Theoretical aspects of associated production of W, Z, γ, H in pair- and single-production of top quarks

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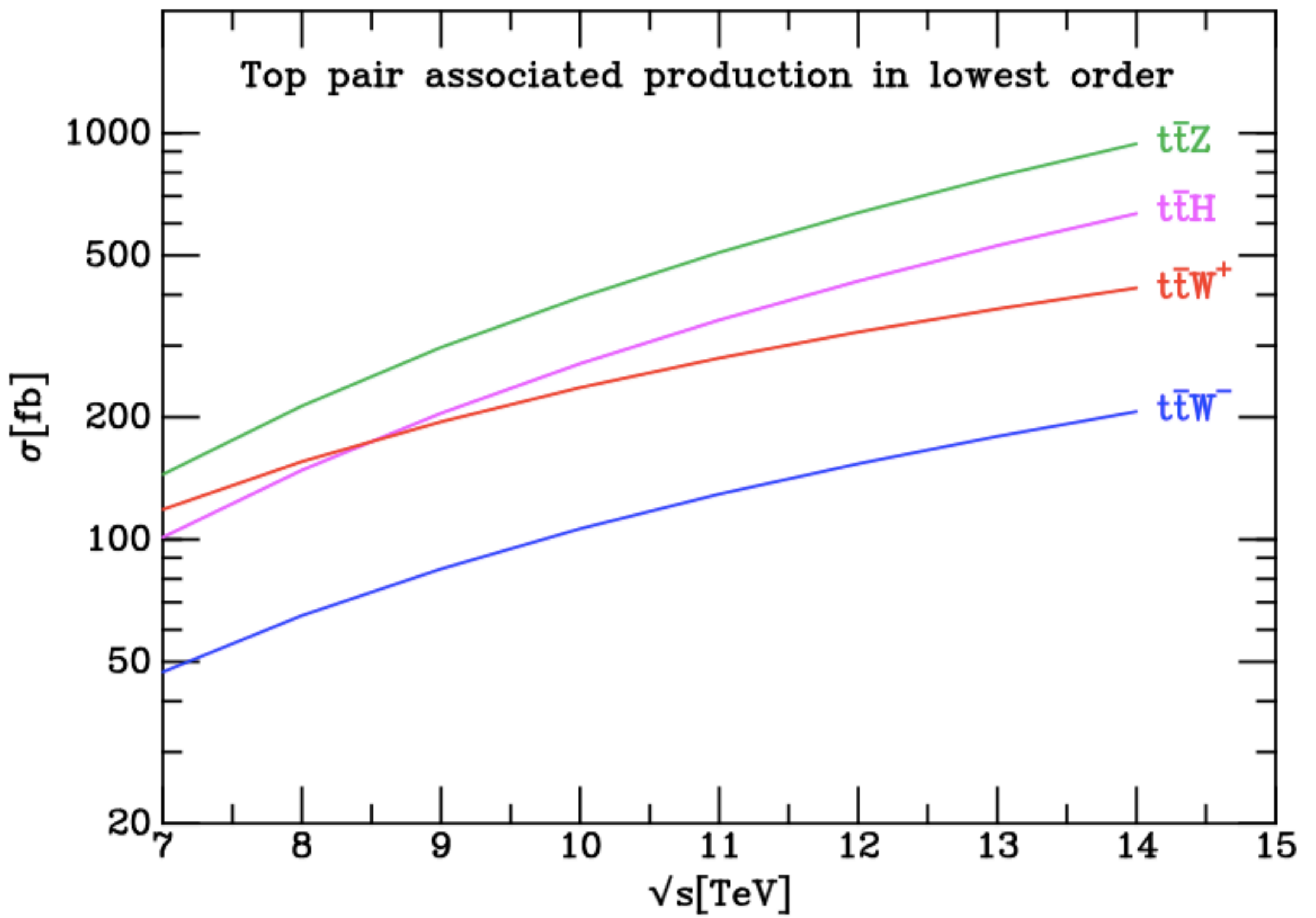
Top quark physics at the precision frontier, 16-17 January, 2018, Fermilab LPC

Overview

- Cross-sections for associated production about a factor of a thousand smaller than for regular top pairs.
- Easily mimic NP signals (top, W, Z, missing E_T, boosted configs, …).
  - important to establish precision tests of Standard Model to validate and improve generators.
- Probe coupling of top quarks to Higgs (and Z, photon) at tree level.



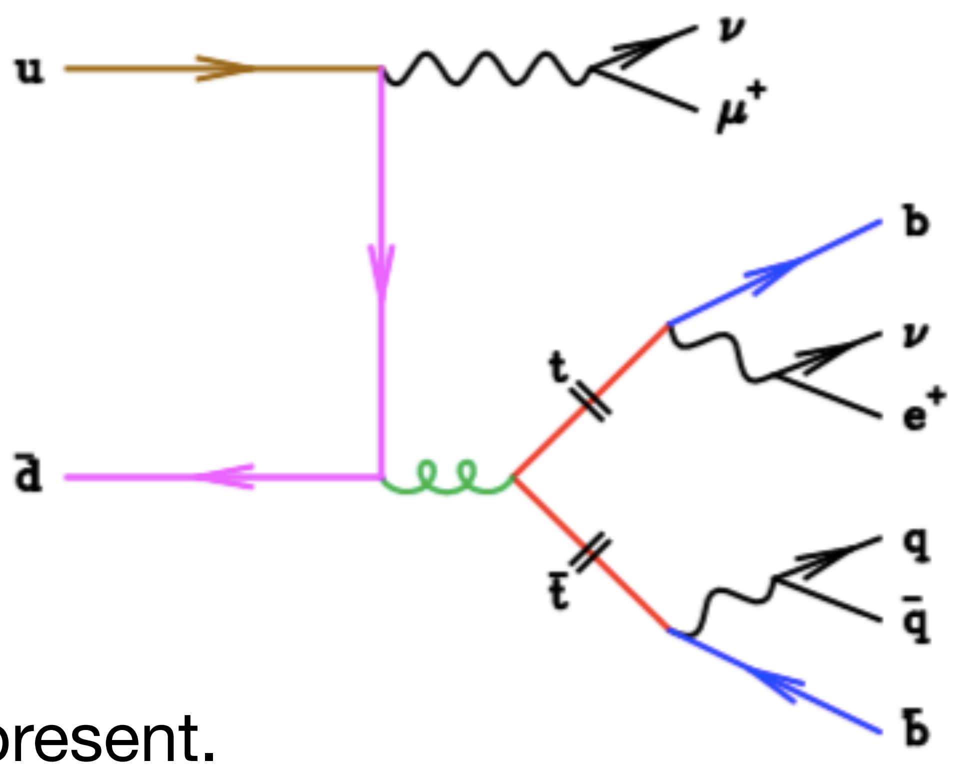
ttV considerations

- Recent theoretical calculations are able to provide predictions up to NLO, including PS, and full treatment of top-quark decay at NLO.

- Intermediate top quarks are treated as on-shell particles.

- More complete treatments, including diagrams with the same final state but not intermediate top quark (a la top-pair) not always available.
  - should not be a limiting factor at present.

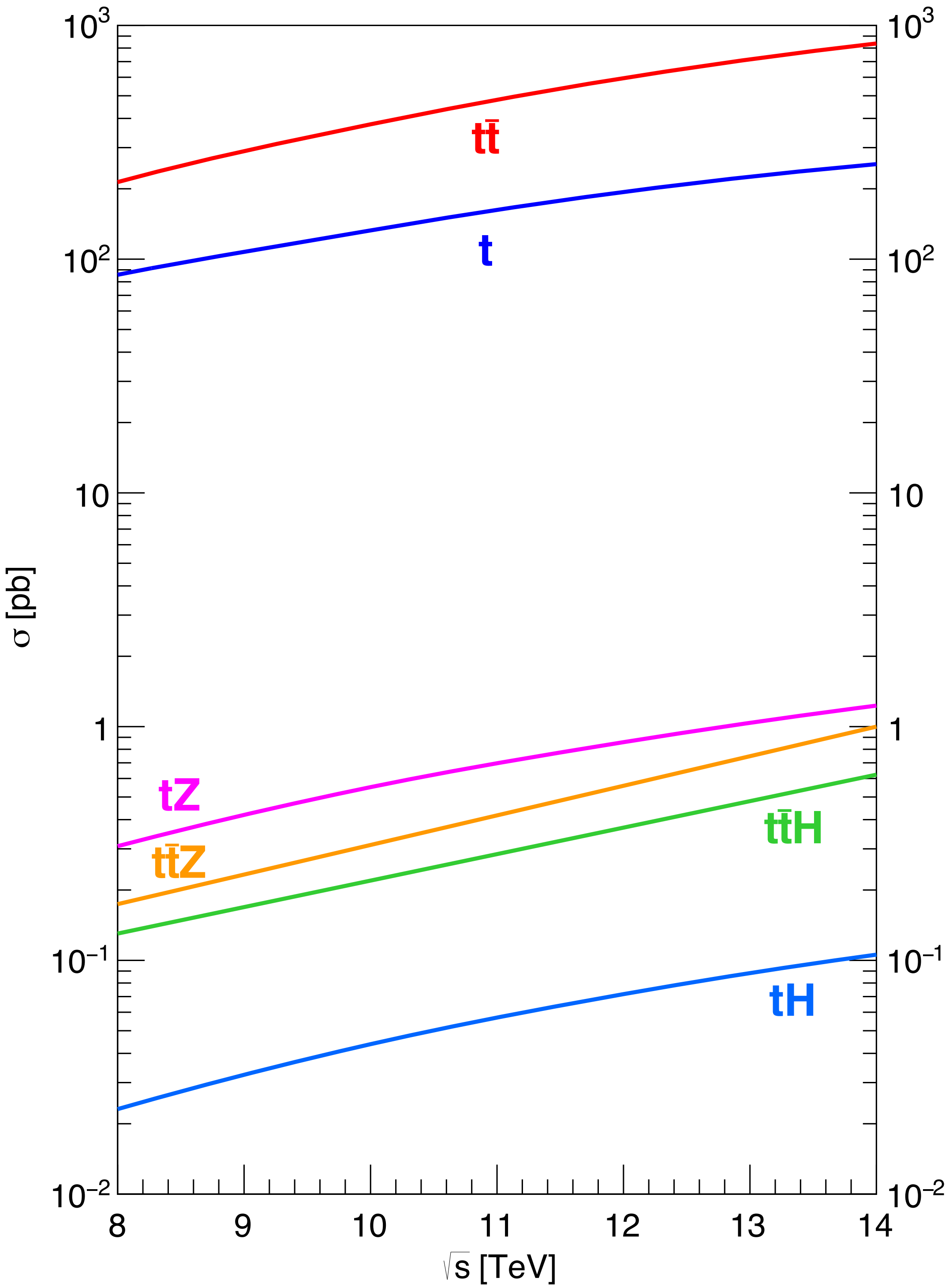
Example: ttW



- Radiation (QCD and QED) in decay can be important.

Top-pair vs. single top

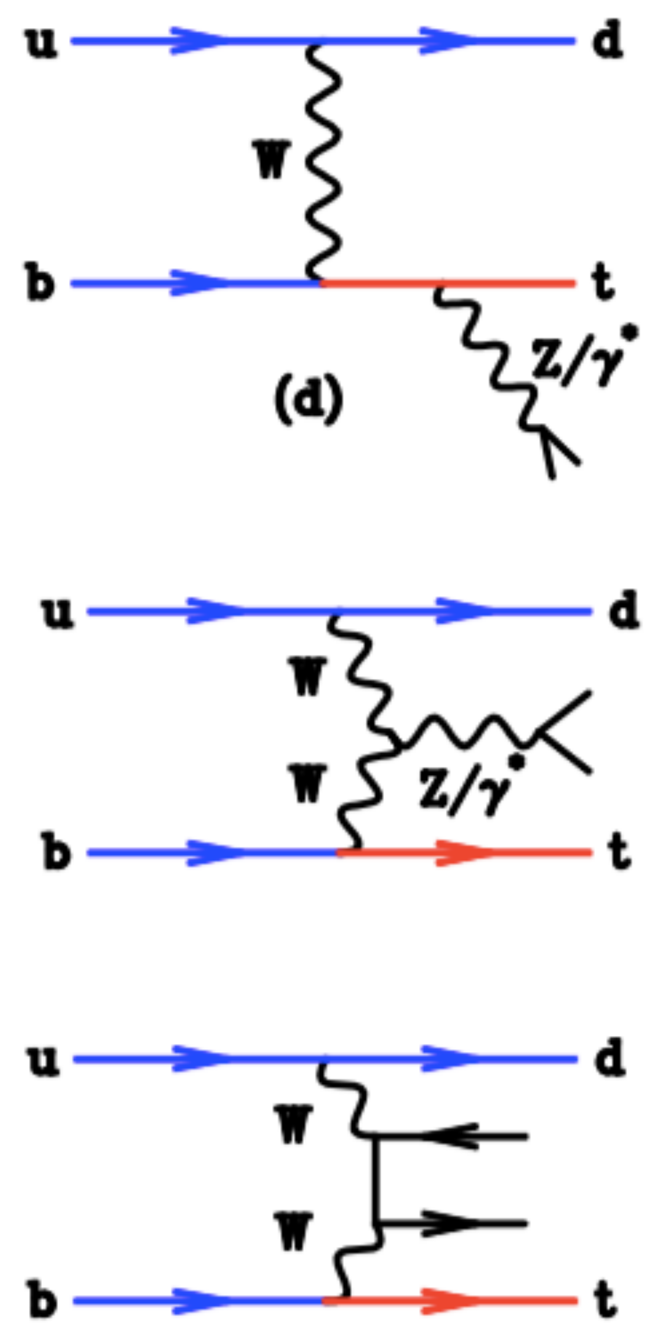
- Standard top production processes have a hierarchy caused by strong/weak nature of mediator.
- This advantage is removed when considering associated Z production.
    - single-top mode equally important.
- Associated Higgs production (unfortunately) retains similar suppression of single-top process.
- ttZ a good proxy for ttH
    - (SM) tH much harder than tZ.



tV considerations

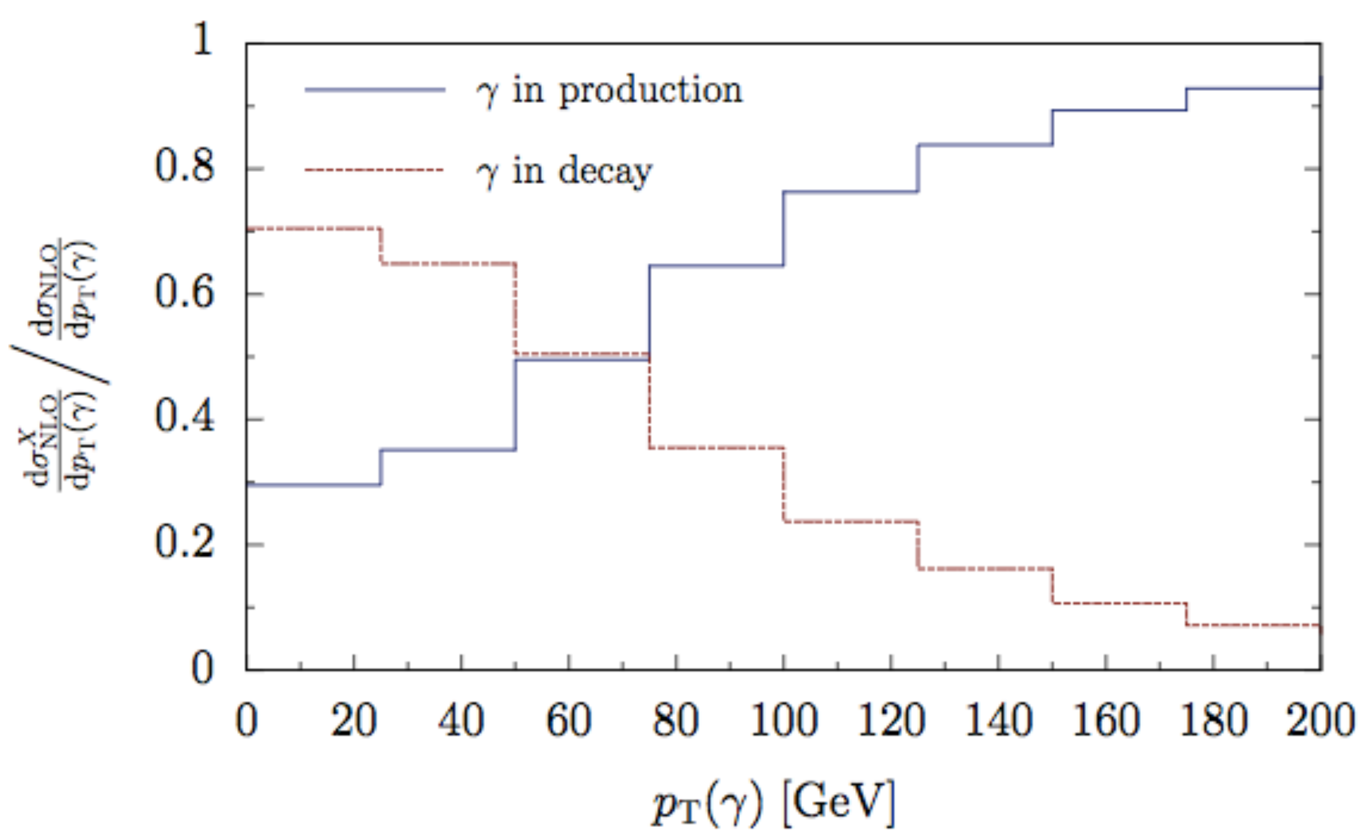
- Not FCNC (tZ) or charged Higgs (tH), but really *t*-channel single top plus extra boson (*s*-channel mode much smaller).
- Processes sensitive to b-PDF (5-flavor); could also perform 4-flavor calculation (explicit g→bb splitting), but usually 5FS.
    - c.f. similar considerations for normal single-top.
- Radiation from intermediate W-boson provides sensitivity to triple coupling.
- Non-resonant diagrams can also exist, important for off-shell contribution.

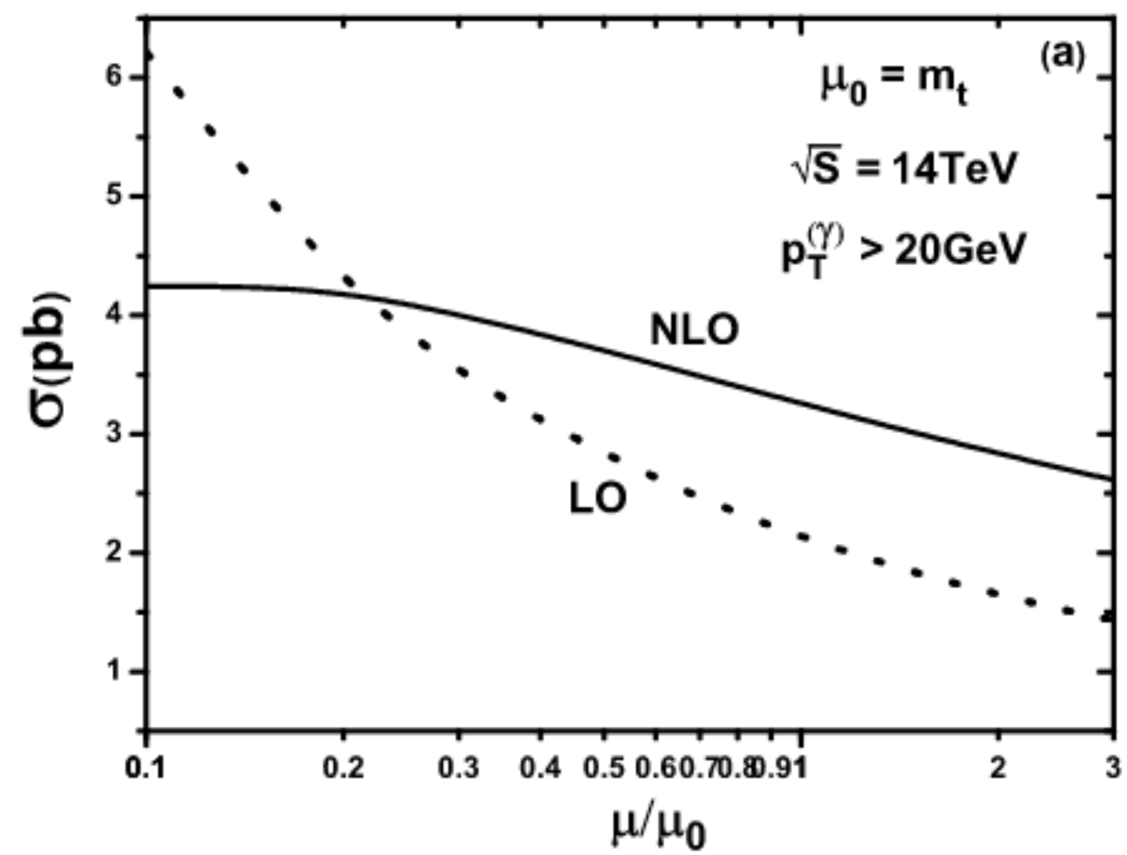
<u>Example: tZ</u>



tt+photon

- Large NLO corrections, known for a long time, starting with stable top quarks (Peng-Fei et al, 0907.1324).





- EW corrections known (Duan et al, 1612.00248), -2% for typical cuts.

- Realistic treatment must include radiation from top decay products — increases *K*-factor and non-trivial kinematic effects (Melnikov et al, 1102.1967).

Charge asymmetry

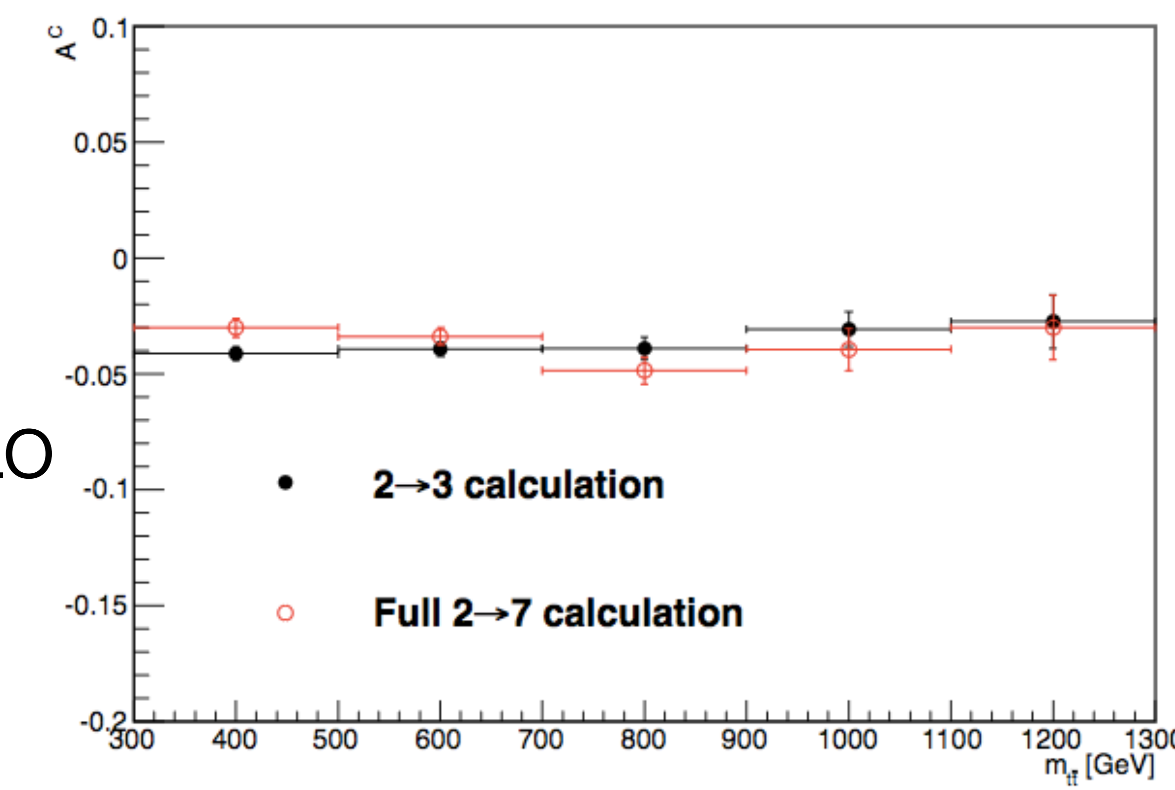
- Just like regular top production, define a charge asymmetry:

$$A_c = \frac{\sigma(|y_t| > |y_{\bar{t}}|) - \sigma(|y_t| < |y_{\bar{t}}|)}{\sigma(|y_t| > |y_{\bar{t}}|) + \sigma(|y_t| < |y_{\bar{t}}|)}$$

- In contrast to top-pairs, presence of photon generates an asymmetry at tree-level due to interference between initial- and final-state radiation.

- Significant reduction in asymmetry at NLO (Maltoni et al, 1507.05640).

13 TeV A_c [%]	$t\bar{t}\gamma$
LO	$-3.93^{+0.26}_{-0.23}\,^{+0.14}_{-0.11} \pm 0.03$
NLO	$-1.79^{+0.50}_{-0.39}\,^{+0.06}_{-0.09} \pm 0.06$



Aguilar-Saavedra et al, 1402.3598

Dipole contraints

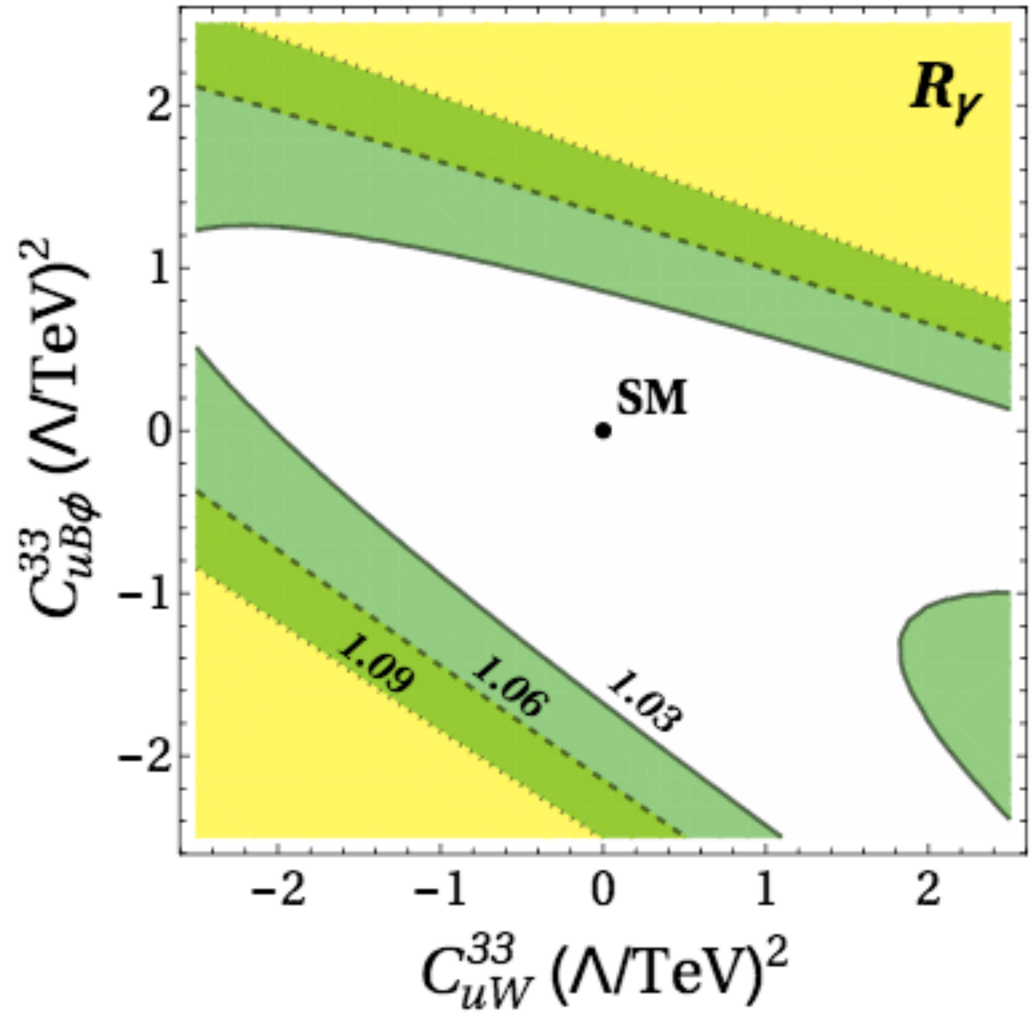
- Can constrain anomalous dipole moments of the top quark (zero at tree-level in SM, generated only through EW interactions).

- e.g. CP-conserving EFT (Schulze and Soreq, 1603.08911)

$$\mathcal{O}_{uW}^{33} = \left(\bar{q}_\mathrm{L}\sigma^{\mu\nu}\tau^I t_\mathrm{R}\right)\tilde{H}W_{\mu\nu}^I$$
$$\mathcal{O}_{dW}^{33} = \left(\bar{q}_\mathrm{L}\sigma^{\mu\nu}\tau^I b_\mathrm{R}\right)HW_{\mu\nu}^I$$
$$\mathcal{O}_{uB\phi}^{33} = \left(\bar{q}_\mathrm{L}\sigma^{\mu\nu}t_\mathrm{R}\right)\tilde{H}B_{\mu\nu},$$

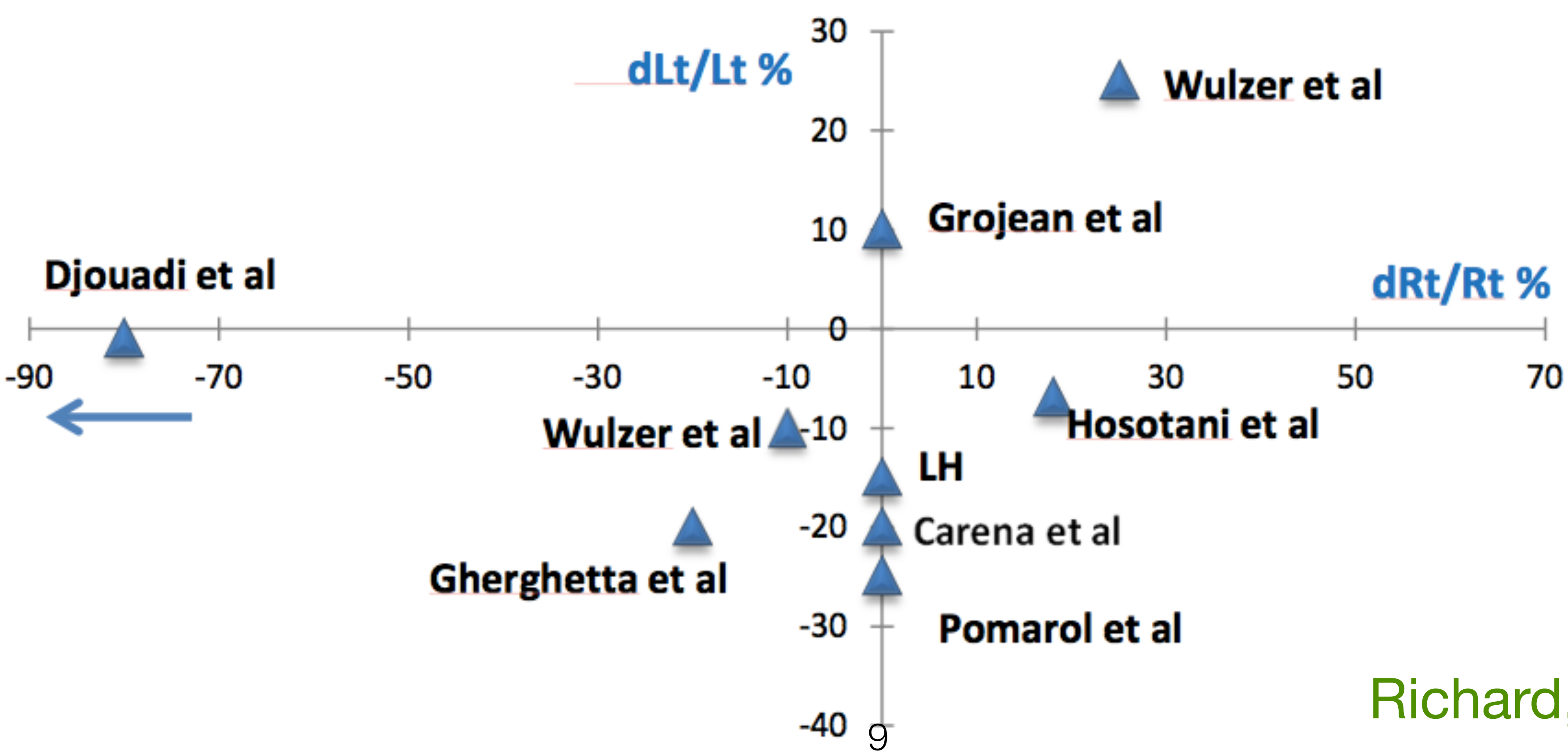
- Measure cross-section relative to top-pair production, ratio that is predicted to about 3%.

$$\mathcal{R}_\gamma^{\mathrm{SM}} \times 10^{-3} = \begin{cases} 11.4^{-0.7\%}_{+0.7\%} & \text{at LO,} \\ 12.6^{+3.1\%}_{-1.8\%} & \text{at NLO QCD} \end{cases}$$



ttZ

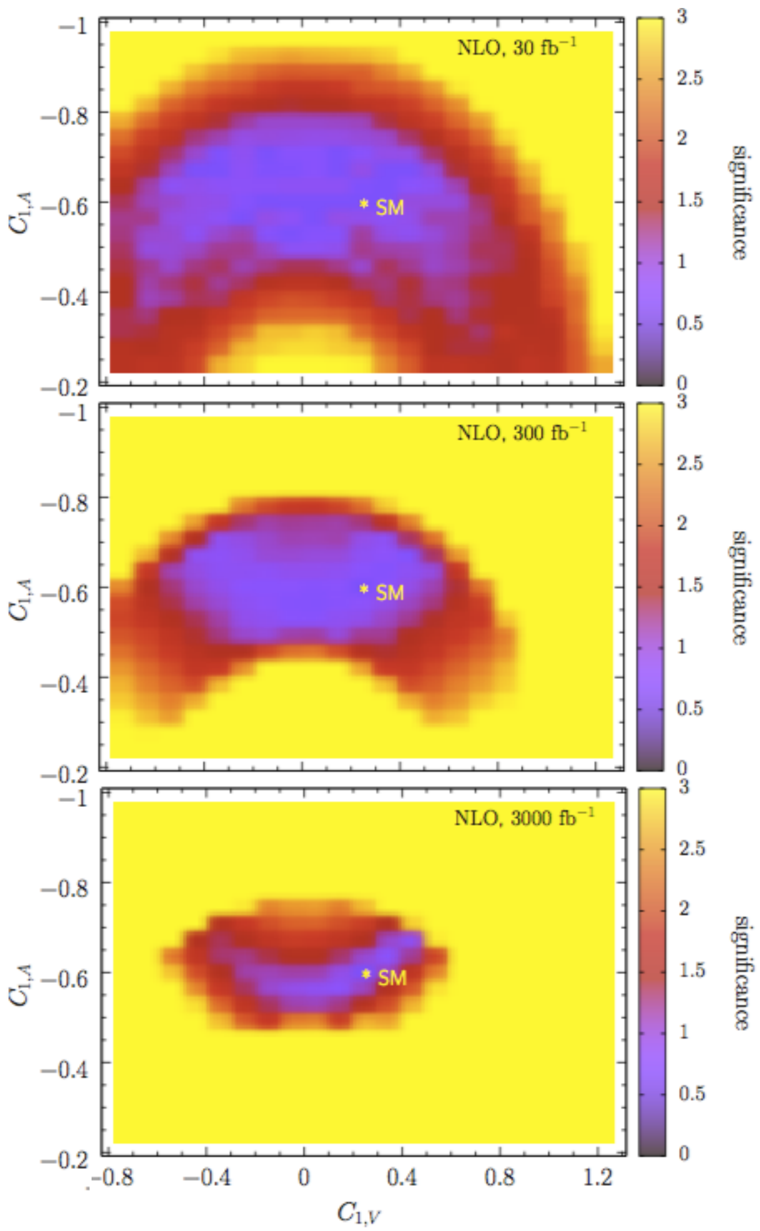
- Known through NLO QCD including decays (0804.2220, 1208.2665), NLO EW (1504.03446) and incorporating soft gluon effects up to NNLL (1702.00800).
- Source of multi-lepton events, background to ttH.
- Provides direct tree-level probe of top-Z coupling; in principle left- and right-handed couplings can vary significantly in models of NP.

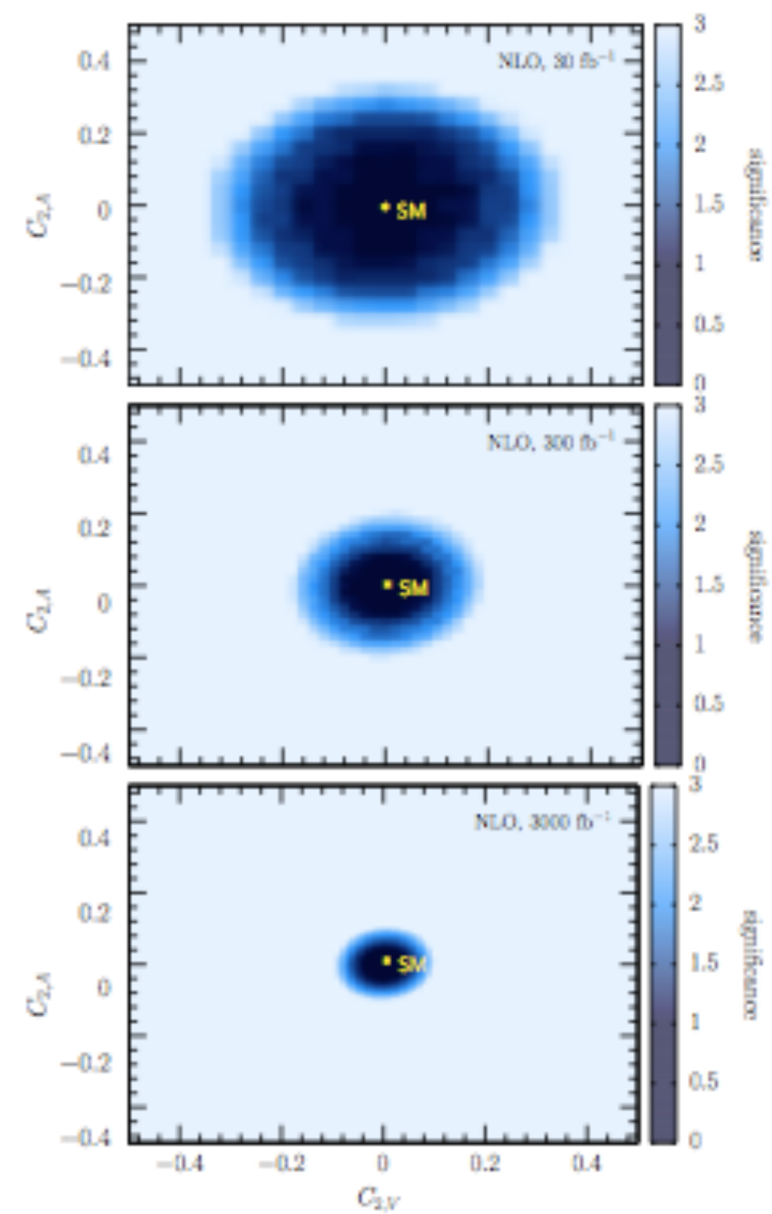


Richard, 2014

Potential for constraints

Rontsch and Schulze, 1501.05939





Run 2

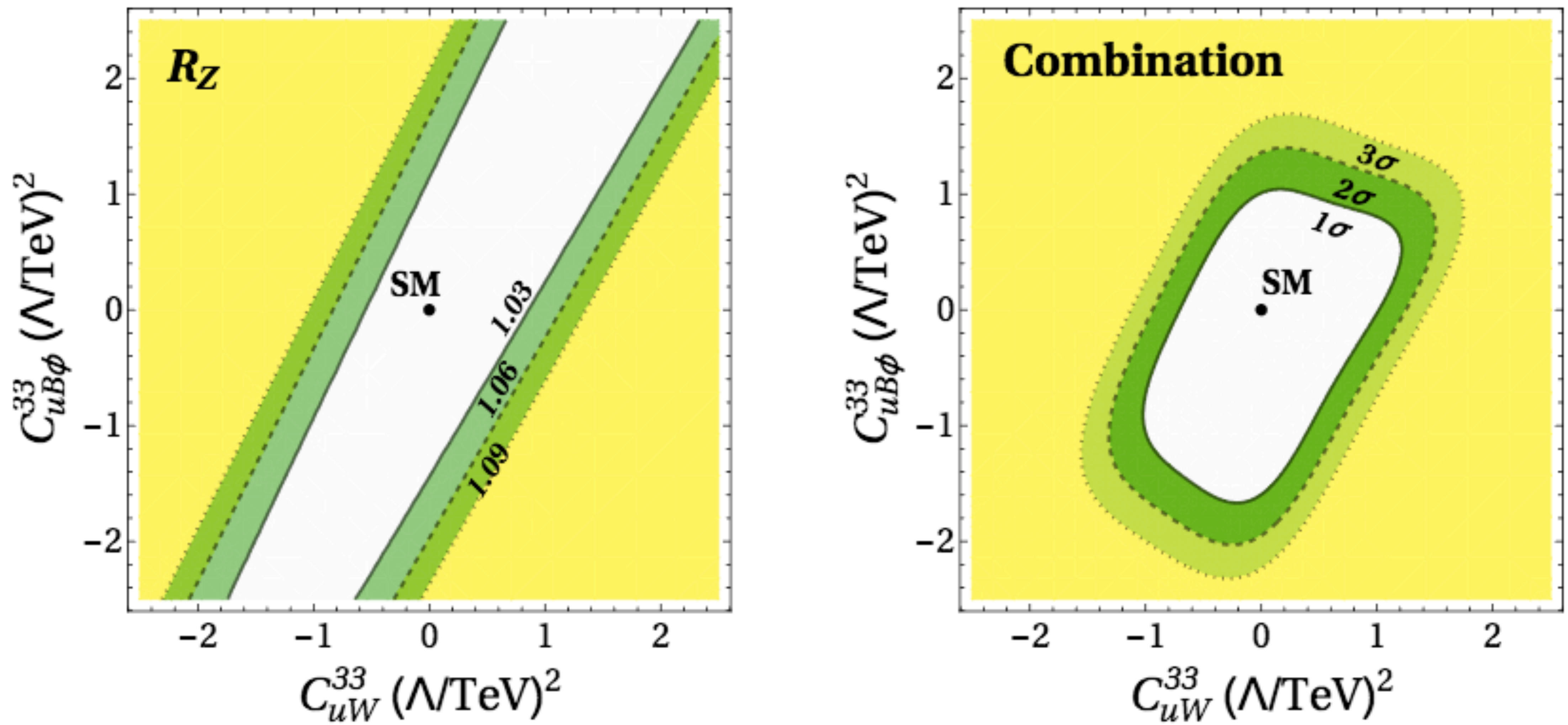
Run 3

HL-LHC

$$\mathcal{L}_{t\bar{t}Z} = e\bar{u}(p_t)\left[\gamma^\mu\left(C^Z_{1,V}+\gamma_5 C^Z_{1,A}\right) + \frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(C^Z_{2,V}+i\gamma_5 C^Z_{2,A}\right)\right]v(p_{\bar{t}})Z_\mu$$

weak dipole moments, tiny in SM

Complementarity

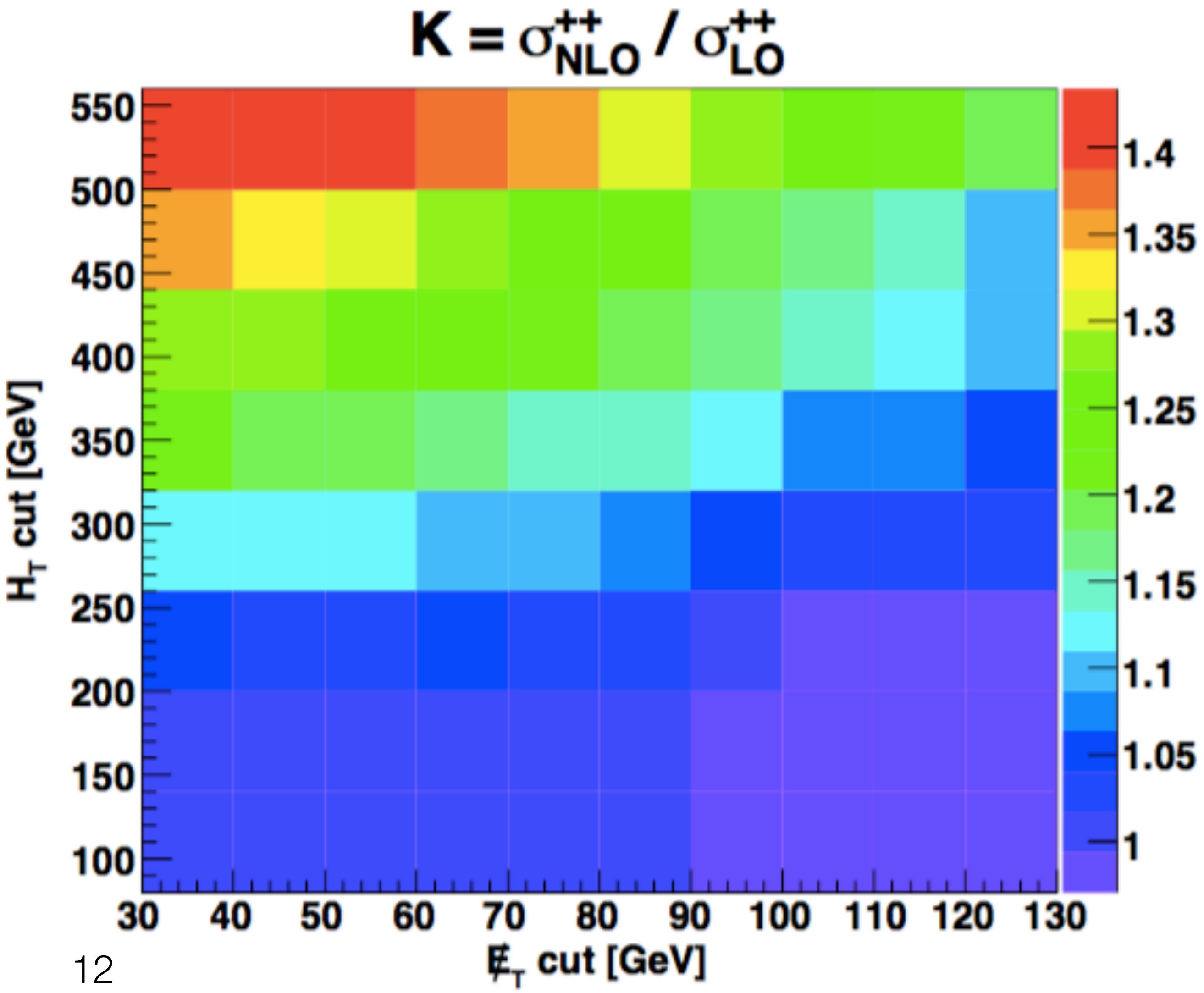


- Orthogonal dependence to tt+photon provides stringent constraints when combined.

ttW

- SM source of same-sign dilepton events, important for many NP searches; background to ttH.
- W radiated from initial quarks, so process not sensitive to t-W coupling; instead useful SM probe.
- Known at NLO including top-quark decays (JC and Ellis, 1204.5678).
- Large *K*-factors at high H_T or p_T(top-pair).
  - new NLO contributions proportional to

$$\alpha_s \log^2 \left[p_T(t\bar{t})/m_W\right]$$

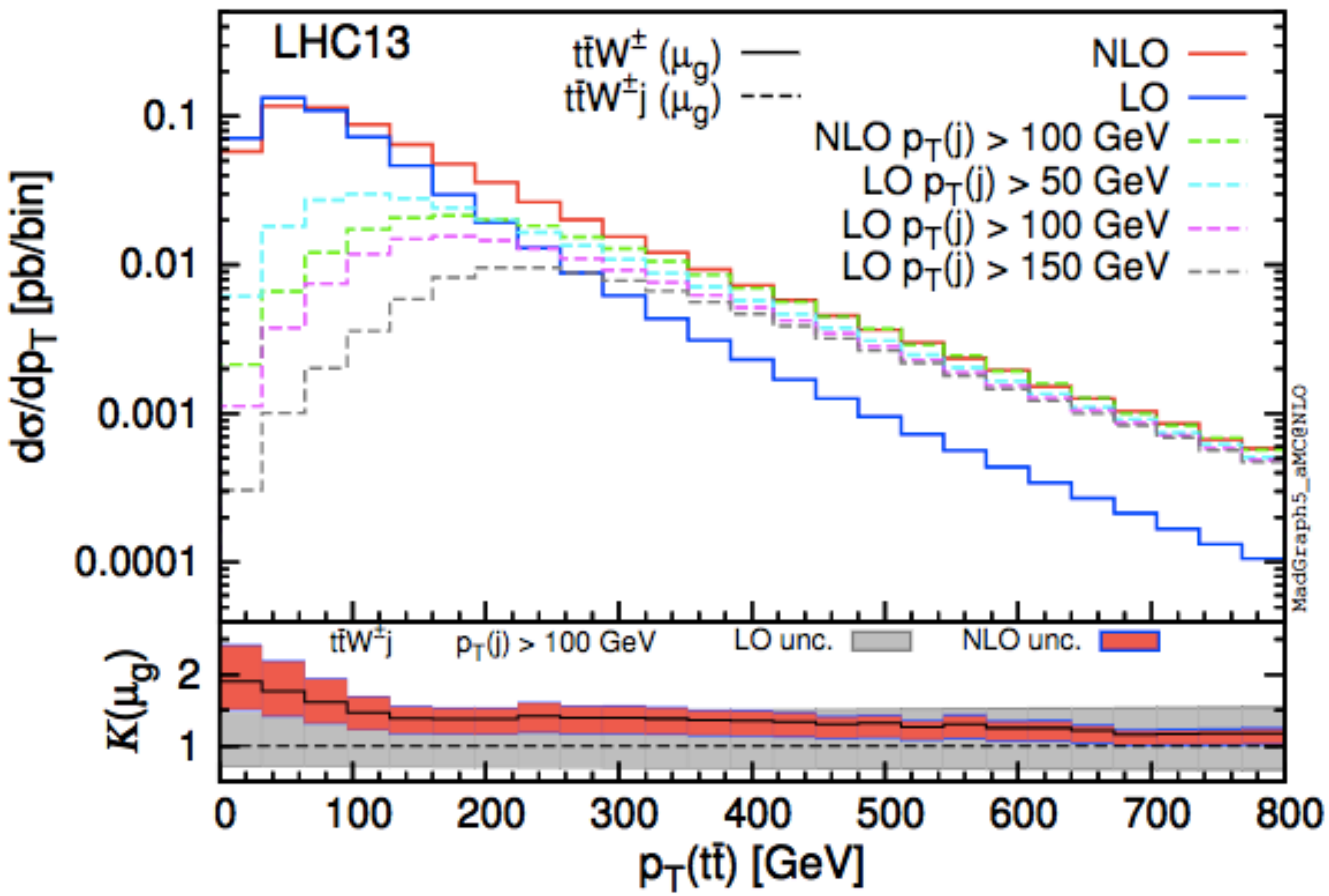


ttW merging

- Might worry that large corrections require NNLO calculation for stability.

- NLO analysis of ttW+jet suggests that this should not be necessary (MG5_aMC@NLO, Maltoni et al, 1507.05640).

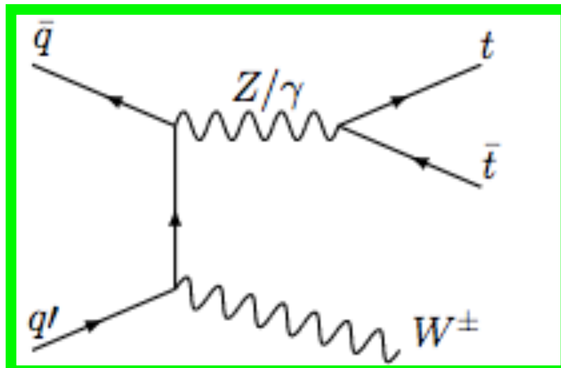
    - merged FxFx sample should suffice for full PS (also extends to other ttV process).



Beyond NLO QCD

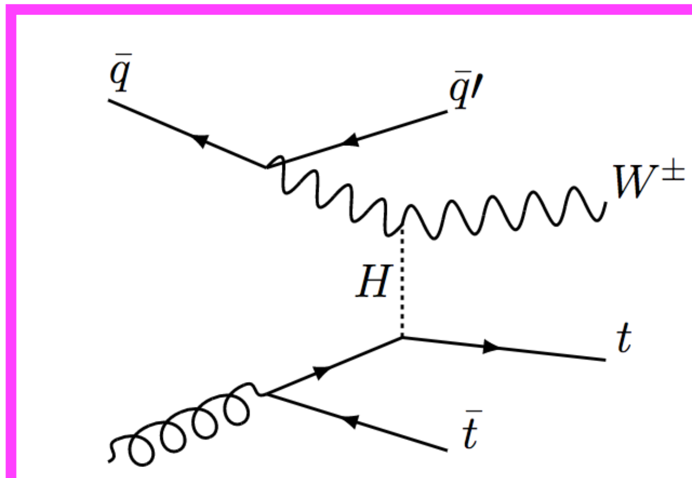
- EW corrections known (Frixione et al, 1504.03446) and soft gluons emission up to NNLL (1409.1460, 1607.05303, 1710.06810).

- Re-examination of perturbative expansion reveals further important contributions (Frederix et al, 1711.02116).



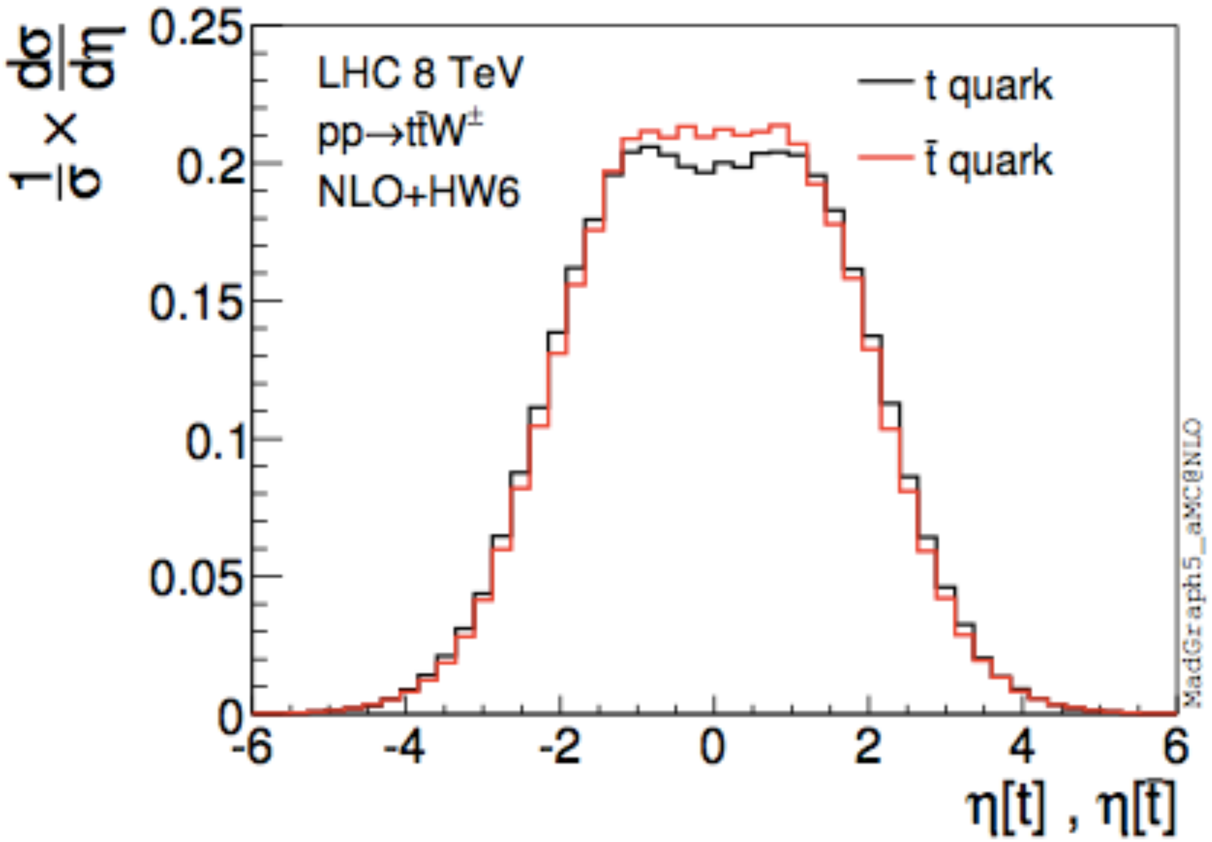
$\delta[\%]$	$\mu = H_T/4$	$\mu = H_T/2$	$\mu = H_T$
LO_2	-	-	-
LO_3	0.8	0.9	1.1
NLO QCD (α_s^3, α) NLO_1	34.8 (7.0)	50.0 (25.7)	63.4 (42.0)
NLO EW (α_s^2, α^2) NLO_2	−4.4 (−4.8)	−4.2 (−4.6)	−4.0 (−4.4)
NLO_3 ('mixed', α_s, α^3)	11.9 (8.9)	12.2 (9.1)	12.5 (9.3)
NLO_4	0.02 (−0.02)	0.04 (−0.02)	0.05 (−0.01)

[relative to LO QCD]



Charge asymmetry

- Much bigger effect than in top-pair production due to fact that emitting W-boson polarizes top quarks (Maltoni et al, 1406.3262).

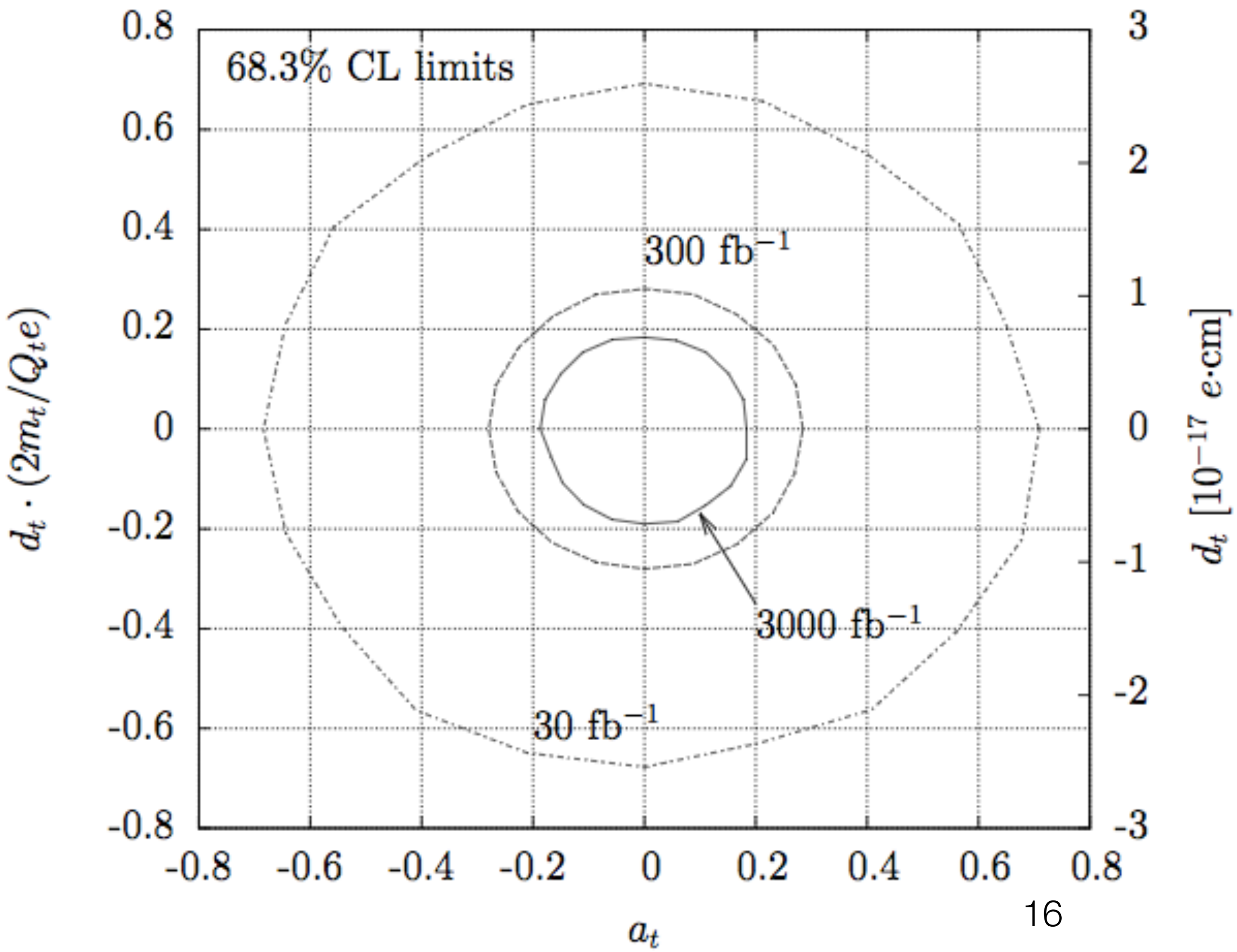


		8 TeV	13 TeV	14 TeV
$t\bar{t}$	σ(pb)	$198^{+15\%}_{-14\%}$	$661^{+15\%}_{-13\%}$	$786^{+14\%}_{-13\%}$
	$A_c^t(\%)$	$0.72^{+0.14}_{-0.09}$	$0.45^{+0.09}_{-0.06}$	$0.43^{+0.08}_{-0.05}$
$t\bar{t}W^\pm$	σ(fb)	$210^{+11\%}_{-11\%}$	$587^{+13\%}_{-12\%}$	$678^{+14\%}_{-12\%}$
	$A_c^t(\%)$	$2.37^{+0.56}_{-0.38}$	$2.24^{+0.43}_{-0.32}$	$2.23^{+0.43}_{-0.33}$
	$A_c^b(\%)$	$8.50^{+0.15}_{-0.10}$	$7.54^{+0.19}_{-0.17}$	$7.50^{+0.24}_{-0.22}$
	$A_c^e(\%)$	$-14.83^{-0.65}_{+0.95}$	$-13.16^{-0.81}_{+1.12}$	$-12.84^{-0.81}_{+1.11}$

t+photon

- Can also use to constrain anomalous dipole moments and W-W-photon coupling.

$$\mathcal{L}_{\text{eff}} = -a_t \frac{Q_t e}{4m_t} \bar{t}\sigma_{\mu\nu} t F^{\mu\nu} + i \frac{d_t}{2} \bar{t}\sigma_{\mu\nu}\gamma_5 t F^{\mu\nu}$$

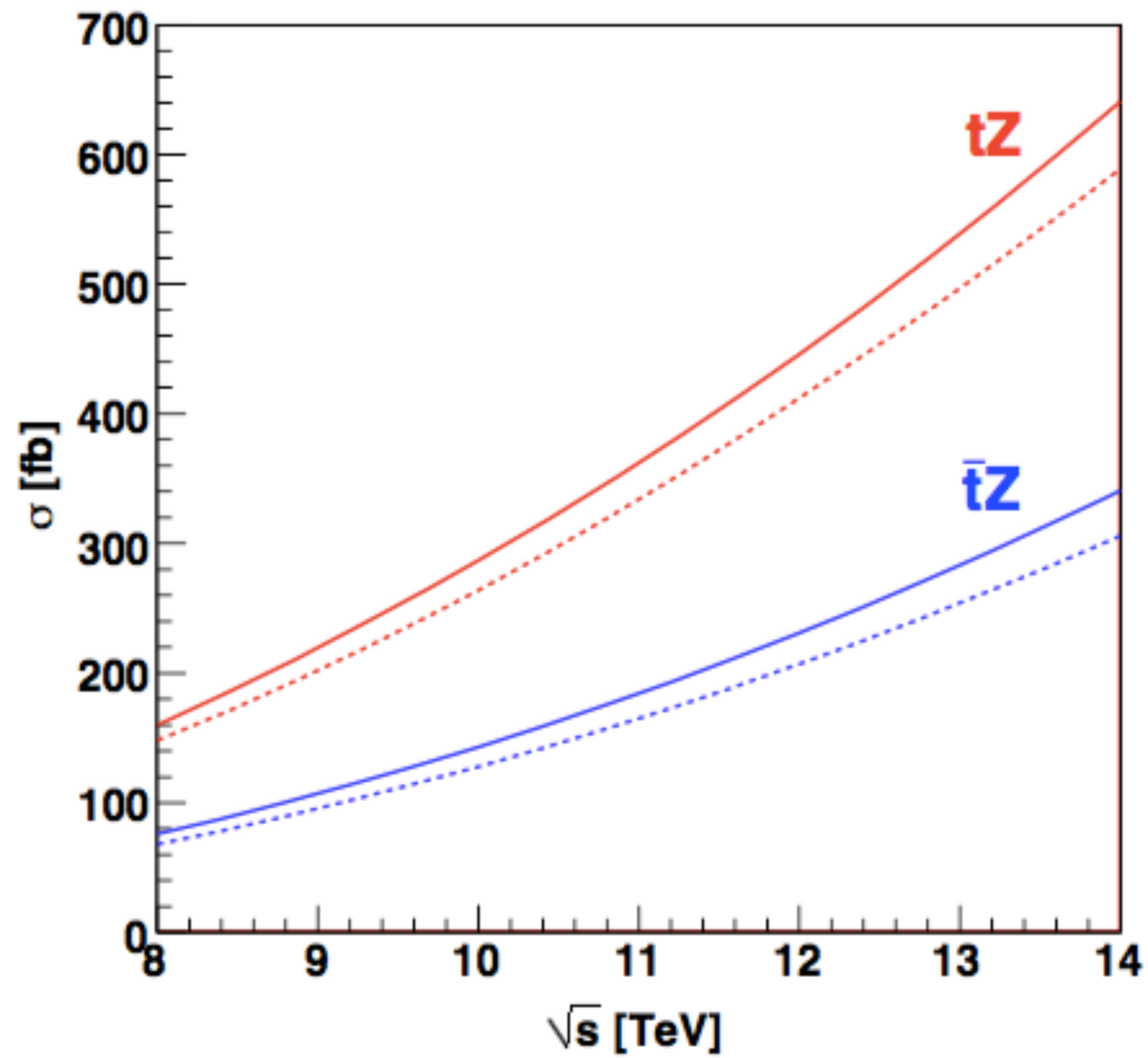


Fael and Gehrmann, 1307.1349

[see also Etesami et al, 1606.02178]

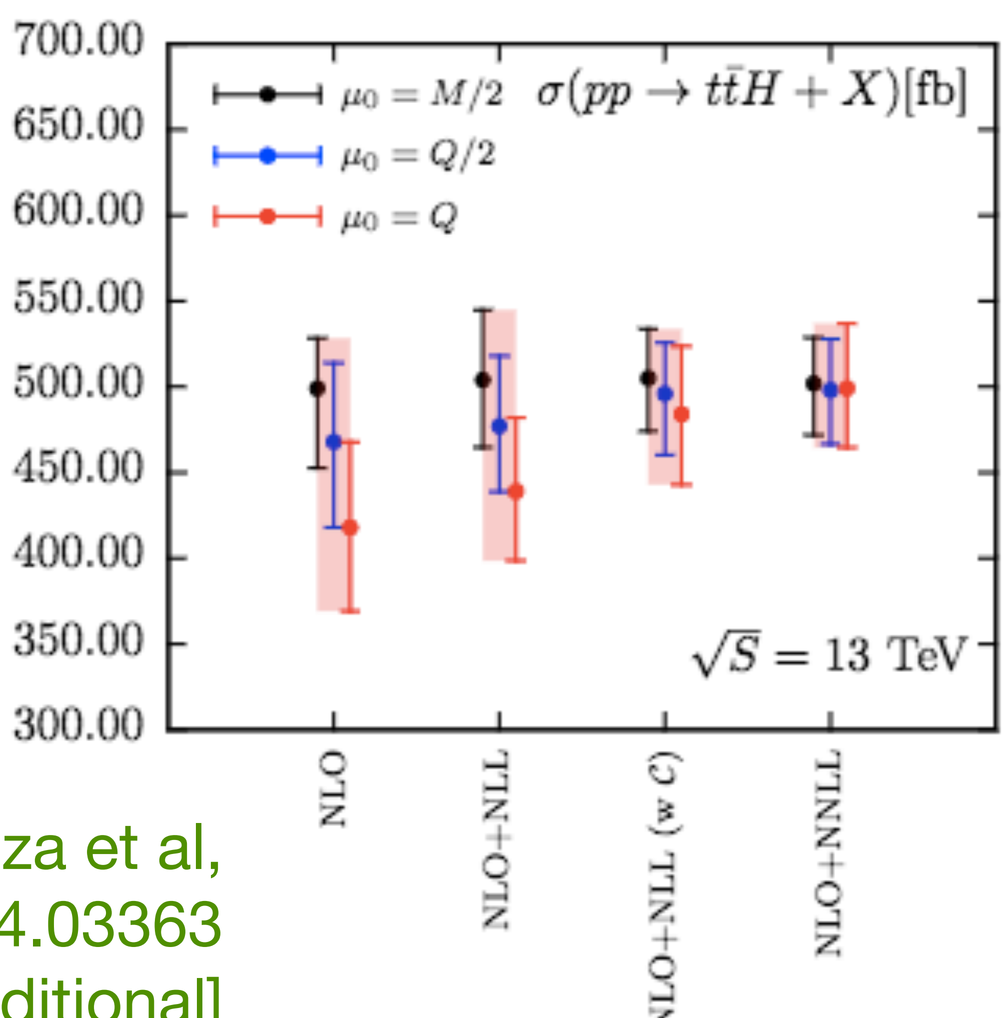
t+Z

- Known to NLO QCD + PS (MG5_aMC@NLO) and including radiation in decay in 5FS (JC et al, 1302.3856); corrections modest.
- Theory otherwise a little behind other channels (NLO EW, soft-gluon effects, …)
- Anomalous FCNC coupling signals are simpler and predicted more accurately (e.g. Kidonakis, 1712.01144).

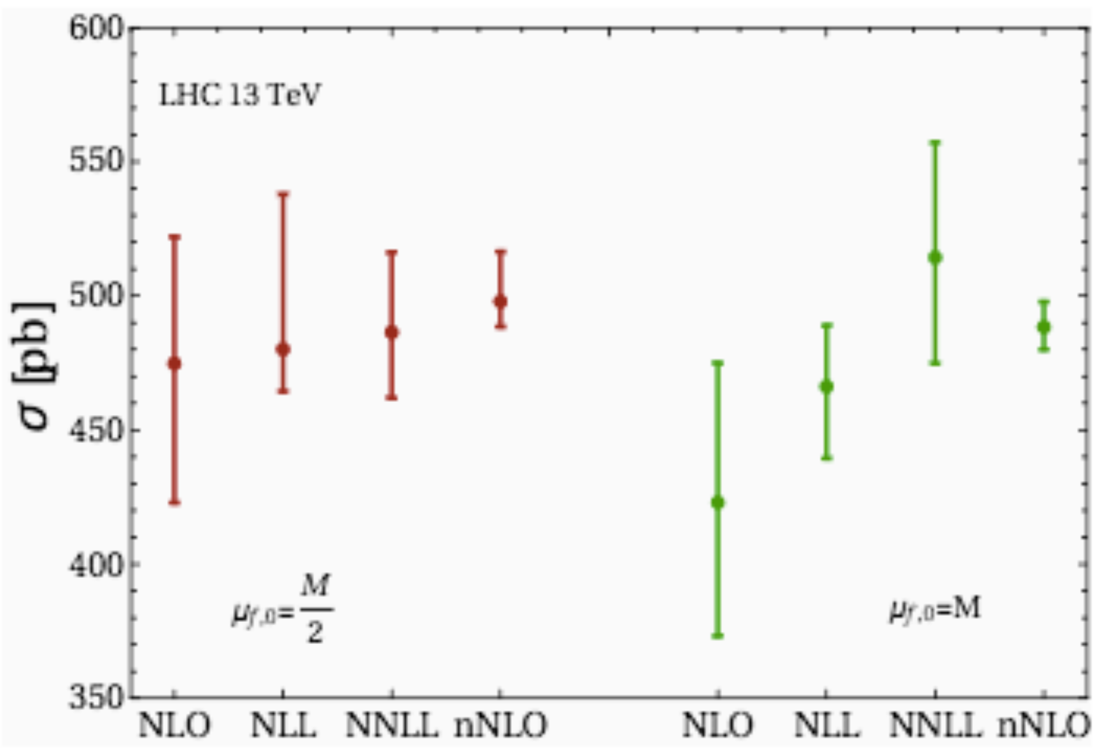


tt+Higgs

- Important direct, tree-level probe of top Yukawa coupling.
- State of the art predictions for total cross-section are NLO QCD + resummation of soft gluon effects at NNLL (c.f. top pairs ~ 10 yrs ago).

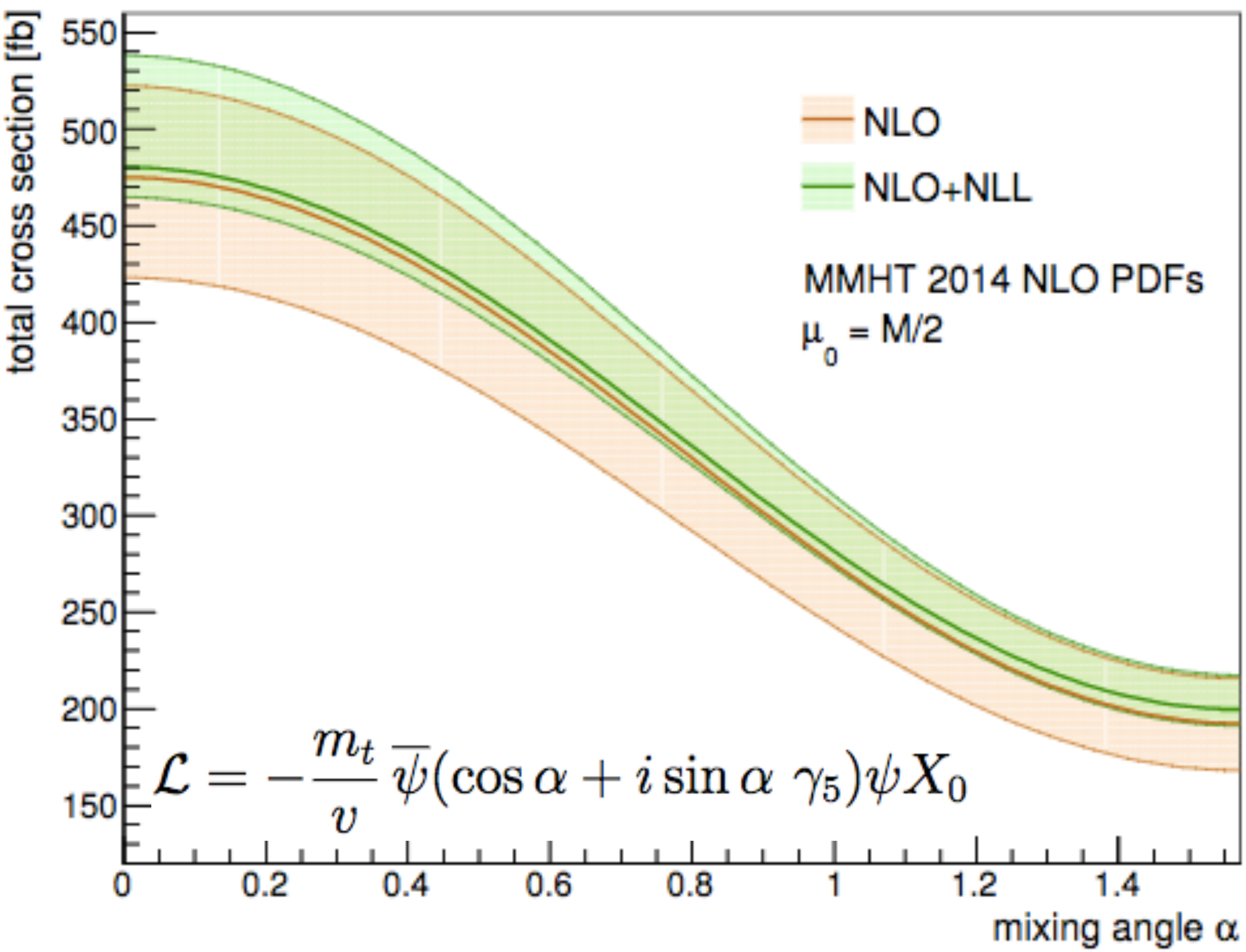


Kulesza et al, 1704.03363 [traditional]



Broggio et al, 1611.00049 [SCET]

Probe of CPV



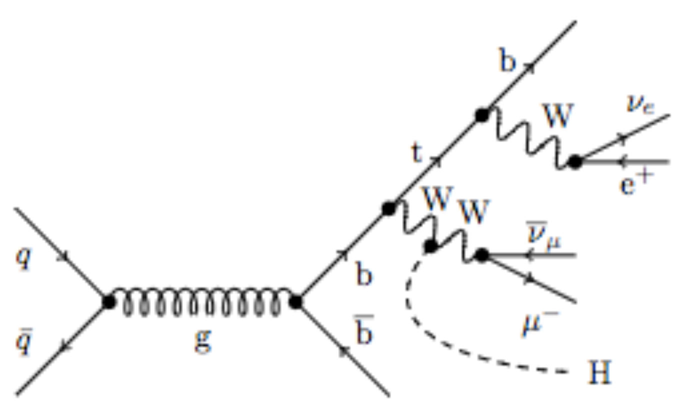
Broggio et al, 1707.01803

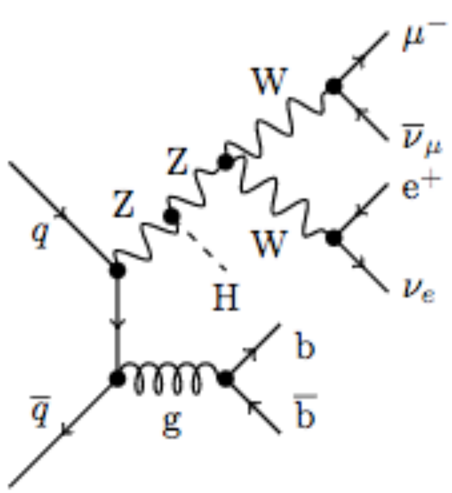
Beyond cross-sections

- Complicated analysis requires more than just cross-sections; NLO+PS available (multiple groups).

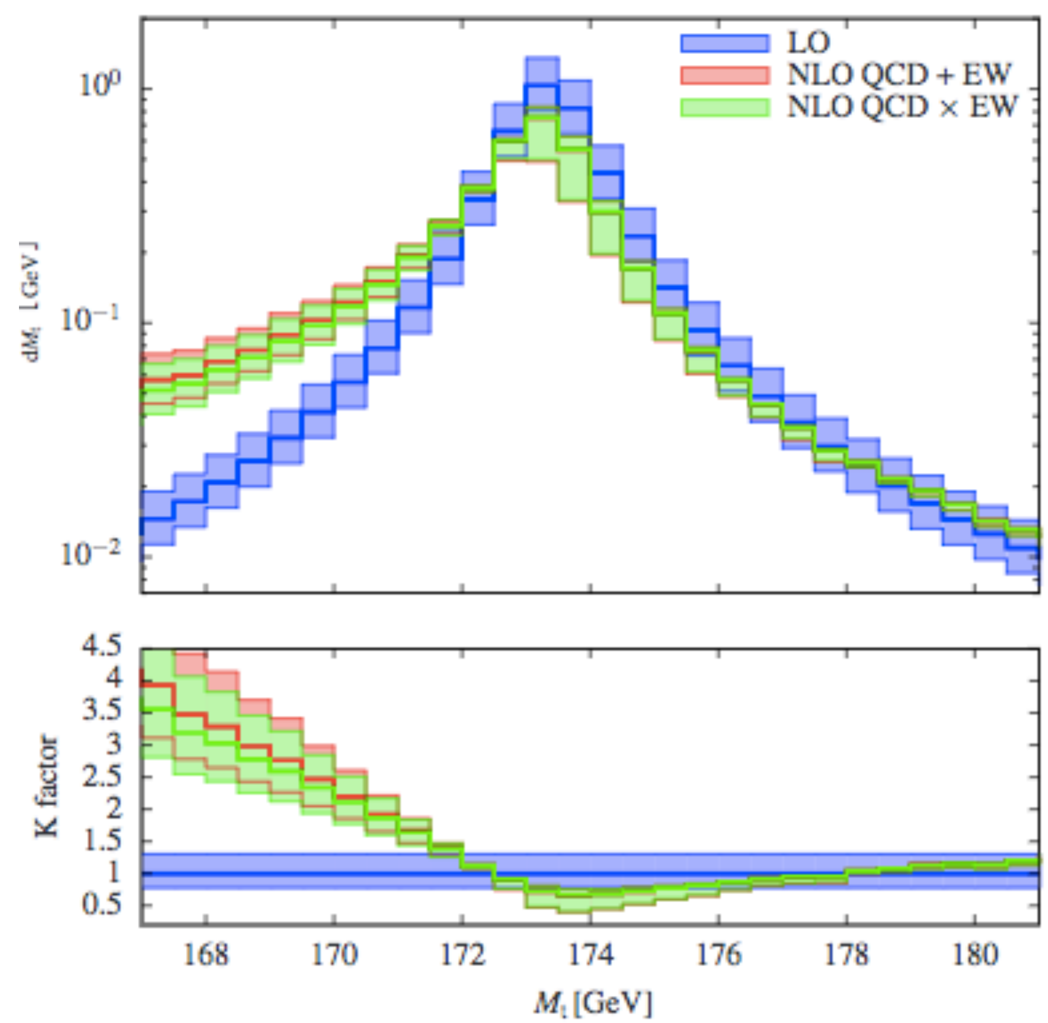
- Also require off-shell top quarks and EW corrections (Denner et al, 1506.07448, 1612.07138).

one on-shell top quark

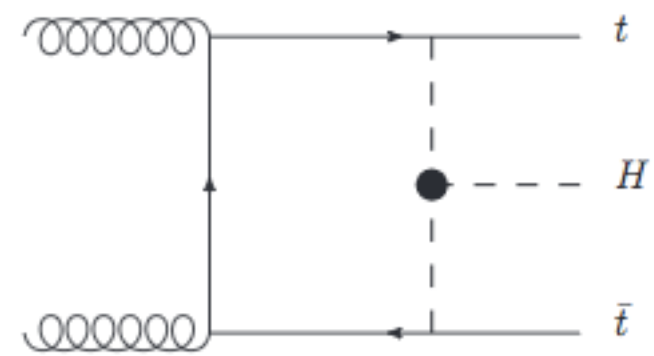




no on-shell top quarks

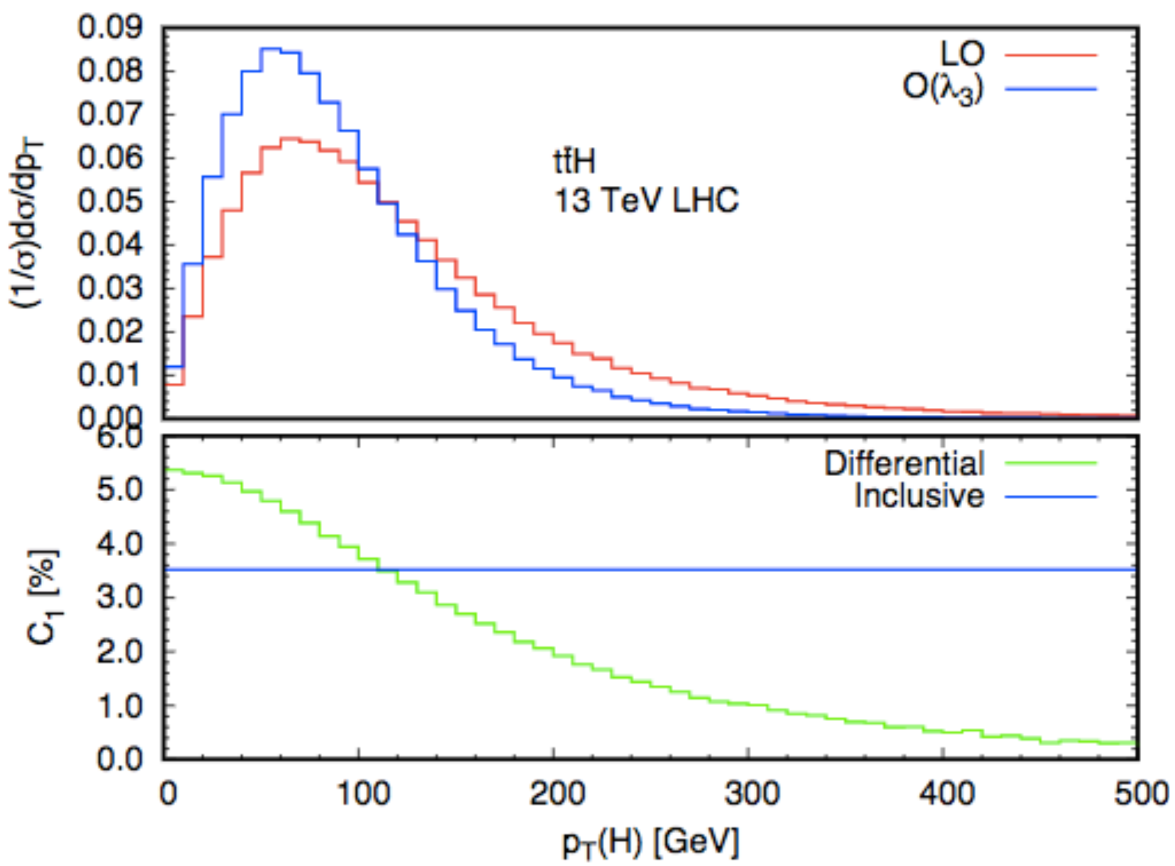


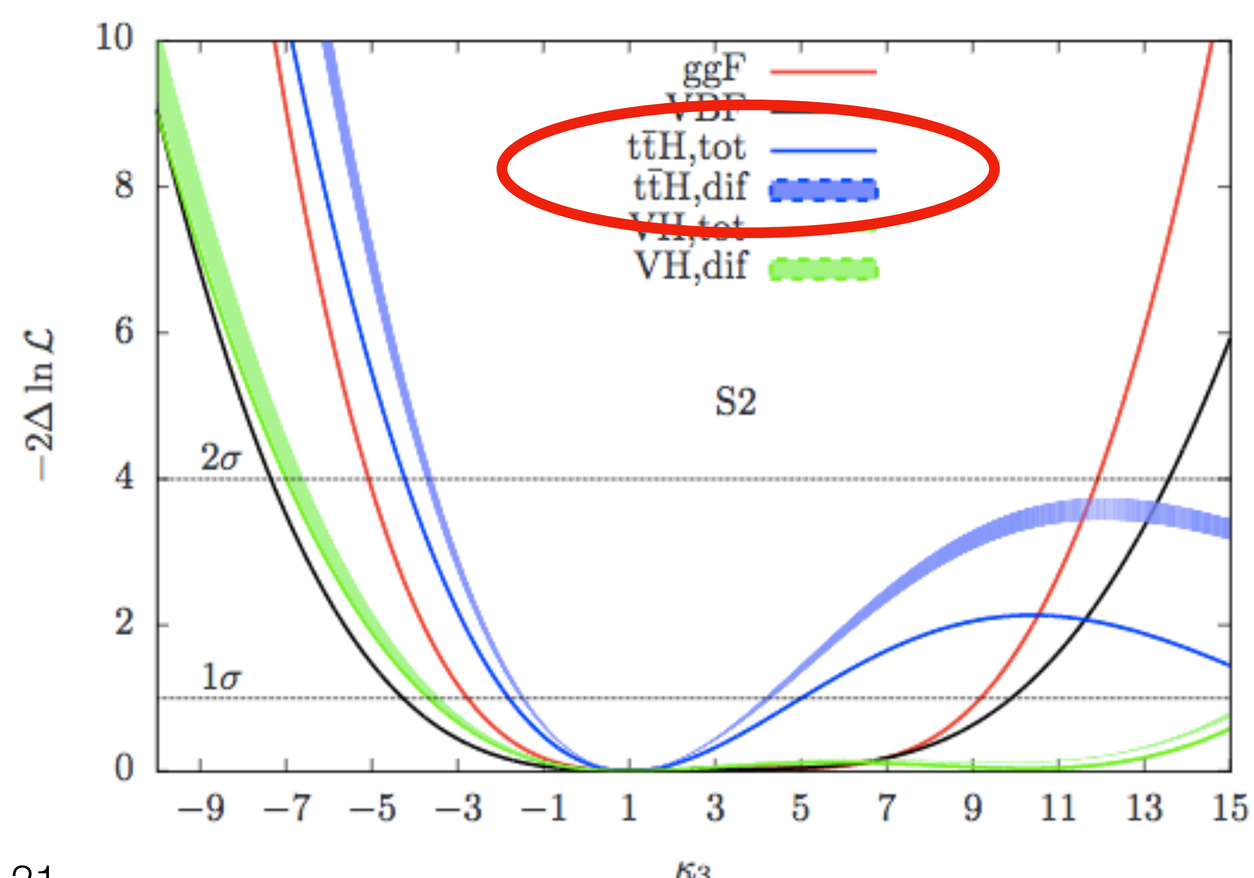
Higgs self-coupling



- Indirect sensitivity to triple-Higgs coupling through EW corrections.
  - significant effect and kinematic dependence a target for HL-LHC (Maltoni et al, 1709.08649).

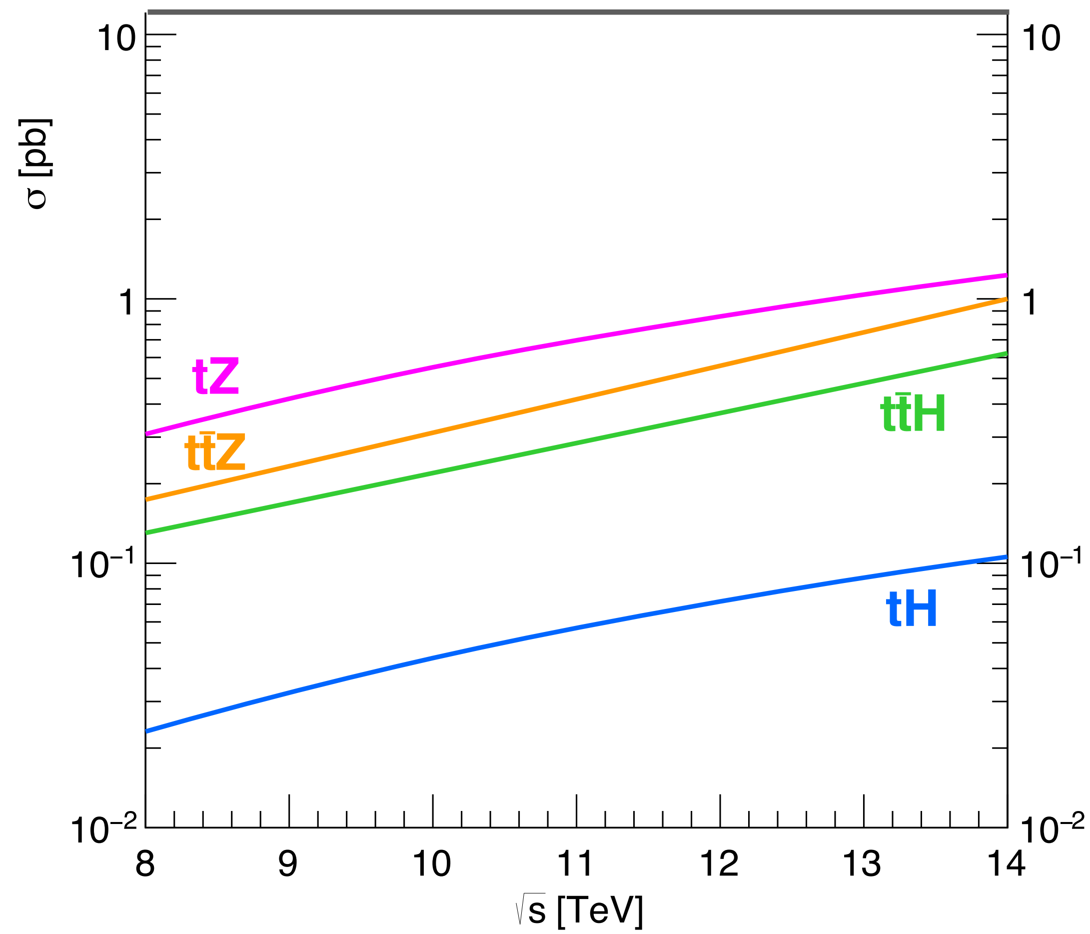
[using ATLAS-HL projection at 14 TeV, exp+th errors]

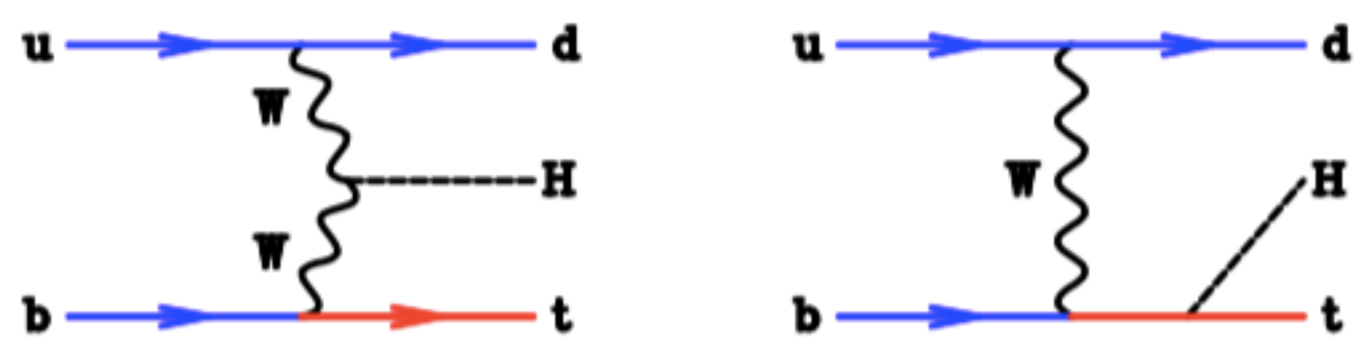




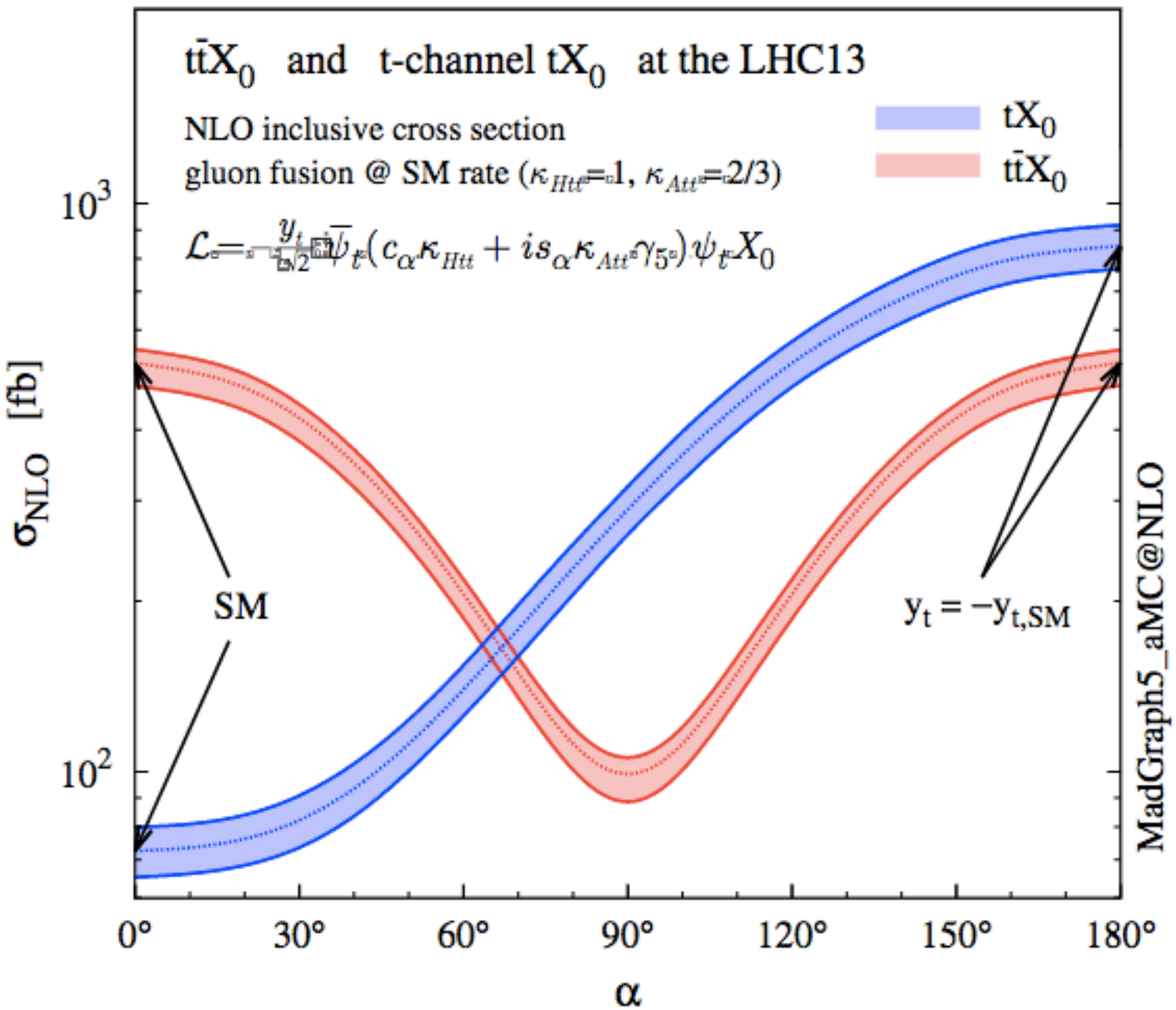
t+Higgs

- Known to NLO QCD + PS in 5FS and 4FS (MG5_aMC@NLO) and including radiation in decay in 5FS (JC et al, 1302.3856).
- Unlike associated Z production, single-top rate is not comparable to top-pair process.
    - destructive interference between radiation from top and from W.
- Consequence of unitarity and a fundamental property of the SM Higgs boson (Maltoni et al, 0106293).





Sensitivity to CP nature

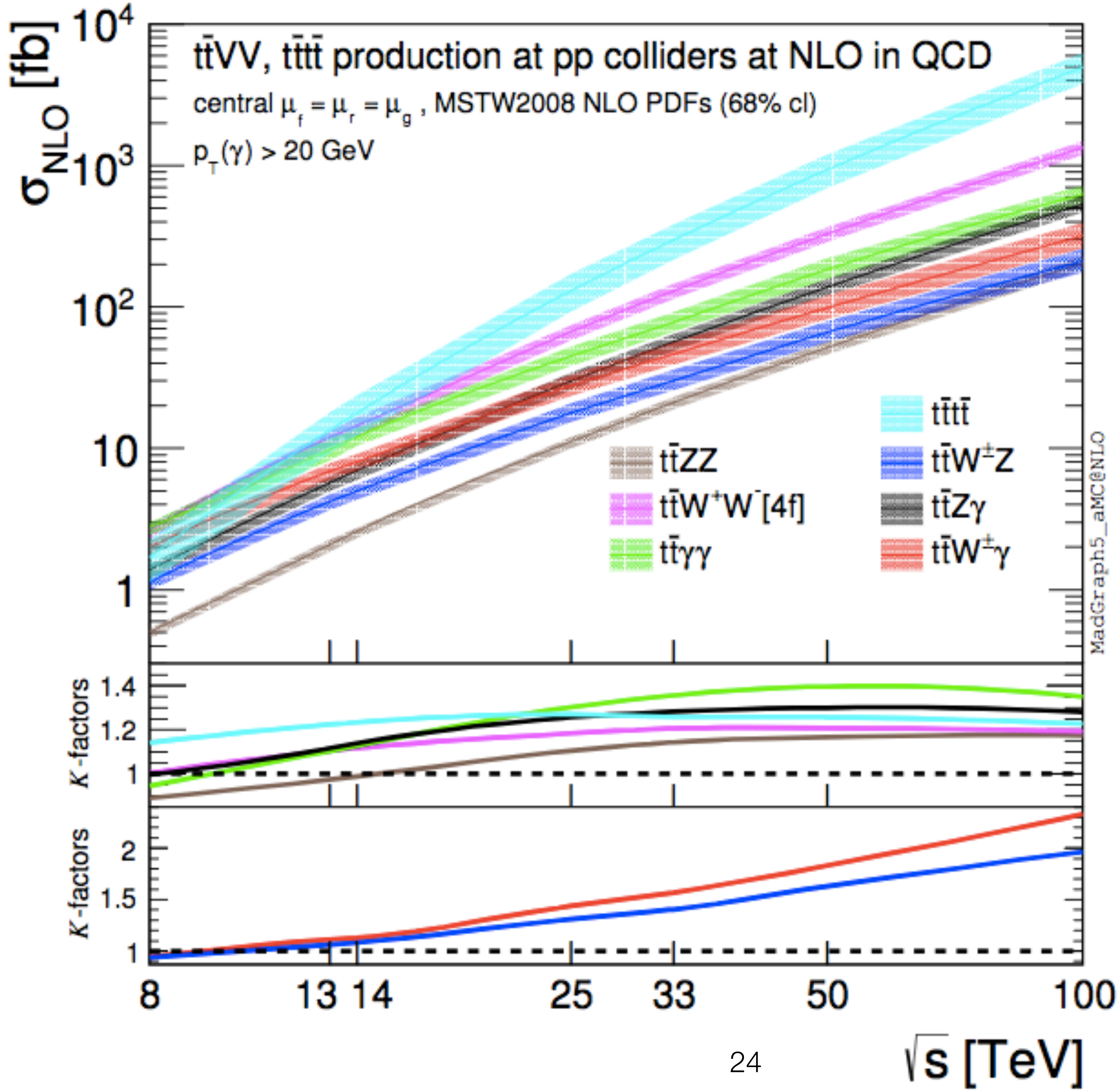


Demartin et al, 1504.00611

[also some sensitivity to Higgs trilinear, as for ttH]

$$\mathcal{L}_0^t = -\bar{\psi}_t\big(c_\alpha\kappa_{Htt}g_{Htt} + is_\alpha\kappa_{Att}g_{Att}\,\gamma_5\big)\psi_t\,X_0$$

For the future: ttVV



MG5_aMC@NLO, Maltoni et al, 1507.05640

(sensitivity to new dipole interactions e.g. Etesami et al, 1712.07184)

Summary

- Top/QCD/EW nature of these processes provides challenging arena for computing and studying perturbative corrections.

- Theoretical predictions for ttV, tV in pretty good shape for foreseeable future — expect (NLO) uncertainties small enough.

- First tests of SM just coming into focus (cross-sections, asymmetries).

- More fundamental tests of SM require bigger data-sets (dipole moments, top Yukawa, Higgs trilinear).

- Lots of room for new ideas between now and then!