Muon Colliders

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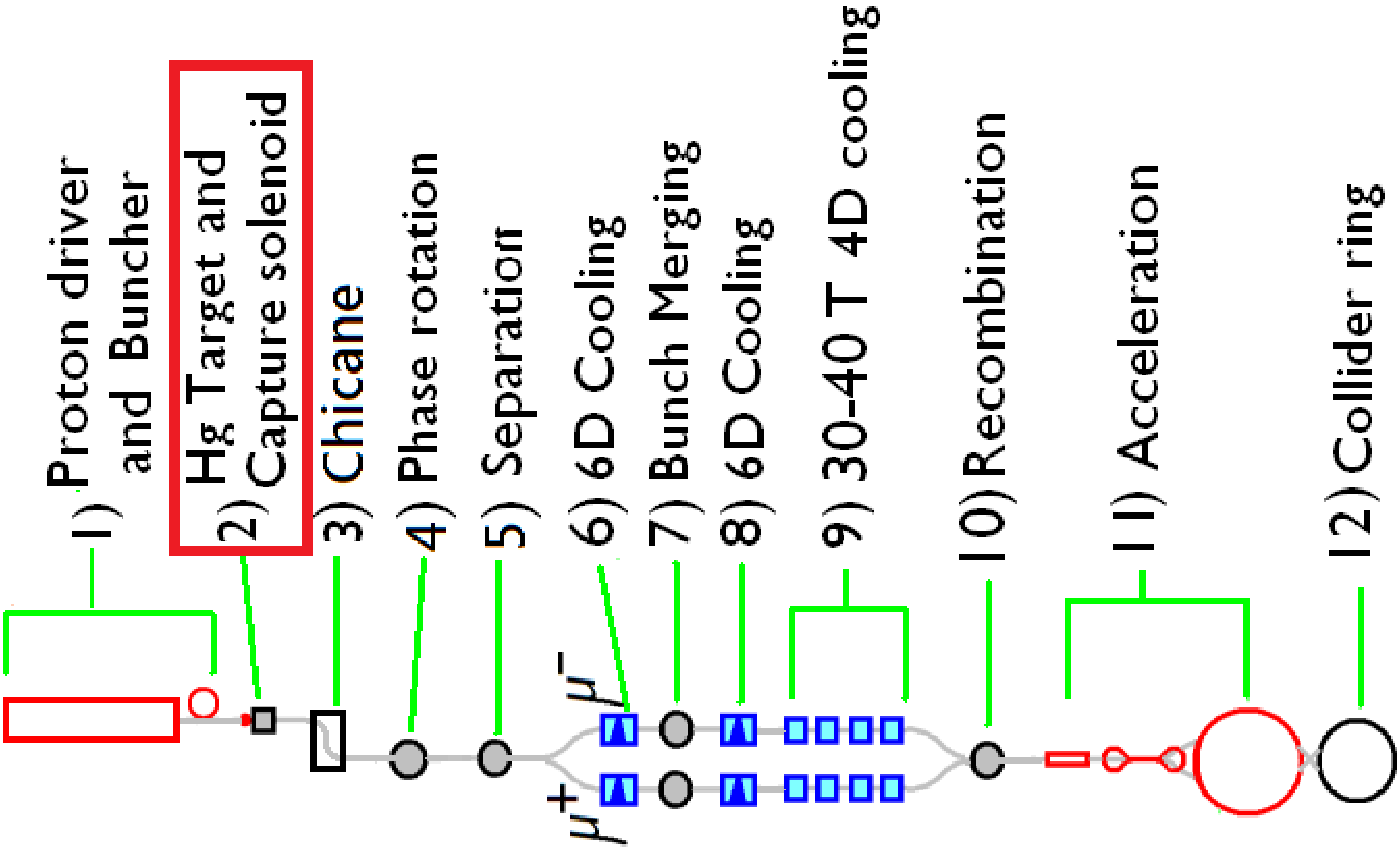
Princeton   12/6/16

- Parameters
- Compare with e^+e^-Collisers
- Compare with p-p Colliders
- Costs using Shiltsev model
- Is $\mu^+\mu^-$really plausible?
- Cavity damage in magnets
- Conclusion

Schematic



1) Proton driver and Buncher
2) Hg Target and Capture solenoid
3) Chicane
4) Phase rotation
5) Separation
6) 6D Cooling
7) Bunch Merging
8) 6D Cooling
9) 30-40 T 4D cooling
10) Recombination
11) Acceleration
12) Collider ring
μ^-
μ^+

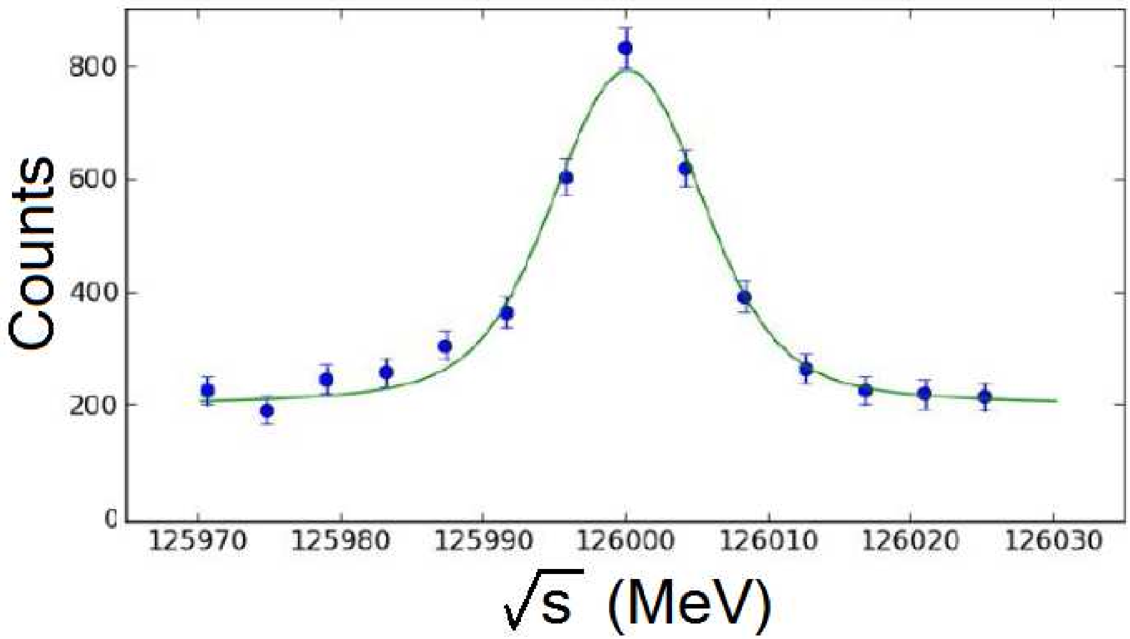
Muon Collider Rings

C of m Energy	0.126	1.5	3	6	TeV
Luminosity	0.008	1	4	12	10^{34} cm^{-2}sec^{-1}
Muons/bunch	4	2	2	2	10^{12}
Ring <bending field>	4.4	6.04	8.4	11.6	T
Ring circumference	0.3	2.6	4.5	6	km
β^* at IP $= \sigma_z$		10	5	2.5	mm
rms momentum spread	0.004	0.1	0.1	0.1	%
Depth		135	135	540	m
Wall Power		216	230	270	MW
Repetition Rate	30	15	12	6	Hz
Proton Driver power	4	4	3.2	1.6	MW
Muon Trans Emittance	200	25	25	25	μm
Muon Long Emittance	1.5	72	72	72	mm

6 TeV case is a blind extrapolation from 1.5 and 3 TeV designs, adjusted for same neutrino radiation

Comment about Higgs Factory

- The Muon Higgs factory makes an order of magnitude fewer Higgs than a 120 GeV FCC ee
- But it alone could measure the Higgs width
- It is too challenging and expensive for this single result
- Only realistic as an add on to a HE Muon Collider



3 TeV $\mu^+\mu^-$ vs. e^+e^- (CLIC)

		$\mu^+\mu^-$	e^+e^-	factor
Luminosity/IP (1%)	10^{34} cm^{-2}s^{-1}	4	2	2
Number of IPs		2	1	2
β^* at IP $= \sigma_z$	mm	5	0.09	56
rms bunch height σ_y	μm	3	0.001	3000
Wall power	MW	216	570	0.38
Lepton power/Wall power	%	20.0	20.3	0.99

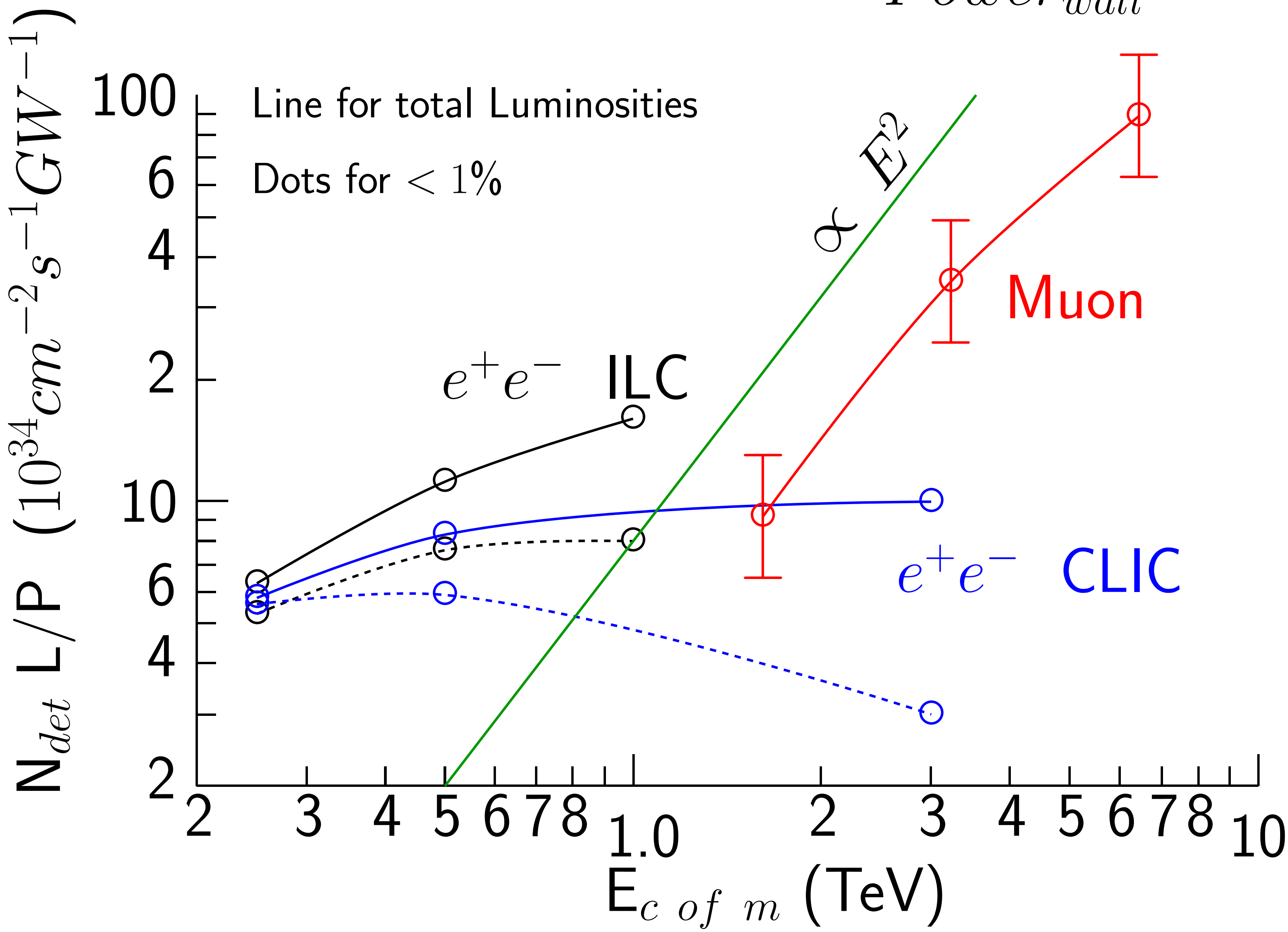
Comments

- Spot sizes and tolerances much easier than CLIC's
- $\mu^+\mu^-$luminosity/detector twice CLIC's (for dE/E $< 1\%$) $\times$ 2 detectors
- Wall power to Lepton Power efficiencies similar
- Wall Power $\approx$ 1/3 CLIC's

Muon advantage is because muons interact $\approx$ 1000 times, but electrons only once

Merit

$$Merit = \frac{Luminosity \times N_{detectors}}{Power_{wall}}$$



Comment on Merits

It has long been argued that a detailed study of 'New Physics' requires a lepton collider with appropriate energy, and from the above one can conclude that

- If 'New Physics' is below 2 TeV then ILC, CLIC or even PWF may be appropriate
- But if 'New Physics' > 2 TeV then a Muon Collider appears to be the only way to achieve needed luminosity with reasonable wall power consumption.

- Plasma acceleration claims double the CLIC efficiency, but with the such loading, low emittance dilution will be even more of a challenge.

Compare with p-p colliders I

If n_{parton} is effective number of partons in a proton, then

$$E_{(parton-parton)} = \frac{E_{(p)}}{n_{(parton)}}$$

$$Lum_{(parton-parton)} \approx Lum_{(p-p)} \times n^2_{(parton)}$$

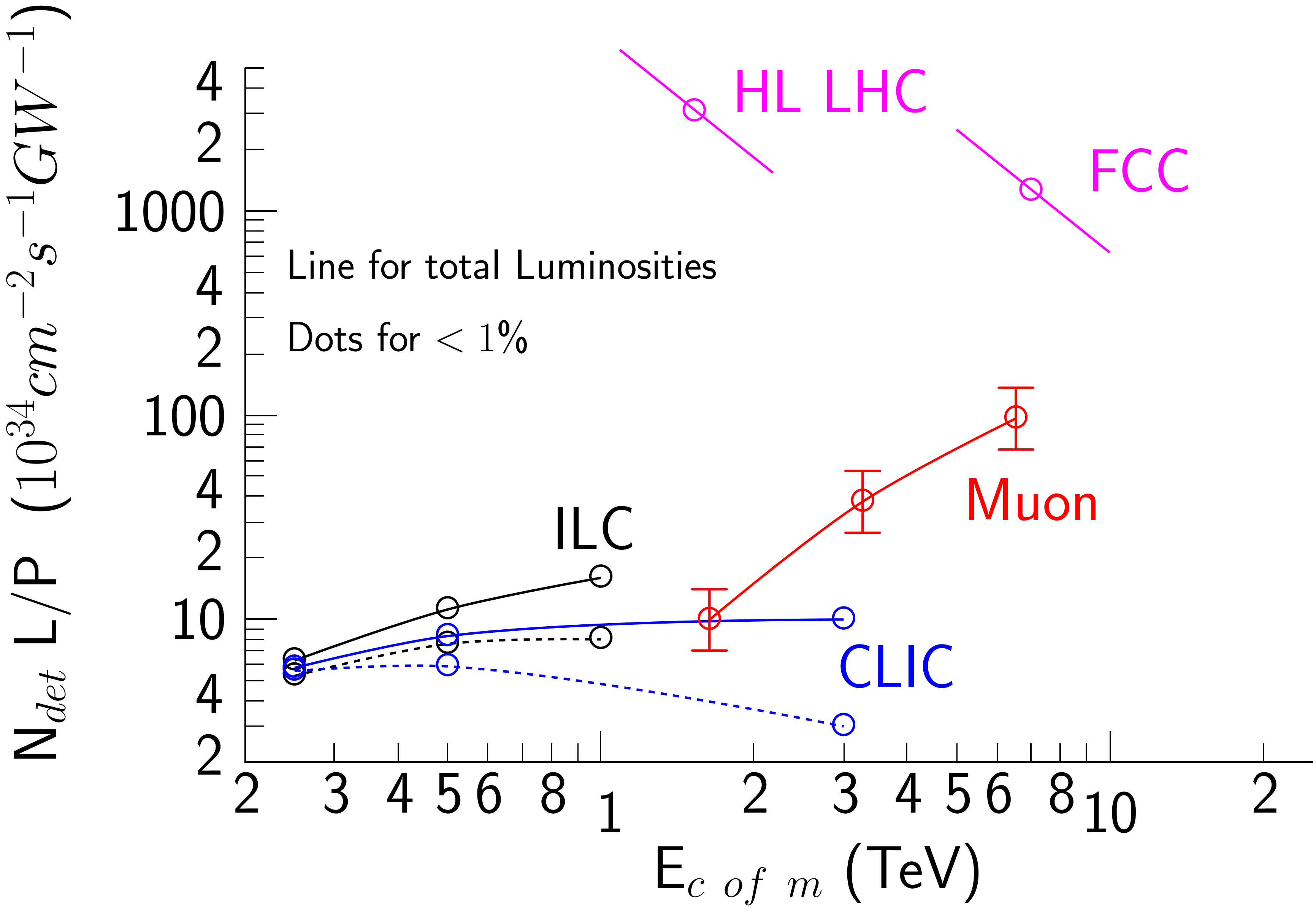
n_{parton} is not a fixed number. It has spreads given by structure functions that depend on the parton. When n_{parton} is higher the lumiosity rises approximately as n^2_{parton} and the energy falls.

p-p parameters

		HL LHC	FCC hh
p-p c-of-m Energy	TeV	14	100
p-p Luminosity/IP	10^{34} cm^{-2}s^{-1}	5	5
Number of Detectors		2	2
Wall power	MW	200	400
n_{parton}		10	10
$E_{parton-parton}$	TeV	1.4	10
$Luminosity_{parton-parton}$	10^{34} cm^{-2}s^{-1}	500	500

This is only qualitative

Compare with p-p colliders II



Comments

- The effective luminosity of HL LHC is $\approx$ 250 times that of CLIC
  LHC for discovery   CLIC for details

- But FCC hh is only $\approx$ 12 times a 6 TeV Muon Collider
- And the gap is closing

A muon collider would be approaching
to be a 'Discovery Machine'

Shiltsev Cost Model Input

- Look at cost data from:
  - Built RHIC, MI, SNS, LHC
  - Under Construction: XFEL, FAIR, ESS
  - Other: SSC, VLHC, NLC,ILC, TESLA, CLIC, Proj-X, Beta-beam, SPL,ν-factory

- Plot and fit:
  - Civil Construction vs. sum of lengths
  - SC rf vs. Energy
  - Infrastructure vs. Wall power consumption

Shiltsev; JINST 9 T07002 (2014) Modified by RBP

Cost of 100 TeV hh Collider

For "conventional" SC dipoles (8.4 T)

- Ring circumference 200 km
- Injector lengths: 27 + 5 = 32 km
- SC Magnets for 2 x 50 TeV
- Wall Power 200 MW

$$Cost \approx \; 2\sqrt{\frac{L}{10km}} + \left(\frac{E}{1TeV}\right)^{0.75} + \sqrt{\frac{P}{100MW}}$$

$$Cost \approx 2\sqrt{232/10} + (100/1)^{0.75} + 2\sqrt{200/100}$$

$$= \quad 9.6 \quad + \quad 31.6 \quad + \quad 2.8 \quad = \quad \mathbf{44\ B\$}$$

Cost of 6 T Muon Collider

- Length of all components $\approx$ 20 Km
- Total acceleration $\approx$ 300 GeV
- Momentum in collider ring $\approx$ 3 TeV
- Momentum in accelerators $\approx$ 4 TeV
- Wall Power $\approx$ 270 MW
- For p Driver $\approx$ 1 B\$/MW ???

L rf mag power Driver

$$Cost \approx 2\sqrt{\frac{20}{10}} + 10\sqrt{\frac{0.3}{1}} + \left(\frac{7}{1}\right)^{0.75} + 2\sqrt{\frac{270}{100}} + 4$$

$$= 2.8 + 5.5 + 4.3 + 1.6 + 4 = \mathbf{18\ B\$}$$

Comment on $\mu^+\mu^-$ vs. p-p

- Luminosity of a 6 TeV Muon Collider is approaching that of a Hadron Collider
- Its Cost should be less

- Both are VERY expensive
- We are NOT talking about the short term

Is a Muon Collider plausible?

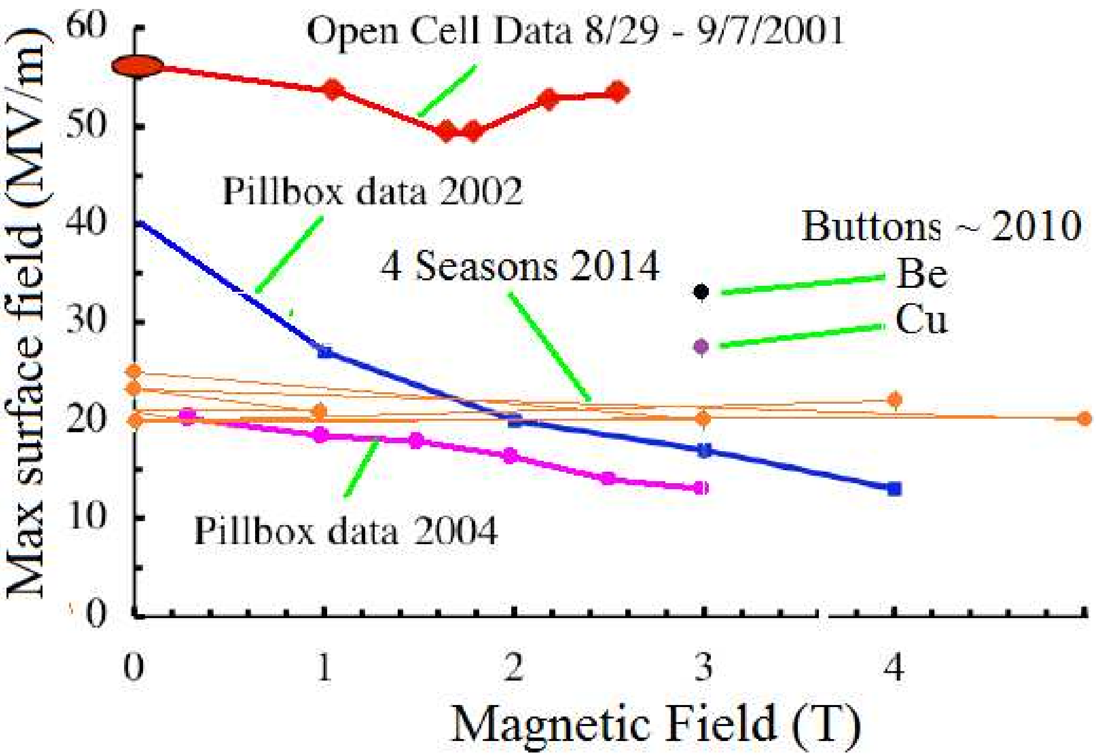
- I am not asking for Baseline selection
- I am not asking for end-end simulation
- This is a more academic question
- It is a much more modest question

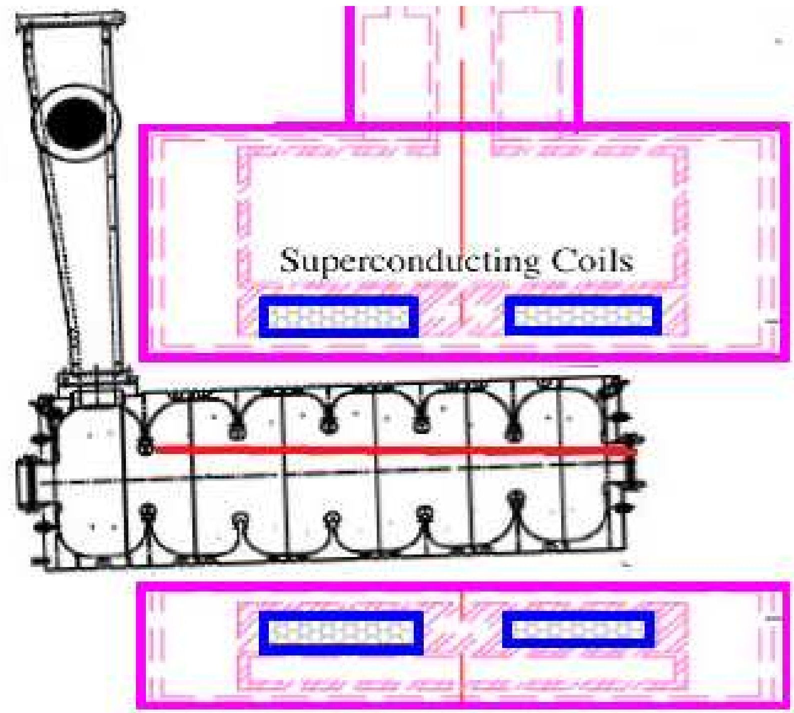
- Do we have plausible approaches for all required systems ?

My Answers

Proton Driver	yes	(Many options)
4 MW Hg Target	yes	Hg jet
Front End	yes	(Recent progress)
Early 6D Cooling	yes	(hybrid 6D ?)
Late 6D Cooling	No	(Vac rf in magnet)
Merge	yes	(Bao simulation)
Final Cooling	No	(too little effort)
Acceleration	yes	(Linac + RLA ?)
Collider rings	yes	(1.5 & 3 TeV)
Machine Detector Interface	yes	(With timing)

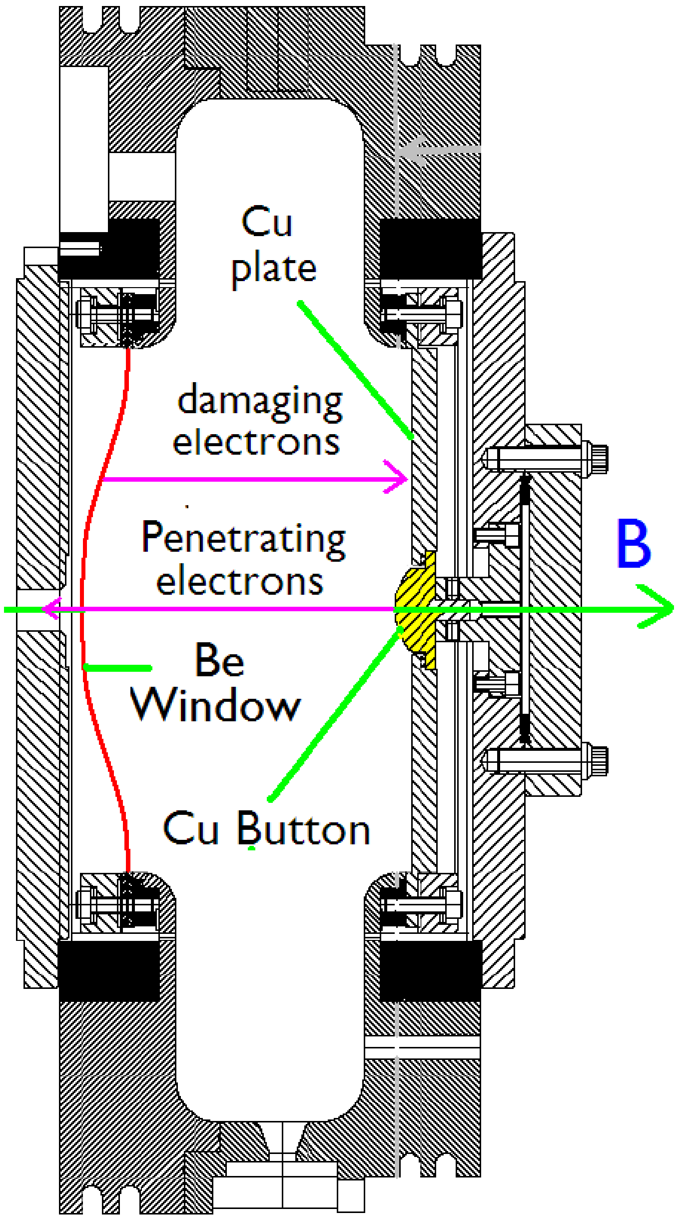
Vac rf Breakdown in magnets

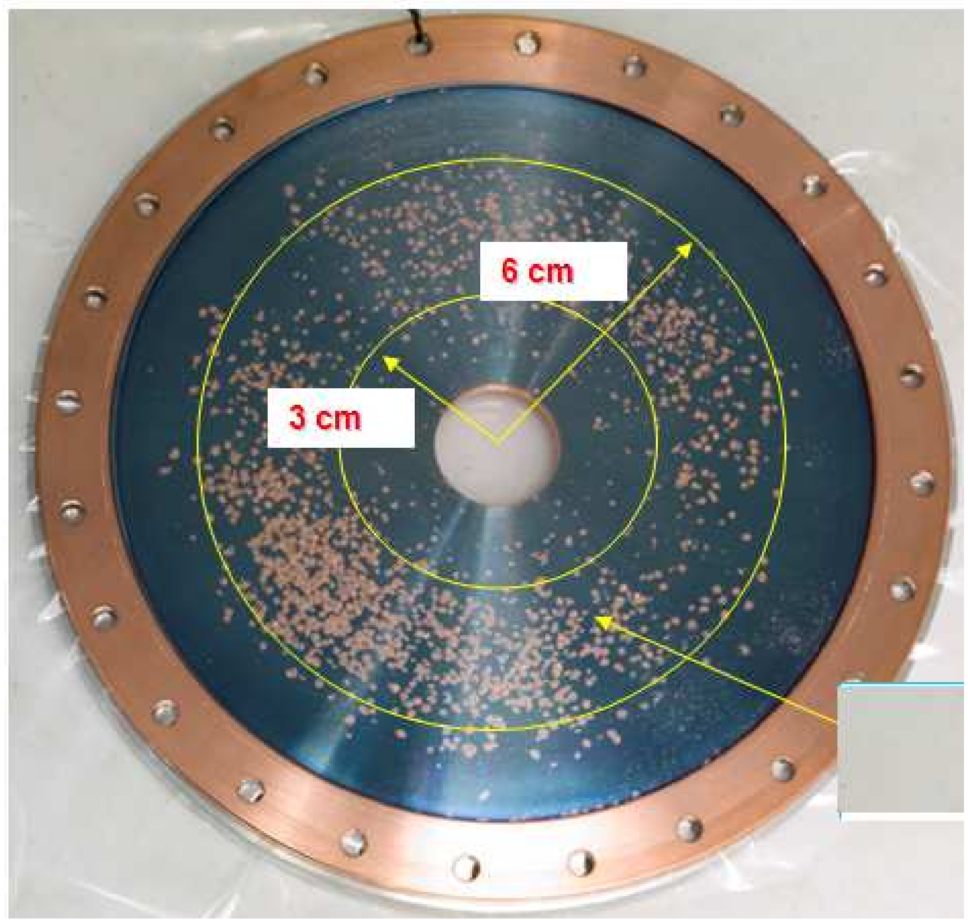




- Strictly: Breakdown is not the problem
- Open cavity achieved > 49 MV/m to ≈3T
- But damage made hole in Ti window
- Damage is the problem

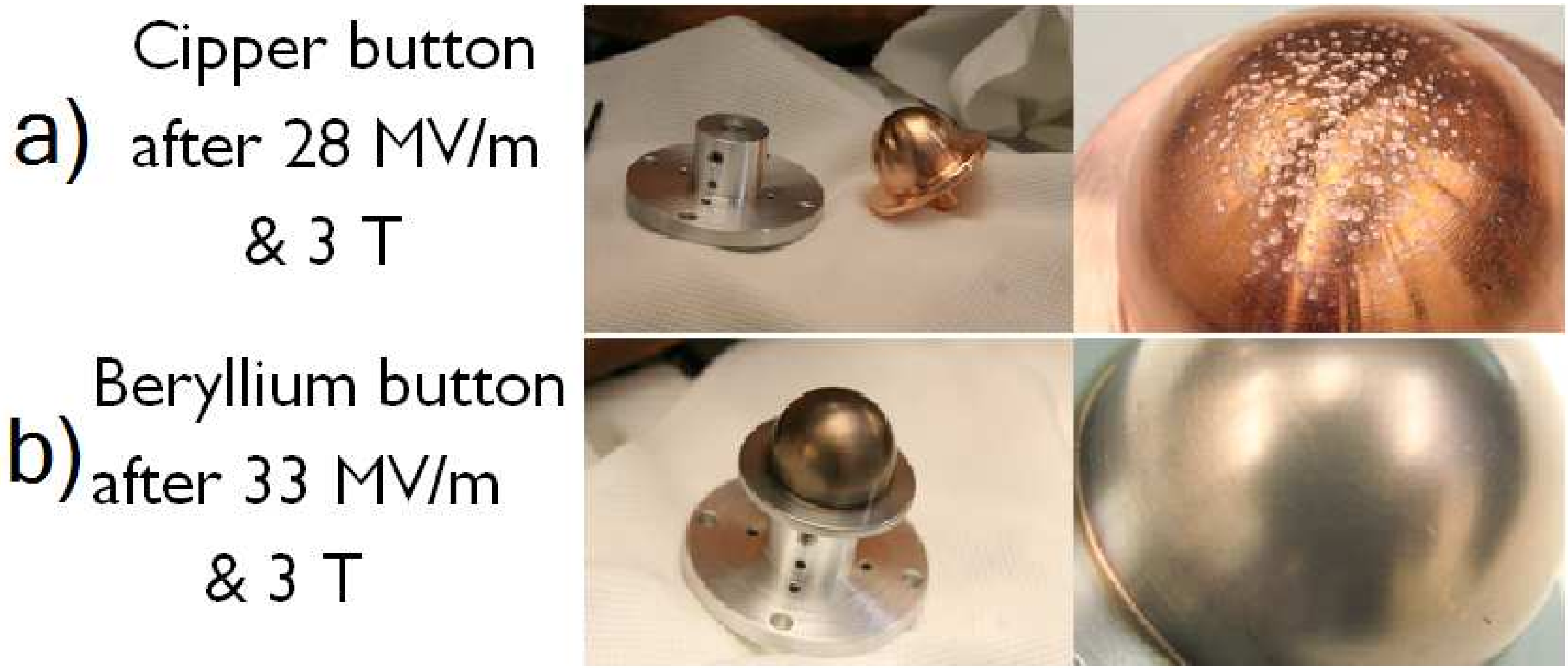
Damage Observation I





- Damage on copper
- None on Be opposite
- No Be dust observed

Damage Observation II



- Negligible damage on Be Button
- No Be dust observed
- Tiny pits. There before experiment ?

Conclusion

- A Muon Collider is the only lepton collider with useful luminosity above ≈ 2 TeV
- A 6 TeV Muon Collider has a luminosity approaching the parton luminosity of a 100 TeV p-p Collider at the same parton energies
- And its cost appears significantly less
- Both are VERY expensive and not likely any time soon

Was P5 Crazy to kill $\mu^+\mu^-$?

- No

  1. HEP Funding in US is falling
  2. R&D for a Muon Collider is expensive
  3. 20% of 20 B$ is 400 M$/year for 10 years
  4. This is not going to happen

- They voted to keep the base alive

But we can always Hope

Hope that support for research returns

Hope there are new ideas

Hope that there will be 'Young Kirks'

with the courage to join new collaborations

and make new contributions

like those of our friends: the 'Old Kirks'