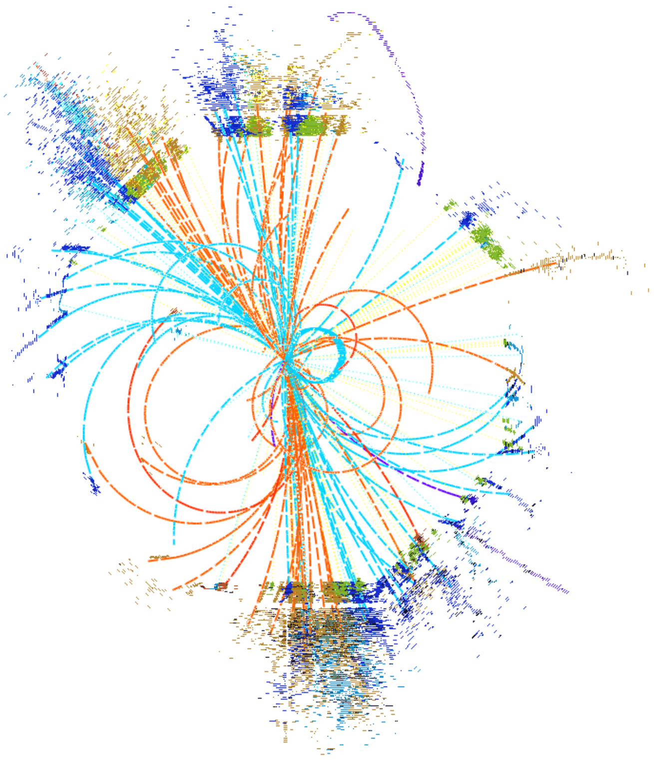
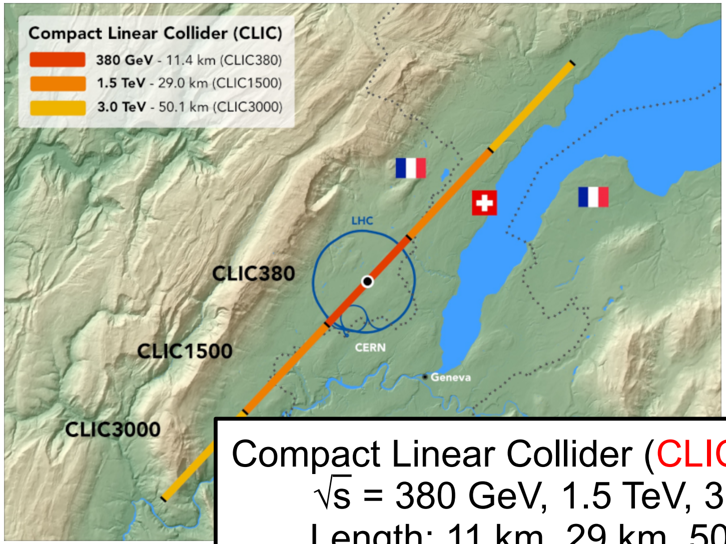
Top-quark physics at future colliders

Philipp Roloff (CERN)
08/09/2021

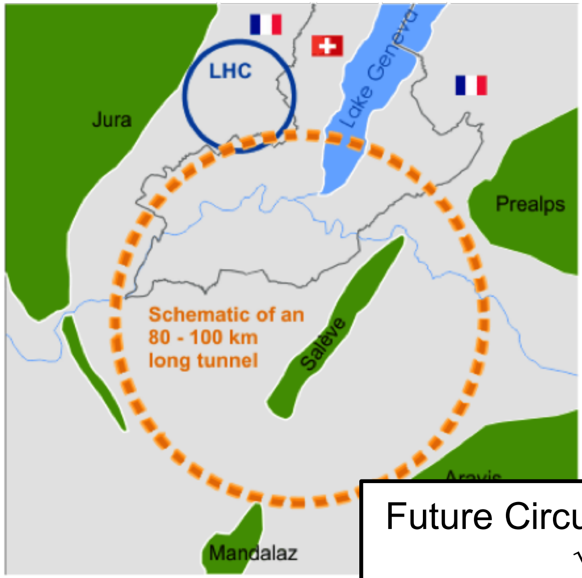


LFC21: Strong Interactions from QCD
to New Strong Dynamics
at LHC and Future Colliders

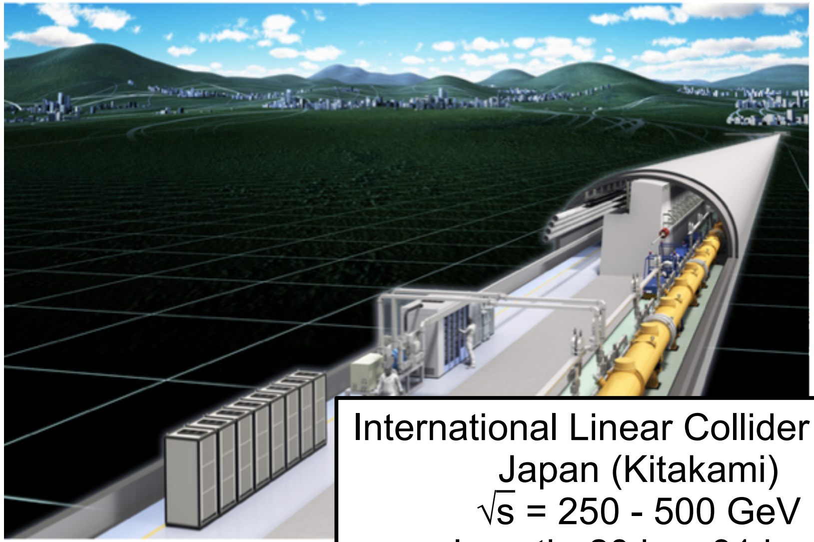
Studies of high-energy e^+e^- colliders



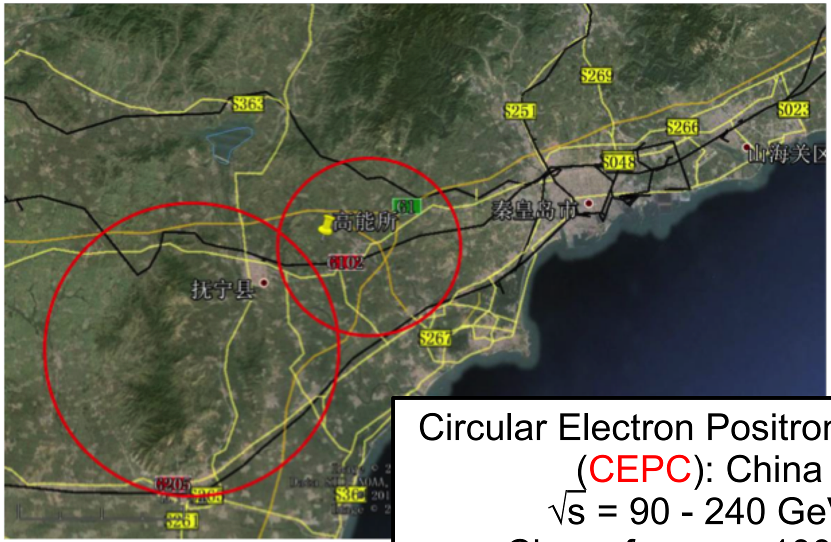
Compact Linear Collider (CLIC): CERN
$\sqrt{s}$ = 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km, 50 km



Future Circular Collider (FCC-ee): CERN
$\sqrt{s}$ = 90 - 365 GeV
Circumference: 97.75 km

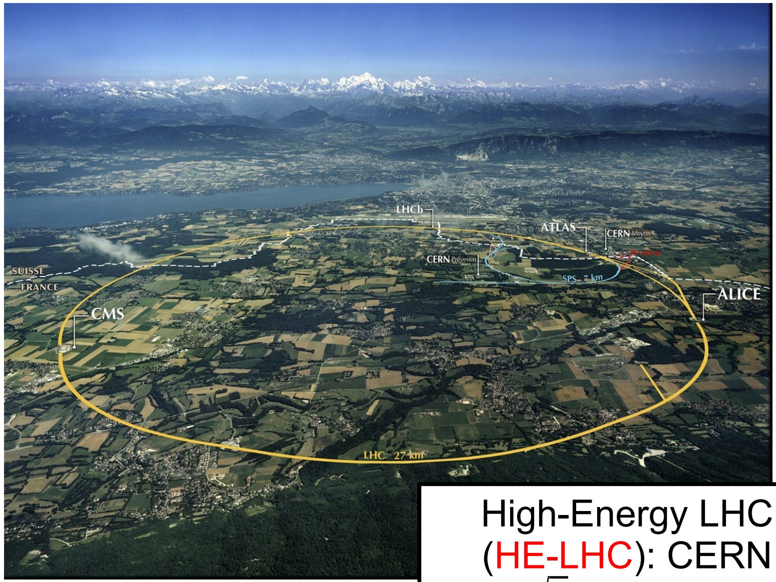


International Linear Collider (ILC):
Japan (Kitakami)
$\sqrt{s}$ = 250 - 500 GeV
Length: 20 km, 31 km

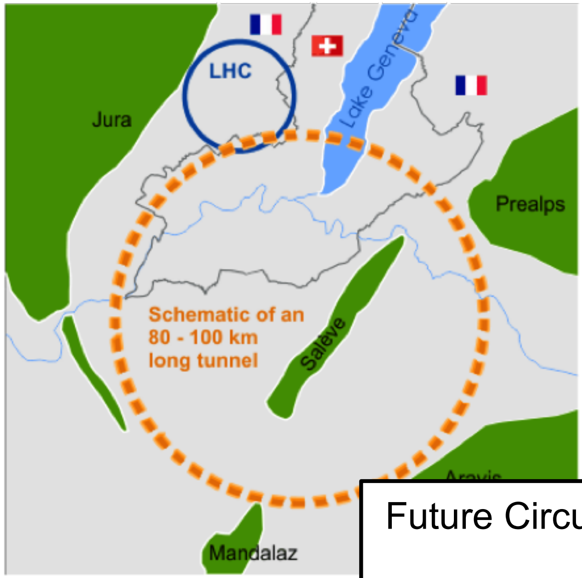


Circular Electron Positron Collider
(CEPC): China
$\sqrt{s}$ = 90 - 240 GeV
Circumference: 100 km

Studies of high-energy pp colliders



High-Energy LHC (HE-LHC): CERN
$\sqrt{s} \approx 27$ TeV
Circumference: 27 km



Future Circular Collider (FCC-hh): CERN
$\sqrt{s} \approx 100$ TeV
Circumference: 97.75 km

→ see talk by S. Gibson

Reminder: collider parameters

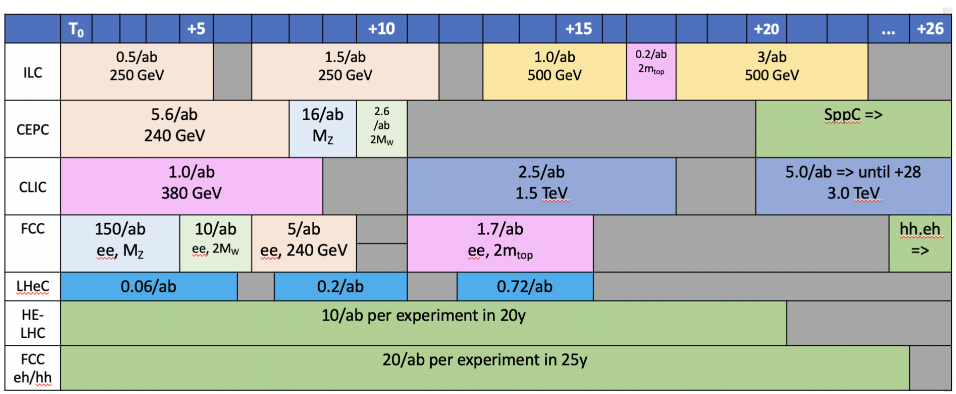
pp colliders

e⁺e⁻ colliders

ep colliders

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N_{Det}	$\mathscr{L}_{\text{inst}}$/Det. $[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	$\mathscr{L}$ $[\text{ab}^{-1}]$	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
		(1y SD before $2m_{top}$ run)					(+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
		(1y SD after 250 GeV run)					(+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
		(2y SDs between energy stages)					(+4)
LHeC	ep	1.3 TeV	–	1	0.8	1.0	15
HE-LHeC	ep	1.8 TeV	–	1	1.5	2.0	20
FCC-eh	ep	3.5 TeV	–	1	1.5	2.0	25

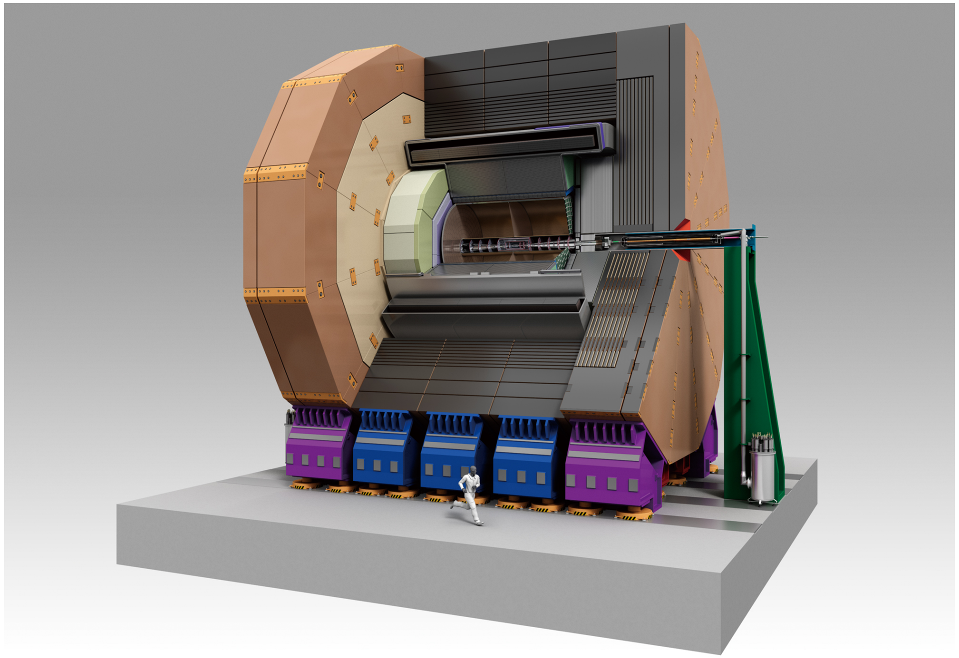
+ muon collider, advanced e⁺e⁻ collider, ...



ESU Physics Briefing Book

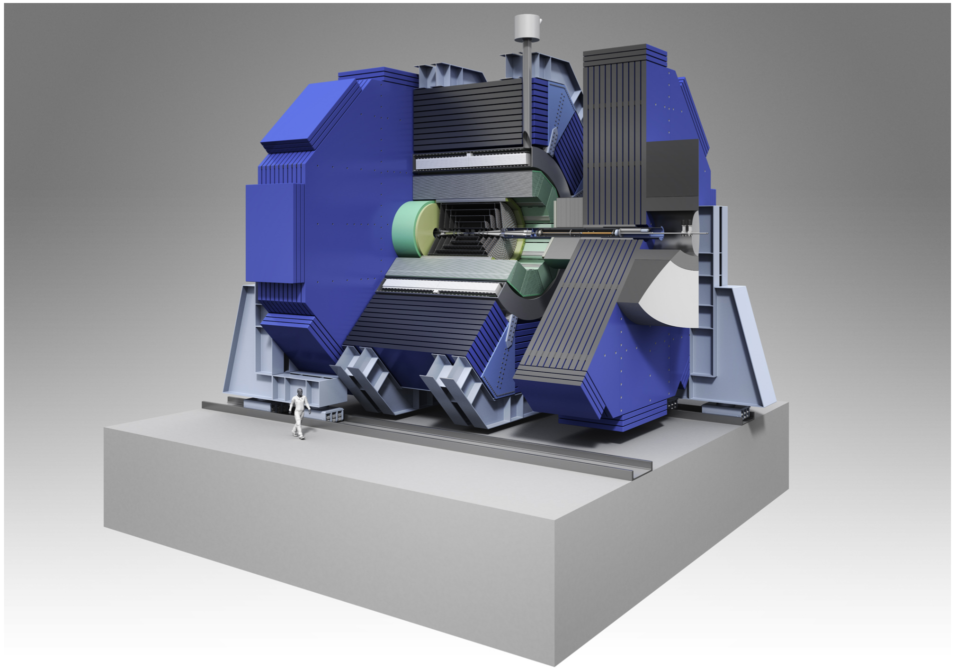
ILC detector concepts

Designed for Particle Flow Calorimetry:
- High granularity calorimeters (ECAL and HCAL) inside solenoid
- Low mass trackers → reduce interactions / conversions



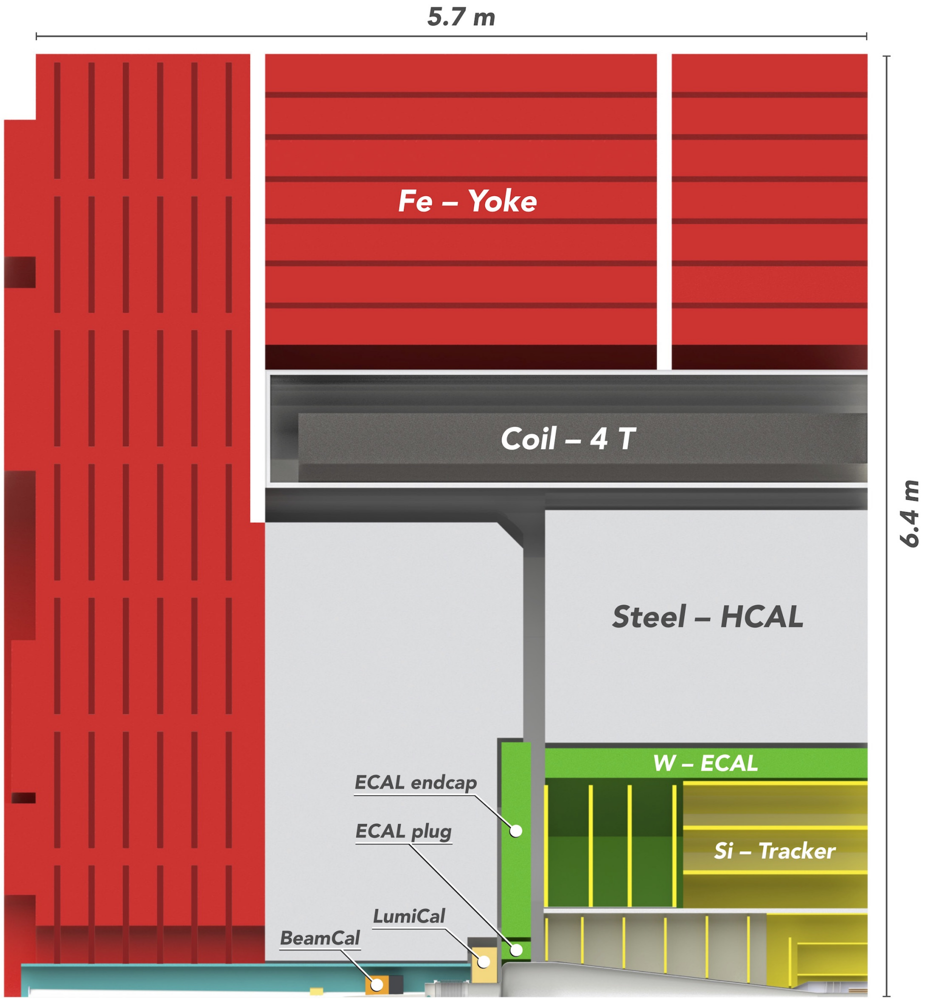
ILD (International Large Detector):
- TPC+silicon envelope, radius: 1.8 m
- B-field: 3.5 T

(small option: 1.46 m / 4 T recently studied)

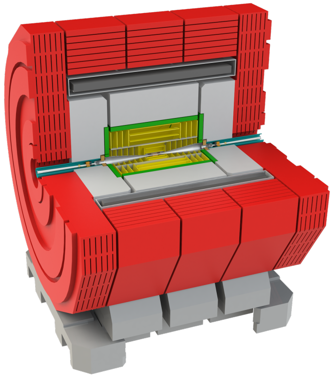


SiD (Silicon Detector):
- Silicon tracking, radius: 1.2 m
- B-field: 5 T

CLIC detector concept: CLICdet

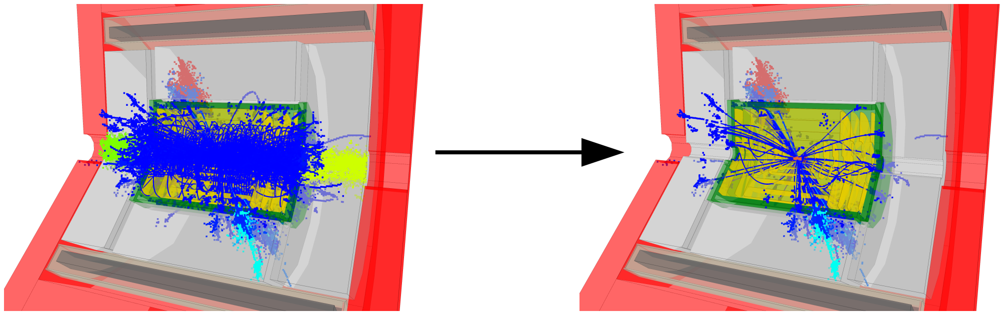


Basic characteristics:
- B-field: 4 T
- Vertex detector with 3 double layers
- Silicon tracking system (1.5 m radius)
- ECAL with 40 layers (22 X_0)
- HCAL with 60 layers (7.5 λ)



Precise timing:
- ≈ 10 ns hit time-stamping in tracking
- 1 ns accuracy for calorimeter hits

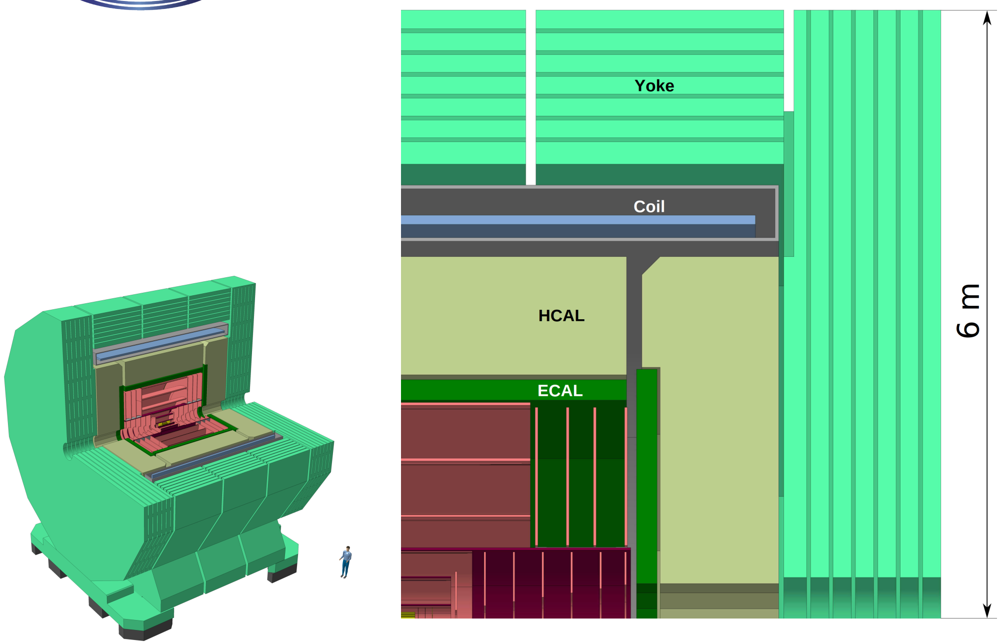
Beam-induced background can be efficiently suppressed by applying p_T-dependent timing cuts on individual reconstructed particles (= particle flow objects)

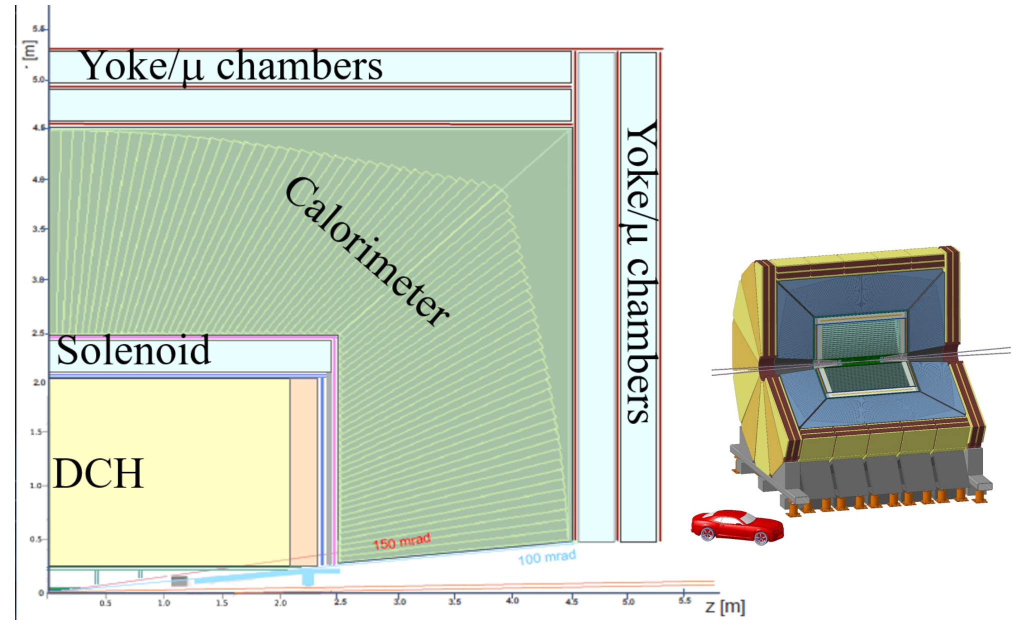


$e^+e^- \rightarrow t\bar{t}$ at 3 TeV with background from γγ → hadrons overlaid

CLICdp-Note-2017-001
arXiv:1812.07337

FCC-ee detector designs



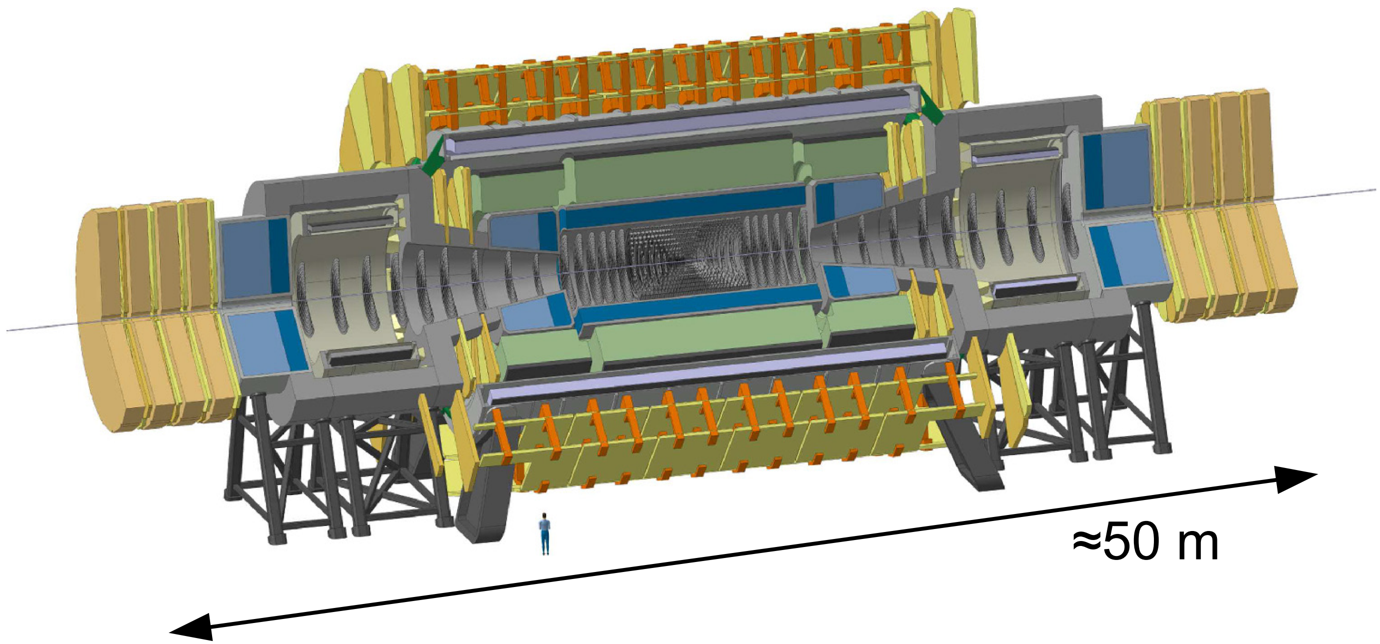


CLD concept (inspired by CLICdet):
- Smaller magnetic field (limited by luminosity goal): 2 T
- Larger tracker radius (2.15 m) to keep similar momentum resolution
- Lower $\sqrt{s} \rightarrow$ HCAL less deep

IDEA detector concept (also for CEPC):
- B-field: 2 T
- Vertex detector: 5 MAPS layers
- Drift chamber with PID, radius: 2 m, 112 layers $\rightarrow$ low material budget
- Double read-out calorimetry
- Instrumented return yoke

arXiv:1911.12230

FCC-hh detector concept

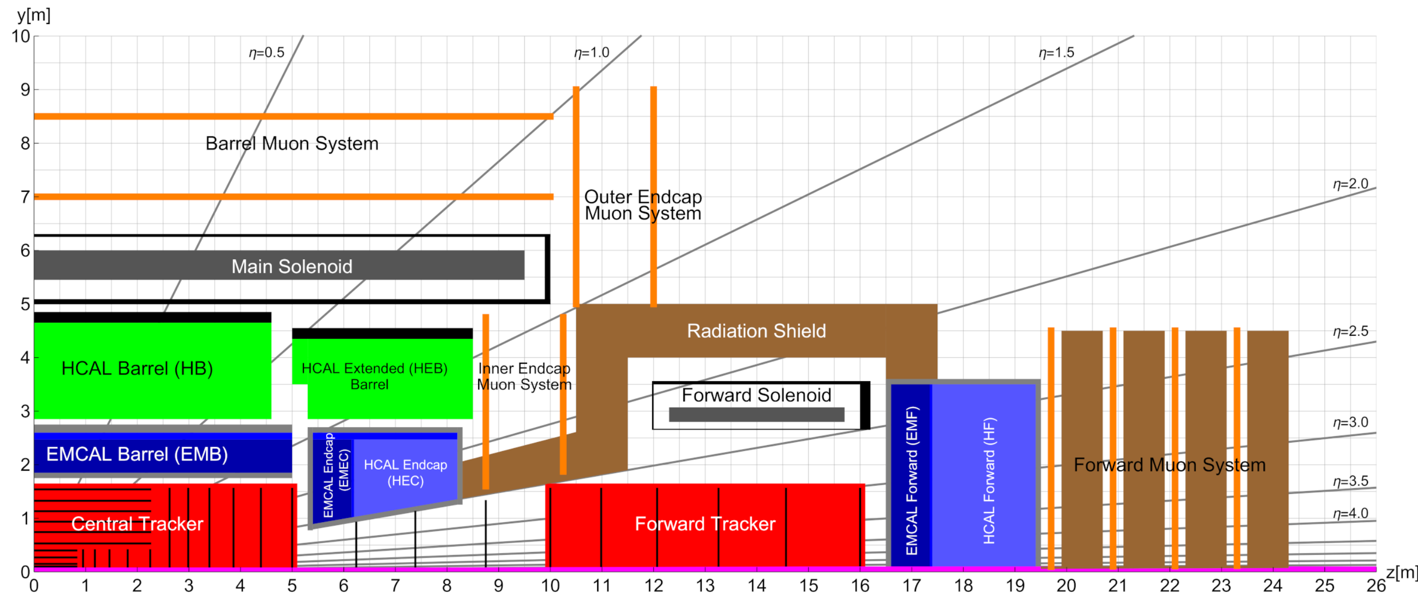


Reference detector in CDR:

- 4 T solenoid, 10 m diameter
- Forward solenoids
- Silicon tracker
- Barrel ECAL LAr
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

- Compared to ATLAS & CMS, the forward calorimeters are moved far out to reduce radiation load and increase the granularity

- A shield (brown) is needed to stop neutrons escaping to the cavern and muon system



FCC-hh CDR

Top-quark physics at future colliders

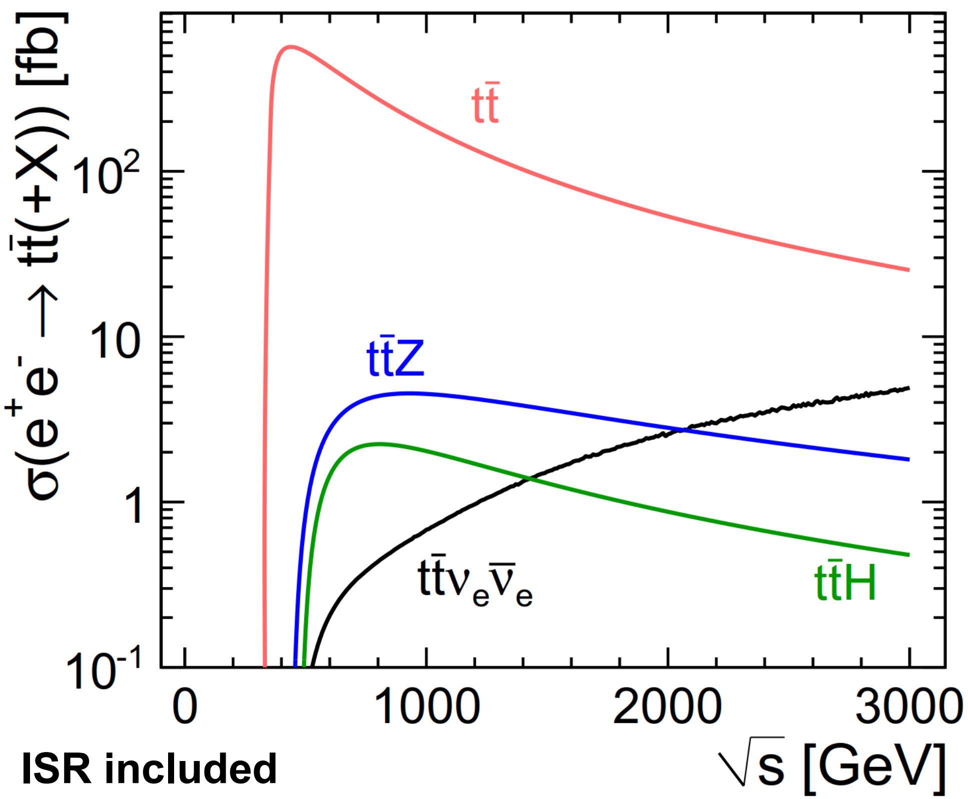
Top-quark pair production at e^+e^- colliders
(mainly based on full simulations)**:**

- Measurements of the mass
- Top-quark EW couplings
- Processes at high energy

A few highlights from FCC-hh

Top-quark FCNC

Top-quark pair production in e^+e^- collisions



ISR included

$e^+e^- \rightarrow t\bar{t}$:

- Production threshold at $\sqrt{s} \approx 2m_{top}$
- 365 - 500 GeV is near the maximum

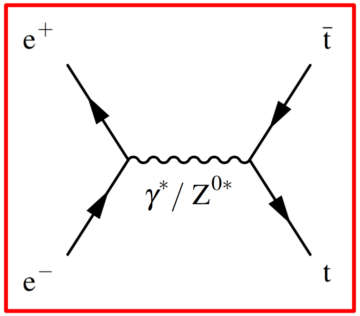
$\rightarrow$ large event samples (for rare decays etc.)

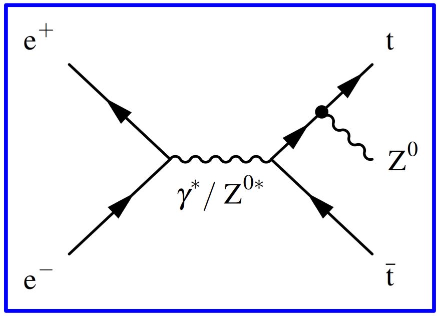
$e^+e^- \rightarrow t\bar{t}H$:

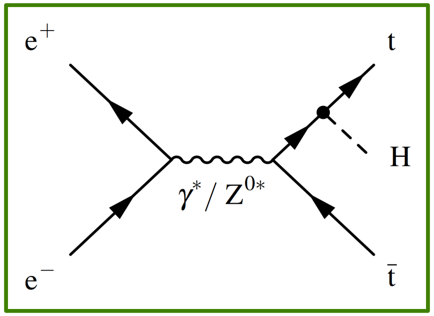
- Maximum near 800 GeV

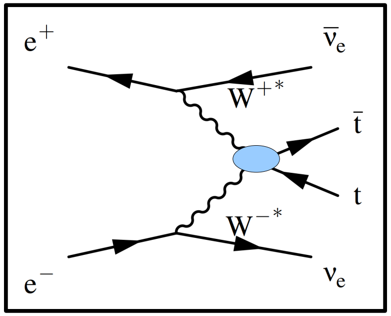
$e^+e^- \rightarrow t\bar{t}\nu_e\bar{\nu}_e$ (Vector Boson Fusion)**:**

- Benefits from highest energies

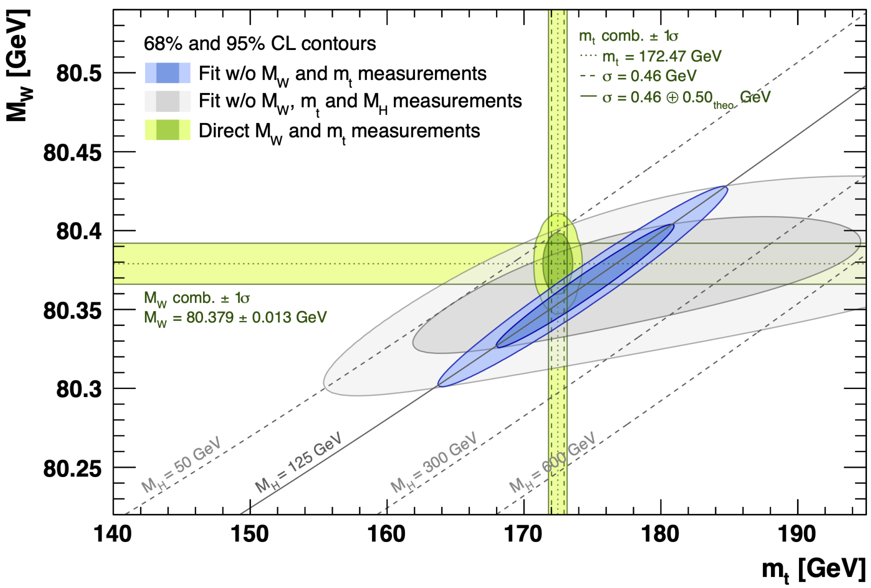




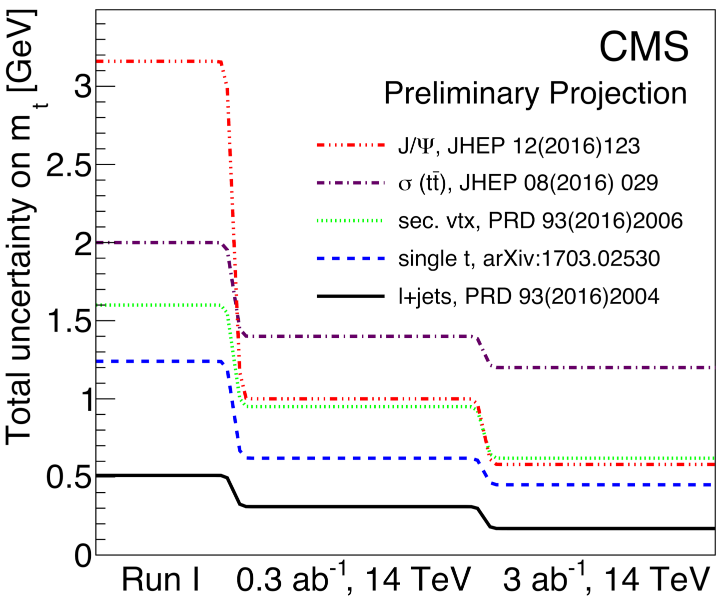




Top-quark mass



Direct and indirect constraints on top (and W) mass



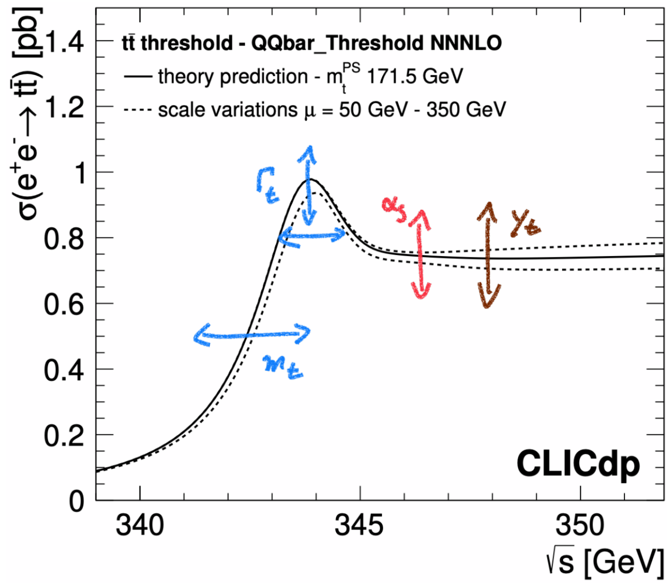
Complementary methods at e^+e^- collider:

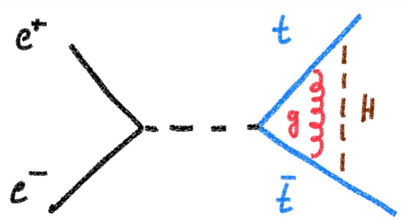
- Threshold scan
- Direct reconstruction
- Radiative events

→ discussed in the following slides

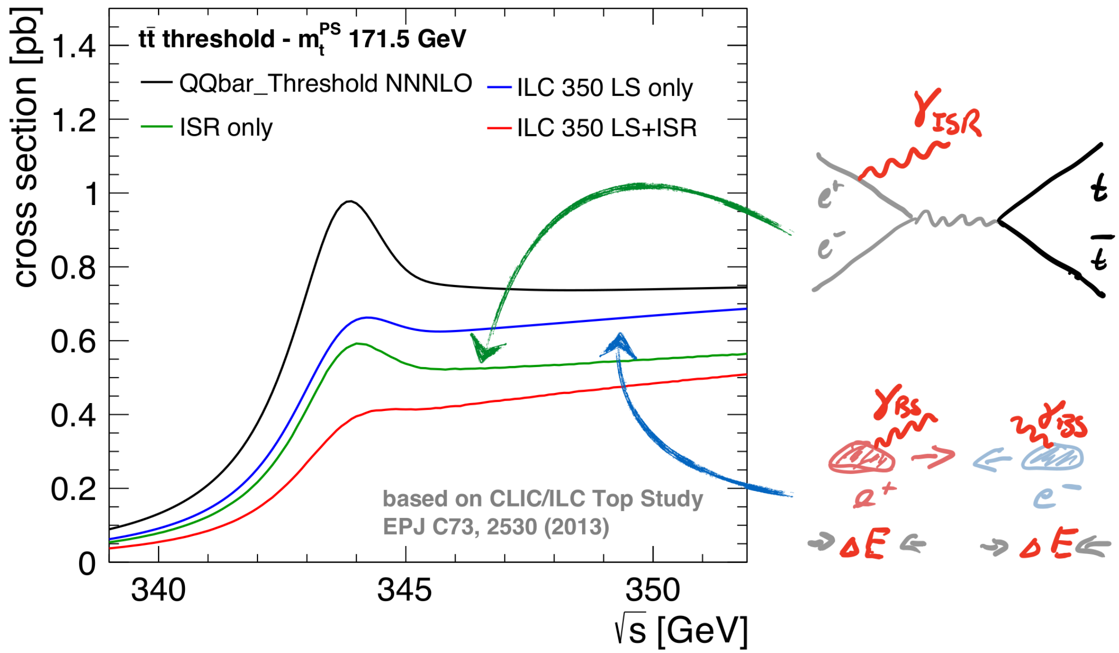
EPJ **C 78**, 675 (2018)
CERN-LPCC-2018-03

Top-quark pair production at threshold





- Exploit precise theoretical calculations of cross section in the threshold region, in well-defined mass schemes (m_t^{PS}, m_t^{1S}…) -> Can be converted directly into MSbar mass.

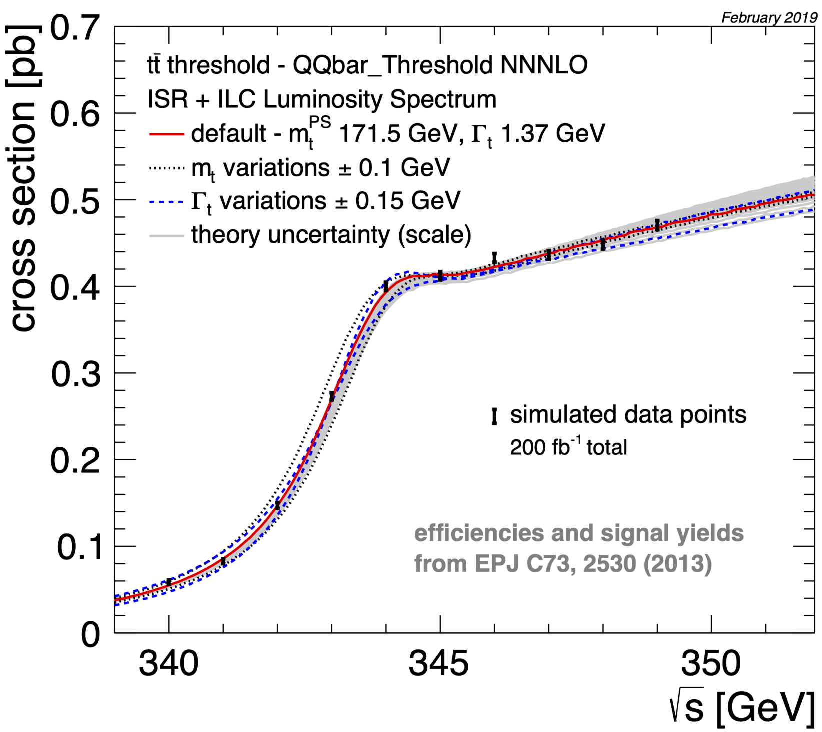


The threshold is sensitive to top quark properties

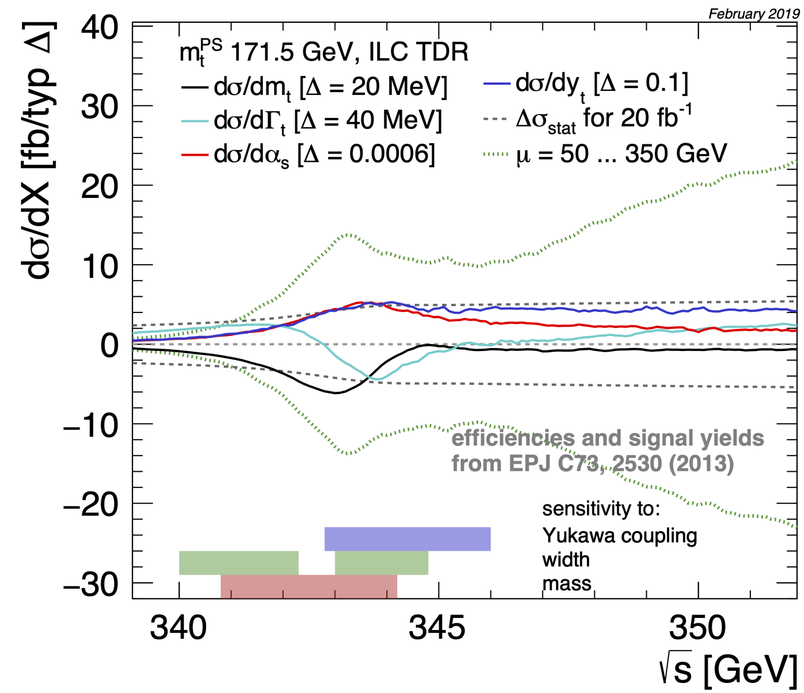
… and influenced by em physics and collider parameters

Frank Simon

Mass: expected sensitivity (2)



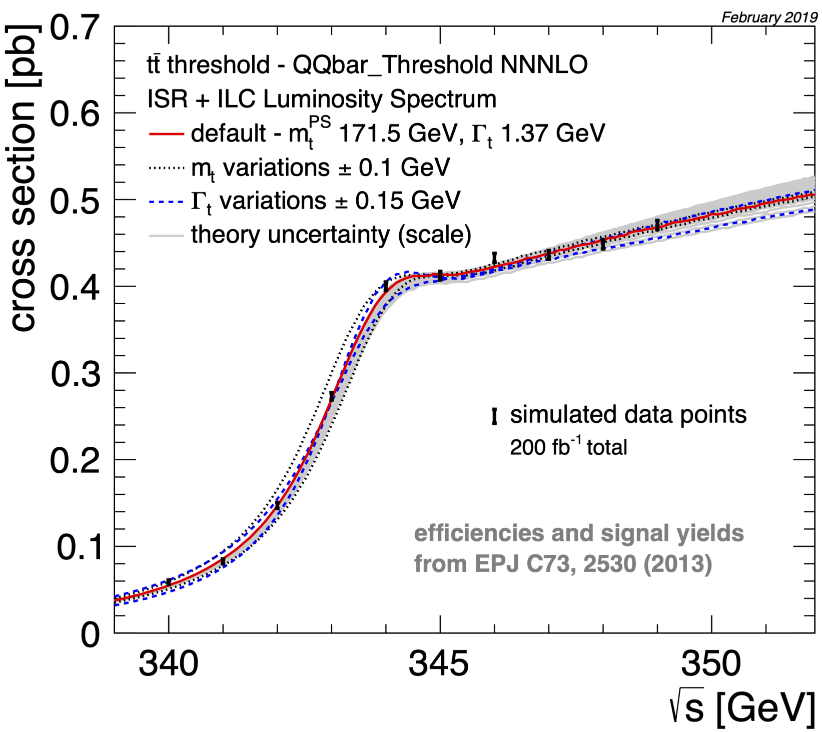
Example: threshold scan at ILC with 200 fb^{-1}



→ sensitivity on different parameters depends on position along the threshold

arXiv:1902.07246

Mass: expected sensitivity (3)



error source	Δm_t^{PS} [MeV]
stat. error (200 fb^{-1})	13
theory (NNNLO scale variations, PS scheme)	40
parametric (α_s, current WA)	35
non-resonant contributions (such as single top)	< 40
residual background / selection efficiency	10 – 20
luminosity spectrum uncertainty	< 10
beam energy uncertainty	< 17
combined theory & parametric	30 – 50
combined experimental & backgrounds	25 - 50
total (stat. + syst.)	40 – 75

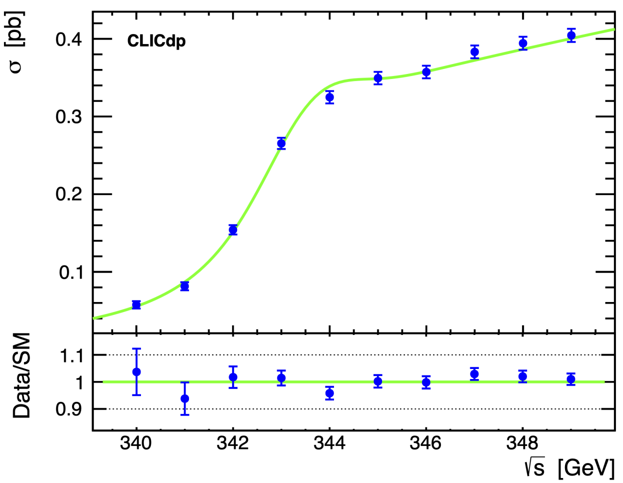
Example: threshold scan at ILC with 200 fb^{-1}

→ theory and parametric uncertainties large compared to statistical precision with current knowledge

arXiv:1902.07246

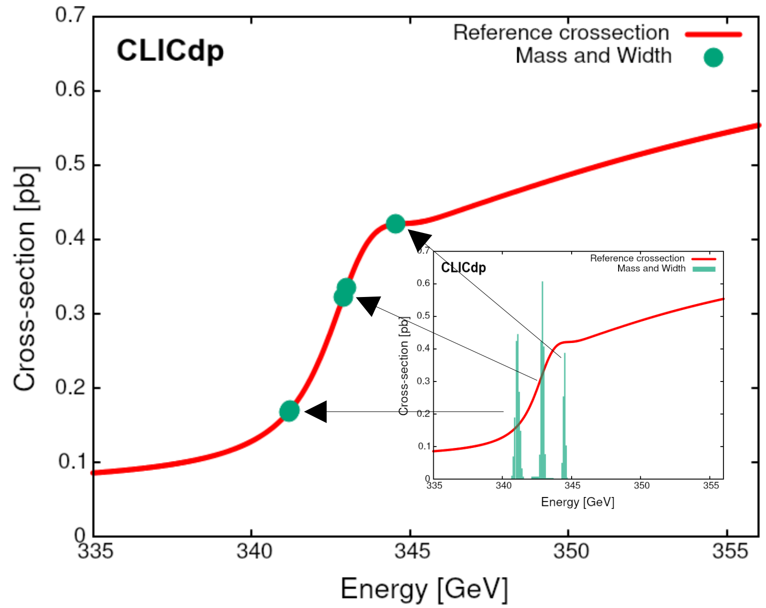
Optimisation of the threshold scan

Baseline scenario:

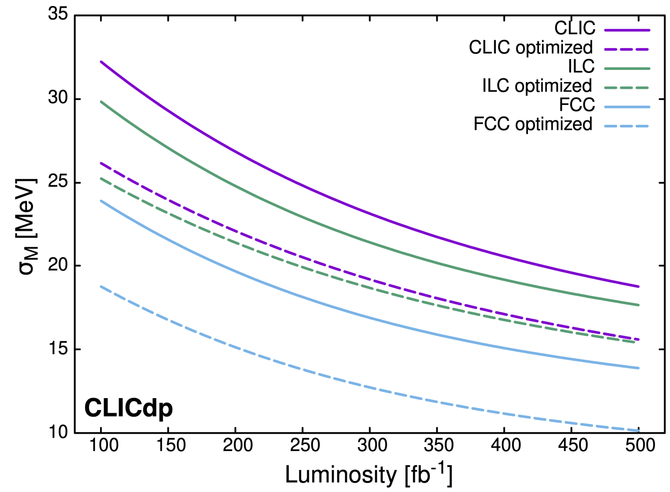


10 points of 10 fb^{-1} each

Optimised for mass & width:

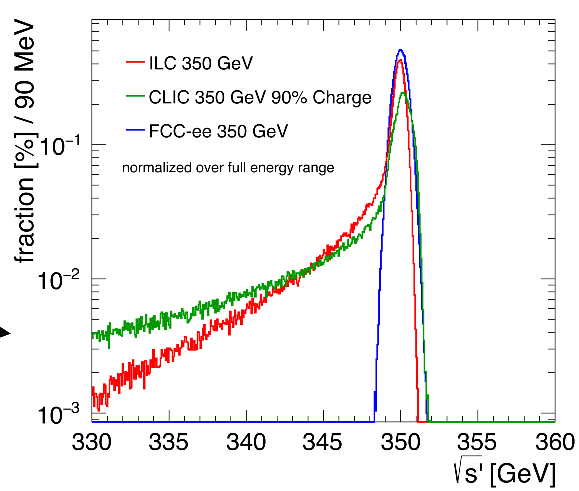


Precision on top mass:



- Optimisation of quantity and centre-of-mass energy for the individual cross section measurements → 25% better statistical precision on top mass compared to 10 equidistant measurements

- Main difference between colliders: luminosity spectra



JHEP **07**, 070 (2021)

Top mass in the continuum

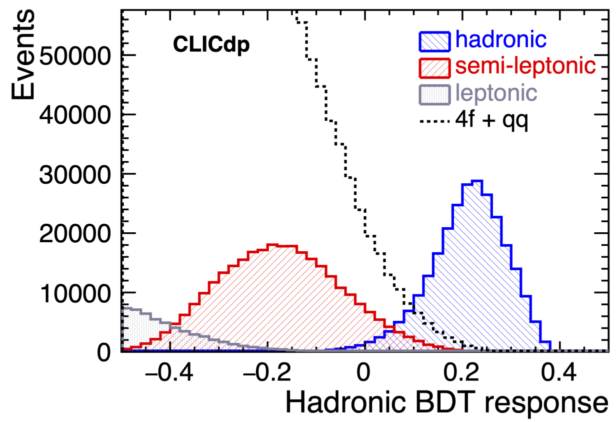
Example: CLIC at 380 GeV

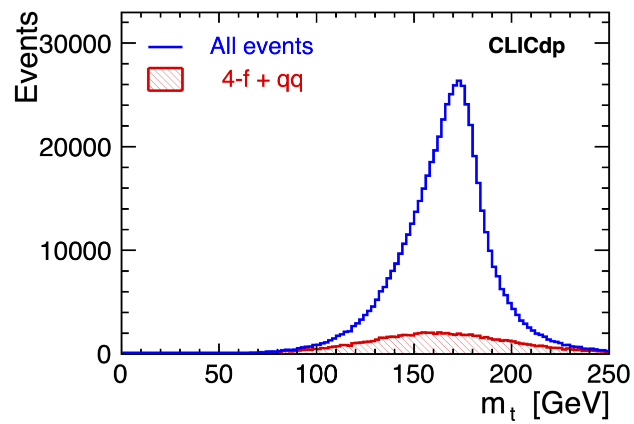
• Template fit to reconstructed top candidate mass distributions: 30 MeV (40 MeV) statistical precision for hadronic (semi-leptonic) events with 1 ab^{-1}

• Excellent knowledge of jet (including b-jet) energy scales needed → short calibration run at Z-pole each year?

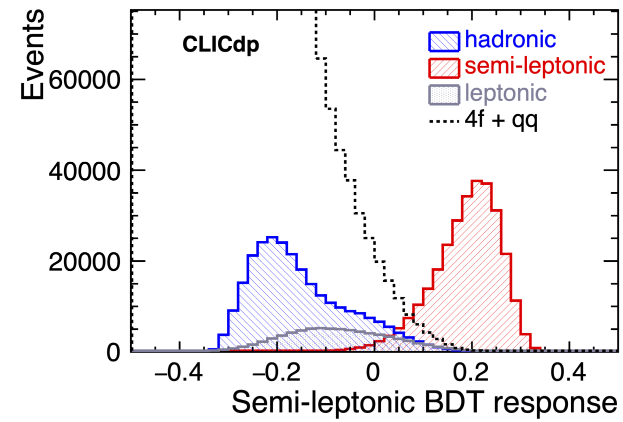
• Interpretation of measured mass value induces significant theoretical uncertainties

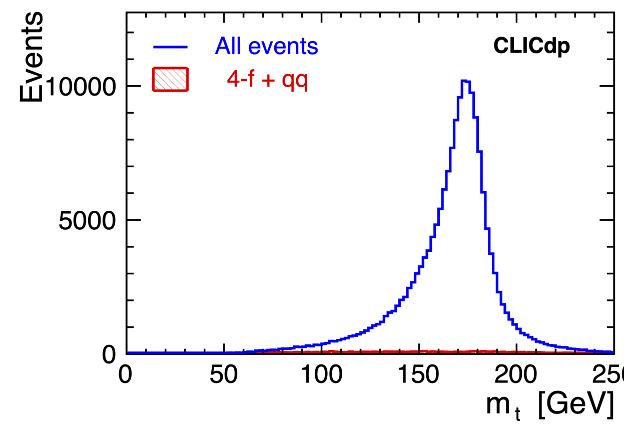
Fully hadronic:





Semi-leptonic:





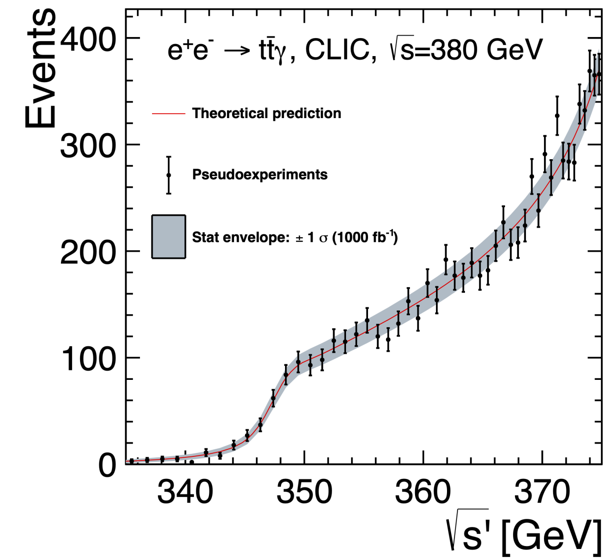
JHEP **11**, 003 (2019)

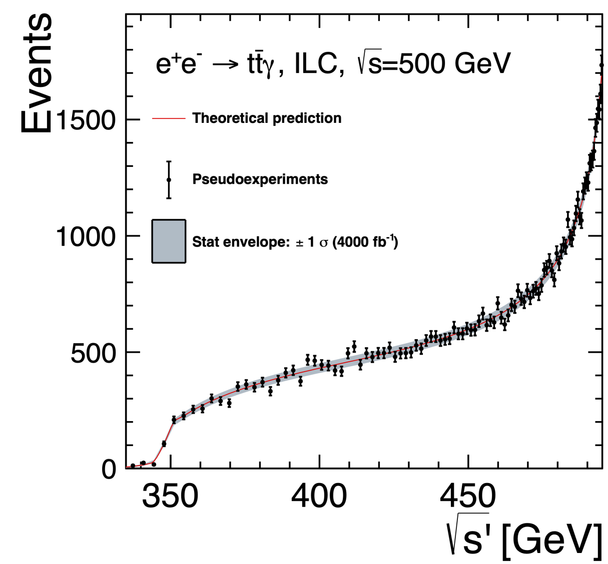
Radiative events: $e^+e^- \rightarrow t\bar{t}\gamma$

• Radiative events allow to extract the top mass in a well-defined mass scheme above threshold

• Using matched NNLL threshold + N³LO continuum calculation and CLIC/ILC luminosity spectra

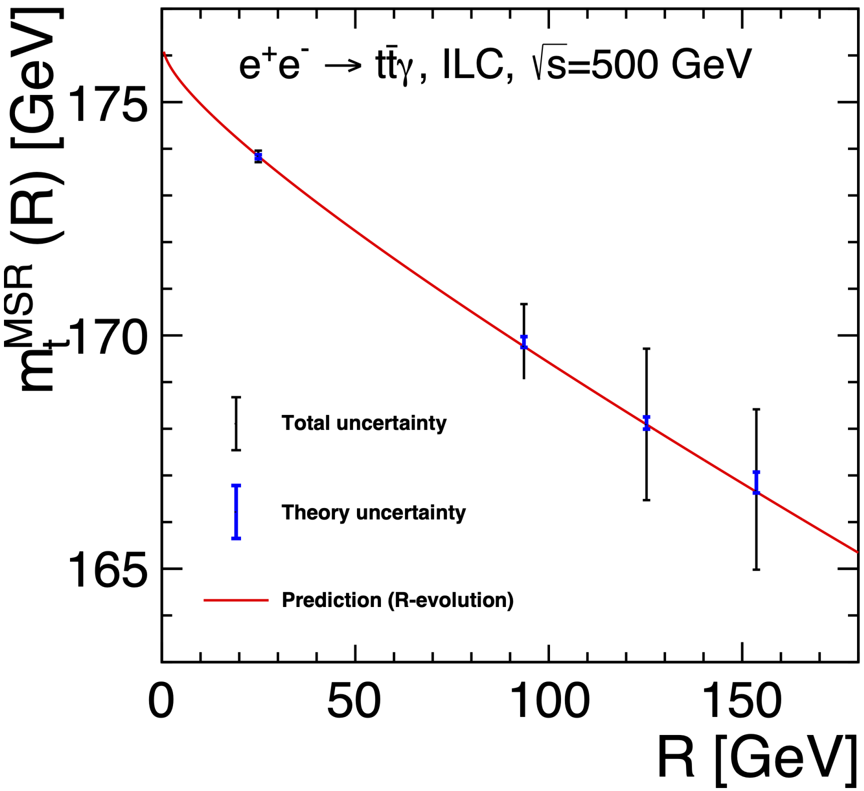
cms energy	CLIC, $\sqrt{s} = 380$ GeV		ILC, $\sqrt{s} = 500$ GeV	
luminosity [fb^{-1}]	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV





PLB **804**, 135353 (2020)

Running of the top-quark mass



→ 5σ evidence for scale evolution (= "running") of MSR mass form the ILC data at 500 GeV

PLB **804**, 135353 (2020)

Top-quark electroweak couplings

- Top quark pairs are produced via Z/γ* in electron-positron collisions
- The general form of the coupling can be described as:

arXiv:hep-ph/0601112

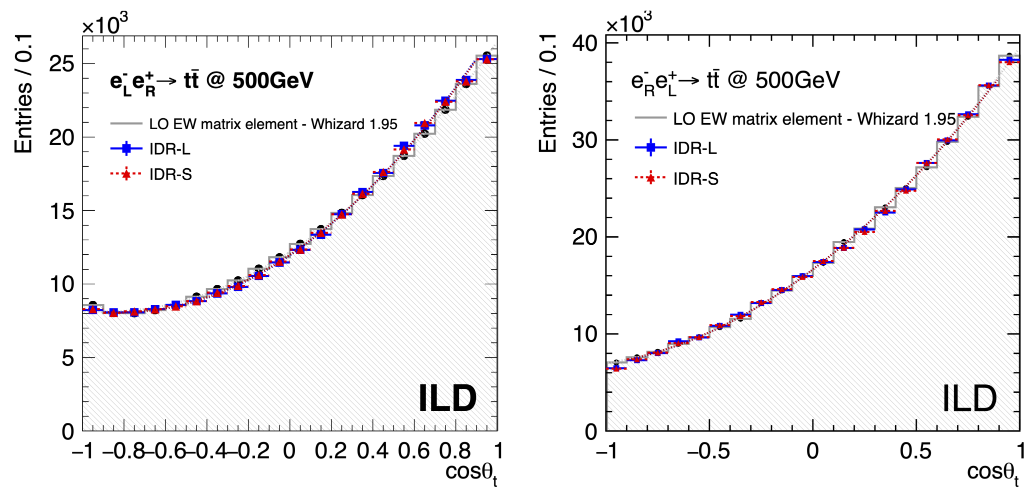
CP conserving **CPV**

$$\Gamma_{\mu}^{ttV}(k^2, q, \bar{q}) = -ie\left\{\gamma_{\mu}\left(F_{1V}^{V}(k^2) + \gamma_5 F_{1A}^{V}(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^{\nu}\left(iF_{2V}^{V}(k^2) + \gamma_5 F_{2A}^{V}(k^2)\right)\right\}$$

- At linear colliders, the γ and Z form factors can be disentangled using beam polarisation
→ measure σ and A_{FB} for different polarisation configurations

- The γ and Z contributions can also be separated using the lepton energy and angular distributions in semi-leptonic events
→ Form-factor measurement also possible at circular colliders

→ Both approaches are complementary



$$A_{FB}^{t} = \frac{N(\cos\theta_t > 0) - N(\cos\theta_t < 0)}{N(\cos\theta_t > 0) + N(\cos\theta_t < 0)}$$

Top-quark electroweak couplings

- Top quark pairs are produced via Z/γ* in electron-positron collisions
- The general form of the coupling can be described as:

arXiv:hep-ph/0601112

CP conserving — CPV

$$\Gamma_\mu^{ttV}(k^2, q, \bar{q}) = -ie\left\{\gamma_\mu \left(F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu \left(iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2)\right)\right\}$$

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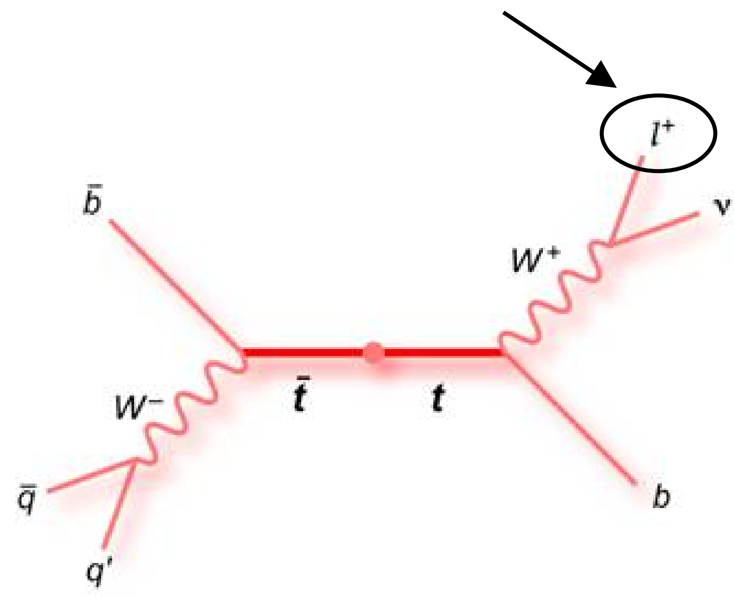


→ Both approaches are complementary

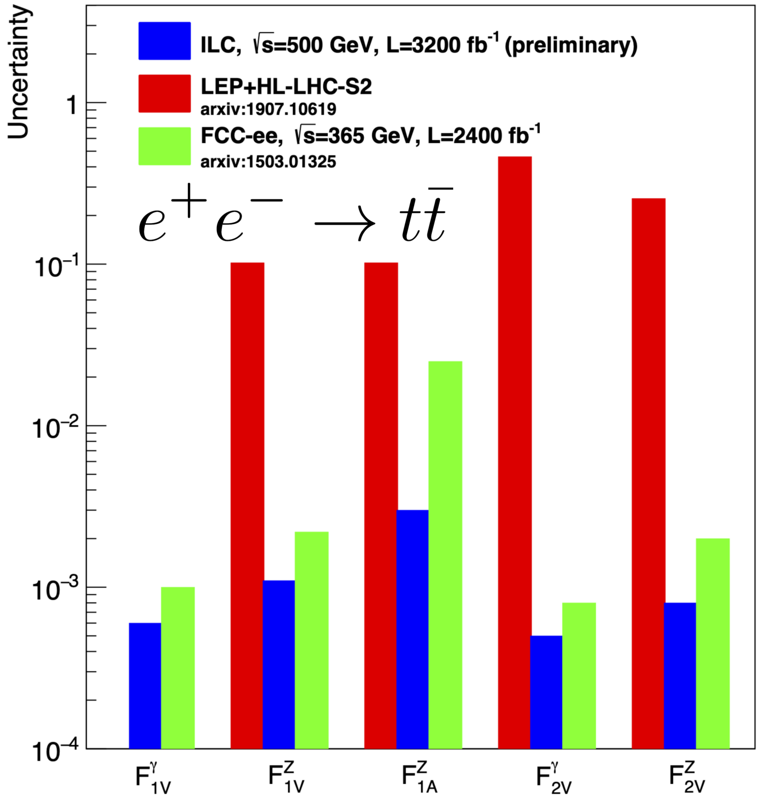
Sensitivity to form factors

- Top quark pairs are produced via Z/γ* in electron-positron collisions
- The general form of the coupling can be described as:

arXiv:hep-ph/0601112

CP conserving ... **CPV**

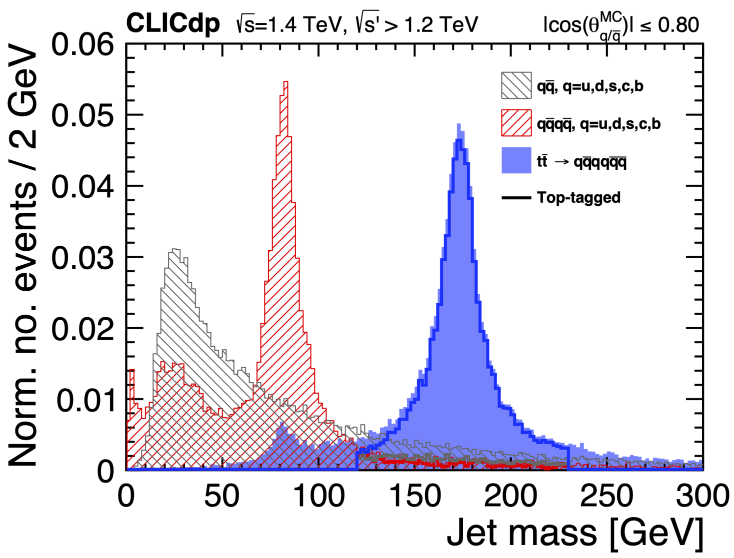
$$\Gamma_\mu^{ttV}(k^2, q, \bar{q}) = -ie\left\{\gamma_\mu\left(F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2)\right)\right\}$$



→ Lepton colliders provide significant improvement compared to HL-LHC

R. Pöschl, EPS-HEP 2021

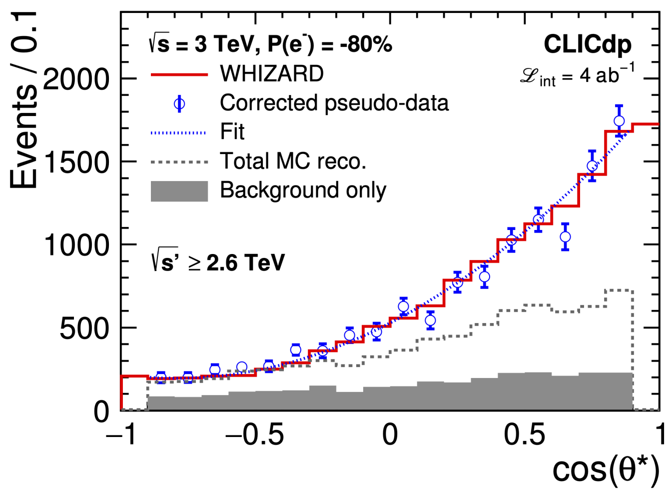
Boosted top quarks at CLIC

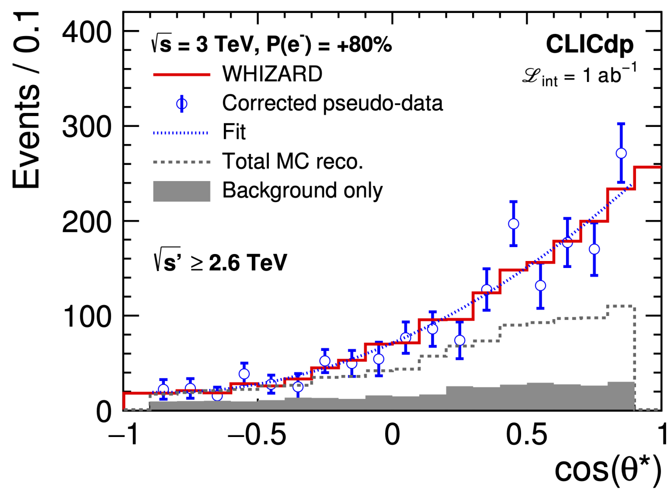


- e^+e^- detectors (fine-grained calorimeters) and clean environment ideal for detailed jet substructure studies

- Boosted hadronic top-quark decays reconstructed using techniques developed for hadron colliders (re-clustering, John Hopkins tagger)

Example: Extraction of A_{FB} at 3 TeV

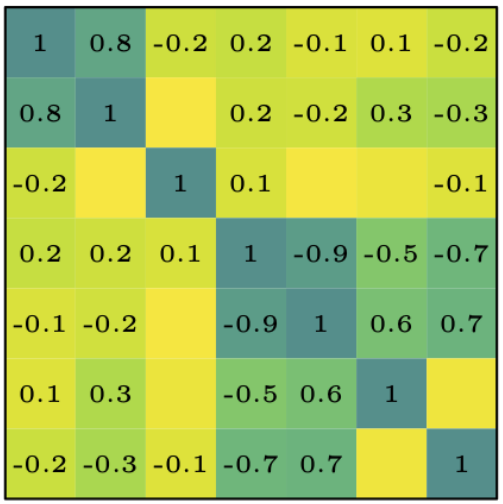


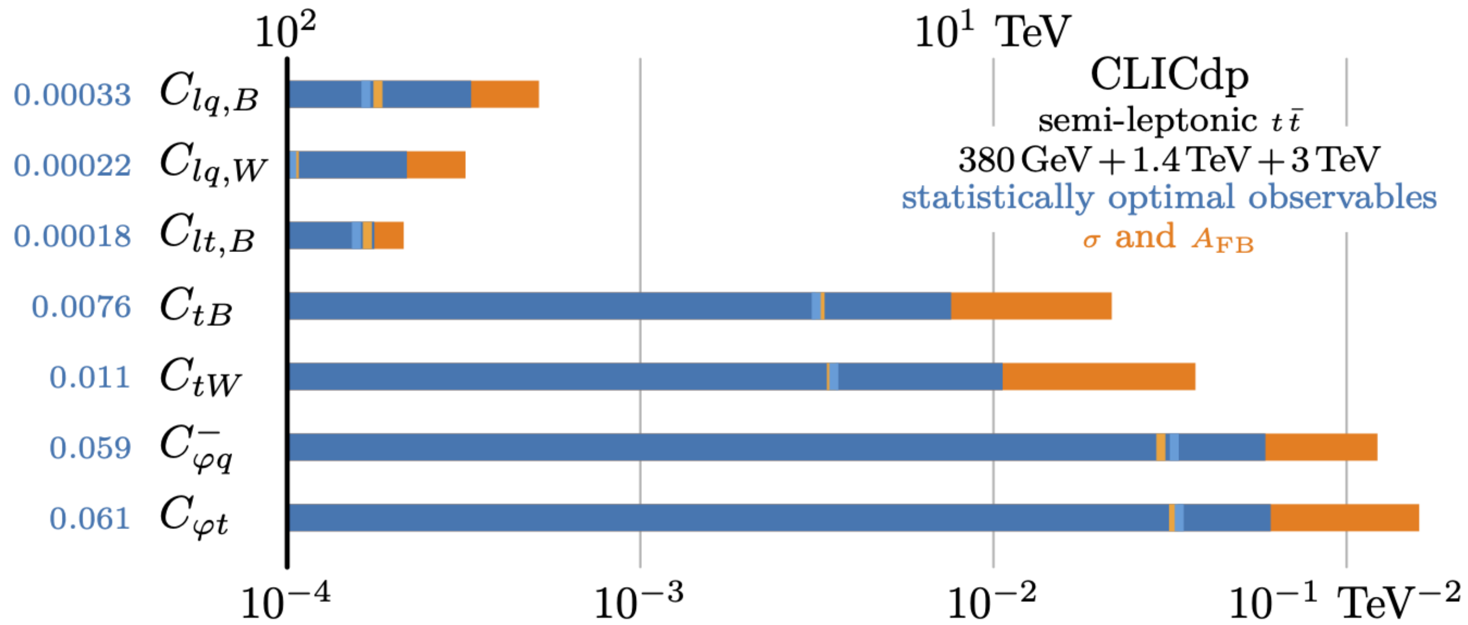


JHEP **11**, 003 (2019)
arXiv:2008.05526

Global EFT analysis of $e^+e^- \to t\bar{t}$

Example: full CLIC program with three energy stages
→ sensitivity to scales far beyond the centre-of-mass energy

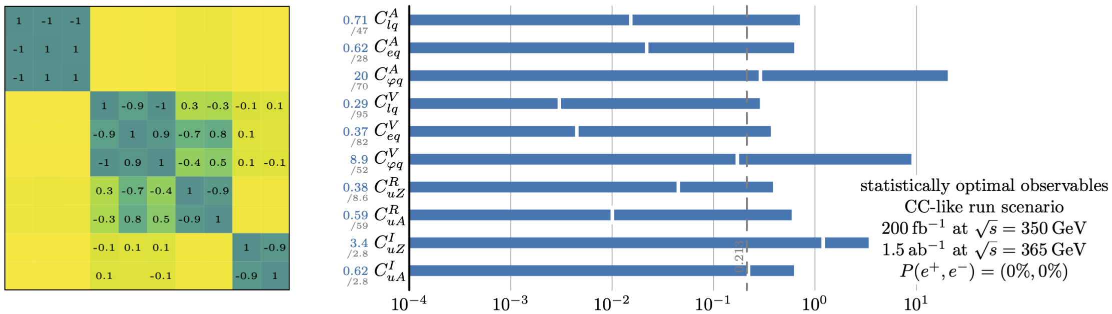




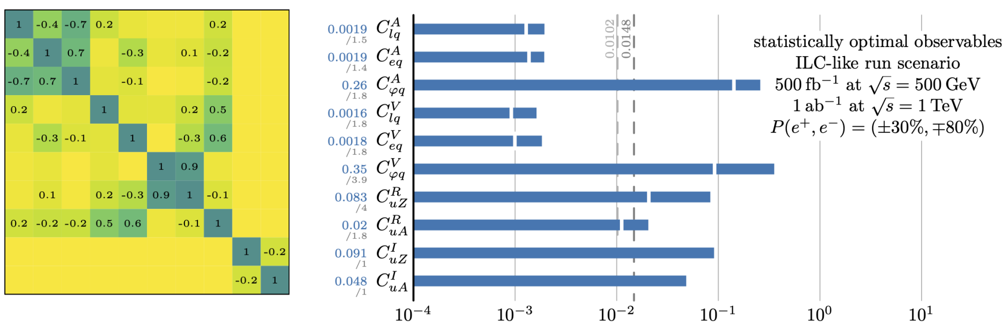
→ Significant improvement from "statistically optimal observables", which make the best use of the fully differential $bW^+\bar{b}W^-$ distributions, instead of σ and A_{FB}

JHEP **11**, 003 (2019)

EFT analysis: comparison of e^+e^- colliders

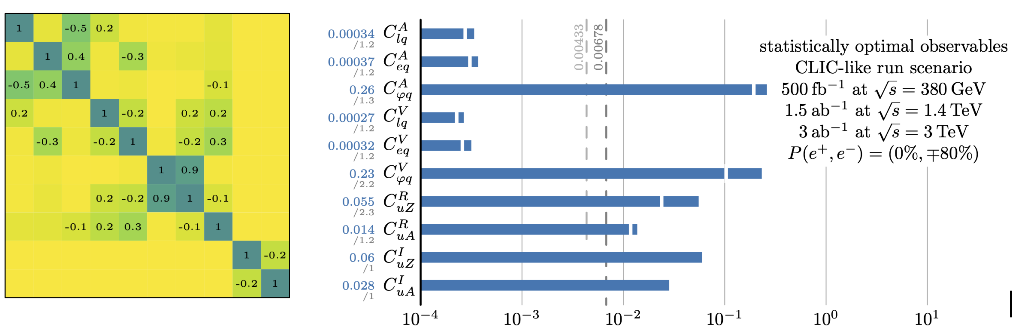


≈ **FCC-ee**



≈ **ILC**

→ Higher energy (and polarisation) significantly enhance the reach

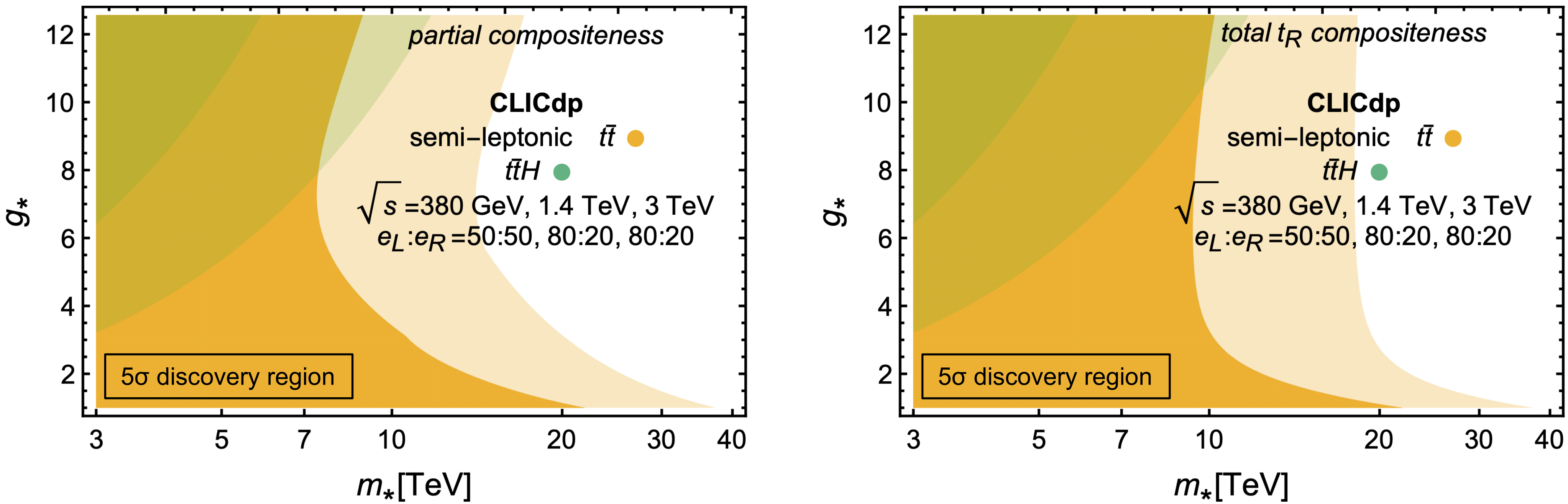


≈ **CLIC**

NB: lower luminosities than in ILC and CLIC baseline projections

JHEP **10**, 168 (2018)

Top-quark compositeness



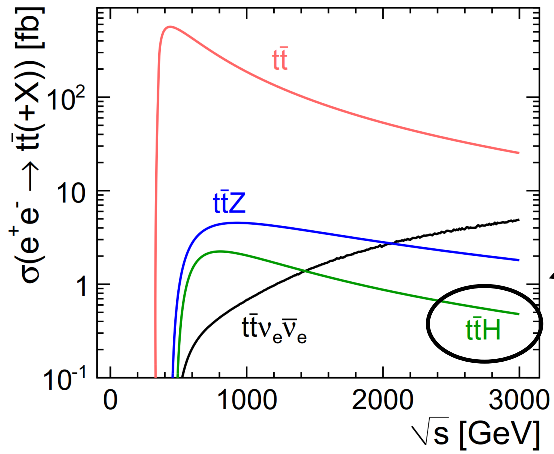
- "optimistic" (light colour) and "pessimistic" (dark colour) 5σ discovery regions in two benchmark scenarios
- Limits for CLIC derived from $t\bar{t}$ global EFT fit and from $t\bar{t}H$ production

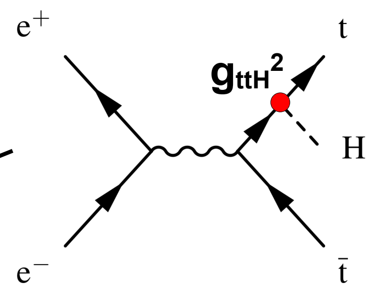
m_*: compositeness scale

g_*: coupling strength of the composite sector

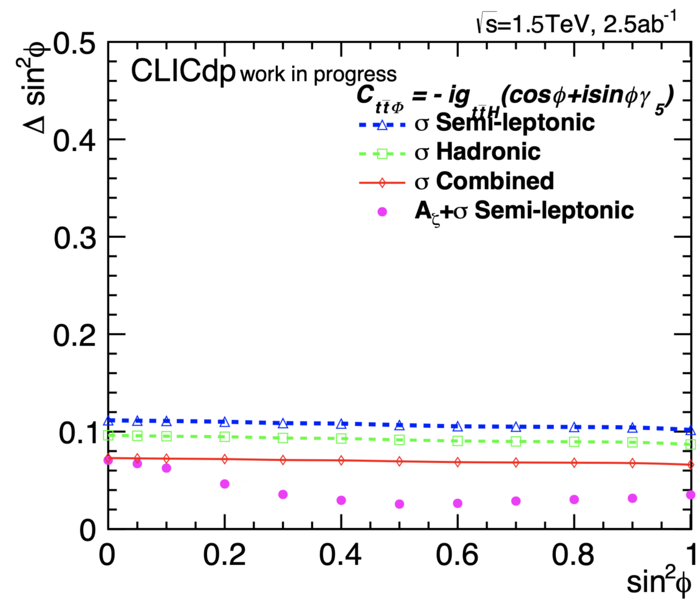
JHEP **11**, 003 (2019)

$e^+e^- \rightarrow t\bar{t}H$ and top-Yukawa coupling





Sensitivity to CP mixing in the ttH coupling:
- Differential information provides significant improvement compared to the cross section alone



Most important final states:
$e^+e^- \rightarrow t\bar{t}H \rightarrow q\bar{q}bl\nu\bar{b}b\bar{b}$
$e^+e^- \rightarrow t\bar{t}H \rightarrow q\bar{q}bq\bar{q}\bar{b}b\bar{b}$
→ Roughly similar sensitivity

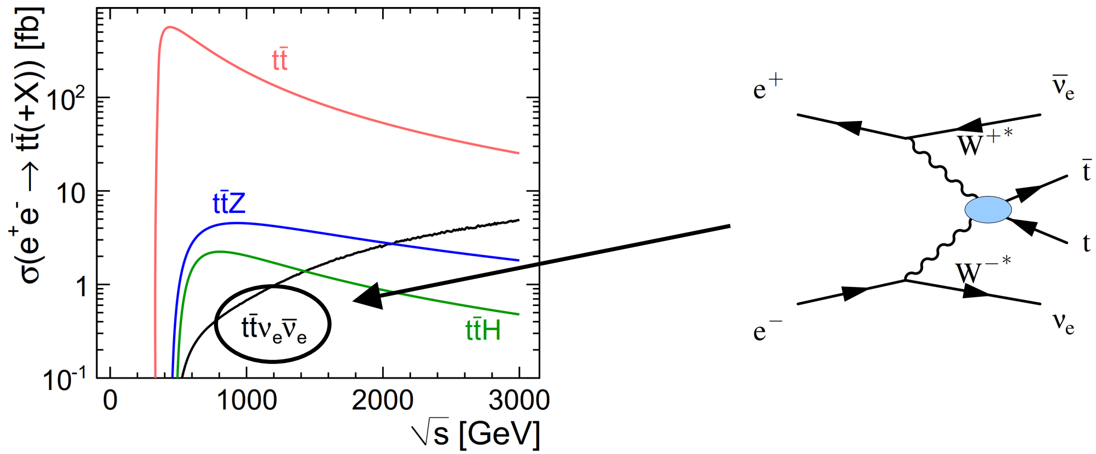
ILC:
- $\sqrt{s}$ = 550 GeV, L = 4 ab^{-1}
→ $\Delta g_{ttH}/g_{ttH}$ = 2.8%
- $\sqrt{s}$ = 1 TeV, L = 2.5 ab^{-1}
→ $\Delta g_{ttH}/g_{ttH}$ = 2%

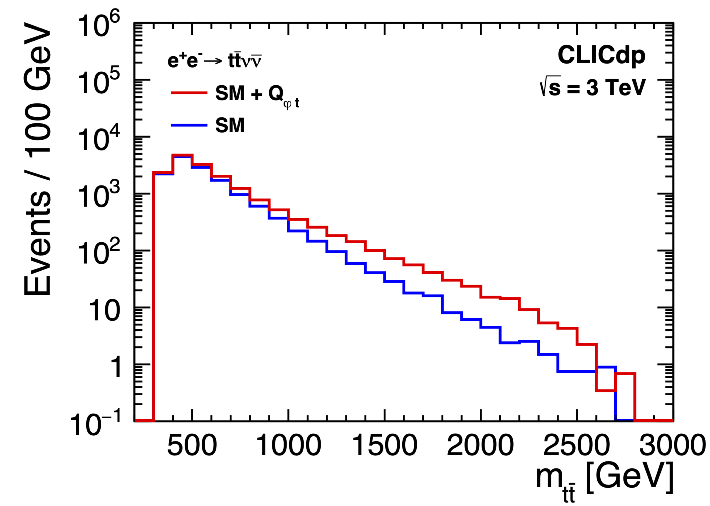
CLIC:
- $\sqrt{s}$ = 1.4 TeV, L = 2.5 ab^{-1}
→ $\Delta g_{ttH}/g_{ttH}$ = 2.7%

- Very interesting for even higher energies (e.g. muon collider, …):
$e^+e^-/\mu^+\mu^- \rightarrow t\bar{t}H\nu_e\bar{\nu}_e$

arXiv:1903.01629
JHEP **11**, 003 (2019)
CERN-THESIS-2020-232

$e^+e^- \rightarrow t\bar{t}\nu_e\bar{\nu}_e$ at high energy



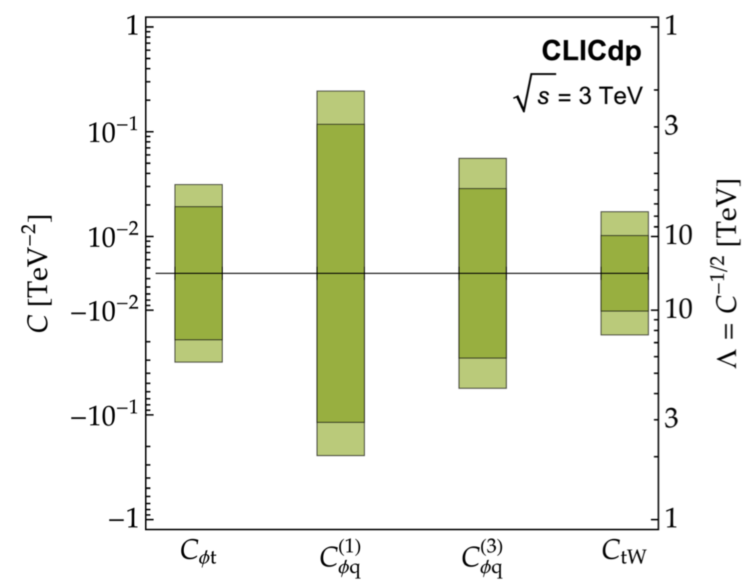


Example: CLIC at 3 TeV

- More detailed simulation studies needed

- Single-operator sensitivities, combination with $e^+e^- \rightarrow t\bar{t}$ could be beneficial

- Very interesting for even higher energies (e.g. muon collider, ...)



JHEP **11**, 003 (2019)

Top-quark physics at future colliders

Top-quark pair production at e^+e^- colliders
(mainly based on full simulations)**:**

- Measurements of the mass
- Top-quark EW couplings
- Processes at high energy

A few highlights from FCC-hh

Top-quark FCNC

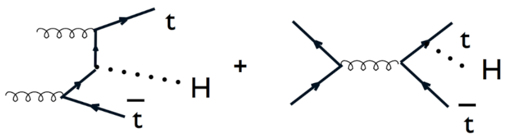
top-Yukawa coupling at FCC-hh

- production ratio **σ(ttH)/σ(ttZ)** $\approx$ **$y_t^2\, y_b^2 / g_{ttZ}^{\ 2}$**
- measure **σ(ttH)/σ(ttZ)** in **H/Z→bb** mode in the boosted regime, in the **semi-leptonic** channel
- perform **simultaneous fit of double Z and H peak**
- (lumi, scales, pdfs, efficiency) **uncertainties cancel out** in ratio

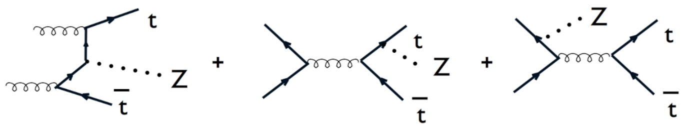
- assuming **g_{ttZ}** and **κ_b** known to 1% (from FCC-ee),

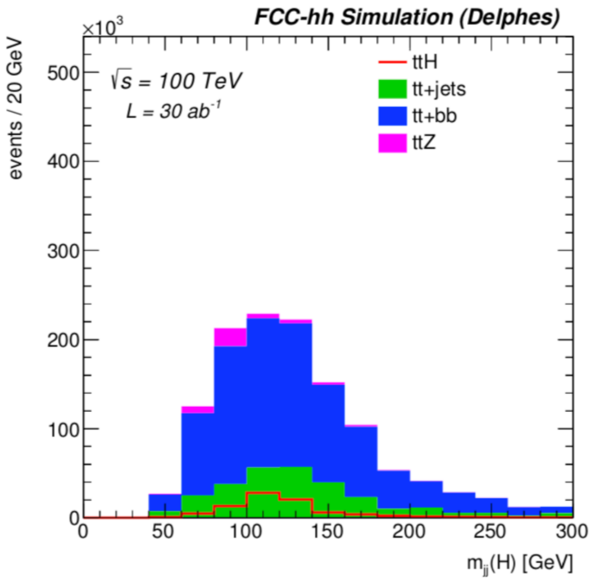
  → measure **y_t** to 1%

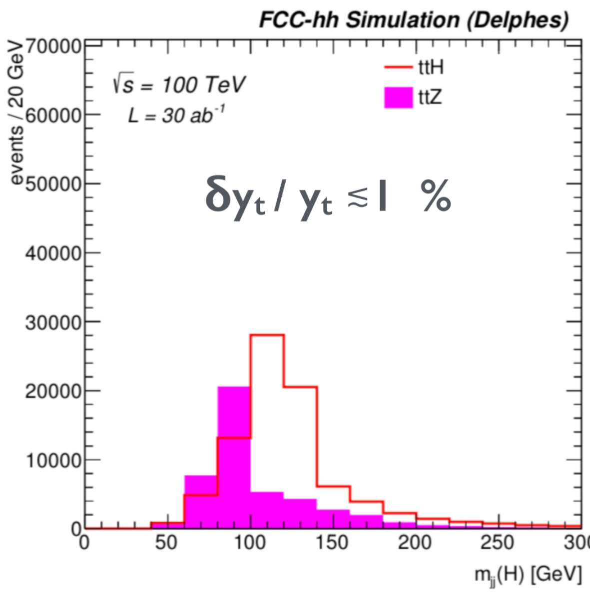
ttH



ttZ







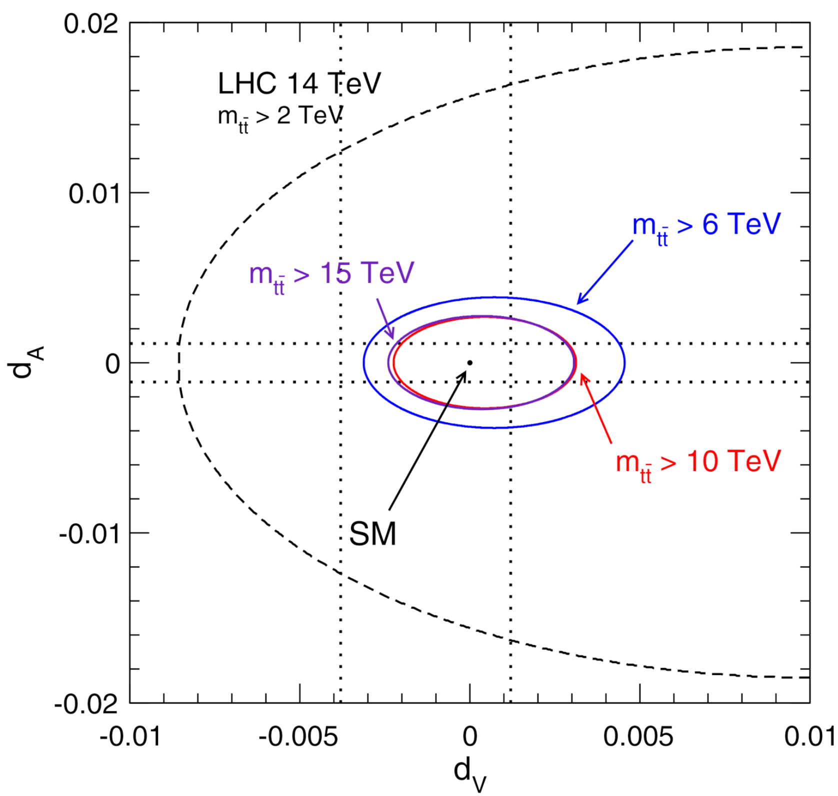
Michele Selvaggi

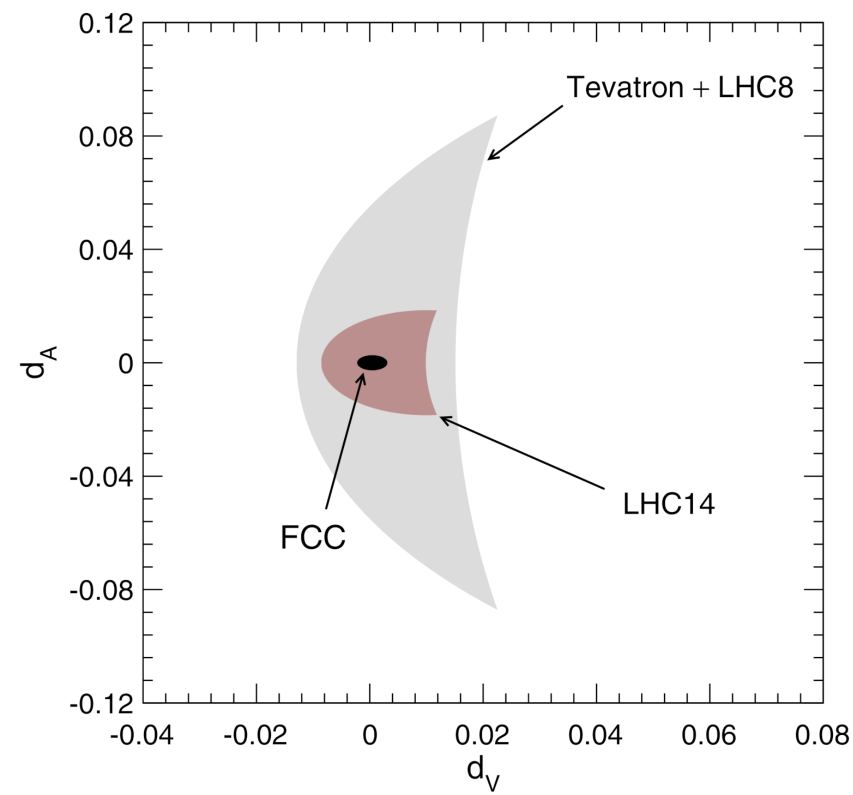
Anomalous top-gluon couplings from pp → $t\bar{t}$

Strongly boosted:
$m_{t\bar{t}}$ > 10 TeV is optimal choice from cross section analysis

$$\delta\mathcal{L} = \frac{g_s}{m_t}\,\bar{t}\sigma^{\mu\nu}(d_V + i\,d_A\gamma_5)\frac{\lambda_a}{2}\,t\,G^a_{\mu\nu}$$

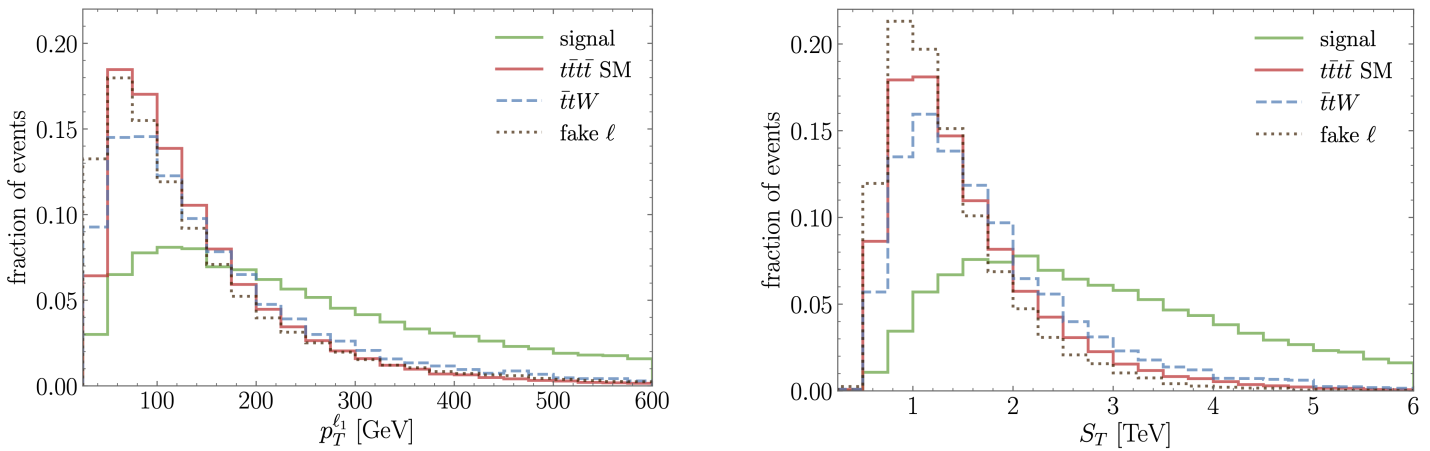
d_V(d_A): chromomagnetic (chromoelectric) diplole moment





FCC-hh CDR

pp → $t\bar{t}t\bar{t}$ at FCC-hh



Example: same-sign di-lepton final state

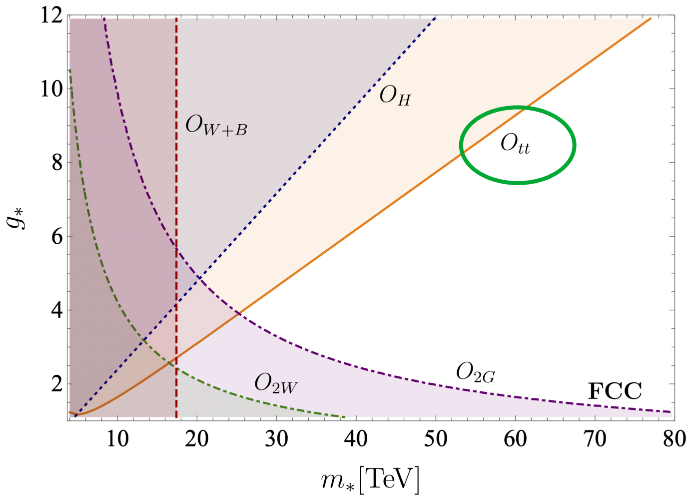
$$\text{FCC-hh}^{pp\to t\bar{t}t\bar{t}}_{100\,\text{TeV},\ 30\,\text{ab}^{-1}}: \quad \Lambda/\sqrt{|c_{tt}|} > 6.5\,\text{TeV}$$

$$\text{CLIC}^{e^+e^-\to t\bar{t}}_{3\,\text{TeV},\ 3\,\text{ab}^{-1}}: \quad \Lambda/\sqrt{|c_{tt}|} > 7.7\,\text{TeV}$$

$$\text{ILC}^{e^+e^-\to t\bar{t}}_{1\,\text{TeV},\ 1\,\text{ab}^{-1}}: \quad \Lambda/\sqrt{|c_{tt}|} > 4.1\,\text{TeV}$$

FCC-hh: same-sign di-lepton and tri-lepton final states combined

Composite Higgs



95% CL limits from individual operators

JHEP **02**, 043 (2021)

Top-quark physics at future colliders

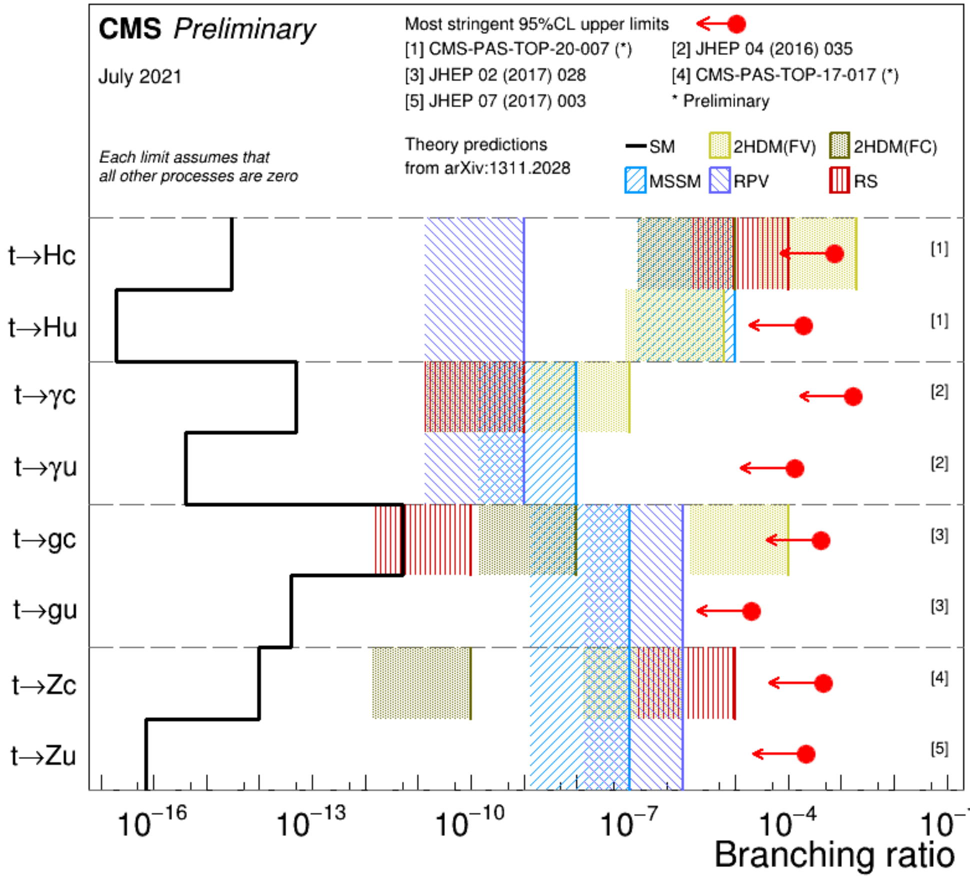
Top-quark pair production at e^+e^- colliders (mainly based on full simulations)**:**

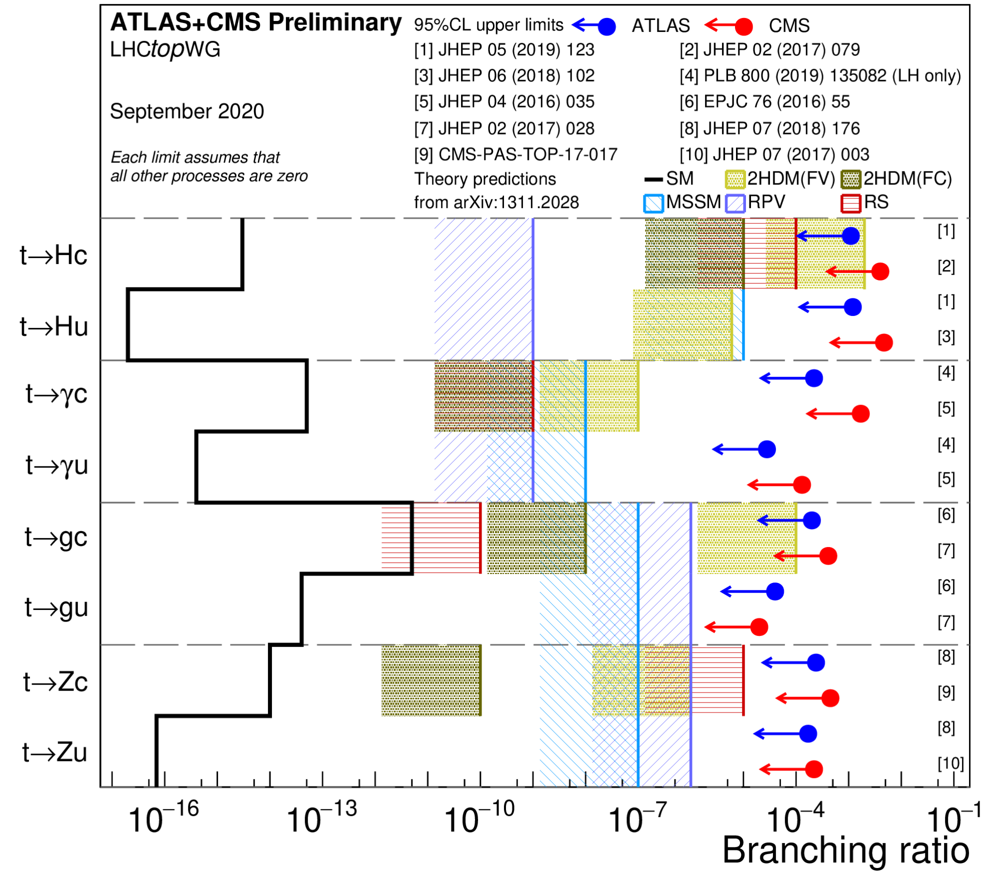
- Measurements of the mass
- Top-quark EW couplings
- Processes at high energy

A few highlights from FCC-hh

Top-quark FCNC

Top-quark FCNC: current status





- SM branching ratios strongly suppressed (10^{-16}...10^{-12})
$\rightarrow$ strong enhancement in certain BSM models possible
- Current 95% CL limits typically at the level of 10^{-3} to 10^{-4}

Top-quark FCNC: t→Hq branching ratios

$BR \times 10^5$	HL-LHC	HE-LHC	ILC_{500}	CLIC_{380}	LHeC	FCC-ee	FCC-hh	FCC-eh
$t \to Hc$			≈ 3	15			1.6	
$t \to Hu$					150			22
$t \to Hq$	10						2.8	
$t \to Zq$	2.4 - 5.8				4	2.4	≈ 0.1	0.6
$t \to \gamma c$	7.4		≈ 1	2.6			0.024	
$t \to \gamma u$	0.86						0.018	
$t \to \gamma q$					1	1.7		0.085
$t \to gc$	3.2	0.19						
$t \to gu$	0.38	0.056						

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:
Based on ATLAS studies using $H \to b\bar{b}$ and $H \to \gamma\gamma$

FCC-hh:
Large statistics allows usage of clean $H \to \gamma\gamma$ decays, combination of semi-leptonic and fully hadronic final states

ESU Physics Briefing Book

Top-quark FCNC: t→Zq branching ratios

$BR \times 10^5$	HL-LHC	HE-LHC	ILC_{500}	$CLIC_{380}$	LHeC	FCC-ee	FCC-hh	FCC-eh
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$t \to gc$	3.2	0.19						
$t \to gu$	0.38	0.056						

FCC-ee:
BR(t→Zq) from anomalous single top production: $e^+e^- \to Z^*/\gamma^* \to t\bar{q}\ (\bar{t}q)$
→ further improvement from combination of both energy stages possible

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

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

FCC-hh:
Estimate using HL-LHC projection

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Top-quark FCNC: $t \to \gamma q$ branching ratios

$BR \times 10^5$	HL-LHC	HE-LHC	ILC_{500}	$CLIC_{380}$	LHeC	FCC-ee	FCC-hh	FCC-eh
$t \to Hc$			≈ 3	15			1.6	
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$t \to gu$	0.38	0.056						

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

FCC-eh and LHeC:
BR($t \to \gamma q$) from 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($t \to \gamma u$) and BR($t \to \gamma u$) 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)

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Top-quark FCNC: t→gq branching ratios

$BR \times 10^5$	HL-LHC	HE-LHC	ILC_{500}	CLIC_{380}	LHeC	FCC-ee	FCC-hh	FCC-eh
$t \to Hc$			≈ 3	15			1.6	
$t \to Hu$					150			22
$t \to Hq$	10						2.8	
$t \to Zq$	2.4 - 5.8				4	2.4	≈ 0.1	0.6
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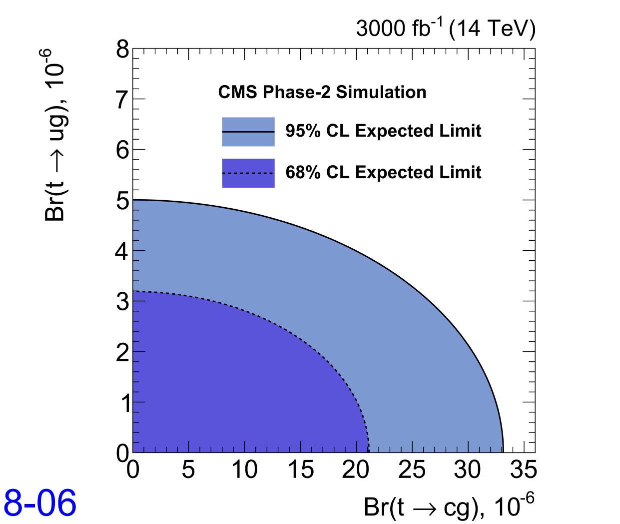
$t \to \gamma q$					1	1.7		0.085
$t \to gc$	3.2	0.19						
$t \to gu$	0.38	0.056						

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



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CERN-LPCC-2018-06

Top-quark FCNC: t→gq branching ratios

$BR \times 10^5$	HL-LHC	HE-LHC	ILC_{500}	$CLIC_{380}$	LHeC	FCC-ee	FCC-hh	FCC-eh
$t \to Hc$			≈ 3	15			1.6	
$t \to Hu$					150			22
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$t \to gu$	0.38	0.056						

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
- By far not all possibilities explored yet!
- Generally improvements by 1-2 orders of magnitude compared to HL-LHC possible

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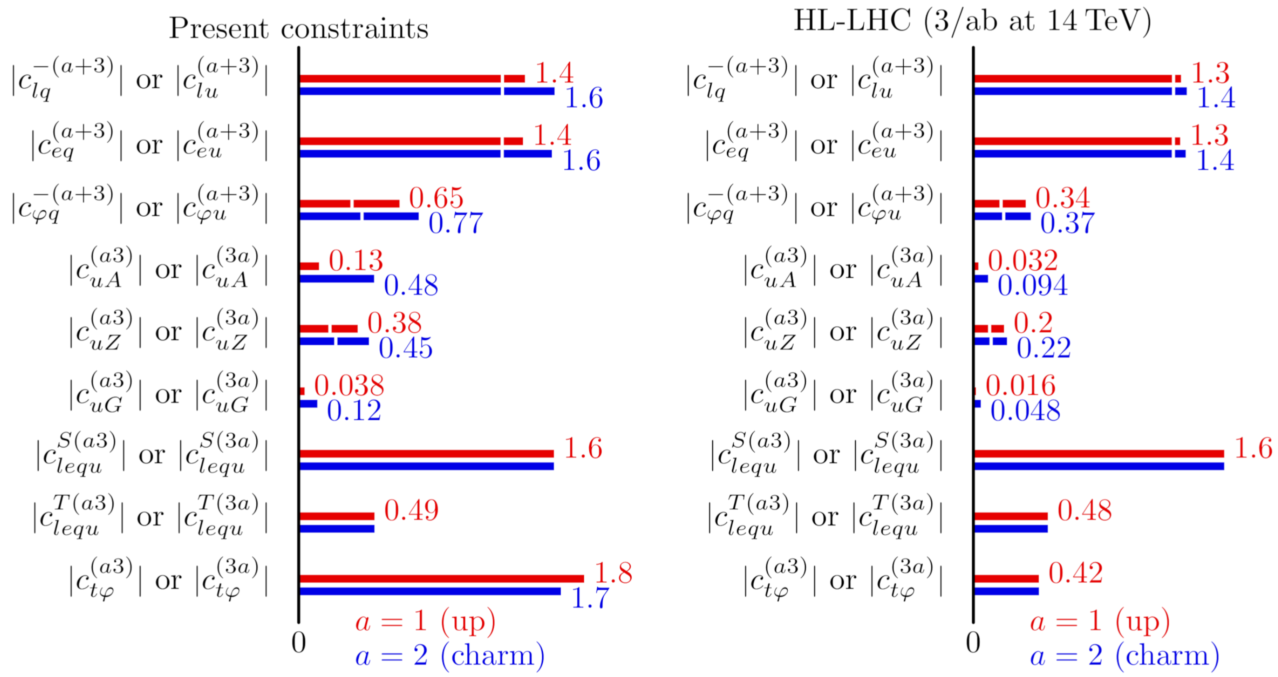
Top-quark FCNC: EFT for HL-LHC

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

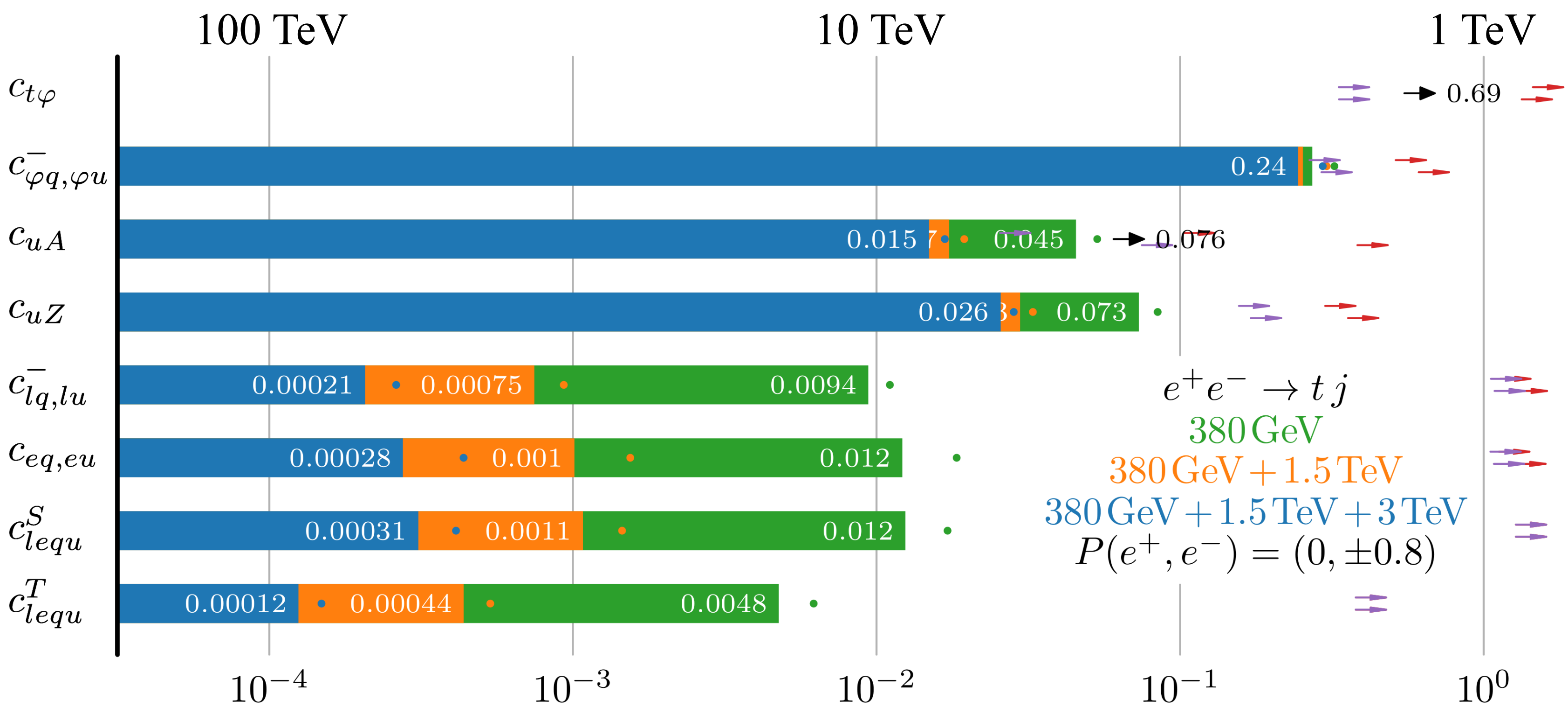
Input: limits on FCNC branching ratios, limits on $e^+e^- \to tj$ from LEP II



<u>White marks:</u> 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

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
- $e^+e^- \to tj$ much more powerful than the decays at high-energy lepton colliders

CERN-2018-009-M

Summary and conclusions

• The top-quark plays an important role at any future high-energy collider facility

• Well-defined program for an e^+e^- collider at and above the pair-production threshold:
- A threshold scan is the best possible mass measurement with ≈ 50 MeV precision
- Operation well above threshold improves the top-quark EW couplings by at least an order of magnitude
- A direct measurement of the top-Yukawa coupling requires at least 550 GeV, also access to CP mixing in the $t\bar{t}H$ coupling

• Four-fermion operators benefit from the highest possible energies (at e^+e^- and hadron colliders)

• Large amount of complementarity between different collider options and energy stages for top-quark FCNC-effects

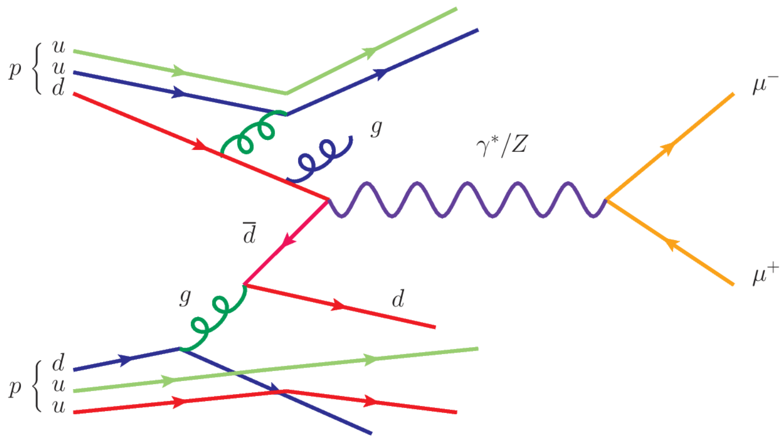
• Many issues still to be studied, in particular for very high energies

Thank you!

Backup slides

Hadron and e^+e^- colliders

Hadron colliders:

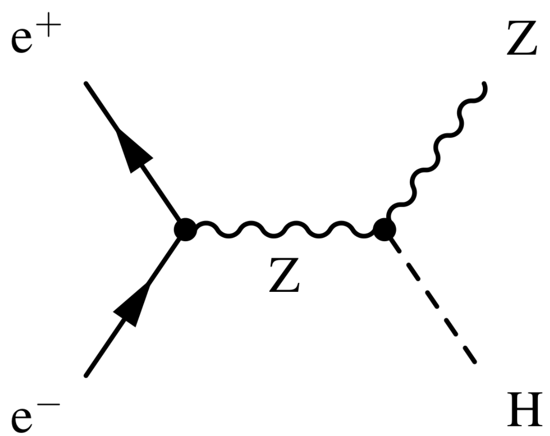


- **Proton is compound object**
→ Initial state unknown
→ Limits achievable precision

- **High-energy circular colliders possible**

- **High rates of QCD backgrounds**
→ Complex triggers
→ High levels of radiation

e^+e^- colliders:

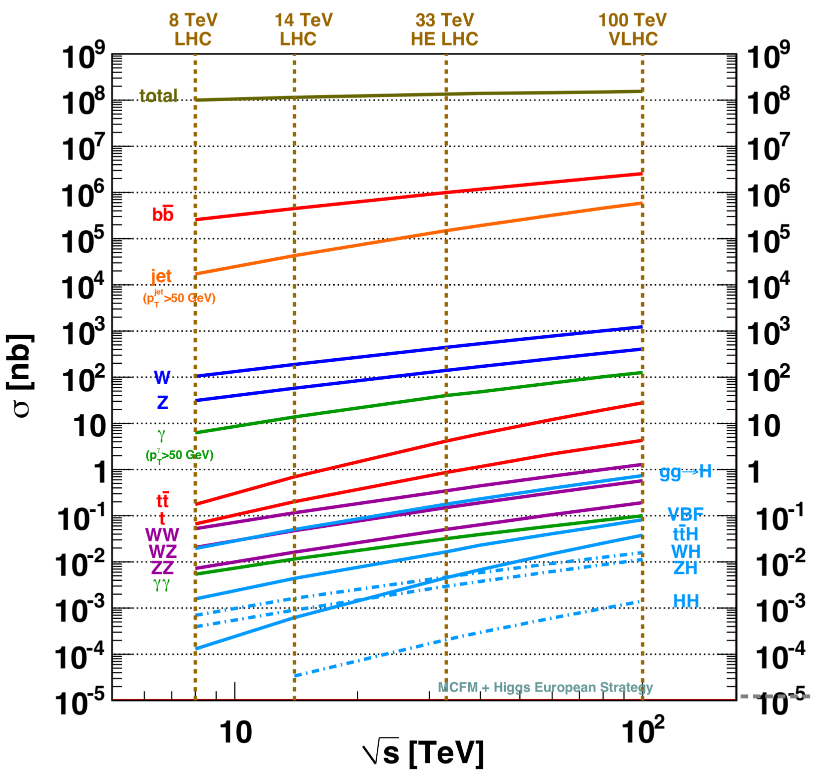


- **e^+e^- are pointlike**
→ Initial state well-defined ($\sqrt{s}$, polarisation)
→ High-precision measurements

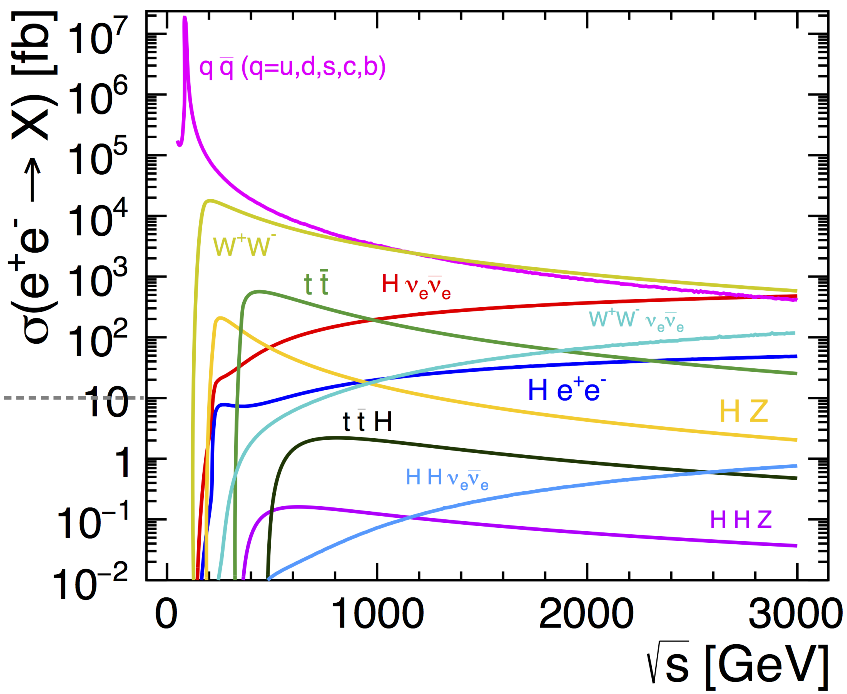
- **High energies ($\sqrt{s} \geq 380$ GeV) require linear colliders**

- **Clean experimental environment**
→ Less / no need for triggers
→ Lower radiation levels

pp and e⁺e⁻ collisions



8 orders of magnitude!



pp collisions:
Interesting events need to be found in huge number of collisions

e^+e^- collisions:
More "clean", all events usable