Challenging channels at HL-LHC: ttH(bb), VH(bb), H(ττ), VBF

Lorenzo Bianchini
ETH Zurich

on behalf of the ATLAS and CMS Collaborations

HL-LHC Workshop, May 11 2015, CERN

Challenging channels

A number of channels will become challenging at HL-LHC

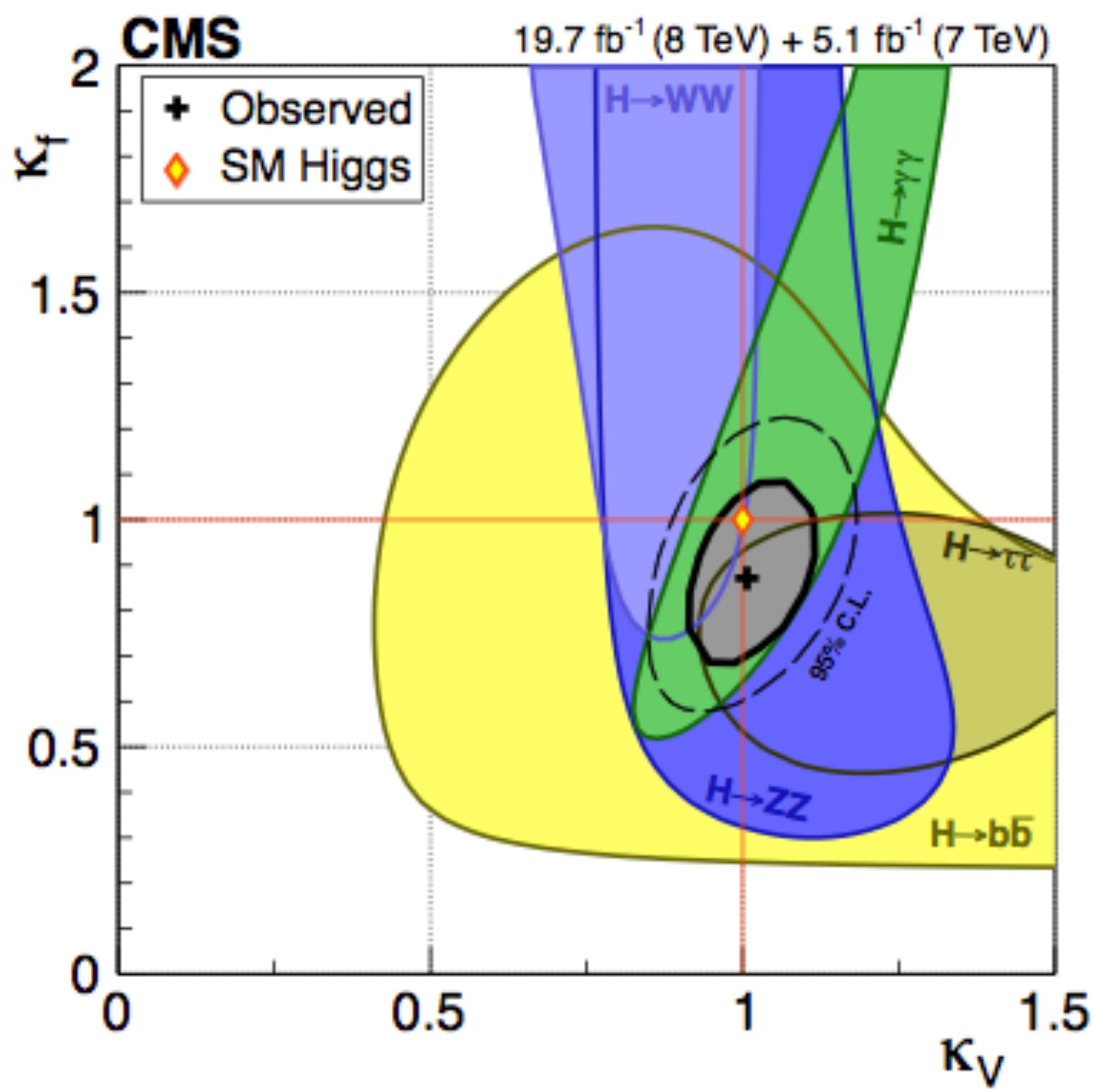
- harsh *pile-up* conditions and instantaneous *rate*

Challenging channels

A number of channels will become challenging at HL-LHC

- harsh *pile-up* conditions and instantaneous *rate*
- directly impacting our projected expectation on Higgs coupling

CMS, arXiv:1412.8662

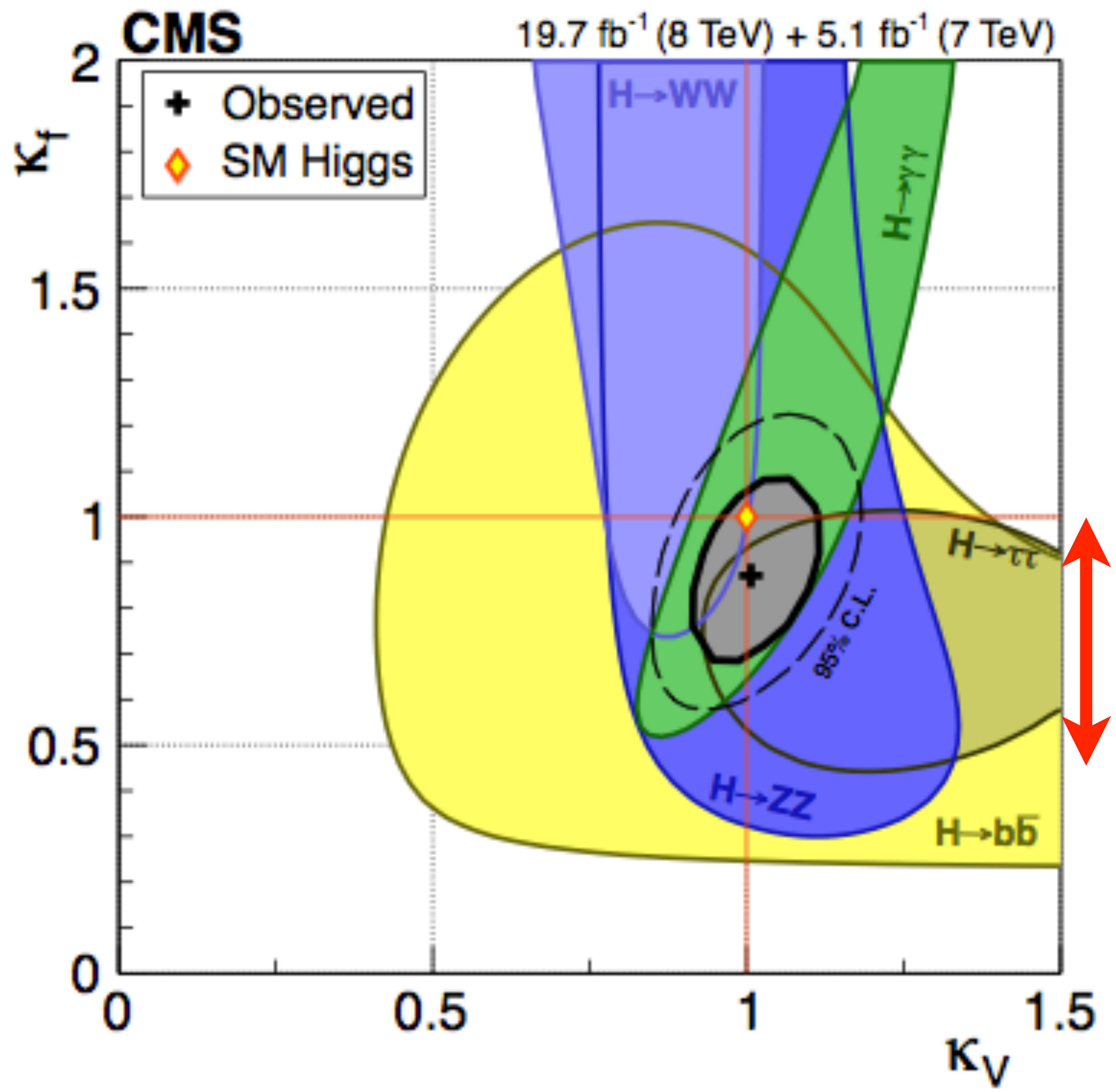


Challenging channels

A number of channels will become challenging at HL-LHC

- harsh *pile-up* conditions and instantaneous *rate*
- directly impacting our projected expectation on Higgs coupling

CMS, arXiv:1412.8662



gg→H→ττ

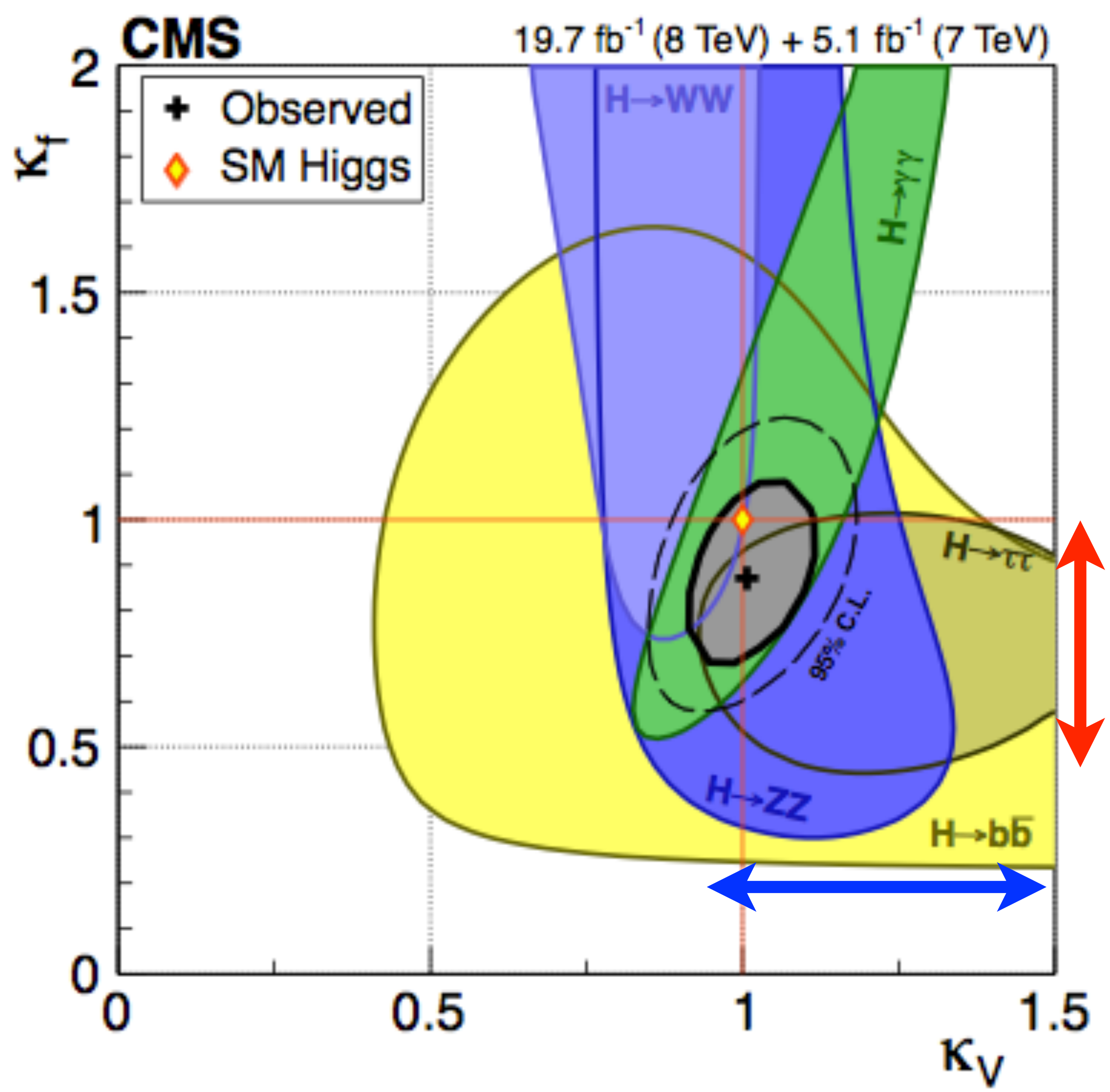
$$\propto \frac{\kappa_f^2 \kappa_f^2}{0.75\kappa_f^2 + 0.25\kappa_V^2}$$

Challenging channels

A number of channels will become challenging at HL-LHC

- harsh *pile-up* conditions and instantaneous *rate*
- directly impacting our projected expectation on Higgs coupling

CMS, arXiv:1412.8662



gg→H→ττ

$$\propto \frac{\kappa_f^2 \kappa_f^2}{0.75\kappa_f^2 + 0.25\kappa_V^2}$$

qqH→ττ

$$\propto \frac{\kappa_V^2 \kappa_f^2}{0.75\kappa_f^2 + 0.25\kappa_V^2}$$

Challenging channels

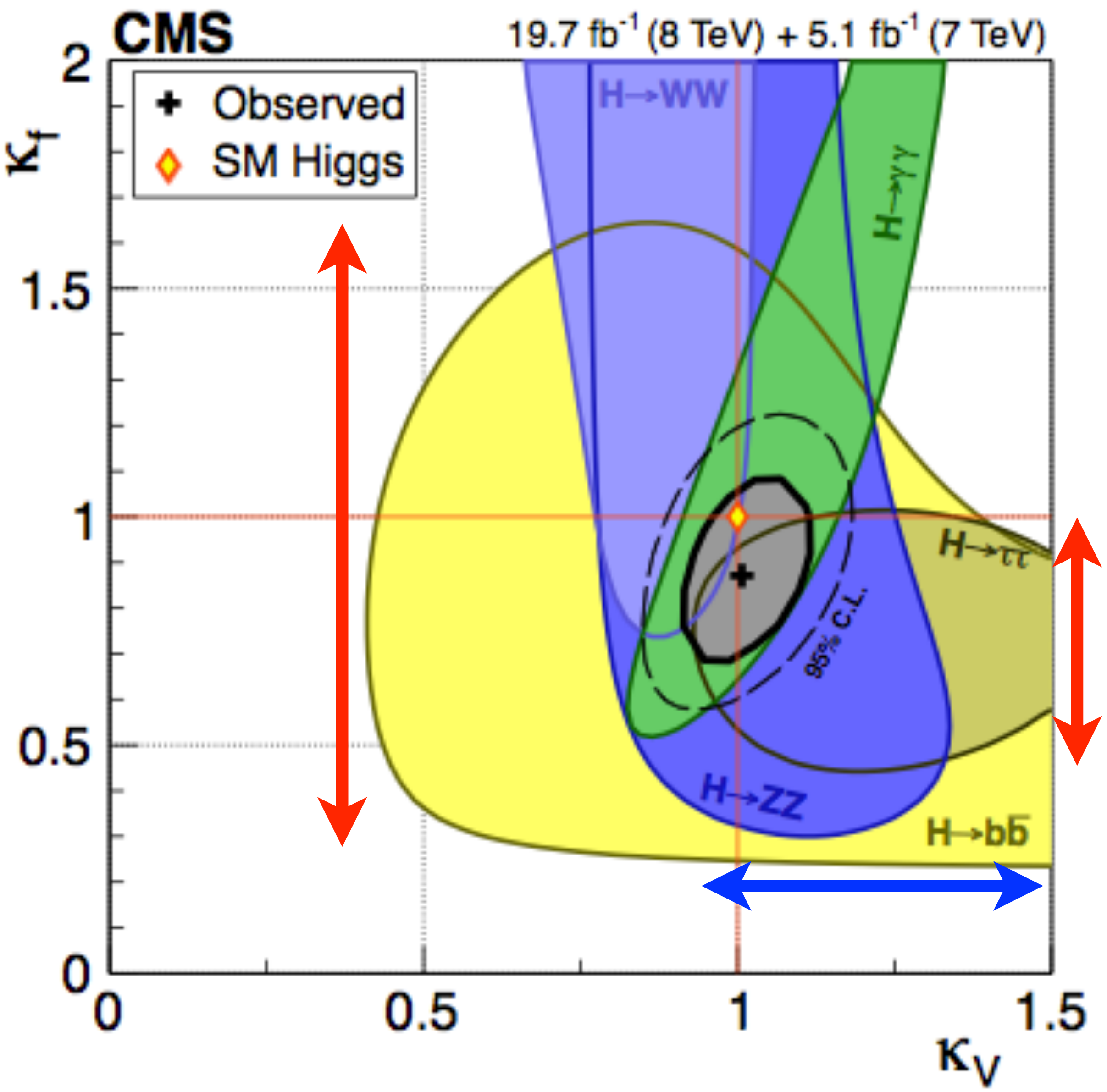
A number of channels will become challenging at HL-LHC

- harsh *pile-up* conditions and instantaneous *rate*
- directly impacting our projected expectation on Higgs coupling

CMS, arXiv:1412.8662

VH→bb

$$\propto \frac{\kappa_V^2 \kappa_b^2}{\kappa_H^2}$$



gg→H→ττ

$$\propto \frac{\kappa_f^2 \kappa_f^2}{0.75\kappa_f^2 + 0.25\kappa_V^2}$$

qqH→ττ

$$\propto \frac{\kappa_V^2 \kappa_f^2}{0.75\kappa_f^2 + 0.25\kappa_V^2}$$

Challenging channels

A number of channels will become challenging at HL-LHC

- harsh *pile-up* conditions and instantaneous *rate*
- directly impacting our projected expectation on Higgs coupling

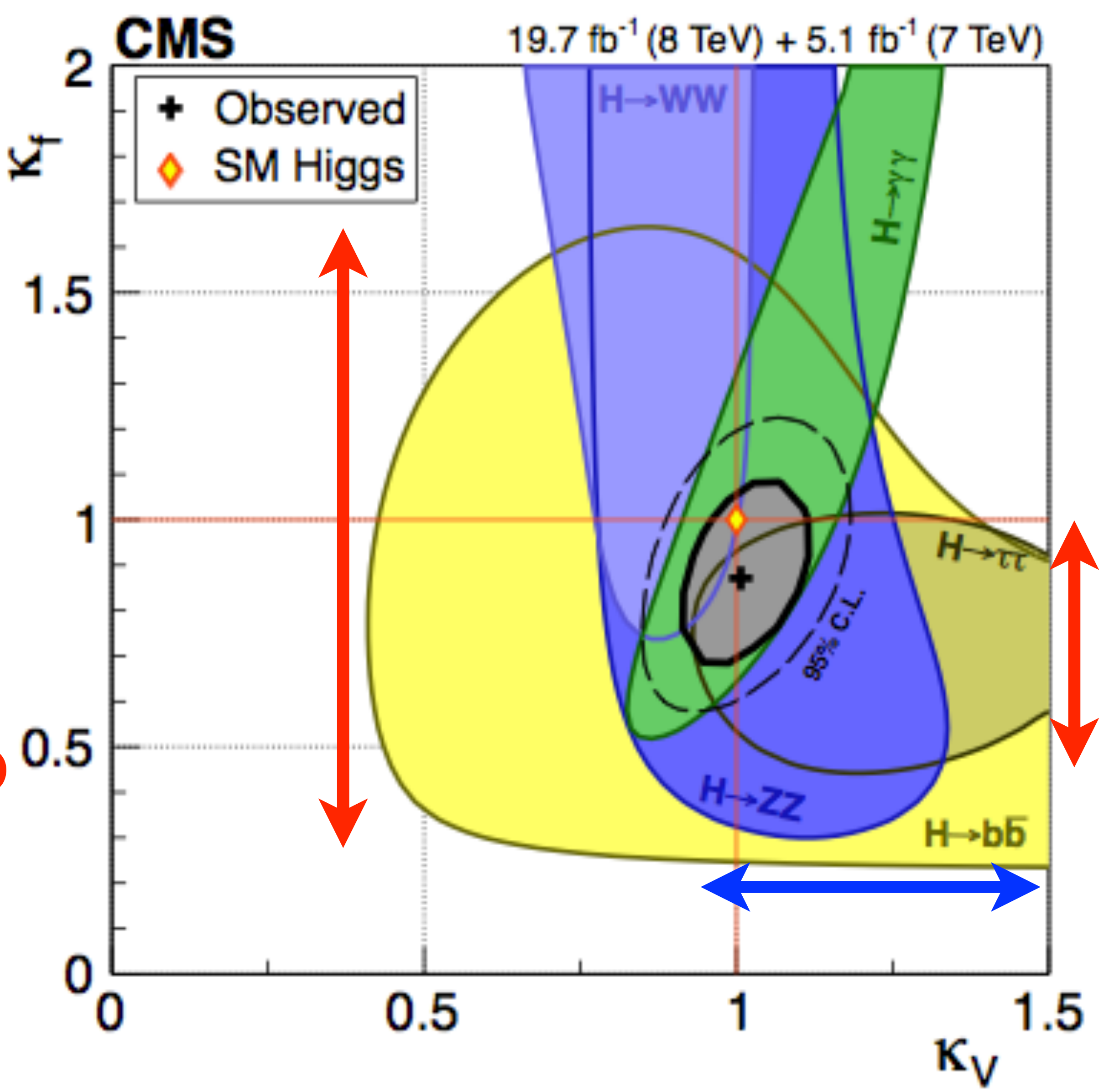
CMS, arXiv:1412.8662

VH→bb

$$\propto \frac{\kappa_V^2 \kappa_b^2}{\kappa_H^2}$$

ttH→bb

$$\propto \frac{\kappa_t^2 \kappa_b^2}{\kappa_H^2}$$



gg→H→ττ

$$\propto \frac{\kappa_f^2 \kappa_f^2}{0.75\kappa_f^2 + 0.25\kappa_V^2}$$

qqH→ττ

$$\propto \frac{\kappa_V^2 \kappa_f^2}{0.75\kappa_f^2 + 0.25\kappa_V^2}$$

Overview

- Highlight features and issues of Run I analyses
  - Assumption: Run I analyses ~optimal ⇔ very close to final HL-LHC ones
  - Then, use Run I analyses to gain insights on
    - detector upgrades
    - theoretical inputs to be improved
    - auxiliary measurements

- Results from public ATLAS and CMS projections for HL-LHC:
  - ATLAS:

    "Simulation smeared by appropriate resolution functions.
    Repeating 8 TeV-like analyses (not always legacy analyses)."
  - CMS:

    "Project Run I analyses data cards (2013) to high-lumi.
    Full simulation of detector upgrade validates projection."
    - not always comparable
    - most of the times, same conclusions can be drawn
    - alternative approaches as a basis to span different scenarios

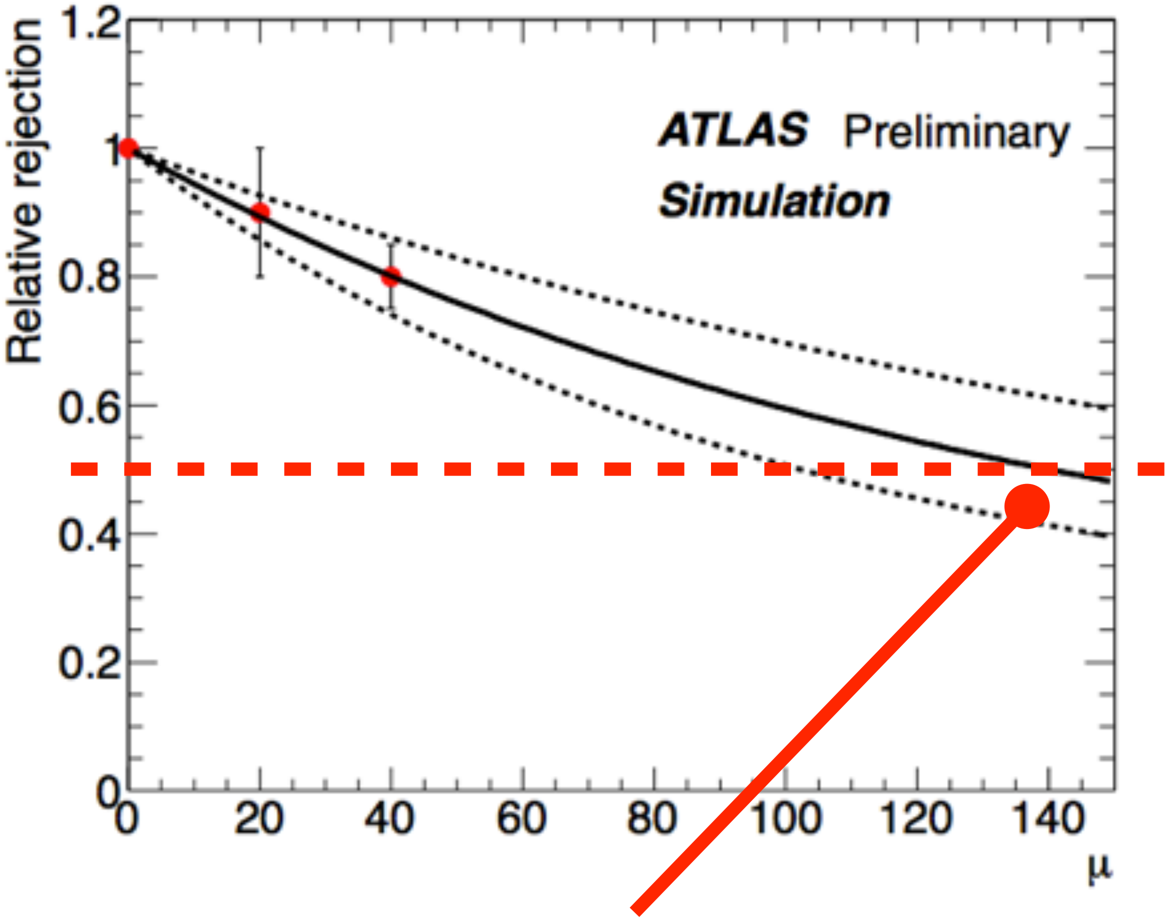
VH(bb)

Experimental challenge: b tagging

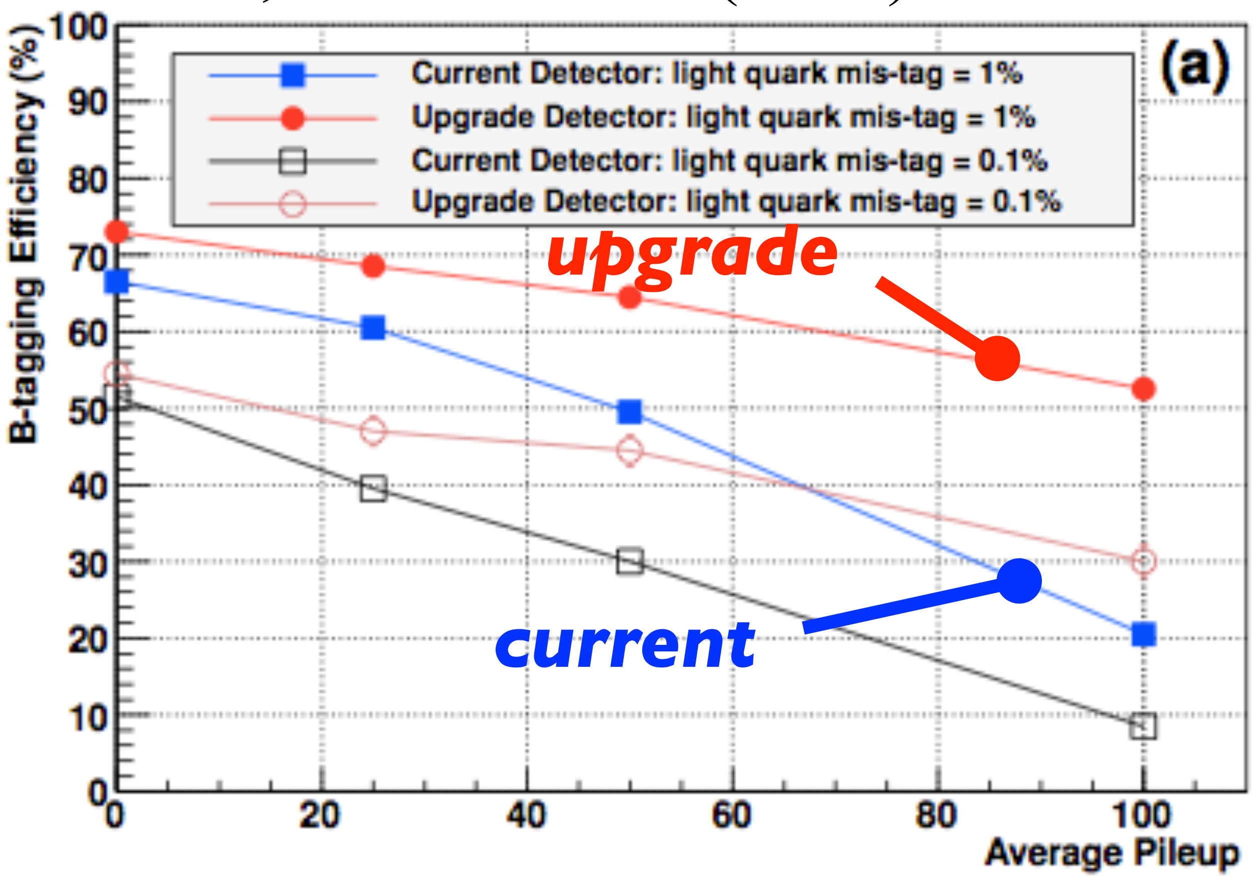
B-tag performances heavily degraded by PU

- extra particles, lower tracking efficiency

ATLAS-PHYS-PUB-2013-004



CMS, NOTE-13-02 (2013)



Light-flavour rejection vs μ_{PU} w/o detector upgrade

Pixel upgrade crucial to recover efficiency

Theory uncertainties: VH

NLO MCs reweighted to best accuracy

- QCD @NNLO and EWK @NLO
- both qqVH and ggZH productions
- uncertainty on acceptance increased by analysis cuts (p_T^V, N_{jet})
  - further enhanced in most senitive BDT bins

ATLAS, JHEP 01 (2015) 069

	Signal
Cross section (scale)	1% ($q\bar{q}$) 50% (gg)
Cross section (PDF)	2.4% ($q\bar{q}$) 17% (gg)
Branching ratio	3.3 %
Acceptance (scale)	1.5%–3.3%
3-jet acceptance (scale)	3.3%–4.2%
p_T^V shape (scale)	S
Acceptance (PDF)	2%–5%
p_T^V shape (NLO EW correction)	S
Acceptance (parton shower)	8%–13%

ggZH ~10%σ_{VH} @14 TeV

e.g. PYTHIA vs HERWIG

Can it be constrained by WZ/ZZ?

$\sigma_{stat}^{WZ/ZZ}$ ~ 2% at 3000 fb^{-1}

PDFs

Can be related to other Drell-Yan measurements?

Background systematics

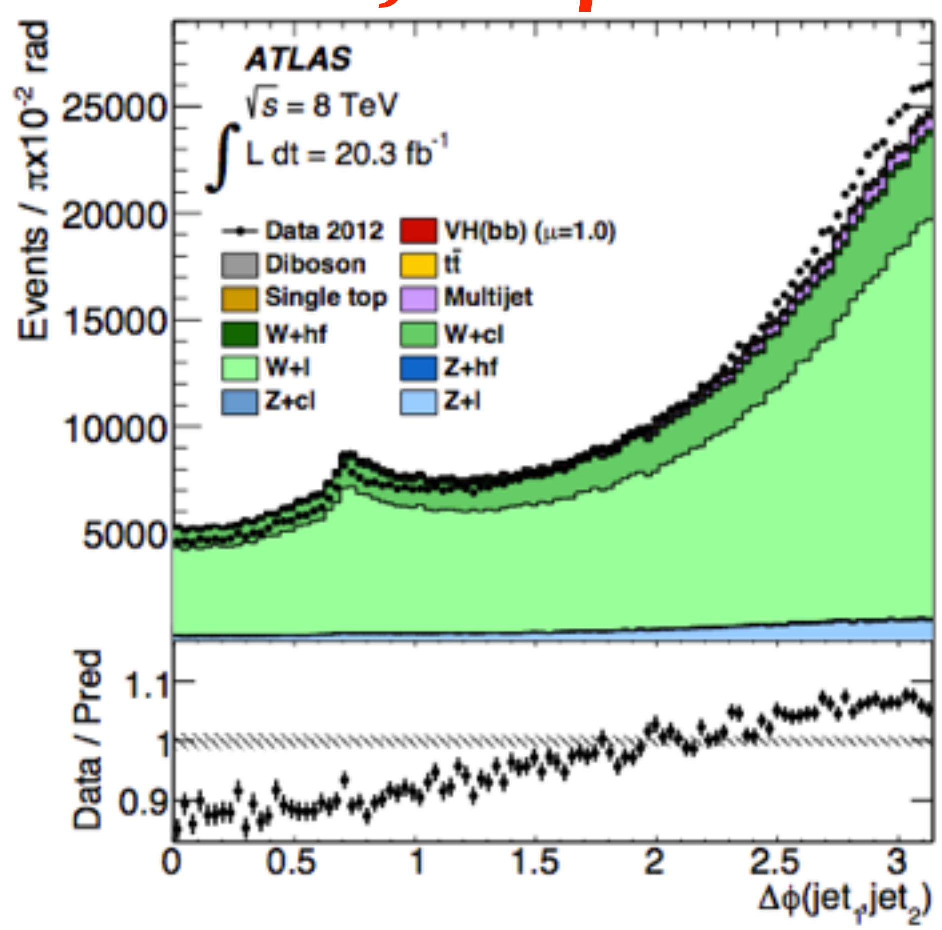
- Shape from MC
  - systematics from MC comparison
- Normalisation from sidebands
  - when statistical power (and purity) large enough
    - scale factors often large (can shapes/extrapolation be trusted at all?)
  - when insufficient lever-arm, constrain ratios of backgrounds
    - 3/2-jet ratio, Wbl/Wbb, Wbc/Wbb,...
    - 10-35% theory unc. on ratios

Improved theoretical prediction on ratios?

CMS, background scale factors

Process	$W(\ell\nu)H$	$Z(\ell\ell)H$	$Z(\nu\nu)H$
Low $p_T(V)$			
W + udscg	$1.03 \pm 0.01 \pm 0.05$	–	$0.83 \pm 0.02 \pm 0.04$
W + b	$2.22 \pm 0.25 \pm 0.20$	–	$2.30 \pm 0.21 \pm 0.11$
W + $b\bar{b}$	$1.58 \pm 0.26 \pm 0.24$	–	$0.85 \pm 0.24 \pm 0.14$
Z + udscg	–	$1.11 \pm 0.04 \pm 0.06$	$1.24 \pm 0.03 \pm 0.09$
Z + b	–	$1.59 \pm 0.07 \pm 0.08$	$2.06 \pm 0.06 \pm 0.09$
Z + $b\bar{b}$	–	$0.98 \pm 0.10 \pm 0.08$	$1.25 \pm 0.05 \pm 0.11$
$t\bar{t}$	$1.03 \pm 0.01 \pm 0.04$	$1.10 \pm 0.05 \pm 0.06$	$1.01 \pm 0.02 \pm 0.04$

ATLAS, W+lf sideband

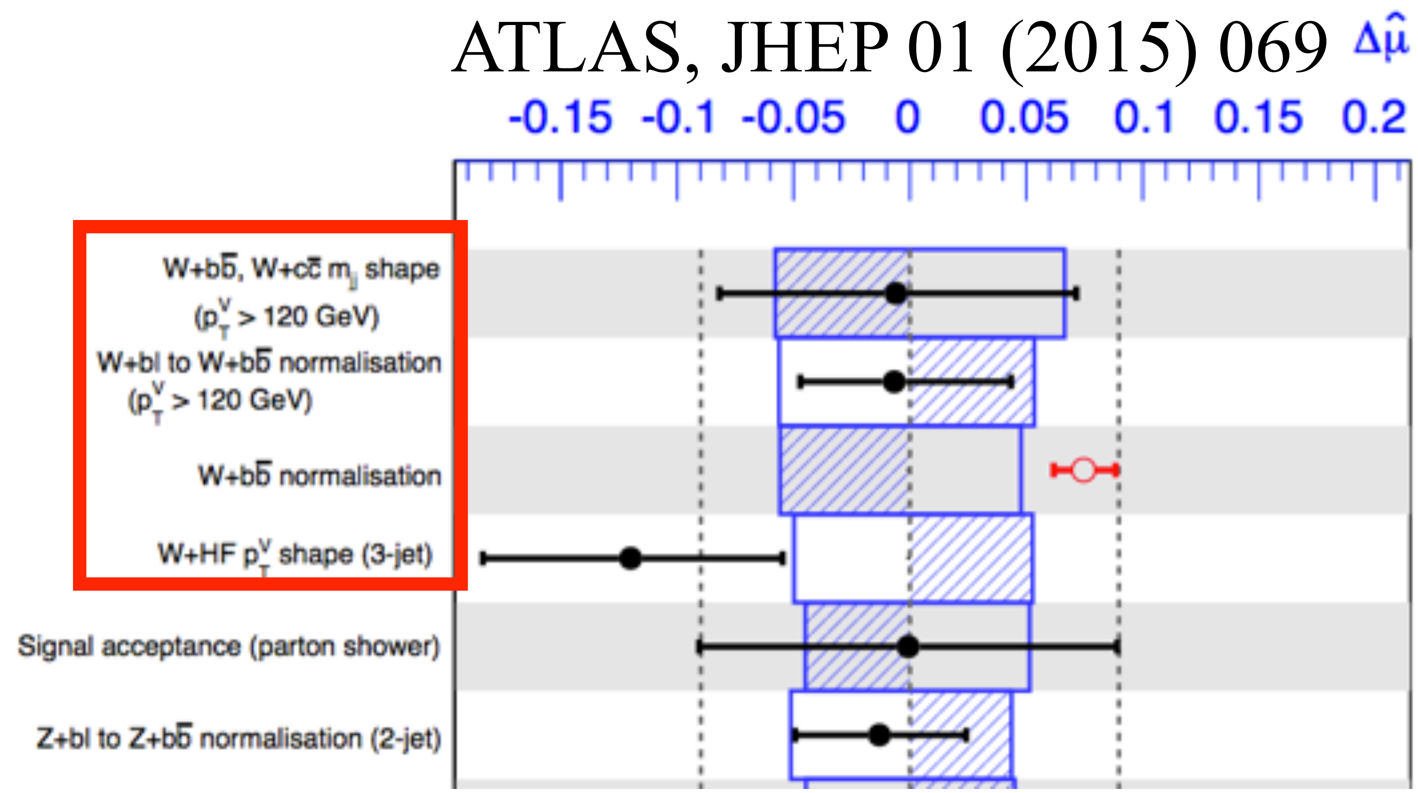


Monday, May 11, 15

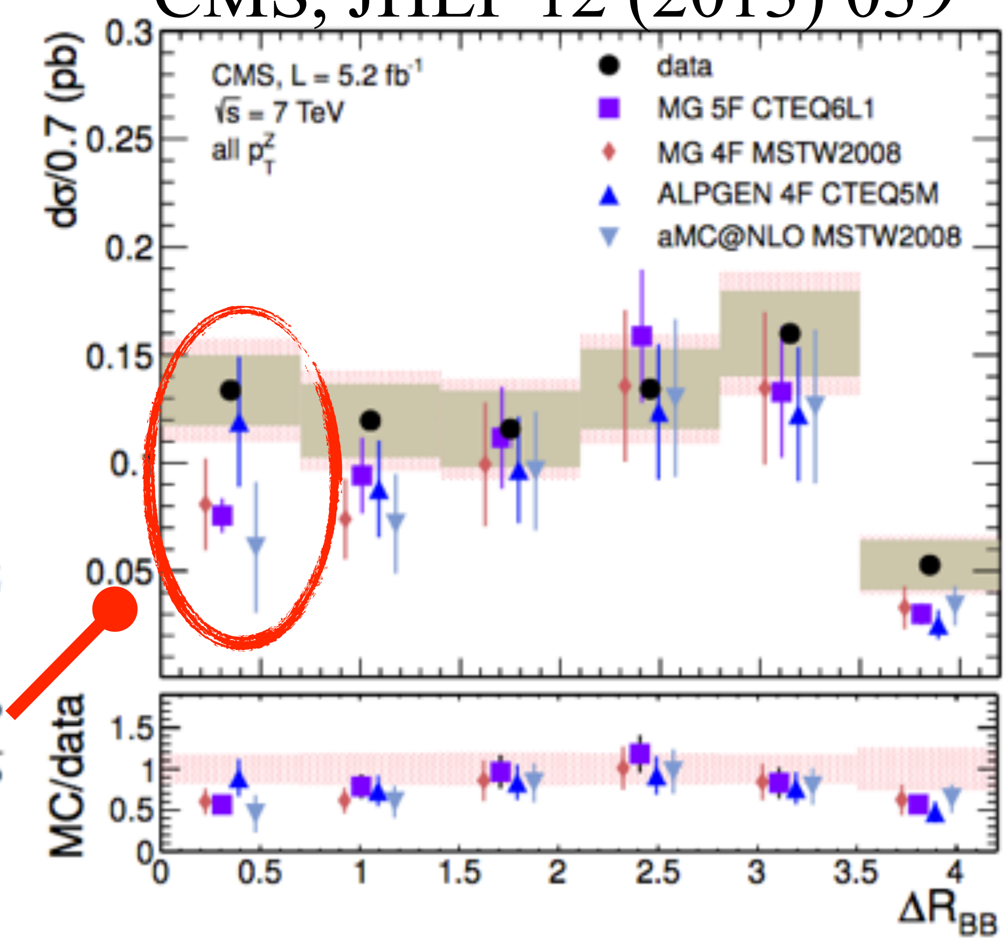
Auxiliary measurements

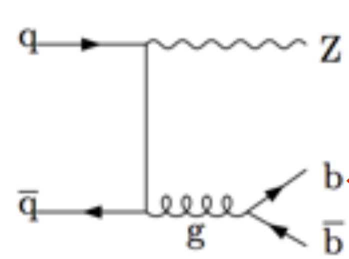
- Impact of background modeling already evident in Run I
  - shape uncertainties won't scale with luminosity
    - overkilling at higher luminosities
- Validation of key backgrounds should be pursued at HL-LHC
  - e.g. measurements of V+b, V+bb cross sections
    - 4F/5F schemes, understanding different parton showers
  - differential distributions also important
    - e.g. Z + secondary vertices sensitive to g→bb splitting

ATLAS, JHEP 01 (2015) 069



CMS, JHEP 12 (2013) 039

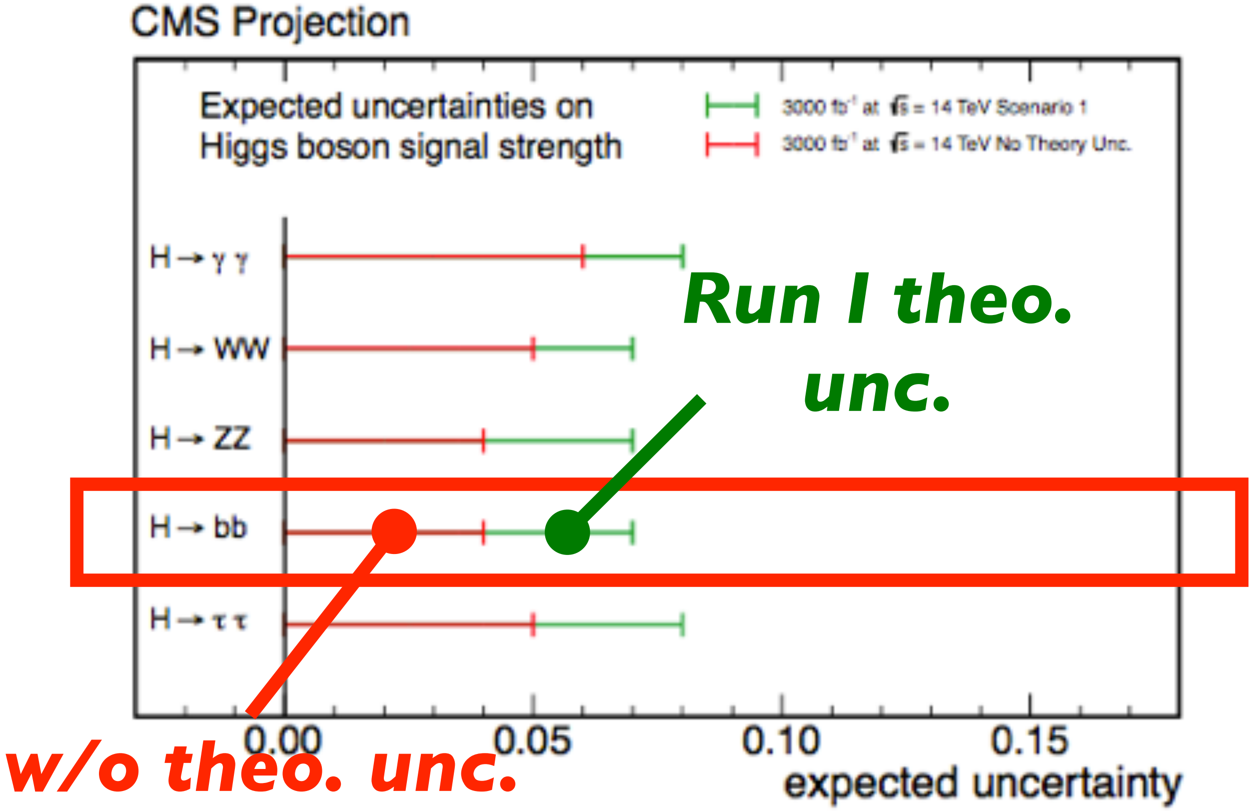




Projections: HL-LHC

Run I:	exp.	obs.
CMS	2.1σ	2.1σ
ATLAS	2.6σ	1.4σ

CMS, NOTE-13-02 (2013)

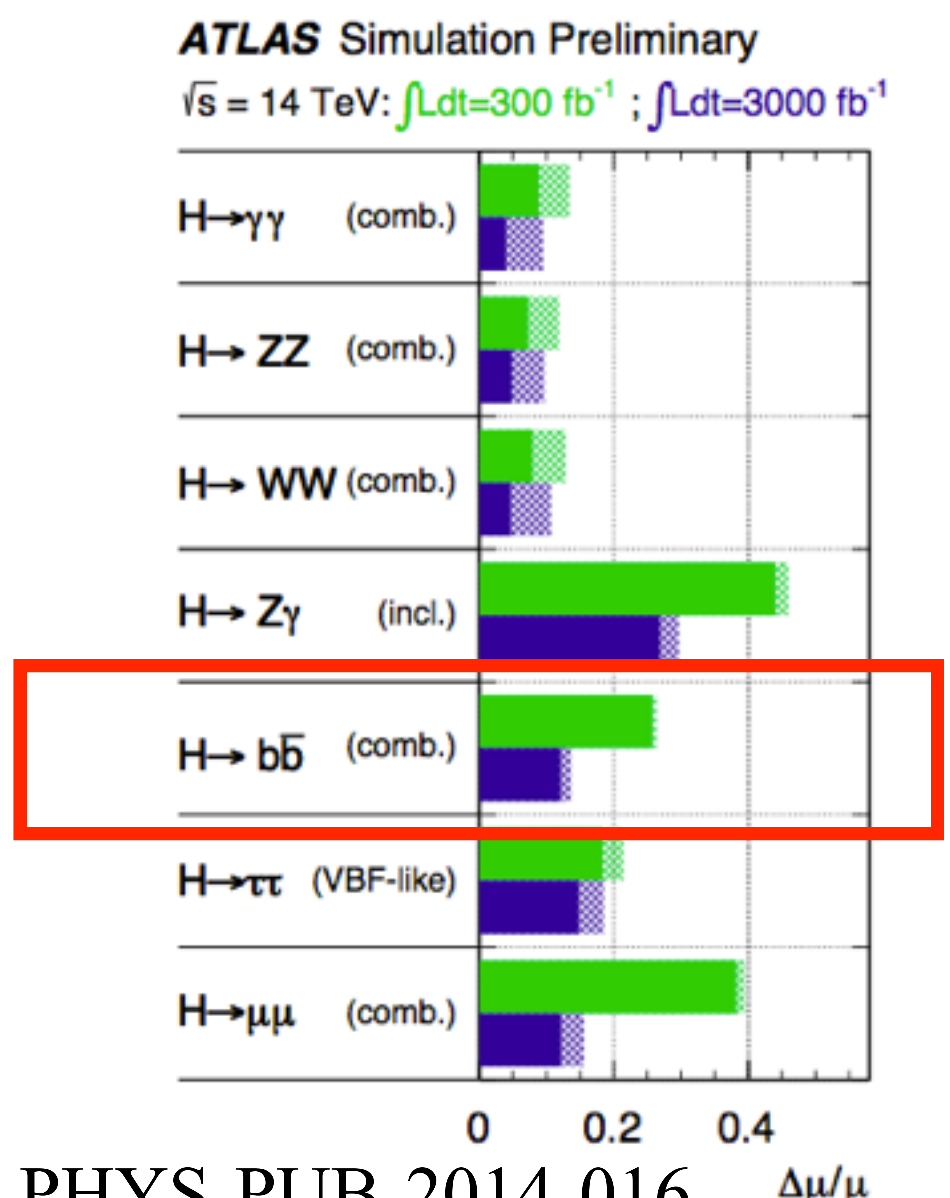


CMS projection:

- Δμ/μ: 7% → 4% w/o theo. unc.

ATLAS projection:

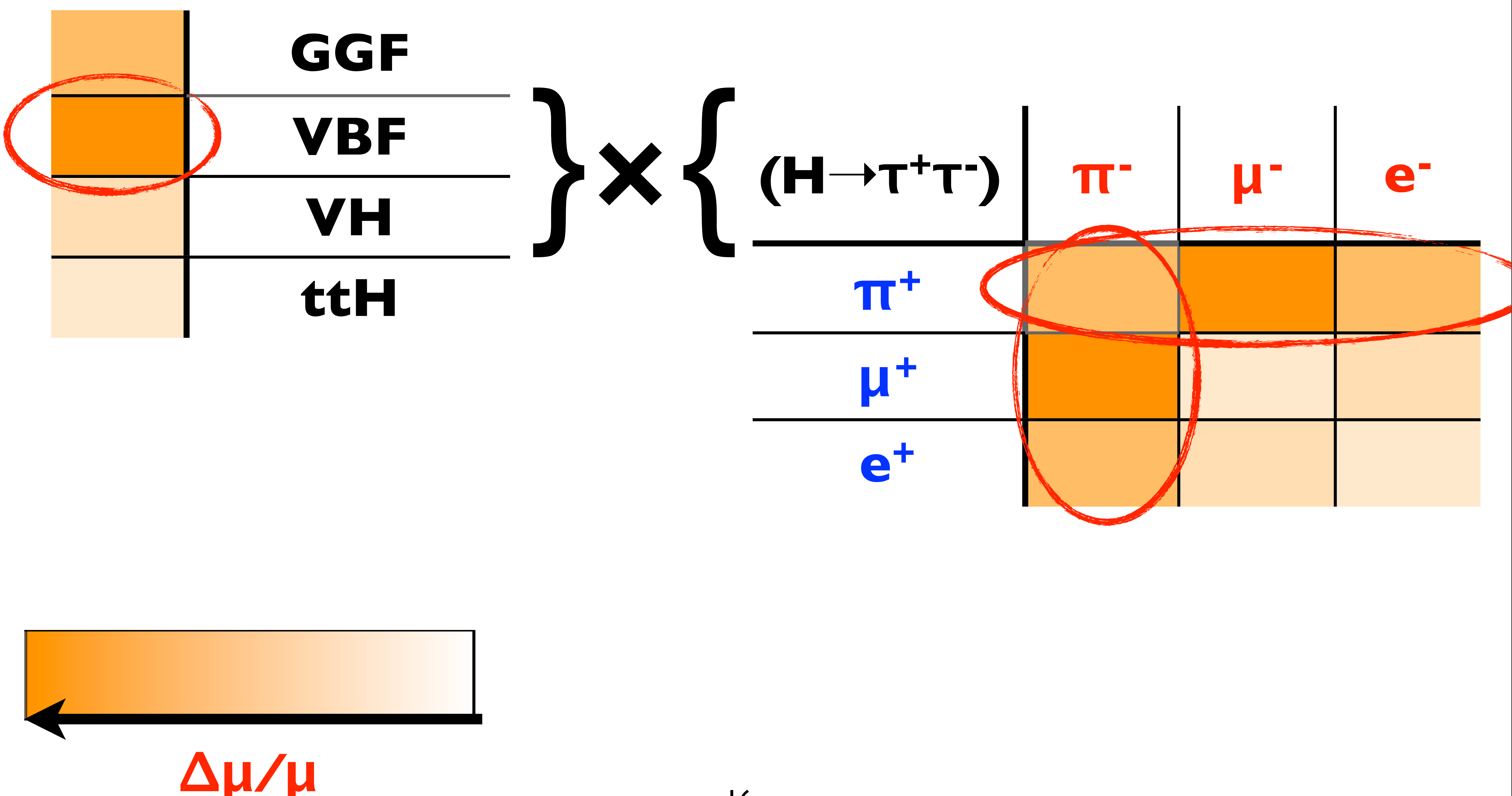
- at first sight, different conclusion, but:
  - not best analysis projected (x2 worse than RunI legacy)
  - no Z(νν) channel either
- largest uncertainties from:
  - signal acceptance (PDF, PS, scale)
  - ttbar and W+bb modeling



ATL-PHYS-PUB-2014-016

H(ττ) and VBF

Sensitivity by production and decay

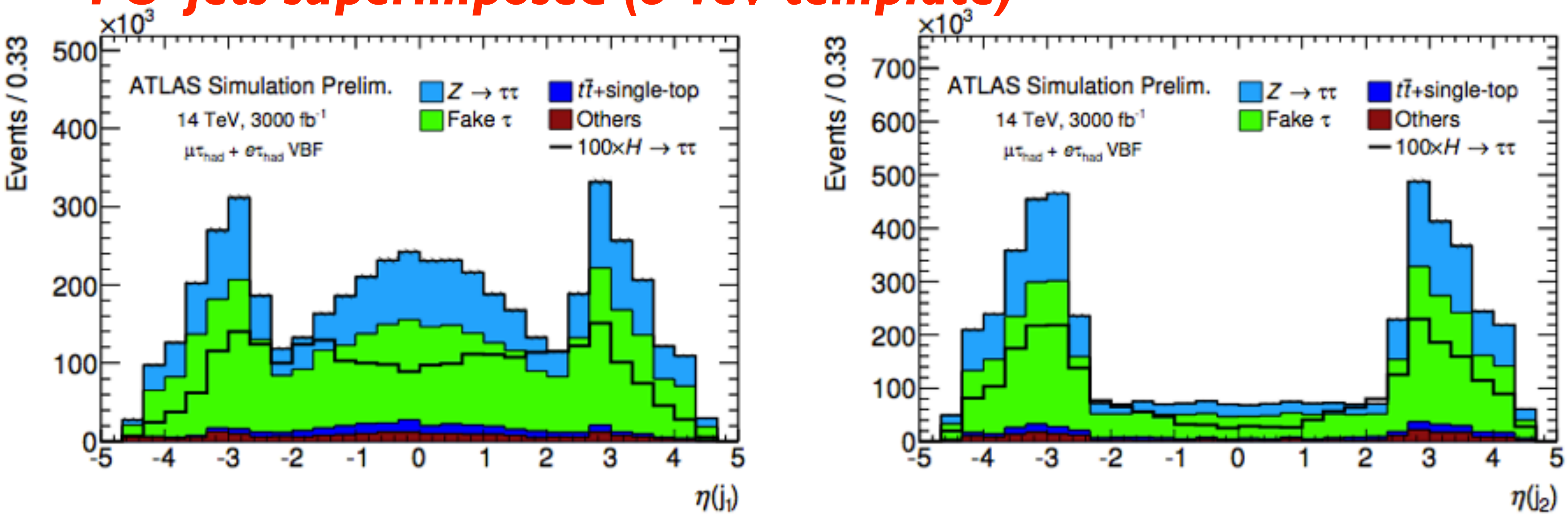


Experimental challenges: PU jets

VBF-like selection based on forward/backward di-jet pairs

- fake VBF signature from pile-up jets

PU-jets superimposed (8 TeV template)



	Leading jet	Trailing jet
% of events w/ a PU jet as...	42%	72%

Impact on Δμ from tracker extension:

forward pile-up jet rejection	50%	75%	90%
forward tracker coverage		$\Delta\mu$	
Run-I tracking volume		0.24	
$\lvert\eta\rvert < 3.0$	0.18	0.15	0.14
$\lvert\eta\rvert < 3.5$	0.18	0.13	0.11
$\lvert\eta\rvert < 4.0$	0.16	0.12	0.08

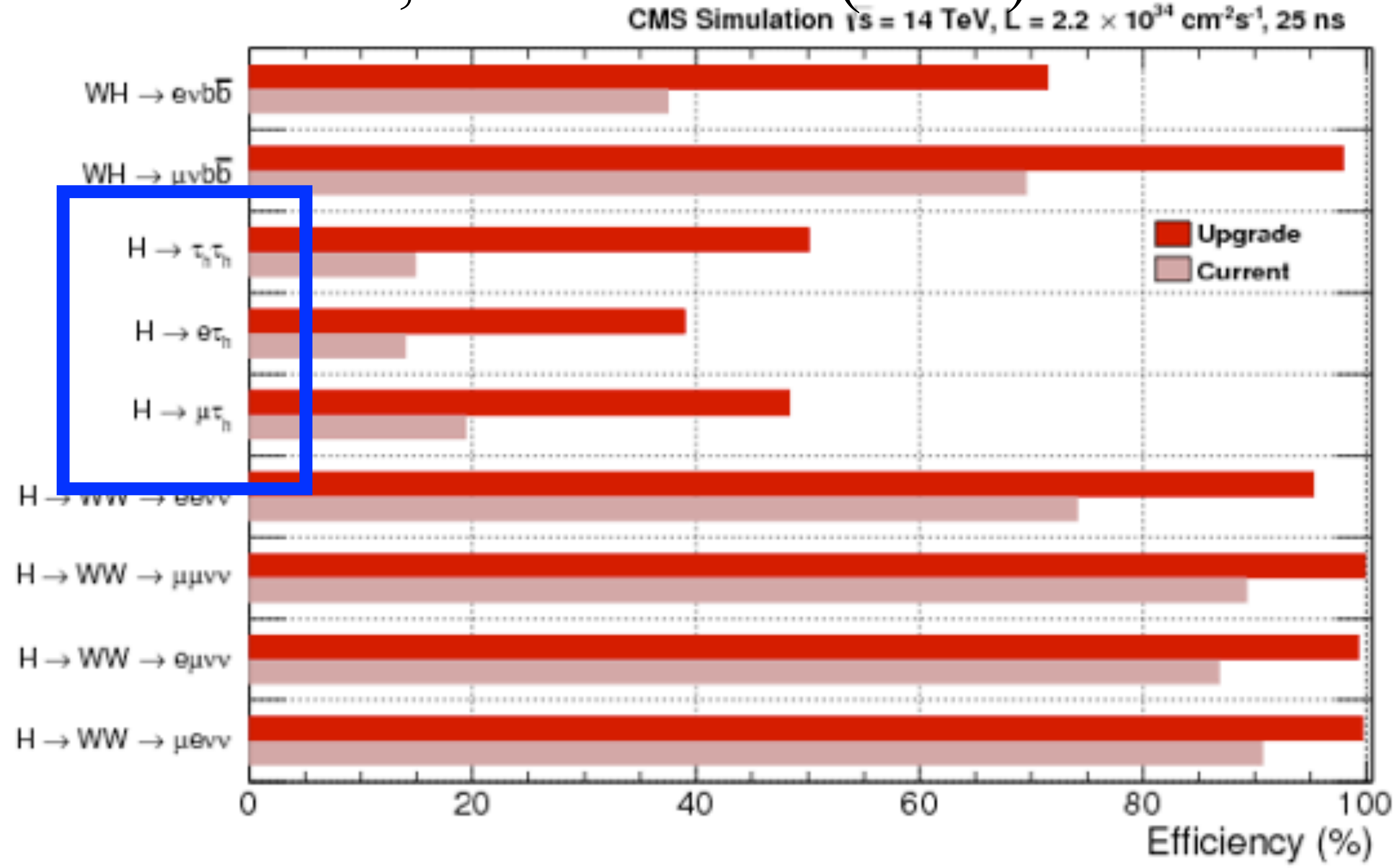
ATL-PHYS-PUB-2014-018

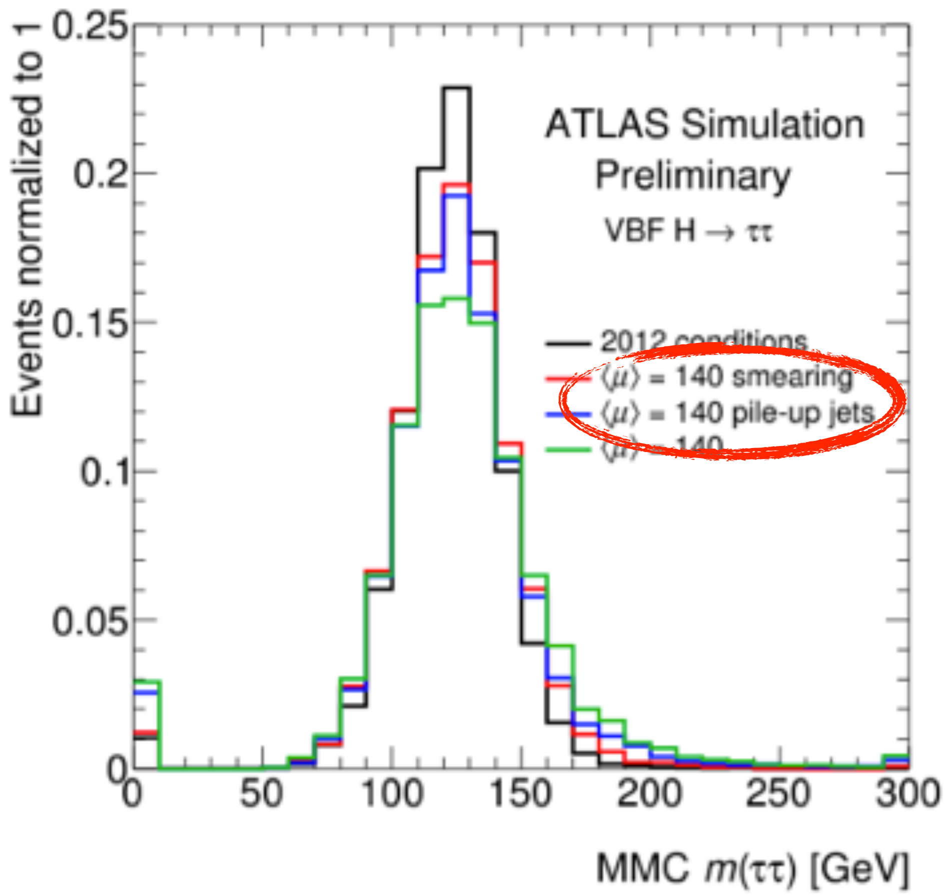
Experimental challenges

Triggers for $\tau_{l/h}\tau_h$

- visible τ p_T soft, but low thresholds challenging due to PU
- upgraded L1 trigger can cope with that

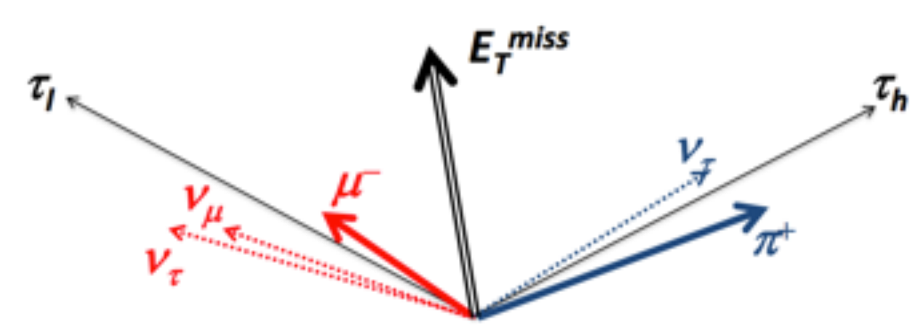
CMS, NOTE-13-02 (2013)





Missing energy used for for dynamical $m_{\tau\tau}$ reconstruction

- MET resolution degraded by PU (σ_{MET} ~ 2 larger than in Run I)



Experimental uncertainties

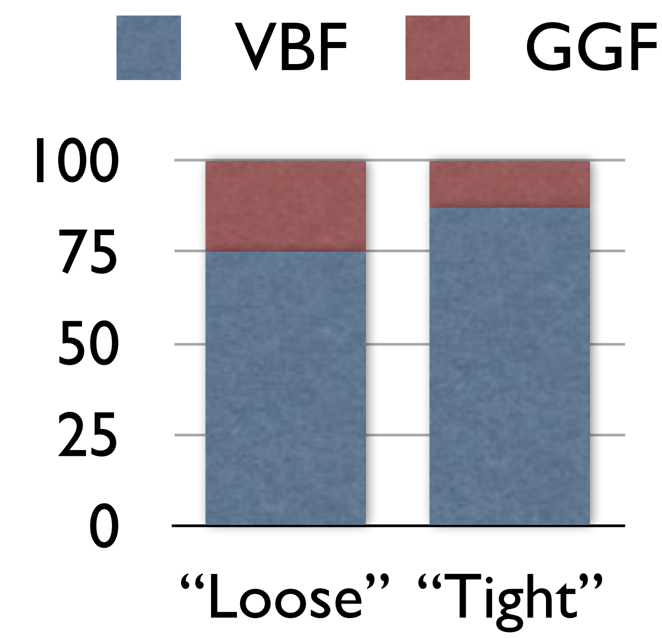
	Object	Process	Method	Projection
Background estimation	Fake taus (jets)	• W+jets • QCD • ttbar	Sidebands extrapolation/ fake method	• ~ $1/\sqrt{L}$ • Systematics be improved *- OS/SS ratio for QCD di-jet* *- OS/SS ratio W+fake off in MC*
	Prompt taus	$Z\rightarrow\tau\tau$	$Z\rightarrow\mu\mu$ embedding	• ~ $1/\sqrt{L}$ • O(1%) systematics
Signal efficiency	Jet Energy Scale	$H\rightarrow\tau\tau$	*In situ* calibration	• ~ $1/\sqrt{L}$ *- large PU contamination in forward region: boosted $W\rightarrow qq$?*
	Tau Energy Scale	$H\rightarrow\tau\tau$	*In situ* ($Z\rightarrow\tau\tau$)	• ~ $1/\sqrt{L}$

CMS, JHEP 05 (2014) 104
ATLAS, JHEP 04 (2015) 117

Theory uncertainties

The VBF selection:

- cutting on $|\Delta\eta_{jj}|$ and/or m_{jj}
  - veto events w/ p_T^{j3} >30 GeV)
- ATLAS uses MVA
  - $\Delta\eta_{jj}$, m_{jj}, $\eta_{j1}\times\eta_{j2}$, ...



NLO MC	Scale	PDF	Parton shower (PYTHIA vs Herwig)	Generator modeling (powheg vs aMC@NLO)	TOT
VBF	•3% QCD •2% EWK	•3% (incl.) •1% (acc.)	up to 8%	2%	~6%
$gg\rightarrow H$	23%	6%	up to 9%	4÷30%	~30÷40%

Increasing with $|\Delta\eta_{jj}|$ (high-x partons)

Sizable model-dependence

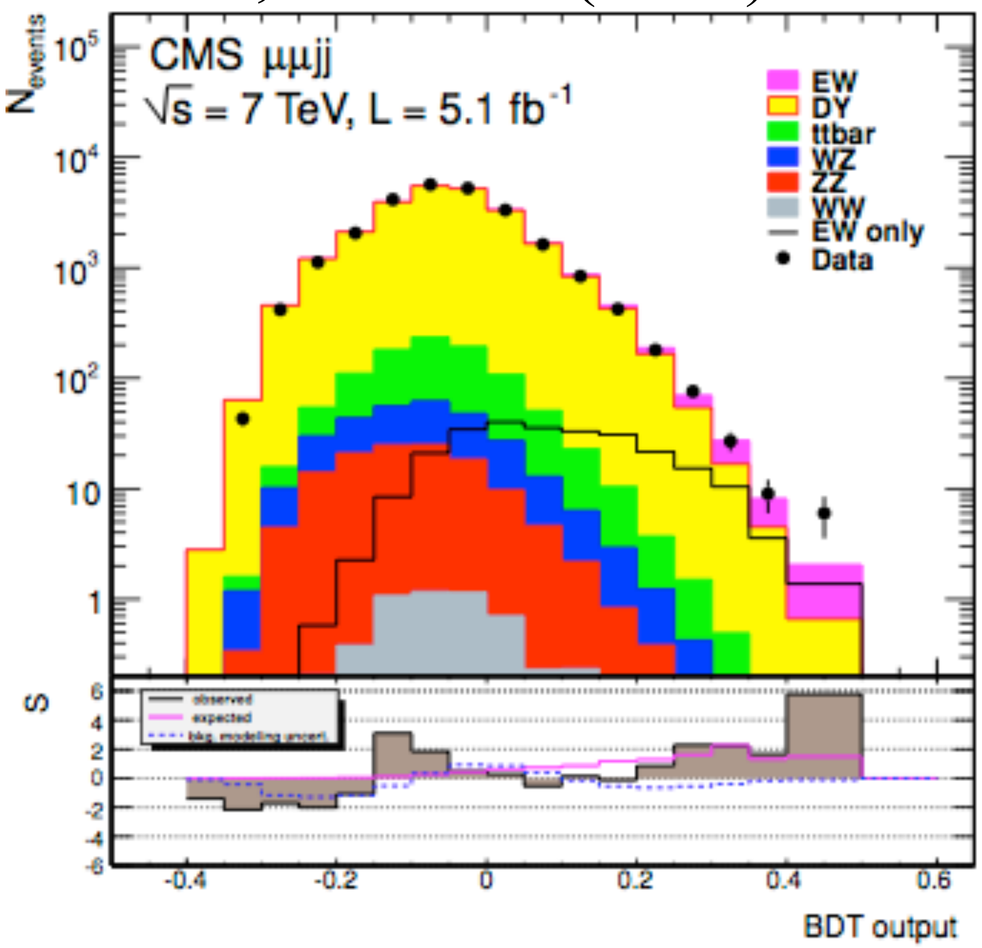
$\Delta\mu_{ggF} \sim \Delta\mu_{VBF}$

Tighter VBF cuts will help.

Can model dependence be reduced?

Can we measure it on data?

CMS, JHEP 10 (2013) 062

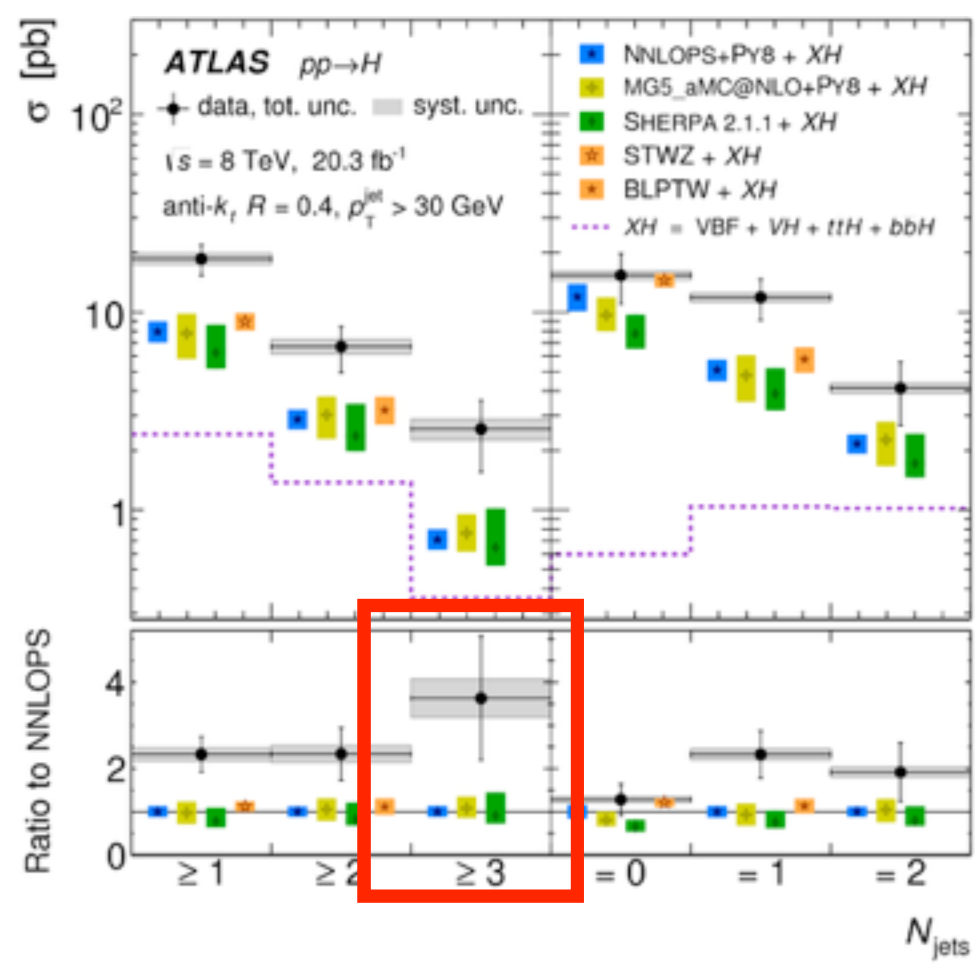


$$\sigma^{\rm EW}_{\ell\ell\ (\ell={\rm e},\mu)} = 154 \pm 24\,({\rm stat.}) \pm 46\,({\rm exp.\ syst.})$$

With 3000 fb^{-1} ⇒ O(1%) stat. on σ^{EW}

Can it be used to reduce the theory uncertainty on the signal?

ATLAS, arXiv:1504.05833



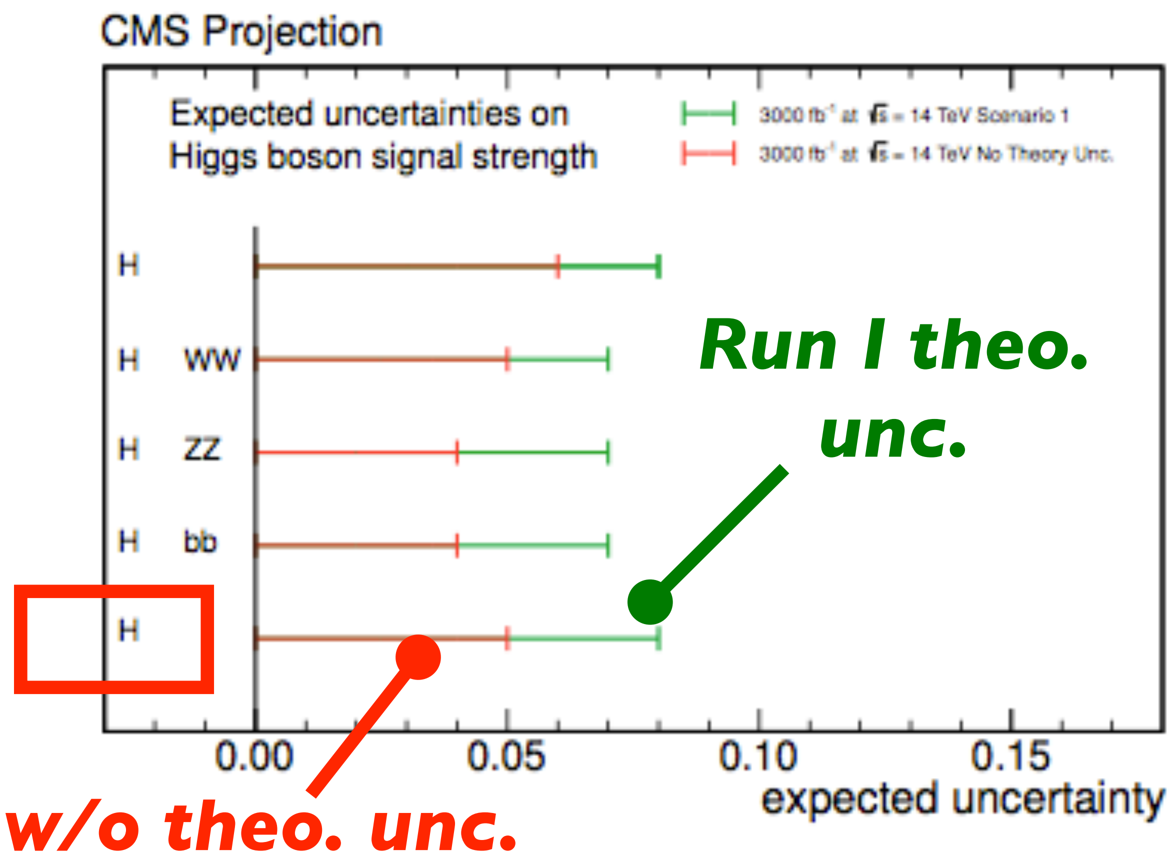
Differential measurements from $H \to \gamma\gamma/ZZ$ could help

- with 3000 fb^{-1}: $\Delta\sigma/\sigma_{\rm stat}{}^{{\rm Njet}\geq 3} \sim O(2\%)$

Extrapolation to VBF-like region?

Projections: H→ττ

Run I:	exp.	obs.
CMS	3.7σ	3.2σ
ATLAS	3.4σ	4.5σ



- CMS projections:
  - assume same cuts and efficiency
  - same di-tau mass resolution

$(\Delta\mu/\mu)_{stat.\,+\,syst.}$ ~ 5%

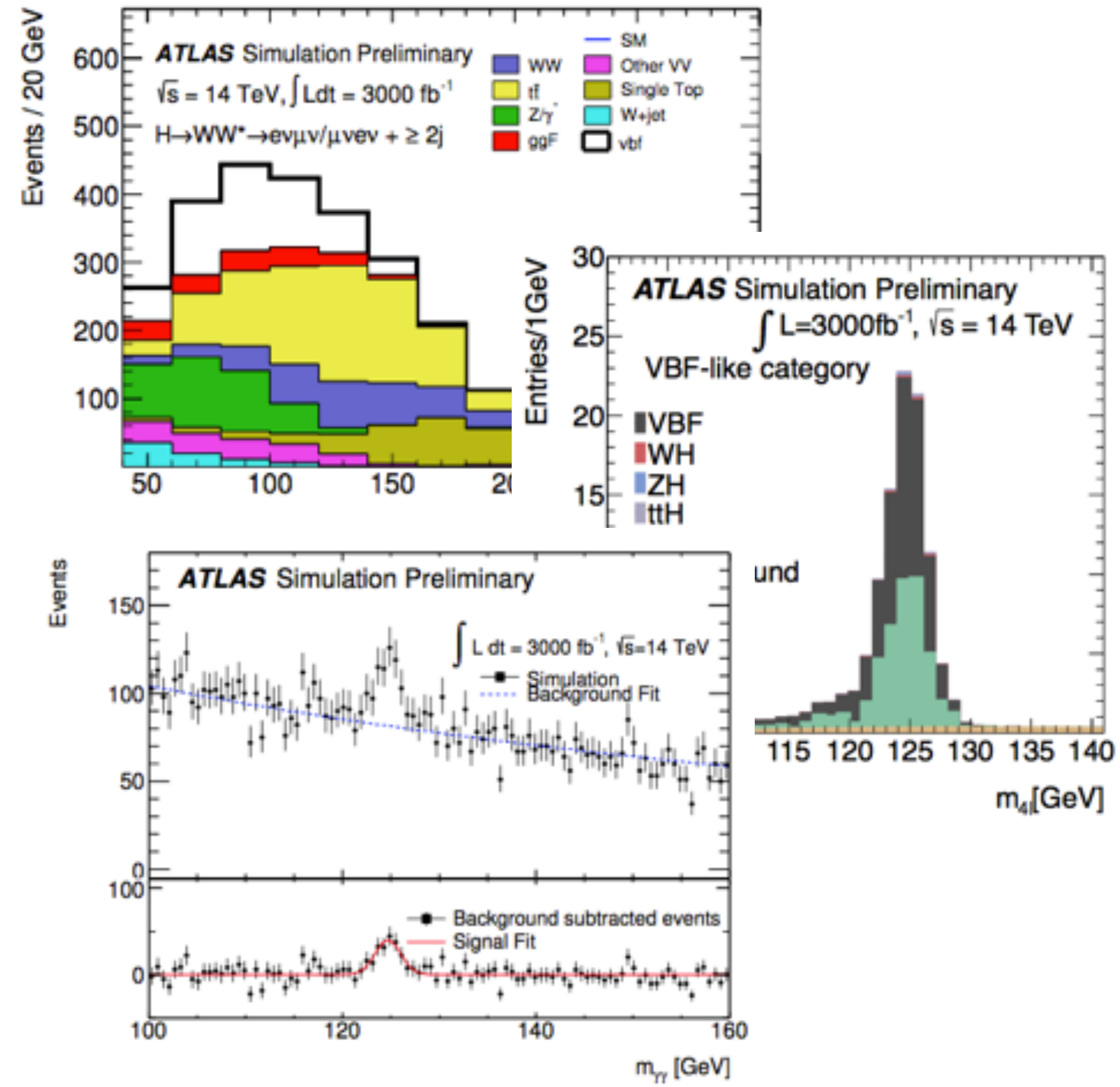
$(\Delta\mu/\mu)_{theor.}$ ~ 6%

- ATLAS projections:
  - consider only VBF $H\to\tau_h\tau_l$
    - ~2 worse than full result
    - PU jets from 8 TeV template
  - theor. unc. relevant ***if*** substantial PU mitigation is possible
    - otherwise limited by systematic

		current $\sigma_S^{theo.}$	no $\sigma_S^{theo.}$
$\sigma_B^{syst.}$	$\sigma_S^{syst.}$	$\Delta\mu$	$\Delta\mu$
10%	5%	0.25	0.24
5%	5%	0.16	0.13

VBF: other channels

- At least four more VBF-like channels explorable
  - H→WW*
  - H→ZZ*
  - H→γγ
  - H→bb
- Same conclusions holds
  - VBF theory uncertainty ~ O(6%)
  - uncertainty from ggF contamination eventually dominating



ATLAS projections 3000 fb^{-1}

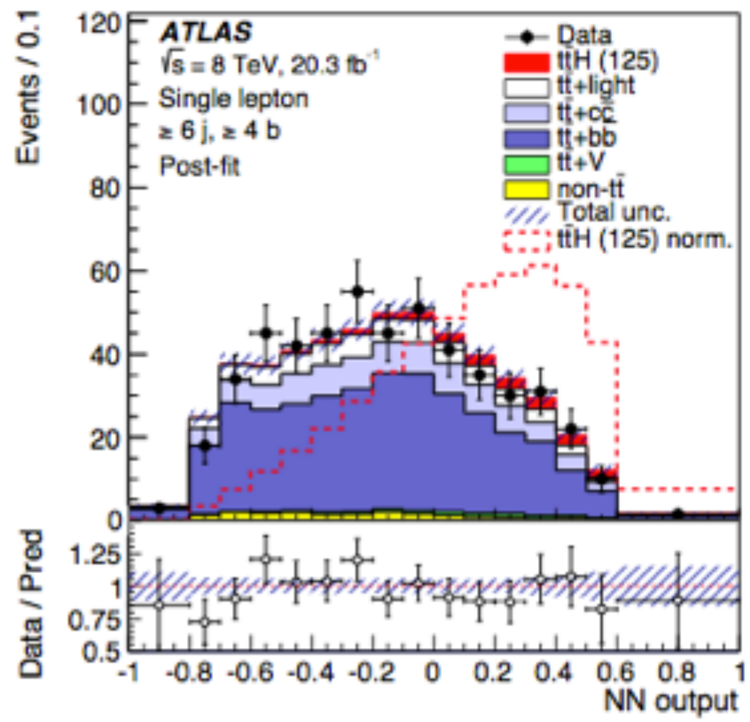
$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$gg \to H$	0.12	0.06	0.11	0.04
VBF	0.18	0.15	0.15	0.09
WH	0.41	0.41	0.18	0.18
$qqZH$	0.80	0.79	0.28	0.27
$ggZH$	3.71	3.62	1.47	1.38
ttH	0.32	0.30	0.16	0.10

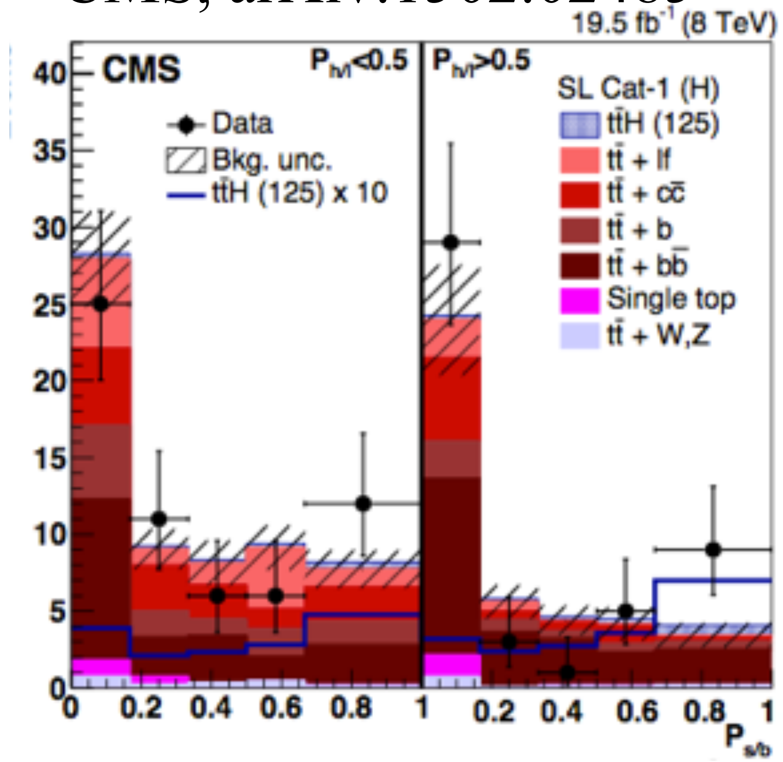
ttH(bb)

ttH(bb): analysis overview

- Event categorisation (N_{jet}, N_{tag})
- Signal extraction from fit to NN output
    - jet-jet correlations
    - event shapes
    - jet b tagging
- Matrix element method for ttH/ttbb separation
    - performing in signal-enriched regions

ATLAS, arXiv:1503.05066 CMS, arXiv:1502.02485



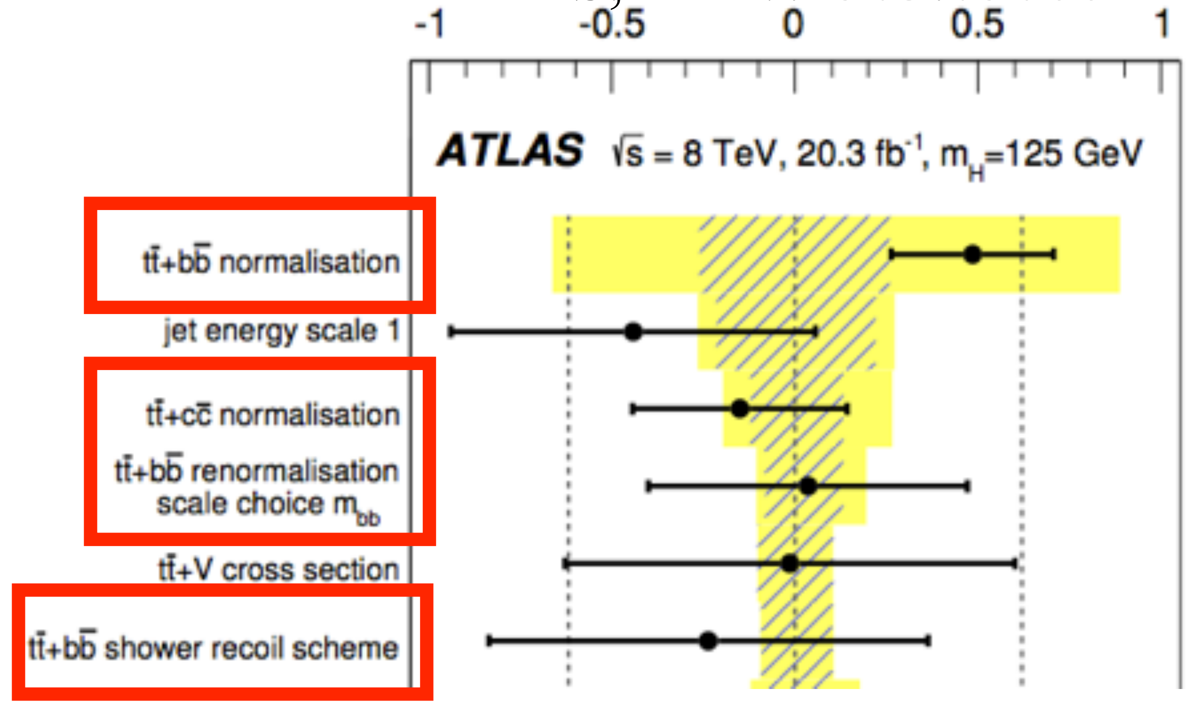


Challenges at HL-LHC	It affects...	Need to...
PU	• smear shape variables • category migration • combinatorics (~N!)	deploy PU jet ID to keep low p_T thresholds
b tagging	increasing tt+lf bkg [σ(tt+lf)/σ(tt+hf) ~ 50]	preserve 70%-1% ratio in ε_S-ε_B

Towards HL-LHC: understanding ttbb

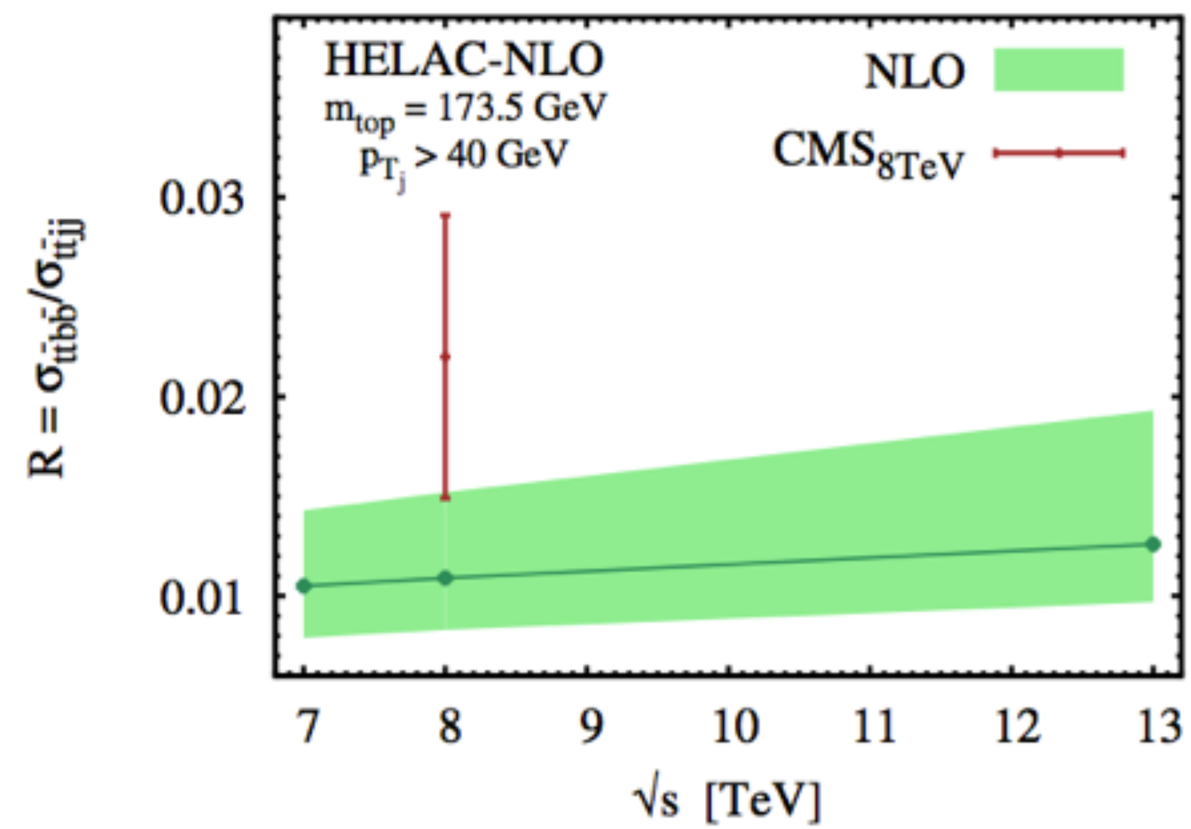
- With the HL dataset:
  - ttbb background limiting factor
    - large negative correlation with μ_{ttH}
    - total rate can simultaneously fit (~20% in Run I)
    - shapes from simulation
  - no full NLO tt+cc simulation available

ATLAS, arXiv:1503.05066



- Measurement of ttbb/ttjj ratio
  - some tension with NLO calculations at 8 TeV

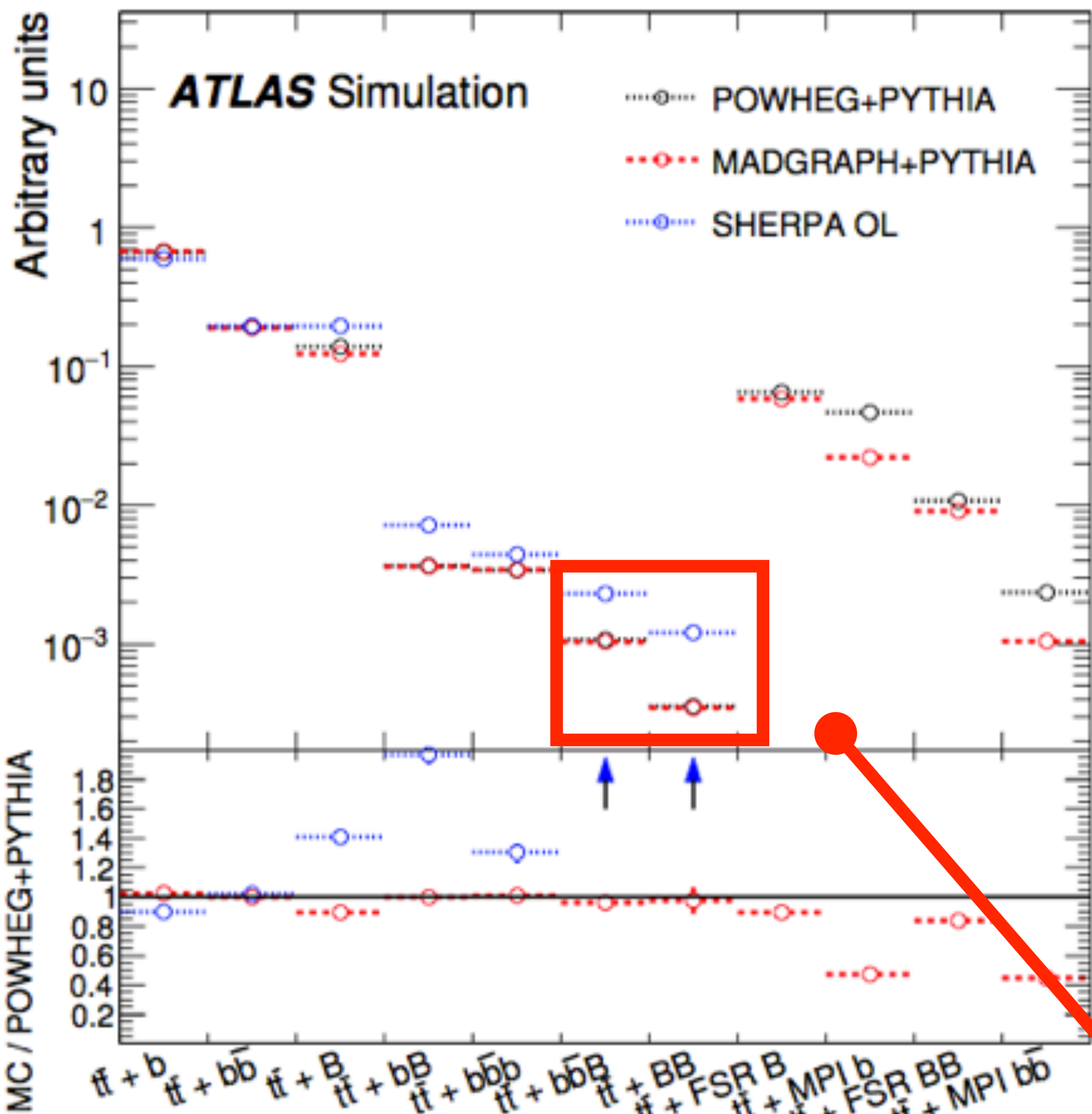
G. Bevilacqua et al., JHEP 07 (2014) 135



Improving on ttbb/ttcc, ttbb/ttjj theoretical ratios ?

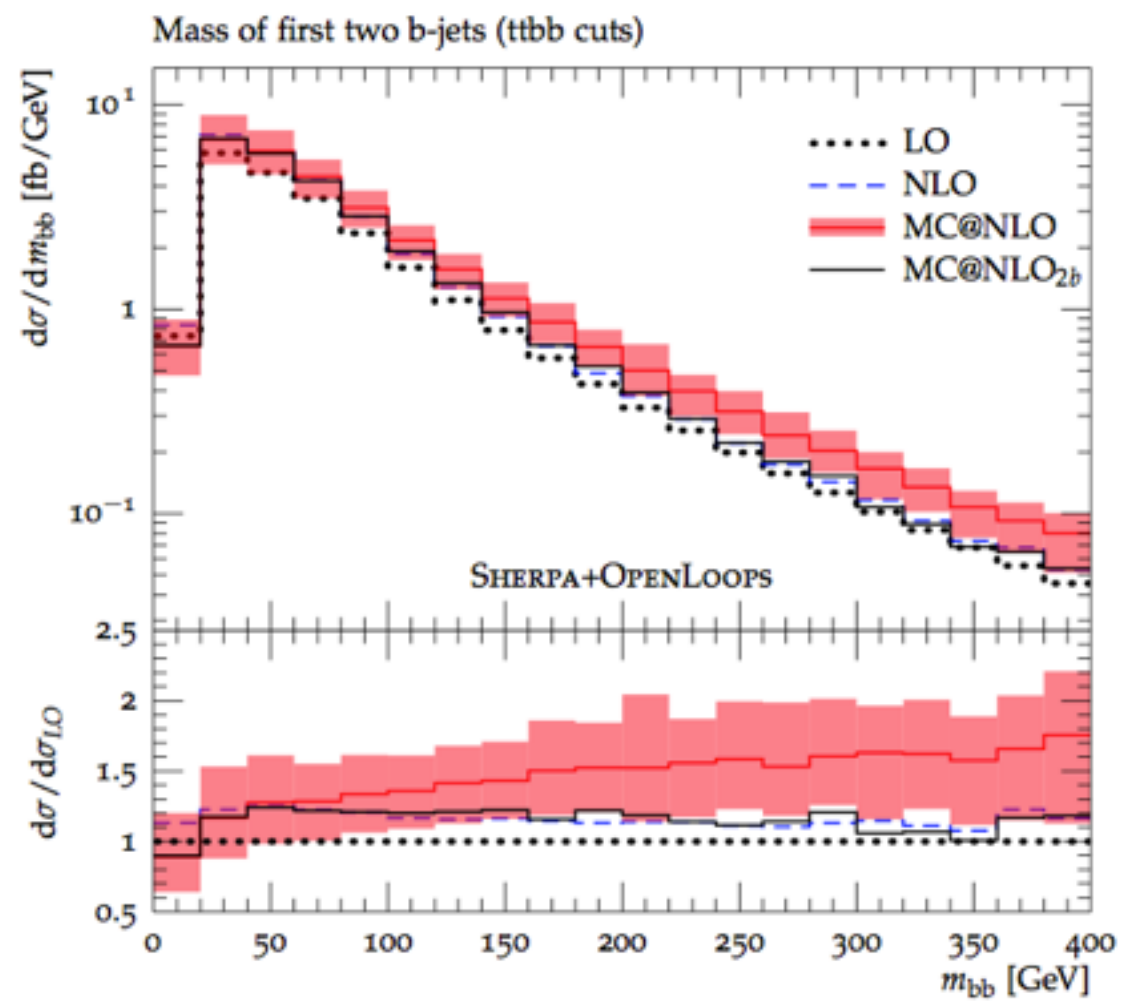
Towards HL-LHC: understanding ttbb

Sizable differences in MC modeling persist



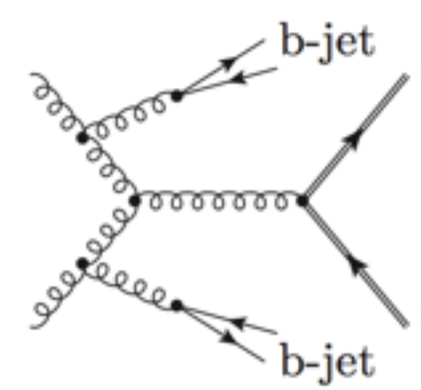
ATLAS, arXiv:1503.05066

NLO k-factor not trivial in key kinematic variables



F. Cascioli et al., PLB 734 (2014) 210

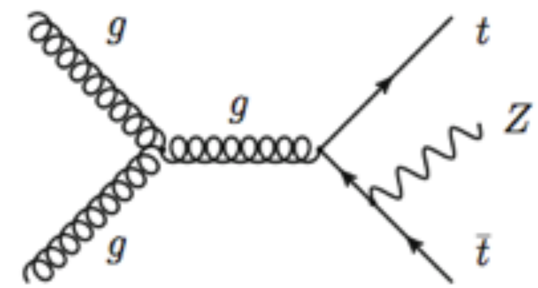
Double-gluon splitting enhanced in SherpaOL (1st ->NLO, 2nd -> PS)



Are Z+g(→bb) measurements of any help?

Why pursuing H(bb)?

- Sensitivity eventually dominated by $H \to \gamma\gamma$
  - systematics-free
  - projections agree between CMS and ATLAS:
    - eventually limited by NLO σ_{ttH}:
      -4/+9% (scale) ⊕ ±8% (PDF+α_S)

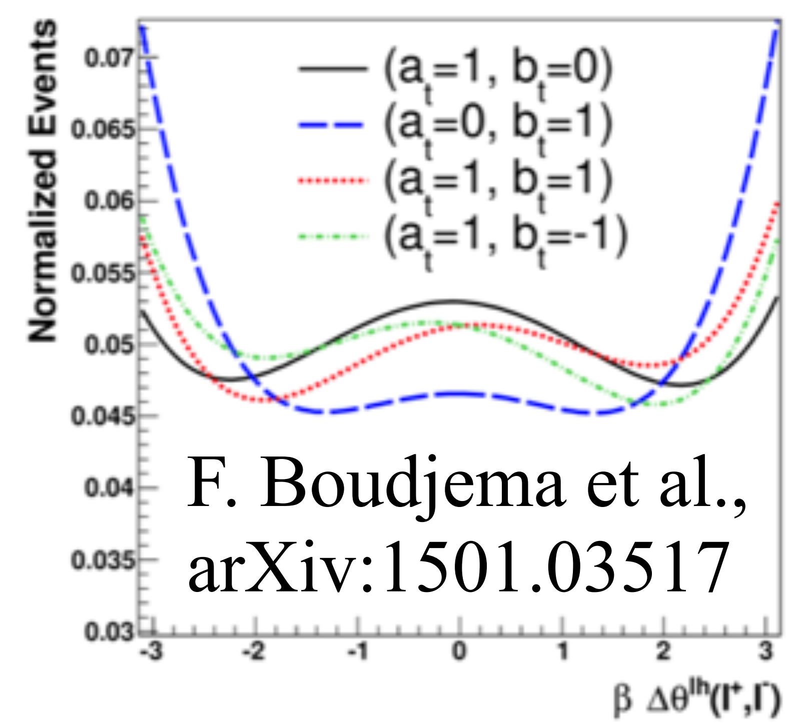


Can it be measured in ttZ events ($\Delta\sigma_{ttZ} \sim 2\%$) ?

CMS, projection of coupling precision

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

- But:
  - no (best) analyses projected by ATLAS (CMS)
    - check sensitivity from best combined analysis
  - in ttH(bb), full top reconstruction possible
    - angular observables from top decays sensitive to CP=-1 fraction
    - MEM should be optimal



Summary (0)

Understanding the challenges of the challenging channels from Run I analyses

- some limitations and potential pitfalls already evident

Summary (1)

Understanding the challenges of the challenging channels from Run I analyses

- some limitations and potential pitfalls already evident

- VH(bb):
  - b tagging
    - detector upgrade
  - MC modeling of V+hf and ttbar shapes
    - reduce dependence on MC modeling (e.g. parton showers)
    - side measurements can prove valuable (e.g. gluon splittings)

Summary (2)

Understanding the challenges of the challenging channels from Run I analyses

- some limitations and potential pitfalls already evident

- H($\tau\tau$) and VBF:
  - Trigger efficiency
    - L1 trigger upgrade
  - PU jets
    - mitigation of PU jets in the forward region mandatory
  - Theory uncertainties
    - large uncertainty on GGF contamination
    - eventually, limiting factor on μ_{VBF}

Summary (3)

Understanding the challenges of the challenging channels from Run I analyses

- some limitations and potential pitfalls already evident

- ttH(bb):
  - b tagging
    - detector upgrade
  - Eventually limited by tt+hf shape uncertainties
    - NLO prediction for tt+cc
    - understanding the double-gluon splitting

Thanks for your attention

Back up

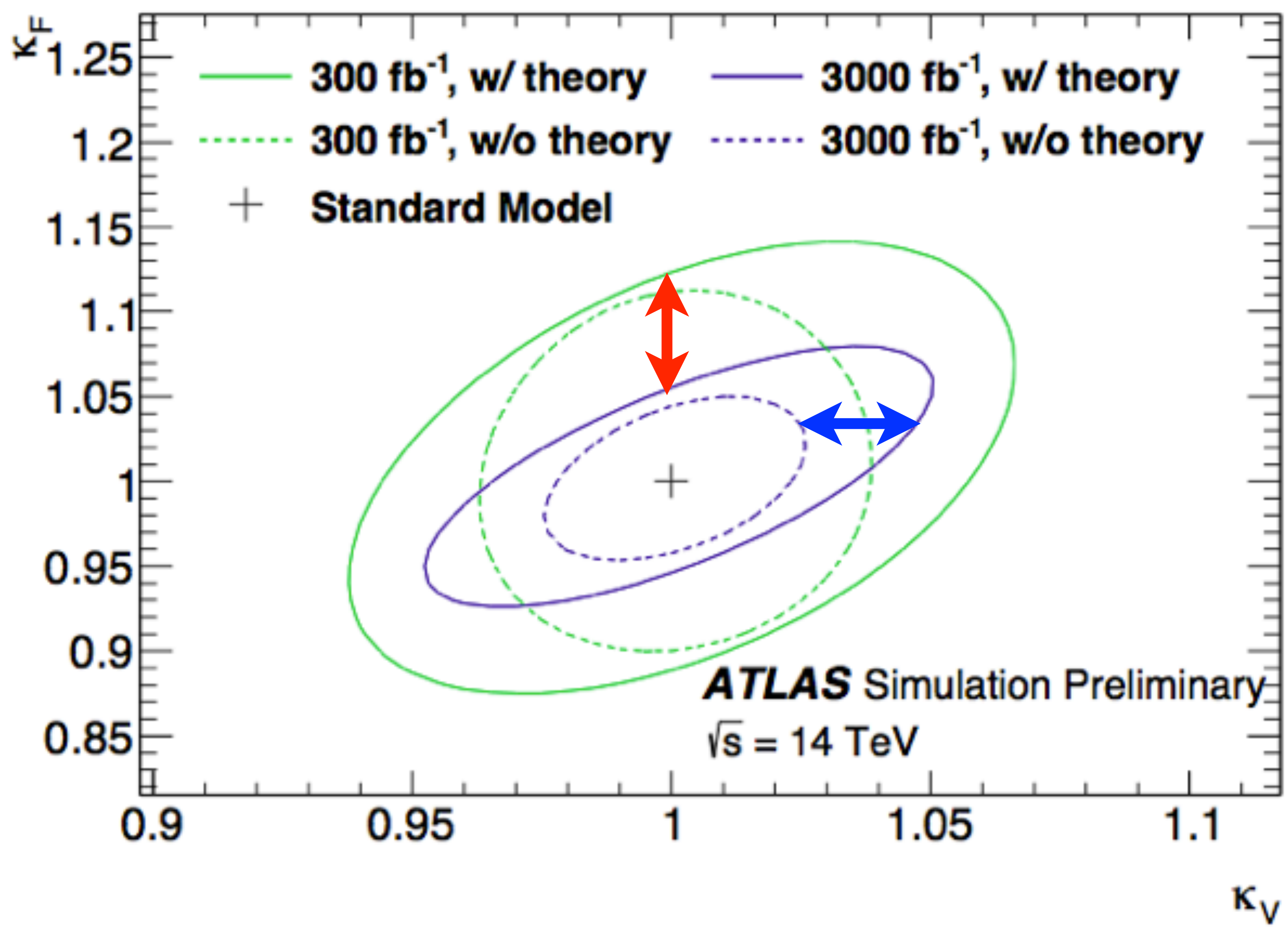
The HL-LHC

Can reach O(5%) precision on most of the Higgs couplings

- necessary (but not sufficient) condition: maintain *detector performances*
- *luminosity* increase and reduction of *theory systematics* complementary

ATLAS-PHYS-PUB-2014-016

coupling to fermions ⇒ luminosity



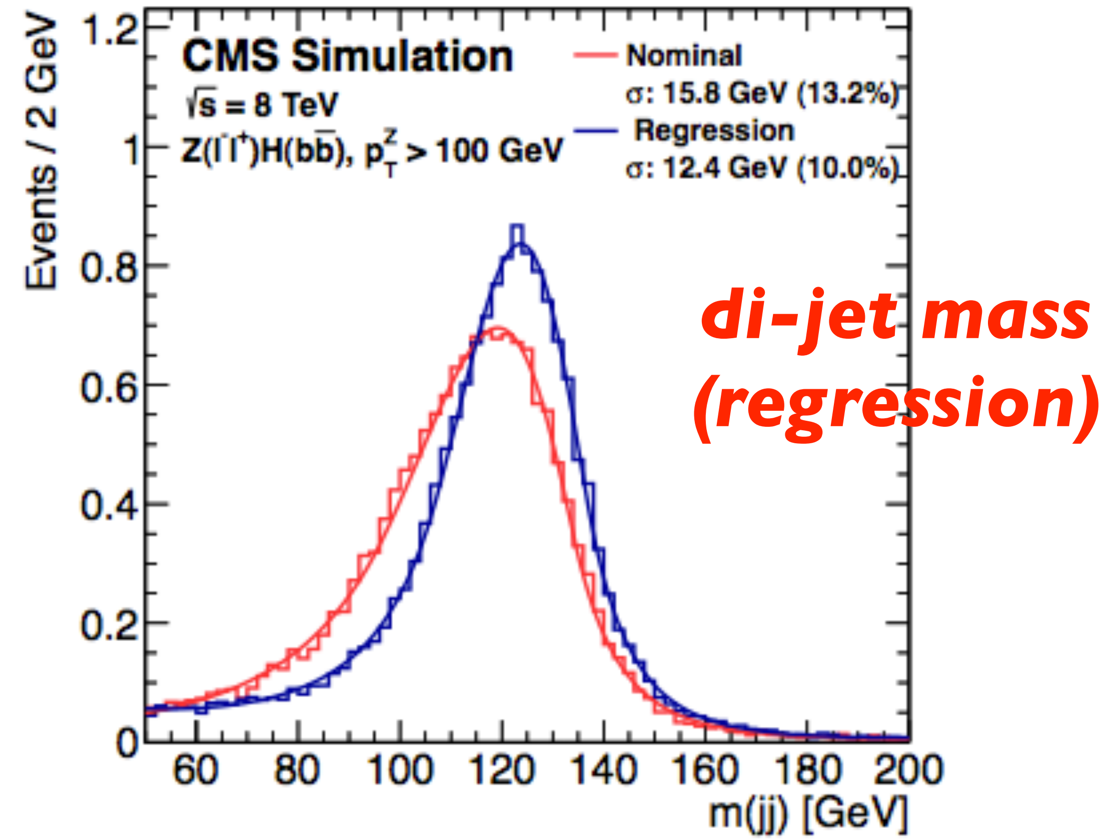
coupling to vectors ⇒ theory

Key analysis aspects: di-jet mass

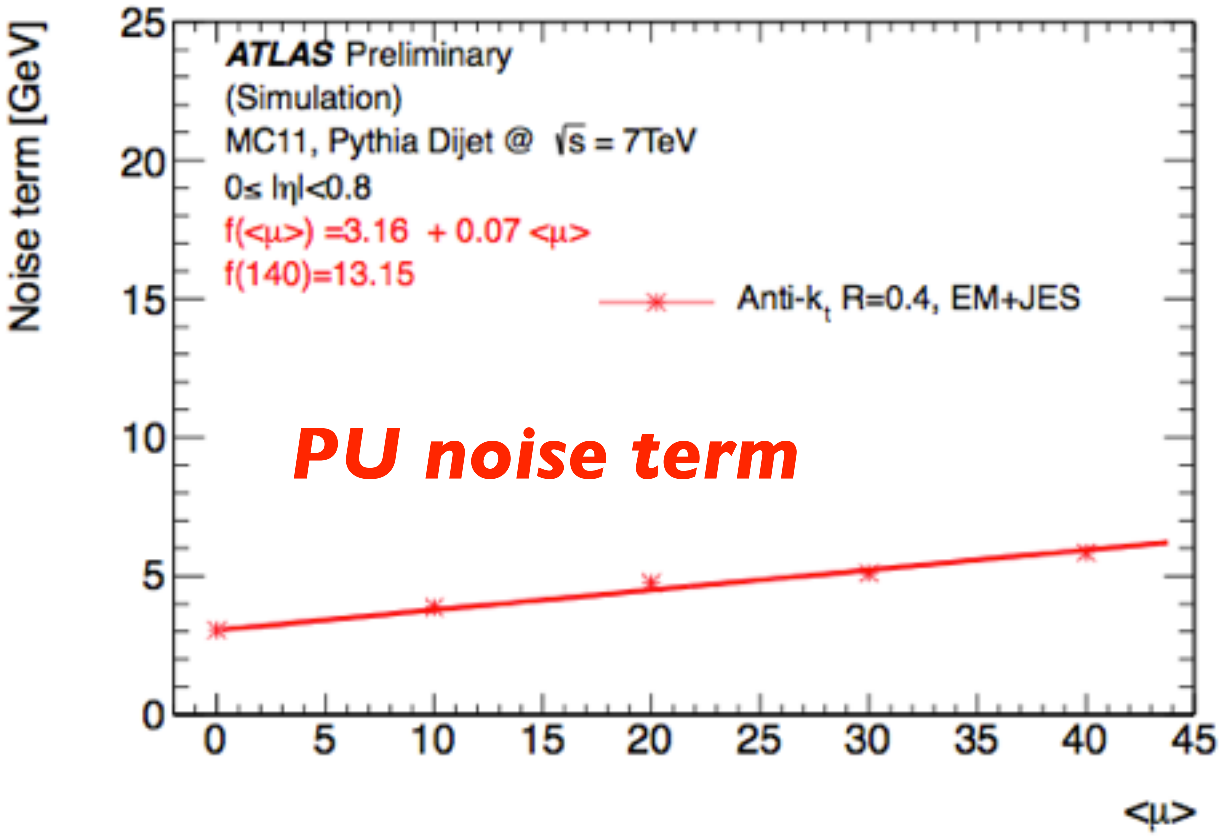
Di-jet mass peak reconstruction

- boosted regime [p_T>200 GeV]
  - bkg suppression & mass resolution
- $\Delta m/m$ ~ 10%
  - kinematical fit / regression

CMS, PRD 89 012003 (2014)



ATLAS-PHYS-PUB-2013-004



At μ_{PU} = 140:

- jet energy resolution degraded:
  - relative contribution from PU: **25→32%** for central jets

Importance of *bb* channels

Higgs width dominated by $\Gamma_{H\to bb}$

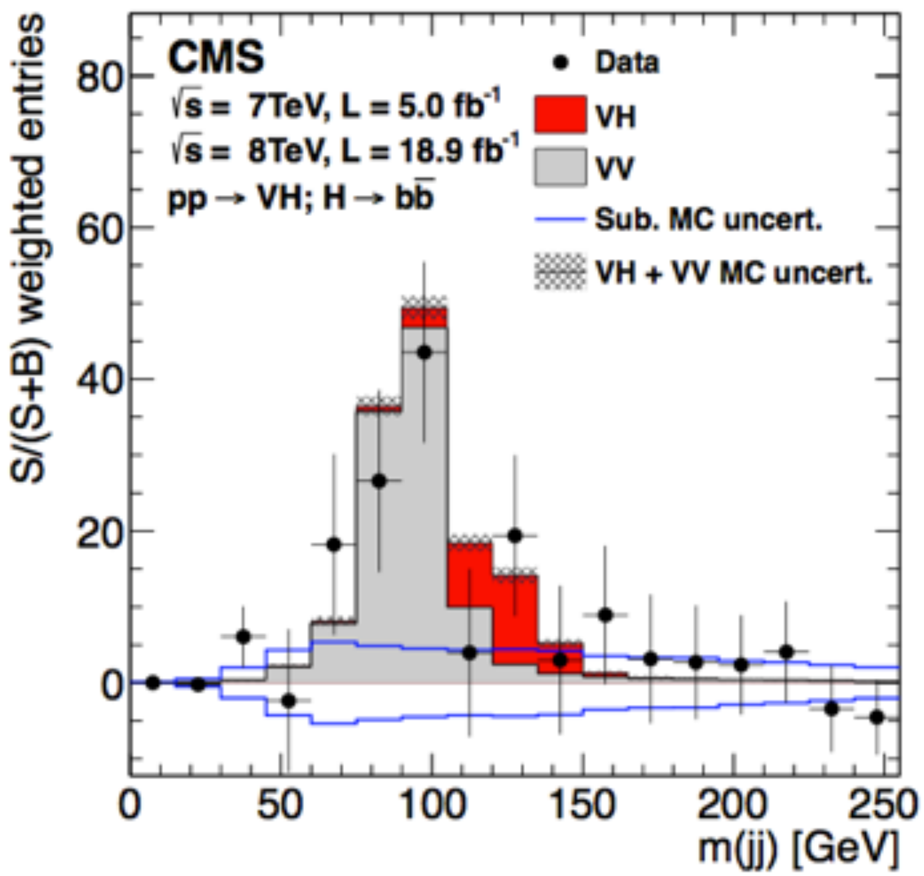
- important to constrain BR_{BSM}

$$\kappa_H^2(\kappa_i, m_H) = \sum_{\substack{j = WW^{(*)}, ZZ^{(*)}, b\bar{b}, \tau^-\tau^+, \\ \gamma\gamma, Z\gamma, gg, t\bar{t}, c\bar{c}, s\bar{s}, \mu^-\mu^+}} \frac{\Gamma_j(\kappa_i, m_H)}{\Gamma_H^{SM}(m_H)}$$

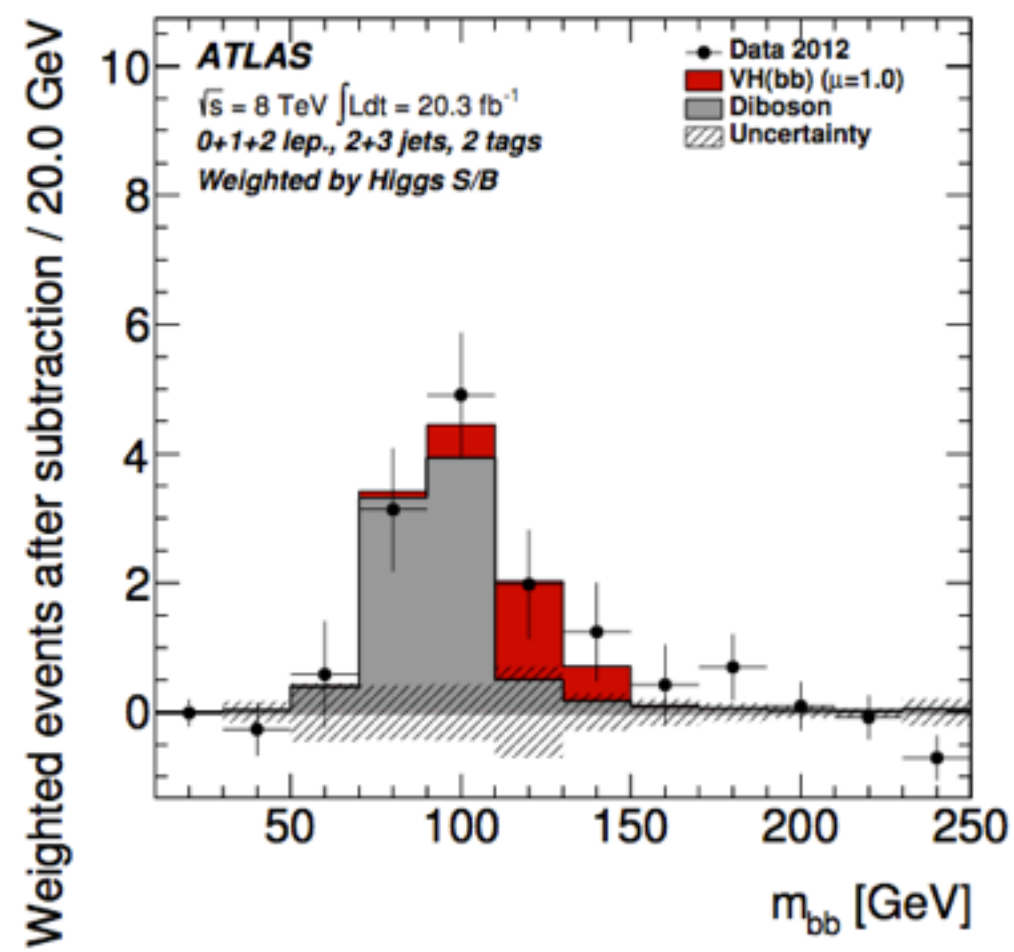
≃**60%**

Channel	Run I (exp)
gg → H	-
VBF	<1σ
VH	2.5σ
ttH	1σ

CMS, PRD 89 012003 (2014)

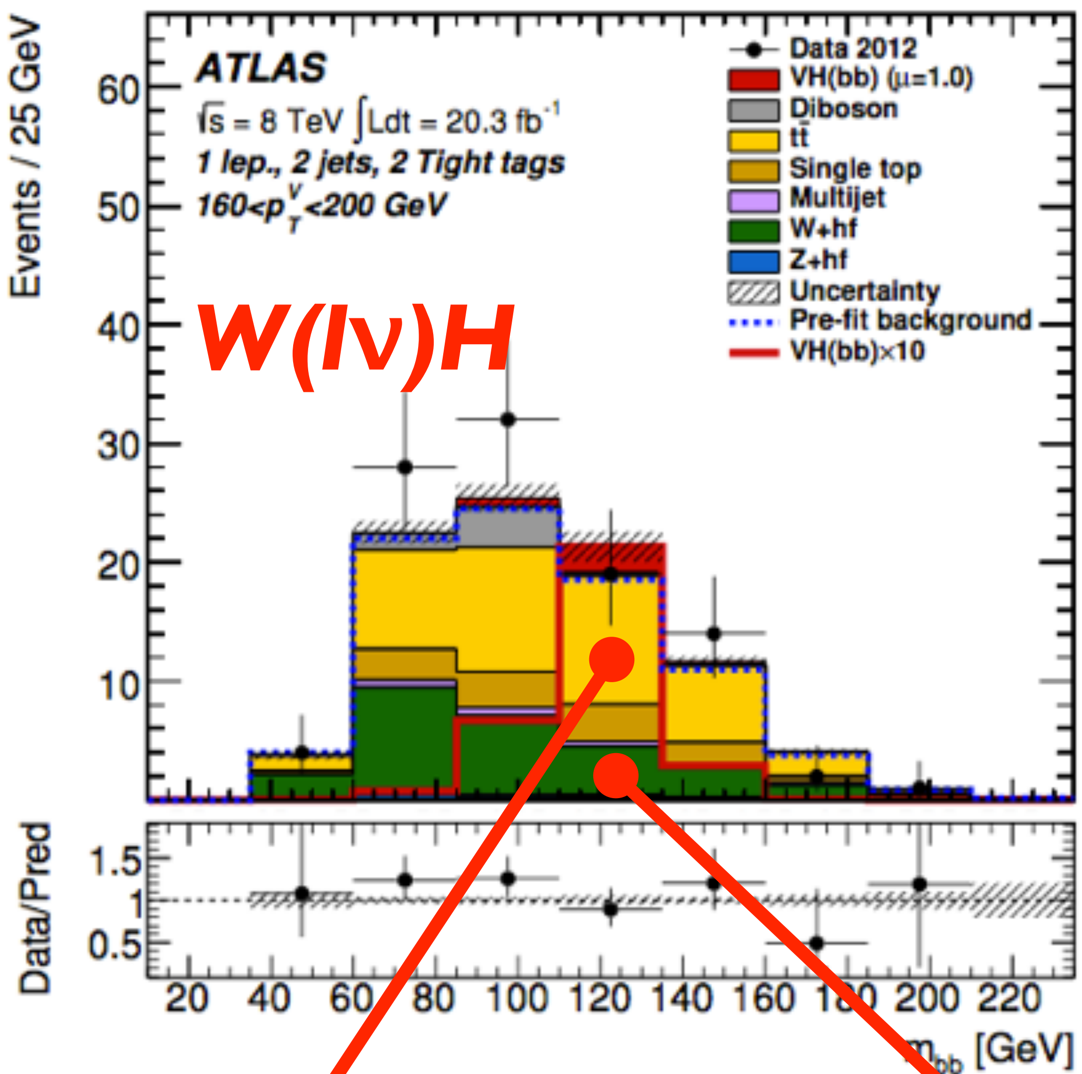


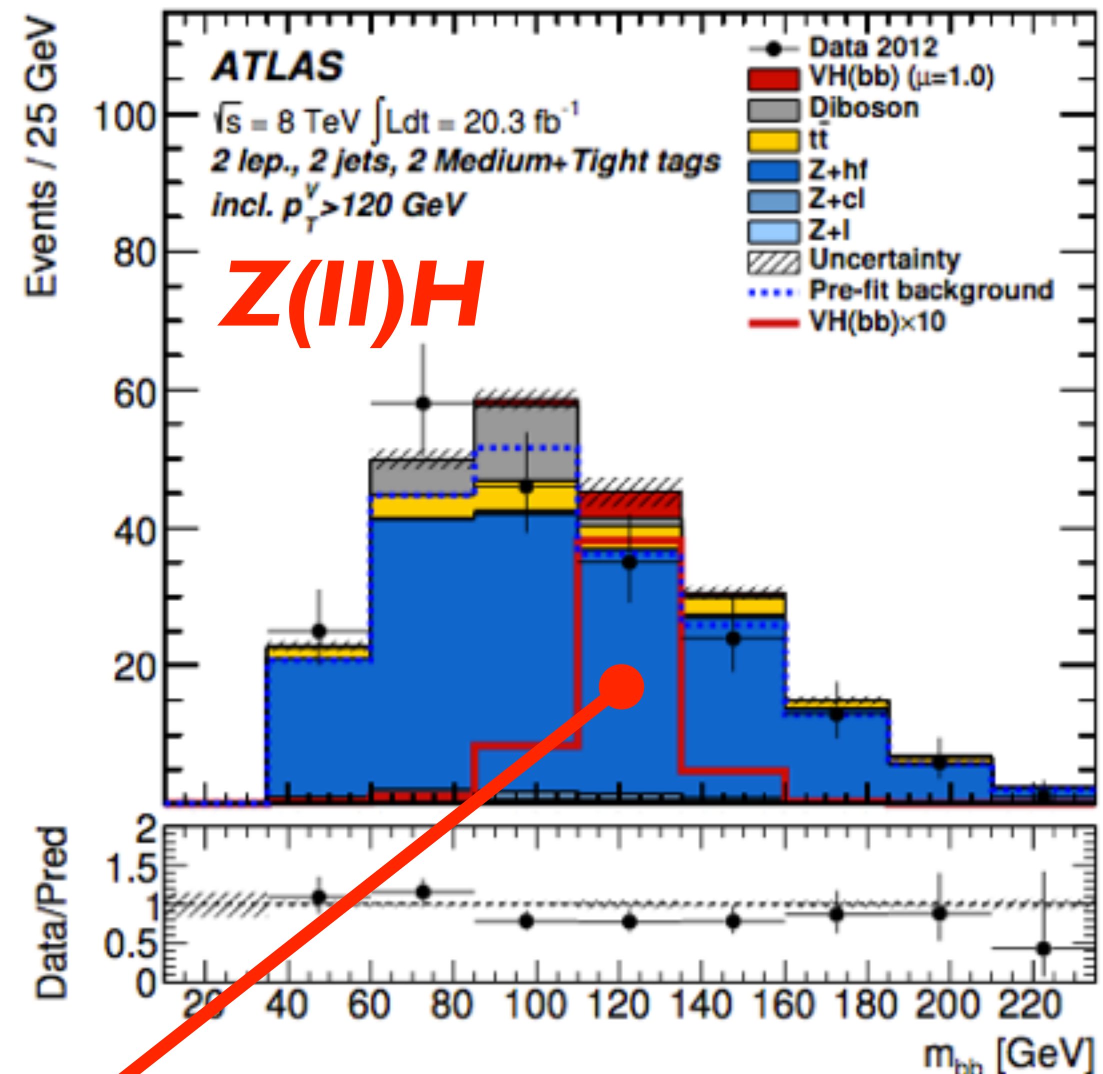
ATLAS, JHEP 01 (2015) 069



VH(bb): main SM backgrounds

ATLAS, JHEP 01 (2015) 069





Top-pairs

- four-fold increase in top pairs at 14 TeV

V+jets

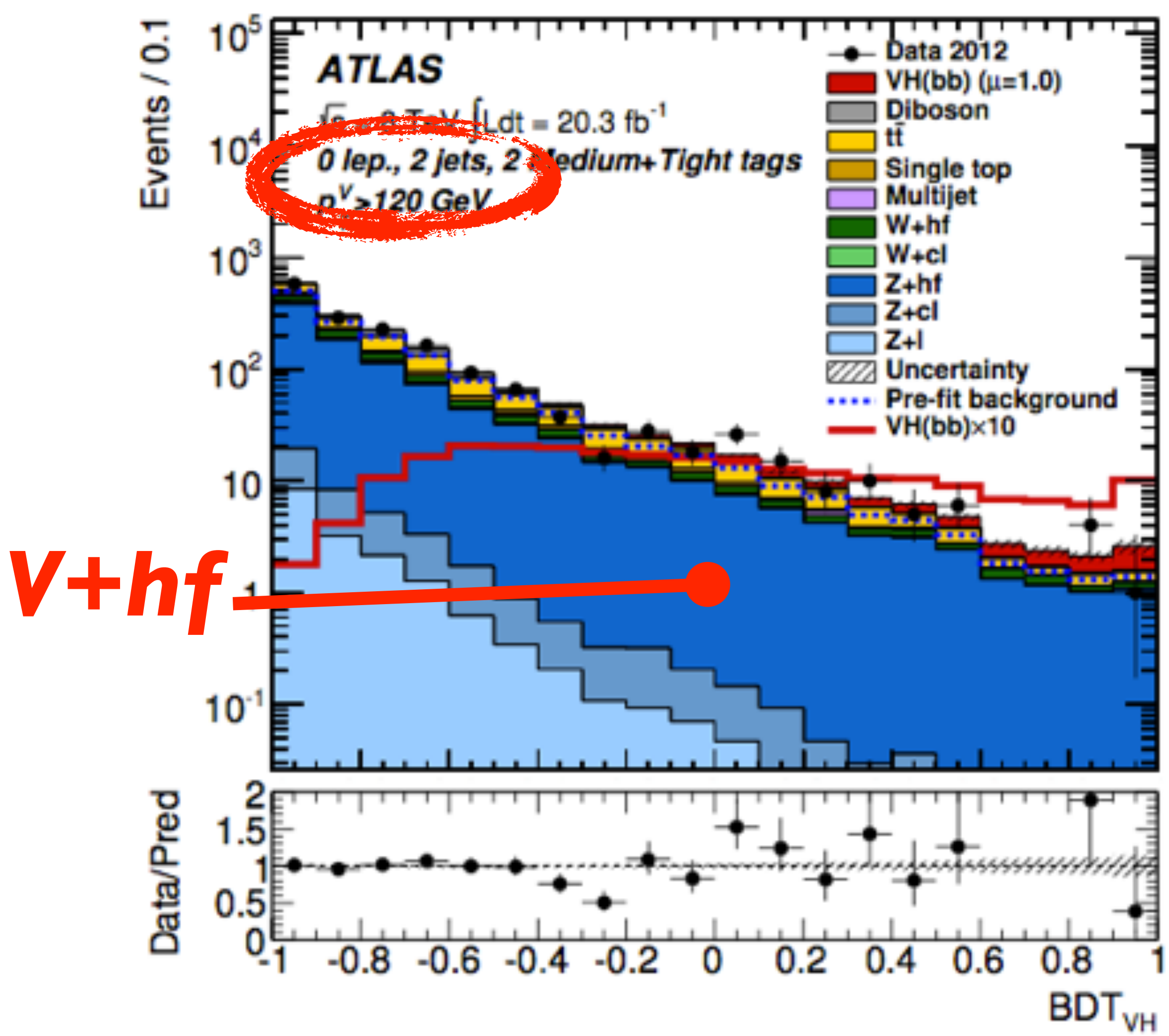
- mixed flavour composition

Rates estimated from sidebands

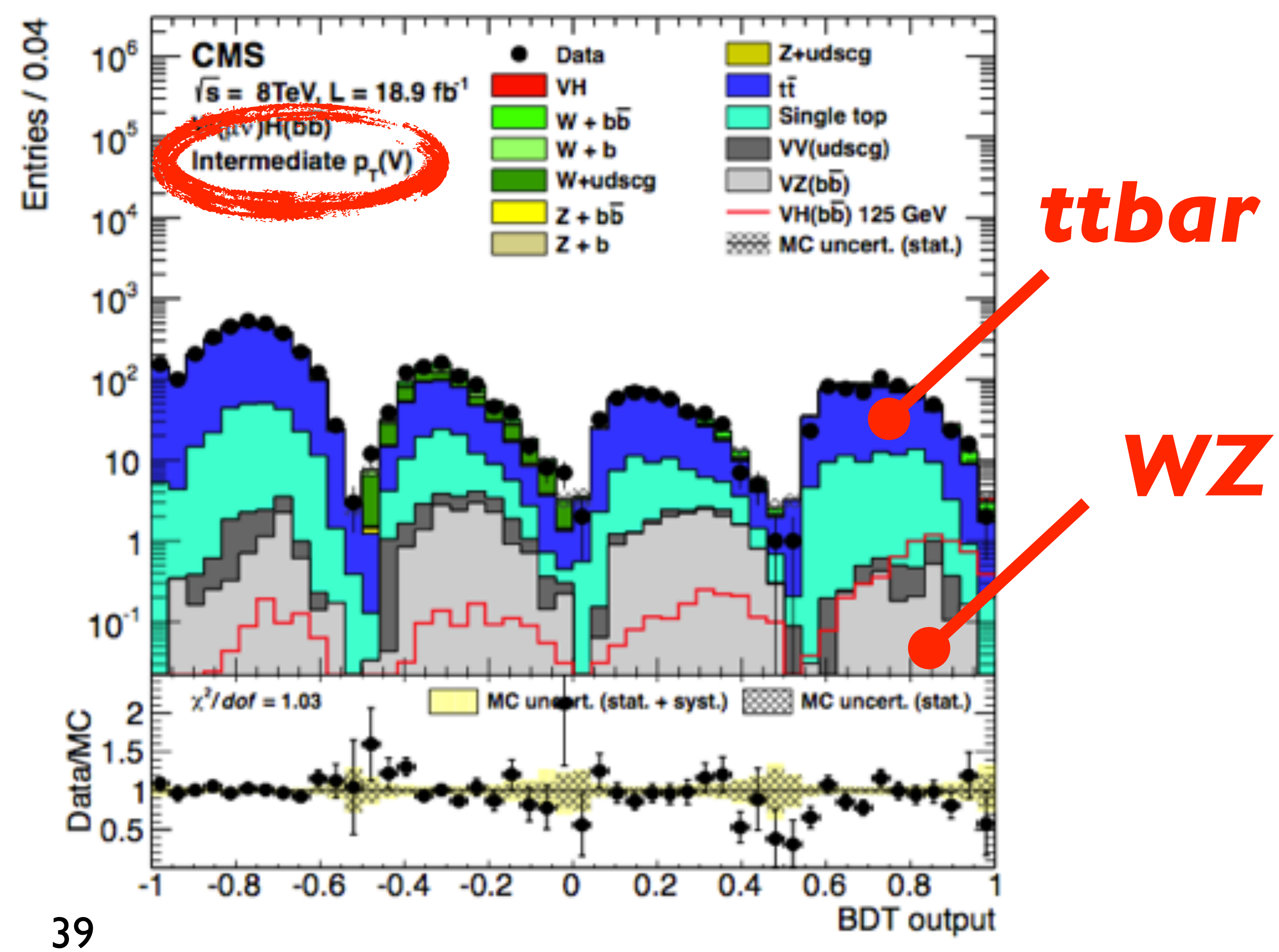
Analysis overview

- Phase-space slicing by p_T^V and/or N_{jet}
  - enhance sensitivity to higher-order corrections (Higgs p_T and jet radiation)
- Main backgrounds: **V+h.f.**, **ttbar**, **diboson**
- MVA approach for maximal S/B
  - modeling of differential distributions & correlations

ATLAS, JHEP 01 (2015) 069



CMS, PRD 89 01 (2014) 012003



The Run I analysis

- Categorise events by p_T^V and N_{jet}
  - enhance signal acceptance sensitivity to higher-order corrections
- Main backgrounds: V+h.f., ttbar, diboson
  - increase separation by BDT

ATLAS, JHEP 01 (2015) 069

Vector p_T → p_T^V

jet-jet correlations → m_{bb}, $\Delta R(b_1, b_2)$, $|\Delta\eta(b_1, b_2)|$

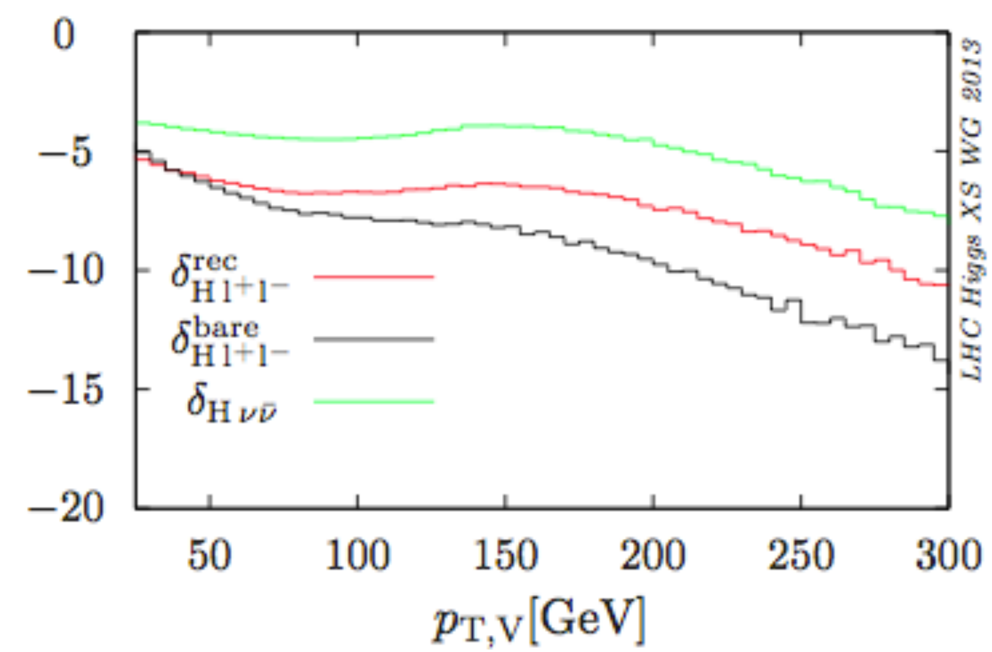
jet-V correlations → $\Delta\phi(V, bb)$, $|\Delta\eta(V, bb)|$, $\min[\Delta\phi(\ell, b)]$

Variable	0-Lepton	1-Lepton	2-Lepton
p_T^V		×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\lvert\Delta\eta(b_1, b_2)\rvert$	×		×
$\Delta\phi(V, bb)$	×	×	×
$\lvert\Delta\eta(V, bb)\rvert$			×
H_T	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
$MV1c(b_1)$	×	×	×
$MV1c(b_2)$	×	×	×
	Only in 3-jet events		
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×

**** CMS also uses N_{jet}***

Theory uncertainties: VH

LHCXSWG, arXiv:1307.1347



NLO MCs reweighted to best accuracy:

QCD	qqVH	NNLO	fully differential
	ggZH	NLO	inifinite-top mass
EWK	NLO		factorised

ATLAS, JHEP 01 (2015) 069

Signal	
Cross section (scale)	1% ($q\bar{q}$) 50% (gg)
Cross section (PDF)	2.4% ($q\bar{q}$) 17% (gg)
Branching ratio	3.3 %
Acceptance (scale)	1.5%–3.3%
3-jet acceptance (scale)	3.3%–4.2%
p_T^V shape (scale)	S
Acceptance (PDF)	2%–5%
p_T^V shape (NLO EW correction)	S
Acceptance (parton shower)	8%–13%

ggZH ~10%σ_{VH} @14 TeV

e.g. PYTHIA vs HERWIG

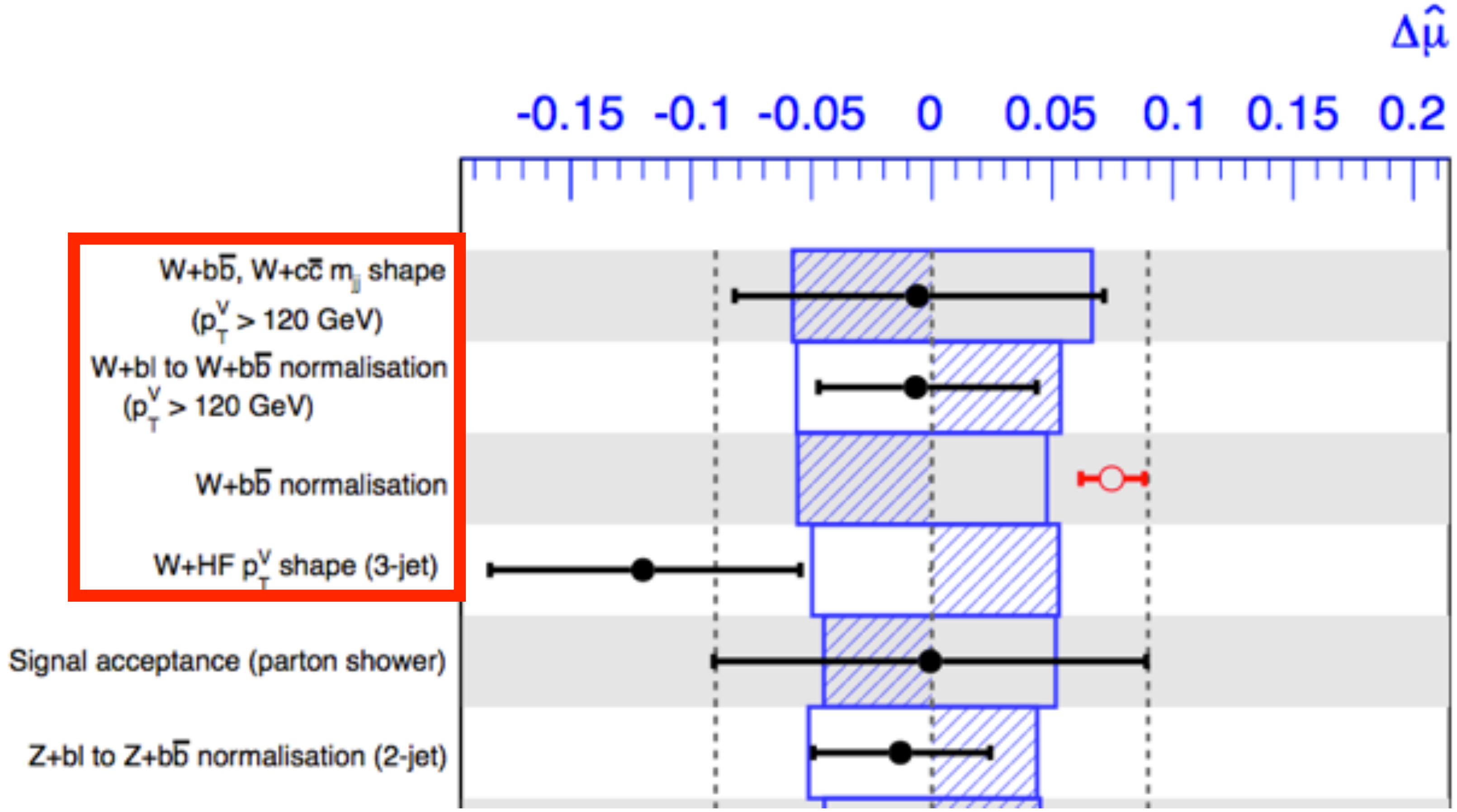
Can it be constrained by WZ/ZZ?

$\sigma_{stat}^{WZ/ZZ}$ ~ 2% at 3000 fb^{-1}

PDFs

Can be related to other Drell-Yan measurements?

Run 1 systematics



ATLAS, JHEP 01 (2015) 069

Source	Type	Event yield uncertainty range (%)	Individual contribution to μ uncertainty (%)	Effect of removal on μ uncertainty (%)
b-tagging	shape	3–15	10.2	2.1
Signal cross section (scale and PDF)	norm.	4	3.9	0.3
Signal cross section (p_T boost, EW/QCD)	norm.	2/5	3.9	0.3
Monte Carlo statistics	shape	1–5	13.3	3.6
Backgrounds (data estimate)	norm.	10	15.9	5.2
Single-top-quark (simulation estimate)	norm.	15	5.0	0.5
Dibosons (simulation estimate)	norm.	15	5.0	0.5
MC modeling (V+jets and tt)	shape	10	7.4	1.1

CMS, PRD 89 012003 (2014)

Background shape uncertainties

CMS:

- take envelope between BDT outputs from independent MCs

" The uncertainty in the background event yields estimated from data is approximately 10%. For V+jets, the difference between the shape of the BDT output distribution for events generated with the MADGRAPH and the HERWIG ++ Monte Carlo generators is considered as a shape systematic uncertainty. For $t\bar{t}$ the differences in the shape of the BDT output distribution between the one obtained from the nominal MADGRAPH samples and those obtained from the POWHEG and MC@NLO [60] generators are considered as shape systematic uncertainties. "

ATLAS:

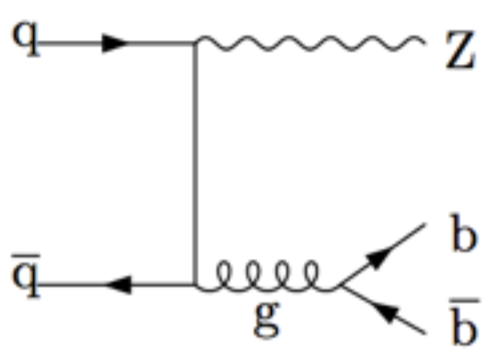
- assess uncertainty on modeling of BDT input variables
  - m_{bb}, p_T^V, N_{jet}

" Details of the assessment of systematic uncertainties are provided below in the context of the MVA. When systematic uncertainties are derived from a comparison between generators, all relevant variables are considered independently. The variable showing the largest discrepancy in some generator with respect to the nominal generator is assigned an uncertainty covering this discrepancy, which is symmetrised. If, once propagated to the BDT_{VH} discriminant, this uncertainty is sufficient to cover all variations observed with the different generators, it is considered to be sufficient. If not, an uncertainty is considered in addition on the next most discrepant variable and the procedure is iterated until all variations of the BDT_{VH} discriminant are covered by the assigned uncertainties. "

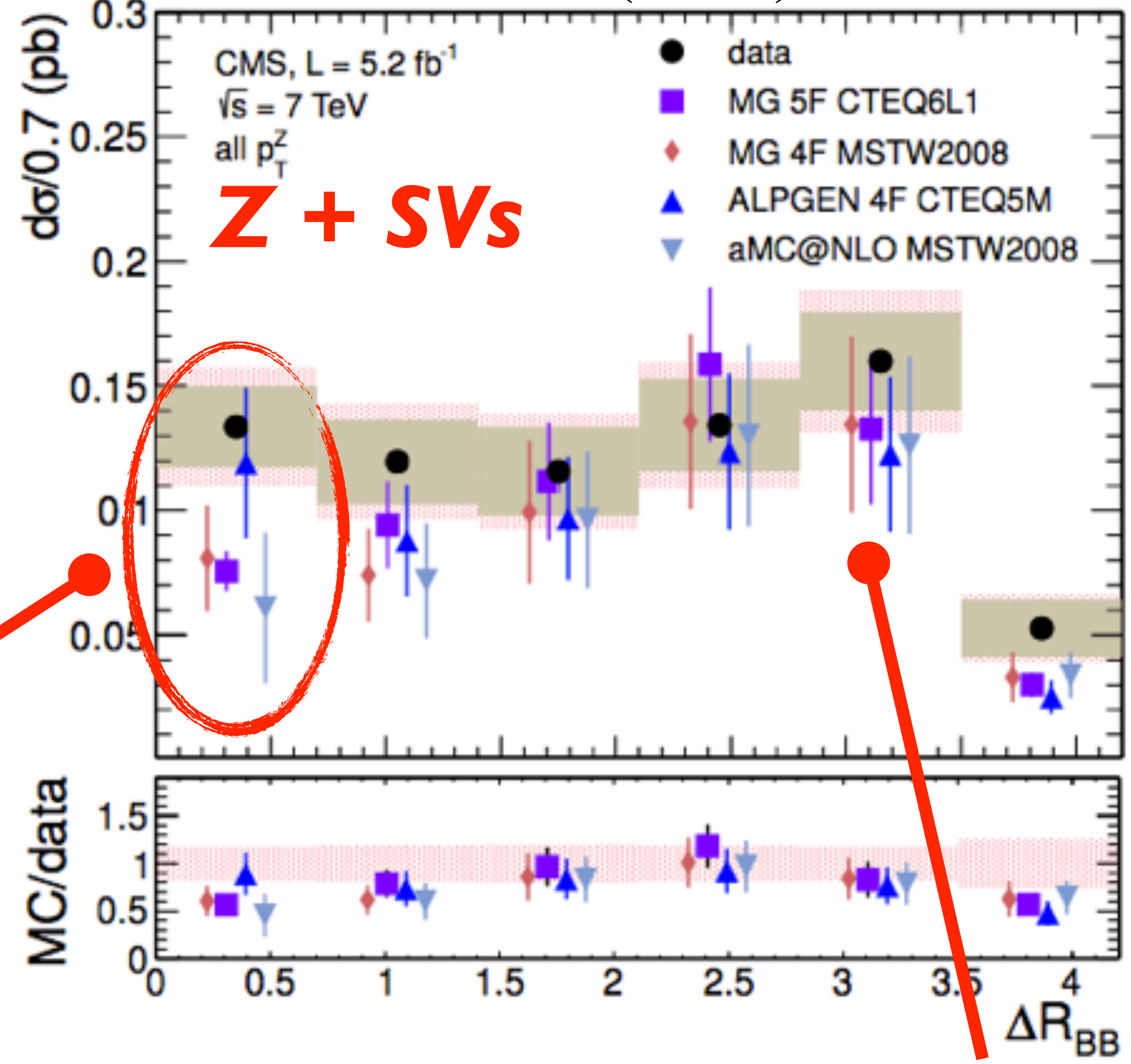
An example: Z + SVs

Z + secondary vertices:

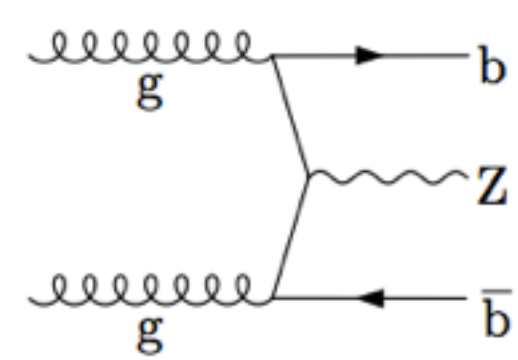
- independent of jet algorithm
  - sensitive to both collinear and resolved b-jet production
- testing angular correlations between b hadrons



CMS, JHEP 12 (2013) 039



“The MG5F MC generator has been one of the standard tools used to simulate backgrounds from associated production of vector bosons and heavy quarks for Higgs boson and new physics searches as well as SM studies. The results reported here indicate that such a description may not be optimal for analyses sensitive to the production of collinear b hadrons. This fact may be particularly important in the simulation of the $Wb\bar{b}$ process, where collinear b-hadron production is expected to be enhanced compared to the $Zb\bar{b}$ process.”



Importance of ττ channels

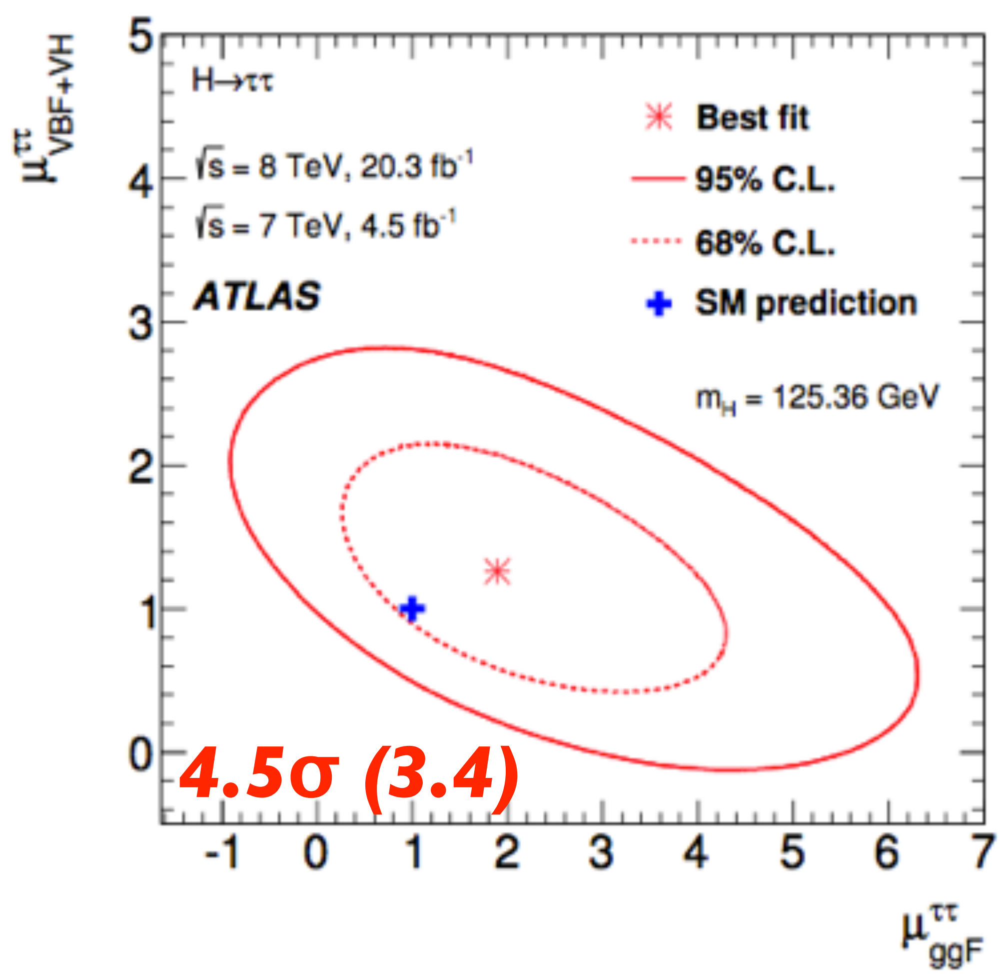
H → ττ:

- coupling to leptons and down-type fermions
- can be triggered irrespectively of production mode
  - sensitivity to both κ_V and κ_f

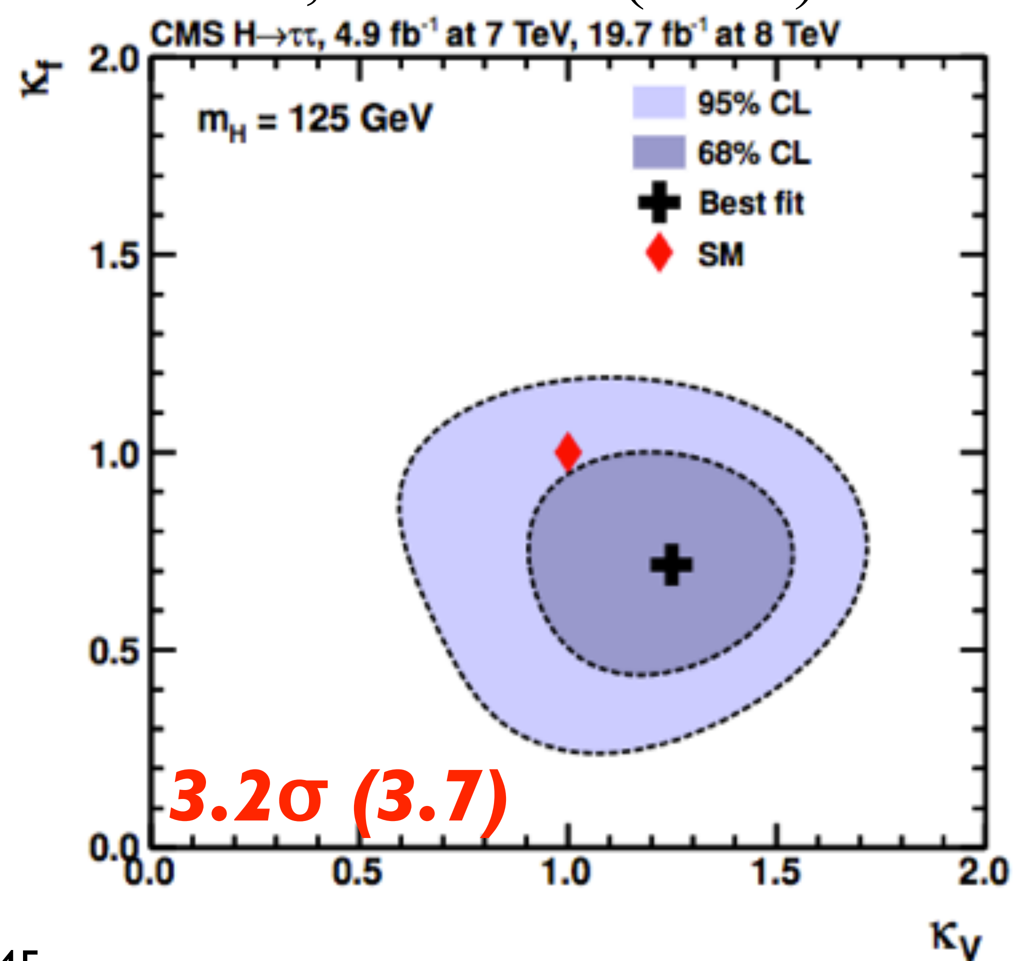
τxτx +

0,1 jet	ggF
≥2 jets	VBF/ggF
1 lept	VH
b jets	ttH

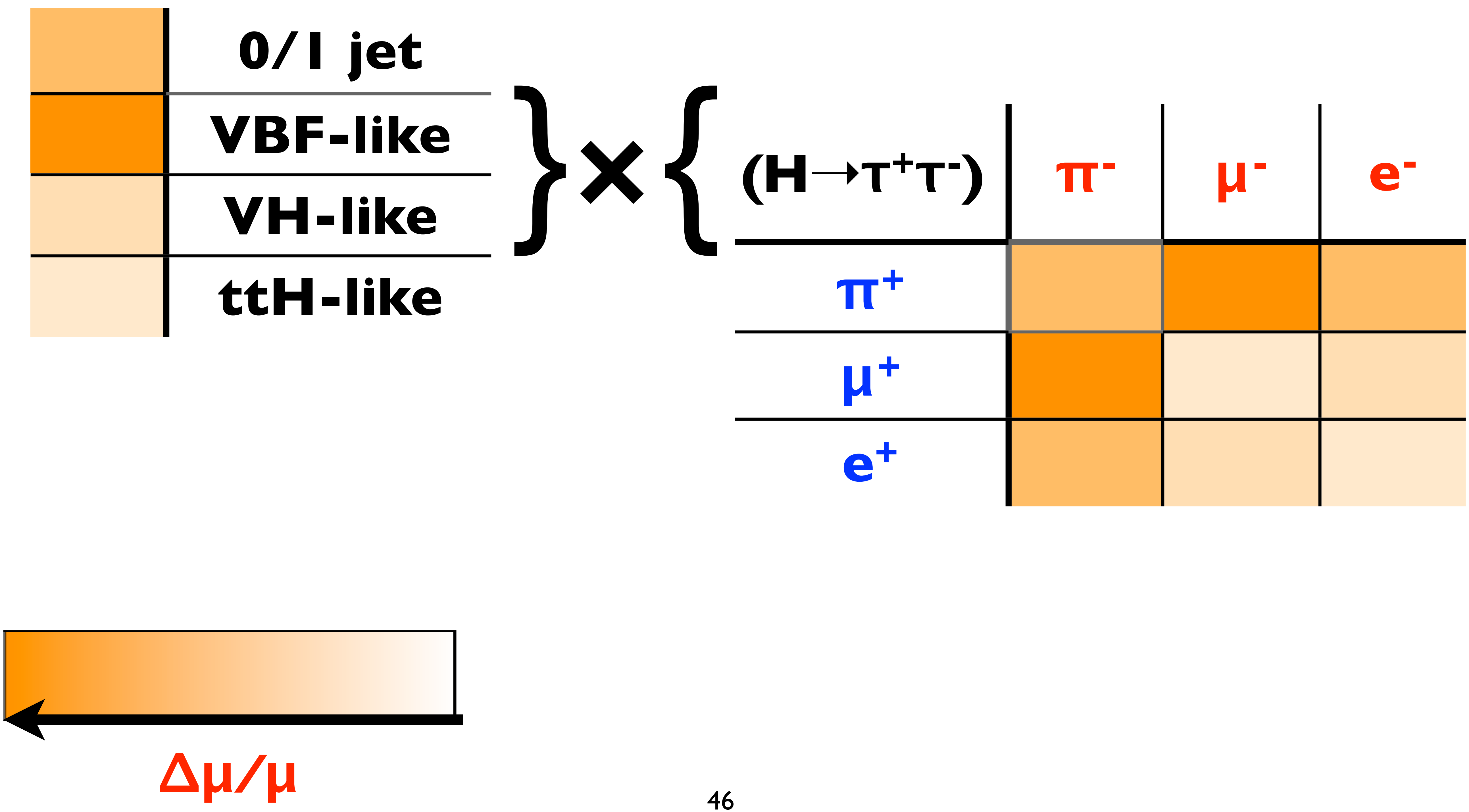
ATLAS, JHEP 04 (2015) 117



CMS, JHEP 05 (2014) 104



Sensitivity by production and decay



PU jets suppression

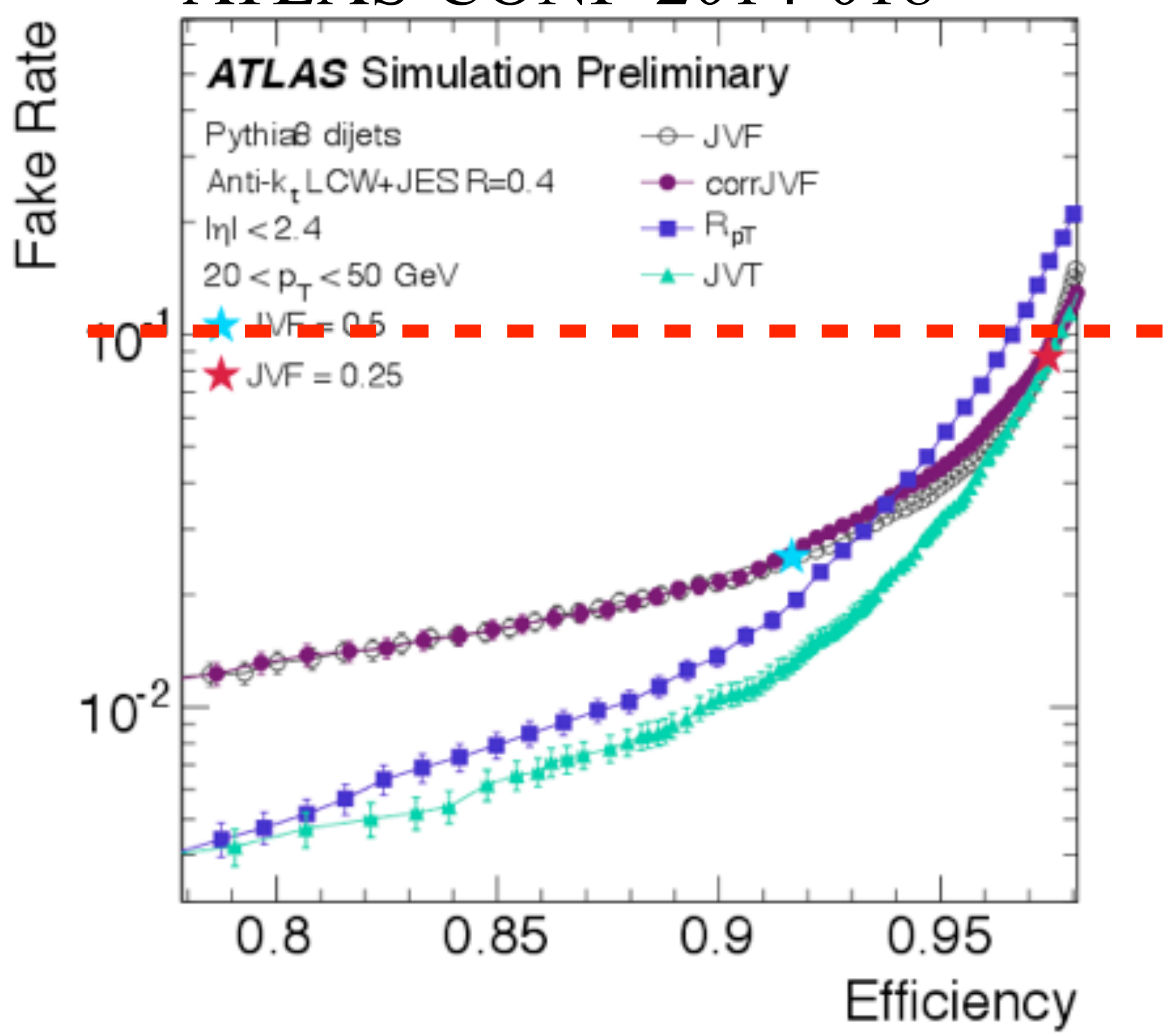
Already studied and deployed in Run I

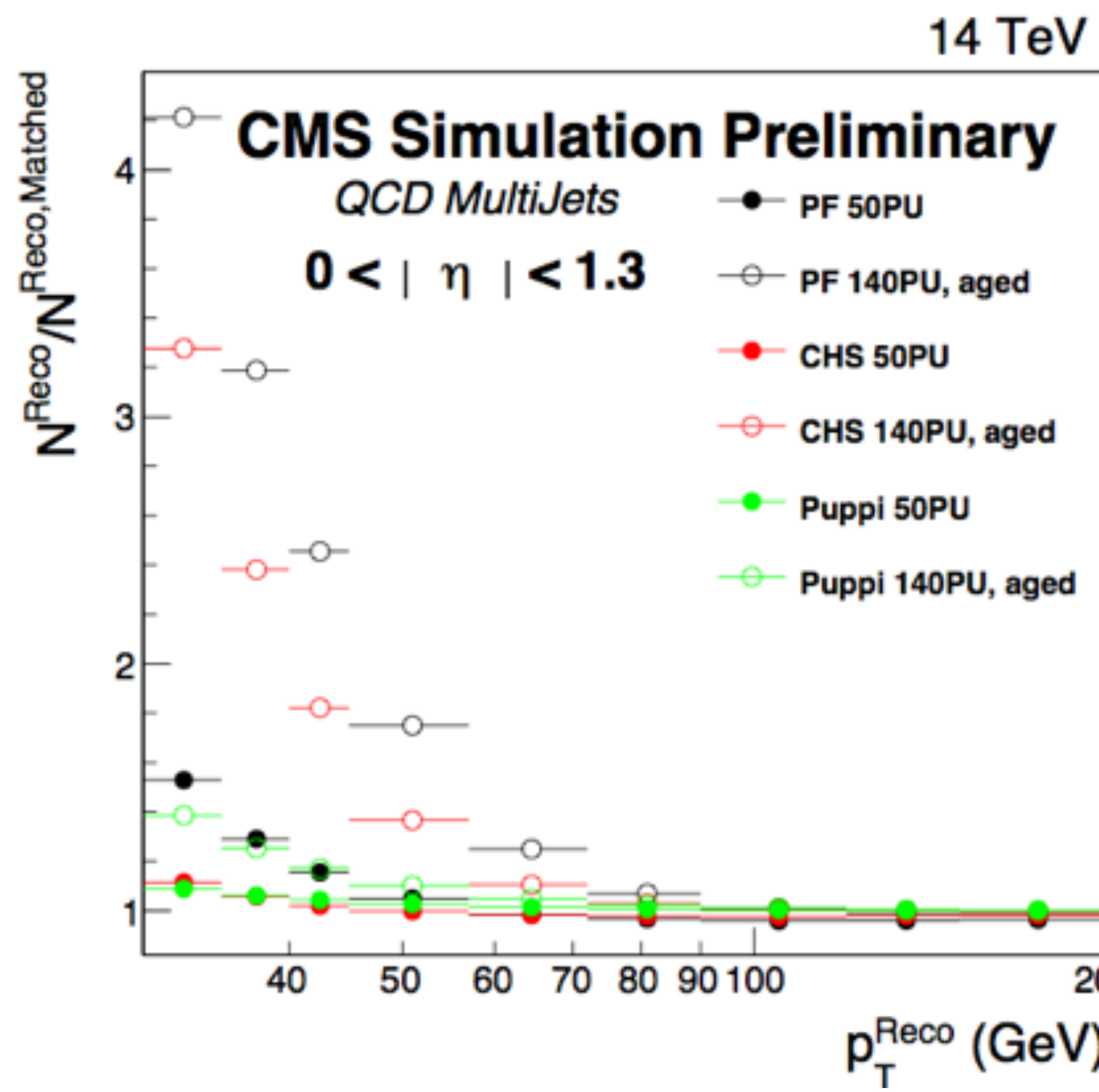
- PU-jet rejection mandatory to preserve acceptance
  - 90% bkg rejection at negligible signal loss within tracker

p_T cut for less than X% fake rate

Eta	10% (GeV)	1% (GeV)
0–2.1	60 (30)	80 (40)
2.1–2.8	50	80
2.8–3.2	50	80
3.2–4.5	30	50

ATLAS-CONF-2014-018

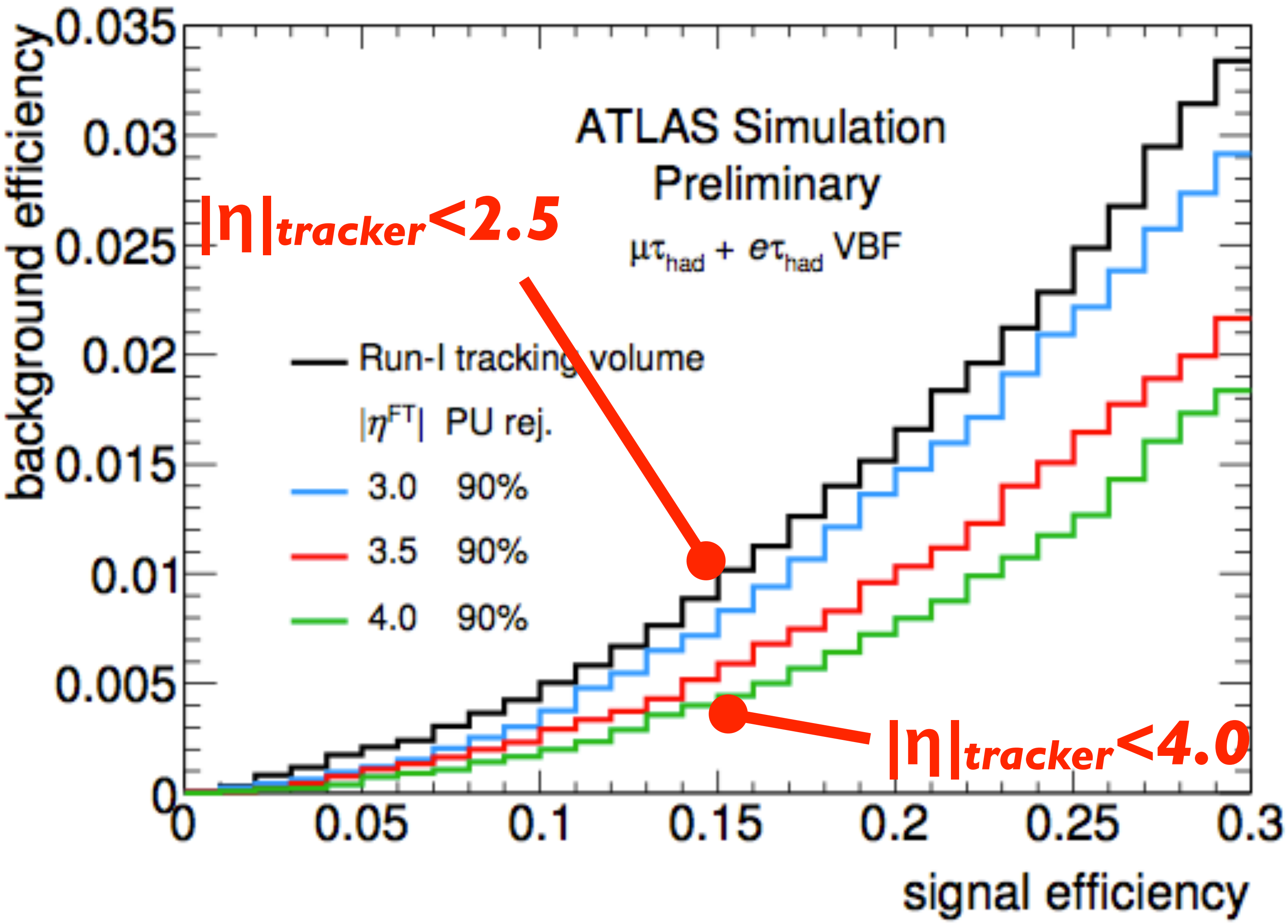




Impact of extended PU rejection

Extension of tracking to forward region

- performances dramatically improved by larger tracking coverage



ATL-PHYS-PUB-2014-018

forward pile-up jet rejection	50%	75%	90%
forward tracker coverage		$\Delta\mu$	
Run-I tracking volume		0.24	
$\lvert\eta\rvert < 3.0$	0.18	0.15	0.14
$\lvert\eta\rvert < 3.5$	0.18	0.13	0.11
$\lvert\eta\rvert < 4.0$	0.16	0.12	0.08

Extension of tracker coverage can provide up to 3 times smaller Δμ !!

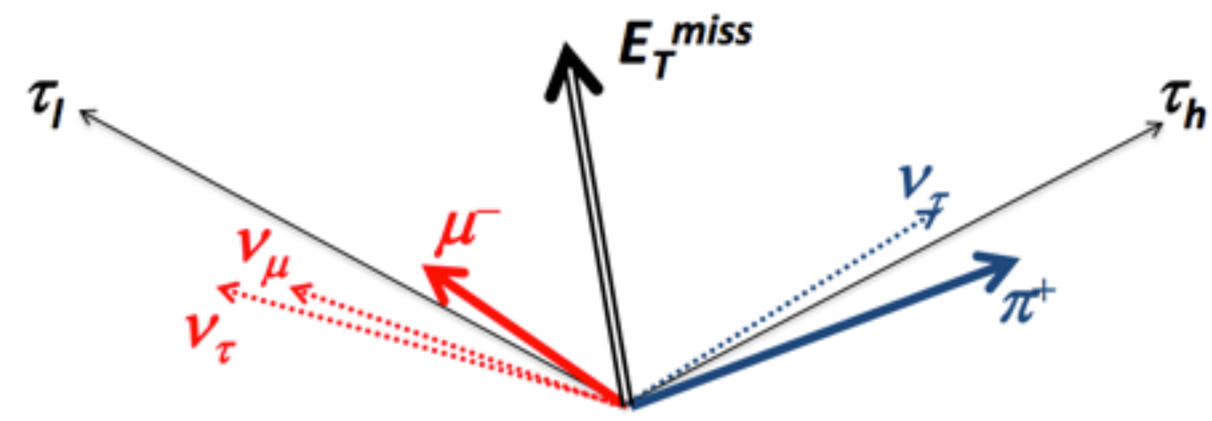
Also studied by CMS for Phase2 upgrade

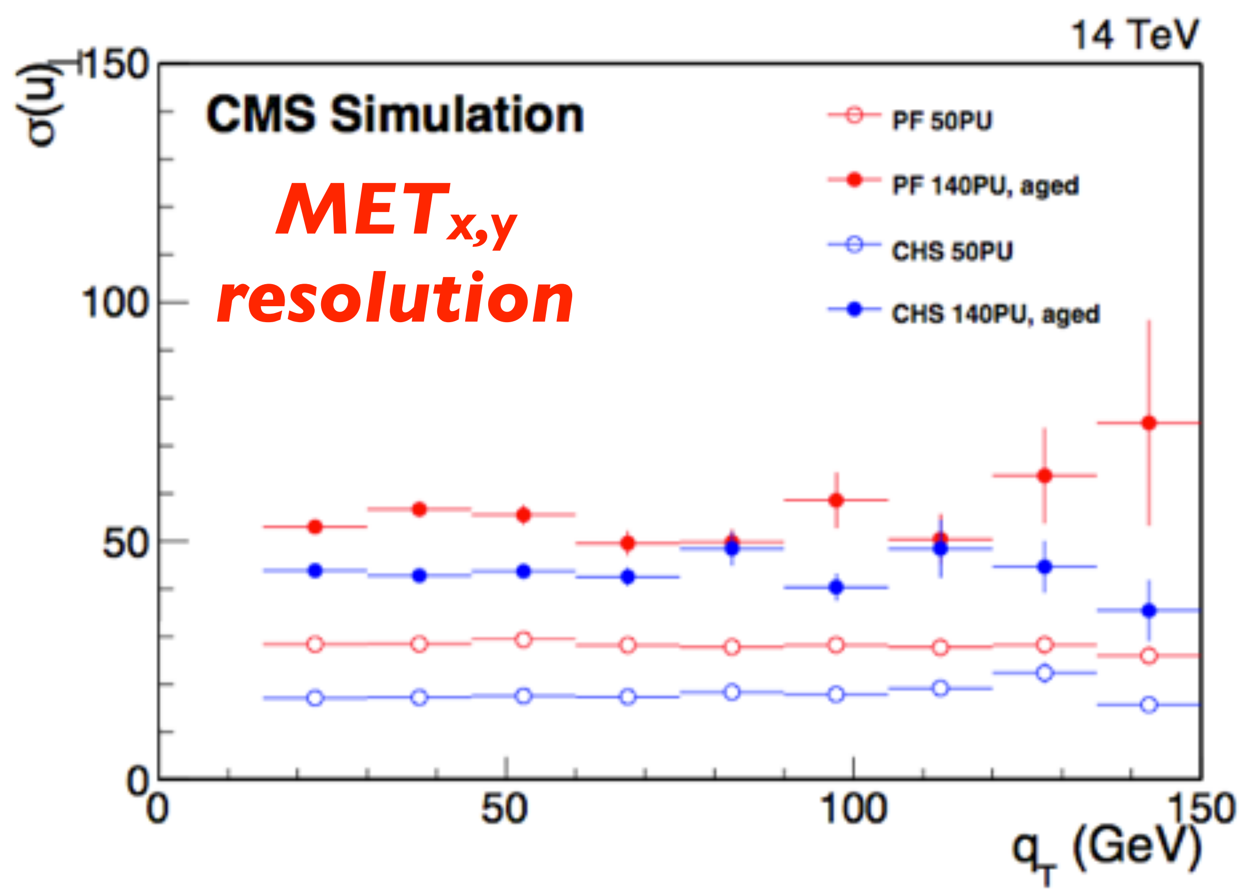
- forward pixel disks and timing in pre-shower

Experimental challenges: MET

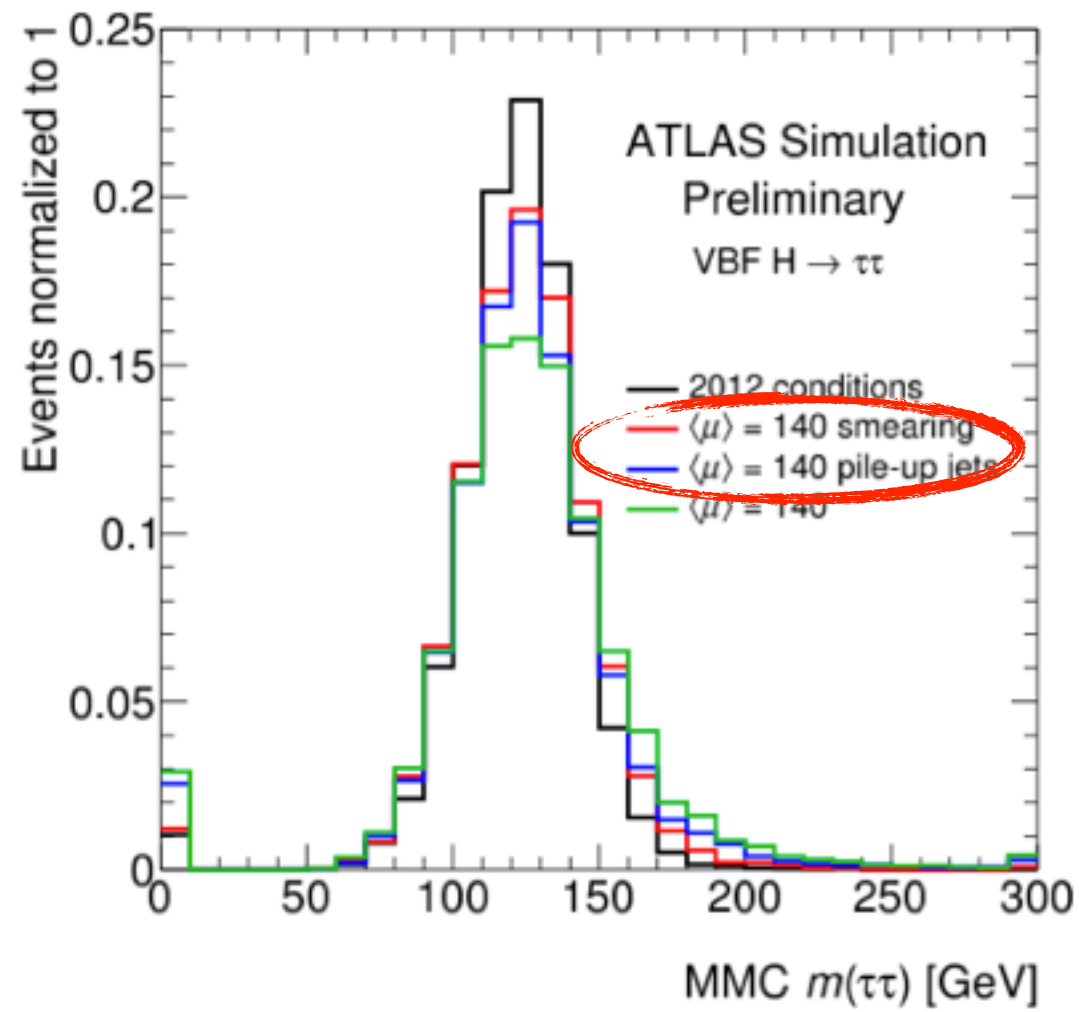
Missing energy used for for dynamical $m_{\tau\tau}$ reconstruction

- MET resolution degraded by PU
  - extra smear (x2 larger RMS)
  - bias from extra jets





ATL-PHYS-PUB-2014-018

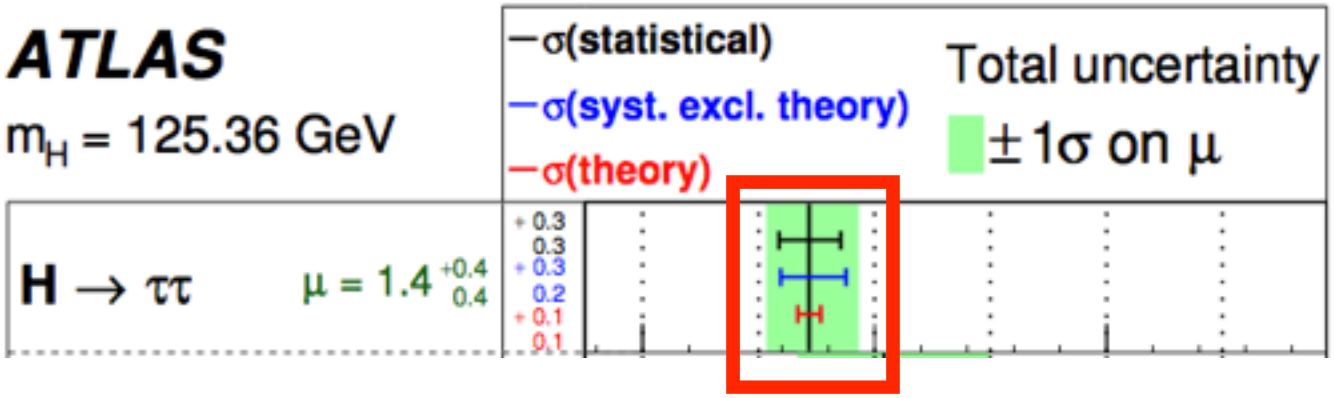


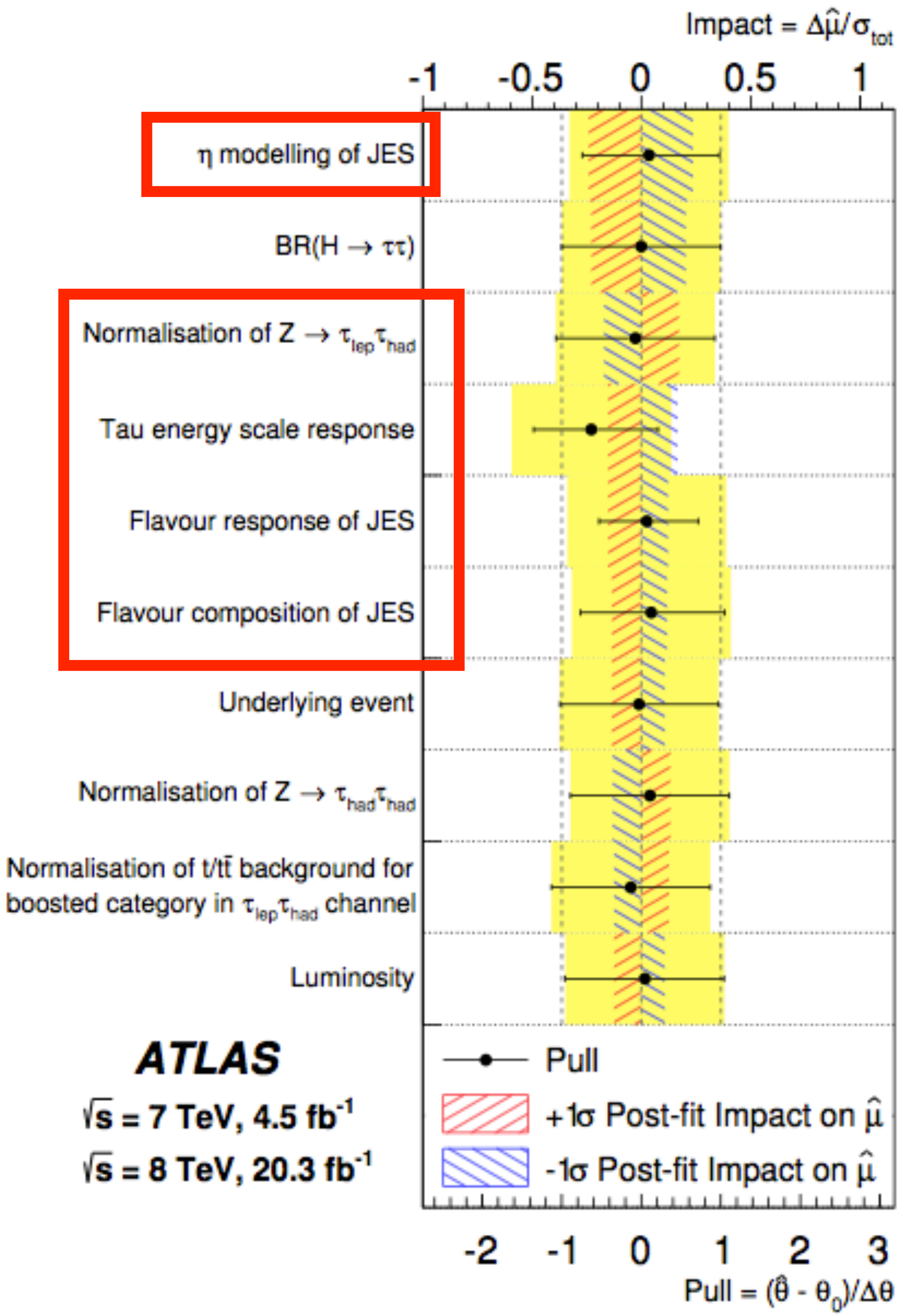
PU mitigation and MET improvement will be important here

Experimental uncertainties

@ RunI: statistical and systematic uncertainties comparable

- experimental systematics mostly from jet and tau modeling





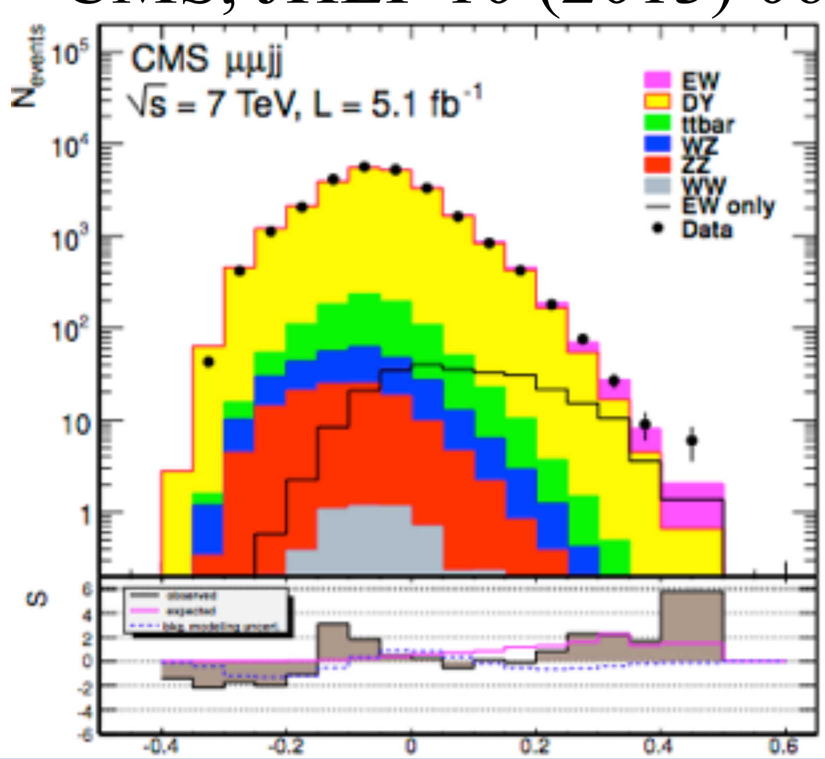
- VBF-like category most sensitive
  - theory uncertainty there will eventually dominate

ATLAS, JHEP 04 (2015) 117

The third jet: VBF

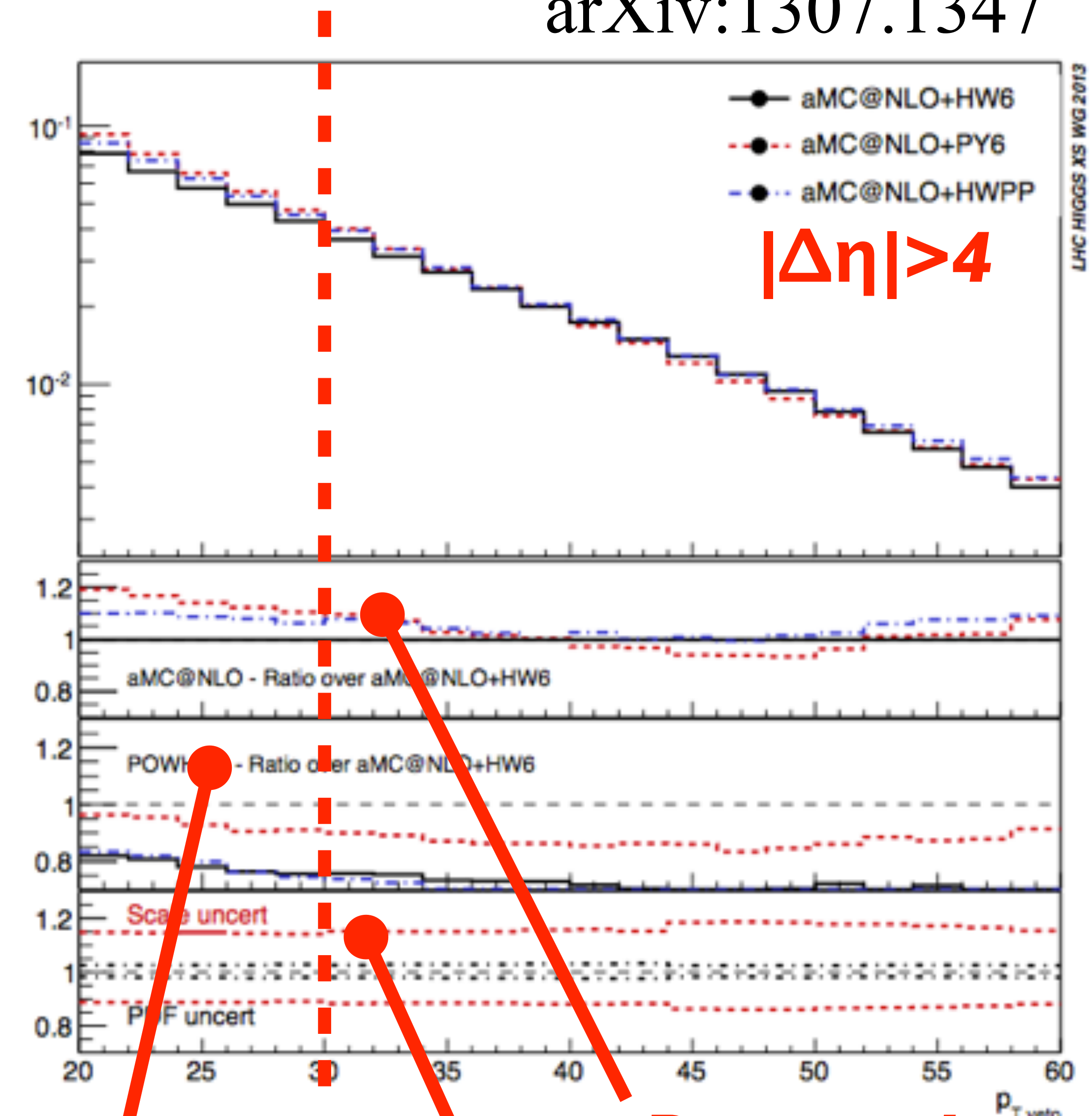
- Tighter VBF-like cuts will enhance jet veto uncertainty
- Current analyses apply jet veto:
  - CMS: jet p_T veto 30 GeV
  - ATLAS: BDT sensitive to 3rd jet
- Can it be improved?
  - e.g. calibrate on EWK Z production?

CMS, JHEP 10 (2013) 062



$$\sigma^{\text{EW}}_{\ell\ell\ (\ell=\text{e},\mu)} = 154 \pm 24\,(\text{stat.}) \pm 46\,(\text{exp. syst.})$$

arXiv:1307.1347



MC modeling (~20%)

Missing orders (~15%)

Parton showers (~10%)

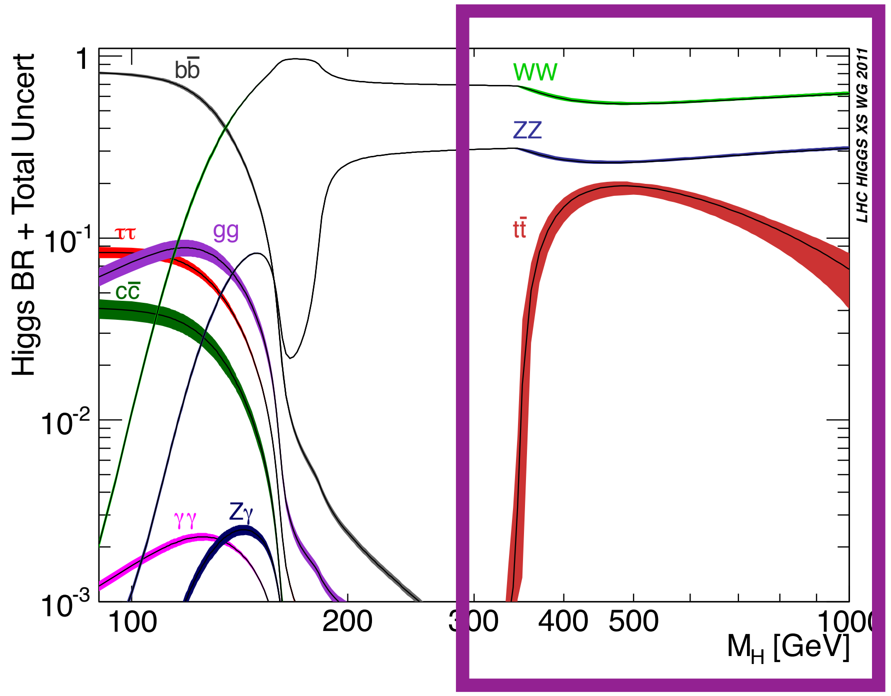
Extrapolating to 3000 fb^{-1} ⇒ O(1%) stat. on σ^{EW}

Monday, May 11, 15

The top quark Yukawa coupling

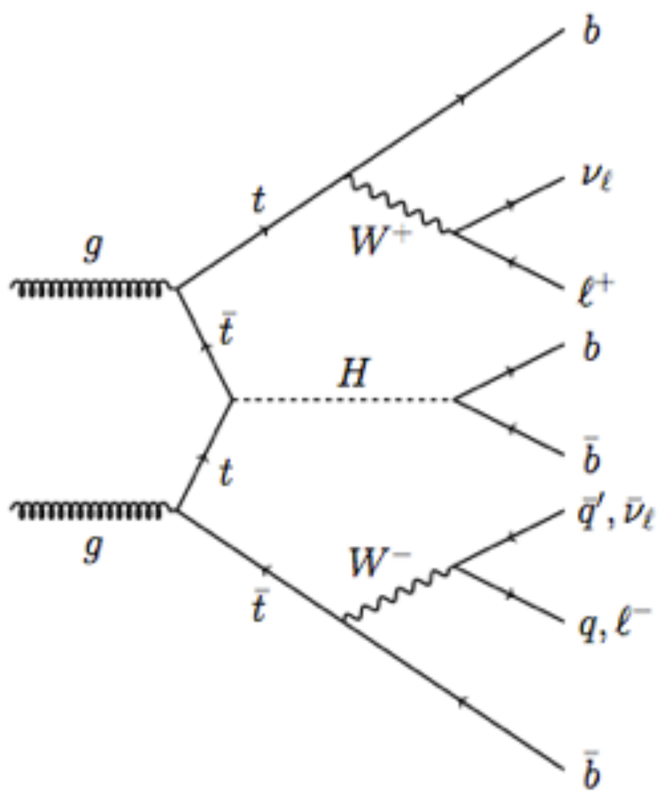
Precise knowledge of Yukawa coupling y_t crucial for characterization of H(125)

- no partial width $\Gamma_{H\to tt}$
  - off-shell H→tt through gg→tt interference? Maybe, but very hard



	H→ZZ*/WW*/ff	H→γγ
σ(pp→H)	κ_t^2 [loop]	$\lvert\kappa_t\mathcal{M}_a + \kappa_V\mathcal{M}_b\rvert^2$ [loop]
σ(pp→ttH)	κ_t^2 [tree]	
σ(pp→tH)	$\lvert\kappa_t\mathcal{M}_a + \kappa_V\mathcal{M}_b\rvert^2$ [tree]	

Tackling H→bb final states

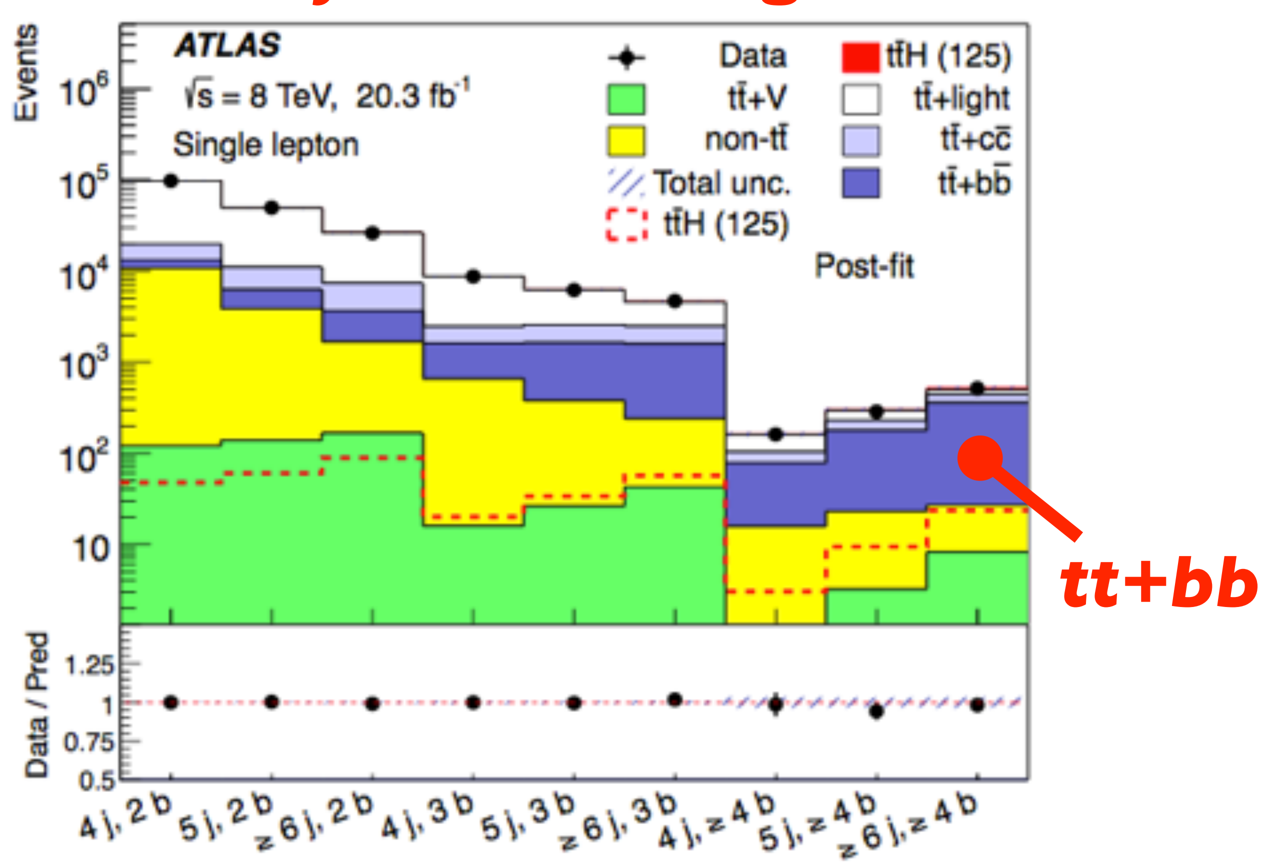


J = $t \to b\, q\, \bar{q}'$ L = $t \to b\, \ell^+\, \nu$

	LL	LJ	JJ
quarks	4	6	8
b-quarks	4	4	4
leptons	2	1	0

- High jet multiplicities
  - up to four b-jets
- Require ≥1 lepton
  - trigger efficiency and negligible multi-jet background
- All-hadronic channel not yet explored
  - ideal case for boosted techniques

#jets vs #b-tags



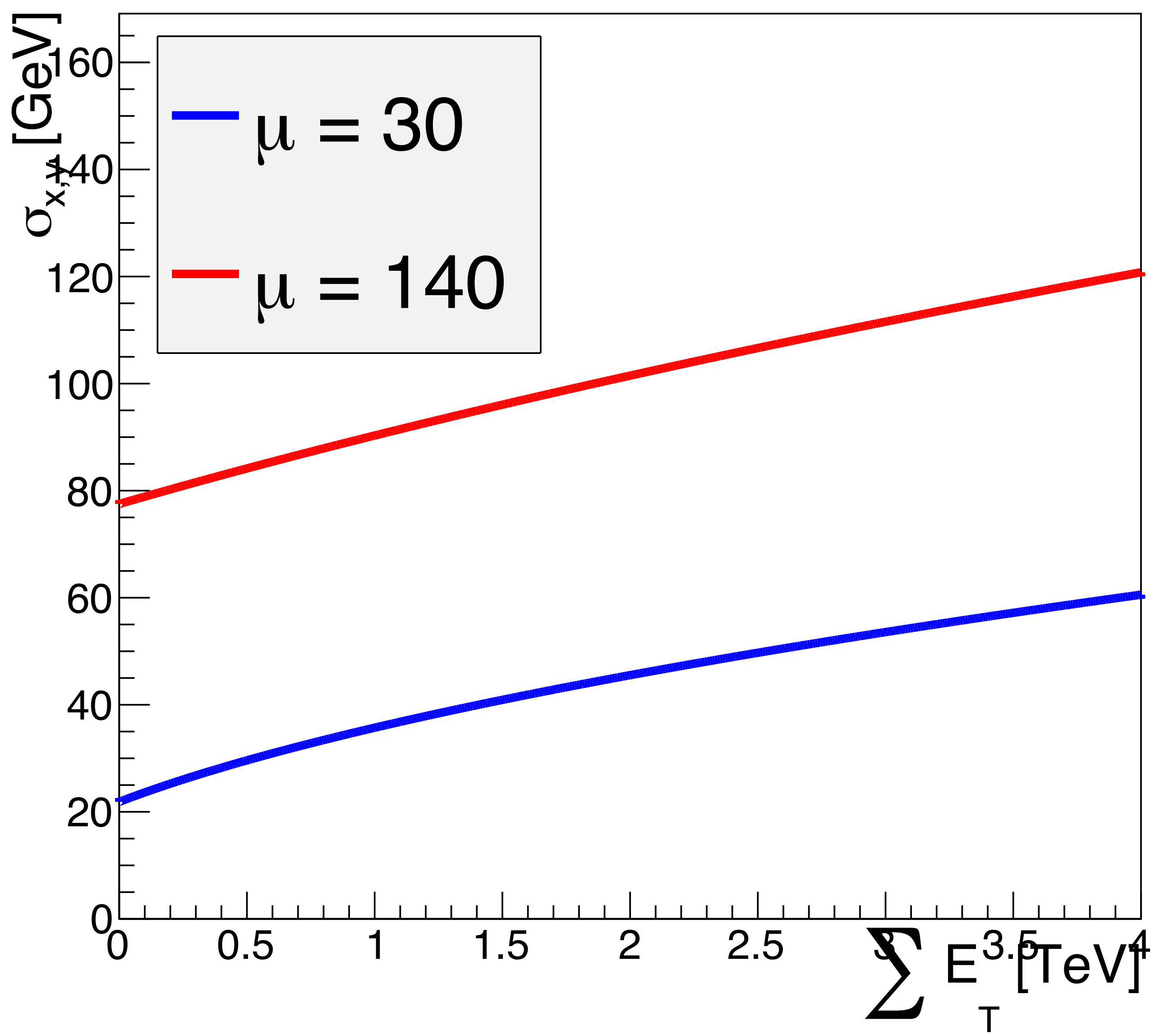
ATLAS, arXiv:1503.05066

ttH: theoretical developments

	Accuracy	Some references
Signal modeling	NLO	PRL 87 (2001) 201805 NPB 653 (2003) PRD 68 (2003) 034022
	bkg interference	arXiv:1412.5290
	EWK corrections	arXiv:1504.03446
	NLO + PS	aMC@NLO+PYTHIA Sherpa+OpenLoops POWHEG+HELAC
Background modeling	tt+bb @NLO	PRL 103 (2009) 012002
	tt+bb @NLO + PS (4FS, 5FS)	PLB 734 (2014) 210 JHEP 07 (2014) 135 JHEP 1503 (2015) 083
	tt+jj @NLO	PRD 84 (2011) 114017
	tt+jj @NLO + PS	arXiv:1402.6293

Experimental challenges: MET

$$\sigma(E_{\mathrm{x,y}}^{\mathrm{miss}})[\mathrm{GeV}] = (0.40 + 0.09 \times \sqrt{\mu}) \times \sqrt{\sum E_{\mathrm{T}}[\mathrm{GeV}] + \mu \times 20}$$



Principle

Assign each reconstructed event with its probability density

$$\mathrm{P}\{\vec{y} \in [\vec{y}_0, \vec{y}_0 + d\vec{y}] \mid S, \boldsymbol{\theta}\} = p_S(\vec{y}_0|\boldsymbol{\theta})d\vec{y}$$

$$\int_{\mathcal{A}} p_S(\vec{y}\,|\boldsymbol{\theta})d\vec{y} = 1$$

observed quantities (e.g. jet, lepton momenta)

model parameters (e.g. JES, particle masses)

normalisation

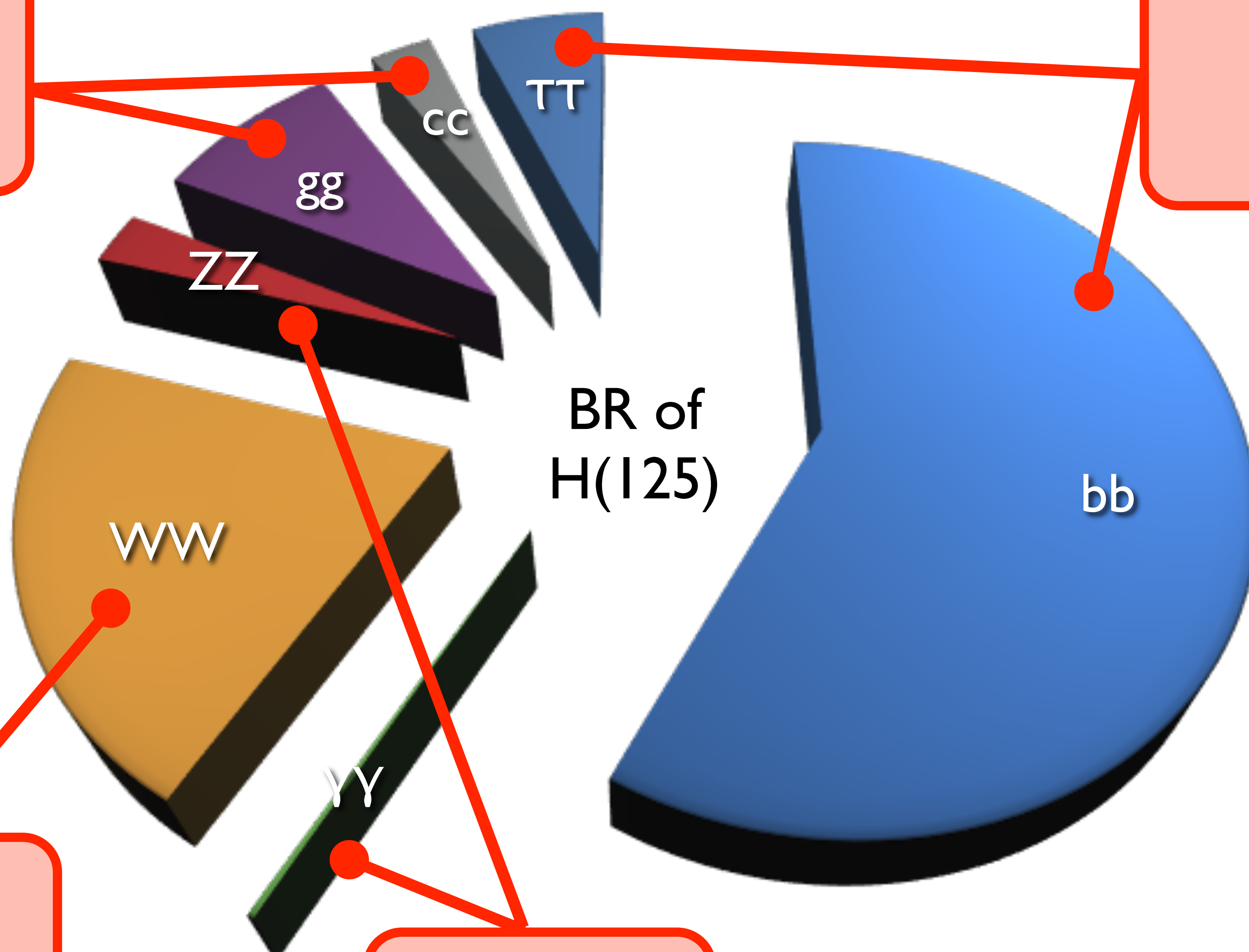
- if the underlying scattering process is theoretically known:

$$p_S(\vec{y}\,|\boldsymbol{\theta}) = \frac{1}{\sigma_S(\boldsymbol{\theta})}\frac{d\sigma_S}{d\vec{y}}(\vec{y},\boldsymbol{\theta})$$

$$d\sigma_S(\vec{y}\,|\boldsymbol{\theta}) = \left[\int d\Phi(\vec{x})dx_\mathrm{a}dx_\mathrm{b}\sum_{i,j}\frac{f_i(x_\mathrm{a})f_j(x_\mathrm{b})}{(1+\delta_{ij})x_\mathrm{a}x_\mathrm{b}s}|\mathcal{M}_S(\vec{x},\boldsymbol{\theta})|^2 W(\vec{y},\vec{x};\boldsymbol{\theta})\right]d\vec{y}$$

- convolution of { ***theoretical prediction*** / ***detector resolution*** }

ttH: experimental break-down



+ Irreducible backgrounds

+ High object multiplicity (overlap, acceptance, combinatorics)

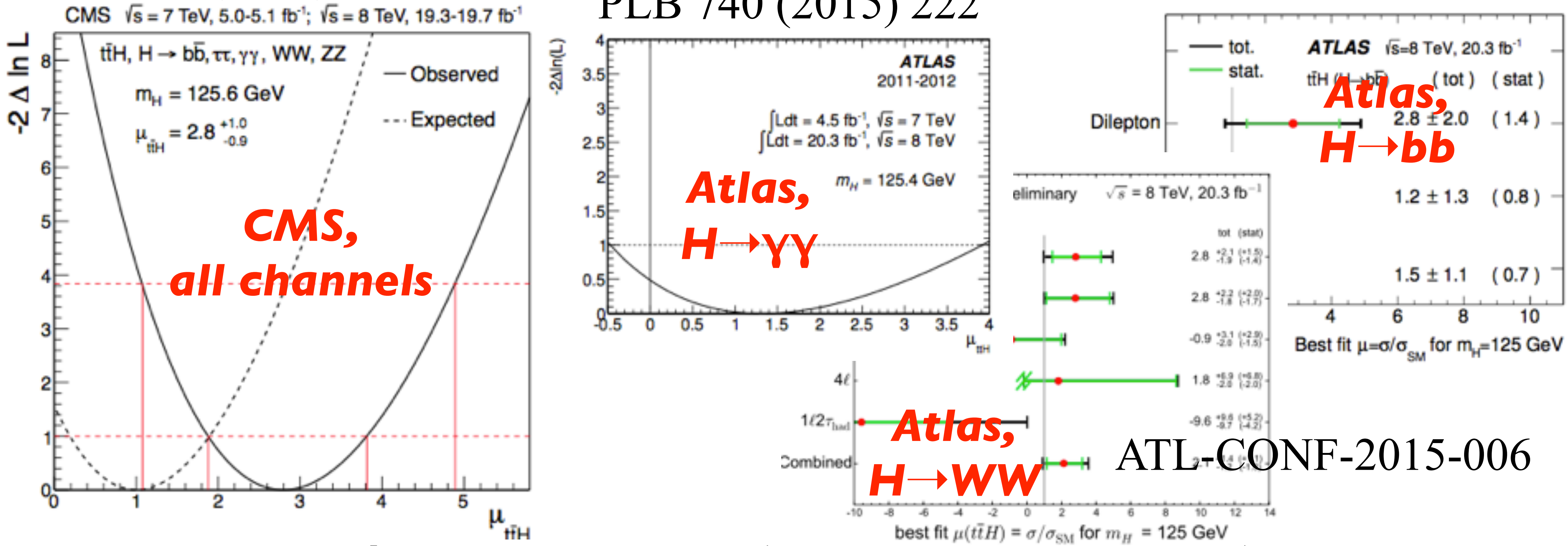
Run I at a glance

JHEP 09 (2014) 087

PLB 740 (2015) 222

ATLAS, arXiv:1503.05066

ATL-CONF-2015-006



	Experiment	obs. (exp.) limit 95% CL	best-fit value ($\pm 1\sigma$)
H → hadrons	CMS	4.1 (3.5)	$0.7^{+1.9}_{-1.9}$
	ATLAS	3.4 (**2.2**)	$1.5^{+1.1}_{-1.1}$
H → photons	CMS	7.4 (**4.7**)	$2.7^{+2.6}_{-1.8}$
	ATLAS	6.7 (4.9)	$1.4^{+2.1}_{-1.4}$
H → leptons	CMS	6.6 (**2.4**)	$3.7^{+1.6}_{-1.4}$
	ATLAS	7.7 (2.4)	$2.1^{+1.4}_{-1.2}$