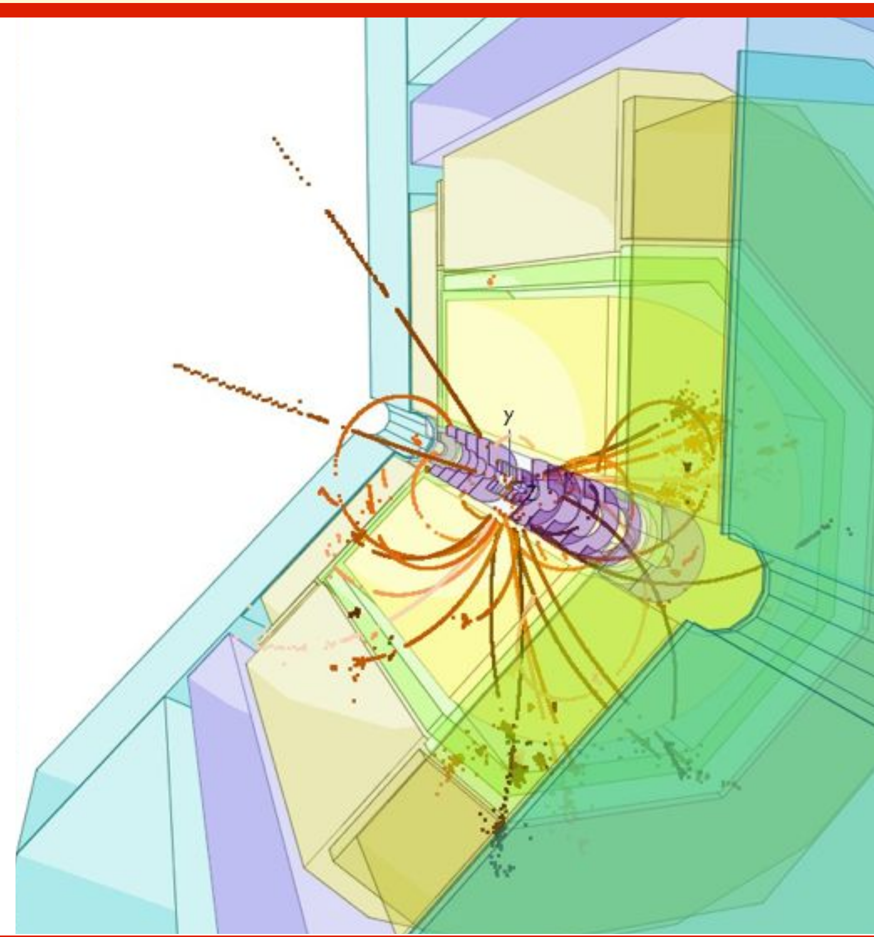
Future e^+e^- Colliders

PPAP Community Meeting, 24 Sept 2015

- Machines context
- Physics motivations
- Accelerator developments
- Detector collaboration developments
- Timelines and outlook

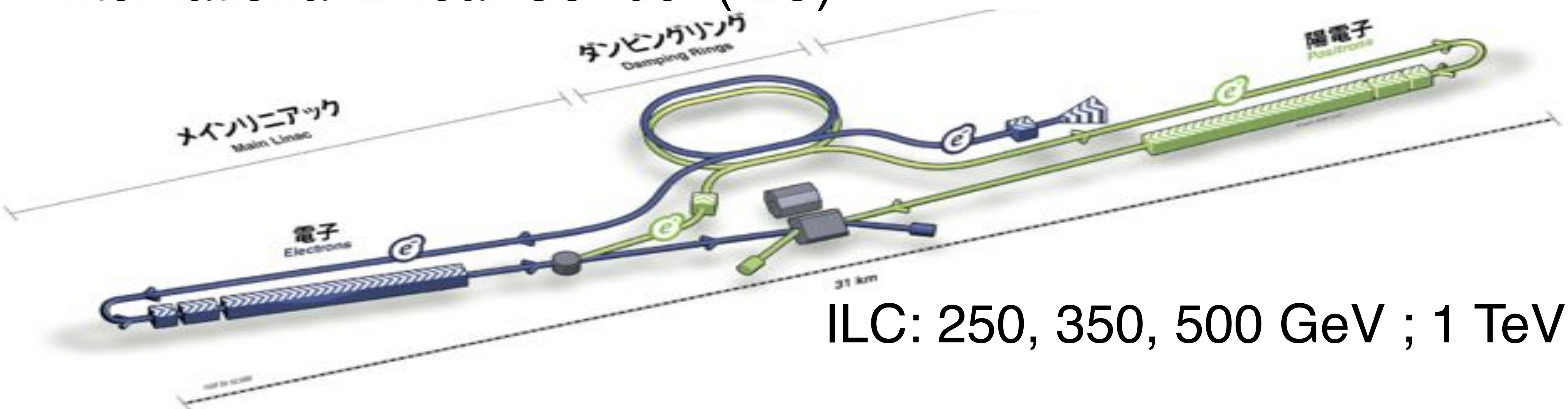
Aidan Robson

University of Glasgow | Experimental Particle Physics

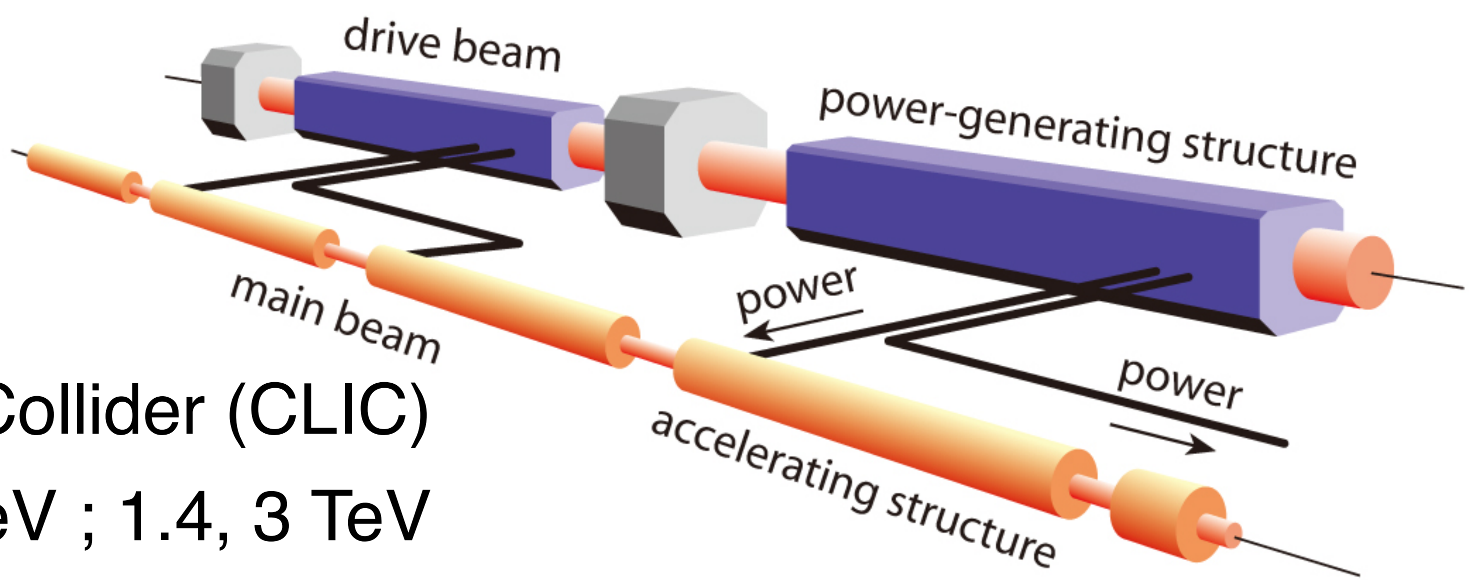


Machines context

International Linear Collider (ILC)



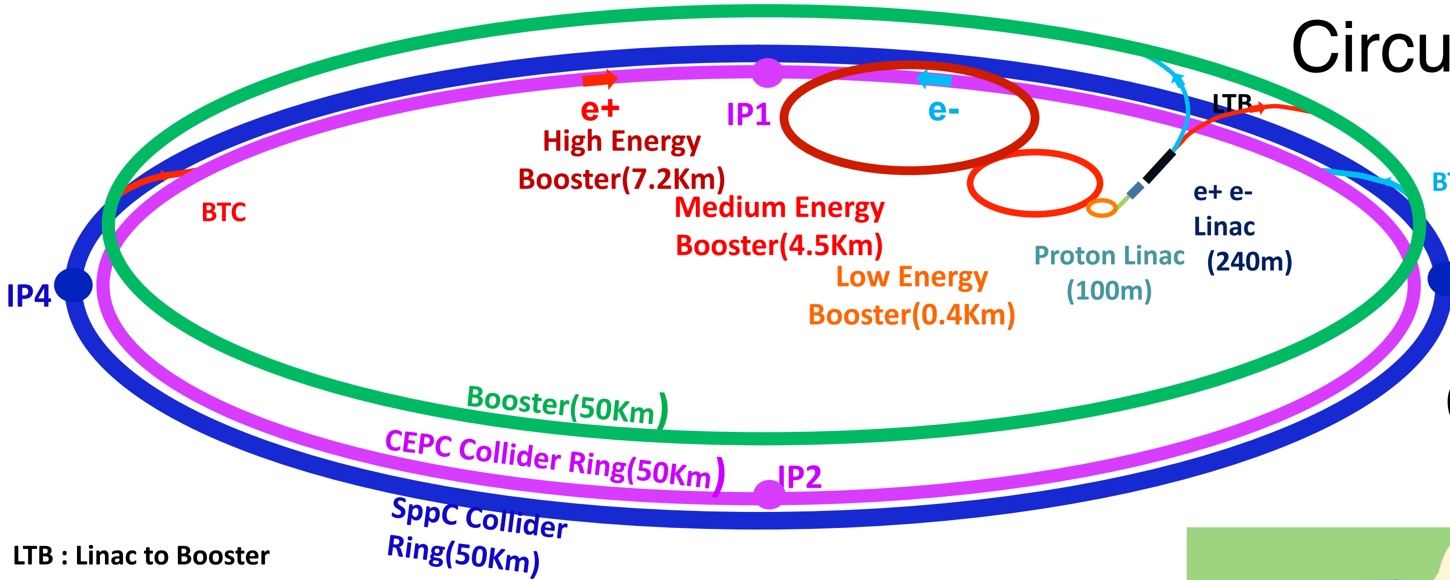
ILC: 250, 350, 500 GeV ; 1 TeV



Compact Linear Collider (CLIC)

CLIC: 380 GeV ; 1.4, 3 TeV

Machines context

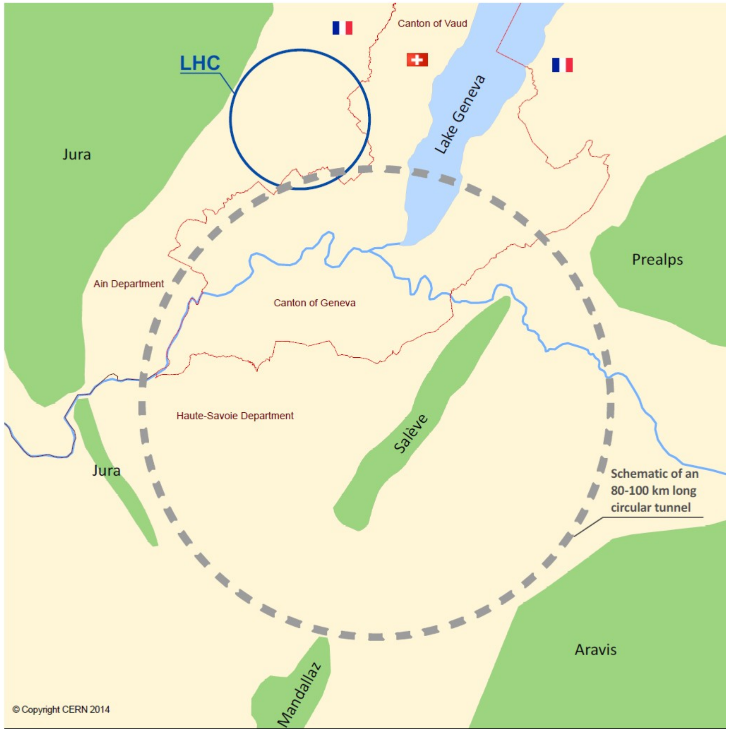


Circular Electron Positron Collider (CEPC)

CEPC: 90–250 GeV

LTB : Linac to Booster

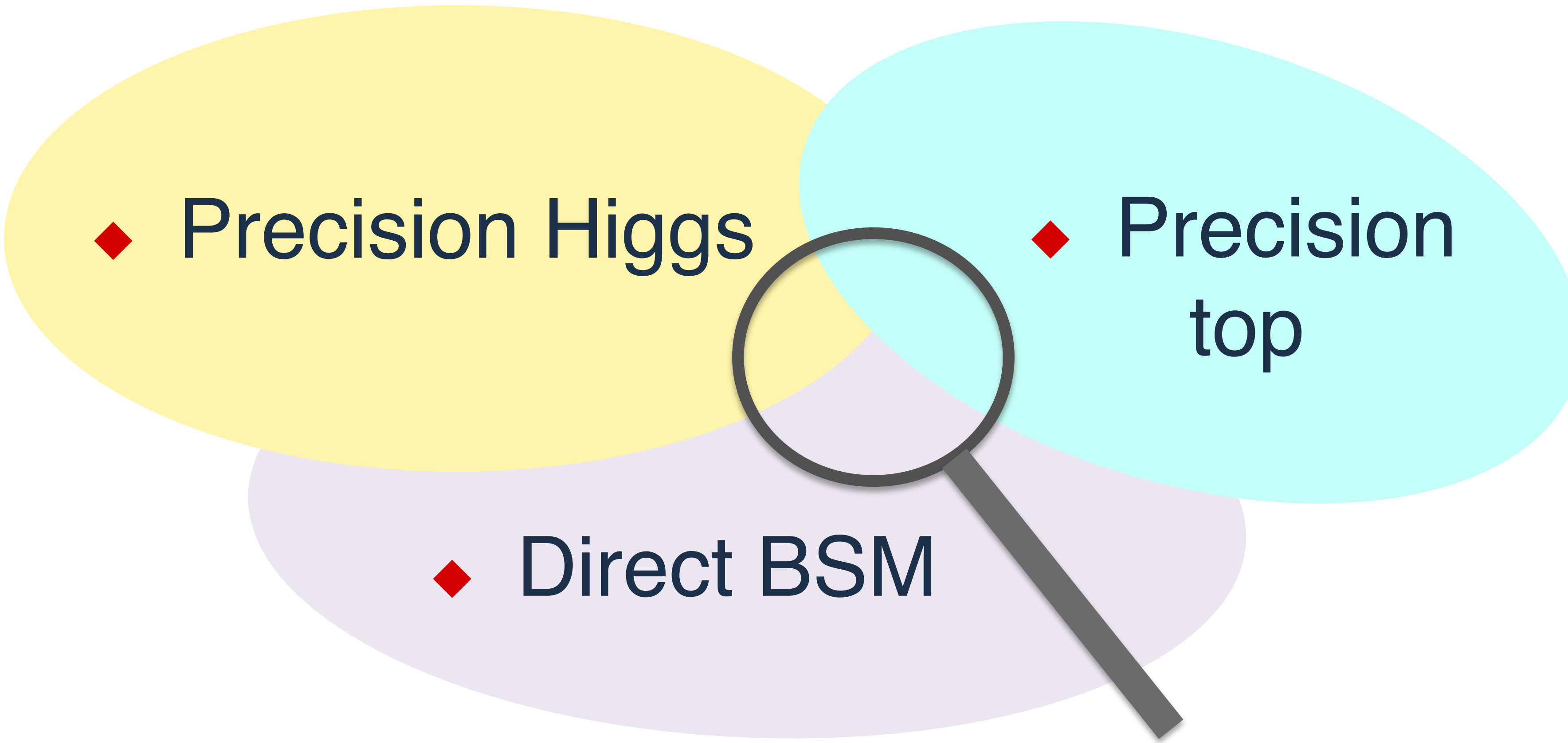
BTC : Booster to Collider Ring



Future Circular Collider (FCC)

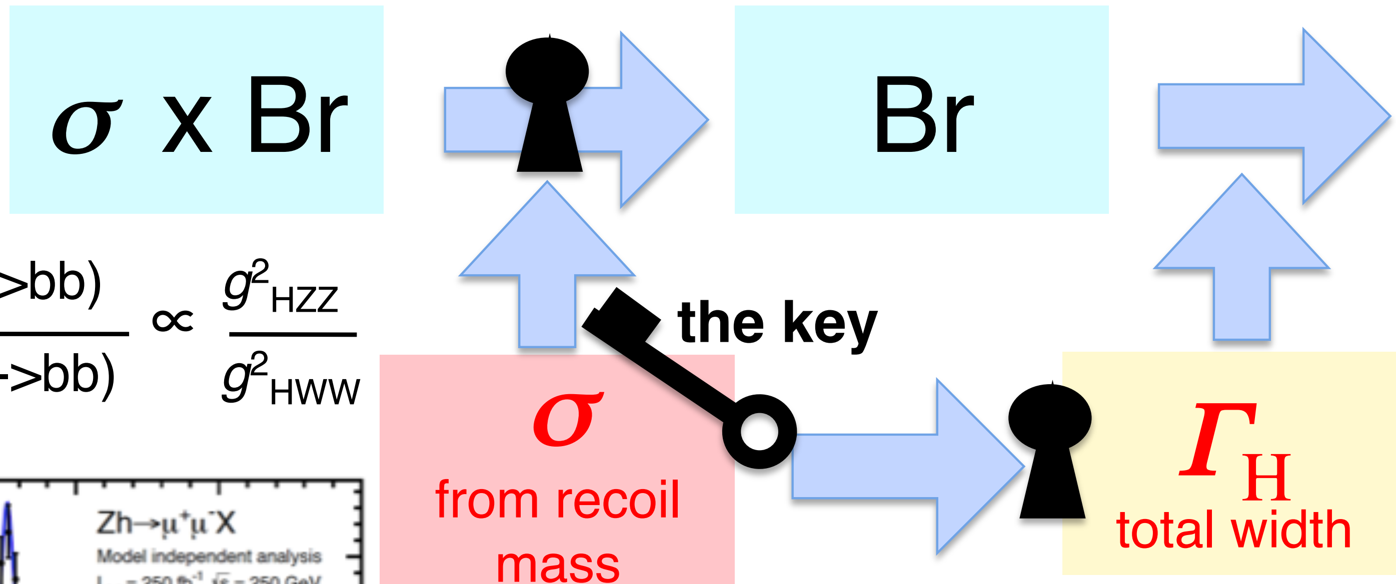
FCC-ee: 90–350 GeV

Physics motivations



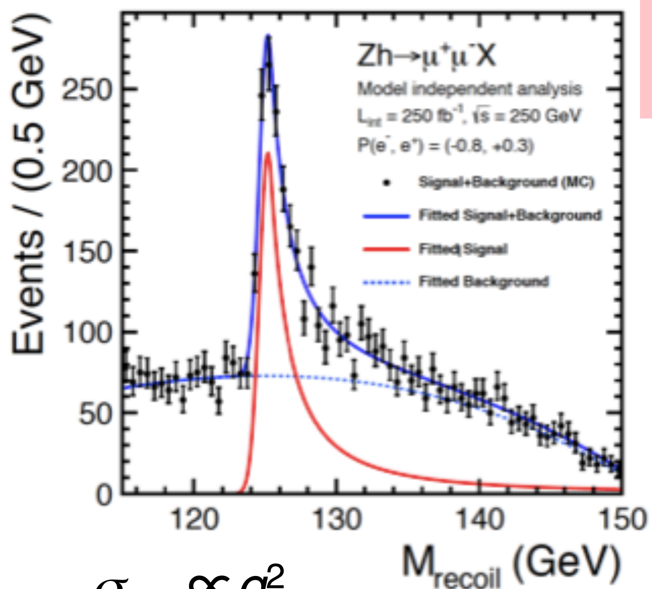
Higgs overview

$$g^2_{HAA} \propto \Gamma(H \rightarrow AA) = \Gamma_H \cdot BR(H \rightarrow AA)$$



$$\frac{\sigma_{ZH}\ .Br(H\text{->}bb)}{\sigma_{\nu\nu H}\ .Br(H\text{->}bb)} \propto \frac{g^2_{HZZ}}{g^2_{HWW}}$$

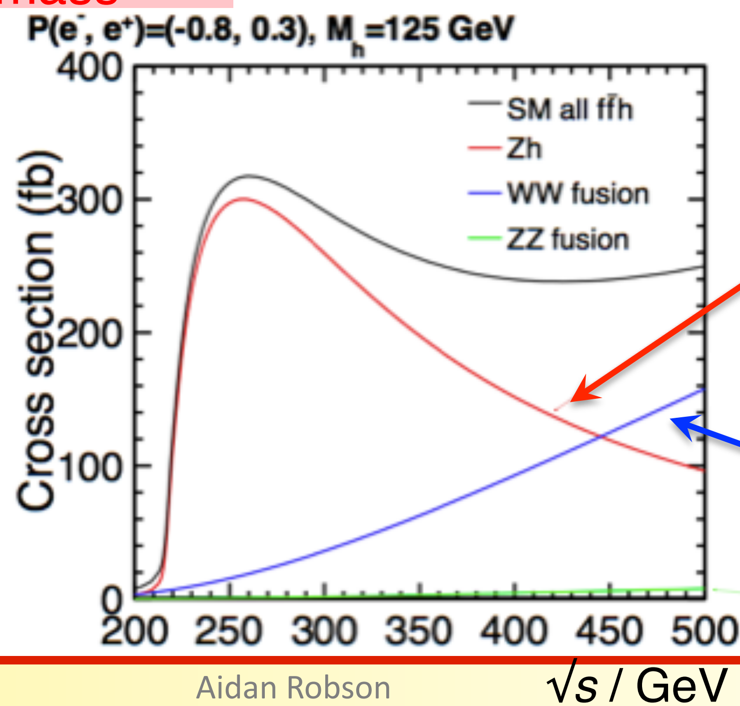
(need WW fusion for precision total width -> higher $\sqrt{s}$)

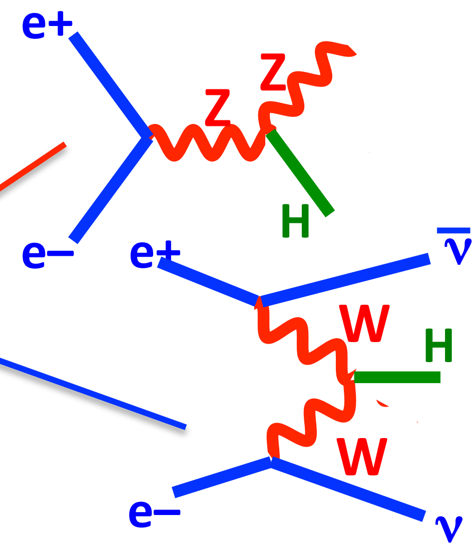


$\sigma_{ZH} \propto g^2_{HZZ}$

$\sigma_{\nu\nu H}\ .Br(H\text{->}WW) \propto g^4_{HWW}/\Gamma_H$

after Fujii/Tanabe





Higgs overview

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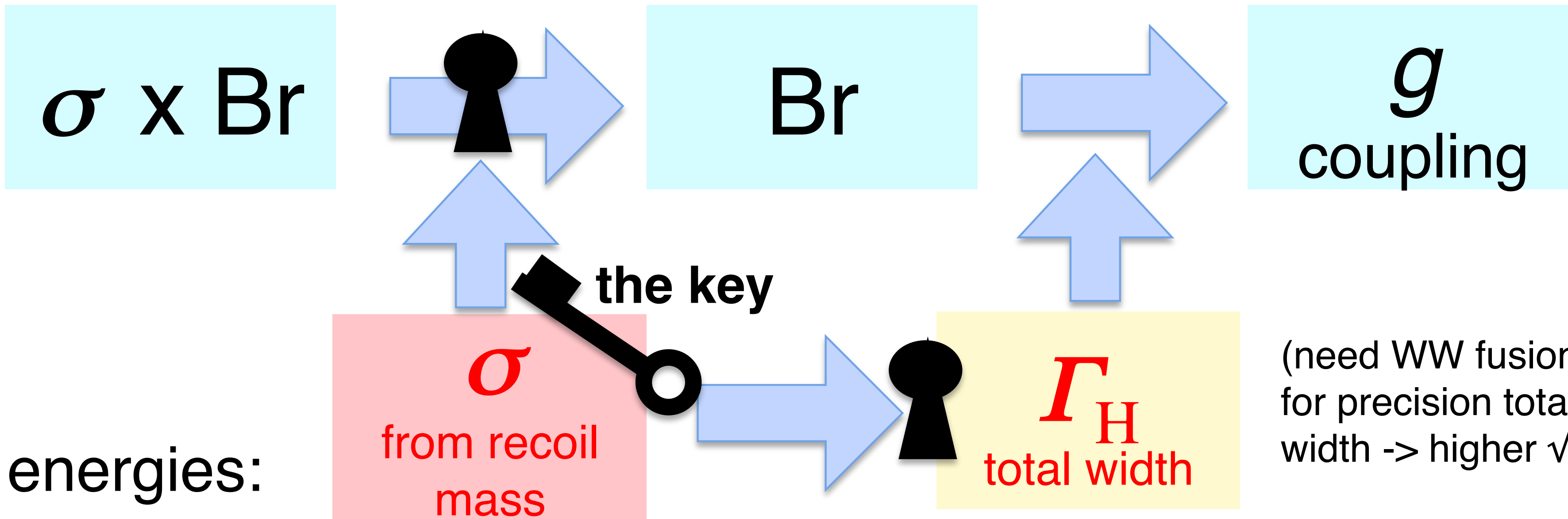
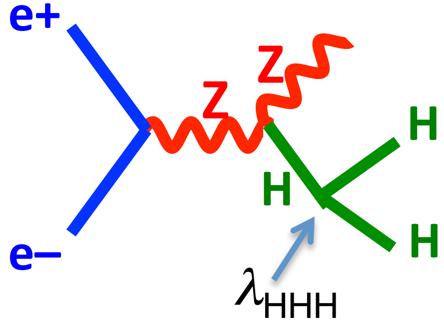
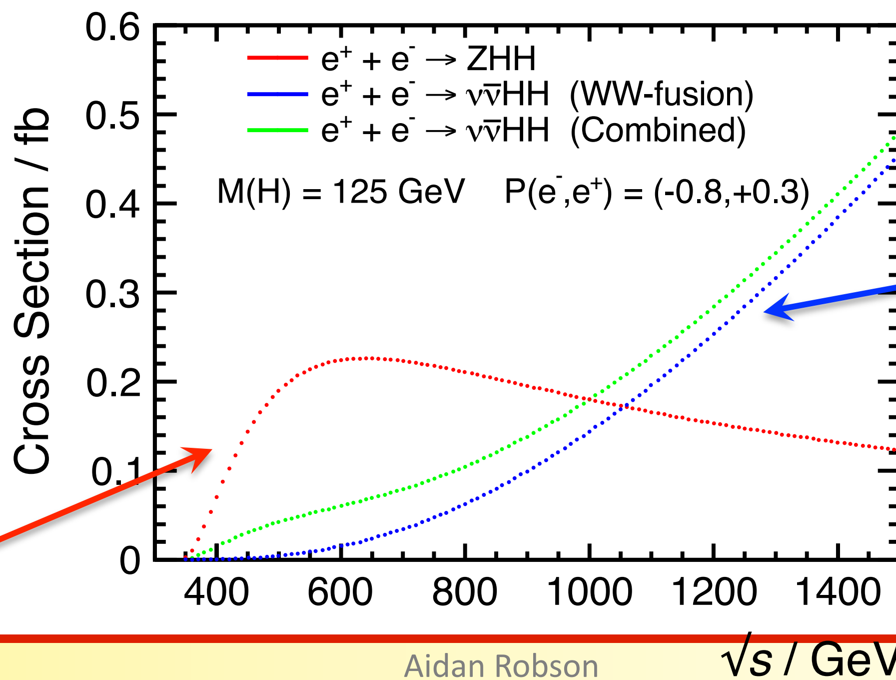


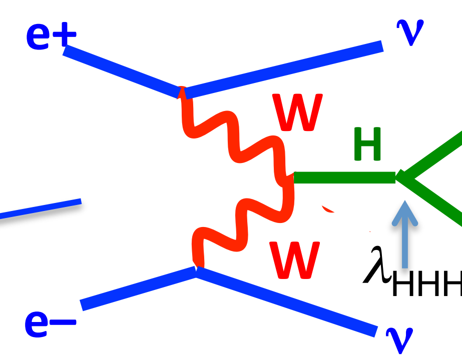
(need WW fusion for precision total width -> higher √s)

Higher energies: ttH, HH



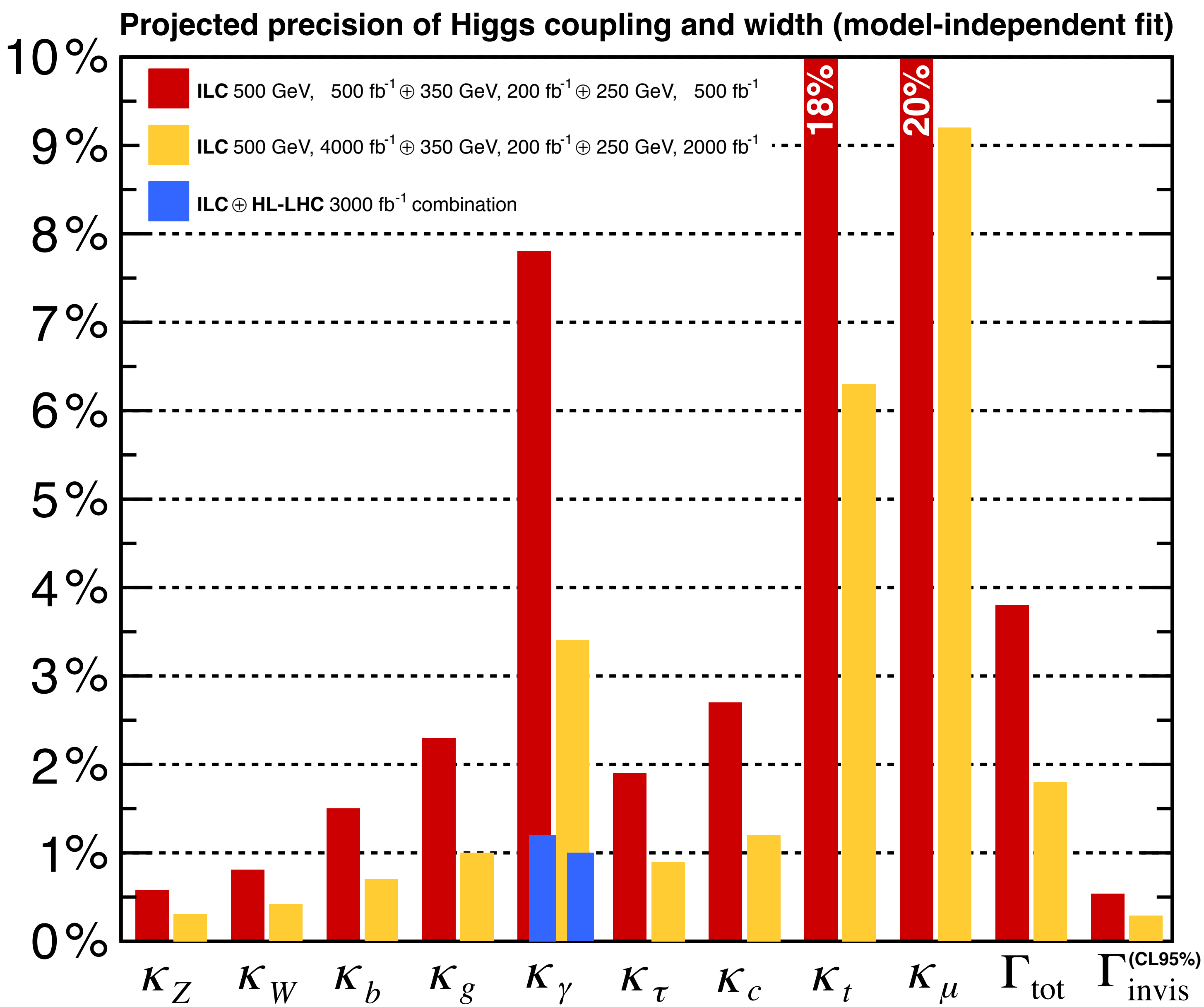
dominates around √s=500GeV





dominates at higher √s

Higgs couplings



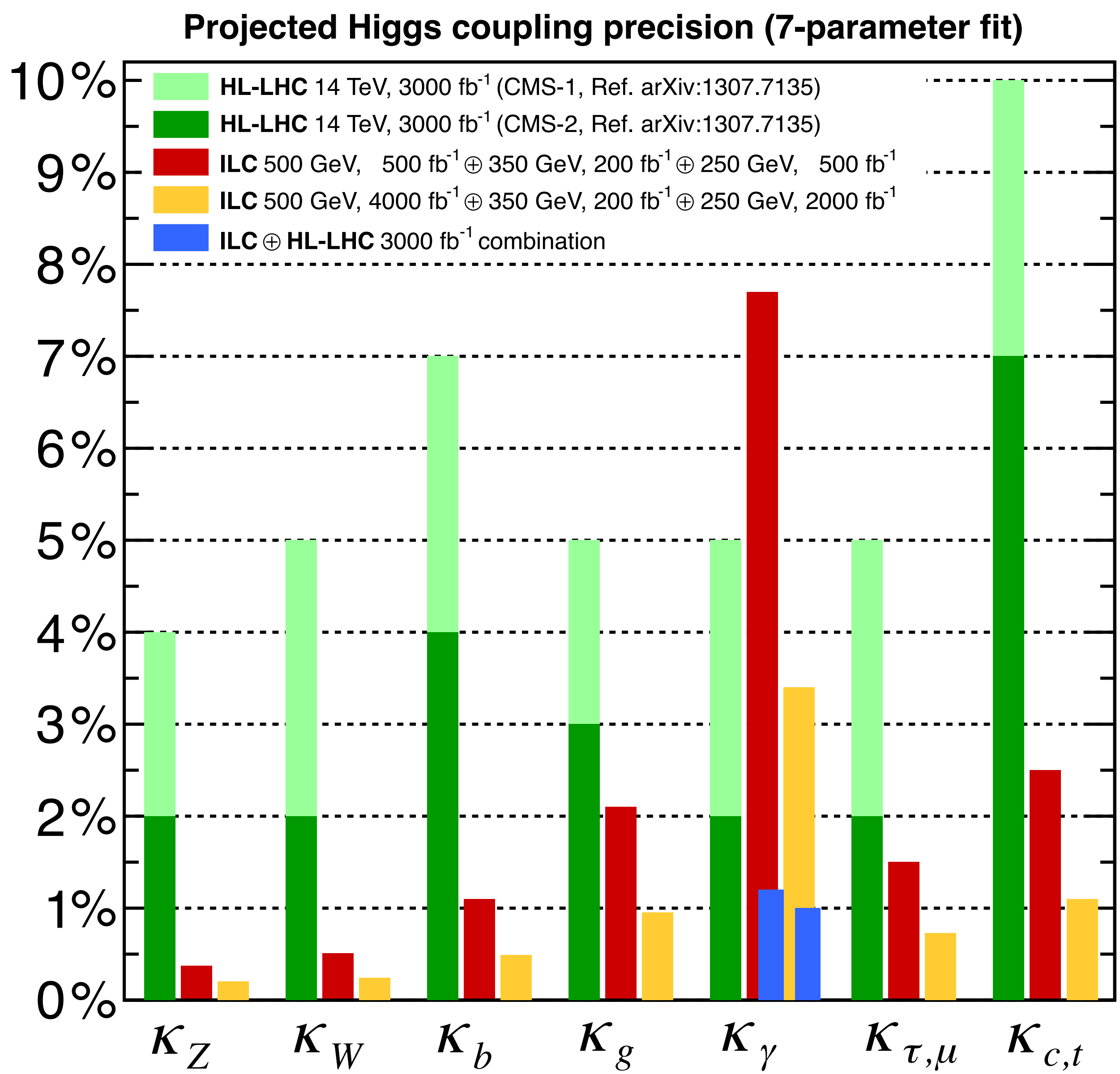
model-independent

- ILC
  - 500GeV, 500 fb^{-1}
  - 350GeV, 200 fb^{-1}
  - 250GeV, 500 fb^{-1}
  - (8 years)
- ILC
  - 500GeV, 4000 fb^{-1}
  - 350GeV, 200 fb^{-1}
  - 250GeV, 2000 fb^{-1}
  - (+10 years)
- ILC+HL-LHC 3000 fb^{-1}

TeV-scale NP gives O(1%) deviations on H couplings

…compare to HL-LHC

with LHC can only compare model-dependent fits:



assumes fractional shift in κ is equal for u,c,t ; for d,s,b ; and for e,μ,τ ; and no Higgs decay to invisible/exotic particles

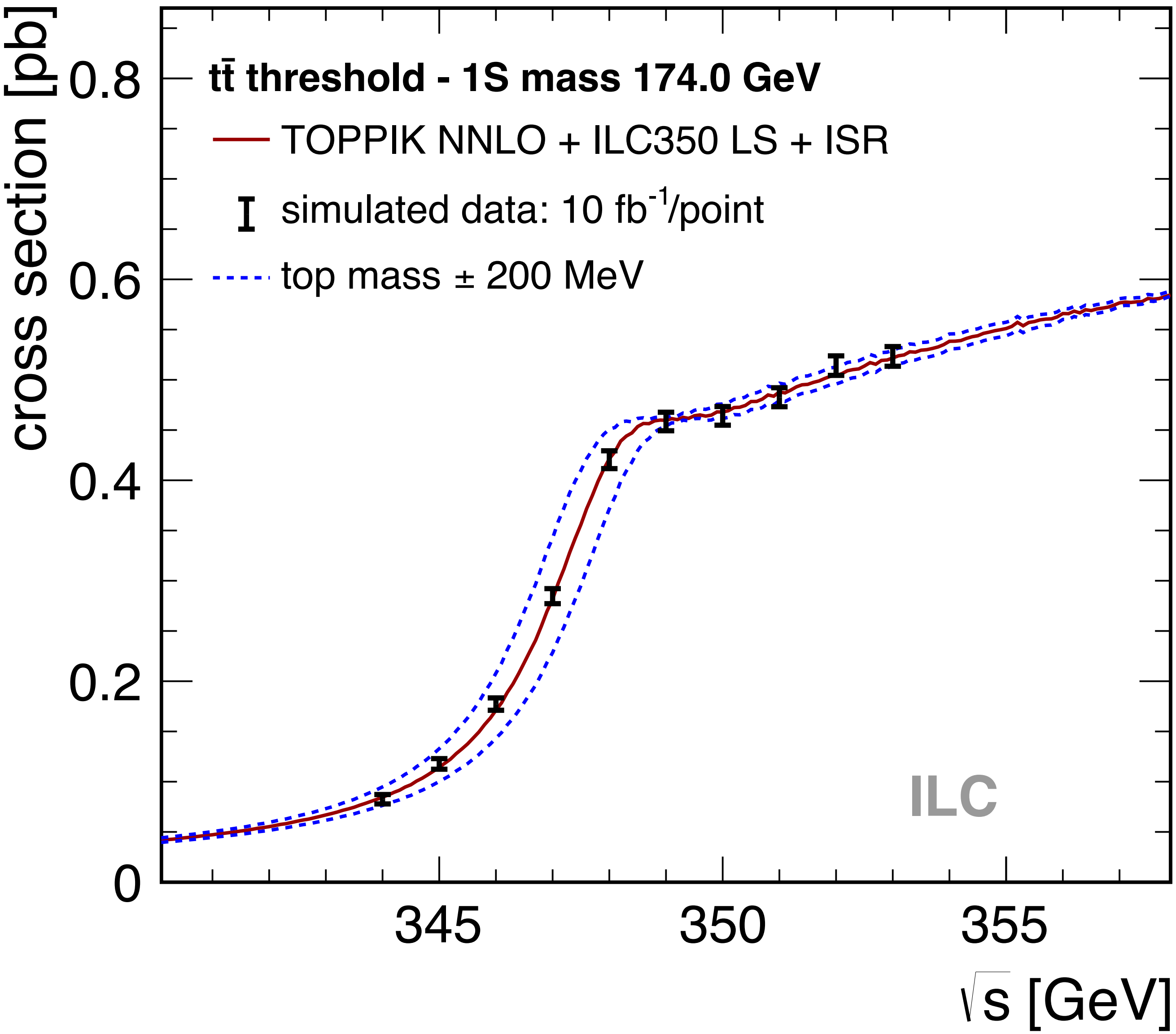
Higgs couplings

Coupling √s (TeV)→ L (fb^{-1}) →	LHC 14 3000(1 expt)	CepC 0.24 5000	FCC-ee 0.24 +0.35 13000	ILC 0.25+0.5 6000	CLIC 0.38+1.4+3 4000	FCC-hh 100 40000
K_W	2-5	1.2	0.19	0.4	0.9	
K_Z	2-4	0.26	0.15	0.3	0.8	
K_g	3-5	1.5	0.8	1.0	1.2	
K_γ	2-5	4.7	1.5	3.4	3.2	< 1
K_μ	~8	8.6	6.2	9.2	5.6	~ 2
K_c	--	1.7	0.7	1.2	1.1	
K_τ	2-5	1.4	0.5	0.9	1.5	
K_b	4-7	1.3	0.4	0.7	0.9	
$K_{Z\gamma}$	10-12	n.a.	n.a.	n.a.	n.a.	
Γ_h	n.a.	2.8	1.	1.8	3.4	
BR_{invis}	<10	<0.28	<0.19	<0.29	<1	
K_t	7-10	--	13% ind. tt scan	6.3	<4	~ 1 ?
K_{HH}	?	35% from K_Z model-dep	20% from K_Z model-dep	27	11	5-10

Units are %

summary table from Fabiola Gianotti LP15

Precision top physics



observe 1S 'bound state'
$\Delta m_t \sim 50$ MeV

separately measure left- and right-handed couplings to Z (sensitive to 10–15TeV Higgs-sector resonance coupling to top)

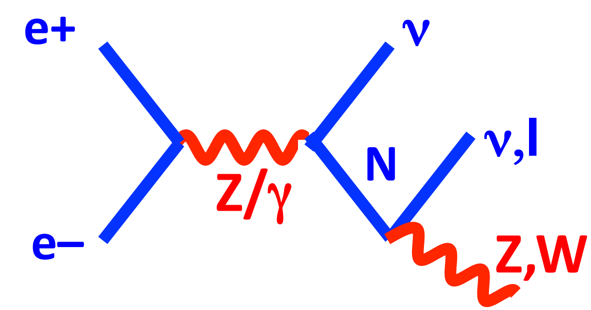
Direct BSM

example: 'compressed' spectrum

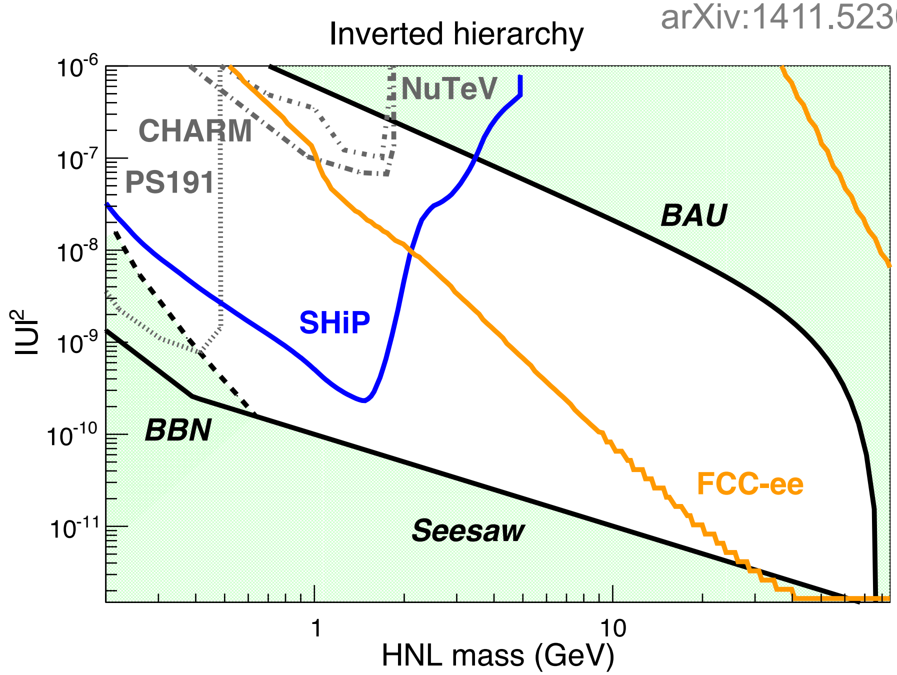
$\tilde{W}$ and $\tilde{B}$ excluded by LHC where well-separated in mass from LSP. But if mass difference < 20GeV, visible decay products too soft to trigger.

example: very rare decays (FCC-ee)

search for right-handed neutrino N in 10^{12} Z decays

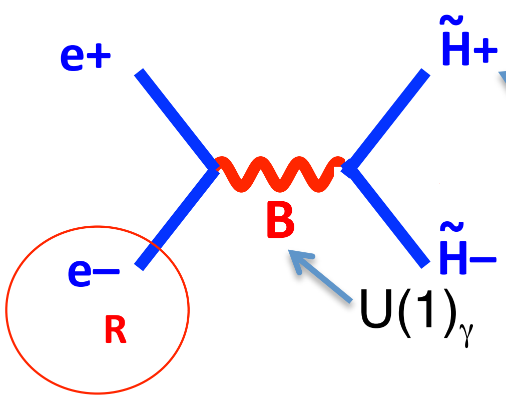


arXiv:1411.5230



example: disentangling couplings to new particle

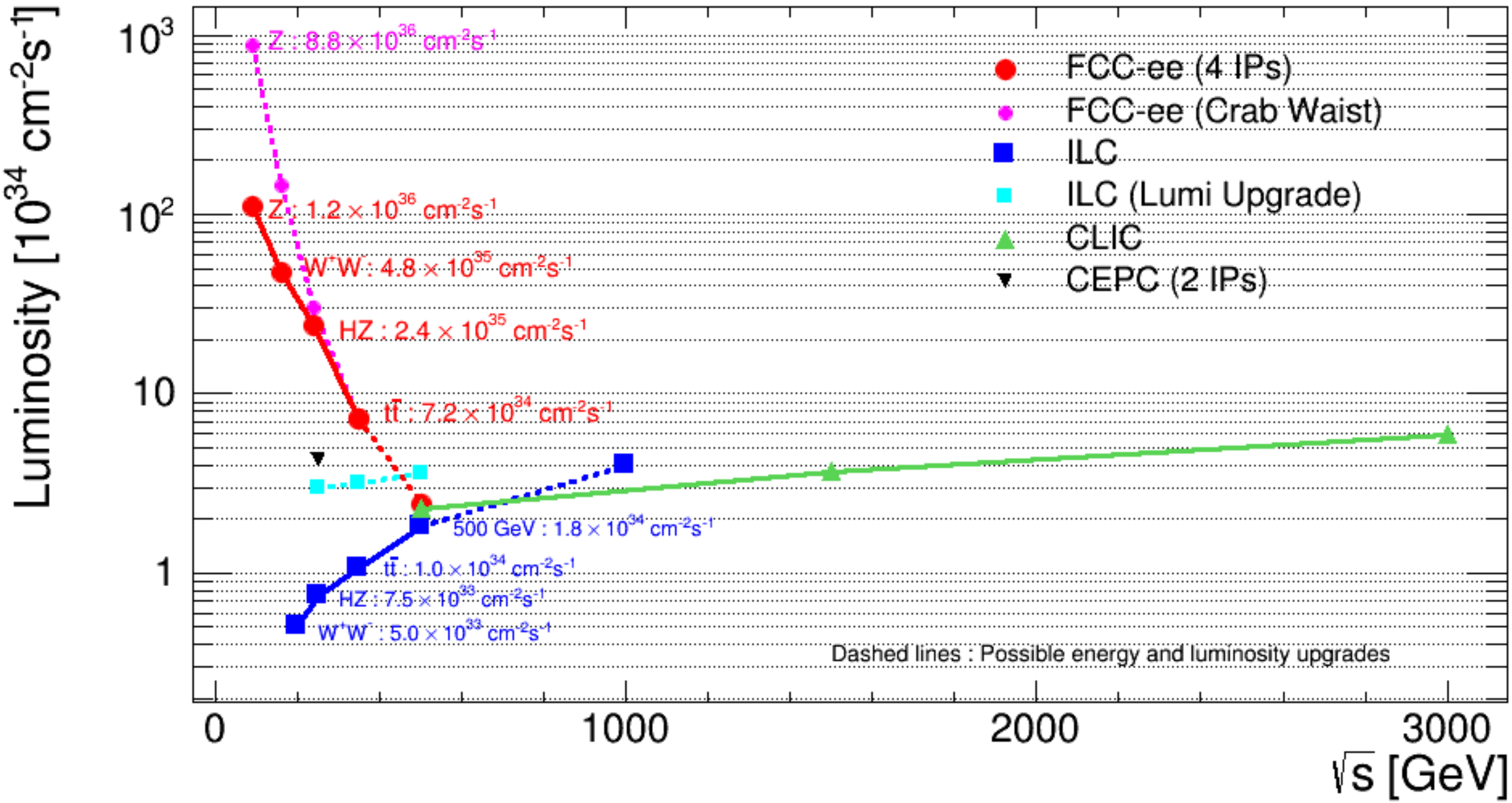
Polarized beams -> decomposition:



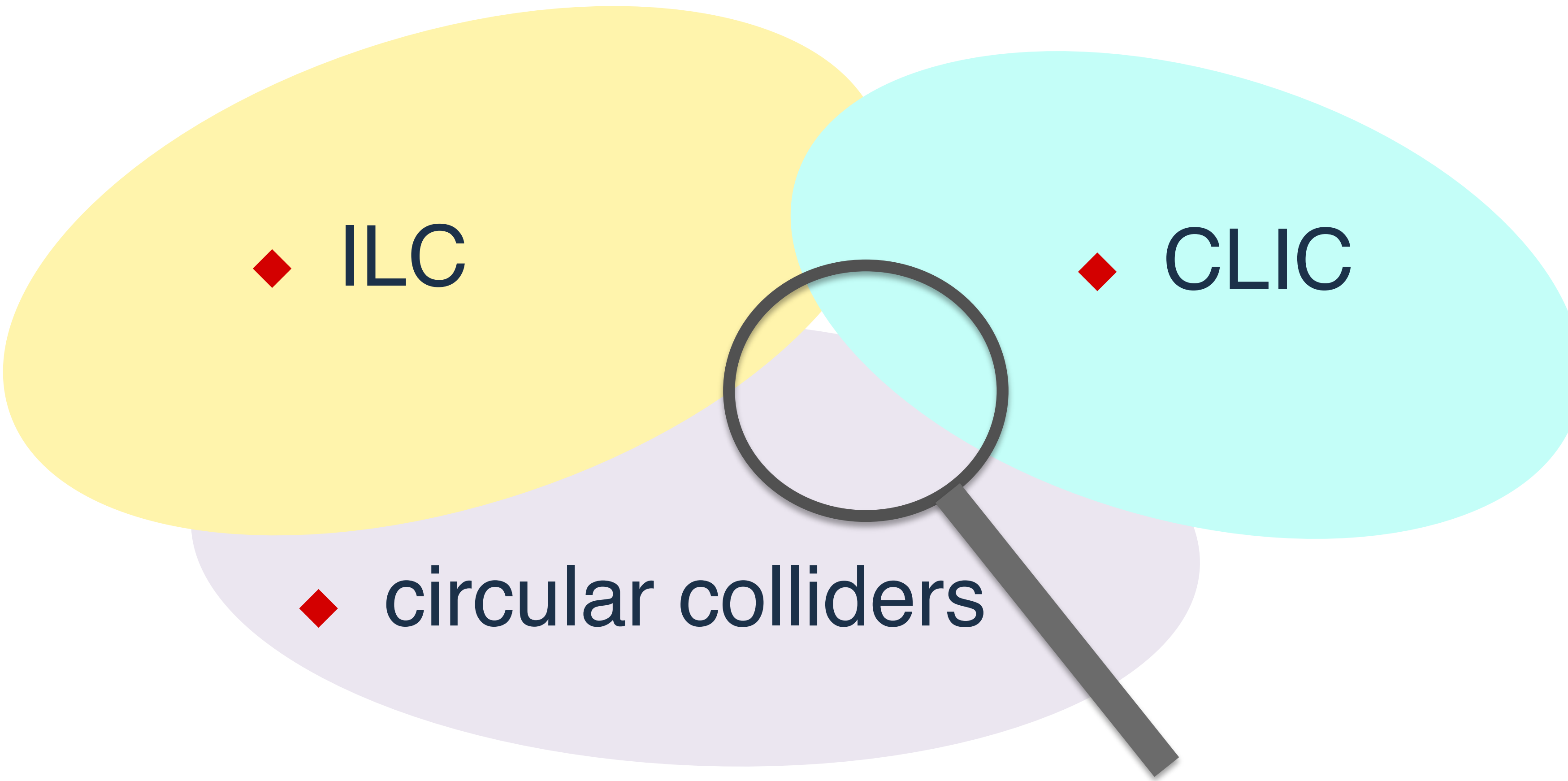
Only $\tilde{H}^{\pm}$ components of $\tilde{\chi}_1^{\pm}$ contribute

$$\tilde{\chi}_1^{\pm} = \alpha\tilde{W}^{\pm} + \beta\tilde{H}^{\pm}$$

Physics reach



Accelerator developments



NB, ‘LCC’ is Linear Collider Collaboration,
– umbrella group directed by Lyn Evans

ILC accelerator developments

Global Design Effort (GDE) 2005–12

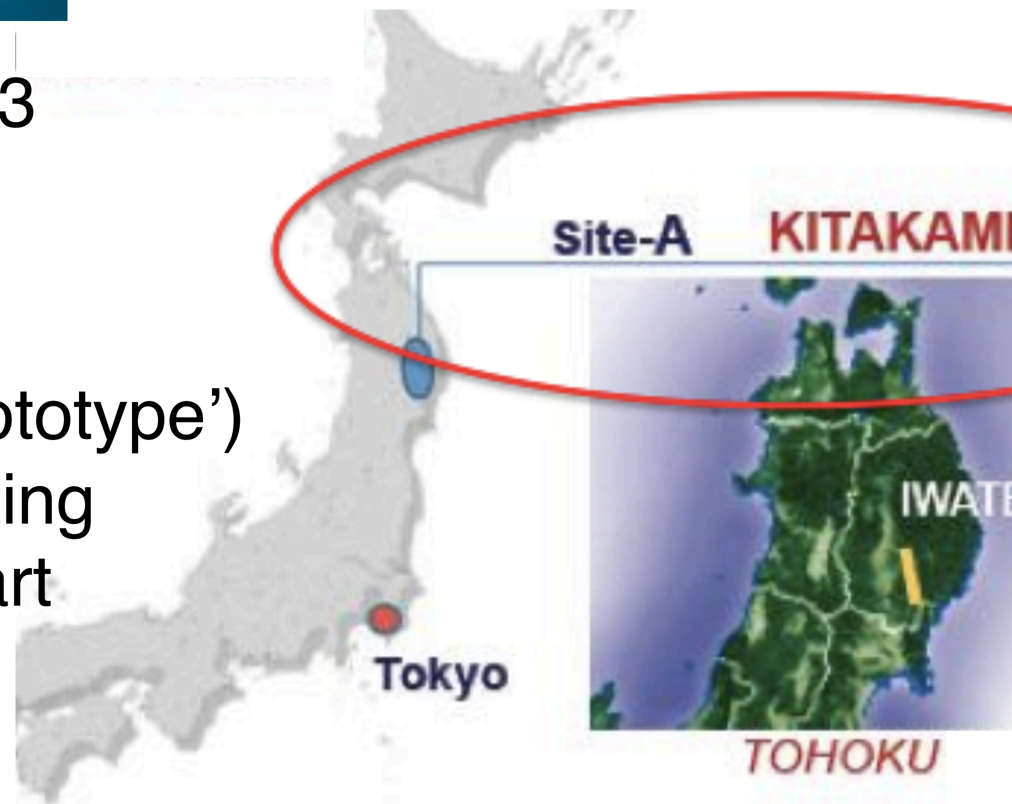
engineering design phase

site-specific design

Reference Design Report 2007

TDR 2013

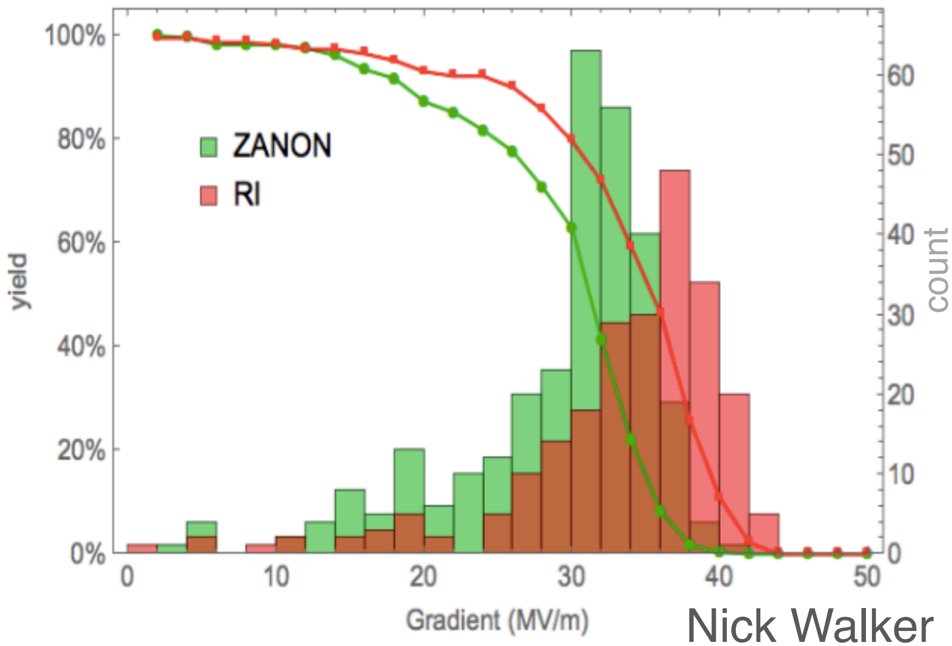
- Mature technology
- XFEL is being constructed (‘prototype’)
- Japan making decision on hosting
- 10-years construction could start ~now -> physics in 2028



ILC accelerator developments

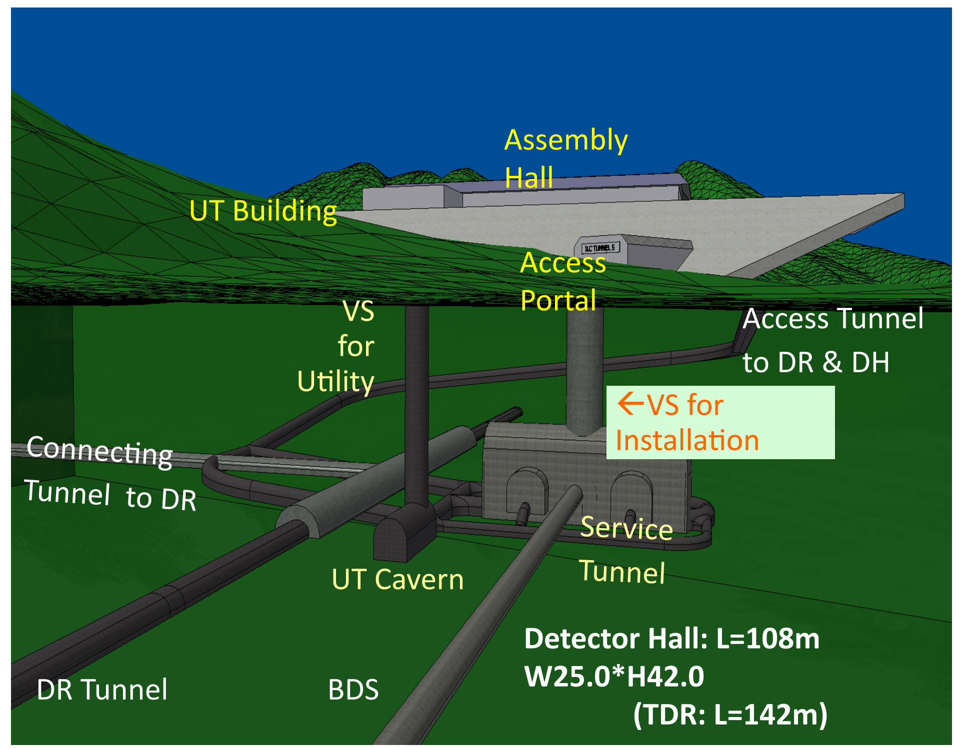
XFEL is 5%-scale 'ILC prototype', needs 24 MV/m ;
ILC needs 31.5 MV/m

European XFEL Test results: MAX GRADIENT



Nick Walker

Site-specific adaptations: vertical shaft



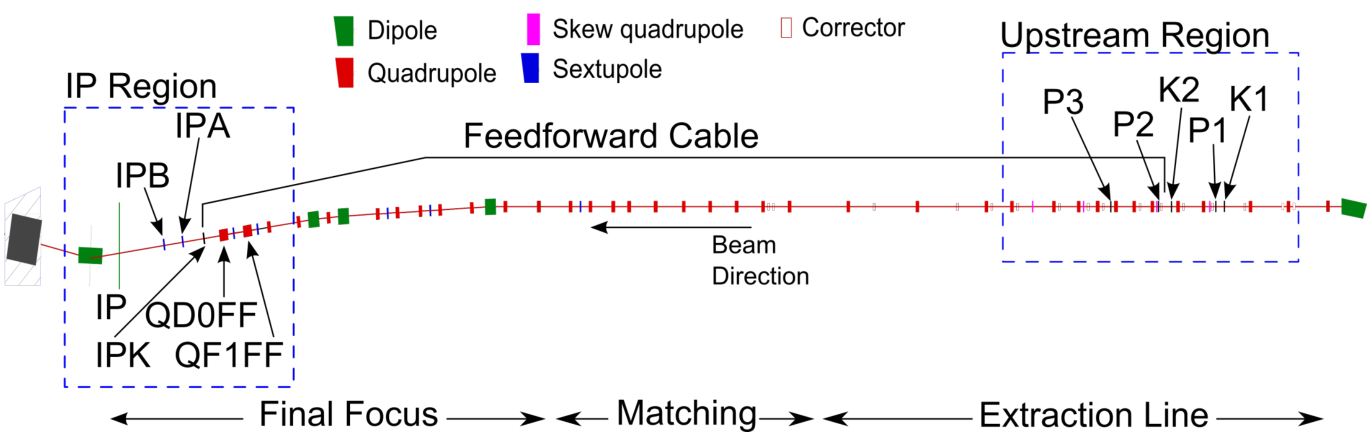
ILC current challenges:

- positron source
- final focus, nm-size beams

Accelerator developments

Example highlight:

FONT – Feedback on Nanosecond Timescale
– for both ILC and CLIC



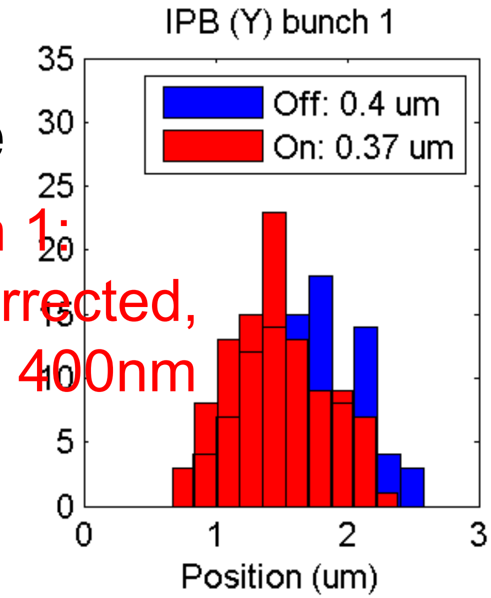
Phil Burrows

At ATF2 (KEK)

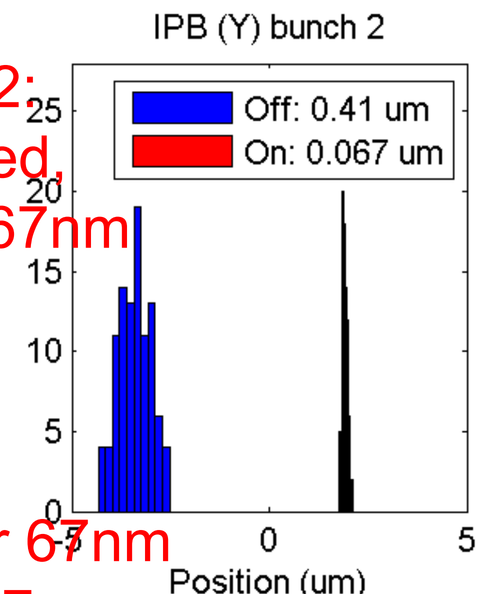
Aim to stabilise beam in IP region using 2-bunch spill:

1. Upstream FB: monitor beam at IP
2. Feed-forward from upstream BPMs → IP kicker (IPK)
3. Local IP FB using IPBPM signal and IP kicker

Aim is 37nm beam



Bunch 1:
not corrected,
jitter ~ 400nm



Bunch 2:
corrected,
jitter ~ 67nm

Corrected jitter 67nm
→ resolution 47nm

Accelerator developments

developing:

- normal-conducting accelerating cavities (Cockcroft)
- cavity diagnostics (Manchester, Liverpool)
- crab cavities and klystrons (Lancaster)
- feed-forward systems and diagnostics (John Adams) – machine–detector interface and beam delivery system
- diagnostics, permanent magnets and RF (ASTeC)

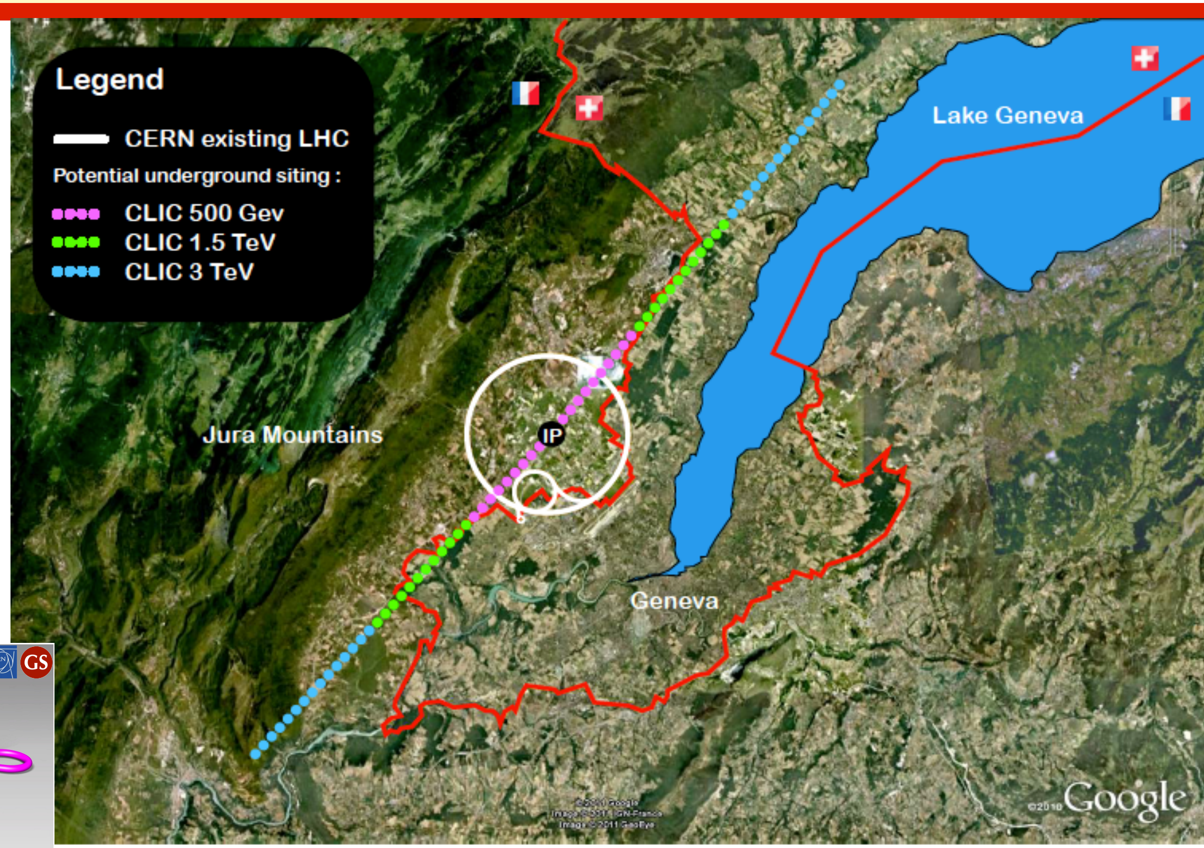
most work is generic, for both ILC and CLIC

CLIC accelerator developments

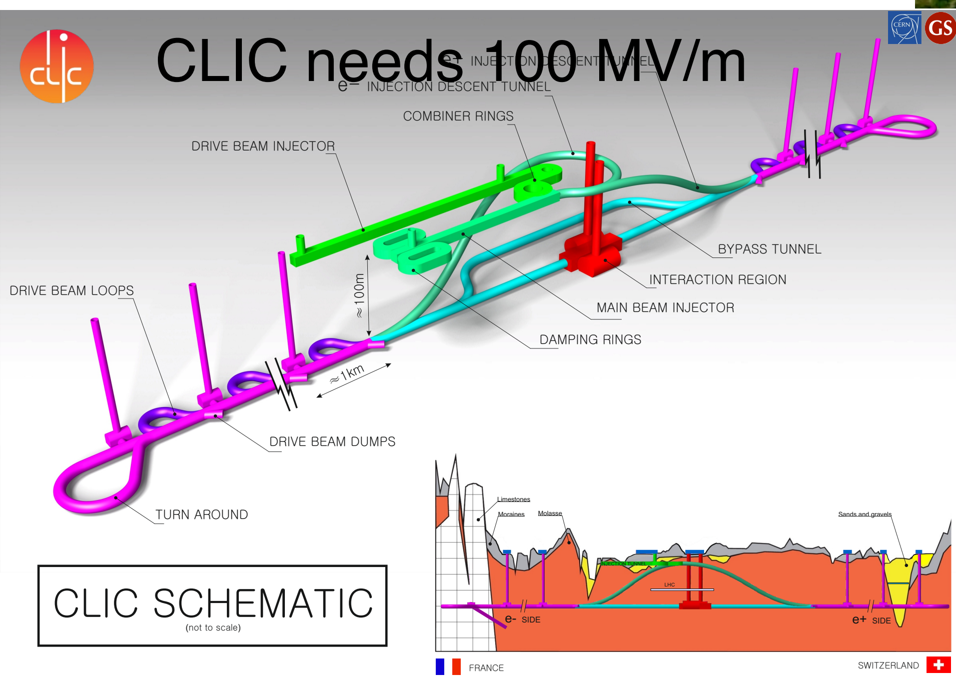
Phil Burrows (Oxford)
Spokesman

(~50 institutes, including ASTeC, Dundee, Lancaster, Manchester, Oxford, RHUL;
CLIC-UK supported by >£5M from CERN since 2011)

CDR 2012. TDR 2022?
Construction 2023–2030?



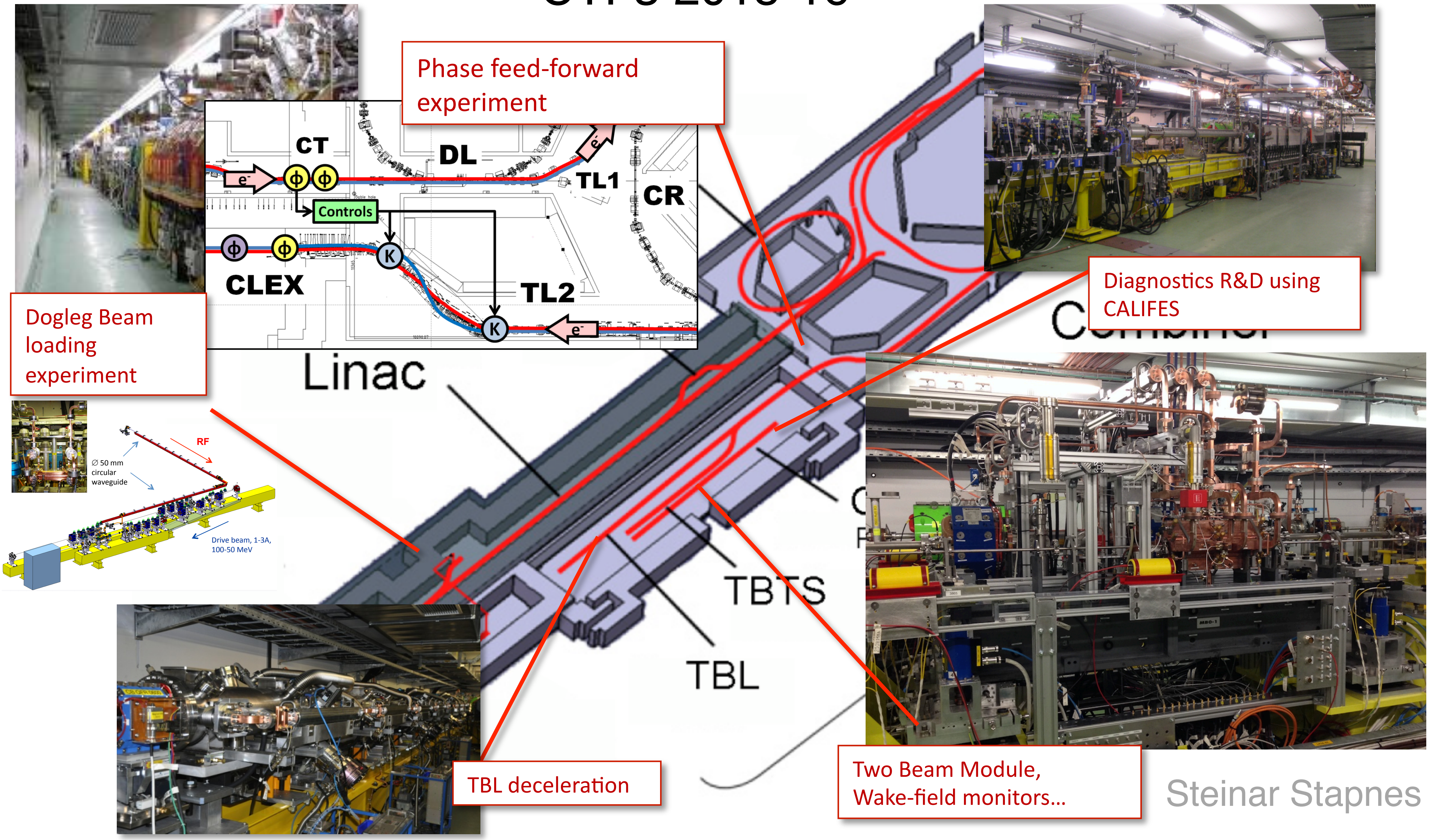
CLIC needs 100 MV/m



- developing project plan 2018 -> TDR 2022?
- high-gradient accelerating structure test results good
- experimental verification at CLIC Test Facility (CTF3) very successful
- looking at power reductions, optimizations

CLIC accelerator developments

CTF3 2015-16



Circular collider developments

CEPC

54km ring
√s=240GeV e+e- with 2IPs
pre-study 2013–15 -> pre-CDR submitted
R&D and Engineering design 2015–20
Construction 2021–27
Data-taking 2028–35

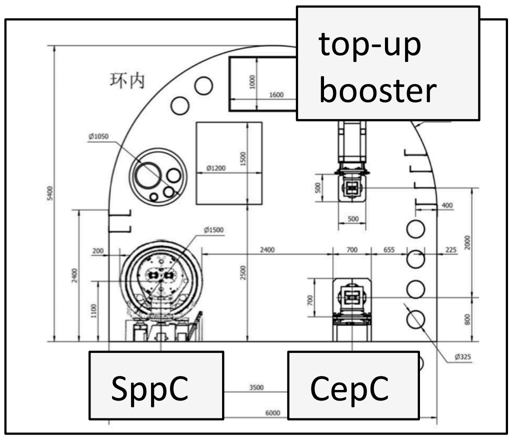
FCC (as presented by Fabiola)

100km ring
Goal: pp, √s=100TeV
Possible intermediate step:
e+e- √s=90–350GeV
Option: ep, √s=3.5TeV
Goal: CDR in ~2018

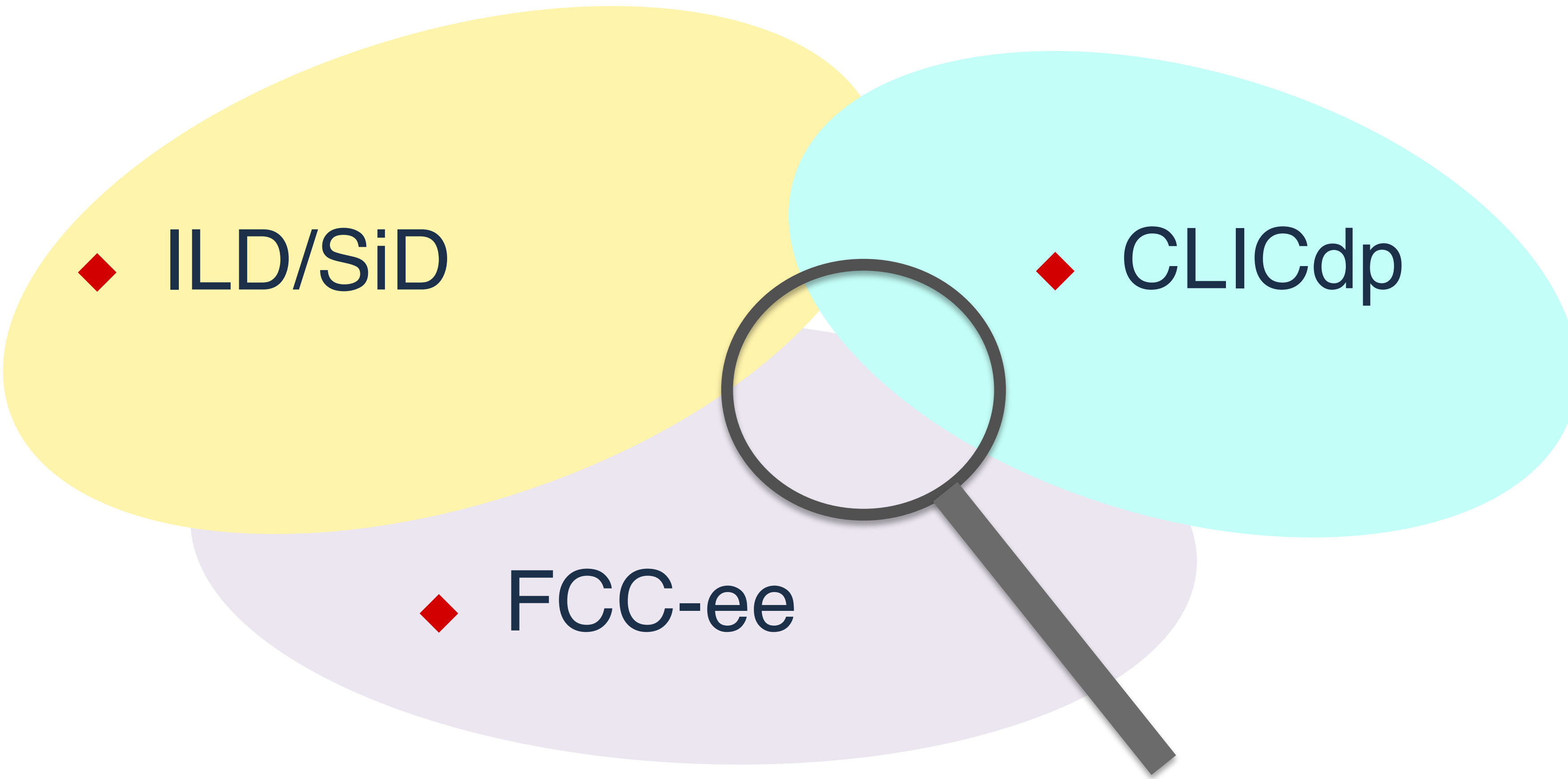
SppC

√s=70TeVpp with 2IPs
pre-study 2013–20
R&D 2020–30
Engineering design 2030–35
Construction 2035–42
Data-taking 2042–

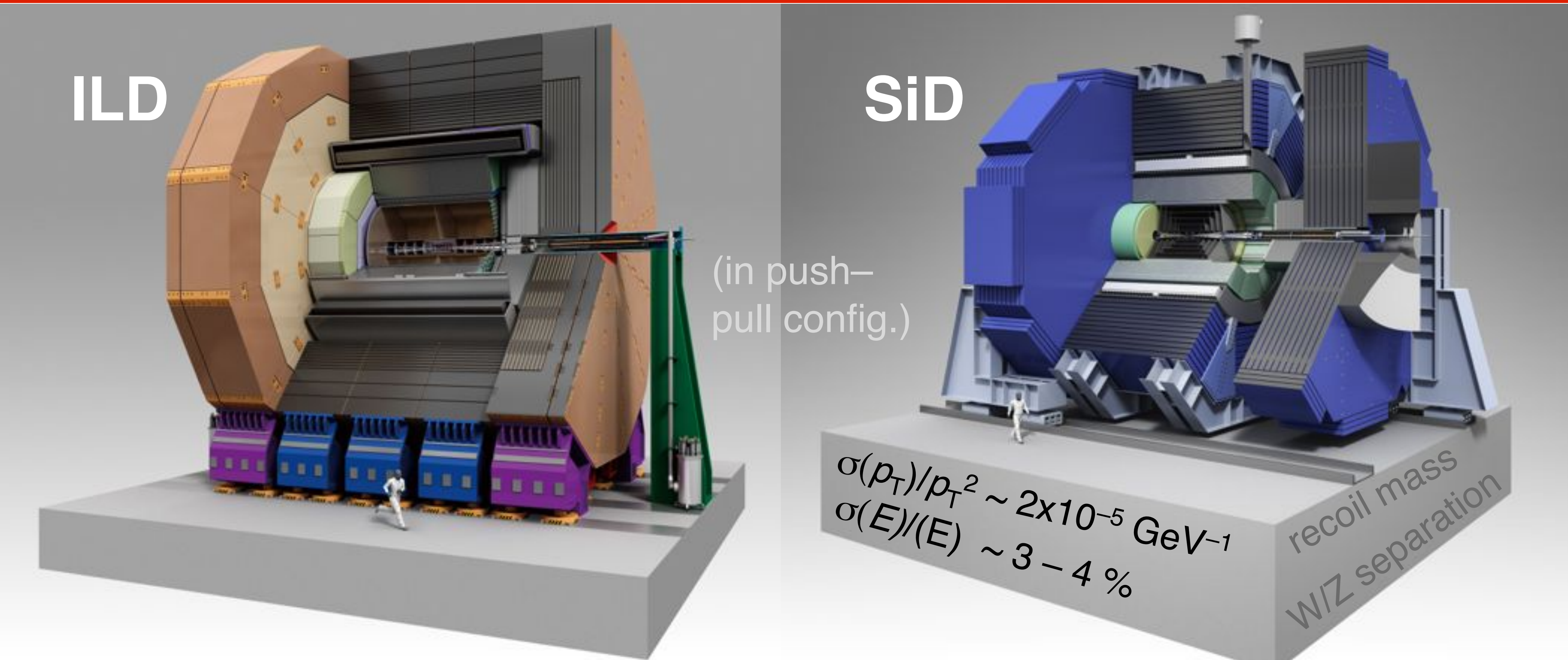
e+e–:
aim to converge on optics and beam dynamics by autumn (crab-waist collision scheme)
need to understand beam-beam effects



Detector collaboration developments



ILC detector collaborations



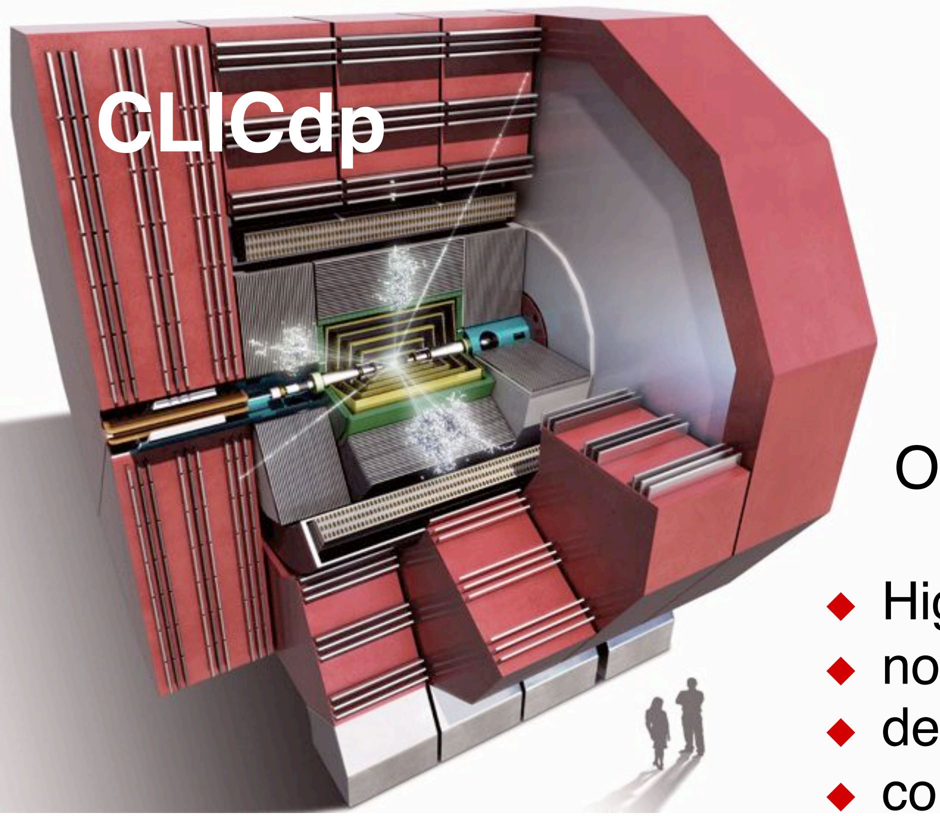
Early leadership of ILD physics/optimization

Joel Goldstein (Bristol) Vertex group convenor

Phil Burrows (Oxford) Collaboration Board chair

- Adopting more formal structures
- LoIs 2009/10; now moving towards TDRs
- Converging on common L*, working on fringe fields…

CLIC detector collaboration



John Marshall (Cambridge)
Physics group convenor

Aidan Robson (Glasgow)
Collaboration Board chair

26 institutes from
16 countries

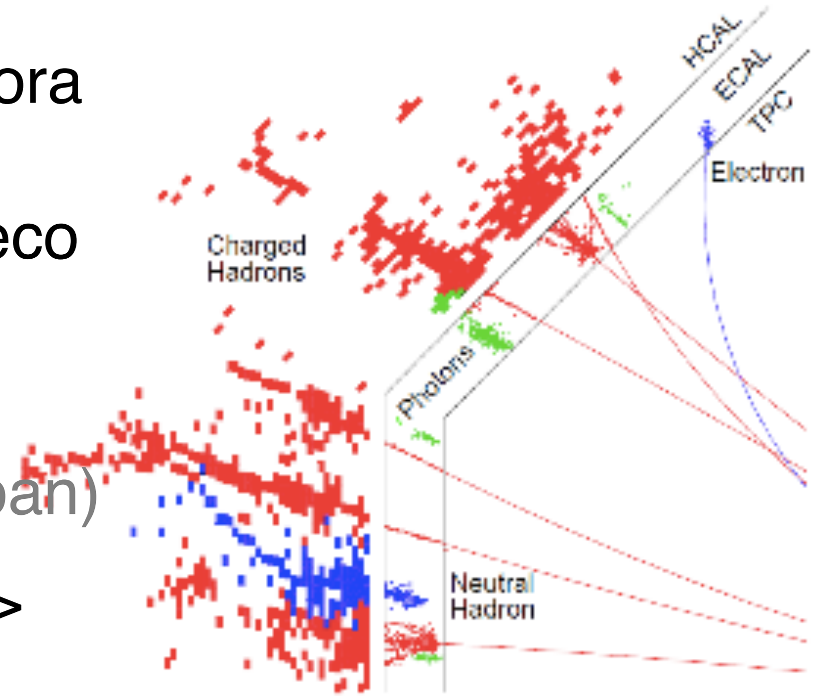
Ongoing priorities:

- Higgs benchmarking studies (paper in progress)
- now focus on top and BSM capabilities
- detector optimisation -> new CLIC detector concept
- continuing vertex technology R&D
- continuation of fine-grained calorimeter R&D
- start of main silicon tracker R&D
- development of new software tools

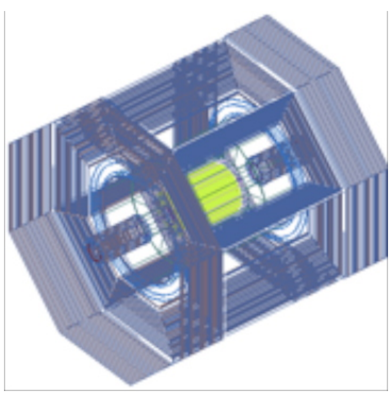
Cambridge, Glasgow, Liverpool, Bristol, Edinburgh active in physics studies, software and simulation development, and silicon hardware development – all overlapping with ILC

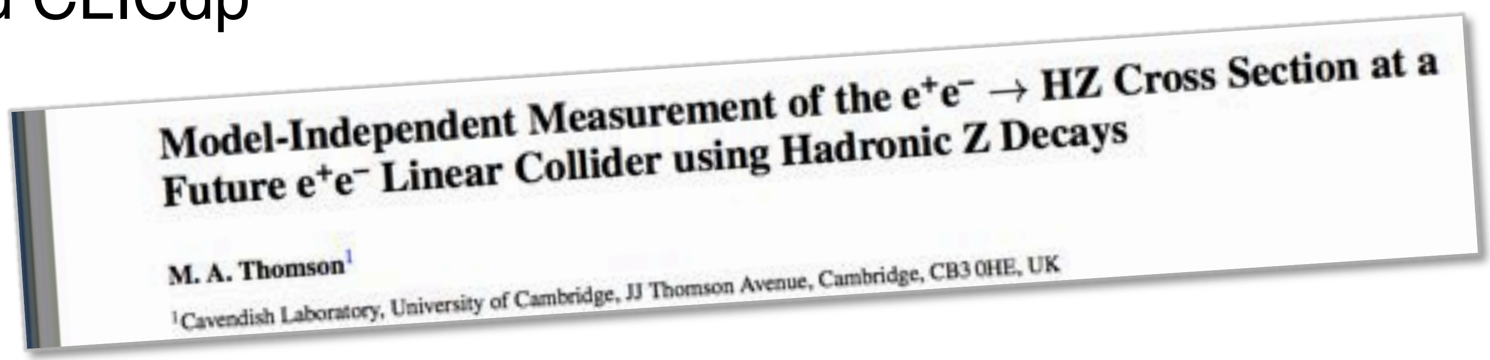
Software and physics

- almost all LC studies based on Pandora C++ software development kit (Cambridge) – flexible particle-flow reco
- almost all LC studies use LCFIVertex flavour-tagging software (written in UK, now maintained in Japan)
- physics studies e.g. hadronic recoil -> staging choices for ILC and CLIC
- provided new ECAL simulation model for both ILD and CLICdp



Typical topology of a simulated 250 GeV jet in ILD




Model-Independent Measurement of the $e^+e^- \to HZ$ Cross Section at a Future e^+e^- Linear Collider using Hadronic Z Decays

M. A. Thomson[1]

[1]Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge, CB3 0HE, UK

ILC Silicon (1)

UK ILC efforts boosted by modest 2-year (travel) budget from PPRP, 2015–16 -> focus detector & physics efforts

UK history: Monolithic Active Pixel Sensors (MAPS)
– CALICE-UK, SPiDer, Arachnid
Materials – Low Mass, PLUME
LCFI

ILC silicon effort focus now: pixel tracker development

Aim: credible design for ILC pixel tracker

advantages in resolution and pattern recognition balanced with implications of timing, cooling etc.

(UK proposed SPT pixel tracker in 2008 – Chris Damerell et al.)

– simulation (Glasgow, Bristol)
– (HV-)CMOS sensor R&D (RAL, OU, Liverpool, Glasgow, Oxford, …)
– mechanics, cooling, alignment (Oxford, Liverpool, Bristol)

– building on existing strong expertise/infrastructure
LHC and HL-LHC build programmes / active R&D programmes

ILC Silicon (2)

- Simulation work
  – to guide layout choice and technology solution
  started from SiD model (Glasgow, Bristol)

- Sensor work

  Long involvement MAPS (RAL, OU, Oxford, Glasgow)

  Broad R&D started in HV-CMOS (both hybrid & standalone sensors)
  – sensor design work (Liverpool, KIT, Geneva)
  – pixel demonstrator engineering run submission
  – TCAD effort towards device optimisation (Liverpool, CERN, Geneva, Paris, Bonn)
  both pixel demonstrator + participation in ATLAS-wide HV-CMOS strip
  – characterisation: testbeam, source, X-ray (Glasgow, Liverpool, Oxford)

- Mechanics

  structures, mechanics, cooling (Oxford, Liverpool, Bristol)
  alignment (Oxford)

ILC DAQ/Online (1)

UK history: Delivered CALICE DAQ in ~2008
–some hardware still being used
Involved in AIDA (EU FP7)

Current institutes:
Bristol, Liverpool, RHUL, RAL, Sussex, UCL, Warwick

Current focus:

- AIDA-2020 'Advanced European Infrastructures for Detectors at Accelerators' (Bristol, Sussex, UCL)

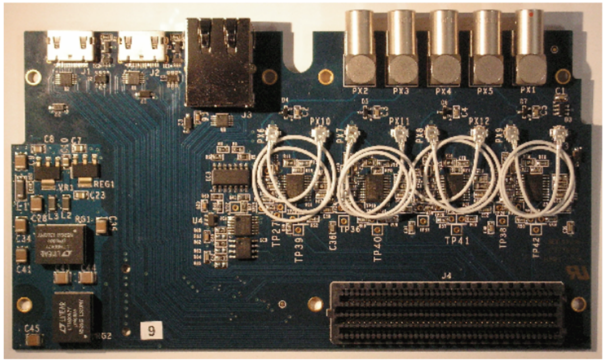
WP5: Data acquisition system for beam tests

David Cussans (Bristol)
Matthew Wing (UCL)
} WP5 leaders

Providing common DAQ to LC detectors in testbeams

e.g. (hardware) control and timing interface (TLU)
(online/data quality monitoring)
EUDAQ software enhancements

(starting PhD student at Sussex)



TLU

ILC DAQ (2)

- Detailed DAQ design studies

  Full timing loop, readout challenges, peak data rate scenarios etc.

- DAQ R&D

  Characterisation of newer architectures (TCA, Scalable Readout System etc.) to establish suitability

  e.g. new collaboration between Oxford Physics and industrial partners VadaTech, Etalon AG, aiming to reduce overall development effort needed for high-speed digitisers with custom signal processing and fast online computation

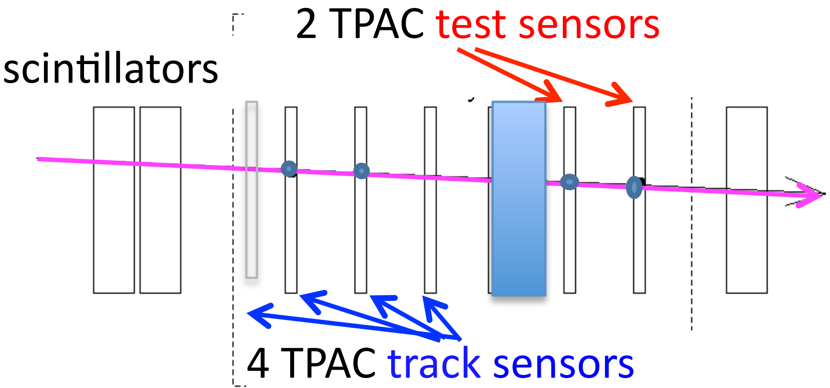
Aim for LC: put UK in a position to lead the DAQ of a sub-detector/overall architecture

ILC Calorimetry

UK history:

CALICE-UK, international R&D programme including :
DAQ, MAPS (digital ECAL concept), test beam analysis, Particle Flow s/w

- some continued UK involvement (Birmingham/ RAL/Sussex) in MAPS for digital calorimetry
- shower profile studies using MAPS sensor 'TPAC' for DECAL calorimeter layer



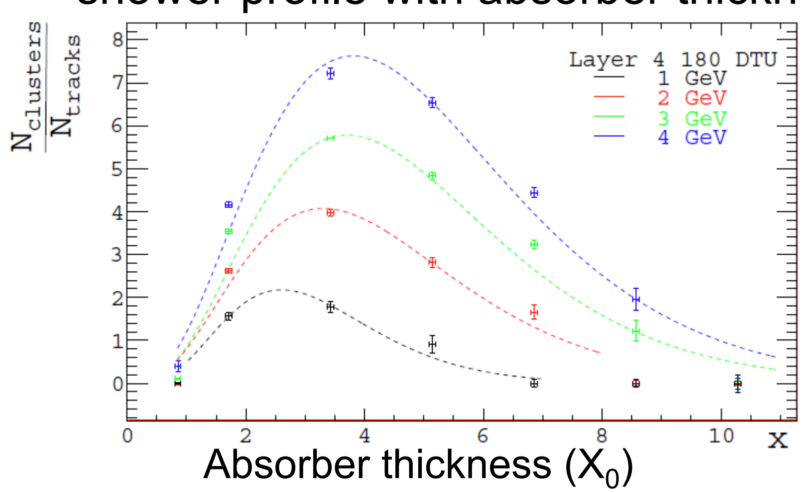
Project tracks to individual test sensors

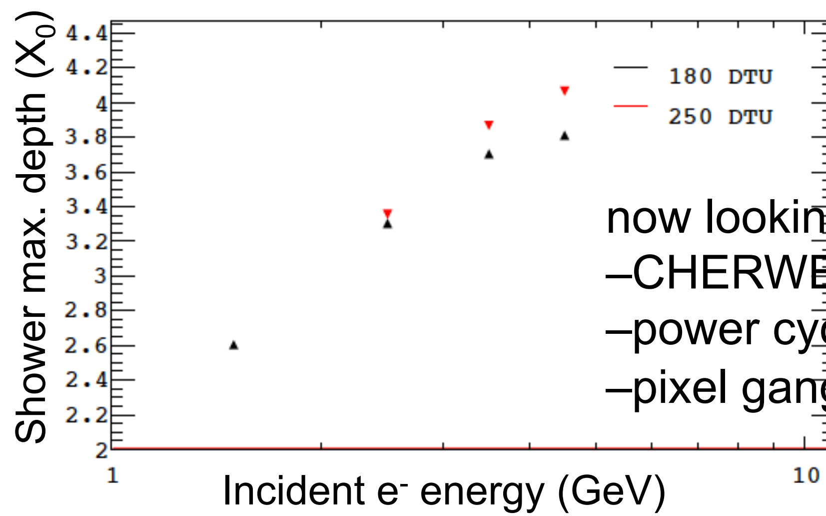
Vary depth of absorber thickness, study downstream hit multiplicity

Purely to cut cost – not ideal

SPiDeR

shower profile with absorber thickness





now looking at:
–CHERWELL sensor
–power cycling
–pixel ganging

Circular collider detector collab

FCC-ee

- **Lepton studies – Coordinators A. Blondel, P. Janot (EXP) + J.Ellis, C.Grojean (TH)**
  - Study the properties of the Higgs and other particles with unprecedented precision

EW Physics (Z pole): R. Tenchini F. Piccinini, S. Heinemeyer

Diboson physics, m_W: R. Tenchini F. Piccinini, S. Heinemeyer

H(125) Properties: M. Klute, K. Peters

Top Quark Physics: P. Azzi

QCD and $\gamma\gamma$ Physics: D. d'Enterria, P. Skands

Flavour Physics: S. Monteil, J. Kamenik

New Physics: M. Pierini C. Rogan, A. Weiler

- Develop the necessary tools
- Understand the experimental conditions

Physics Software: C. Bernet, B. Hegner
Common with FCC-hh/eh, Synergies with LHC, LC

Online & Trigger: E. Perez, C. Leonidopoulos

Exp'tal Environment: N. Bacchetta
Synergy with FCC-hh and Linear Colliders

- Set constraints on the possible detector designs to match statistical precision

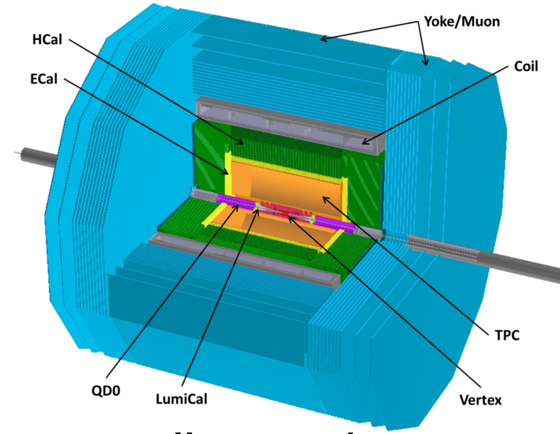
Detector Designs: A. Cattai, G. Rolandi
Synergy with Linear Collider detectors and others

David d'Enterria


John Ellis (KCL)
Lepton study coordinator


Christos Leonidopoulos (Edin)
Online & Trigger group convenor

CEPC



ILD-like detector but:

shorter L* (1.5m) → smaller tracker

no power-pulsing → cooling issues

limited √s → smaller calorimeter

lower radiation→ vertex detector closer

- Currently mostly Chinese
- New Centre for Future High Energy Physics set up (director: Nima Arkani-Hamed)
- CEPC international advisory board to be formed

"Complementary with ILC"
… "ILC can give up push–pull"
(Wang at AsiaLCW15)

Global status 1: ILC

The ILC story so far…

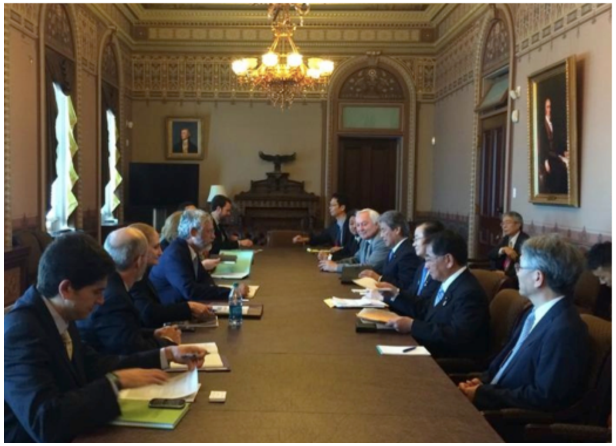
Japanese HEP community proposed to host ILC
Kitakami site was chosen
Science Council of Japan (~Royal Society) made report with reservations
MEXT (Japanese ministry) set up committee to investigate:

- significance of physics, readiness of technology
- regional economic effects
- costs profile and international cost-sharing prospects

- Internal Japanese process ongoing. Interim MEXT report Aug 2015:
  asks for more clarity on BSM prospects
  includes statement allowing initiation of serious talks with other countries
  recommends more engagement by public & other science communities

- Final reports to MEXT in spring 2016
- Expect decision some time in 2017?

There is high-level Japanese government support
e.g. Federation of Diet members for the ILC
and Prime Minister Abe



Lyn Evans & Japanese delegation at the White House

ILC Timelines

1980's
Project Start

Design &
Manufacturing Processes

2004

Technology choice

OECD Ministerial Statement

Discussions w/ Funding Agencies

Site-related studies
by scientists/civil engineers

2007

Baseline Design

First Cost Estimate

2008

Begin cooperation
Government/Industry/Academica

Site studies by
local groups

International R&D

XFEL Experience

Cost/Design Optimization

Global Design

Geological studies

CERN/LHC
Higgs Discovery

2012
2013
2014
2015

Technical
Design Report

Science Council
of Japan Report

Domestic Site
Evaluation

Government budget for project evaluation
Project reviews by MEXT start

Today

Site-specific design
International collaboration
Setting regulations
Engineering design
Preparing construction

Government reviews
Talks between governments

Greenlight /
International Agreement

Site-specific design
Activities in Local area
Environmental assessment

Establish International Laboratory

2018–27?

Construction (~9 yrs)

2028 on?

Operation (~20 yrs)

Satoru Yamashita

Global status 2

- CLIC development continues, preparing Project Plan for 2018 ready for next European Strategy update

  CLIC TDR 2022?
  Construction 2023–2030?

- FCC study continues -> CDR in 2018

  Construction after 2025?
  Operation for ~10 years post HL-LHC, 2035?

- CERN medium-term plan (5 years) foresees choice between FCC and CLIC at next European Strategy and FCC & CLIC fusing into common ‘energy frontier’ budget from 2020

- CEPC pre-CDR is with Chinese government and international advisory ctte planned

  Chinese govt 5-yr budget plan by end year
  R&D and Engineering design 2015–20
  Construction 2021–27 ?
  Data-taking 2028–35 ?

Outlook

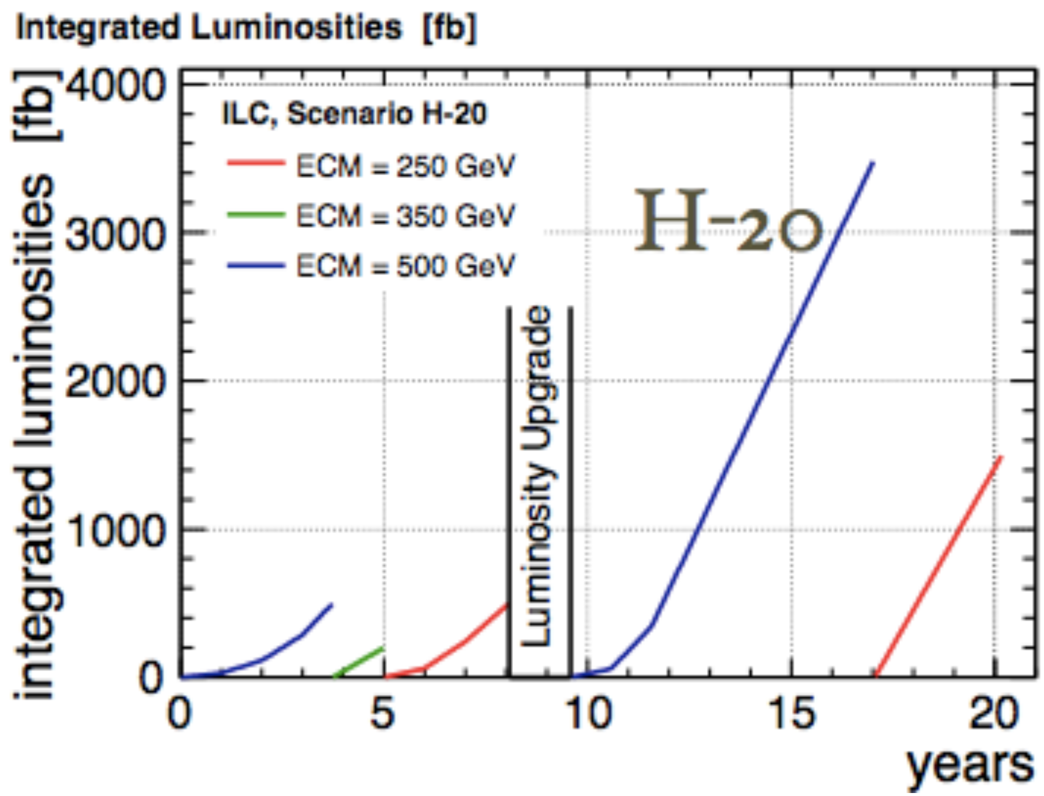
- Internationally, ILC, CLIC, CEPC, FCC-ee proceeding in parallel
- ILC is mature and ready for construction!
- UK working in range of linear collider areas:
  accelerators
  detectors
  software
  physics studies,
  – particularly where ILC and CLIC overlap – with good visibility/leadership.

  Modest PPRP 2-year funding has focused ILC effort on detector & physics
- Also small UK effort in circular colliders
- Next few years critical for decision-making

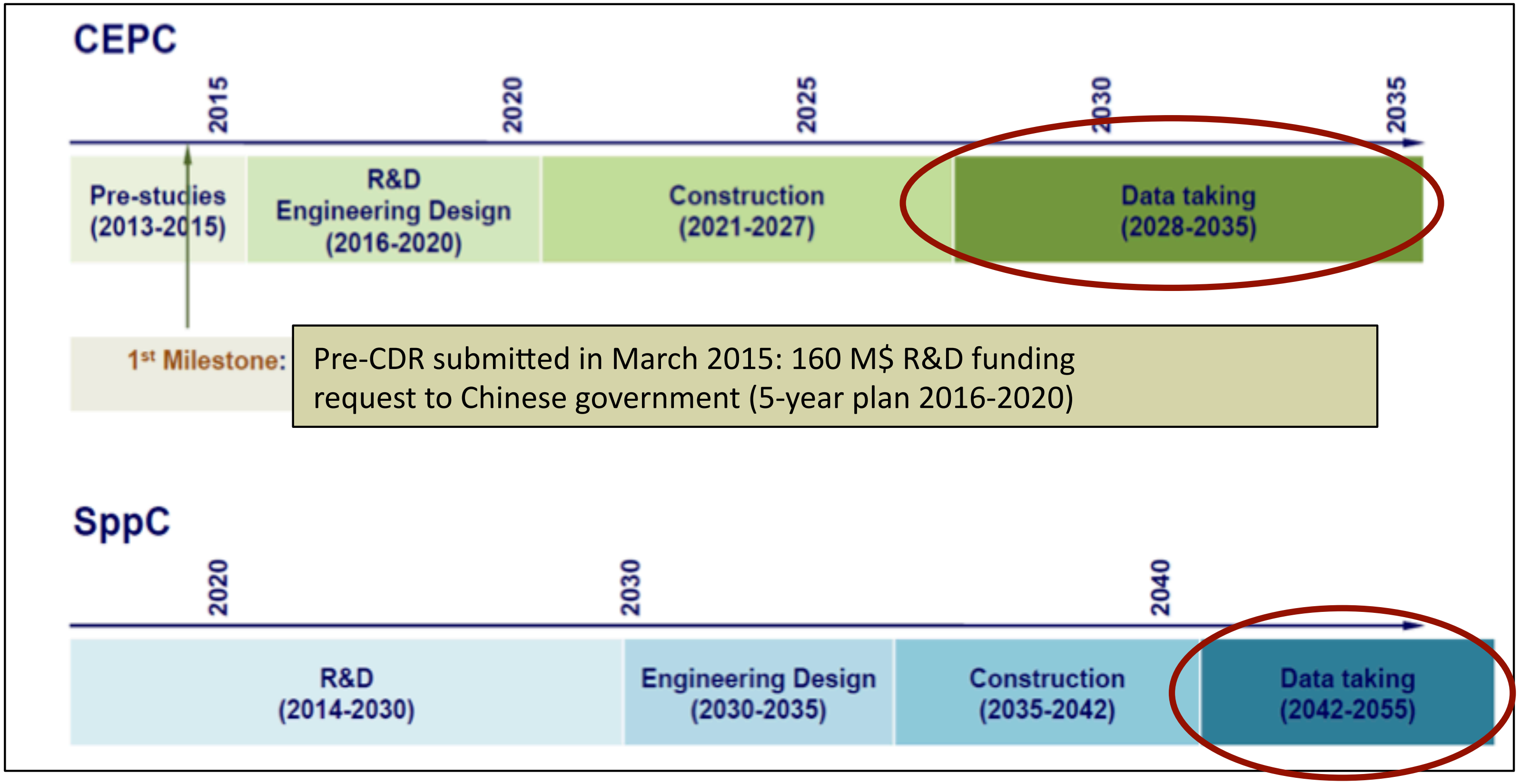
Thanks to all who contributed:
Phil Burrows, Mark Thomson, Joost Vossebeld, Veronique Boisvert, Matt Wing, Nigel Watson, Fergus Wilson, Christos Leonidopoulos

Backup

ILC H-20 scenario



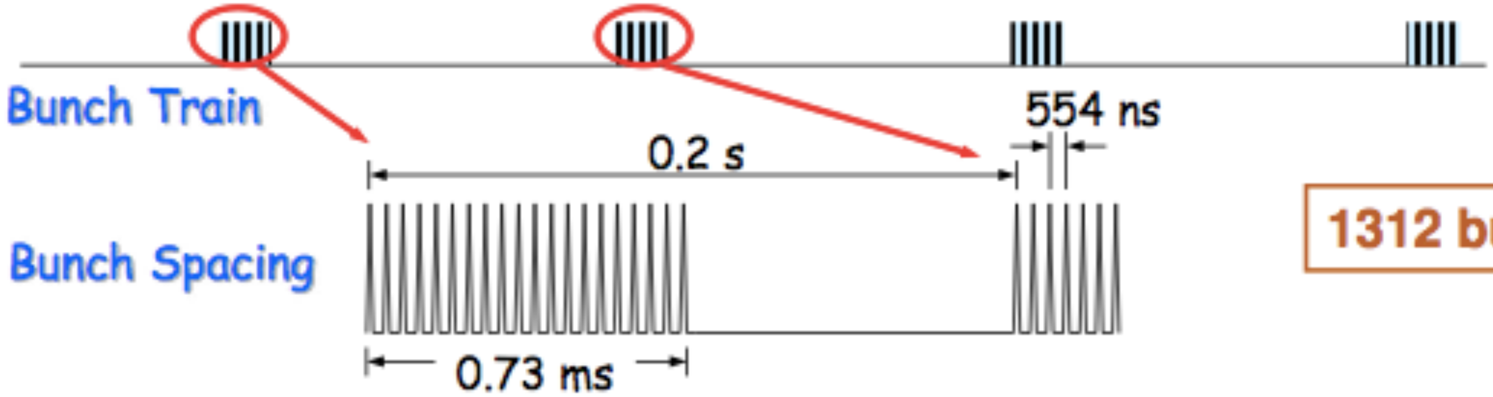
CEPC / SppC timelines



Preliminary CEPC parameter list

Parameter	Unit	Value	Parameter	Unit	Value
Beam energy [E]	GeV	120	**Circumference [C]**	m	54752
Number of IP[N_{IP}]		2	**SR loss/turn [U_0]**	GeV	3.11
Bunch number/beam[n_B]		50	**Bunch population [Ne]**		3.79E+11
SR power/beam [P]	MW	51.7	**Beam current [I]**	mA	16.6
Bending radius [ρ]	m	6094	**momentum compaction factor [α_p]**		3.36E-05
Revolution period [T_0]	s	1.83E-04	**Revolution frequency [f_0]**	Hz	5475.46
emittance (x/y)	nm	6.12/0.018	**β_{IP}(x/y)**	mm	800/1.2
Transverse size (x/y)	μm	69.97/0.15	**$\xi_{x,y}$/IP**		0.118/0.083
Beam length SR [$\sigma_{s.SR}$]	mm	2.14	**Beam length total [$\sigma_{s.tot}$]**	mm	2.65
Lifetime due to Beamstrahlung (simulation)	min	47	**lifetime due to radiative Bhabha scattering [τ_L]**	min	52
RF voltage [V_{rf}]	GV	6.87	**RF frequency [f_{rf}]**	MHz	650
Harmonic number [h]		118800	**Synchrotron oscillation tune [ν_s]**		0.18
Energy acceptance RF [h]	%	5.99	**Damping partition number [$J\varepsilon$]**		2
Energy spread SR [$\sigma_{\delta.SR}$]	%	0.132	**Energy spread BS [$\sigma_{\delta.BS}$]**	%	0.119
Energy spread total [$\sigma_{\delta.tot}$]	%	0.163	**n_γ**		0.23
Transverse damping time [n_x]	turns	78	**Longitudinal damping time [n_ε]**	turns	39
Hourglass factor	Fh	0.658	**Luminosity /IP[L]**	$cm^{-2}s^{-1}$	2.04E+34

ILC



1312 bunches/train

CLIC

Parameter	Units	$\sqrt{s} = 500$ GeV	$\sqrt{s} = 3$ TeV
θ_c	mrad	18.6	20
f_{rep}	Hz	50	50
n_b		354	312
Δt	ns	0.5	0.5
N		$6.8 \cdot 10^9$	$3.72 \cdot 10^9$
σ_x	nm	≈ 200	≈ 45
σ_y	nm	≈ 2.3	≈ 1
σ_z	μm	72	44
β_x	mm	8	4
β_y	mm	0.1	0.07
L* [a]	m	3.5	3.5
$\mathscr{L}$	$cm^{-2}s^{-1}$	$2.3 \cdot 10^{34}$	$5.9 \cdot 10^{34}$
$\mathscr{L}_{0.01}$	$cm^{-2}s^{-1}$	$1.4 \cdot 10^{34}$	$2.0 \cdot 10^{34}$
n_γ		1.3	2.1
$\Delta E/E$		0.07	0.28