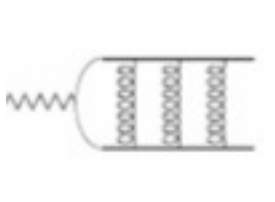
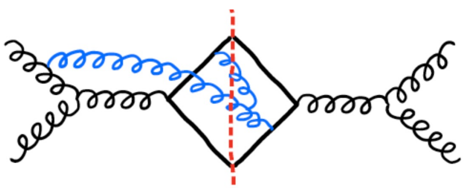
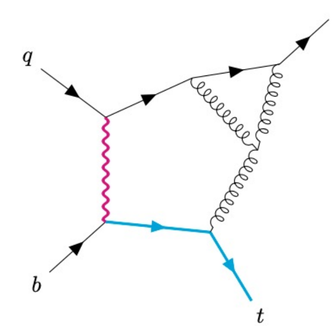
14th International Workshop on Top Quark Physics
TOP2021



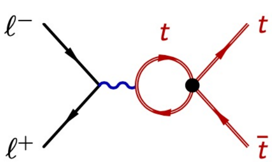


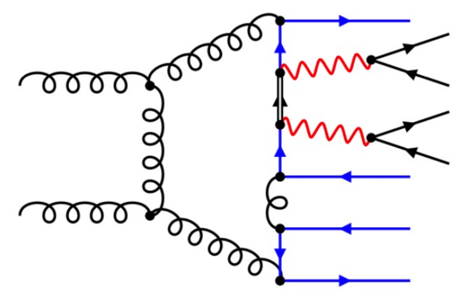


Theory Summary

Doreen Wackeroth

University at Buffalo





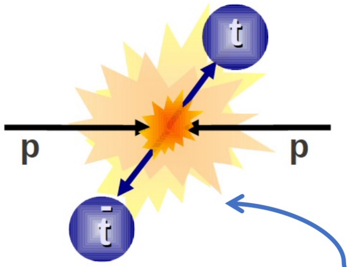
Zoom meeting, 13-17 September 2021

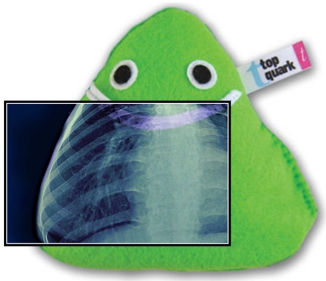
The Many Facets of Top Quark Physics

0) It is there!
and we have the opportunity to study its properties

Andrea Wulzer

- Top properties are essential ingredients for SM predictions
  we must know them precisely
- The Top is a portal to EWSB
  Composite Higgs ⇒ Composite Top
  The 4-tR vertex opportunity
- The (Top) EFT
  A **clear** path towards top couplings characterisation
  A full-fledged BSM search strategy, with discovery potential
  Clear ≠ Easy ! Needs EXP/QCD/PDF/BSM work





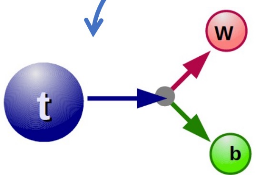
Malgorzata Worek

Intrinsic properties:

- Mass
- Charge
- Lifetime
- Width
- …

Production:

- Production rate
- Differential distributions
- New production mechanisms
- Single top-quark production
- Top-quark pair production
- Associated production of top quarks with $W, Z, \gamma, H, j, bb, tt, jj, \gamma\gamma$ ...
- ...

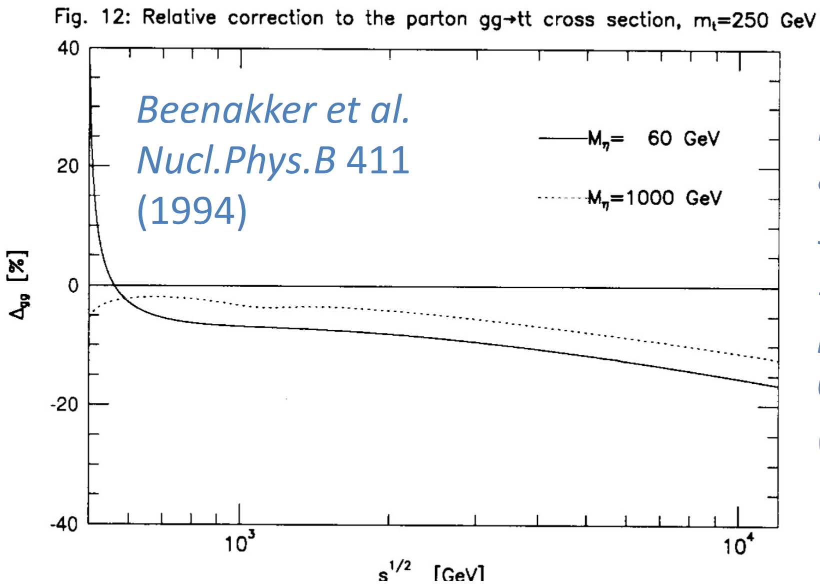


Decays:

- Various decay channels
- SM & BSM
- Couplings W, Z, γ & H
- Spin correlations
- …

Exploration of Top-pair production in 1994 and 27 years later …

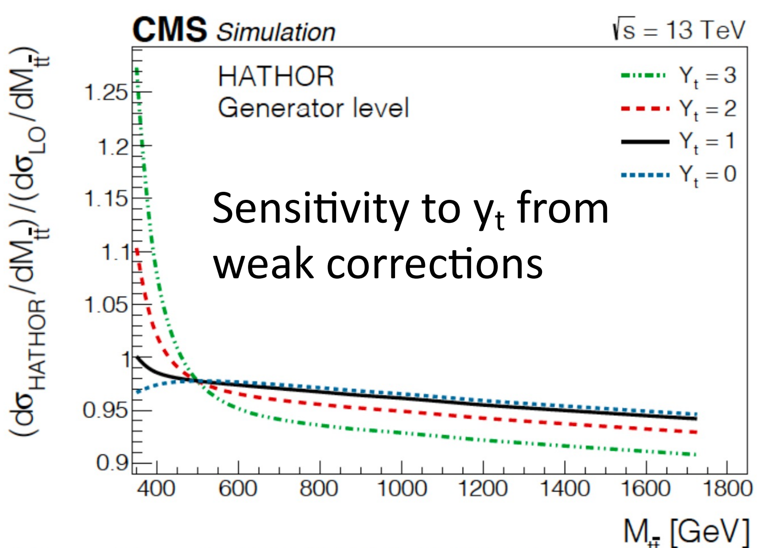
Weak 1-loop corrections to top-pair production



Beenakker et al. Nucl.Phys.B 411 (1994)

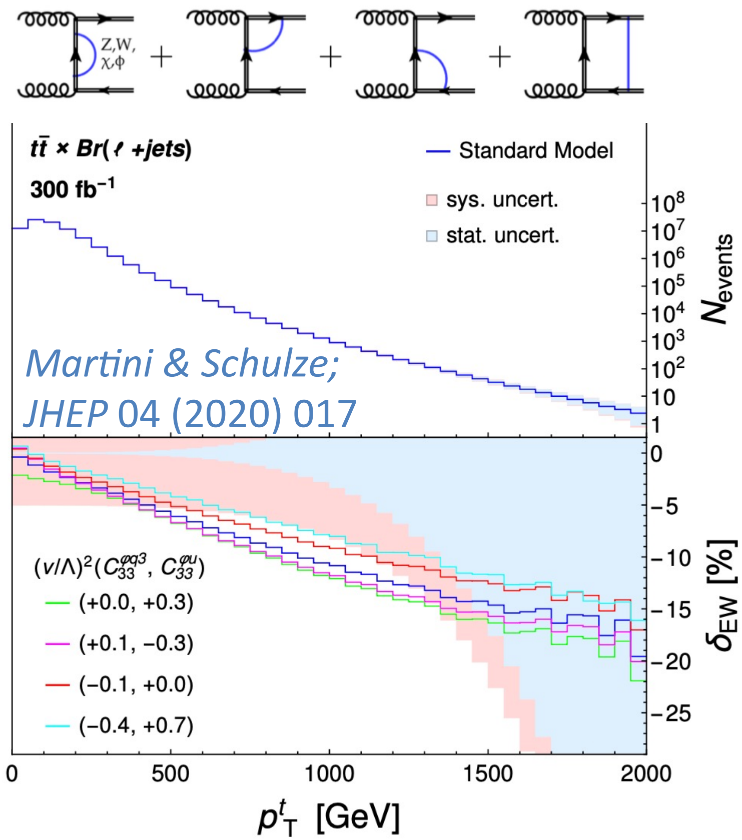
Update: Kühn, Scharf & Uwer; PRD 91 (2015) 1,014020] [PRD 100, 072007 (2019)]

Now in:
Hathor
MCFM



Sensitivity to y_t from weak corrections

Weak corrections in SMEFT



Martini & Schulze; JHEP 04 (2020) 017

See Ken Mimasu's talk

See Sebastian Wuchter's talk

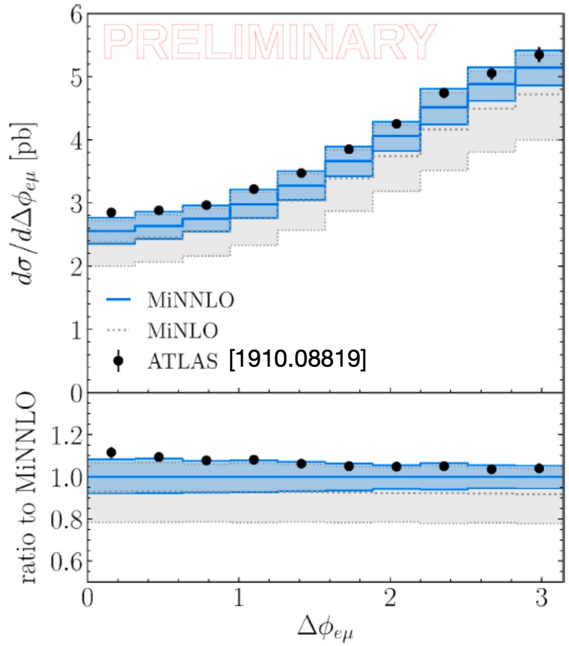
$$Y_t = 1.16^{+0.07}_{-0.08}\,(\text{stat})^{+0.23}_{-0.34}\,(\text{syst})$$

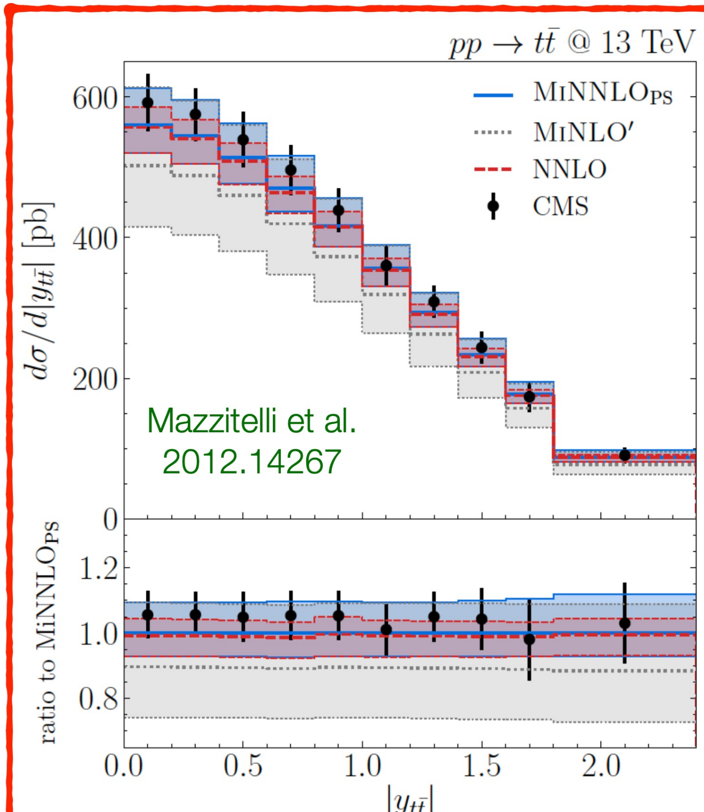
Top-pair production: NNLO+PS

Giulia Zanderighi

- Presented results for tt matched to parton shower preserving NNLO accuracy using MiNNLO$_{PS}$ procedure
- Code implemented in POWHEG BOX V2 and publicly available upon request
- First NNLO+PS generator for a coloured process
- Validation with NNLO results
- Good agreement with ATLAS/CMS data
- Preliminary results including top-decays with spin correlations
- Further phenomenological studies (e.g. scale settings) and further validation to come

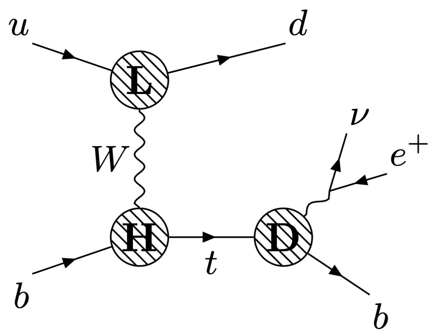
$$\frac{d\sigma}{dp_T\, d\Phi_{t\bar t}} = \frac{d}{dp_T}\left\{ \sum_c \frac{e^{-\tilde{S}_c(p_T)}}{2m_{t\bar t}^2} \langle M_{c\bar c}^{(0)} | (\mathbf{V}_{\mathrm{NLL}})^\dagger\, \mathbf{V}_{\mathrm{NLL}} | M_{c\bar c}^{(0)} \rangle \sum_{i,j} \left[\mathrm{Tr}(\tilde{\mathbf{H}}_c \mathbf{D})\, (\tilde{C}_{ci} \otimes f_i)\, (\tilde{C}_{\bar c j} \otimes f_j) \right]_\phi \right\} + R_f + \mathcal{O}(\alpha_s^5)$$





Single top production: t-channel@NNLO

John Campbell



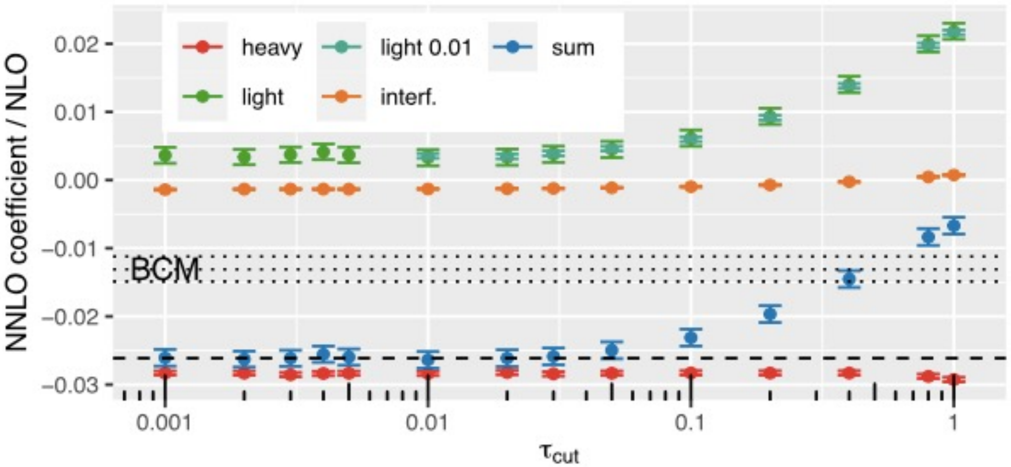
Berger, Gao, Yuan, Zhu, https://arxiv.org/abs/1606.08463; https://arxiv.org/abs/1708.09405

Brucherseifer, Caola, Melnikov, https://arxiv.org/abs/1404.7116

- New calculation based on SCET approach, all ingredients re-computed from scratch and independently verified where possible.

JC, Neumann, Sullivan, https://arxiv.org/abs/2012.01574)

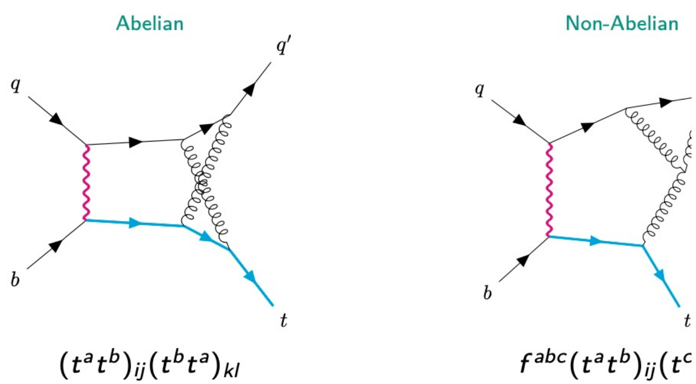
		$\sigma_{\rm NNLO}^{\rm BGZ}$	$\sigma_{\rm NNLO}$
7 TeV	top	$42.05^{+1.2\%}_{-0.6\%}$	$41.99(4)^{+1.4\%}_{-0.7\%}$
	anti-top	$21.95^{+1.2\%}_{-0.7\%}$	$21.90(3)^{+1.4\%}_{-0.8\%}$
14 TeV	top	$153.3^{+1.1\%}_{-0.5\%}$	$153.2(2)^{+1.2\%}_{-0.6\%}$
	anti-top	$91.81^{+1.0\%}_{-0.5\%}$	$91.5(1)^{+1.2\%}_{-0.7\%}$

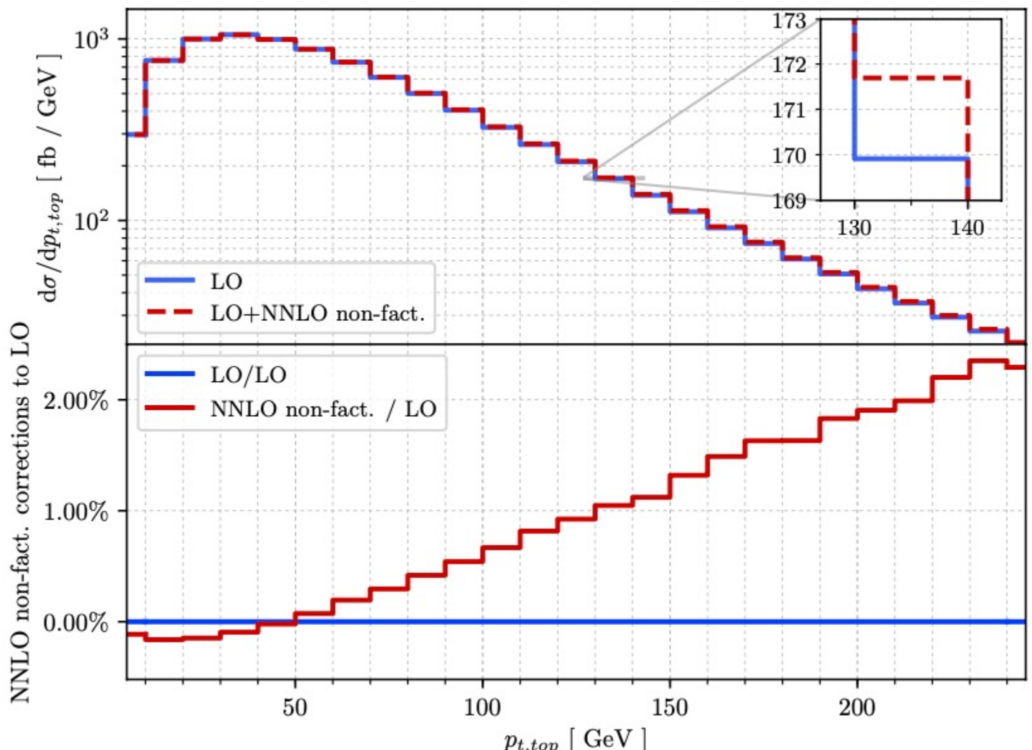


same O(1%) difference with BCM

Single top production: t-channel@NNLO
Non-factorizable corrections

Christian Bronnum-Hansen





- Double-virtual cross-section calculation from fixed grid of 100k points

$$\sigma^{ub}_{pp\to dt} = \left(90.3 + 0.3\left(\frac{\alpha_s(\mu_{\rm nf})}{0.108}\right)^2\right)\ \text{pb}$$

arXiv:2108.09222

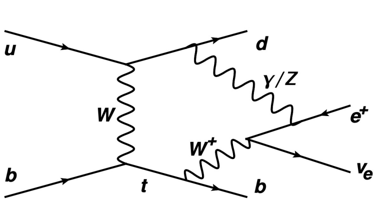
- Correction of about 0.3% for $\mu_{\rm nf} = 173$ GeV

Single top production: all contributions at NLOPS+EW

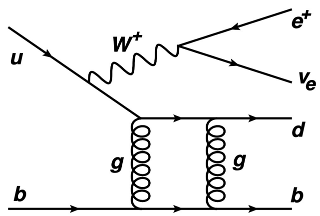
John Campbell

- Study including all NLO QCD and EW effects + QCD shower in MG5_aMC@NLO
  - t-channel signature: lepton, light jet, b-jet, missing E_T

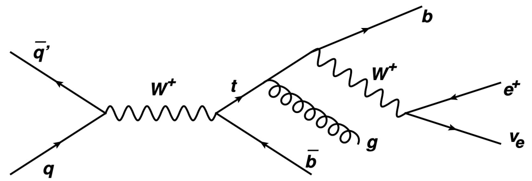
Frederix, Pagani and Tsinikos, https://arxiv.org/abs/1907.12586



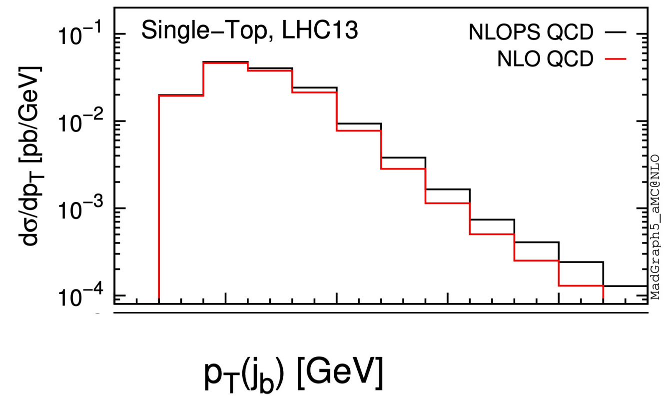
"NLO EW t-channel"



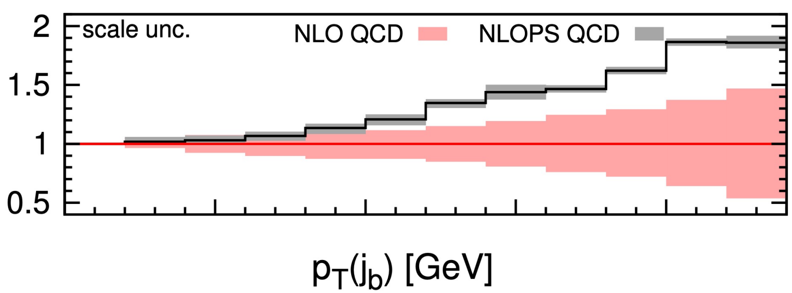
"NLO QCD W+2 jets"



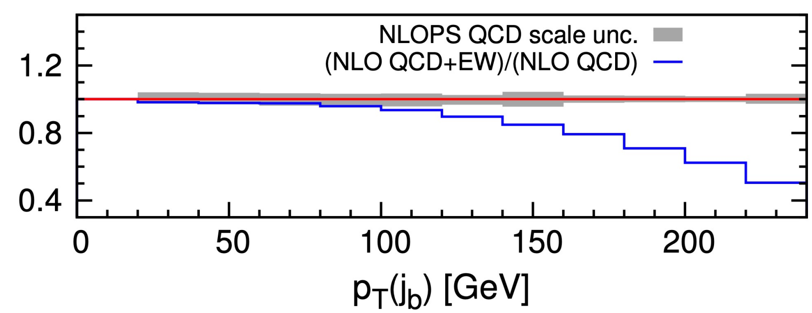
"NLO QCD s-channel"



- Complementary approach: include all contributions to a given final-state signature (at some order), traditional channels emerge by applying cuts
  - less assumptions, e.g. reliance on narrow-width approximation ✔
  - much more complicated, not highest formal accuracy (no NNLO) ✘



Large uncertainty at fixed order due to jet veto remedied in NLOPS.



EW effects substantial in distributions.

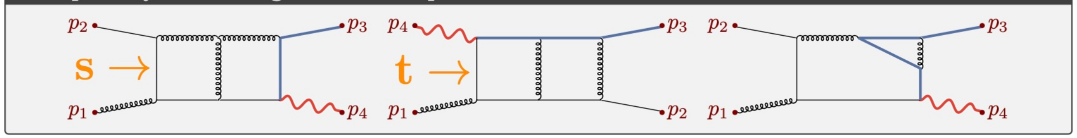
Single top production: Towards tW-channel@NNLO

Ming-Ming Long

Consider the partonic process below at NNLO QCD,

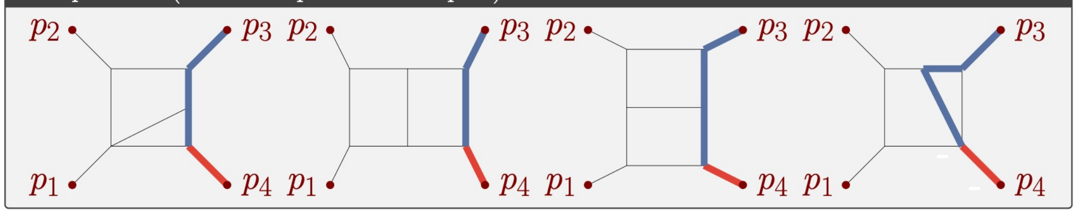
$$g(p_1)+b(p_2)\to t(p_3)+W(p_4), \text{with } p_{1,2}^2=0, p_3^2=m_t^2 \text{ and } p_4^2=m_W^2.$$

Sample Feynman diagrams with up to 3 massive internal lines



We can identify two integral families. Family 1 (**60 MIs**) includes first two diagrams. Second family (**36 MIs**) contains the last diagram.

Sample MIs (most complicate examples)



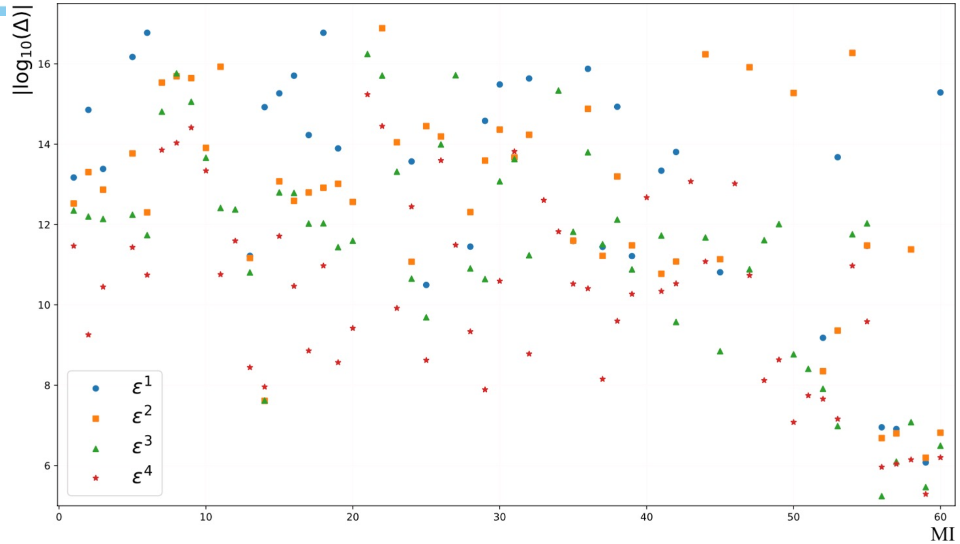
See also Long-Bing Cheng, Jian Wang, arXiv:2106.12093 (integral family with one massive propagator)

Analytic results for MIs in terms of Goncharov polylogarithms.

- Comparison with pySecDec [3] at $r = (-6, -13, 5, 12)$ for MIs of family 1.

$\Delta = |1 - \text{Numerical integration/Analytical evaluation}|$.

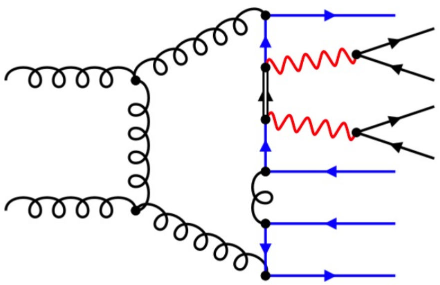
Locating at higher means better agreement.



Full Off-shell $t\bar{t}b\bar{b}$ @NLO QCD

Manfred Kraus

A quick glimpse at the complexity of $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$



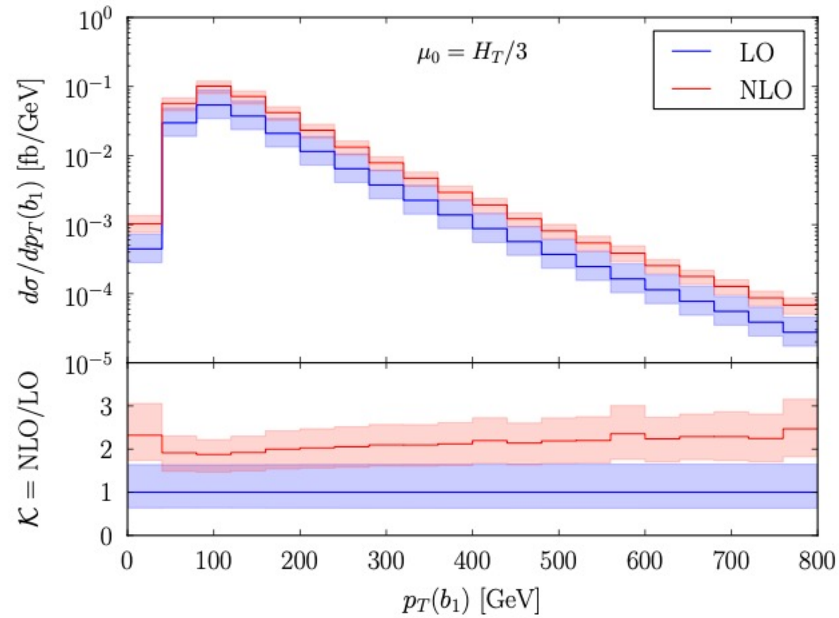
271528 loop diagrams,
up to 90 CS Dipoles;
Calculation based on
HELAC-NLO

Comparison with results from Denner, Lang, Pellen '20

Integrated cross section

$$\sigma^{\rm NLO}_{\rm HELAC} = 10.28(1)^{+18\%}_{-21\%}\ \text{fb} \qquad \sigma^{\rm NLO}_{\rm DLP} = 10.28(8)^{+18\%}_{-21\%}\ \text{fb}$$

$p_T(b)$	$\sigma^{\rm LO}$ [fb]	$\delta_{\rm scale}$	$\sigma^{\rm NLO}$ [fb]	$\delta_{\rm scale}$	$\delta_{\rm PDF}$	$\mathcal{K} = \sigma^{\rm NLO}/\sigma^{\rm LO}$
			$\mu_R = \mu_F = \mu_0 = m_t$			
25	6.998	+4.525 (65%) −2.569 (37%)	13.24	+2.33 (18%) −2.89 (22%)	+0.19 (1%) −0.19 (1%)	1.89
30	5.113	+3.343 (65%) −1.889 (37%)	9.25	+1.32 (14%) −1.93 (21%)	+0.14 (2%) −0.14 (2%)	1.81
35	3.775	+2.498 (66%) −1.401 (37%)	6.57	+0.79 (12%) −1.32 (20%)	+0.10 (2%) −0.10 (2%)	1.74
40	2.805	+1.867 (67%) −1.051 (37%)	4.70	+0.46 (10%) −0.91 (19%)	+0.08 (2%) −0.08 (2%)	1.68
			$\mu_R = \mu_F = \mu_0 = H_T/3$			
25	6.813	+4.338 (64%) −2.481 (36%)	13.22	+2.66 (20%) −2.95 (22%)	+0.19 (1%) −0.19 (1%)	1.94
30	4.809	+3.062 (64%) −1.756 (37%)	9.09	+1.66 (18%) −1.98 (22%)	+0.16 (2%) −0.16 (2%)	1.89
35	3.431	+2.191 (64%) −1.256 (37%)	6.37	+1.07 (17%) −1.36 (21%)	+0.11 (2%) −0.11 (2%)	1.86
40	2.464	+1.582 (64%) −0.901 (37%)	4.51	+0.72 (16%) −0.95 (21%)	+0.09 (2%) −0.09 (2%)	1.83



- Large shape distortions (+90% – 135%)
- Scale dependence: ±20 – 30%
- PDF uncertainties small-ish (≤ 10%)

$p_T^{\rm veto}(j) = 50$ GeV

$K = 1.11$ & $K = 1.23$

Full Off-shell $t\bar{t}b\bar{b}$ @NLO QCD

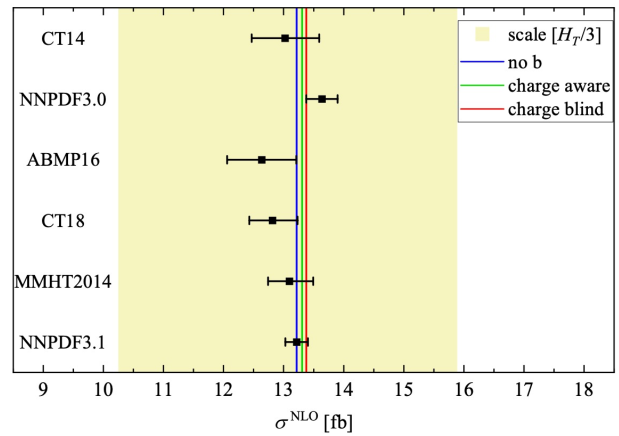
Michele Lupattelli

$pp \to e_+ \nu_e \mu_- \bar{\nu}_\mu b\bar{b}\, b\bar{b}$ @ LHC_{13TeV}

Theoretical predictions	$\sigma_{e\mu+4b}$ [fb]
SHERPA+OPENLOOPS (4FS)	17.2 ± 4.2
POWHEG-BOX+PYTHIA 8 (4FS)	16.5
POWHEL+PYTHIA 8 (5FS)	18.7
POWHEL+PYTHIA 8 (4FS)	18.2
HELAC-NLO (5FS)	20.0 ± 4.3
Experimental result (ATLAS)	25 ± 6.5

[ATLAS collaboration '18, Bevilacqua et al. '21]

Is there sensitivity to b-initiated processes?



We investigated the contribution of the b-quark initial states. We defined two b-jet tagging schemes:

- **Charge aware tagging scheme** ($b\bar{b} \to g$, $bb \to b$, $\bar{b}\bar{b} \to \bar{b}$, $bg \to b$ $\bar{b}g \to \bar{b}$) $N_b \geq 2$ & $N_{\bar{b}} \geq 2$
- **Charge blind tagging scheme** ($b\bar{b} \to g$, $bb \to g$, $\bar{b}\bar{b} \to g$, $bg \to b$ $\bar{b}g \to \bar{b}$) $N_{b/\bar{b}} \geq 4$

b-jet tagging	σ^{LO} [fb]	$\frac{\sigma_i}{\sigma_{\text{no } b}} - 1$ [%]	σ^{NLO} [fb]	$\frac{\sigma_i}{\sigma_{\text{no } b}} - 1$ [%]
no b	6.813(3)	-	13.22(3)	-
aware	6.822(3)	0.1	13.31(3)	0.7
blind	6.828(3)	0.2	13.38(3)	1.2

A New Flavor-sensitive IRC-safe jet algorithm

The argument for introduction of the flavor k_T algorithm:
Starting from NNLO a wide angle soft quark-anti-quark pair leads to incorrect flavor assignment
Banfi, Salam, Zanderighi, '06

Distance measure depends on flavor:

$$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} \begin{cases} \max(k_{ti}, k_{tj})^\alpha \min(k_{ti}, k_{tj})^{2-\alpha} & \text{softer of } i,j \text{ is flavoured,} \\ \min(k_{ti}, k_{tj})^\alpha & \text{softer of } i,j \text{ is unflavoured} \end{cases}$$

$0 < \alpha \leq 2$
typically
$\alpha = 2$

$$d_{i\bar{B}} = \begin{cases} \max(k_{ti}, k_{t\bar{B}}(y_i))^\alpha \min(k_{ti}, k_{t\bar{B}}(y_i))^{2-\alpha} & \text{softer of } i,j \text{ is flavoured,} \\ \min(k_{ti}, k_{t\bar{B}}(y_i))^\alpha & \text{softer of } i,j \text{ is unflavoured} \end{cases}$$

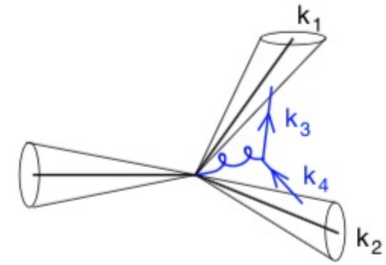
$$k_{tB}(y) = \sum_i k_{ti} \left(\Theta(y_i - y) + \Theta(y - y_i)\, e^{y_i - y}\right)$$

$$k_{t\bar{B}}(y) = \sum k_{ti} \left(\Theta(y - y_i) + \Theta(y_i - y)\, e^{y - y_i}\right)$$

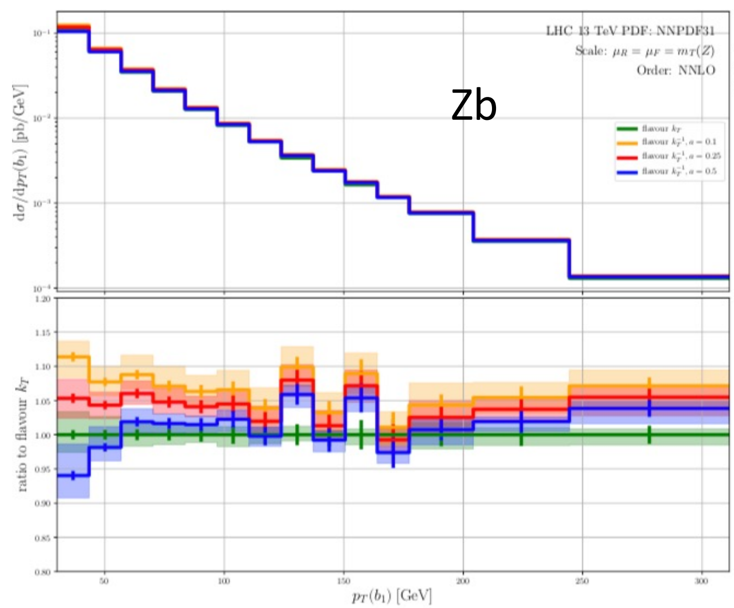
- Flavor anti-k_T algorithm proposal MC, A. Mitov, R. Poncelet

$$d_{ij}^{(F)} = d_{ij} \begin{cases} \mathcal{S}_{ij} & \text{if } i,j \text{ is a flavoured pair} \\ 1 & \text{else} \end{cases}$$

$$\mathcal{S}_{q\bar{q}}^a = 1 - \theta(1 - x)\cos\left(\frac{\pi}{2}x\right) \quad \text{with} \quad x = \frac{k_T(q)^2 + k_T(\bar{q})^2}{a 2 k_{T,\max}^2}$$



Michal Czakon

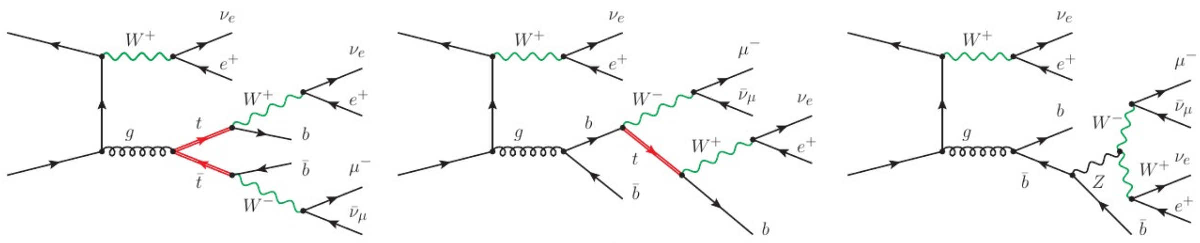


Process defined with the flavor k_T algorithm in
Gauld, Gehrmann-De Ridder, Glover, Huss, Majer '20

Studies also for top-pair production.
New flavor anti-k_T is close to classic anti-k_T.

Full Off-shell $t\bar{t}W^{\pm}$@NLO QCD

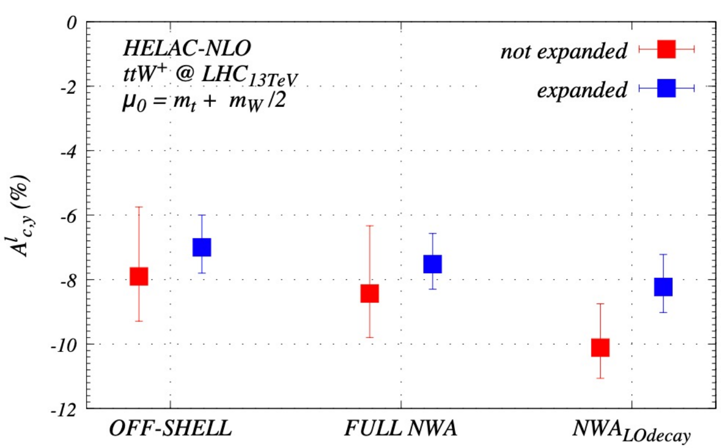
Jasmina Jasufi



- First NLO QCD calculation with full off-shell effects in this channel completed in 2020
G. Bevilacqua, H.-Y. Bi, H. B. Hartanto, M. Kraus, and M. Worek, JHEP 08, 043 (2020)
- Independent computation NLO QCD with full off-shell
A. Denner, G. Pelliccioli (2020), 2007.12089
- Results for combined NLO QCD+EW with full off-shell effects A. Denner and G. Pelliccioli (2021), 2102.03246

	$\sigma_{\rm NLO}^{t\bar{t}W^+}$ [ab]	$\sigma_{\rm NLO}^{t\bar{t}W^-}$ [ab]
Full off-shell	$124.4^{+3\%}_{-6\%}$	$68.6^{+5\%}_{-7\%}$
NWA	$124.2^{+3\%}_{-6\%}$	$68.7^{+5\%}_{-7\%}$
NWA$_{LOdec}$	$130.7^{+10\%}_{-10\%}$	$72.0^{+11\%}_{-11\%}$

Bevilacqua et al., Eur. Phys. J. C 81, 675 (2021)



$$\mathcal{R} \equiv \sigma^{NLO}_{t\bar{t}W^+}/\sigma^{NLO}_{t\bar{t}W^-} = 1.81 \pm 0.03(\text{scale}) \pm 0.03(\text{PDF})$$

NNLO $(2\% - 3\%)$ precision <u>independent</u> of modelling!

$$A_{c,y} = \frac{\sigma\left(\Delta|y| > 0\right) - \sigma\left(\Delta|y| < 0\right)}{\sigma\left(\Delta|y| > 0\right) + \sigma\left(\Delta|y| < 0\right)} \qquad \Delta|y| \equiv |y_{\ell_t}| - |y_{\ell_{\bar{t}}}|$$

Modelling impacts central value and theoretical uncertainties.

Impact of Off-shell Effects in DM Searches

Calculate signal strength exclusion limits to quantify the relevance of these effects

Jonathan Herman

Signal: $pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu\chi\bar{\chi}$ (tt+DM)

-> Spin-0 s-channel mediator model, DMsimp implementation Backović, Krämer, Maltoni, Martini, Mawatari, Pellen '15

-> generated with MadGraph Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro '14

-> always kept at NLO with LO decays

Background: $pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu$ (tt) Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '11

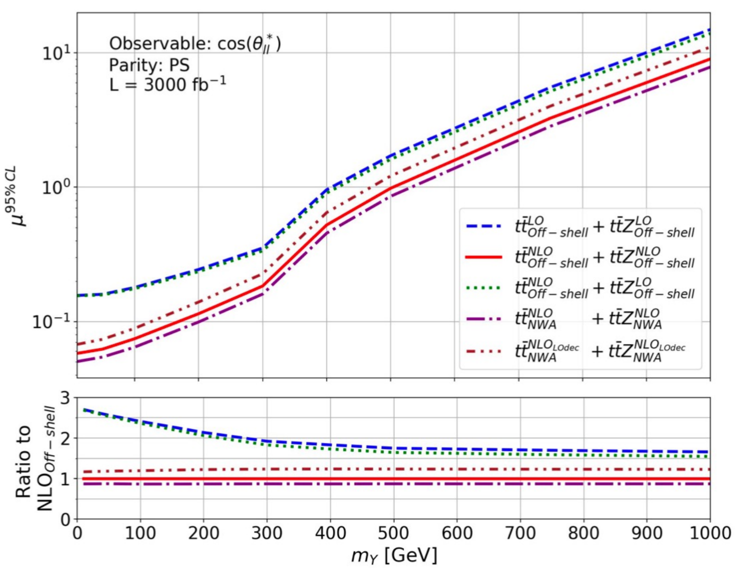
$pp \to b\bar{b}e^+\mu^-\nu_e\bar{\nu}_\mu\nu_\tau\bar{\nu}_\tau$ (ttZ) Bevilacqua, Hartanto, Kraus, Weber, Worek '19

-> generated with HELAC-NLO Bevilacqua, Czakon, Garzelli, van Hameren, Kardos, Papadopoulos, Pittau, Worek '11

-> Compare LO & NLO as well as NWA & full off-shell

Exclusion limits - Modelling

TTK Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY



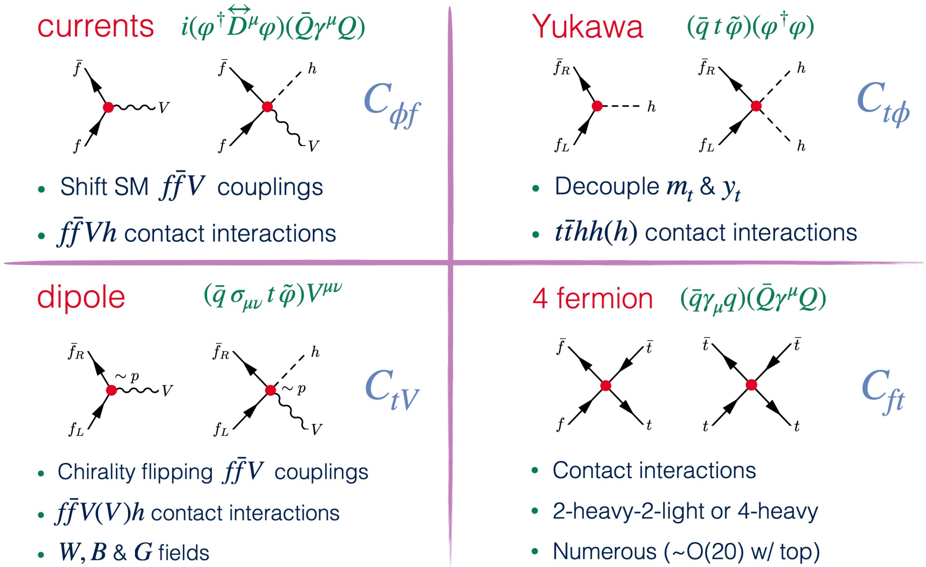
- LO inadequate due to large uncertainties, even if only using it for ttZ
- NLO with LO decays still too large due to large uncertainties and overestimated normalization
- In NWA, tt contribution is zero
- Full NWA results are too good due to missing off-shell tt contribution

JH, Worek, arXiv:2108.01089

Interpretation of Precision Top Measurements: SMEFT

Top operator glossary

Ken Mimasu



Indirect: new physics is heavy ⇒ modifies top "properties"

- Precision measurements seeking new physics via new interactions
- Complementary to direct searches

Established framework: **SMEFT** $\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^{D-4}} \mathcal{O}_i^D$

The future is bright for top physics in SMEFT

- Global SMEFT analyses are rapidly expanding & probing model space
- New precision tools available (`SMEFTatNLO`): NLO & loop-induced effects
- Being incorporated into experimental interpretations
- Rare EW top production: high energy & high multiplicity
- Towards global measurements for global fits

Interpretation in SMEFT: Theory Challenges

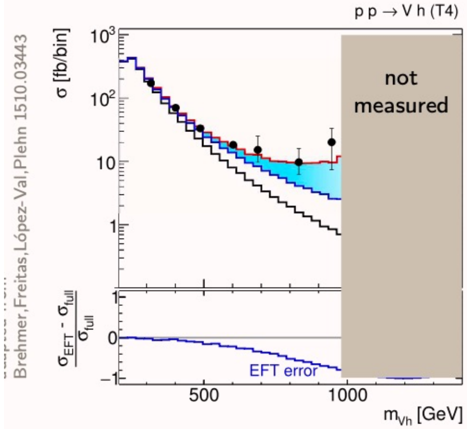
Good news:

- ~common conventions for bases, tools for translation
- consistent formulation with/without flavor symmetries
- correct treatment of input parameters
- LO predictions fully automated (any operator in any process), NLO QCD to a good extent
- understanding of NLO EW improved substantially
- 1-loop RGE running well understood and automated
- 1-loop matching to BSM models automated
- 1-loop matching to LEFT/WET
- good understanding of measurements' constraining power
- global analyses with up to ~ 30 free parameters
- strategies to handle unconstrained directions (PCA) and understand fit structure (Fisher info)

How about theoretical uncertainties due to missing higher EFT orders?

Ilaria Brivio

EFT obtained from matching to full model



top-down: C_i fixed by matching
→ EFT not valid in high-E region

bottom-up: fit C_i to data
tends to make EFT match full result
→ find wrong values of C_i

how to keep this into account?

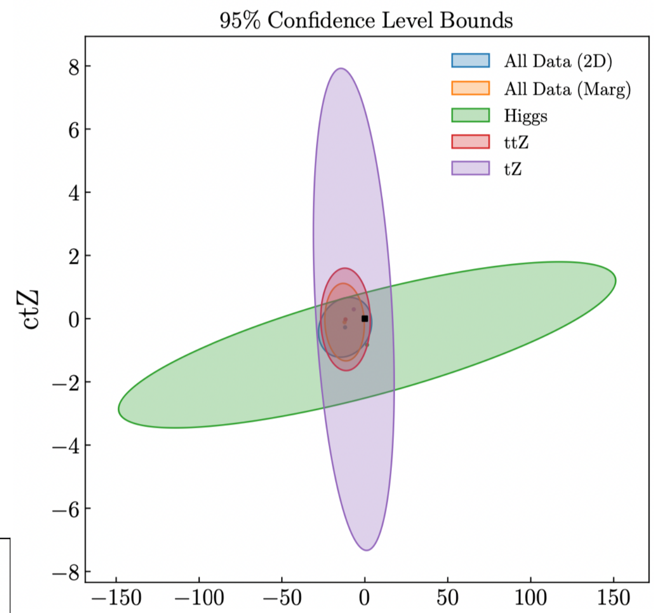
More challenges:

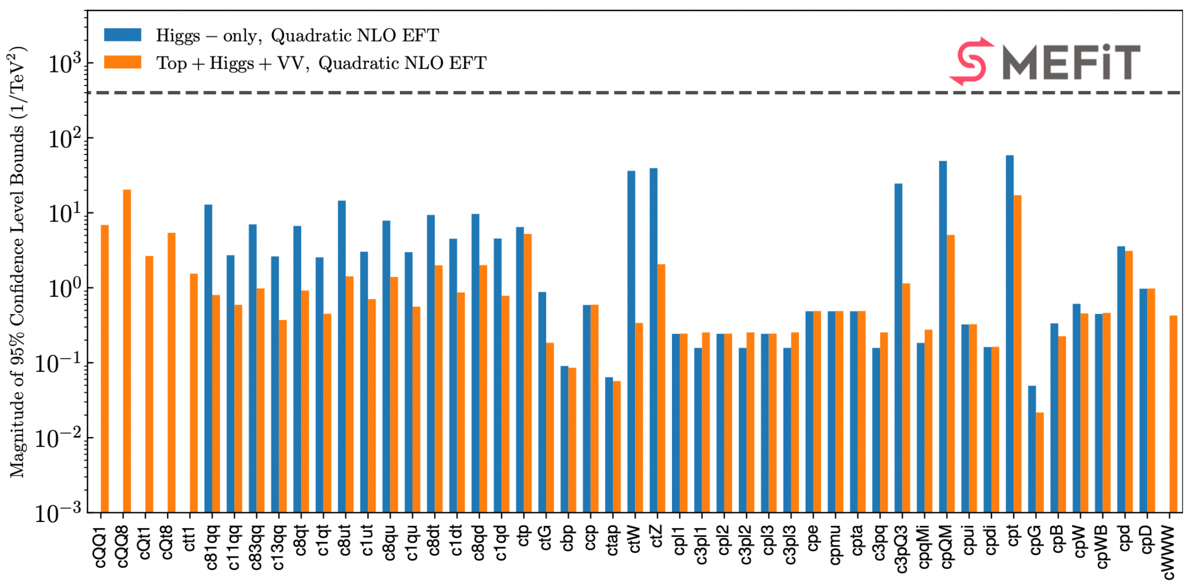
- Inclusion of CP violating terms
- Unified flavor treatment → combination with low-E
- Streamlining/automating NLO EW calculations in SMEFT
- 2-loop RGE running (consistency with 1-loop matching)
- Treatment of scale uncertainties in NLO SMEFT calculations
- Implementation of unitarity constraints & positivity bounds
- Handling fits with 50+ parameters → bayesian?
- Interplay with direct searches
- SMEFT in non-perturbative effects? PDF, hadronization...

Interpretation in SMEFT: Top-Higgs interplay

Category	Processes	$n_{\rm dat}$
Top quark production	$t\bar{t}$ (inclusive)	94
	$t\bar{t}Z$, $t\bar{t}W$	14
	single top (inclusive)	27
	tZ, tW	9
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6
	Total	**150**
Higgs production and decay	Run I signal strengths	22
	Run II signal strengths	40
	Run II, differential distributions & STXS	35
	Total	**97**
Diboson production	LEP-2	40
	LHC	30
	Total	**70**
Baseline dataset	**Total**	**317**

Luca Mantani





Plans: Add new data (e.g. VBS); improve theory (e.g. more systematic in including NLO QCD,EW; improve fit methodology

J. Ethier, F. Maltoni, E. Nocera, J. Rojo, E. Slade, E. Vryonidou and C. Zhang, arXiv:2105.00006

Interpretation in SMEFT: Towards a Global Fit

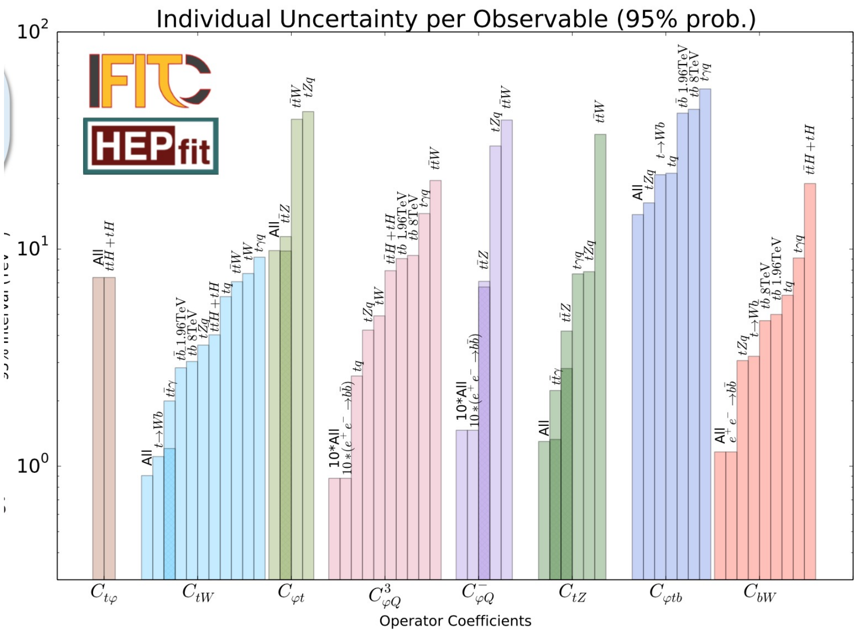
Process	Observable	$\sqrt{s}$	$\int \mathscr{L}$	Experiment
$pp \to t\bar{t}H$ NLO	cross section	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}W$ NLO	cross section	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{t}Z$ NLO	(differential) x-sec.	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}\gamma$ NLO	(differential) x-sec.	13 TeV	140 fb^{-1}	ATLAS
$pp \to tZq$ NLO	cross section	13 TeV	140 fb^{-1}	CMS
$pp \to t\gamma q$ NLO	cross section	13 TeV	36 fb^{-1}	CMS
$pp \to tb$ (s-ch) NLO	cross section	8 TeV	20 fb^{-1}	ATLAS+CMS
$pp \to tW$ NLO	cross section	8 TeV	20 fb^{-1}	ATLAS+CMS
$pp \to tq$ (t-ch) NLO	cross section	8 TeV	20 fb^{-1}	ATLAS+CMS
$t \to W^+b$ NLO	F_0, F_L	8 TeV	20 fb^{-1}	ATLAS+CMS
$p\bar{p} \to t\bar{b}$ (s-ch) LO	cross section	1.96 TeV	9.7 fb^{-1}	Tevatron
$e^-e^+ \to b\bar{b}$ LO	R_b , A_{FBLR}^{bb}	$\sim$ 91 GeV	202.1 pb^{-1}	LEP

Maria Moreno Llacer

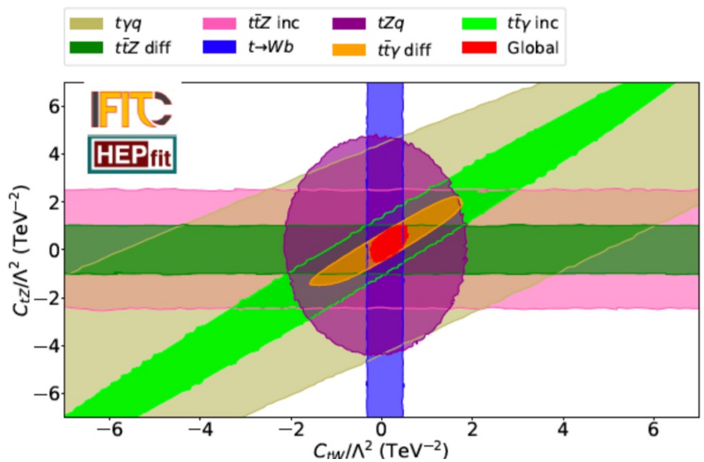
Here, we consider **8 dim-six operators** in the **Warsaw basis:**

- Left/Right-handed couplings of top/bottom to Z: $O_{\varphi t}, O^{-}_{\varphi Q}, O^{(3)}_{\varphi Q}$
- EW dipole operators: O_{tZ}, O_{tW}, O_{bW}
- Top Yukawa: $O_{t\varphi}$
- Charged current interaction: $O_{\varphi tb}$

arXiv: 2107.13917



2D 95% probability contours showing complementarity between measurements



Towards a Global View: Impact of B anomalies on Top

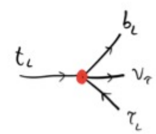
David Marzocca

Implications for top physics - top decays

CC top decays

Solutions addressing $R(D^{(*)})$ only via LH couplings contribute to

$$\left[\mathcal{O}_{\ell q}^{(3)}\right]^{3333} = \left(\bar{\ell}^3_L \gamma_\mu \ell^3_L\right)\left(\bar{q}^3_L \gamma^\mu q^3_L\right) \supset V^*_{tb}\left(\bar{\nu}_\tau \gamma_\mu \tau_L\right)\left(\bar{b}_L \gamma^\mu t_L\right)$$



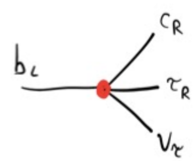
Buttazzo, Greljo, Isidori, DM 1706.07808

with a typical size of O(few %) of the SM amplitude: $C_{tb\tau\nu} \sim (2\,\mathrm{TeV})^{-2}$ ⟶ $Br_{BSM} \sim 10^{-7}$

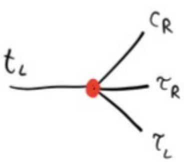
FCNC top decays

Solutions addressing $R(D^{(*)})$ via mixed LH and RH interactions, such as via S_1 and R_2 leptoquarks, also require a sizeable coupling to c_R.

$$\mathcal{L}_{EFT} = \frac{\lambda^{1R}_{c\tau}\lambda^{1L*}_{b\tau}}{2M_1^2}\left[\left(\bar{\ell}^3_L \tau_R\right)\varepsilon\left(\bar{q}^3_L c_R\right) - \frac{1}{4}\left(\bar{\ell}^3_L \sigma_{\mu\nu}\tau_R\right)\varepsilon\left(\bar{q}^3_L \sigma^{\mu\nu} c_R\right)\right] \longrightarrow$$



Directly correlated with $R(D^{(*)})$



$$\sim \frac{\lambda^R_{c\tau}\lambda^L_{b\tau}}{M_1^2} \sim (2\,\mathrm{TeV})^{-2}$$

$Br_{FCNC} \sim 10^{-7}$

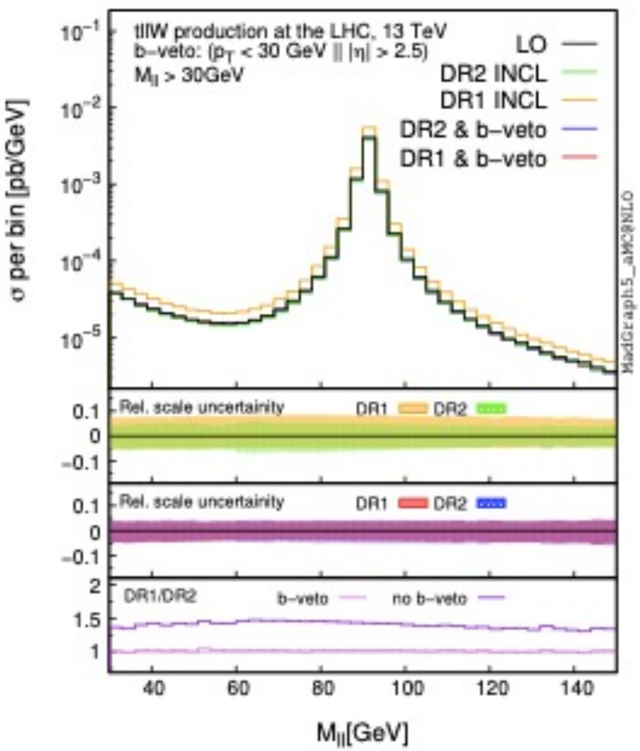
- While in most models NP has **sizeable couplings to top quark**, **effects in top decays** are expected to be **very small**, due to the large scale of NP.
- Top quarks play instead a **major role as final states of leptoquark searches**, crucial to discovery or putting limits.

Interpretation in SMEFT: tWZ production at NLO QCD

Hesham El Faham

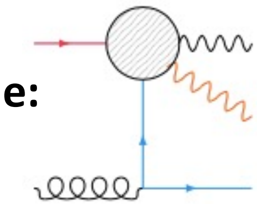
tWZ at NLO is non-trivial due to its overlap with other processes:

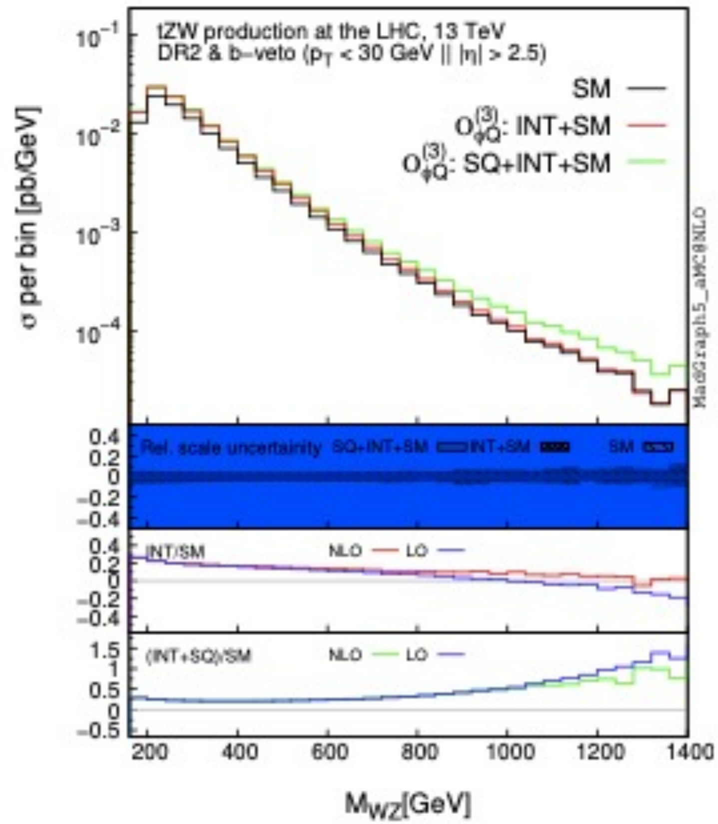
The ***tWZb*** final state can also have resonant contributions, from ***ttZ***,***t*** → ***Wb***, or ***tt***,***t*** → ***WZb*** and not necessarily the non-resonant ***tWZb***



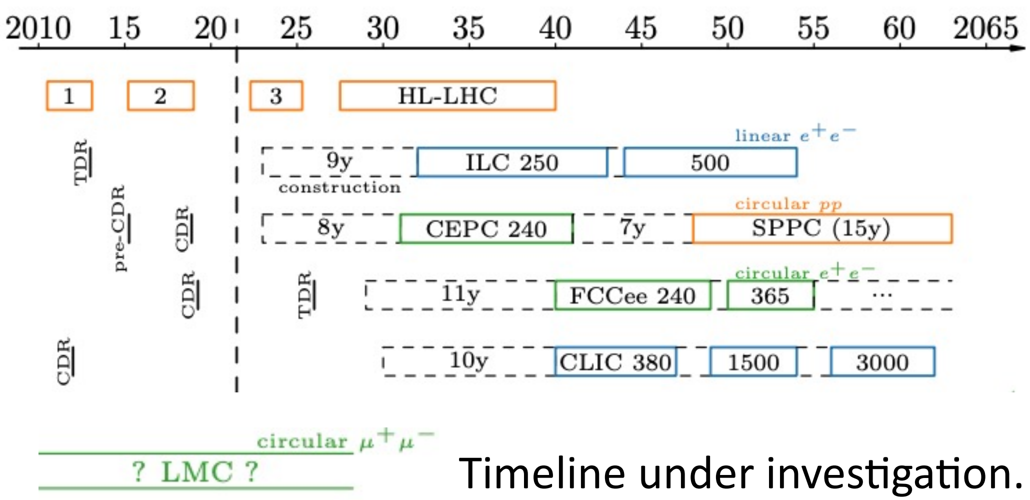
***tWZ* in the SMEFT**

The *bW* → *tZ* sub-amplitude:





Many Possible Paths to an Exciting Future!

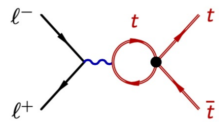


Timeline under investigation.

Gauthier Durieux

Leptons for tops

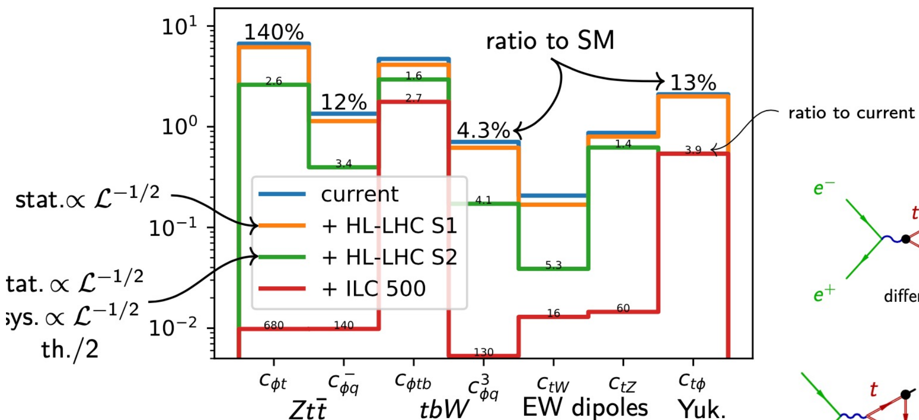
ideal for electroweak couplings ... as clean as a dream

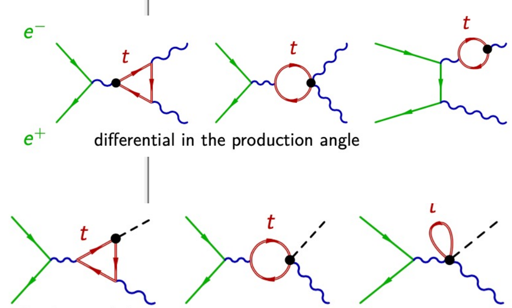


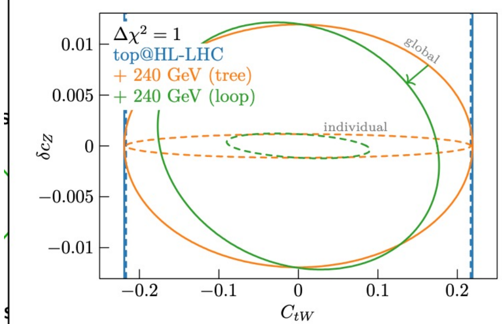
beating LHC on four-fermions
... with great potential for heavy BSM

reaching quantum/loop sensitivities
... Higgs processes become also top processes

[GD, Irles, Miralles, Peñuelas, Pöschl, Perellò, Vos '19]







· extra parameter space covered thanks to loop sensitivity
· room for improvement between glo. and ind. constraints

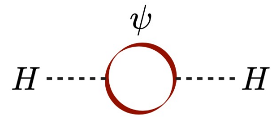
[GD, Gu, Vrionidou, Zhang '18]

Top Compositeness @ Future Colliders

Javier Serra-Mari

- Top (effective) compositeness is a very motivated target for high-energy colliders.

  In particular because of its connection to the origin of the electroweak scale.



$$m_H^2 \sim y_\psi^2 m_*^2$$

- Current LHC measurements are becoming very interesting.

  Probes of genuine strong 4-top production competitive with Higgs precision.

- Future colliders would provide very powerful tests of a strongly-interacting top.

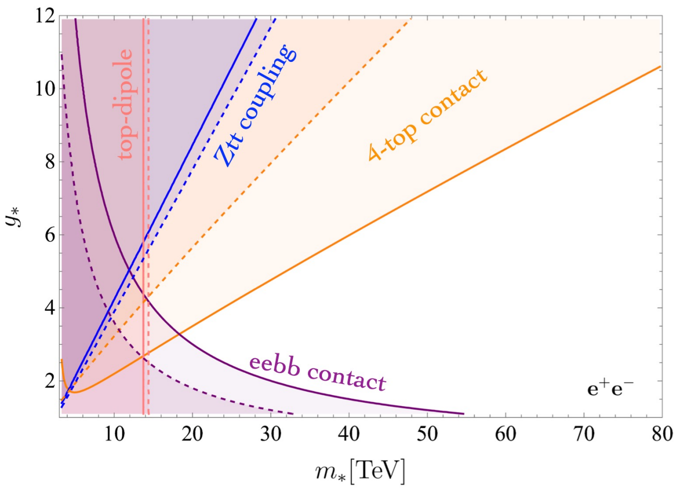
  Hadron colliders, directly via strong *tt*-scattering in 4-top production.

  Lepton colliders, indirectly via RGE effects in top-pair production.

$$\left.\frac{m_*}{g_*}\right|_{\mathrm{LHC,\,36/fb}}^{4t} \gtrsim 0.73\ \mathrm{TeV} \qquad \left.\frac{m_*}{g_*}\right|_{\mathrm{FCC-hh}}^{4t} \gtrsim 6.5\ \mathrm{TeV} \qquad \left.\frac{m_*}{g_*}\right|_{\mathrm{CLIC\ 3}}^{t\bar{t}} \gtrsim 7.7\ \mathrm{TeV} \qquad \left.\frac{m_*}{g_*}\right|_{\mathrm{muon\ 10}}^{t\bar{t}} \gtrsim 18\ \mathrm{TeV}$$

$$\boxed{\frac{c_{\psi\psi}}{m_*^2}(\bar{\psi}\gamma_\mu\psi)^2}$$

$$c_{\psi\psi} \sim g_*^2$$



CLIC
$\sqrt{s} = 0.38,\ 1.4,\ 3$ TeV
$L = 0.5,\ 1.5,\ 3$ /ab

ILC
$\sqrt{s} = 0.5,\ 1$ TeV
$L = 0.5,\ 1$ /ab

Based on reinterpretation of results for sensitivity to the individual operators: Durieux, Perelló, Vos, Zhang '18. See also Durieux, Matsedonskyi '18.

Top Physics Opportunities @ HL-LHC

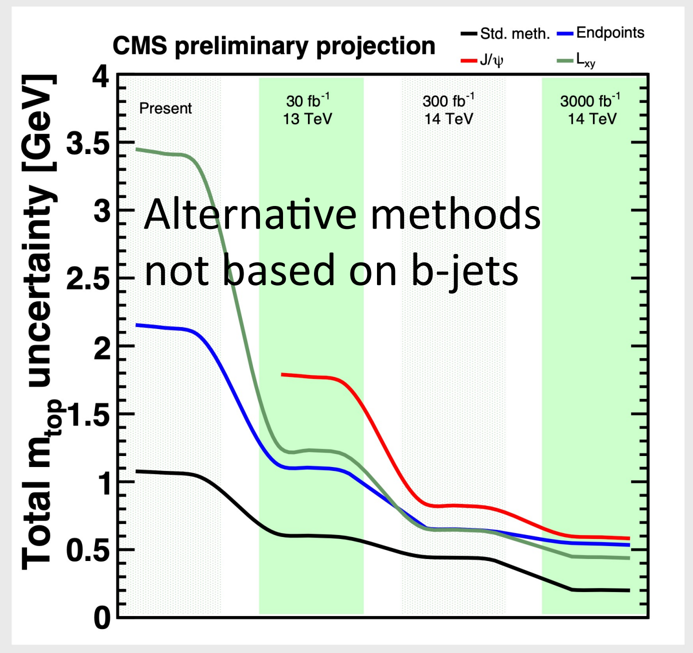
- Top quark mass
- Yukawa coupling
- CP   tth, th+X, tt+mET
- $$\mathcal{L}_{ht} = -\frac{y_t}{\sqrt{2}}\bar{t}(\kappa + i\tilde{\kappa}\gamma_5)th$$

Roberto Franceschini

For each observable used in top quark mass measurement with b-jets a derived observable can be defined using the B-hadron instead of the b-jet (and JES ↔ Hadronization)

m(b-jet,lepton) ⇒ m(B-hadron,lepton)

What are the hadronization uncertainties ?



1712.05801 Corcella, RF, Kim

Sensitivity to shower and hadronization PYTHIA parameters of the top quark mass extracted from the first Mellin moment of mass-sensitive observables:

Mellin-1	$\Delta^{(O)}_{m_t}$	$\frac{dm_t}{dM_1}$	$\Delta_\theta^{(m_t)}$					
			$\alpha_{s,FSR}$	$p_{T,\min}$	recoil	r_B	a	b
E_B	1.1	2.4	0.43	0.019	0.028	0.039	0.020	0.039
$E_B + E_B$	1.2	0.99	0.42	0.019	0.032	0.046	0.023	0.034
$p_{T,B}$	1.2	3.3	0.43	0.021	0.027	0.043	0.022	0.042
$p_{T,B} + p_{T,B}$	1.2	1.47	0.36	0.017	0.024	0.042	0.016	0.044
$m_{B\ell,\min}$	1.0	2.6	0.26	0.011	0.016	0.041	0.011	0.031
$m_{B\ell,\text{true}}$	1.2	1.63	0.24	0.008	0.013	0.031	0.009	0.022

α_s needed at 1%

a, b, r_B, recoil, and $p_{T,\min}$: determining them to a 10% accuracy should be enough to warrant a 0.5% precision on m_t.

Agashe, Airen, RF, Kim, Sathyan – B decay length

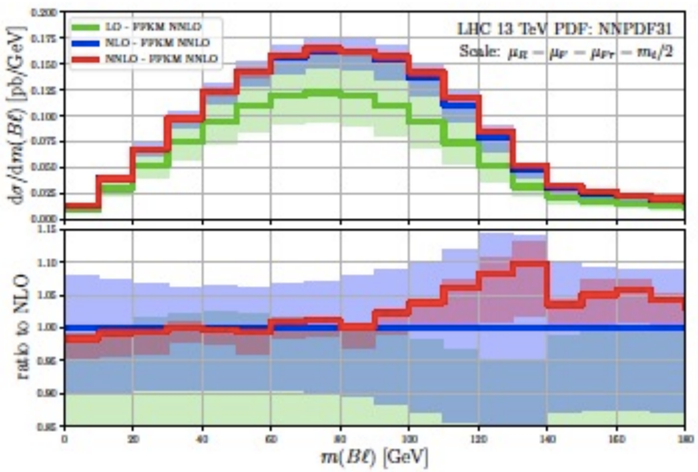
Top-pair production with B hadrons @ NNLO QCD

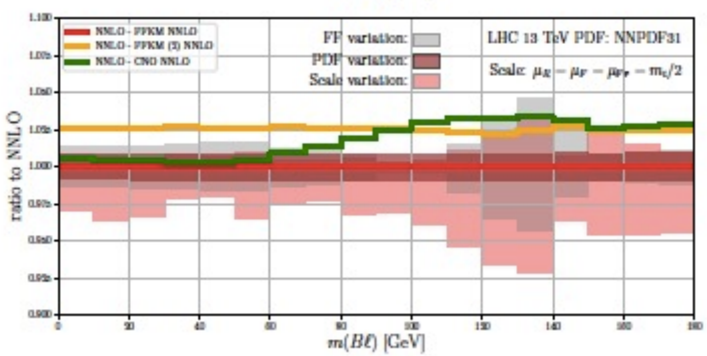
Terry Generet

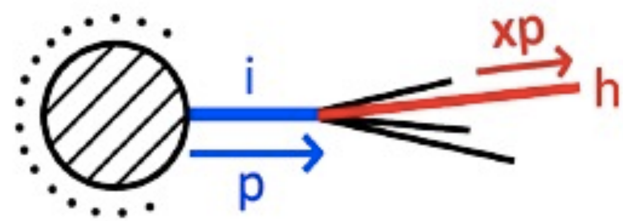
- Process considered:

$$p\,p \to t(\to B\,W^+ + X)\,\bar{t}(\to \bar{b}\,W^-)$$

$\quad\quad\quad\quad\quad\quad\quad\quad \hookrightarrow \ell^+\nu_\ell \quad\quad\quad\quad\quad\quad \hookrightarrow \ell^-\bar{\nu}_\ell$







- Implementation of fragmentation in a numerical code for NNLO cross sections

- "Standard" recipe for theory errors:

$$\sigma_{tot} = \sigma_{scale} \oplus \sigma_{PDF} \oplus \sigma_{FF}$$

Michał Czakon, **Terry Generet**, Alexander Mitov, René Poncelet
arXiv:2102.08267

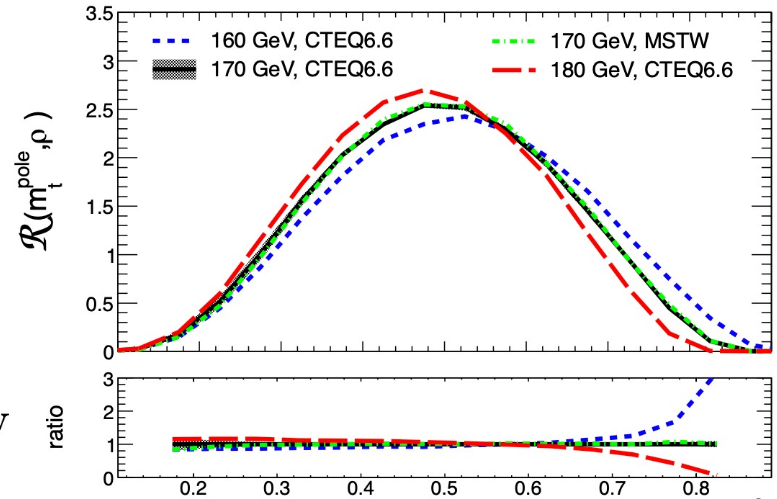
M_{top} from $t\bar{t}j$ @ LHC: scale uncertainty

$$\mathcal{R}(m_t,\rho) = \frac{1}{\sigma_{t\bar{t}+1\text{ jet}}}\frac{d\sigma_{t\bar{t}+1\text{ jet}}}{d\rho}(m_t,\rho)$$

$$\rho = \frac{2m_0}{m_{t\bar{t}j}}, \quad m_0 = 170\,\text{GeV}$$

arXiv:1303.6415

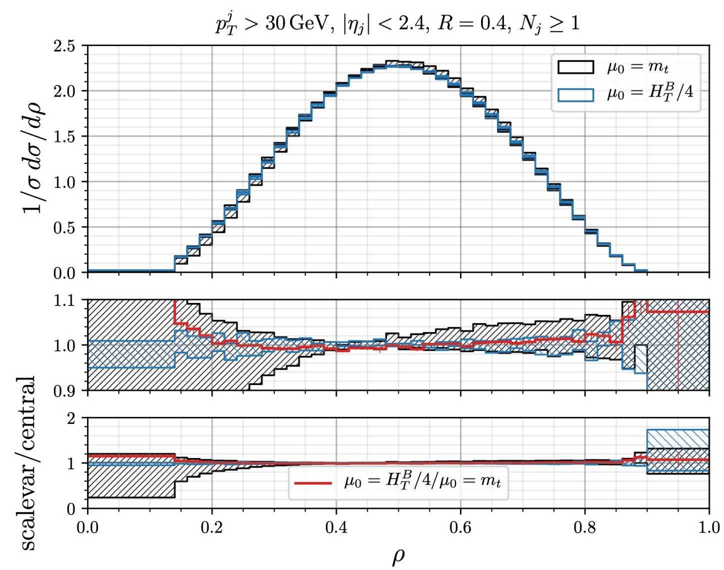
Katharina Voss



ATLAS measurement ($\sqrt{s} = 8\,\text{TeV}$, 2019)[2]

$$m_t^{\text{pole}} = 171.1 \pm 0.4(\text{stat}) \pm 0.9(\text{sys}) \,^{+0.7}_{-0.3}(\text{th})\,\text{GeV}$$

arXiv:1905.02302



- POWHEG-BOX $t\bar{t}j$ reimplementation V2 (previous version V1[3])
- $N_j \geq 1$, $p_T^j > 30\,\text{GeV}$, $|\eta_j| < 2.4$, anti-k_T with $R = 0.4$
- PDF set: CT18NLO

Study of fixed ($\mu_0 = m_t$) and dynamical scale ($\mu_0 \in \{H_T^B/2, H_T^B/4\}$)

$$H_T^B = \left(\sqrt{{p_{T,t}^B}^2 + m_t^2} + \sqrt{{p_{T,\bar{t}}^B}^2 + m_t^2} + p_{T,j}^B\right)$$

arXiv:1609.01659

ttH(M_{top}(MSbar)) @ LHC

Andrej Saibel

- First study of $t\bar{t}H$ production with top quark running mass!

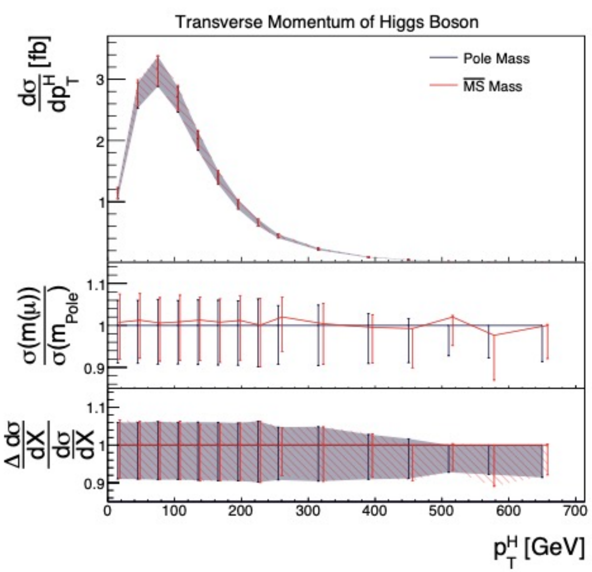
With MARIA ALDAYA MARTIN, SVEN-OLAF MOCH

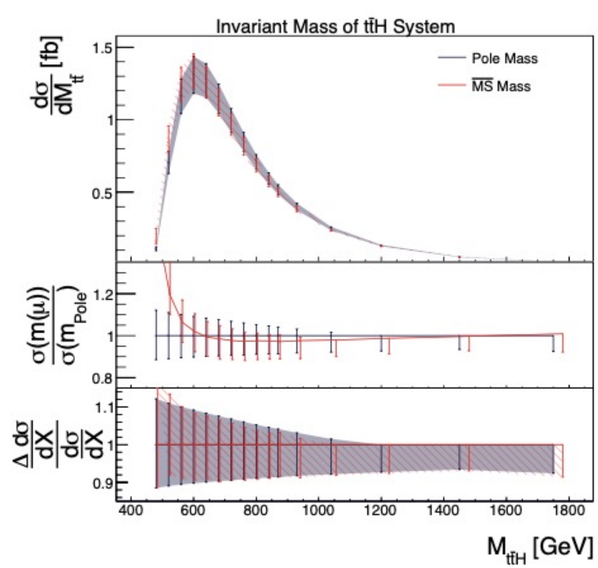
Using the relationship

$$m_t^{\text{pole}} = m(\mu_R)\left(1 + \frac{\alpha_s}{\pi} d_1 + \dots\right)$$

$\sigma\left(m_t^{\text{pole}}\right)$ is used to calculate $\sigma\left(m\left(\mu_R\right)\right)$

- Energy dependence of mass (mq (μR))
- **Improved convergence** and **smaller scale dependences** compared to pole mass shown for $\bar{t}t$ production



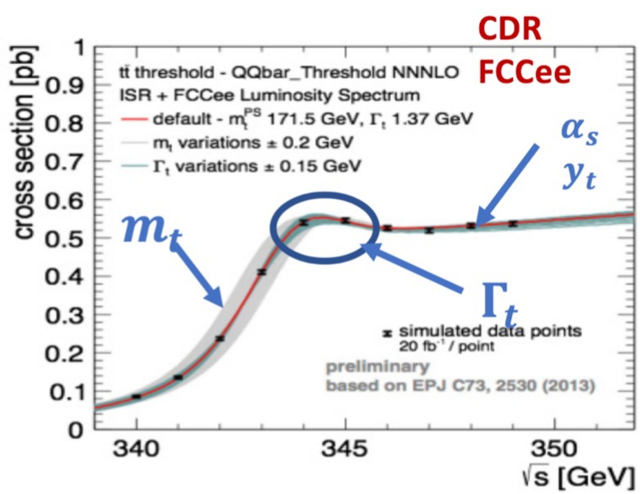


Impact on reduction of scale uncertainties small

– Largest impact on $M_{\bar{t}tH}$

Top Threshold Physics @e^+e^- Colliders

- Threshold runs: ILC, CLIC, FCC-ee
- Typical: 100 fb^{-1} integrated luminosity
- Typical: $\sigma_{tot} \sim 1$ pb $\rightarrow$ 10^5 ttbar pairs
- Threshold scan: high precision method for top quark mass measurement in a well-defined scheme: ($\Delta m_t^{PS,1S,MSR} \sim 50$ MeV)
- Sensitivity to Γ_t, α_s, y_t
- Need: precise knowledge of beam effects



Andre Hoang

$v \sim \alpha_s \sim 0.1$

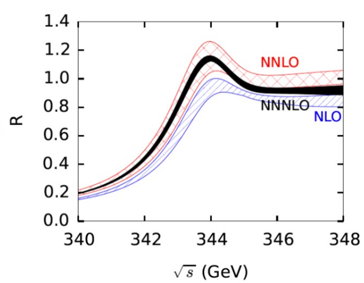
Requires resummation of singular velocity terms done within nonrelativistic QCD (NRQCD) by solving a Schroedinger- type eq. for propagation of the top–anti-top system.

- Simple factorization formula up to NNLO/NNLL$_{QCD}$ + LO$_{EW}$:

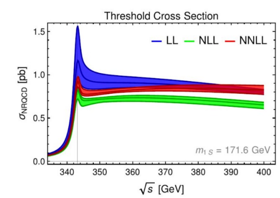
$$\sigma_{t\bar{t}} \propto c(\nu)^2 \, \mathrm{Im}\, G(0,0,\sqrt{s}) + \ldots$$

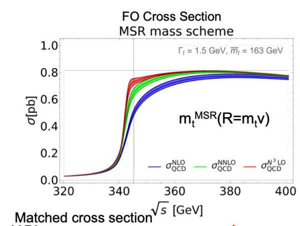
$\longrightarrow$ More complicated beyond

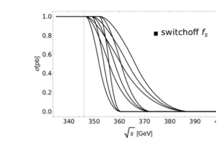
$$\left(-\frac{\nabla^2}{m} - \frac{\nabla^4}{4m^3} + V(\mathbf{r}) - (\sqrt{s} - 2m - 2\delta m) - i\Gamma_t\right) G(\mathbf{r},\mathbf{r}') = \delta^{(3)}(\mathbf{r}-\mathbf{r}')$$

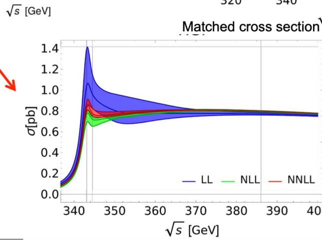


- Total cross section in good shape: $d\sigma_{tot}/\sigma_{tot} \sim$ 2-3% (for NNLL$_{QCD}$ / NNNLO$_{QCD}$)
- Combination of NNLL$_{QCD}$ and NNNLO$_{QCD}$ to be done.









Scale-setting subtle!

Dependence on matching function smaller than scale-dependence.

Uncertainties much larger in the pole mass scheme.

Combination of the of NNNLO FO and NNLO+NNLL threshold cross section

$$\boxed{\sigma_{\mathrm{matched}} = \sigma_{\mathrm{QCD}} + (\sigma_{\mathrm{vNRQCD}} - \sigma_{\mathrm{double\text{-}counted}}) \cdot f_s}$$

Switchoff- function

Fully differential treatment + MC simulations still in infancy.

Differential cross sections in Whizard (NLOFO + LLthreshold) Bach, Neja, AHH, Kilian, Reuter '17

Heavy flavor and top quark physics @ Snowmass 2021

EF03 Topical Group Conveners:

Reinhard Schwienhorst (schwier@msu.edu), DW (dw24@buffalo.edu)

- We invite you to contribute to Top/Heavy Flavor production studies
  - EF03 wiki page at https://snowmass21.org/energy/heavy_flavour
  - Email the conveners: schwier@msu.edu, dw24@buffalo.edu
  - Mailing list SNOWMASS-EF-03-TOP_HEAVY-FLAVOR@FNAL.GOV
  - Please contact conveners to schedule a presentation at our biweekly meetings
- Many opportunities to contribute to Top/Heavy Flavor production physics
  - So far most input from ILC and HL-LHC,
  - Top physics potential talks from FCC-ee, LHeC and FCC-eh
  - Study top at other colliders (new: muon collider)
  - Need many more HL-LHC studies to explore full program
- Informal (incomplete) list of projects, possible collaborations, open questions, etc.: https://docs.google.com/document/d/17aPp9XpJAlmmPlnPNtgV21rG2zEiFS2IHkO-ooC4rcQ

Thank you!

International Advisory Committee:
Jorgen D'Hondt, VUB Brussels
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Christopher Neu, University of Virginia
Reinhard Schwienhorst, Michigan State University (Chair)
Pekka Sinervo, University of Toronto

Special thanks to the speakers and poster presenters for making this such an exciting workshop!