



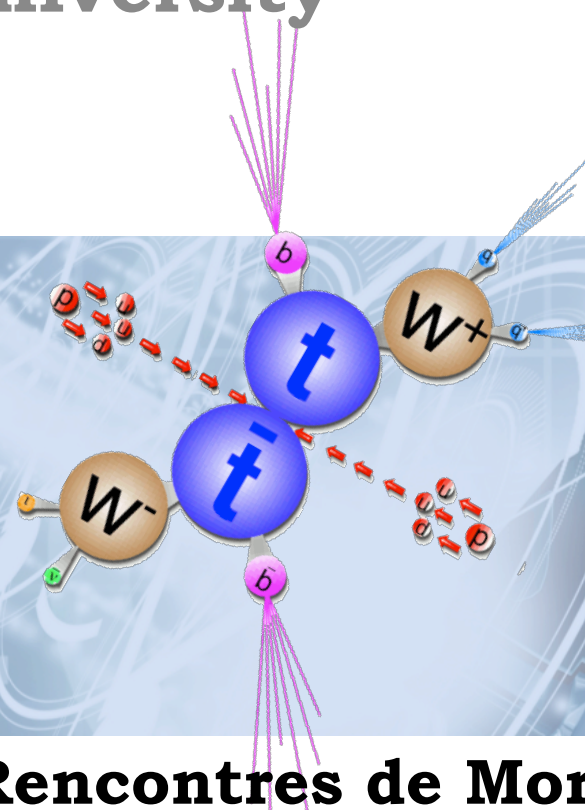
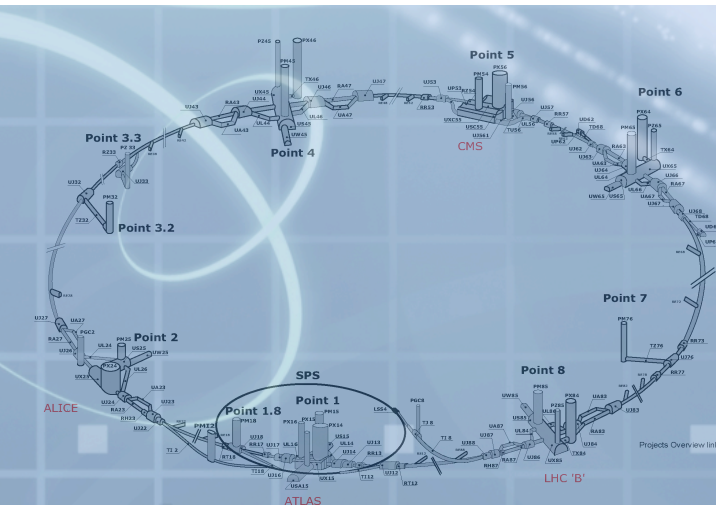
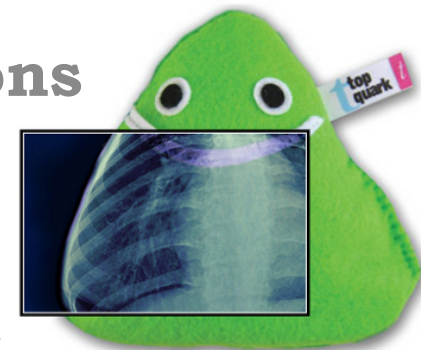
# ATLAS+CMS top production and properties: Run1 legacy



Andrey Loginov

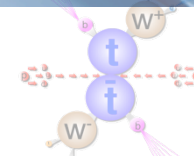
for the CMS and ATLAS Collaborations

Yale University



Moriond/EW: 50<sup>th</sup> Rencontres de Moriond

14-21 March 2015, La Thuile

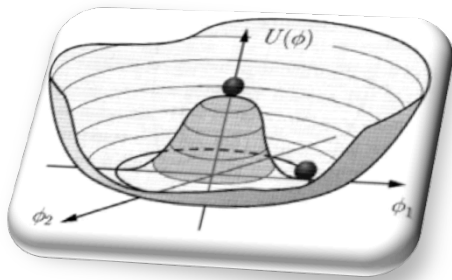
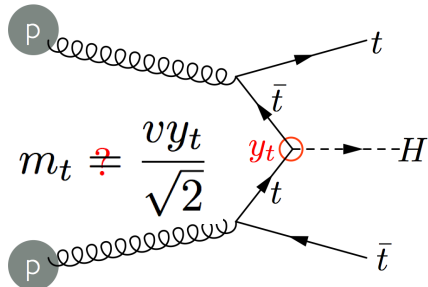




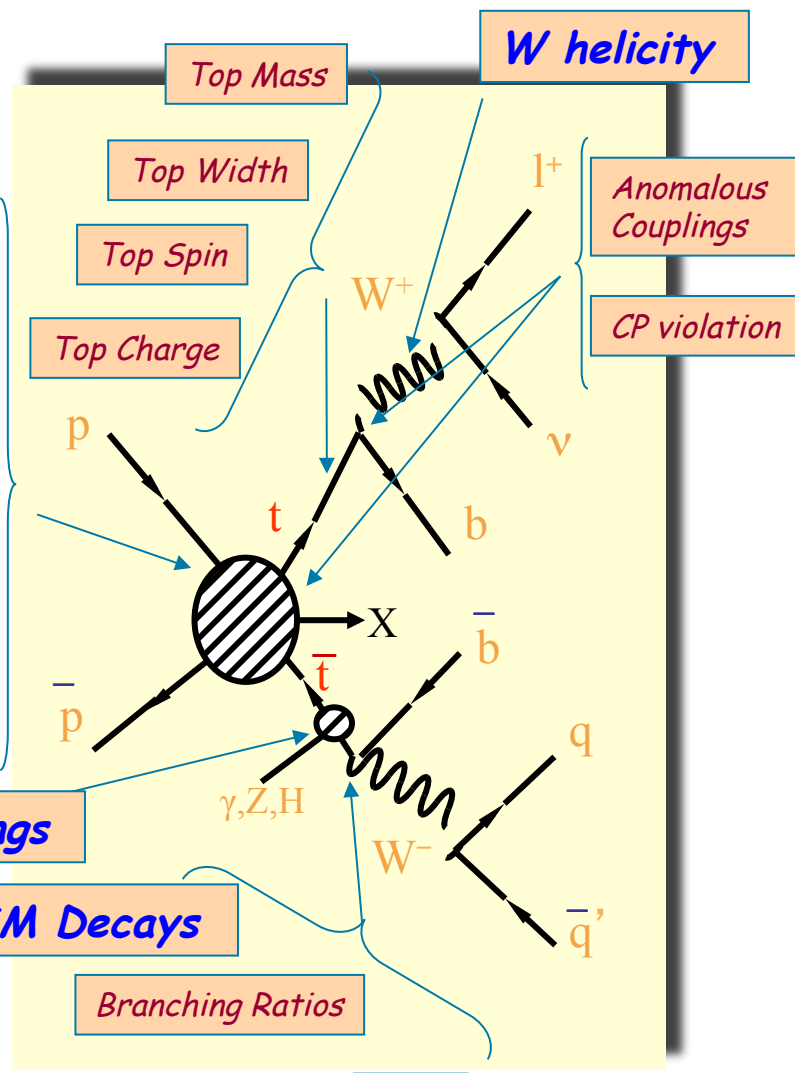
# The Top Quark



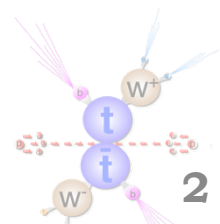
- The **heaviest particle** discovered
  - Strong **top Yukawa coupling**
- Plays **key role** in many important physics processes
  - Flavor physics, Electro-weak processes
- Speculated to play a special role in a number of **Beyond the Standard Model** theories



- Production cross section**
  - Resonant production
- Production kinematics**
  - Top Spin Polarization
- Couplings**
- Rare/non SM Decays**
- Branching Ratios
- $|V_{tb}|$



$v$  = vacuum expectation value (246 GeV)  
 $y_t$  = top Yukawa coupling



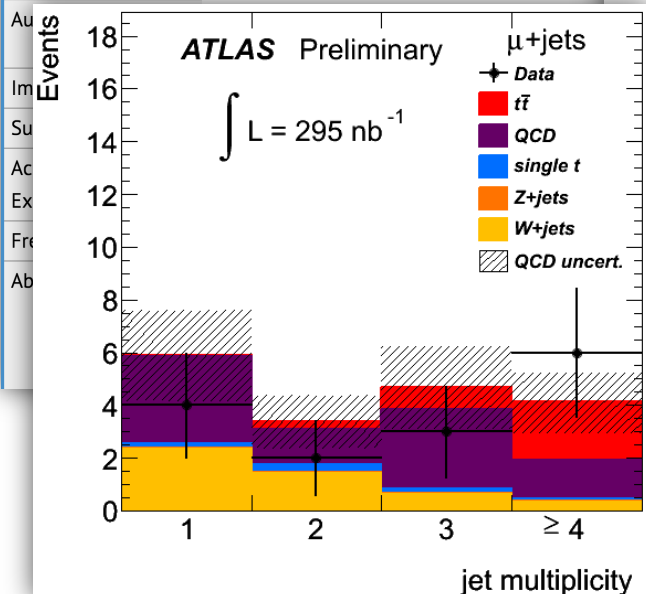


# Before LHC became “top quark factory”

Internal Note

Report number ATLAS-COM-CONF-2010-046  
Title Search for top pair candidate events in ATLAS

Show all 200 authors



Show all 200 authors

- Early Run 1, ATLAS perspective

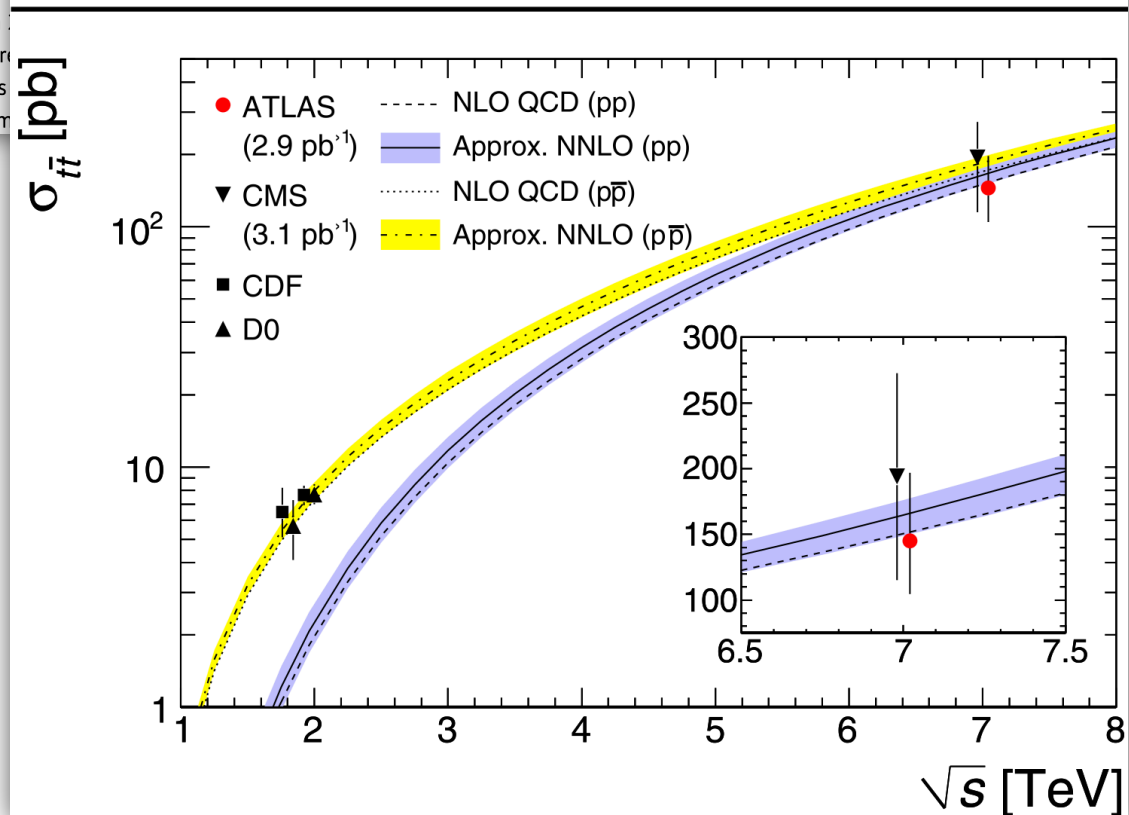
- July 28, 2010 (CONF note):

“A search is performed for events consistent with top quark pair production in **280 nb<sup>-1</sup>** of ATLAS pp collision data...”

Eur. Phys. J. C (2011) 71: 1577

- March 17, 2011 (paper):

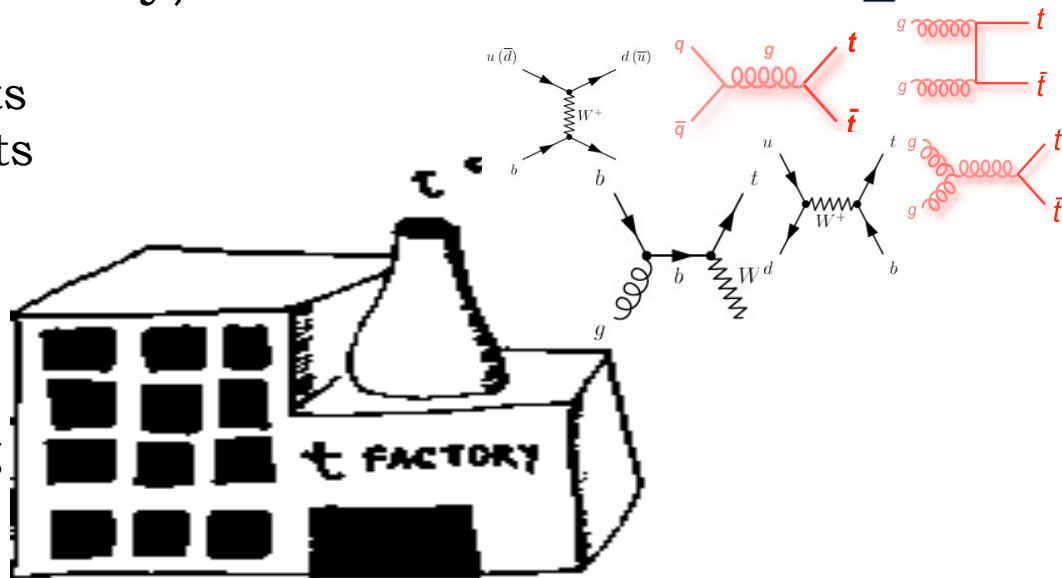
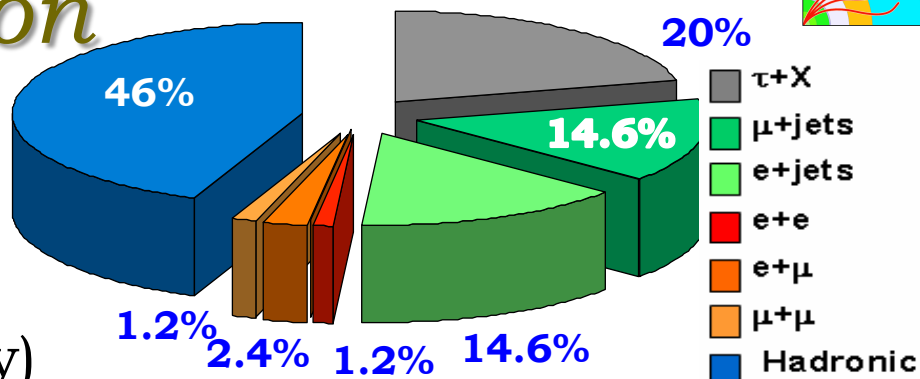
- ATLAS: “...in a data sample of **2.9 pb<sup>-1</sup>**, **37** candidate events are observed in the **single-lepton topology** and **9** events in the **dilepton topology.**”
  - CMS: **11 dilepton** candidate events



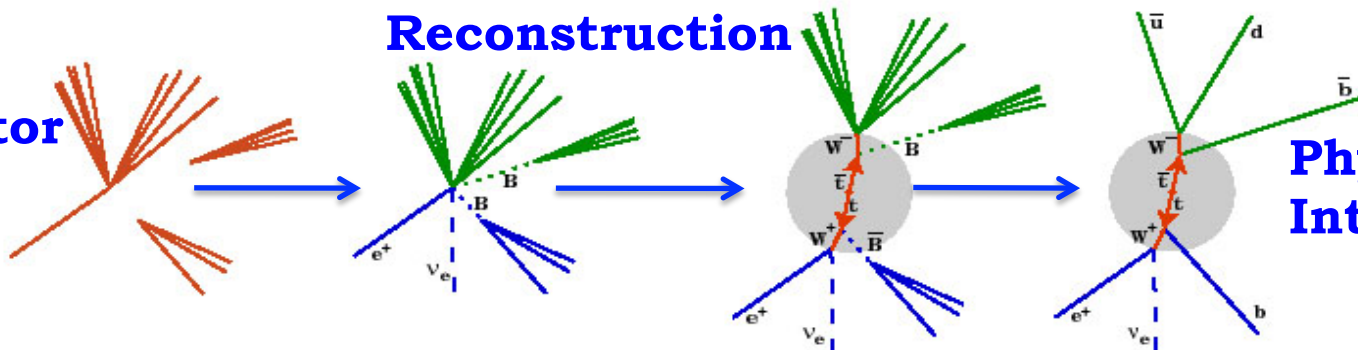


# Top-Quark(s) Production

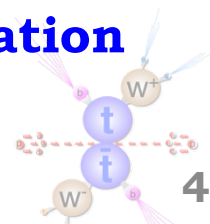
- **Top pair** production at the LHC through gg (**dominant**) and qq
- **Single-top** production
  - t-, Wt-, s-channel
- **Run 1:** per experiment (approximately)
  - **6M** top-quark pair events
  - **2M** t-channel single-top events
  - **150k** s-channel single-top events
  - **10k** tt+W/Z
  - **3k** tt+Higgs
  - **20** tttt
- $t \rightarrow Wb$ ,  $W \rightarrow$  jets or lepton +  $\nu$ 
  - The more jets, the more challenging the systematic uncertainties get (**jet energy scale, ISR/FSR** etc)



**Detector View**



**Physics Interpretation**









# Inclusive top-pair production

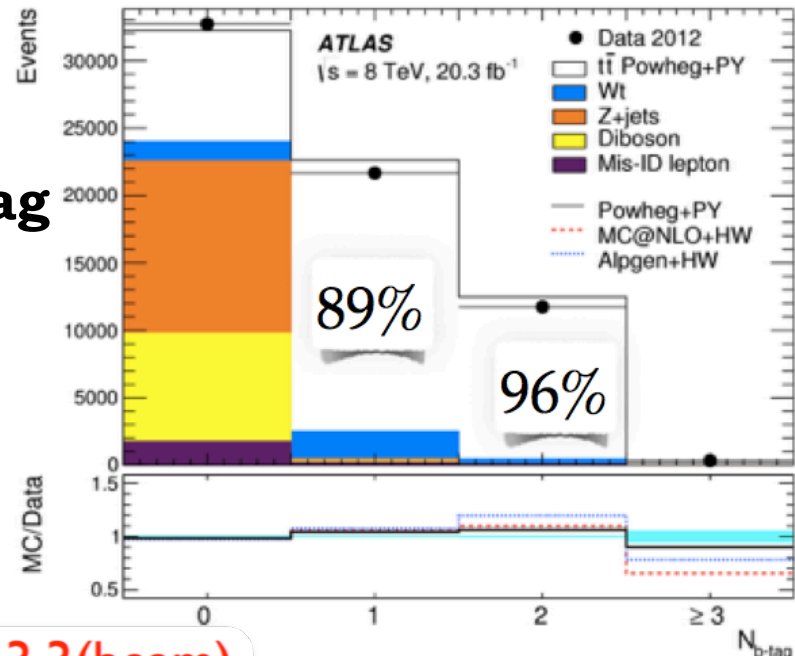


- **Opposite-sign  $e\mu$  + 1 or 2  $b$ -tagged jets**
  - Fewer jets && smaller Z+jets contamination
- Reduce jet and b-tag uncertainties by performing **simultaneous fit for 1 or 2 b-tag**

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

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

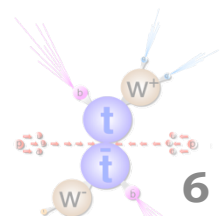
- **Systematics:** luminosity(2-3%), beam energy(1.7-1.8%), tt modelling(~1.4%), PDF(~1.1%).



7 TeV  $\sigma = 182.9 \pm 3.1(\text{stat}) \pm 4.2(\text{syst}) \pm 3.6(\text{lumi}) \pm 3.3(\text{beam})$   
 8 TeV  $\sigma = 242.4 \pm 1.7(\text{stat}) \pm 5.5(\text{syst}) \pm 7.5(\text{lumi}) \pm 4.2(\text{beam})$

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

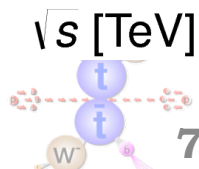
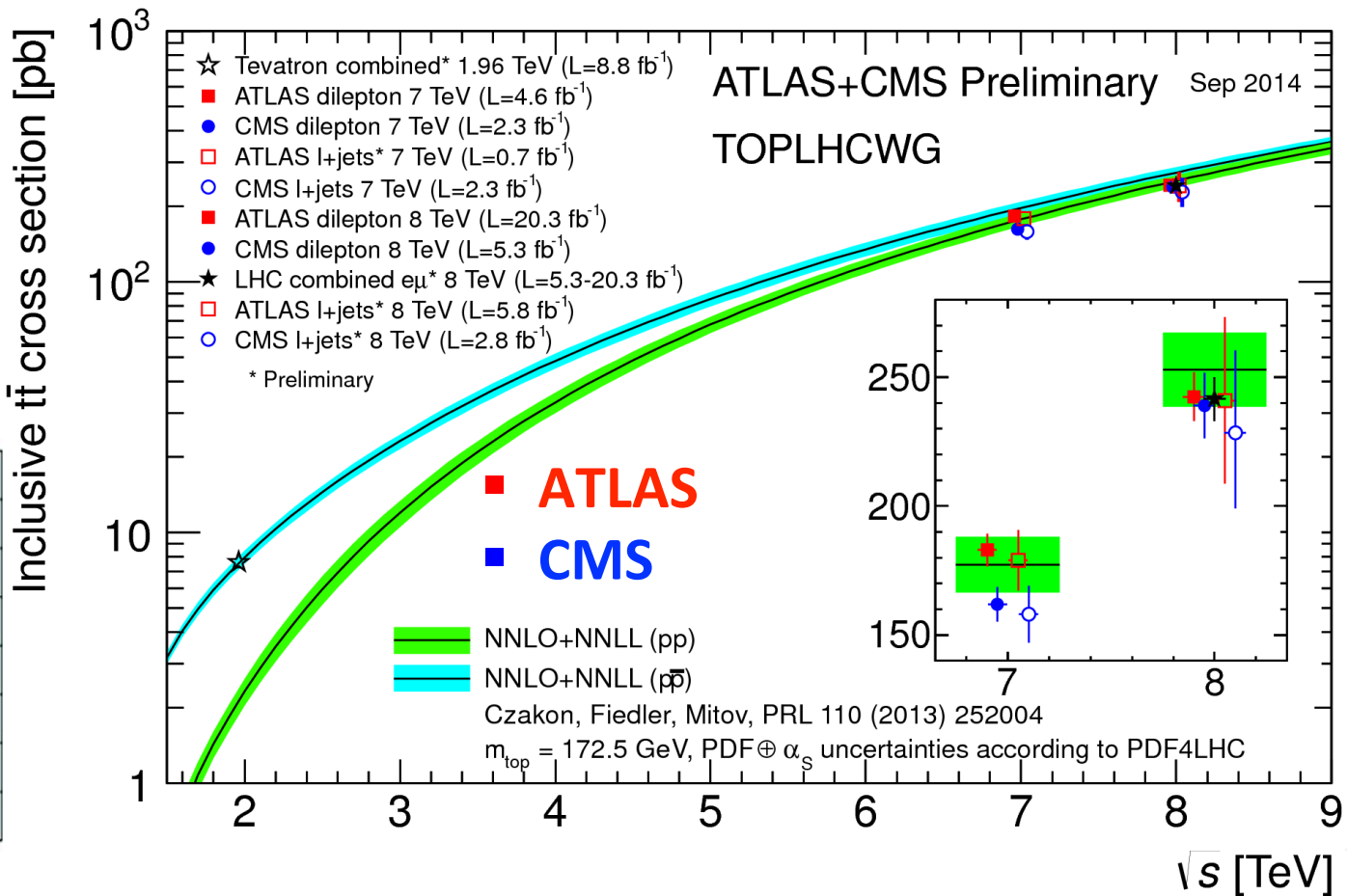
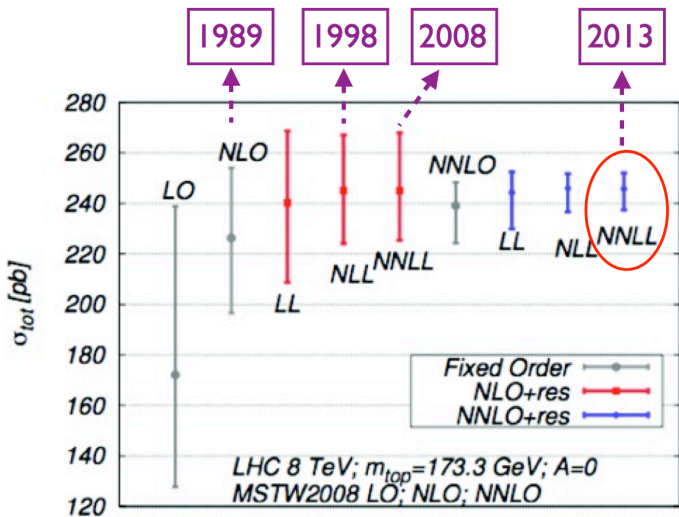
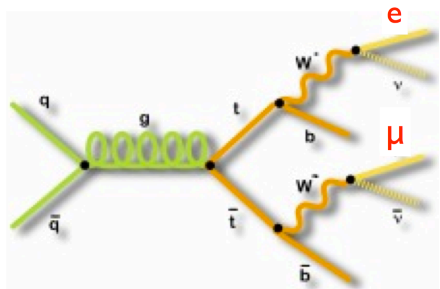
- **Fiducial:**  $\epsilon_{e\mu} = A_{e\mu} \times G_{e\mu}$ 
  - $A_{e\mu}$ : acceptance;  $G_{e\mu}$ : reconstruction efficiency
  - No extrapolation from the measured phase space (PS) to the full PS
    - **PDF: 1.1 -> 0.3**
    - **QCD scale choice: 0.3 -> 0.0**





# Inclusive top-pair production: Summary

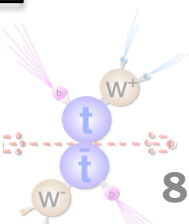
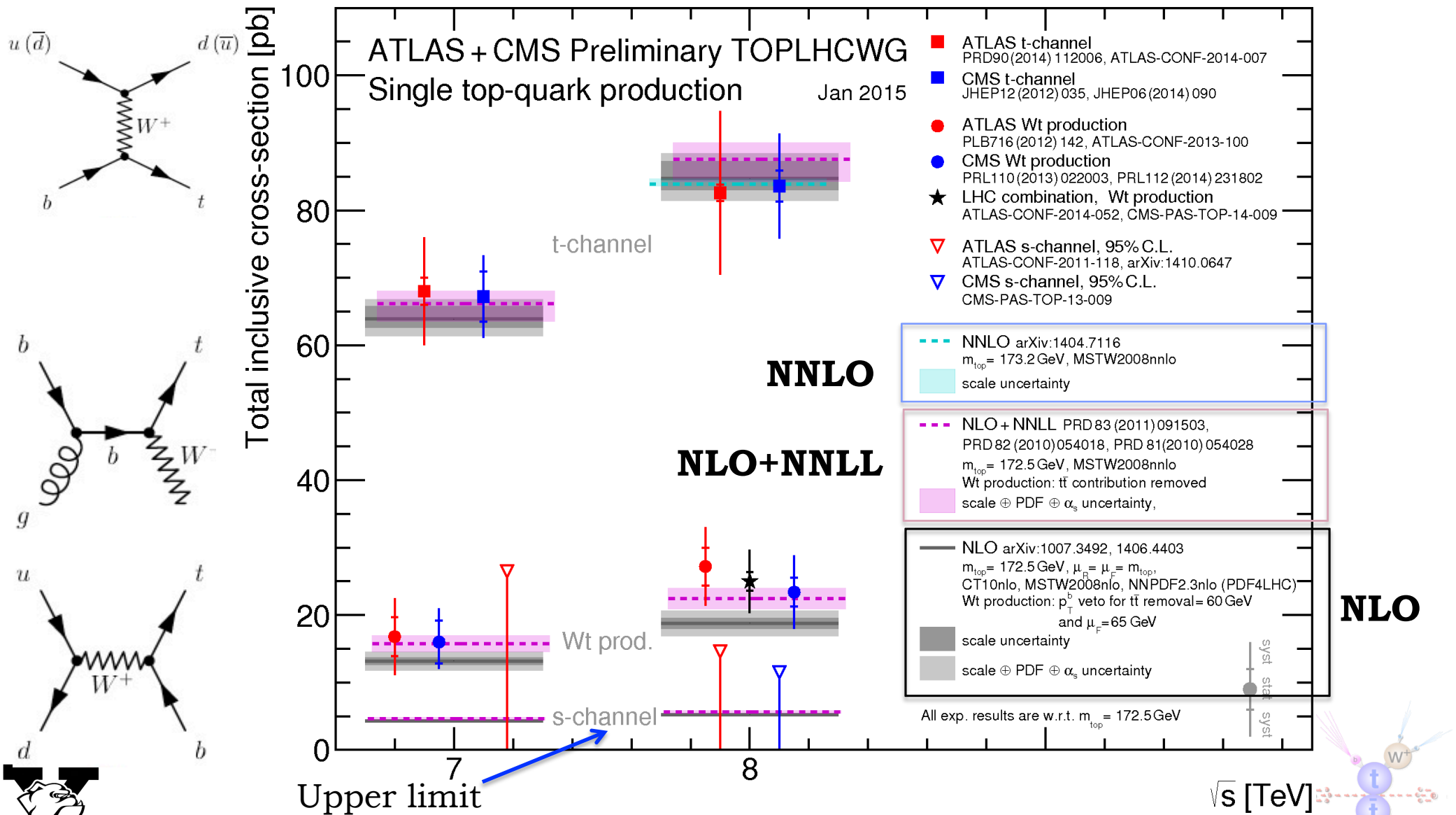
- Summary of LHC (and Tevatron) measurements of top-pair production cross sections
  - Excellent progress both on the theory and experiment sides!**





# Single-top-quark production: Summary

- Different processes sensitive to **different new physics mechanisms**







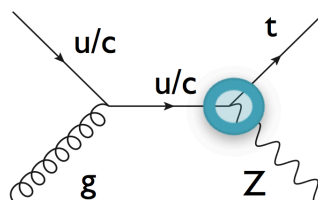
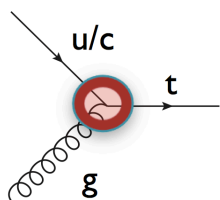
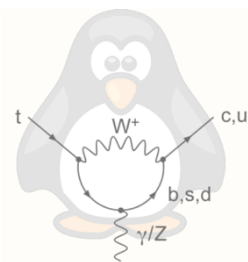
# FCNC



- Extremely low SM cross sections
  - A number of BSM theories that predict enhancement (both in **production** and **decay**)

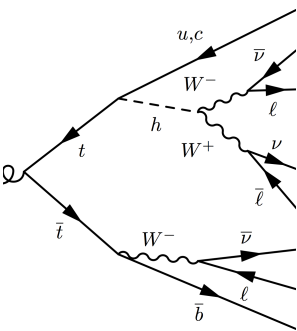
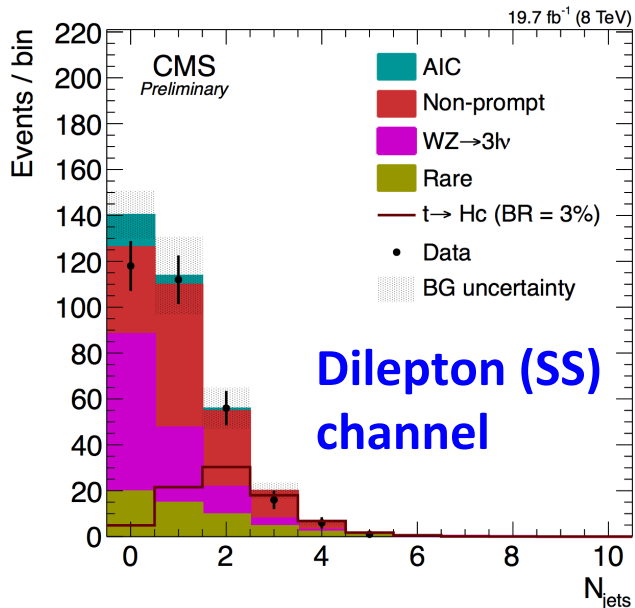
- New CMS result **NEW**

- $pp \rightarrow tt \rightarrow cH + Wb$ 
  - Same-sign and trileptons
- $\text{Br}(t \rightarrow Hc) < 0.93\%$ 
  - Expected limit  $[0.89^{+0.33} / -0.24]\%$



arXiv:hep-ph/0409342v4

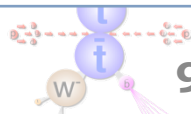
	SM	2HDM	$\mathcal{R}$ SUSY
$t \rightarrow uZ$	$8 \times 10^{-17}$	—	$3 \times 10^{-5}$
$t \rightarrow u\gamma$	$3.7 \times 10^{-16}$	—	$1 \times 10^{-6}$
$t \rightarrow ug$	$3.7 \times 10^{-14}$	—	$2 \times 10^{-4}$
$t \rightarrow uH$	$2 \times 10^{-17}$	$5.5 \times 10^{-6}$	$\sim 10^{-6}$
$t \rightarrow cZ$	$1 \times 10^{-14}$	$\sim 10^{-7}$	$3 \times 10^{-5}$
$t \rightarrow c\gamma$	$4.6 \times 10^{-14}$	$\sim 10^{-6}$	$1 \times 10^{-6}$
$t \rightarrow cg$	$4.6 \times 10^{-12}$	$\sim 10^{-4}$	$2 \times 10^{-4}$
$t \rightarrow cH$	$3 \times 10^{-15}$	$1.5 \times 10^{-3}$	$\sim 10^{-6}$



EXP.	$\sqrt{s}, \text{TeV}$	$\text{Br}(t \rightarrow uy)$	$\text{Br}(t \rightarrow cy)$	Reference
CMS	8	$1.61 \times 10^{-4}$	$1.82 \times 10^{-3}$	CMS PAS TOP-14-003
		$\text{Br}(t \rightarrow uZ)$	$\text{Br}(t \rightarrow cZ)$	
CMS	7	$5.1 \times 10^{-3}$	0.114	CMS PAS TOP-12-021
ATLAS	7	$7.3 \times 10^{-3}$		JHEP 09 (2012) 139
CMS	7 & 8	$5 \times 10^{-4}$		PRL 112 (2014) 171802
		$\text{Br}(t \rightarrow ug)$	$\text{Br}(t \rightarrow cg)$	
CMS	7	$3.5 \times 10^{-4}$	$3.4 \times 10^{-3}$	CMS PAS TOP-14-007
ATLAS	8	$3.1 \times 10^{-5}$	$1.6 \times 10^{-4}$	ATLAS CONF 2013-063
		$\text{Br}(t \rightarrow uH)$	$\text{Br}(t \rightarrow cH)$	
ATLAS	7 & 8	$7.9 \times 10^{-3}$		JHEP 06 (2014) 008
CMS	8	$5.6 \times 10^{-3}$		CMS PAS HIG-13-034



CMS PAS TOP-13-017

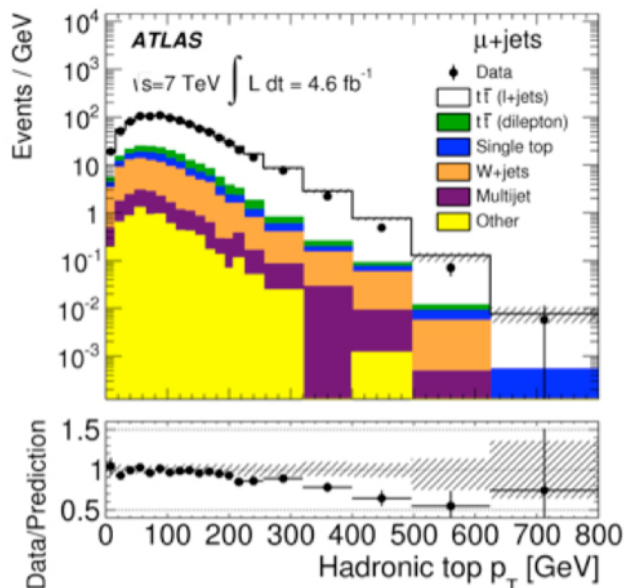
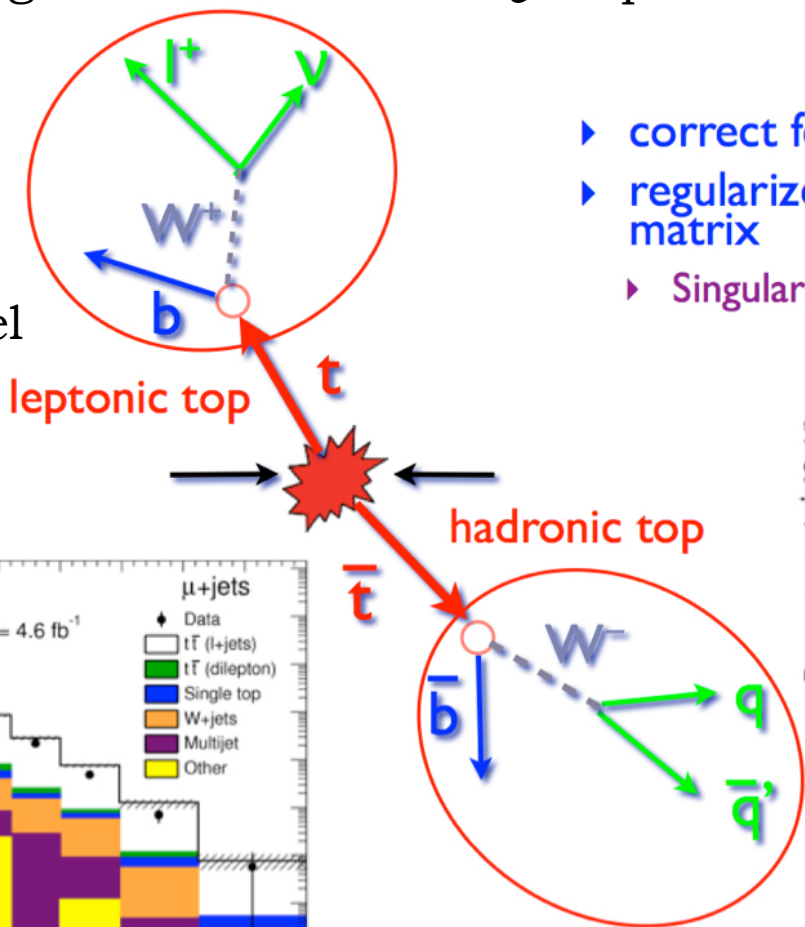


# Differential: introduction

- Differential cross sections test of QCD calculations
  - Compare generators and NLO QCD predictions to unfolded data distributions

- ▶ correct for resolution effects (unfolding)
- ▶ regularized inversion of the migration matrix
- ▶ Singular Value Decomposition method

For instance, for the parton-level measurement



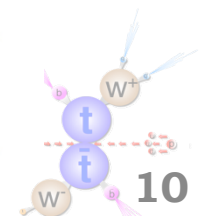
ATLAS Simulation  $\sqrt{s}=7$  TeV  $\mu$ +jets

800	0.0%	0.0%	0.1%	0.1%	0.4%	7.9%	82.7%
350	0.2%	0.3%	0.6%	2.4%	16.1%	70.5%	6.7%
250	0.7%	1.1%	2.4%	12.4%	53.9%	8.2%	2.3%
200	2.8%	4.3%	13.5%	52.9%	14.5%	4.8%	1.7%
150	11.8%	19.6%	53.5%	18.3%	7.6%	3.6%	3.0%
100	34.4%	59.1%	22.9%	10.2%	5.5%	3.5%	2.6%
50	50.0%	15.6%	7.0%	3.6%	2.0%	1.4%	1.0%
0							

Reconstructed  $p_T^i$  [GeV] vs Parton-level  $p_T^i$  [GeV]  
correlation: 0.84

subtract background

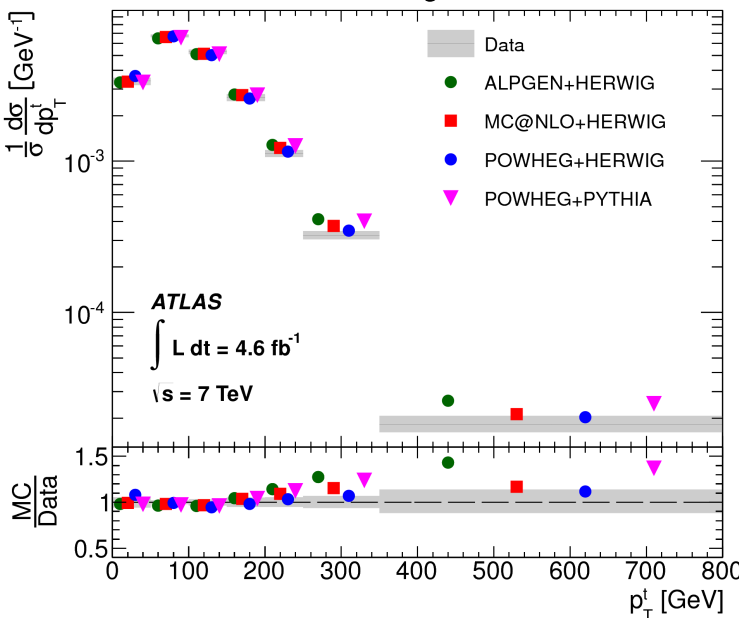
correct each bin for efficiency to pass selection



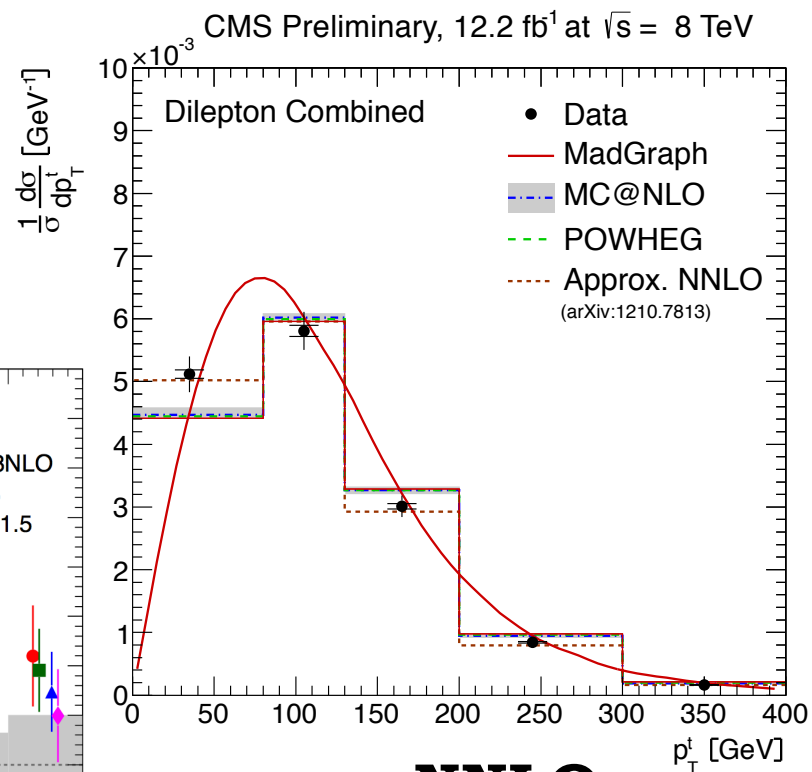
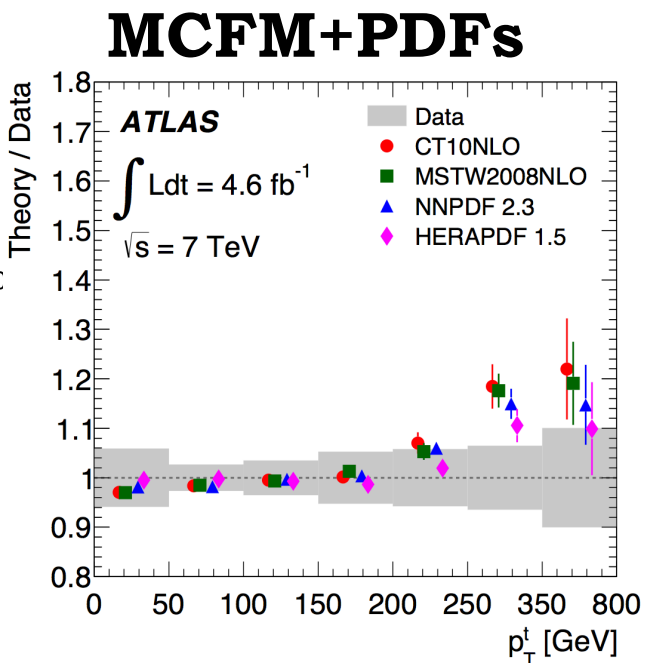


# Differential

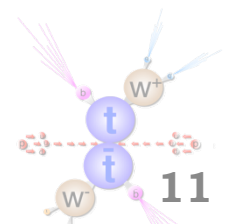
- Differential cross sections test QCD calculations
  - compare different generators, PDFs and (N)NLO QCD predictions to unfolded data distributions
    - **Study kinematics of top pair, top quark  $p_T$**



## Generators



## NNLO



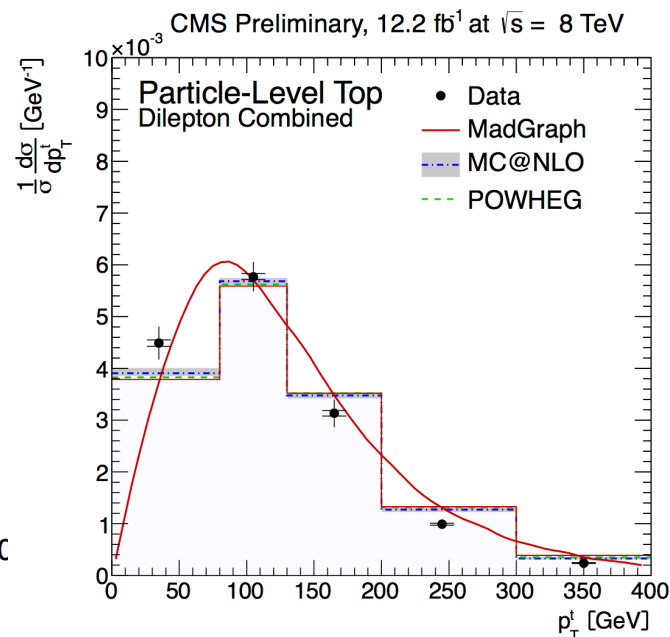
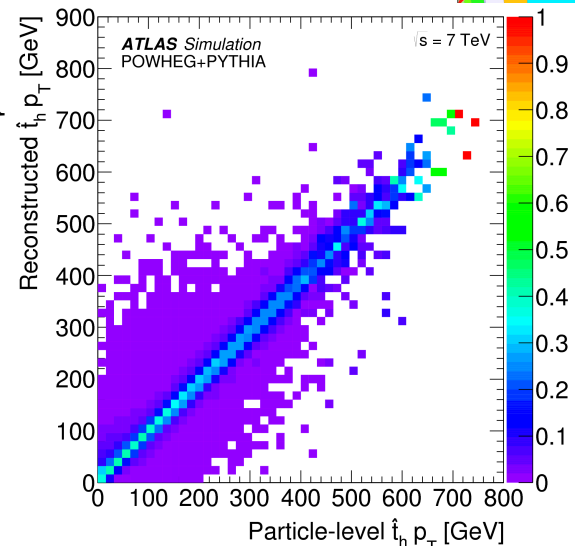
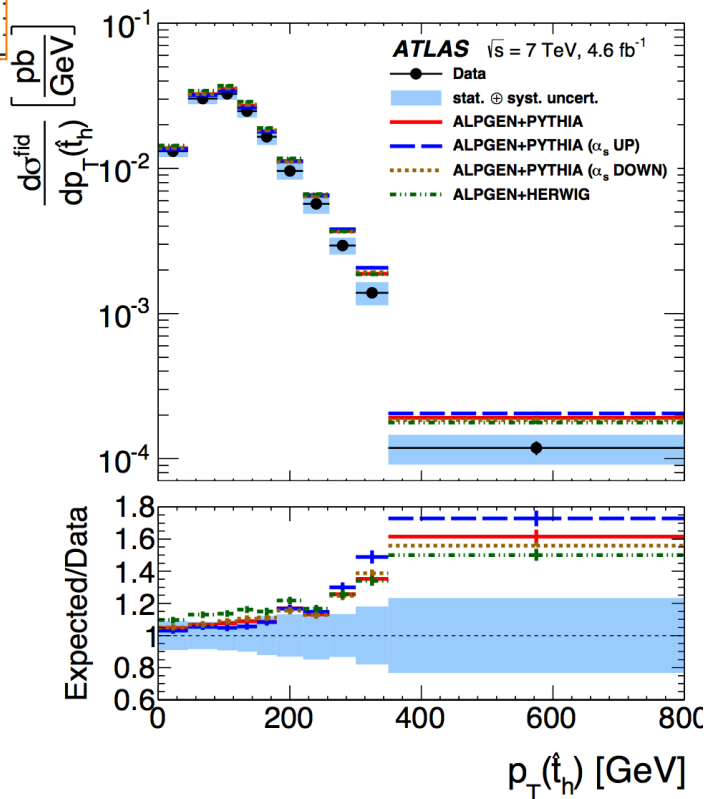
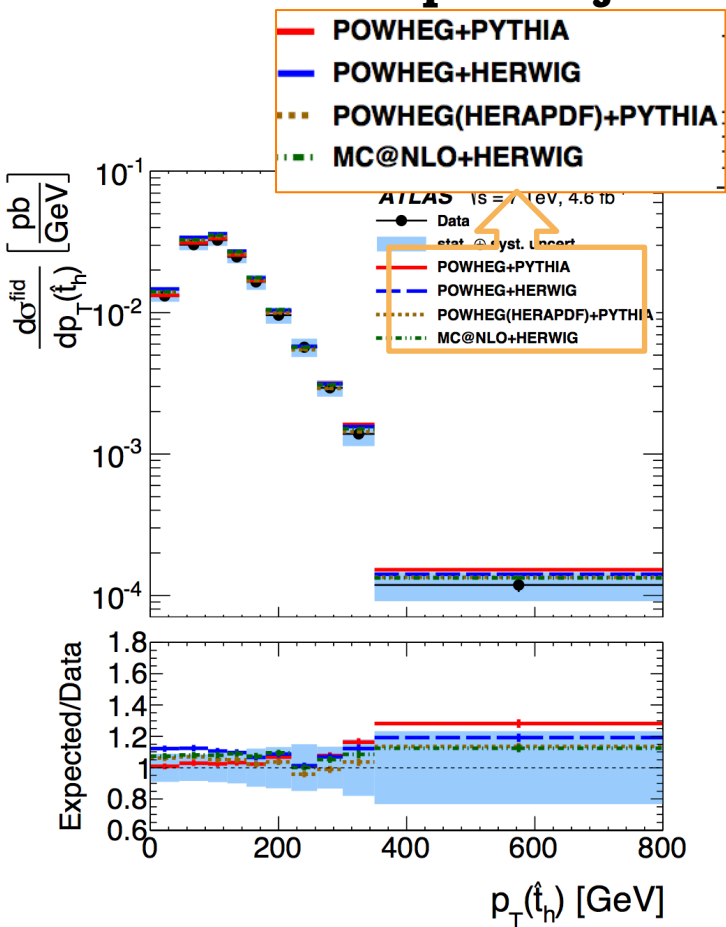


# Differential: pseudo-top

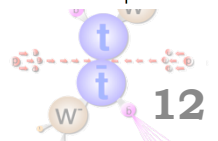


- Pseudo-top and tt built from objects directly related to particle-level observables (leptons, jets,  $E_{\text{miss}}^T$ )

- **CMS: dilepton**
- **ATLAS: lepton + jets**



[CMS-PAS-TOP-12-028 \(additional material\)](#)  
[e-print arXiv:1502.05923](#)

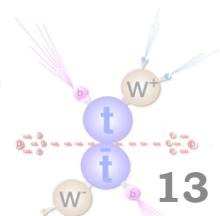
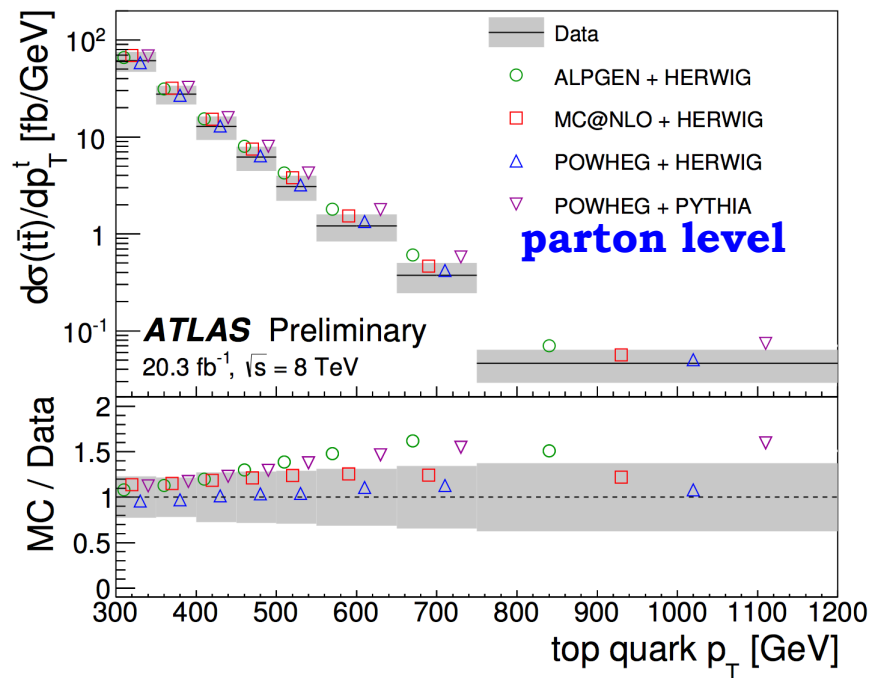
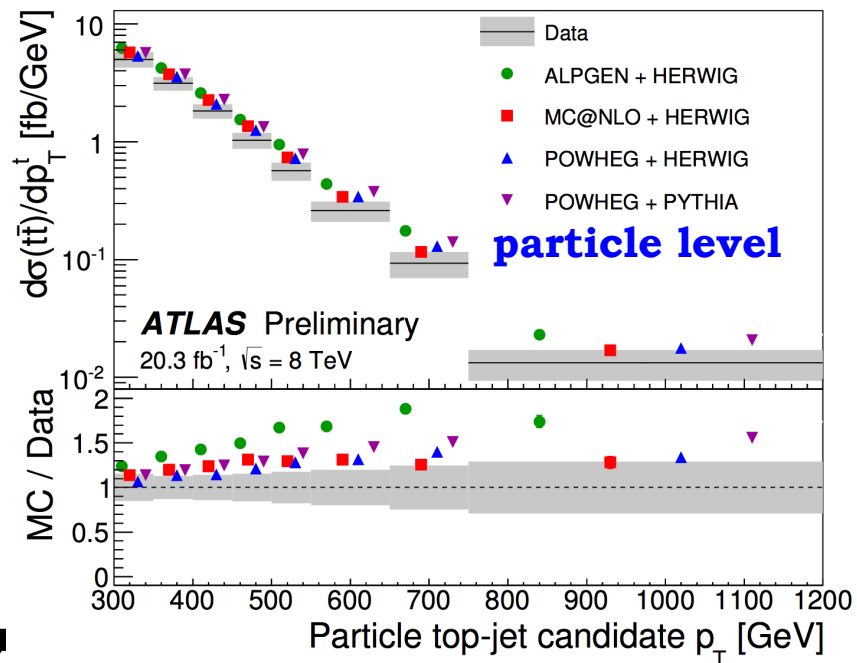
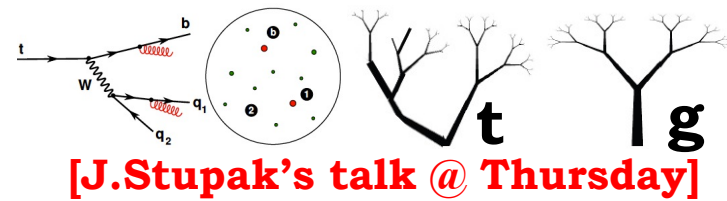
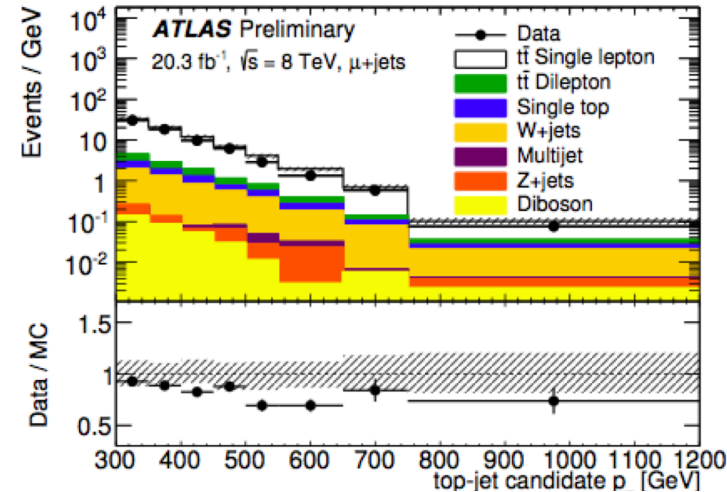






# Differential: boosted

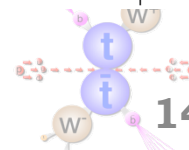
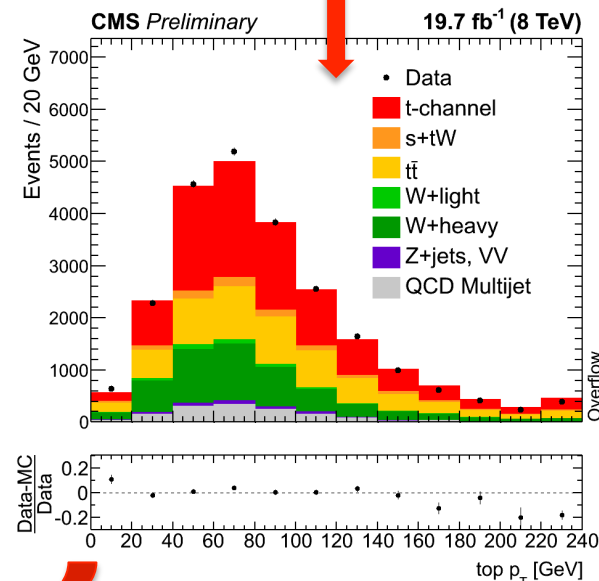
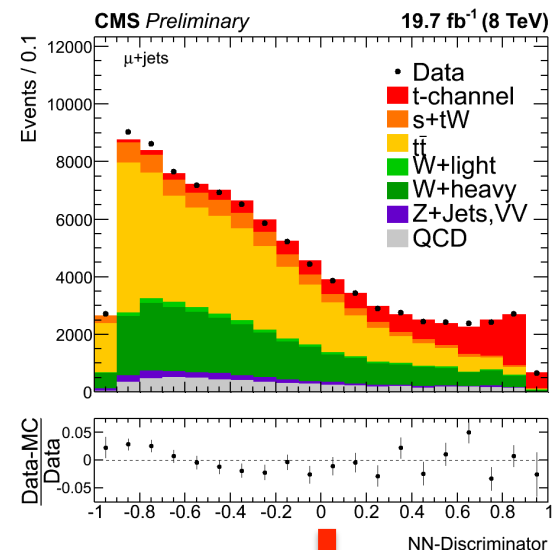
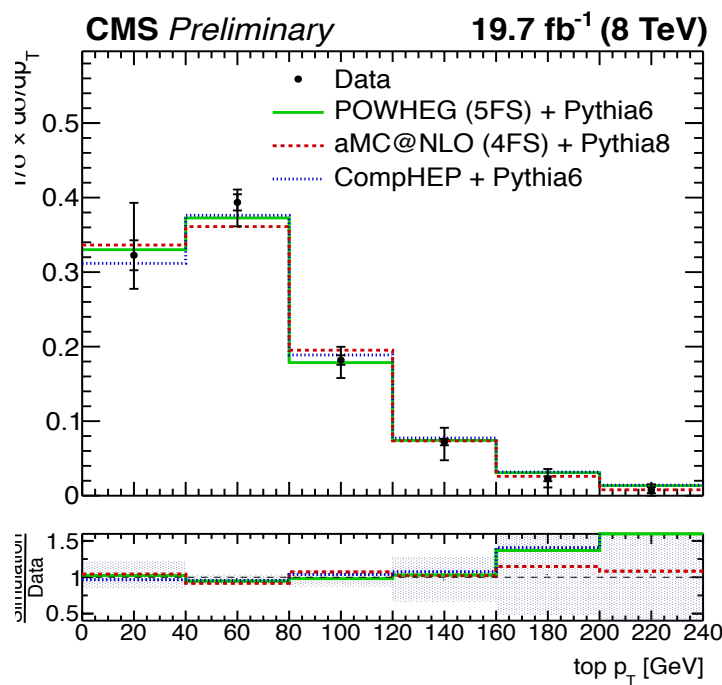
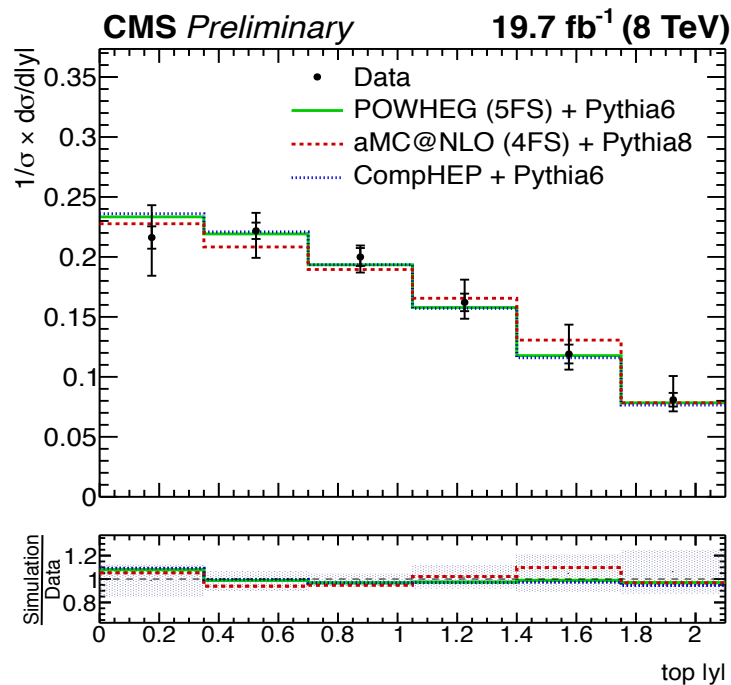
- Top  $p_T$  measured for the first time using boosted jet reconstruction algorithms up to TeV range
  - Fiducial phase-space particle level
  - Full phase-space parton level
- MCs are above data, increasing with  $p_T$** 
  - Better description by **Powheg+Herwig** at parton level





# Differential: single top t-channel

- Differential cross sections as functions of top  $p_T$  and rapidity
  - Comparison with MC using different modeling for b-quarks, showering/hadronization

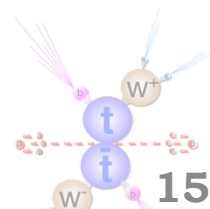
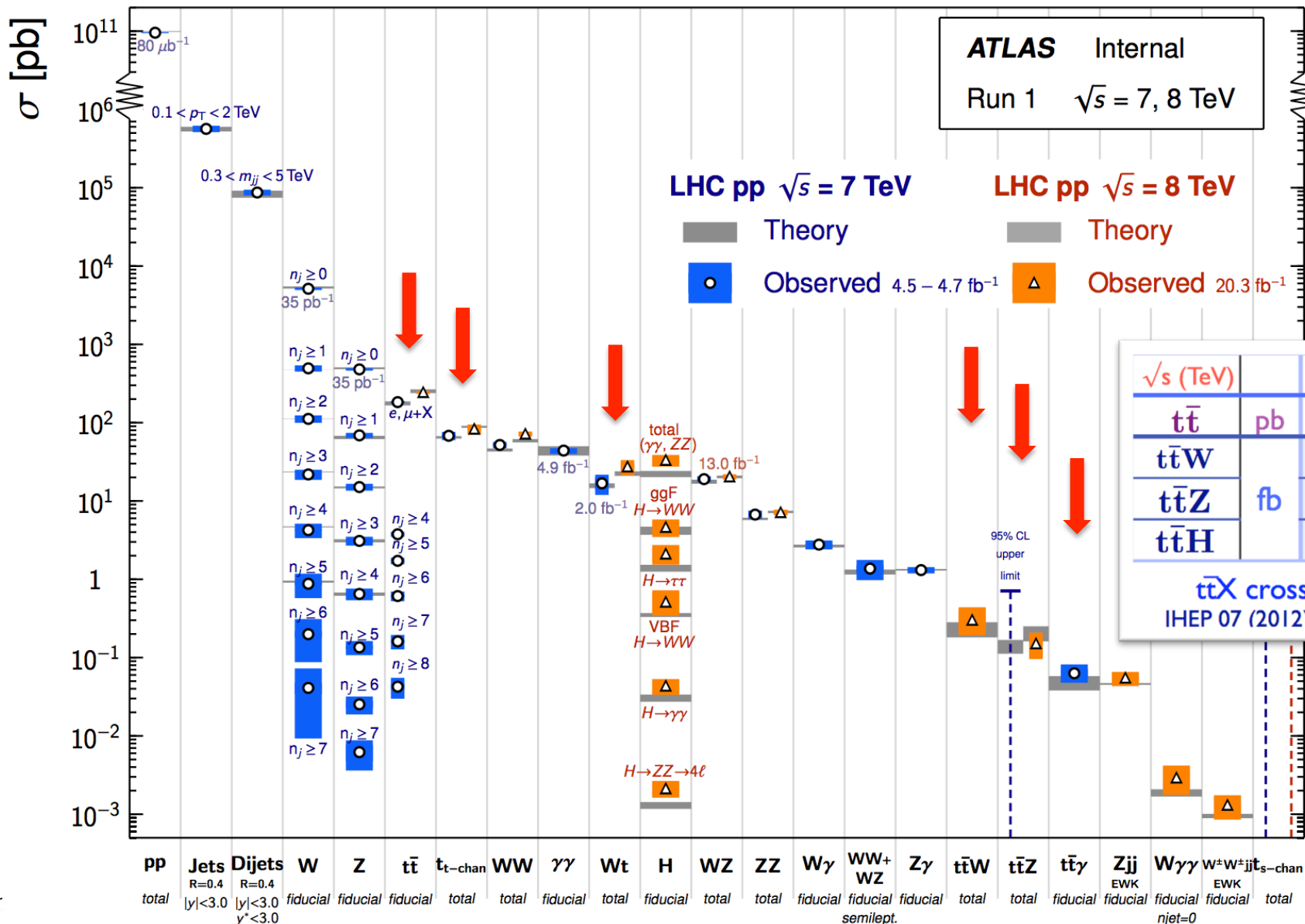




# Top-pair + X (and other SM measurements)

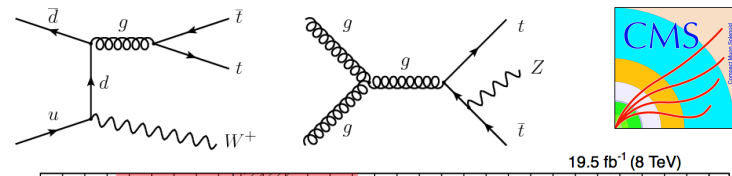
## Standard Model Production Cross Section Measurements

Status: March 2015





# Top-pair + X, X=W,Z



19.5 fb<sup>-1</sup> (8 TeV)

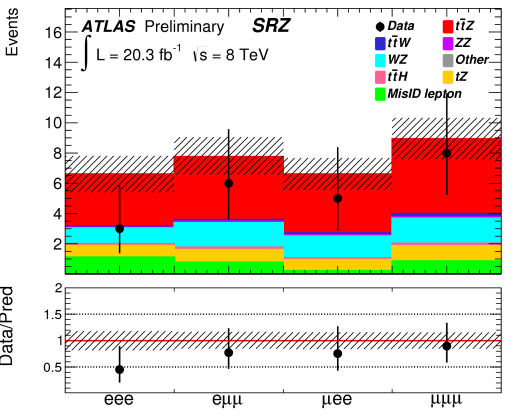
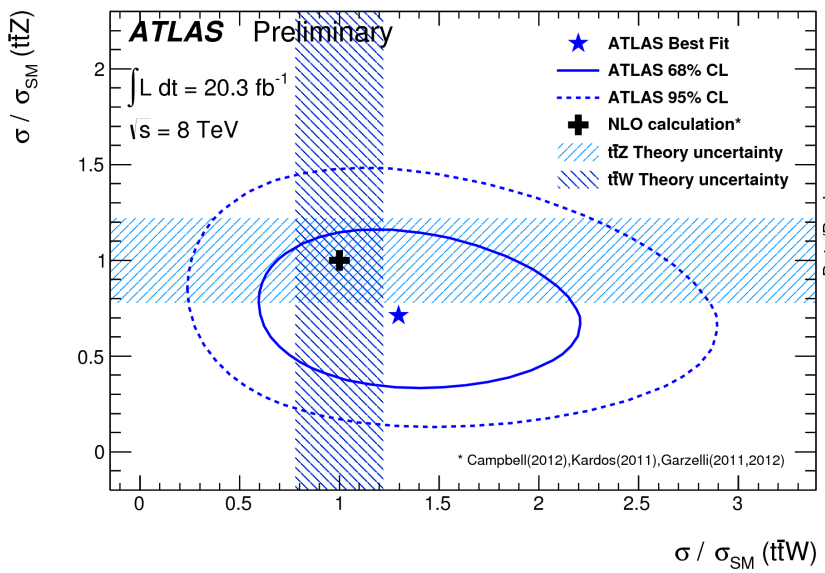
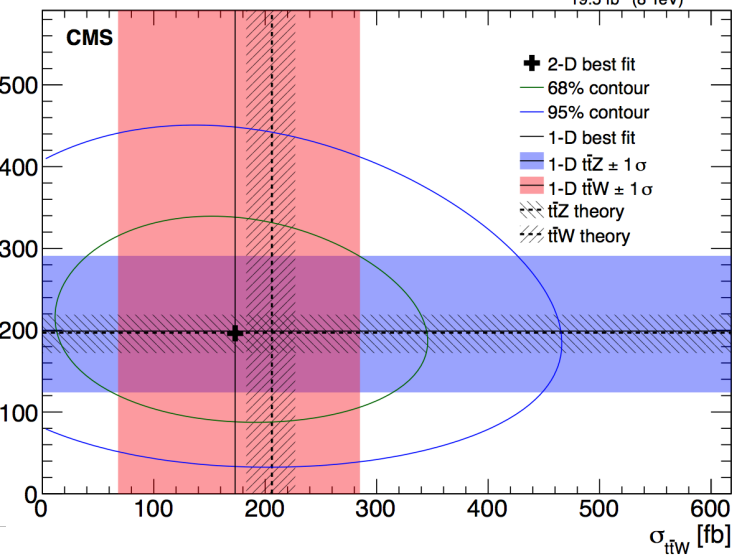
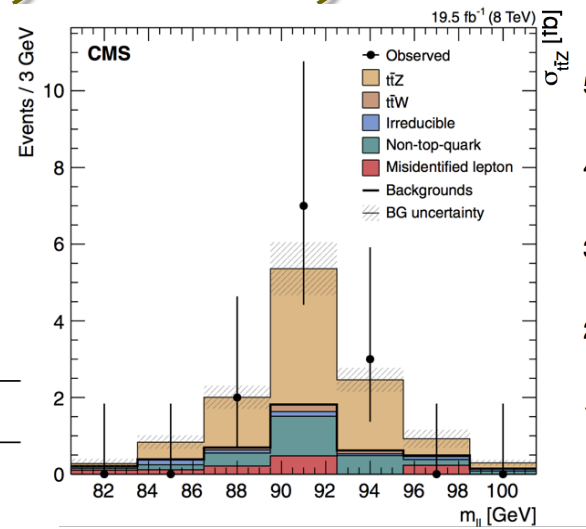
**CMS:** Search in 3 channels

- 2l (SS), 3l, 4l
- Observation of ttZ and ttW**

$$\sigma_{t\bar{t}V} = 380^{+100}_{-90} \text{ (stat)}^{+80}_{-70} \text{ (syst)} \text{ fb}$$

ttW cross section	ttZ cross section
170 <sup>+110</sup> <sub>-100</sub> (total) fb	200 ± 90 (total) fb

[Eur. Phys. J. C 74 \(2014\) 3060](#)

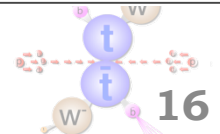


**ATLAS:** Search in 3 channels

- 2l (SS), 2l (OS), 3l
- Observation of ttZ, ttW**
  - ttV @ 4.9σ

[ATLAS-CONF-2014-038](#)

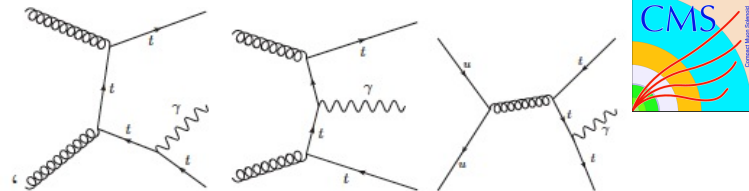
Process	Measured cross-sections	Observed σ	Expected σ
ttZ	150 <sup>+58</sup> <sub>-54</sub> (total) = 150 <sup>+55</sup> <sub>-50</sub> (stat.) ± 21 (syst.) fb	3.1	3.7
ttW	300 <sup>+140</sup> <sub>-110</sub> (total) = 300 <sup>+120</sup> <sub>-100</sub> (stat.) <sup>+70</sup> <sub>-40</sub> (syst.) fb	3.1	2.3



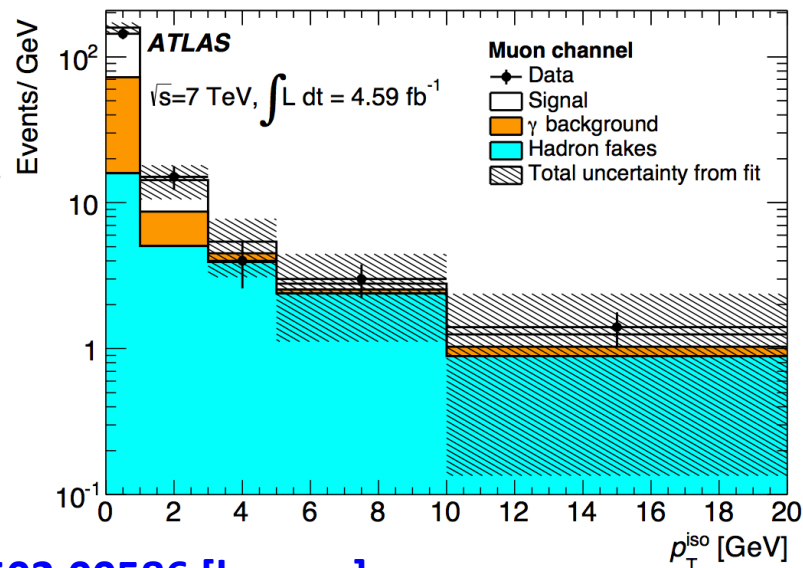




# Top-pair + X, X=photon



- Sensitive to top charge and to **top-photon couplings**
  - Control sample / Background to  $tt+H, H \rightarrow \gamma \gamma$
- **ATLAS@7 TeV: observation + fiducial cross section**
- Extract fiducial cross section by template fit to the photon track isolation distribution
- Background determination
  - Data-driven where possible
  - Single-top, diboson estimated with MC



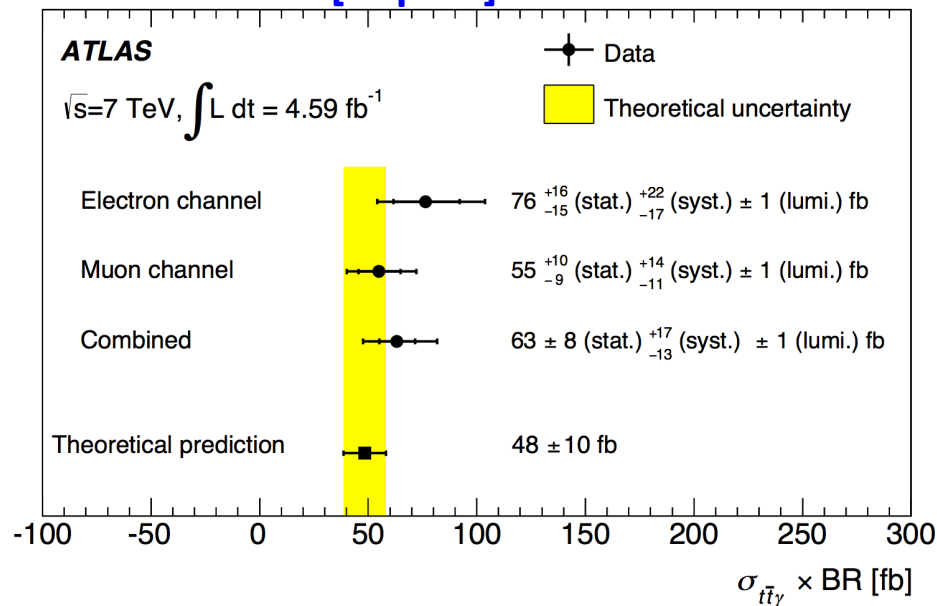
**NEW**

[arXiv:1502.00586 \[hep-ex\]](https://arxiv.org/abs/1502.00586)

## CMS@8TeV: cross section

- Muon channel
- $E_T(\gamma) > 20 \text{ GeV}, \Delta R(\gamma, b) > 0.1$
- $\sigma(tt\gamma) / \sigma(tt) = (1.07 \pm 0.07(\text{stat}) \pm 0.27(\text{syst})) \times 10^{-2}$ 
  - $\Rightarrow \sigma(tt\gamma) = 2.4 \pm 0.2(\text{stat}) \pm 0.6(\text{syst}) \text{ pb}$
  - SM:  $1.8 \pm 0.5 \text{ pb}$  (Melnikov et al)

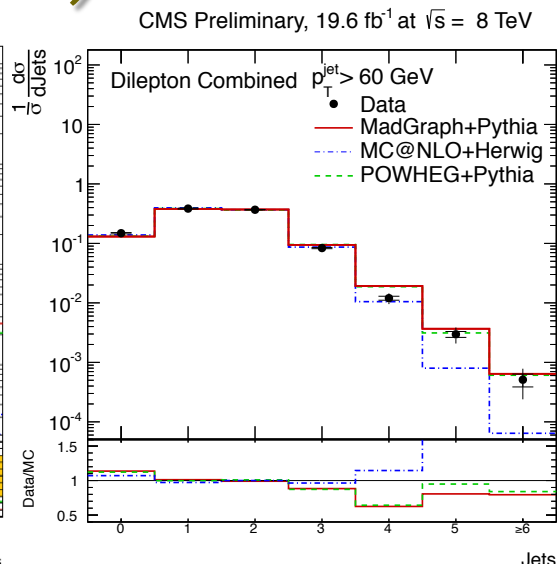
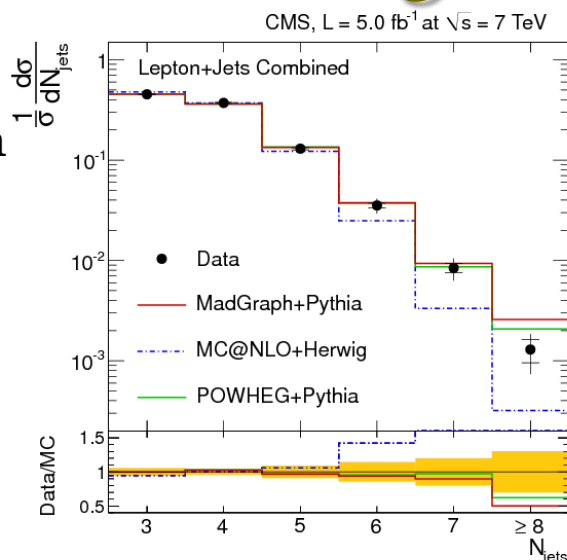
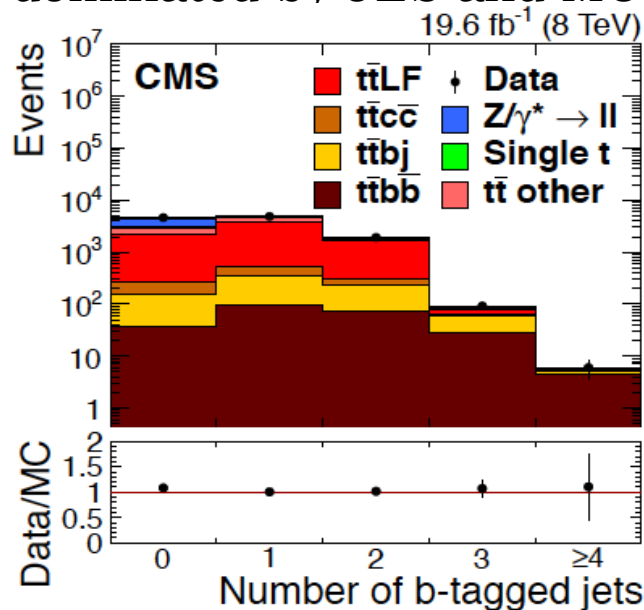
**CMS-PAS-TOP-13-011**





# Top-pair + jets (including HF)

- **>50%** tt events with extra hard jets
  - **Tune & test QCD ISR/FSR modeling**
- **Normalized** differential cross section as a function of  $N_{\text{jets}}$ 
  - with different **jet  $p_T$  thresholds**
- Large uncertainties at high  $N_{\text{jets}}$  dominated by JES and MC modeling



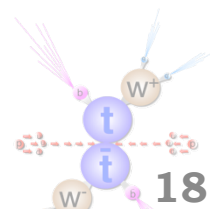
- Top Yukawa coupling => ttH => **ttbb final state**
  - ttbb is an **irreducible background**
- **CMS @ 8 TeV:** Ratio extracted via fit to the output of the b-tagging algorithm for the 3<sup>rd</sup> and 4<sup>th</sup> jets
- Ratio in full phase space with jet  $p_T > 40$  GeV

[Phys.Rev. D89 \(2014\) 072012](#)

- **ATLAS @ 7 TeV:** Ratio tt+(b or c)/tt+jets
  - 2D fit: (jet  $p_T$ , vertex mass)

$$R_{\text{HF}} = [6.2 \pm 1.1 \text{ (stat.)} \pm 1.8 \text{ (syst.)}] \%$$

- ALPGEN+HERWIG = 3.4%
- POWHEG+HERWIG = 5.2%



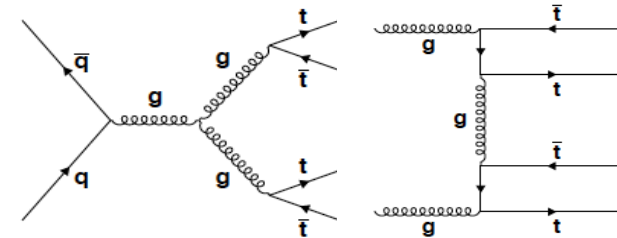
$$\frac{\sigma_{t\bar{t}b\bar{b}}}{\sigma_{t\bar{t}jj}} = 0.022 \pm 0.004(\text{stat.}) \pm 0.005(\text{syst.})$$

$$\frac{\sigma_{t\bar{t}b\bar{b}}}{\sigma_{t\bar{t}jj}} (\text{NLO QCD}) = 0.011 \pm 0.003$$

[arXiv:1411.5621](#)



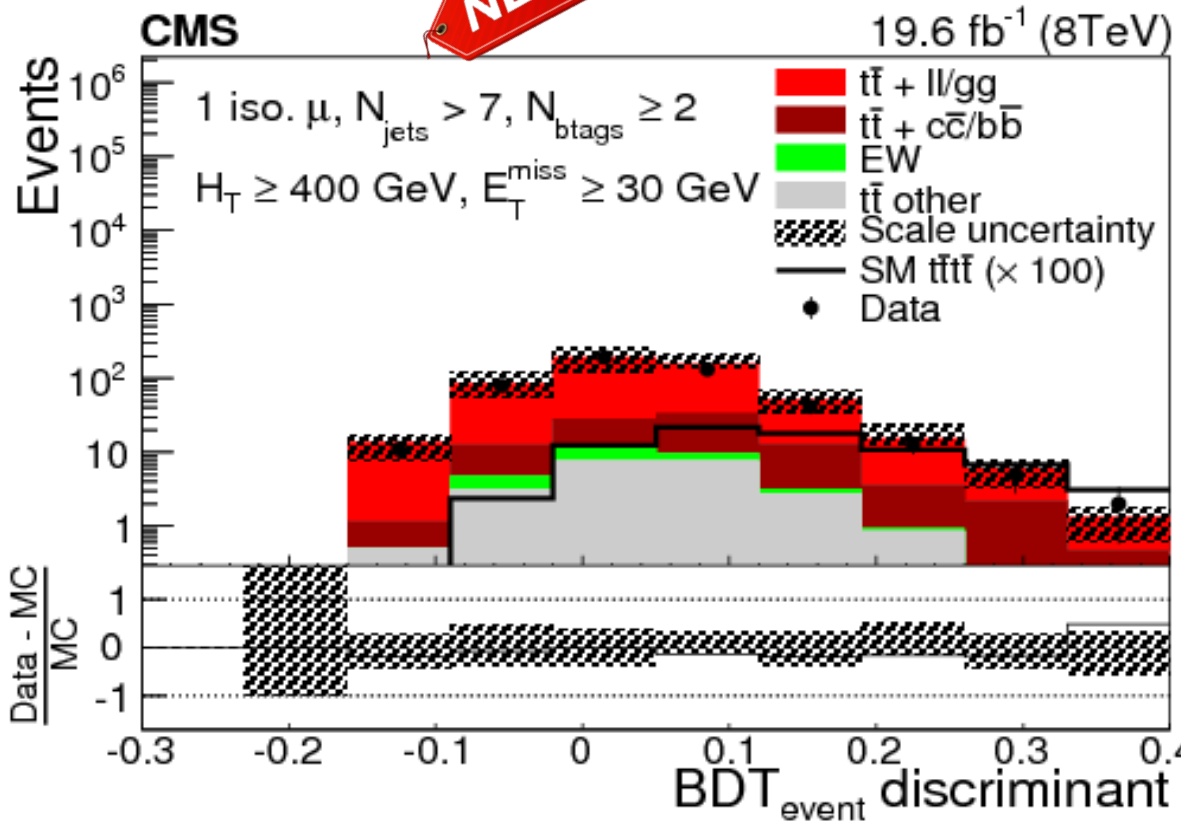
# Multi-top production



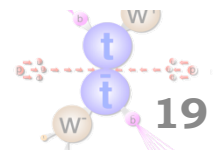
- More data, higher  $\sqrt{s}$  => rare processes are becoming accessible
  - $\sigma(tttt)_{SM} \approx 1 \text{ fb @ } 8 \text{ TeV}$ 
    - Generated with MadGraph
  - Many BSM models predict enhancement of this cross section (SUSY squark/gluino decays)



- No significant excess observed over SM expectations
- Cross section limit:
  - Observed: 32 fb (25 x SM)**
  - Expected: 32 ± 17 fb**
- Will be of interest for Run 2
  - 4-top production cross section **~9--15 times larger**

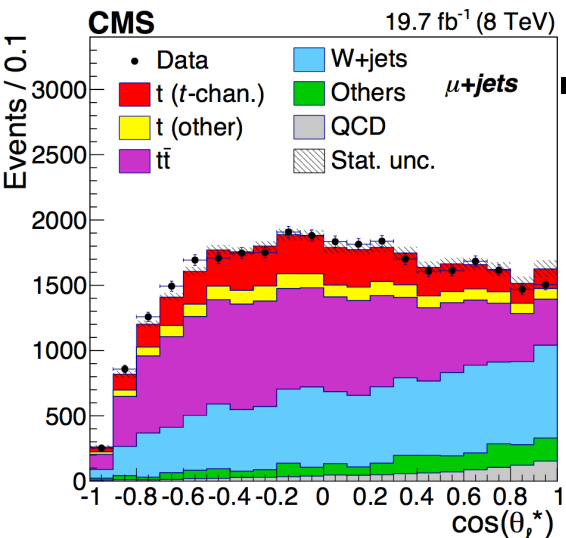
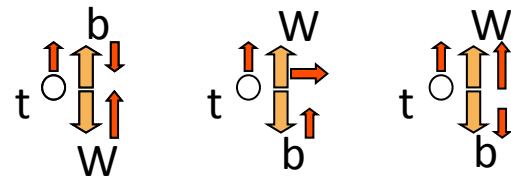


CERN-PH-EP-2014-222  
 arXiv:1409.7339  
 JHEP 11 (2014) 154





# W helicity in top production



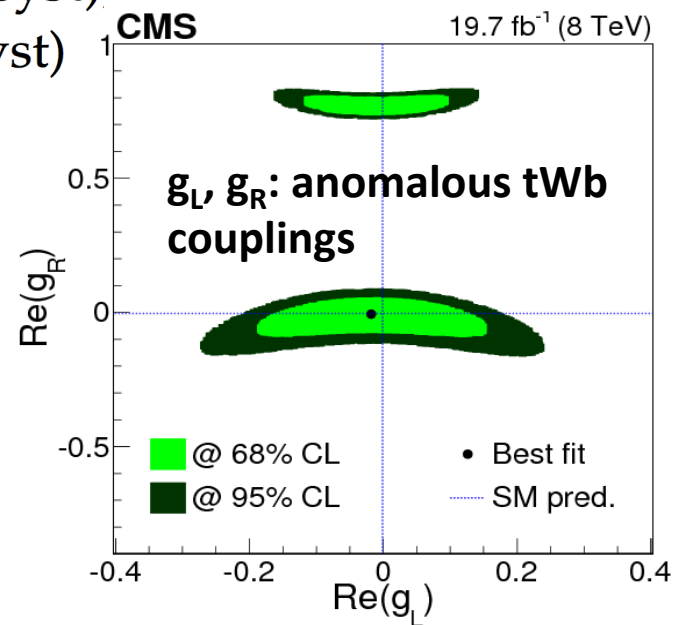
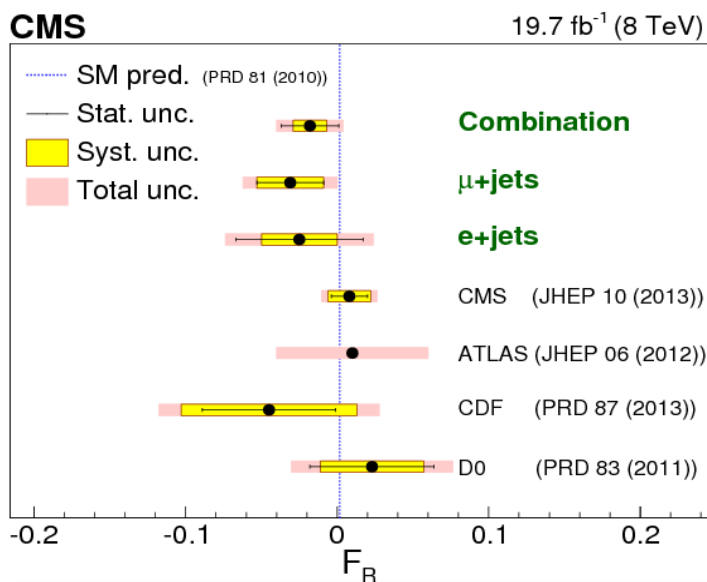
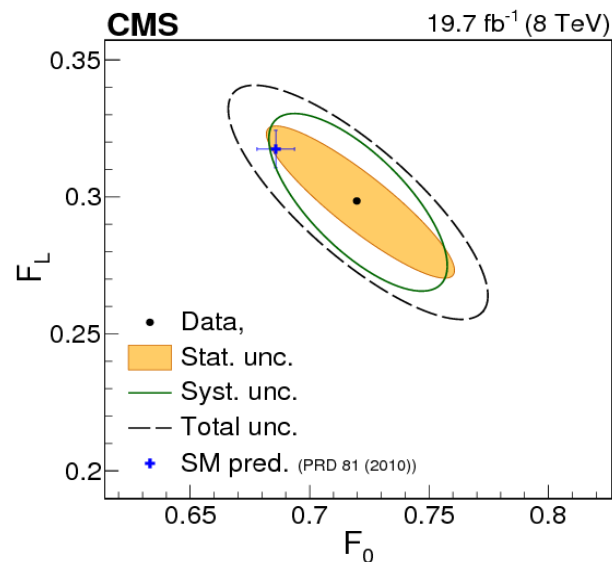
$t \rightarrow Wb$ ,  $W$ : left-, right-handed, or longitudinal helicity

- => measure the **helicity fractions**
- W polarization sensitive to non-SM  $tWb$  couplings
- **First measurement using events containing a single top quark**

- 1 lepton + 2 jets (1 b-tag) +  $E_T^{\text{miss}}$

$$F_0 = 0.720 \pm 0.039 \text{ (stat)} \pm 0.037 \text{ (syst)}$$

$$F_L = 0.298 \pm 0.028 \text{ (stat)} \pm 0.032 \text{ (syst)}$$



JHEP 01 (2015) 053  
arXiv:1410.1154v2

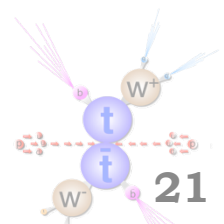
$$\mathcal{L}_{tWb}^{\text{anom.}} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W^-_\mu - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{m_W} (g_L P_L + g_R P_R) t W^-_\mu + \text{h.c.}$$





# What We still Need to Learn

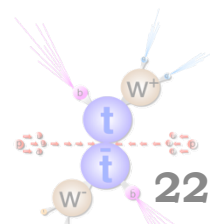
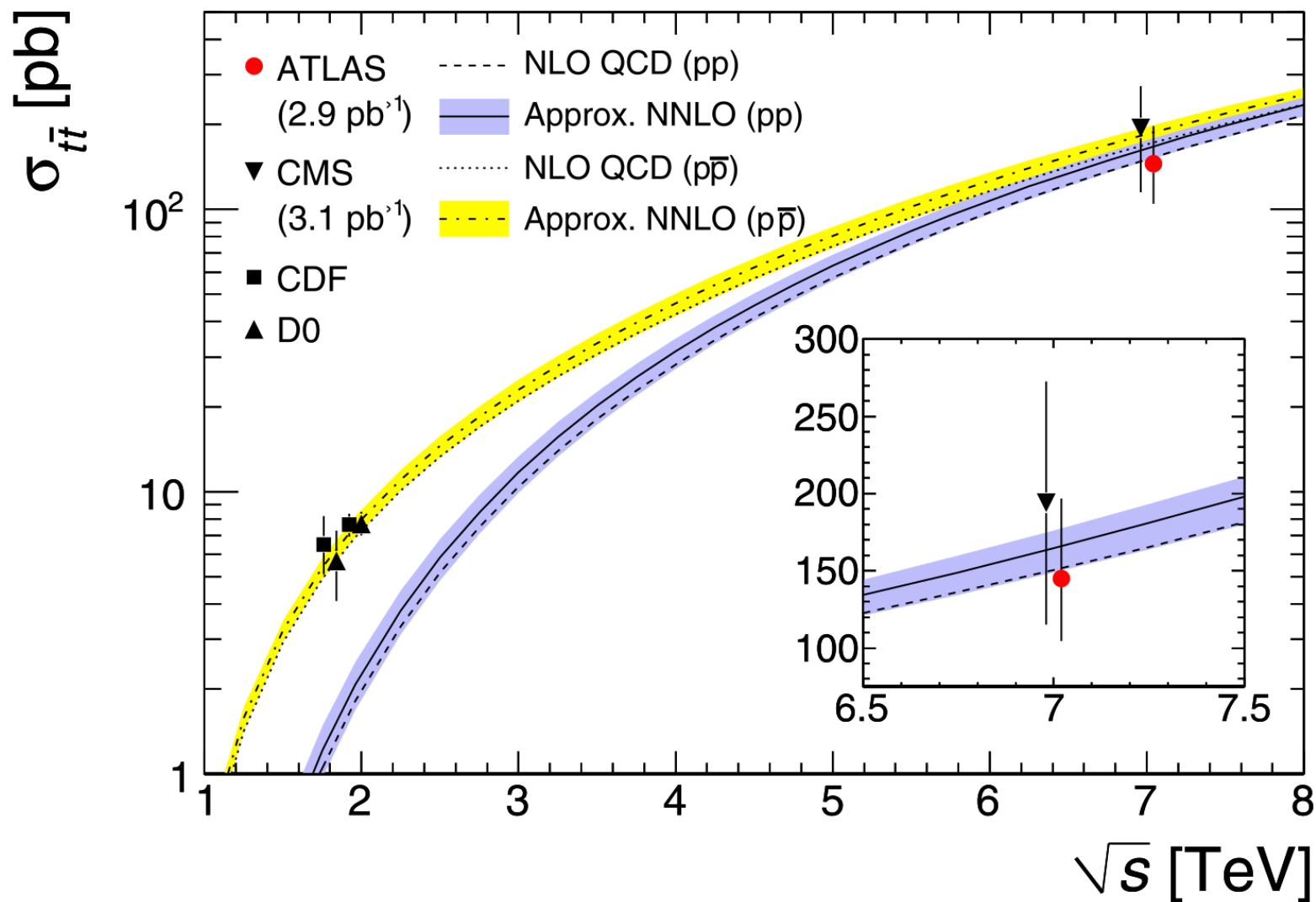
- **Rich and mature** top physics program @ Run 1
  - Many things to learn from a bigger data sample!
    - A factor of 2 top-pair events in 2015
      - Expect  $10 \text{ fb}^{-1}$  @ 13 TeV **[M.Lamont's talk @ Tuesday]**
- **Top Properties**
  - Many properties are still unknown (to the desired precision)
    - Couplings to photon, Z
    - Coupling to Higgs **[S.Majewski's talk @ Thursday]**
      - and maybe some other new heavy particles?
    - Charge asymmetry in top pair production
- **FCNC**
  - many channels to test
- **Precise** cross section measurements
  - Differential measurements to test pQCD
    - PDF studies
- Thank...





# Top-quark pair production: 2011

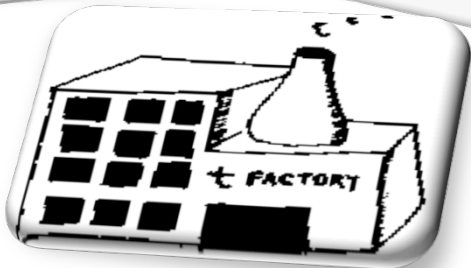
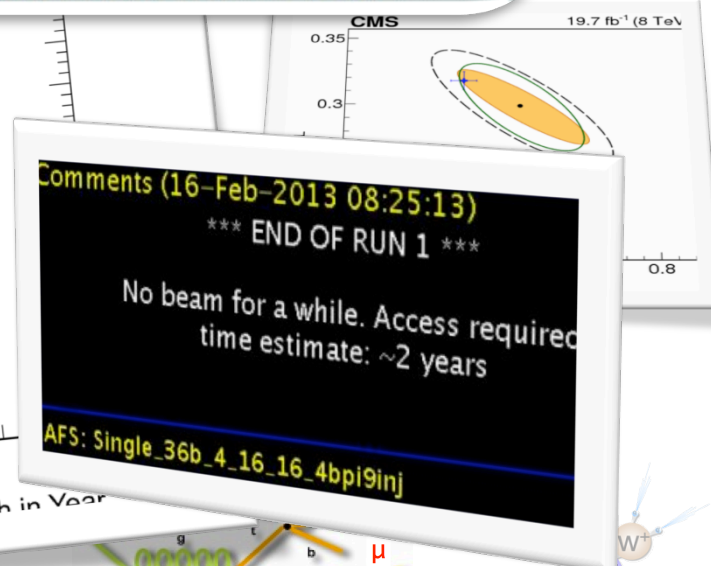
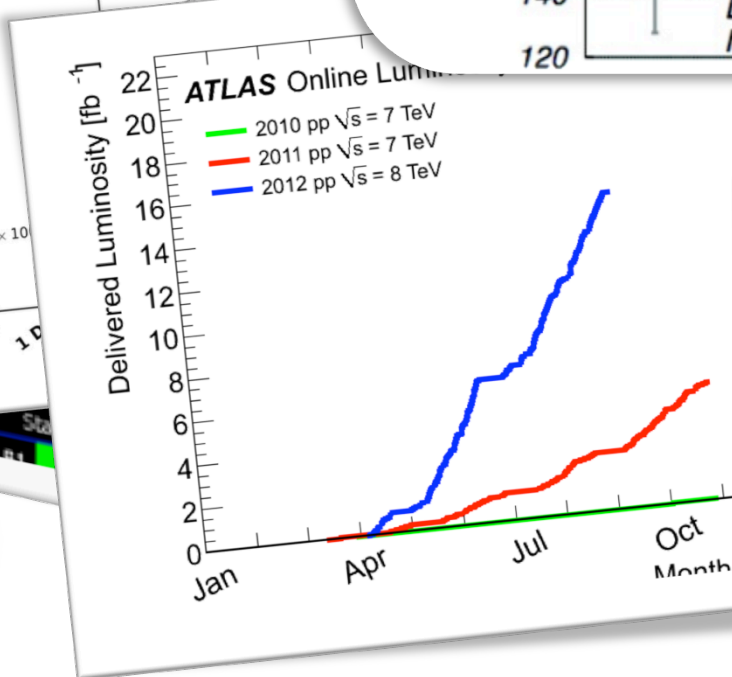
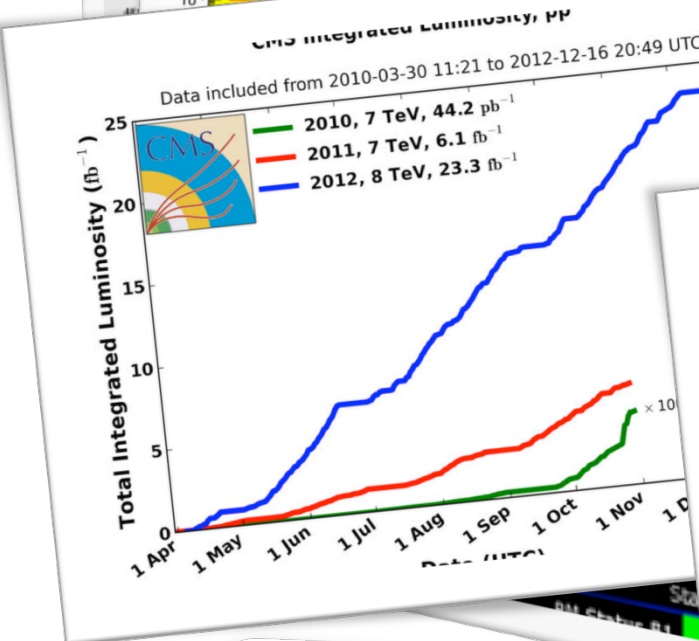
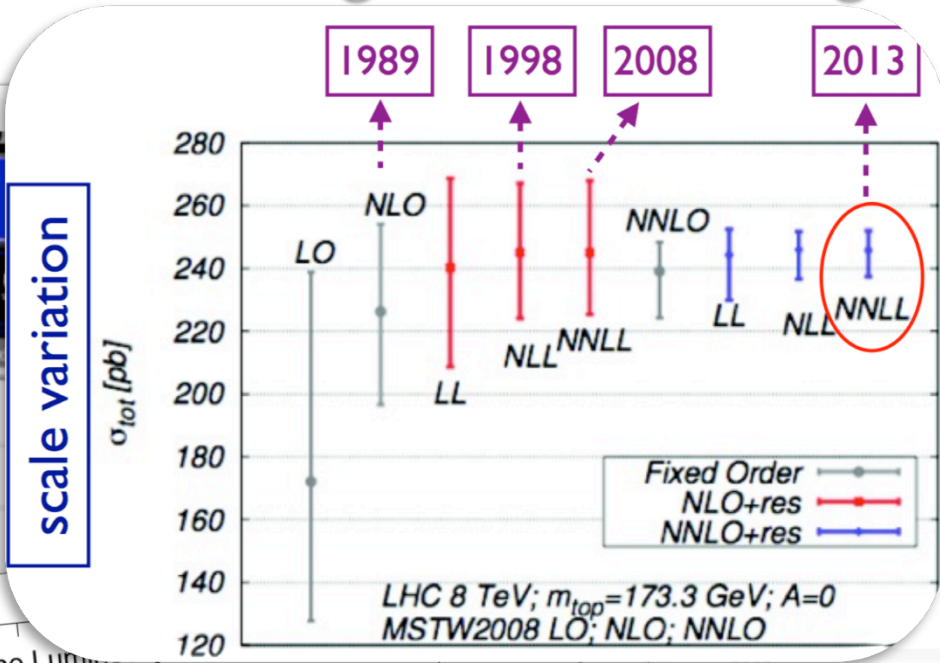
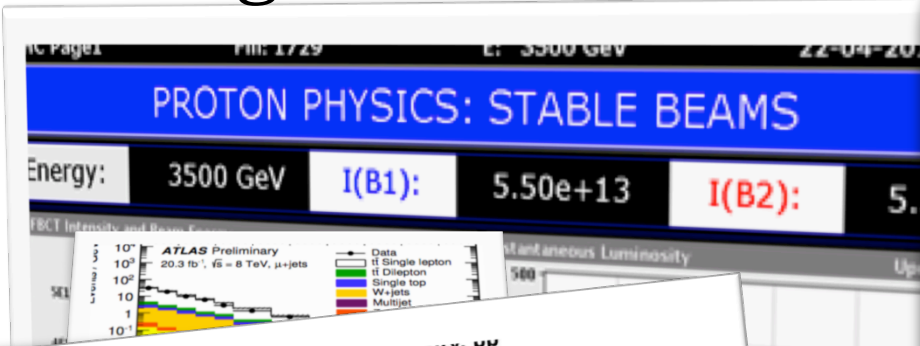
- First Summary of LHC and Tevatron measurements of top-pair production cross sections





# LHC + ATLAS + CMS + Theory Community

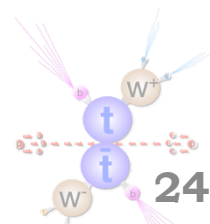
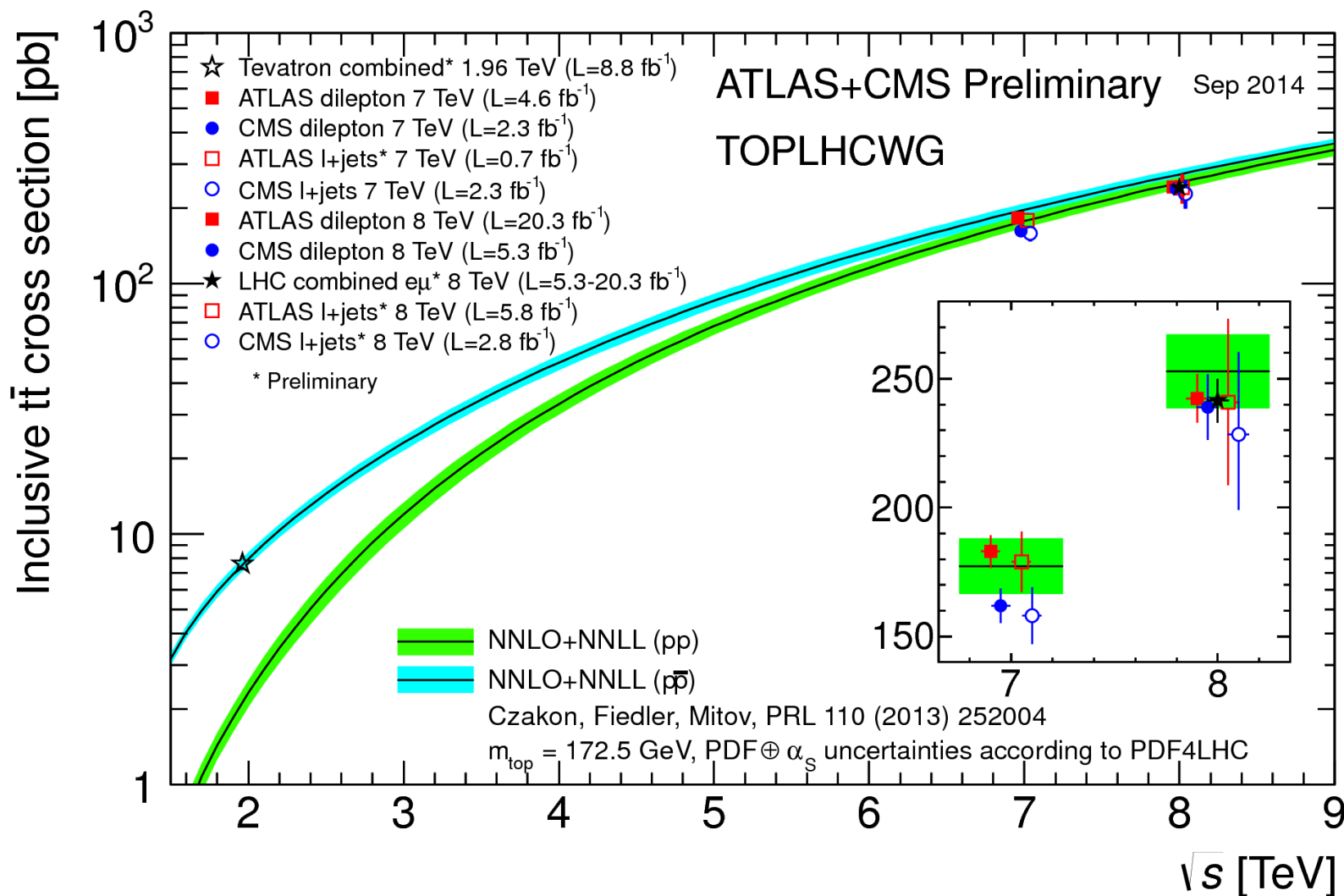
- Huge effort!



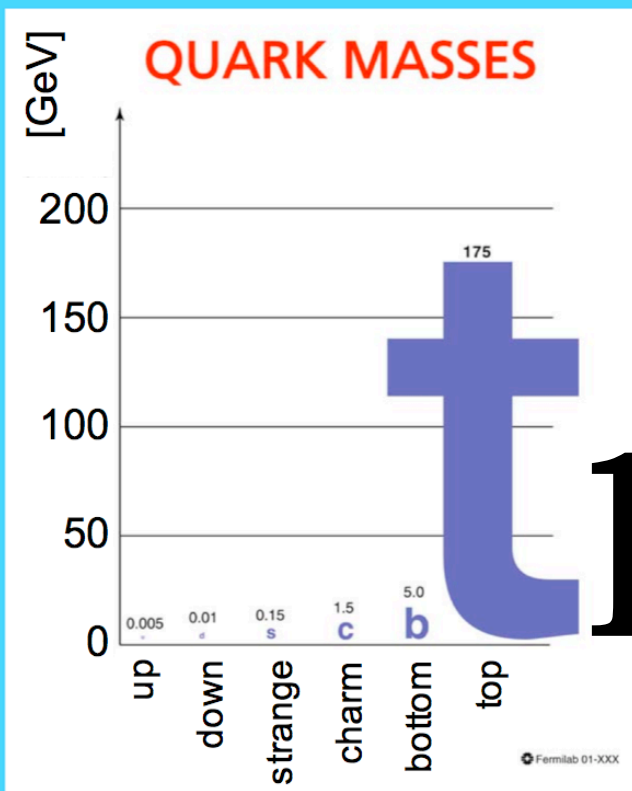


# Top-quark pair production: 2015

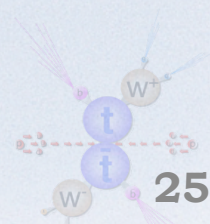
- Summary of LHC and Tevatron measurements of top-pair production cross sections







# Thank you!



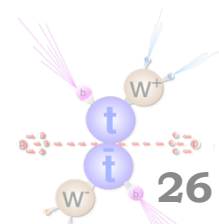




# Backup



- Detectors
- ATLAS + CMS Charge asymmetry
- ATLAS  $t\bar{t}+HF$
- FCNC prospects
- Various summary plots



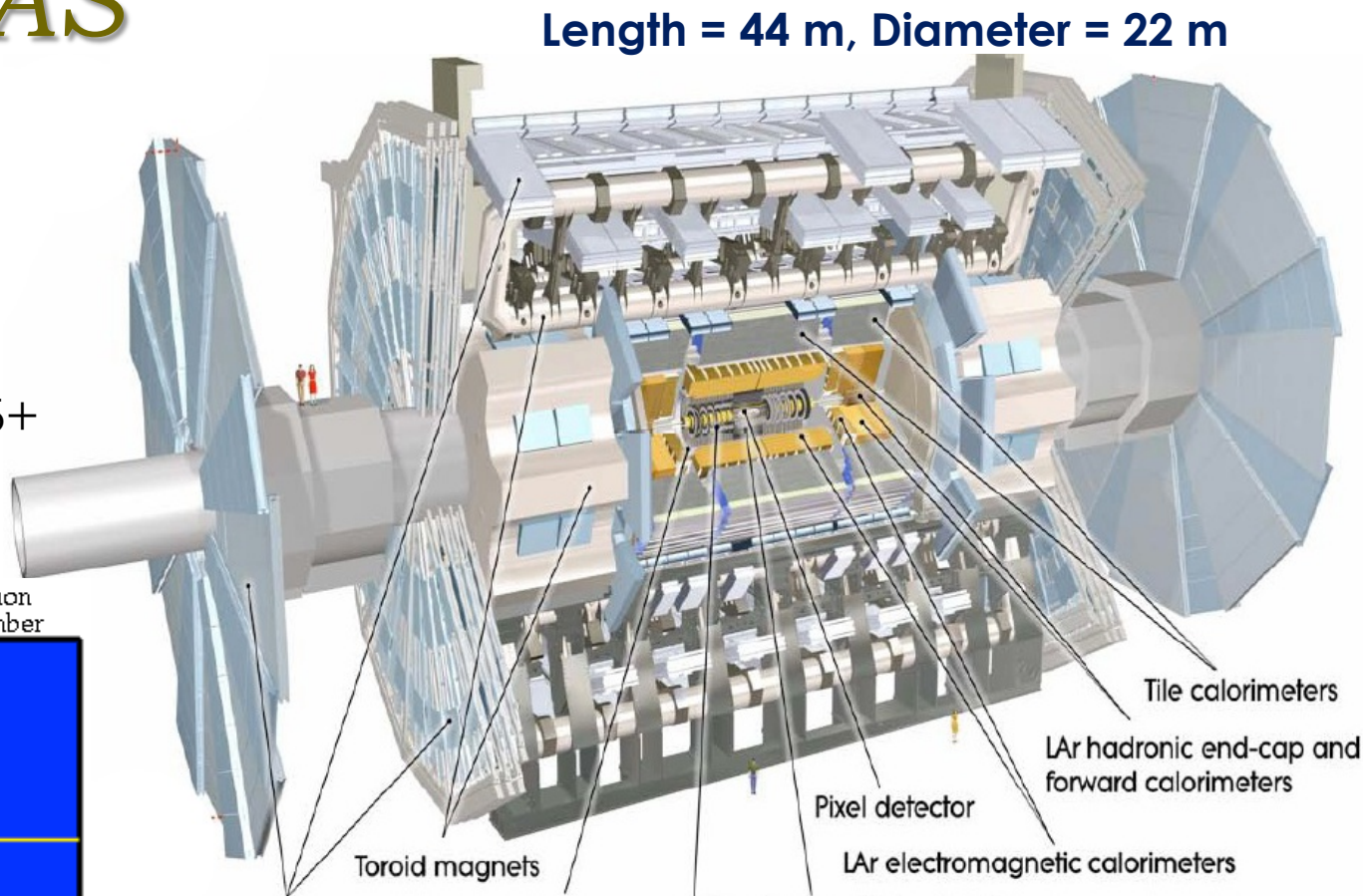


# LHC / ATLAS

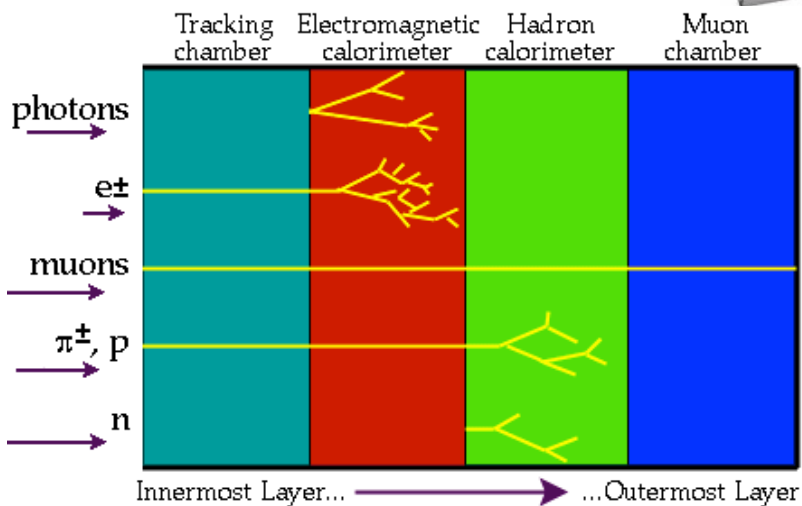
## Large Hadron Collider

- p-p collider
- Center of mass energy
  - $\sqrt{s} = 7 \text{ TeV @ 2010-11}$
  - $\sqrt{s} = 8 \text{ TeV @ 2012}$
  - $\sqrt{s} = 13-14 \text{ TeV @ 2015+}$
- Multi-purpose experiments:

## ATLAS and CMS

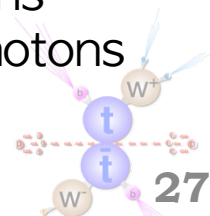
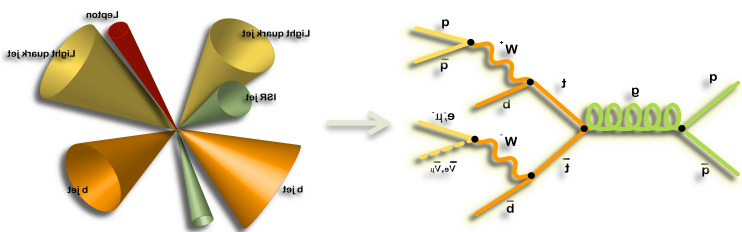


Length = 44 m, Diameter = 22 m



## Subdetectors and identified objects:

- Trackers: electrons, muons, jets, taus, photons
- Calorimeters: electrons, muons, jets, taus, photons
- Muon Detectors: muons





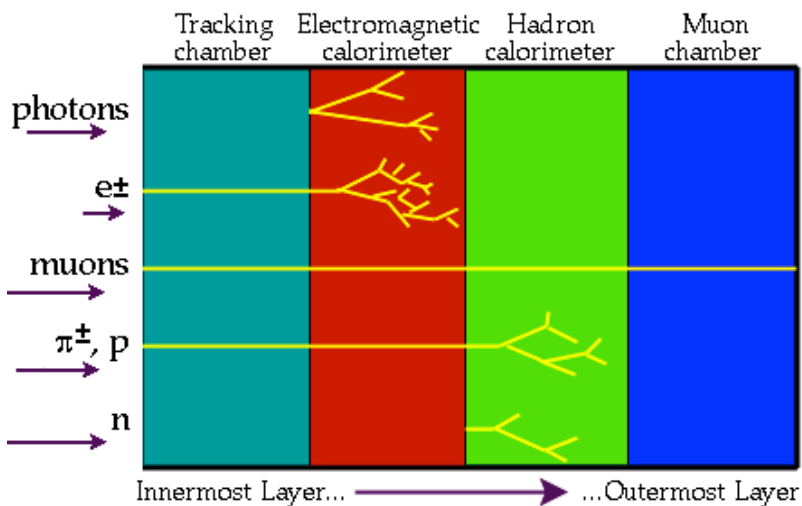
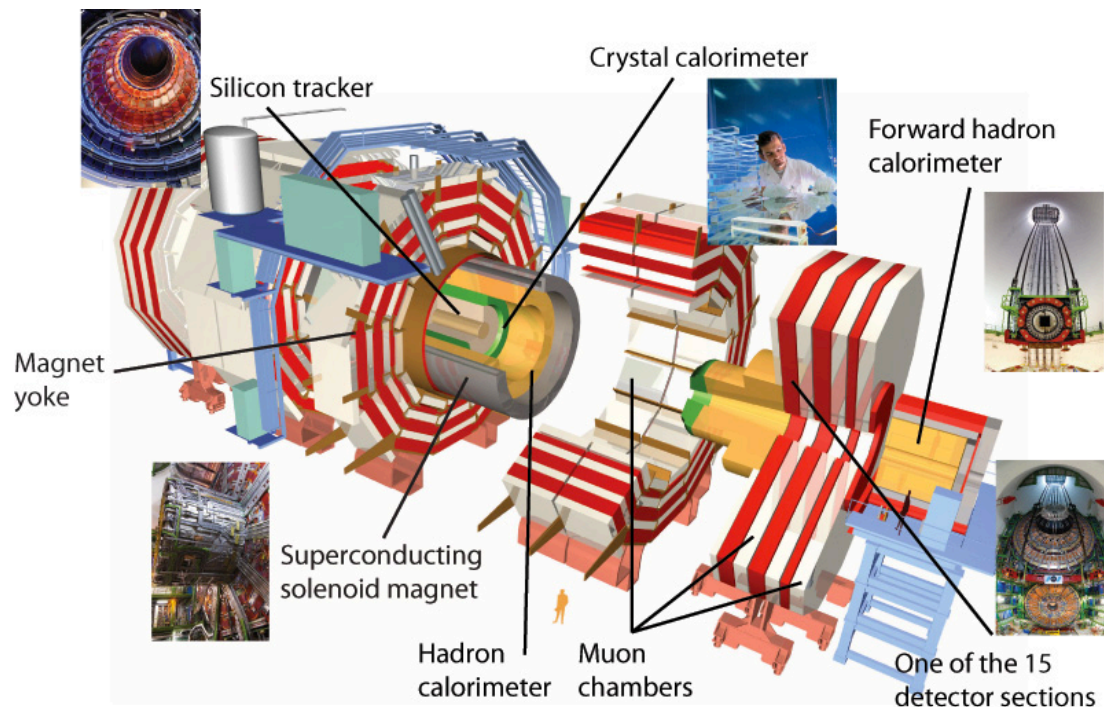
# LHC / CMS

Length = 21.6m, Diameter = 15m

## Large Hadron Collider

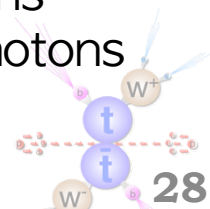
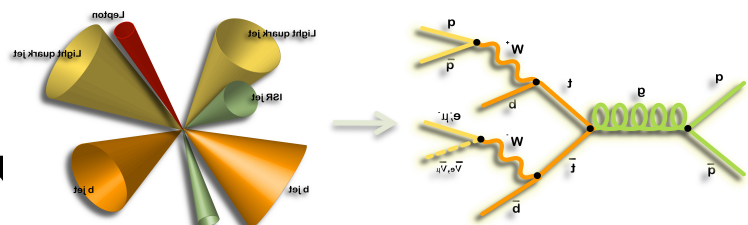
- p-p collider
- Center of mass energy
  - $\sqrt{s} = 7 \text{ TeV @ 2010-11}$
  - $\sqrt{s} = 8 \text{ TeV @ 2012}$
  - $\sqrt{s} = 13-14 \text{ TeV @ 2015+}$
- Multi-purpose experiments:

## ATLAS and CMS



## Subdetectors and identified objects:

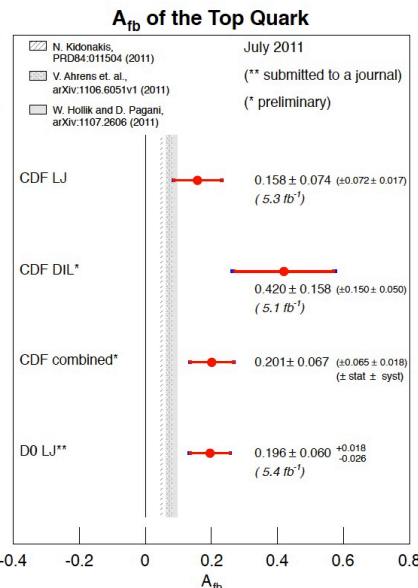
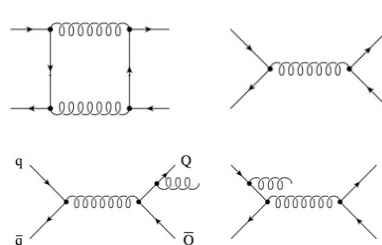
- Trackers: electrons, muons, jets, taus, photons
- Calorimeters: electrons, muons, jets, taus, photons
- Muon Detectors: muons





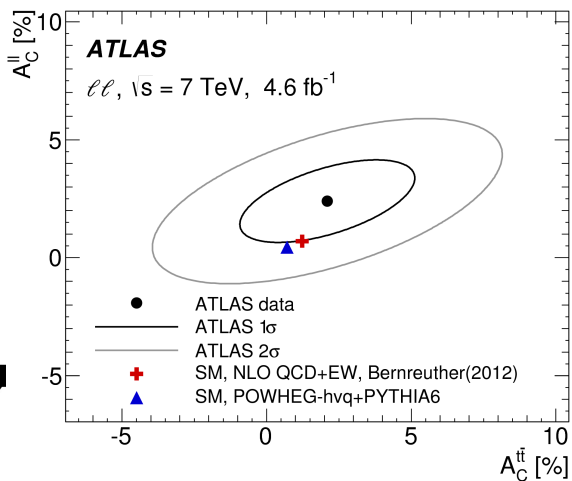
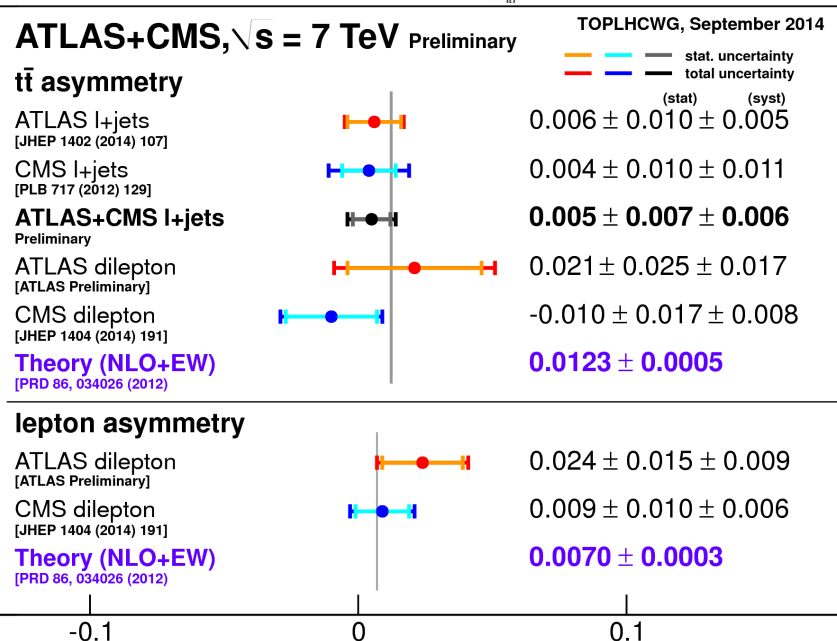
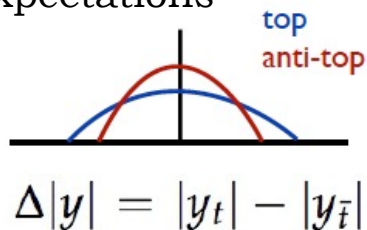


# Charge Asymmetry



- At LO top-antitop is symmetric
- At NLO interferences between box and ISR/FSR diagrams that are not symmetric under the exchange of t and tbar cause a preferred direction of the t and tbar and hence an asymmetry
  - deviation from the SM prediction could indicate physics beyond the SM
- Tevatron results
  - 3.4 sigma deviation in AFB for M<sub>tt</sub> > 450 GeV (CDF)
    - [arXiv:1101.0034](https://arxiv.org/abs/1101.0034), Phys.Rev.D83:112003,201
- LHC: pp collisions
  - Asymmetry arises from qqbar top pair production
  - Results are consistent with SM expectations

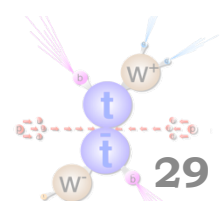
$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$



e-print [arXiv:1501.07383](https://arxiv.org/abs/1501.07383)

Channel	A <sub>C</sub> <sup>ll</sup>	A <sub>C</sub> <sup>t<math>\bar{t}</math></sup>
ee	0.101 ± 0.052 ± 0.021	0.025 ± 0.069 ± 0.027
eμ	0.009 ± 0.019 ± 0.009	0.007 ± 0.032 ± 0.018
μμ	0.047 ± 0.030 ± 0.012	0.043 ± 0.045 ± 0.013
Combined	0.024 ± 0.015 ± 0.009	0.021 ± 0.025 ± 0.017
SM, NLO QCD+EW [10]	0.0070 ± 0.0003 (scale)	0.0123 ± 0.0005 (scale)

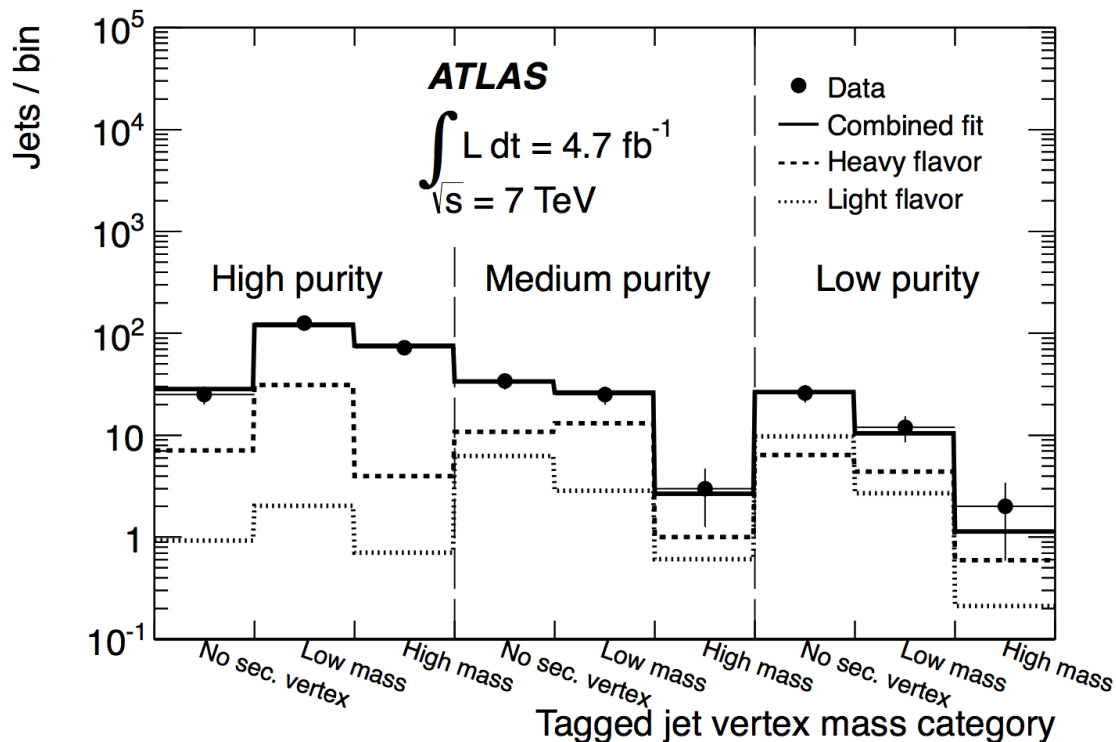
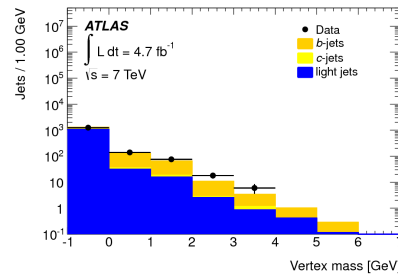
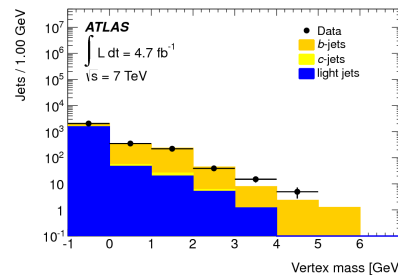
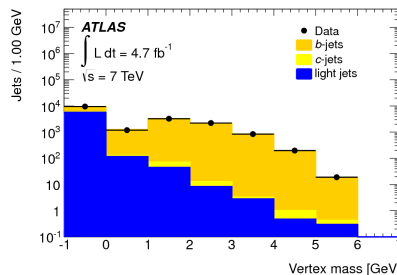
Moriond/EW: 50th Rencontres de Moriond





# tt + HF

- Constrain models of HF quark production at top quark mass scale
  - Measure ratio tt+HF/tt+jets
- $\sqrt{s} = 7$  TeV, dilepton decay channel with at least one additional jet
  - 2-D Template fit: displaced vertex mass and jet  $p_T$ 
    - using different b-tag operating points
- Largest systematics – HF tagging efficiency and fragmentation modeling
- SM predictions
  - ALPGEN+HERWIG = 3.4%
  - POWHEG+HERWIG = 5.2%



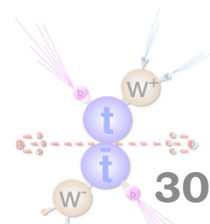
$$R_{HF} = [6.2 \pm 1.1 \text{ (stat.)} \pm 1.8 \text{ (syst.)}] \%$$

Phys.Rev. D89 (2014) 072012

CERN-PH-EP-2013-030

arXiv:1304.6386 [hep-ex]

Moriond/EW: 50th Rencontres de Moriond

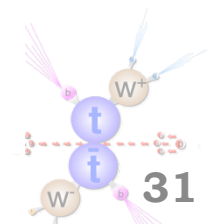
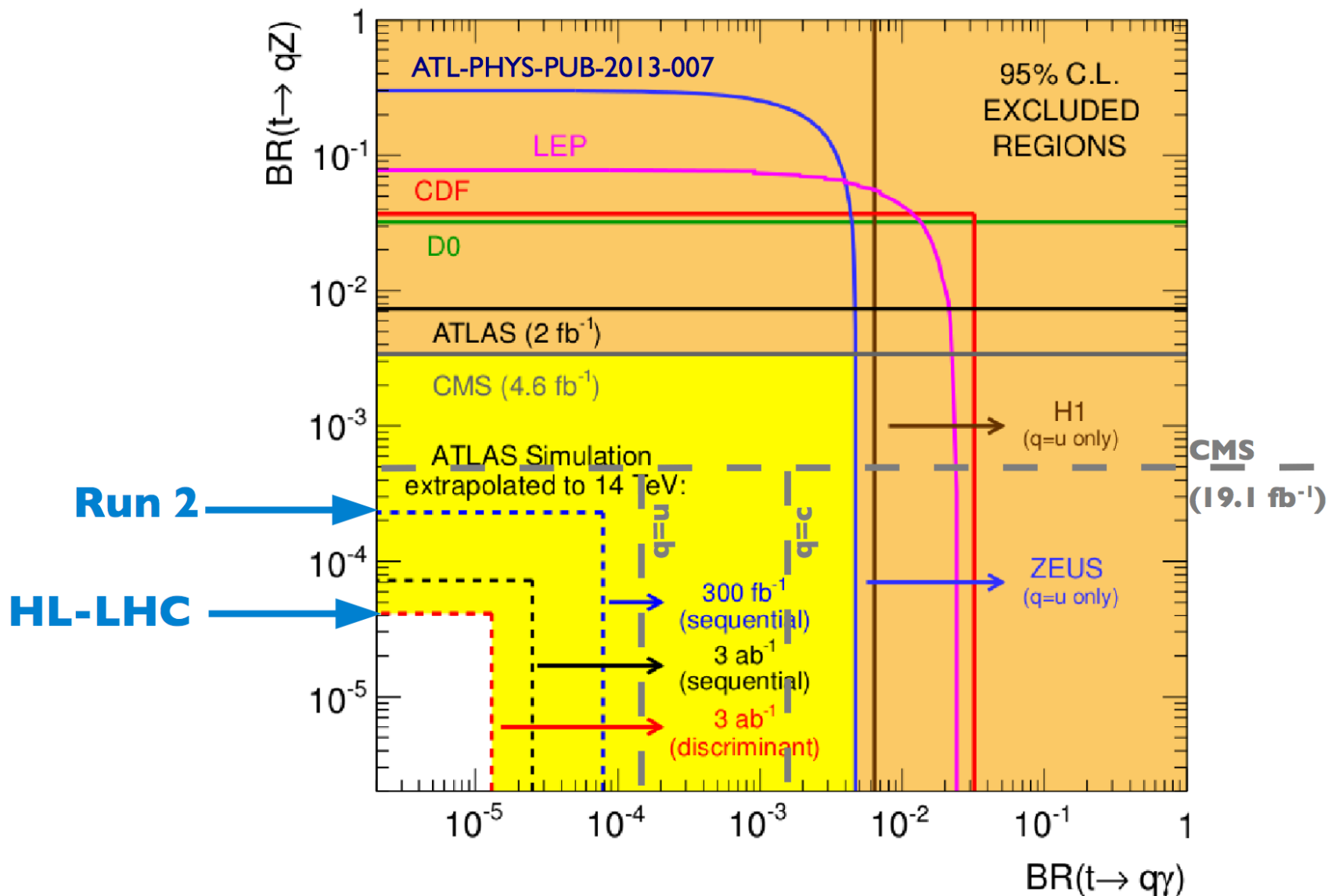






# FCNC prospects

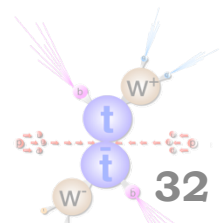
- Expect further (significant!) improvements at Run 2 and beyond





# *A few LHC summary plots*

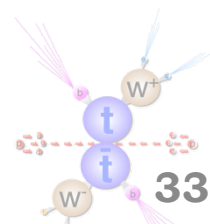
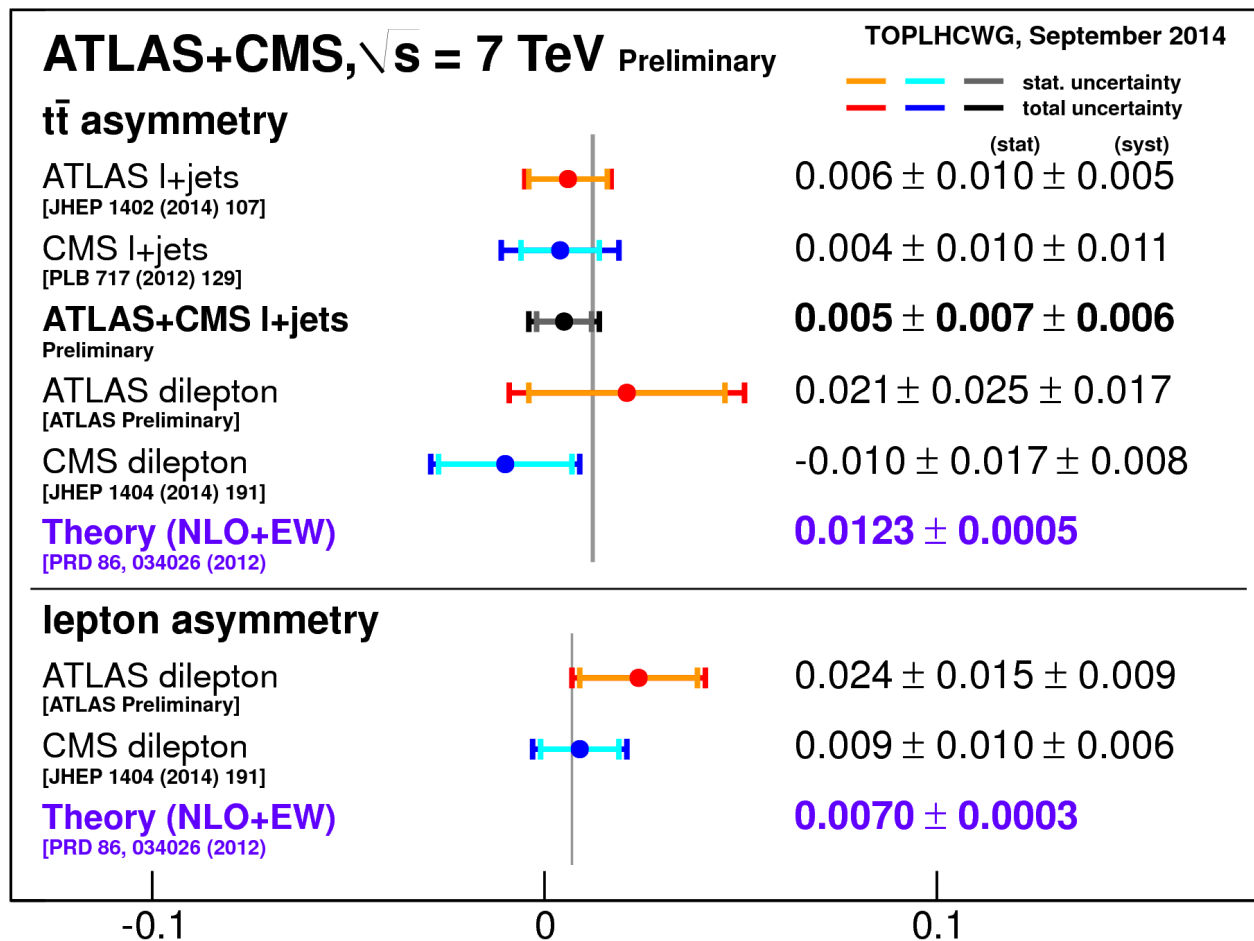
- Charge asymmetry
- Single top-quark production
- Top-quark pair production
- Results are summarized at
  - CMS
    - <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP>
  - ATLAS
    - <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults>
  - LHC WG
    - <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TopLHCWG>





# Charge asymmetry

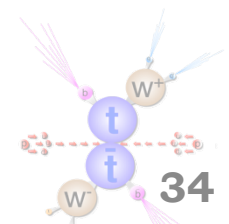
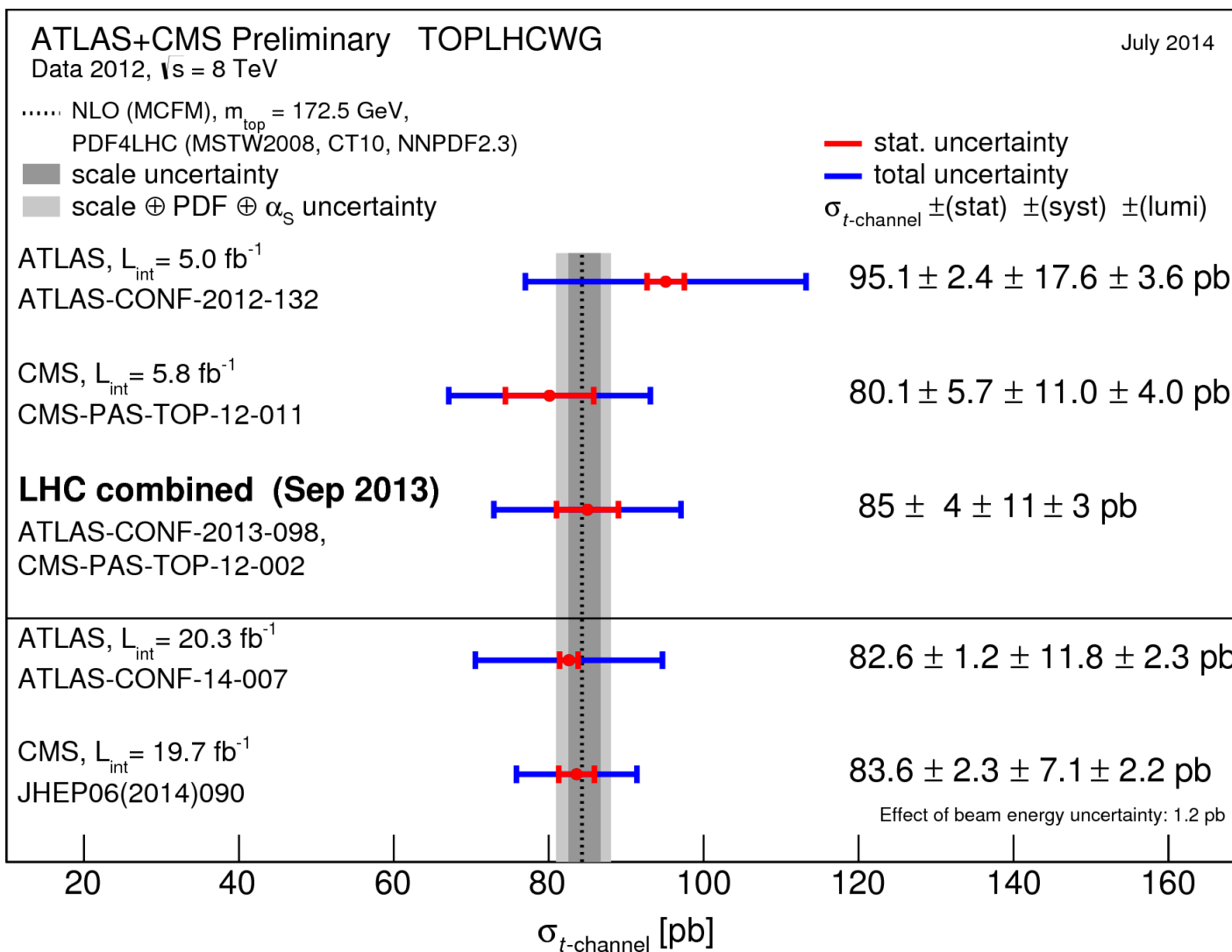
- Summary of the charge asymmetry measurements on ATLAS and CMS showing both the  $t\bar{t}$ -based and lepton-based asymmetry measurements
  - The uncertainty on the theory predictions is shown but is very small





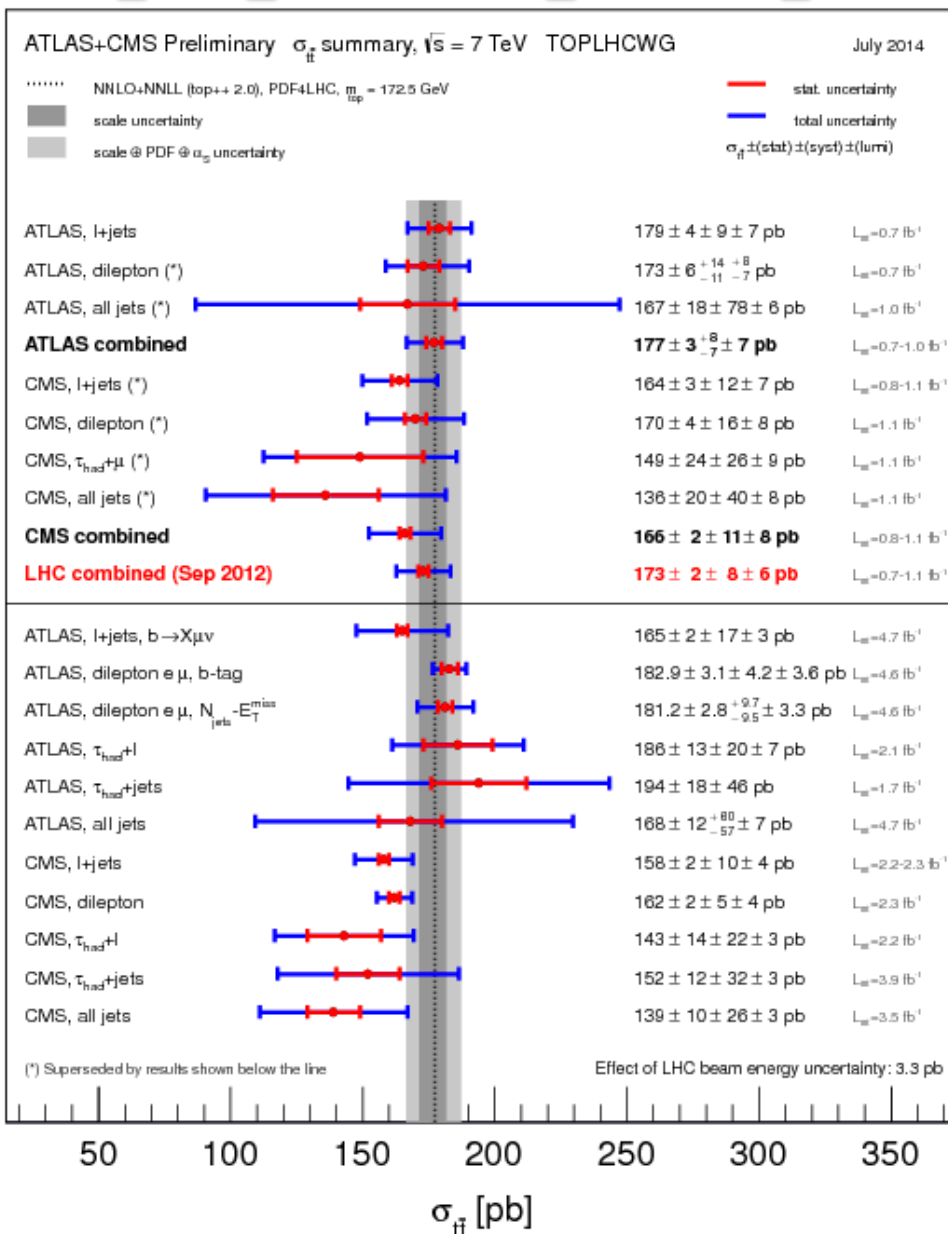
# Single top-quark: t-channel @ 8 TeV

- Summary of ATLAS and CMS measurements of the single top production cross section in t-channel @ 8 TeV



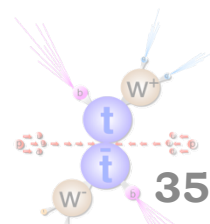


# Top-quark pair production @ 7 TeV



- Summary of ATLAS and CMS measurements of top-quark-pair production @ 7 TeV

- The theory band represents uncertainties due to renormalisation and factorisation scale, parton density functions and the strong coupling

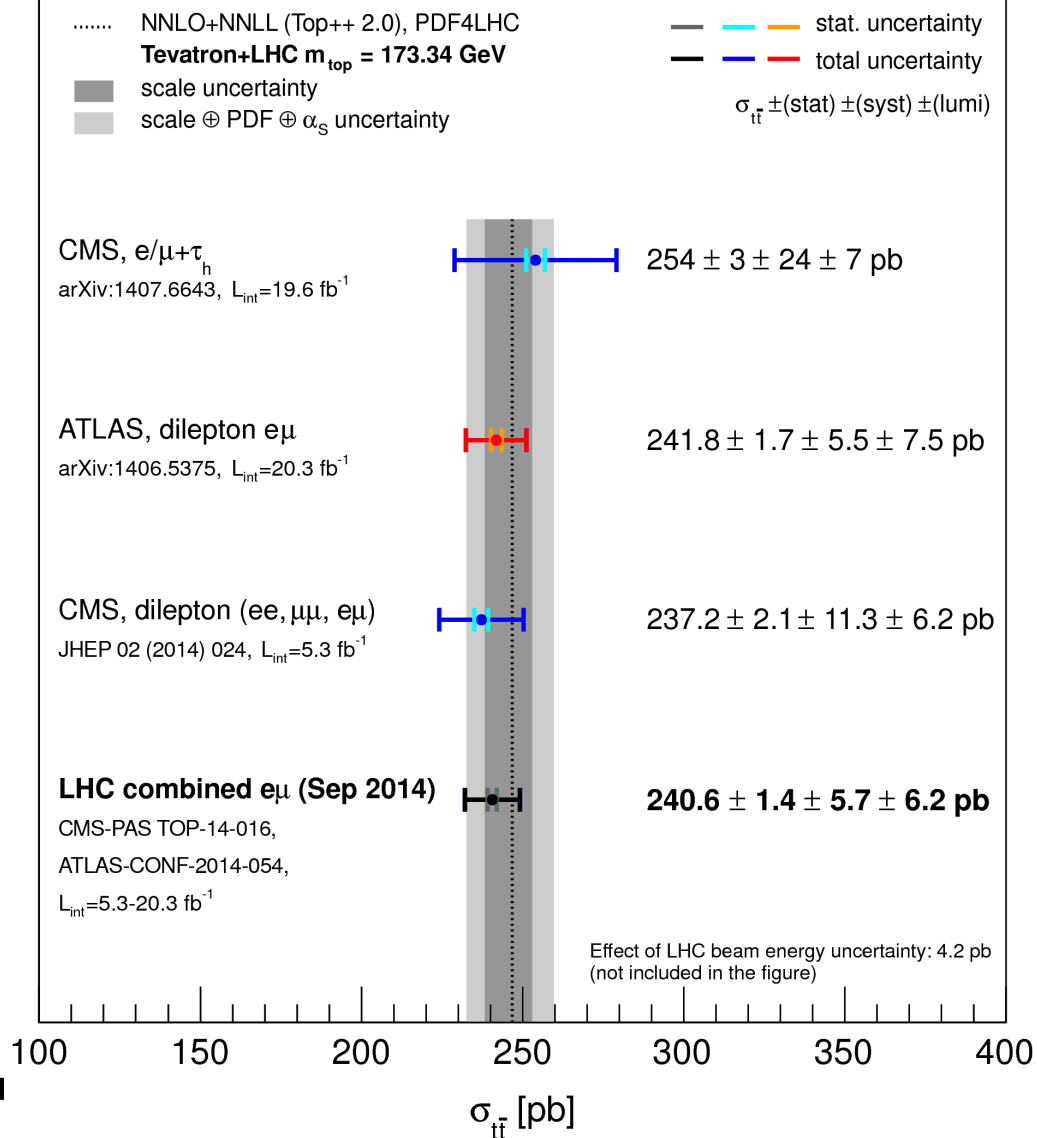






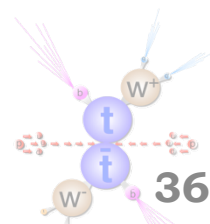
# Top-quark pair production @ 8 TeV

ATLAS+CMS Preliminary  $\sigma_{t\bar{t}}$  summary,  $\sqrt{s} = 8$  TeV TOPLHCWG Sep 2014



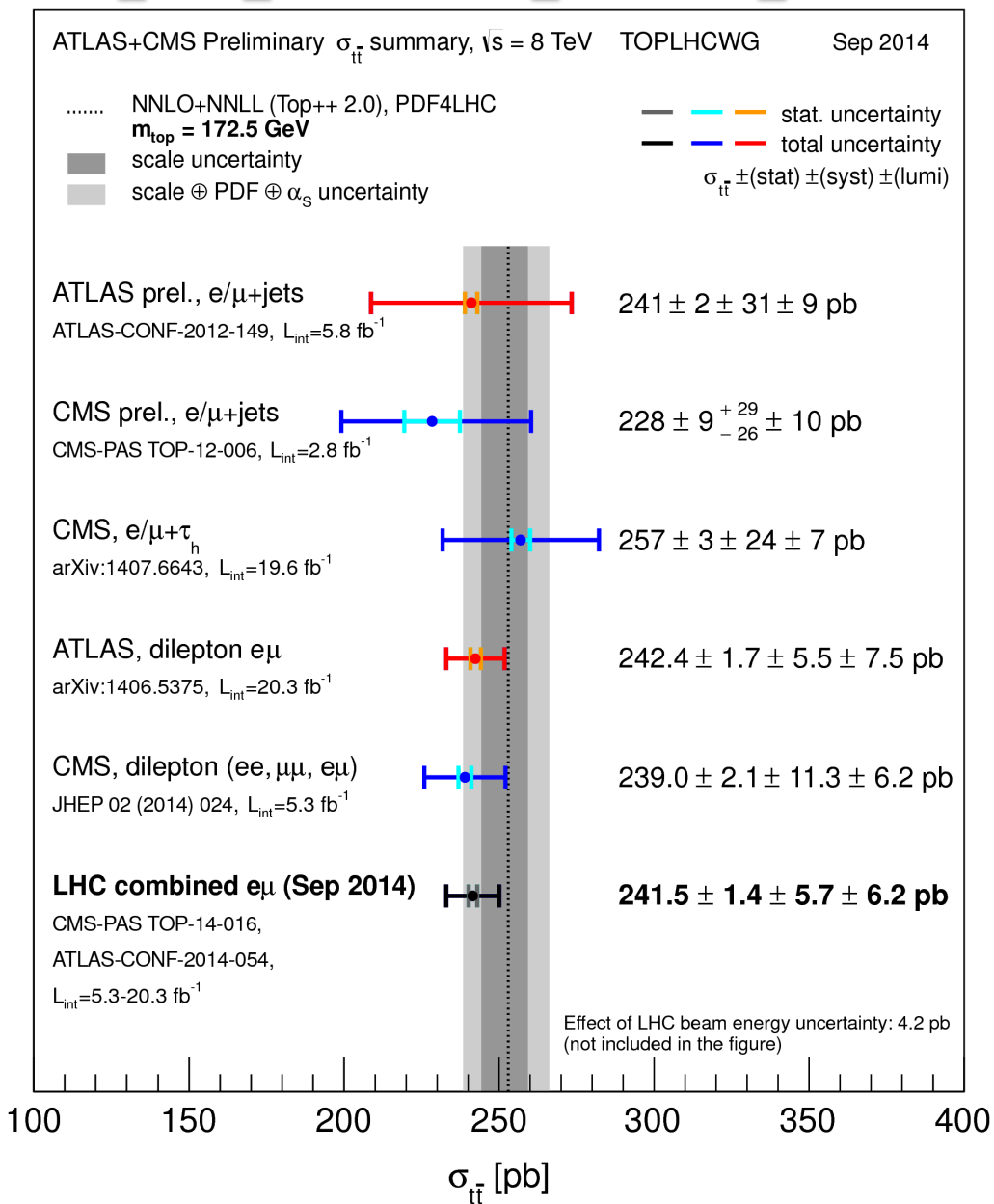
## Summary of ATLAS and CMS measurements of top-quark-pair production @ 8 TeV

- The theory band represents uncertainties due to renormalisation and factorisation scale, parton density functions and the strong coupling





# Top-quark pair production @ 8 TeV



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