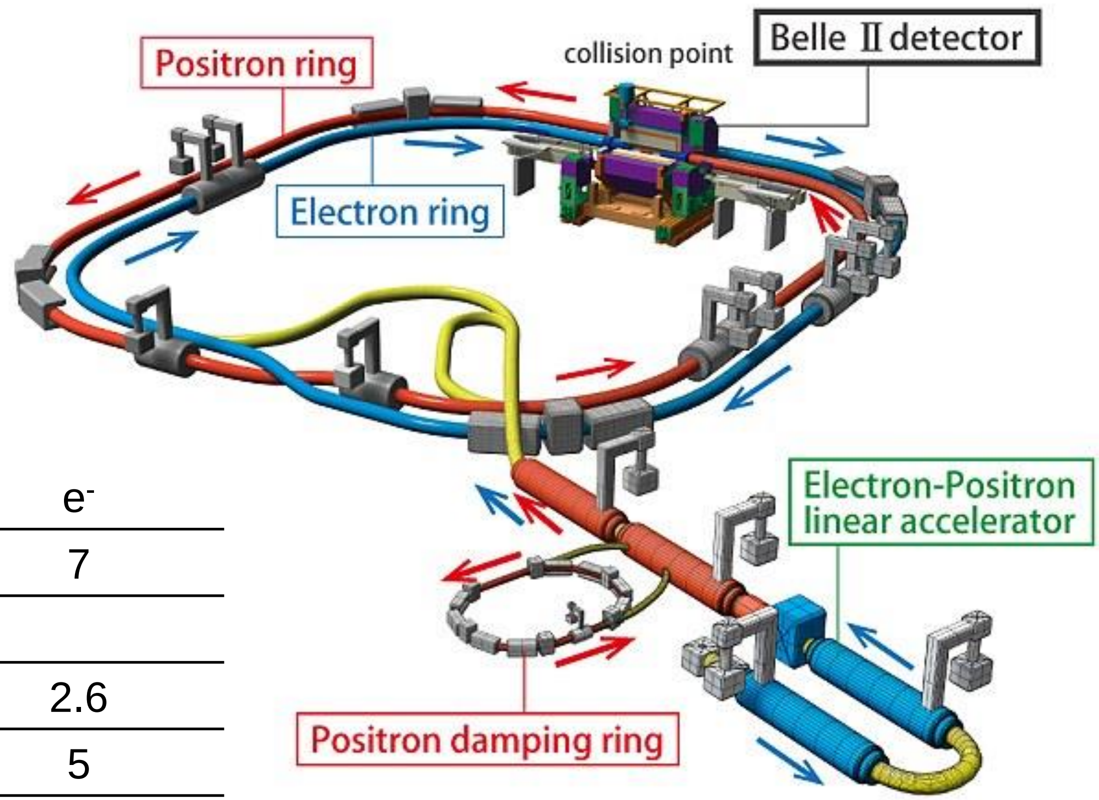
Very Asymmetric Collider

- High-quality low-energy electron beam from a linac
  + High-quality high-energy positron beam stored in a ring
  = Small $s = 4E_+E_-$



Ring-Ring Collider, e.g. SuperKEK-B

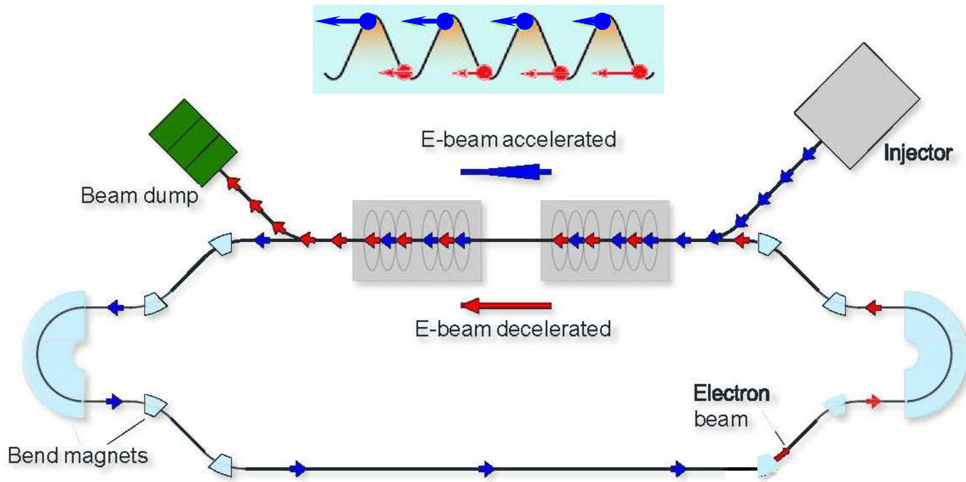
- Ring-ring collider
  - High energy
  - High current
  - High brightness
  - High luminosity



		e^+	e^-
E	GeV	4	7
f	MHz	248.5	
I	A	3.6	2.6
σ_z	mm	6	5
$\varepsilon_x/\varepsilon_y$	nm/pm	3.2/8.64	4.6/12.9
β_x^*/β_y^*	mm	32/0.27	25/0.30
σ_x^*/σ_y^*	μm/nm	10/48	11/62
ξ_x/ξ_y		0.0028/0.088	0.0012/0.081
L	**$cm^{-2}s^{-1}$**	**8×10^{35}**	

Energy Recovery Linac

- Electrons pick energy up during acceleration and then deposit it back during deceleration with >99.9% efficiency



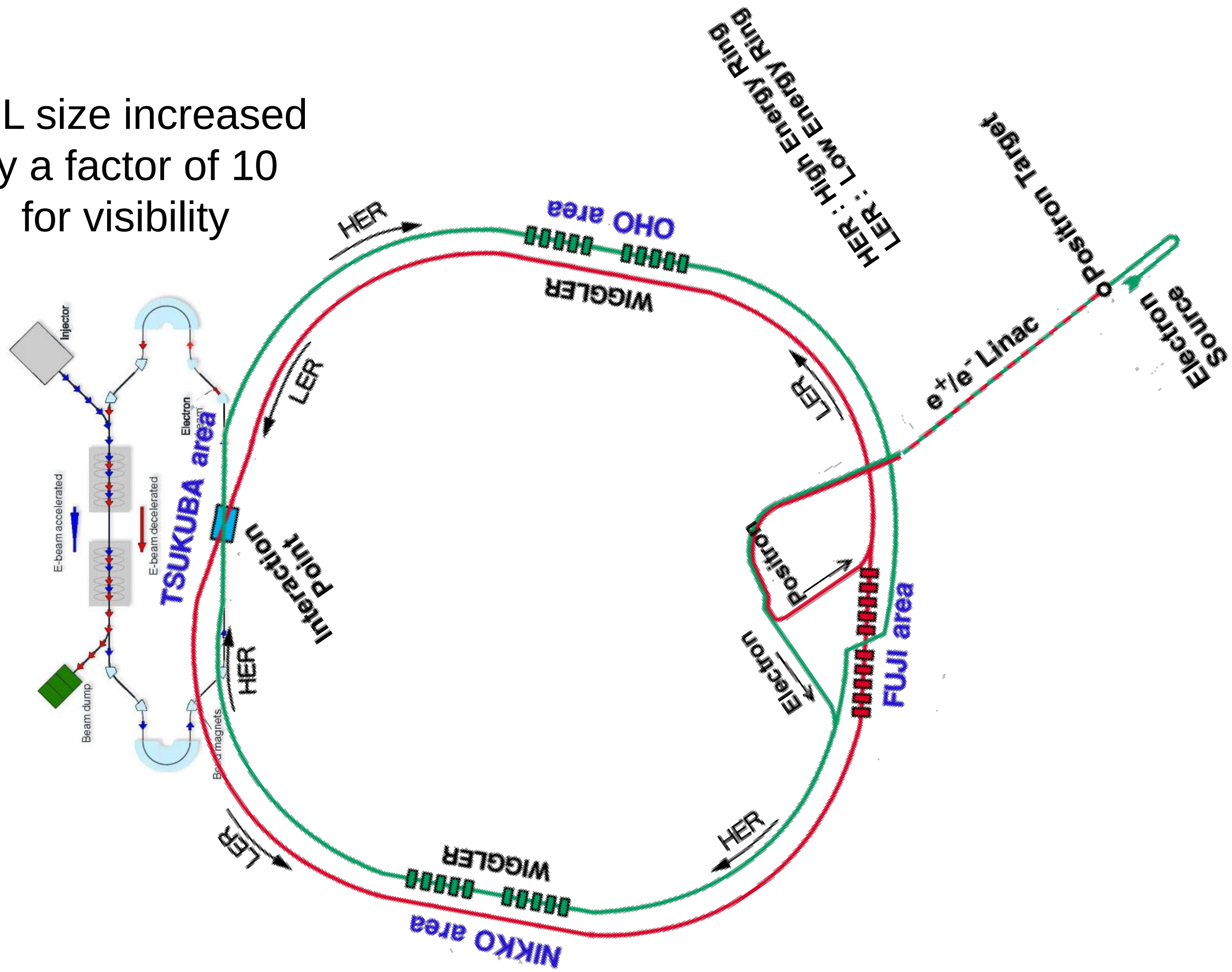
- Electrons from an energy-recovery linac
  - High energy efficiency (determined by injector/dump energy)
  - Relatively low current
  - High brightness

Cornell ERL project

E	GeV	5
f	GHz	1.3
I	A	0.1
σ_z	mm	0.6
$\varepsilon_x/\varepsilon_y$	pm	31/31
$\varepsilon_x^N/\varepsilon_y^N$	μm	0.3/0.3

Linac-Ring Collider

ERL size increased
by a factor of 10
for visibility



Why Asymmetric Linac-Ring?

- Positrons stored in a ring
  – High energy of ~3-5 GeV
  – High current of ~2-3 A
  – Small beam size
  – High rigidity
- Electrons from an energy-recovery linac
  – High energy efficiency
  – Low energy for $\sqrt{s} < 1$ GeV
  – Relatively large current for a linac of ~100 mA
  – Small beam size
  – Low rigidity but can be disrupted much stronger than a stored beam
- Combination meets physics and detection requirements

Key Collider Parameters

- Luminosity assuming matched beam sizes

$$L = \frac{N_+ N_- f_c}{4\pi\sigma_x^* \sigma_y^*}$$

- Beam-beam tune shift for stored positrons: number of oscillations due to focusing by electron beam

$$\xi_{y+} = \frac{r_e N_- \beta_{y+}^*}{2\pi\gamma_+ \sigma_{y-}^* (\sigma_{x-}^* + \sigma_{y-}^*)} \lesssim 0.08$$

- Disruption parameter for electrons from linac: related to number of oscillations n due to focusing by positron beam

$$D_{y-} = \frac{2 r_e N_+ \sigma_{z+}}{\gamma_- \sigma_{y+} (\sigma_{x+} + \sigma_{y+})} \lesssim 20\,, \qquad n \approx \frac{\sqrt{D_{y-}}}{4}$$

- Hour-glass effect

$$R(t_x, t_y) = \int_{-\infty}^{\infty} \frac{dt}{\sqrt{\pi}} \exp(-t^2) \left[(1 + t^2/t_x^2)(1 + t^2/t_y^2)\right]^{-1/2}\,, \qquad t_y \approx \frac{\beta_y^*}{\sigma_z}$$

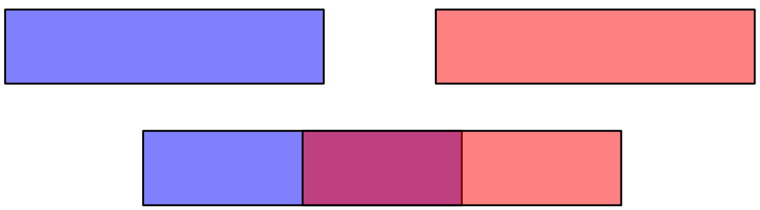
- Crossing angle

$$R_L \approx [1 + (\tan\phi \cdot \sigma_z/\sigma_x^*)^2]^{-1/2}$$

Hour-Glass Effect

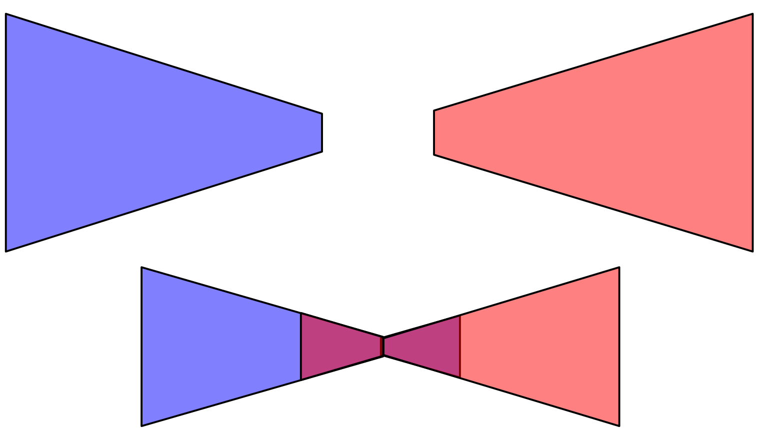
- No hour glass effect
  $\beta^* \gtrsim \sigma_z$ ($\sigma_z \equiv$ bunch length)

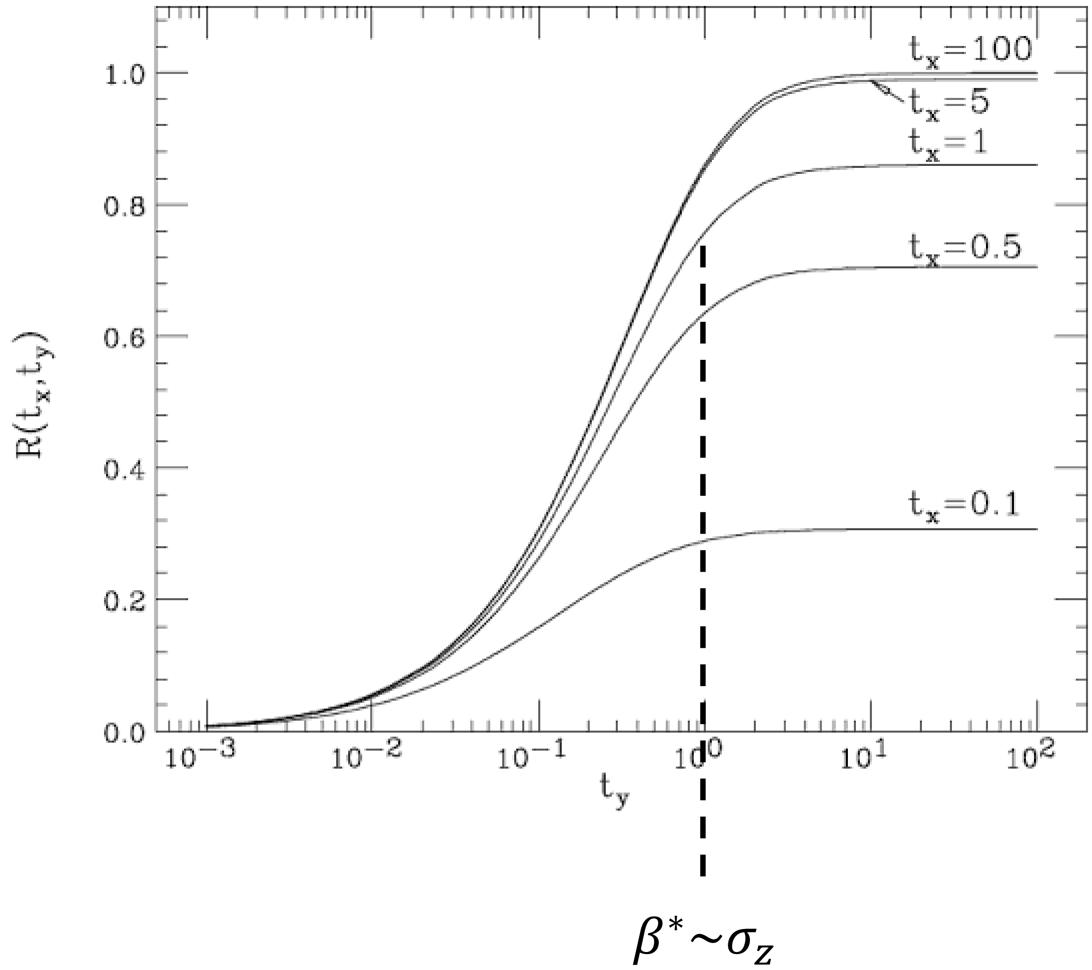
e^- bunch $\rightarrow$ $\leftarrow$ e^+ bunch



- Strong hour-glass effect
  $\beta^* \ll \sigma_z$

e^- bunch $\rightarrow$ $\leftarrow$ e^+ bunch





Disruption Parameter

- Focusing of the linac beam by the opposing beam

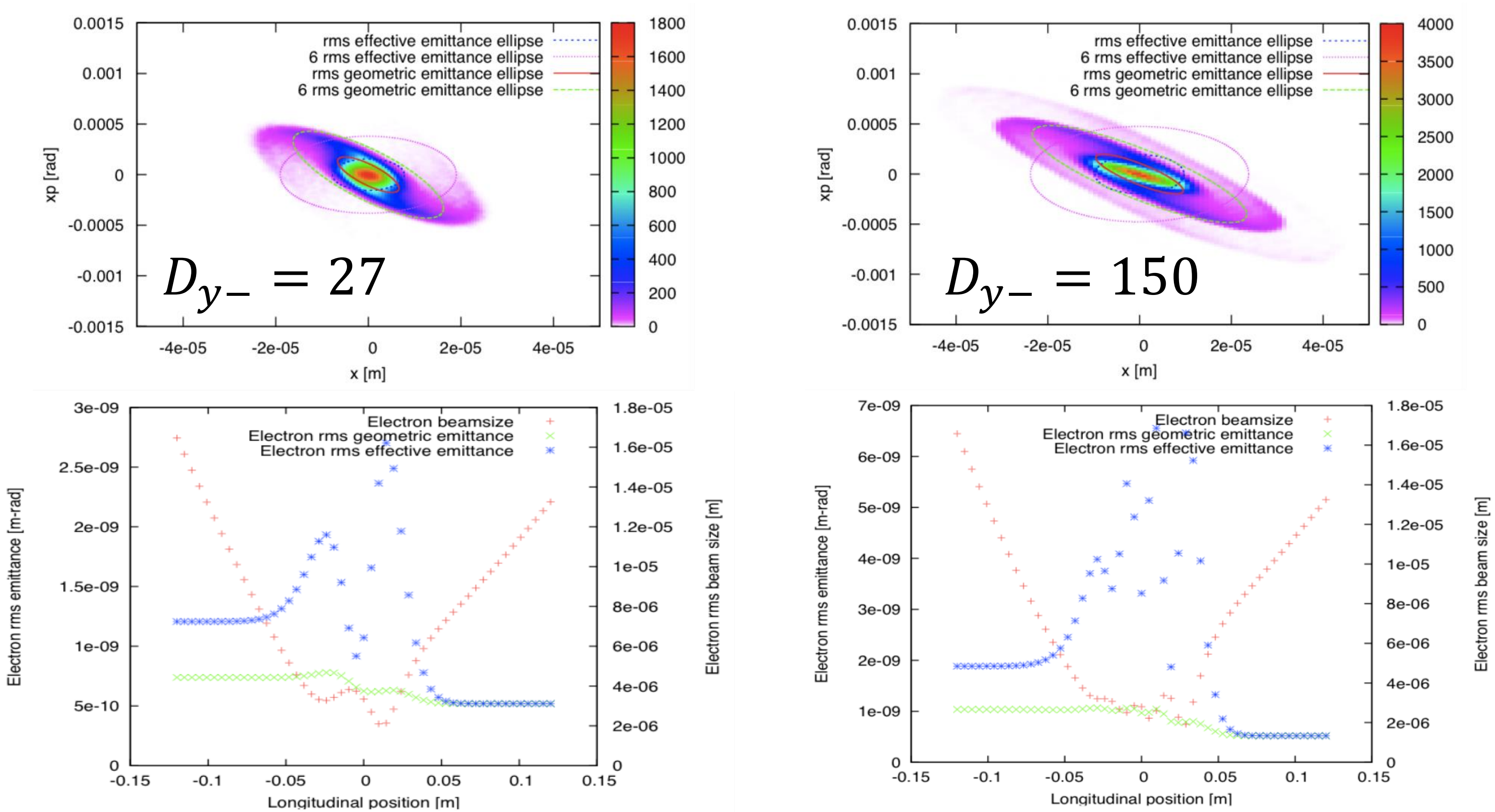
  Electron $D_{y-} \equiv$ positron bunch length / electron beam-beam focal length

  Number of electron oscillations $n = \sqrt{D_{y-}}/4$

- May cause emittance growth of the linac
- May cause kink instability of the stored beam
- Disruption parameters of up to 300 have been considered fro aggressive designs but typically $D_{y-} \lesssim 20$

Disruption Parameter Continued

- Y. Hao et al., “Beam beam study of ERL based eRHIC”, arXiv:1410.6000v1 [physics.acc-ph] (2014)



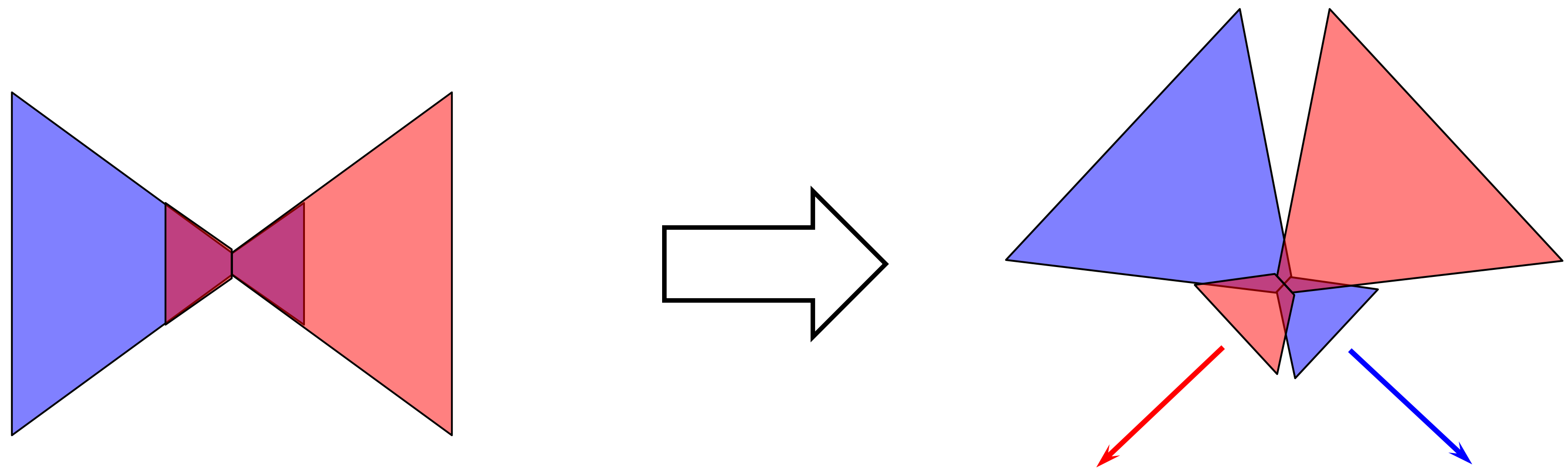
Problem due to Low Energy of Electrons

- How well can a linac-ring do at the limit of positron beam-beam tune shift?

		SuperKEK-B LER	Cornell ERL	Linac-Ring	
		e^+	e^-	e^+	e^-
E	GeV	4	5	**4**	**0.1**
f	MHz	248.5	1300	**248.5**	
I	A	3.6	2.6	**3.6**	0.095
σ_z	mm	6	0.6	**6**	**1**
$\varepsilon_x/\varepsilon_y$	pm/pm	3200 / 8.64	31 / 31	850 / 850	5100 / 5100
$\varepsilon_x^N/\varepsilon_y^N$	μm/μm	25 / 0.07	0.3 / 0.3	6.7 / 6.7	**1 / 1**
β_x^*/β_y^*	mm	32 / 0.27		6 / 6	1 / 1
σ_x^*/σ_y^*	μm/μm	10 / 0.048		2.3 / 2.3	2.3 / 2.3
ξ_x/ξ_y		0.0028 / 0.088		**0.08 / 0.08**	
D_x/D_y					**1530 / 1530**
$R_{h.-g.}$				0.41	
L	**$cm^{-2}s^{-1}$**	**8×10^{35}**		**Could be 3.4×10^{34} but**	

Proposed Solution: SuperKEK-B-Type Scheme

- Collide bunches at an angle and over-focus
  - Keep high luminosity from the waist
  - Eliminate negative dynamical effect from the rest of the bunch



- Then what enters into the equations for disruption parameter, beam-beam tune shift, and hour-glass effect are
  effective positron bunch length: $\tilde{\sigma}_{z+} = \sigma_{x+} / \tan\theta$
  effective positron current: $\tilde{I}_{+} = I_{+}\tilde{\sigma}_{z+}/\sigma_{z+}$
- Luminosity restored by focusing stronger in the vertical plane

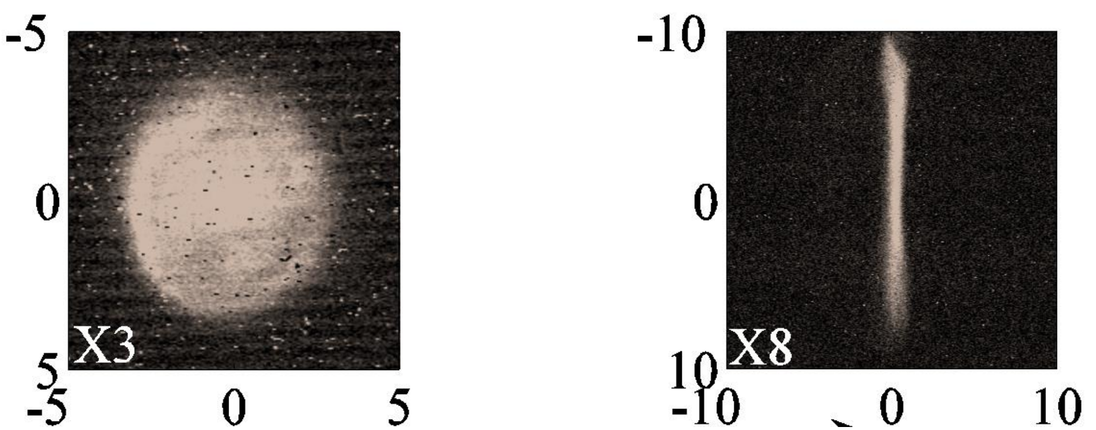
SuperKEK-B-Type Scheme

- Assuming crossing angle of $10\ mrad \Rightarrow \tilde{\sigma}_{z+} = 0.2\ mm, \tilde{I}_{+} = 120\ mA$

		SuperKEK-B LER	Cornell ERL	Linac-Ring	
		e^+	e^-	e^+	e^-
E	GeV	4	5	4	0.1
f	MHz	248.5	1300	248.5	
I	A	3.6	2.6	3.6	0.095
σ_z	mm	6	0.6	6	1
$\varepsilon_x/\varepsilon_y$	pm/pm	3200 / 8.64	31 / 31	850 / **85**	5100 / **255**
$\varepsilon_x^N/\varepsilon_y^N$	μm/μm	25 / 0.07	0.3 / 0.3	6.7 / **0.67**	1 / **0.05**
β_x^*/β_y^*	mm	32 / 0.27		6 / **0.6**	1 / **0.2**
σ_x^*/σ_y^*	μm/μm	10 / 0.048		2.3 / **0.23**	2.3 / **0.23**
θ	mrad	83		**10**	
ξ_x/ξ_y		0.0028 / 0.088		**0.016 / 0.016**	
D_x/D_y					**1.7 / 17**
$R_{h.-g.}$				**0.9**	
$R_{c.-a.}$				**0.7**	
L	**$cm^{-2}s^{-1}$**	**8×10^{35}**		**Achievable 1.7×10^{34}**	

Magnetized Beam

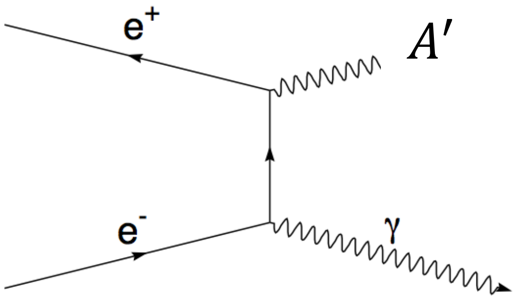
- Electron beam born in solenoid field has two transverse canonical emittances
  - Large one associated with beam size
  - Small one associated with Larmor motion
- Space charge sets a limit only on the large emittance
  - Emittance ratio can reach a factor of ~100
  - Magnetized beam property is routinely used in electron cooling
  - Round beam after acceleration can be transformed to flat
    Y.-E Sun et al., Phys. Rev. ST Accel. Beams 7, 123501 (2004).

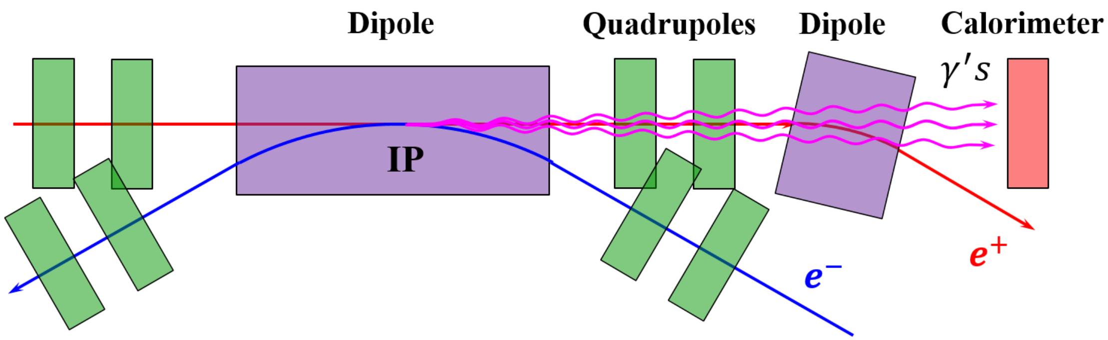


- An ERL for a magnetized beam is under development at JLab in the context of Jefferson Lab Electron-Ion Collider (JLEIC)

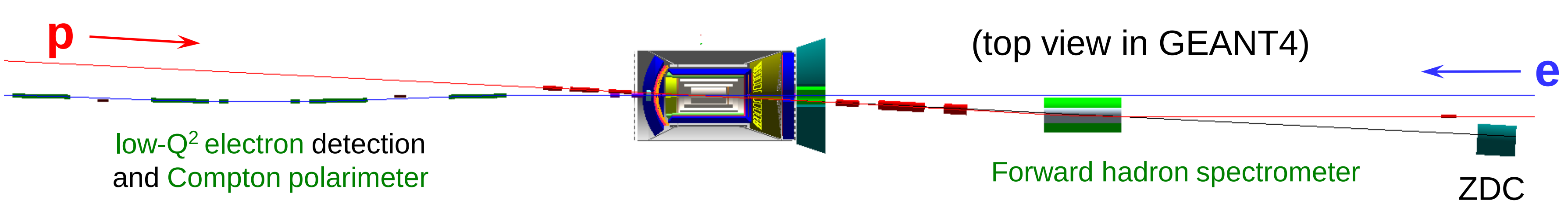
Possible Interaction Region Layout

- Experiment with detect **a single high-energy photon**
- Azimuthal angle cover of only 30% needed





- Detection requirements are conceptually similar to but much simpler than forward detection system that is being developed for JLEIC



Discussion

- Considered case of $\sqrt{s}$ = 1.3 GeV but can reach lower $\sqrt{s}$ by lowering linac energy;
  L = const if $I_- \sim 1/E_e$ $\Rightarrow$ $I_- \sim 1$ A at $E_e \sim 10$ MeV
- Considered only high-level parameters, more detailed study is needed
- Currently considering a ring-ring scheme with electrons and positrons moving in the same direction: luminosity is suppressed by low CM energy but beams can be quite small

Conclusion

- Linac-ring collider for dark matter search in the region of photon mass of 0.1-1 GeV with $L > 10^{34}$ $cm^{-2}s^{-1}$ can be built on the basis of an electron ERL and a positron storage ring
- The proposed design is based on proven concepts
  - SuperKEK-B type beam crossing scheme
  - Energy-recovery linac
  - Magnetized electron beam
- Linac-ring is perhaps a relatively low cost option for such a collider with two orders of magnitude higher luminosity than other colliders of similar energy