top physics at CLIC
– recent progress at IFIC Valencia

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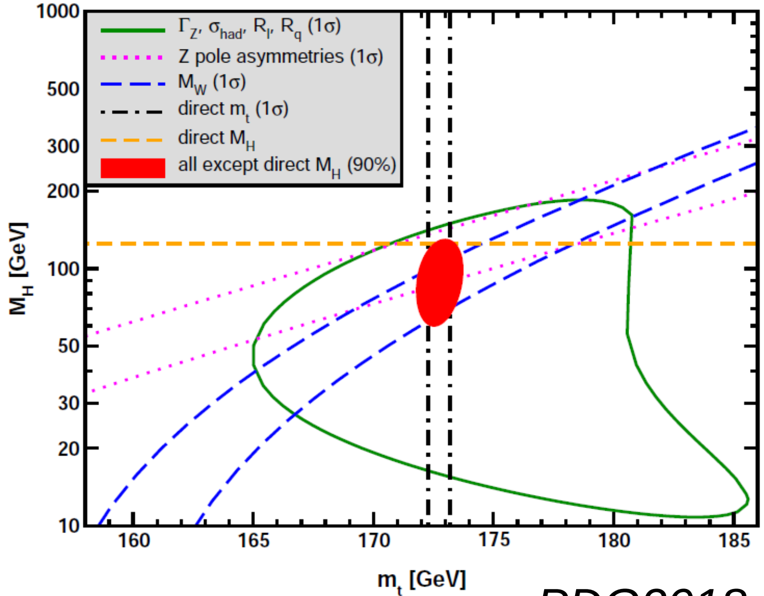
Top mass

One of the most important SM parameters
Must be determined experimentally!
Precise top mass measurement allows to verify internal consistency of the theory



PDG2018

Ph.D. thesis Marça Boronat, U. Valencia, 2017

Ph.D. thesis Pablo Gomis, foreseen 2019

EW fit

Indirect determination of the W mass:

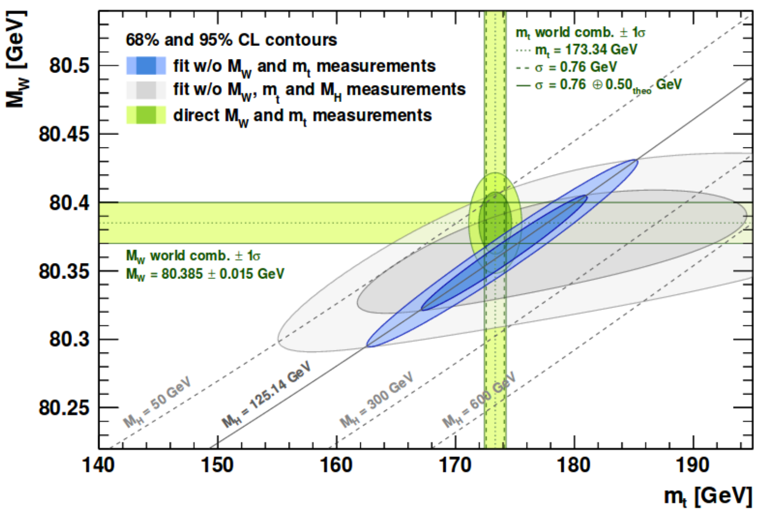
$$\begin{aligned} m_W = \quad & 80.3584 \quad \pm 0.0055_{m_{top}} \pm 0.0025_{m_Z} \pm 0.0018_{\alpha_{QED}} \\ & \qquad\qquad \pm 0.0020_{\alpha_S} \pm 0.0001_{m_H} \pm 0.0040_{theory} \text{ GeV} \\ = \quad & 80.358 \quad \pm 0.008_{total} \text{ GeV}, \end{aligned}$$

Todays direct measurement:

$$m_W = 80.379 \pm 0.012 \text{ GeV}$$

Snowmass EW, arXiv:1310.6708
TLEP physics case, arXiv:1308.6176

Direct W mass measurement will improve ($\pm$ 0.002 GeV)
To match this precision with the indirect determination, m_t (and theory) must be made more precise



arXiv:1407.3792

Progress at the LHC: top quark mass revisited

The interpretation and the theory uncertainties of top quark mass measurements are still hotly debated.

Calibrate MC mass parameter:	*Hoang et al., PRL117*
Parton shower analytics:	*Hoang et al., arXiv:1807.06617*
Improve MC precision:	*Nason et al., arXiv:1607.04538, arXiv:1801.03944*
Renormalon ambiguity:	*Beneke et al., arXiv:1605.03609*

"direct mass" vs "pole mass", prospects at the HL-LHC

The direct top quark mass measurements at the Tevatron and LHC experiments have reached approximately 500 MeV precision[1–3] (world average: $m_t = 172.9 \pm 0.4$ GeV[4], the χ^2 of 6.7 has led the author to scale the uncertainty by a factor 1.3). The experimental uncertainties are expected to improve to approximately 200 MeV at the HL-LHC[5], while work is ongoing to clarify the interpretation[6]. Pole mass extractions from (differential) cross-section measurements at the LHC have achieved GeV precision[7,8] (world average: $m_t^{pole} = 173.1 \pm 0.9$ GeV[4]). At electron-positron colliders, a very precise measurement of the top quark mass, with a total uncertainty of approximately 50 MeV, is possible by scanning the centre-of-mass energy through the $t\bar{t}$ production threshold[9–11].

4 **Particle Data Group** Collaboration, M. Tanabashi *et al.*, *Review of Particle Physics*, *Phys. Rev.* **D98** (2018), no. 3 030001, numbers correspond to the 2019 update.

5 **HL-LHC, HE-LHC Working Group** Collaboration, P. Azzi *et al.*, *Standard Model Physics at the HL-LHC and HE-LHC*, `arXiv:1902.04070`.

6 A recent review is found in Ref.[5], which summarizes the situation as follows: "from a theoretical point of view, much work is still needed to put the top mass measurements at the HL-LHC on a solid ground.". However, the authors are optimistic that "in spite of the many challenges, one can expect that a theoretical precision matching the foreseeable experimental errors for top mass measurements at the HL-HLC can be achieved.".

Remember: HL-LHC prospects anno 2005: 1 GeV precision

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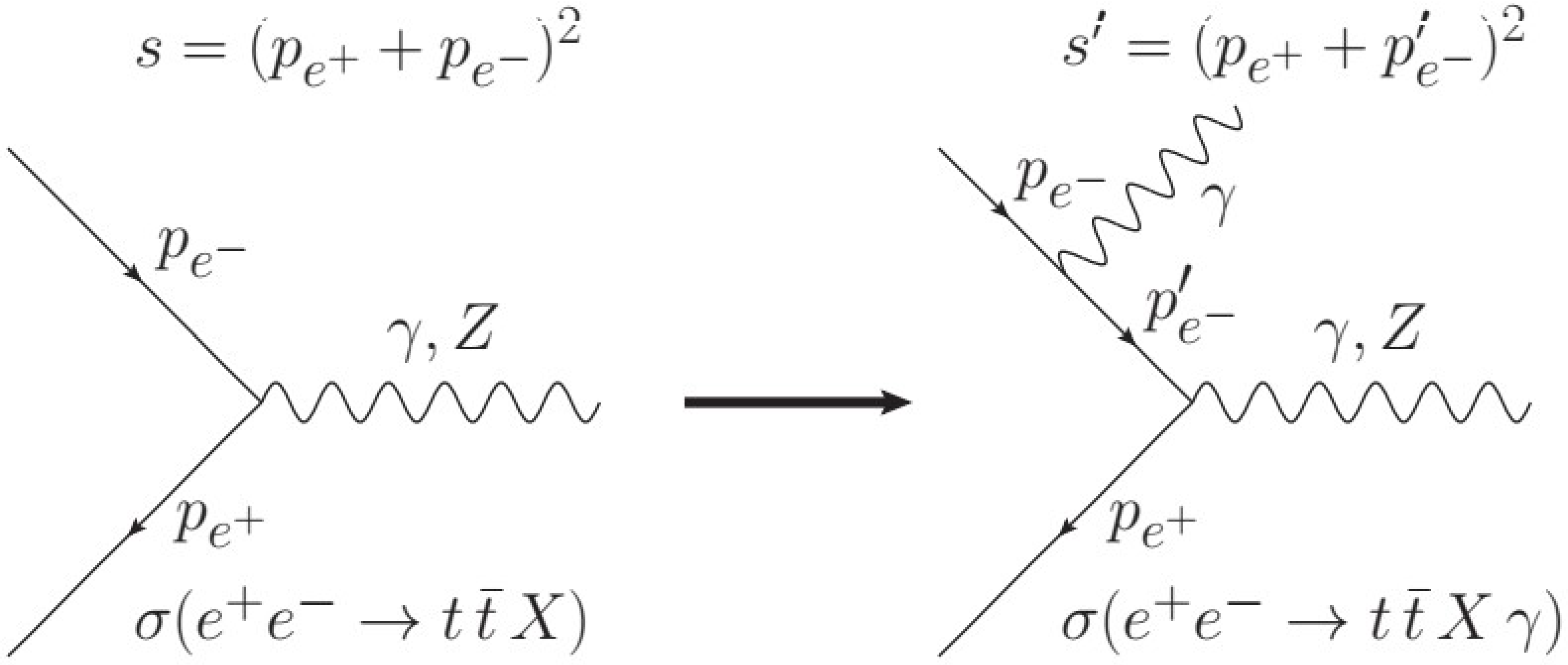
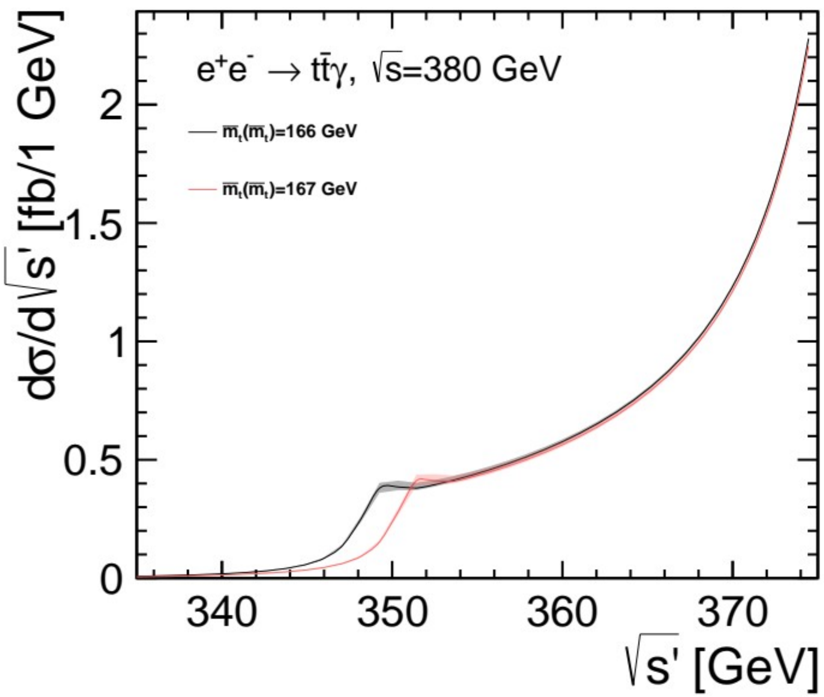
Top mass in radiative events



Initial State Radiation (ISR) modifies the available centre-of-mass energy

As the photon carries away energy, the $t\bar{t}$ system only sees sqrt(s’) instead of sqrt(s)

Top mass in radiative events - experiment



ISR can turn a “continuum” event into a “threshold” event (return-to-the-threshold)

The normalized differential $t\bar{t}\gamma$ cross section vs. sqrt(s’) is very sensitive to the top mass

No further ingredients and in particular no top candidate reconstruction

The sqrt(s’) spectrum can be reconstructed precisely

$$s' = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$

Nominal sqrt(s) is precisely known

E_γ is precisely measured

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Top mass in radiative events - experiment

Spectrum binned in agreement with the expected photon energy resolution: 5 bins across threshold

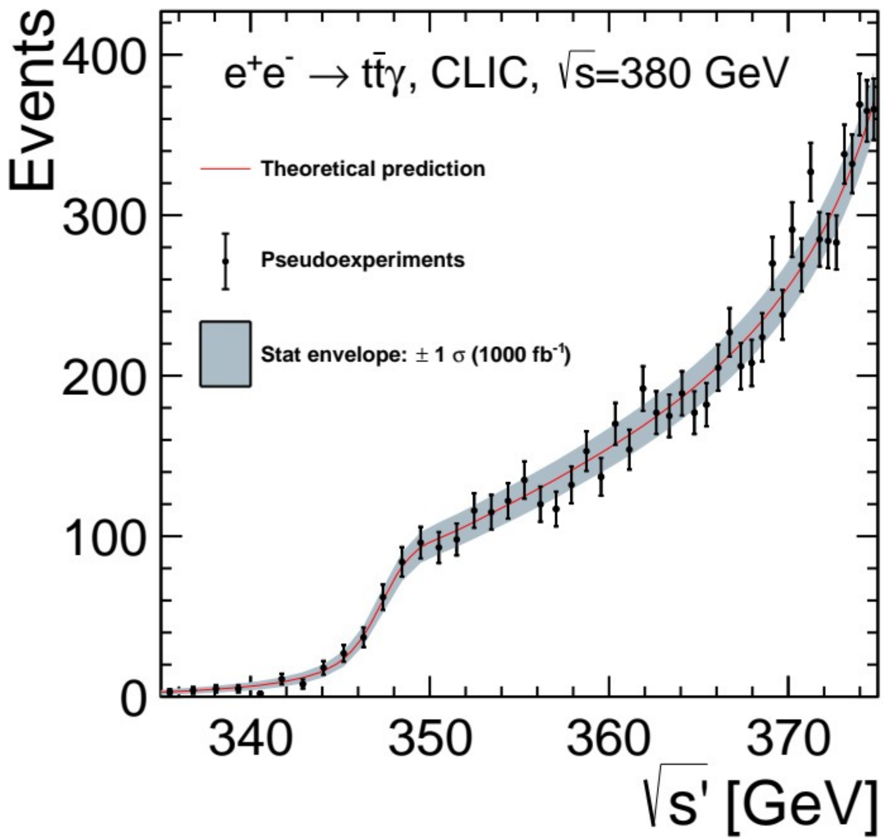
Statistical uncertainty with 1000 fb^{-1} indicated by grey band; data points and error bars represent one pseudo-experiment

Statistical uncertainty:

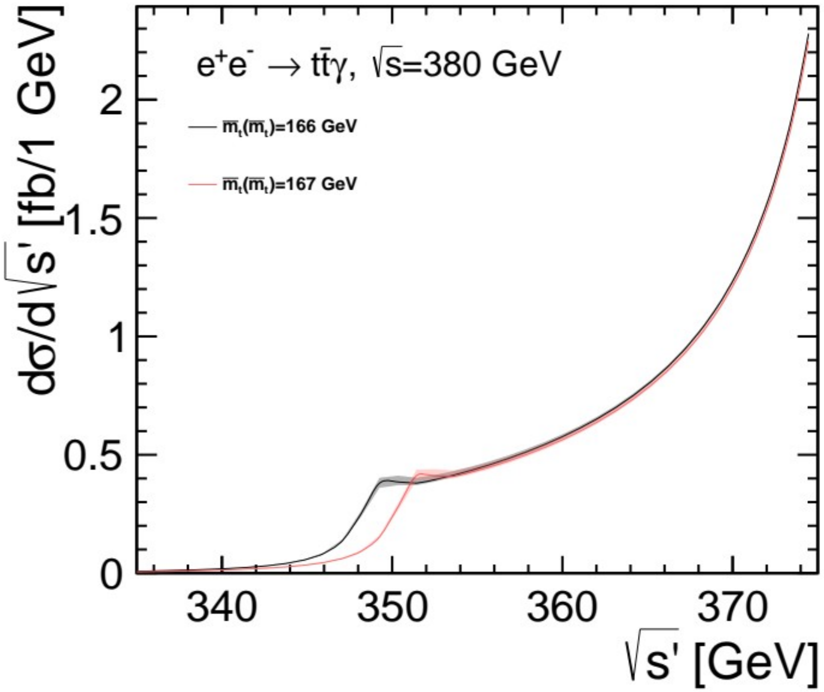
Δm_t = 90 MeV*

1000 fb^{-1}, 50% efficiency*, acceptance down to 8 degrees

*includes $t\bar{t}$ selection, photon reconstruction and isolation (against FSR), but not the photon acceptance



Top mass in radiative events - theory



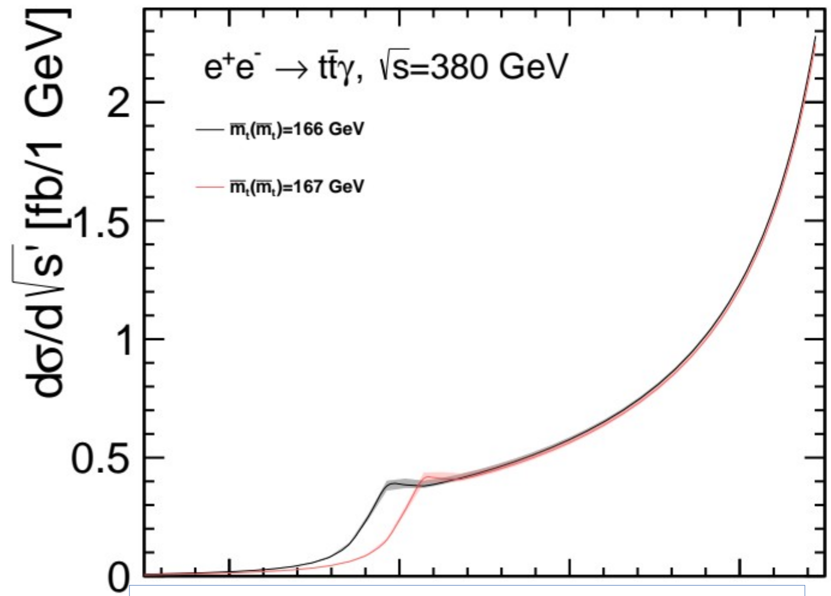
ISR can turn a "continuum" event into a "threshold" event (return-to-the-threshold)

The normalized differential $t\bar{t}\gamma$ cross section vs. sqrt(s') is very sensitive to the top mass

The sqrt(s') spectrum can be predicted precisely with a matched NNLL/NNLO calculation (A. Hoang, V. Mateu, A. Widl)

NNLL (threshold)	NNLO (continuum)	resummed (ISR)
Hoang et al., 2013	*Since 1982, see i.e. Chen, 2016*	*Since forever*

Top mass in radiative events - theory



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Match threshold and continuum, see:
Reuter, Hoang, et al., arXiv:1811.03950

The sqrt(s ... ed precisely with a matched NNLL/NNL ... . Mateu, A. Widl)

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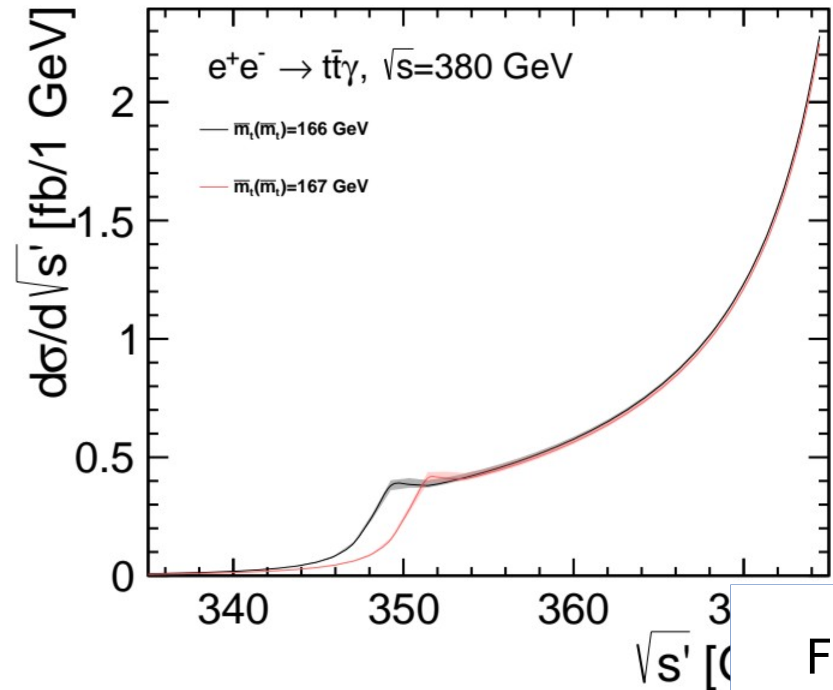
Top mass in radiative events - theory



ISR can turn a "continuum" event into a "threshold" event (return-to-the-threshold)

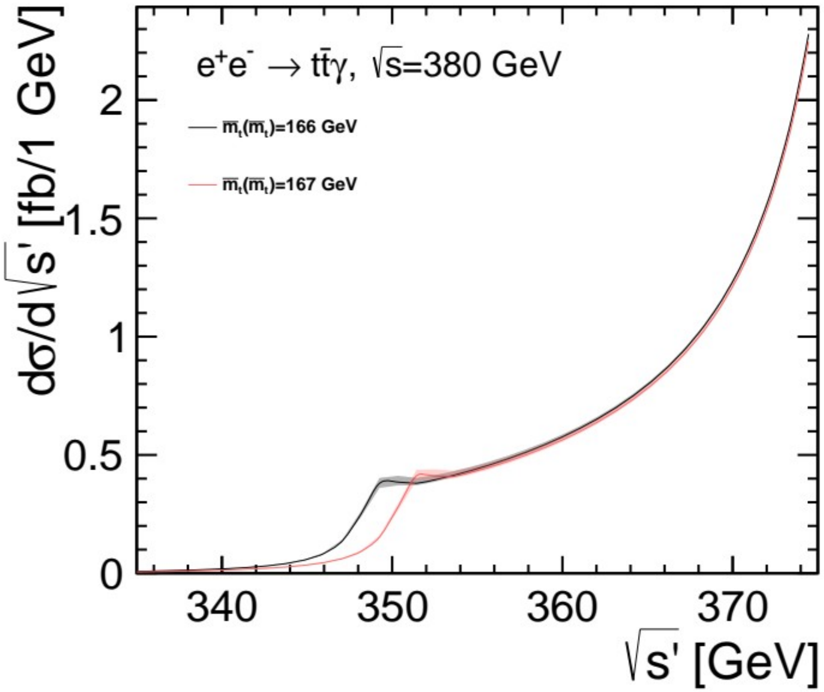
The normalized differential $t\bar{t}\gamma$ cross section vs. sqrt(s') is very sensitive to the top mass

Factorize $t\bar{t}$+X and ISR emission:
V. Mateu and *A. Hoang*

The sqrt(s') spectrum can be pred ... ched NNLL/NNLO calculation (A. Hoang

NNLL (threshold)	NNLO (continuum)	resummed (ISR)
Hoang et al., 2013	*Since 1982, see i.e. Chen, 2016*	*Since forever*

Top mass in radiative events – theory uncertainty



* increases to ~70 MeV if evaluated at detector level

The matched calculation has three scales: The scales h, hf and hf^2 correspond roughly to the top-quark mass, top-quark 3-momentum, and the $t\bar{t}$ kinetic energy

h	1/2	1/2	1/2	1	1	1	2	2	2
f	2	3/2	1	1	$\sqrt{2}$	$\sqrt{1/2}$	1	3/4	1/2
CLIC: $\Delta\overline{m}_t$ [MeV]	−45	−47	−44	0	−1	+9	+28	+30	+45

Envelope of scale variations yields theory uncertainty:

Δm_t = 45 MeV*

Conclusions so far

A new method is proposed to measure the top quark mass in radiative events

It has all the pretty features of the threshold scan:

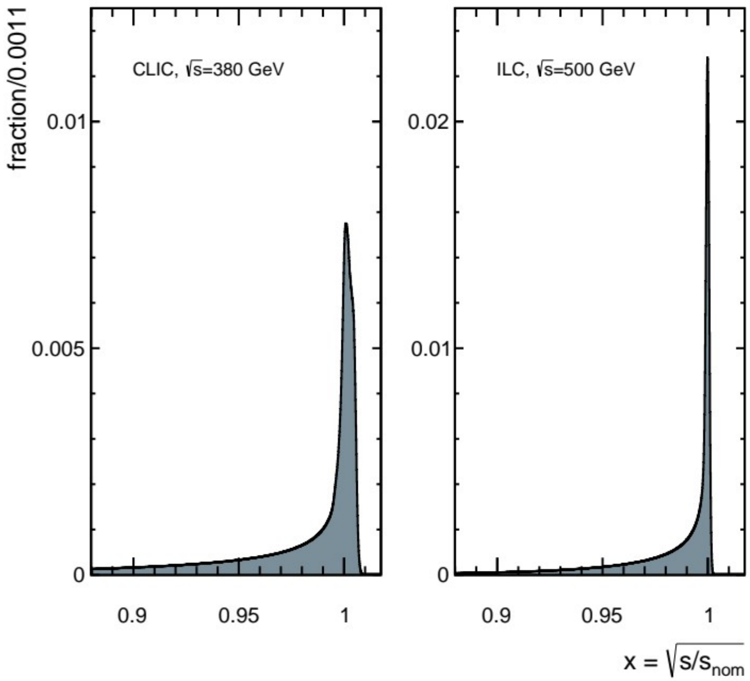
- no top reconstruction
- precise theory available
- rigorous control over mass scheme

But it does not require a dedicated run

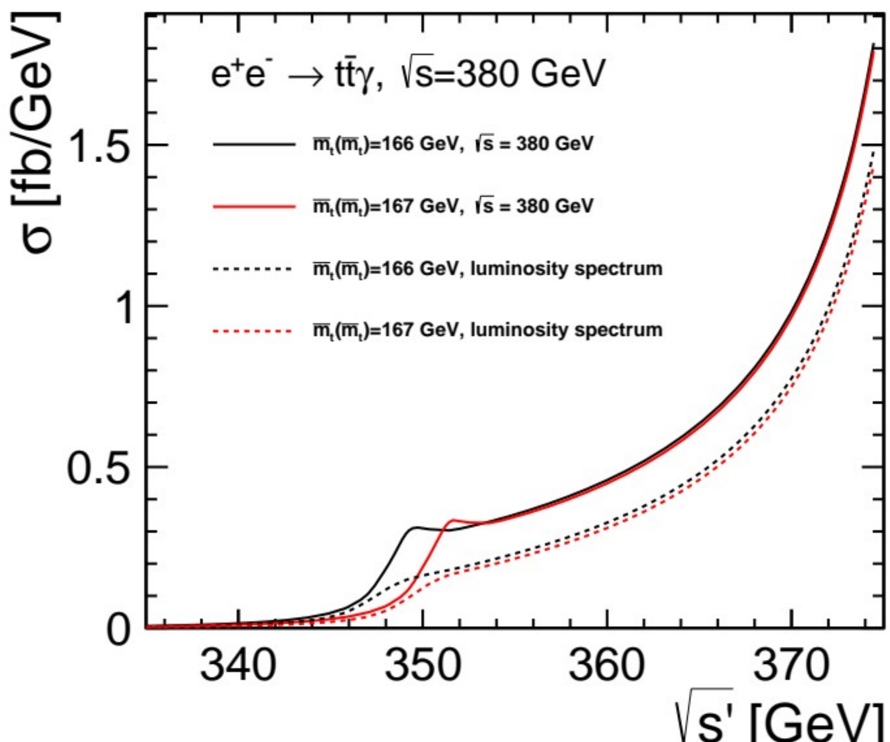
- can be performed in 380 GeV run, while doing Higgs physics

Experimental systematics

Thanks to André Sailer
and Dominik Arominski



Of course, sqrt(s) is not a constant



The luminosity spectrum causes:
- loss of statistics
- less clear threshold shape

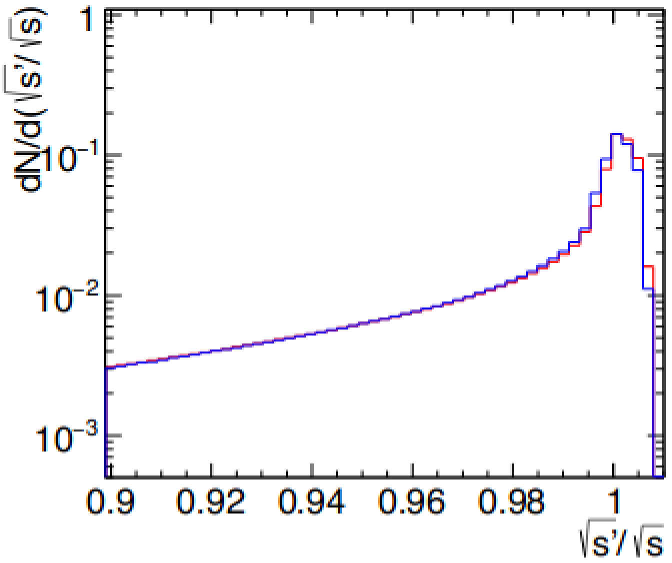
The luminosity spectrum must be precisely known

Luminosity spectrum reconstruction and uncertainties

Luminosity spectrum can be measured in-situ using Bhabha events,
We follow: Poss and Sailer, EPJC74 (2014) no. 4, 2833

Uncertainties on reconstructed spectrum:

fit parameter variations (19 params):	7 MeV
e^- angular resolution off by <25%:	10 MeV
e^- energy resolution off by <15%:	16 MeV
Total uncertainy:	20 MeV



Esteban Fullana, André Sailer, Philipp Zehetner, see also:
https://indico.cern.ch/event/703821/contributions/3102578/

Photon energy response

Measurement relies heavily on photon energy response

The photon energy resolution:

16.6%/sqrt(E) ++ 1.1%

The photon energy scale:

CLIC momentum scale known to $<10^{-4}$ [Blaising et al. CLICdp-note-2019-003]

Muon momentum scale → Electron energy scale → photon energy scale?

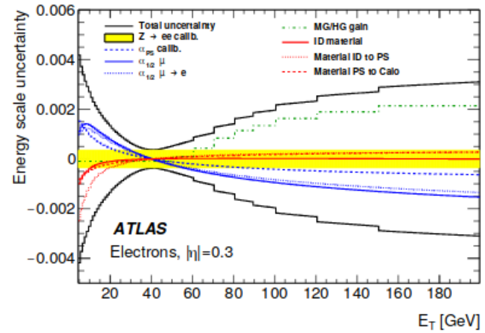
Not needed (Z→ee)

?

Photon energy response

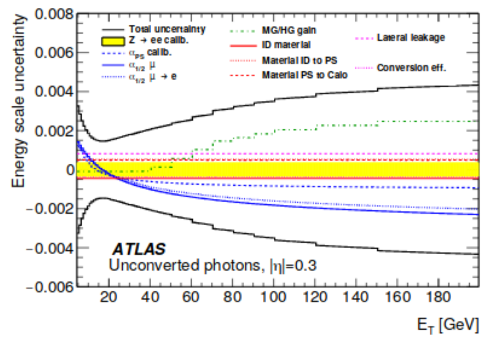
Measurement relies heavily on photon energy response

The photon energy scale, LHC experience:
Z → ee indeed gives very good constraint (< 10^{-3})
Transfer to different energy non-trivial
(detector gains, important for ILC at sqrt(s) = 500 GeV)
Transfer to photon energy scale non-trivial
(conversions, leakage → material)

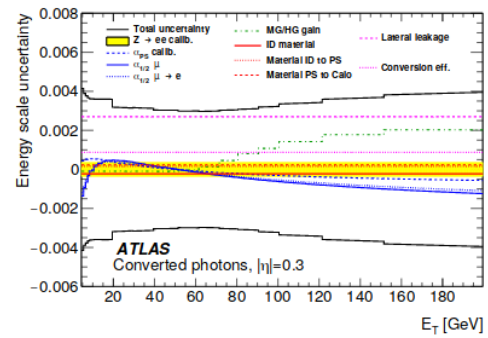


(a)

ATLAS collaboration,
2019 JINST14 P03017



(b)



(c)

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Photon energy response

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The photon energy scale, LHC experience:
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Transfer to different energy non-trivial
(detector gains, important for ILC at sqrt(s) = 500 GeV)
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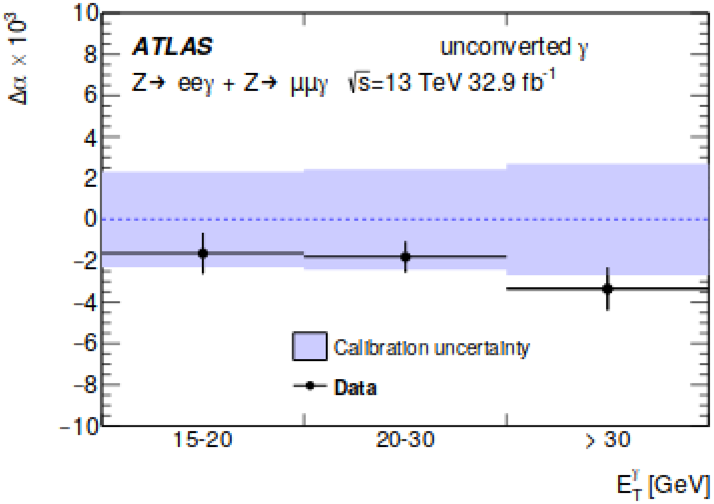
(conversions, leakage → material)

Systematic category	Photon energy scale uncertainty $\times 10^3$			
	$\|\eta\| < 1.37$		$1.52 < \|\eta\| < 2.37$	
	Unconverted	Converted	Unconverted	Converted
$Z \to ee$ calib.	0.45	0.45	1.41	1.41
Cell energy non-linearity	0.88	0.10	3.89	0.38
Layer (presampler, E1/E2, scintillator) calibration	2.34	0.29	3.04	0.60
ID material	0.96	0.82	3.71	3.89
Other material	1.66	0.26	3.19	1.02
Conversion reconstruction	0.40	0.99	0.76	0.97
Lateral shower shape modelling	1.03	1.95	3.20	0.85
Total	3.37	2.41	7.81	4.50



ATLAS collaboration, 2019 JINST14 P03017

Obviously, CLICdet has less material
Still, it is probably wise to use a more conservative estimate: 10^{-3}

Top mass: final summary

Final numbers for top mass paper are ready

cms energy	CLIC, $\sqrt{s}$ =380 GeV		ILC, $\sqrt{s}$ =500 GeV	
luminosity [fb^{-1}]	500	1000	500	4000
statistical	140 MeV	90 MeV	400 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		?	
photon response	16 MeV		85MeV	
total	150 MeV	110 MeV	410 MeV	150 MeV

Write-ups advancing:

- Pablo Gomis → Ph.D. thesis
- Esteban Fullana → note on lumi. Spectrum + impact top mass
- MV → paper draft on new method + calculation + prospects

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Indirect sensitivity

Quantify BSM sensitivity in a model-agnostic way with limits on anomalous D6 operator coefficients in Effective Field Theory

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

EFT analyses "by sector" are in full swing at the LHC. A linear collider can deliver the solid, and precise constraints that are crucial for a global SM EFT fit.

Global EFT fit of top EW couplings

Durieux, Perello, Zhang, Vos, arXiv:1807.02121
CLIC top paper, arXiv:1807.02441

Circular Collider 350+365

Sensitivity to four-fermion operators increases strongly with energy

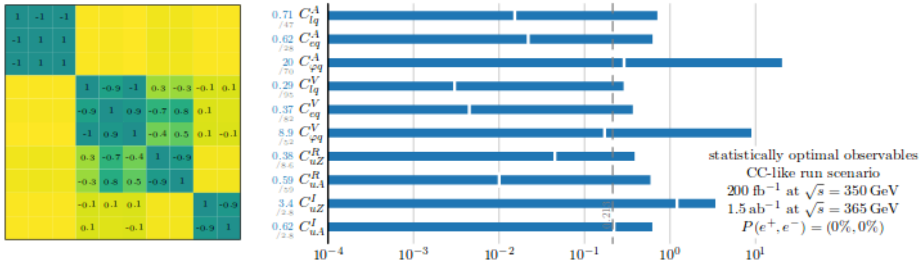

Figure 23. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables in a circular collider (CC-)like benchmark run scenario.

ILC500+ ILC1000

Ultimate precision in global EFT fit requires a collider with two energy stages and polarization

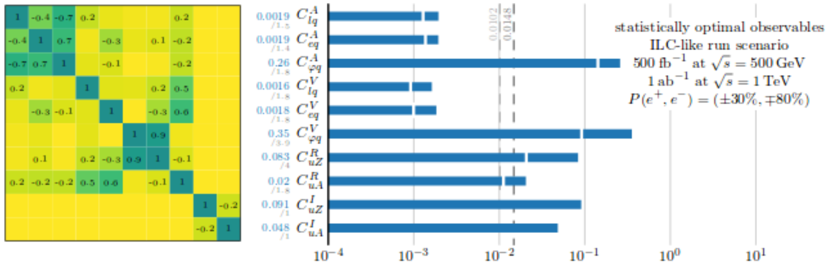

Figure 24. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables, in an ILC-like benchmark run scenario.

CLIC380+ CLIC1500+ CLIC3000

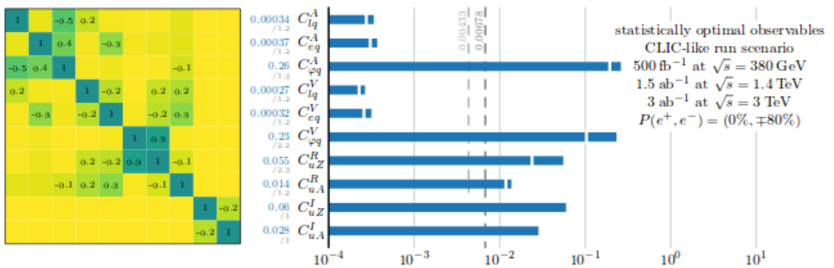

Figure 25. Global one-sigma constraints and correlation matrix arising from the measurement of statistically optimal observables in a CLIC-like benchmark run scenario.

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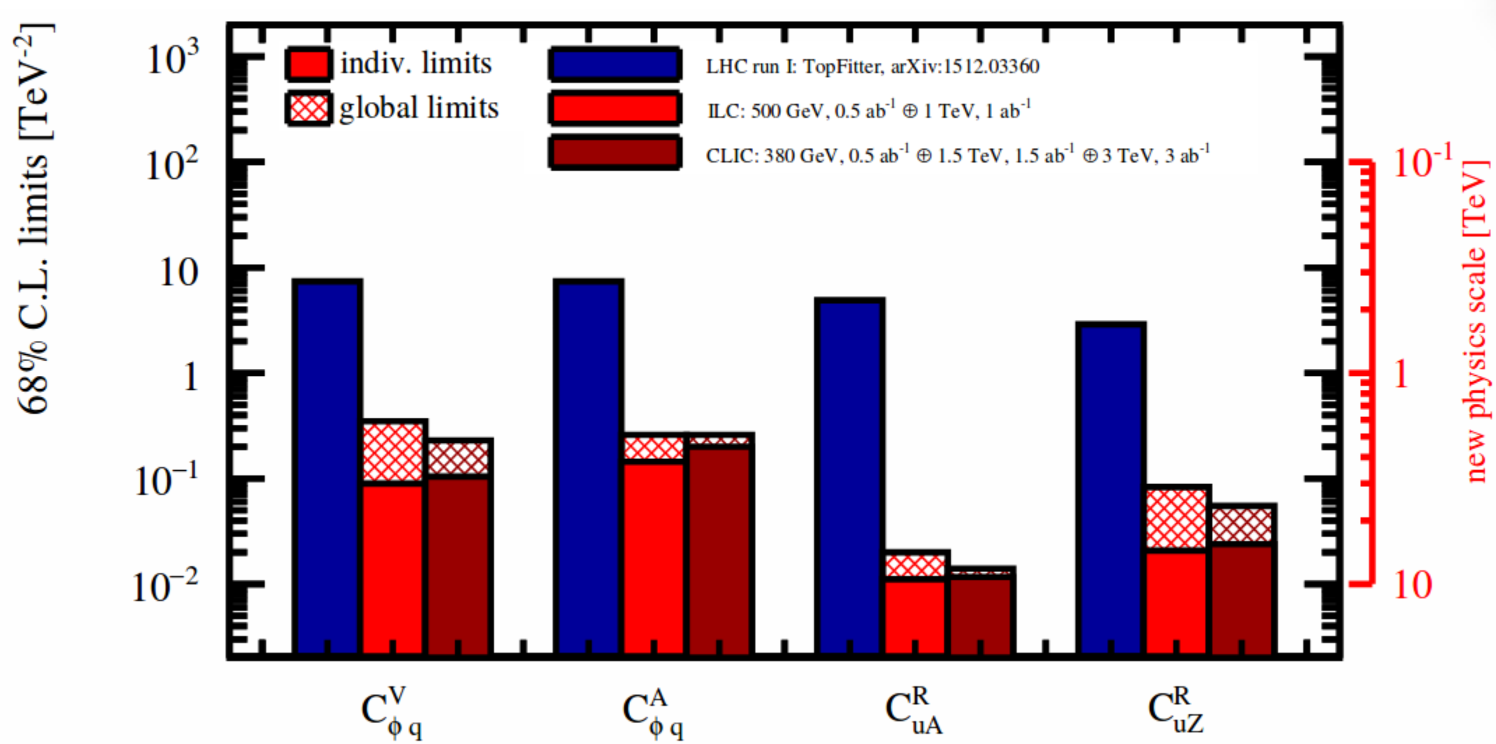
Top EFT fit at the LC

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLICdp top paper, arXiv:1807.02441



Two-fermion operator limits exceed LHC results by a large factor

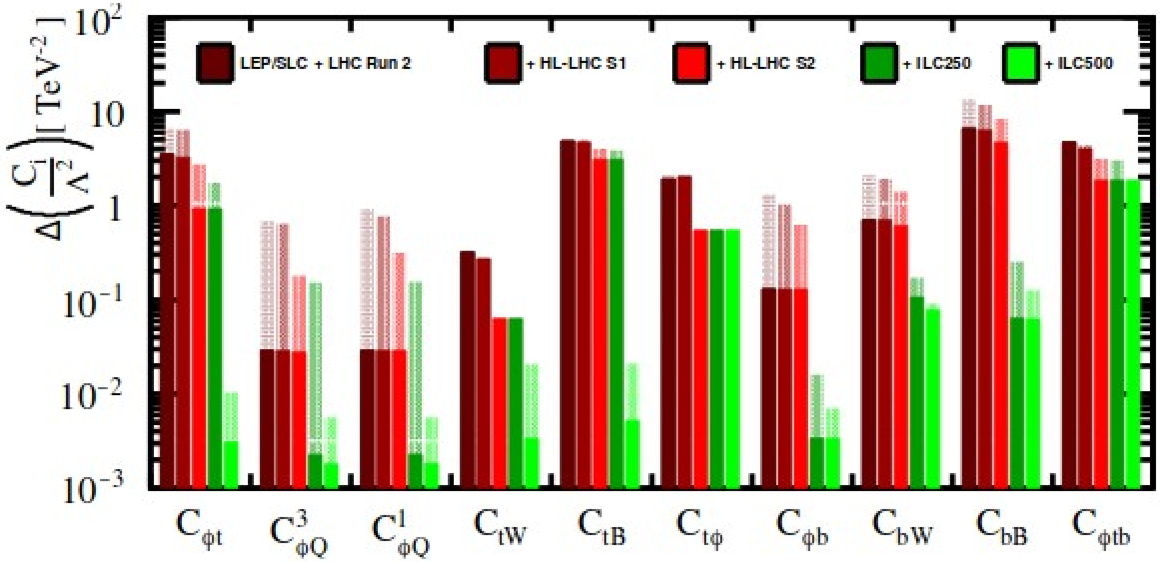
Constraints on 4-fermion and dipole moment operators probe very high scale

- TeV LC competitive with qq → tt at the LHC and possibly FCChh

Top EFT fit at the LHC

New paper: Durieux et al., arXiv:1907.10619

Fits to: LHC run 2+LEP/SLC, ILC250 e+e- → bb, ILC500 e+e- → tt



Two-fermion operator limits exceed HL-LHC prospects by a large factor