Top Quark Physics at the LHC: Probing the Energy Frontier

Carmen Diez Pardos
DESY

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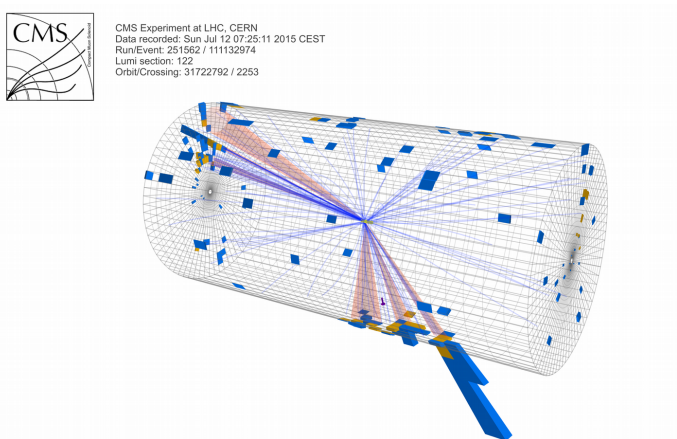
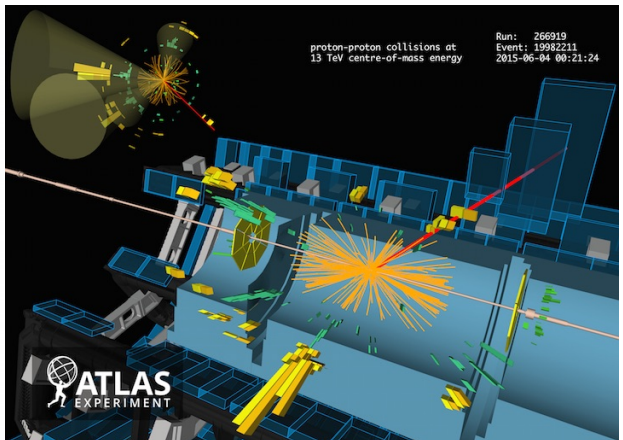
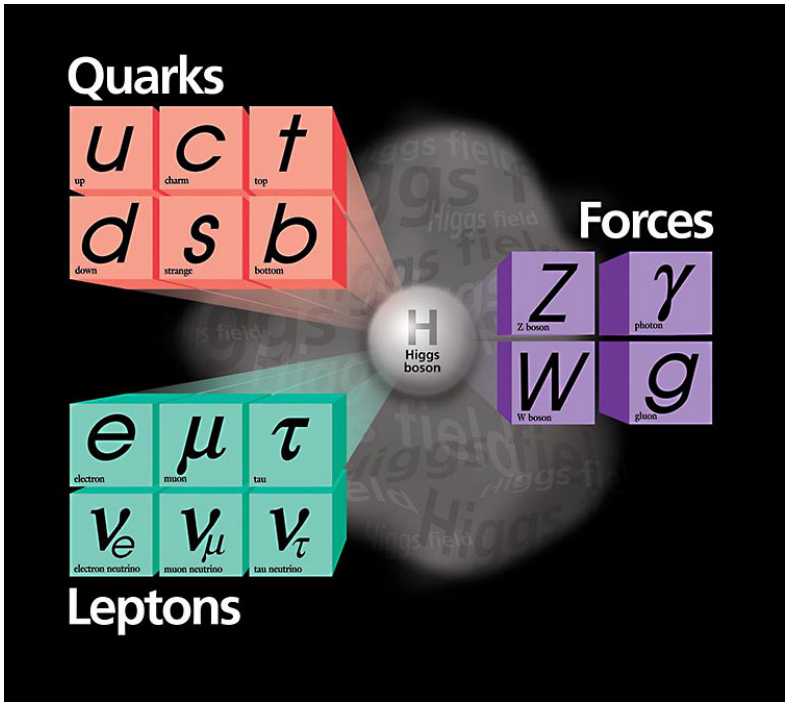


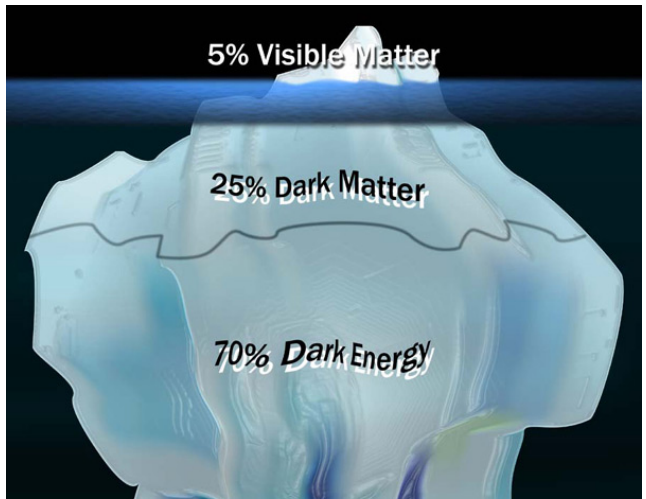


The fundamental building blocks of matter

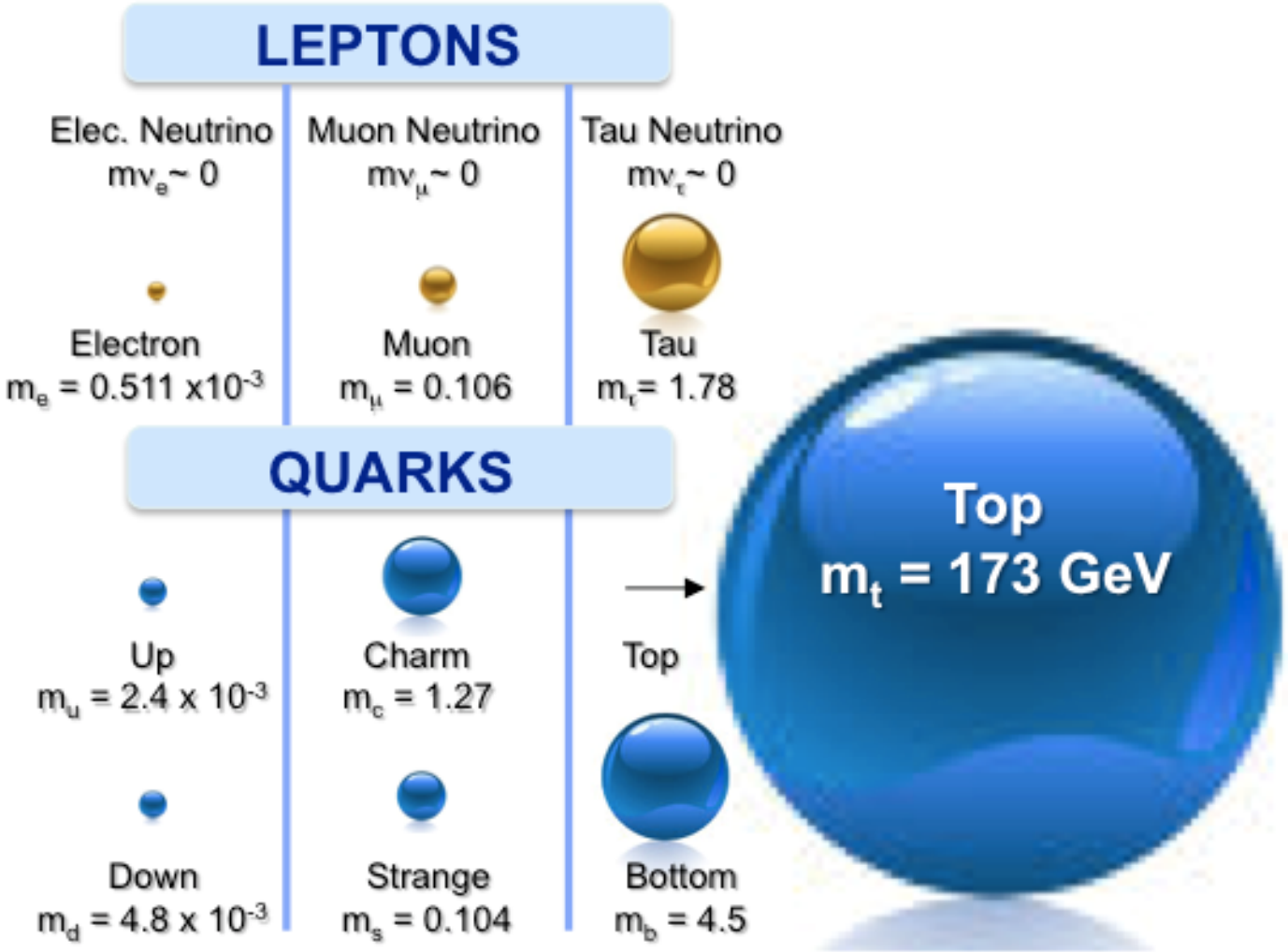


- SM: Successful description of elementary particles and interactions
- LHC experiments discovered a new Higgs-like boson
- Candidate to close the long-standing puzzle of how elementary particles acquire mass in the SM
- But does it behave like the SM Higgs?

- There are several open questions that the SM cannot answer
- Extensive search for possible SM extensions, but no signs of New Physics yet



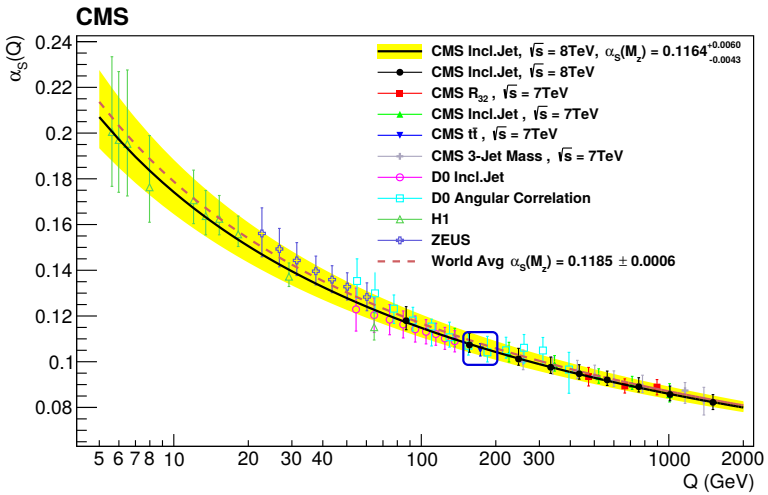
The top quark: a special particle



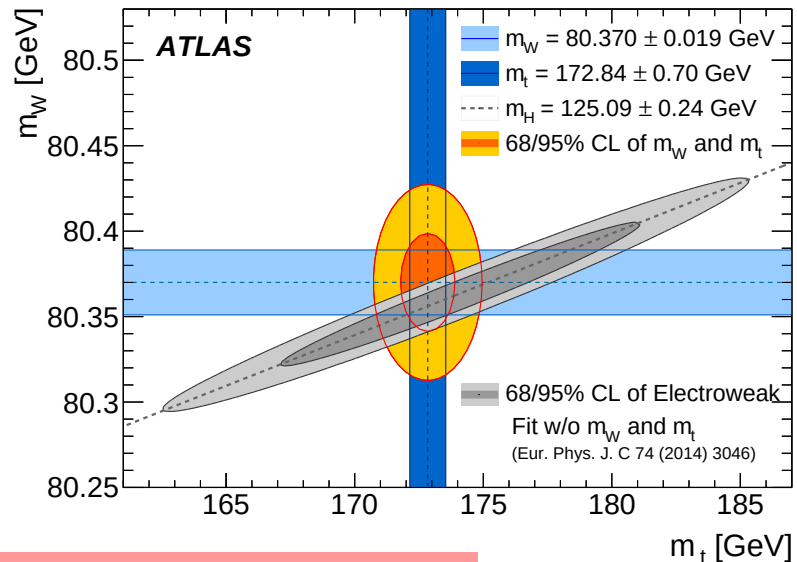
Study in detail strong, EWK, Higgs interactions and New Physics

1.- Constraining the Standard Model

- Determination α_s
- Test QCD predictions and help constraining the PDFs (especially gluon distribution)



- Determination of m_t
- Participates in quantum loop radiative corrections to m_W together with m_H: assessment of self-consistency within SM
- Other properties: couplings, asymmetries predicted by the SM



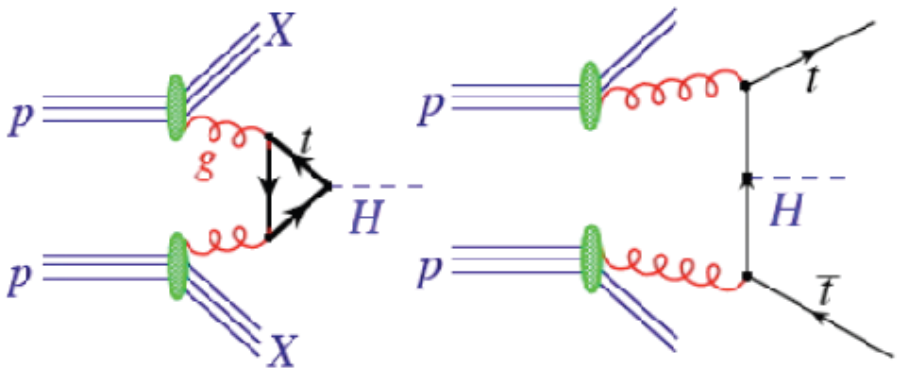
→ Precision measurements could reveal the SM breaking down

Top quarks are a unique tool for stringent tests of the SM

2. - The top quark and the Higgs boson

In the SM, elementary particles acquire mass via their interaction with the Higgs field

- The most massive known particle → large couplings
- Essential to study Higgs properties, measure top Yukawa coupling
- Several open questions
  - Is the mass of the top quark generated by the Higgs mechanism?
  - Role in electroweak symmetry breaking?

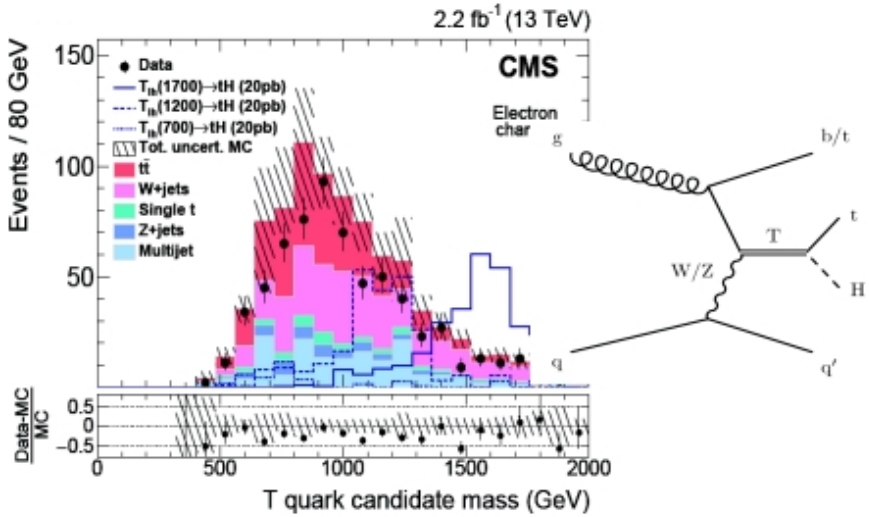


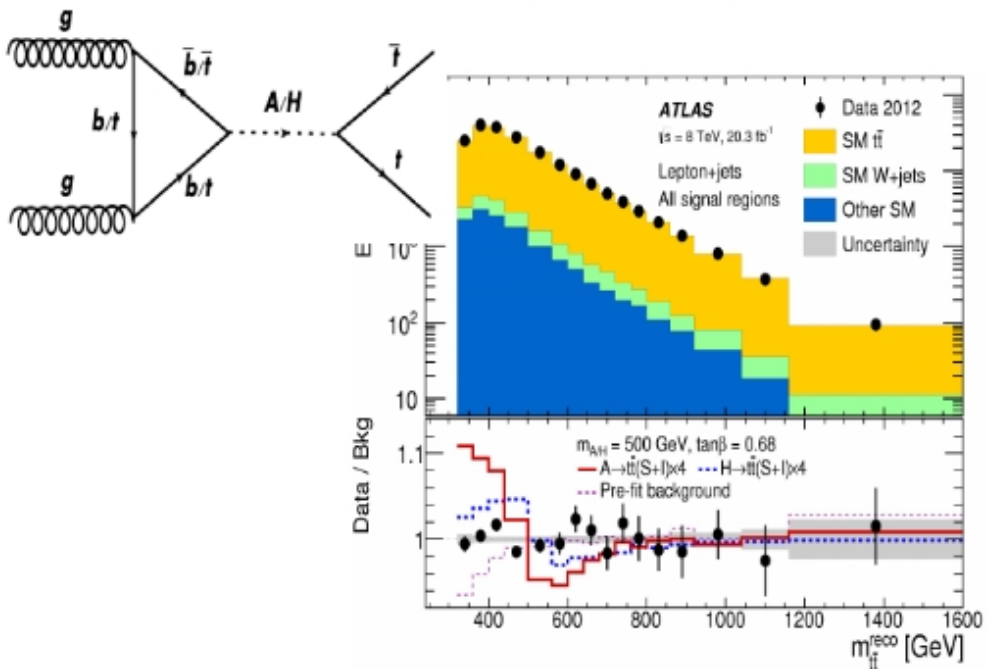
Top quarks at the LHC are crucial to pin down the SM nature of the Higgs

3.- Special role in New Physics?

- Main background for Higgs and many searches for New Physics
- Top quark is a main ingredient of many BSM scenarios
  - Exotic partners, rare decays, heavy resonances decaying to top, new particles produced with top, ...

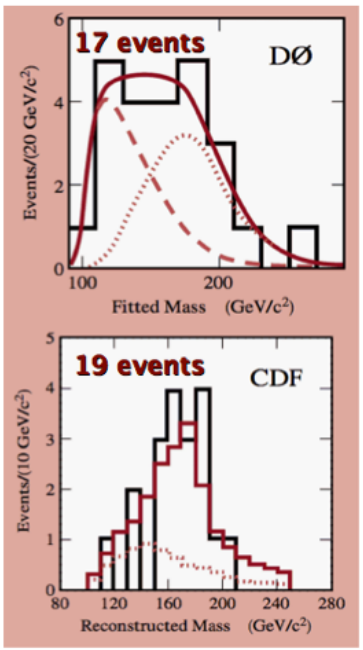
... and a sensitive probe for New Physics



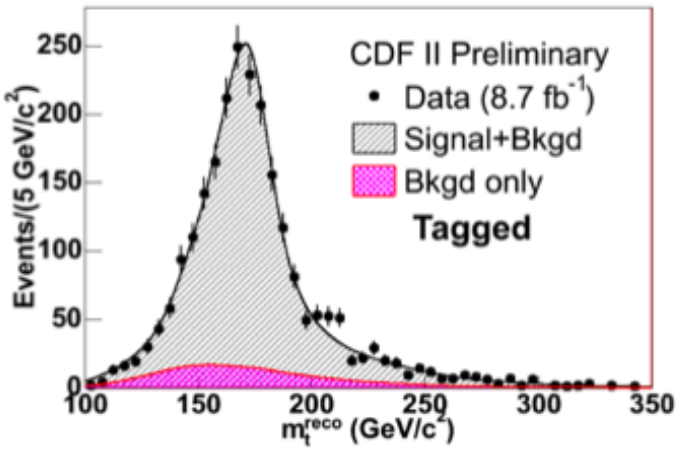


The top quark: Before...

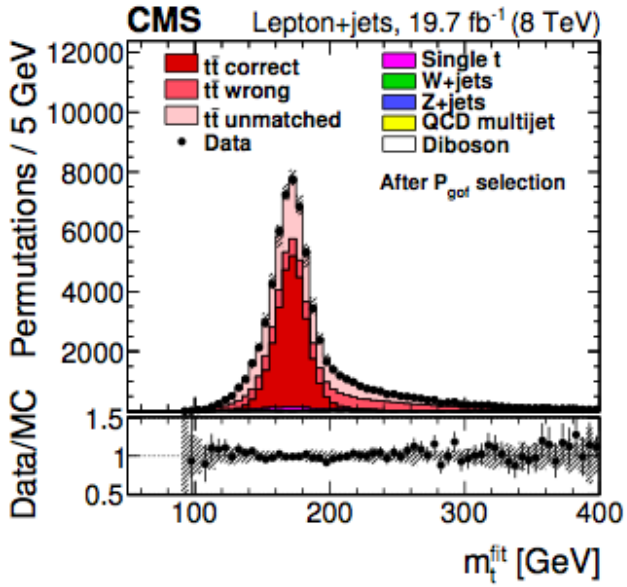
36 events



1000s events



100000s events



1995 — 2009 — 2010 — 2012

Tevatron $p\bar{p}$ 1.96 TeV

"Birthplace" of the top

First observation of single top production

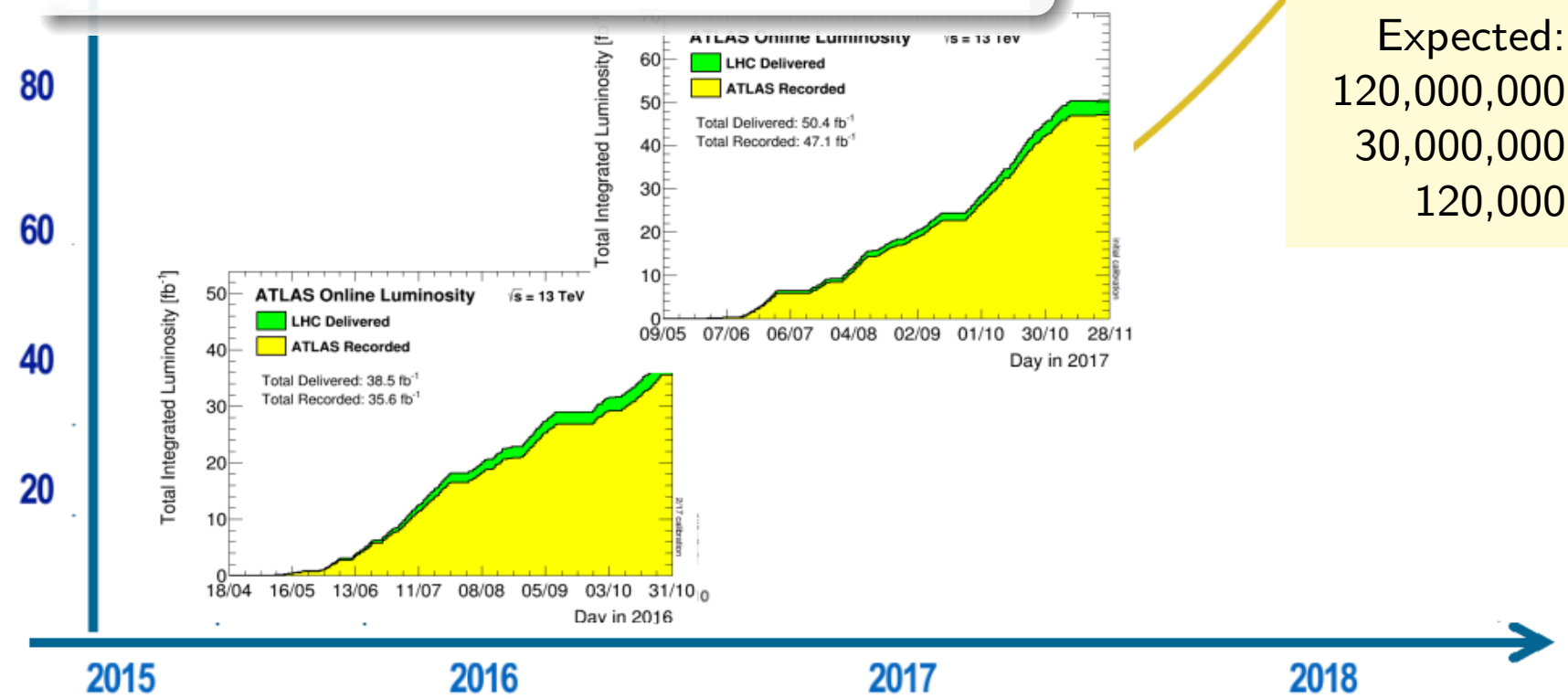
LHC Run-1 pp (7 and 8 TeV)

top factory: 25 fb^{-1}

... and now: LHC 13 TeV

Run-2 top quark physics, up to 150 fb^{-1}

- Ultimate precision measurements
- Low cross section frontier: $t\bar{t}$+X and t+X (X=q,b, $t\bar{t}$, W/Z, H)
- Properties and couplings ($t\bar{t}$ and t)



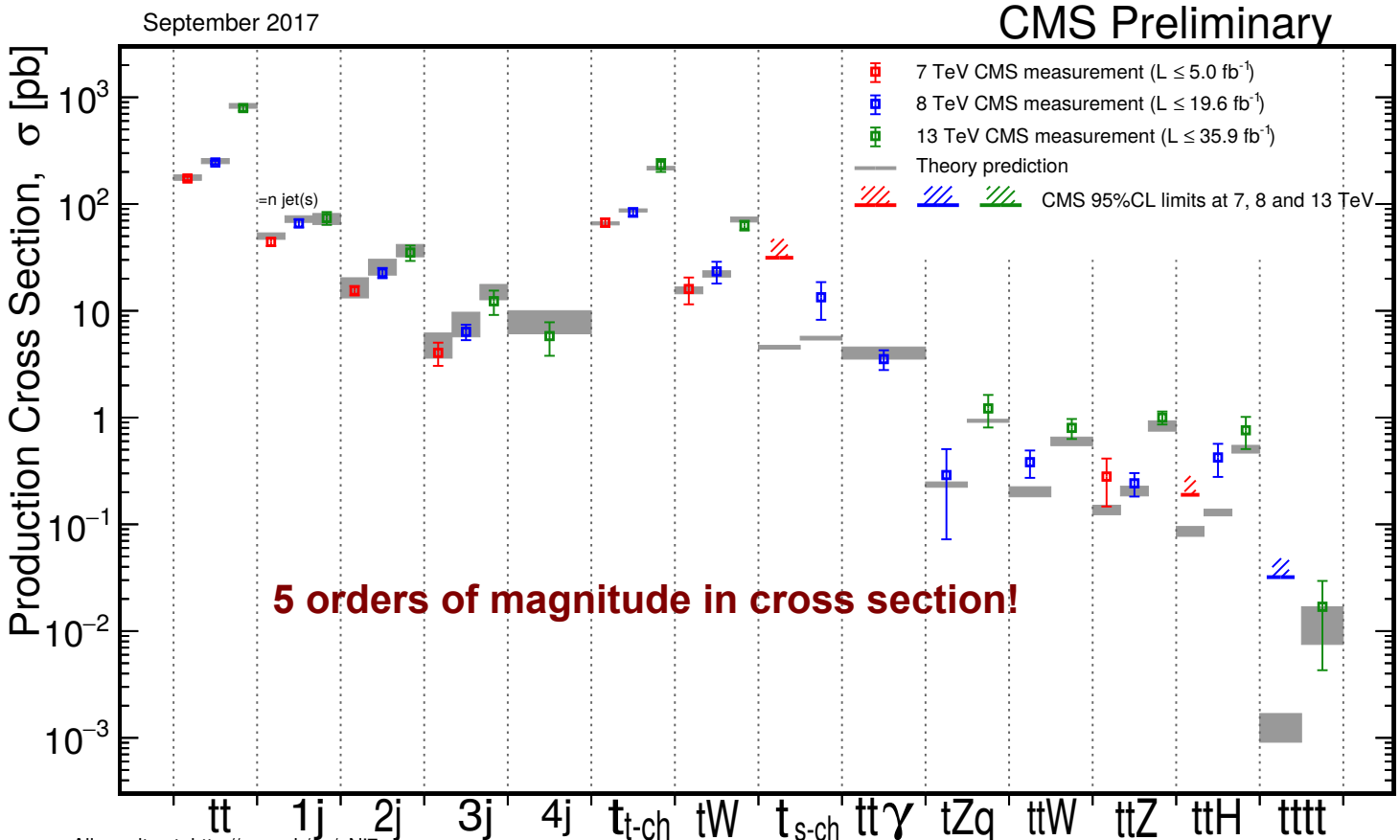
Expected:

120,000,000	$t\bar{t}$
30,000,000	t
120,000	$t\bar{t}Z$, tZ

Today's talk

Personal selection of results, mostly from Run-2

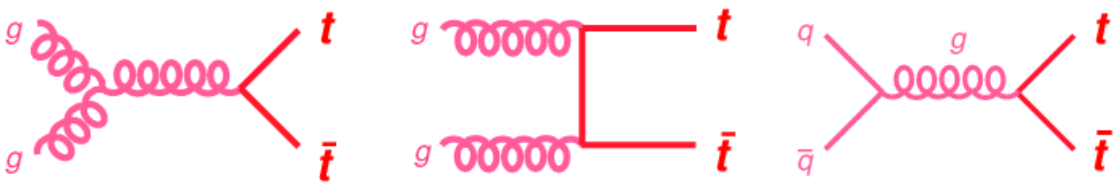
- $t\bar{t}$ rate and dynamics
- $t\bar{t}$ + "Friends" (W/Z, H, $t\bar{t}$)
- Single top quark



All results at: http://cern.ch/go/pNj7

Top quark production

$t\bar{t}$ production mainly by gluon fusion at LHC (~85% at 13 TeV)



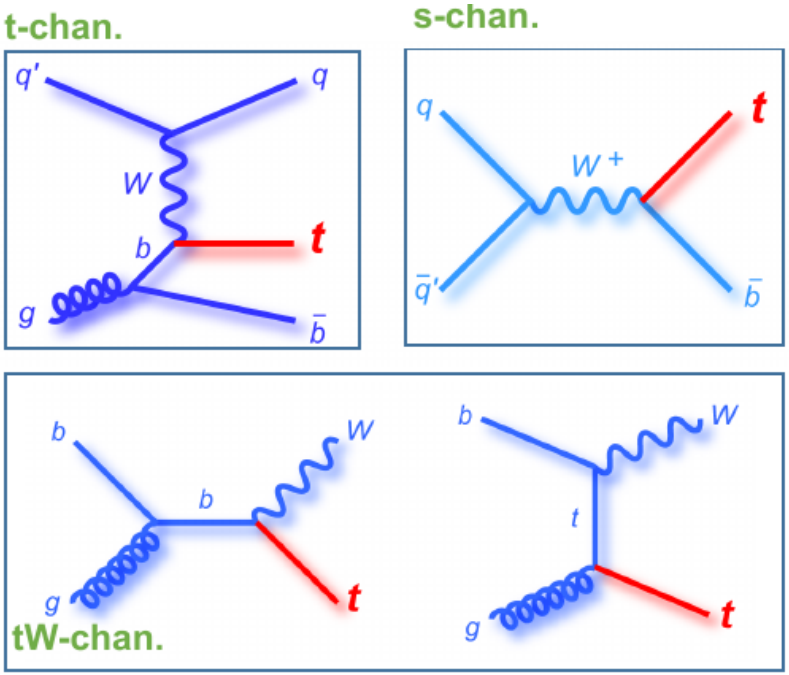
- NNLO+NNLL calculation
  PRL 110 (2013) 252004

  $\sigma(8\text{TeV}) = 245\ \text{pb} \pm 6\%$

  $\sigma(13\text{TeV}) = 832\ \text{pb} \pm 5\%$

  $R_{13/8}$=3.3

t production via EWK interaction

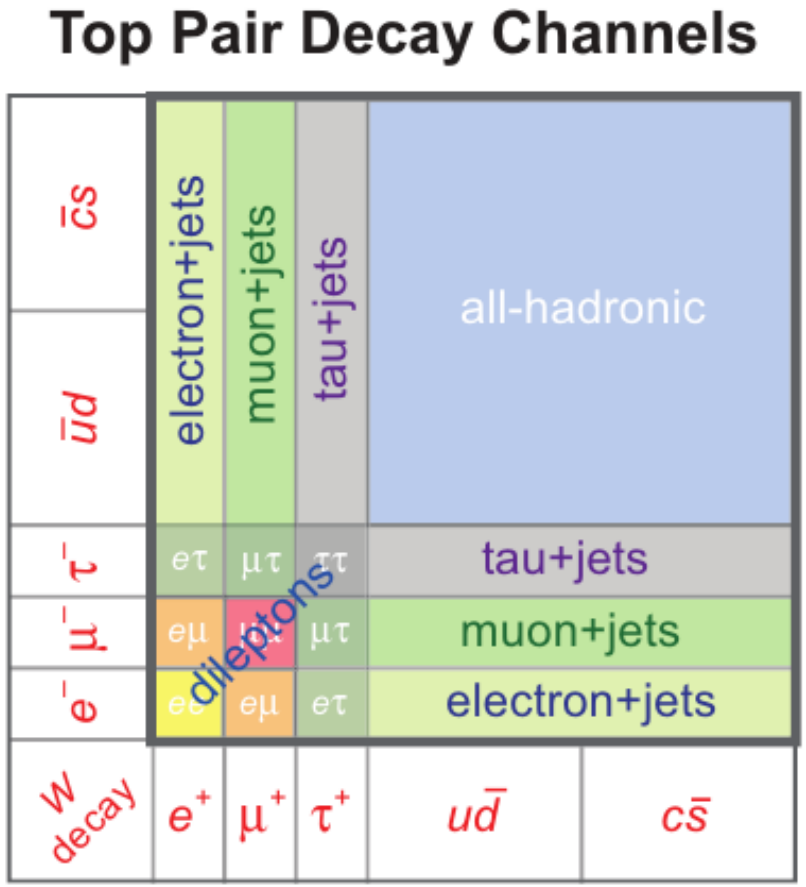


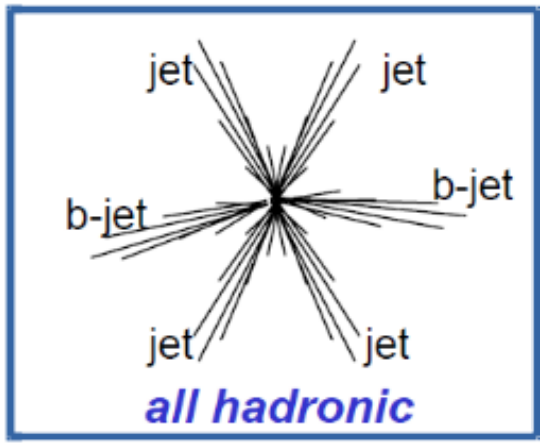
- t-channel $\sigma(13\text{TeV}) = 217\ \text{pb} \pm 4\%$
  $R_{13/8}$=2.6
- tW-channel $\sigma(8\text{TeV}) = 71\ \text{pb} \pm 5\%$
  $R_{13/8}$=3.2
- s-channel $\sigma(13\text{TeV}) = 10.3\ \text{pb} \pm 4\%$
  $R_{13/8}$=1.9

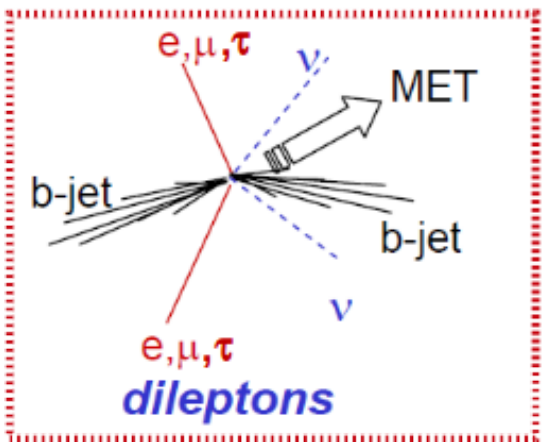
  Cross sections at NLO or NNLO tW (arXiv:1311.0283)

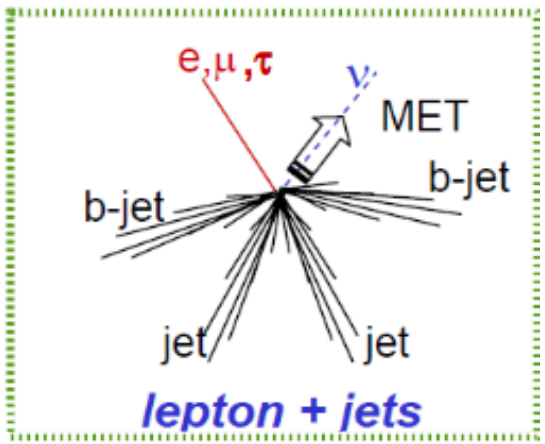
Top quark decay signatures

In the SM $t \to Wb$ almost 100%, W decay defines final state

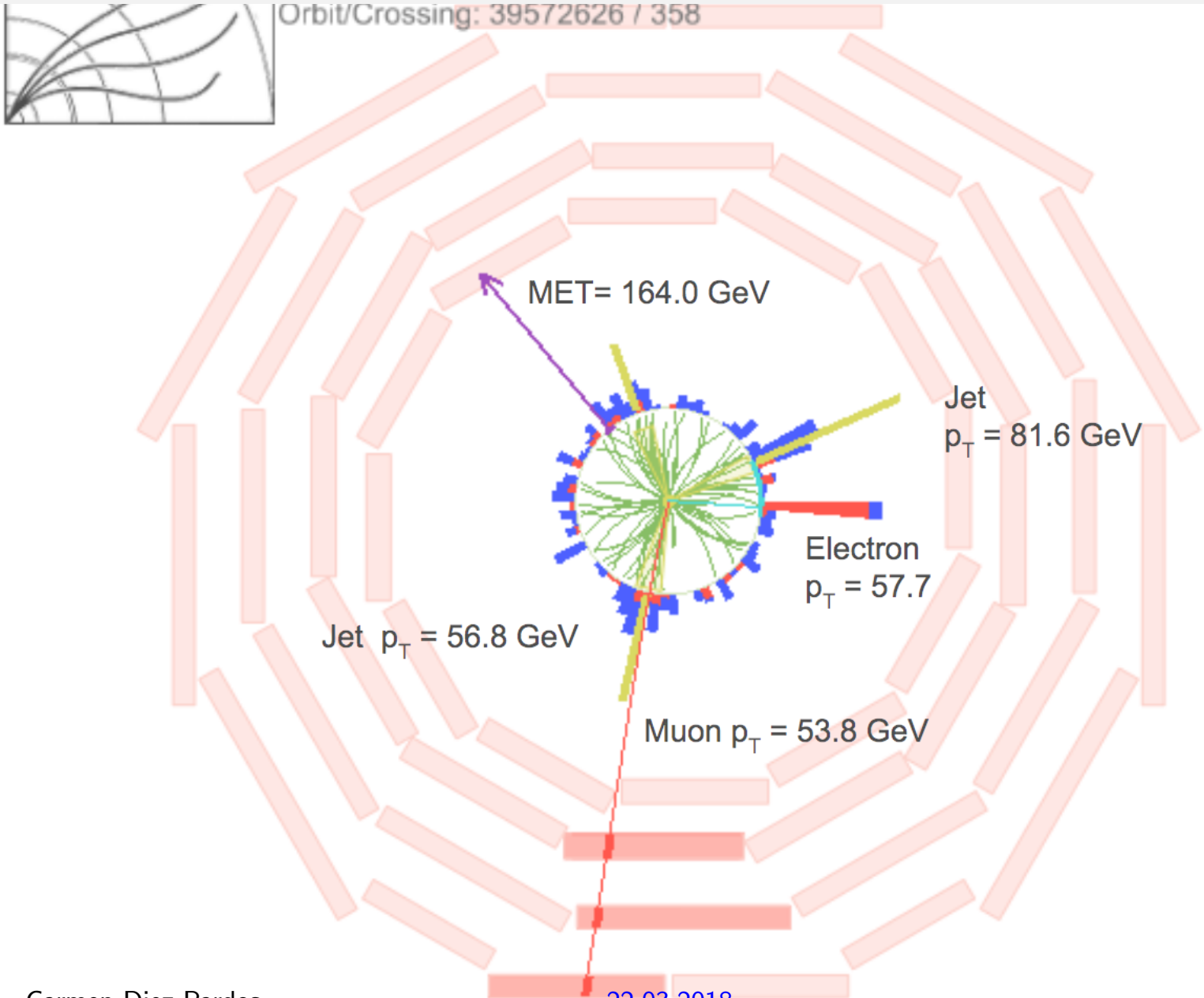








Identifying top quarks



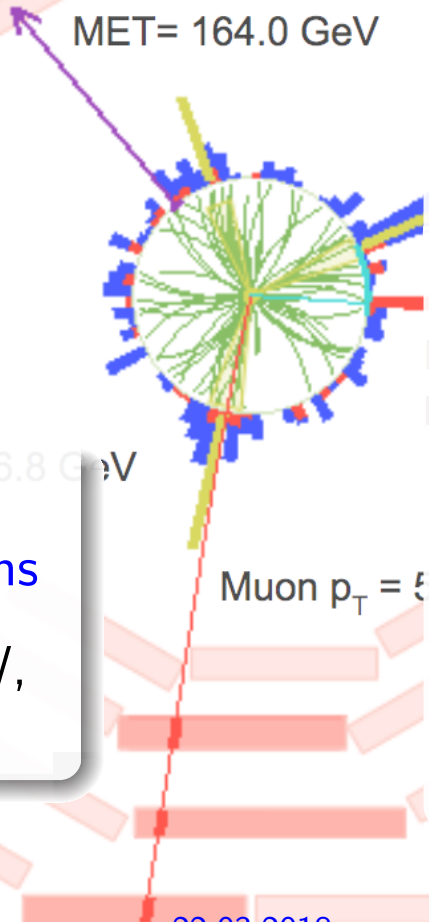
Identifying top quarks

MET

- Missing energy from undetected neutrinos

Jets

- Two to six high p_T jets (up to 2 b-tags)

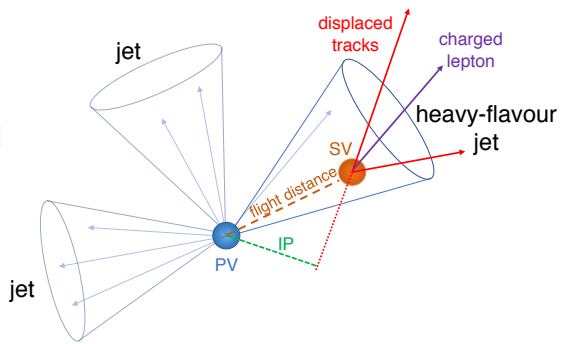


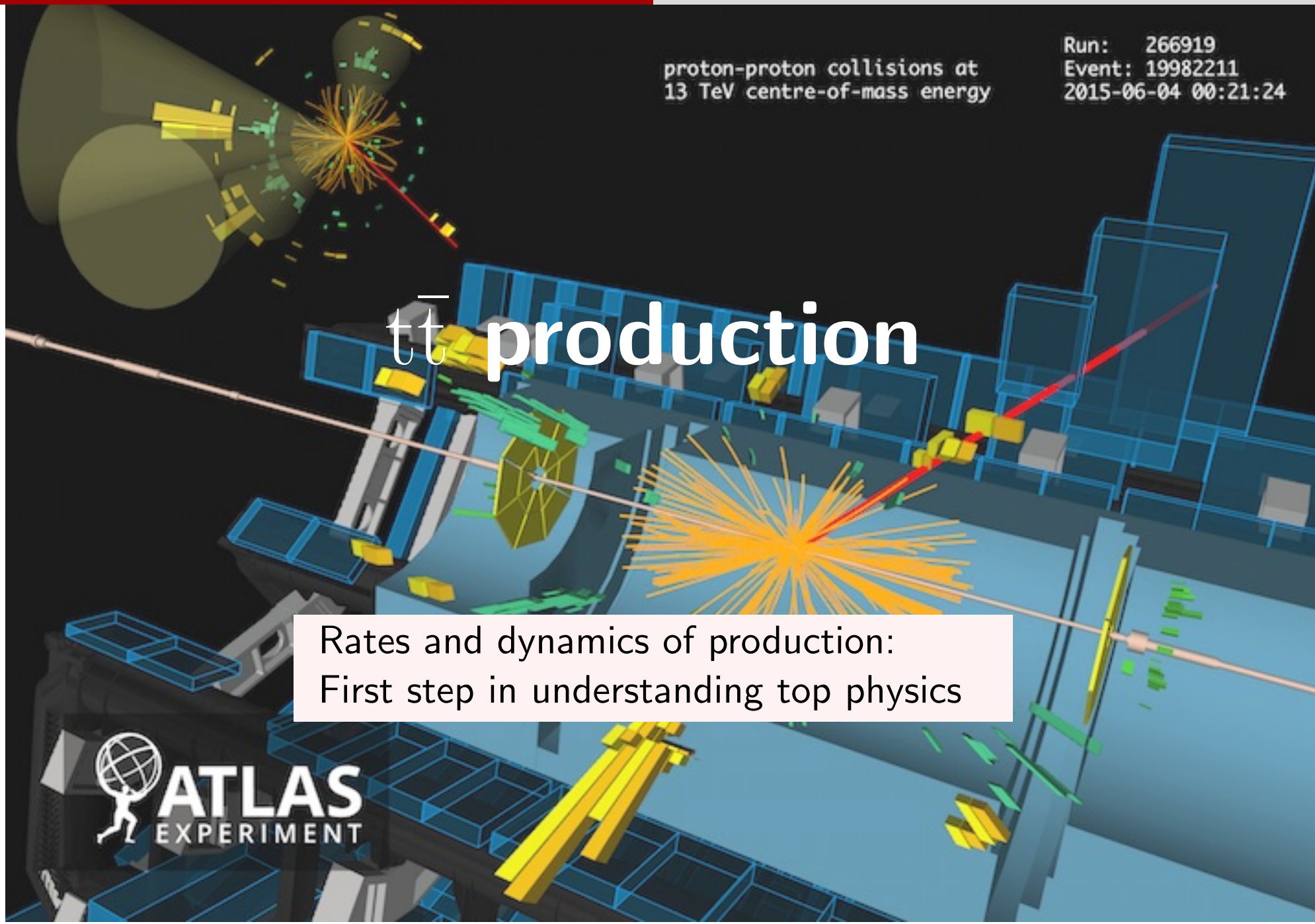
Leptons

- Up to two high p_T leptons
- Isolated, high p_T from W, soft leptons in b-jets

b-jet ID (b-tagging)

- B-hadron properties: large lifetime ~1.5 ps and decay length

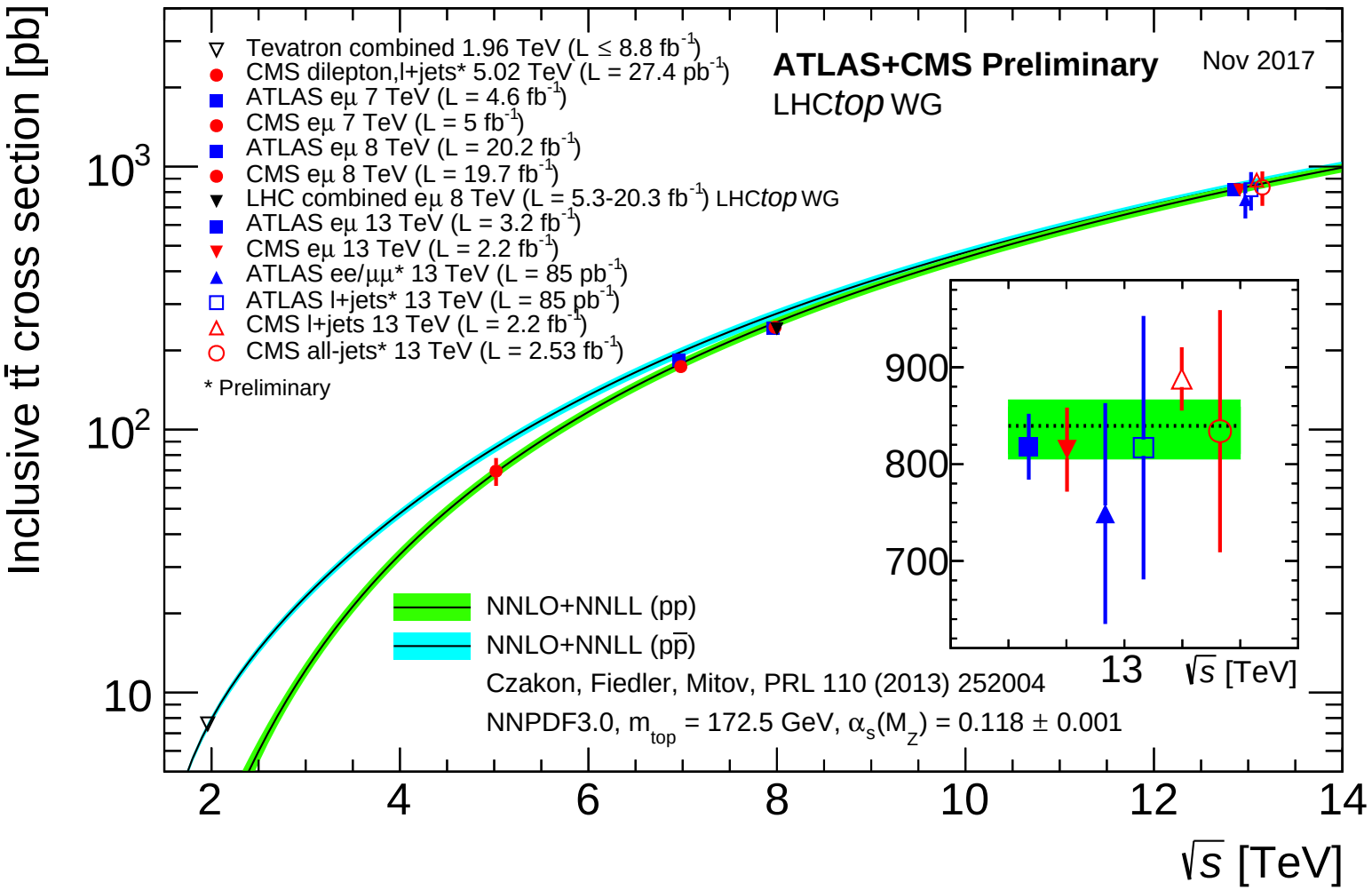




$t\bar{t}$ production

Rates and dynamics of production:
First step in understanding top physics

$t\bar{t}$ cross section measured at all energies



Dependence as a function of $\sqrt{s}$ well understood!

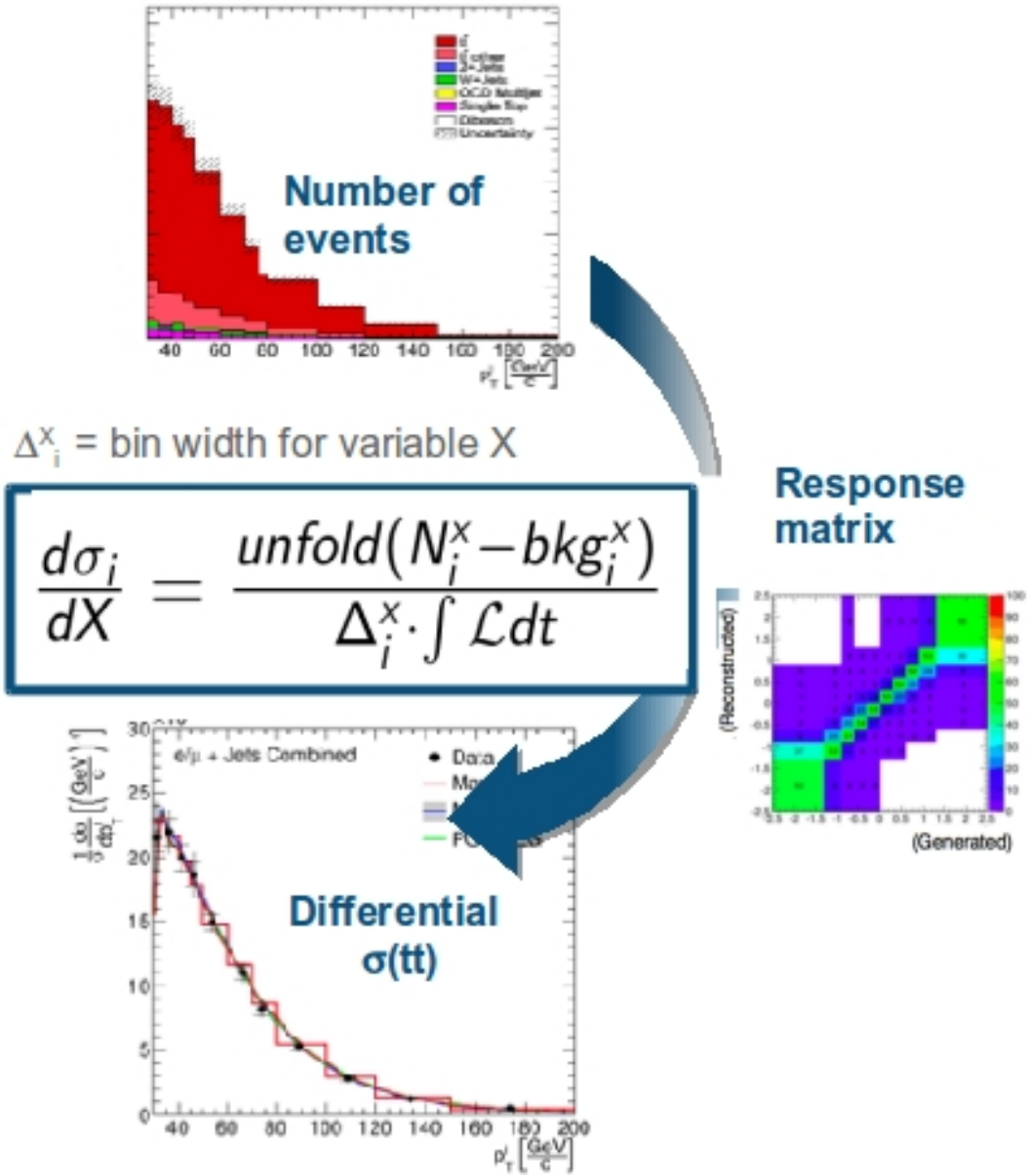
Differential regime

Scrutinize $t\bar{t}$ production as a function of many kinematic observables:

- Comparisons with state-of-the-art predictions (and future calculations)
- Extraction of mass, α_S, constrain PDF

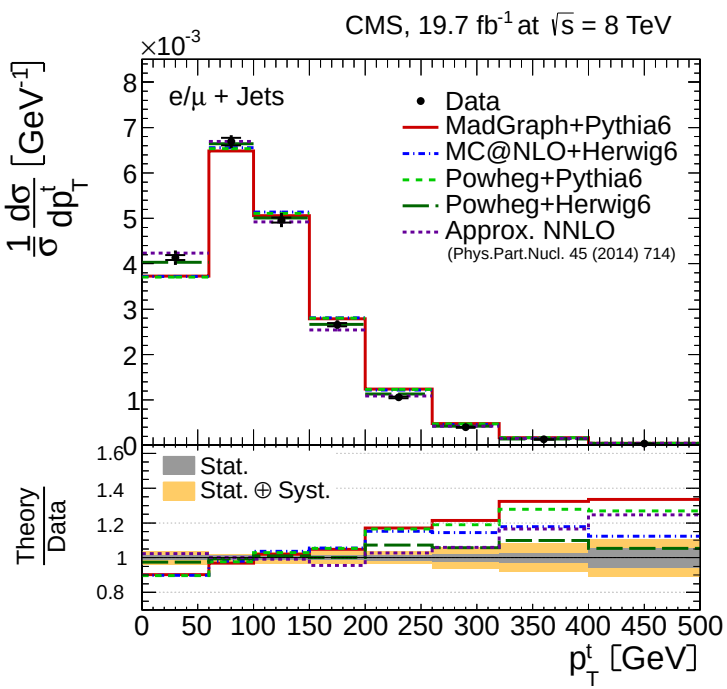
Wealth of results available

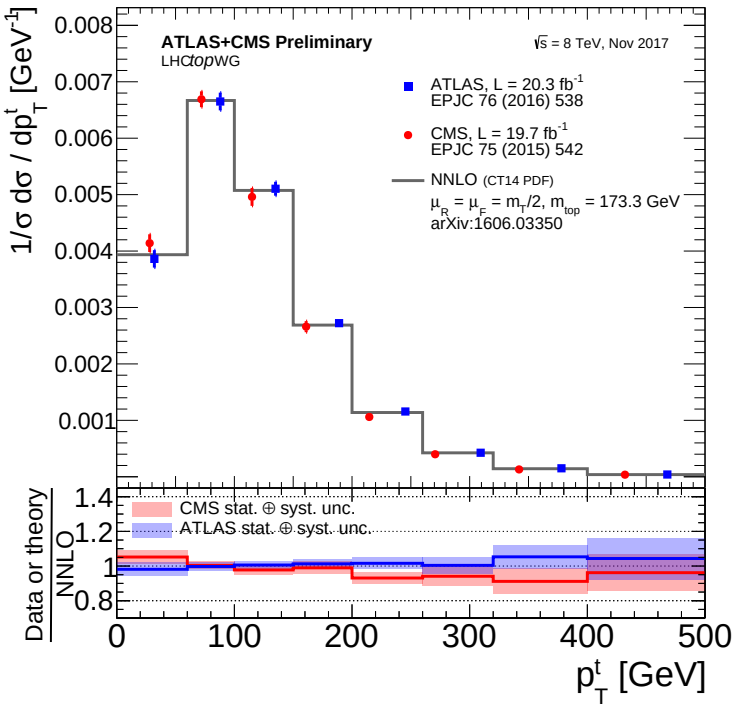
In general agreement with SM predictions for all measured distributions



Top quark p_{T} distribution

- Run-I "discovery": p_{T}^{t} spectrum is softer in data than in (most) MC simulations

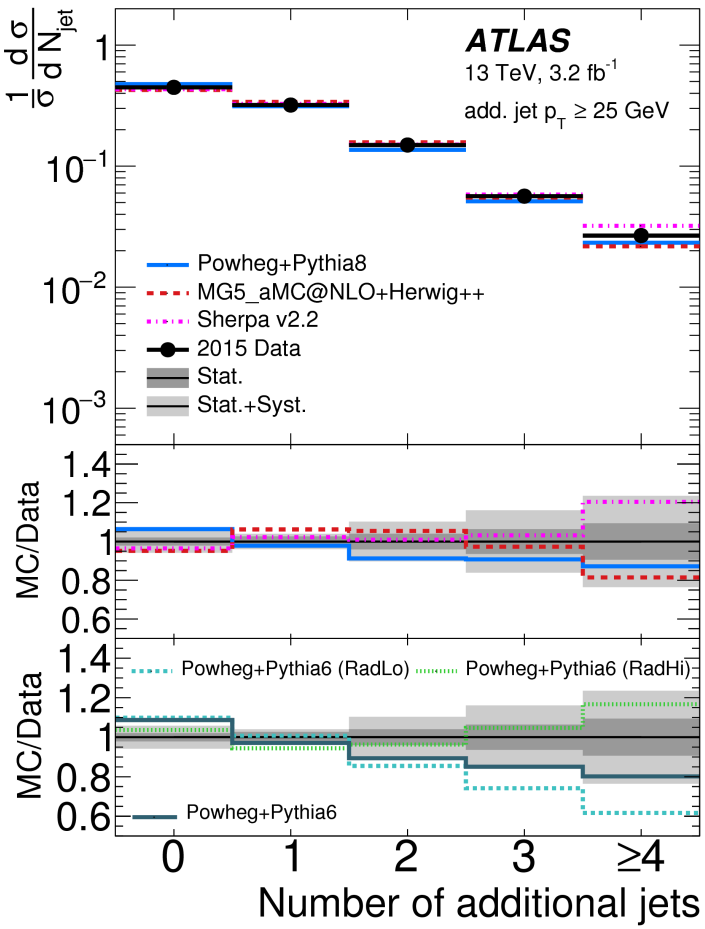


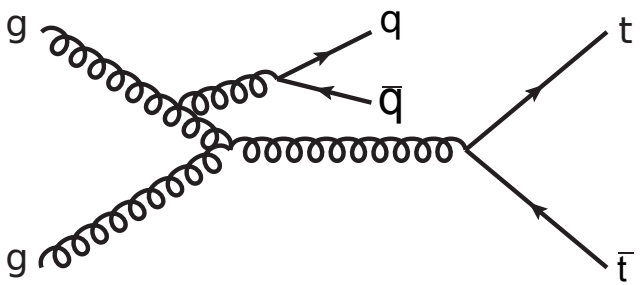


- Results in all final states: NLO calculations do not describe p_{T}^{t}
  Also observed at 13 TeV
- NNLO calculation available: CMS and ATLAS data well described

$t\bar{t}$+jets

At LHC energies, about half of $t\bar{t}$ events are produced with additional hard jets

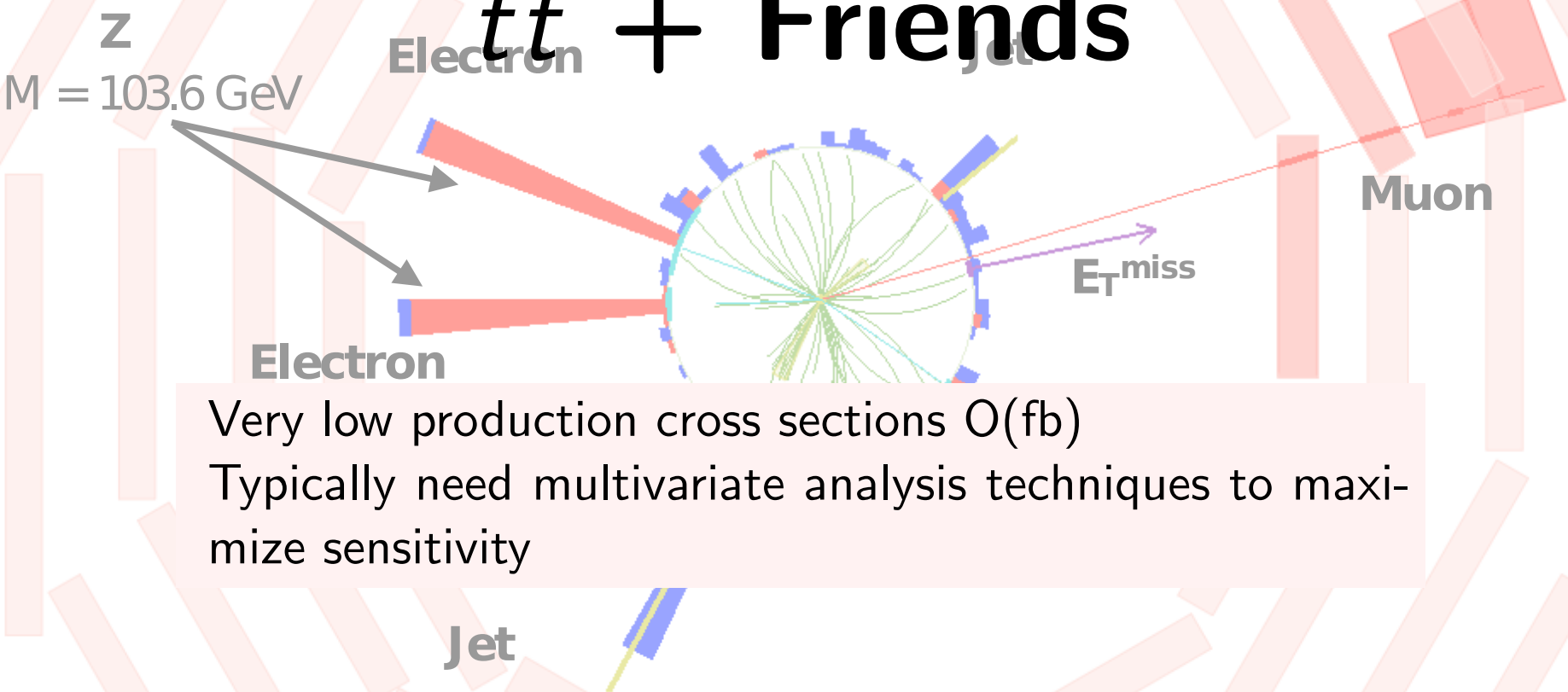




- Reveal presence of new physics in $t\bar{t}$+jets final states, background for $t\bar{t}H$
- Investigate MC description of QCD radiation

CMS Experiment at LHC, CERN
Data recorded: Sun Nov 1 23:42:02 2015 CET
Run/Event: 260576 / 281864880
Lumi section: 137

$t\bar{t}$ + Friends

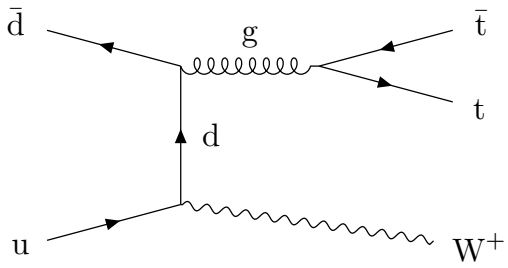


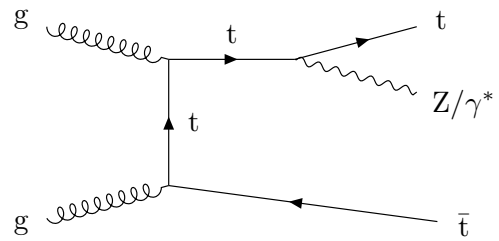
Very low production cross sections O(fb)

Typically need multivariate analysis techniques to maximize sensitivity

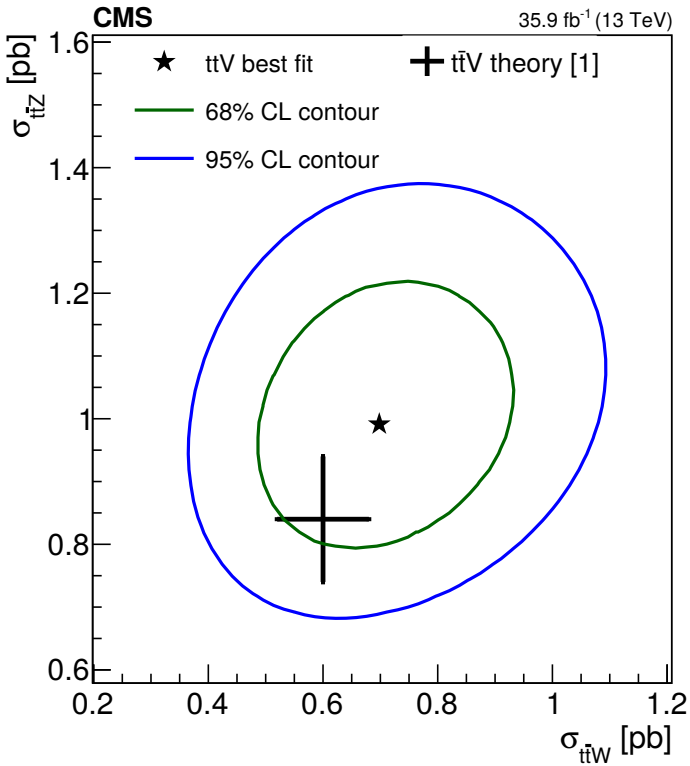
Couplings to bosons: $t\bar{t}$+W/Z

- Measure couplings to bosons
- Important background for BSM searches





- Analyses are performed in bins of the number of selected leptons (2,3,4)
- Different number of leptons $\rightarrow$ different admixture of $t\bar{t}W$ and $t\bar{t}Z$ processes



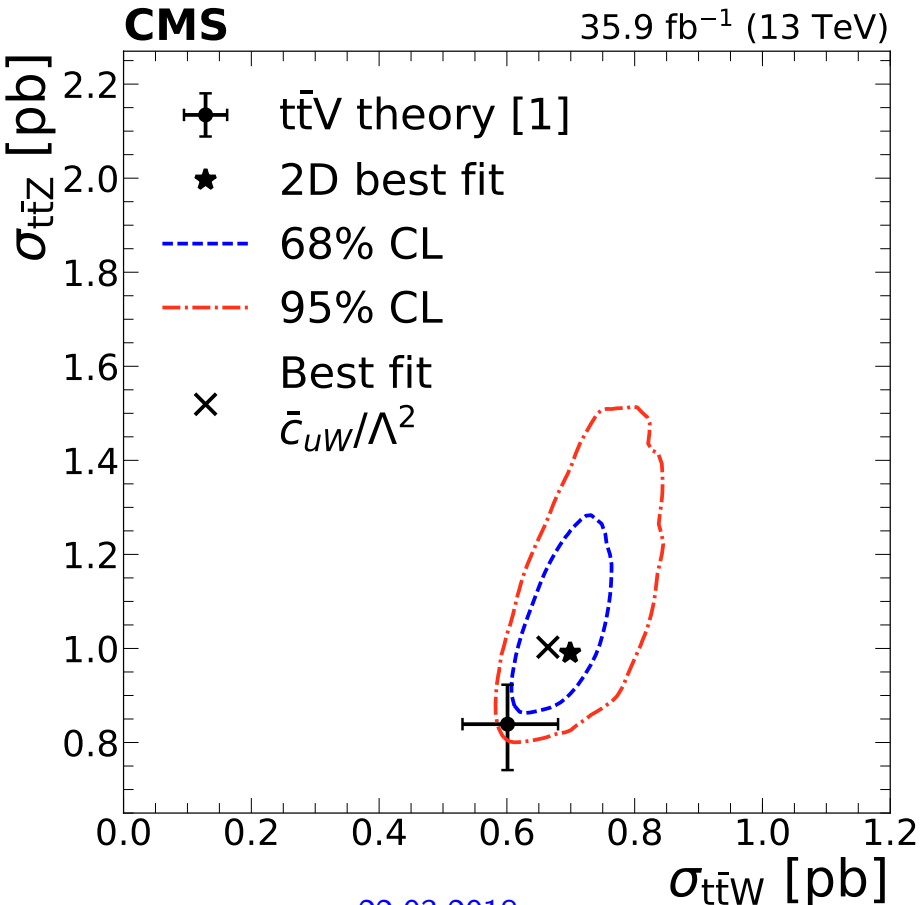
$> 5\sigma$ for both processes simultaneously!

Results: Effective Field Theory Interpretation

Model independent search for new phenomena

$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_i c_i\mathcal{O}_i + \frac{1}{\Lambda^2}\sum_j c_j\mathcal{O}_j + \cdots$

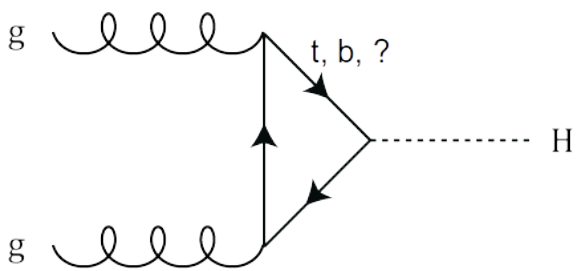
Constraints on dimension-6 operators

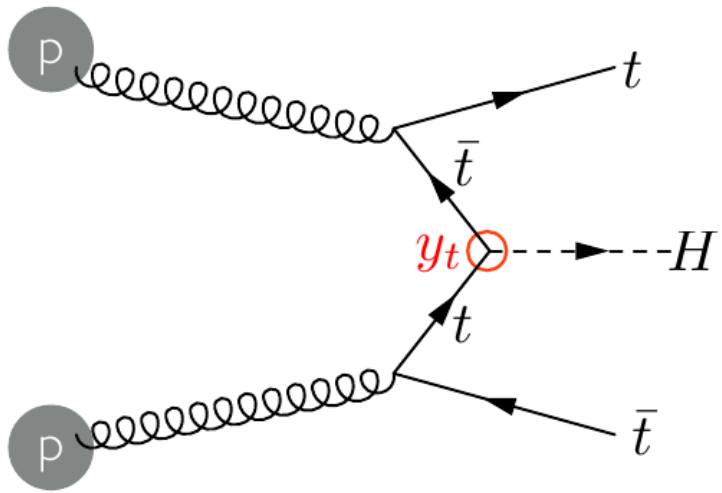


Top-Higgs coupling: the hunt for $t\bar{t}H$

Best direct probe of the top-Higgs Yukawa coupling, vital step towards verifying the SM nature of the Higgs boson

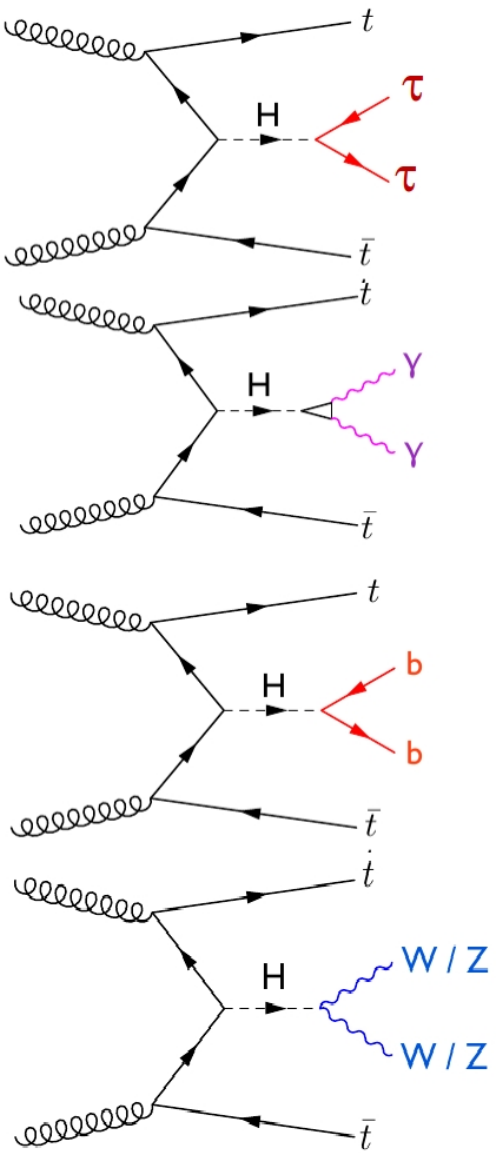
- Top quark is the most strongly-coupled SM particle ($y_t \sim 1$)
- Direct measurement of y_t in $t\bar{t}H$ production:
  - Allows probing new physics in gg→H and H→ $\gamma\gamma$ effective vertices

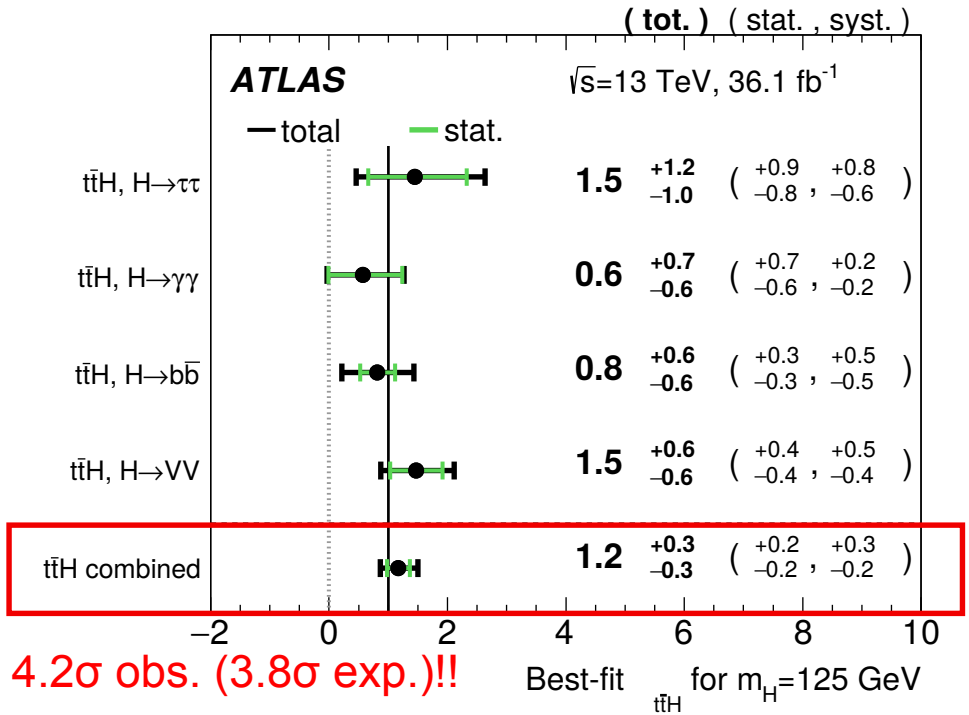




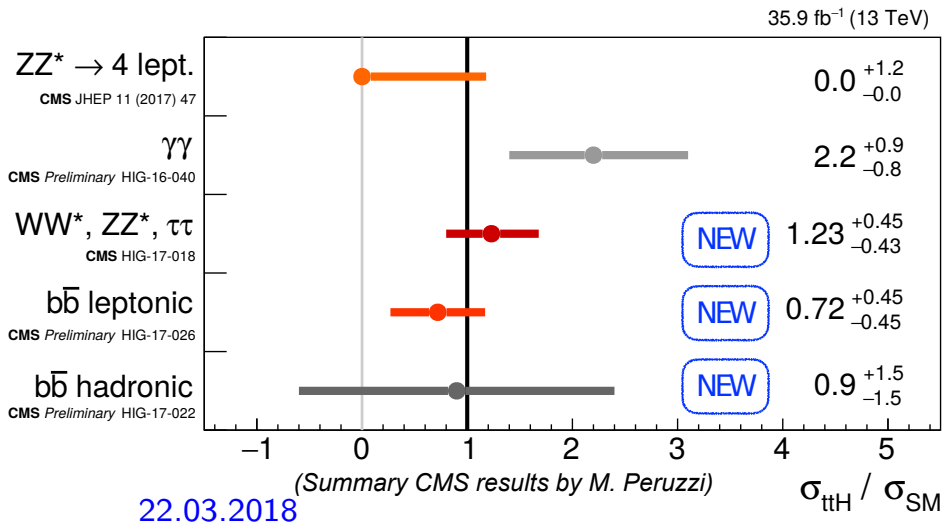
- One of the physics targets for Run-2: $\sigma \approx 0.5$ pb at $\sqrt{s}$=13TeV (m_H=125GeV), understanding of $t\bar{t}$+X is crucial

$t\bar{t}H$: Observation is around the corner

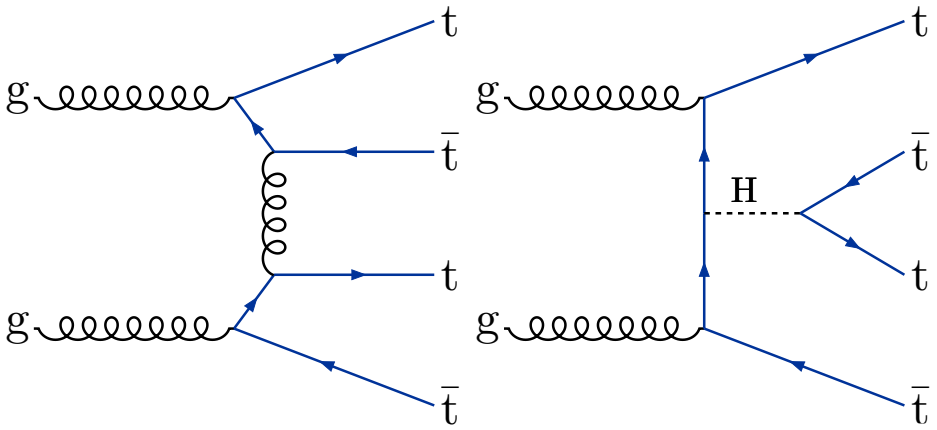




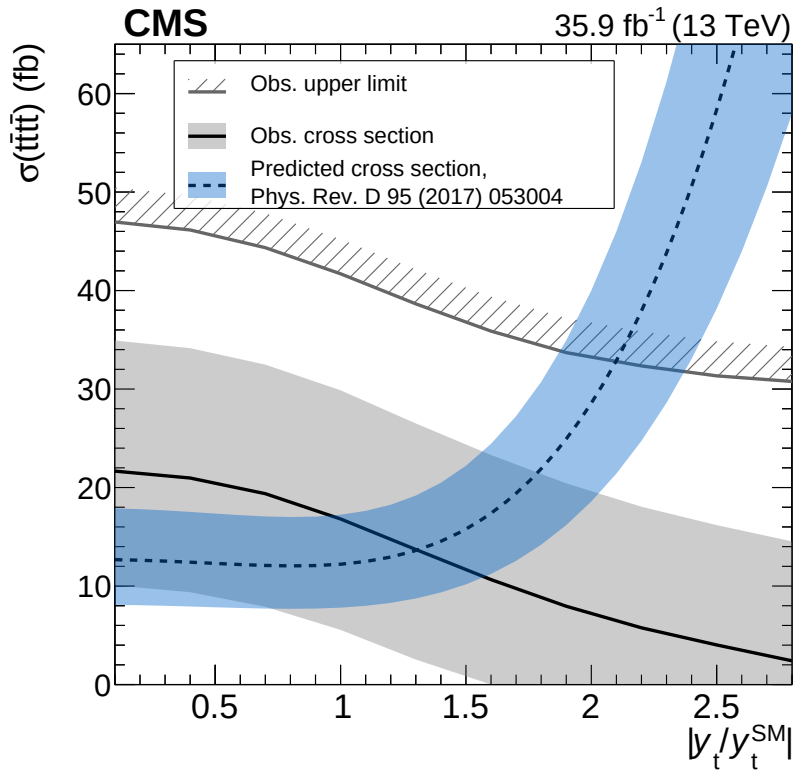
4.2σ obs. (3.8σ exp.)!!

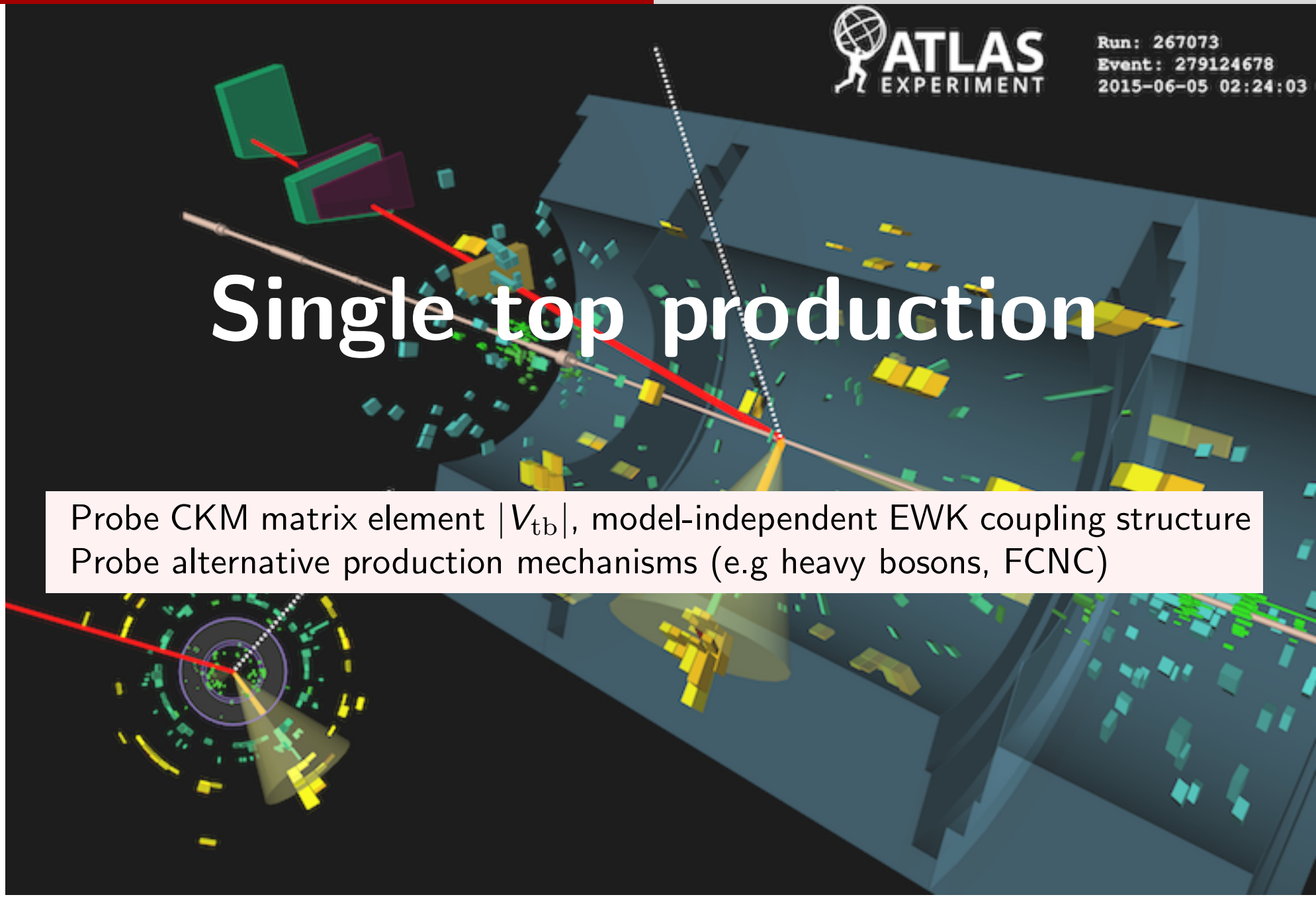


Search for SM four top quark production



- Tiny cross section in SM:
  $\sigma^{SM}_{t\bar{t}t\bar{t}} \sim 10$ fb@13 TeV
- Many BSM models predict an increase:
  Particles decaying to top quarks or modified couplings, massive coloured bosons, composite Higgs/top, extra dimensions, SUSY...
- Meausurements can be used to constrain y_t

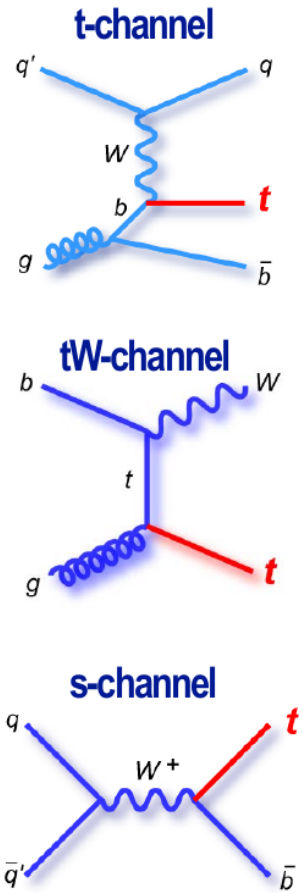


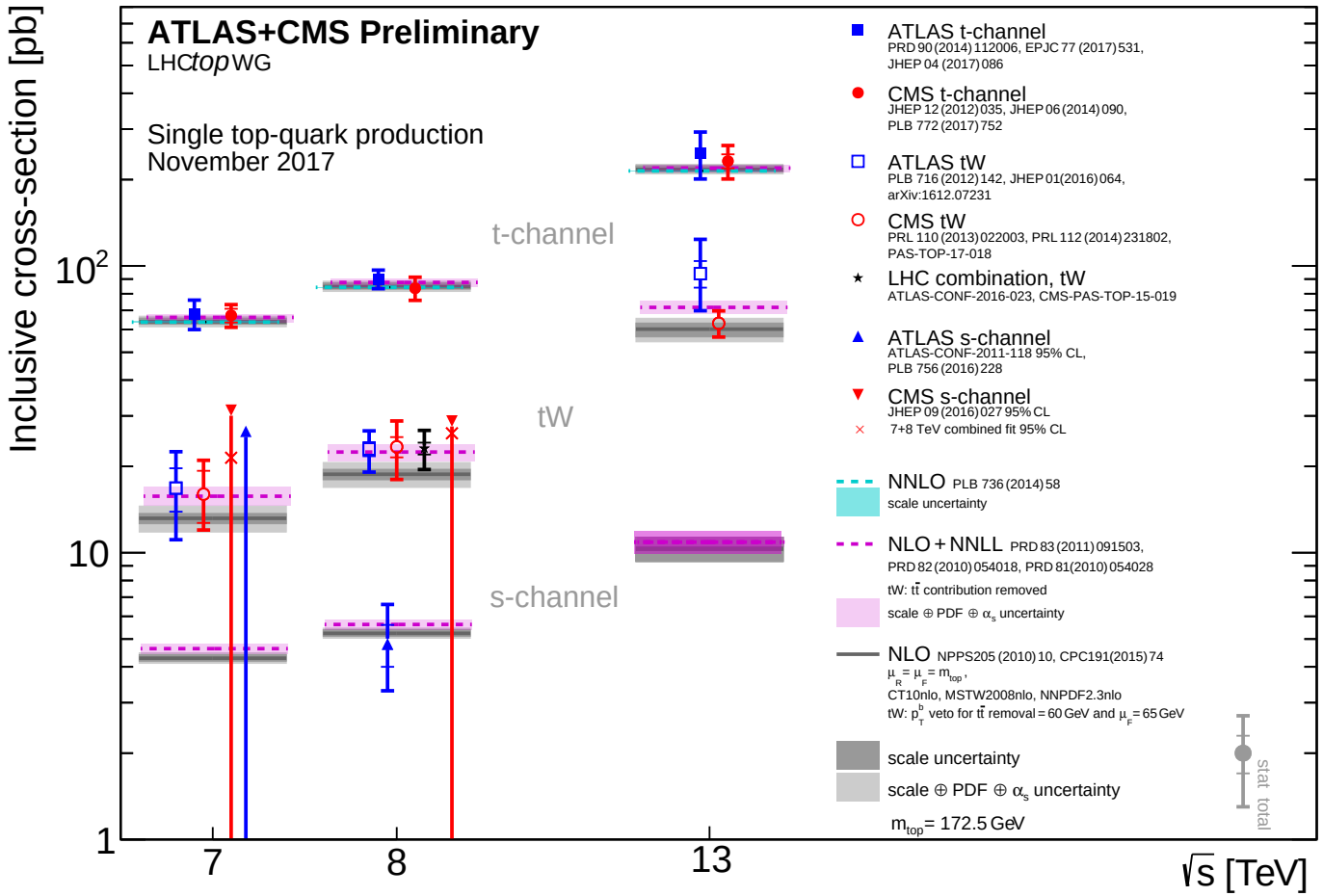


Single top production

Probe CKM matrix element $|V_{\mathrm{tb}}|$, model-independent EWK coupling structure
Probe alternative production mechanisms (e.g heavy bosons, FCNC)

Single top production via EWK interaction

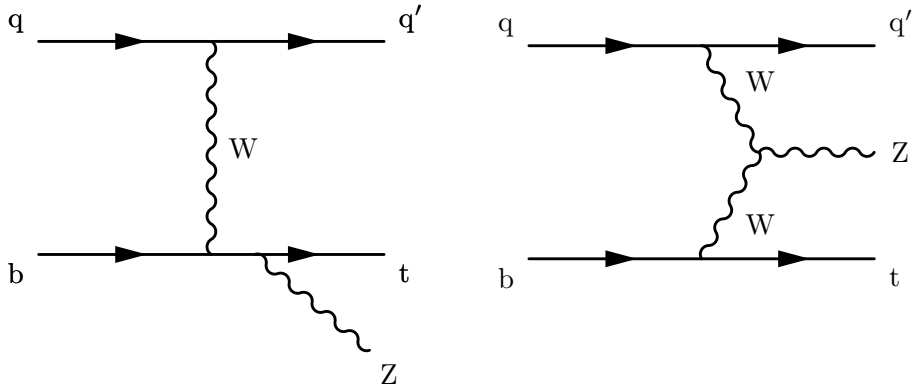




Single top quark cross section at 13 TeV as large as the $t\bar{t}$ cross section at 7-8 TeV

Ramping up towards new era of high-precision in single top quark!

Evidence for SM tZq production

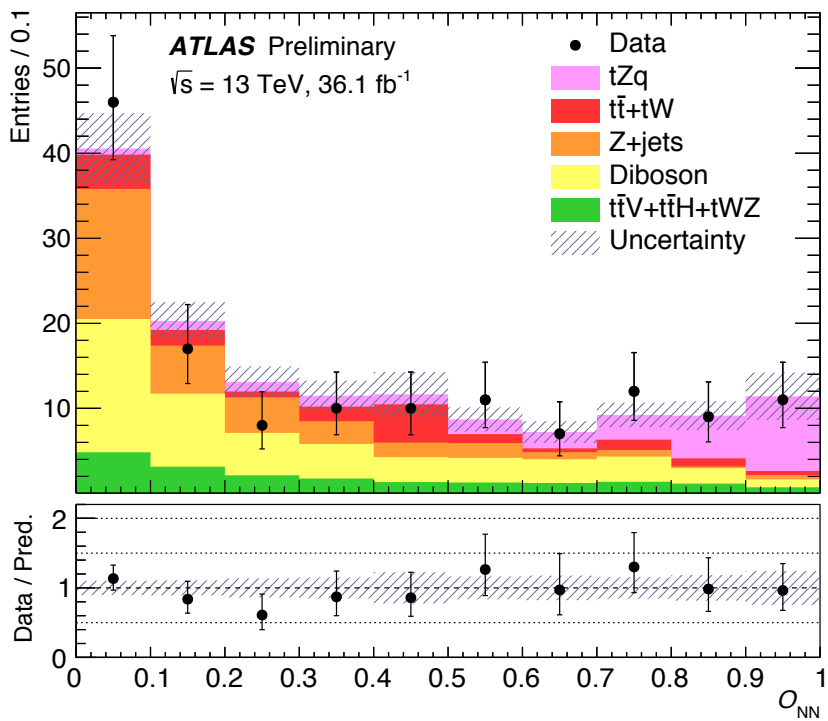


- Sensitive to tZ-coupling, triple-boson coupling, backgrounds for searches
- Trilepton channel most promising for first observation

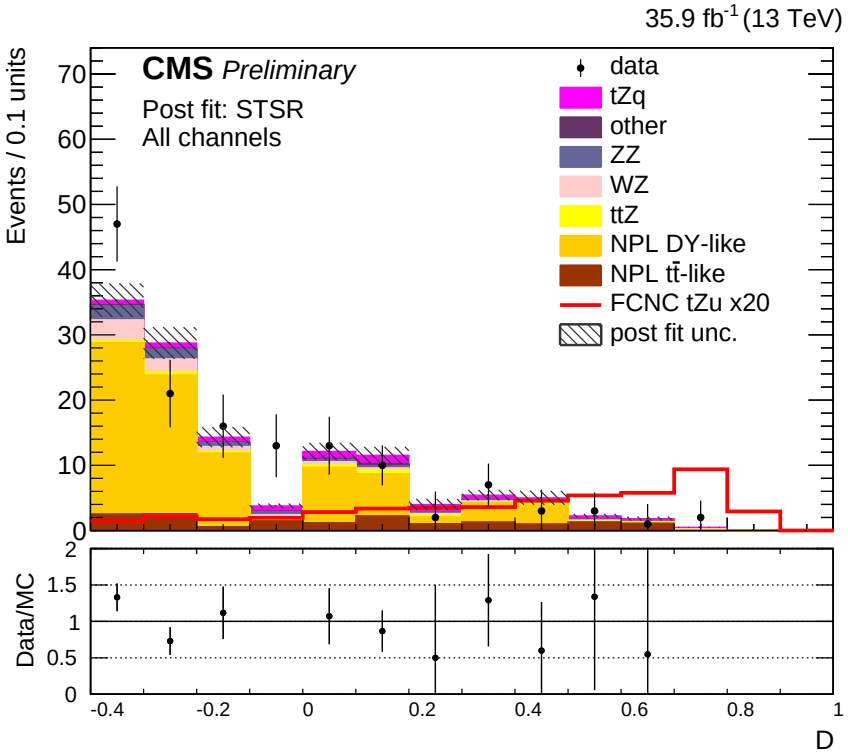
$$\sigma_{tZq} = 600 \pm 170(\text{stat}) \pm 140(\text{syst})\ \text{fb}$$

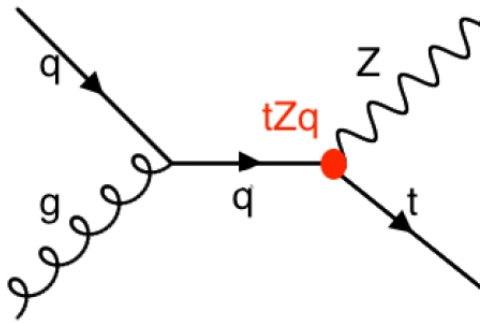
4.2 σ obs. (5.4 σ exp.)

Another milestone in the cross section frontier!



Search for FCNC tZ production



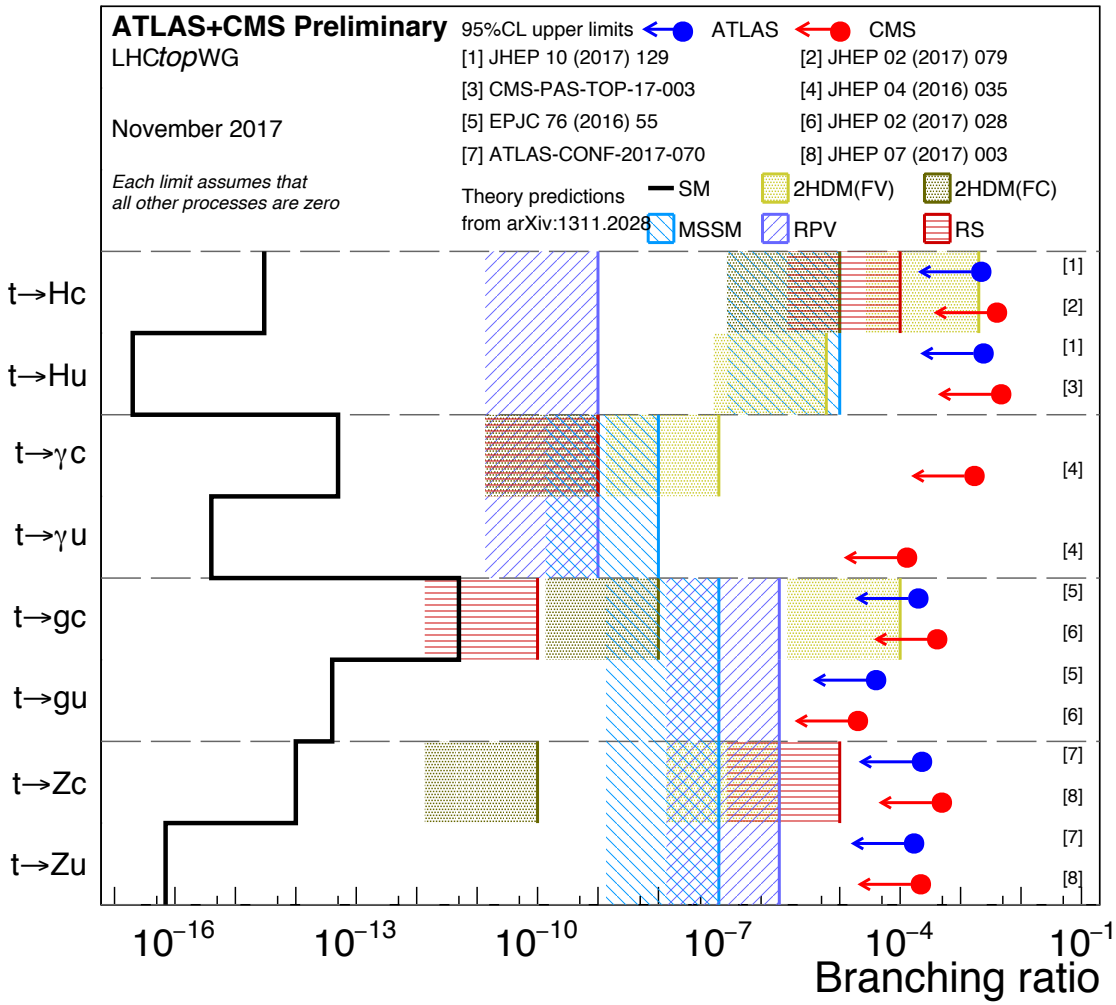


- Sought for t→Zq:
  BR SM = O(10^{-15})
- In models beyond SM:
  BR BSM ∼ O(10^{-5})-O(10^{-6})
- Decay can be found in the FCNC production mode gg→ $t\bar{t}$ →tZq

$$\kappa_{tZu} = 0 \,\&\, \kappa_{tZc} \neq 0 : \mathcal{B} < 0.045\% \,(0.037\%) \quad \text{and}$$

$$\kappa_{tZu} \neq 0 \,\&\, \kappa_{tZc} = 0 : \mathcal{B} < 0.024\% \,(0.015\%).$$

Status of search for FCNC rare decays



No signs of flavour physics associated to top quarks, approaching sensitivity to BSM

Summary and outlook

- The LHC is a real *top quark factory*
  - Top quark measurements entered precision regime
  - Started to challenge theory predictions in many respects
- 13 TeV data is taking a central stage in SM top quark studies
  - Single top quark and $\mathrm{t\bar{t}}$ inclusive cross sections
  - Plethora of differential measurements
  - Rare processes ($\mathrm{t\bar{t}V}$, $\mathrm{t\bar{t}t\bar{t}}$, tZq)
- ... and BSM searches with top quarks ongoing in a multitude of channels
- Coming up Next: More precision measurements of properties and top quark mass, FCNC, anomalous couplings, EFT with 13 TeV data, direct searches

The ultimate potential for top quark physics at the LHC is ahead of us!

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
CMS: http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/index.html