Physics at FCC-eh

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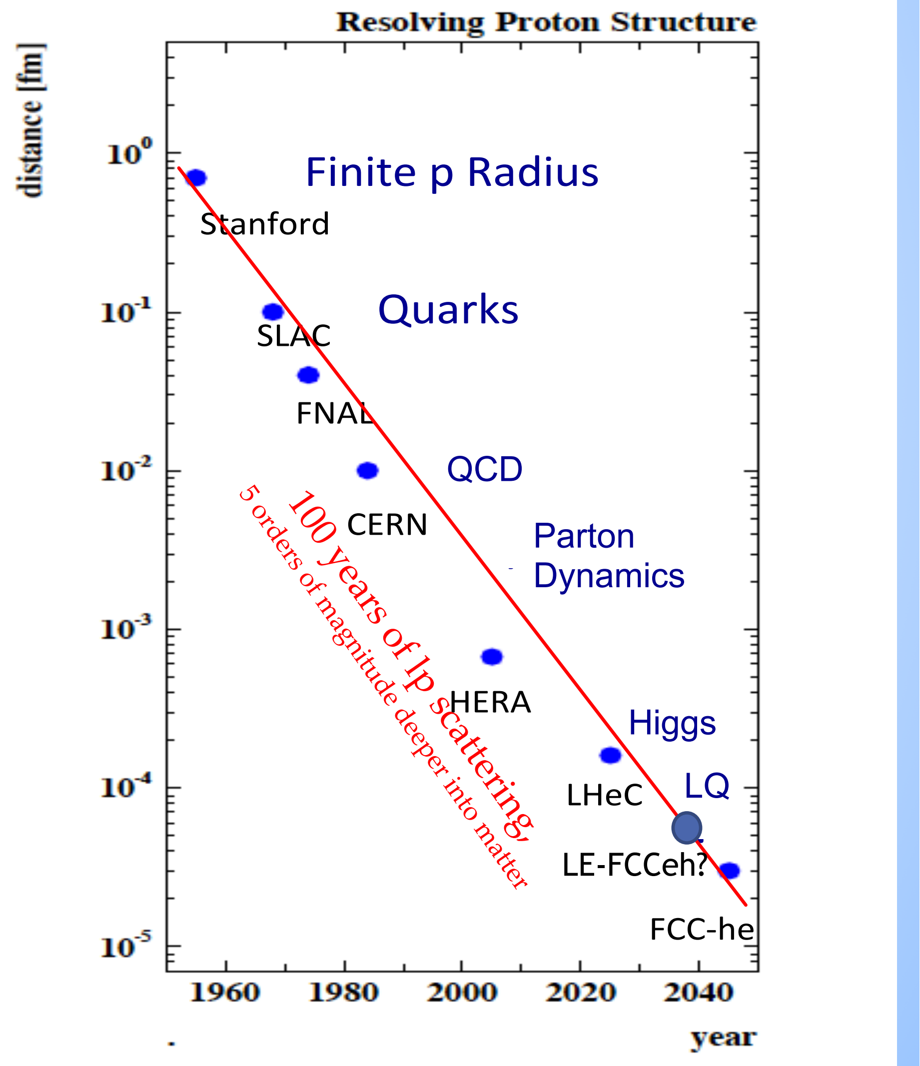
University of Liverpool

LHeC/FCC-eh Workshop 2019
Chavannes, Switzerland, 25/10/2019



Introduction and outline

- Several excellent talks at this workshop have shown the potential of LHeC (and FCC-eh in some cases), covering a broad number of topics
  - PDF, small-x physics, Heavy flavor physics, eA physics (A. Stasto, C. Gwenlan, L. Harland-Lang, O. Zenaiev, F. Hautmann, P. Newman, N.A. Perez)
  - Higgs, Top and EWK physics (B. Mellado, C Schwanenberger, D. Britzger, L. Aperio Bella, M. Boonekamp)
  - BSM searches (G. Azuelos, O. Fischer)
- In this talk, I will show a few highlights for **FCC-eh** (and complementarities with FCC-hh), as well as the potential of possible ‘intermediate’ stage(s) between LHeC and FCC-eh
  - **HE-LHeC or Low Energy FCC**
  - Complementarities and reach for e-p [using only a few available examples]
  - Status of the art

From LHeC to FCC-eh

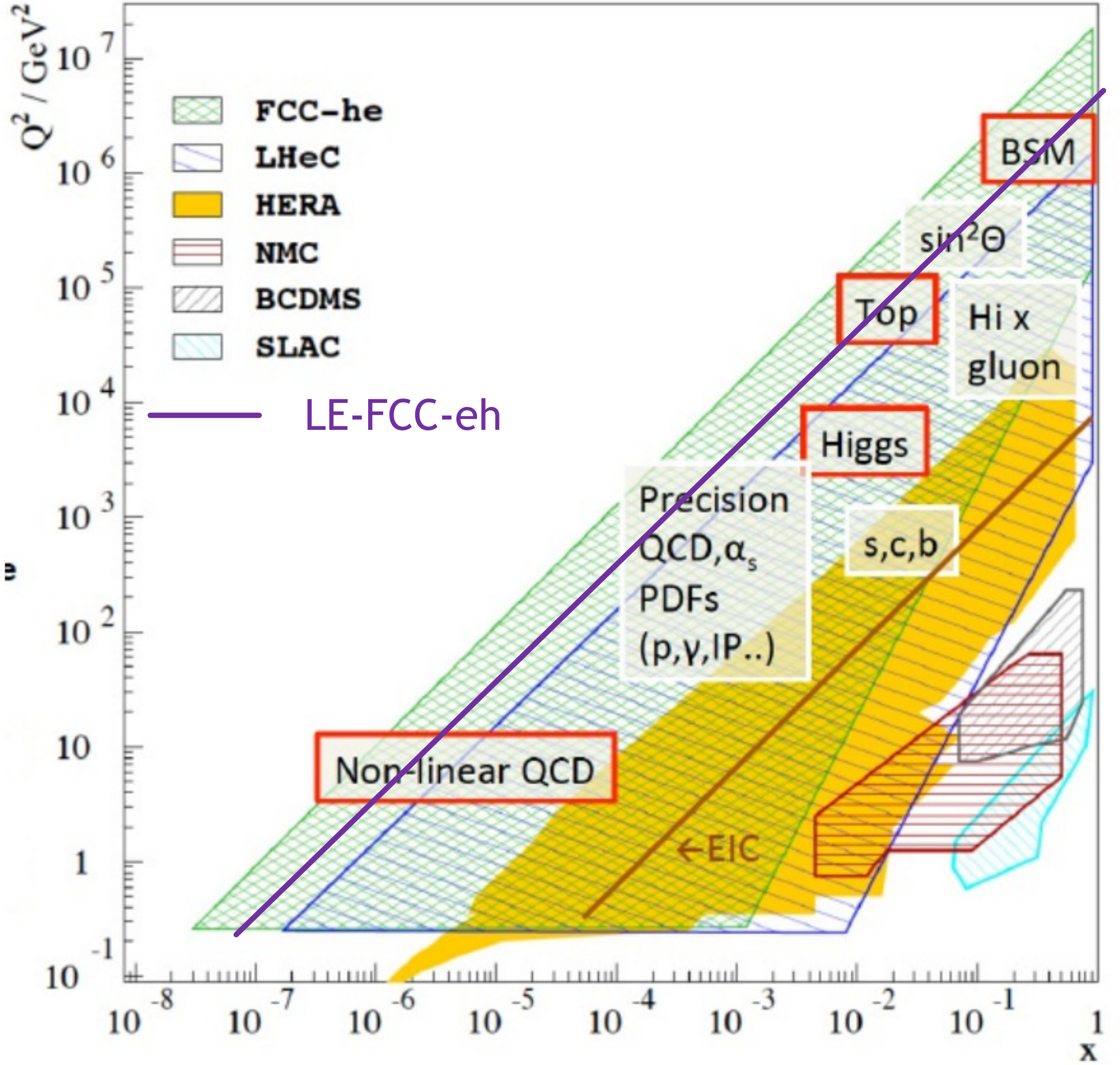
- Cases studied so far:

parameter	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	12.5	50
E_e [GeV]	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.7	3.5

Additional proposal for a low-energy (LE)-FCC → proton beam ~ 19 TeV
p-p c.o.m. ~ 38 TeV

LE-FCC-eh: 60 GeV E_e - 19 TeV E_p
e-p c.o.m. → 2.1 TeV

Interesting to notice that c.o.m. energy is equivalent to having an electron beam Ee ~140-150 GeV and a proton beam of 7 TeV
[of course, events would be very different!]



e-A collisions equally possible for LE-FCC

HL-LHC/HE-LHC/LE-FCC/FCC

- The physics potential of the HL-LHC (14 TeV) and a possible HE upgrade (27 TeV) has been studied in detail for the Update to the European Strategy.
- FCC CDR illustrates the potential of FCC-hh with complementarities to ep and physics at e+e- (several results are even presented conjunctly)
- The low-energy option for FCC-hh has been considered after the symposium
  - https://cds.cern.ch/record/2681366/files/CERN-FCC-PHYS-2019-0001.pdf
  - Idea is to present a scenario where costs are minimized for a future hadron collider hosted in the FCC 100km tunnel: 6 T dipoles, operating at 1.9K, leading to a centre of mass energy of 37.5 TeV, with an expected integrated luminosity of 10 ab^{-1} during the 20-year lifetime.
  - Pileup conditions for the experiments will be similar to those of the HE-LHC or FCC-hh

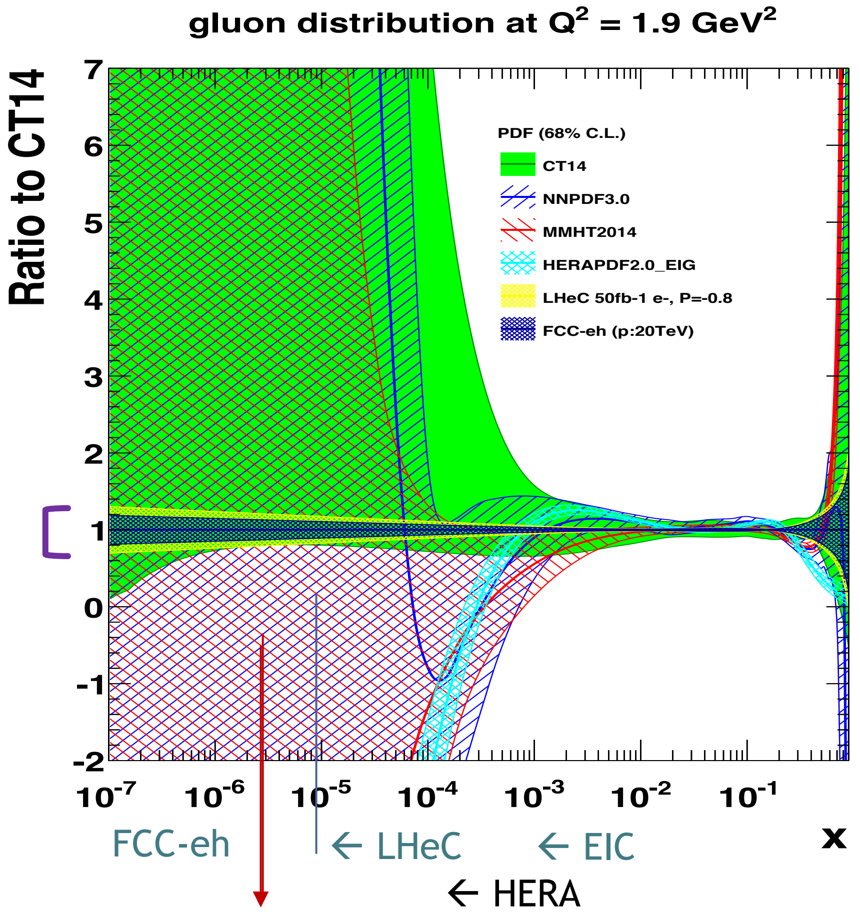
The briefing book for ES is now out and include all these options:
http://cds.cern.ch/record/2691414

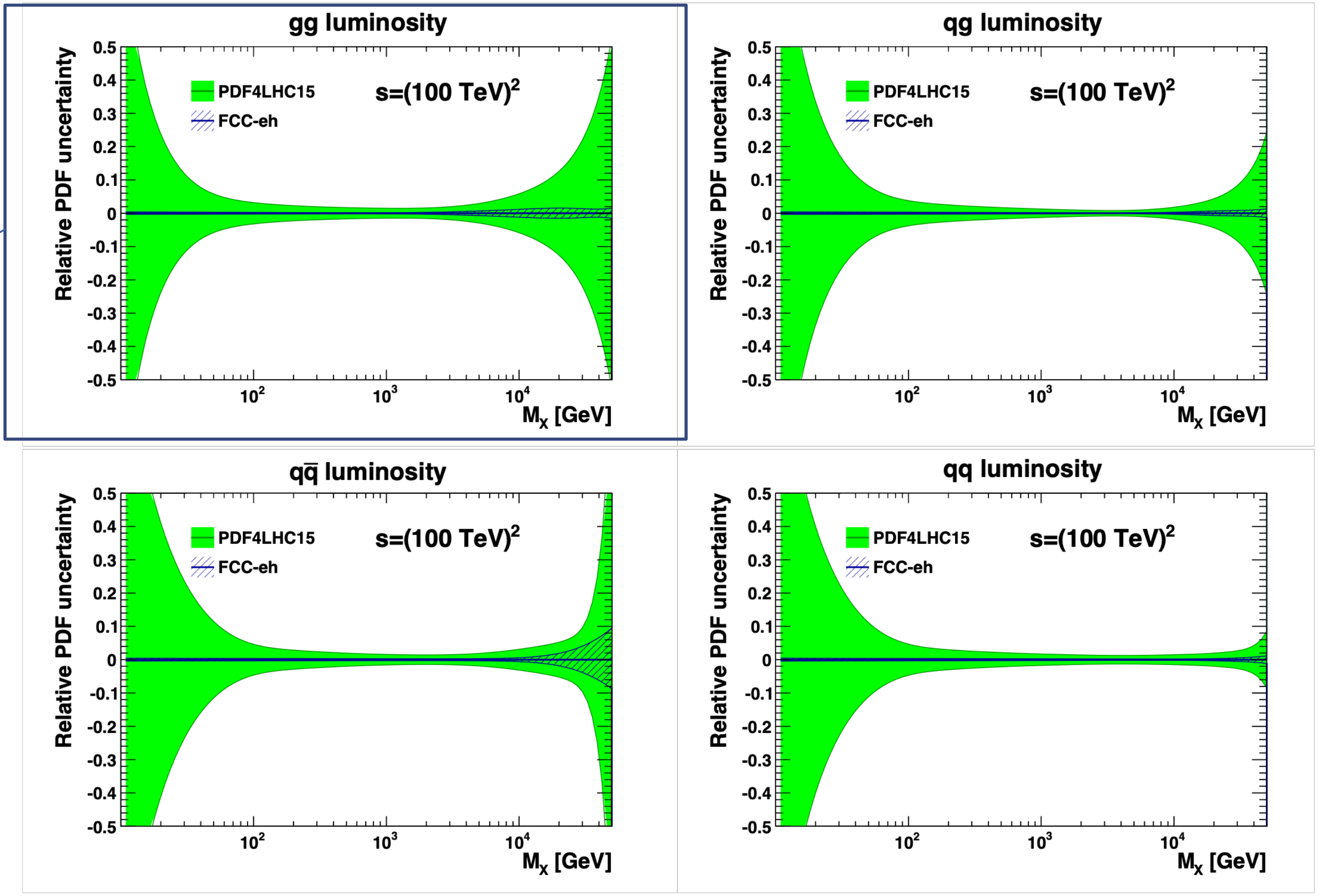
Several results presented for LHeC / FCC-eh and intermediate options for strong interactions, electroweak physics, Higgs, new physics searches, dark matter, heavy ion physics and more

Strong interactions: PDF @ FCC-eh and small-x

- FCC-eh [as LHeC] allows high precision on PDF and reaches 1 or more additional orders of magnitude at low x.

Plot also in the briefing book



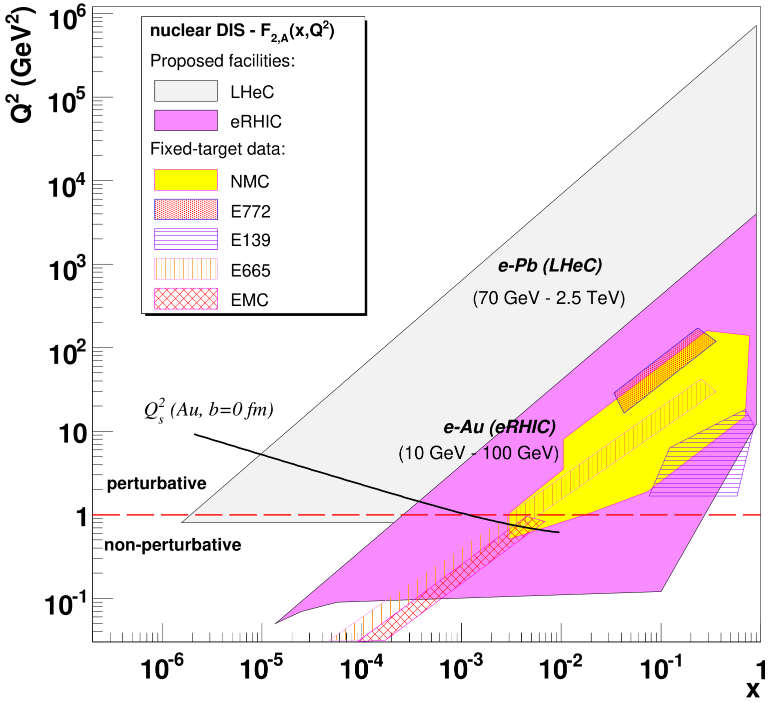


LE-FCC-eh would provide intermediate reach and would obviously be equivalently crucial for hh

Strong interactions: eA and nuclear structure

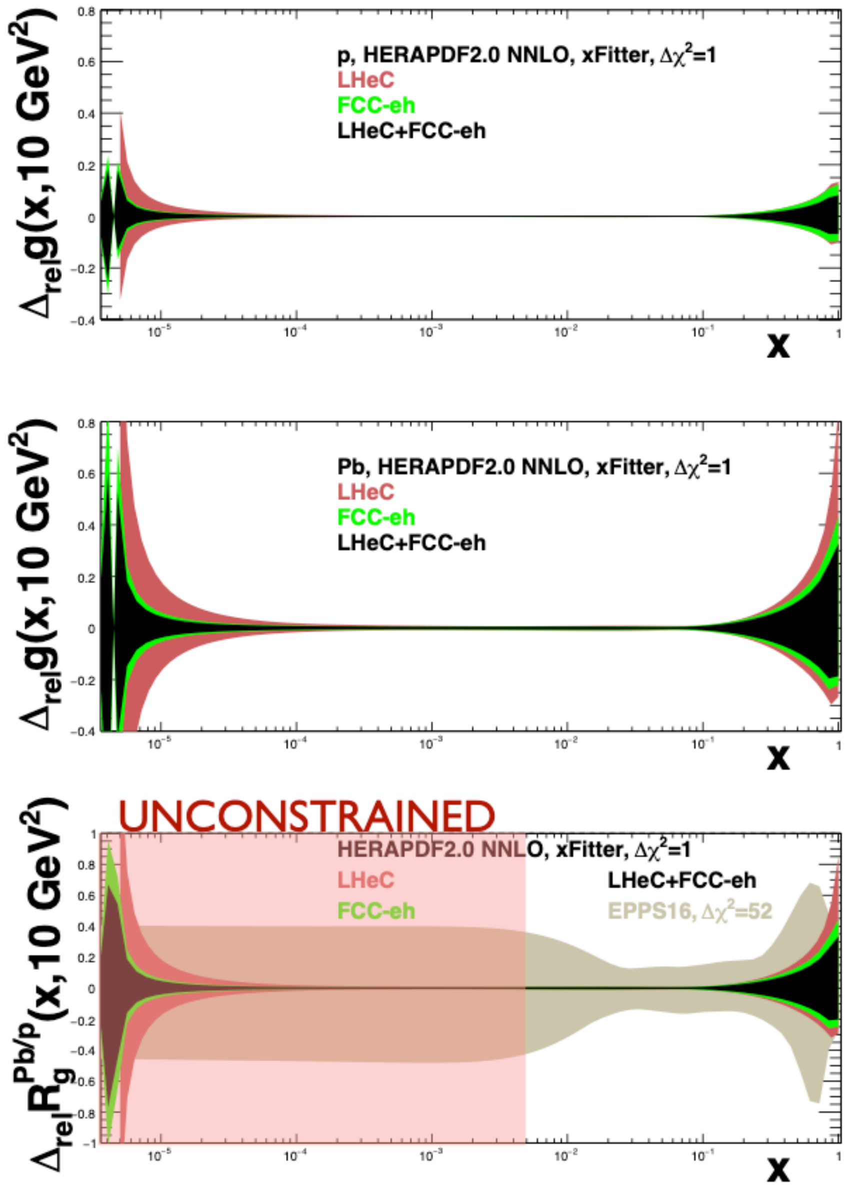
- Extraction of **Pb-only** PDFs by fitting NC+CC pseudodata, using xFitter

parameter [unit]	LHeC (HL-LHC)	eA at HE-LHC	FCC-he
E_{Pb} [PeV]	0.574	1.03	4.1
E_e [GeV]	60	60	60
$\sqrt{s_{eN}}$ electron-nucleon [TeV]	0.8	1.1	2.2



Large improvements at all x

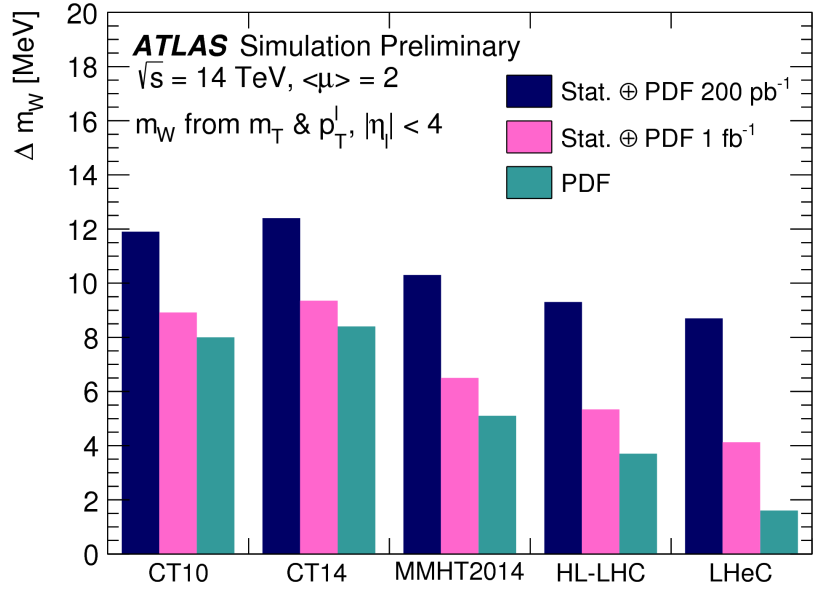
Fit to a single nucleus possible



Impact on W mass and $\sin^2\theta_{eff}$ precision measurements

- **@ HL-LHC W mass** precision measurement uses dedicated dataset at low <mu>
  → exploit the extended leptonic coverage
  → LHeC will provide additional precision through PDF

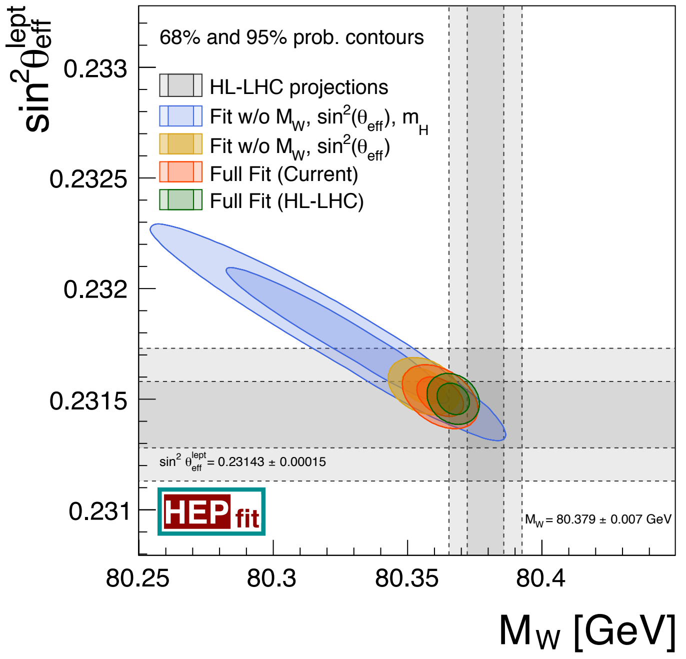
Δm_W = ±6 MeV (with reduced PDF unc from HL LHC)
Δm_W = ±2 MeV (with improved PDF from LHeC)



ATL-PHYS-PUB-2018-026

- Precision better than $5 \cdot 10^{-5}$ for $\sin^2\theta_{eff}$
→ **$1 \cdot 10^{-5}$ if PDF uncertainties are improved with LHeC**

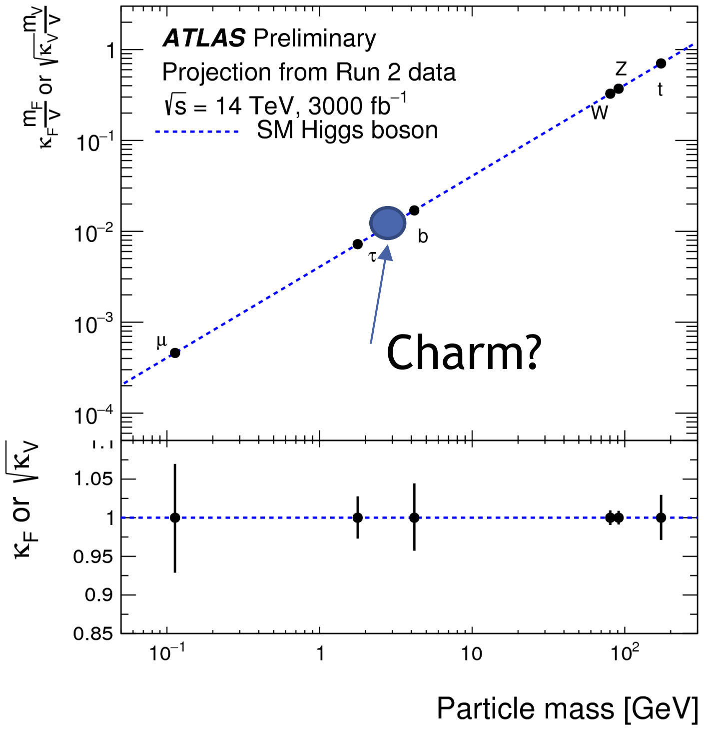
EW global fits

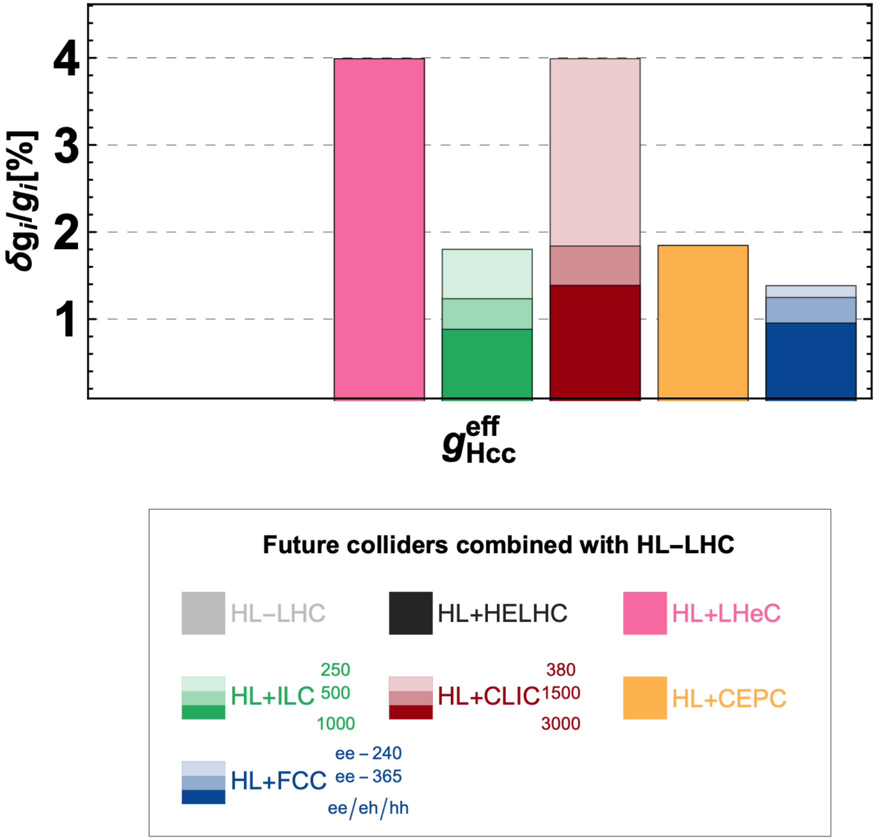


→ Difficult to fold in the additional value of a LE-FCC although it is clear that improved PDF have an enormous impact on EWK parameters

Higgs physics at (LE)FCC eh and hh

- At the end of HL-LHC, rate measurements will reach **percent level precision for most couplings - no real sensitivity expected for charm couplings**





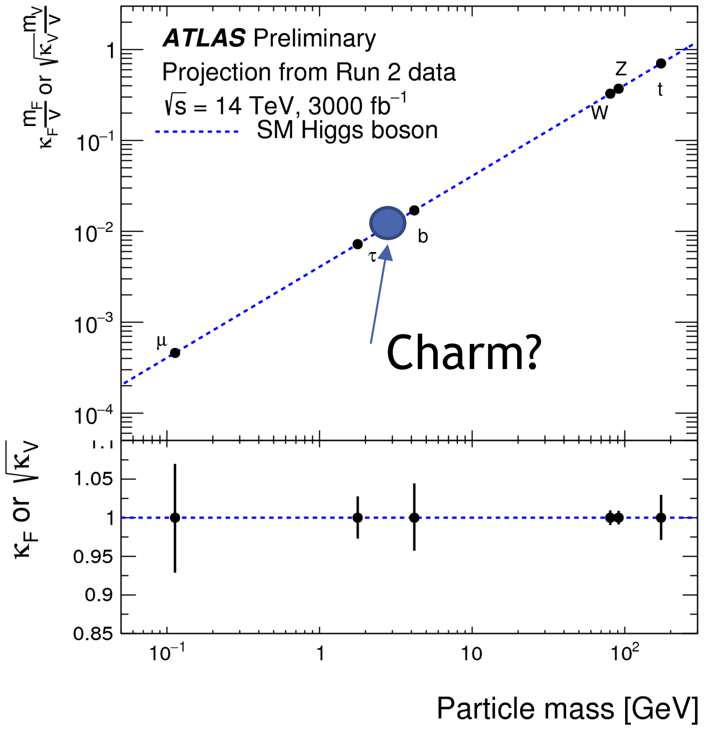
Results of a fit corresponding on the Effective Field Theory benchmark, expressed in terms of effective couplings

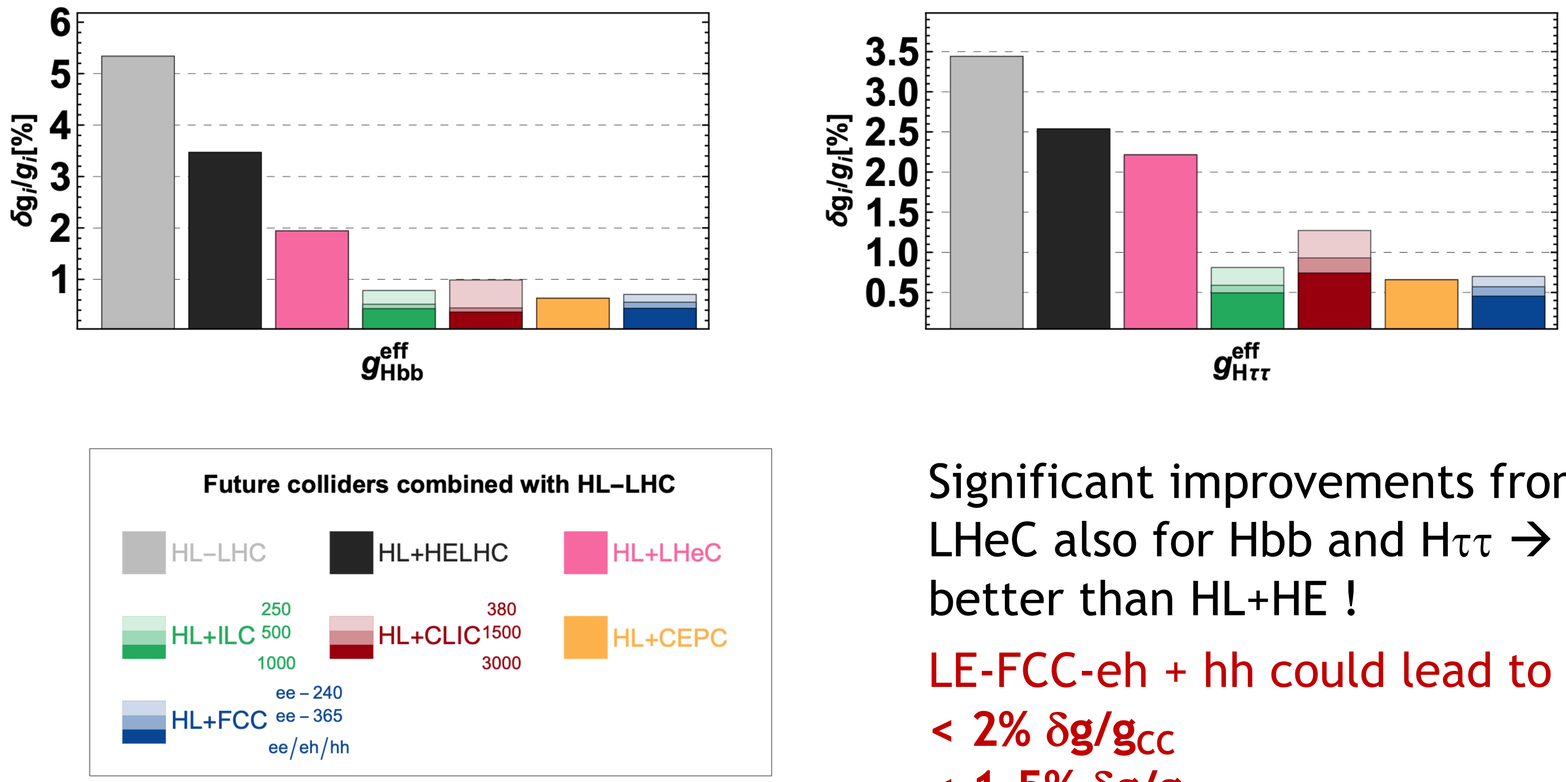
Hcc not estimated for HL-LHC

HL-LHC+LHeC and HL+FCC ee/eh/hh (dominated by eh) will be as effective as e+e- colliders

Higgs physics at (LE)FCC eh and hh

- At the end of HL-LHC, rate measurements will reach **percent level precision for most couplings - no real sensitivity expected for charm couplings → LHeC!**





Significant improvements from LHeC also for Hbb and Hττ → better than HL+HE !

LE-FCC-eh + hh could lead to

< 2% $\delta g/g_{cc}$

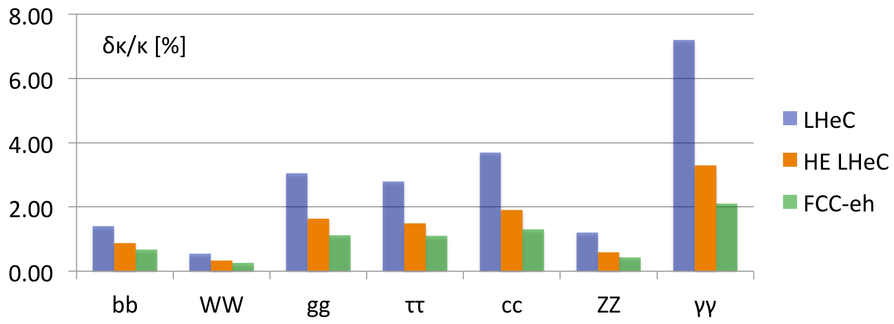
< 1.5% $\delta g/g_{bb}$

< 1.5% $\delta g/g_{\tau\tau}$

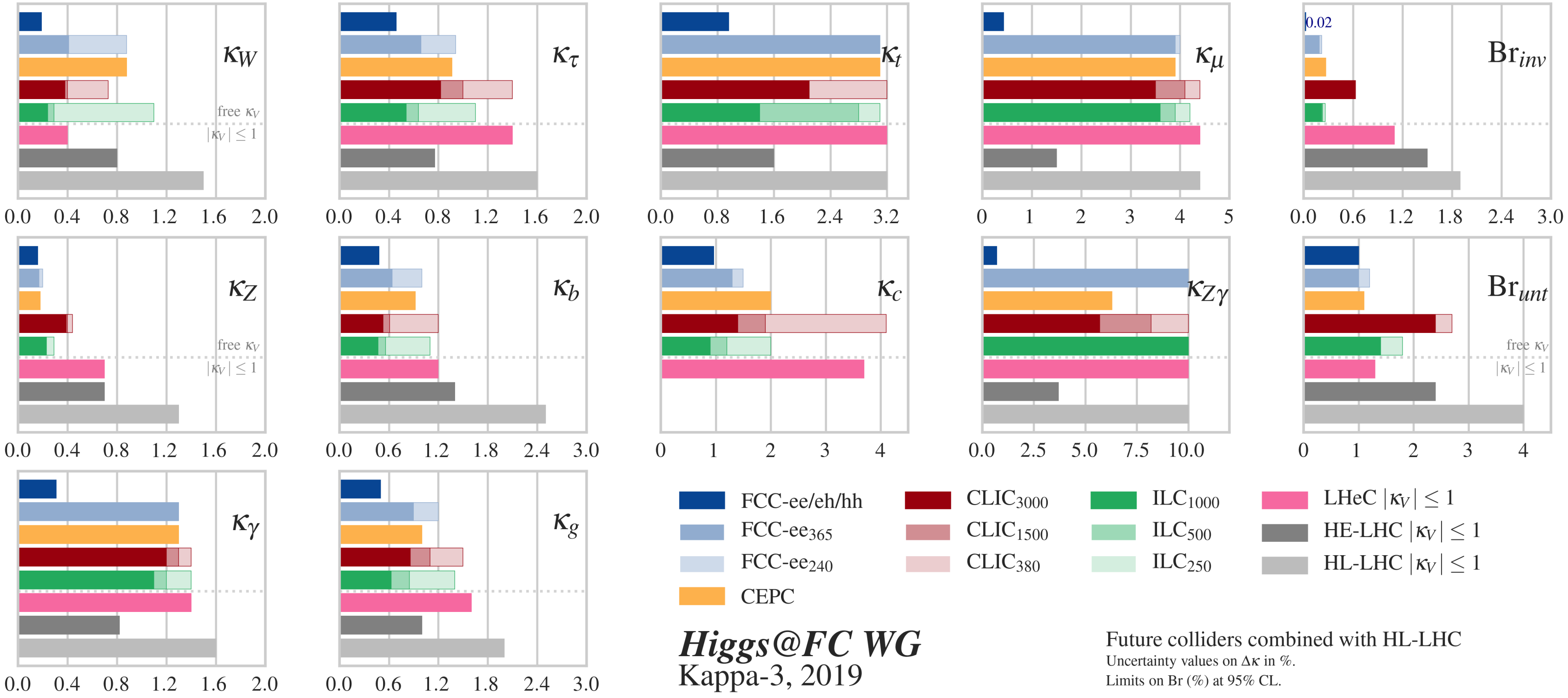
Higgs physics at (LE)FCC eh and hh

M. Klein

- κ_i : coupling strength modified parameters



From the briefing book: uncertainties on κ_i



Results for FCC-eh at 20 TeV E_p x 60 GeV E_e

Uncertainties on kappa

Decay FCCep

bb	0.9
WW	0.3
gg	1.7
tau	1.5
cc	1.9
ZZ	0.5
γγ	3.3

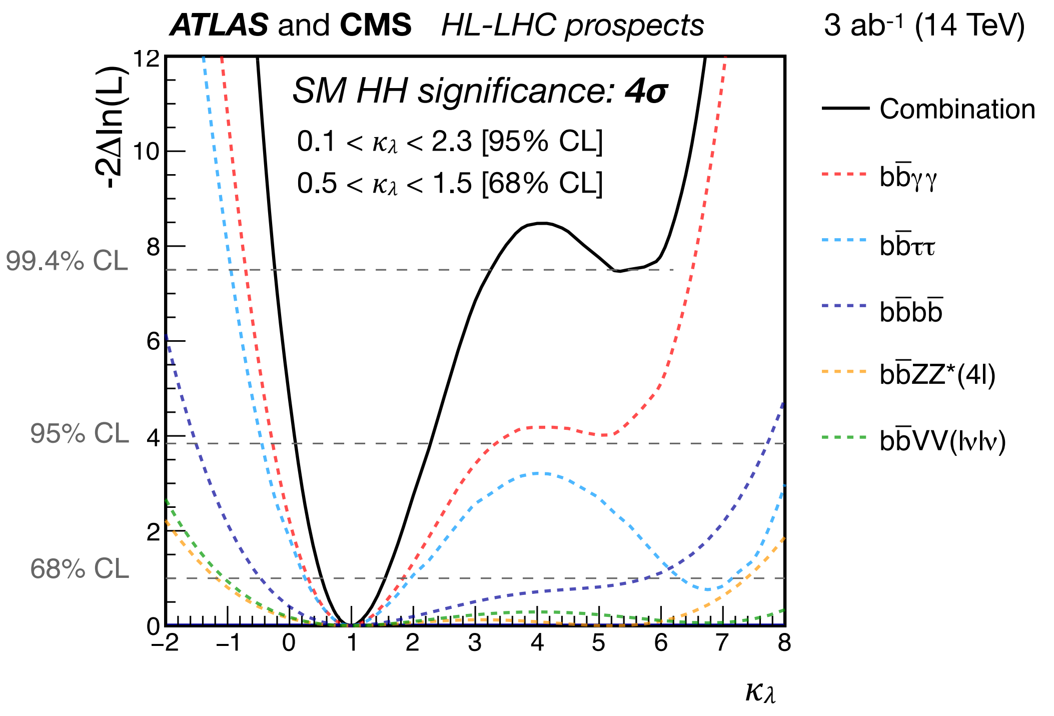
in percent. SM width.

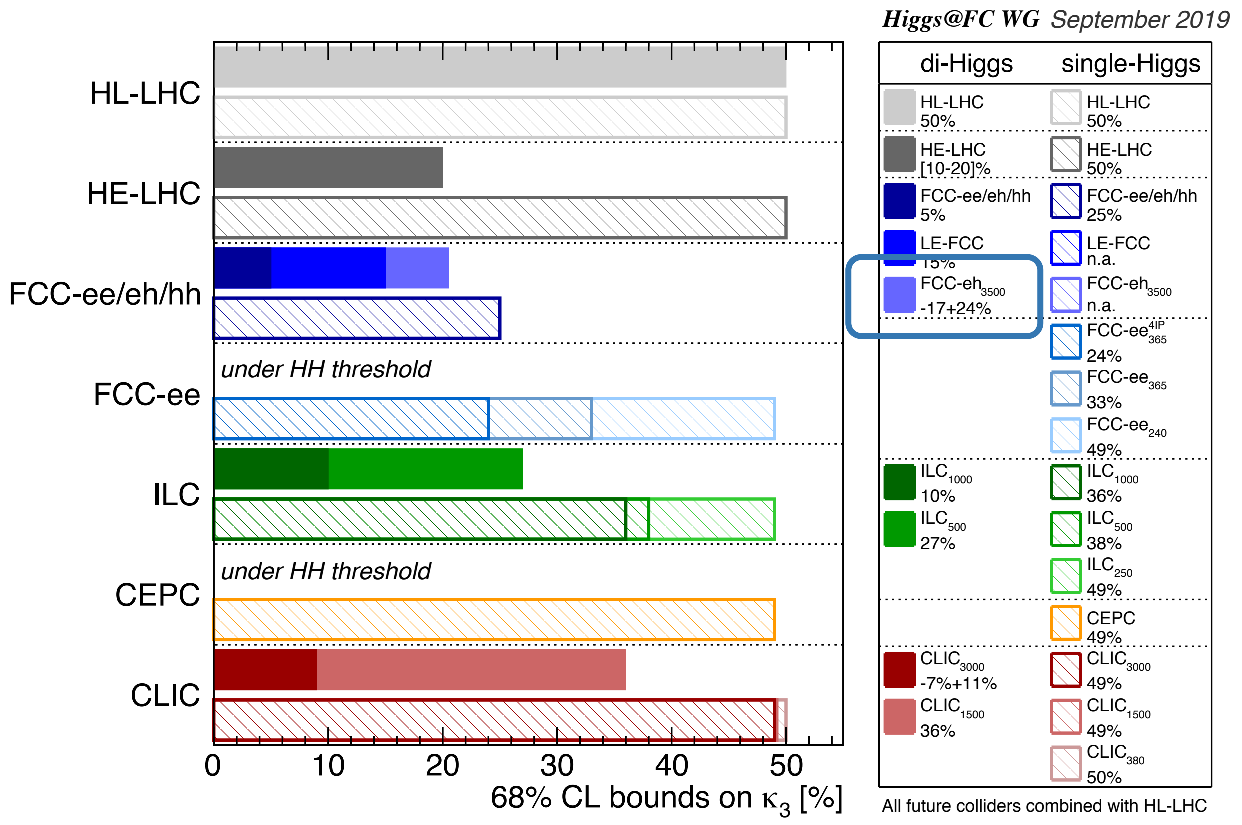
Di-higgs prospects @ (LE)FCC eh and hh

Assuming SM Higgs self-coupling λ

- **@ HL-LHC** observation sensitivity of 3 s.d. per exp., 4 s.d. combined

  constraint on the Higgs self-coupling of **0.5 < κ_λ < 1.5** at the 68% CL → **down to +/-10% for FCC-ee/eh/hh**





secondary minimum can be excluded at 99.4% CL

Higgs as portal to New Physics

HL/HE/FCC will enhance the sensitivity to BSM physics

Important e-p contributions to higgs invisible sensitivity

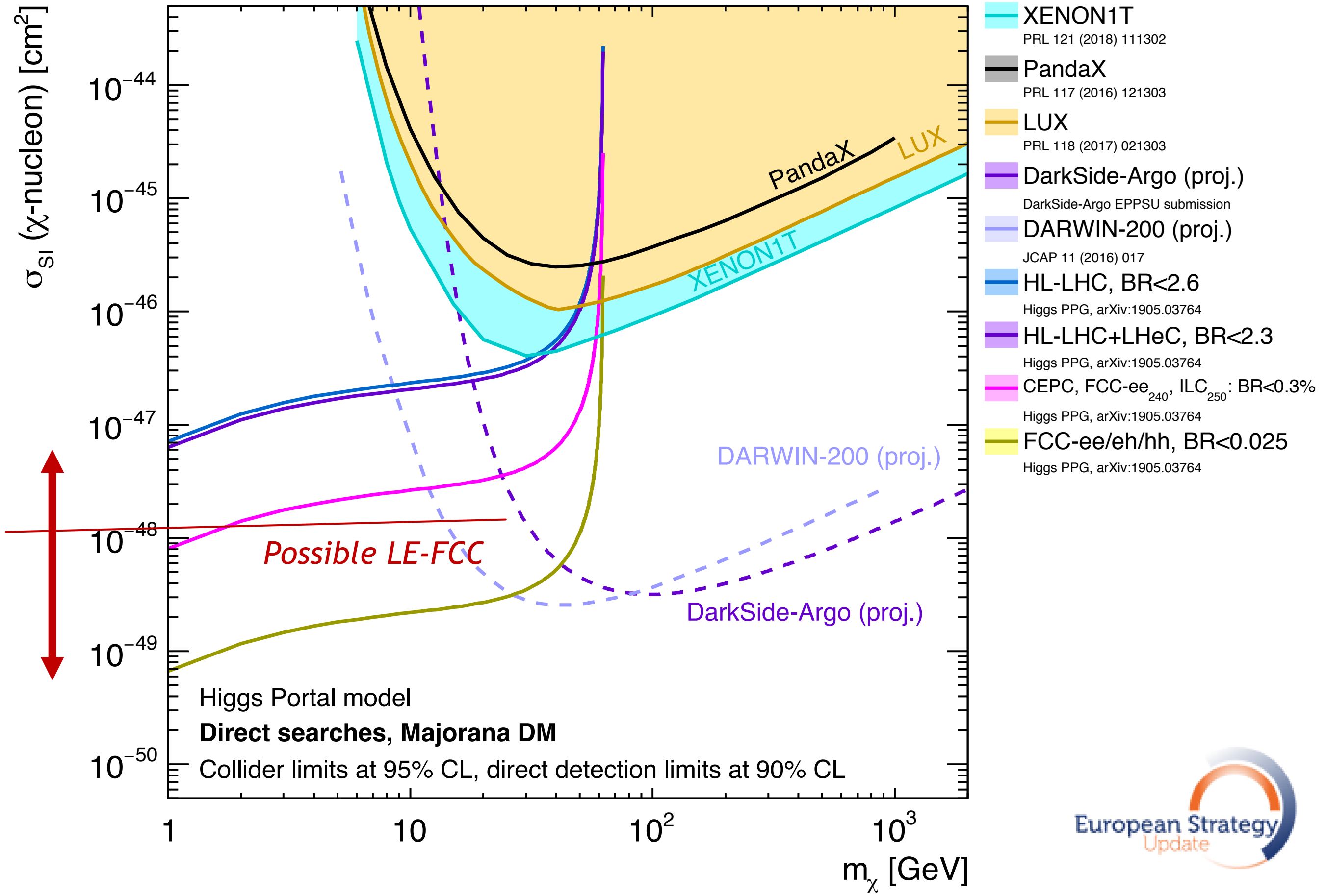
Minimal Higgs - Dark Matter portal models

$$\mathcal{L} \supset -\frac{1}{4}\lambda_{hSS} H^\dagger H S^2 \qquad \text{(scalar DM)} \quad \text{or}$$
$$\mathcal{L} \supset +\frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu \qquad \text{(vector DM)} \quad \text{or}$$
$$\mathcal{L} \supset -\frac{1}{4}\frac{\lambda_{h\chi\chi}}{\Lambda} H^\dagger H \bar{\chi}\chi \qquad \text{(fermion DM)},$$

Scalar or Vector quartic interaction of the SM Higgs doublet field H with the DM field

If $M_{\mathrm{DM}} < M_H/2 \simeq 62.5\mathrm{GeV}$

→ Higgs invisible constraints can be translated in terms of upper limits on λ → related to $\sigma_{\text{DM-nucleon}}$

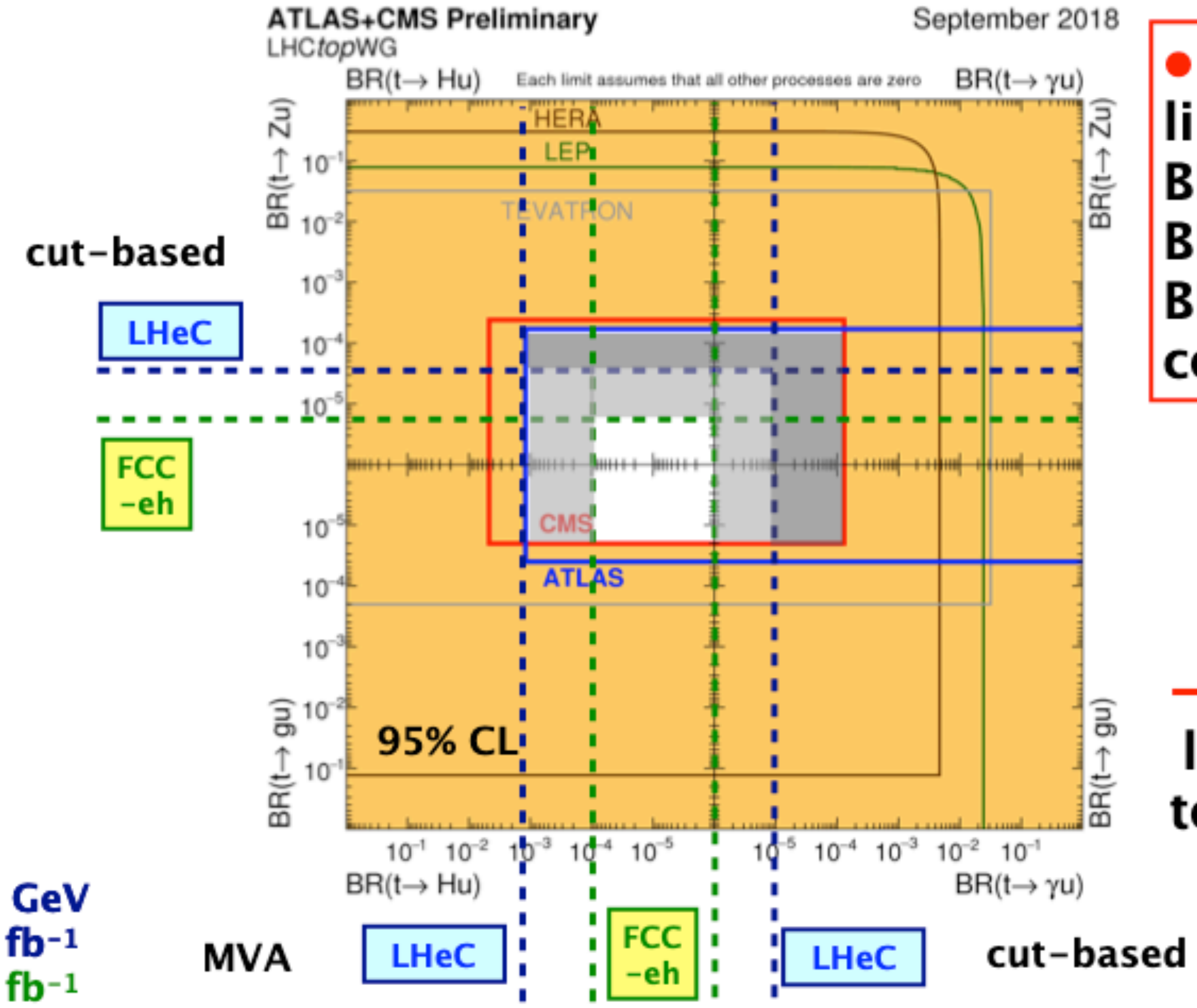


European Strategy Update

LE-FCC could push constraints at the same level as CEPC,FCC-ee,ILC

New physics: FCNC

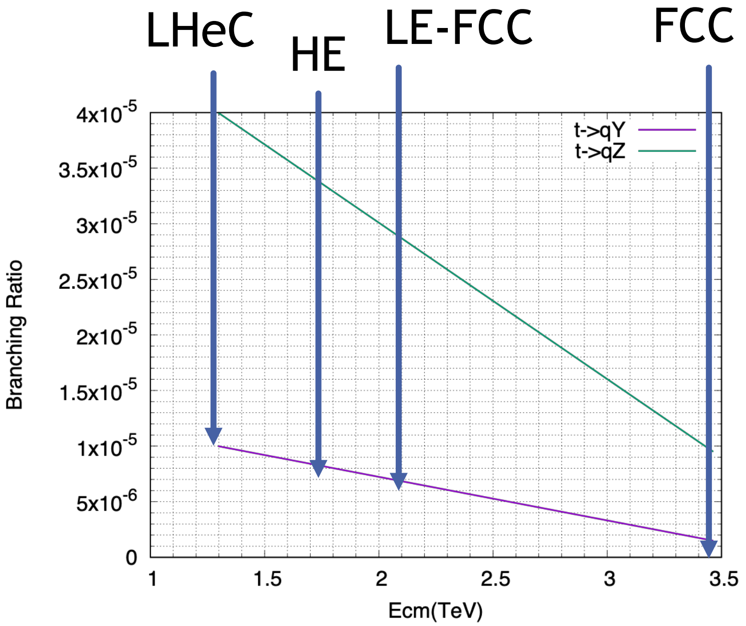
Flavor changing neutral currents are forbidden at tree level, and strongly suppressed by GIM mechanism – SM predicts O(10^{-12} – 10^{-16}), BSM extensions allow significant enhancements



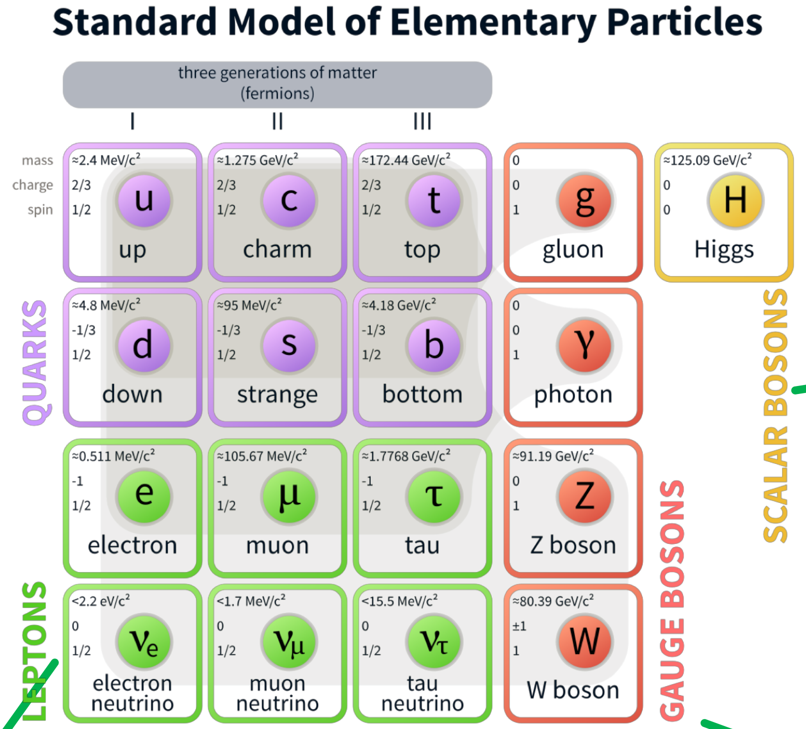
- improve limits on BR(t→γu), BR(t→Zu), BR(t→Hu) considerably

→ test SUSY, little Higgs, technicolor…

E_e=60 GeV
1000 fb^{-1}
2000 fb^{-1}



Searching for New Physics: much more to look for!



Non minimal Higgs sector

- Exotics / Rare / Invisible decays
- Higgs as portal to DM
- Extended: Two-Higgs-Doublet-Models, MSSM, NMSSM and more
- Charged Scalars
- Composite Higgs

"Exotics": referred to a large variety of theories and models

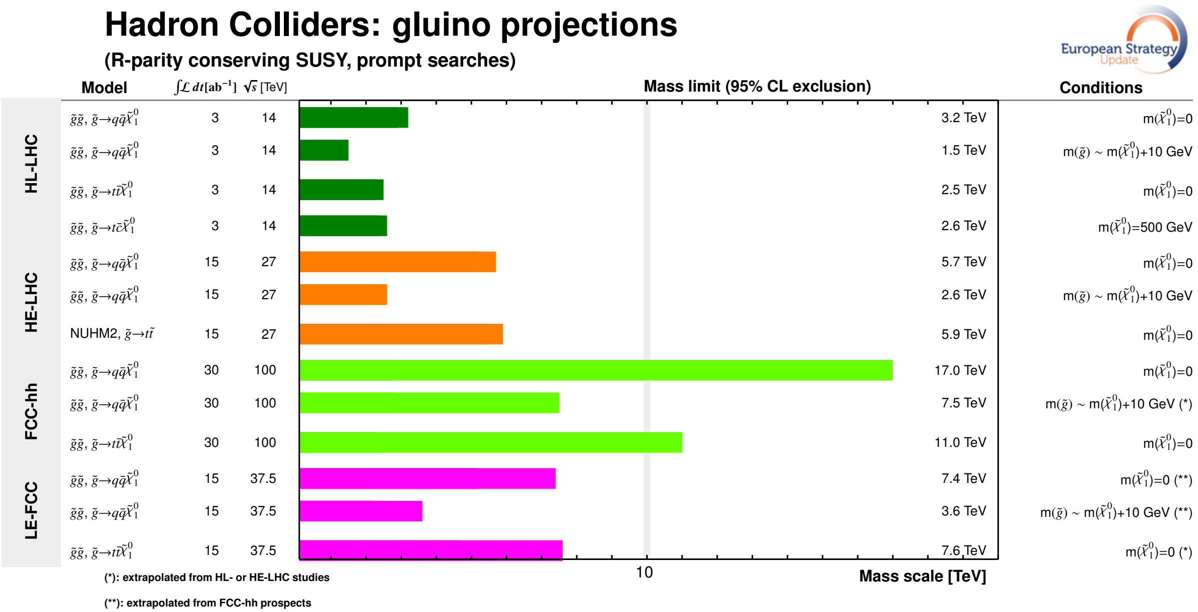
- Heavy vector bosons, vector-like quarks, excited quarks, non-SUSY Dark-Matter models, lepto-quarks, dark/hidden sectors and more
- **The unknown!**

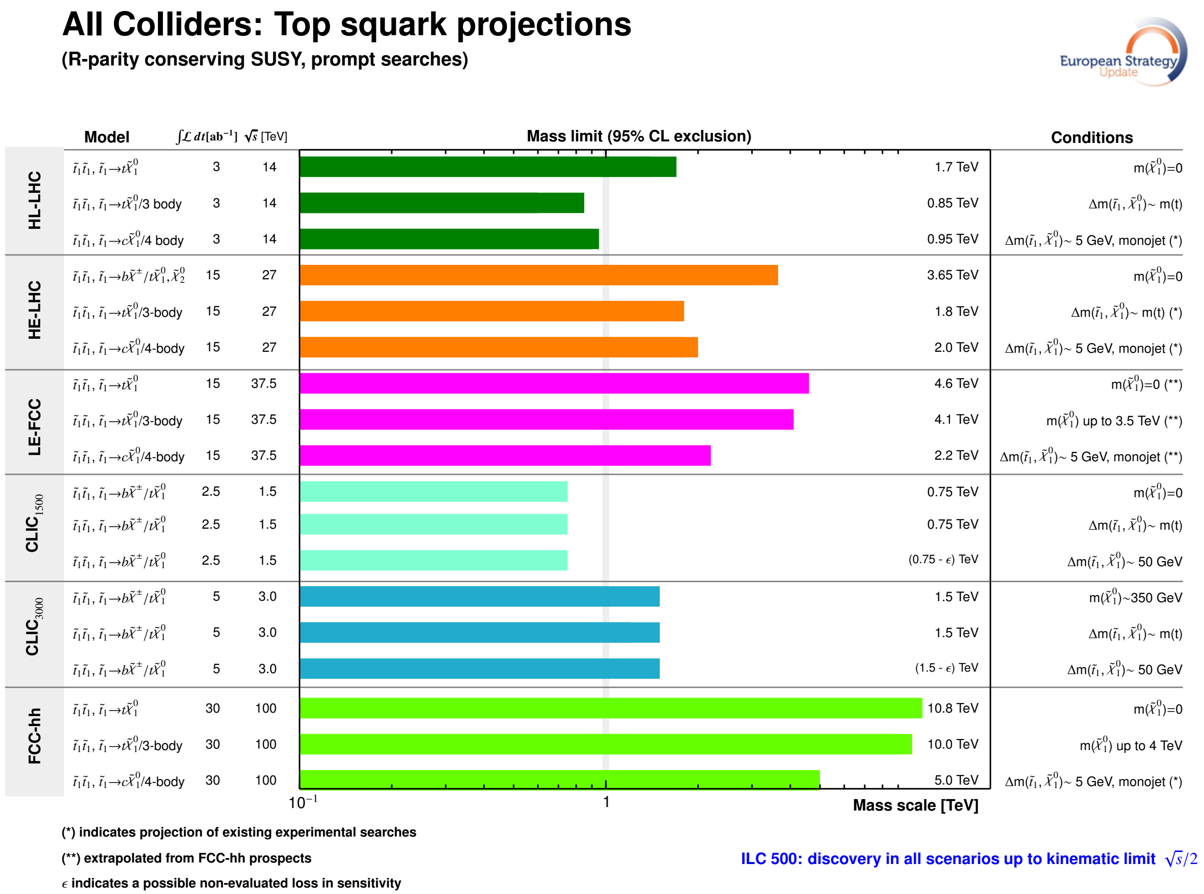
SUSY, SUSY-inspired

- many variants and kind (MSSM, NMSSM, R-parity conservation or violation..)
- mostly heavy super-partners, prompt or long-lived, several Higgs bosons

pp reach for BSM

- Strongly-produced new particles (e.g. top squarks, gluinos) and high mass resonances (Z', W') will be totally dominated by pp high energy colliders

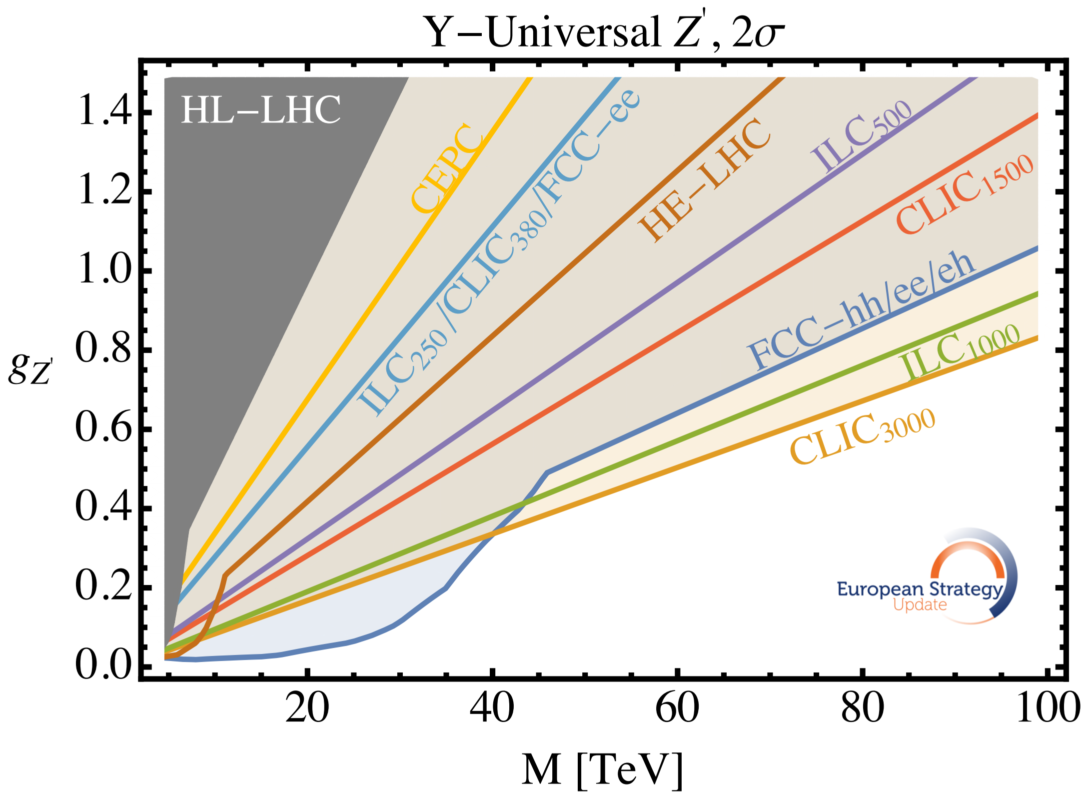




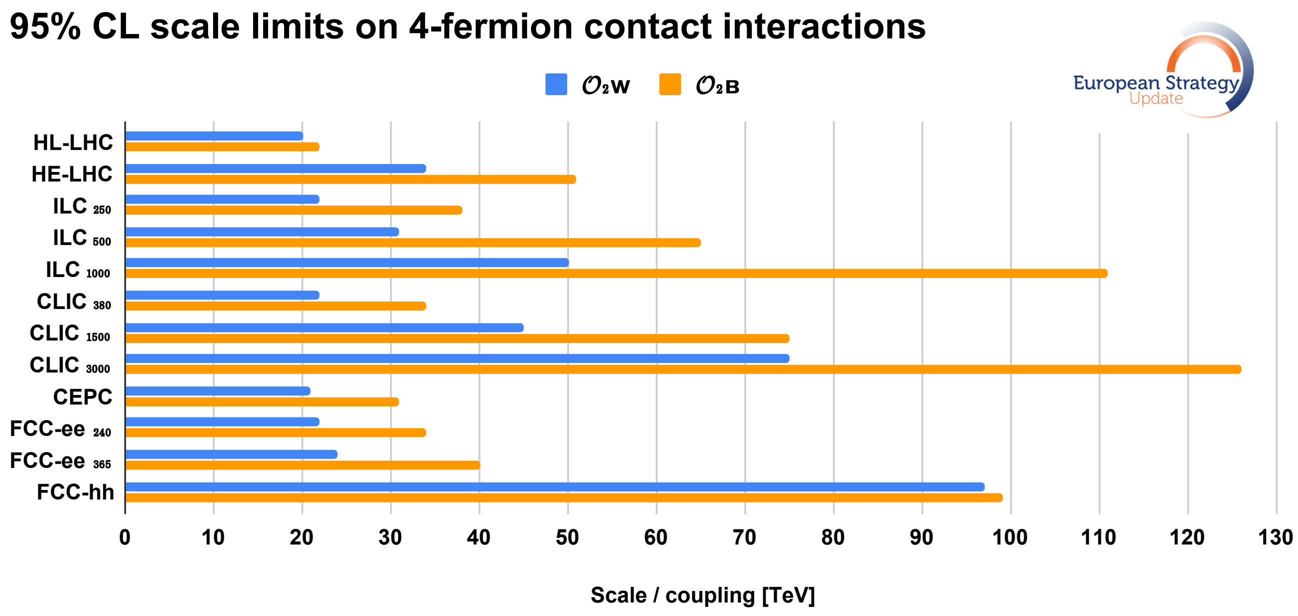
pp and e$^+$e$^-$ reach for BSM

- Strongly-produced new particles (e.g. top squarks, gluinos) and high mass resonances (Z', W') will be totally dominated by pp high energy colliders
- Lepton colliders sensitive to [mass/coupling] ≫ √s

representative example of classes of theories

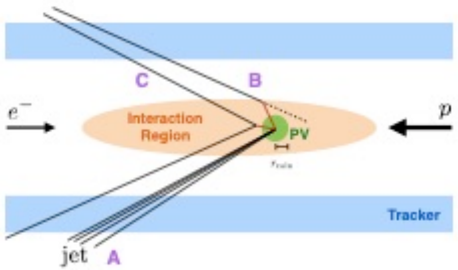


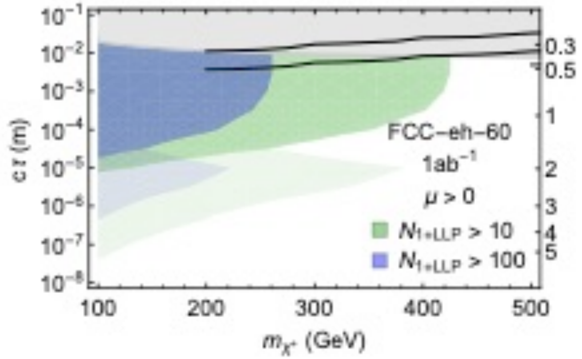
Contact interactions also reaching o(20-50 TeV)



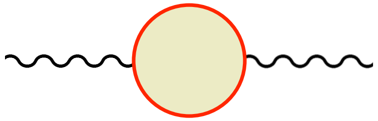
Complementarity of e-p

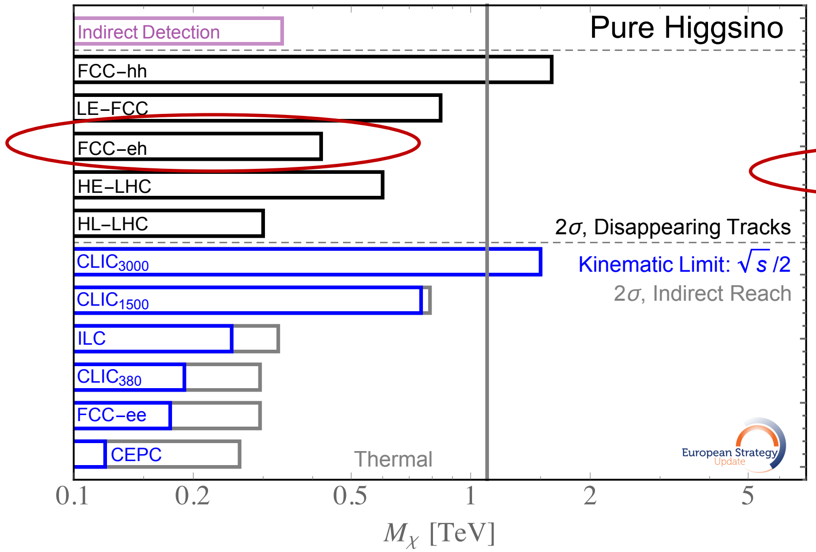
- Weakly produced and/or non-promptly decaying particles very challenging at pp and ee colliders → good complementarity with e-p colliders
  - @ pp: low production cross section, high background and very high level of pile-up
- Few examples:
  - **dark matter (SUSY-inspired wino and higgsino)**
    - Using disappearing tracks (non-prompt)

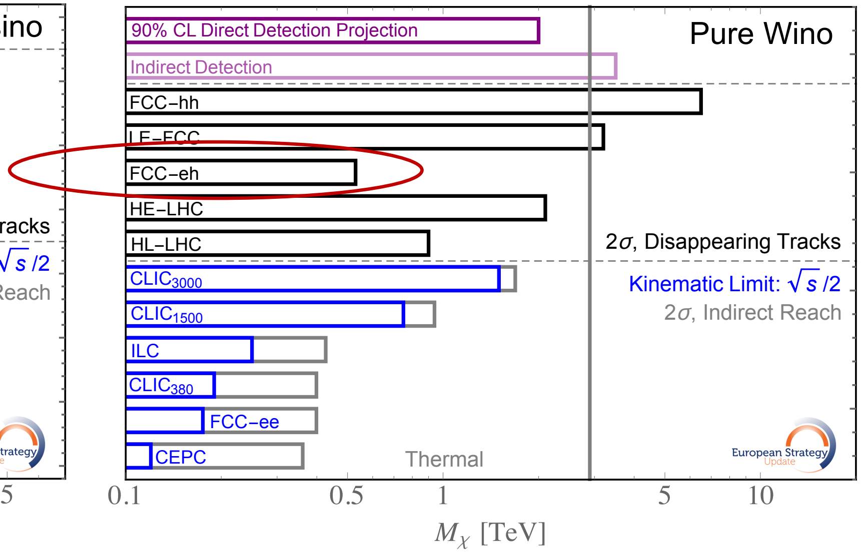




EWKinos in loop change prop
(W, Y parameters)







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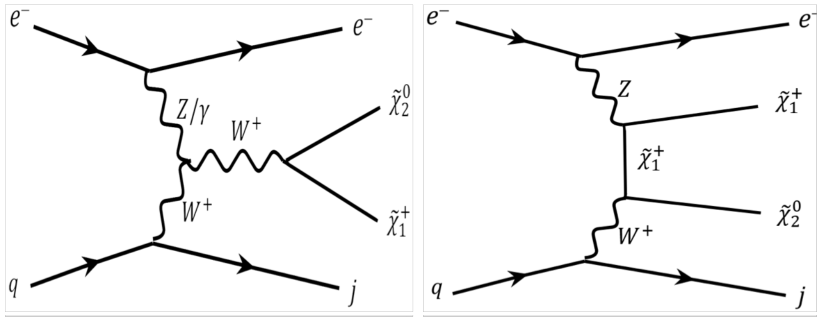
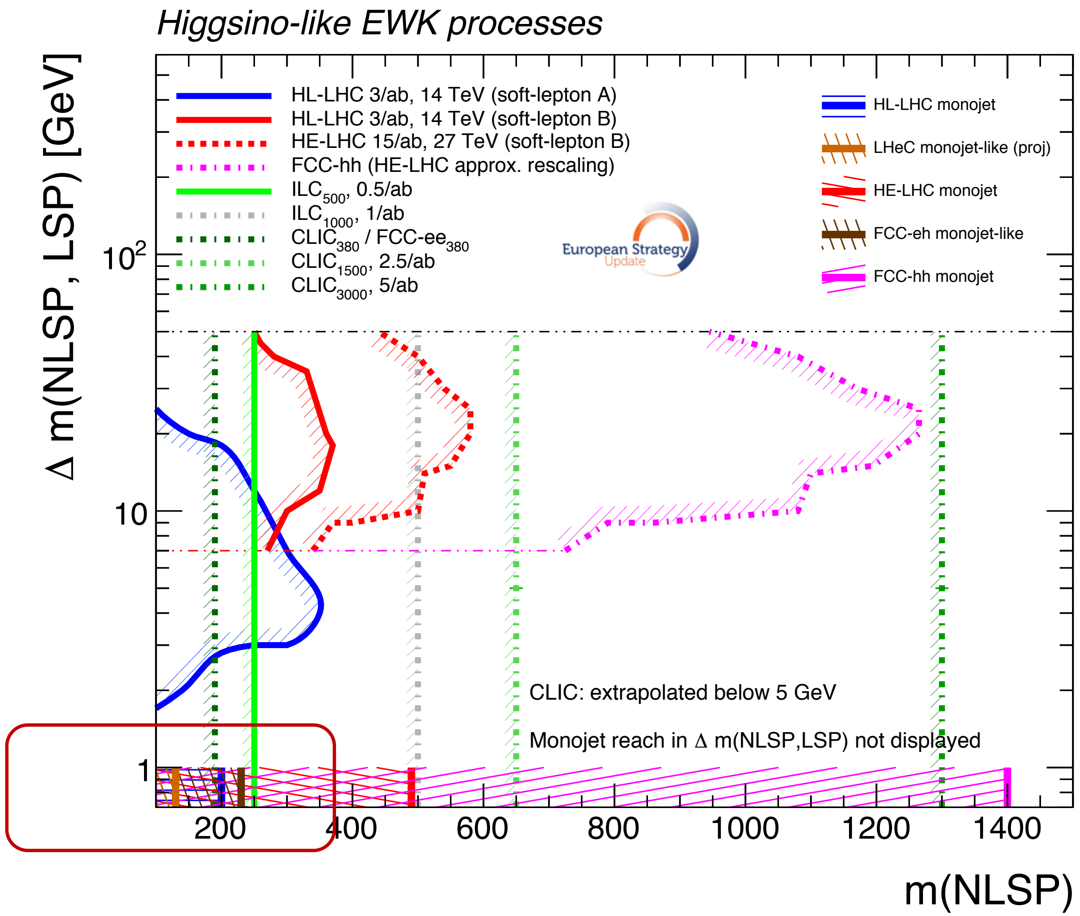
- Few examples:
  - **dark matter (SUSY-inspired wino and higgsino)**
    - Using mono-jet (prompt) → more difficult!



→better prospects are expected for models with intermediate coannihilator particles [e.g. sleptons]

K.Wang et al. in preparation



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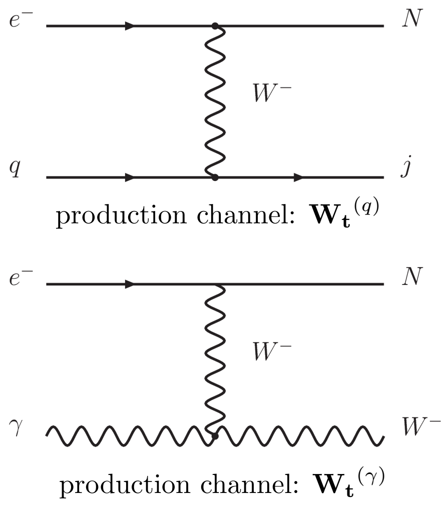
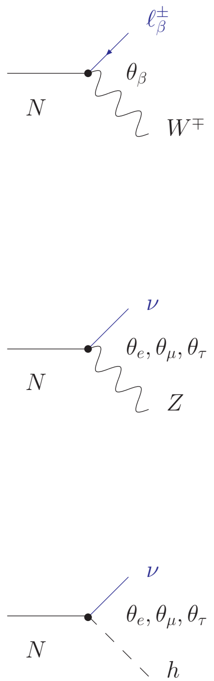
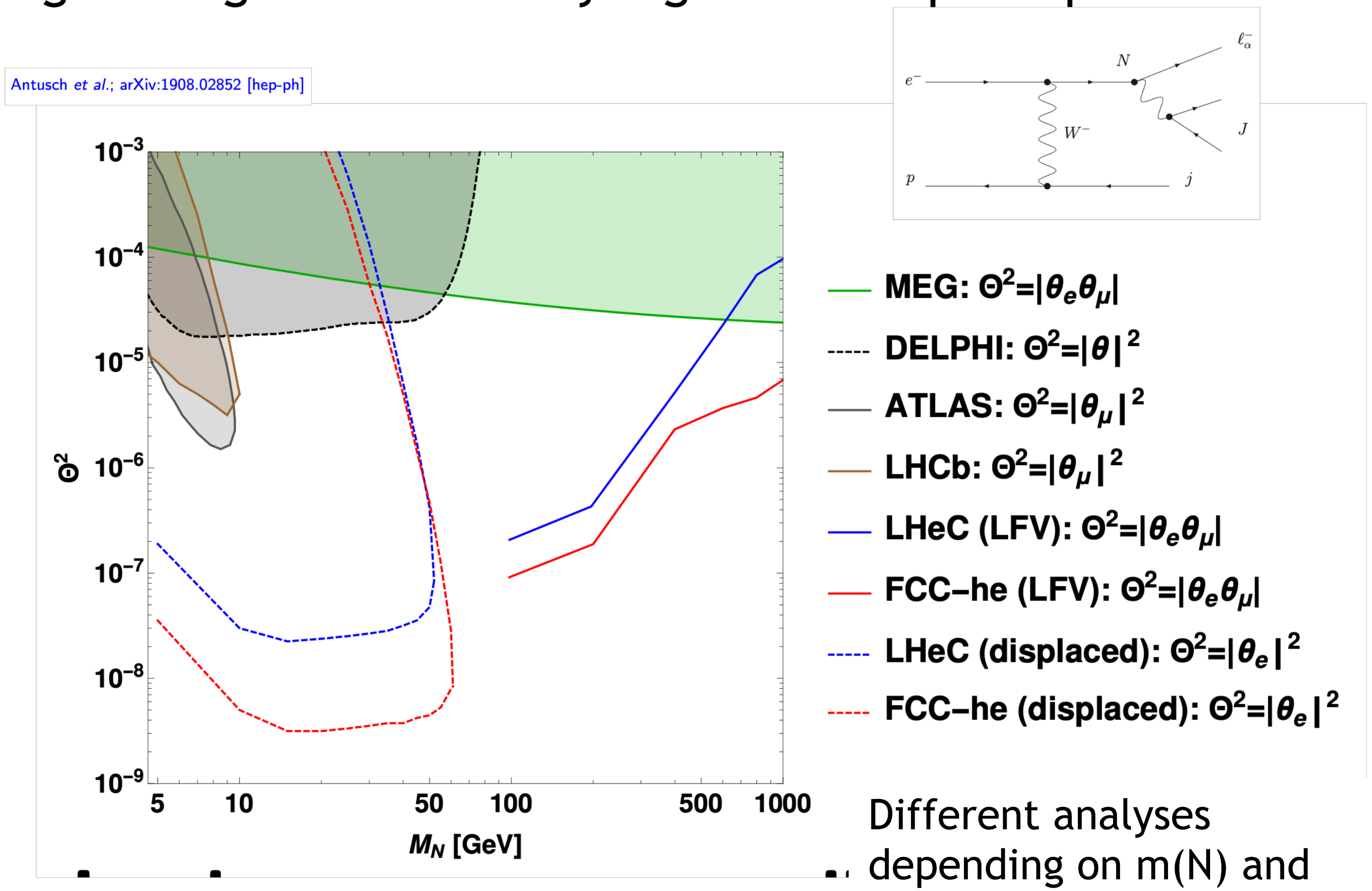
- Few examples:
  - **Sterile neutrinos**







Different analyses depending on m(N) and m(W) relations

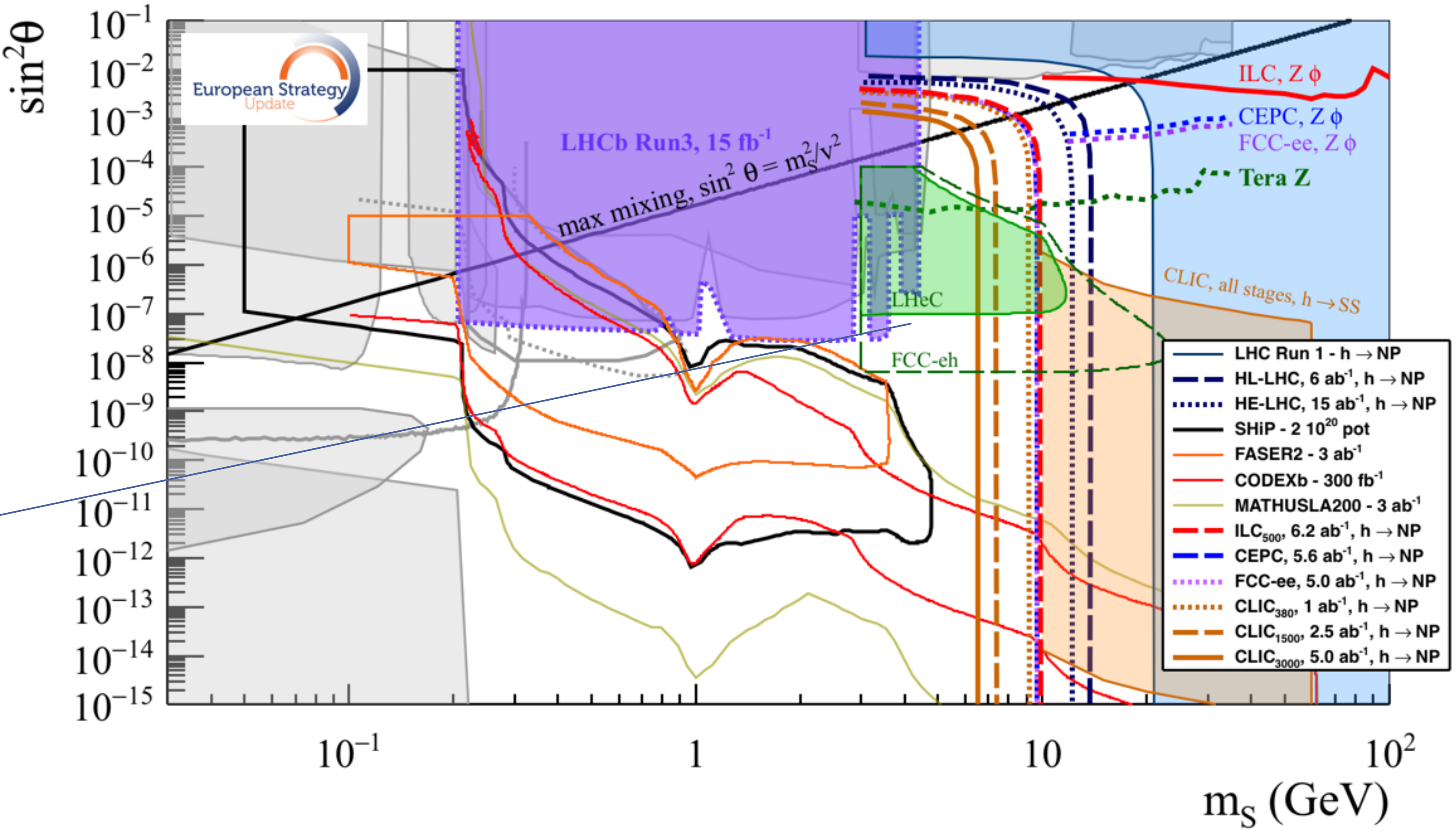
Complementarity of e-p

- Weakly produced and/or non-promptly decaying particles very challenging at pp and ee colliders → good complementarity with e-p colliders
  - @ pp: low production cross section, high background and very high level of pile-up
- Few examples:
  - New dark scalars

$$(\mu S + \lambda_{HS} S^2) H^\dagger H$$

Covering important regions between pp and ee / low-energy experiments

Intermediate coverage expected for LE-FCC



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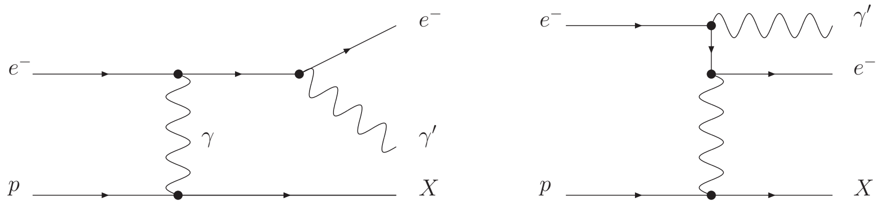
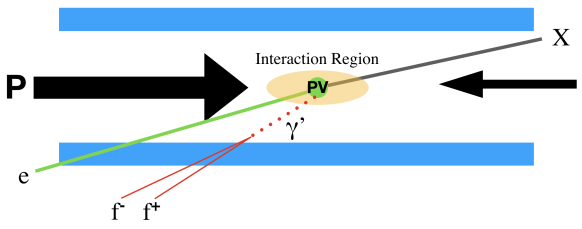
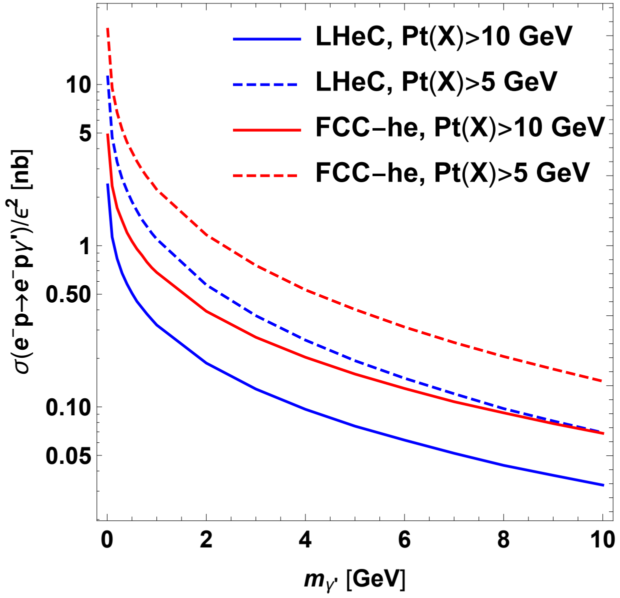
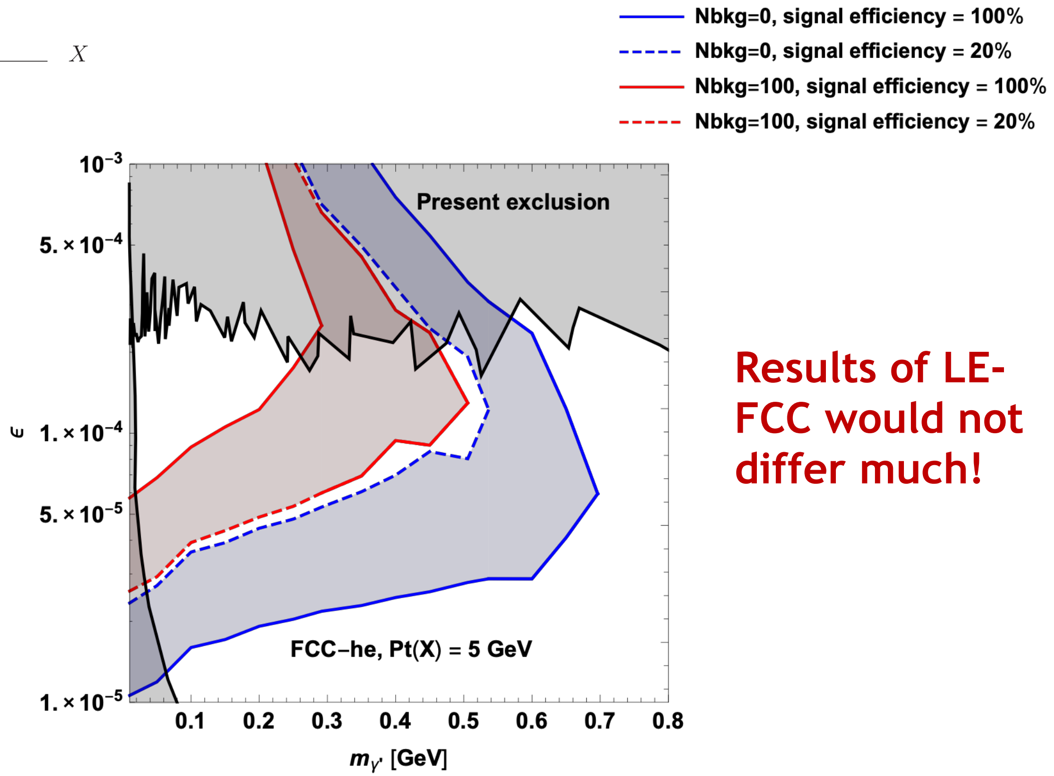
https://arxiv.org/pdf/1909.02312.pdf

- Few examples:
  - Dark photons









Results of LE-FCC would not differ much!

Complementarity of e-p

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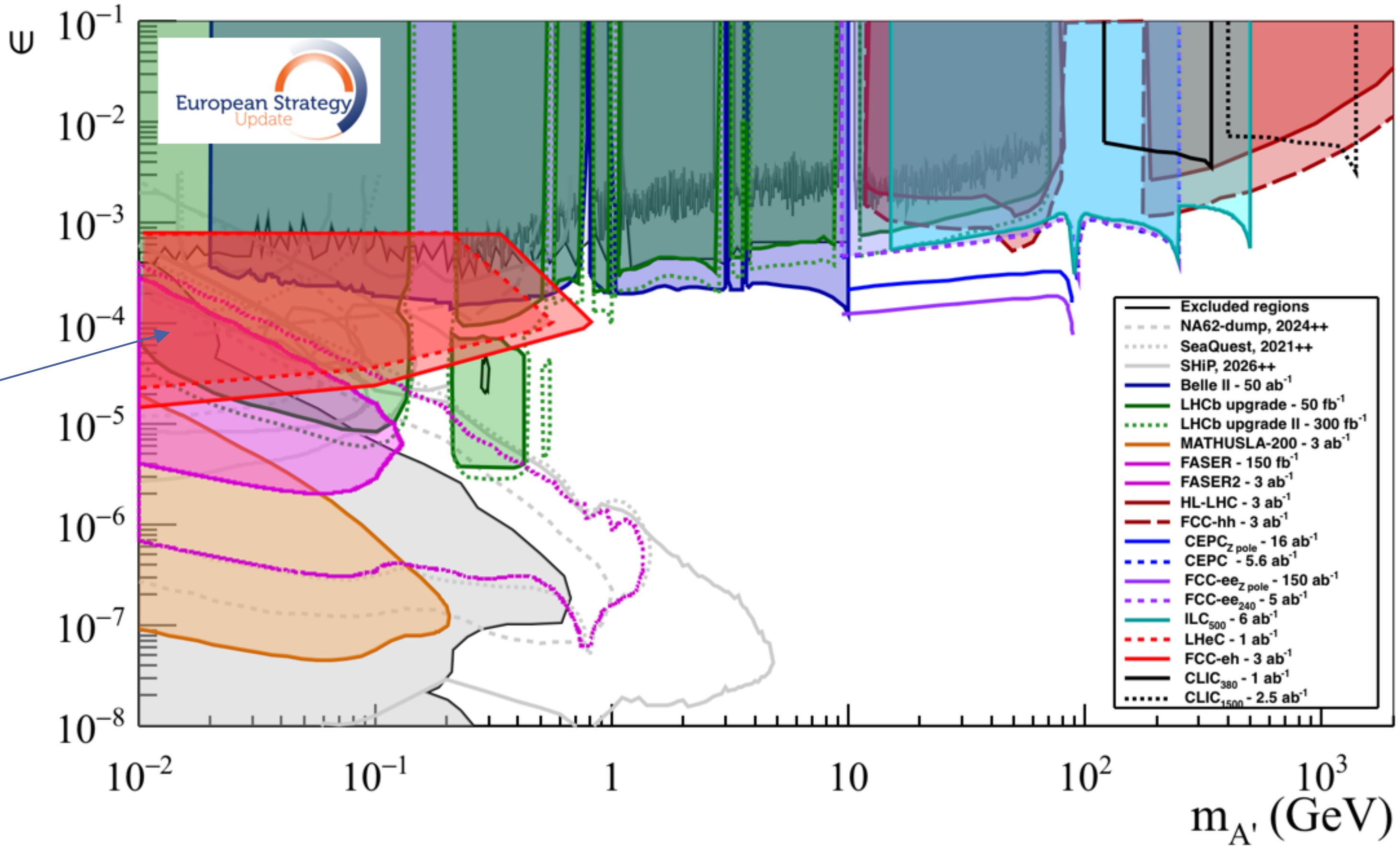
Covering important regions between pp and ee / low-energy experiments



Conclusions

- FCC-eh offers a variety of opportunities for Higgs measurements, strong interactions, top physics and BSM searches in a lot of expected and maybe unexpected scenarios
- A low-energy version of FCC, with concurrent ep and pp would have lot of potential in several scenarios, although it has not been fully quantified
- Several new ideas still being explored and on-going – potential as a function of c.o.m. energy depending on proton beam energy to be fully explored, e.g.
  - Potential on higgs measurements, and di-higgs studies
  - Lepto-quarks
  - SUSY EWK studies
  - Dark scalars in Higgs decays
  - Anomalous couplings

Great opportunity for new ideas - all being documented in the CDR !

Back up

The LE-FCC hh physics case in a nutshell

- Studies utilize extrapolations from HE-LHC or FCC-hh
  - concrete studies at 27 and 100 TeV allows to test the validity of the PDF extrapolation, and to justify the interpolation to 37.5 TeV
- New physics reach at high mass: "easier" extrapolation, compare with HE and FCC

Collider	$Z'_{SSM} \to \tau^+\tau^-$	$Z'_{SSM} \to t\bar{t}$	$G_{RS} \to WW$	$Z'_{TC} \to t\bar{t}$	$Q^* \to jj$	$Z'_{SSM} \to \ell^+\ell^-$
FCC [4] (TeV)	18	18	22	23	40	43
HE-LHC [4] (TeV)	6	6	7	8	12	13
FCC/HE-LHC	3	3	3.1	2.9	3.3	3.3
FCC/HE CR	2.7	2.7	2.9	2.9	3.1	3.2
LE-FCC CR (TeV)	7.5	7.5	9	10	16	17
LE-FCC/HE-LHC	1.25	1.25	1.3	1.25	1.3	1.3

~ gain 25-30% wrt to HE-LHC

- Most difficult: Higgs properties and precision measurements

Cross section increase ~ 50-100% depending on process

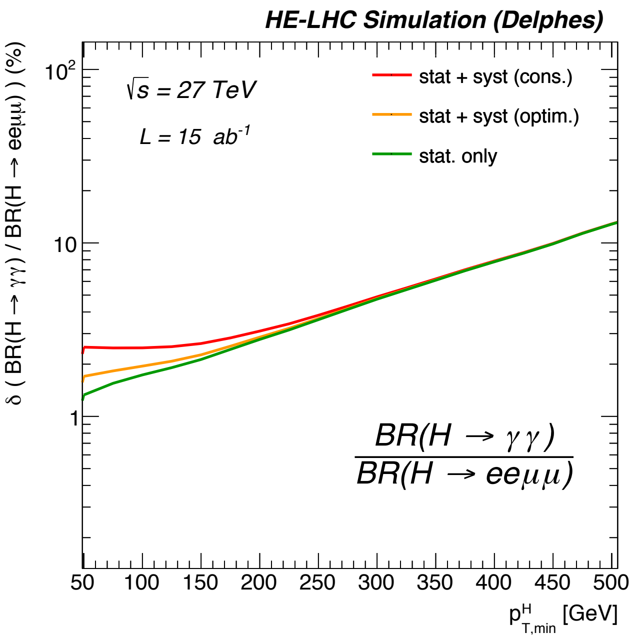
	$gg \to H$	VBF	WH	ZH	ttH	HH
σ(37.5 TeV) (pb)	230	19	5	3	5.8	0.26
27/14	2.7	2.7	2.3	2.4	4.8	3.8
37.5/14	4.2	4.4	3.3	3.5	9.5	7.0
100/14	15	16	10	13	53	34
37.5/27	1.6	1.6	1.5	1.5	2.0	1.8

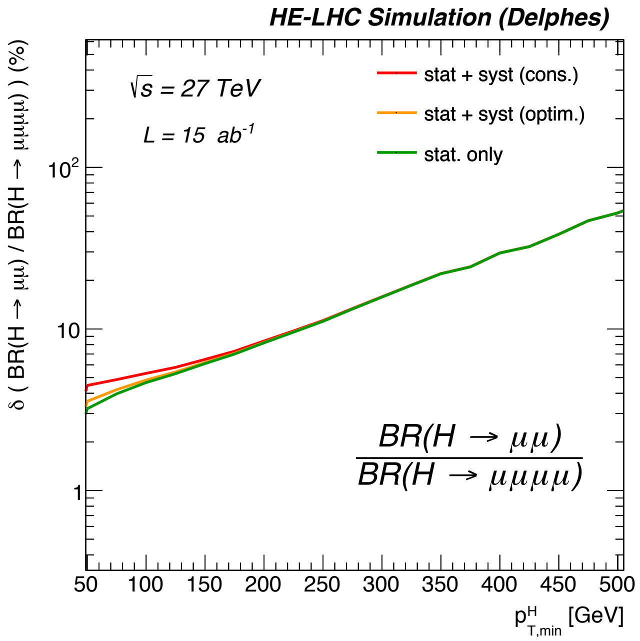
precision reach for some rare processes

$\delta R/R$	HE-LHC	LE-FCC	FCC-hh
$R = B(H\to\gamma\gamma)/B(H\to 2e2\mu)$	1.7%	1.5%	0.8%
$R = B(H\to\mu\mu)/B(H\to 4\mu)$	3.6%	2.9%	1.3%
$R = B(H\to\mu\mu\gamma)/B(H\to\mu\mu)$	8.4%	6%	1.8%
$R = B(H\to\gamma\gamma)/B(H\to 2\mu)$	3.5 %	2.8%	1.4%

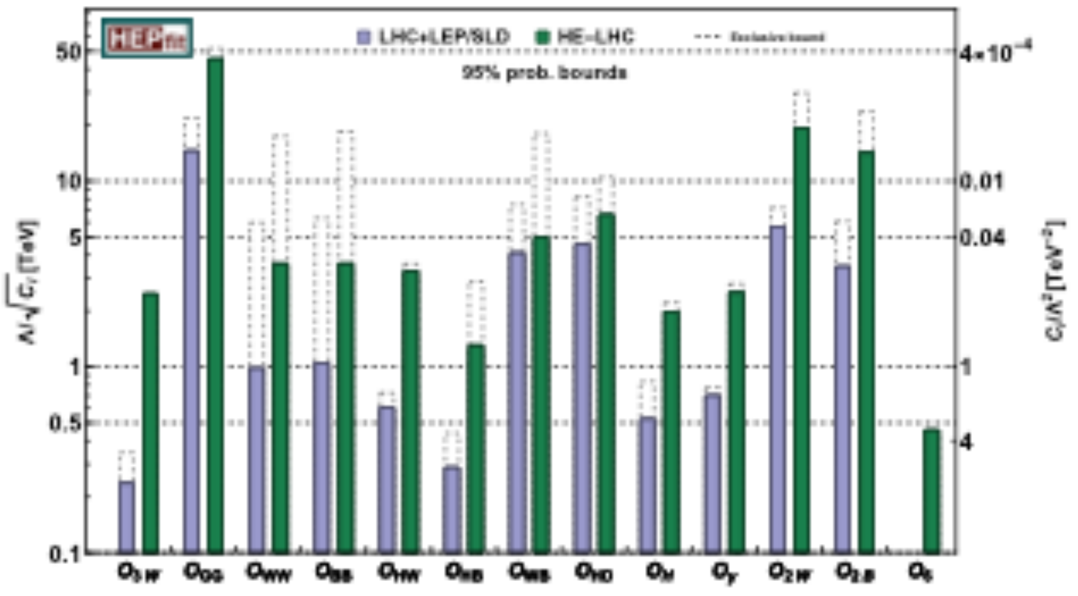
Prospects for High-Energy

- For Higgs boson transverse momenta between 50 and 500 GeV, a precision in the range of 2-4% is achievable for the ratios BR(H→μμ)/BR(H→γγ) and BR(H→ 4l)/BR(H→γγ), and therefore of order 1-2% for the ratios of the relevant Higgs couplings.





constraints on the EFT operators



- Potential for discovery of deviations will grow considerably, allowing to test energy scales ~ 25 TeV
- Other highlights: longitudinal scattering, exotics Higgs decays, heavier additional higgses

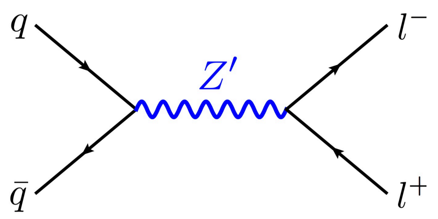
Direct vs indirect constraints

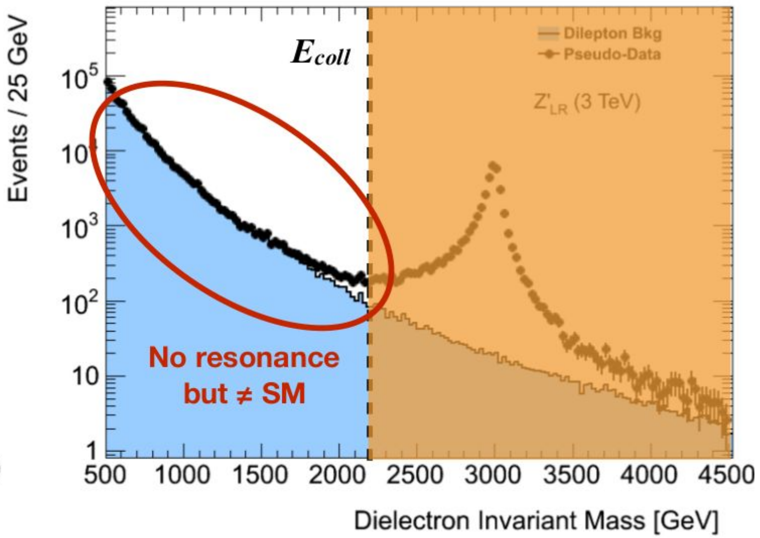
J. De Blas

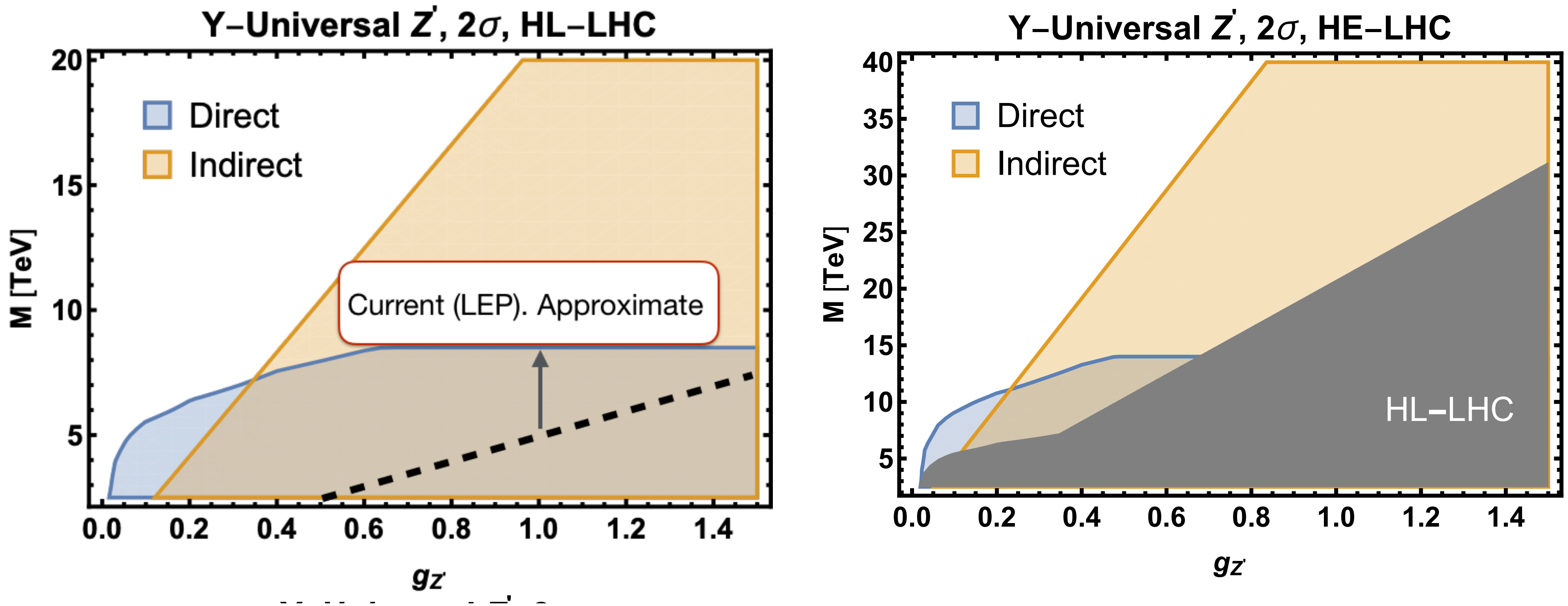
- If mZ'>>5 TeV, main contributions from interference effects modifying DY
- Complementarities hadron / lepton colliders
- Hadron colliders relevant for $g_{Z'} > g_{SM}$

couplings: [mass/coupling] ≫ 0.5√s

(lepton colliders; sensitive to [mass/coupling] ≫ √s)







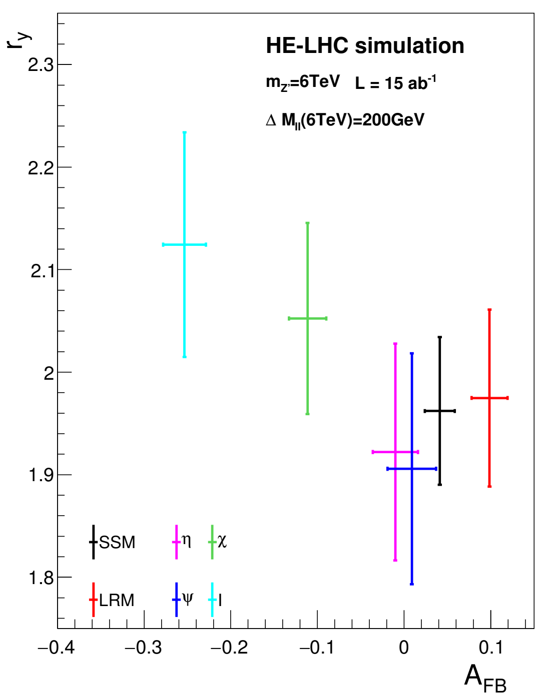
A. Wulzer Granada '19

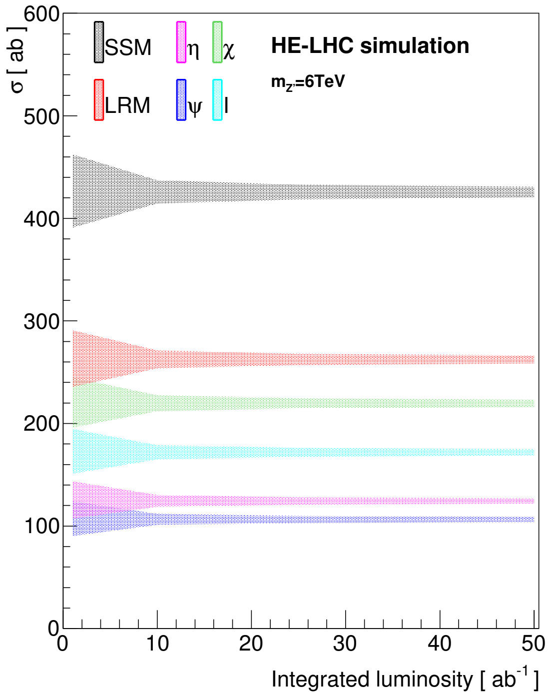
Characterizing a discovery @ HE-LHC

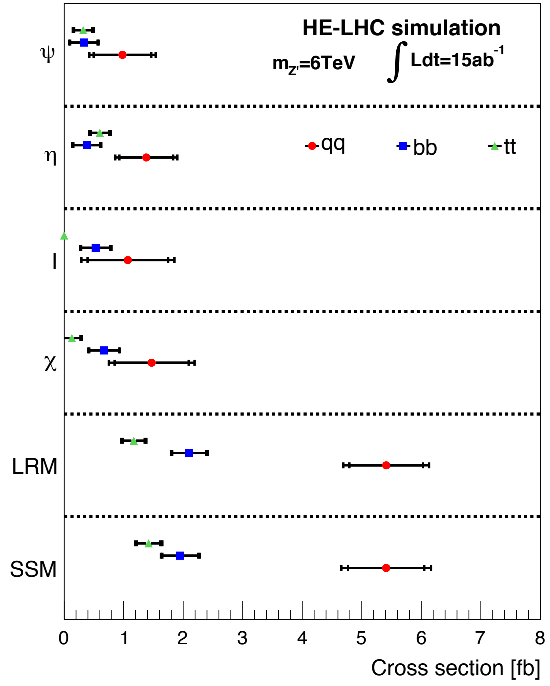
- IF a Z' resonance of 6 TeV is seen at HL-LHC, it can be "characterized" at HE-LHC via cross sections, AFB and central/forward ratios

$$A_{FB} = A_C = \frac{\sigma(\Delta|y| > 0) - \sigma(\Delta|y| < 0)}{\sigma(\Delta|y| > 0) + \sigma(\Delta|y| < 0)},$$

$$r_y = \frac{\sigma(|y_{Z'}| < y_1)}{\sigma(y_1 < |y_{Z'}| < y_2)}, \quad y_1 = 0.5 \text{ and } y_2 = 2.5$$

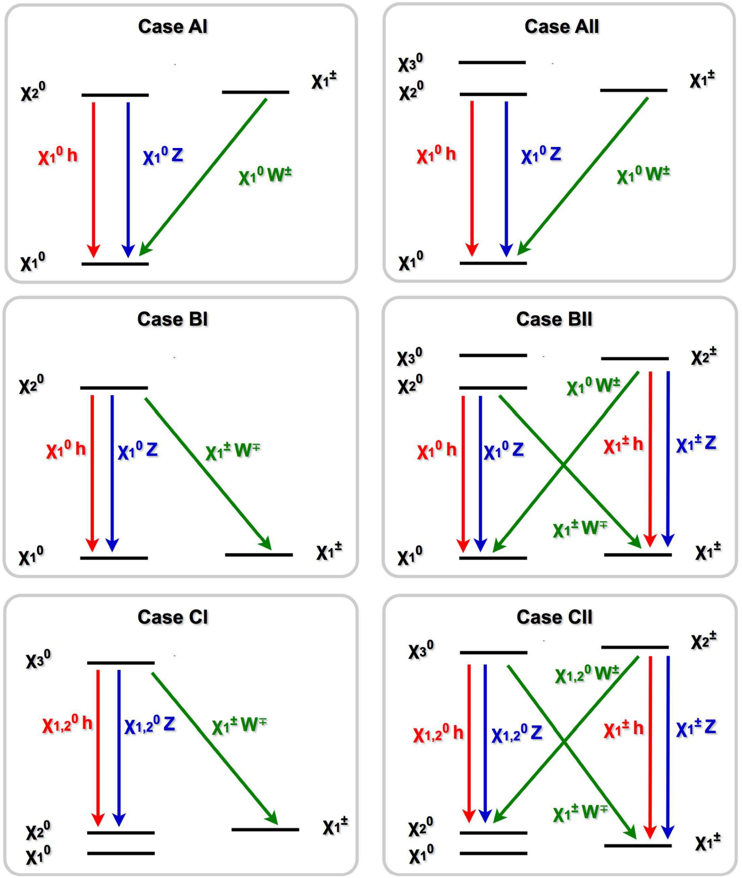






SUSY EWK production: Phenomenology

- Mass and hierarchy of the four neutralinos and the two charginos, as well as their production cross sections and decay modes, depend on the M_1, M_2, μ (bino, wino, higgsino) values and hierarchy
  - EWK phenomenology broadly driven by the LSP and Next-LSP nature
  - Examples of classifications (cf: arXiV: 1309.5966)



- **Scenario A:** $M_1 < M_2,\ |\mu|$

  Bino LSP

- **Scenario B:** $M_2 < M_1,\ |\mu|$

  Wino LSP

- **Scenario C:** $|\mu| < M_1,\ M_2$

  Higgsino LSP

Used as benchmarks:

- Bino LSP, wino-bino cross sections
  (1) Mass($\chi^{\pm}_1$) = Mass (χ^0_2)
  (2) $\chi^+_1\chi^-_1$ and $\chi^{\pm}_1\chi^0_2$ processes

$$\sigma_W(\chi^{\pm}_1\chi^0_2) \sim 2\ \sigma_W(\chi^+_1\chi^-_1)$$

- Higgsino-LSP, higgsino-like cross sections
  (1) Small mass splitting $\chi^0_1, \chi^{\pm}_1, \chi^0_2$
  (2) Consider triplets for cross sections
  (3) Role of high-multiplicity neutralinos and charginos also relevant

$$\sigma_H(\chi^{\pm}_1\chi^0_2 + \chi^+_1\chi^-_1 + \chi^{\pm}_1\chi^0_1) < 0.7\ \sigma_W(\chi^{\pm}_1\chi^0_2)$$

[depending on masses!]