4-top Production Studies for the HL/HE-LHC Yellow Report

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with material and input from:
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WG1

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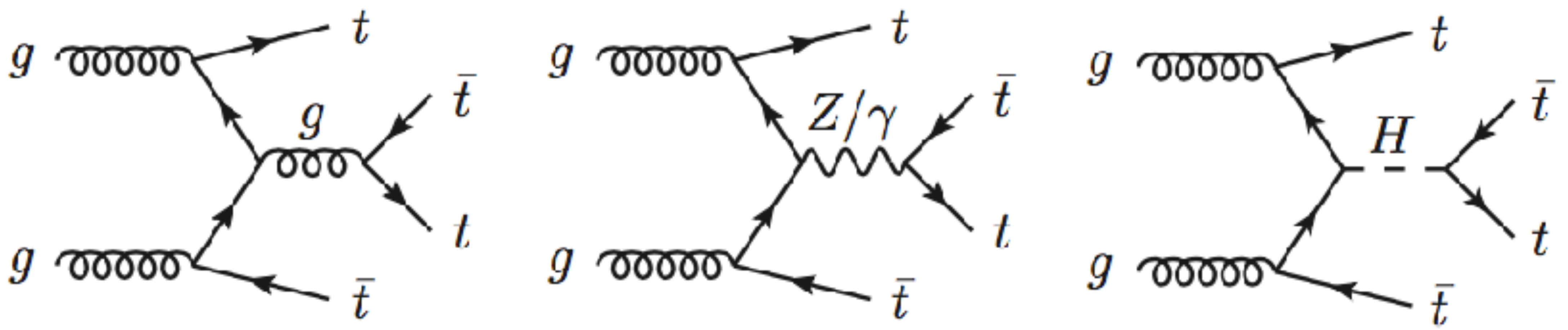
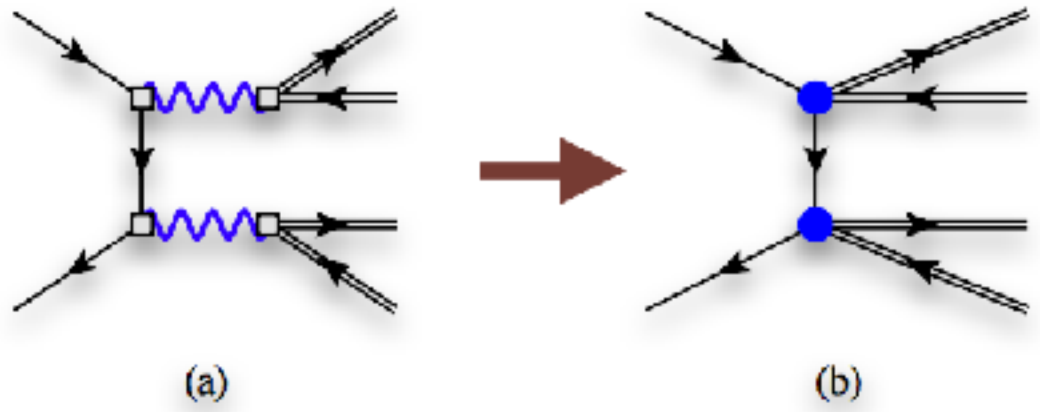
Motivation and status of the Run 2 results

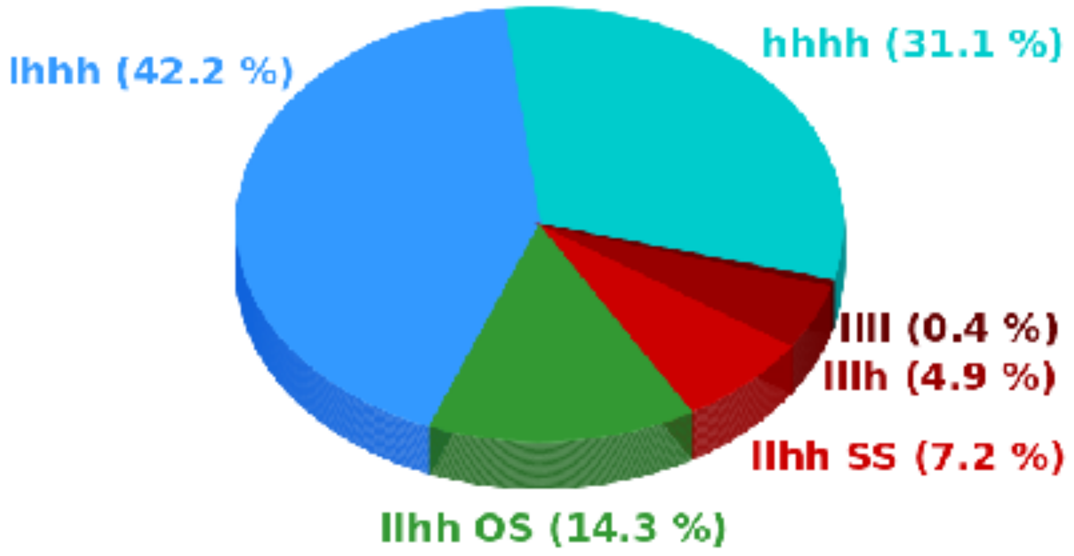
- the $t\bar{t}t\bar{t}$ process
  - rare process predicted by the Standard Model, not measured yet
  - very sensitive to New Physics: color-octet/singlet vectors/scalars, top compositeness, EFT: 4t operator is not constrained elsewhere
  - Higgs width: off-shell Higgs also contributes to 4 tops production



- The YR experimental studies will concentrate on the multi lepton channel
  - main background ttV, ttH and fake lepton

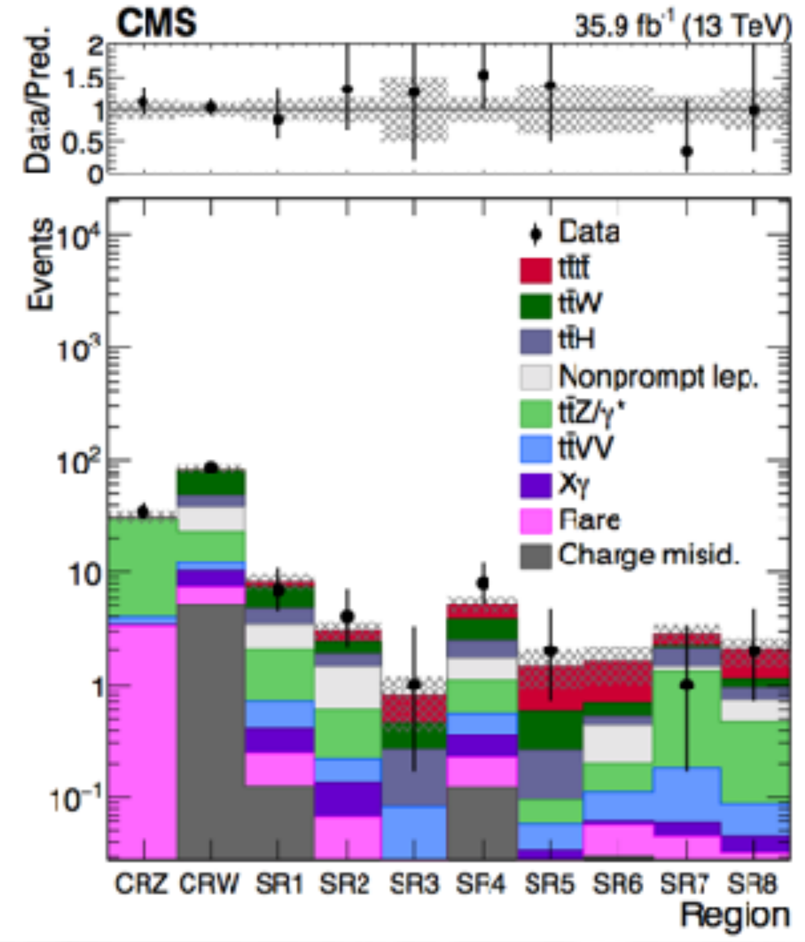


Two dim-6



- CMS latest Run 2 result (EPJC 78 (2018) 140)
  - latest results using 36 fb^{-1} in the multilepton final state
  - upper limit on μ or σ_{SM}: 4.5 (exp: $2.3^{+1.18}_{-0.79}$), 42 fb (exp: $20.8^{+11.2}_{-6.9}$ fb)
    signal strength: $16.9^{+13.8}_{-11.4}$ fb

N_ℓ	N_b	N_{jets}	Region
2	2	≤5	CRW
		6	SR1
		7	SR2
		≥8	SR3
	3	5, 6	SR4
		≥7	SR5
	≥4	≥5	SR6
≥3	2	≥5	SR7
	≥3	≥4	SR8
Inverted Z veto			CRZ



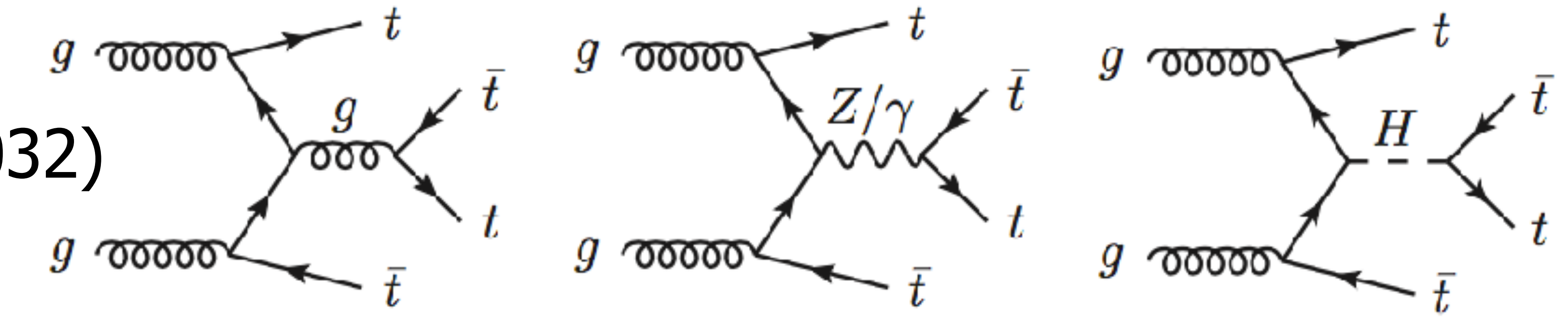
- ATLAS latest Run 2 result
  - multilepton final state using 3.2 fb^{-1} (ATLAS-CONF-2016-020)
    - upper limit on μ: 10.5 (exp: 11.8)
  - 36 fb^{-1} result to be published soon

arXiv:1711.02116

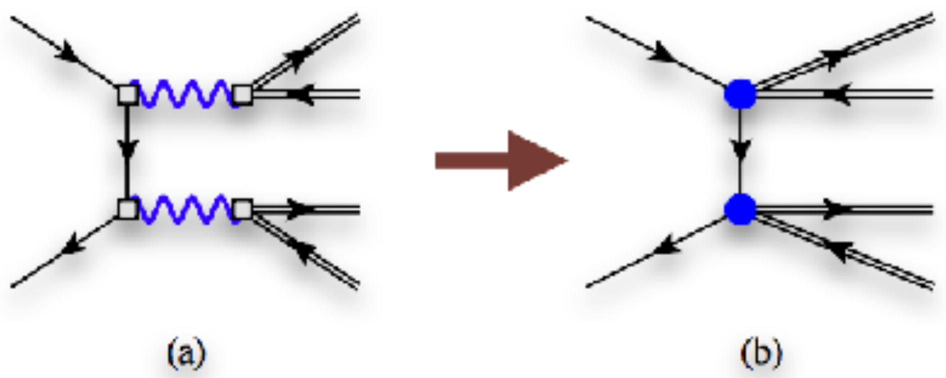
σ[fb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO(+NLO)}}{\mathrm{LO_{QCD}(+NLO_{QCD})}}$
$\mu = H_T/4$	$6.83^{+70\%}_{-38\%}$	$11.12^{-19\%}_{-23\%}$	$7.59^{-64\%}_{-36\%}$	$\boxed{11.97^{+18\%}_{-21\%}}$	1.11 (1.08)

4 top cross section Yellow Report outline

- theory part
  - precision:
    - complete NLO predictions for the 4 top cross section numbers at 14 TeV and 27 TeV
      - Frederix, Pagani, Zaro (based on arXiv:1711.02116)
    - sensitivity of the cross section measurement
      - Alvarez, Faroughy, Kamenik, Morales, Szynkman (based on arXiv:1611.05032)



  - 4 tops as a probe for new physics
    - constraints on the EFT qqtt 4-fermion operator at 14 TeV and 27 TeV
      - Zhang (based on arXiv:1708.05928)
    - constraints on chromo-magnetic and chromo-electric dipole moments at 14 TeV and 27 TeV
      - Ebadi, Khanpour, Khatibi, Mohammadi Najafabad (based on arXiv:1804.05598)
    - Higgs width and top quark Yukawa coupling
      - Cao, Chen, Liu (based on arXiv:1602.01934)



Two dim-6

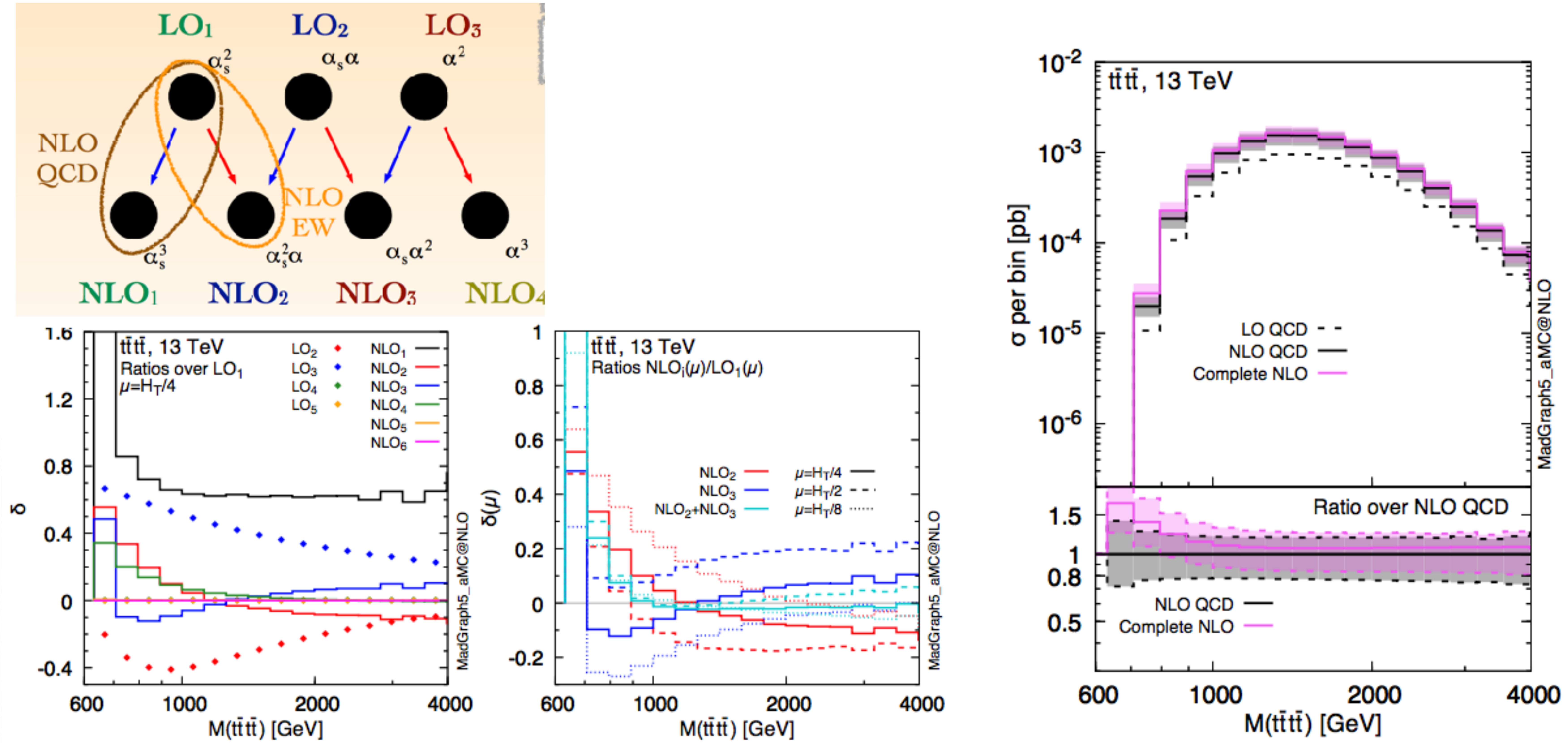
- experimental part
  - inclusive and differential results in the multilepton channel at 14 TeV
    - fast simulation analysis (ATLAS) and extrapolation (CMS)
  - Description of ATLAS analysis, yields with guessed uncertainties
  - Description of CMS extrapolation, yields with guessed uncertainties
  - ATLAS and CMS results: estimated cross section uncertainties and examples for differential distributions

  - the original plan was to also have HE-LHC results, not sure time will allow it

Complete NLO predictions 4 top cross sections at 14 TeV and 27 TeV

Frederix, Pagani, Zaro

- complete NLO computations including EW effects
  - main contribution from NLO_1, NLO_2 and NLO_3
  - cancelations among terms at LO ($LO_{2,3}$) and NLO ($NLO_{2,3}$)
  - numerical relevant near the $t\bar{t}t\bar{t}$ threshold



Results for the 4 top cross sections at 14 TeV and 27 TeV

Frederix, Pagani, Zaro

14

σ[fb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO(+NLO)}}{\mathrm{LO_{QCD}(+NLO_{QCD})}}$
$\mu = H_T/4$	$9.04^{+69\%}_{-38\%}$	$14.72^{+19\%}_{-23\%}$	$10.04^{+63\%}_{-35\%}$	$15.83^{+18\%}_{-21\%}$	1.11 (1.08)

x 5

27

σ[fb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO(+NLO)}}{\mathrm{LO_{QCD}(+NLO_{QCD})}}$
$\mu = H_T/4$	$45.34^{+59\%}_{-35\%}$	$71.31^{+16\%}_{-20\%}$	$48.57^{+54\%}_{-33\%}$	$73.94^{+15\%}_{-18\%}$	1.07(1.04)

Preliminary

x 56

100

σ[pb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO(+NLO)}}{\mathrm{LO_{QCD}(+NLO_{QCD})}}$
$\mu = H_T/4$	$2.37^{+49\%}_{-31\%}$	$3.98^{+18\%}_{-19\%}$	$2.63^{+44\%}_{-28\%}$	$4.18^{+17\%}_{-17\%}$	1.11 (1.05)

δ[%]	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
$\mathrm{LO_2}$	−25.8	−28.1	−30.4
$\mathrm{LO_3}$	32.5	38.9	45.8
$\mathrm{LO_4}$	0.2	0.3	0.4
$\mathrm{LO_5}$	0.0	0.0	0.1
$\mathrm{NLO_1}$	14.7	62.9	103.3
$\mathrm{NLO_2}$	8.1	−3.5	−15.1
$\mathrm{NLO_3}$	−10.0	1.8	15.8
$\mathrm{NLO_4}$	2.2	2.7	3.4
$\mathrm{NLO_5}$	0.1	0.2	0.2
$\mathrm{NLO_6}$	0.00	0.00	0.00
$\mathrm{NLO_2+NLO_3}$	−1.9	−1.7	0.7

δ[%]	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
$\mathrm{LO_2}$	−22.2	−24.4	−26.5
$\mathrm{LO_3}$	25.8	31.1	36.8
$\mathrm{LO_4}$	0.2	0.3	0.4
$\mathrm{LO_5}$	0.0	0.1	0.1
$\mathrm{NLO_1}$	14.3	57.3	93.8
$\mathrm{NLO_2}$	6.2	−2.4	−11.2
$\mathrm{NLO_3}$	−10.0	−2.7	6.3
$\mathrm{NLO_4}$	2.8	3.5	4.3
$\mathrm{NLO_5}$	0.2	0.3	0.3
$\mathrm{NLO_6}$	< 0.01	< 0.01	< 0.01
$\mathrm{NLO_2+NLO_3}$	−2.8	−5.1	4.9

δ[%]	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
$\mathrm{LO_2}$	−18.7	−20.7	−22.8
$\mathrm{LO_3}$	26.3	31.8	37.8
$\mathrm{LO_4}$	0.05	0.07	0.09
$\mathrm{LO_5}$	0.03	0.05	0.08
$\mathrm{NLO_1}$	33.9	68.2	98.0
$\mathrm{NLO_2}$	−0.3	−5.7	−11.6
$\mathrm{NLO_3}$	−3.9	1.7	8.9
$\mathrm{NLO_4}$	0.7	0.9	1.2
$\mathrm{NLO_5}$	0.12	0.14	0.16
$\mathrm{NLO_6}$	< 0.01	< 0.01	< 0.01
$\mathrm{NLO_2+NLO_3}$	−4.2	−4.0	2.7

Phenomenological extrapolation of the cross section sensitivity

E. Alvarez, D. Faroughy, J. Kamenik, R. Morales, A. Szynkman

- phenomenological studies using 300 fb^{-1} (arXiv:1611.05032)
  - same-sign and trilepton channels
  - signal region (SR7j and SR5j)
    - combined: S/√B<1.87 at 95% CL
  - assumptions:
    - 12% and 13% uncertainties for ttZ/W
    - 50% for fakes and charge mis-ID background (at 13.2 fb^{-1})
    - Scale the uncertainties from fakes and charge mis-ID with sqrt(luminosity)

- theory extrapolation:
  - Rescale # of events by the signal cross section at 14/27 TeV (for both signal and background) yields
    - 14 TeV 3 ab^{-1}: 0.55<S/√B<1.45
    - 27 TeV 15 ab^{-1}: 0.79<S/√B<1.21
  - including theory uncertainties, precision:
    - 58% for 14 TeV 3 ab^{-1}
    - 40% for 27 TeV 15 ab^{-1}

$\mathcal{L}$=300 fb^{-1}	SR6j	SR7j	SR8j
N_{exp}	139 (171)	85 (101)	43 (51)
$t\bar{t}t\bar{t}$	**16.7**	**13.5**	**8.9**
$t\bar{t}W$	60.7	35.0	17.1
$t\bar{t}Z$	32.1	20.3	10.7
$t\bar{t}h$	5.5	3.1	1.3
Fakes	12.5 (17.3)	7.1 (9.8)	3.3 (4.6)
Q-flip	7.6 (34.4)	3.7 (16.6)	1.6 (7.4)
Other	4.4	2.4	1.0
S/B	**0.14 (0.11)**	**0.19 (0.15)**	**0.26 (0.21)**
S/$\sqrt{B}$	**1.51 (1.34)**	**1.60 (1.44)**	**1.53 (1.37)**

$\mathcal{L}$=300 fb^{-1}	SR4j	SR5j	SR6j
N_{exp}	31 (32)	25 (26)	17 (17)
$t\bar{t}t\bar{t}$	**8.6**	**7.8**	**6.0**
$t\bar{t}Z$	9.9	8.0	5.1
$t\bar{t}W$	6.7	4.9	2.9
$t\bar{t}h$	2.3	1.8	1.2
Fakes	2.5 (3.5)	1.7 (2.4)	0.9 (1.3)
Other	1.4	1.0	0.5
S/B	**0.38 (0.36)**	**0.45 (0.43)**	**0.57 (0.54)**
S/$\sqrt{B}$	**1.80 (1.76)**	**1.87 (1.84)**	**1.84 (1.80)**

Constraints from 4tops on the EFT 4-fermion operator at 14 TeV and 27 TeV

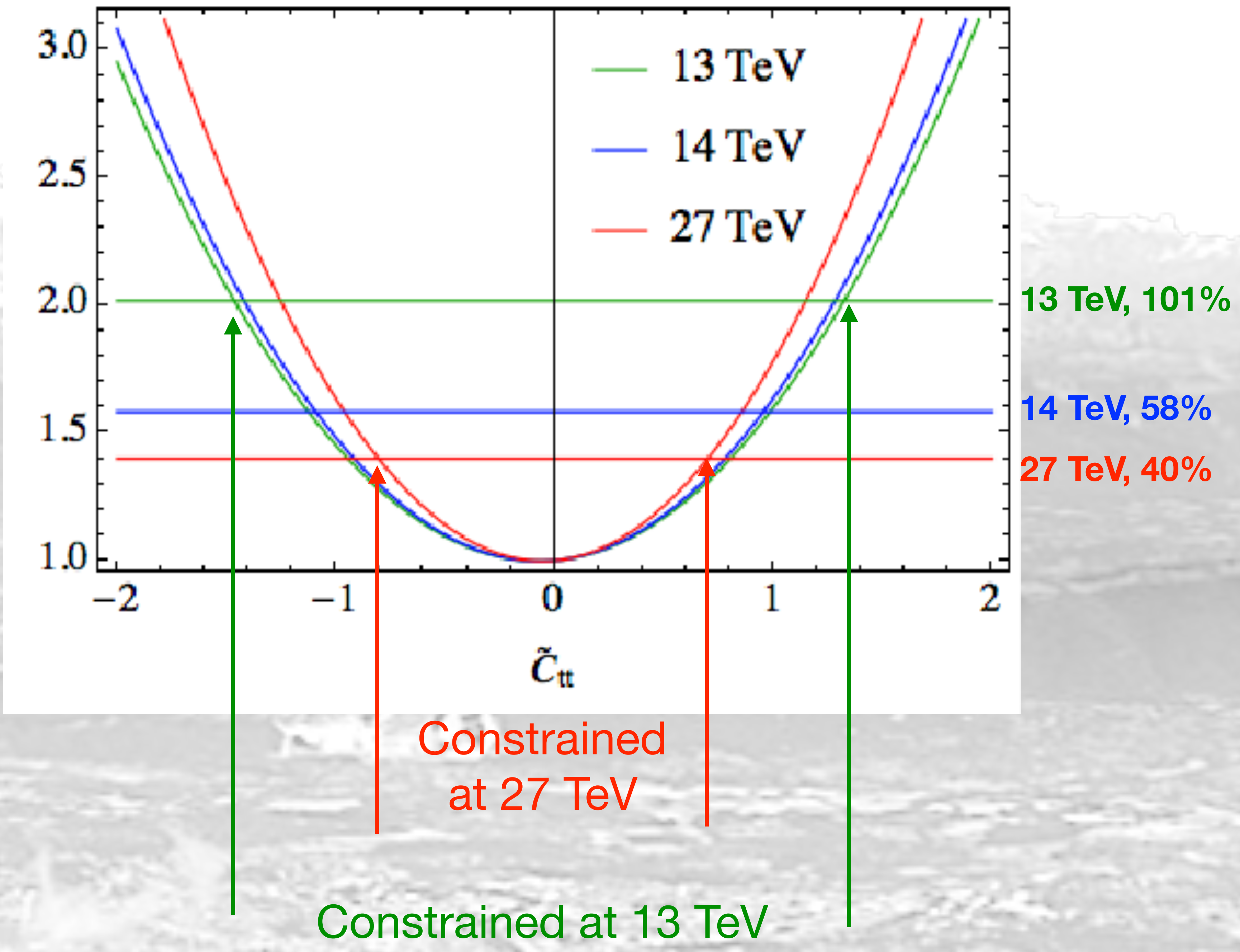
C. Zhang

- $t\bar{t}t\bar{t}$ operators
  - 5 relevant tttt operators in the Warsaw basis, 4 d.o.f's are relevant (1 LLLL, 1 RRRR, 2 LLRR with color singlet and octet)
  - Interesting for BSM states that mainly couple to 3rd generation
  - Cross section is a quadratic function of C

$$\mathcal{O}_{QQ}^{(+)} \equiv \frac{1}{2}\mathcal{O}_{qq}^{(1)(3333)} + \frac{1}{2}\mathcal{O}_{qq}^{(3)(3333)},$$
$$\mathcal{O}_{tt} \equiv \mathcal{O}_{uu}^{(3333)},$$
$$\mathcal{O}_{Qt}^{(1)} \equiv \mathcal{O}_{qu}^{(1)(3333)};$$
$$\mathcal{O}_{Qt}^{(8)} \equiv \mathcal{O}_{qu}^{(8)(3333)};$$

- $q\bar{q}t\bar{t}$ operators
  - 14 relevant qqtt operators
  - Cross section is a quartic function of C, due to double insertion
  - interesting because resulting constraints are already comparable with $t\bar{t}$ measurements
    - Dominant sensitivity comes from C^4 terms
    - EFT validity requires kinematic cut M_{cut} on the energy scale of the analyzed events

σ_{EFT}/σ_{SM},
for tttt operator



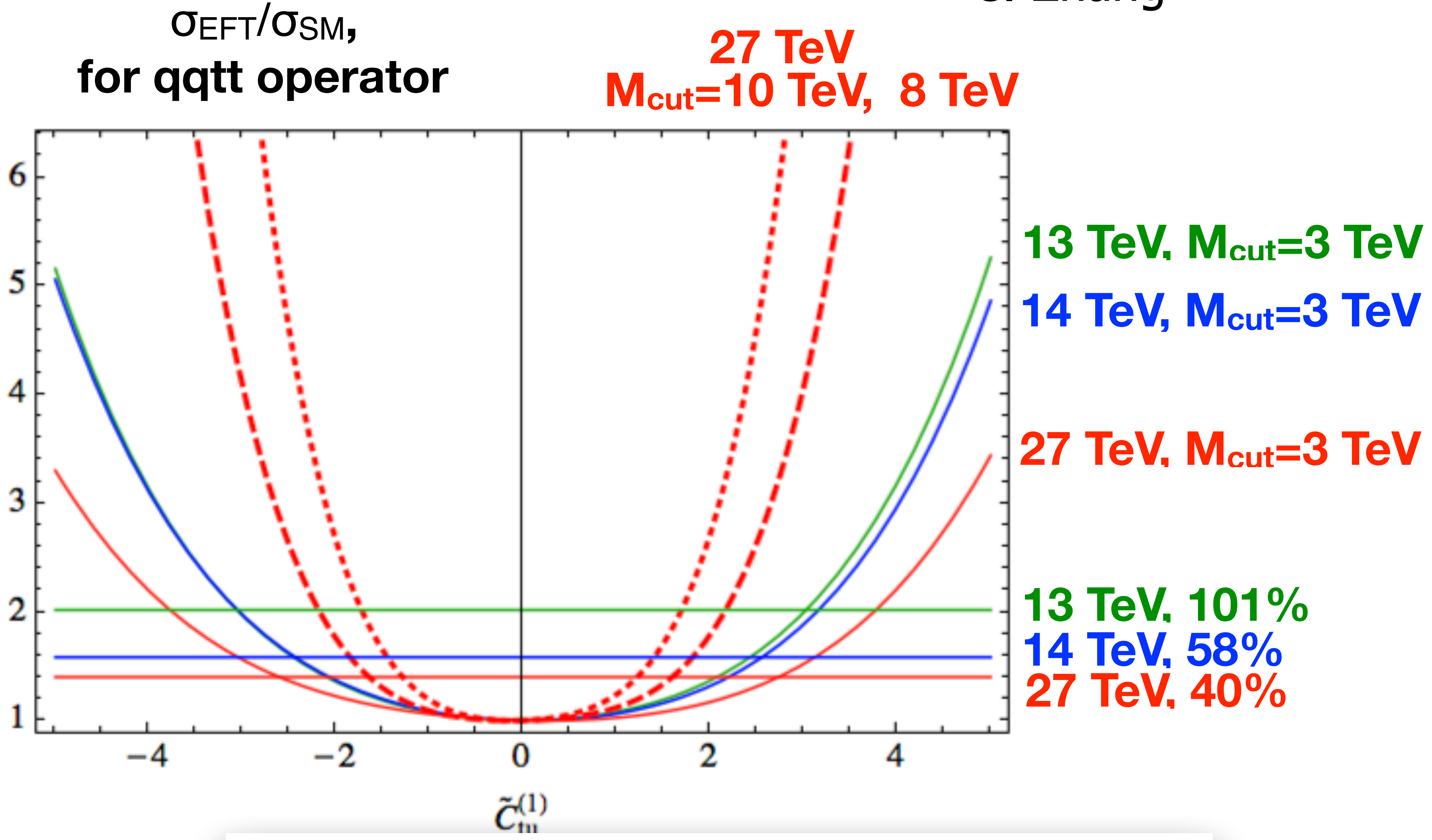
- extrapolation
  - Constraints on operator coefficients can be obtained by comparing the signal strength as a function of C with expected precision on the cross section
    - Assuming M_{cut} does not affect the projections very much
    - Constraints always come from upper bound on the cross section

- results for the constraints on $t\bar{t}t\bar{t}$ operators
  - bounds on operators coefficients improve at high energies
    - Improved precision on cross section
    - Slightly better sensitivities

Constraints from 4tops on the EFT 4-fermion operator at 14 TeV and 27 TeV

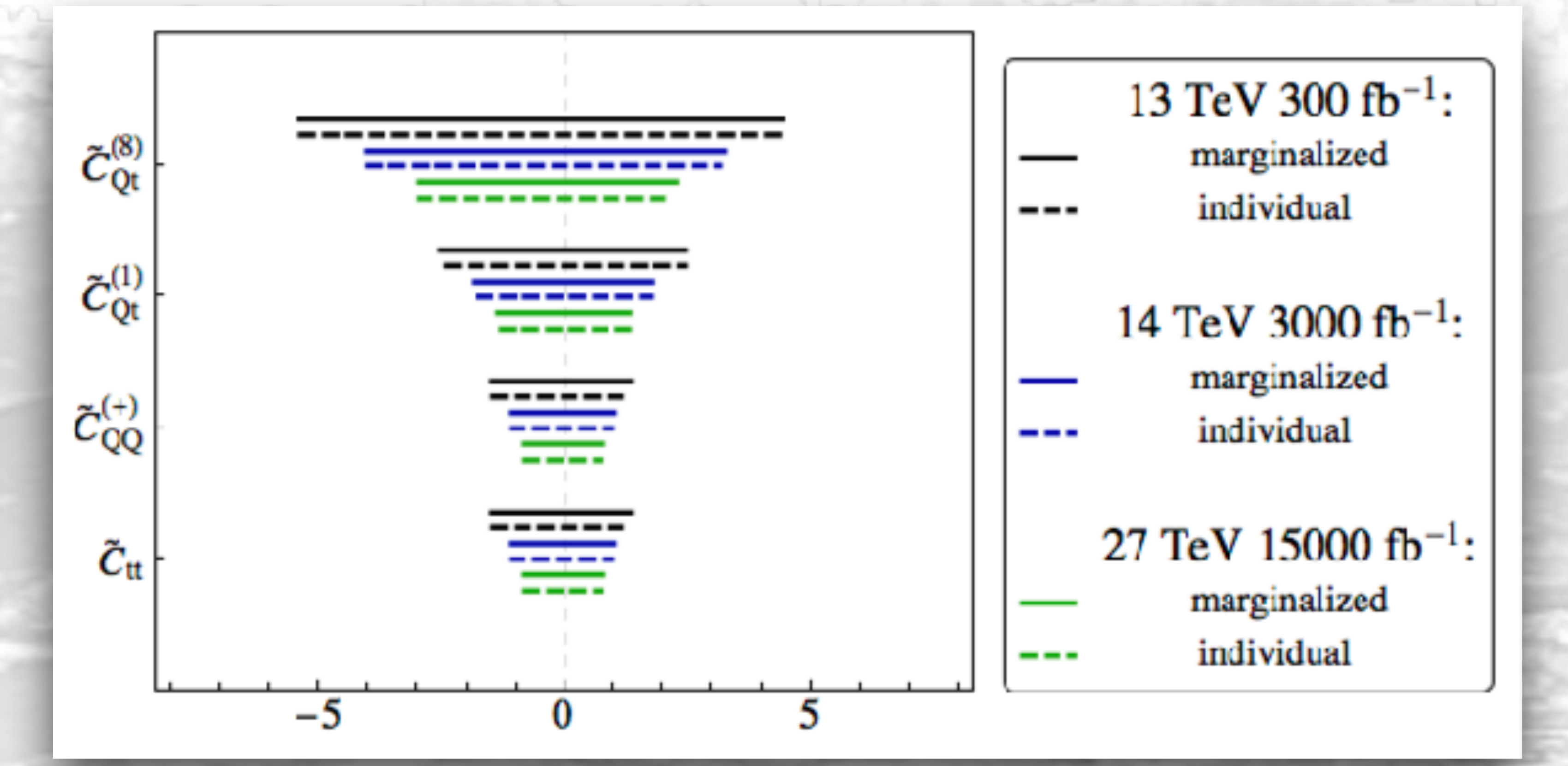
- results for the constraints on $q\bar{q}t\bar{t}$ operators
  - bounds don't improve at 27 TeV: sensitivity to operators becomes smaller at 27 TeV, if M_{cut} =3 TeV is kept
  - Dominant contributions at 27 TeV come from larger energy scale. M_{cut} =~10 TeV is required to capture those and reach better sensitivities. However 10 TeV is too large for EFT interpretation.
  - Possible reason: double insertion diagrams dominate, but they are qq initiated.

C. Zhang

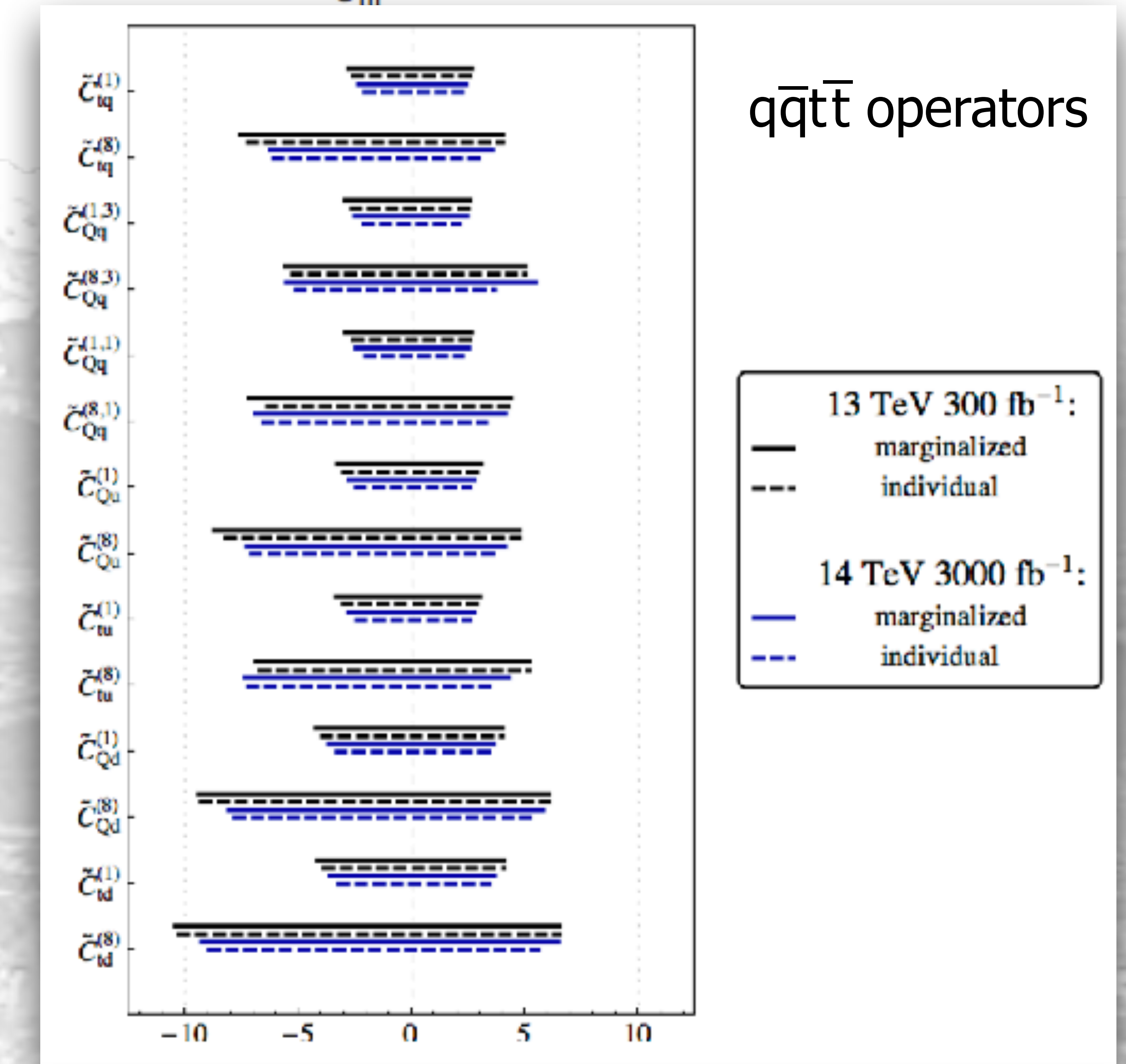


- projected limits on operators coefficients
  - Only based on inclusive cross section (below cut). In principle a tailored analysis can yield better results (~ factor of 2). M_{cut} needs to be taken into account.

$t\bar{t}t\bar{t}$ operators



$q\bar{q}t\bar{t}$ operators

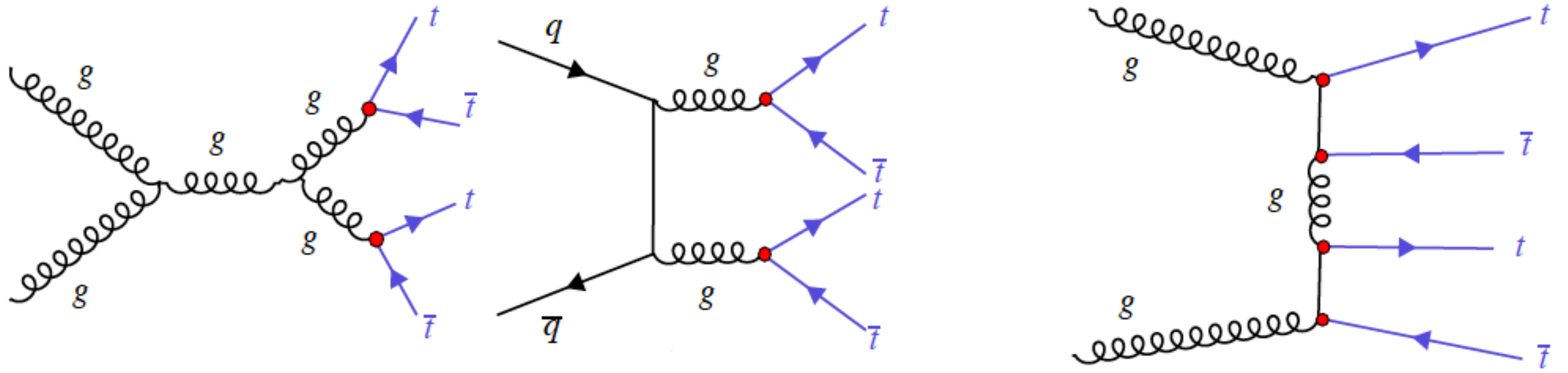


Constraints on chromo-magnetic and chromo-electric dipole moments at 14 TeV and 27 TeV

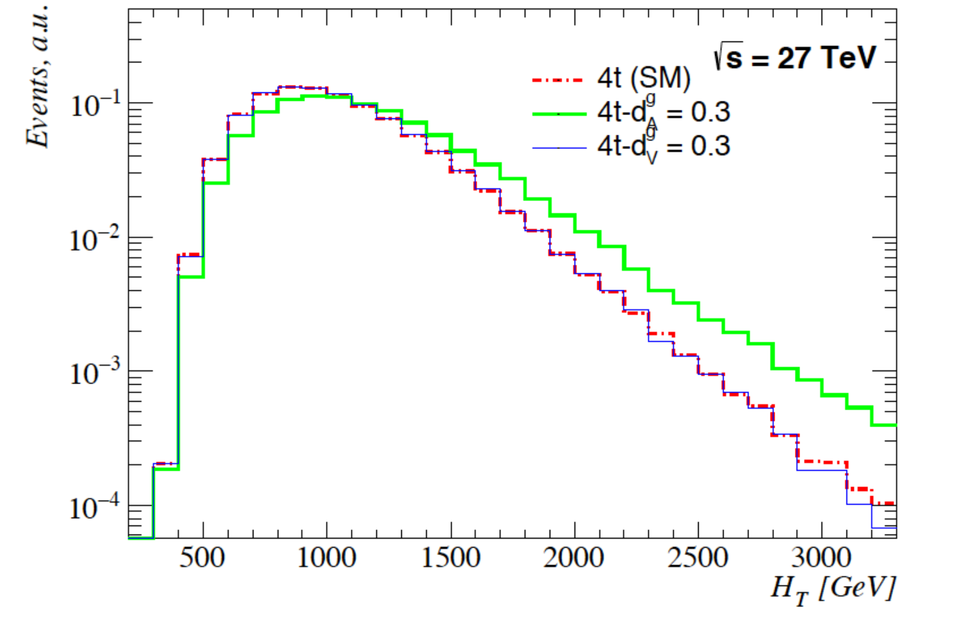
Ebadi, Khanpour, Khatibi, Mohammadi Najafabad

- Top quark strong dipole moments
  - most general gtt coupling considering 6D operators
    - d^g_V and d^g_A are the chromo-magnetic and chromo-electric dipole moments of the quark (=0 at LO in the SM)
  - latest experimental limits (Tevatron + LHC8):
    $-0.012 < d^g_V < 0.023$ and $|d^g_A| < 0.087$

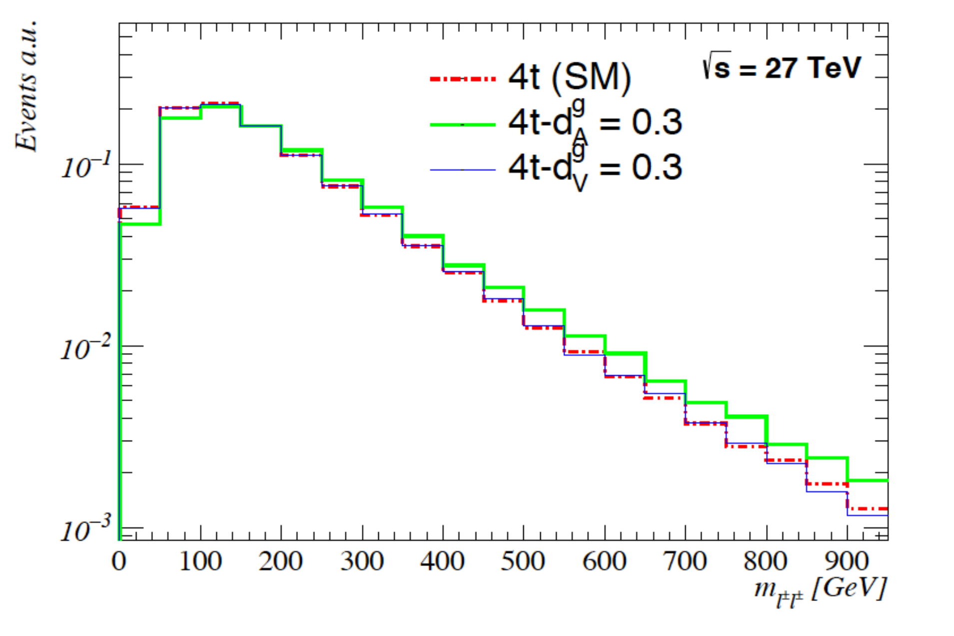
$$\mathcal{L}_{gt\bar{t}} = -g_s\bar{t}\frac{\lambda^a}{2}\gamma^\mu t G^a_\mu - g_s\bar{t}\lambda^a\frac{i\sigma^{\mu\nu}q_\nu}{m_t}(d^g_V + i d^g_A\gamma_5)tG^a_\mu$$



- 4top production is affected by anomalous gtt coupling
  - study concentrated on the same-sign dilepton channel
  - signal and backgrounds are generated by LO MadGraph5_aMC@NLO
    - main background considered ttZ and ttW
  - jets are reconstructed using the anti-kt algorithm



- selection
  - Exactly two same-sign charged leptons with pT > 25 GeV and |η| < 2.5
  - The missing transverse energy has to be larger than 30 GeV
  - At least eight jets with pT > 30 GeV and |η|< 2.5 from which at least three b-tagged jets
  - Well isolated objects in the final state by requiring ΔR (i,j) > 0.4



- results (95% C.L)

Coupling	*HL-LHC, 14 TeV,Â 3 ab⁻¹*	*HE-LHC, 27 TeV, 15 ab⁻¹*
d^g_V	Â $-0.084 < d_V{}^g < 0.009$	Â $-0.063 < d_V{}^g < 0.001$
d^g_A	$-0.030 < d_A{}^g < 0.030$	$-0.011 < d_A{}^g < 0.011$

Extraction of the Higgs width and top quark Yukawa coupling using $t\bar{t}H$ and 4top

Cao, Chen, Liu

- assumption
  - $t\bar{t}t\bar{t}$ is supposed to be SM like, while the top-Higgs Yukawa couplings could be altered by new physics
  - expectation for $\mu_{t\bar{t}H(b\bar{b})} = 1.00 \pm 0.01$ (100 TeV prospects)
- method
  - $t\bar{t}t\bar{t}$ cross section extraction by performing a Delphes analysis in the same-sign dilepton channel
  - 5σ discovery expected with 2.1 ab^{-1} at 14 TeV, $\kappa_t \leq 1.406$

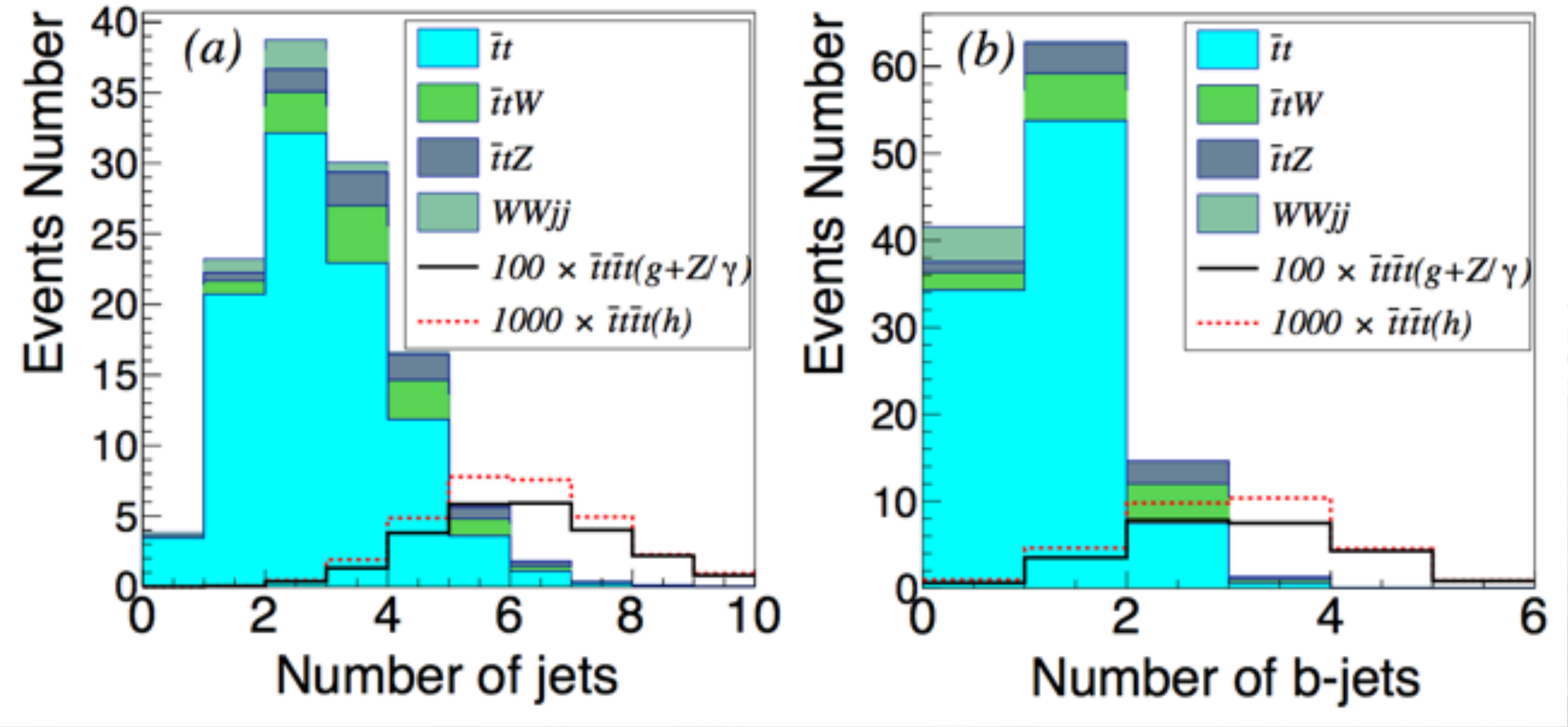
$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \kappa_t^2 \sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int} + \kappa_t^4 \sigma^{\rm SM}(t\bar{t}t\bar{t})_H$$

$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} \propto \left|\mathcal{M}_g + \mathcal{M}_{Z/\gamma}\right|^2 \qquad \kappa_t \equiv y_{Htt}/y_{Htt}^{\rm SM}$$

	14 TeV	100 TeV
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma}$:	13.140 fb,	3276 fb,
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_H$:	1.515 fb,	271.3 fb,
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int}$:	−2.007 fb,	−356.9 fb.

collision energy	14 TeV	100 TeV
Basic	$p_T^{j,\ell} \geq 20$ GeV, $\lvert\eta^{j,\ell}\rvert < 2.5$	$p_T^{j,\ell} \geq 20$ GeV, $\lvert\eta^{j,\ell}\rvert < 2.5$
SSL	$N_{\ell^\pm} = 2$	$N_{\ell^\pm} = 2$
Jets	$N_{\rm jets} \geq 5$, $N_{b-\rm jets} \geq 3$	$N_{\rm jets} \geq 6$, $N_{b-\rm jets} \geq 3$
$\not{E}_T$	$\not{E}_T \geq 100$ GeV	$\not{E}_T \geq 150$ GeV
m_T	$m_T \geq 100$ GeV	$m_T \geq 100$ GeV
H_T	$H_T \geq 700$ GeV	$H_T \geq 800$ GeV

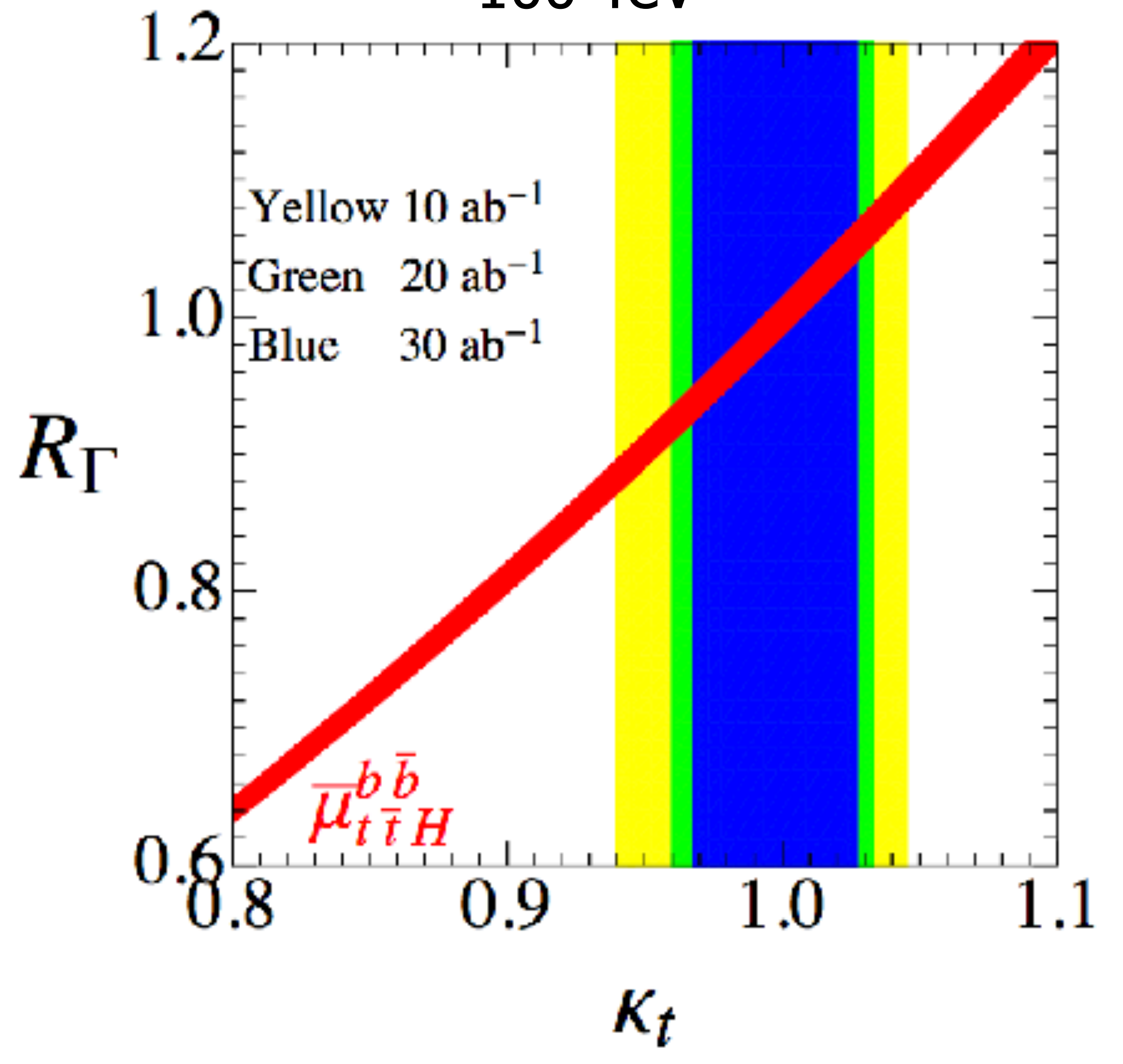
1fb^{-1}, 14 TeV



300 fb^{-1}, 14 TeV

	Basic	SSL	Jets	$\not{E}_T$	m_T	H_T
$t\bar{t}t\bar{t}_H$	577.22	9.82	4.68	2.43	1.33	1.21
$t\bar{t}t\bar{t}_{g+Z/\gamma}$	5006.34	78.15	37.02	19.25	11.09	10.16
$t\bar{t}t\bar{t}_{\rm int}$	-764.67	-12.79	-6.19	-3.23	-1.93	-1.77
$t\bar{t}$	2.5×10^8	28802.4	44.1	18.9	0	0
$t\bar{t}W^+$	32670	2359.5	36.9	17.7	12.3	8.7
$t\bar{t}W^-$	16758	1397.1	49.5	9.9	4.5	4.5
$t\bar{t}Z$	24516	2309.4	20.1	10.8	10.8	9.3
$W^\pm W^\pm jj$	4187.7	1147.5	0.11	0	0	0

100 TeV



Conclusion

- On-going efforts to release 4top results for the Yellow Report
  - clear plan established for this section
  - great theory progress on several fronts:
    - precision: complete NLO predictions for the 4 top cross section numbers at 14 TeV and 27 TeV
    - 4 tops as a probe for new physics
      - constraints on the EFT qqtt 4-fermion operator at 14 TeV and 27 TeV
      - constraints on chromo-magnetic and chromo-electric dipole moments at 14 TeV and 27 TeV
      - Higgs width and top quark Yukawa coupling

  - Experimental results in progress
    - analysis strategy based on upcoming Run2 results
    - fast simulation analysis starting