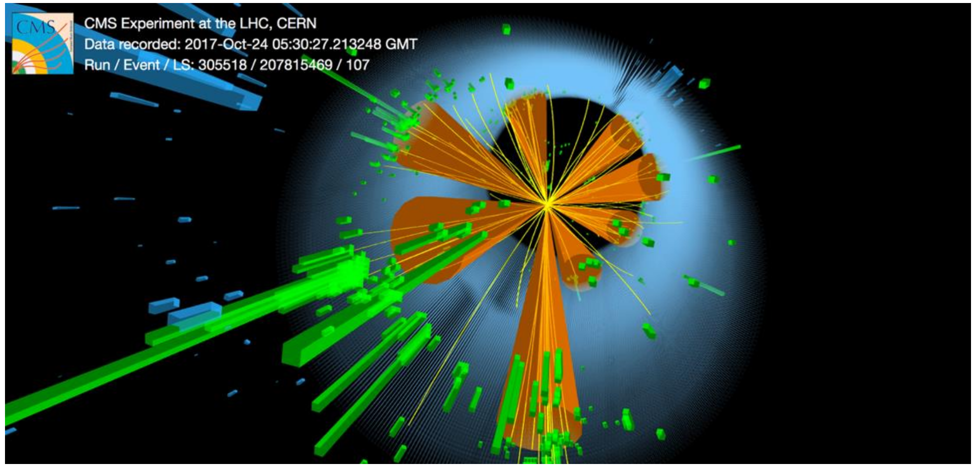
GRK2497: Physics of the Heaviest Particles at the LHC

Spokesperson: Michal Czakon



$pp \to t\bar{t}H(H \to b\bar{b})$

Mission Statement

- The Research Training Group is centred around **Large Hadron Collider** research
- The experimental groups are part of the **CMS collaboration** and have contributed substantially to the detector construction, its upgrades, computing and data analyses
- The theoretical group covers a broad range of topics from **precision calculations in quantum chromodynamics** to the **phenomenology of dark matter**
- The RTG is designed to study the **heaviest particles both known and theorised**:

  1) the Higgs boson, as a potential window to New Physics
  2) the top quark, as the heaviest of the quarks with likely relation to spontaneous symmetry breaking
  3) most plausible heavy, yet undiscovered, New Physics particles

- **1st Funding period: 1.10.2019 – 31.3.2024** → **2nd Funding period: 1.4.2024 – 30.9.2028**
- **23 submitted theses**

Senior Researchers & Profile of RTG

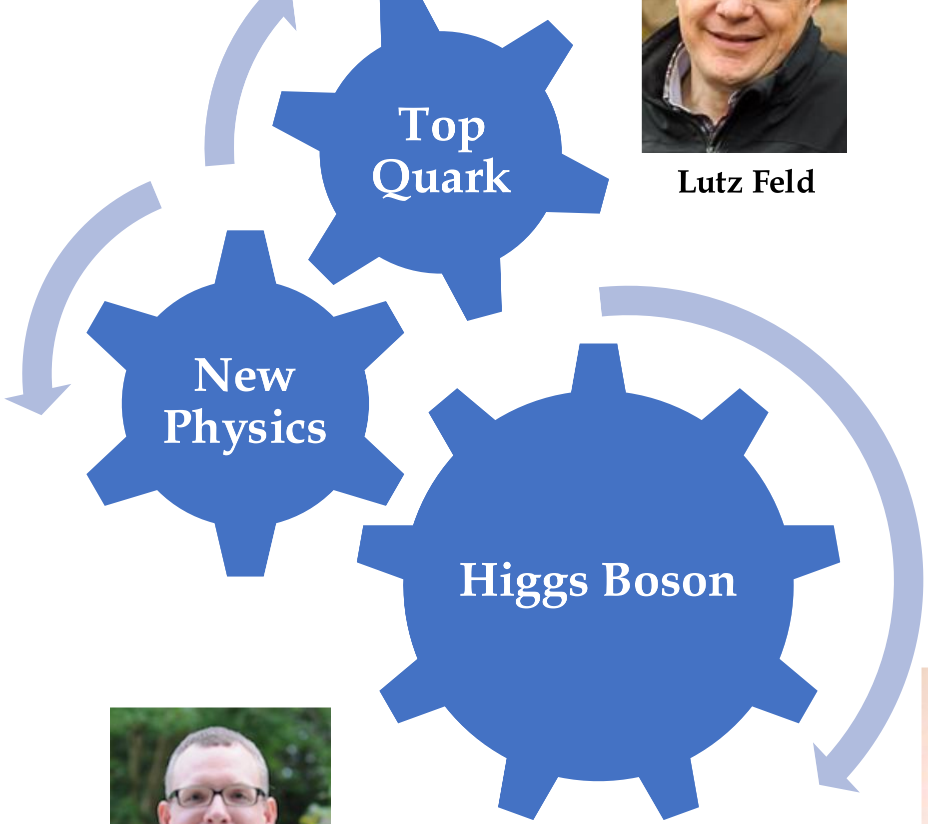
Thomas Hebbeker

Kerstin Borras

Michael Krämer

Robert Harlander

Alexander Schmidt



Lutz Feld

Michał Czakon

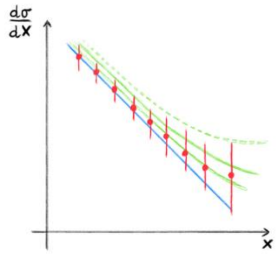
Małgorzata Worek

Martin Erdmann

Johannes Erdmann

Scientific Collaborations

- Strong topical connection between doctoral researchers
- Similar tools used by theory and experiment



tt & tt + New Physics

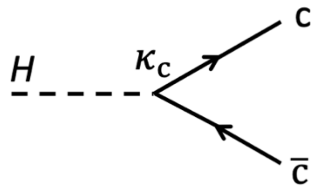
Danilo Meuser
Terry Generet
Jonathan Hermann

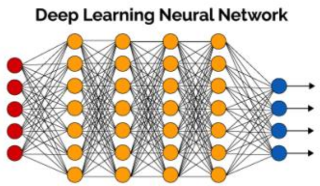
Higgs & light quarks

Ming-Yan Lee
Spandan Mondal
Annika Stein
Jan-Lukas Späh
Florian Mausolf

pp → VH

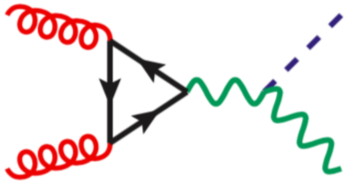
Svenja Diekmann
Alena Dodonova
Niclas Eich
Lukas Simon





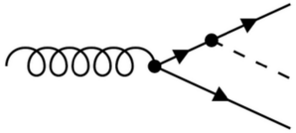
top to Higgs fragmentation

Colomba Brancaccio
Terry Generet
Florian Mausolf

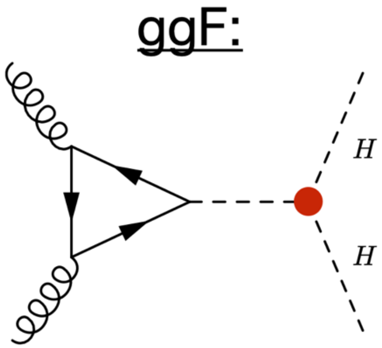


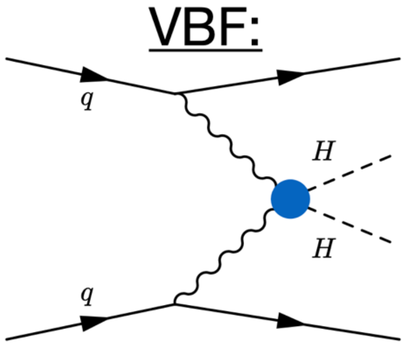
Machine Learning

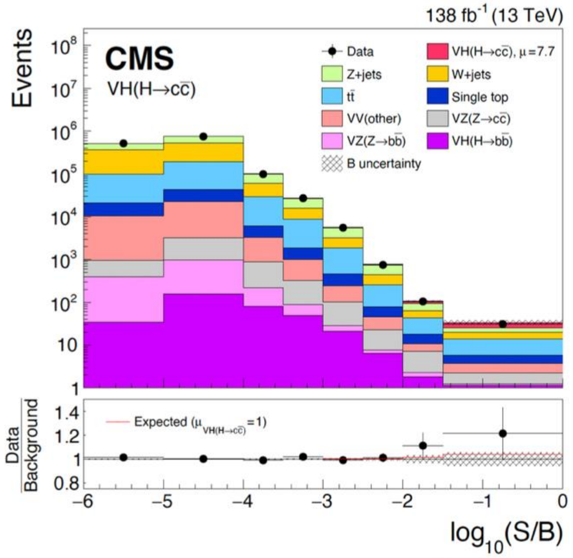
14 students

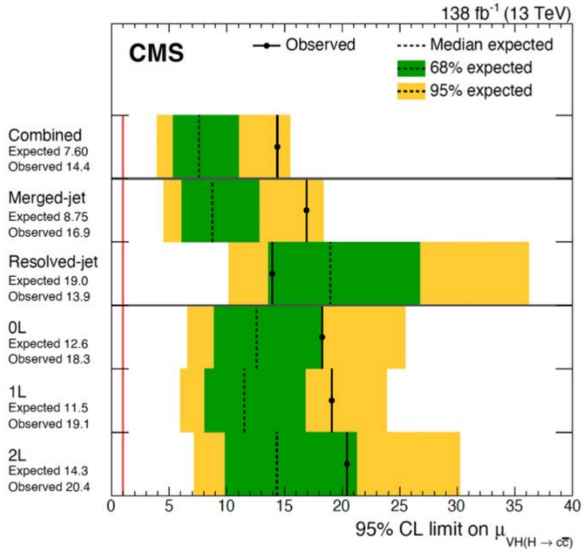


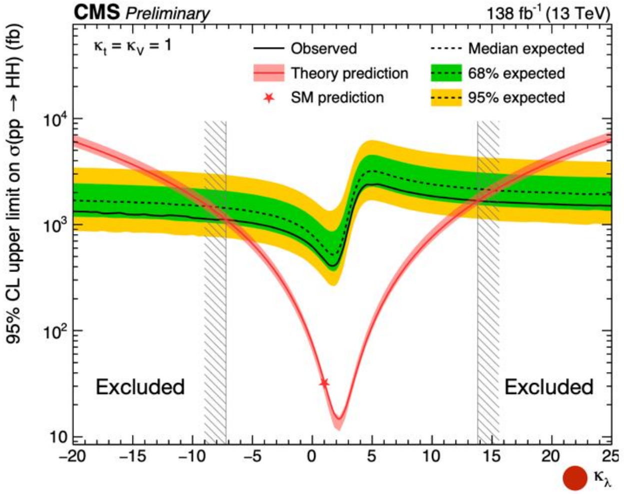
Scientific Highlights: Higgs Boson

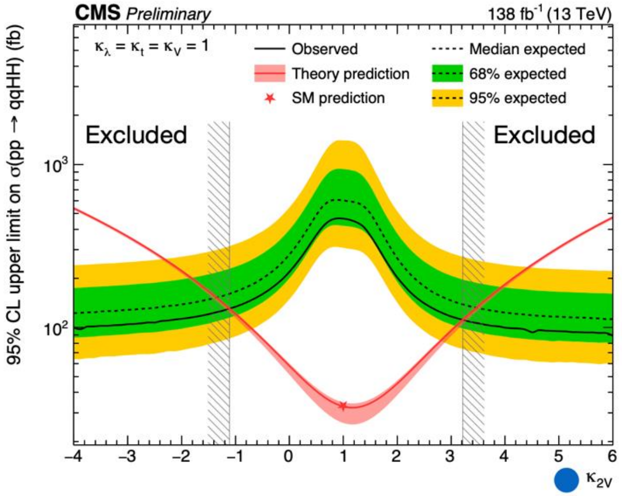








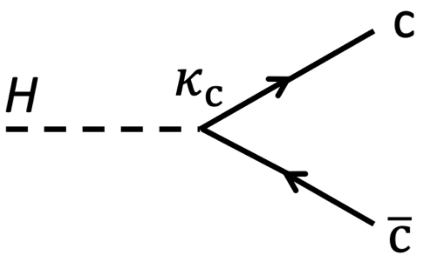




Obs. (Exp.) upper limit of **14.4 (7.6)** $\times$ **SM expectation**

Constraint on coupling modifier: **1.1 < $|\kappa_c|$ < 5.5**

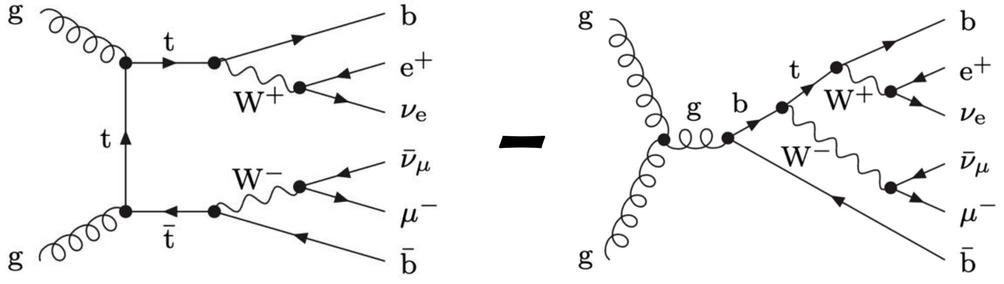
Most stringent direct limits to date!

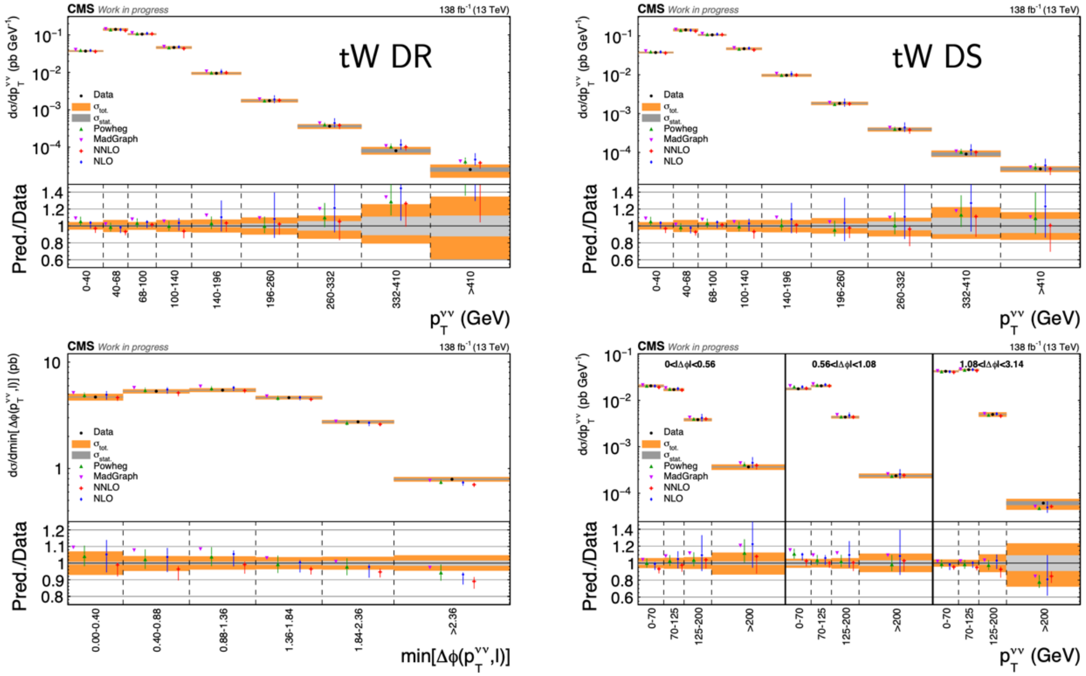


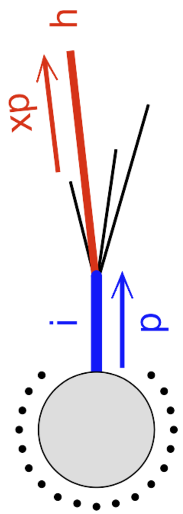
Dennis Noll

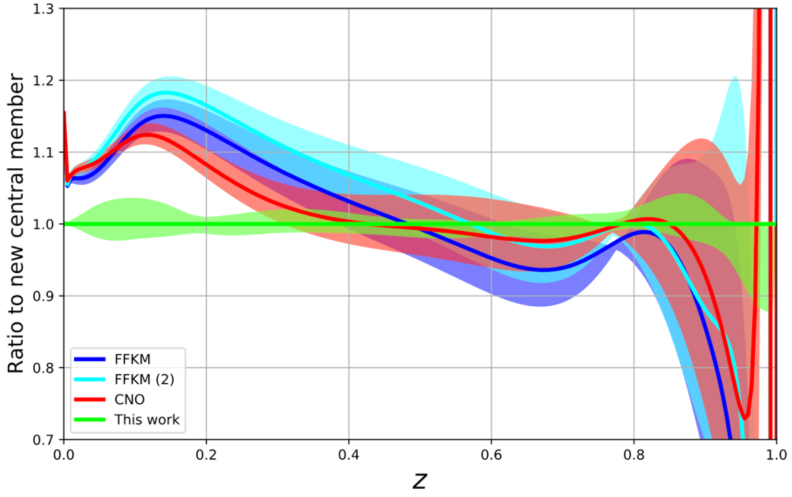
Spandan Mondal

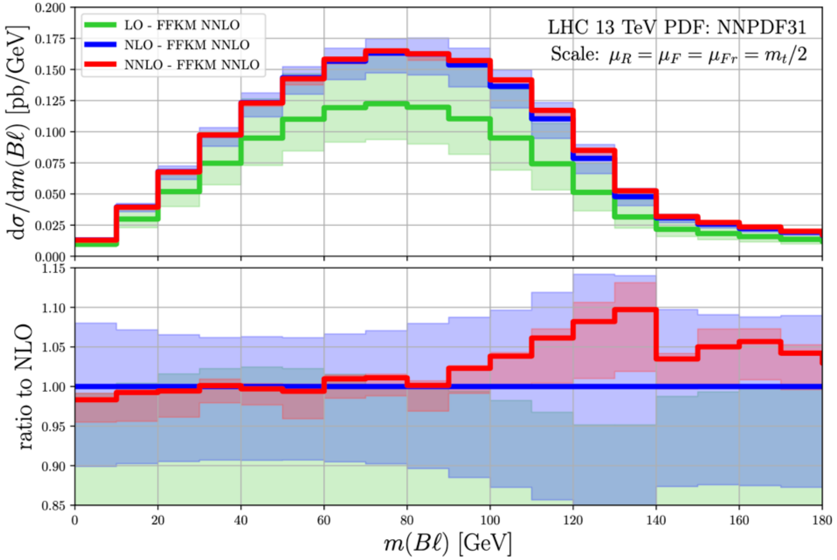
Scientific Highlights: Top Quark

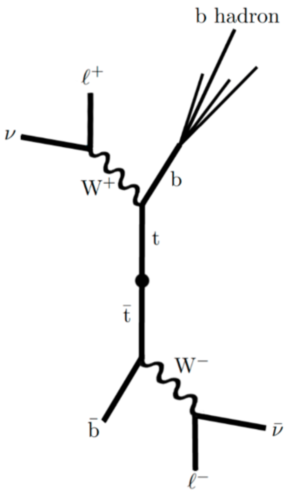










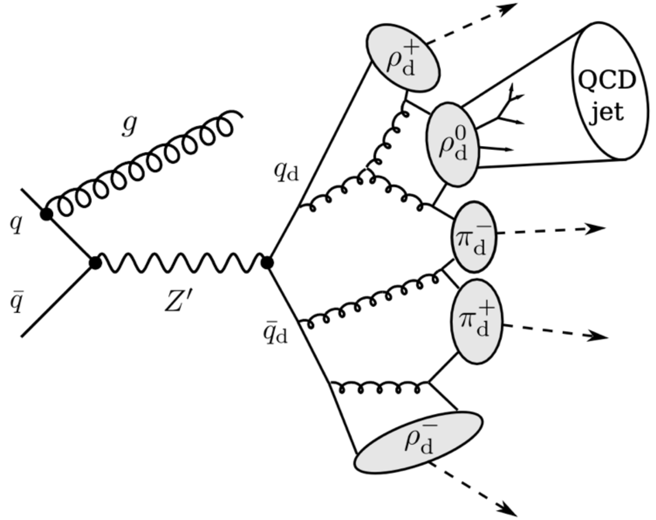


Danilo Meuser

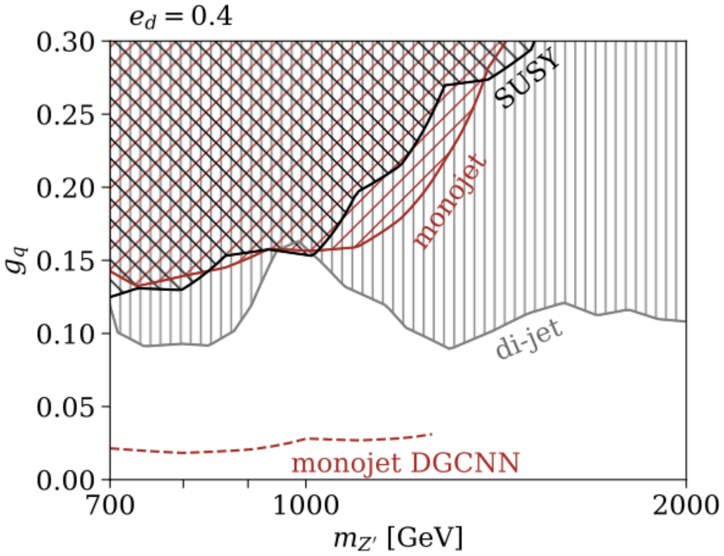
Terry Generet

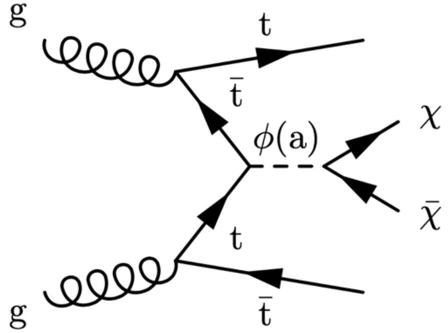
Scientific Highlights: New Physics

Dark quarks are produced via mediator

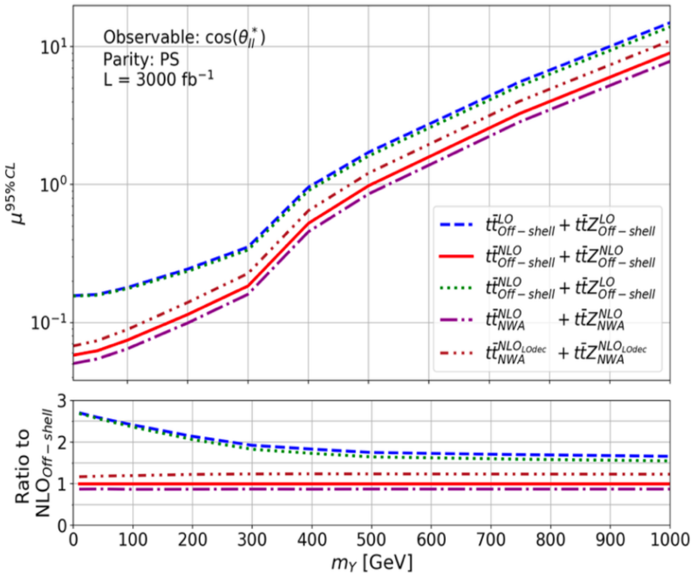


Dark quarks hadronize to dark hadrons

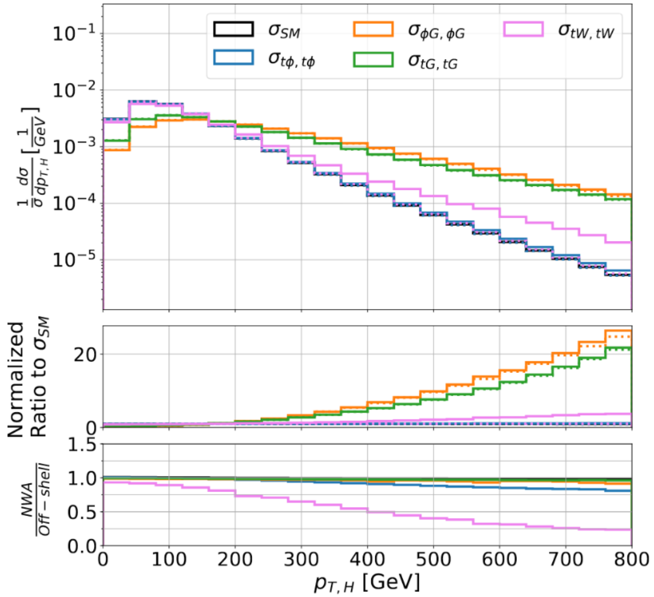




$pp \to t\bar{t} + DM/t\bar{t}/t\bar{t}Z(Z \to \nu_\ell \bar{\nu}_\ell)$



$pp \to t\bar{t}H$



$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d>4} \sum_i \frac{\mathcal{C}_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Elias Bernreuther

Jonathan Hermann

Networks

- Embedding in CMS
- Strong connection to DESY
- Association with a Collaborative Research Centre

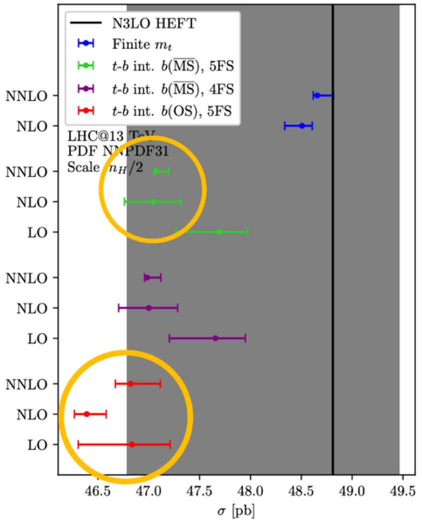
Collaborative Research Center TRR 257

P H

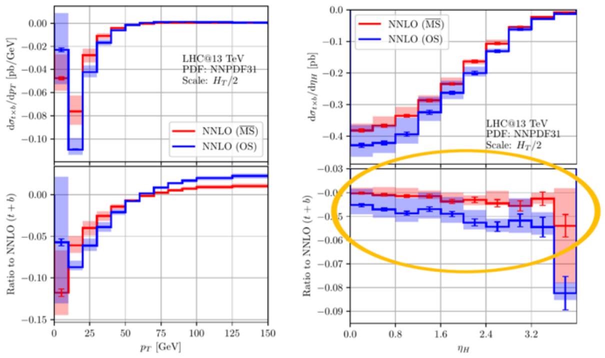
Particle Physics Phenomenology after the Higgs Discovery

Higgs production: closing a leading theory uncertainty

NNLO top-bottom interference sharpens gluon-fusion inputs for precision Higgs physics



Inclusive σ(pp→H): finite-mass and interference effects



Differential p_T and rapidity effects

+ 15.33 pb	(+33.17%)	(LO rHTL)
+ 19.99 pb	(+43.26%)	(NLO cor. rHTL)
+ 9.20 pb	(+19.91%)	(NNLO cor. rHTL)
+ 1.56 pb	(+3.38%)	(N^{3}LO cor. rHTL)
+ 0.14 pb	(+0.30%)	(N^{4}LO cor. rHTL in s.-v. approx.)
+ 2.02 pb	(+4.37%)	(NLO EW-QCD)
− 0.16 pb	(−0.35%)	(NNLO finite top-quark mass)
− 0.23 pb	(−0.50%)	(NLO top-charm interference)
+ 0.10 pb	(+0.22%)	(NLO pure bottom-quark effects)
− 1.74 pb	(−3.77%)	(NNLO top-bottom interference)
46.21 pb	(100%).	

$$\boxed{\sigma_{pp\to HX}(13\ \text{TeV}) = 46.21^{+0.35}_{-1.76}\ (\text{theory})\ ^{+1.52}_{-1.50}\ (\text{PDF} + \alpha_s)\ \text{pb.}}$$

Final 13 TeV theory budget

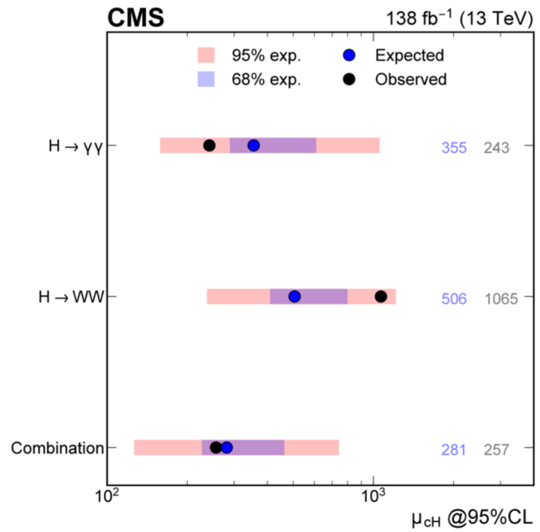
- Computed the NNLO top-bottom interference contribution to inclusive gg → H and differential spectra
- Scale uncertainties are significantly reduced
- The MS mass scheme gives better perturbative convergence than OS
- 4FS and 5FS agree, and the rapidity spectra are new results for the analysis

Key result: top-bottom interference shifts the 13 TeV Higgs-production budget by -1.74 pb (-3.77%)

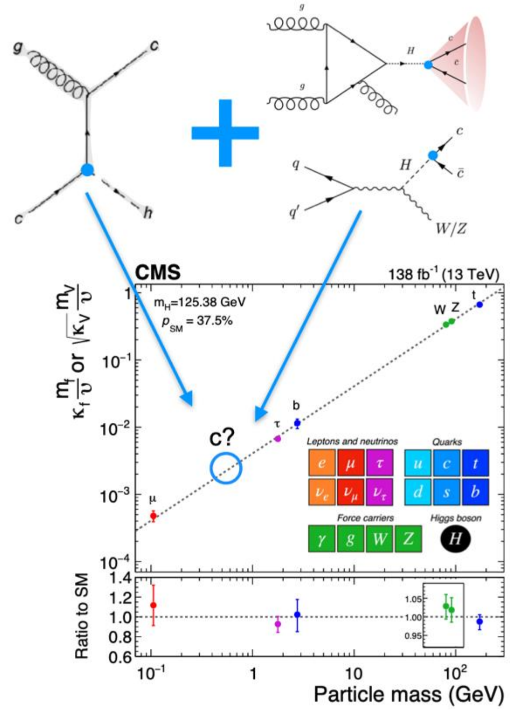
Source: Tom Schellenberger, Quark-Mass Effects in Higgs Production

Charm Yukawa: direct cH searches become competitive

Associated cH production gives an independent handle on the least-constrained Yukawa coupling



Combination of cH(H→γγ) and cH(H→WW)



Direct cH contribution to the κc program

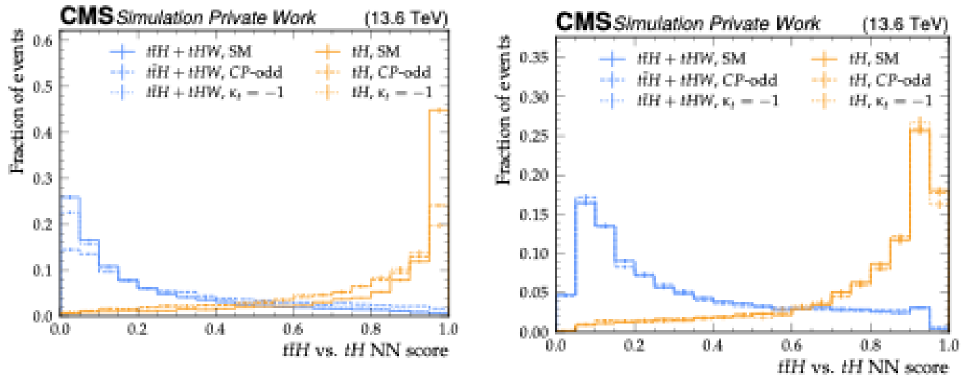
- First cH (H→ WW) search using H → WW→ eμνν and charm-tagged jets
- A 2D BDT and control-region likelihood fit separate cH from ttbar and Higgs-background components
- Combined with cH (H → γγ), the analysis delivers the strongest cH-based κc constraint at the LHC

Key result: Most stringent constraint on $|\kappa_c|$ using cH production @ LHC
$|\kappa_c|$ < 47 (51) observed (expected) @ 95% CL

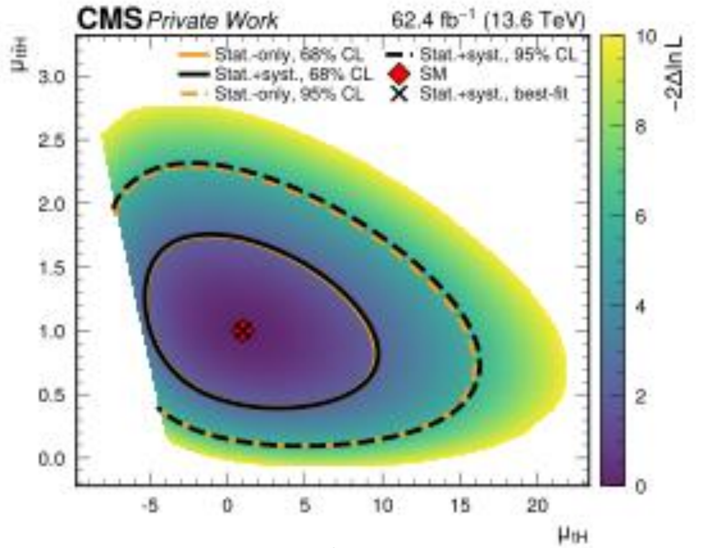
Source: Ming-Yan Lee, Search for a Higgs boson produced in association with a charm quark (cH)

Top Yukawa CP: Run 3 ttH/tH in H → γγ

A fiducial cross-section measurement designed to stay reinterpretable for anomalous CP structure



Classifier output before and after CP-decorrelation



Expected 2D rate-parameter scan for ttH and tHq

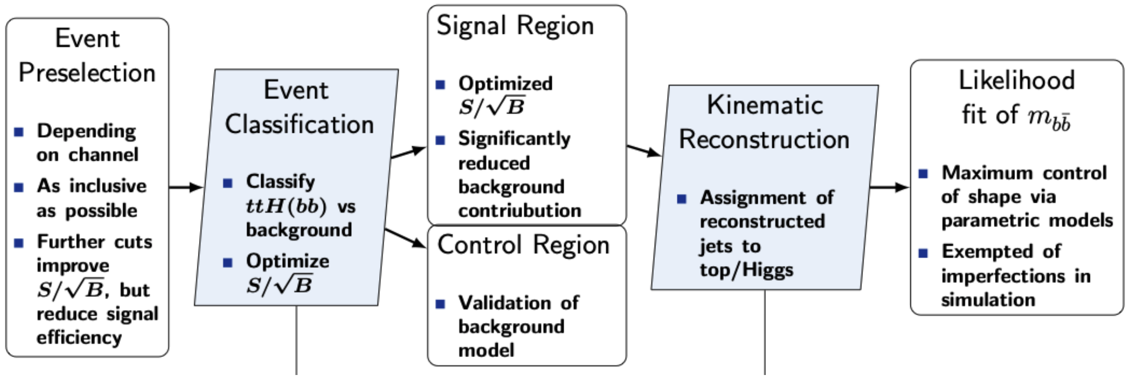
- Uses 2022+2023 CMS Run 3 data at 13.6 TeV, about 62 fb^{-1}
- Adds a hadronic tH channel in H → γγ for the first time in a CMS analysis
- Adversarial ML decorrelation reduces classifier dependence on CP states and improves reinterpretability

Key result: expected ttH+tHW sensitivity of 2.8σ and a tHq 95% CL upper limit of 10.2 × SM

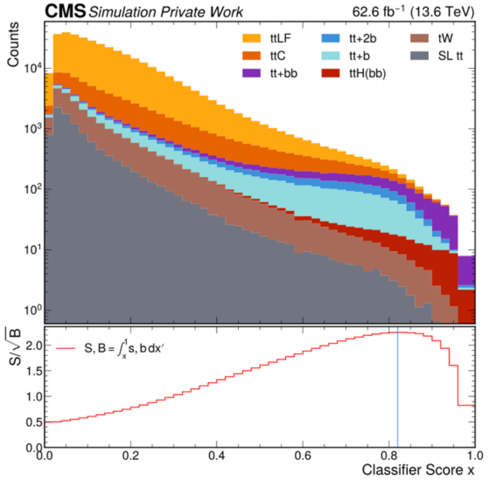
Source: Florian Mausolf, ttH/tH cross sections and CP properties

ttH(bb): Run 3 strategy in the dilepton channel

A physics-motivated mbb fit is paired with modern ML classification and jet assignment



Adapted Analysis Strategy from VBF



SPANet signal-background classification

- H → bb has the largest branching fraction, but tt+bb is an irreducible background around ten times the ttH rate
- **SPANet** exploits event symmetries and performs classification plus jet assignment in the same model
- An analytic unbinned fit to mbb aims to reduce dependence on simulated background shapes.

Key result: SPANet reaches AUC ≈ 0.86, with an optimal signal-region score cut around 0.83

Source: Philipp Nattland, Analysis strategy for ttH(bb) in Run 3 with the dileptonic channel

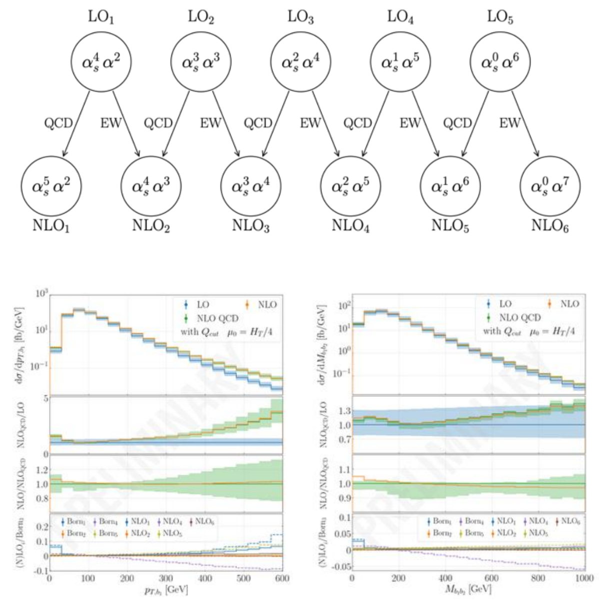
Off-shell ttbar in ℓ+jets: complete NLO precision

Full QCD+EW treatment reaches the high-statistics semi-leptonic top channel

		σ_i [pb]	Ratio to Born$_3$
Born$_1$	$\mathcal{O}(\alpha_s^4\alpha^2)$	0.069(1)	0.44%
Born$_2$	$\mathcal{O}(\alpha_s^3\alpha^3)$	0.00012(5)	0.00%
Born$_3$	$\mathcal{O}(\alpha_s^2\alpha^4)$	15.632(2)	100.00%
Born$_4$	$\mathcal{O}(\alpha_s^1\alpha^5)$	0.06678(7)	0.43%
Born$_5$	$\mathcal{O}(\alpha_s^0\alpha^6)$	0.04839(5)	0.31%
NLO$_1$	$\mathcal{O}(\alpha_s^5\alpha^2)$	+ 0.072(2)	+ 0.46%
NLO$_2$	$\mathcal{O}(\alpha_s^4\alpha^3)$	− 0.0011(2)	− 0.01%
NLO$_3$	$\mathcal{O}(\alpha_s^3\alpha^4)$	− 0.95(1)	− 6.10%
NLO$_4$	$\mathcal{O}(\alpha_s^2\alpha^5)$	+ 0.056(1)	+ 0.36%
NLO$_5$	$\mathcal{O}(\alpha_s^1\alpha^6)$	+ 0.0932(3)	+ 0.60%
NLO$_6$	$\mathcal{O}(\alpha_s^0\alpha^7)$	+ 0.001142(9)	+ 0.01%
LO		$13.6207(9)^{+30.7\%}_{-22.0\%}$	0.871
Born		$15.817(2)^{+30.7\%}_{-22.0\%}$	1.012
NLO$_{QCD}$		$14.86(1)^{+1.4\%}_{-6.0\%}$	0.951
NLO		$15.08(1)^{+1.5\%}_{-5.6\%}$	0.965

NLO$_{QCD}$: Born$_1$ + ... + Born$_5$ + NLO$_3$

Integrated fiducial cross sections with W-mass window



Subleading NLO effects in tails of distributions

- First complete NLO QCD+EW calculation including all Born channels for pp → ℓvbbjj
- IR-safety issues from photons and jet definitions are handled with dedicated conversion and fragmentation functions
- Differential tails show EW Sudakov effects of O(-10%) and up to 14% NLO vs NLO$_{QCD}$ differences

HELAC-NLO framework

All resonant and non-resonant diagrams, photon-induced channels, fragmentation functions, and photon-to-jet conversion functions are consistently included

Key result: with $|m_{jj} - m_W| < 20$ GeV, $\sigma^{NLO} = 15.08$ pb and the scale uncertainty is +1.5% and -5.6%

Source: Leon Mans, Complete NLO corrections to off-shell tt production in the ℓ + j channel

Status and plans

- Focus shifted towards precision Standard Model physics and the HL-LHC
- Analyses of Run III data incoming
- Great emphasis on Machine Learning