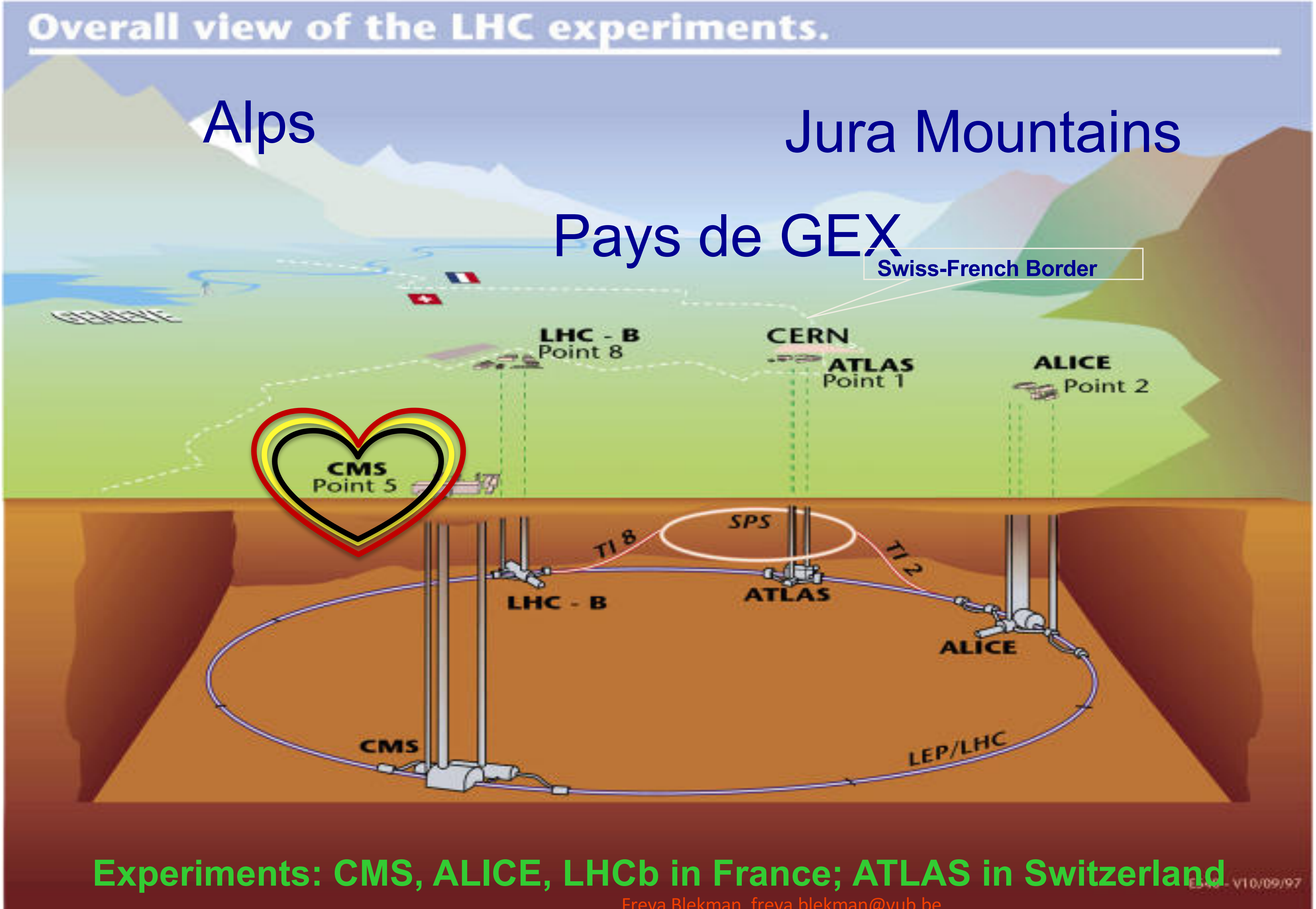
four top quarks

Be.h annual meeting

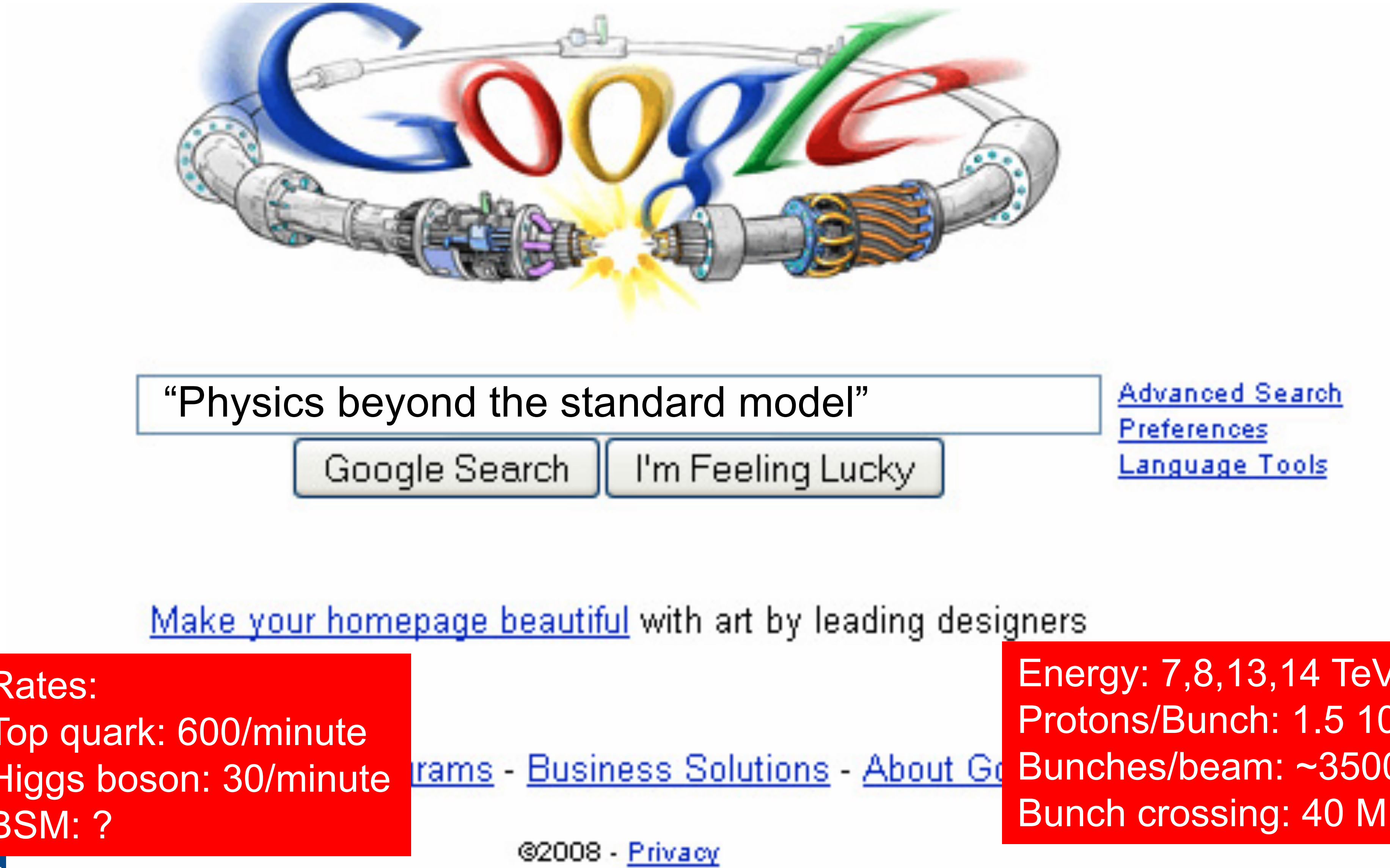
Freya Blekman

IIHE, Vrije Universiteit Brussel

FNAL LHC Physics Centre
distinguished Researcher 2020


Overall view of the LHC experiments.
Alps
Jura Mountains
Pays de GEX
Swiss-French Border
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
Experiments: CMS, ALICE, LHCb in France; ATLAS in Switzerland

LHC: search engine



Rates:
Top quark: 600/minute
Higgs boson: 30/minute
BSM: ?

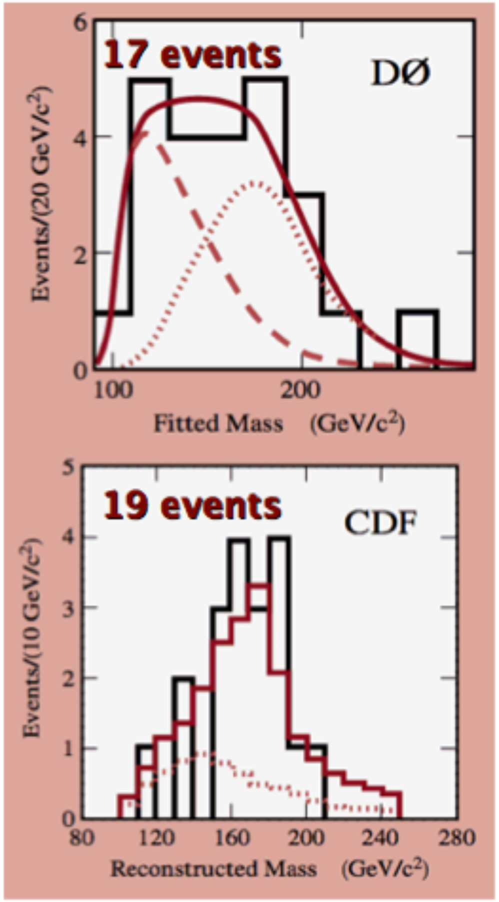
Energy: 7,8,13,14 TeV
Protons/Bunch: 1.5 10^{11}
Bunches/beam: ~3500
Bunch crossing: 40 MHz

Freya Blekman, freya.blekman@vub.be

History top quark – at the start of LHC

discovery

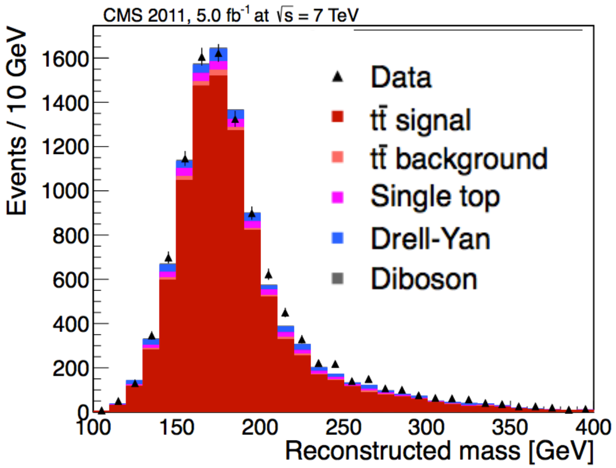
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

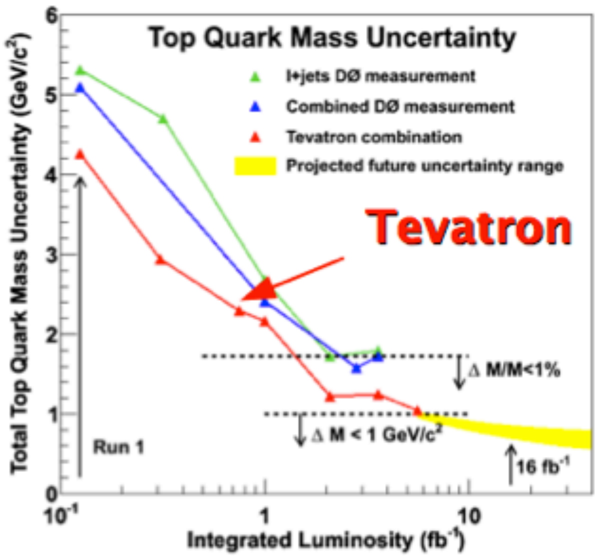
2011

10000s of events



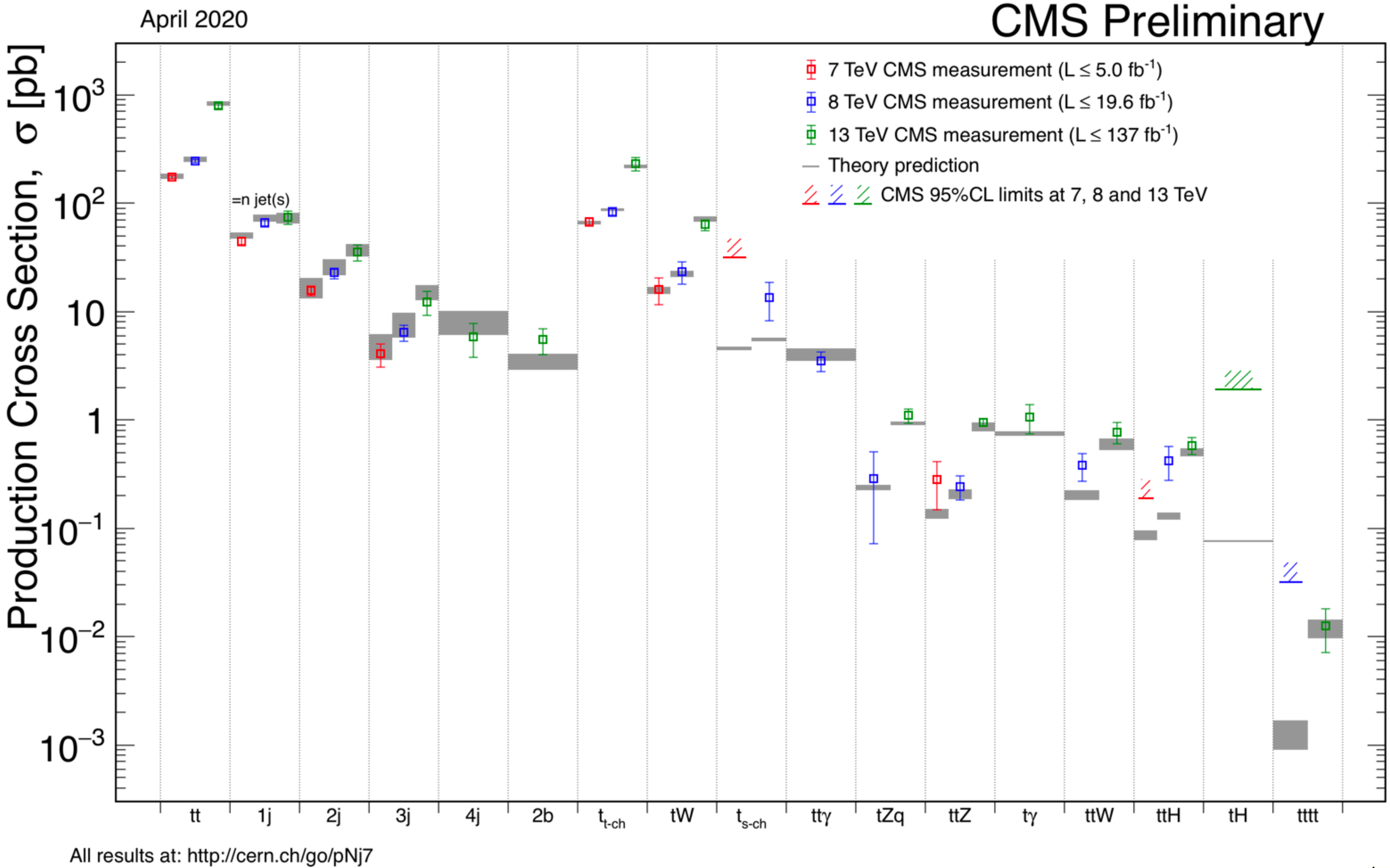
LHC: top quark factory

precision

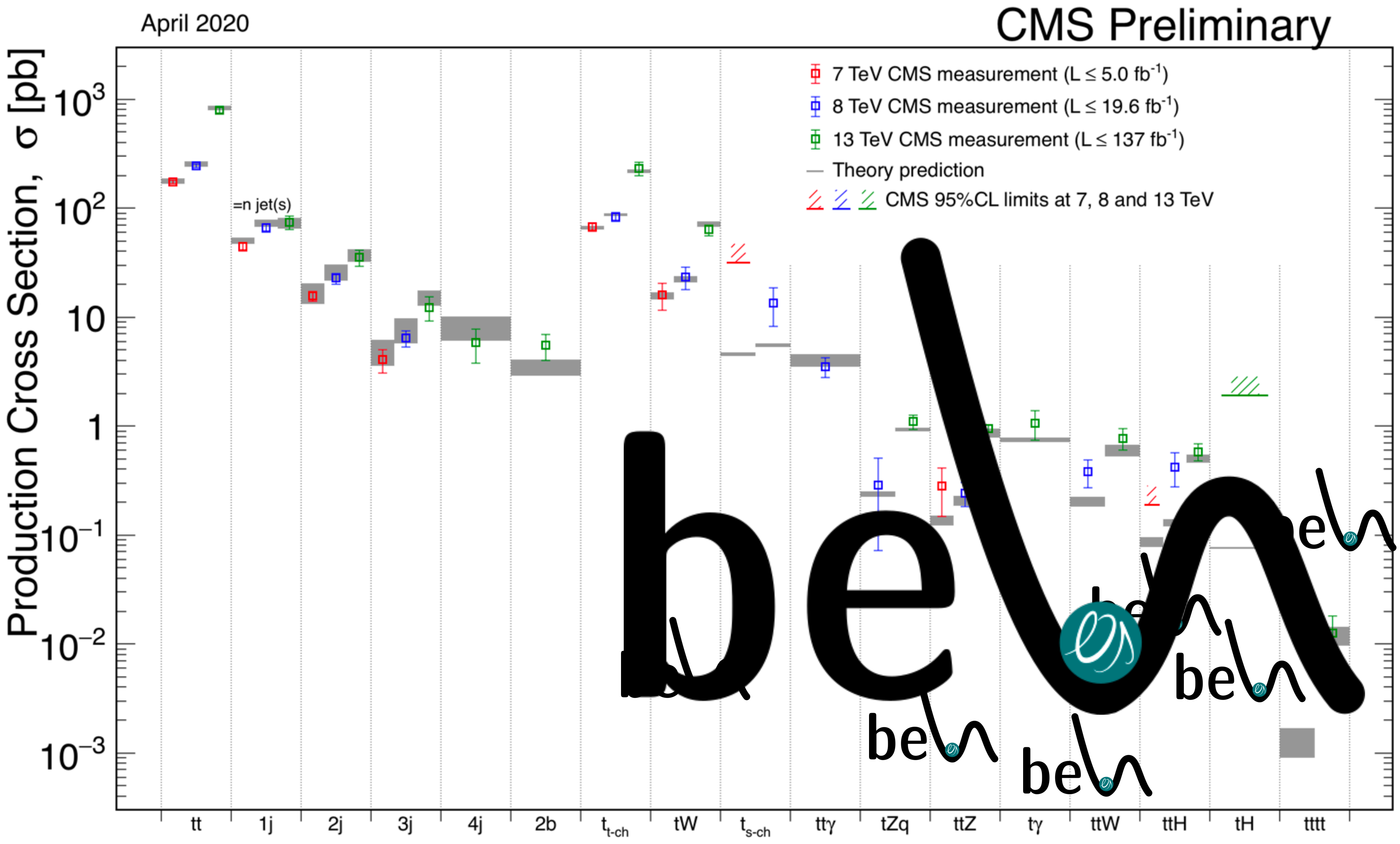


searches

Top quark: now



Top quark: now



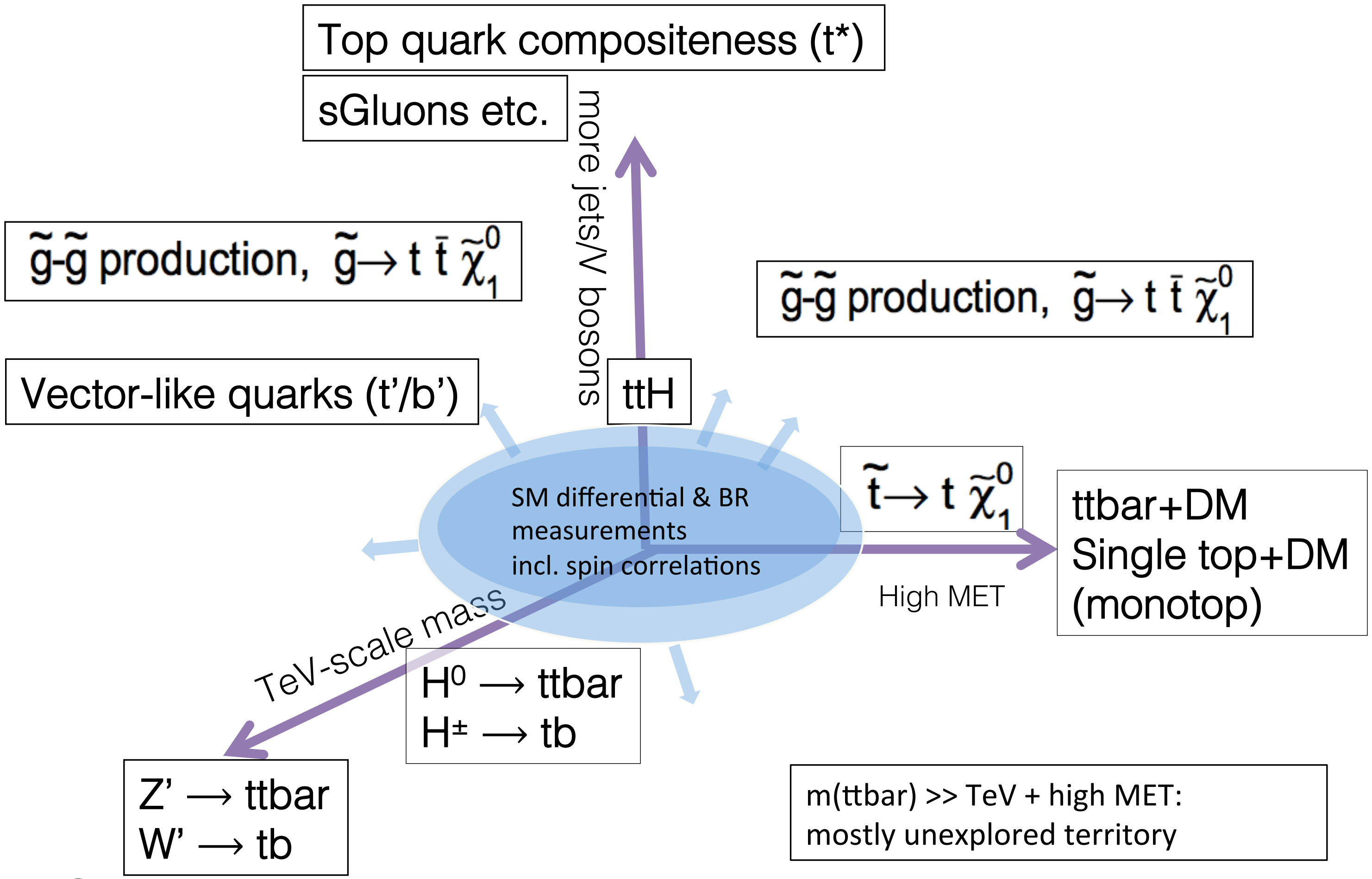
All results at: http://cern.ch/go/pNj7

Why?

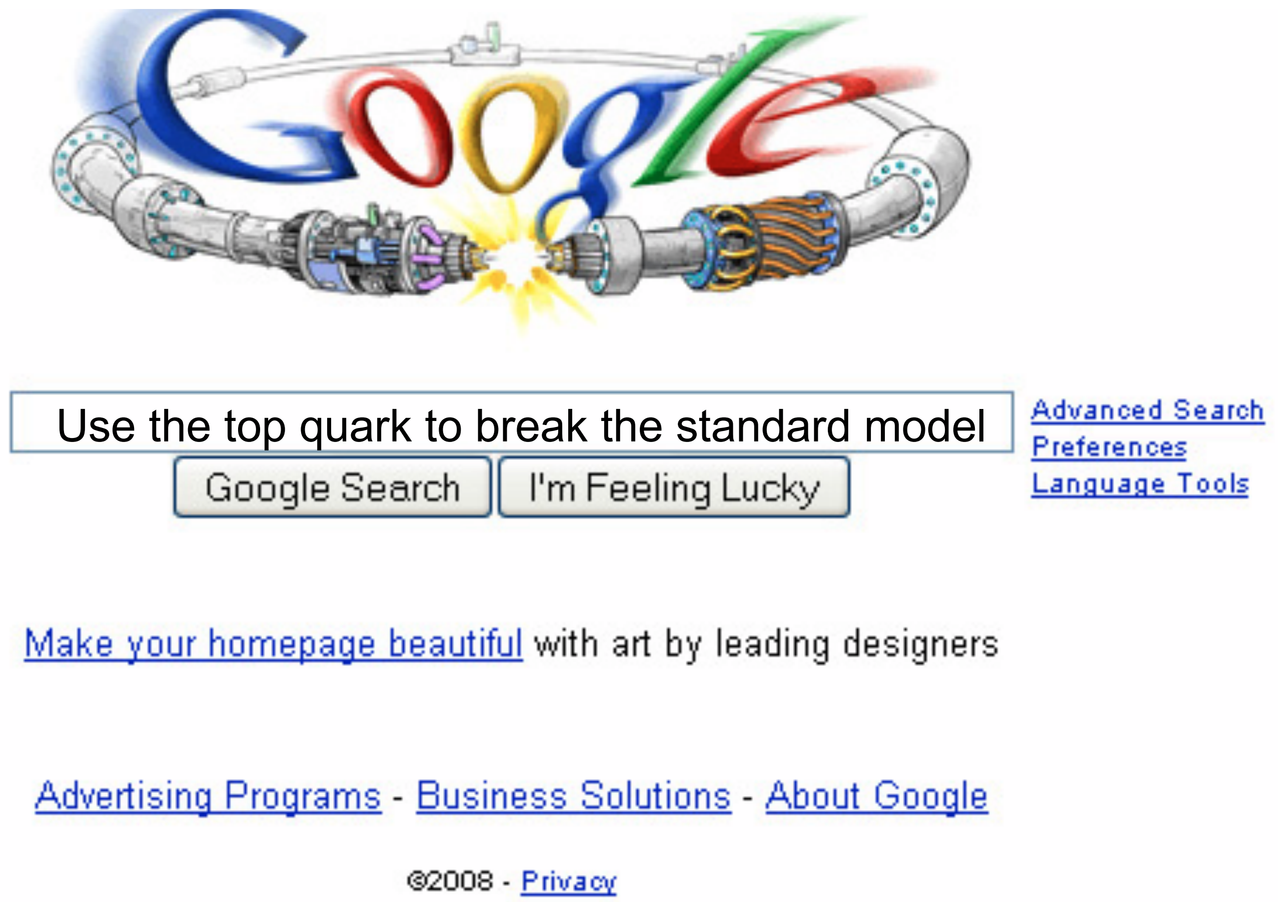
- Standard model predicts top kinematics
- Top physics = SM cross check
- Deviations are signs of new physics
- This new physics is at large mass scales, making it a good candidate to fix the holes in the SM

(
Top pair production rate
Top mass
Single top production rate
B($t \rightarrow Wb$)
$|V_{tb}|$
W helicity
Top polarization
Anomalous couplings
Spin correlations
Rare decays
Rare production mechanisms
Top width
…
)

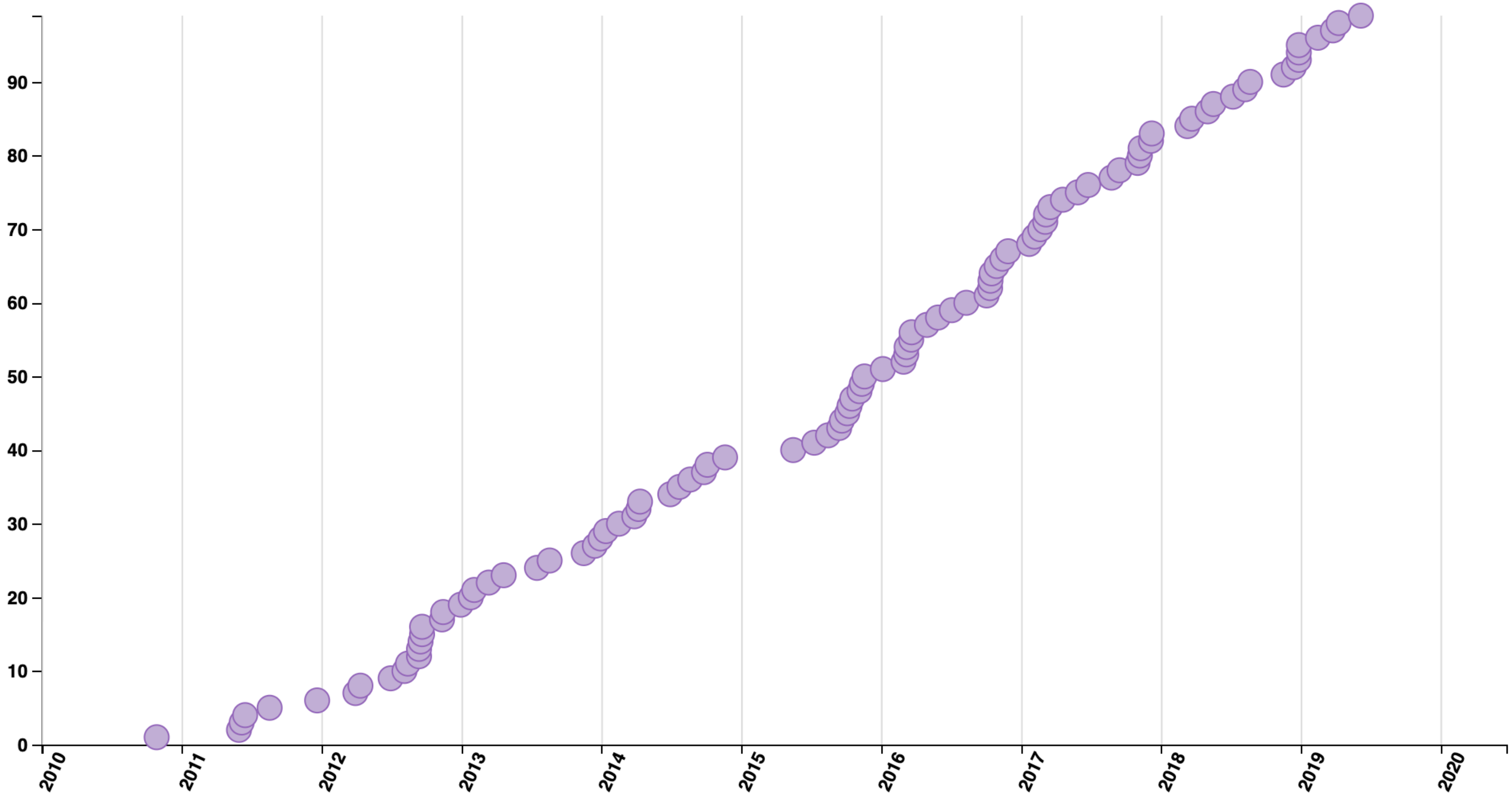
BSM signatures in the ttbar phase space



See also: Czakon et al. arXiv:1501.01112


Google
Use the top quark to break the standard model
Google Search
I'm Feeling Lucky
Advanced Search
Preferences
Language Tools
Make your homepage beautiful with art by leading designers
Advertising Programs - Business Solutions - About Google
©2008 - Privacy

99 ways to examine the top quark



News flash!

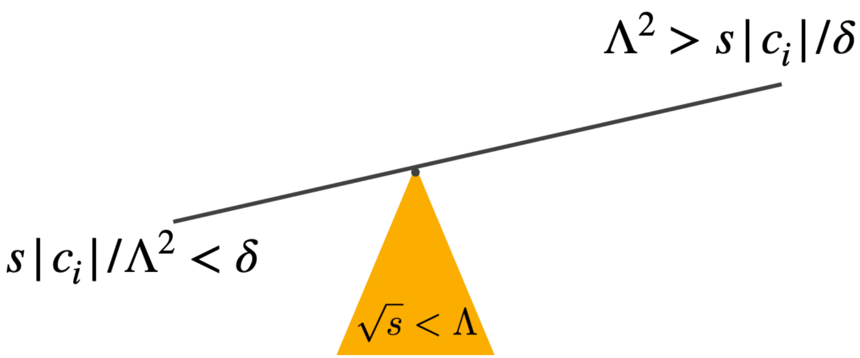
Use top quark to constrain SM and learn more

Precision…what for?

Searching for new interactions with an EFT

The matter content of SM has been experimentally verified and there is no evidence for light states. SM measurements can be interpreted as searches for deviations from the dim=4 SM Lagrangian predictions.

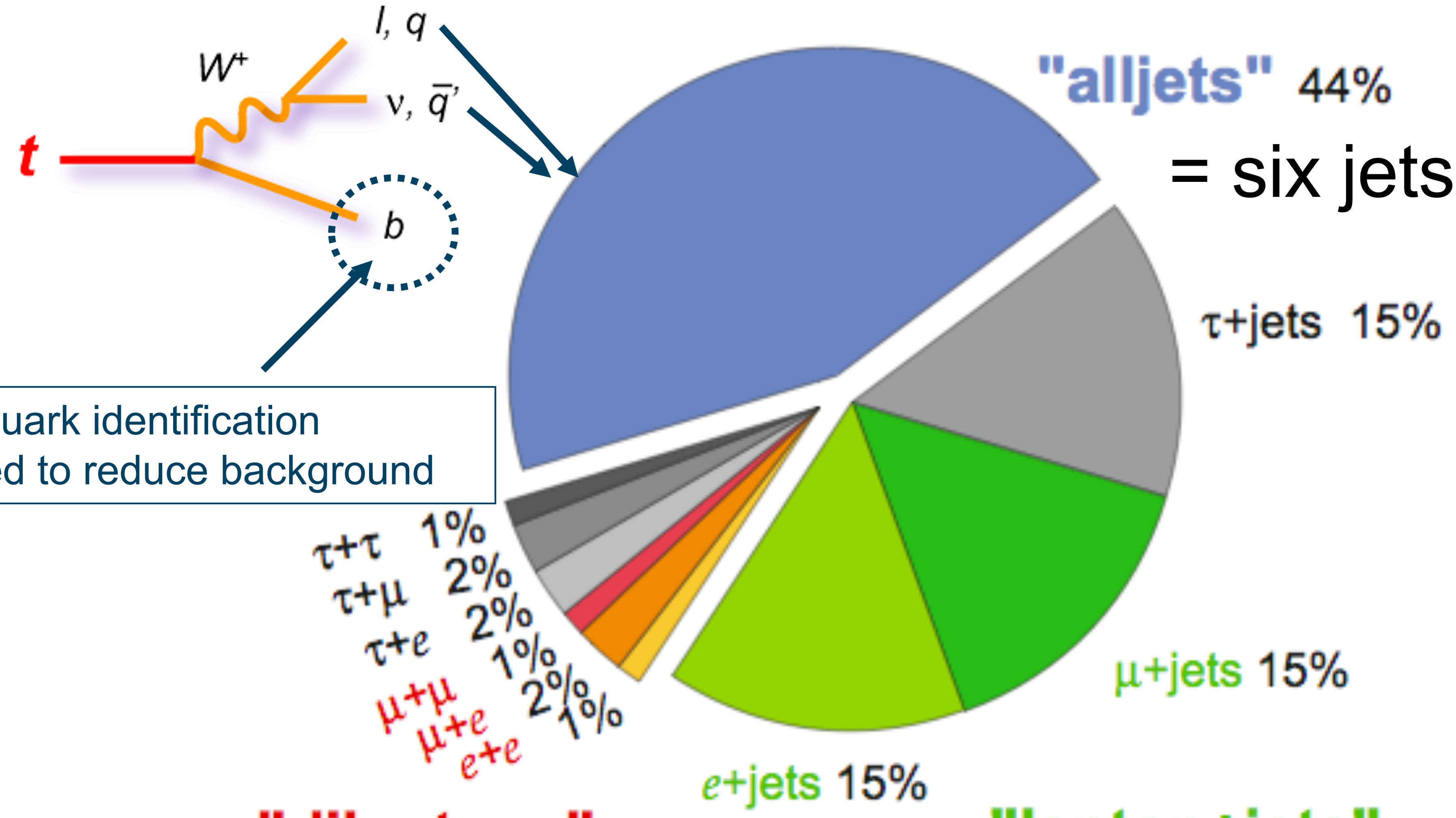
$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots$$



BSM goal of the precision LHC programme: determination of the couplings of the SMEFT lagrangian.

Source: Fabio Maltoni @LHCP2020

Top pair branching fractions

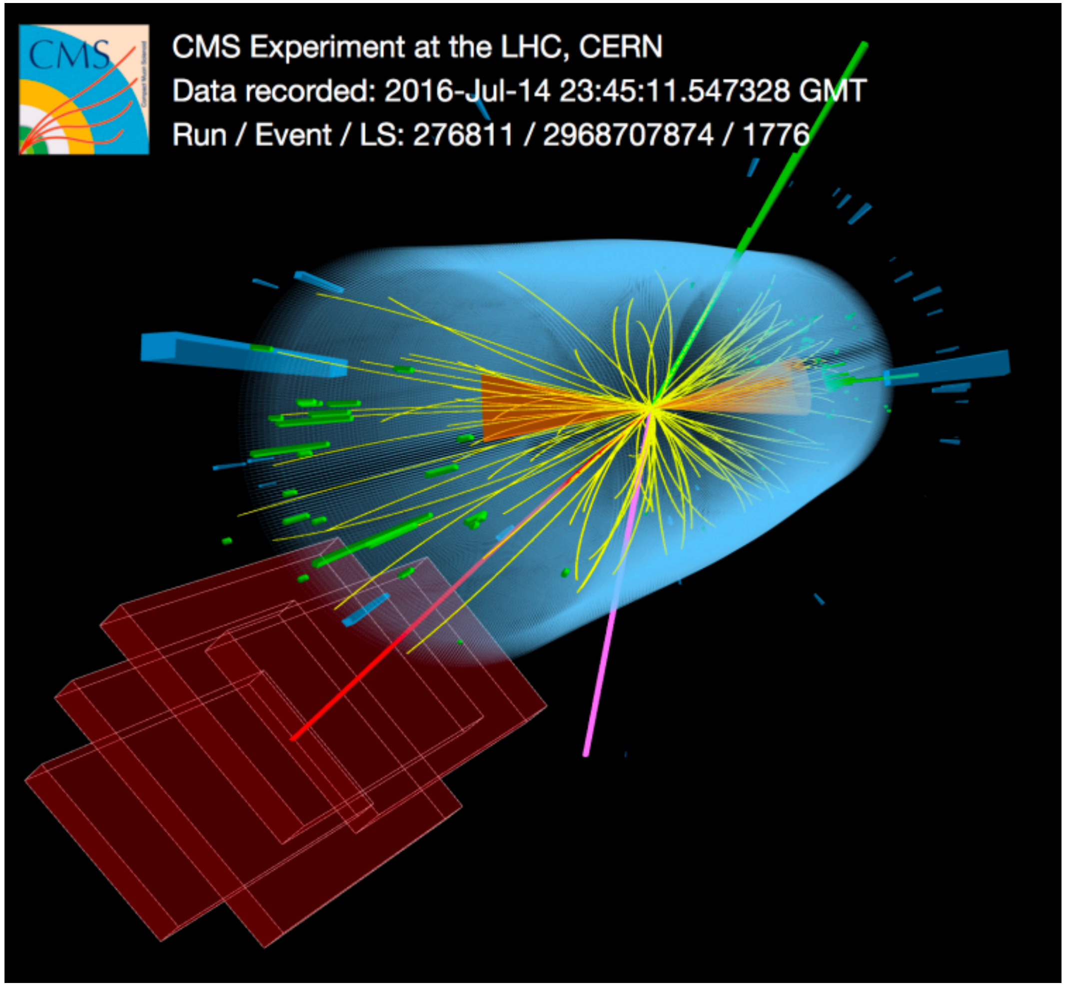


B-quark identification
used to reduce background

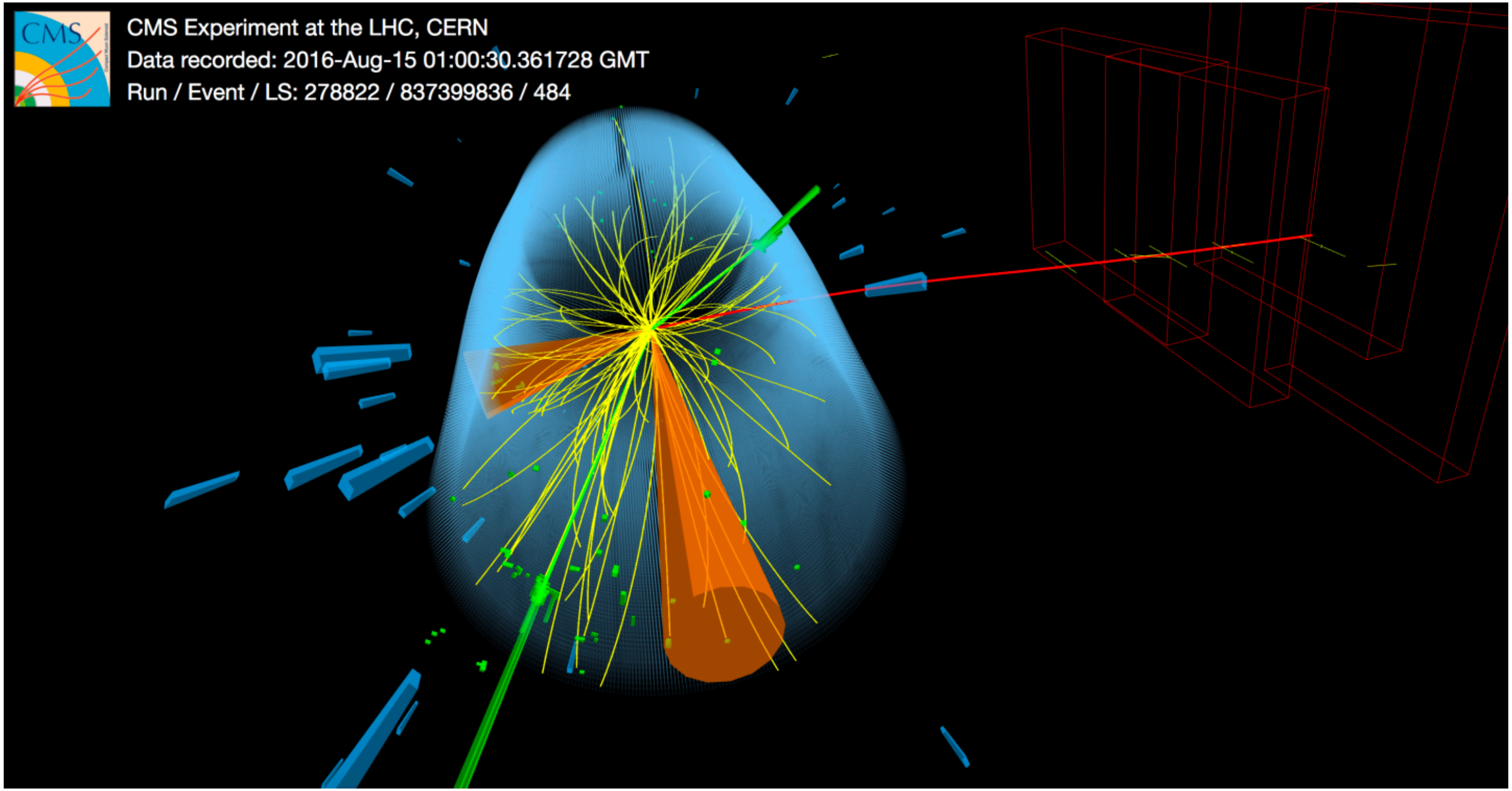
= two jets, two leptons, MET

= four jets, lepton, MET

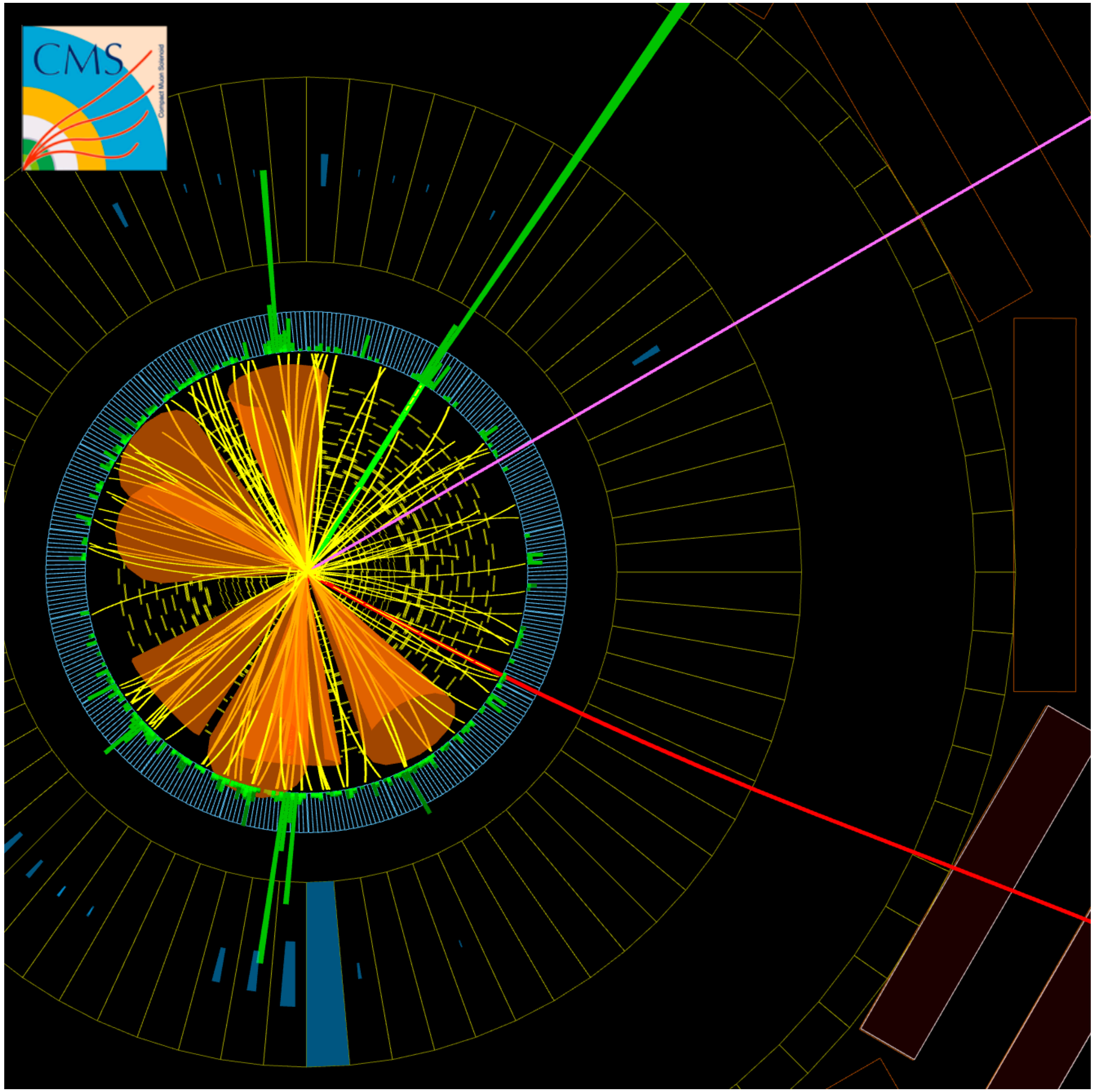
Top quark pair: both W bosons into leptons



Top quark pair: together with a Z boson



Top quark pair together with a Higgs



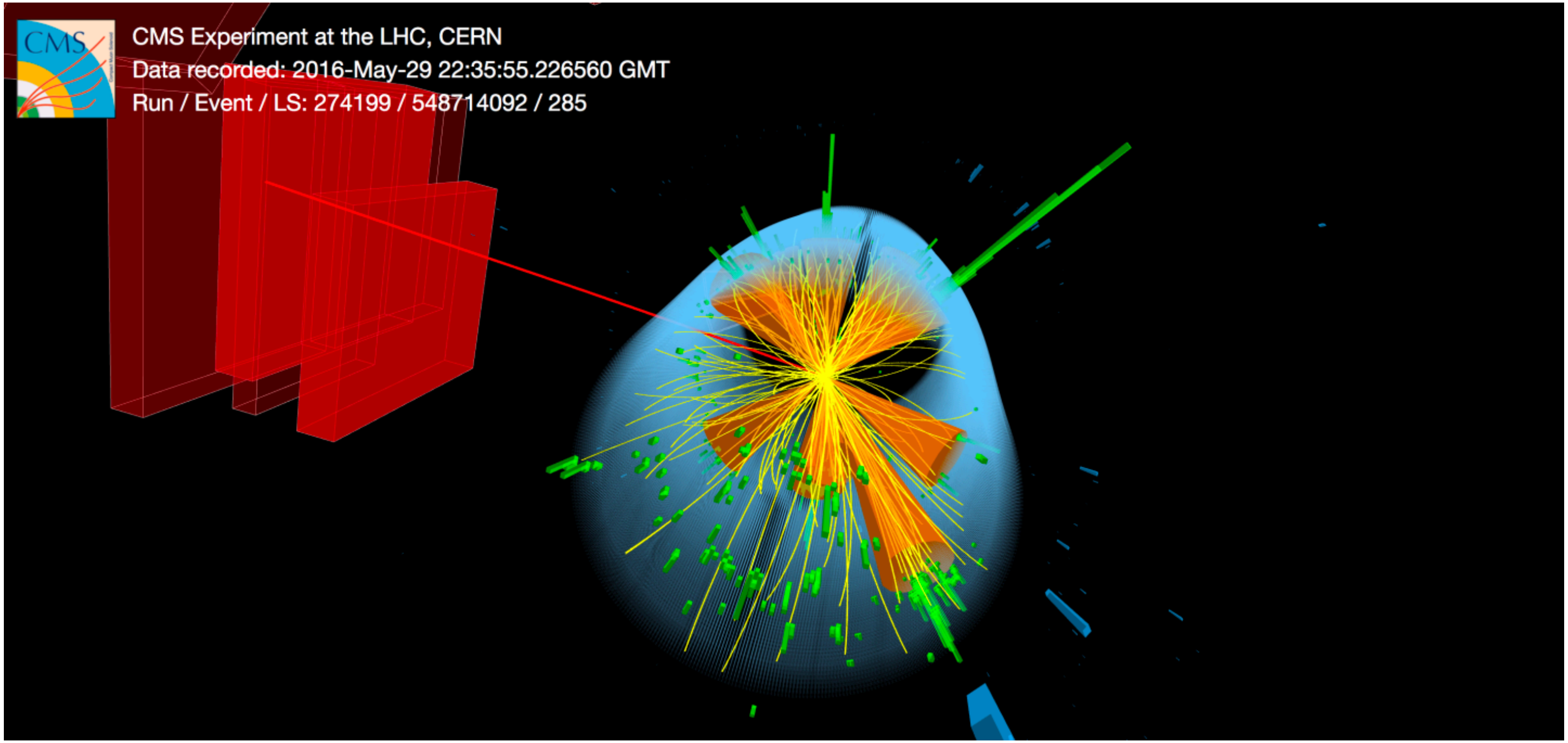
Top physics: decay channel choice

- Difficulty of isolation of top quark events inversely proportional to the complexity of the mass reconstruction

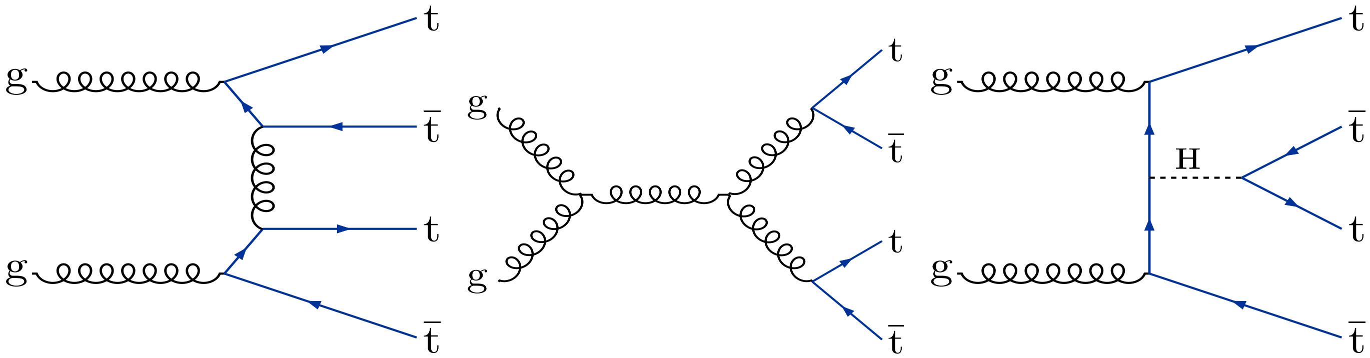
	Isolation signal	Reconstruction
Di-lepton	Relatively easy	Two neutrinos, ambiguities
Lepton+jets	Reasonable	One neutrino, use missing transverse energy
All-hadronic	Very difficult	Possibility to observe top as ‘peak’ in invariant mass spectrum, no energetic neutrinos

Freya Blekman, freya.blekman@vub.be

Let’s take it up some steps: more top quarks

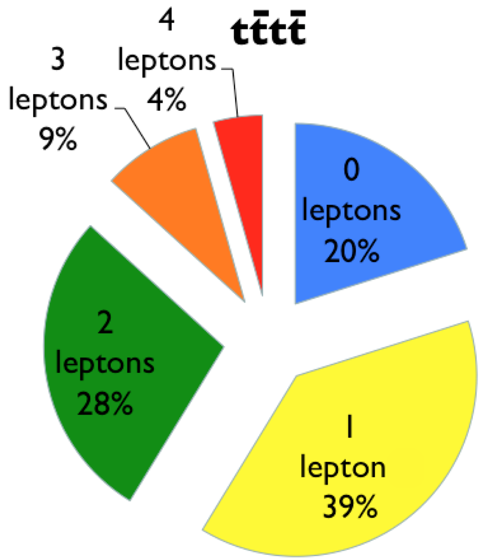


tttt: theory and strategy



Cross section ~1 order of magnitude smaller than ttH

Signatures: 4leptons4b - 3leptons4b2j – 2leptons4b4j -1lepton4b6j – 4b8j



Cross section at NLO QCD+EWK calculation available that gives ~12 fb
Frederix, Pagani, Zaro arXiv:1711.02116

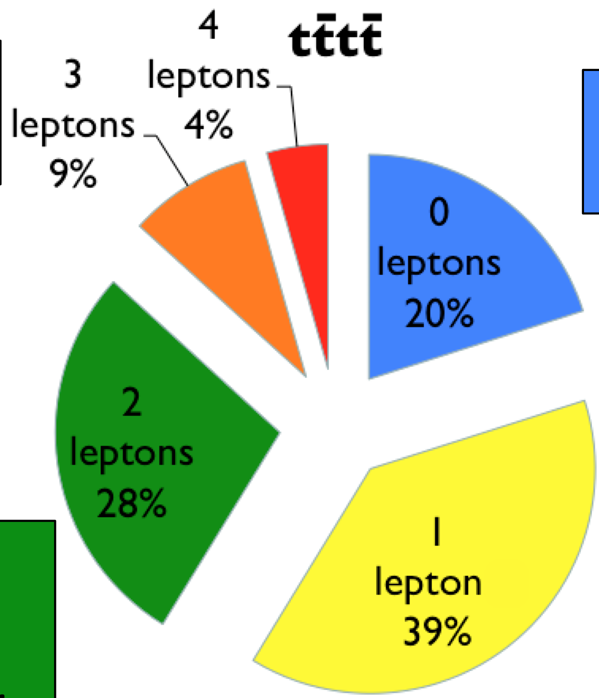
2016 data results use the previous NLO (QCD only) cross section at 9.2 fb

- easier to compare results. No influence on most limits/measurements

Analysis strategy

- Depends on final state
  - (similar ttH analysis: fewer leptons = more work)

Dominant background:
ttW/Z/H, dibosons, fakes



Dominant background:
multijet QCD

Refs SS dileptons/multileptons:
ATLAS arxiv 1807.11883 (36 fb^{-1})
CMS arxiv 1908.06463 (137 fb^{-1})

Dominant background:
OS dileptons: ttbar+HF
SS dileptons: ttW/Z/H, dibosons, fakes

Dominant background:
ttbar+HF

Refs l+jets, OS dileptons:
ATLAS arxiv 1811.02305 (36 fb^{-1})
CMS arxiv 1906.02805 (36 fb^{-1})

Different approaches to EFT

- ATLAS: BSM-like EFT looking for dramatic changes in shape at high scale
- CMS: SM-like EFT trying to constrain small changes cross section limit/uncertainties and mapping fit cross section limits to Wilson coefficients

- Both have pros and cons

EFT interpretation

- Like many rare processes involving loop diagrams, four-top production is extremely sensitive to new physics
- SM effective field theory at order 6

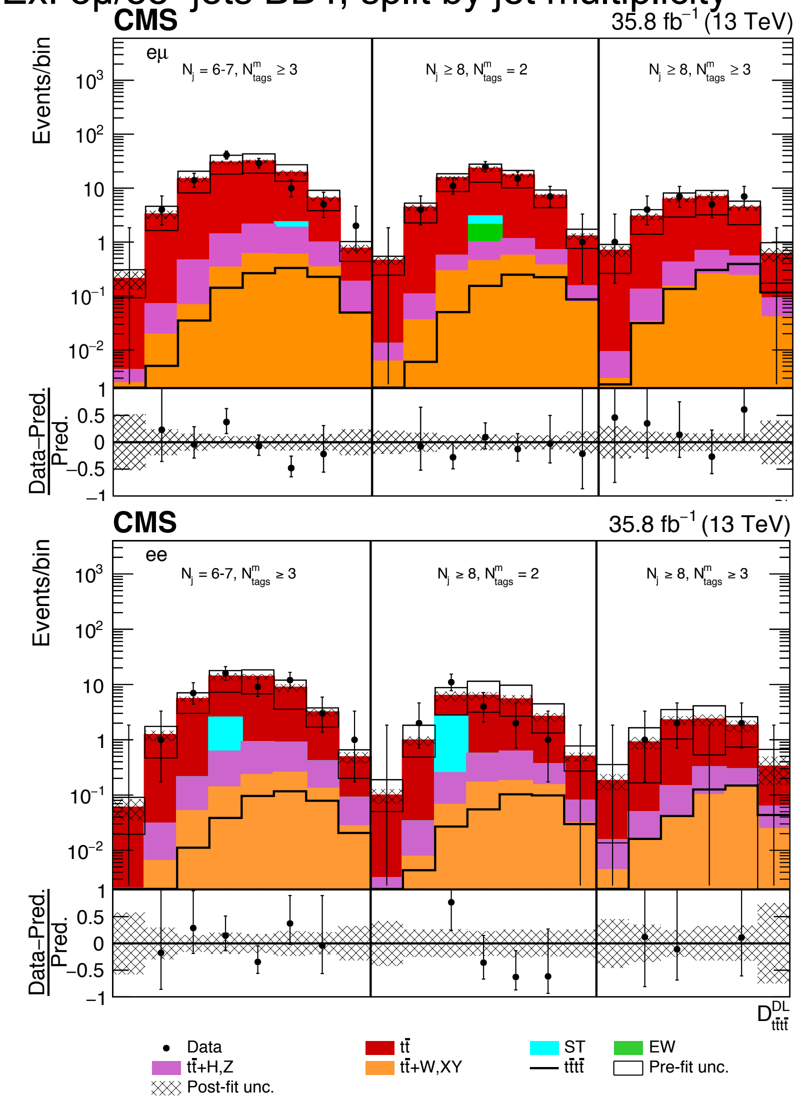
$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)}\mathcal{O}_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)}\mathcal{O}_k^{(6)} + o\left(\frac{1}{\Lambda^2}\right)$$

- ATLAS: use $\mathcal{L}_{\mathrm{EFT}}$ - $\mathcal{L}_{\mathrm{SM}}^{(4)}$ as signal model, constrain Λ
- CMS: constrain $\mathcal{L}_{\mathrm{EFT}}$ / $\mathcal{L}_{\mathrm{SM}}^{(4)}$ with $\Delta\sigma_{tttt}/ \sigma_{tttt}$, fix Λ, constrain C_k

CMS l+jets and OS dileptons: strategy

- MC based simultaneous fit of a boosted decision tree, using MC shapes including full theory uncertainties (source: Powheg)
  - BDT trained on kinematic, b-tagging and resolved top tagging information
  - Lower tag multiplicity and jet multiplicity 7-8 jets used to constrain (large) systematic uncertainties during simultaneous fit
  - Strategy similar to simultaneous fits used for ttbar cross section
- Weakness: many systematic uncertainties driven by theory uncertainties such as tt+HF via gluon splitting (largest), renormalization scale, etc
  - Conservative choice of systematic uncertainties creates weak limit when little statistics in control region part of fit
  - Plus: Method expected to gain precision with larger datasets when more statistics in control regions

Ex: eμ/ee+jets BDT, split by jet multiplicity



CMS arxiv 1906.02805 (36 fb^{-1})

CMS l+jets and OS dileptons: results

- OS dilepton analysis has lack of tttt candidate events creating 0 fb limit (single lepton has some sensitivity)
- Refitting improves also result 2016 same-charge and multilepton and gives CMS grand combination for tttt

cross section limits interpreted in EFT for separate Wilson parameters (also 2D) incl. marginalization over all other physical free parameter values
Using EFT basis recommended by TOP LHCWG arxiv:1802.07237

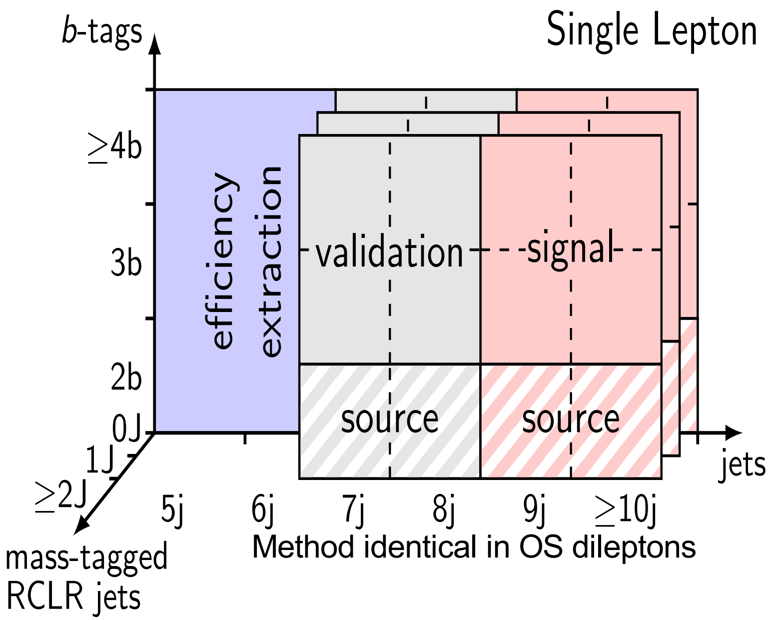
Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{tt}$	[−2.0, 1.9]	[−2.2, 2.1]
$\mathcal{O}^1_{QQ}$	[−2.0, 1.9]	[−2.2, 2.0]
$\mathcal{O}^1_{Qt}$	[−3.4, 3.3]	[−3.7, 3.5]
$\mathcal{O}^8_{Qt}$	[−7.4, 6.3]	[−8.0, 6.8]

SM tttt limits	Expected (μ)	Observed (μ)	Expected (fb)	Observed (fb)	Signal strength (μ)	Signal strength (fb)
CMS 1L+OS2L 36 fb^{-1}	5.7	5.2	52 fb	48 fb	$0^{+2.2}$	0^{+20} fb
CMS 2016 combination 36 fb^{-1}	2.2	3.6	20 fb	33 fb	$1.4^{+1.2}_{-1.0}$	13^{+11}_{-9} fb
ATLAS >=3L-SS2L 36 fb^{-1}	3.2	7.5	29 fb	69 fb		

ATLAS, l+jets and OS dileptons: method

- Dominant background is ttbar+bbbar+jets
  - The additional jets are the main difference with ttH analysis strategies
  - ATLAS derives tagging efficiencies in ttbar+2 jet dominated region, verifies in ttbar+3-4 jet region
  - extrapolates from ttbar+no extra tags to ttbar+1/2 extra tags
  - Signal region in ttbar+5 or more jets plus 1 or 2 extra b tags
  - Includes category with top-tagged large cone jets
  - Misidentification leptons from QCD background is small and taken from data

Preselection requirements		
Requirement	Single-lepton	Dilepton
Trigger	Single-lepton triggers	
Leptons	1 isolated	2 isolated, opposite-sign
Jets	≥5 jets	≥4 jets
b-tagged jets	≥2 *b*-tagged jets	
Other	$E_T^{miss} > 20$ GeV	$m_{\ell\ell} > 50$ GeV
	$E_T^{miss} + m_T^W > 60$ GeV	$\|m_{\ell\ell} - 91 \text{ GeV}\| > 8$ GeV



Method identical in OS dileptons

ATLAS arxiv 1811.02305 (36 fb^{-1})

ATLAS, l+jets and OS dileptons: method

- Dominant background is ttbar+bbbar+jets
  - The additional jets are the main difference with ttH analysis strategies
  - ATLAS derives tagging efficiencies in ttbar+2 jet dominated region, verifies in ttbar+3-4 jet region
  - extrapolates from ttbar+no extra tags to ttbar+1/2 extra tags
  - Signal region in ttbar+5 or more jets plus 1 or 2 extra b tags
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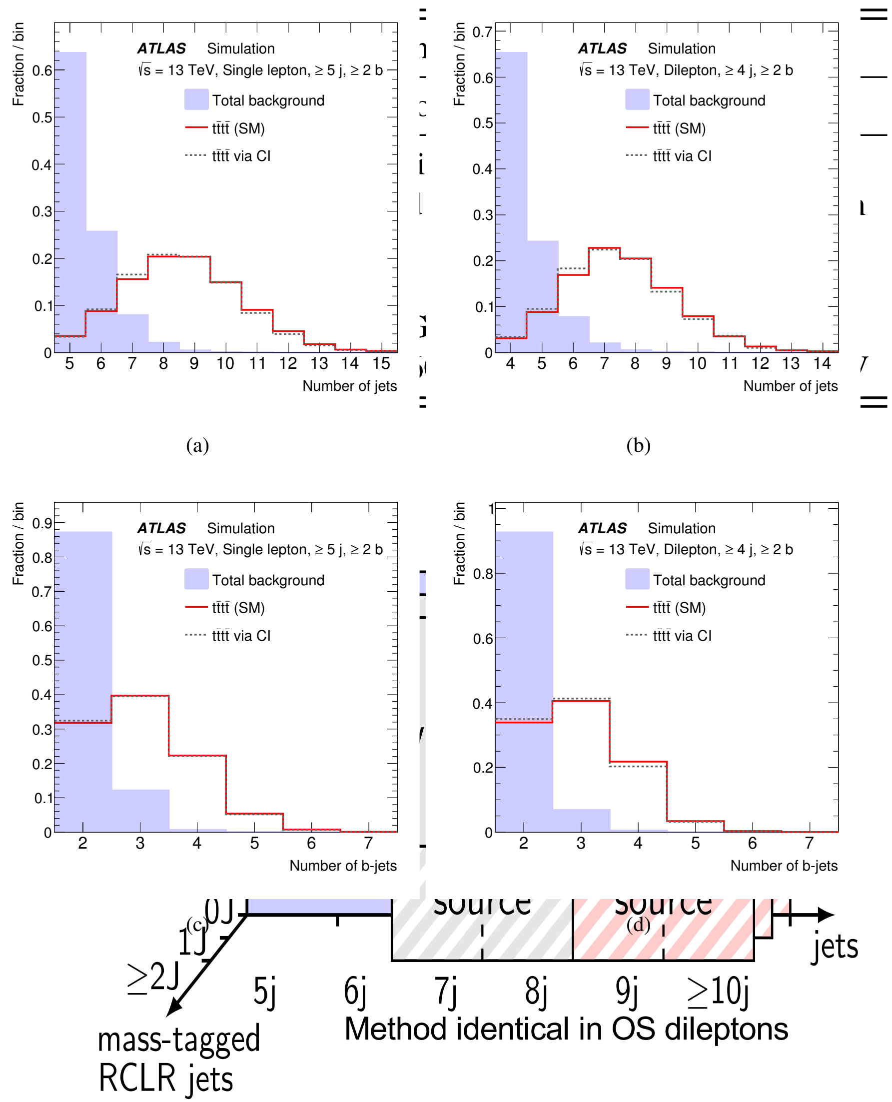
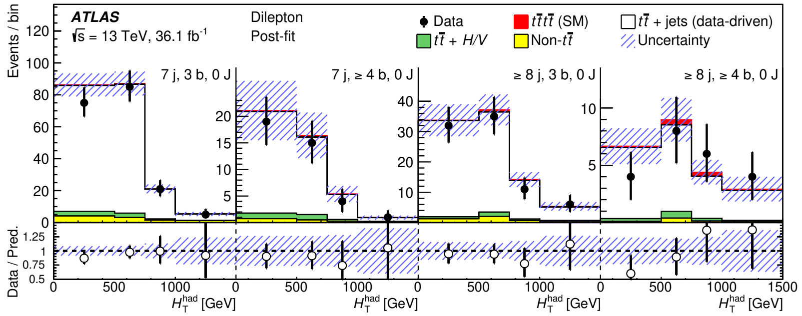


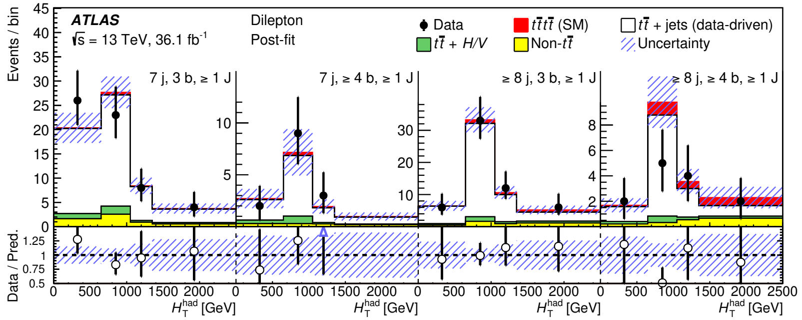
ATLAS arxiv 1811.02305 (36 fb^{-1})

ATLAS, l+jets and OS dileptons: Results

- Data-driven backgrounds plus binned simultaneous fit to H_T
- Results are compared to NLO QCD $\sigma_{tttt} = 9.2\ ^{+2.9}_{-2.4}$ (scale) +/- 0.5 (pdf) fb
- EFT interpretation set uppper limits on scale of BSM $|C_{tttt}|/\Lambda^2 < 1.9\ \mathrm{TeV}^{-2}$
- Combination with SS/multilepton result provided, lowers upper limit σ_{tttt} to 21 fb



(a)

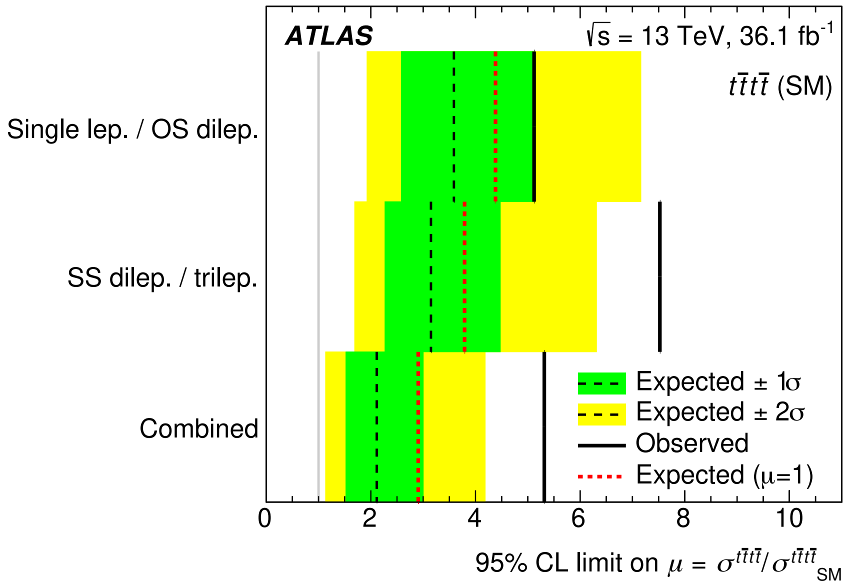


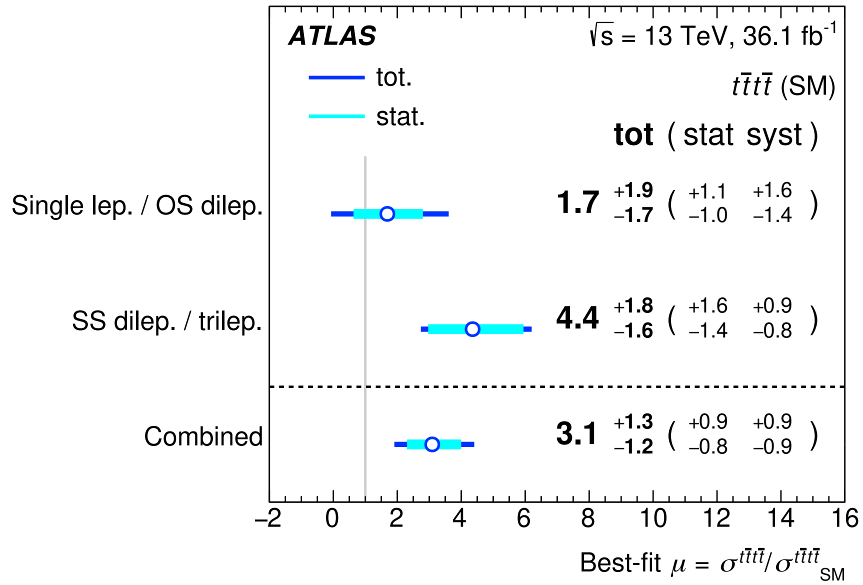
Single lepton has analogue distributions

SM tttt limits (σ_{tttt} = 9.2 fb)	Expected limit (μ)	Observed limit (μ)	Expected limit (fb)	Observed limit (fb)	Signal strength (μ)	Cross section (fb)
ATLAS 1L-OS2L 36 fb^{-1}	3.6	5.1	33 fb	47 fb	$1.7\ ^{+1.9}_{-1.7}$	$15.6^{+17.5}_{-15.6}$

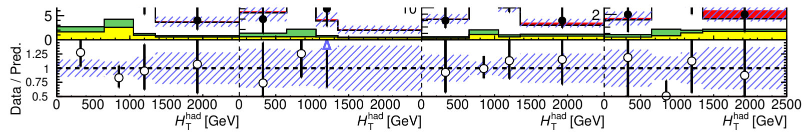
ATLAS arxiv 1811.02305 (36 fb^{-1})

ATLAS, l+jets and OS dileptons: Results





- Combination with SS/multilepton result provided, lowers upper limit σ_{tttt} to 21 fb



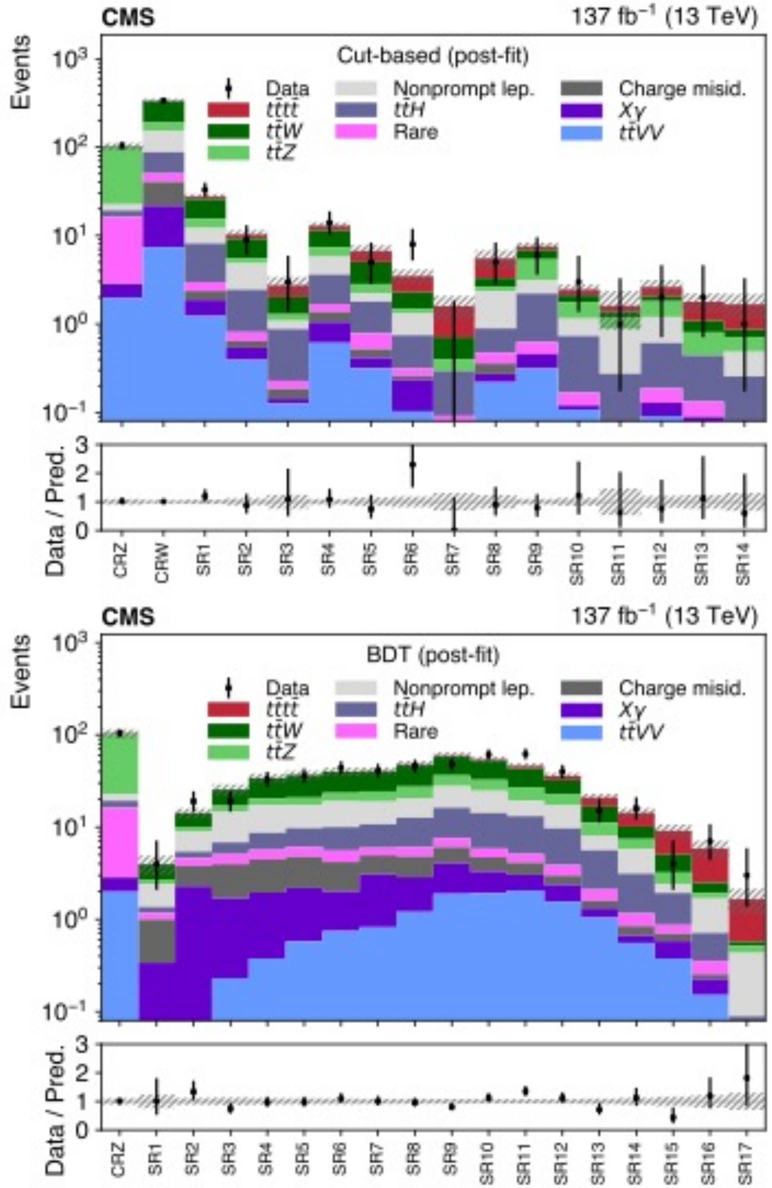
Single lepton has analogue distributions

SM tttt limits (σ_{tttt} = 9.2 fb)	Expected limit (μ)	Observed limit (μ)	Expected limit (fb)	Observed limit (fb)	Signal strength (μ)	Cross section (fb)
ATLAS 1L-OS2L 36 fb^{-1}	3.6	5.1	33 fb	47 fb	1.7 $^{+1.9}_{-1.7}$	15.6$^{+17.5}_{-15.6}$

ATLAS arxiv 1811.02305 (36 fb^{-1})

CMS SS/multi-leptons: strategy

- Analysis in same-charge and multileptons
  - So dominated by ttH, ttZ/ttW and misidentification backgrounds
- Uses simultaneous fit in multiple lepton flavours and b-tag, jet categories
  - Dominant uncertainties:
    - modelling of SM backgrounds
    - Data-driven charge-misidentification estimates
    - knowledge heavy flavour tt+HF
- Boosted Decision tree to get optimal sensitivity
- Substantial improvement over cut-and-count approach but is available for recasting tools



CMS arxiv 1908.06463 (137 fb^{-1})

CMS SS/multi-leptons: results

- Significance of BDT analysis has 2.6 standard deviations significance (2.7 expected) over background-only hypothesis!
  - Combination with other channels planned – stay tuned
  - Although not “officially” significant yet, main result is σ_{tttt} with about 45% uncertainty
  - Agrees well within uncertainties with NLO QCD+EWK value of $\sigma_{tttt}=12.0^{+2.2}_{-2.5}$ fb (Frederix et al arXiv:1711.02116)

SM tttt limits	Expected limit (μ)	Observed limit (μ)	Expected limit (fb)	Observed limit (fb)	Signal strength (μ)	Cross section (fb)
CMS SS2L+>=3L 137 fb^{-1}				22.5 fb		$12.6^{+5.8}_{-5.2}$fb

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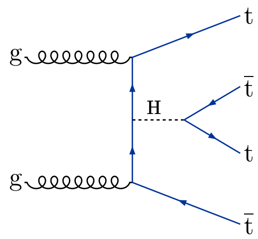
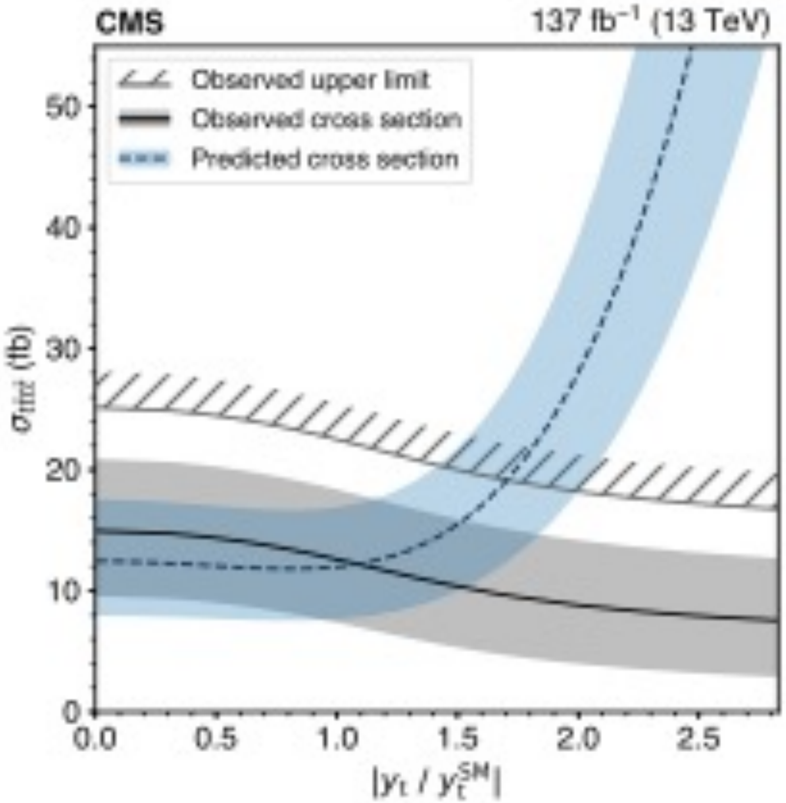
CMS SS/multi-leptons: interpretation y_t

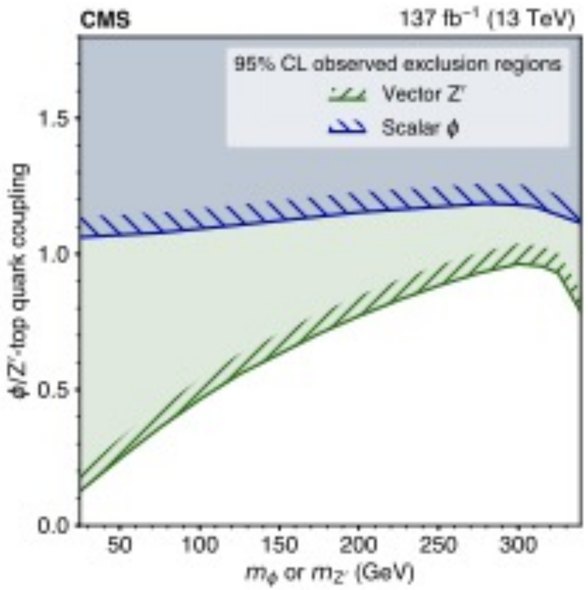
- About 20% of tttt production diagrams contain H, and y_t has substantial influence on value σ_{tttt}
- $\sigma_{tttt} = 12.6\ ^{+5.8}_{-5.2}$ fb measurement used according to Cao et al, arXiv:1602.01934
- ttH is included in background so scaling is not obvious
  - Most conservative scenario $|y_t/y_t^{SM}| < 1.7$ at 95% C.L.





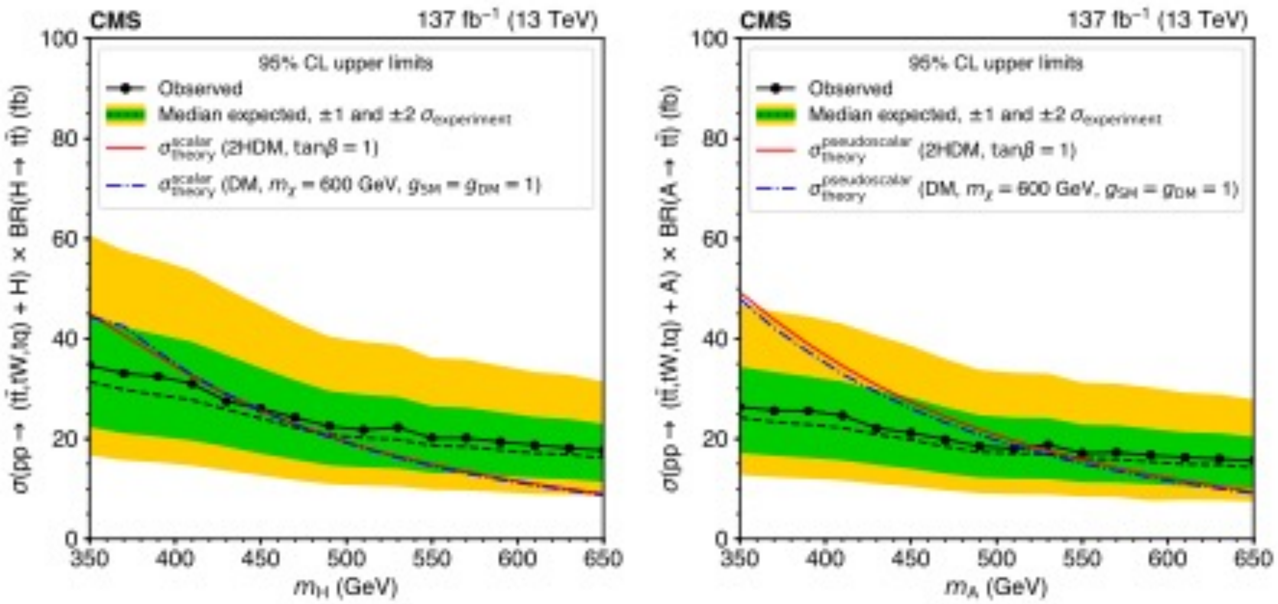
CMS arxiv 1908.06463 (137 fb⁻¹)

CMS SS/multi-leptons: interpretation other BSM



- Treat SM tttt as background see how BSM tttt Z' (or ϕ) enhances gives competitive limits at low masses
- Complementary to high mass ttbar resonance searches and competitive to direct searches sensitive to SM interference/spectrum modifications

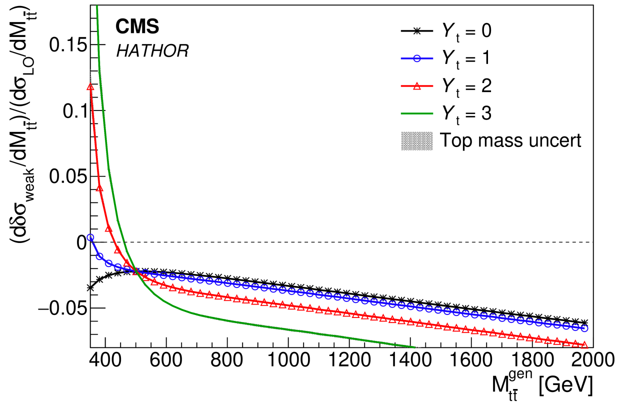
- 2HDM (type II) limits on scalar and pseudoscalar

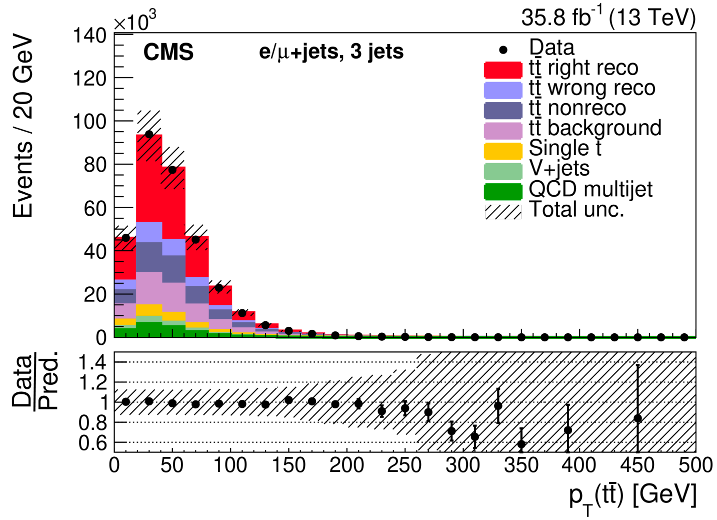


CMS arxiv 1908.06463 (137 fb^{-1})

Other indirect y_t measurements: ttbar differential cross section

- Top quark pair production at threshold is sensitive to exchanges virtual particles including H
- Precision differential measurements can indirectly constrain top Yukawa this way
- CMS uses full reconstruction of top quark pair system and interprets kinematics (rapidity, pT, invariant mass, jet multiplicity) of top quark pairs in lepton+jets channel to compare to y_t
- Results:
  - $|y_t/y_t^{SM}|=1.07^{+0.34}_{-0.43}$
  - Upper limit $|y_t/y_t^{SM}| < 1.67$ (95% CL)



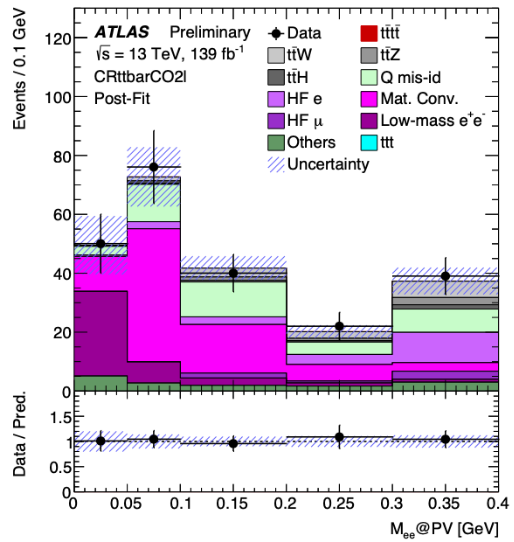


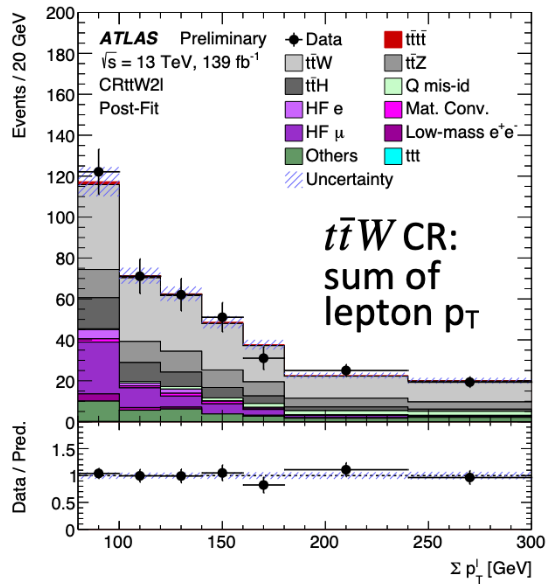
CMS arxiv 1907.01590 (36 fb^{-1})

Fresh off the press!
First shown 2 weeks ago at LHCP2020

New ATLAS result:

- Basic selection
  - **2 same sign charged leptons**
  - **OR >= 3 charged leptons**
  - **>=4 jets, >=1 b-jets**
- Backgrounds come from top quark pair production + extra objects
- Possible to gain extra leptons from jets mimicking leptons
  - "fake" background determined in side band
- Shapes determined from simulation
  - Free parameters:
    - Fake electron from HF
    - Fake muon from HF
    - Material conversions
    - Internal conversions
- ttW production known to be poorly normalized in simulation so left free when fitting data



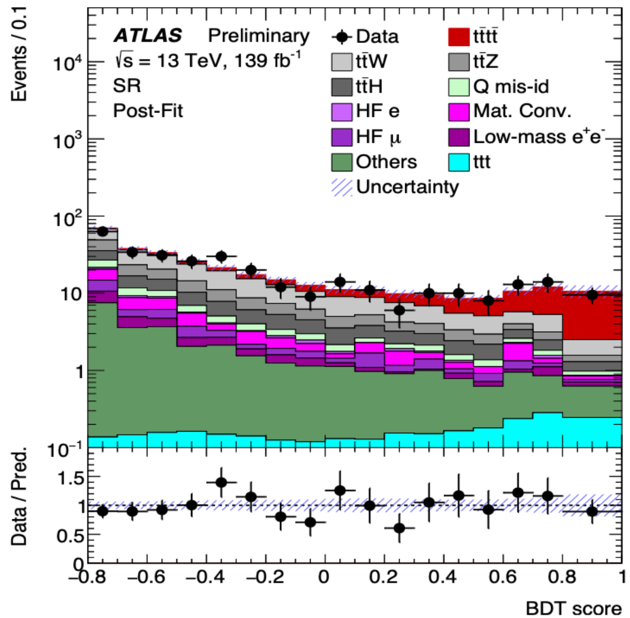


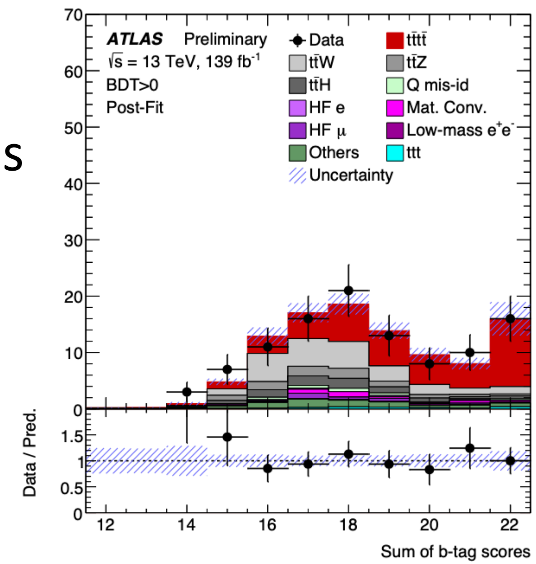
Parameter	$NF_{t\bar{t}W}$	NF_{CO}	NF_{γ^*}	NF_{HFe}	$NF_{HF\mu}$
Value	1.6 ± 0.3	1.6 ± 0.5	0.9 ± 0.4	0.8 ± 0.4	1.0 ± 0.4

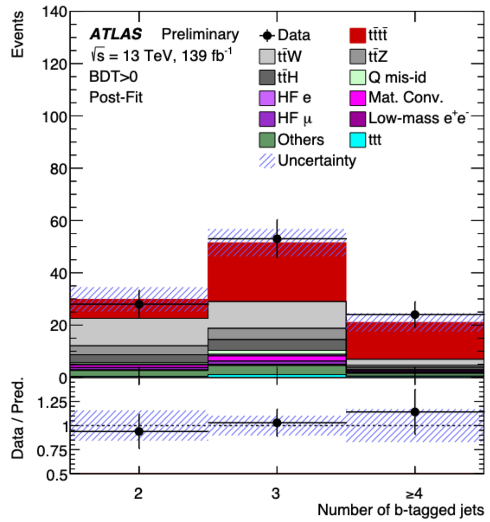
Fresh off the press!
First shown 2 weeks ago at LHCP2020

New ATLAS result:

- Signal region, SS/ML plus:
  - >=6 jets, >= b-jets, HT>500 GeV
- Train BDT to separate signal from background
- Simultaneous fit to BDT and control regions for backgrounds not-so-well modeled by simulation







- Cross section: 24^{+7}_{-6} fb
- **Significance: 4.3 σ observed**
- Significance: 2.4 σ expected
- Consistent with the SM prediction at 1.7 σ

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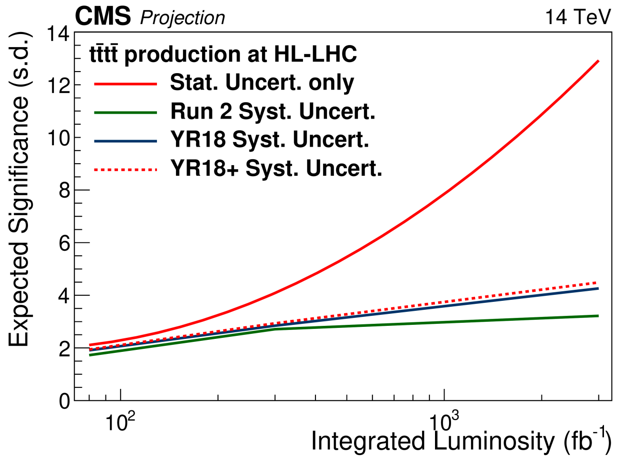
What about four-tops in the future?

Int.Lumi at HL-LHC	ATLAS (shape analysis)	CMS (counting exp in categories)
300 fb^{-1}	5 s.d. signficance	Stat uncertainty 4 s.d. significance (deterioration with syst uncertainties)
3 ab^{-1}	Uncertainty xsec 11% (dominated by stat.uncertainty)	Uncertainty xsec 9% (stat only) to 28% (current syst.uncertainties)



Projections SS dileptons/multileptons:
ATLAS ATL-PHYS-PUB-2018-047
CMS PAS FTR-18-031
See also the HL-LHC/HE-LHC Yellow Reports

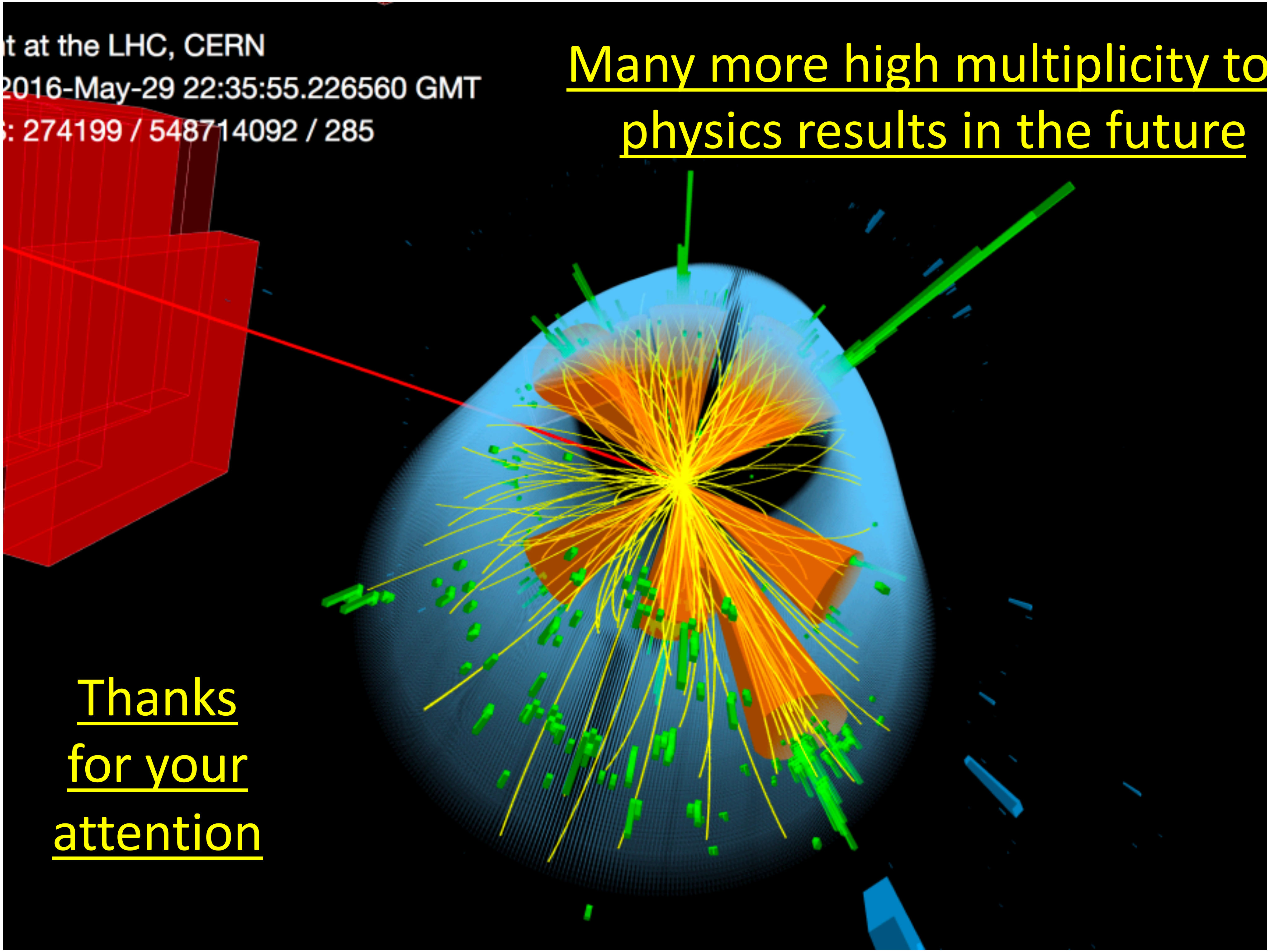
- ATLAS projection includes a full analysis for 3 ab^{-1} at HL-LHC (sqrt(s)=14 TeV) in SS dilepton/multileptons
  - Includes simultaneous fit in multiple tag/jet multiplicity categories, discriminating variable H_T
- CMS projection is scale-up of 2016 SS dilepton/multilepton counting experiment analysis for HL-LHC and HE-LHC
  - Includes EFT projections and various scenarios regarding systematic uncertainties also expected cross section uncertainties at HE-LHC
  - 1% exp. uncert. on xsec with full HE-LHC sample
- General conclusion: need about 300 fb^{-1} to get statistical significance up to 5 sigma depending complexity analysis
- Systematic uncertainties depend on experiment
  - ATLAS binned likelihood fit: not very important
  - CMS counting experiment: become important at large integrated luminosities

Summary

Production of four top quarks is being actively examined by ATLAS and CMS collaboration.
σ_{tttt} in SM (NLO QCD+EWK) 12 fb, and very sensitive to modifications from BSM

	Expected limit (μ)	Observed limit (μ)	Expected limit (fb)	Observed limit (fb)	Signal strength (μ)	Cross section (fb)
ATLAS 1L-OS2L 36 fb^{-1}	3.6	5.1	33 fb	47 fb	$1.7^{+1.9}_{-1.7}$	$15.6^{+17.5}_{-15.6}$ fb
CMS combination 36 fb^{-1}	2.2	3.6	20 fb	33 fb	$1.4^{+1.2}_{-1.0}$	13^{+11}_{-9} fb
CMS >=3L-SS2L 137 fb^{-1}				22.5 fb		$12.6^{+5.8}_{-5.2}$fb
ATLAS >=3L-SS2L 137 fb^{-1}					$2.0^{+1.2}_{-1.0}$(stat) $^{+0.7}_{-0.5}$ (syst)	24^{+7}_{-6} fb

- **With large LHC Run 2 dataset, ATLAS sees first observation of production of four top quarks!**
- **Evidence of 4.3 standard deviations observed**
  (2.4 standard deviations expected significance)
- With similar size dataset, CMS had 2.6 standard deviations excess in 2019
  (2.7 standard deviations expected significance)
  - measurement of $\Delta\sigma_{tttt}/\sigma_{tttt} \approx 45\%$ means CMS could constrain $|y_t/y_t^{SM}| < 1.7$ at 95% C.L.
- Collaborations are interpreting σ_{tttt} beyond just the SM value, in EFT and various BSM models
- HL-LHC: single channel observation possible at 5 standard deviations (in multilepton/SS dilepton channel) with 10%ish uncertainties on σ_{tttt}



Many more high multiplicity to physics results in the future

Thanks for your attention