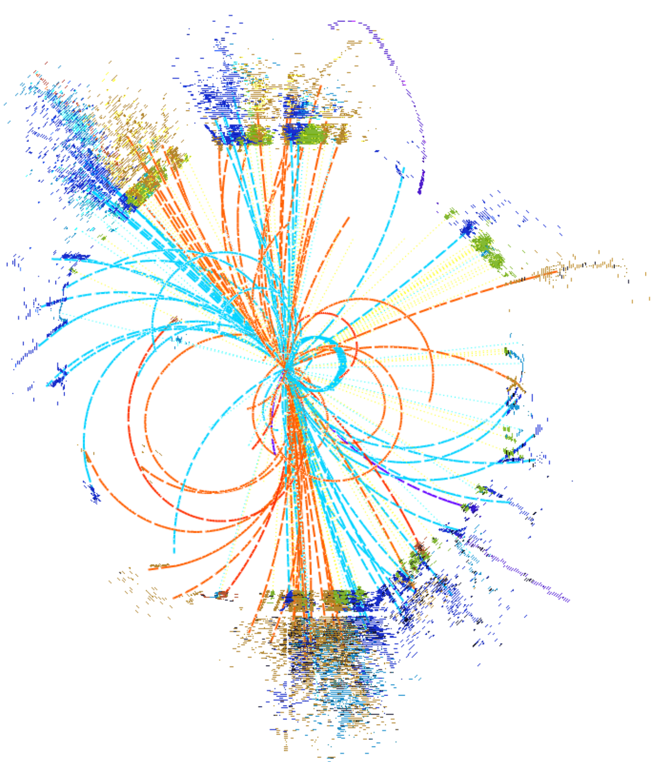
Extended Higgs sectors and high-energy flavour dynamics: what we can expect from experiments

Philipp Roloff (CERN)
14/05/2019
Granada Conference Center



CERN Council Open Symposium on the Update of

European Strategy for Particle Physics

13-16 May 2019 - Granada, Spain

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Topics of this presentation

This talk: prospects of future collider facilities in the following areas

Extended Higgs sectors:

• Standard Model + real scalar singlet: can lead to a strong 1^{st} order EW phase transition
• Two-Higgs doublet models: heavy MSSM Higgs bosons as example
• Doubly-charged Higg bosons: exist in type-II seesaw models
→ connection to neutrino masses

High-energy flavour dynamics:

• FCNC effects in top-quarks physics: decays and EFT analysis of high-energy processes
• Leptoquarks: renewed interest triggered by flavour anomalies

→ see the next talk by Veronica Sanz for the theoretical context

A few caveats

- The topics listed on the previous slide were chosen to well represent the input provided to the 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})

- Invisible and exotic Higgs decays (e.g. to new scalars), flavour physics at the Z pole covered in other presentations

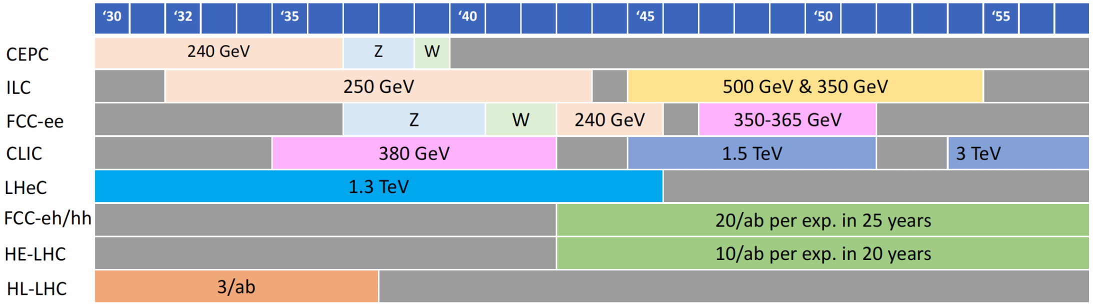
Reminder: collider parameters

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

pp colliders

e^+e^- colliders

ep colliders



arXiv:1905.03764

Standard Model + real scalar singlet

Potential for SM Higgs and a single real scalar:

$$V_0 = -\mu^2 |H|^2 + \lambda |H|^4 - \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4 + \lambda_{HS} |H|^2 S^2$$

Higgs-singlet mixing:

$h = h_0 \cos\gamma + S \sin\gamma$

$\phi = S \cos\gamma - h_0 \sin\gamma$

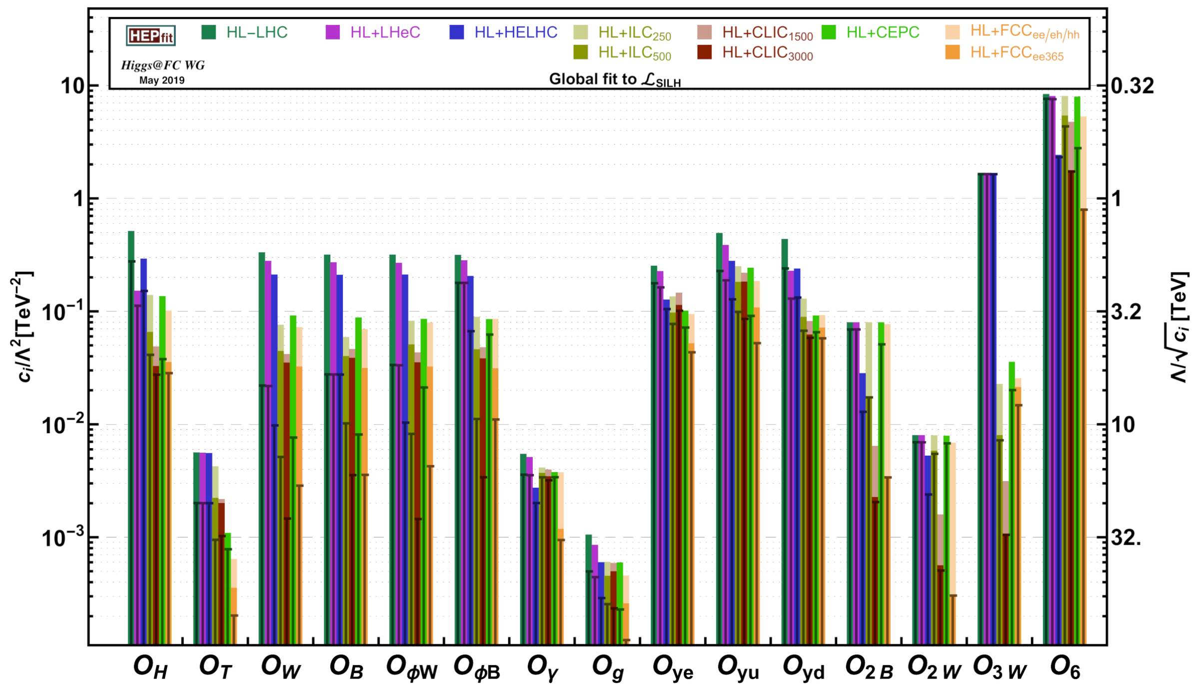
Equivalence theorem:

BR($\phi \to hh$) = BR($\phi \to ZZ$) = 25%

Indirect sensitivity:

EFT fit by ECFA WG on Higgs at future colliders

arXiv:1905.03764



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Equivalence theorem:

$BR(\phi \rightarrow hh) = BR(\phi \rightarrow ZZ) = 25\%$

Sensitivity from Higgs couplings:

c_H is overall scaling of the Higgs couplings (using sensitivity for this individual operator) →

Facility	95% C.L. lumit on $\sin^2\gamma$
HL-LHC	0.034
LHeC	0.013
HE-LHC	0.018
ILC 250 GeV	0.0073
ILC 500 GeV	0.0050
CLIC 380 GeV	0.0093
CLIC 1.5 TeV	0.0048
CLIC 3 TeV	0.0033
CEPC	0.0046
FCC-ee 240 GeV	0.0053
FCC-ee	0.0046
FCC-ee/-eh/-hh	0.0034

Sensitivity from EW precision observables:

S and T parameters derived from from $c_{\phi WB}$ and c_T (simultaneous fit of both operators)

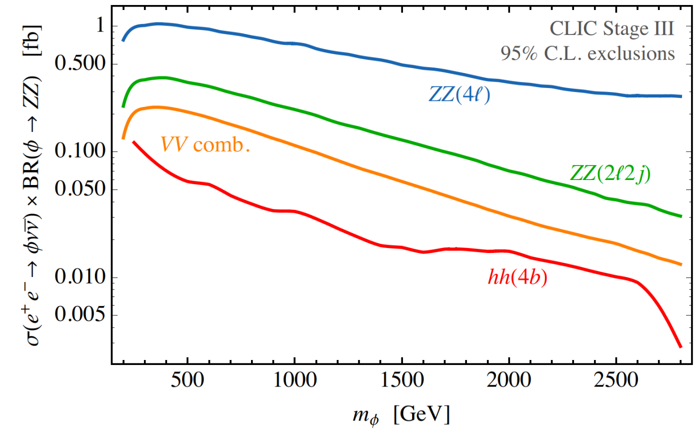
SM + singlet: direct searches

<u>Lepton colliders:</u>

- CLIC study of $e^+e^- \rightarrow \nu\bar{\nu}\phi$ (Delphes) at 1.5 and 3 TeV: $\phi \rightarrow hh \rightarrow b\bar{b}b\bar{b}$ most powerful channel

- $\mu^+\mu^- \rightarrow \nu\bar{\nu}\phi$; $\phi \rightarrow hh$ studied on generator level for 5 ab^{-1} at $\sqrt{s}$ = 6 and 20 ab^{-1} at 14 TeV (also valid for an e^+e^- collider based on novel accelerator techniques)

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



<u>Hadron colliders:</u>

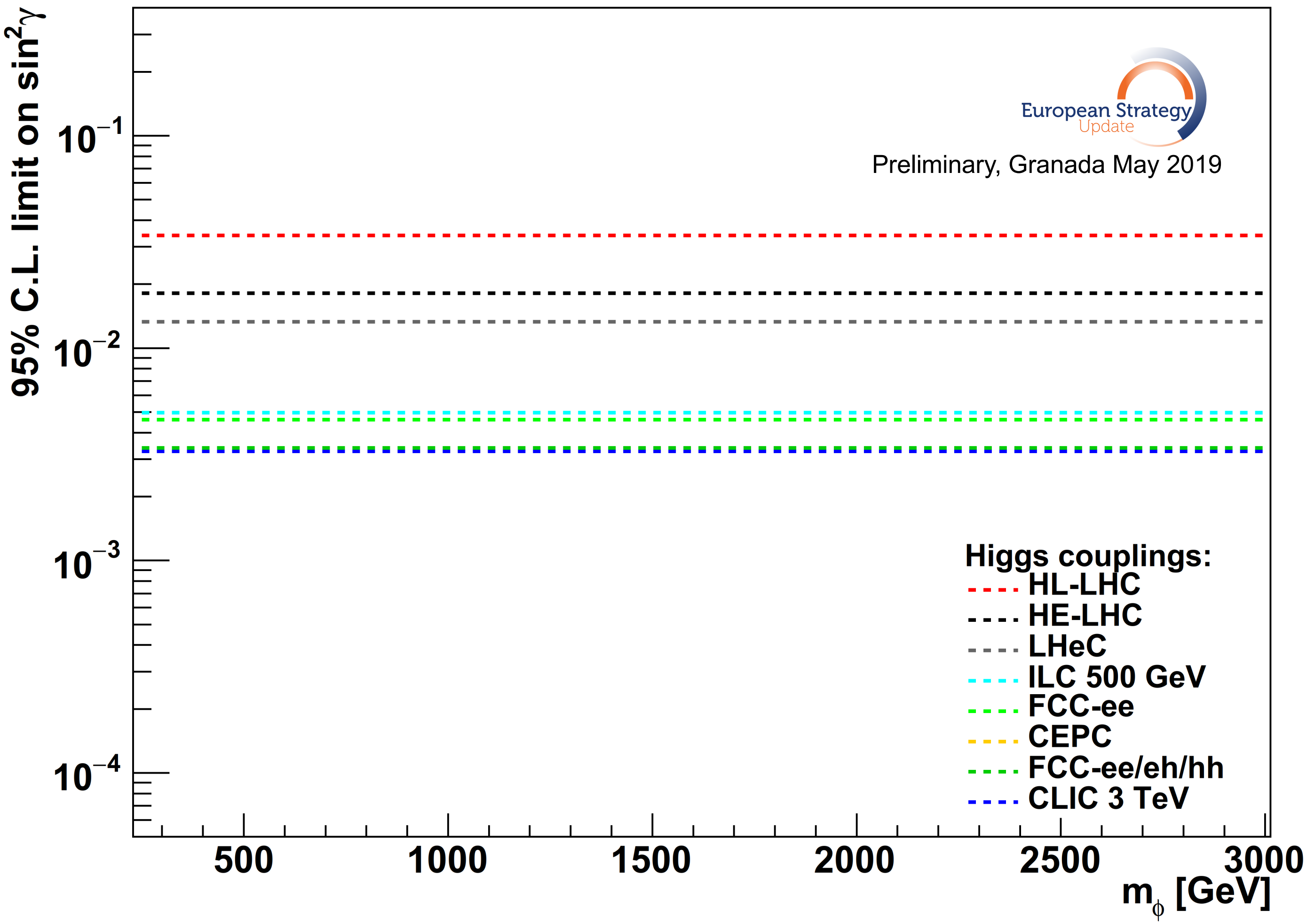
- Current LHC sensitivity dominated by $\phi \rightarrow ZZ$ search (36 ab^{-1} at 13 TeV)

JHEP 06, 127 (2018)

- Extrapolation using quark parton luminosities to HL-LHC (3 ab^{-1} at 14 TeV), HE-LHC (15 ab^{-1} at 27 TeV), FCC-hh (30 ab^{-1} at 100 TeV)

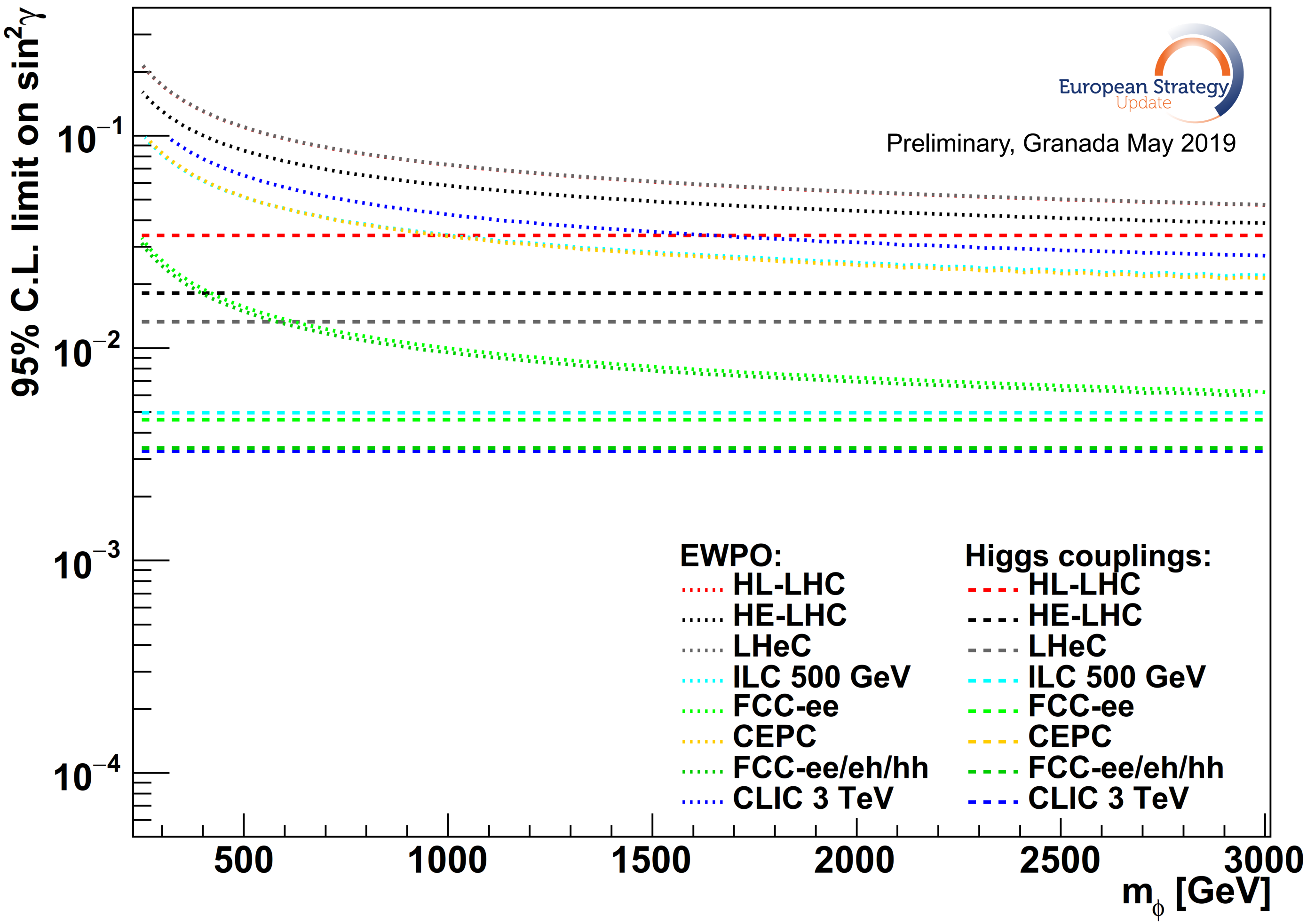
Sec. 6.1.4 of CERN-LPCC-2018-005
JHEP 11,144 (2018)

SM + singlet: precision Higgs



• e^+e^- colliders provide significant improvement compared to hadron colliders
NB: The lines for FCC-ee and CEPC are identical

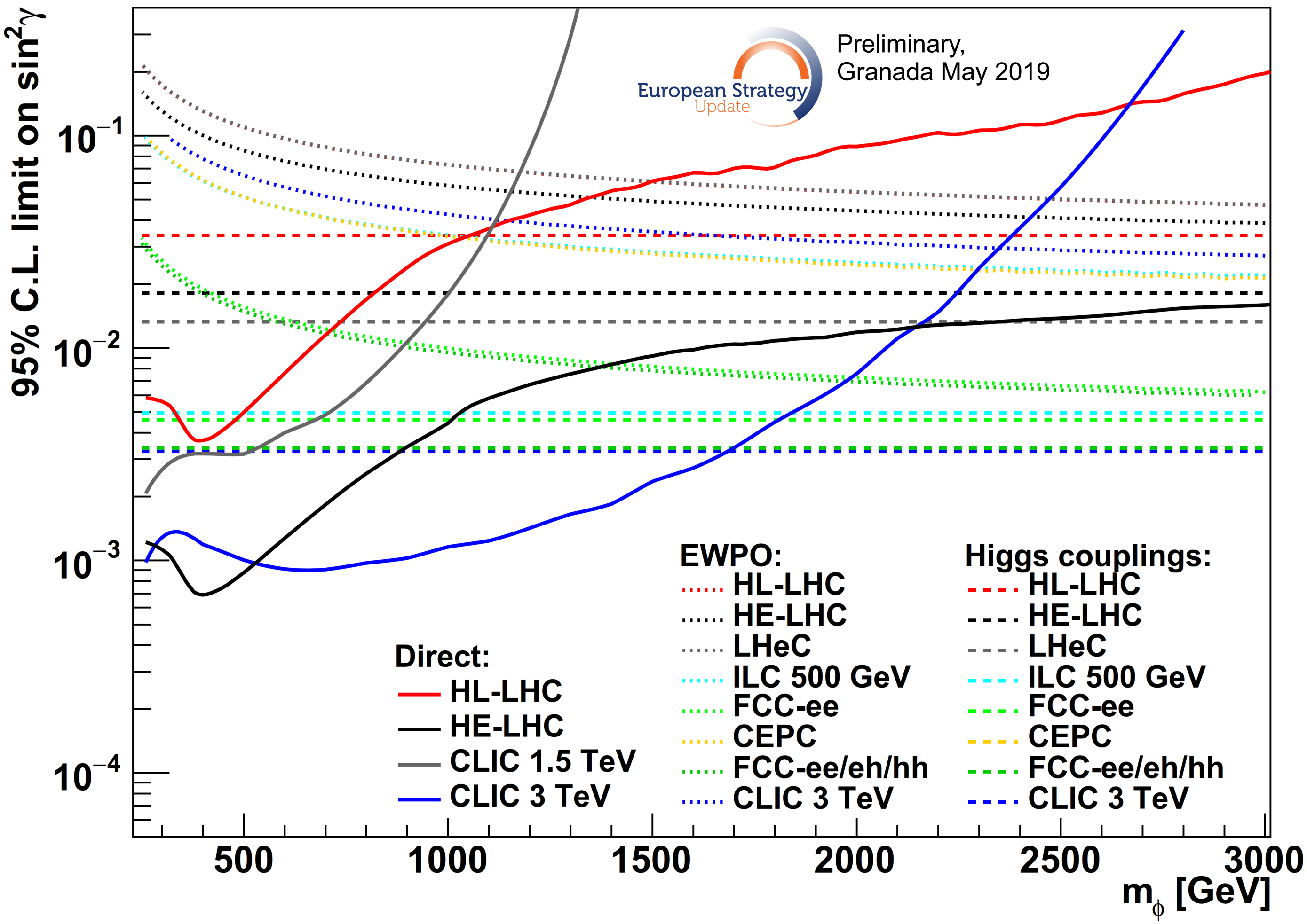
SM + singlet: S and T



- Higgs couplings are better than S and T for all collider options

NB: The EPWO curves for HL-LHC and LHeC are identical

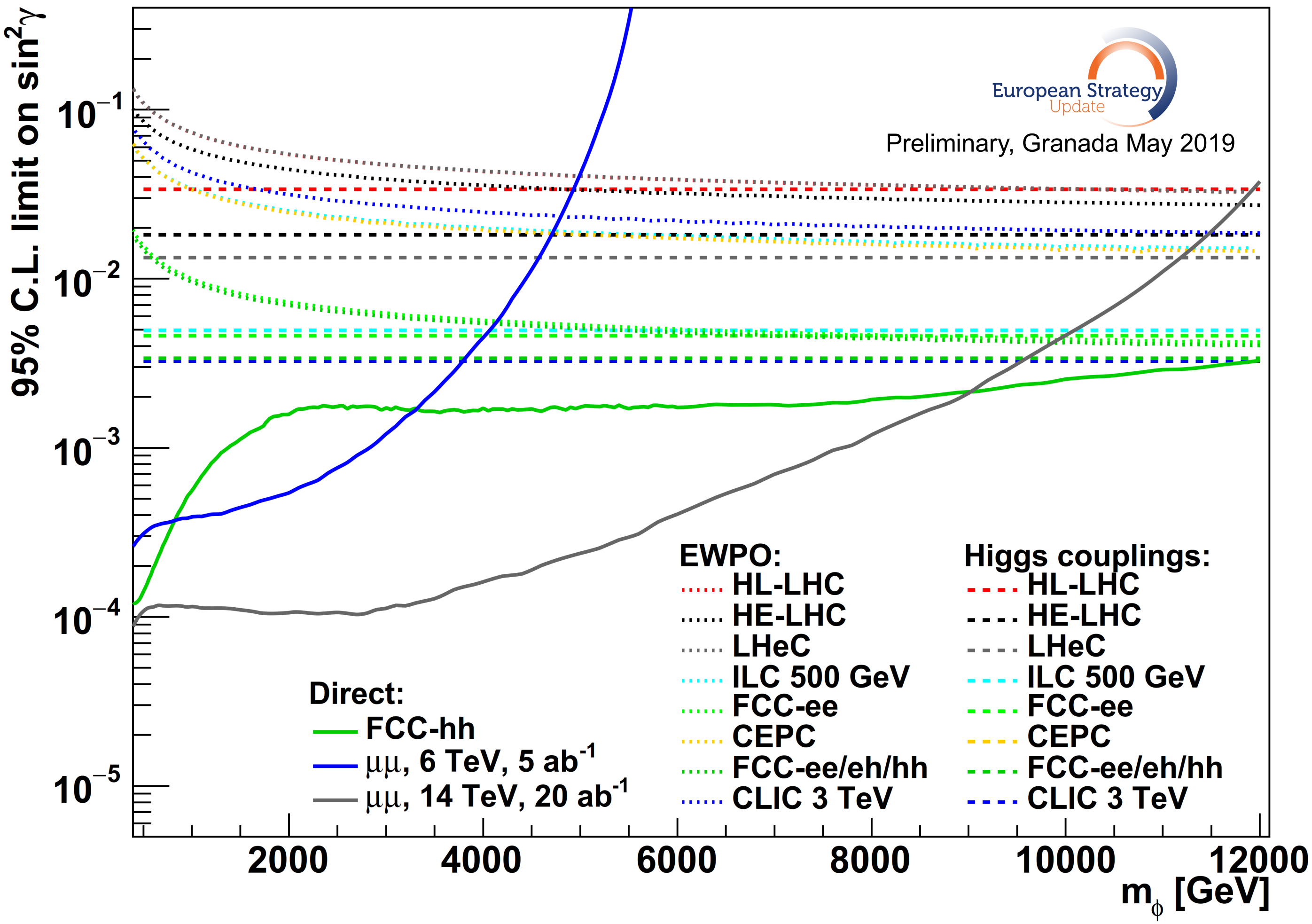
SM + singlet: direct



- At HL-LHC, HE-LHC and CLIC direct and indirect searches provide complementary information

NB: FCC-hh and the muon colldier will follow on the next slide

SM + singlet: high-mass region



- Direct reach at FCC-hh better than precision Higgs couplings below 12 TeV

No mixing limit

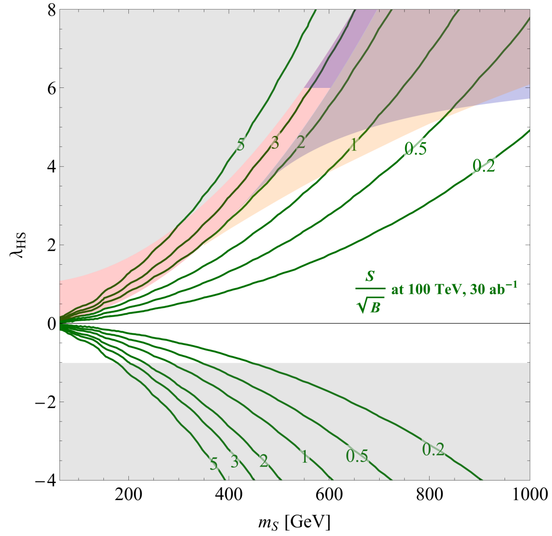
Potential for SM Higgs and a single real scalar:

$$V_0 = -\mu^2 |H|^2 + \lambda |H|^4 - \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4 + \lambda_{HS} |H|^2 S^2$$

Unbroken Z_2 symmetry:
no Higgs-singlet mixing → new scalar escapes undetected

Sensitivity from Higgs couplings: limit on λ_{HS} from c_H

JHEP 11, 127 (2014)
Sec. 11 of CERN-ACC-2018-0056

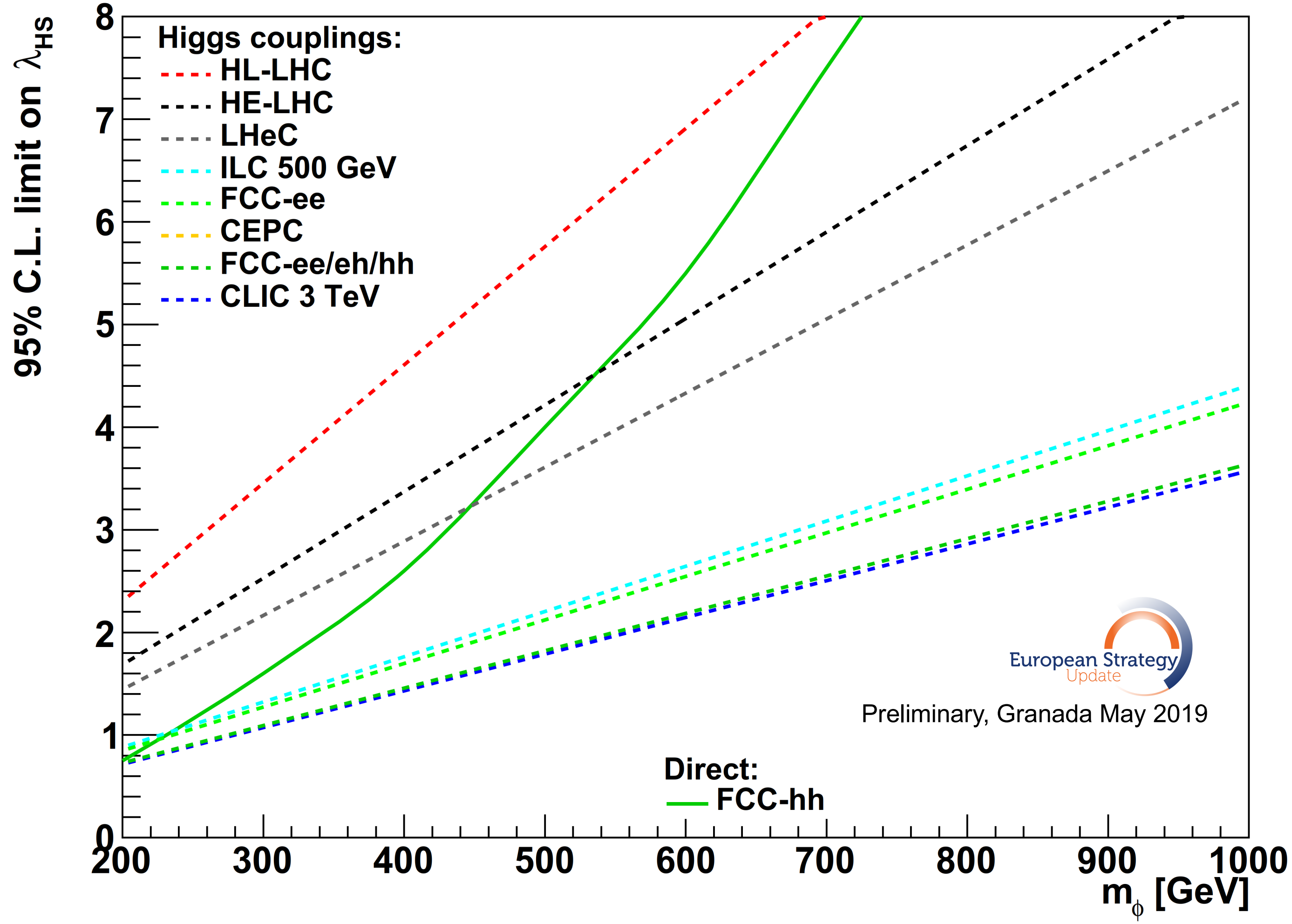


Direct sensitivity:

Hadron colliders:
FCC-hh study of pp → ϕϕjj using VBF jets (Delphes)

Lepton colliders:
No projection for $e^+e^- \to \phi\phi e^+e^-$ or $\mu^+\mu^- \to \phi\phi\mu^+\mu^-$ avaiable yet

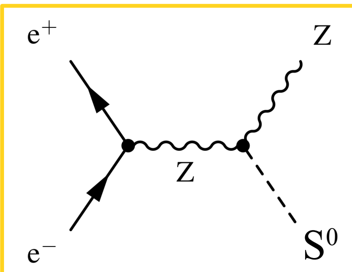
No mixing: direct vs. indirect



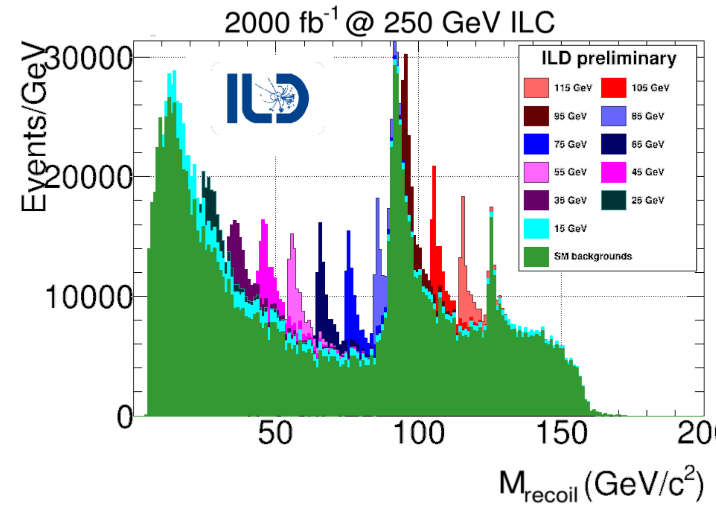
NB: The lines for FCC-ee and CEPC are identical

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:



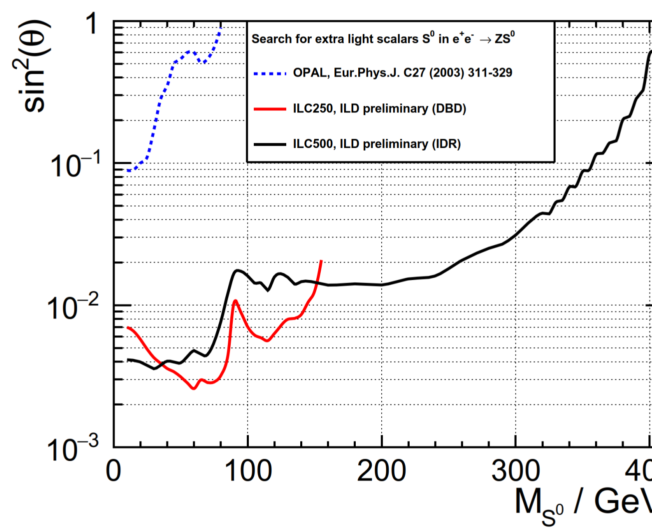
$$M^2_{recoil} = (\sqrt{s} - E_Z)^2 - |\vec{p}_Z|^2$$



→ independent of new scalar decay

- Studied for ILC at 250 and 500 GeV, but also possible at CEPC, FCC-ee and 380 GeV CLIC

- 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:1903.01629

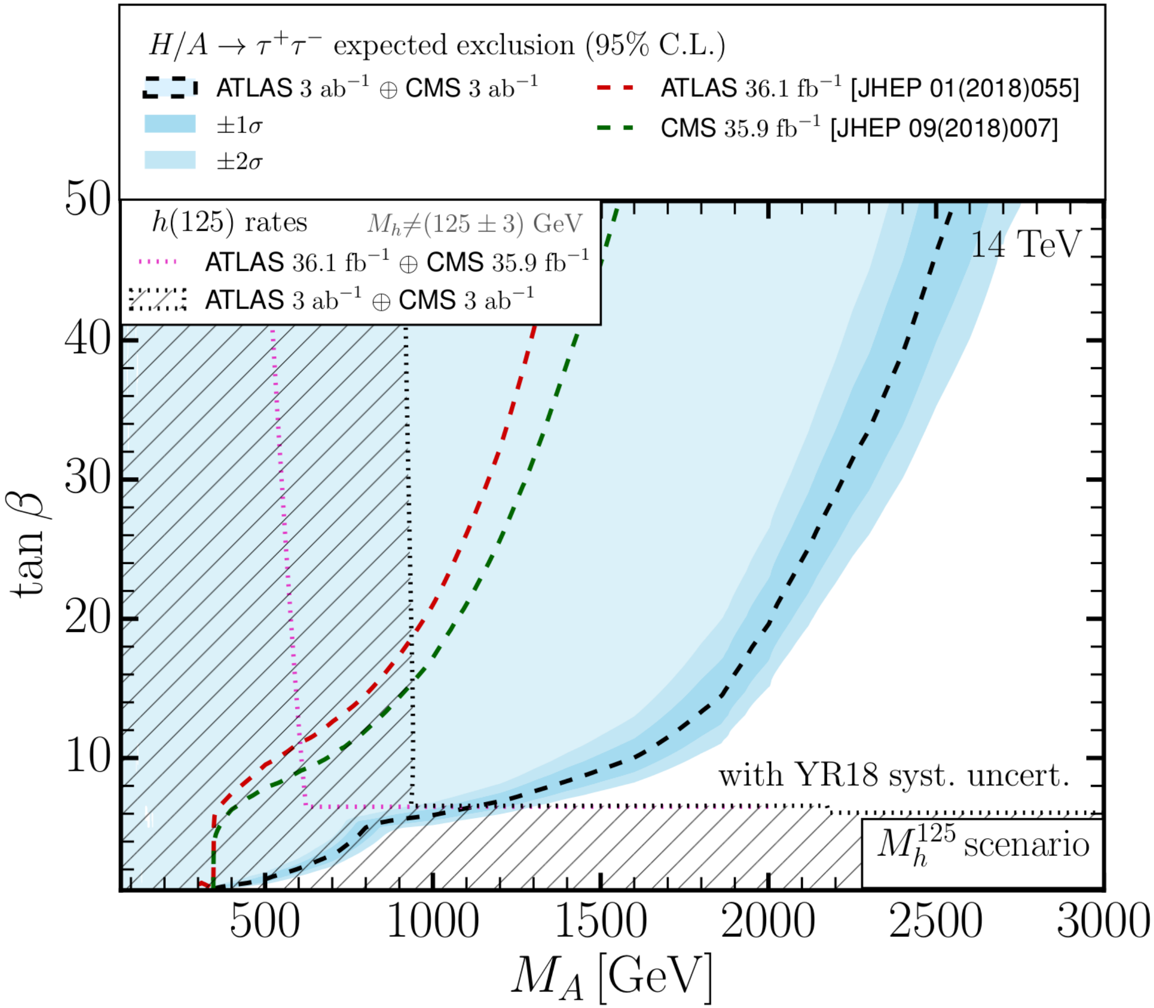
Heavy MSSM Higgs bosons

Lepton colliders: mass reach generally close to $\sqrt{s}$ / 2 independent on tan β, e.g. using $e^+e^- \to H^+H^-$ or $e^+e^- \to AH$

Hadron colliders: access to the highest possible masses, benchmarks discussed in the following:

- $A/H \to \tau^+\tau^-$ at HL-LHC
- $pp \to A \to ZH$ at HL-/HE-LHC
- MSSM Higgs bosons at FCC-hh

A/H → $\tau^+\tau^-$ at HL-LHC



Sec. 9.5 of CERN-LPCC-2018-04

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

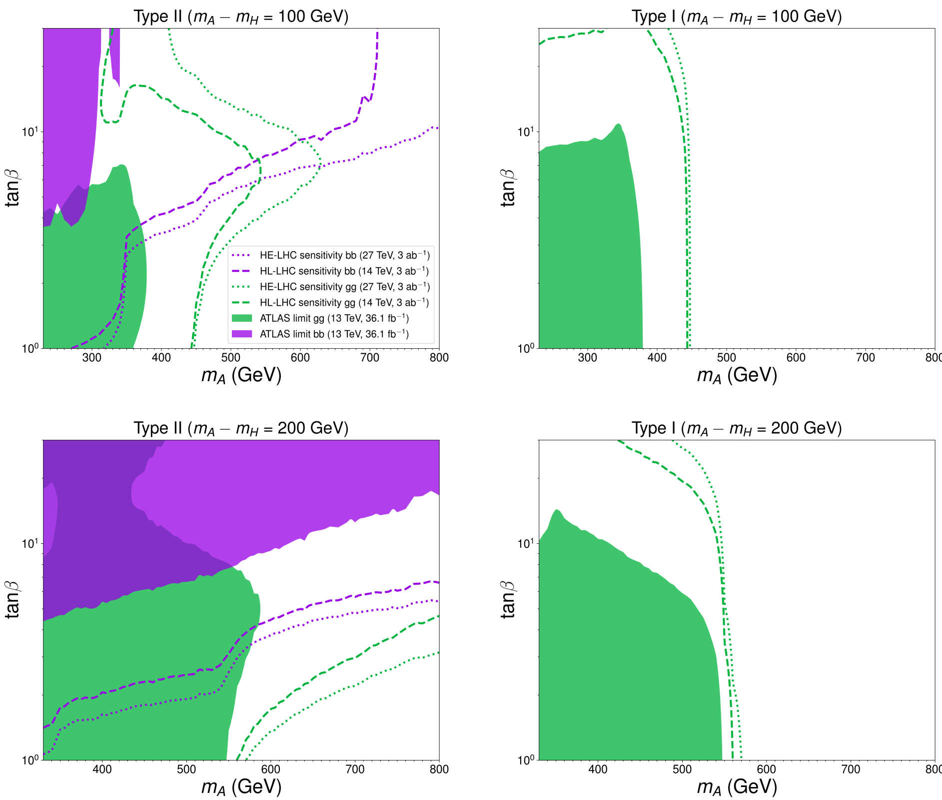
- Direct access to heavy Higgs bosons of 2.5 TeV for tan β > 50

- Region of low tan β could be improved by A/H → $t\bar{t}$

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)

Higgs-to-Higgs decays 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)

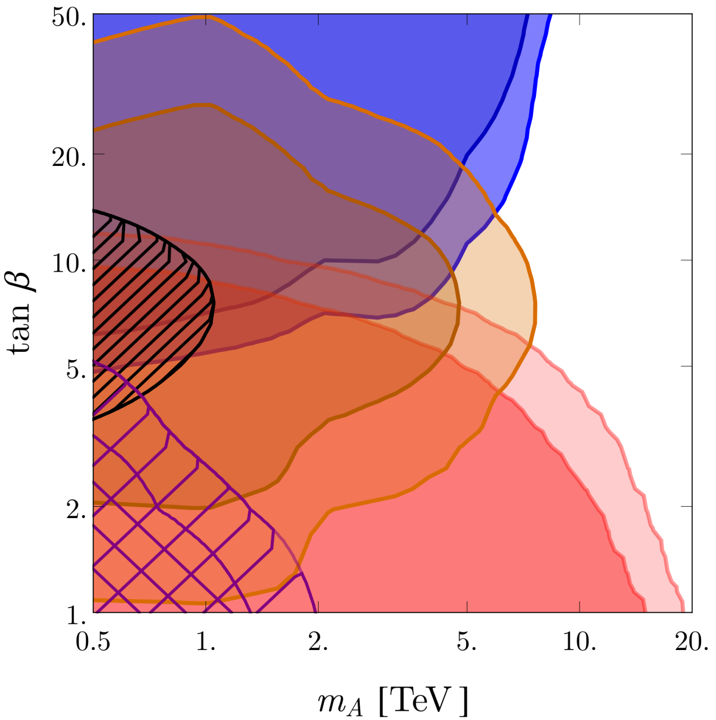
For Type-II 2HDM the region of low β and and large m_H could be covered by:

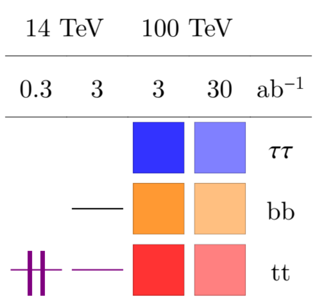
$A \to ZH$; $Z \to \ell^+\ell^-$; $H \to t\bar{t}$

- 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})

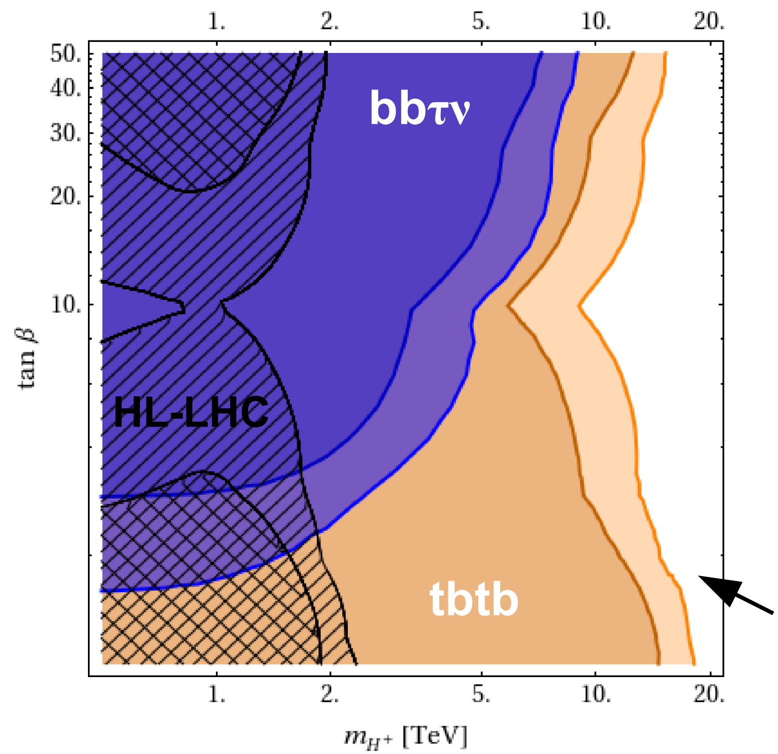
MSSM Higgs bosons at FCC-hh

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





pp → btH± → bbτν
pp → btH± → tbtb



95% C.L. exclusion limits

- 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⁺

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

Doubly-charged Higgs bosons

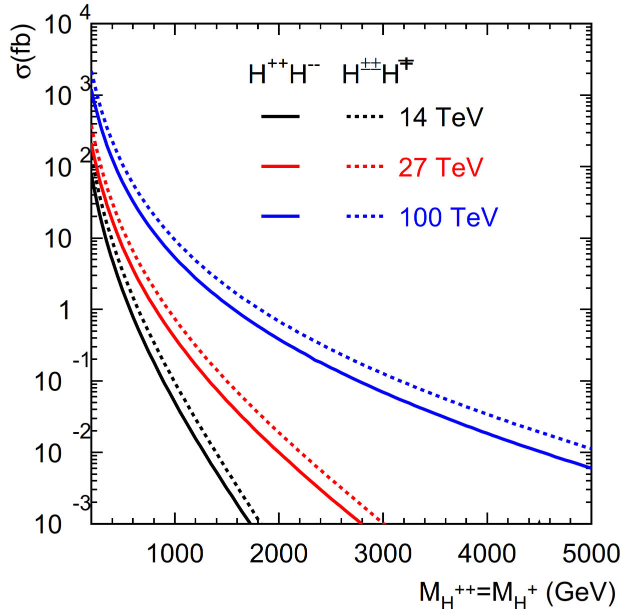
- Type II seesaw: hadron colliders
- Type II seesaw: lepton colliders

Type II seesaw: hadron colliders

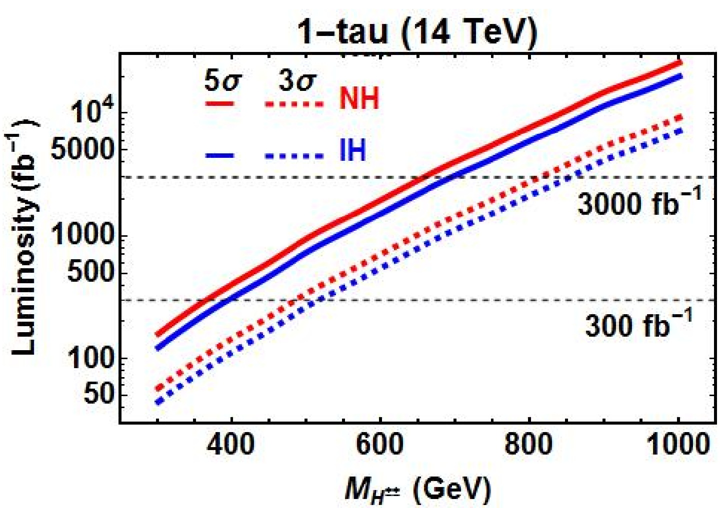
- Type II seesaw: new scalar triplet couples to SM leptons to produce the light neutrino masses (no sterile neutrinos)

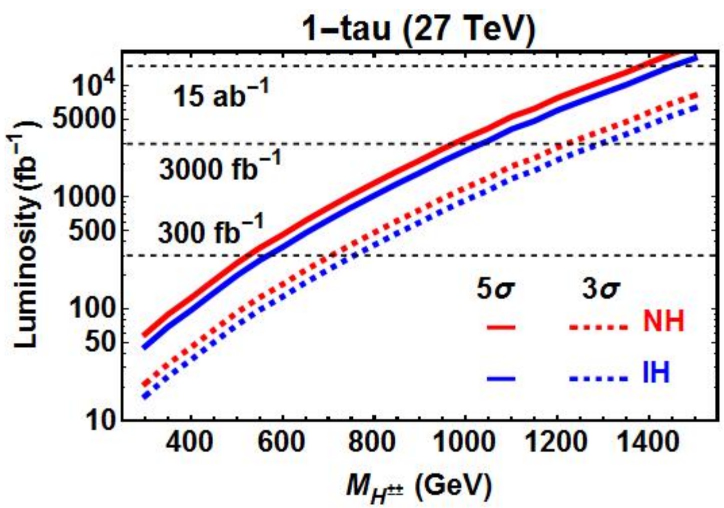
- Doubly charged Higgs production in hadron collisions:
$pp \rightarrow Z^*/\gamma^* \rightarrow H^{++}H^{--}$ and $pp \rightarrow W^* \rightarrow H^{++/--}H^{-/+}$

- **Benchmark:** $H^{++}H^{--} \rightarrow \tau_h \ell^{+/-}\ell^{-/+}\ell^{-/+}$; $\tau^\pm \rightarrow \pi^\pm \nu$
→ tau polarisation can help to discriminate between different heavy scalar mediated neutrino mass mechanisms



JHEP **09**, 079 (2018)
Sec. 5.1 of CERN-LPCC-2018-005





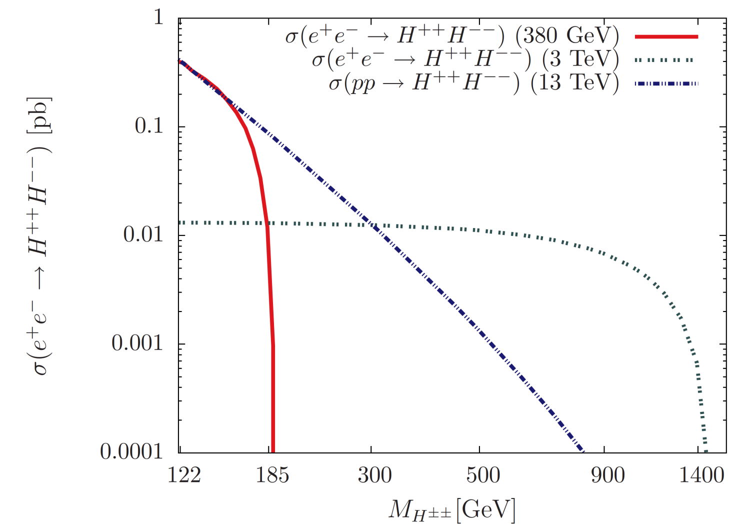
$M(H^{\pm\pm}) > 1930$ GeV / 2070 GeV for NH / IH using 3 ab^{-1} at 100 TeV (3 sigma)

Type II seesaw: lepton colliders

- Pair production cross section almost flat up to the kinematic limit: $e^+e^- \to H^{++}H^{--}$

Benchmark: triplet vev $v_\Delta = 10^{-2}$ GeV
→ BR($H^{++} \to W^+W^+$) = 100%
(cross section in VBF at LHC very small)

- CLIC study for 380 GeV and 3 TeV (Delphes) shows sensitivity almost up to the kinematic limit
(also expected for other e^+e^- colliders)

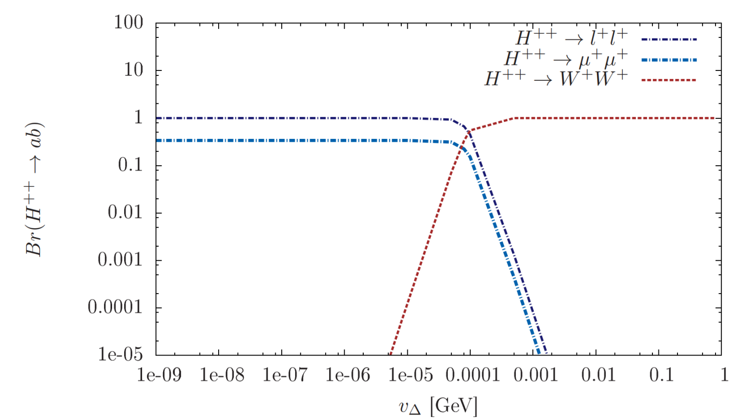


$\sqrt{s}$ = 380 GeV:

$e^+e^- \to H^{++}H^{--} \to N_j \geq 7j$		
Mass (GeV)	n_s	$\mathcal{L}$ (fb^{-1})
121	1.54	1054.14
137	4.48	124.56
159	10.48	22.76
172	10.15	24.26
184	2.69	345.48

$\sqrt{s}$ = 3 TeV:

$e^+e^- \to H^{++}H^{--} \to W^+W^+W^-W^- \to Nj_{\text{fat}}$		
Masses (GeV)	n_s (2, 3-tagged $\mathcal{L} = 500$ fb^{-1})	$\mathcal{L}$(fb^{-1})(with 2,3-tagged)
800	17.96(2-tag)	38.75
1000	13.95(2-tag)	64.23
1120	11.49(2-tag)	94.68
1350	5.48(3-tag)	416.24
1400	3.95(3-tag)	801.15



→ Luminosity for 5σ discovery smaller than expectation at CLIC

NB: $M(H^{++}) < M(H^+)$

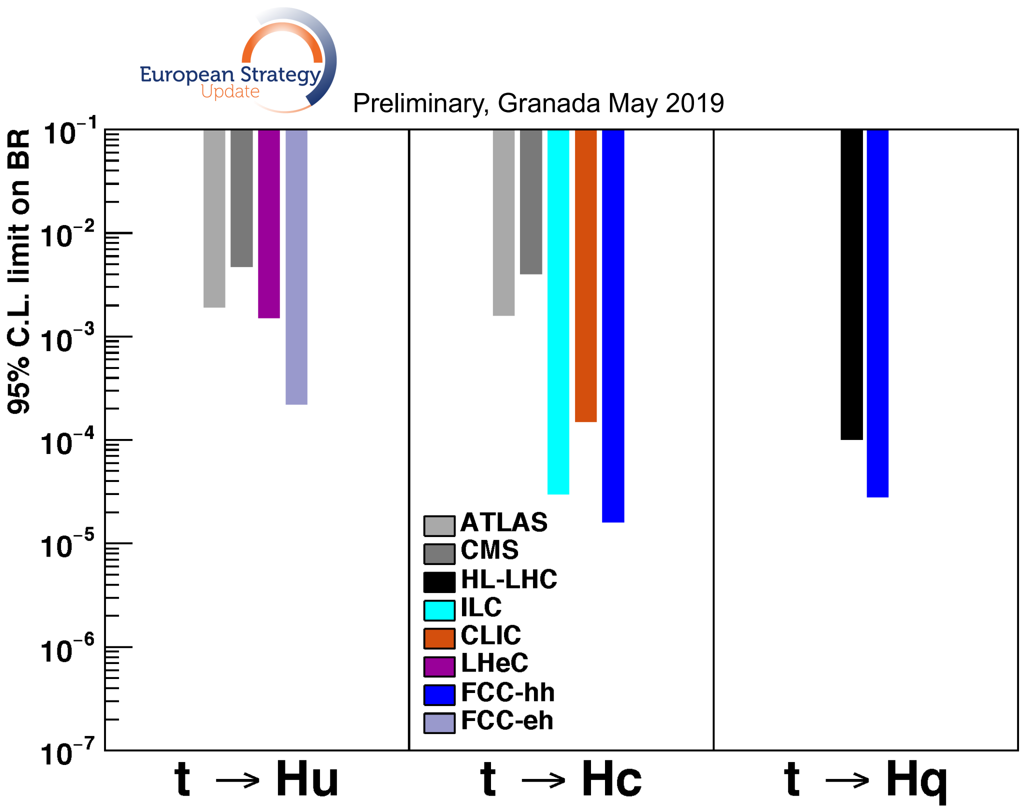
NB: FCC-hh would be sensitive to $H^{++}H^{--} \to W^+W^+W^-W^-$ below ≈1.7 TeV for $v_\Delta > 10^{-4}$ GeV JHEP 01, 101 (2019)

Phys. Rev. **D 98**, 015024 (2018)
Sec. 7.1 of CERN-2018-009-M

High-energy flavour dynamics

- Top-quark FCNC: branching ratios
- Top-quark FCNC: Effective Field Theory
- Leptoquarks

Top-quark FCNC: t→Hq branching ratios



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

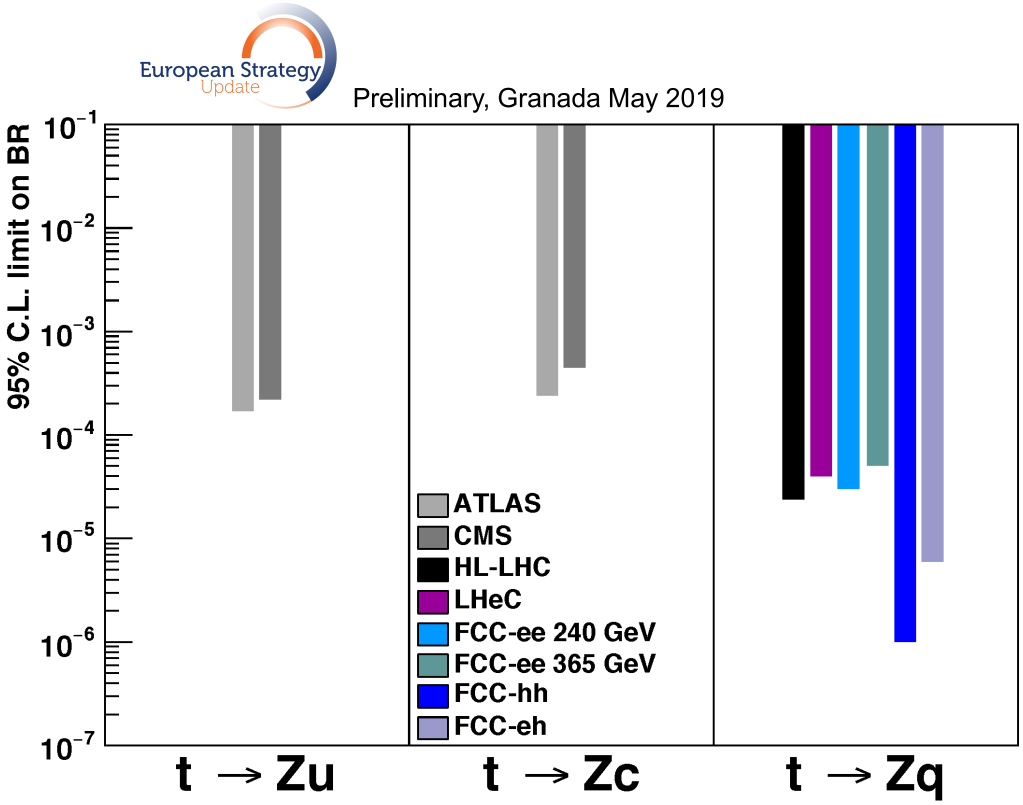
500 GeV ILC and 380 GeV CLIC:
A few million top decays near threshold, H→b$\bar{b}$ decays used, best suited for decays with charm quarks

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: $e^+e^- \rightarrow Z^*/\gamma^* \rightarrow t\bar{q}\ (\bar{t}q)$
→ further improvement from combination of both energy stages possible

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
CLIC: Sec. 10 of arXiv:1807.02441
LHeC: EPPSU submisson #159
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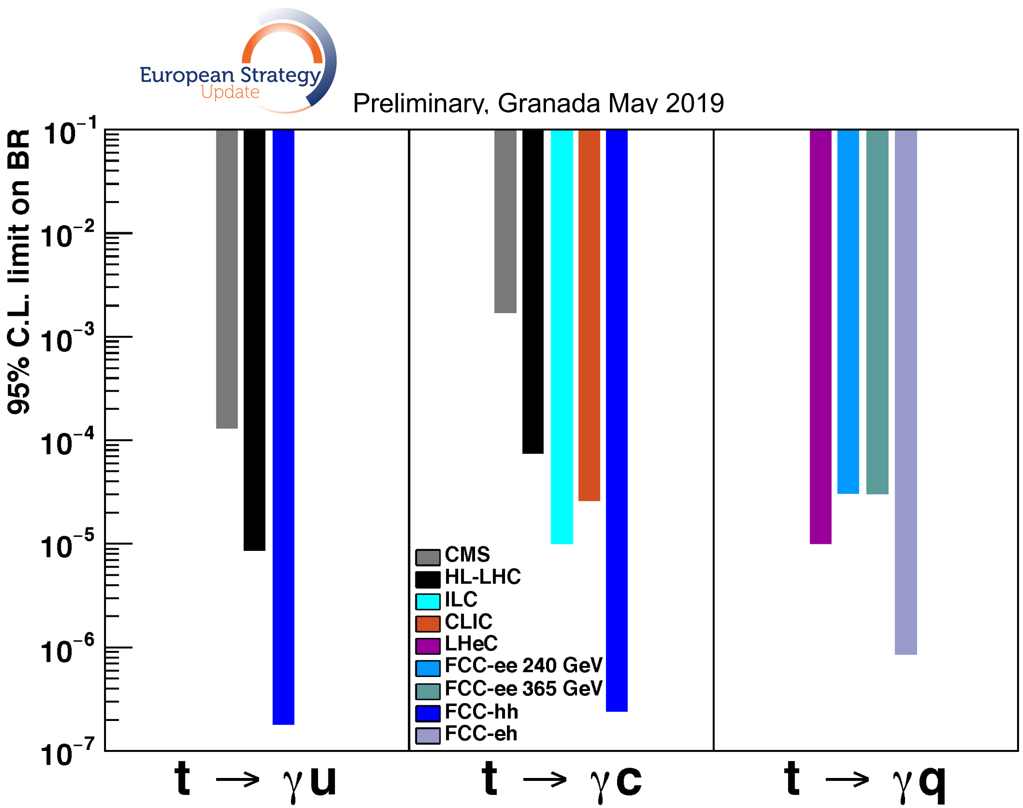
FCC-hh/-eh: Sec. 6 of CERN-ACC-2018-0056

Top-quark FCNC: t→γq branching ratios



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

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

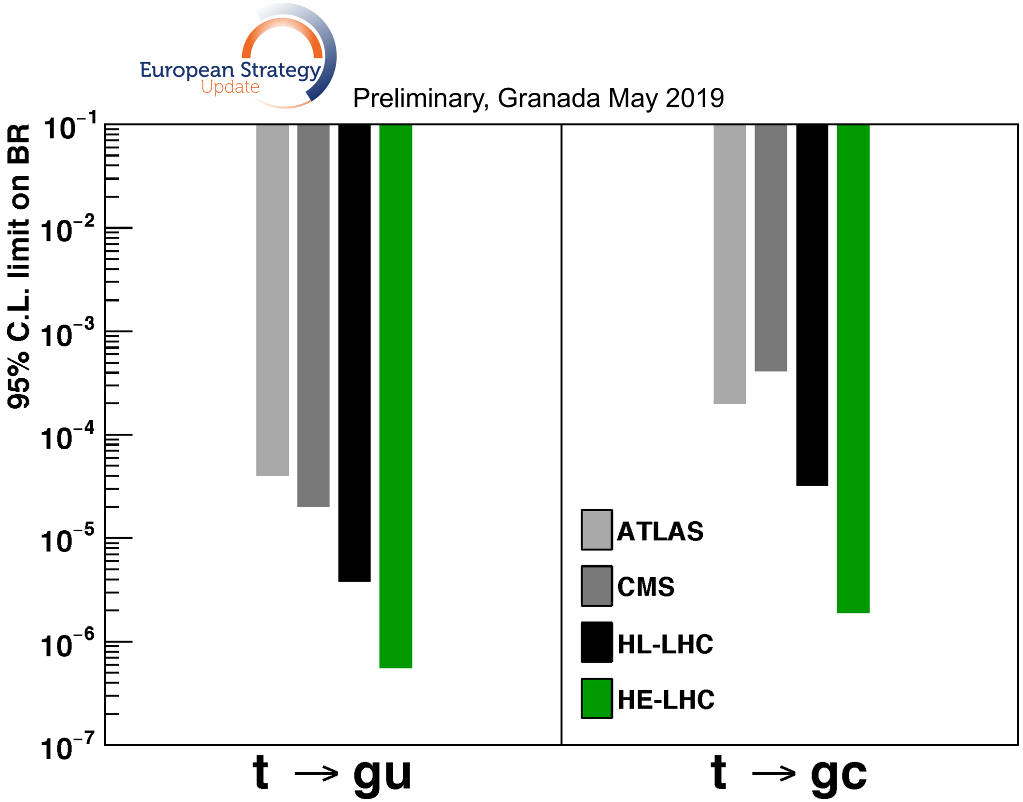
FCC-eh and LHeC:
BR(t→Zq) from NC DIS production of single top quarks

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→γu) from CMS study of single top production in association with a photon

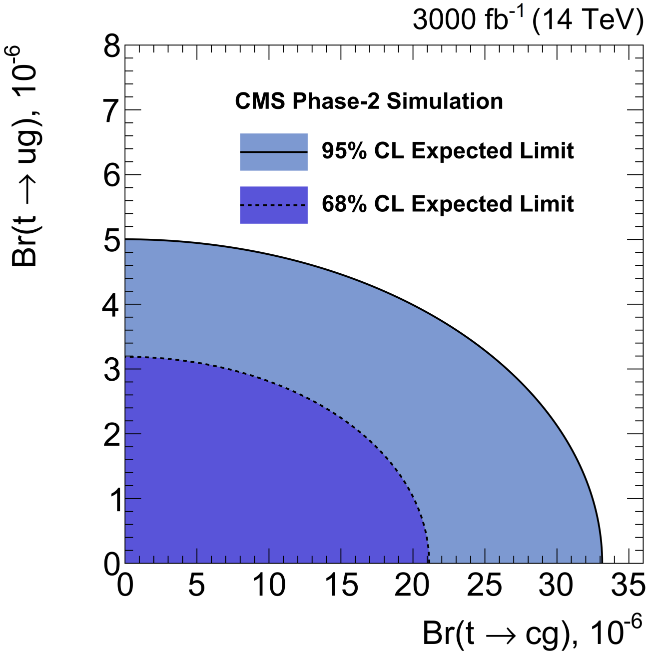
FCC-hh:
Delphes study focussing on the boosted top regime (p_T > 400 GeV)

Top-quark FCNC: t→gq branching ratios



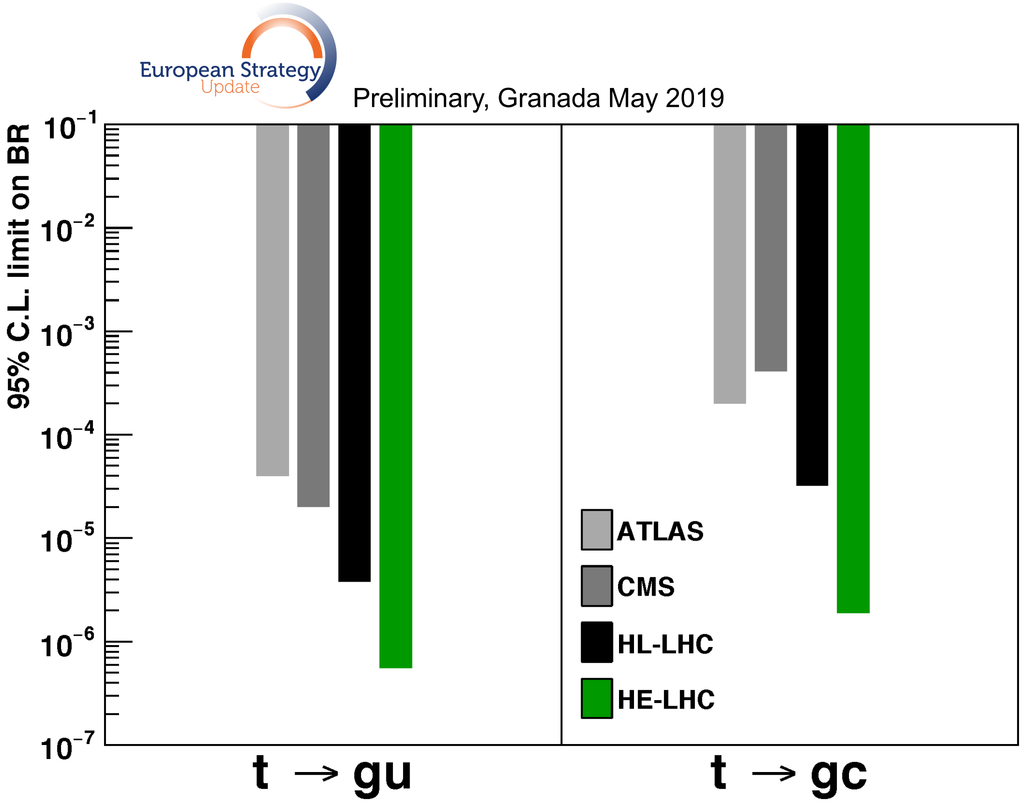
HL-LHC:
BR(t→gu) and BR(t→gu) from CMS study of single top production

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



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→gq branching ratios



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

HE-LHC:
BR(t→gu) and BR(t→gu) 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
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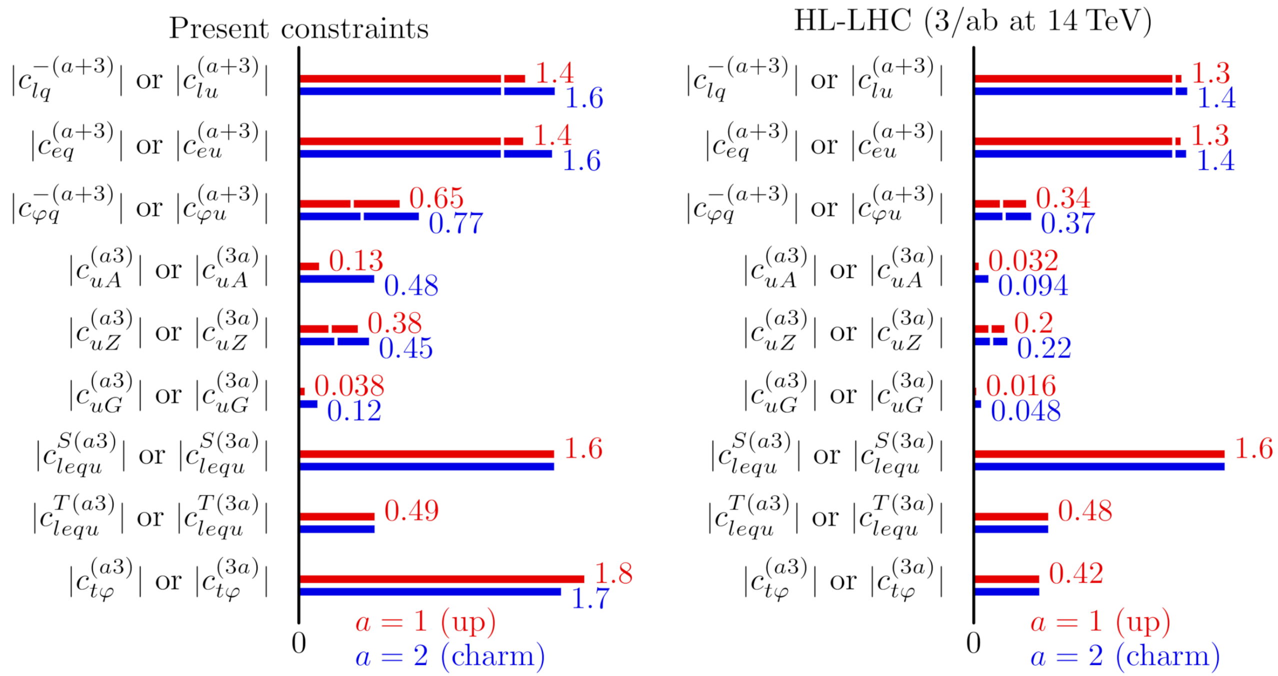
Top-quark FCNC: EFT for HL-LHC

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

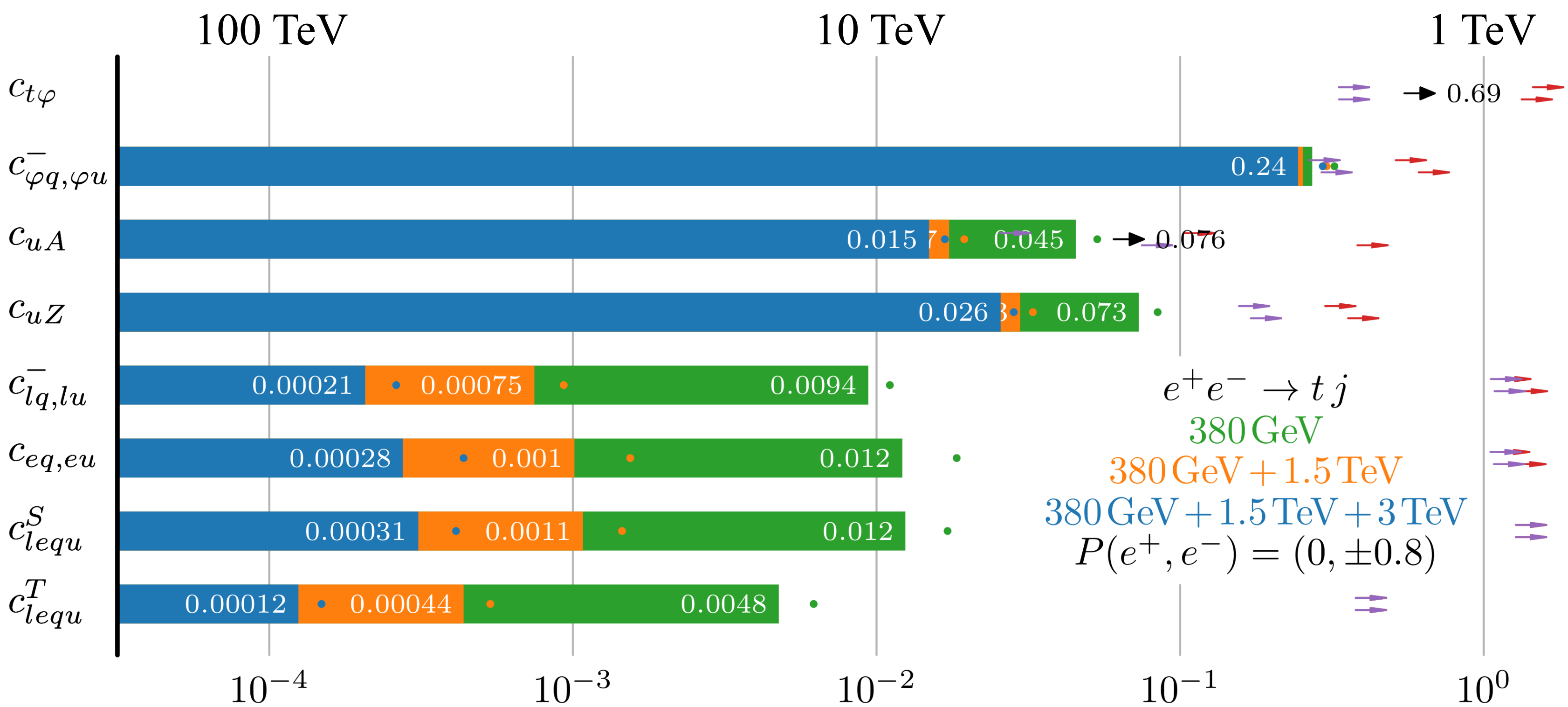
Input: limits on FCNC branching ratios, limits on $e^+e^- \to tj$ from LEP II



White marks: individual limits

Sec. 8.1 of CERN-LPCC-2018-06

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



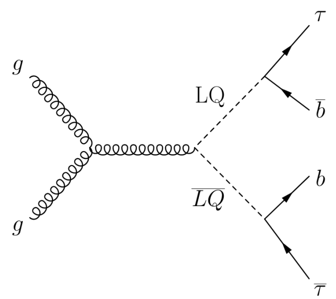
95% C.L. limits on top-quark FCNC operator coefficients

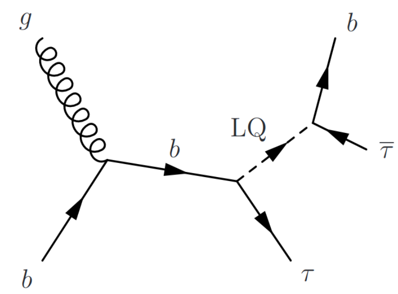
<u>Black arrows:</u> decays at CLIC (see slide X)
<u>Red arrows:</u> current LHC
<u>Magenta arrows:</u> HL-LHC projections
<u>Dots:</u> CLIC without beam polarisation

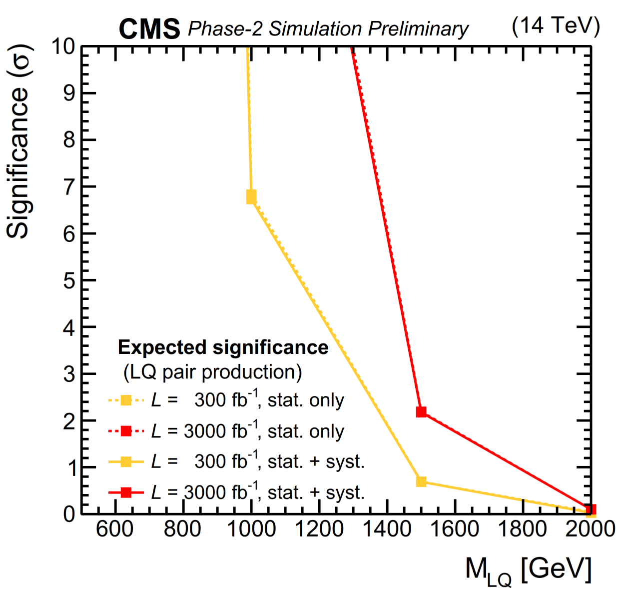
- The high-energy runs significantly improve the sensitivity for “four-fermion” operators
- $e^+e^- \to tj$ much more powerful than the decays at high-energy lepton colliders

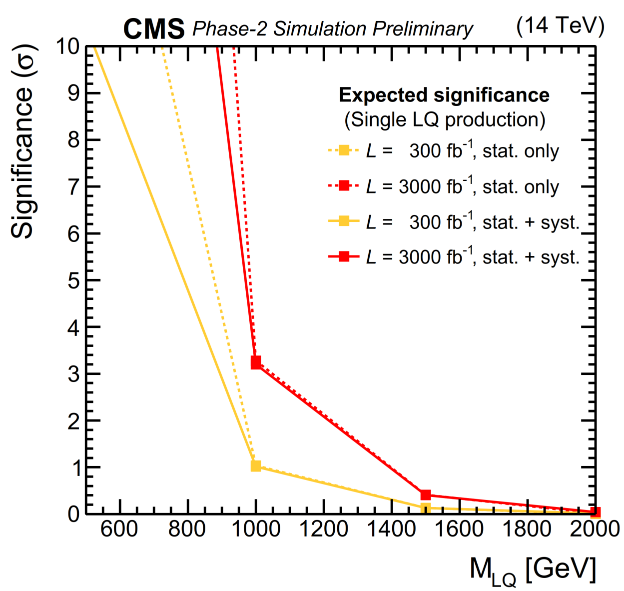
CERN-2018-009-M

Leptoquarks decaying to τ and b (1)







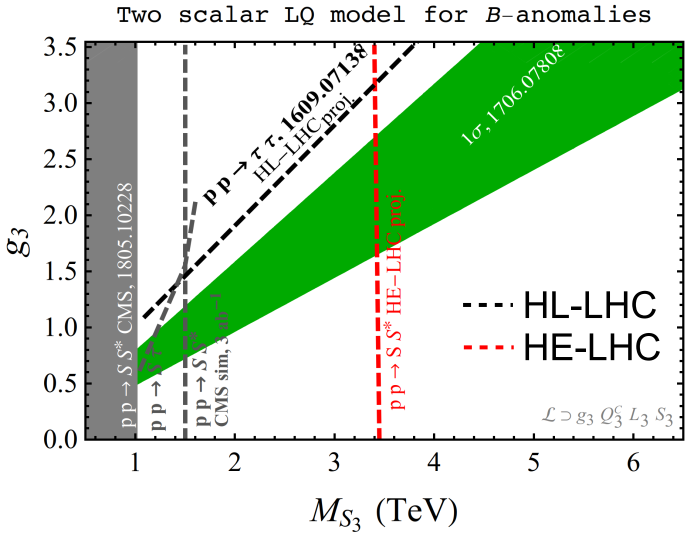


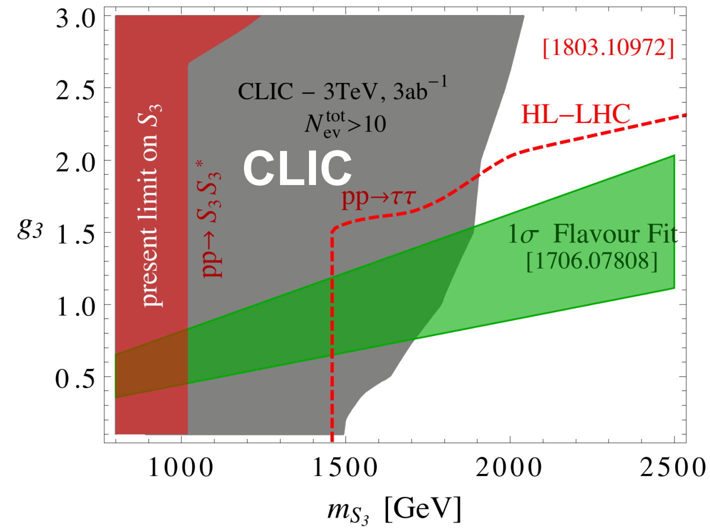
- CMS study of single and double leptoquark production (Delphes)
- 5σ discovery significance for masses below 1.5 TeV (double production) and 1 TeV (single production)

CMS-PAS-FTR-18-028
Sec. 5.2.3 of CERN-LPCC-2018-005

Leptoquarks decaying to τ and b (2)

Triplet $S_3 = (\bar{\mathbf{3}},\mathbf{3},-1/3)$:

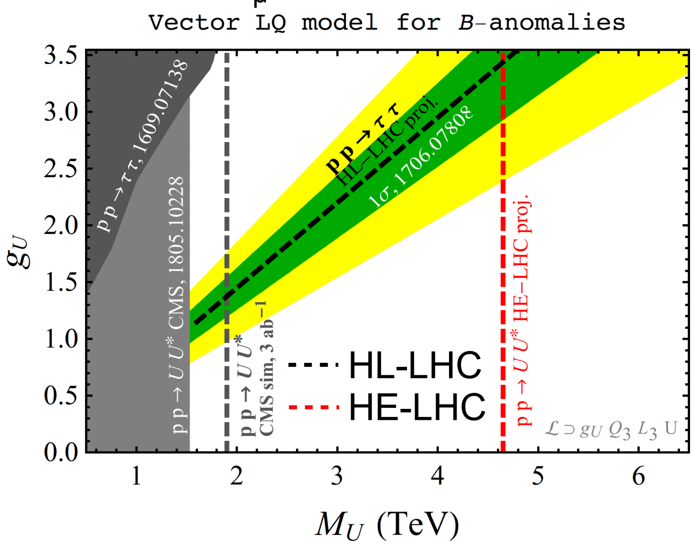




Sec. 3.3 of CERN-2018-009-M

NB: Background negligible in multi-TeV e^+e^- collisions (2b2τ final states)

$U_\mu = (\bar{\mathbf{3}},\mathbf{1},2/3)$:

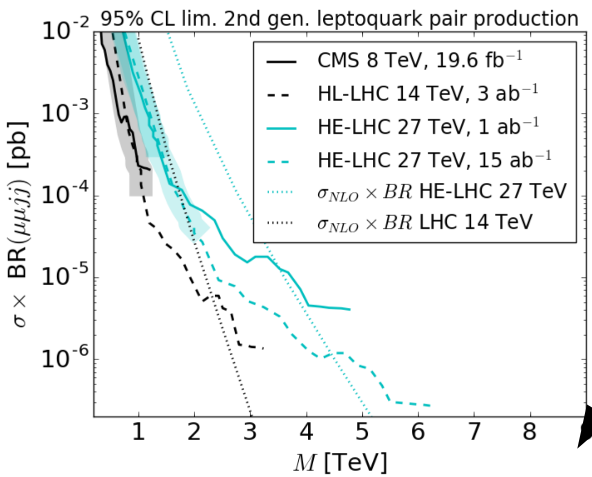


- b→cτν anomaly suggests rather light LQ that couples predominantly to the third generation fermions of the SM → see talk by Veronica Sanz
- LQ pair production and pp → $\tau^+\tau^-$ complementary
- Small improvement in mass reach for S_3 at from CLIC up to $g_3 \approx 1.5$
- HE-LHC improves the direct mass reach by more than a factor 2 compared to HL-LHC

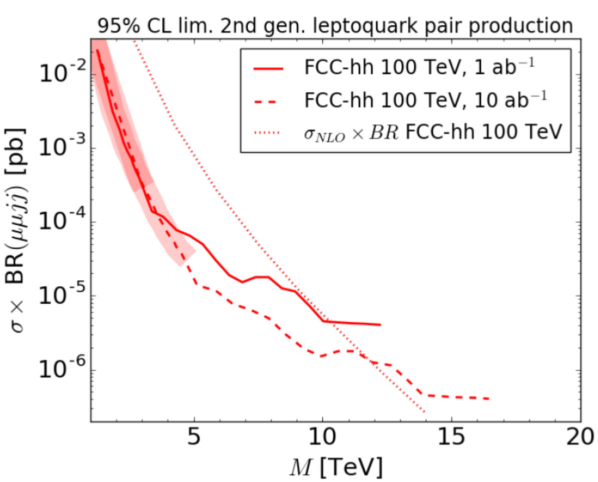
Sec. 5.3.2 of CERN-LPCC-2018-005

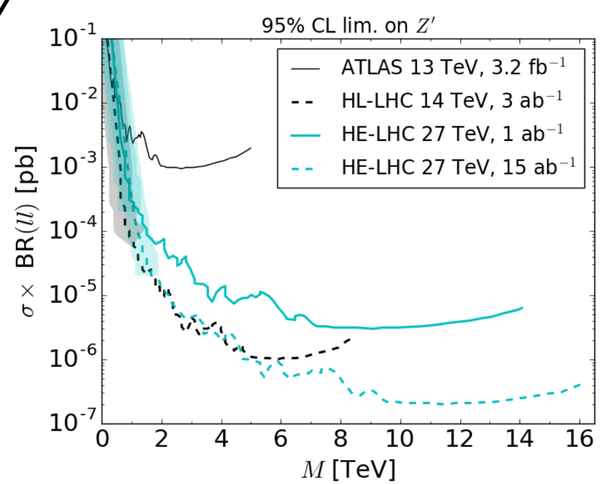
More projections

HL-/HE-LHC, FCC-hh: $gg \rightarrow S_3 S_3^* \rightarrow (\mu^- j)(\mu^+ j)$
and $Z' \rightarrow \mu^+\mu^-$ motivated by anomaly in $b \rightarrow s\ell\ell$



Scalar leptoquark
$S_3 = (\bar{\mathbf{3}},\mathbf{3},-1/3)$

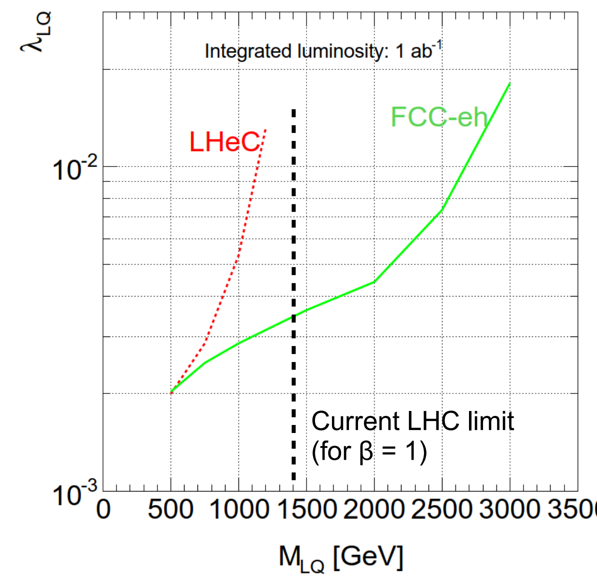




→ more on Z' in the talk by Juan Alcaraz Maestre

Sec. 5.2 of CERN-LPCC-2018-005
Sec. 14.3 of CERN-ACC-2018-0056

LHeC and FCC-eh:



Example: scalar LQ coupling to d-quark and electron

- If accessible, FCC-eh could measure the LQ properties (fermion number, spin, coupling, ...)

Sec. 15.3 of CERN-ACC-2018-0056

Some observations

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

• Large amount of complementarity:

- Direct and indirect sensitivity (e.g. SM + heavy singlet, heavy MSSM Higgs bosons)

- Hadron and lepton collisions (e.g. doubly charged Higgs)

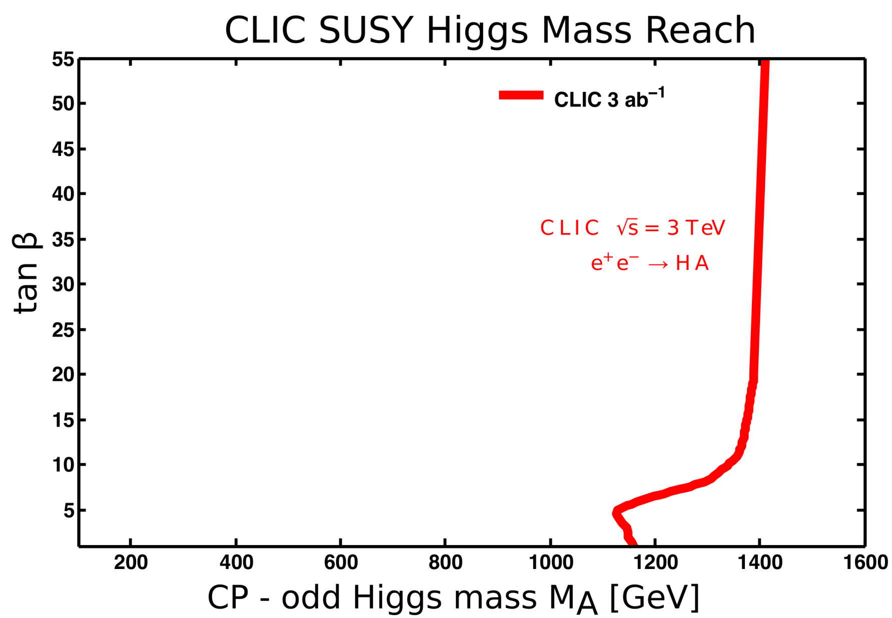
- Different energy stages of a lepton collider (e.g. top-quark FCNC effects)

Thank you!

Backup slides

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 $e^+e^- \rightarrow H^+H^-$



Sec. 1 of CERN-2012-003

FCNC top branching ratios: input

BR x 10^5 95% C.L.	HL-LHC 14 TeV	HE-LHC 27 TeV	ILC 500 GeV	CLIC 380 GeV	LHeC 1.3 TeV	FCC-ee 240 GeV	FCC-ee 365 GeV	FCC-hh 100 TeV	FCC-eh 3.5 TeV
$t \rightarrow Hc$			≈ 3	15				1.6	
$t \rightarrow Hu$					150				22
$t \rightarrow Hq$	10							2.8	
$t \rightarrow Zq$	2.4 - 5.8				4	3	5	≈ 0.1	0.6
$t \rightarrow \gamma c$	7.4		≈ 1	2.6				0.024	
$t \rightarrow \gamma u$	0.86							0.018	
$t \rightarrow \gamma q$					1	3	3		0.085
$t \rightarrow gc$	3.2	0.19							
$t \rightarrow gu$	0.38	0.056							

Comments:
- q = u,c inclusive
- FCC-ee numbers for 240 GeV and 365 GeV will be combined in the future

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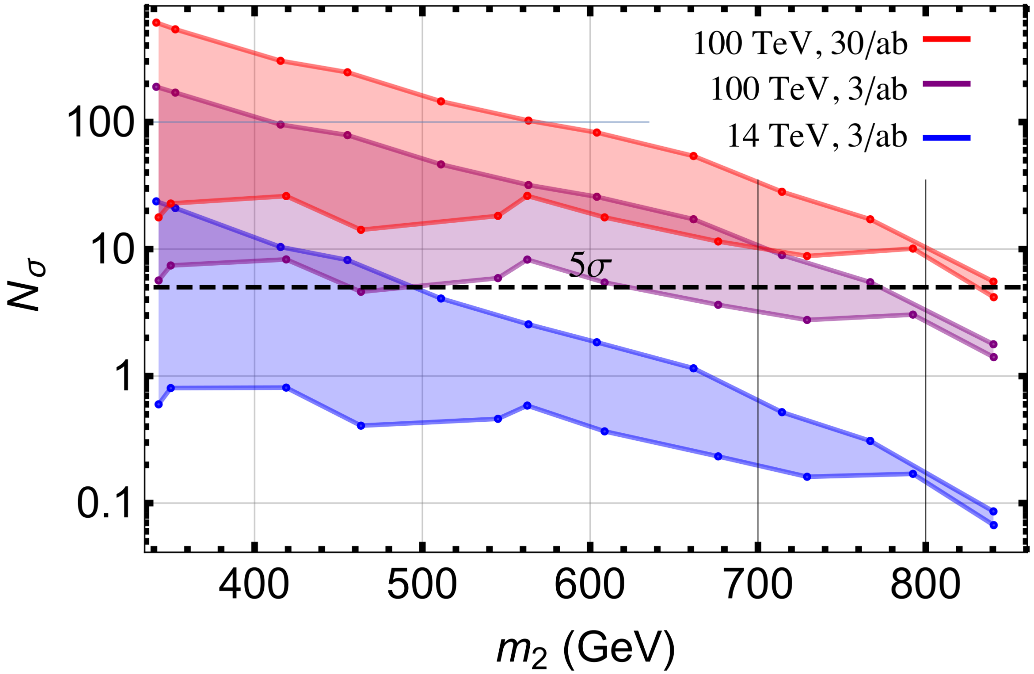
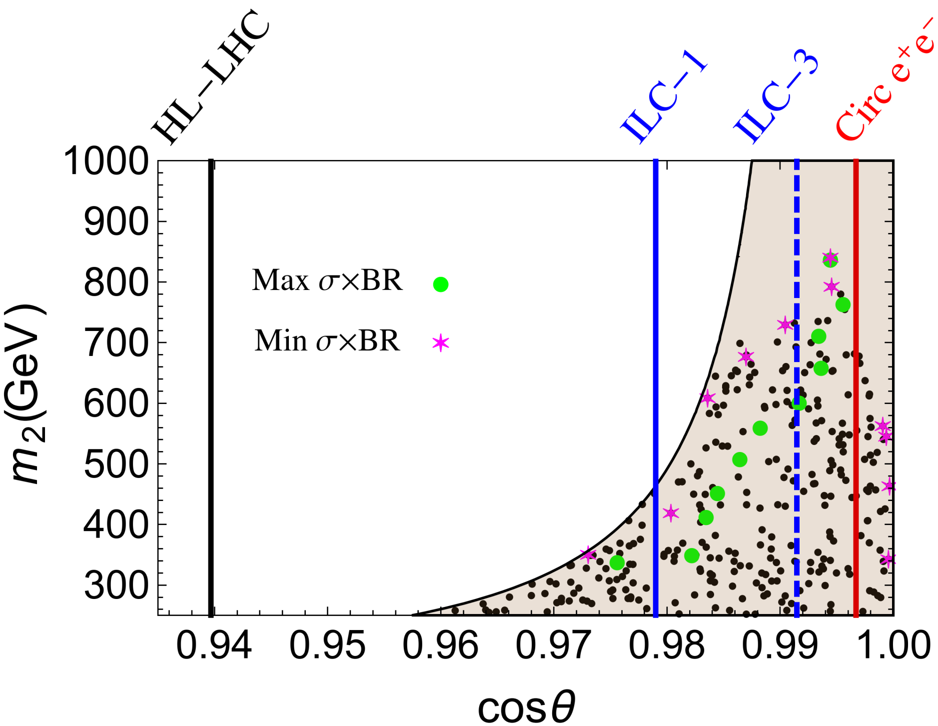
LHeC: EPPSU submisson #159
FCC-ee: Phys. Lett. **B755**, 25 (2017)
FCC-hh/-eh: Sec. 6 of CERN-ACC-2018-0056

Strong first-order EW phase transition





- $h_2 \rightarrow h_1 h_1$
- 4τ and $b\bar{b}\gamma\gamma$ final states (generator level)
- Benchmark points minimising and maximising the cross section

Comments:

- The e^+e^- numbers in this plot are outdated

$h_1 = h \cos\theta + s \sin\theta$

$h_2 = -h \sin\theta + s \cos\theta$

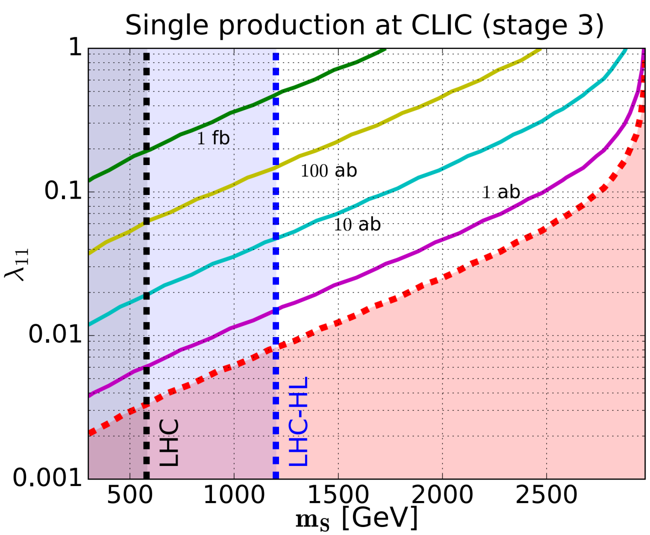
CERN-ACC-2018-0056

Phys. Rev. D 94, 035022 (2016)

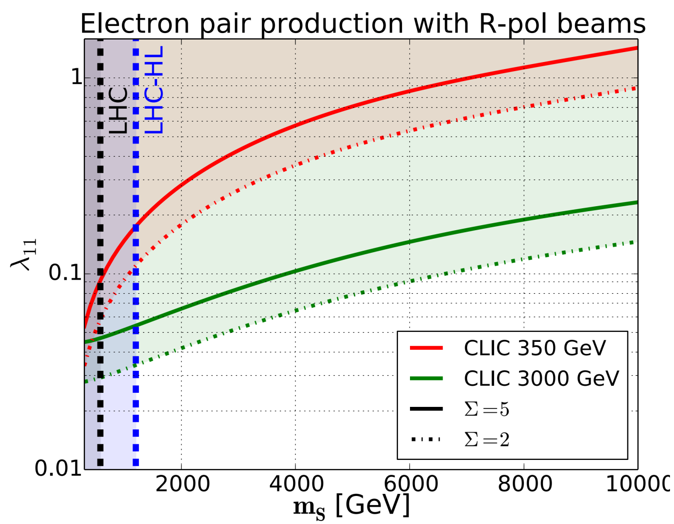
Direct vs. indirect constraints

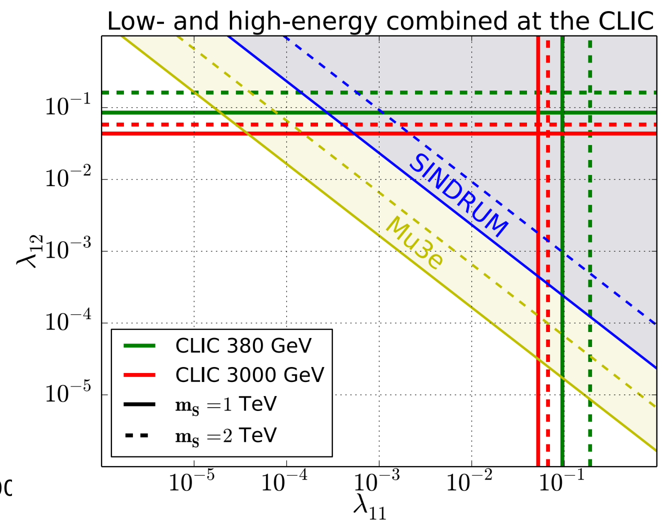
- Doubly-charged scalar which is a singlet under the SU(2) weak symmetry of the SM

Direct: $e^+e^- \rightarrow S^{++}e^-e^-$



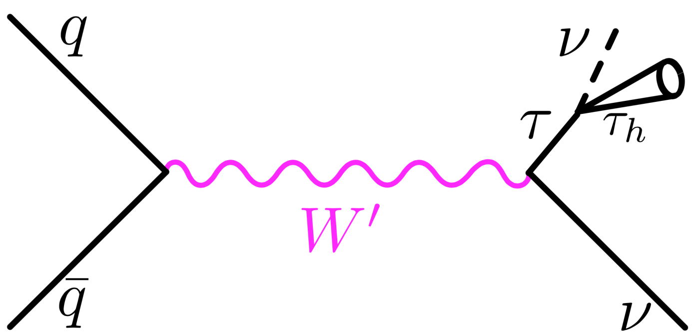
Indirect: $e^+e^- \rightarrow e^+e^-$ and $\mu^+\mu^-$

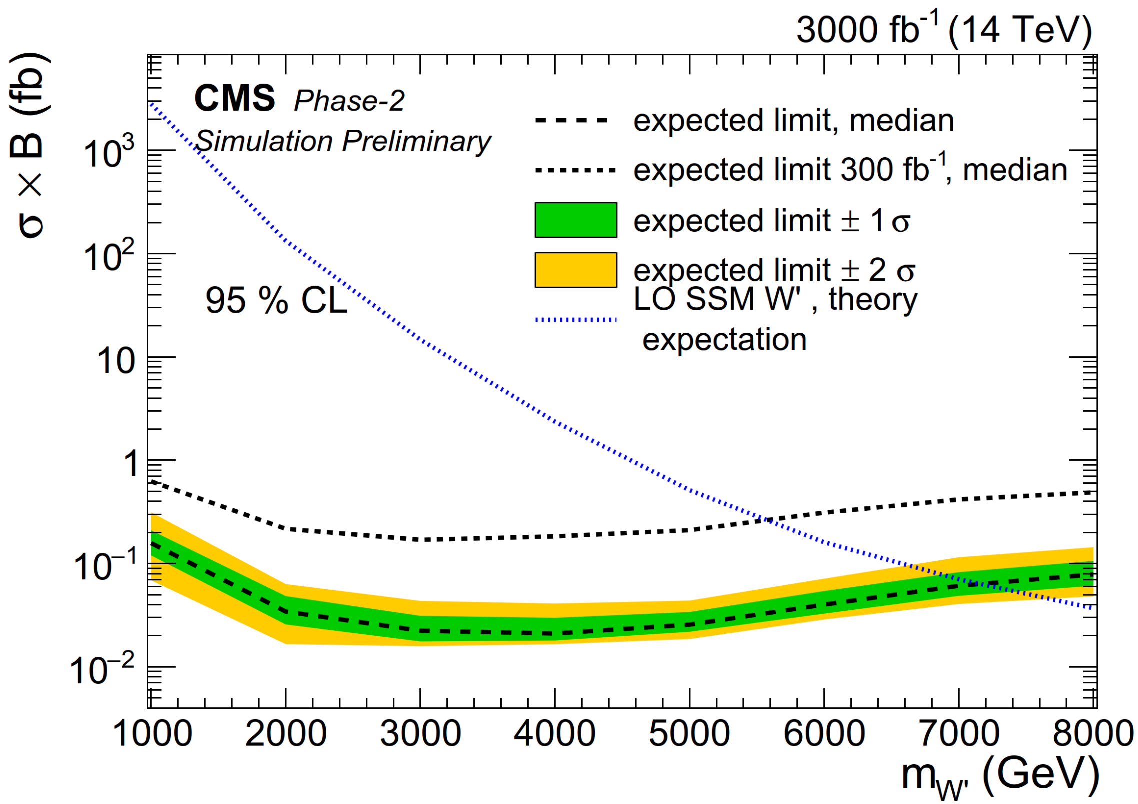




Sec. 7.3 of CERN-2018-009-M

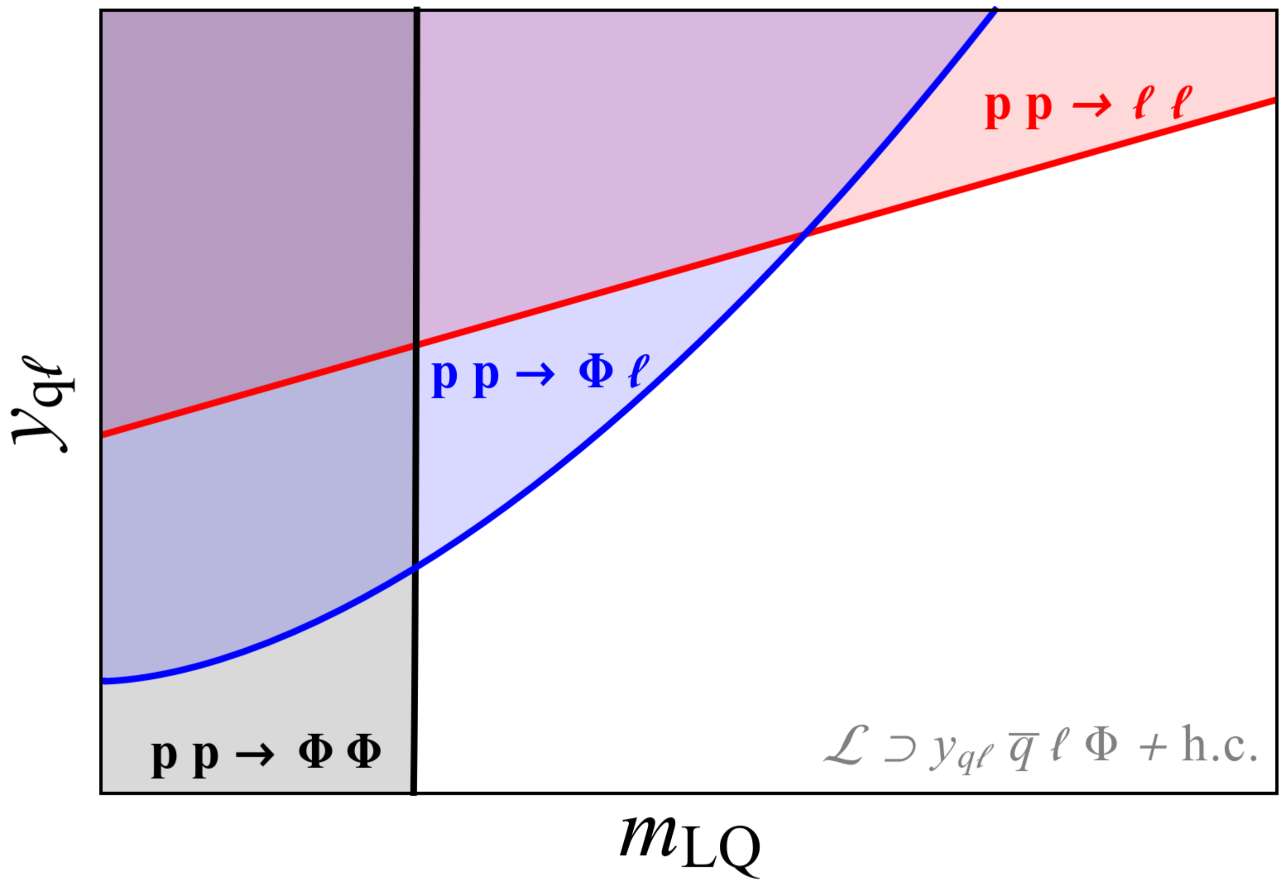
W' → τν at HL-LHC





CMS-PAS-FTR-18-030

LQ search strategy



JHEP **05**, 126 (2018)