HL/HE-LHC physics prospectives in top quark physics

HL/HE-LHC CERN Yellow Report activities

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top LHC-France
LPNHE, 25 May 2018

Introduction

- High-Luminosity LHC and High-Energy LHC
  - CERN is preparing a Yellow Report for the end of 2018 as input to the European Strategy for Particle Physics
  - Assessment of the physics reach of the upgraded detectors with 3 ab^{-1}
  - Assessment the physics reach of the energy doubler

- HL/HE-LHC reference parameters
  - HL-LHC: $\sqrt{s}$ = 14 TeV, 3 ab^{-1}
  - HE-LHC: $\sqrt{s}$ = 27 TeV, 15 ab^{-1}

- YR organisation and timeline
  - 5 WG (chapters): SM&TOP, Higgs, BSM, Flavour, Heavy Ion
  - timeline:
    - 18-20 June 2018 - Plenary meeting @CERN (table of contents)
    - September 2018: Full Draft Chapters (one per WG 150 Pages each)
    - December 2018: Submission

	13 TeV - 30 fb^{-1}	**13/14 TeV - 3000 fb^{-1}**
$t\bar{t}$	30 Mevts	3 Gevts
$t\bar{t}$ (fiducial)	1.55 Mevts	155 Mevts
$t\bar{t}$ with $M_{t\bar{t}} > 1$ TeV (fiducial)	30 kevts	3 Mevts
$t\bar{t}$ with $M_{t\bar{t}} > 2$ TeV (fiducial)	480 evts	48 kevts
t-channel	6 Mevts	600 Mevts
Wt-channel	2 Mevts	200 Mevts
s-channel	300 kevts	30 Mevts
ttV	30 kevts	3 Mevts
tZ	3 kevts	300 kevts
tH	300 evts	30 kevts

Organisation

YR Steering

Overall Coordination

[Michelangelo Mangano]

+

ATLAS Contact – CMS Contact – LHCb Contact – ALICE Contact – Theory Contact

Aleandro Nisati — Andreas Meyer — Mika Vesterinen — Andrea Dainese — Gavin Salam

WG1: Standard Model

Alessandro Tricoli – ATLAS
Patrizia Azzi – CMS
Stephen Farry – LHCb
Paolo Nason – Theory
Dieter Zeppenfeld – Theory

WG2: Higgs

Marumi Kado – ATLAS
Maria Cepeda – CMS
Phil Ilten – LHCb
Stefania Gori – Theory
Francesco Riva – Theory

WG3: BSM

Monica D'onofrio – ATLAS
Keith Ulmer – CMS
Xabier Cid Vidal – LHCb
Patrick J Fox – Theory
Riccardo Torre – Theory

WG4: Flavour Physics

Alex Cerri – ATLAS
Sandra Malvezzi – CMS
Vladimir Gligorov – LHCb
Jorge Camalich – Theory
Jure Zupan – Theory

WG5: Heavy Ions

Zvi Citron – ATLAS
Yen-Jie Lee – CMS
Michael Winn – LHCb
Jan Fiete Grosse-Oetringhaus – ALICE
Urs Wiedemann – Theory
John Jowett – LHC

WG1 Chapter draft

- studies are currently on-going
  - joint theory and experimental efforts
  - no public results yet
  - see plans at the May 2nd WG1 meeting

- Target for whole chapter: ~150 pages.
- Page allocation per section is approximate
  - Introduction - 10 pages
  - Theoretical Tools 25 pages
    - MC Generators (5 pages), High Order QCD calculations (5 pages), EW corrections (5 pages), PDF tools (5 pages), EFT tools (5 pages)
  - Electroweak processes - 35 pages
    - Vector boson fusion processes (5 pages), Vector Boson scattering (10 pages), Triboson production (5 pages), Precision EW measurements (10 pages), Forward EW physics (5 pages)
  - Strong Interactions - 26 pages
    - Jets and photons (8 pages), Ultimate Parton Densities (10 pages), Forward and Soft QCD physics (8 pages)
  - Top Physics - 36 pages
    - Top cross section (5 pages), Top properties (10 pages), Top couplings (5 pages) , Top mass (8 pages), FCNC (8 pages)
  - Effective coupling interpretations - 10 pages

$t\bar{t}$ cross section

- theory studies
  - provide numbers/distributions at 14 TeV
  - 27 TeV $t\bar{t}$ cross section 4x larger than at 14 TeV

✓ At a 27 TeV HE-LHC the top-pair production cross-section is very large:

$$\sigma_{tot} = 3727^{+119(3.2\%)}_{-180(4.8\%)} \text{(scales)}^{+31(0.8\%)}_{-31(0.8\%)} \text{(pdf)} \ \text{[pb]} \quad \text{(in NNLO QCD)}$$
$$\sigma_{tot} = 3794^{+88\ (2.3\%)}_{-142(3.7\%)} \text{(scales)} \ \text{[pb]} \quad \text{(in NNLO+NNLL QCD)}$$

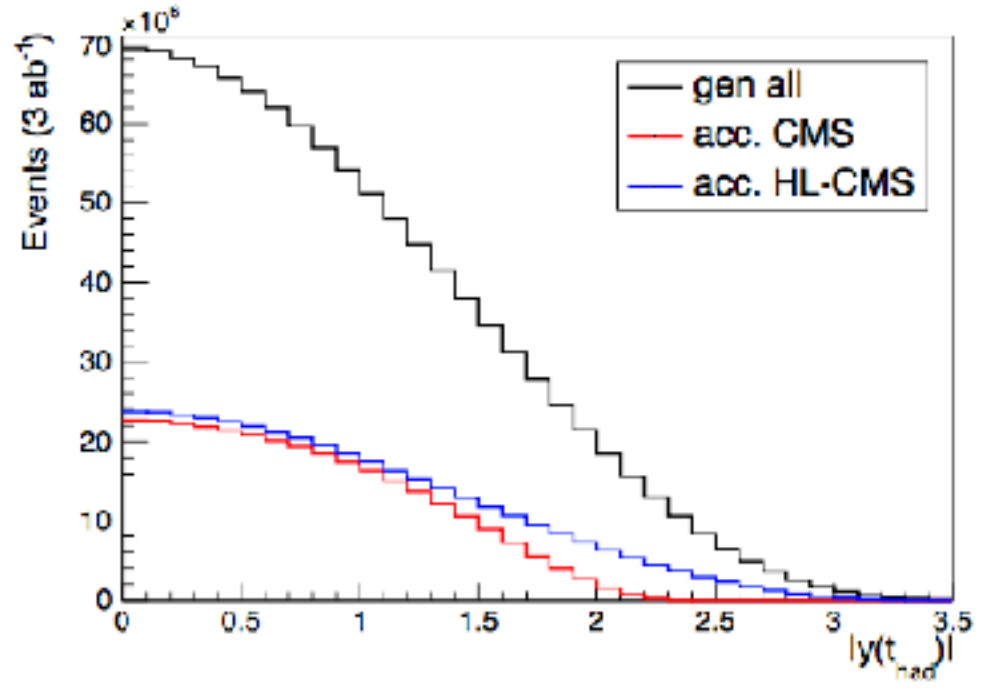
- working on soft gluon resummation and EW corrections

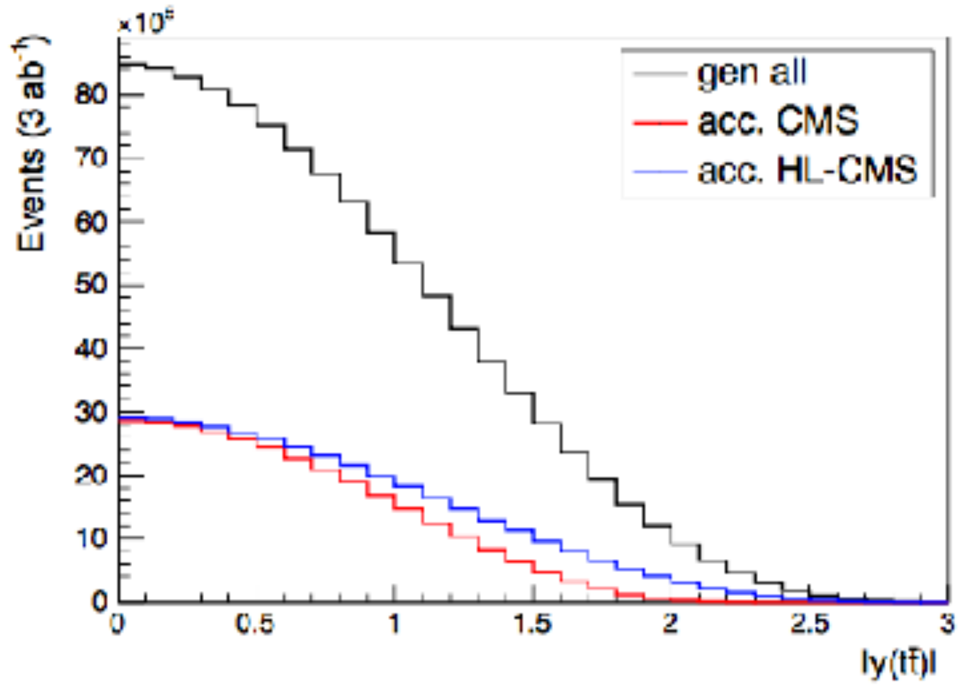
- experimental plans
  - 1D-2D distributions with higher acceptance
  - understand pile-up
  - how to scale systematic uncertainties ?

■ **Jet energy scale:** today highest uncertainty is 2–3% (for $|\eta| < 2.4$) →preliminary recommendations for upgrade 1% for all jets $|\eta| < 3.8$.

■ **Final and initial scale shower:** preliminary recommendations suggests reduction by factor 1/2, same for all theoretical uncertainties including PDFs.

■ **Luminosity** reduction from 2.7% to about 1%.





✓ At LHC at 27 TeV very large M_{tt} can be reached

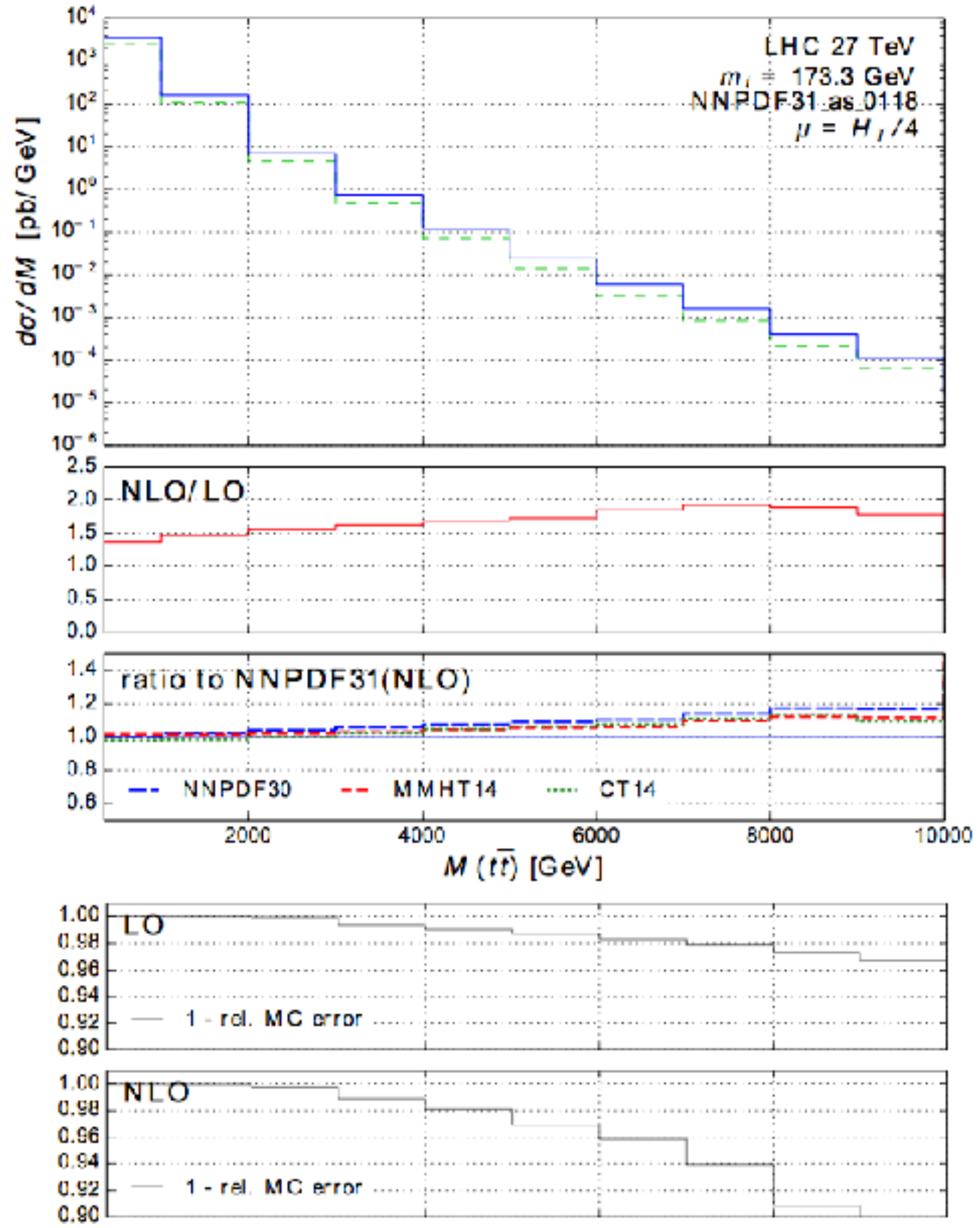
✓ Estimates at LO and NLO:

✓ 10% effect in the tails from NNPDF3.1 w/r to older sets

✓ MC error can be handled up to M_{tt}~10TeV

✓ The dynamic scales behave OK (at least) up to 10 TeV

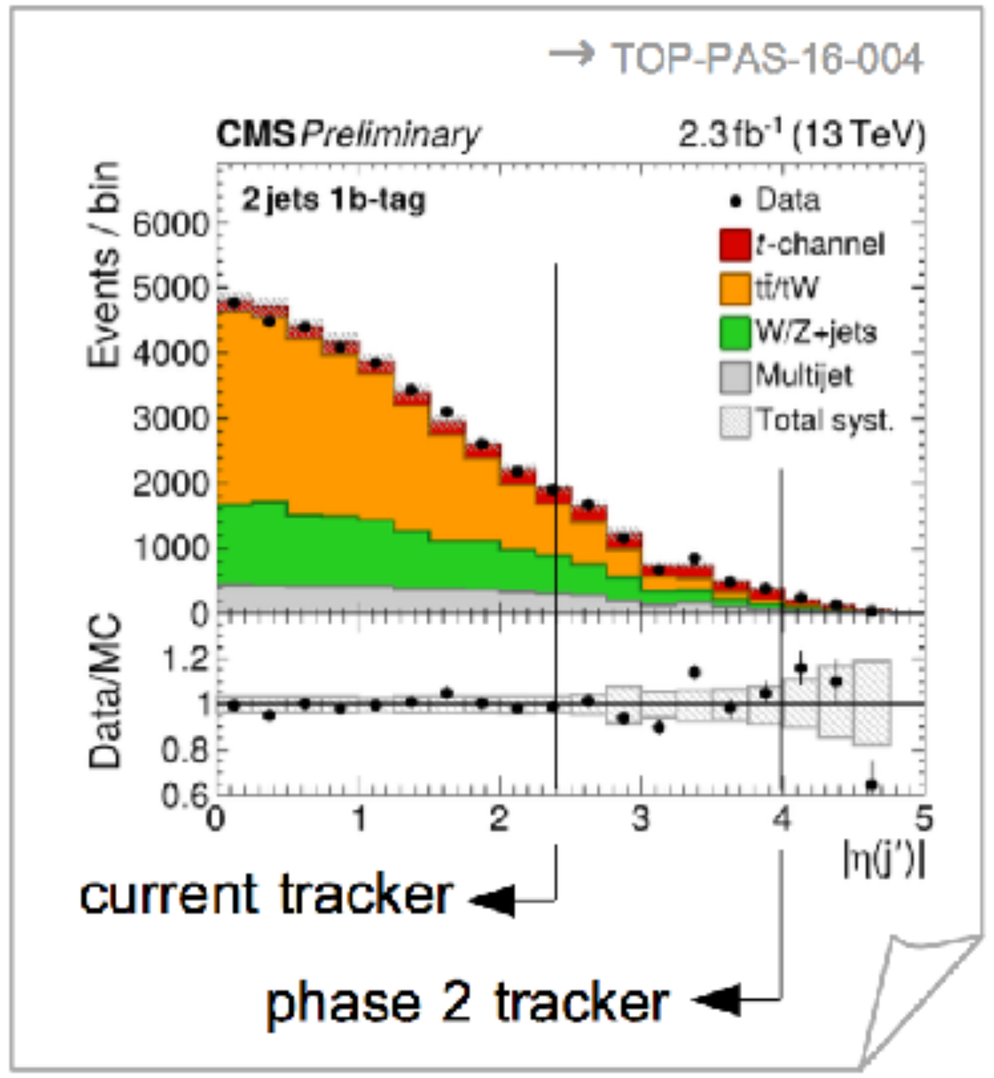
✓ Very modest growth of scale error



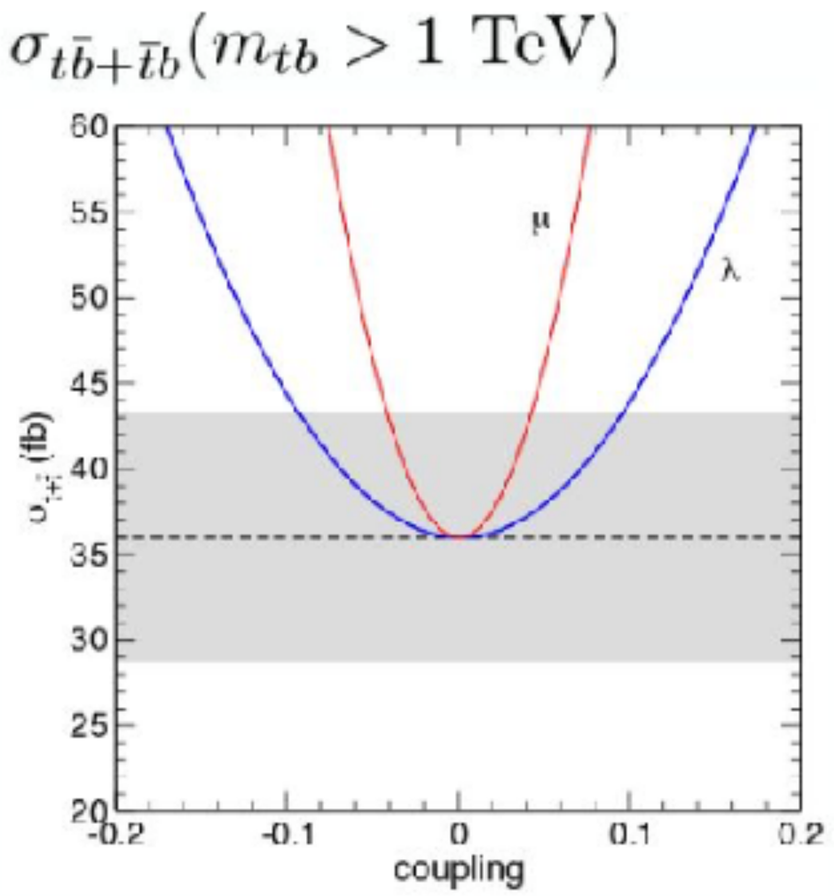
Single top

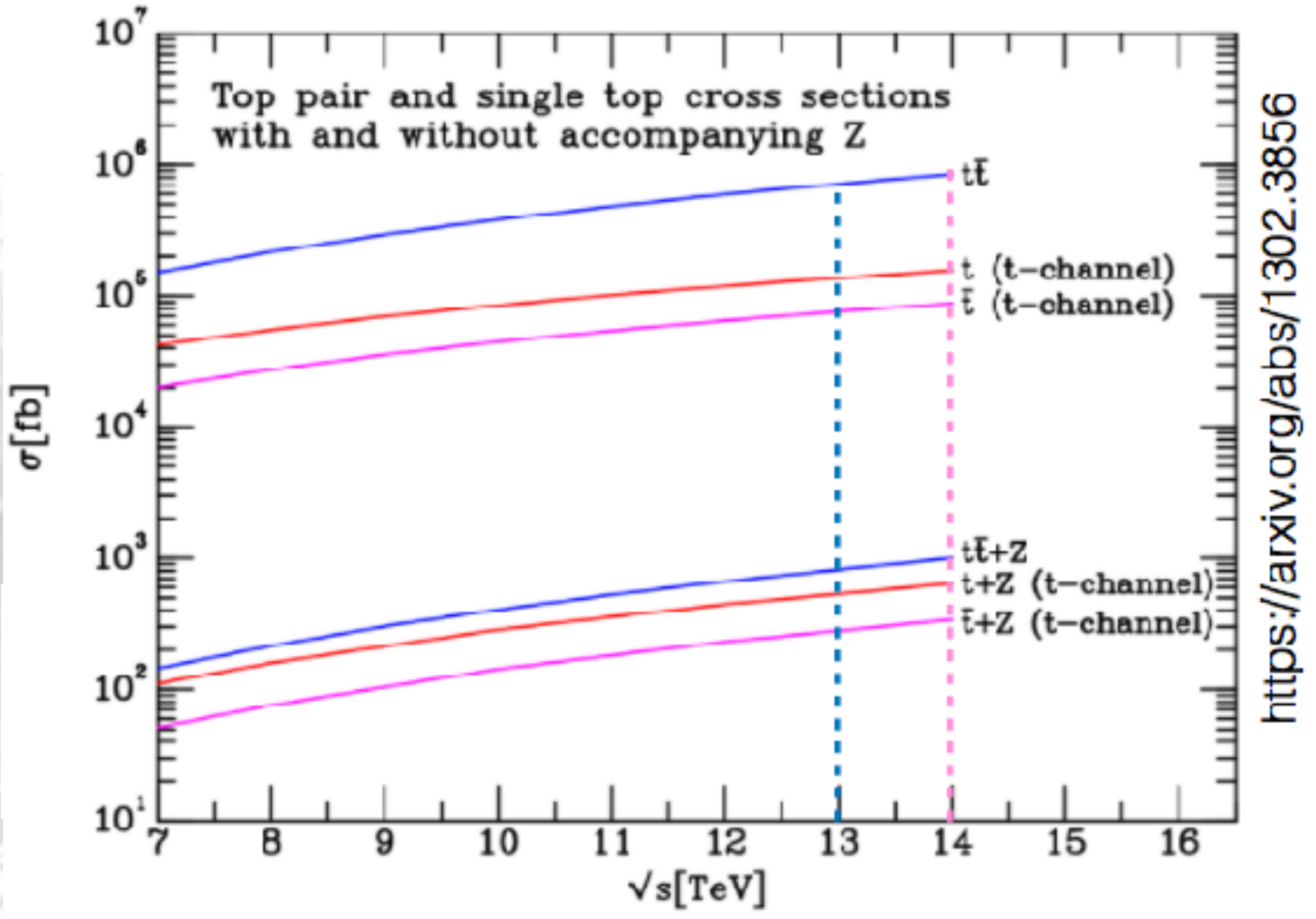
- theory studies
  - Cross-sections and differential distributions for HE
  - Tails of distribution at HL/HE, EW corrections ?
  - Channel separation (t,s,Wt), potential issues with HL precision
  - Modeling, 4FNS/5FNS, NNLOPS

- experimental plans
  - t-channel differential measurement (larger acceptance, HL-LHC result sensitivity to EFT and PDF)
  - s-channel measurement (HL-LHC as a benchmark, HE-LHC: High-q2 analysis, limits on Wtb couplings)
  - tZq measurement (inclusive and differential HL-LHC results)

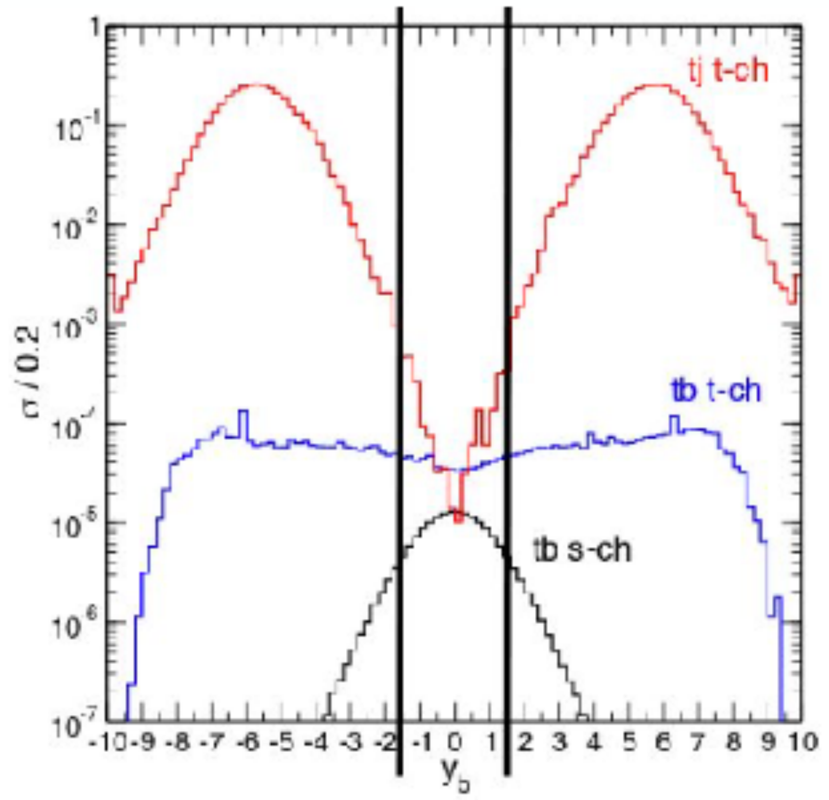


m_{tb}>1 TeV



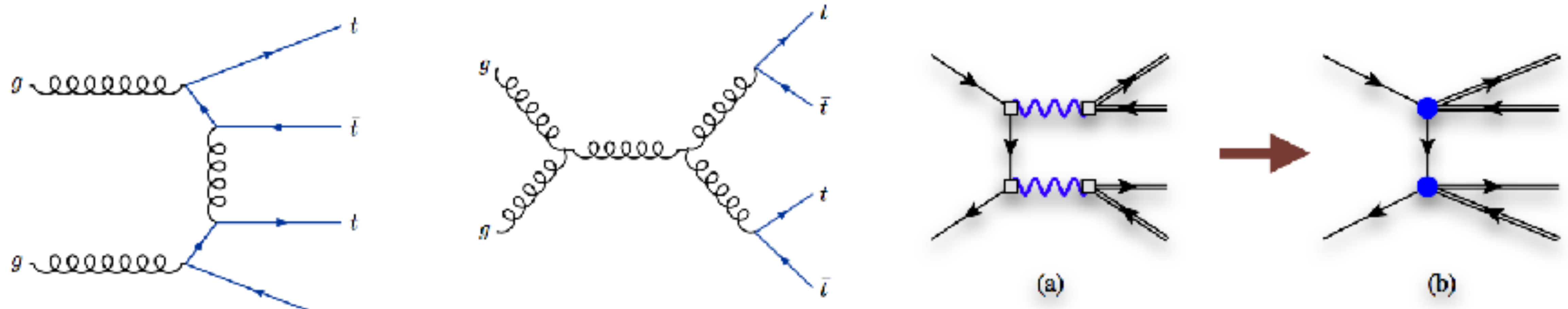


m_{tb}>10 TeV

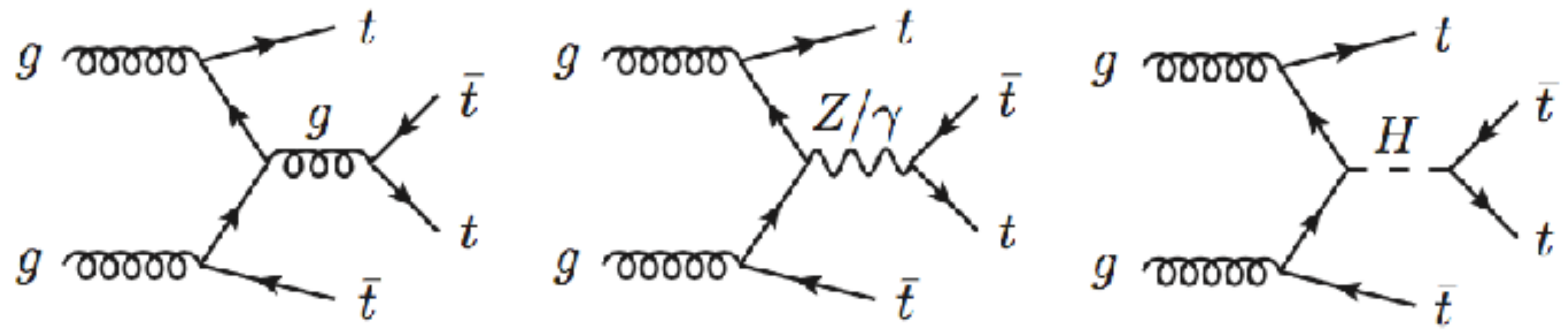


4 top cross section

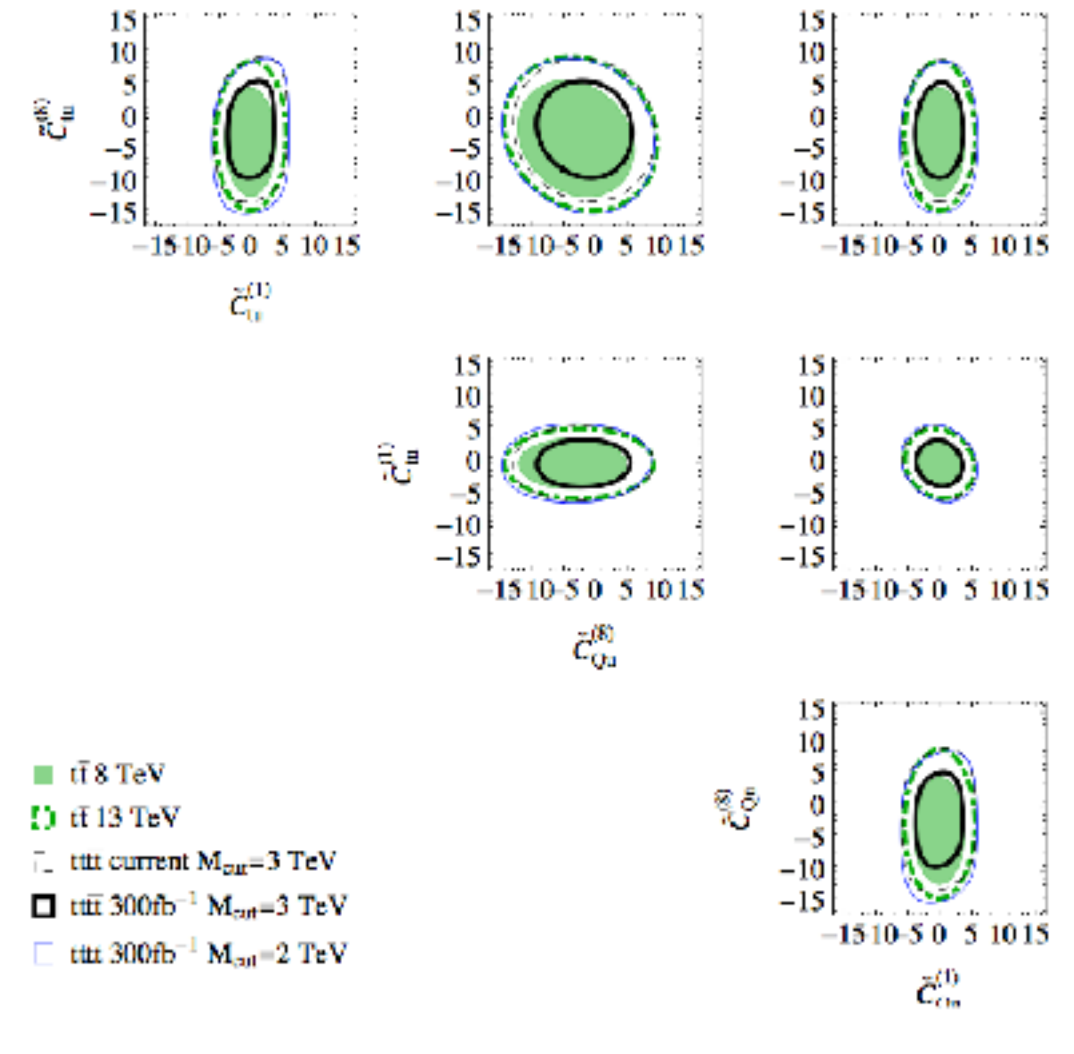
- theory studies
  - provide complete NLO predictions
  - four tops as a probe to new physics:
    - Constraining qqtt operators in the EFT
    - Constraining top quark flavor violation and dipole moments through three and four-top quark productions at the LHC
    - Higgs width and top quark Yukawa coupling



Two dim-6



- experimental plans
  - inclusive and differential results in the multilepton channel
    - fast simulation analysis or extrapolation



Use 3 and 4 tops to constrain FCNC top decays

Branching fraction	three-top, 300 fb^{-1}	three-top, 3 ab^{-1}	other-channels, HL-LHC, 3 ab^{-1}
$\mathcal{B}(t \to uH)$	1.03×10^{-3}	3.09×10^{-4}	2.4×10^{-4} [105]
$\mathcal{B}(t \to cH)$	8.52×10^{-3}	2.54×10^{-3}	2.0×10^{-4} [105]
$\mathcal{B}(t \to ug)$	4.00×10^{-4}	1.19×10^{-4}	-
$\mathcal{B}(t \to cg)$	4.51×10^{-3}	1.35×10^{-3}	-
$\mathcal{B}(t \to uZ) - \sigma_{\mu\nu}$	2.73×10^{-3}	8.18×10^{-4}	4.3×10^{-5} [105]
$\mathcal{B}(t \to cZ) - \sigma_{\mu\nu}$	2.67×10^{-2}	7.98×10^{-3}	5.8×10^{-5} [105]
$\mathcal{B}(t \to uZ) - \gamma_{\mu}$	5.73×10^{-3}	1.71×10^{-3}	4.3×10^{-5} [105]
$\mathcal{B}(t \to cZ) - \gamma_{\mu}$	4.52×10^{-2}	1.35×10^{-2}	5.6×10^{-5} [105]
$\mathcal{B}(t \to u\gamma)$	2.18×10^{-3}	6.53×10^{-4}	2.7×10^{-5} [106]
$\mathcal{B}(t \to c\gamma)$	2.14×10^{-1}	6.40×10^{-2}	2.0×10^{-4} [106]

4 tops xsect constrains on dipole moments

Coupling	Current four-top with 35.6 fb^{-1}	Future four-top with 300 fb^{-1}
d_V^g	[-0.20, 0.11]	[-0.07,0.03]
d_A^g	[-0.16, 0.16]	[-0.05, 0.05]
d_V^Z	[-1.42,1.45]	[-0.45, 0.47]
d_A^Z	[-1.65, 1.65]	[-0.53, 0.53]

13

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

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)

100

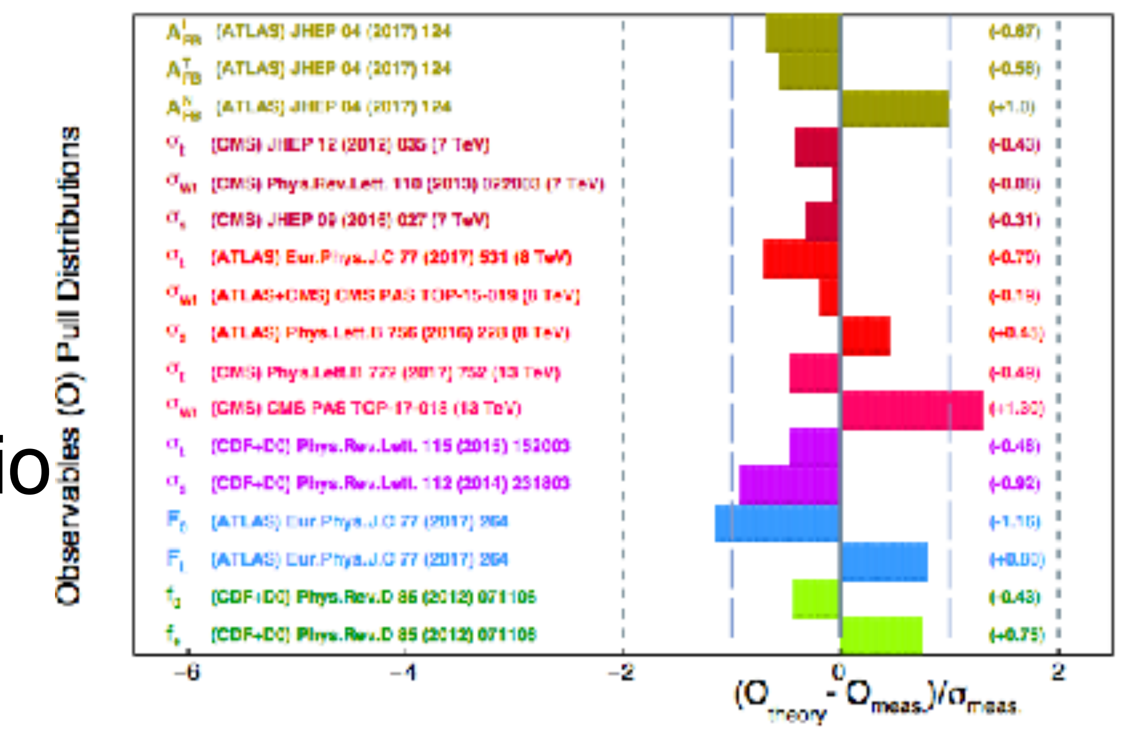
σ[pb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO(+NLO)}}{\mathrm{LO_{QCD}(+NLO_{QCD})}}$
$\mu = H_T/4$	$2.37^{+49\%}_{-31\%}$	$3.98^{+18\%}_{-19\%}$	$2.63^{+44\%}_{-28\%}$	$4.18^{+17\%}_{-17\%}$	1.11 (1.05)

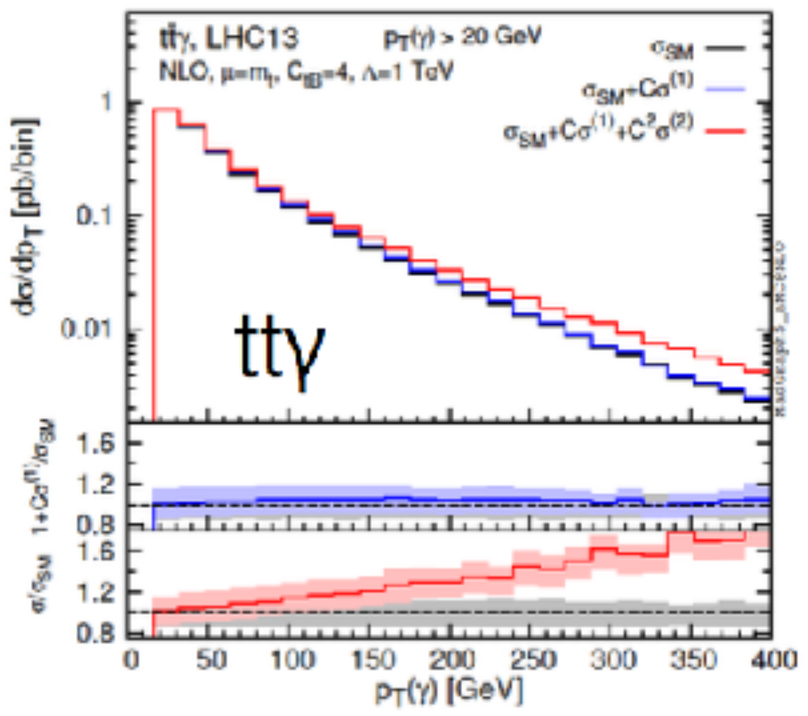
top couplings

- theory studies
  - Provide benchmark EFT cross-sections for HE-LHC
  - Investigate EFT effects in distributions for rare processes
  - Combine LHC13 predictions with HL-LHC projections to extract potential sensitivities

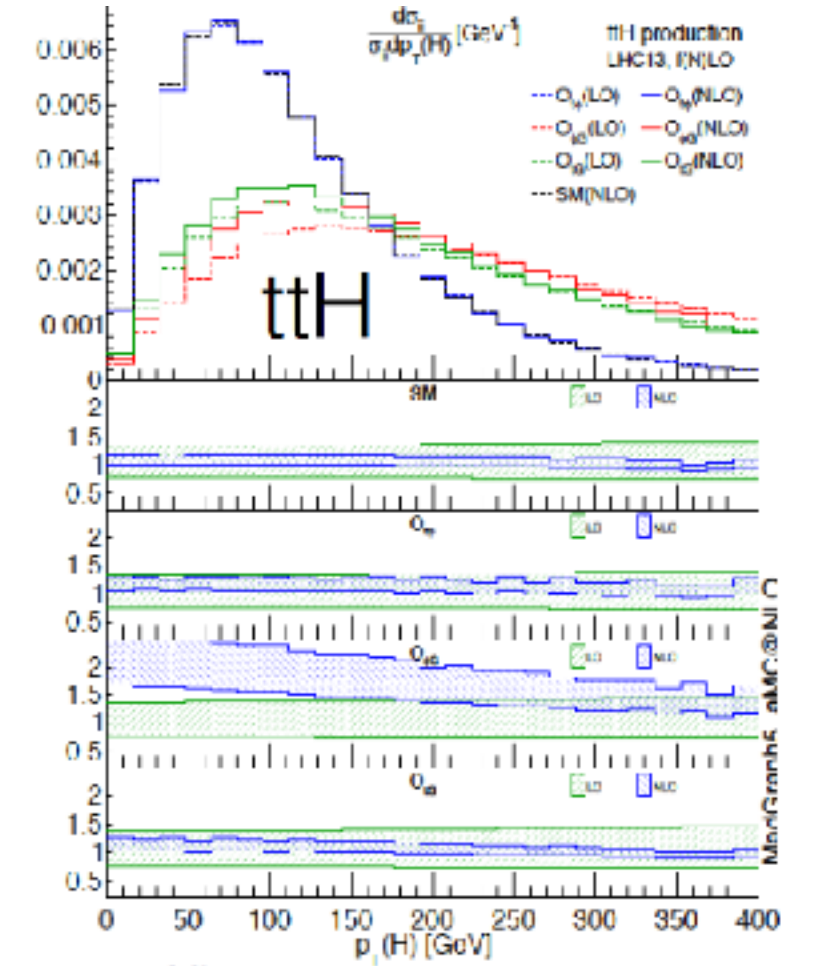
- experimental plans
  - ttV and ttγ
    - unfolded to particle level (ttZ pt(Z), ttW asymmetry, differential ttγ)
    - obtain projections of EFT sensitivity for HL-LHC scenario
  - Wtb: global fit using $t\bar{t}$ and single top distributions

PRD 97 (2018) no.1, 013007

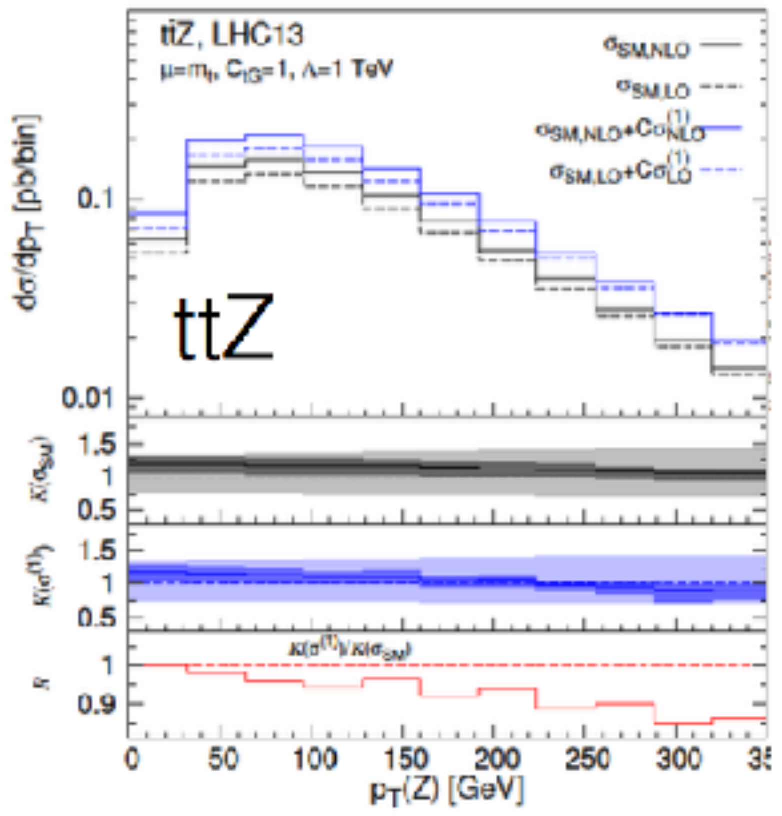


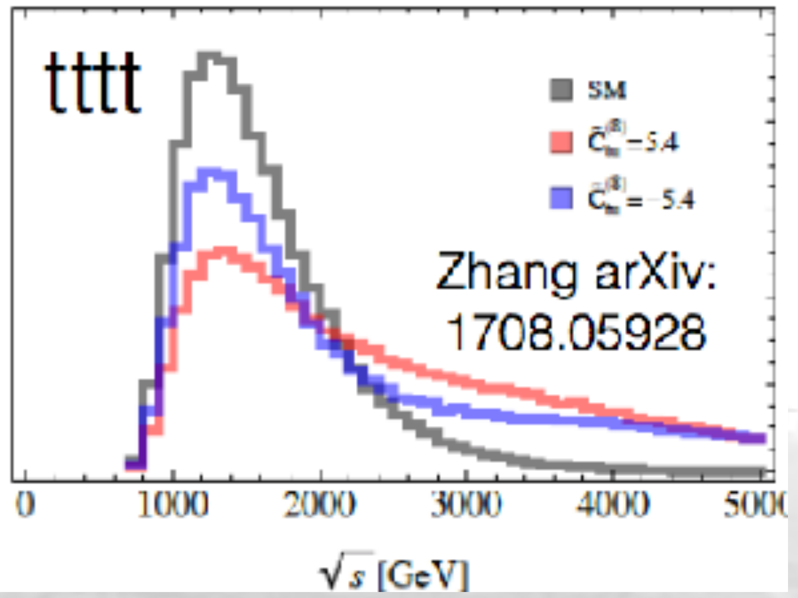


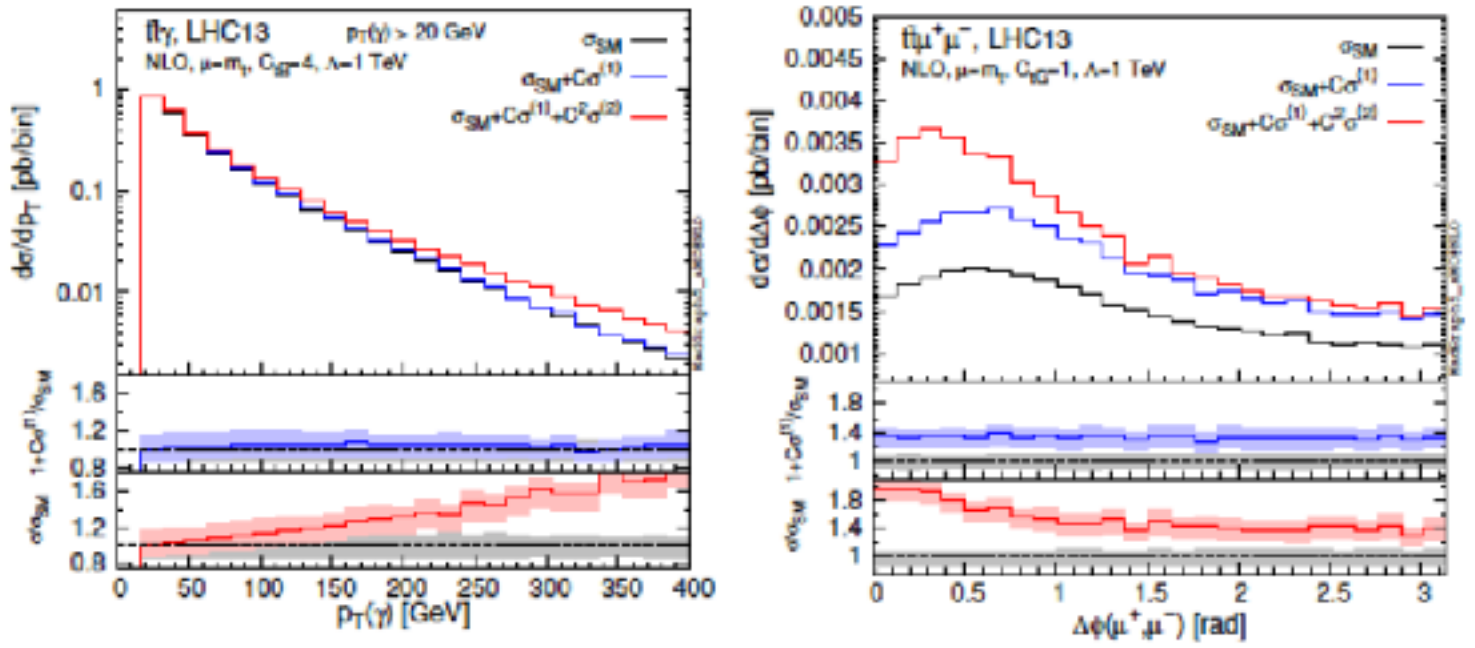
arXiv:1601.08193



arXiv:1607.05330

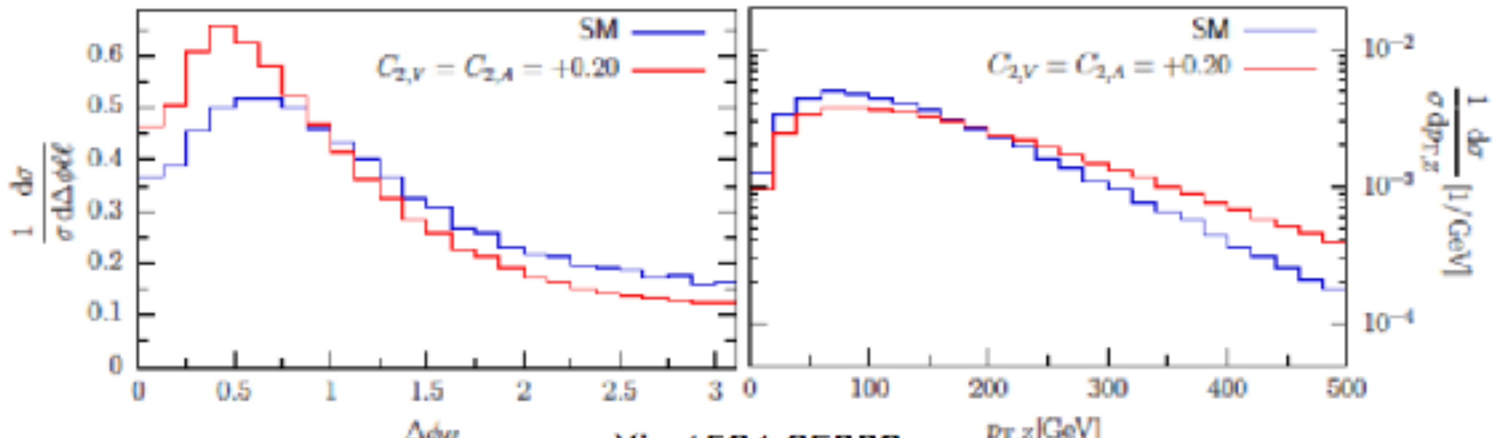




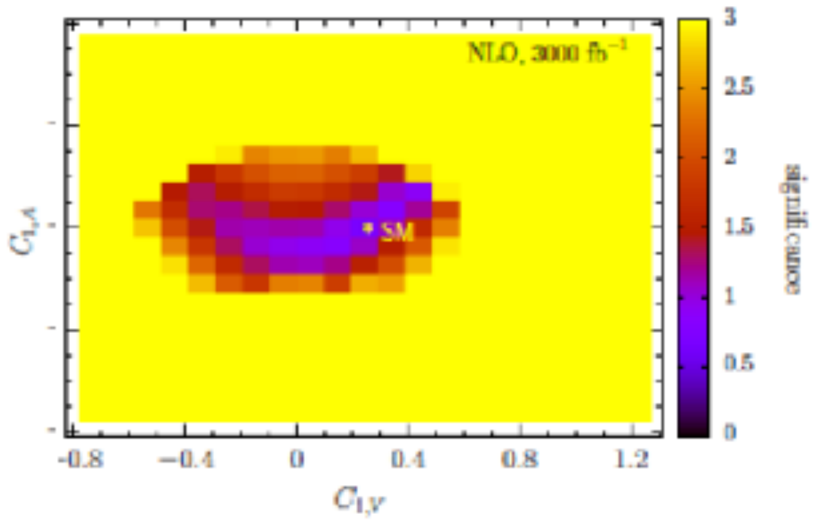


arXiv:1601.08193

Pheno studies already demonstrating the importance of differential information



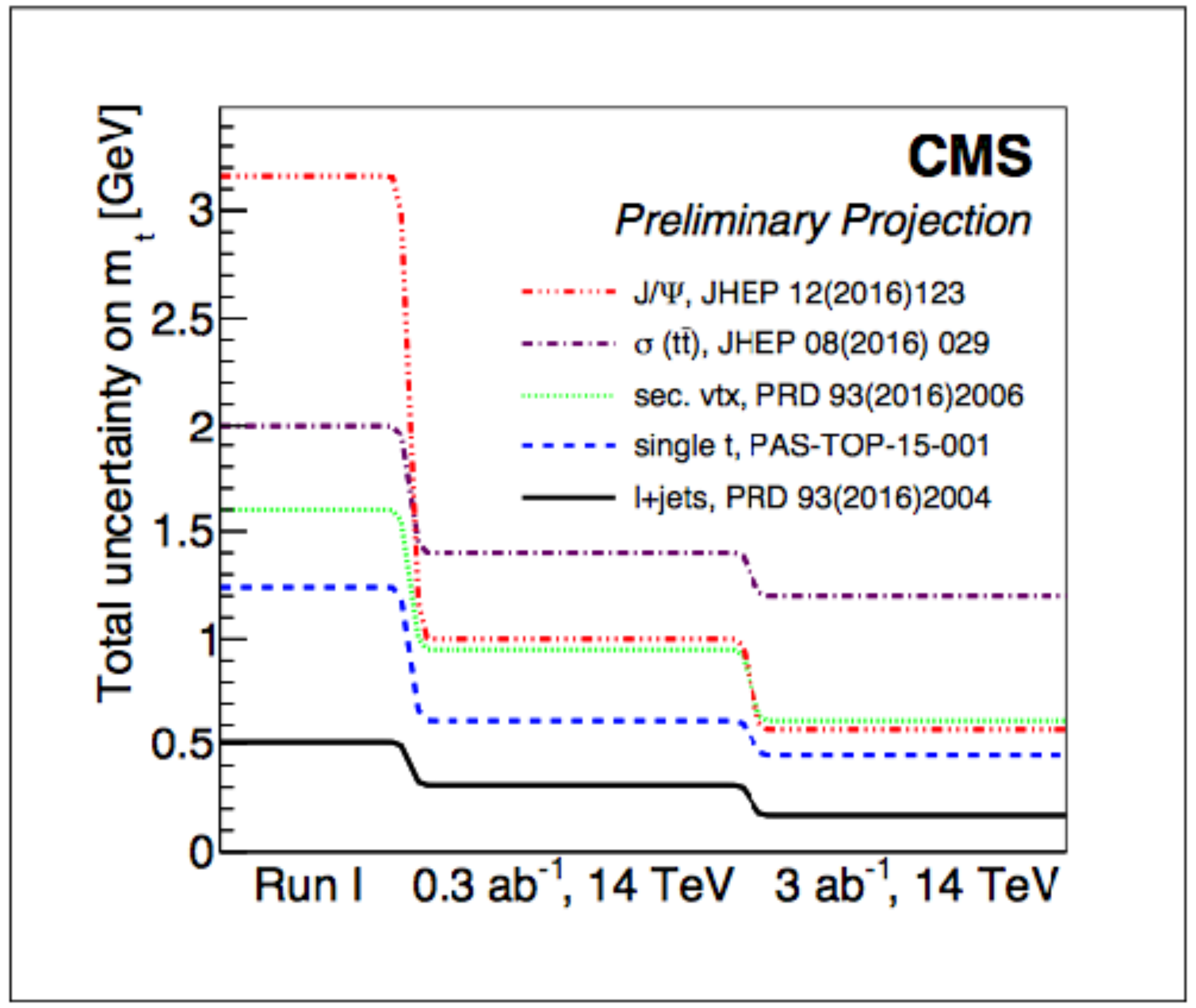
arXiv:1501.05939



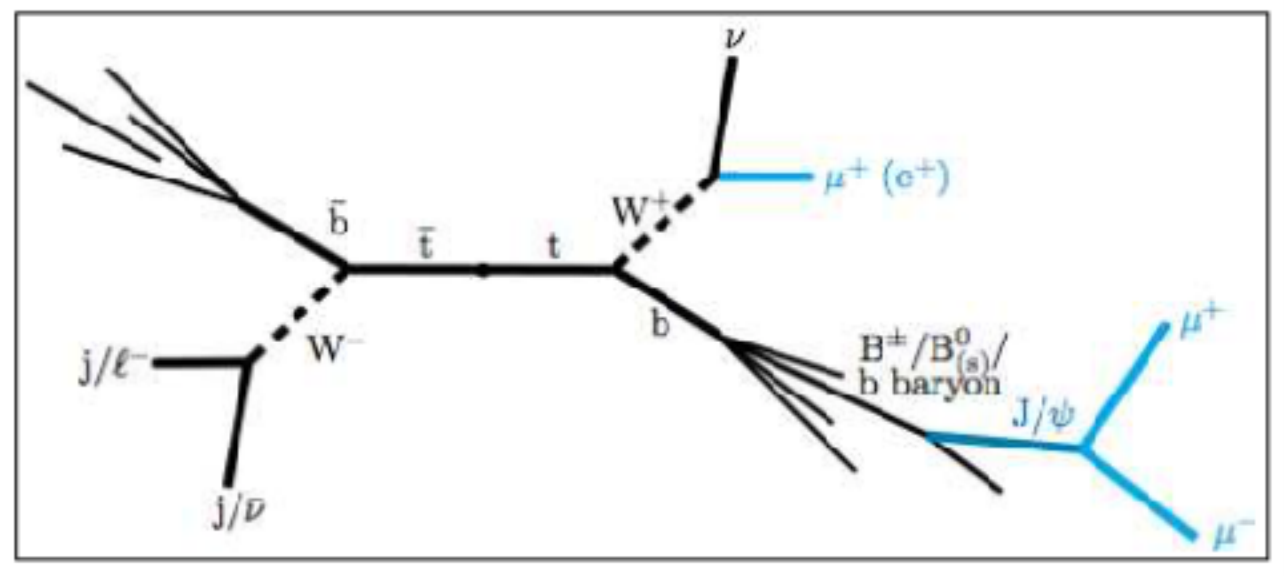
	OtW	OtG	OtB
sinlepton (36 fb^{-1})	0 +/- 1.2	0 +/- 0.54	0 +/- 0.7
sinlepton (3 ab^{-1})	0 +/- 0.14	0 +/- 0.06	0 +/- 0.077
dilepton (36 fb^{-1})	0 +/- 1.9	0 +/- 0.74	0 +/- 1.1
dilepton (3 ab^{-1})	0 +/- 0.24	0 +/- 0.083	0 +/- 0.13

top mass

- theory studies
  - interpretation of direct measurements
    - When using a LO Monte Carlo, do we extract a LO mass (i.e. do we expect corrections of order αsmt at NLO level?)
    - Is there a way to relate the Monte Carlo parameter to a well defined field theoretical mass definition? (Pole mass, MS mass, MSr mass, etc.)
    - How do we quantify the related uncertainties?
  - alternative measurements
    - Currently have large errors. Are there error sources that can be reduced with High Luminosity?
    - Are there theoretical hard limits on precision?

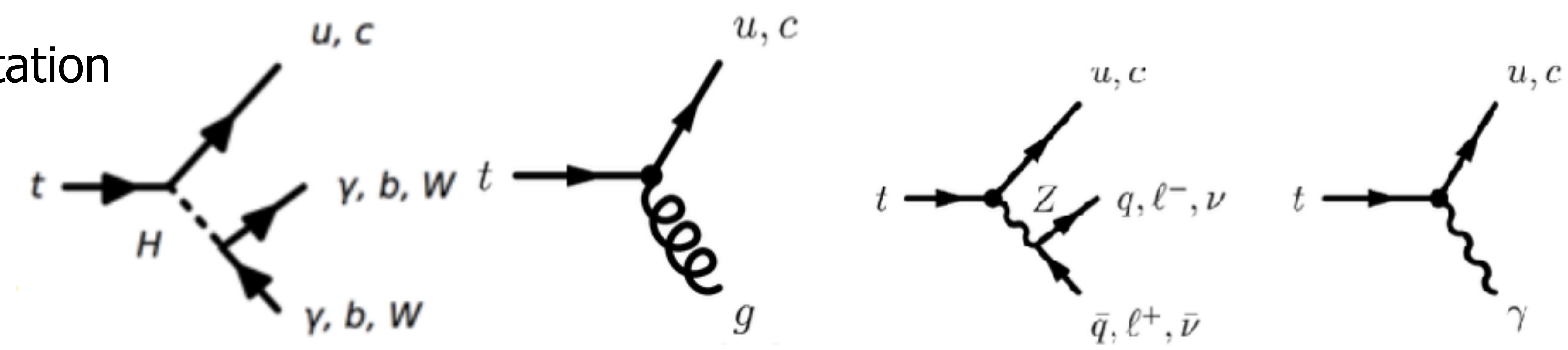


- experimental plans
  - CMS already have extrapolation studies
  - ATLAS is working on the sensitivity to the mass from J/ψ (statistical error should go to ~150 MeV)
  - main question: how to scale the systematic uncertainties



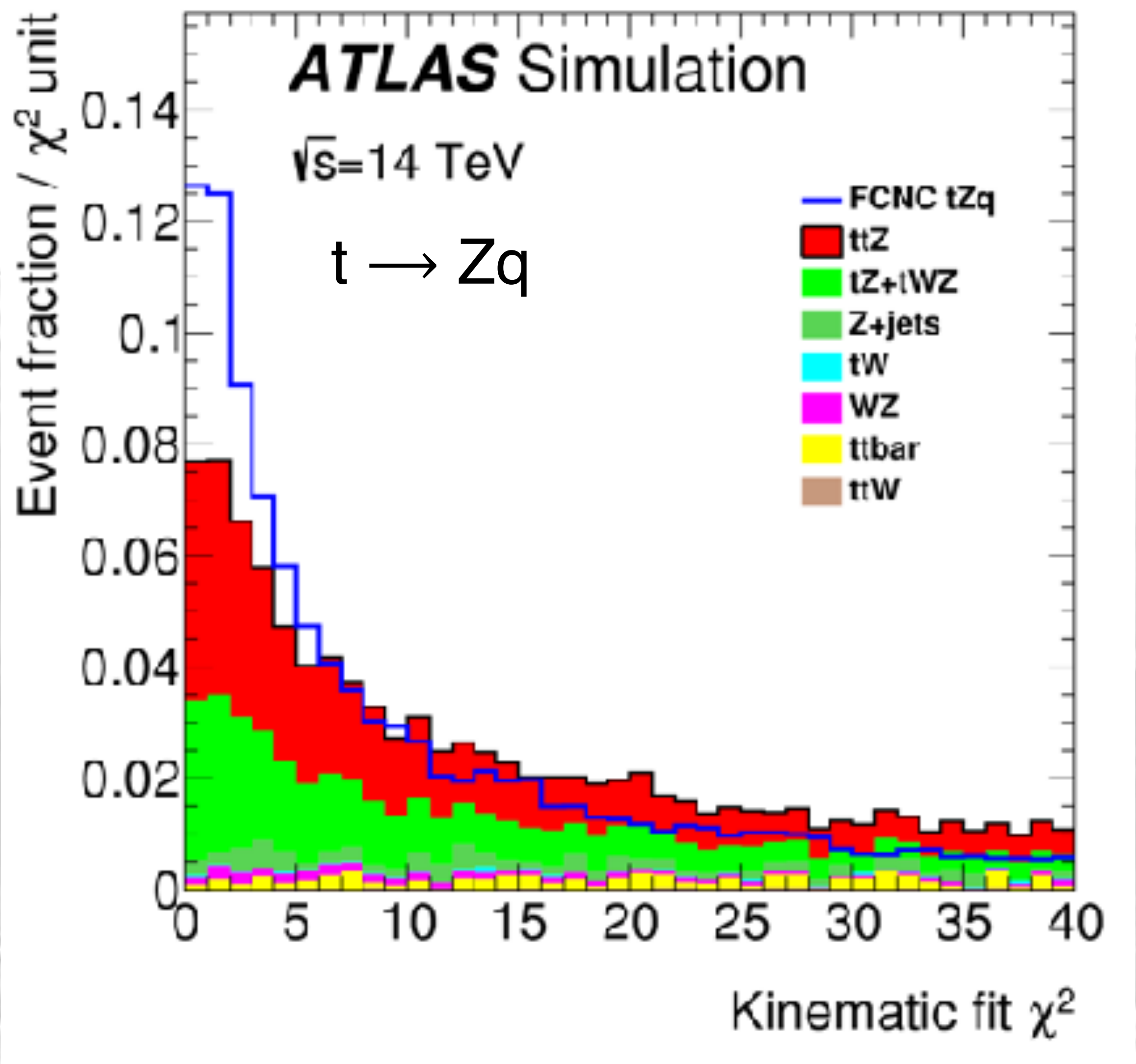
top FCNC

- theory studies
  - description of the theoretical framework and the EFT interpretation
  - description of the simulation

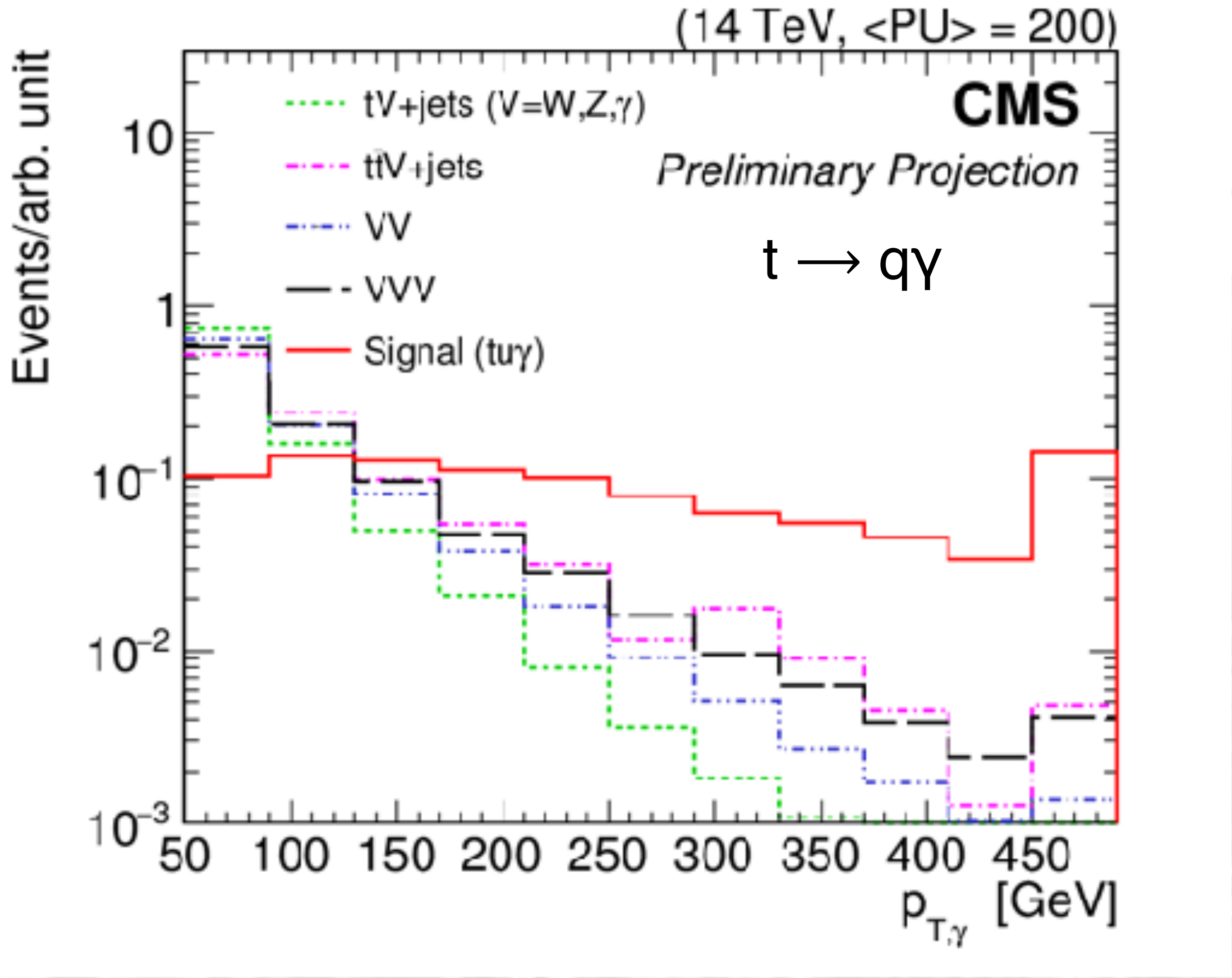


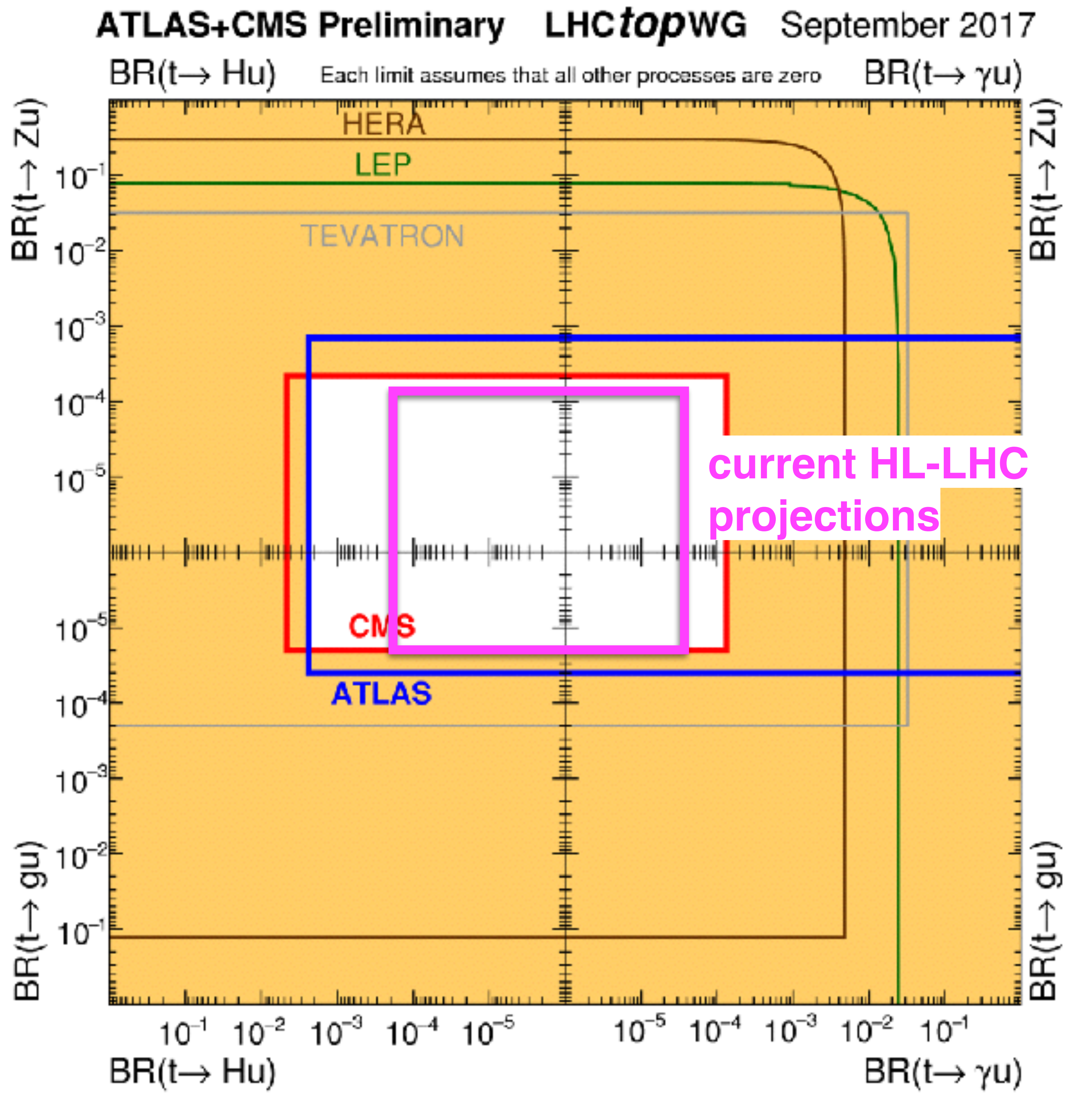
- experimental plans
  - focus on tZq, tHq, tqg and tqγ
  - some previous results already exist

ATL-PHYS-PUB-2016-019



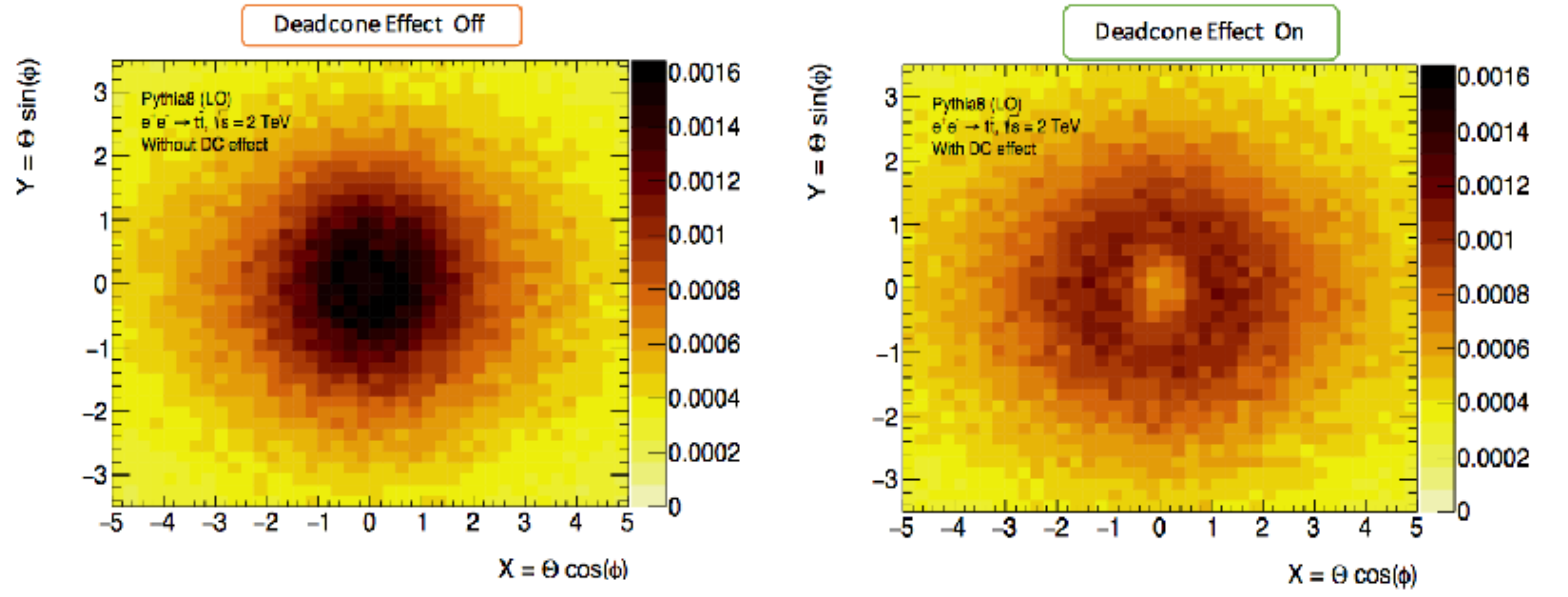
CMS PAS FTR-16-006



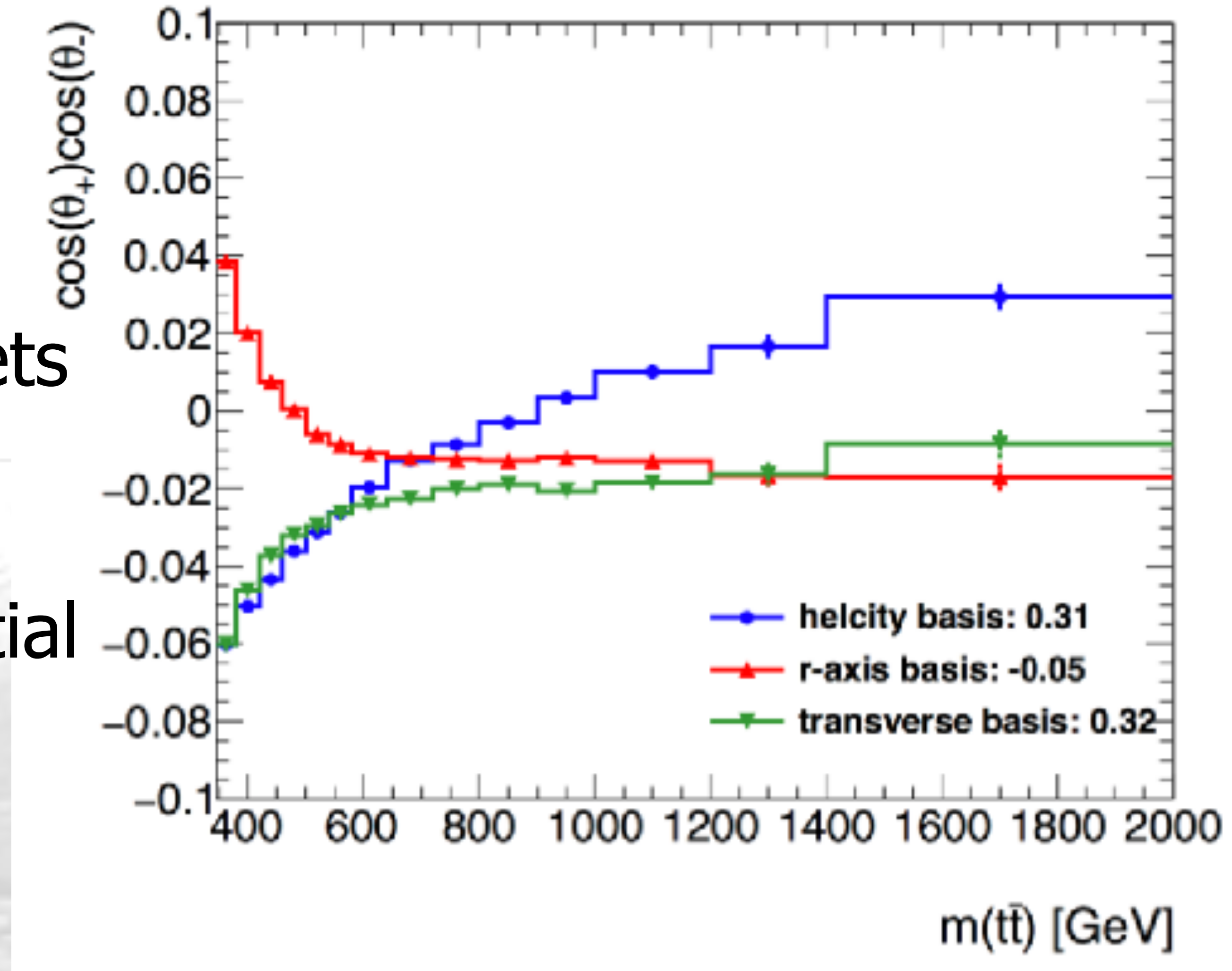


dead cone and angular variables

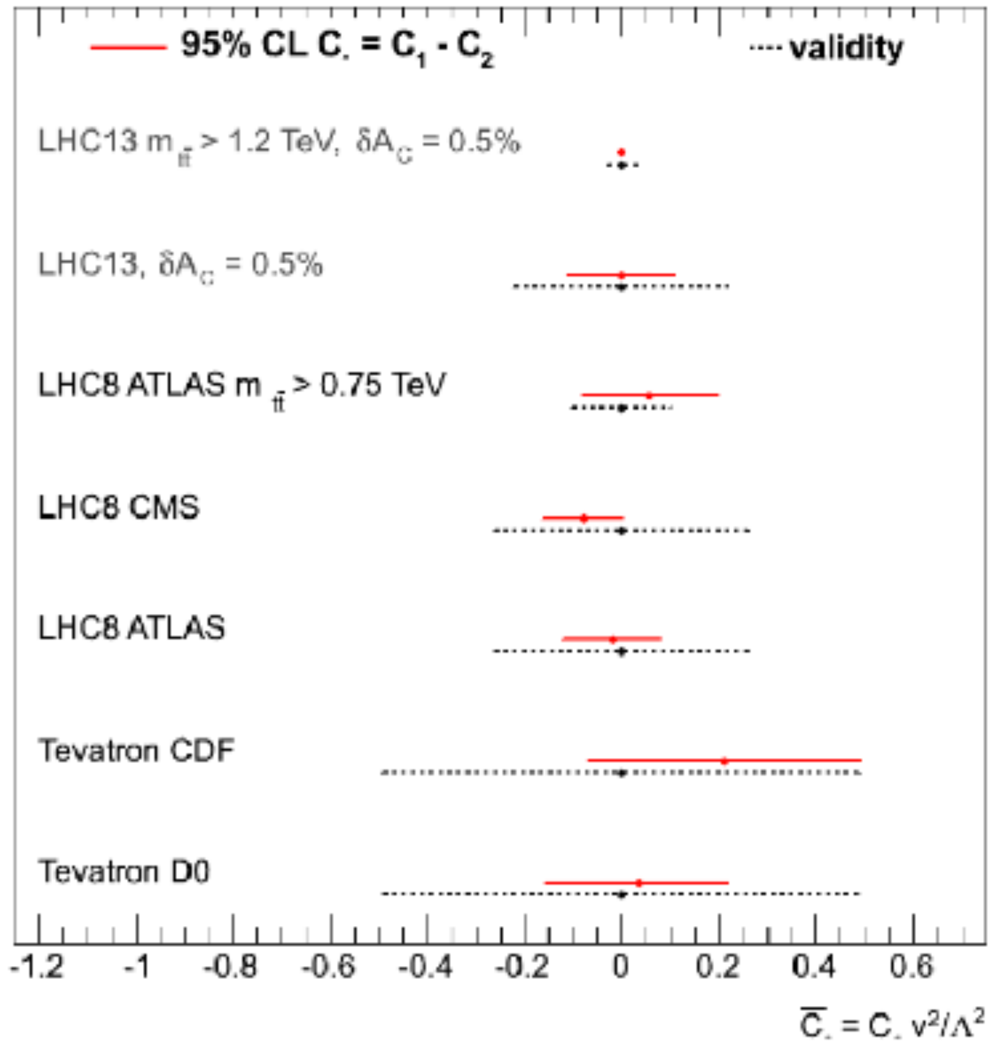
- theory studies
  - dead cone:
    - Fundamental predication of radiation in gauge invariant QFTs
    - introduction and motivation in arXiv:1606.03449
  - spin correlation:
    - differential measurements would benefit from HL-LHC statistics
  - charge asymmetry:
    - high $m_{t\bar{t}}$ bins would benefit from HL-LHC statistics



- experimental plans
  - dead cone:
    - never been measured yet
    - assess sensitivity using boosted and resolved cases in the lepton+jets channel
  - spin correlation:
    - explore the reach in $m_{t\bar{t}}$ and the possibility of going double differential
    - EFT interpretation
  - charge asymmetry:
    - explore high boost and high rapidity regions



ArXiv:1512.07542



Conclusion

- Large effort currently on-going to assess the HL-LHC and HE-LHC physics reach
  - top physics gives interesting opportunity within the overall physics reach
    - precision top pair and single top production
    - rare process: 4tops, ttV, high-q2 s-channel
    - top couplings
    - top angular properties
    - FCNC

- new ideas ?
  - the step from Run 2 to HL/HE-LHC for top physics could be as large as the one from Tevatron to LHC

- join the next HL/HE-LHC plenary workshop at CERN
  - 18-20 June 2018