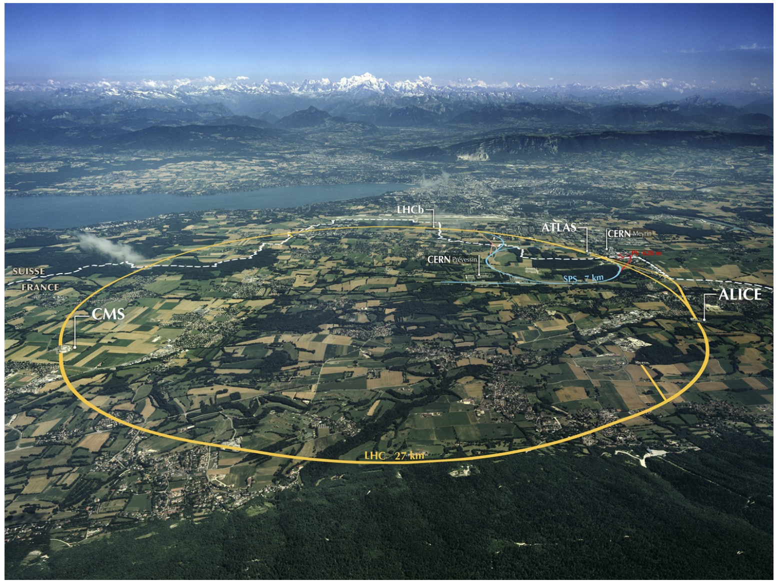
Top quark studies



(Introduction)
- → Production
- → Production asymmetries, spin correlations and W helicity
- → Anomalous couplings
- → tt + W, Z, γ cross sections
- → Mass
- → Conclusions & Outlook

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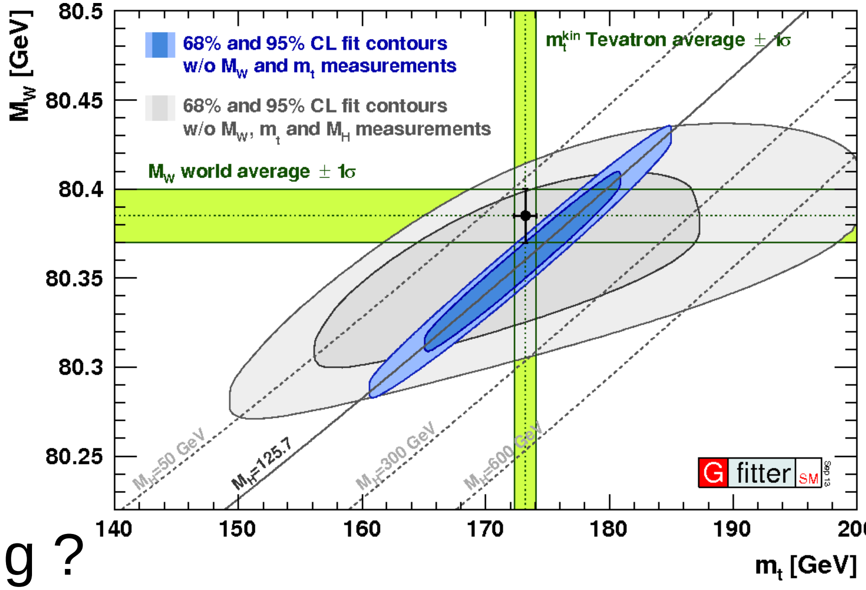
July 11th, 2016

Top quark introduction

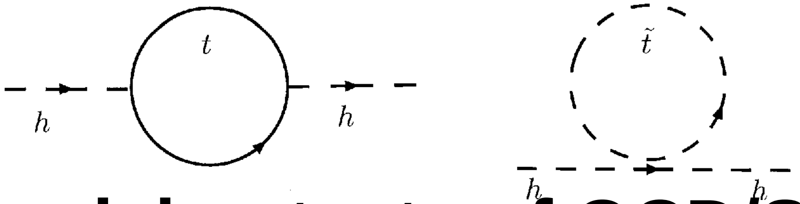
- Top is the heaviest fundamental particle discovered so far
  → m_t = 173.34 ± 0.76 GeV
  [arxiv:1403.4427]

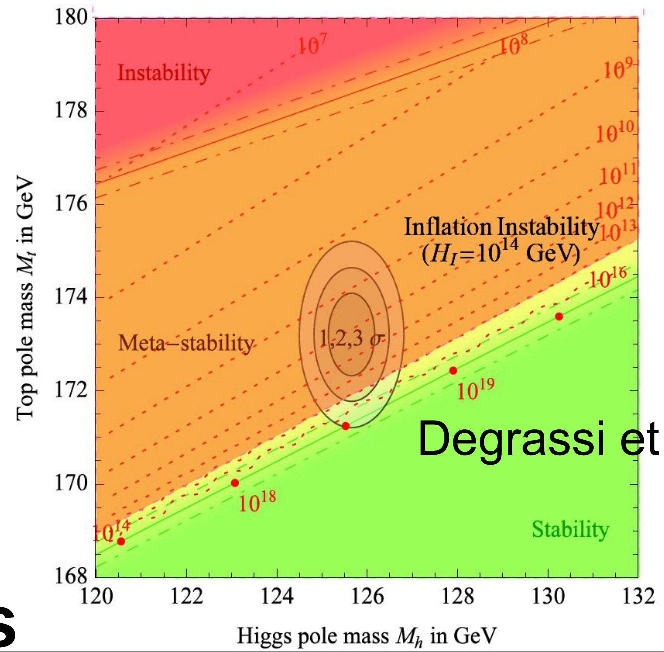


- Lifetime: τ ~ $5x10^{-25}$ s << Λ_{QCD}
  → **Observe bare quark properties**

- Large Yukawa coupling to Higgs boson
  → λ_t **~ 1**
  special role in electroweak symmetry breaking ?

- If we could calculate the Higgs mass:
  → Large corrections to the Higgs mass from top quark “loops” (Hierarchy problem)

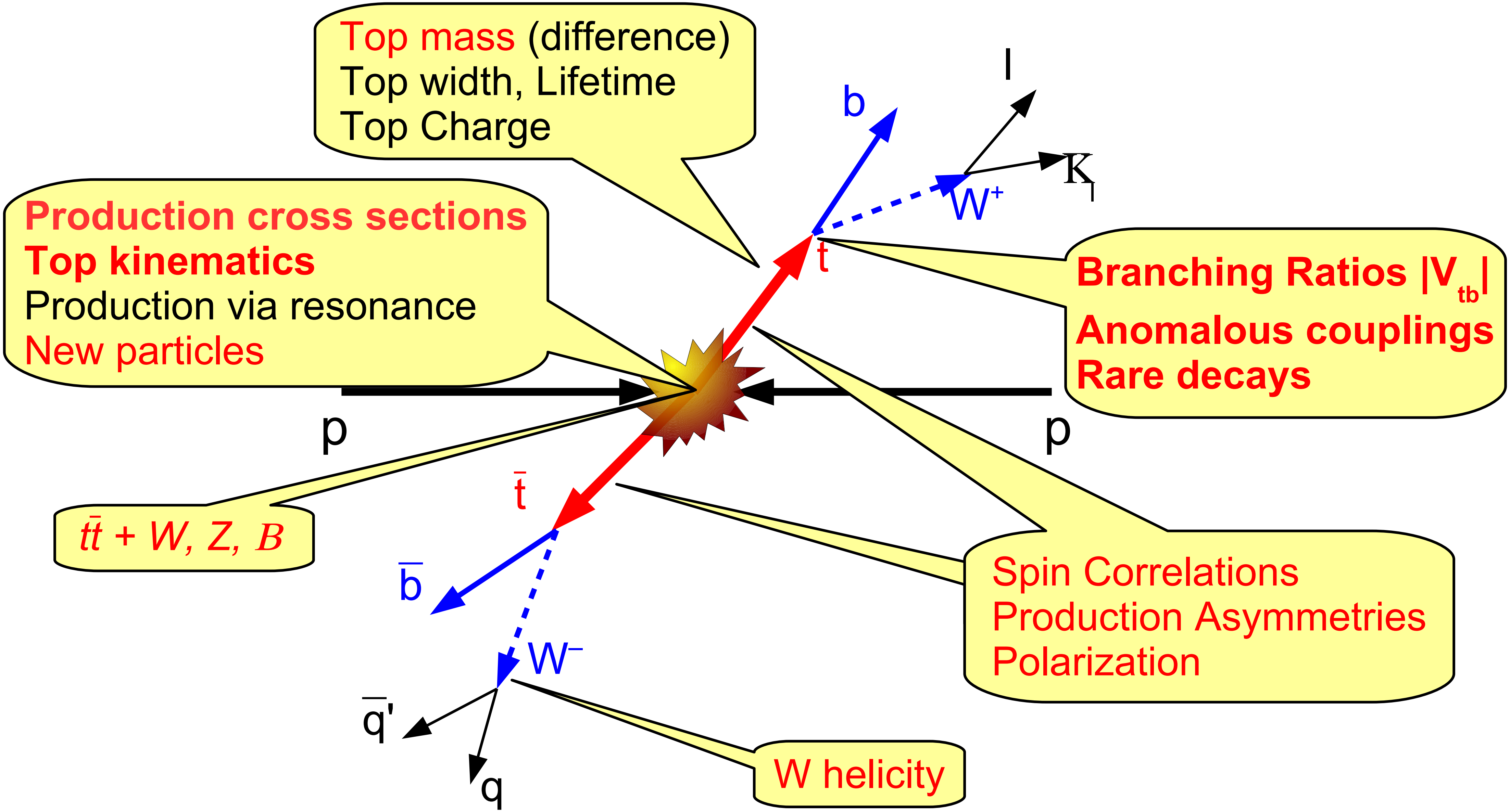




Degrassi et al.

High precision tests of QCD/SM
Tops are background to many searches
→ Top quarks as window to new physics

Content



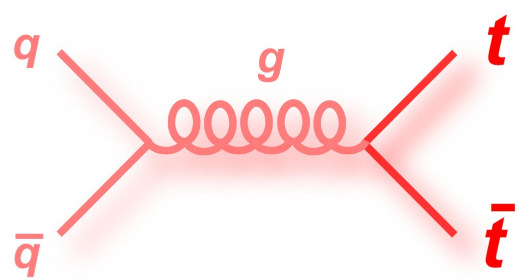
→ **Selection of results, focus on most recent and/or precise results**

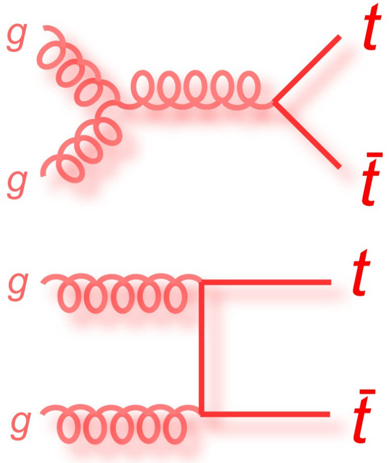
Top quark introduction

- Strong interaction: Top pairs

LHC (7/8 TeV):

$q\bar{q}$: ~15/13% (~10%, 13 TeV)
gg: ~85/87% (~90%, 13 TeV)

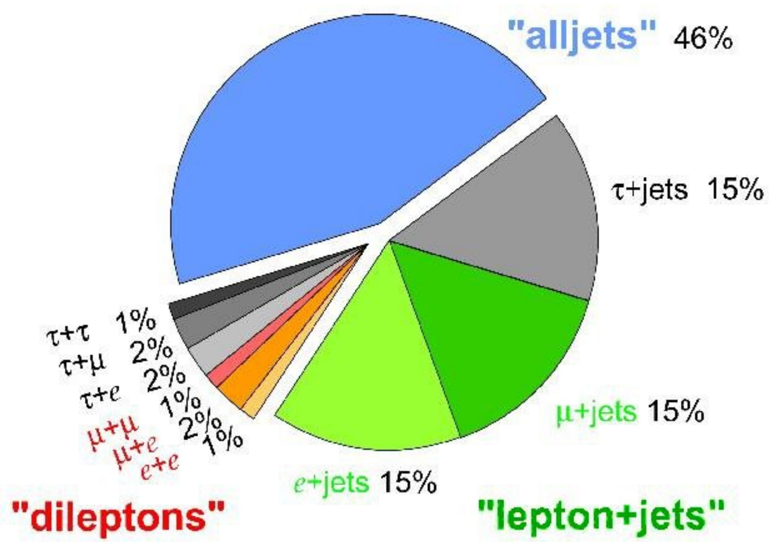




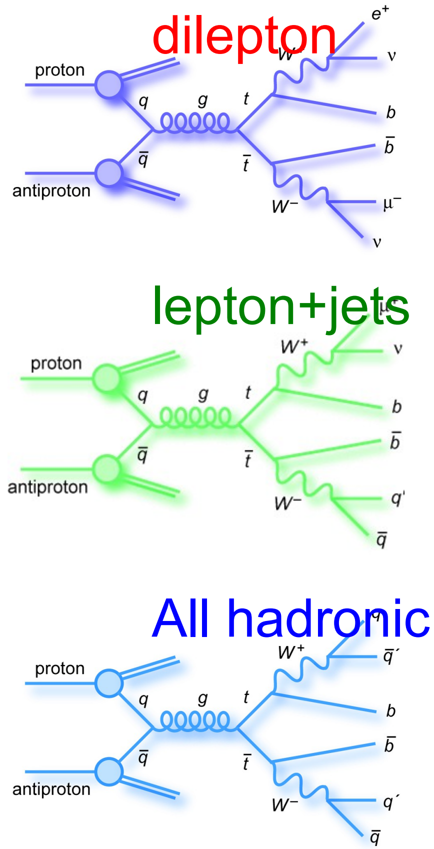
gg fusion

- Decay channels:

Top Pair Branching Fractions



BR, bg increase



BR, bg decrease

Theory (NNLO+NNLL):

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 13 TeV $\sigma = 832^{+40}_{-46}$ pb

Top quark production

- Extremely clean, very high purity
- Method: simultaneously determine $\sigma(t\bar{t})$ and the efficiency to reconstruct & *b*-tag jets
  → **reduces related systematic uncertainties !**

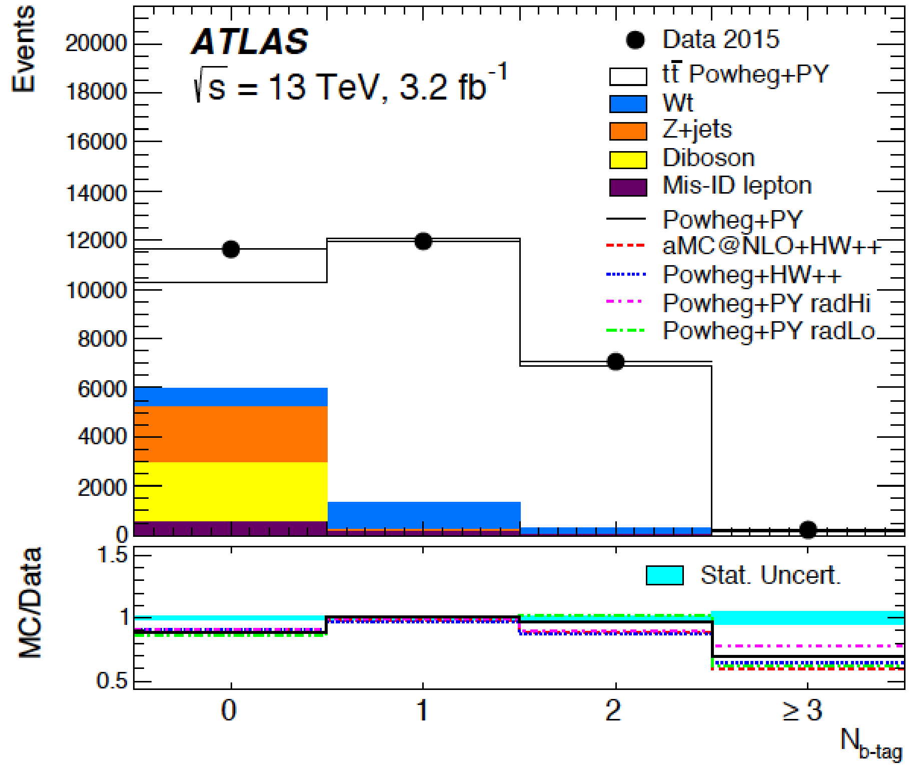
$$N_1 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\mathrm{bkg}}$$

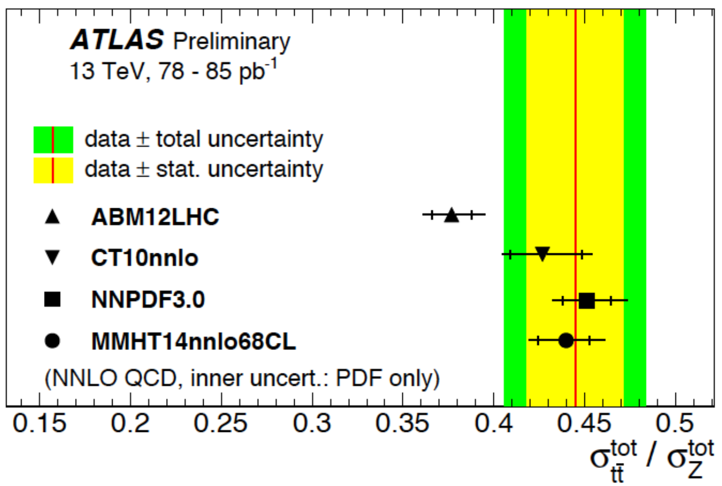
$$N_2 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}C_b\epsilon_b{}^2 + N_2^{\mathrm{bkg}}$$

- Event selection:
  - Single e- or μ-trigger
  - ≥ 1 jets: p_T > 25 GeV, |η| < 2.5
  - Reconstructed e and I with p_T > 25 GeV, |η| < 2.5
- 1 or 2 jets identified as *b*-jet

→ σ = 818 ± 8 (stat.) ± 27 (syst.) ± 19 (lumi.) ± 12 (beam) pb

δσ/σ = 4.4%





Top quark production

- CMS 1st cross section measurement at 5TeV in eμ dilepton
- Relative precision: δσ/σ = 28%

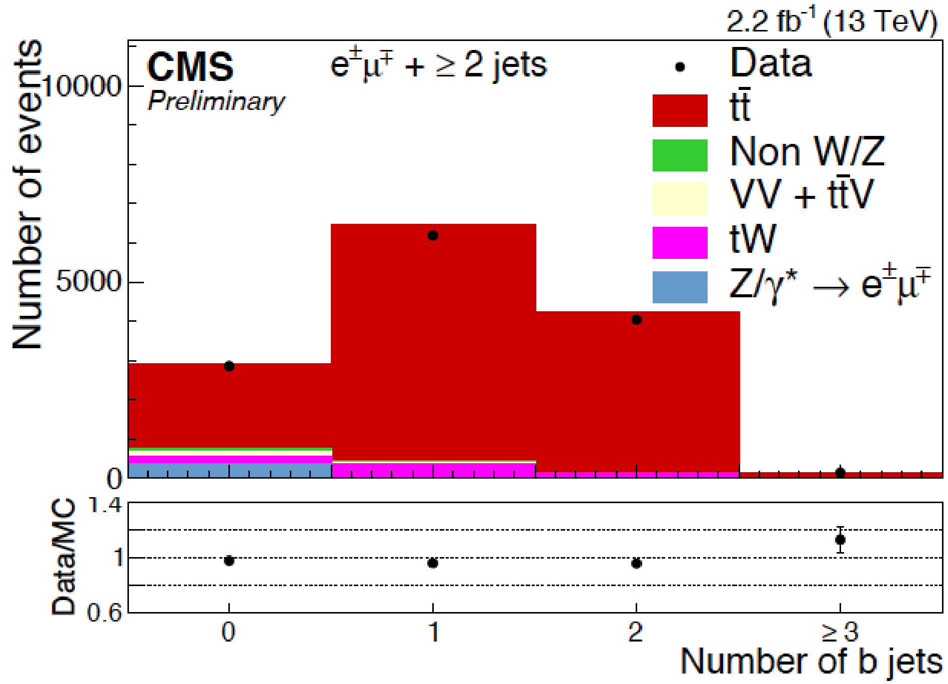
→ σ = 82 ± 20 (stat.) ± 5 (syst.) ± 10 (lumi.) pb

Source	Number of events $e^{\pm}\mu^{\mp}$
Drell–Yan	1.6 ± 0.4
Non W/Z	1.0 ± 0.9
tW	0.89 ± 0.02
WV	0.41 ± 0.02
Total background	3.9 ± 0.8
Signal ($t\bar{t} \to e\mu$)	16.7 ± 0.2
Data	24

- CMS cross section measurement in the dilepton channel @13TeV, **δσ/σ = 5.6%**
- Dominated by Hadronisation, JES

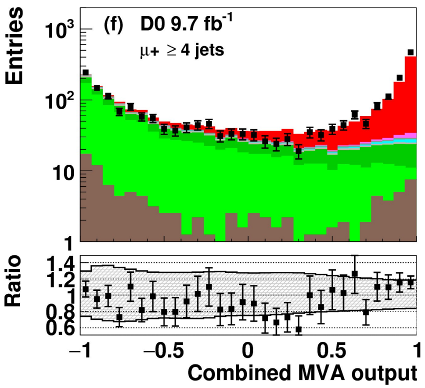
→ σ = 793 ± 8 (stat.) ± 38 (syst.) ± 21 (lumi.) pb

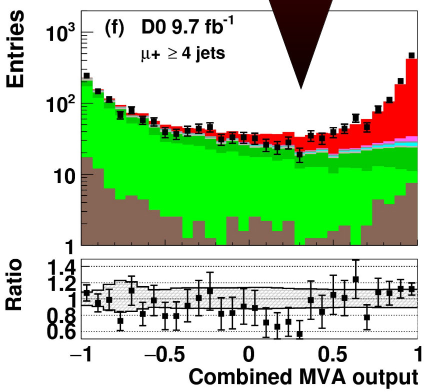
Source	Number of $e^{\pm}\mu^{\mp}$ events
Drell–Yan	$24 \pm 9 \pm 4$
Non-W/Z leptons	$109 \pm 50 \pm 33$
Single top quark	$463 \pm 6 \pm 145$
VV	$15 \pm 2 \pm 5$
$t\bar{t}$ V	$31 \pm 1 \pm 10$
Total background	$642 \pm 52 \pm 149$
$t\bar{t}$ dilepton signal	$10199 \pm 14 \pm 462$
Data	10368

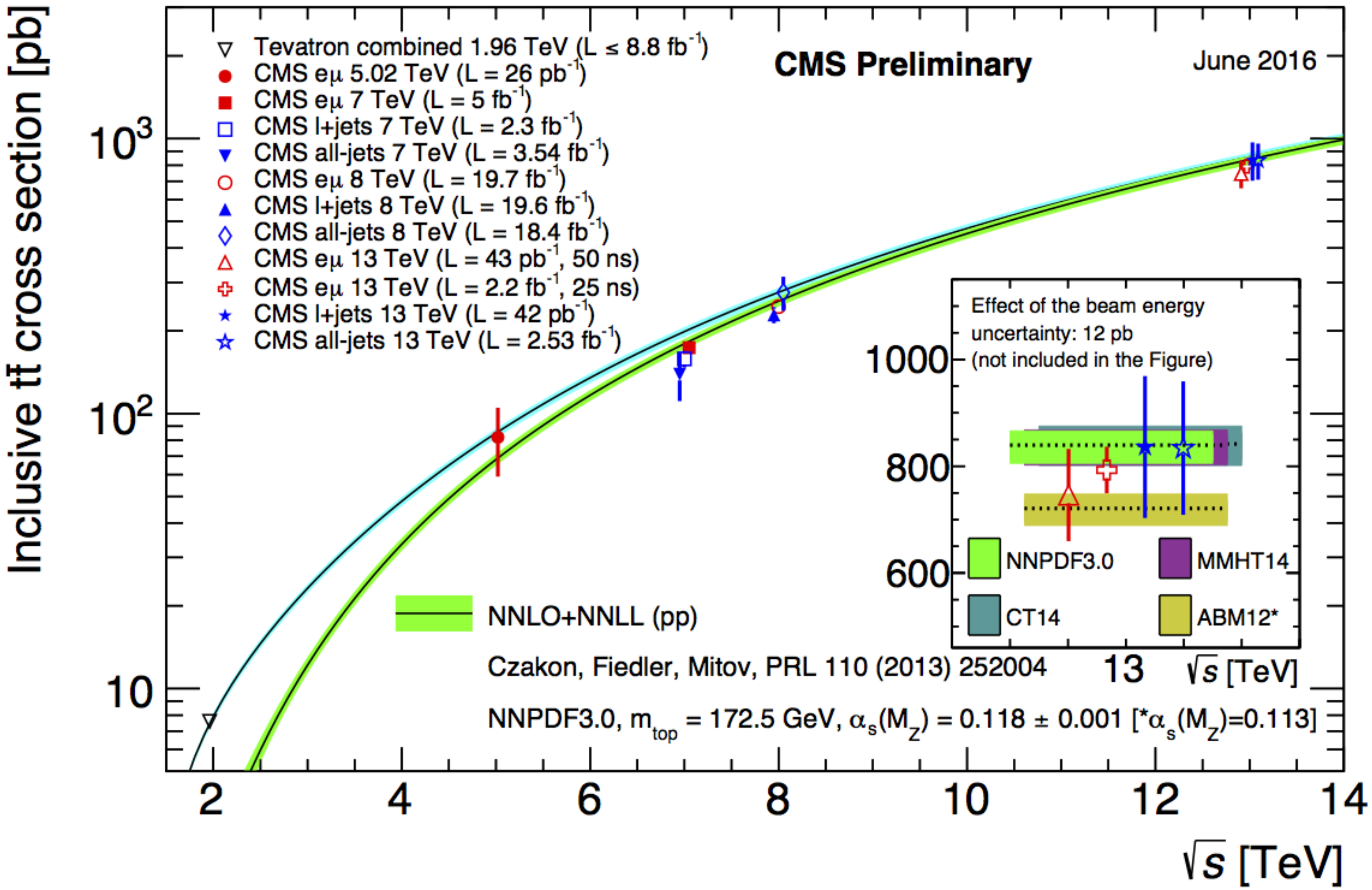


Top quark production

- New measurements at 2, 5 and 13 TeV – agreement with the SM
- Profile log-LH fit by D0:
  - Reduced uncertainties
  - Optimized to extract pole mass







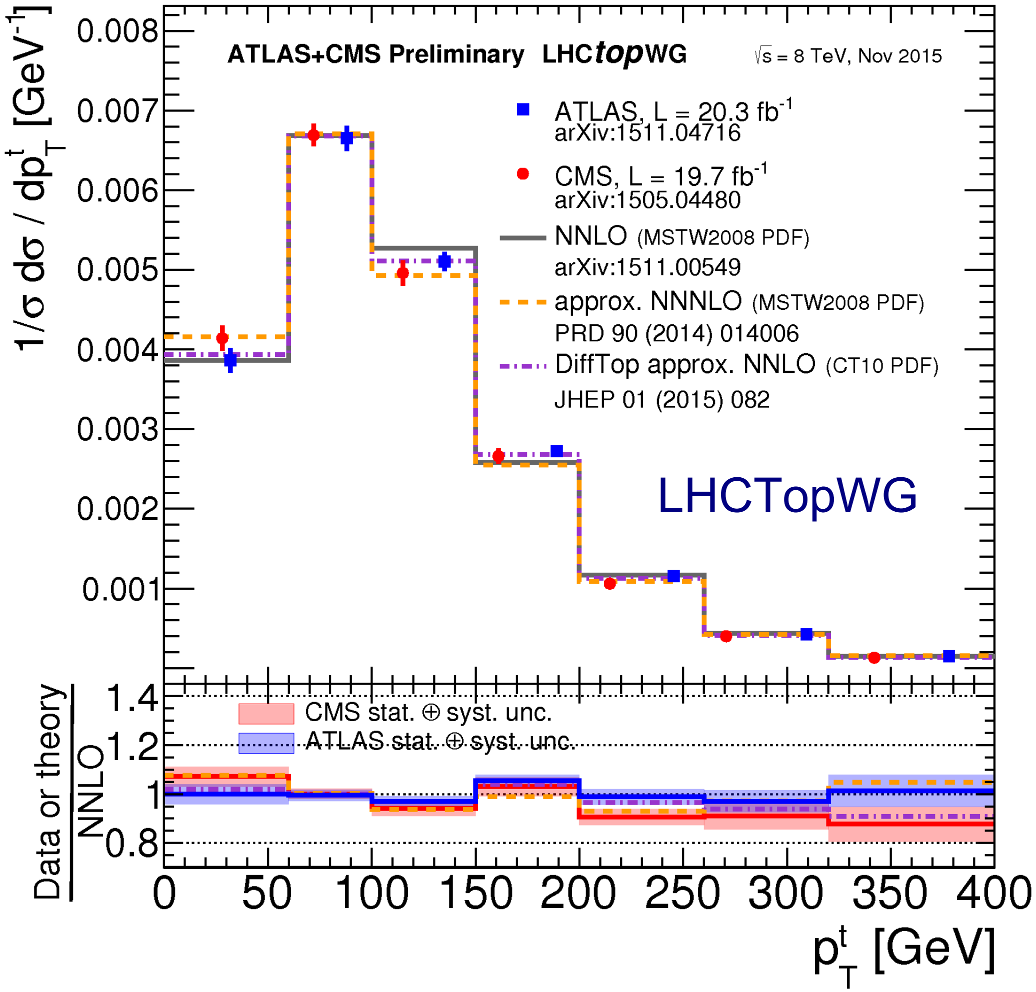
Combination of dilepton & l+jets:

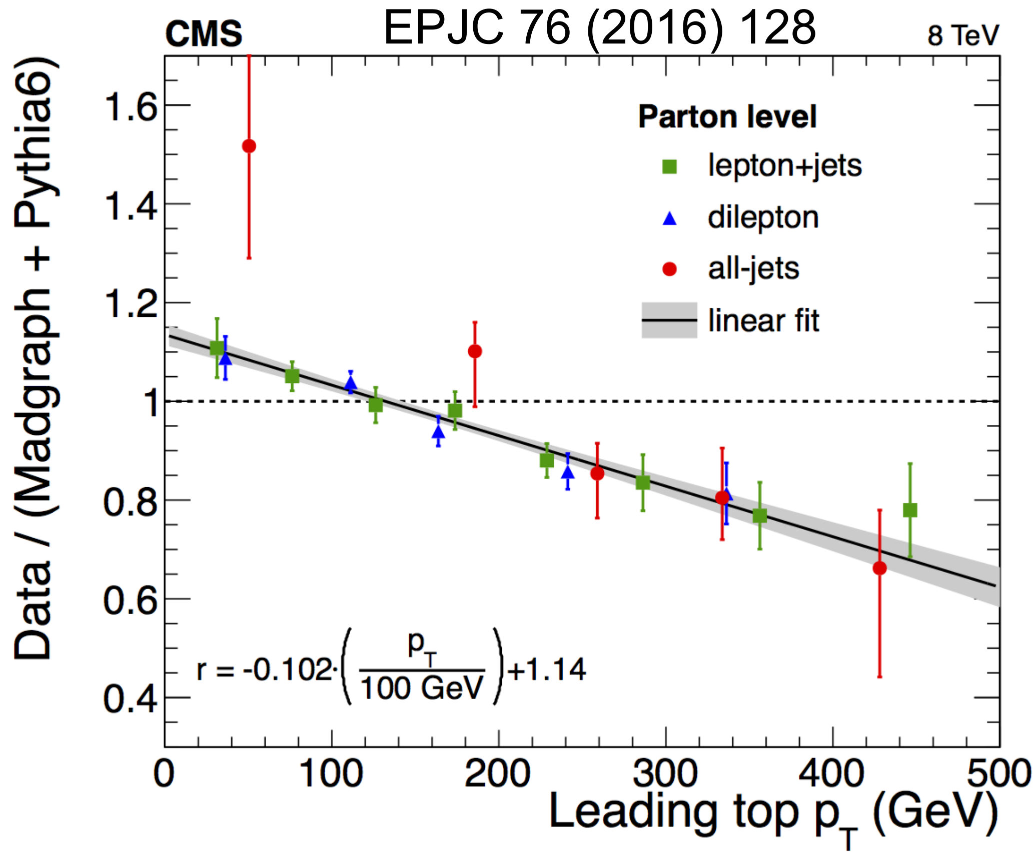
σ = 7.26 ± 0.13 (stat.) ± 0.57/0.50 (syst.) pb

$\delta\sigma/\sigma$ = 7.6% D0 [arxiv:1605.06168]

Differential cross sections

- Run I **top pT** measurements at ATLAS/CMS **not described** by NLO and most MCs
- Data is more soft: consistently seen in all decay channels



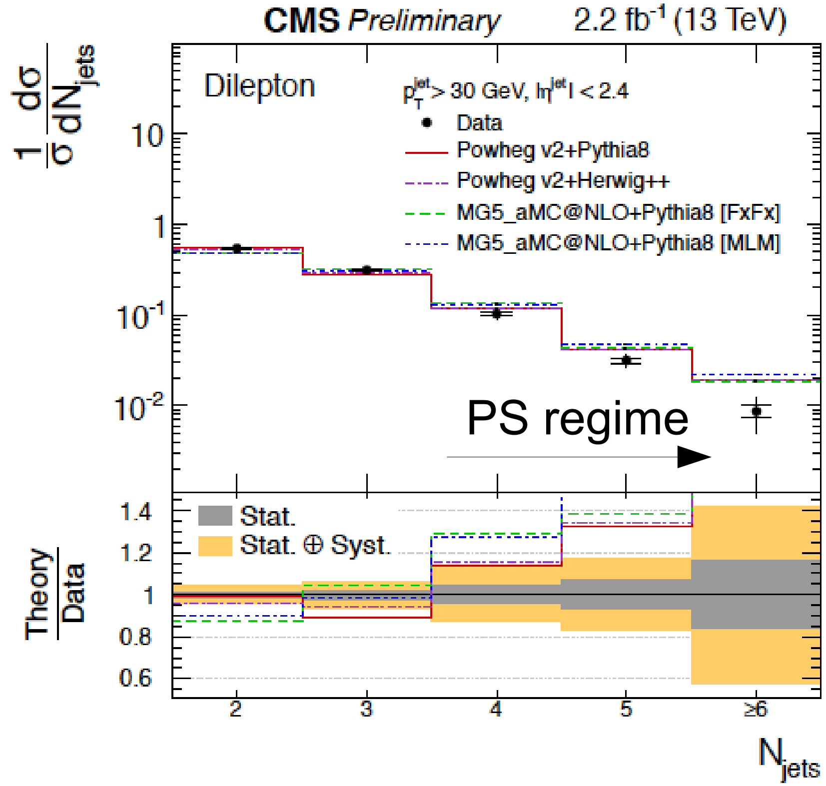


Spectra are described by NNLO+NNLL calculations by Czakon et al.

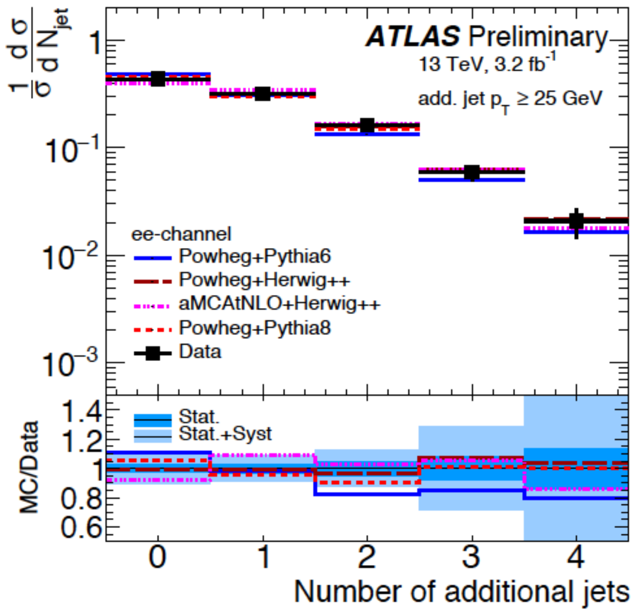
Differential cross sections

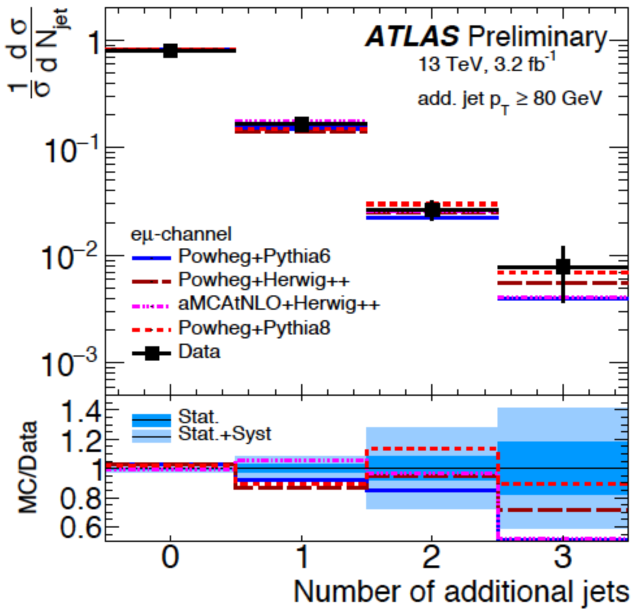
- CMS: 13 TeV data shows less jets than MC
  - Regime of the parton showers (PS)
  - NNLO describes top pT
  - Already systematically limited, better understanding of signal model needed

Dilepton CMS-PAS-TOP-16-011
l+jets CMS-PAS-TOP-16-008



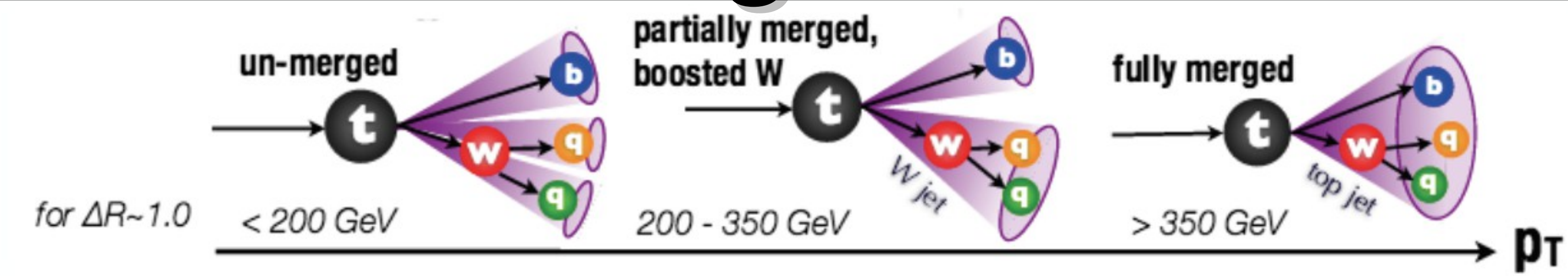
- ATLAS measures # additional jets with different thresholds
- Systematically limited, JES will improve



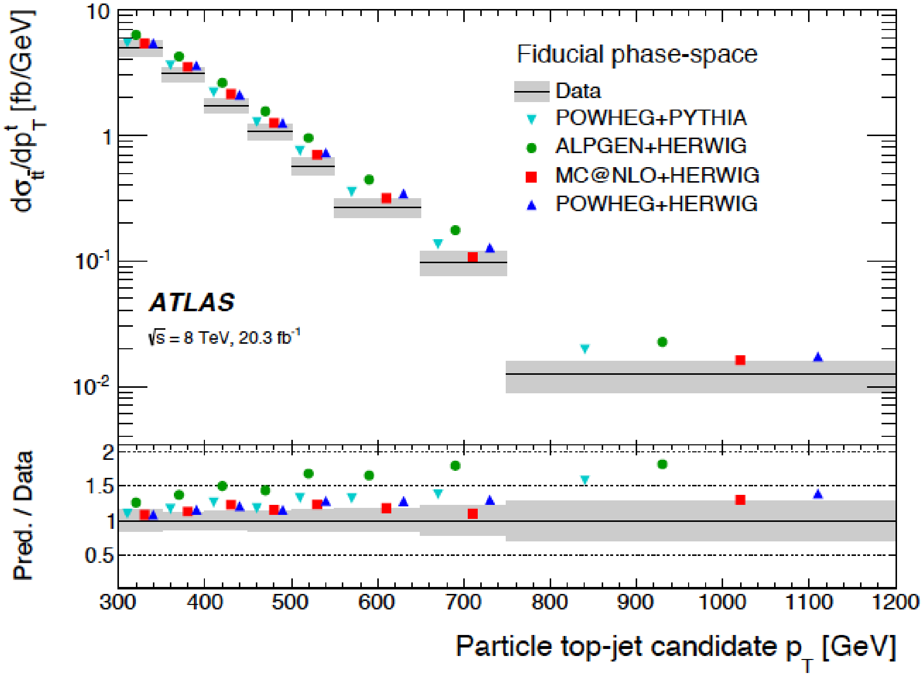


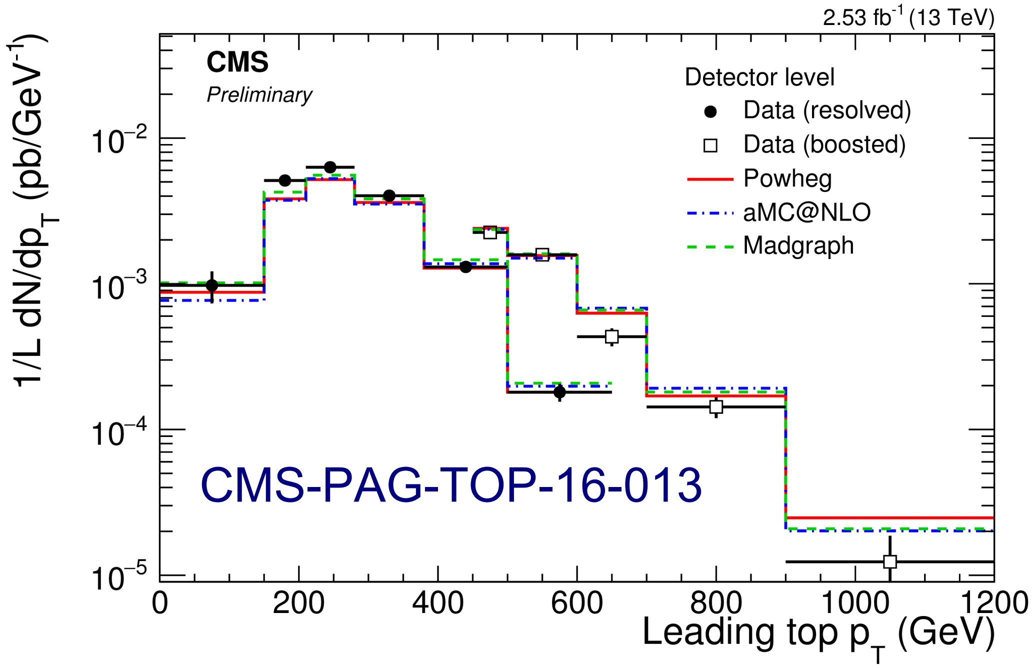
Differential cross section as a function of event variables: Submitted to PRD
CMS-PAG-TOP-12-042

Boosted regime



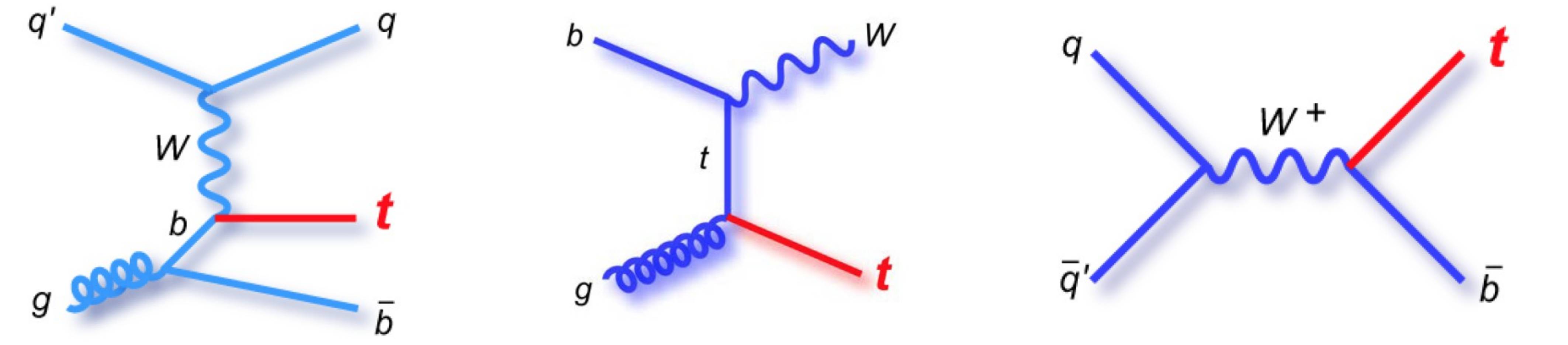
PRD 93, 032009 (2016)





- ATLAS boosted regime: pT > 300, trimmed large-R 1.0
- Consistent picture in boosted and resolved phase space
- Parton level results receive larger systematic uncertainties
- CMS 13 TeV all-hadronic combined resolved and boosted analysis

Single t quark production



- Test of EW interactions
- **Single top cross section as high as $t\bar{t}$ at 8 TeV – large samples**

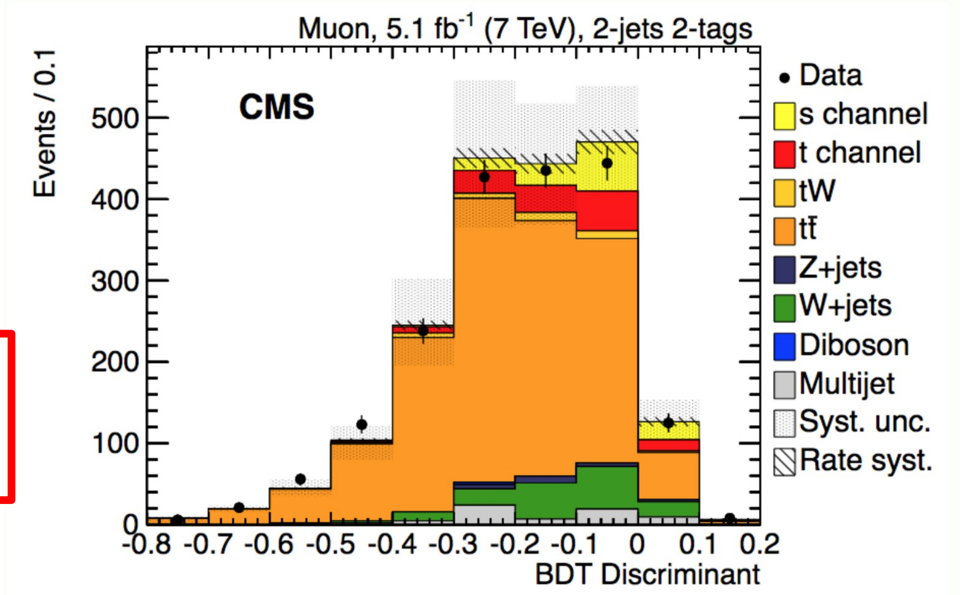
- Extract V_{tb}
- Search for flavor changing neutral currents, highly suppressed in SM
- Sensitivity to proton PDFs: especially b and u/d-ratio

Energy	Process	Cross section [pb]
Tevatron (1.96 TeV)	t	2.10 ± 0.13
	s	1.05 ± 0.06
	Wt	0.25 ± 0.03
LHC (7 TeV)	t	$65.9\ ^{+2.1}_{-0.7}$ (scale) $^{+1.5}_{-1.7}$ (PDF)
	s	4.56 ± 0.07 (scale) $^{+0.18}_{-0.17}$ (PDF)
	Wt	15.6 ± 0.4 (scale) ± 1.1 (PDF)
LHC (8 TeV)	t	$87.2\ ^{+2.8}_{-1.0}$ (scale) $^{+2.0}_{-2.2}$ (PDF)
	s	5.55 ± 0.08 (scale) ± 0.21 (PDF)
	Wt	22.2 ± 0.6 (scale) ± 1.4 (PDF)
LHC (13 TeV)	t	$216.99^{+6.62}_{-4.64}$ (scale) ± 6.16 (PDF)
	s	10.3 ± 0.4
	Wt	71.1 ± 3.8

s-channel single top

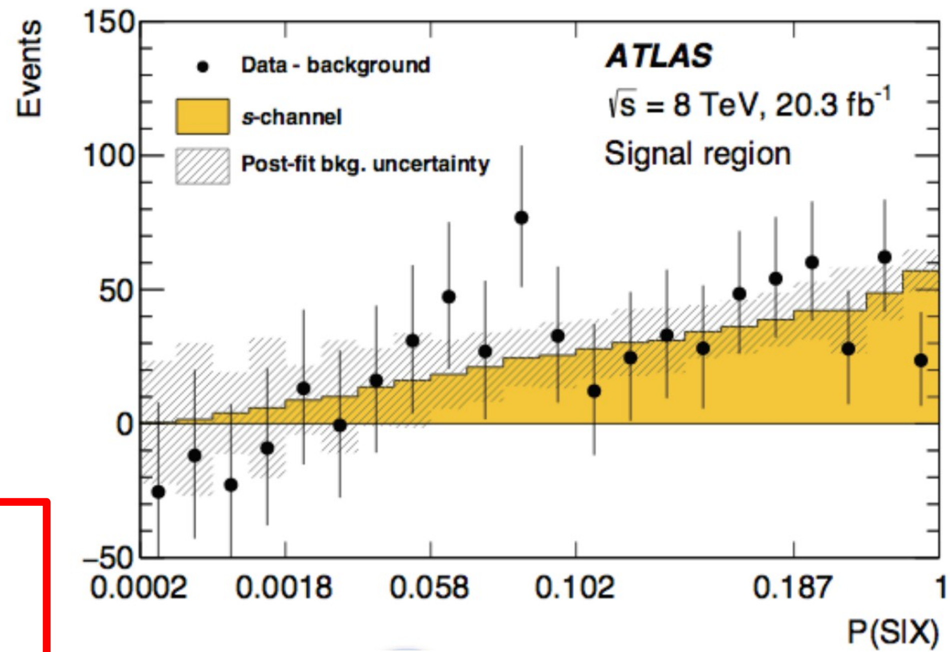
- CMS combines 7 and 8 TeV data
  - Categorized by #b-tags, #jets
  - Binned maximum-likelihood fit to a BDT discriminant

→ σ = 13.4 ± 7.3 (stat. + syst.) pb [δσ/σ=55%]
Observed 2.5 SD (1.0 SD expected)



- ATLAS sees **evidence for s-channel** at 8 TeV
  - Applies ME-method improving BDT result by about 50%
  - Other half of improvement from object Ids, evt selection, etc.
  - Binned maximum likelihood fit to ME discriminant and lepton charge

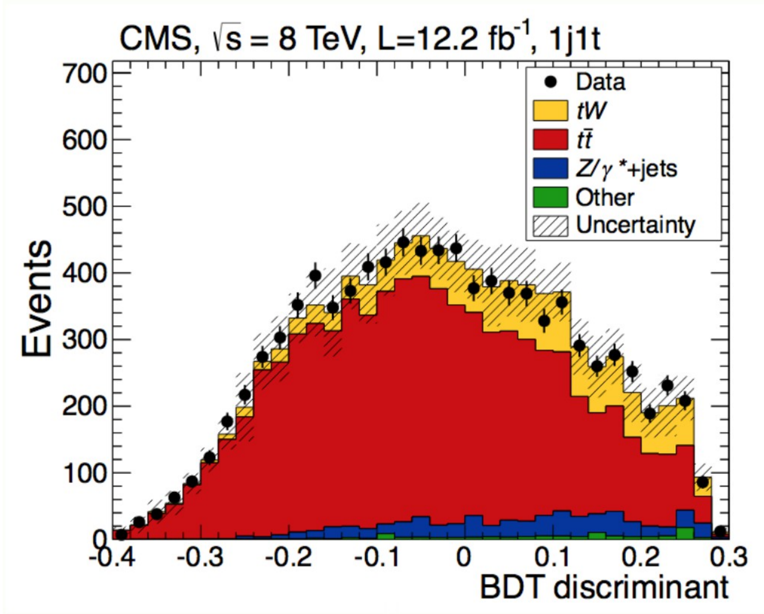
→ σ = 4.8 ± 0.8 (stat.) ± 1.6/1.3 (syst.) pb [δσ/σ=35%] Observed 3.2 SD (3.9 SD expected)



tW-channel single top

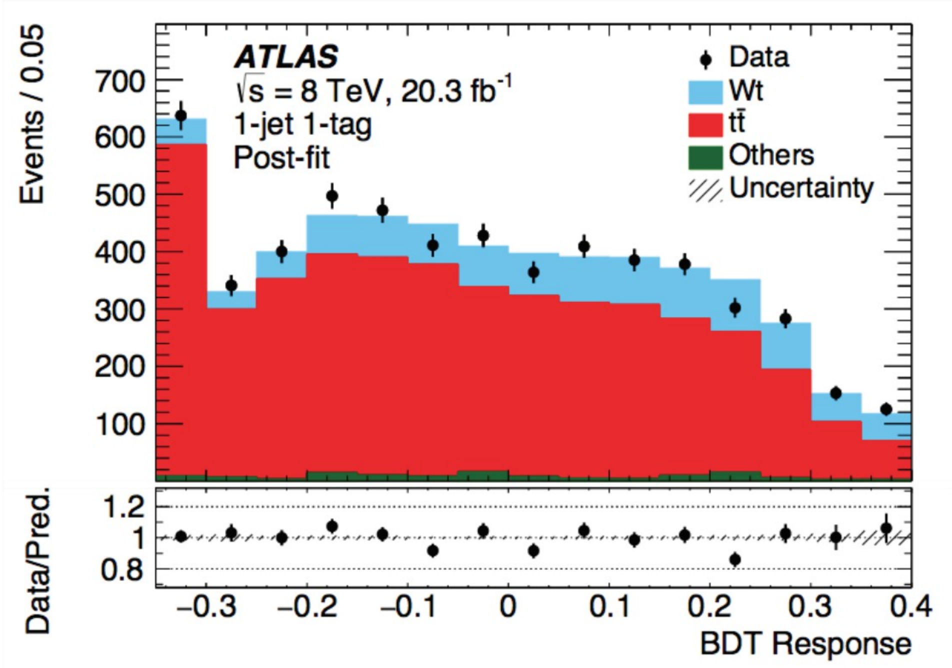
- CMS 1st tW-channel observation at 8 TeV
  - Categorized by #b-tags, #jets
  - Binned maximum-likelihood fit to a BDT discriminant

→ σ = 23.4 ± 5.4 (stat. + syst.) pb [$\delta\sigma/\sigma$=23%]
6.1 SD (5.4 SD expected)



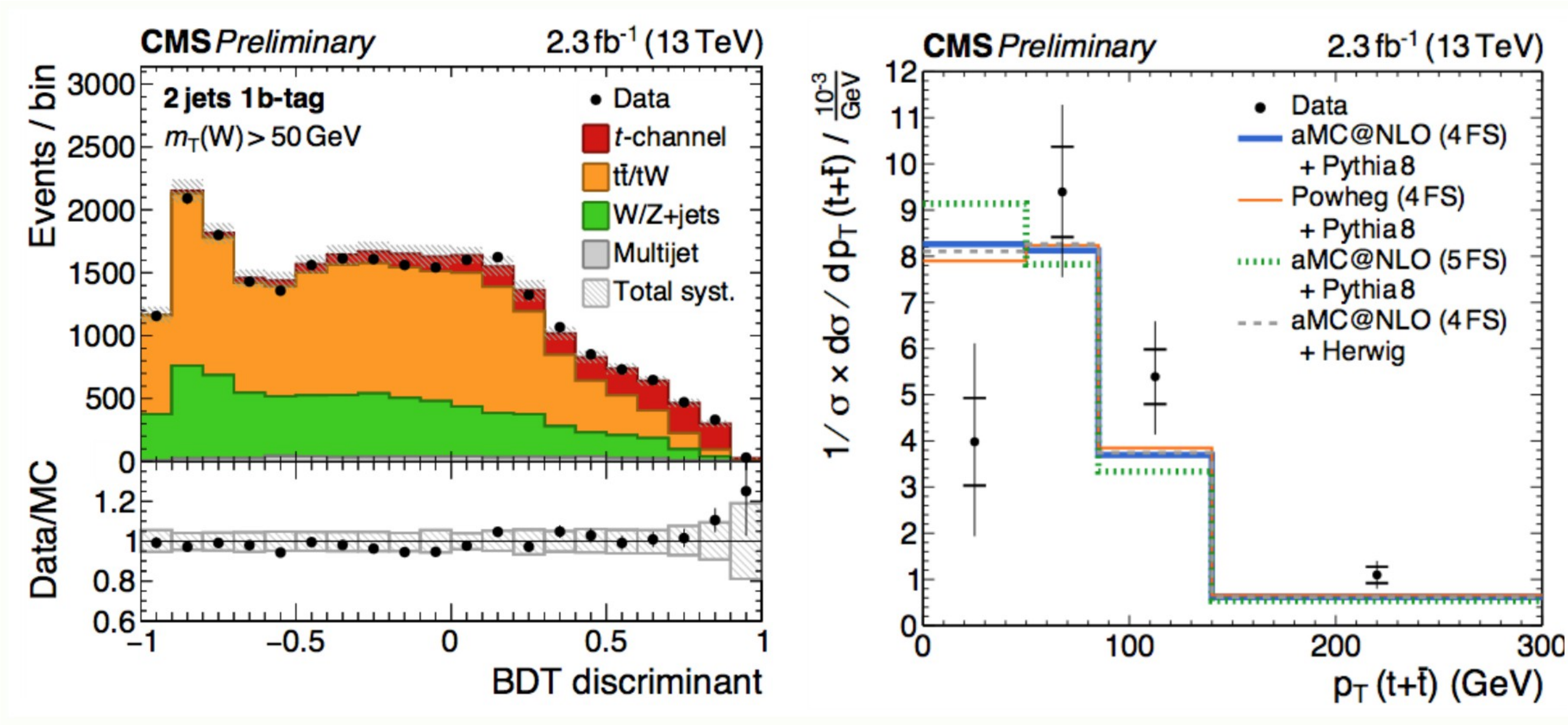
- ATLAS observes tW-channel at 8 TeV
  - Two oppositely charged leptons
  - Profile likelihood fit for signal + bg
  - First measure fiducial volume than full phase space (uncertainty of 9%)

→ σ = 23.0 ± 1.3 (stat.) ± 3.4/3.7 (syst.) pb
[$\delta\sigma/\sigma$=17%] and 7.7 SD (6.9 SD expected)



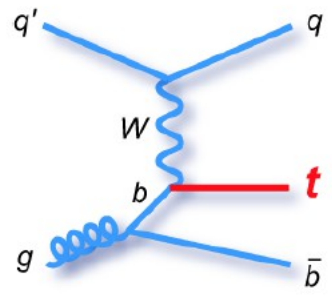
Single top goes differential

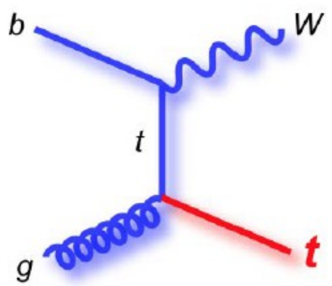
- CMS: First differential measurement of **t-channel top** production @13 TeV
- Muon-channel only employing a BDT discriminator and maximum likelihood fit
- Correct detector and measure parton level cross section for pT and y

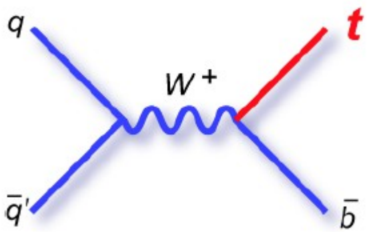


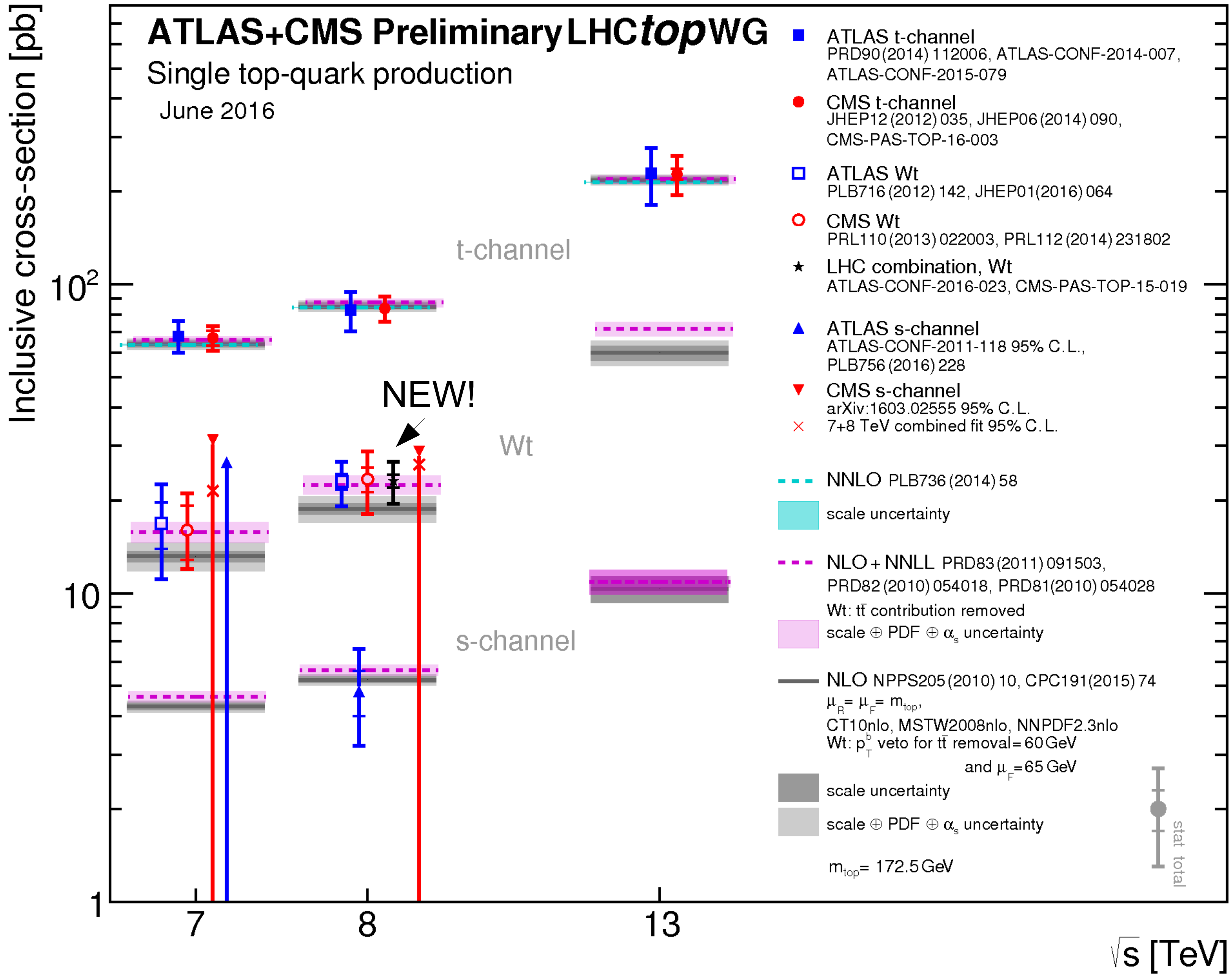
Single top quark - summary

- Decay channels:

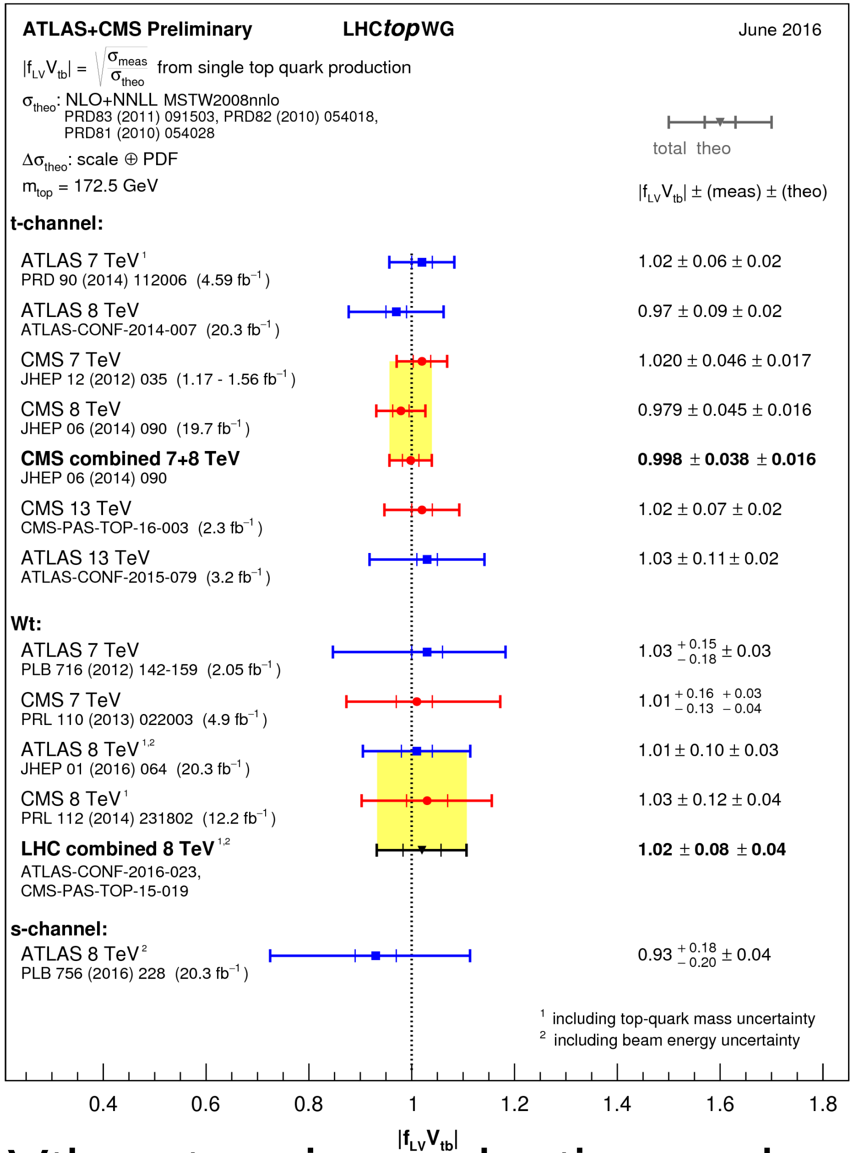




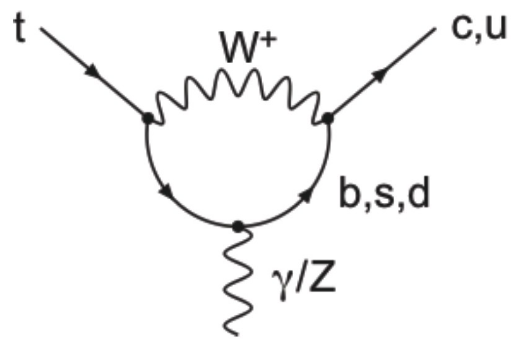




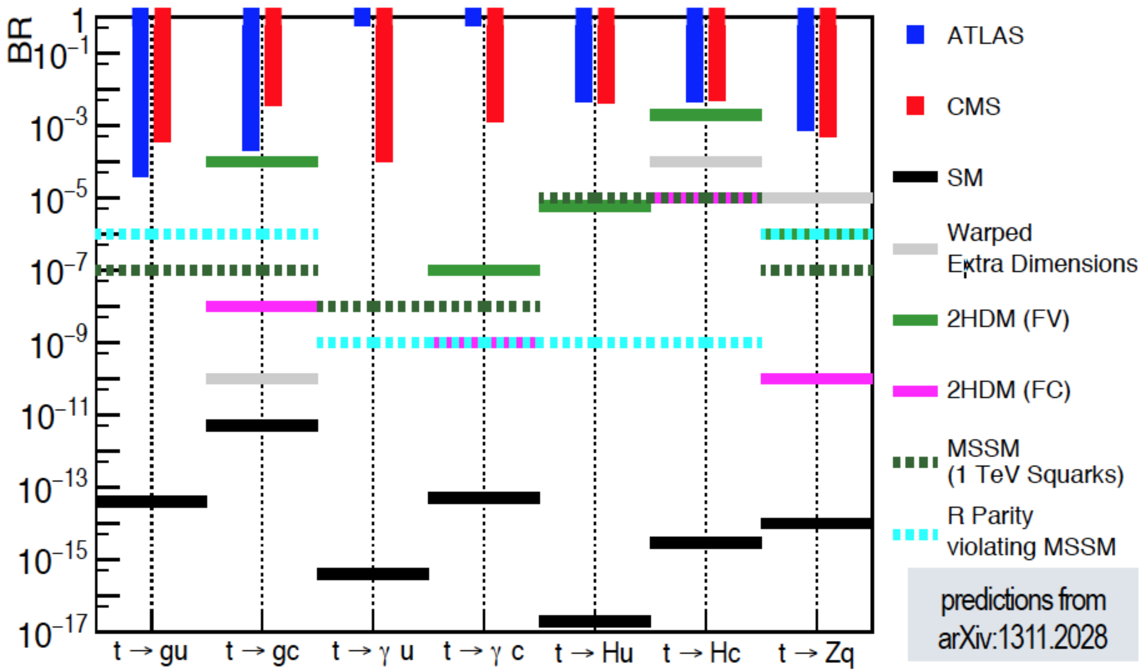
Vtb & FCNC



Flavor Changing Neutral Currents are highly suppressed in SM



Still above SM predictions but reached sensitivity to certain BSM models



- Vtb enters in production and decay: $\sigma \sim |V_{tb}|^2$

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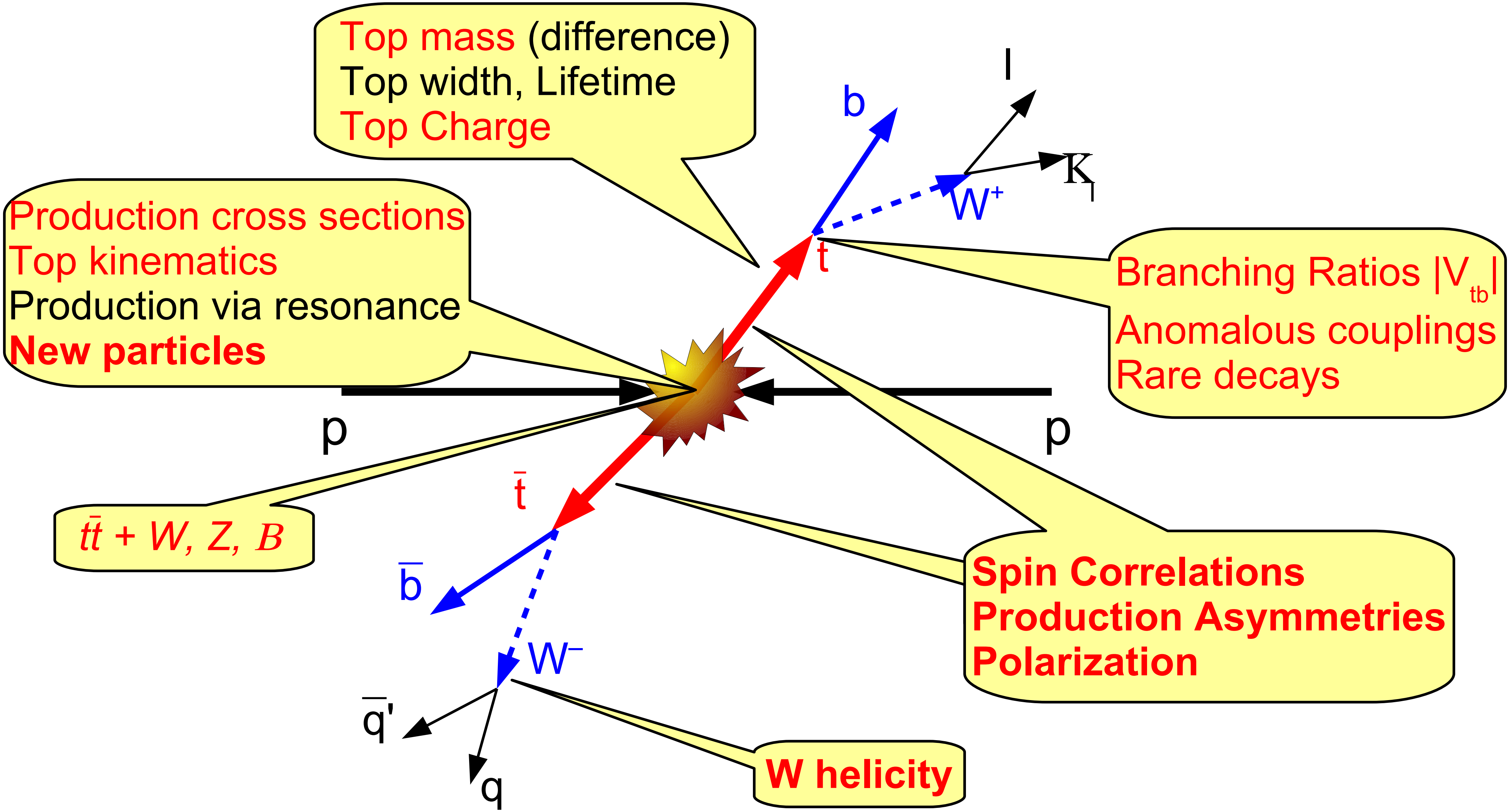
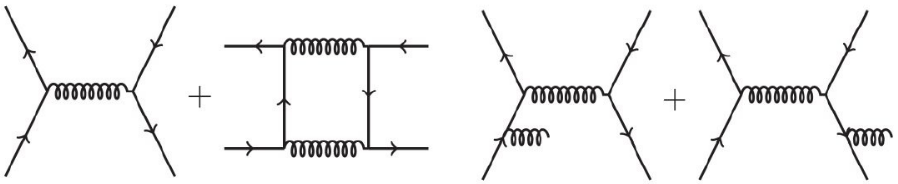
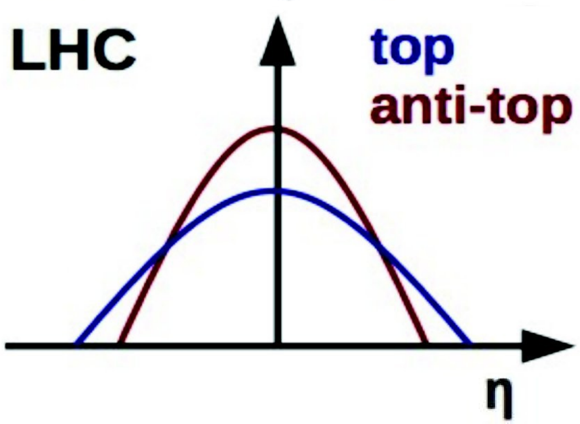


→ **Selection of results, focus on most recent and/or precise results**

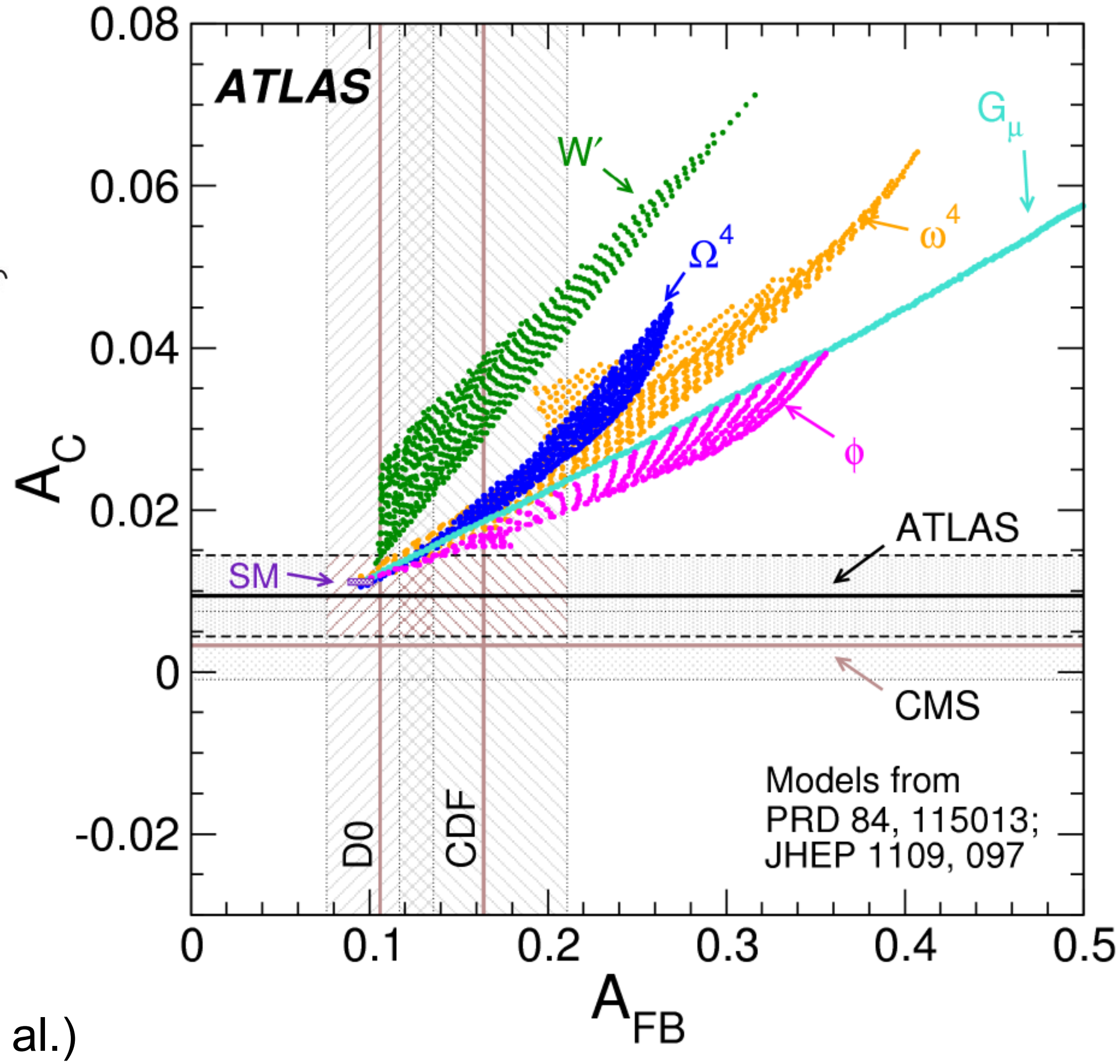
Top quark asymmetries

- <u>Measurements at Tevatron & LHC are complementary</u>
  - Variety of models (large parameter space) still allowed → W', G, ω, ϕ, Ω
  - $q\bar{q}$ initial state, in gg is zero
  - NLO is 1st appearance





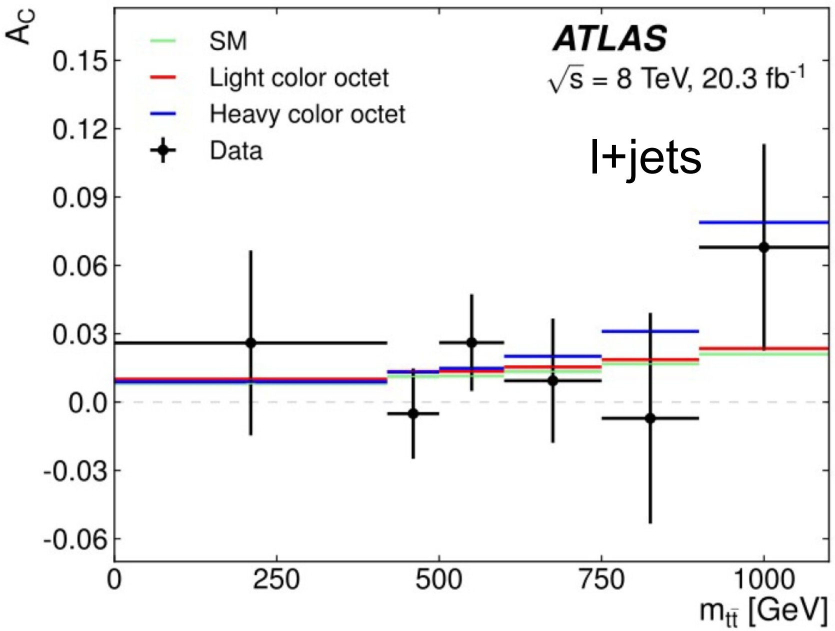
$$A_C = \frac{N(\Delta|y_t| > 0) - N(\Delta|y_t| < 0)}{N(\Delta|y_t| > 0) + N(\Delta|y_t| < 0)}$$



- NLO+EW prediction (Bernreuther, et al.)
  → $A_C^{t\bar{t}} = +0.011 \pm 0.0004$

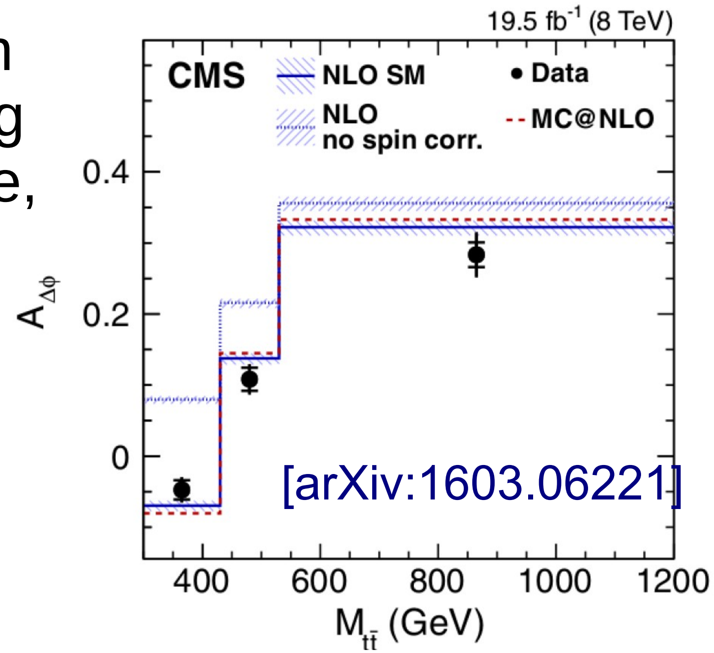
More on asymmetries: D. Millar

Charge asymmetries



[arXiv:1604.05538]

- Lepton+jets & Dilepton
- Fully Baysian unfolding
- Individual channels (ee, μμ, eμ) are combined



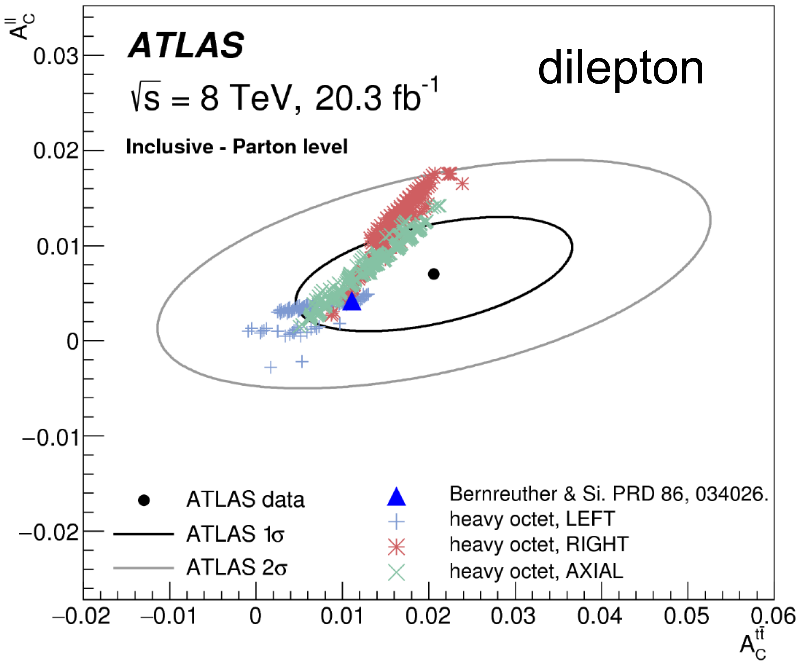
→ Measure top and lepton based asymmetry, as well as differential

In agreement with SM:

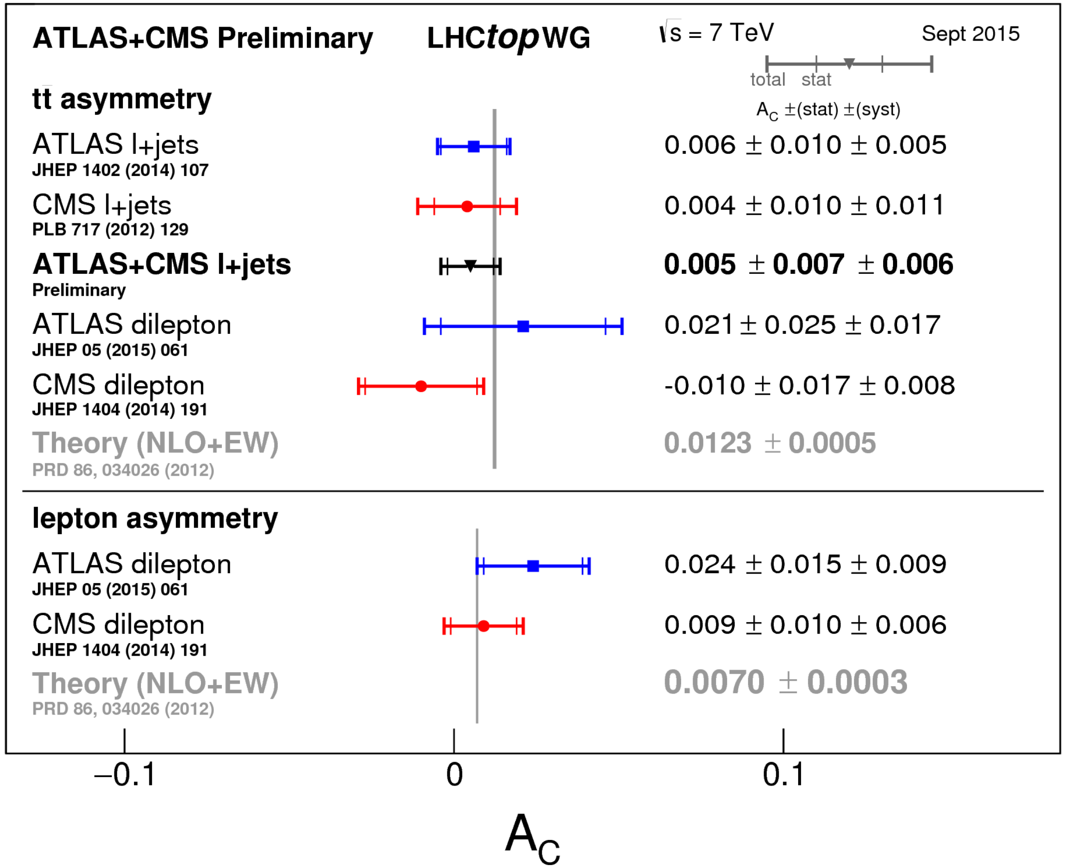
A_C^{ll} = 0.008 ± 0.006 (tot)

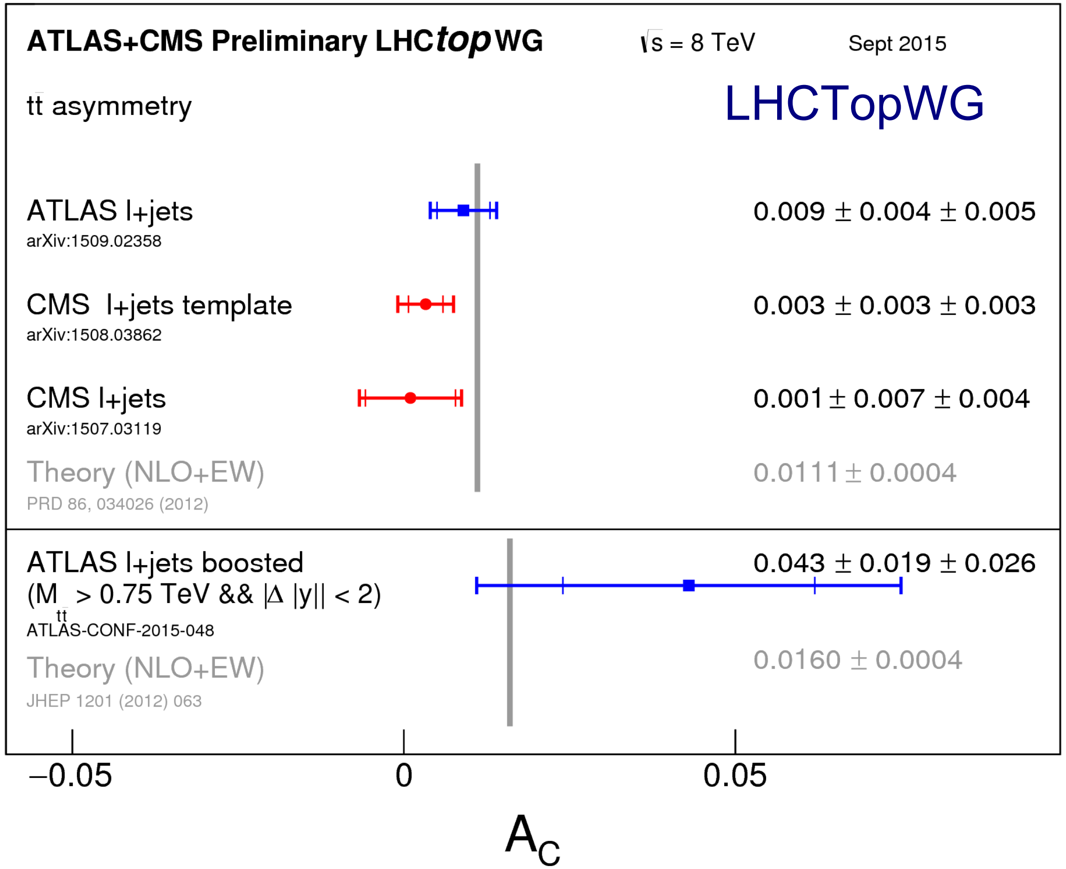
$A_C^{t\bar{t}}$ = 0.021 ± 0.016 (tot)

$A_C^{t\bar{t}}$ = 0.009 ± 0.005 (tot) [l+jets]



Top quark asymmetries





Summary of the current Situation:

- Experiment: Dominated by stats & signal model dominates systematic unc's
- Theory: Need QCD predictions at NNLO

→

- All measurements are (so far) in agreement with SM
- At 13 TeV and new methods: expect to observe SM asymmetries
  - Larger gg fraction reduces them → improved methods, e.g. [arxiv:1309.2889]

Top quark spin correlations

- Top quark spins expected to be correlated in SM (short life time)
- Spin analyzing power of leptons is 1, measure lepton distributions
- Powerful handle to search for BSM in difficult phase space regions

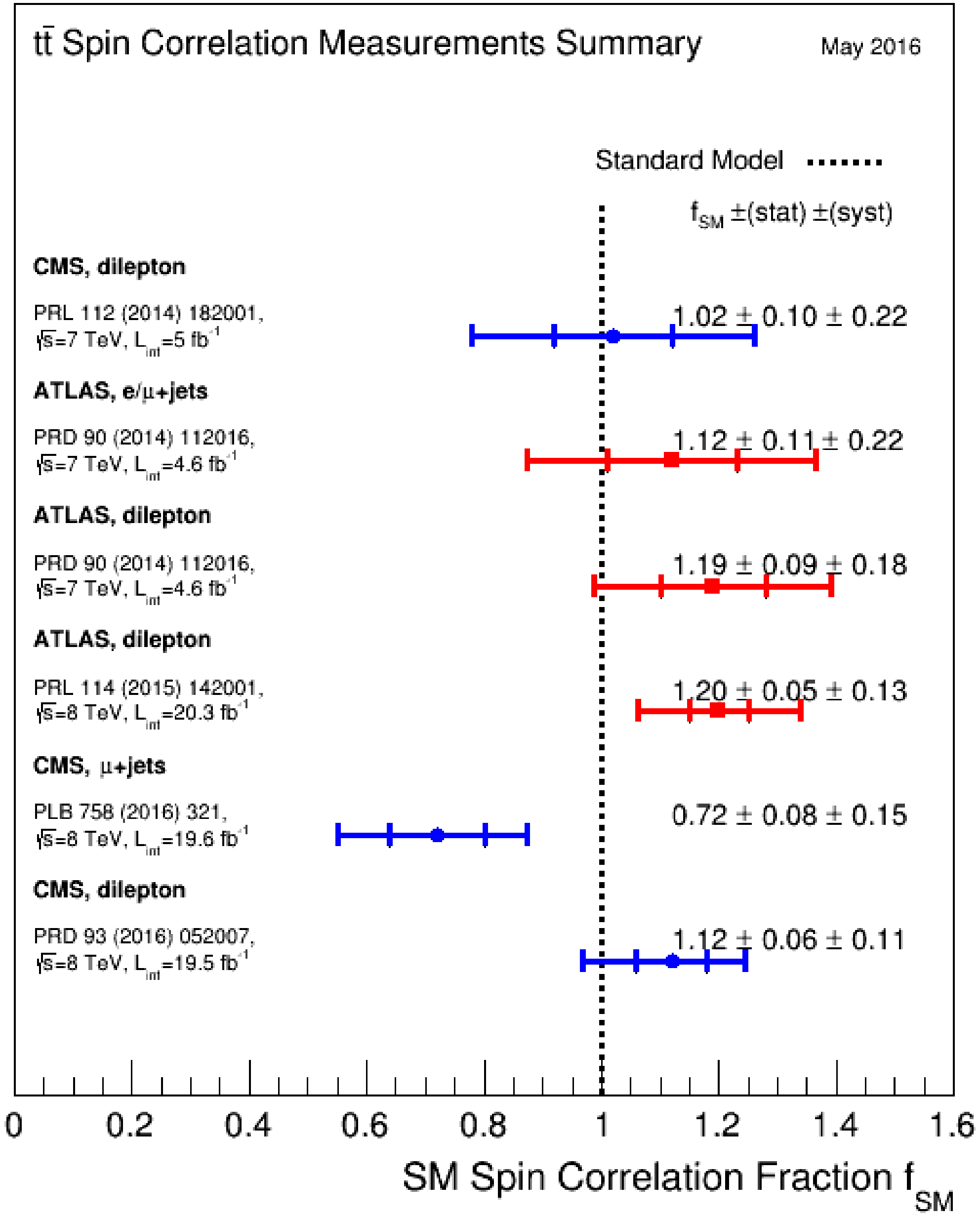
- Spin correlation strength:

$$A = \frac{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}) - (N_{\uparrow\downarrow} + N_{\downarrow\uparrow})}{(N_{\uparrow\uparrow} + N_{\downarrow\downarrow}) + (N_{\uparrow\downarrow} + N_{\downarrow\uparrow})}$$

$$f = \frac{N^{t\bar{t}}_{SM}}{N^{t\bar{t}}_{SM} + N^{t\bar{t}}_{uncor}}$$

$$A^{meas}_{basis} = A^{SM}_{basis} \cdot f$$

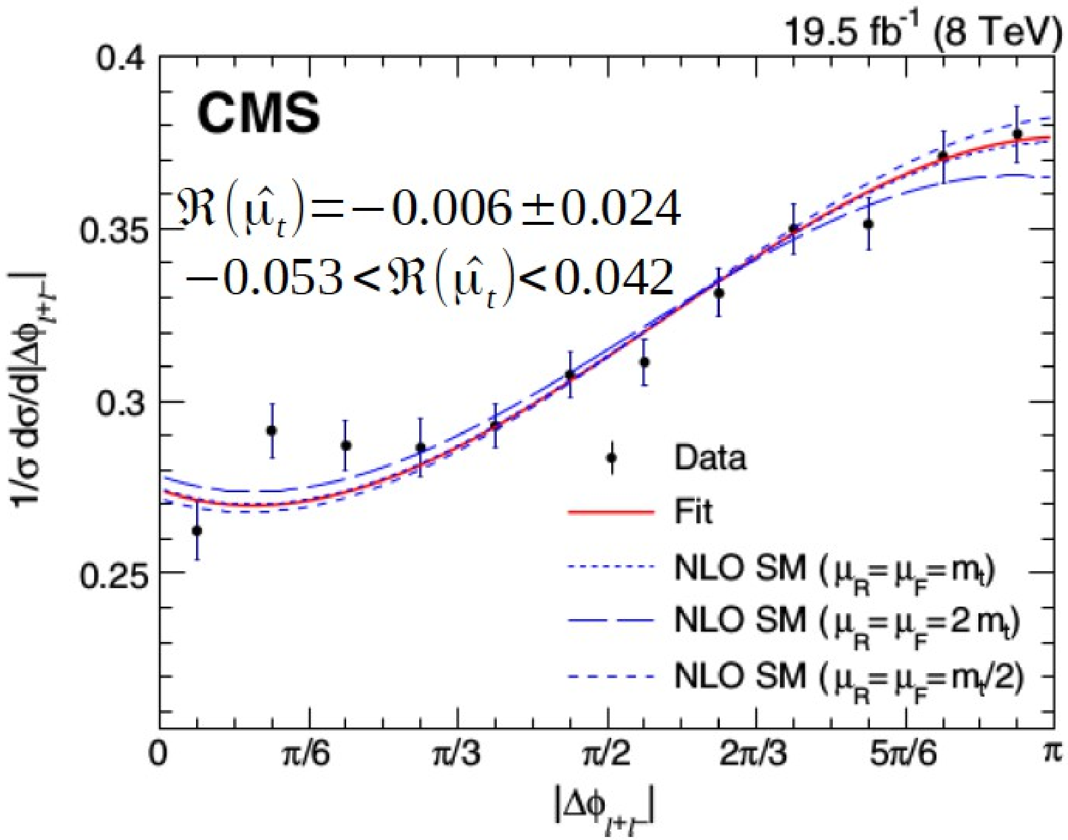
→ A depends on basis, energy, production mechanism
→ f represents degree of SC relative to the SM



Top quark spin correlations

- Top quark spins expected to be correlated in SM
- Reconstruction based on leptons → Dilepton decay channel, ≥ 2 jets
- Inclusive and differential measurements @ parton level by reg. Unfolding
- <u>Dominated by:</u> Unfolding & top p_T reweighting

→ **Results agree with NLO QCD: Spins correlated!**



•Search for top chromomagnetic anomalous couplings using differential cross section distribution

PRD 93, 052007 (2016)

CP-conserving dipole moment   CP-violating dipole moment

$$\mathcal{L}_{\mathrm{eff}} = -\frac{\tilde{\mu}_t}{2}\bar{t}\sigma^{\mu\nu}T^a t G^a_{\mu\nu} - \frac{\tilde{d}_t}{2}\bar{t}i\sigma^{\mu\nu}\gamma_5 T^a t G^a_{\mu\nu}$$

Re(μ_t) = -0.006 ± 0.024 (tot.)

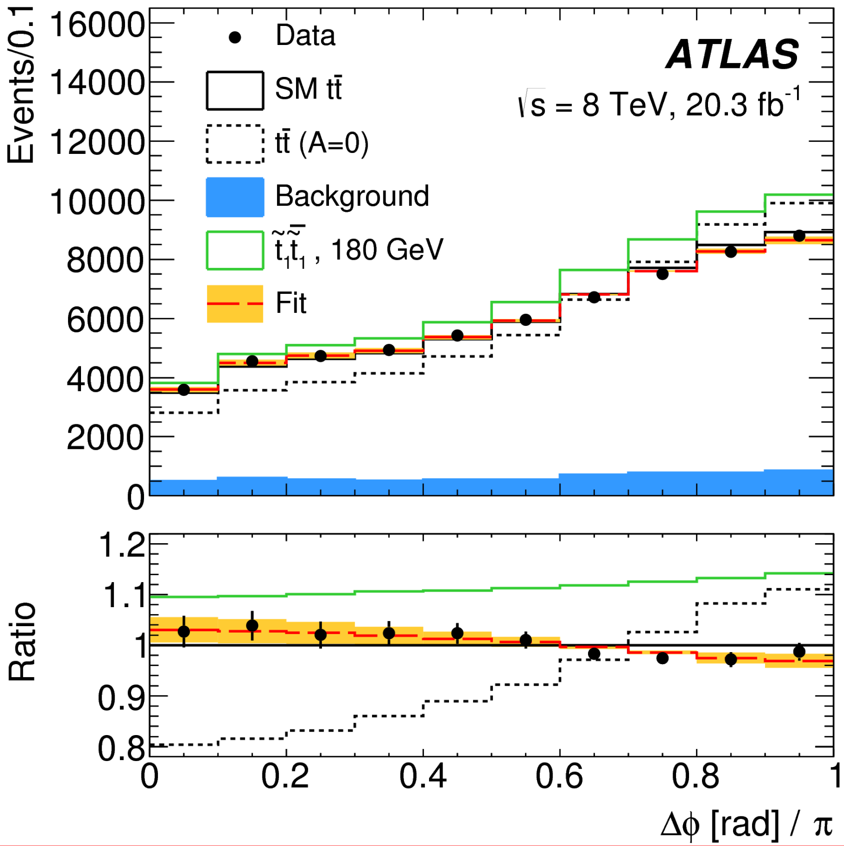
– 0.053 < Re(μ_t) < 0.042 at 95% CL

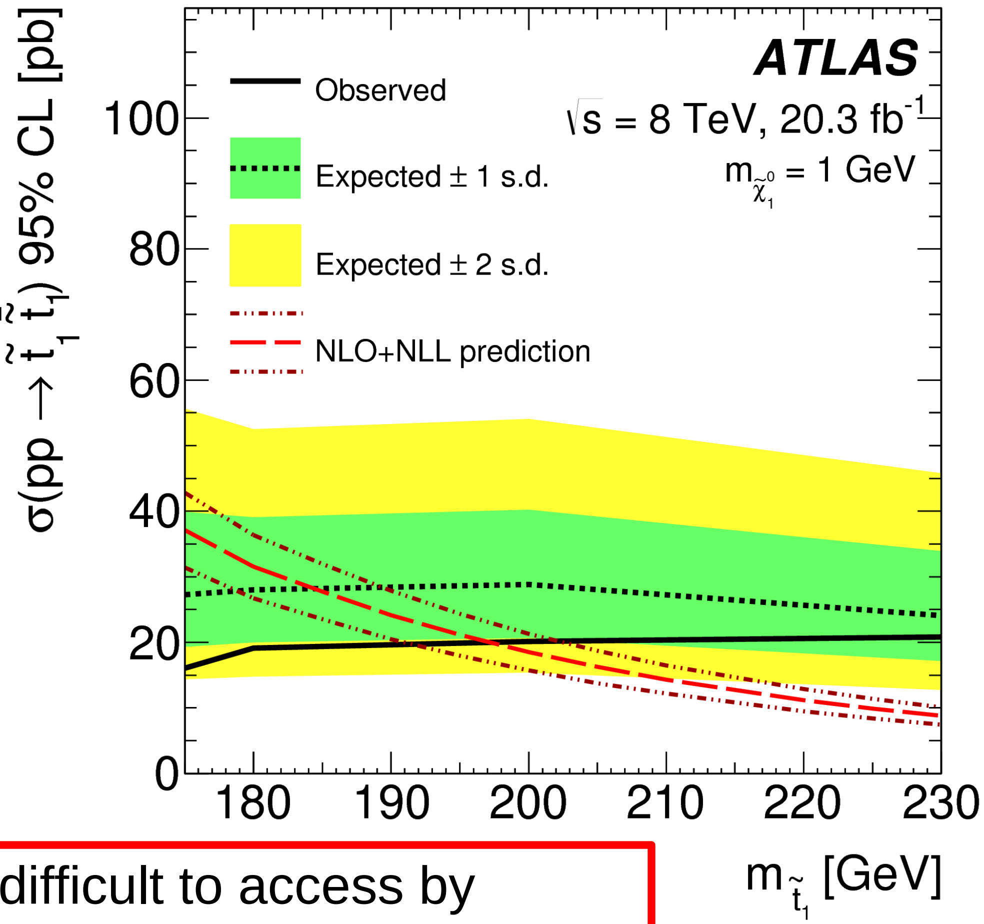
– 0.068 < Re(d_t) < 0.067 at 95% CL

Top quark spin correlations

- High precision SM measurements, more and more important in Run II
- Access top squarks (MSSM: 100% $t \rightarrow \tilde{t}\vartheta$) of similar mass as m_t
- Uncertainties dominated by: signal model (Hadronization and ISR/FSR)

PRL. 114, 142001 (2015)

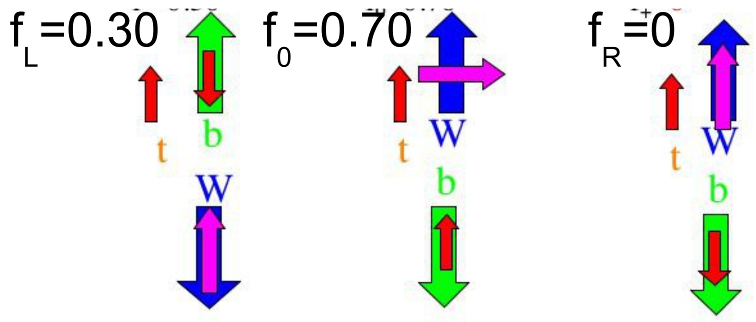




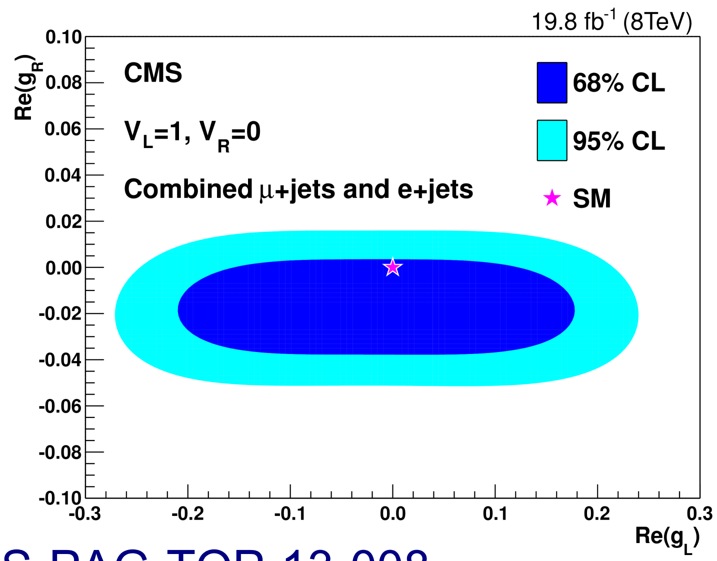
Exclusion between m_t and 191 GeV at 95% CL, difficult to access by "standard" searches PRL 114, 142001 (2015)

W helicity

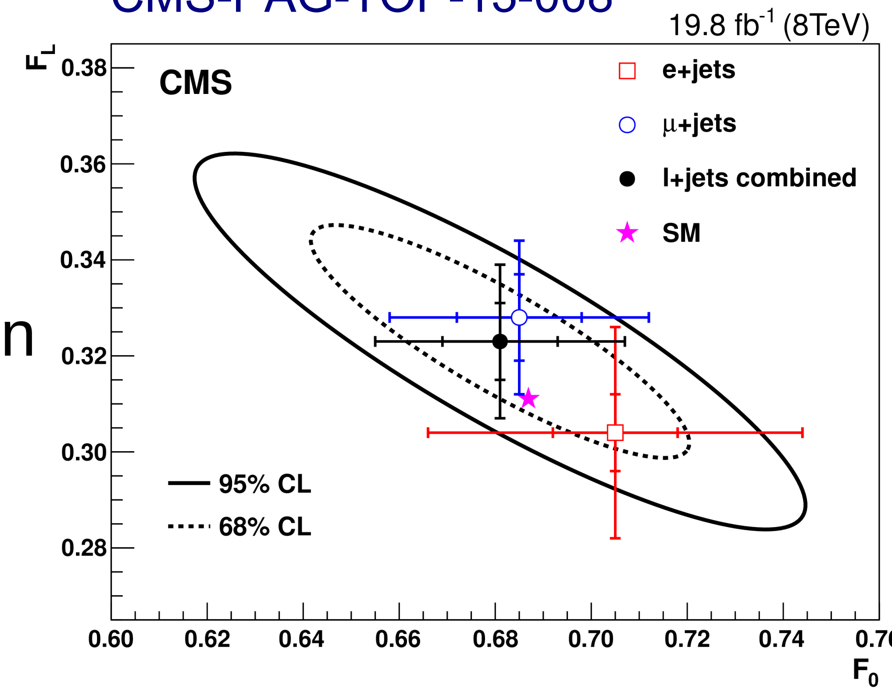
- W helicity in SM:



- W helicity in top pair l+jets channel
- CMS also measured W helicity in single top events
  - Similar precision but <u>orthogonal</u> systematic uncertainties in single top channels
  - Signal model & template statistics



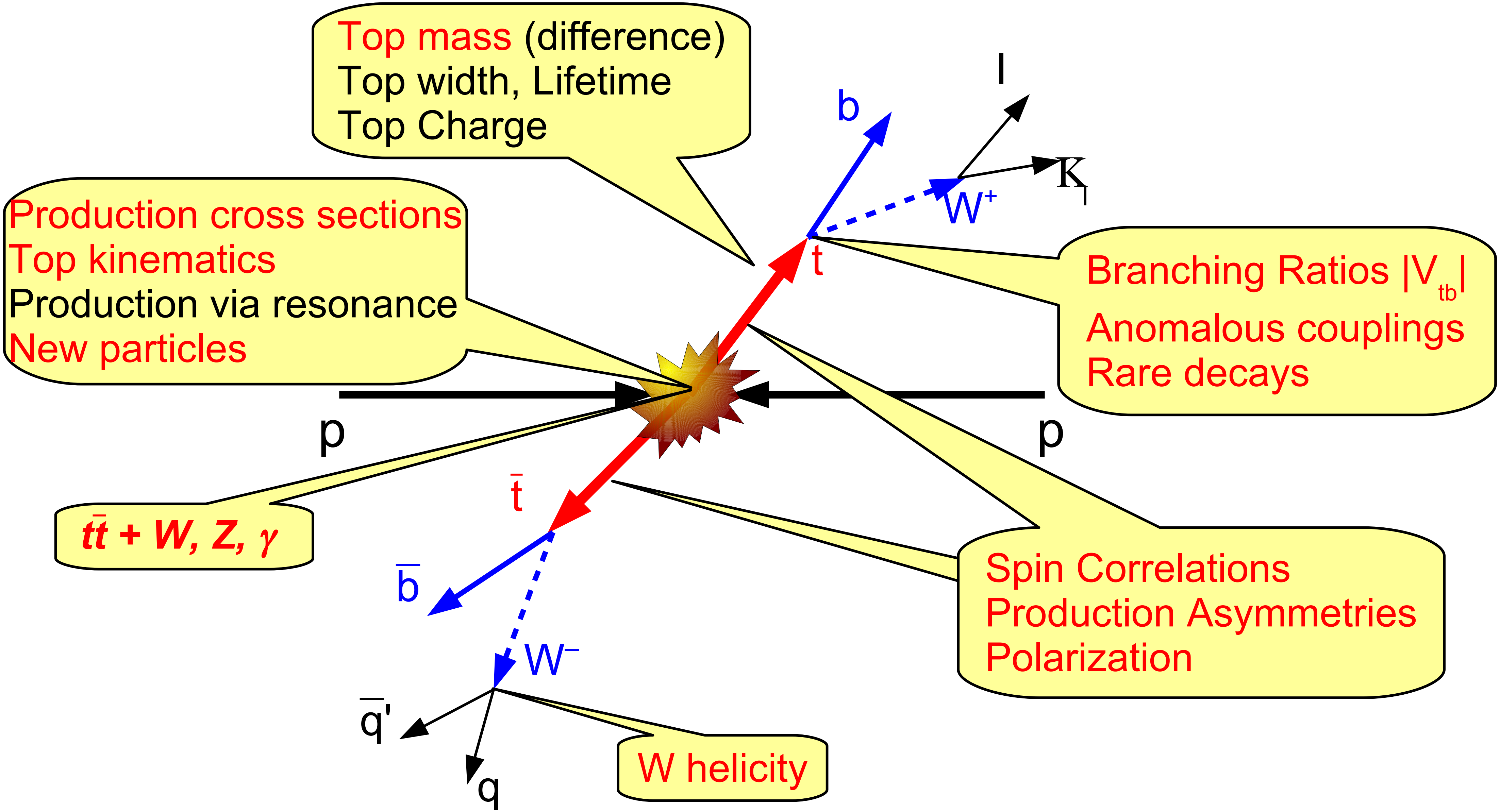
CMS-PAG-TOP-13-008



Most accurate experimental determination

$$F_0 = 0.681 \pm 0.012 \text{ (stat.)} \pm 0.023 \text{ (syst.)}$$
$$F_L = 0.323 \pm 0.008 \text{ (stat.)} \pm 0.014 \text{ (syst.)}$$
$$F_R = 0.004 \pm 0.005 \text{ (stat.)} \pm 0.014 \text{ (syst.)}$$

Content

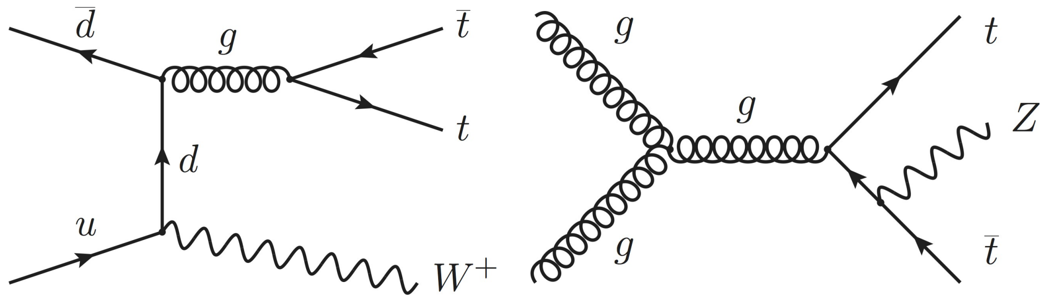


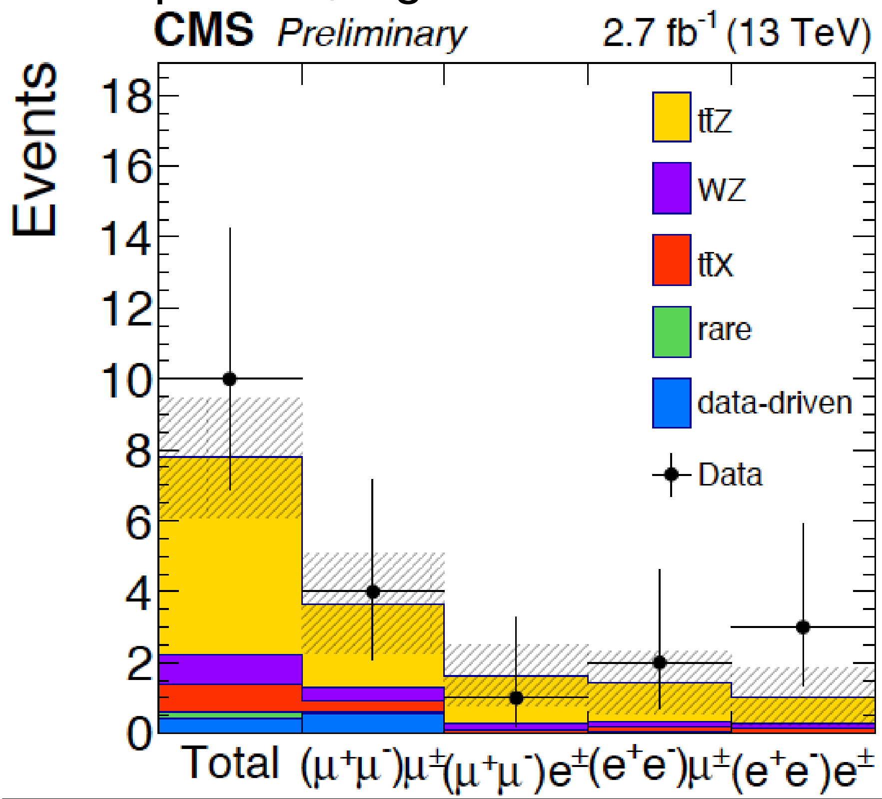
→ **Selection of results, focus on most recent and/or precise results**

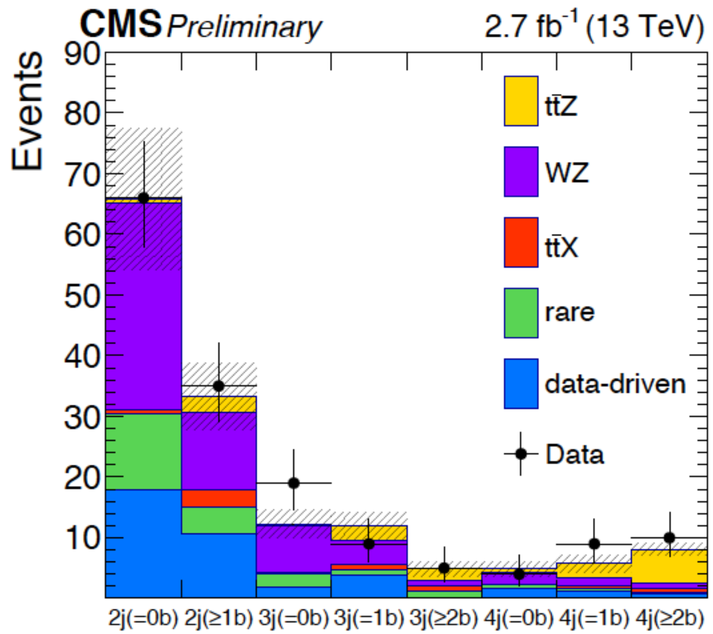
Ttbar + X: W, Z, γ

CMS-PAG-TOP-16-009

- Associated production of *W* and *Z* in the SM (different mechanisms)
- Observations at 8 TeV at ATLAS and CMS
- 13 TeV ATLAS & CMS:
  - Extract σ employing binned profile LH fit
  - ATLAS various signal & control regions, CMS includes 3 & 4 lepton final states
  - Systematic unc's dominated by: Lepton ID, signal model







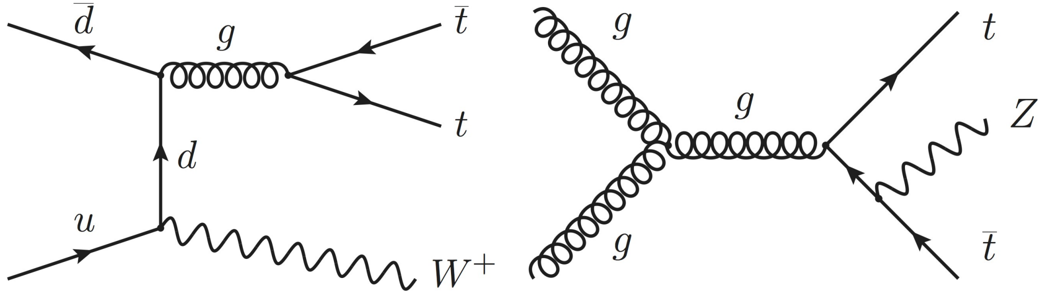
→ $\sigma(t\bar{t}Z) = 1.1 \pm 0.4$ (stat.) ± 0.2 (syst.) pb

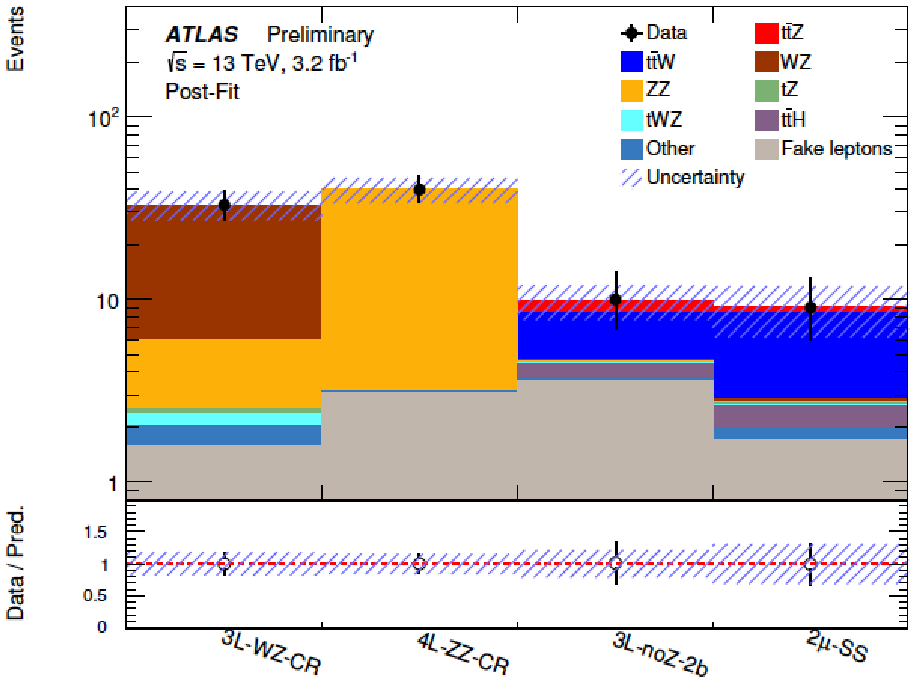
[δσ/σ=36%] Observe 3.6 SD (3.1 expected)

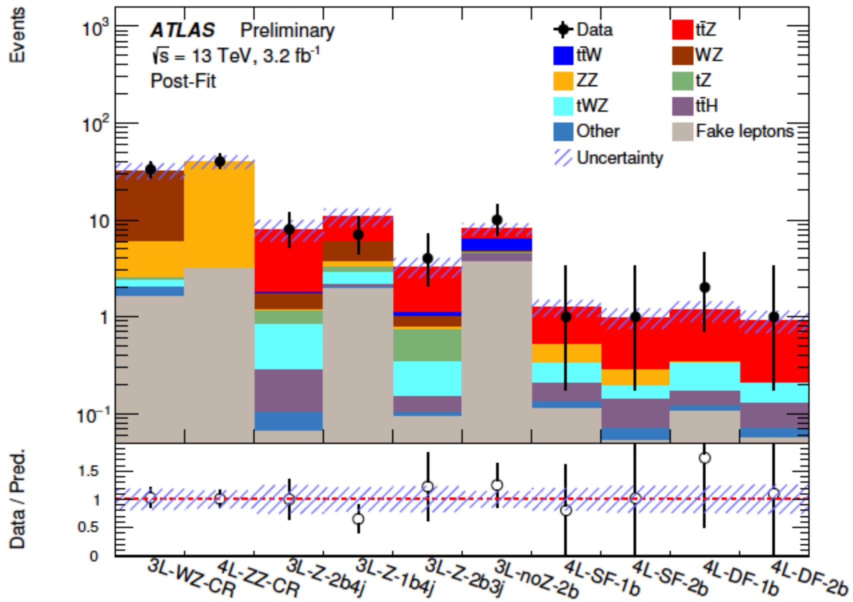
Ttbar + X: W, Z, γ

ATLAS-CONF-2016-003

- Associated production of *W* and *Z* in the SM (different mechanisms)
- Observations at 8 TeV at ATLAS and CMS
- 13 TeV ATLAS & CMS:
  - Extract σ employing binned profile LH fit
  - ATLAS various signal & control regions, CMS includes 3 & 4 lepton final states
  - Systematic unc's dominated by: Lepton ID, signal model



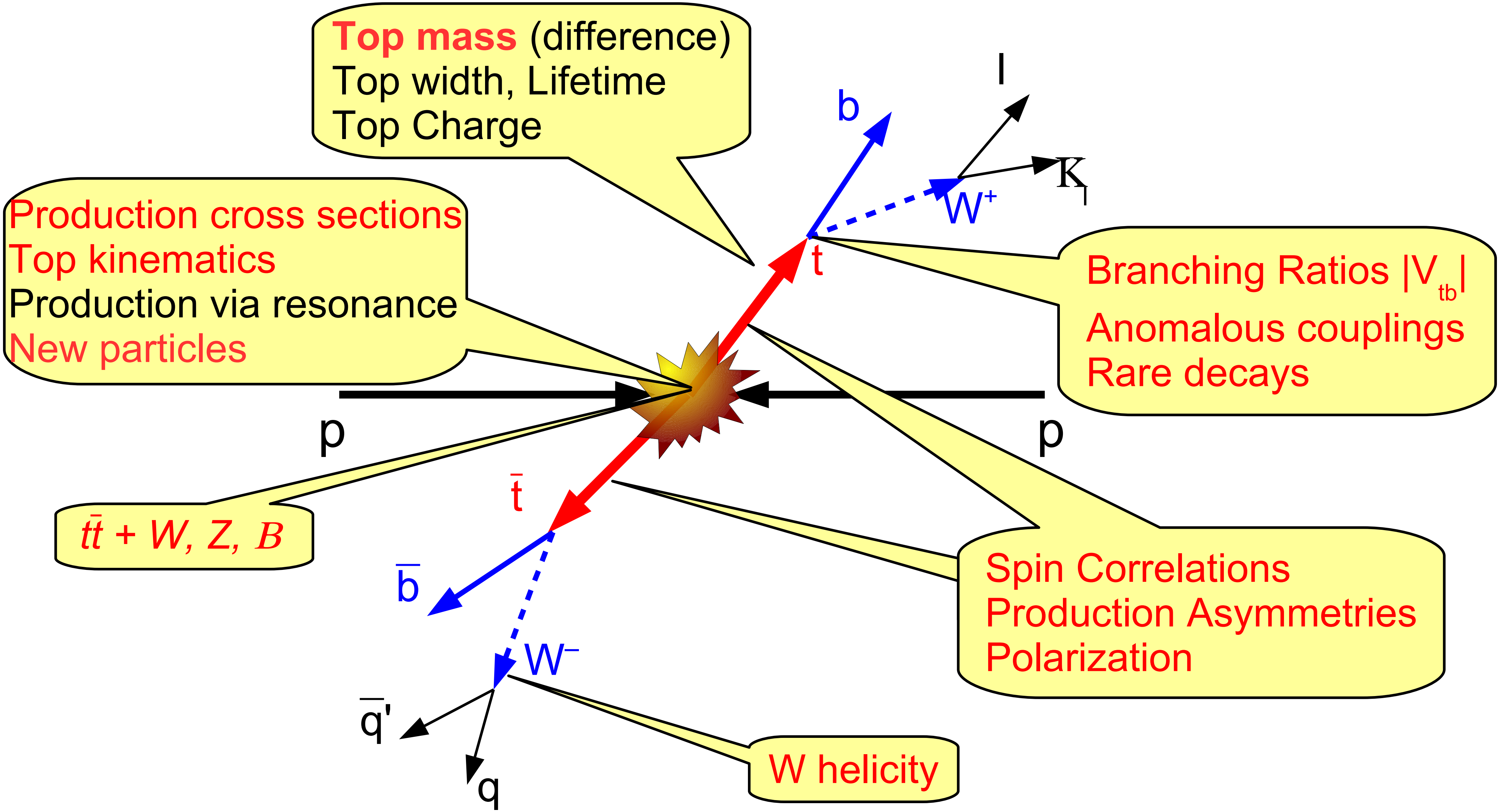




→

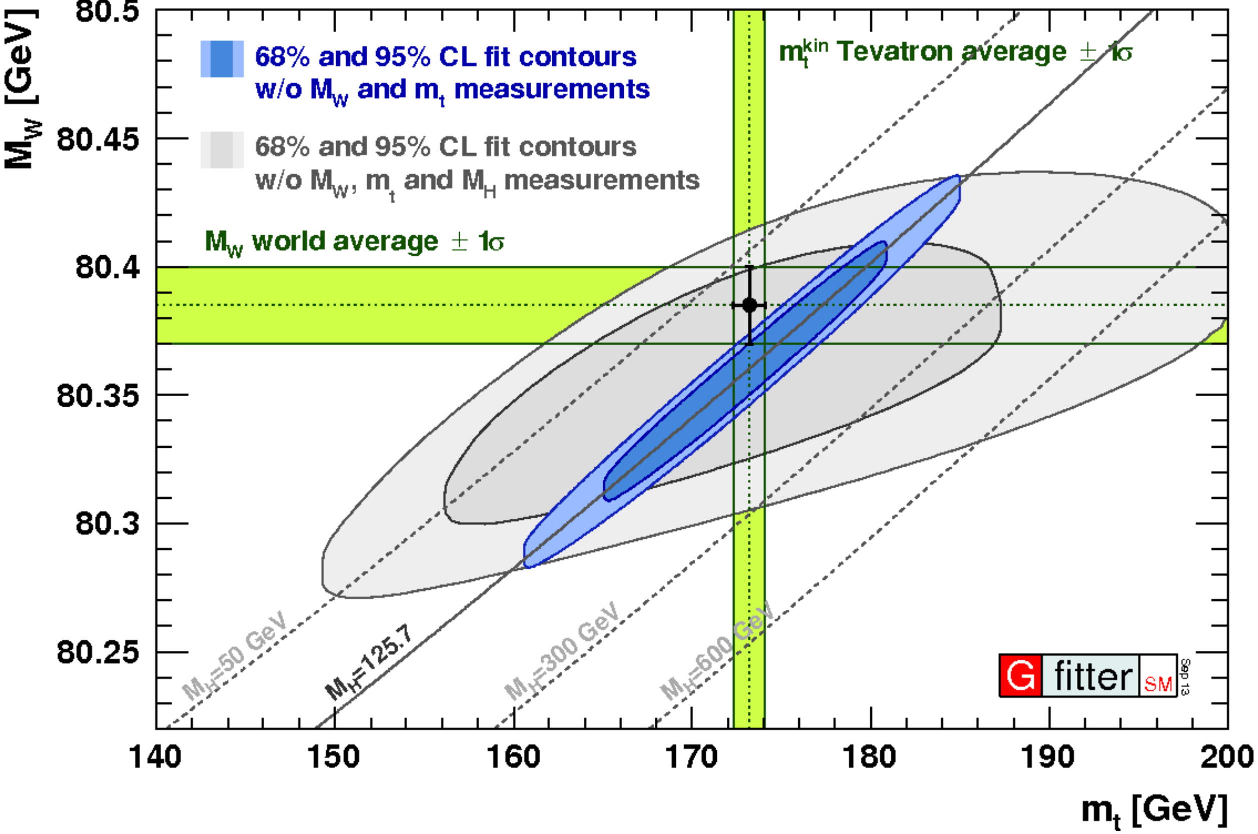
$\sigma(t\bar{t}Z)$ = 0.9 ± 0.3 (stat.) ± 0.1 (syst.) pb
$\sigma(t\bar{t}W)$ = 1.4 ± 0.7 (stat.) ± 0.3 (syst.) pb

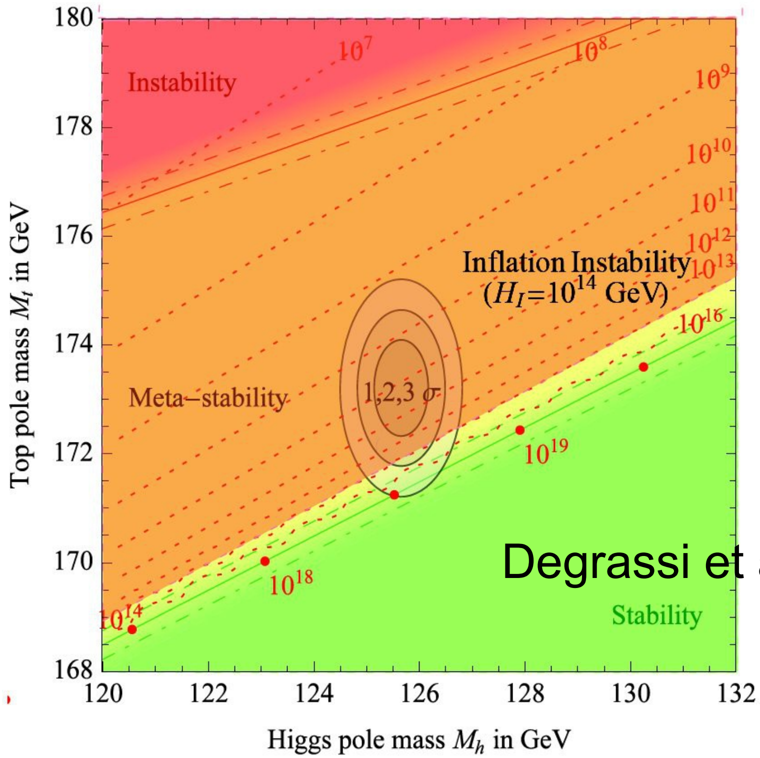
Content



→ **Selection of results, focus on most recent and/or precise results**

Top quark mass





Degrassi et al.

More on EW stability: K. Mukaida

- Self-consistency test of the SM & stability of the EW vacuum both rely/use pole mass – what we measure depends on the method
  - Indirect extraction from e.g. cross section, end point, J/psi method → top quark pole mass
  - Direct methods e.g. template, matrix element, likelihood, ideogram → "MC" mass with O(1 GeV) difference to pole mass

Top quark mass

ATLAS [arXiv:1606.02179]
CMS-PAS-TOP-14-022

- Direct measurements combined using BLUE
  - Takes correlations into account
- Latest ATLAS combination
  - Precision of 0.4% (!)

    m_{top} = 172.84 ± 0.70 GeV
  - Latest update (dilepton)

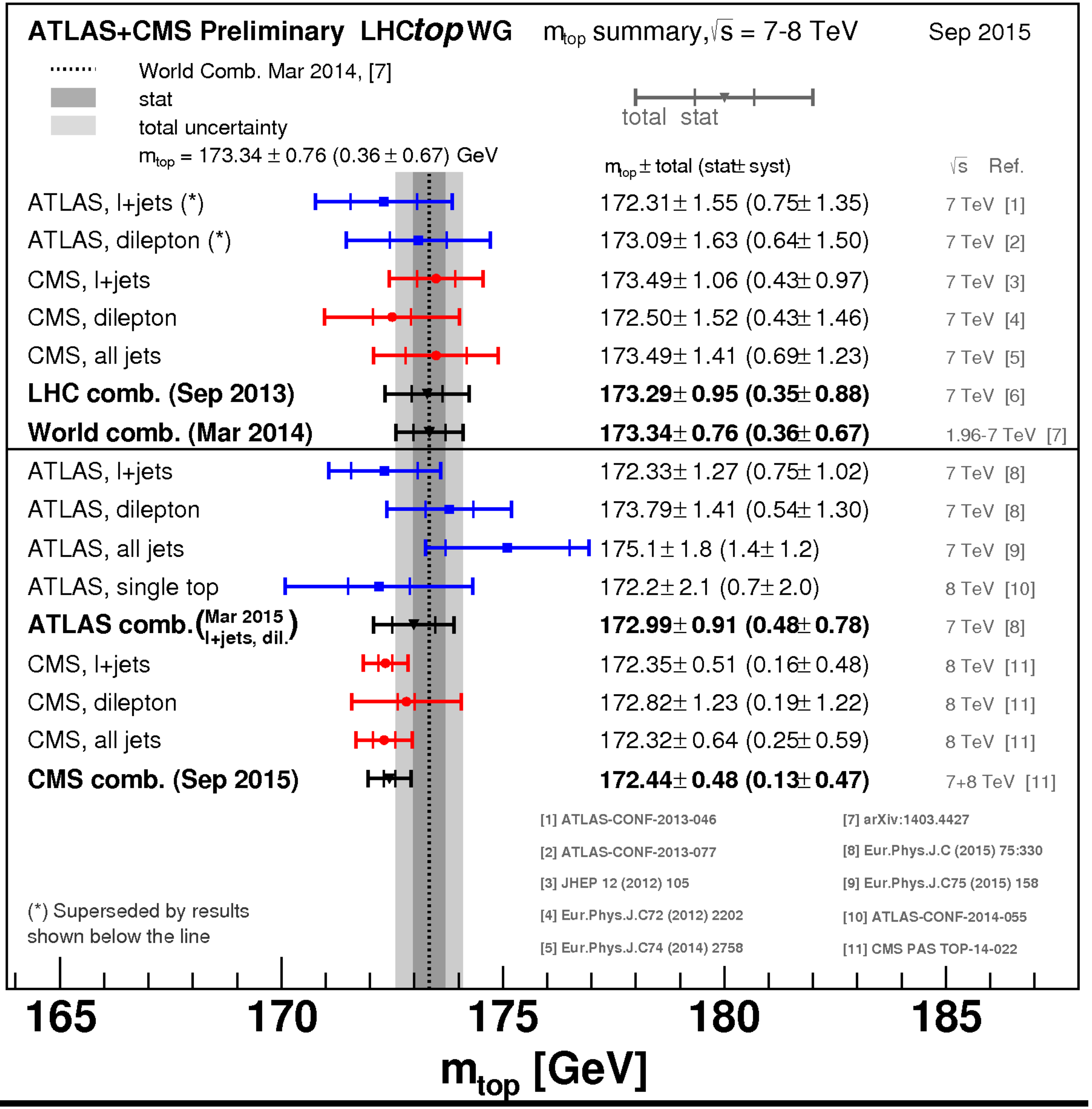
    m_{top} = 172.99 ± 0.84 GeV
- Latest CMS combination
  - Precision of 0.3% (!)

    m_{top} = 172.44 ± 0.48 GeV
- World average

  m_{top} = 174.34 ± 0.76 GeV
- Latest D0 update (dilepton)

  m_{top} = 173.93 ± 1.83 GeV

  [arXiv:1606.02814]

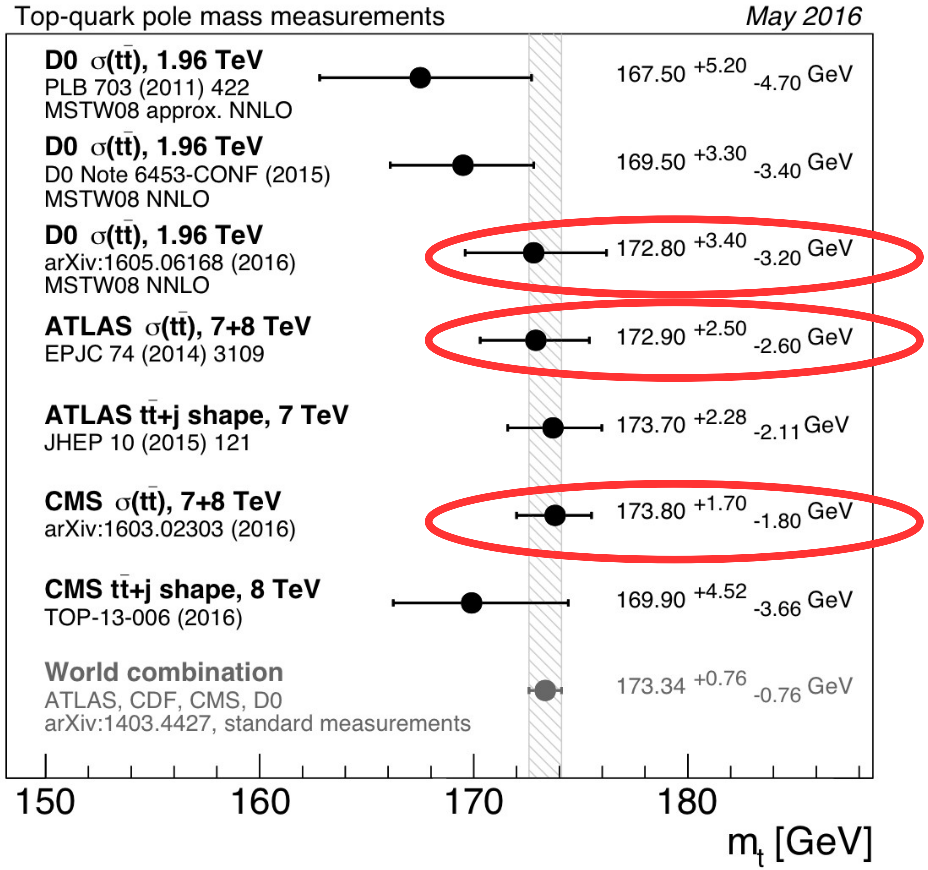


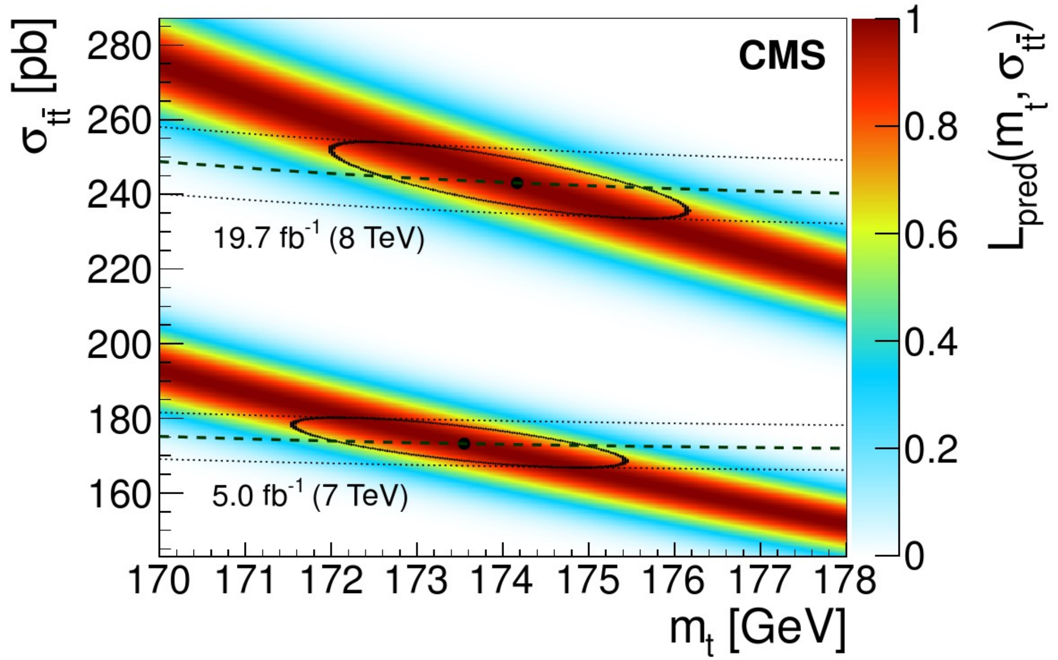
Top quark mass

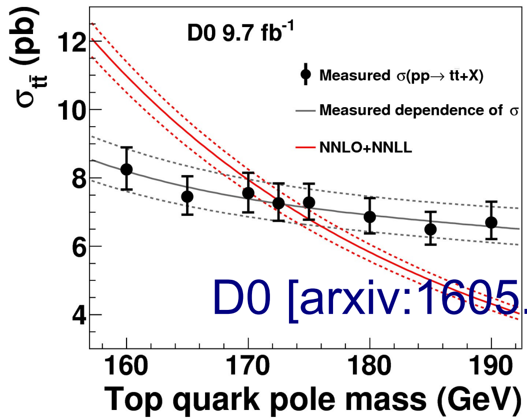
CMS [arXiv:1603.02303]
ATLAS EPJC 74 (2014) 3109

- Extraction from production cross section not (yet) competitive with direct measurements – but getting closer
- CMS precision at 1%; ATLAS: 1.45%
- D0 precision (best at Tevatron): ~ 1.9%

- With ~5% theory uncertainty and ~2% exp
  → <u>can reach 0.5% on pole mass</u>

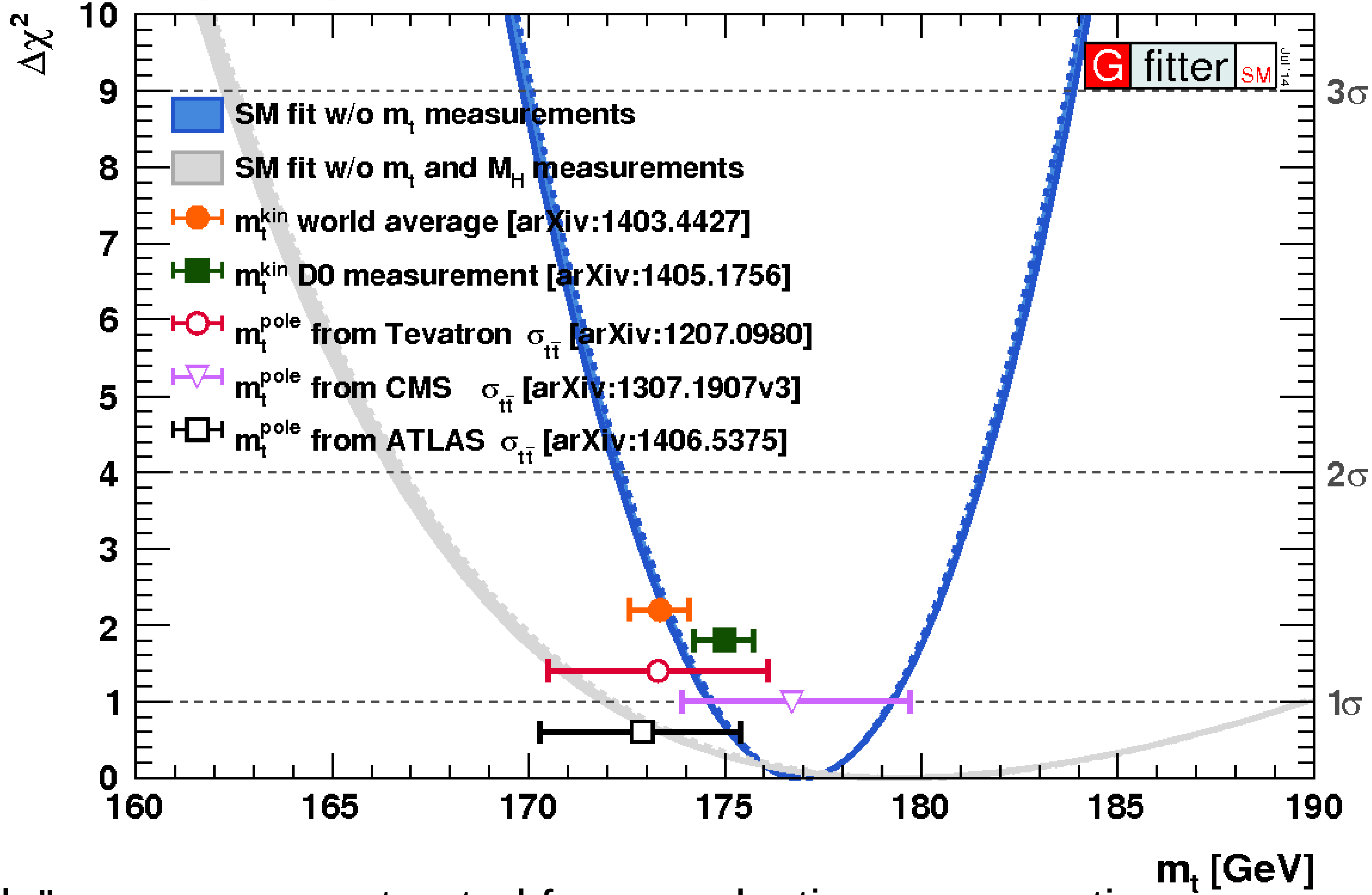






D0 [arxiv:1605.06168]

Top quark mass



→ "pole" means extracted from production cross sections
→ "kin" means direct measurements, e.g. matrix element method

Conclusions

- Large data sets allow to constrain PDFs, understand signal modeling
- High precision top quark property measurements, also accessible now in **single top quark production** (*t*-channel)
- Single top now differential – opening up a new realm
- Results on Asymmetry are not yet completely conclusive...

Evidence for associated production of *W, Z,* γ

→ No significant deviations seen from SM expectations at LHC Run I or early Run II results

Only small limited selection of results shown, more information:

ATLAS Top Web pages

CMS Top Web pages

CDF Top Web pages

D0 Top Web pages

Thank you!

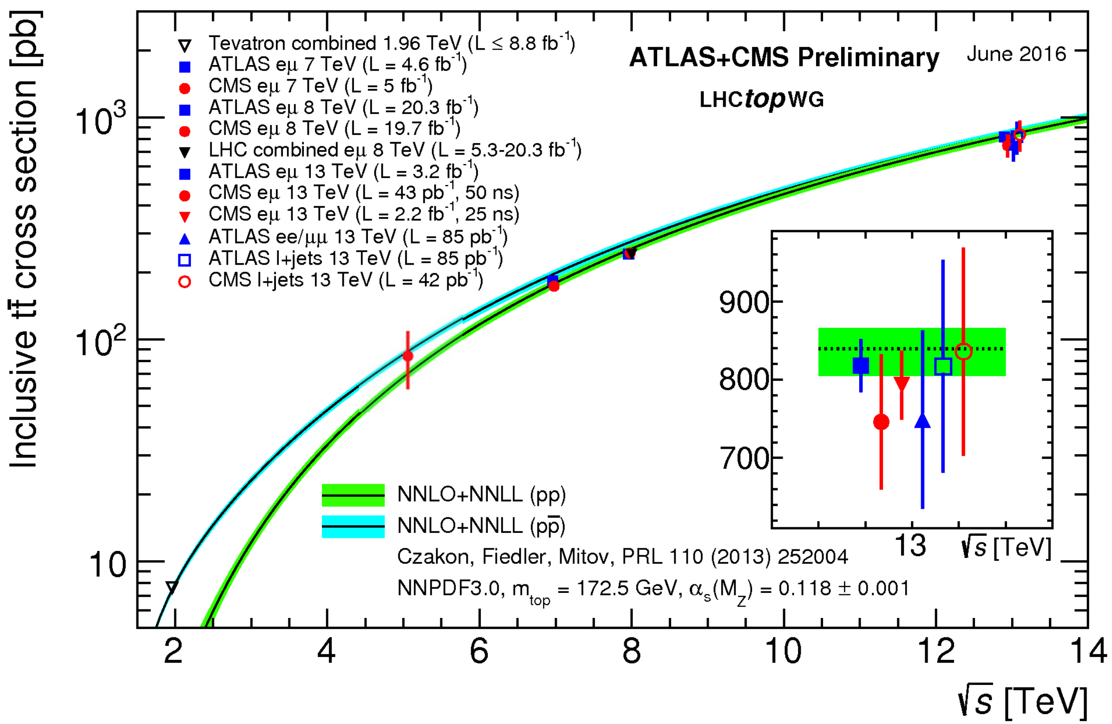
Outlook

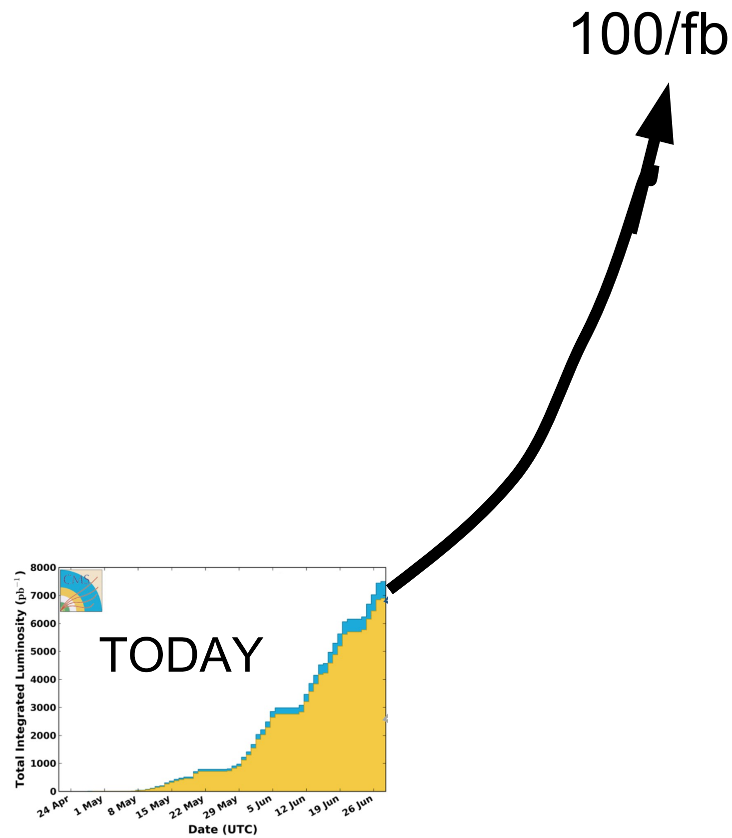
Run II just started!

→ We will get about 80 million $t\bar{t}$ events

→ Allows for multi-dimensional & simultaneous measurements of σ, α_s, PDFs and properties as well – ultra precision results

→ FCNCs and other statistically limited processes will significantly improve!

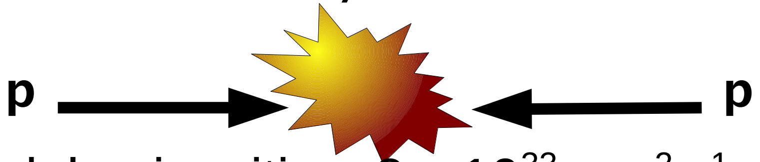




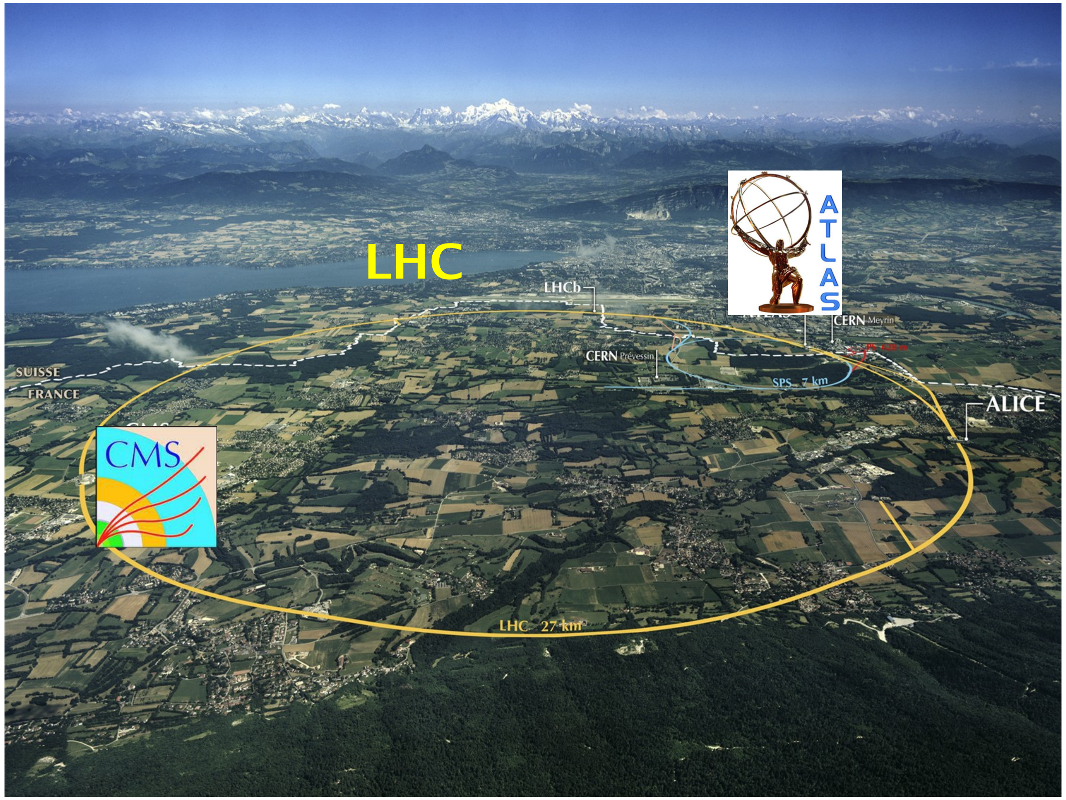
Backup

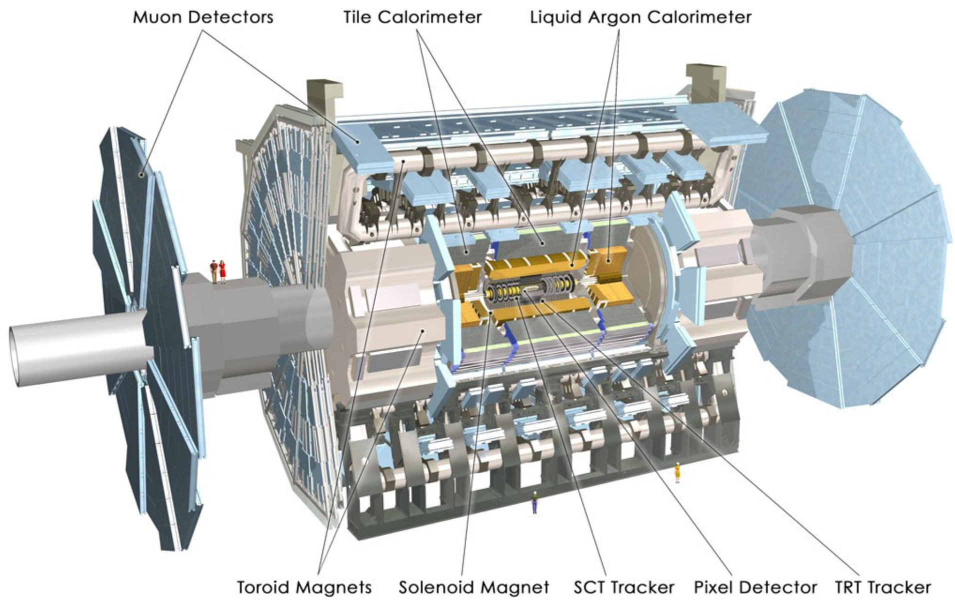
LHC and detectors

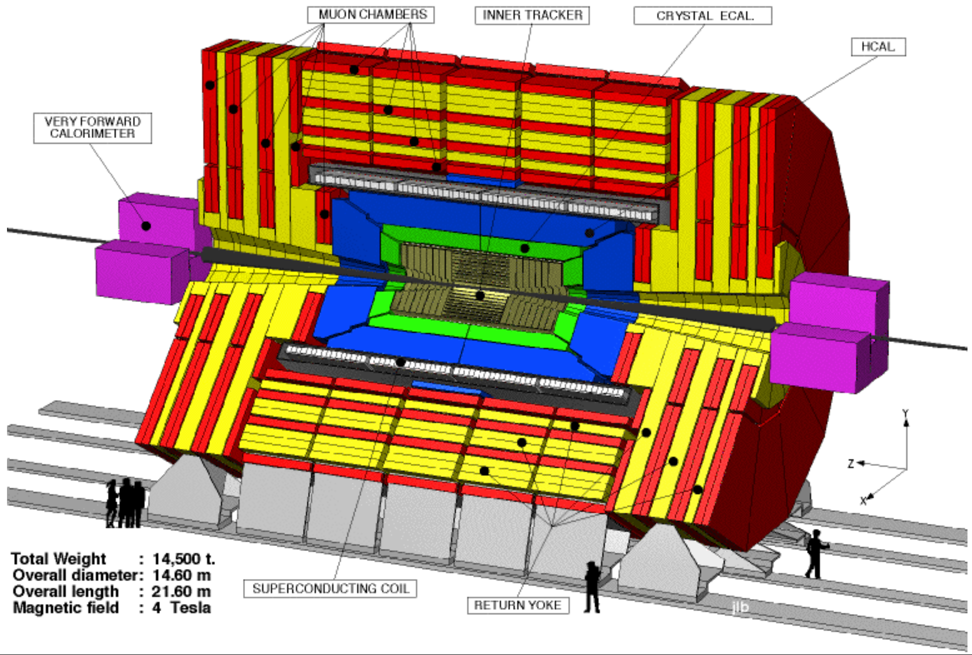
$\sqrt{s}$=7/8 TeV



- Peak luminosities: 8 x 10^{33} $cm^{-2}s^{-1}$
- ~5 (25) fb^{-1}/experiment recorded
- LHC consolidation/upgrades till 2015



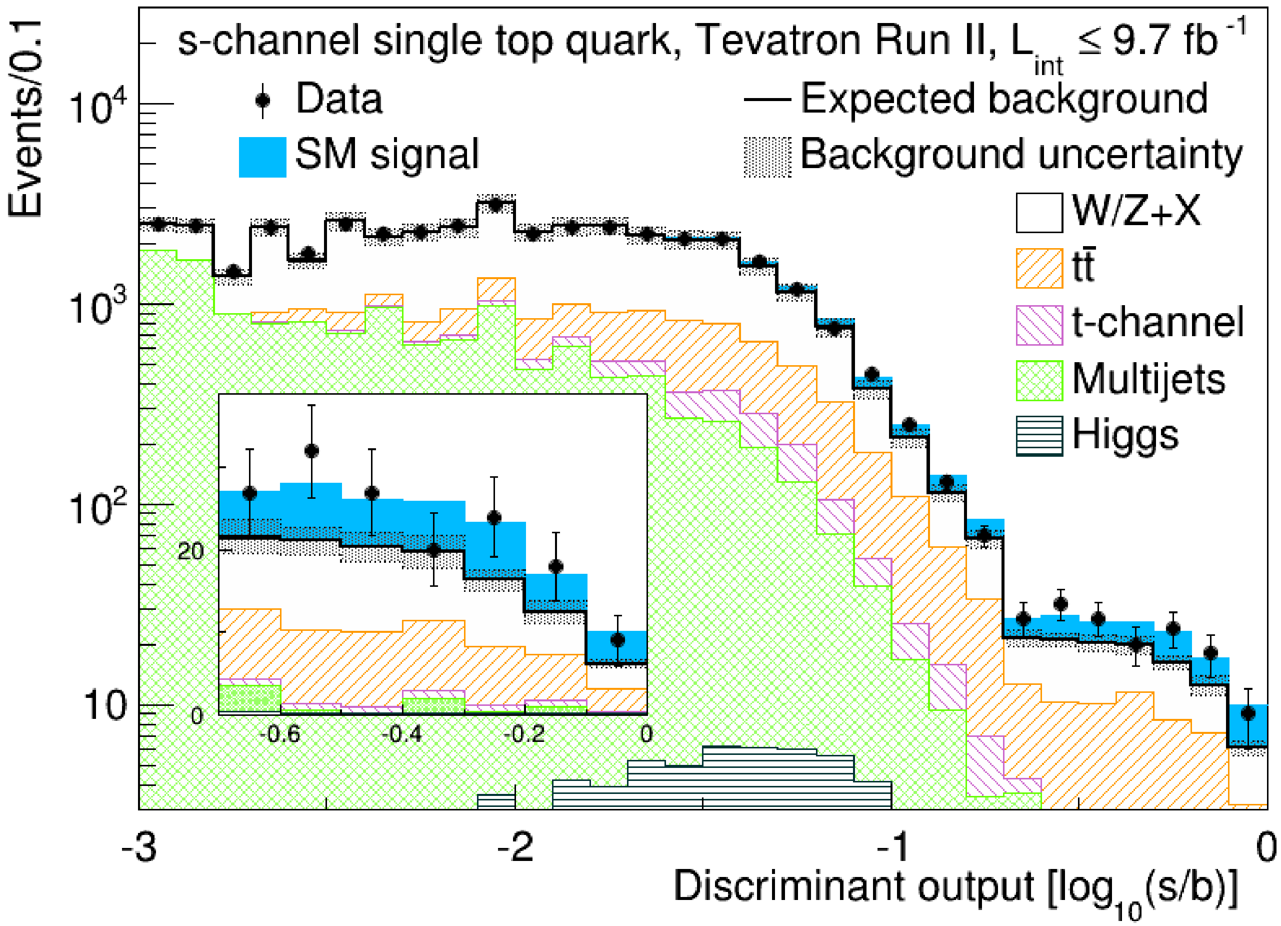


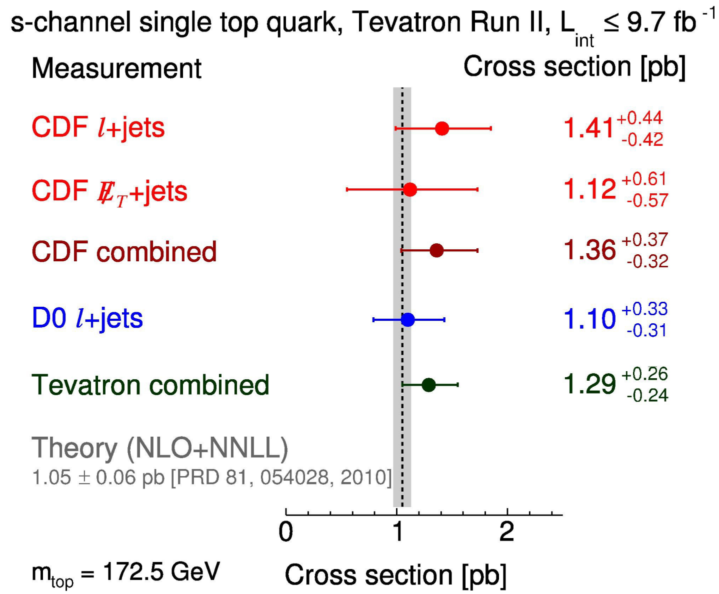


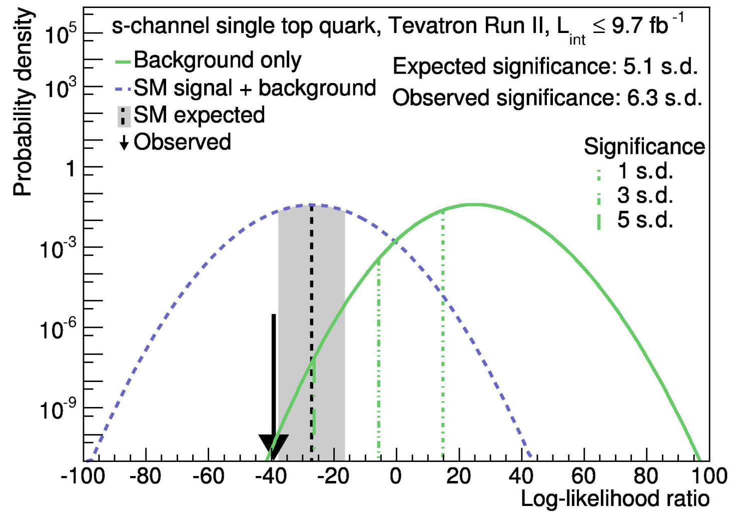
Single top production

- Combine CDF (l+jets and MET+jets) & D0 discriminants (l+jets)
- Include all systematic uncertainties and correlations
- **First observation of s-channel single top (6.3 s.d.)**

Phys. Rev. Lett. 112, 231803 (2014)

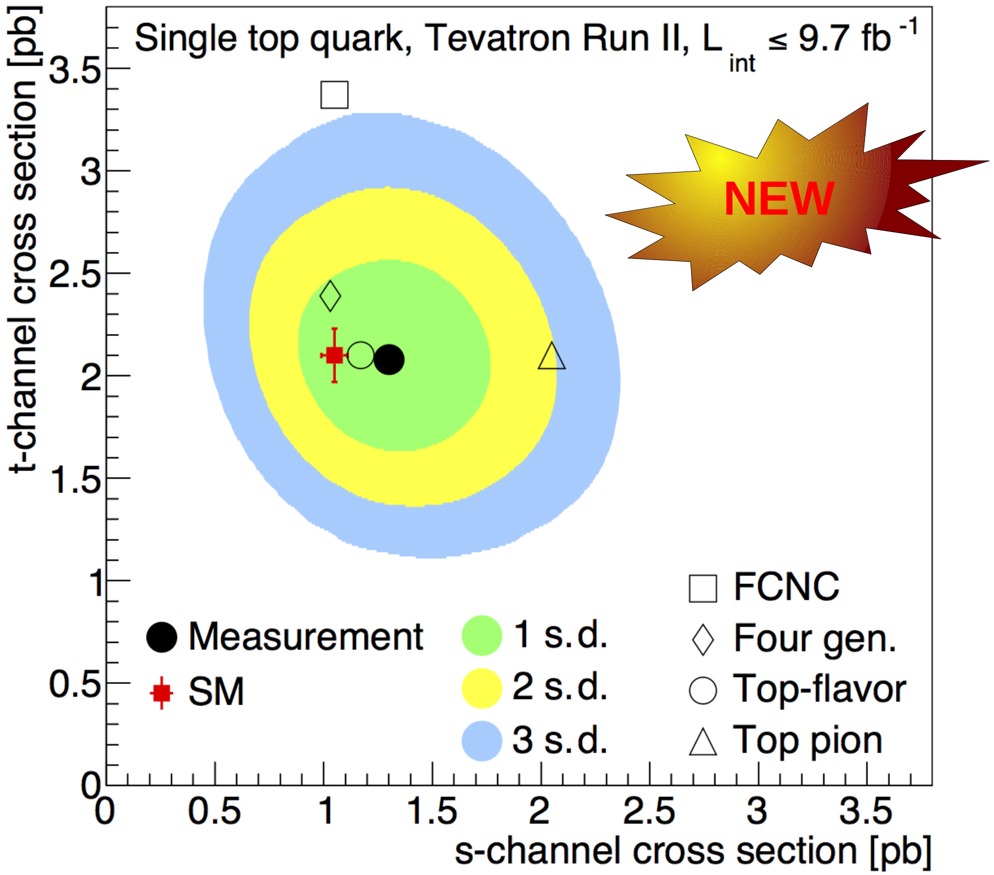


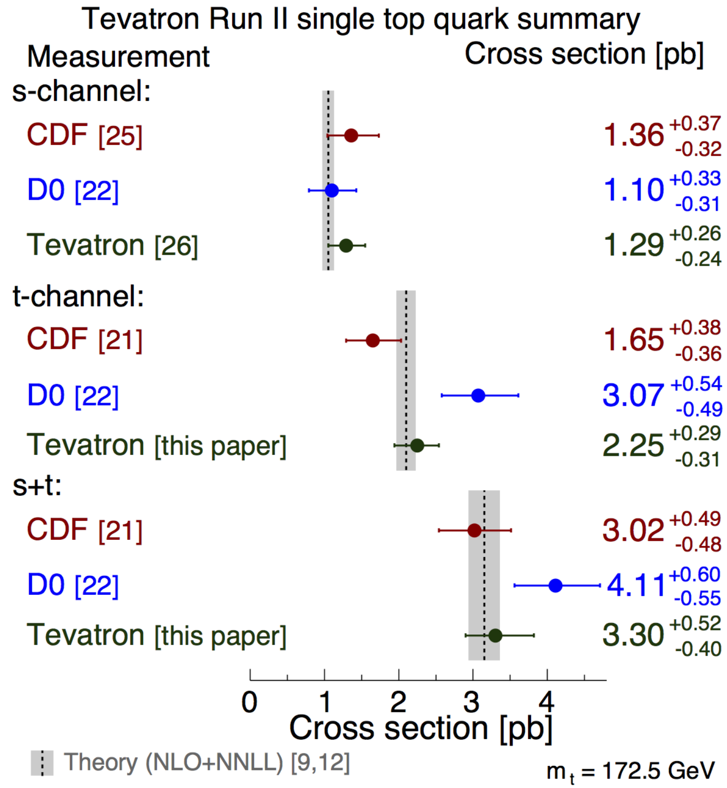


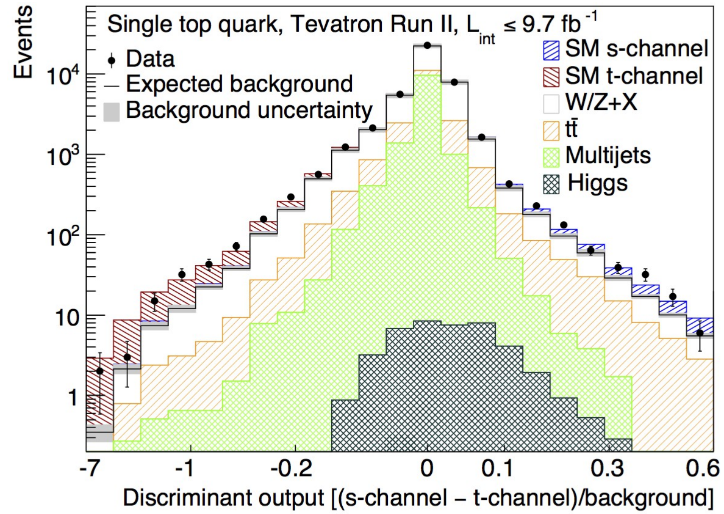


Single top production

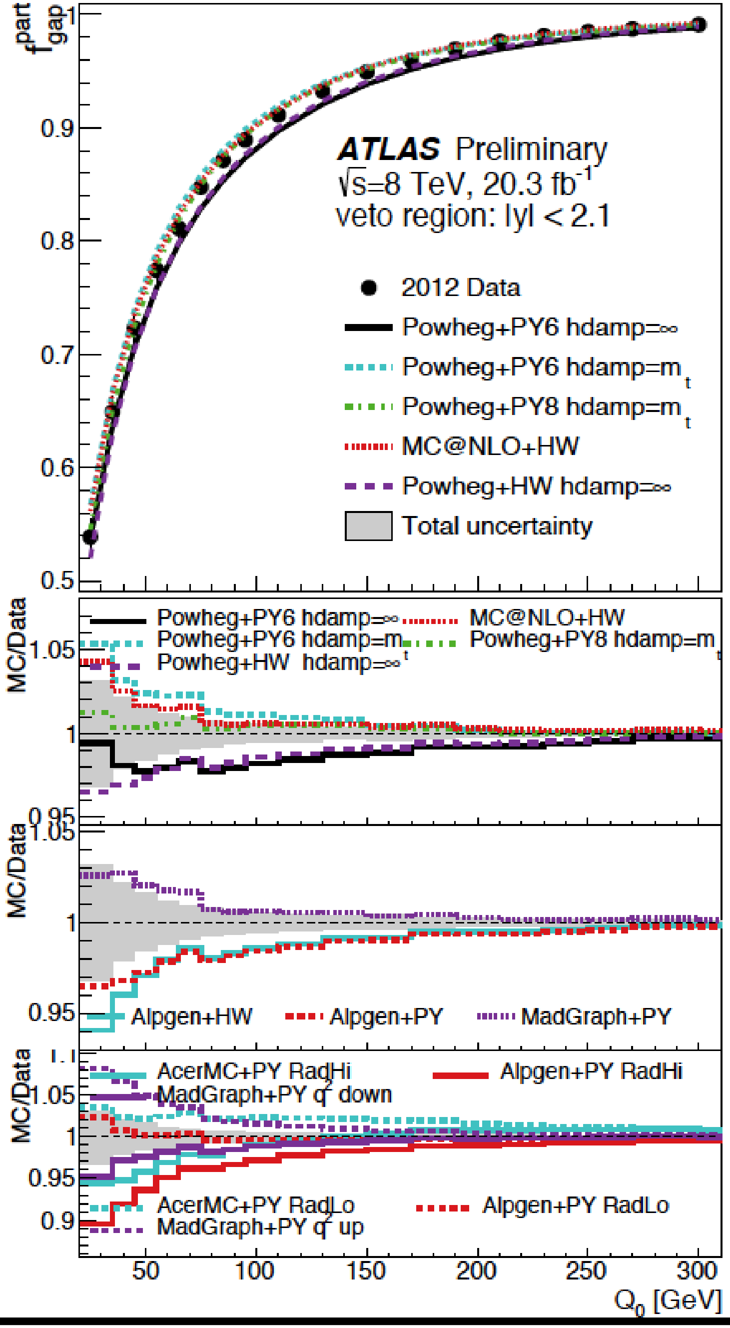
- Not assuming O_s/O_t SM value
- **Concludes** single top Tevatron program
- Agreement with the SM, no indications for non-SM contributions

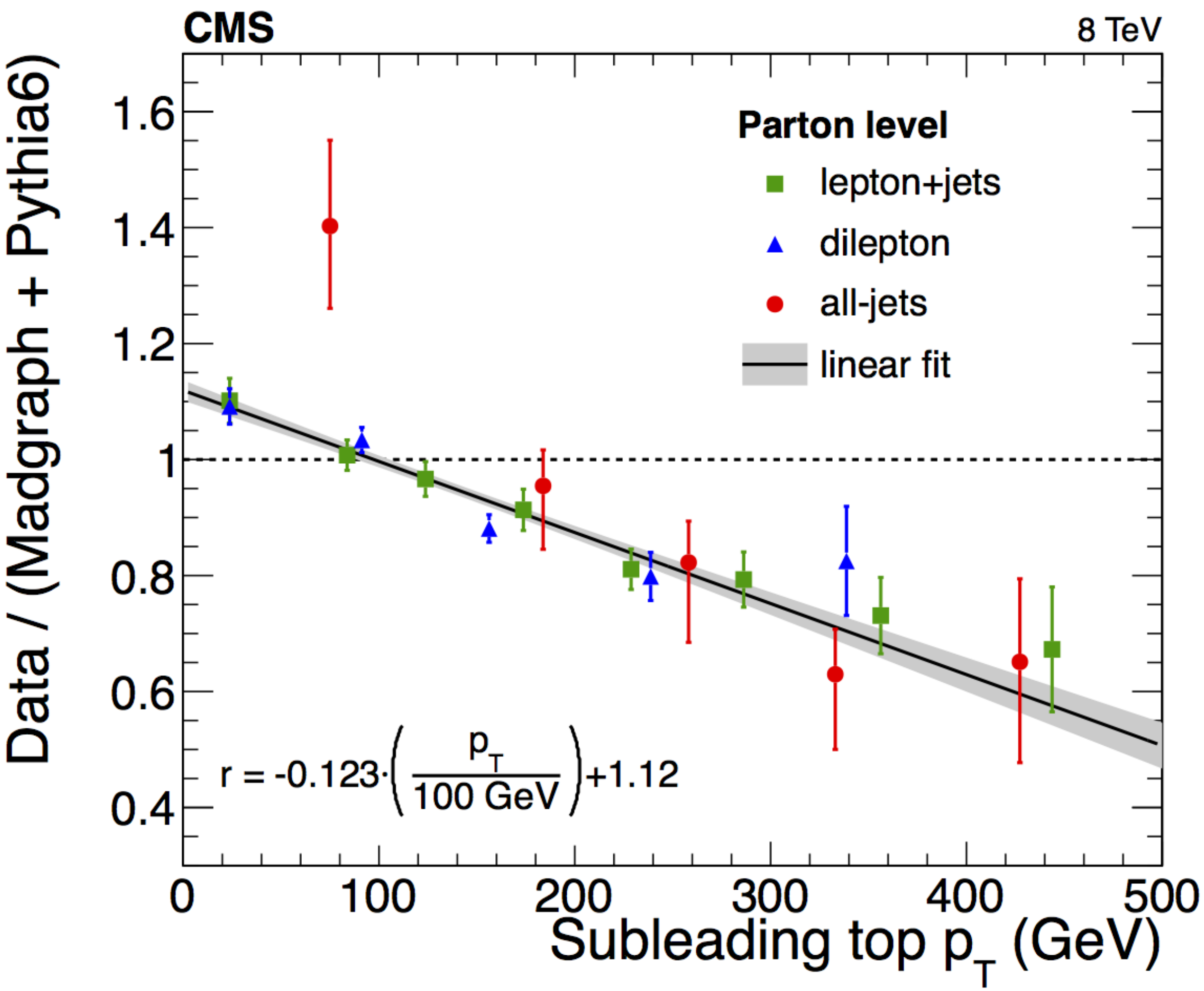




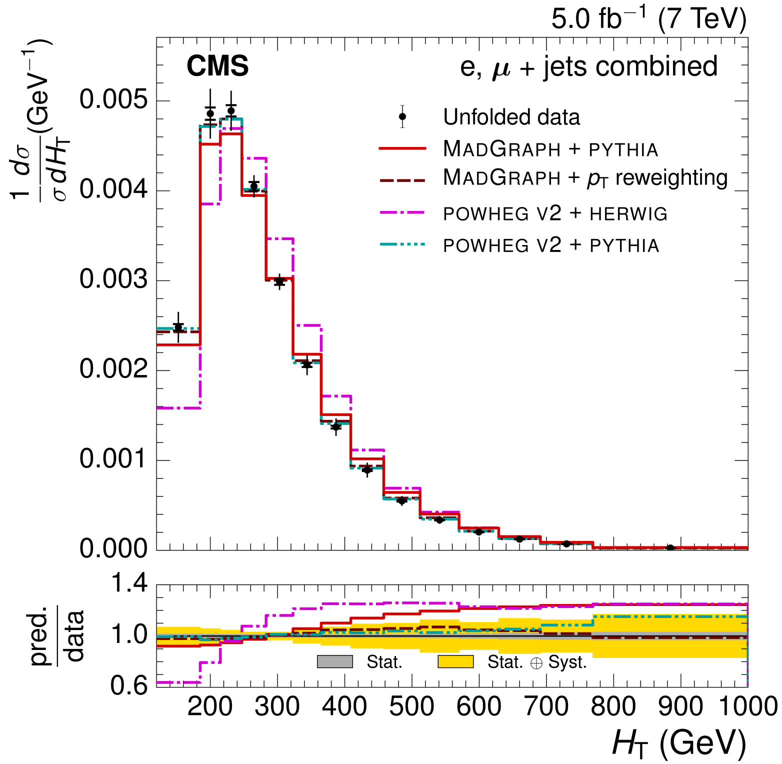


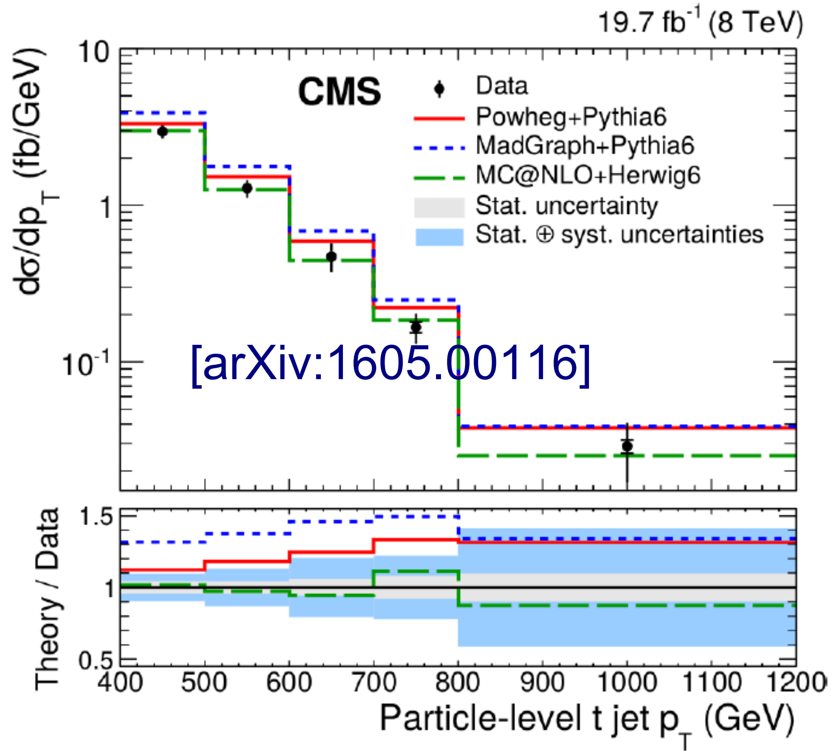
Differential cross sections





Differential cross sections



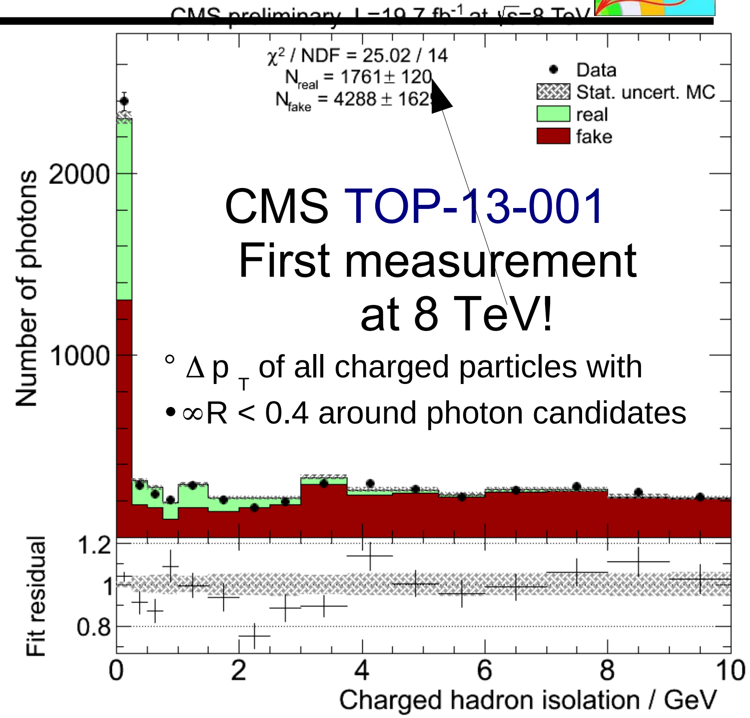


Ttbar + X: W, Z, B

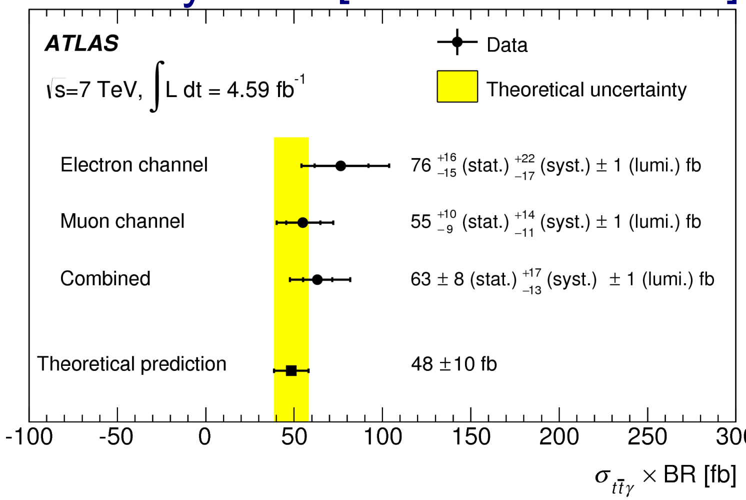
- Tight photon ID requirements and cuts to suppress the bg
- Observation at 7 TeV by ATLAS and first measurement at 8 TeV by CMS

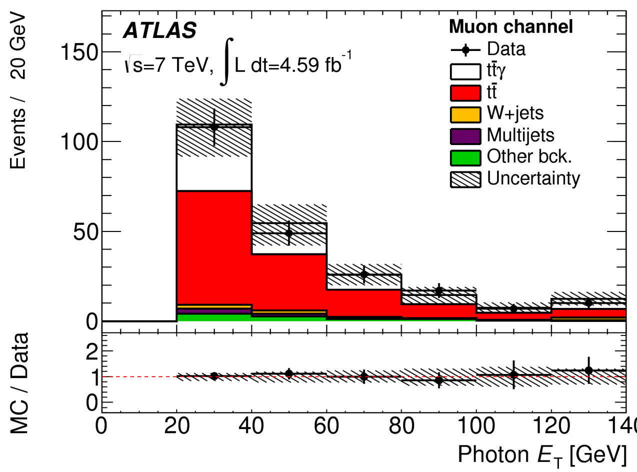
$$R = \sigma_{\bar{t}t+\gamma}/\sigma_{\bar{t}t} = (1.07 \pm 0.07(\text{stat.}) \pm 0.27(\text{syst.})) \cdot 10^{-2}$$

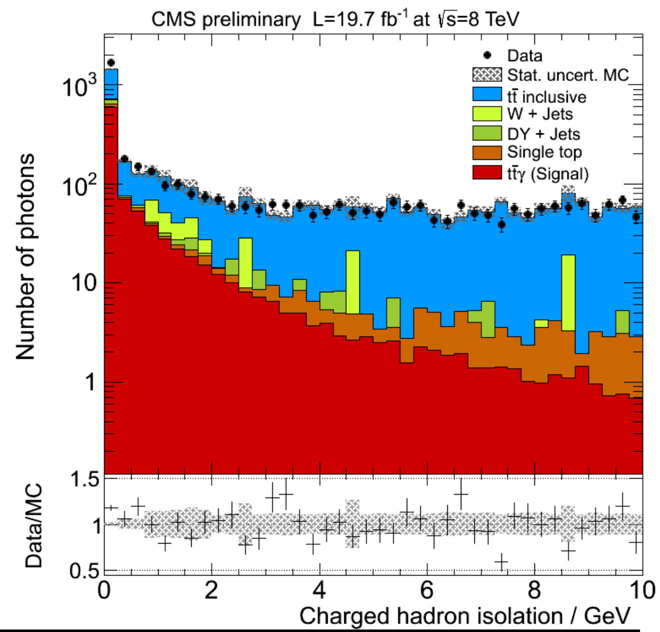
$$\sigma_{t\bar{t}+\gamma} = R \cdot \sigma_{\bar{t}t}^{\text{CMS}} = 2.4 \pm 0.2(\text{stat.}) \pm 0.6(\text{syst.})\,\text{pb}$$



Acc. by PRD [arXiv:1502.00586]



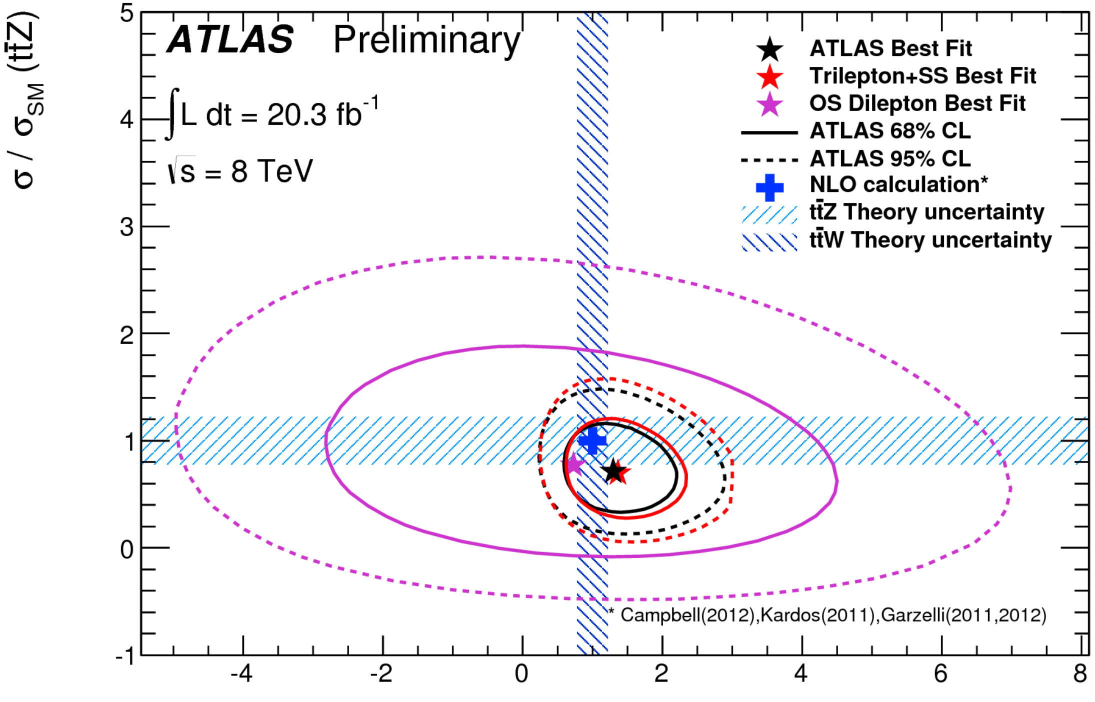




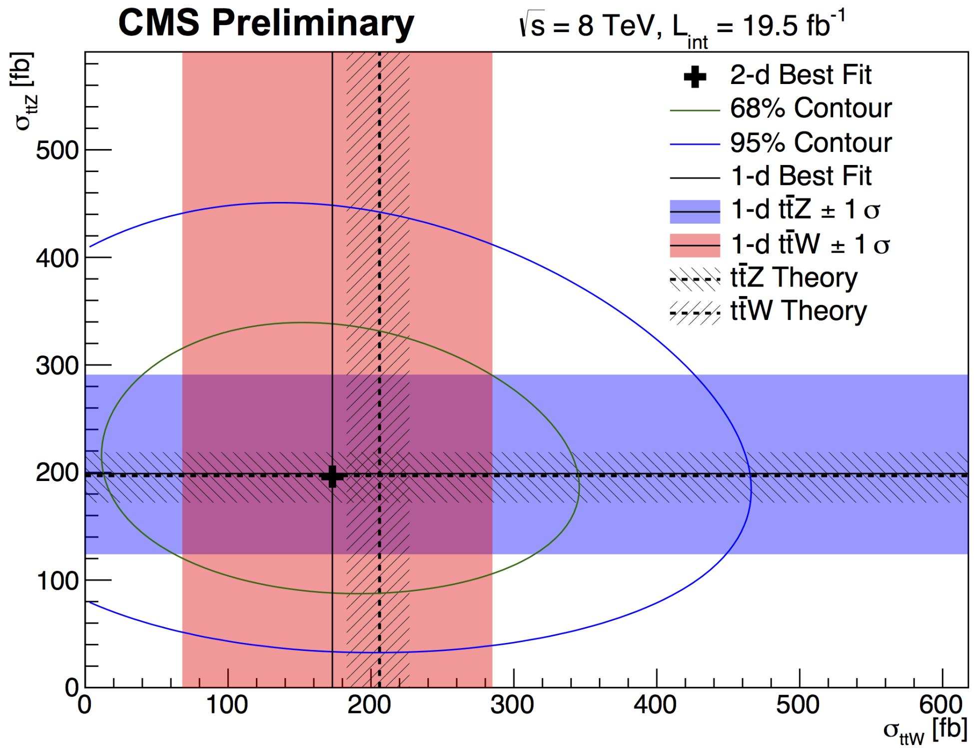
- Dominated by object IDs (jets, photon, btag) and signal model related

Ttbar + X: W, Z, γ

- 2D fit of *ttW* and *ttZ* cross sections, dominated by statistical unc's
- <u>SM (NLO):</u> σ(ttZ) = 206 ± 29 fb and σ(ttW) = 203 ± 25 fb



ATLAS-CONF-2014-038



EPJ C74 3060 (2014)

Process	Cross section	Sign.
ttZ	150^{+55}_{-50} (stat.) ± 21 (syst.) fb	3.1σ
ttW	300^{+120}_{-100} (stat.) $^{+70}_{-80}$ (syst.) fb	3.1σ

Process	Cross section	Significance
$t\bar{t}W$	170^{+90}_{-80}(stat.)$^{+70}_{-70}$(syst.) fb	1.6 σ
$t\bar{t}Z$	200^{+80}_{-70}(stat.)$^{+40}_{-30}$(syst.) fb	3.1 σ
$t\bar{t}W + t\bar{t}Z$	380^{+100}_{-90}(stat.)$^{+80}_{-70}$(syst.) fb	3.7 σ

Top quark polarization

- In $t\bar{t}$ production: New physics polarizes top quarks
- Polarization introduced by CP conserving or violating process:

→ $\in P_{CPC}$ = -0.035 ± 0.014 (stat.) ± 0.037 (syst.)
$\in P_{CPV}$ = 0.020 ± 0.016 (stat.) $\pm^{0.013}_{0.017}$ (syst.)

∈: Spin analyzing power, P_{CPX}: top quark polarization

PRL 111, 232002 (2013)

- Good agreement with SM (negligible polarization), also seen

by: → CMS:
→ D0:

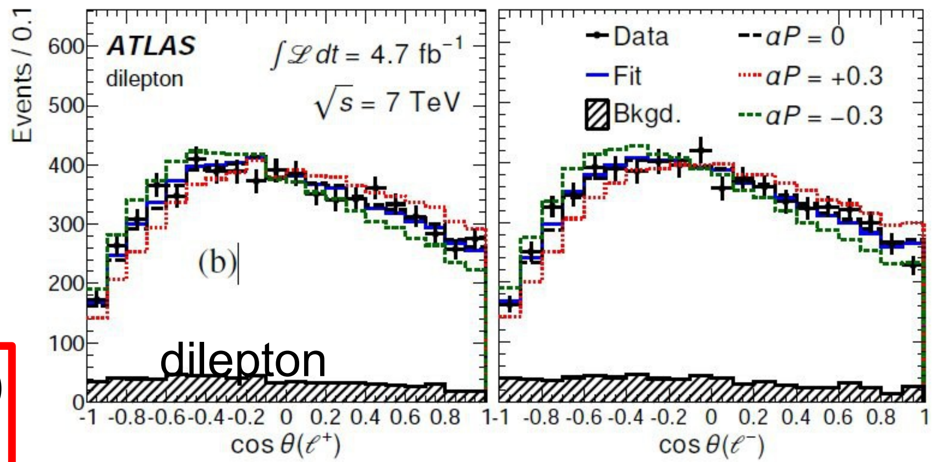
PRL 112 (2014) 182001

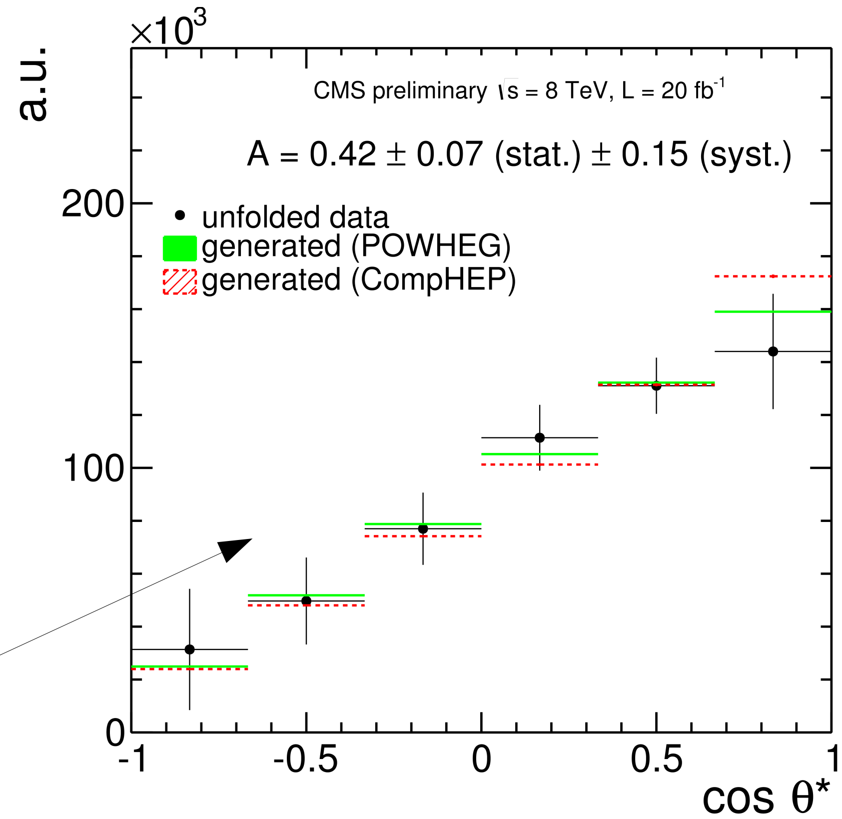
PRD 87, 011103(R) (2013)

- In single top production, measure polarized top quarks as expected

→ P_t = 0.82 ± 0.12 (stat.) ± 0.32 (syst.)

CMS-PAS-TOP-13-001

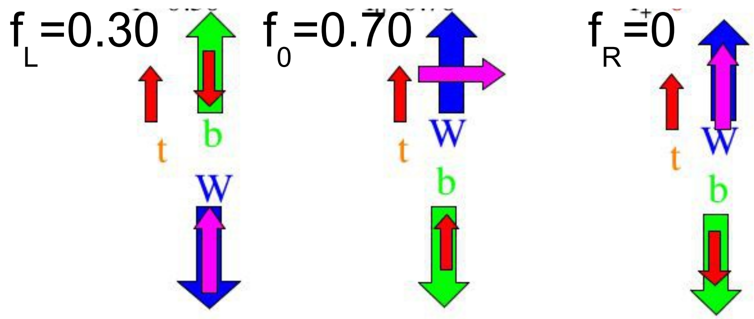


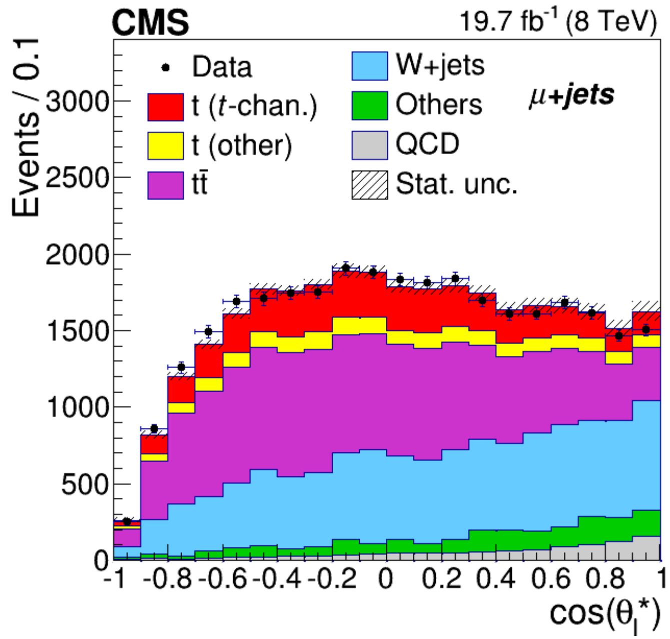


W helicity in single top production

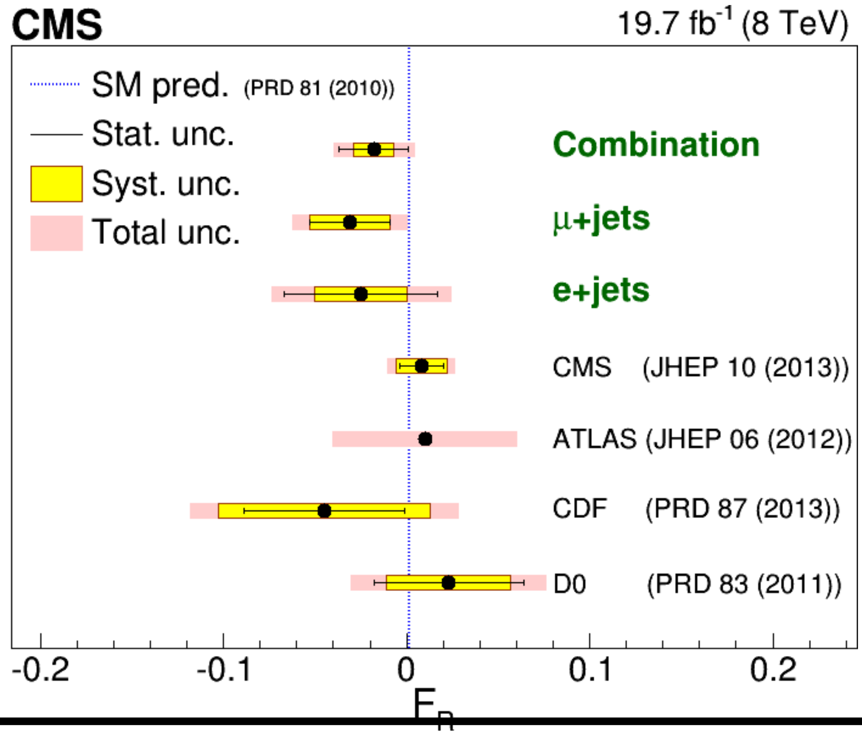
JHEP 01 (2015) 053

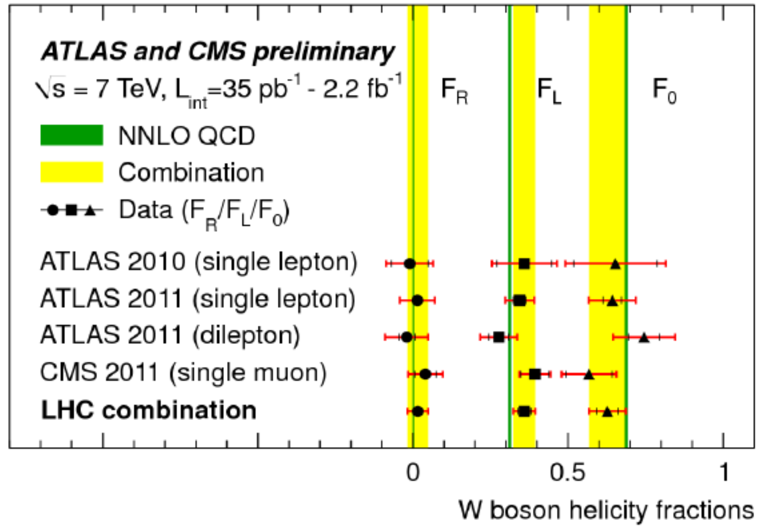
- W helicity in SM:





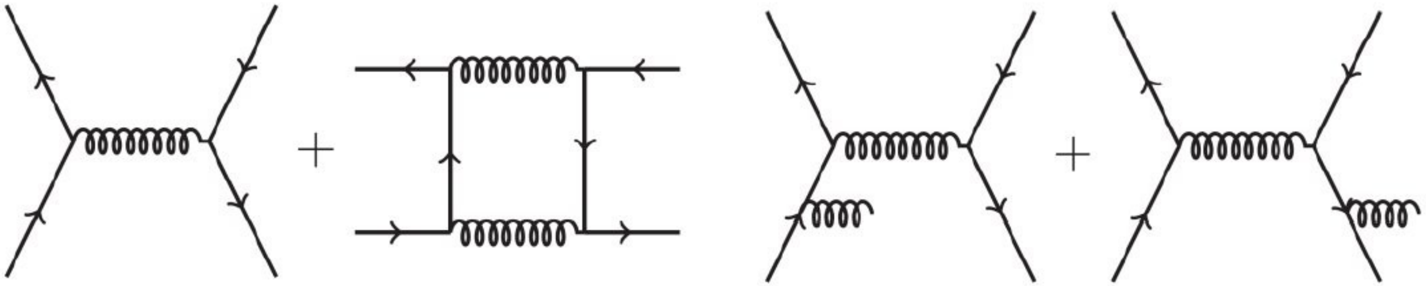
- Complements results in pair production
- Similar precision but <u>orthogonal</u> systematic uncertainties in single top channels
  - Signal model & template statistics





Top quark asymmetries

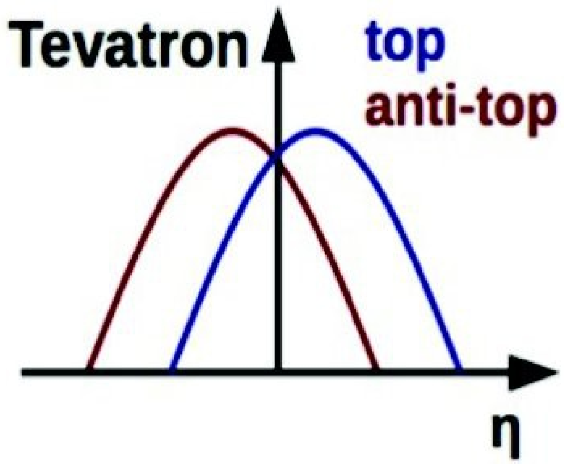
- Interference appears at NLO QCD:



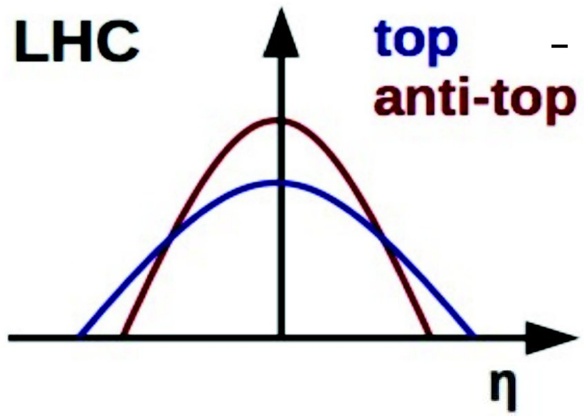
Positive asymmetry — Negative asymmetry

→ Only occurs in $q\bar{q}$ initial state; gg is fwd-bwd symmetric

- This is a forward-backward asymmetry at Tevatron
- No valence anti-quarks at LHC → $\bar{t}$ more central



- SM predictions at NLO (QCD+EWK)
  → Tevatron: **A_{FB} ~ 8-9 %** vs. LHC: **A_C ~ 1 %**
  (waiting for full NNLO pQCD predictions)



- Experimentally: Asymmetries based on decay leptons or fully reconstructed top quarks

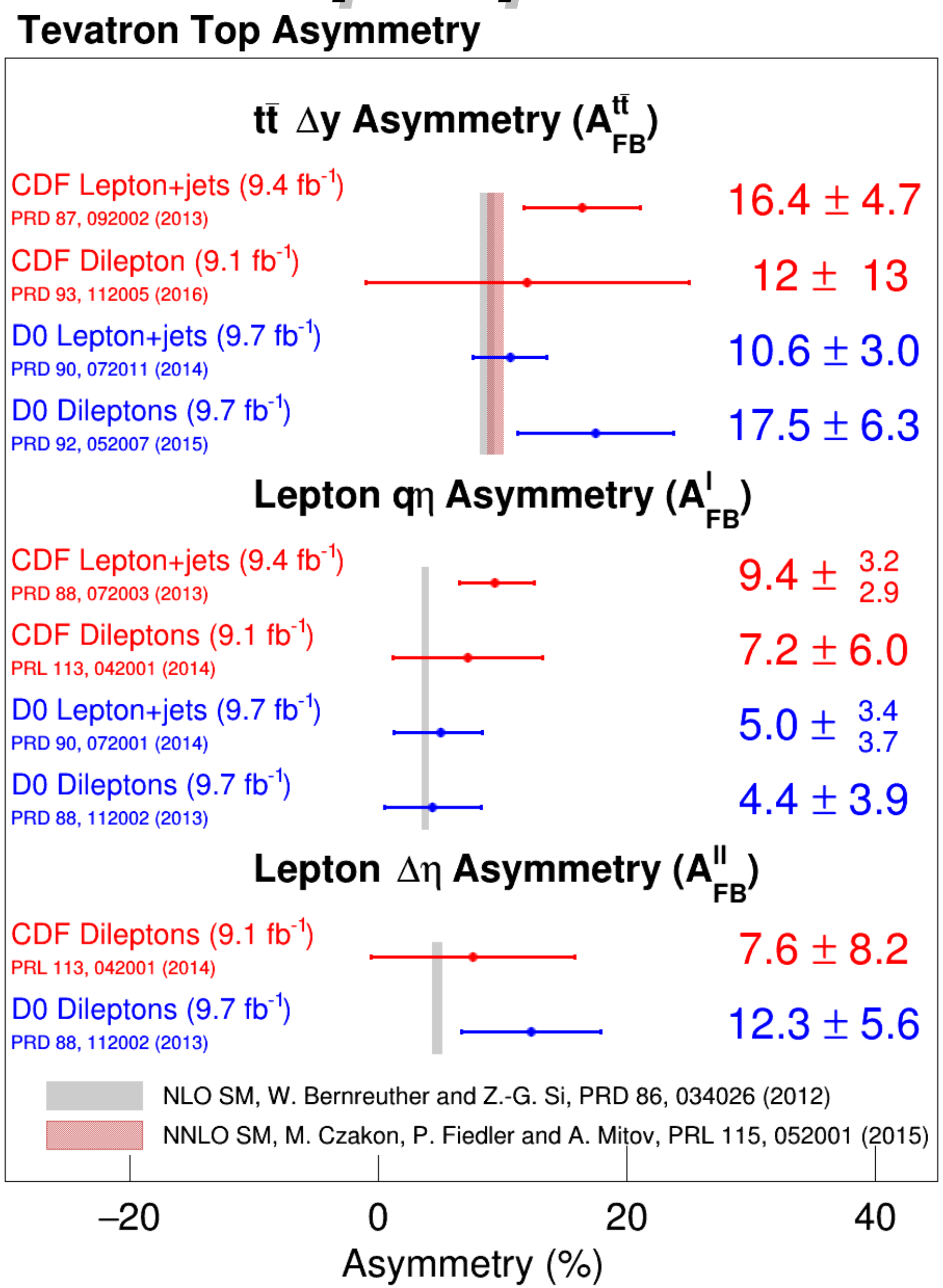
"easier"

$$A_C = \frac{N(\Delta|y_t| > 0) - N(\Delta|y_t| < 0)}{N(\Delta|y_t| > 0) + N(\Delta|y_t| < 0)}$$

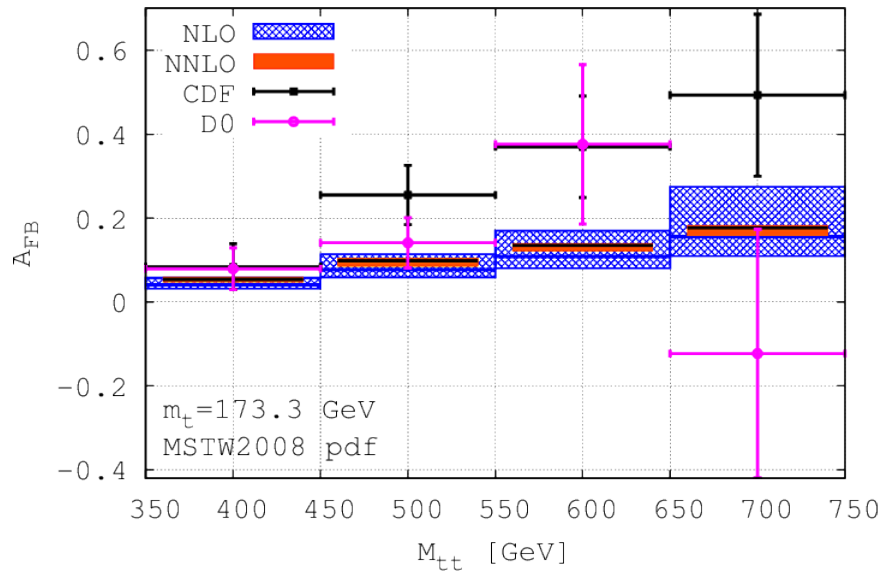
"harder"

$$A_C^{lep} = \frac{N(\Delta|\eta_\ell| > 0) - N(\Delta|\eta_\ell| < 0)}{N(\Delta|\eta_\ell| > 0) + N(\Delta|\eta_\ell| < 0)}$$

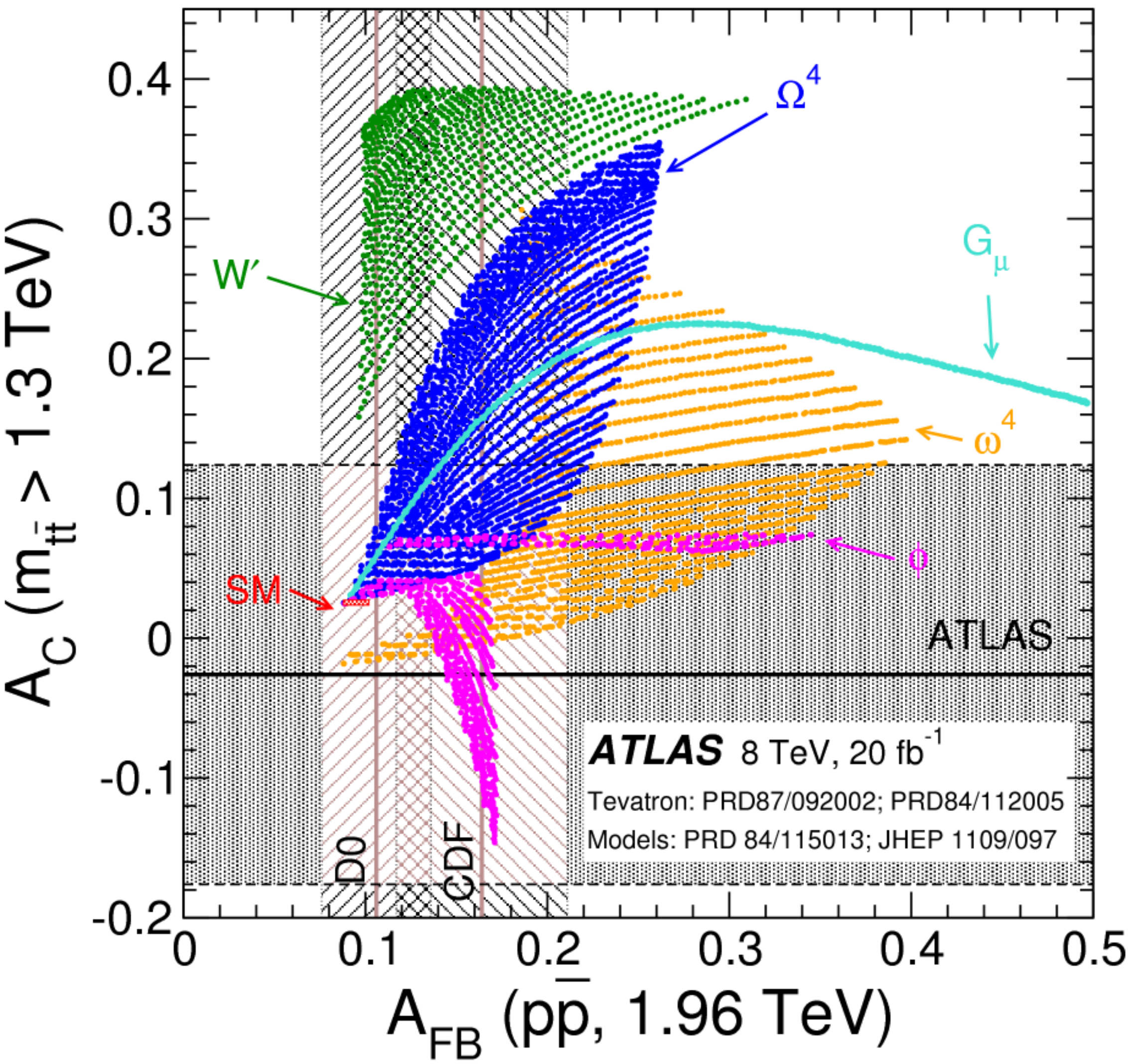
Top quark asymmetries



- All Tevatron results use full data sets
- Expect final results and Tevatron combination very soon
- Agreement with latest theory predictions



Top quark asymmetries



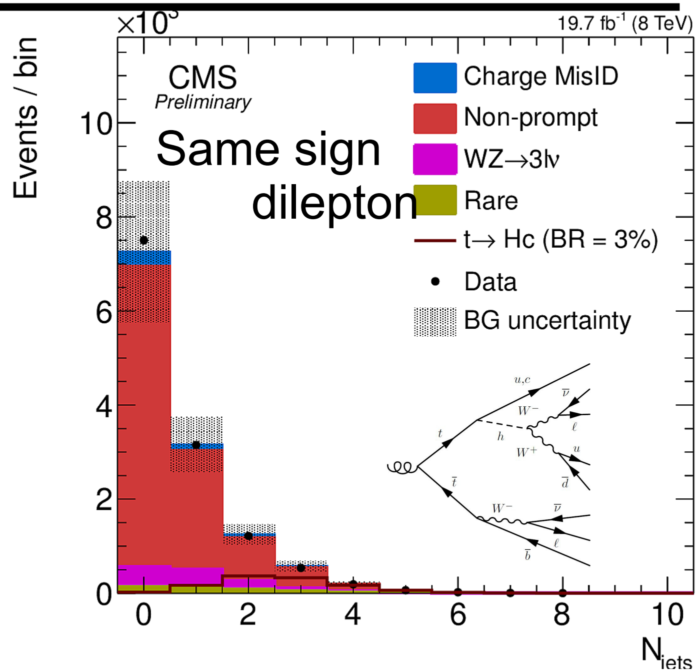
Top quark: FCNC

CMS PAS-TOP-13-017

- Flavor Changing Neutral Currents are highly suppressed in SM, but enhancement in many models of new physics
- Search for FCNC involving Z bosons:

→ $B(t \to ug) < 5.7 \cdot 10^{-5}$ $B(t \to ug) < 3.55 \cdot 10^{-4}$
$B(t \to cg) < 2.7 \cdot 10^{-4}$ $B(t \to cg) < 3.44 \cdot 10^{-3}$

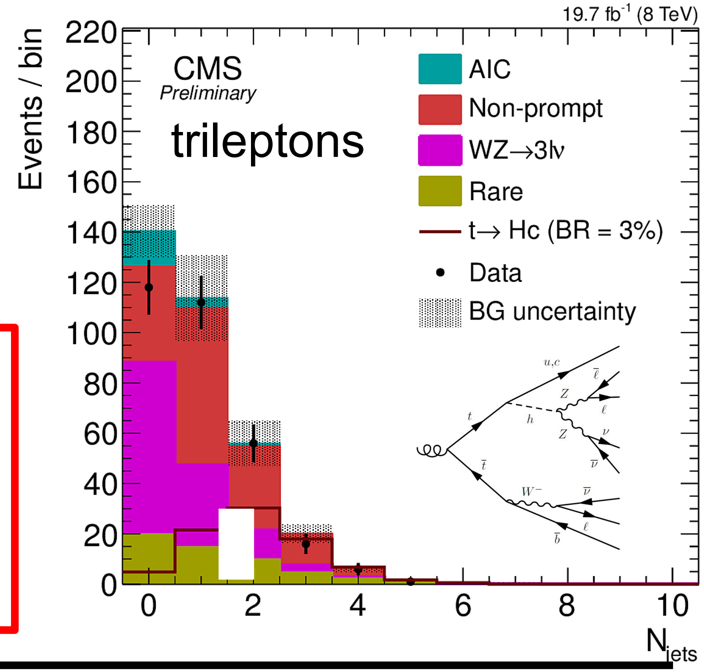
- Search for Higgs boson production in the dilepton (same sign) and trilepton channel
- Systematic uncertainties dominated by:
  Background modeling / cross sections



- Limit on top-charm flavor-violating Higgs Yukawa coupling & upper limits for branching fractions:

→
- $\sqrt{(|\lambda^H_{tc}|^2 + |\lambda^H_{ct}|^2)} < 0.18$ at 95% CL

	$-\sigma$	$BR_{exp}(t \to Hc)$	$+\sigma$	$BR_{obs}(t \to Hc)$
trilepton	0.95	1.33	1.87	1.26
same-sign dilepton	0.68	0.93	1.26	0.99
combined	0.65	0.89	1.22	0.93

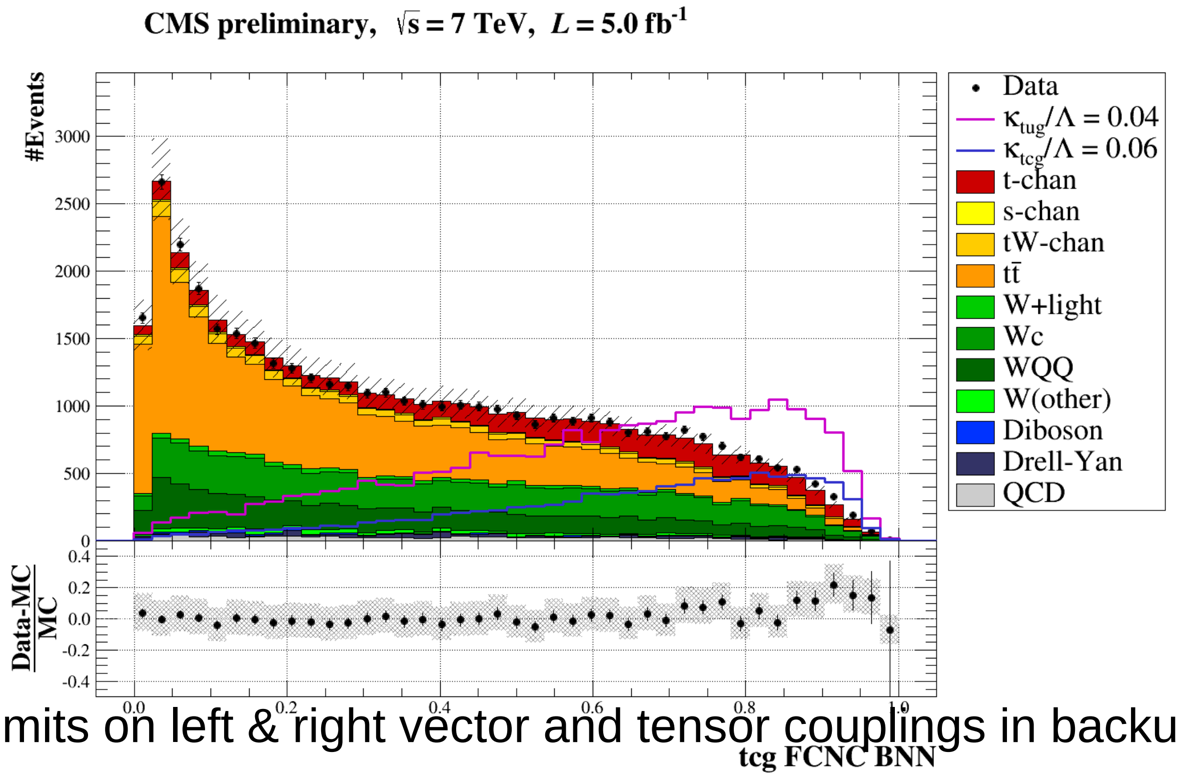


Top quark: FCNC

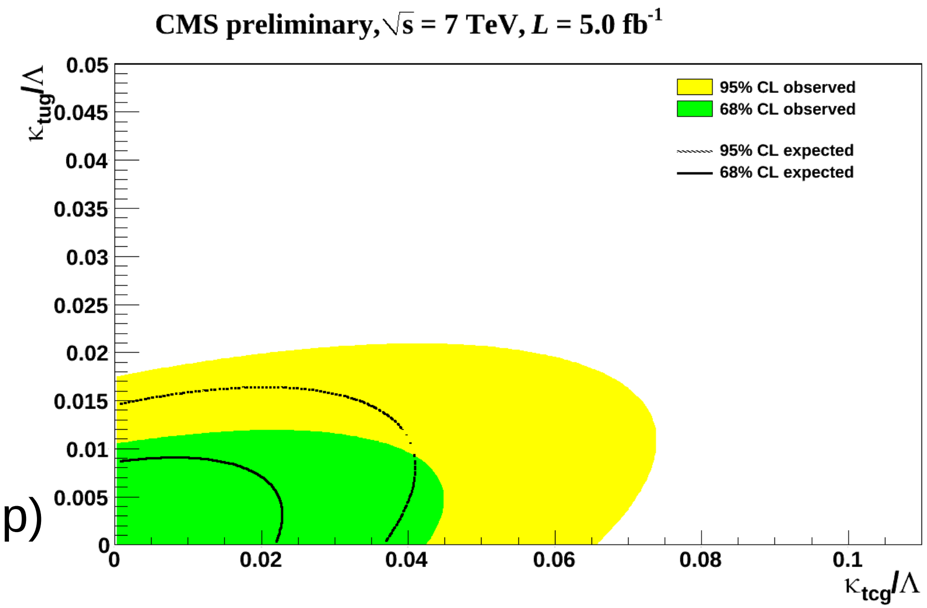
- Search in single top production (t-channel)
- MVA technique to: suppress QCD, separate signal & bg, search for *Wtb* couplings & FCNC interactions
- Systematic uncertainties dominated by:
  Background normalization

CMS-PAS-TOP-14-007

Process	Uncertainty
top-quark pair production	15%
single top, *s*-channel	15%
single top, tW-channel	13%
W+jets, “WQQ”	100%
W+jets, “Wc”	100%
W+jets, “W+light”	50%
W+jets, “WQX (UE)”	50%
QCD (data-driven)	100%
Drell-Yan process	30%
WW, WZ, ZZ	30%

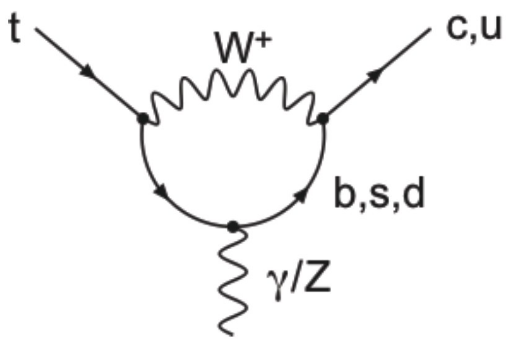


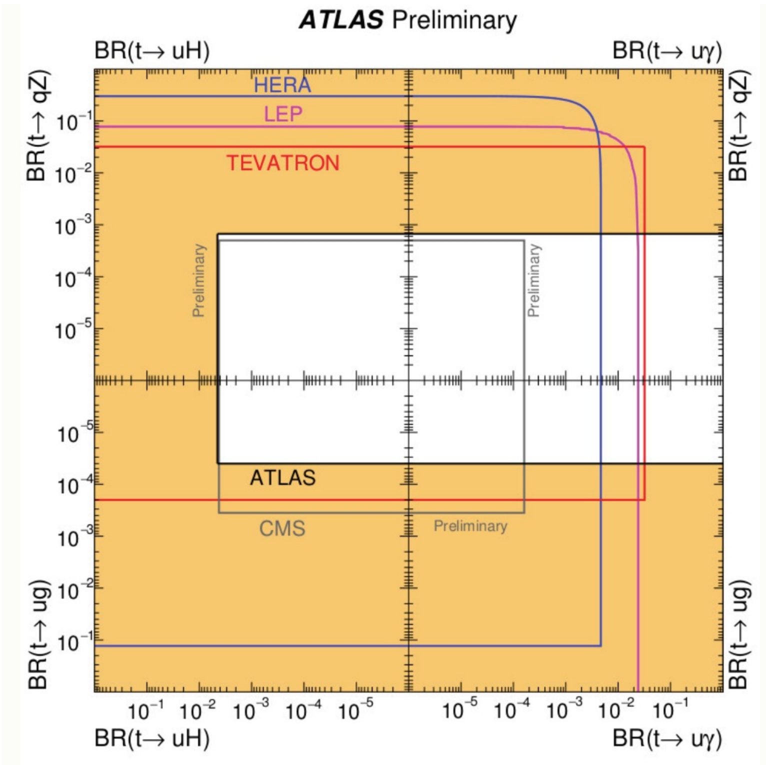
(Limits on left & right vector and tensor couplings in backup)

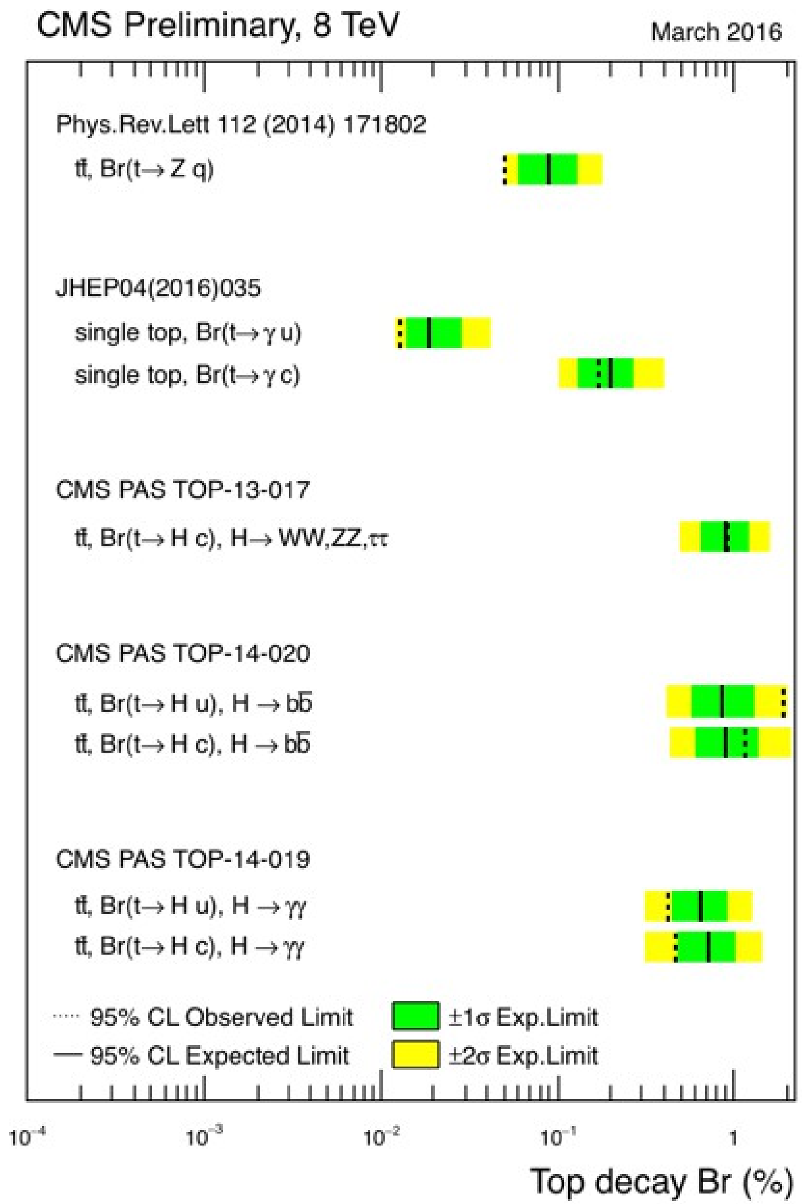


Top quark: FCNC

- Flavor Changing Neutral Currents are highly suppressed in SM
- Analyses assume all anomalous couplings zero but one
- Still above SM predictions but reached sensitivity to certain BSM models







Measurement methods

- **Matrix Element method** (leading order) calculates event probability densities from $d\sigma/dX$

$$P(x, m_t) = \frac{1}{\sigma(m_t)} \int \sum \underbrace{d\sigma(y, m_t)}_{\text{LO ME}} dq_1 dq_2 \underbrace{f(q_1) f(q_2)}_{\text{PDFs}} \underbrace{W(y, x, k_{\text{JES}})}_{\text{Transfer function}}$$

- **Ideogram method** event likelihood based on Breit-Wigner (signal) convoluted with detector resolutions

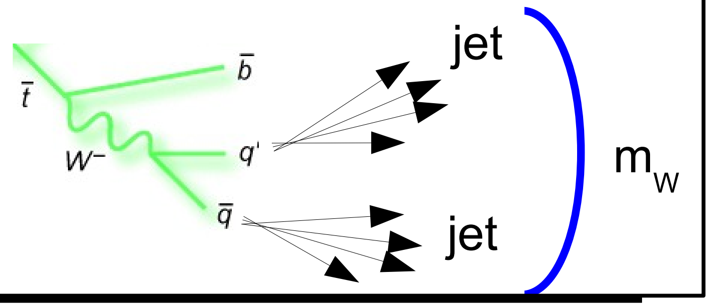
$$\mathcal{L}(\text{sample}|m_t, \text{JSF}) = \prod_{\text{events}} \left(\sum_{i=1}^{n} P_{\text{gof}}(i) \left(\sum_j f_j P_j(m_{t,i}^{\text{fit}}|m_t, \text{JSF}) \times P_j(m_{W,i}^{\text{reco}}|m_t, \text{JSF}) \right) \right)^{w_{\text{event}}}$$

- **Template method** compares histograms in data to simulations (including detector resolutions)

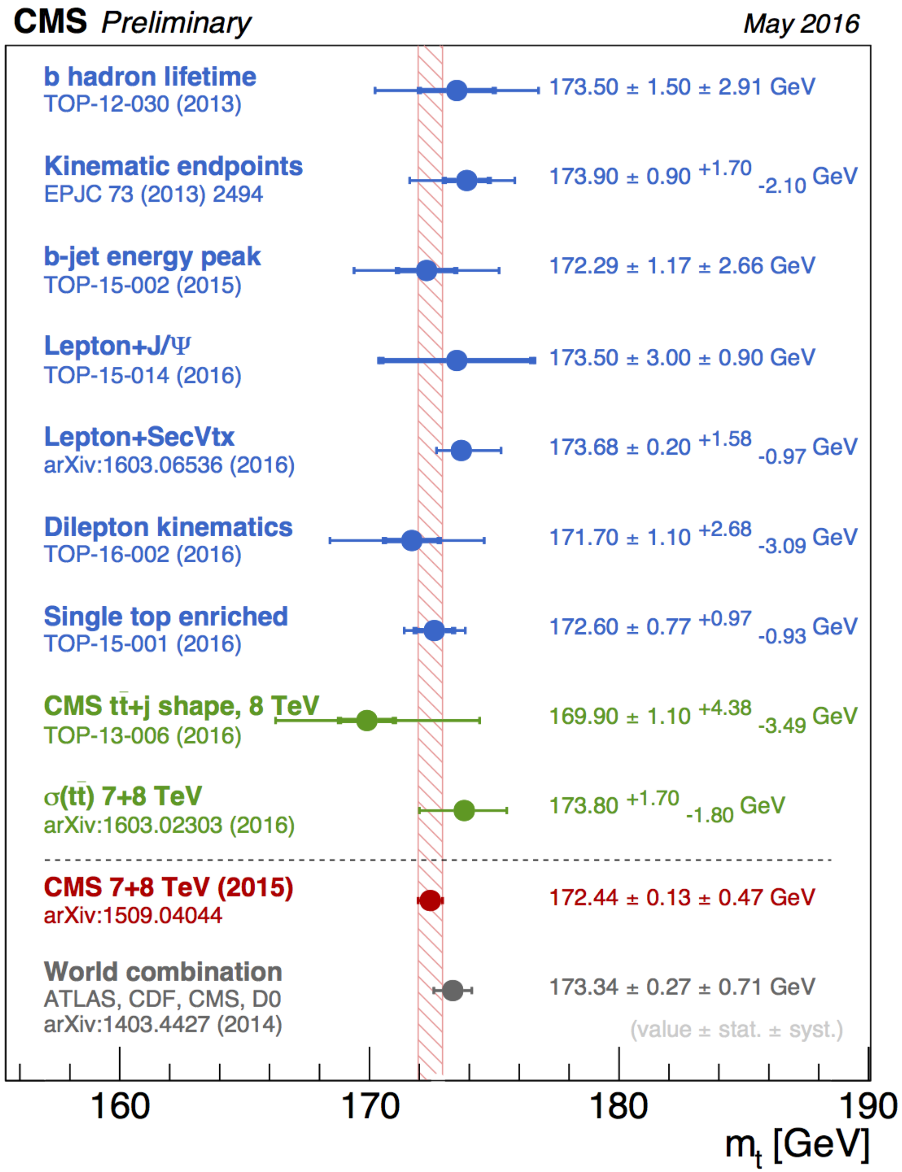
- Depend on MC → We measure "MC mass"

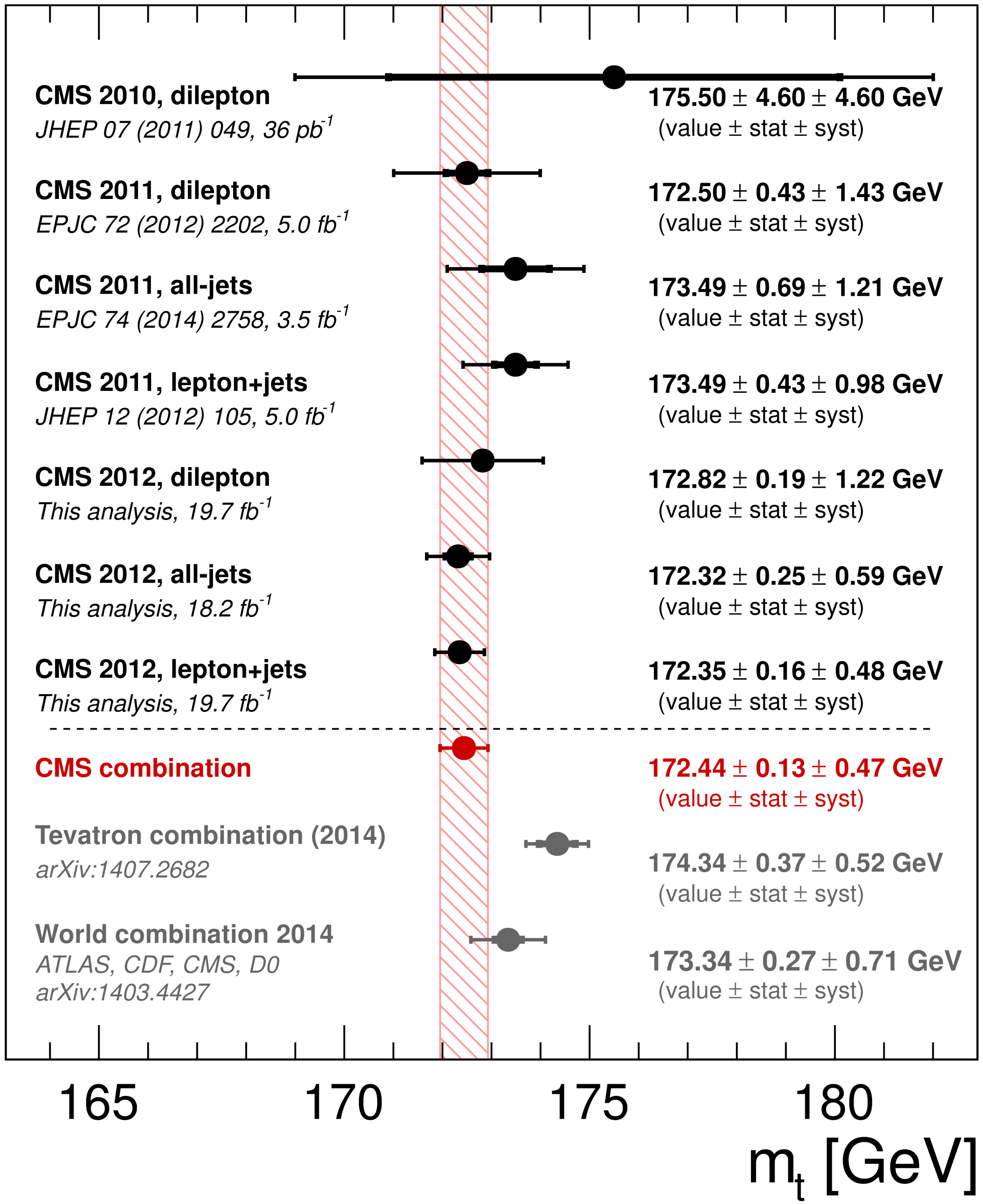
- **Alternative methods** ("End-point", J/Φ, "σ")

W boson fully reconstructed:
→ In-situ calibration, Constrain reconstructed m_W to m_W



Top quark mass



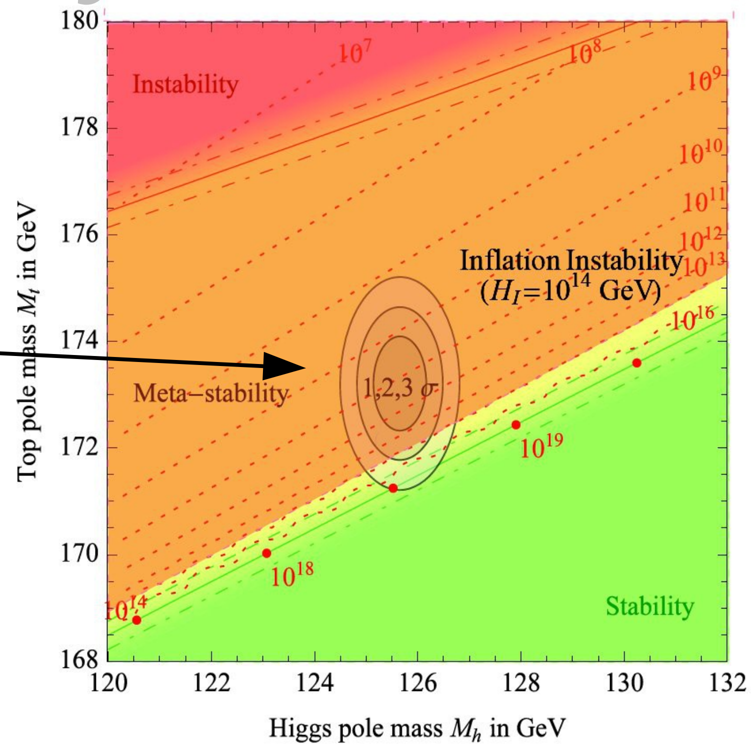


SM vacuum stability

- With the Higgs discovery the SM can be extrapolated to Planck scale energies
- “Test” the stability of the electroweak vacuum, under assumption of no new physics:

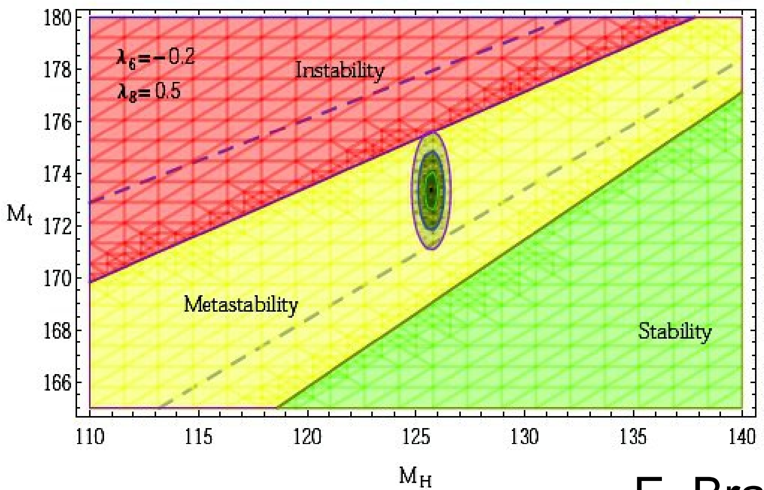
→ meta-stable, life time > O(10^{80}) $t_{universe}$

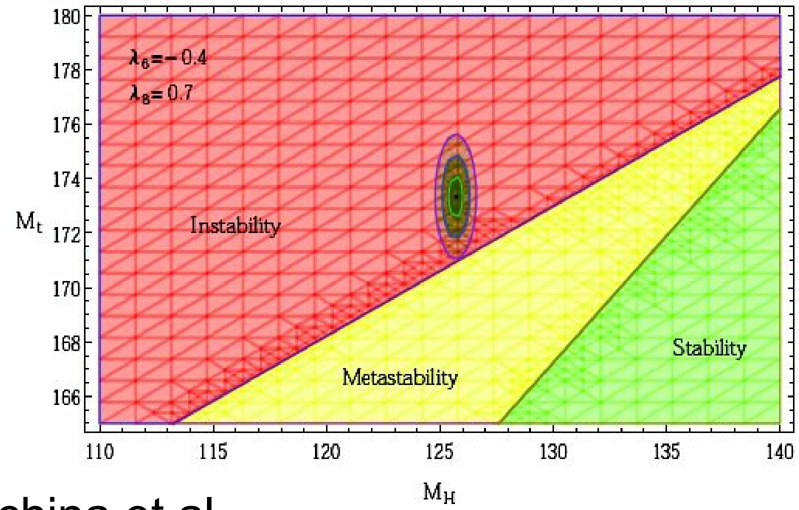
→ but new physics can change that dramatically



$$V(\phi) = \frac{\lambda}{4}\phi^4 + \frac{\lambda_6}{6}\frac{\phi^6}{M_P^2} + \frac{\lambda_8}{8}\frac{\phi^8}{M_P^4}$$

SM Higgs potential | dim 6 & 8 BSM modifications





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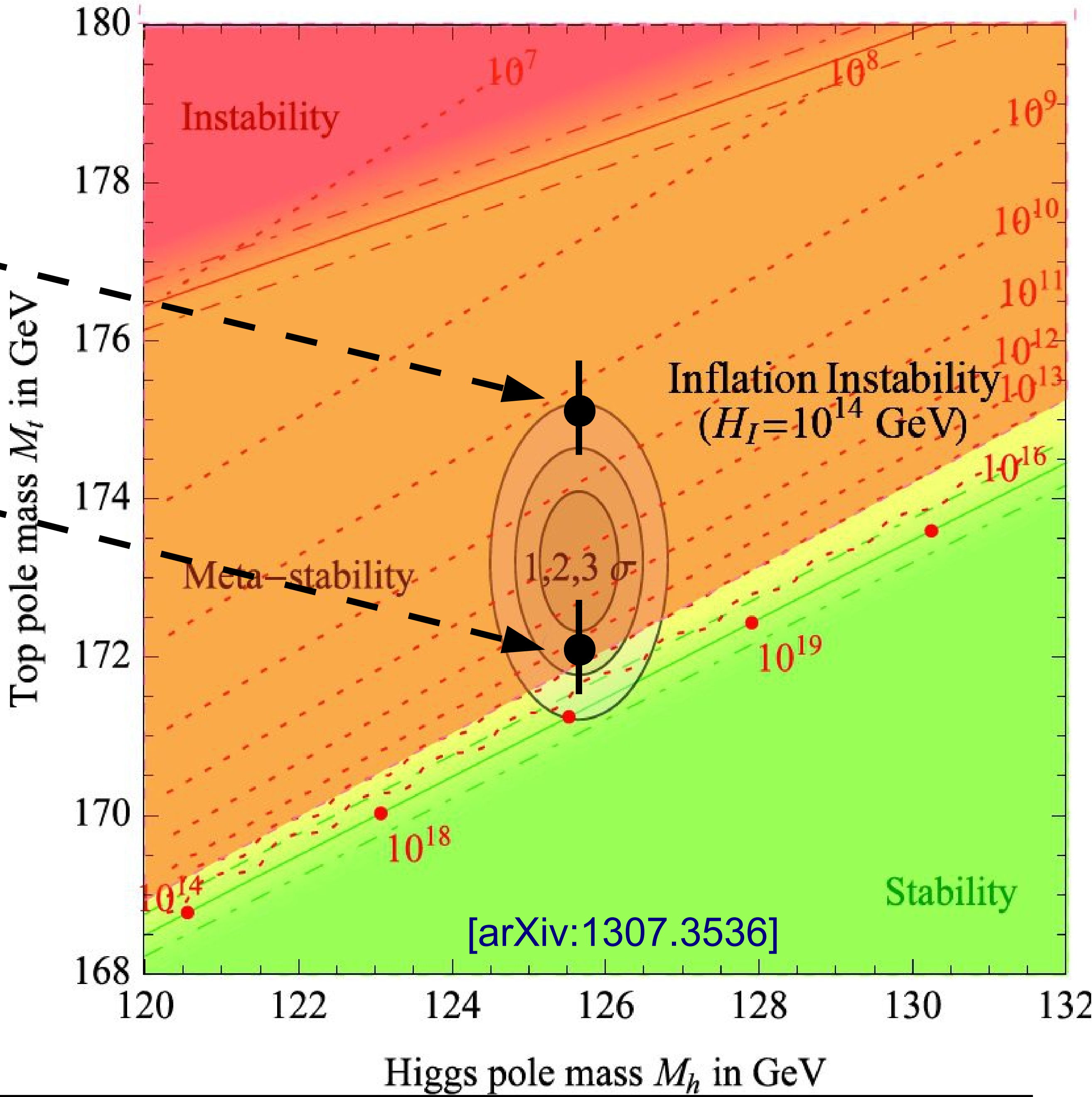
Fate of the Universe

- Add latest measurements:
  D0 m_t = 174.98 ± 0.76 GeV

  CMS m_t = 172.02 ± 0.77 GeV



- "MC mass" vs. pole mass: all QCD effects taken into account ?
  - Internal inter-collaboration study group

    Members of the group working on this subject as well