Top Quark Physics

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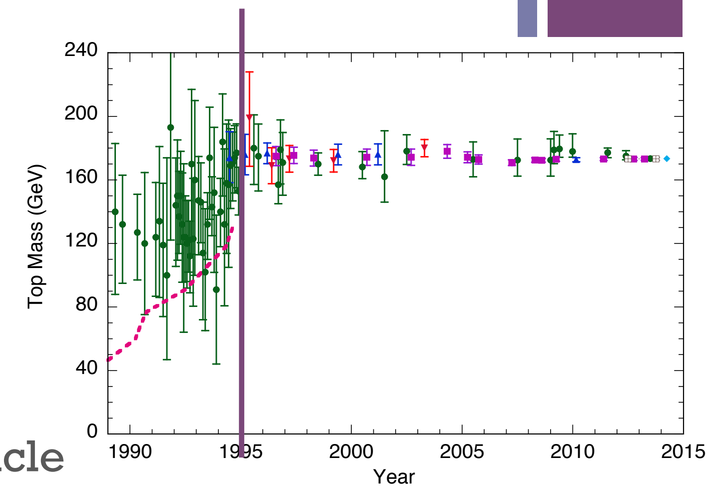
Aspen 2016

+ Top quark reaching drinking age Many properties well measured…

- 2015 was the 20th anniversary of the discovery
  - CDF: PRL74 2626-2631 (1995)
  - D0: PRL74 2632-2637 (1995)

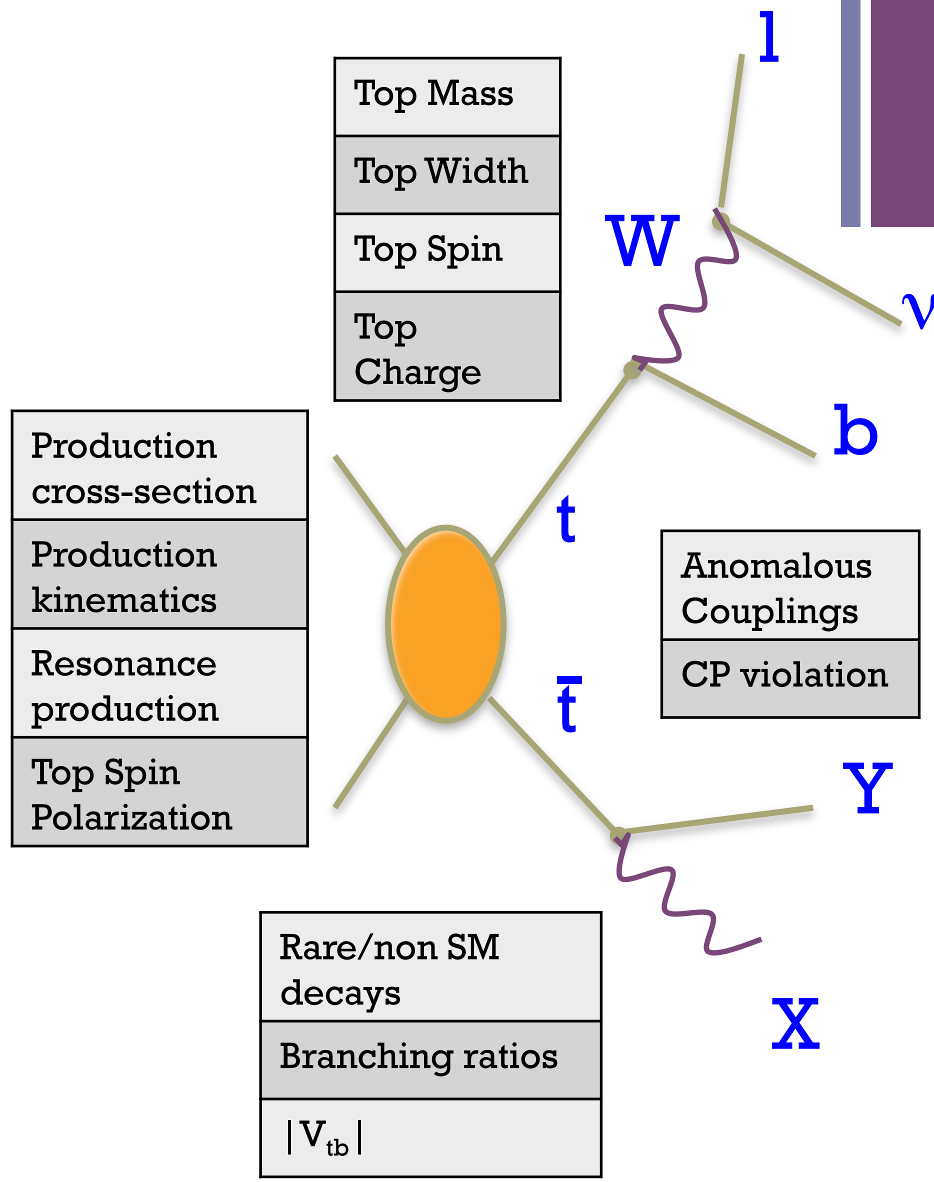


- It completes the SM 3 family structure
  - top is the weak-isospin partner of the b-quark
  - spin = ½ & charge = + ⅔|e|
- Top quark is the heaviest known fundamental particle
  - $m_t = 173.34 \pm 0.76$ GeV [World comb.(2014), arXiv:1403.4427]
  - $m_t = 172.99 \pm 0.91$ GeV [ATLAS Combination (March 2015)]
  - $m_t = 172.44 \pm 0.48$ GeV [CMS Combination (Sept. 2015)]
- Top decays (almost exclusively) through $t \to bW$, $BR(t \to bW) \sim 100\%$
  - $BR(t \to sW) \leq 0.18\%$, $BR(t \to dW) \leq 0.02\%$
- $\Gamma_t^{SM} = 1.42$ GeV
  - $\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25}$ s * $<< \Lambda_{QCD}^{-1} \sim 10^{-23}$ s (hadronization time)
    - Top quark decays before hadronization takes place

*[D0, PRD 85 091104, 2012]
More precise # from LHC available

+ Top properties makes it a great probe

- Precision test of both QCD and EWK
  - Strong coupling to Higgs
- Sensitive to Physics Beyond the SM
- Can be used to measure important parameters like α_s, m_t etc.
- Mayor background to important searches
- Interesting playground to develop new analysis techniques



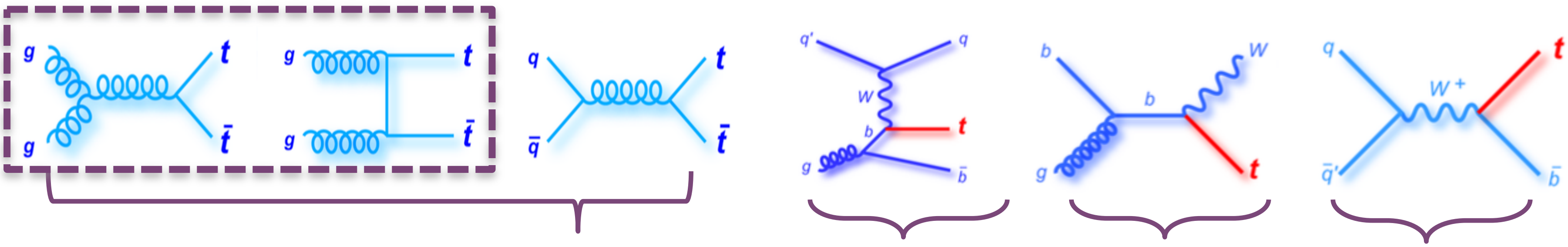
Too much progress in the past six month… I will run out of time

- Underlying event
- tt Cross section measurements
  - Inclusive
    - ✓ tt and tt/Z
  - Differential
    - ✓ Resolved
    - ✓ Boosted
  - Associate production with bosons ttV (V = γ, Z, W, H)
  - tt plus jets
- Single top cross section
  - V_{tb}
- Top quark beyond the SM
  - FCNC processes (tqX, X= γ, Z, g, H)
  - Charge asymmetry
  - anomalous couplings
  - Probing the top quark spin
- Top quark mass

+ Top quark production: Tevatron versus the LHC top factory

- At the LHC
  - 1 ttbar event per sec
  - top quarks are mainly produce in ttbar pairs → Strong interaction
  - At a lower rate: single top quark → EWK interaction

@LHC ~ 90% of total rate



@ NLO

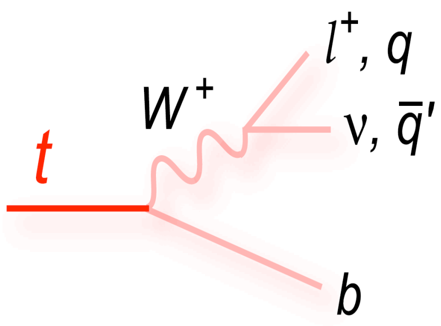
σ [pb]*	ttbar	t-channel	tW	s-channel
Tevatron (1.96TeV)	7.08	2.08	0.22	1.046
LHC @ 7 TeV	177.31	63.89	15.74	4.29
LHC @ 8 TeV	252.89	84.69	22.2	5.24
LHC @ 13 TeV	831.76	216.99	71.2	10.32

* m_t=172.5 GeV

$\sigma_{\text{top}} \neq \sigma_{\text{Anti-top}}$ (t-channel)

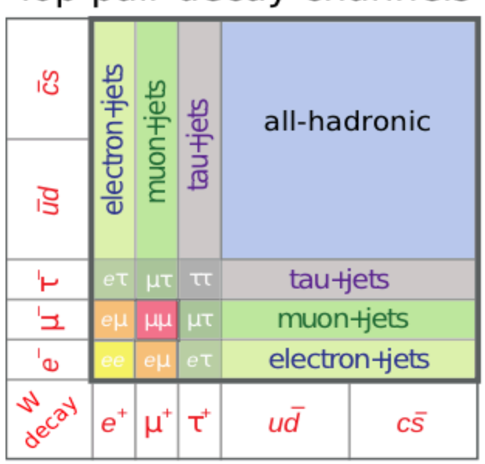
$\sigma_{\text{top}} \neq \sigma_{\text{Anti-top}}$ (s-channel)

+ $t\bar{t}$: Basic Top – AntiTop topology

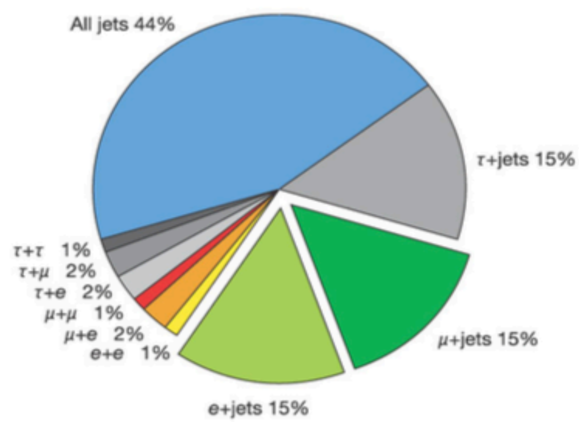


(not inc. τ)	BR	background
dilepton	~5%	low
lepton + jets	~30%	moderate
all hadronic	~44%	high

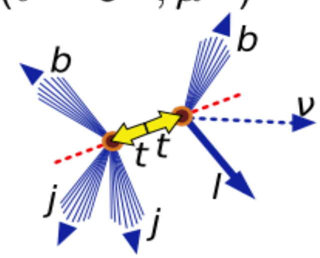
Top pair decay channels



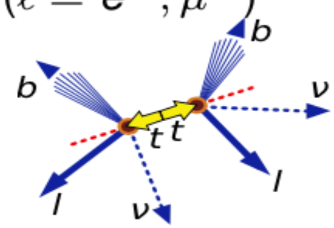
Top pair branching fractions



$\Longrightarrow$ Lepton+jets ($\sim$ 30%):
$(\ell = e^{\pm}, \mu^{\pm})$



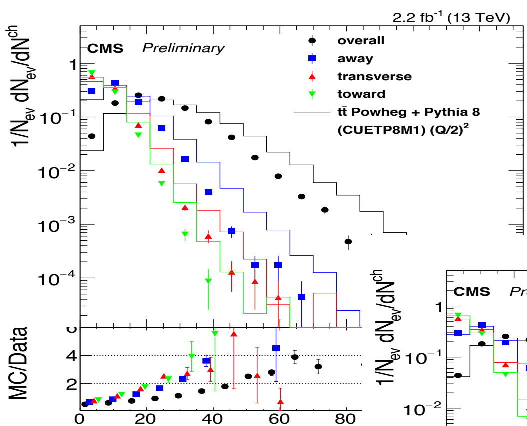
$\Longrightarrow$ Dilepton ($\sim$ 5%):
$(\ell = e^{\pm}, \mu^{\pm})$

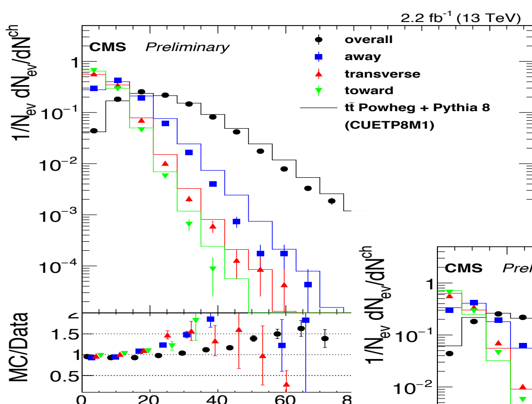


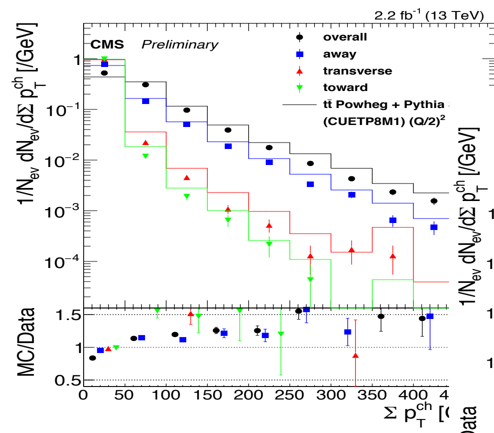
13 TeV Underlying events tuning checked with tt events in μ+jets

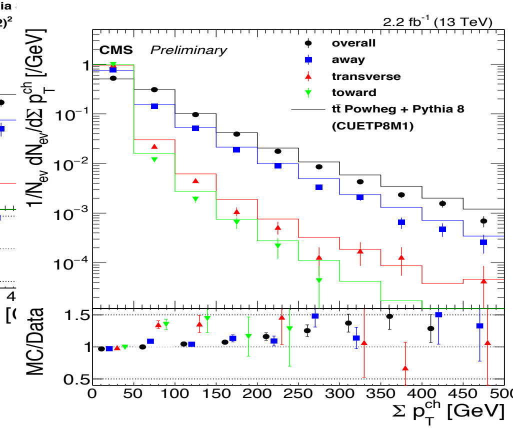
➔ Scale at generator "Q^2" set to m_T of top quark in tt rest frame

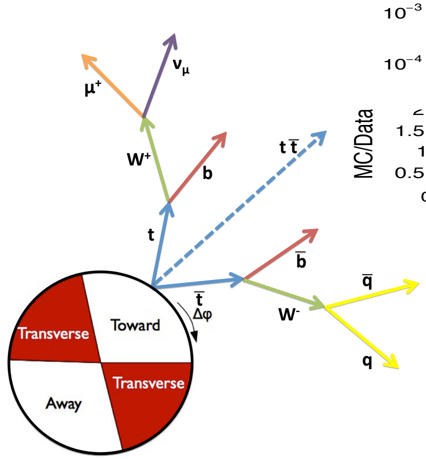
CMS PAS TOP-15-017

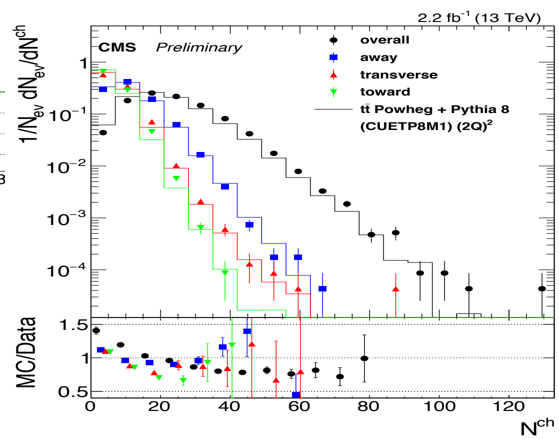


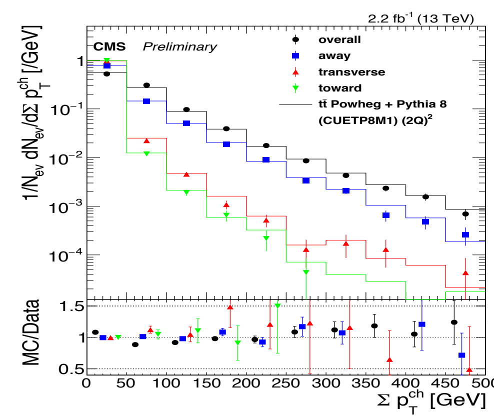








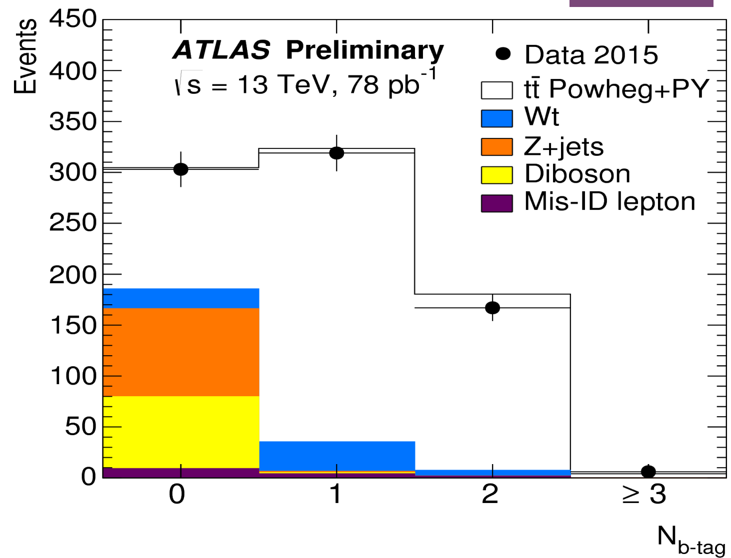


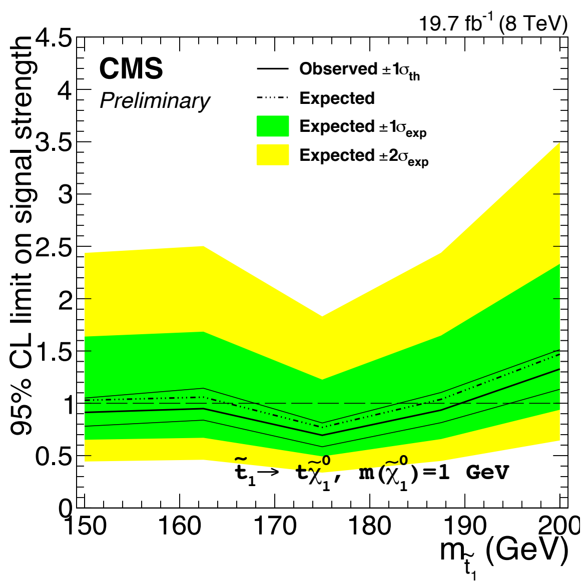


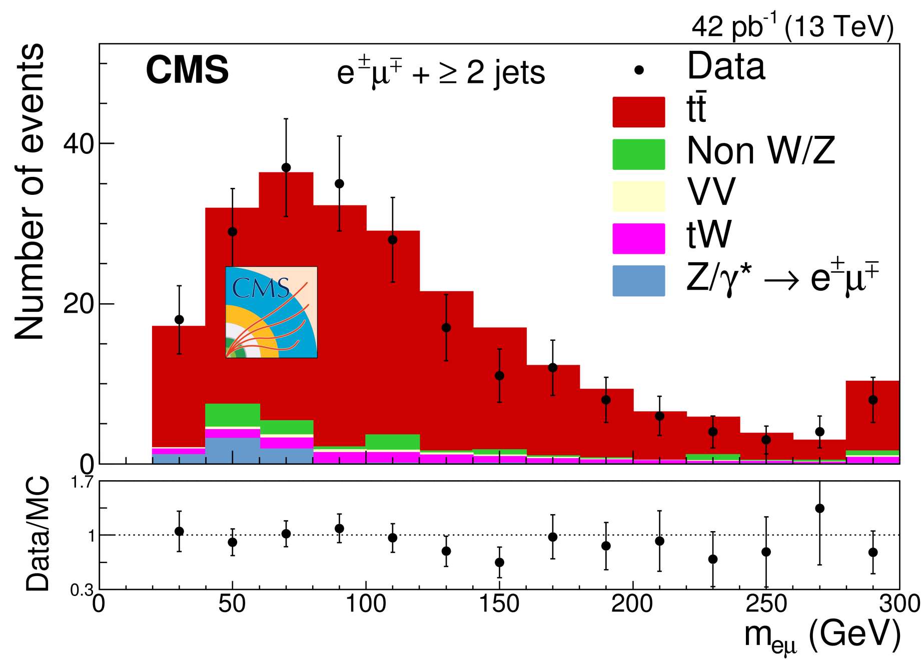
+ Purest tt samples: μe channel

Best sample for 1st measurements of inclusive top pair X-sections

$$\sigma_{t\bar{t}} = \frac{N_{\rm data} - N_{\rm bkg}}{\varepsilon A \mathcal{L}}$$







Purest tt samples: μe channel

Best sample for 1st measurements
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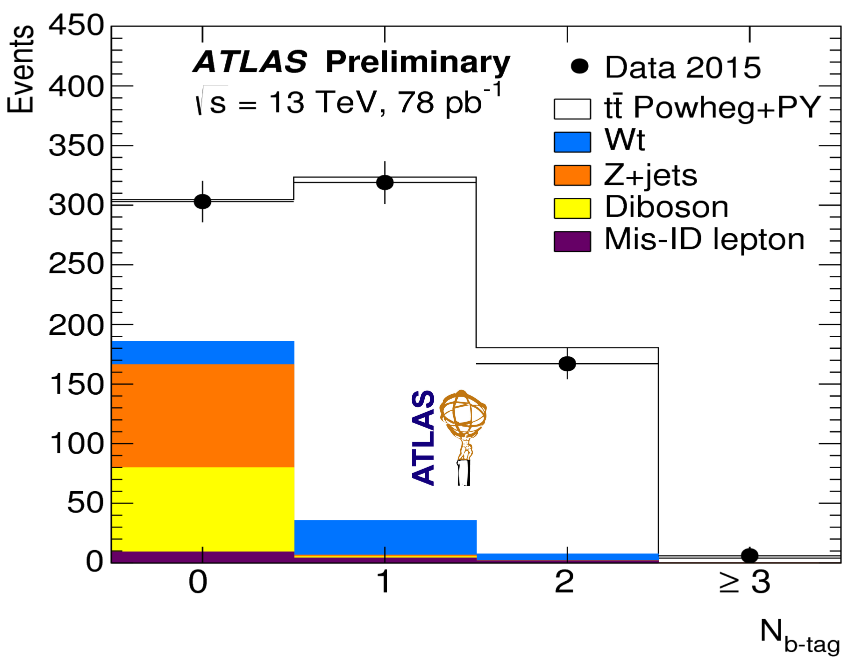
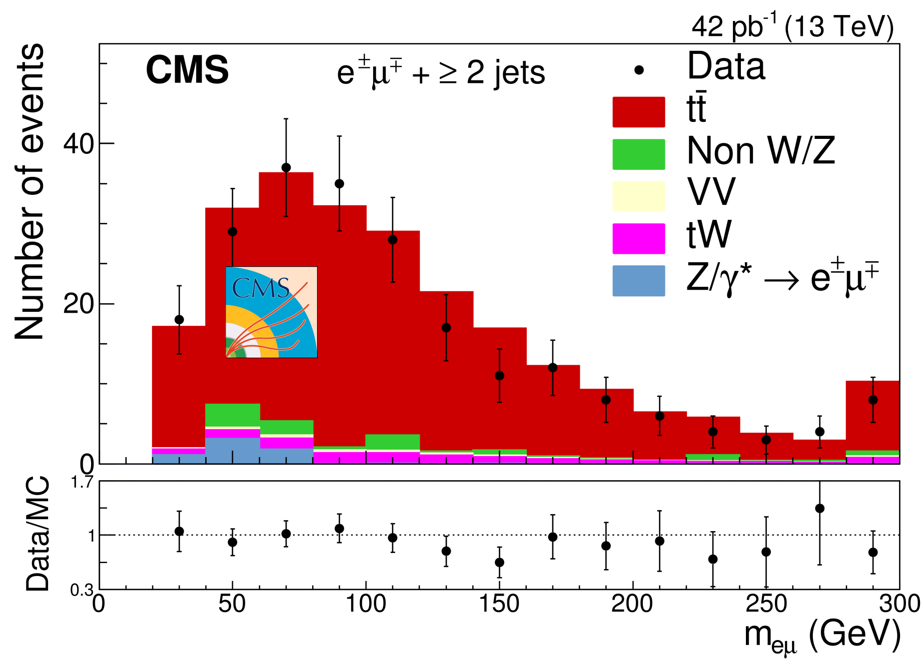
13 TeV Results

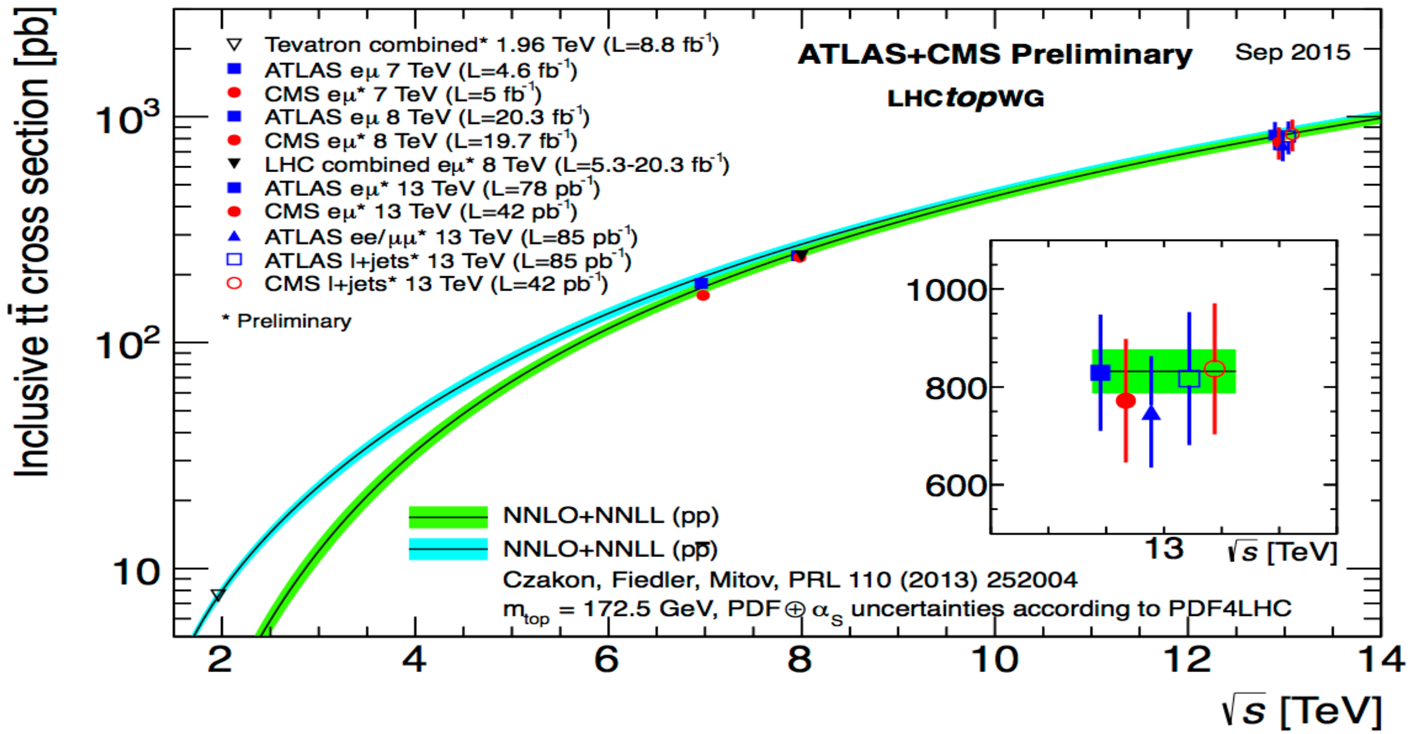


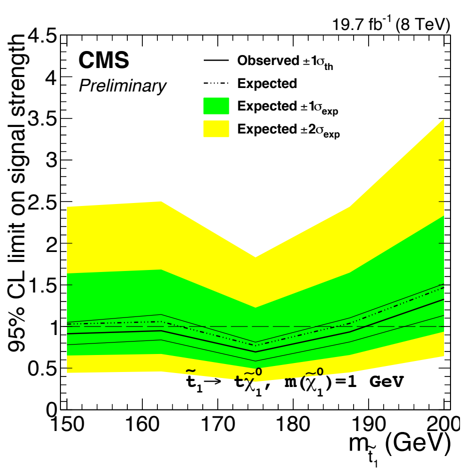


+ Inclusive top pair cross sections

ATLAS-CONF-2015-033/049

CMS PAS TOP-15-003 13-004





Best precision so far…

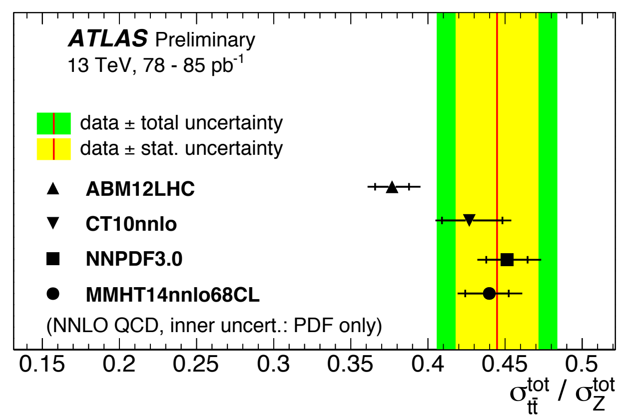
5.9% @ 7 TeV

3.5% @ 8 TeV,

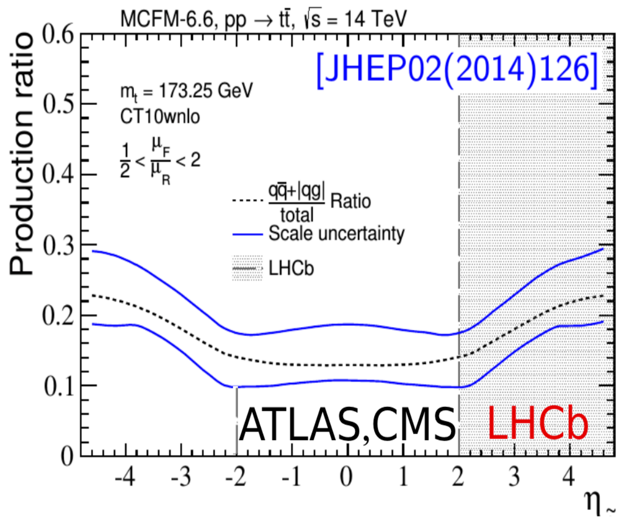
13.5%@13TeV

←Use to set limit in BSM

Compared to other SM→



+ tt production in the forward region



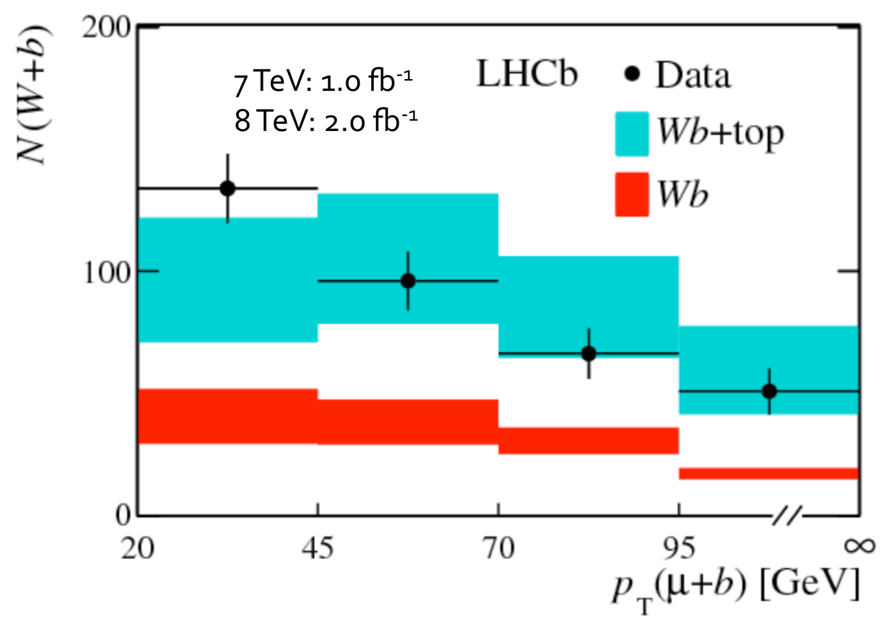
Motivation for studies in forward region:

- test for the differential predictions
- reduced gg production
  - ✓ more sensitive to tt charge asy.
- probes poorly constrained high-x gluon PDF

Fiducial:

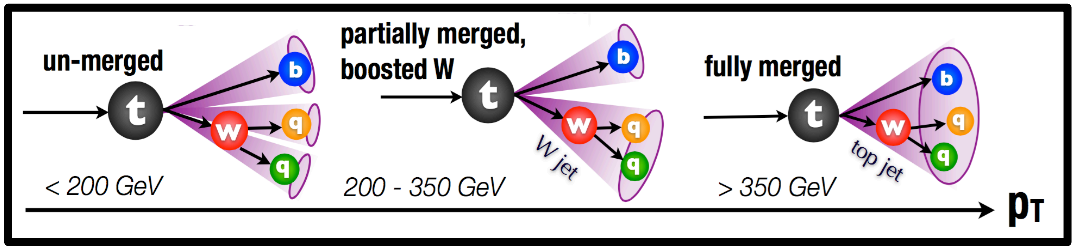
$$\sigma(\text{top})[7\,\text{TeV}] = 239 \pm 53\,(\text{stat}) \pm 33\,(\text{syst}) \pm 24\,(\text{theory})\,\text{fb}$$
$$\sigma(\text{top})[8\,\text{TeV}] = 289 \pm 43\,(\text{stat}) \pm 40\,(\text{syst}) \pm 29\,(\text{theory})\,\text{fb}$$

$$\sigma_{\text{NLO(MCFM)}}\,[7\,\text{TeV}] = 180^{+51}_{-41}\ \text{fb}$$
$$\sigma_{\text{NLO(MCFM)}}\,[8\,\text{TeV}] = 312^{+83}_{-68}\ \text{fb}$$



+ Top pair differential cross sections

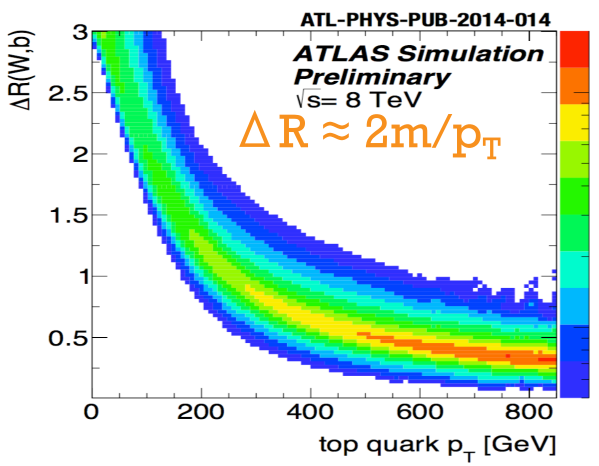
CHALLENGE: Reconstruct, identify & correctly assign decay products to original top quarks



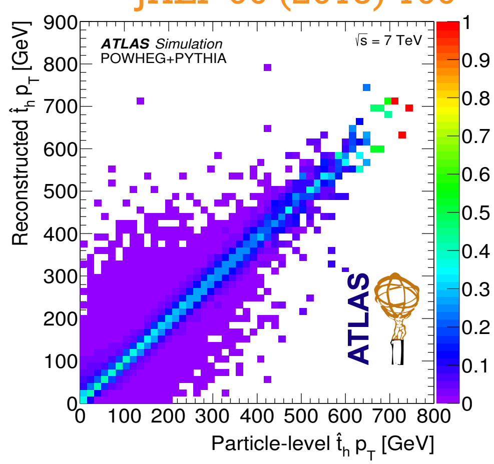
- Resolved regime:
  - well separated jets
  - isolated leptons
- Boosted regime:
  - overlapping decay
  - Non-isolated leptons

Many BSM searches with boosted tops:

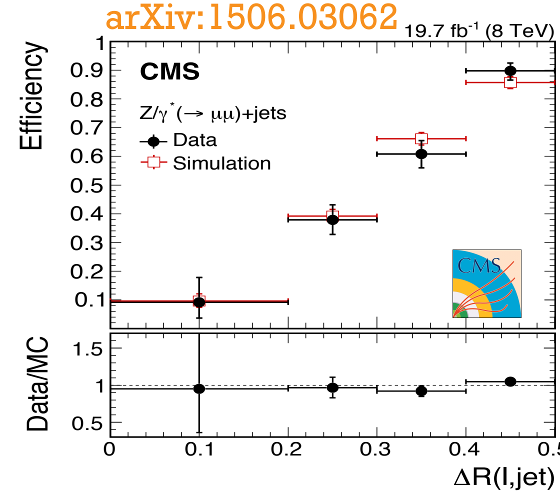
- tt / tb / tH resonances, stop quarks, vector-like quarks, …



JHEP 06 (2015) 100

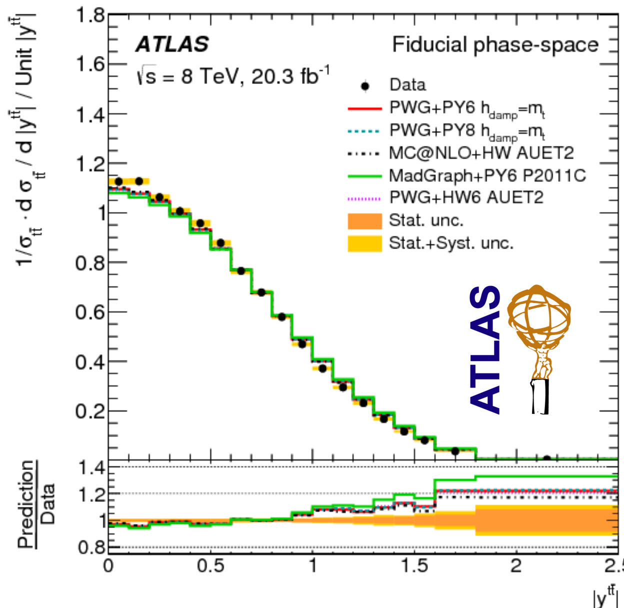


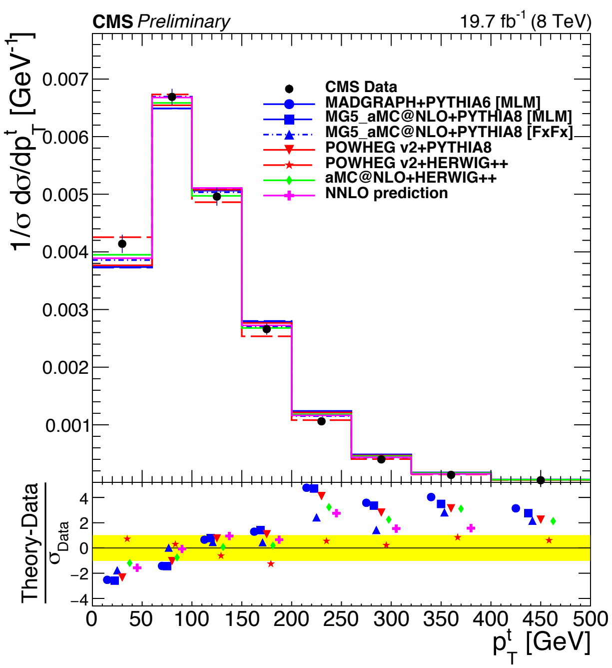
arXiv:1506.03062

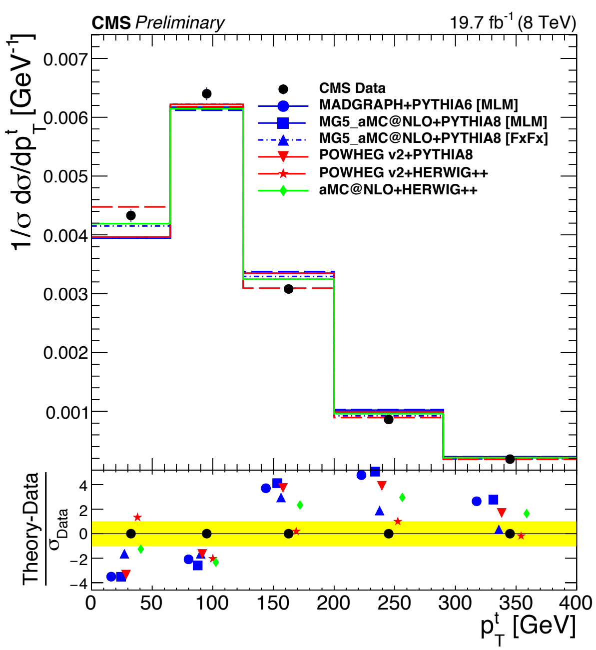


Resolved: differential distribution @ 8 TeV

- e/ μ +jets and dilepton for ATLAS and CMS find $p_T(t)$ and rapidity softer than predicted by PYTHIA-6
- Better agreement now found in new comparison with other generators



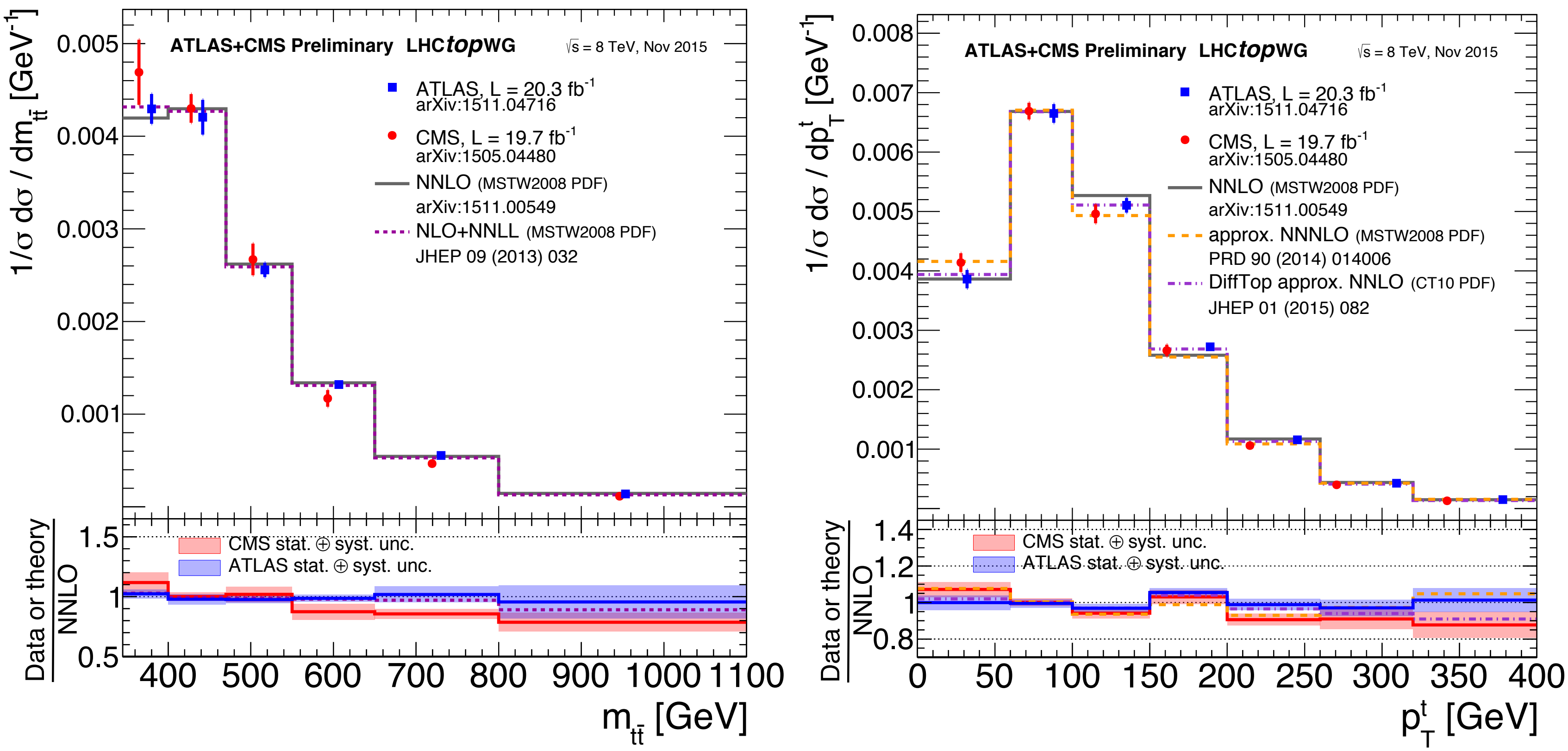




ATLAS:
arXiv:1511.04716

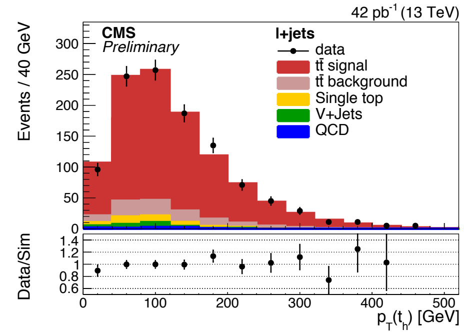
CMS:
CMS-PAS-TOP-15-011

Resolved data and theory comparison revised @ 8 TeV

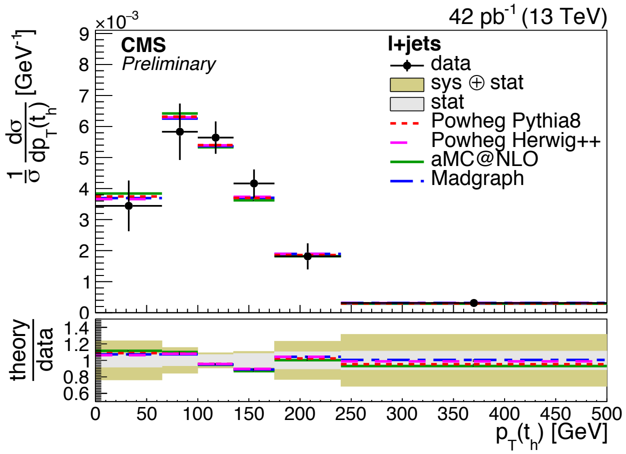


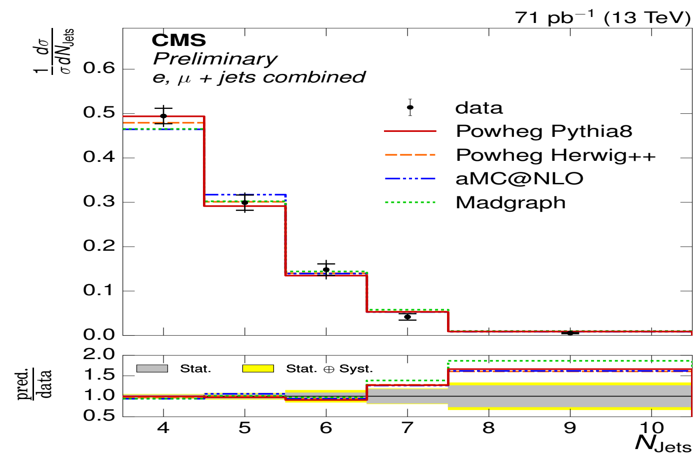
➔ Improvements with Pythia-8 are also observed at 8 TeV (not shown)

+ @ 13 TeV Resolved regime: Differential distribution

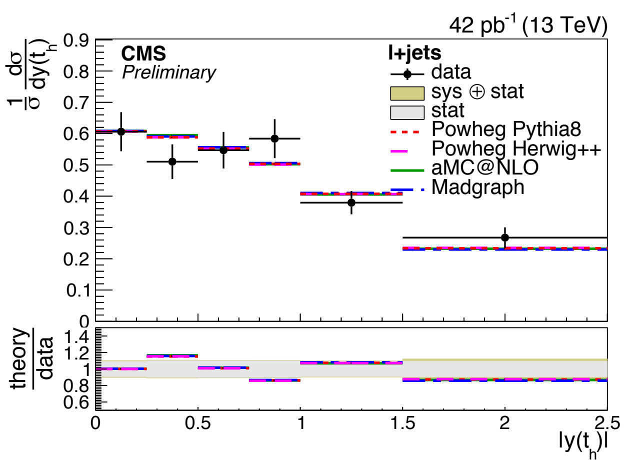


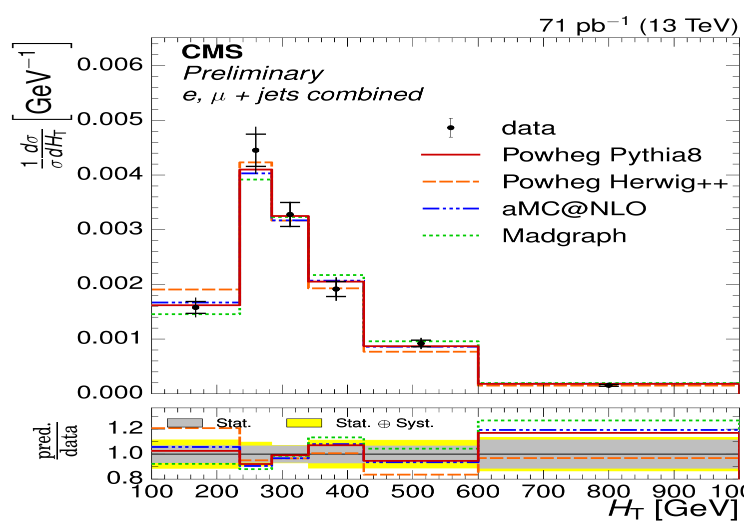
CMS PAS-TOP-15-005





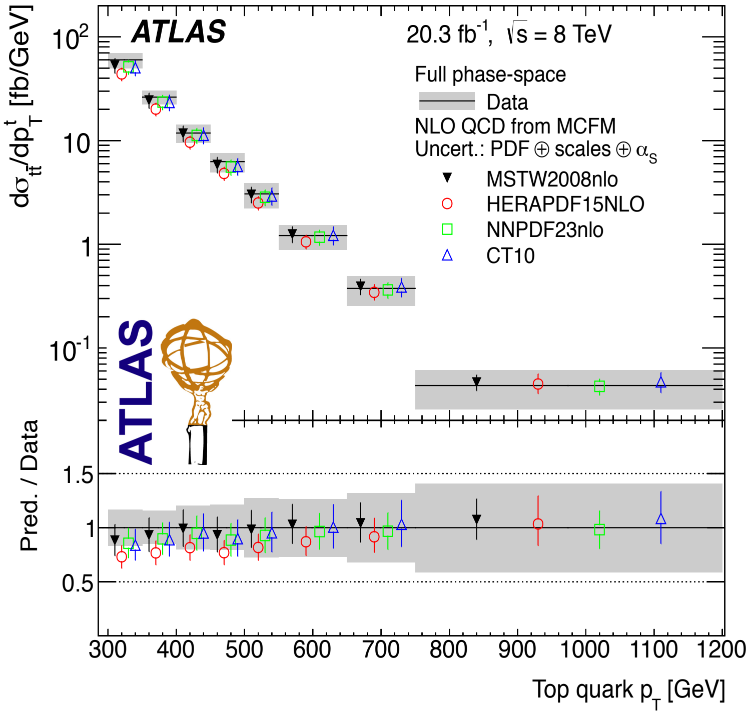
CMS-PAS-TOP-15-013

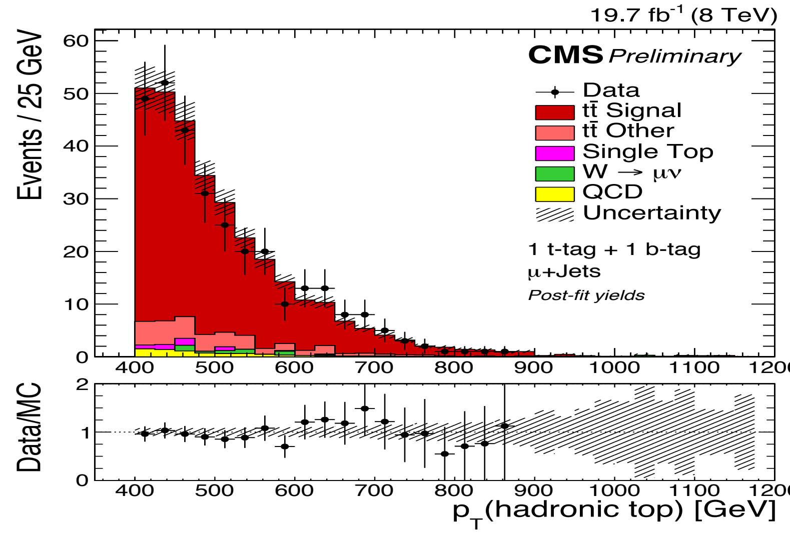


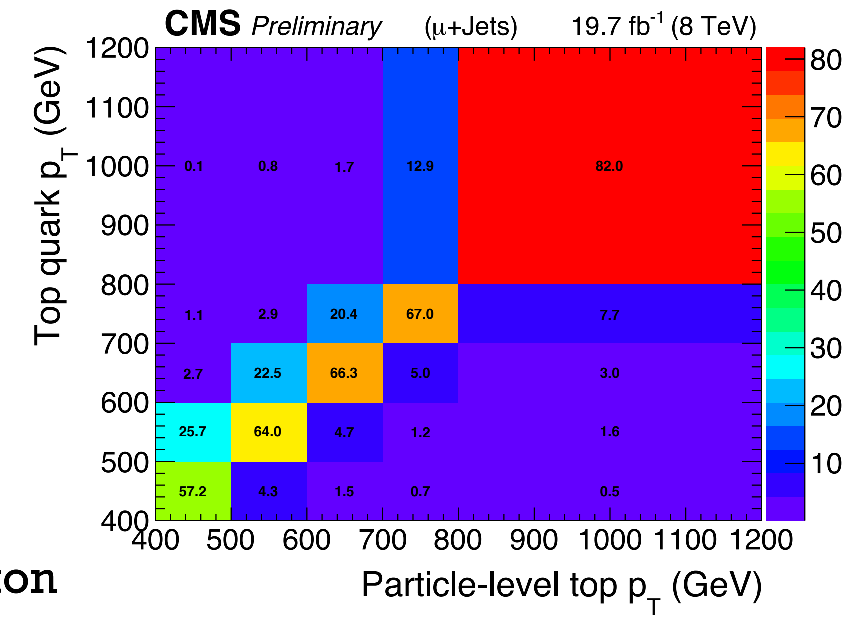


+ Boosted @ 8 TeV

TOPQ-2014-15







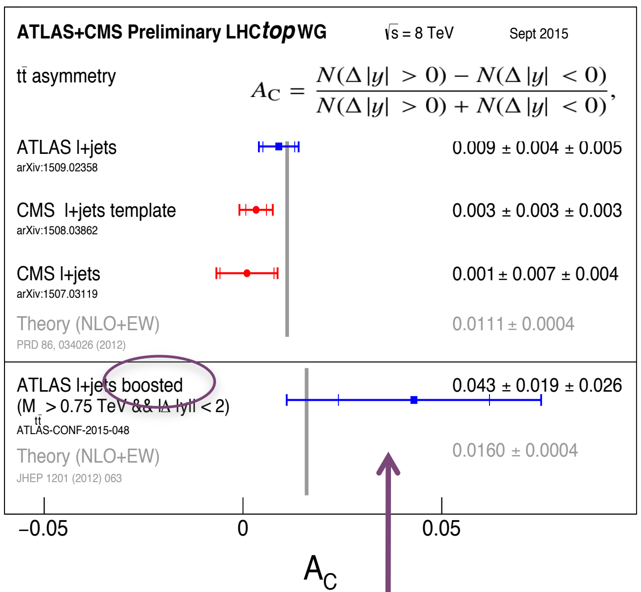
CMS PAS-TOP-14-012

Powheg: 1.49 pb Particle; 1.67 pb Parton

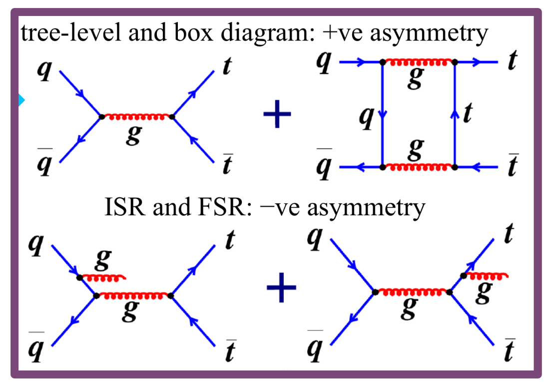
Particle σ ($p_T t$ > 400 GeV) = 1.28 ± 0.09 (stat.+syst.) ± 0.10 (PDF) ± 0.09 (Q^2) ± 0.03 (lumi.) pb

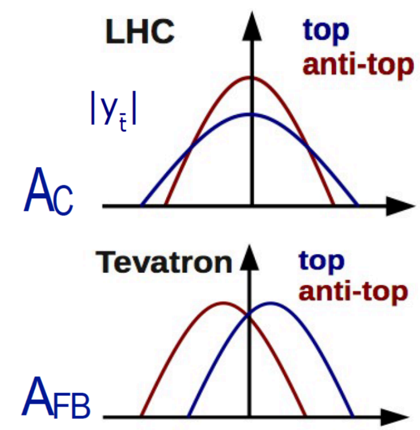
Parton σ ($p_T t$ > 400 GeV) = 1.44 ± 0.10 (stat.+syst.) ± 0.13 (PDF) ± 0.15 (Q^2) ± 0.04 (lumi.) pb

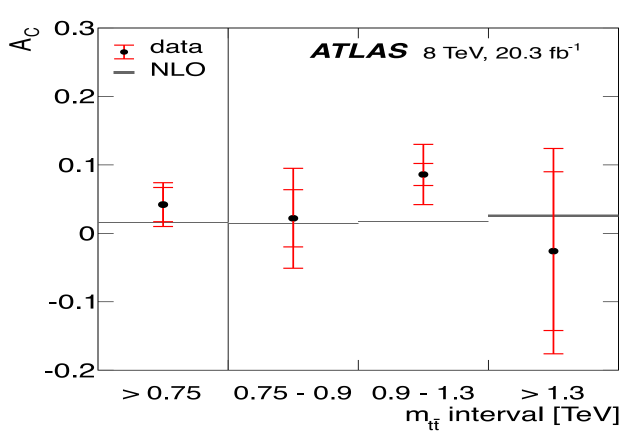
Boosted: 1st Charge asymmetry in boosted top-quark pair production

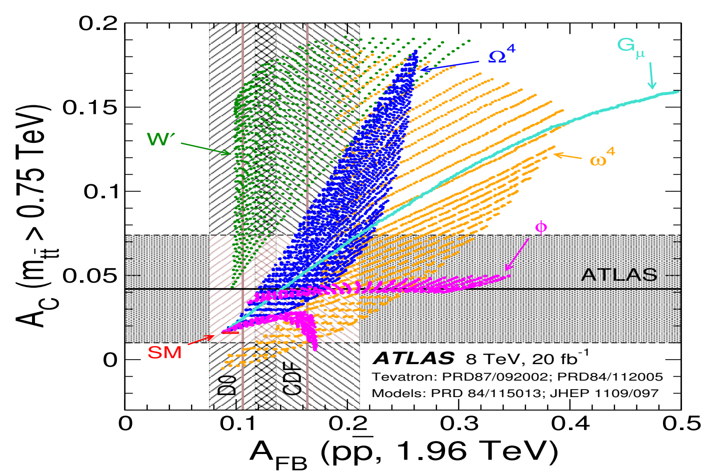


LO symmetric, A≠0 due to interference

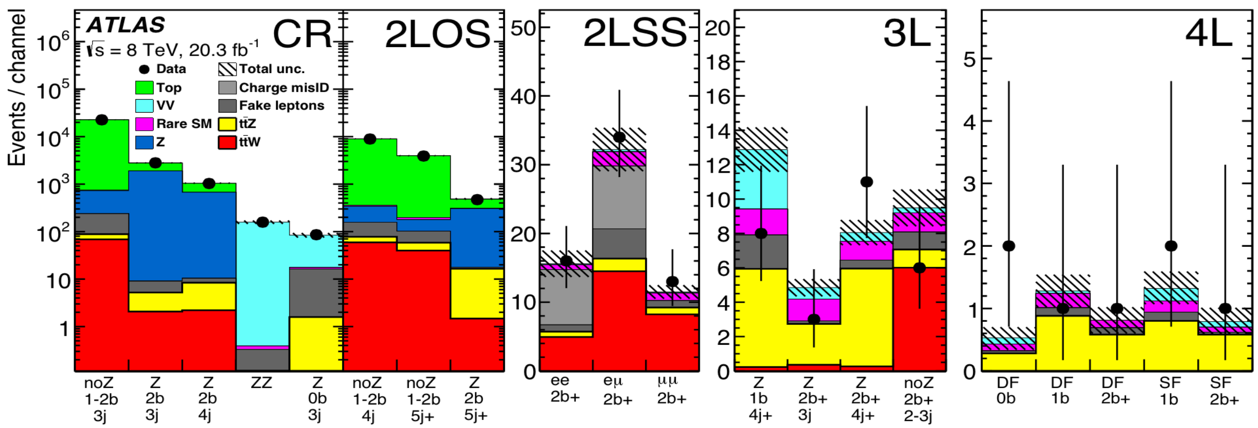


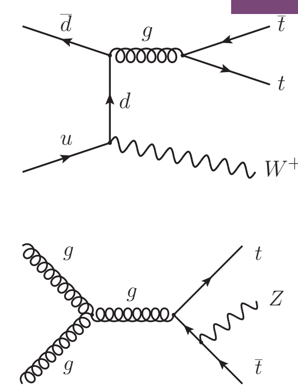






ttW, ttZ cross sections @ 8 TeV





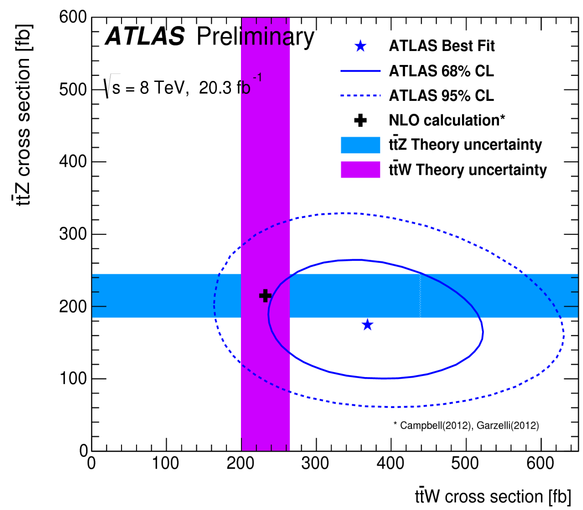
Measured cross sections:

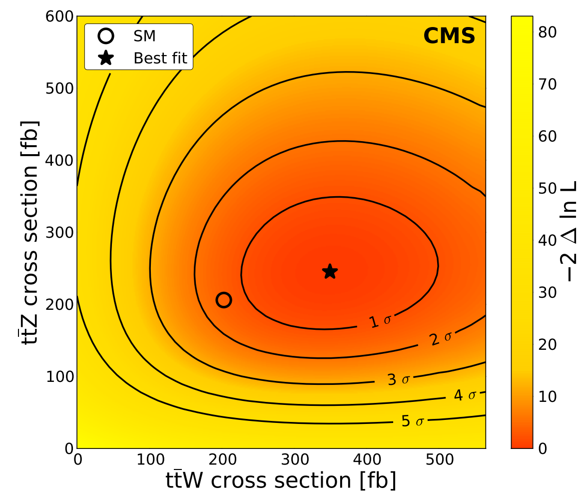
$$\sigma_{t\bar{t}W} = 369^{+86}_{-79}\,(\mathrm{stat}) \pm 44\,(\mathrm{syst})\ \mathrm{fb}$$

$$\sigma_{t\bar{t}Z} = 176^{+52}_{-48}\,(\mathrm{stat}) \pm 24\,(\mathrm{syst})\ \mathrm{fb}$$

The observed (expected) significance of:

- ttW is 5.0σ (3.2σ)
- ttZ is 4.2σ (4.5σ)





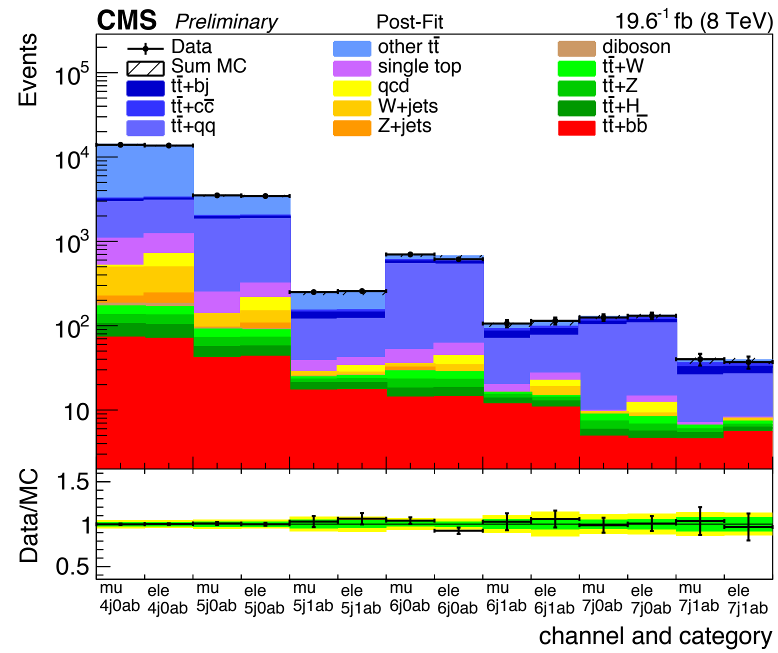
ATLAS-CONF-2015-032

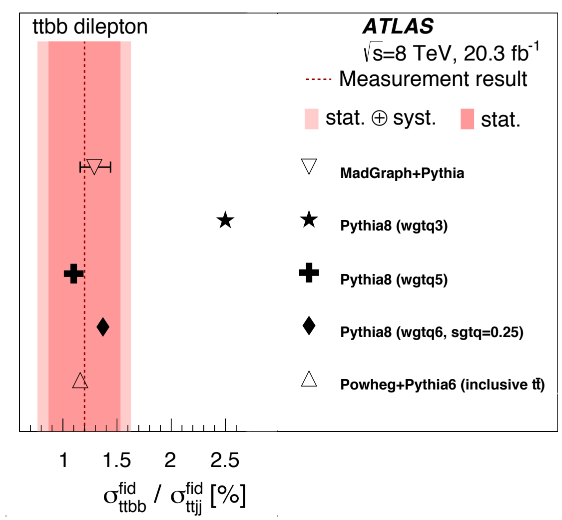
CMS-PAS-TOP-14-021

+ 8 TeV: Cross section for tt + heavy quarks

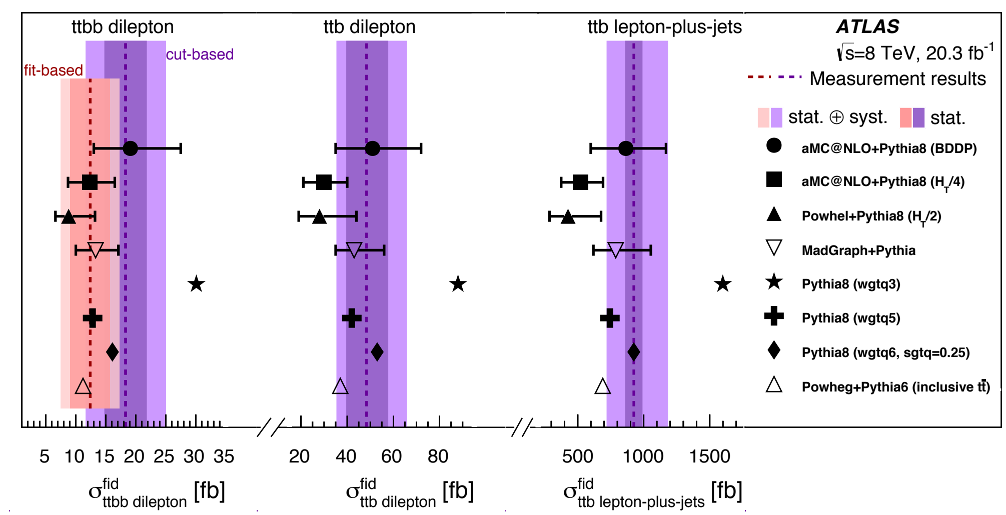
CMS-PAS-TOP-13-016

	$\sigma(t\bar{t}b\bar{b})$	$\sigma(t\bar{t}jj)$	$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj)$
hardB:			
this analysis	271 fb ± 40%	23.1 pb ± 16%	0.012 ± 34%
theory NLO$^{(arXiv:1403.2046)}$	229 fb $^{+18\%}_{-24\%}$	21.0 pb $^{+15\%}_{-13\%}$	0.011 $^{+39\%}_{-13\%}$
MADGRAPH+PYTHIA	174 fb ± 28%	24.3 pb ± 20%	0.007 ± 10%
hadronB:			
this analysis	348 fb ± 38%	23.1 pb ± 16%	0.015 ± 32%
CMS dilepton$^{(arXiv:1411.5621)}$	360 fb ± 36%	16.1 pb ± 14%	0.022 ± 29%
MADGRAPH+PYTHIA	216 fb ± 35%	24.3 pb ± 20%	0.009 ± 14%

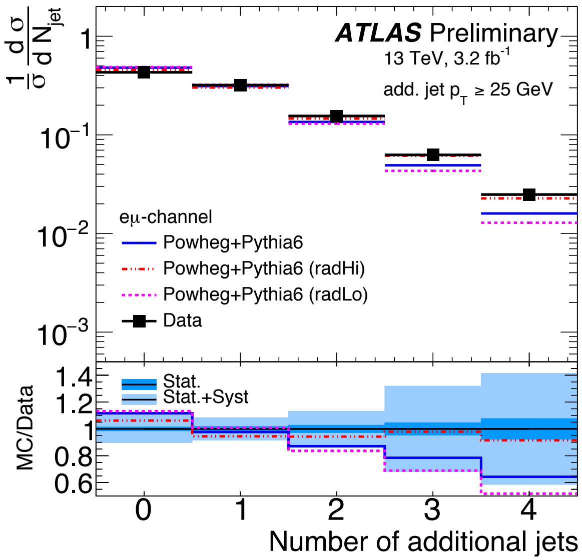




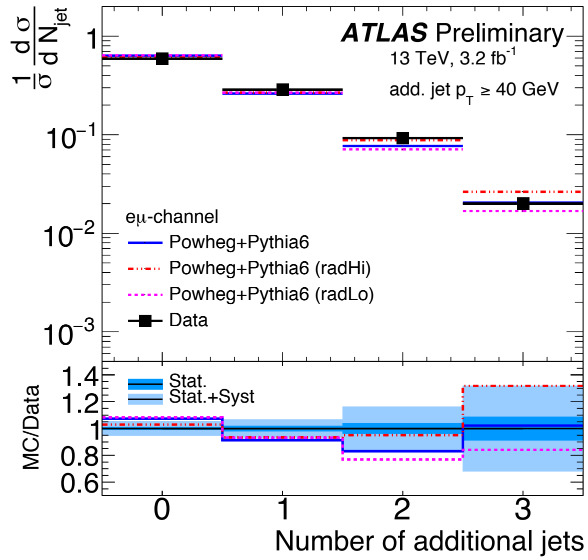
arXiv:1508.06868

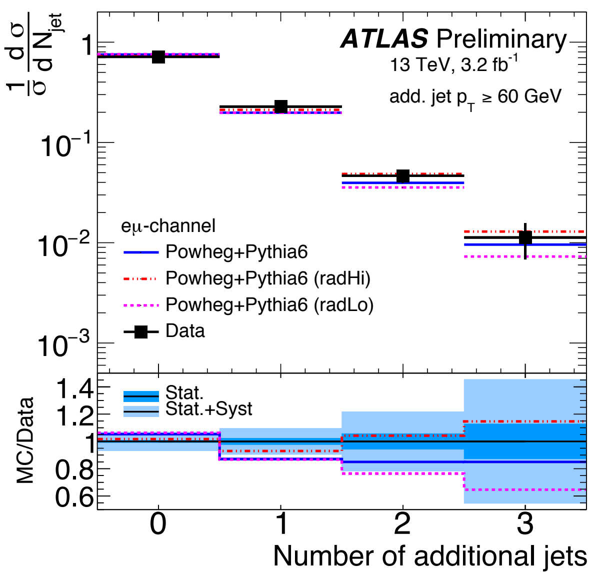


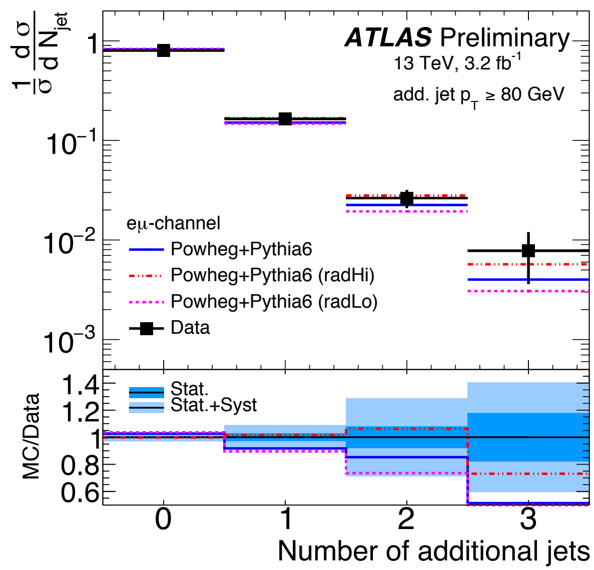
+ 13 TeV: tt + jet differential (eμ+2b)



ATLAS-CONF-2015-065





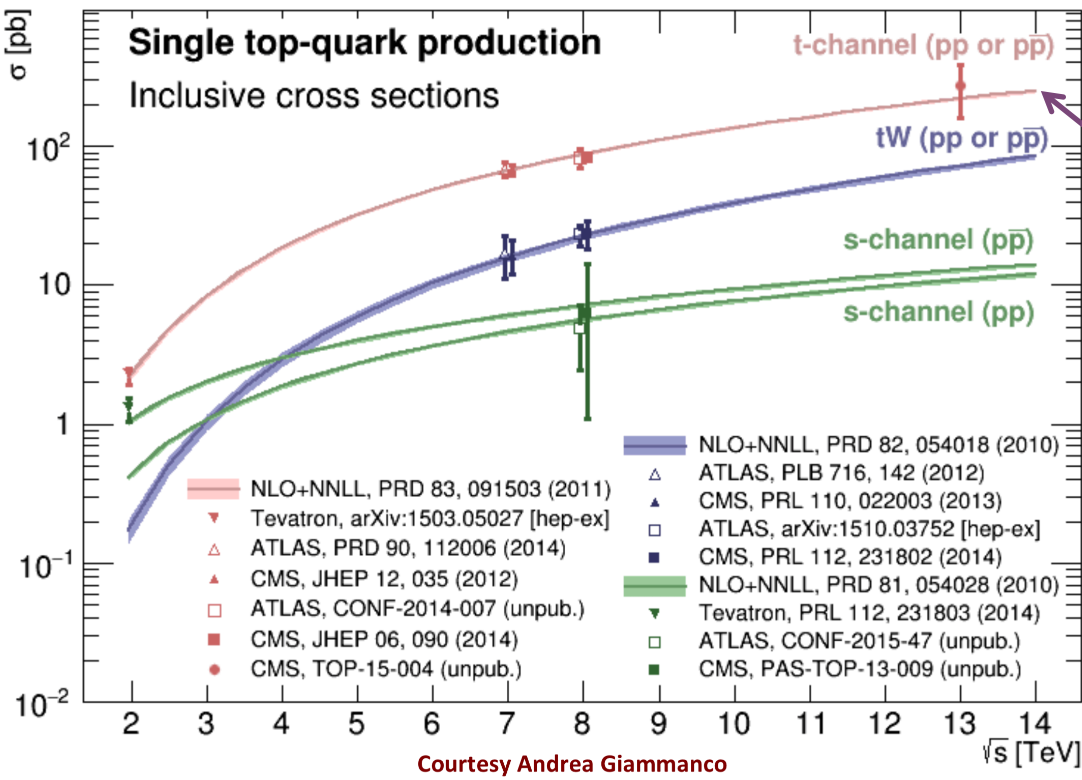


Also see

arXiv:1510.03072

+

Single Top Status



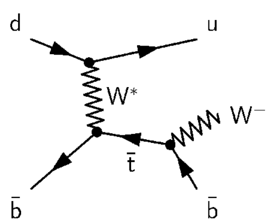
Courtesy Andrea Giammanco

3.2 fb^{-1}

Missing: 13 TeV t-channel
ATLAS-CONF-2015-079

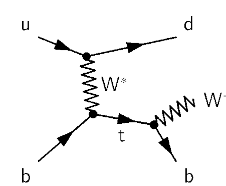
$\sigma\,(t\,q+\bar{t}\,q) = 229\pm48$ pb

$|f_{LV} \cdot V_{tb}|=1.03\pm0.11$



$\sigma\,(t\,q)=133\pm6(\text{stat.})\pm24(\text{syst.})\pm7(\text{lumi.})$ pb

$\sigma\,(\bar{t}\,q)=96\pm5(\text{stat.})\pm23(\text{syst.})\pm5(\text{lumi.})$ pb



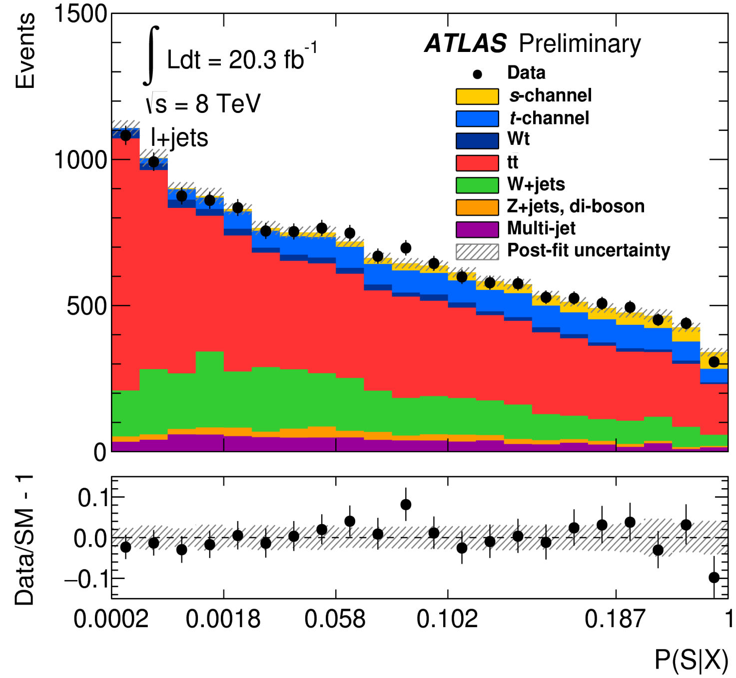
Single top s-channel first evidence @ the LHC

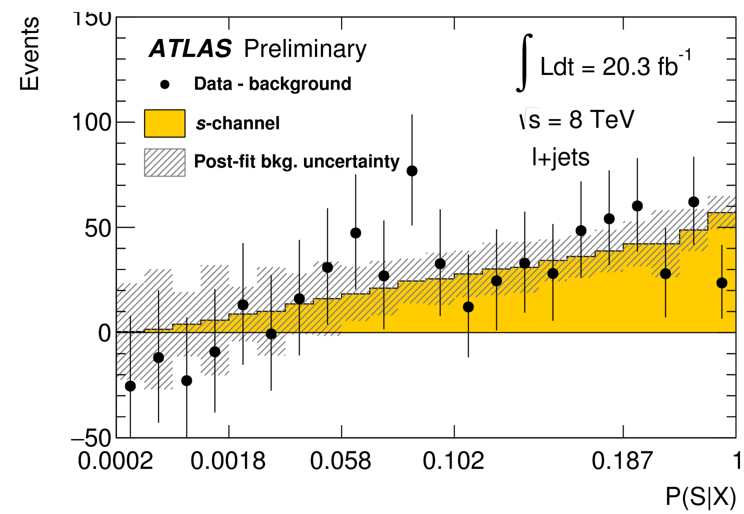
- Signal extraction based on a Matrix Element Method

σ_s=4.8

±1.1(stat.)

+2.2−2.0(syst.)pb





ATLAS-CONF-2015-047

Extracting $|V_{tb}|$

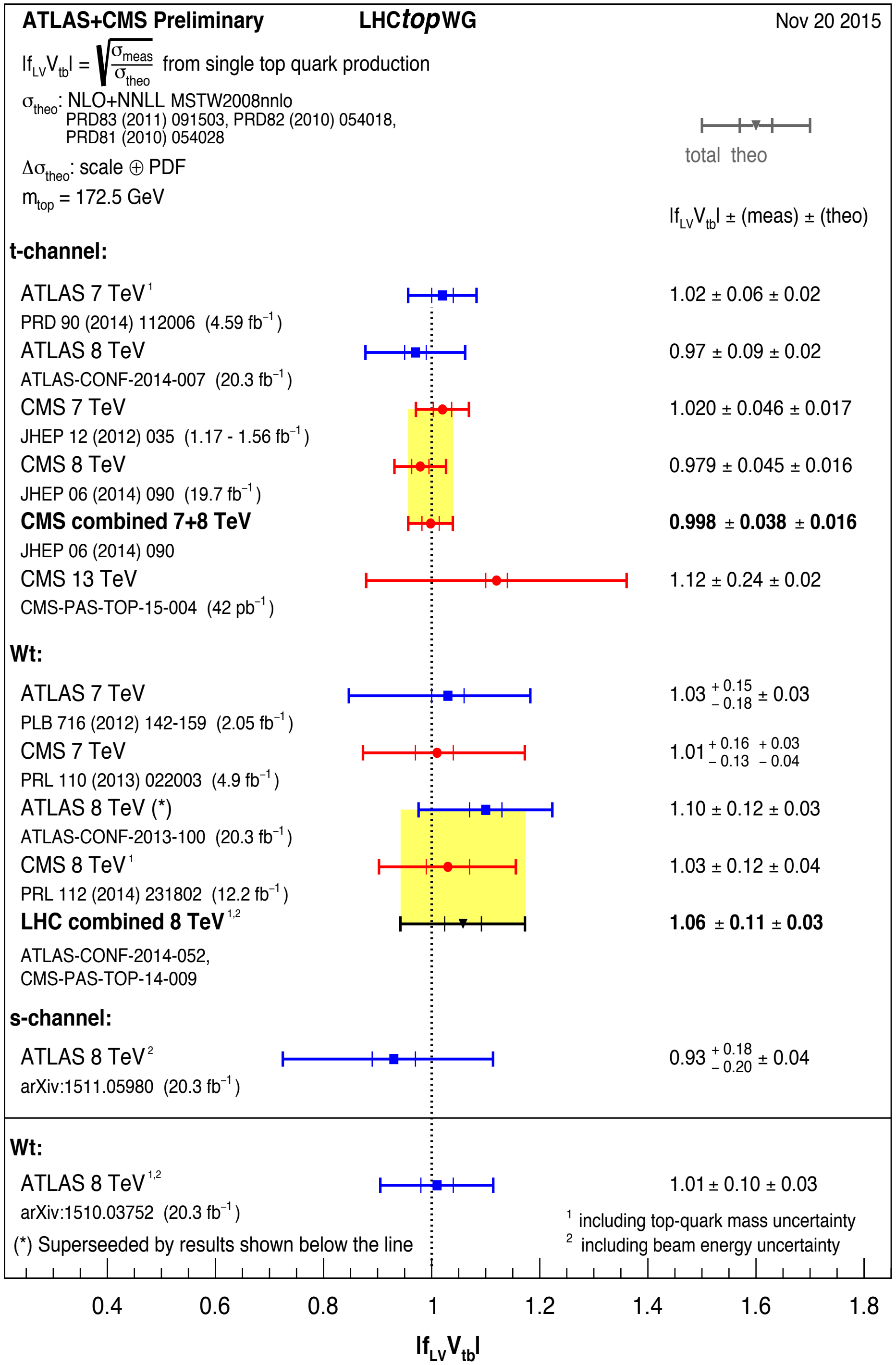
Direct determination of the matrix element $|V_{tb}|$:

- Test the unitary of the CKM Matrix
- Sensitivity to new physics

Measure $|V_{tb}|$ assuming left-handed SM-like W-t-b coupling (and $|V_{tb}| >> |V_{ts}|, |V_{td}|$):

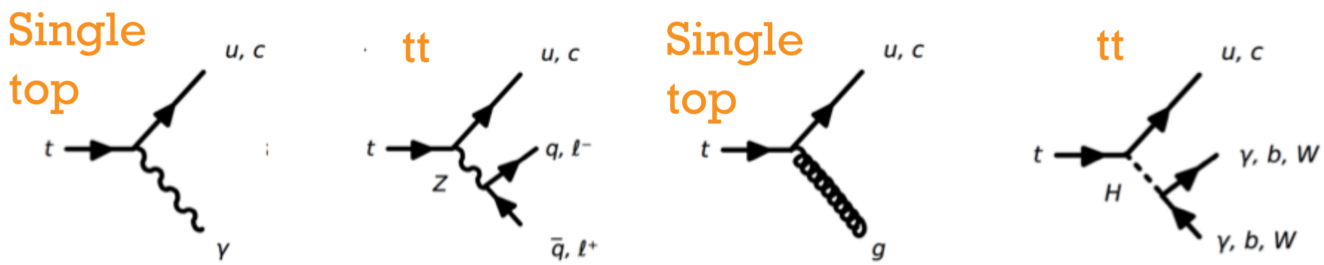
$$|V_{tb} \cdot f_{LV}| = \sqrt{\frac{\sigma_{obs}}{\sigma_{theory}}}$$

with $f_{LV} = 1$ in the SM.



+ Flavor Changing Neutral Currents

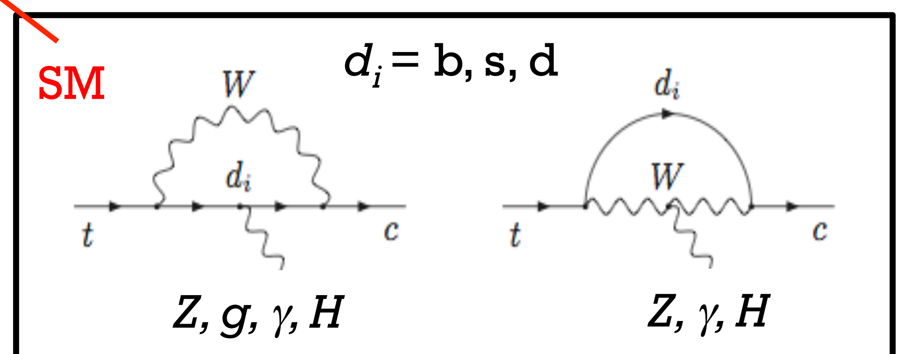
Search channel



Theoretical predictions for the BR of FCNC top quark decays

Process	SM	QS	2HDM	FC 2HDM	MSSM	$\not R$ SUSY	RS
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}	—
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}	—
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}	—
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	—	10^{-5}	$\sim 10^{-6}$	—
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}	$\lesssim 10^{-5}$
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}	$\lesssim 10^{-9}$
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}	$\lesssim 10^{-10}$
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$	$\lesssim 10^{-4}$

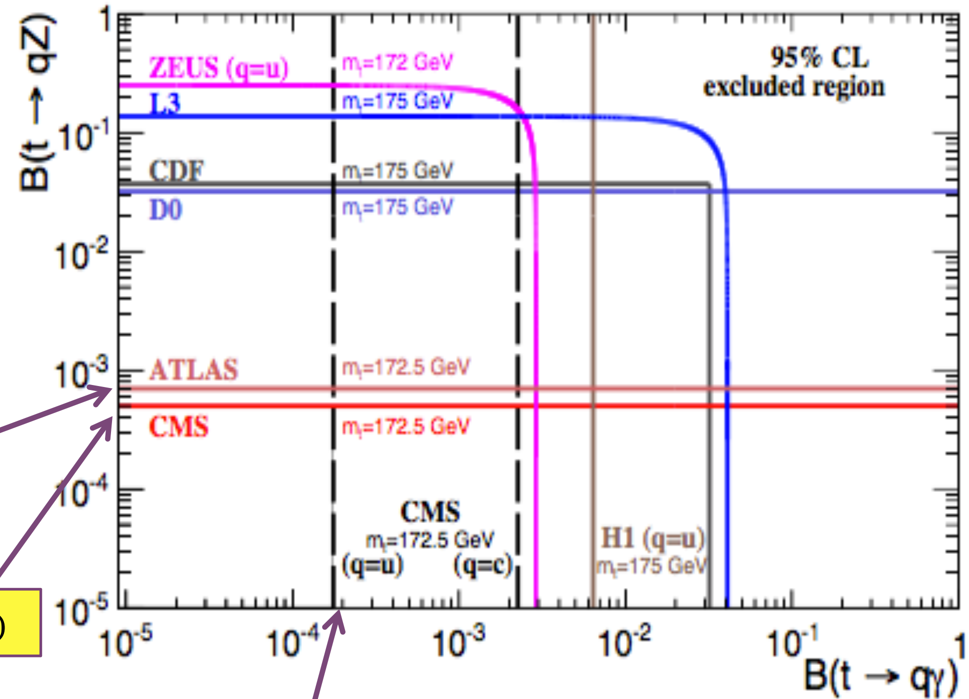
Acta Phys.Polon.**B35**,2695(2004), arXiv:1311.2028



Flavor Changing Neutral Currents
tqZ, tqg, tqγ

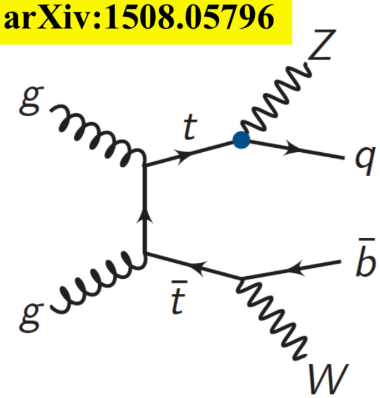
Decay Channel	95% CL Limit	Data Set and Exp.
$B(t \to qg)$	4.0×10^{-5} $(q = u)$	ATLAS-TOPQ-2014-13-002
	1.70×10^{-4} $(q = c)$	(8 TeV, 20.3 fb^{-1})
	3.55×10^{-4} $(q = u)$	CMS-PAS-TOP-14-007
	3.44×10^{-3} $(q = c)$	(7TeV,5.0 fb^{-1})

From Single top

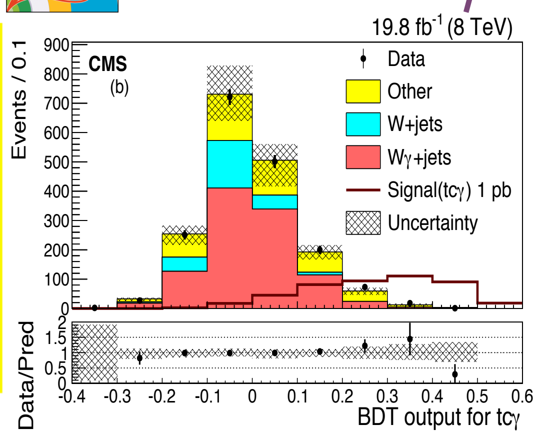


arXiv:1508.05796

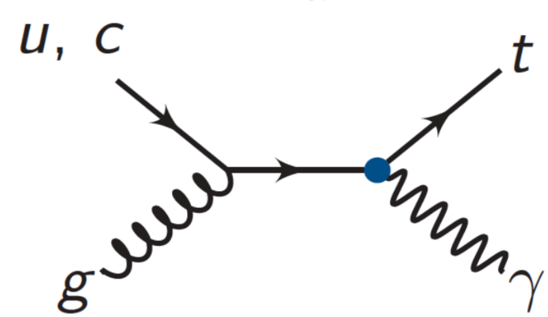
PRL 112, 171802b(2014)



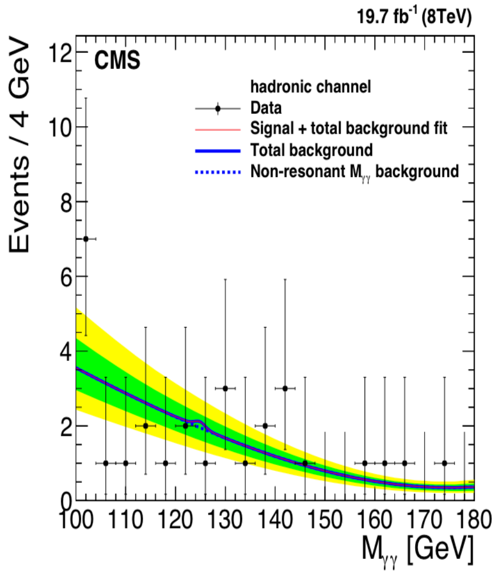
CMS TOP-14-003

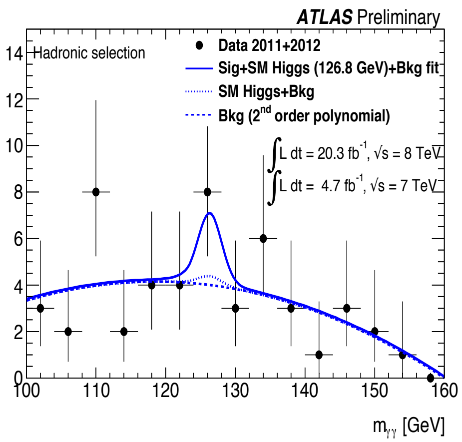


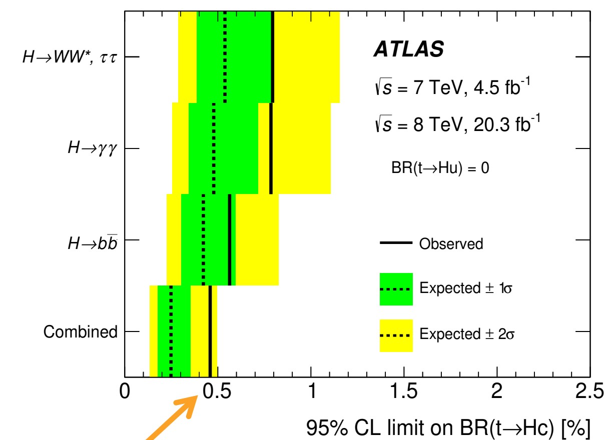
BR(t→ qγ)



FCNC tqH < 0.4% @ 95% CL: H→ multi-leptons, γγ, bb



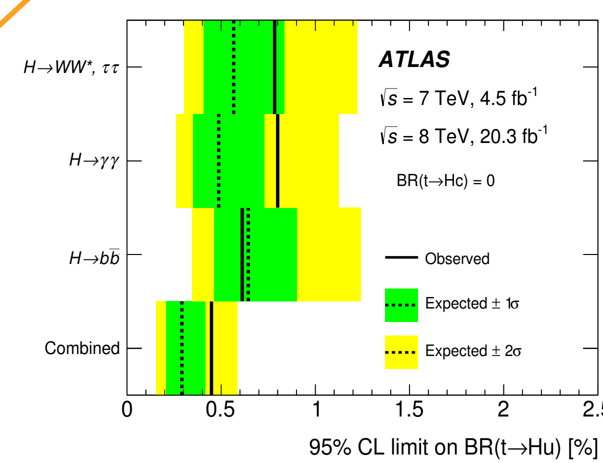




CMS: PAS-TOP-2013-017
CMS: PAS-TOP-2014-019
CMS: PAS-TOP-2014-020

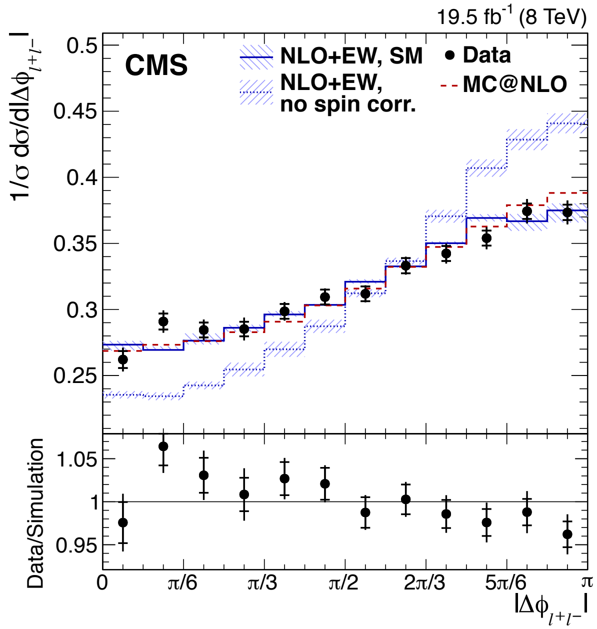
ATLAS: JHEP 12 (2015)

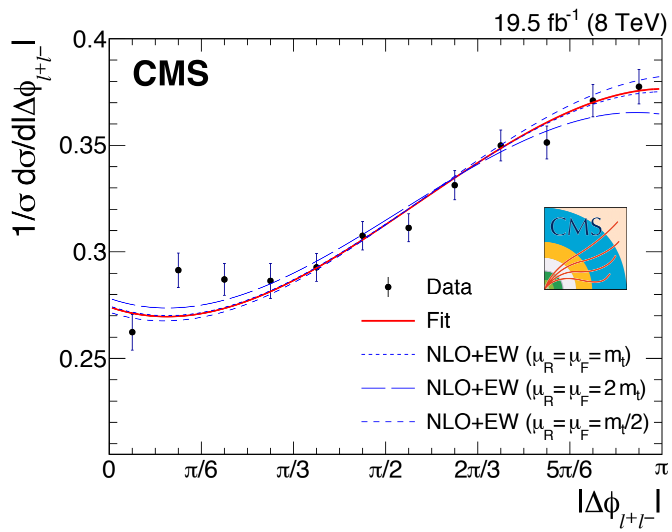
	$-\sigma$	$\mathcal{B}_{exp}$(t→ Hc)	$+\sigma$	$\mathcal{B}_{obs}$(t→ Hc)
Trilepton	0.95	1.33	1.87	1.26
Same-sign dilepton	0.68	0.93	1.26	0.99
Multilepton combined	0.65	0.89	1.22	0.93
Diphoton combined	0.44	0.67	1.06	0.47
b-jet plus lepton	0.60	0.89	1.37	1.16
Final combination	0.30	0.43	0.64	0.40
	$-\sigma$	$\mathcal{B}_{exp}$(t→ Hu)	$+\sigma$	$\mathcal{B}_{obs}$(t→ Hu)
Trilepton	1.05	1.47	2.09	1.34
Same-sign dilepton	0.62	0.85	1.16	0.93
Multilepton combined	0.60	0.82	1.14	0.86
Diphoton combined	0.39	0.60	0.96	0.42
b-jet plus lepton	0.57	0.84	1.31	1.92
Final combination	0.27	0.40	0.58	0.55

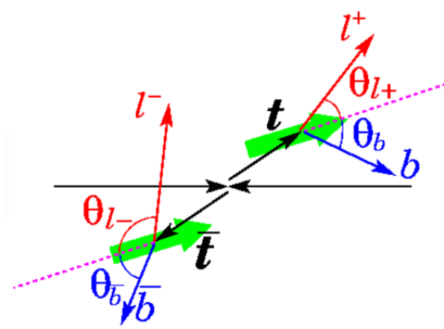


+ Probing top quark spin Correlations & PBSM

CMS-TOP-14-023





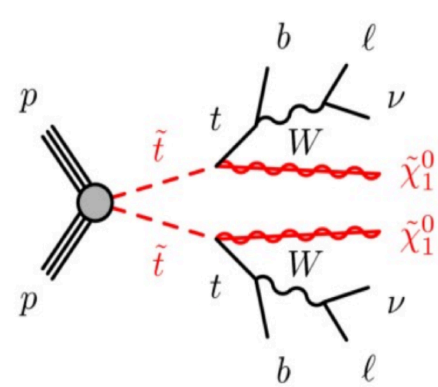


Top quarks are produced unpolarised **BUT** their spins are correlated in the SM

arXiv:1511.06170

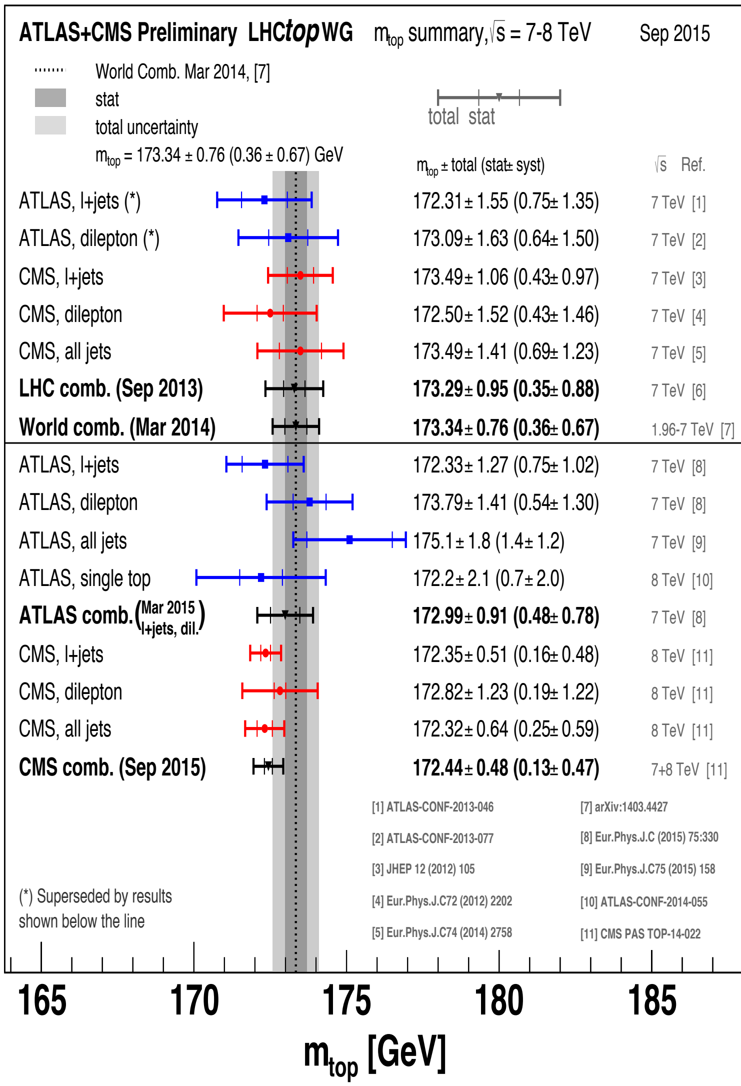
- Differences from PBSM predictions
  - New: CMS 8 TeV
    - Chromo-magnetic anomalous couplings
  - Older: ATLAS
    - Stop

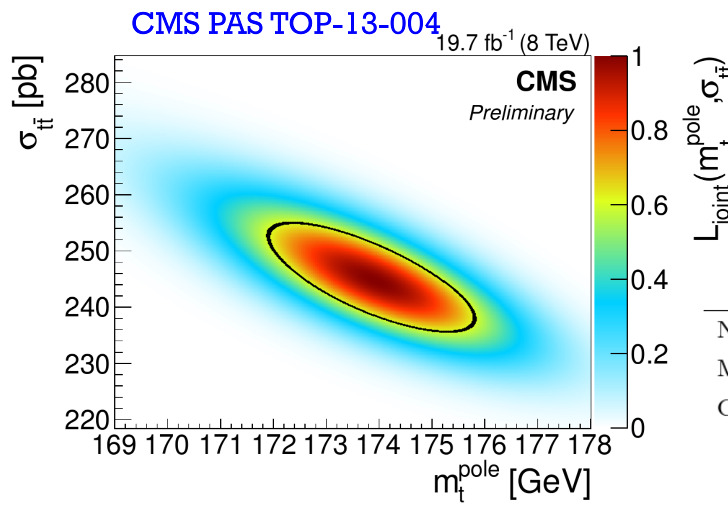
Exclude top squark between m_t and 191 GeV at 95% CL



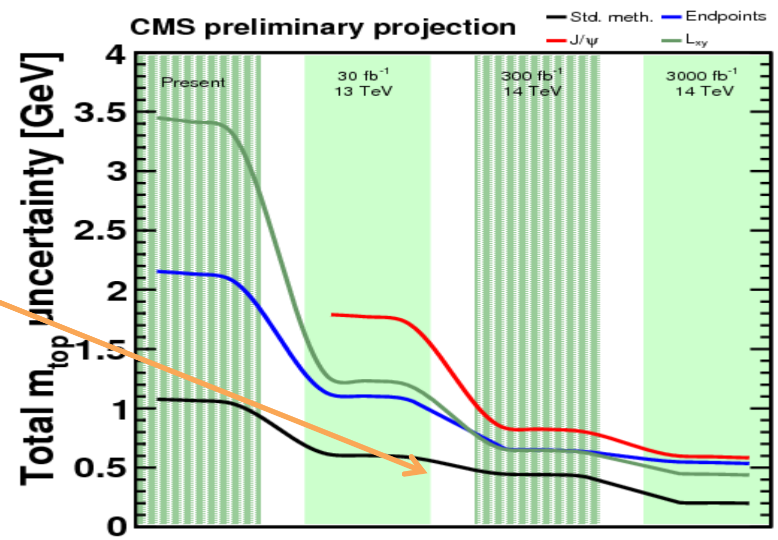
PRL 114, 142001 (2015)

+ Precision in Top Mass: Beyond expectation…





	m_t
NNPDF30	$173.6 \pm^{1.7}_{1.8}$ GeV
MMHT2014	$173.9 \pm^{1.8}_{1.9}$ GeV
CT14	$174.1 \pm^{2.1}_{2.2}$ GeV



Conclusions

- The LHC continues to be a powerful tool for top physics
  - Unprecedented precision in Run-1
  - First Run-2 tt and single top t-channel analyses already available
- Signatures with top could be key to future discoveries
  - Required understanding and tools for Run-2 are advanced

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

CMS https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP