Projections for future colliders

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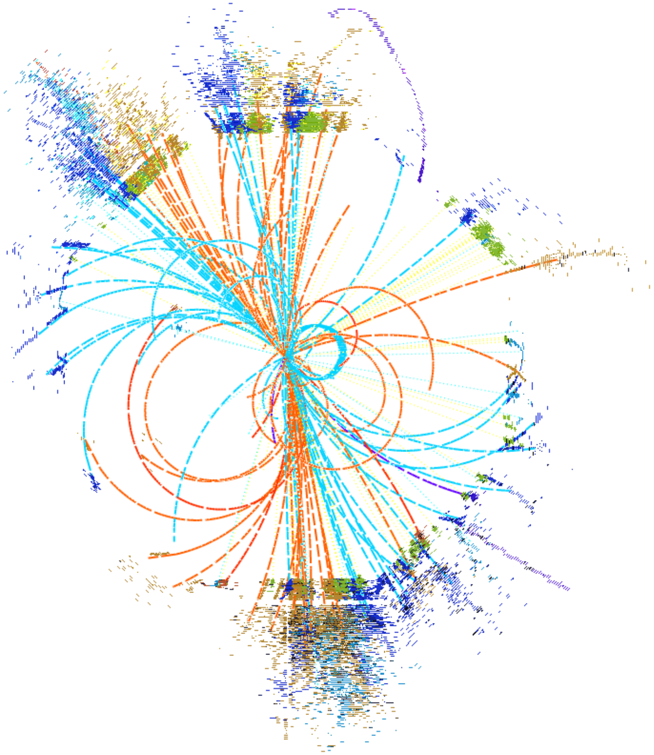
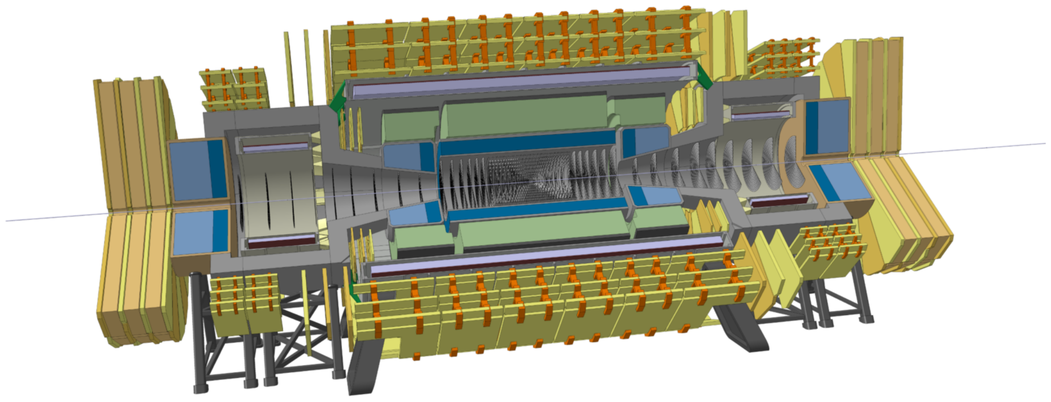
12/06/2020
Snowmass EF02 topical group
2HDM meeting





A few caveats

• Material mainly from input to the European strategy process by the various future collider communities

• Results shown in the following are based on very different levels of sophistication: from generator-level estimates up to full detector simulations
→ differences will be mentioned if relevant

• In some cases projections were not available from all collider options
→ physics capabilities typically most dependent on centre-of-mass energy and integrated luminosity (especially for lepton colliders)

• Unless stated explicitly, HL-LHC projections are for one experiment (3 ab^{-1})

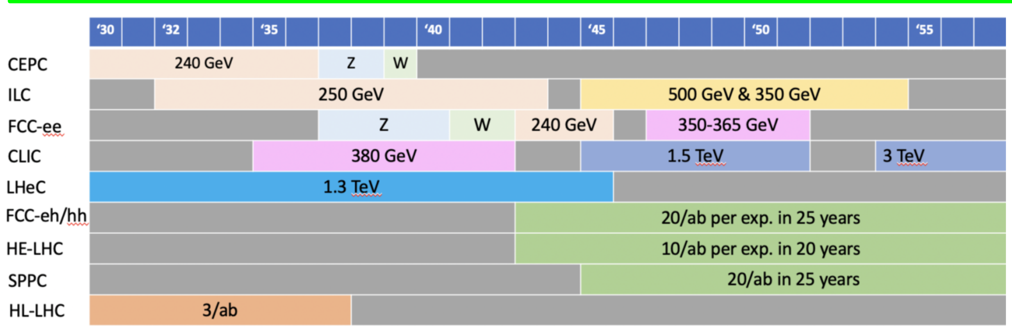
Future collider parameters

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]$ cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[13]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[13]	HE-LHC
FCC-hh$^{(*)}$	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 14]	ILC$_{250}$
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)		(1y SD after 250 GeV run)
		1000 GeV	±80/±20	1	3.6/7.2	8.0	8.5	[4]	ILC$_{1000}$
							(+1-2)		(1-2y SD after 500 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[15]	CLIC$_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC$_{3000}$
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[12]	LHeC
HE-LHeC	ep	1.8 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

pp colliders

e$^+$e$^-$ colliders

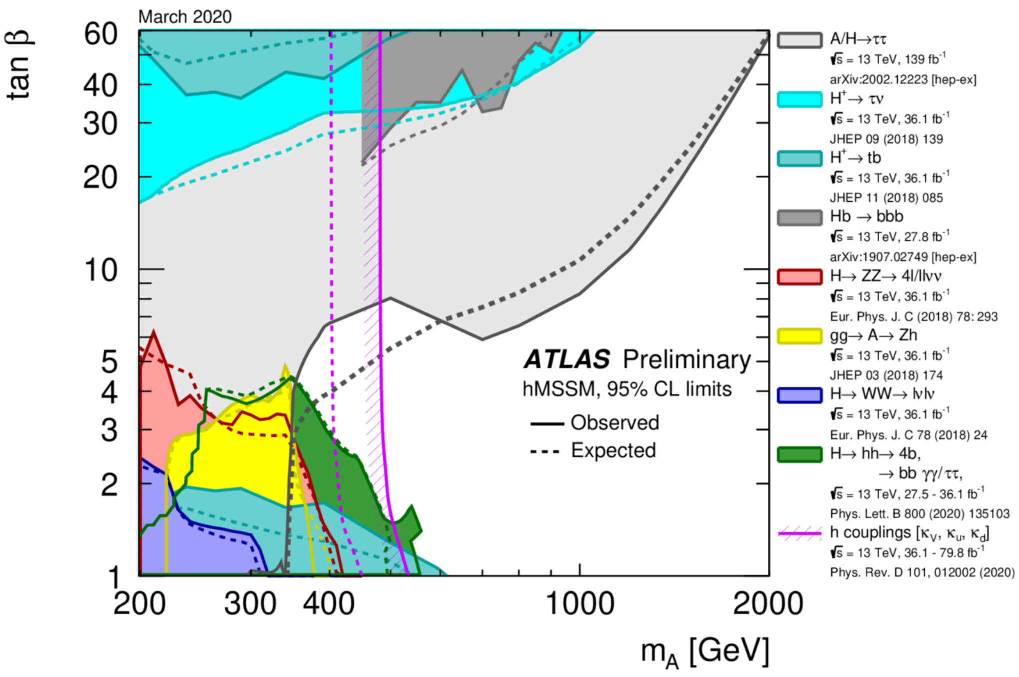
ep colliders

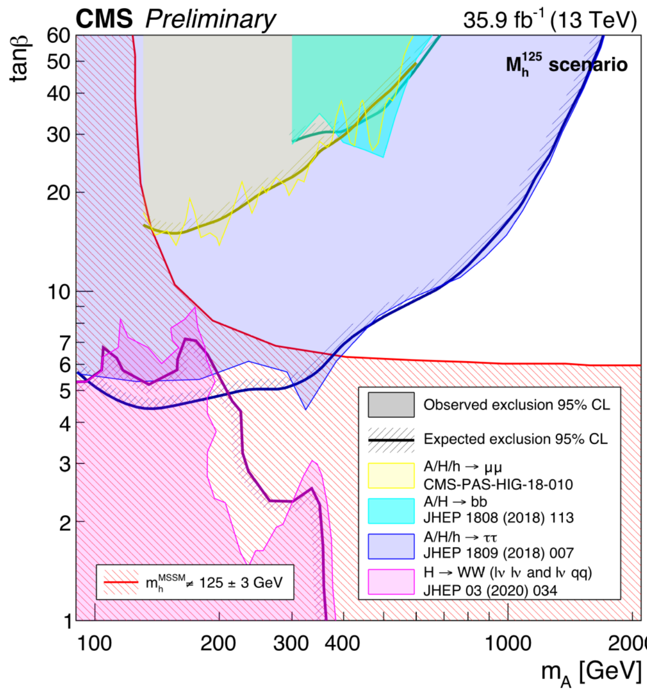


+ muon collider, advanced (dielectric, PWFA) e$^+$e$^-$ colliders

arXiv:1905.03764

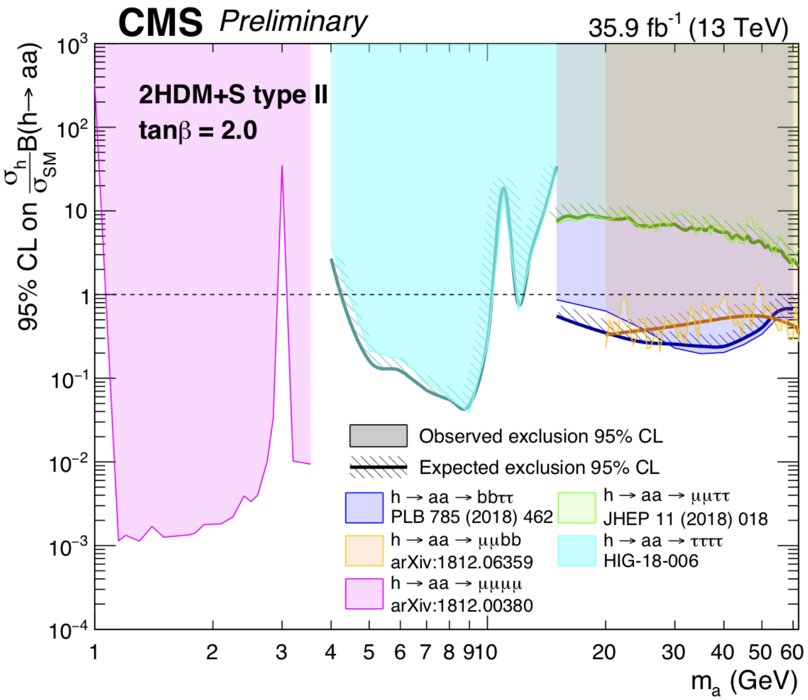
BSM Higgs searches at the LHC

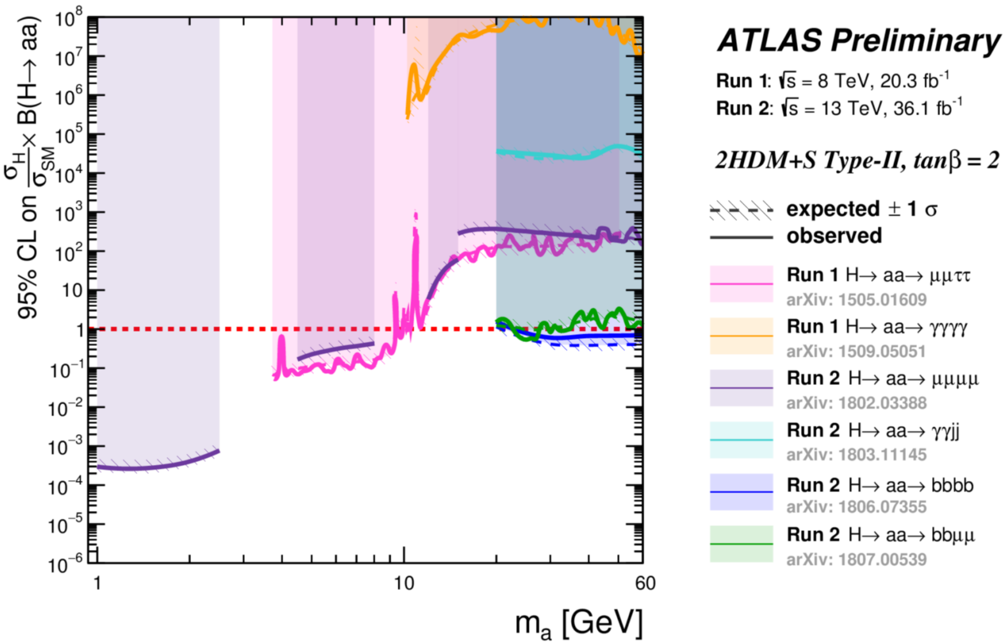




- Comparison of the latest results in specific MSSM benchmark scenarios (hMSSM, M_h^{125})
- Best direct sensitivity from $A/H \rightarrow \tau^+\tau^-$ at large tan(β), $H \rightarrow hh/WW$ at small tan(β)
- No plots for other variants (e.g. Type-I 2HDM) yet

Higgs decays to light scalars at LHC





- Comparison of the latest results in 2HDM + one complex scalar singlet benchmark model with tan(β) = 2

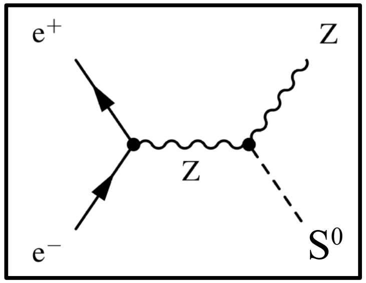
Direct BSM Higgs searches at future colliders

Available material somewhat limited, examples discussed in the following:

- Generic: $e^+e^- \rightarrow ZH$ using recoil method
- Fermionic final states: $A/H \rightarrow \tau^+\tau^-$ at HL-LHC and MSSM Higgs bosons at FCC-hh
- $A \rightarrow ZH$ at HL-/HE-LHC
- Resonant ZZ and hh production at HL-LHC, CLIC and FCC-hh

Scalar searches using recoil method

• A lepton collider could search for new scalars with a small (but non-vanishing) coupling to the Z boson using the recoil technique:

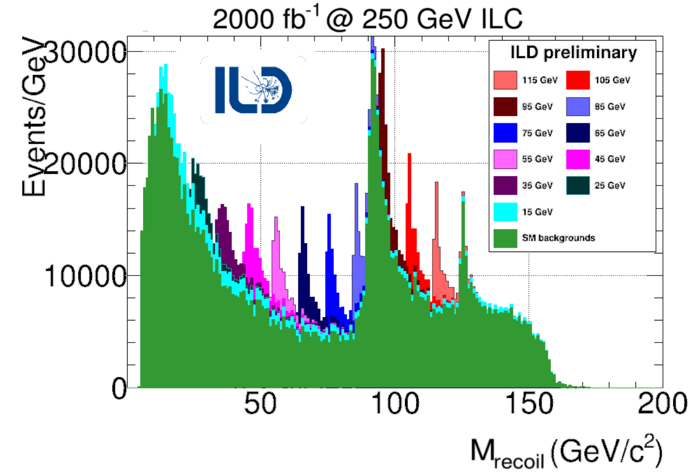


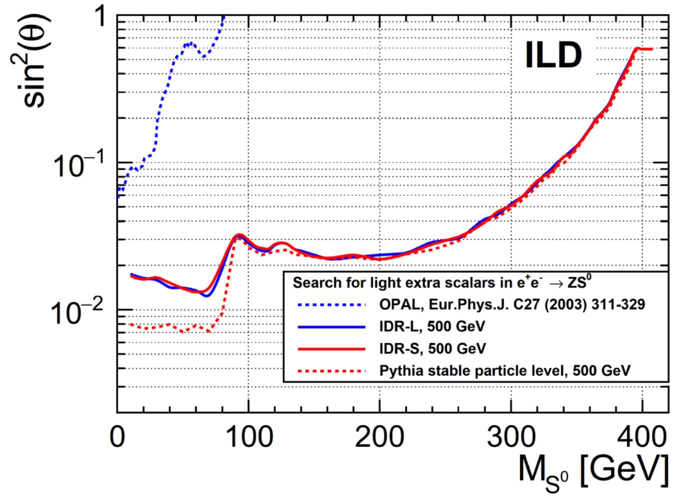
$$M^2_{recoil} = \left(\sqrt{s} - E_Z\right)^2 - |\vec{p}_Z|^2$$

→ independent of new scalar decay

• Examples for ILC at 250 and 500 GeV, but also possible at CEPC, FCC-ee and CLIC (arXiv:2002.06034)

• Less powerful at high energy (lower cross section, detector resolution, ISR & linear collider luminosity spectra)

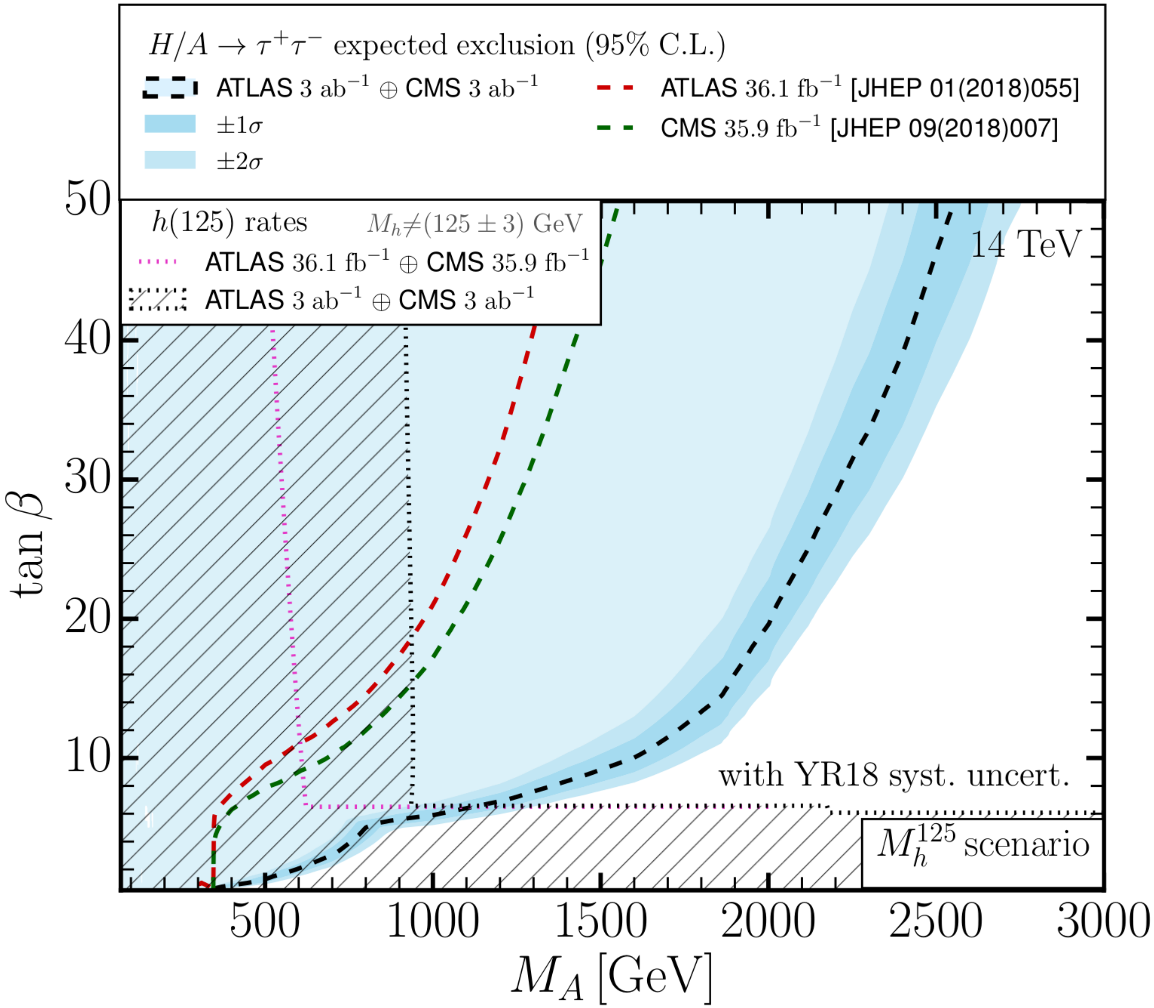




$\sin^2(\theta)$: cross section limit normalised to the cross section for a SM Higgs of the same mass

arXiv:2003.01116

A/H → $\tau^+\tau^-$ at HL-LHC



- Combination of CMS and ATLAS Projections (6 ab^{-1} in total)

- Direct access to heavy Higgs bosons of 2.5 TeV for tan β > 50

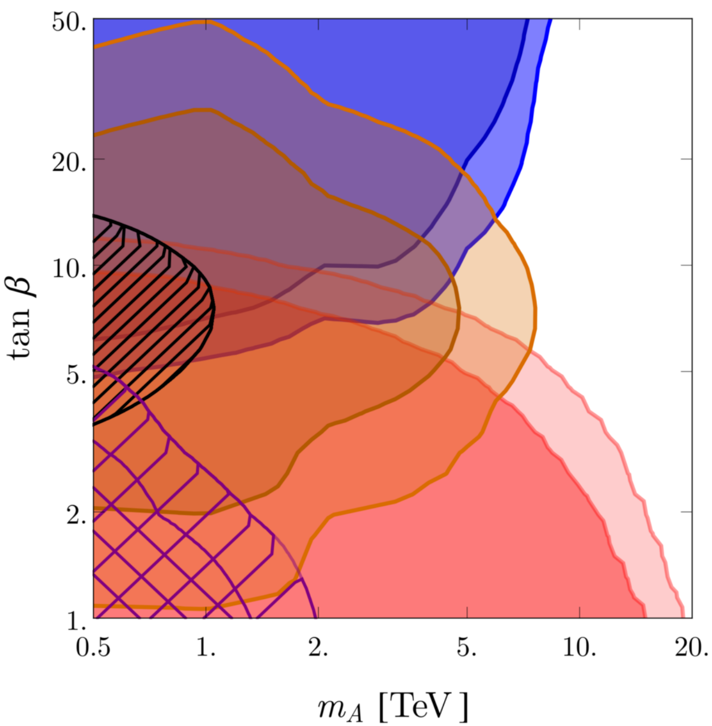
M_h^{125} scenario:

- tan β < 6 → light Higgs below 122 GeV
- M_A < 900 excluded by Higgs signal strengths (dependent on the benchmark scenario used)

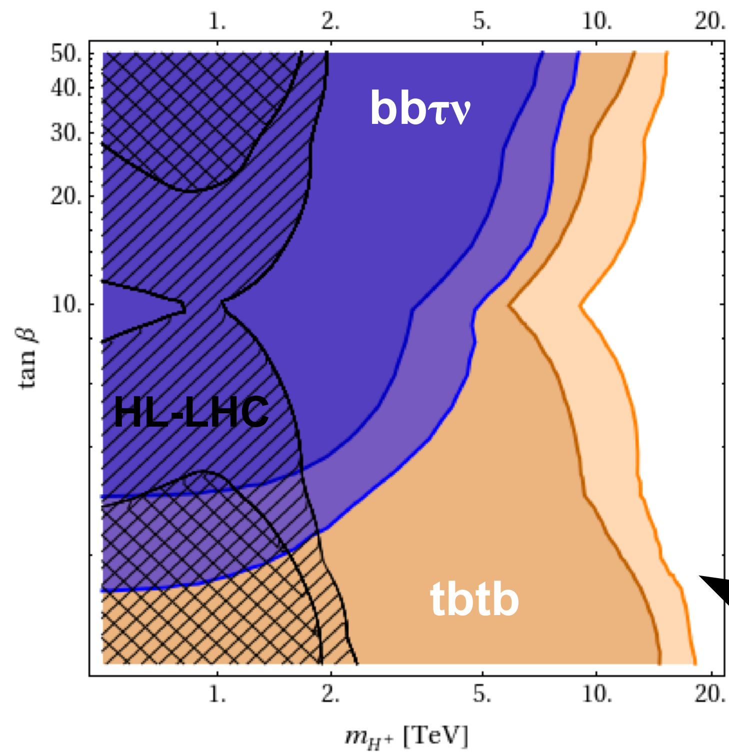
Sec. 9.5 of CERN-LPCC-2018-04

MSSM Higgs bosons at FCC-hh

pp → bbH⁰/A → bbττ (large tanβ)
pp → bbH⁰/A → ttbb (int. tanβ)
pp → ttH⁰/A → tttt (low tanβ)

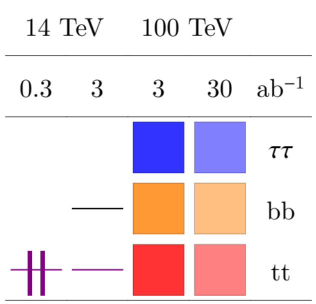


pp → btH± → bbτν
pp → btH± → tbtb



30 ab⁻¹

- Studies using Delphes
- Exclusion limits better than 5 TeV for H⁰/A (20 TeV at low tan β)
- Exclusion limits in the range 10 - 15 TeV for H⁺

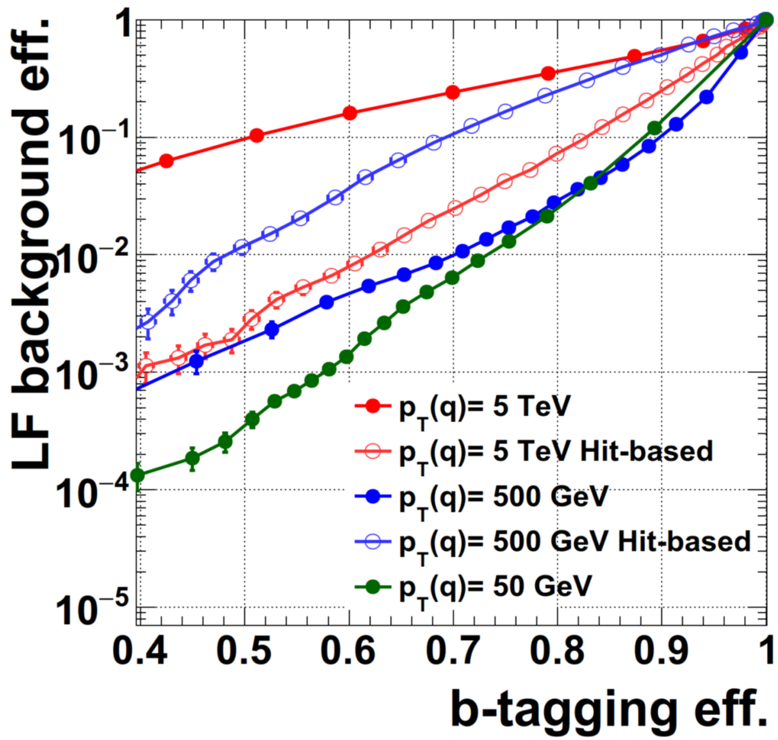


95% C.L. exclusion limits

JHEP **01**, 018 (2017)
JHEP **11**, 124 (2015)
Sec. 6.7 of CERN-TH-2016-113

b-tagging in 100 TeV pp-collisions

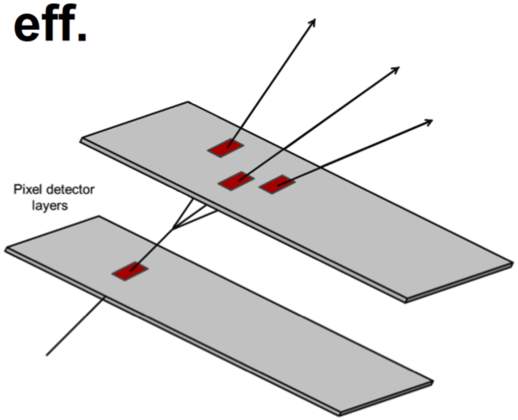
$pp \rightarrow jj, |\eta(j)| \approx 0$

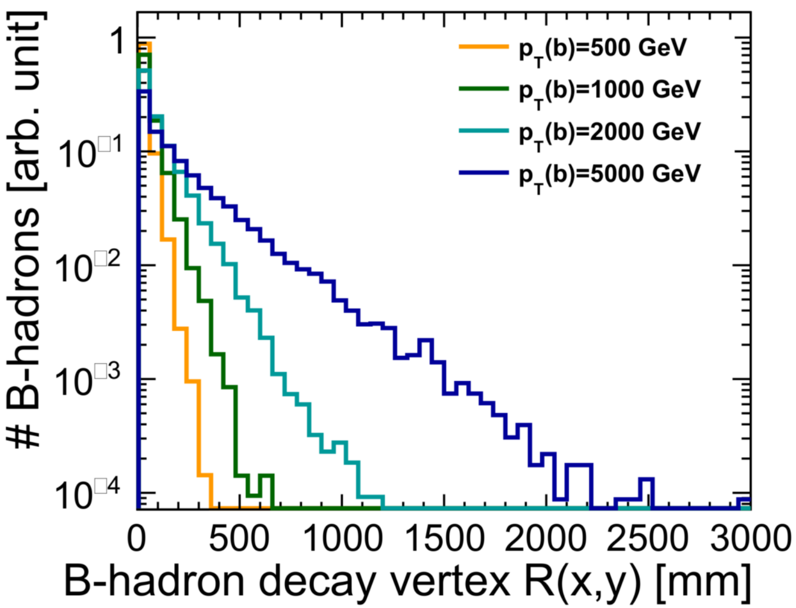


p_T(q) = 50 & 500 GeV: good performance using normal flavour tagging based on tracks and secondary vertices

Multi-TeV b-jets: tracking challenging (decay length, B-decay products very collimated) → better flavour tagging performance using hit-based approach

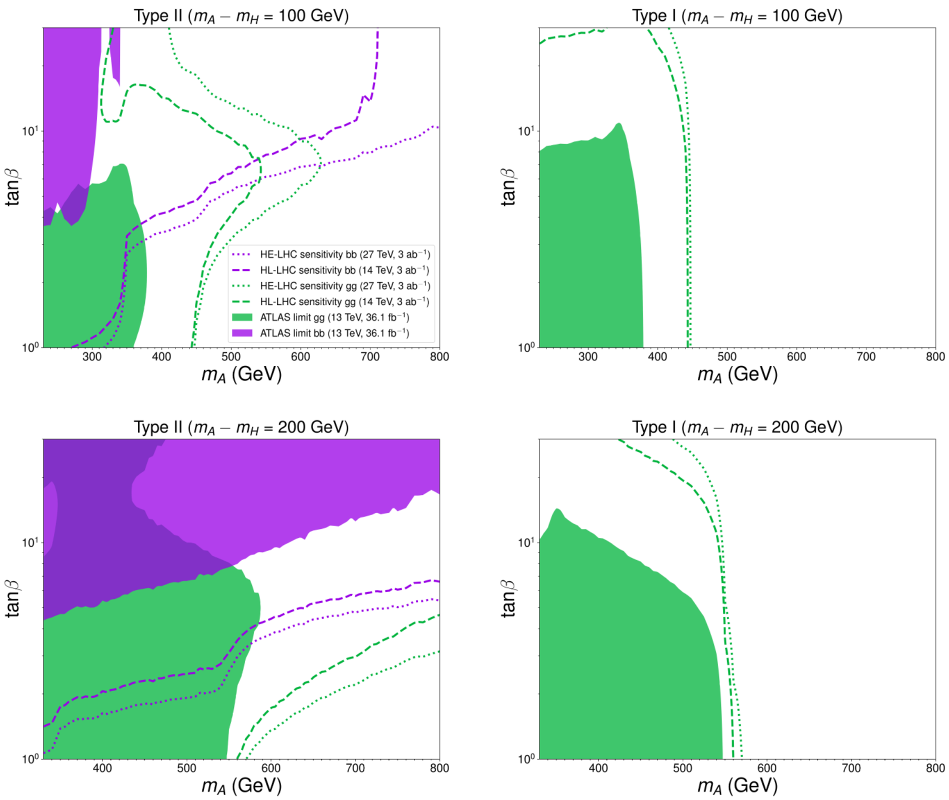
Full detector simulation using LC software tools





CERN-ACC-2018-0023

A→ZH at HL-/HE-LHC



Sec. 9.4 of CERN-LPCC-2018-04

"gg": gluon fusion
"bb": bb-associated production

Benchmark points:

- Type-I and Type-II 2HDM in the alignment limit (lighter CP-even Higgs h has SM couplings)
- $m_A - m_H$ = 100 GeV and 200 GeV

Extrapolation of $A \to ZH$; $Z \to \ell^+\ell^-$; $H \to b\bar{b}$ search from ATLAS

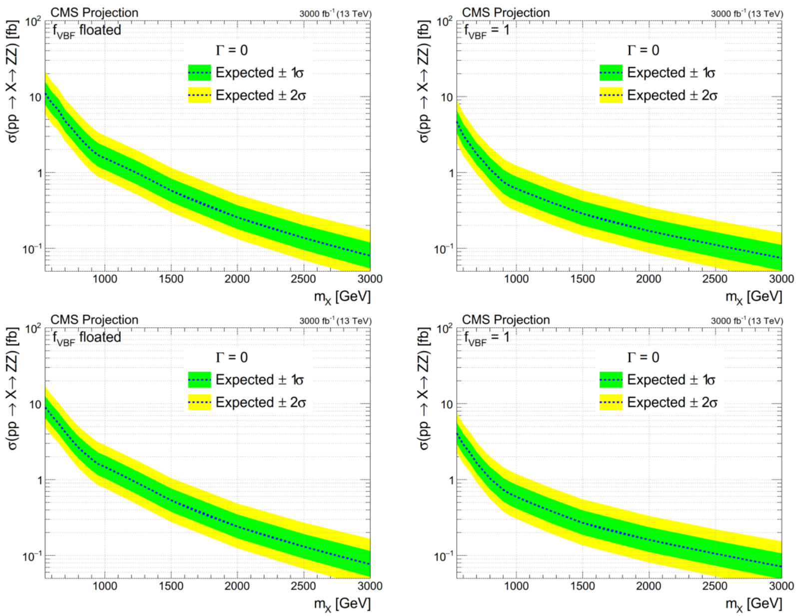
Phys. Lett. B 783, 392 (2018)

For Type-II 2HDM the region of low β and and large m_H could be covered by:
$A \to ZH$; $Z \to \ell^+\ell^-$; $H \to t\bar{t}$

- HE-LHC sensitivity bb (27 TeV, 3 ab^{-1})
- HL-LHC sensitivity bb (14 TeV, 3 ab^{-1})
- HE-LHC sensitivity gg (27 TeV, 3 ab^{-1})
- HL-LHC sensitivity gg (14 TeV, 3 ab^{-1})
- ATLAS limit gg (13 TeV, 36.1 fb^{-1})
- ATLAS limit bb (13 TeV, 36.1 fb^{-1})

Resonant ZZ and hh production at HL-LHC

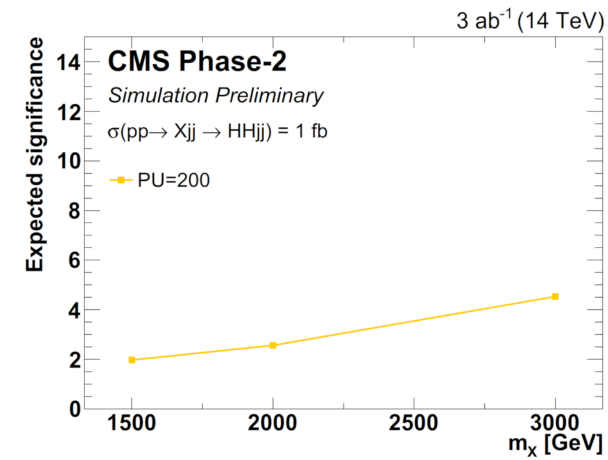
X→ZZ:



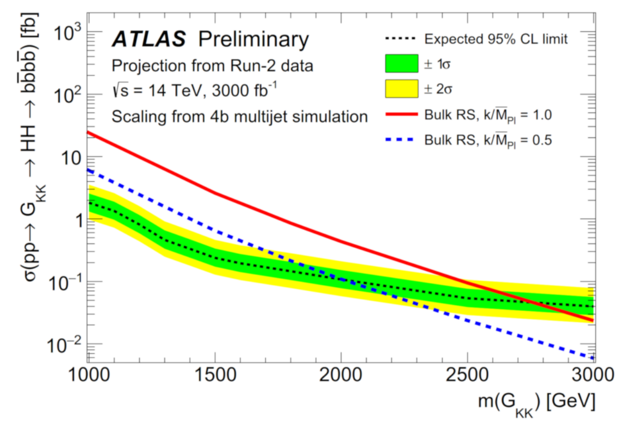
f_{VBF}: fraction of VBF production

arXiv:1902.10229
CMS-FTR-18-040

X→hh: KK gravitons used as benchmark:

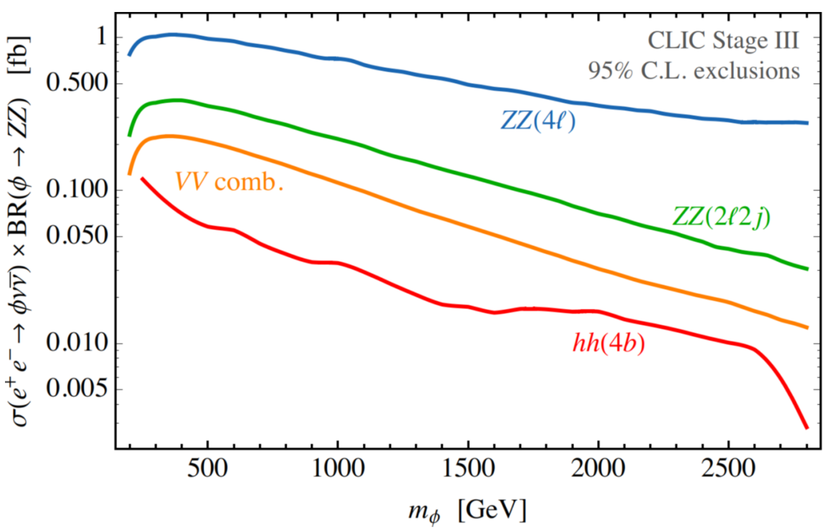


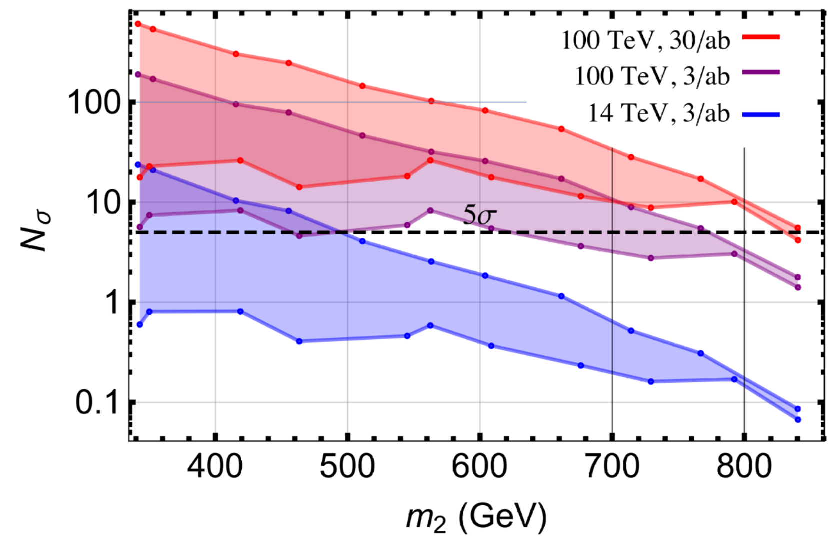
arXiv:1902.10229
CMS PAS FTR-18-003



arXiv:1902.10229
ATL-PHYS-PUB-2018-028

Resonant H→hh: CLIC and FCC-hh





CLIC at 3 TeV:

- BR(ϕ→hh) = BR(ϕ→ZZ) = 25%
- Delphes study
- hh → $b\bar{b}b\bar{b}$ more sensitive than ZZ or WW (all limited by statistics, backgrounds are lowest)

FCC-hh:

- $h_2 \to h_1 h_1$
- 4τ and $b\bar{b}\gamma\gamma$ final states (generator level)
- SM+S benchmark points for strong first-order EW phase transition minimising and maximising the cross section

→ More studies very desirable

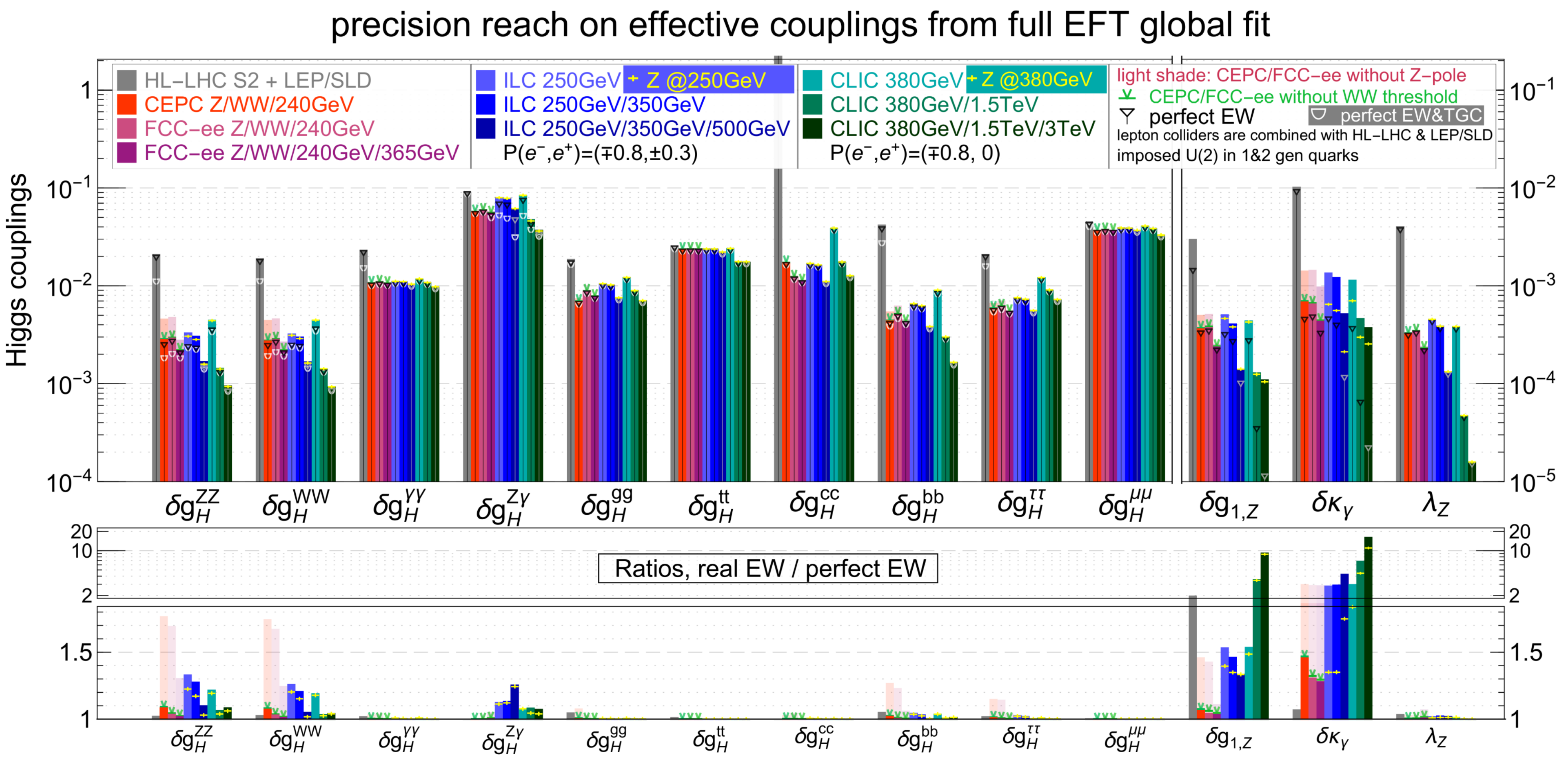
Sec. 4.2 of CERN-2018-009-M
JHEP 11,144 (2018)

CERN-ACC-2018-0056
Phys. Rev. D 94, 035022 (2016)

Precision measurements

- Higgs couplings
- EWPO at the Z-pole and using return-to-Z events
- Some examples
- FCNC top-quark decays

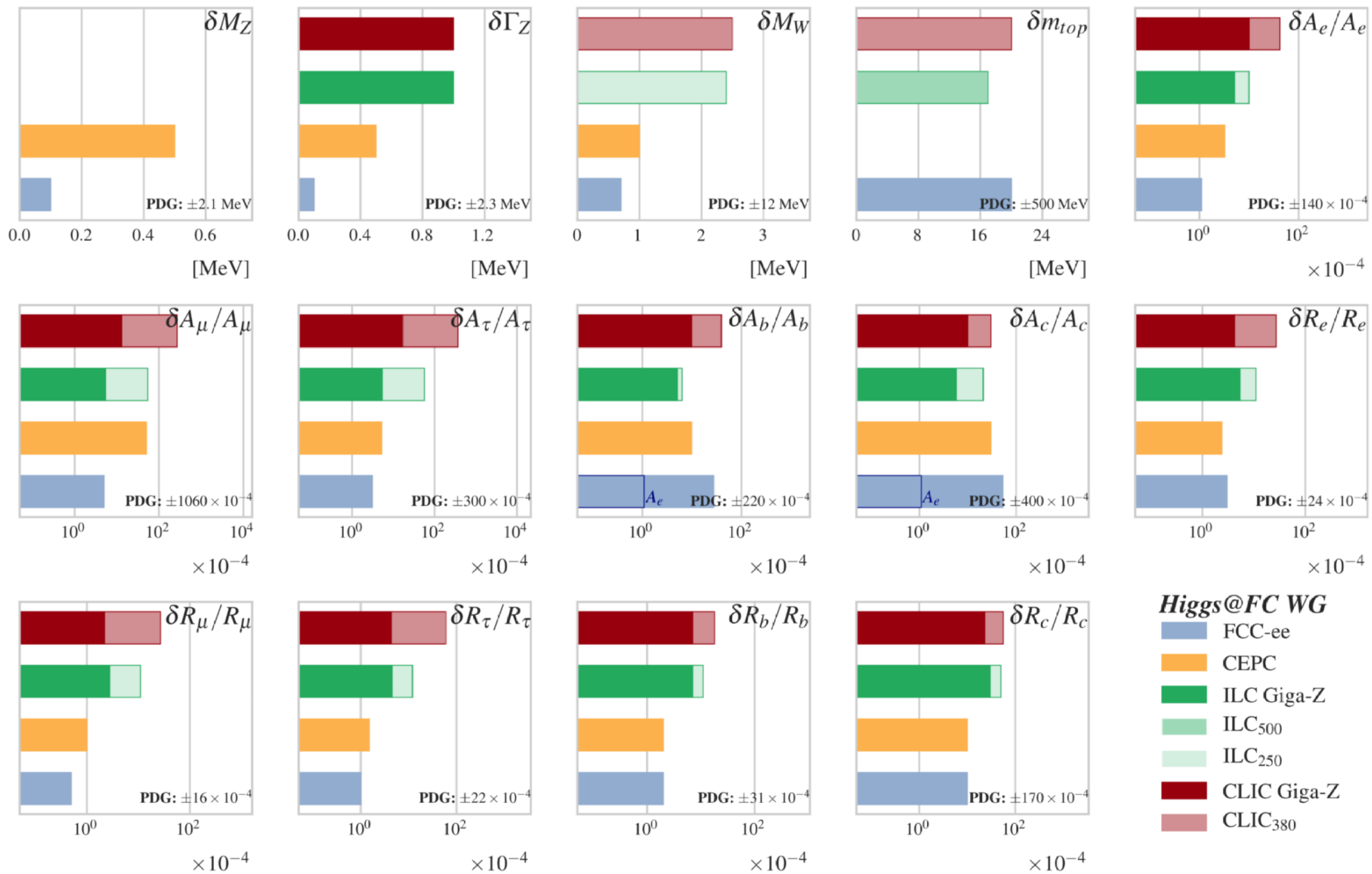
Precision measurements: Higgs couplings



- Many Higgs couplings can be measured significantly better at e^+e^- colliders compared to HL-LHC
- $H \rightarrow c\bar{c}$ very challenging at hadron colliders
- Impact of EWPO on the Higgs coupling extraction small
- Many measurements limited by statistics

arXiv:1907.04311

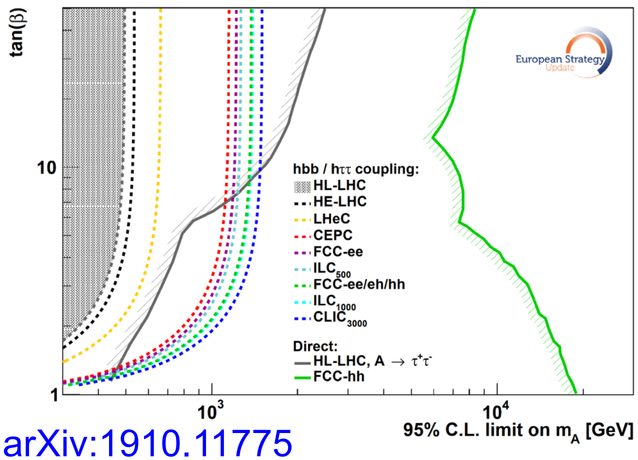
Precision measurements: Z-pole and return-to-Z events



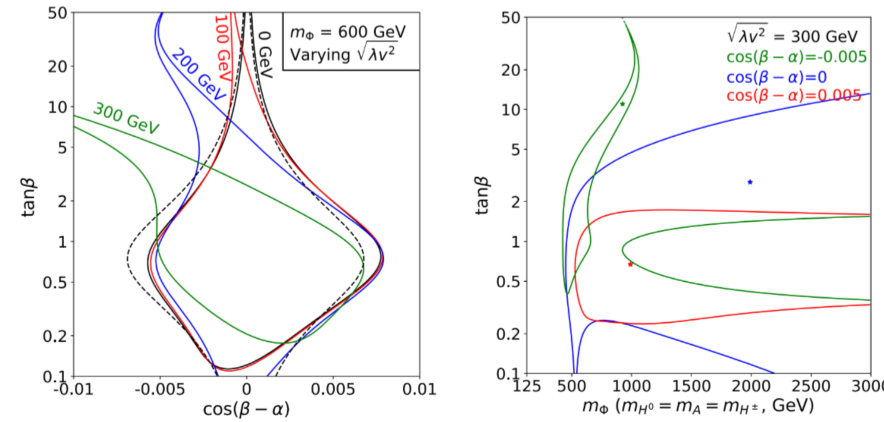
- Operation at the Z-pole part of FCC-ee and CEPC programs, option for ILC and CLIC ("Giga-Z")
- Lower luminosity at linear colliders partially compensated by beam polarisation
- Achievable precisions limited by systematic uncertainties
- These estimates are not based on detailed detector simulations yet!

arXiv:1910.11775

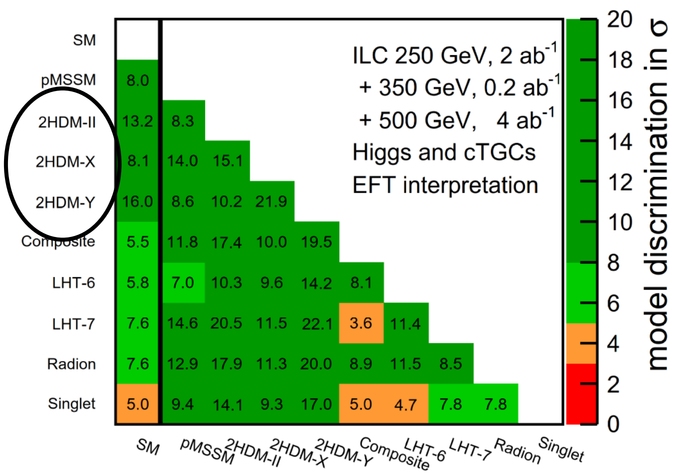
Sensitivity from precision measurements: some recent examples



arXiv:1910.11775

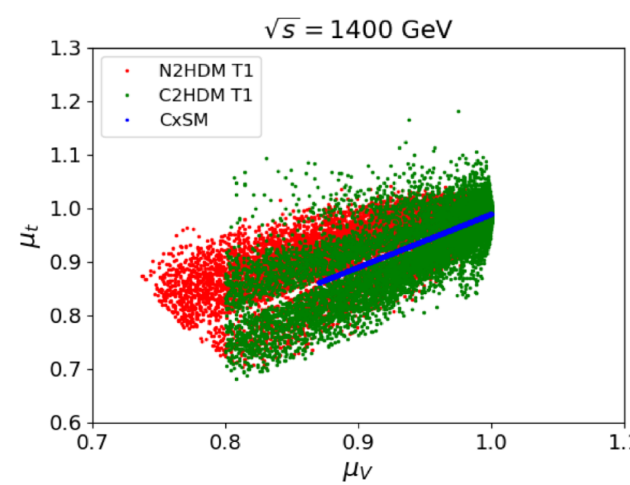


CEPC CDR Volume 2
arXiv:1808.02037



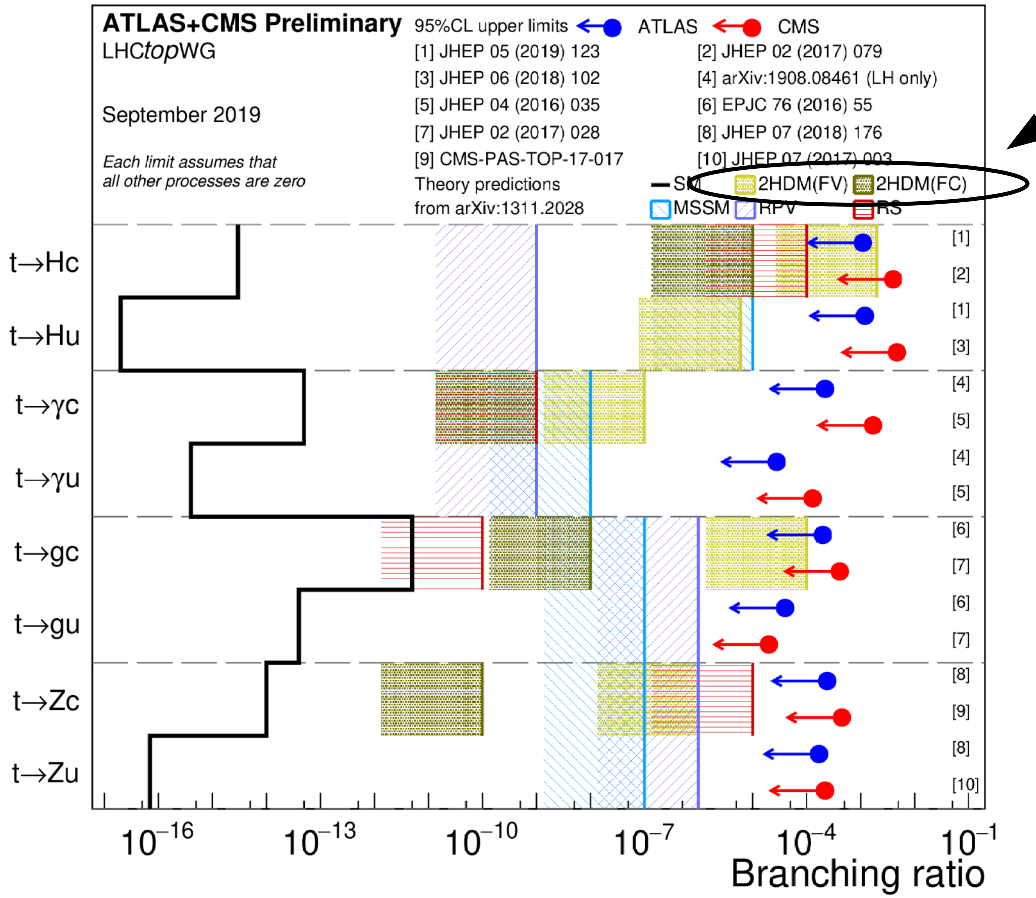
arXiv:1710.07621

→ more results in this session



arXiv:1812.02093
arXiv:1808.00755

FCNC top-quark decays



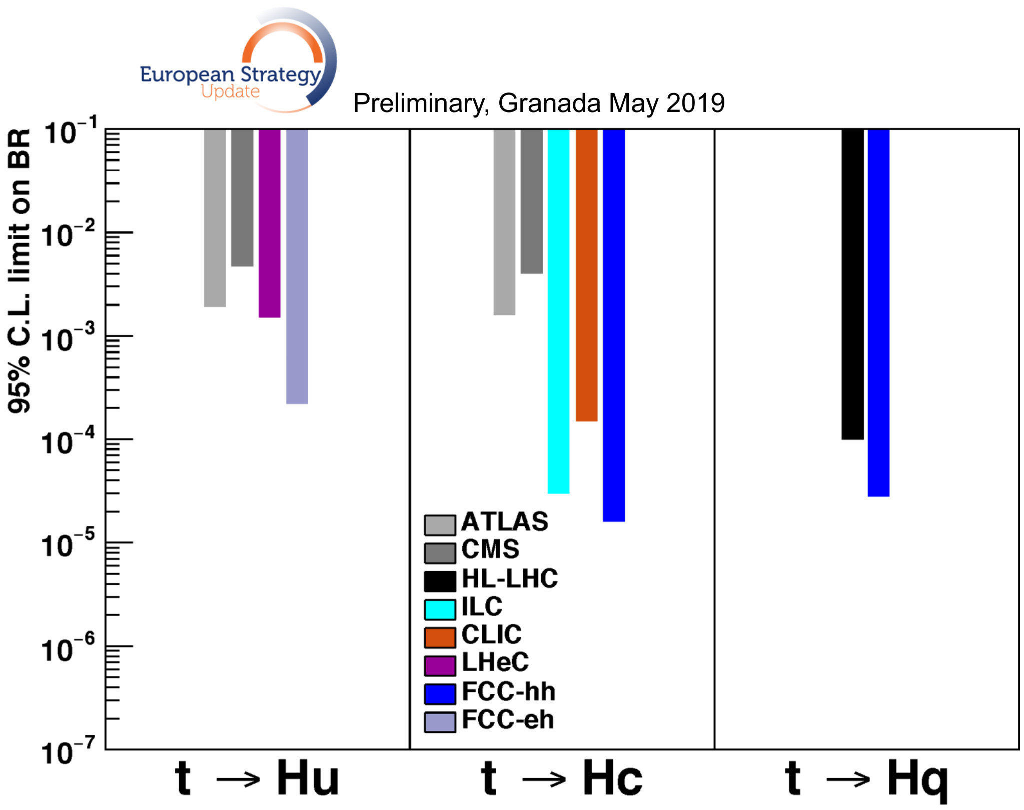
From 2013 Snowmass top WG report:

2HDM(FV): 2HDM with flavour violating Yukawa couplings

2HDM(FC): 2HDM flavour conserving

→ Experimental precision reaches branching ratios possible in the 2HDM(FV) case

Top-quark FCNC: t→Hq branching ratios



FCC-eh and LHeC:
BR(t→Hu) from the process ep → ν_eHb; H→b$\bar{b}$

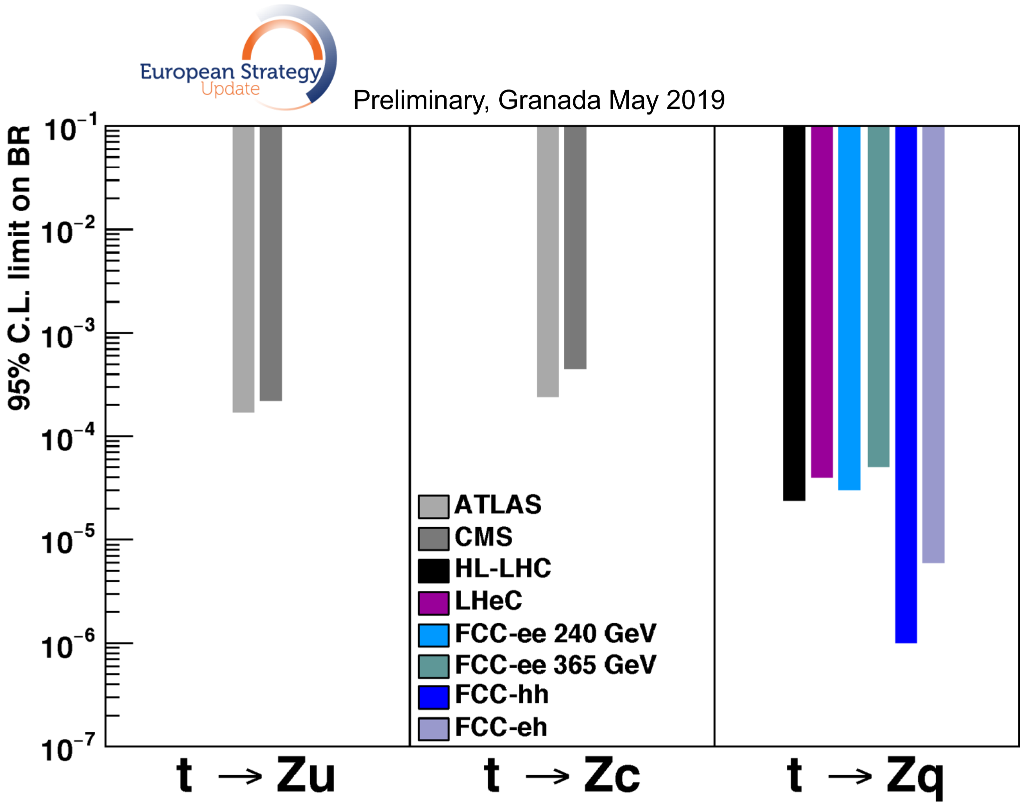
500 GeV ILC and 380 GeV CLIC:
A few million top decays near threshold, H→b$\bar{b}$ decays used, best suited for decays with charm quarks

HL-LHC:
Based on ATLAS studies using H→b$\bar{b}$ and H→γγ

FCC-hh:
Large statistics allows usage of clean H→γγ decays, combination of semi-leptonic and fully hadronic final states

HL-/HE-LHC: Sec. 8.1 of CERN-LPCC-2018-06
ILC: Sec. 10.3 of arXiv:1903.01629
CLIC: Sec. 10 of arXiv:1807.02441
LHeC: EPPSU submisson #159
FCC-ee: Phys. Lett. **B755**, 25 (2017)
FCC-hh/-eh: Sec. 6 of CERN-ACC-2018-0056

Top-quark FCNC: t→Zq branching ratios



FCC-ee:
BR(t→Zq) from anomalous single top production: $e^+e^- \rightarrow Z^*/\gamma^* \rightarrow t\bar{q}$ ($\bar{t}q$)

FCC-eh and LHeC:
BR(t→Zq) from NC DIS production of single top quarks

HL-LHC:
Based on ATLAS study for
$t\bar{t} \rightarrow bWqZ \rightarrow b\ell\nu q\ell\ell$

FCC-hh:
Estimate using HL-LHC projection

HL-/HE-LHC: Sec. 8.1 of CERN-LPCC-2018-06
ILC: Sec. 10.3 of arXiv:1903.01629
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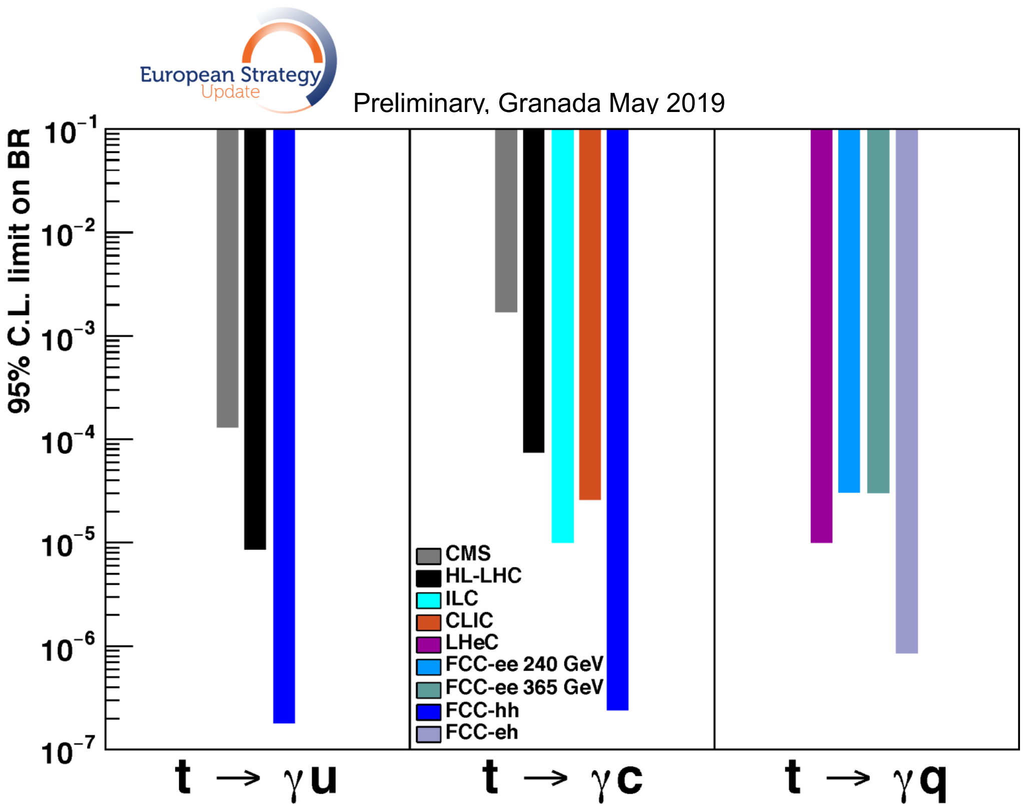
Top-quark FCNC: t→γq branching ratios



Latest ATLAS result:

Observable	Vertex	Coupling	Obs.	Exp.
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tu\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	LH	22	27^{+11}_{-7}
$\mathcal{B}(t \to q\gamma)\,[10^{-5}]$	$tc\gamma$	RH	18	28^{+12}_{-8}

arXiv:1908.08461

FCC-ee:
BR(t→γq) from anomalous single top production: $e^+e^- \to Z^*/\gamma^* \to t\bar{q}\ (\bar{t}q)$

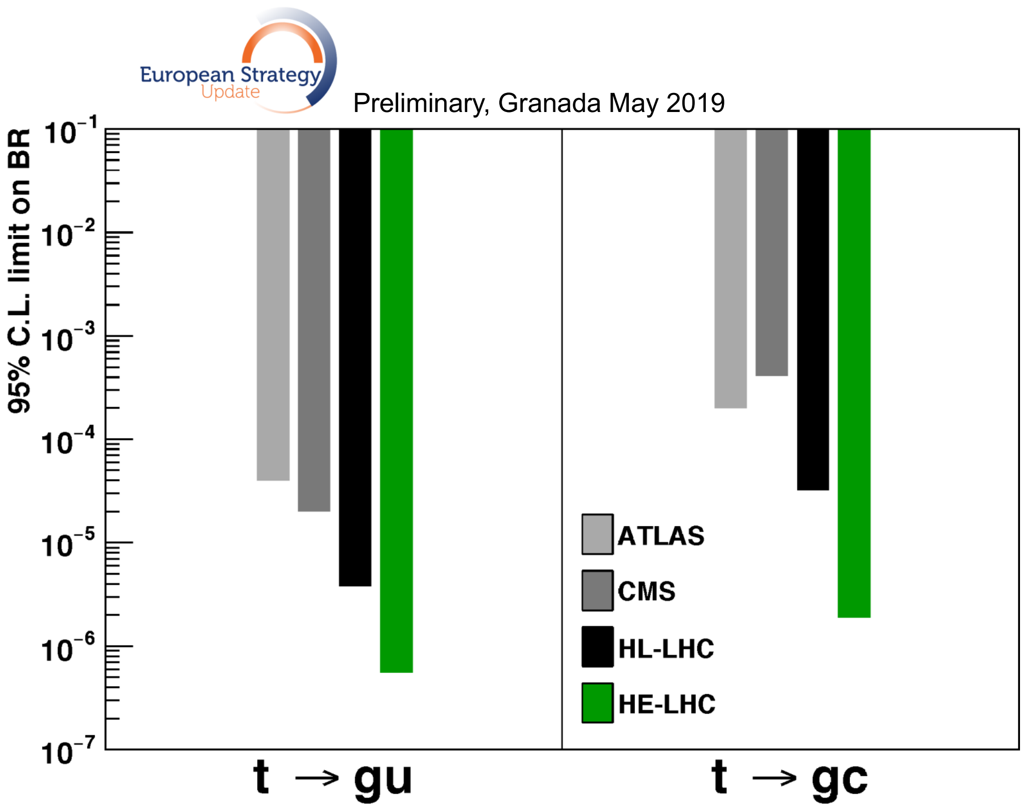
FCC-eh and LHeC:
BR(t→γq) from NC DIS production of single top quarks

500 GeV ILC and 380 GeV CLIC:
A few million top decays near threshold, $H \to b\bar{b}$ decays used, best suited for decays with charm quarks

HL-LHC:
BR(t→γu) and BR(t→γc) from CMS study of single top production in association with a photon

FCC-hh:
Delphes study focussing on the boosted top regime (p_T > 400 GeV)

Top-quark FCNC: t→gq branching ratios



HL-/HE-LHC: Sec. 8.1 of CERN-LPCC-2018-06
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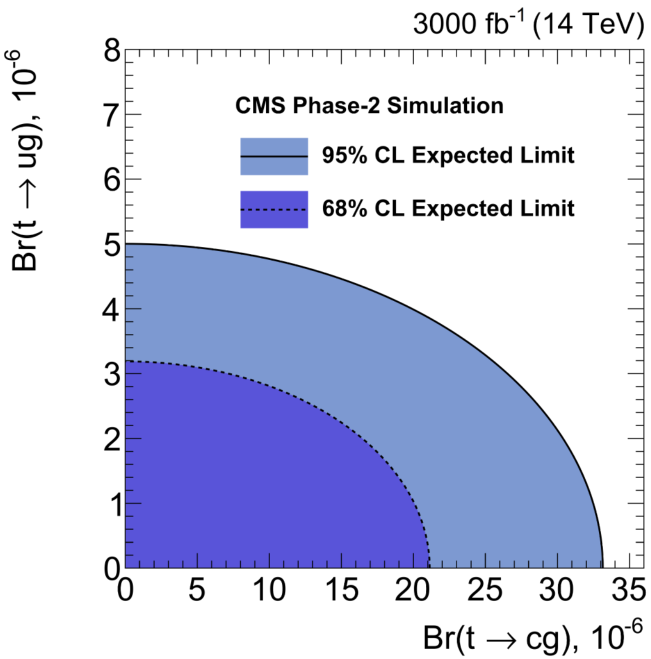
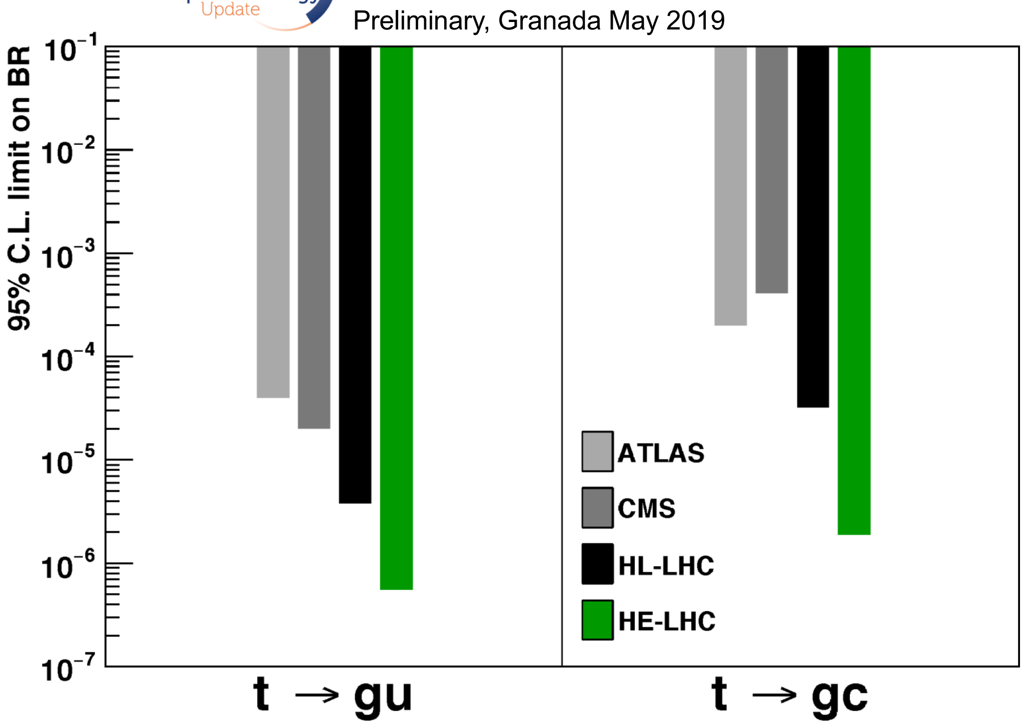
LHeC: EPPSU submisson #159
FCC-ee: Phys. Lett. **B755**, 25 (2017)
FCC-hh/-eh: Sec. 6 of CERN-ACC-2018-0056

HL-LHC:
BR(t→gu) and BR(t→gc) from CMS study of single top production

HE-LHC:
BR(t→gu) and BR(t→gc) from CMS study of single top production



Top-quark FCNC: t→gq branching ratios



HL-LHC:
BR(t→gu) and BR(t→gc) from CMS study of single top production

HE-LHC:
BR(t→gu) and BR(t→gc) from CMS study of single top production

Conclusions:

- Complementary set of possible measurements in e^+e^-, ep and pp colliders
- Not all possibilities explored yet
- Generally improvements by 1-2 orders of magnitude compared to HL-LHC possible

HL-/HE-LHC: Sec. 8.1 of CERN-LPCC-2018-06
ILC: Sec. 10.3 of arXiv:1903.01629
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FCC-hh/-eh: Sec. 6 of CERN-ACC-2018-0056

Some observations

• Substantial improvement with respect to HL-LHC possible for all discussed physics topics

• Large amount of complementarity to be explored: direct and indirect sensitivity, hadron and lepton collisions, different energy stages of a lepton collider

• Lots of opportunities for additional studies, especially direct sensitivity in highest-energy lepton and hadron collisions not well covered

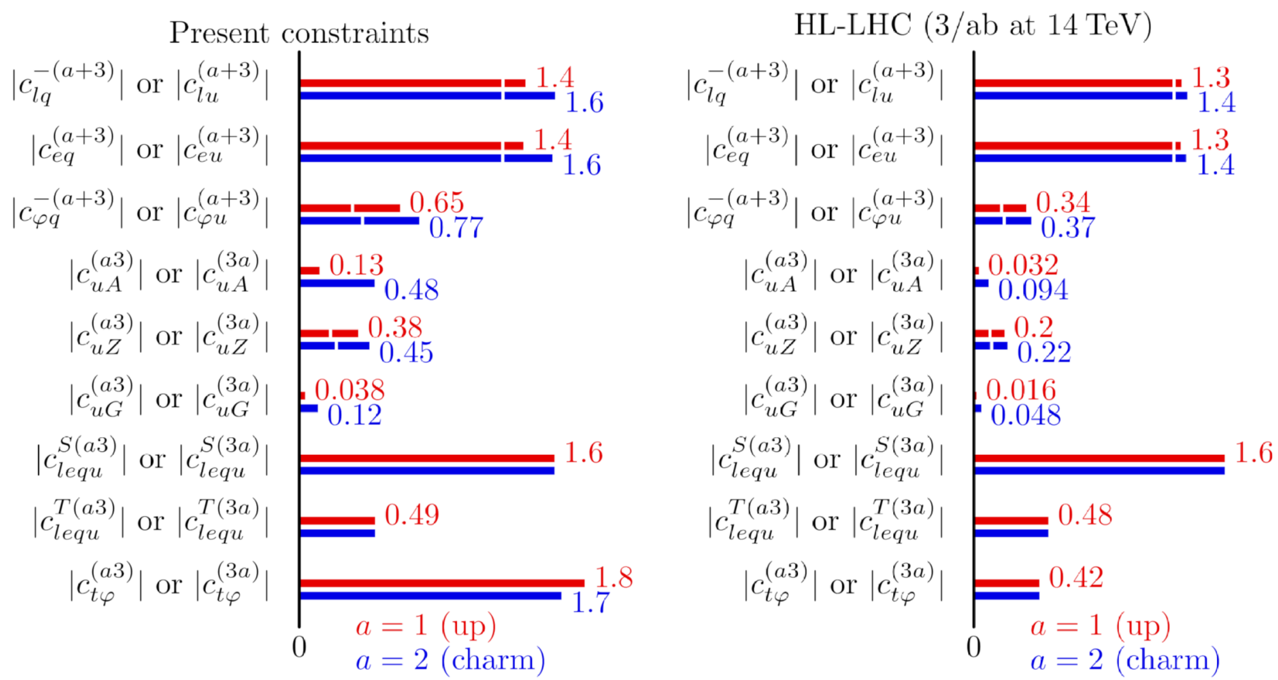
Thank you!

Backup slides

Top-quark FCNC: EFT for HL-LHC

Sensitivity to top-quark FCNC effects can be studied using EFT

Input: limits on FCNC branching ratios, limits on $e^+e^- \rightarrow tj$ from LEP II



<u>White marks:</u> individual limits

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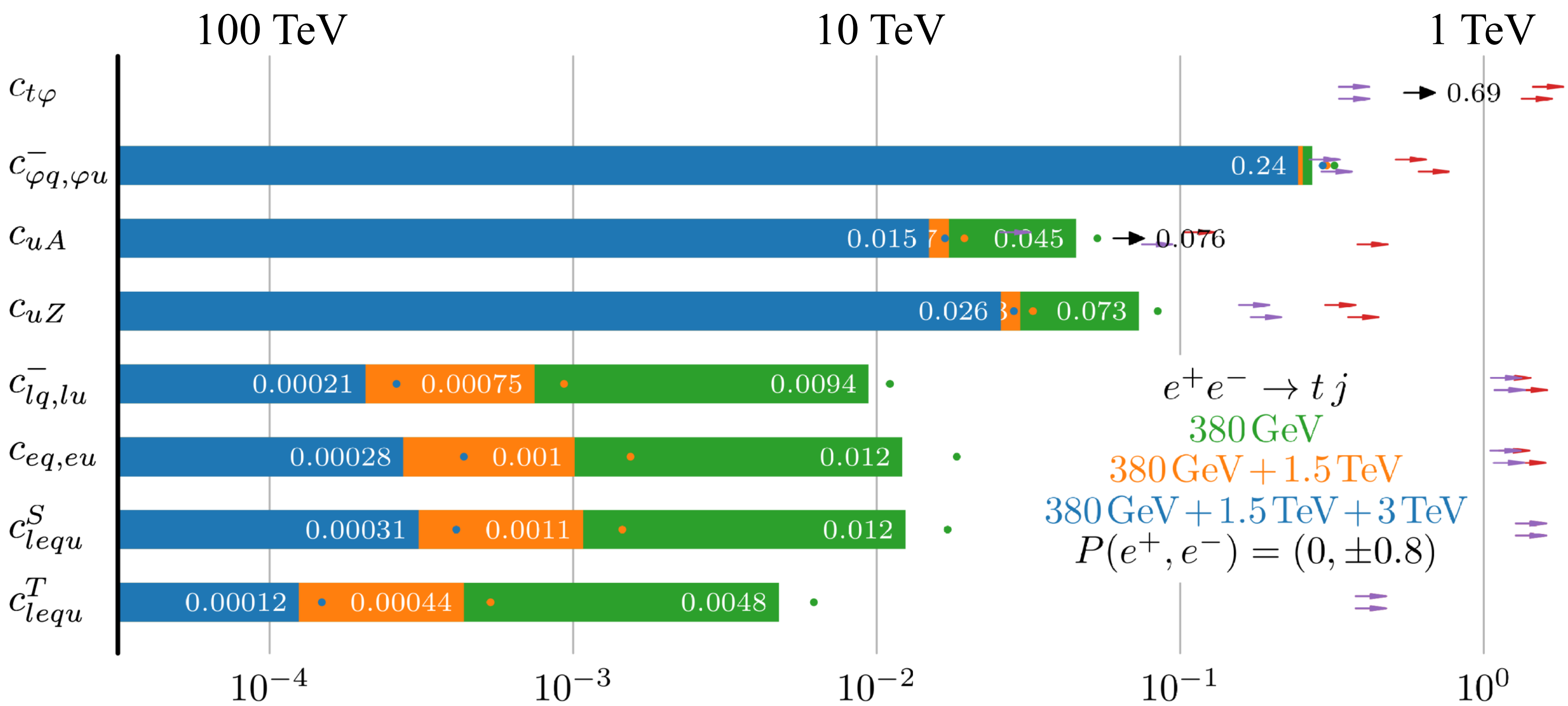
Top-quark FCNC: $e^+e^- \rightarrow tj$ at CLIC



95% C.L. limits on top-quark FCNC operator coefficients

Black arrows: decays at CLIC (see slide X)
Red arrows: current LHC
Magenta arrows: HL-LHC projections
Dots: CLIC without beam polarisation

- The high-energy runs significantly improve the sensitivity for "four-fermion" operators
- $e^+e^- \rightarrow tj$ much more powerful than the decays at high-energy lepton colliders

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Lepton colliders

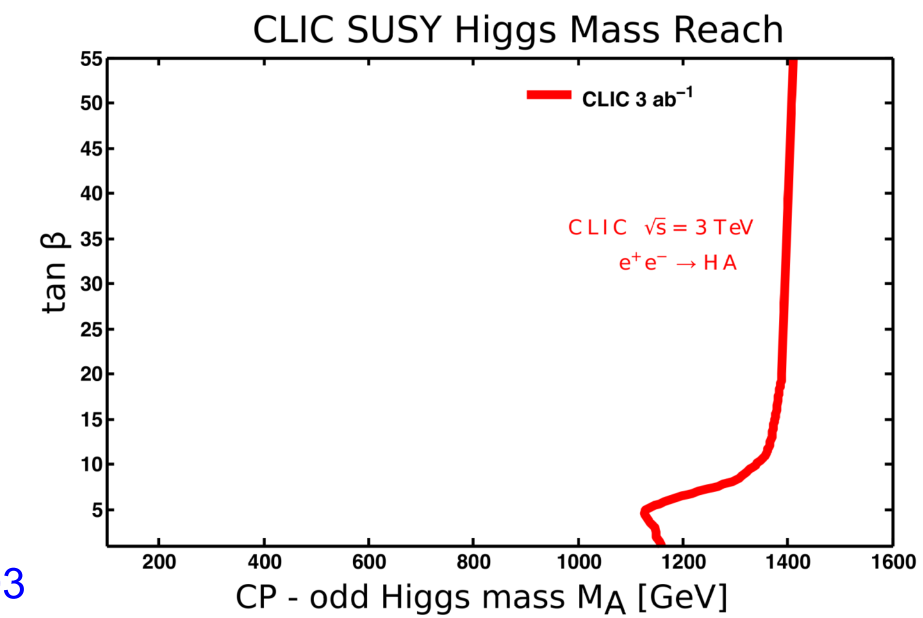
- Generally, mass reach close to $\sqrt{s}$ / 2 for all values of tan β

- Beam polarisation and threshold scans might help to constrain the underlying theory

- **Example:** $e^+e^- \rightarrow HA$ at 3 TeV CLIC

- Combination of the $b\bar{b}b\bar{b}$, $b\bar{b}t\bar{t}$ and $t\bar{t}t\bar{t}$ final states

- Similar reach for $e^+e^- \rightarrow H^+H^-$



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