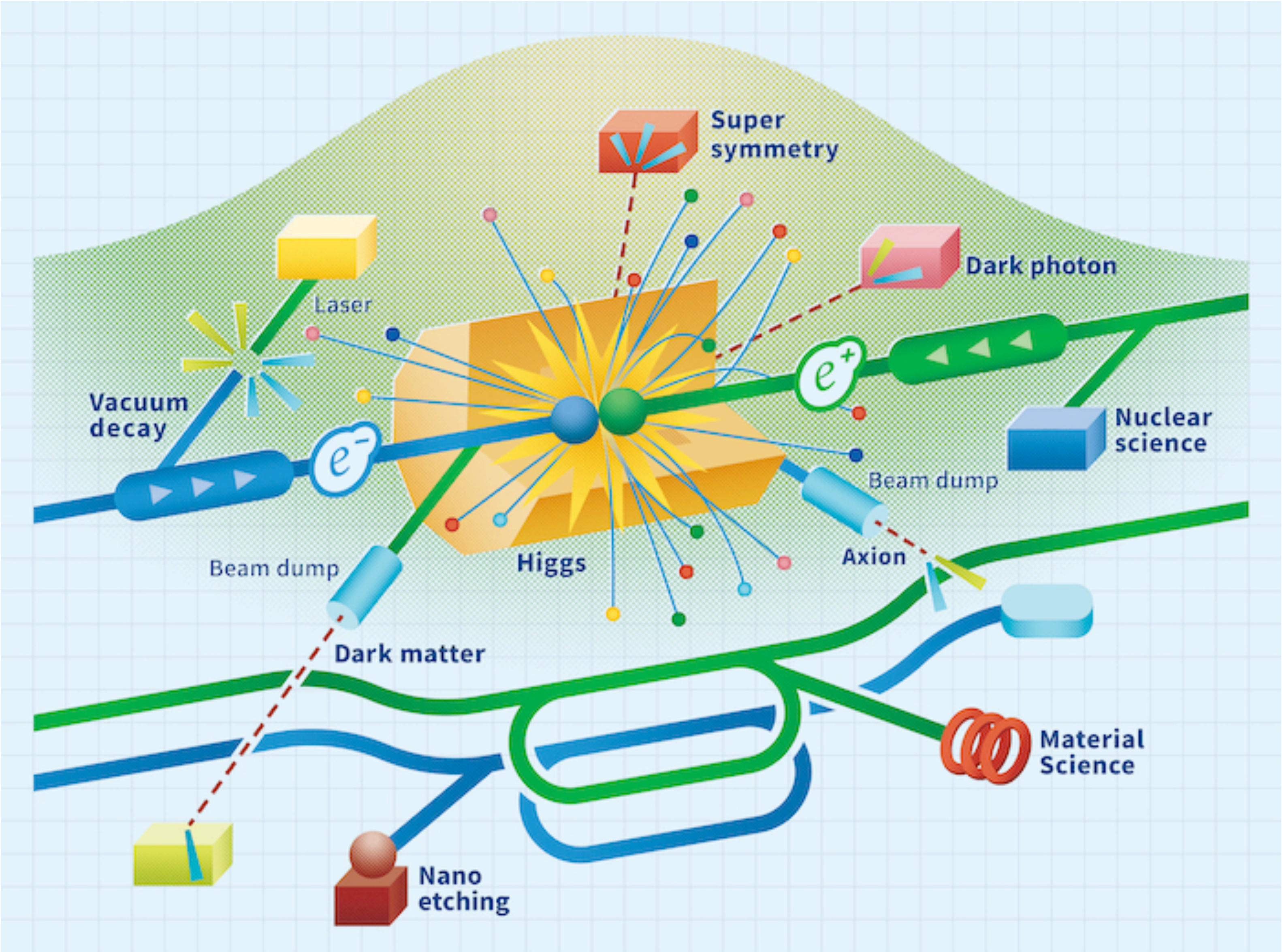
Welcome to the Open Discussion: A Global Vision for a Linear Collider Facility!



LCWS 2024
Tokyo University
July 8, 2024

LC Vision Team: T. Barklow, T. Behnke, M. Demarteau, A. Faus-Golfe, B. Foster, M. Hogan, M. Ishino, D. Jeans, B.List, J.List, V. Litvinenko, S. Michizono, T. Nakada, E. Nanni, M. Nojiri, M. Peskin, R. Patterson, R. Pöschl, A. Robson, D. Schulte, S. Stapnes, T.Suehera, C. Vernieri, M. Wenskat, J. Zhang

What to expect for the next 90 minutes

Overview

- **sequence of 5-minute kick-off presentations, without breaks / discussion**
  - this intro :)
  - Topic 1: Stages and physics goals from 91 GeV to 800-1000 GeV (M.Peskin)
  - Topic 2: ILC at CERN compared to FCC-ee (R.Pöschl)
  - Topic 3: SCRF / ILC-like realization of full physics program 91-1000 GeV (S. Michizono)
  - Topic 4: CLIC/C3 realization of full physics program as upgrade of ILC250 (S.Stapnes)
  - Topic 5: RELIC upgrade of ILC250 and physics need for higher luminosity (V.Litvinenko)
  - Topic 6: Realizations of the full physics program with plasma wakefield upgrade of ILC250 (B.Foster)
  - Topic 7: Beyond-collider program (M.Nojiri)
  - Topic 8: Implications for exploring the 10 TeV parton energy scale (D.Schulte)
- **45' plenary discussion**
  - **guided by your online submitted questions!**

What is this Global LC Vision?

We are all here at LCWS because we think that

- the exploration of the fundamental laws of our universe requires, in addition to the HL-LHC and Belle II, a long-term e+e- program over a wide range of energies - not just a “gap-filler”
- this program should start “now” by unveiling the mysteries of the Higgs boson, with an affordable project based on technology at-hand - and then evolve from there
- the long-term program should not be statically defined “today” for decades into the future, but instead the initial facility must be sufficienctly versatible to allow choices to be taken as scientific knowledge and technologies advance - or even see revolutions
- this applies to the evolution of the e+e- facility itself as well as for the choice of the best avenue to eventually explore the 10-TeV parton-energy scale, for all of which sufficient resources for R&D and demonstrators must remain available

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A few months ago, a spontaneous “think-tank”, aka LC Vision Team, formed to reflect on these ideas — and today we invite you to discuss them with us!

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Evolve this into **a joint Linear Collider Vision input at the EPPSU**, complementing more technical "project inputs" ?

A few months ago, a spontaneous "think-tank", aka LC Vision Team, formed to reflect on these ideas — and today we invite you to discuss them with us!

And after today's discussion?

Some ideas

- we hope that discussions will continue through out the workshop
- an attempt of a summary on the LC Vision discussion will be given in the closing plenary
- we need to prepare for the EPPSU
  - should - in addition to specific technology-oriented individual submissions - all Linear Colliders team up to present a joint vision for the field based on a linear Higgs factory as the first step?
  - how do we already now reach out to the HEP community, i.e. to make sure national pre-EPPSU discussion are informed about this idea?
  - how to organize the LC Vision effort in the future?

And now it is your turn!

Slido

Please connect now!

- **scan QR code**
  - **or enter code on web site**
- **try “Type your question”**
  - **please enter your name the first time**
- **during talks and discussion you can**
  - enter new questions
  - “like” other questions
  - **answer** questions

  => please use with care and respect!
- **our moderators will pick popular questions and address them to the LC vision representants on stage**

https://slido.com
#2754 288

Slido

Please connect now!

- **scan QR code**
  - **or enter code on web site**
- **try “**
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  - **“**
  - **a**

  => please use with care and respect!
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Warm-up excercise:
What makes you enthusiastic about Linear Colliders?

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#2754 288

Topic 1: Stages and physics goals from 91 GeV to 800-1000 GeV (M.Peskin)

Physics Goals of the Full Higgs Factory Program

M. E. Peskin
LCWS 2024
LC Vision
July 2024

There is a “Full Higgs Factory Program”.

This follows the idea that we should measure all possible properties of the Higgs boson with current collider technologies, while we prepare for experiments at 10 TeV.

This requires a number of energy stages for e+e- colliders. And, some of these are beyond the reach of FCC-ee.

In the following, I will list these stages in order of increasing CM energy. This is not necessarily chronological order. We will want to measure the Higgs directly in the first stage.

The purpose of a Higgs Factory is not to improve the error bars. The purpose is to make discoveries.

Since the Higgs boson is most closely connected to the mysteries of the Standard Model, closer study of the Higgs boson gives us this opportunity.

For a discovery, uncertainties should be defensible and improvable. This is the most important advantage of an e+e- collider.

Two features enhance this capability:

1. e- and e+ polarization offers multiple data sets with complementary information

2. parameters are often measurable in complementary reactions (denoted 2nd! in the following)

91 GeV: Z resonance

enhanced precision EW tests, also needed for SMEFT fitting

SM PEW closure test error : GigaZ w. pol.: 1.3 , TeraZ no pol: 1.0 $\times 10^{-5}$

160 GeV: WW threshold

W mass, precision EW test for LC only useful for enhanced luminosity upgrades

SM PEW closure test error: ILC 250 : 5.3 FCC-ee: 1.7 $\times 10^{-5}$

250 GeV: peak of the tagged Higgs cross section $e^+e^- \to ZH$

Higgs couplings to W, Z, b, τ, g, c to 1% (absolutely normalized)

search for exotic Higgs decays to BR ~ 10^{-4} invisible to BR ~ 10^{-3}

W mass to 2 MeV (see above)

precision study of $e^+e^- \to W^+W^-$, [4] $e^+e^- \to f\bar{f}$ for global SMEFT fits, multi-TeV BSM sensitivity, CP violation probes

350 GeV: top quark threshold

a short run (200 fb-1) gives m(t) to < 50 MeV

550 - 600 GeV: above the ttH, ZHH thresholds

Higgs couplings to 1% in $WW \to H$ 2nd!

top quark EW form factors (SMEFT parameters) to parts per mil

measurement of top Yukawa in $e^+e^- \to t\bar{t}H$ to 3%

measurement of triple H coupling in $e^+e^- \to ZHH$ to 20%

precision study of $e^+e^- \to W^+W^-$, $e^+e^- \to f\bar{f}$ for global SMEFT fits,
10's -TeV BSM sensitivity, CP violation probes 2nd!

800 - 1000 GeV: final Higgs Factory stage

Higgs couplings to <1% in $WW \to H$ 3rd!

top quark EW form factors (SMEFT parameters) to parts per mil 2nd!, resolution of degeneracies in SMEFT fit

measurement of top Yukawa in $e^+e^- \to t\bar{t}H$ to 1% 2nd!

measurement of top Yukawa in $WW \to t\bar{t}$ to few % 3rd!

measurement of triple H coupling in $e^+e^- \to \nu\bar{\nu}HH$ to 10% 2nd!

precision study of $e^+e^- \to W^+W^-$, $e^+e^- \to f\bar{f}$ for global SMEFT fits, 100 -TeV BSM sensitivity, CP violation probes 3rd!

Topic 2: ILC at CERN (250 GeV) compared to FCC-ee (R.Pöschl)

(I)LC@CERN vs. FCCee

Roman Pöschl
on behalf of the LCVision Team

LCWS 2024 – Tokyo (JP) – July 2024

I am indebted to the LCVision-Team and in particular to Jenny, Michael and Benno for their help with preparing these slides

Linear vs. circular e+e- machines – Instantaneous luminosities

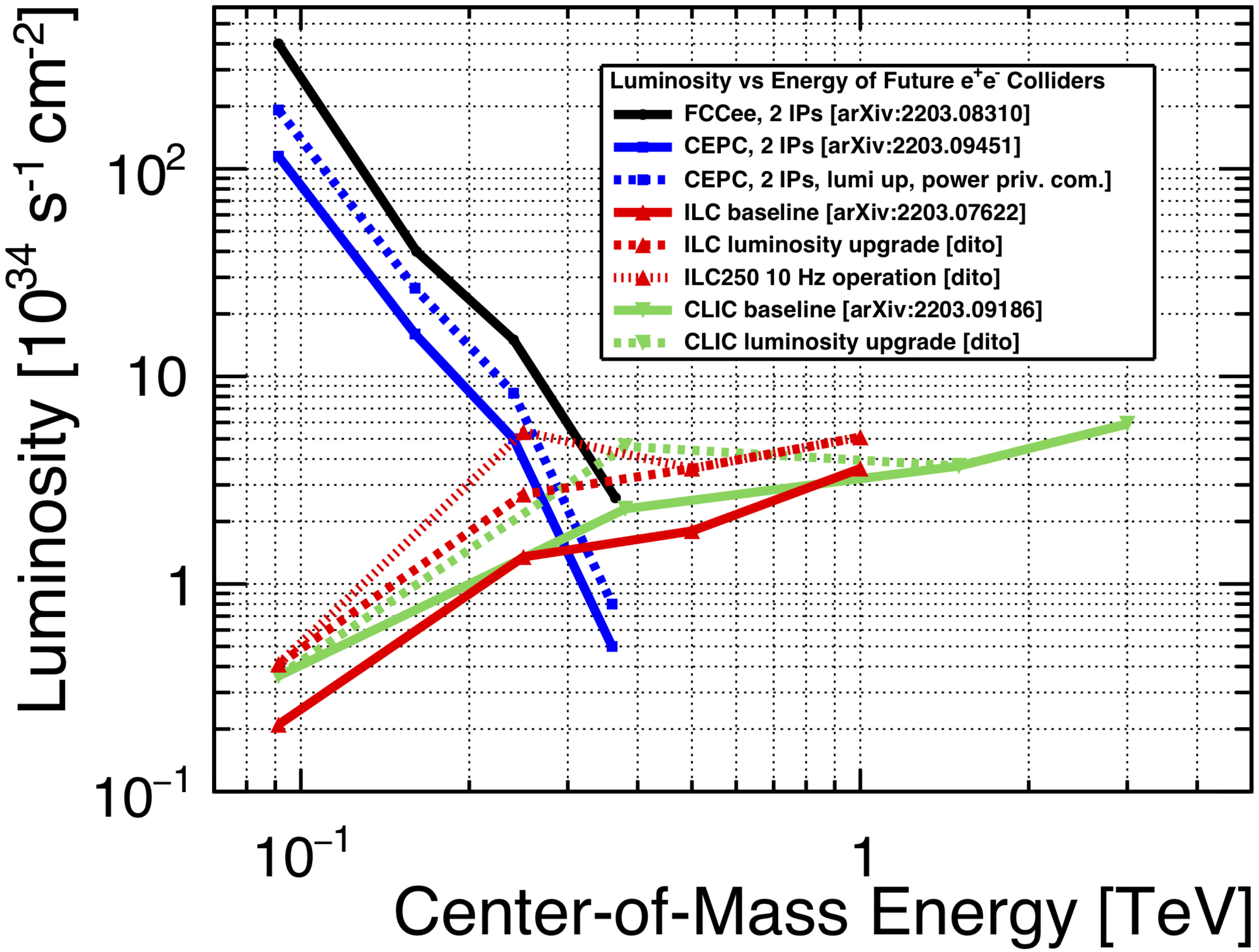
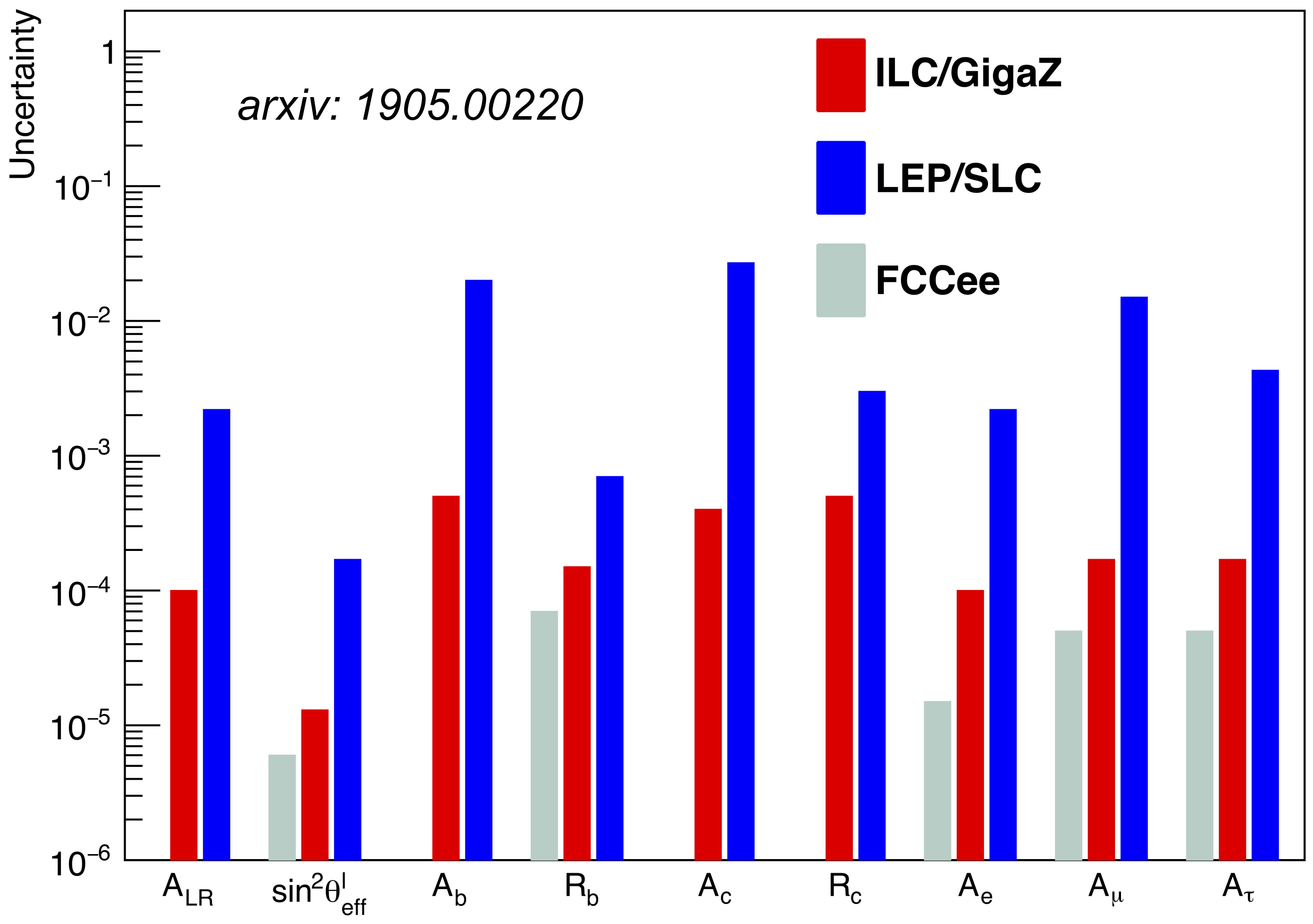


Figure J. List

- High energies ~above tt-threshold
  Domain of linear colliders
- Low energies e.g. Z-pole
  Domain of circular machines
  However, ...
- Transition region, i.e. HZ threshold
  Comparable Higgs Couplings uncertainties for all proposals (see later)
- Linear colliders are more versatile to test chiral theory due to polarised beams

$$\sigma_{P,P'} = \frac{1}{4}\left[(1-PP')(\sigma_{LR}+\sigma_{RL}) + (P-P')(\sigma_{RL}-\sigma_{LR})\right]$$

Precision on Z-pole

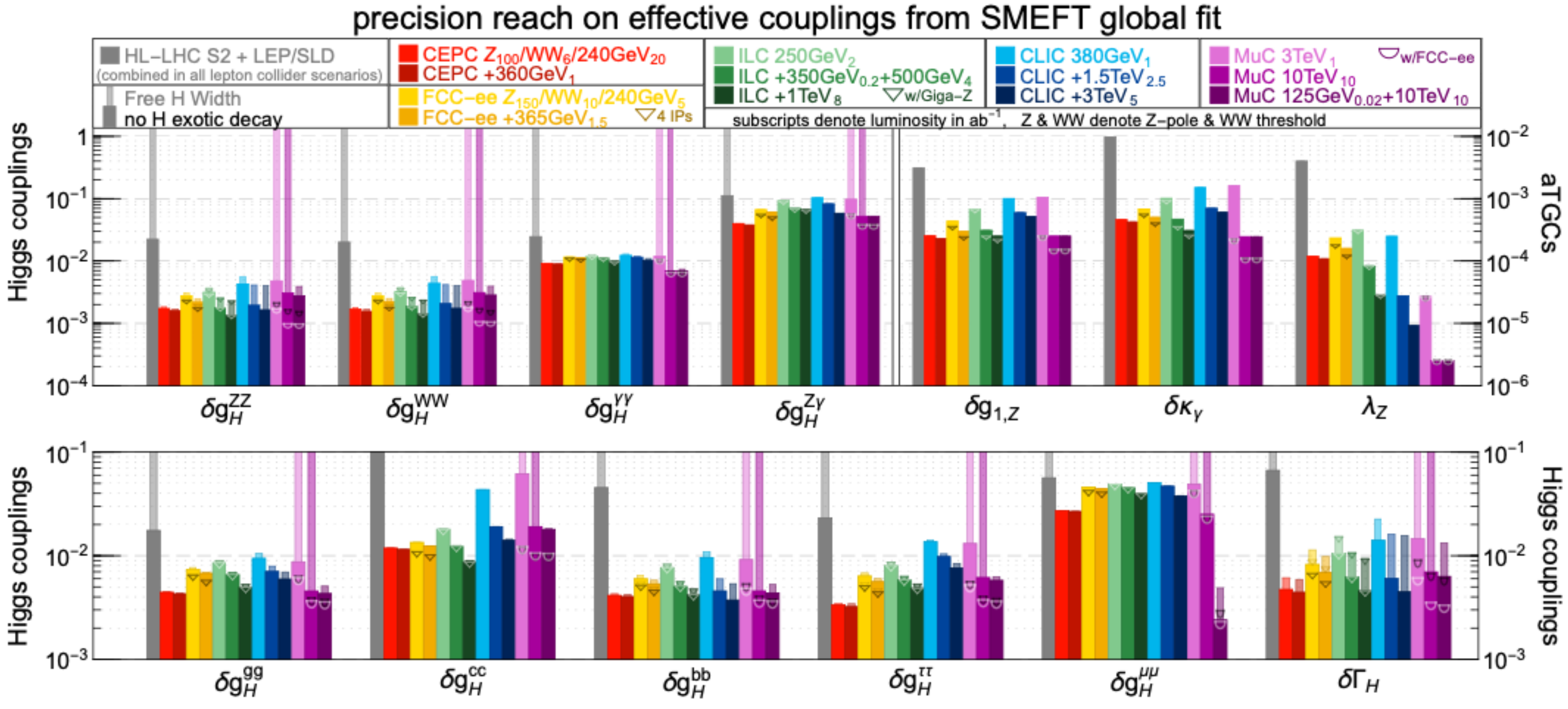


- Linear collider with beam polarisation is for many measurements competitive with circular colliders despite 1000 times less luminosity on Z pole
- Precise measurement of $\sin^2\theta^{\ell}_{\mathrm{eff}}$.
  - Around 13 times better than LEP/SLD and a factor three better than current world average
- Clearly, with O(1000) times less luminosity ILC could carry out only a limited Heavy Flavor programme compared with FCCee
  - … although potential worth another look

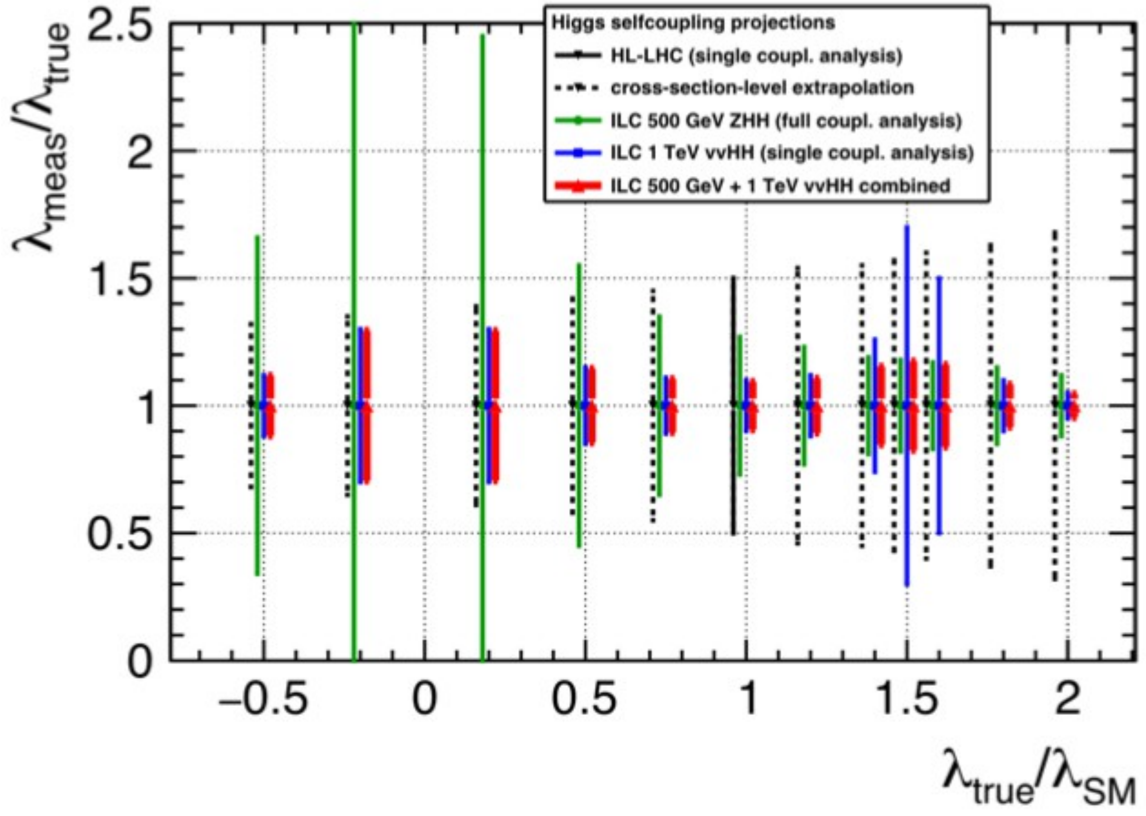
Higgs production at e+e- colliders

Arxiv: 2206.08326

Higgs interactions



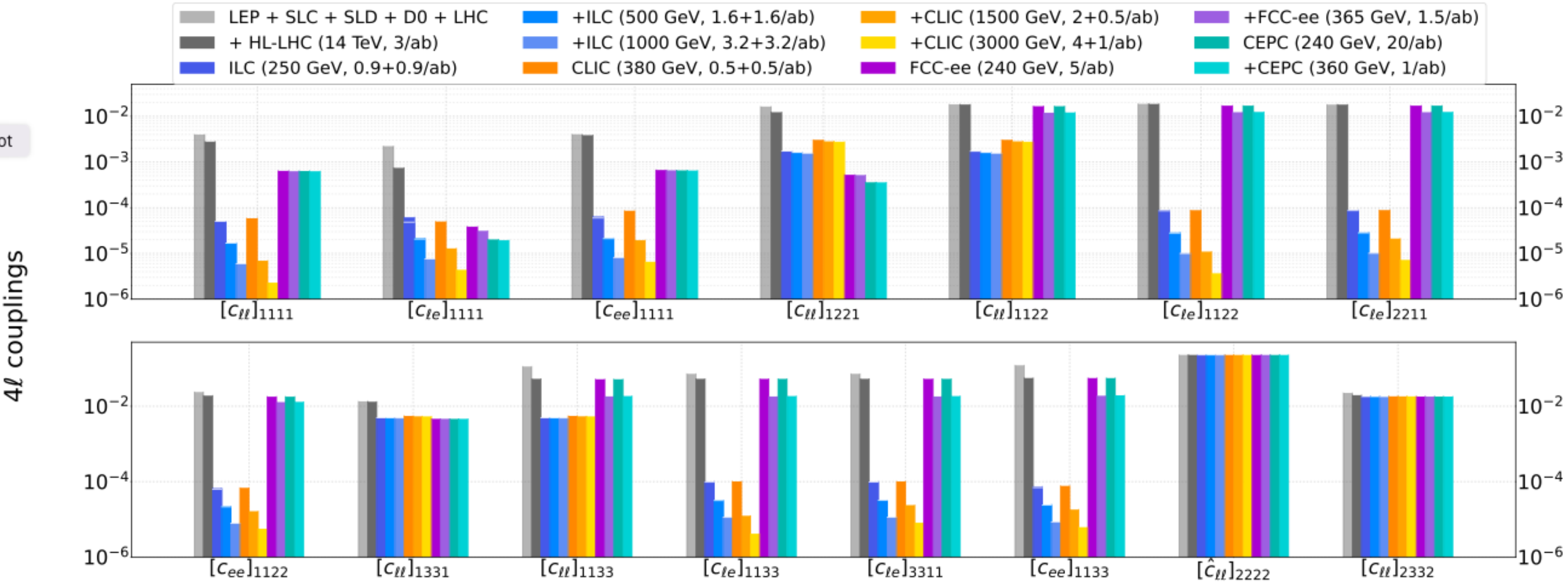
Higgs self-coupling measurement



- All planned e+e- machines will deliver O(1%) precision on Higgs couplings
  - Beam polarisation at LC catches up for smaller luminosity
- Higher energies increase the precision and allow for measuring the Higgs self-coupling

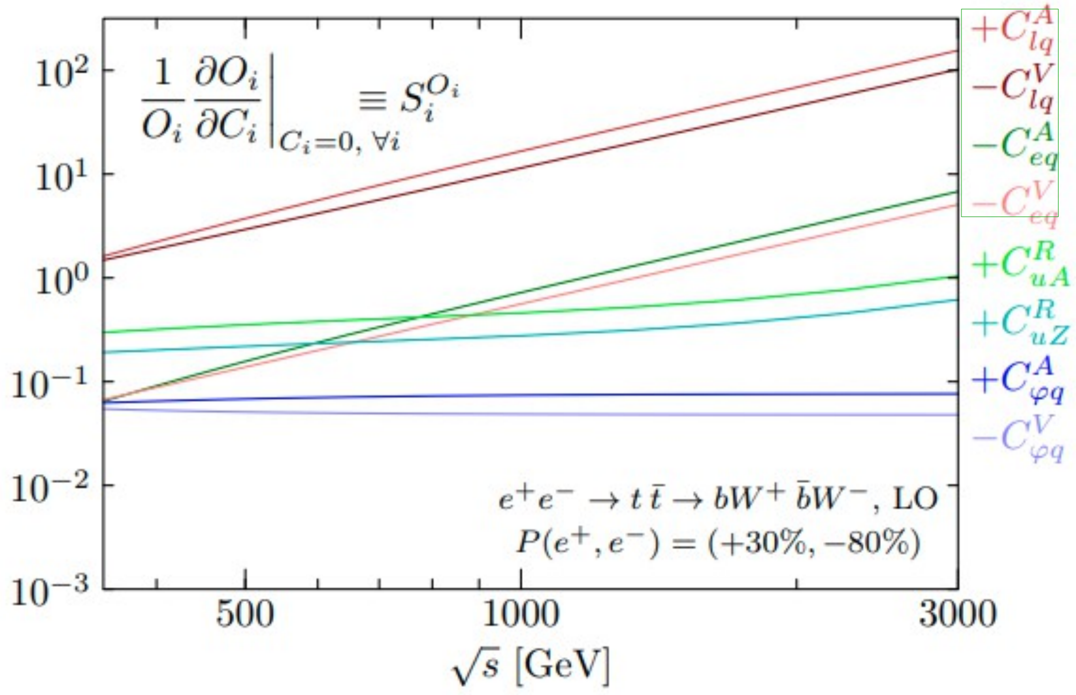
Two fermion processes

4-fermion operators in EFT (arxiv:2209.08078)



Development of EFT Operators

arxiv:1807.02121



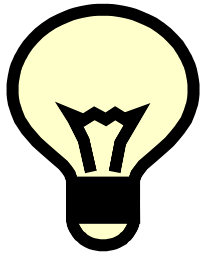
2f processes bear discovery potential

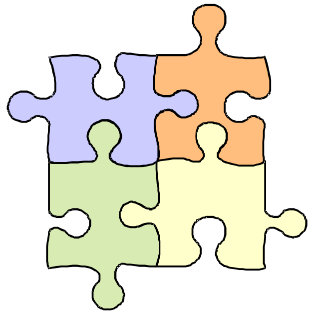
Will benefit from polarisation <u>and</u> higher energies

Already ILC250 outperforms FCCee!!!

Increased sensitivity to operators representing four-fermion interactions

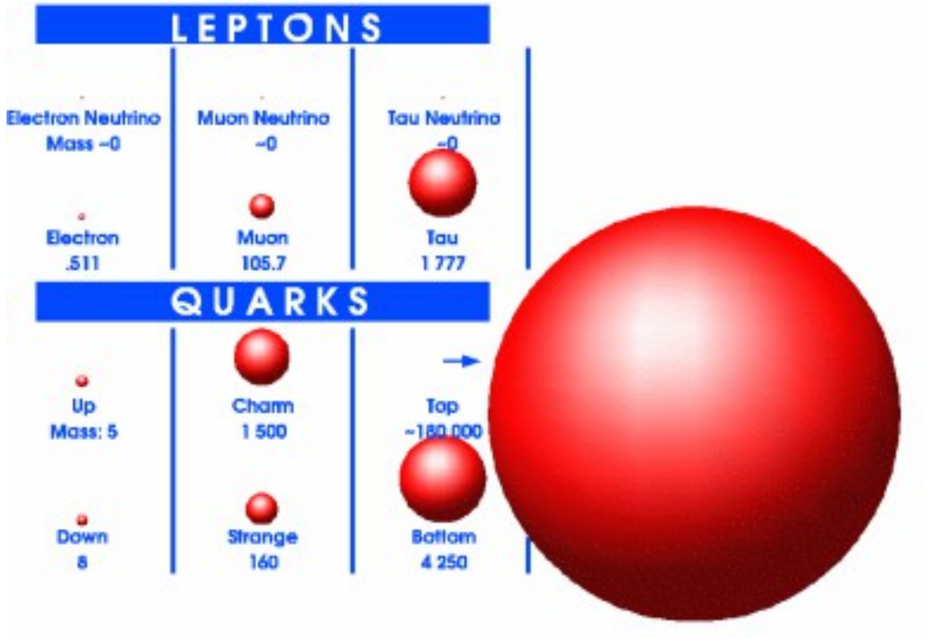
Top Yukawa Coupling

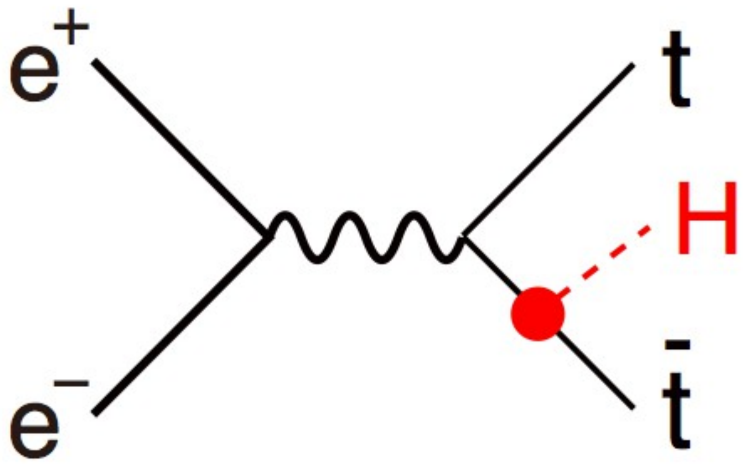




Elementary Scalar?

Composite object?





Estimation on δyt/yt in 2203.07622 for ilc

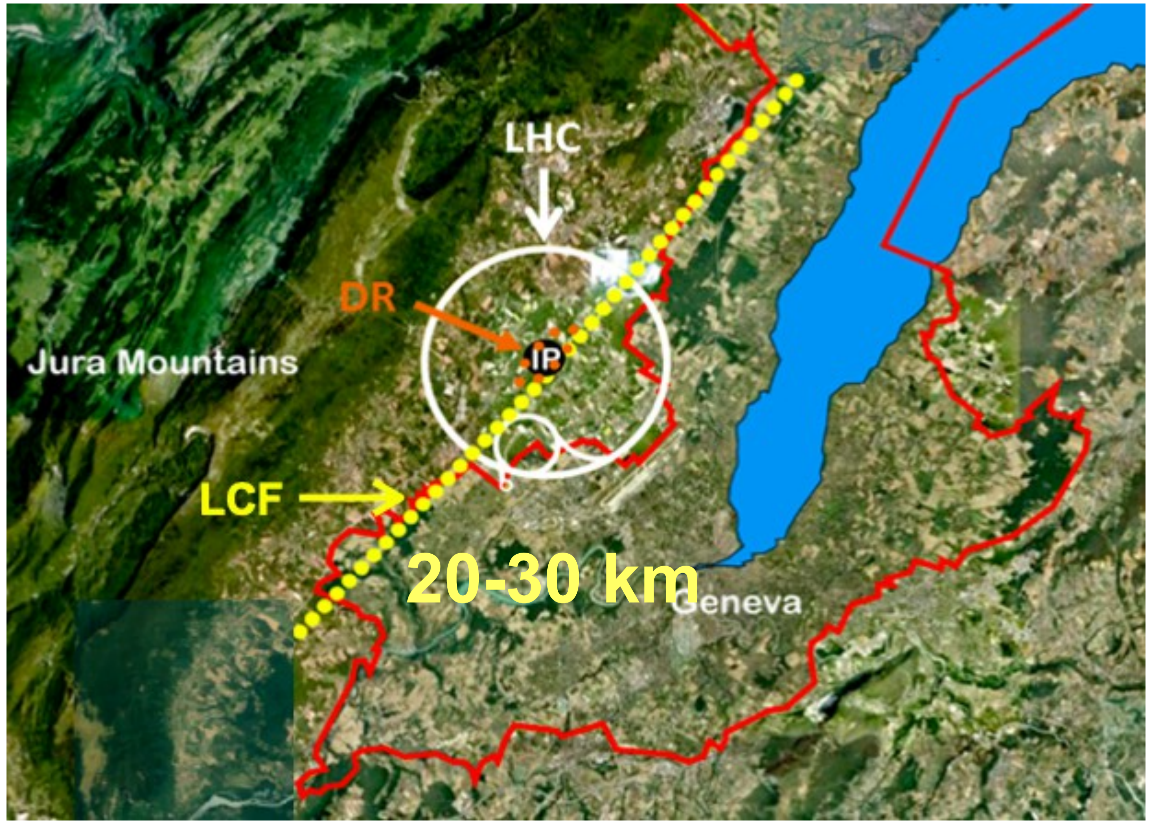
√s[GeV]	550	1000
L[ab-1]	4	8
δyt/yt[%]	2.8	1.0

- Higgs and top quark are intimately coupled! Top Yukawa coupling y_t O(1) !
- Linear collider perfectly suited to study their interaction

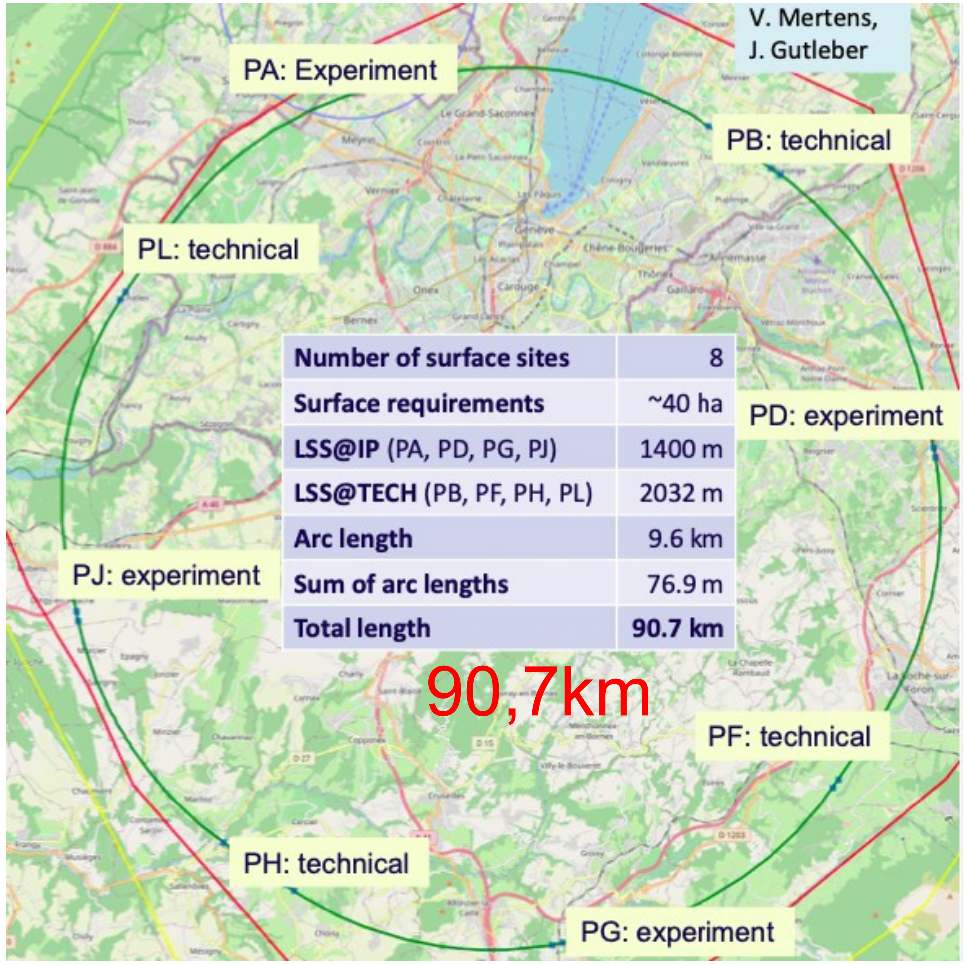
Similar prospects exist for CLIC

(I)LC or FCCee as next CERN Project?

Linear Collider Facility at CERN



FCCee at CERN



Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

- Length (ILC250) << Length (FCCee)
- Cost and environmental footprint?

Cost ILC* compared with FCCee

ILC

- TDR: **ILC500** costed at **7.6 BILCU*** for European site
  - ILCU = $US in 2012
  - Price tag is in Purchasing Power Parity PPP!
  - Inflation ~35% since 2012
- 2017 staging report*: **ILC250** around **5.2 BILCU**
- Labour estimate:
  - 22.6 Mh for ILC500 and 18.5 Mh for ILC250
- ILC cost does not include cost preceding the ground breaking
  - All would benefit from CLIC work and existing infrastructure at CERN
- ILC assumes one interaction region with push-pull
  - May want to add 2nd interaction region instead

FCCee

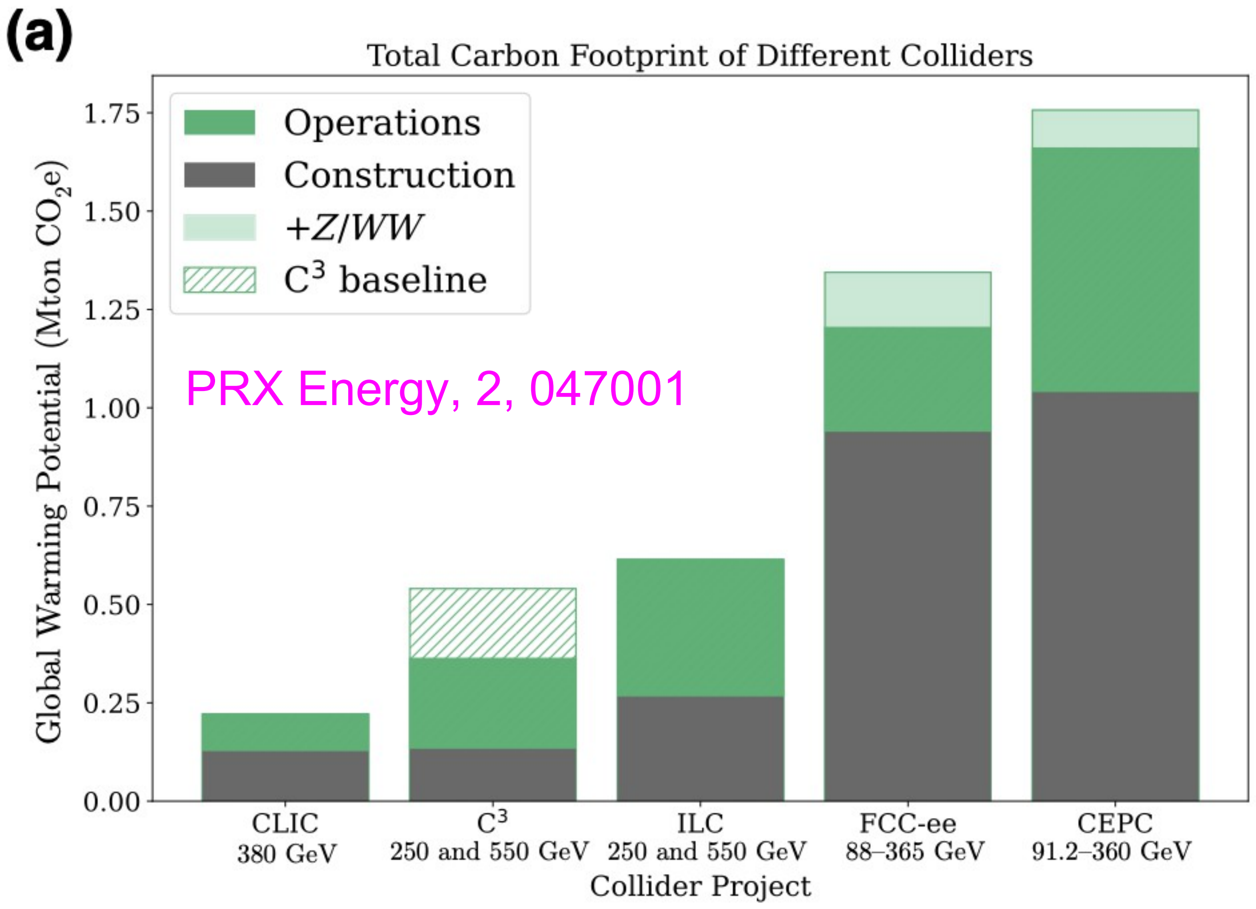
Midterm Review Public V2, May 24

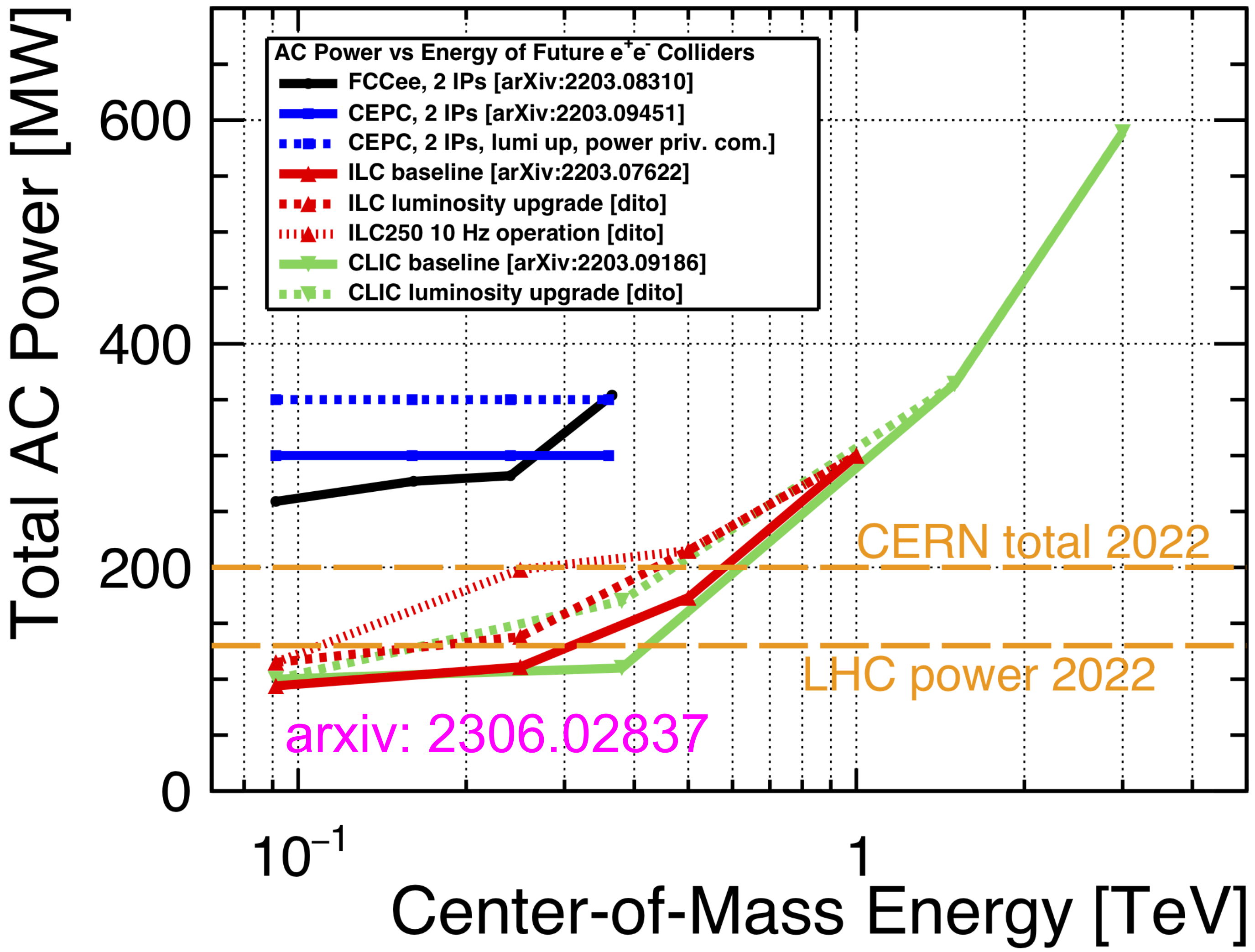
- Total Price tag: **12.8 BCHF**
  - 2 experiments w/o top
  - Add 2.2 BCHF for 4 exp. and top
- Includes accelerators, injection and Transfer lines, civil engineering, technical infrastructure, Experiments (CERN Contribution) and territorial development
  - The latter two account for ~450 MCHF

It is safe to suppose that the cost of ILC250 is considerably smaller than that of FCCee

*Arxiv:1711.00568

Higgs Factories – Carbon Footprint, Power Consumption and Running Cost





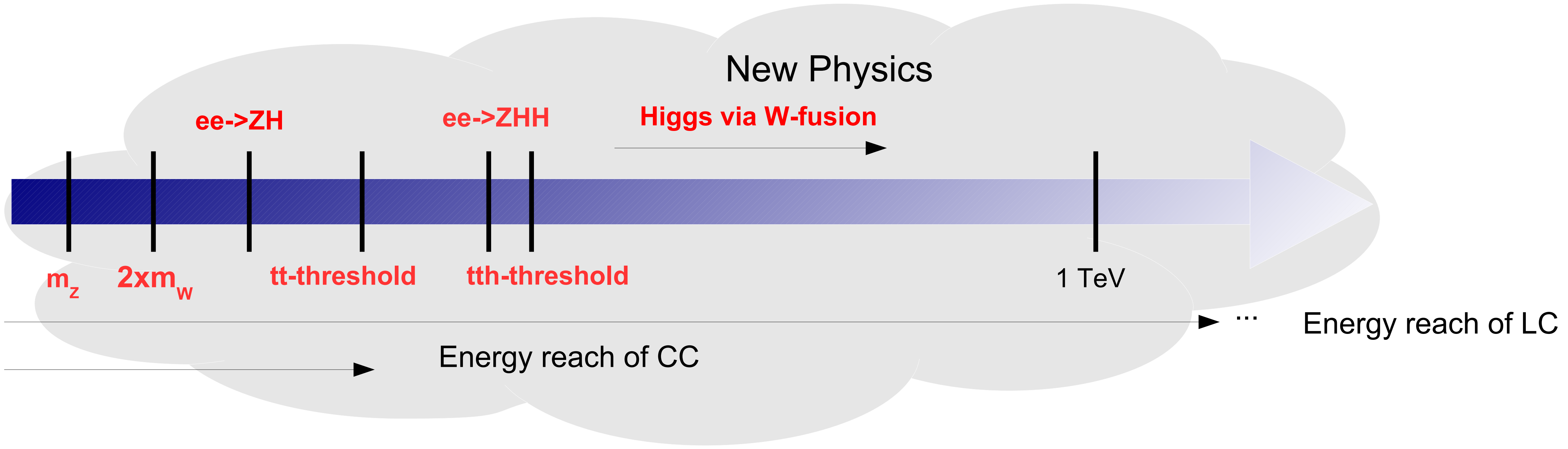
- Carbon footprint of all LC projects << Carbon footprint of circular machines
- Until ~500 GeV power consumption remains in ball park of current CERN power consumption
- Estimated operation cost for ILC ~390 MILC (plus 700-1000 FTE)
  - Compare with 1.3 BCHF for FCCee as estimated by German BMBF

Summary and Conclusions

- Input by ILC250 to understanding of electroweak symmetry breaking (at least) equal to FCCee
  - ILC250 adds strong input for 500 GeV and above
  - A circular machine may deliver complementary input
- Cost an environmental footprint for (I)LC smaller than for FCCee
  - IDT task force is working on an updated costing for ILC (250-350-550), with a review envisaged for December 2024, public in January 2025
- (I)LC can be built within the CERN budget
  - … and would not preclude the development of advanced accelerator facilities
  - … and would allow CERN to maintain a divers and rich physics programme

Backup

e+e- Physics program

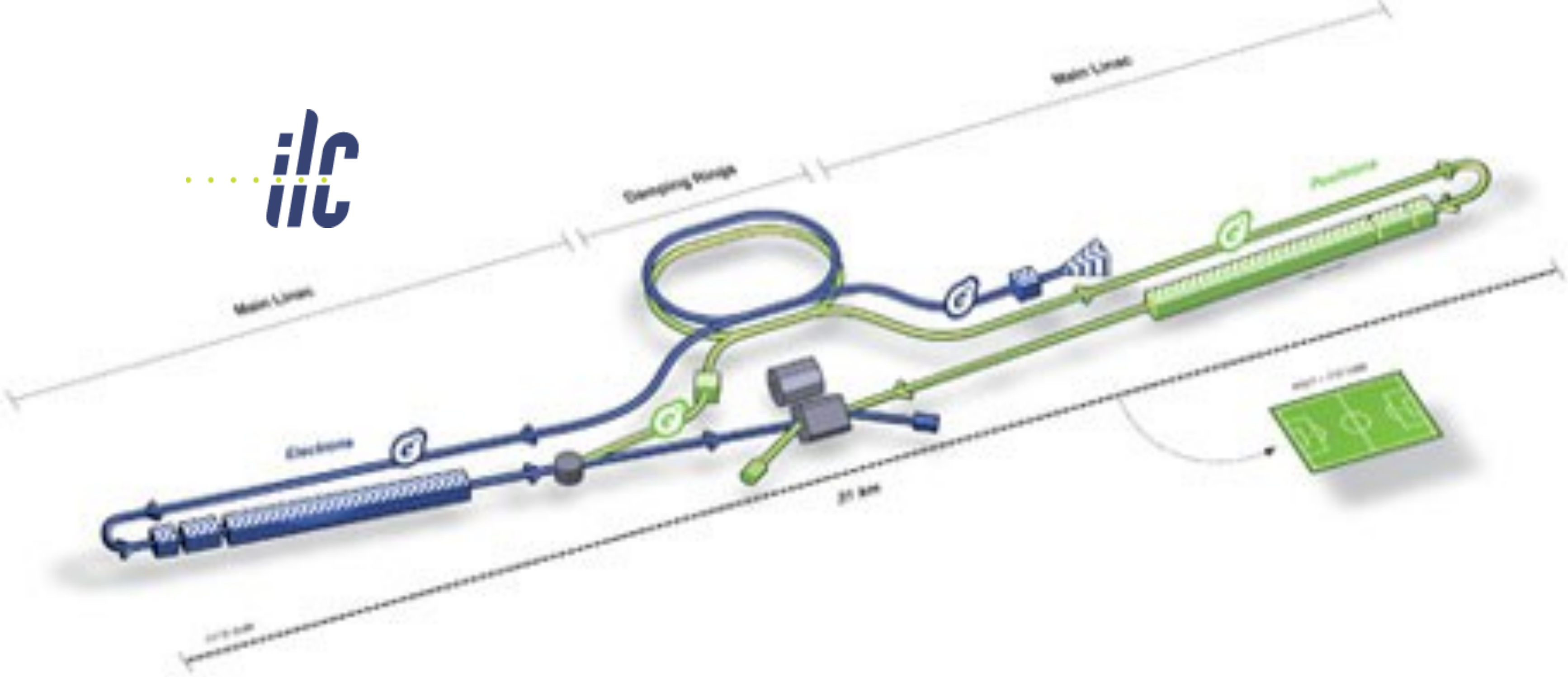


- All Standard Model particles within reach of planned e+e- linear colliders
- High precision tests of Standard Model over wide range to detect onset of New Physics
- Machine settings can be "tailored" for specific processes
  - Centre-of-Mass energy
  - Beam polarisation (straightforward at linear colliders)

$$\sigma_{P,P'} = \frac{1}{4}\left[(1 - PP')(\sigma_{LR} + \sigma_{RL}) + (P - P')(\sigma_{RL} - \sigma_{LR})\right]$$

- **Background free** searches for BSM through beam polarisation

Linear Electron Positron Colliders - ILC



Under discussion in Japanese Gouvernment and international community

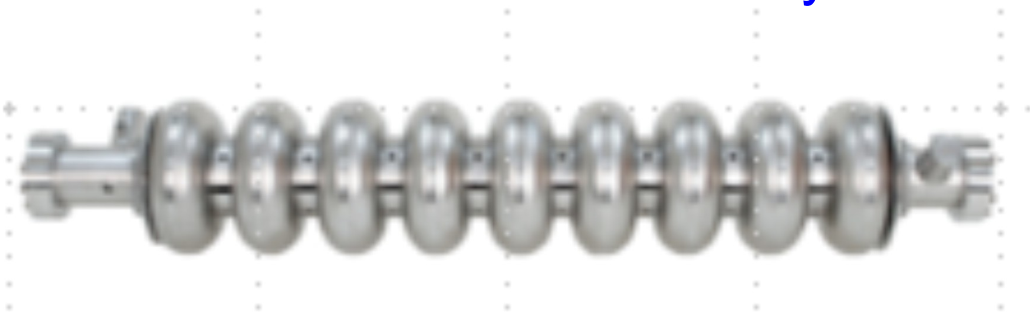
Energy: 0.1 - 1 TeV
Electron (and positron) polarisation
TDR in 2013
+ DBD for detectors
Footprint 31 km

Initial Energy 250 GeV – Footprint ~20km

ILC design parameters	
$\sqrt{s}$	91-500 GeV
$\mathcal{L}$	2×10^{34} cm^{-2}s^{-1}
P_{e^-}	>80%
P_{e^+}	upto 30%
Length	~31 km

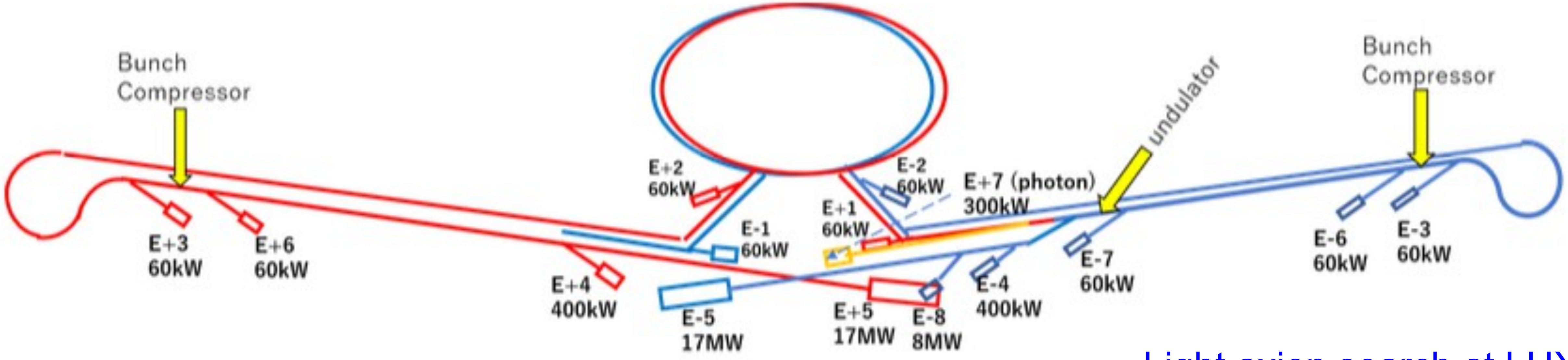
Design Gradient: 31,5 MV/m

ILC Nine-Cell SRF Cavity

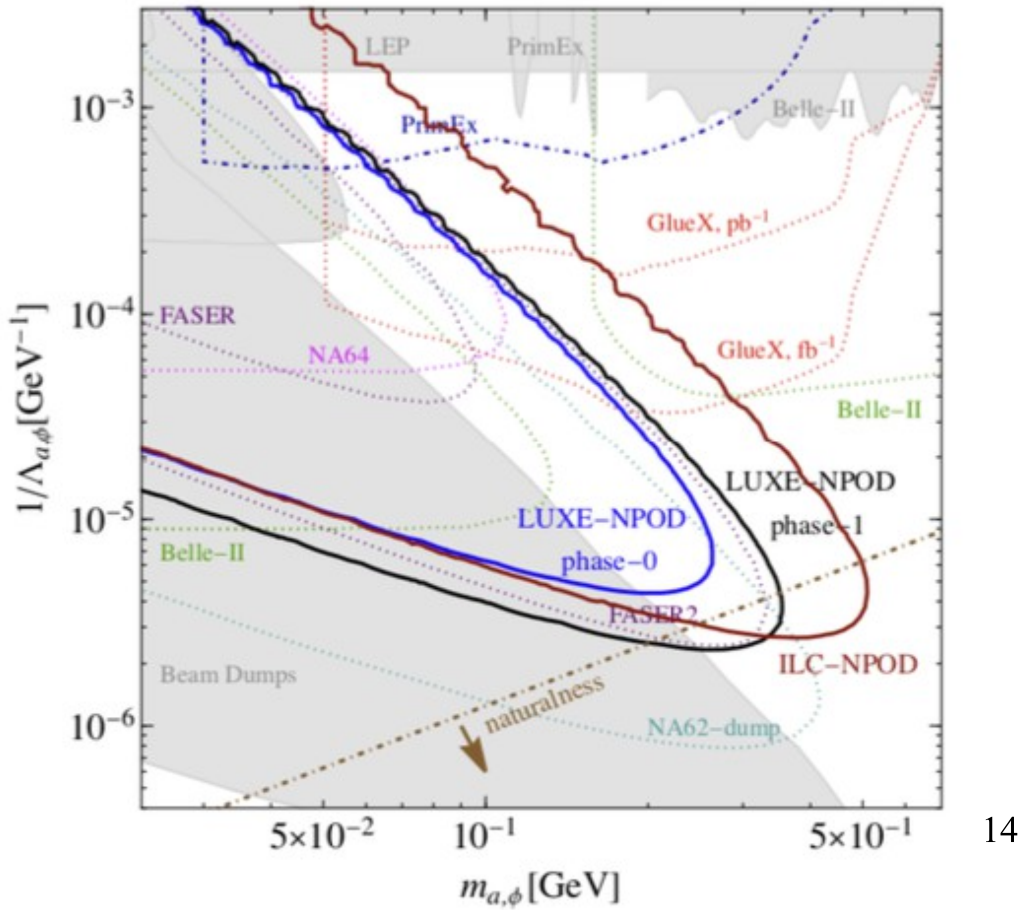


- Since 2020 ILC Development is organised within International Development Team
https://linearcollider.org/team/

ILC – More than a collider



Light axion search at LUXE and ILC



- The colliding beam experiments can be complemented with a series of fixed targat experiments
  - Enabling nuclear, hadron physics experiments and resources for accelerator development
  - Material science?
- Details see 2203.07622

How to make progress?

1) Collisions at energies well above the electroweak scale
   - Requires now and in the foreseeable future Hadron colliders
   - Direct production of new particles
   - Produce large number of rare particles and study rare decays
   - First precision measurements of key particles of electroweak theory

-> High energy, High luminosity LHC

2) e+e-Collisions at energies at the electroweak scale and above
   - Probe the electroweak scale with high precision
   - ... in particular particles that carry the “imprint of the Higgs Field such as W, Z and top”

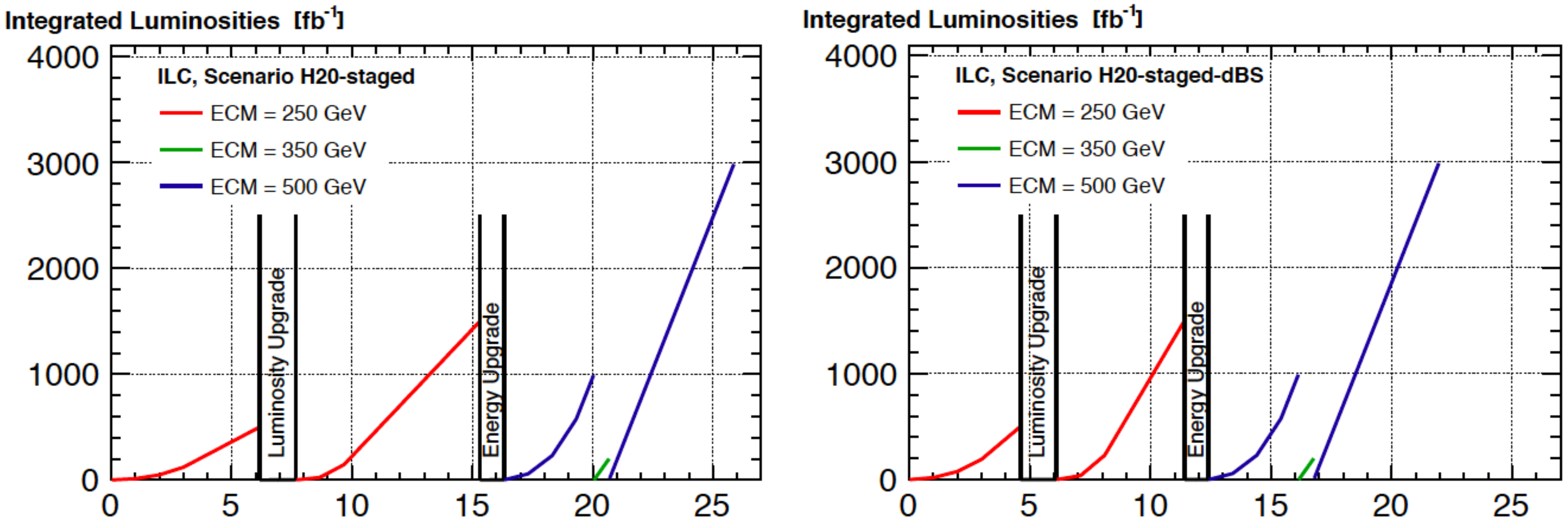
-> LC

3) e+e- collisions at 'smaller' energies
   - Requires high luminosity to get sensitive to tiny quantum effects

-> SuperKEKB

ILC Running Scenarios

arXiv:1506.07830



In 2019 – Revision of capabilities to run on the Z Pole - GigaZ

	$\mathrm{sgn}(P(e^-), P(e^+)) =$				
	(-,+)	(+,-)	(-,-)	(+,+)	sum
luminosity [fb^{-1}]	40	40	10	10	
$\sigma(P_{e^-}, P_{e^+})$ [nb]	83.5	63.7	50.0	40.6	
Z events [10^9]	2.4	1.8	0.36	0.29	4.9
hadronic Z events [10^9]	1.7	1.3	0.25	0.21	3.4

- Pole running can happen before and after the luminosity upgrade
- Further details see arxiv: 2203.07622

New physics?

EFT: Two distinct observations

Observables at fixed mass m
(e.g. Z pole of Higgs decays)

$$\frac{\sigma}{\sigma_{SM}} \approx |1 + \frac{c_6 m^2}{\Lambda^2}|^2$$

Increasing UV scales probed in EFT achieved solely by increasing the measurement precision

$c_6 \sim (g^*)^2$

Typical experimental precision 0.1-1%

High energy tails of distributions
(e.g. Drell-Yan Productions

$$\frac{\sigma}{\sigma_{SM}} \approx |1 + \frac{c_6 E^2}{\Lambda^2}|^2$$

Increasing UV scales probed in EFT achieved solely by increasing the energy scale of measurement precision

Typical experimental precision 10%

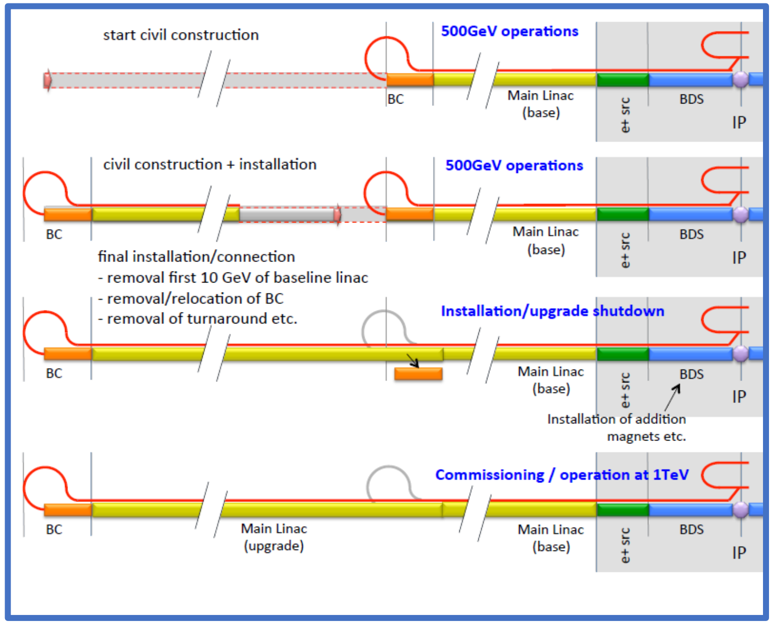
A. Falkowski, Journée Grands Accél., LAL

Topic 3: SCRF / ILC-like realization of full physics program 91-1000 GeV (S. Michizono)

ILC Baseline and the Upgrades

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	E / $\mathcal{L}$ Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	80(20)
Repetition frequency	f_{rep}	Hz	5	5	3.7	5	10	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312/2625	1312/2625	2625	2450
Bunch population	N_e	10^{10}	2	2	2	2	2	1.74
Linac bunch interval	Δt_b	ns	554	366	554/366	554/366	366	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	5.8/8.8	5.8/8.8	8.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727/961	727/961	961	897
Accelerating gradient	G	MV/m	31.5	31.5	31.5	31.5	31.5	45
Average beam power	P_{ave}	MW	5.3	10.5	1.42/2.84*)	10.5/21	21	27.2
RMS bunch length	σ_z^*	mm	0.3	0.3	0.41	0.3	0.3	0.225
Norm. hor. emitt. at IP	$\gamma\epsilon_x$	μm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	nm	35	35	35	35	35	30
RMS hor. beam size at IP	σ_x^*	nm	516	516	1120	474	516	335
RMS vert. beam size at IP	σ_y^*	nm	7.7	7.7	14.6	5.9	7.7	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	99 %	58.3 %	73 %	44.5 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %	0.16 %	4.5 %	2.6 %	10.5 %
Site AC power *	P_{site}	MW	111	138	94/115	173/215	198	300
Site length	L_{site}	km	20.5	20.5	20.5	31	31	40

Energy upgrades:
- 500GeV (**31.5 MV/m Q_0=1** x 10^{10})
  - 1TeV (**45 MV/m Q_0=2** x 10^{10}, 300 MW)
  - more SCRF, tunnel extension

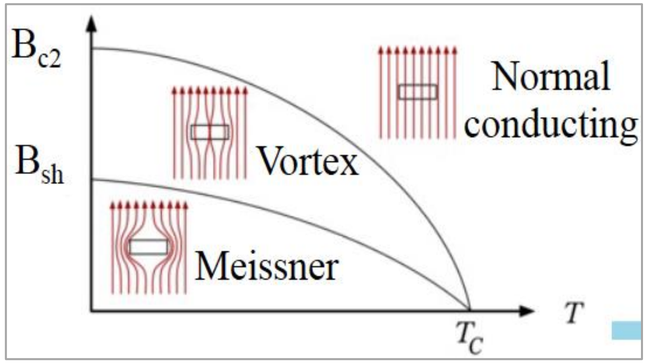


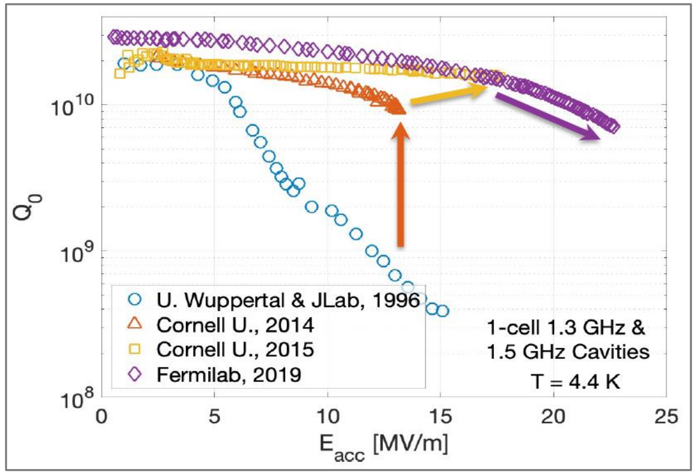
Further energy upgrades can be realized by
- Nb_3Sn cavity (>80MV/m)
- Nb Traveling Wave (TW) structures (>70MV/m)

Nb_3Sn / multilayer cavity for the future upgrade

Nb_3Sn

Courtesy, S. Posen





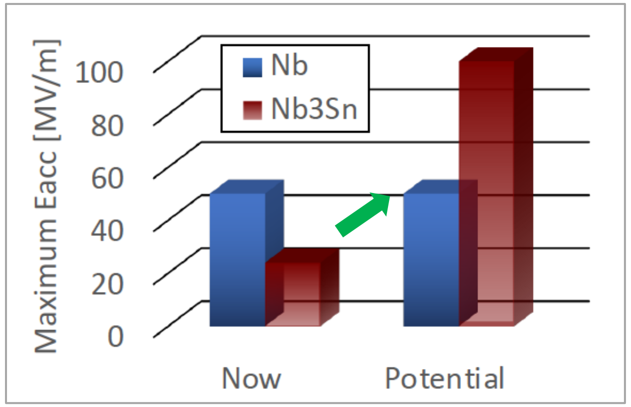
Nb_3Sn Potential in high-G future

SRF cavity

- B_{sh} = practical limit for SRF
  - $Bs_{sh\text{-}Nb}$: 210 mT
  - $Bs_{sh\text{-}Nb3Sn}$: 430mT

x2

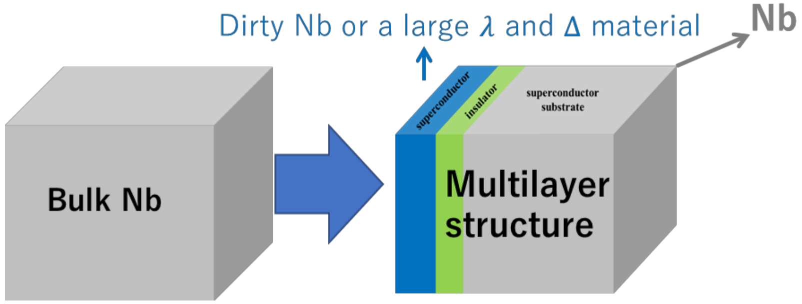
>80 MV/m in future

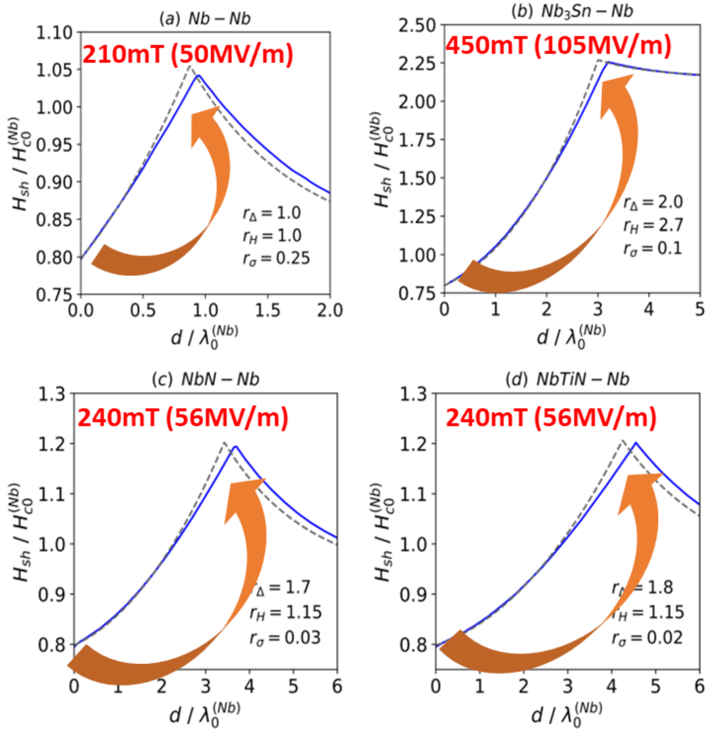


Nb_3Sn progress at Fermilab.

S. Posen et al., SUST, 34, 02507 (2021)

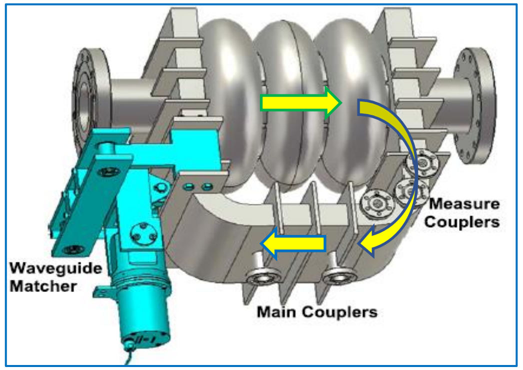
multilayer



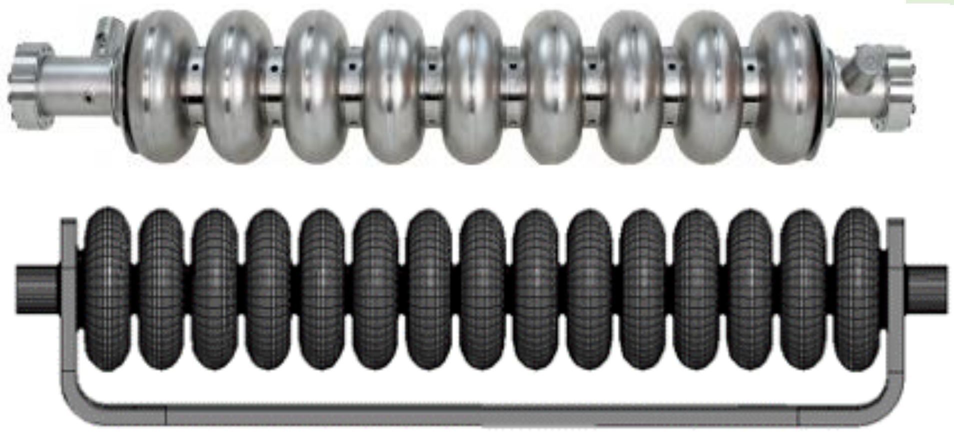


A new concept for SRF proposed for ILC-3TeV and Helen: Traveling Wave (TW) SRF cavity, compared with Standing Wave

Courtesy: H. Padamsee et al., for ILC-3TeV
S. Belomestnykh et al., for HELEN



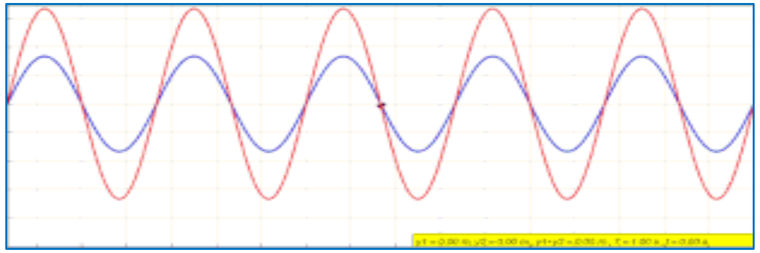
Prototype TW structure under test



SW: TESLA cavity (ILC baseline)

TW: proposed for ILC-3TeV, Helen

>70 MV/m operation



← Red standing wave – High Peak Fields,

← Green (acc.) and Blue (Return) Waves are Travelling Waves Lower peak fields,

← **Guide blue** wave in a return wave-guide to avoid SW peak fields

– attached to both ends

HELEN: A LINEAR COLLIDER BASED ON ADVANCED SRF TECHNOLOGY*

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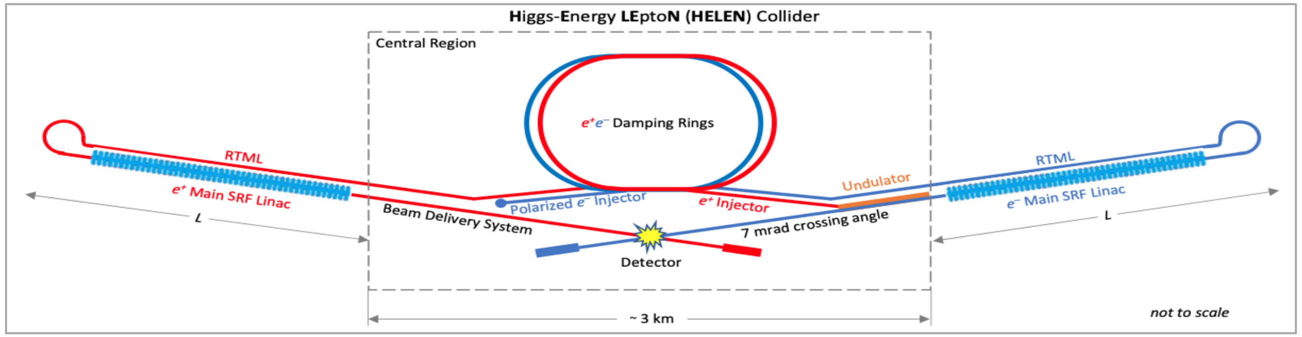
https://doi.org/10.48550/arXiv.2209.01074



Summary of future upgrade using SRF

	ECM [GeV]	Gradient [MV/m]	Length [km]	#of cavities	AC power [MW] [*5]	Additional material cost [MILCU[*1]]	Technology ready
TDR	250	31.5	20.5	~8,000	~110	(~5,000 MILCU)	---
TDR	500	31.5	33.5	~16,000	~170	+3,000 MILCU	---
TDR	1,000	45	44.5	~23,000	~300	+3,000+7,100 MILCU	In 10 years
Nb3Sn/multilayer or TW	500	63	20.5	~8,000[*2]	~180[*6]	?	In 20 years
NB3Sn/multilayer & TW	1,000	126[*3]	20.5	~8,000[*4]	~260[*7]	?	In >20 years

[*1] based on the ILC TDR and referring the ILC unit as of 2012.
[*2] Requires RF source upgrade (x2) + Cryogenic upgrade (~x2)
[*3] Surface discharge etc. can happen at such a high gradient operation
[*4] Requires RF source upgrade (x4) + Cryogenic upgrade (~x4)

[*5] further reduction will be done by higher efficiency of cryogenics and RF (65%->80%?), etc.
[*6] Q0=3e10, 4.5K operation (1/3.5 cryo-power)
[*7] Q0=3e10, 4.5K operation (1/3.5 cryo-power) and 1ms filling for TW

		500 GeV	TeV Upgrade			
		Baseline	Scenario A	Scenario B		Scenario C
				upgrade	base	
Energy range	GeV	15–250	15–500	15–275	275–500	15–500
Gradient	MV/m	31.5	31.5	45	31.5	45
Num. of cavities		7400	15 280	8190	7090	10 700
				total cavities: 15280		
Linac length	km	12	25	9.5	11.5	17.5
				total length: 21.0		

15.12.2.2 Summary of Value and Labour changes

The total Value changes associated with scenario A, B and C are 6,706, 5,489 and 7,082 MILCU, respectively. These increases correspond to 81%, 66%, and 86%, respectively, of the 500 GeV Value estimate for the baseline with luminosity upgrade. The total Labour changes associated with scenario A, B and C are 11,988, 9,416 and 14,256 thousand person-hrs, respectively. These increases correspond to 50%, 42%, and 59%, respectively, of the 500 GeV baseline Labour estimate with luminosity upgrade.

[19] This is not quite correct, since some of the baseline RTML Value and Labour is associated with the beamlines from the damping rings to the long 5 GeV transfer line. The RTML contribution to the 1 TeV upgrade is thus slightly overestimated.

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Topic 4: CLIC/C3 realization of full physics program as upgrade of ILC250 (S.Stapnes)

CLIC or C3 technologies in a 250 GeV ILC tunnel

Point to consider (not exhaustive):

- Typical parameters for both, with increased gradient significant energy increases can be made in the 20.5 km available.
- Different beam structures wrt to ILC imply that most of the equipment need to be replaced including (most of) injectors/DRs.
- Crossing angle and laser straightness to be checked.
- For CLIC adding drivebeam and turn-arounds. The latter is messy.
- For C3 use of LN2 will probably require a full change of the cryosystem but compatibility should be checked (e.g. installation infrastructure as pipes and equipment caverns) ?
- Beamdump specs – 18 MW in ILC TDR 1 for TeV: https://agenda.linearcollider.org/event/7889/contributions/42535/attachments/33900/52047/LCWS2018-ilcmaindump-upload.pdf

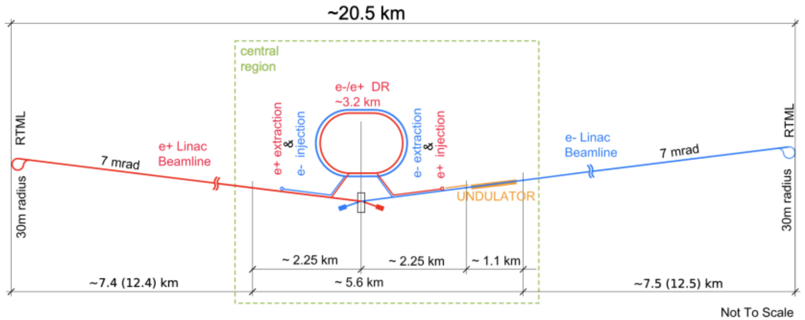
- Cost and power – some limited comments
- Can the ILC SRF modules be re-used ?

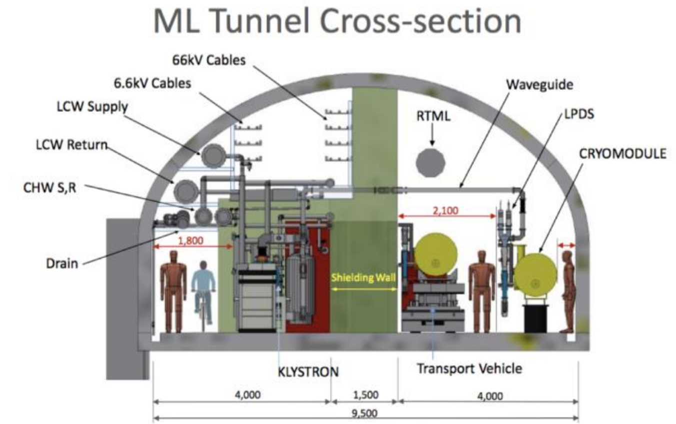
- If this change is done after ILC 550 GeV a ~30km tunnel is available

ILC parameters

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	80(20)
Repetition frequency	f_{rep}	Hz	5	5	3.7	5	10	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312/2625	1312/2625	2625	2450
Bunch population	N_{e}	10^{10}	2	2	2	2	2	1.74
Linac bunch interval	Δt_{b}	ns	554	366	554/366	554/366	366	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	5.8/8.8	5.8/8.8	8.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727/961	727/961	961	897
Average beam power	P_{ave}	MW	5.3	10.5	1.42/2.84*)	10.5/21	21	27.2
RMS bunch length	σ^*_{z}	mm	0.3	0.3	0.41	0.3	0.3	0.225
Norm. hor. emitt. at IP	$\gamma\epsilon_{\text{x}}$	μm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_{\text{y}}$	nm	35	35	35	35	35	30
RMS hor. beam size at IP	σ^*_{x}	nm	516	516	1120	474	516	335
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7	14.6	5.9	7.7	2.7
Luminosity in top 1 %	$\mathcal{L}_{0.01}/\mathcal{L}$		73 %	73 %	99 %	58.3 %	73 %	44.5 %
Beamstrahlung energy loss	δ_{BS}		2.6 %	2.6 %	0.16 %	4.5 %	2.6 %	10.5 %
Site AC power	P_{site}	MW	111	138	94/115	173/215	198	300
Site length	L_{site}	km	20.5	20.5	20.5	31	31	40

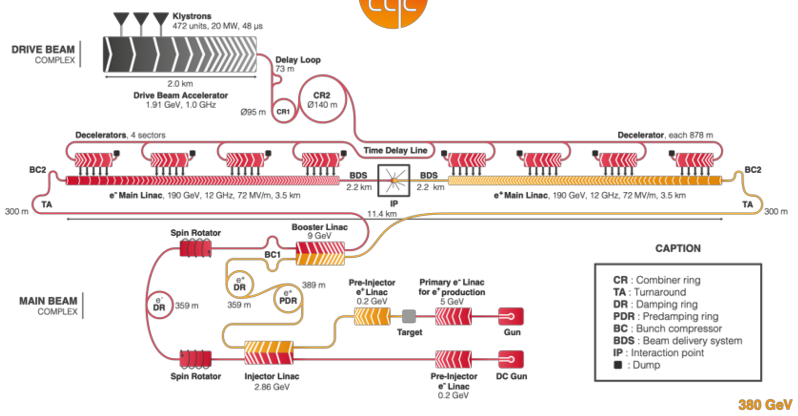
Table 4.1: Summary table of the ILC accelerator parameters in the initial 250 GeV staged configuration and possible upgrades. A 500 GeV machine could also be operated at 250 GeV with 10 Hz repetition rate, bringing the maximum luminosity to $5.4 \cdot 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$ [26]. *): For operation at the Z-pole additional beam power of 1.94/3.88 MW is necessary for positron production.





Not laser straight, crossing angle 14 mrad, DR’s large (3.2km), maybe not ”conventual” e+ system available as used in CLIC/C3, cryo (relevant for C3?)

CLIC to 3 TeV



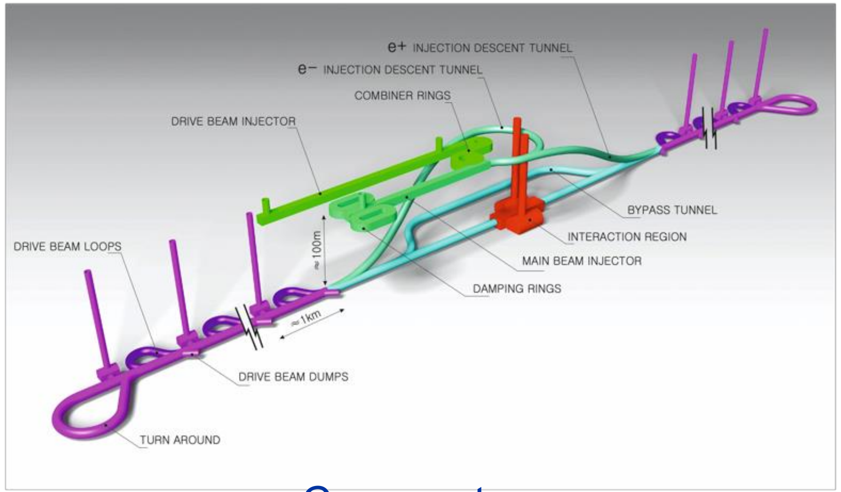
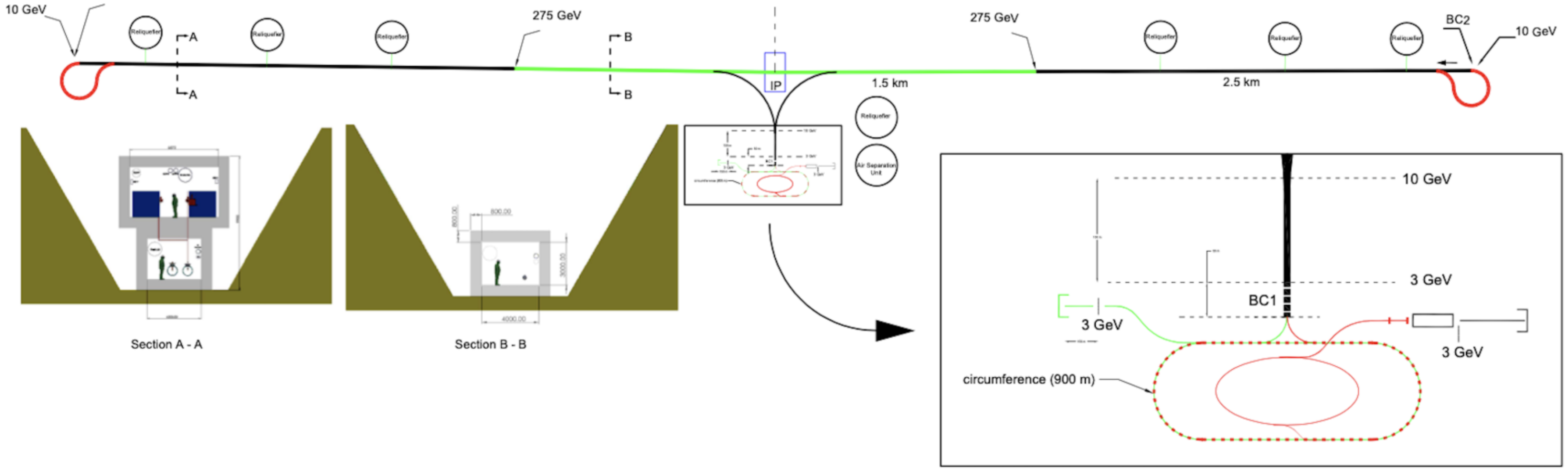


Table 1.1: Key parameters of the CLIC energy stages.

Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	1×10^{9}	5.2	3.7	3.7
Bunch length	μm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20

Comments:

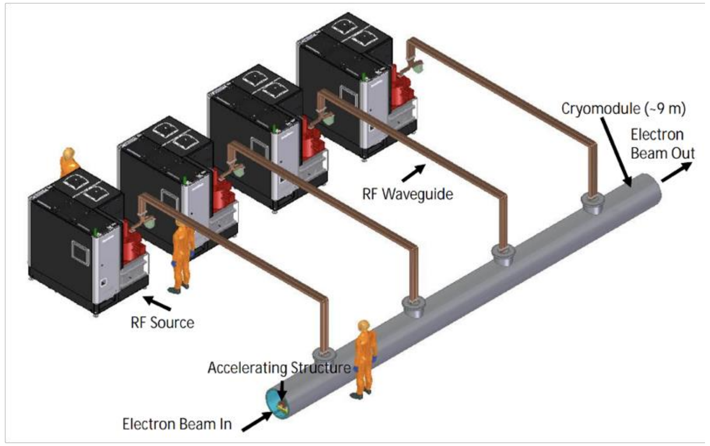
- CLIC damping rings are ~350m, might be possible to re-use ILC DRs (3.2km)
- Drivebeam complex is needed on surface
- Tunnel well suited but the drivebeam turn-arounds need to be added
- It is laser straight
- Around 1000 GeV can be reached in 20.5 km
- Power likely in 250 MW range



Comments:

- C3 damping rings are ~900m, might be possible to re-use ILC DRs
- Tunnel well suited
- More than 1500 GeV can be reached in 20.5 km (but 7500 klystrons?)
- Power likely in 350-450 MW range
- The two latter can be optimised ...

C^3 Main Linac Cryomodule
9 m (600 MeV/ 1 GeV)



Cryogenic temperature (LN_2 at 80k) elevates gradient performance, can parts of the ILC cryo-system be used ?

Table 1. Beam parameters for C^3.

CM Energy [GeV]	250	550
Luminosity [$\times 10^{34}$/cm^{2}s]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Strucutre Aperture [mm]	3.55	3.55
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~ 150	~ 175

home.cern

Personnel estimate, cost. power – Higgs factories

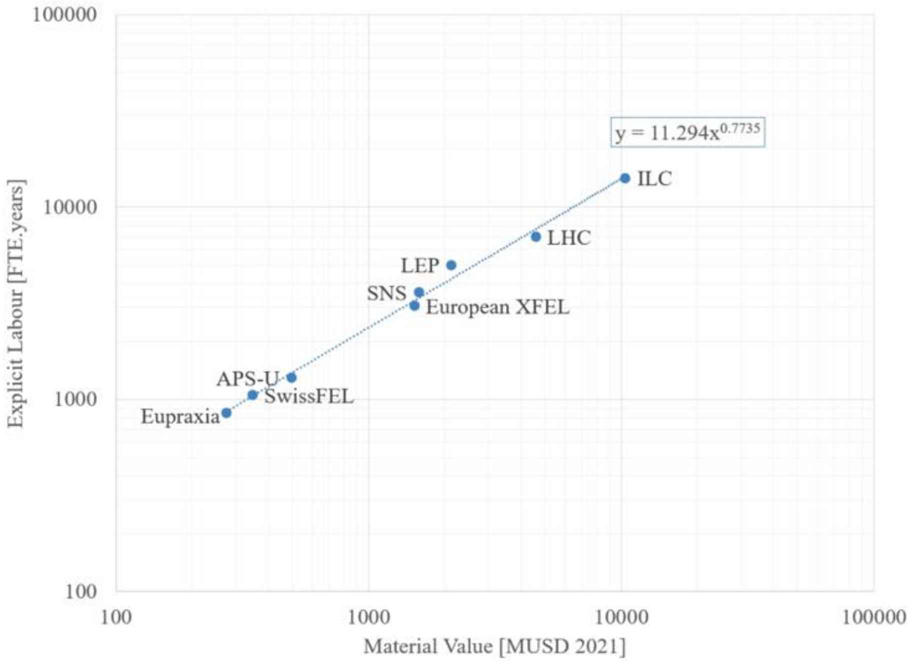


Figure 5: Explicit labor for several large accelerator projects vs. project value.

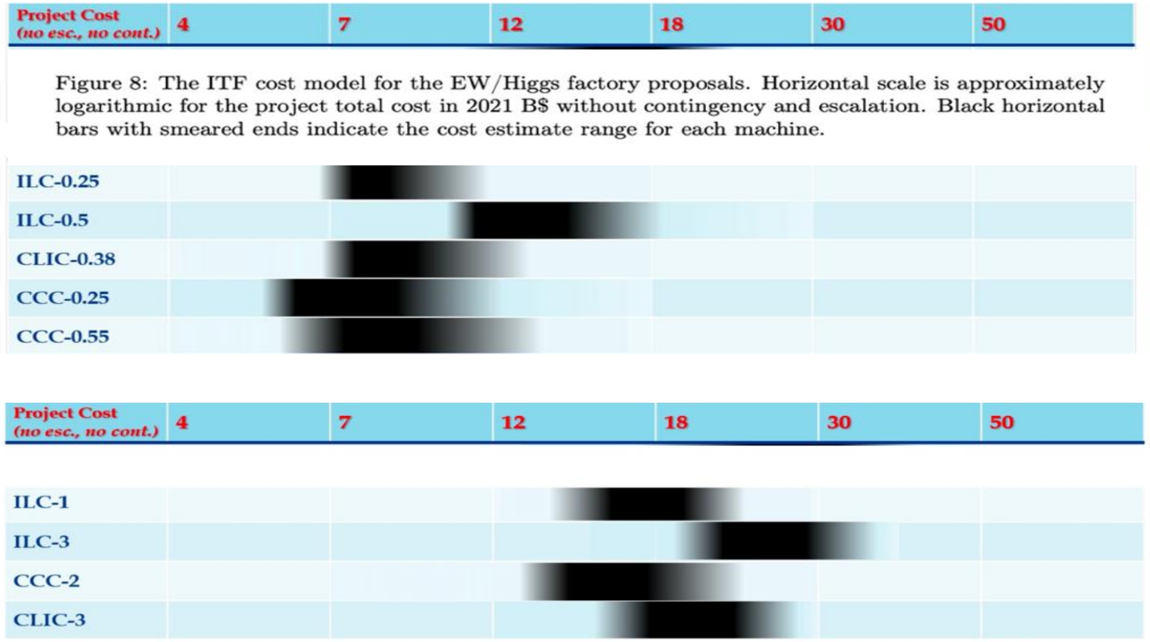
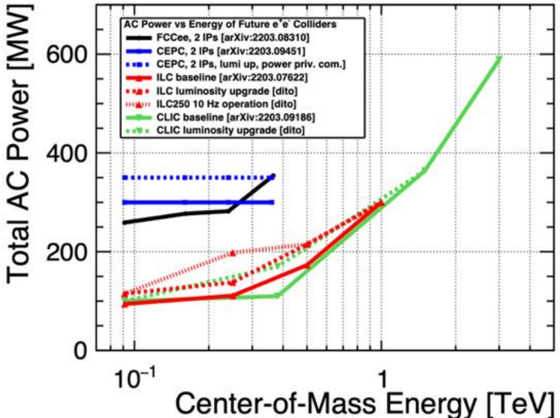


Figure 8: The ITF cost model for the EW/Higgs factory proposals. Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends indicate the cost estimate range for each machine.

This estimate from the Snowmass process includes personnel costs (usually kept separate, e.g. ILC and CLIC)

One FTEy estimated to 200kUS$

Detailed PBS/WBS based reviewed number exists for ILC and CLIC, but not yet consistently updated to 2023 including currency changes and inflation – nevertheless good agreement



Topic 5: RELIC upgrade of ILC250 and physics need for higher luminosity (V.Litvinenko)

RELIC upgrade of ILC250 and physics need for higher luminosity

Vladimir N Litvinenko
Stony Brook University

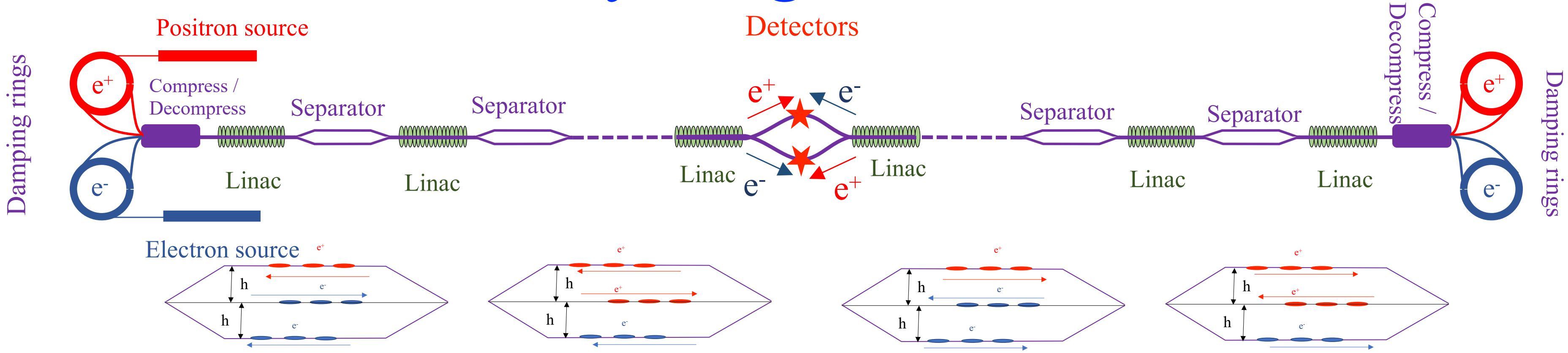
Global Vision for an LCF discussion session at LCWS

Stony Brook University

CASE
Center for Accelerator Science and Education

BROOKHAVEN
NATIONAL LABORATORY

ReLiC – Recycling Linear Collider



- Flat beams cooled in damping rings with “top off” to replace burned-off particles
- Bunches are ejected with collision frequency, determined by the distance between beam separators
- Beams are accelerated **on-axis** in SRF linacs collide in one of detectors
- After collision at the top energy, they are decelerated in the opposite linacs
- Bunch trains are periodically separated from opposite beam, with accelerating beam propagating **on-axis**
- Decelerated beams are injected into cooling rings
- After few damping times the trip repeats in the opposite direction and beams collide in a detector located in the opposite branch of the final separator …..

$$F_x = \pm e\left(E_x + \frac{v_z}{c}B_y\right) = \begin{cases} 0, acclerating \\ 2eE_x, decelerating\ postions \\ -2eE_x, decelerating\ electrons \end{cases}$$

ReLiC collider recycles polarized electrons and positrons

- Reusing electron and positron beams beam cooled in damping rings provides for natural polarization of both beam via Sokolov-Ternov process. Depolarization in the trip between damping ring is minuscular, which would provide for high degree of polarization. With lifetime ~ 10 hours, necessary replacement of electrons and positrons is at 1 nA level – this is major advantage of ReLiC

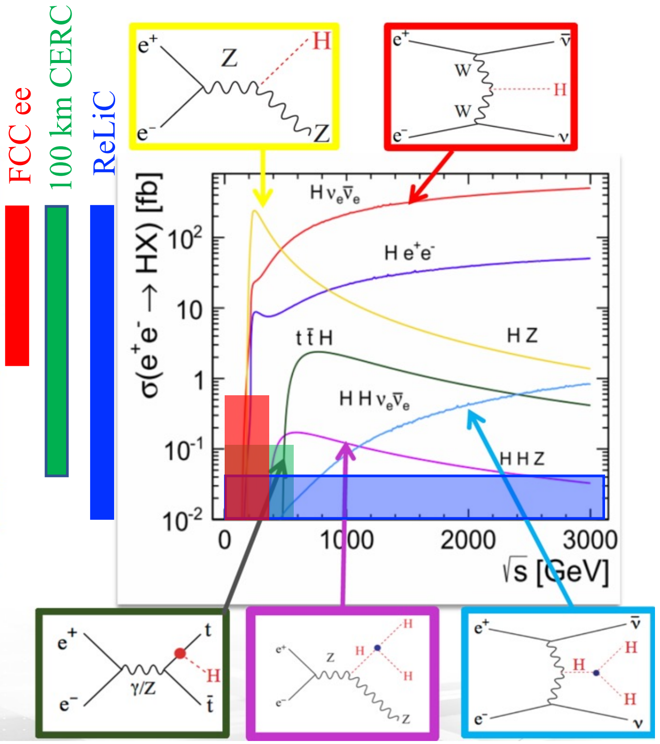
Physics: Energy and Luminosities reach

e+e- colliders

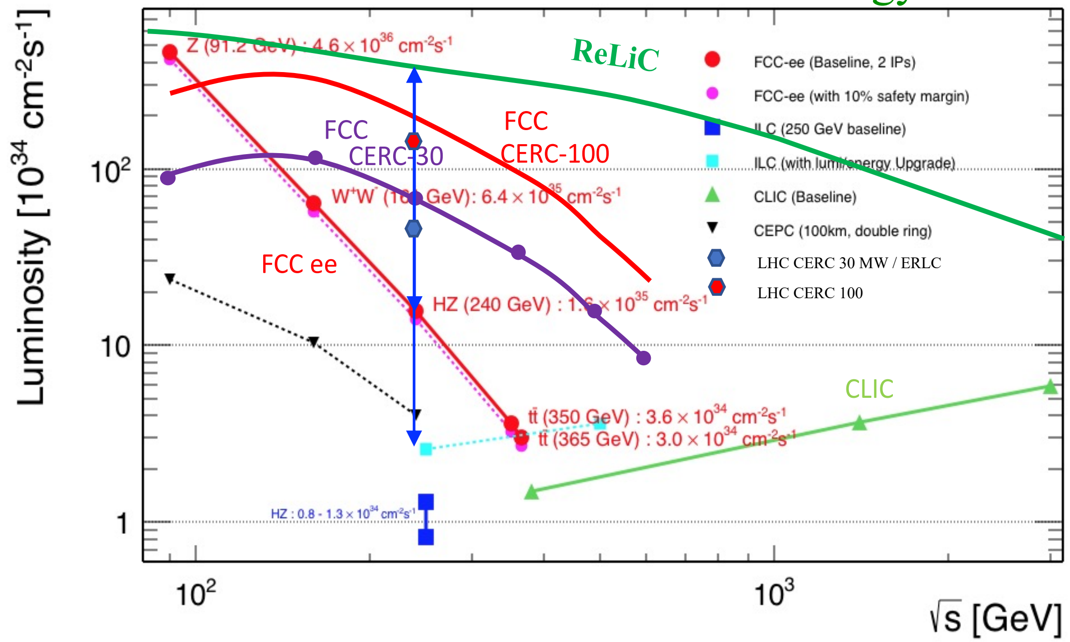
125 Direct HIGS production $e^+e^- \rightarrow H$

$\sqrt{s}$ [GeV]	Science Drivers
90-200	EW precision physics, Z, WW V
250	Single Higgs physics (HZ) Hvv V
365	tt
500-600	HHZ, ttH direct access to Higgs self-couplings, top Yukawa couplings
1000-3000	HH$\nu\nu$ Higgs self-couplings in VBF

Precision measurement and search for new physics studying deviations from the SM
→ Need high luminosity (and energy)



ERLs could offer luminosity boosts from 40 to 200 at HIGS energy



- Main features
  - Recycling used particles - no need for high intensity positron source
  - Energy recovery
  - High luminosity – important for for high precision physics and investigating low-cross-section branching channels
  - High polarization of both electron and positron beams
  - Low beamstrahlung offers high accuracy in collision energy
  - Very small energy spread: important for high precision physics , including but ton limited to direct channel $e^+e^- \rightarrow H$ at $\sqrt{s}$=125 GeV
  - ReLiC be extended to few TeV c.m. energy in the future

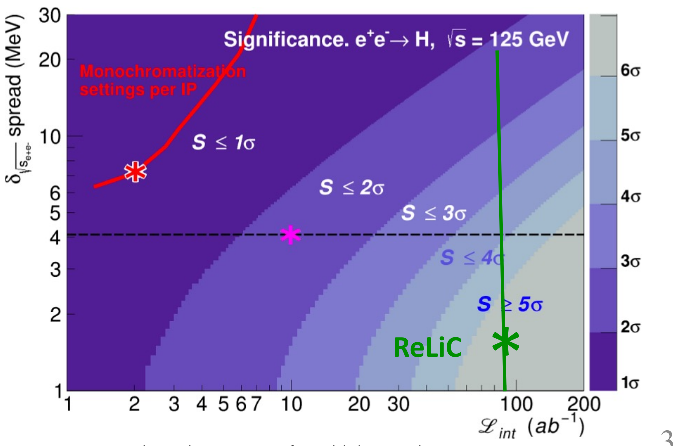


Figure is courtesy of David d'Enterria

ReLiC parameter in the ILC tunnel

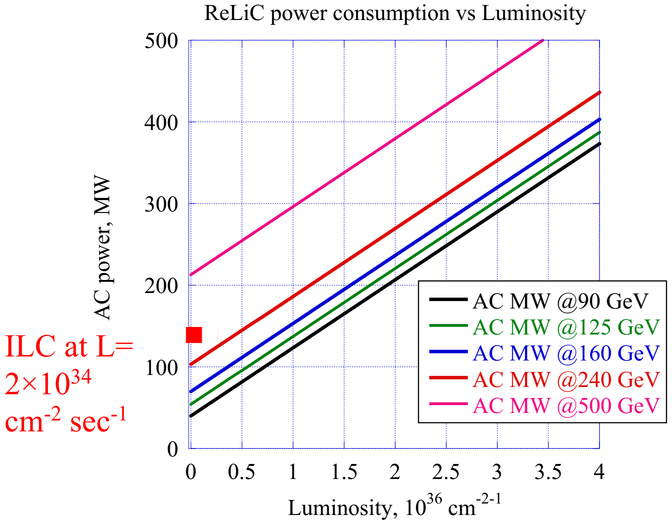
Main assumptions

- ✓ This collider with benefits from CW operation:
  - ✓ Very high luminosity
  - ✓ Accuracy and stability of beam energy
  - ✓ Orbit stability and feedback
  - ✓ Low energy spread
- ✓ Tesla type 5-cell HOM damped SRF cavities
- ✓ 12.5 MV/m real estate gradient, 19 MV/m acceleration gradient, $Q=4\times10^{10}$
- ✓ 2 x 10 km linacs with separators in the ILC tunnel –
  Note: fitting in 2x 7.5 km ILC-250 will require 35% more AC power for cryogenics
- ✓ Nominal c.m. energy – 250 GeV with extension to 500 GeV and above (either increasing Q or refrigerator efficiency)
- ✓ Staging by increasing energy from Z-pole at 90 GeV, to direct H production at 125.35 GeV, W^+W^- at 160 GeV and HZ at 240-250 GeV
- ✓ At this – relatively low energies for linear collider – main power consumption is coming from the synchrotron radiation needed to cool used e+ and e- beam after the collisions
- ✓ Improving efficiency of He refrigerators and razing Q of the SRF cavities are critical to get to higher energies and reducing power consumption

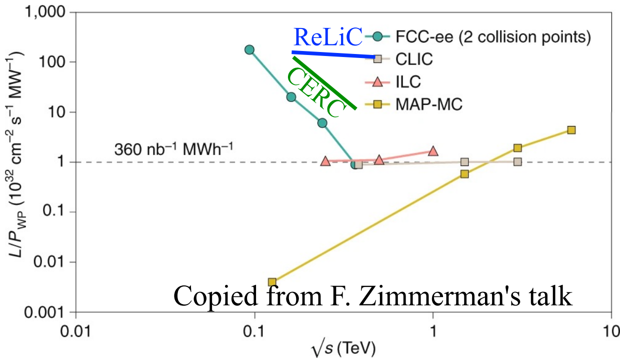
Power consumption at top luminosity 4×10^{36} cm^{-2} sec^{-1} at $Q=4\times10^{10}$

Physics	Ec.m.. GeV	Cryo, MW	Damping Rings, MW	Others, MW	Total. MW
Z	91.2	34	274	6	314
H	125.35	47	274	7	328
W+W-	160	60	274	10	344
HZ	240	90	274	13	377
HHZ	500	188	283	25	496

At $\sqrt{s}$ =240 GeV and below the ReLiC power consumption is dominated by compensating for SR losses in damping ring – i.e. it is proportional to the ReLiC's luminosity

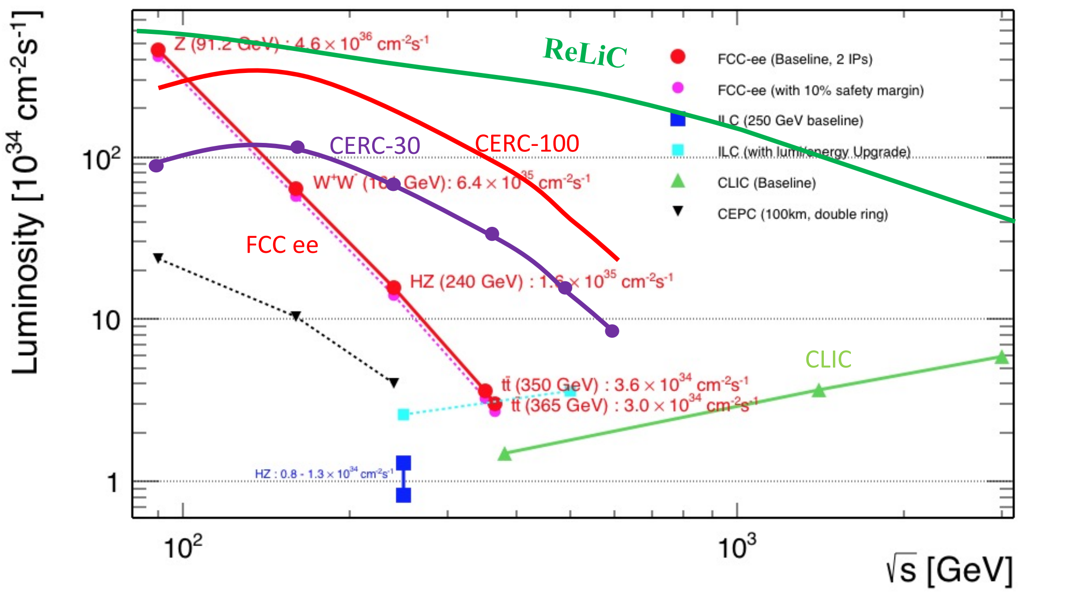


ReLiC would have superb efficiency measured in Lumi/MW



Summary

- ReLiC can be a natural option for upgrading ILC using SRF linac option capable of operating at high average currents
- It can be initially used for Z, WW and direct HIGS production physics and later extend to HZ channel, t-tbar, and ZHH
- To make the upgrade smooth, ILC should use SRF cavity with HOM damping and provide room for separators (~ 15-20 m between 250 meter sections of SRF linac)
- One of possible challenges is angle between linacs used in ILC

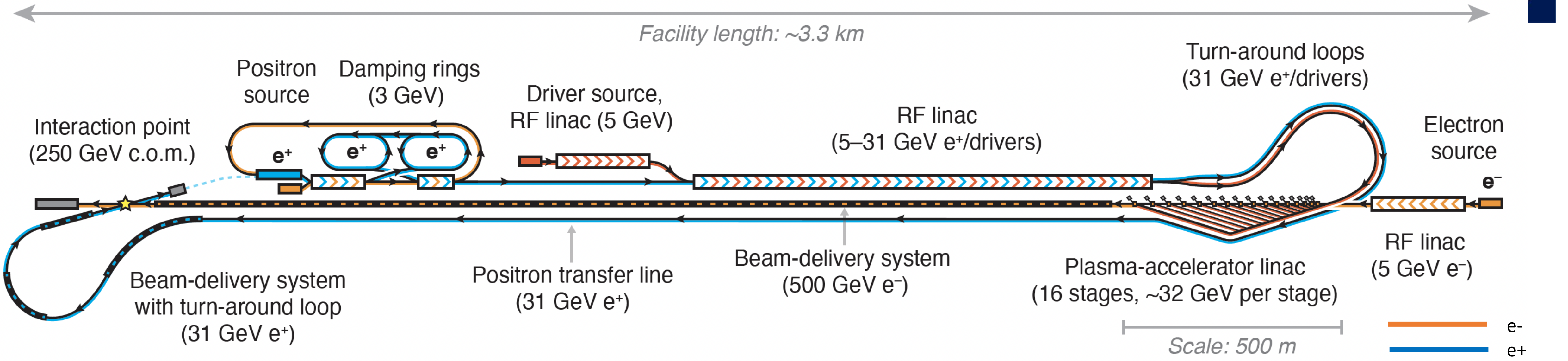


Topic 6: Realizations of the full physics program with plasma wakefield upgrade of ILC250 (B.Foster)

6. Realizations of the full program with plasma wakefield

B. Foster, Oxford/DESY

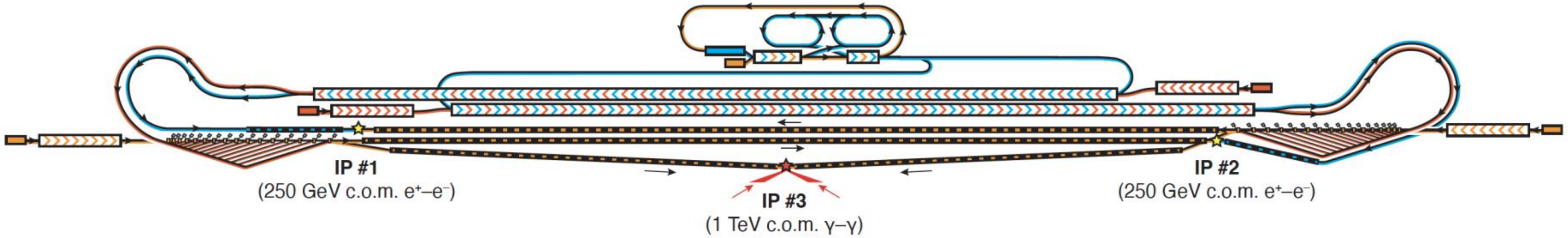
HALHF Concept



- Exploit high gradient of e^- acceleration in PWFA and avoid difficulty of e^+ acceleration by using conventional RF linac, reducing cost by low $E(e^+)$ (31 GeV)=> high $E(e^-)$ (500 GeV), boost γ ~ 2.7 => E_{CM} ~ 250 GeV.
- Reduce running costs by increasing current $\mathbf{I}(e^+)$ and reducing $\mathbf{I}(e^-)$; this & asymmetric emittance (increased for e^-) ease PWFA requirements.
- ~ 400m length PWFA stage (PWFA gradient~ 6.4 GV/m; <gradient>~ 1.2 GV/m) => facility length ~ 3.3 km and cost ~ ¼ of ILC/CLIC - $1.9B (2022 $).

Outline of Upgrade Suite

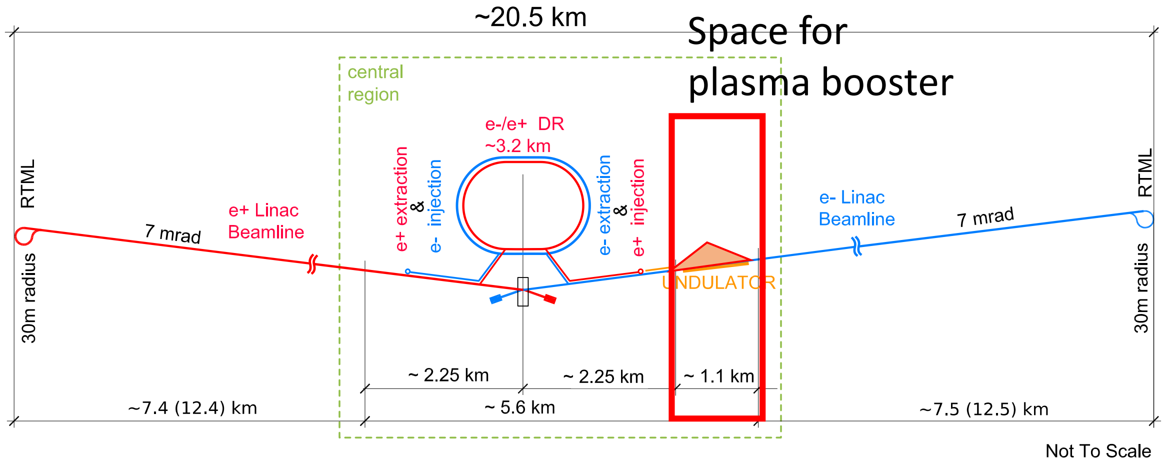
- Energy upgrade to ttbar (380 GeV).
  - 47.5 GeV positrons / 760 GeV electrons(same # of stages, same boost)
  - => +130 m PWFA linac; Added cost ~23%; >~25% more power.
- Energy upgrade to Higgs self-coupling, ttH Yukawa (550 GeV).
- 68.5 GeV positrons / 1.1 TeV electrons(same # of stages, same boost;
- => Roughly 48% increase in cost cf Higgs factory; power increases by 90 MW to 190 MW.
- γγ & Multi-TeV



ILC Energy Upgrade a la HALHF

- Basis: ILC250 Higgs factory ⇒ 2x125GeV linacs available
- Apply HALHF concept:
  Collide plasma accelerated electrons with conventionally accelerated positrons
- Upgrade **electron arm** to 500GeV with plasma
  ⇒ 137.5 x 550GeV ⇒ 550 GeV CME
  ⇒ upgrade a higgs factory to a tth / Zhh factory
  - Reduce electron linac energy by 4 to 34.4GeV
  - Drive 16 stage plasma accelerator
- Use space for undulator source between electron ML and BDS to install plasma booster
- Feed boosted electrons into existing BDS (already laid out for 500GeV)

(B. List idea)

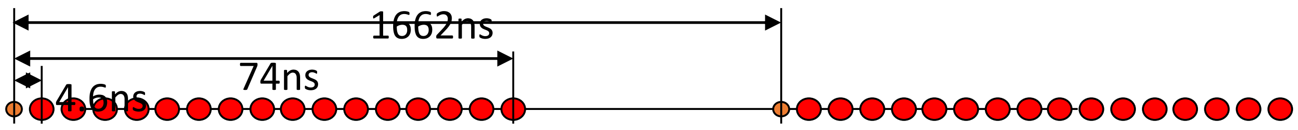


		E- (drive)	E- (Collide)	E+
Beam energy	GeV	34.4	34.4 → 550	137.5
Linac Gradient	MV/m	8.7		35
CoM energy	GeV	550		
Bunch charge	nC	4.3	1.6	6.4
Bunches/pulse		10496	656	656
Rep rate	Hz	5		
Beam power	MW	8.0	0.18 → 2.9	2.9
Lumi (approx.)	$cm^{-2}s^{-1}$	$\sim 1 \cdot 10^{34}$		

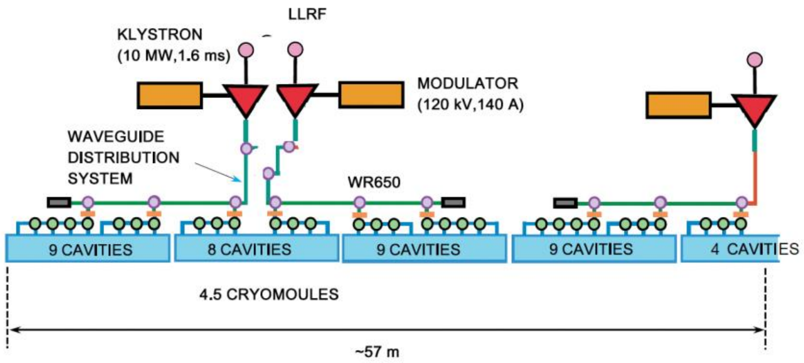
B. Foster, LCWS Tokyo, 7/24

ILC Energy Upgrade a la HALHF

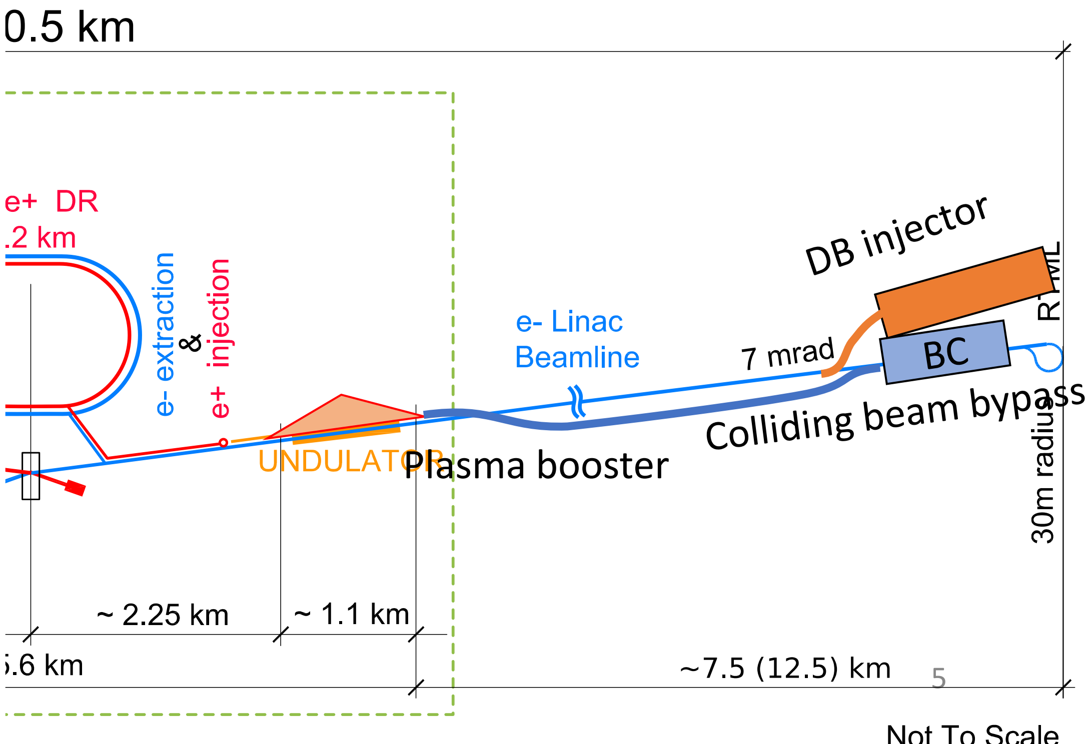
- Requires 3x more klystrons than in baseline configuration (baseline: 2 klystrons for 9 cryomodules) -> fits RF cell structure



Overall: 656 mini trains in pulse -> pulse length 1090us



- Can't inject DB @ 15 GeV - $$$ - so separate DB &CB
- CB Bunch length is a challenge:
  shorter bunches in DR or low-emittance source without DRs, same as HALHF?
- Positron source very challenging: undulator requires very high yield, alternative (e-driven) has no polarisation



To infinity & beyond…

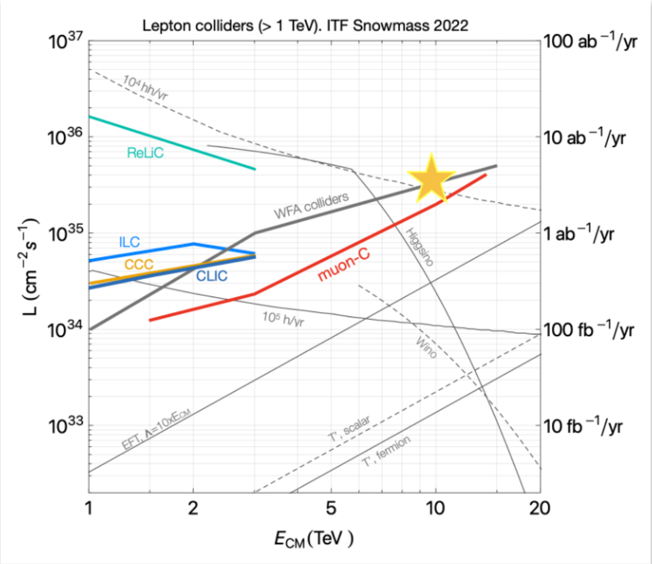
Design Study for a 10 TeV Wakefield Accelerator Collider

The P5 Report recommends:

Vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies. . .

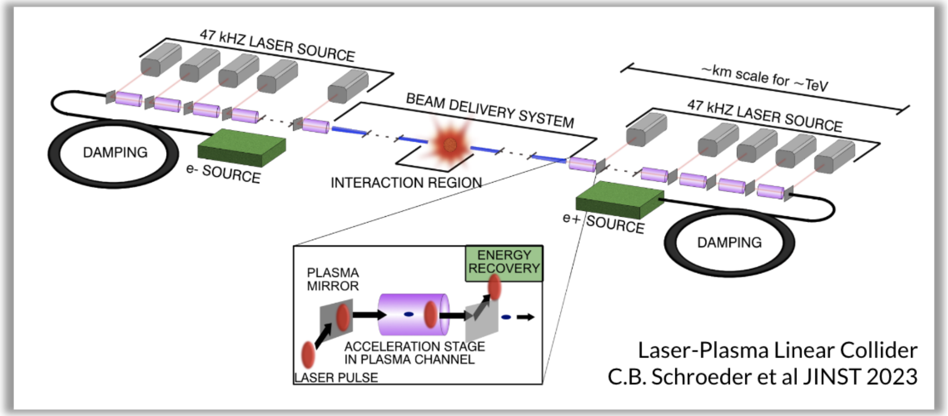
And requests a design study on wakefield colliders:

A critical next step is the delivery of an end-to-end design concept, including cost scales, with self-consistent parameters throughout.



The US Advanced Accelerator Community will pursue an end-to-end design of a 10 TeV Wakefield Collider. We aim to engage with our colleagues worldwide in this process.

Working groups, timelines, and deliverables will be announced at the AAC24 Workshop in July.



Laser-Plasma Linear Collider
C.B. Schroeder et al JINST 2023

B. Foster, LCWS Tokyo, 7/24

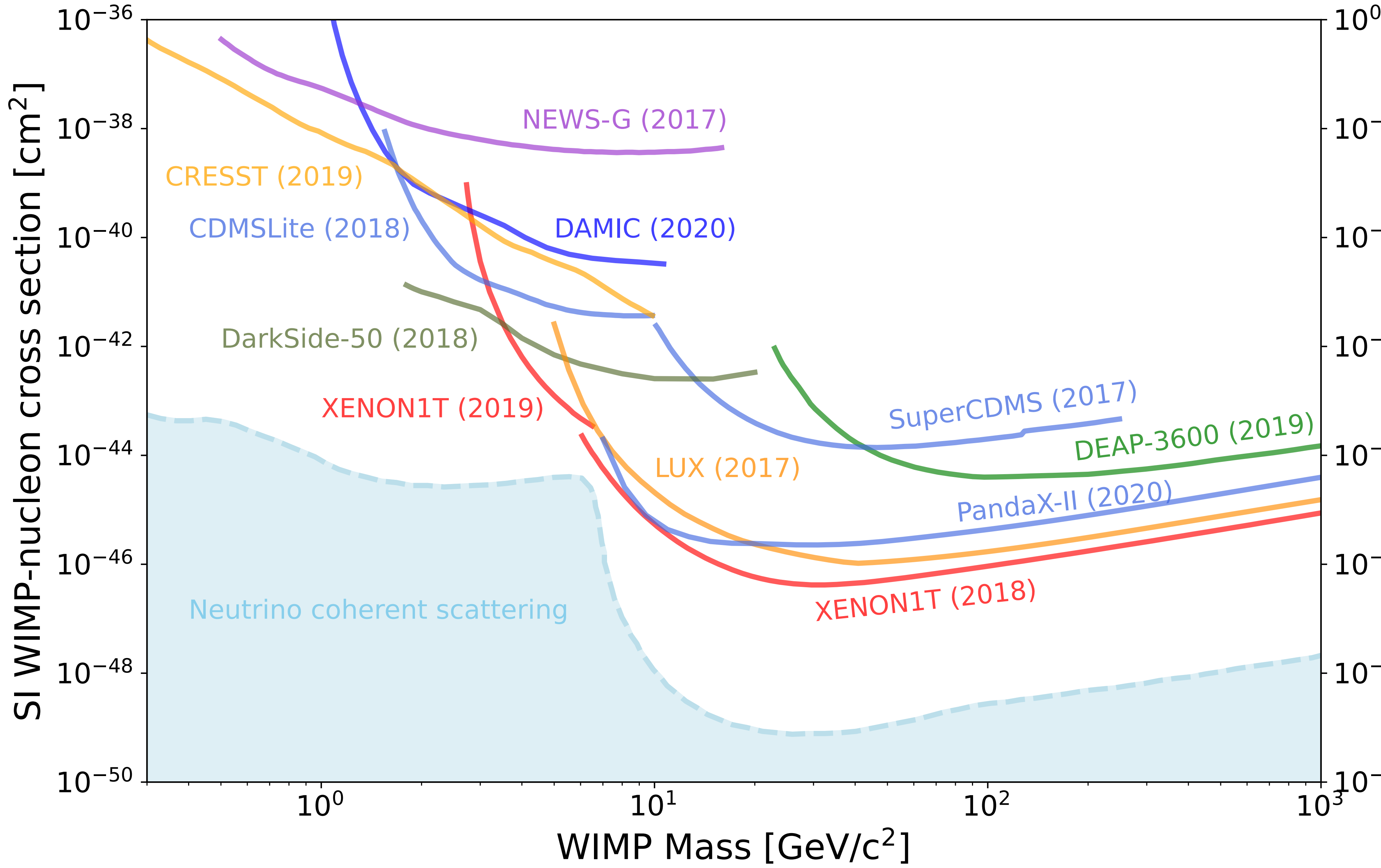
Summary & Outlook

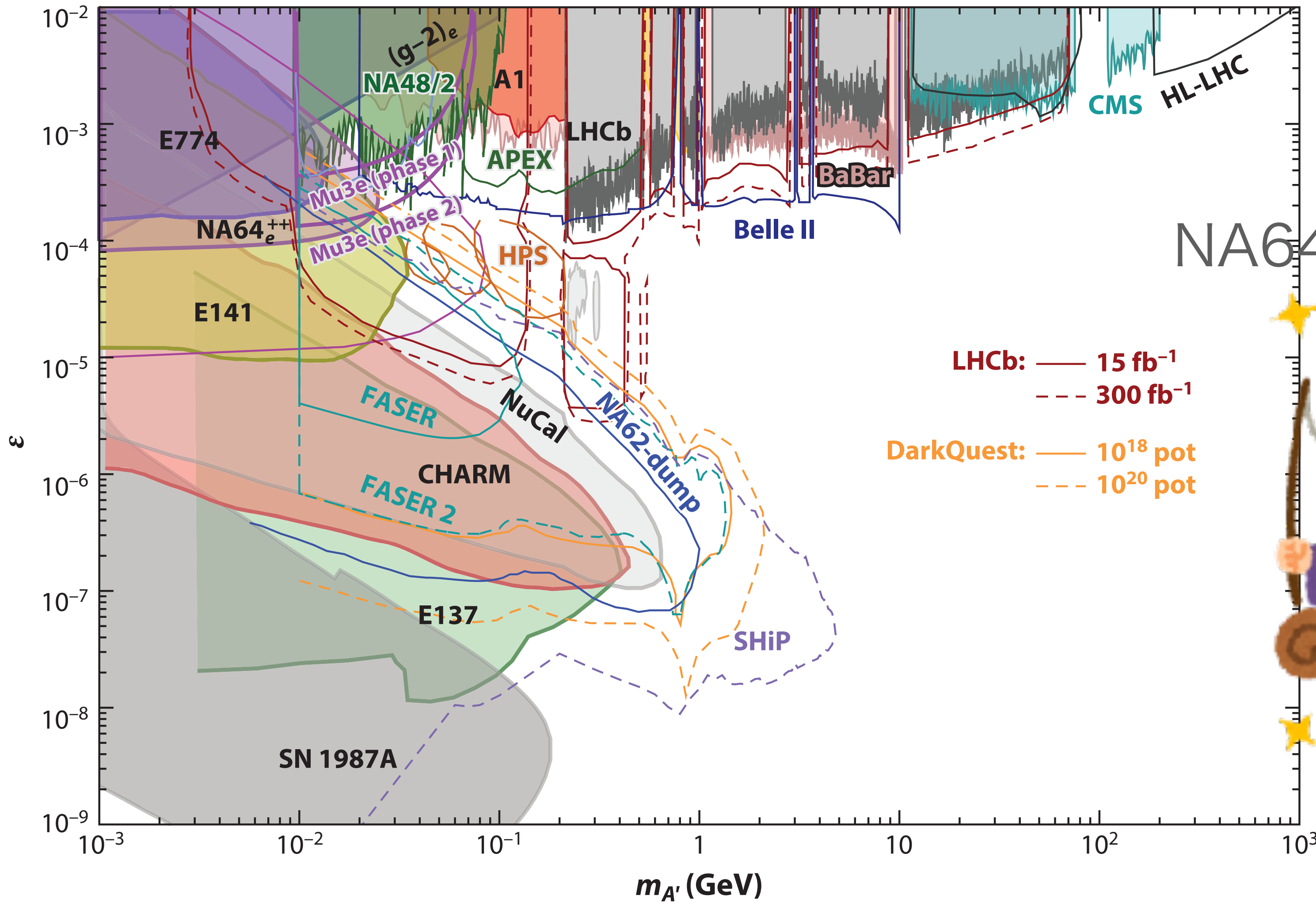
- HALHF + plausible upgrades can reach into the multi-TeV range
- A “HALHF” type plasma booster for ILC 250 could boost the CoM energy to ~550 GeV -> enough to reach tth threshold
- Overall beam intensity would be half compared to ILC250 or full ILC500 -> half of luminosity
- Compared to full ILC500 further luminosity reduction from larger emittance / asymmetric beams -> needs to be studied
- BDS of ILC designed for 500GeV beams -> should work
- Bunch Compressors are an issue
- US work oriented towards 10 TeV frontier

Topic 7: Beyond-collider program (M.Nojiri)

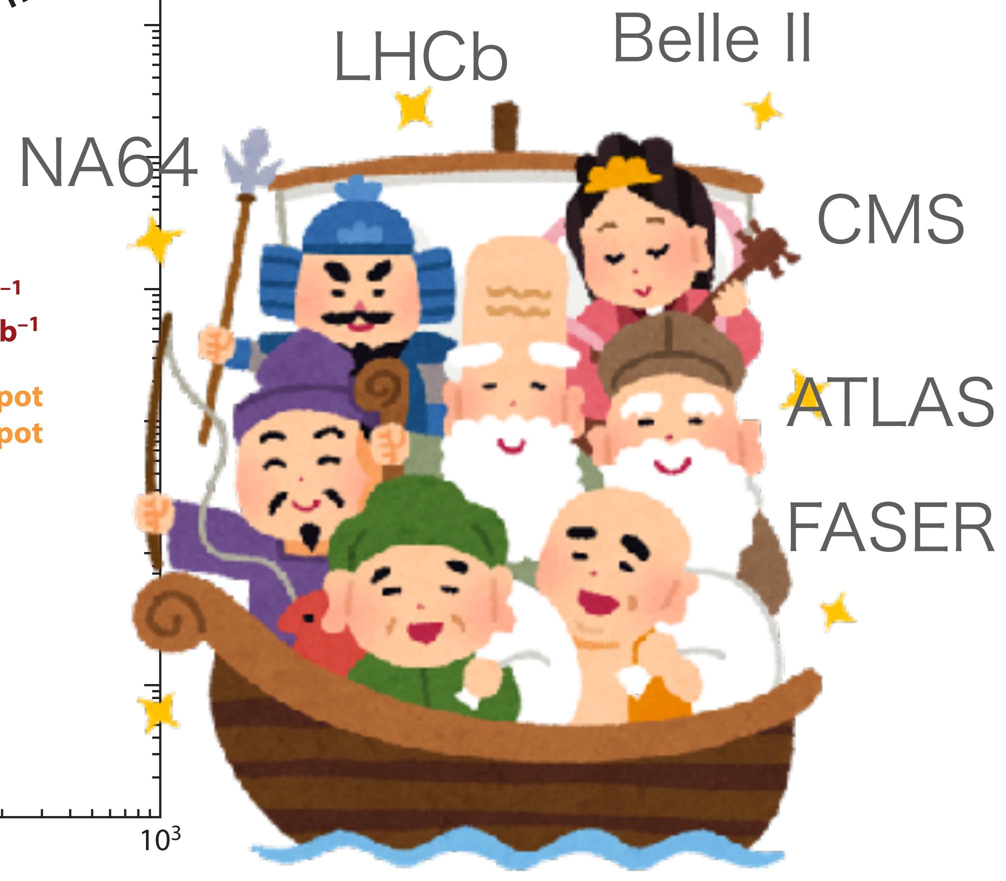
Topic 7 Beyond-collider program

- ILC is Ultimate High intensity Frontier: 4×10^{21} EOT /year (2.6MW) Rich physics program.
  - SHiP: 10^{20} POT for 5 years
  - Large energy/particles will be discarded at the beam dump Concerns on public Image.. my dream is ERL
- Increasing "theoretical demand" to look for light dark sector as Heavy dark matter searches advance. (Axion, Dark sector particles, Heavy neutrino..) Active field involving many experiments.
- SHiP approval: potential resource of simulation/experience/ detector of $\$10^8$.
- Other ideas (non-linear QED, neutron and muon source : see Sakaki-san's talk)



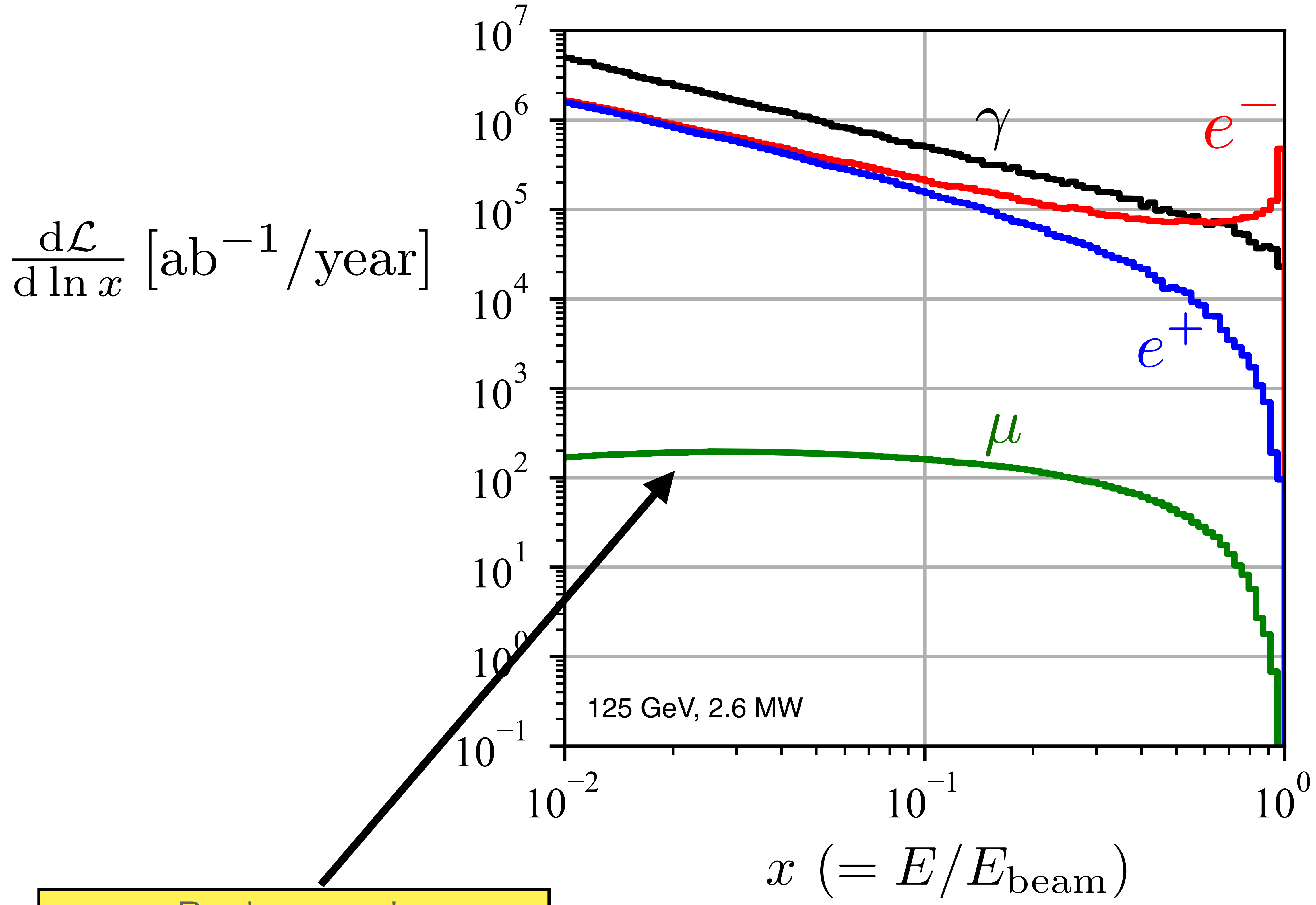


dark photon searches from Ann Rev. Nucl.Part. Sci 71 Lanfranchi, Pospelov, and Schuseter



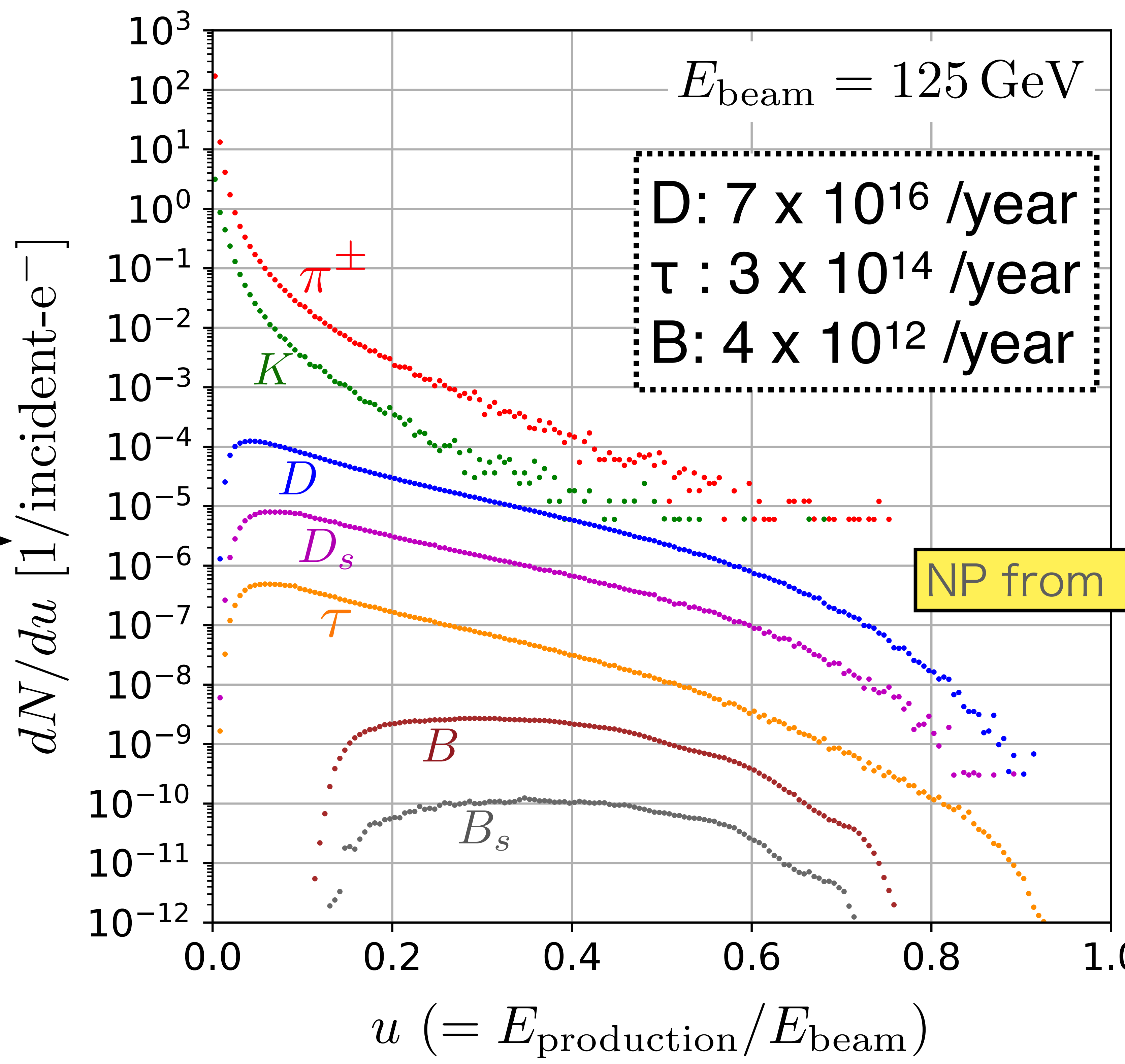
Large number of interaction between photons/electon to proton/neutron which induce huge number of Heavy flavor particles as well

Light particle couple to photon and electron



muon :Background source

Heavy particle from γN interactions



NP from τ、D, B decay

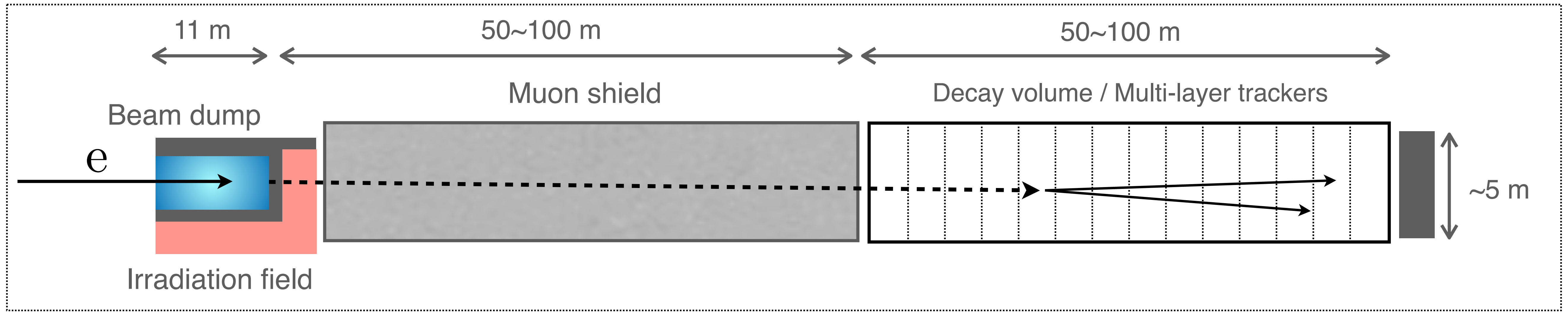
M.M.Nojiri, YS, K.Tobioka, D.Ueda. 2206.13523

complexity
γN interaction for c, b production
(data back in 80's)
energy loss of charged mesons

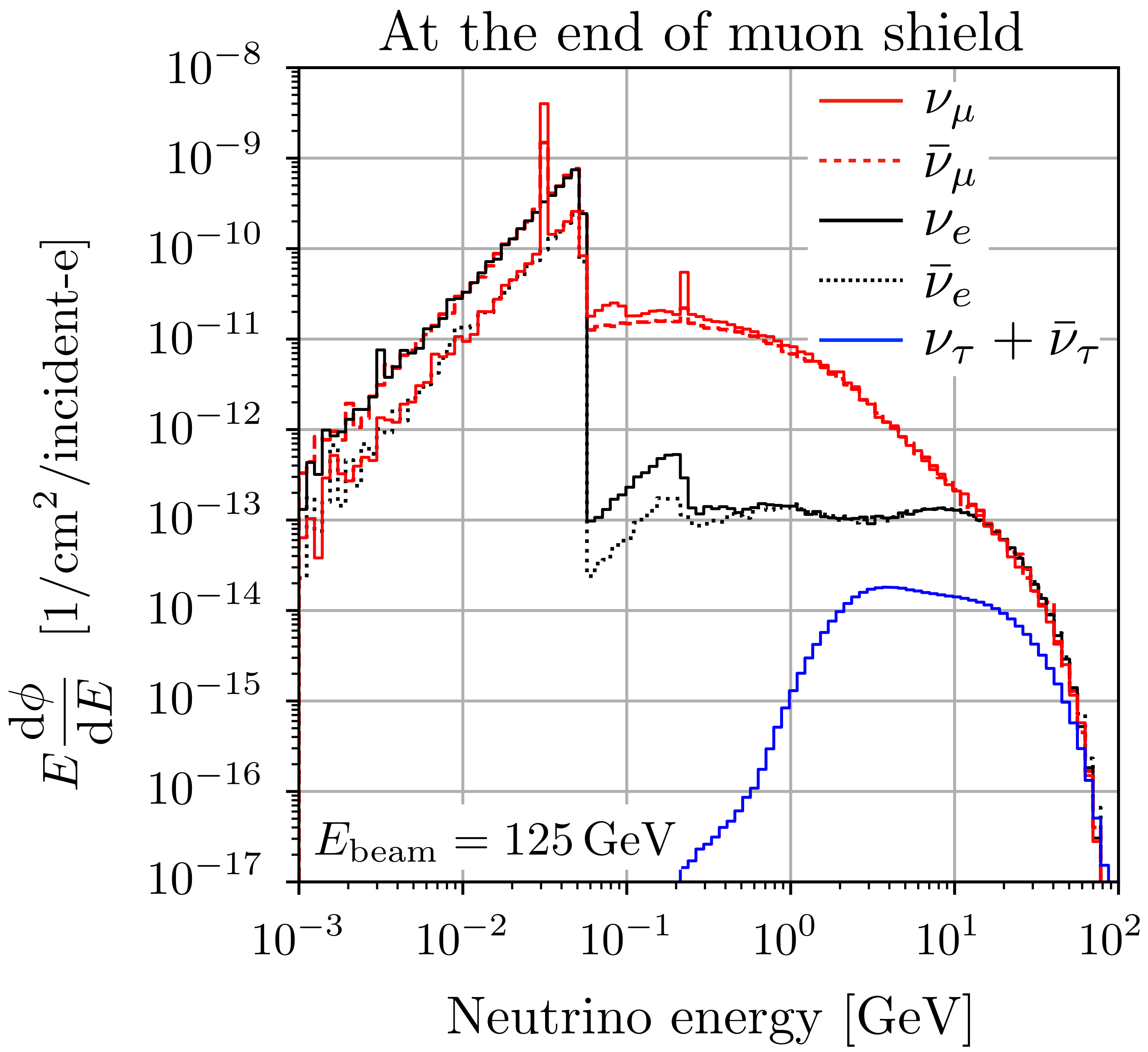
Pythia8

PHITS

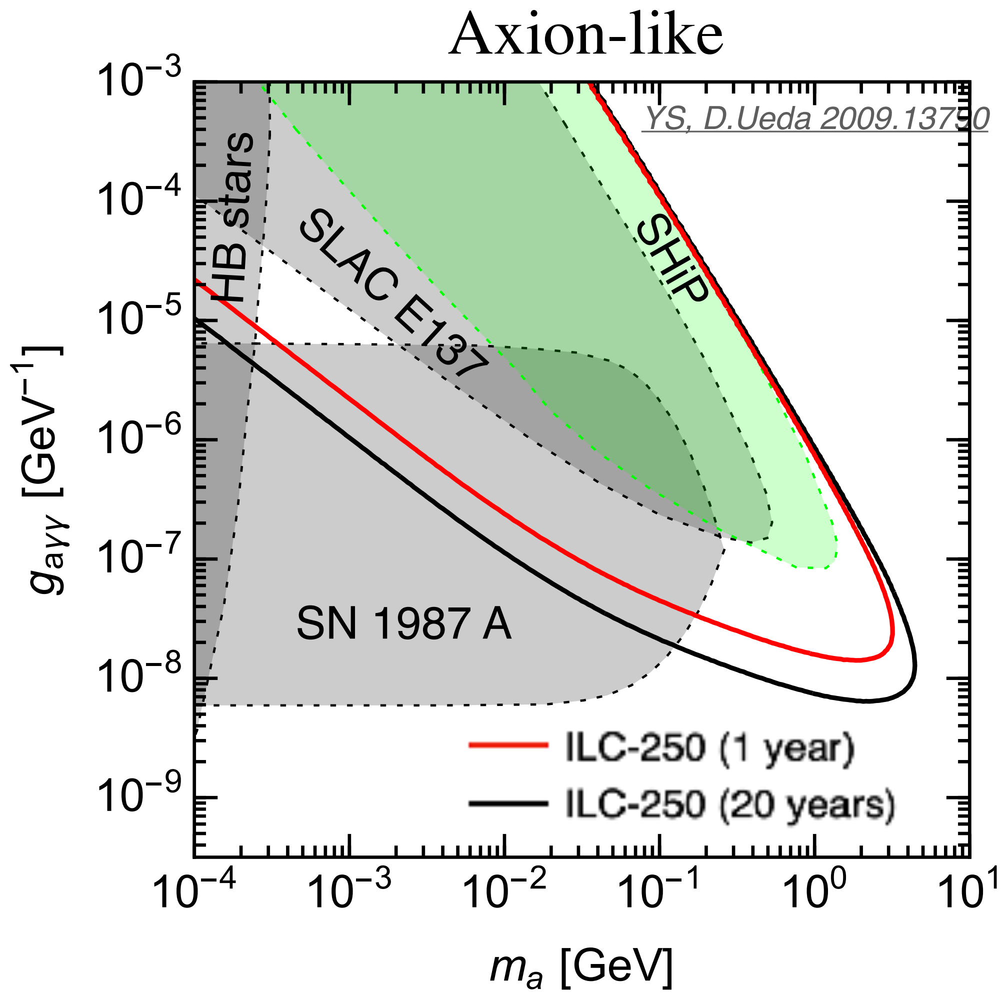
Estimating Physics Outputs

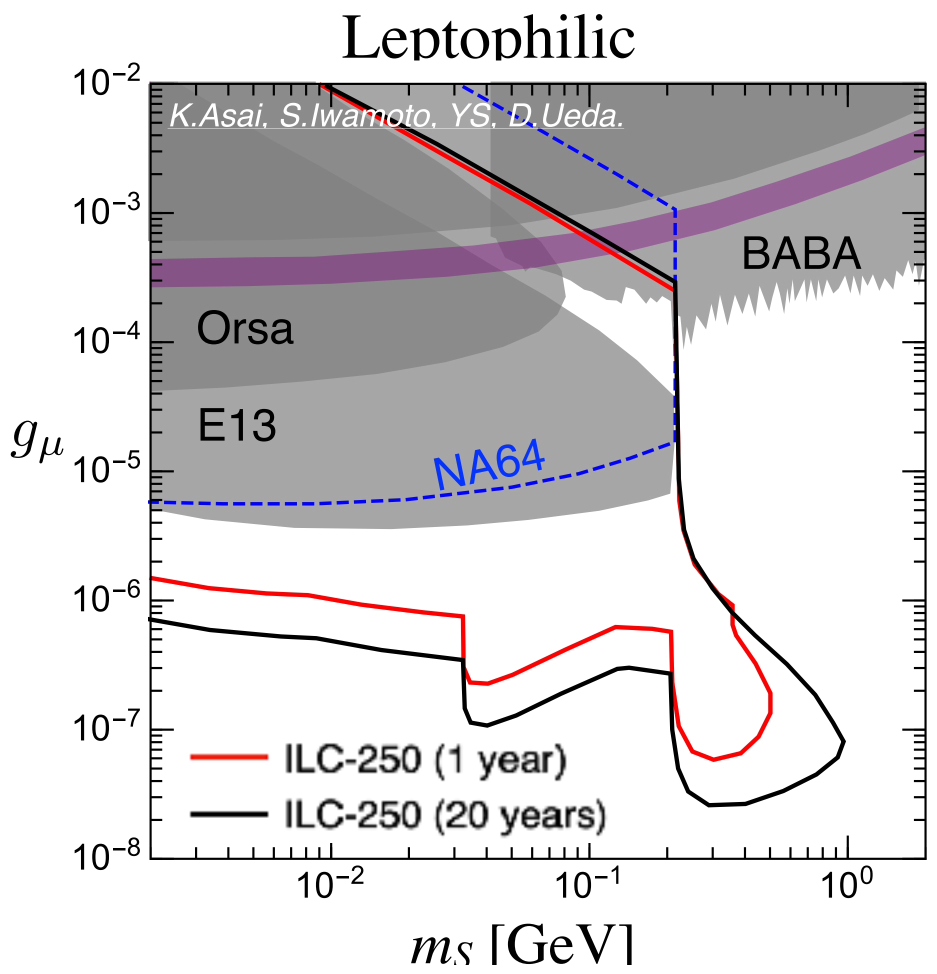


detector model with long muon sheild (you lose sensitivity in short distance with never ending muon background)



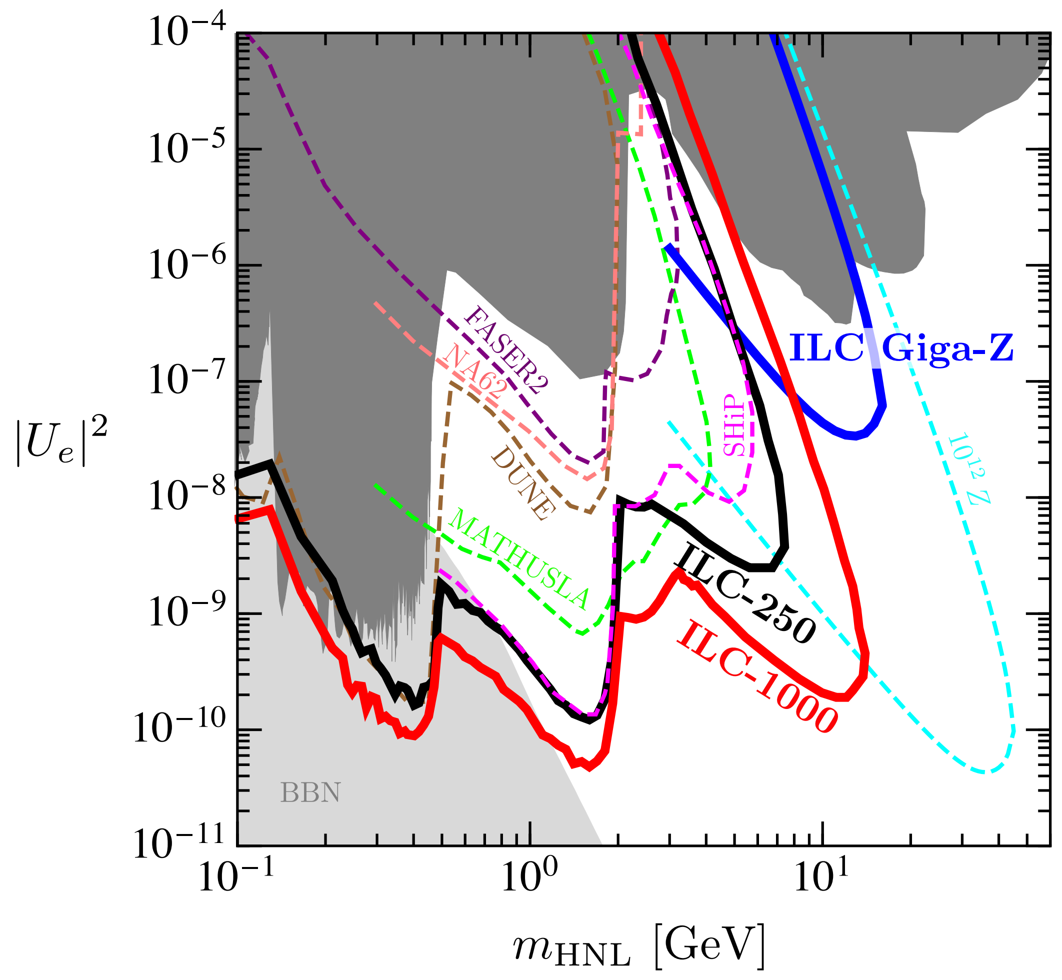
neutrino background can be serious



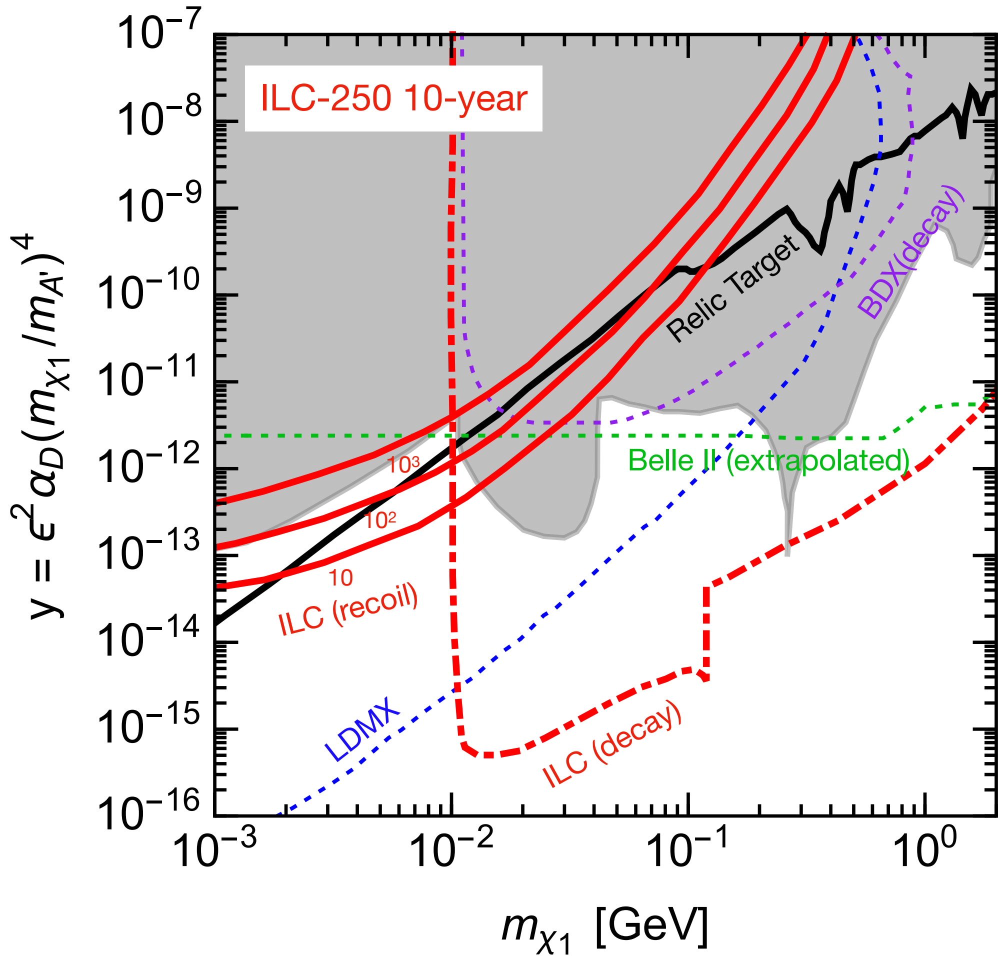


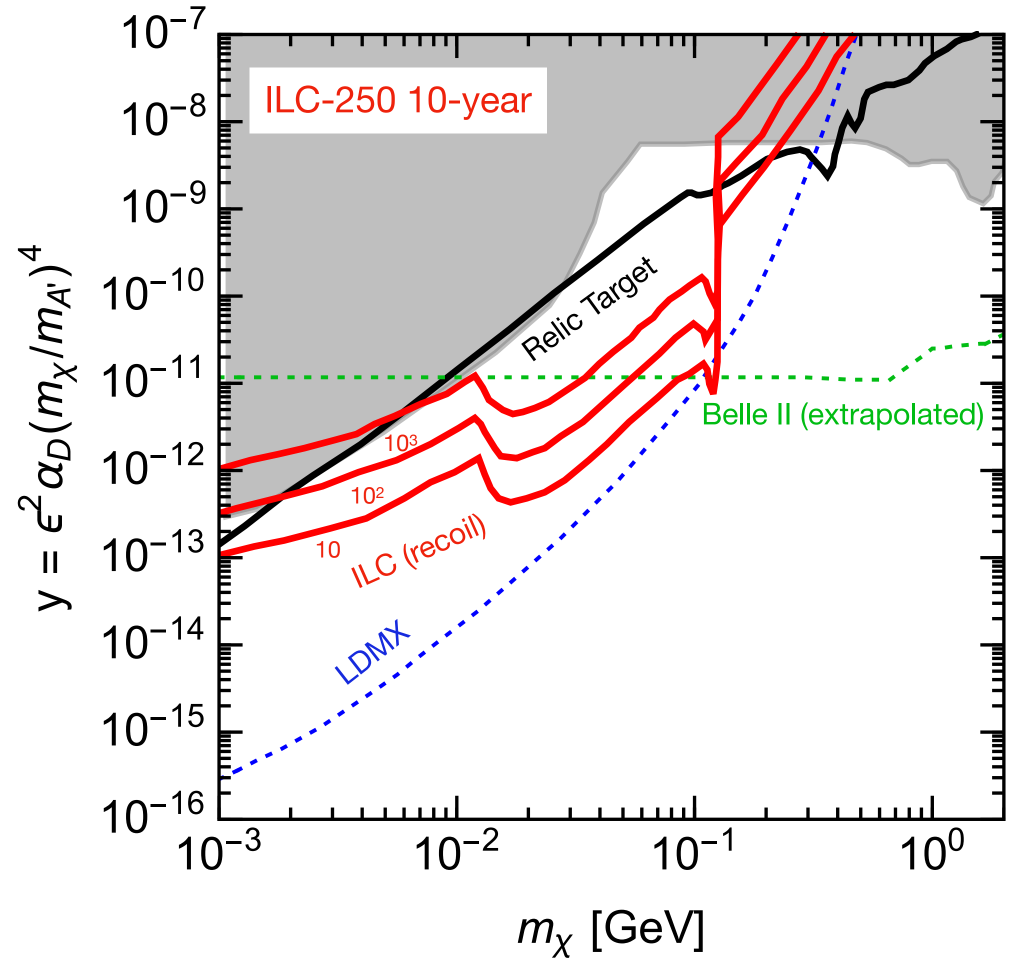
1st study: S.Kanemura, T.Moroi, T.Tanabe, 1507.02809

Heavy neutral leptons



M.M.Nojiri, YS, K.Tobioka, D.Ueda. 2206.13523





K.Asai, S.Iwamoto, M.Perelstein, YS, D.Ueda. 2301.03816

Learning from SHiP(Search for Hidden Particle)

SHiP
Search for Hidden Particles

from 2030~

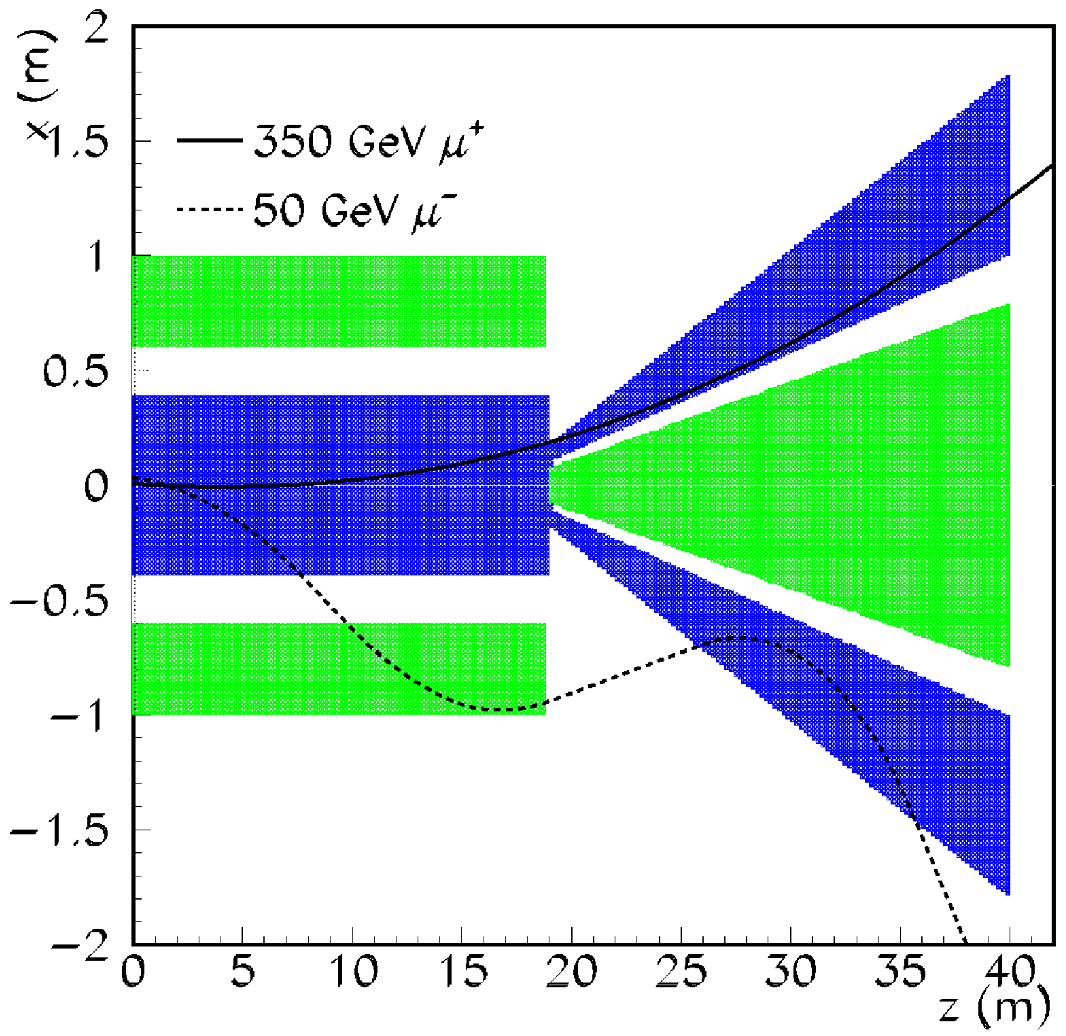


Figure 2. Cross section at y=0 shows the principle of magnetic shielding. The magnetic field is along the y-axis, and its polarity is indicated by the blue/green color of the iron poles of the magnets. The trajectories of a 350 GeV/c muon and 50 GeV/c muon are shown with a full and dashed line, respectively.

- Reduce the muon going though the shield
- Add surrounding detector to the decay volume.

total cost of order of O($10^8)

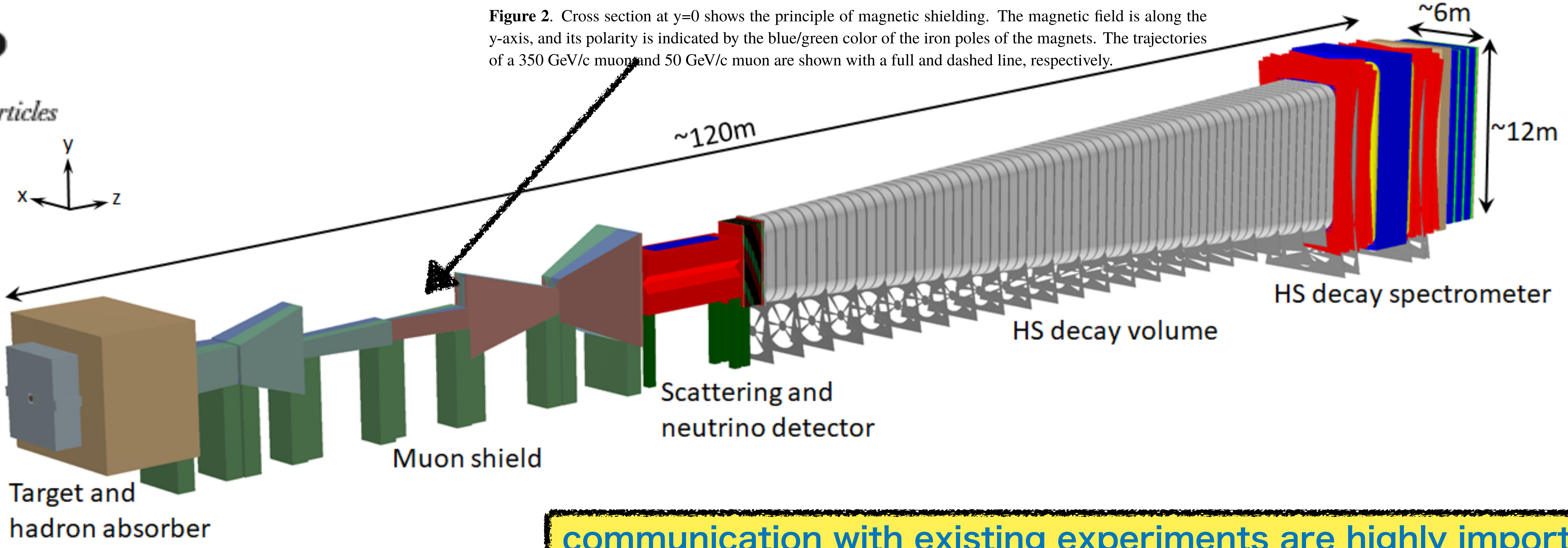
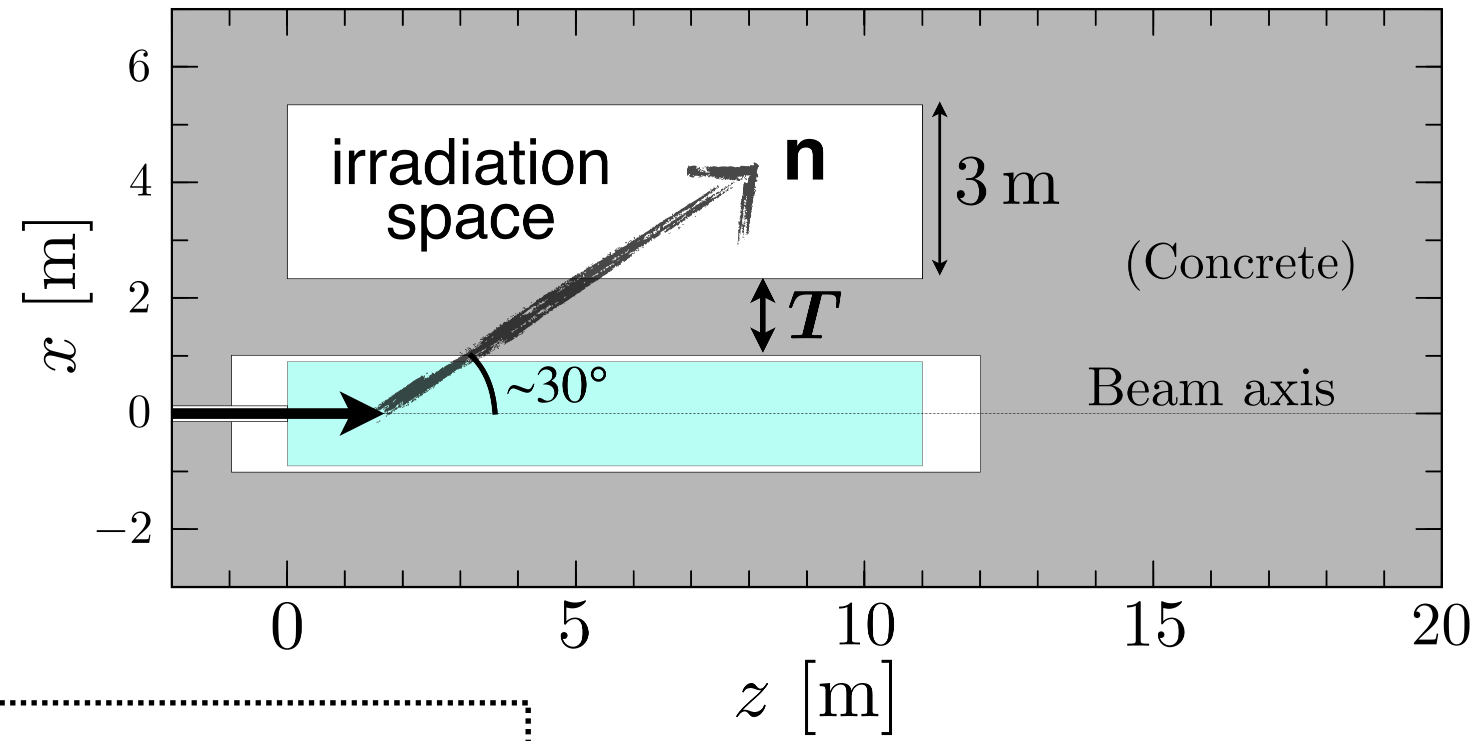


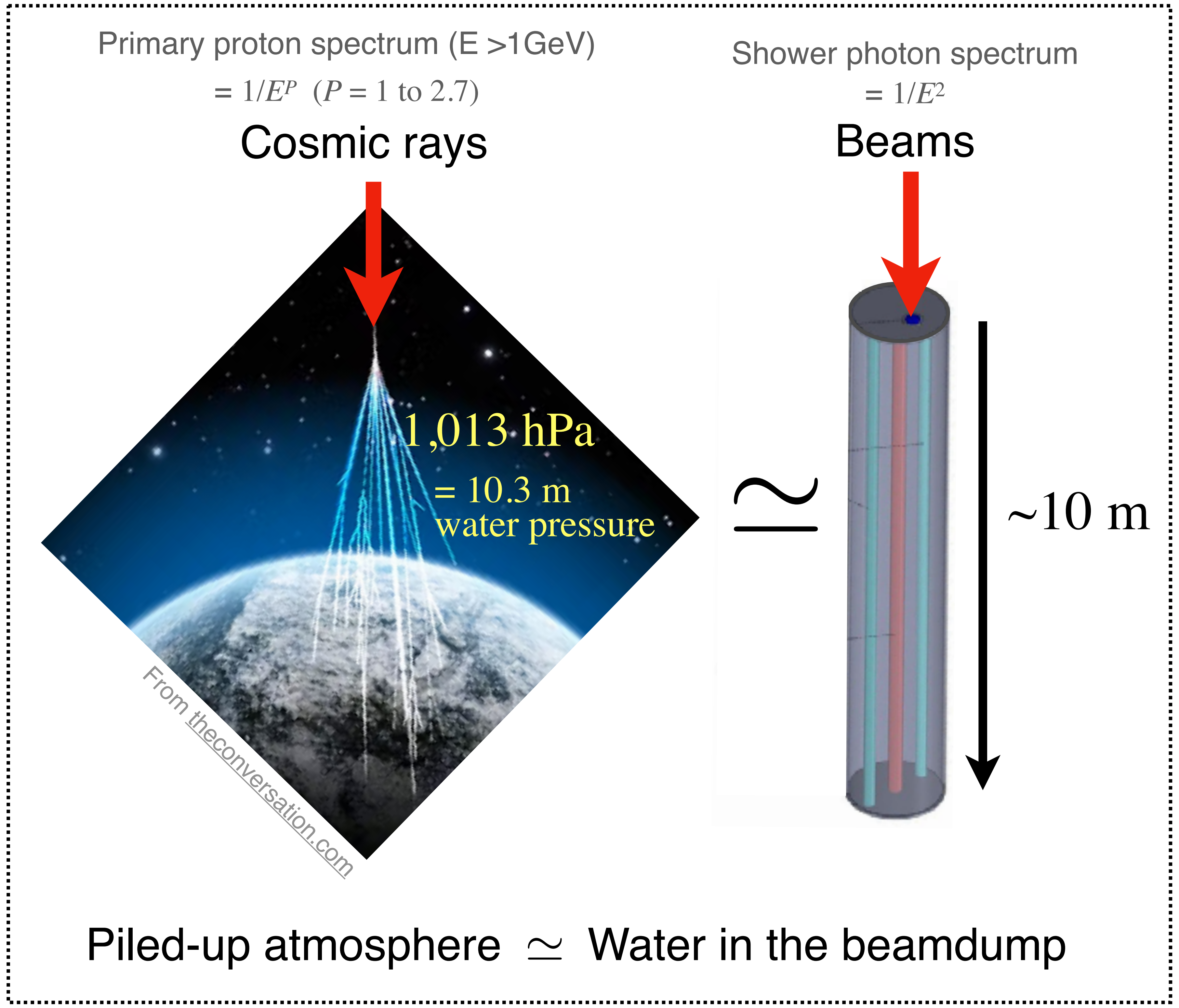
Fig. 2 Overview of the SHiP experiment as impleme

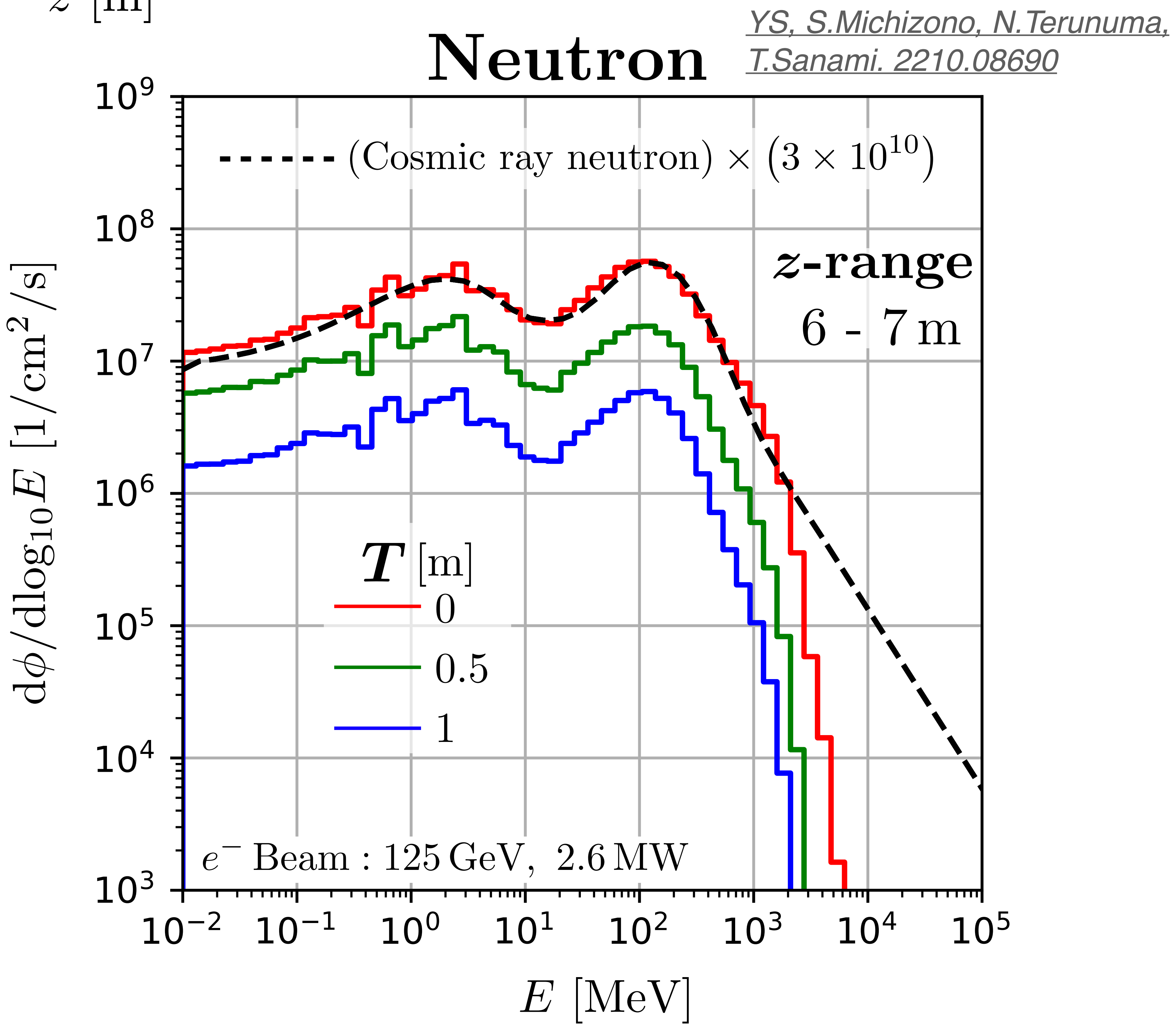
communication with existing experiments are highly important
Large investments of full simulation/detector development has been made already

From Sakaki-san's slide

Neutrons



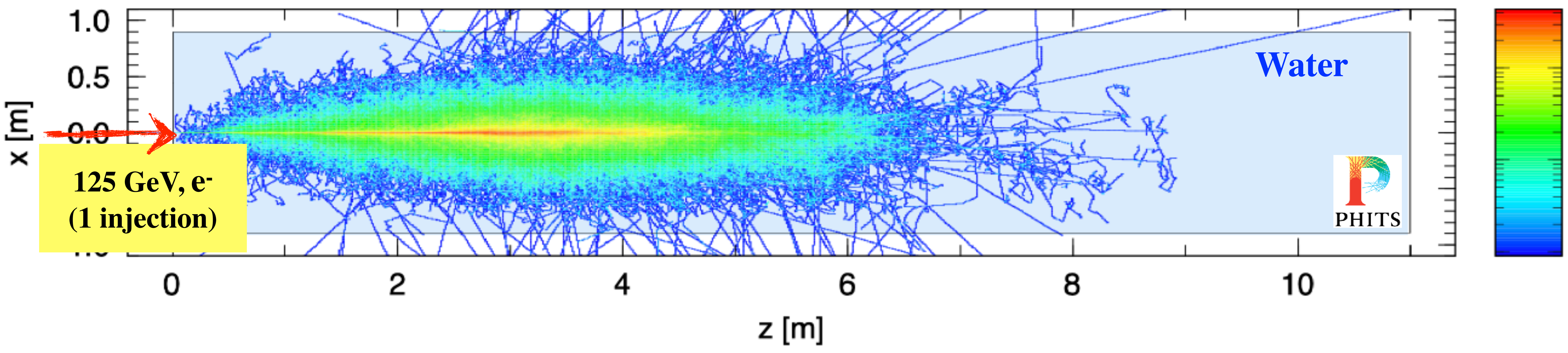


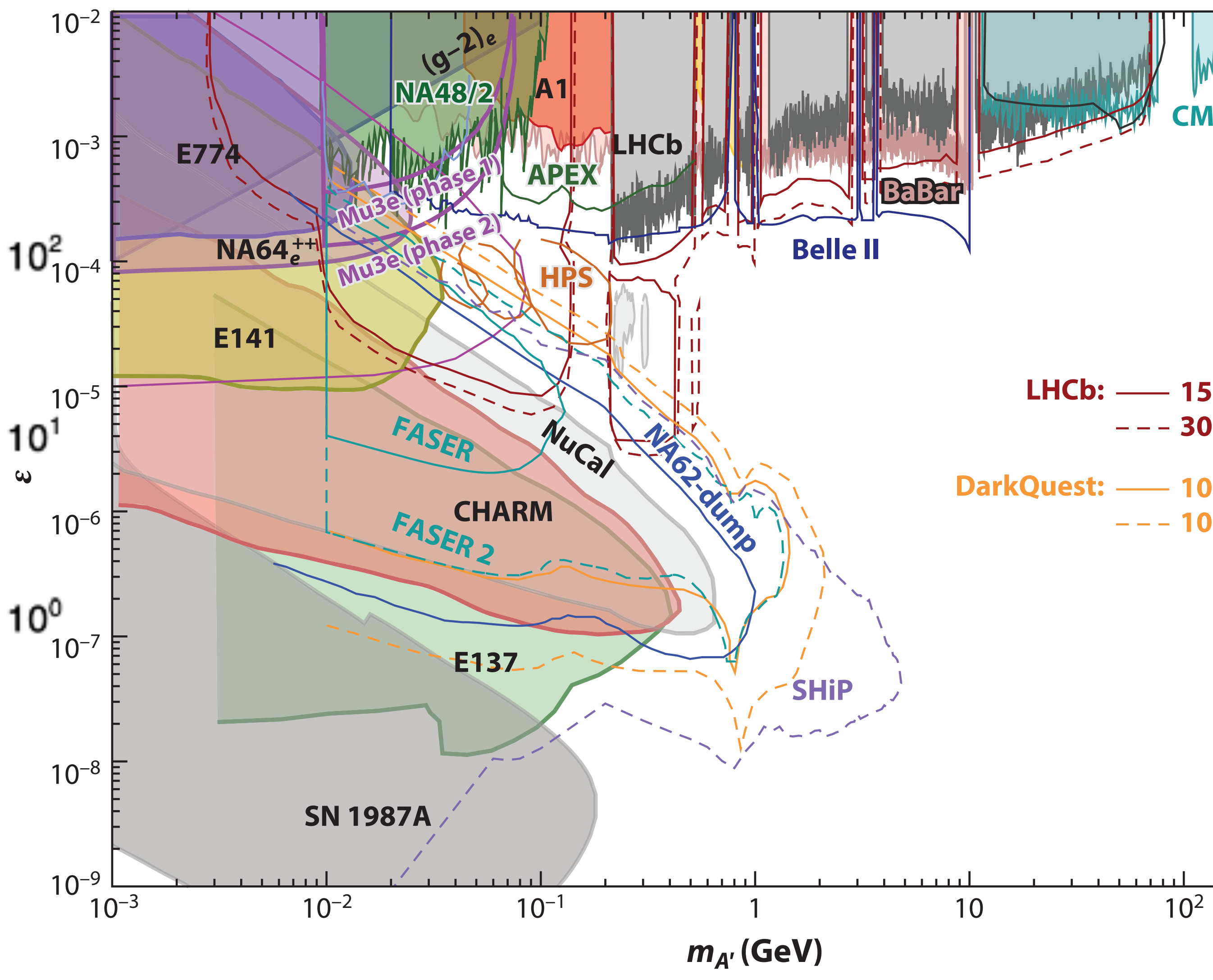


- Atmospheric-like neutrons are obtained. (Consistent up to a few GeV.)
- An irradiation field suitable for studying soft errors in integrated circuits, etc.

  ➡ Industrial applications of the ILC

Topic 7 Beyond-collider program





- ILC "High intensity frontier" . Extend the projected limit of SHiP significantly.

- various experiments has been contributing to the similar searches already. Forward and beam dump activity of the on-going experiments are potential resource of simulation/ experience/detector

Topic 8: Implications for exploring the 10 TeV parton energy scale (D.Schulte)

Considerations on the Path to 10 TeV pCM

D. Schulte

Comments:

- Hope they are useful to trigger discussions
- If this is deemed useful one would need to have a team make concrete timelines for the scenarions and put up to date cost numbers if they become available in time

Contenders

Hadron colliders

- FCC-ee and SPPC
- Fast-track version of FCC-hh with lower performance magnets (aggressive assumption 2050+)

CLIC

- 2-3 TeV is mature but is only a step toward 10 TeV pCM

Muon collider

- Important R&D required for cost, power consumption, performance and risk
- Staged approach aims at collider by 2050
    - Needs strong funding

Plasma-based linear collider

- I think these are not very mature and need inventions to become a realistic option

Current Highest-energy Ambitions

The US has the ambition of a 10 TeV pCM collider

- Muon collider, proton collider, plasma-based collider

Europe has the ambition of a highest-energy collider

- After the higgs factory
- FCC-hh
- Muon collider and CLIC as other options

China has the ambition to go to the high-energy frontier in the long run

- With SPPC following CEPC

There is potentially sufficient complementarity between a 10 TeV pCM lepton and a 10 pCM proton collider to want to build both, even if expensive

The complementarity between 3-10 TeV pCM lepton and proton colliders should be clearly established

- Also considering an earlier higgs factory

Role of Higgs Factory

The community wants a higgs factory as a first step

- Will explore important questions and may point to new physics
- A higgs factory is currently considered in Japan (ILC), China (CEPC) and Europe (FCC-ee, LC at CERN)
- Need additional budget for CEPC, ILC and FCC, but probably not for linear collider at CERN
- The highest-energy facility would have to come after the higgs factory if it where in the same region

Note: I think that Europe will strive to maintain CERN as a leading laboratory with continued or increased budget

Catch:

Higgs factory results are unlike available when a decision for 10 TeV has to be taken

- Most optimistic is CEPC approved 2025, ready 2035, results 2040
- Lead time 15-20 years if sufficient preparation has been done

Consideration:

- We should strive to move toward the highest-energy facility with the largest discovery potential

Scenarios

Higgs factory in China

- CERN could go directly for a highest-energy collider
  - Fast-track FCC-hh, requires competitive spirit because of SPPC
  - Muon collider
  - Linear collider (limit in reach, I guess only if other options fail because of cost or maturity)
  - FCC-ee (seems late competition to me)
- US could go for any 10 TeV pCM, but muons probably best option
- Japan might still maintain ILC
- 3-10 pCM collider by 2050 might be possible

Higgs factory in Japan

- CERN could go directly for a highest-energy facility
  - FCC-hh
  - Muon collider
- The US could compete with CERN or join in the project
- Unclear if China would want to go for SPPC directly
- 3-10 pCM collider by 2050 might be possible

Scenarios

Higgs factory at CERN

- China is likely not be interested in particle physics (since did not go for CEPC)
- Japan has not invested in higgs factory
- US could go for a muon collider
  - This would allow 3-10 TeV pCM by 2050
  - Complementary to or in competition with FCC-hh?
  - Maybe can still be followed by FCC-hh at CERN

If US did not go for 10 TeV pCM collider, CERN can follow up later with FCC-hh or a muon collider

- FCC-ee followed by FCC-hh or muon collider
- Linear collider followed by muon collider or FCC-hh
- This would delay 10 TeV pCM to 2070 or so
- If plasma-based collider turns out feasible, this may be an option

Considerations

A sequence of a circular electron and proton collider is attractive

- But a single host has to provide support
- Substantial initial commitment required (and probably implicit for the whole project)

A linear collider and a muon collider can make the scenarios much more flexible

- A linear collider makes the initial project cheaper
- Muon collider is an attractive option in addition to an electron, proton ring sequence
    - Allows CERN and the US to have competitive programme if CEPC/SPPC is realized
        - Alternatively CERN could go for FCC-hh directly
    - Allows the US to to have competitive programme if FCC-ee/FCC-hh is realized
    - Fast path to 10 TeV pCM
- If a linear collider is realized, a muon collider can be the 10 TeV pCM stage
    - In another site even as a fast path to 10 TeV pCM
    - Alternative option is a proton ring
- A muon collider might even replace a proton collider after an electron ring, provided it is cheap enough

Example Global Cost Consideration

Numbers from last ESPPU (need to update, ILC similar to CLIC):

a) FCC-ee + FCC-hh = 11.6 GCHF + 17 GCHF = 28.6 GCHF

b) CLIC-380 + FCC-hh = 5.9 GCHF + 24 GCHF = 29.9 GCHF

c) CLIC-380 + muon collider, not known but likely less than FCC-ee+hh

d) FCC-ee + muon collider, may still be cheaper than FCC-ee+hh

Conclusions:

One way: If one believes that FCC-hh will be funded, FCC-ee is cost effective

The other way: If one starts with a linear collider, one will not have to pay more but keep flexibility and one can get the initial commitment more easily. However, FCC-hh may be more difficult to obtain.

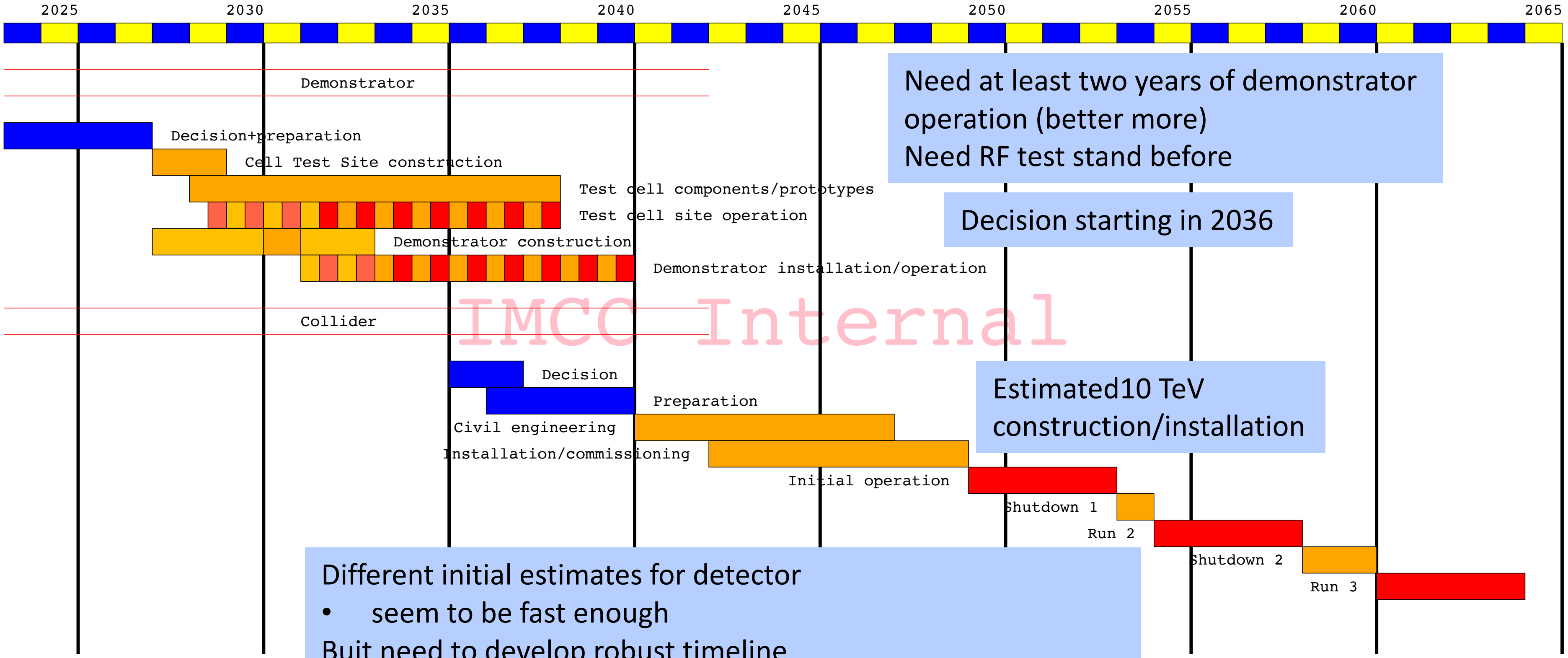
If one builds a linear collider, one can potentially split the host cost between different regions

Reserve

Timeline Considerations

MuCol

Only a basis to start the discussion, will review this year



Need at least two years of demonstrator operation (better more)
Need RF test stand before

Decision starting in 2036

Estimated10 TeV construction/installation

Different initial estimates for detector
- seem to be fast enough

Buit need to develop robust timeline

Plenary Discussion

https://slido.com
#2754 288