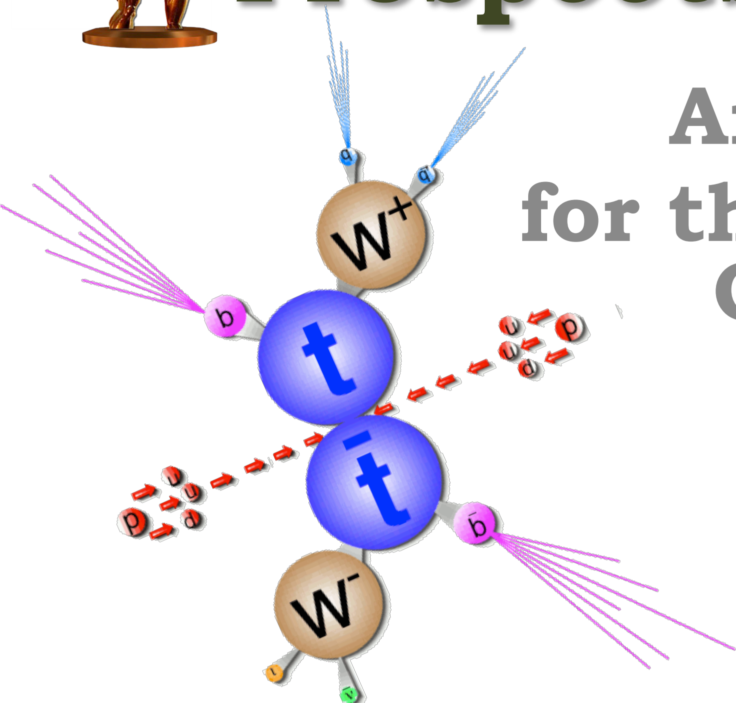
Top Properties and Future Prospects from the LHC



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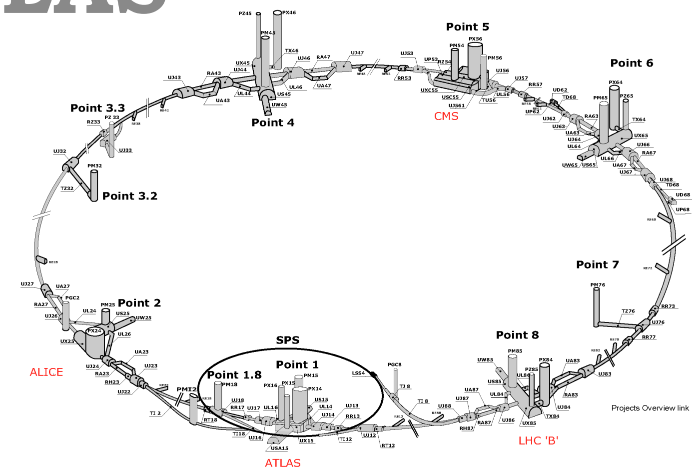
for the CMS and ATLAS Collaborations

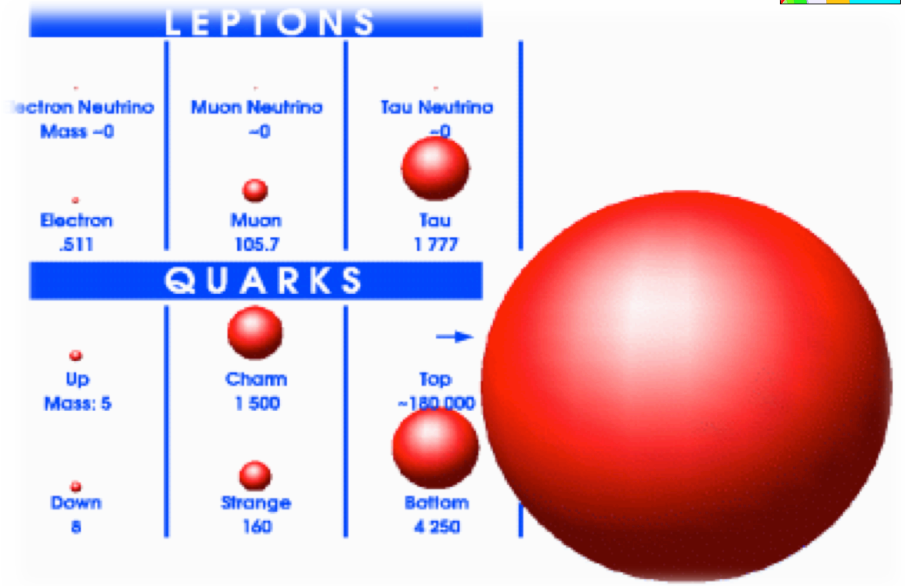
1 Yale University

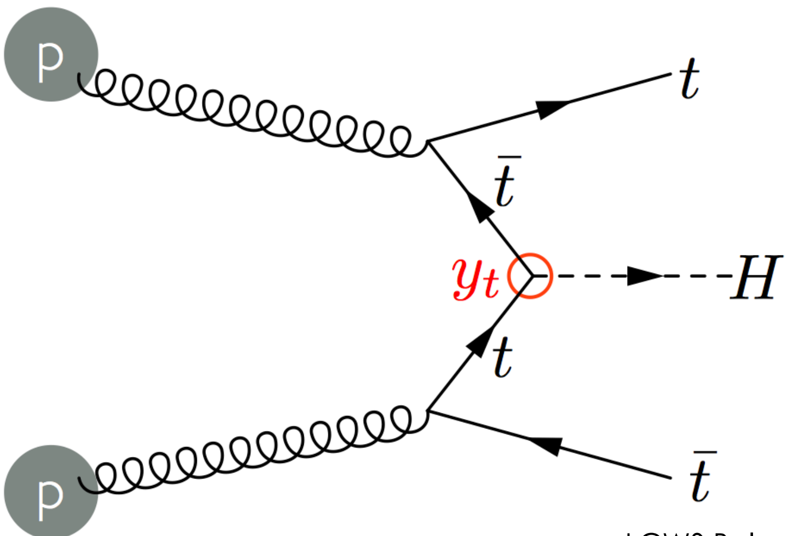


International Workshop on Future Linear Colliders
October 6-10, 2014

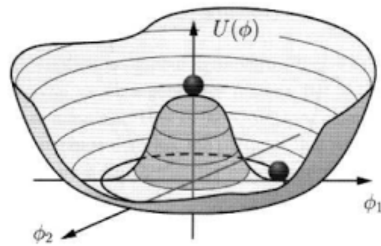
The Top Quark

- The only fermion which has a significant coupling to the Higgs
  - The **heaviest particle** discovered so far
  - Strong **top Yukawa coupling**
- Plays key role in many important physics processes
  - Flavor physics, Electro-weak processes
- Plays a special role in a number of **Beyond the Standard Model** theories as well





$$m_t \stackrel{?}{=} \frac{v y_t}{\sqrt{2}}$$



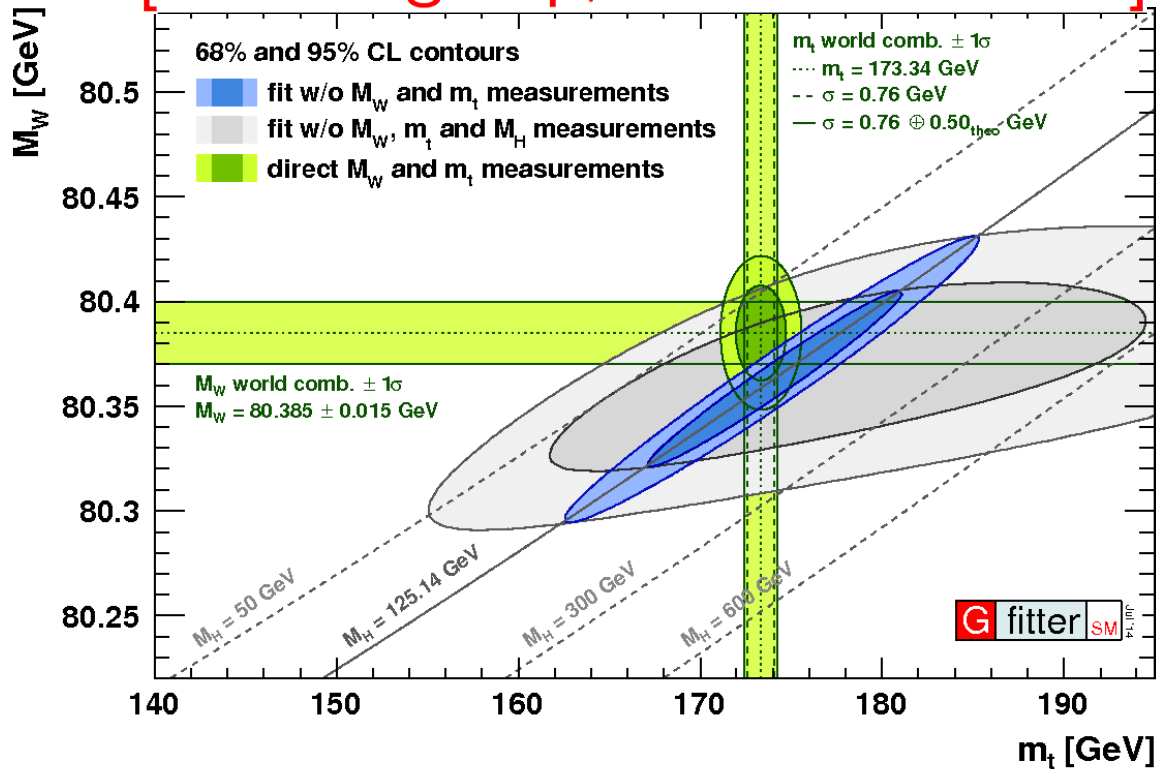
v = vacuum expectation value (246 GeV)

y_t = top Yukawa coupling

Probing the Standard Model

- SM is self-consistent model accounting all particle physics phenomena at energy of current accelerators
  - with m_H all parameters of SM are known

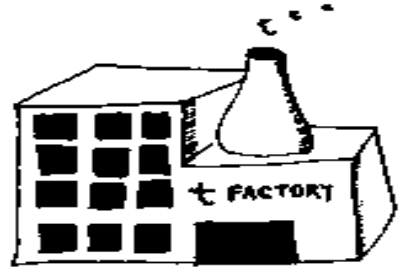
[GFitter group, arXiv:1407.3792]

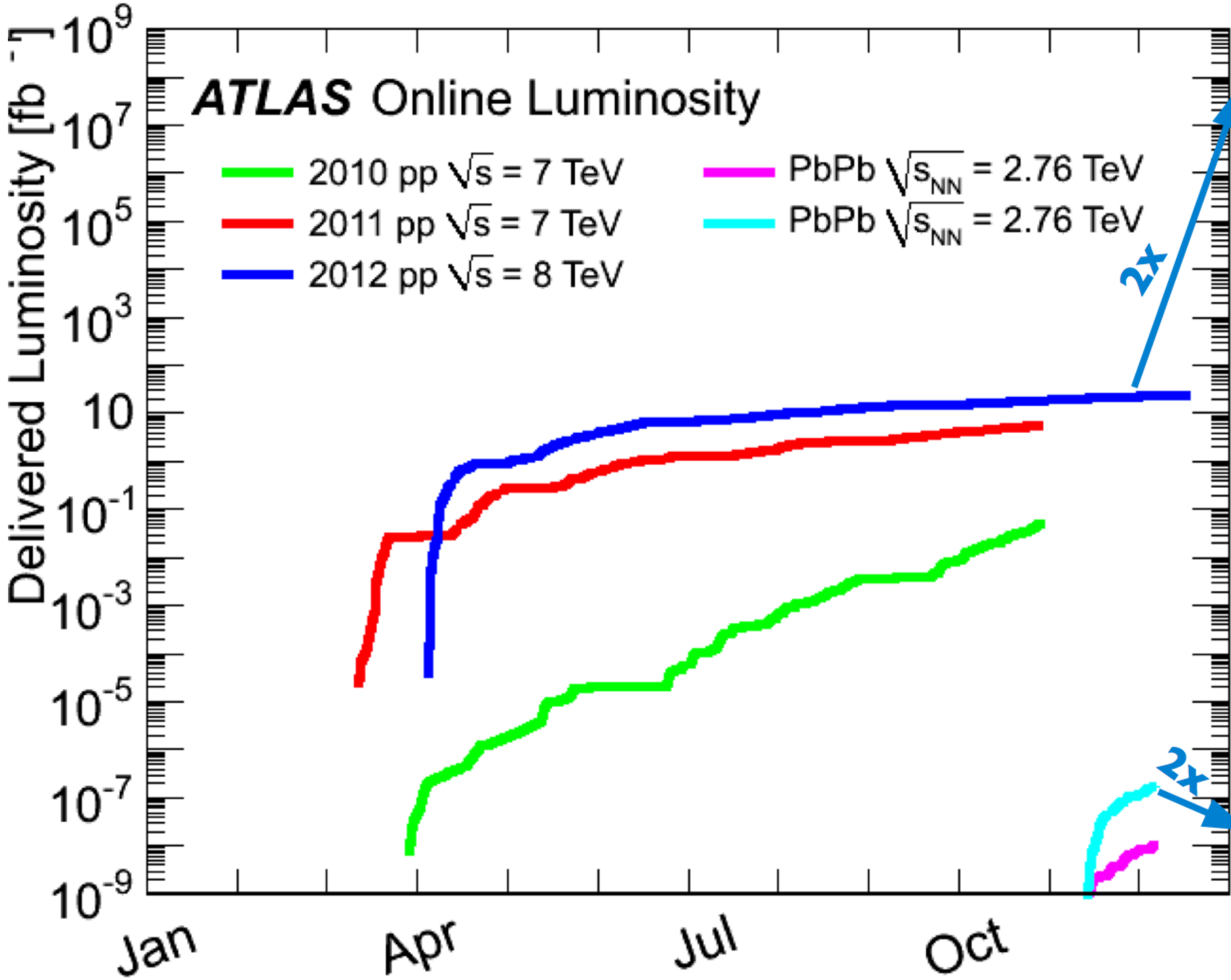


m_W = 80385 ± 15 MeV
m_t = 173.34 ± 0.76 GeV
m_H = 125.36 ± 0.41 GeV
Current p-value for (data|SM)=0.2
Need to improve m_W, m_t and m_H

Precision tests of further consistency of the SM are mandatory

Run 1 Top Factory





≈ 7.4 x 10⁶ top quark pairs
$\sigma(t\bar{t}) \sim 246$ pb PRL 110 (2013) 252004

≈ 2.6 x 10⁶ single top (t-ch)
$\sigma_t(t) \sim 87$ pb arXiv:1205.3453

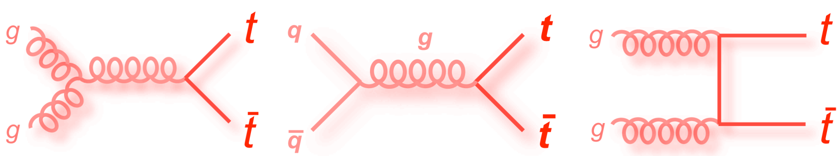
≈ 1.7 x 10⁵ single top (s-ch)
$\sigma_s(t) \sim 5.6$ pb arXiv:1205.3453

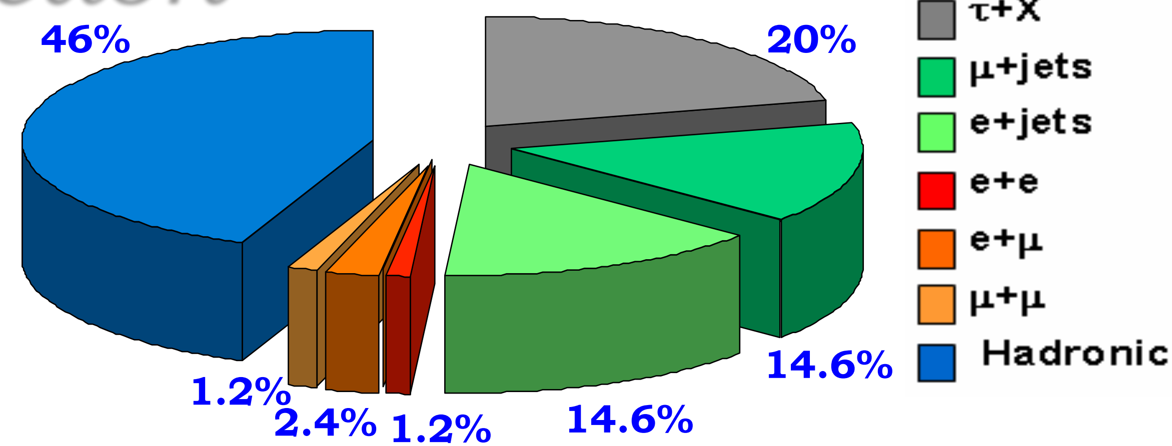
≈ 12 x 10³ tt+W/Z
$\sigma(t\bar{t}+V) \sim 0.403$ pb JHEP07(2014)079

≈ 3.9 x 10³ tt+H
$\sigma(t\bar{t}+H) \sim 0.129$ pb CERN-2013-004

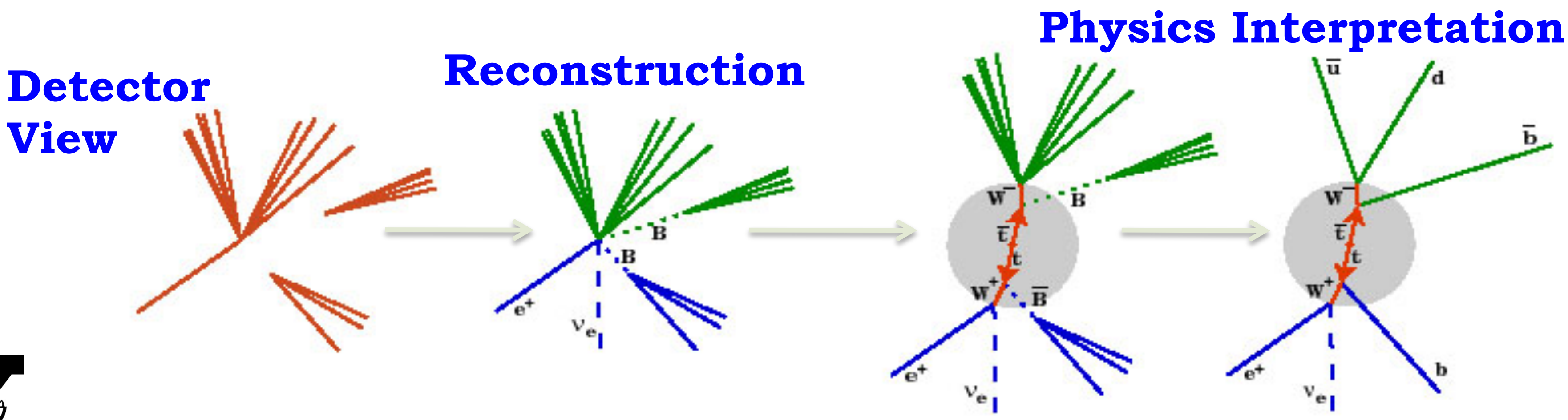
≈ 560 top quark pairs
$\sigma_{PbPb}(t\bar{t}) \sim 3.5\ \mu b$ arXiv:1210.0116

Top Pair Production





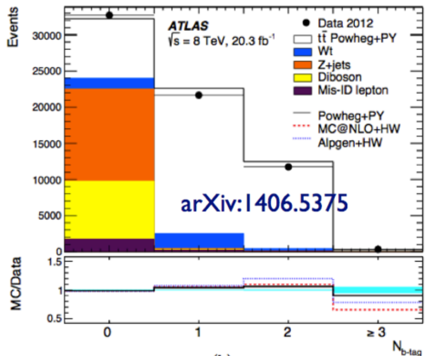
- Top pair production at the LHC through gg (**dominant**) and qqbar
- Top pair decay modes
  - The more jets, the more challenging the systematic uncertainties get (**Jet energy scale**, **ISR/FSR** etc)



What was Learned about the Top Quark

- Every topic deserves a dedicated long presentation
  - **CMS** Public Page: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
  - **ATLAS** Public Page: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

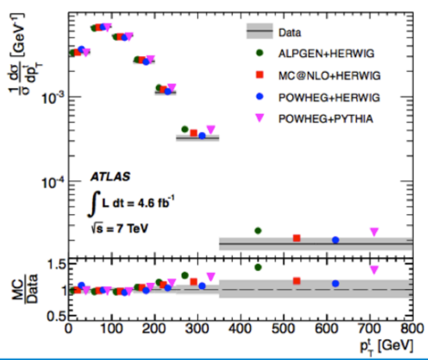
Cross sections



CMS-PAS-TOP-14-016 ATLAS-CONF-2014-054	$\sigma(t\bar{t}) = 241.5 \pm 8.5$ pb	3.5% unc.
CMS-PAS-TOP-12-002 ATLAS-CONF-2013-098	$\sigma(t-\mathrm{ch}) = 85 \pm 12$ pb	14% unc.
CMS-PAS-TOP-14-009 ATLAS-CONF-2014-038	$\sigma(tW) = 25.0 \pm 4.7$ pb	18% unc.
CMS-PAS-TOP-13-009 arXiv:1410.0647	$\sigma(s-\mathrm{ch}) < 11.5$ pb	

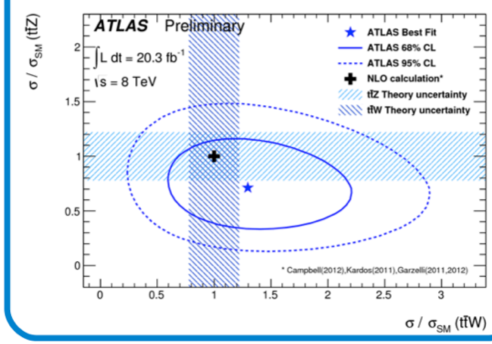
testing pQCD predictions

arXiv:1407.0371, EPJ C73 (2013) 2339

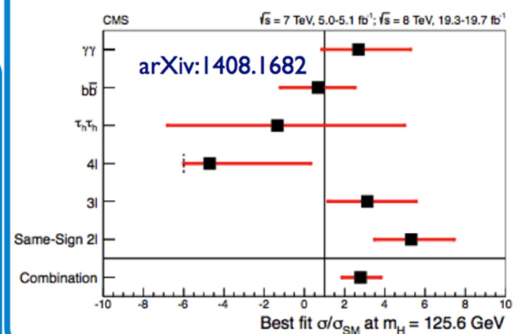


evidence for associated production with W or Z

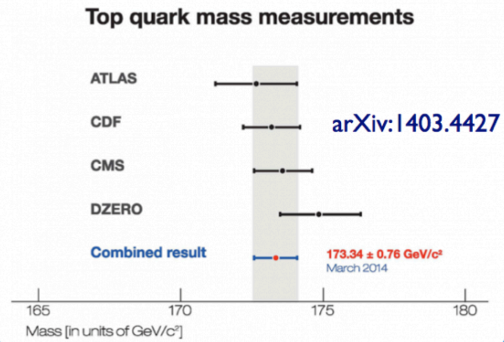
arXiv:1406.7830, ATLAS-CONF-2014-038



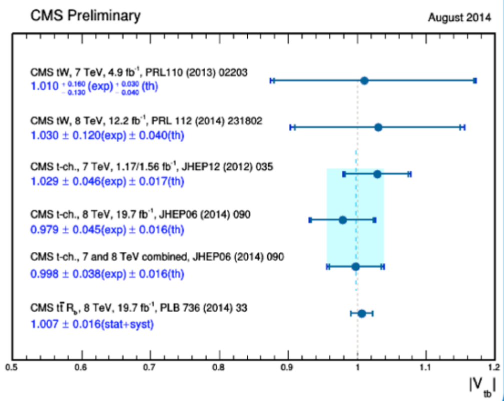
approaching ttH vertex



m_{top} : 0.4% unc.



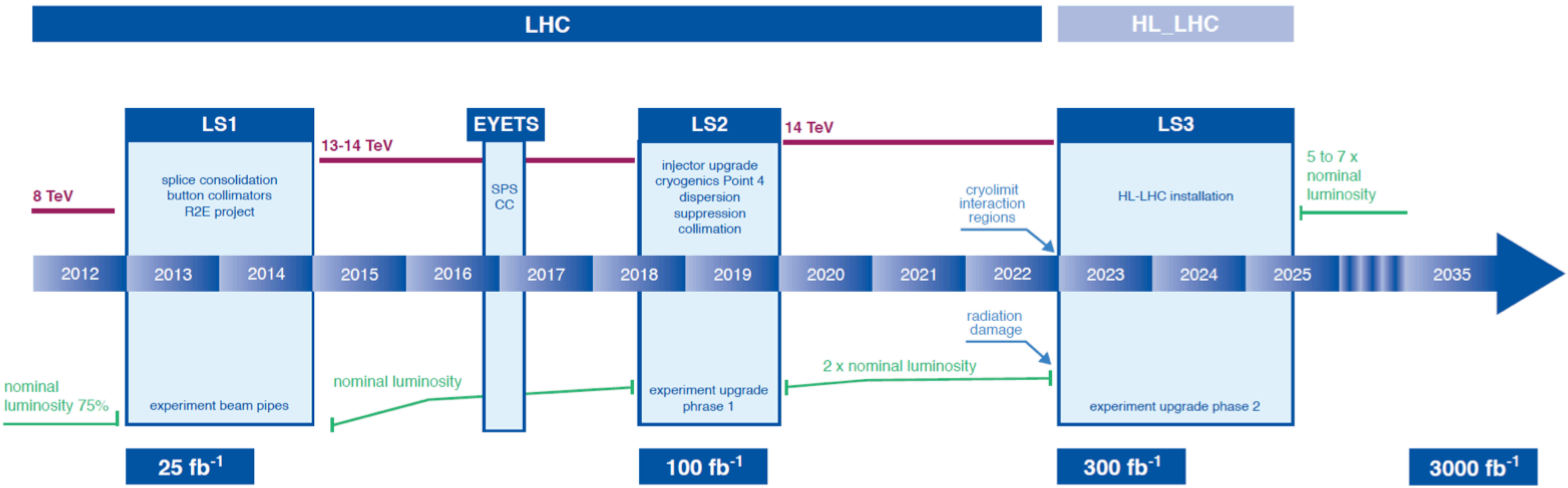
$|V_{tb}|$: 1.6% unc.
Γ_t : 9% unc.



What We still Need to Learn

- Couplings to photon, Z, Higgs
  - and maybe some other new heavy particles?
- FCNC?
  - many channels to test
- Charge asymmetry in top pair production
- Precise cross section and mass measurements
  - Differential measurements to test pQCD
  - PDF studies
- And more
  - see the SnowMass'2013 Top Quark WG report arXiv:1311.2028 [hep-ph]

The LHC Roadmap

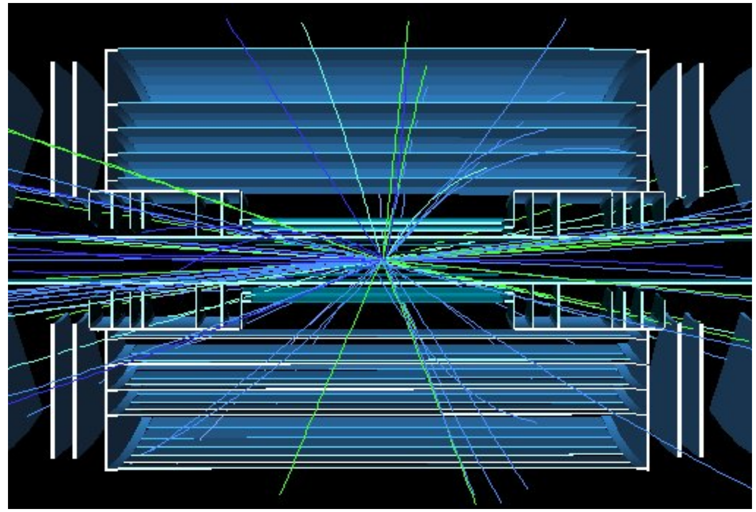


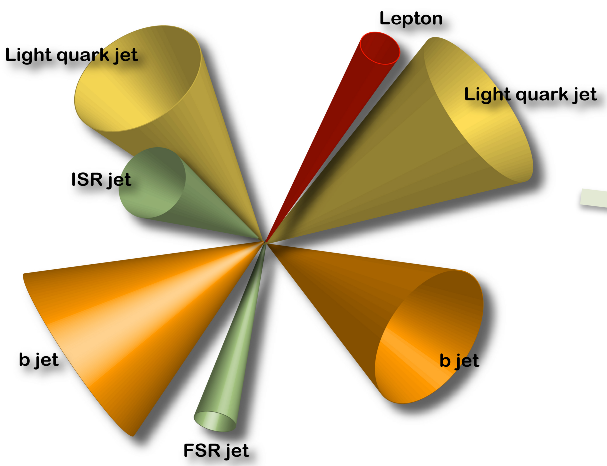
- LHC **approved running** to deliver **300 fb^{-1}** by 2021
- Post LS3 operation: **3000 fb^{-1}** over 10 years
  - Major upgrades required on the LHC
  - Need **strong physics motivation** for HL-LHC
- Detector Upgrades during Long Shutdowns (LS)
  - LS1 = Phase 0, LS2 = Phase 1, LS3 = Phase 2

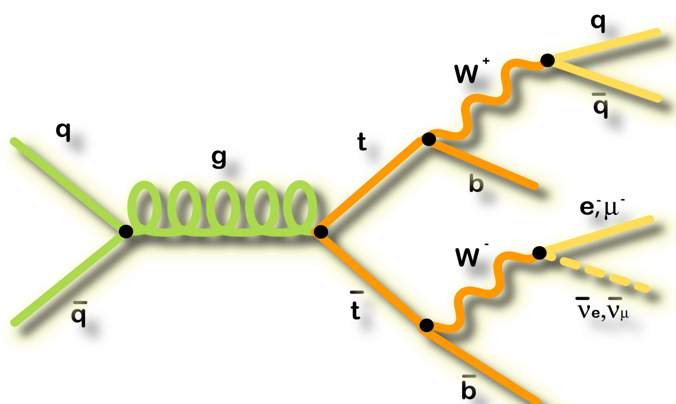
Detector Challenges

- Higher bunch luminosity
  - => **occupancy / event size**
- Higher average luminosity
  - => **trigger rates / radiation damage**
- The goal is to achieve **the same (or better)** performance **(resolution etc.)** at the HL-LHC as at the LHC, despite the large increase in event rate

$0.2 \times 10^{34}\ cm^{-2}s^{-1}$



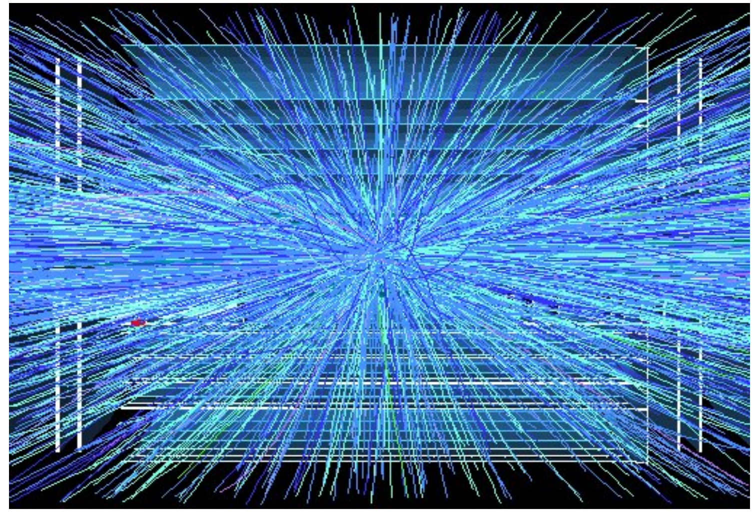


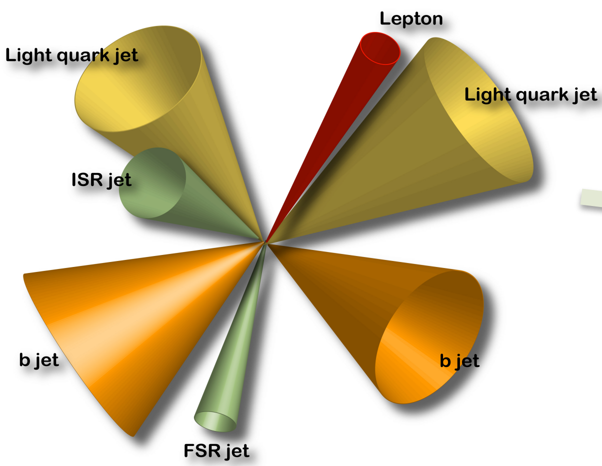


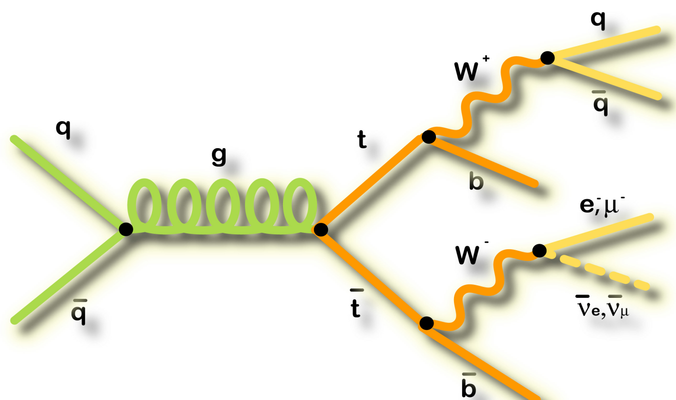
Detector Challenges

- Higher bunch luminosity
  - => **occupancy / event size**
- Higher average luminosity
  - => **trigger rates / radiation damage**
- The goal is to achieve **the same (or better)** performance **(resolution etc.)** at the HL-LHC as at the LHC, despite the large increase in event rate

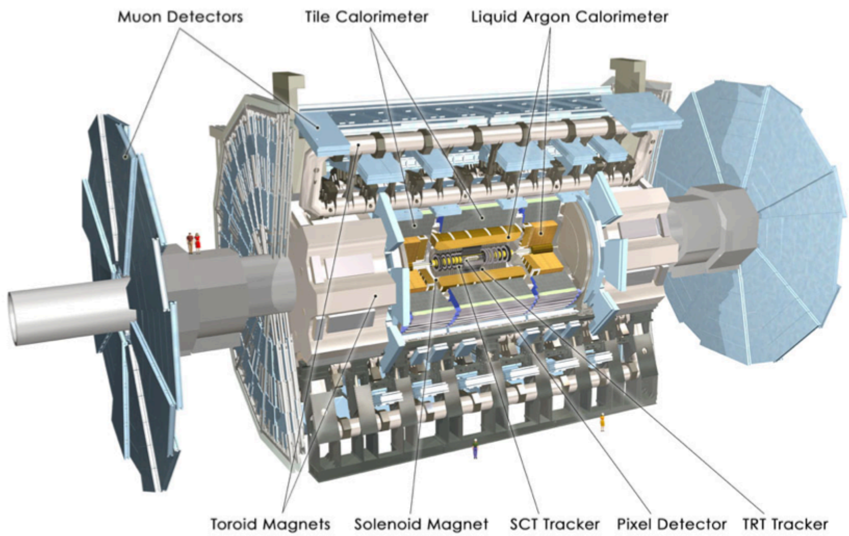
10×10^{34} cm^{-2}s^{-1}

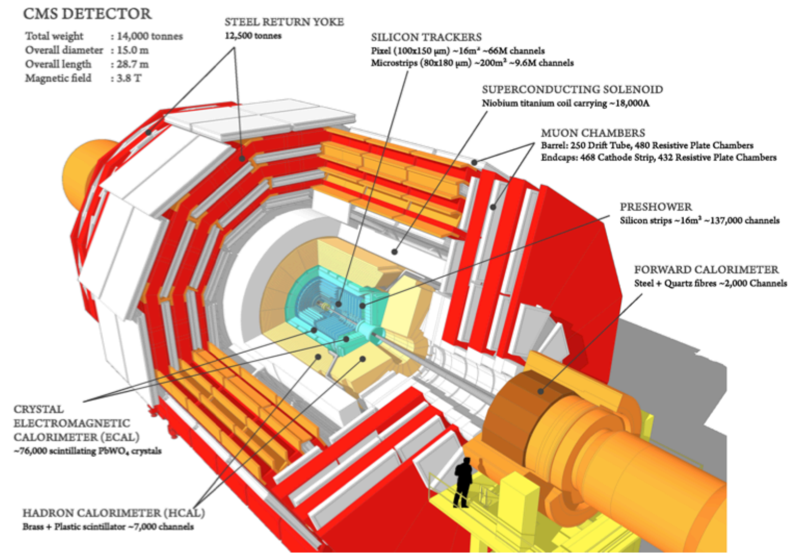






Upgrade Strategies





Consolidate detectors, address operational issues, prepare for high pileup

Phase 0

2013-2014

- complete muon coverage, improve muon trigger, new smaller radius beam pipes
- CMS : Replace HCAL forward PMTs and outer HPD → SiPM
- ATLAS : Diamond beam monitor, additional pixel layer

End of the year Technical Stop

Mantain / improve performance at high pileup

Phase I

2018-2019

- CMS: new pixels, HCAL SiPMs, electronics, and L1-Trigger
- ATLAS: L1 trigger improvement, fast track trigger at L2, new muon small wheels

Mantain / improve performance at extreme pileup : sustain rate + radiation doses

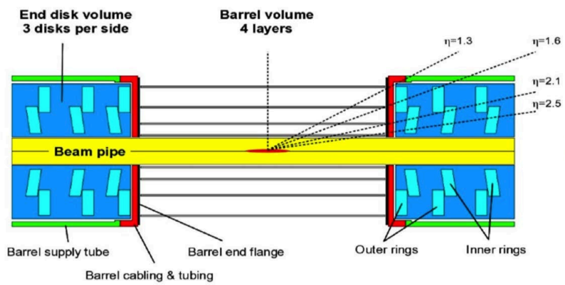
Phase II

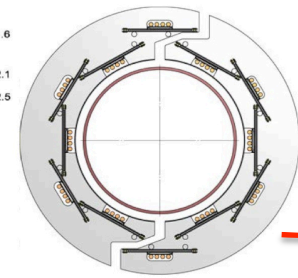
2023-2024

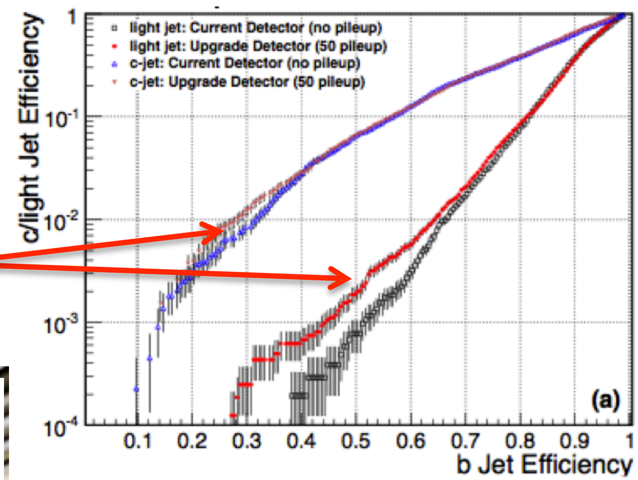
- New inner detector, new calorimeter electronics, muon extension, trigger and DAQ upgrade
- CMS: track trigger, replace endcap calorimeters
- ATLAS: replace inner tracker, new forward calorimeter

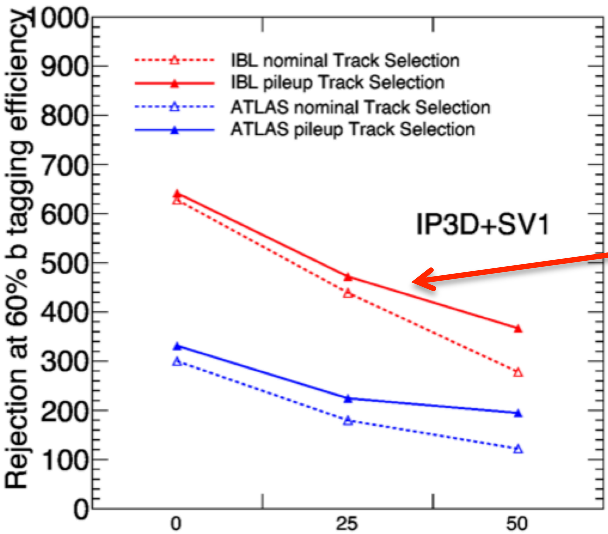
Btagging @ Run 2 and beyond

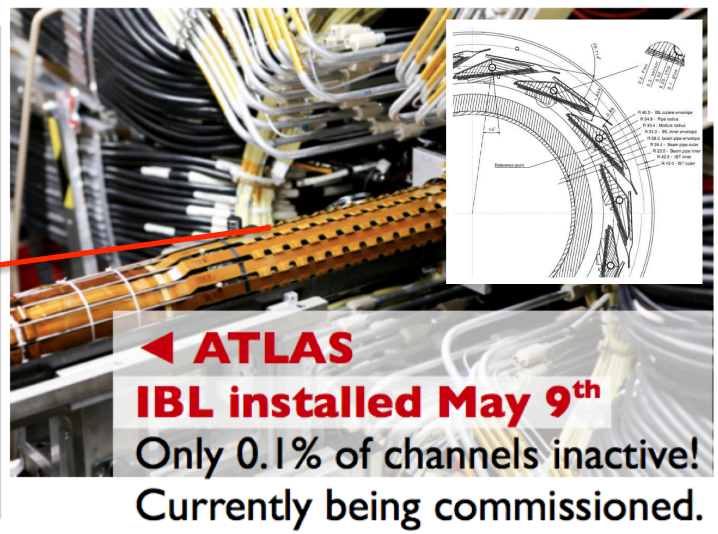
- Upgrade is mandatory for performance at high pile-up
  - IBL @ ATLAS (installed)
  - new pixel detector @ CMS during the "End of the Year Extended Technical Stop"
- Studies done with top pair MC events @ 13 TeV





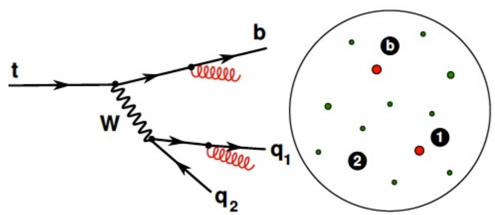


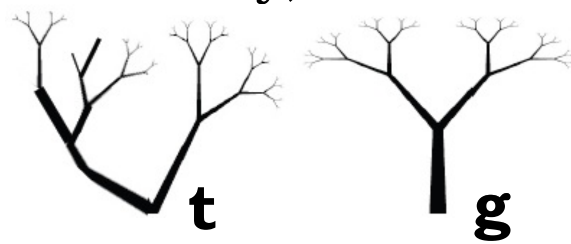




Run 2 and beyond: Techniques

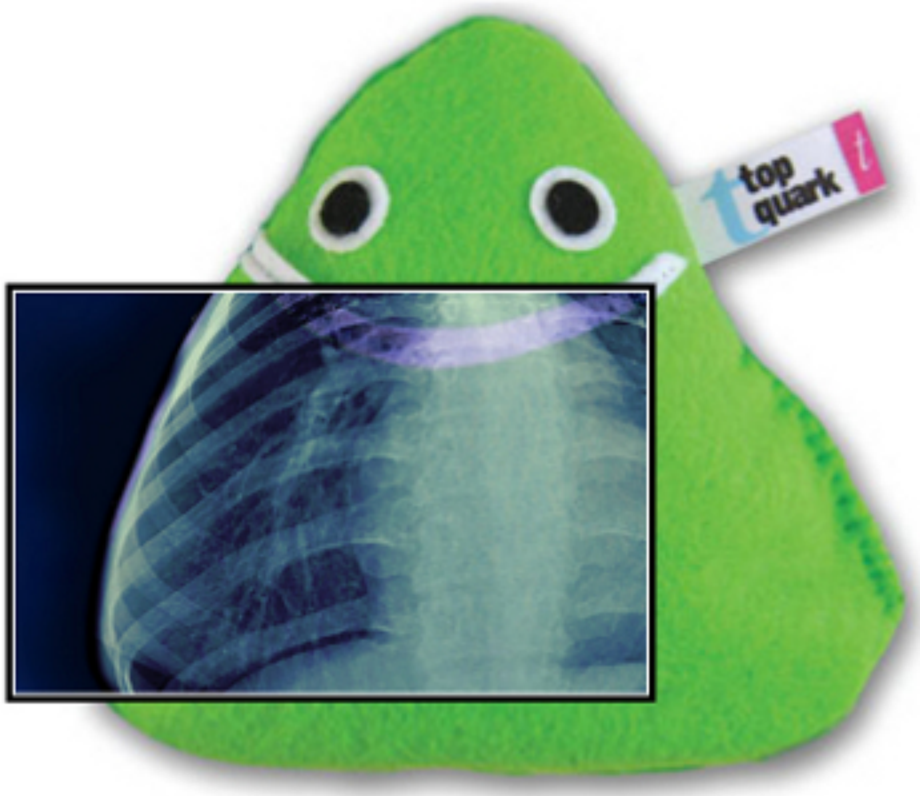
- Limitations
  - Pile-up, trigger thresholds etc.
- New Approaches
  - Tighter trigger requirement for leptons will help sustain approximately the same p_T thresholds
  - Need more careful study of the isolation, in particular **effect of out-of-time pileup**
  - Main concern for top physics: **jets**
    - Jet rate increases, jet resolution degrades
      - See "**Jet finding techniques at hadron colliders**" presentation by D. Boumediene @ Detector: Top: Boosted jets - joint with Sim/Reco on Thursday, 14:00 - 15:30





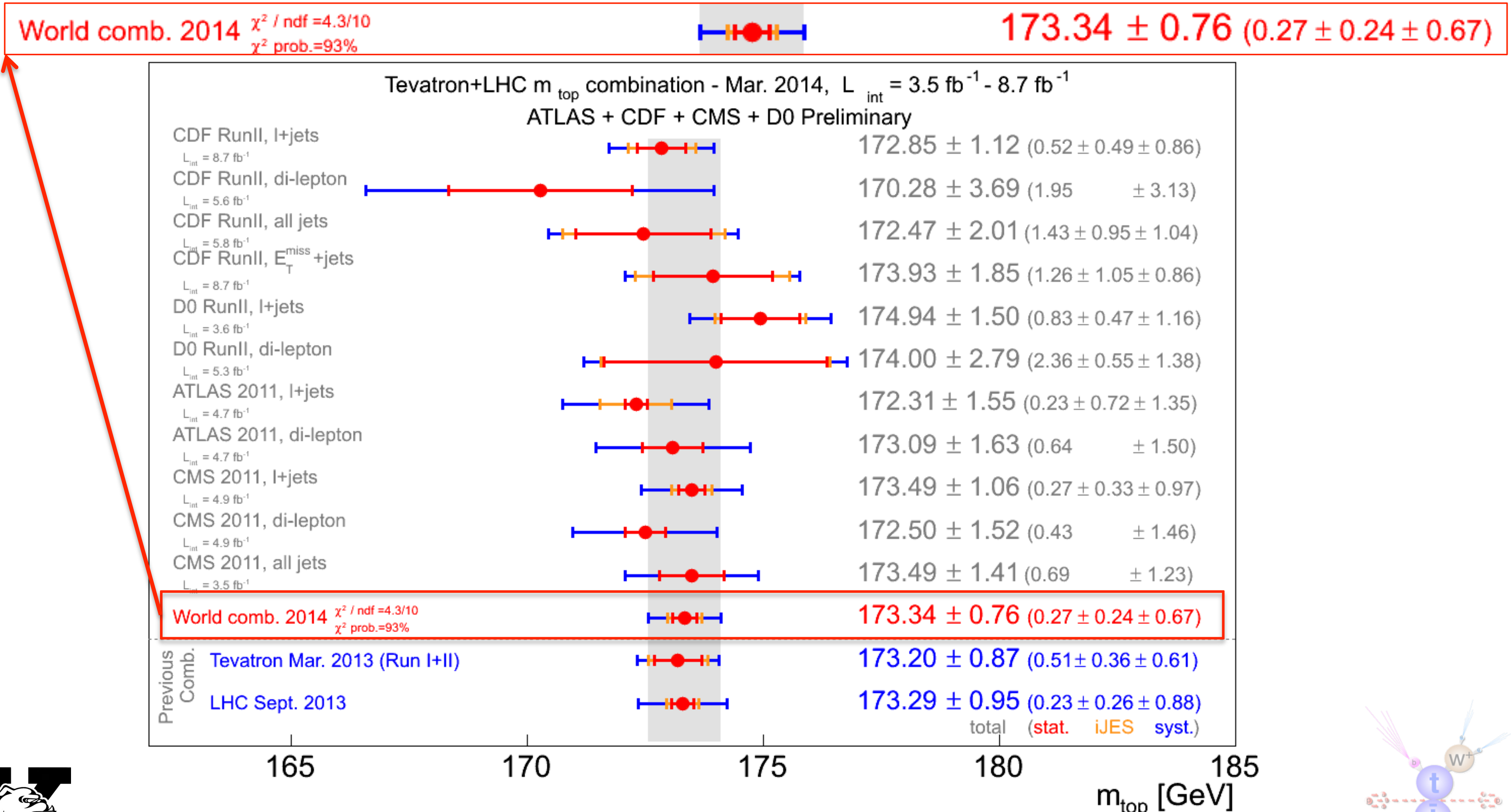
Top Mass

- Precision matters



Top Mass: Combination

- LHC (**7 TeV**) + Tevatron first combination
  - arXiv:1403.4427 [hep-ex]



Top Mass: Combination Systematics

- LHC (**7 TeV**) + Tevatron first combination
  - arXiv:1403.4427 [hep-ex]

All values in GeV	CDF	D0	ATLAS	CMS	Tevatron	LHC	WA
Values	173.19	174.85	172.65	173.58	173.58	173.28	173.34
							0.27
							0.24
							0.20
							0.12
							0.25
							0.38
							0.21
							0.31
							0.09
							0.10
							0.11
							0.02
							0.10
							0.07
							0.05
							0.04
Total Syst	0.85	1.25	1.40	0.99	0.82	0.92	0.71
Total	1.00	1.48	1.44	1.03	0.94	0.94	0.76
χ^2/ndf	1.09 / 3	0.13 / 1	0.34 / 1	1.15 / 2	2.45 / 5	1.81 / 4	4.33 / 10
χ^2 probability [%]	78.1	72.0	56.2	56.2	78.4	77.1	93.1

- **iJES**: in situ ttbar (t→Wb, W→qqbar) calibration procedures
- **stdJES**: non-flavor specific part of JES
- **flavourJES**: different jet energy response for different flavors
- **bJES**: modelling of the response of jets originating from b-quarks

- **MC: MC modeling**
- **Rad: modeling of QCD radiation**
- **CR: color reconnection**

Detector modeling

b-tag: modeling of the b-tagging efficiency and the light-quark jet rejection factors in MC vs data

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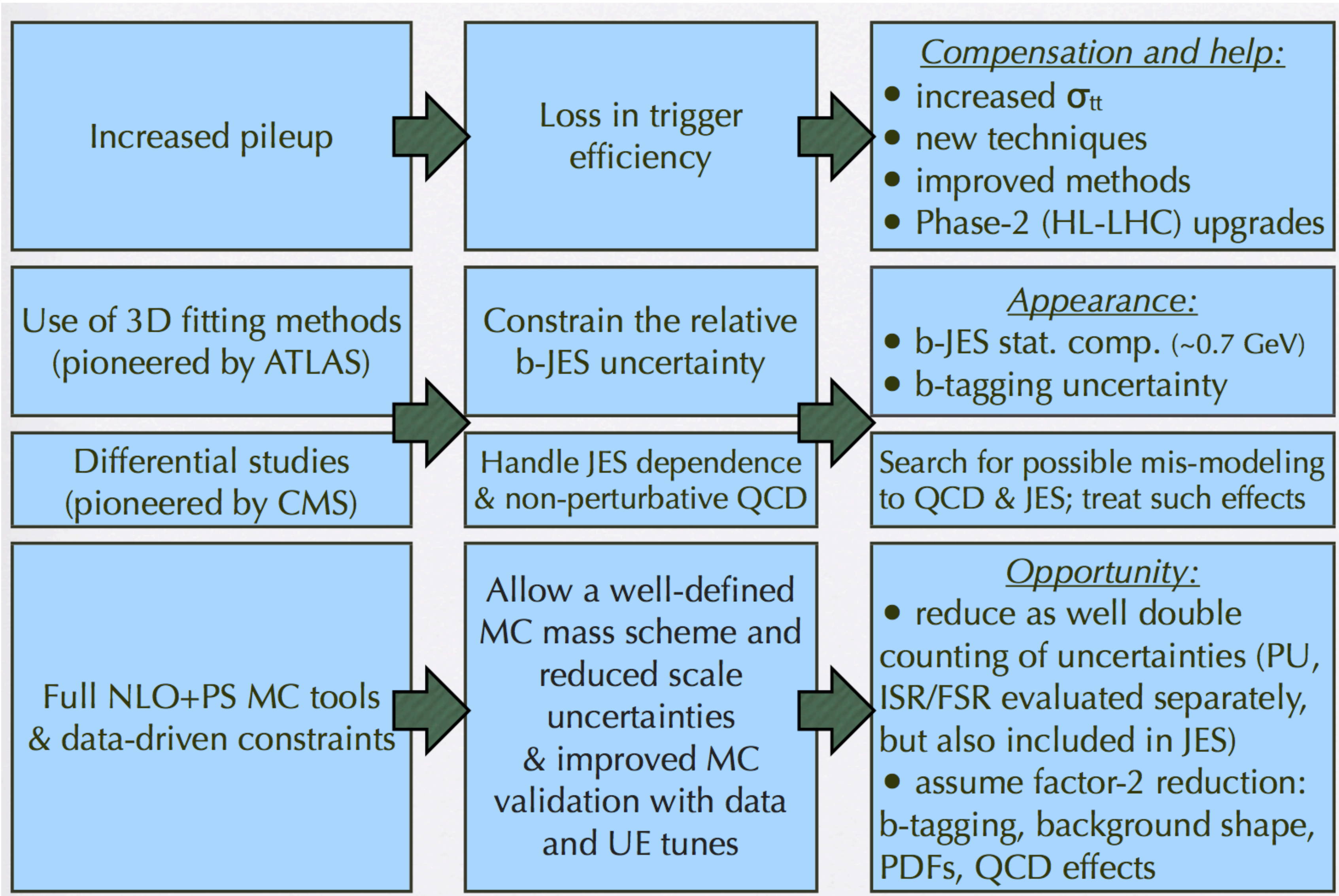
All values in GeV	CDF	D0	ATLAS	CMS	Tevatron	LHC	WA
Values	173.19	174.85	172.65	173.58	173.58	173.28	173.34
Stat	0.52	0.78	0.31	0.29	0.44	0.22	0.27
iJES	0.44	0.48	0.41	0.28	0.36	0.26	0.24
stdJES	0.30	0.62	0.78	0.33	0.27	0.31	0.20
flavourJES	0.08	0.27	0.21	0.19	0.09	0.16	0.12
bJES	0.15	0.08	0.35	0.57	0.13	0.44	0.25
MC	0.56	0.62	0.48	0.19	0.57	0.25	0.38
Rad	0.09	0.26	0.42	0.28	0.13	0.32	0.21
CR	0.21	0.31	0.31	0.48	0.23	0.43	0.31
PDF	0.09	0.22	0.15	0.07	0.12	0.09	0.09
DetMod	<0.01	0.37	0.22	0.25	0.09	0.20	0.10
b-tag	0.04	0.09	0.66	0.11	0.04	0.22	0.11
LepPt	<0.01	0.20	0.07	<0.01	0.05	0.01	0.02
BGMC	0.10	0.16	0.06	0.11	0.11	0.08	0.10
BGData	0.15	0.19	0.06	0.03	0.12	0.04	0.07
Meth	0.07	0.15	0.08	0.07	0.06	0.06	0.05
MHI	0.08	0.05	0.02	0.06	0.06	0.05	0.04
Total Syst	0.85	1.25	1.40	0.99	0.82	0.92	0.71
Total	1.00	1.48	1.44	1.03	0.94	0.94	0.76
χ^2/ndf	1.09 / 3	0.13 / 1	0.34 / 1	1.15 / 2	2.45 / 5	1.81 / 4	4.33 / 10
χ^2 probability [%]	78.1	72.0	56.2	56.2	78.4	77.1	93.1

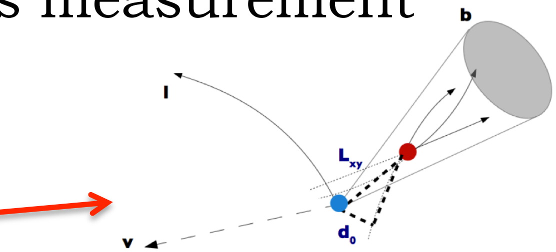
Extrapolating standard methods

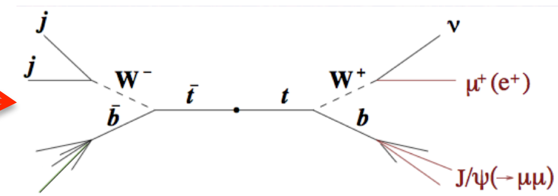
- Run 1 -> Run 2 and beyond

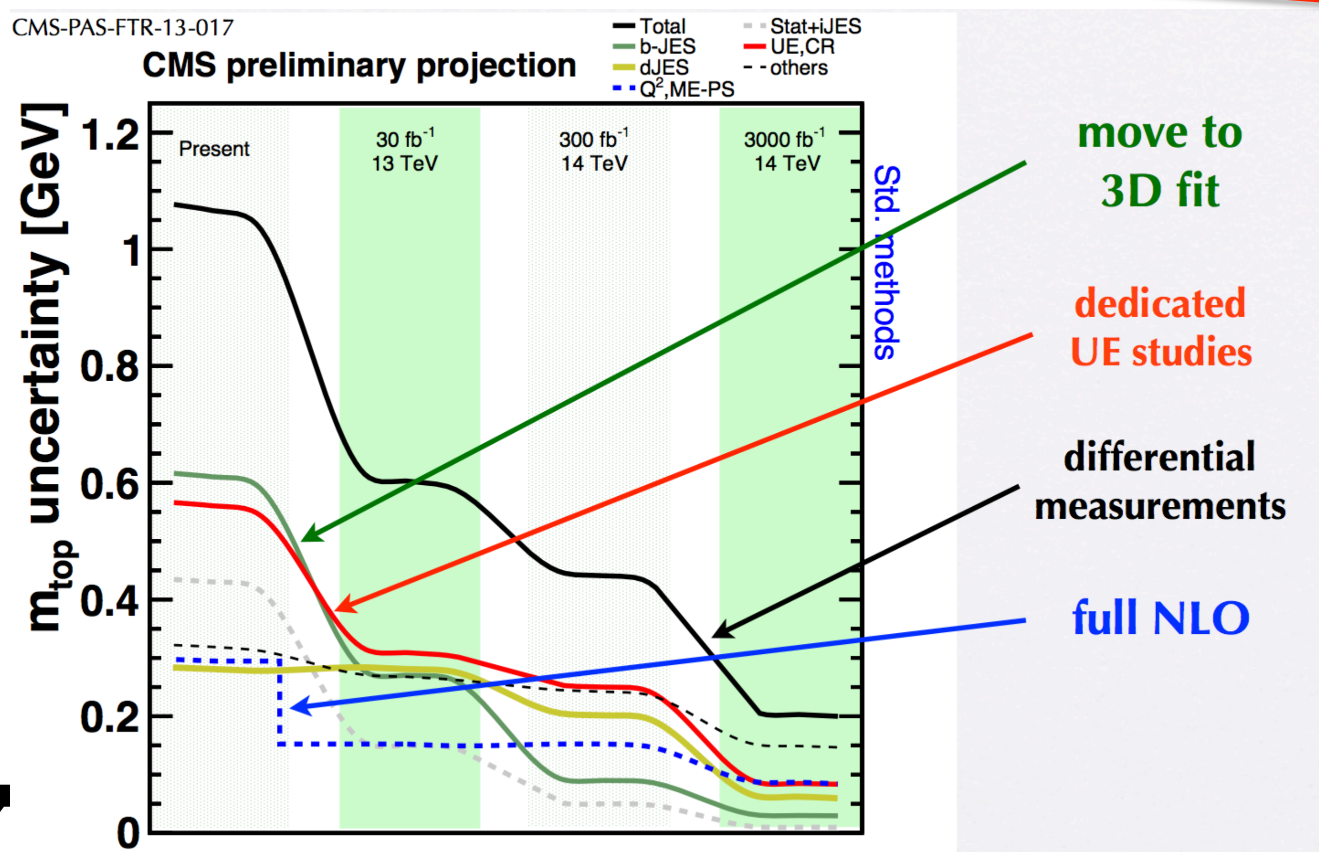


Top Mass Outlook

- For the projections used the baseline lepton+jets measurement at 7 TeV: JHEP **12** (2012) 105
  - CMS PAS FTR-13-017
  - And more methods with higher stats
    - Kinematic endpoints **(M_{lb} distribution)**
    - B-hadron lifetime (aka Lxy)
    - J/Psi method





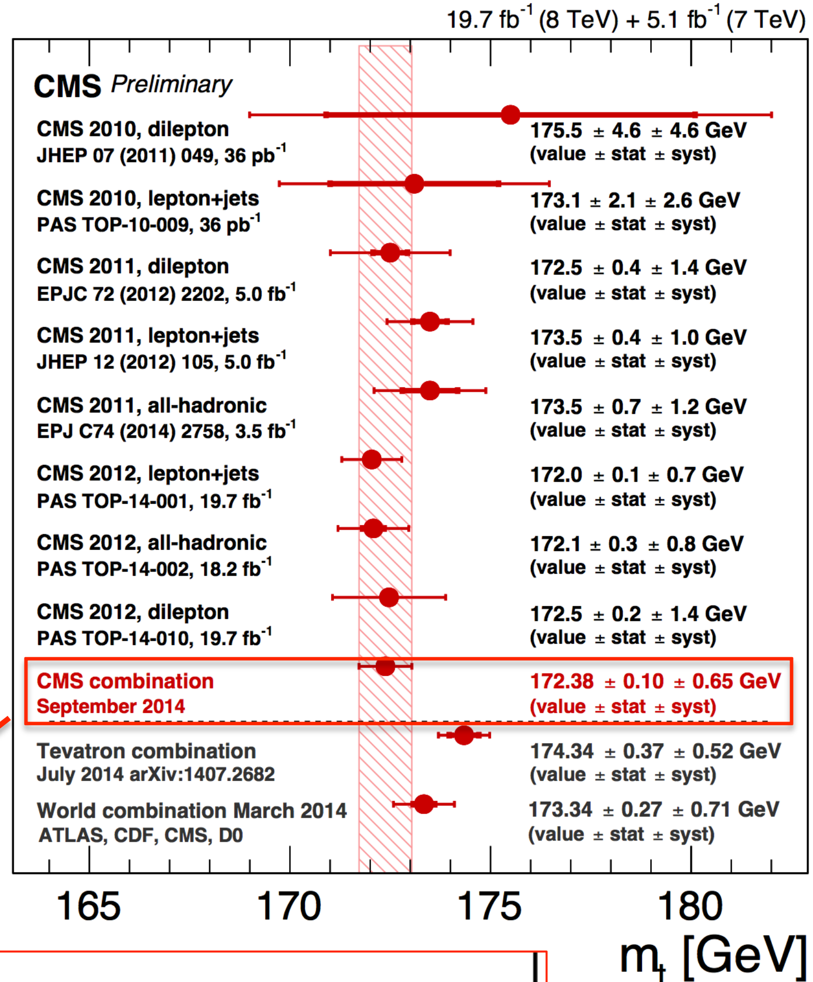


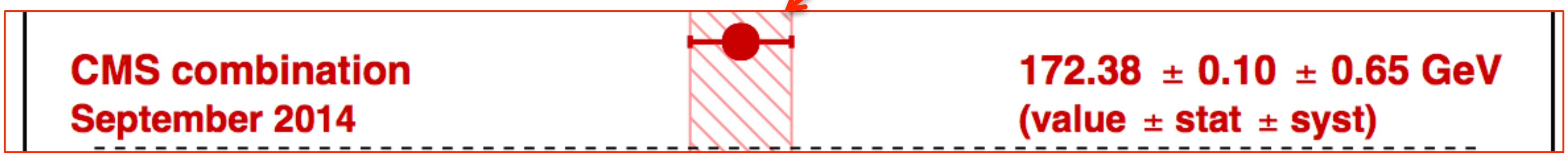
CM (TeV)	7	13	14
L int (fb⁻¹)	*5*	*30*	*300*
J/ψ		*1.8*	***0.8***
Lxy (8 TeV)	*3.4*	*1.3*	***0.6***
Endpoints	*2.1*	*1.1*	***0.6***
Standard	1.1	0.6	**0.4**

CMS updated combination

- Legacy Run I measurement from CMS (preliminary)
  - **New!** **CMS PAS TOP-14-015**

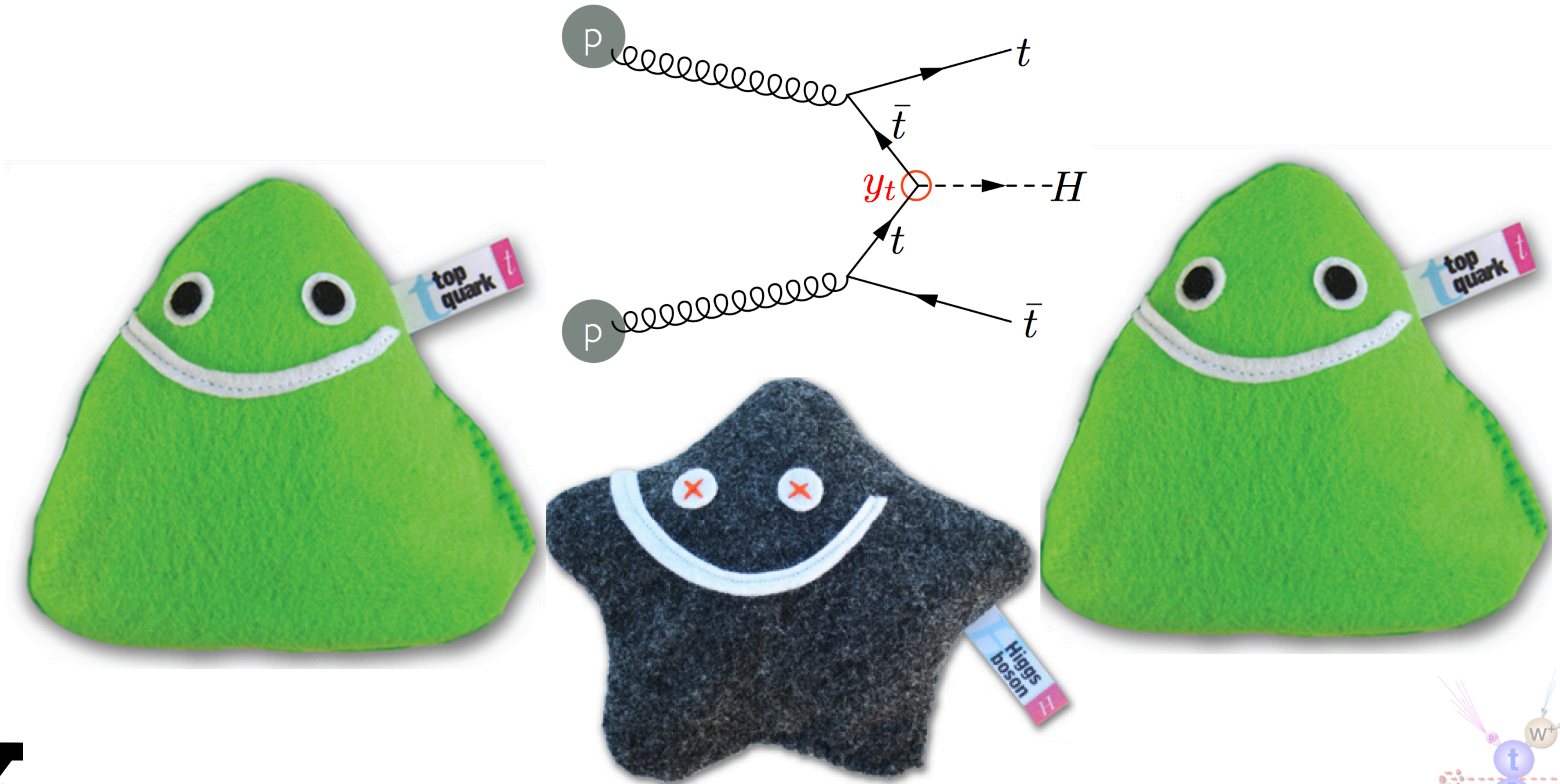
Analysis		Reference	m_t (GeV)	Stat. uncertainty (GeV)	Syst. uncertainty (GeV)
2010	di-l	[4]	175.50	4.60	4.52
	$l+$jets	[5]	173.10	2.10	2.66
2011	di-l	[6]	172.50	0.43	1.46
	$l+$jets	[7]	173.49	0.27	1.03
	all-jets	[8]	173.49	0.69	1.23
2012	di-l	[9]	172.47	0.17	1.40
	$l+$jets	[10]	172.04	0.11	0.74
	all-jets	[11]	172.08	0.27	0.84



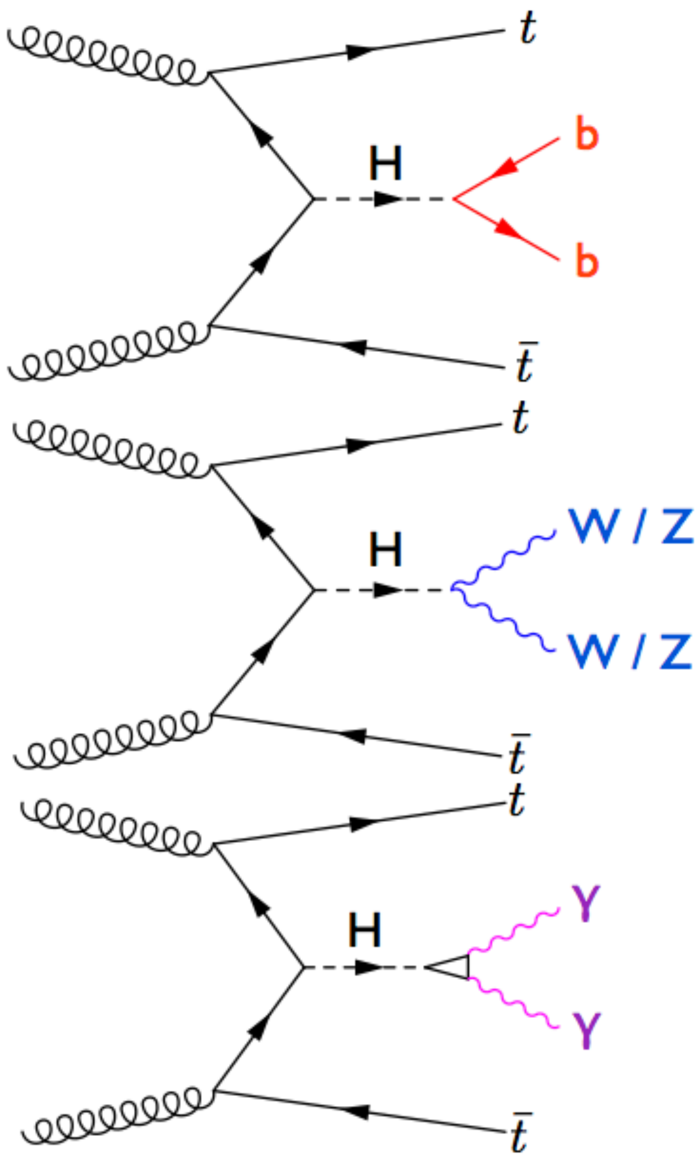


ttH

- **ttH** => square of top Yukawa coupling
  - **One of the key points** of Higgs physics program



ttH: Overview



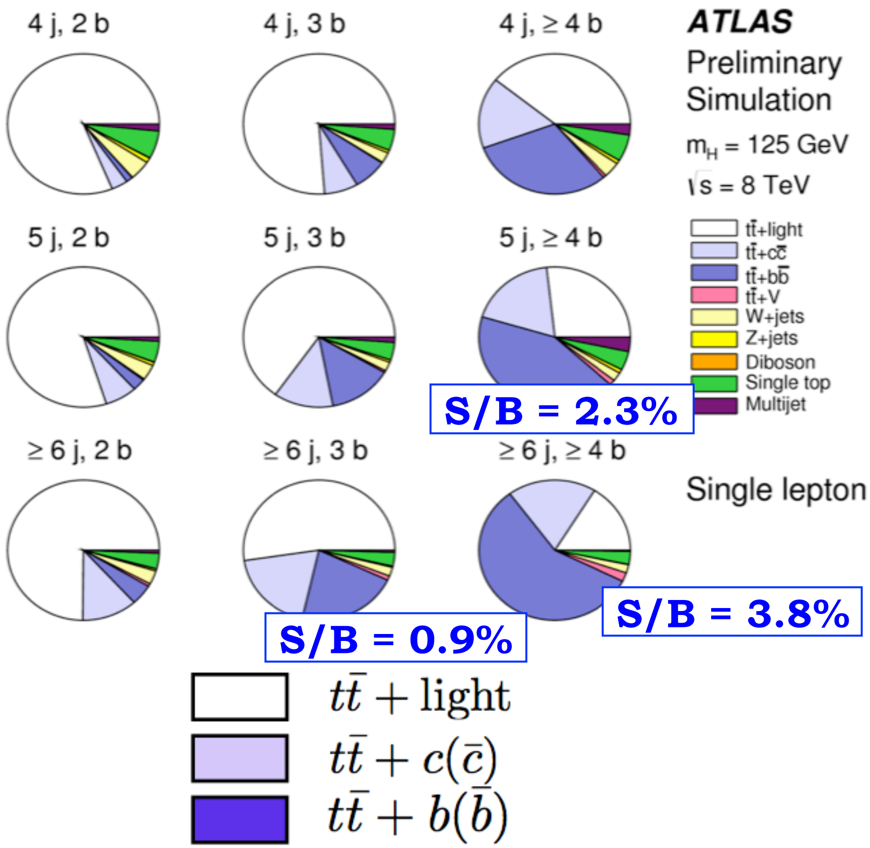
- Branching Ratio (BR) = 58%.
- Multiple b-quarks => challenging to reconstruct Higgs
  - Large background from **ttbar + jets** (including heavy flavor)

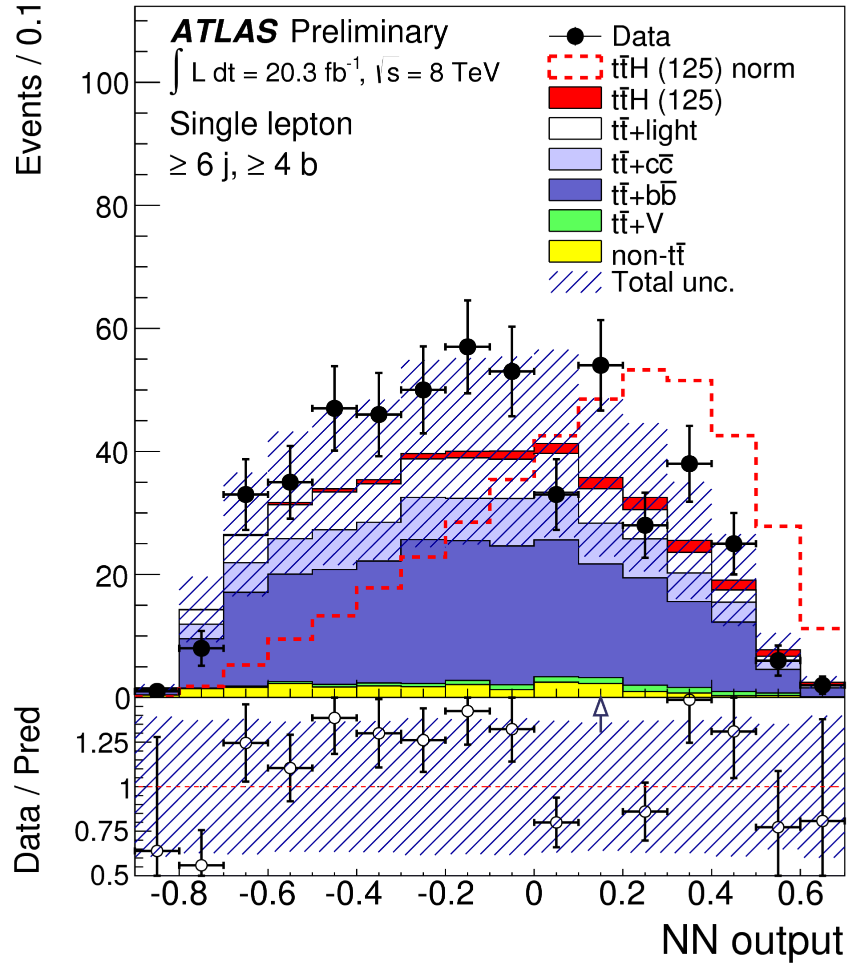
- Br(H→VV) = 22%
- Leptonic decays of W / Z bosons and tau decays can give distinct **multilepton signatures**
  - ZZ is the best VV channel to reconstruct Higgs.
- Main background from ttbar+W/Z and non-prompt leptons

- BR (H → diphoton) 0.2%
- Higgs boson reconstructed as a **narrow peak**
- Non-Higgs backgrounds from ttbar+0/1/2 photon(s) and QCD multi-photon / jet final states

ttH, H → bb

- ttbar + jets (incl.HF) backgrounds are highly important
  - Low N_{jets}, $N_{b\text{-}jets}$ region (5j, 3b) allows to constrain HF systematics
    - Would profit from knowing the exact HF content in ttbar + HF
  - ATLAS-CONF-2014-011

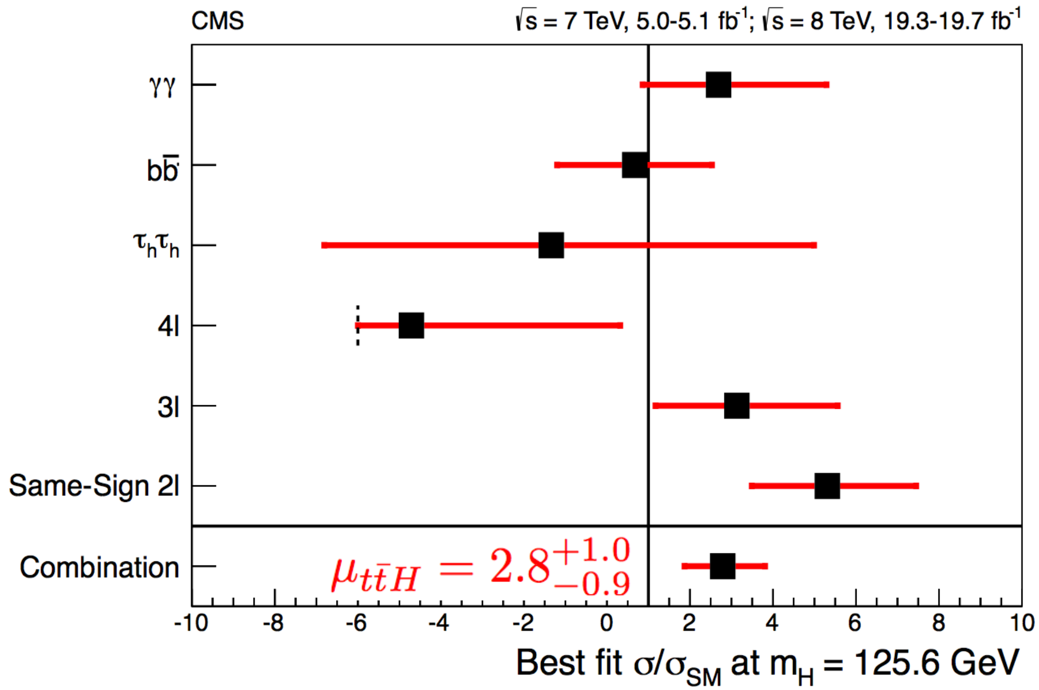


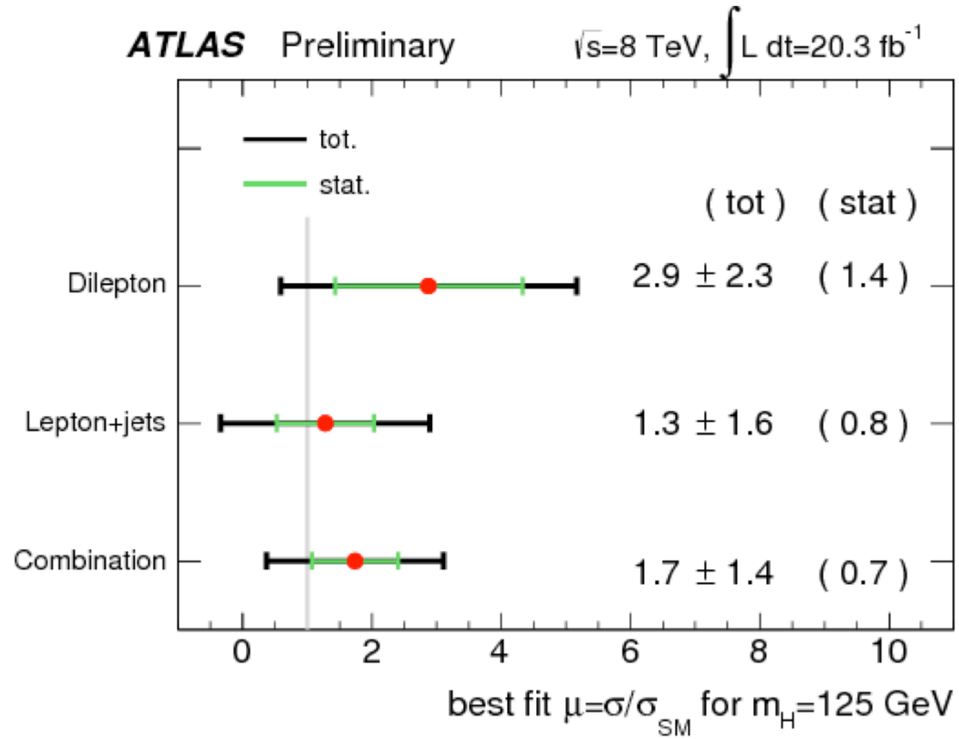


- Similar approach in the dilepton channel

ttH, Run 1

- Some ATLAS and CMS Run 1 results
  - Combination for CMS and H → bb (dilepton and lepton+jets) for ATLAS
- Run 2 will answer many questions





arXiv:1408.1682v1

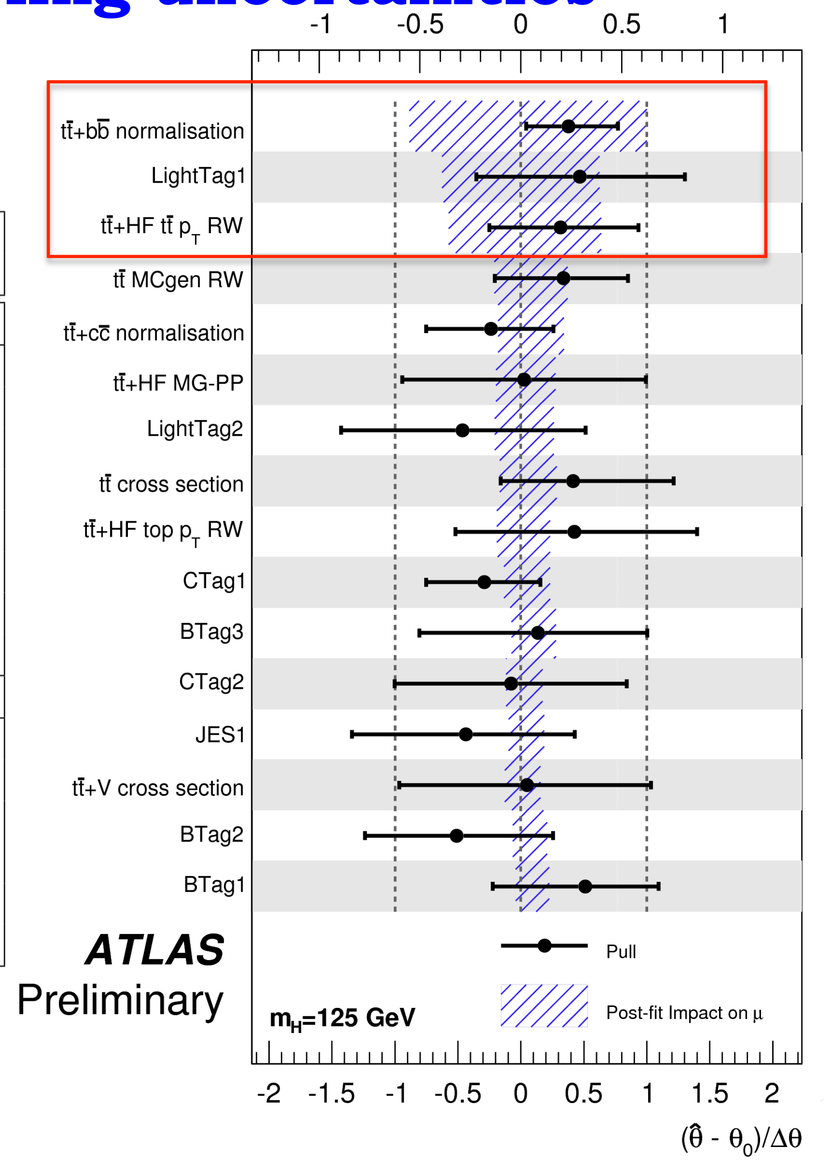
ATLAS-CONF-2014-011

ttH, Run 2: Systematics

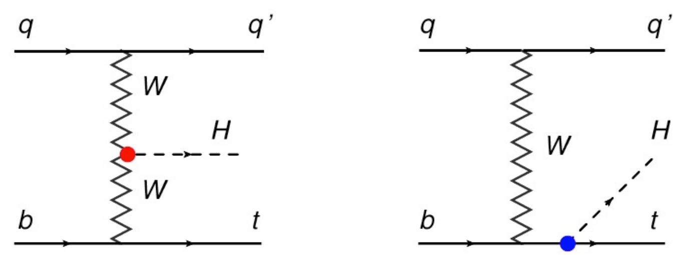
- CMS and ATLAS

Source	Rate uncertainty: Signal	Rate uncertainty: Backgrounds	Shape
Experimental			
Integrated luminosity	2.2–2.6%	2.2–2.6%	No
Jet energy scale	0.0–8.4%	0.1–11.5%	Yes
CSV b-tagging	0.9–21.7%	3.0–29.0%	Yes
Lepton reco. and ID	0.3–14.0%	1.4–14.0%	No
Lepton misidentification rate ($H \to$ leptons)	—	35.1–45.7%	Yes
Tau reco. and ID ($H \to$ hadrons)	11.3–14.3%	24.1–28.8%	Yes
Photon reco. and ID ($H \to$ photons)	1.6–3.2%	—	Yes
MC statistics	—	0.2–7.0%	Yes
Theoretical			
NLO scales and PDF	9.7–14.8%	3.4–14.7%	No
MC modeling	2.3–5.1%	0.9–16.8%	Yes
Top quark p_T	—	1.4–6.9%	Yes
Additional hf uncertainty ($H \to$ hadrons)	—	50%	No
H contamination ($H \to$ photons)	36.7–41.2%		No
WZ (ZZ) uncertainty ($H \to$ leptons)	—	22% (19%)	No

Modeling uncertainties



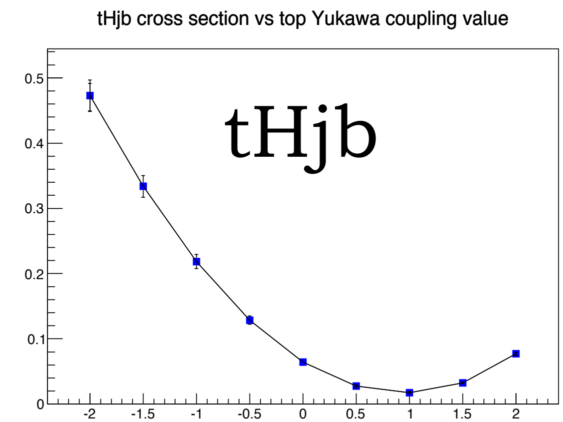
ttH & tH, H → diphotons



- Why Higgs to diphoton channel?
  - **Excellent mass resolution**
- **tH** => Strong interference between tH diagrams
  - Sensitive to the relative sign of ttH and WWH couplings

arXiv:1211.3736v2 [hep-ph]

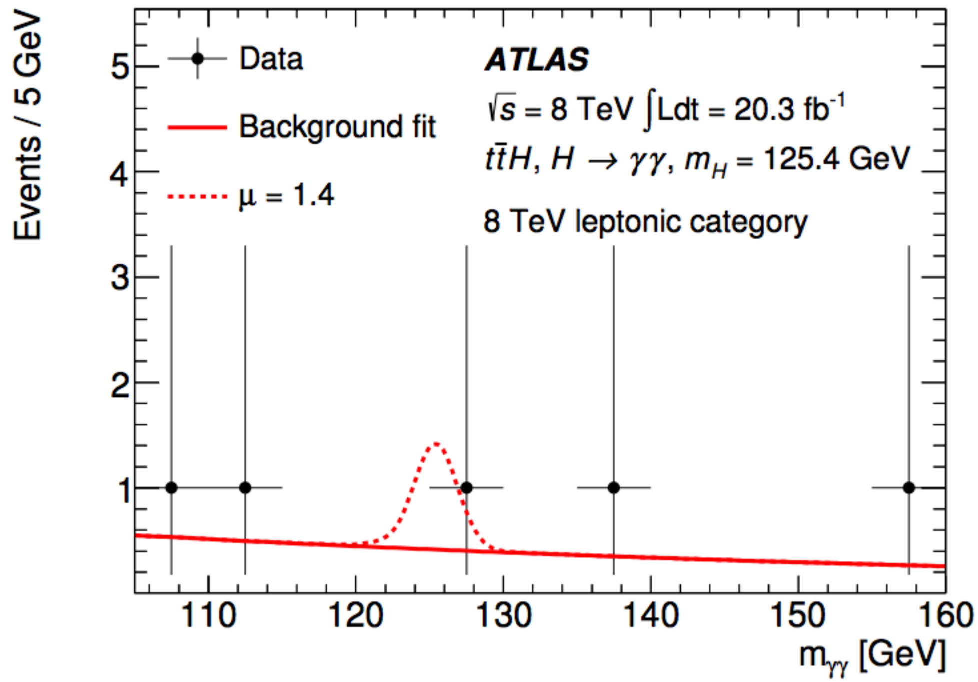
	$\sigma^{\mathrm{LO}}(pp \to thj)$ [fb]		$\sigma^{\mathrm{LO}}(pp \to thjb)$ [fb]	
	$c_F = 1$	$c_F = -1$	$c_F = 1$	$c_F = -1$
8 TeV	17.4	252.7	5.4	79.2
14 TeV	80.4	1042	26.9	363.5



- **Analysis selection**
  - Same trigger and photon selection requirement as in H to diphoton
  - $p_T^e > 15$ GeV, $p_T^\mu > 10$ Ge, $p_T^j > 25$ GeV
- **Hadronic** channel: **5/6j, ≥1/≥2 b-tags, lepton veto**
  - Optimization
    - Suppress non-Higgs processes
    - High purity of ttH w.r.t. non-ttH Higgs processes (ggF)
- **Leptonic** channel : $\mathbf{N_{lep} \geq 1}$, $\mathbf{M_{e\gamma}}$ **veto**, $\mathbf{N_{btag} \geq 1}$, **minimal MET**
  - Optimization: High ttH signal efficiency

Run 2: Recap

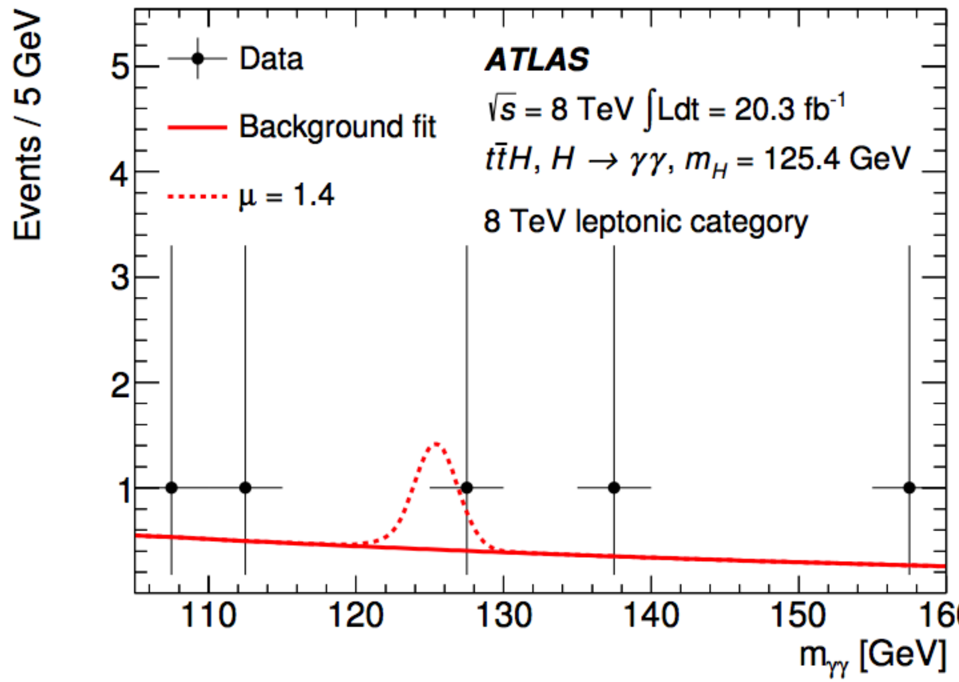
- 8 TeV Run 1 ATLAS paper submitted to PLB
  - [arXiv:1409.3122 [hep-ex]]
  - μ(ttH) > 6.7xSM (4.9xSM) excluded (expected)
  - Top Yukawa coupling limits
    - $\mathbf{c_t} < \mathbf{-1.3}$ and $\mathbf{c_t} > \mathbf{+8.0}$ are excluded



Category	N_H	ggF	VBF	WH	ZH	$t\bar{t}H$	$tHqb$	WtH	N_B
7 TeV leptonic selection	0.10	0.6	0.1	14.9	4.0	72.6	5.3	2.5	$0.5^{+0.5}_{-0.3}$
7 TeV hadronic selection	0.07	10.5	1.3	1.3	1.4	80.9	2.6	1.9	$0.5^{+0.5}_{-0.3}$
8 TeV leptonic selection	0.58	1.0	0.2	8.1	2.3	80.3	5.6	2.6	$0.9^{+0.6}_{-0.4}$
8 TeV hadronic selection	0.49	7.3	1.0	0.7	1.3	84.2	3.4	2.1	$2.7^{+0.9}_{-0.7}$

Run 2: Recap

- 8 TeV Run 2 ATLAS paper submitted to PLB
  - arXiv:1409.3122 [hep-ex]
  - μ(ttH) > 6.7xSM (4.9xSM) excluded (expected)
  - Top Yukawa coupling limits
    - $\mathbf{c_t}$ **< -1.3** and $\mathbf{c_t}$ **> +8.0** are excluded



	$t\bar{t}H$ [%]		$tHqb$ [%]		WtH [%]		ggF [%]	WH [%]
	had.	lep.	had.	lep.	had.	lep.	had.	lep.
Luminosity	±2.8							
Photons	±5.6	±5.5	±5.6	±5.5	±5.6	±5.5	±5.6	±5.5
Leptons	< 0.1	±0.7	< 0.1	±0.6	< 0.1	±0.6	< 0.1	±0.7
Jets and E_T^{miss}	±7.4	±0.7	±16	±1.9	±11	±2.1	±29	±10
Bkg. modeling	0.24 evt.	0.16 evt.	applied on the sum of all Higgs boson production processes					
Theory ($\sigma \times$ BR)	+10,−13		+7,−6		+14,−12		+11,−11	+5.5,−5.4
MC Modeling	±11	±3.3	±12	±4.4	±12	±4.6	±130	±100

Run 2 and beyond: Conditions

- Higher center-of-mass energy
  - **Acceptance x Efficiency should stay the ~same**
    - Larger momenta of ttH decay products
    - Might need to increase some object p_T cuts (jet p_T? lepton p_T?)
- Photon ID, lepton isolation, jet resolution
  - Don't expect huge changes
- **A lot more data**
  - New categories?
  - Better optimizations?
- In Run 2 systematic uncertainties did not have a large impact on the limits
  - **In Run 2 (and beyond) this will change**

Systematics: Run 1 -> 2 (and beyond)

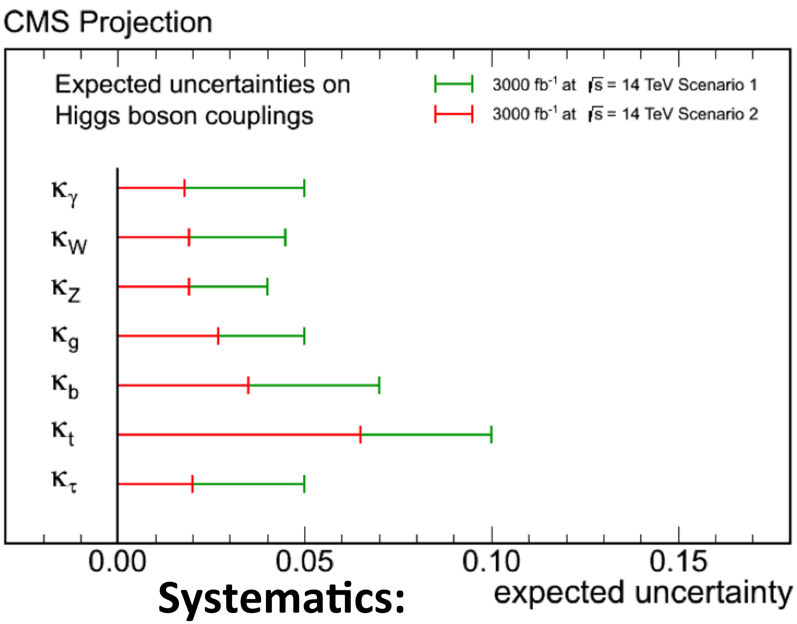
- $\mathbf{N_{jets}}$ **and HF** uncertainties are essential for many optimizations
  - With higher statistics they will **greatly limit the sensitivity**
- $\mathbf{N_{jets}}$: will be constrained with more data
  - ggF + jets (hadronic), WH + jets (leptonic)
  - **Additional $\mathbf{N_{jet}}$ categories**?
- **HF**
  - ggF + HF (hadronic), WH + HF (leptonic)
  - **Additional $\mathbf{N_{bjet}}$ categories**?
  - Learn from tt+HF and from tt+H(bbbar)
    - These will help to improve theory predictions too
- **JES** and other typical top analyses uncertainties
  - Profiling?
  - JES-independent observables?

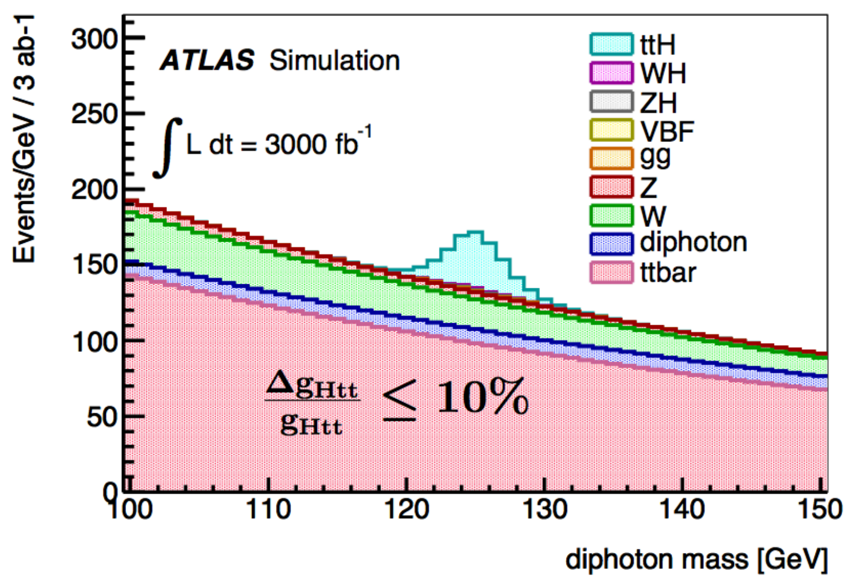
More channels

- More data = better selection optimization
  - **Dilepton category**
    - Including Lepton+tau
  - **Tau + jets category**
    - Expect low S/B
  - **Reoptimize all-hadronic category?**
    - Requires **reduction of N_{jets} and HF uncertainties**
    - Discriminate ggF vs ttH (hadronic) to gain ttH signal
      - **Need Monte Carlo simulation of H + ≥4 jets production**
      - For instance, can then go down to 4 jets selection
  - **Split in N_{jets}, N_{bjets} bins**
  - **Inputs to a Multi-Variate discriminant**
    - Photon kinematics to distinguish ttH from non-ttH

HL-LHC prospects

- HL-LHC is the benchmark Higgs factory
  - Theoretical uncertainties affect the ultimate precision achievable by LHC experiments
    - Reducing them it is for sure worth the effort
    - Both in MC and data-driven way (the latter would be preferable but not always possible)





Systematics:

Scenario 1: unchanged

Scenario 2: scaled 1/sqrt(L)

Outlook

- Really looking forward to Run 2 and beyond
- **Top Mass**
    - Challenging measurement, but expect to reduce systematic uncertainty to **few hundred MeV**
- **ttH**
    - Get from setting limits to performing the measurements
    - Test the anomalous top-Yukawa coupling
        - Exclude C_t=-1 early on in Run 2
    - Re-optimize, add channels, get the most from the available data
- (many other) **Top Properties**
    - Many things are still unknown (to the desired precision)