Energy Frontier: Reflections from Granada

STFC Community Meeting, IOP 1st July 2019

Sinead Farrington
University of Edinburgh

Reflections on the (UK) process

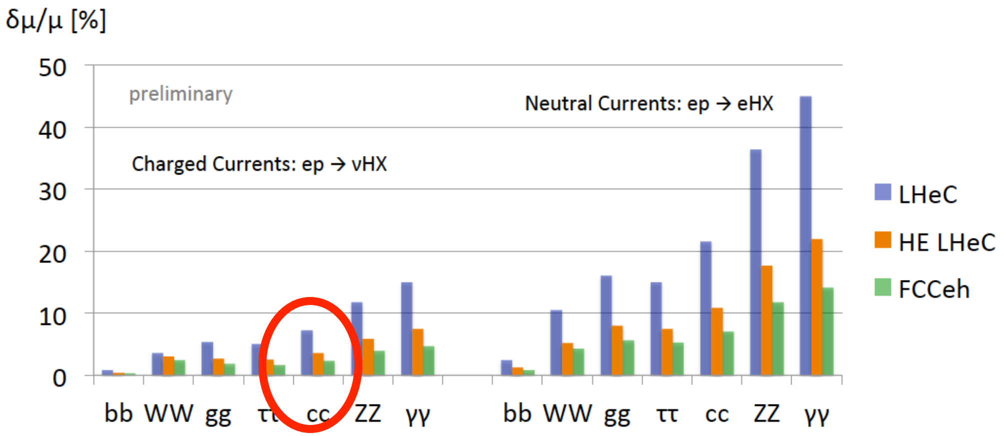
- Have read the recent UK group submissions for today.
- A lot of thought is going into this process
  - Many colleagues have also been engaged with putting options on the table for our future a lot longer than this strategy process
- There are several sound and self-consistent options each adding something to our knowledge of the fundamental scales
  - the difficult question is how to prioritise, as we must, and how to take forward our case
  - Make progress by setting the science questions at the centre.

Granada Highlights (based on your input)

- Renewed excitement about muon colliders
  - and building excitement about plasma wakefield options
- Full HL-LHC exploitation is highest priority
- Call for CLiC TDR
- Calls for standalone hadron collider program to be evaluated
- Call for European/CERN support for e^+e^- Asia programs
- Support for a strong non-collider program as a complement to the collider program
- Reading across all submissions for today’s meeting, there is not a consensus. It is in our grasp to coalesce on several aspects, in several scenarios.

Issues raised in UK submissions

- (much subtle argument, I cannot do it justice here)
- Retain flexibility in strategy (international scene)
- Desire for an upgradeable facility
- Higgs sector exploration is fascinating and imperative
- Concerns over single-interaction-point facilities
- Funding concerns; the need to marshall arguments
- LHeC full exploration

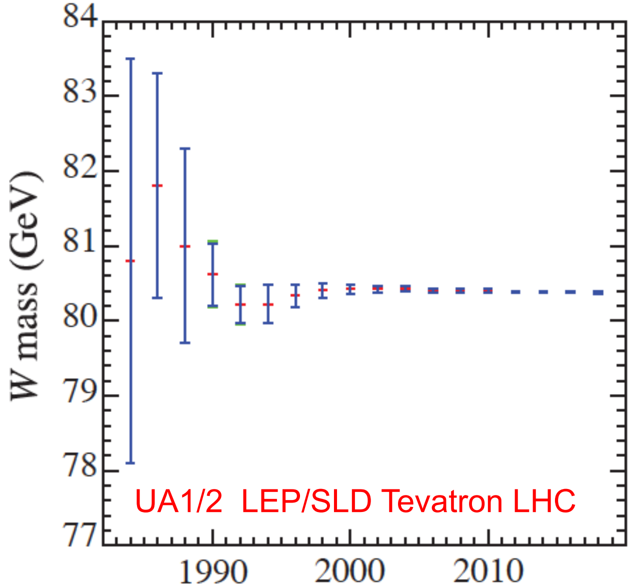


- LHCb upgrade
  - Flavour session

Proposal

- For the next collider we want (at least) an order of magnitude improvement in *something*
- Something = Precision OR New Physics reach

  [or likelihood of surprises?! tautologous and hard to pin down]
- Seems reasonable based on the past?
  - UA1/UA2 to LEP/SLD
  - LEP to Tevatron/Babar/Belle
  - Tevatron to LHC



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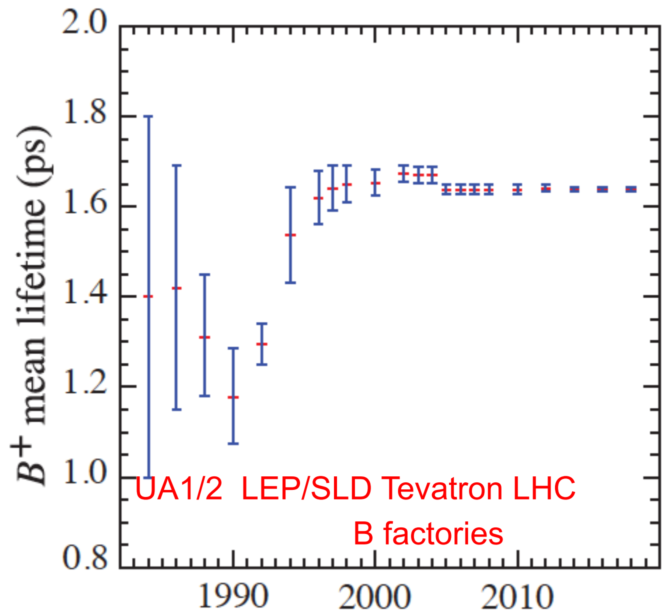

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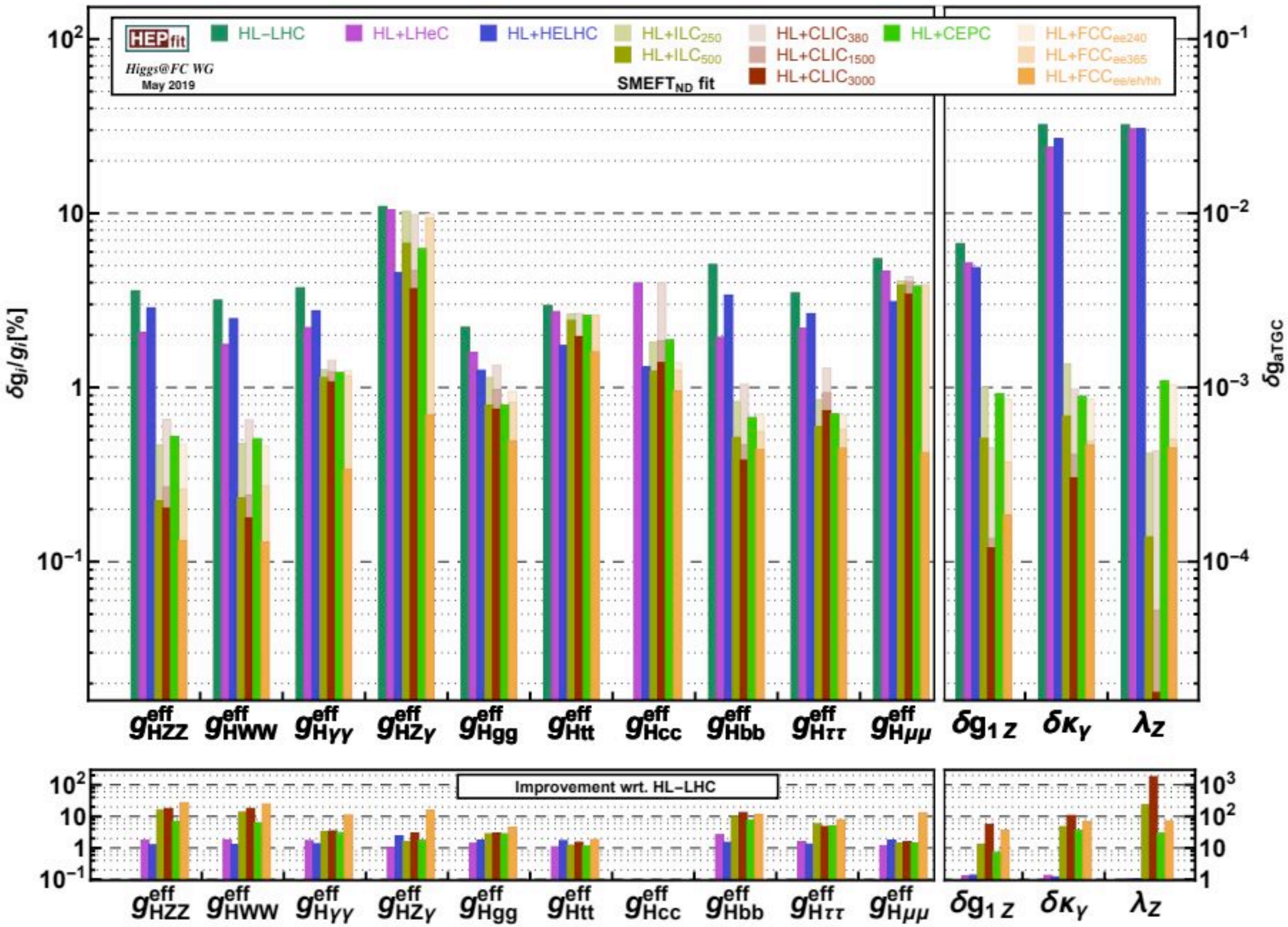
- Can this principle guide us now?
- Let's look at the options, trying to highlight key physics parameters
  - Aiming to be an honest broker, not affiliated to any future collider project.

Precision

Not covering top (e^+e^- powerful if above 350 GeV, hh also powerful), QCD, flavour.

Time necessitates that I cannot do justice to all of the studies.

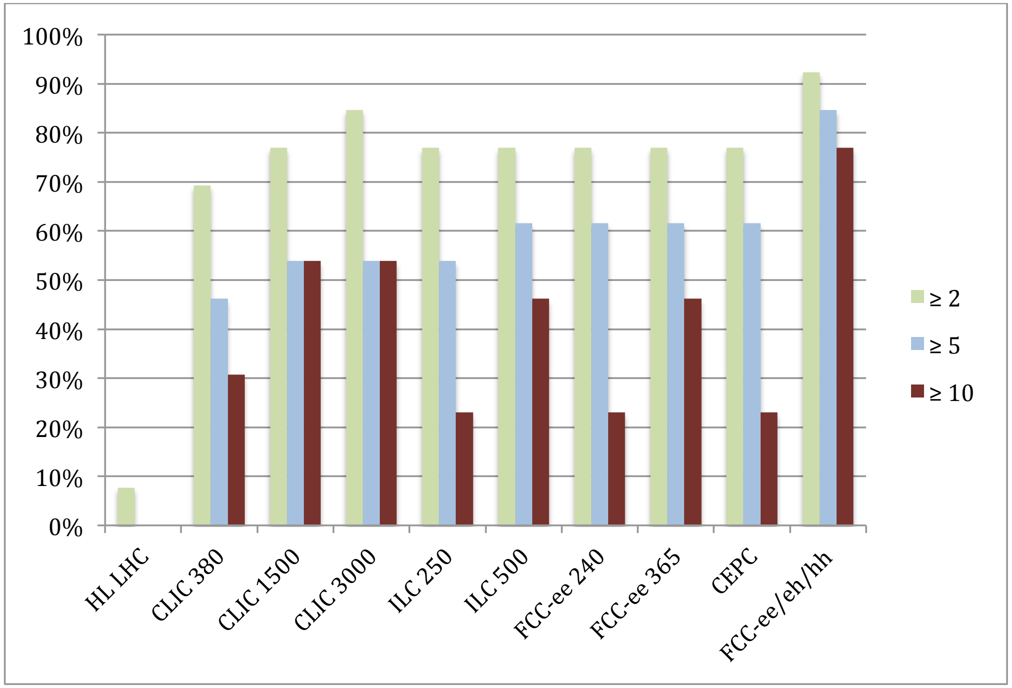
Higgs+aTGCs



HEPfit
Higgs@FC WG
May 2019
HL-LHC
HL+LHeC
HL+HELHC
HL+ILC250
HL+ILC500
SMEFTND fit
HL+CLIC380
HL+CLIC1500
HL+CLIC3000
HL+CEPC
HL+FCCee240
HL+FCCee365
HL+FCCee/eh/hh
δgi/gi[%]
δgaTGC
Improvement wrt. HL-LHC

Higgs/EW number of "largely improved" couplings

	Factor ≥ 2	Factor ≥ 5	Factor ≥ 10	
HL LHC	1 / 8%	0 / 0%	0 / 0%	
CLIC 380	9 / 69%	6 / 46%	4 / 31%	
CLIC 1500	10 / 77%	7 / 54%	7 / 54%	
CLIC 3000	11 / 85%	7 / 54%	7 / 54%	
ILC 250	10 / 77%	7 / 54%	3 / 23%	
ILC 500	10/ 77 %	8 / 62%	6 / 46%	
FCC-ee 240	10 / 77%	8 / 62%	3 / 23%	
FCC-ee 365	10 / 77%	8 / 62%	6 / 46%	
CEPC	10 / 77%	8 / 62%	3 / 23%	
FCC-ee/eh/hh	12 / 92%	11 / 85%	10 / 77%	



after B. Heinemann

Higgs/EW number of "largely improved" couplings

after B. Heinemann

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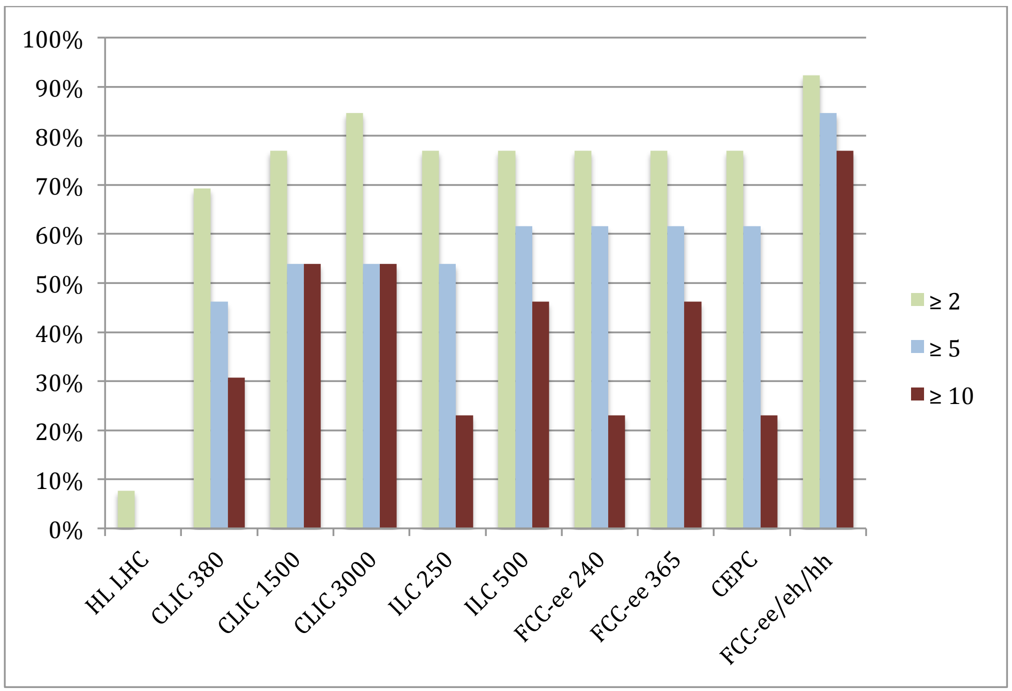


Definition of precision?

Note model dependencies

Must have FCC separated out.

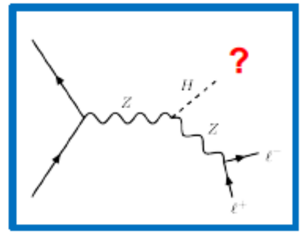
Higgs Width in e^+e^-

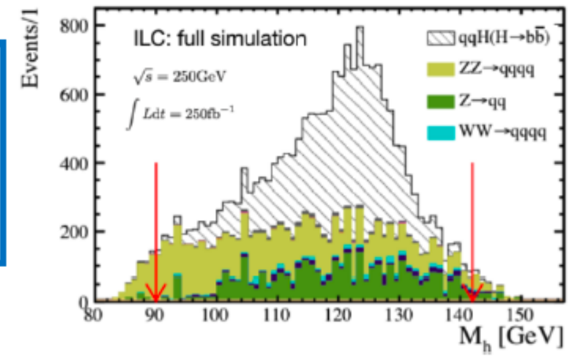
B. Heinemann

Higgs width and/or untagged decays

Unique feature of lepton-lepton colliders:

- Detecting the Higgs boson without seeing decay: "recoil method"
- Measure ZH cross section with high precision without assumptions on decay
- Often interpreted as quasi-direct measurement of width





$$\frac{\sigma(e^+e^- \to ZH)}{\mathrm{BR}(H \to ZZ^*)} = \frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^- \to ZH)}{\Gamma(H \to ZZ^*)}\right]_{\mathrm{SM}} \times \Gamma_H$$

In kappa-framework: $\Gamma_H = \dfrac{\Gamma_H^{SM} \cdot \kappa_H^2}{1 - (BR_{inv} + BR_{unt})}$

=> Will probe width with 1-2% precision

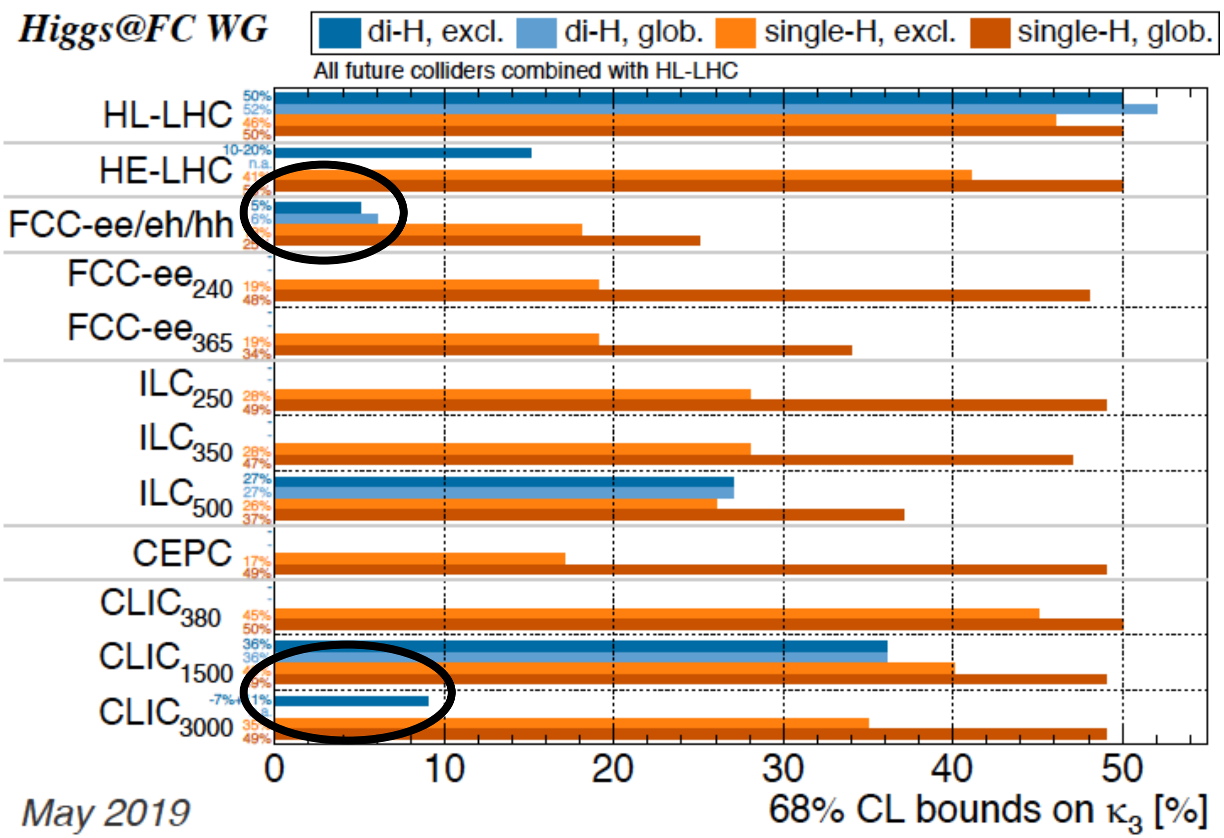
Collider	$\delta\Gamma_H$ (%) from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ (%) kappa-3 fit
ILC_{250}	2.4	EFT fit [3]	2.4
ILC_{500}	1.6	EFT fit [3, 11]	1.1
CLIC_{350}	4.7	κ-framework [85]	2.6
CLIC_{1500}	2.6	κ-framework [85]	1.7
CLIC_{3000}	2.5	κ-framework [85]	1.6
CEPC	3.1	$\sigma(ZH, \nu\bar{\nu}H)$, $\mathrm{BR}(H \to Z, b\bar{b}, WW)$ [90]	1.8
$\mathrm{FCC\text{-}ee}_{240}$	2.7	κ-framework [1]	1.9
$\mathrm{FCC\text{-}ee}_{365}$	1.3	κ-framework [1]	1.2

arXiv:1905.03764

(HL-LHC will reach SM width sensitivity via indirect measurement that assumes off-shell μ = on-shell μ)

Higgs Self-Coupling

Arguably the singly most special of the Higgs' properties



FCCee/eh/hh or CLiC 3000 (di-Higgs) meet the order of magnitude criterion (can infer that FCChh is the driver for FCC)

New Physics Reach

Bump-hunt Searches

G. Giudice

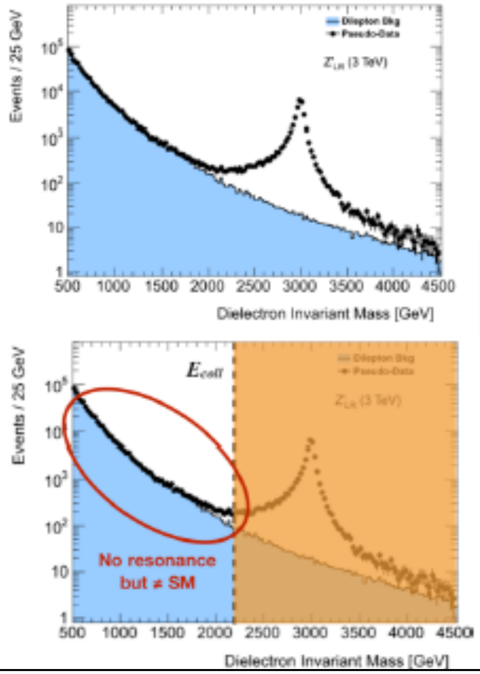
Seeing the peak. Reach:

- $M < \sqrt{s}$ for lepton colliders
- $M \lesssim 0.3\text{-}0.5\sqrt{s}$ in hadron colliders for couplings ~ weak couplings

Deviations in high-M tails:

- Better suited for lepton colliders; sensitive to [mass/coupling] $\gg \sqrt{s}$
- Hadron colliders relevant for $g_{Z'} > g_{SM}$ couplings: [mass/coupling] $\gg 0.5\sqrt{s}$

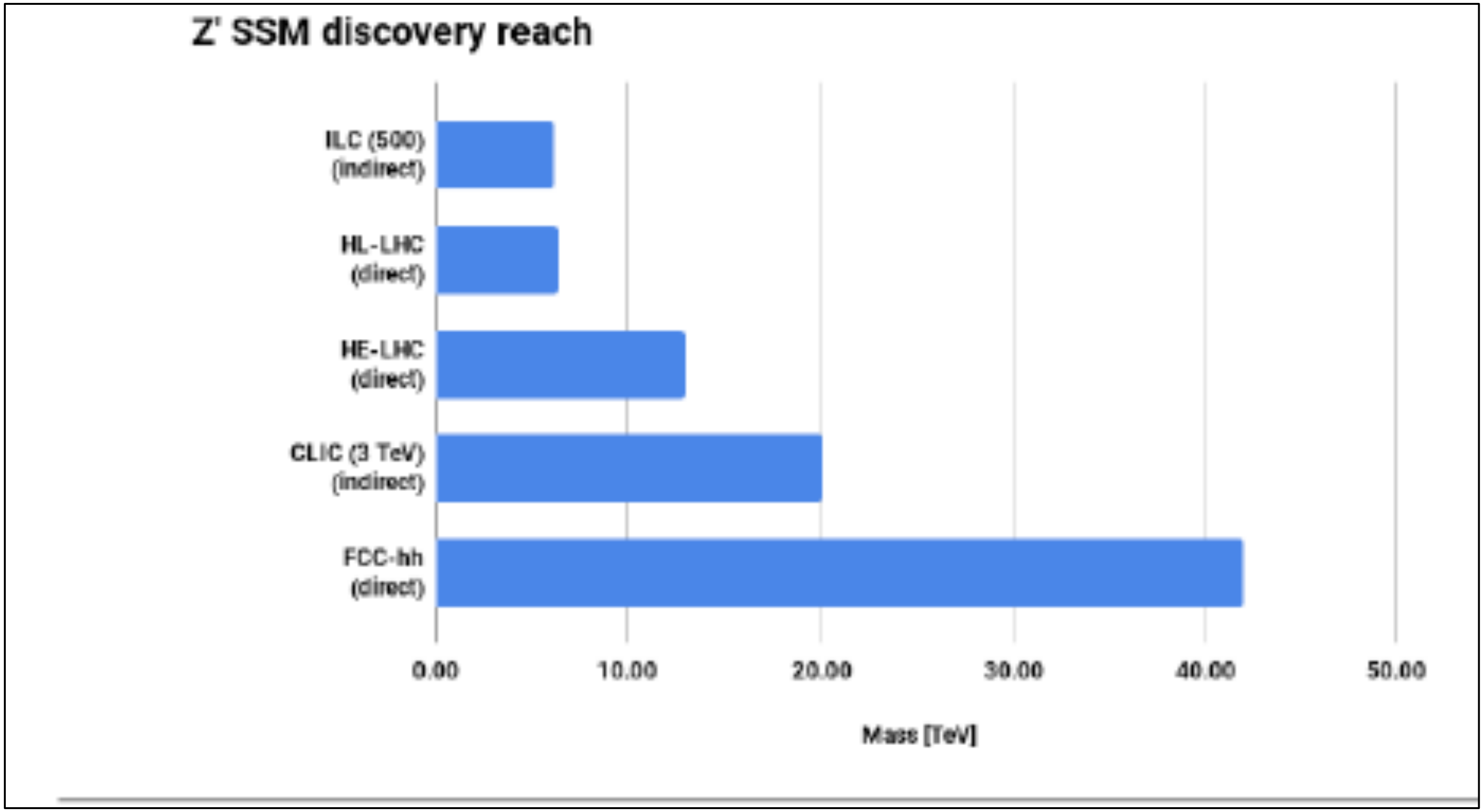
Z' SSM discovery reach



Courtesy: J. De Blas

Bump-hunt Searches

G. Giudice



Order of magnitude criterion implies FCChh (indirect not quoted, but factor ~2-4 higher than direct reach has been evaluated for HL-LHC) ..$E=mc^2$

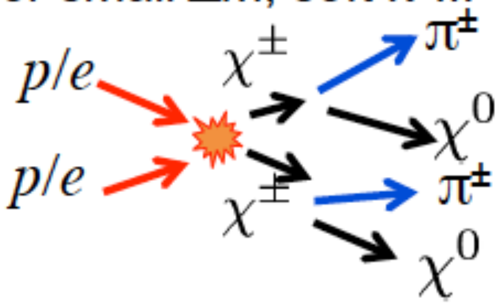
Phys.Rev.Lett. 120 (2018) no.10, 101801

Dark Matter: WIMPs

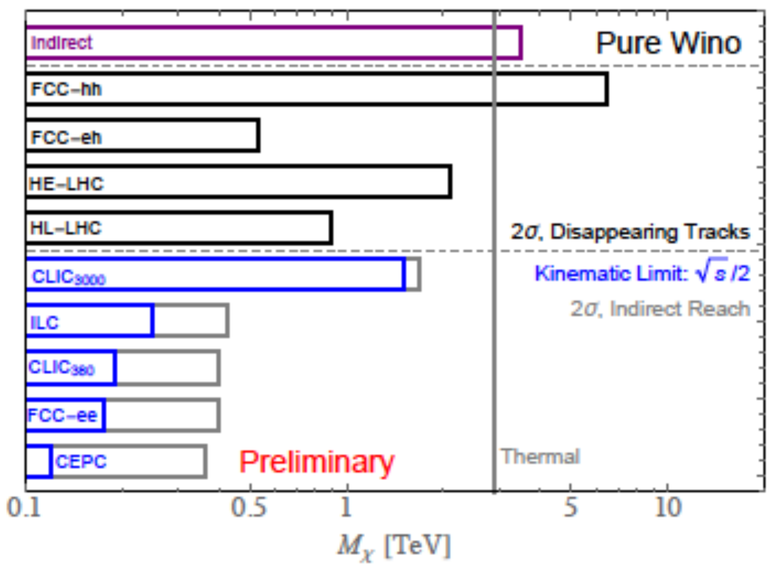
G. Giudice

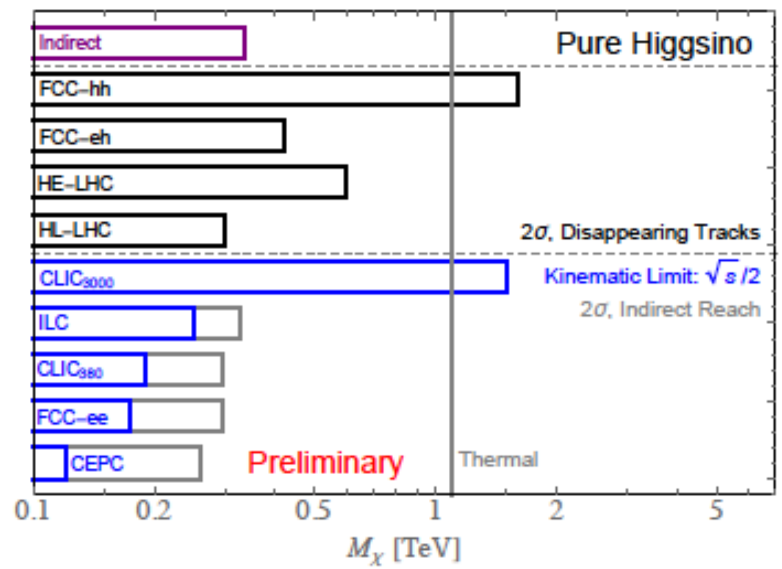
- **Two "extremes", pure Wino, pure Higgsino**
  - **Main "tools": disappearing track, propagator modifications**

For small Δm, soft $\pi^{\pm}$...



EWKinos in loop change prop (W, Y parameters)

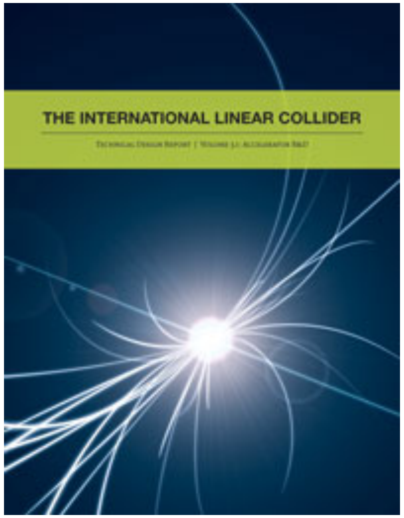




Points to FCChh, CLiC 3000 for Higgsino, indirect

Reality check

- What *can* we build? – ILC has a TDR

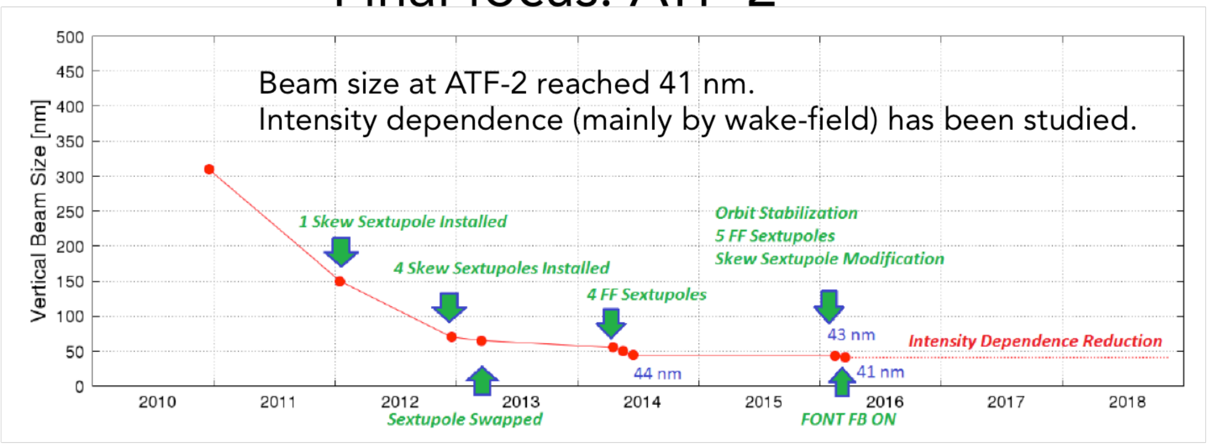


Reality check

- **What *might* we build?**
  - CLiC with investment towards TDR (CDR done)

S. Stapnes

Final focus: ATF-2



ATF2 IP beam size of 41nm is comparable to ILC250 beam size of 7.7nm
Intensity dependence effect is evaluated to a couple % of ILC250 IP beam size growth

Work continues: wakefields, stability, ultra low beta options
Common LC programme - also involving many European groups

Reality check

- **What *might* we build?**
  - FCC ee/eh/hh (CDR done)
    - ee with ~existing technology in 100km tunnel
    - hh needs magnet R&D

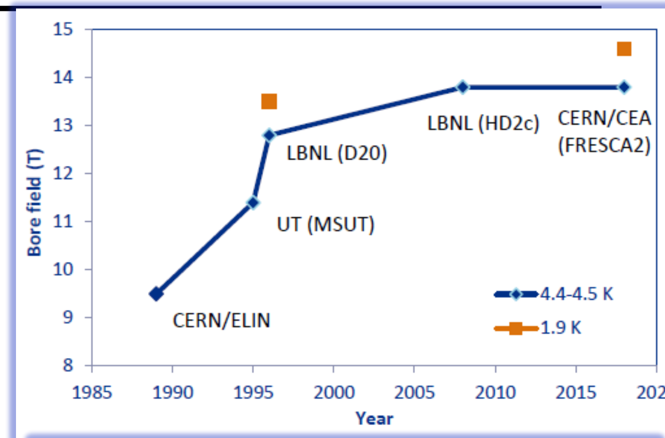
Reality check

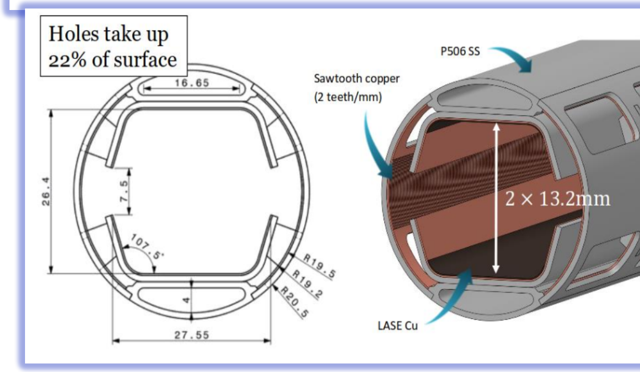
- **What *might* we build?**
  - FCC hh – no standalone proposal/CDR. Called for at Granada.
    - Dependent on magnet technology sooner

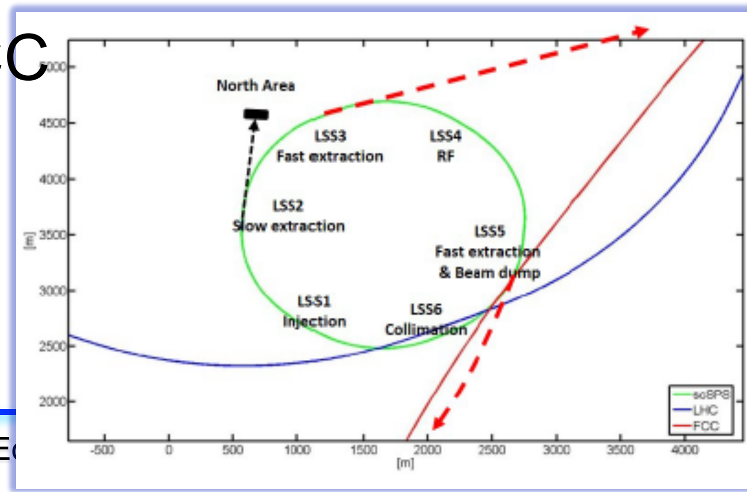
Strategic R&D Ahead :

V. Shiltsev

- **High field dipoles:**
  - Nb3Sn 16 T / iron-based 12 T, wire
  - (see also Akira's talk)
- **Intercept of synchr radiation :**
  - 5 MW FCC-hh / 1 MW CepC
- **Collimation :**
  - x7 LHC circulating beam power
- **Optimal injector:**
  - 1.3TeV scSPS, 3.3 TeV in LHC/FCC
- **Overall machine design :**
  - IRs, pileup, vacuum, etc
  - Power and cost reduction







•All that might take 12-18 years

Reality check

- **What *might* we build?**
  - Muon collider (timescale of “20 years” debated)
    - Threshold “no cooling” proposal generating interest

Physical Review Accelerators and Beams 21, 061005 (2018)

  - Plasma wakefield accelerator
  - LHeC (requires accelerator R&D)

The alternatives

1. Support e^+e^- in europe: fund R&D on CLiC TDR 2025, aim for a 30 year e^+e^- program in Europe.

2. Support e^+e^- in Asia: fund magnet R&D, aim for FCChh (or highest doable energy hh) in Europe on 2040s timescale.

2a. What if no e+e- in Asia? Report based on hh alone should be provided for the ESU process.

3. Support the integrated FCCee/eh/hh program.

4. Invest in a new accelerator technology providing a solution for a multi-TeV collider and/or hope for new information that points the way.

How to decide?

1. Which parameters/new phase spaces do we most care about measuring?

2. What factor improvement is worth the investment of people/facilities/funds?

Extras

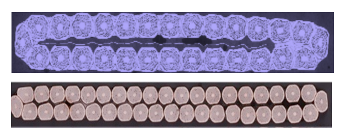
US-DOE /Europe/China engaged with High field magnets

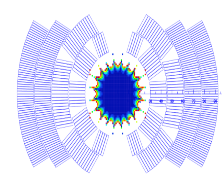
A. Yamamoto

- **MDP Goals:**
  1. Explore Mb_3Sn magnet limit
  2. Demonstrate HTS magnet (5 T – self fied)
  3. Investigate fundamentals for performance and cost reduction
  4. Pursue Nb3Sn and HTS conductor R&D

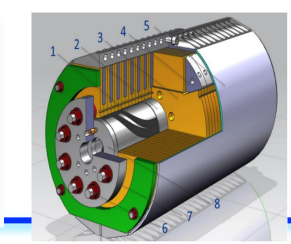
- **Step 1:** **(we are here in 2019)**
  - Realize 14 T w/ mechanical design for 16 T
  - Will be **tested soon (2019).**
- **Step 2:**
  - Realize 15 T w/ pre-stress optimization
- **Step 3:**
  - Challenge to realize 16 T, with SC conductor satisfying 1,500 A/mm2 and sufficiently controlled mechanical design

- Courtesy: S. Prestemon S. Belomstr





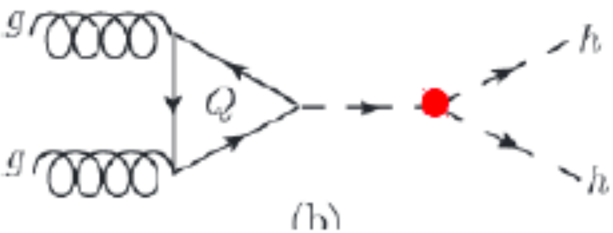
- L1-L2: 28 strands, 1 mm RRP 150/169
- L3-L4: 40 strands, 0.7 mm RRP 108/127

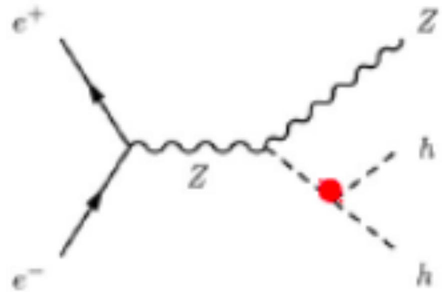


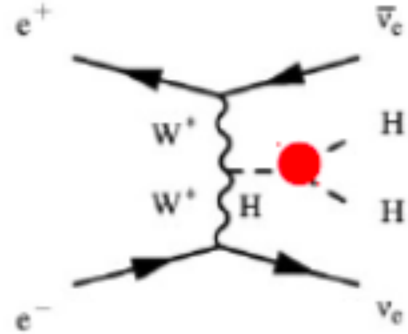
- Before test, at Fermi

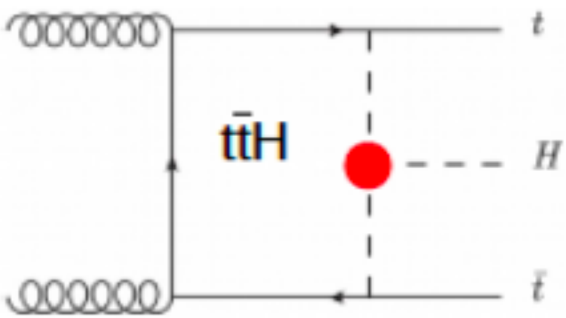
Higgs Self-Coupling

Arguably the singly most special of the Higgs' properties









Higgs

	HL-LHC	LH-eC	ILC	CLIC	CLIC (HE)§	FCC-ee	FCC-eh	CepC	FCC-hh / SppC
E	13 TeV	e(60 GeV) p(7 TeV) / p(14 TeV)	250 GeV	350 GeV	1.4 / 3 TeV	240 (+350) GeV	e(60GeV) p(50TeV)	240-250 GeV	100 TeV
L	3 ab^{-1}	1 / 2 ab^{-1}	2 ab^{-1}	0.5 ab^{-1}	1.5 / 2 ab^{-1}	5 (+1.5) ab^{-1}	2 ab^{-1}	5 ab^{-1}	20 ab^{-1}
m_H	?	-	0.01	0.09	0.04 / 0.04	?	-	0.005	-
Couplings are 'model-dependent', except for ILC EFT fits see remark % below									
Γ_H	50*	-	2.5-4	6.7	3.7 / 3.5 ✢	1.55	-	2.8	-
κ Z	3.8-4.4	1.2 / 0.6	0.88	0.6	0.4 / 0.3 ✢	0.16	0.43	0.16	1-2
κ W	4.2-5.1	0.6 / 0.33	0.67	1.1	0.2 / 0.1 ✢	0.41	0.26	1.2	-
κ g	5-9	3 / 1.6	1.7	3.0	1.5 / 1.1 ✢	1.23	1.17	1.5	-
κ γ	4-5	7.1 / 3.2	1.2	-	5.6 / 3.1 ✢	2.18	2.35	4.7	1-2
κ τ	8.8-9.7	2.8 / 1.5	1.2	3.9	1.5 / 1.1 ✢	0.78	1.1	1.2	-
κ b	10-12	1.5 / 0.9	1.1	1.8	0.4 / 0.2 ✢	0.58	0.7	1.3	-
κ c	< 2.2**	3.8 / 1.9	1.9	5.8	2.1 / 1.7 ✢	1.05	1.35	1.6	-
κ t	7.6-11	- / 5.5	-	-	4.1 / -	-	1.9	-	1
κ μ	~10	-	5.6#	-	14.1 / 7.8 ✢	9.6	-	8.6	1-2
B(inv)	< 2.8 - 20 **	-	< 0.32 **	< 0.97 ^	-	< 0.63-0.92**	-	< 0.28 **	-
λ_3	< 1.37 - 1.44 **	-	-	-	40-54 / 19-26 ✢	28***	-	35***	5

N. Wardle,
V. Martin,
C. Englert,
T. Scanlon

Width

Couplings

(see write-up for footnotes)

Self-couplings

Higgs Factories

- ILC: 640000
- CLIC 380: 160000
- CLIC 3000: “millions”
- HL-LHC: >15 million
- FCChh: “billions”

•iopscience.iop.org/article/10.1088/1674-1137/41/6/063102/pdf

•CDR

•CDR

•arXiv:1902.10229

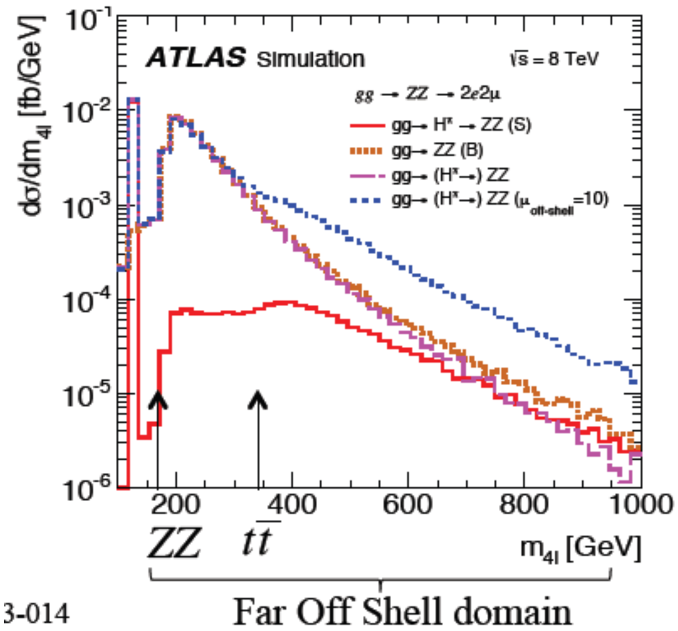
Higgs Width in hh collider

- Probe via off-shell couplings
  - Assume off-shell μ is the same as on-shell

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \quad \text{and} \quad \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

JHEP 08, 116 (2012),
PRD 88, 054024 (2013),
JHEP 04, 060 (2014)

  - HL-LHC will bring sensitivity at SM-level:
    - $\Gamma=4.2^{+1.5}_{-2.1}$ MeV



PRD 92 (2015) 012004

PLB 736 (2014) 64

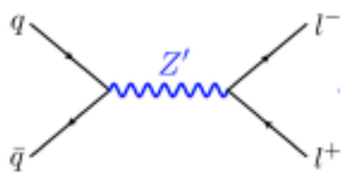
Exotics

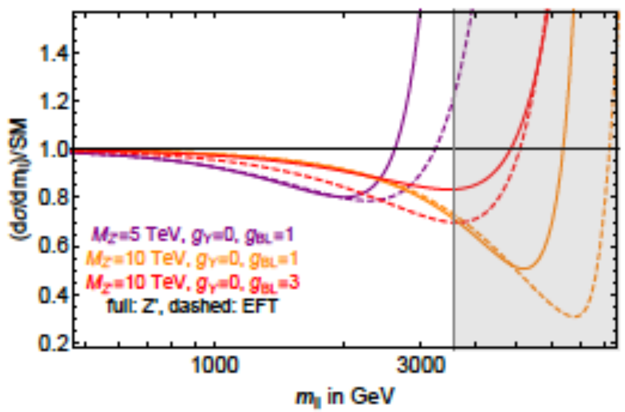
Indirect constraints on Z'

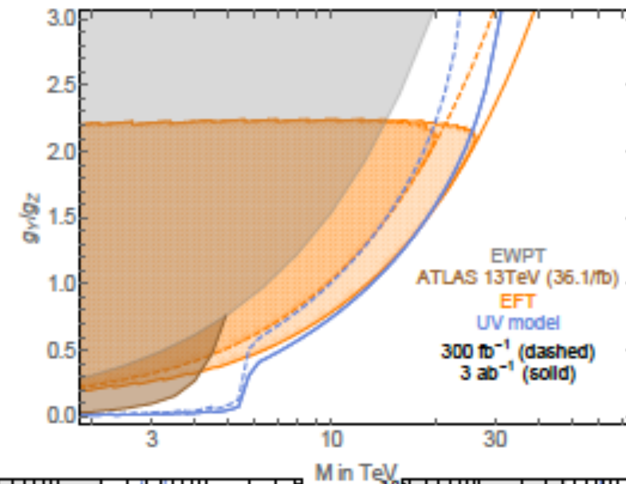
- If mZ'>>5 TeV, main contributions from interference effects modifying DY
- The precision of e^+e^- colliders help but LHC (and HL-LHC) can do a lot

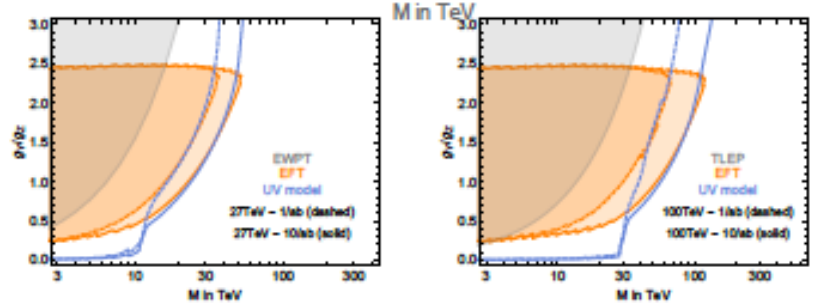
Alioli, Farina, Pappadopulo, JTR, Phys. Rev. Lett. **120**, no. 10, 101801 (2018)

M. D'Onofrio









17 Monica D'Onofrio, UK Inputs, IPPP 17/04/2018

of "largely" improved H couplings (EFT)

B. Heinemann

	Factor ≥2	Factor ≥5	Factor ≥10	Years from T_0
CLIC380	9	6	4	7
FCC-ee240	10	8	3	9
CEPC	10	8	3	10
ILC250	10	7	3	11
FCC-ee365	10	8	6	15
CLIC1500	10	7	7	17
HE-LHC	1	0	0	20
ILC500	10	8	6	22
CLIC3000	11	7	7	28
FCC-ee/eh/hh	12	11	10	>50

13 quantities in total

NB: number of seconds/year differs: ILC 1.6×10^7, FCC-ee & CLIC: 1.2×10^7, CEPC: 1.3x