Top quark physics at FCC-ee and FCC-hh

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FUTURE CIRCULAR COLLIDER

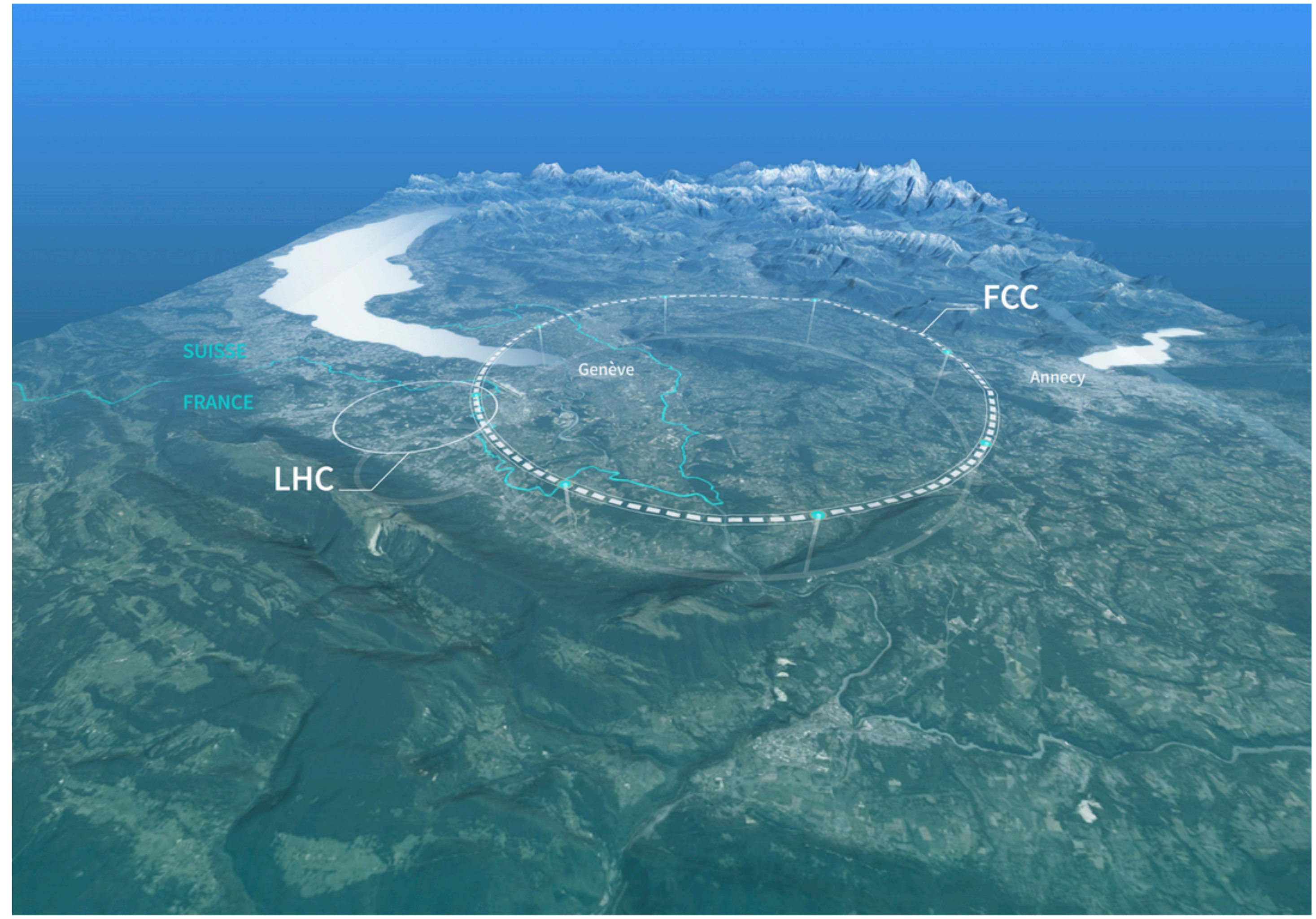
CERN

Future circular collider (FCC) @CERN

- FCC-ee: High-luminosity e+e- circular collider; machine design for highest luminosities at Z, WW, ZH and ttbar working points

- Unprecedented precision measurements for all SM parameters

- Potential to directly or indirectly discover BSM physics



- 91 km ring beneath France & Switzerland

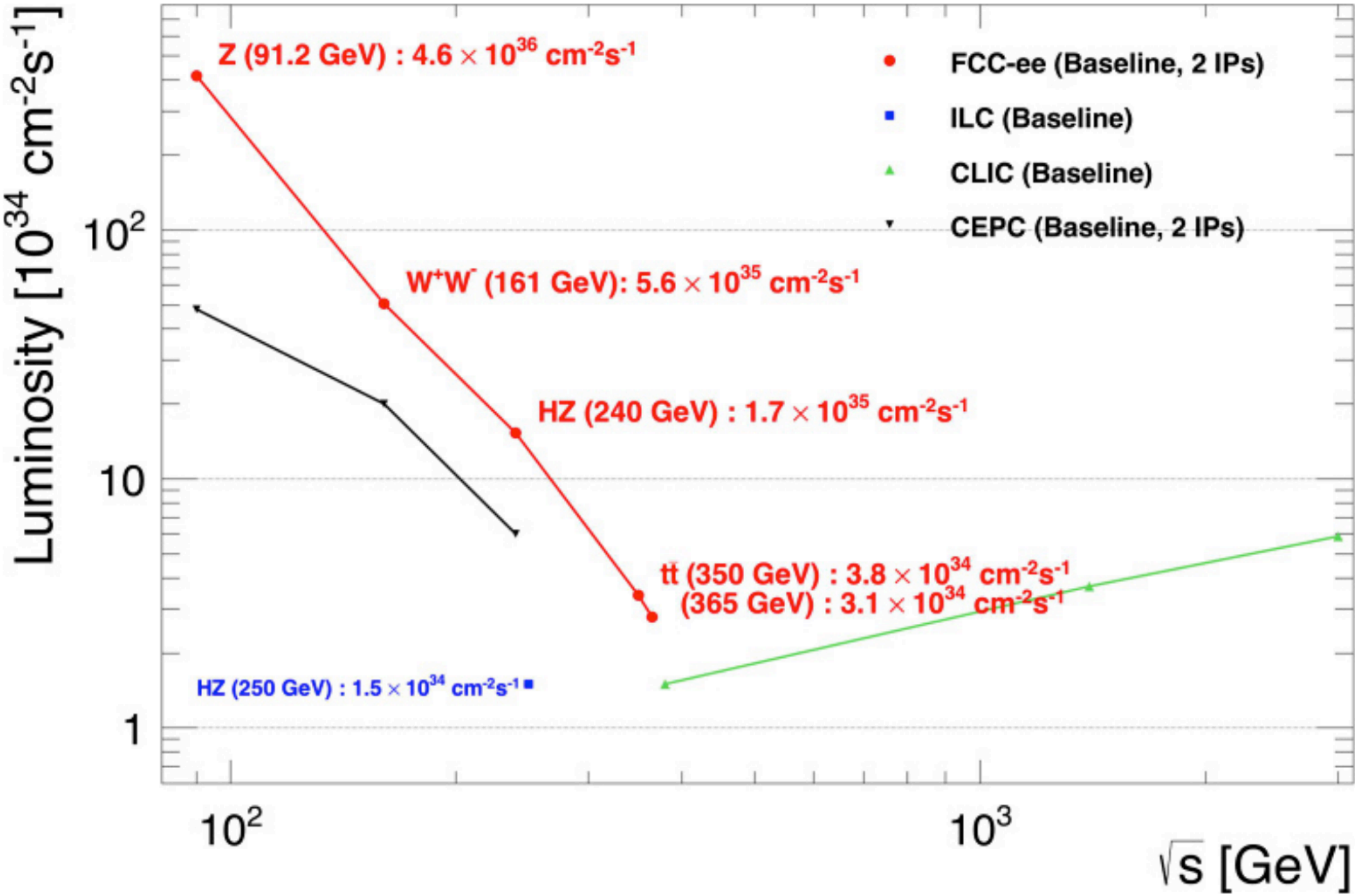
- Schedule (and physics) complementary to LHC followed by FCC-hh (reaching energies up to eight times those of the LHC)

- Eight surface sites for up to four experiments.

Feasibility Study Report:

Future Circular Collider Conceptual Design Report Volume 2

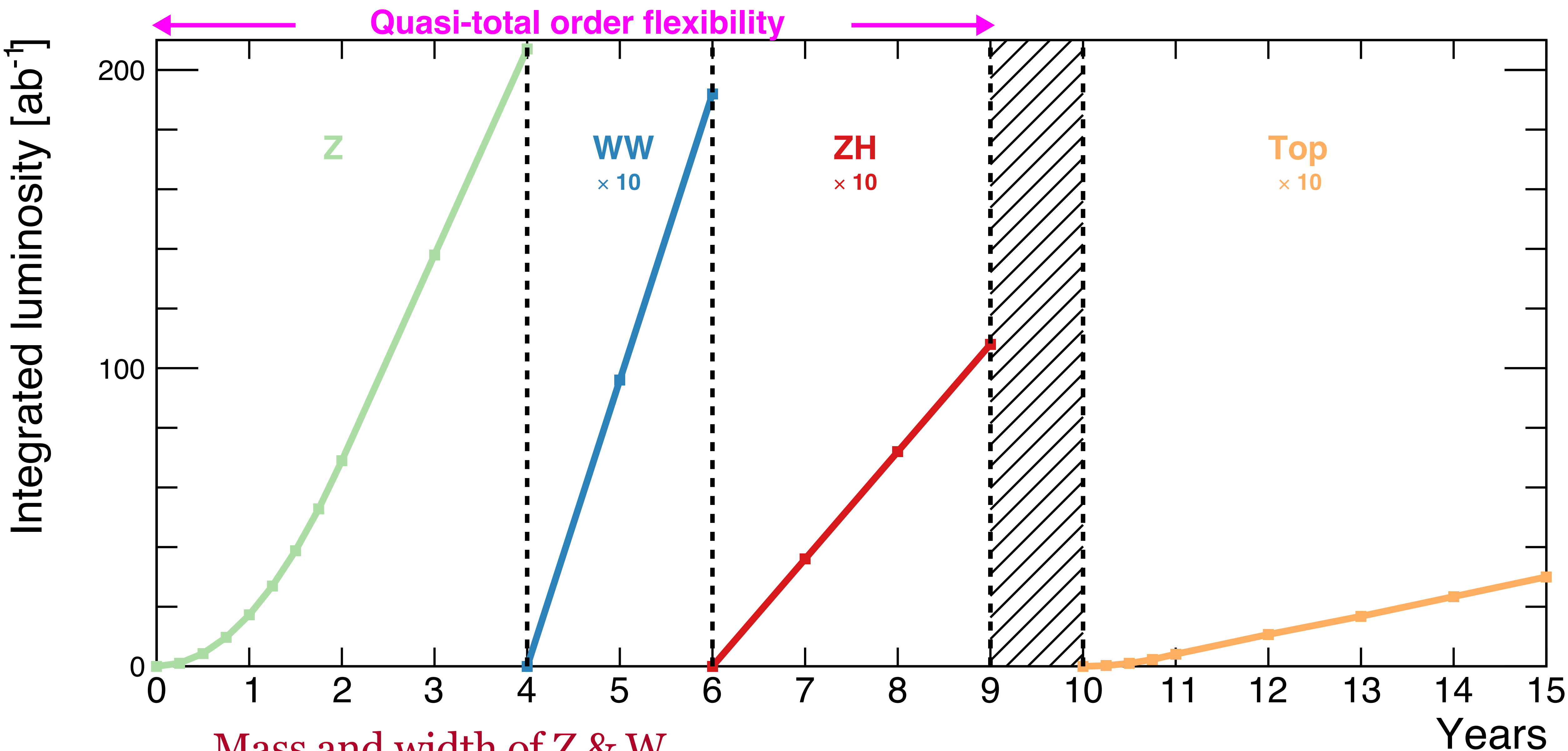
Future lepton colliders luminosities



Clear advantage in luminosity for circular colliders vs. linear colliders
CLIC has higher energy reach, but less than LHC

Top quark physics at FCC-ee

- Measure total production cross section as a function of √s
- 345-365 GeV runs
- Compare to standalone theory prediction to extract physical parameters (mass, total width…) Requires excellent control over beam and luminosity calibration



Mass and width of Z & W

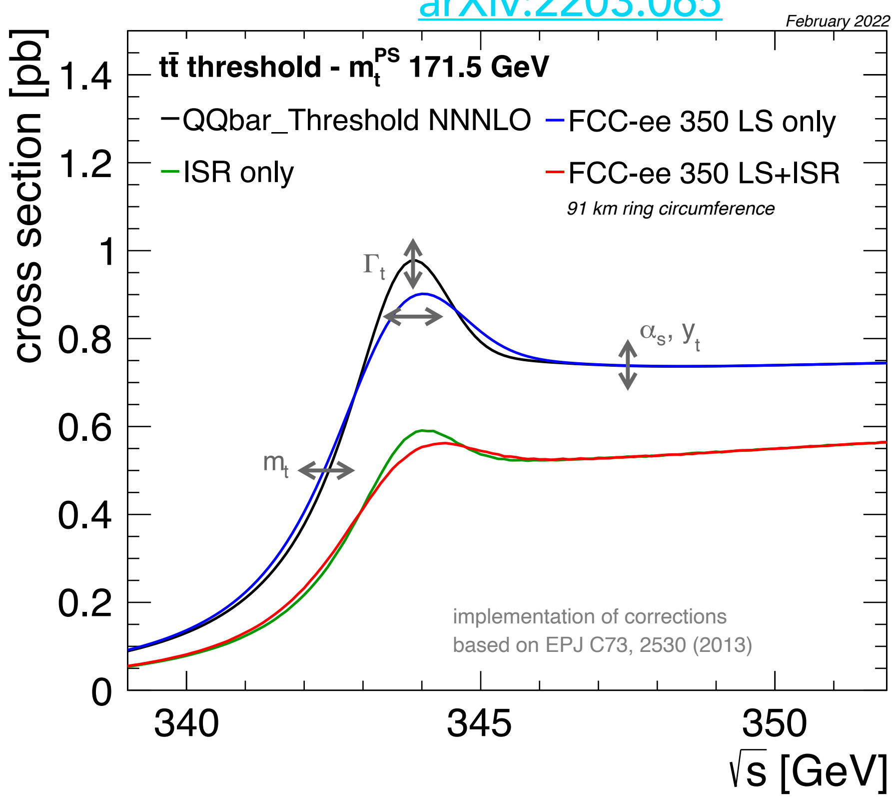
Need for $t\bar{t}$ threshold scan at FCC-ee

- Measurement of WbWb total rate around the $t\bar{t}$ production threshold
- Cross section shape depends strongly on top quark mass (m_{top}), width (Γ_{top}), α_s and top-Yukawa (y_{top})
- Lepton colliders aim to measure α_s with very high precision (0.1% for FCC-ee, 0.6% for LC) at Z pole and m_W at WW threshold

FCC advantages

- Better $\sqrt{s}$ precision and accuracy → beneficial for m_t and Γ_t
- Access to precise direct determination of **α_s from Z pole run**

arXiv:2203.065



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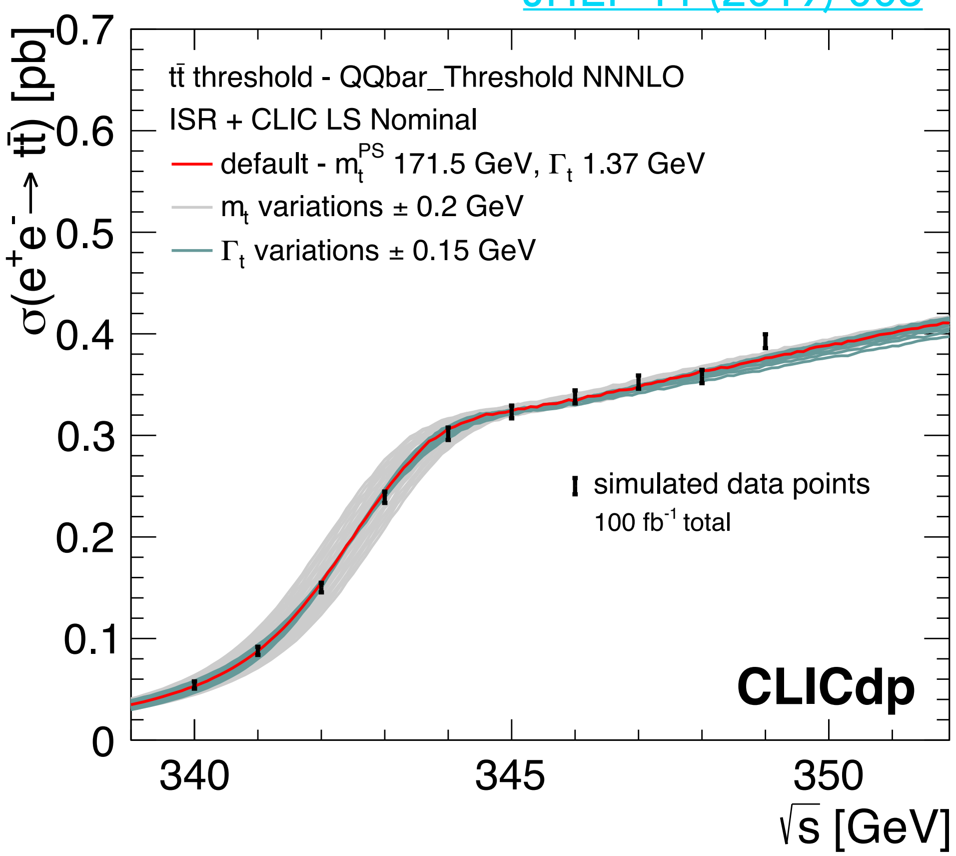


LC advantages (not directly related to threshold scan)

- Beam polarisation → interesting for top quark couplings
- Access to higher energies (ttH)

LS: Luminosity spectrum

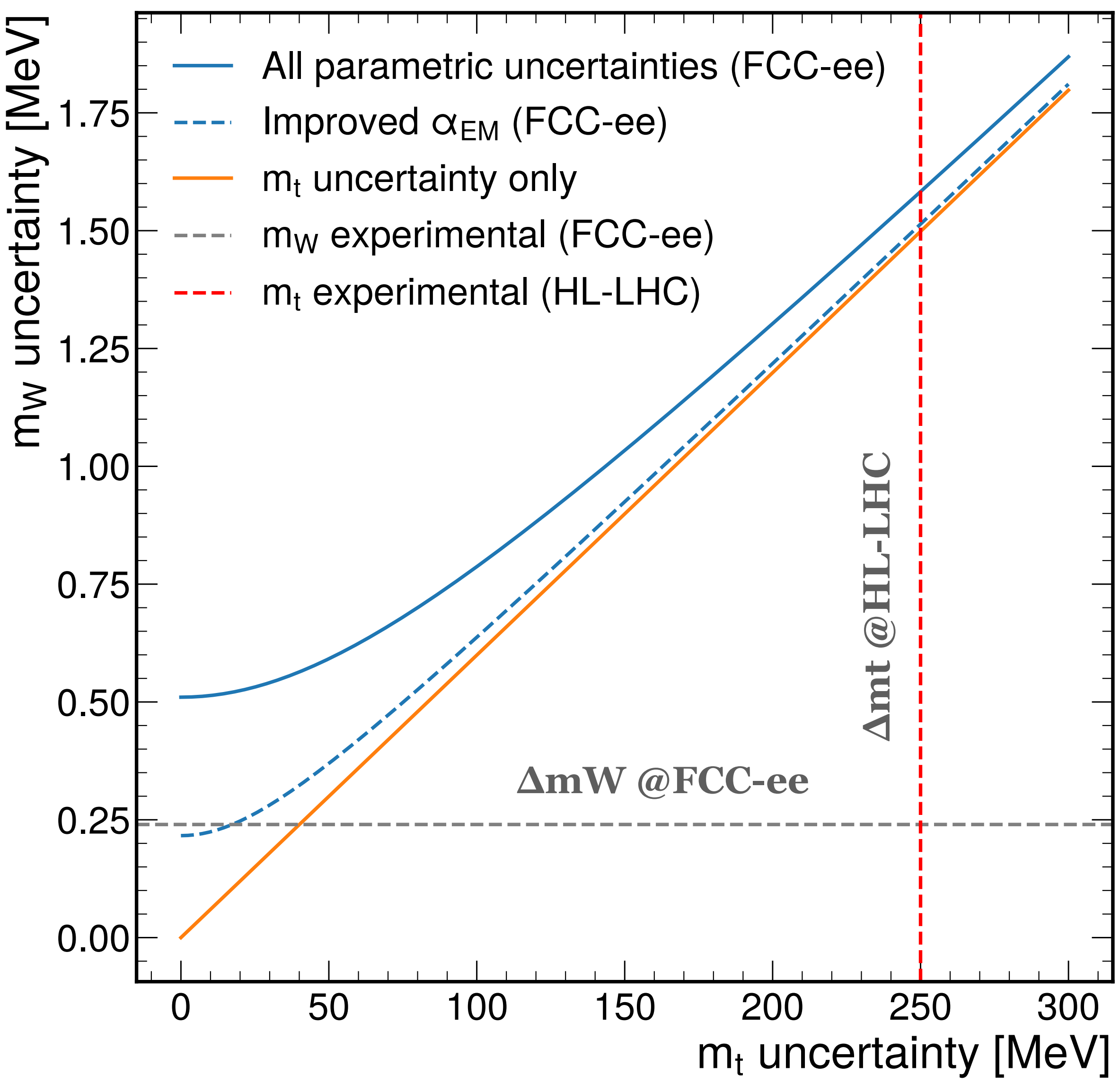
$t\bar{t}$ threshold scan at FCC-ee

ECFA report arXiv:2503.18713

Submitted to JHEP

- Measurement of WbWb production cross section at different center-of mass energies (340-365 GeV) around $t\bar{t}$ production threshold in e+e- collisions at FCC-ee
- Different center-of mass energy points offer measurements of m_{top}, Γ_{top}, and y_{top}
- Even possible to search for new physics indirectly at 365 GeV

m_W measurements at FCC-ee: 0.24 MeV→ need to measure m_{top} with < 20 MeV precision



- Targeting semi-hadronic and hadronic decay modes (total branching fractions ~75%)
- $\mathscr{L}_{int.}$ = 41 fb^{-1} per e.c.m @340-355 GeV & 2.65 ab^{-1} @ 365 GeV

Detector level studies

- Signal: WbWb production including $t\bar{t}$, single top, and non-resonant contributions
- Background contributions from WW, ZZ, WWZ($\rightarrow b\bar{b}$), and $q\bar{q}$
- MC simulation samples from Pythia & Whizard

Expected number of signal events: 2e6 for 41 fbinv

Process	Decays	Generator	Order	Cross section [pb]		
				340 GeV	345 GeV	365 GeV
WbWb	inclusive	WHIZARD+Pyhtia6	LO	0.1	0.5	0.5
WWZ	$Z \rightarrow b\bar{b}$	WHIZARD+Pyhtia6	LO	2.02×10^{-3}	1.46×10^{-3}	1.32×10^{-3}
$q\bar{q}$	n.a.	WHIZARD+Pyhtia6	LO	26.3	25.6	22.8
ZZ	inclusive	Pythia8	LO	0.932	0.916	0.643
WW	inclusive	Pythia8	LO	12.1	11.9	10.7

- Lepton acceptance (isolated leptons with momentum > 12 GeV) >99% across all e.c.m. points
- Inclusive jet clustering (generalised anti-kT algorithm with cone size 0.5)
- Variables of interest: Number of jets in different bins of number of b-tagged jets (0,1,≳2)
- Parameterised b-tagging efficiencies

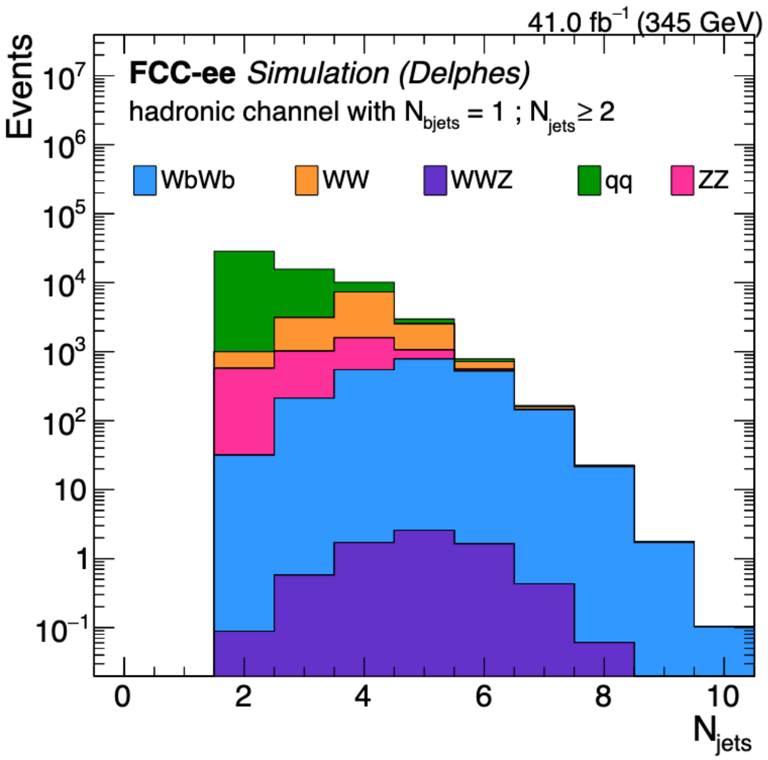
Zero btagged category → WW

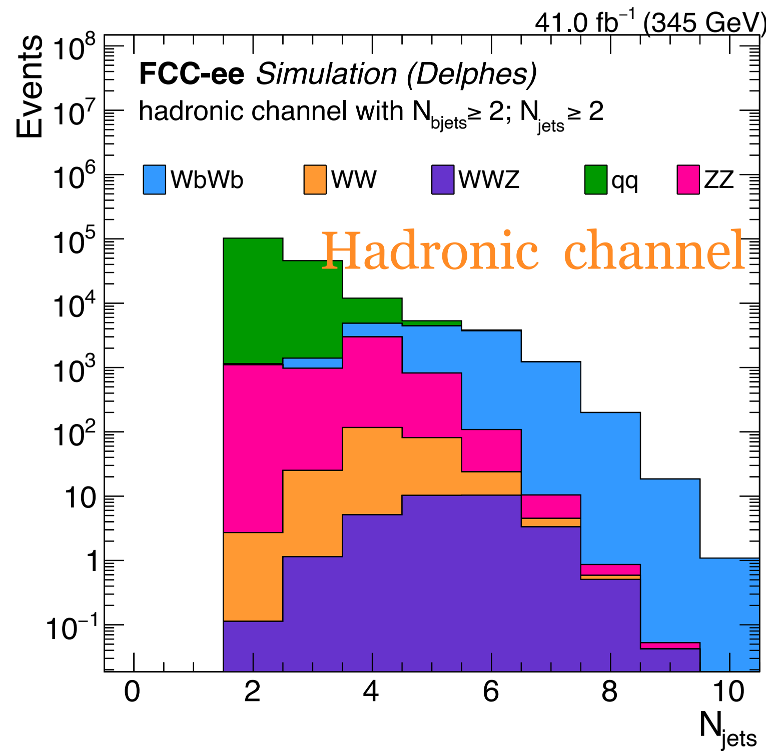
≳ 1 btagged category → signal

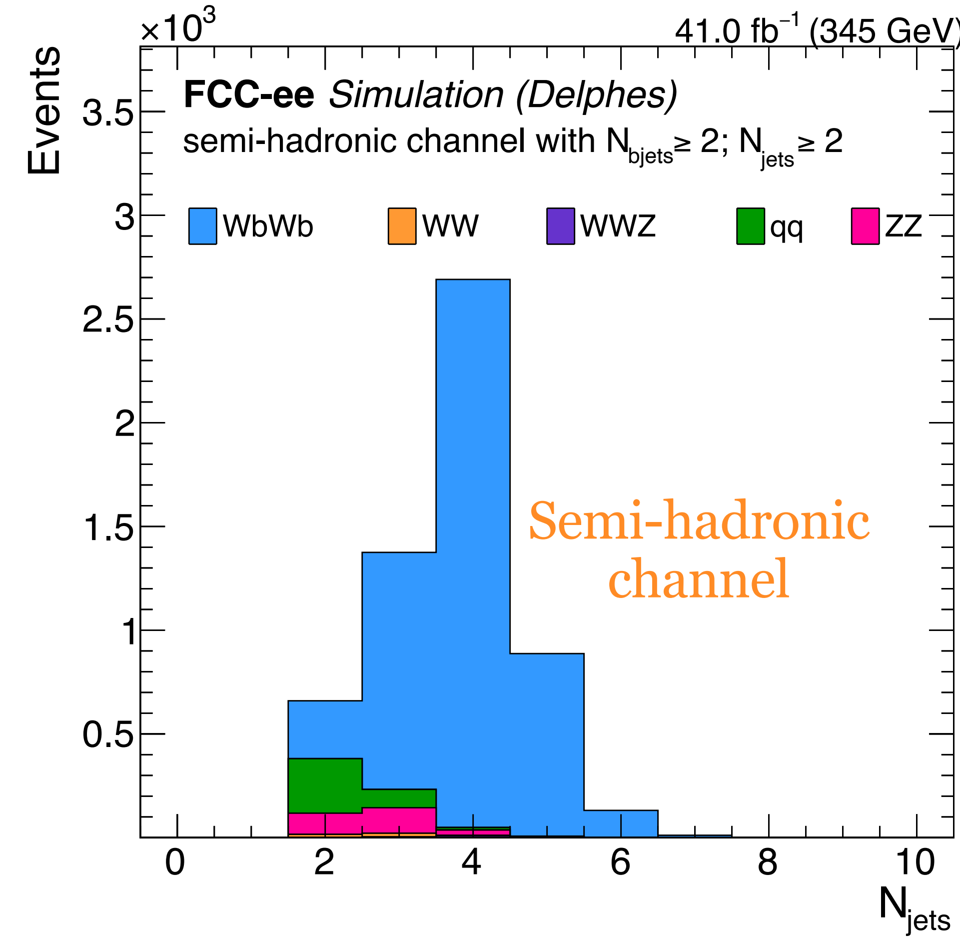
One btagged category → signal with one unidentified b-tagged jet

Detector level studies

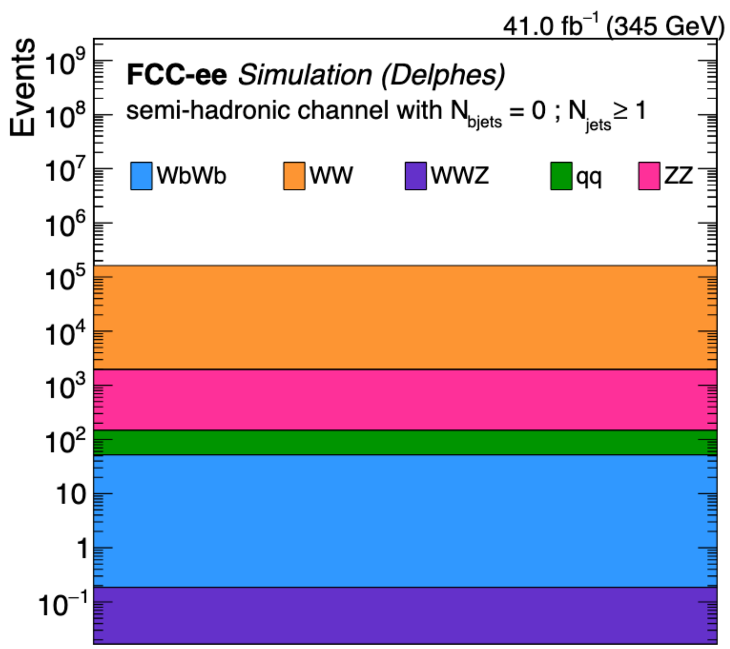
Profile-likelihood fit in jet & b-tag multiplicity to extract total rates → measure b-tagging efficiency in-situ







Relevant systematic effects controlled well below statistical uncertainty

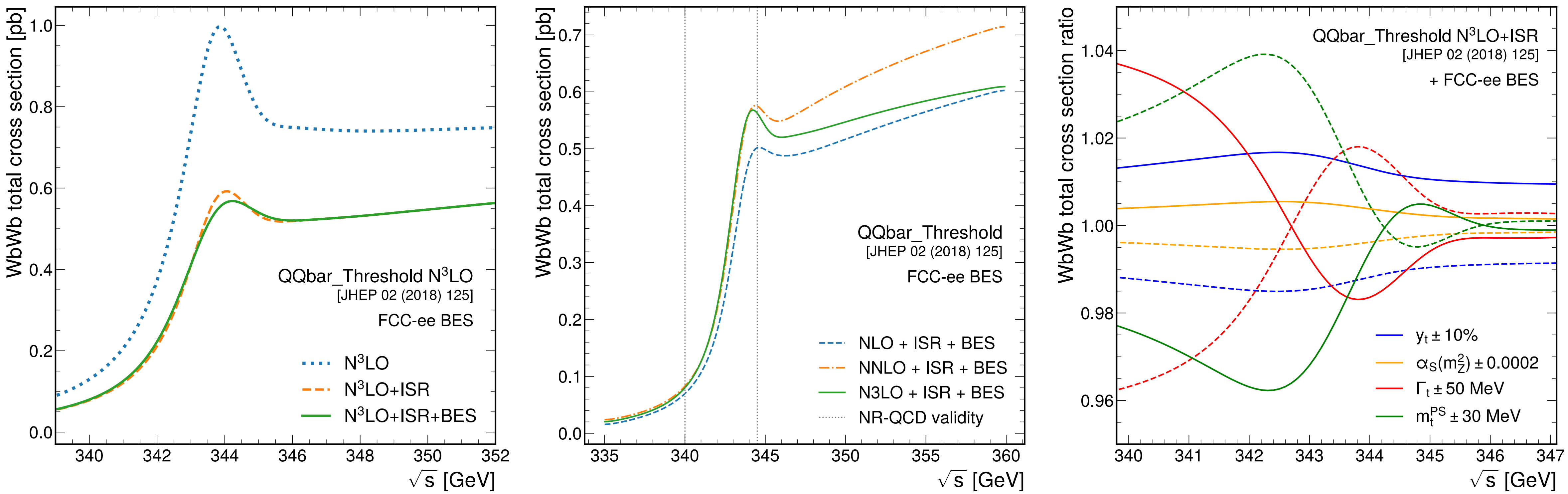


Extremely clean in WW

Helps to constrain normalisation of WW

Uncertainty source	Impact on σ_{WbWb} [%]		
	340 GeV	345 GeV	365 GeV
Integrated luminosity	0.12	0.11	0.02
b tagging	0.11	0.06	0.01
ZZ had. norm.	0.46	0.19	0.04
ZZ semihad. norm.	0.23	0.07	0.03
WW had. norm.	0.17	0.09	0.02
WW semihad. norm.	0.06	0.04	0.03
$q\bar{q}$ had. norm.	0.12	0.09	0.02
$q\bar{q}$ semihad. norm.	0.18	0.06	0.01
WWZ norm.	0.03	0.01	0.01
Total (incl. stat)	2.31	0.89	0.12

Theoretical calculation



- Top quarks form a quasi-bound state → non-relativistic QCD calculation (NR-QCD) at N^{3}LO
- Initial state radiation (ISR) effectively reduces total cross section (LL precision)
- Calculation convoluted with expected FCC beam energy spread (BES): 0.18% / beam

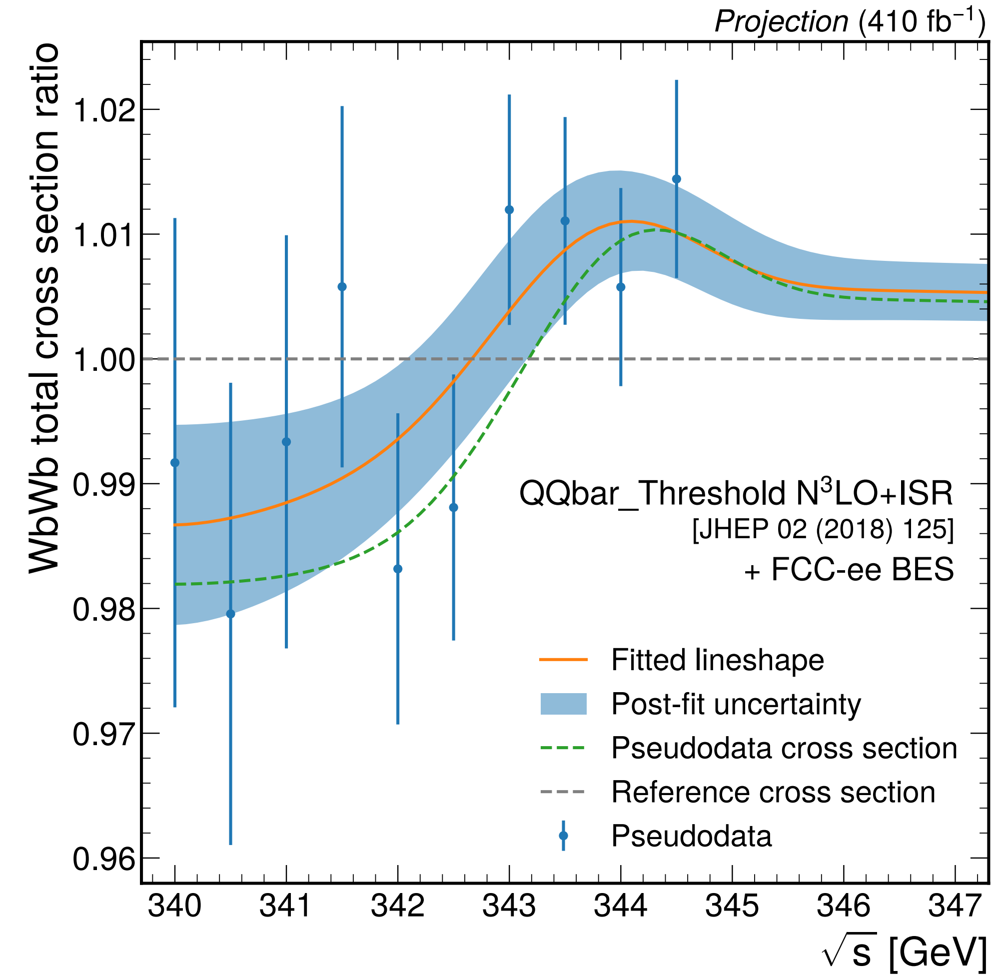
- Calculation only valid in the vicinity of threshold, where the sensitivity to the parameters lies

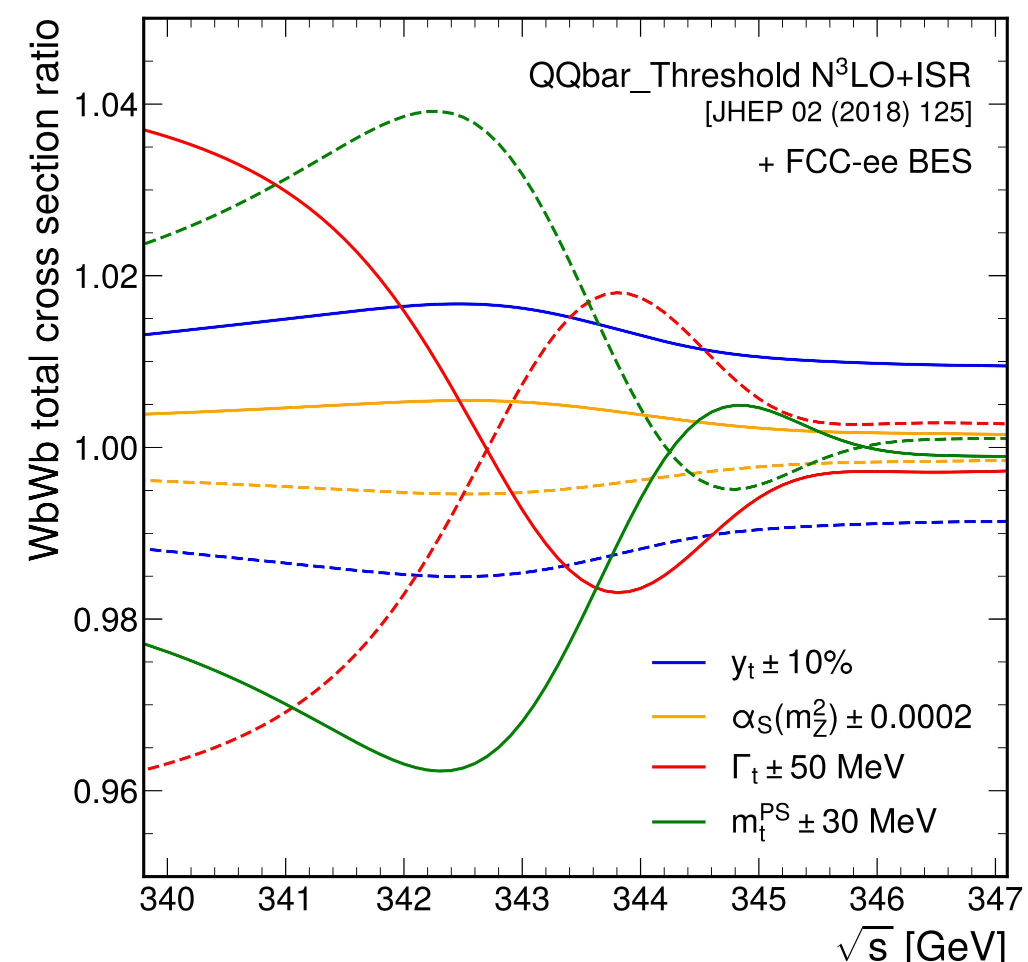
Fit results

- 3D fit of m_{top}, Γ_{top}, and y_{top} with profiled α_s and calibration parameters
- 10 equally-spaced points with equal luminosity
- Additional sensitivity to y_{top} from 365 GeV run

Uncertainty source	m_t^{PS} [MeV]	Γ_t [MeV]	y_t [%]
Experimental (stat. ×1.2)	4.2	10.0	1.5
Parametric m_t	–	5.3	1.2
Parametric Γ_t	3.0	–	0.8
Parametric y_t	3.8	4.8	–
Parametric α_S	2.2	1.6	0.2
Luminosity calibration (uncorr.)	0.6	1.1	0.2
Luminosity calibration (corr.)	1.0	0.7	0.9
Beam energy calibration (uncorr.)	1.3	1.9	0.1
Beam energy calibration (corr.)	1.3	< 0.1	< 0.1
Beam energy spread (uncorr.)	0.3	0.9	< 0.1
Beam energy spread (corr.)	< 0.1	1.1	< 0.1
Total profiled	6.5	11.7	2.1
Theory	35	25	?

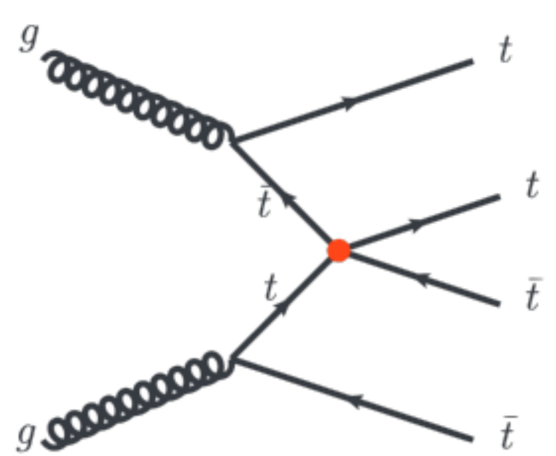
Need to reduce the theoretical scale uncertainties to match the expected experimental precision

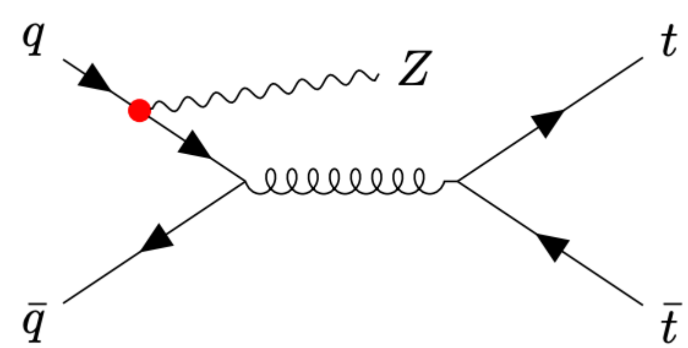




FCC-hh analyses: Motivation

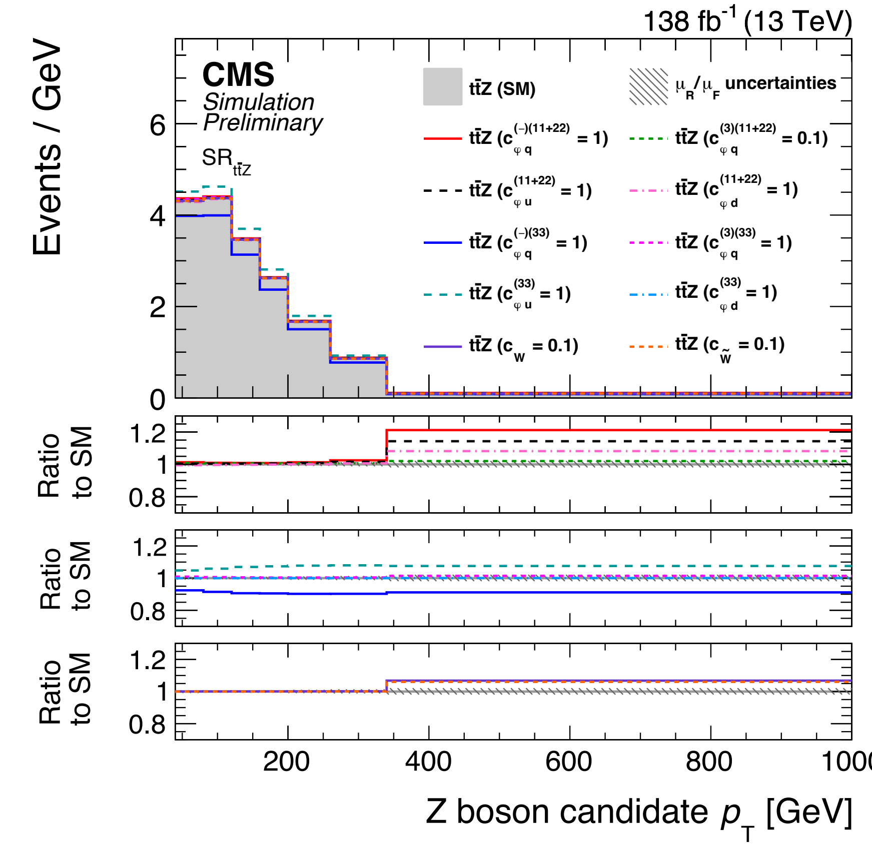
- 30ab^{-1} integrated luminosity at 84 TeV proton-proton collisions
- FCC-ee constrains EW coupling, FCC-hh probes rare processes and boosted topologies
- Higher sensitivity to EFTs energy growing effect (e.g. top self coupling, ttZ production)

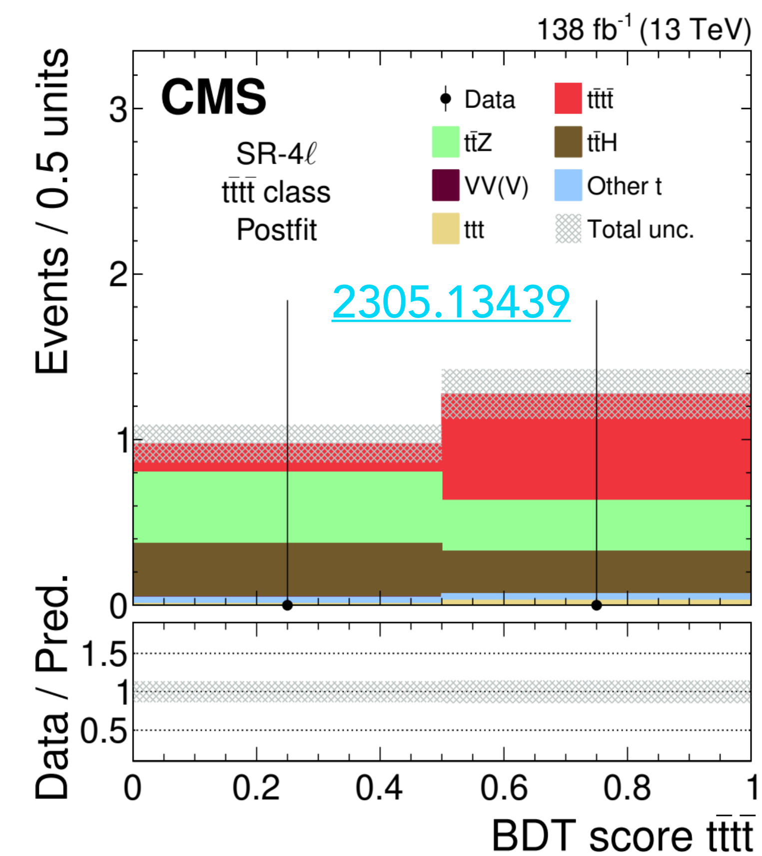




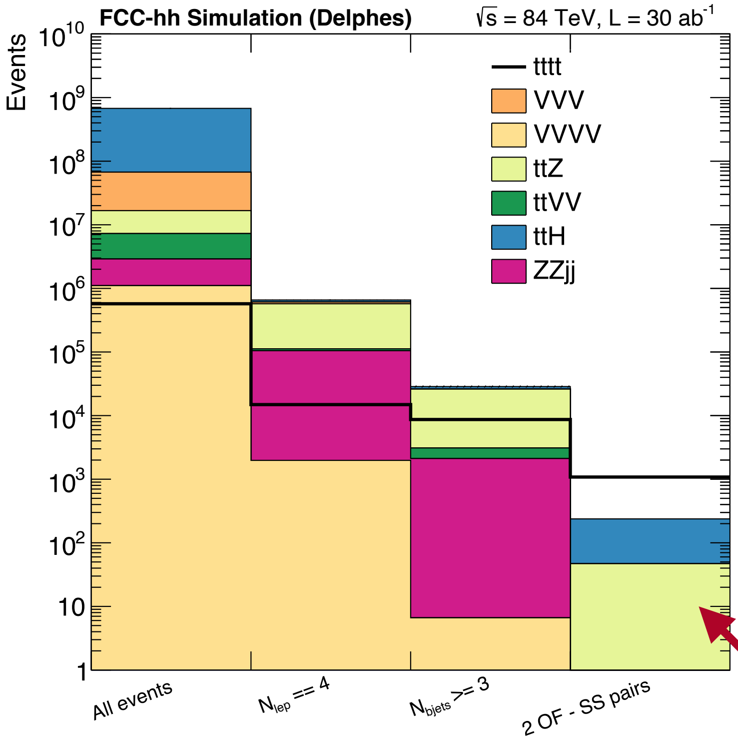
- Very high statistics allowing to target each process individually by applying very restrictive selection

- Limited sensitivity to 4-top operators @ FCC-ee
- Large margin of improvement compared to HL-LHC

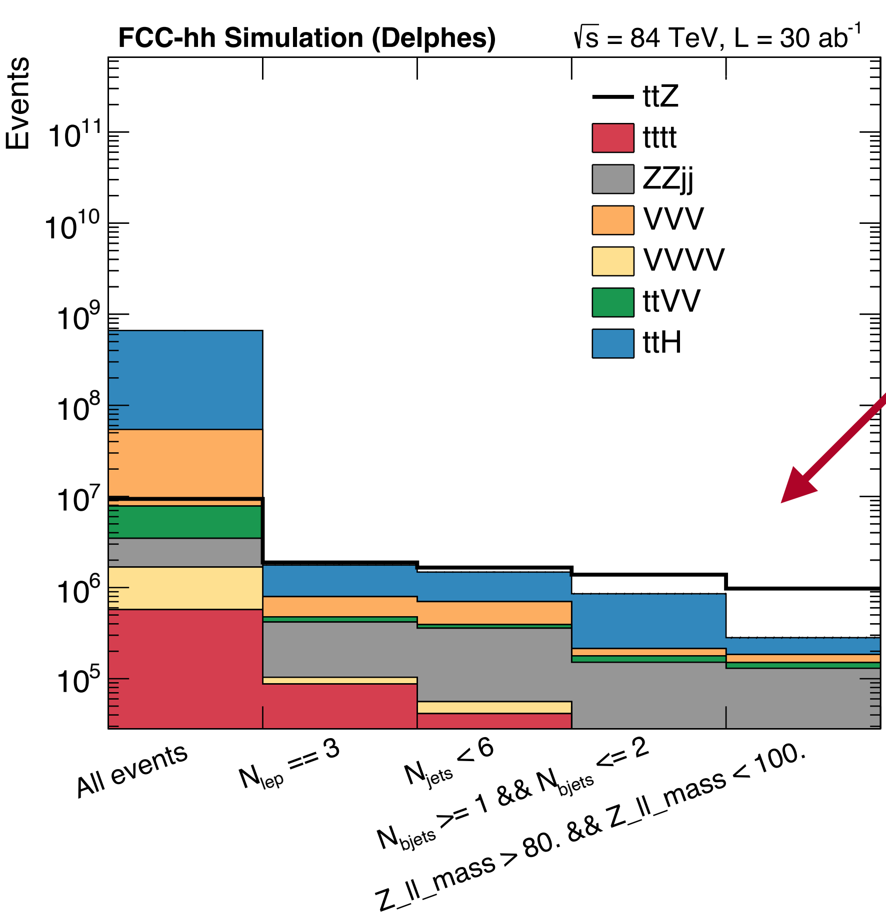




FCC-hh 4t & ttZ analyses: Strategy



Cutflow for 4t and ttZ analyses



Selection criterion for 4t and ttZ

Criteria	ttZ - 4l	tttt
Lepton Selection		
p_T	> 30 GeV	> 30 GeV
$\|\eta\|$	< 4	< 4
Number of leptons	Exactly 4	Exactly 4
Pairing	OS, SF (1st); OS (2nd)	OFSS (both)
Invariant mass (1st pair)	80–100 GeV	–
Jets Selection		
p_T	> 30 GeV	> 30 GeV
$\|\eta\|$	< 4	< 4
B-tagged jets	1 or 2, medium WP	> 2, medium WP
Total jets	< 6	–

Correlations between 4t & ttZ strongly mitigated by the restrictive cutflow

- To improve final statistics will require increase in lepton selection efficiency
- Right now, ~40% on single electron and ~60% on muon

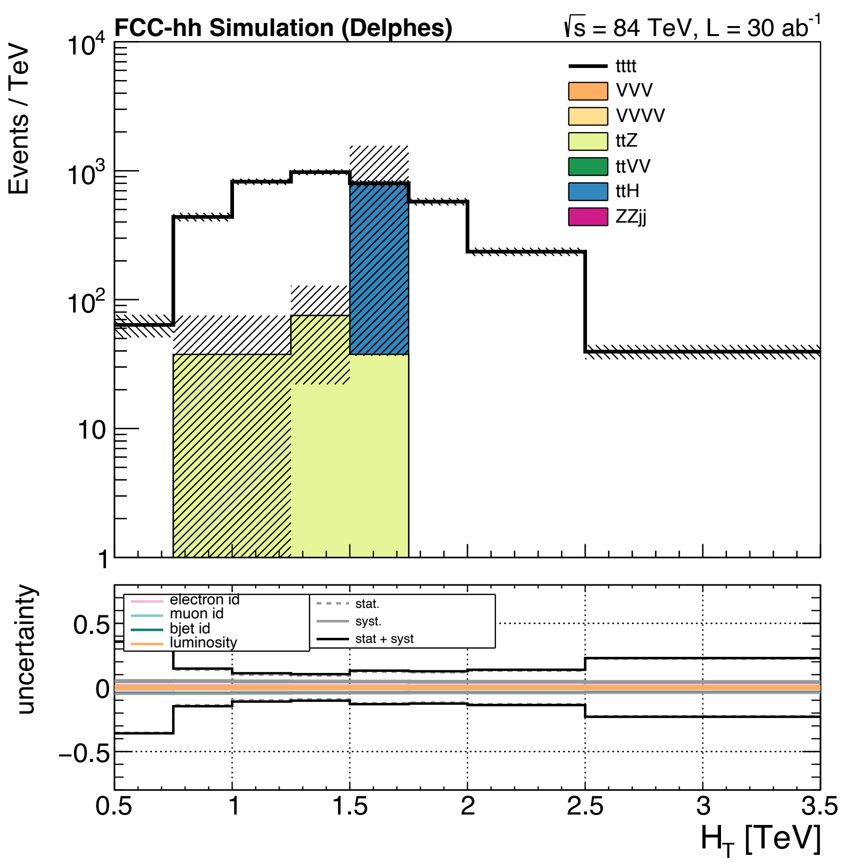
Only ~2.5% of events pass in the 4l channel

A small increase in the single lepton efficiency would have great effects in multi-lepton channels!

FCC-hh 4t & ttZ analyses: Results

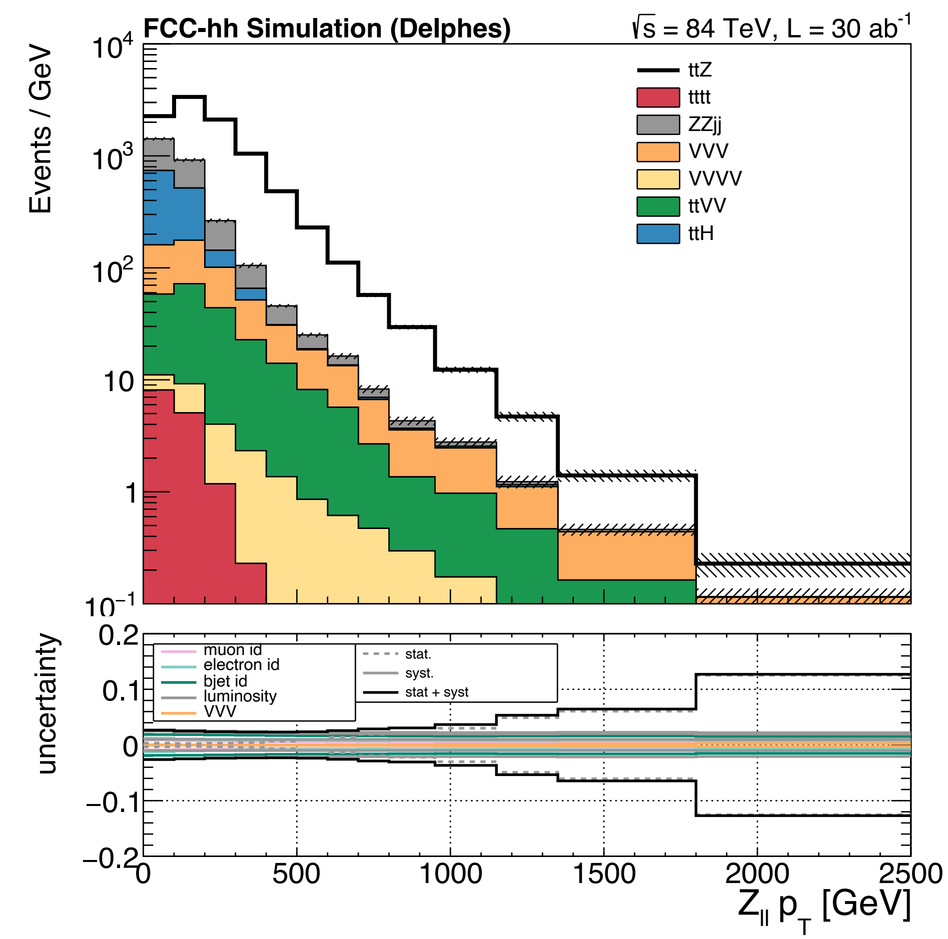
Reach of 3.5 TeV in H_T for 4t and of 2.5 TeV in p_T^Z for ttZ
Systematics at the 5% level or better

H_T defined as the scalar sum of transverse momenta of all **visible final objects**



- Clear H_T distribution for 4t events, with ttZ and ttH backgrounds effectively reduced by applying a strict OFSS selection on recollected leptons
- H_T variable sensitive to EFT energy growing effect

ttZ



- Clean ttZ signal obtained, with strong suppression of 4t background through charge and flavor requirements on selected leptons.
- Tail of the p_T^Z distribution is cleaner for EFT signals

Conclusions

- Rich (and complementary) top-quark physics program at FCC-ee and FCC-hh

- Outlined physics case for a tt threshold run at FCC-ee
- Precision measurement
  - Complete study of tt threshold including detector-level, machine-related, and parametric uncertainties
  - Shown that <u>systematic effects are well under control</u>
  - Theoretical progress needed to fully profit from physics potential of FCC-ee
  - High potential to constrain top quark couplings and BSM decays at the 365 GeV FCC-ee run

- New opportunities (and challenges) for top physics at FCC-hh starting to be explored
- BSM physics searches
  - Outlined physics case for ttZ & 4top production process
  - Achieved high-purity ttZ and 4t selection.
  - Reduced ttZ-4t correlation compared to LHC
  - Reaches visible H_T up to 4.5 TeV for 4t and p_T^Z up to 2.5 TeV for ttZ
  - Results will significantly benefit from improved lepton identification, with ongoing work to optimize selection efficiency