Standard Model and Top physics prospects

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SM and Top physics

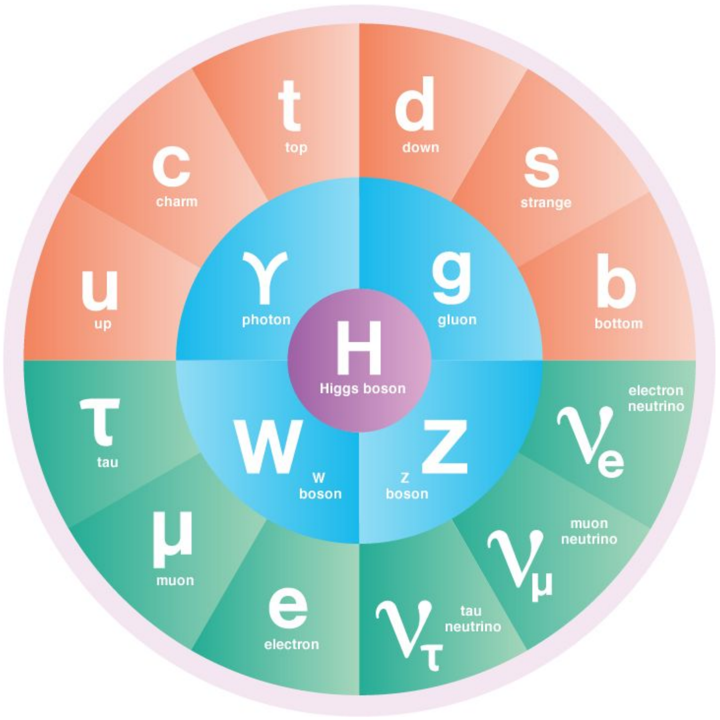
Standard Model physics isn't the headline reason for the HL-LHC, FCC, or linear colliders, but it's central to everything they'll do:

detector interactions & calibration;
search backgrounds; Higgs/EW-sector consistency…

… plus intrinsic interest in scaling and rare processes. Significant routes to indirect BSM sensitivity

Not everything is ideal for SM studies: high pile-up can degrade jet resolutions and ~kills MPI/DPS studies; LC plans are mutually exclusive on EW/Top; ...

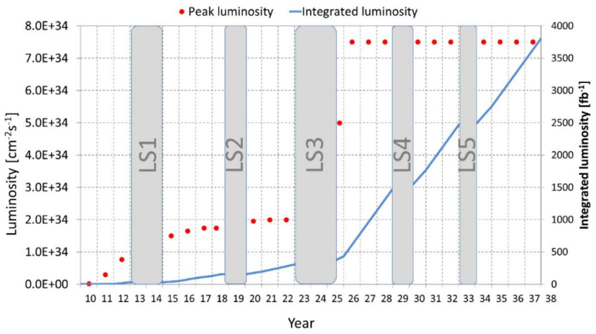
A lot will change if direct BSM is observed!



Future colliders from SM/Top perspective

HL-LHC

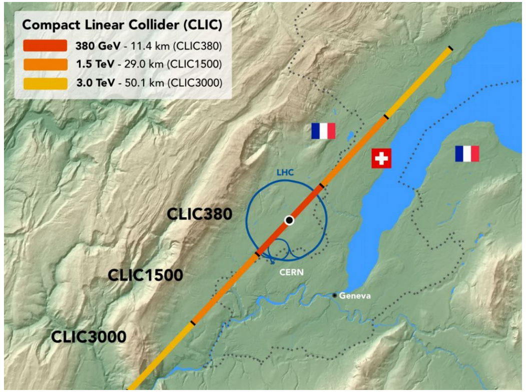
Lumi increase ⇒ μ ~ 200 pile-up ⇒ naive syst degradation.
Some offset from extended lepton trigger/ID angular acceptance and lower lepton trigger p_T thresholds.
Focus on systematics estimation, reduction, counteraction
Activity: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHEWG1



ILC/CLIC

Linear colliders cleaner, but limited SM physics:

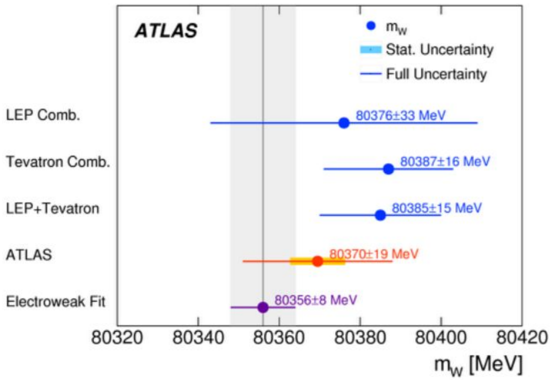
- ILC plans 10+ years at 250 GeV: great for Higgs, good for EW SM, poor for Top
- CLIC startup 100 /fb at top threshold, 500 /fb at e^+e^- ttbar cross-section peak: poor for EW SM
- Complementary!



FCC: huge SM cross-sections, modulo trigger. Phase-space corners, pQCD/EW & PDFs...

Precision electroweak measurements

With m_H ~ 125 GeV, both m_W and θ_W are predicted by the SM:



W mass **[Liverpool, Oxford]**

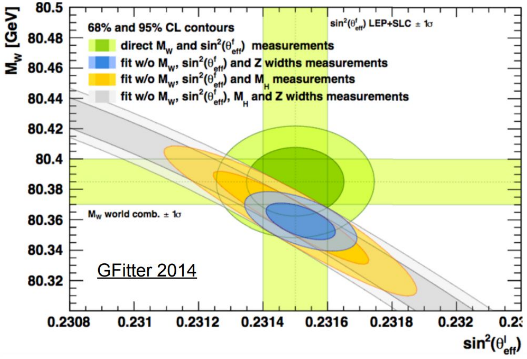
ATLAS m_W measurement (2011 data only) [arXiv:1701.07240] is syst-limited!

No gain from high-lumi, some from lepton reco extension.

Best potential from GPD combination with distinct LHCb phase-space

$\sin^2\theta_W$ weak mixing angle **[QMUL]**

ATLAS measurement with triple-differential cross-section (in $m_{\ell\ell}$, $y_{\ell\ell}$ & $\cos\theta^*$): Run 2 sensitivity ~ e^+e^- colliders. Important gain from central-forward lepton pairs: precision > LEP/SLD in HL-LHC



High-mass Drell-Yan **[Liverpool, QMUL]**

Model-independent probes of BSM via $m_{\ell\ell}$ and $m_{T,\ell\nu}$ up to TeV scale.

HL-LHC extends statistical reach, lepton extension ⇒ constraint of more EFT operators

Precision EW at LHCb

LHCb is very interesting for SM due to its unique forward-acceptance phase space.

W mass

GPD m_W measurement systematically limited by PDF uncertainties: these anti-correlate between central and forward rapidities ⇒ large benefit to combined GPD & LHCb fit, despite low fwd W rate.

Using 2014 PDF sets, a toy-study combination of $p_{T\ell}$-based m_W measurements gave up to a 30% improvement on PDF systematics [arXiv:1508.06954] ~3 MeV. Run 2 is sufficient, but HL-LHC will both enhance the LHCb rate and give greater lepton acceptance overlap with GPDs.

$\sin^2\theta_W$ weak mixing angle

Measured from fwd-bwd asymmetry: requires incoming quark-antiquark direction identification. Hard in LHC central region cf. Tevatron, but better defined at forward rapidity. PDF improvements also help (aided by LHCb data) + possibility of *in situ* PDF reweighting.

“Radiative” processes: jets and photons

There are *always* tails, wherever your stats run out. Observables falling as power-law vs. stats scaling as sqrt(N). Typical radiative effects scale as ~ log Q, so *major* leap in energy/pT stat reach needed to test scaling.

V + jets [Glasgow, Imperial, QMUL]
Major technical challenge is need for higher-order EW corrections: testbed for pQFT and interplay of QCD and EW. Heavy flavour QCD benefits from HL-LHC stats, e.g. differential V+b/c. Radiative tops & vector bosons (“Jets+V”) need theory advances in large-HT limit. Testbed for developing boosted methods essential at higher-energy colliders, e.g. FCC.

Inclusive jets and inclusive photon [Manchester]: HL-LHC stat gains on p_T tails + extended tracking maintain/improve jet-energy resolution. Overall gain ⇒ further PDF & α_s inputs

Tests calcs & MC tech: important for background control, but “standalone interesting”? [arXiv:1802.02100]

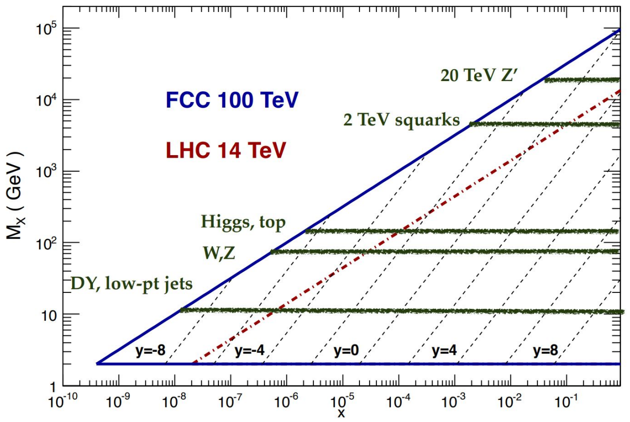
Parton distributions

Most LHC "hard" SM measurements — jet to EW to top — enter PDFs. UK fitting: MMHT & NNPDF global fits + ATLAS/xFitter. Paralleled by theory developments: NNLO incl jets, matched MC in fits?, massive-quark calcs? … [Edinburgh, Oxford, UCL]

HL-LHC stat increases mean moderate increases in scale-reach from GPDs, plus lepton acceptance

LHCb EW measurements very influential, e.g. W lepton kinematic distributions, forward top, intrinsic charm. Higher lumi helps small forward EW cross-sections. Increased eta overlap with GPDs good for cross-calibration.

LHeC: gluon density, BFKL regime. FCC = new regime for very high Q, very low-x, and the top as a resummed parton. (NB. massless approx still bad)



Vector boson fusion/scattering (VBF/VBS)

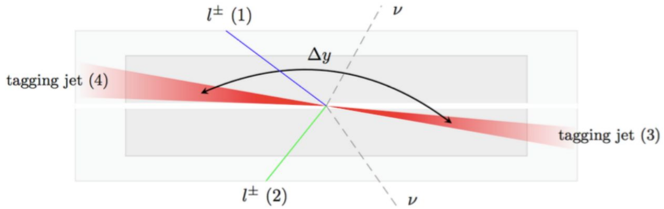
Single and pair particle production via EW t-channel
⇒ distinct event topology with hadronic rapidity gap

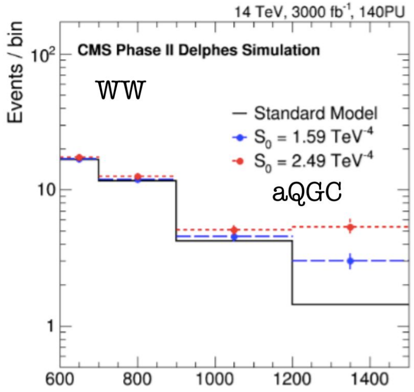
Linked to SM unitarisation: cancellations of EW couplings & Higgs exchange make it sensitive to BSM. Important dimension-8 SM EFT operators

ATLAS: forward jets at 50 GeV difficult with μ ~ 200: forward tracking/timing would help. Fine dσ measurements at high m_{jj} ⇒ strong constraints on aT/QGCs [Manchester]

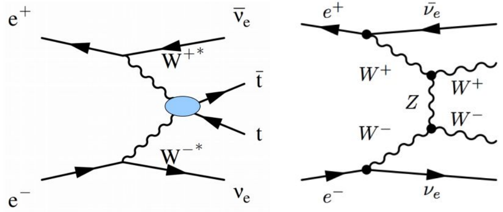
CMS estimate 3 /ab VBS discovery significance at 2.75 σ
Main HL-LHC gains from (again) forward lepton reco

CLIC can study VBF tt production, and e+e- WW VBS: in fully hadronic qqqqνν mode unlike LHC: extra aGCs





CMS SMP-14-008



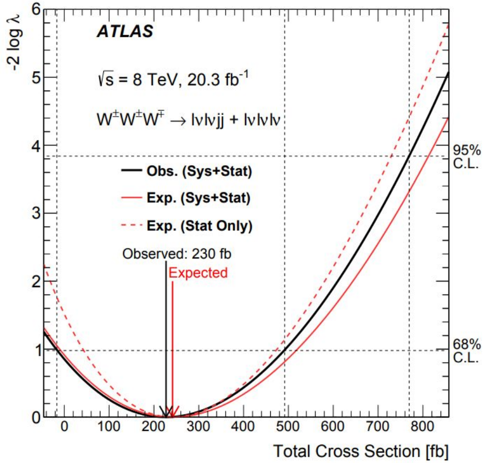
Multi-boson production

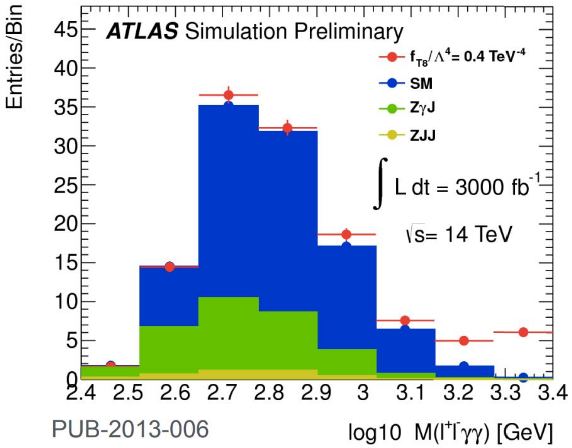
Diboson and triboson searches and measurements. Headline interpretation is TGC/QGC EFT fits [Cambridge, UCL]

Diboson observed at LHC: stats allow differential measurement to further probe couplings: HL-LHC lumi and lepton acceptance help. Triboson channels love high stats.

250 GeV ILC programme also focuses on diboson TGC and interpretation, but without any detailed precision studies available so far [arXiv:1710.07621]

100 TeV FCC has enormous phase space: potential for measurement of “extreme” multiboson states e.g. VVVVV. *How fundamentally interesting is this?*





PUB-2013-006

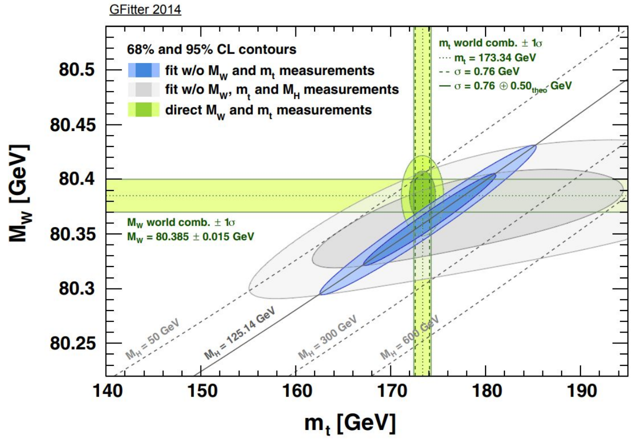
Top mass

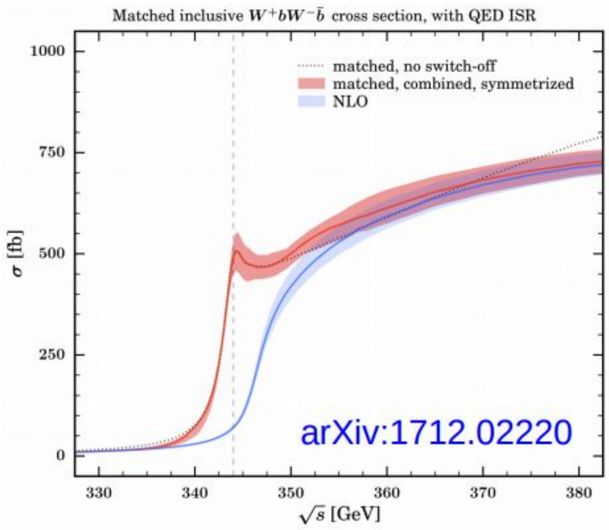
m_t is a fundamental SM parameter — and the best-measured quark mass ~ 0.28%. Crucial precision check of EW consistency, vacuum stability, etc.

Current LHC measurements of MC mass are
ATLAS: m_t = 172.51 ± 0.27 (stat) ± 0.42 (syst) GeV,
CMS: m_t = 172.44 ± 0.13 (stat) ± 0.47 (syst) GeV
Will improve the precision of the world average [arXiv:1801.02390]

MC mass measurements (i.e. template fits to MC) already syst-limited. HL-LHC gains: multi-differential dσ, b→J/ψ
+ *measurement-driven improvement of modelling systematics*

ILC 250 below tt threshold; CLIC 350-380 threshold scan would deliver super-precise mass measurement ~ 50 MeV





Top kinematics

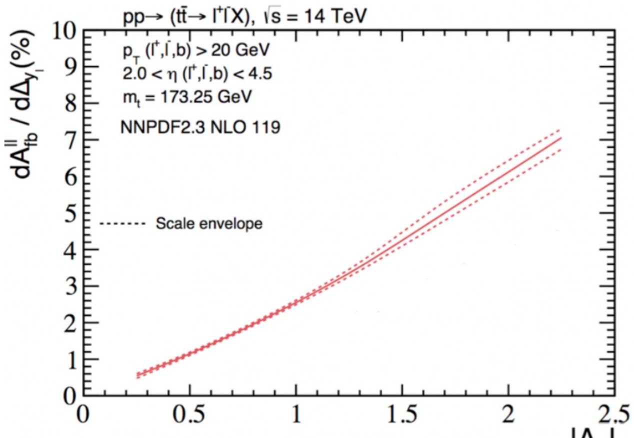
Top pair: MC mismodelling, NNLO resummed theory. More important tests for pQCD. [Bristol, Glasgow, Manchester, RHUL]

Multi-differential distributions and fine-grained charge asymmetry possible with HL-LHC stats.

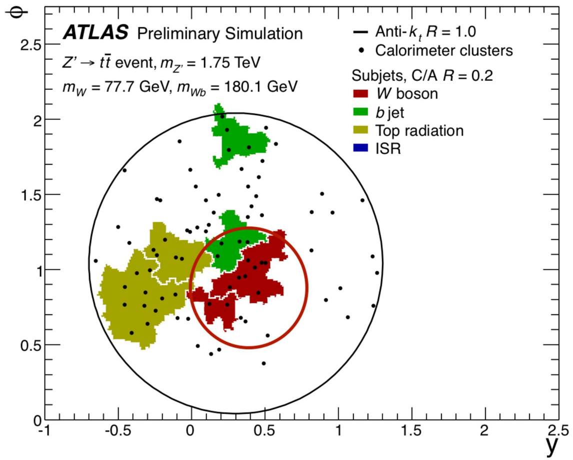
Forward top at LHCb ⇒ HL stats for differential distributions.
Larger sensitivity to asymmetries, and BSM via low-mass t-channel exchange

Boosted tops & tagging development (cf. FCC and 3 TeV CLIC): HL-LHC stats help.

EFT interpretations of many distributions: top EFT global fits [Glasgow, QMUL]



Based on R. Gauld, PRD 91, 054029 (2015)



Rare top processes

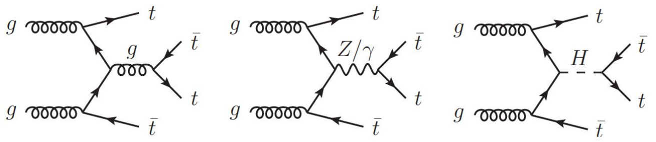
Single-top: differential distributions, s-channel

ttZ/gamma: (HL-)LHC: rare process benefits from statistics and increased lepton triggering [Glasgow].
tt production intrinsically via Z*/ɣ* in e^+e^- collisions, i.e. CLIC

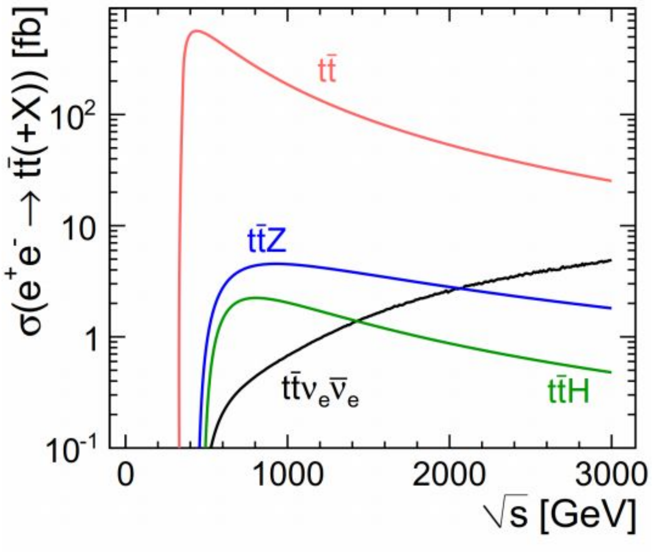
tttt: constraint on top Yukawa from QCD, EW, and Higgs diagram interference (cf. quadratic eq on RHS) [Bristol]

Top FCNC: very strongly suppressed in SM. tZq and tHq at HL-LHC with BR sensitivity ~ 10^{-4}. [Brunel]
Similar sensitivity from CLIC, but also for tHc, tɣc & c+E_{miss} channels, difficult at hadron colliders

More EFT interpretation possible for all processes



$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \kappa_t^2 \sigma_{\rm int}^{\rm SM} + \kappa_t^4 \sigma^{\rm SM}(t\bar{t}t\bar{t})_H$$



Summary & conclusions

Very wide programme of SM and Top measurement possible across a combination of future colliders. HL-LHC already “locked in”; ILC, CLIC, etc. still up in the air.

Devil’s Advocacy: not all SM measurement is obviously necessary nor a priority for its own sake. Is there a target accuracy/reach beyond which returns are too diminished?

HL-LHC: main benefits are statistics (obviously), and forward lepton tracking/trigger coverage. Estimated that improvements in jet calibration will offset pile-up resolution degradation, but some physics suffers without dedicated low-μ runs. Others already syst-limited, e.g. EW masses.

Forward leptons a major benefit for GPD SM physics. But combination with LHCb even more powerful: prioritise? Will HL-LHC lumi also make LHCb syst-limited for SM measurements?

ILC & CLIC mutually exclusive on much of SM/Top: complementary?

Theory will co-move with experiment; can computing / algorithm scaling keep up? Reanalysis?