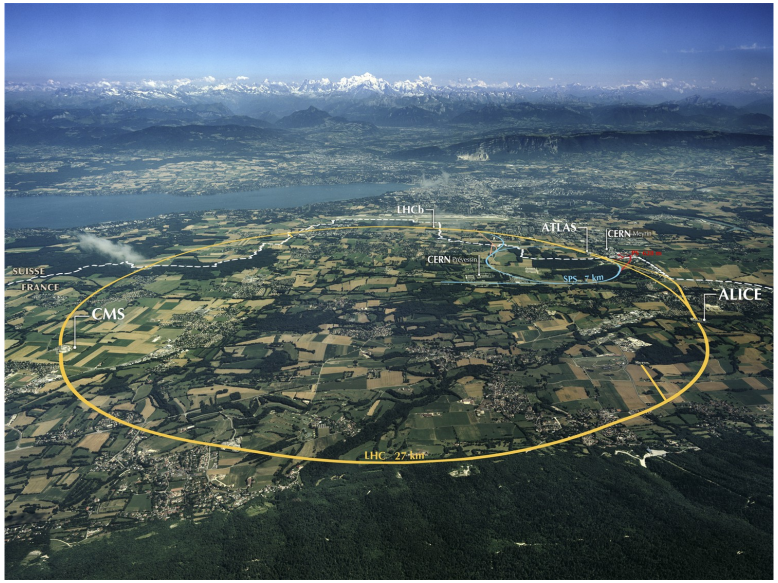
CMS Top quark results



(Introduction)

→ Inclusive & Differential Production
→ Spin correlations and W helicity
→ Anomalous couplings
→ tt + W, Z, γ cross sections
→ Mass
→ Conclusions & Outlook

Andreas Jung for the CMS collaboration

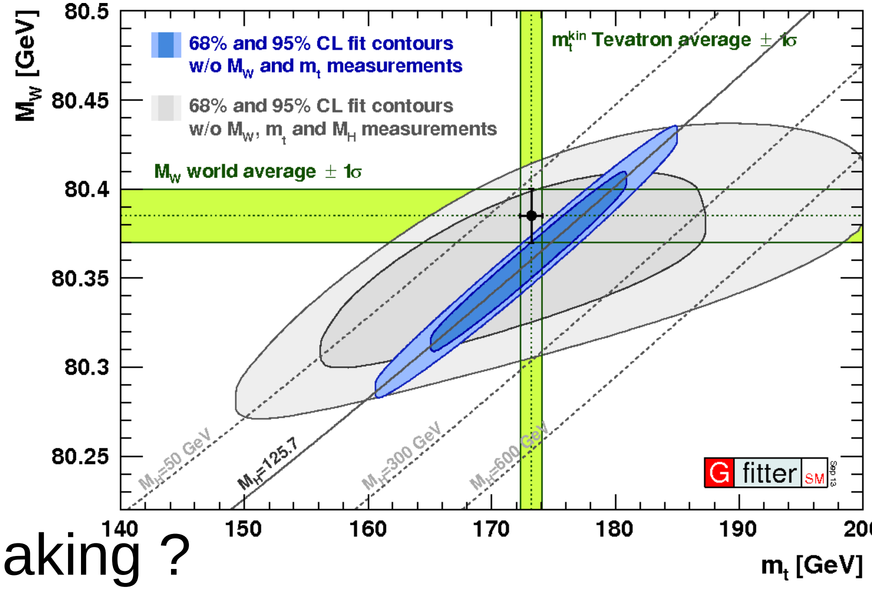
PURDUE UNIVERSITY

Aspen Winter Conference – From the LHC to DM and beyond

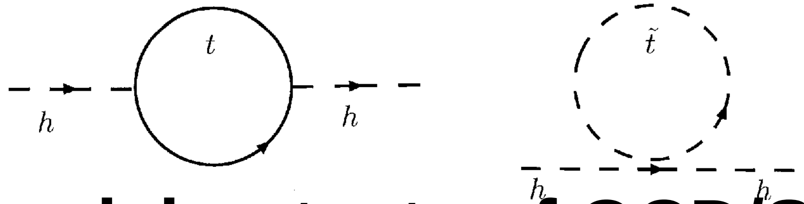
March 24th, 2017

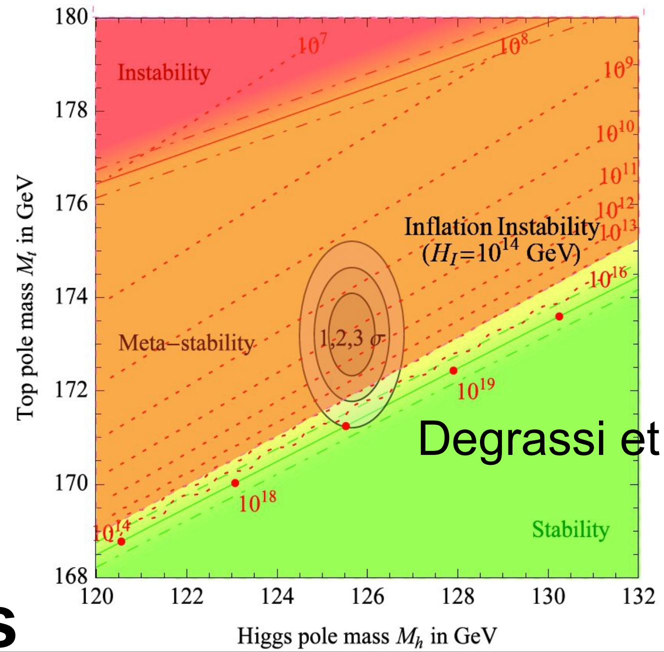
Top quark introduction

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



- Lifetime: $\tau \sim 5\times10^{-25}$ s, $\tau < 1/\Lambda_{QCD} << m_t/\Lambda^2_{QCD}$
  → **Observe bare quark properties**
- Large Yukawa coupling to Higgs boson
  → $\lambda_t \sim 1$ **only m_t is natural mass**
  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)

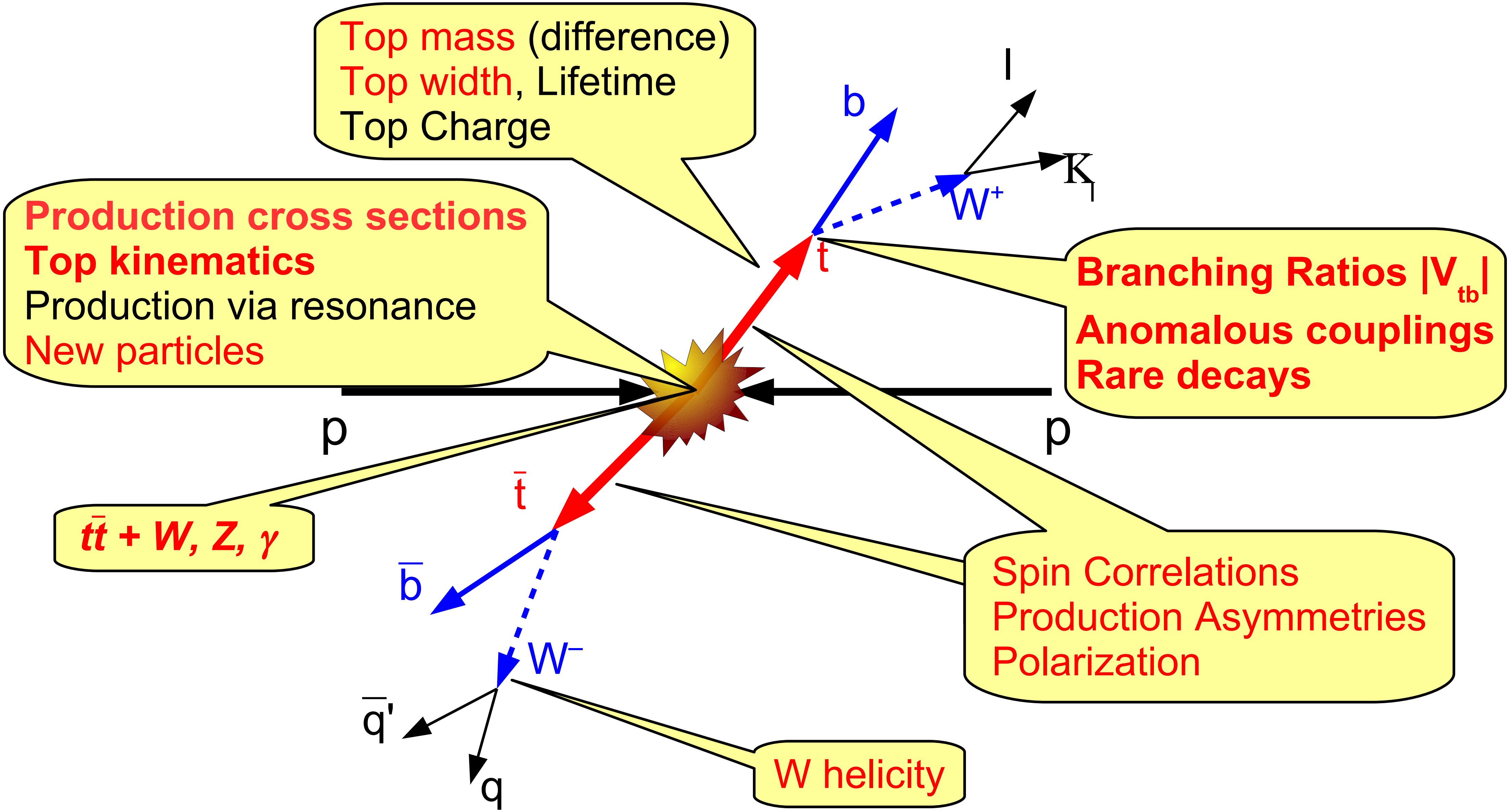




Degrassi et al.

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

Content



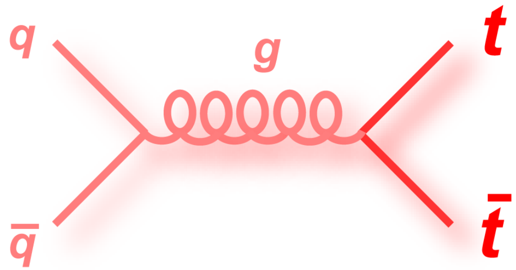
→ **Focus mostly on 13 TeV results and/or most precise results**

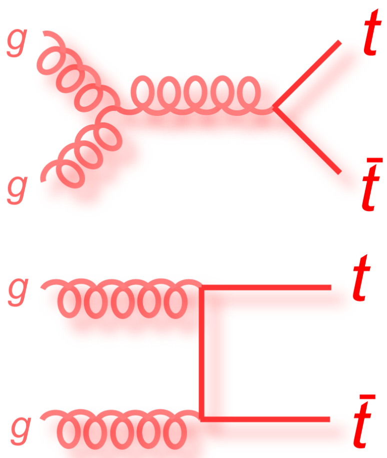
Top quark introduction

- Strong interaction: Top pairs

LHC (7/8 TeV):

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

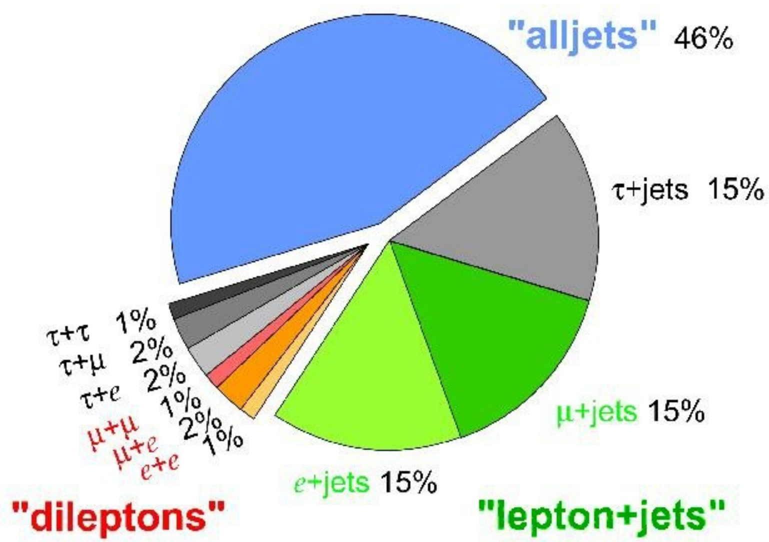


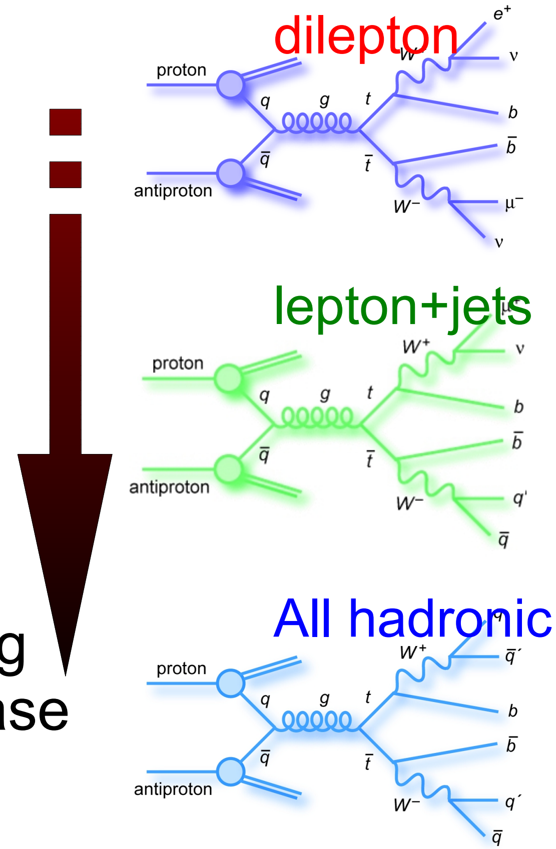


gg fusion

- Decay channels:

Top Pair Branching Fractions





BR, bg decrease

BR, bg increase

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	$^{+6.2(2.5\%)}_{-8.4(3.4\%)}$	$^{+6.2(2.5\%)}_{-6.4(2.6\%)}$

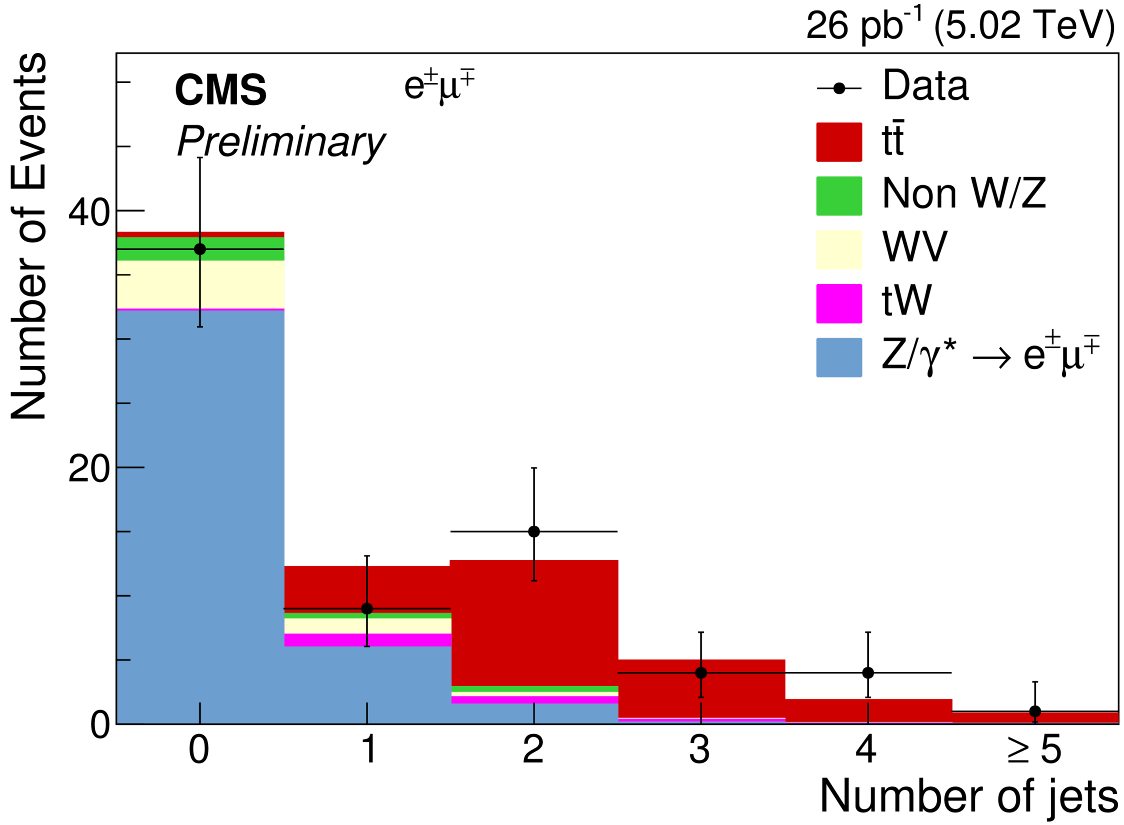
LHC 13 TeV $\sigma = 832^{+40}_{-46}$ pb

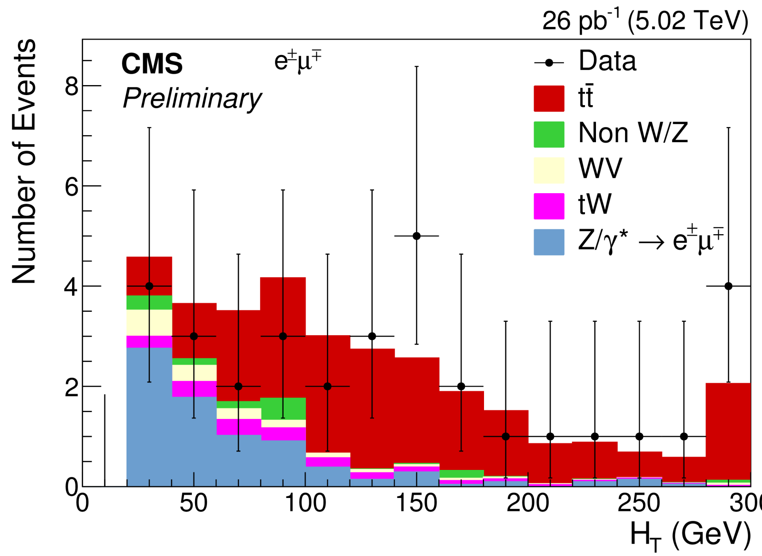
Top quark production

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

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

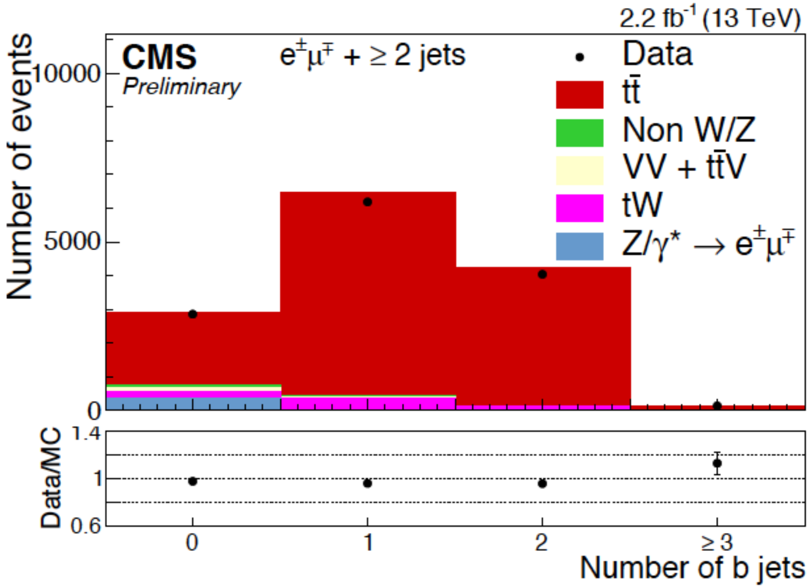
Source	Number of events $e^{\pm}\mu^{\mp}$
Drell–Yan	1.6 ± 0.4
Non W/Z	1.0 ± 0.9
tW	0.89 ± 0.02
WV	0.41 ± 0.02
Total background	3.9 ± 0.8
Signal ($t\bar{t} \to e\mu$)	16.7 ± 0.2
Data	24





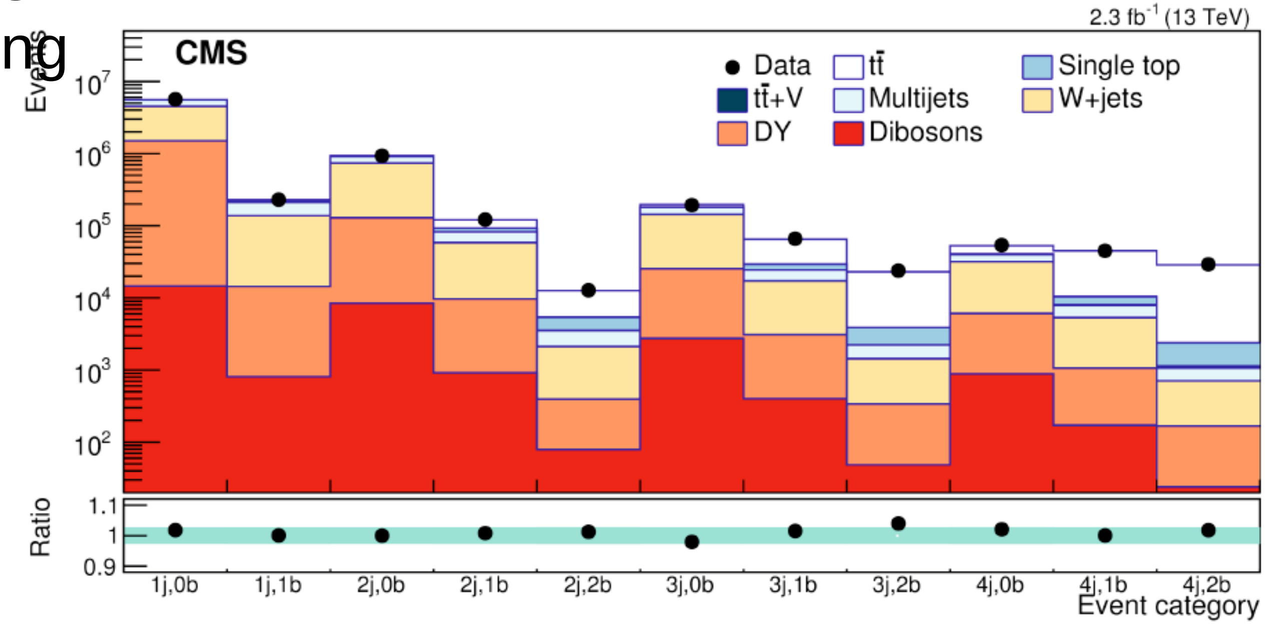
Top quark production

- CMS cross section measurement in the dilepton channel @13TeV, $\delta\sigma/\sigma$ = 5.6%
- Dominated by Hadronisation, JES



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

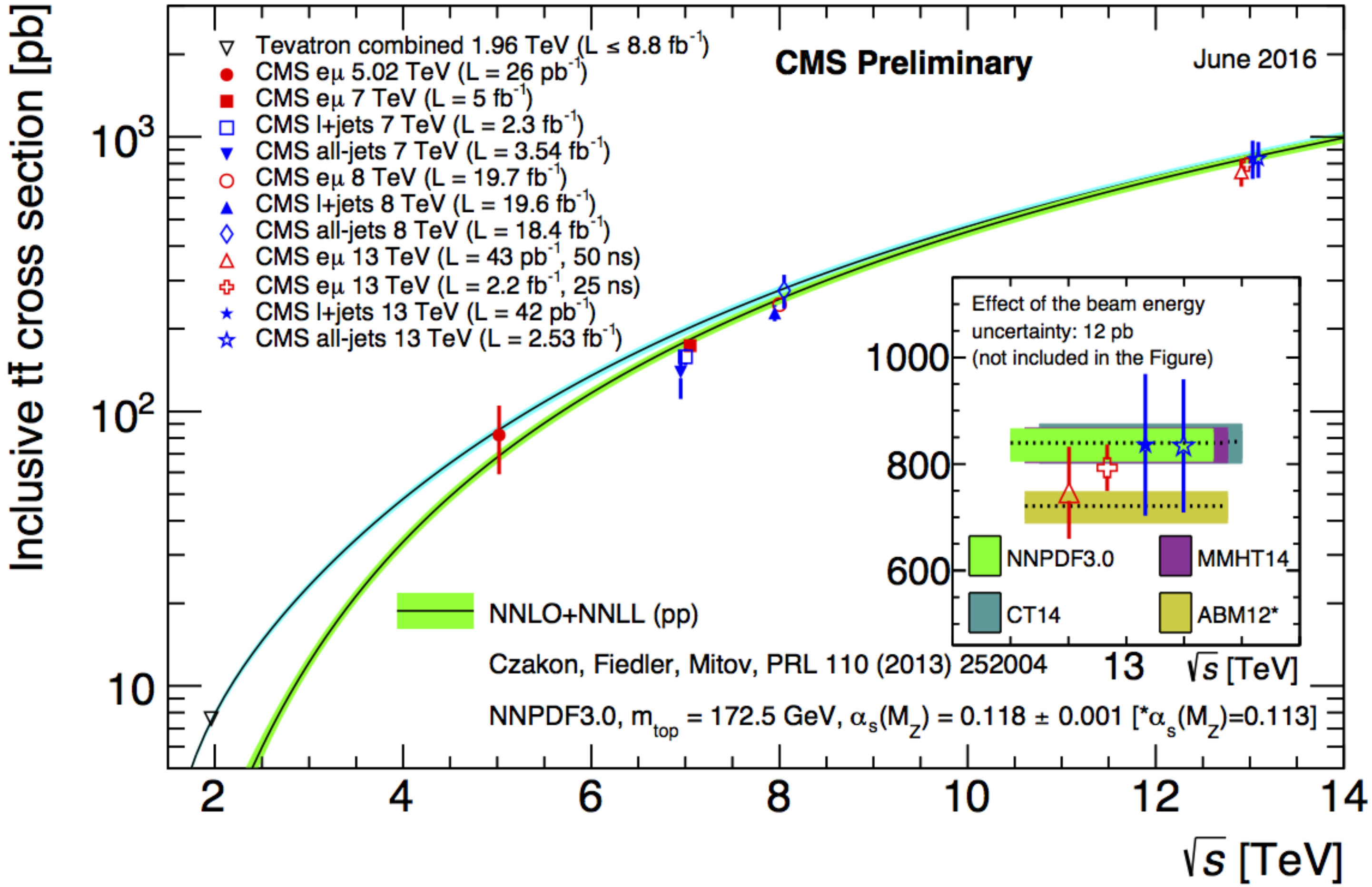
- Most precise measurement at 13 TeV
- In-situ constrains on systematics
- Fit jet and *b*-jet categories starting 1 jet to reduce systematics
- <u>Relative precision:</u> $\delta\sigma/\sigma$ = 3.9%
- l+jets decay channel

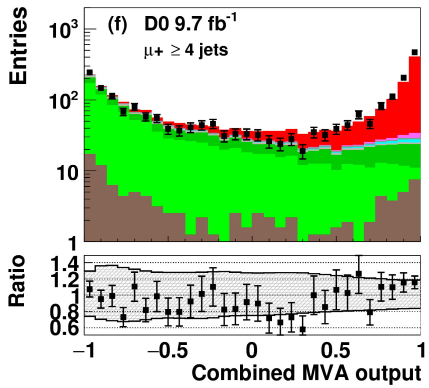


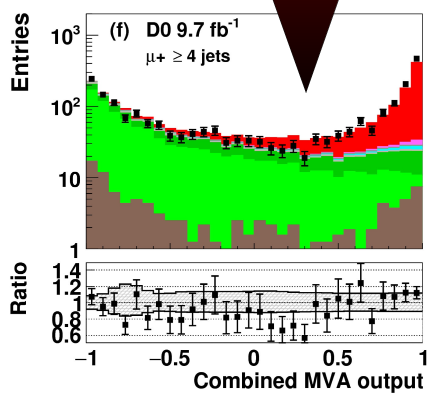
σ = 835 ± 3 (stat.) ± 23 (syst.) ± 23 (lumi.) pb

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:

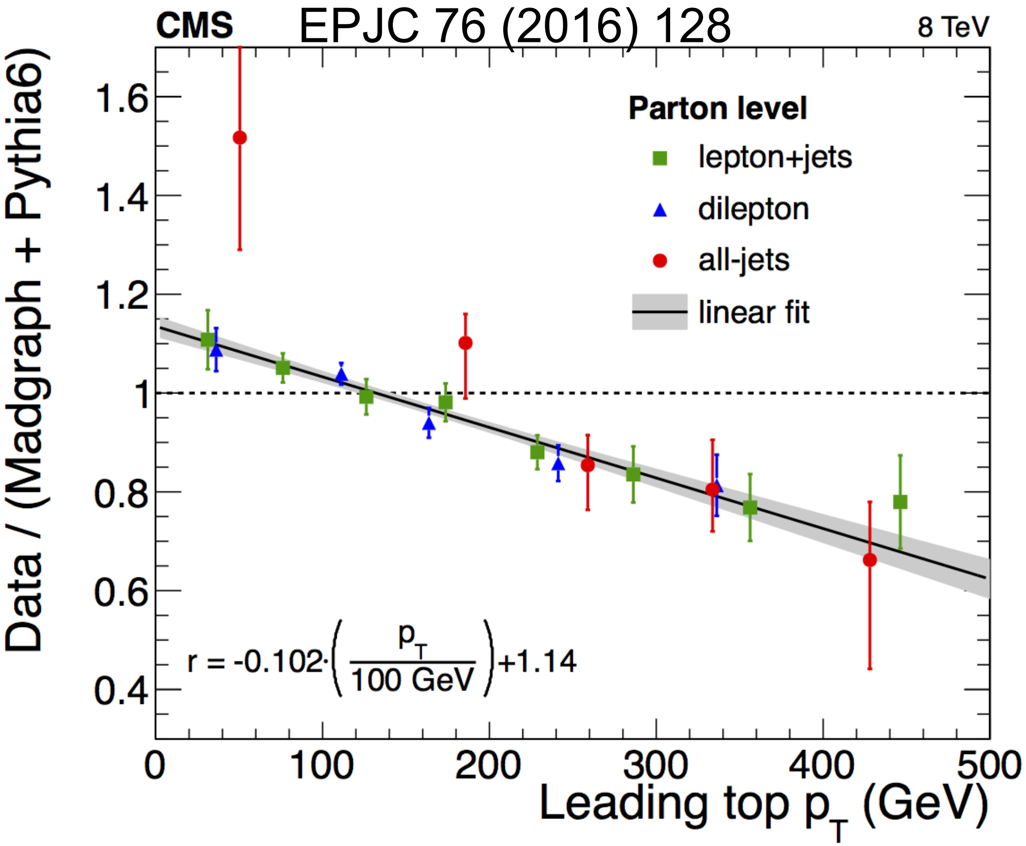
$\sigma = 7.26 \pm 0.13\ \text{(stat.)} \pm 0.57/0.50\ \text{(syst.)}$ pb

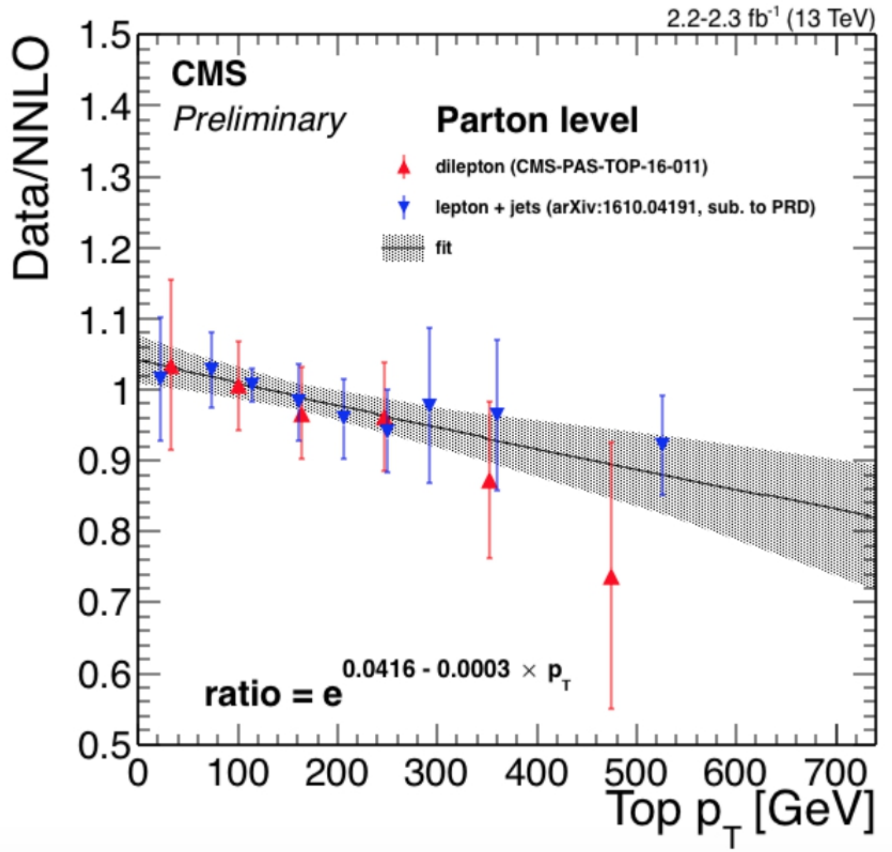
$\delta\sigma/\sigma$ = 7.6%

Phys. Rev. D 94 092004 (2016)

Differential cross sections

- Run I & Run II **top pT** measurements at ATLAS/CMS **not described** by NLO and most MCs
- Data is more soft: consistently seen in all decay channels, **also at 13 TeV**





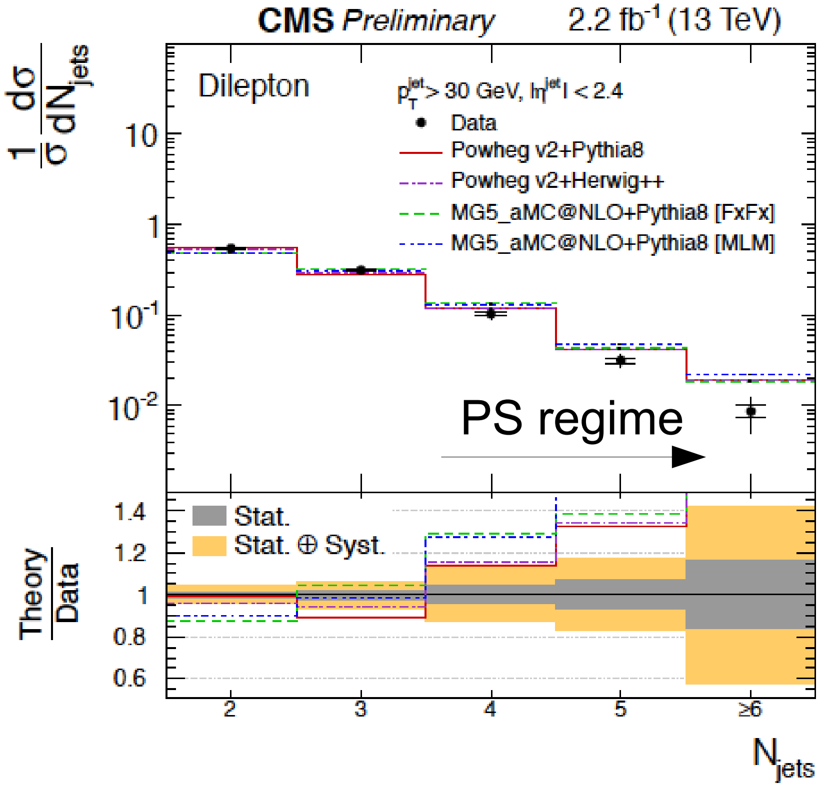
→ The pT spectra are described by NNLO calculations
→ First indications of a slope wrt NNLO in 13 TeV data, not yet significant

Differential cross sections

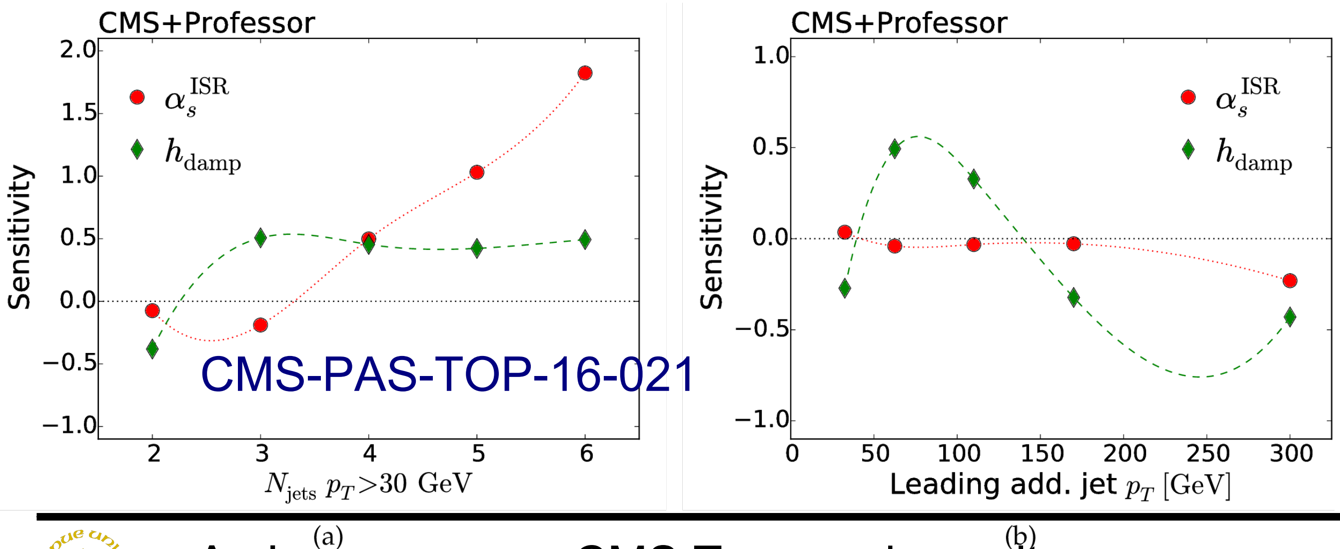
Dilepton CMS-PAS-TOP-16-011
l+jets CMS-PAS-TOP-16-008

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

- Use 8 TeV dilepton channel results to tune MC parameters, than check description in 8 TeV l+jets and in 13 TeV for both channels
  - Improve high Njets phase space
    - h_{damp}: control ME/PS matching
    - α_{ISR}: α_S for initial state radiation



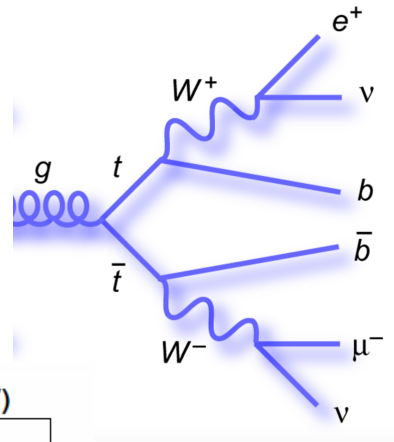
Differential cross section as a function of event variables:
Phys. Rev. D 94 (2016) 052006

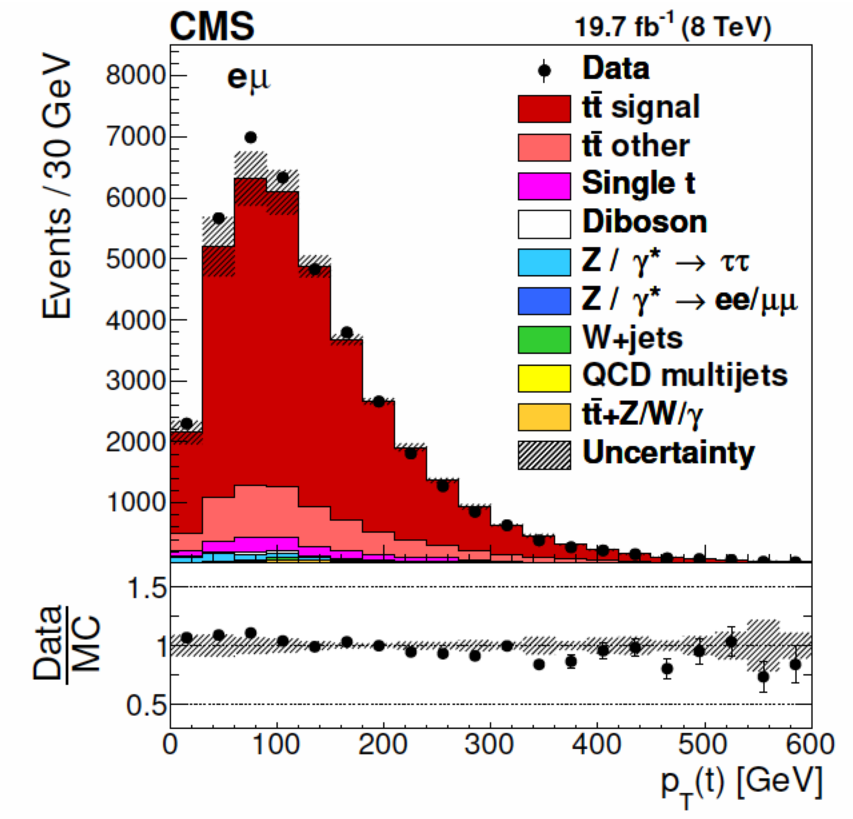


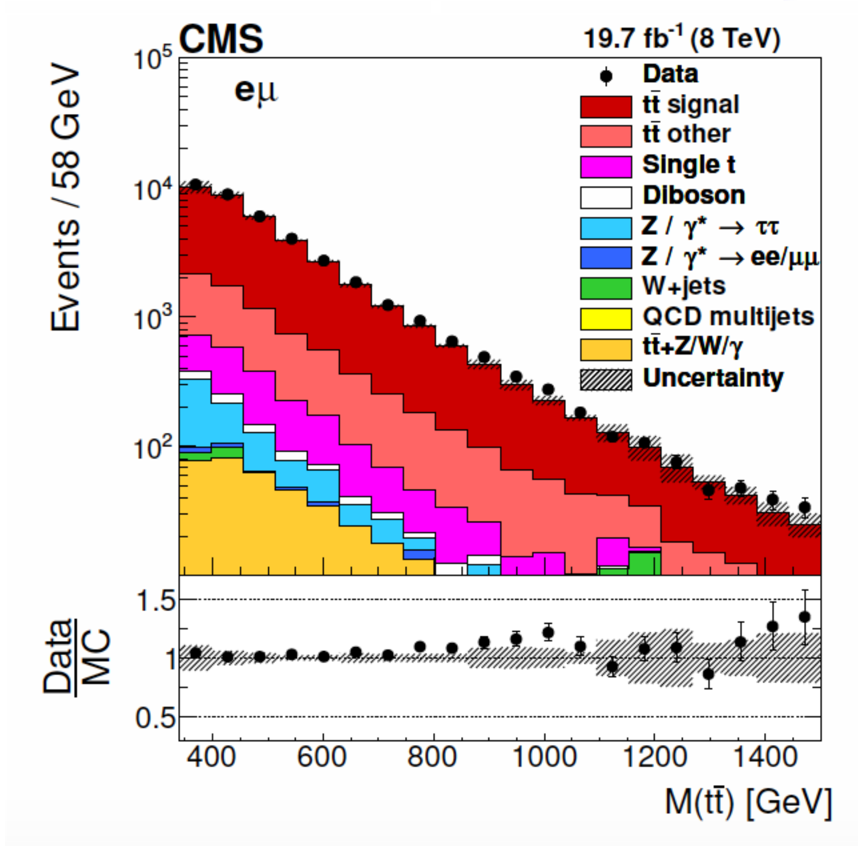
Differential cross sections

CMS-TOP-14-013

- First 2D cross section measurement of this type at the LHC
- Dilepton eμ channel – very good S/B
- Provide single & double differential cross sections



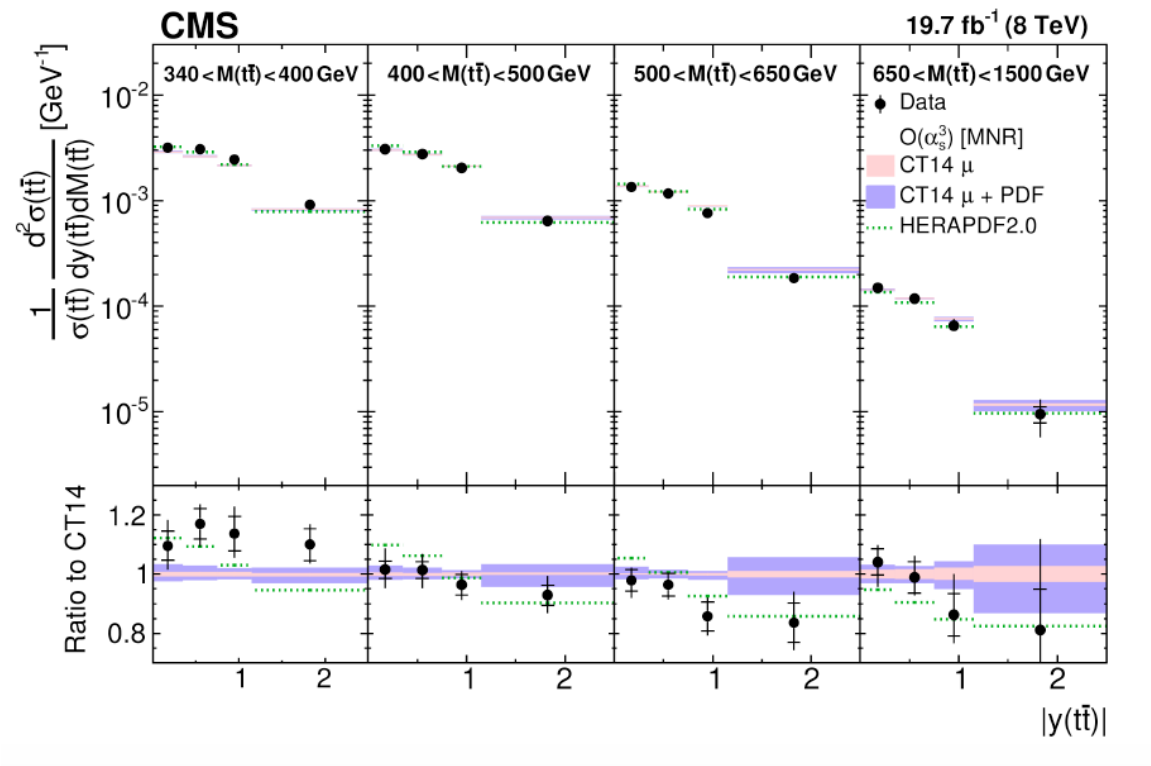


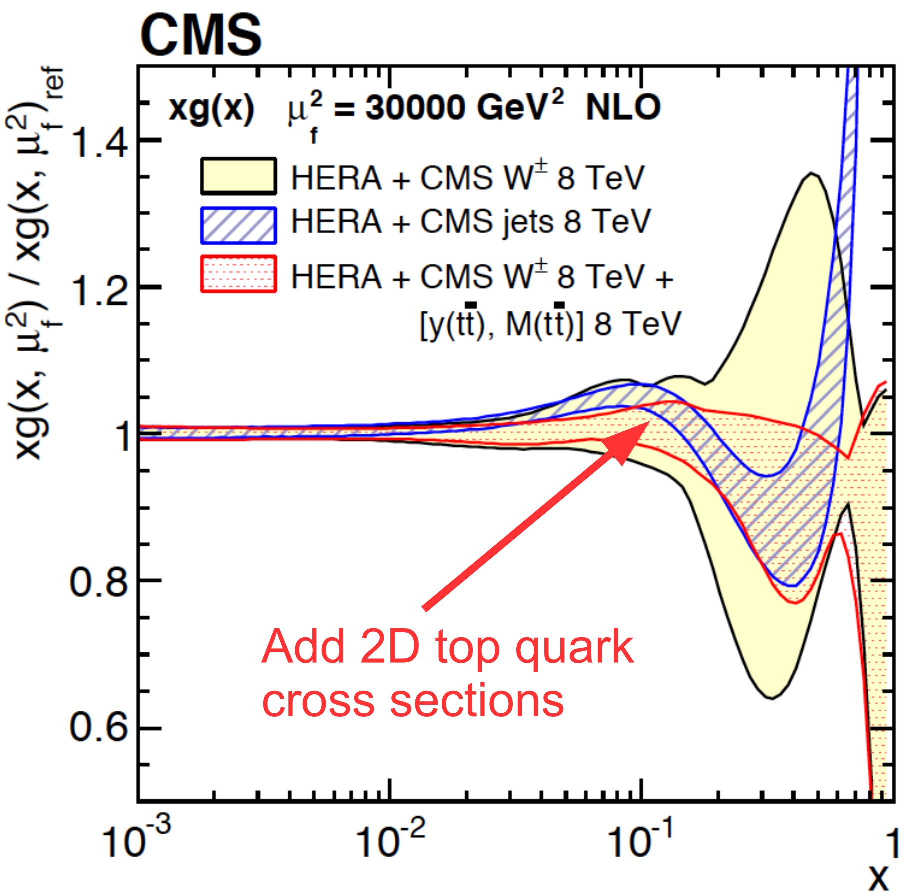


Differential cross sections

CMS-TOP-14-013

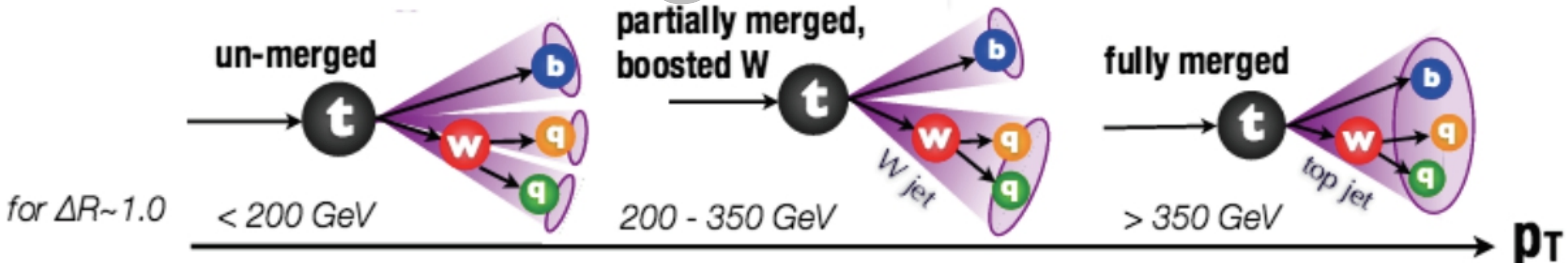
- First 2D cross section measurement of this type at the LHC
- Dilepton eμ channel – very good S/B
- Provide single & double differential cross sections
  - 2D cross sections more sensitive to large x PDFs
  - Constrain PDFs at large x

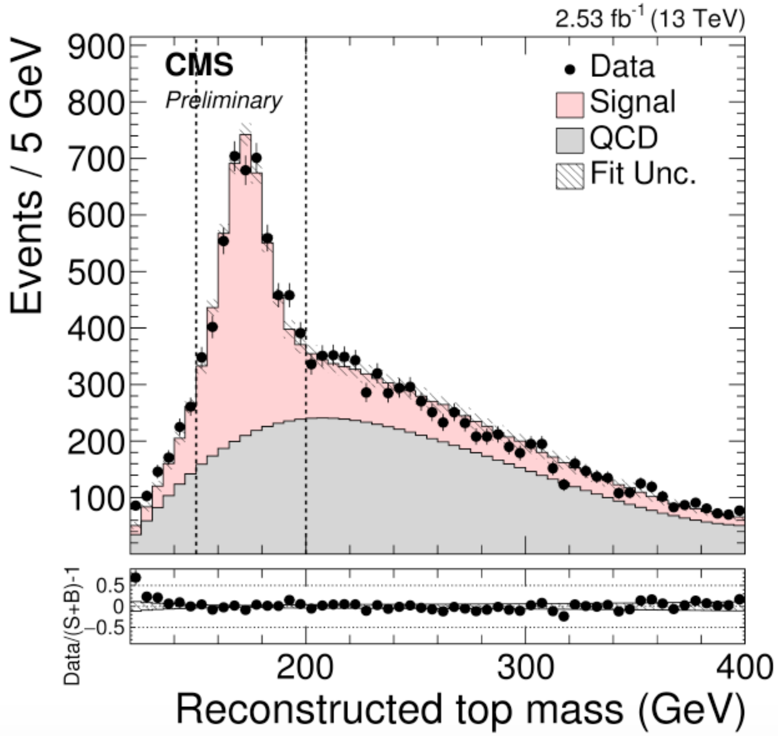


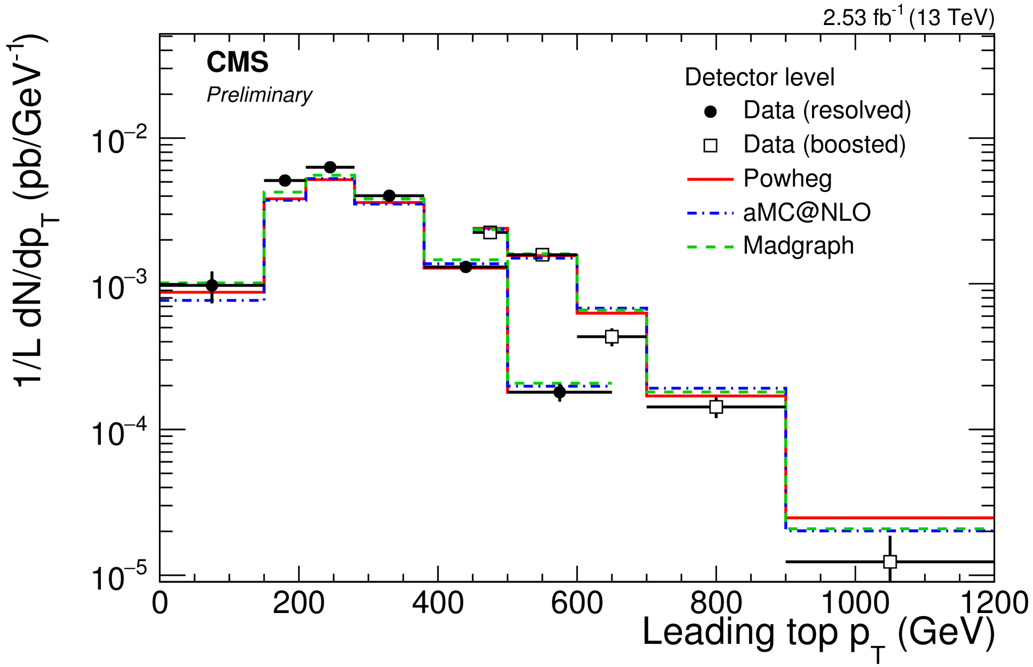


Boosted regime

CMS-PAG-TOP-16-013

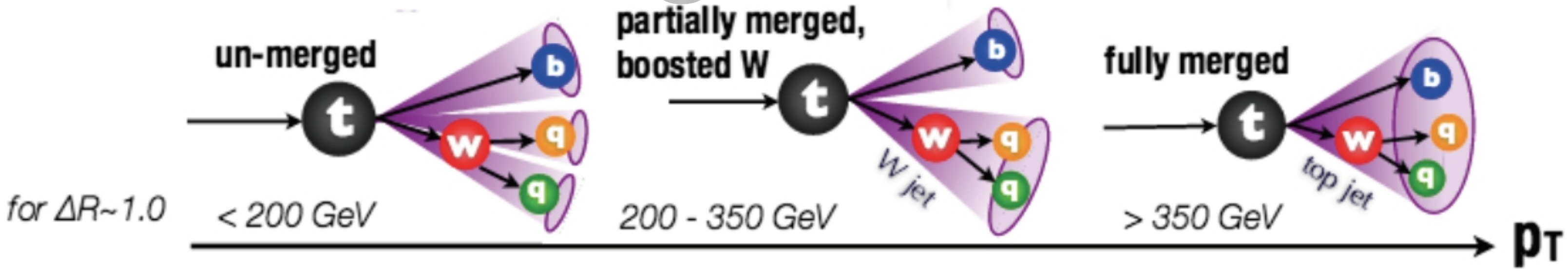


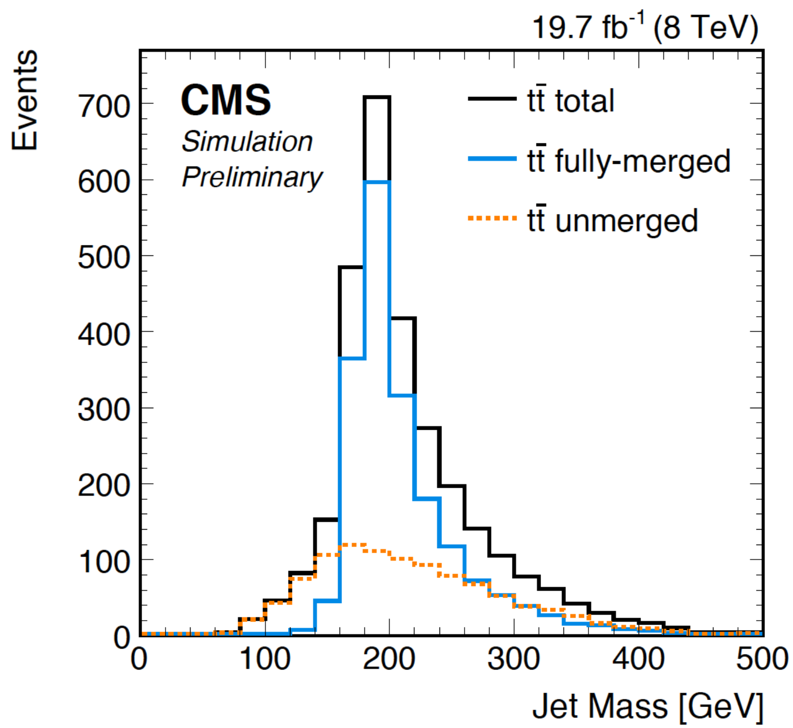


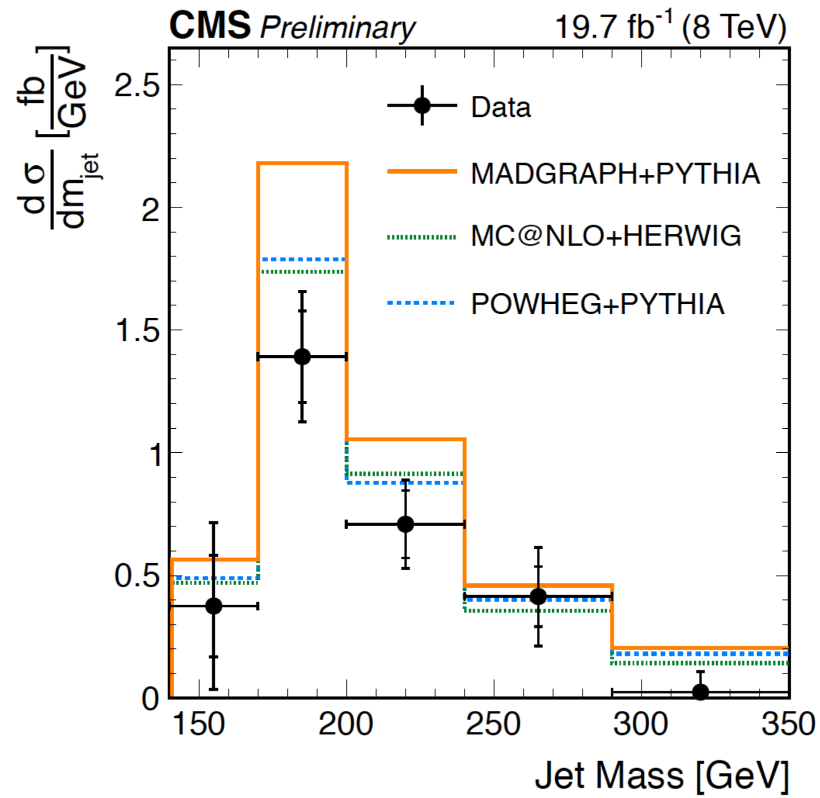


- All-hadronic channel: Use reconstructed top mass to derive bg norm+shape
- Consistent picture in boosted and resolved phase space
- Parton level results receive larger systematic uncertainties
- CMS 13 TeV all-hadronic combined resolved and boosted analysis

Boosted regime





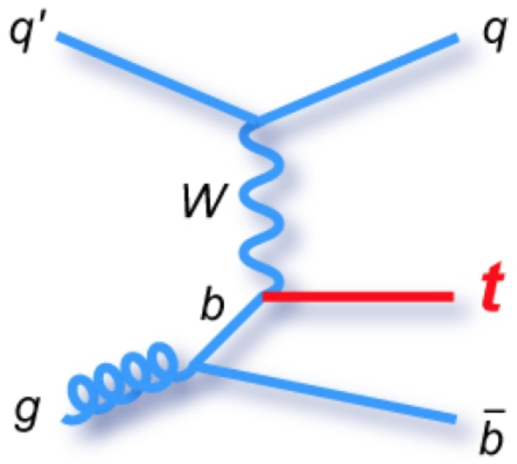


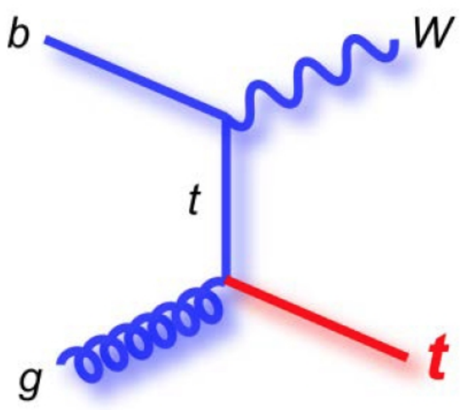
- Hadronic decay products reconstructed with single jet R = 1.2
- Peak position of m_{jet} sensitive to m_t

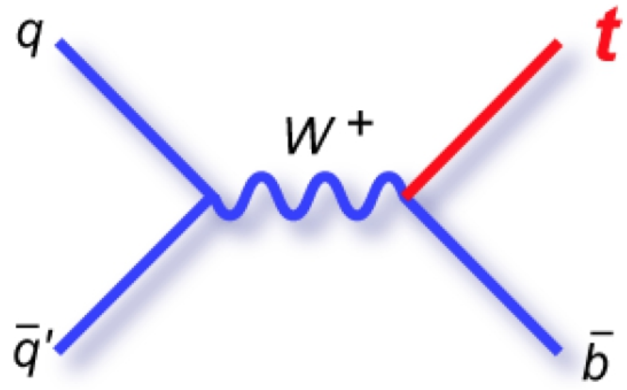
→ M_{top} = 171.8 ± 9.5 (tot) GeV

- Detailed understanding of jet substructure observable crucial for boosted topologies

Single top quark production







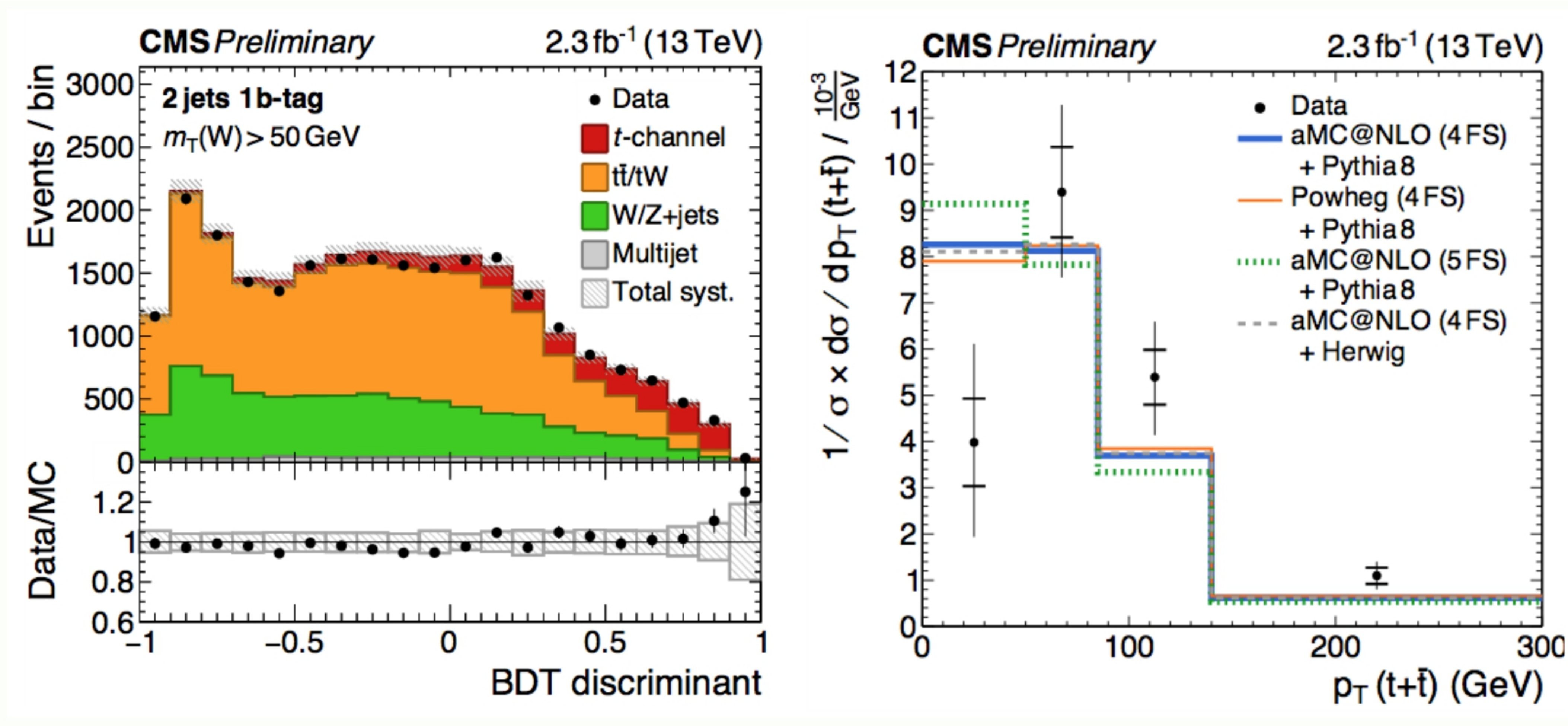
- Test of EW interactions
- **Single top cross section as high as $t\bar{t}$ at 8 TeV – large samples**

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

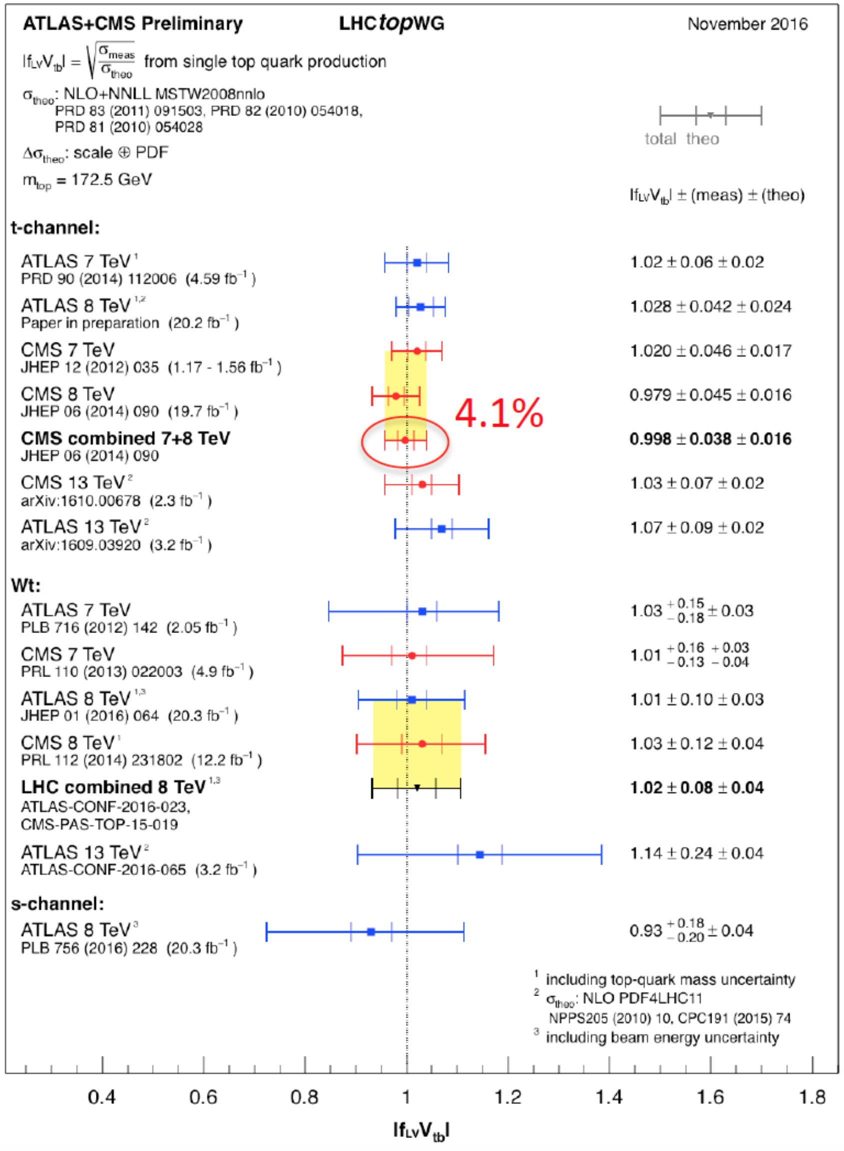
Energy	Process	Cross section [pb]
Tevatron (1.96 TeV)	t	2.10 ± 0.13
	s	1.05 ± 0.06
	Wt	0.25 ± 0.03
LHC (7 TeV)	t	$65.9\ ^{+2.1}_{-0.7}$ (scale) $^{+1.5}_{-1.7}$ (PDF)
	s	4.56 ± 0.07 (scale) $^{+0.18}_{-0.17}$ (PDF)
	Wt	15.6 ± 0.4 (scale) ± 1.1 (PDF)
LHC (8 TeV)	t	$87.2\ ^{+2.8}_{-1.0}$ (scale) $^{+2.0}_{-2.2}$ (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

Single top quark production

- 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



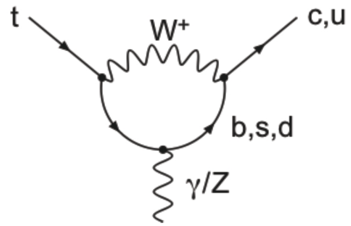
Vtb and FCNC



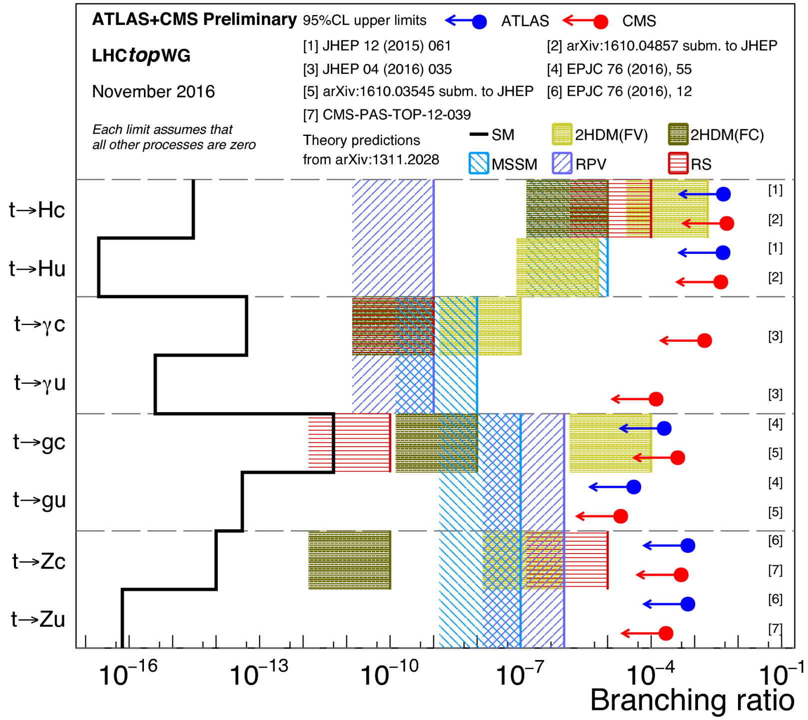
CMS-TOP-PAS-16-004

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

Flavor Changing Neutral Currents are highly suppressed in SM



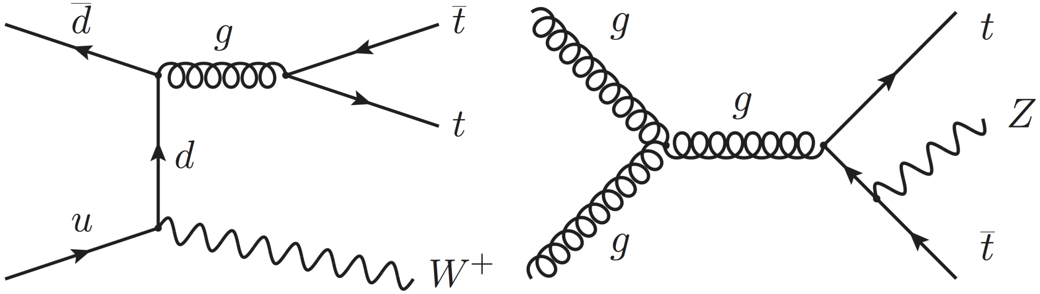
Still above SM predictions but reached sensitivity to certain BSM models

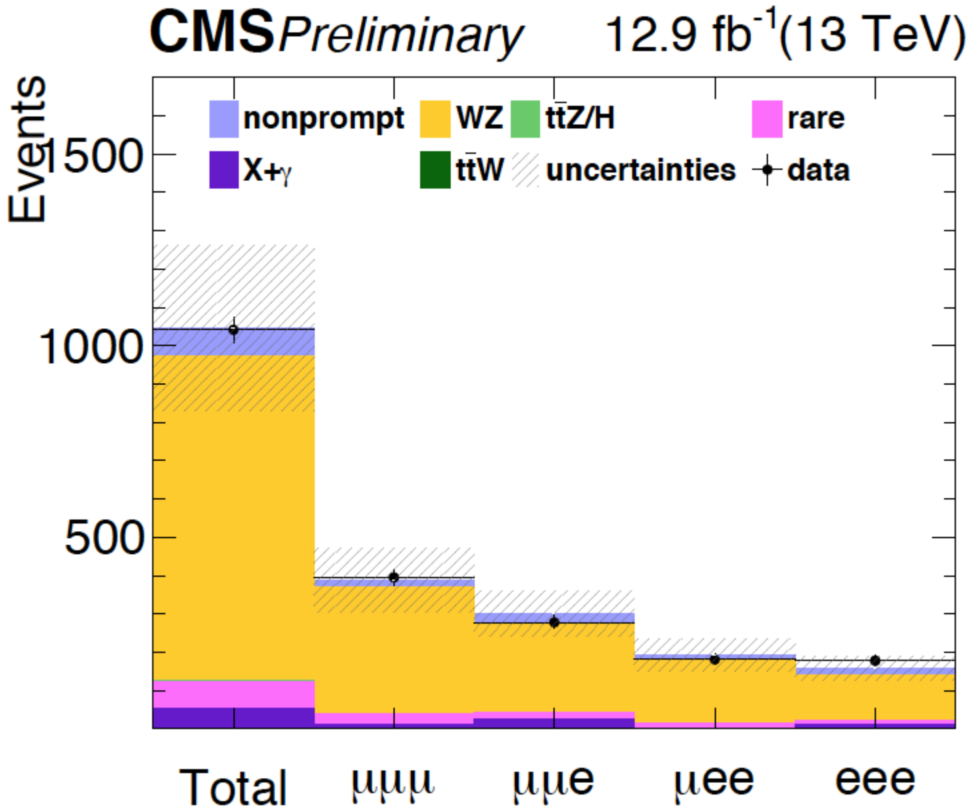


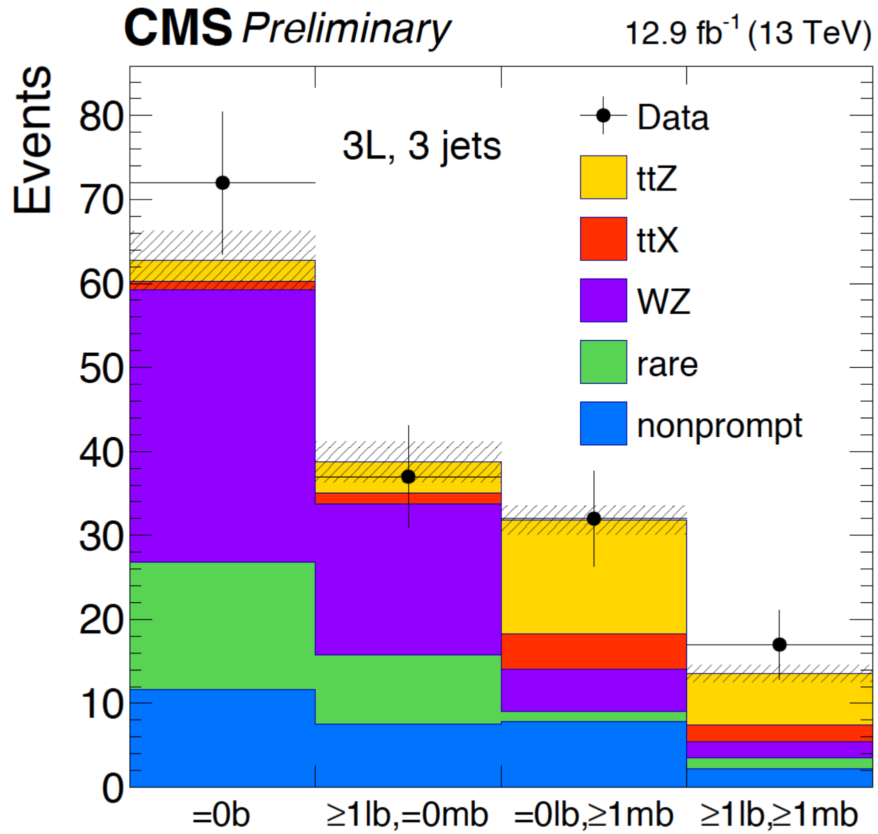
Ttbar + X: W, Z, γ

CMS-PAS-TOP-16-017

- 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
  - CMS includes 3 & 4 lepton final states
  - Systematic unc's dominated by: Lepton ID, signal model







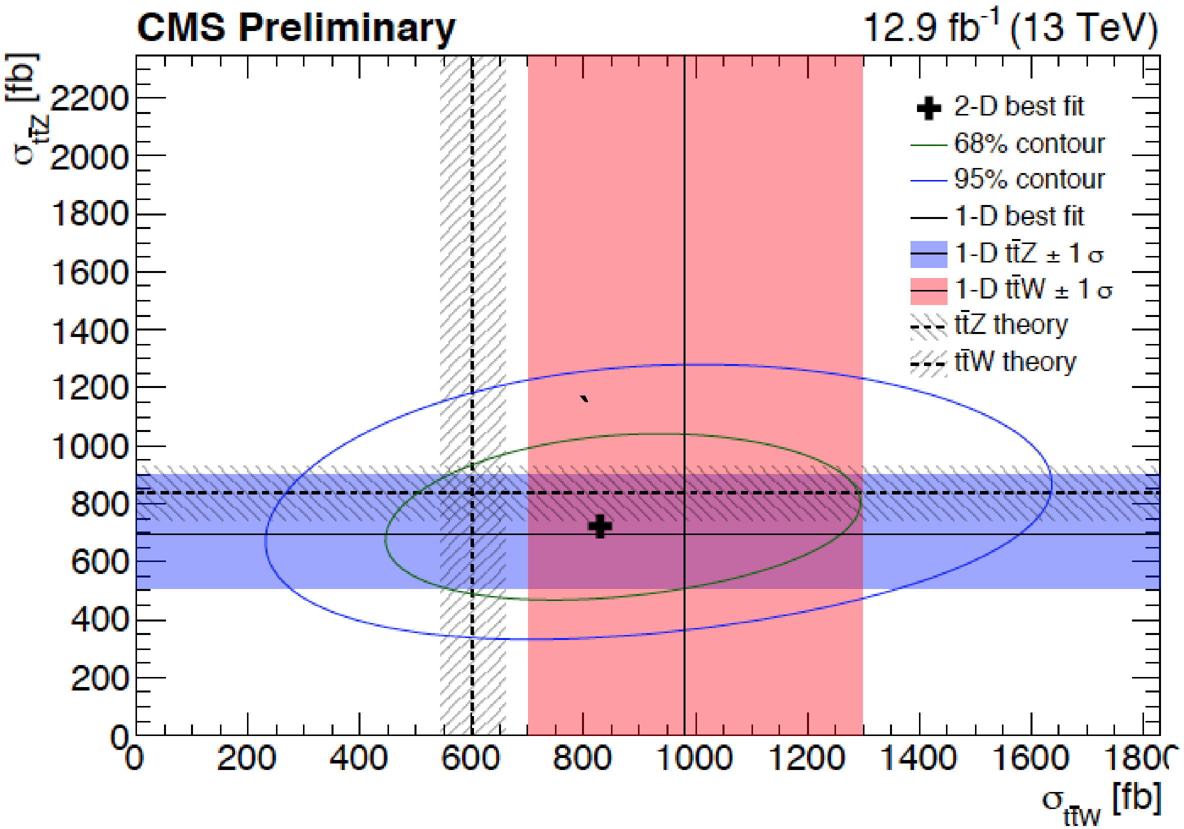
Ttbar + X: W, Z, γ

CMS-PAS-TOP-16-017

SM (NLO): σ(ttZ) = 839 ± 93 fb and σ(ttW) = 601 ± 55 fb

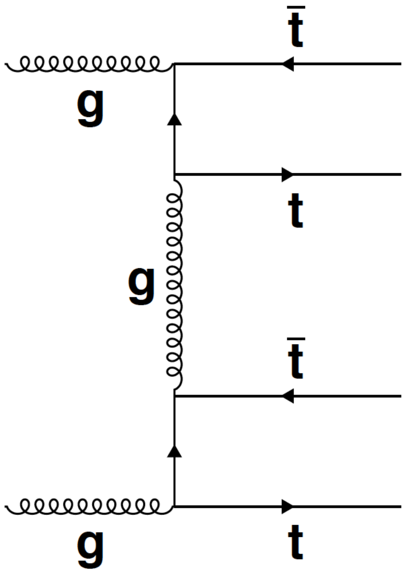
$\sigma(t\bar{t}Z)$ = 0.70 ± 0.16/0.15(stat.) ± 0.14/0.12(syst.) pb
Expected (observed) significance of 5.8 (4.6)

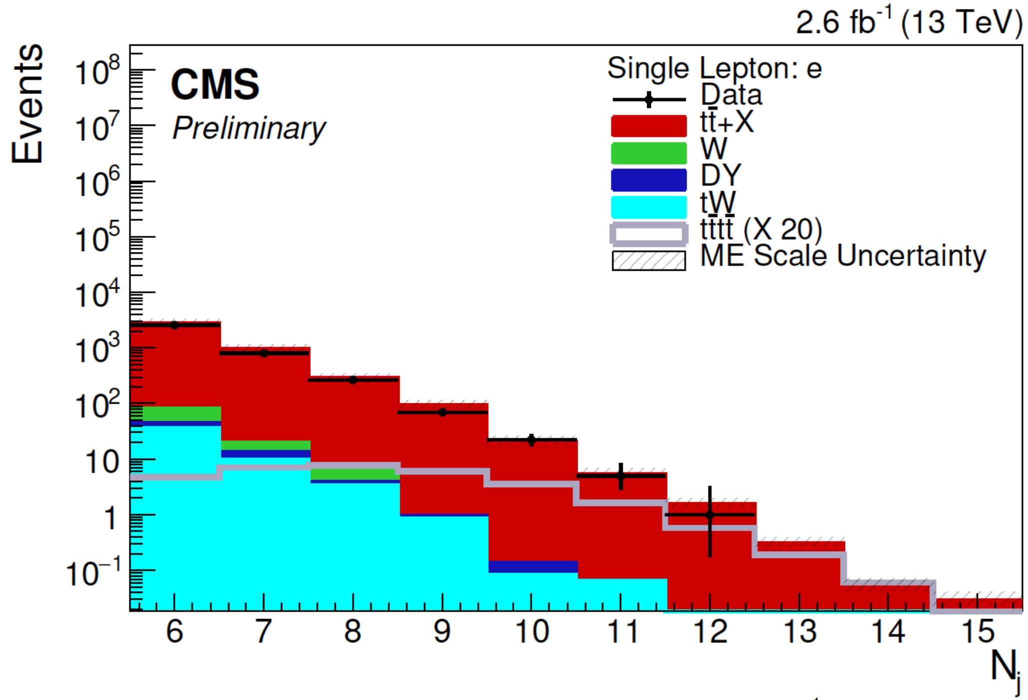
$\sigma(t\bar{t}W)$= 0.98 ± 0.23/0.22(stat.) ± 0.22/0.18(syst.) pb
Expected (observed) significance of 2.6 (3.9)



Ttbar + Ttbar

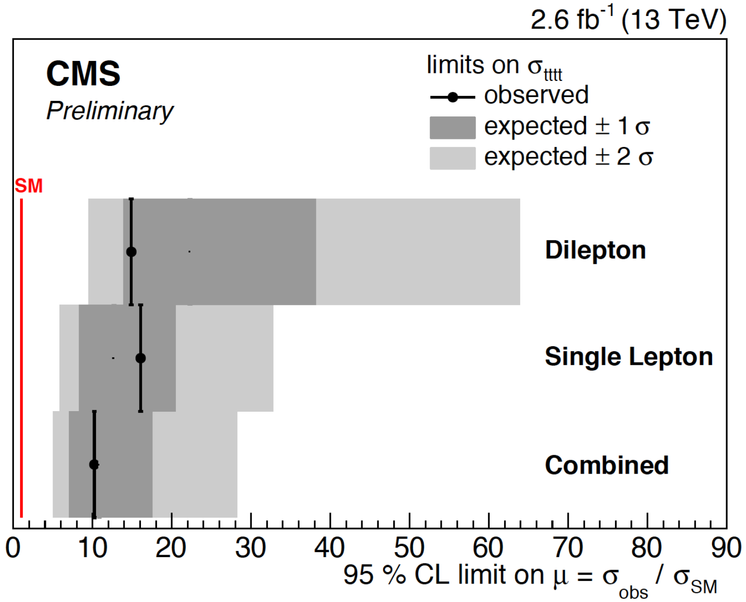
SM (NLO): $\sigma(tt+tt) = 9$ fb





- Dilepton & l+jets channels, at least 2 b-jets
- Use boosted decision tree to enhance signal

→ Upper limit for Ttbar+Ttbar @95% CL:
– Observed 10.2 x σ(SM, tt+tt)
– Observed 10.8 +6.7-3.8 x σ(SM, tt+tt)



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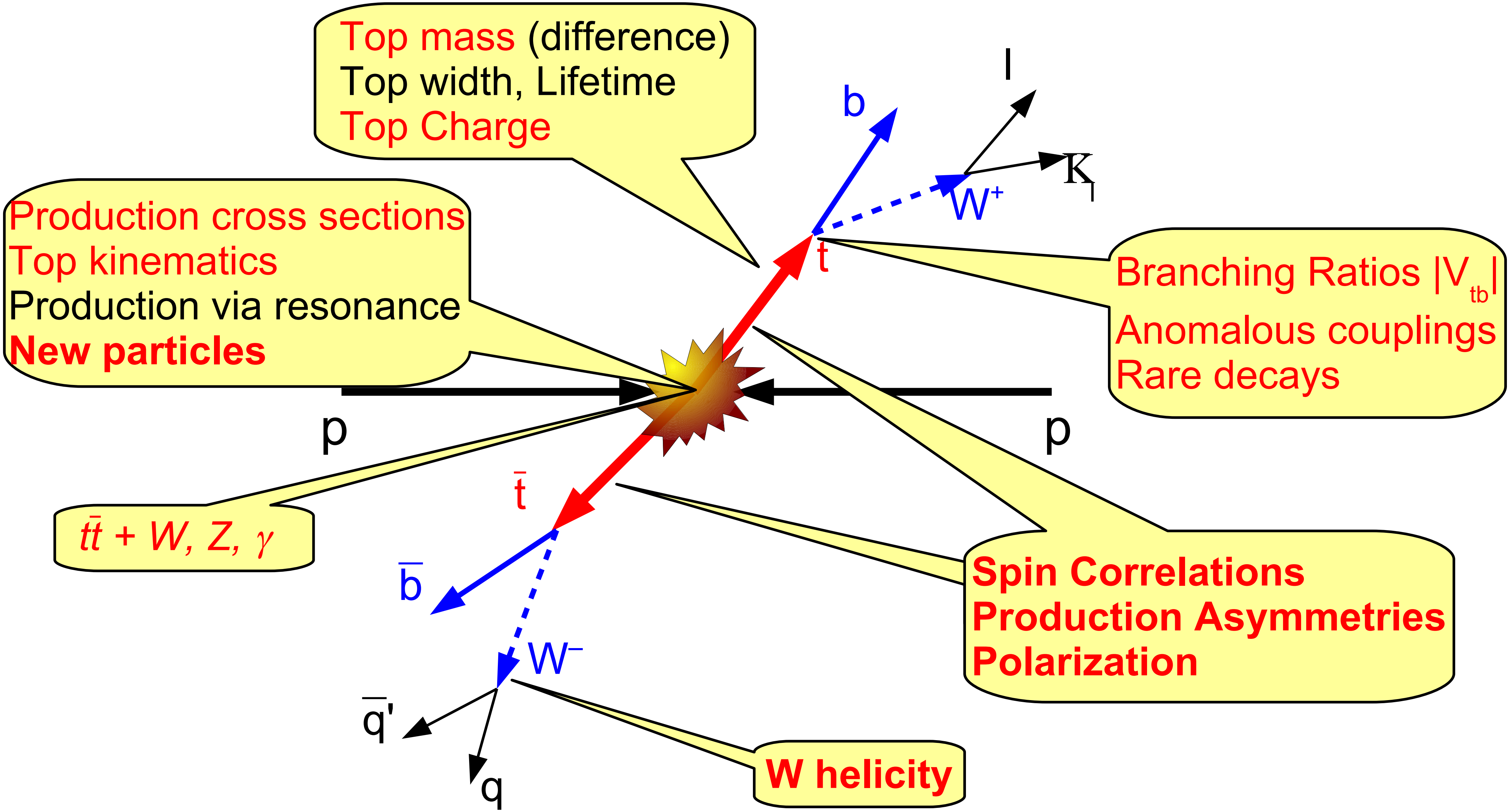


→ **Selection of results, focus on most recent and/or precise results**

Top quark spin correlations

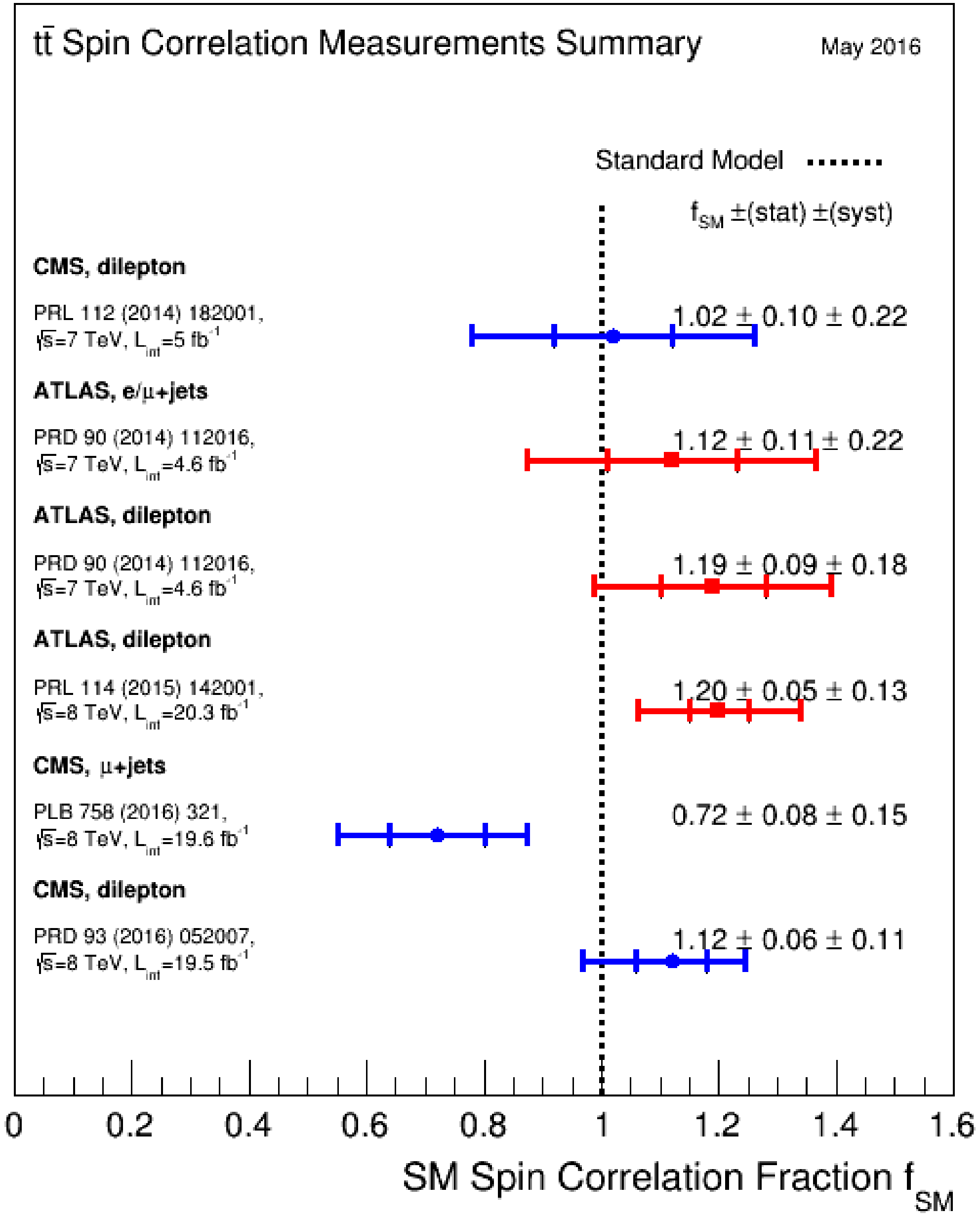
- Top quark spins expected to be correlated in SM (short life time)
- Spin analyzing power of leptons is 1, measure lepton distributions
- Powerful handle to search for BSM in difficult phase space regions

- Spin correlation strength:

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

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

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

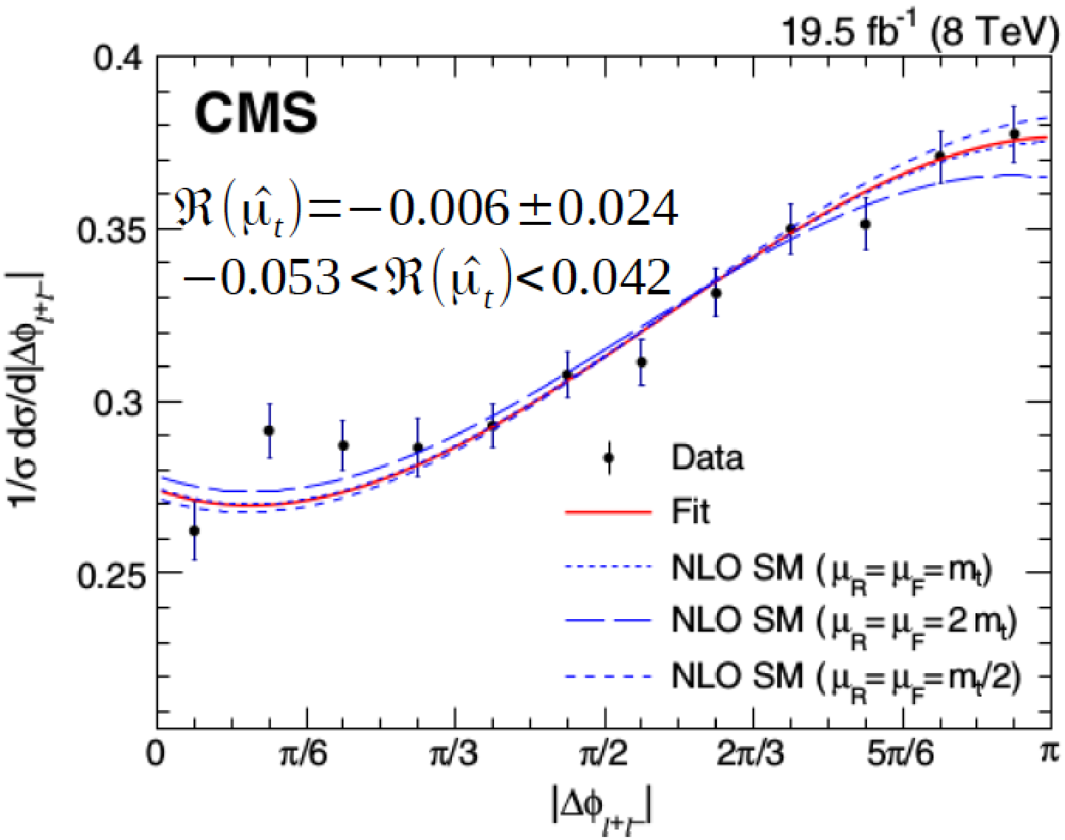


→ A depends on basis, energy, production mechanism
→ f represents degree of SC relative to the SM

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
- Dominated by: Unfolding & top p_T reweighting

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



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

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CP-conserving dipole moment   CP-violating dipole moment

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

$Re(\mu_t) = -0.006 \pm 0.024$ (tot.)

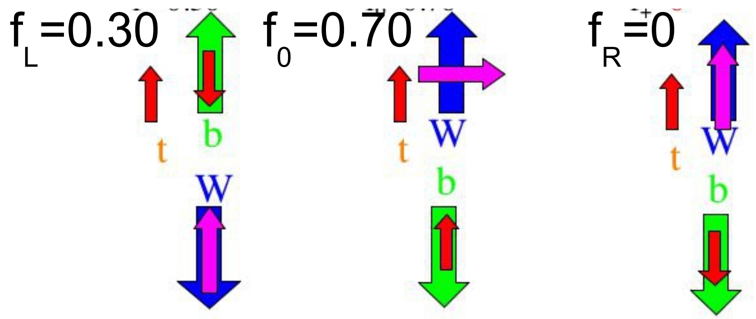
$-0.053 < Re(\mu_t) < 0.042$ at 95% CL

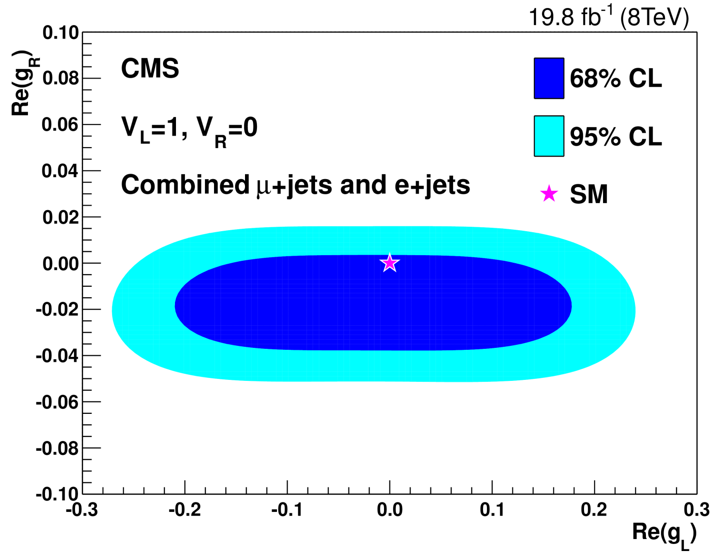
$-0.068 < Re(\int_t) < 0.067$ at 95% CL

W helicity

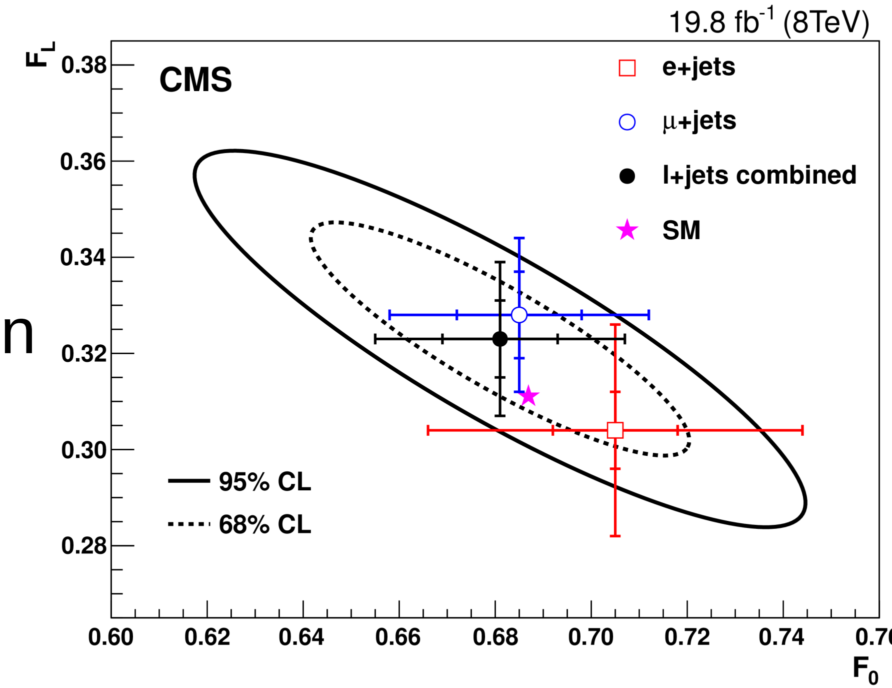
PLB 762 (2016) 512

- 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



Most accurate experimental determination

$F_0 = 0.681 \pm 0.012$ (stat.) ± 0.023 (syst.)

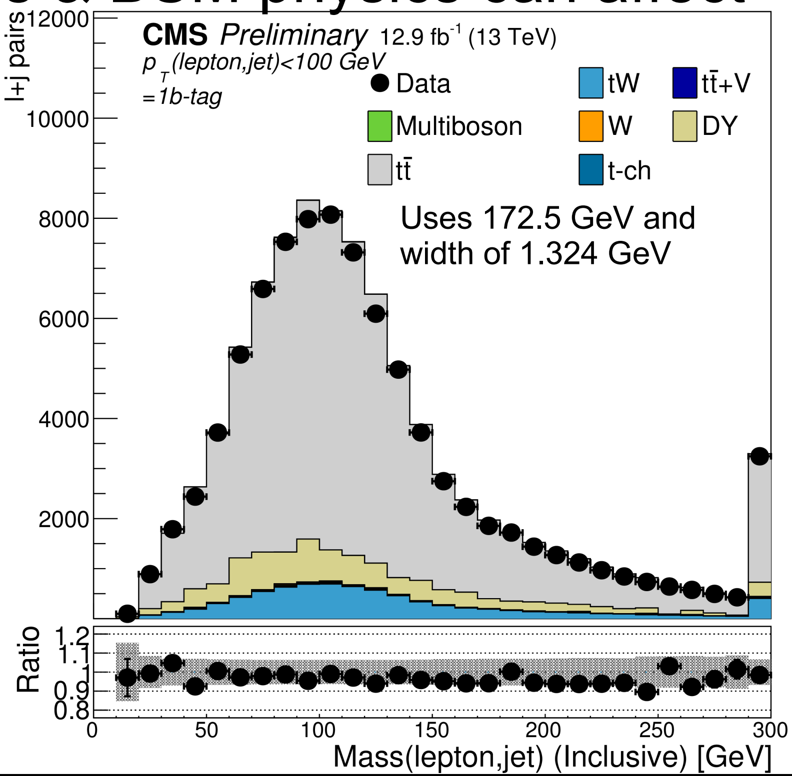
$F_L = 0.323 \pm 0.008$ (stat.) ± 0.014 (syst.)

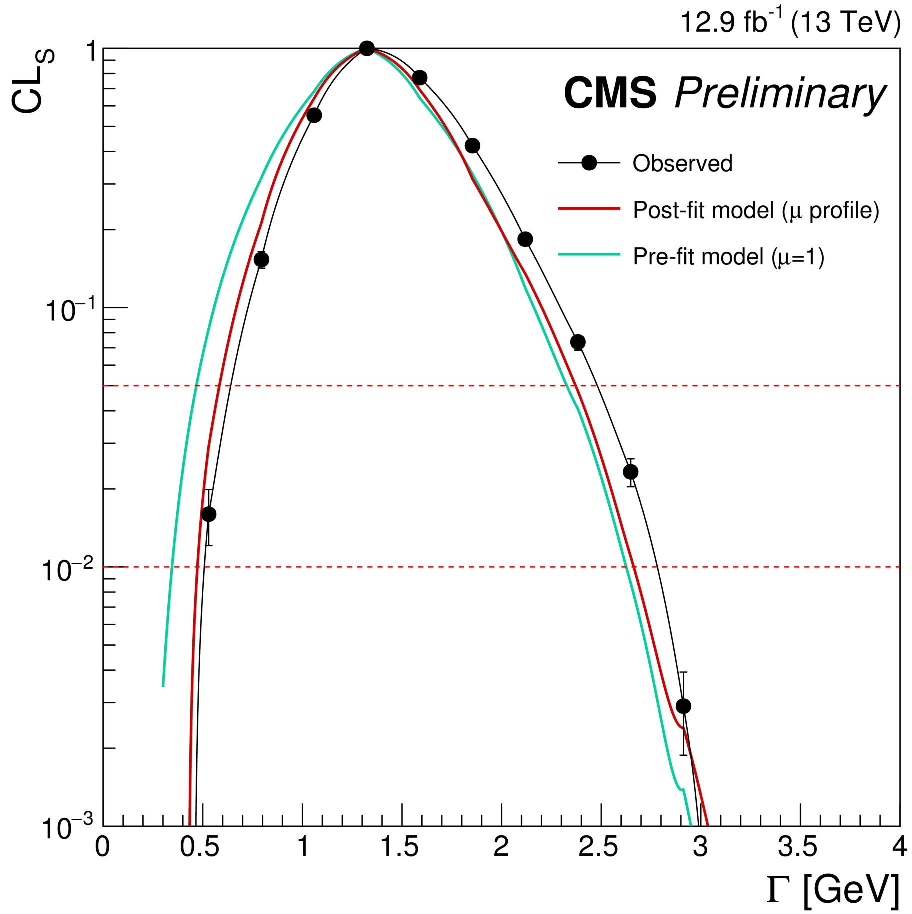
$F_R = 0.004 \pm 0.005$ (stat.) ± 0.014 (syst.)

Top quark width

CMS-PAS-TOP-16-019

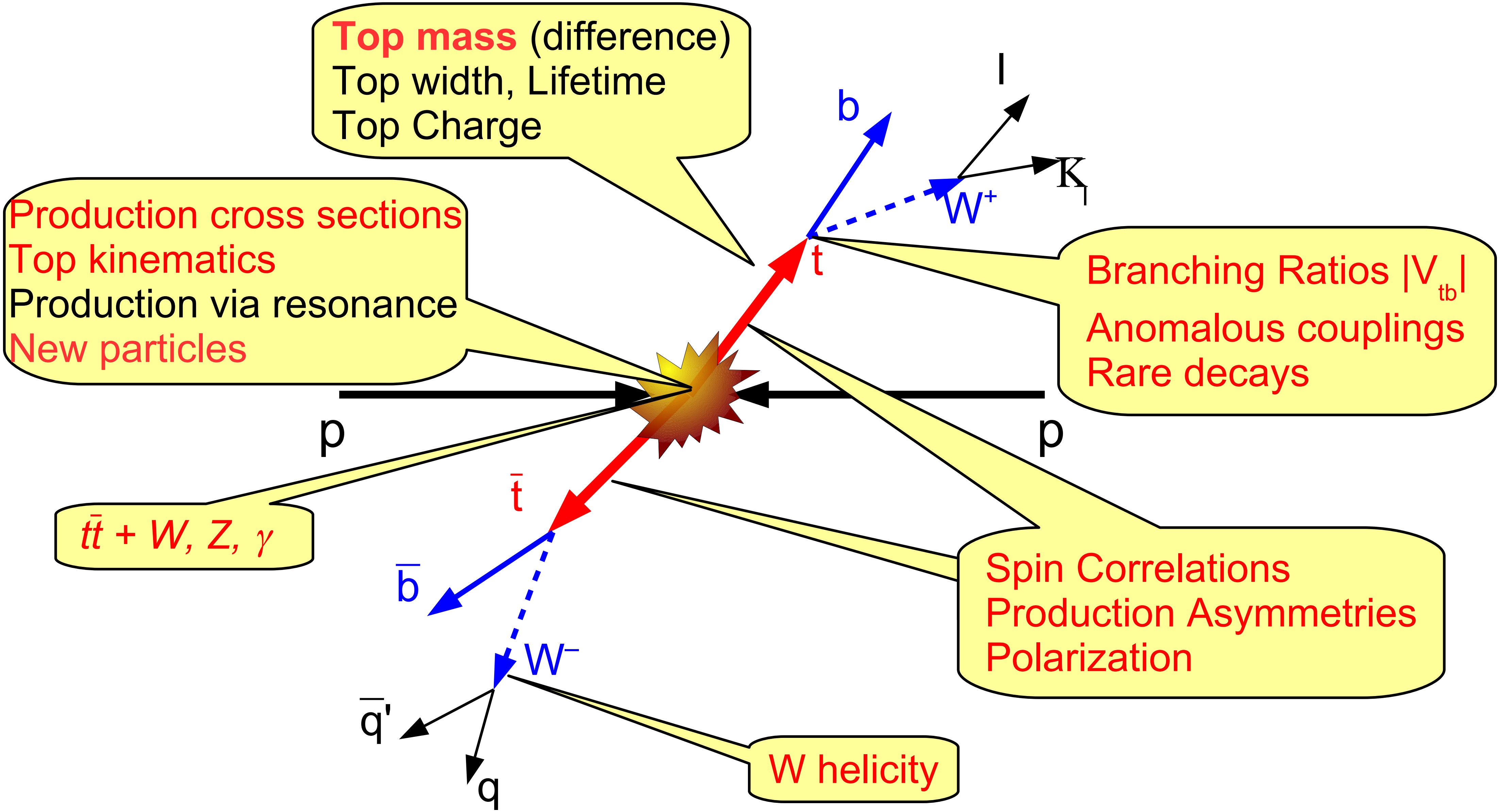
- Requires 2 leptons (e,μ) and at least 2 jets (> 0 identified as b-jet)
- Direct bound on top quark decay width
- Likelihood approach using simulated MCs for different decay widths
- MC's accurate to NLO in production and LO in decay
- Missing orders & BSM physics can affect the extraction





$0.6 < \Gamma < 2.5$ GeV @95% CL
(expected $0.6 < \Gamma < 2.4$ GeV)

Content



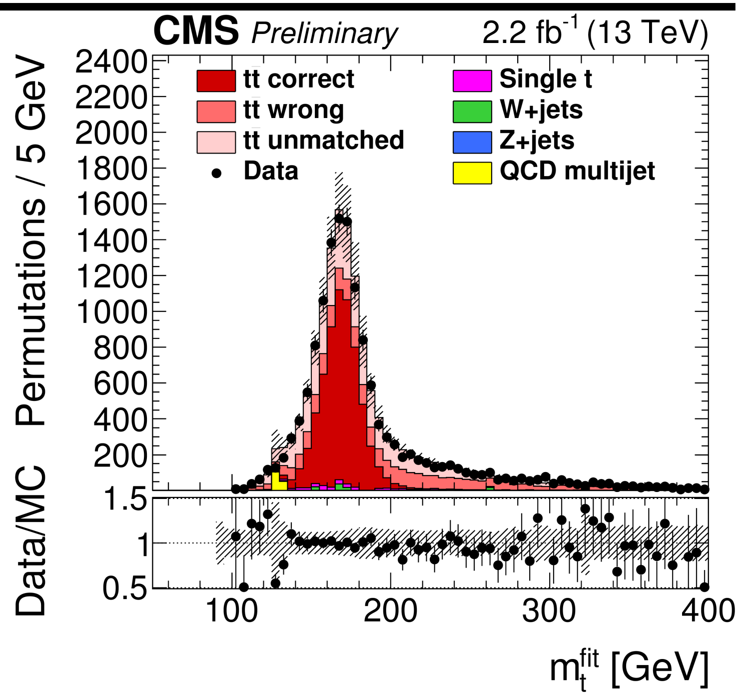
→ **Selection of results, focus on most recent and/or precise results**

Top quark mass

- First measurement at 13 TeV, μ+jets decay channel: CMS-TOP-PAS-016-022
- Follows same strategy as the 8 TeV measurement:
  - 2D fit of m(top) vs. Jet energy scale factor

M_{top} = 172.62 ± 0.38 (stat+JSF) ± 0.70 (syst.) GeV

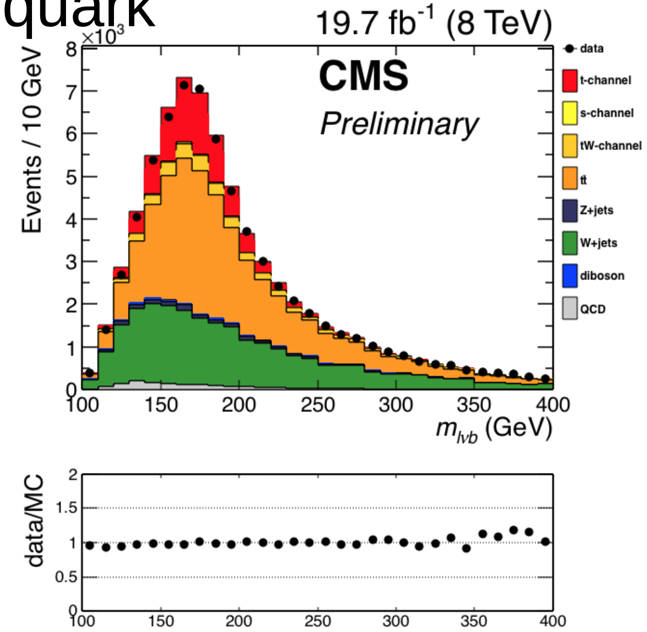
$\delta m_t/m_t$ = 0.46%

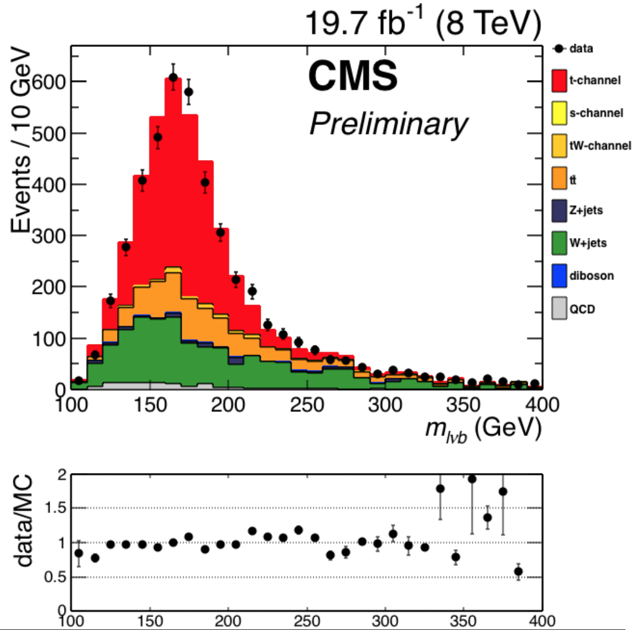


- Top quark mass in single top quark production: CMS-TOP-PAG-15-001
- Blinded analysis
- Employ m_{lvb} distribution

m_{top} = 172.60 ± 0.77(stat.) ± 0.97/0.93(syst.) GeV

$\delta m_t/m_t$ = 0.71%



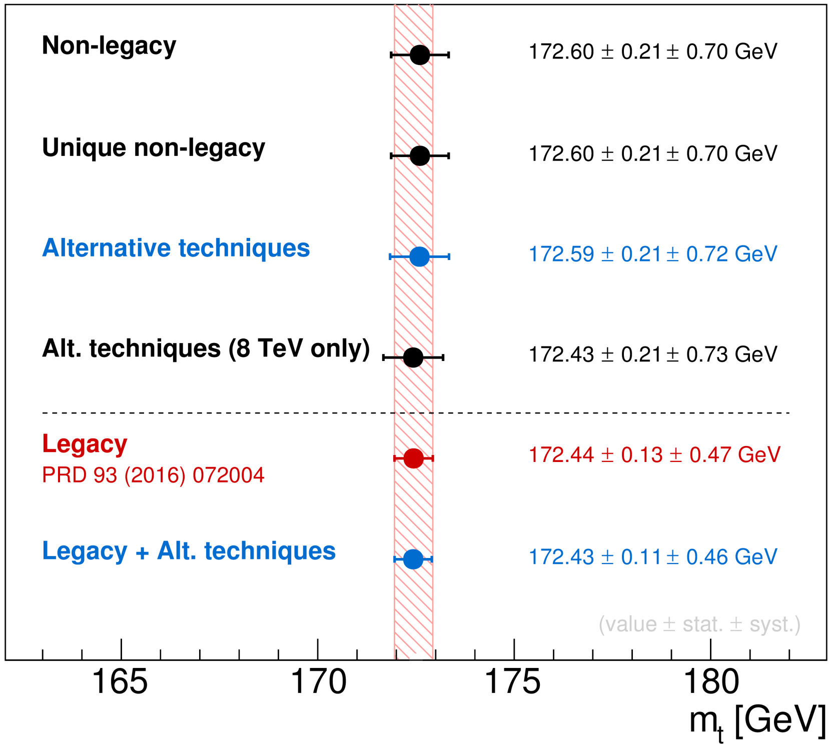


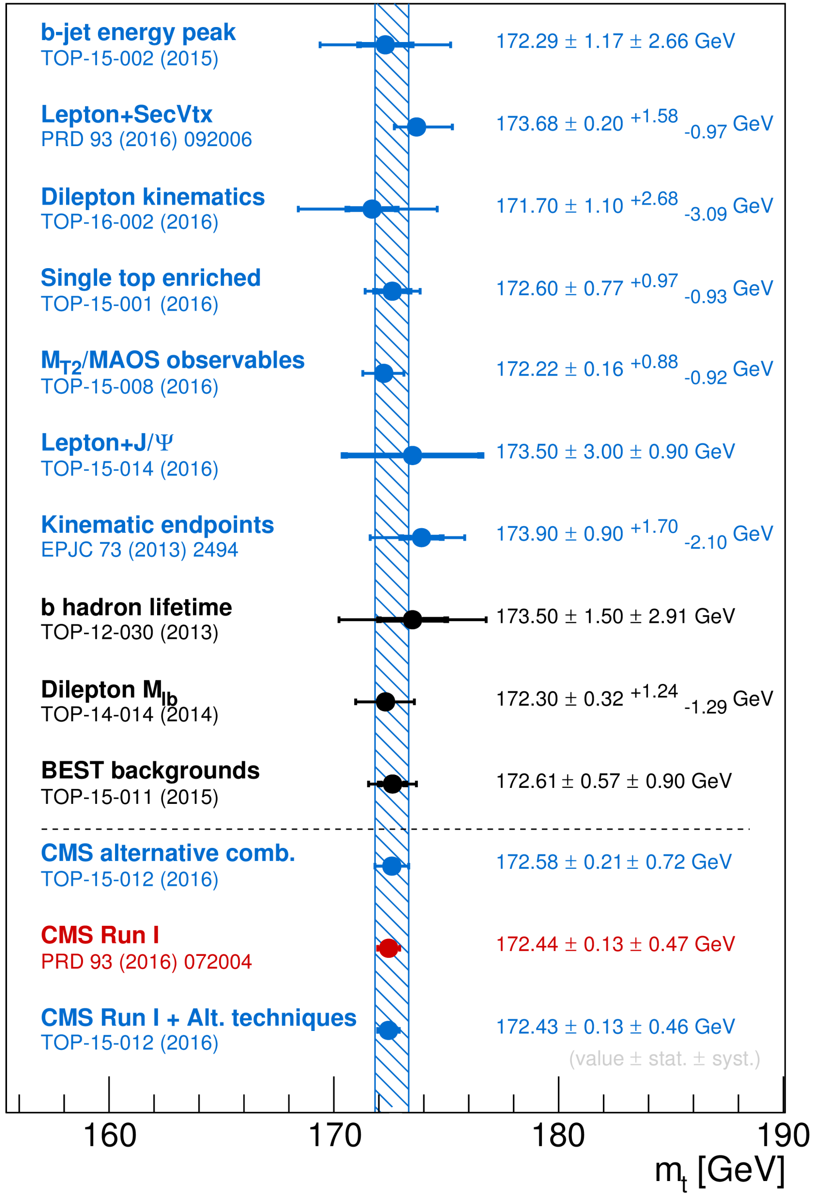
Top quark mass

CMS-PAS-TOP-15-012

- Direct measurements combined using BLUE – consistent among methods/channels
- Latest CMS combination, $\delta m_t/m_t$ = 0.28%

m_{top} = 172.44 ± 0.48 GeV





- World combination, $\delta m_t/m_t$ = 0.44%

m_{top} = 174.34 ± 0.76 GeV

- Final D0 combination, $\delta m_t/m_t$ = 0.43%

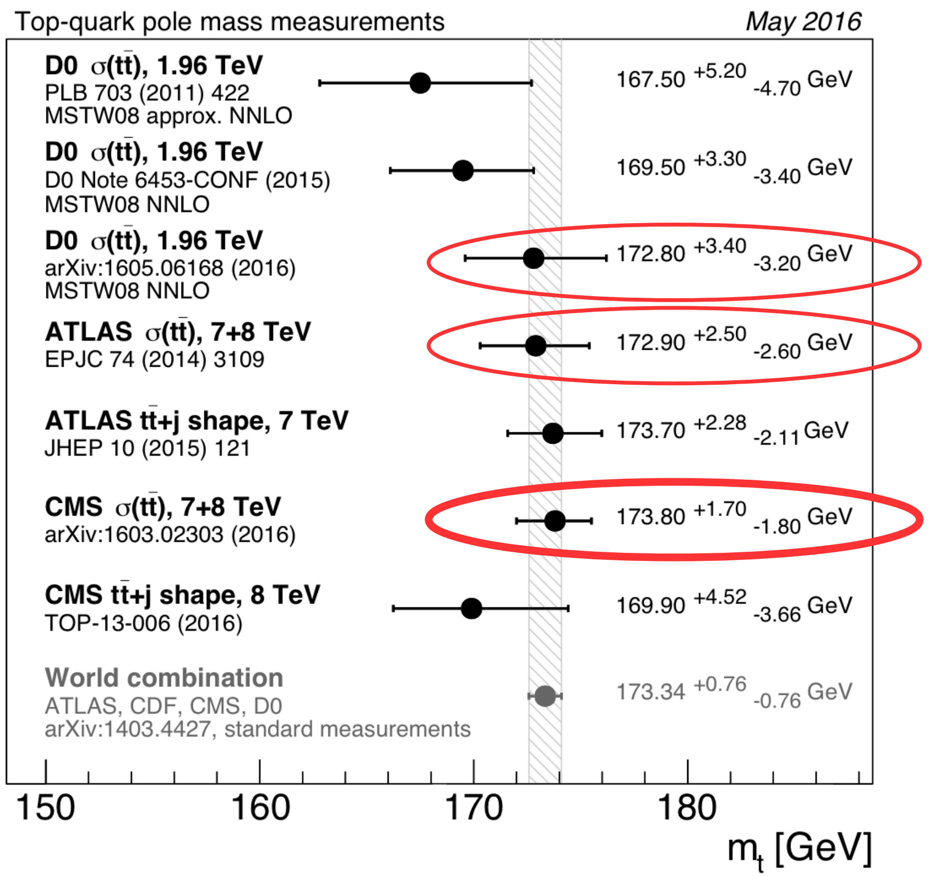
m_{top} = 174.95 ± 0.75 GeV [arXiv:1703.06994]

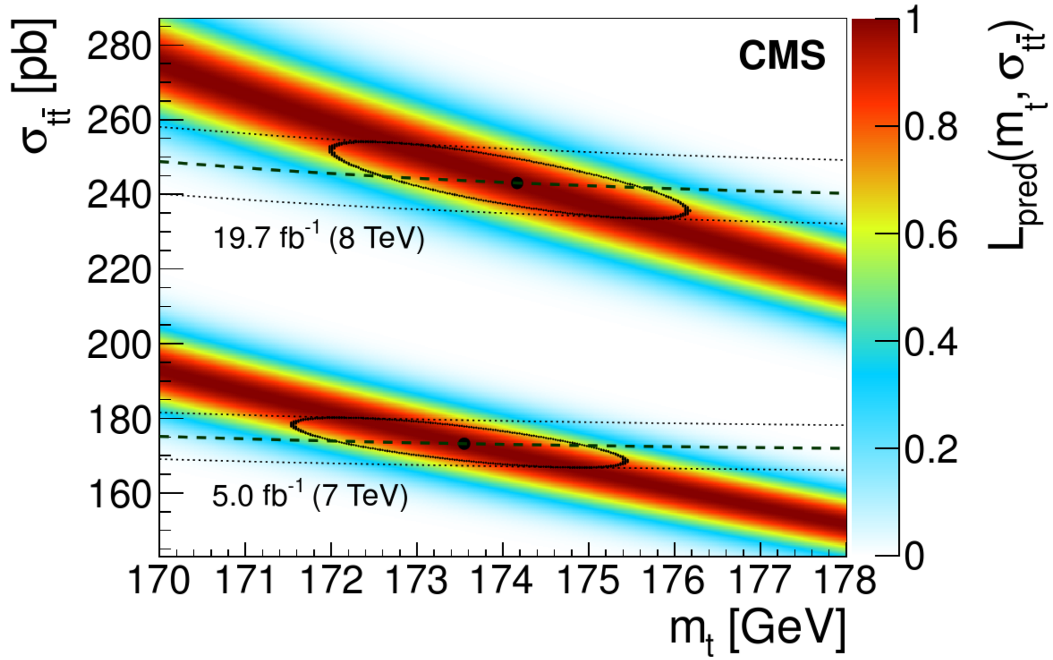
Top quark mass

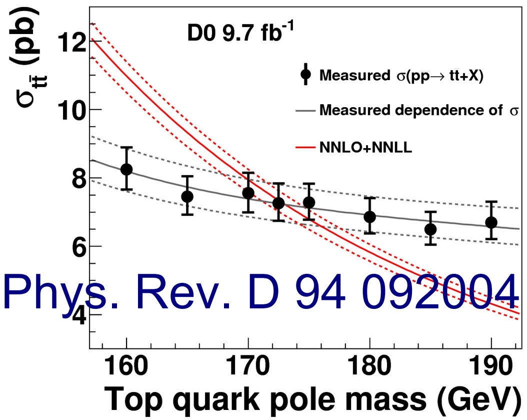
CMS [arXiv:1603.02303]

- 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 → can reach 0.5% on pole mass



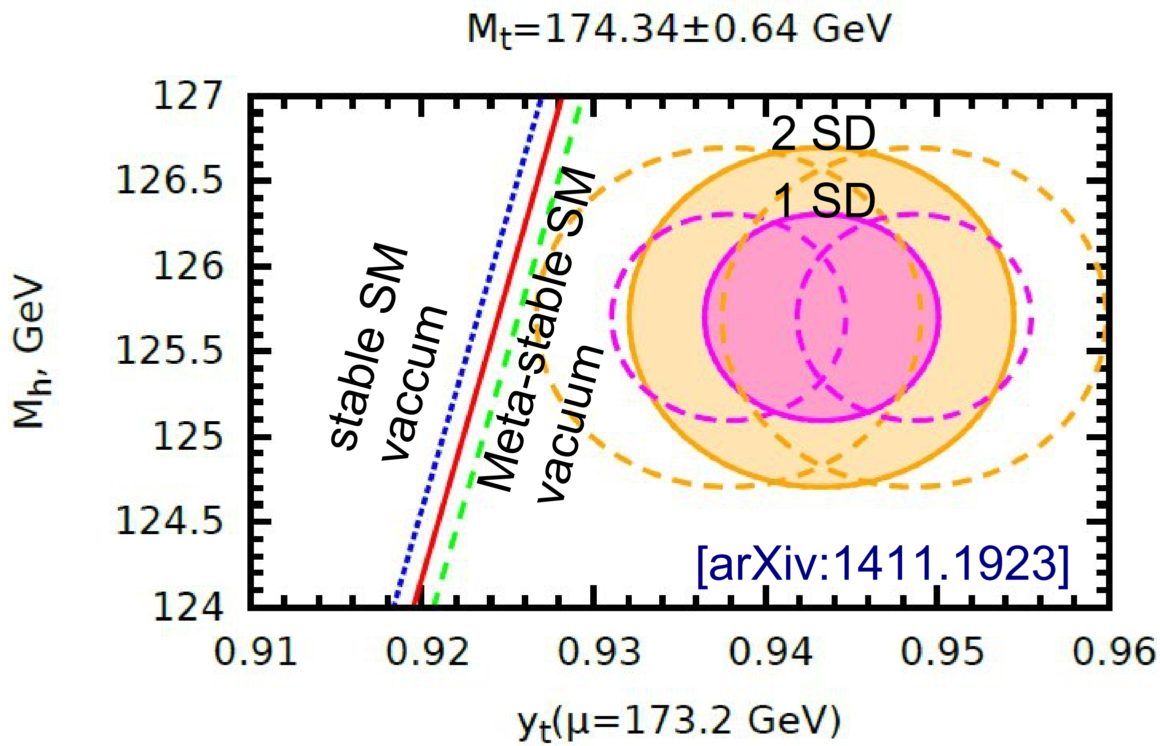


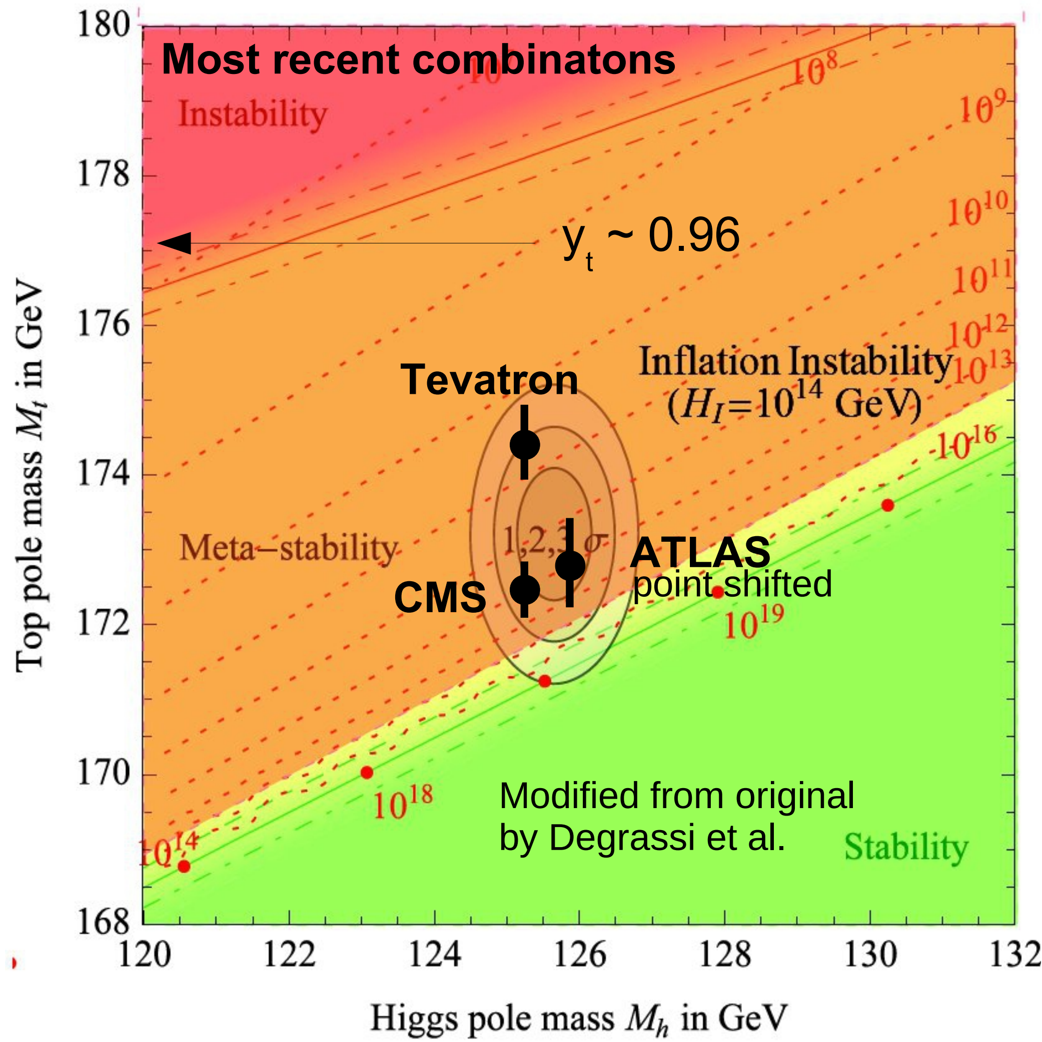


Phys. Rev. D 94 092004 (2016)

EW vacuum stability

- Very subjective but illustrative, combined latest results from CMS and D0
- Assumes SM to be true





Caveat:

- Direct methods e.g. template, matrix element, likelihood, ideogram measure the “MC” mass, lots of effort to “calibrate” the “MC” mass
- Estimates: O(0.5 GeV) difference to pole mass PRL 117, 232001 (2016)

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:

Thank you!

CMS Top Web pages

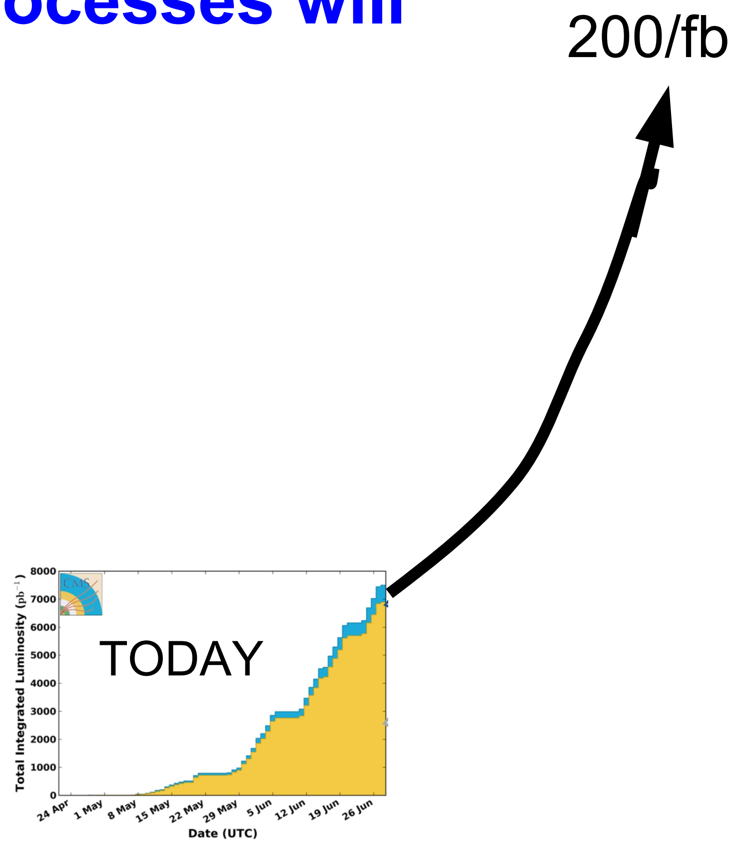
Outlook

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 via measurements @ parton level & fiducial particle level**

→ **FCNCs and other statistically limited processes will significantly improve!**

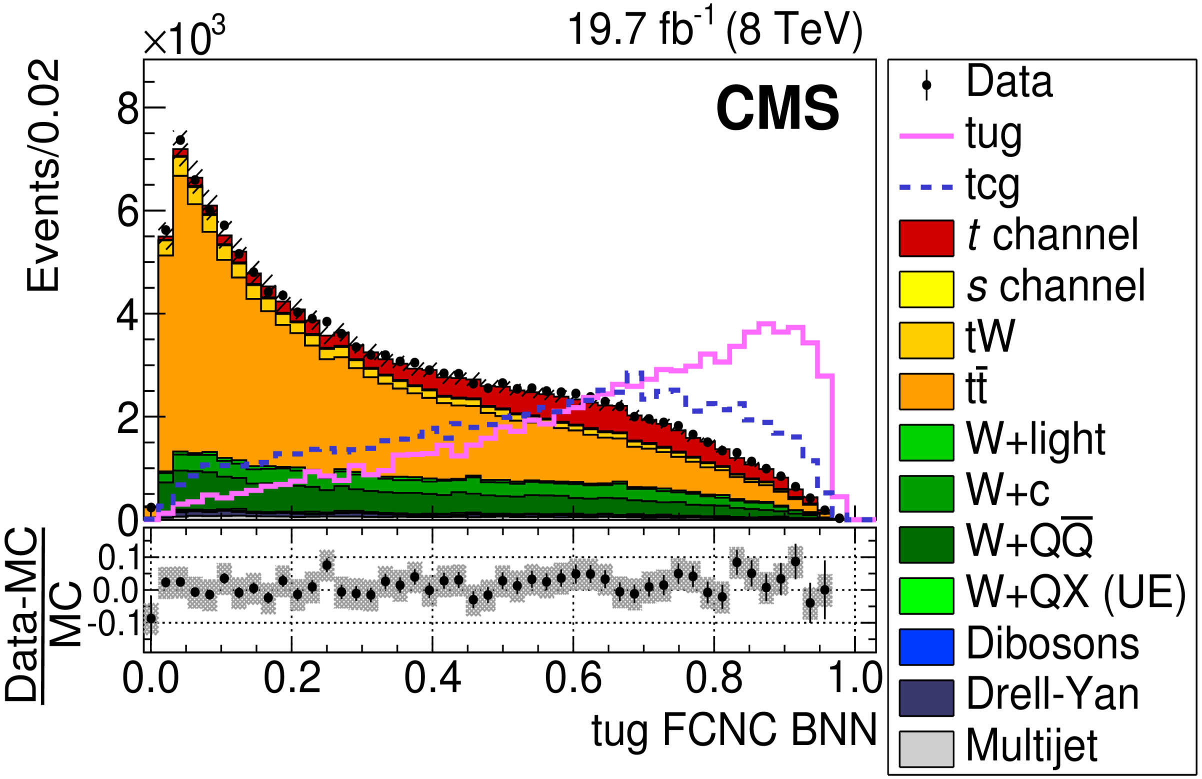


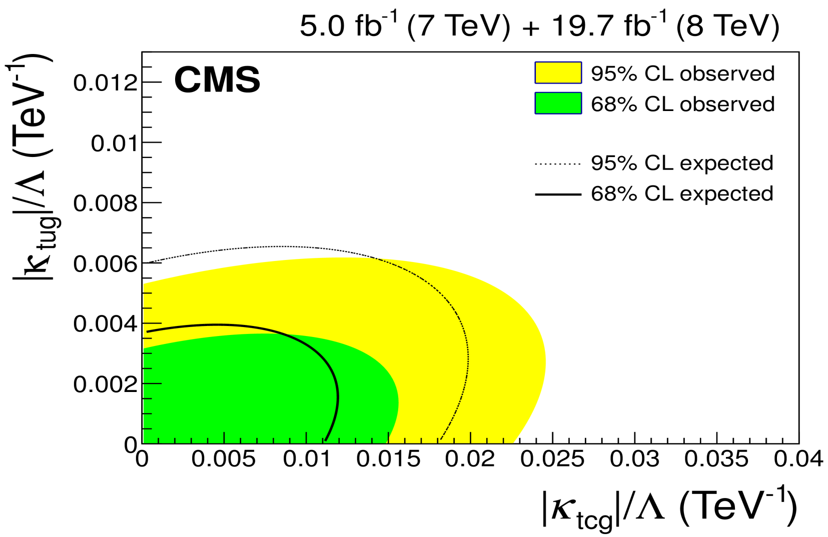
Backup

Top quark: FCNC

Accepted by JHEP
CMS-TOP-14-007

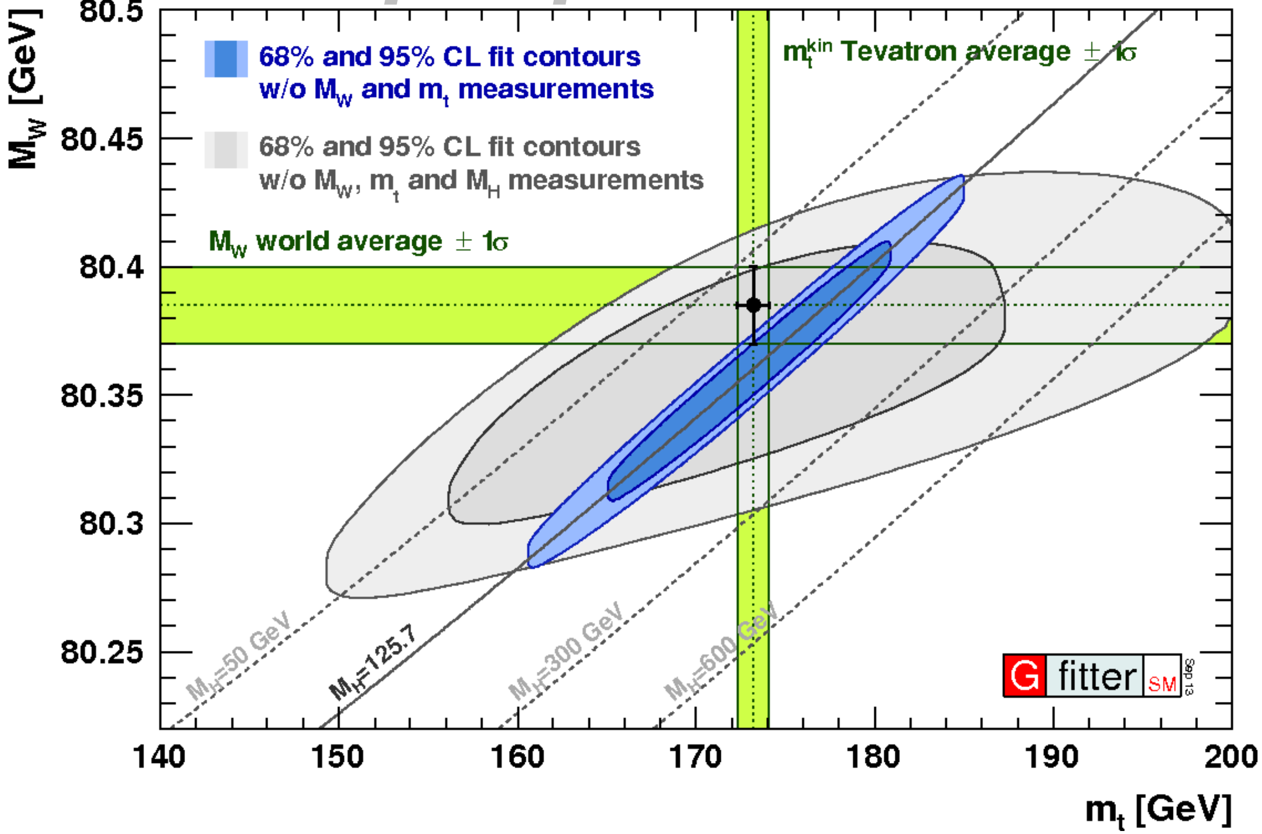
- Search in single top production (t-channel)
  - Combine 7 and 8 TeV data
- MVA technique to: suppress QCD, separate signal & bg, search for *Wtb* couplings & FCNC interactions
- Systematic uncertainties dominated by: Background normalization

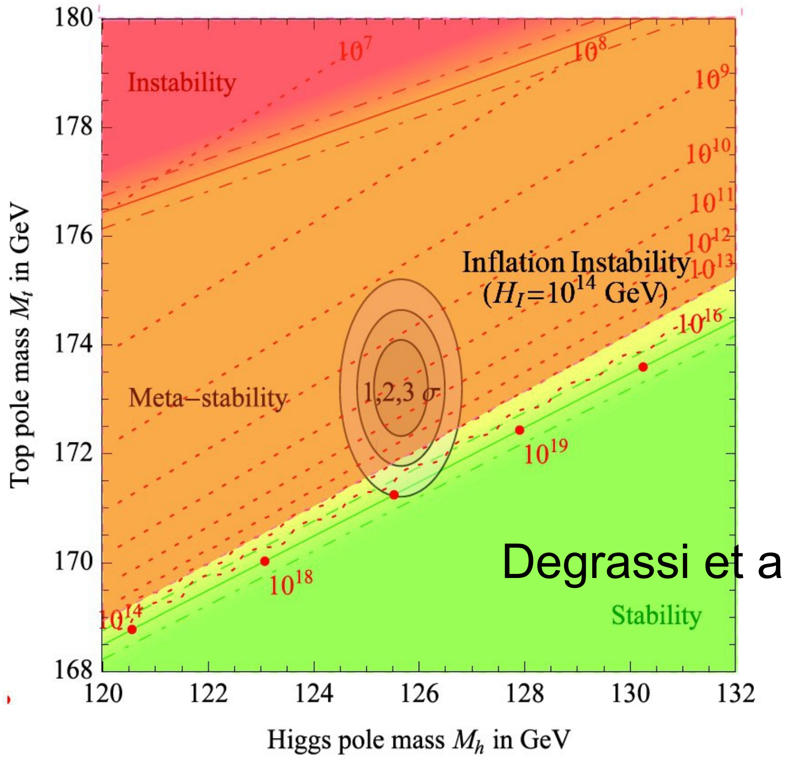




(Limits on left & right vector and tensor couplings via link top right)

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, close to pole mass

Top quark mass

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

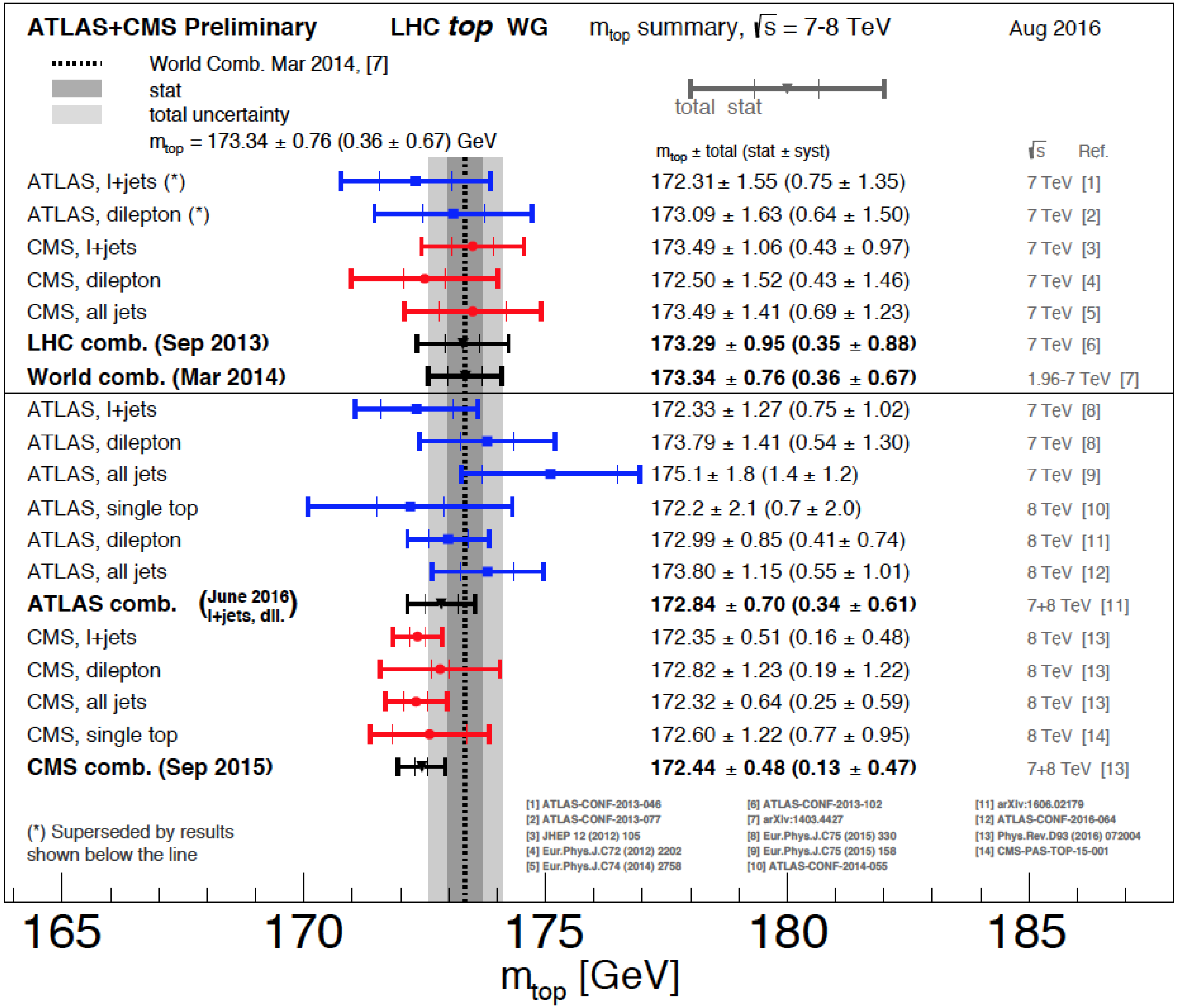
    $m_{top} = 172.84 \pm 0.70$ GeV
- Latest CMS combination
  - Precision of 0.3% (!)

    $m_{top} = 172.44 \pm 0.48$ GeV
- World average
  - Precision of 0.4% (!)

    $m_{top} = 174.34 \pm 0.76$ GeV
- Final D0 combination
  - Precision of 0.4% (!)

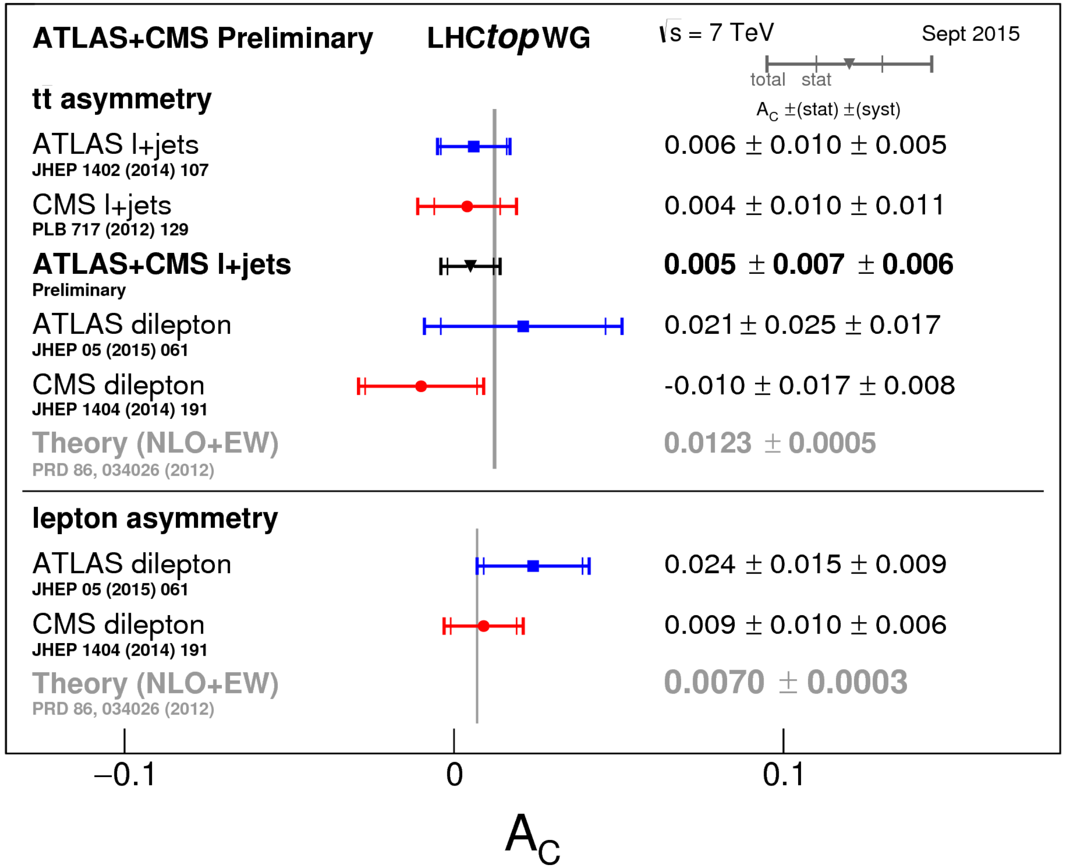
    $m_{top} = 174.95 \pm 0.76$ GeV

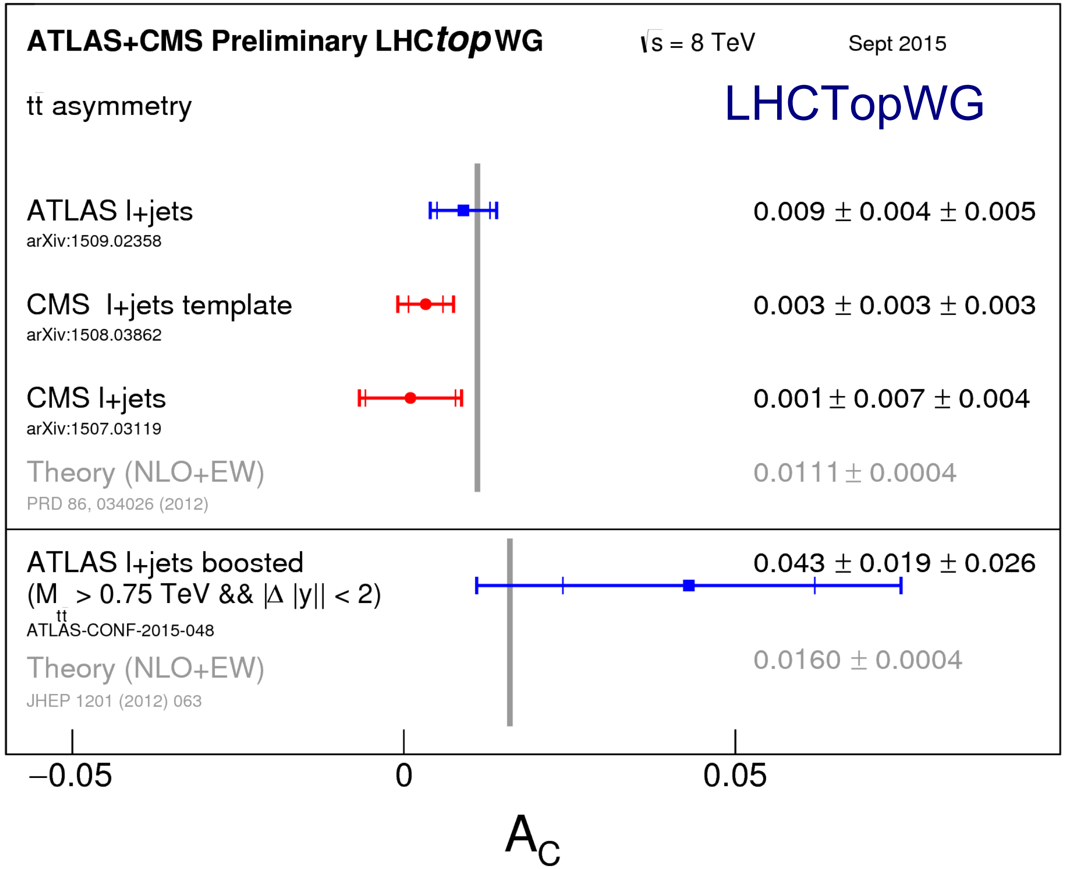
D0 note 6485



PRD 93 (2016) 072004

Top quark asymmetries





Summary of the current Situation:

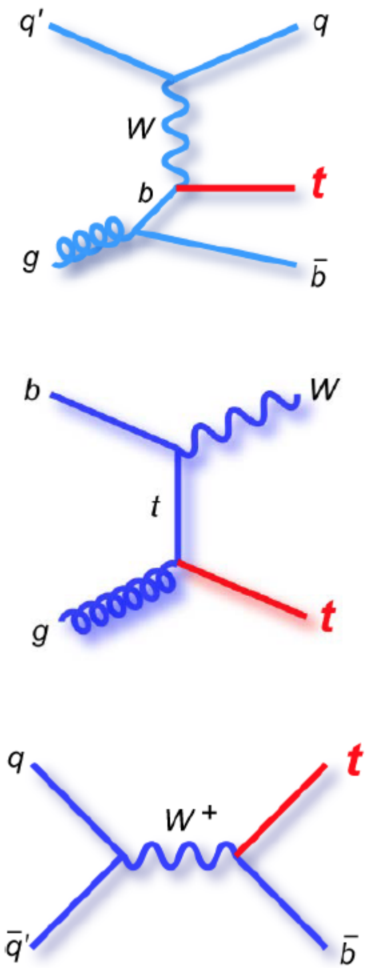
- Experiment: Dominated by stats & signal model dominates systematic unc's
- Theory: Need QCD predictions at NNLO

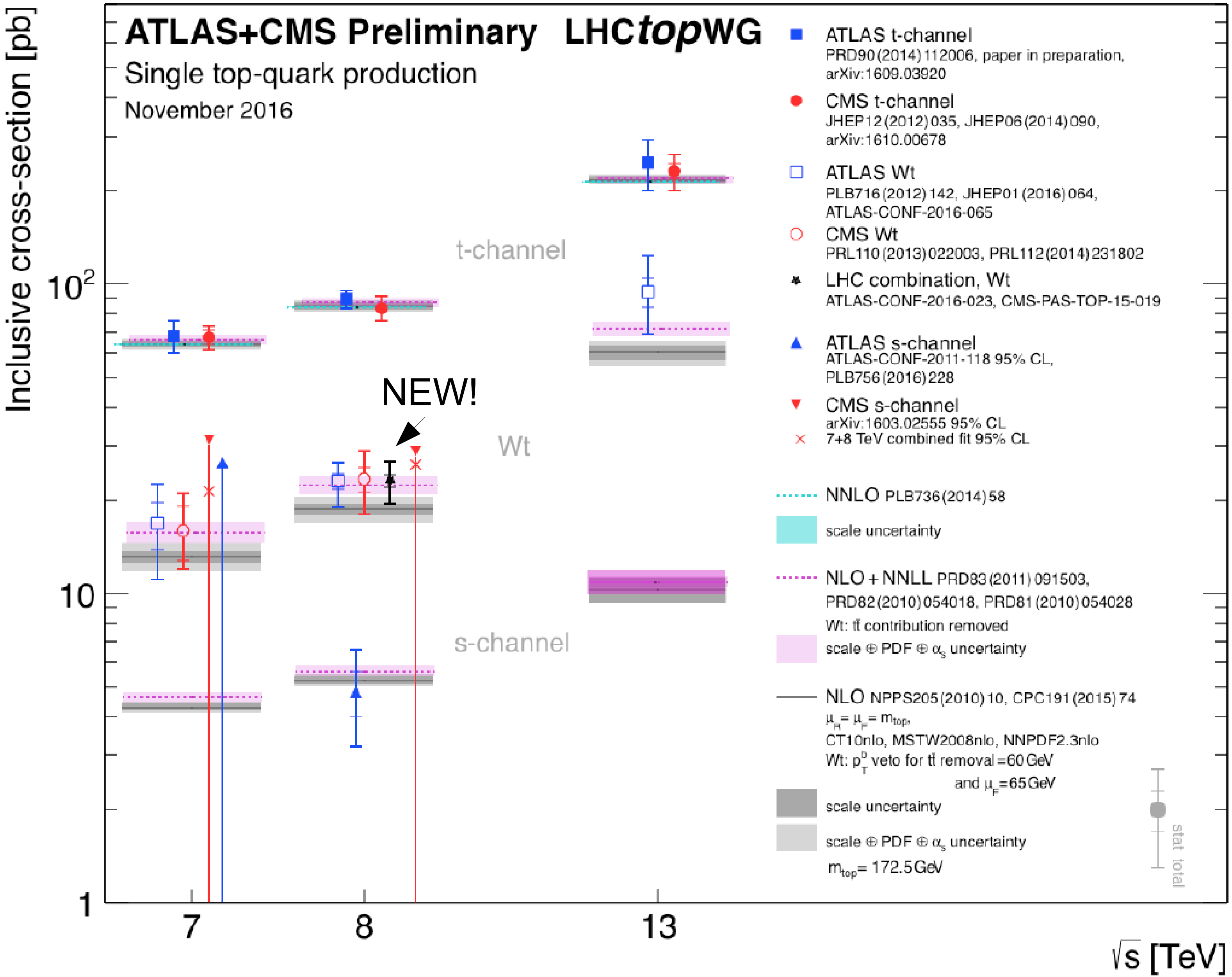
→

- 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]

Single top quark – summary

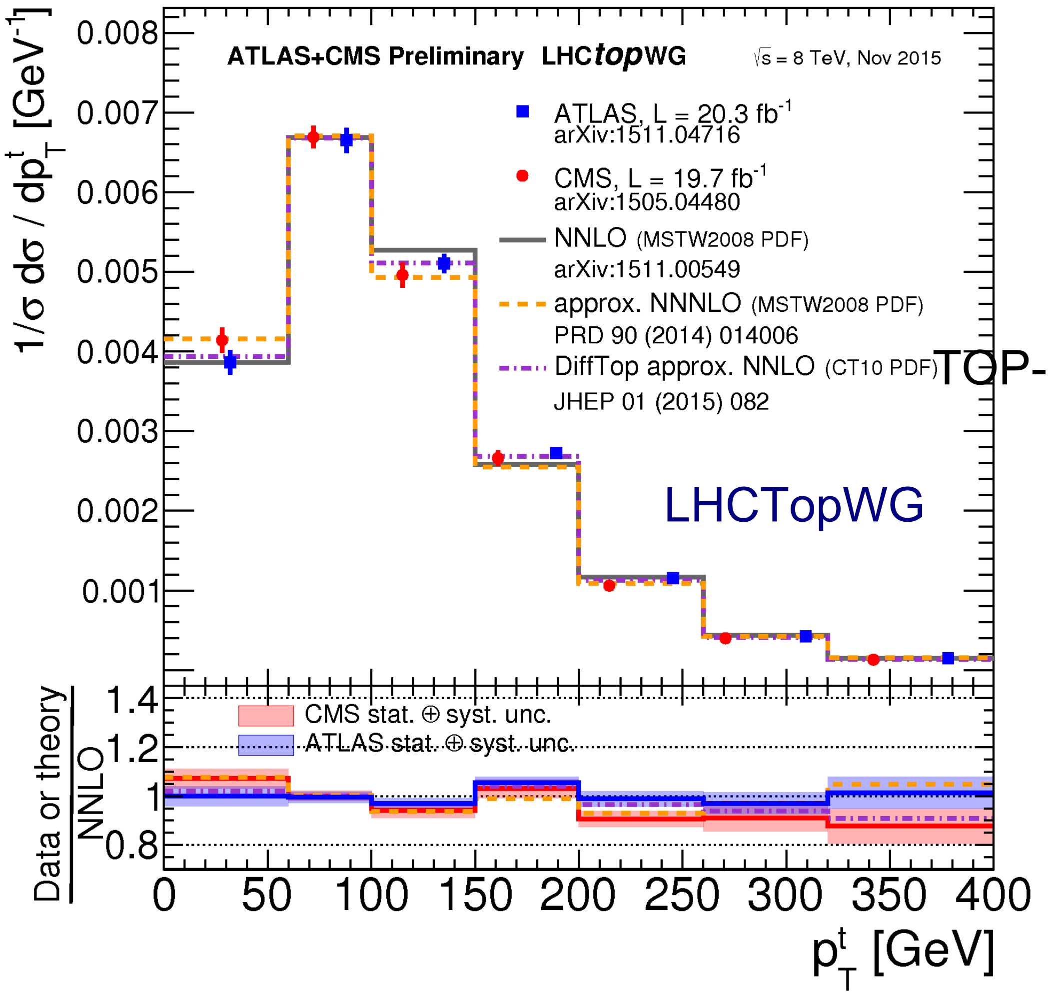
- Decay channels:



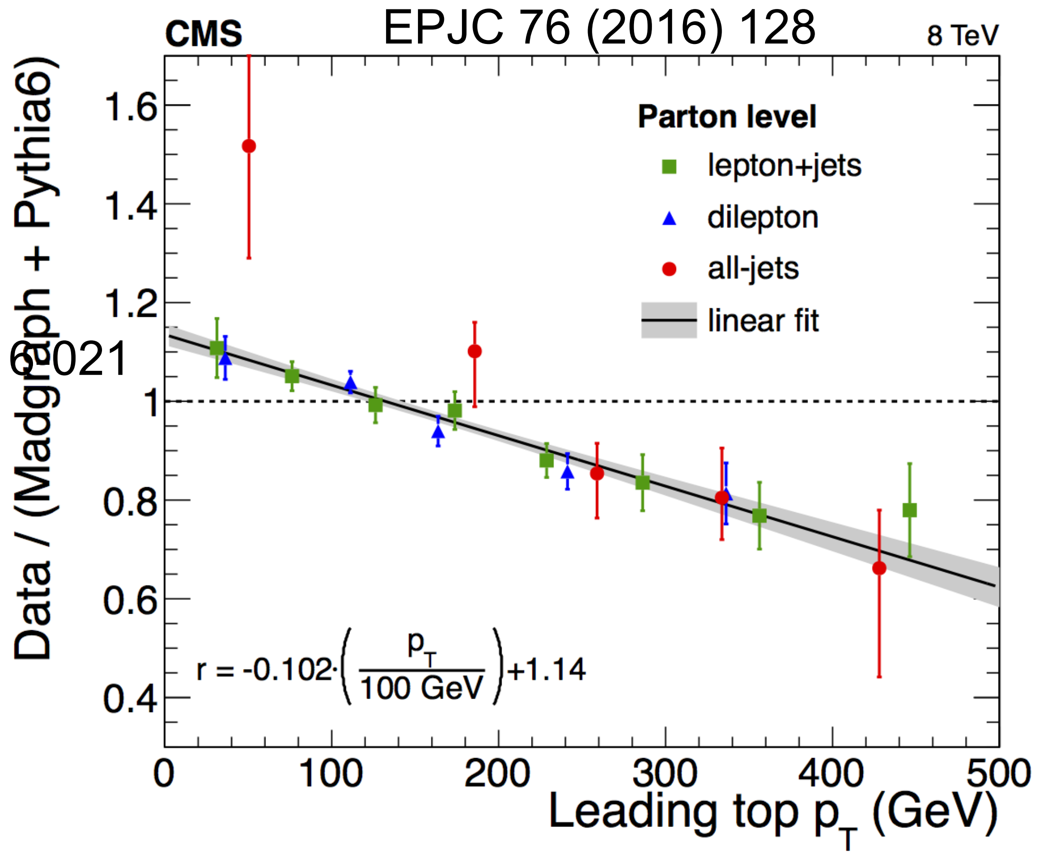


Differential cross sections

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



TOP-16-021

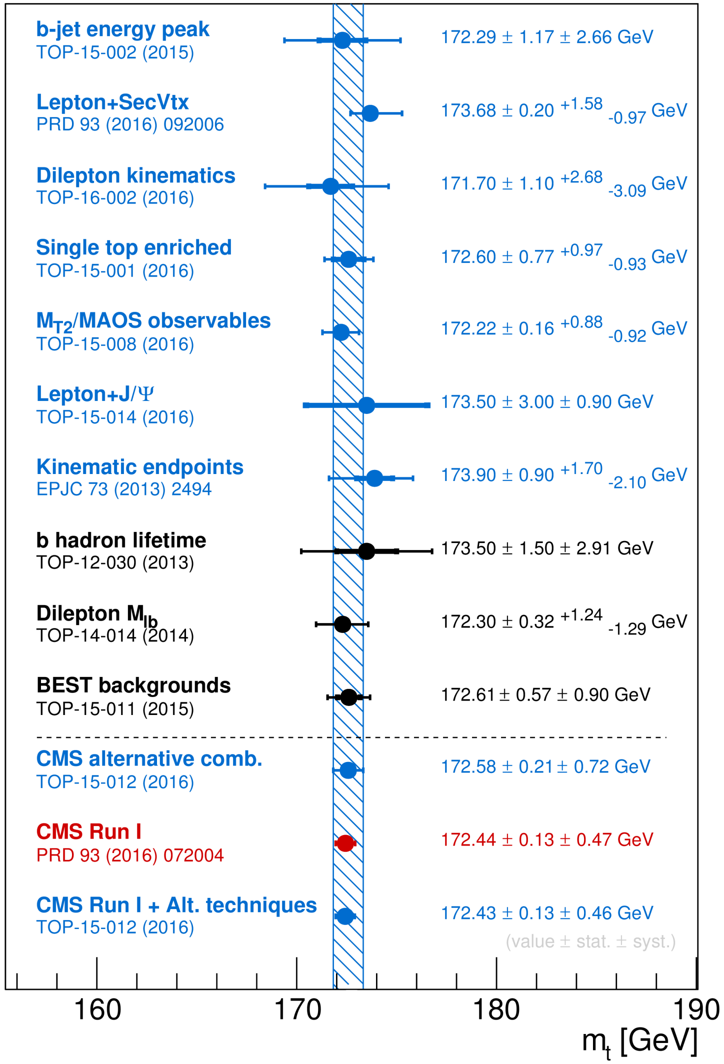


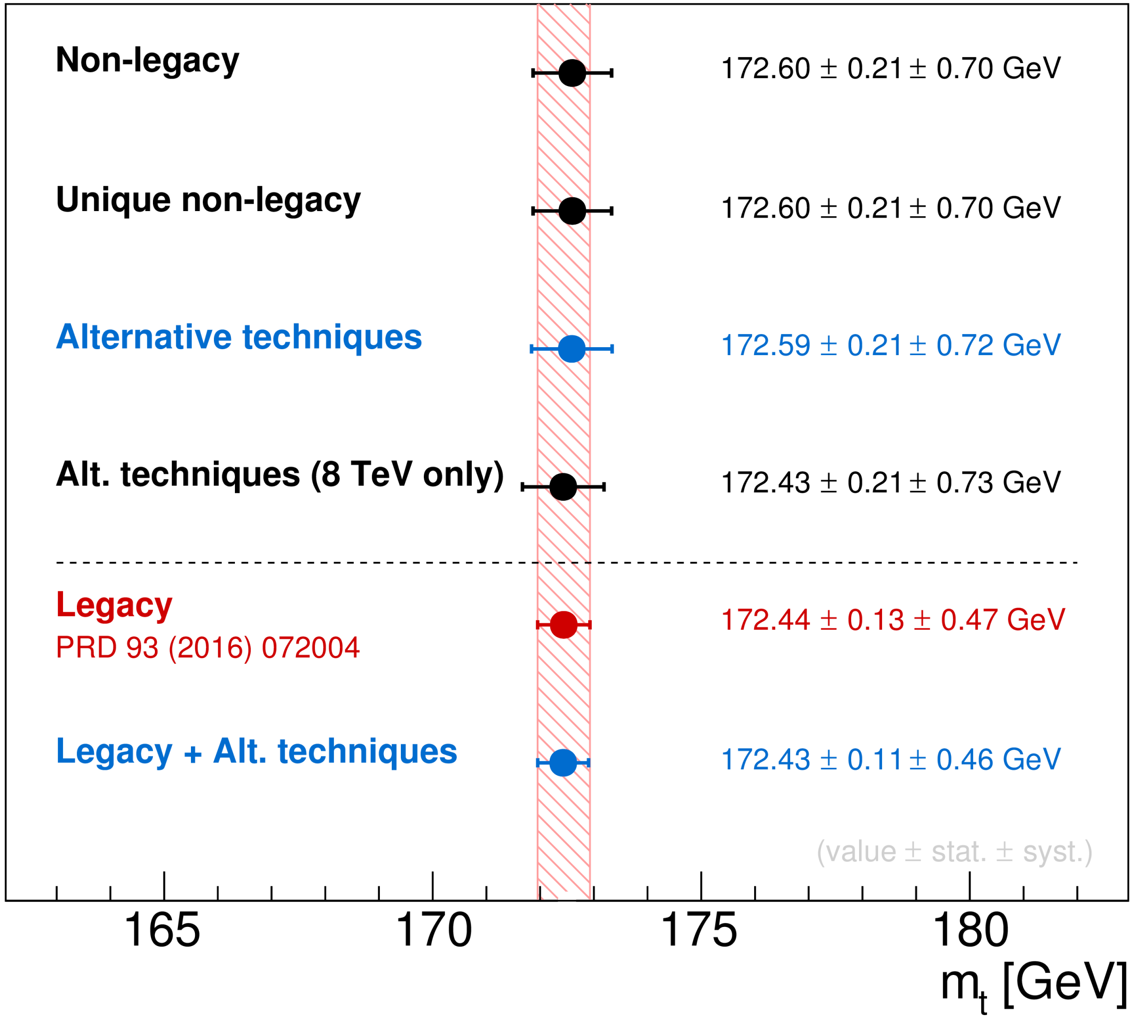
Spectra are described by NNLO+NNLL calculations

Differential cross sections

Channel	Quantities	$\sqrt{s}$ (TeV)	Int. Lum. (fb^{-1})	Analysis [RIVET] [Reference]
lepton+jets	$p_T(t_h)$, $\lvert y(t_h)\rvert$, $p_T(t_\ell)$, $\lvert y(t_\ell)\rvert$ $p_T(t\bar{t})$, $\lvert y(t\bar{t})\rvert$, $M(t\bar{t})$, N_{add-j}	13	2.3	A [CMS_2016_I1434354] [8]
dilepton	N_j >30, 60, 100 GeV p_T^{j1}, p_T^{j2} $m(jj)$, $\Delta R(jj)$ p_T^{bj1}, p_T^{bj2} $m(b\bar{b})$, $\Delta R(b\bar{b})$ **** (p_T^{j1}, p_T^{j2}, H_T) vs GF(inclusive) GF($\lvert\eta\rvert < 0.8$) GF($0.8 < \lvert\eta\rvert < 1.5$) GF($1.5 < \lvert\eta\rvert < 2.4$)	8	19.7	B [CMS_2015_I1397174] [18]
lepton+jets	MET, H_T, S_T, p_T^W	8	19.7	C [CMS_2016_I1473674] [19]
lepton+jets	p_T^t, y_t, p_T^{tj}, y_{tj}	8	19.7	D [CMS_2015_I1388555] [20]
lepton+jets	N_j >30 GeV	8	19.7	E [21]

Top quark mass

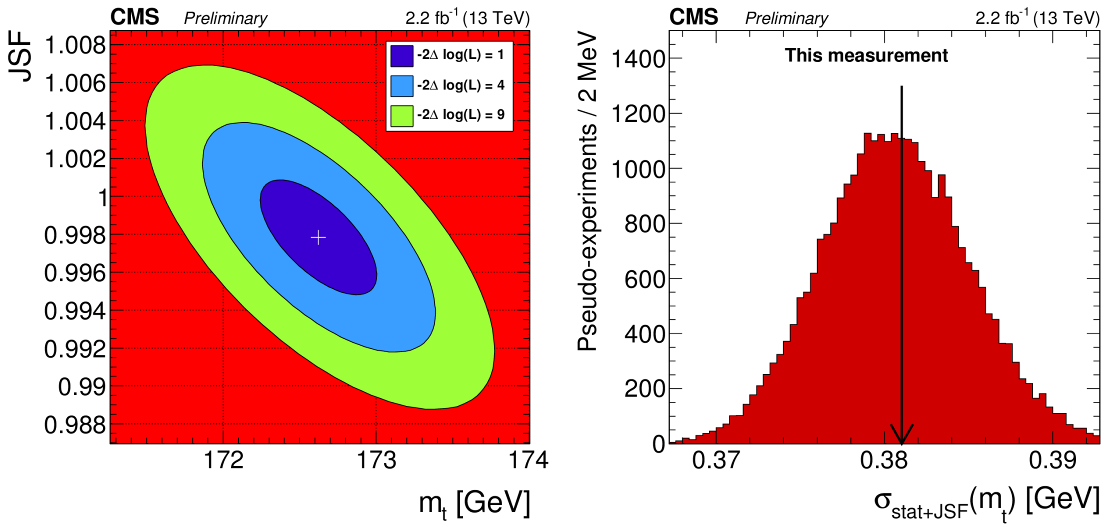




Top quark mass

CMS-TOP-PAS-016-022

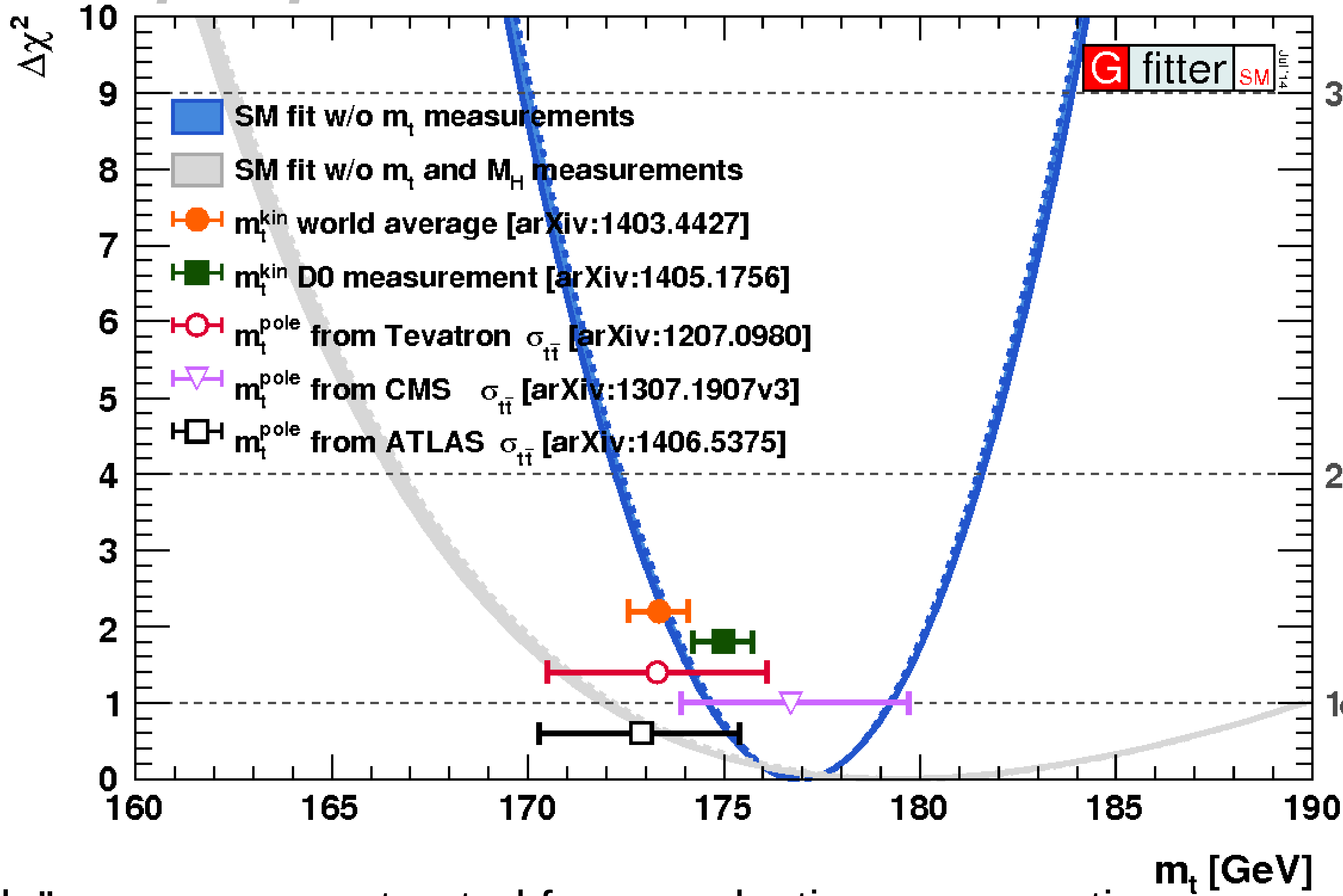
- First measurement at 13 TeV, μ+jets decay channel
- Follows same strategy as the 8 TeV measurement:
  - 2D fit of m(top) vs. Jet energy scale factor



(a) (b)

CMS-TOP-PAG-15-001

Top quark mass

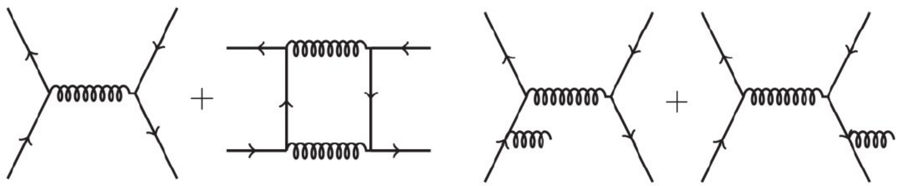


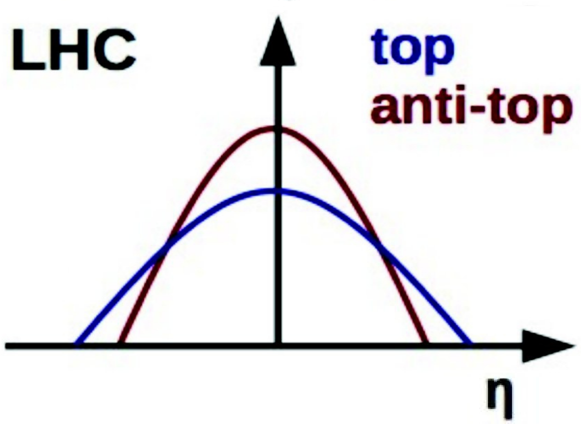
→ “pole” means extracted from production cross sections

→ “kin” means direct measurements, e.g. matrix element method

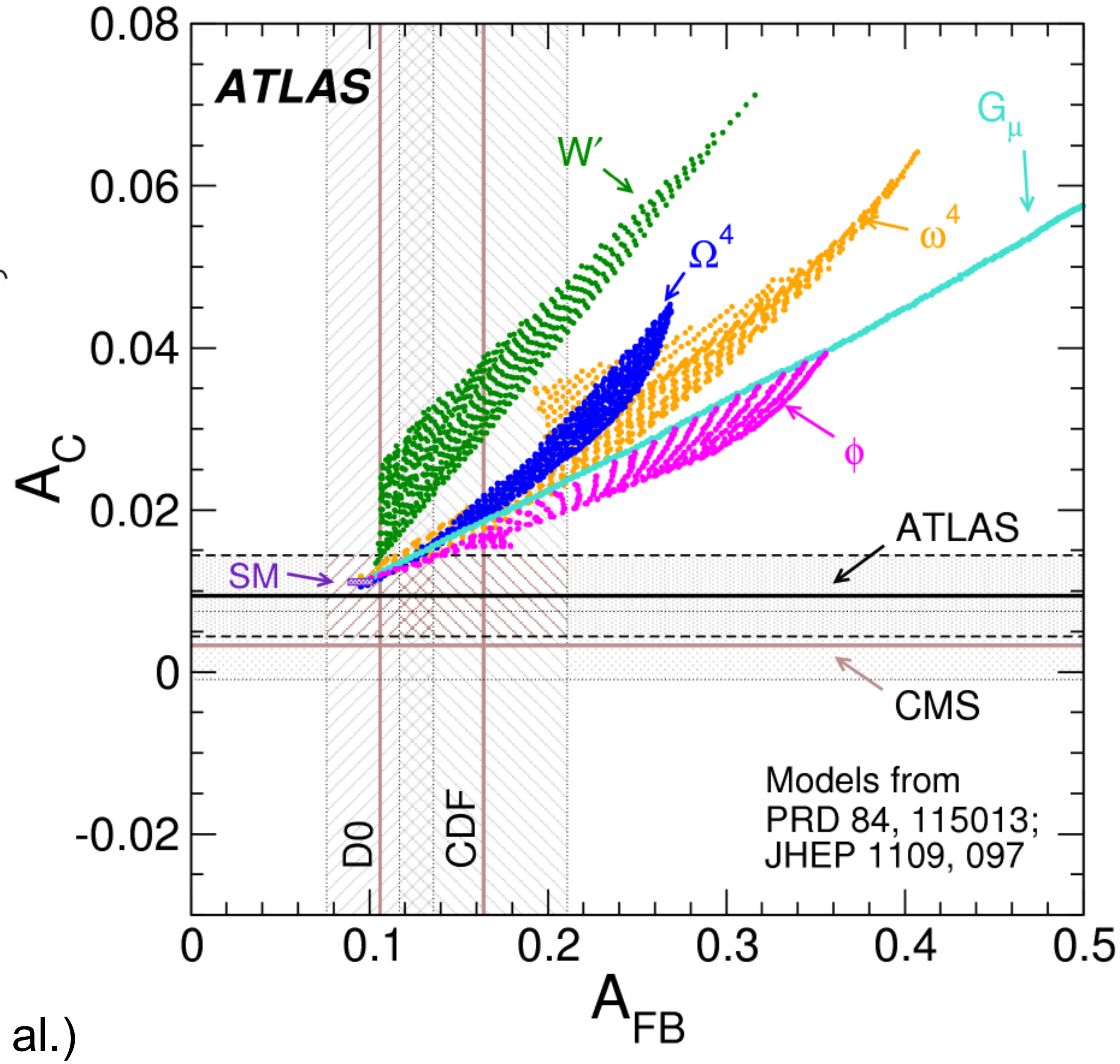
Top quark asymmetries

- <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





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

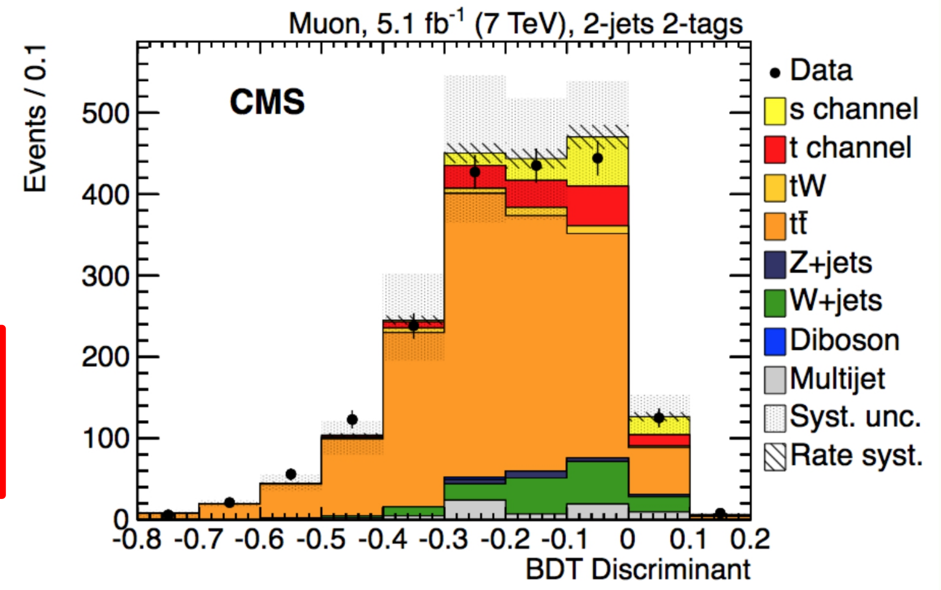


- NLO+EW prediction (Bernreuther, et al.)
  → $A_C^{t\bar{t}} = +0.011 \pm 0.0004$

Single top quark production

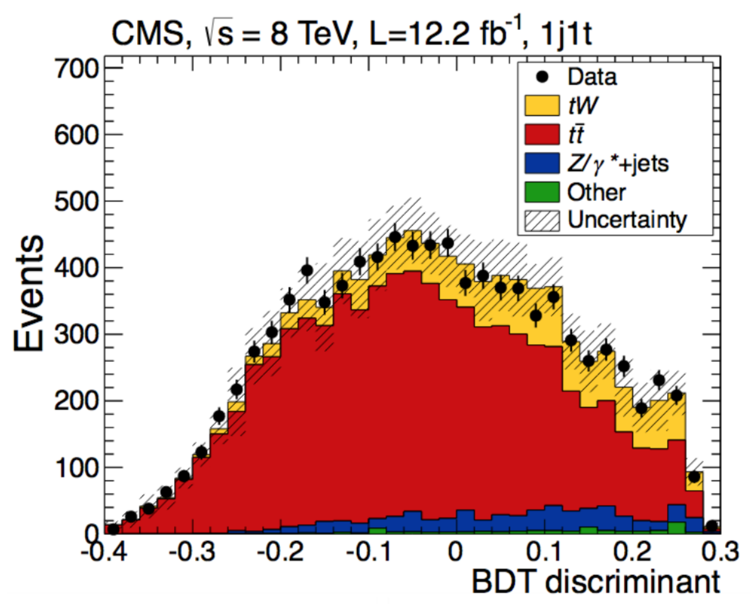
- CMS combines 7 and 8 TeV data
  - Categorized by #b-tags, #jets
  - Binned maximum-likelihood fit to a BDT discriminant

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

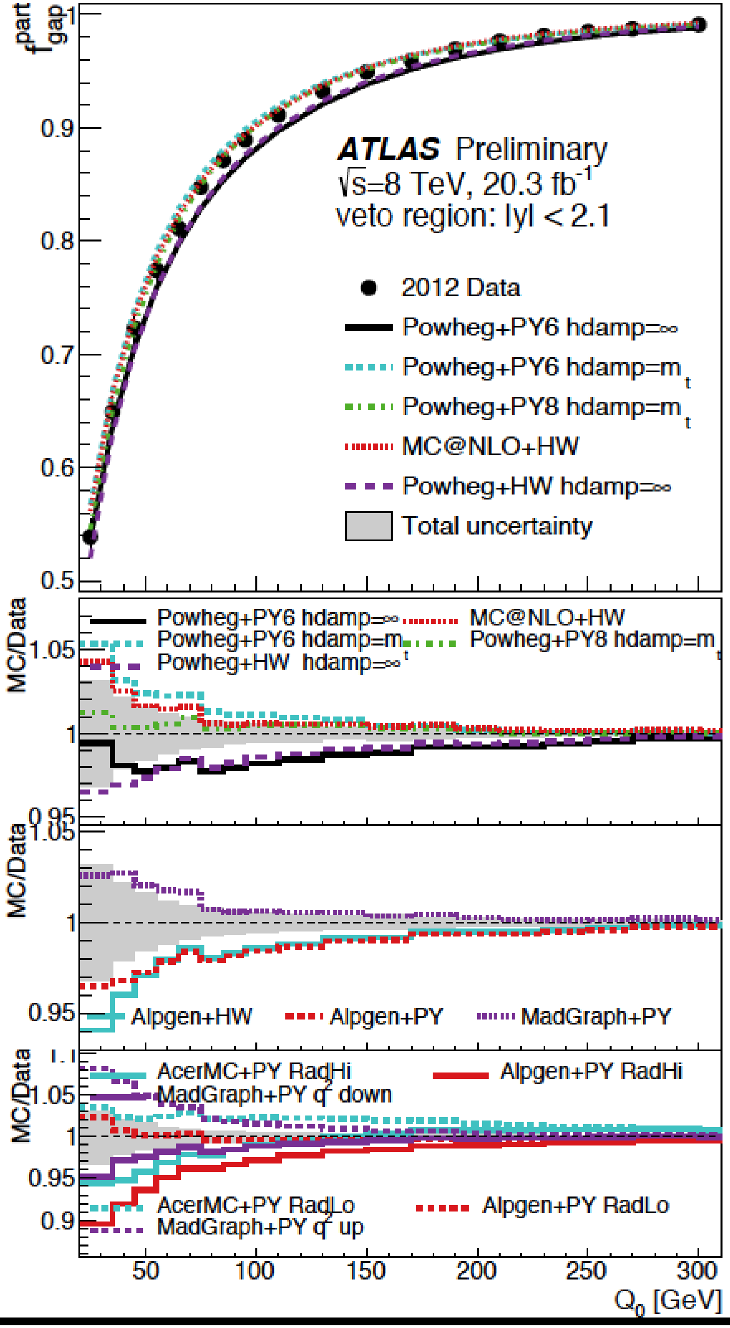


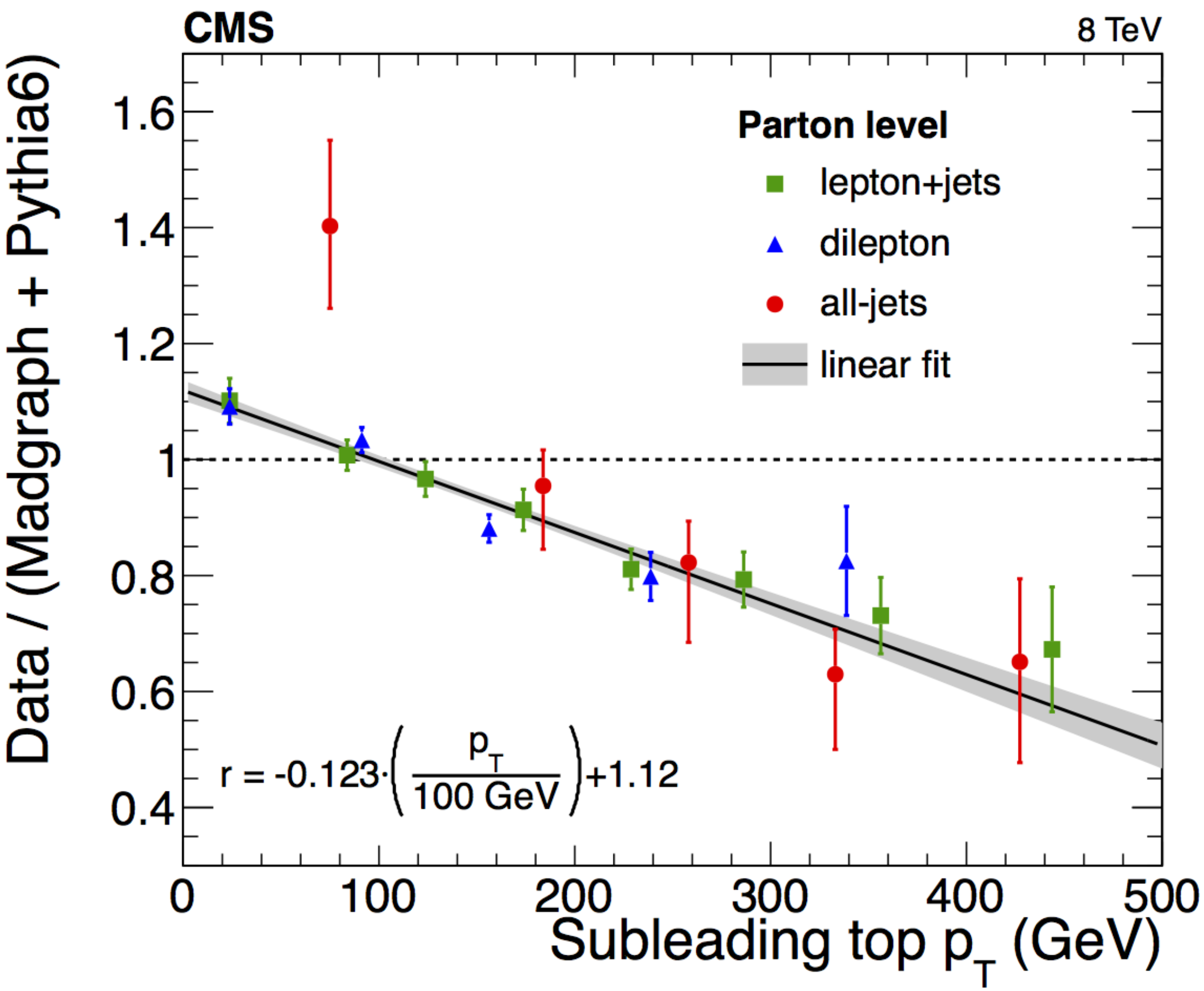
- CMS 1st tW-channel observation at 8 TeV
  - Categorized by #b-tags, #jets
  - Binned maximum-likelihood fit to a BDT discriminant

σ = 23.4 ± 5.4 (stat. + syst.) pb [δσ/σ=23%]
6.1 SD (5.4 SD expected)

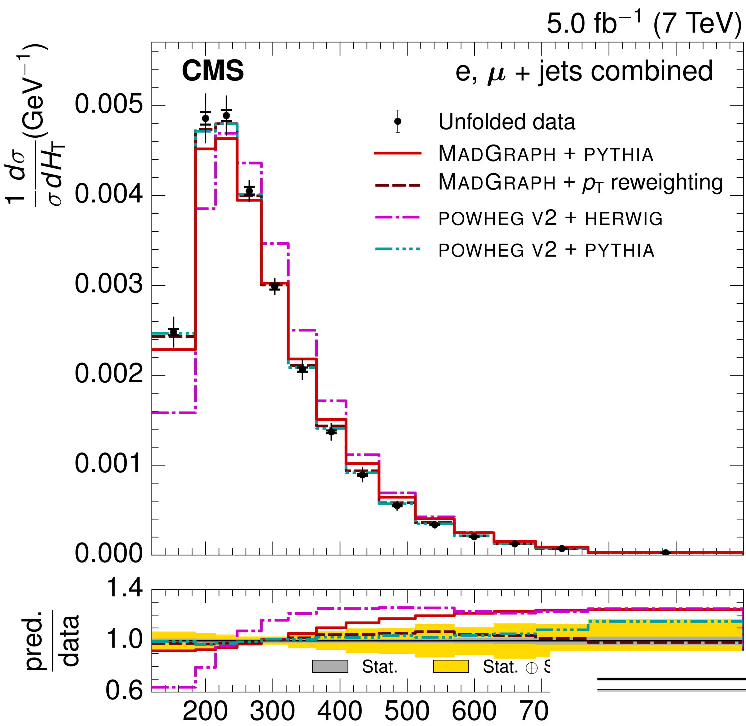


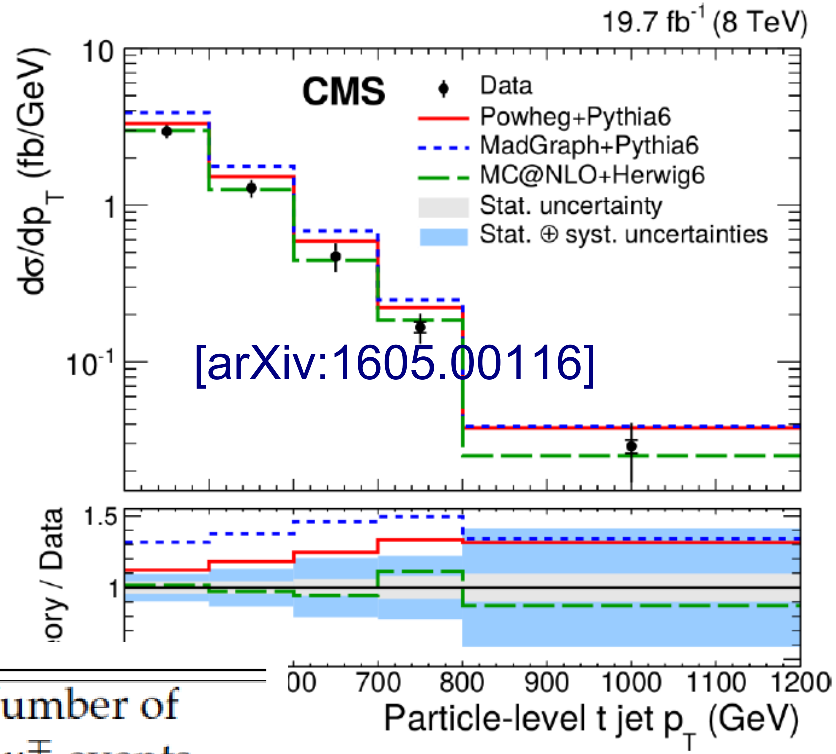
Differential cross sections





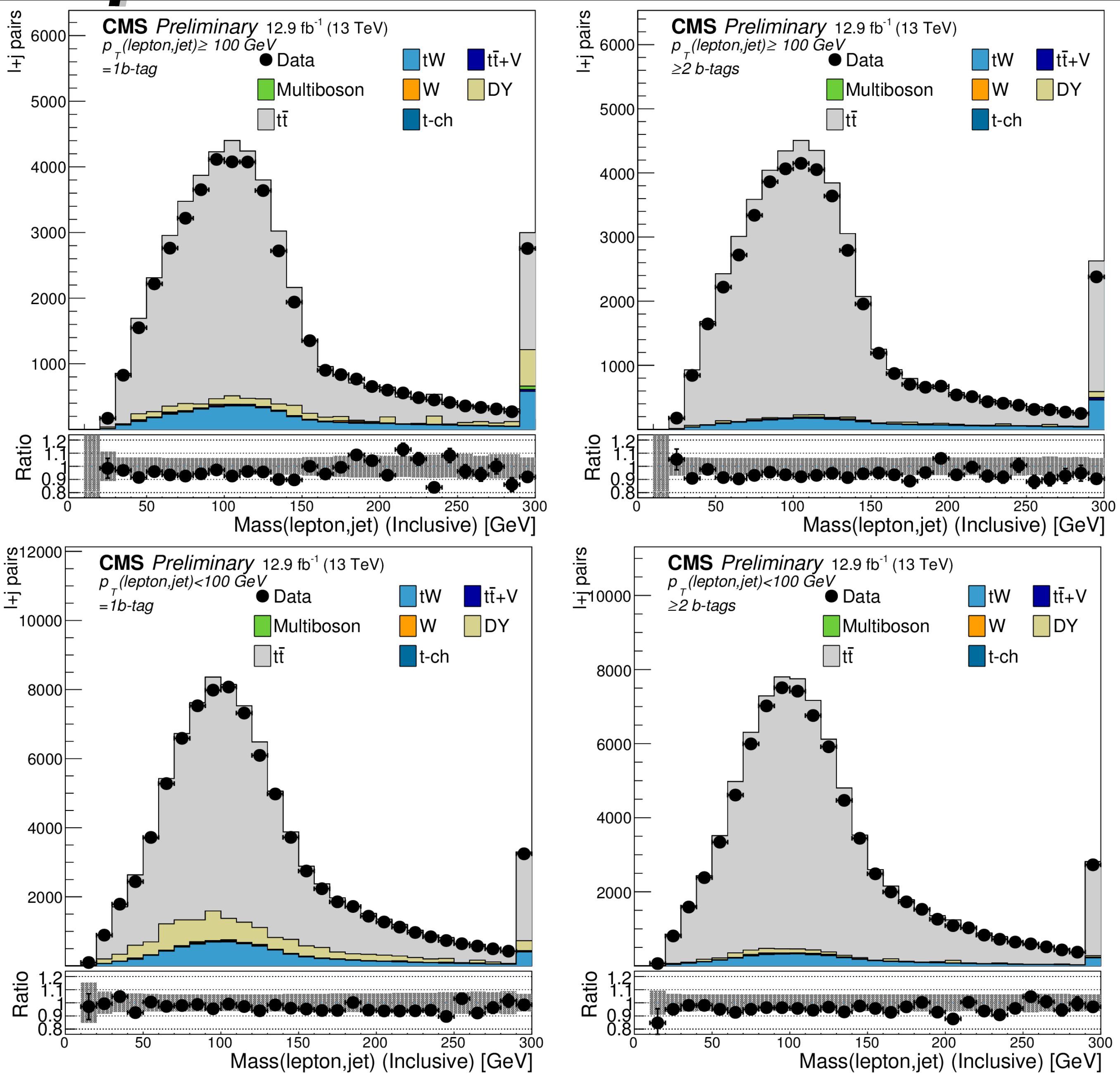
Differential cross sections





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 width

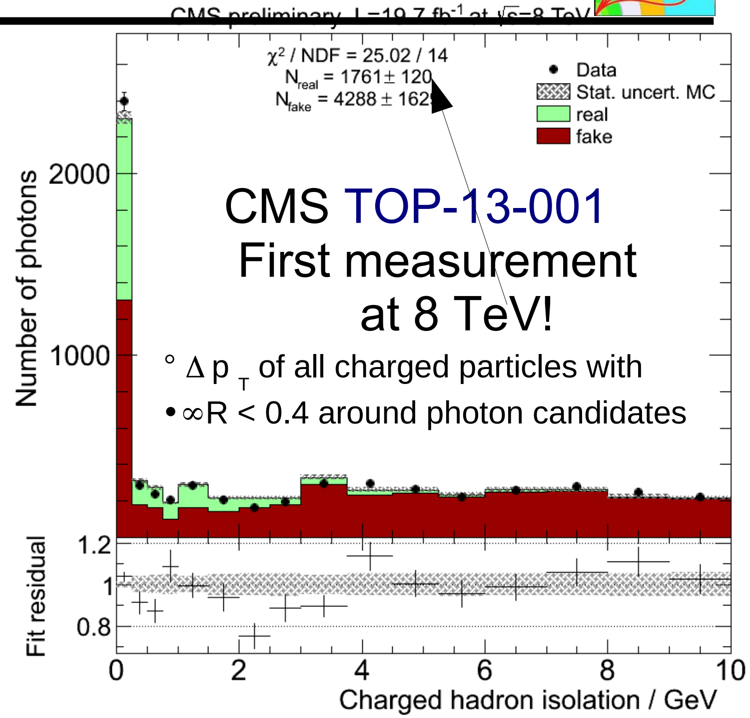


Ttbar + X: W, Z, B

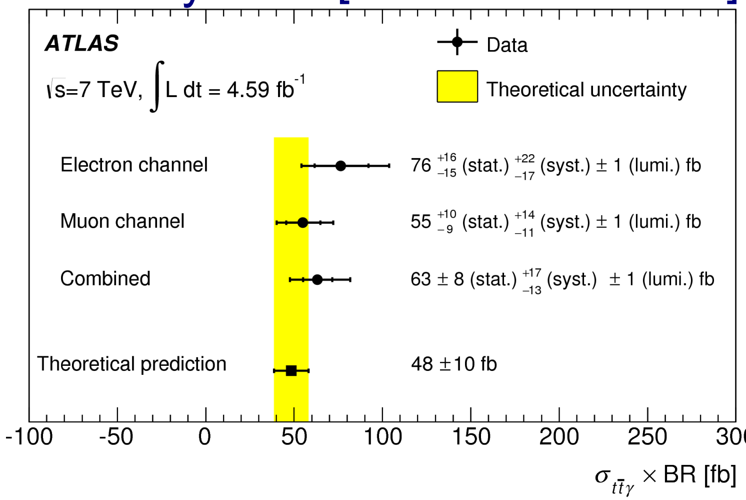
- Tight photon ID requirements and cuts to suppress the bg
- Observation at 7 TeV by ATLAS and first measurement at 8 TeV by CMS

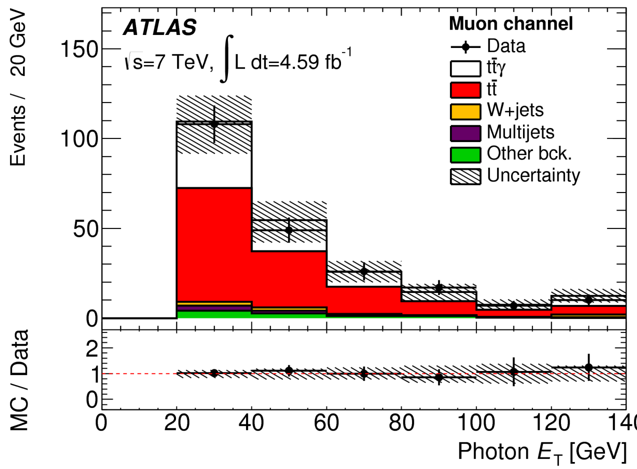
$$R = \sigma_{\bar{t}t+\gamma}/\sigma_{\bar{t}t} = (1.07 \pm 0.07(\text{stat.}) \pm 0.27(\text{syst.})) \cdot 10^{-2}$$

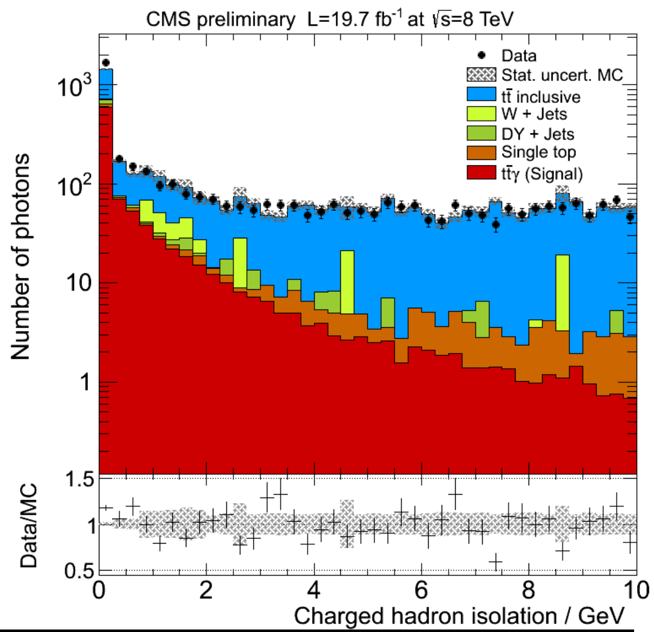
$$\sigma_{t\bar{t}+\gamma} = R \cdot \sigma_{\bar{t}t}^{\text{CMS}} = 2.4 \pm 0.2(\text{stat.}) \pm 0.6(\text{syst.})\,\text{pb}$$



Acc. by PRD [arXiv:1502.00586]



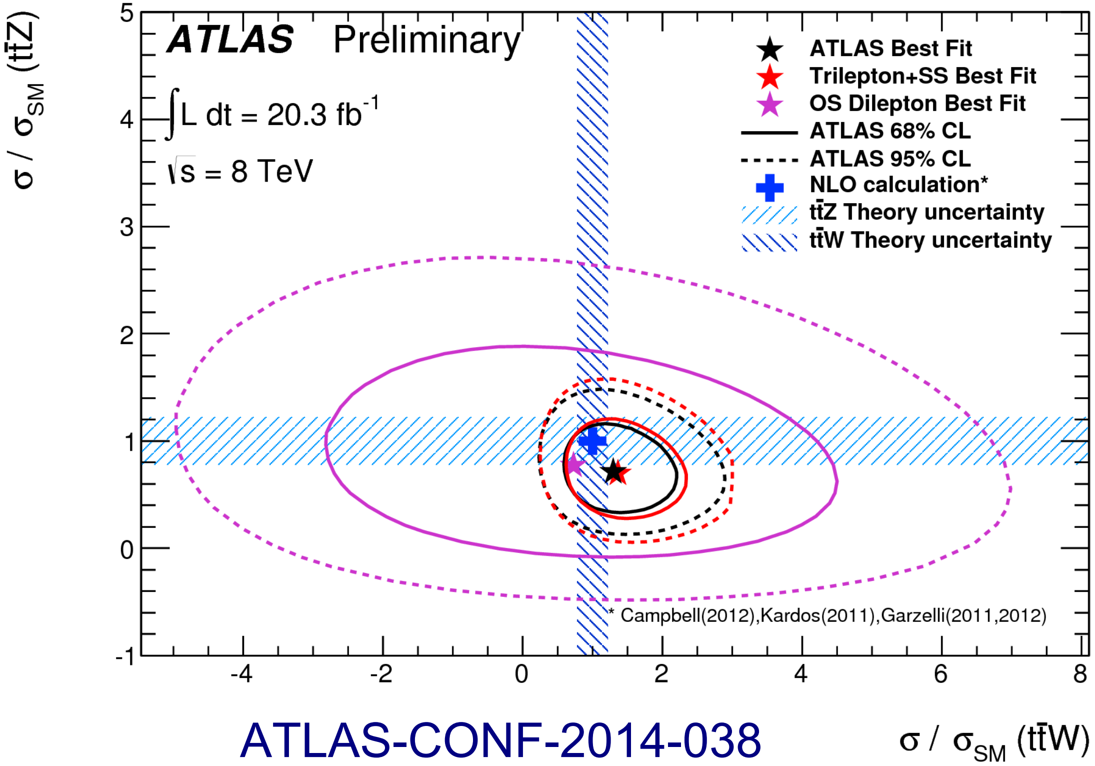




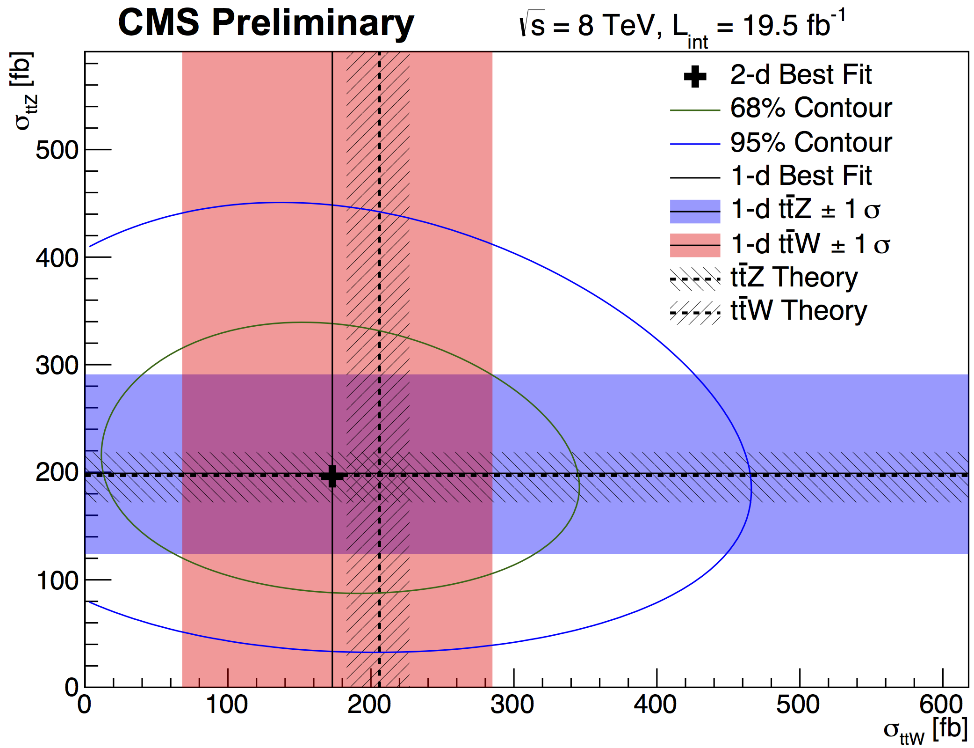
- Dominated by object IDs (jets, photon, btag) and signal model related

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
tt̄W	170^{+90}_{-80}(stat.)$^{+70}_{-70}$(syst.) fb	1.6 σ
tt̄Z	200^{+80}_{-70}(stat.)$^{+40}_{-30}$(syst.) fb	3.1 σ
tt̄W + tt̄Z	380^{+100}_{-90}(stat.)$^{+80}_{-70}$(syst.) fb	3.7 σ

Top quark polarization

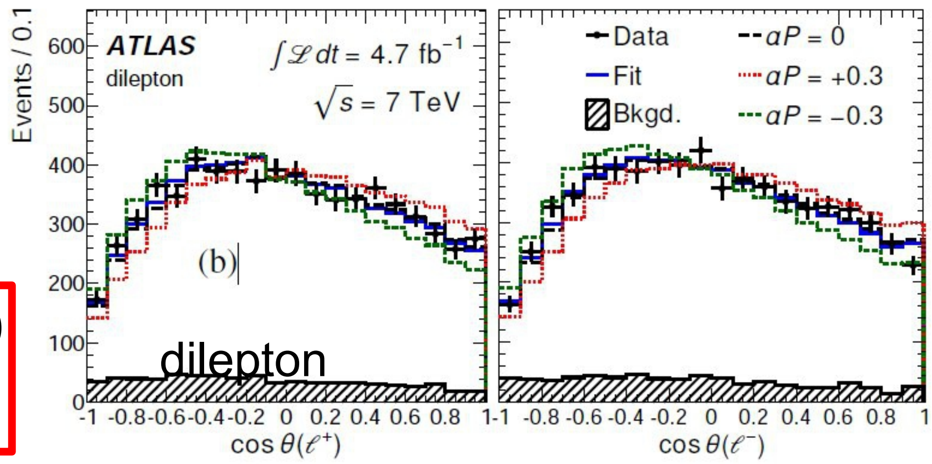
- In $t\bar{t}$ production: New physics polarizes top quarks
- Polarization introduced by CP conserving or violating process:

→ $\in P_{CPC}$ = -0.035 ± 0.014 (stat.) ± 0.037 (syst.)

$\in P_{CPV}$ = 0.020 ± 0.016 (stat.) ± $^{0.013}_{0.017}$ (syst.)

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

PRL 111, 232002 (2013)

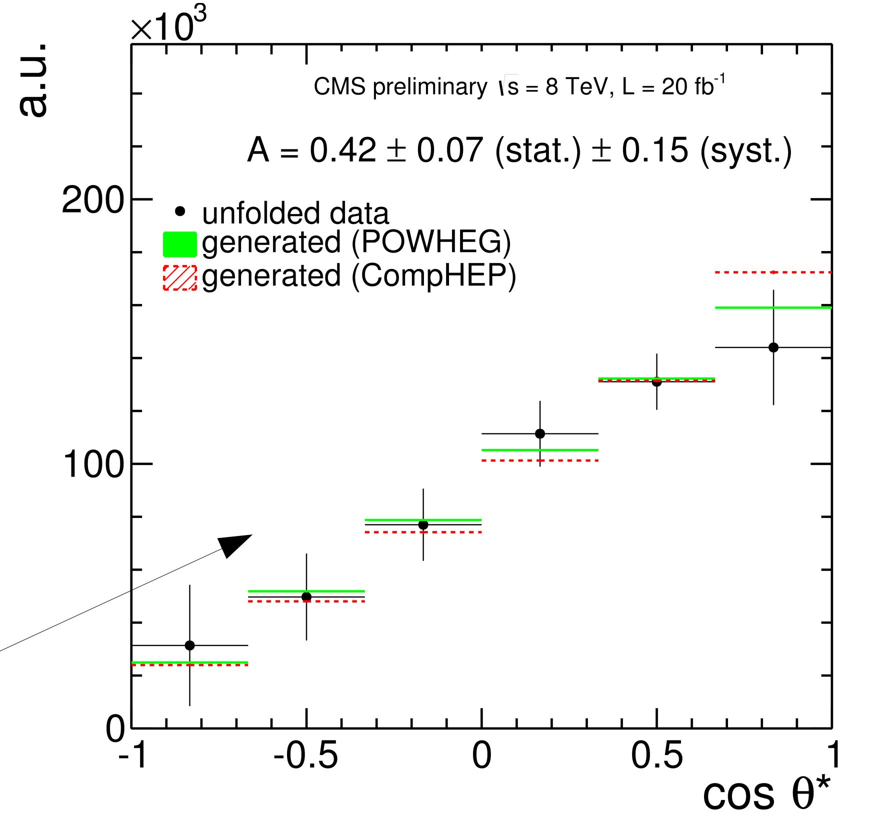


- Good agreement with SM (negligible polarization), also seen by: → CMS: PRL 112 (2014) 182001
  → D0: PRD 87, 011103(R) (2013)

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

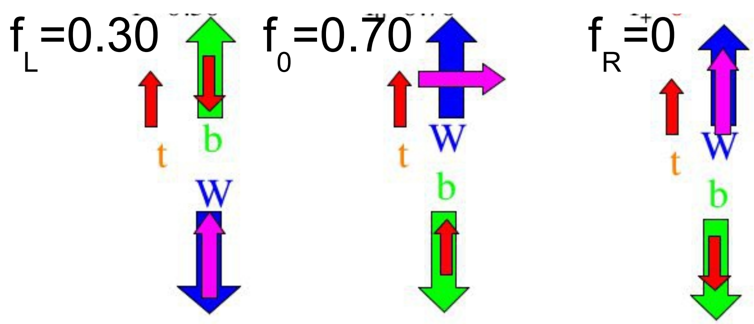
→ P_t = 0.82 ± 0.12 (stat.) ± 0.32 (syst.)

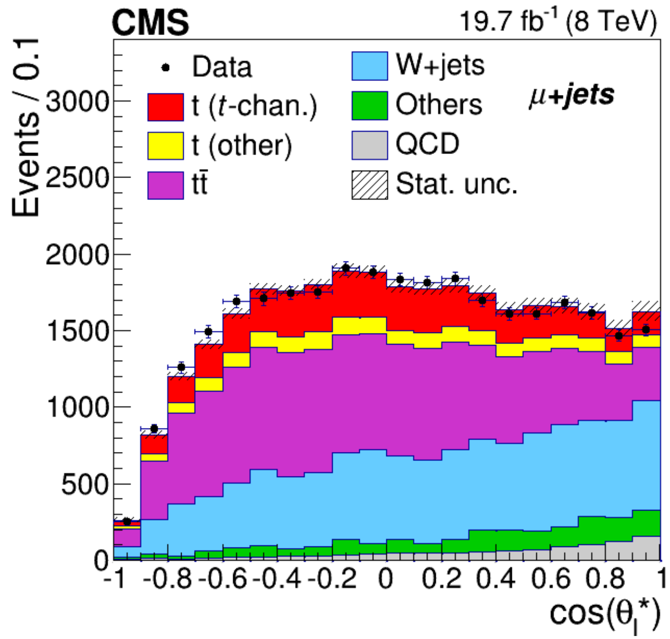
CMS-PAS-TOP-13-001



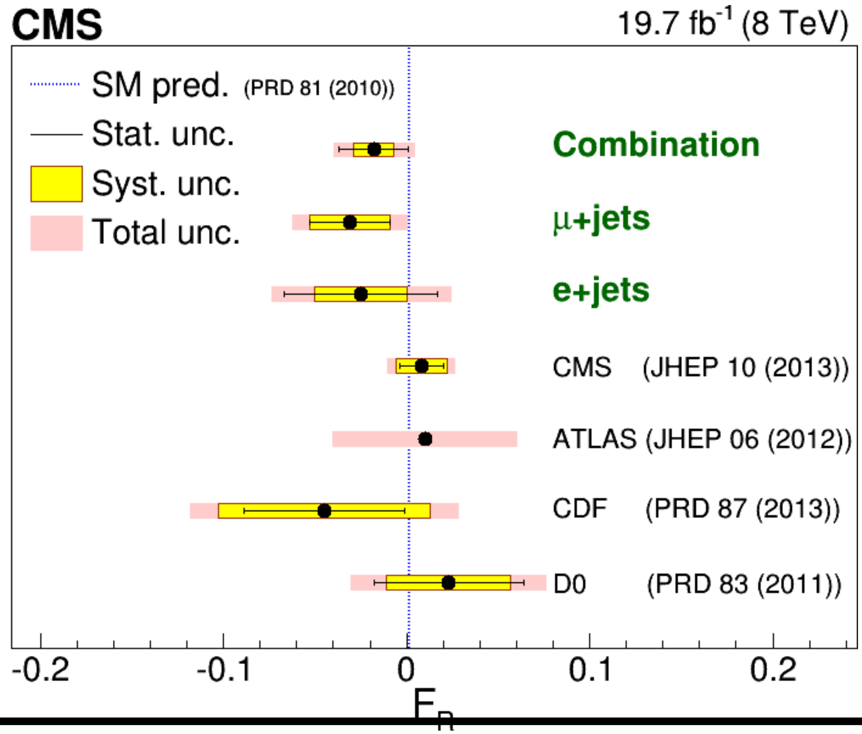
W helicity in single top production

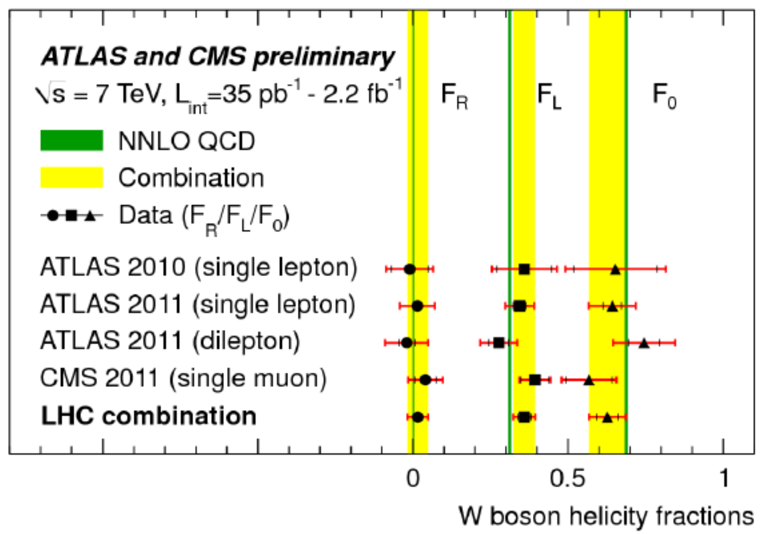
- W helicity in SM:





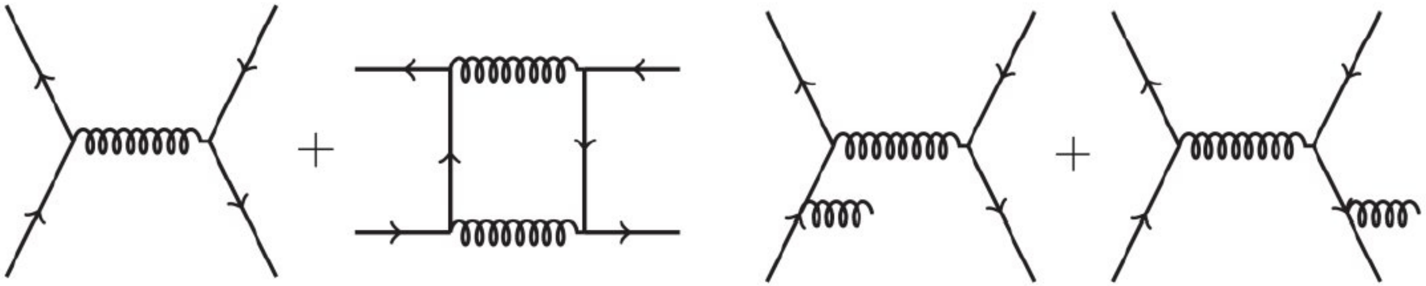
- Complements results in pair production
- Similar precision but orthogonal systematic uncertainties in single top channels
  - Signal model & template statistics



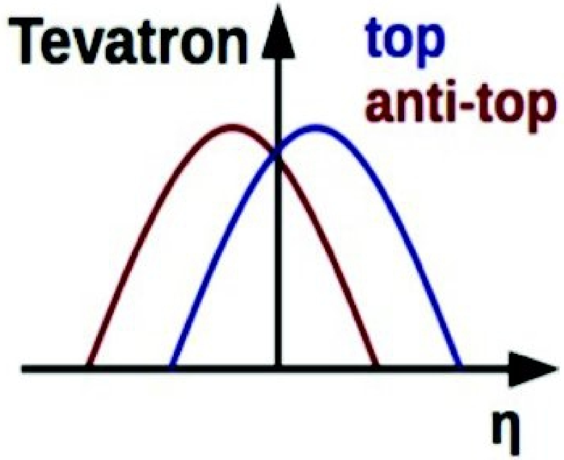


Top quark asymmetries

- Interference appears at NLO QCD:

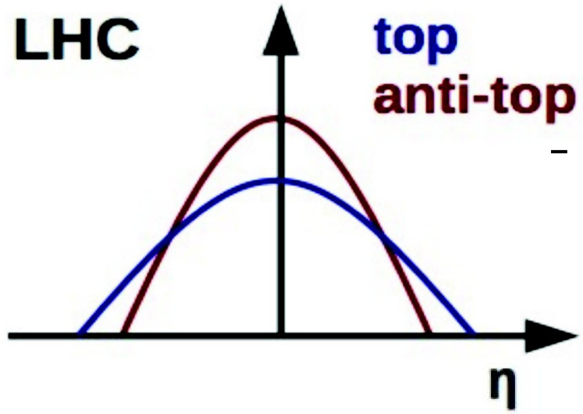


Positive asymmetry — Negative asymmetry



→ 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: $\mathbf{A_{FB} \sim 8\text{-}9\ \%}$ vs. LHC: $\mathbf{A_C \sim 1\ \%}$

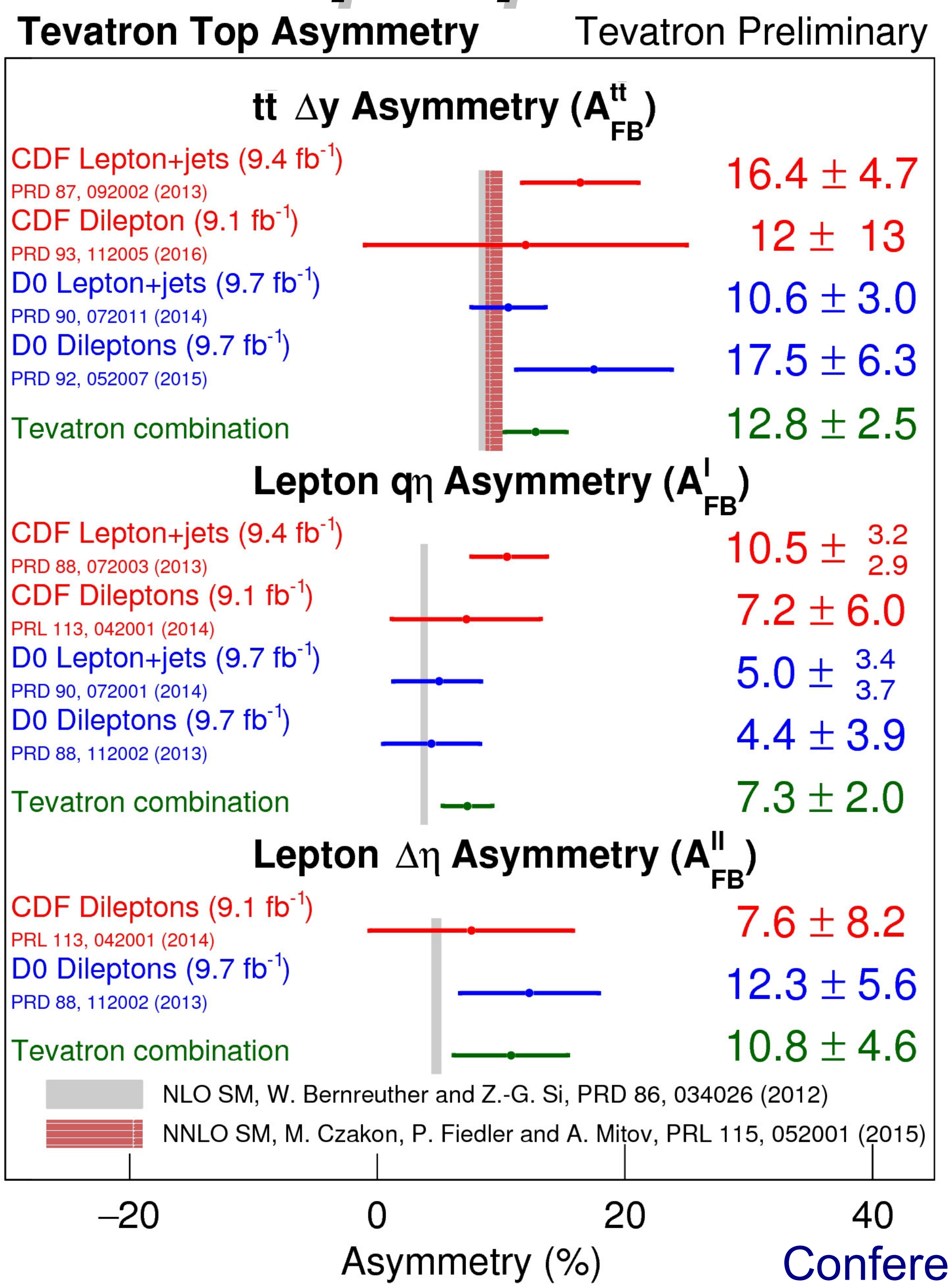
  (waiting for full NNLO pQCD predictions)

- Experimentally: Asymmetries based on decay leptons ("easier") or fully reconstructed top quarks ("harder")

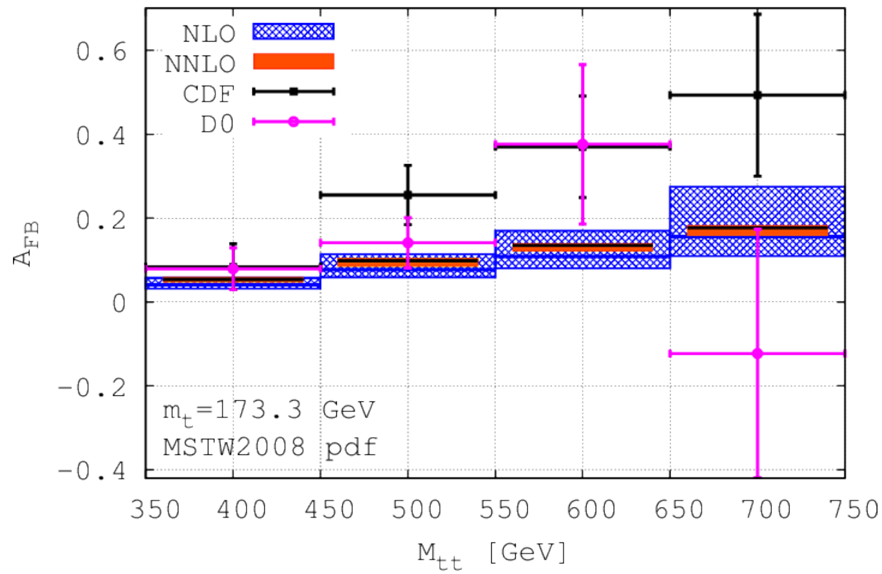
$$A_C = \frac{N(\Delta|y_t| > 0) - N(\Delta|y_t| < 0)}{N(\Delta|y_t| > 0) + N(\Delta|y_t| < 0)}$$

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

Top quark asymmetries



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



Conference Note 6492

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:

→

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

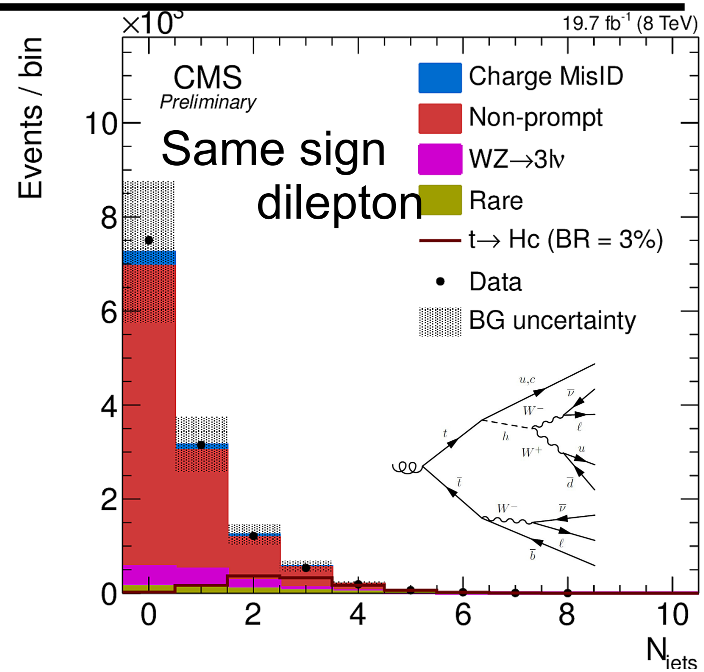
- Search for Higgs boson production in the dilepton (same sign) and trilepton channel
- Systematic uncertainties dominated by:
  Background modeling / cross sections

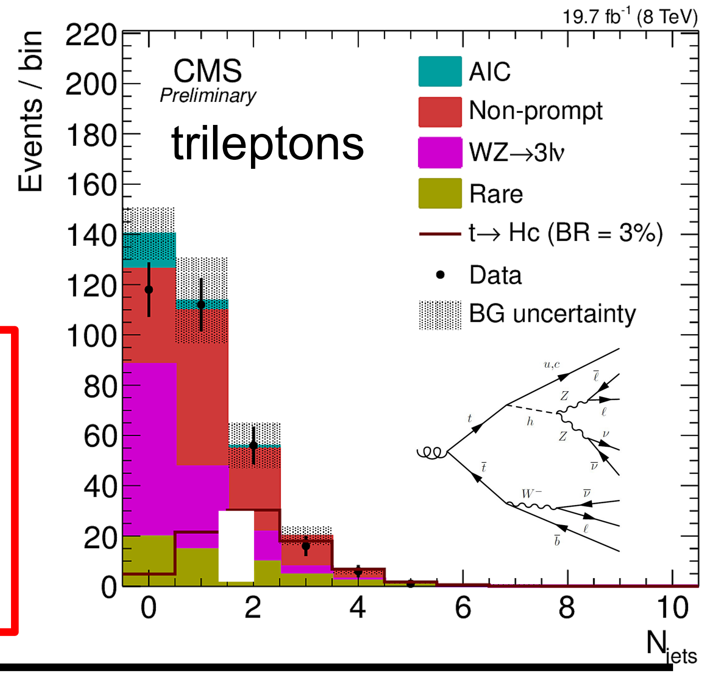
- Limit on top-charm flavor-violating Higgs Yukawa coupling & upper limits for branching fractions:

→

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

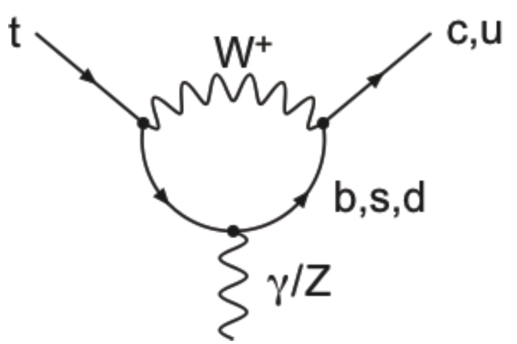
	$-\sigma$	$BR_{exp}(t \to Hc)$	$+\sigma$	$BR_{obs}(t \to Hc)$
trilepton	0.95	1.33	1.87	1.26
same-sign dilepton	0.68	0.93	1.26	0.99
combined	0.65	0.89	1.22	0.93

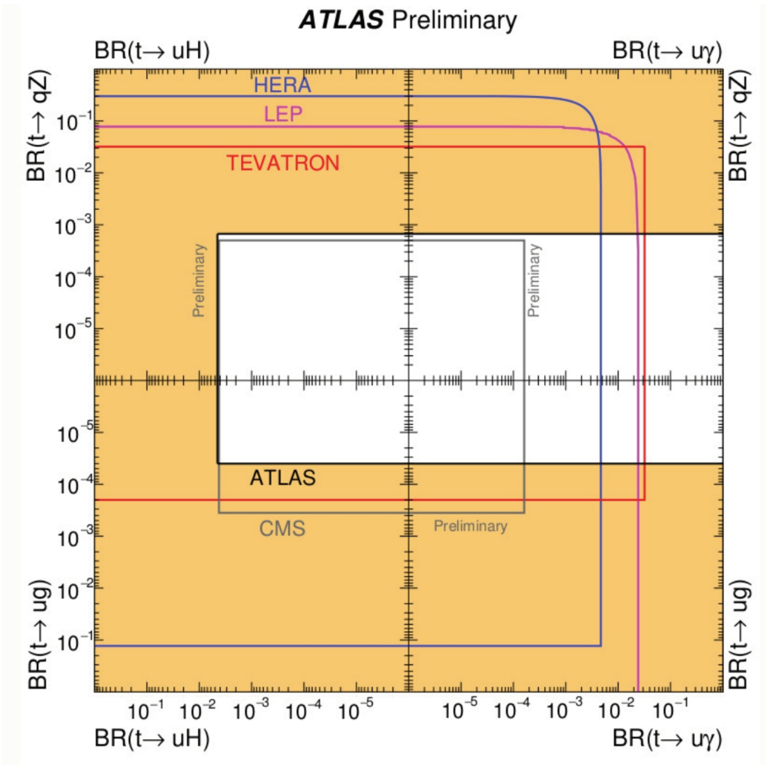


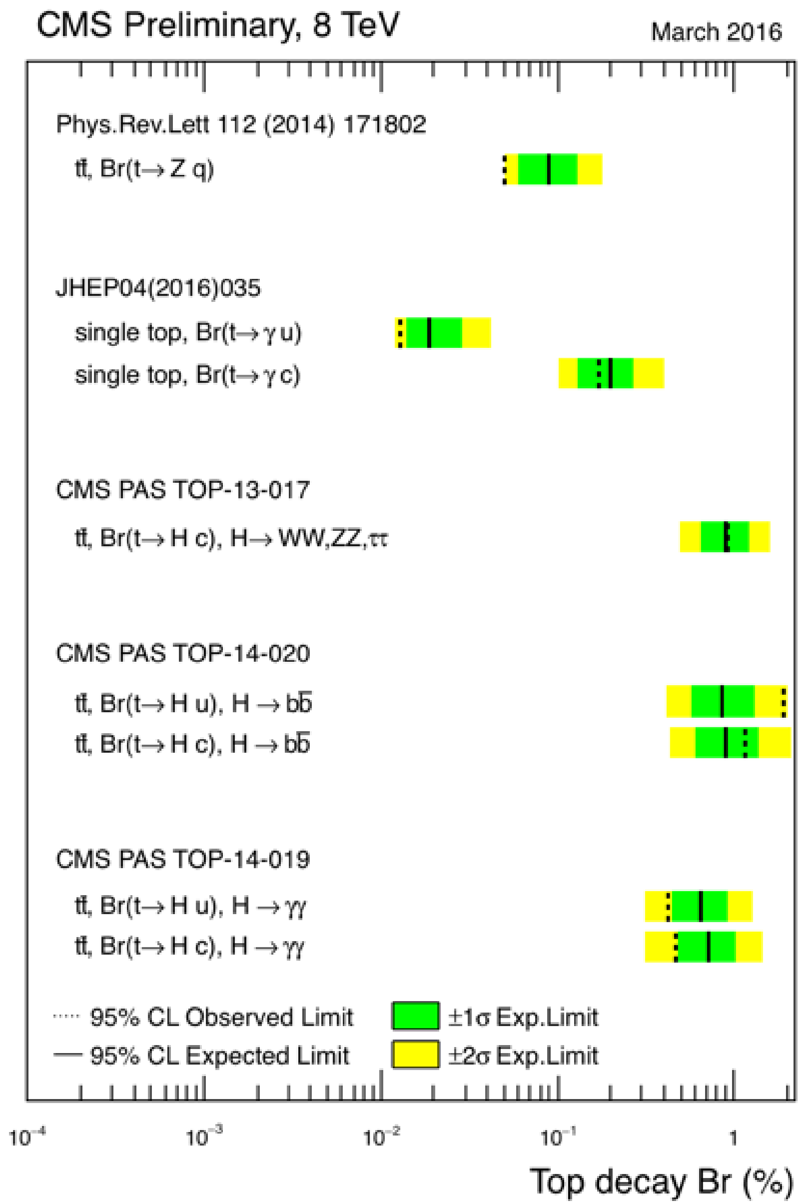


Top quark: FCNC

- 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 dσ/dX

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

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

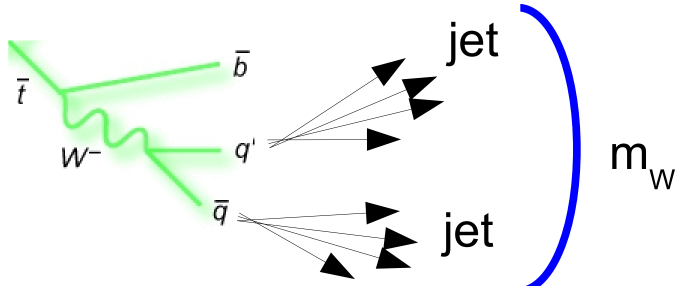
$$\mathcal{L}\left(\text{sample}|m_t, \text{JSF}\right) = \prod_{\text{events}} \left(\sum_{i=1}^{n} P_{\text{gof}}(i) \left(\sum_j f_j P_j(m_{t,i}^{\text{fit}}|m_t, \text{JSF}) \times P_j(m_{W,i}^{\text{reco}}|m_t, \text{JSF}) \right) \right)^{w_{\text{event}}}$$

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

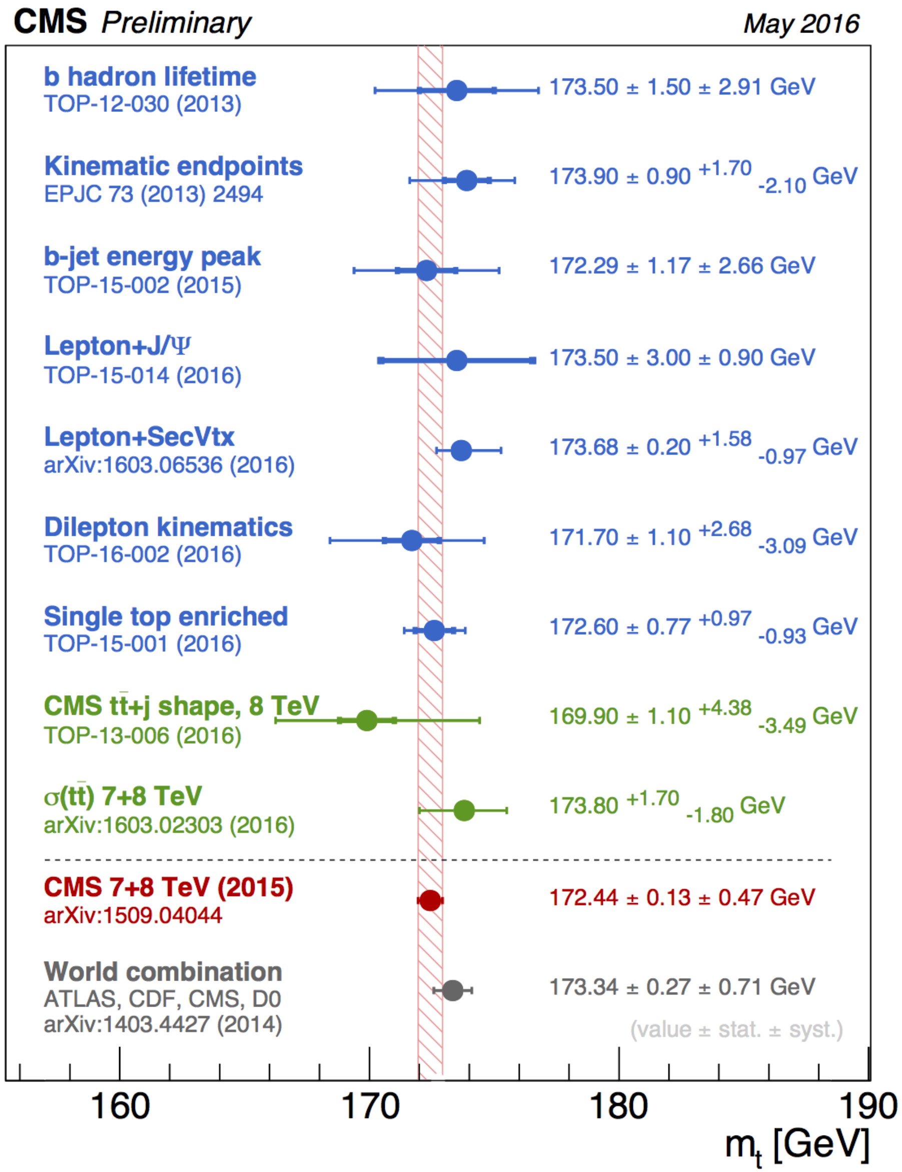
- <u>Depend on MC → We measure "MC mass"</u>

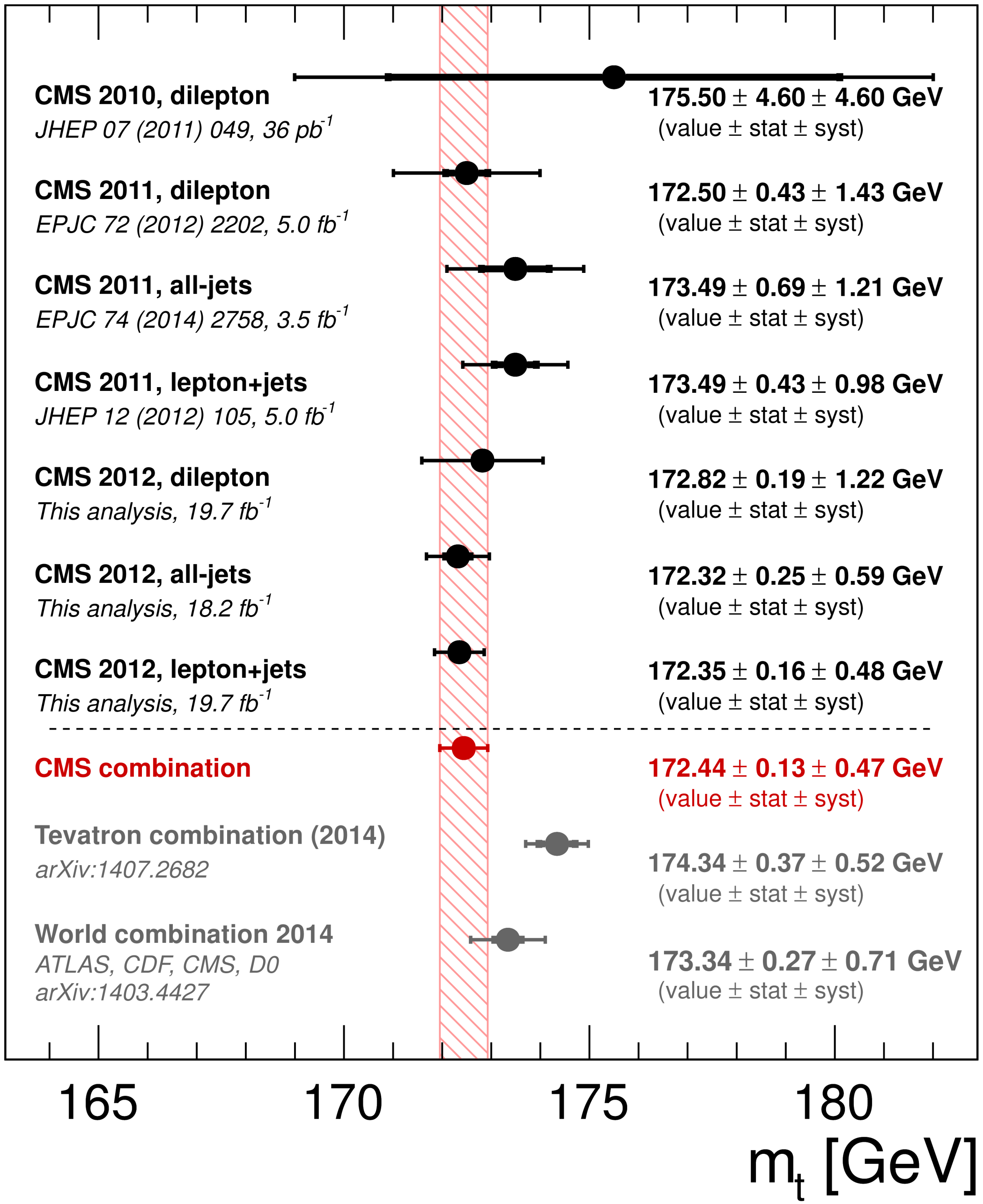
- **Alternative methods** ("End-point", J/Φ, "σ")

<u>W boson fully reconstructed:</u>
→ <u>In-situ calibration</u>, Constrain reconstructed m_W to m_W



Top quark mass



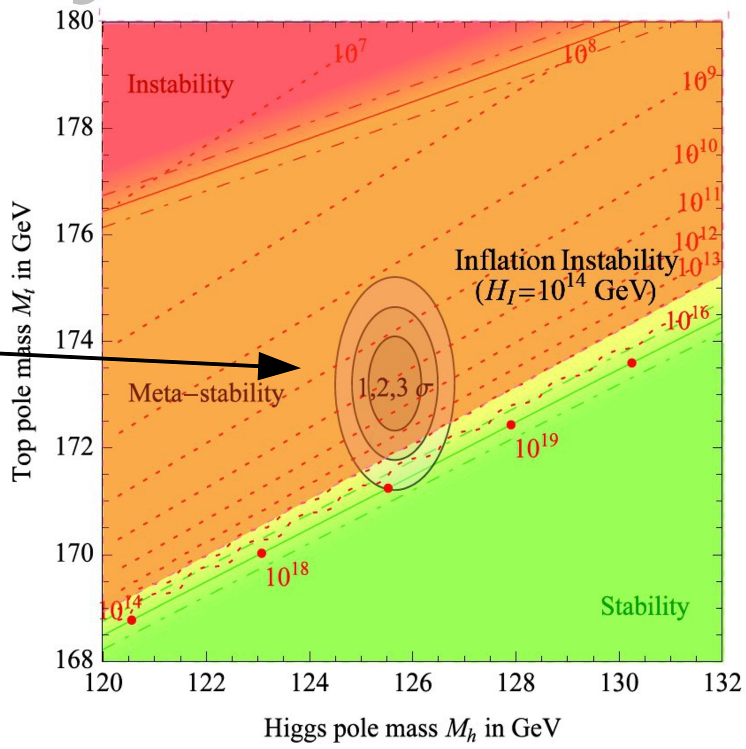


SM vacuum stability

- 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}) $t_{universe}$

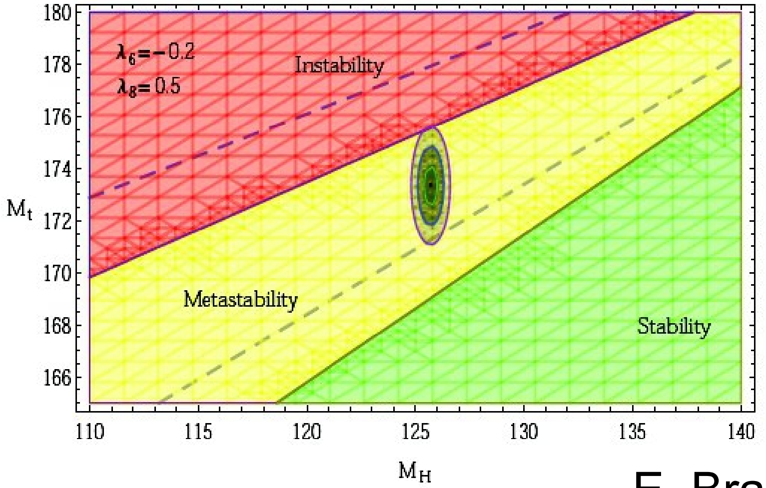
→ but new physics can change that dramatically

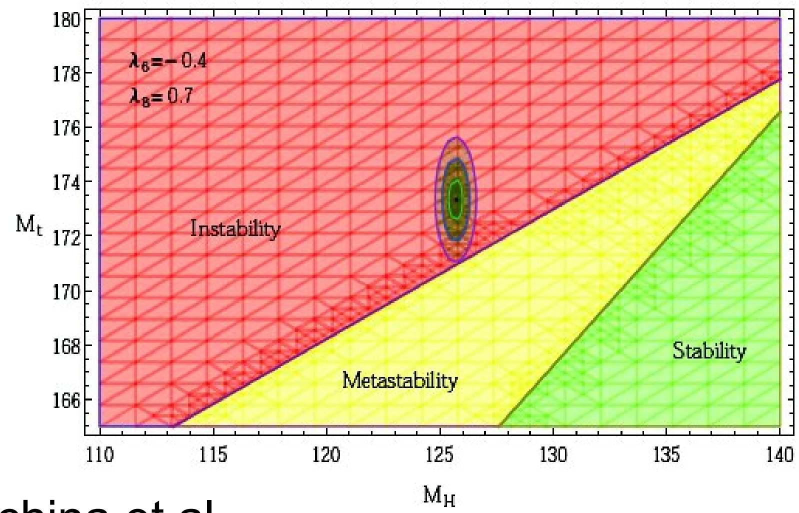


$$V(\phi) = \frac{\lambda}{4}\phi^4 + \frac{\lambda_6}{6}\frac{\phi^6}{M_P^2} + \frac{\lambda_8}{8}\frac{\phi^8}{M_P^4}$$

SM Higgs potential

dim 6 & 8 BSM modifications





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