The XXIII International Workshop
High Energy Physics and Quantum Field Theory
June 26– July 3, 2017
Yaroslavl, Russia

Top physics at LHC

Roberto Tenchini

INFN

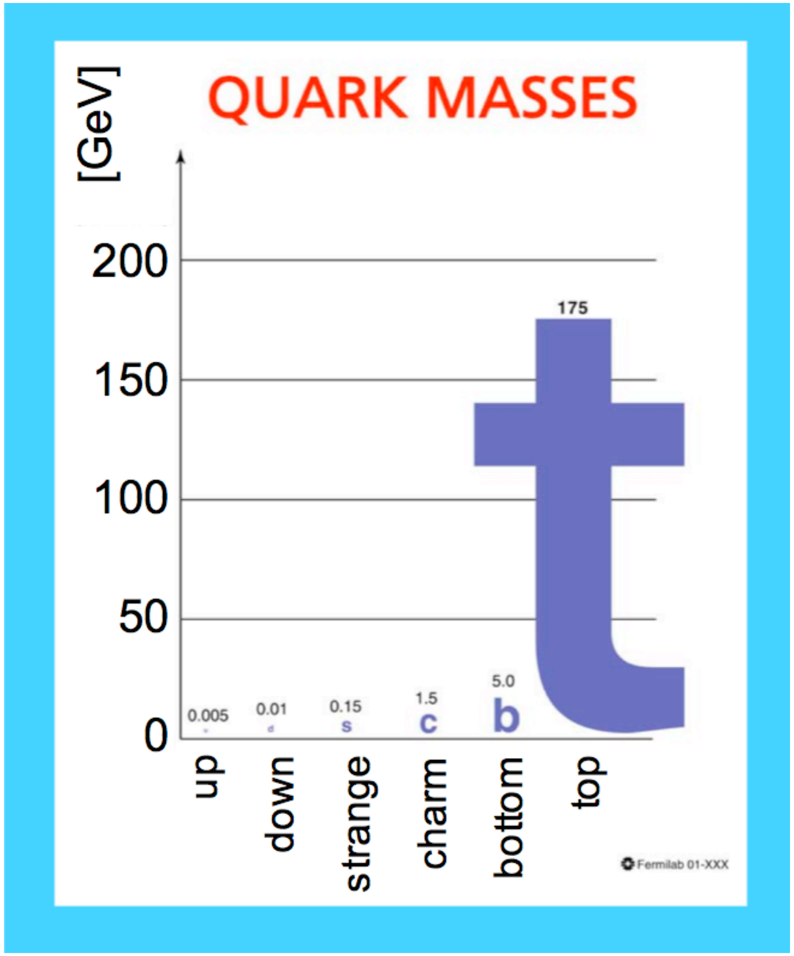
Pisa

Its highness, the top quark

- The up-like quark of the third family, the top quark, has **a mass comparable to a tungsten atom** !
- In other words, **the top – Higgs Yukawa coupling is large (≈1)**:
    - *top is a window to electroweak symmetry breaking*

$$Y = \sqrt{2}\,\frac{m_{top}}{\text{v.e.v.}(\sim 246\ \text{GeV})}$$

$$\Gamma(H \to f\bar{f}) = \frac{N_c g^2 m_f^2}{32\pi m_W^2}\beta^3 m_H$$



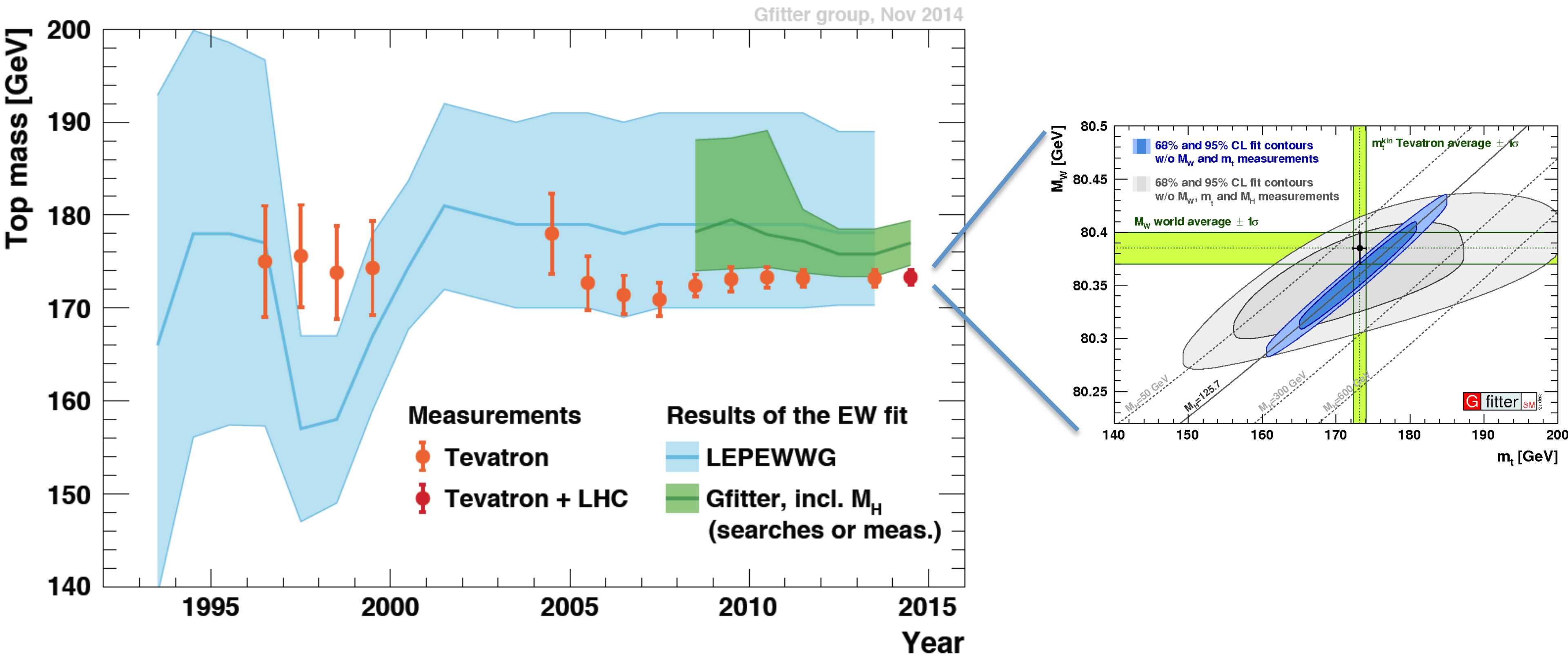
Some consequences of the large top mass (the large top-Higgs Yukawa coupling)

- Due to the non-decoupling properties of electroweak interactions (Veltman, 1977) the top quark gives large contributions to pure EWK radiative corrections $\approx G_F m_t^2$
- Very short lifetime: bound states are not formed, opportunity to study a free quark

$\tau_{top} \simeq 0.4 \times 10^{-24}\, s$

$$\Gamma(t \to bW) = \frac{G_F}{8\pi\sqrt{(2)}} m_t^3 |V_{tb}|^2 \approx 1.5\,\mathrm{GeV}/\mathrm{c}^2.$$

Top mass and electroweak physics

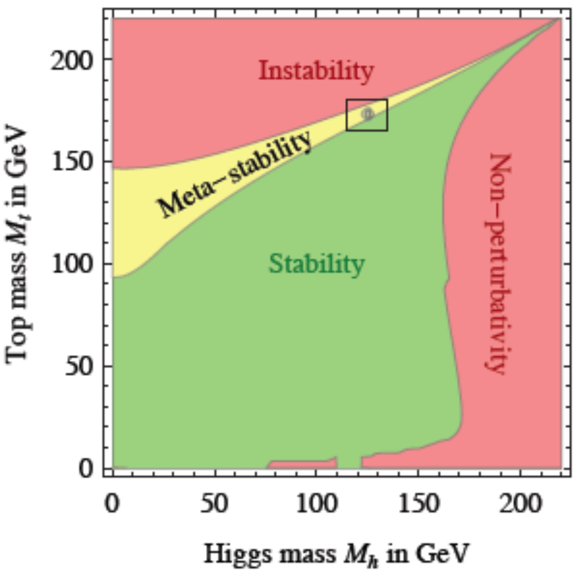


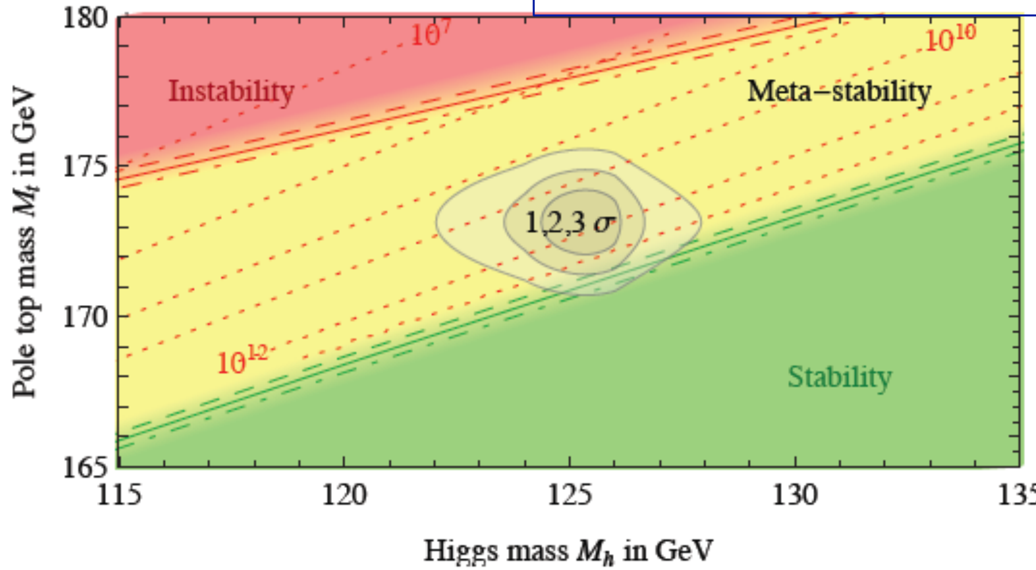
Courtesy of Roman Kogler

Relation between top and Higgs masses and stability of the vacuum in our universe

Electroweak Vacuum → $V = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda(scale)\Phi^4$

De Grassi et al. ArXiv:1205.6497

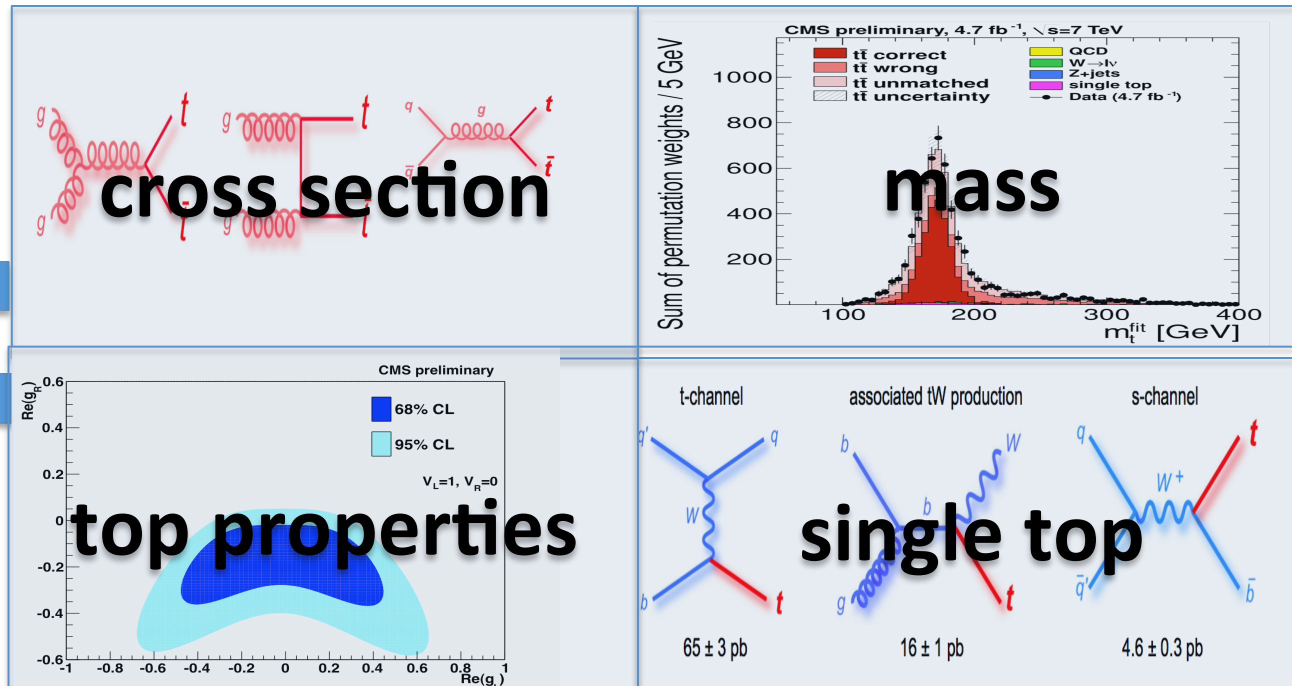




The top areas of study

Total and differential cross sections, Test of production mechanism(QCD, EWK), tt +jets production, measure PDF

Precision measurement of top mass, ΔM(t-tbar) (CPT test)



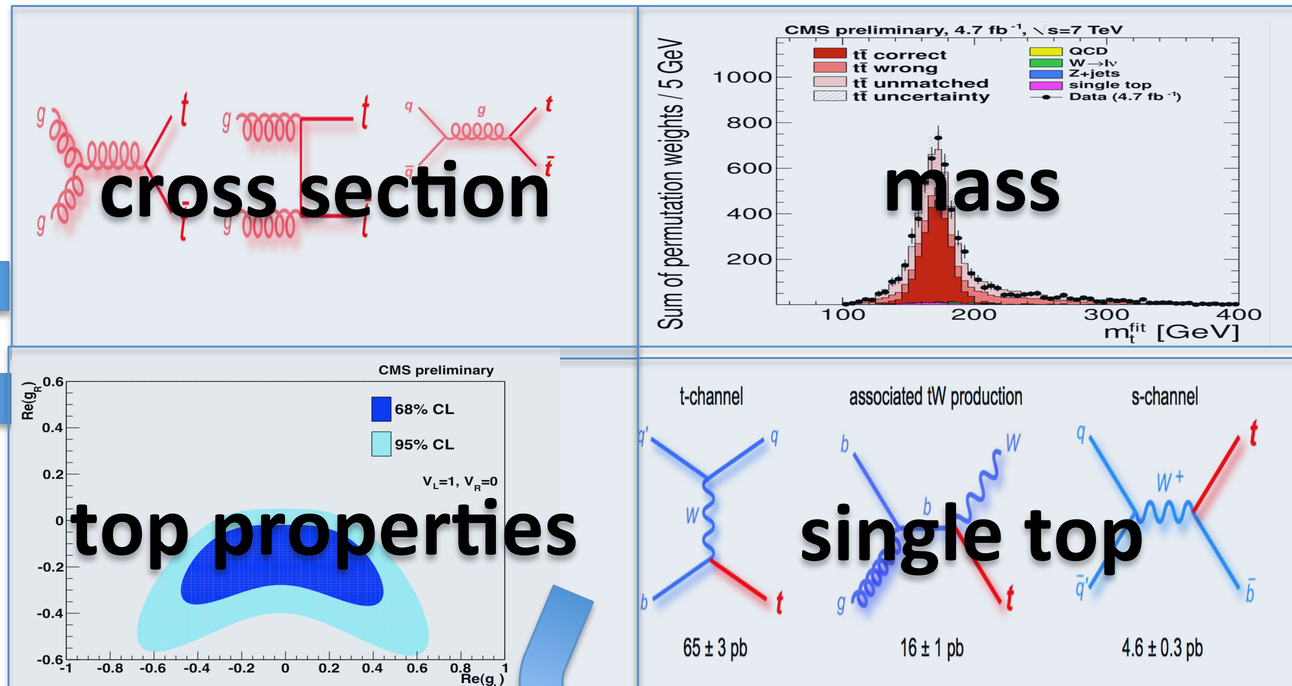
Couplings, branching ratios, charge, width, W helicity, spin correlations, charge asymmetry associated production (ttW, ttZ, ttH, tt+MET)

t, s and tW channels, EWK production properties, Vtb measurement, new physics in single top

The role of top in the Higgs era

ttbar is our monitoring for gluon gluon fusion !

Do we interpret the top mass correctly when we match top, W and Higgs Masses ?



Are top properties consistent with our view of electroweak symmetry breaking ?

Is there any sign of new physics in top production and decay ?

Top physics at LHC
with examples from recent results of ATLAS and CMS

Disclaimer: what comes next is a personal selection of topics and results, with some emphasis on the top mass measurement, a complete account of the very rich top physics programme covered by ATLAS and CMS can be found at

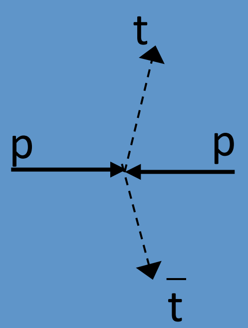
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/index.html

TOP PRODUCTION AND DECAY

Top Quark Production at the LHC

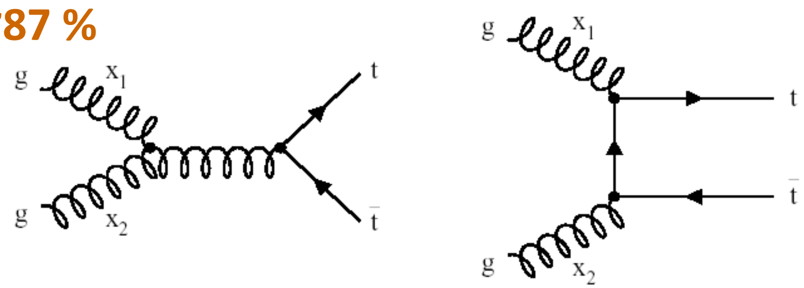
top pairs

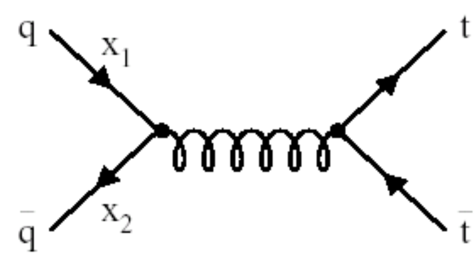


10 $t\bar{t}$ pairs per day @ Tevatron → 1 $t\bar{t}$ pair per second @ LHC

$q\bar{q} \rightarrow t\bar{t}$: 85% *$gg \rightarrow t\bar{t}$: 87%*

~87 %

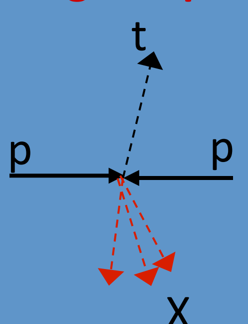




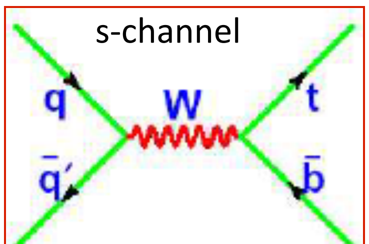
- NLO cross-section σ^{NLO} = **232** pb at 8 TeV ? ~2 M events/10fb^{-1}
- NNLO calculations now available, Czakon, Mitov (2013) arXiv:1303.6254

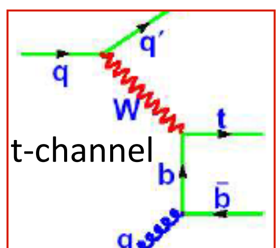
Some references (not a complete list!): (top pairs) N.Nason *et al.* Nucl.Phys. B303 (1988) 607, S.Catani *et al.* Nucl.Phys. B478 (1996) 273, M.Beneke *et al.* hep-ph/0003033, N.Kidonakis and R.Vogt, Phys.Rev. D68 (2003) 114014, W.Bernreuther et al. Nucl.Phys. B690 (2004) 81-137 (single-top) T.Stelzer et al. Phys.Rev. D56 (1997) 5919, M.C.Smith and S.Willenbrock Phys.Rev. D54 (1996) 6696, T.M.Tait Phys.Rev. D61 (2000) 034001

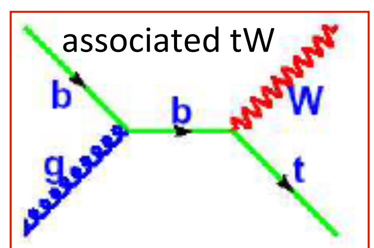
single-top



? 30 single-tops per minute @ LHC







σ_{top} & $\sigma_{anti\text{-}top}$ not equal

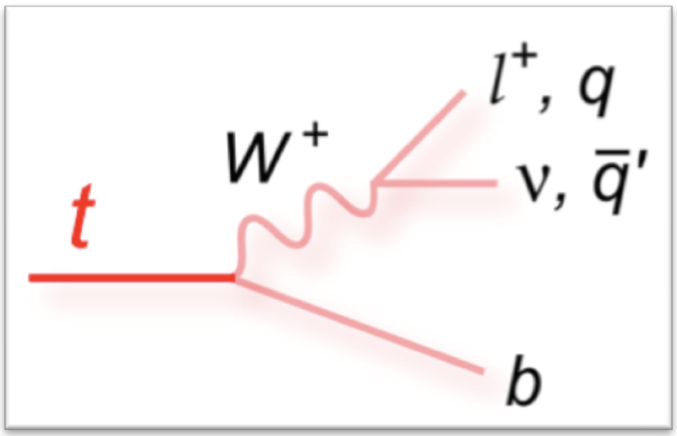
σ^{NLO}(total) 8 TeV = **112** pb

~1 M events/10fb^{-1}

s-channel	t-channel	associated tW	
σ^{NLO} = 3.4 pb	σ^{NLO} = 53 pb	σ^{NLO} = 11 pb	→ top production
σ^{NLO} = 2.1 pb	σ^{NLO} = 30 pb	σ^{NLO} = 11 pb	→ anti-top production

Top Quark decays

It decays almost excusively to Wb, from CKM elements V_{tu}, V_{ts}, V_{tb} :



$$\frac{BR(t \to Wb)}{BR(t \to Wq)} \approx 0.99825 \pm 0.00005$$

$$BR(t \to cZ, c\gamma, cg) \approx O(10^{-33})$$

W decays are used to classify top final states

Decay topologies for ttbar :

- Dileptonic
- Lepton+jets
- Fully hadronic

For single top measurements only W leptonic decays are used

ttbar topologies

Lepton + jets ≈ 34%

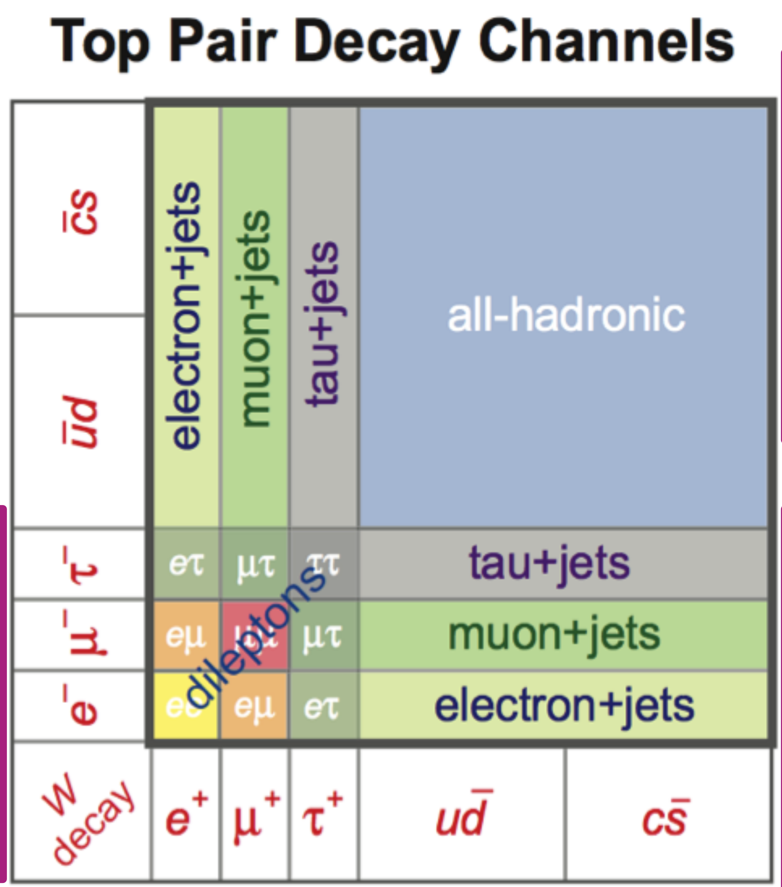
Low background

Main background:
W + jet

Dileptonic ≈ 6%

Very low background

main background:
Drell-Yan



Fully hadronic ≈ 46%

important background from QCD multijet events

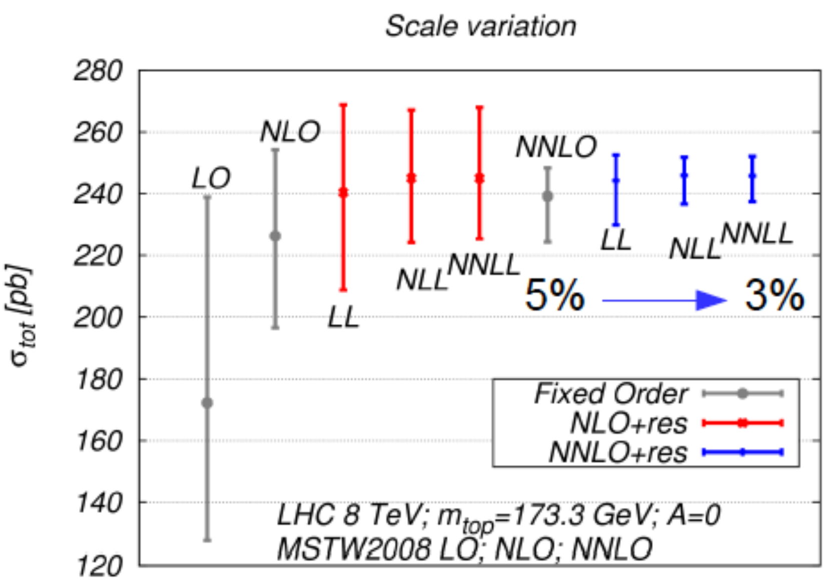
Tau channels ≈ 14%

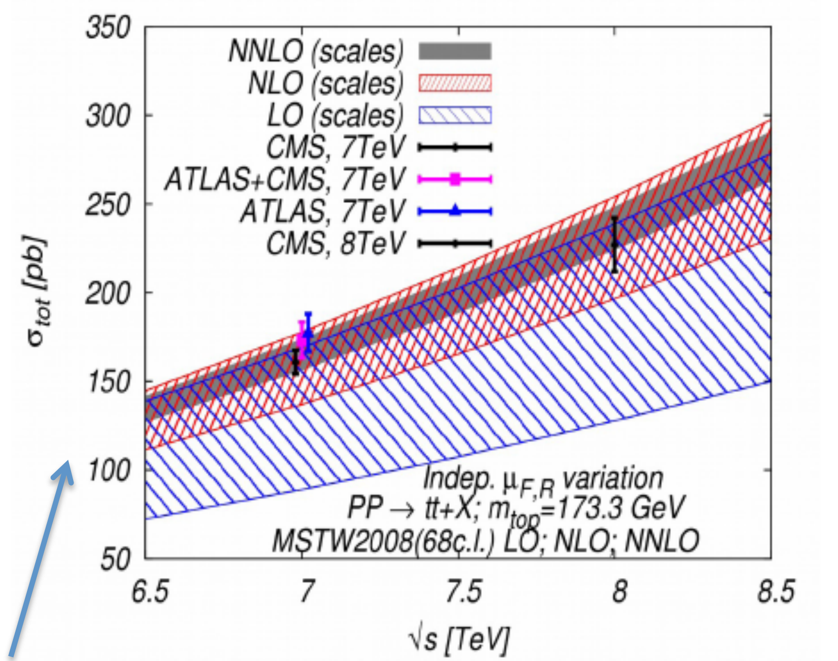
Important background from W + jet, QCD, other ttbar decays

THE INCLUSIVE CROSS SECTION

Inclusive cross section computed at NNLO (+NNLL)

[Czakon, Fiedler, Mitov; 2013]





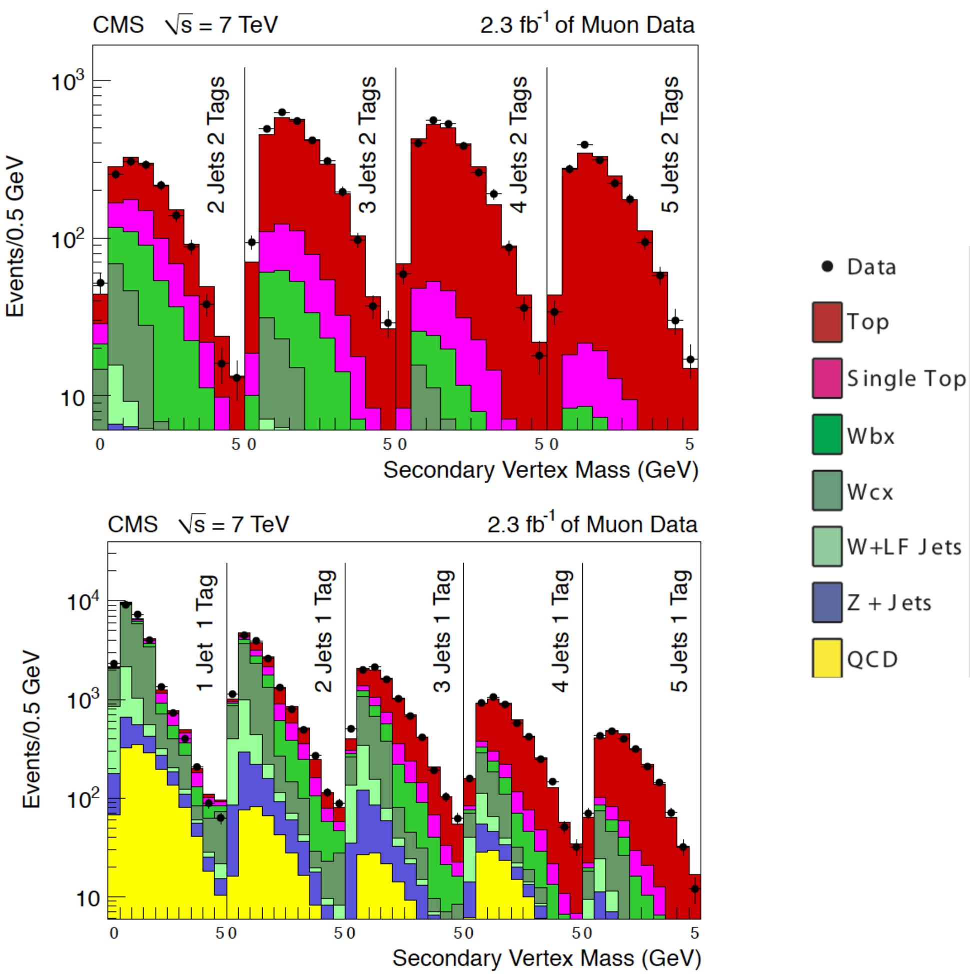
good perturbative convergence

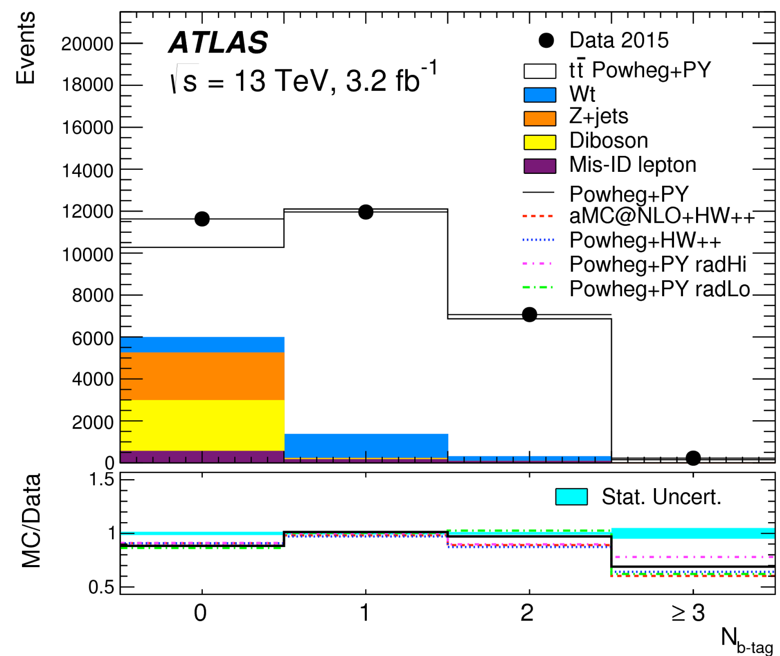
- Uncertainties
  - Scales: ~ 3 %
  - PDF (68% cl): ~ 2 – 3 %
  - Top – mass: ~ 3 %
  - Coupling: ~ 1.5 %

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$+0.110(1.5\%)$ $-0.200(2.8\%)$	$+0.169(2.4\%)$ $-0.122(1.7\%)$
LHC 7 TeV	172.0	$+4.4(2.6\%)$ $-5.8(3.4\%)$	$+4.7(2.7\%)$ $-4.8(2.8\%)$
LHC 8 TeV	245.8	$+6.2(2.5\%)$ $-8.4(3.4\%)$	$+6.2(2.5\%)$ $-6.4(2.6\%)$
LHC 14 TeV	953.6	$+22.7(2.4\%)$ $-33.9(3.6\%)$	$+16.2(1.7\%)$ $-17.8(1.9\%)$

Leptons+jets and dileptons (e, μ)

- Excellent background control thanks to jet categorization, b tagging and in situ measurement of jet-energy scale



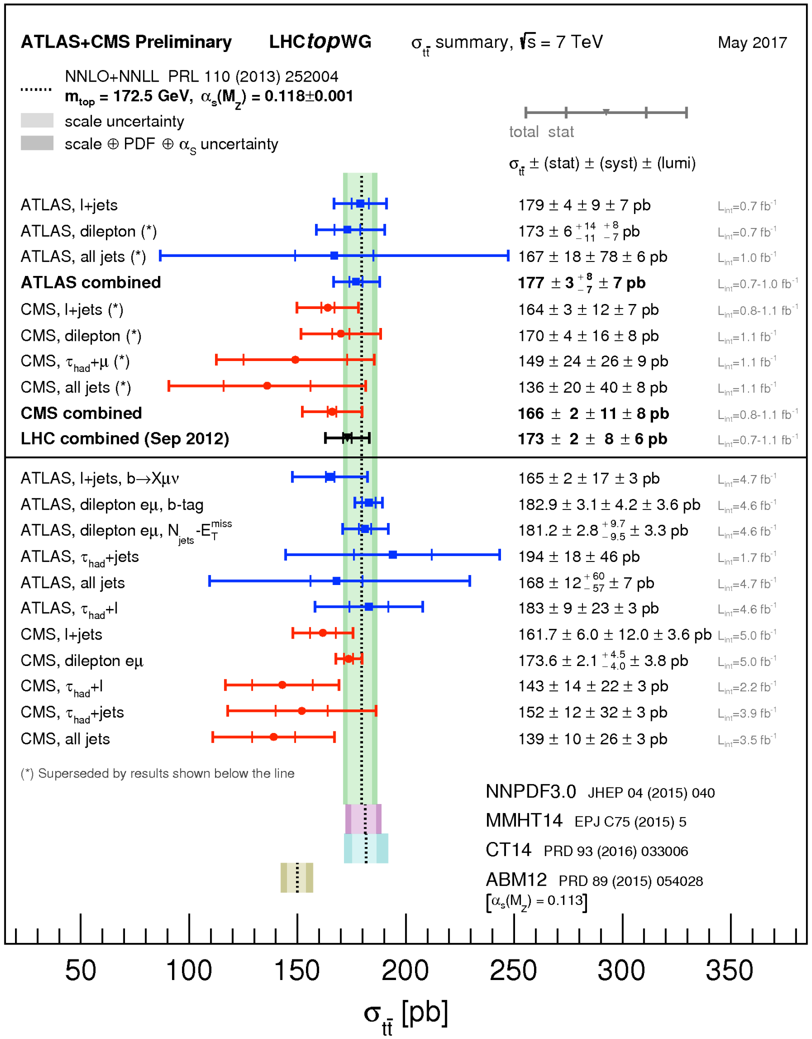


[Phys. Lett. B761 (2016) 136]

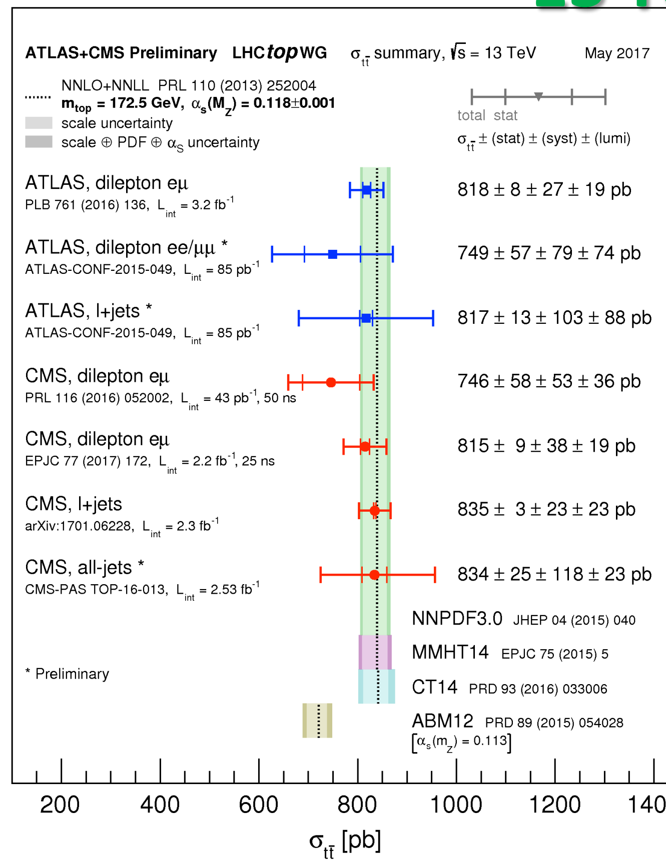
[Phys. Lett. B 720 (2013) 83-104]

Inclusive top pair cross-sections

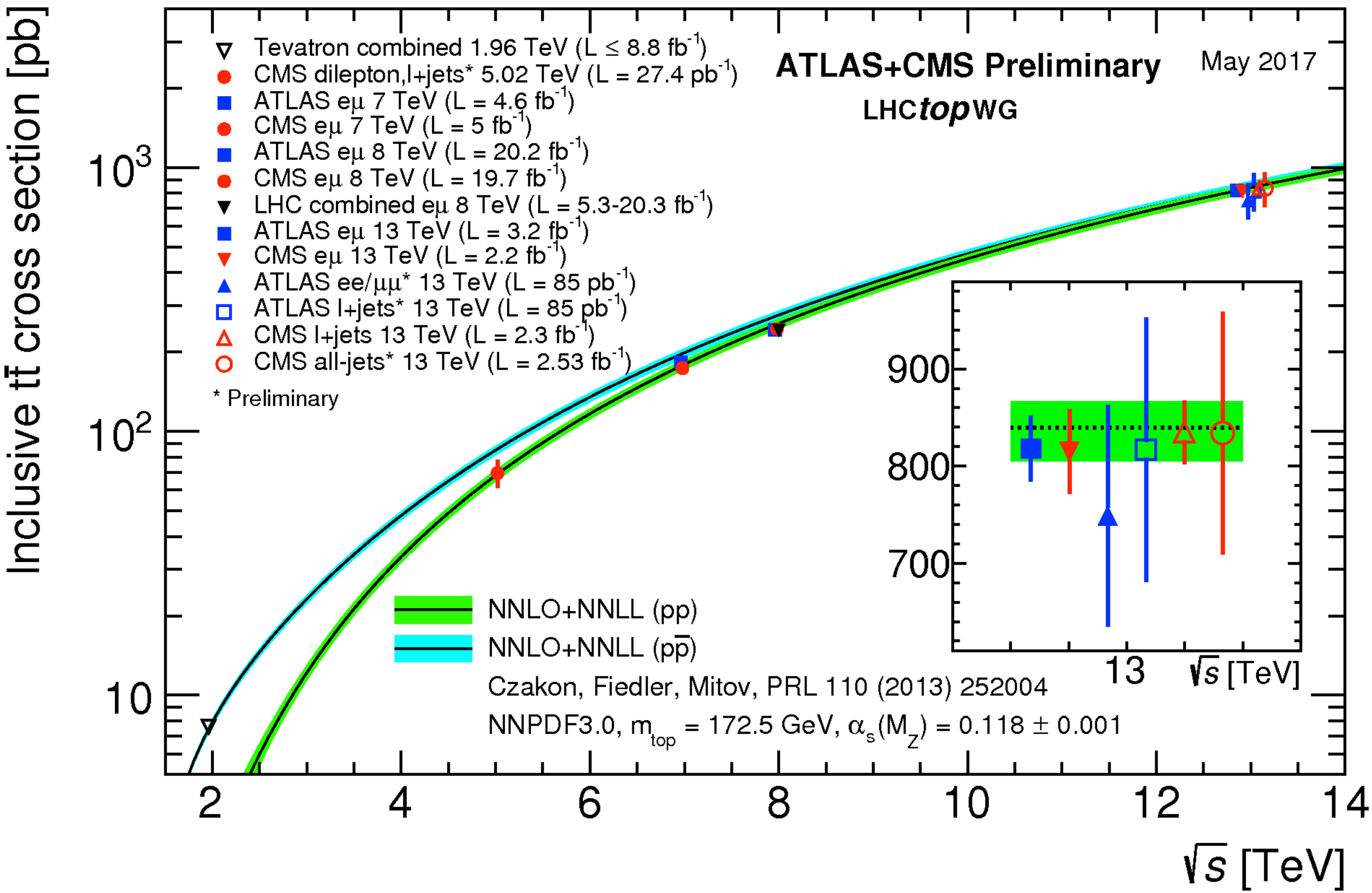
7 TeV



13 TeV

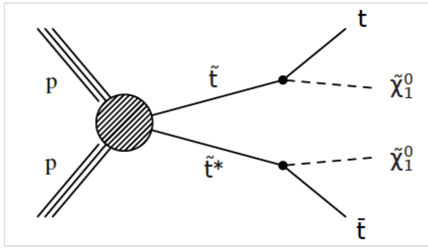


- All channels covered and consistent with SM
- Good agreement with NNLO+NNLL
- Precision of ~4% (di-lepton channel), similar to theoretical prediction


ATLAS+CMS Preliminary
LHCtopWG
May 2017
Tevatron combined 1.96 TeV (L ≤ 8.8 fb-1)
CMS dilepton,l+jets* 5.02 TeV (L = 27.4 pb-1)
ATLAS eμ 7 TeV (L = 4.6 fb-1)
CMS eμ 7 TeV (L = 5 fb-1)
ATLAS eμ 8 TeV (L = 20.2 fb-1)
CMS eμ 8 TeV (L = 19.7 fb-1)
LHC combined eμ 8 TeV (L = 5.3-20.3 fb-1)
ATLAS eμ 13 TeV (L = 3.2 fb-1)
CMS eμ 13 TeV (L = 2.2 fb-1)
ATLAS ee/μμ* 13 TeV (L = 85 pb-1)
ATLAS l+jets* 13 TeV (L = 85 pb-1)
CMS l+jets 13 TeV (L = 2.3 fb-1)
CMS all-jets* 13 TeV (L = 2.53 fb-1)
* Preliminary
NNLO+NNLL (pp)
NNLO+NNLL (pp̄)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
NNPDF3.0, m_top = 172.5 GeV, α_s(M_Z) = 0.118 ± 0.001
Inclusive tt̄ cross section [pb]
√s [TeV]
10
10^2
10^3
2
4
6
8
10
12
14
900
800
700
13
√s [TeV]

Top Squark Pair Production

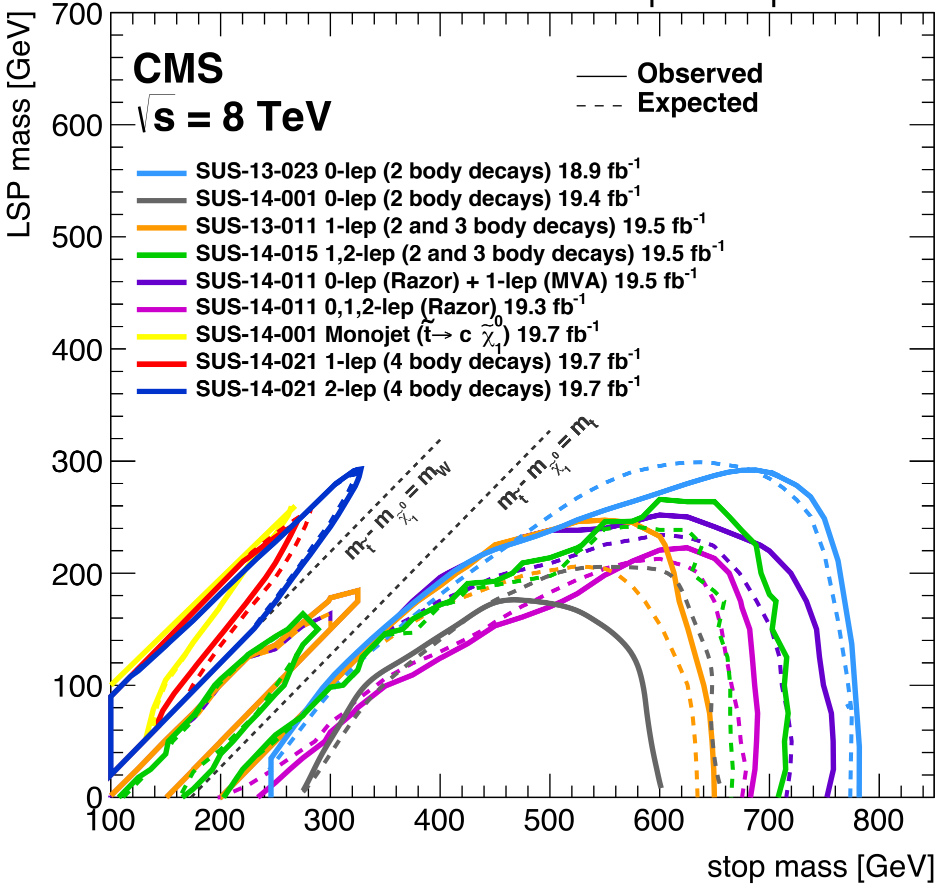
arXiv:1603.02303



$m(\tilde{t}) \approx m(\tilde{\chi}_1^0) + m_t \rightarrow \sigma_{t\bar{t}}$ (and ttbar spin correlations)

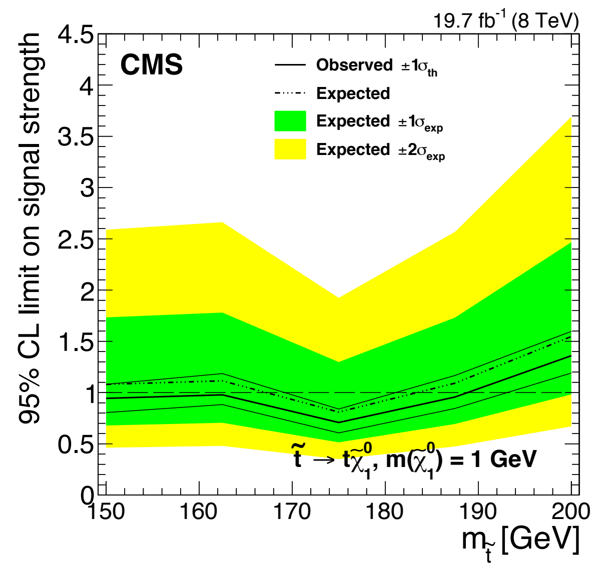
more sensitive than standard SUSY searches for low $m(\tilde{\chi}_1^0)$ and $m(\tilde{t}) \approx m_t$

$\tilde{t}$-$\tilde{t}$ production, $\tilde{t} \rightarrow t\,\tilde{\chi}_1^0 / c\,\tilde{\chi}_1^0$



Simplified model with two parameters:

$$m(\tilde{t}), m(\tilde{\chi}_1^0)$$

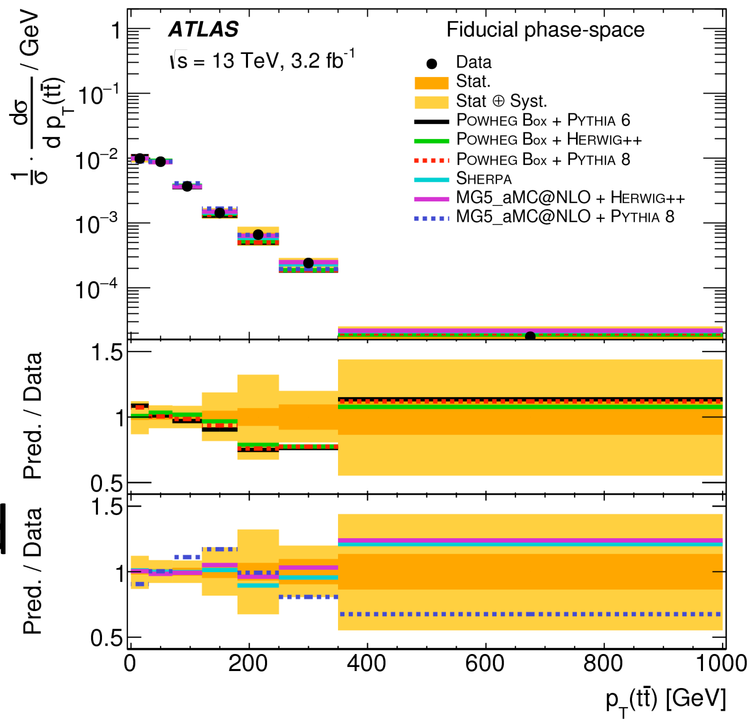


$$m(\tilde{t};\tilde{\chi}_1^0 = 1\ GeV) > 189\ GeV$$

$$m(\tilde{t};\tilde{\chi}_1^0) \notin 185-189\ GeV$$

Differential cross sections

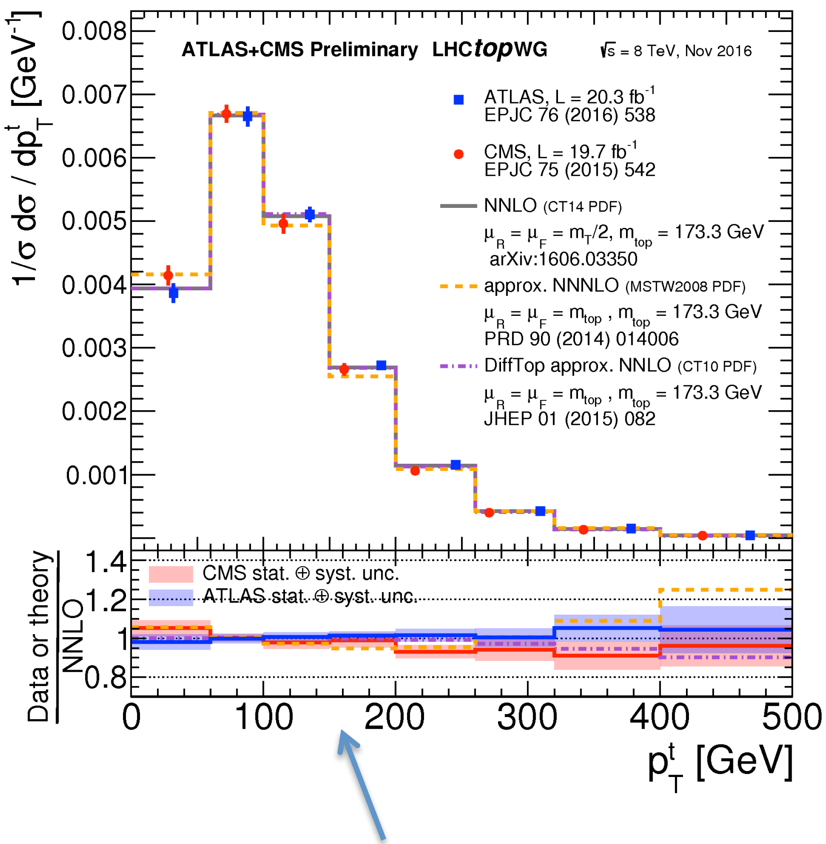
- Important measurements, they play an important role
  - investigate limitations of present MC (which QCD predictions and models describe our data best, in the search areas like high m(tt) and high multiplicities)
  - will provide independent interpretations (e.g. mass AND alpha_s from cross section)

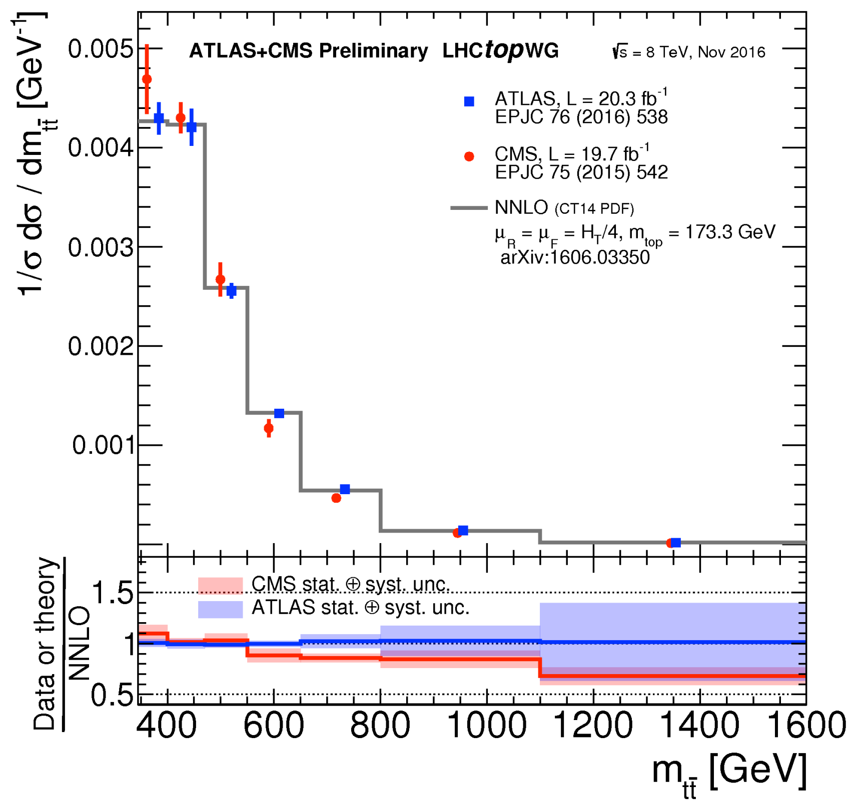


Eur. Phys. J. C77 (2017) 299

Differential cross sections

Comparisons of ATLAS and CMS results with common particle-level cross section definition to NNLO calculations

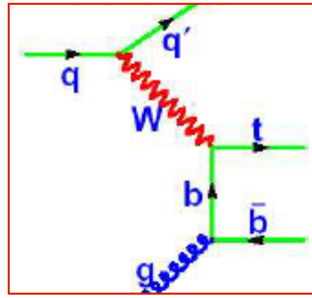


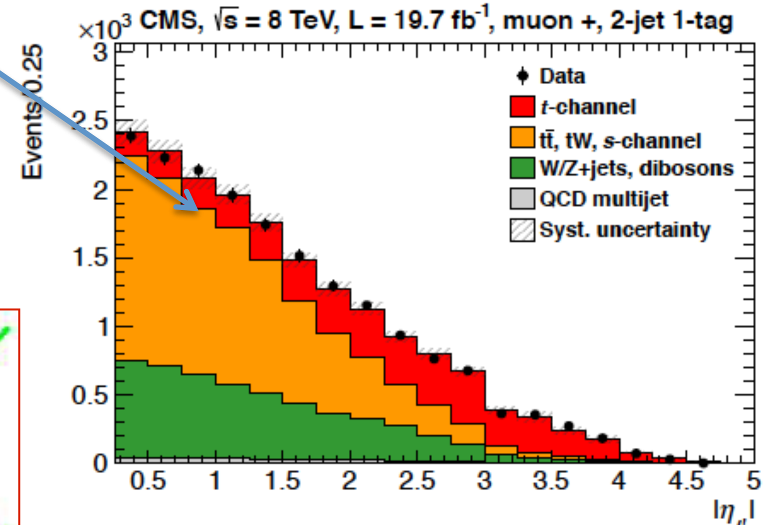


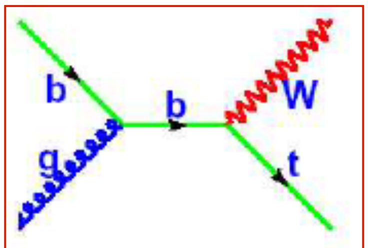
Long standing “tension” between data and MC for top pt essentially disappears at NNLO

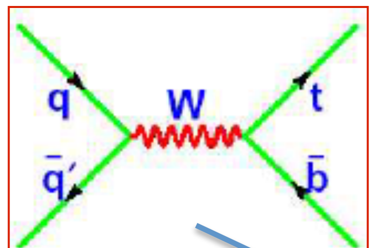
Single top production

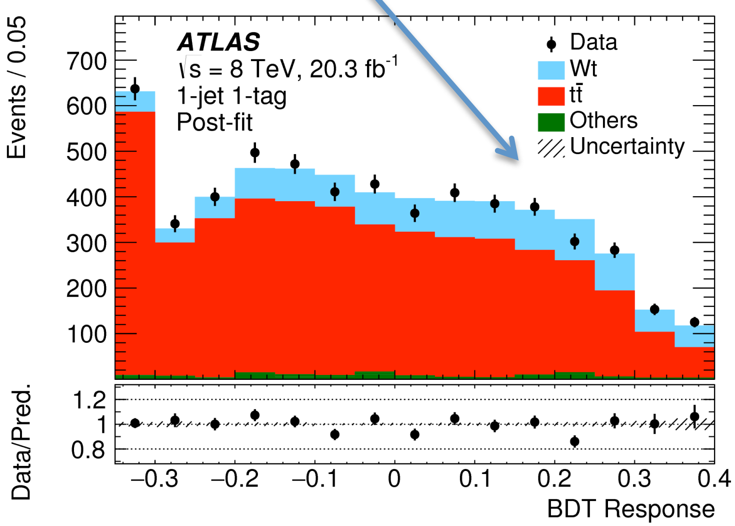
From t-channel to Wt and s-channels: different features and very different S/B

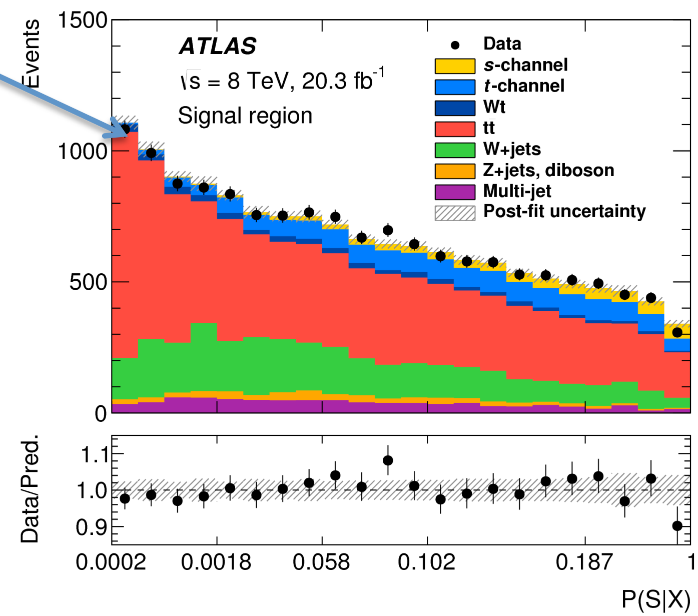


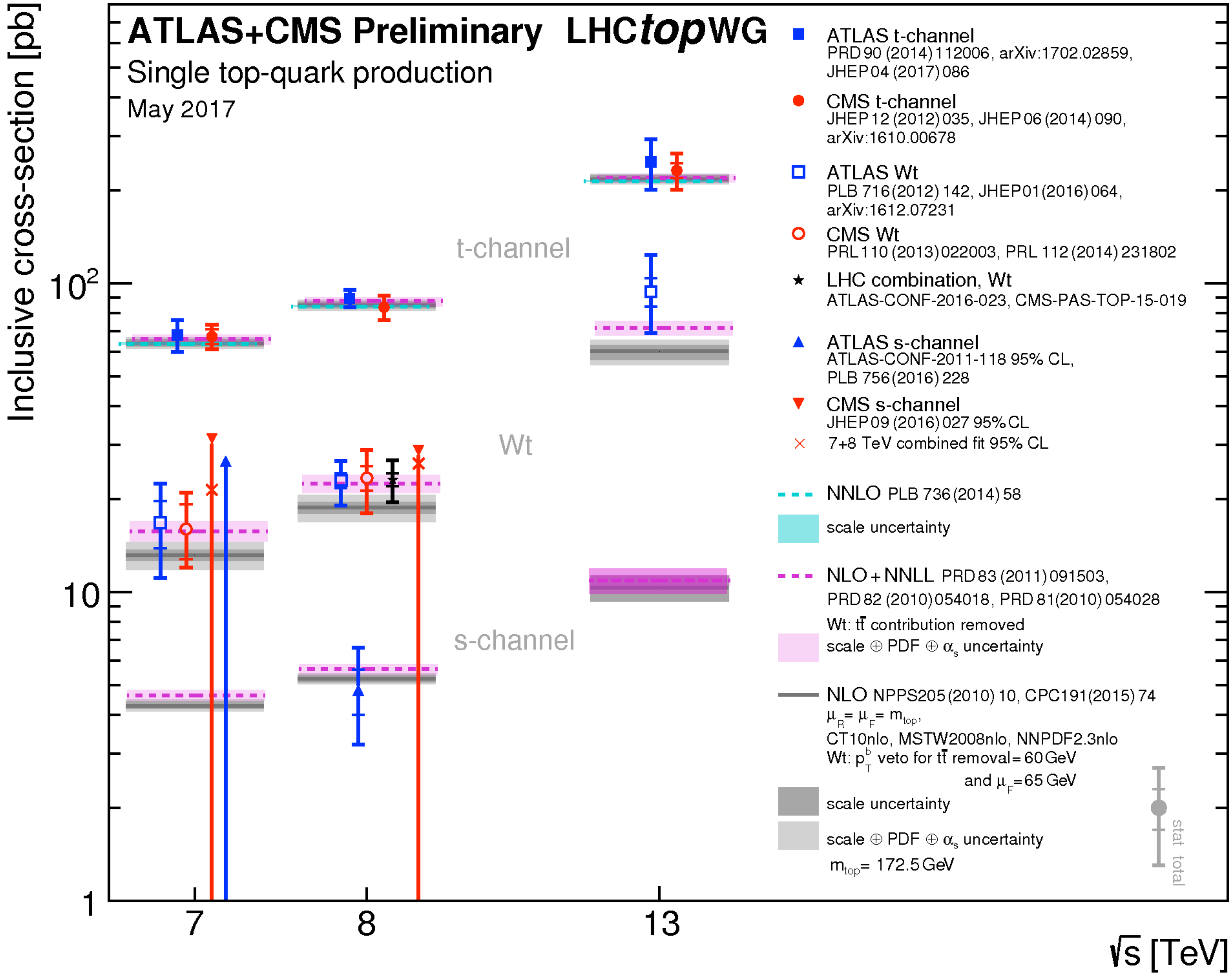






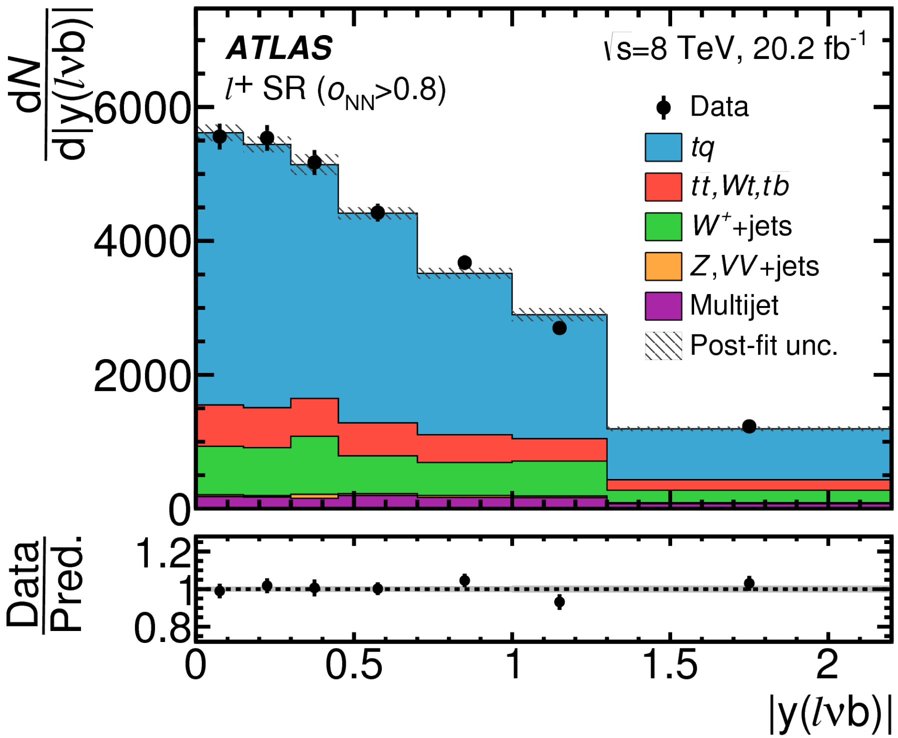




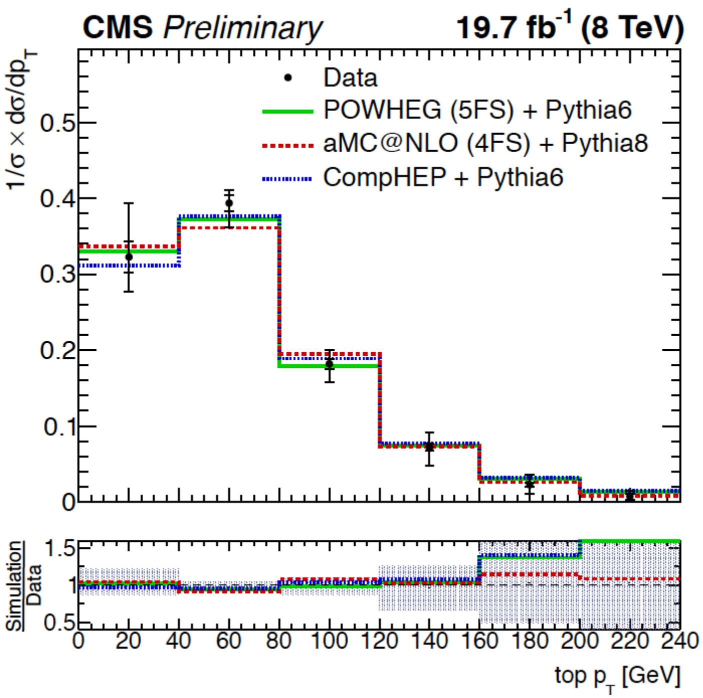

ATLAS+CMS Preliminary LHCtopWG
Single top-quark production
May 2017
Inclusive cross-section [pb]
t-channel
Wt
s-channel
ATLAS t-channel
PRD 90 (2014) 112006, arXiv:1702.02859, JHEP 04 (2017) 086
CMS t-channel
JHEP 12 (2012) 035, JHEP 06 (2014) 090, arXiv:1610.00678
ATLAS Wt
PLB 716 (2012) 142, JHEP 01 (2016) 064, arXiv:1612.07231
CMS Wt
PRL 110 (2013) 022003, PRL 112 (2014) 231802
LHC combination, Wt
ATLAS-CONF-2016-023, CMS-PAS-TOP-15-019
ATLAS s-channel
ATLAS-CONF-2011-118 95% CL, PLB 756 (2016) 228
CMS s-channel
JHEP 09 (2016) 027 95% CL
7+8 TeV combined fit 95% CL
NNLO PLB 736 (2014) 58
scale uncertainty
NLO + NNLL PRD 83 (2011) 091503, PRD 82 (2010) 054018, PRD 81 (2010) 054028
Wt: $t\bar{t}$ contribution removed
scale ⊕ PDF ⊕ α_s uncertainty
NLO NPPS205 (2010) 10, CPC191 (2015) 74
$\mu_R = \mu_F = m_{top}$,
CT10nlo, MSTW2008nlo, NNPDF2.3nlo
Wt: p_T^b veto for $t\bar{t}$ removal = 60 GeV
and μ_F = 65 GeV
scale uncertainty
scale ⊕ PDF ⊕ α_s uncertainty
m_{top} = 172.5 GeV
stat
total
10^2
10
1
7
8
13
$\sqrt{s}$ [TeV]

Differential cross sections now available also for single top !

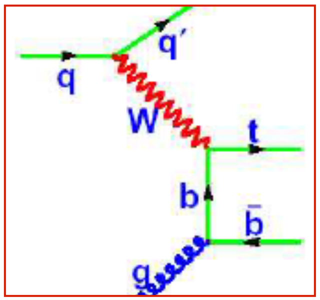
arXiv:1702.02859

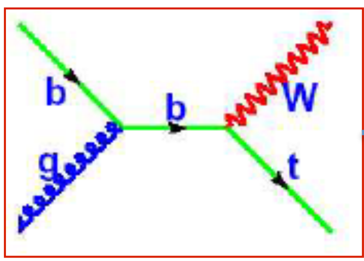


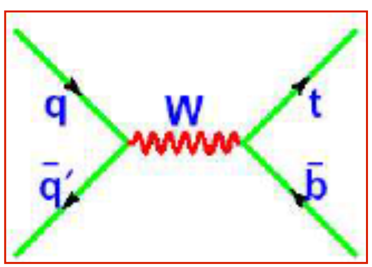
CMS-PAS-TOP-14-004



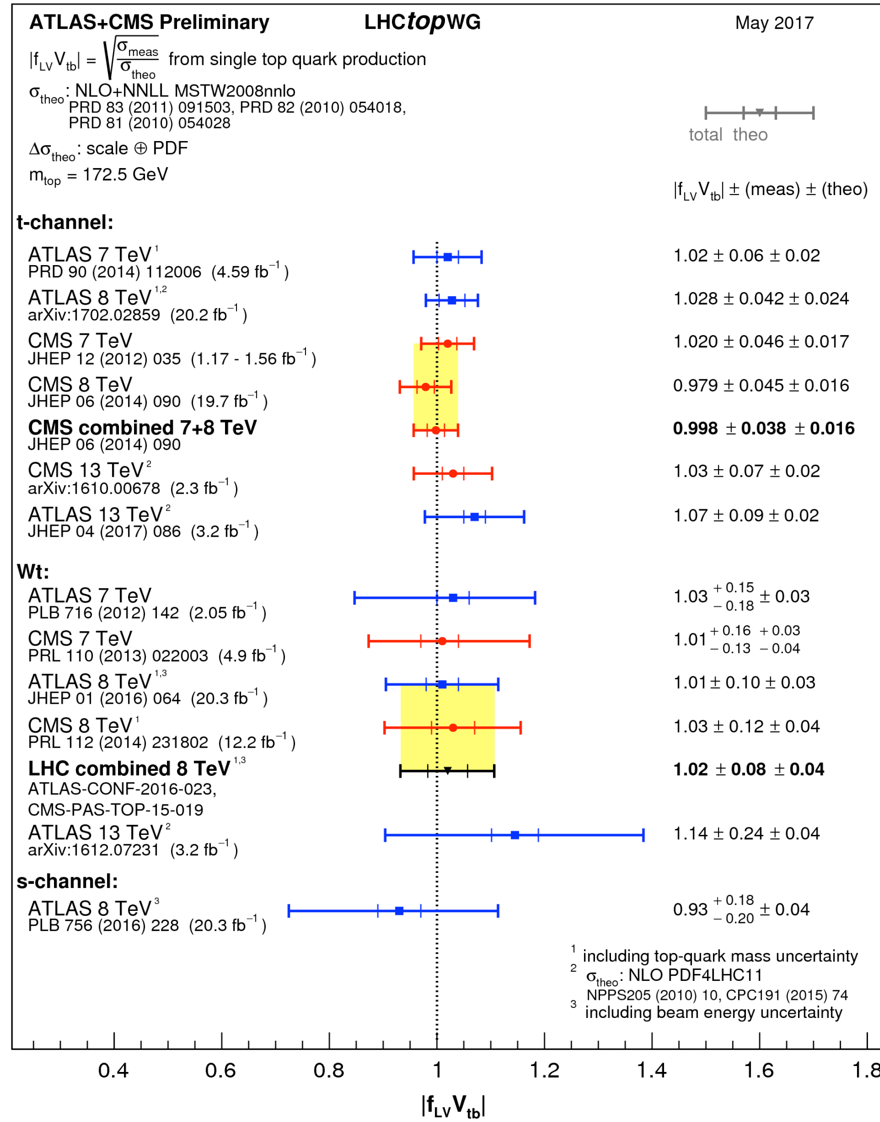
Single top and $|V_{tb}|$



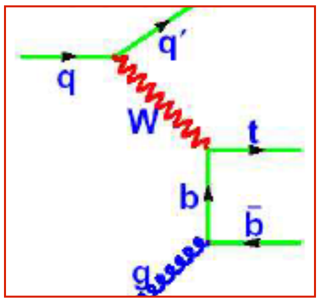


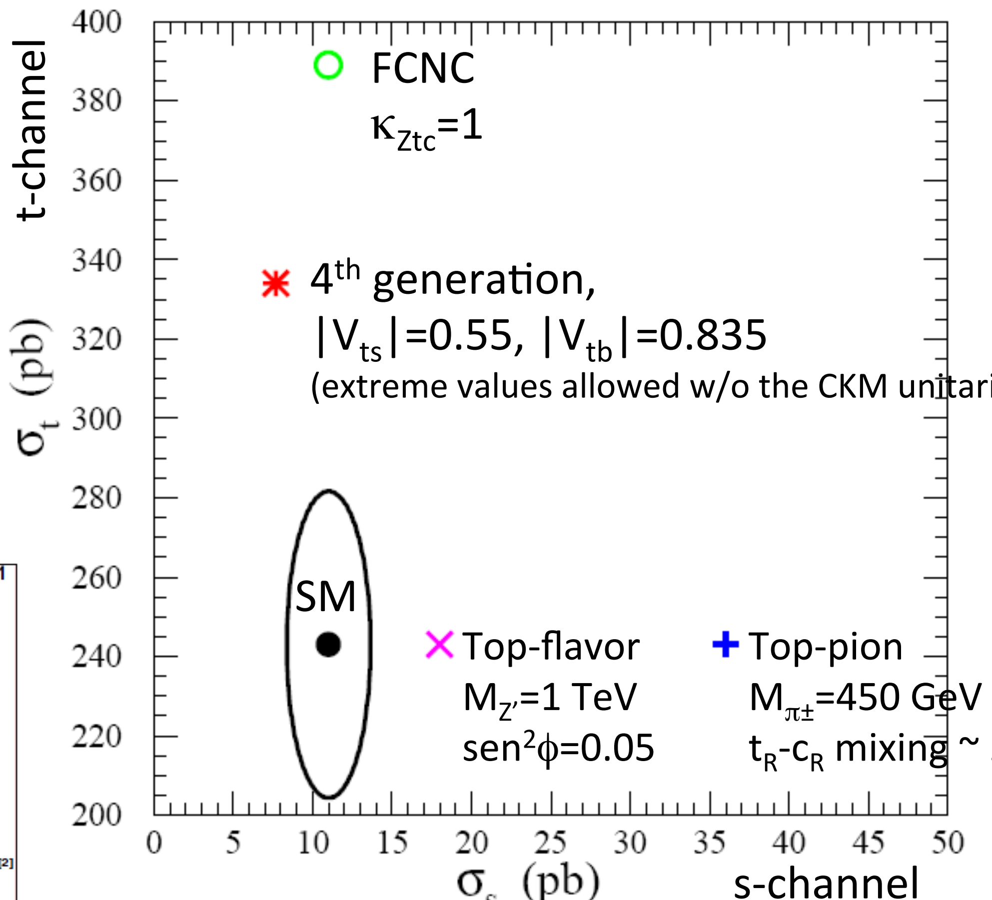


$$\sigma \propto |V_{tb}|^2$$

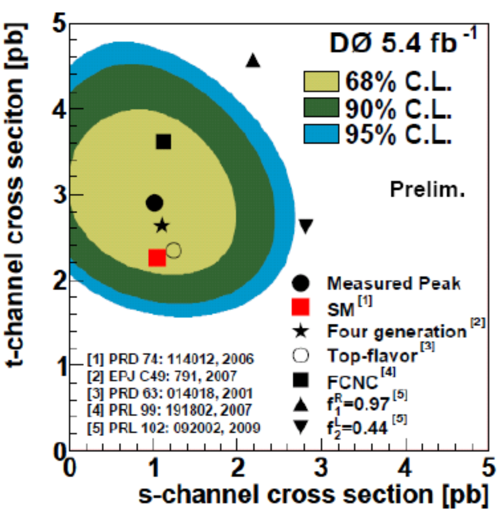


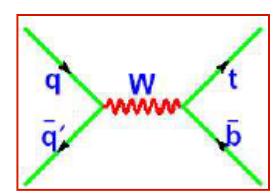
Single top in t and s channel sensitive to different aspects of New Physics (tW, too !)





(plot for 14 TeV)





T.Tait, C.-P.Yuan, Phys.Rev. D63 (2001) 0140018

EXPERIMENTAL METHODS FOR TOP MASS MEASUREMENTS:

- DETAILED EXAMPLE IN THE LEPTON+JETS – OTHER CHANNELS

- WHAT ARE WE MEASURING ?

- ALTERNATIVE METHODS

- DIFFERENTIAL TOP MASS

Methods for top mass measurement (1)

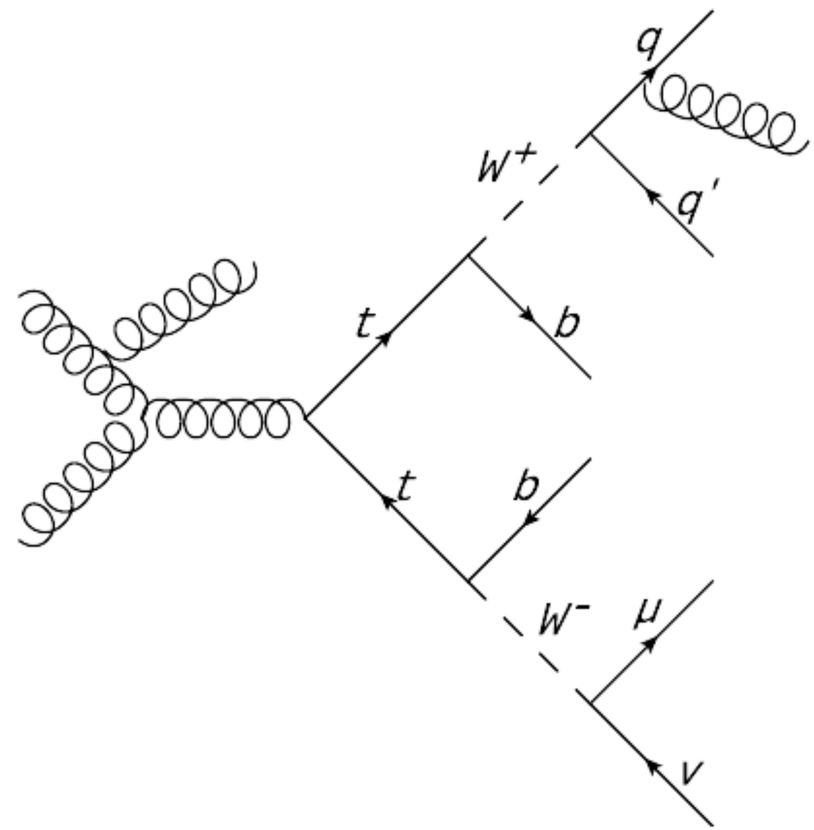
- *Standard methods* at hadron colliders: measure the top mass from the decay products in a specific **top pair decay channel**
  - from the simplest versions: measure invariant mass of, e.g. three jets in lepton+jets events
  - to the more sophisticated versions: use of the full event information to gain sensitivity, e.g. Matrix Element method
- The *standard methods* are the most precise with the current statistics
  - they are used in current LHC, Tevatron, World combinations
  - the top mass in EWK fits comes from these methods
- Crucial points for the *standard methods*
  - accurate calibration of physics objects, in particular Jet Energy Scale: use of kinematic fits for JES calibration in situ, e.g. use the W mass to constraint light quarks **jet energy scale (JES)** from two-jet invariant mass
  - associate measured objects (jets, leptons, missing E_T) to top candidate: e.g. use b-tagging to choose the right b-jet for the 3-jet combination

An example from the lepton+jets channel

Event selection: lepton+jets final state

[example from CMS, TOP-14-001 / arXiv:1509.04044]

- Trigger for isolated muon [or electron] + jets (pT > 24 GeV [27 GeV])
- Exactly 1 isolated lepton with p_T >33 GeV, $|\eta|<2.1$ (veto additional isolated e, μ)
- ≥ 4 "particle flow" jets (anti-kt , R = 0.5) with $p_T > 30$GeV, $|\eta|<2.4$
- 2 jets b-tagged among the 4 leading jets
- Composition:
  - 93% $t\bar{t}$, 4% W+jets, 2% single-top, 1% other
- 105000 events in 19.7 fb^{-1} at 8 TeV selected

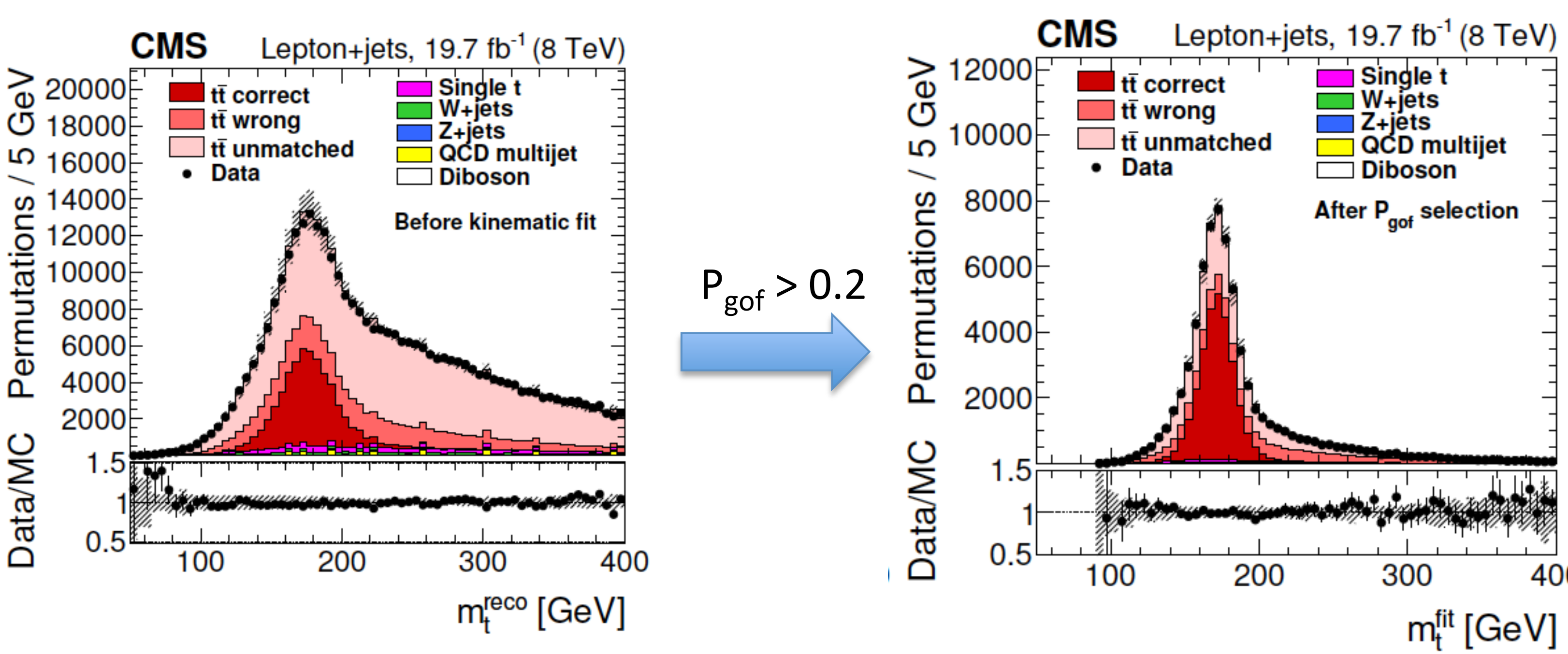


Compare with selections at Tevatron with full statistics: about 2500 events

Event reconstruction

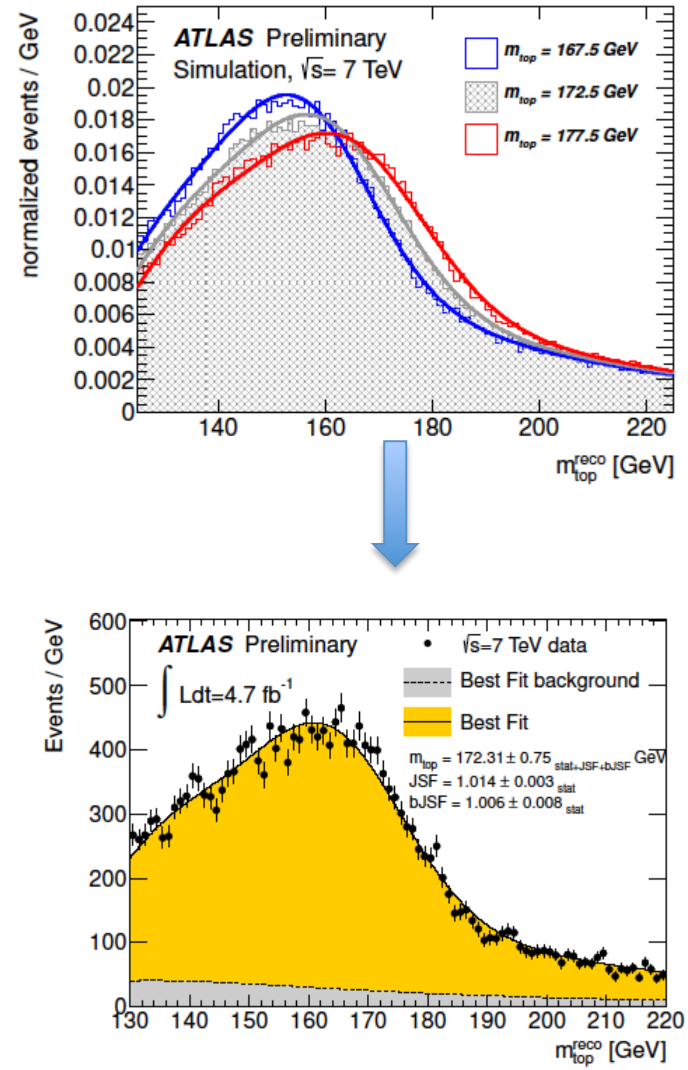
[example from CMS, TOP-14-001 / arXiv:1509.04044]

- Assign 4 leading jets to partons from $t\bar{t}$ decay (obey b-tag)
  - Kinematic fit with constraints: m_W = 80.4 GeV, $m_t = m_{tbar}$
  - Weight each permutation by $P_{gof} = \exp-(1/2\chi^2)$, select $P_{gof} > 0.2$
- 28295 events in 19.7 fb^{-1} 2012 data (94% $t\bar{t}$, 44% correct perm.)



Top mass fitting techniques
[example from ATLAS, CONF-2013-046]

- Invariant mass distributions are distorted by
  - phase space constraints
  - detector resolution
  - wrong particle assignments to jets
  - backgrounds, pileup
  - selection cuts
- Need a MC simulation, tuned to data, to construct templates or probability densities
  - **important: at this stage the top mass definition in MC is not too relevant.**



Construct probability densities: ideogram method

[example from CMS, TOP-14-001 / arXiv:1509.04044]

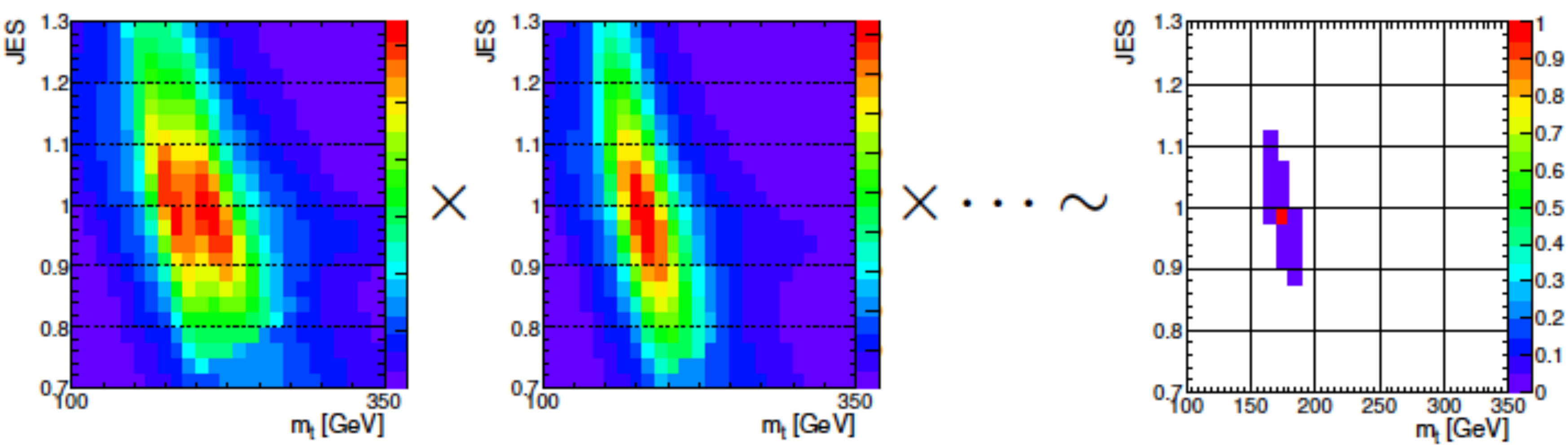
- Calculate likelihood for event with n permutations, j denotes *correct*, *wrong* and *unmatched* permutations

$$\mathcal{L}\left(\text{event}|m_t,\text{JES}\right) = \sum_{i=0}^{n} P_{gof}\left(i\right) P\left(m_{t,i}^{fit}, m_{W,i}^{reco}|m_t,\text{JES}\right),$$

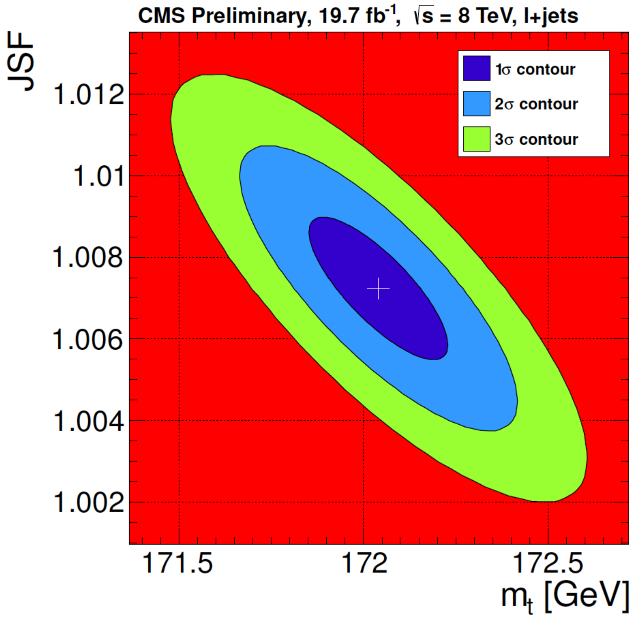
$$P\left(m_{t,i}^{fit}, m_{W,i}^{reco}|m_t,\text{JES}\right) = \sum_{j} f_j P_j\left(m_{t,i}^{fit}|m_t,\text{JES}\right) \cdot P_j\left(m_{W,i}^{reco}|m_t,\text{JES}\right)$$

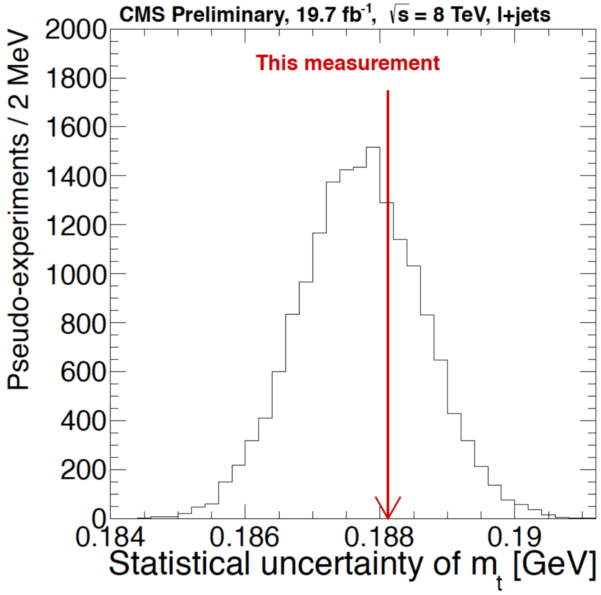
- Most likely m_t and JES by maximizing

$$\mathcal{L}\left(m_t,\text{JES}|\text{sample}\right) \sim \prod_{\text{events}} \mathcal{L}\left(\text{event}|m_t,\text{JES}\right)^{w_{\text{event}}}$$



Result for lepton+jet channel [TOP-14-001]





$$
\begin{aligned}
m_{\mathrm{t}} &= 172.04 \pm 0.19\,(\mathrm{stat.{+}JSF}) \pm 0.75\,(\mathrm{syst.})\,\mathrm{GeV}, \\
\mathrm{JSF} &= 1.007 \pm 0.002\,(\mathrm{stat.}) \pm 0.012\,(\mathrm{syst.}).
\end{aligned}
$$

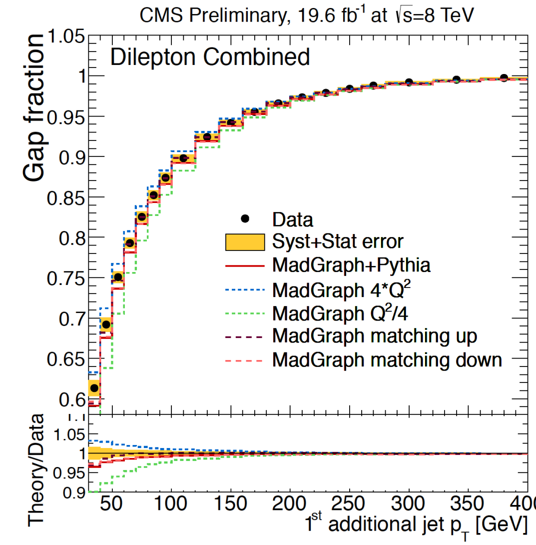
(Note: this was the preliminary result, kept for illustration, for the final measurement see arXiv:1509.04044)

Main sources of systematic uncertainties

[for l+jet measurements]

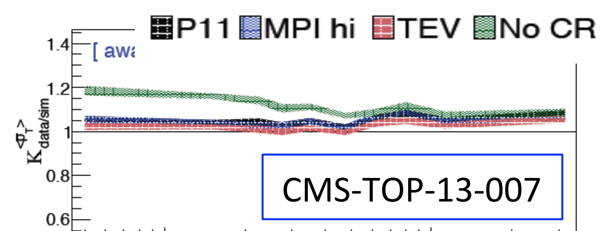
- Jet Energy Scale (depends on technique and jet reco, in situ statistical not included)
  - light jets, detector response [0.2-0.7 GeV]
  - b jets [0.1-0.6 GeV]
- Modeling of gluon radiation [0.3 – 0.45 GeV]
- Modeling of underlying event [0.1 – 0.2 GeV]
- Modeling of Colour Reconnection [0.2 – 0.5 GeV]
- Proton PDF [0.1 – 0.2 GeV]
- Hadronization, b-fragmentation (included also in JES) [0.3 -0.6 GeV]
- b-tagging [0.1 – 0.8 GeV]
- pileup modeling (included also in JES) (0.1-0.3 GeV)

[The numbers are ranges for illustration only, more details in specific analysis and LHC combination notes]



can use data to constrain radiation

CMS-TOP-12-018



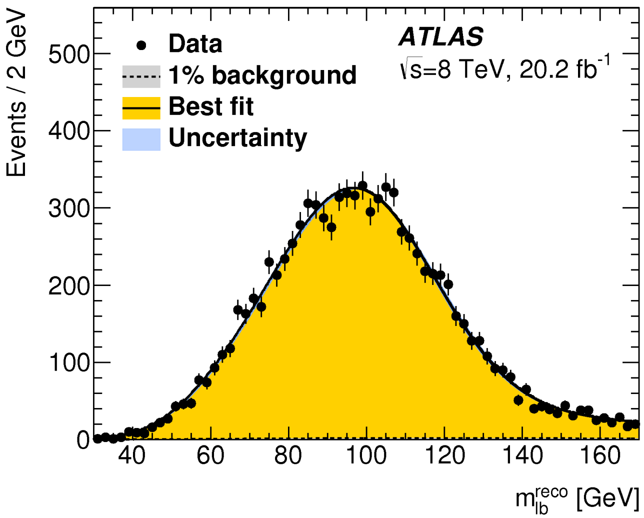
CMS-TOP-13-007

can use data to constrain generator modeling

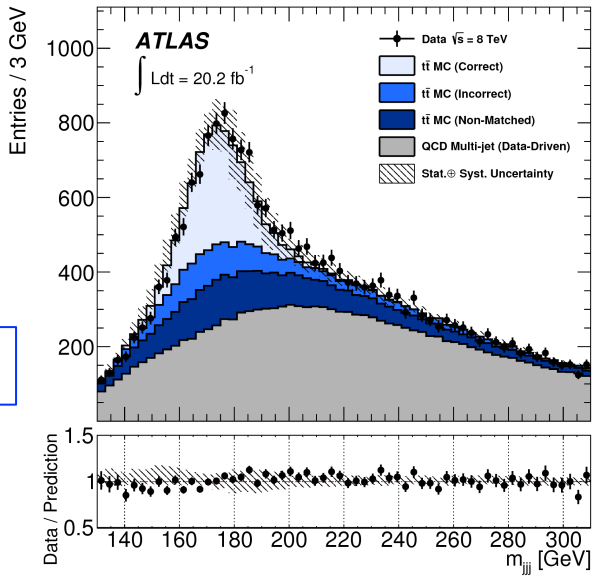
Dilepton and all-hadronic channels

Phys. Lett. B761 (2016) 350

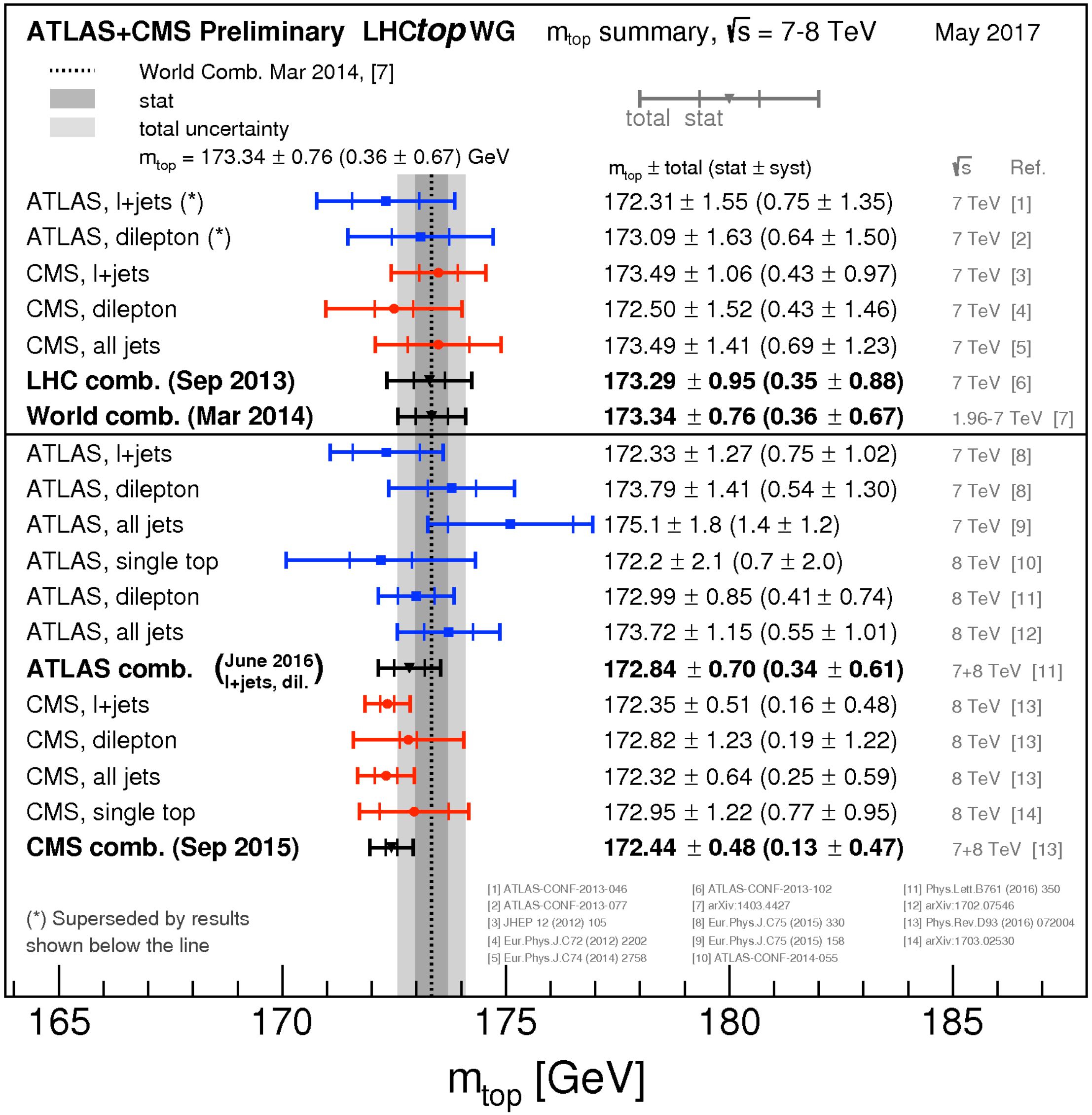
- The dilepton and all-hadronic decay channels provide and important cross check, given the difference in colour structure of the final state. The dilepton channel is kinematically underconstrained (2 ν's), but with low background
- The all-hadronic channel can profit of an accurate in-situ fit of the JES



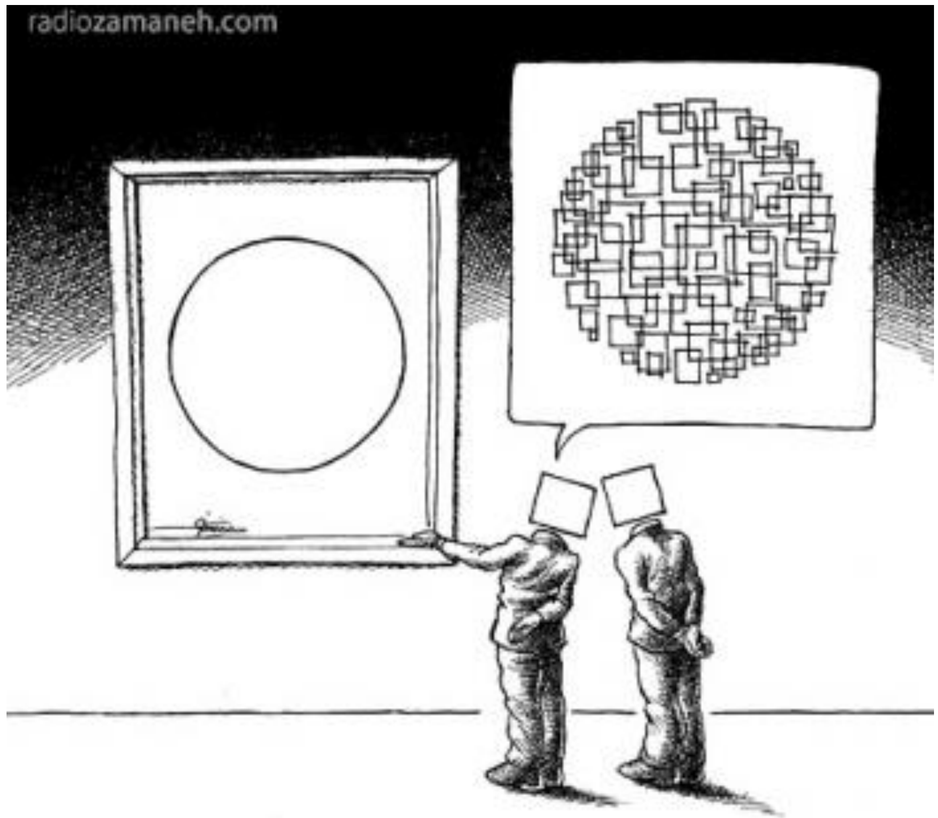
arXiv:1702.07546



Grand LHC table



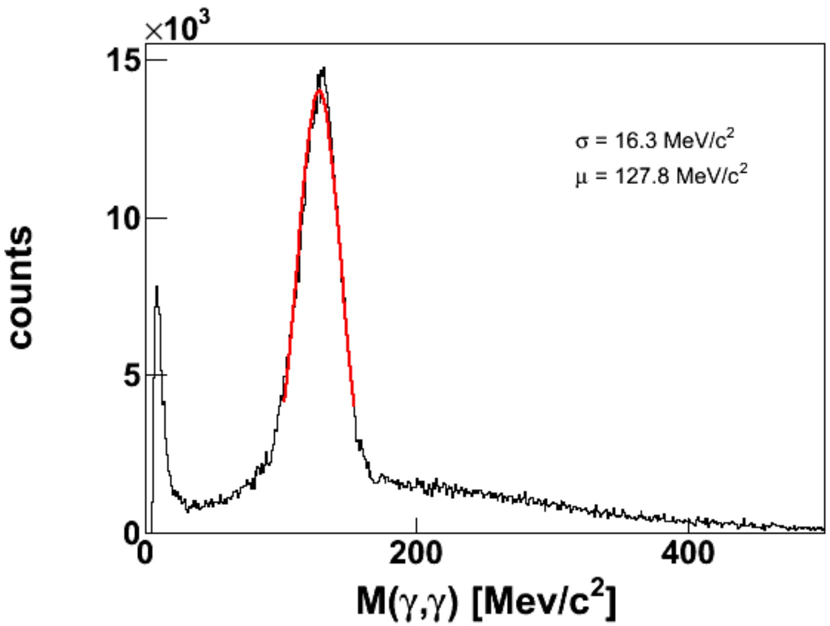
INTERPRETATION OF TOP MASS MEASUREMENTS



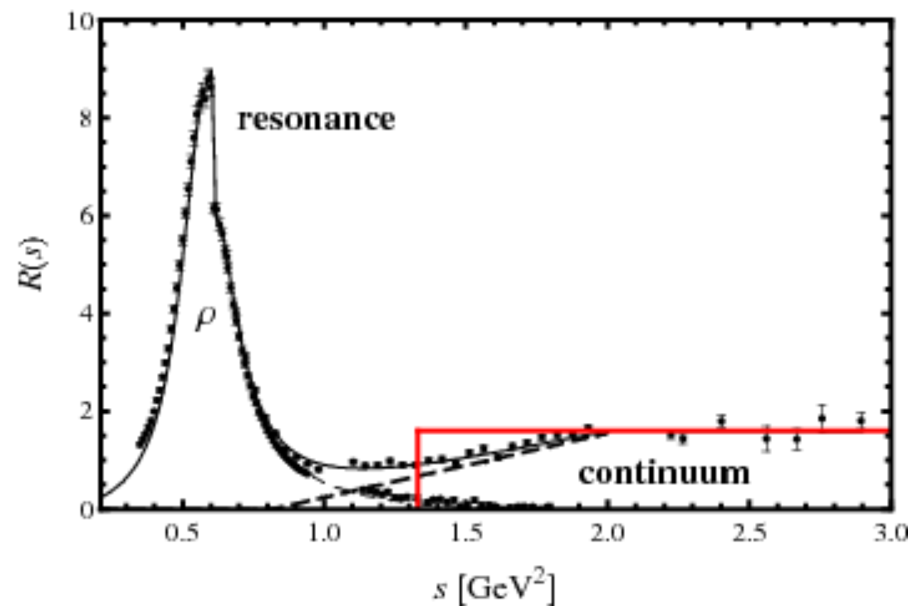
MEASURING A MASS FROM DECAYS PRODUCTS

TWO extreme cases

π^0 mass from 2 photons



ρ^0 mass from 2 pions



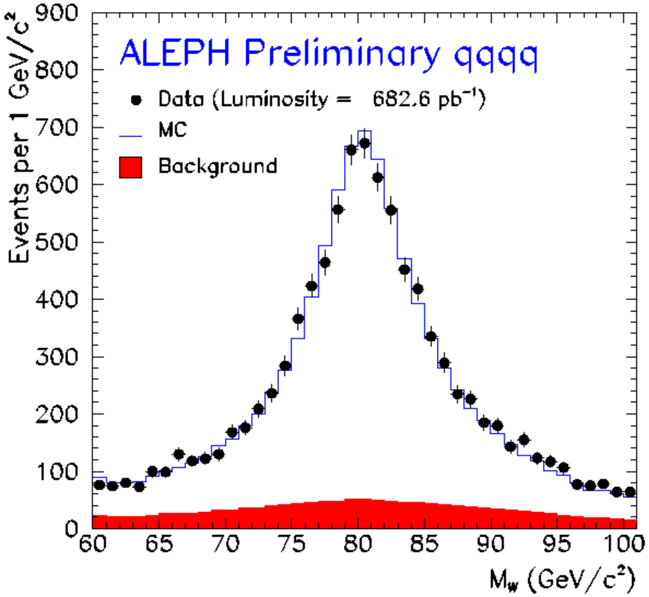
case 1. Experimental resolution much lower than natural width: the experiment provides a mass measurement

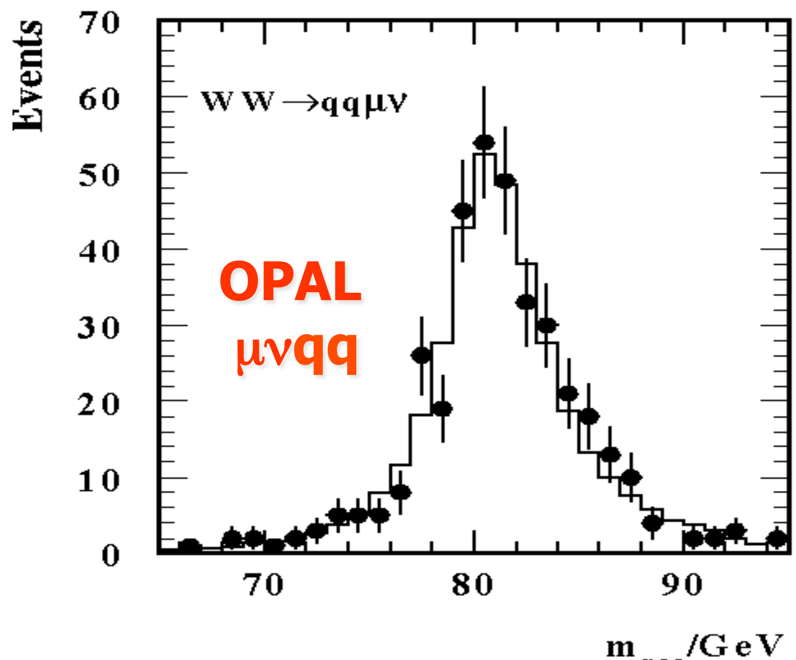
case 2. Experimental resolution much higher than natural width: the experiment provides data points to fit a resonance.

MEASURING A MASS FROM DECAYS PRODUCTS

Example of an intermediate case

The W mass measured from the decay products: a Monte Carlo simulation, tuned at the Z, is used to extract the mass. The mass scheme used in the MC is relevant to interpret the measurement (e.g. Breit Wigner with fixed-width scheme (W) vs a running-width scheme (Z), difference of 27 MeV, sizeable given the precision)





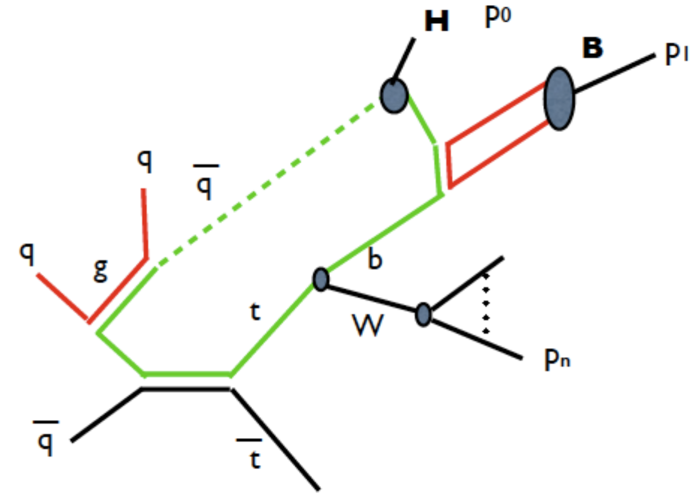
Issues in top mass interpretation

- There are three different issues related to the interpretation of current (and future !) measurements
  - **top pole mass**: higher order corrections to self energy (recent progress on this)
  - **mass scheme used in simulation vs fixed order calculations** (work ongoing, no reason to believe it cannot be solved)
  - **color reconnection** (the hard one, where experiments should concentrate)

The real issue: top decay products have to (re)connect !

- **Top is a coloured fermion**, it decays before hadronizing, but the b quark from its decay must hadronize
  - **there is no way to assign final state particles only to the original top**, the concept is ill-defined
  - the effect is expected to be of the order of $\Lambda_{QCD} \approx 0.2$ GeV but the actual impact depends on the experimental method

1. **important to test variables sensitive to the final state definition**
2. **important to measure the mass with alternative techniques**

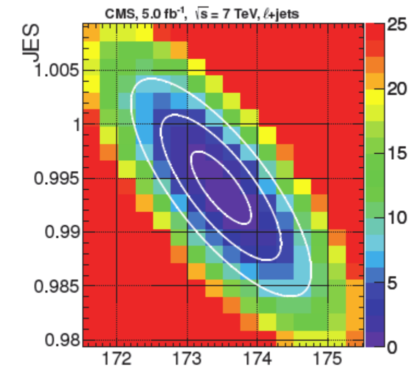


plot courtesy of Michelangelo Mangano

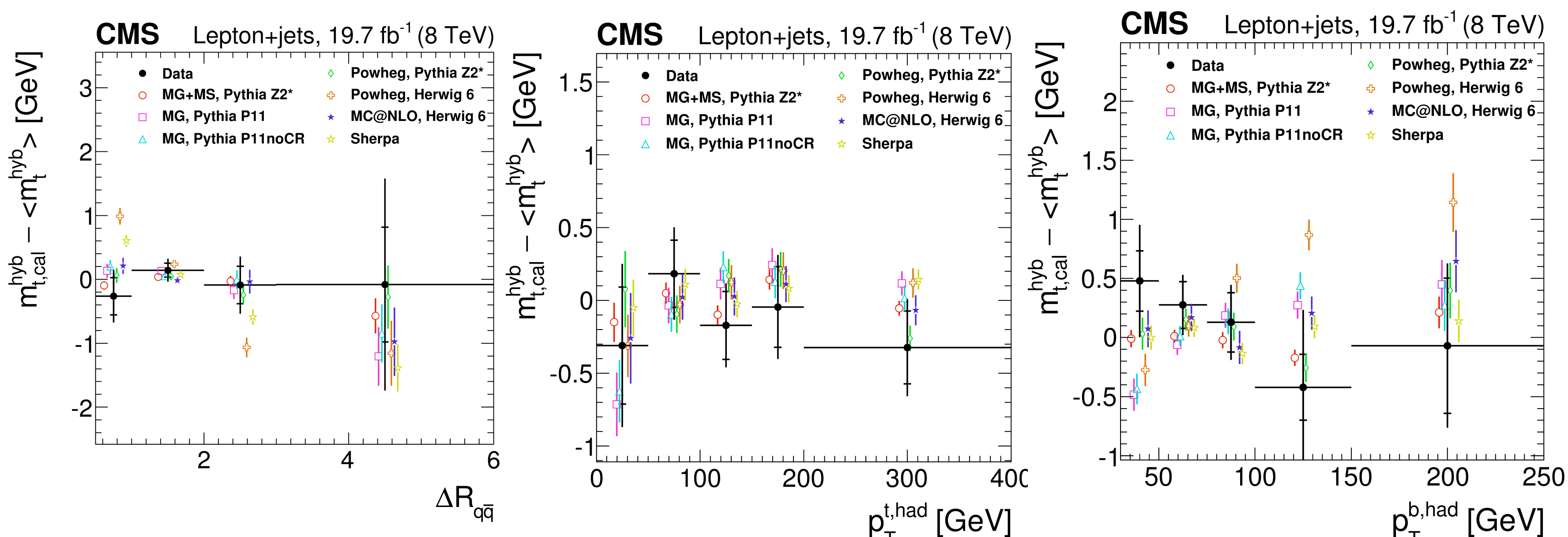
In prospect **1** and **2** will take advantage of the large LHC statistics

Dependence of Top Mass observable on event kinematics

- test variables sensitive to the final state definition
  - kinematic dependence on final state properly modeled by MC? → 12 kinematic variables checked, related to Color Reconnection, ISR/FRS, b-jet kinematics
  - Good data/MC agreement rules out dramatic effects → need to pursue the study with Run 2 high statistics !!



JHEP 12 (2012) 105



[Phys. Rev. D 93 (2016) 072004]

Methods for top mass measurement (2)

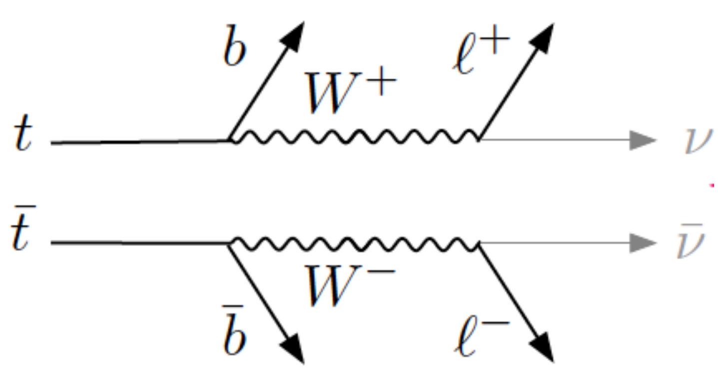
- Given the potential bias in measuring the top mass from its decay products, important to explore **alternative techniques**, e.g.
  - Measure the **decay length** (the boost) of B hadrons produced in top decays, the boost is related to the original top mass
  - Select **specific channels**, for example top with $W \rightarrow l\, \nu$ and $B \rightarrow J/\psi + X$ decays and measure the three-lepton invariant mass
  - Measure the **endpoint** of the lepton **spectrum** or other quantities in top decays
  - Measure the **mass from single top events**
- <u>Alternative methods have typically larger statistical uncertainties, however at LHC we have large ttbar samples</u>
  - Systematic uncertainties can be controlled with data, again large samples help.
- Another alternative: move away from properties of the decay products
  - **extract the top mass from the top cross section**

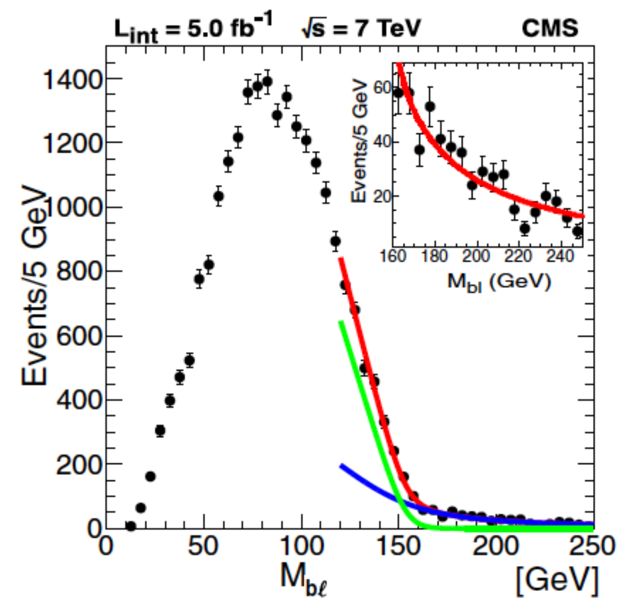
TOP mass from dilepton endpoint

- Example of a technique already yielding interesting precision: Endpoint method
- The shape of the signal can be computed analytically, background data-driven
- Use of MC limited to study underlying assumption: independent decay of two tops (color connections and reconnections violate this assumption)

arXiv:1304.7498

$$M_t = 173.9 \pm 0.9\,(\text{stat.})^{+1.6}_{-2.0}\,(\text{syst.})\,\text{GeV}$$

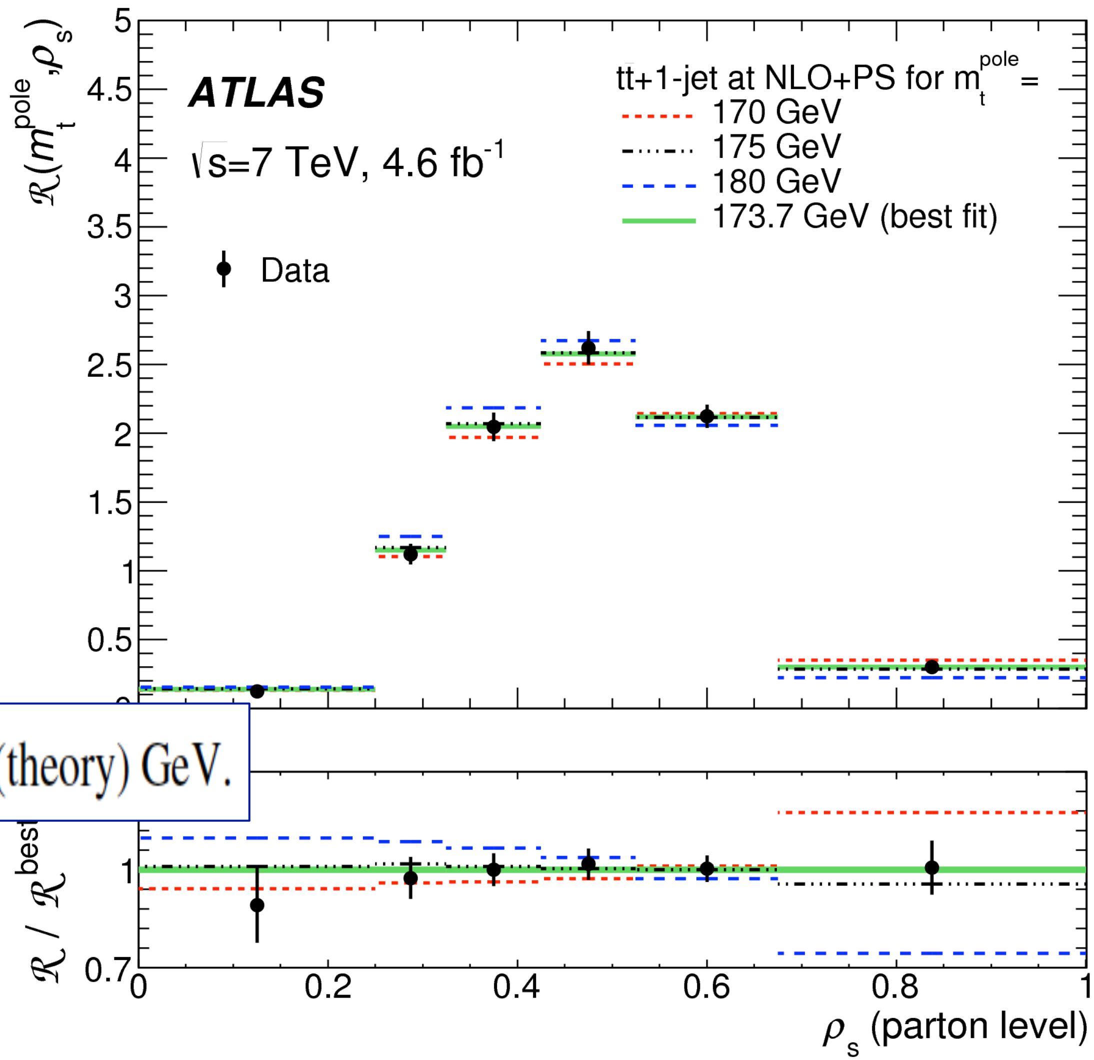




Top mass from ttbar+ 1 jet events

JHEP 10 (2015) 121

Use normalized differential cross section for top-quark pair production in association with at least one jet, studied as a function of the inverse of the invariant mass of the $t\bar{t}$+1-jet system.



$$m_t^{\text{pole}} = 173.7 \pm 1.5\,(\text{stat.}) \pm 1.4\,(\text{syst.})\,^{+1.0}_{-0.5}\,(\text{theory})\ \text{GeV}.$$

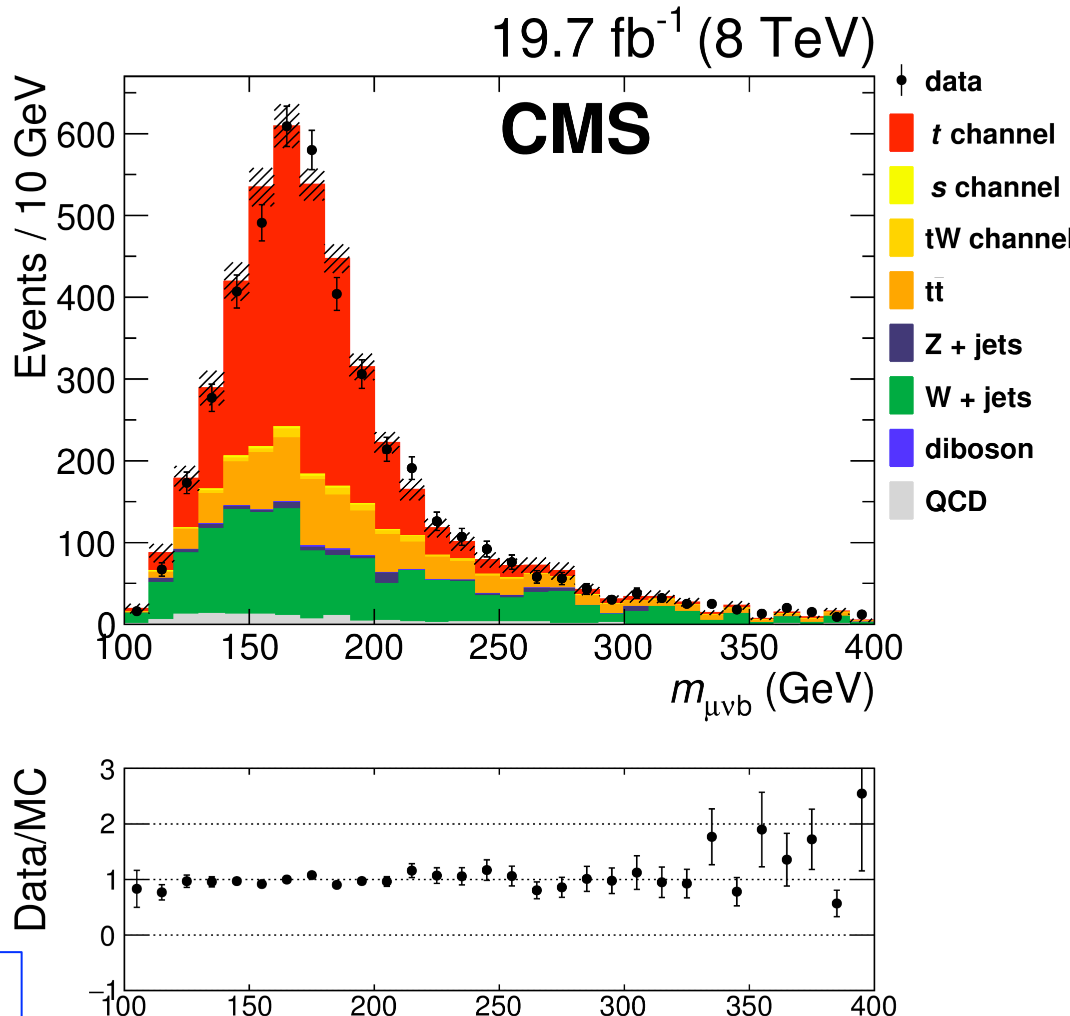
$$\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{-jet}}}}$$

Top mass from single top

arXiv:1703.02530

- Topology and kinematic properties of single top quark events in the *t* channel used to enhance the purity of the sample, suppressing the contribution from top quark pair production.
- Fit to the invariant mass distribution yields a value of the top quark mass of

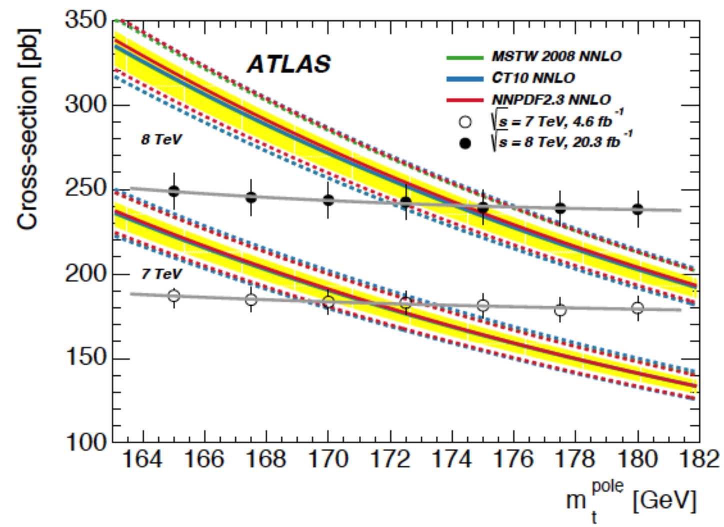
172.95 ± 0.77 (stat) $^{+0.97}_{-0.93}$ (syst) GeV



ttbar cross section: mass interpretation

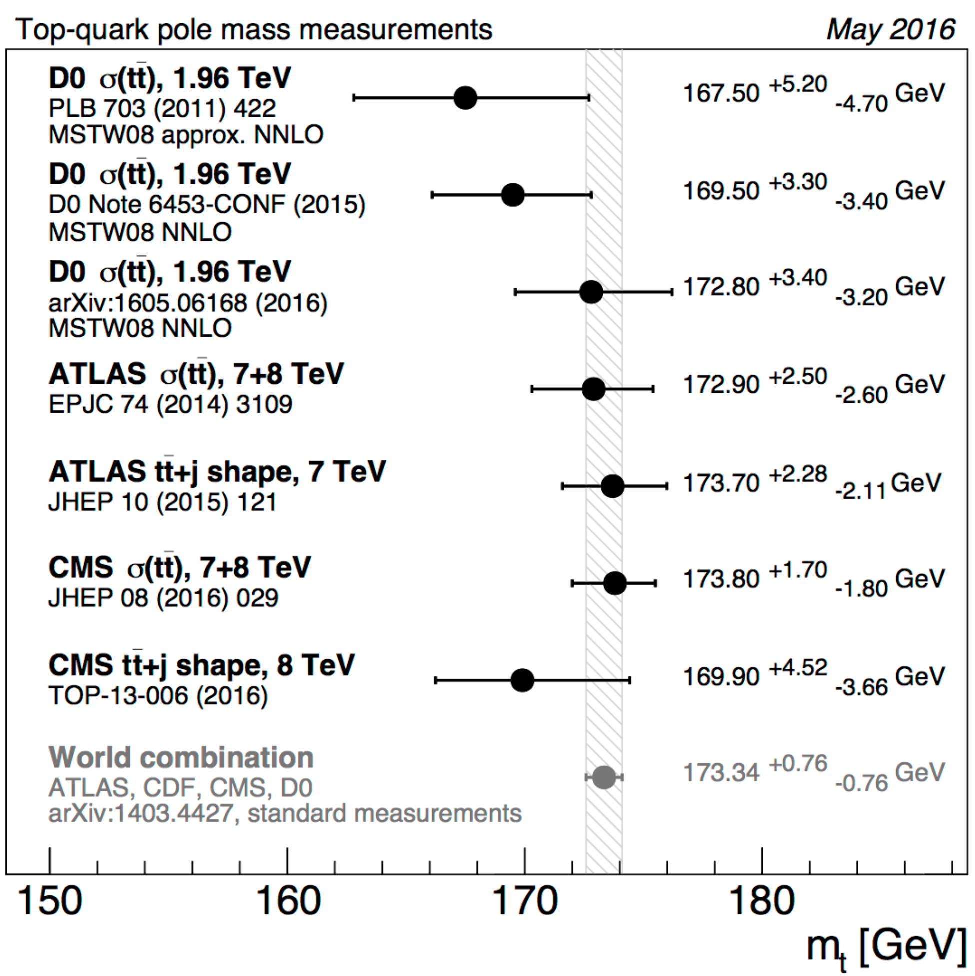
[example from ATLAS, arXiv:1406.5375]

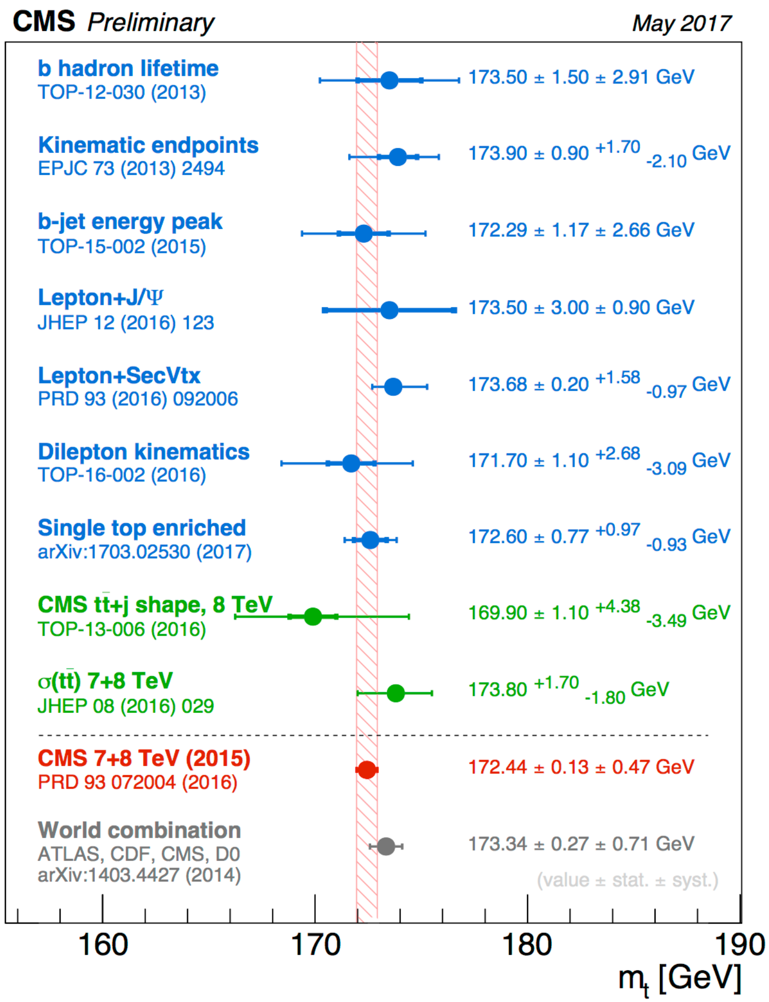
- Measure cross section in the most precise channel: dilepton eμ
- Use b-tagging and double tag method to avoid dependence on b-tag efficiency
  - interesting by-product: acceptance dependence on m_t is flat because of cancelation with Wt background !
- Use recent NNLO calculation of top pair cross section to extract m_t
- The method takes advantage of the excellent luminosity knowledge at LHC (~2%), which is also the long-term experimental limitation, together with the knowledge of the beam energy



$$m_t = 172.9^{+2.5}_{-2.6}\ \text{GeV}$$

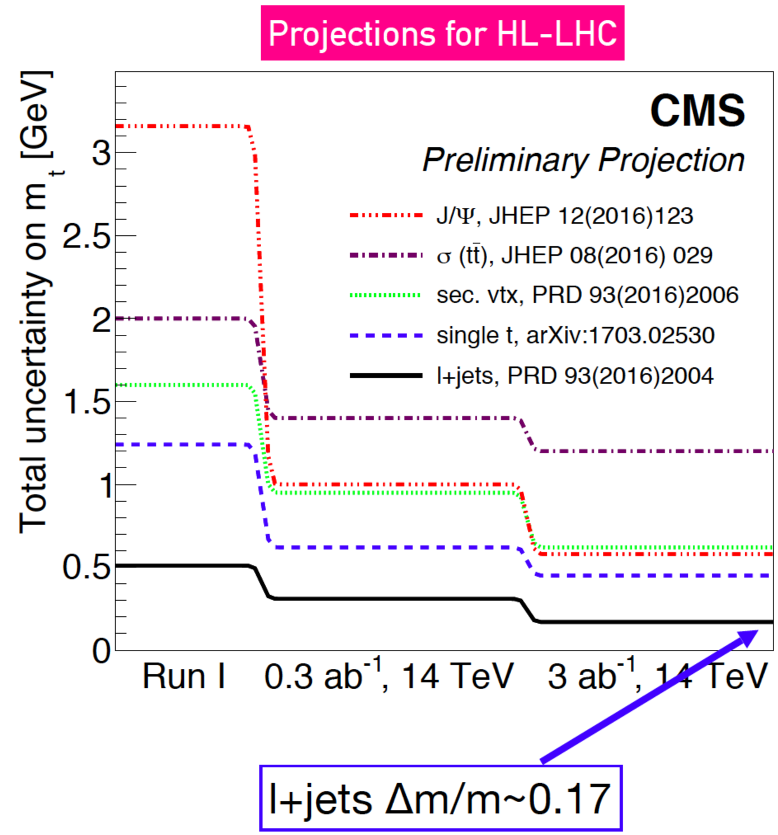
Top mass from cross section and alternative techniques





Prospects for top mass at the LHC

• There is potential to improve standard methods, taking advantage of the high statistics for, e.g., in-situ JES calibration, constraining models from differential studies, etc.
• There is even greater potential for alternative methods, most of the current systematic uncertainties can be reduced with higher statistics, e.g. top pt modeling, in-situ JES again
• Improvements on the cross section method are linked to improvements in the luminosity and beam energy uncertainties at LHC
• A optimistic view (maybe realistic give past experience at colliders !) of the evolution in precision is given in the picture

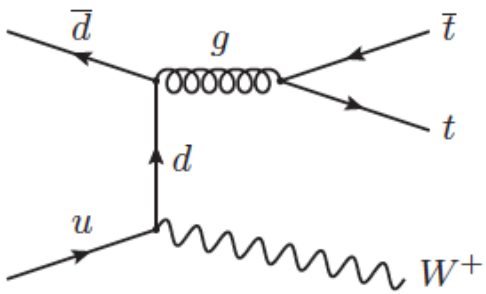


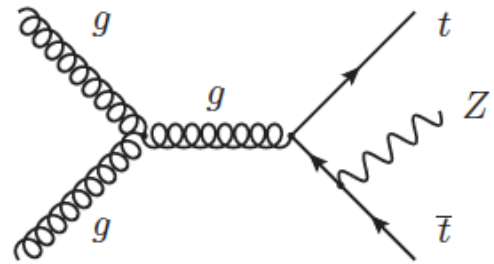
CMS-PAS-FTR-16-006

A FIELD WITH A LOT OF ACTIVITY AND RECENT DEVELOPMENTS→

ASSOCIATED PRODUCTION OF TOP AND BOSONS (AND MORE ...)

Associated production of top pair and **vector** boson





JHEP 01 (2016) 096
CMS-PAS-TOP-17-005

ATLAS
JHEP11(2015)172
Eur. Phys. J. C77 (2017) 40

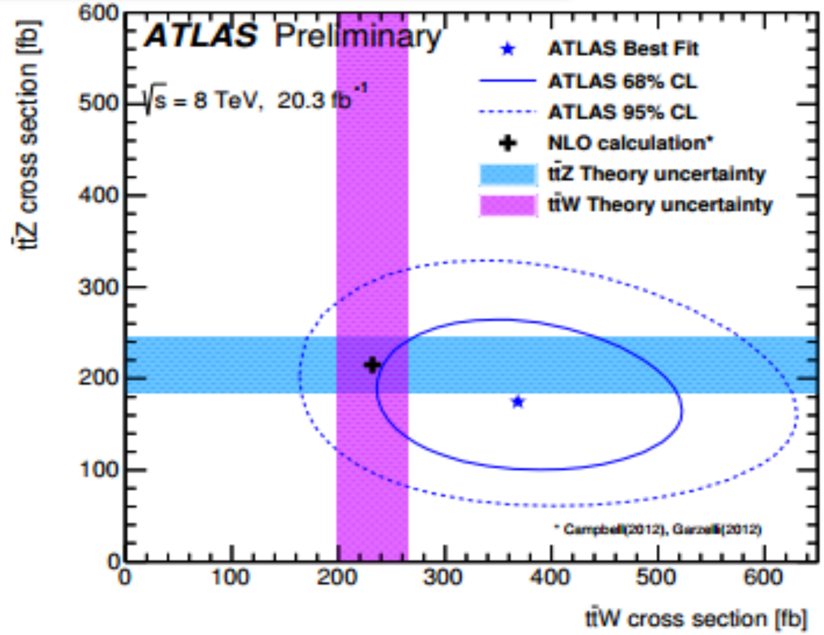
- The ttZ process provides direct access to Z-top couplings
- Both ttW and ttZ processes can be altered by BSM physics
- Measurement of **ttW** and **ttZ** cross sections in multilepton (e or μ) final states
  - **ttZ measured in channels with two, three, or four leptons, with exactly one pair of same-flavor opposite-sign (OS) leptons close to the Z mass**.
  - **ttW measured in in channels with two same-sign (SS) leptons or three leptons, where no lepton pair is consistent with coming from a Z boson decay.**
  - **full or partial reconstruction of the ttW or ttZ system with a linear discriminant that matches leptons and jets to their parent particles using mass, charge, and b tagging information.**

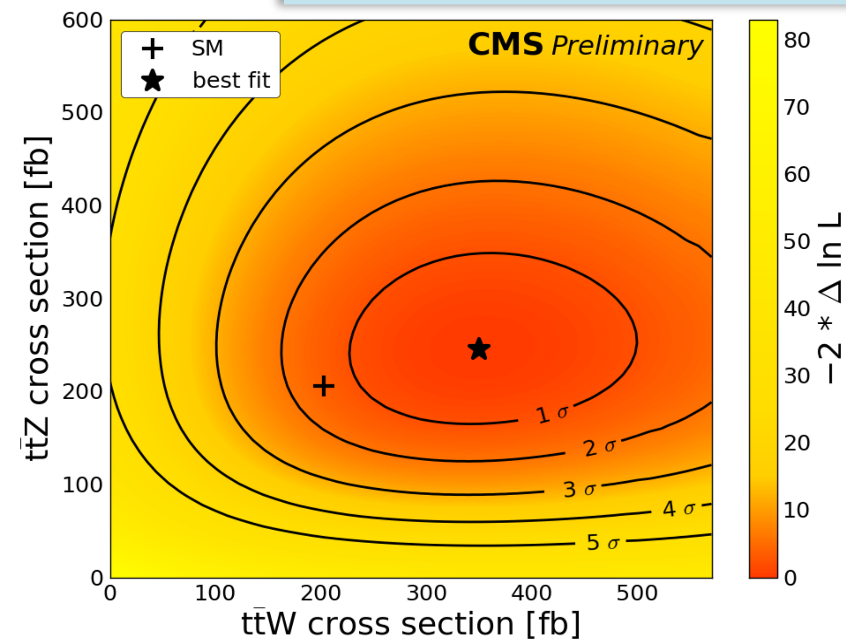
ttV: Observation !

ttW: 3.2 σ (exp) 5.0 σ (obs)
ttZ: 4.5 σ (exp) 4.2 σ (obs)

TOP 2015

ttW: 3.8 σ (exp) 4.8 σ (obs)
ttZ: 5.7 σ (exp) 6.4 σ (obs)





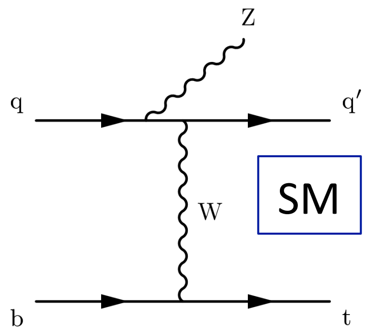
arXiv:1509.05276

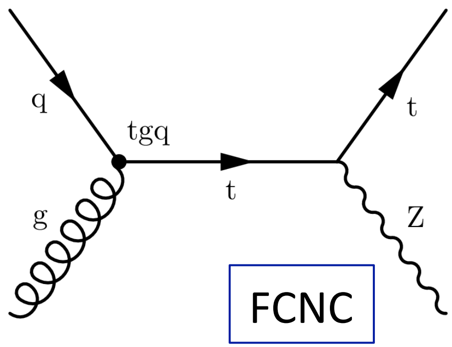
J. High Energy Phys. 01 (2016) 096

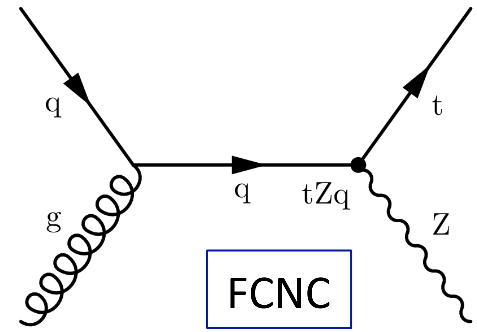
Constraints on dimension-6 operators

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}

Associated production of single top and a Z boson (tZq production)

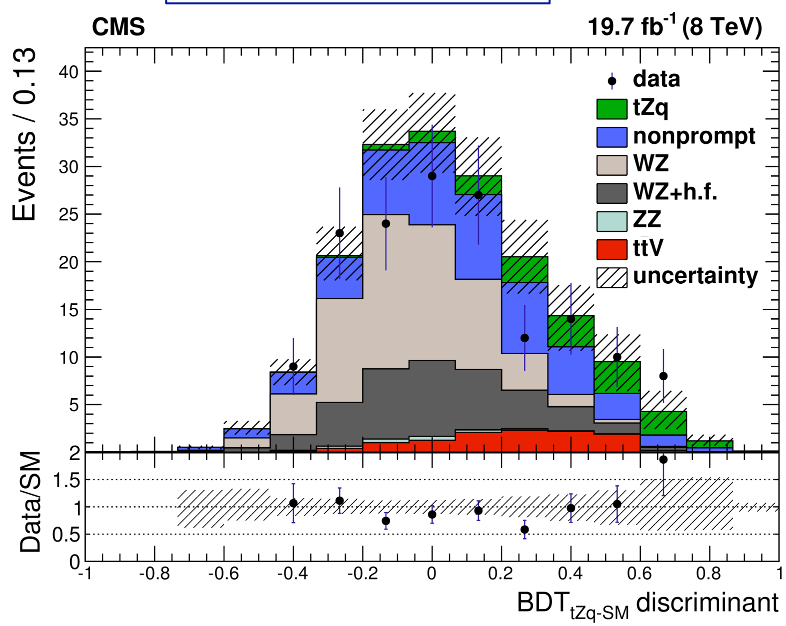


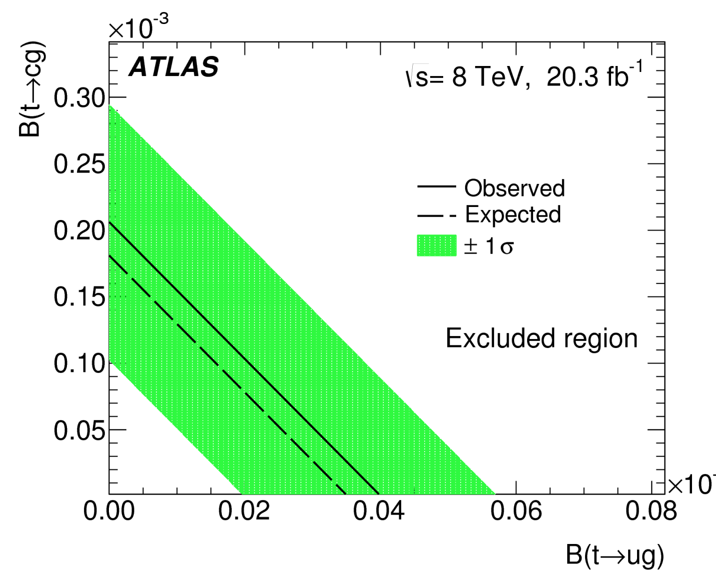




arXiv:1702.01404

arXiv:1509.00294



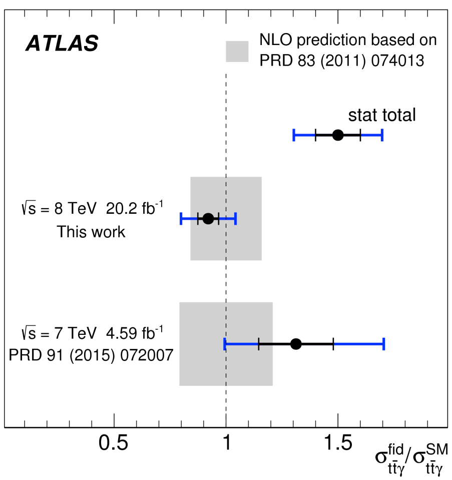


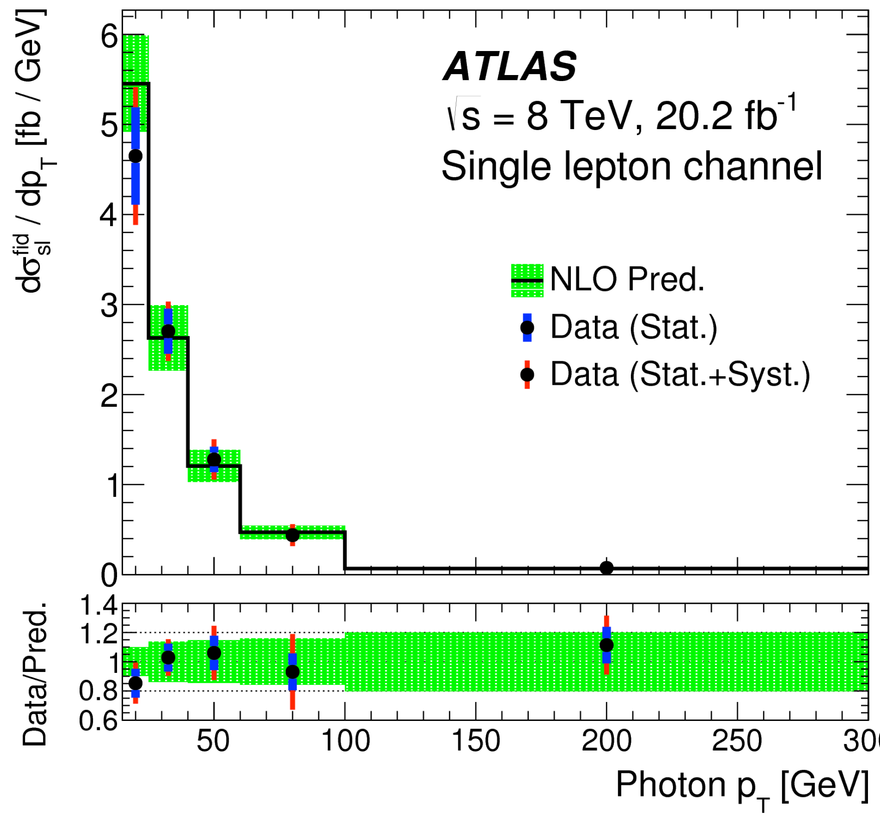
Associated production of ttbar+photon

arXiv:1706.03046

Select events that contain

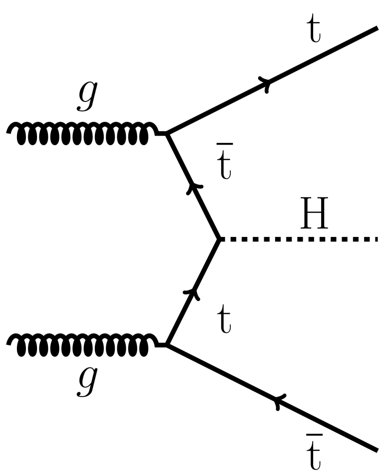
- a photon with transverse momentum p_T>15 GeV,
- an isolated lepton with large transverse momentum,
- large missing transverse momentum
- at least four jets, where at least one is identified as originating from a *b*-quark.

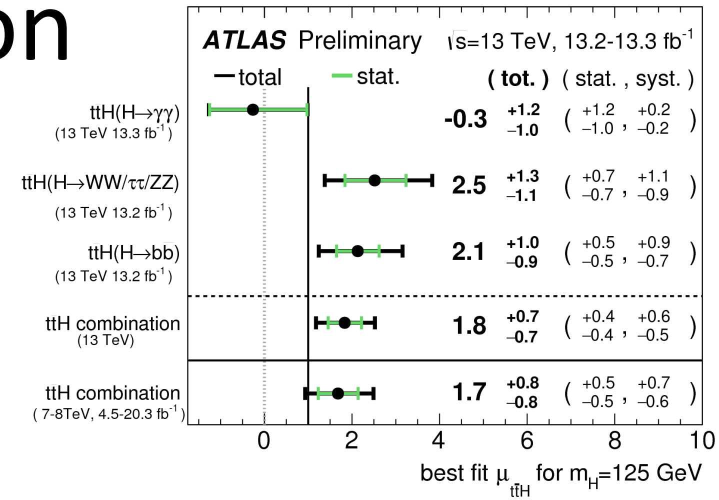




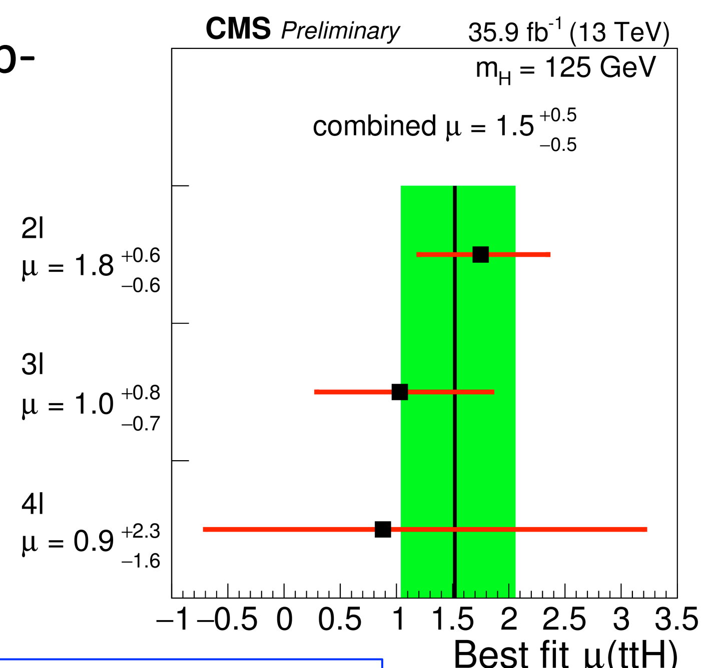
Deviations could indicate anomalous top electric dipole moments or excited top ($t^* \rightarrow t\gamma$)

Associated production of top pair and **scalar** boson



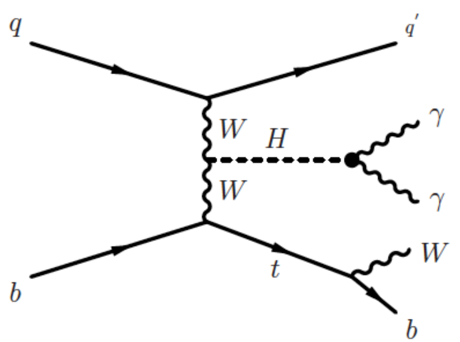


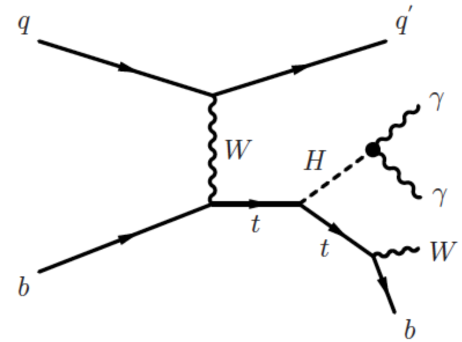
- The ttH process gives direct access to the top-Higgs Yukawa coupling.
- The process can be altered by BSM physics
- Measurement performed in several final states
  - top pair all hadronic, lepton+jets, dilepton
  - with H→hadrons, H→ leptons, H→ γγ
  - categorization includes H→bb and H→ ττ



Multilept: observed (expected) significance 3.3σ (2.5σ) [CMS-PAS-HIG-17-004]

Associated production of single top and Higgs boson





- Potentially gives the relative sign of the top-Higgs Yukawa coupling with respect to the Higgs-W coupling
- The **two diagrams interfere destructively in the SM (σ=18 fb)**, but with **flipped sign cross section increases by a factor 15**
- Analysis performed in the H→γγ (and bb) channels: **observed 95% UL is set at 4.1 times (6.0 times) the expected cross section with inverted Ct (= -1)** CMS-PAS-HIG-14-001 / HIG-16-019
- Measurements also done in the multilepton channel to set combined limits to tH+ttH production CMS-PAS-HIG-17-005

Search for Dark Matter produced in association with top pairs

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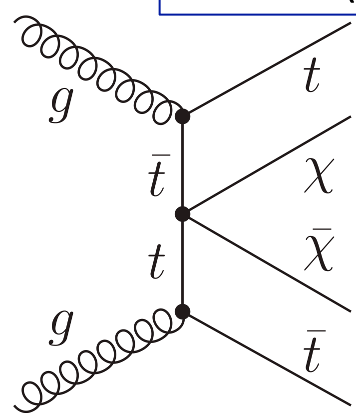
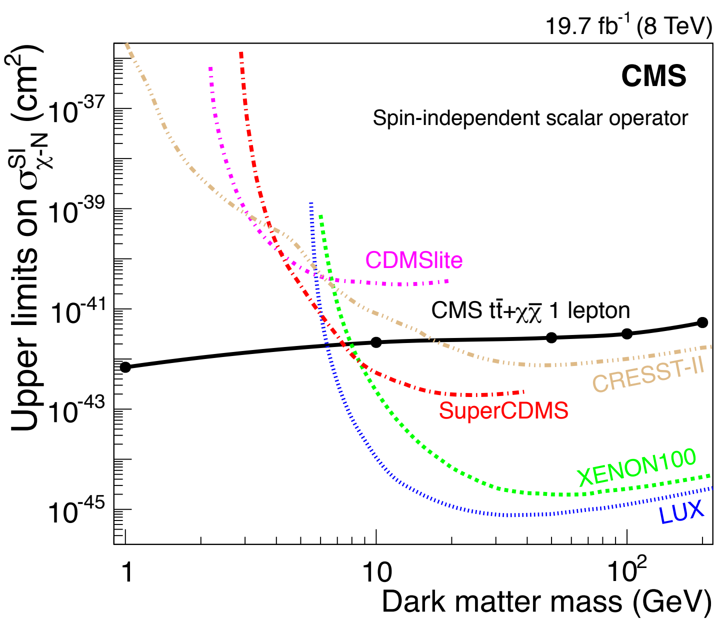
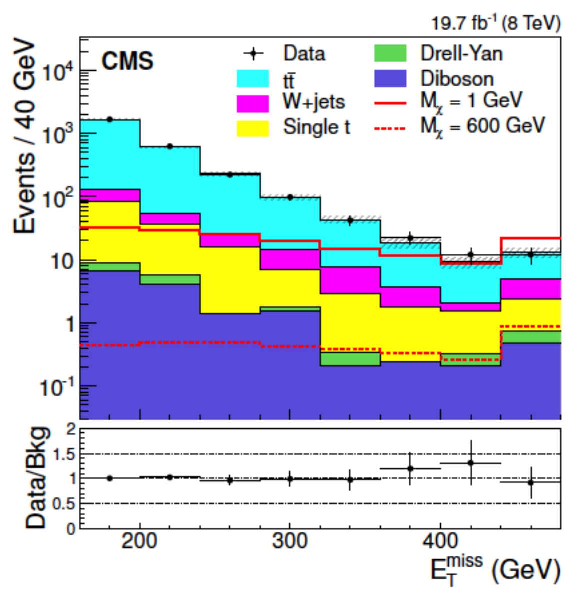
- Dark matter could couple to heavy fermions through contact interactions
- Search requires the presence of one lepton, multiple jets, and large missing transverse energy.

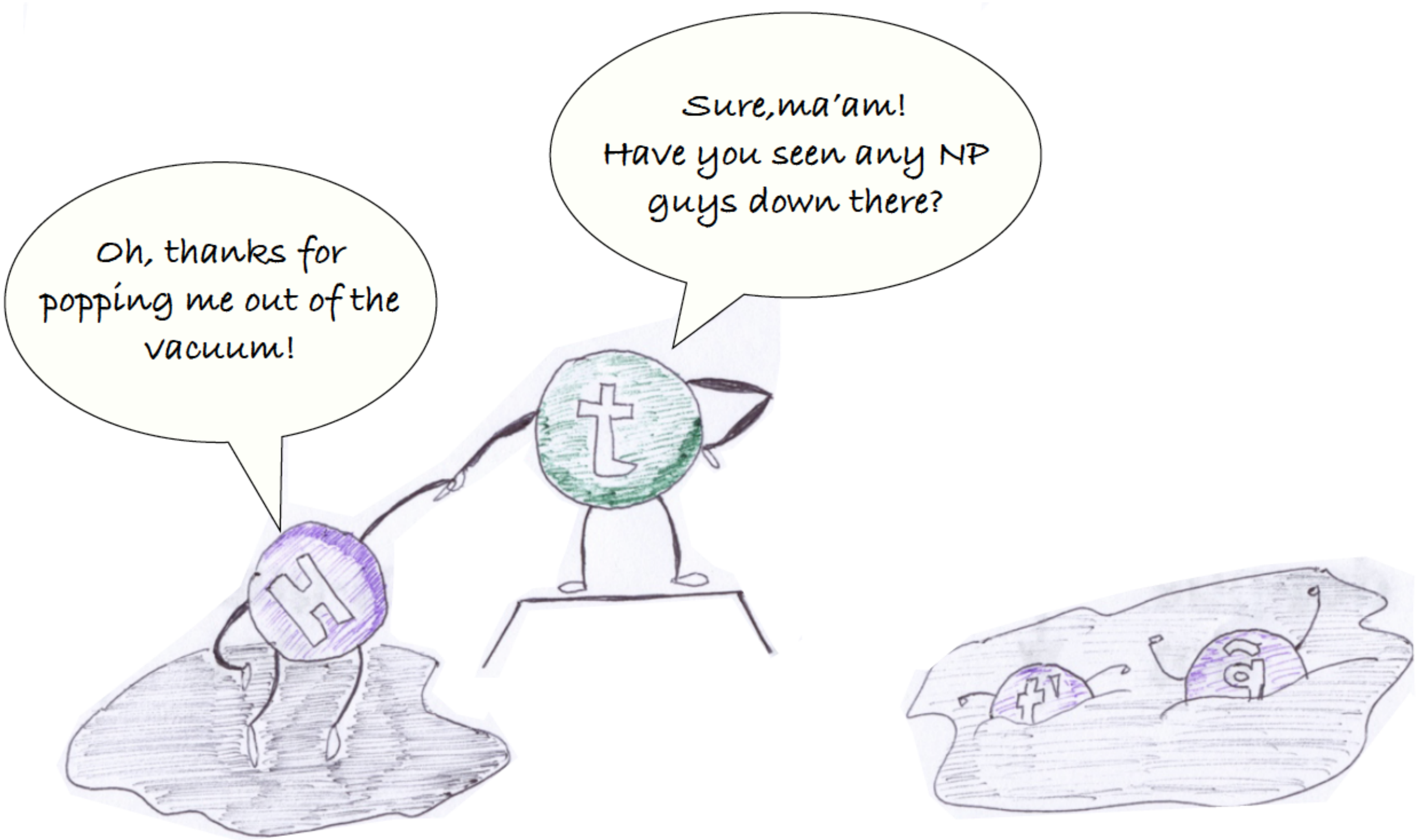






Final comment on top @ LHC

- **Top physics an important sector of electroweak-symmetry-breaking studies**
  - **A necessary complement to Higgs measurements**
- After first five years of top-production **at the LHC-top-factory**, now entering a new phase
- **Entering uncharted territory in terms of (statistical) precision, use statistics as a tool to reduce systematic uncertainties**

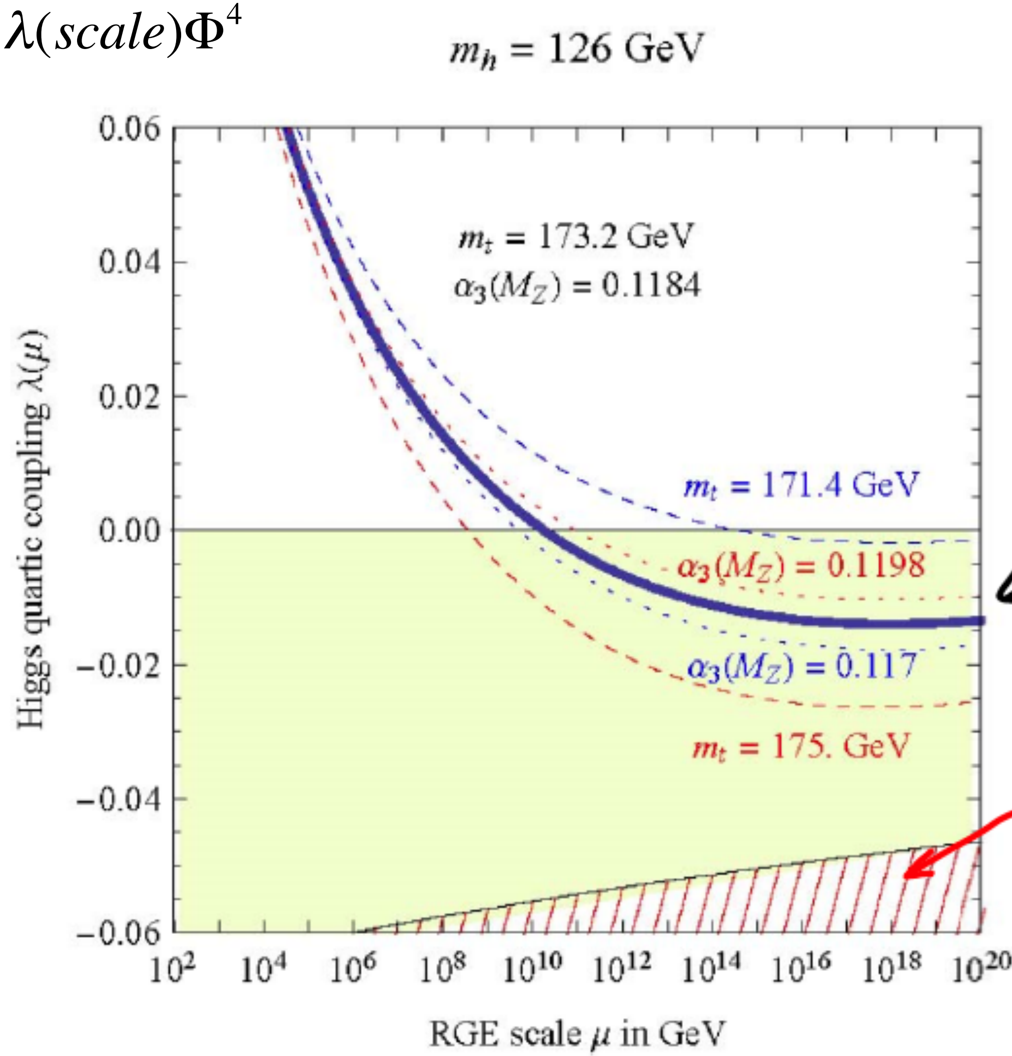


Courtesy of Fabio Maltoni

BACKUP SLIDES

LIFE IN A METASTABLE VACUUM

$$V = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda(scale)\Phi^4$$



Lifetime $\propto \exp \frac{1}{|\lambda|}$

$\gg$ age of Universe

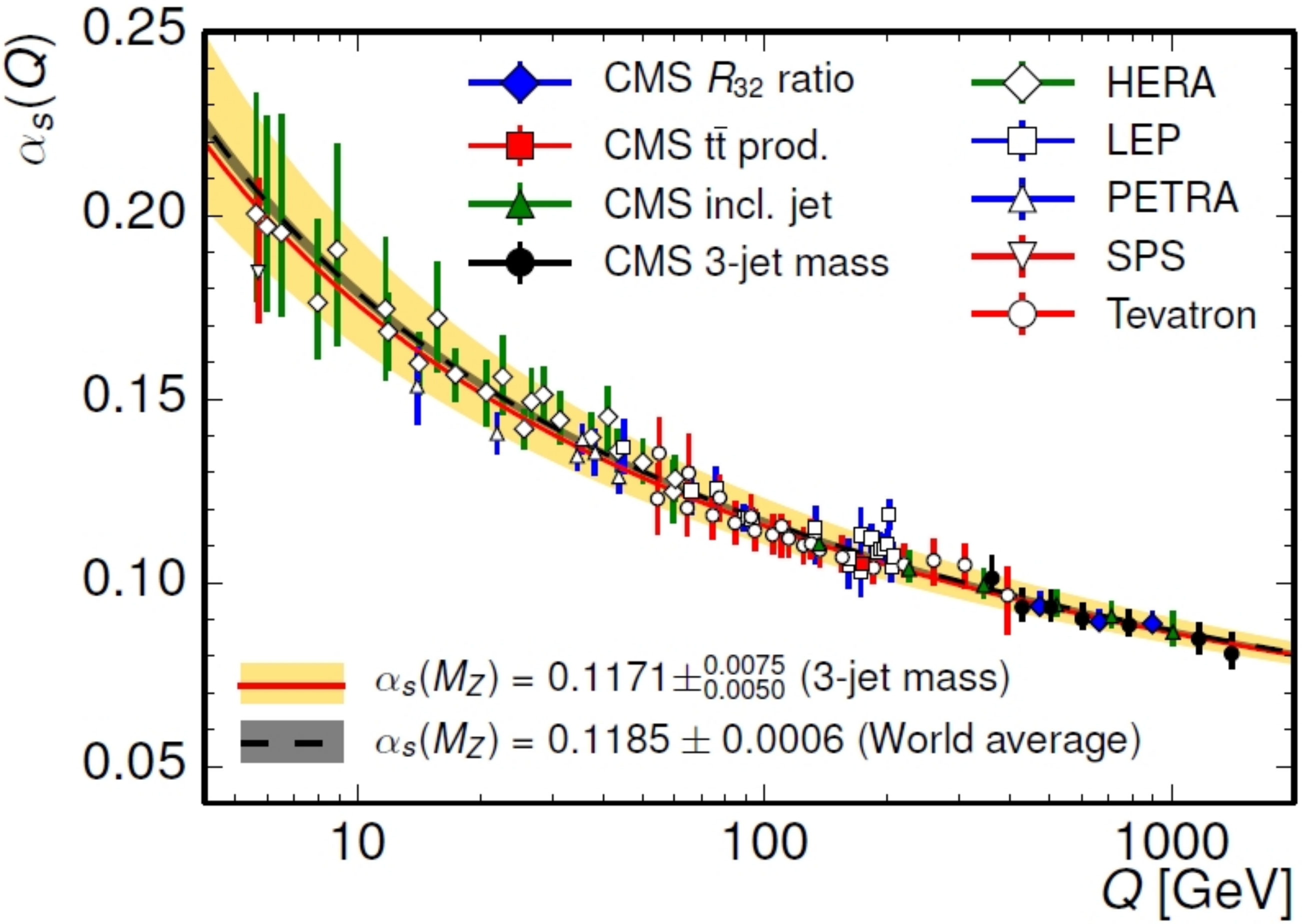
$p > 1$

Unstable vacuum

($M_h \downarrow$)

J.R. Espinosa at top2015

Running of α_s
- a very precise point from ttbar -

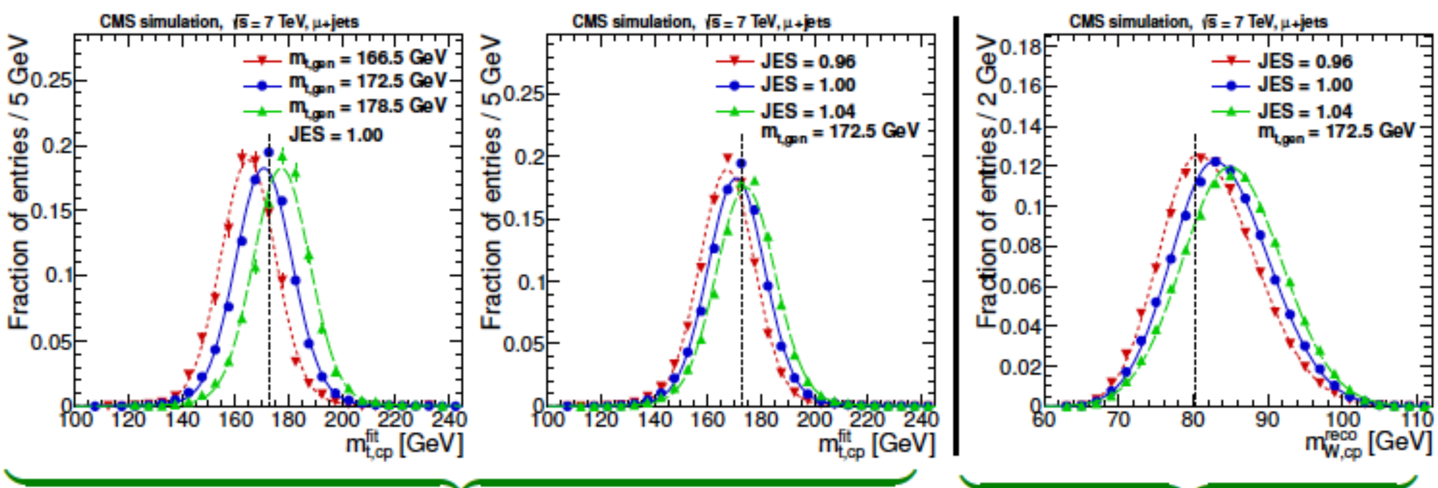


Construct probability densities: ideogram method

[example from CMS, TOP-14-001 / arXiv:1509.04044]

- Simulated samples with
  - 9 different top masses: 161.5–184.5 GeV
  - 3 different JES: 0.96, 1.00, 1.04
- Fit $m(top)_{fit}$, $m(W)_{reco}$ distributions with analytical expressions
- Parametrize linearly in m_t , JES, $m_t \times$ JES
- Take into account correct, wrong and unmatched permutations

Example: *correct permutations*



$P_{cp}\left(m_t^{\mathrm{fit}} | m_t, \mathrm{JES}\right)$ $P_{cp}\left(m_W^{\mathrm{reco}} | \mathrm{JES}\right)$