



SM and Top quark results at LHC

Huaqiao ZHANG (IHEP)

Results from ATLAS and CMS collaboration

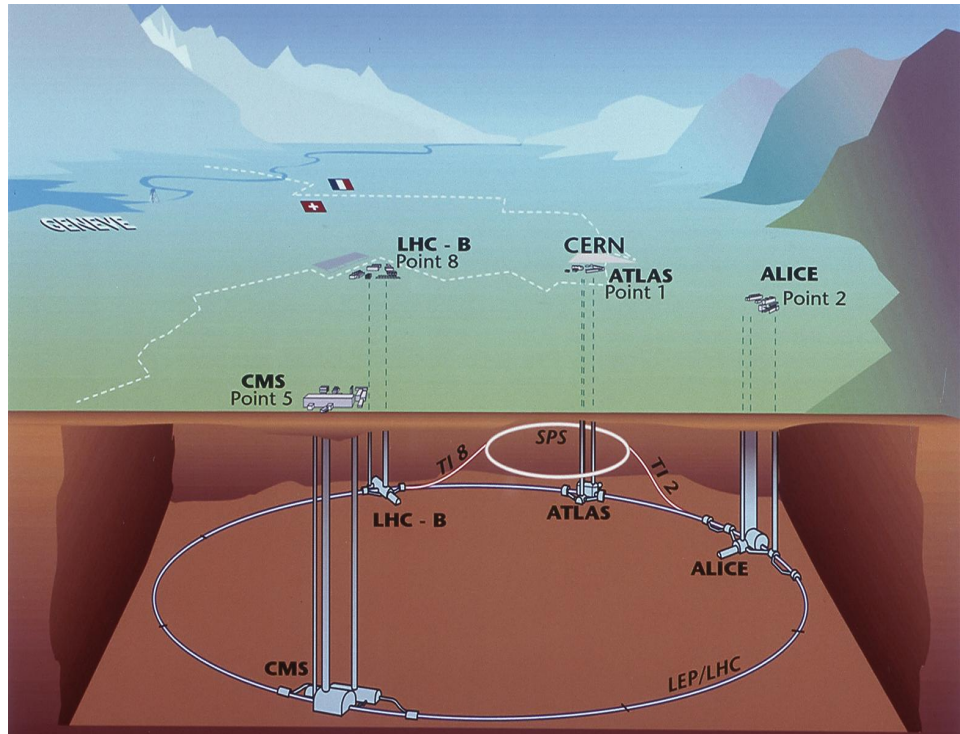
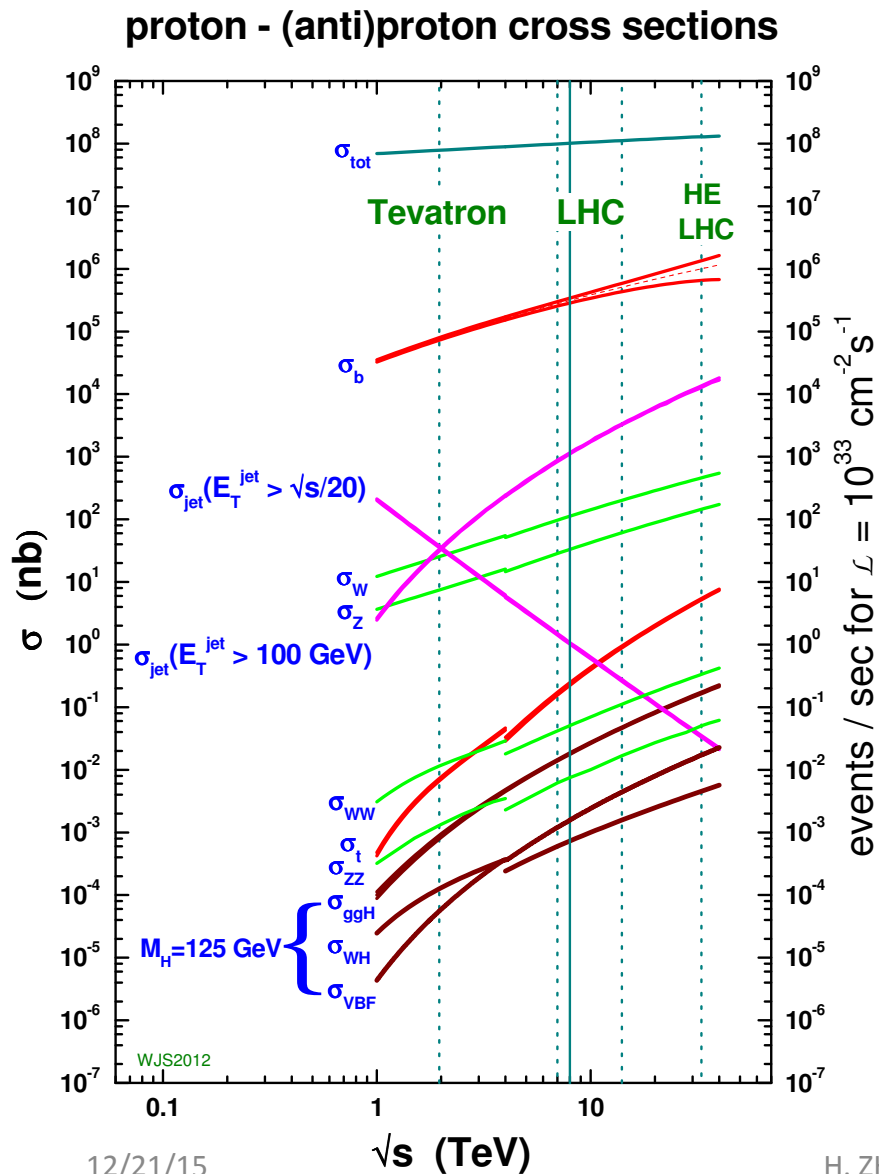
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic>

<http://cms-results.web.cern.ch/cms-results/public-results/publications>

Outline

- Introduction
- SM and top quark results of 8 TeV @ LHC
 - Soft QCD
 - Vector boson results
 - Top quark results
- SM and top quark results of 13 TeV @ LHC

LHC: The energy frontier

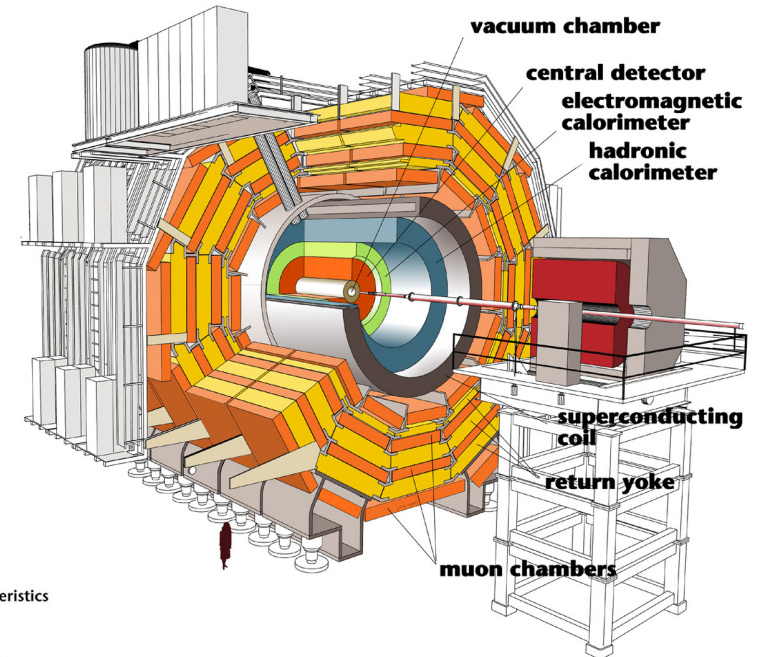
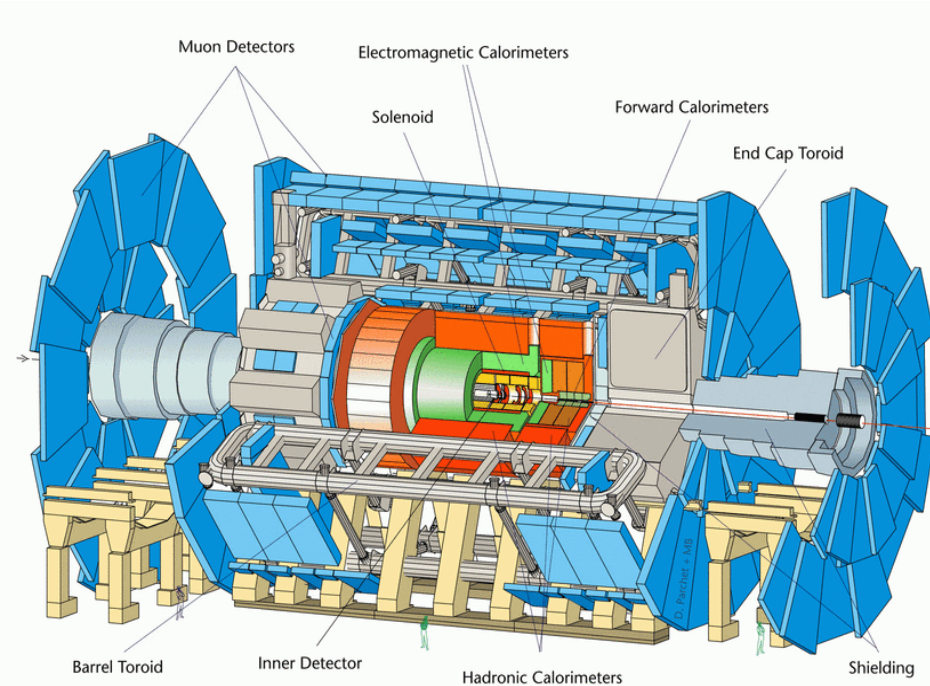


Large Hadron Collider (LHC):

A machine that has highest E_{cm} that mankind ever made

Located at CERN, 27km tunnel, 14 TeV E_{cm}

ATLAS and CMS: eyes at LHC



Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

Precise Inner Tracking including pixel for vertex

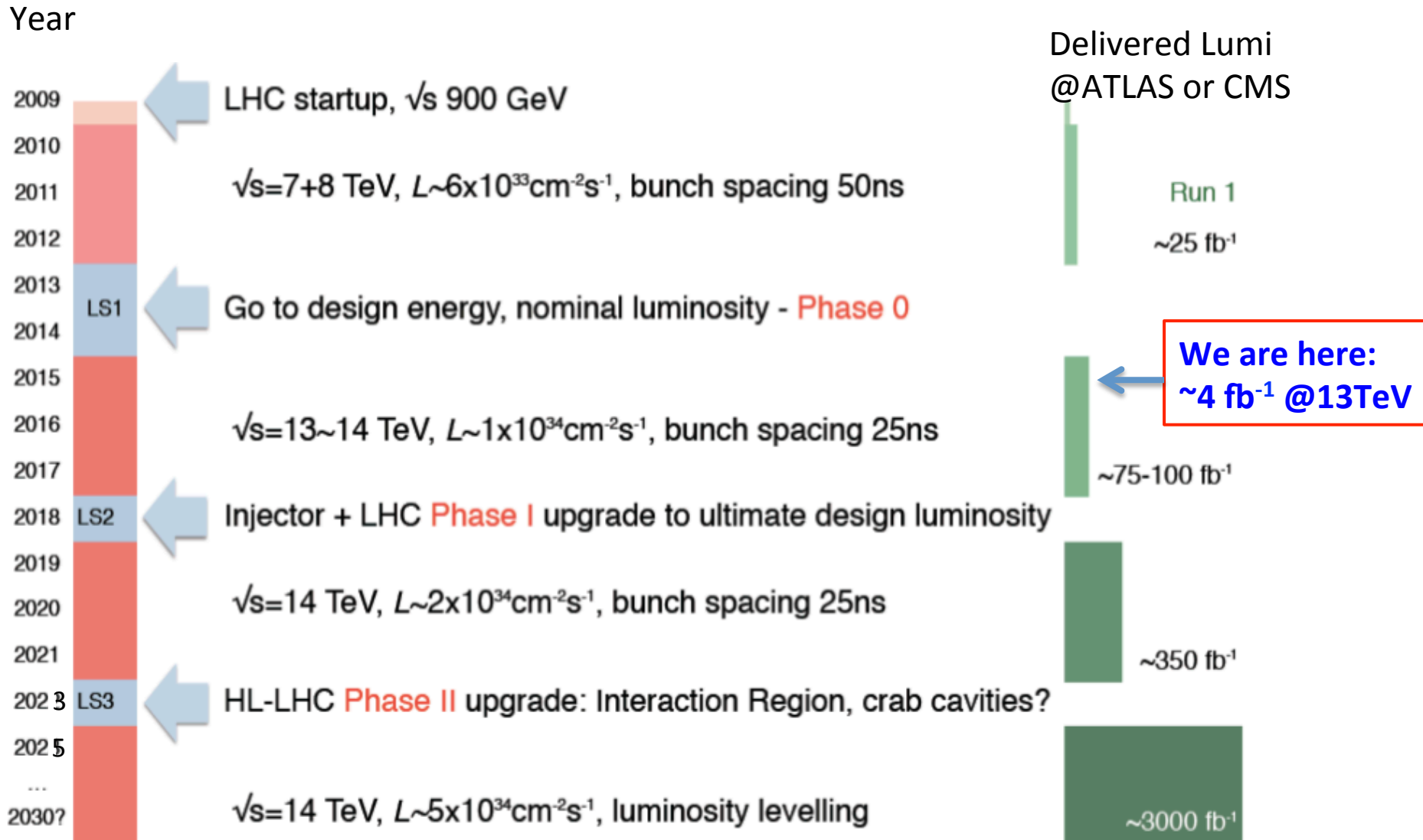
Dedicated EM and Hadronic calorimeter

Accurate Muon spectrometer

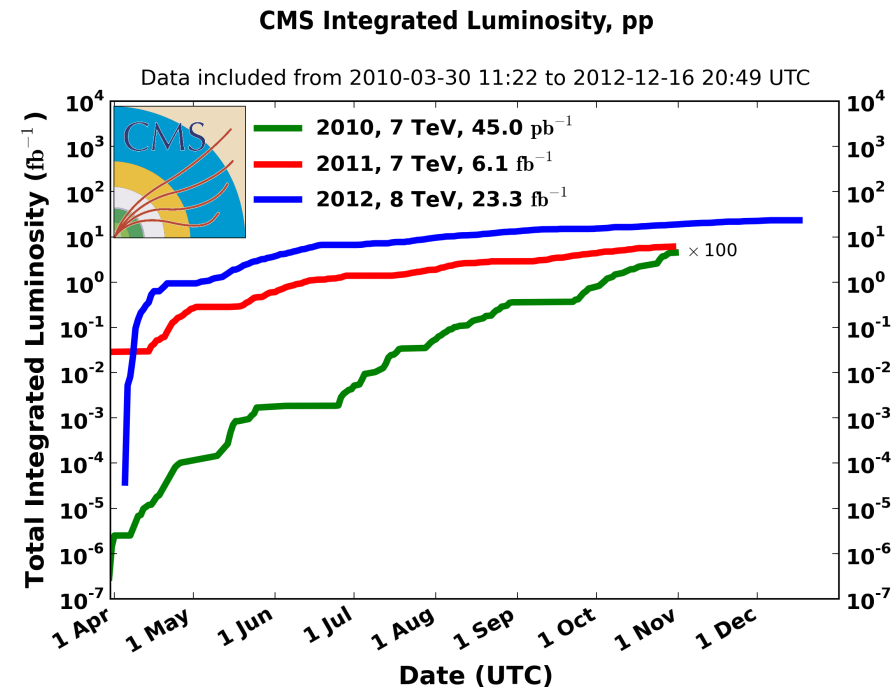
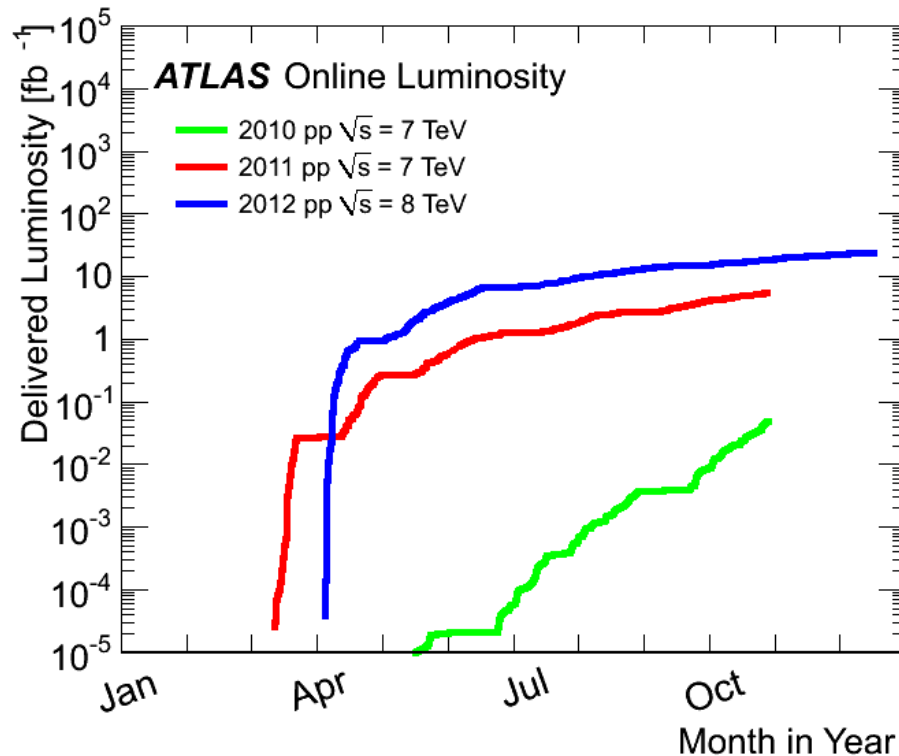
**ID elec/gamma,
Muon, Jet, tau,
B-taging, MET**

**=> Guaranty
Physics outputs**

Schedule of LHC running



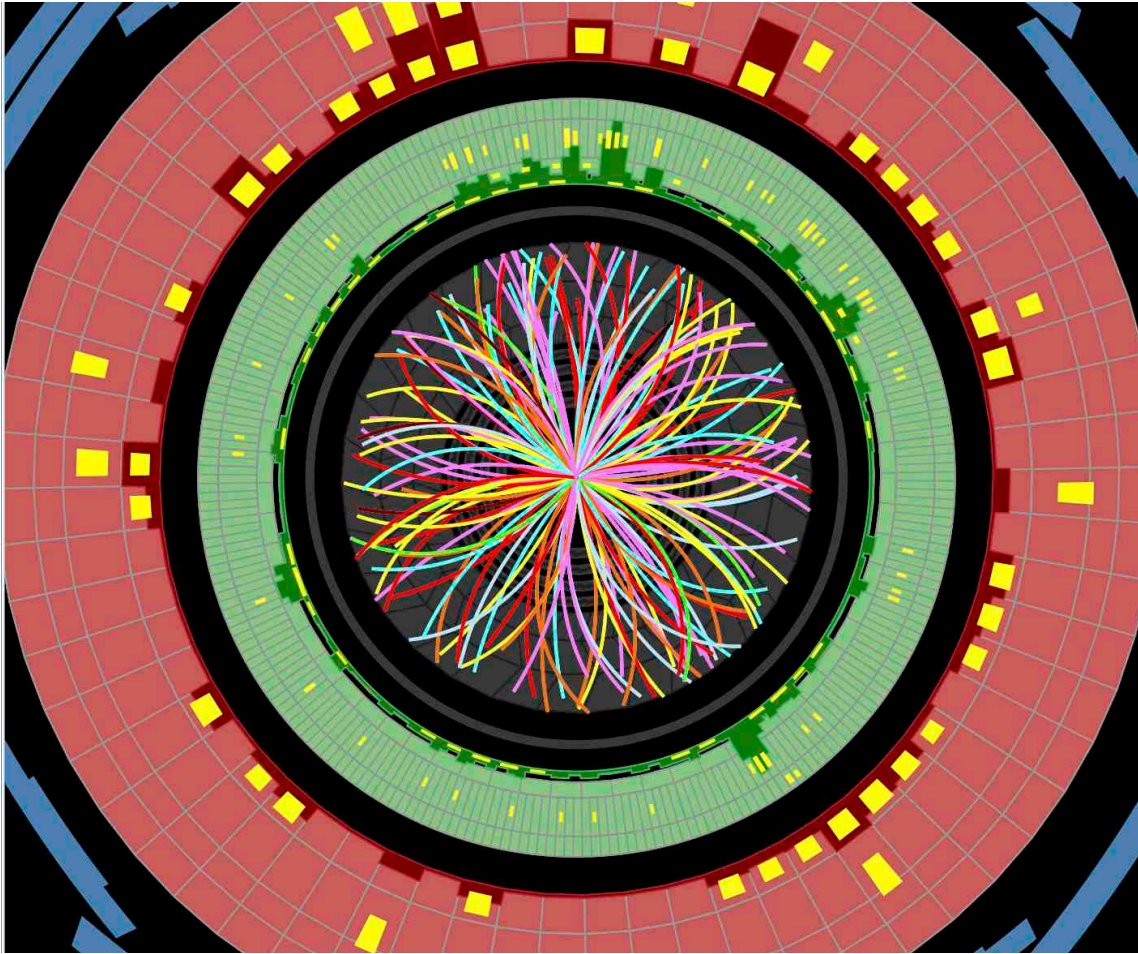
Precision SM/top tests at 7/8 TeV



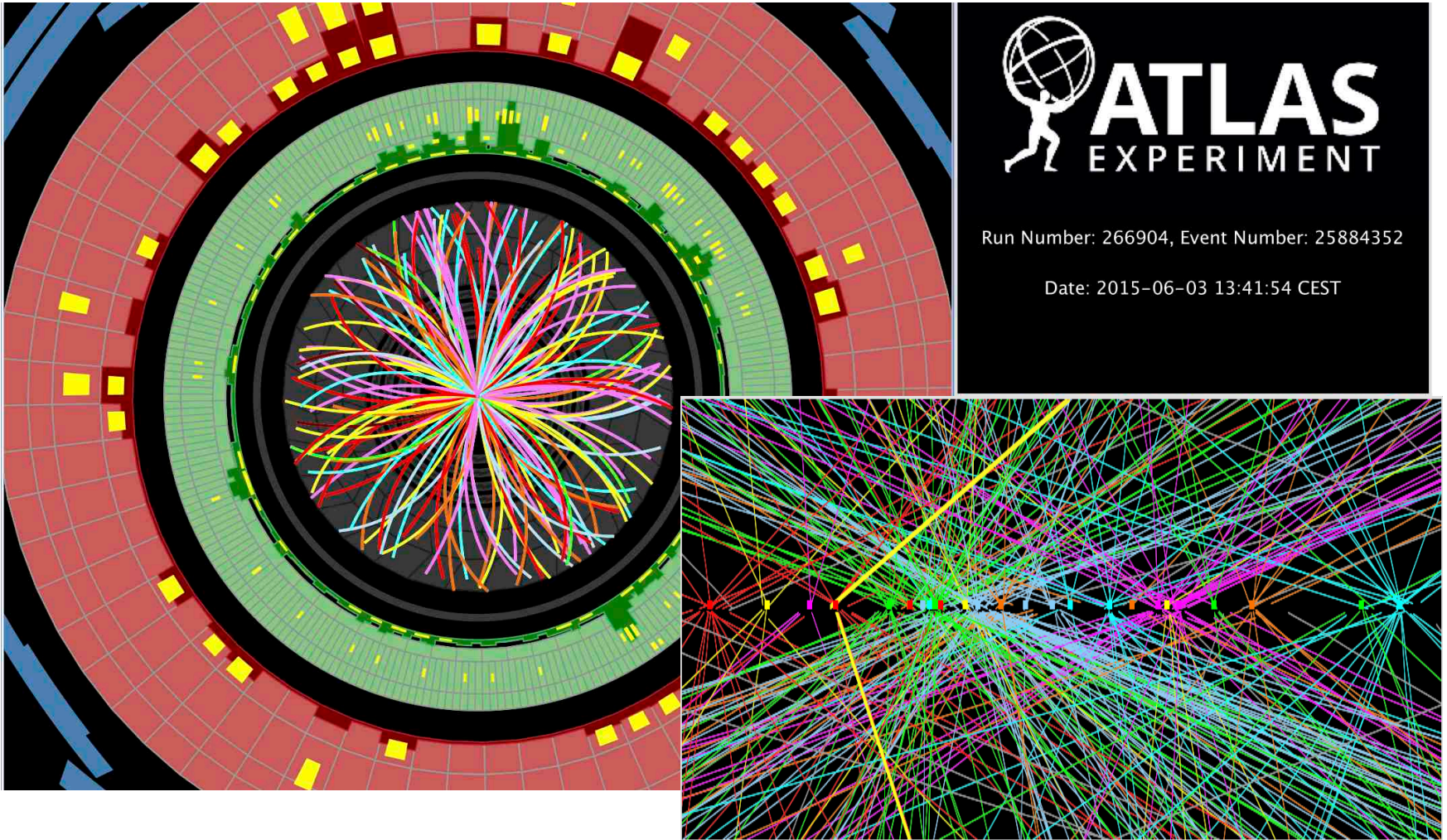
ATLAS and CMS each has accumulated $\sim 25 \text{ fb}^{-1}$ 7/8TeV data during 2010-2012

- Soft QCD analysis
- Vector boson analysis
- top quark analysis
- Precision SM/top tests can be done!

A typical event at ATLAS/CMS

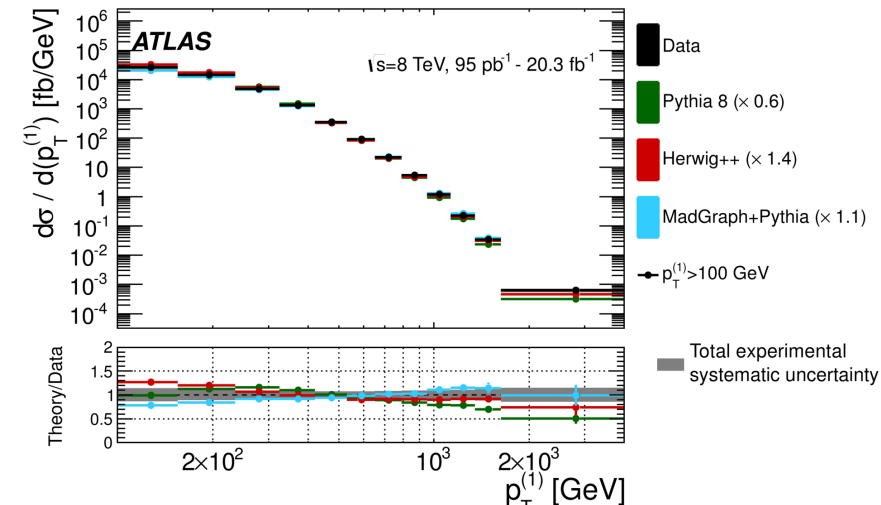
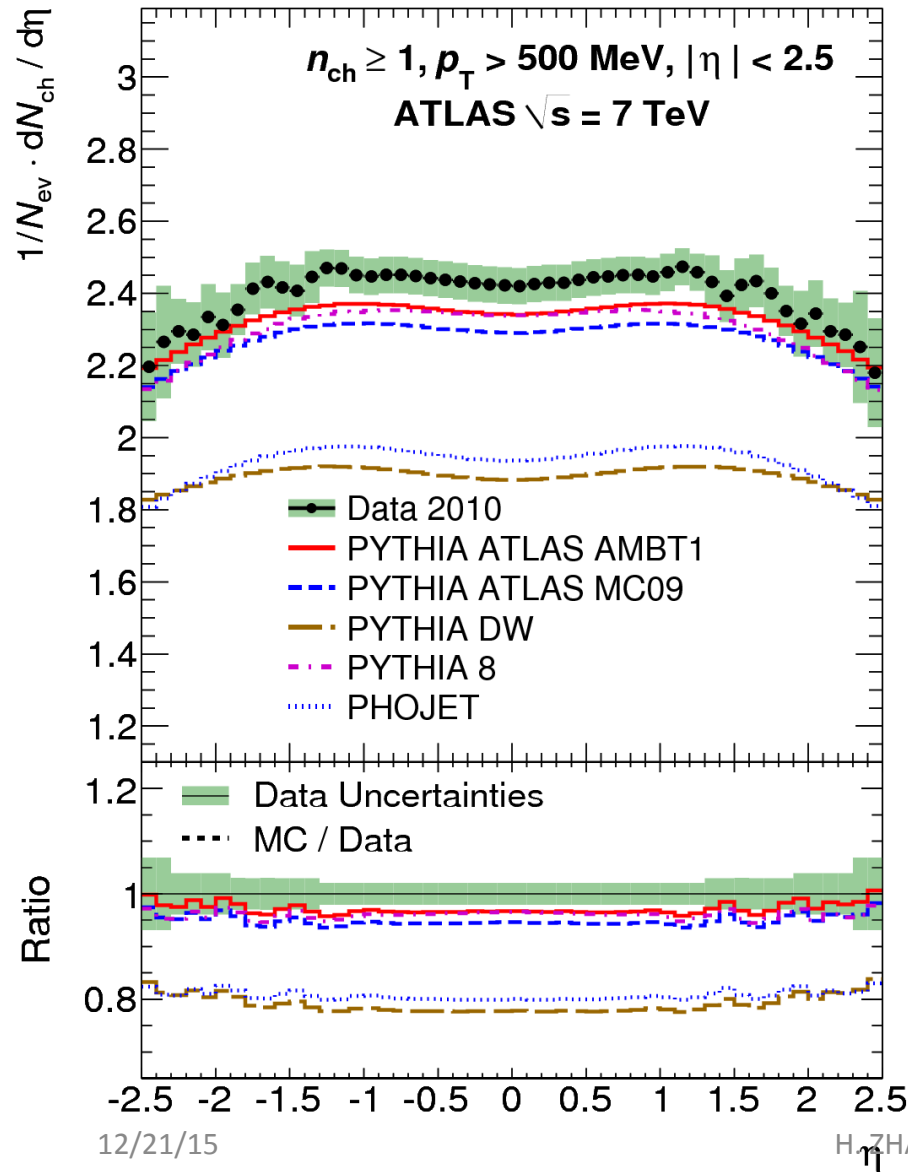


A typical event at ATLAS/CMS

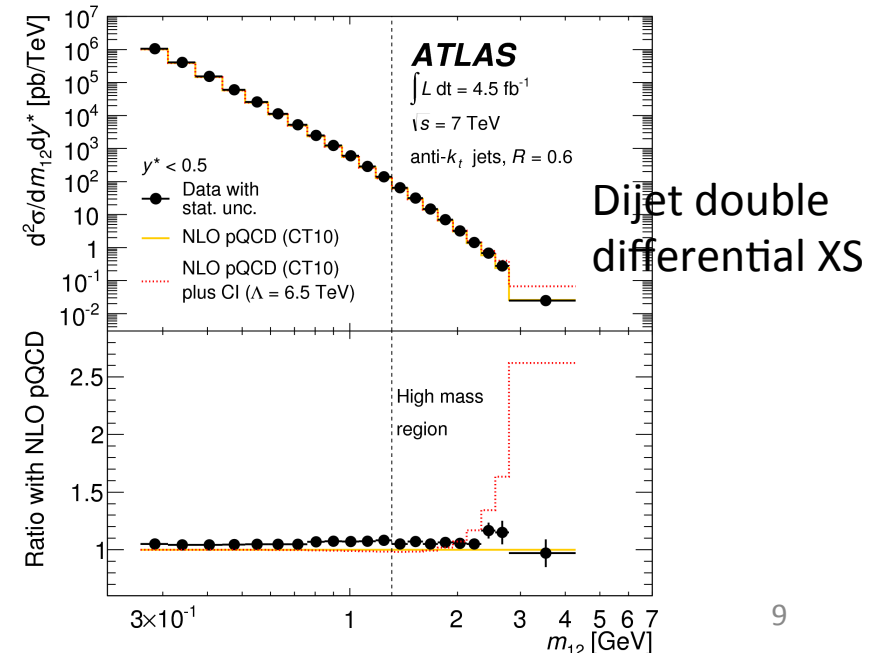


It is mandatory to understand all these SM process before claim a discovery!

Multi-jet and underlying events



4 jet differential cross section

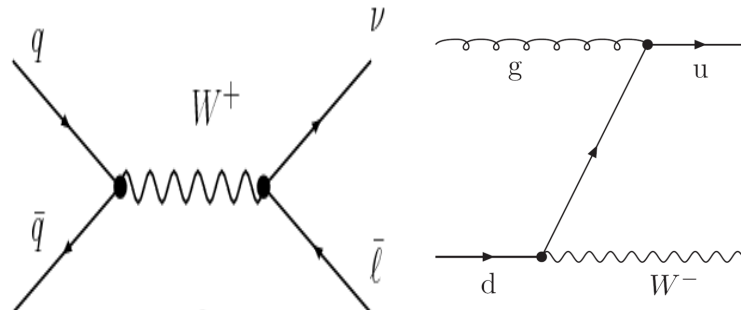
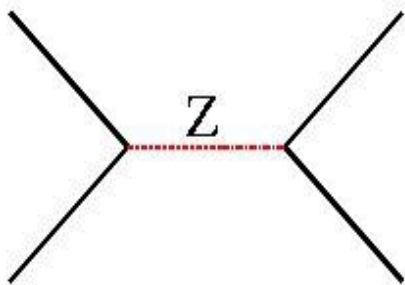
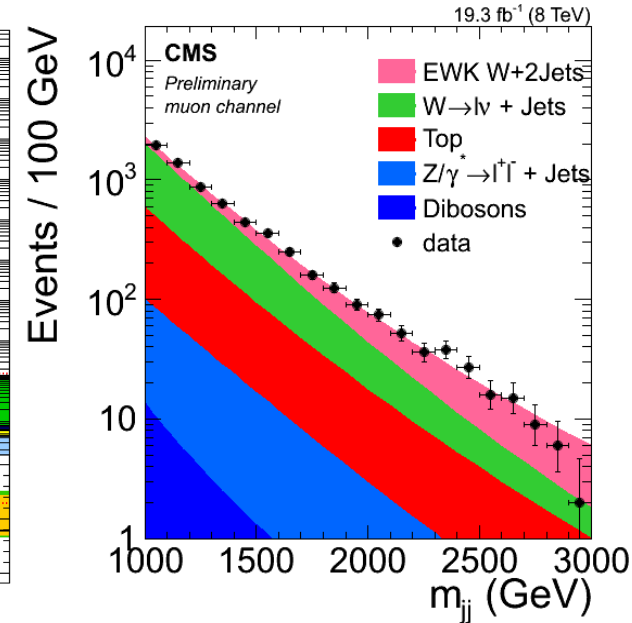
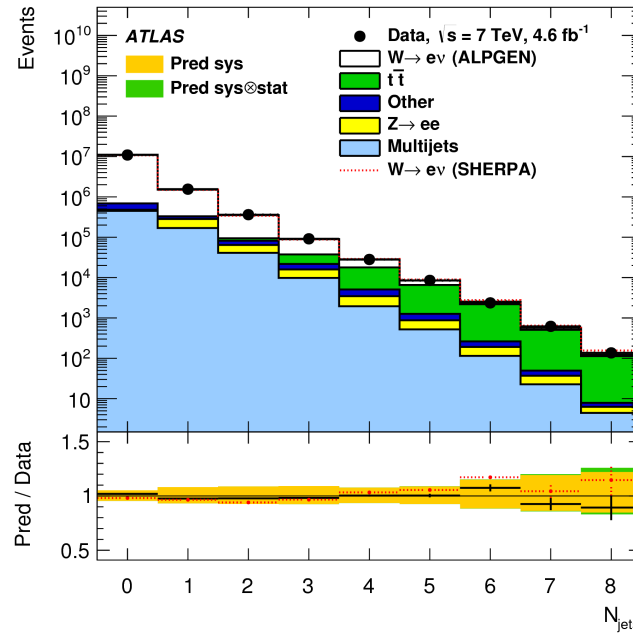
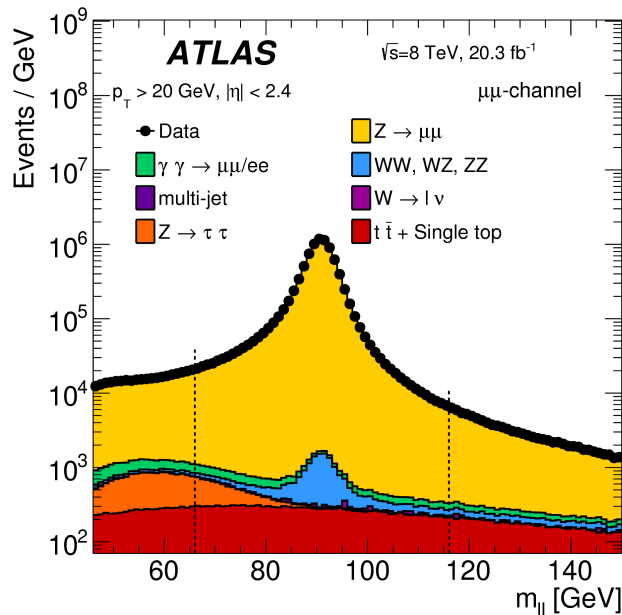


W+jets and Z+jets production@LHC

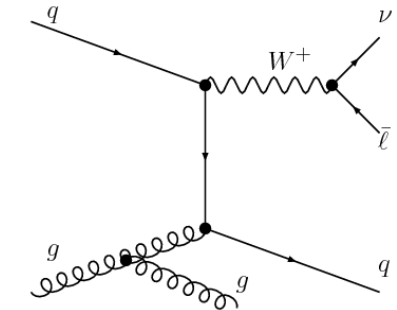
arXiv:1512.02192

Eur. Phys. J. C (2015) 75:82

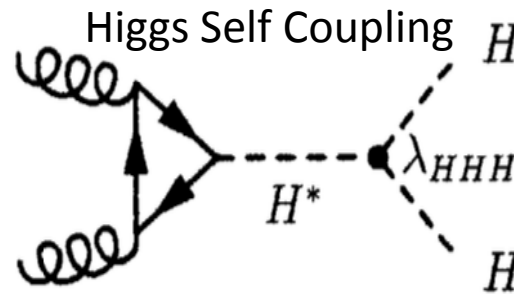
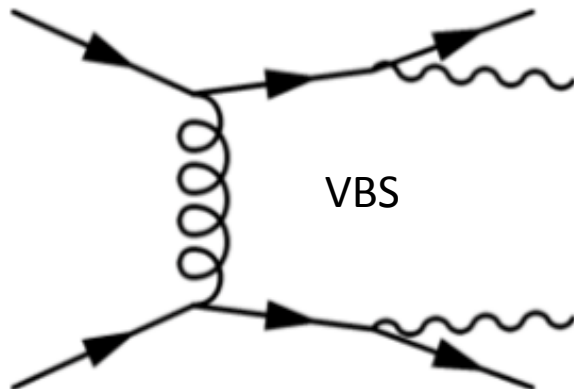
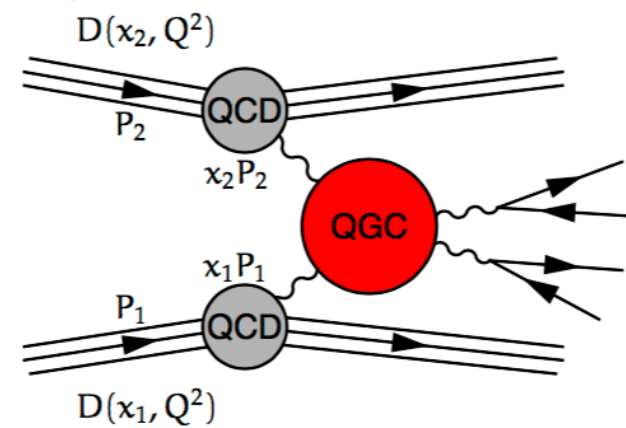
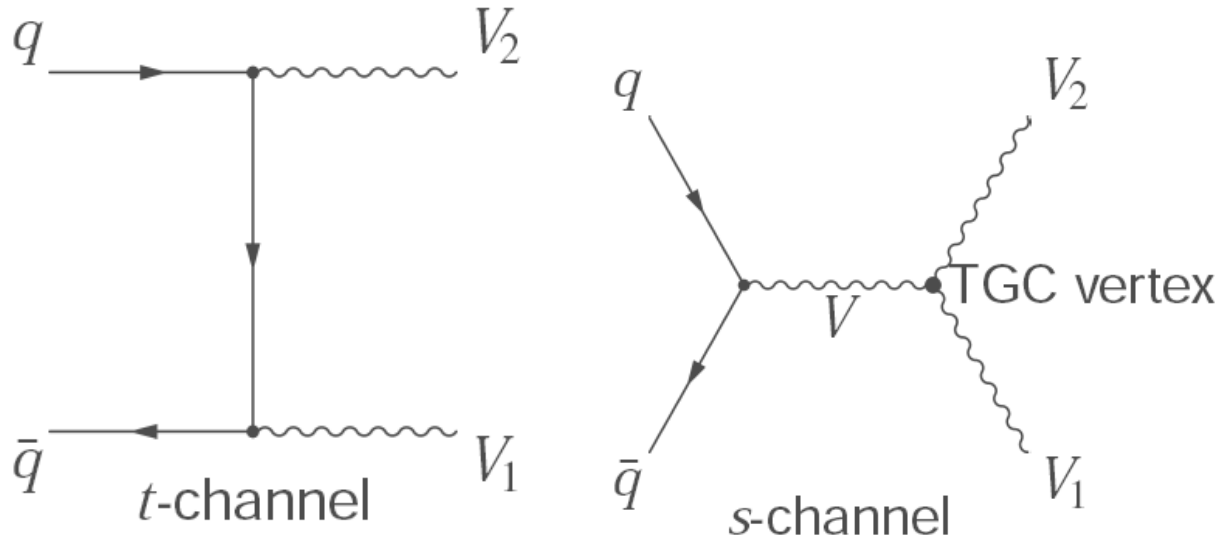
CMS-PAS-SMP-13-012



W+2jets, by Li J.



Multi-boson production @ LHC

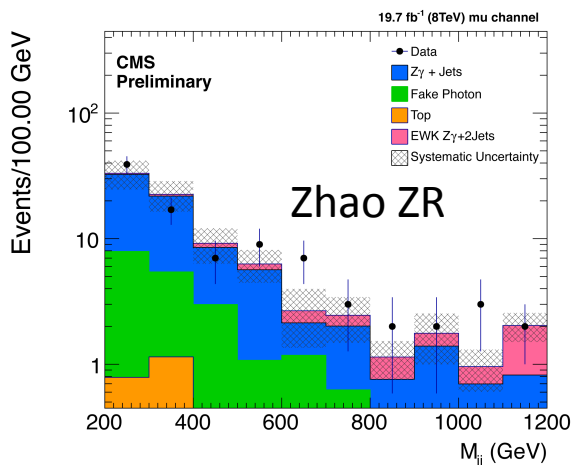


Lot's of (new) physics

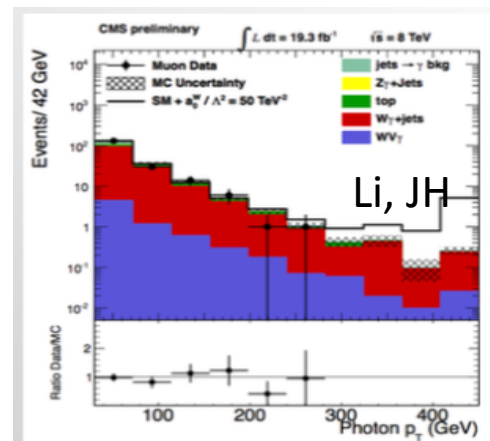
Multi-boson+X

Covered by Chinese?	Gamma+X	W+X	Z+X	H+X
gamma	Y	Y	Y	?
W		Y	Y	Y
Z			Y	Y
H				Y

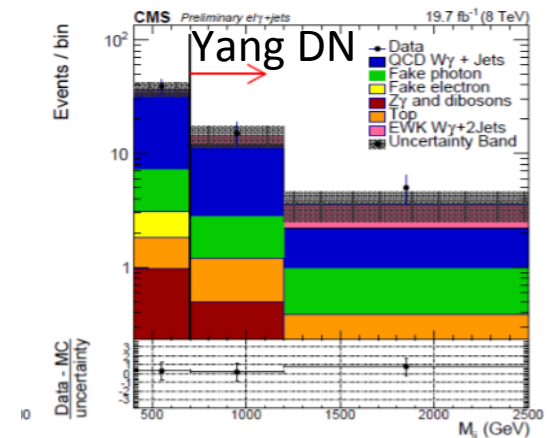
- Chinese colleagues join all multi-boson analysis
 - Except H+gamma+X that I am not aware of anyone did
 - Many contact person/editor/approval talk



First Zgamma+2jets evidence



W/Z+gamma search limit

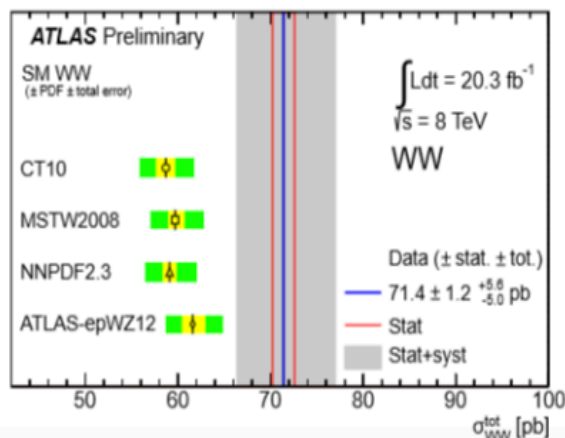
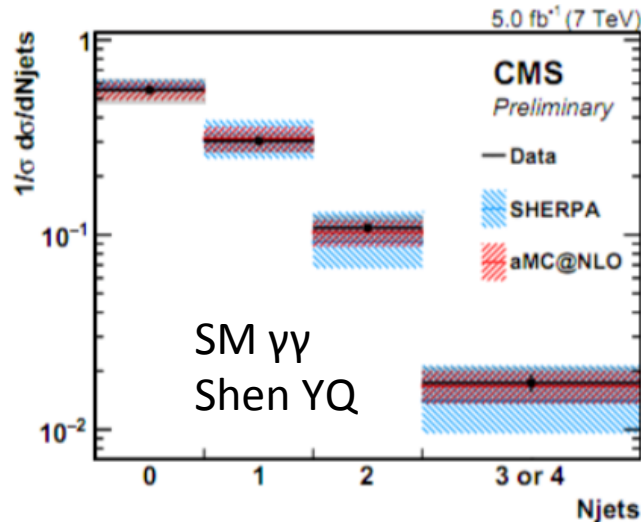
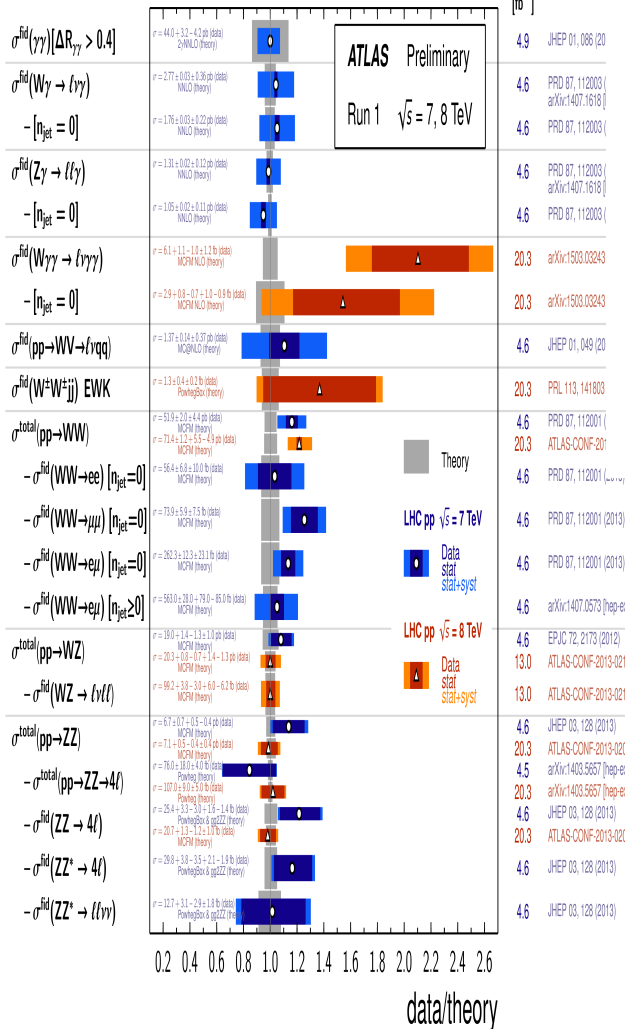


W+gamma+2jets search

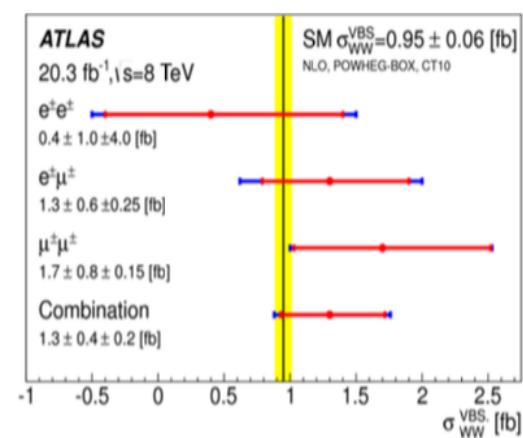
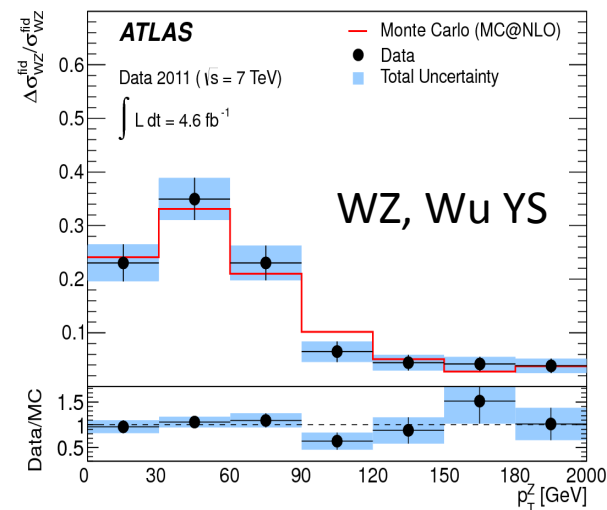
Multi-boson+X results

Multiboson Cross Section Measurements

Status: Nov 2015



WW, Li S, et al
H. ZHANG (IHEP)



VBS, Liu J.B.

Why Top Quark

Top quark

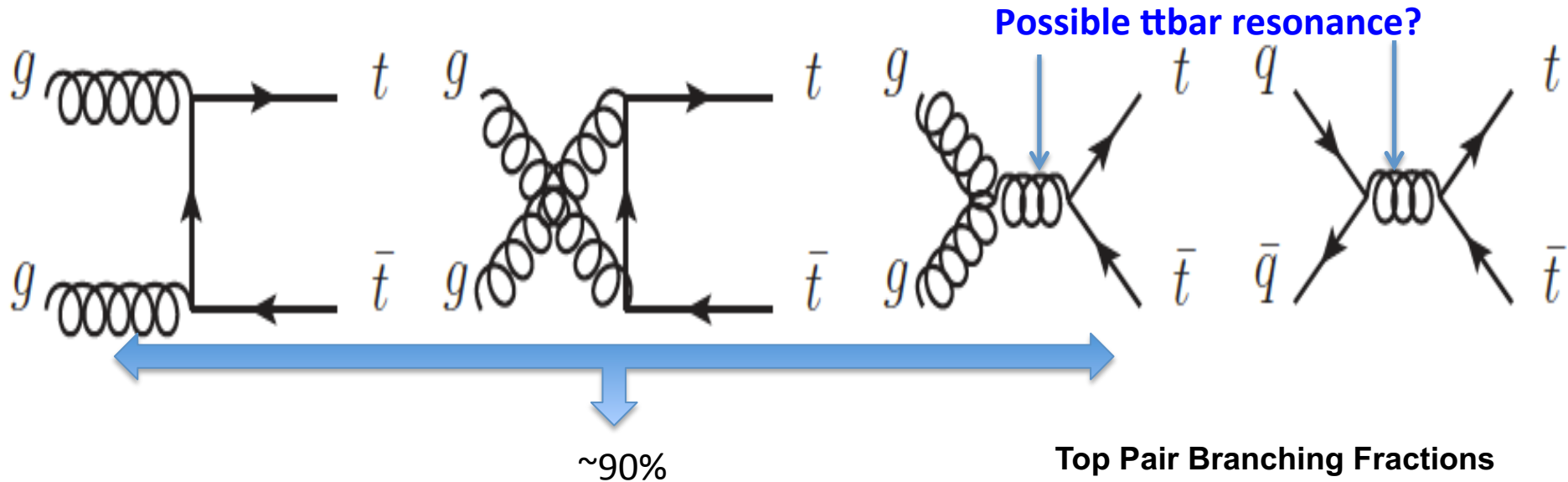


mass →	≈2.3 MeV/c ²	≈1.275 GeV/c ²	≈173.07 GeV/c ²	0	≈126 GeV/c ²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs boson
QUARKS					
	≈4.8 MeV/c ²	≈95 MeV/c ²	≈4.18 GeV/c ²	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d down	s strange	b bottom	γ photon	
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	91.2 GeV/c ²	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS					
	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	80.4 GeV/c ²	
	0	0	0	±1	
	1/2	1/2	1/2	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					GAUGE BOSONS

- **Mass:** ~173 GeV
 - The known heaviest element
- Large **Yukawa Couplings**
 - With Higgs: $Y_t = \sqrt{2}M_t/v_{\text{ev}} \sim 1$
- **Life time:** $\sim 4 \times 10^{-25}$
 - Decay before hadronization
→ bare quark
- Produced with strong or electroweak interaction
- Precision test of SM
 - $\alpha_s(M_t) \sim 0.1$
 - pQCD calculation accurate

top quark pair production @ LHC

- Predicted by SM, production via **strong** interaction



164^{+13}_{-10} pb @ 7TeV

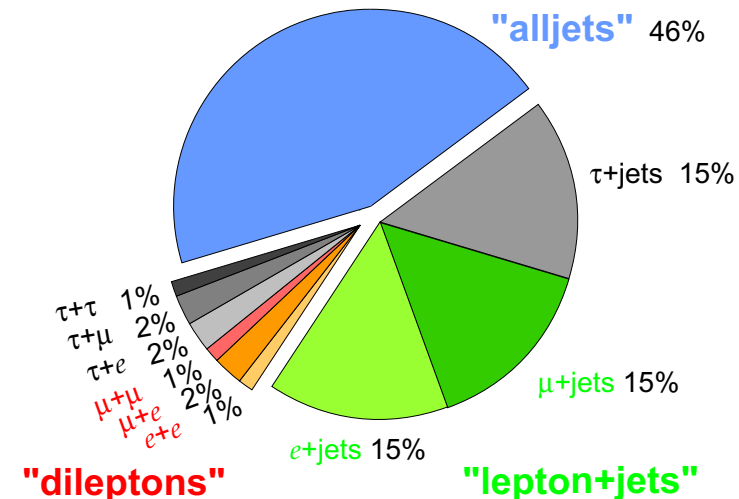
238^{+22}_{-24} pb @ 8TeV

830 pb @ 13TeV

Comput. Phys. Commun. 182 (2011) 1034

- First time observed at Tevatron in 1995

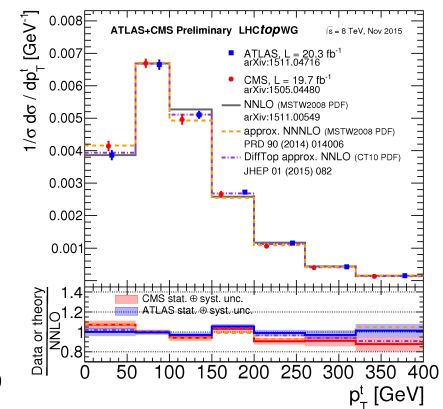
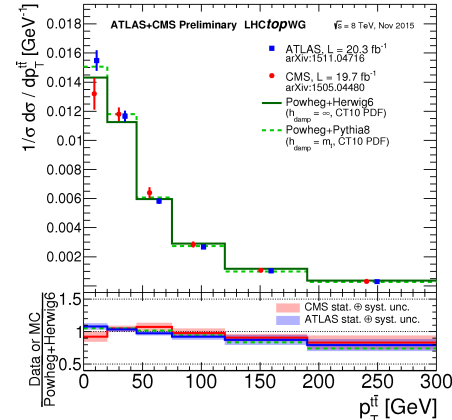
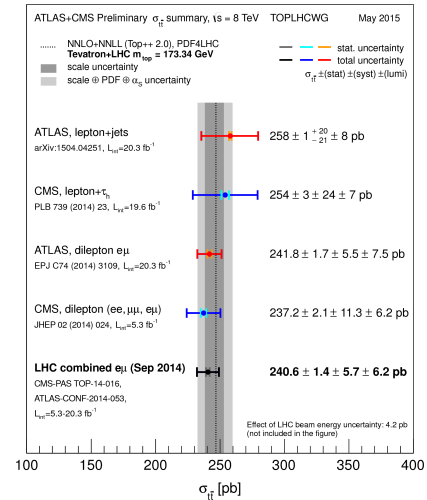
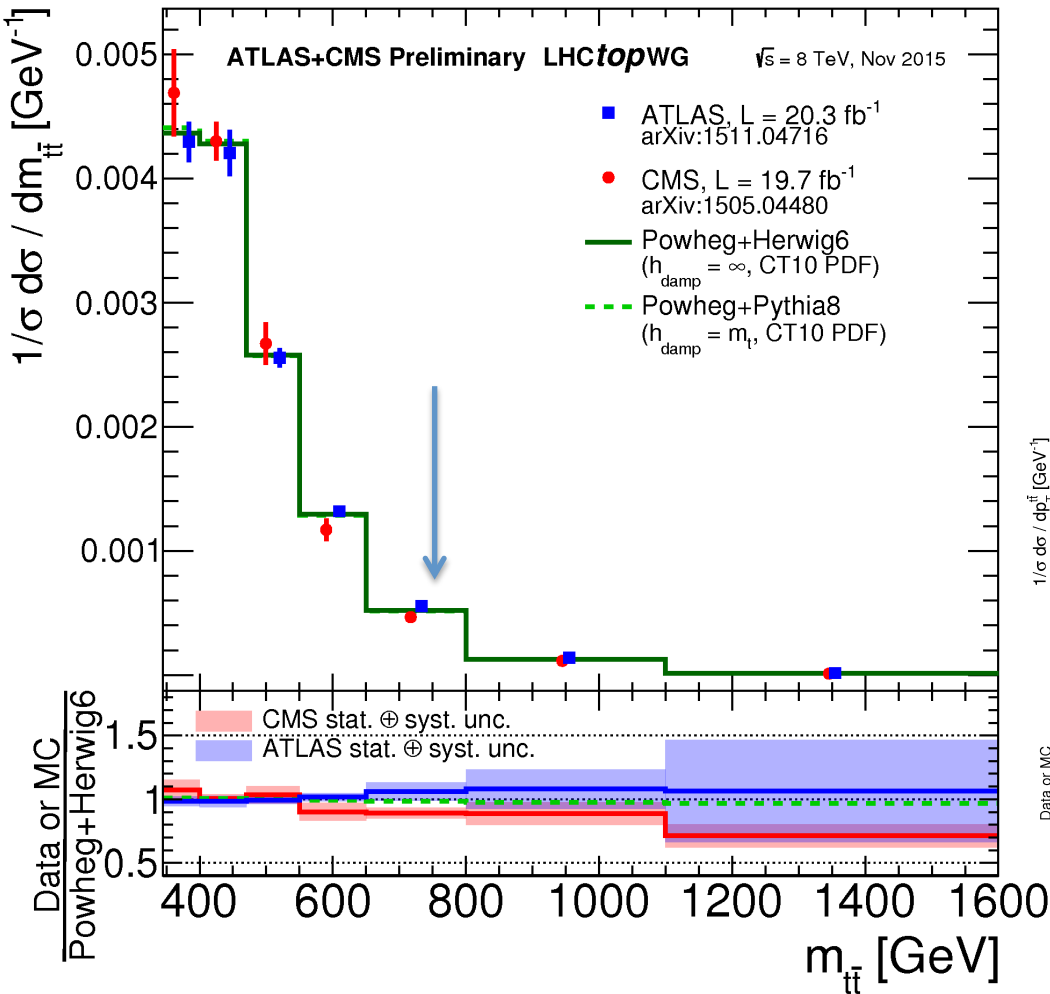
Top Pair Branching Fractions



Top pair event selection

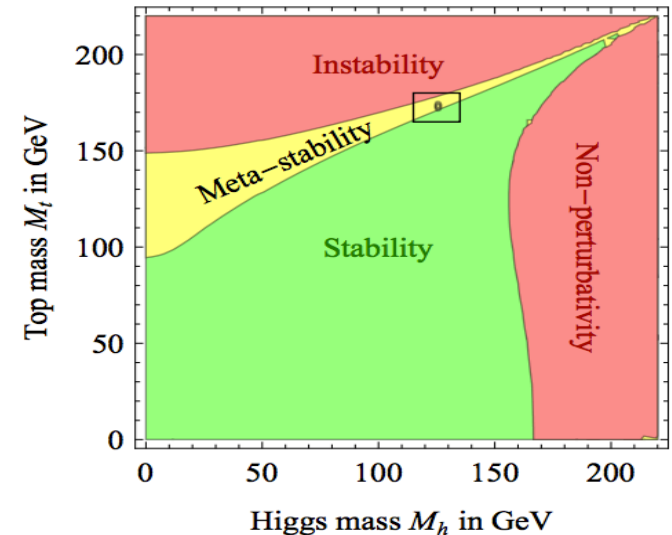
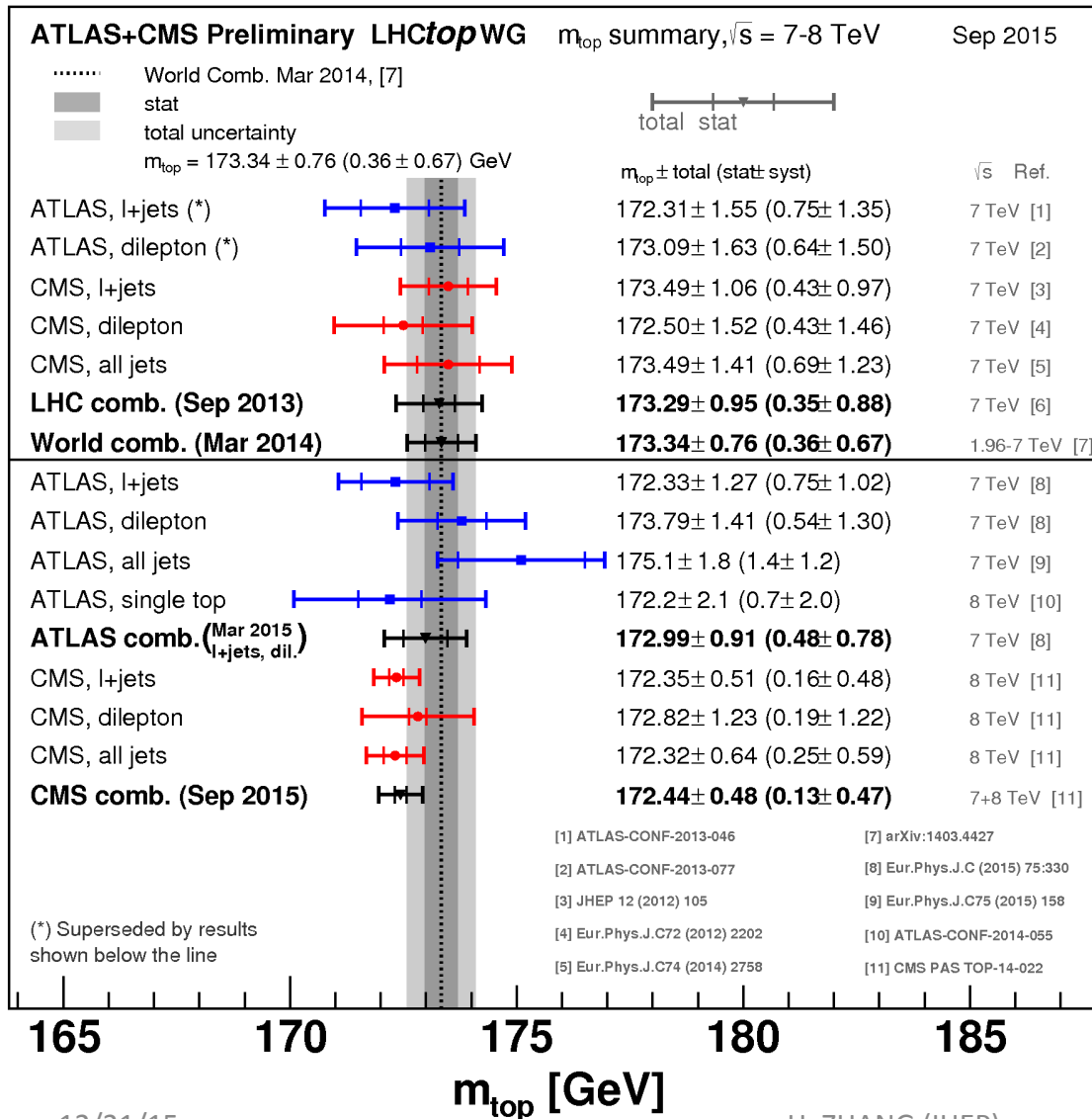
- Selection according to event final states
- **Lepton + jets channel**
 - One high Pt lepton (e/mu), typical $P_t > 25$ GeV
 - At least 4 high Pt jets, typical $P_t > 25$ GeV
 - B-jets multiplicity requires, typically =2
- **Dilepton channel**
 - Two high Pt lepton (e/mu), typical $P_t > 25$ GeV
 - At least 2 jets, typical $P_t > 25$ GeV
 - B-jets multiplicity requires, typically =2
- **Full hadronic channel**
 - At least 6 high Pt jets, of which 2 are b jets
- **Channel involve tau lepton**
 - Hadronic tau ID (tau equal e/mu in other topology)

Top pair production



Difference cross section as function of invariant mass of top pair
Pt of top pair or one top quark

Top quark mass

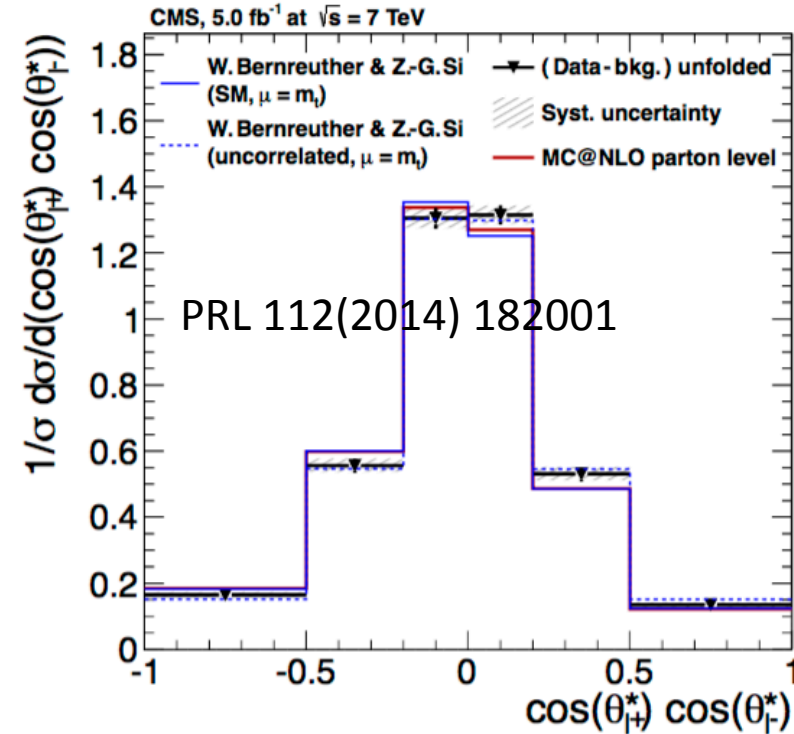
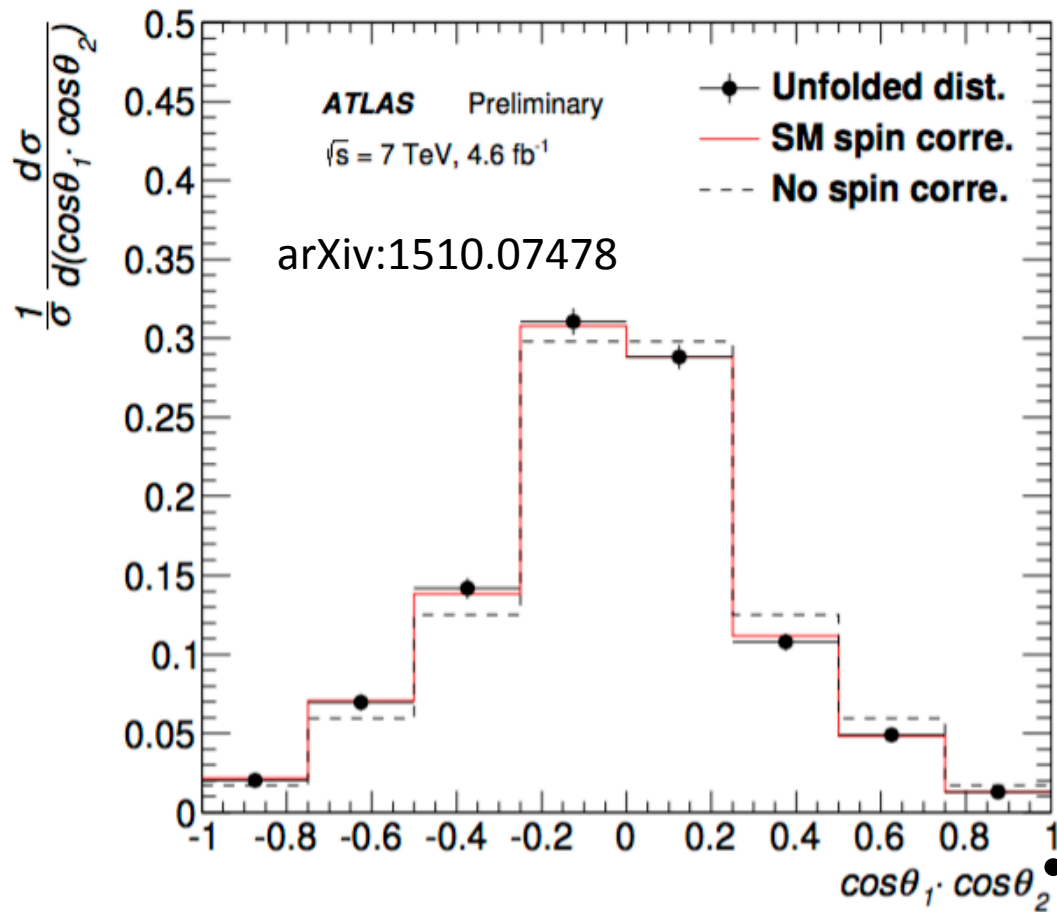


Top quark mass are measured in the **lepton+jets**, **dilepton** and **all jets** final states in $t\bar{t}$ events
 single top also contributes

World comb. (Mar. 2014)
 $173.34 \pm 0.36(\text{stat}) \pm 0.67(\text{syst})\text{ GeV}$

CMS comb. (Sep 2015)
 $172.44 \pm 0.13(\text{stat}) \pm 0.47(\text{syst})\text{ GeV}$

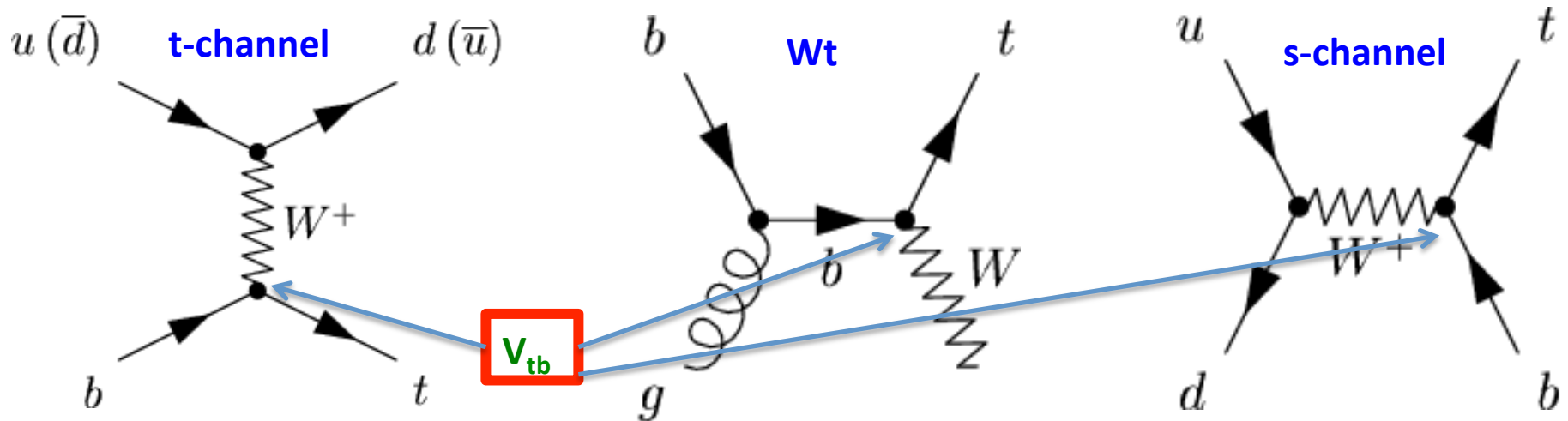
Top pair: spin correlation



- The decayed lepton from top pair correlated
- SDU contributed both to theory and ATLAS results

Single top-quark production @ LHC

- Predicted by SM, production via **electroweak** interaction: $|V_{tb}|$


$$64.6^{+2.7}_{-2.0} \text{ pb @ 7TeV}$$
 $87.8^{+3.4}_{-1.9} \text{ pb @ 8TeV}$

Calculated at NNLO approx.
N. Kidonakis, Phys. Rev. D 83
(2011) 091503

First observation
2009 @ Tevatron

12/21/15

15.7±1.1 pb @ 7TeV

22.4±1.5 pb @ 8TeV

Calculated at NNLO approx.
N. Kidonakis, Phys. Rev. D 82
(2010) 054018

First observation
2014 @ LHC

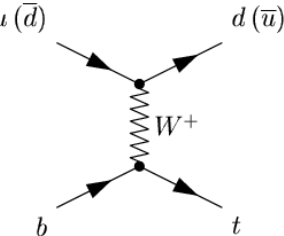
H. ZHANG (IHEP)

$4.6 \pm 0.2 \text{ pb @ 7TeV}$

$5.6 \pm 0.2 \text{ pb @ } 8\text{TeV}$

Calculated at NNLO approx.
N. Kidonakis, Phys. Rev. D 81
(2010) 054028

First observation
2014 @ Tevatron

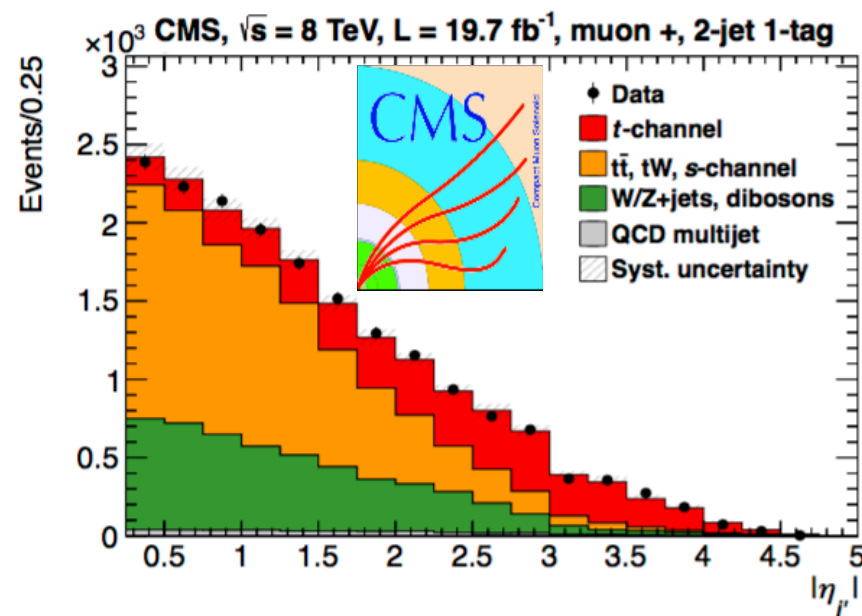
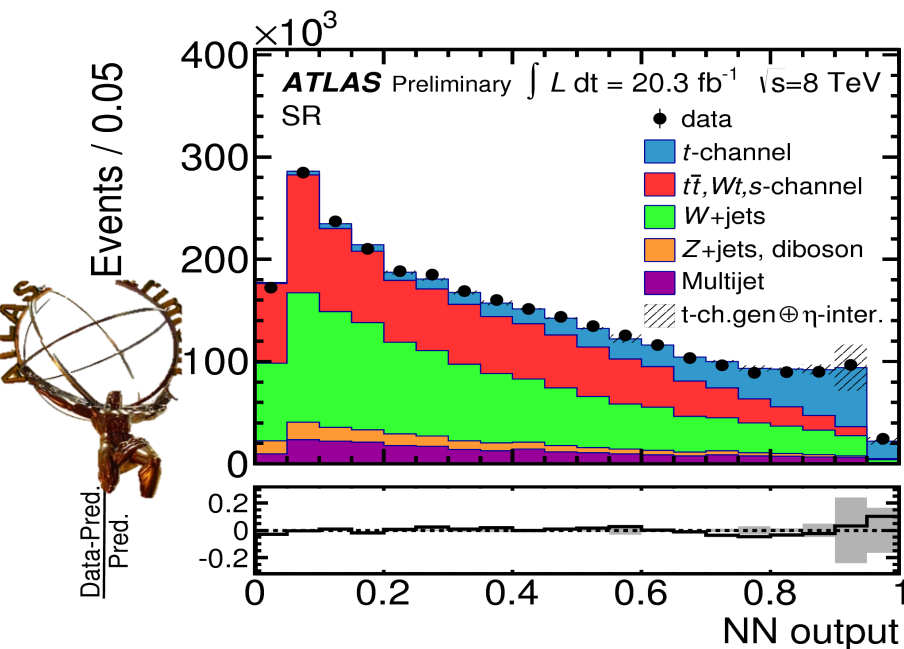


t-channel: measurement @ 8 TeV

ATLAS-CONF-2014-007/JHEP 06 (2014) 090

- Use Neural Network to combine several variables
- Fit the NN output to extract signal

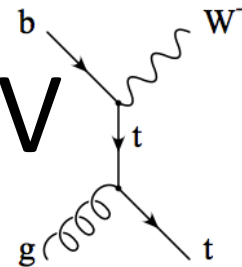
- Fit the recoil light jet $|\eta|$ to extract signal
- Direct measurement of $|V_{tb}|$



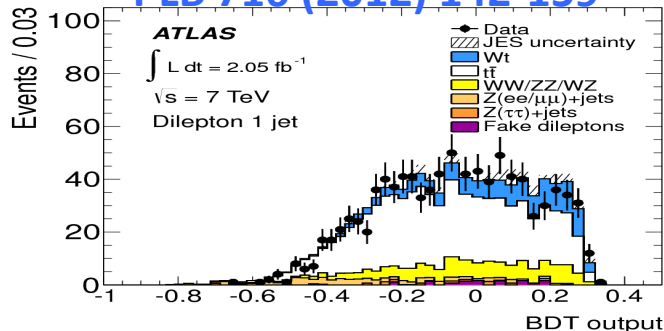
Dominate uncertainties both ATLAS/CMS: JES/b-tag/modeling

	Lumi	T-channel cross section	$ V_{tb} $
ATLAS	20.3fb ⁻¹	82.6±1.2(stat)±11.4(syst)±3.1(PDF)±2.3(Lumi)	0.97+0.09-0.10
CMS	19.7fb ⁻¹	83.6±2.3(stat) ± 7.4(syst)	0.998±0.038±0.016

tW measurement @ 8 TeV



PLB 716 (2012) 142-159

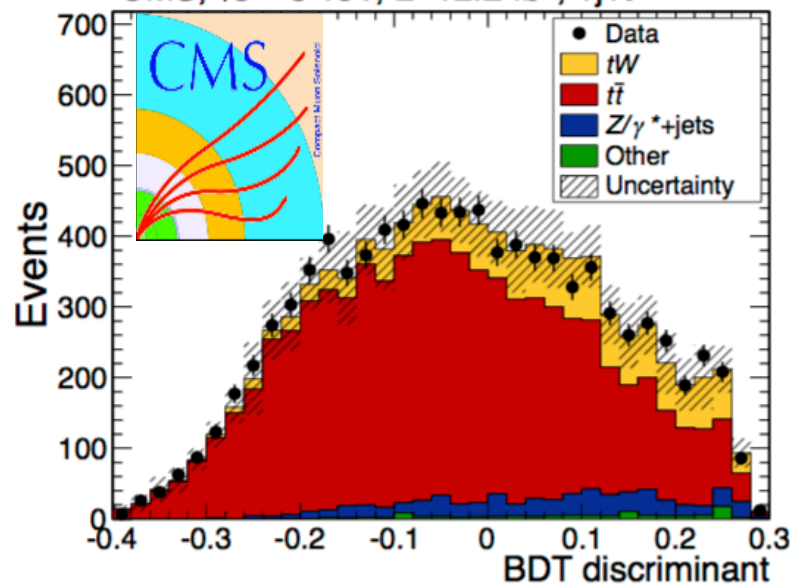


First Evidence: 2012

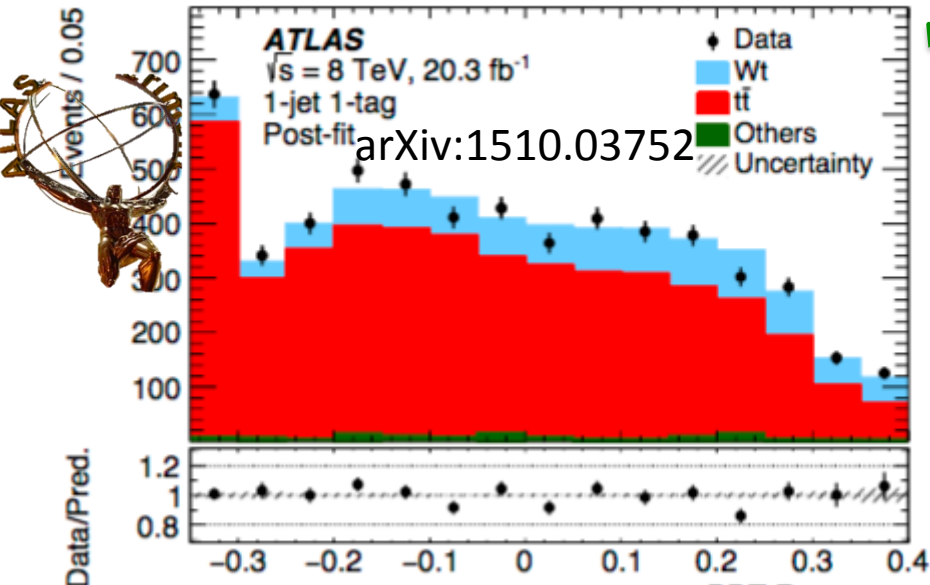
First Observation: 2014

Most accurate meas.

CMS, $\sqrt{s} = 8 \text{ TeV}$, $L = 12.2 \text{ fb}^{-1}$, 1j1t

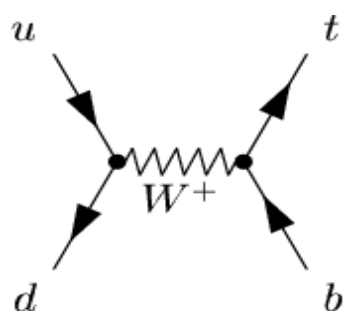


PRL 112 (2014) 231802



$23.0 \pm 1.3 \text{ (stat.)}_{-3.5}^{+3.2} \text{ (syst.)} \pm 1.1 \text{ (lumi.) pb,}$

$23.4 \pm 5.4 \text{ pb,}$



S-channel single top

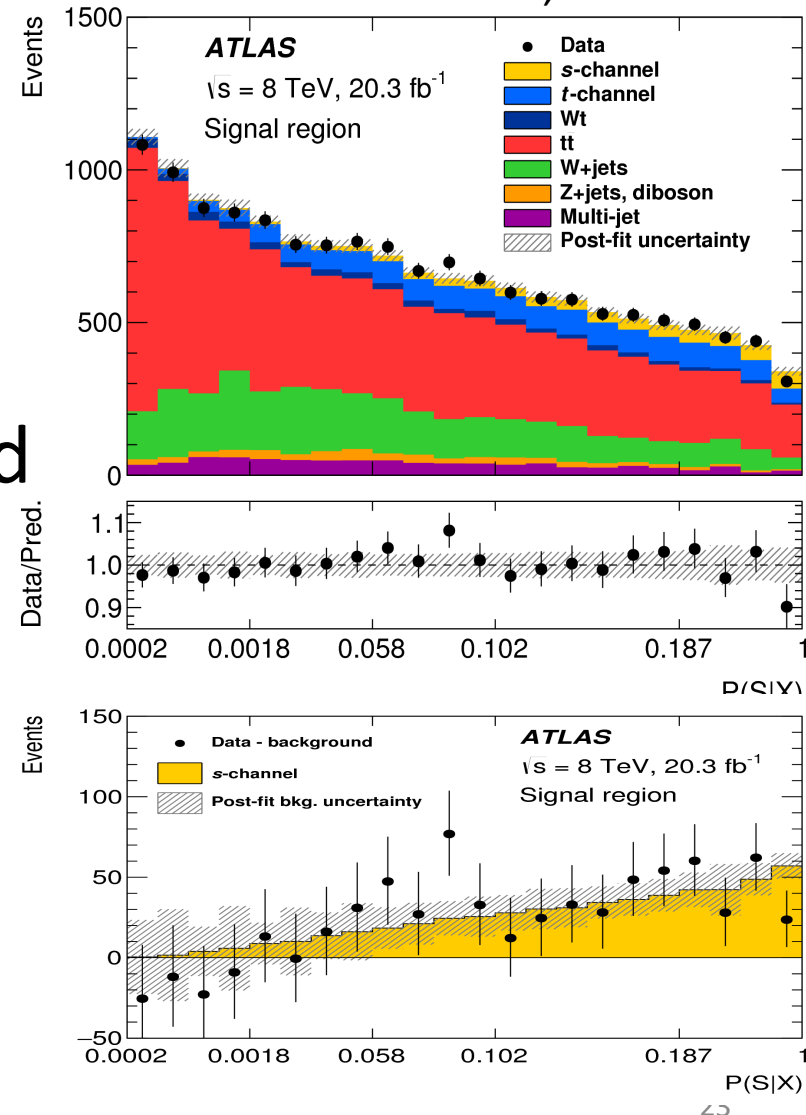
arXiv:1511.05980, sub. PLB

- Searching s-channel
 - Lepton+ 2 b-jets
- Matrix element method used

$$\sigma_s = 4.8 \pm 0.8(\text{stat.})_{-1.3}^{+1.6}(\text{syst.}) \text{ pb,}$$

Obs. **3.2 σ**

First evidence at LHC



$|f_{LV} V_{tb}| = \sqrt{\frac{\sigma_{\text{meas}}}{\sigma_{\text{theo}}}}$ from single top quark production

σ_{theo} : NLO+NNLL MSTW2008nnlo
PRD83 (2011) 091503, PRD82 (2010) 054018,
PRD81 (2010) 054028

$\Delta\sigma_{\text{theo}}$: scale $\oplus$ PDF

$m_{\text{top}} = 172.5 \text{ GeV}$

total theo

$|f_{LV} V_{tb}| \pm (\text{meas}) \pm (\text{theo})$

t-channel:

ATLAS 7 TeV¹

PRD 90 (2014) 112006 (4.59 fb⁻¹)

ATLAS 8 TeV

ATLAS-CONF-2014-007 (20.3 fb⁻¹)

CMS 7 TeV

JHEP 12 (2012) 035 (1.17 - 1.56 fb⁻¹)

CMS 8 TeV

JHEP 06 (2014) 090 (19.7 fb⁻¹)

CMS combined 7+8 TeV

JHEP 06 (2014) 090

CMS 13 TeV

CMS-PAS-TOP-15-004 (42 pb⁻¹)

$1.02 \pm 0.06 \pm 0.02$

$0.97 \pm 0.09 \pm 0.02$

$1.020 \pm 0.046 \pm 0.017$

$0.979 \pm 0.045 \pm 0.016$

$0.998 \pm 0.038 \pm 0.016$

$1.12 \pm 0.24 \pm 0.02$

Wt:

ATLAS 7 TeV

PLB 716 (2012) 142-159 (2.05 fb⁻¹)

CMS 7 TeV

PRL 110 (2013) 022003 (4.9 fb⁻¹)

ATLAS 8 TeV (*)

ATLAS-CONF-2013-100 (20.3 fb⁻¹)

CMS 8 TeV¹

PRL 112 (2014) 231802 (12.2 fb⁻¹)

LHC combined 8 TeV^{1,2}

ATLAS-CONF-2014-052,

CMS-PAS-TOP-14-009

$1.03^{+0.15}_{-0.18} \pm 0.03$

$1.01^{+0.16}_{-0.13} \pm 0.03$

$1.10 \pm 0.12 \pm 0.03$

$1.03 \pm 0.12 \pm 0.04$

$1.06 \pm 0.11 \pm 0.03$

s-channel:

ATLAS 8 TeV²

arXiv:1511.05980 (20.3 fb⁻¹)

$0.93^{+0.18}_{-0.20} \pm 0.04$

Wt:

ATLAS 8 TeV^{1,2}

arXiv:1510.03752 (20.3 fb⁻¹)

$1.01 \pm 0.10 \pm 0.03$

(*) Superseeded by results shown below the line

¹ including top-quark mass uncertainty

² including beam energy uncertainty

12/21/15

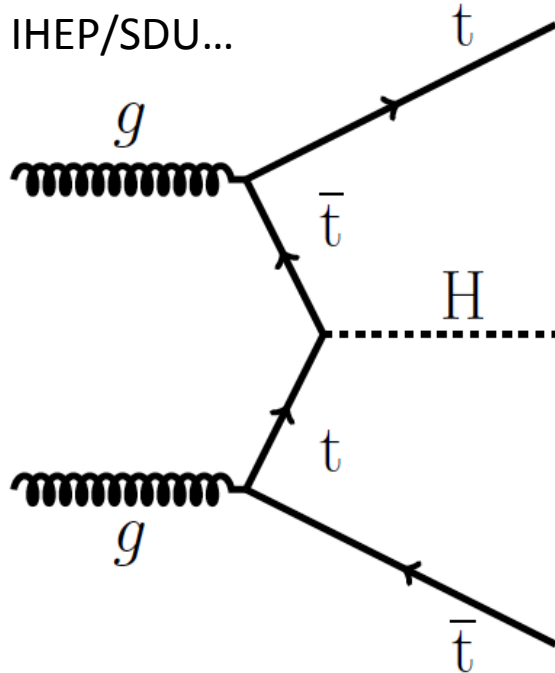
H. ZHANG (IHEP)

Measure V_{tb}

- CKM=>CP violation
- Direct measurement from single top
 - More sensitive
- Result consistent with SM
 - $(t) 0.998 \pm 0.038 \pm 0.016$**
- Important contribution from SDU and IHEP to Wt

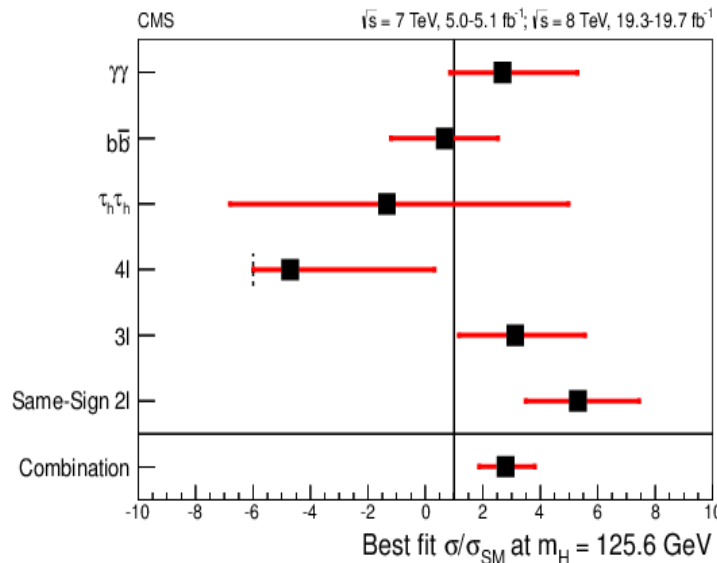
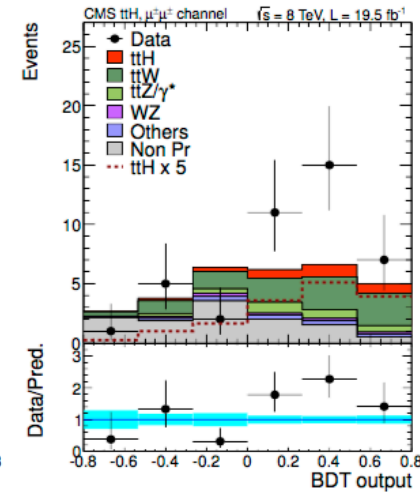
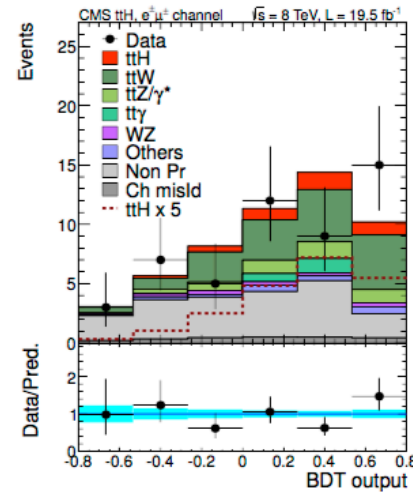
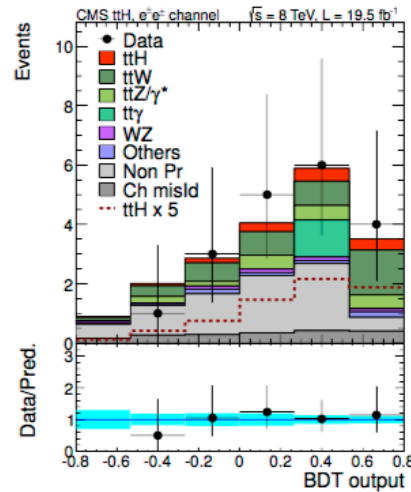
top-higgs Yukawa Coupling

IHEP/SDU...



- $H \rightarrow \gamma\gamma$
- $H \rightarrow b\bar{b}/\tau\tau$
- $H \rightarrow \text{multi-lepton}$

JHEP09(2014)087



$$\mu = 2.8 \pm 1.0$$

2 σ deviation

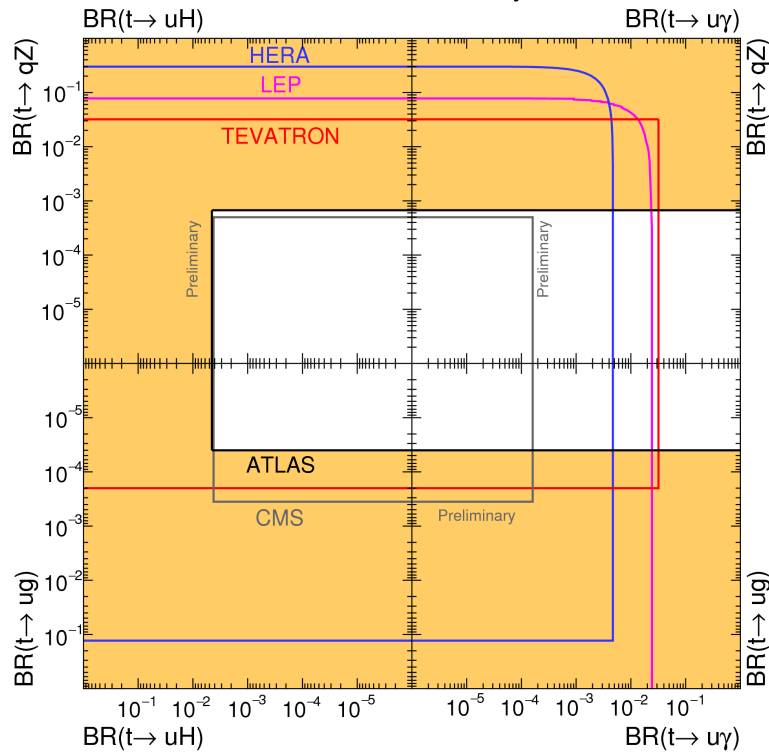
CMS obs. **3.4 σ**

ATLAS $\mu < 3.4$

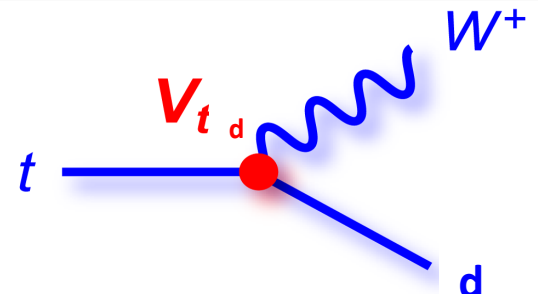
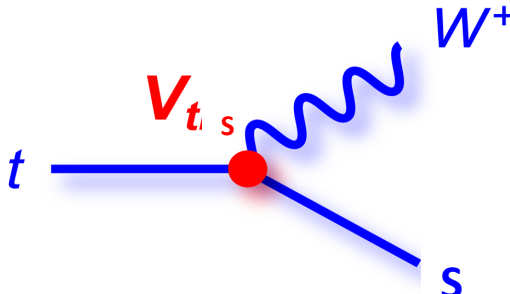
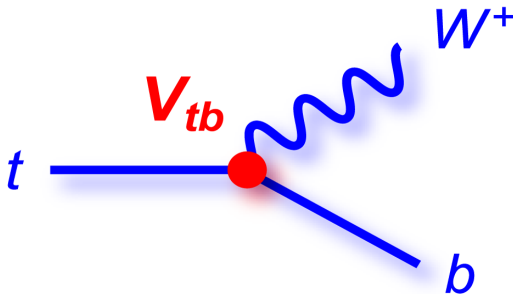
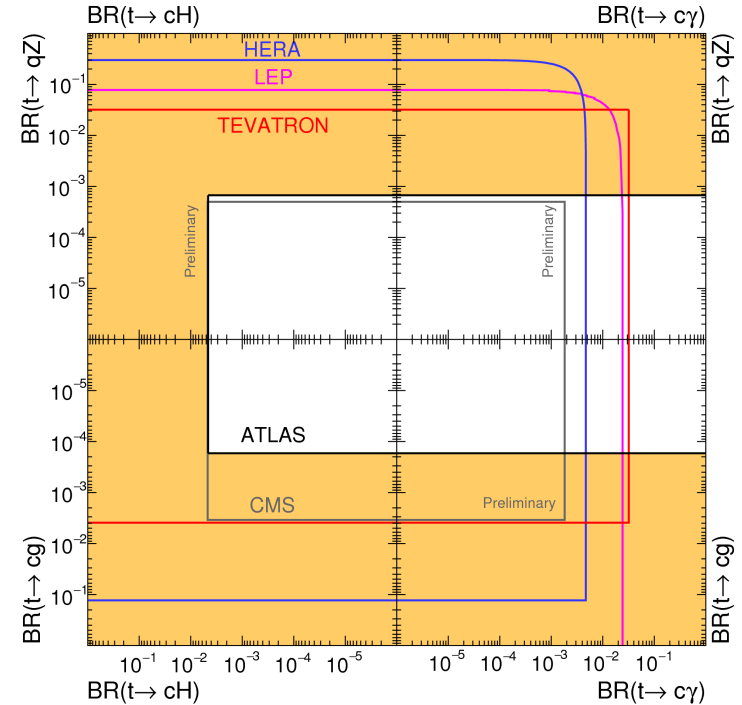
FCNC top quark decays

$t \rightarrow uX, t \rightarrow cX$, where $X = (H, g, Z, \gamma)$

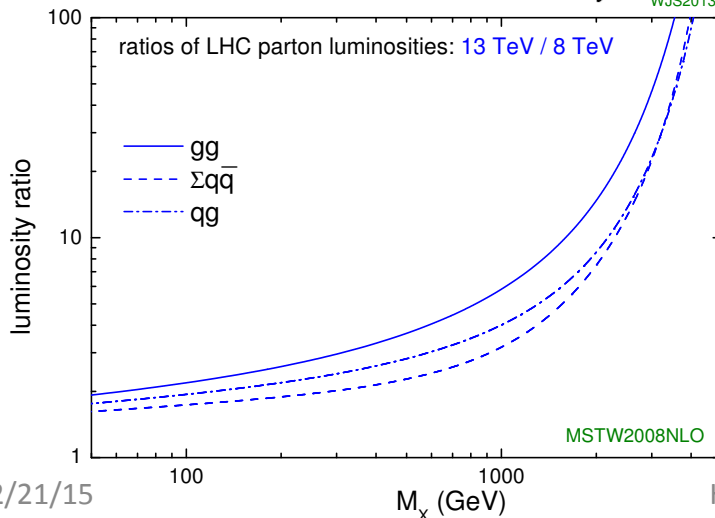
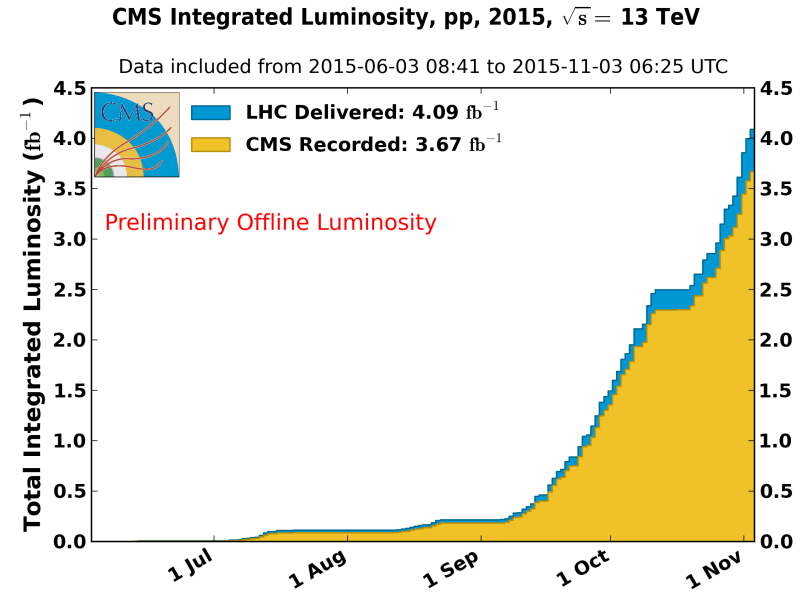
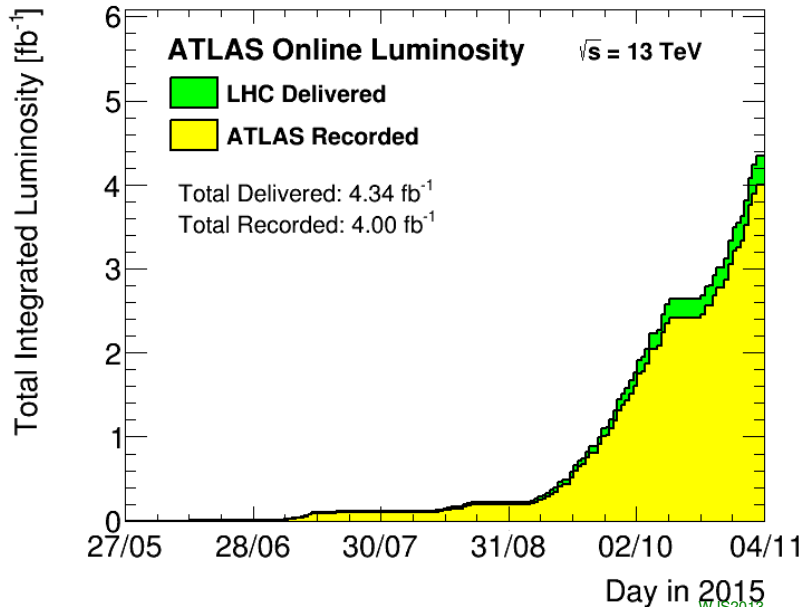
ATLAS Preliminary



ATLAS Preliminary



Fresh results from 13 TeV

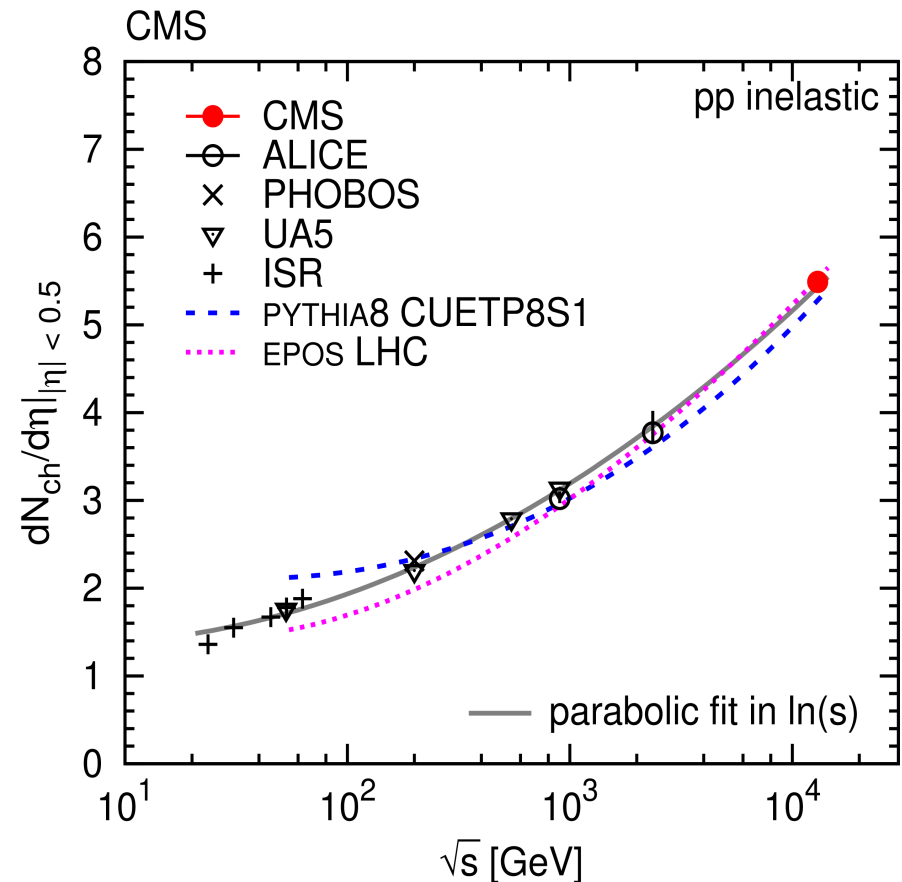
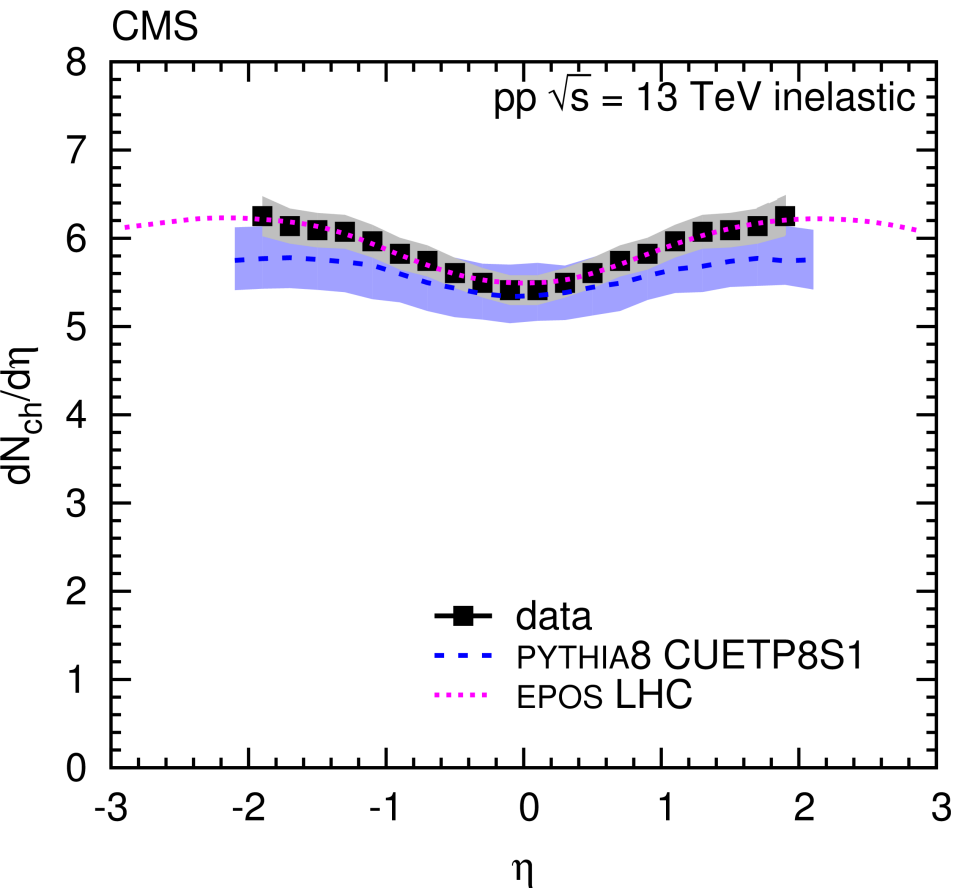


13 TeV Data taken from May to Nov. 2015

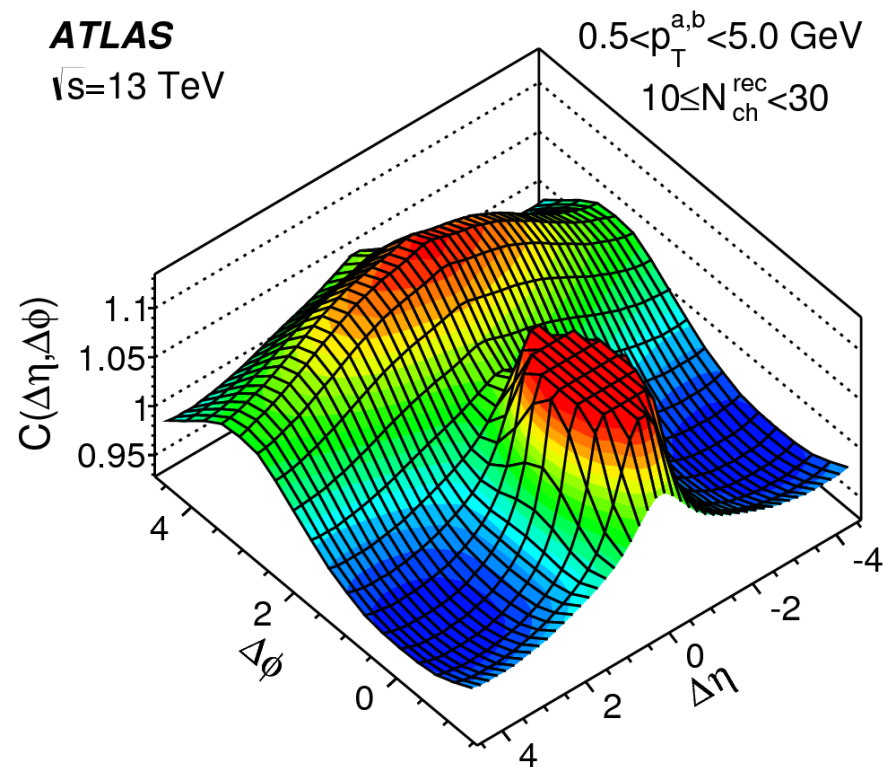
- > 3 fb⁻¹ data recorded by ATLAS or CMS
- Benefits from high E_{cm} than 8 TeV

Underlying events

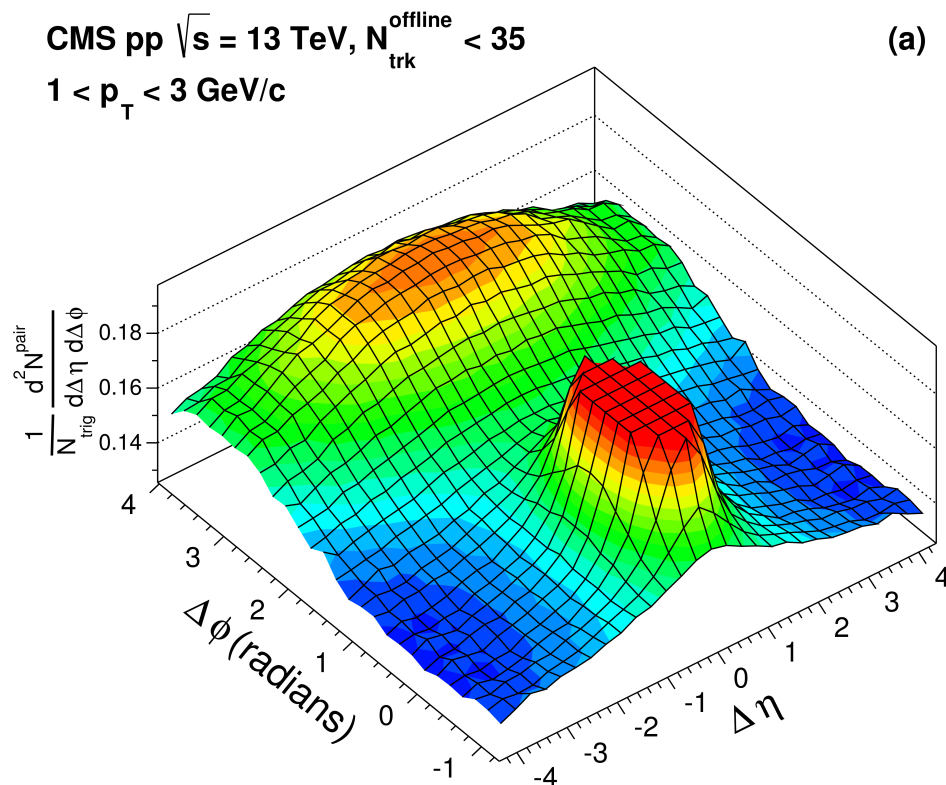
- PLB 715 (2015) 143



Long-range Angular correlation



arXiv:1509.04766



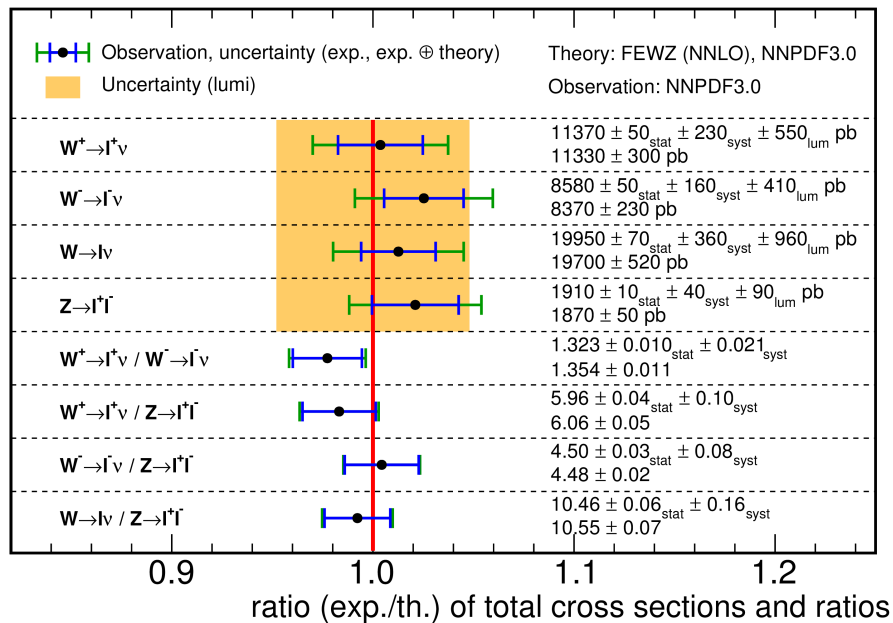
arXiv:1510.03068

W/Z bosons and top

CMS-PAS-SMP-15-004

CMS Preliminary

43 pb⁻¹ (13 TeV)

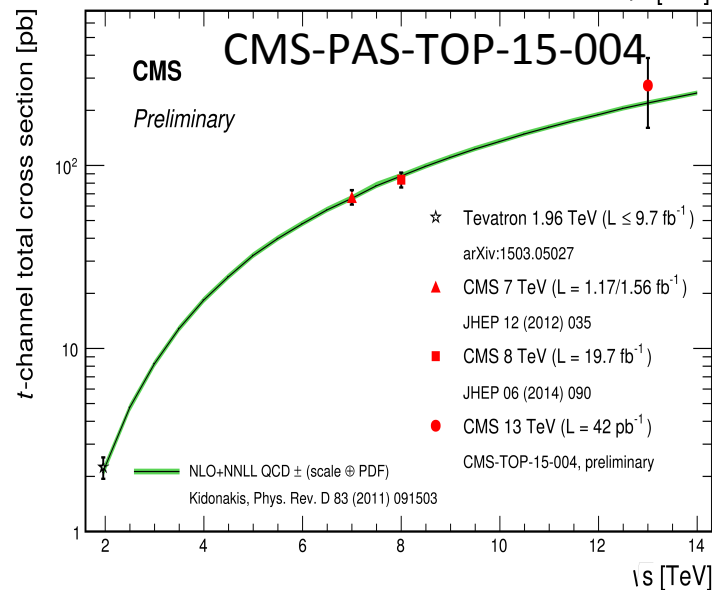
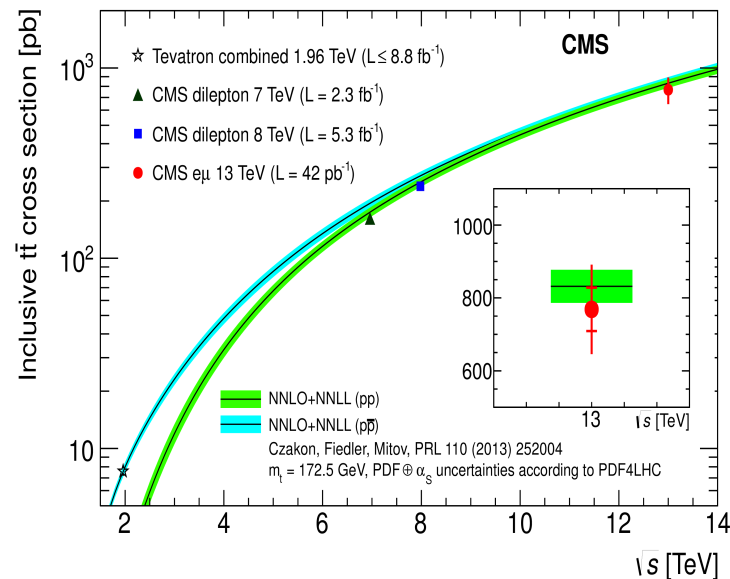


W/Z/t are as expected

12/21/15

H. ZHANG (IHEP)

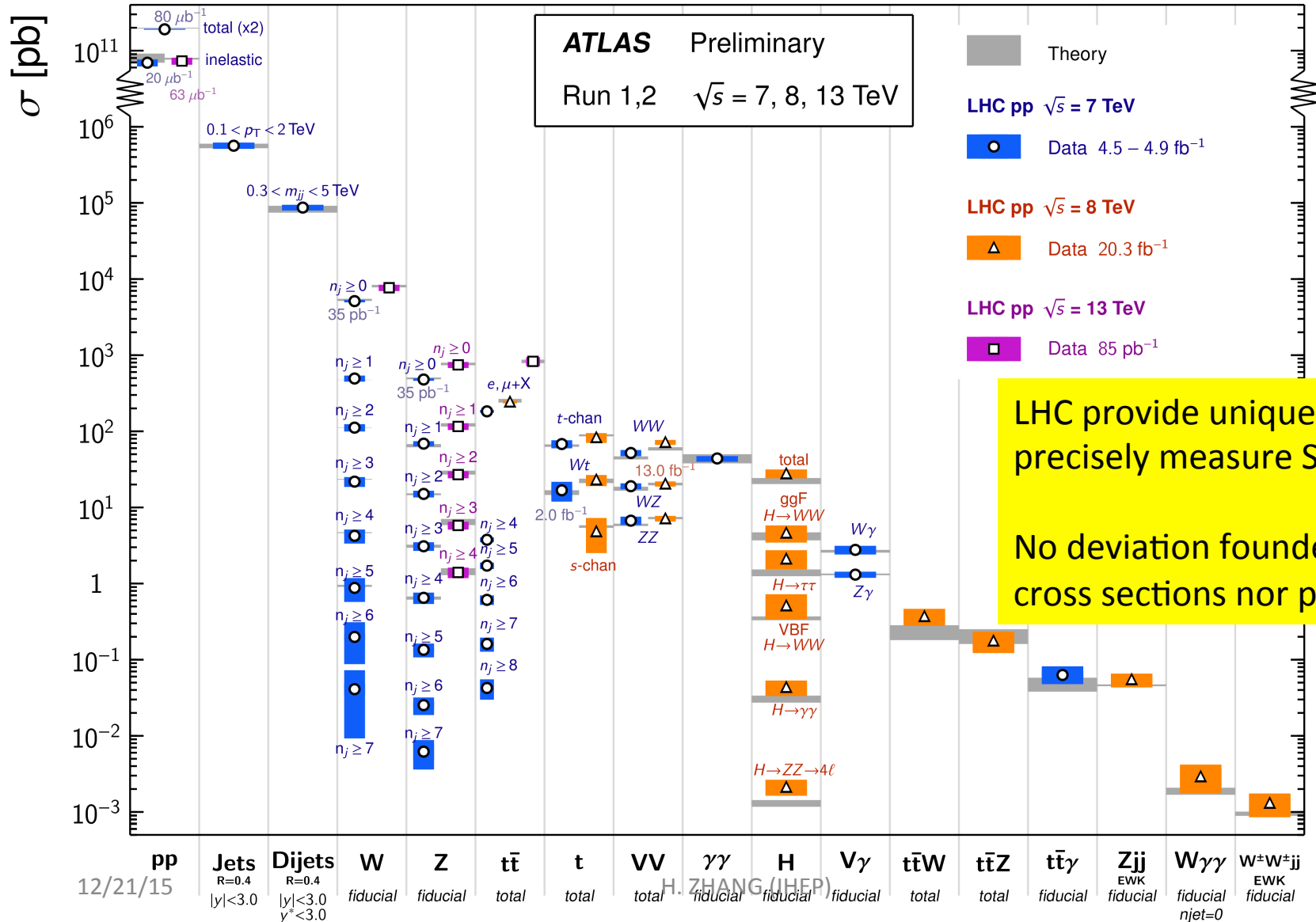
arXiv:1510.05302



Summary (1)

Standard Model Production Cross Section Measurements

Status: Nov 2015



Summary (2)

CMS Preliminary

July 2015

