On Future HEP Facilities and Directions of the Accelerator R&D in the US

an invitation for discussion at the
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Content

- Phenomenological Model of the Cost of Big Accelerators: **L..E..P**
- Examples and Outlook for **H E P**
- (An attempt to draw some)

  Conclusions on:

  – directions for HEP

  – directions for Accelerator R&D

Three Major Cost Drivers

- Length (circumference) **L**
- Energy (c.o.m. for colliders) **E**
- Power (total site power) **P**

(already a simplification – there are other factors)

- So, in the simplest form the **Cost** with good approximation is some combination of growing function of these parameters, eg:

$$\text{Cost} = f_1(\text{L}) + f_2(\text{E}) + f_3(\text{P})$$

NB: easy to see that the functions are not linear

Method

- There are many cost estimates known by now
  - ILC-0.5TeV and ILC-0.25 TeV, CLIC-0.5 and CLIC-3, VLHC (since 2001), Project-X, Super-B, Neutrino Factory, etc
- They cover huge range of **L** and **E** and **P**
- I will try to parameterize their costs by
  - nonlinear functions – power laws
  - coefficients optimized to get <~30% error

Arguments for power law

- Recent numerical example: cost of ILC-0.25 is 67-71% of ILC-0.5, that is close to **sqrt(2)=**0.71, cost CLIC-0.5 ≈ 40-50% of CLIC-3
- From experience, cost of electric components scales roughly as ***sqrt*(Power)**
- From ILC and PrX costing exercises cryo Cost= constant + (power)^0.6, that is closer to ***sqrt*(Power)** over wider range of **P**
- From VLHC and ILC costing exercises cost of the tunnel scales slower than linear (if compare "apples and oranges")
- Also: 1)when it comes to increase of the scope **(L, E, P)** accelerator builders either enjoy benefits of commercialization or do great job on optimization; 2) "Zero Energy cost" of injection complex
- I will use ***sqrt*(X)** functions – an approximation that does not change conclusions by much but makes numerical examples close to factual. ***Also, most numbers are rounded! Don't expect accuracies better than +-1/3 of the "actual cost"!***

Phenomenological Cost Model

- The resulting (overly simplified) cost model is:

$$\text{Cost} = \alpha\, L^{1/2} + \beta\, E^{1/2} + \gamma\, P^{1/2}$$

where α,β,γ – constants

- E.g. if **L** is in units of [10 km], E in units of [1 TeV], P in units of [100 MW] & "in the US accounting"
  - **α≈ 2B$/sqrt(L)**
  - **β≈ 10B$/sqrt(E)** for RF, **≈3B$/sqrt(L)** for SC magnets, **≈ 1B$ /sqrt(E)** for NC magnets
  - **γ≈ 2B$/sqrt(P)**

Examples

30 km ↓ 0.5 TeV ↓ 233 MW ↓

- ILC: Cost = $2\cdot3^{1/2} + 10\cdot0.5^{1/2} + 2\cdot2.3^{1/2} =$ $3.5+7.1+3.1=$**13.6** .... vs 16.5 (2008)
- CLIC: Cost = $2\cdot6^{1/2} + 10\cdot3^{1/2} + 2\cdot5.6^{1/2} =$ $4.9+17.3+4.7=$**26.9** .... vs “~15” eur.ac. (2008)
- CLIC-0.5: Cost = $2\cdot2^{1/2} + 10\cdot0.5^{1/2} + 2\cdot2.5^{1/2}$ = $2.8+7.1+3.1=$**13.0** .... vs 7.6 e.a. (2012)
- Pr-X: Cost = $2\cdot0.1^{1/2}+10\cdot0.003^{1/2}+2\cdot0.23^{1/2} =$ $0.6+0.6+1.0=$**2.2** .... vs 1.8 (2012)

Examples (cont.)

some 6 km ↓ · 12GeV SC magnets ↓ · 12GeV SC RF ↓

- **NeutrF:** Cost=$2\cdot 0.6^{1/2}+(3\cdot 0.012^{1/2}+10\cdot 0.012^{1/2})$
  $+2\cdot 1^{1/2}$ = 1.5+1.5+2.0=**4.0** …vs 4.7-6.5 (2012)
- **Super B:** Cost = $2\cdot 0.05^{1/2} + 3\cdot 0.01^{1/2} + 2\cdot 0.1^{1/2}$
  = 0.4+0.3+0.6=**1.3** ……vs "1.0"e.a.
- **Higgs F:** Cost = $2\cdot 1.6^{1/2} + (1\cdot 0.25^{1/2}+10\cdot .015^{1/2})$
  $+2\cdot 5^{1/2}$ = 2.5+2.5+4.5=**9.5** …vs "~5"e.a.
- **TLEP HF:** Cost = $2\cdot 8^{1/2} + (1\cdot 0.25^{1/2} + 10\cdot .005^{1/2})$
  $+ 2\cdot 5^{1/2}$ = 5.7+1.2+4.5=**11.4**

Examples (cont.)

- μμHF: Cost = $2\cdot 0.7^{1/2} + (3\cdot 0.12^{1/2} + 10\cdot 0.01^{1/2}) + 2\cdot 1^{1/2}$ = 1.6+4.1+2=**6.7** … (less 2 for PD)
- μ+μ- 3: Cost = $2\cdot 2.0^{1/2} + (3\cdot \mathbf{3}^{1/2} + 10\cdot 0.05^{1/2}) + 2\cdot 2.3^{1/2}$ = 2.4+7.3+3.0= **13.1** (less 2 for PD)
- Daedalus: Cost =3 x $(3\cdot 0.001^{1/2} + 2\cdot 0.2^{1/2})$ = = 3 x (0.1+0.9)= **3 (for three cyclotrons)**
- VLHC: Cost =$2\cdot 23^{1/2} + 3\cdot 175^{1/2} + 2\cdot 5^{1/2}$ = 9.6+39.7+4.5= **53.8**
- SHELHC: Cost =$2\cdot 8^{1/2} + 3\cdot 100^{1/2} + 2\cdot 5^{1/2}$ = = 5.7+30+4.5=**40.2** (less ~15 cost of inj.)
- VLHC-I: Cost =$2\cdot 23^{1/2} + 1\cdot 40^{1/2} + 2\cdot 2^{1/2}$ = = 9.6+2.1+1.4=**13.1** vs 4.1x1.4x2.5= 14.4

↑ 2001 “Eur.acct.” ↑ Infl’n ↑ Convert US Acct’ng

If one goes beyond proven…

- While desired **L**, **E**, and **P** are more or less known, coefficients are not, especially **β** (cost per *sqrt*(TeV))
- Let's take <u>plasma-collider</u> "as of now" (10 km, 10 TeV (2e15 cm-3 density), 140 MW) and cost 15M$/10 GeV at **1 Hz** (BELLA numbers) that corresponds to **β≈26B$/sqrt(E)** at **300 Hz***

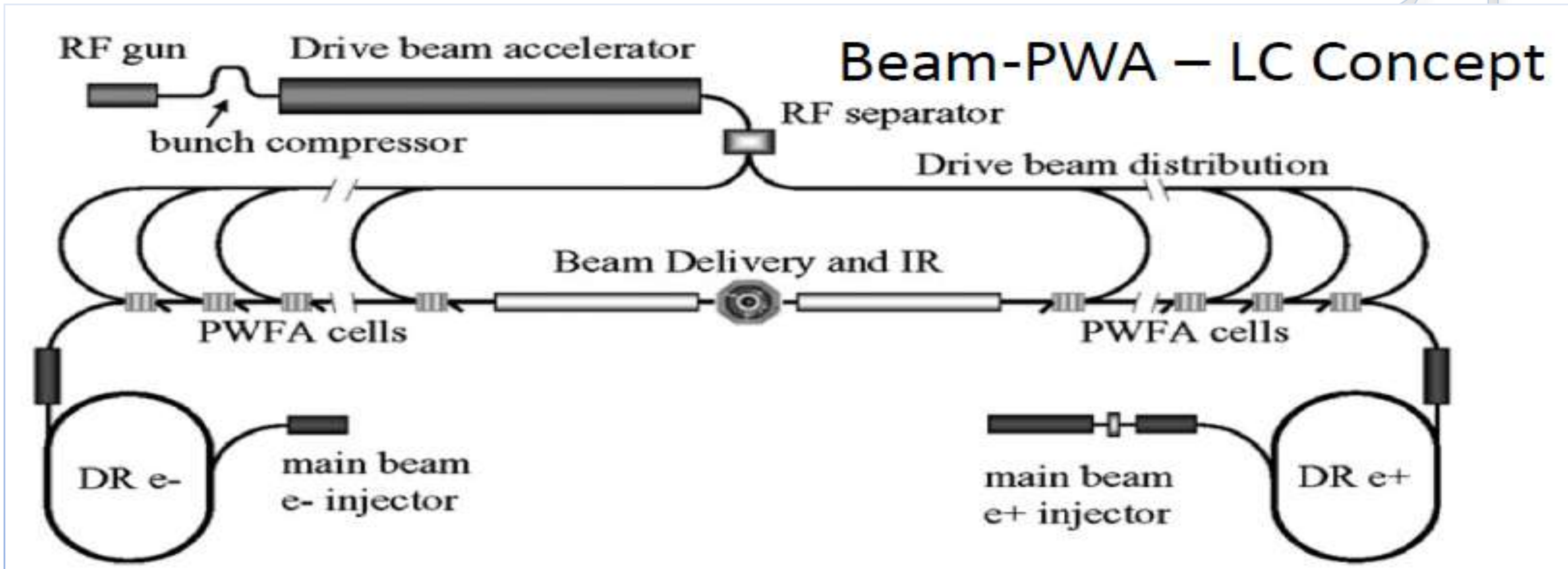
** scaled as sqrt(P)*

LPWA-LC $=2\cdot 1^{1/2} + 26\cdot 10^{1/2} + 2\cdot 1.4^{1/2}$

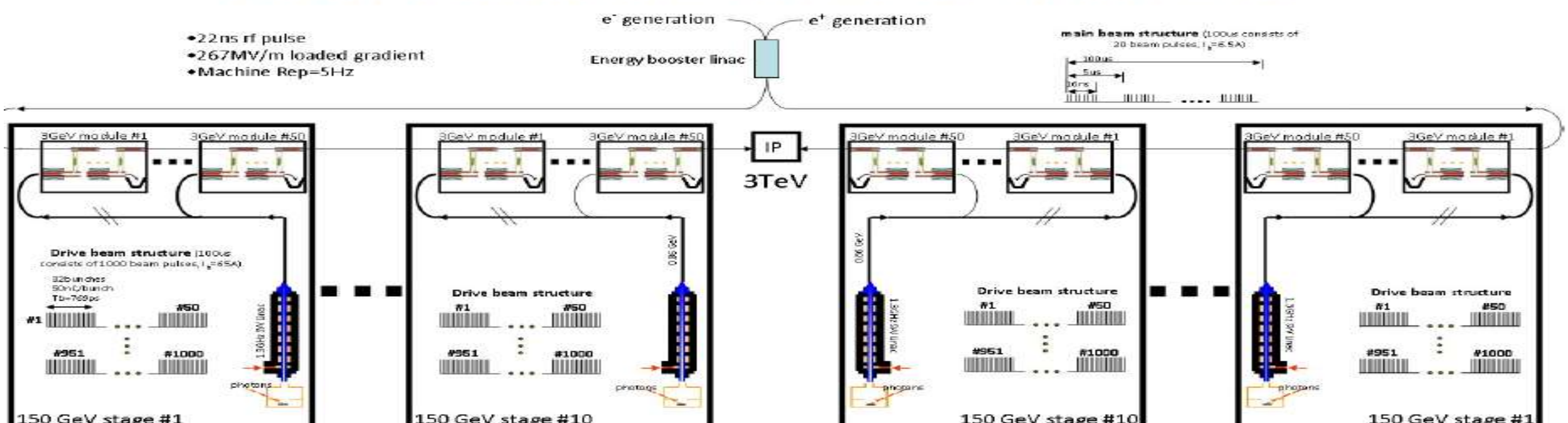
$= 2 + 82.2 + 2.4 =$ 86.6 ** (29.4 for 1TeV)

*** or conversely, ~10 fold cost reduction needed to get on par with SC magnets*

Beam-Driven e+e- LCs



ANL Flexible Linear Collider*



From Wei Gai, Chungunag Jing

On "Beam-Driven"-LCs

- Cost of the accelerator proper (plasma cells) is not known well
- Cost of power drivers ("conventional") can be estimated:
  - *cost of only one 60MW 25 GeV drive linac (good for only 1 TeV BPWA-LC) is ~**8B$** … its ~15x Project X in Power and 3x Energy*
  - *…need 2 or 3 for 3 TeV option (to be compared with CLIC) → **20-24?***
  - *another option (ANL) calls for 20 SC RF pulsed linacs ~7 MW each – formulae gives minimum **19 B$** for power drivers alone*

Another approach – estimate wrt to CLIC

- 3 TeV machines will be ~10 km long, and mb a factor of 2 more efficient than CLIC
- If the cost per TeV will be as in CLIC

BPWA: Cost = $2\cdot1^{1/2} + 10\cdot3^{1/2} + 2\cdot2.8^{1/2} =$ 2+17.3+3.3= **22.6**

- If (as unproven technology) the cost per TeV will be **2xCLIC**

BPWA: Cost = $2\cdot1^{1/2} + 20\cdot3^{1/2} + 2\cdot2.8^{1/2} =$ 2+34.6+3.3= **39.9**

	Known Est.	This Est	Comments	$L_{[10km]}$	$E_{[1TeV]}$	$P_{[0.1GW]}$
Super B e+e-	1.0 Eur. Acc	1.3	? 2012 ?	0.05	0.01	0.1
Project X p	1.8	2.2	Est. 2012	0.1	0.008	0.23
DAEDALUS p		3	For 3 cyclotrons		0.001	1
Neutrino Factory p→μ	4.7-6.5	4.0	Accounting not clear	0.6	0.012	1
μ+μ- Higgs Factory		6.7	-2 if PD exists	0.7	0.12	1
Higgs e-e+ site filler		9.5	-3.4 if tunnel exists	1.6	0.25	5
ILC-0.25 TeV e+e- HF		9.5	70% of ILC-0.5	~1.5	0.25	~1.2
TLEP Higgs Factory		11.4		8	0.25	5
μ+μ- Collider 3/6 TeV		13/16	-2+ if Prot. Driver exists	2.0	**3**/6	2.3
VLHC-I 40 TeV p-p	14.4	13.1	2001 est (**4.1**)x3.5; - inj	23	40	2
ILC-0.5 TeV e+e-	(16.5)	13.6	2007 est , **6.7 Eur Acct**	3	0.5	2.3
CLIC-0.5 TeV e+e-	7.4-8.3 E.A.	12.4	Coeff β_{CLIC} must be $>\beta_{ILC}$	2	0.5	2.5
Beam-PWA ee LC 3TeV		19-39	60 MW driver alone >8	1	3	2.8
CLIC-3 TeV e+e-	">15" E. A.	26.9	No public cost range	6	3	5.6
SHE LHC 100 TeV p-p		40.2	Deduct ~15 of injector	8	100	5
Laser-PWA 1/10 TeV e+e-		29/86.6	scaled today's laser cost	1	1/**10**	1.4
VLHC-II 175 TeV p-p		53.8		23	175	5

Comments

- Note that performance (eg luminosity of the colliders) is not guaranteed - even if **L, E, P** and **cost** are given, there might be ~order(s) of magnitude uncertainties related to important details (beam quality, etc)
- Beamstrahlung and radiation in focusing channel make *e+e-* colliders not that attractive for energies above 1-3 TeV

Conclusions on HEP machines

- **US alone** – with HEP budget 0.8B$/yr – can shoot for (25% x 0.8B$ x 10 yrs) = 2 B$
  - Super B or Project X
- With **Int'l partners** or **doubled** construction budget (extra 0.2B$/yr) the limit is 4 B$
  - ν-Factory (?) or 3 x 1 MW cyclotrons or ($\mu\mu$HF if PD exists)
- **CERN alone** – with ~1-1.2B$/yr budget can go after (0.4B$ - 0.5B$) x 10 yrs = 4-5 B$
  - SPL or LHeC or m.b. e+e- Higgs Factory **in LHC tunnel**
- **Truly Global** project – with overall HEP budget of ~3B$/yr – can possibly be afforded at 8-12 B$
  - LEP3 (not expandable)
  - ν-Factory or Muon Collider (expandable to higher **E** and performance)
  - ILC-0.25 (expandable only to 0.5 TeV)
  - m.b. TLEP Higgs Factory, m.b. ILC-0.5, m.m.b. CLIC-0.5 (all - not expandable)

Possible Conclusions (2)

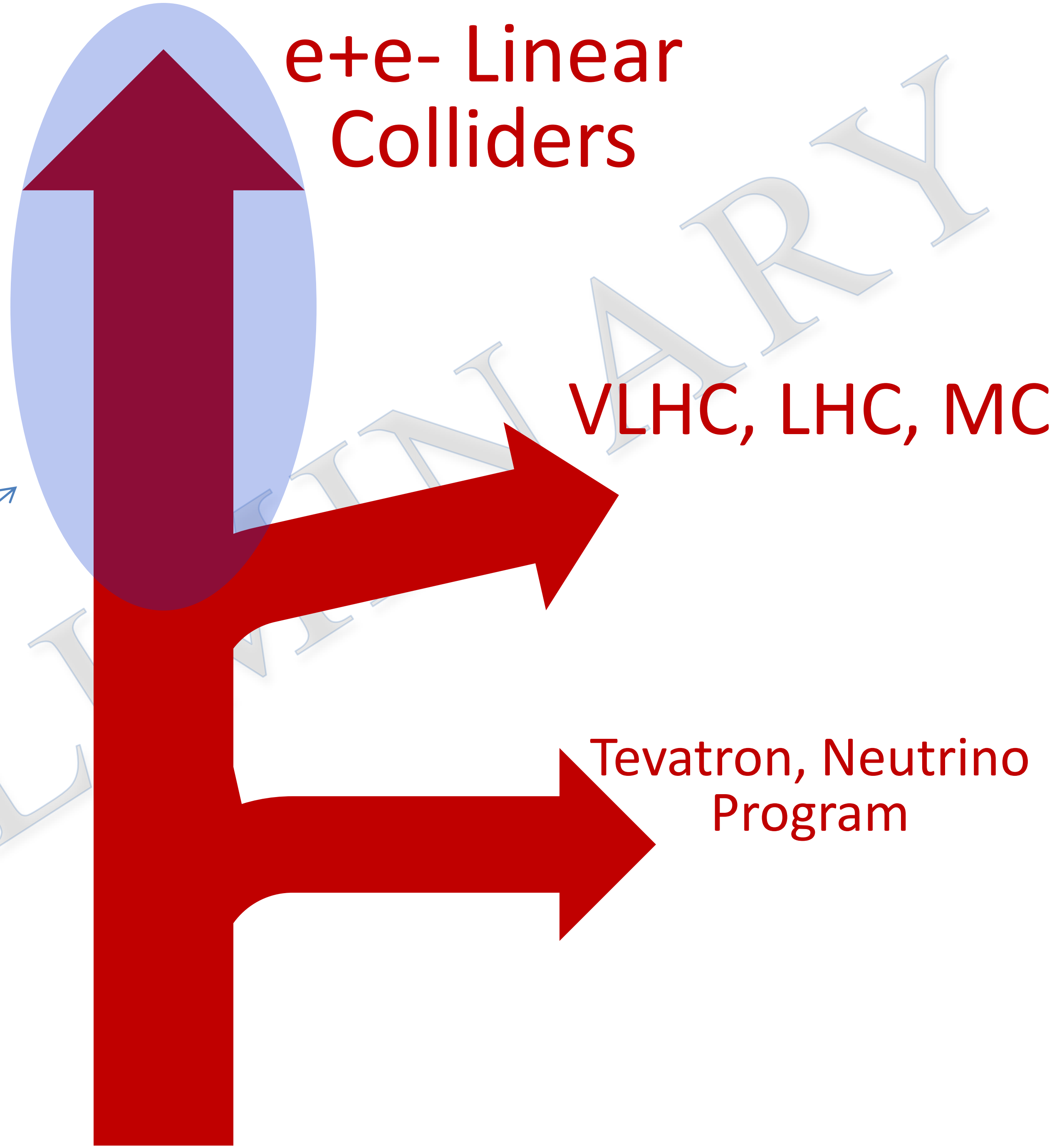
- List of "interesting facilities" with cost estimates shows that :
  - **Not affordable** : all *e+e-* Colliders >0.5 TeV and all *pp* colliders after LHC
  - **Possibly affordable** : Muon Collider, Higgs factories
  - **Affordable:** Accelerators for *Intensity Frontier*
- Due to radiation , it is hard to believe that electrons (positrons) are the path to *Energy Frontier*
- Muons or Protons are *Energy Frontier* particles of choice

Accelerator R&D

- Goals:
  - 1) cost savings / performance improvements for next facilities
  - 2) new concepts for facilities beyond next (AARD)
  - 3) training next generation
- Current structure of Accelerator R&D program has been formed and reflects our thinking from 10-15 years ago :
  - Tevatron and beyond (upgrades, LHC, VLHC, etc)
  - Linear e+e- collider(s) @ ~1 TeV and upgrades
  - (only recently – Muon Collider R&D and SRF GAD)
  - That is reflected in the Accel R&D facilities we have established up to now

Acc. R&D priorities from ca 2000 to “up to now”

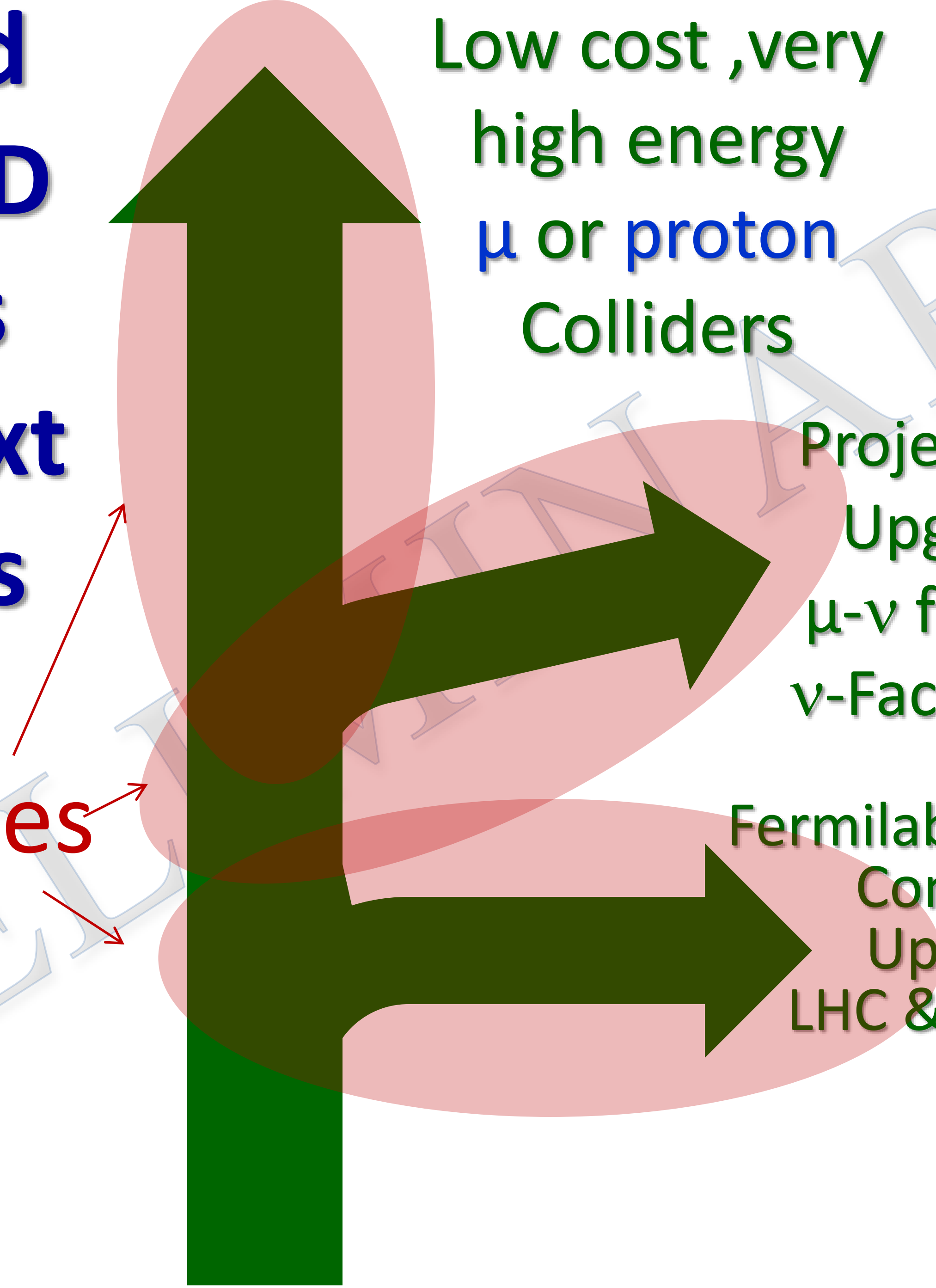
Current AARD facilities



Required Accelerator R&D

- Should reflect new realities and long-term goals:
  - 1) cost savings / performance improvements for Intensity Frontier facilities (incl SRF and Beam Dynamics studies)
  - 2) cover possible transition from Intensity Frontier to Energy Frontier (now – Muon Collider)
  - 3) electrons are not particles of choice for IF and EF facilities beyond next – muons and protons are
  - 4) AARD should aim at new concepts which offer drastic cost reduction for >10x LHC energy (muons or protons)
- At present, there is a lack of suitable Accelerator R&D facilities to effectively serve these goals:

suggested Accel. R&D priorities for the next 2 decades



Reservations

- The author is by no means an expert in cost estimates of large accelerator facilities – and though he got consulted by few “real” pro’s, all the criticism should go solely on him (me).
- I also discussed the topic with about a dozen people, and in case this analysis appreciated – the credit should be given to them.