# Snowmass Energy Frontier: An Overview

LFC22: Strong interactions from QCD to new strong dynamics at LHC and Future Colliders

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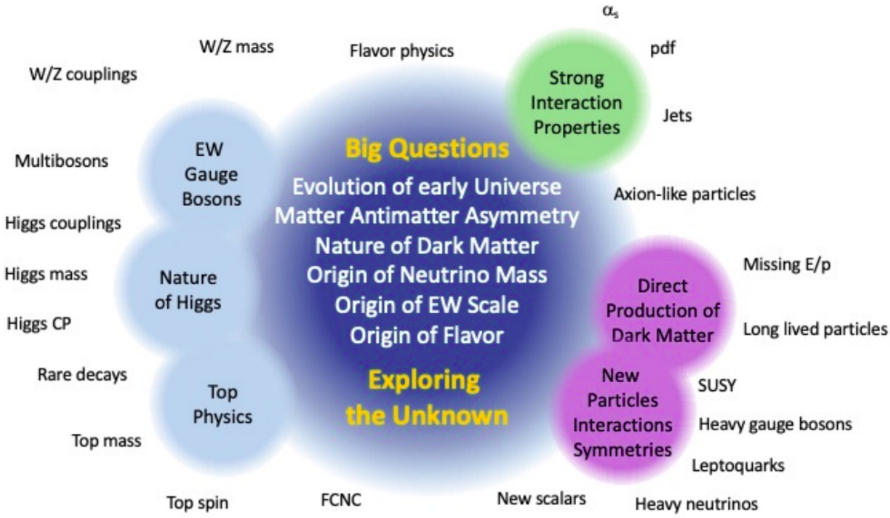
# Outline

1.- Goals and contributions of Snowmass Energy Frontier

2.- QCD and strong interactions
    2.1.- Developments at future facilities
    2.2.- Developments of $\alpha_s$ measurements
    2.3.- Developments on Parton Distribution Functions
    2.4.- Developments on hadronisation and fragmentation functions

3.- Heavy flavour and top-quark physics
    3.1.- Top-quark mass
    3.2.- Top-quark production
    3.3.- Top-quark couplig measurements from EFT fits
    3.4.- Top-quark Yukawa

# Goals of Snowmass Energy Frontier



# Organisation and contributions

| **Topical Group** | **Contributions** |
|---|---|
| EF01: EW Physics: Higgs Boson properties and couplings | 20 |
| EF02: EW Physics: Higgs Boson as a portal to new physics | 8 |
| EF03: EW Physics: Heavy flavor and top quark physics | 10 |
| EF04: EW Physics: EW Precision Physics and constraining new physics | 13 |
| EF05: QCD and strong interactions: Precision QCD | 2 |
| EF06: QCD and strong interactions: Hadronic structure and forward QCD | 8 |
| EF07: QCD and strong interactions: Heavy Ions | 3 |
| EF08: BSM: Model specific explorations | 13 |
| EF09: BSM: More general explorations | 26 |
| EF10: BSM: Dark Matter at colliders | 14 |
| **EF General** | **32** |
| **Total** | **149** |

# QCD and strong interactions

# Introduction

- Quantum Chormodynamics play a unique role in the SM
- Many QCD effects are universal and their related uncertainties are often a limiting factor in SM measurements
- The strong coupling constant is the least well measured
- The upcoming era will be a new golden age for QCD (HL-LHC, Belle II, EIC, lattice QCD...)
- PDFs and FFs will play a prominient role in future precision experiments
- Implementation of two- and three-loop computations of radiative contributions would be requiered to exploit the future precision experiments

# Future Facilities

HiLumi
HL-LHC PROJECT

- High-luminosity LHC
- Forward Physics Facility
- The Electron Ion Collider
- The Belle II Experiment
- Future Electron-Positron Collider
- Future Muon-Muon Collider
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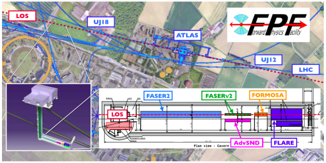
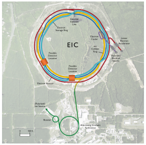
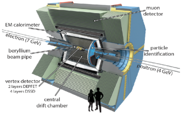
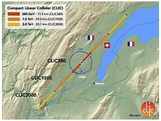
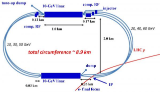


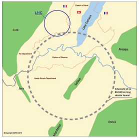








International
MUON Collider
Collaboration



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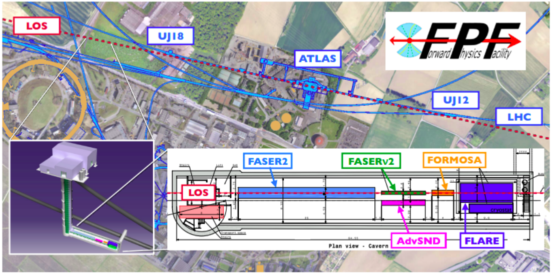
HiLumi
HL-LHC PROJECT

- Additional measurements of jet, photon and top-quark cross-sections
- Test of pQCD, PDFs, FFs and $\alpha_s$ running
- Challenges on reconstruction performance since the pileup increases
- Studies on jet substructure could mitigate the impact of the pileup

# Future Facilities



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- Located at 617-682 m west of the ATLAS IP would detect $10^6$ $\nu$ at TeV
- Sensitive to the very forward production of light hadrons and charmed mesons
- Access the very low-x and the very high-x regions of the colliding protons
- Acts as a neutrino-induced DIS experiment with TeV neutrino beams

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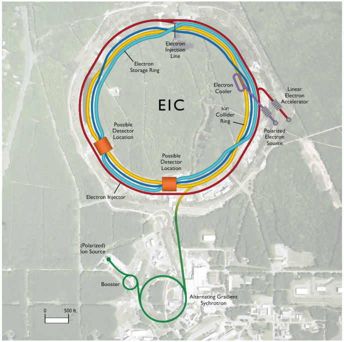

- Precise measurements of hadron structure electron-proton(nucleus) DIS for $\sqrt{s} = 20 - 140$ GeV
- Probe unpolarised proton PDFs and flavour composition for $x > 0.1$ for scales of few GeV
- Phenomenological PDFs would be great benchmarks for lattice QCD

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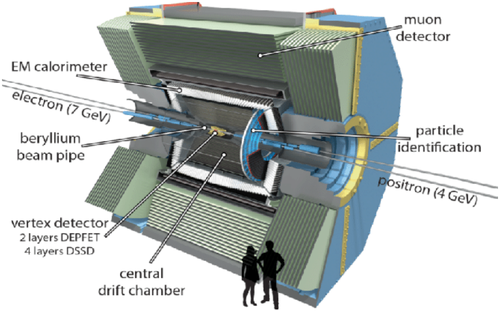

- The LO hadronic contribution to $a_\mu$ can be obtained from $e^+e^- \rightarrow \mathrm{had.}$
- Belle II can resolve the discrepancy between BABAR and KLOE
- Measurements of mulitdimensional correlation of momenta and polarisation of final-state hadrons will increase our understanding of soft QCD

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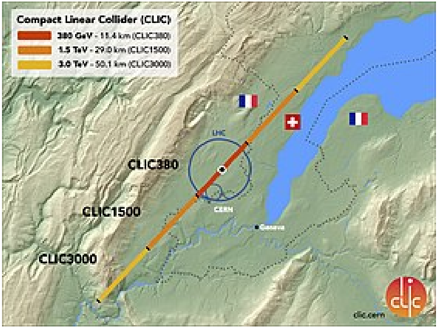

- Neutral QCD initial state → precision well beyond hadron colliders
- Able of studing pure samples of gluon jets ($e^+e^- \to HZ$), poorly modeled and copiously produced at the LHC
- Improvement in understanding the $b$ showering and hadronisation

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International
MUON Collider
Collaboration

- Physical reach for discoveries similar to high-energy hadron colliders
- Similar advantages as $e^+e^-$ colliders
- Final state more complicated
- Critical difference → large beam-induced background ($\mu \to e\nu\bar{\nu}$)

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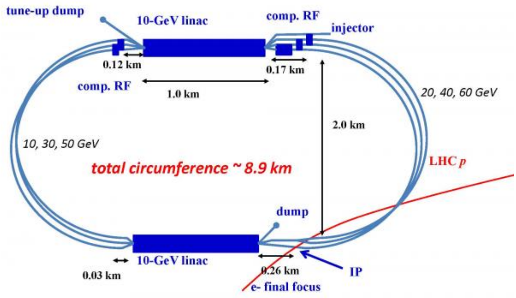

- The LHeC would extend DIS into the TeV energy range
- A muon-hadron collider in existing facilities could have an energy reach in DIS similar to LHeC or FCC-eh
- A Muon-Ion Collider could succeed the EIC in 2040

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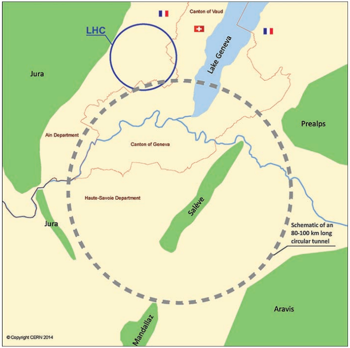


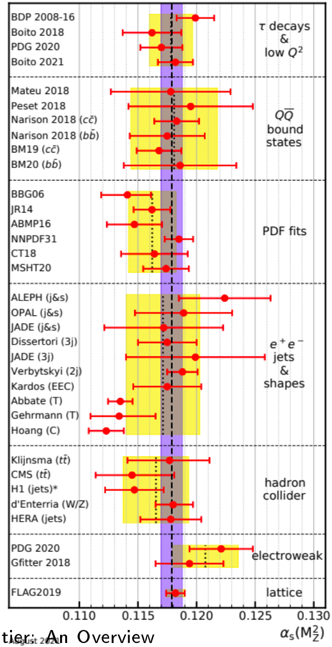
- Best opportunity to study a wide range of precision measurements of pQCD and non-pQCD
- Two major proposals → FCC-hh and SPPC with $\sqrt{s} = 100$ TeV and 25 $\text{ab}^{-1}$
- Breakthroughs in accelerator technology, detector design, and physics object reconstruction

# Measurements $\alpha_s$

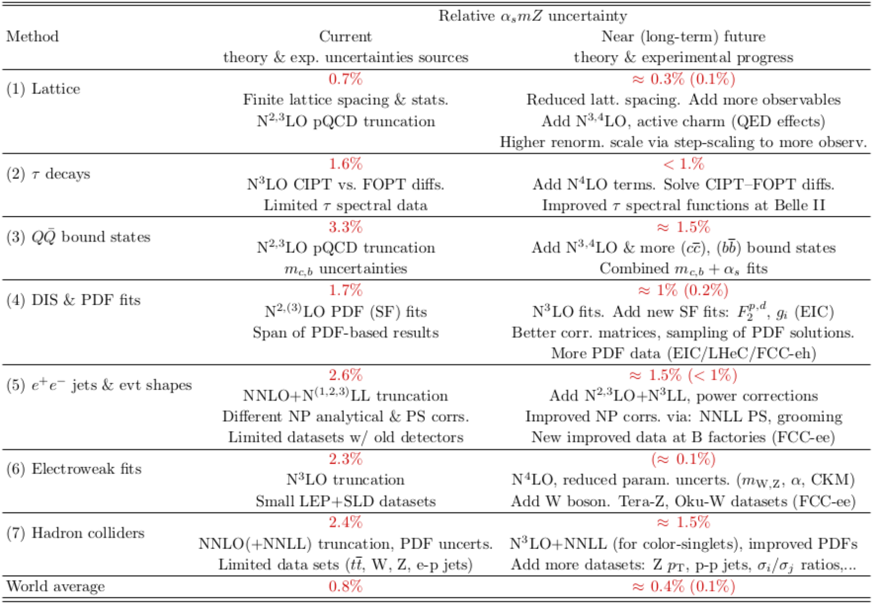
World average

$\alpha_s(\mathrm{M_Z}) = 0.1179 \pm 0.0009\ (\pm 0.8\%)$

- Hadronic tau decay
  $\alpha_s(\mathrm{M_Z}) = 0.1178 \pm 0.0019\ (\pm 1.6\%)$
- Quarkonia
  $\alpha_s(\mathrm{M_Z}) = 0.1181 \pm 0.037\ (\pm 3.3\%)$
- DIS and PDFs fits
  $\alpha_s(\mathrm{M_Z}) = 0.1162 \pm 0.0020\ (\pm 1.7\%)$
- $e^+e^- \to$ had. final states
  $\alpha_s(\mathrm{M_Z}) = 0.1171 \pm 0.0031\ (\pm 2.6\%)$
- Hadron collider measurements
  $\alpha_s(\mathrm{M_Z}) = 0.1165 \pm 0.0028\ (\pm 2.4\%)$
- Electroweak precision fits
  $\alpha_s(\mathrm{M_Z}) = 0.1208 \pm 0.0028\ (\pm 2.3\%)$
- Lattice-QCD
  $\alpha_s(\mathrm{M_Z}) = 0.1182 \pm 0.0008\ (\pm 0.7\%)$



# Measurements $\alpha_s$



| Method | Relative $\alpha_s mZ$ uncertainty |  |
|---|---|---|
|  | Current<br>theory & exp. uncertainties sources | Near (long-term) future<br>theory & experimental progress |
| (1) Lattice | 0.7%<br>Finite lattice spacing & stats.<br>$N^{2,3}LO$ pQCD truncation | $\approx$ 0.3% (0.1%)<br>Reduced latt. spacing. Add more observables<br>Add $N^{3,4}LO$, active charm (QED effects)<br>Higher renorm. scale via step-scaling to more observ. |
| (2) $\tau$ decays | 1.6%<br>$N^3LO$ CIPT vs. FOPT diffs.<br>Limited $\tau$ spectral data | $<$ 1.% <br>Add $N^4LO$ terms. Solve CIPT–FOPT diffs.<br>Improved $\tau$ spectral functions at Belle II |
| (3) $Q\bar{Q}$ bound states | 3.3%<br>$N^{2,3}LO$ pQCD truncation<br>$m_{c,b}$ uncertainties | $\approx$ 1.5%<br>Add $N^{3,4}LO$ & more $(c\bar{c})$, $(b\bar{b})$ bound states<br>Combined $m_{c,b} + \alpha_s$ fits |
| (4) DIS & PDF fits | 1.7%<br>$N^{2,(3)}LO$ PDF (SF) fits<br>Span of PDF-based results | $\approx$ 1% (0.2%)<br>$N^3LO$ fits. Add new SF fits: $F_2^{p,d}$, $g_i$ (EIC)<br>Better corr. matrices, sampling of PDF solutions.<br>More PDF data (EIC/LHeC/FCC-eh) |
| (5) $e^+e^-$ jets & evt shapes | 2.6%<br>NNLO+$N^{(1,2,3)}LL$ truncation<br>Different NP analytical & PS corrs.<br>Limited datasets w/ old detectors | $\approx$ 1.5% ($<$ 1%)<br>Add $N^{2,3}LO+N^3LL$, power corrections<br>Improved NP corrs. via: NNLL PS, grooming<br>New improved data at B factories (FCC-ee) |
| (6) Electroweak fits | 2.3%<br>$N^3LO$ truncation<br>Small LEP+SLD datasets | ($\approx$ 0.1%)<br>$N^4LO$, reduced param. uncerts. ($m_{W,Z}$, $\alpha$, CKM)<br>Add W boson. Tera-Z, Oku-W datasets (FCC-ee) |
| (7) Hadron colliders | 2.4%<br>NNLO(+NNLL) truncation, PDF uncerts.<br>Limited data sets ($t\bar{t}$, W, Z, e-p jets) | $\approx$ 1.5%<br>$N^3LO$+NNLL (for color-singlets), improved PDFs<br>Add more datasets: Z $p_T$, p-p jets, $\sigma_i/\sigma_j$ ratios,... |
| World average | 0.8% | $\approx$ 0.4% (0.1%) |

# Parton Distribution Functions: State of the art

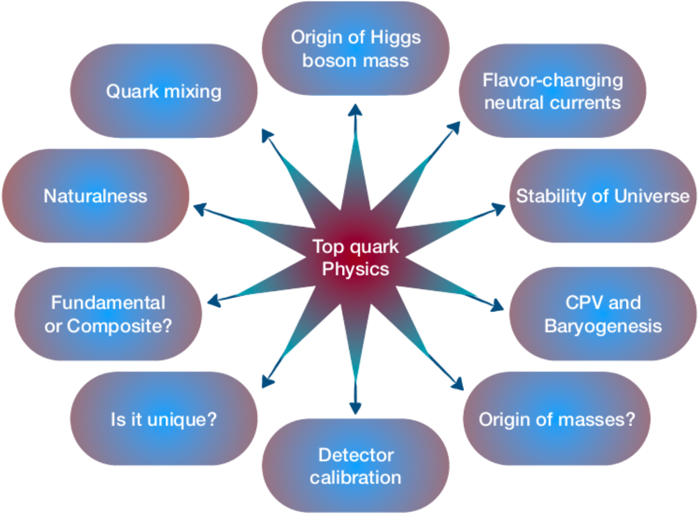
| **TOPIC** | **STATUS, Snowmass'2013** | **STATUS, Snowmass'2021** |
|---|---|---|
| Achieved accuracy of PDFs | $N^2LO$ for evolution, DIS and vector boson production | $N^2LO$ for all key processes; $N^3LO$ for some processes |
| PDFs with NLO EW contributions | MSTW'04 QED, NNPDF2.3 QED | LuXQED and other photon PDFs from several groups; PDFs with leptons and massive bosons |
| PDFs with resummations | Small x (in progress) | Small-x and threshold resummations implemented in several PDF sets |
| Available LHC processes to determine nucleon PDFs | $W/Z$, single-incl. jet, high-$p_T$ $Z$, $t\bar{t}$, $W+c$ production at 7 and 8 TeV | + $t\bar{t}$, single-top, dijet, $\gamma/W/Z$+jet, low-Q Drell Yan pairs, … at 7, 8, 13 TeV |
| Current, planned & proposed experiments to probe PDFs | LHC Run-2<br>DIS: LHeC | LHC Run-3, HL-LHC<br>DIS: EIC, LHeC, MuIC, … |
| Benchmarking of PDFs for the LHC | PDF4LHC'2015 recommendation in preparation | PDF4LHC'21 recommendation issued |
| Precision analysis of specialized PDFs | | Transverse-momentum dependent PDFs, nuclear, meson PDFs |
| | **NEW TASKS in the HL-LHC ERA** | |
| Obtain complete $N^2LO$ and $N^3LO$ predictions for PDF-sensitive processes | Improve models for correlated systematic errors | Find ways to constrain large-x PDFs without relying on nuclear targets |
| Develop and benchmark fast $N^2LO$ interfaces | Estimate $N^2LO/N^3LO$ theory uncertainties | New methods to combine PDF ensembles, estimate PDF uncertainties, deliver PDFs for applications |

# Hadronisation and fragmentation functions: Future Facilities

- To reach the new level of precision a better understanding of hadronisation is required
- Increasing the precision of the MCEG requires a model for correlated production of multiple hadrons → Belle II becomes a level arm
- EIC will provide a solid ground for phenomenological analysis to obtain transverse-momentum dependent PDFs and FFs
- Nonperturbative uncertainties from final-state hadronic effects can be reduced with FCC-ee data

# Top-quark physics and heavy flavour production

# Introduction



Origin of Higgs boson mass

Quark mixing

Flavor-changing neutral currents

Naturalness

Stability of Universe

Top quark Physics

Fundamental or Composite?

CPV and Baryogenesis

Is it unique?

Origin of masses?

Detector calibration

# Top-quark mass

- A precision in the top-quark mass of 100 MeV corresponds to a precision of W boson of about 1 MeV
- The top-quark mass is not a physical parameter and depends on the renormalisation scheme
- Most NLO and NNLO calculations are only available in a particular scheme
- The on-shell condition has an intrinsic renormalon ambiguity of 110 to 250 MeV
- The most precise measurements are done in the MC scheme
- The relation with the $m_t^{MC}$ with other well defined schemes is not known with high enough precision
- Top-quark mass measurement in a well defined scheme rely on measuring cross-sections that depend on the mass

# Top-quark mass: Measurements

## Direct top-quark mass measurements at hadron colliders

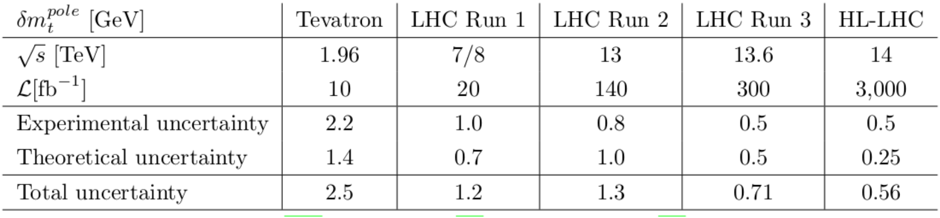
- Obtained from direct reconstruction of the top decay products
- Top-quark mass measured in the Monte Carlo scheme ($m_t^{\mathrm{MC}}$)
- Issues in the universality of the results between different MCs
- Difficulties in the interpretation in terms of well-defined mass schemes
- $m_t^{\mathrm{MC}}$ and $m_t^{\mathrm{pole}}$ differ by 500-200 MeV
- Need further precision when HL-LHC measurements are available

| $\delta m_t^{MC}$ [MeV] | Tevatron | LHC | | | | | HL-LHC |
|---|---|---|---|---|---|---|---|
| | | Run 1 | | Run 2 | | Run 3 | |
| | | ATLAS | CMS | ATLAS | CMS | | |
| $\sqrt{s}$ [TeV] | 1.96 | 7,8 | 7,8 | 13 | 13 | 13.6 | 14 |
| $\mathcal{L}[\mathrm{fb}^{-1}]$ | 9.7 | 5, 20 | 5, 20 | 36 | 36 | 300 | 3,000 |
| Statistical uncert. | 350 | 250 | 130 | 400 | 40 | 40 | 20 |
| Systematic uncert. | 540 | 410 | 470 | 670 | 380 | 300 | 170 |
| Total uncert. | 650 | 480 | 480 | 780 | 380 | 310 | 170 |

# Top-quark mass: Measurements

## Indirect top-quark mass measurements at hadron colliders

- Obtained from measuring cross sections sensitive to the top mass
- Methods usually rely on the total inclusive $t\bar{t}$ production cross section based on NNLO QCD calculations
- Huge sensitivity on $\alpha_s$ and the gluon PDFs which produce the leading uncertainty
- Using differential cross sections increases the sensitivy on the top mass → Needs increasing the precision on the theoretical predictions
- The $t\bar{t}$ invaraint mass distribution is highly sensitive to the top mass in the threshold region

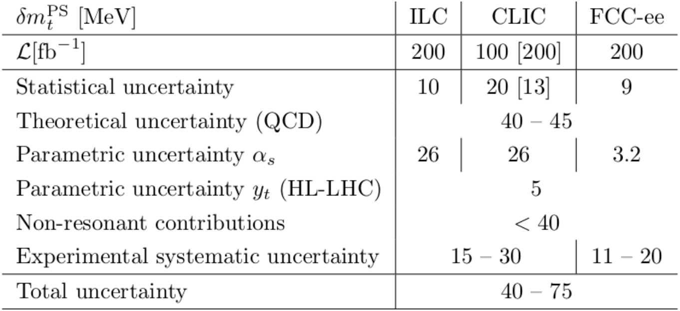


| $\delta m_t^{pole}$ [GeV] | Tevatron | LHC Run 1 | LHC Run 2 | LHC Run 3 | HL-LHC |
|---|---|---|---|---|---|
| $\sqrt{s}$ [TeV] | 1.96 | 7/8 | 13 | 13.6 | 14 |
| $\mathcal{L}$[fb$^{-1}$] | 10 | 20 | 140 | 300 | 3,000 |
| Experimental uncertainty | 2.2 | 1.0 | 0.8 | 0.5 | 0.5 |
| Theoretical uncertainty | 1.4 | 0.7 | 1.0 | 0.5 | 0.25 |
| Total uncertainty | 2.5 | 1.2 | 1.3 | 0.71 | 0.56 |

# Top-quark mass: Measurements

Measurements at $e^+e^-$ colliders

- The methods developed at LHC can be used → cleaner hadronic enviroment
- Dependence on PDF is replaced by the one on the beam's luminosity spectrum
- Threshold scan method becomes extremely promising



| $\delta m_t^{\mathrm{PS}}$ [MeV] | ILC | CLIC | FCC-ee |
|---|---|---|---|
| $\mathcal{L}[\mathrm{fb}^{-1}]$ | 200 | 100 [200] | 200 |
| Statistical uncertainty | 10 | 20 [13] | 9 |
| Theoretical uncertainty (QCD) | 40 – 45 | | |
| Parametric uncertainty $\alpha_s$ | 26 | 26 | 3.2 |
| Parametric uncertainty $y_t$ (HL-LHC) | 5 | | |
| Non-resonant contributions | $< 40$ | | |
| Experimental systematic uncertainty | 15 – 30 | | 11 – 20 |
| Total uncertainty | 40 – 75 | | |

# Top-quark production

- At LHC the top-quark is predominantly produced in $t\bar{t}$ pairs
- The N$^3$LO QCD corrections are not available yet but aN$^3$LO including third-order soft-gluon corrections from NNLL resummation
- Single production provides an opportunity for direct studies of EW properties of the top-quark
- The sensitivity of the single top production to the CKM can be enhanced measuring rations
- At lepton colliders single top production is produced through lepton-photon scattering (could be observed above 0.5 TeV)

| $K$-factors for $t\bar{t}$ production in $pp$ collisions | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $K$-factor | 7 TeV | 8 TeV | 13 TeV | 13.6 TeV | 14 TeV | 27 TeV | 50 TeV | 100 TeV |
| NLO/LO | 1.47 | 1.48 | 1.50 | 1.50 | 1.50 | 1.52 | 1.55 | 1.58 |
| NNLO/LO | 1.65 | 1.66 | 1.67 | 1.67 | 1.67 | 1.69 | 1.71 | 1.75 |
| aN$^3$LO/LO | 1.72 | 1.72 | 1.72 | 1.72 | 1.72 | 1.73 | 1.75 | 1.78 |
| aNLO/NLO | 1.01 | 1.00 | 0.99 | 0.99 | 0.99 | 0.97 | 0.95 | 0.92 |
| aNNLO/NNLO | 1.01 | 1.01 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 0.98 |

# Top-quark production: $pp \to t\bar{t}X$

- The measurements at HL-LHC could only be beat by high-energy lepton colliders and future hadron colliders
- $pp \to t\bar{t}j$: First steps towards NNLO QCD corrections for on-shell production
- $pp \to t\bar{t}\gamma$: Challenging due to the decay $t \to Wb\gamma$ which generates up to 50% of the signal. NNLO QCD necessary to exploit the potential of the future data set
- $pp \to t\bar{t}Z$: Current measurements already at the accuracy of theoretical predictions at NLO+NNLL
- $pp \to t\bar{t}H$: Efforts to extend the inclusive production to NNLO QCD necessary for HL-LHC data
- $pp \to t\bar{t}W$: NNLO QCD corrections for the production part are needed for the HL-LHC run
- $pp \to t\bar{t}t\bar{t}$: Hard to imagine that NNLO QCD corrections necessary to match the 10% accuracy of HL-LHC are available soon.

# SMEFT operators relevant for the top-quark

## 2-quark operators

### Couplings of the t- and b-quark to the $Z$

$$O^{3}_{\varphi Q} \equiv \left(\bar{Q}\tau^{I}\gamma^{\mu}Q\right)\left(\varphi^{\dagger}i\overleftrightarrow{D}^{I}_{\mu}\varphi\right)$$

$$O^{1}_{\varphi Q} \equiv (\bar{Q}\gamma^{\mu}Q)\left(\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi\right)$$

$$O_{\varphi t(b)} \equiv (\bar{t}(\bar{b})\gamma^{\mu}t(b))\left(\varphi^{\dagger}i\overleftrightarrow{D}_{\mu}\varphi\right)$$

### EW dipole operators

$$O_{uW} \equiv \left(\bar{Q}\tau^{I}\sigma^{\mu\nu}t\right)\left(\varepsilon\varphi^{*}W^{I}_{\mu\nu}\right)$$

$$O_{tB} \equiv (\bar{Q}\sigma^{\mu\nu}t)\,(\varepsilon\varphi^{*}B_{\mu\nu})$$

### Chromo-magnetic dipole op.

$$O_{tG} \equiv \left(\bar{Q}\sigma^{\mu\nu}T^{A}t\right)\left(\varepsilon\varphi^{*}G^{A}_{\mu\nu}\right)$$

### t-quark yukawa

$$O_{t\varphi} \equiv (\bar{Q}t)\left(\varepsilon\varphi^{*}\,\varphi^{\dagger}\varphi\right)$$

## 4-quark operators

### Couplings of light quarks with t- and b-quarks

$O^{8}_{tu}$ $O^{8}_{td}$ $O^{1,8}_{Qq}$ $O^{8}_{Qu}$ $O^{8}_{Qd}$ $O^{3,8}_{Qq}$ $O^{8}_{tq}$

## 2-quark 2-lepton operators

### Couplings of light leptons with t- and b-quarks

$O_{eb}$ $O_{lb}$ $O_{et}$ $O_{lt}$ $O_{eQ}$ $O^{+}_{lQ}$ $O^{-}_{lQ}$

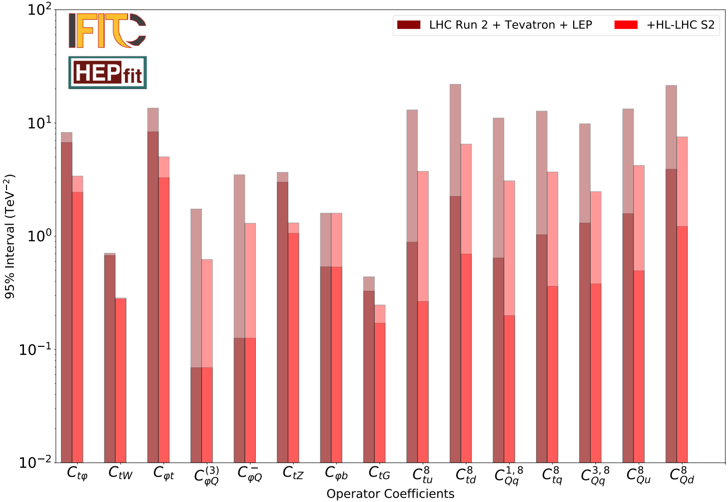
# Observables from current colliders (LEP/SLC, Tevatron, LHC run 1 & 2)

- Here we show the observables included that have been measured in the actual colliders

| Process | Observable | $\sqrt{s}$ | $\int \mathscr{L}$ | Experiment |
|---|---|---|---|---|
| $pp \to t\bar{t}$ | $d\sigma/dm_{t\bar{t}}$ (15+3 bins) | 13 TeV | 140 fb$^{-1}$ | CMS |
| $pp \to t\bar{t}$ | $dA_C/dm_{t\bar{t}}$ (4+2 bins) | 13 TeV | 140 fb$^{-1}$ | ATLAS |
| $pp \to t\bar{t}Z$ | $d\sigma/dp_T^Z$ (7 bins) | 13 TeV | 140 fb$^{-1}$ | ATLAS |
| $pp \to t\bar{t}\gamma$ | $d\sigma/dp_T^\gamma$ (11 bins) | 13 TeV | 140 fb$^{-1}$ | ATLAS |
| $pp \to t\bar{t}H + tHq$ | $\sigma$ | 13 TeV | 140 fb$^{-1}$ | ATLAS |
| $pp \to tZq$ | $\sigma$ | 13 TeV | 77.4 fb$^{-1}$ | CMS |
| $pp \to t\gamma q$ | $\sigma$ | 13 TeV | 36 fb$^{-1}$ | CMS |
| $pp \to t\bar{t}W$ | $\sigma$ | 13 TeV | 36 fb$^{-1}$ | CMS |
| $pp \to t\bar{b}$ (s-ch) | $\sigma$ | 8 TeV | 20 fb$^{-1}$ | LHC |
| $pp \to tW$ | $\sigma$ | 8 TeV | 20 fb$^{-1}$ | LHC |
| $pp \to tq$ (t-ch) | $\sigma$ | 8 TeV | 20 fb$^{-1}$ | LHC |
| $t \to Wb$ | $F_0$, $F_L$ | 8 TeV | 20 fb$^{-1}$ | LHC |
| $p\bar{p} \to t\bar{b}$ (s-ch) | $\sigma$ | 1.96 TeV | 9.7 fb$^{-1}$ | Tevatron |
| $e^-e^+ \to b\bar{b}$ | $R_b$ , $A_{FBLR}^{bb}$ | $\sim$ 91 GeV | 202.1 pb$^{-1}$ | LEP/SLD |

# Current constraints vs expected HL-LHC constraints

Shadowed (solid) bars →marginalised from global (individual) fit



# Measurements at $e^+e^-$ colliders: $b\bar{b}$ production

| Machine | Polarisation | Energy | Luminosity | Observable |
|---|---|---|---|---|
| ILC | P($e^+$, $e^-$):($-30\%, +80\%$)<br>P($e^+$, $e^-$):($+30\%, -80\%$) | 250 GeV | 2 ab$^{-1}$ | $\sigma_{b\bar{b}}$<br>$A_{\text{FB}}^{b\bar{b}}$ |
| | | 500 GeV | 4 ab$^{-1}$ | |
| | | 1 TeV | 8 ab$^{-1}$ | |
| CLIC | P($e^+$, $e^-$):($0\%, +80\%$)<br>P($e^+$, $e^-$):($0\%, -80\%$) | 380 GeV | 2 ab$^{-1}$ | $\sigma_{b\bar{b}}$<br>$A_{\text{FB}}^{b\bar{b}}$ |
| | | 1.5 TeV | 2.5 ab$^{-1}$ | |
| | | 3 TeV | 5 ab$^{-1}$ | |
| CEPC/FCC-*ee* | Unpolarised | Z-pole | 57.5/150 ab$^{-1}$ | $\sigma_{b\bar{b}}$<br>$A_{\text{FB}}^{b\bar{b}}$ |
| | | 240 GeV | 20/5 ab$^{-1}$ | |
| | | 360/365 GeV | 1/1.5 ab$^{-1}$ | |

- These observables set constraints on the EW precision observables $C_{\varphi Q}^{+} = C_{\varphi Q}^{1} + C_{\varphi Q}^{3}$ and $C_{\varphi b}$
- Also relevant for 2-quark 2-lepton operators $C_{lQ}^{+}$, $C_{lb}$ and $C_{eb}$
- The higher-energy measurement are more relevant for the 2-quark 2-lepton operators

# Measurements at $e^+e^-$ colliders: $t\bar{t}$ production

| Machine | Polarisation | Energy | Luminosity | Observable |
|---|---|---|---|---|
| ILC | P($e^+$, $e^-$):(−30%, +80%)<br>P($e^+$, $e^-$):(+30%, −80%) | 500 GeV | 4 $\text{ab}^{-1}$ | Optimal Observables |
| | | 1 TeV | 8 $\text{ab}^{-1}$ | |
| CLIC | P($e^+$, $e^-$):(0%, +80%)<br>P($e^+$, $e^-$):(0%, −80%) | 380 GeV | 2 $\text{ab}^{-1}$ | Optimal Observables |
| | | 1.5 TeV | 2.5 $\text{ab}^{-1}$ | |
| | | 3 TeV | 5 $\text{ab}^{-1}$ | |
| CEPC/FCC-*ee* | Unpolarised | 350 GeV | 0.2 $\text{ab}^{-1}$ | Optimal Observables |
| | | 365 GeV | 1/1.5 $\text{ab}^{-1}$ | |

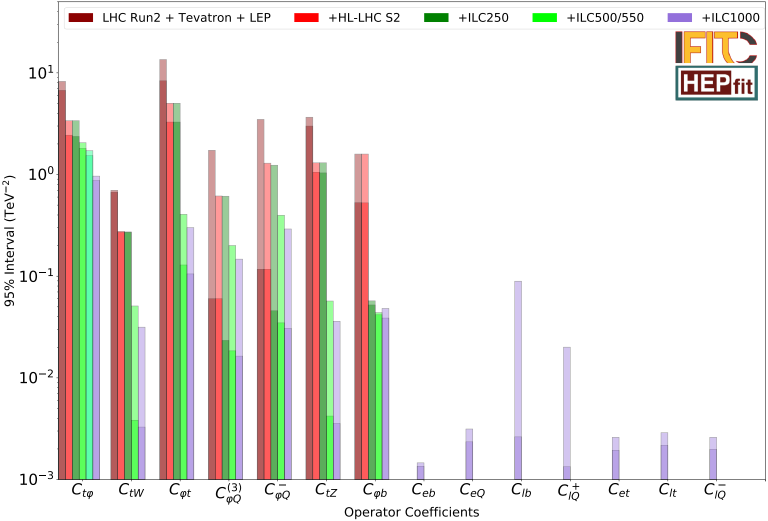
- Optimal observables maximally exploit the information in the fully differential $e^+e^- \to t\bar{t} \to bW^+\bar{b}W^-$ distribution
- These constrain the 2-fermion operators $C^-_{\varphi Q}$, $C_{\varphi t}$, $C_{tW}$ and $C_{tZ}$
- Also the 2-quark 2-lepton operators $C^-_{lQ}$, $C_{lt}$, $C_{et}$ and $C_{eQ}$
- With these we eliminate blind directions in the $C^{(1)}_{\varphi Q} - C^{(3)}_{\varphi Q}$ plane
- Two different energies above the $t\bar{t}$ threshold are needed to constrain all the 2- and 4-fermion operators

# Measurements at $e^+e^-$ colliders: $t\bar{t}H$ production

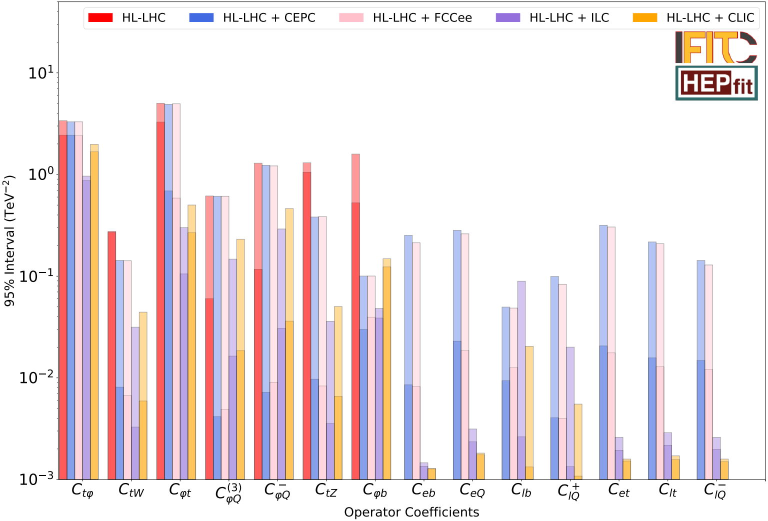
| Machine | Polarisation | Energy | Luminosity | Observable |
|---|---|---|---|---|
| ILC | P($e^+$, $e^-$):($-30\%$, $+80\%$)<br>P($e^+$, $e^-$):($+30\%$, $-80\%$) | 500/550 GeV | 4 ab$^{-1}$ | Inclusive cross section |
| | | 1 TeV | 8 ab$^{-1}$ | |
| CLIC | P($e^+$, $e^-$):($0\%$, $+80\%$)<br>P($e^+$, $e^-$):($0\%$, $-80\%$) | 1.5 TeV | 2.5 ab$^{-1}$ | Inclusive cross section |

- Essential measurement in order to improve the limits on the top-quark Yukawa
- The effect of an ILC run at 550 GeV has been studied
- At ILC550 the production cross section increases a factor of 3 w.r.t. ILC500 improving the statistical sensitivity by more than a 50%
- ILC550 and CLIC1500 have a similar sensitivity as HL-LHC
- ILC1000 improves the expected HL-LHC sensitivity by a factor of two

# Expected constraints for different $e^+e^-$ operation energies



# Comparison of future colliders



# Top-quark Yukawa coupling uncertainties

| Values in % units | | LHC | HL-LHC | ILC500 | ILC550 | ILC1000 | CLIC |
|---|---|---|---|---|---|---|---|
| $\delta y_t$ | Global fit | 6.12 | 2.53 | 1.57 | 1.30 | 0.739 | 1.48 |
| | Indiv. fit | 5.08 | 1.85 | 1.41 | 1.17 | 0.705 | 1.26 |

- Since the sensitivity at ILC500 is worse than in HL-LHC there is no a huge improvement for the individual constraint
- For the global fit the improvement is relevant even for ILC500, thanks to constraining the Yukawa with more than one observable
- Increasing the energy by 50 GeV provides an important improvement in the constraints thanks to the growth in the cross section
- Similar results are found for CLIC
- An improvement higher than a factor of 2.5 would be obtain at the final stage of ILC w.r.t. the HL-LHC

# Summary

- The potential of the future facilities to improve our knowledge of QCD have been summarised
- The EIC machine will be crutial in reducing the uncertainties on the PDFs and a possible FPF could cover additinal regions
- Many advancements on determining $\alpha_s$ and the inclusion of higher corrections is expected for the next decades
- For the top-quark a better understainding of the relation of the MC mass and the masses on well-defined schemes is needed
- With a high-energy lepton collider a precise measurement in a well-defined scheme would be possible
- More QCD corrections should be included in the production processes to guarantee that the theoretical error does not dominate the total uncertainty in the HL-LHC
- Lepton colliders working above the $t\bar{t}$ threshold are needed to significantly reduce the error on the top-quark EW couplings
- Significant improvements for the limits on the top-quark yukawa are found when operating above 550 GeV

Thank you!