SnowMass2021

EF03 EW Physics: Heavy flavor and top quark physics

Co-conveners:

Reinhard Schwienhorst
(schwier@msu.edu)

Doreen Wackeroth
(dw24@buffalo.edu)

EF Kick-off meeting, May 21, 2020

Top Quark Physics: *Explore the Unknown*

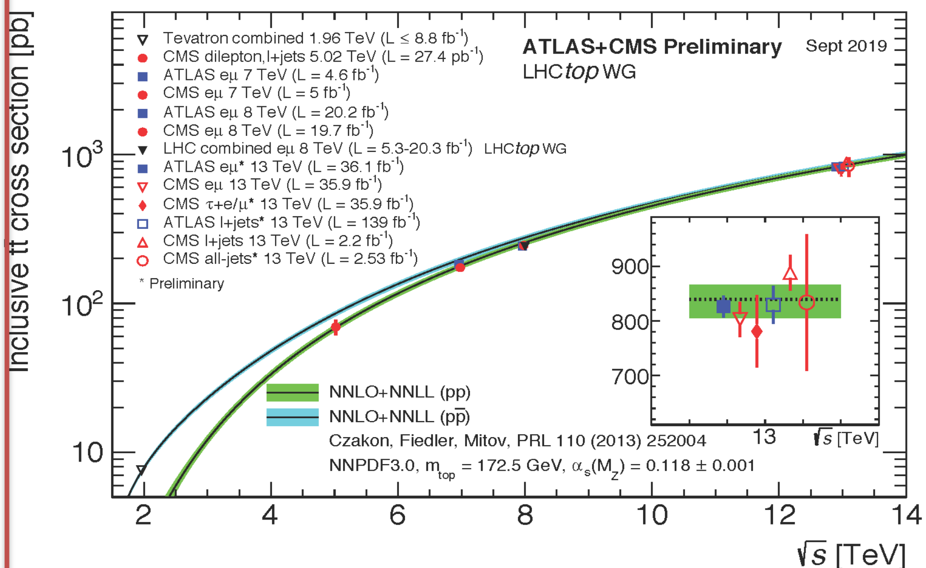
- The top quark is special: it is (still) the heaviest elementary particle with strong connections to the electroweak symmetry breaking sector:

$$y_t = \frac{\sqrt{2} m_t}{v} \sim 1 \qquad \delta m_h^2 \propto y_t^2 \Lambda^2 \qquad \lambda(Q^2) \propto y_t^4 \log\left(\frac{Q^2}{v^2}\right)$$

- Its detailed exploration may provide a first glimpse of physics beyond the Standard Model.
- It decays before hadronization and spin information is transferred to its decay products.
- Copious production of top quarks at the LHC motivate advances on both the experimental and theory side which enables a very rich and successful top physics program:
  - precision measurements of top quark properties: mass, couplings, …
  - searches for rare processes: single top, $t\bar{t}V$, $t\bar{t}t\bar{t}$, FCNC, …
  - measurements of a wide variety of observables and in new kinematic regimes: spin correlations, asymmetries, polarization, boosted top, jet substructure, …

Inclusive top-pair production cross section

Tevatron and LHC



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

100 TeV pp collider

PDF	σ(nb)	δ_{scale}(nb)	(%)	δ_{PDF}(nb)	(%)
CT14	34.692	$^{+1.000}_{-1.649}$	$^{(+2.9\%)}_{(-4.7\%)}$	$^{+0.660}_{-0.650}$	$^{(+1.9\%)}_{(-1.9\%)}$
NNPDF3.0	34.810	$^{+1.002}_{-1.653}$	$^{(+2.9\%)}_{(-4.7\%)}$	$^{+1.092}_{-1.311}$	$^{(+3.1\%)}_{(-3.8\%)}$
PDF4LHC15	34.733	$^{+1.001}_{-1.650}$	$^{(+2.9\%)}_{(-4.7\%)}$	±0.590	(±1.7%)

https://arxiv.org/pdf/1607.01831.pdf

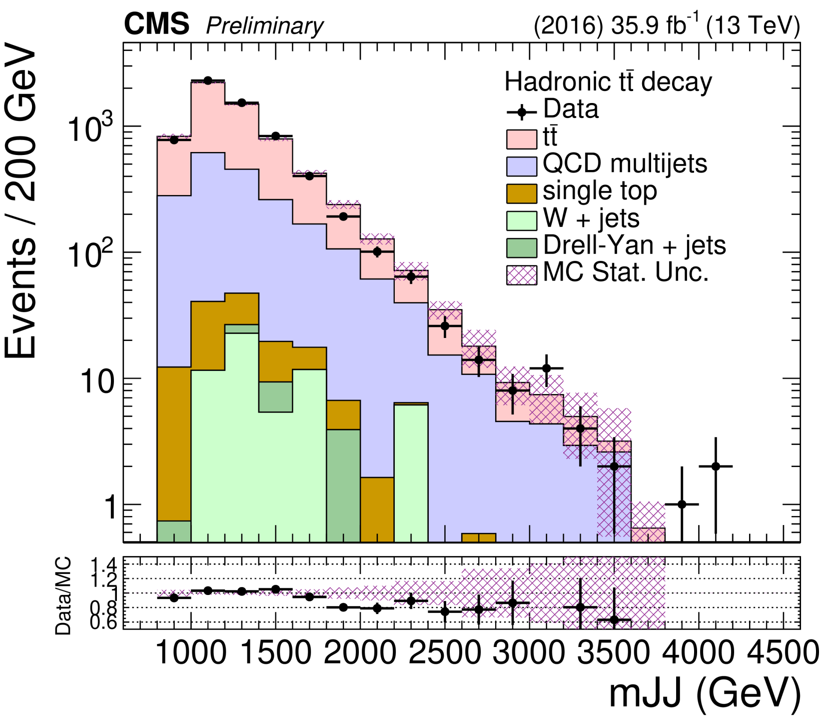
CLIC $e^+ e^-$ Linear Collider

$\sqrt{s}$	380 GeV[a]		1.4 TeV[b]		3 TeV[b]	
P(e^-)	-80%	+80%	-80%	+80%	-80%	+80%
$\sigma_{t\bar{t}}$[c] [fb]	161.00	75.97	18.44	9.84	3.52	1.91
stat. unc. [fb]	0.77	0.52	0.21	0.29	0.07	0.09

https://arxiv.org/abs/1807.02441

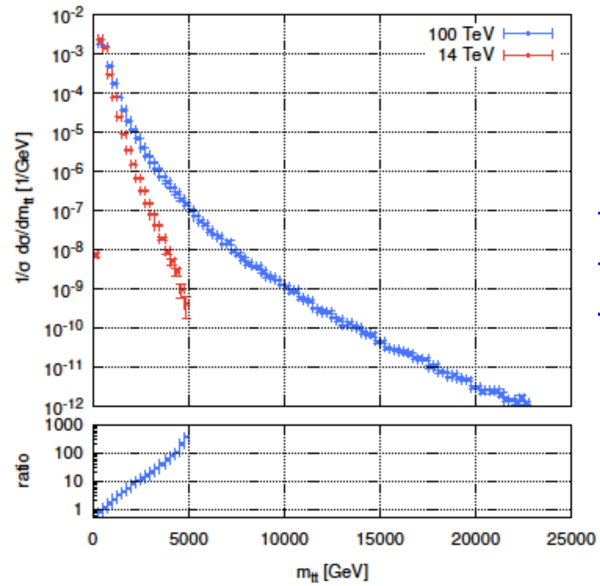
Accessing new kinematic regimes with top-quark pairs

13 TeV LHC



http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TOP-18-013/

100 TeV pp collider



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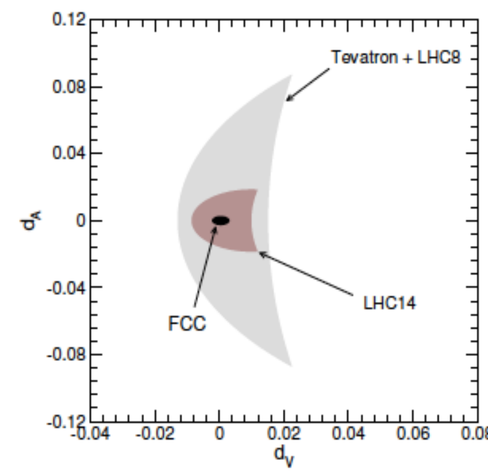


Sensitivity to anomalous top-gluon couplings:

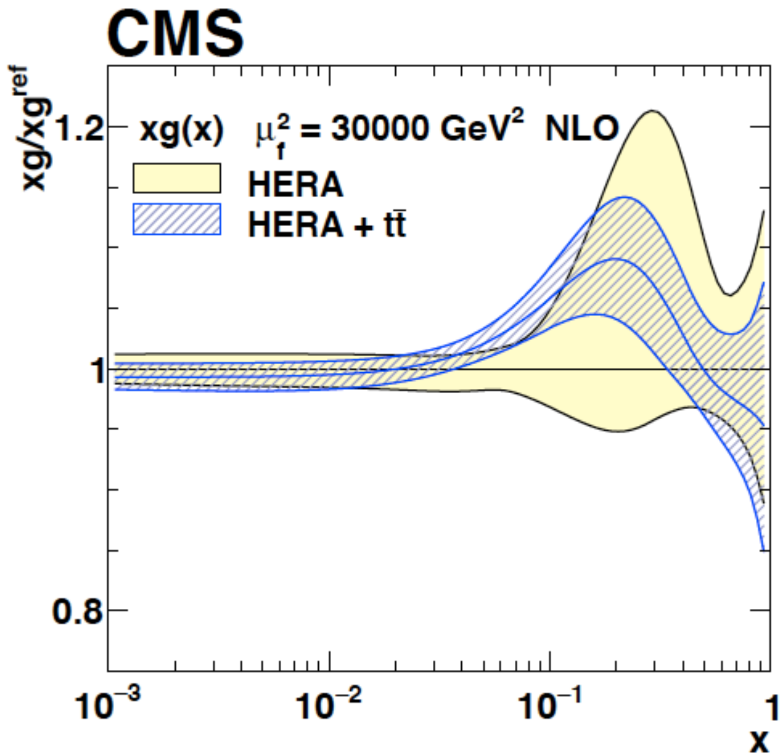
$$\frac{g_s}{m_t}\bar{t}\sigma^{\mu\nu}(d_V + i d_A \gamma_5)\frac{\lambda_a}{2} t\, G^a_{\mu\nu}$$

https://arxiv.org/pdf/1412.6654.pdf

α_s, m_t^{pole}, and gluon PDF from triple differential cross sections ($M(t\bar{t}), y(t\bar{t}), N_{jet}$) at the 13 TeV LHC

$$\alpha_S(m_Z) = 0.1135 \pm 0.0016(\text{fit})^{+0.0002}_{-0.0004}(\text{model})^{+0.0008}_{-0.0001}(\text{param})^{+0.0011}_{-0.0005}(\text{scale}) = 0.1135^{+0.0021}_{-0.0017}(\text{total}),$$

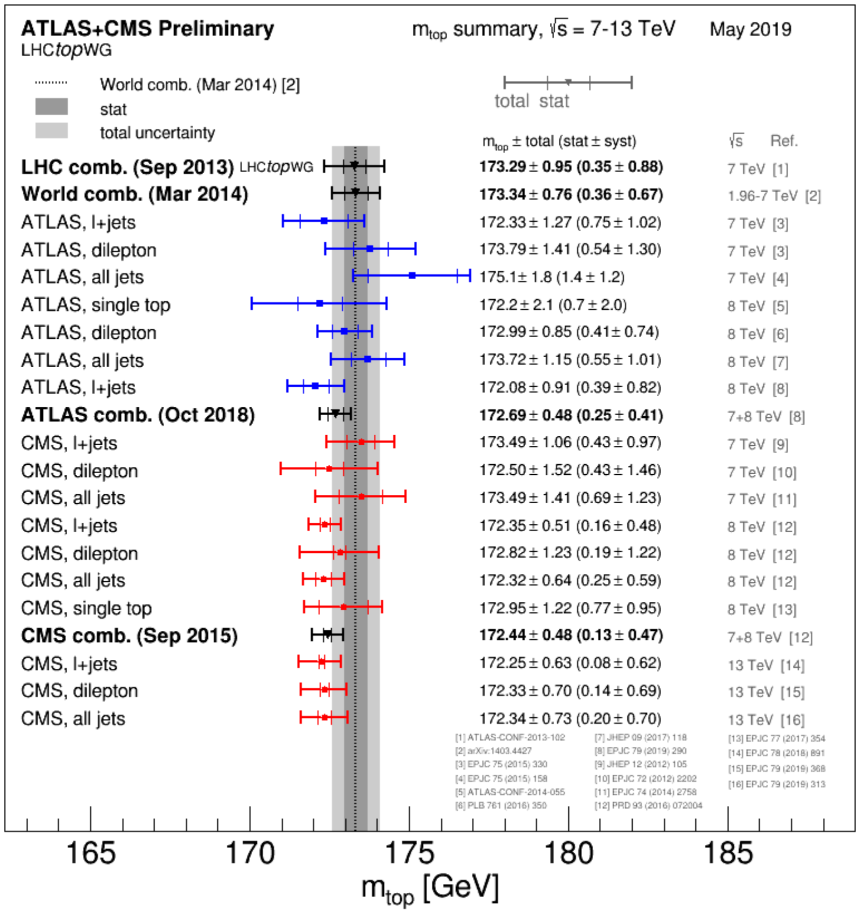
$$m_t^{pole} = 170.5 \pm 0.7(\text{fit}) \pm 0.1(\text{model})^{+0.0}_{-0.1}(\text{param}) \pm 0.3(\text{scale})\,\text{GeV} = 170.5 \pm 0.8(\text{total})\,\text{GeV}.$$



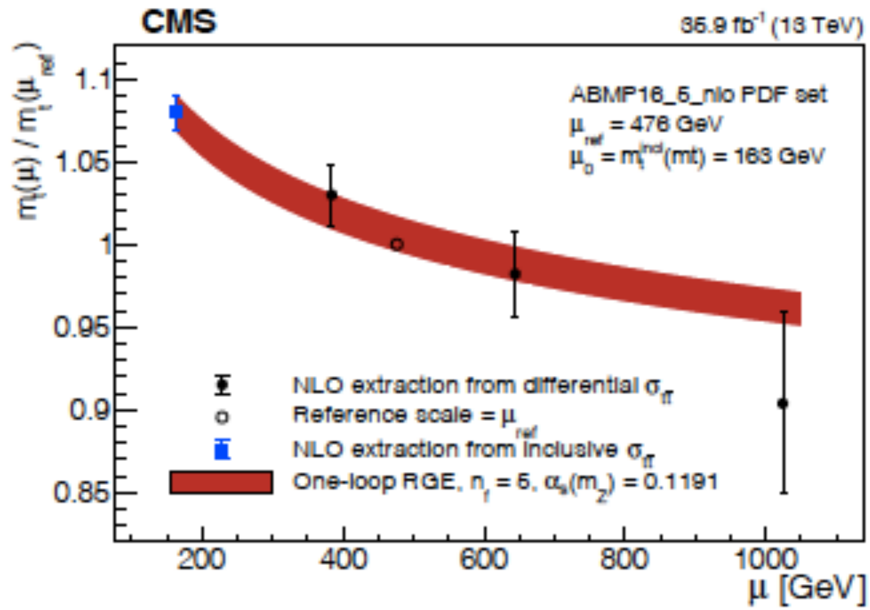
From a simultaneous fit to NLO QCD predictions.

https://arxiv.org/pdf/1904.05237.pdf

Top-quark mass measurements at the LHC



Running top quark mass ($\overline{\mathrm{MS}}$ scheme) from $\mathrm{d}\sigma_{t\bar{t}}/\mathrm{d}m_{t\bar{t}}$ at the 13 TeV LHC



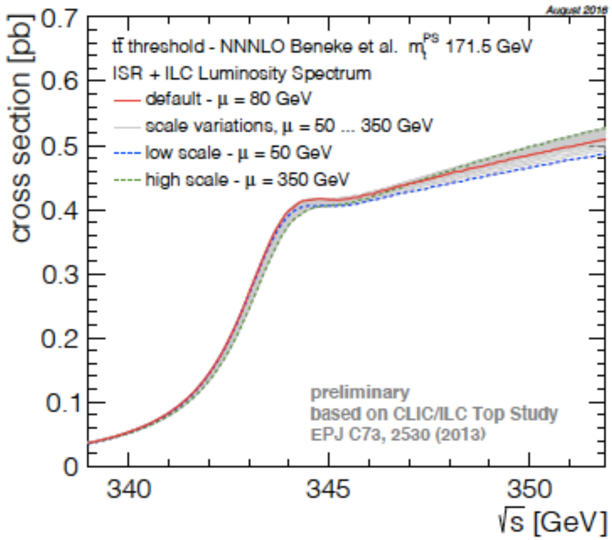
$$\mu^2 \frac{\mathrm{d}m(\mu)}{\mathrm{d}\mu^2} = -\gamma(\alpha_S(\mu))\, m(\mu)$$

https://arxiv.org/pdf/1909.09193.pdf

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

Top-quark mass from $t\bar{t}$ threshold scans at e^+e^- colliders

ILC



FCC-ee

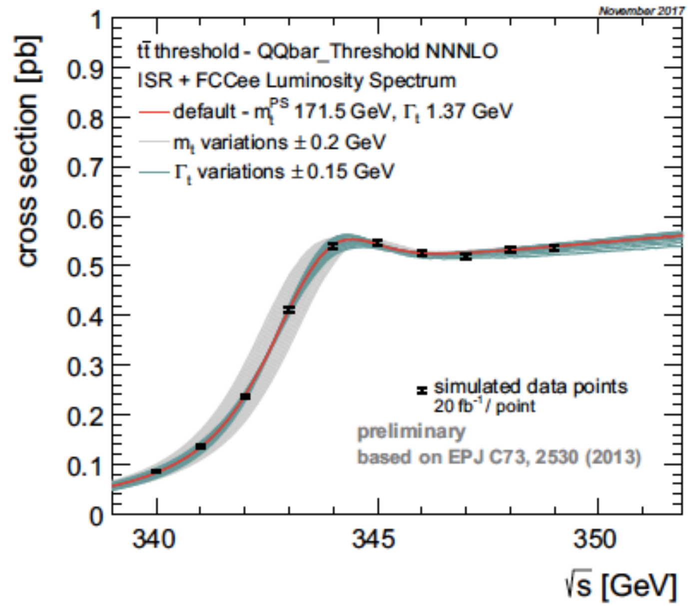


Table 1. Summary of the results of 1D and 2D fits for the two threshold scan scenarios. I
2D fits, the statistical uncertainties give the extent of the 1 σ contour in the respective dire

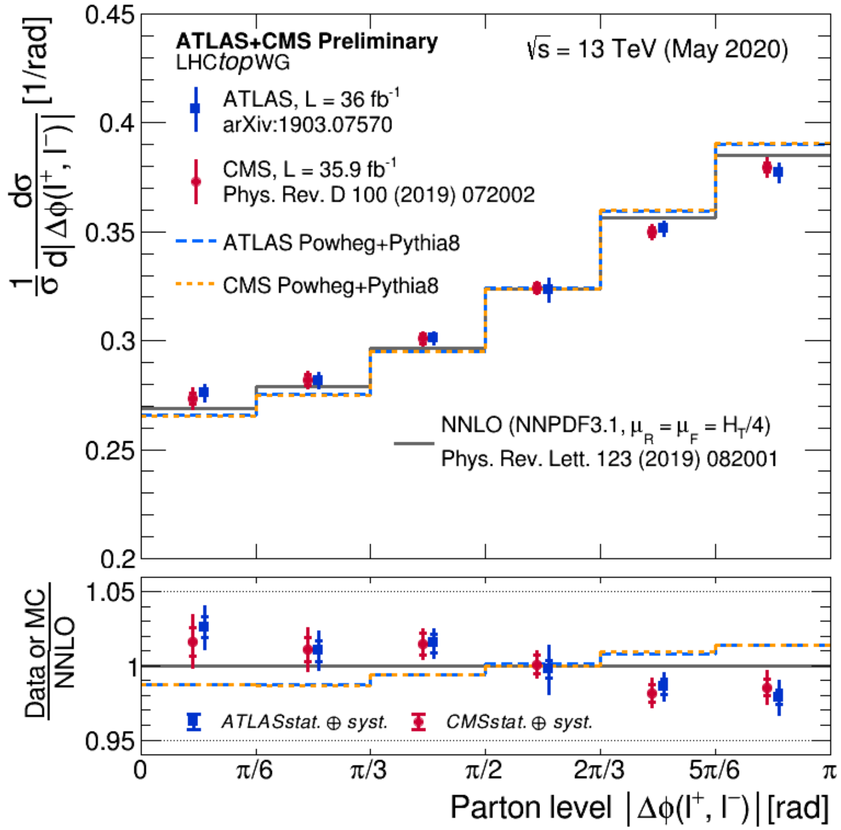
parameter	8 point scan	10 point scan
1D fit		
m_t	$(\pm 10.3_{(stat)} \pm 44_{(theo)})$ MeV	$(12.2_{(stat)} \pm 40_{(theo)})$ MeV
2D fit m_t and Γ_t		
m_t	$(^{+20.7}_{-24.3}{}_{(stat)} \pm 45_{(theo)})$ MeV	$(^{+29.7}_{-25.3}{}_{(stat)} \pm 43_{(theo)})$ MeV
Γ_t	$(^{+50}_{-55}{}_{(stat)} \pm 32_{(theo)})$ MeV	$(^{+80}_{-55}{}_{(stat)} \pm 39_{(theo)})$ MeV
2D fit m_t and y_t		
m_t	$(\pm 35_{(stat)} \pm 45_{(theo)})$ MeV	$(^{+34}_{-31}{}_{(stat)} \pm 42_{(theo)})$ MeV
y_t	$^{+0.12}_{-0.14}{}_{(stat)} \pm 0.09_{(theo)}$	$^{+0.128}_{-0.112}{}_{(stat)} \pm 0.132_{(theo)}$

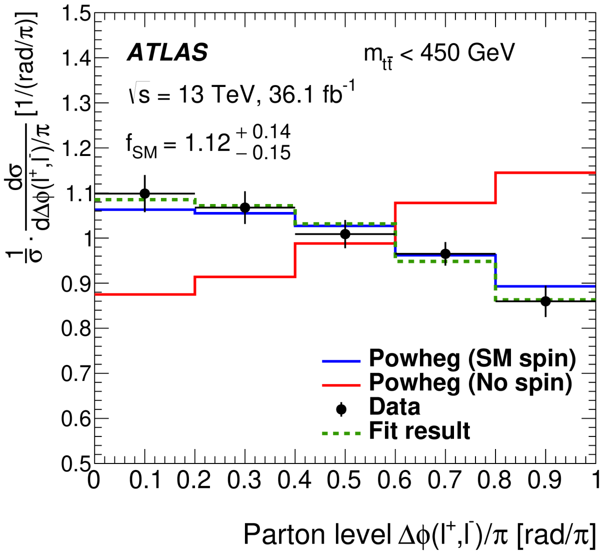
https://link.springer.com/article/10.1140/epjc/s10052-019-6904-3

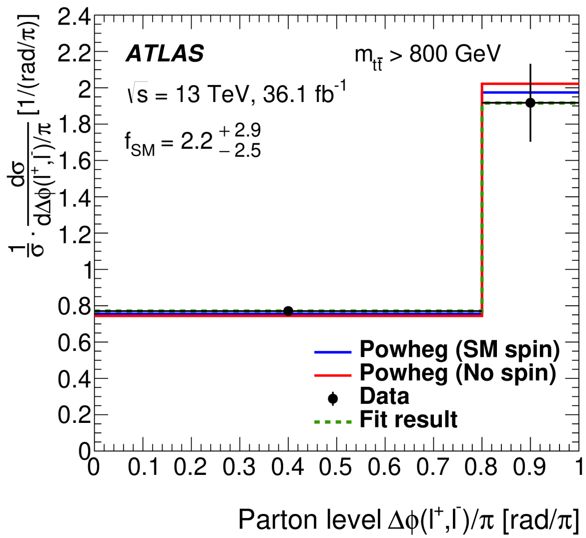
Estimated uncertainties in the Potential-subtracted (PS) top quark mass.

https://arxiv.org/pdf/1902.07246.pdf

Spin correlations in top-pair production at the 13 TeV LHC





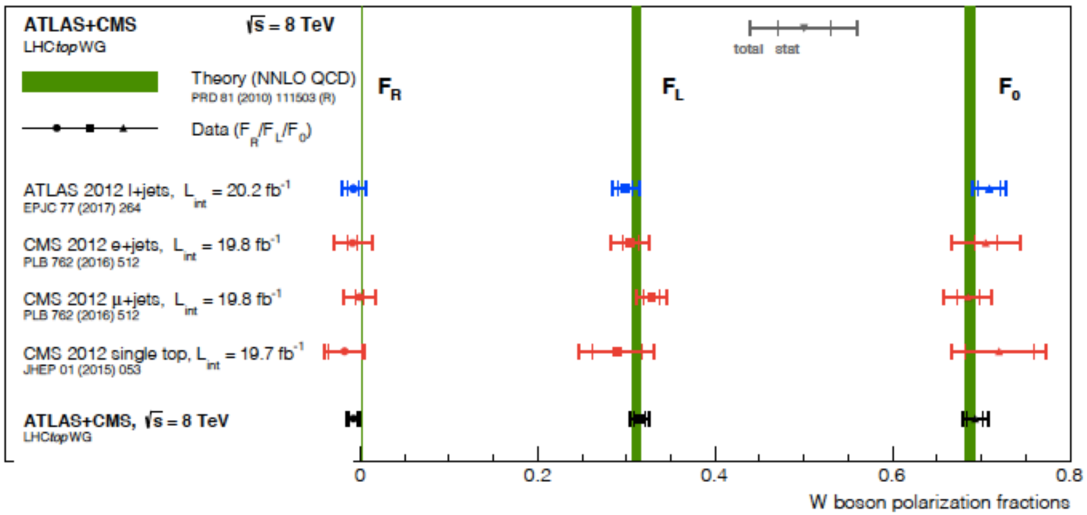


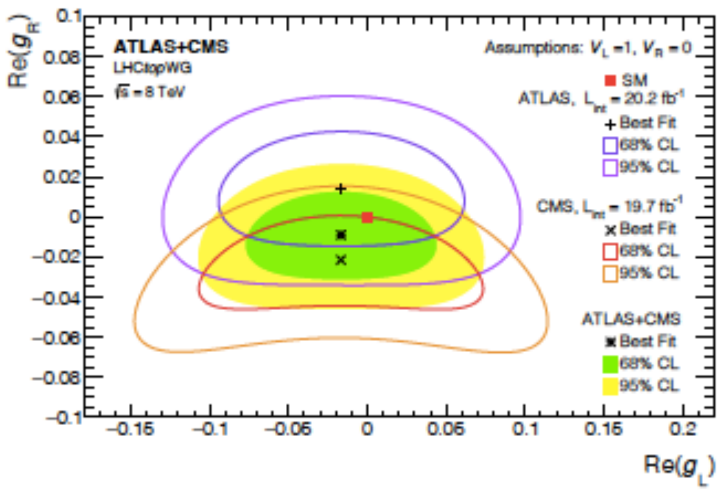
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

https://arxiv.org/pdf/1903.07570.pdf

W polarization and anomalous tWb couplings from top decays in top-pair production at the 8 TeV LHC

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_{\mathrm{L}} + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_{\mathrm{R}}.$$





Allowed regions for anomalous tWb tensor couplings.

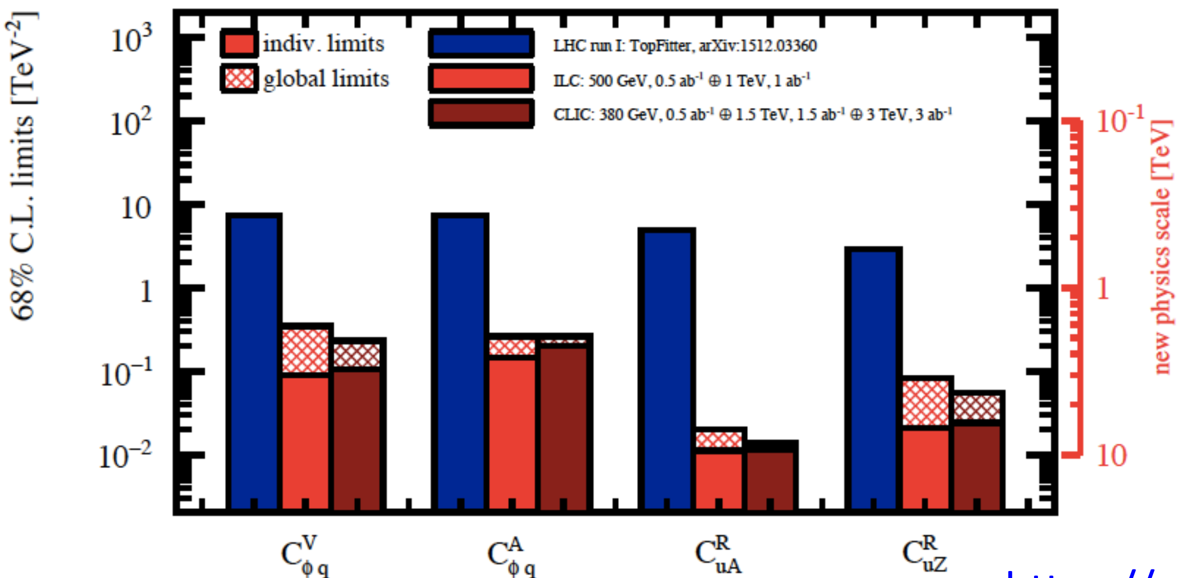
$$\mathcal{L}_{\mathrm{tWb}} = -\frac{g}{\sqrt{2}}\bar{\mathrm{b}}\,\gamma^{\mu}\left(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}}\right)\mathrm{t}\,\mathrm{W}^{-}_{\mu} - \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{m_{\mathrm{W}}}\left(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}}\right)\mathrm{t}\,\mathrm{W}^{-}_{\mu}$$

https://arxiv.org/pdf/2005.03799.pdf

Top EW couplings from global EFT fits

Individual 95% C.L. limits:

	existing		expected at high luminosity					expected at e^+e^-		
	TopFitter	Ref. [74]	Ref. [74]	$t\bar{t}V$ [14, 75]	$t\bar{t}V$ 10%	$t\bar{t}V$ 3%	tZj [76]	CC	ILC	CLIC
$C^1_{\varphi q}$	[−12, 13]			[−1.3, 1.0]	[−2.0, 2.0]	[−0.6, 0.6]	[−17, 17]	0.14	0.076	0.098
$C^3_{\varphi q}$	[−5.3, 3.1]			[−1.0, 1.3]	[−2.0, 2.0]	[−0.6, 0.6]	[−2.8, 1.5]	0.14	0.076	0.089
$C_{\varphi u}$	[−20, 17]			[−1.3, 3.0]	[−3.4, 2.8]	[−0.8, 1.0]	[−26, 20]	0.29	0.15	0.18
$C_{\varphi ud}$		[−11, 14]	[−8.4, 11]				[−8.4, 8.4]			
C_{uB}	[−20, 14]			[−4.8, 4.8]	[−12, 12]	[−6.6, 4.0]	[−12, 11]	0.022	0.022	0.024
C_{uW}	[−2.0, 2.8]	[−2.7, 1.6]	[−1.3, 1.3]	[−1.4, 1.4]	[−3.6, 3.8]	[−2.2, 2.2]	[−1.3, 1.3]	0.015	0.014	0.016
C_{dW}		[−3.4, 3.6]	[−2.9, 3.1]							



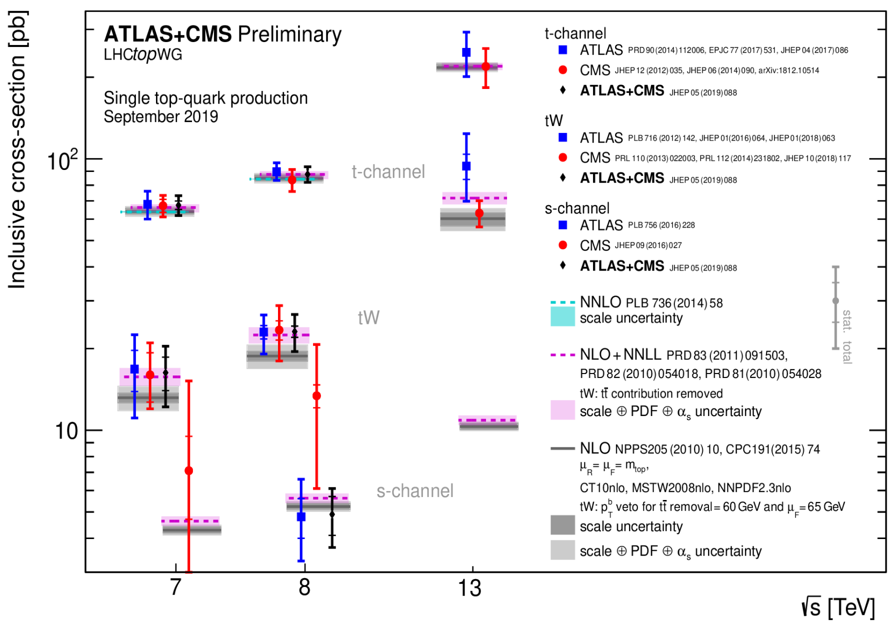
Observables:

$\sigma_{t\bar{t}}, A_{\text{FB}},$
top-quark and W polarization,
CP-odd observables,
…

https://arxiv.org/abs/1807.02121

Single-top quark production

7, 8, 13 TeV LHC

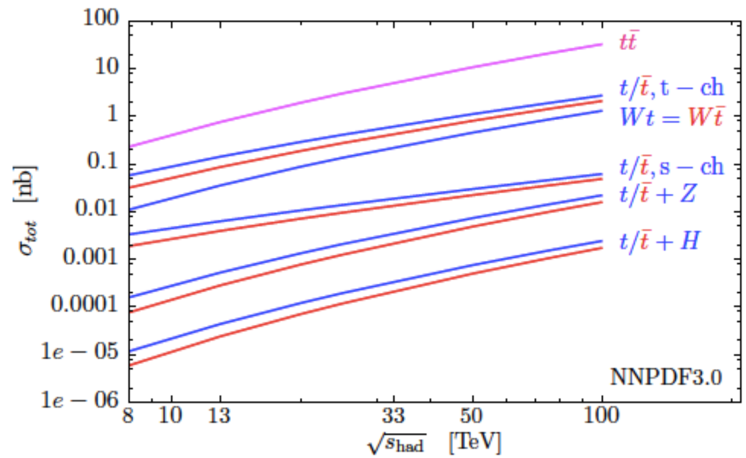


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

Right bottom:
https://arxiv.org/abs/1910.09788

Right top plot:
https://arxiv.org/pdf/1607.01831.pdf

100 TeV collider



	14 TeV		27 TeV		100 TeV	
	$1b$	$2b$	$1b$	$2b$	$1b$	$2b$
tj	0.113	1.98×10^{-3}	0.610	0.0135	4.80	0.142
tb	3.37×10^{-3}	6.24×10^{-3}	0.0134	0.0242	0.0778	0.134
$t\bar{t}$	0.432	0.275	2.78	1.81	53.9	26.3
$b\bar{b}$	0.011	0.020	0.0725	0.131	0.333	0.570
jj	0.23	6.9×10^{-3}	0.92	0.037	18	0.68

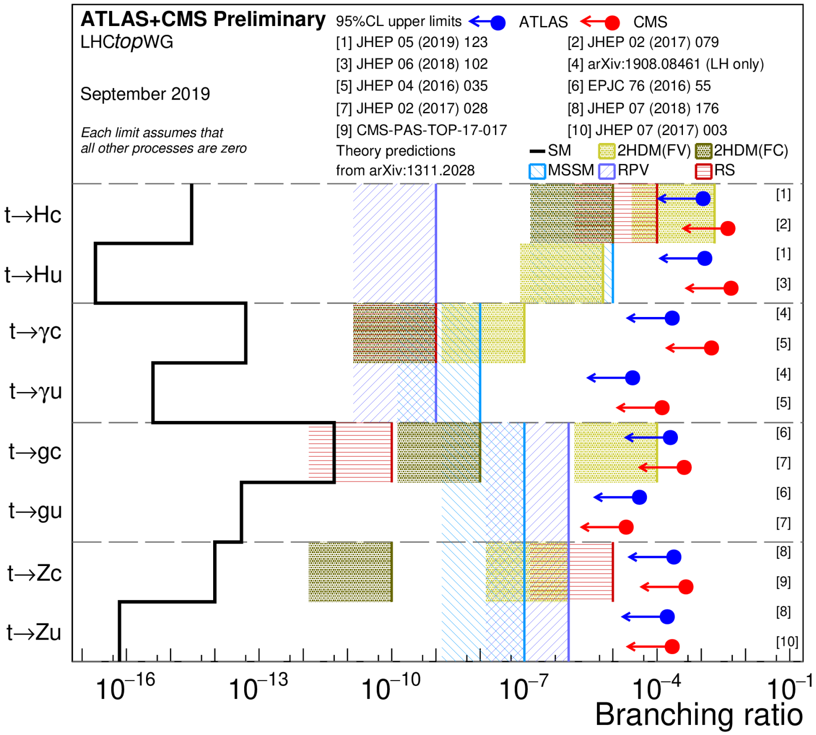
TABLE IV: Cross sections (in fb) for the different processes in the $1b$ and $2b$ samples with the final selection, for $z_1 \geq 0.6$.

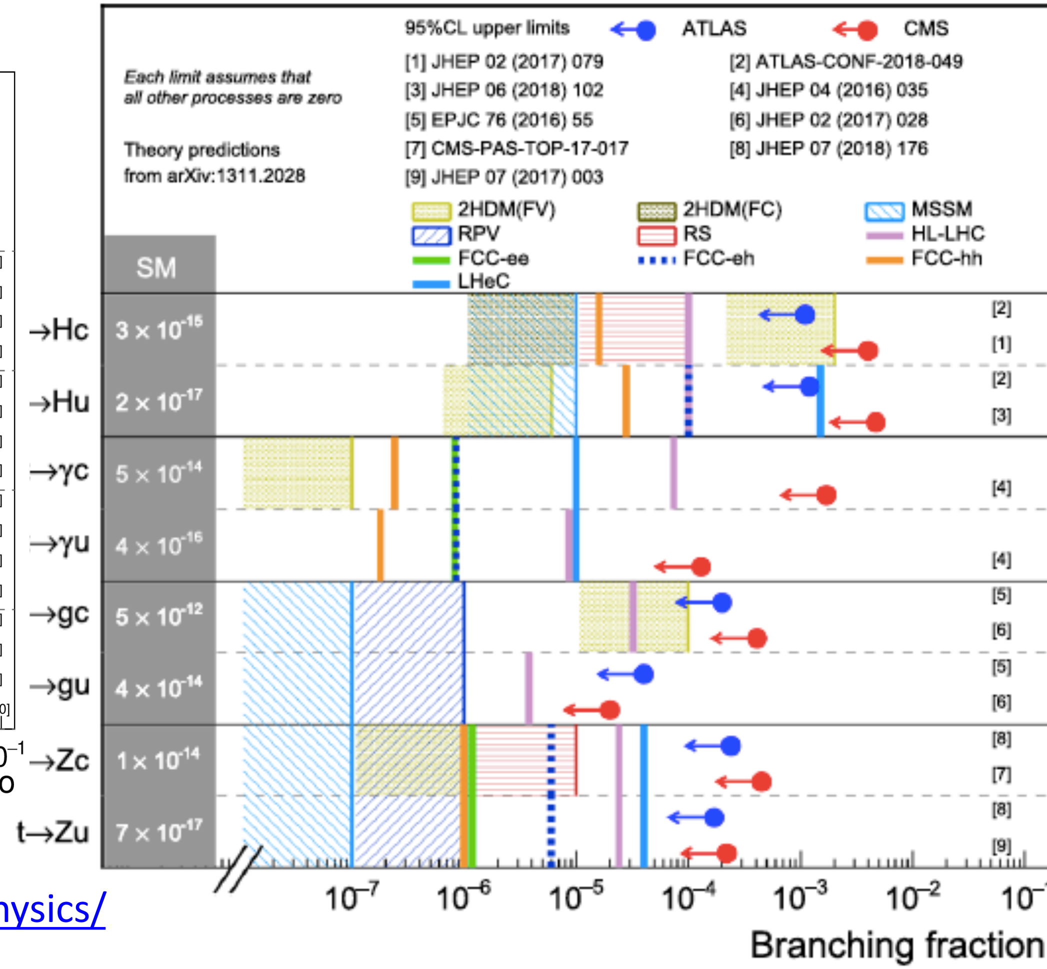
$$1b: \quad |g_L| \leq 0.046\ [0.033]\,,$$
$$2b: \quad |g_L| \leq 0.043\ [0.031]\,.$$

$$-\frac{g}{\sqrt{2}M_W} g_L \bar{b}_R \sigma^{\mu\nu} t_L \partial_\mu W_\nu^-$$

(assuming 10% systematic uncertainty)

Search for FCNC top decays



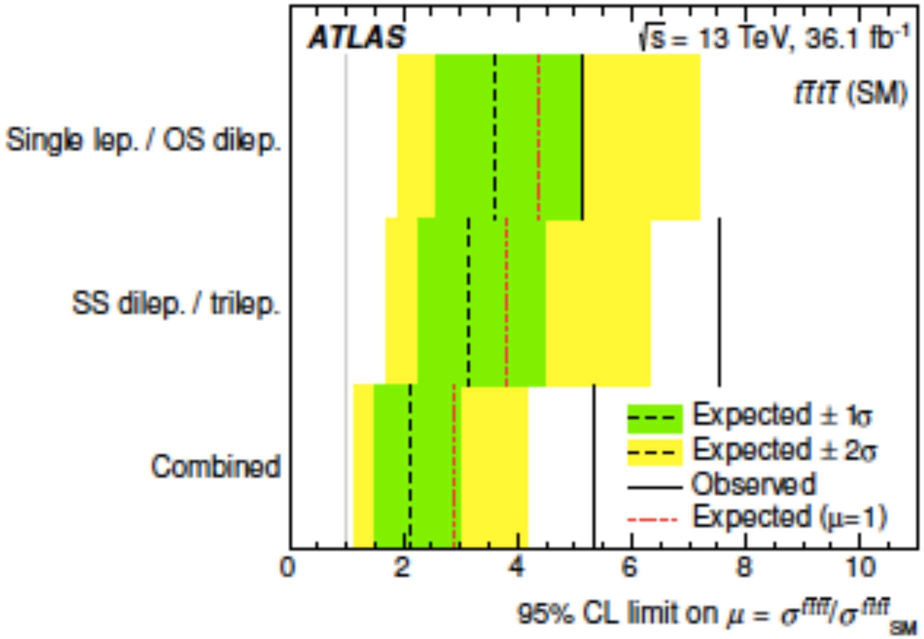


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

FCC Physics Opportunities:
https://link.springer.com/article/10.1140/epjc/s10052-019-6904-3

Multiple top-quark production

13 TeV LHC

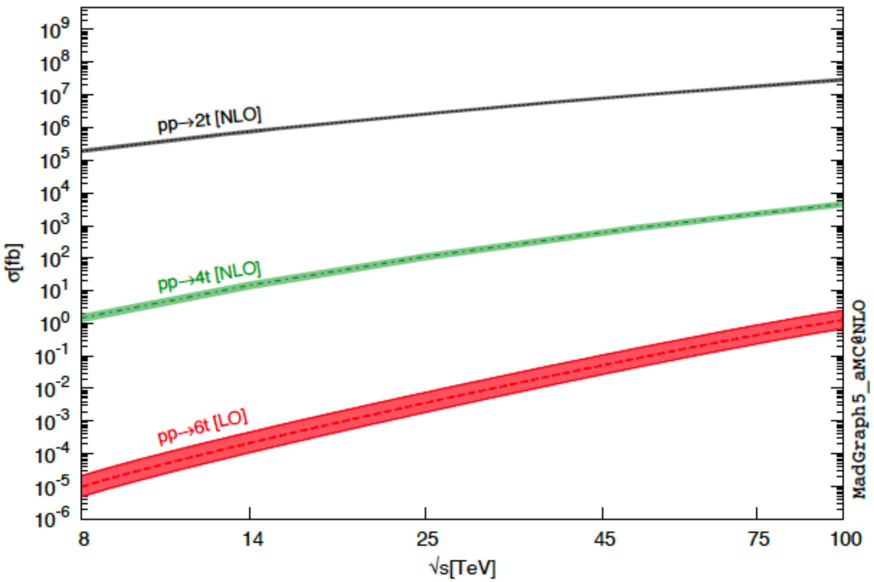


Limit on 4 top-quark contact interaction:

$$|C_{4t}|/\Lambda^2 < 1.9\ \text{TeV}^{-2}$$

https://arxiv.org/abs/1811.02305

Future pp colliders



https://arxiv.org/pdf/1405.6119.pdf

Heavy Flavor Physics (bottom, charm)

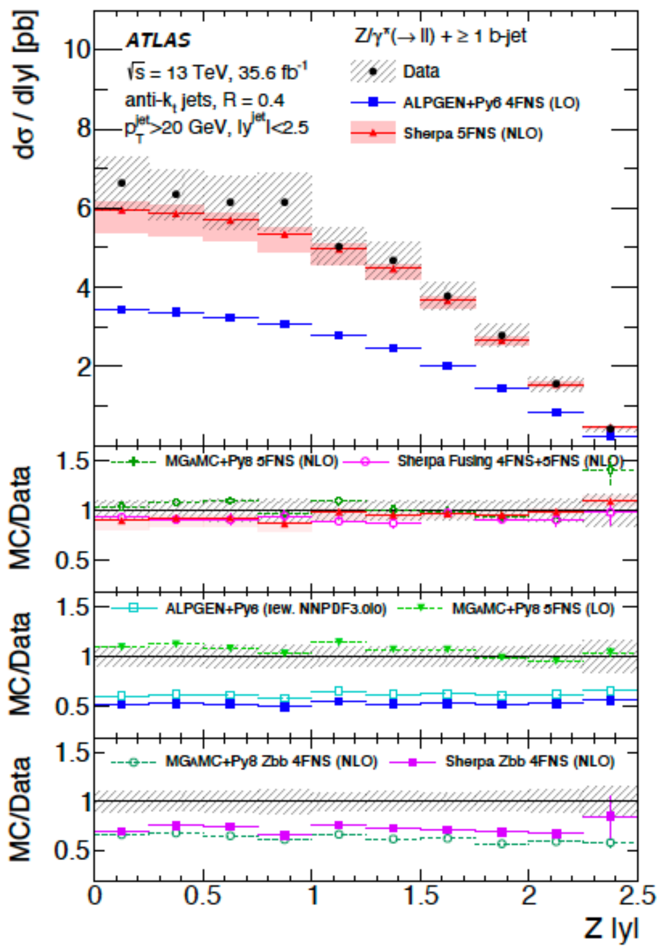
- Decays of b and c quarks is covered in the Rare Processes and Precision Measurements TG RF1.

- Here we will study the prospects for heavy flavor production (bottom and charm) in association with EW gauge bosons:

  - Precision probes of pQCD and heavy-quark factorization schemes
  - W+c production accesses the strange quark content of the proton
  - Z+b production probes the b-quark PDF

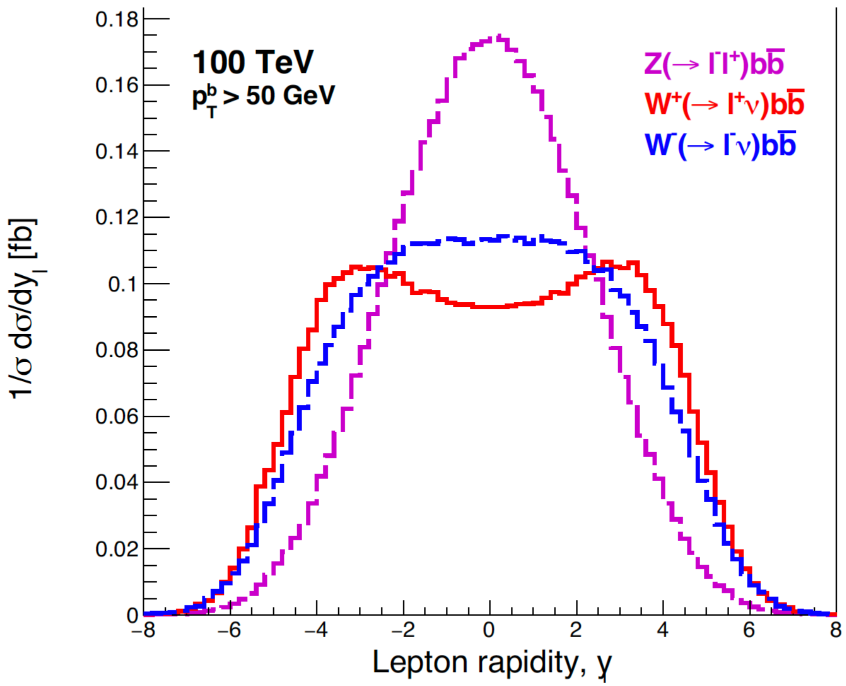
Z+b-jets production

13 TeV LHC



https://arxiv.org/pdf/2003.11960.pdf

100 TeV pp collider



https://arxiv.org/pdf/1607.01831.pdf

Many connections with other Frontiers and TGs

- Rare Processes and Precision:
  - RF1: Weak Decays of b and c quarks - direct sharing of topics
- Cosmic:
  - CF1: Dark matter particle-like – when dark matter is produced at a collider in association with top
- Theory:
  - TF02: EFT
  - TF06: Theory techniques for precision physics
  - TF07: Collider Phenomenology
  - TF08: BSM model building
- Accelerator:
  - AF3: Accelerators for EW/Higgs (Top?)
  - AF4, Multi-TeV Colliders
- Energy Frontier:
  - EF01 – ttH, EF04, EF05 - in particular MC generators, EF06: PDFs, EF08, EF09 - EFT fits, new fermions, EF10

Here is how to get involved:

- Join our email list by emailing to listserv@fnal.gov and keep the subject line blank and type in the body:

  SUBSCRIBE SNOWMASS-EF-03-TOP_HEAVY-FLAVOR@FNAL.GOV FIRSTNAME LASTNAME
- Email the conveners: schwier@msu.edu, dw24@buffalo.edu
- Share your ideas for Snowmass-specific studies in form of a Letter of Interest (at most 2 pages):
  - Deadline: August 31, 2020
  - Instructions: https://snowmass21.org/loi
- Participate in our first EF03 TG meeting on May 28, 1-3pm EDT: https://indico.fnal.gov/event/43491/

Some Resources

- ATLAS and CMS public top quark physics results:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

- ATLAS and CMS public V+heavy flavor (b,c) results:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/VHF.html

- LHCb public physics results:

http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_QEE.html

- CLIC:

http://clic-study.web.cern.ch

- ILC TDR:

https://ilchome.web.cern.ch/publications/ilc-technical-design-report

- FCC CDR:

http://fcc-cdr.web.cern.ch

- CEPC:

http://cepc.ihep.ac.cn

We are in the process of creating a collection of Top+HF physics specific resources for future colliders and very much appreciate your input.