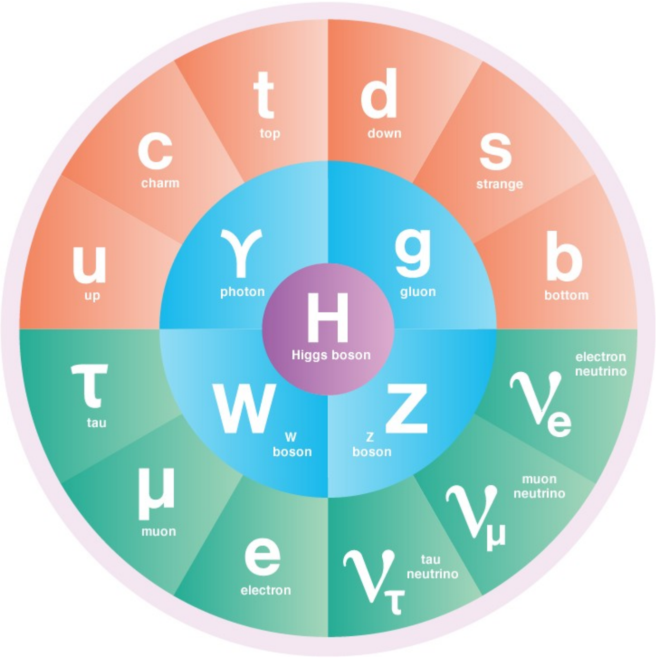
Future Colliders Physics Prospects - Part 1

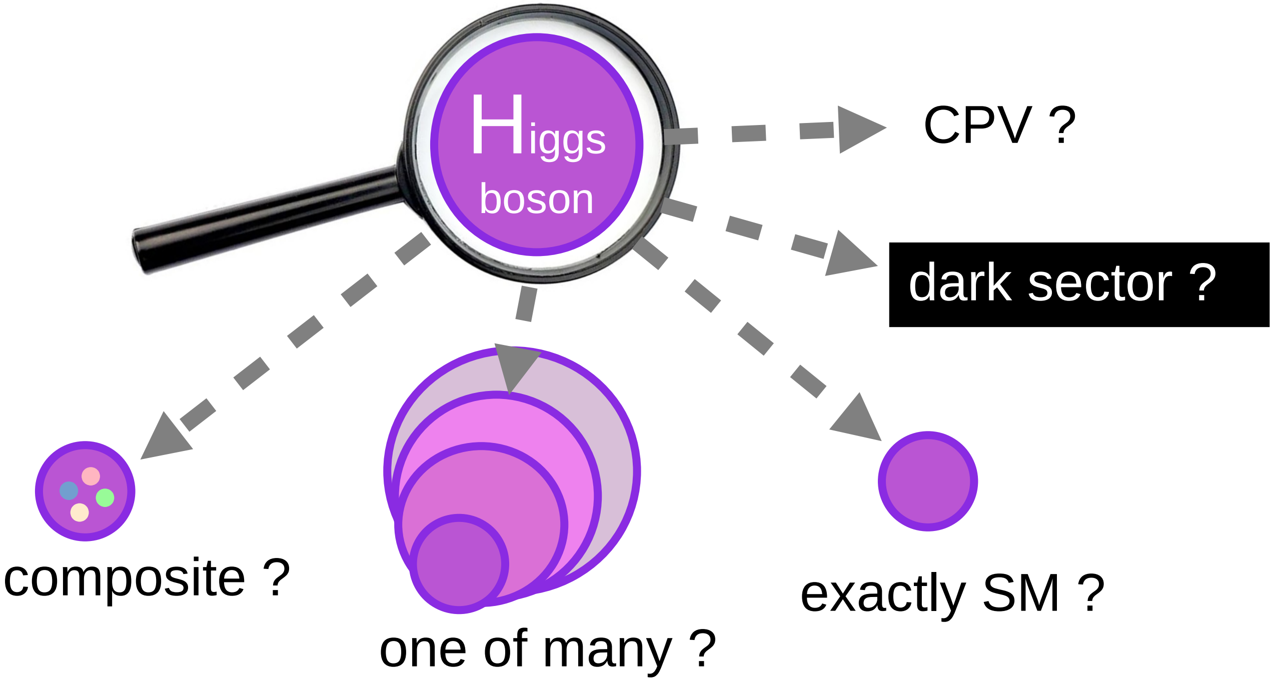
Higgs factories and
high energy lepton colliders

Daniel Jeans, KEK/IPNS

Physics in LHC and Beyond, Matsue 2022 / 5 / 12-15

Higgs as a tool for discovery





CPV ?

dark sector ?

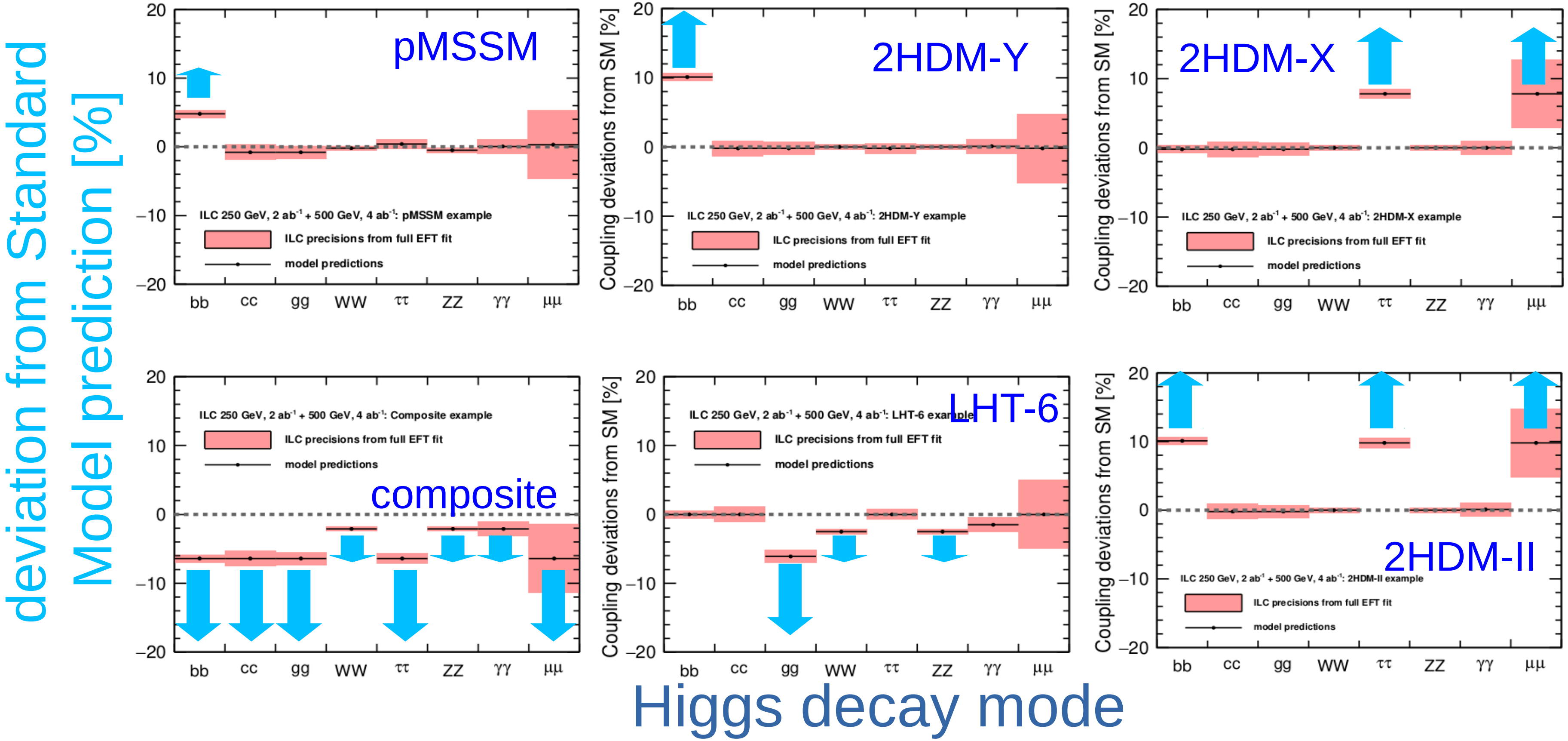
composite ?

one of many ?

exactly SM ?

a unique window

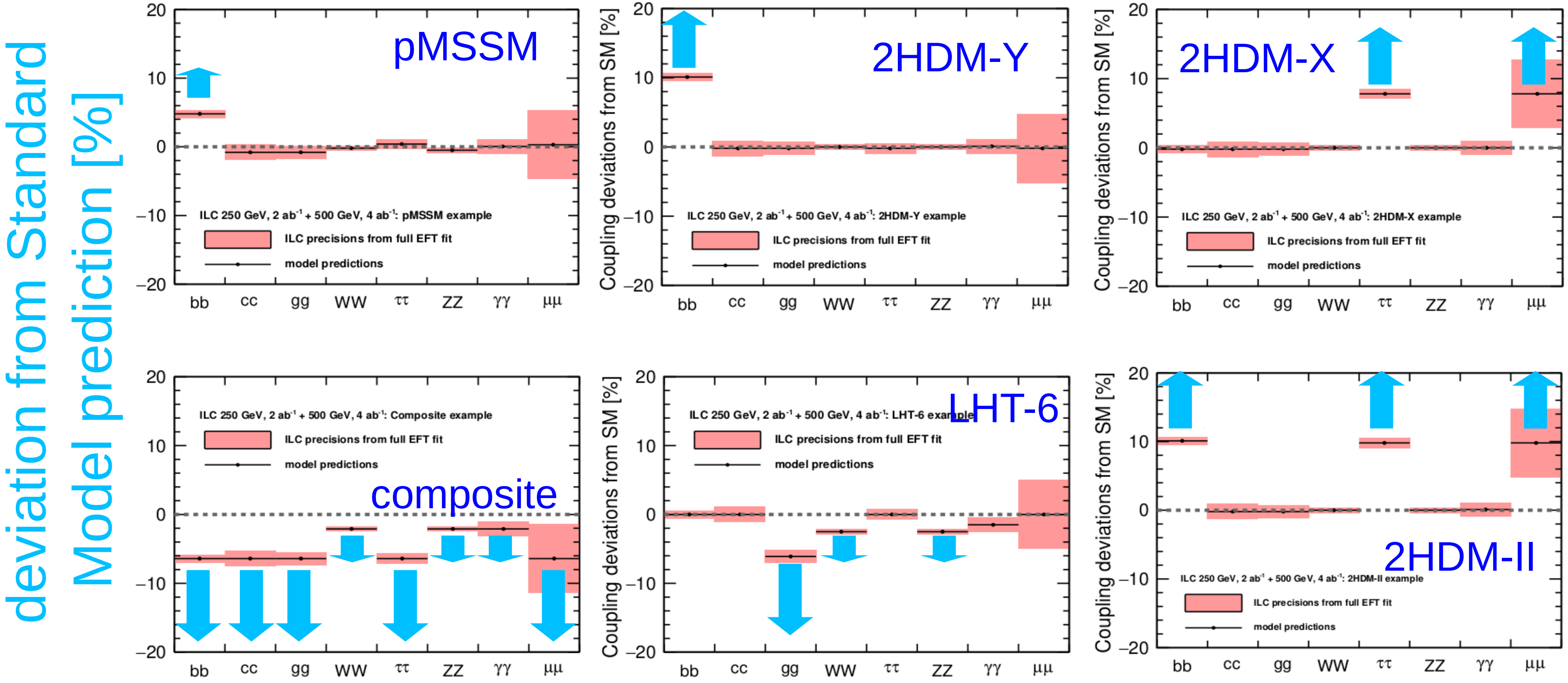
Deviations in Higgs couplings in BSM models



arXiv:1708.08912

different BSM models induce different deviations
measured deviations → distinguish BSM models

Deviations in Higgs couplings in BSM models



arXiv:1708.08912

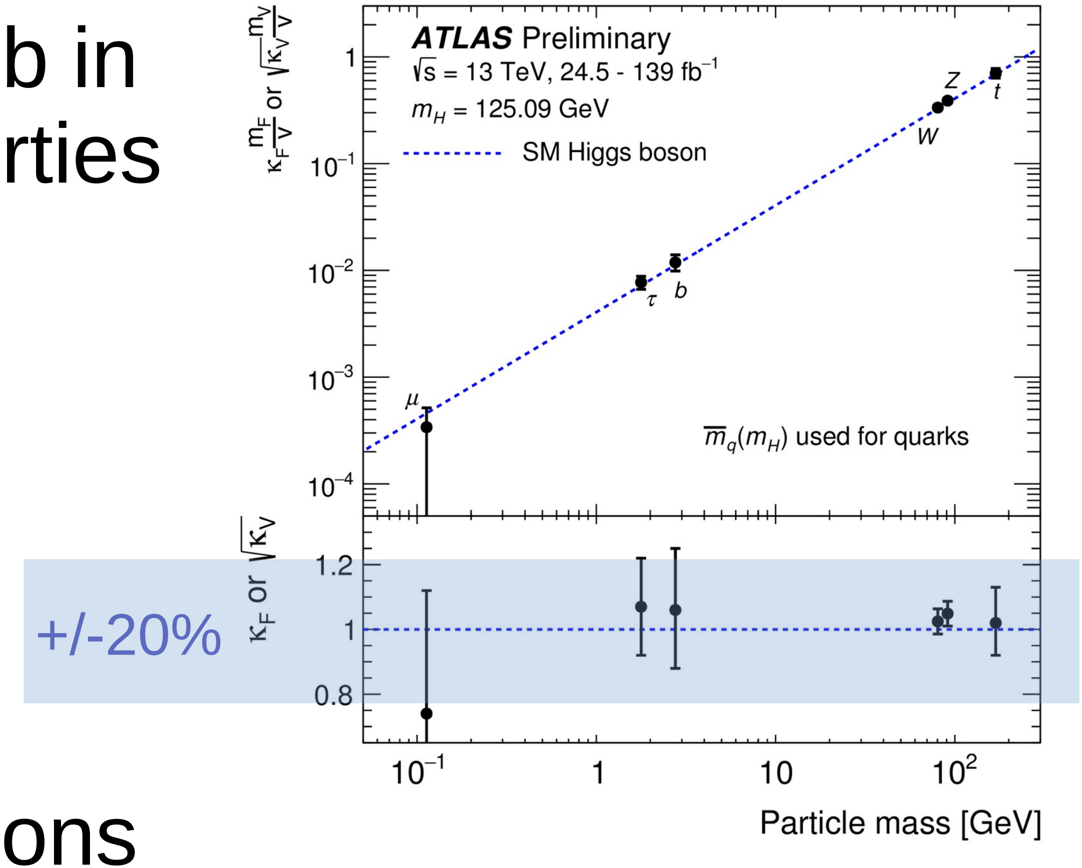
For new physics around TeV-scale,
typically few-% deviations in Higgs couplings

LHC is doing fantastic job in in exploring Higgs properties

H(125) looks SM-like

current coupling precision >> 1%

blind to few-% modifications



predicted Higgs coupling precisions: HL-LHC + e^+e^- (ILC)

HL-LHC

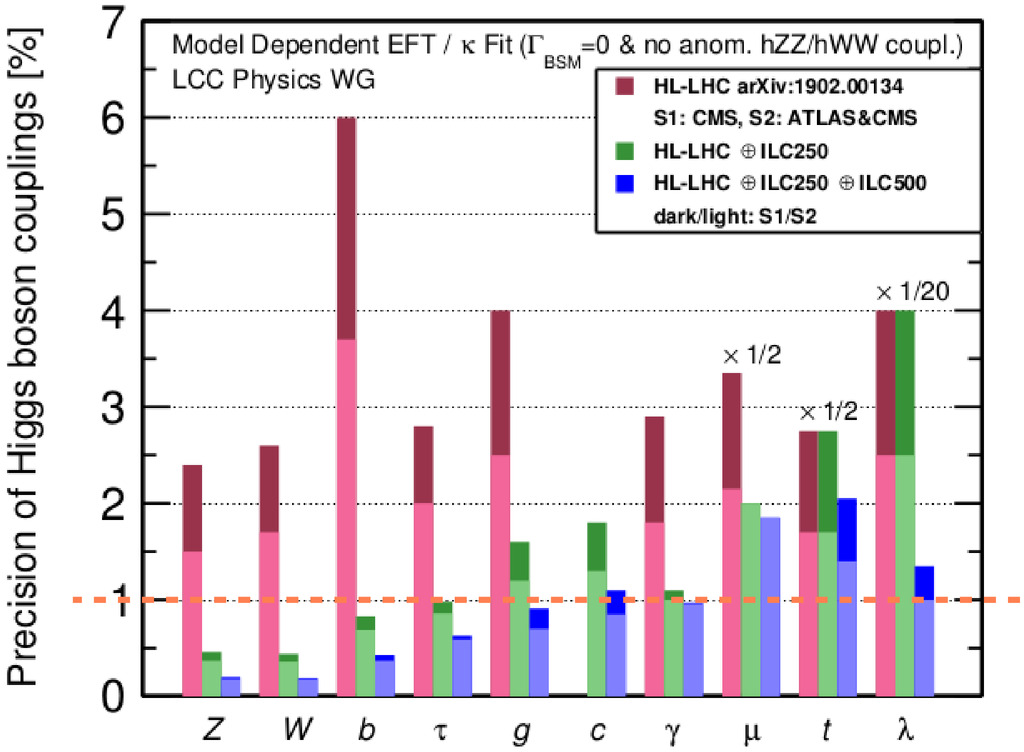
~100 M Higgs

+ ILC250

~0.5 M Higgs

+ ILC500

~2 M Higgs



1 %

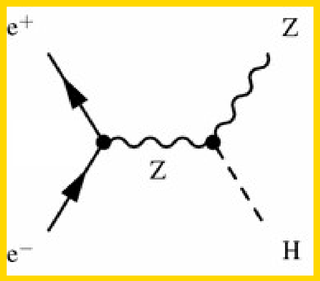
→ HL-LHC will struggle to reach 1% coupling precisions

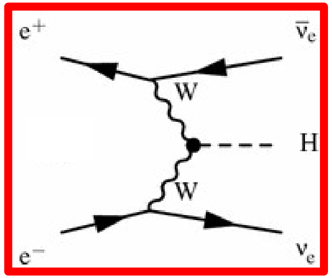
→ HL-LHC + e^+e^- Higgs factory can achieve ~1% or better

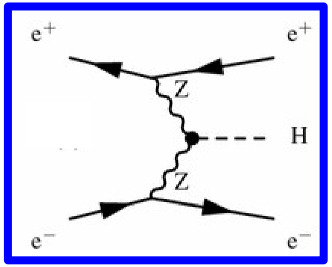
→ resolve signs of new physics

Higgs production in electron-positron collisions

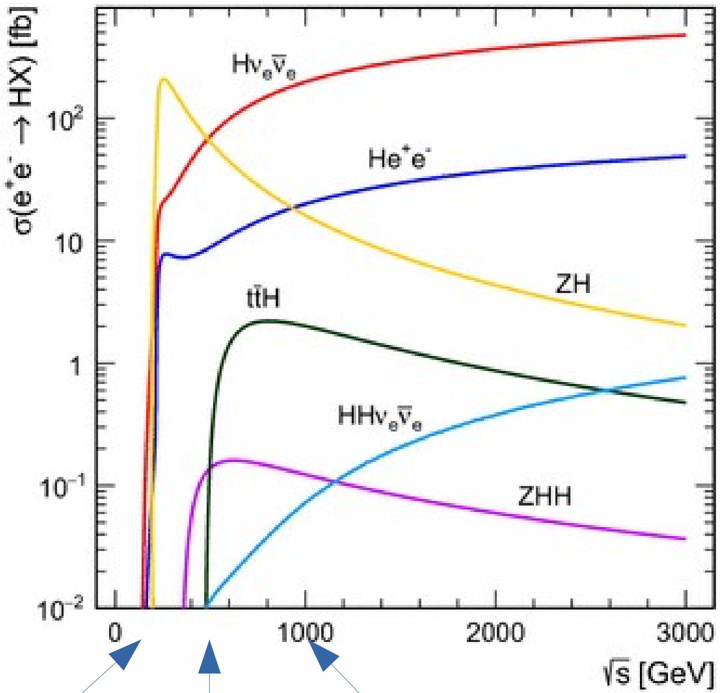
associated Higgs production







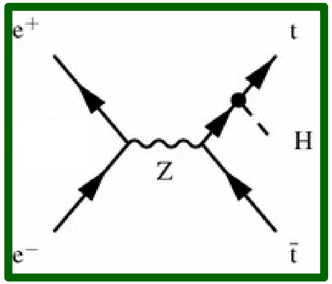
ZZ & WW fusion

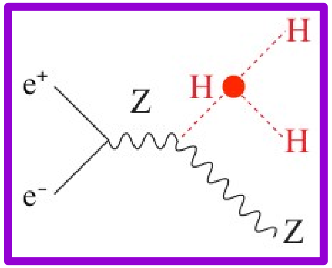


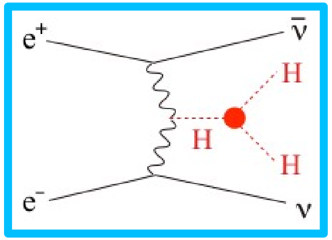
250 500 1000 GeV

Higgs studies can start at **250 GeV**
full set of Higgs measurements:
require ~**1000+ GeV**

top quark Yukawa

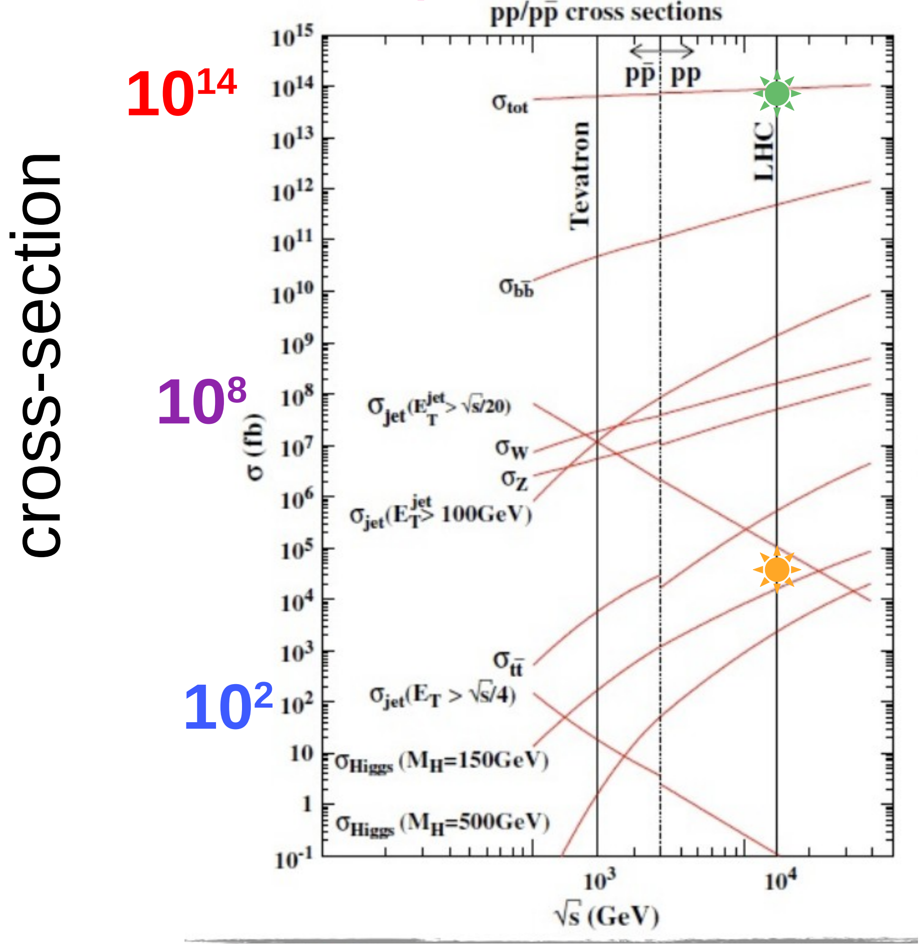




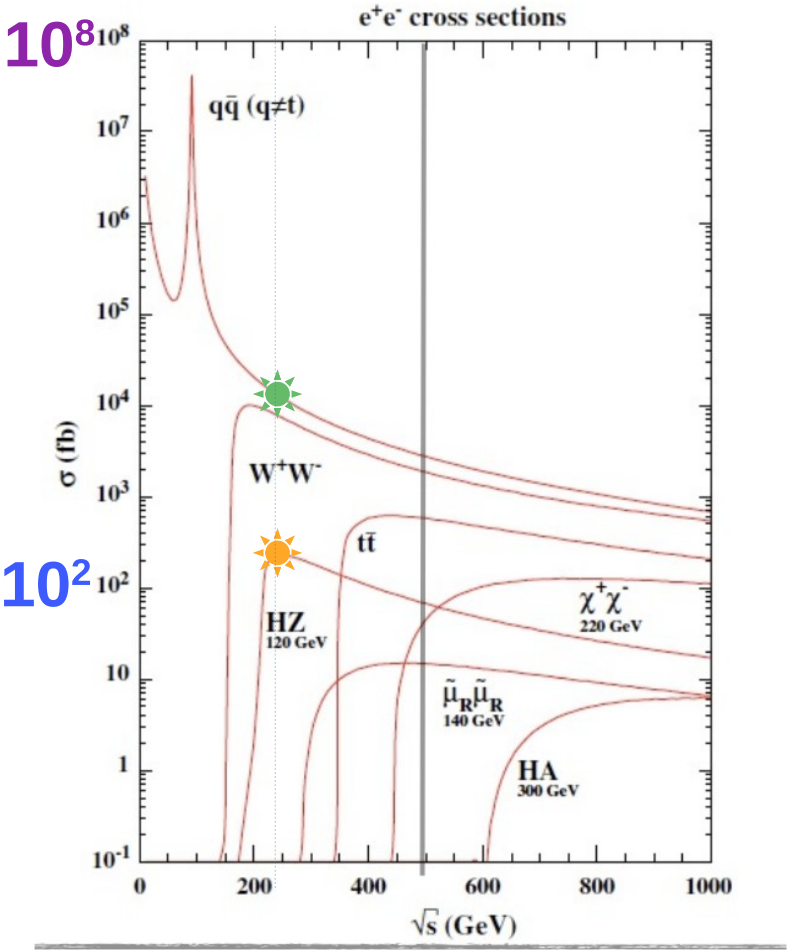


Higgs boson self-coupling

proton collider



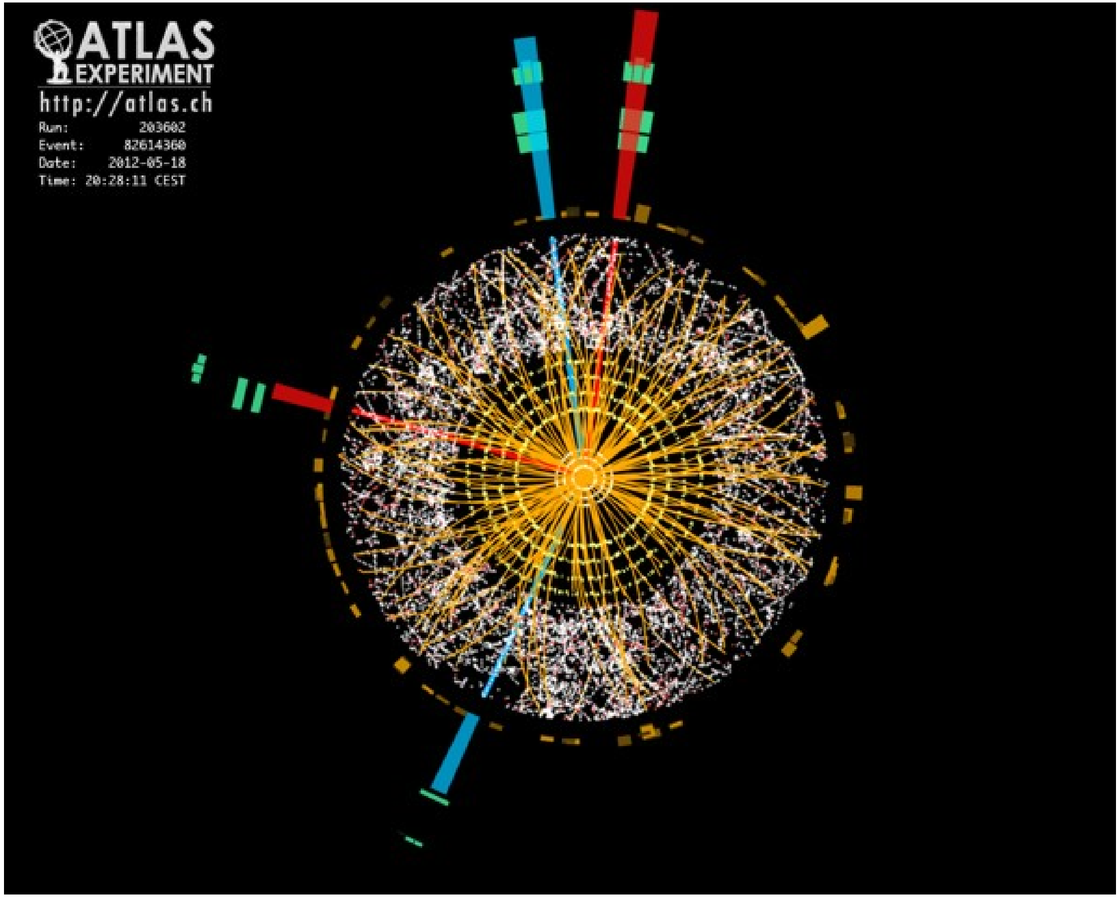
e+ e- collider

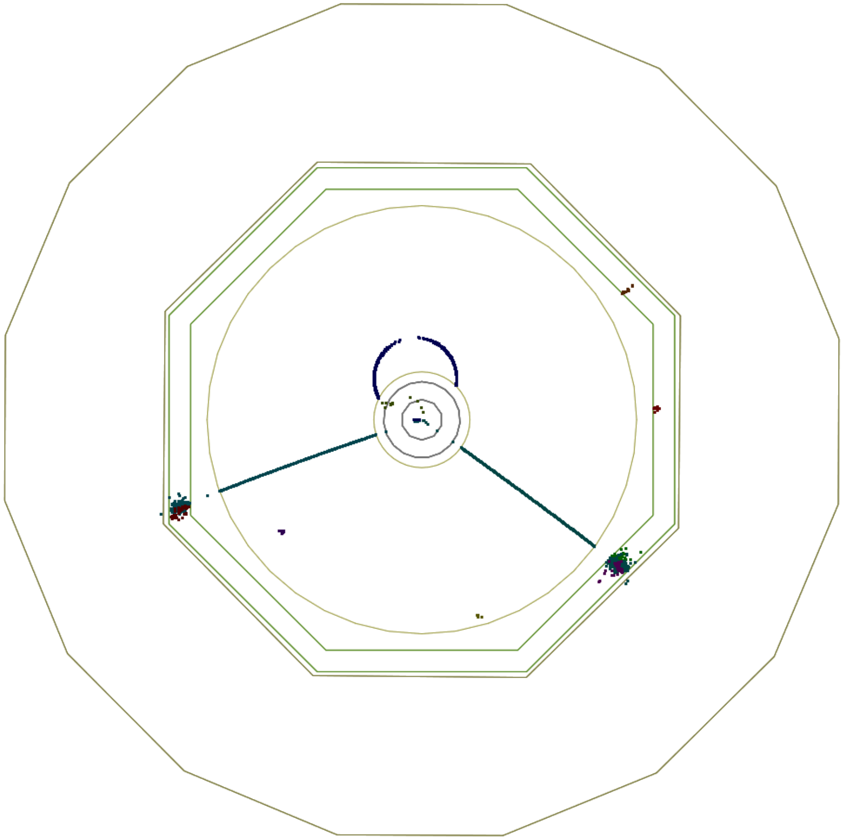


G. Weiglein et al. / Physics Reports 426 (2006) 47–358

Higgs cross-section ~ 10^2 time smaller @ e+e-

Higgs / total cross-sections: LHC~10^{10} , e+e- ~ 10^2





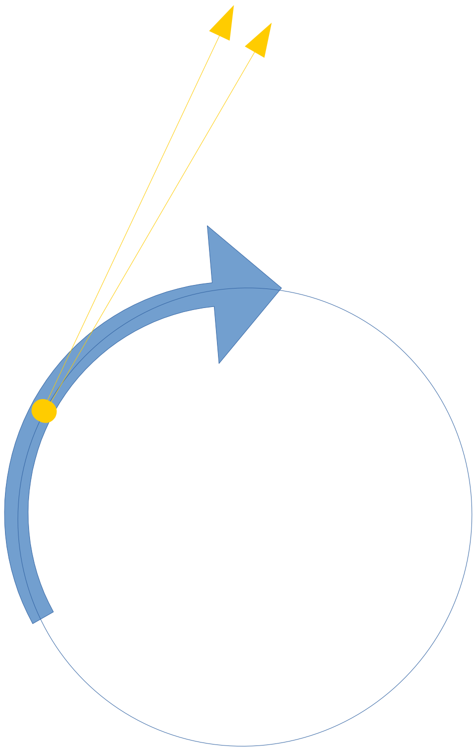
Higgs @ LHC

Higgs @ e+ e-

thanks to its simple & clean experimental environment
an electron-positron collider
can achieve significantly improved Higgs precision

even with a rather small number of produced Higgs

How to build such a e+ e- Higgs factory ?

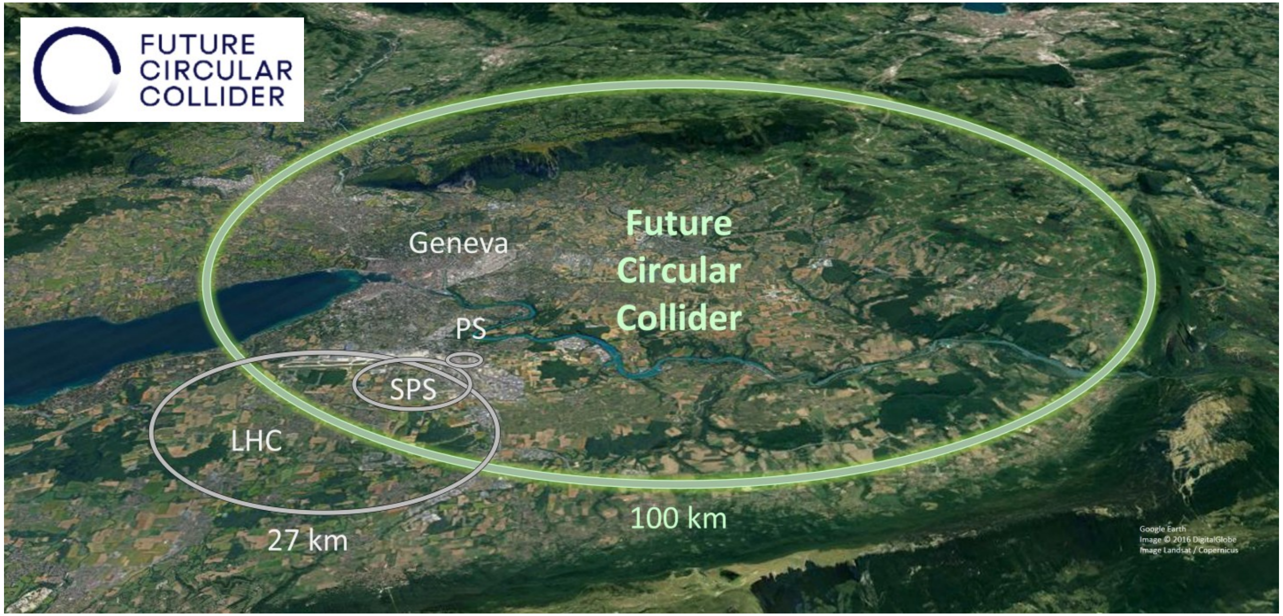


$$\text{power loss} \sim \frac{(\text{beam energy})^4}{(\text{particle mass})^4\,(\text{ring radius})^2}$$

beam energy and particle mass* decided

to control required power, need large radius ring

* see later for μ collider



Large ring

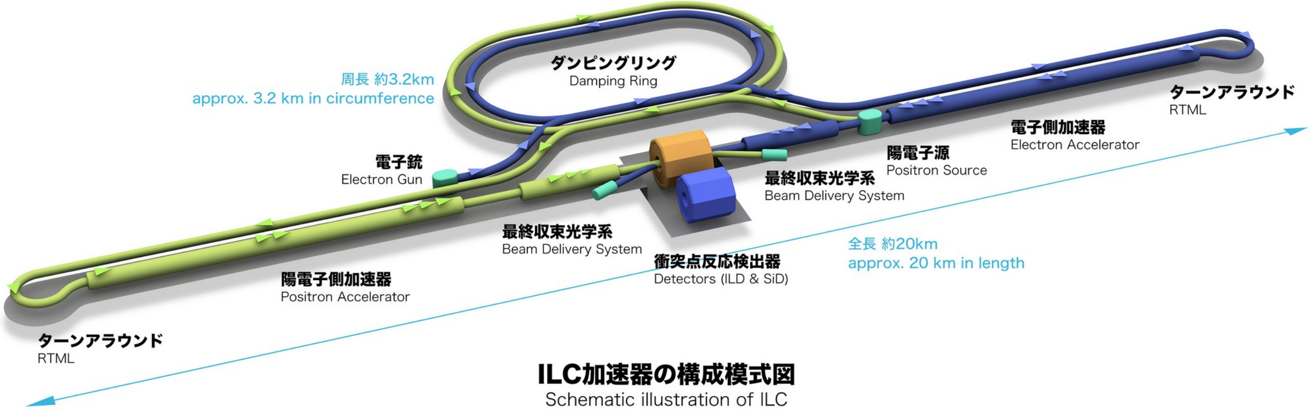
FCCee, CEPC

* radius ~ 100km / 2π

* multiple IPs / experiments

[see next talk P. Azzi]

or



ILC加速器の構成模式図
Schematic illustration of ILC

Linear collider

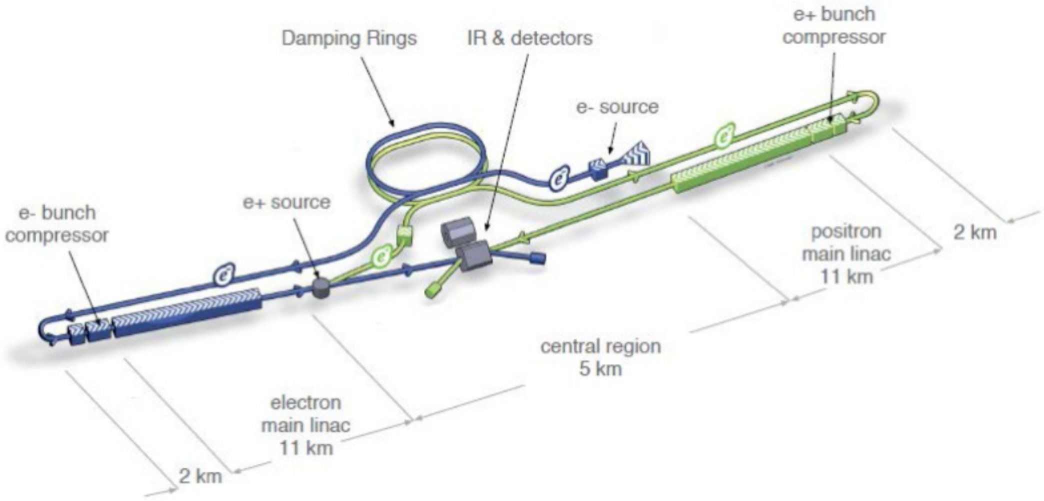
ILC, CLIC, C^3

* radius ~ infinite

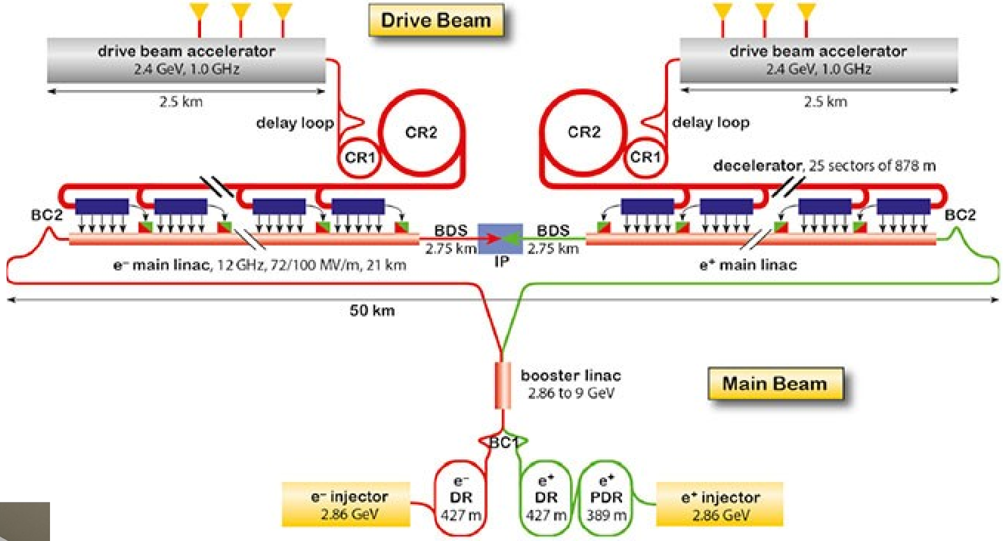
* beam polarization

Linear collider : different accelerating technologies

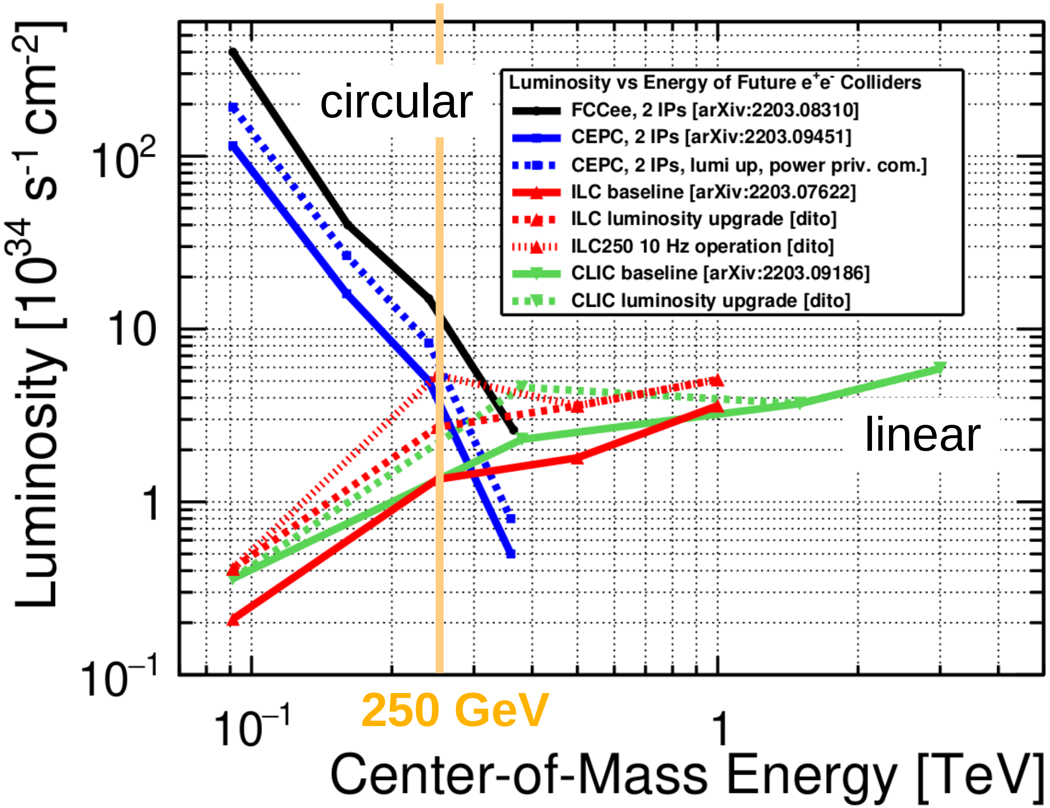
ILC : superconducting RF acceleration



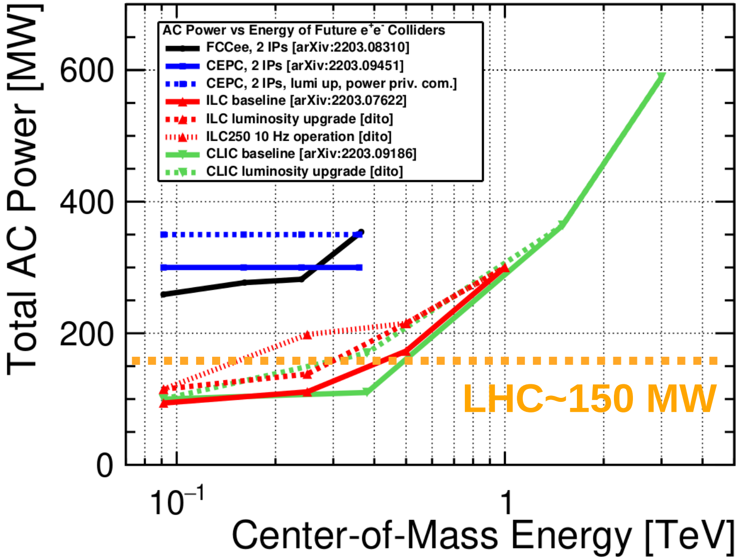
CLIC : 2-beam acceleration



C3: normal conducting
@ liquid N_2



Luminosity limited by assumed available electrical power

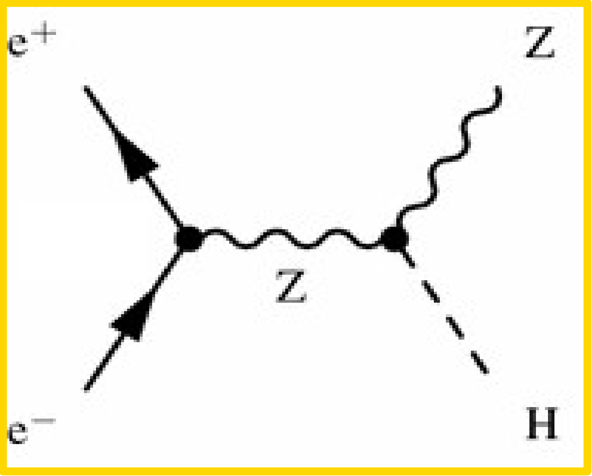


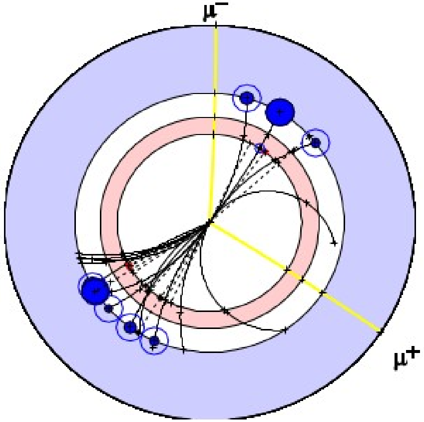
Low energies → Circular collider
High energies → Linear collider
Cross-over around Higgs threshold region

All projects propose to operate at several CM energies

Physics highlights

Higgs-strahlung



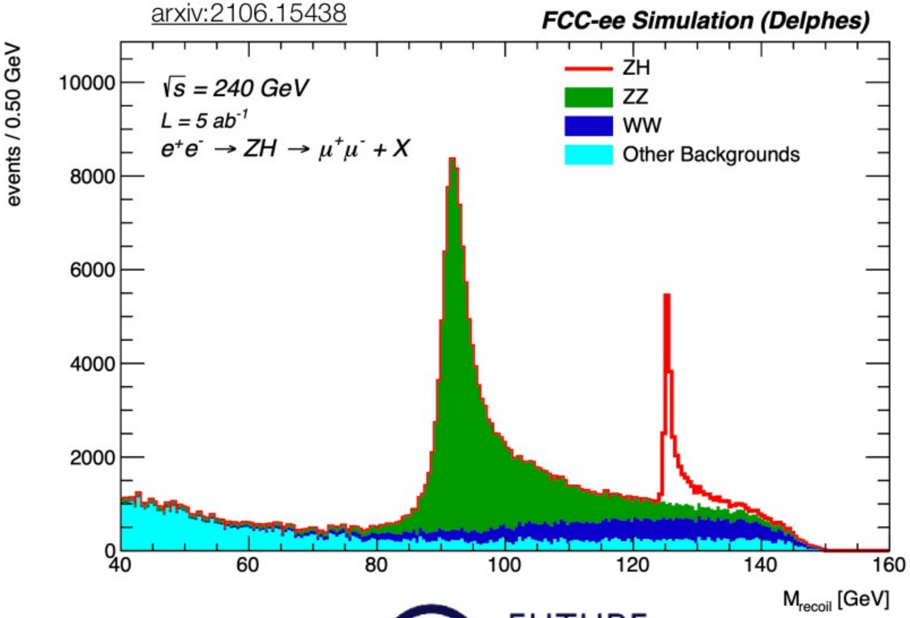


key to model-independent
measurement of Higgs couplings

known initial 4-momentum – measured Z 4-mom
→ recoil 4-mom → “recoil mass”
detect Higgs boson without reconstructing its decay

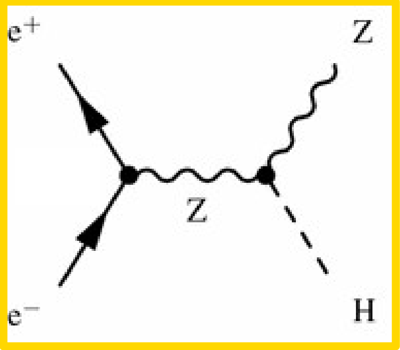
measure σ($e^+ e^-$ → Z H), independent of Higgs deca
unbiased sample of Higgs bosons

arxiv:2106.15438

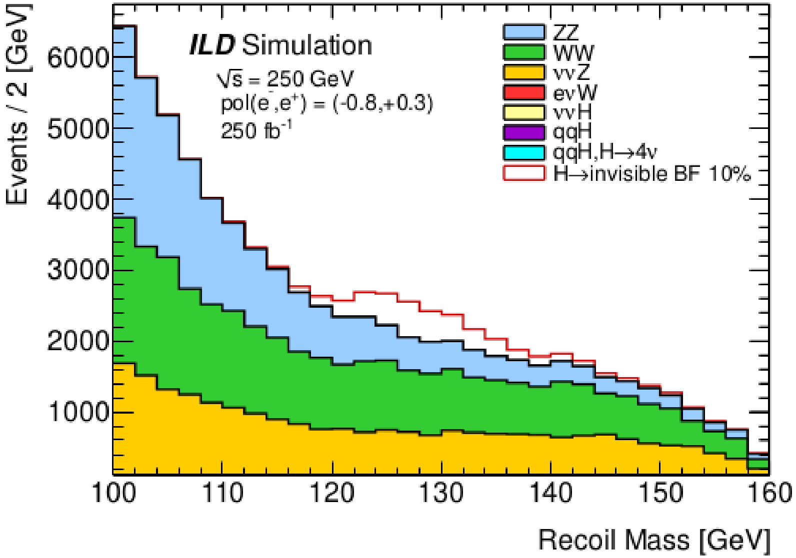


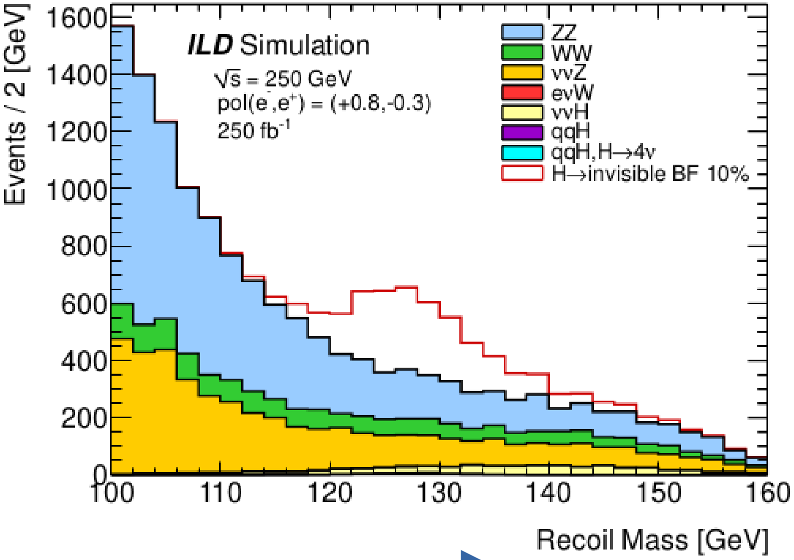
FUTURE
CIRCULAR
COLLIDER

Higgs decay to invisible final states



Higgs-strahlung sensitive to *any* Higgs decay:
e.g. invisible final states ~ dark matter ?





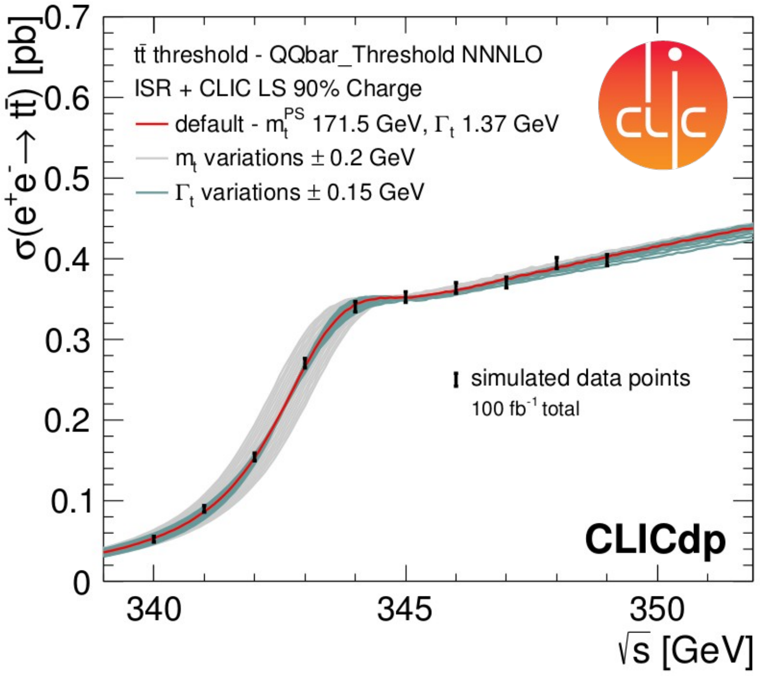
additional background suppression by beam pol.

measure $\Gamma_{\text{invisible}}$ to ~ 0.5%

arXiv:1909.07537

Top quark

mass & width from threshold scan

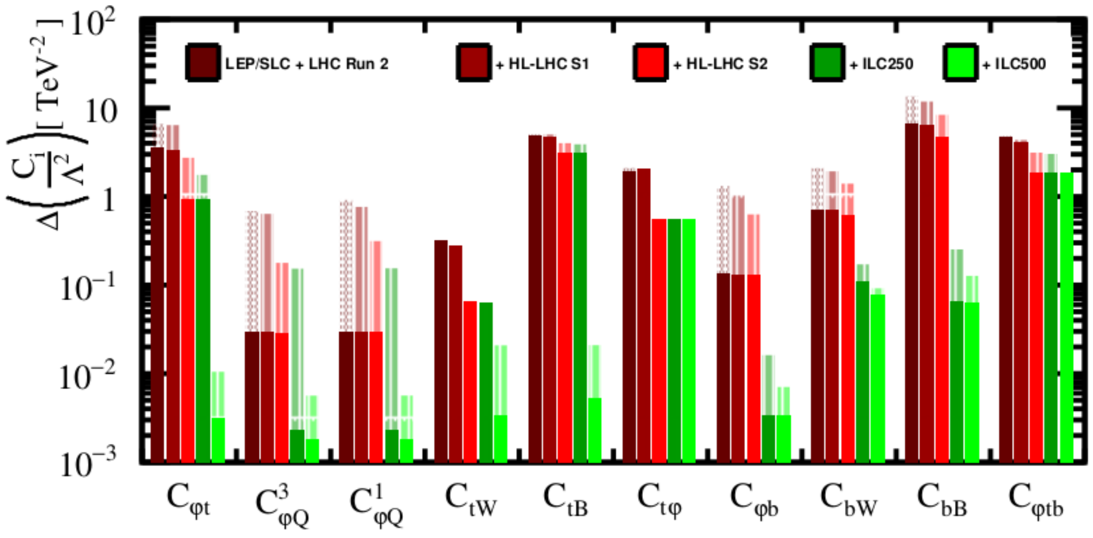


δm_{top} ($\overline{\mathrm{MS}}$) ~ 20 MeV (stat.) / 70 MeV (total)

Much closer to “pole mass”
→ easier to interpret

top quark EW couplings

benefit from being above threshold



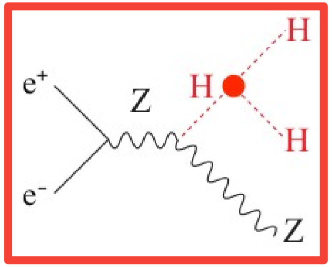
Wilson coefficients of various CP-conserving couplings

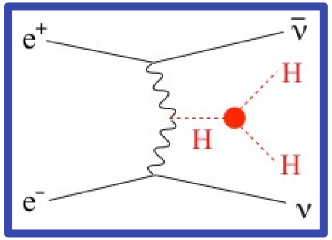
arXiv:1907.10619

Higgs self-coupling λ

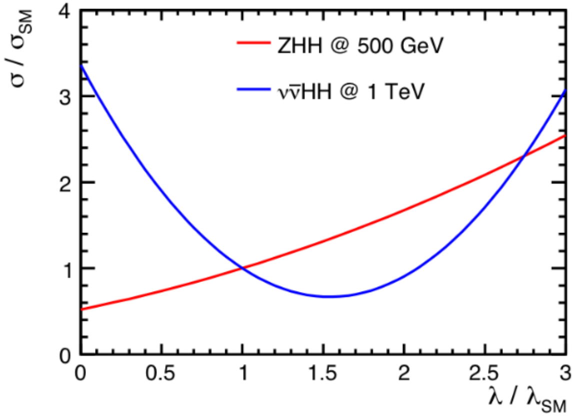
direct sensitivity

500 GeV &
1000 GeV

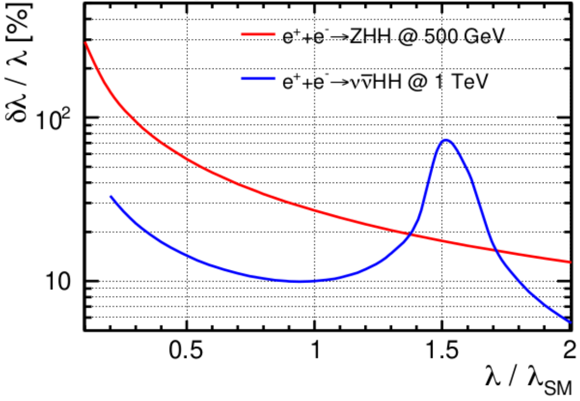




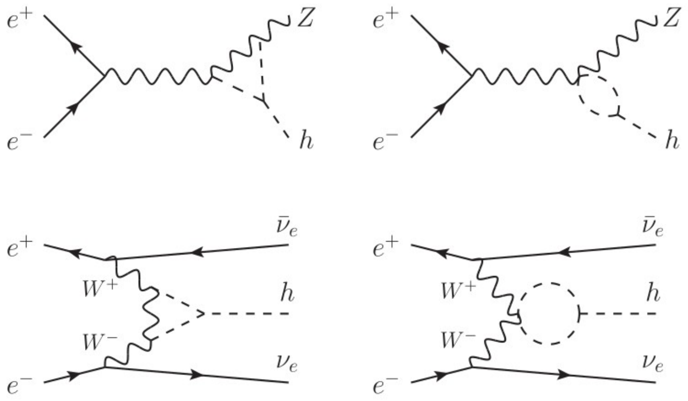
Cross-sections vs. λ

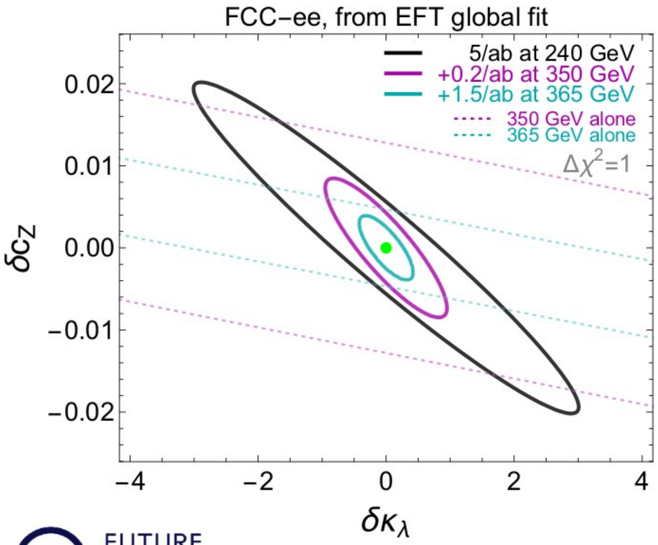


precision on λ



indirect sensitivity





FUTURE
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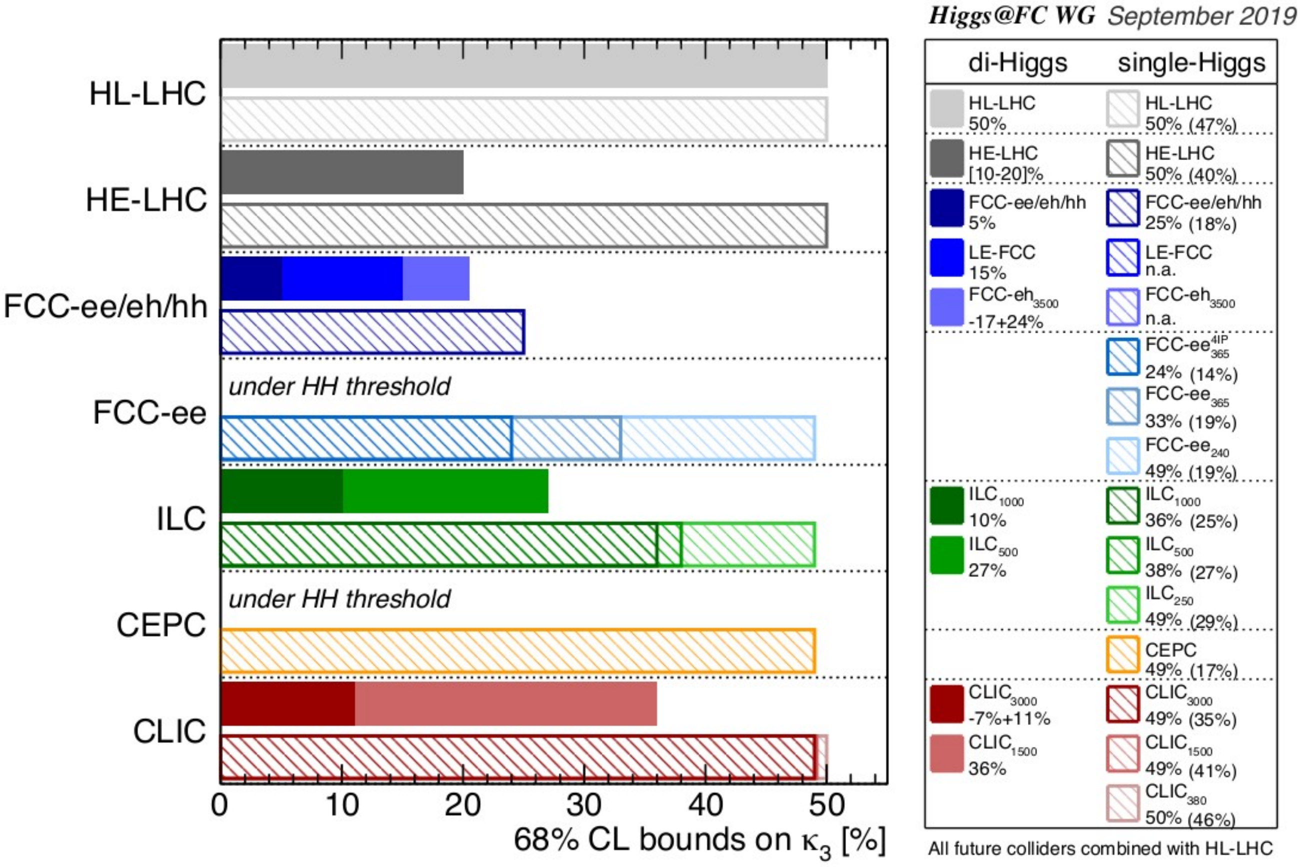
Higgs self-coupling λ

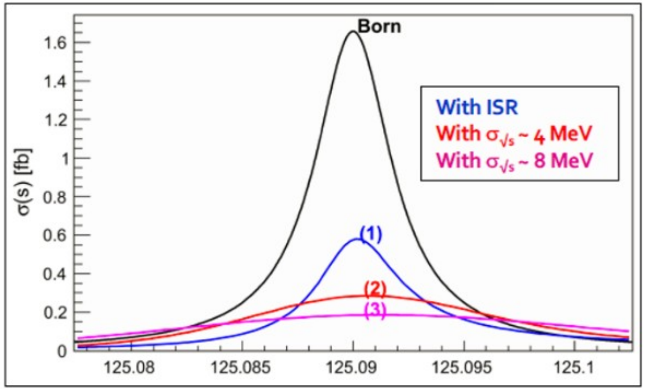


indirect (di-Higgs) ~20~50 %
direct (single-Higgs) ~10~35 %

Ideally test consistency

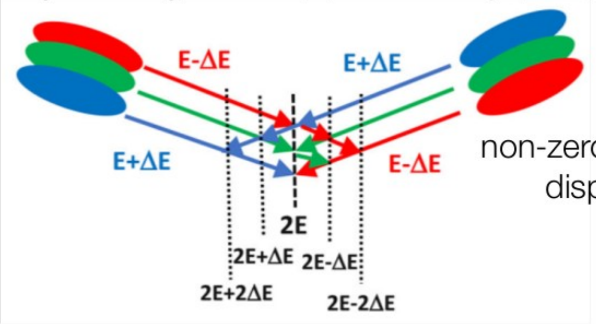
Higgs Physics

- **Electron Yukawa coupling** via s-channel $e^+e^- \rightarrow H$ under study [unique at FCC-ee]
- Exciting challenges/requirements:
  - Higgs mass $\delta m_H \simeq 3$ MeV
  - Beam monochromatization to reduce $\delta_{\sqrt{s}}$
  - Continuous adjustment of $\sqrt{s}$
  - Huge integrated luminosity
  - Extremely sensitive event selection (e.g. $H \rightarrow gg$ and $H \rightarrow WW^* \rightarrow \ell\nu + 2\text{ jets}$)
- Expect $y_e \lesssim 1.6\, y_e^{\mathrm{SM}}$, 100 (30)x HL-LHC (FCC-hh)
  - Assuming $\delta_{\sqrt{s}}$ = 7 MeV and 16 ab^{-1} (2 years w/ 4 IPs)
  - $\Lambda_{\mathrm{BSM}} \gtrsim 110$ TeV in Higgs-electron coupling



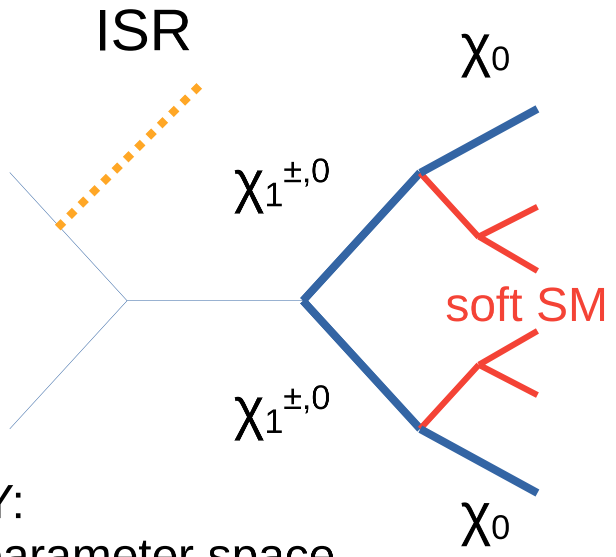
monochromatization:

with separate e^+ and e^- rings, one can distribute low and high energies in opposite way (in x, z, time)

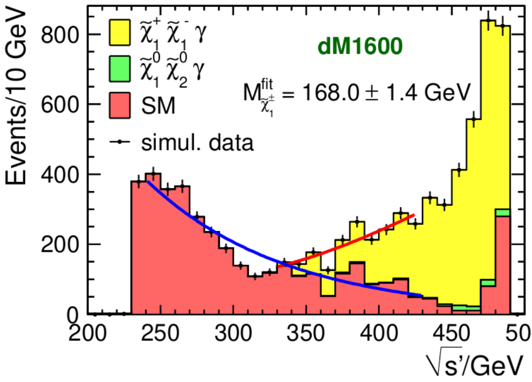


non-zero horizontal dispersion

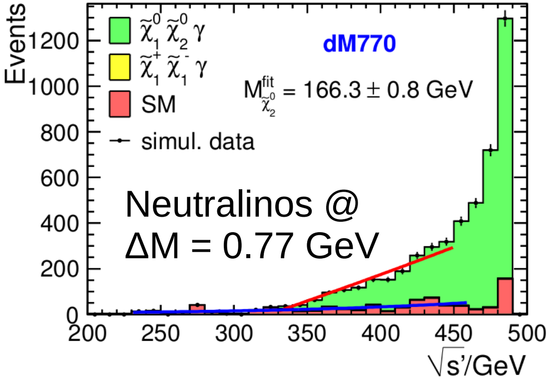
Searches for BSM particle production



Kinematic reach limited by collider energy,
modest total event rates → very loose triggers, or none
→ collect even the softest or most unexpected signatures

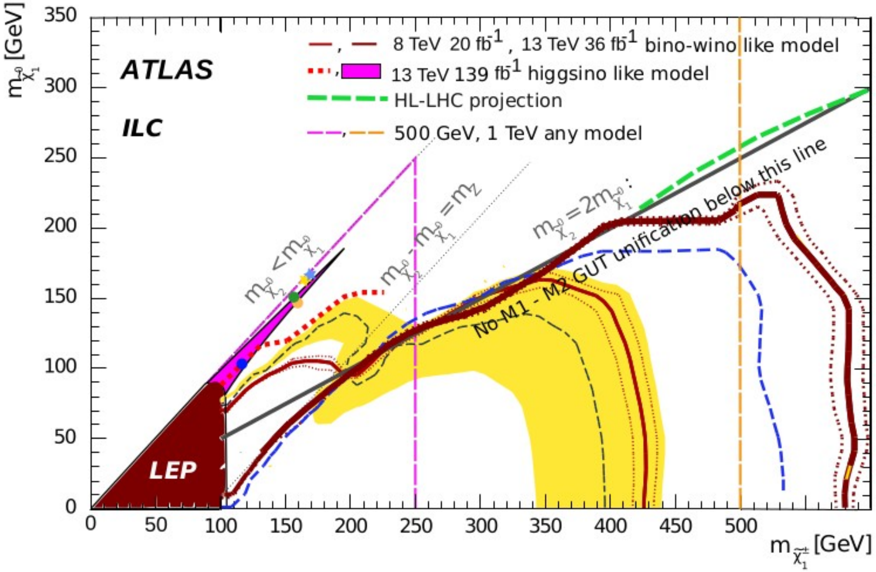


Charginos @
ΔM = 1.6 GeV



Neutralinos @
ΔM = 0.77 GeV

e.g. small mass-splitting SUSY:
cover all kinetically-available parameter space



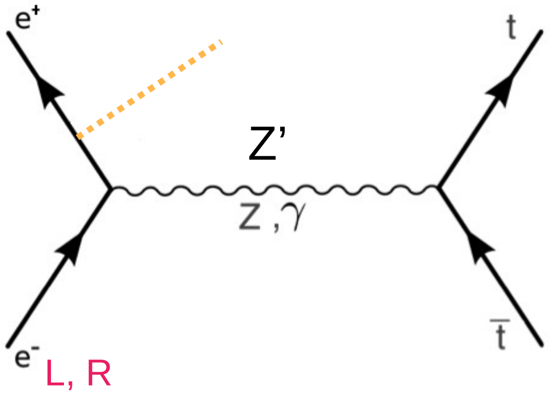
Electro-weak physics

precision EW measurements

orders of magnitude more data than LEP(2) / SLC

in some cases with beam polarisation
left- and right- are very different in E-W

better detectors



high energy 250 ~ 1000 GeV
radiative returns to Z
Z pole

QCD

Clean samples of QCD systems of varying mass:

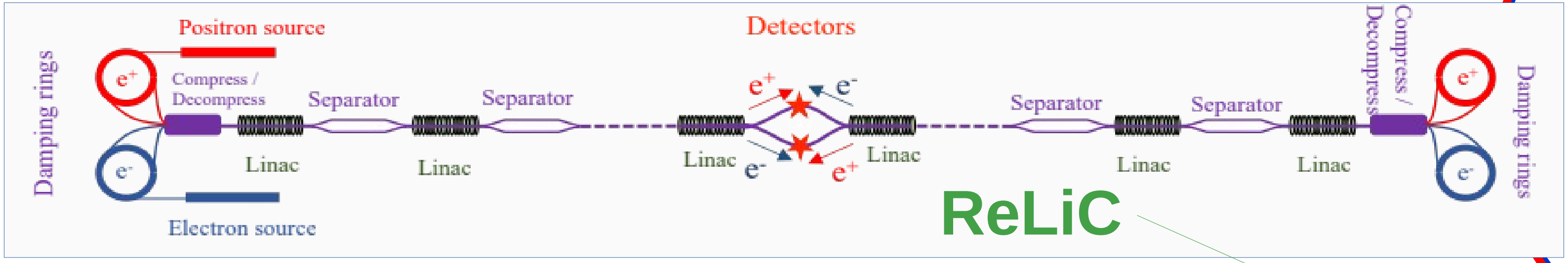
Quark jets of all flavours

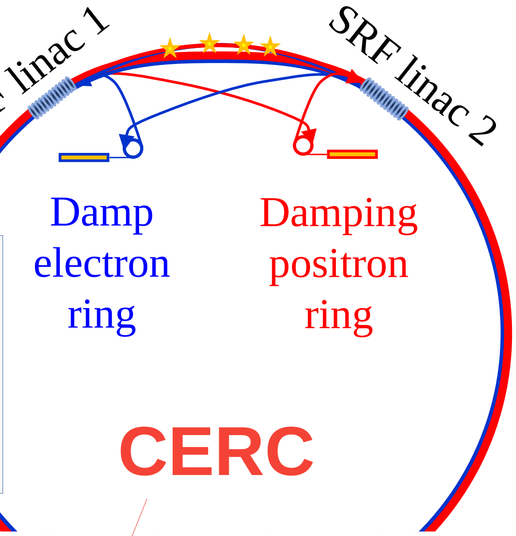
** Gluon jets from Higgs

More futuristic possibilities

many open conceptual and/or engineering issues

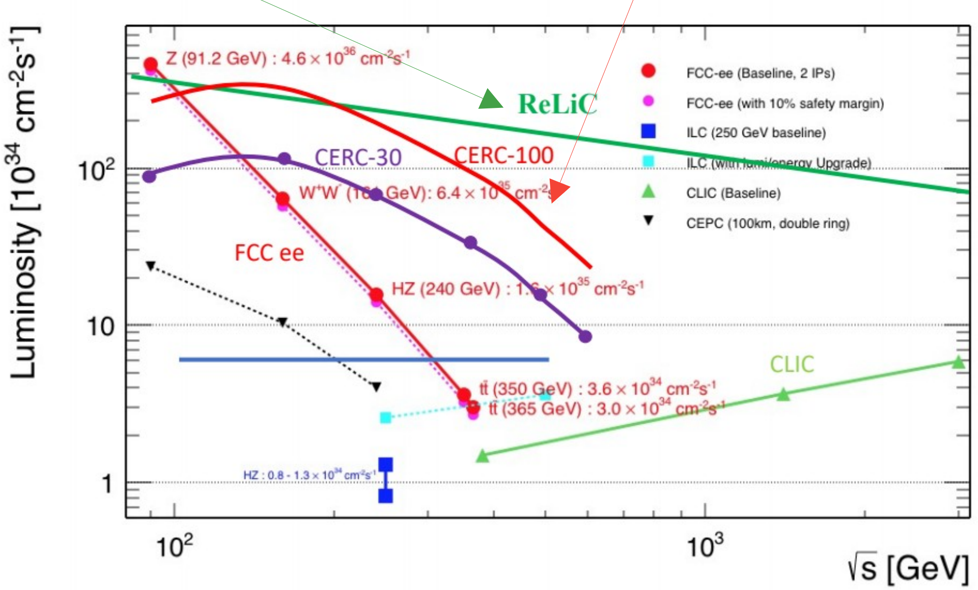
Energy recovery linacs





Recover & reuse (e+, e-) beam energy
→ operate linac “in reverse”
on collided beam

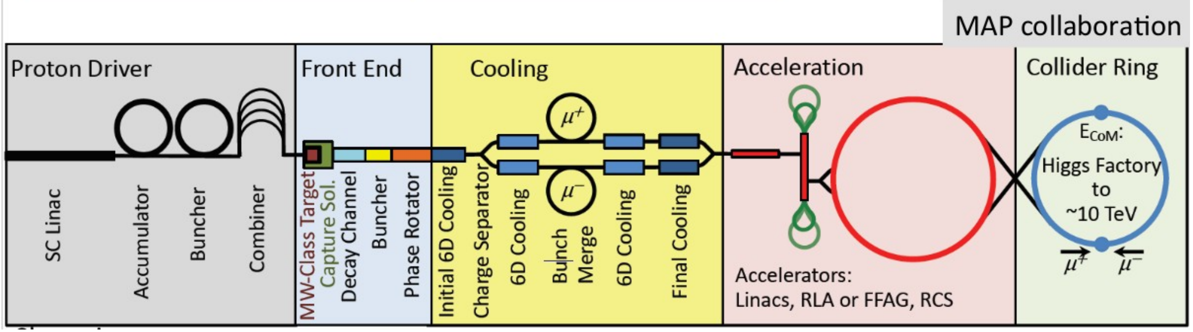
Promises greatly increased
energy efficiency at both
circular and linear colliders
→ higher luminosity

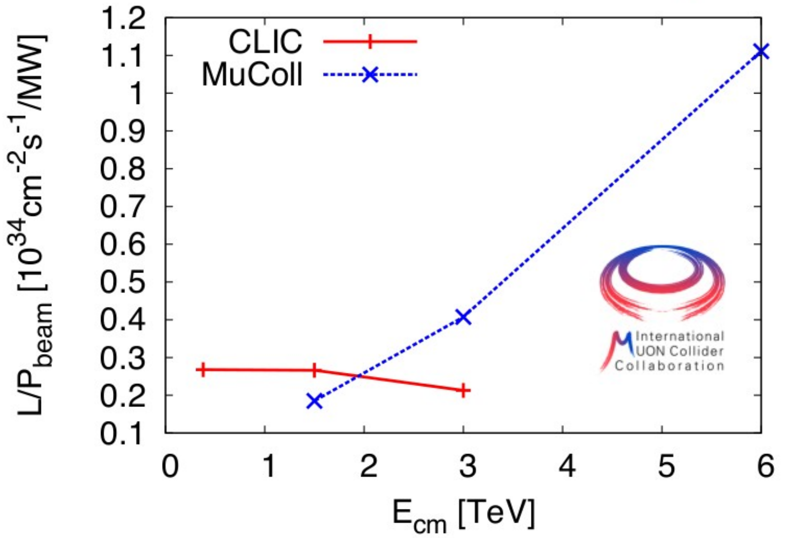


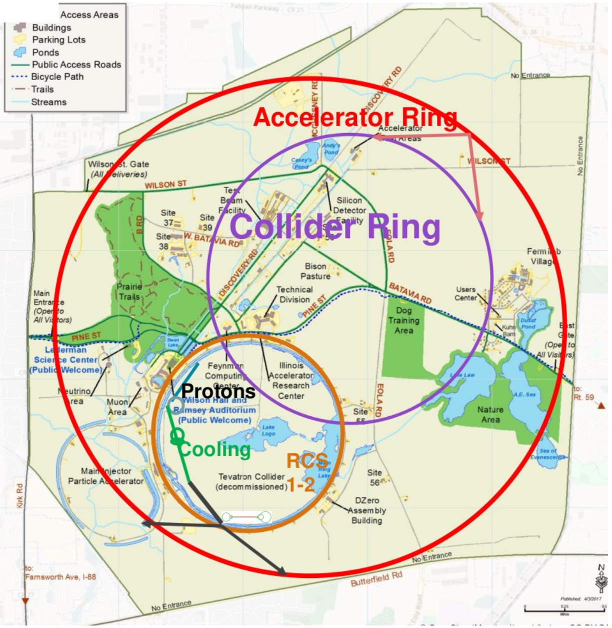
Muon colliders

$$\text{power loss} \sim \frac{(\text{beam energy})^4}{(\text{particle mass})^4\,(\text{ring radius})^2}$$

Muon collider design is driven by finite muon lifetime


MAP collaboration





Fermilab

High energy lepton collisions,
in a modest footprint

Plasma wakefield accelerators

Overcome current limits on
accelerating gradient 30~100 MV/m

laser or particle beam induces wakefield in plasma

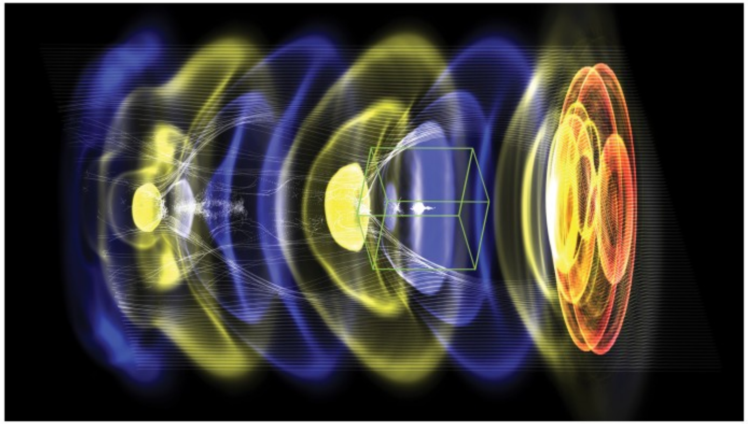
wakefield accelerates particle bunch:
1~10 GV/m >> 30-100 MV/m

Compact, high energy linac

Structure-based wakefield accelerator (SWFA)

Plasma wakefield accelerator (PWFA)

Laser wakefield accelerator (LWFA)



Example: a laser or particle beam (red) drives a density wave (blue to yellow) in plasma, accelerating electrons (white) with fields of order 10 GeV/m

Summary

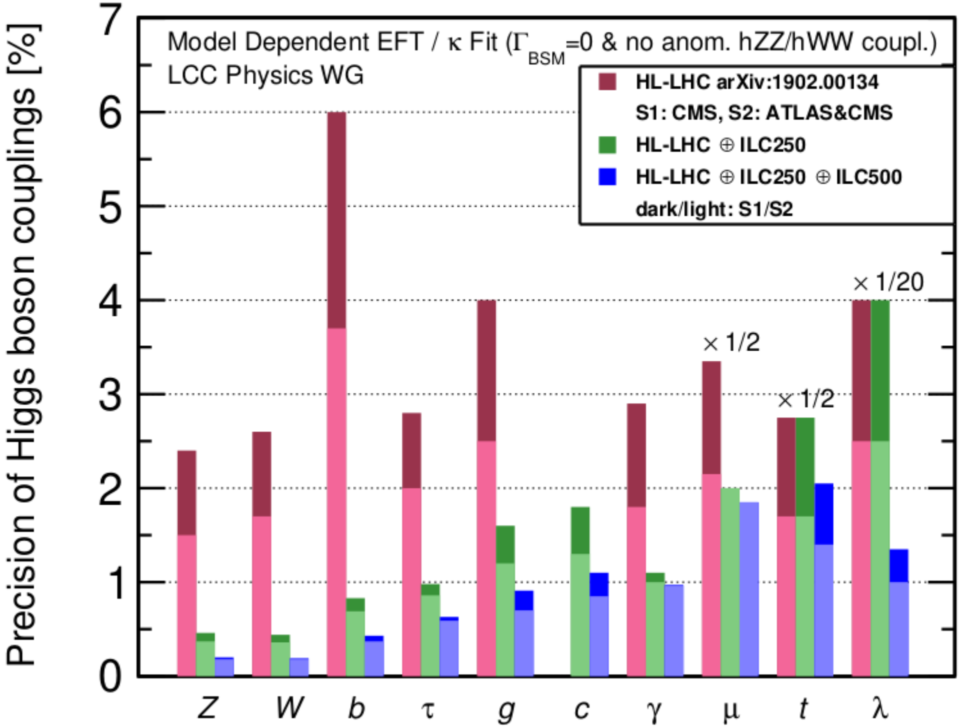
Higgs is a unique tool to probe BSM physics
    <1% precision to probe TeV-scale models

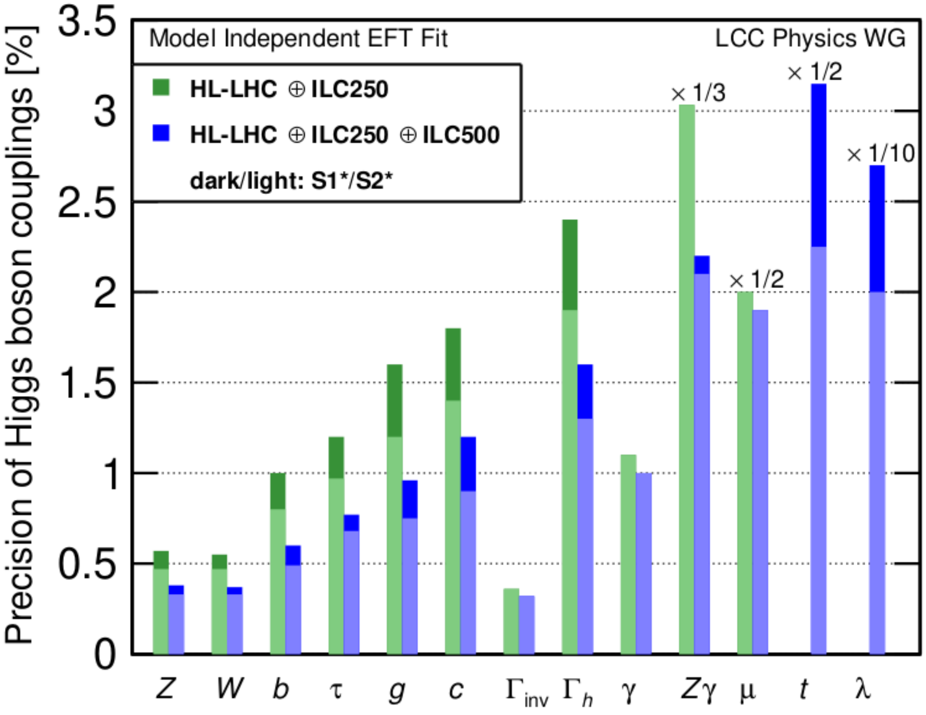
e+e- Higgs factory can achieve this precision
    many other opportunities in E-W, BSM, QCD physics

a few proposals for “short/mid”-term realisation of Higgs factory
    → we should realise at least one!

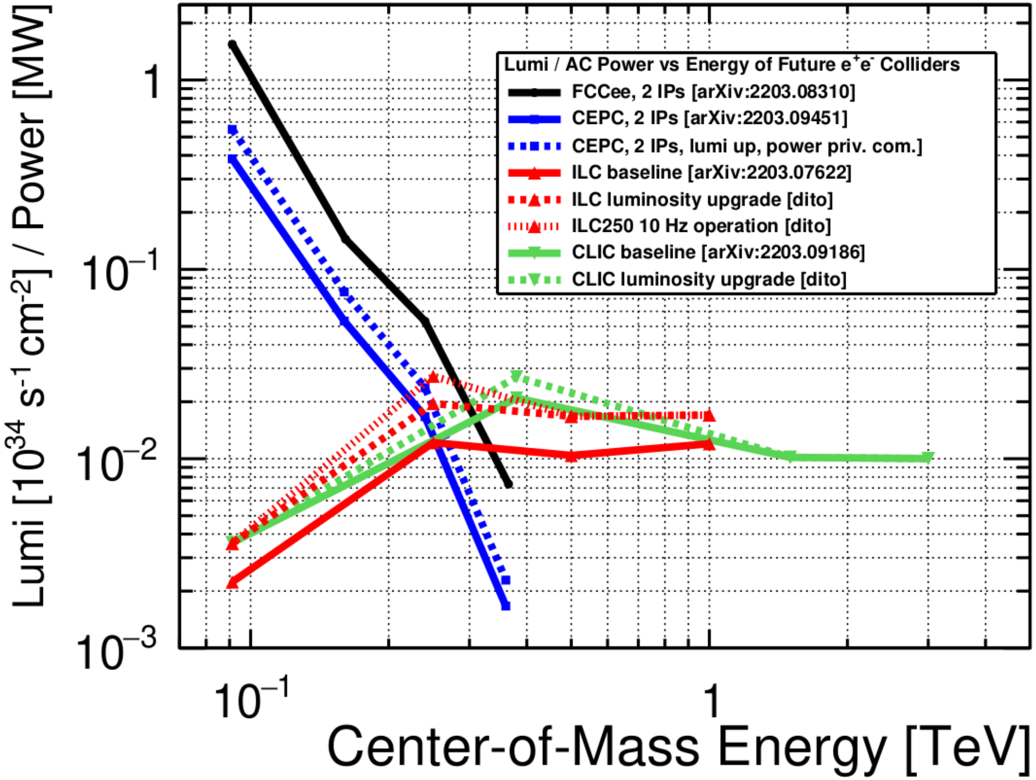
several intriguing ideas for the far future

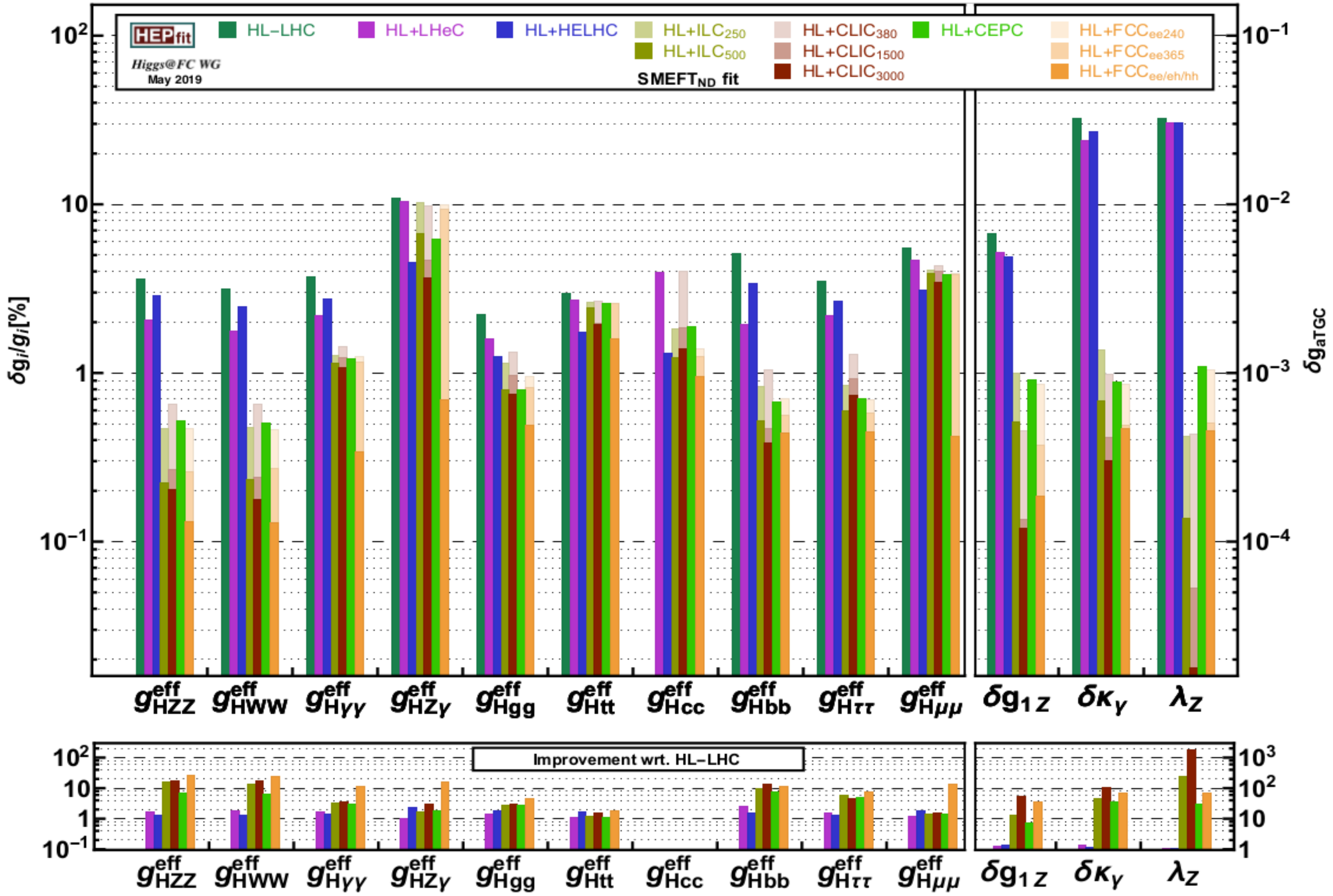
backup



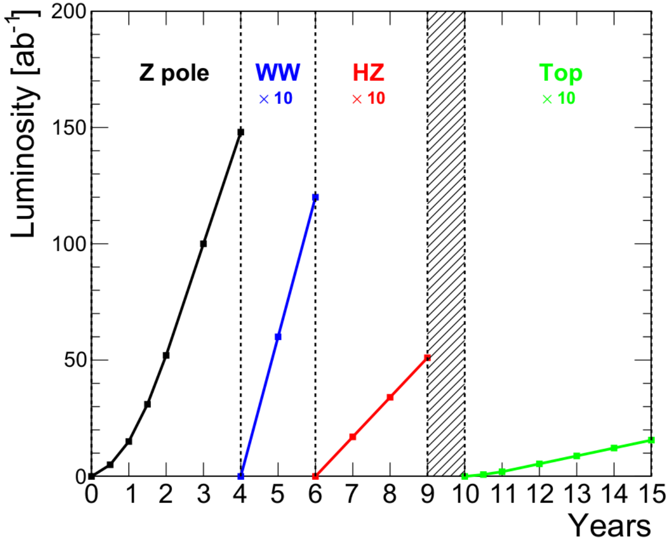


arXiv:1903.01629


Lumi / AC Power vs Energy of Future e^+e^- Colliders
FCCee, 2 IPs [arXiv:2203.08310]
CEPC, 2 IPs [arXiv:2203.09451]
CEPC, 2 IPs, lumi up, power priv. com.]
ILC baseline [arXiv:2203.07622]
ILC luminosity upgrade [dito]
ILC250 10 Hz operation [dito]
CLIC baseline [arXiv:2203.09186]
CLIC luminosity upgrade [dito]
Lumi [10^{34} s^{-1} cm^{-2}] / Power [MW]
1
10^{-1}
10^{-2}
10^{-3}
10^{-1}
1
Center-of-Mass Energy [TeV]

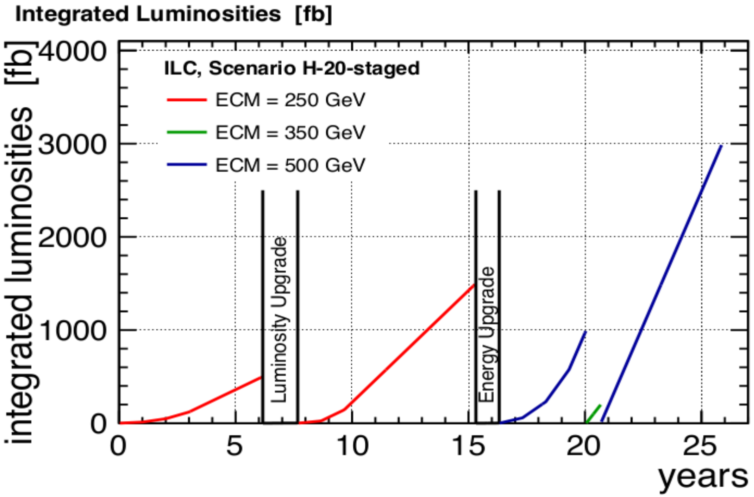


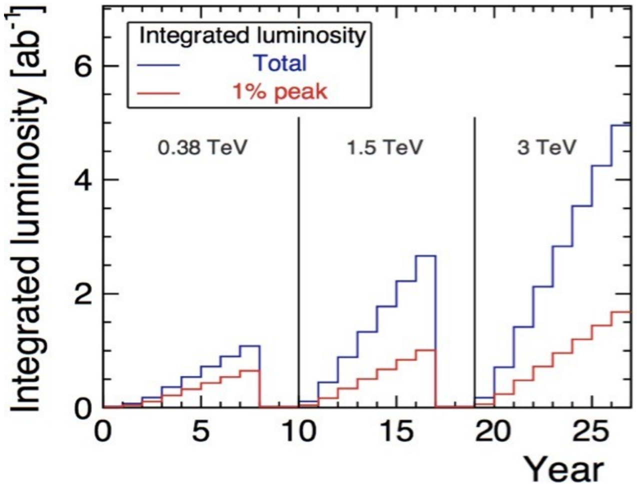
arXiv:1905.03764



staged operation

Operation mode	$\sqrt{s}$ (GeV)	L per IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	Years	Total $\int L$ (ab^{-1}, 2 IPs)	Event yields
H	240	3	7	5.6	1×10^{6}
Z	91.2	32 (*)	2	16	7×10^{11}
$W^{+}W^{-}$	158–172	10	1	2.6	2×10^{7} (†)





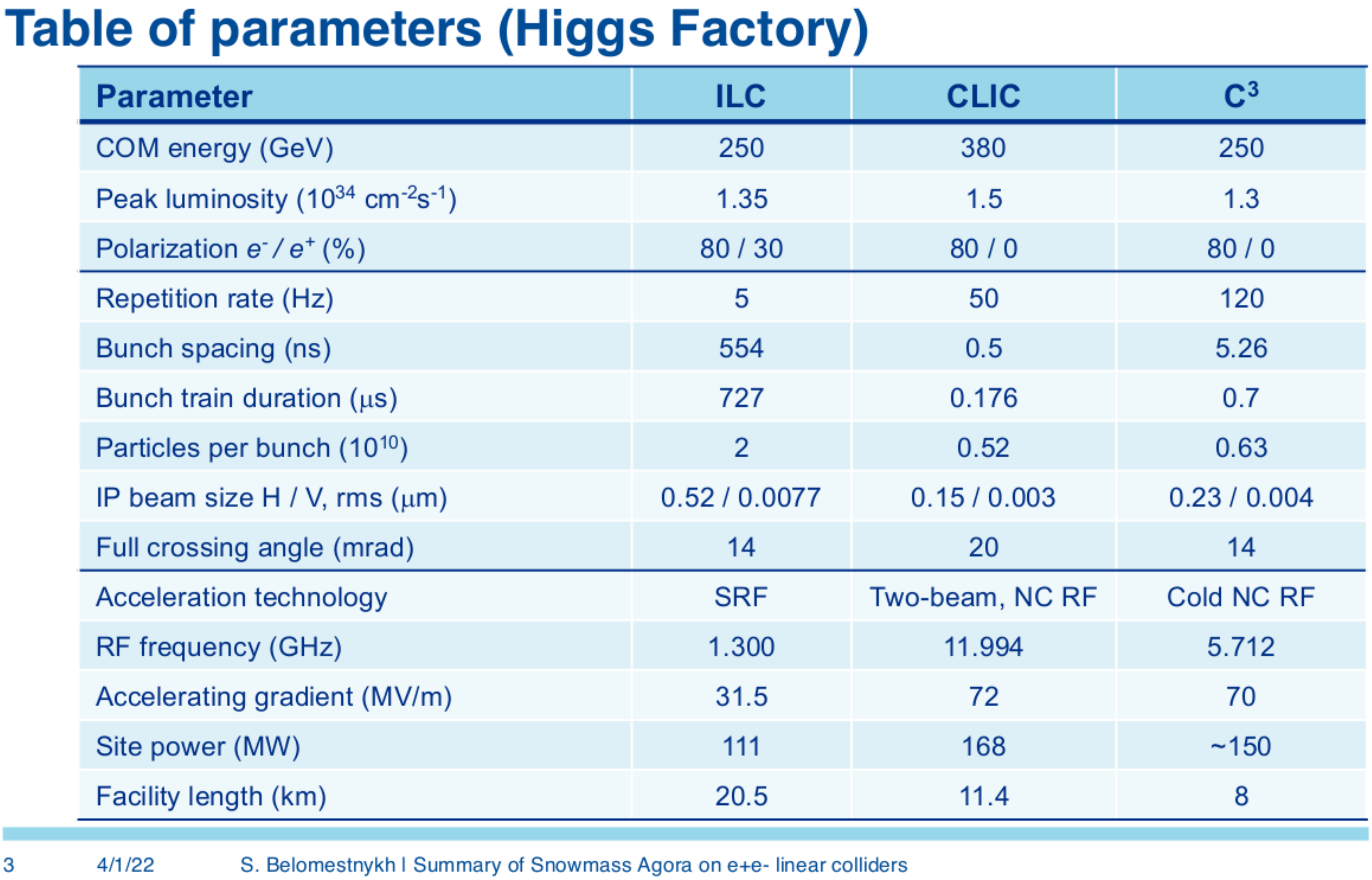
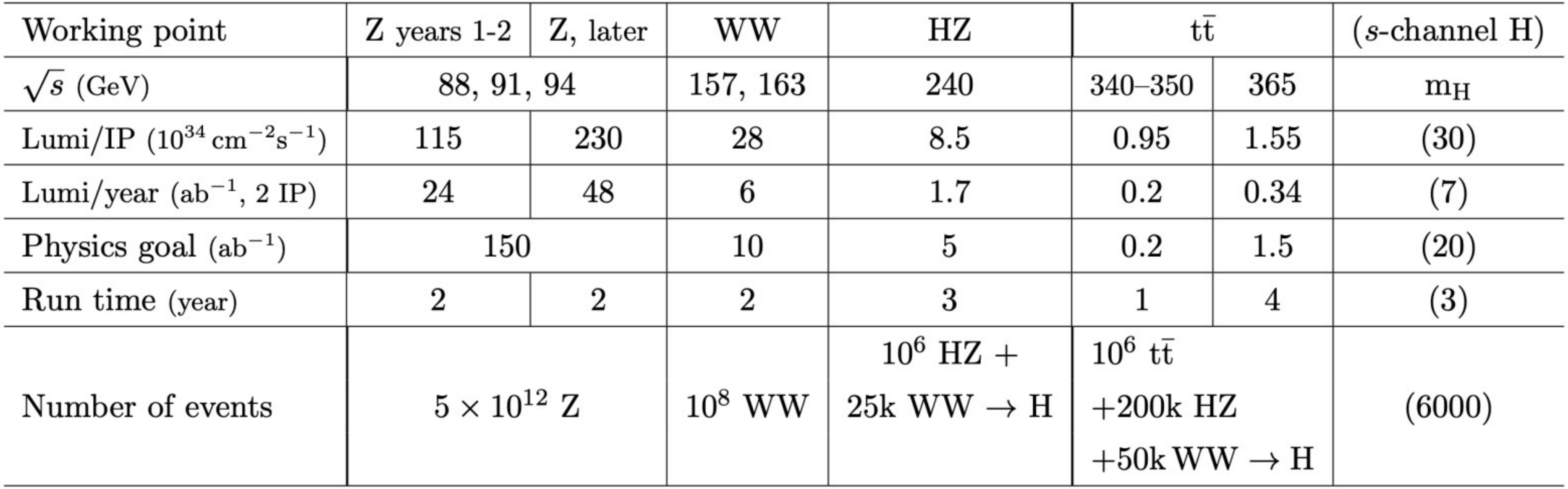


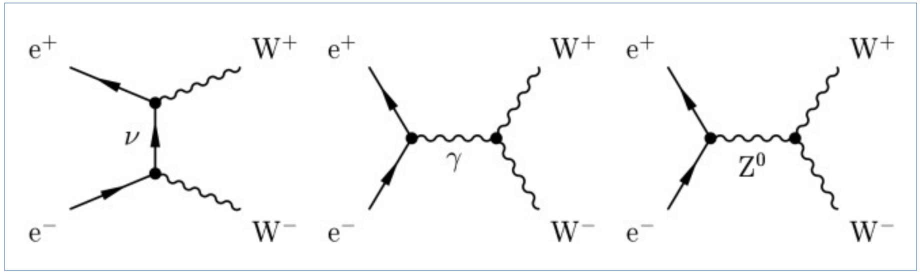
Table of parameters (Higgs Factory)

Parameter	ILC	CLIC	C^3
COM energy (GeV)	250	380	250
Peak luminosity (10^{34} $cm^{-2}s^{-1}$)	1.35	1.5	1.3
Polarization e^- / e^+ (%)	80 / 30	80 / 0	80 / 0
Repetition rate (Hz)	5	50	120
Bunch spacing (ns)	554	0.5	5.26
Bunch train duration (μs)	727	0.176	0.7
Particles per bunch (10^{10})	2	0.52	0.63
IP beam size H / V, rms (μm)	0.52 / 0.0077	0.15 / 0.003	0.23 / 0.004
Full crossing angle (mrad)	14	20	14
Acceleration technology	SRF	Two-beam, NC RF	Cold NC RF
RF frequency (GHz)	1.300	11.994	5.712
Accelerating gradient (MV/m)	31.5	72	70
Site power (MW)	111	168	~150
Facility length (km)	20.5	11.4	8

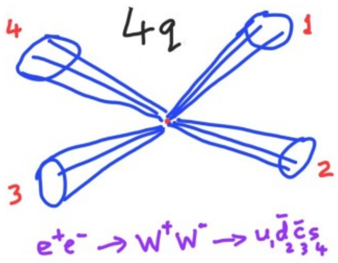


Working point	Z years 1-2	Z, later	WW	HZ	$t\bar{t}$		(s-channel H)
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340–350	365	m_H
Lumi/IP ($10^{34}\,cm^{-2}s^{-1}$)	115	230	28	8.5	0.95	1.55	(30)
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34	(7)
Physics goal (ab^{-1})	150		10	5	0.2	1.5	(20)
Run time (year)	2	2	2	3	1	4	(3)
Number of events	5×10^{12} Z		10^8 WW	10^6 HZ + 25k WW → H	10^6 $t\bar{t}$ +200k HZ +50k WW → H		(6000)

W mass in e^+e^-

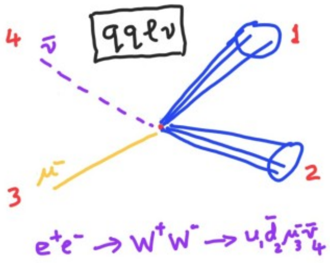


fully hadronic $q\bar{q}q\bar{q}$



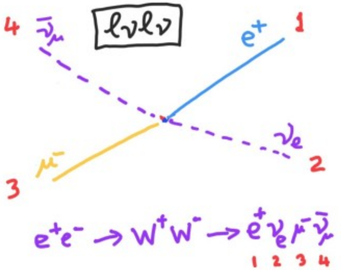
$B_h^2 = 45.4\%$

semi-leptonic $q\bar{q}\ell\nu_\ell$



$6B_\ell B_h = 43.9\%$

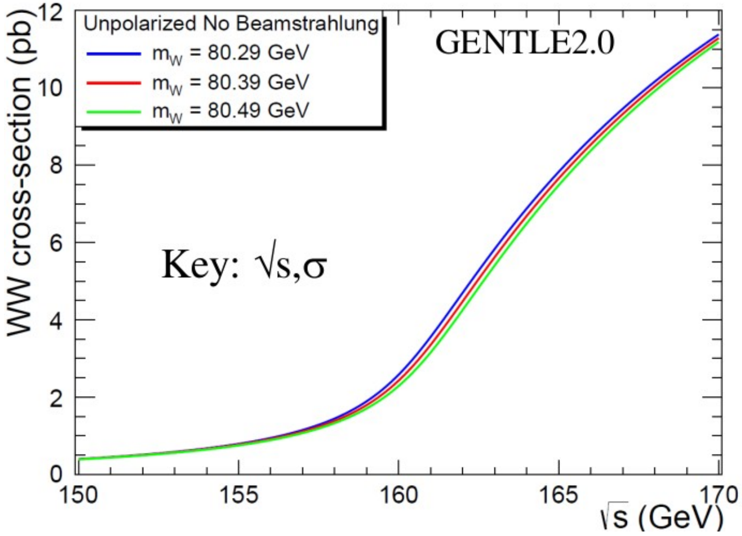
fully leptonic $\ell\nu_\ell\ell'\bar{\nu}_{\ell'}$

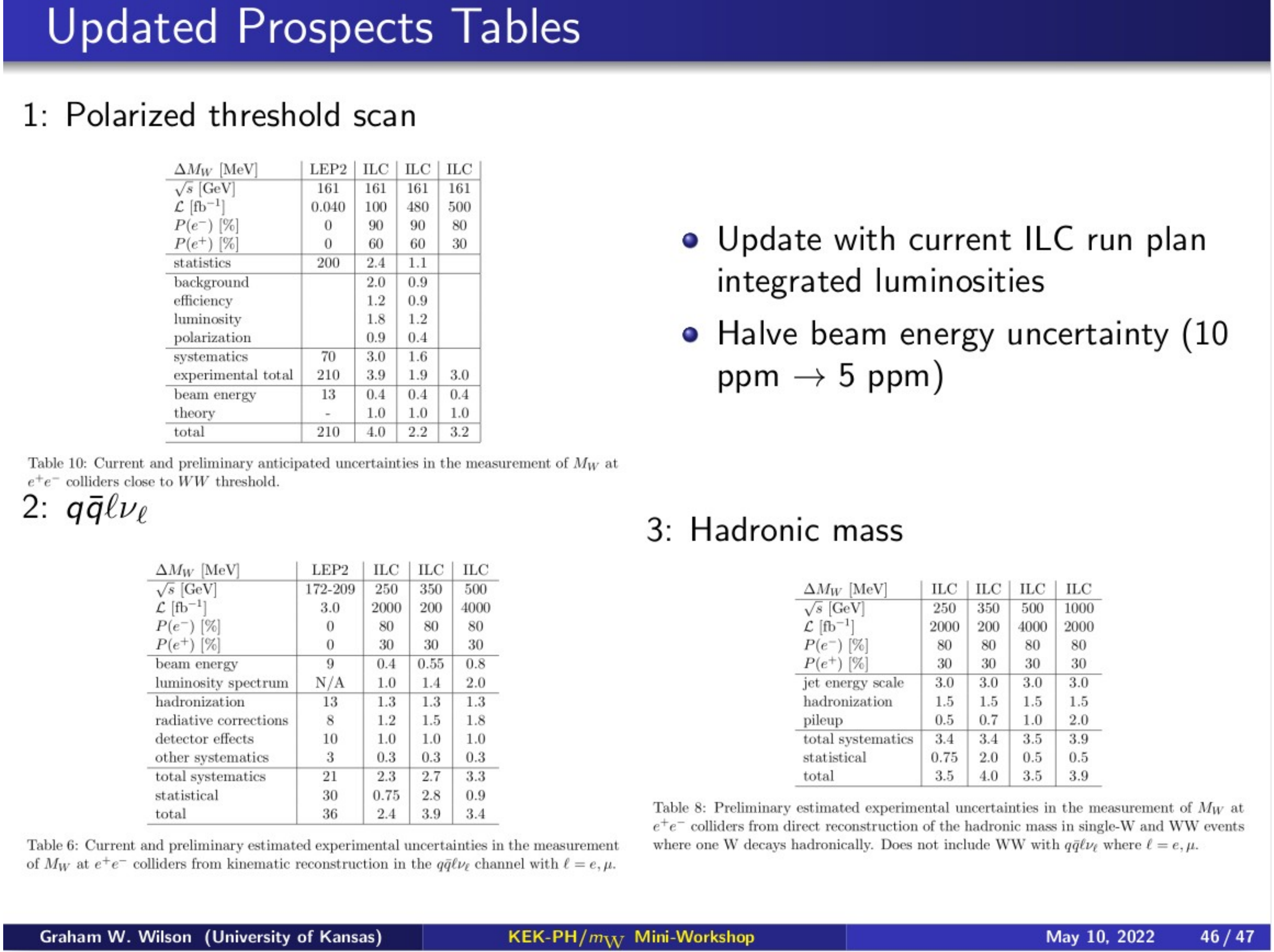


$9B_\ell^2 = 10.6\%$

There are several promising approaches to measuring m_W at an e^+e^- collider:

1. Polarized Threshold Scan Measurement of the W^+W^- cross-section near **threshold** with longitudinally polarized beams. Requires dedicated luminosity well below Higgs threshold; can it not be done well enough in other ways?
2. Constrained Reconstruction Kinematically-constrained reconstruction of W^+W^- using constraints from **four-momentum conservation** and optionally mass-equality: the LEP2 work-horse. Primarily using semileptonic events. Color reconnection assumed to dog fully hadronic - really?
3. Hadronic Mass Direct measurement of the **hadronic mass**. This can be applied particularly to single-W events decaying hadronically or to the hadronic system in semi-leptonic W^+W^- events (especially for $q\bar{q}\tau\nu_\tau$).
4. Lepton Endpoints The 2-body decay of each W leads to endpoints in the lepton (or jet) **energy** at $E_\ell = E_b(1 \pm \beta)/2$ where β is the W velocity. These can be used to infer m_W. Can use for WW events with ≥ 1 prompt lepton.
5. Fully Leptonic Reconstruction Pseudomass method (Apply 5C).





Updated Prospects Tables

1: Polarized threshold scan

ΔM_W [MeV]	LEP2	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	161	161	161	161
$\mathcal{L}$ [fb^{-1}]	0.040	100	480	500
$P(e^-)$ [%]	0	90	90	80
$P(e^+)$ [%]	0	60	60	30
statistics	200	2.4	1.1	
background		2.0	0.9	
efficiency		1.2	0.9	
luminosity		1.8	1.2	
polarization		0.9	0.4	
systematics	70	3.0	1.6	
experimental total	210	3.9	1.9	3.0
beam energy	13	0.4	0.4	0.4
theory	-	1.0	1.0	1.0
total	210	4.0	2.2	3.2

Table 10: Current and preliminary anticipated uncertainties in the measurement of M_W at e^+e^- colliders close to WW threshold.

- Update with current ILC run plan integrated luminosities
- Halve beam energy uncertainty (10 ppm → 5 ppm)

2: $q\bar{q}\ell\nu_\ell$

ΔM_W [MeV]	LEP2	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	172-209	250	350	500
$\mathcal{L}$ [fb^{-1}]	3.0	2000	200	4000
$P(e^-)$ [%]	0	80	80	80
$P(e^+)$ [%]	0	30	30	30
beam energy	9	0.4	0.55	0.8
luminosity spectrum	N/A	1.0	1.4	2.0
hadronization	13	1.3	1.3	1.3
radiative corrections	8	1.2	1.5	1.8
detector effects	10	1.0	1.0	1.0
other systematics	3	0.3	0.3	0.3
total systematics	21	2.3	2.7	3.3
statistical	30	0.75	2.8	0.9
total	36	2.4	3.9	3.4

Table 6: Current and preliminary estimated experimental uncertainties in the measurement of M_W at e^+e^- colliders from kinematic reconstruction in the $q\bar{q}\ell\nu_\ell$ channel with $\ell = e, \mu$.

3: Hadronic mass

ΔM_W [MeV]	ILC	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	250	350	500	1000
$\mathcal{L}$ [fb^{-1}]	2000	200	4000	2000
$P(e^-)$ [%]	80	80	80	80
$P(e^+)$ [%]	30	30	30	30
jet energy scale	3.0	3.0	3.0	3.0
hadronization	1.5	1.5	1.5	1.5
pileup	0.5	0.7	1.0	2.0
total systematics	3.4	3.4	3.5	3.9
statistical	0.75	2.0	0.5	0.5
total	3.5	4.0	3.5	3.9

Table 8: Preliminary estimated experimental uncertainties in the measurement of M_W at e^+e^- colliders from direct reconstruction of the hadronic mass in single-W and WW events where one W decays hadronically. Does not include WW with $q\bar{q}\ell\nu_\ell$ where $\ell = e, \mu$.