Precision observables for new physics searches

Arnd Behring

Institut für Theoretische Teilchenphysik (TTP)
Karlsruher Institut für Technologie

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Status of new physics searches today

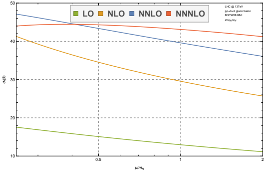
- No direct evidence for new physics at the LHC (so far)
- Use available data to maximum extent possible
- Use precision calculations to search for / constrain new physics

Goals of this talk

- Show progress in precision calculations for the LHC
- Highlight examples with connection to BSM searches
- Discuss future challenges for higher-order calculations

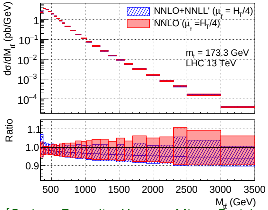
Precision calculations for the LHC

$gg \to h$



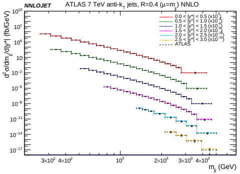
[Anastasiou, Duhr, Dulat, Herzog, Mistlberger '15]

$pp \to t\bar{t}$



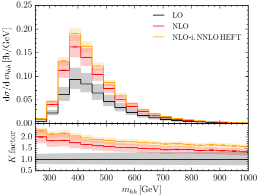
[Czakon, Ferroglia, Heymes, Mitov, Pecjak, Scott, Wang, Yang '18]

$pp \to jj$



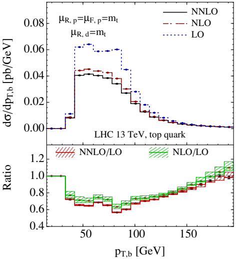
[Currie, Gehrmann-De Ridder, Gehrmann, Glover, Huss, Pires '17]

$pp \to hh$



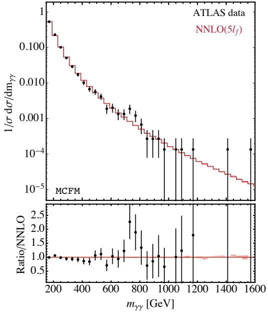
[Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke '16]

$pp \to tX \to b\ell\nu X$



[Berger, Gao, Yuan, Zhu '16]

$pp \to \gamma\gamma$

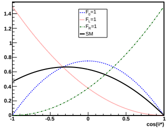


[Campbell, Ellis, Li, Williams '16]

New physics searches using precision calculations

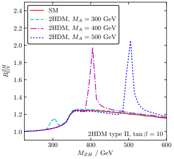
- Precision calculations become increasingly important for new physics searches
- New physics searches become possible that would not be possible otherwise

W helicity fractions



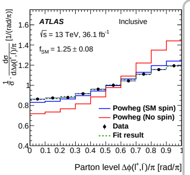
$\rightarrow$ tWb vertex

ZH/WH



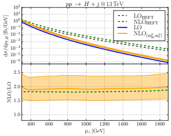
$\rightarrow$ BSM in ZH

$t\bar{t}$ spin correlations



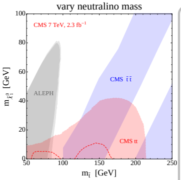
$\rightarrow$ stealth stops & CMDM operator

Higgs @ high p_T



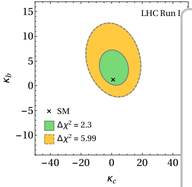
$\rightarrow$ ggH vertex: y_t vs. c_g

$t\bar{t}$ cross-section



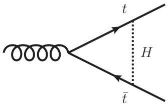
$\rightarrow$ stealth stops

Higgs @ low p_T



$\rightarrow$ light Yukawas

$m_{t\bar{t}}$ distributions



$\rightarrow$ top Yukawa

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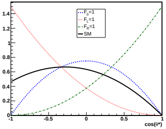

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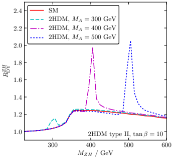

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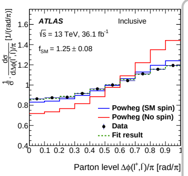

$\rightarrow$ stealth stops & CMDM operator

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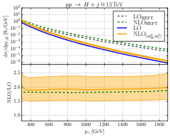

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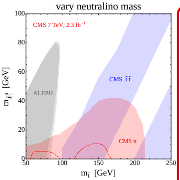

$\rightarrow$ stealth stops

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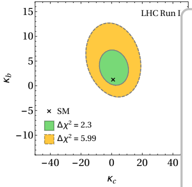

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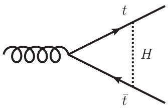


$\rightarrow$ top Yukawa

...

Top decay: W helicity fractions

Observable

- Top decay: Differential distribution of charged lepton/d-type quark

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta^*} = \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{4}(\sin\theta^*)^2 F_0 + \frac{3}{8}(1+\cos\theta^*)^2 F_R$$

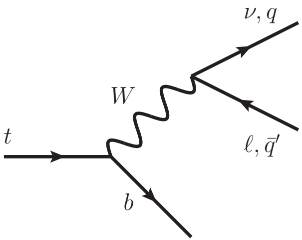
- $\cos\theta^*$: Angle between charged lepton/d-type quark and reversed direction of b quark in W rest frame

W helicity fractions

- W is massive vector boson
  $\Rightarrow$ 3 polarisations: L, R & longitudinal

$$F_{L,R,0} = \frac{\Gamma_{L,R,0}}{\Gamma}$$

- Measures production mode of W bosons in top decays

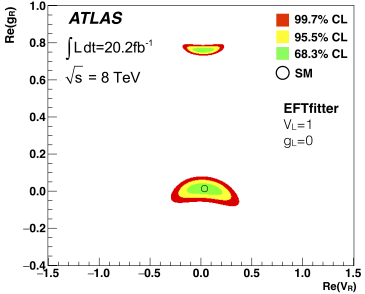


Relevance for BSM searches

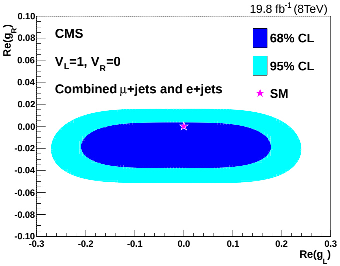
- Sensitive to structure of tWb vertex, e.g.,

$$\mathcal{L}_{tWb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW^-_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}(g_L P_L + g_R P_R)tW^-_{\mu} + \text{h.c.}$$

- Longitudinal W polarisation related to Goldstone bosons $\Rightarrow$ sensitive to modified Higgs sector
- Used by ATLAS and CMS to set limits on anomalous couplings



[ATLAS '16]

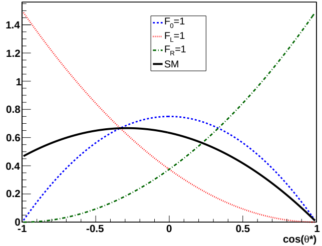


[CMS '16]

Experimental situation

Use angular distribution of W decay products to measure helicity of W boson

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{4}(\sin\theta^*)^2 F_0 + \frac{3}{8}(1+\cos\theta^*)^2 F_R$$



[CMS '16]

	F_0	F_L	F_R
ATLAS [ATLAS '17]	0.709 ± 0.019	0.299 ± 0.015	-0.008 ± 0.014
NNLO QCD + NLO EW	0.687 ± 0.005	0.311 ± 0.005	0.0017 ± 0.0001

[Czarnecki, Körner, Piclum '10]

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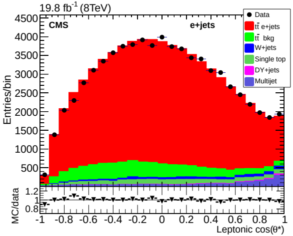

[CMS '16]

Measurement

- $t\bar{t}$ production in lepton+jets channel
- Reconstruct $t\bar{t}$ system
  $\Rightarrow$ associate b jet correctly
- Extrapolate fiducial to inclusive measurement
- Fit distribution to extract $F_{L,R,0}$

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[Czarnecki, Körner, Piclum '10]

Precision predictions

W helicity fractions

- Measured very precisely (percent level accuracy)
- Perturbative corrections converge well [Czarnecki, Körner, Piclum '10]

  e.g., $F_L = 0.3032 \cdot (1_{\mathrm{LO}} + 2.15\%_{\mathrm{NLO}} + 0.70\%_{\mathrm{NNLO}})$
- Question: How close is what is calculated to what is being measured?
  - Decay in isolation:
    Impossible to compute an observable following a set-up similar to experimental one
  - No realistic selection criteria, no contamination from the production, no combinatorics

  $\Rightarrow$ Experiments have to extrapolate from fiducial to inclusive measurement

Recent developments

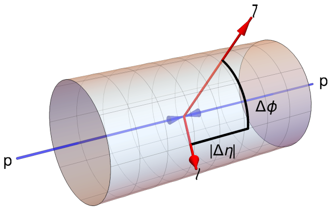
- Progress in fixed-order calculations:
  $\Rightarrow$ $t\bar{t}$ production with decays at NNLO QCD
- More realistic description of final states

$\rightarrow$ Moves interface between theory and experiment closer to experimental side

Spin correlations in $t\bar{t}$ production

Observable

- $t\bar{t}$ production in dilepton channel
- Tops and anti-tops from $t\bar{t}$ essentially unpolarised, but spins highly correlated
- Differential distributions of lepton kinematics in lab frame
  - Lepton azimuthal opening angle $\Delta\phi(\ell, \bar{\ell})$
  - Lepton rapidity difference $|\Delta\eta(\ell, \bar{\ell})|$



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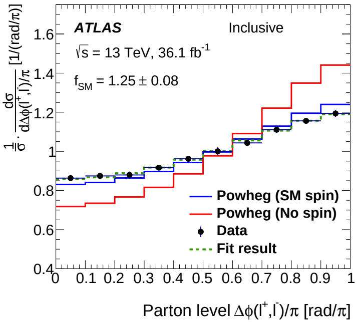


[ATLAS '19]

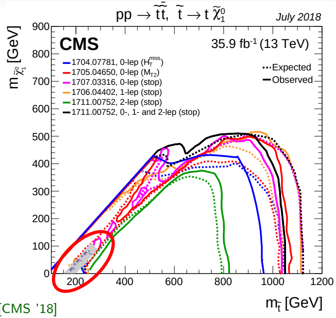
Competing effects

- Boosts of top quarks enhance anti-parallel leptons
- Spin correlations counteract and enhance parallel leptons

New physics searches with $t\bar{t}$ spin correlations

Example: Stealth stops

- Top squarks can be light in the MSSM
- Light stops have mostly been excluded by direct searches
- But if $m_{\tilde{t}} \approx m_t$: Difficult to distinguish from SM tops → "Stealth stops"
- Squarks are scalar particles
  ⇒ Use spin correlations to search for stealth tops



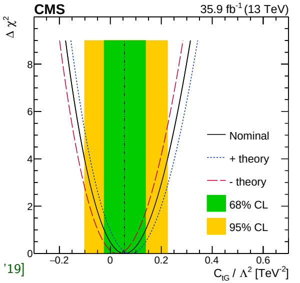
[CMS '18]

Example: Top quark CMDM operator

- Chromomagnetic dipole moment operator

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^a t)\tilde{\phi} G^a_{\mu\nu}$$

- Modifies $t\bar{t}$ spin correlations
- Can be constrained using these observables



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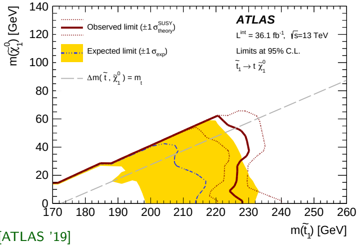

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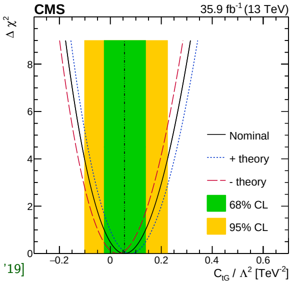
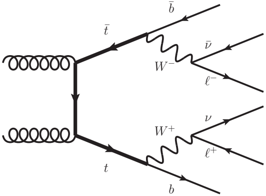


[CMS '19]

NNLO predictions for $t\bar{t}$ spin correlations

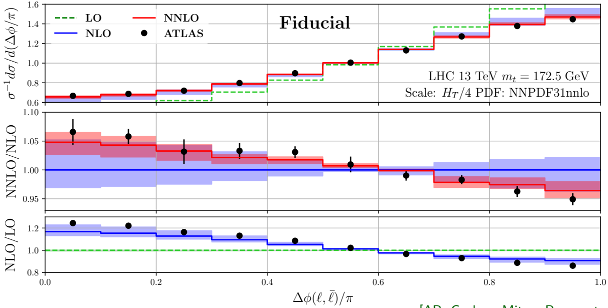
Why has this not been possible before?

- Complicated process with complex final state
  $\Rightarrow$ Use narrow width approximation (NWA) to factorise production and decay
- Virtual corrections: Needs polarised 2-loop ME
  - Decay: Available since $\sim$ 2008 [Bonciani, Ferroglia '08] [Asatrian, Greub, Pecjak '08] [Beneke, Huber, Li '09]
  - Production: Recently completed [Chen, Czakon, Poncelet '18]
- Real radiation: Needs efficient subtraction for many IR limits
  $\Rightarrow$ Extension of sector improved residue subtraction scheme for NWA



$\rightarrow$ Payoff: NNLO QCD predictions for realistic final states

Dilepton $\Delta\phi(\ell,\bar{\ell})$ distributions at NNLO



[AB, Czakon, Mitov, Papanastasiou, Poncelet '19]

- Agreement between data and theory improves at NNLO
- Higher-order corrections ($\rightarrow$ additional radiation) can mimic spin-correlations

$\rightarrow$ Precision calculations are important to model observables accurately

Higgs p_T distribution

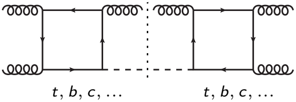
Motivation

- Charm Yukawa coupling y_c is mostly unconstrained so far, $\kappa_c = \frac{y_c}{y_c^{\text{SM}}}$
- y_c is difficult to measure directly @ LHC

Idea: Detect/place limits on deviations of y_Q

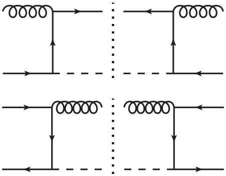
Use p_T spectrum of Higgs at $m_c \ll p_T \ll m_h$ [Bishara, Haisch, Monni, Re '17] [Soreq, Zhu, Zupan '16]

- $gg \to hg$:
  $d\sigma = d\sigma_{tt} + d\sigma_{tQ} + d\sigma_{QQ} + \ldots$



- $d\sigma_{tQ}$: $\kappa_Q \frac{m_Q^2}{m_h^2} \ln^2\left(\frac{p_\perp^2}{m_Q^2}\right)$ terms
  $\Rightarrow$ enhance b and c contributions at low p_T
- Most relevant for $\kappa_Q \lesssim 10$

- $gQ \to hQ$ and $Q\bar{Q} \to hg$:



- Scales like $\kappa_Q^2 \frac{m_Q^2}{m_h^2}$
- But suppressed by PDFs
- Most relevant for $\kappa_Q \gtrsim 10$

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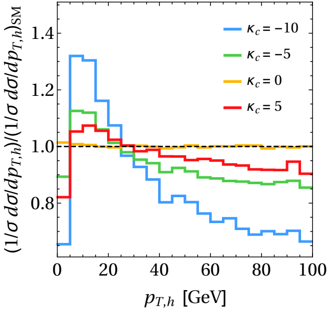
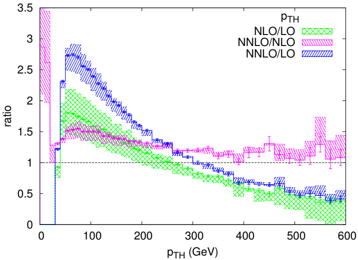


[Bishara, Haisch, Monni, Re '17]

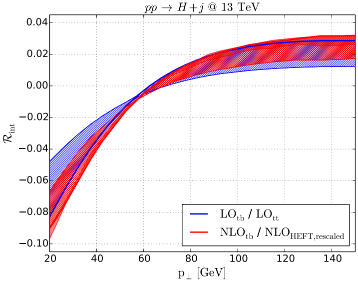
- Higgs p_T spectrum receives large perturbative corrections
- Charm contribution is small compared to corrections from top loop

Precision predictions

- Top-loop contributions known
  - to NNLO + N^{3}LL with $m_t \to \infty$ (HEFT)
  - to NLO with full m_t dependence
- Top-bottom & top-charm interference known
  - to LO with full m_Q
  - to NLO with $m_Q \to 0$
- Contributions from b and c quarks are $O(1-5\%)$ effects in the SM



[Chen, Gehrmann, Glover, Jaquier '14]

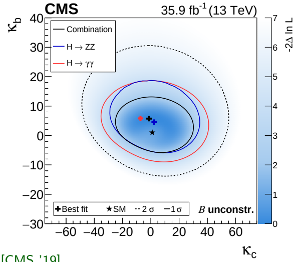


[Lindert, Melnikov, Tancredi, Wever '17]

$\to$ Requires precision calculations since perturbative corrections are large

Experimental situation

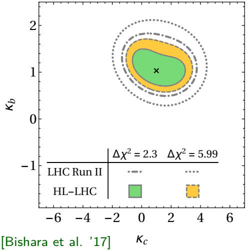
Current situation



[CMS '19]

- Based on NLO QCD calculation
- Corresponds to LO for top-charm interference
- Constrains $-33 < \kappa_c < 38$ at 95% CL

Projections for Run II and HL-LHC



[Bishara et al. '17]

- Assumptions on theoretical uncertainties for
  - Run II: $\pm 5\%$
  - HL-LHC: $\pm 2.5\%$
- Requires at least NLO top-charm interference
- Would constrain charm Yukawa coupling to
  - Run II: $-1.4 < \kappa_c < 3.8$
  - HL-LHC: $-0.6 < \kappa_c < 3.0$

Challenges for the future

Recent developments allow us to think about new challenging opportunities

- Mixed QCD-EW corrections to $Z + j$ at high p_T
    - Background to dark matter studies at LHC
    - Amplitudes with nearly massless EW gauge bosons
      $\rightarrow$ Progress from expansion techniques?
- $gg \rightarrow ZH$
    - Search for new physics in top loop
    - Evaluation of integrals with different masses
      $\rightarrow$ Progress from numerical techniques?
- tth production
    - Measure top Yukawa coupling precisely
    - Many masses/scales
      $\rightarrow$ challenging integral reductions
      $\rightarrow$ evaluation of very complicated integrals
- ttZ production
    - Probe top gauge couplings
    - Similar challenges as for tth

Conclusions

- Remarkable progress in higher-order corrections in recent years
- More realistic final states and fiducial calculations become possible
- Precision calculations enable us to make the most of (HL-)LHC data
- New physics searches profit from increased precision
  $\rightarrow$ New opportunities for measurements that would be impossible otherwise
- Communication with different communities (experiment, EFT, model building, mathematics, ...) will be helpful to guide and inspire progress