Top quark properties

Jacob Linacre (FNAL)
on behalf of the ATLAS and CMS collaborations

FPCP 2015
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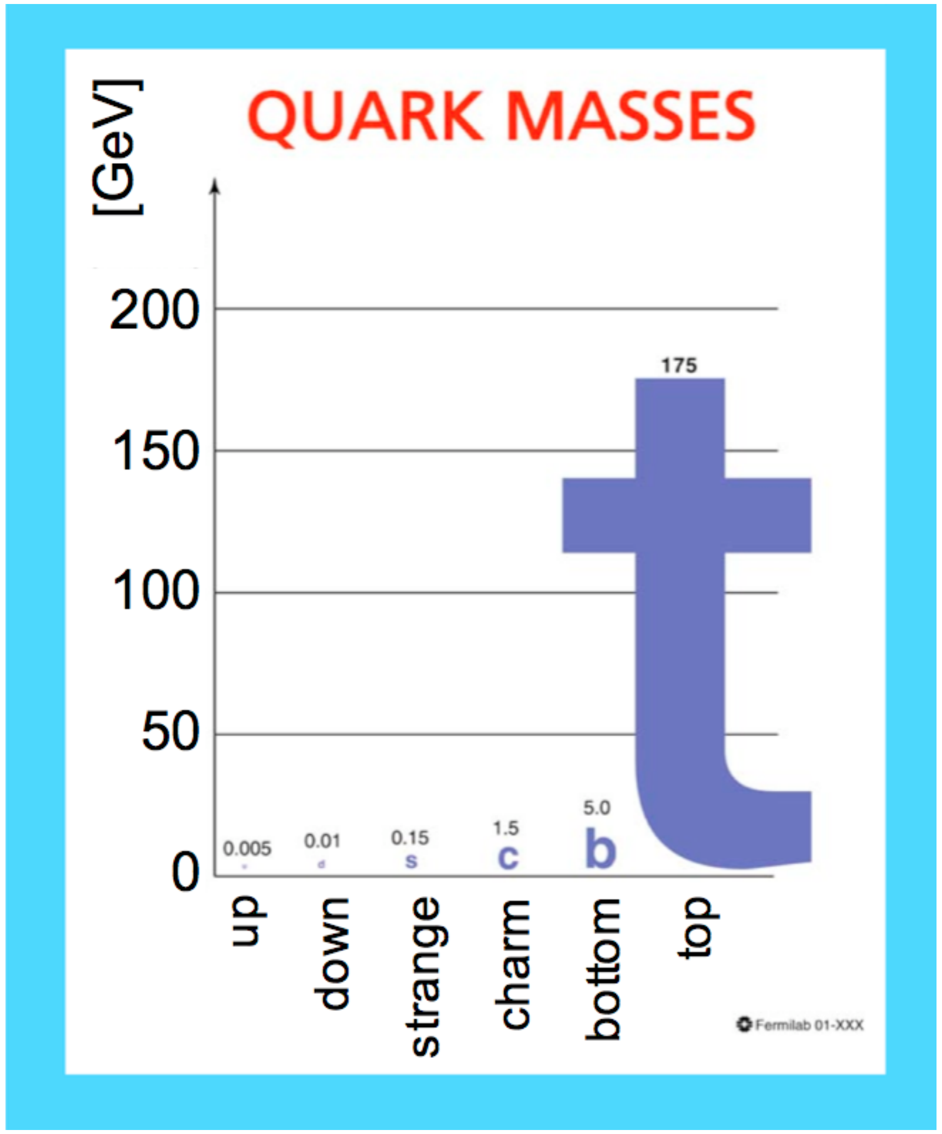
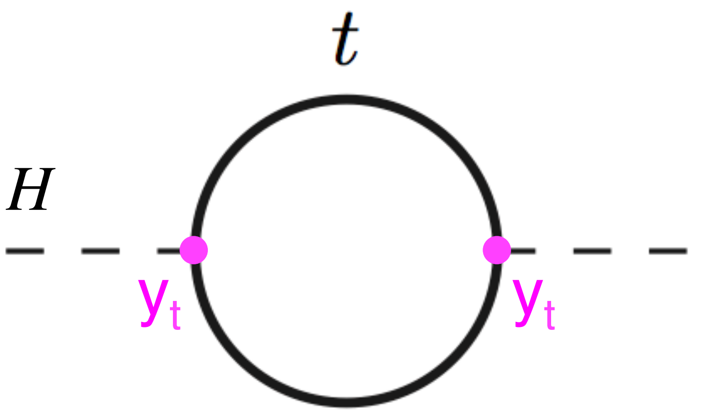
Top quark properties

- Why are **top properties** interesting?
  - top quark **decays before it can form bound states**
    - unique opportunity to study a “bare” quark (using the decay products)
  - **heaviest elementary particle known** (m_t ~ 173 GeV)
    - large coupling to Higgs boson suggests special role in EWSB
  - top properties measurements test SM and **probe new physics**



$\Delta m_H^2 =$


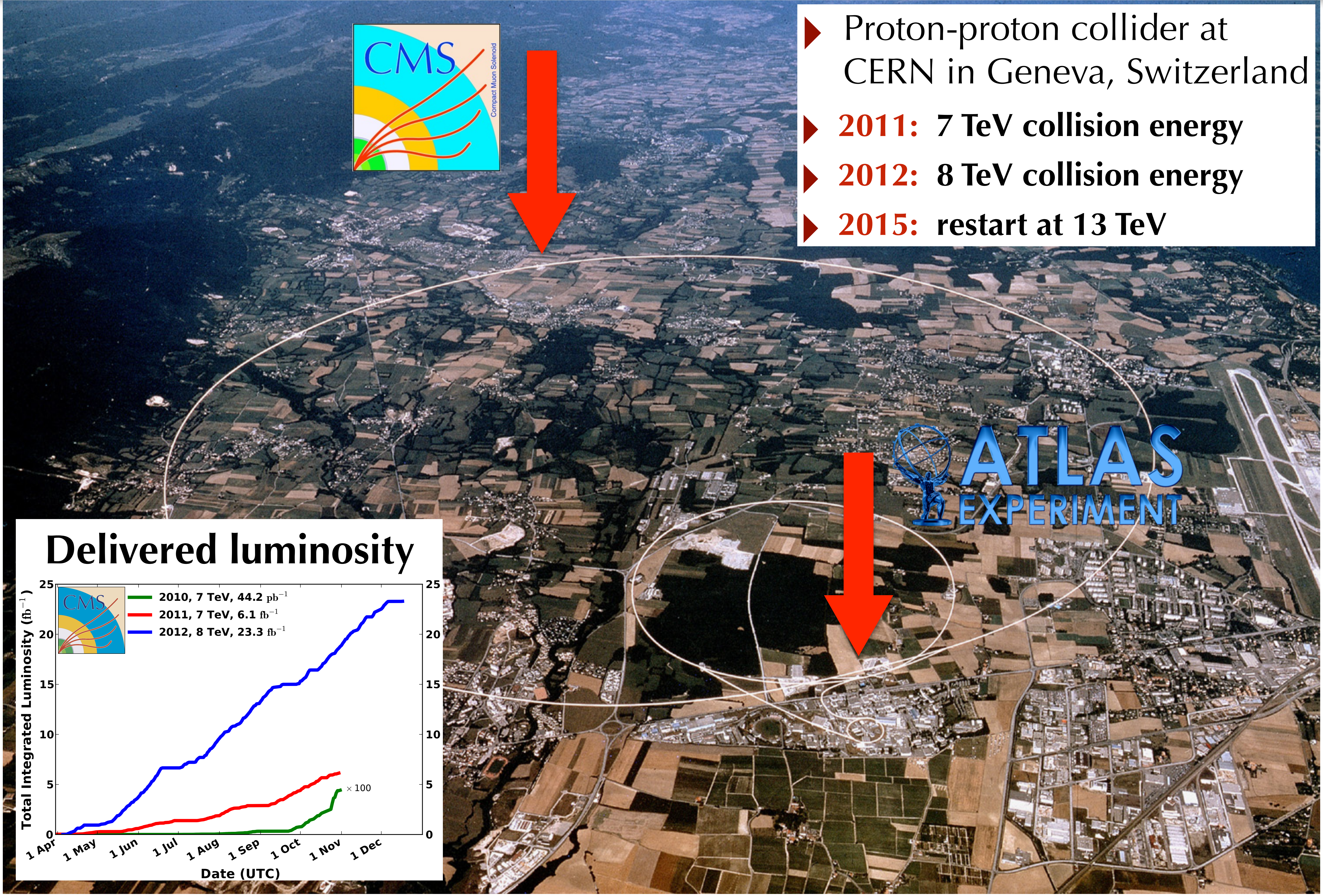
$+ \ldots$

Top quark properties

- Today I'll show just a few of the many important results from ATLAS and CMS at the LHC
  - focusing on results in $t\bar{t}$ pair production from the last 1 year
    - top quark mass
    - $t\bar{t}$ spin correlations
    - production of $t\bar{t}$ + vector boson
    - flavour changing neutral currents in $t\bar{t}$ events

- A complete summary can be found on the experiments' public twiki pages:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

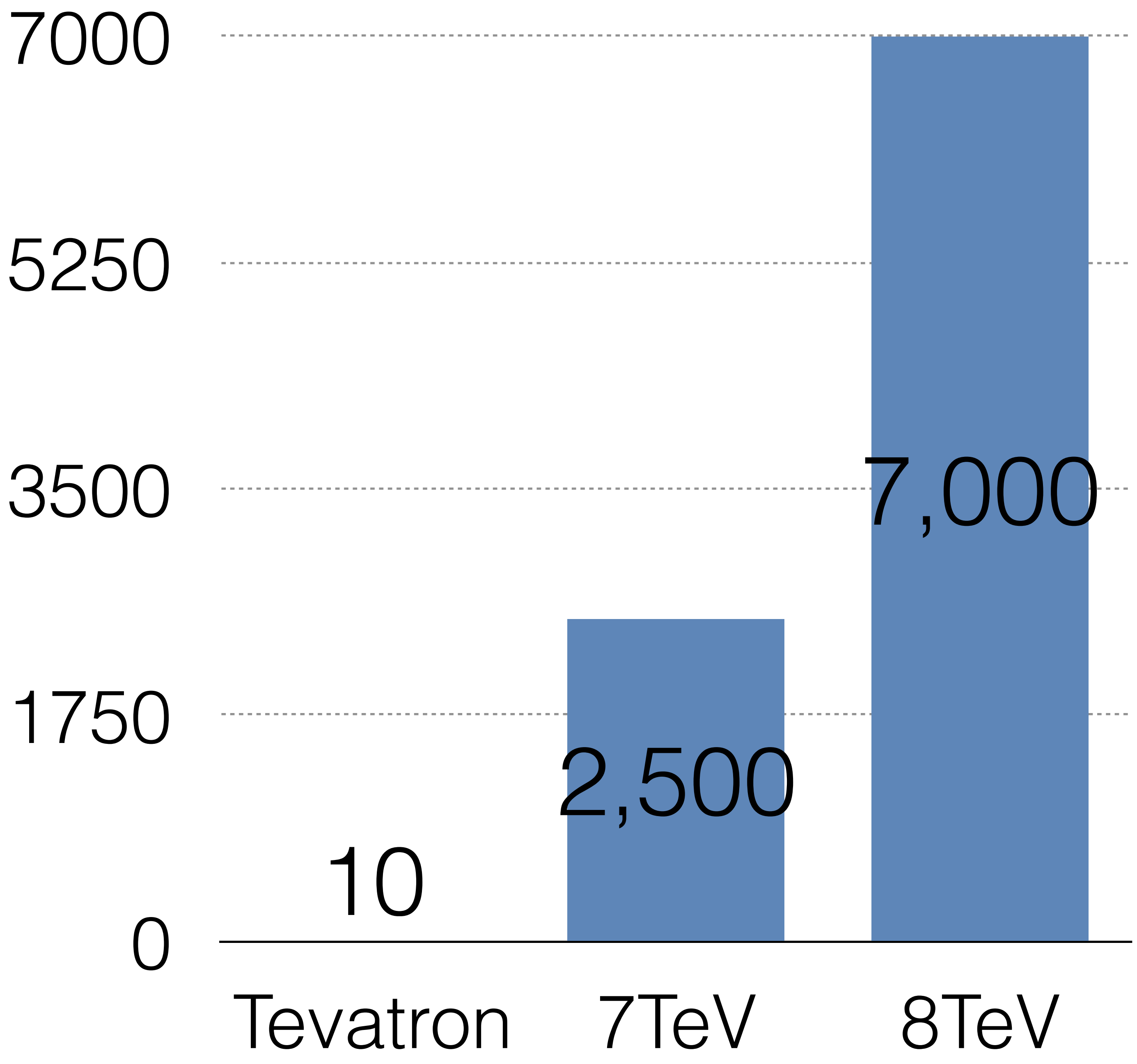
LHC



- Proton-proton collider at CERN in Geneva, Switzerland
- **2011: 7 TeV collision energy**
- **2012: 8 TeV collision energy**
- **2015: restart at 13 TeV**

LHC is a top factory

Top Quark Pairs **per hour** at peak inst. luminosity

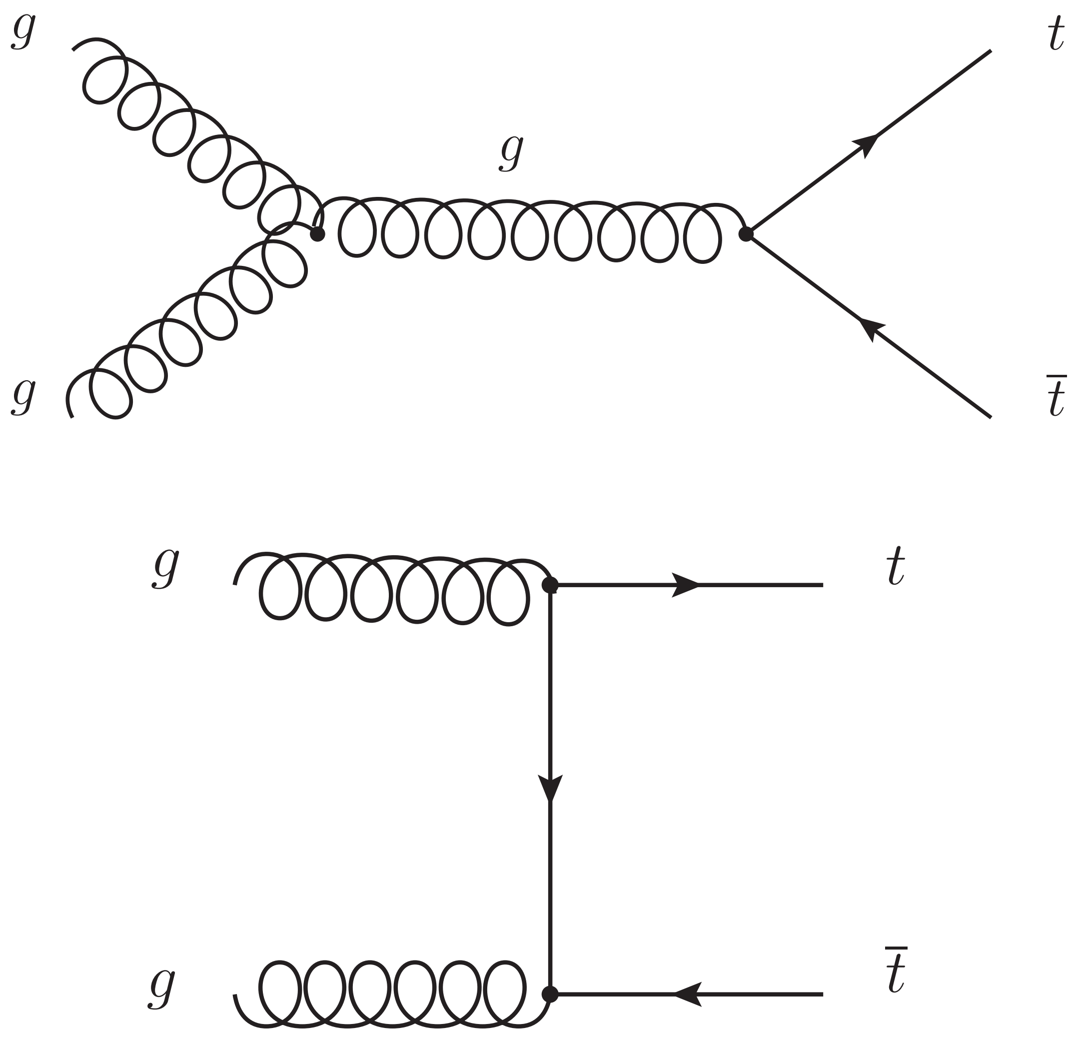


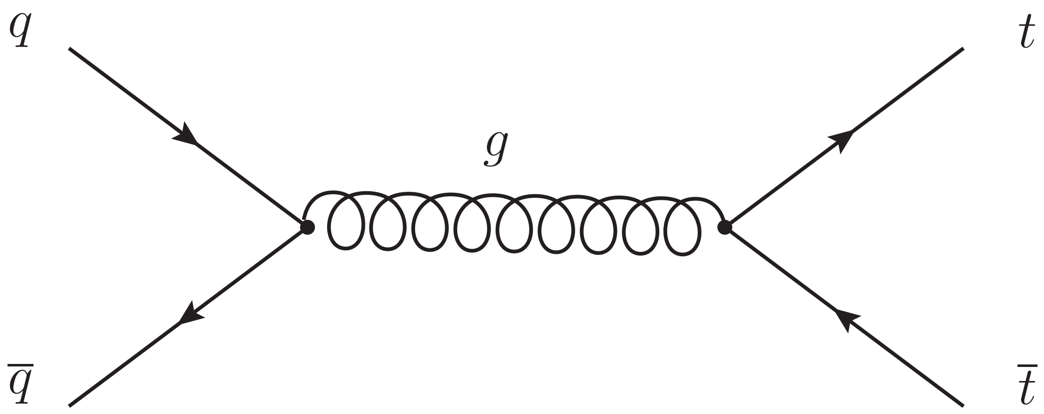
cross sections from arXiv:1303.6254: Tevatron ~7pb, LHC@7TeV ~172pb, LHC@8TeV ~246pb. Peak inst. luminosity: Tevatron: ~4x10^{32}cm^{-2}s^{-1}, LHC@7TeV: ~4x10^{33}cm^{-2}s^{-1}, LHC@8TeV: ~8x10^{33}cm^{-2}s^{-1}

- The LHC at 8 TeV produced **700 times more top quark pairs** per hour than the Tevatron
  - 5M top pairs per experiment in 2012!
- **LHC is a true top factory!**
  - **study top quark with unprecedented precision**

Top quark pair production

- Top quark-antiquark pairs ($t\bar{t}$) produced via strong interaction





gluon fusion:

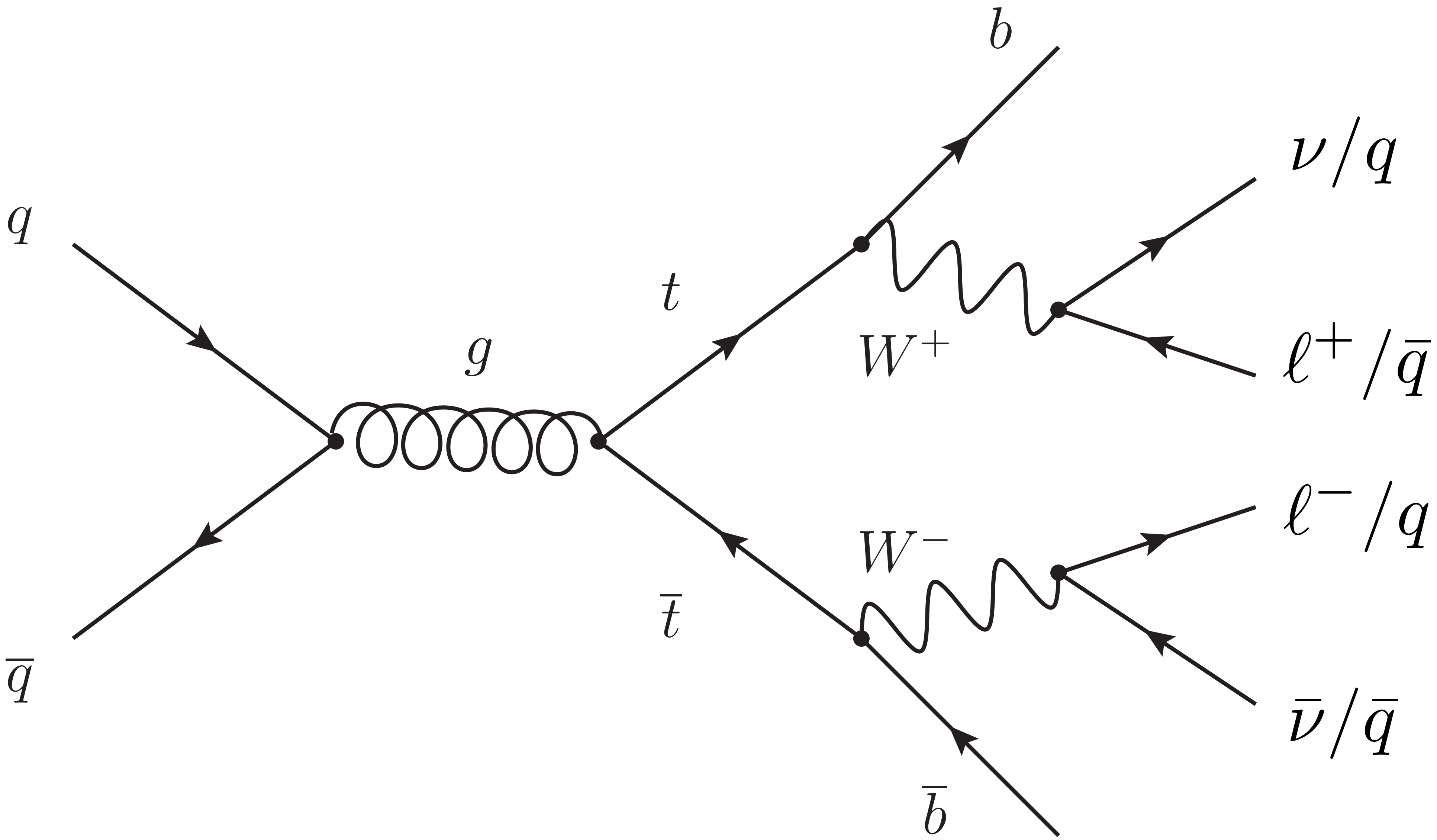
~85% at the LHC

$q\bar{q}$ annihilation:

~15% at the LHC

Top quark decay

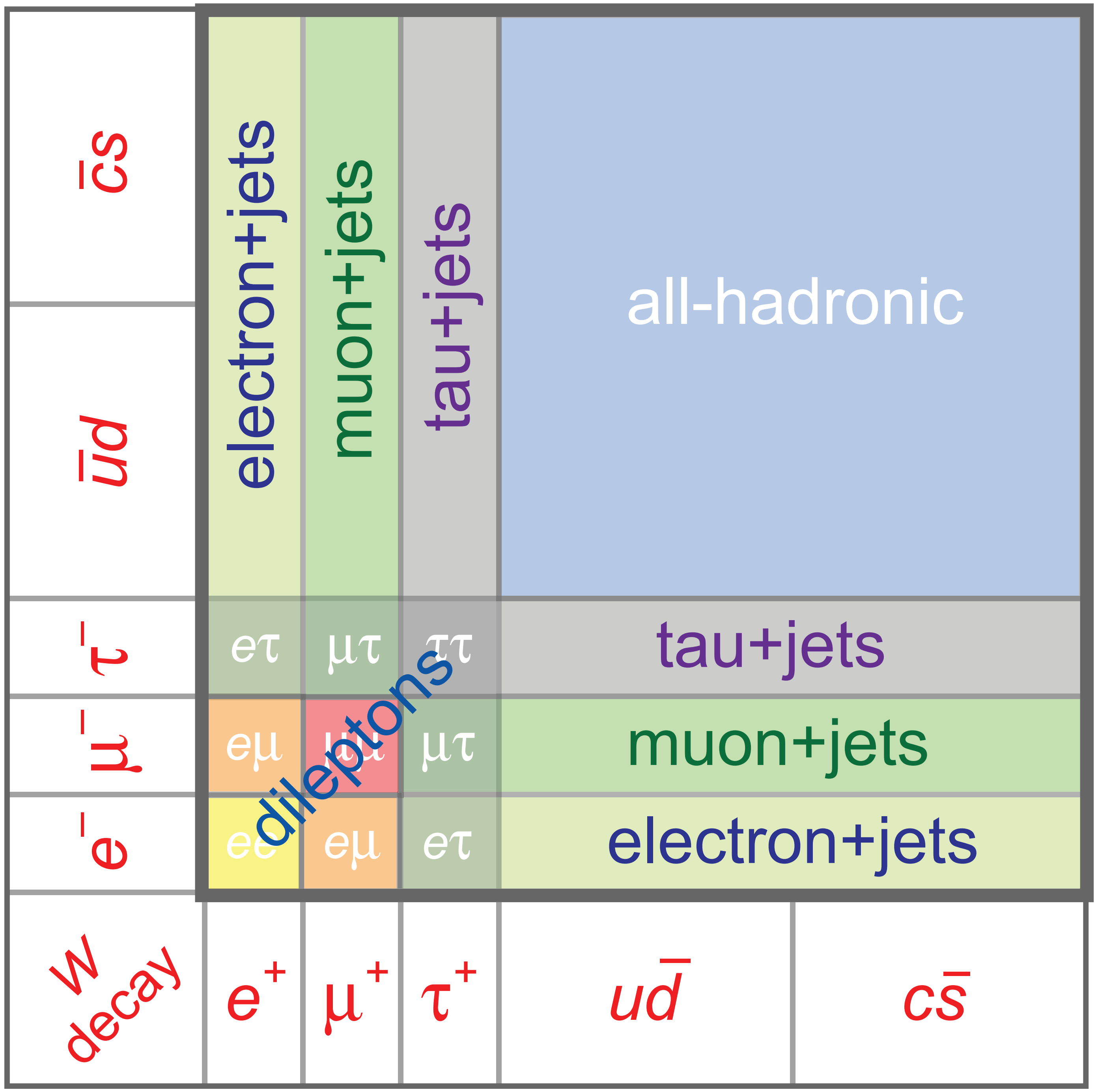
- Top decays via weak interaction
  - almost exclusively to a **b-quark and a W boson**



- W boson decays to quark+antiquark (68%) or lepton+neutrino (32%)

$t\bar{t}$ decay channels

- **Decay channel categories** based on how the two W bosons decay



W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
$c\bar{s}$	electron+jets	muon+jets	tau+jets	all-hadronic	
$u\bar{d}$					
τ^-	$e\tau$	$\mu\tau$	$\tau\tau$	tau+jets	
μ^-	$e\mu$	$\mu\mu$	$\mu\tau$	muon+jets	
e^-	ee	$e\mu$	$e\tau$	electron+jets	

all-hadronic

46%

largest branching fraction but largest backgrounds

lepton+jets

(ℓ=e,μ)

34%

Large branching fraction and manageable backgrounds

dilepton

(ℓ=e,μ)

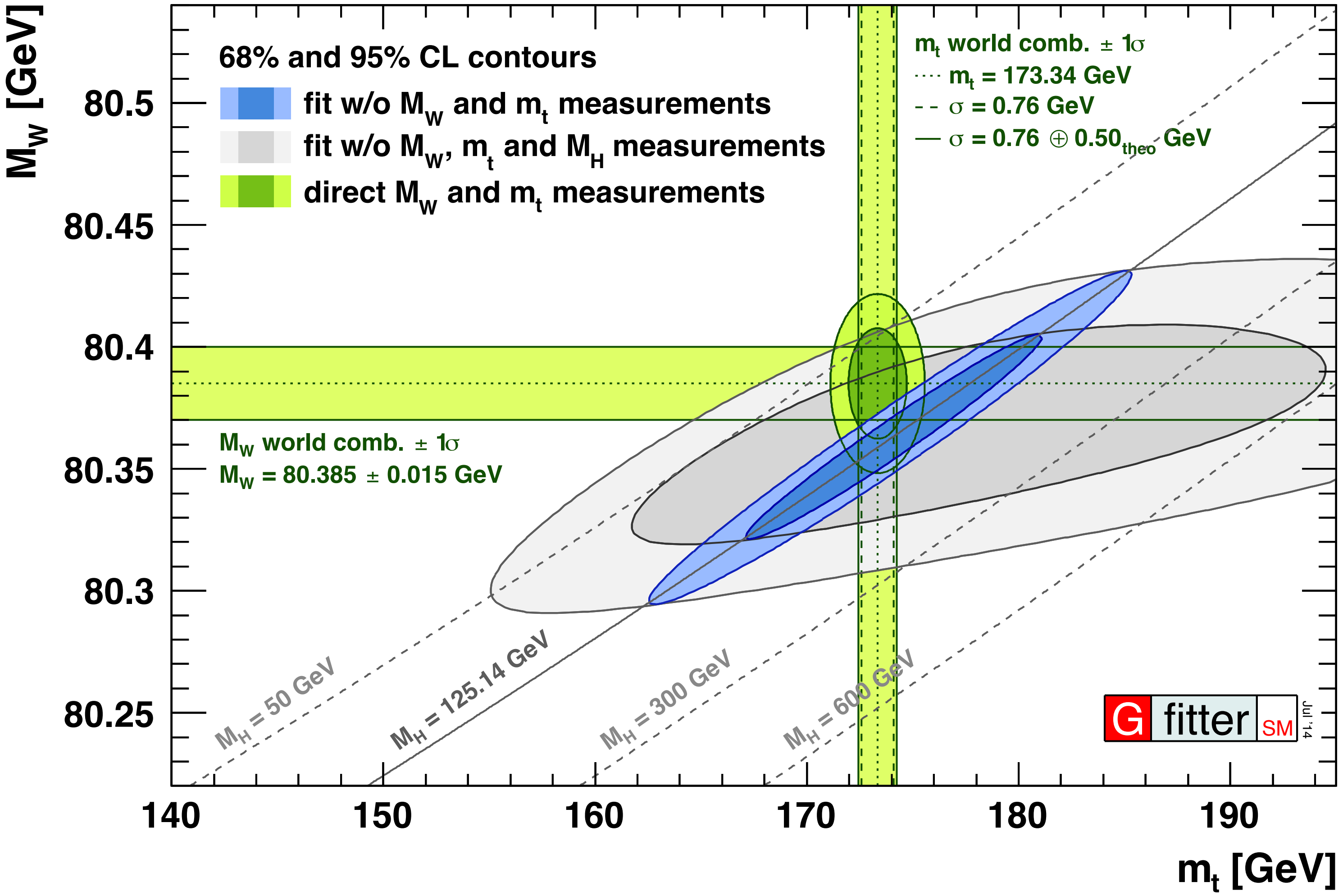
6%

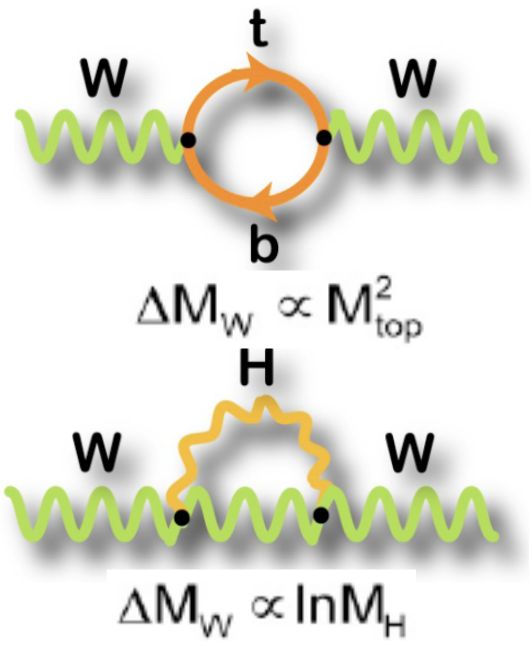
small branching fraction but small backgrounds

Top quark mass

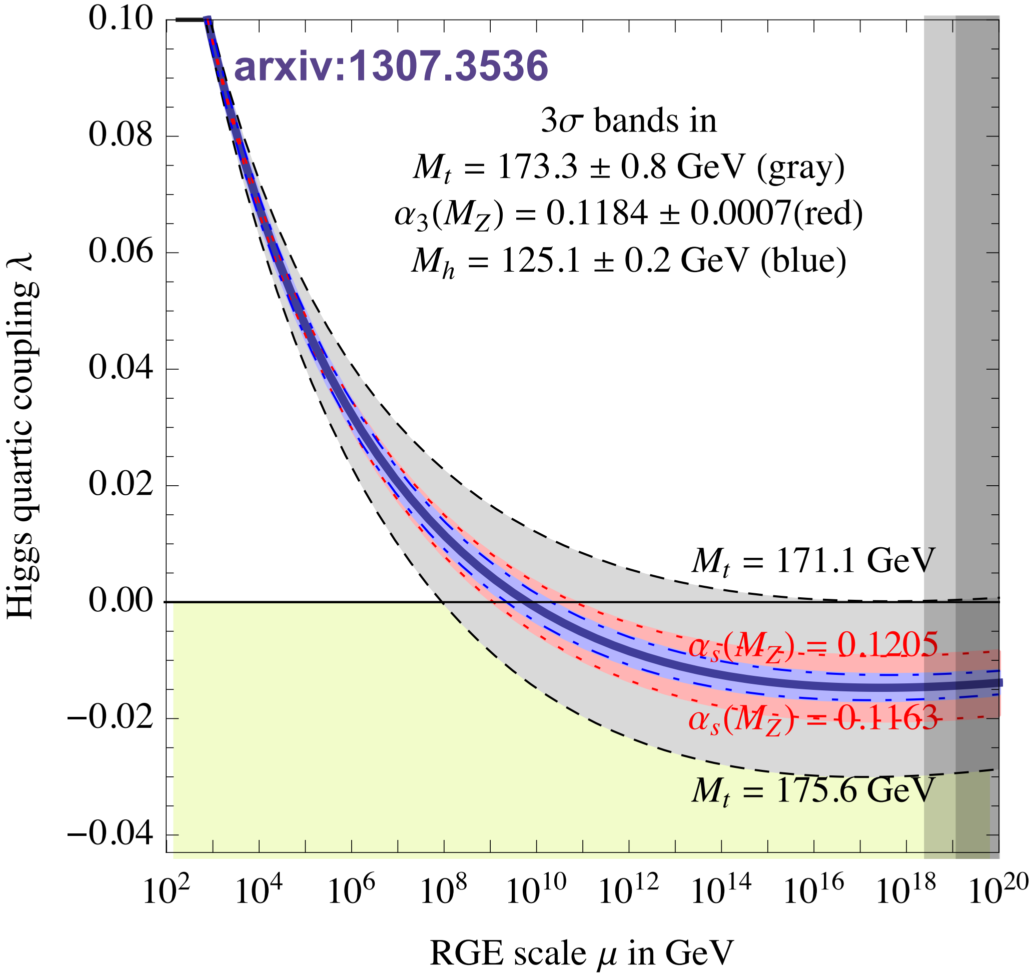
Top quark mass (m_t)

- m_t important input to **test SM self-consistency**



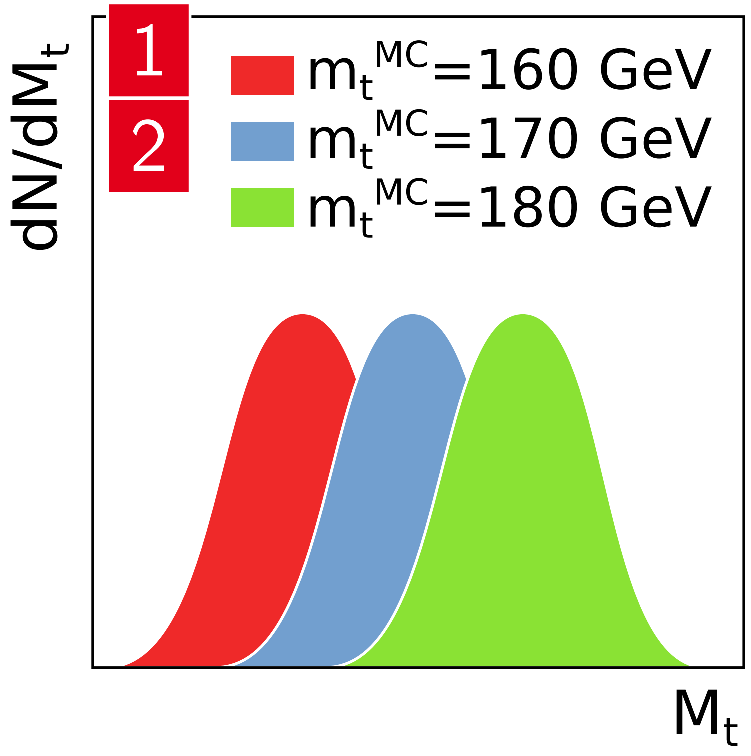


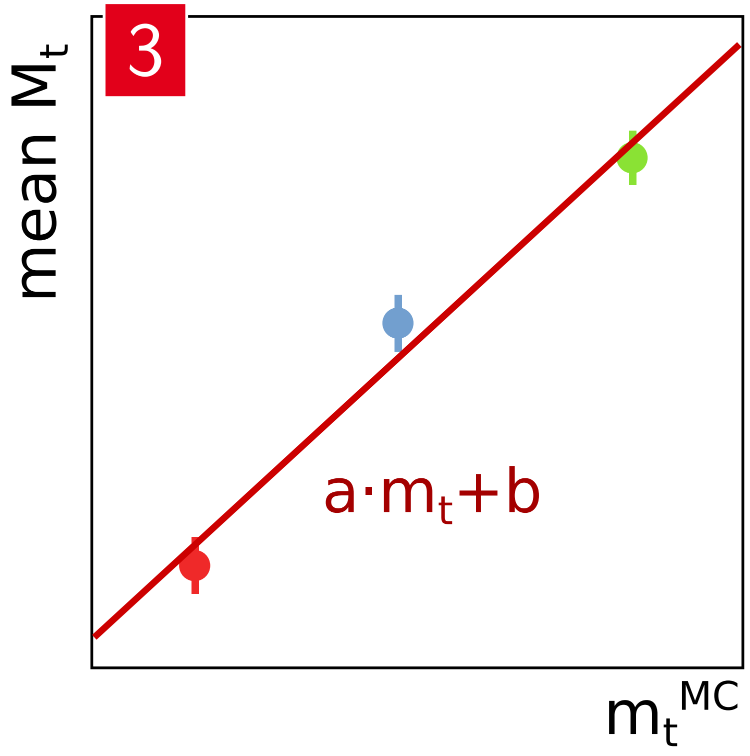
- SM vacuum stability boundary coincides closely with measured m_t
  - unstable when Higgs quartic coupling λ runs < 0
  - just a coincidence, or insight to new physics?

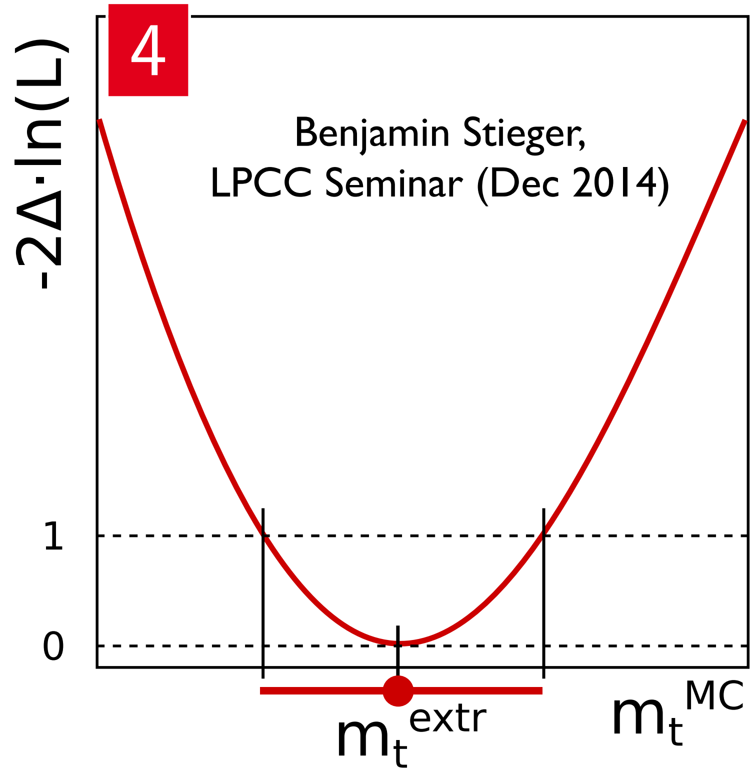


Top quark mass measurement

- General approach:
  - **1) select** $t\bar{t}$ events
  - **2)** construct **observable** sensitive to m_t
  - **3) parametrise** observable in m_t using MC simulation
  - **4) fit** to data, extract mass







Benjamin Stieger, LPCC Seminar (Dec 2014)

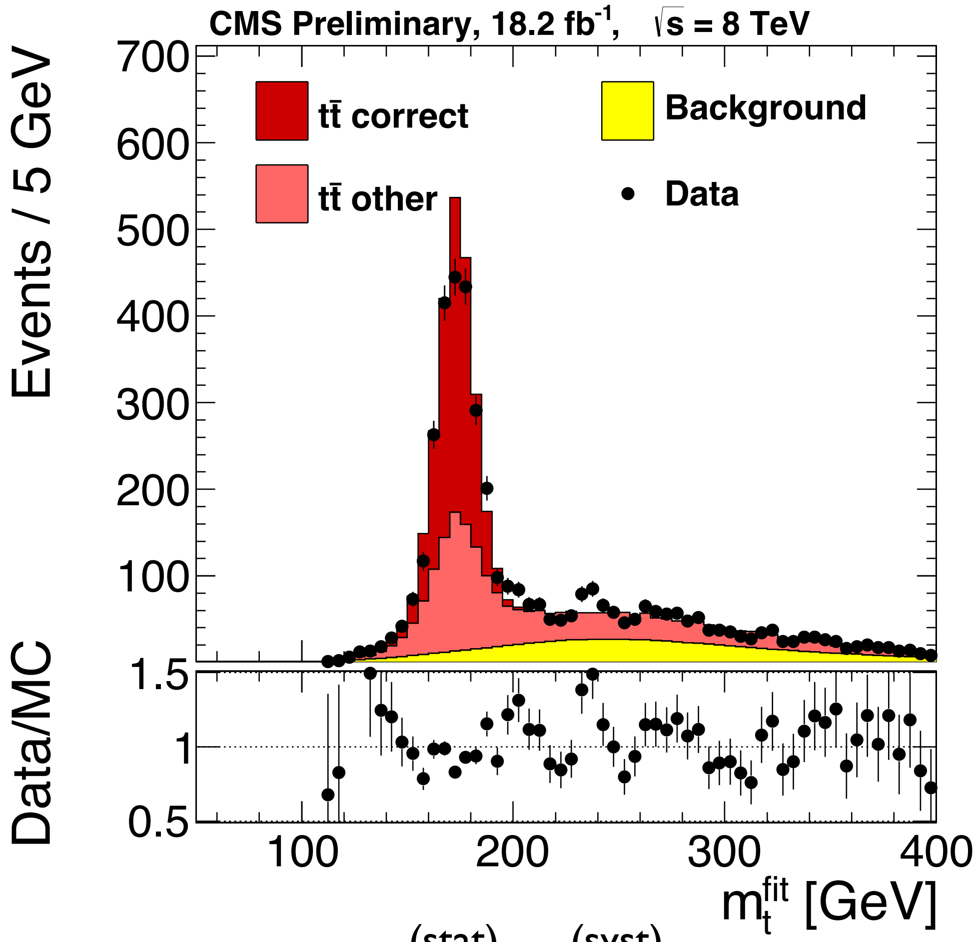
- As a result of the calibration these measurements measure the **MC mass** parameter
  - does not precisely correspond to well-defined theoretical definition
  - implies additional uncertainty ~0.5 GeV when input to theory

CMS measurements (20 fb^{-1} 8 TeV)

- Reconstruct m_t using kinematic constraints
- Fit data using templates as a function of m_t^{reco}
  - 2D fit including m_W^{reco} for jet energy calibration (all-hadronic and lepton+jets)

All-hadronic

Large QCD multijet background

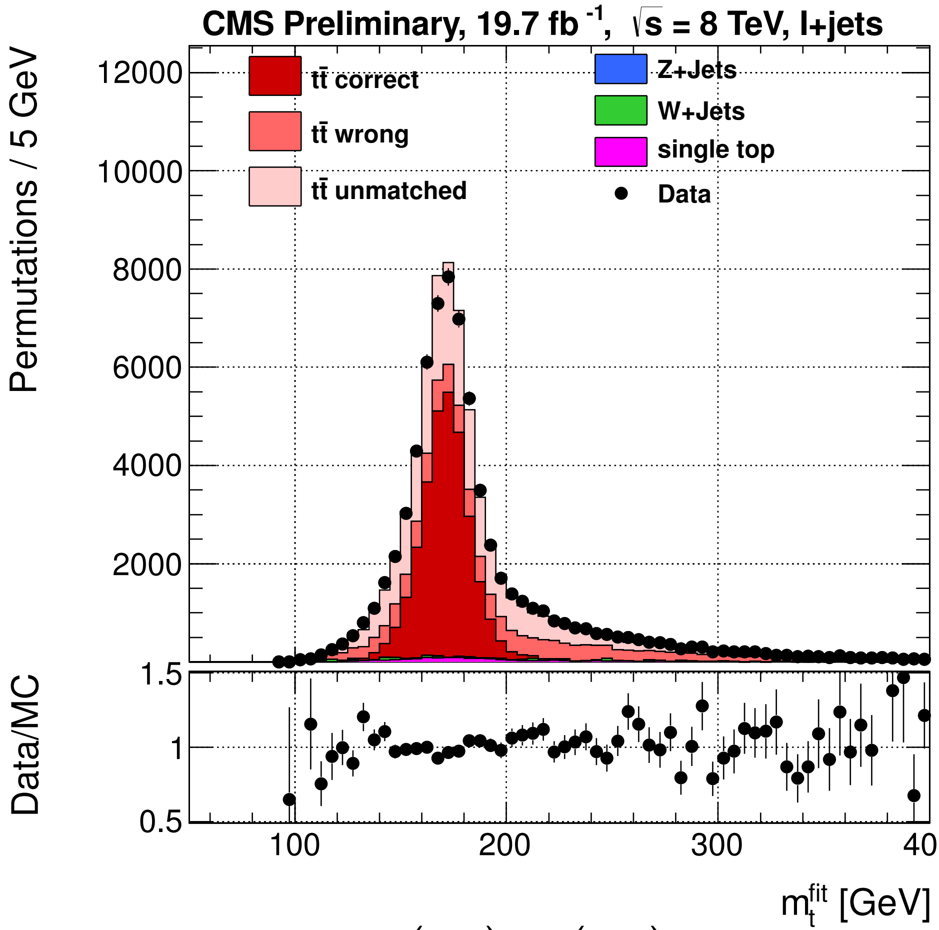


$m_t = 172.1 \pm \overset{\text{(stat)}}{0.3} \pm \overset{\text{(syst)}}{0.8}$ GeV

(0.5%)

Lepton+jets

Most precise channel

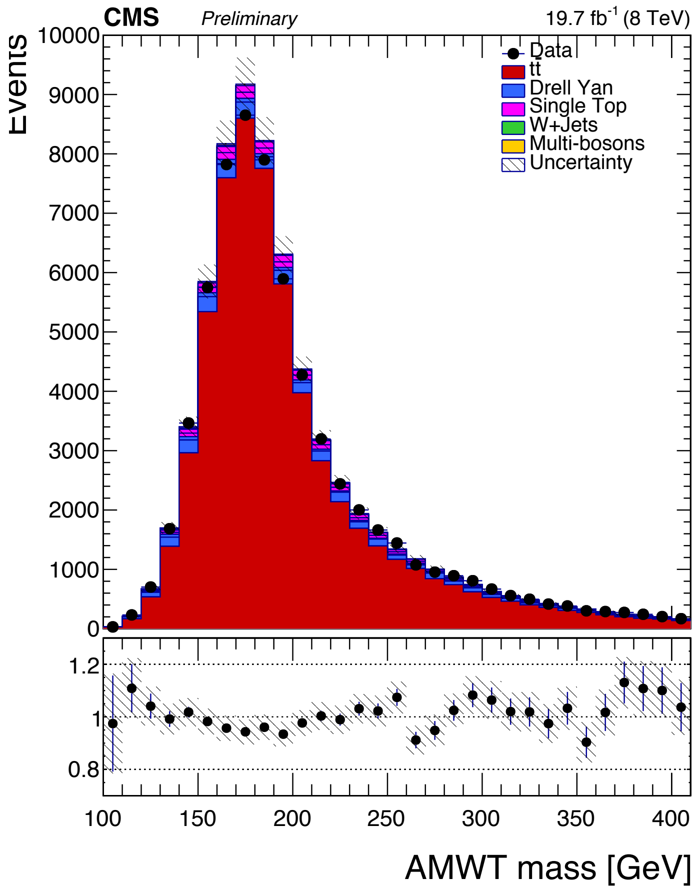


$m_t = 172.0 \pm \overset{\text{(stat)}}{0.1} \pm \overset{\text{(syst)}}{0.7}$ GeV

(0.4%)

Dilepton

Very clean but 2 neutrinos



$m_t = 172.5 \pm \overset{\text{(stat)}}{0.2} \pm \overset{\text{(syst)}}{1.4}$ GeV

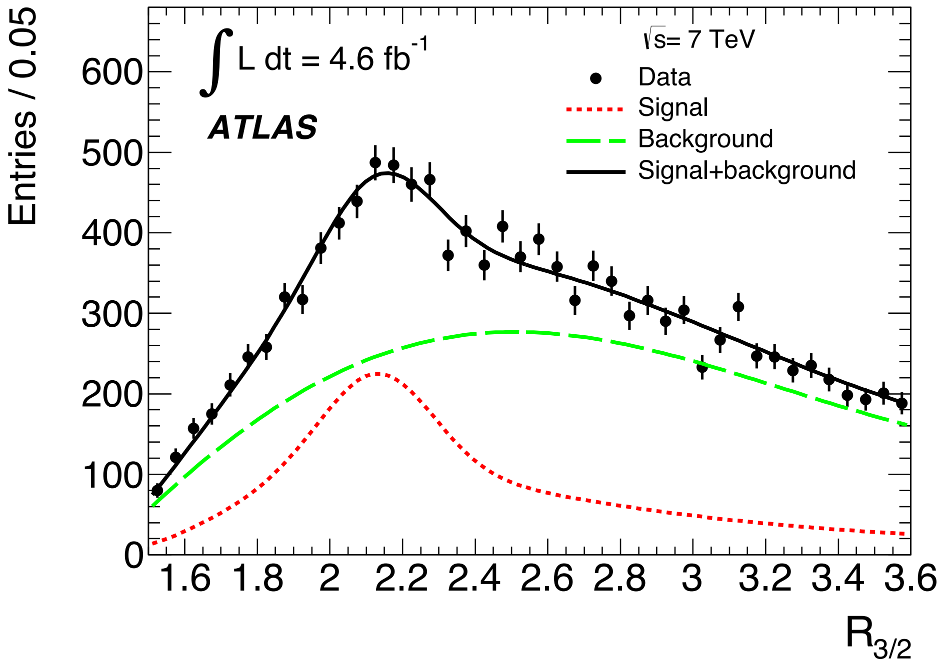
(0.8%)

ATLAS measurements (5 fb^{-1} 7 TeV)

- Reconstruct m_t-sensitive variable
- Fit data using templates as a function of m_t-sensitive variable
  - 3D fit to constrain light and b jet energy calibration (lepton+jets)
  - Fit ratio $R_{3/2} = m_t^{reco}/m_W^{reco}$ (all-hadronic)

All-hadronic

Large QCD multijet background

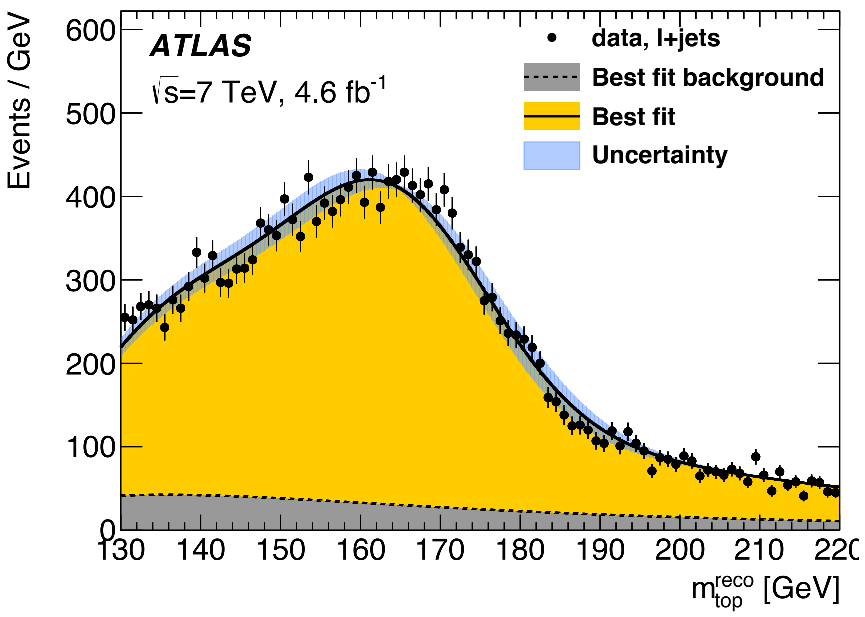


$m_t = 175.1 \pm \overset{\text{(stat)}}{1.4} \pm \overset{\text{(syst)}}{1.2}$ GeV

(1.0%)

Lepton+jets

Most precise channel

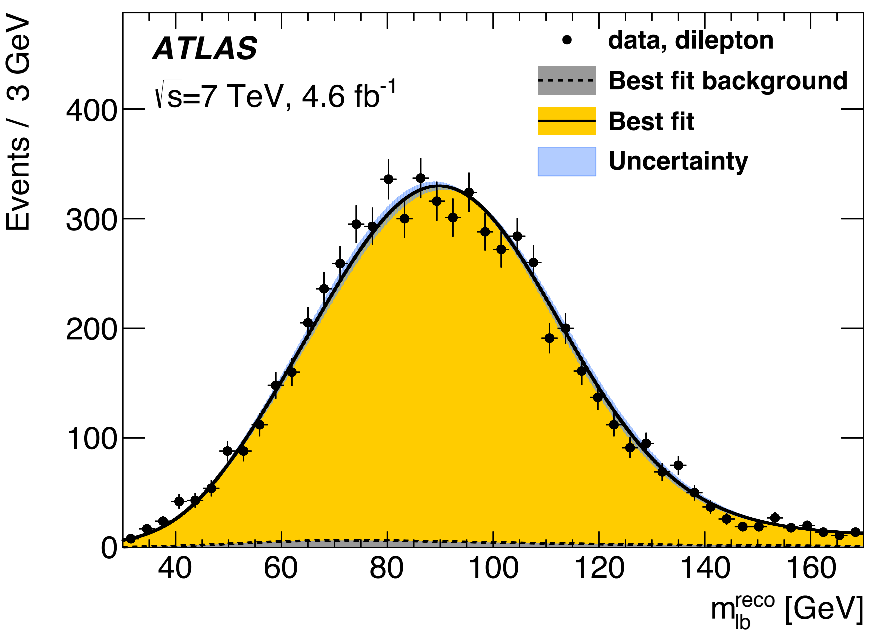


$m_t = 172.3 \pm \overset{\text{(stat)}}{0.8} \pm \overset{\text{(syst)}}{1.0}$ GeV

(0.7%)

Dilepton

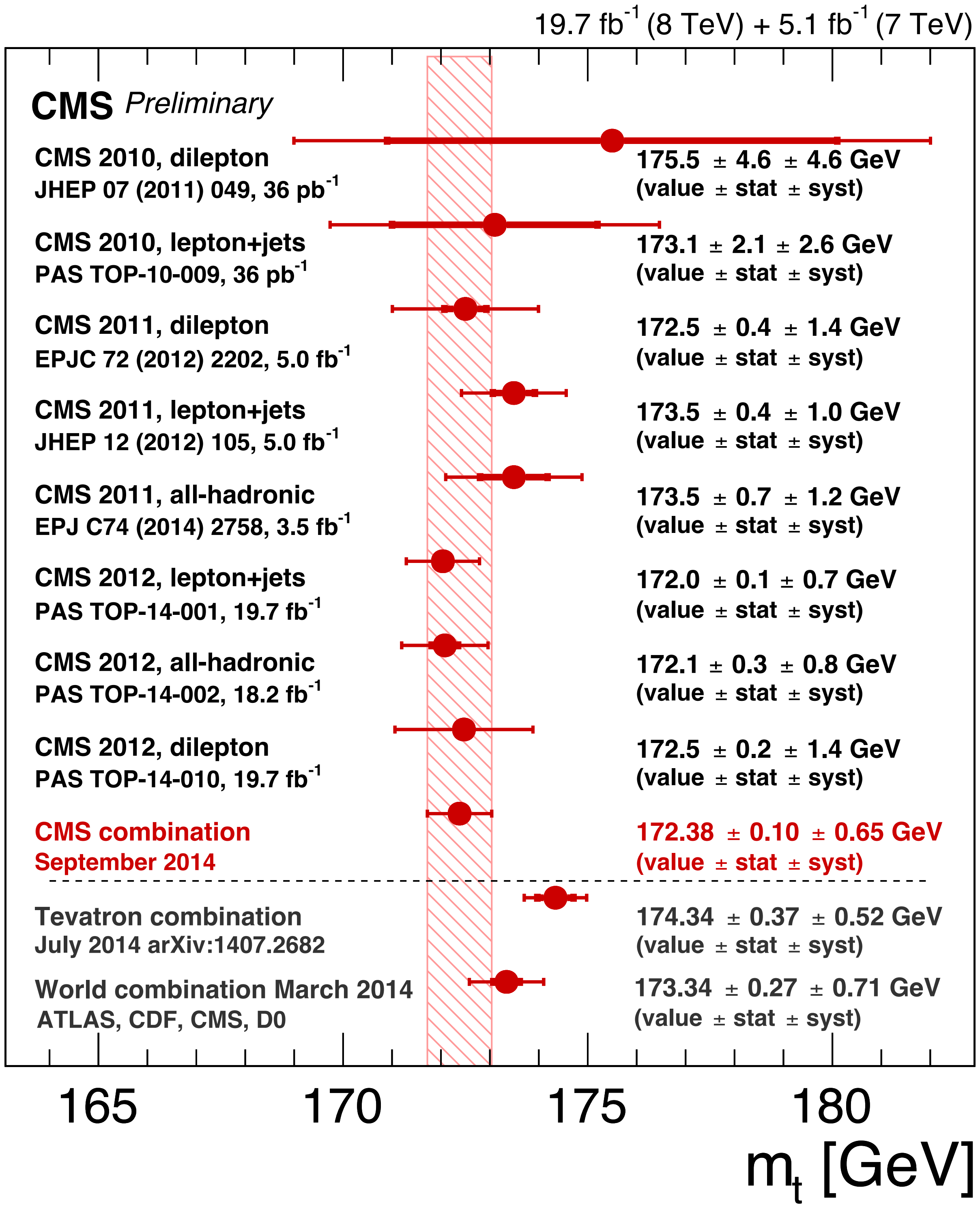
Very clean but 2 neutrinos

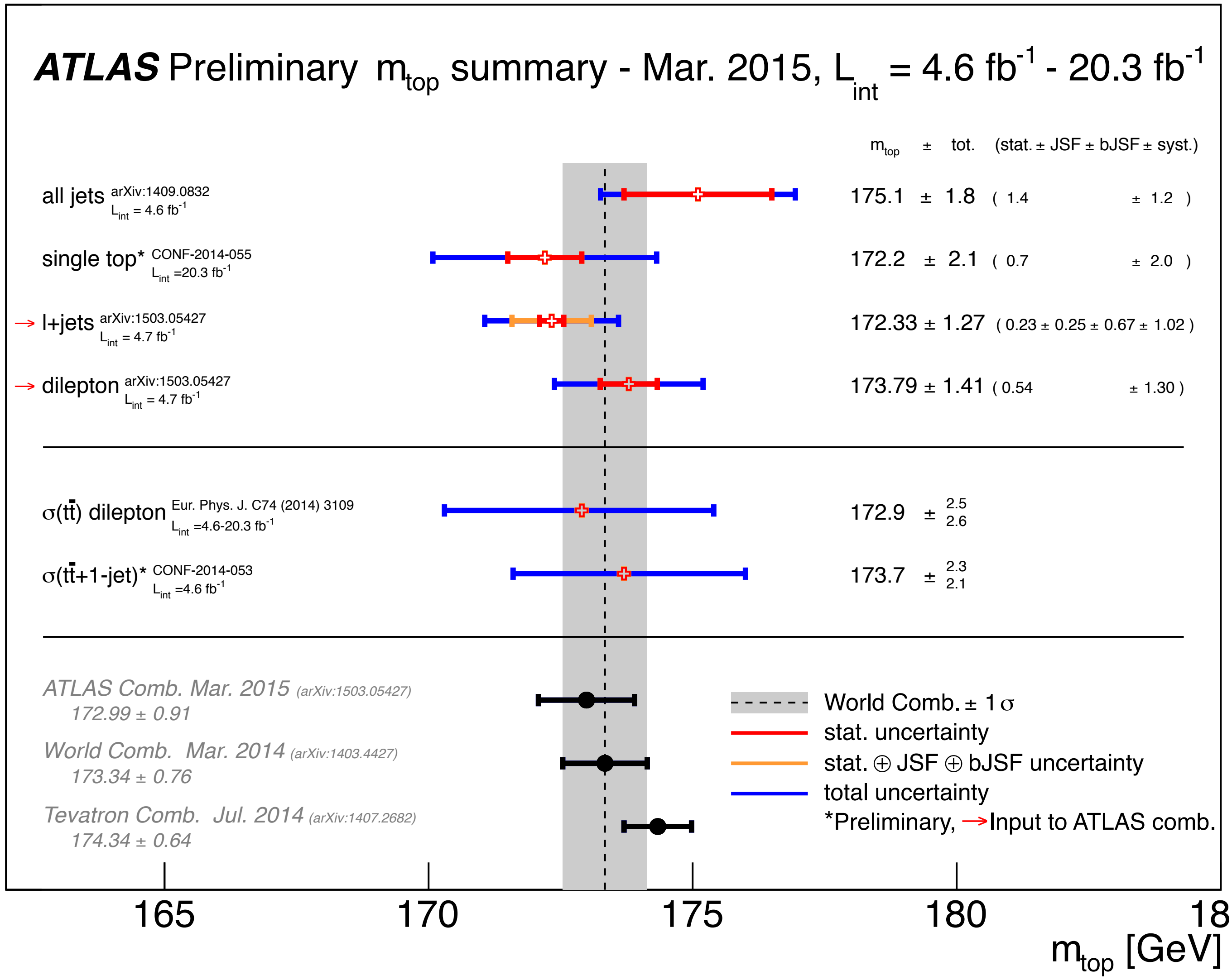


$m_t = 173.8 \pm \overset{\text{(stat)}}{0.5} \pm \overset{\text{(syst)}}{1.3}$ GeV

(0.8%)

Combinations





m_t = 172.99±0.91 GeV (0.5%)

This ATLAS combination only includes 7 TeV dilepton and lepton+jets

- Reached **sub-GeV precision** where exact definition of mass parameter is very important!
- Uncertainties **systematics dominated**
  - largest systematic typically from differences in the jet energy response for different jet flavours

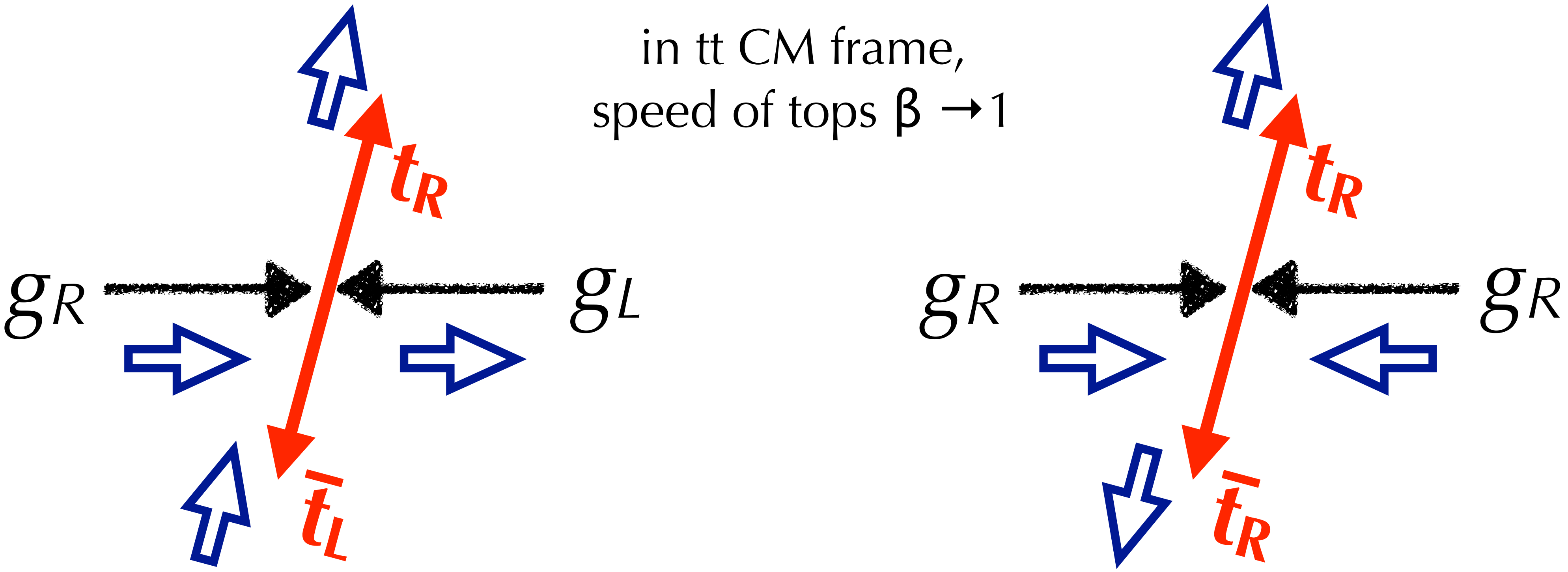
m_t = 172.38±0.66 GeV (0.4%)

preliminary CMS combination: conservative treatment of systematic uncertainty correlations

Spin correlations

Introduction to tt spin correlations

- **Same** and **opposite** helicity gluon fusion contributions **impart different spin correlations to the top quark pairs**



in tt CM frame,
speed of tops β →1

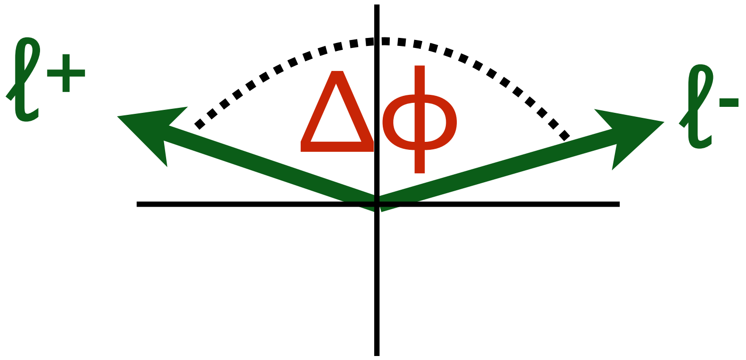
Opposite helicity gluons
Negative spin correlations

Same helicity gluons
Positive spin correlations

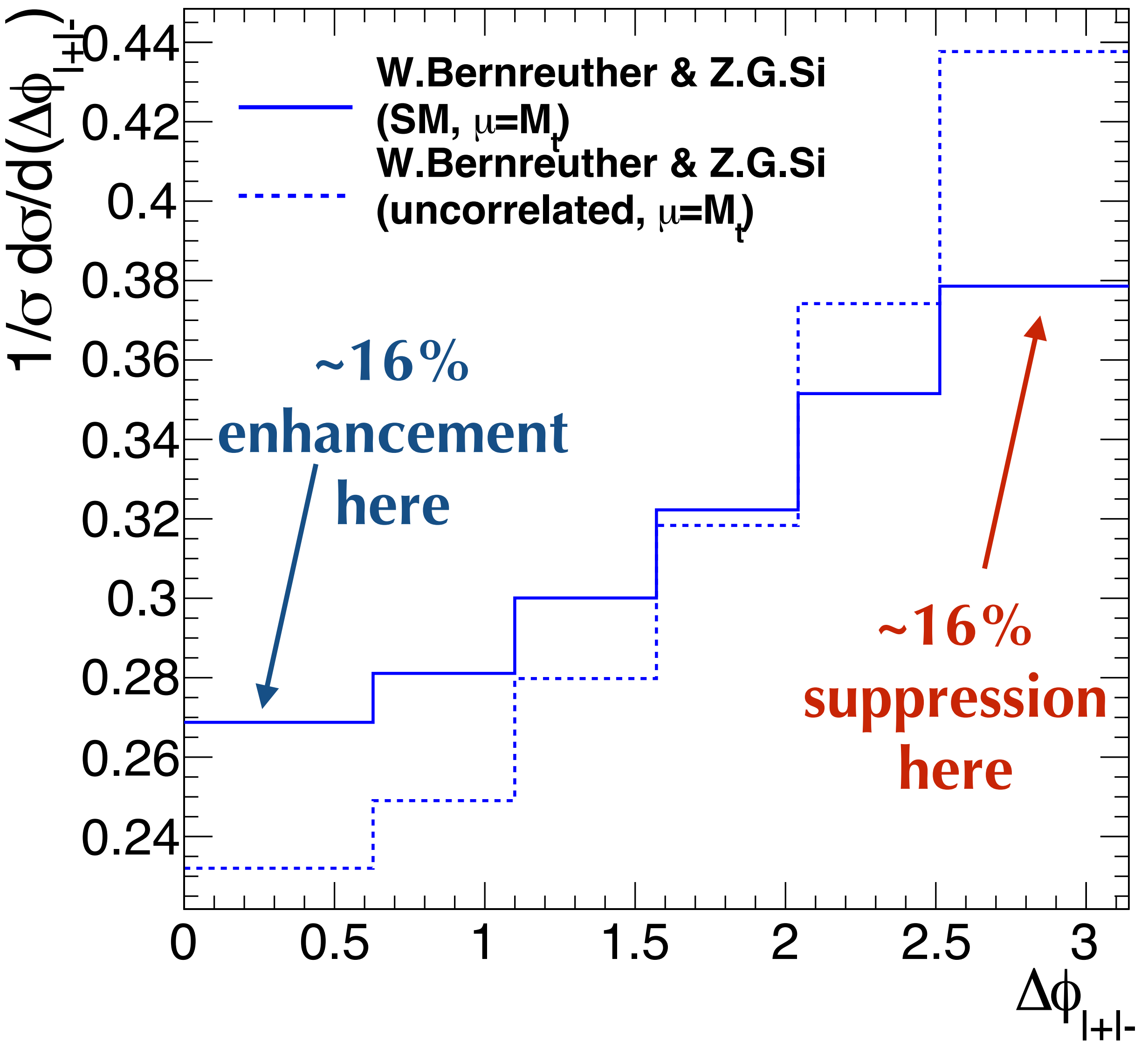
- **Same helicity** contribution is **dominant near threshold**
- Opposite helicity becomes dominant when $E_t >> m_t$ (helicity conservation)
- Expected net spin correlation strength of **~30%** at the LHC
  - **modified in many new physics scenarios**

Lepton Δφ distribution

- In $t\bar{t}$ dilepton final state, spin correlations in same-helicity gluon fusion give **alignment in Δφ**
  - lab frame azimuthal angle between two leptons



Δφ distribution in presence and absence of spin correlations



~16% enhancement here

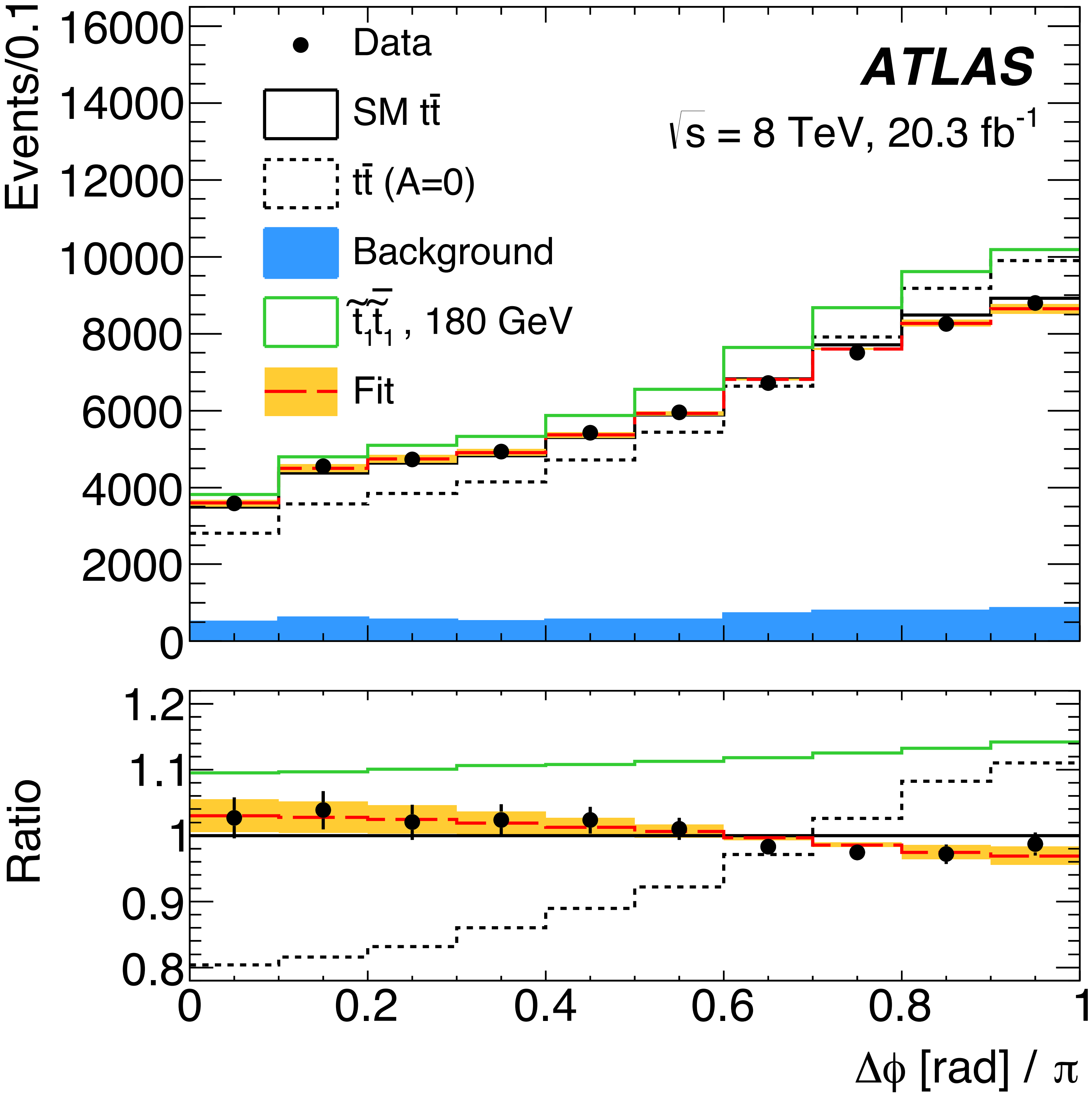
~16% suppression here

- Kinematically, high Δφ is preferred because the tops are produced back to back
  - **relative enhancement at low Δφ due to spin correlations**
- Lepton angles have excellent experimental resolution
  - Δφ most precise probe of spin correlations (unique to LHC)

Δϕ measurement

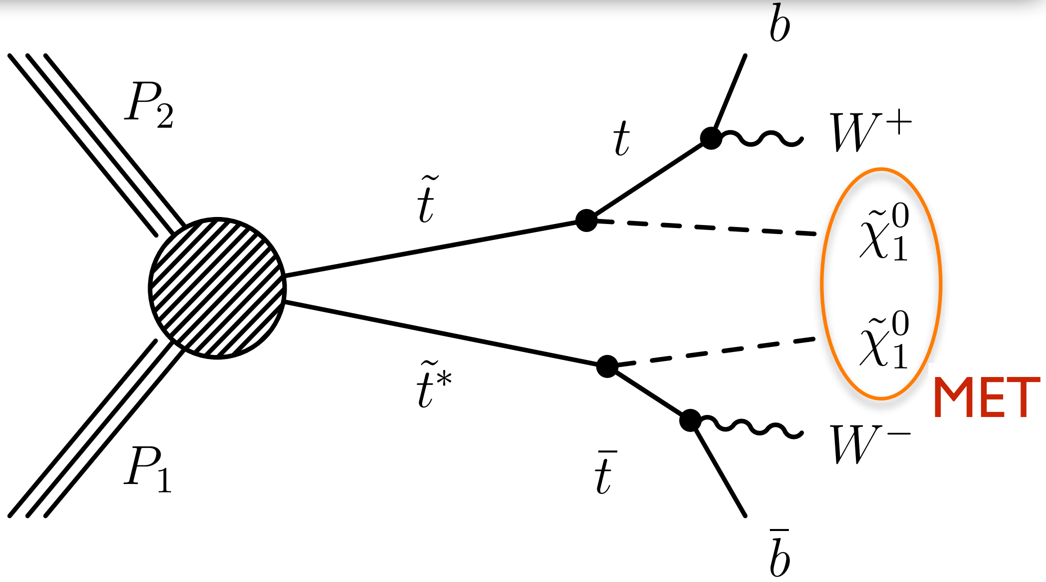
- Select $t\bar{t}$ events in dilepton final state
  - data-driven prediction for dominant Z/γ^*+jets background
- Quantify spin correlation strength as fraction “f” of SM expectation
  - template fit using simulated correlated and uncorrelated $t\bar{t}$
- $f = 1.20 \pm 0.05 \pm 0.13$
  - proof top really behaves like a bare quark!

arxiv:1412.4742

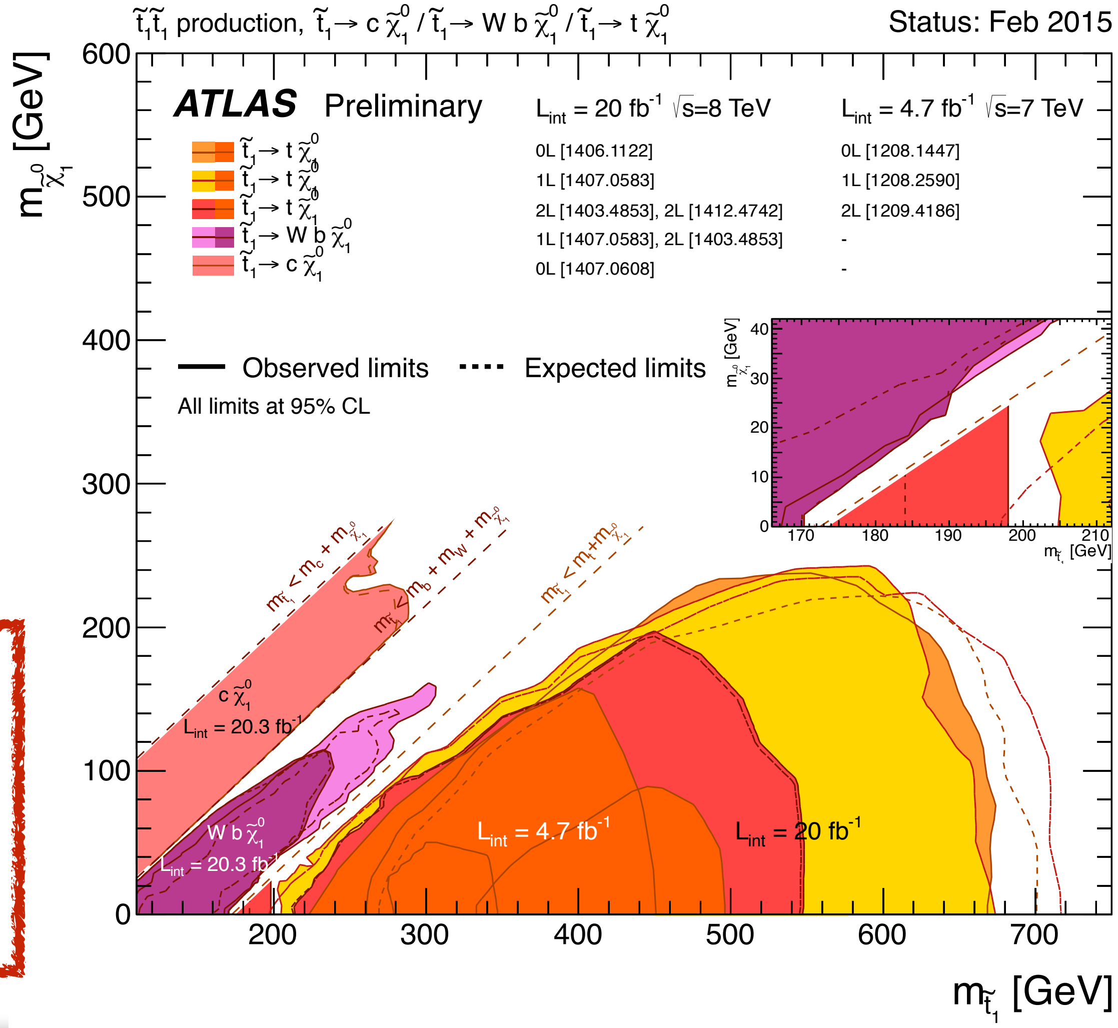


Probing SUSY with spin correlations

- Supersymmetric top squark pair production looks like $t\bar{t}$ + **MET**
- Squarks have spin-zero
  - daughter top quarks look similar to **uncorrelated** $t\bar{t}$ events
  - but only ~1/6 of the $t\bar{t}$ cross section for $m_{stop} = m_t$
- **Total cross section measurement** also sensitive to stops
  - combining the two, beginning to have sensitivity
- ATLAS excludes **$m_t < m_{stop} < 191$ GeV**



Direct searches insensitive when $\tilde{\chi}_1^0$ soft

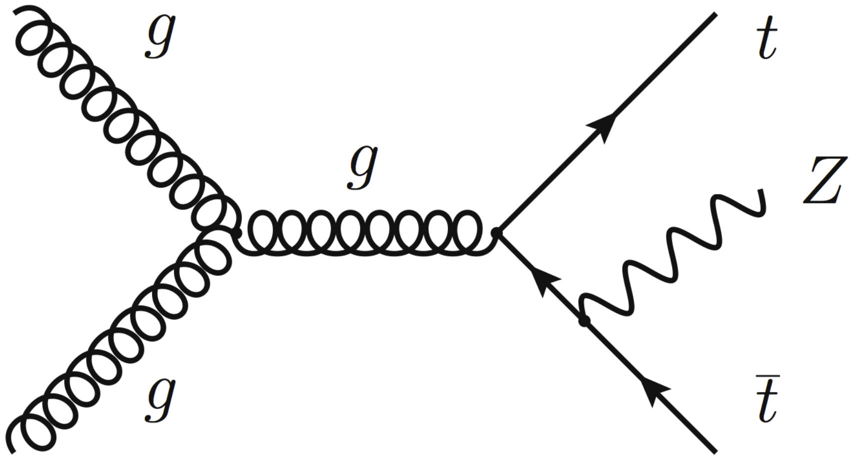


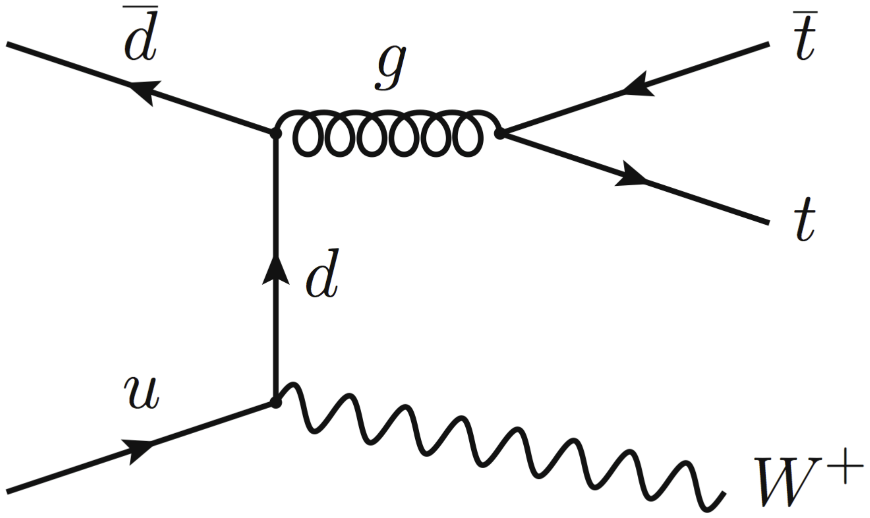
Important region to probe based on naturalness considerations

ttZ and ttW

ttZ and ttW

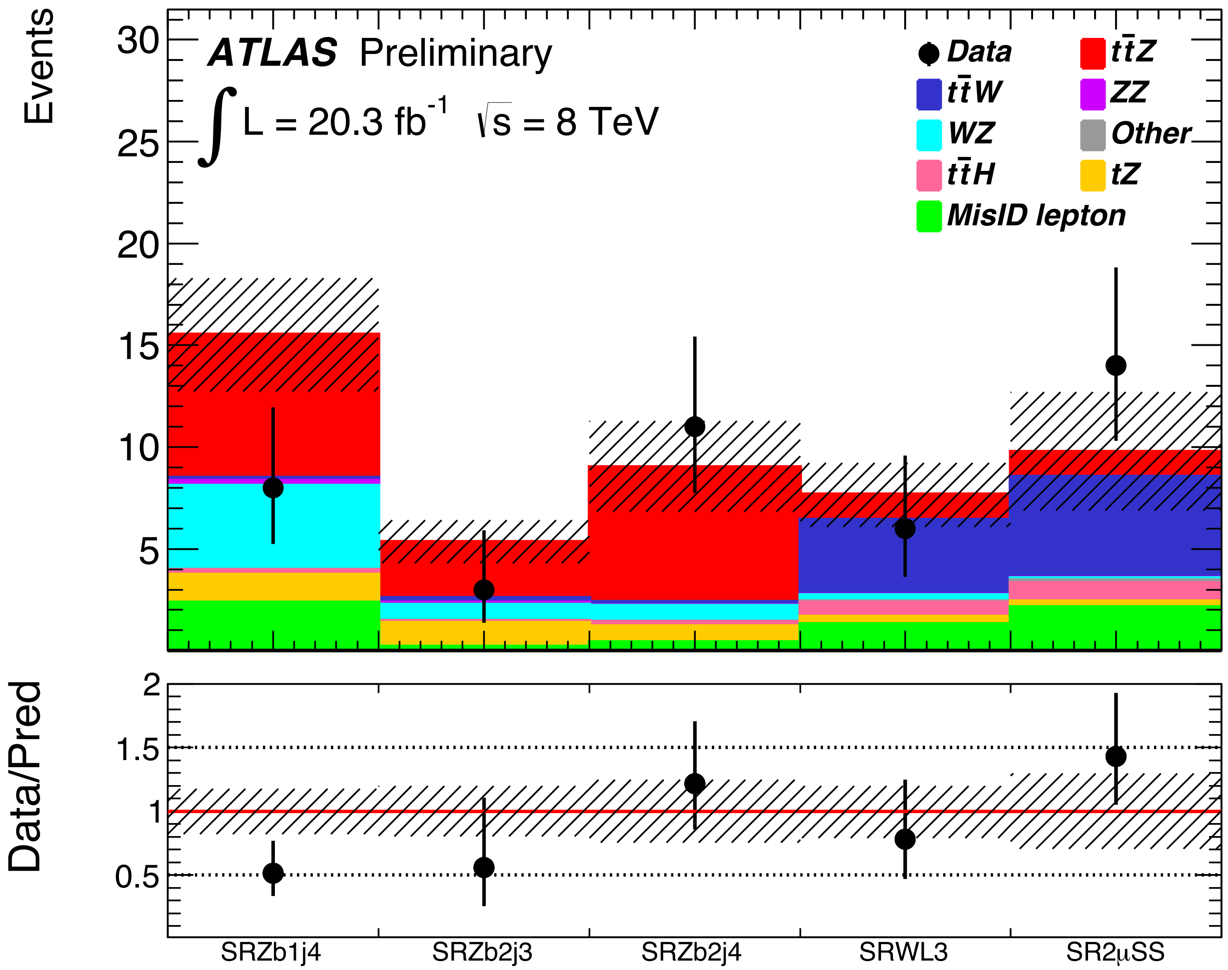
- ttZ provides **first experimental measurement of top-Z coupling**
  - (ttW does not measure top-W coupling)
- ttW/Z production can be enhanced by new physics
  - composite Higgs, Z′, Little Higgs
- Same 3 channels as for $t\bar{t}$ but additional charged lepton(s) from W (Z) decay
  - look for 2ℓ, 3ℓ, 4ℓ final states with Z mass or same charge



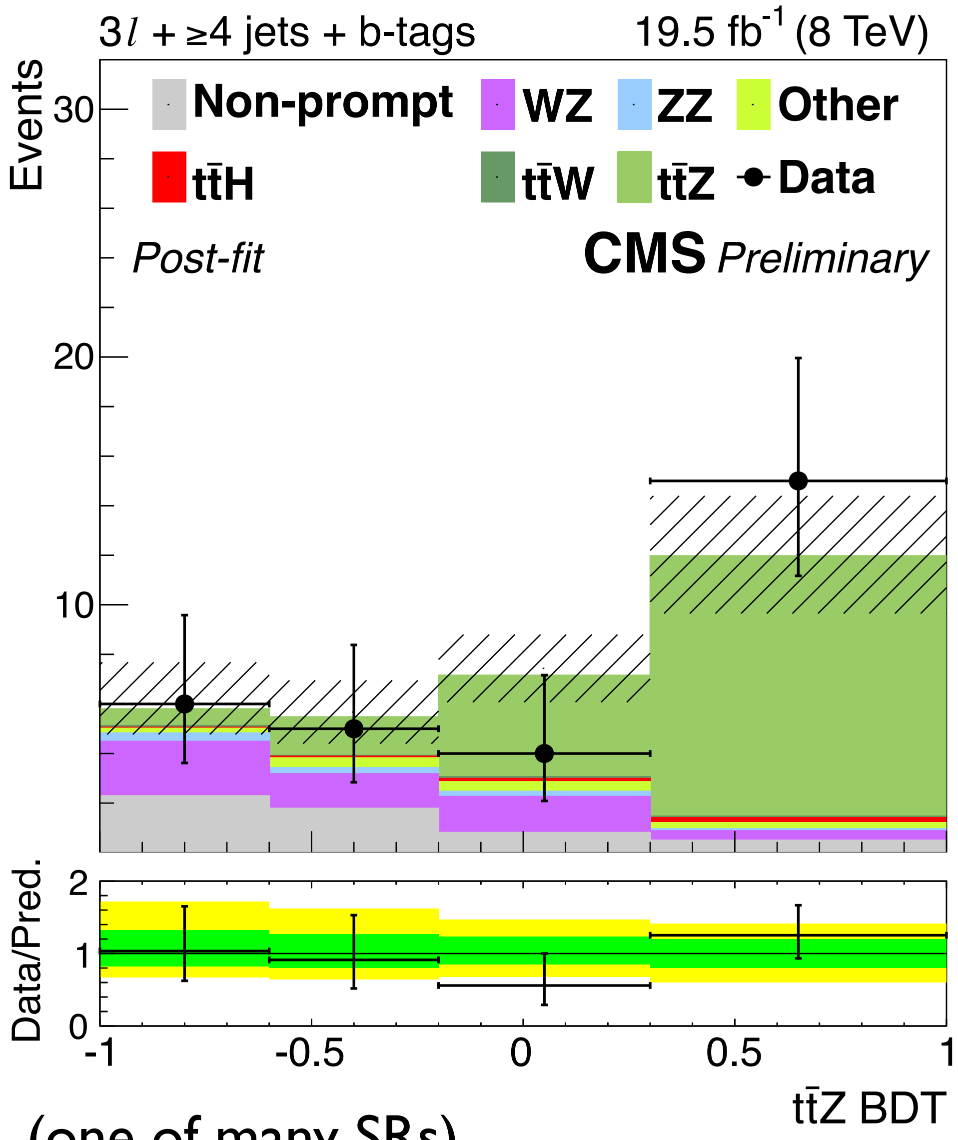


ttW and ttZ measurement

- ATLAS: mostly cut-based analysis
- CMS: multivariate approach to signal and background event reconstruction and discrimination
- Data driven approach to estimate large non-prompt lepton background
- Sensitivity still limited by statistics



ATLAS-CONF-2014-038



(one of many SRs)

CMS Preliminary (public twiki)

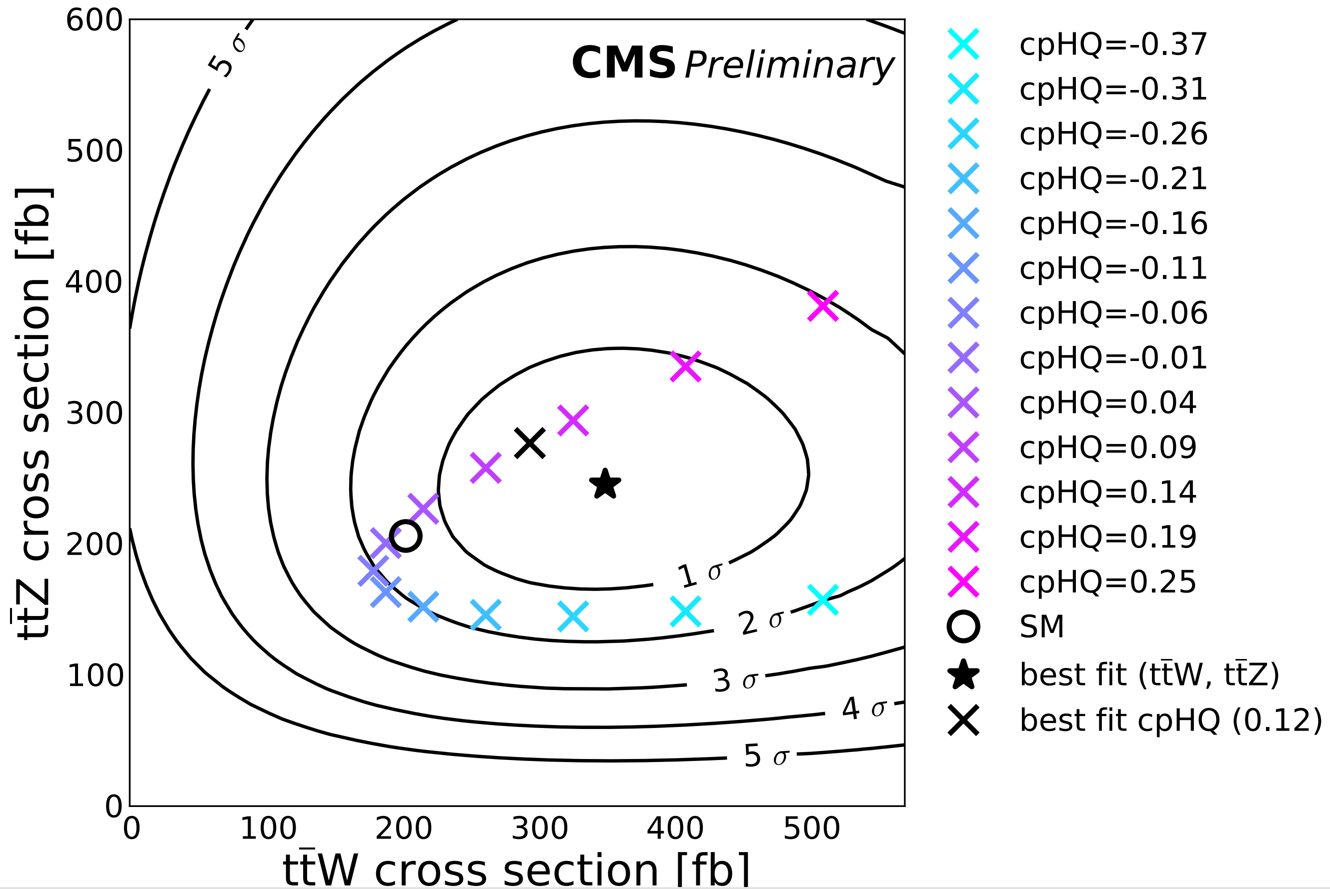
ttZ and ttW results

- CMS **observes** ttZ (6.4σ), both experiments see evidence for ttW

ttW and ttZ measurements	ttW				ttZ			
	Cross section		Significance		Cross section		Significance	
	Theory* (fb)	Observed (fb)	Expected	Observed	Theory* (fb)	Observed (fb)	Expected	Observed
ATLAS	203	300	2.3σ	**3.1σ**	206	150	3.4σ	**3.1σ**
CMS (prelim.)		382	3.5σ	**4.8σ**		242	5.7σ	**6.4σ**

*NLO xsecs from JHEP 11 (2012) 056

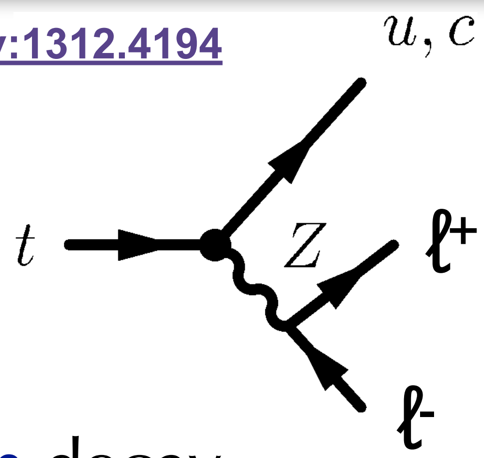
- Constraints on dimension-6 operators parameterising NP
  - select 5 possible operators with small effect on inclusive H and $t\bar{t}$ production, but large effect on ttW/Z
  - all consistent with SM



Flavour changing neutral currents

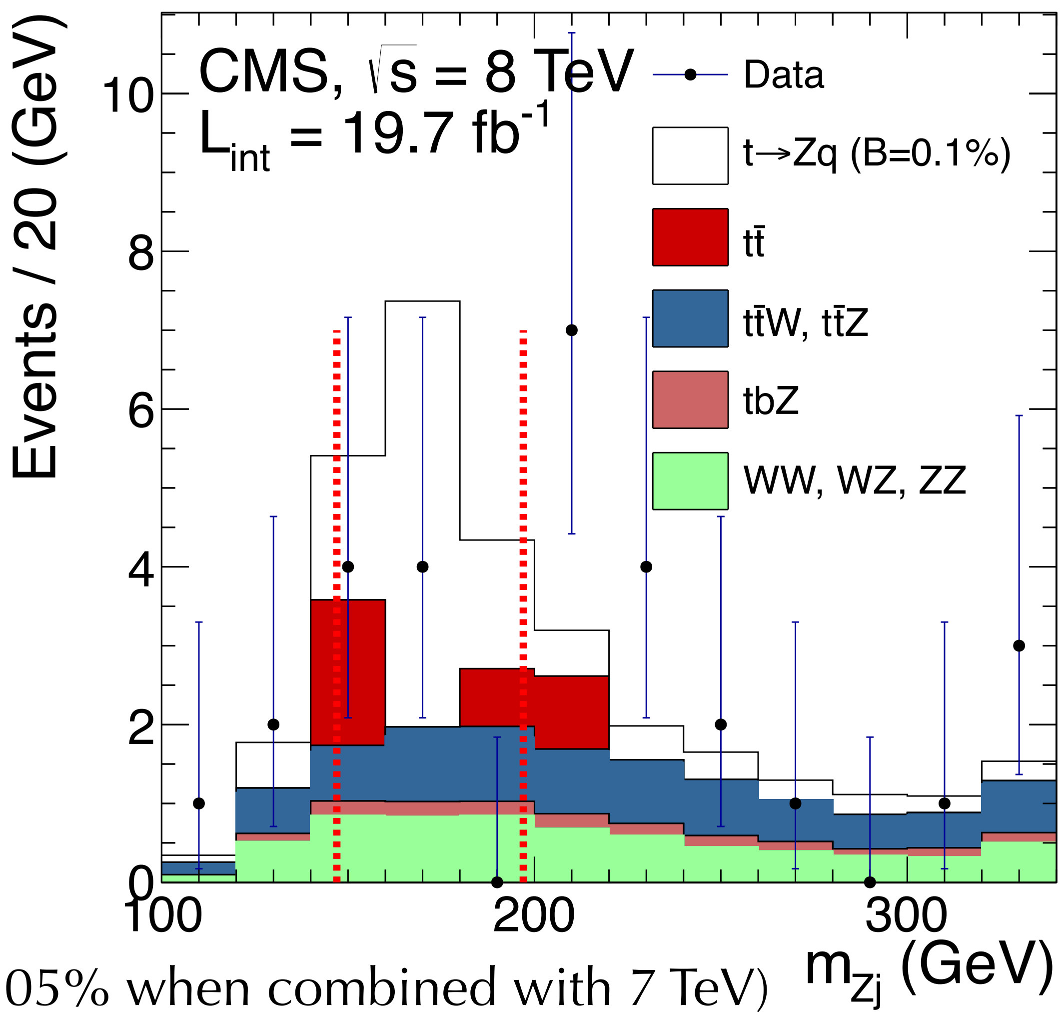
Search for FCNC in top decays

arxiv:1312.4194



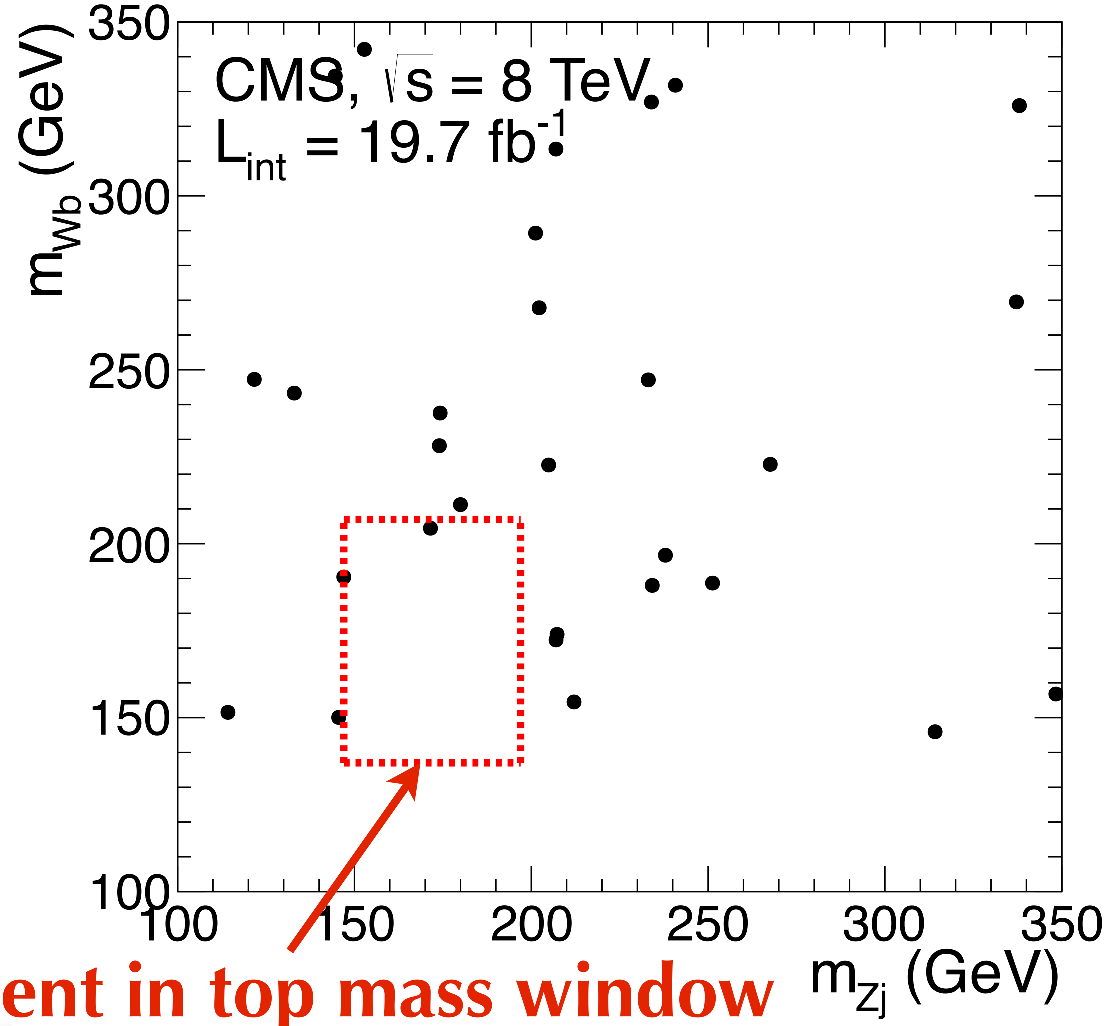
- Flavour changing neutral currents highly suppressed in SM
- Search for $t\bar{t}$ events with a FCNC decay, $t \rightarrow Zq$
  - $tt \rightarrow Wb + Zq \rightarrow \ell\nu b + \ell\ell q$
- Require two opposite-sign, isolated leptons (e or μ) **consistent with Z-boson** decay and an extra charged lepton **consistent with W-boson** decay
- Perform counting experiment in signal region: $\mathcal{B}(t \rightarrow Zq) < 0.06\%$ (95% CL)

m_{Zj} distribution (before m_{Wj} requirement)



(B<0.05% when combined with 7 TeV)

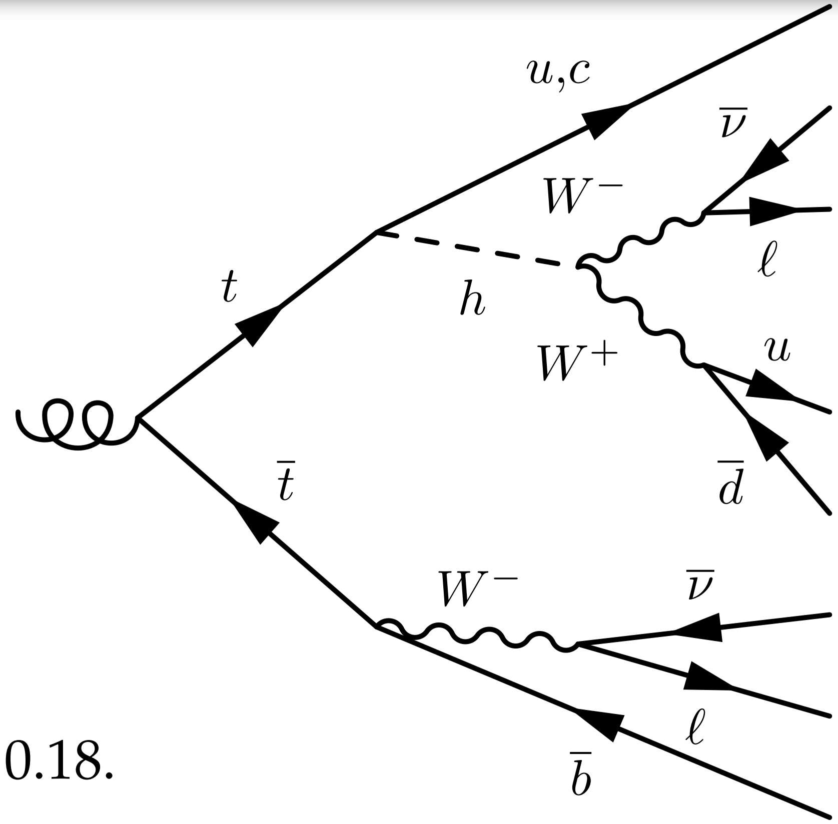
m_{Wb} vs m_{Zj} distribution



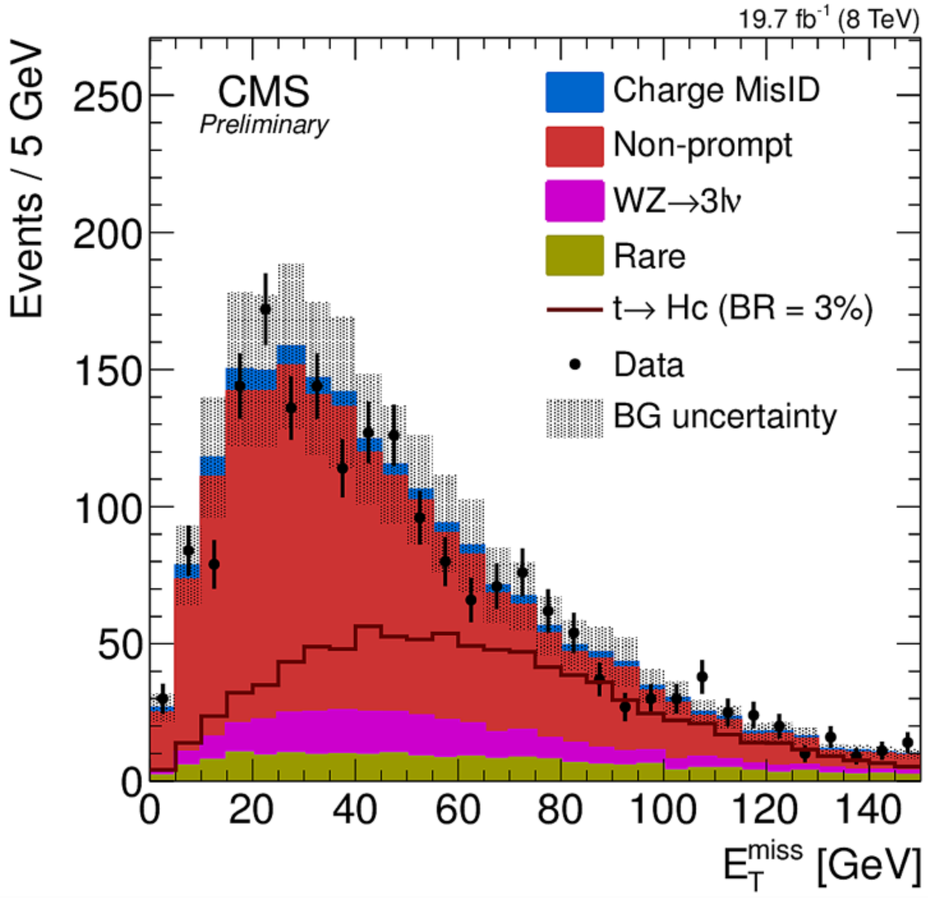
1 event in top mass window

FCNH search (multileptons)

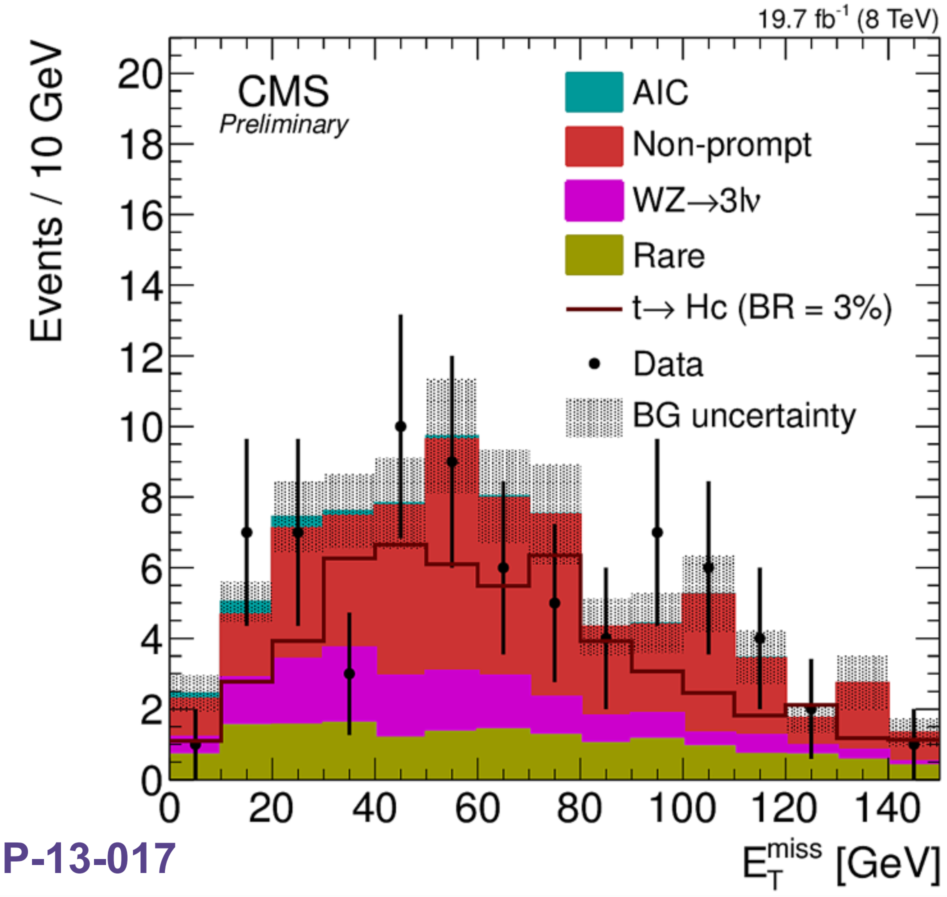
- Cut based analysis
  - look for 3ℓ or same-charge 2ℓ
    - (a bit like ttW final state)
- Data driven approach to estimate large non-prompt lepton background
- B(t→Hc) < 0.93% (95% CL)
- Flavour-violating Yukawa coupling $\sqrt{|\lambda^H_{tc}|^2 + |\lambda^H_{ct}|^2} < 0.18.$



2ℓ



3ℓ



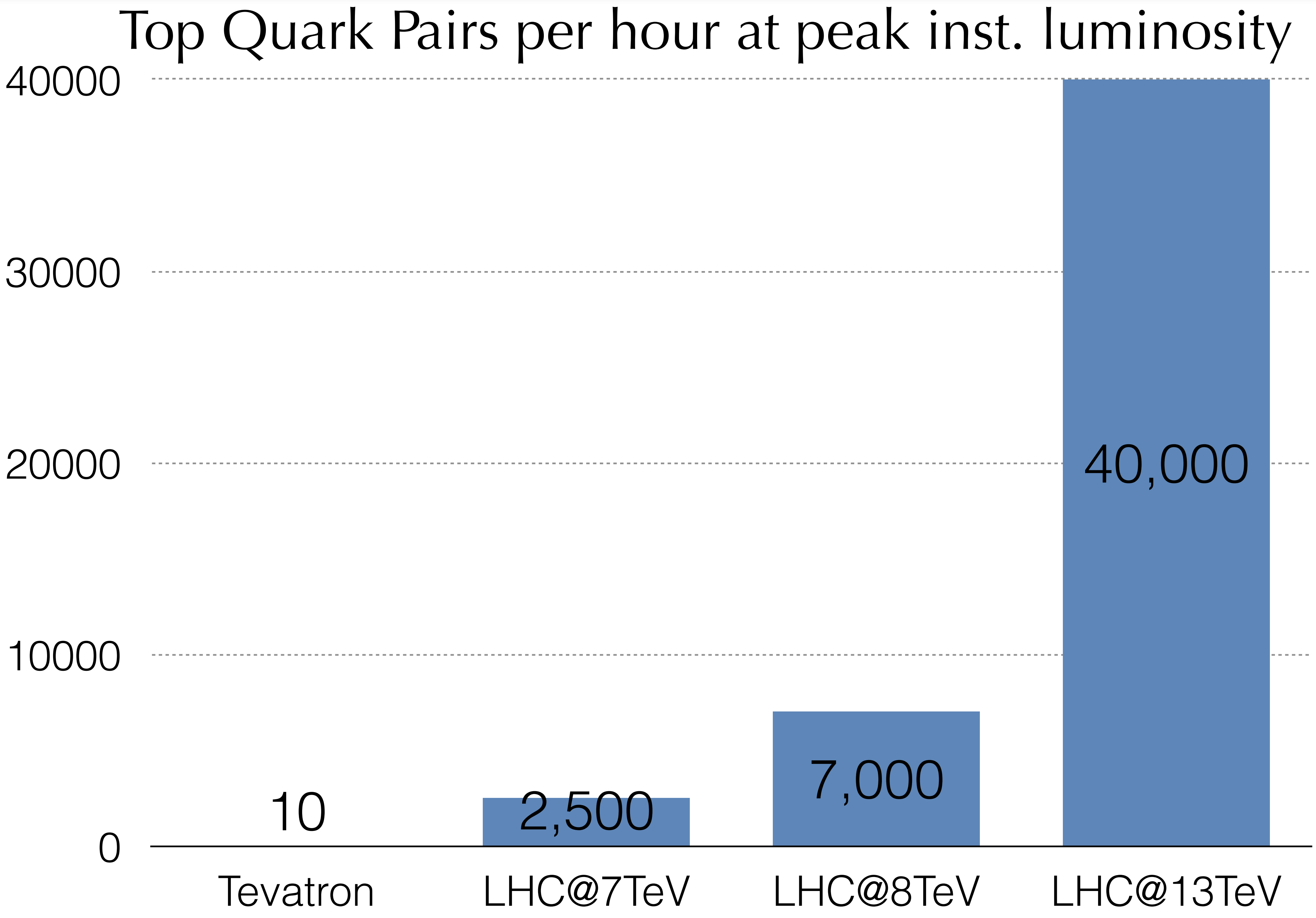
CMS PAS TOP-13-017

Summary and Outlook

Summary

- No significant deviations seen from SM expectations in LHC Run 1
  - Mass measurement has reached remarkable precision
    - systematics dominated, unlikely to be surpassed quickly in Run 2
  - Observation of $t\bar{t}$ correlated spins
    - probe of new physics including low-mass top squark pairs
  - Observation of ttZ
    - Run 2 statistics will allow us to measure ttZ differentially, along with other rare processes (ttW, ttH, ttγ)
  - No evidence for FCNCs

Outlook for LHC Run 2



cross sections from arXiv:1303.6254: Tevatron ~7pb, LHC@7TeV ~172pb, LHC@8TeV ~246pb, LHC@13TeV ~806pb
peak inst. luminosity: Tevatron: ~4x10^{32}cm^{-2}s^{-1}, LHC@7TeV: ~4x10^{33}cm^{-2}s^{-1}, LHC@8TeV: ~8x10^{33}cm^{-2}s^{-1}, LHC@13TeV: ~1.3x10^{34}cm^{-2}s^{-1}(estimate for 2015)

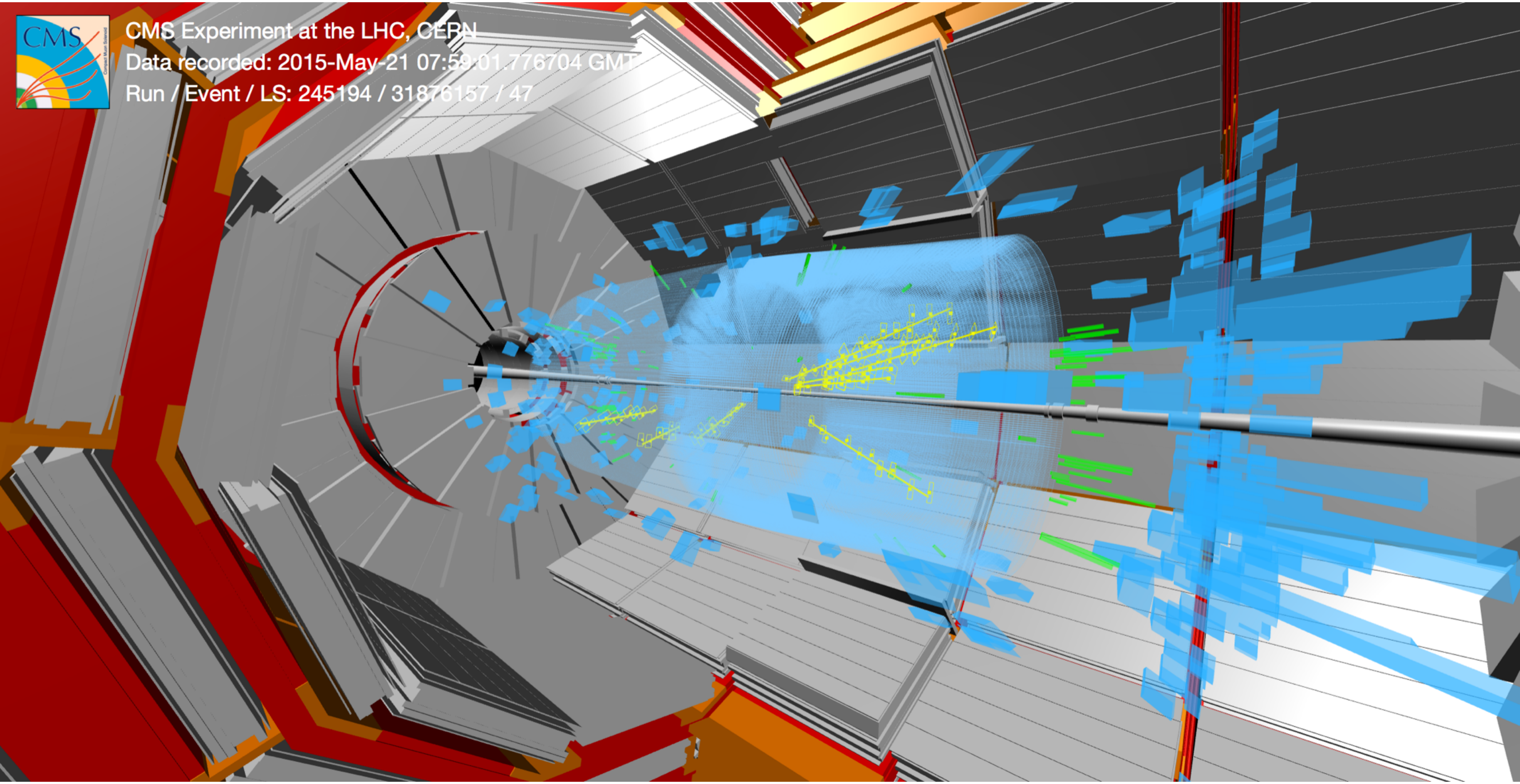
- Another order of magnitude increase for $t\bar{t}$ pair production!

Outlook for LHC Run 2

- LHC is a top quark factory, and with Run 2 will reach ultimate statistical precision
  - improvements in systematic and theoretical uncertainties will be essential to keep pace

- Could new physics show up first in $t\bar{t}$ in Run 2?

First test 13 TeV collisions last week!



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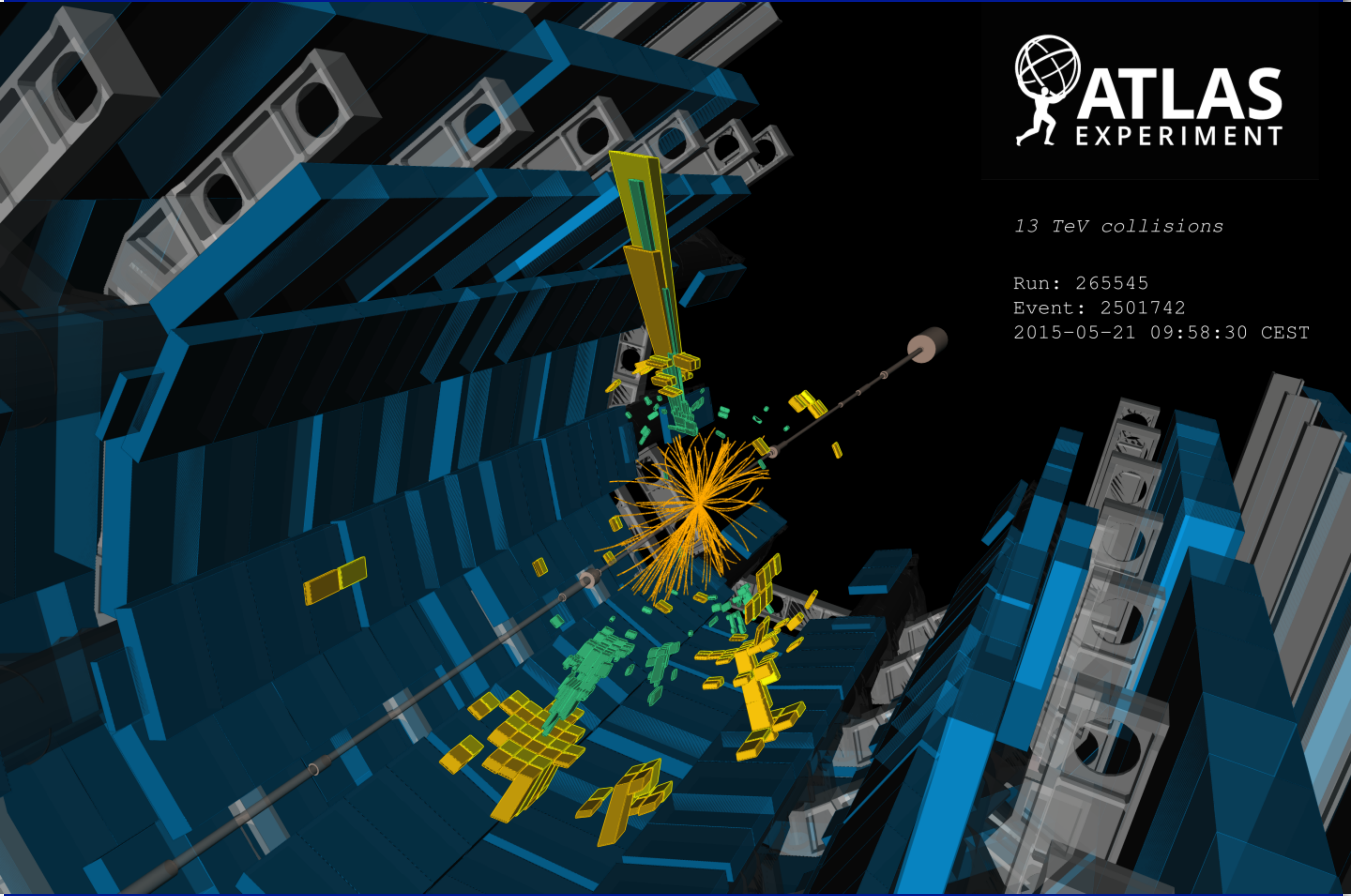


Backup

top mass combination systematics

ATLAS

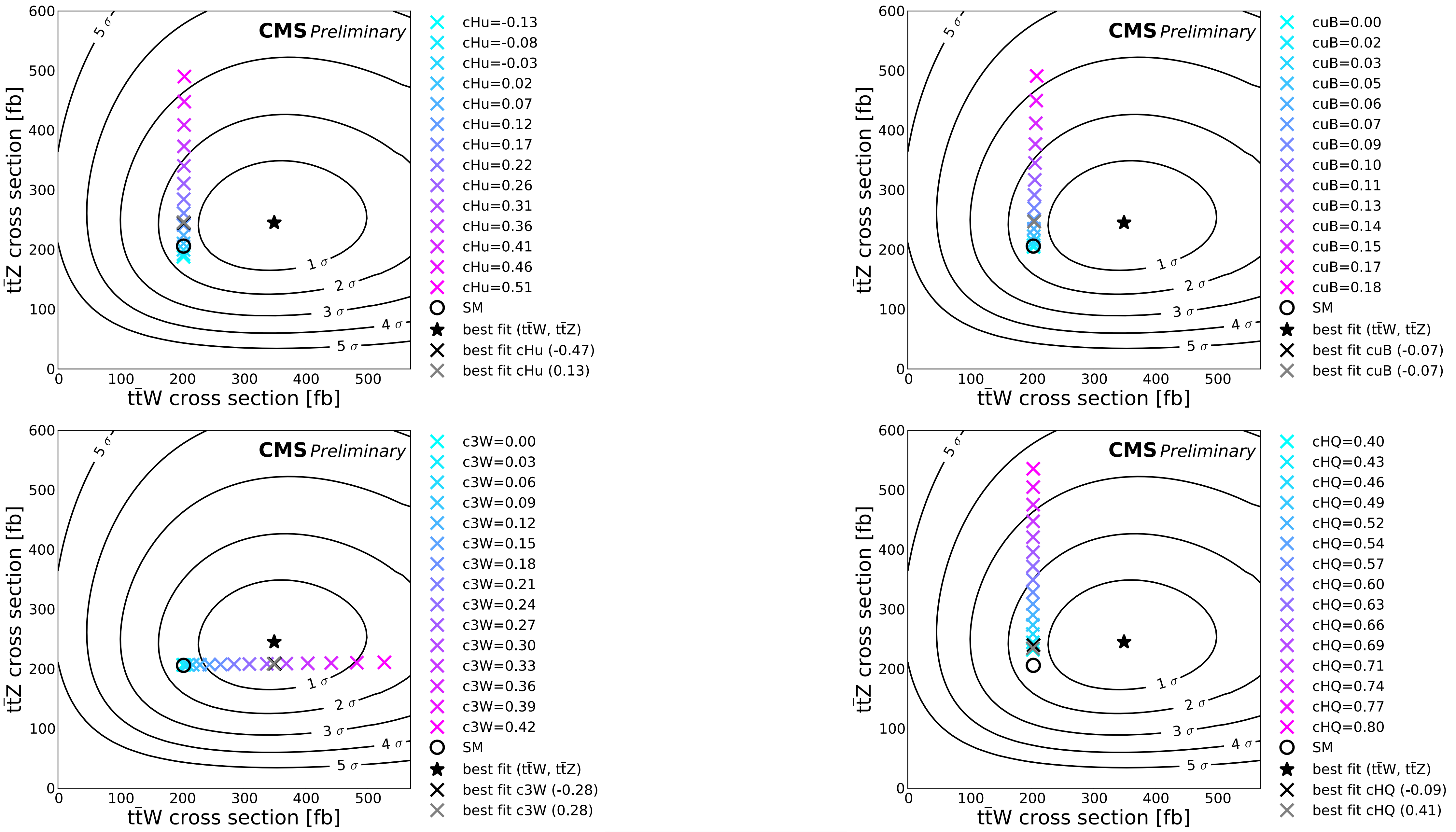
	$t\bar{t} \to$ lepton+jets			$t\bar{t} \to$ dilepton	Combination	
	$m_{\mathrm{top}}^{\ell+\mathrm{jets}}$ [GeV]	JSF	bJSF	$m_{\mathrm{top}}^{\mathrm{dil}}$ [GeV]	$m_{\mathrm{top}}^{\mathrm{comb}}$ [GeV]	ρ
Results	172.33	1.019	1.003	173.79	172.99	
Statistics	0.75	0.003	0.008	0.54	0.48	0
– *Stat. comp.* (m_{top})	*0.23*	*n/a*	*n/a*	*0.54*		
– *Stat. comp. (JSF)*	*0.25*	*0.003*	*n/a*	*n/a*		
– *Stat. comp. (bJSF)*	*0.67*	*0.000*	*0.008*	*n/a*		
Method	0.11 ± 0.10	0.001	0.001	0.09 ± 0.07	0.07	0
Signal MC	0.22 ± 0.21	0.004	0.002	0.26 ± 0.16	0.24	+1.00
Hadronisation	0.18 ± 0.12	0.007	0.013	0.53 ± 0.09	0.34	+1.00
ISR/FSR	0.32 ± 0.06	0.017	0.007	0.47 ± 0.05	0.04	−1.00
Underlying event	0.15 ± 0.07	0.001	0.003	0.05 ± 0.05	0.06	−1.00
Colour reconnection	0.11 ± 0.07	0.001	0.002	0.14 ± 0.05	0.01	−1.00
PDF	0.25 ± 0.00	0.001	0.002	0.11 ± 0.00	0.17	+0.57
W/Z+jets norm	0.02 ± 0.00	0.000	0.000	0.01 ± 0.00	0.02	+1.00
W/Z+jets shape	0.29 ± 0.00	0.000	0.004	0.00 ± 0.00	0.16	0
NP/fake-lepton norm.	0.10 ± 0.00	0.000	0.001	0.04 ± 0.00	0.07	+1.00
NP/fake-lepton shape	0.05 ± 0.00	0.000	0.001	0.01 ± 0.00	0.03	+0.23
Jet energy scale	0.58 ± 0.11	0.018	0.009	0.75 ± 0.08	0.41	−0.23
b-Jet energy scale	0.06 ± 0.03	0.000	0.010	0.68 ± 0.02	0.34	+1.00
Jet resolution	0.22 ± 0.11	0.007	0.001	0.19 ± 0.04	0.03	−1.00
Jet efficiency	0.12 ± 0.00	0.000	0.002	0.07 ± 0.00	0.10	+1.00
Jet vertex fraction	0.01 ± 0.00	0.000	0.000	0.00 ± 0.00	0.00	−1.00
b-Tagging	0.50 ± 0.00	0.001	0.007	0.07 ± 0.00	0.25	−0.77
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.15 ± 0.04	0.000	0.001	0.04 ± 0.03	0.08	−0.15
Leptons	0.04 ± 0.00	0.001	0.001	0.13 ± 0.00	0.05	−0.34
Pile-up	0.02 ± 0.01	0.000	0.000	0.01 ± 0.00	0.01	0
Total	1.27 ± 0.33	0.027	0.024	1.41 ± 0.24	0.91	−0.07

CMS

	Correlations		Combined uncertainty
	ρ_{year}	ρ_{chan}	
Experimental uncertainties			
In-situ JSF factor	0	0	0.10
Inter-calibration JES component	1	1	0.01
MPF *in-situ* JES component	1	1	0.05
Uncorrelated JES component	0	1	0.14
Other JES uncertainties	0	0	0.00
Lepton energy scale	1	1	0.02
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	1	1	0.06
Jet energy resolution	1	1	0.17
b-tagging	1	1	0.03
Trigger	0	0	0.04
MHI(Pileup)	0	1	0.20
Background Data	0	0	0.05
Background MC	1	1	0.07
Fit calibration	0	0	0.05
Modeling of hadronization			
Flavor JES component	1	1	0.05
Flavor-dependent hadronization uncertainty	1	1	0.36
b fragmentation and B branching fractions	1	1	0.14
Modeling of the hard scattering process and radiation			
Parton distribution functions	1	1	0.06
Renormalization and factorization scales	1	1	0.17
ME-PS matching threshold	1	1	0.16
ME generator	1	1	0.13
Top quark p_T	1	1	0.12
Modeling of non-perturbative QCD			
Underlying event	1	1	0.16
Color reconnection	1	1	0.18
Statistical uncertainty			0.10
Total systematic uncertainty			0.65
Total uncertainty			0.65

Limits from ttZ/W

operator	best fit point(s)	1σ CL	2σ CL
$\bar{c}_{uB}$	-0.07 and 0.07	{-0.11, 0.11}	{-0.14, 0.14}
$\bar{c}'_{HQ}$	0.12	{-0.07, 0.18}	{-0.33, -0.24} and {-0.02, 0.23}
$\bar{c}_{HQ}$	-0.09 and 0.41	{-0.22, 0.08} and {0.24, 0.54}	{-0.31, 0.63}
$\bar{c}_{Hu}$	-0.47 and 0.13	{-0.60, -0.23} and {-0.11, 0.26}	{-0.71, 0.37}
$\bar{c}_{3W}$	-0.28 and 0.28	{-0.36, -0.18} and {0.18, 0.36}	{-0.43, 0.43}



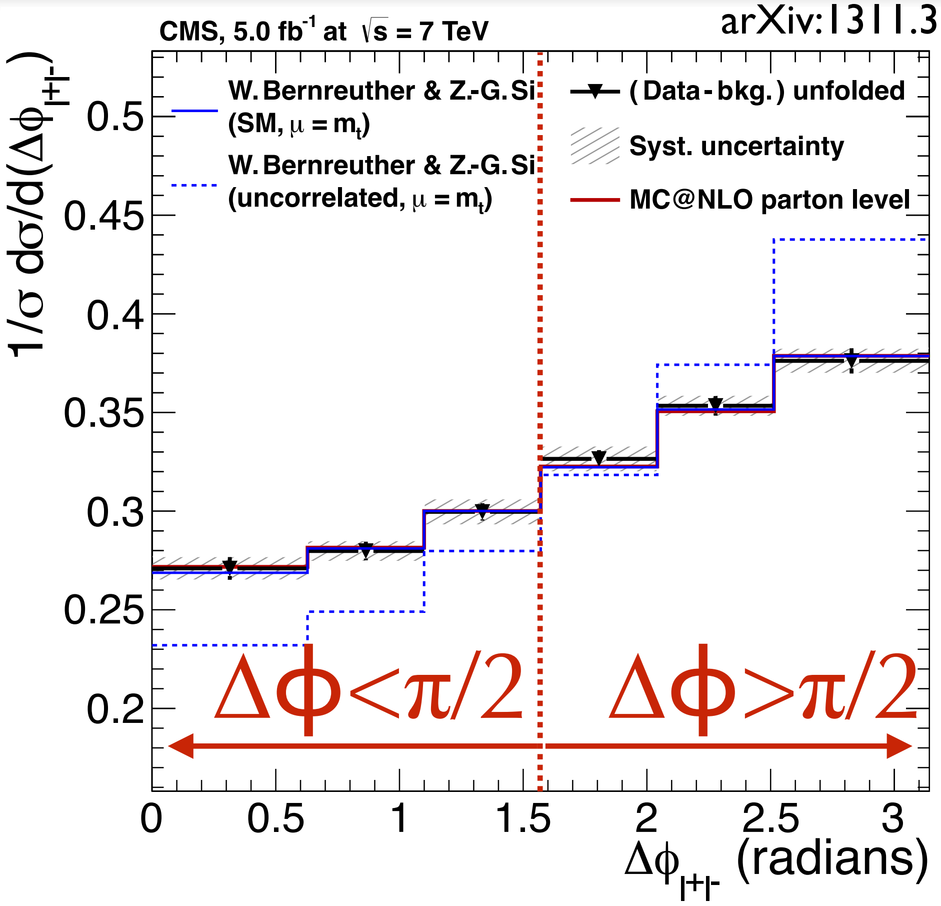
CMS spin correlations

- Quantify the Δϕ shape with an asymmetry variable:

$$A_{\Delta\phi} = \frac{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) - N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) + N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}$$

- **5.2σ separation** between data and uncorrelated prediction
- Experimental proof the top quark behaves like a bare quark!

arXiv:1311.3924



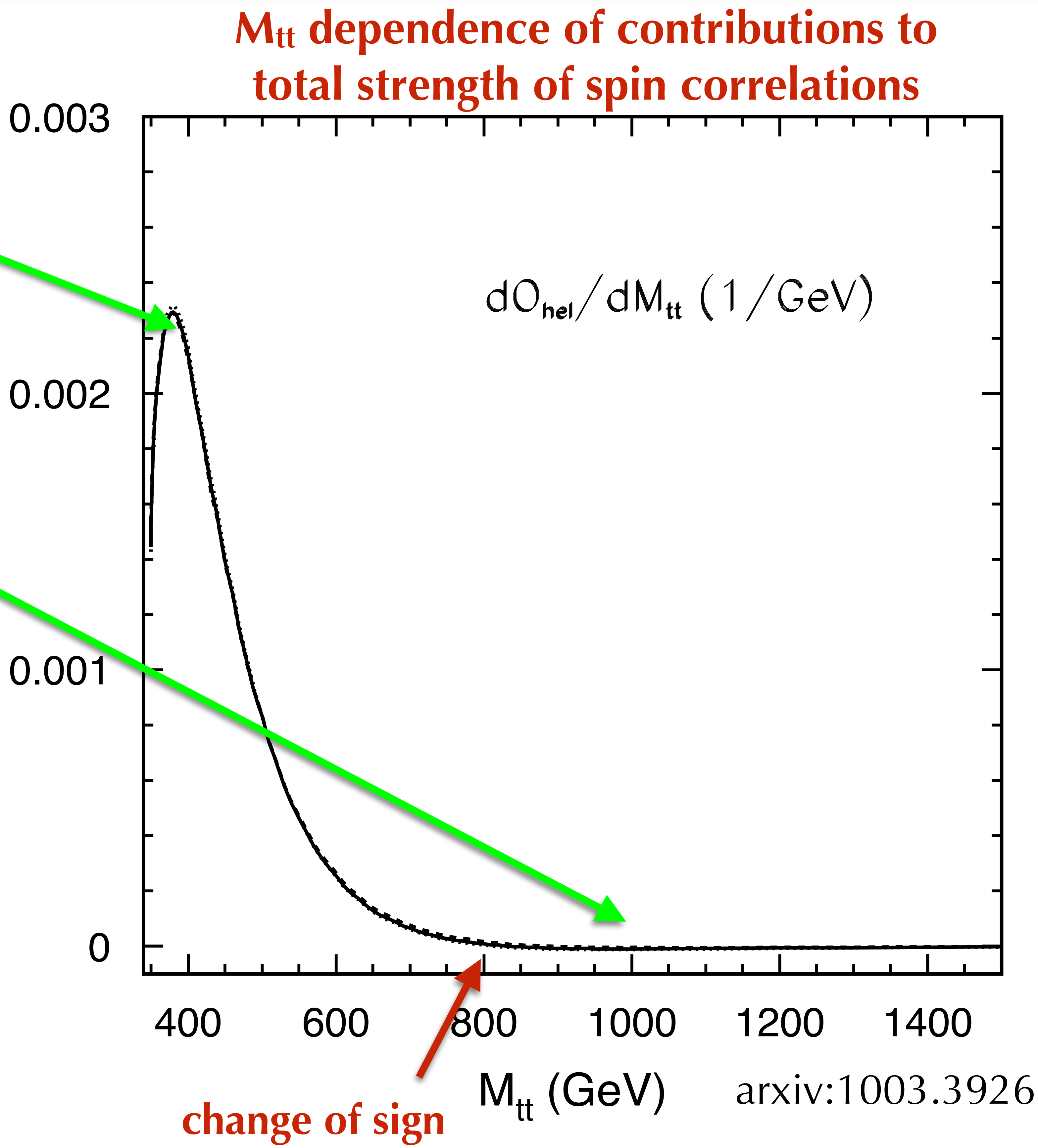
	$A_{\Delta\phi}$
NLO (uncorrelated)	(21.0 $^{+1.3}_{-0.8}$) %
NLO (SM, correlated)	(11.5 $^{+1.4}_{-1.6}$) %
Data (unfolded)	**(11.3 ± 1.0 ± 0.6 ± 1.2) %**

stat. syst. top p_T reweighting

5.2σ

SM spin correlations

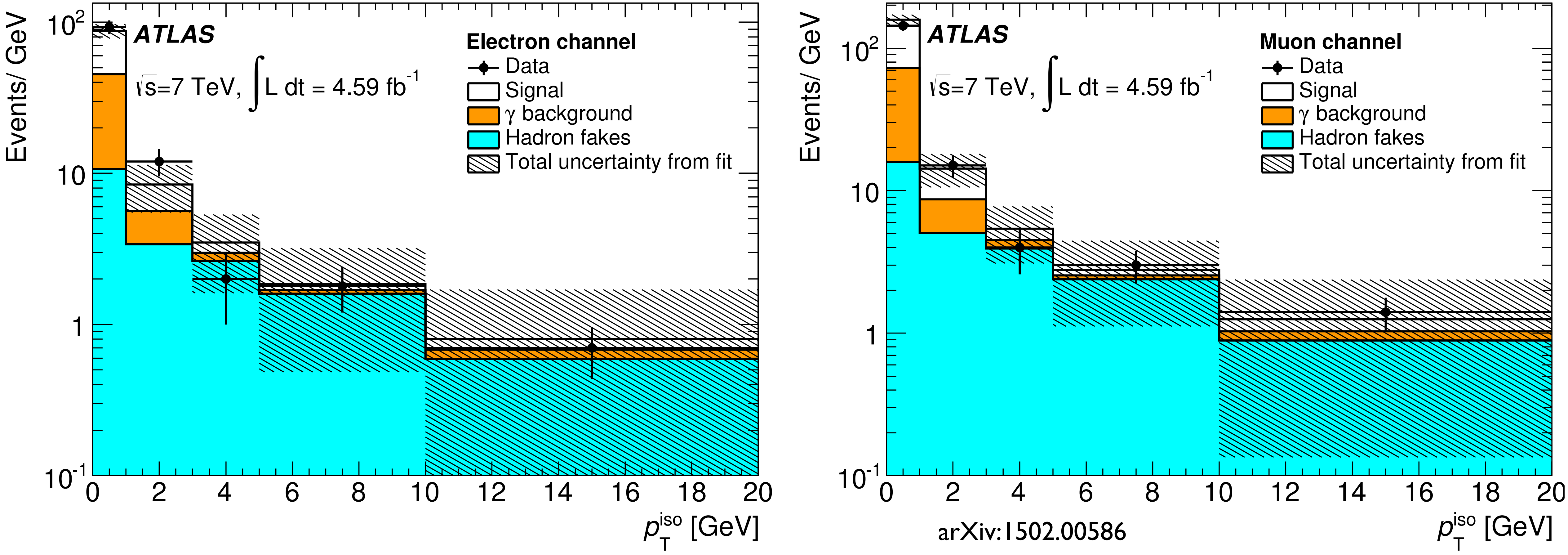
- **Same helicity** contribution is **dominant near threshold**
- Opposite helicity becomes dominant when $E_t \gg m_t$
  - helicity conservation
- Net spin correlation strength of **~30%** (LHC)



M_{tt} dependence of contributions to total strength of spin correlations

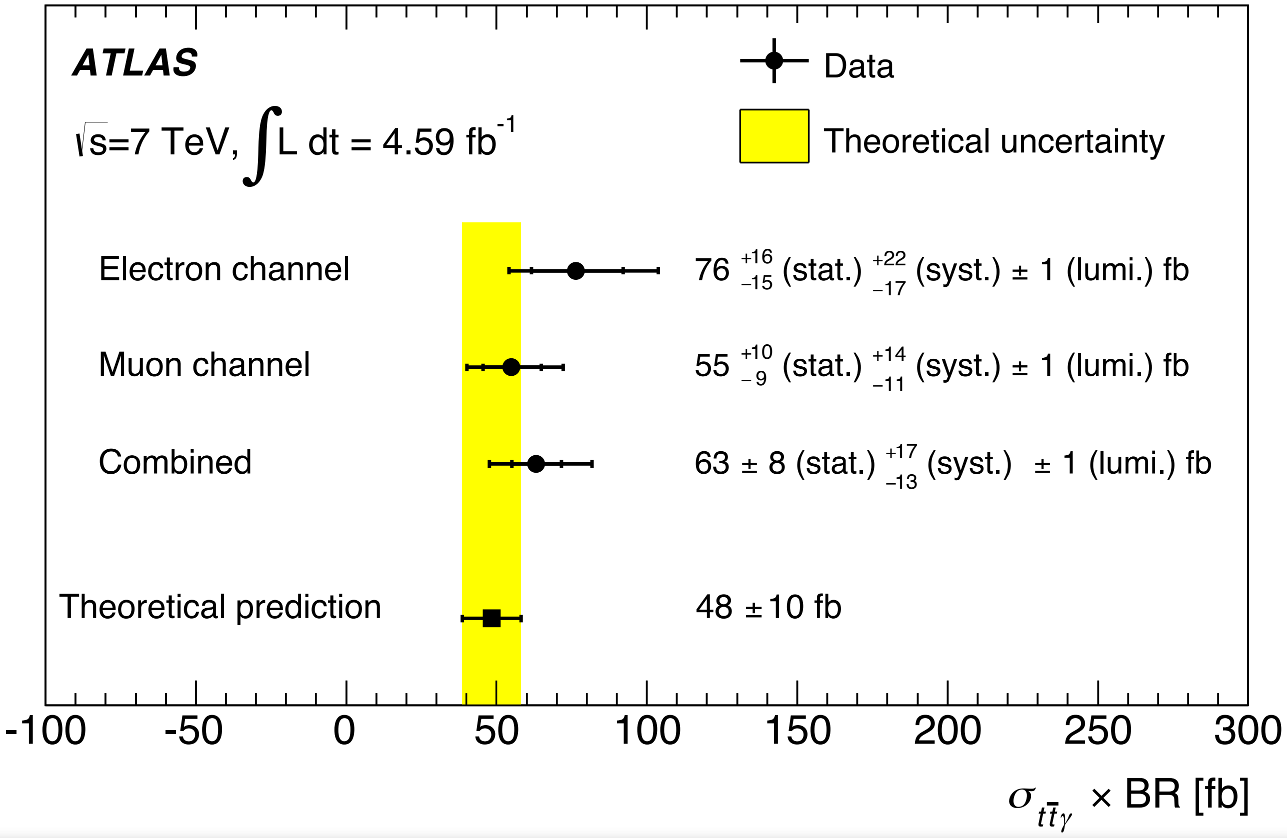
arxiv:1003.3926

ttγ



arXiv:1502.00586

- 5.3σ observation of tt+γ final state

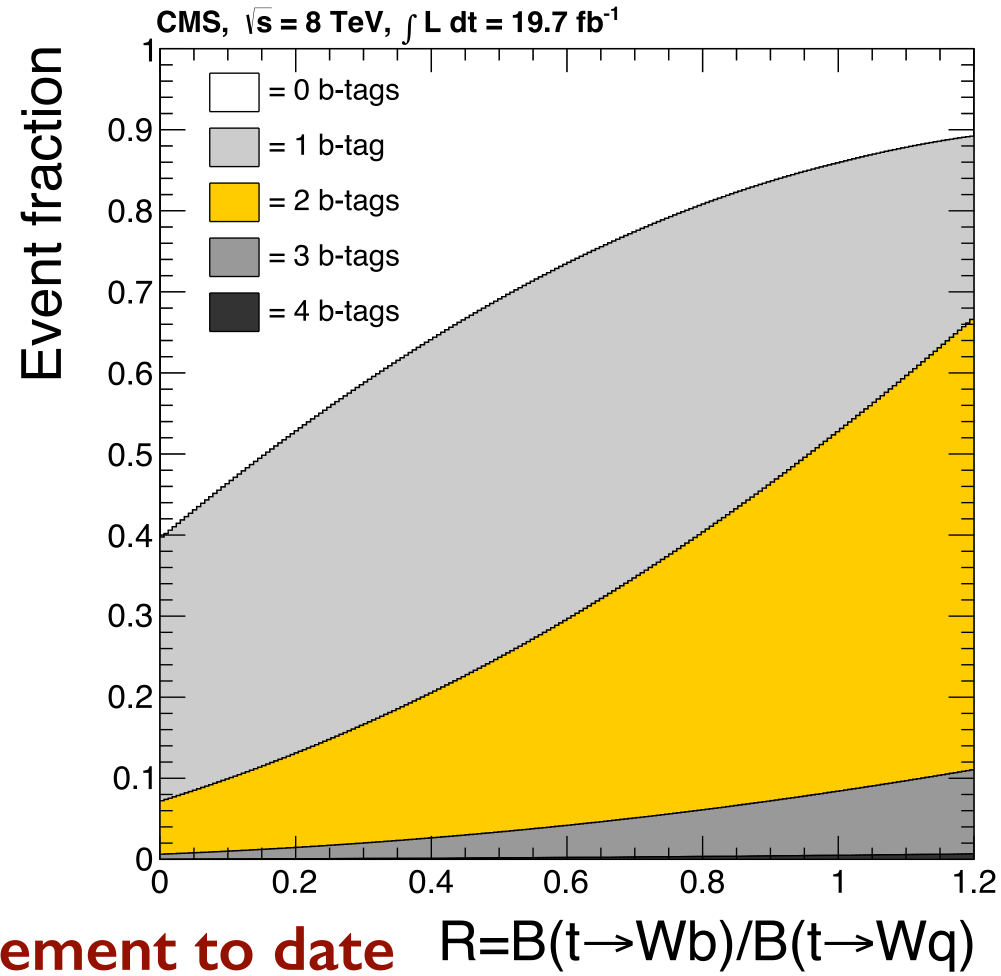


Ratio B(t → Wb)/B(t → Wq)

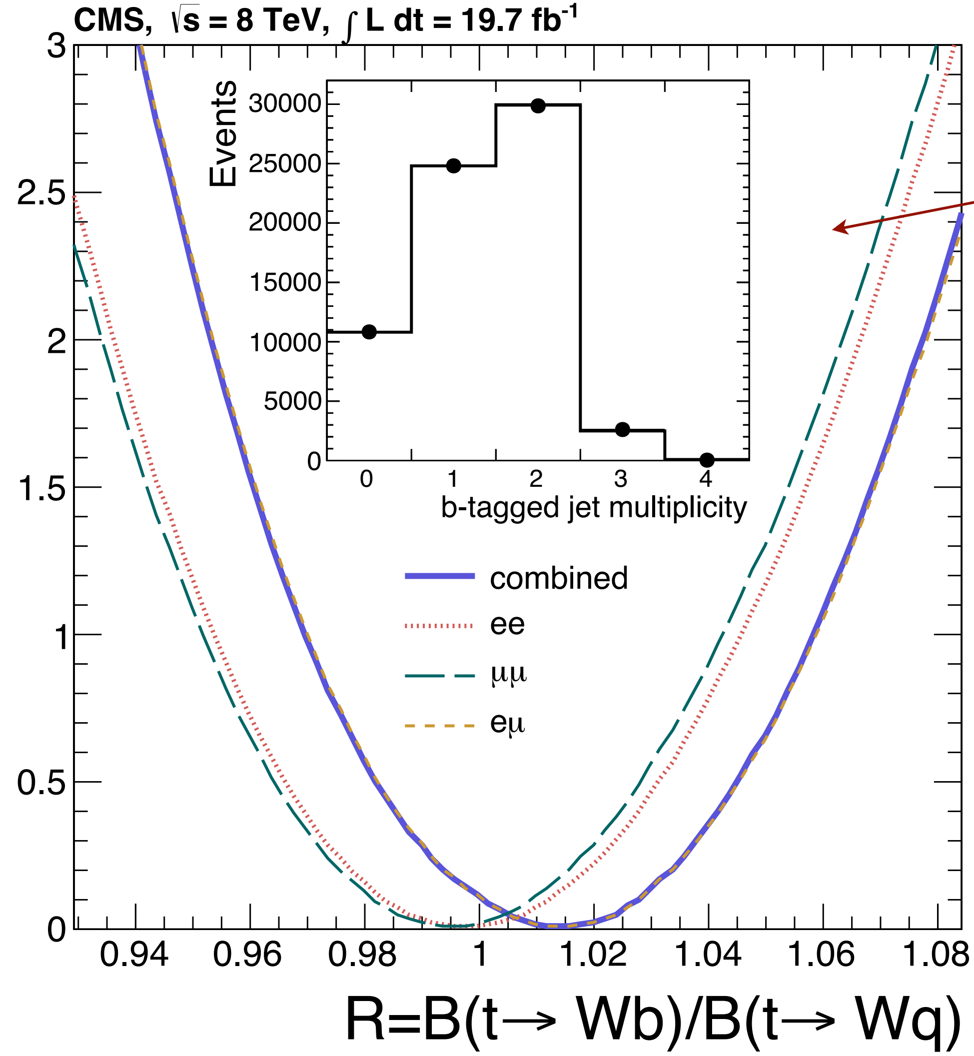
- Measurement in dilepton final state with 19.7 fb^{-1} 8 TeV data
- Construct probability model for expected b-tag multiplicities vs R where $\mathcal{R} = B(t \to Wb)/B(t \to Wq)$
  - done separately for different event categories based on channel (ee, eμ, μμ) and jet multiplicity
- Likelihood fit for R using observed b-tag multiplicity distribution

arXiv:1404.2292

Probability model as a function of R



log likelihood for the 3 channels



b-tag multiplicity distribution (inclusive)

most precise measurement to date

$$\mathcal{R} = 1.014 \pm 0.003\,(\text{stat}) \pm 0.032\,(\text{syst})$$

$$|V_{tb}| = 1.007 \pm 0.016 \qquad (\text{using } \mathcal{R} = |V_{tb}|^2\,)$$

$$\Gamma_\text{t} = \frac{\sigma_{t\text{-ch.}}}{\mathcal{B}(\text{t} \to \text{Wb})} \cdot \frac{\Gamma(\text{t} \to \text{Wb})}{\sigma^{\text{theor.}}_{t\text{-ch.}}}$$

$$\Gamma_\text{t} = 1.36 \pm 0.02\,(\text{stat})^{+0.14}_{-0.11}\,(\text{syst})\,\text{GeV}$$