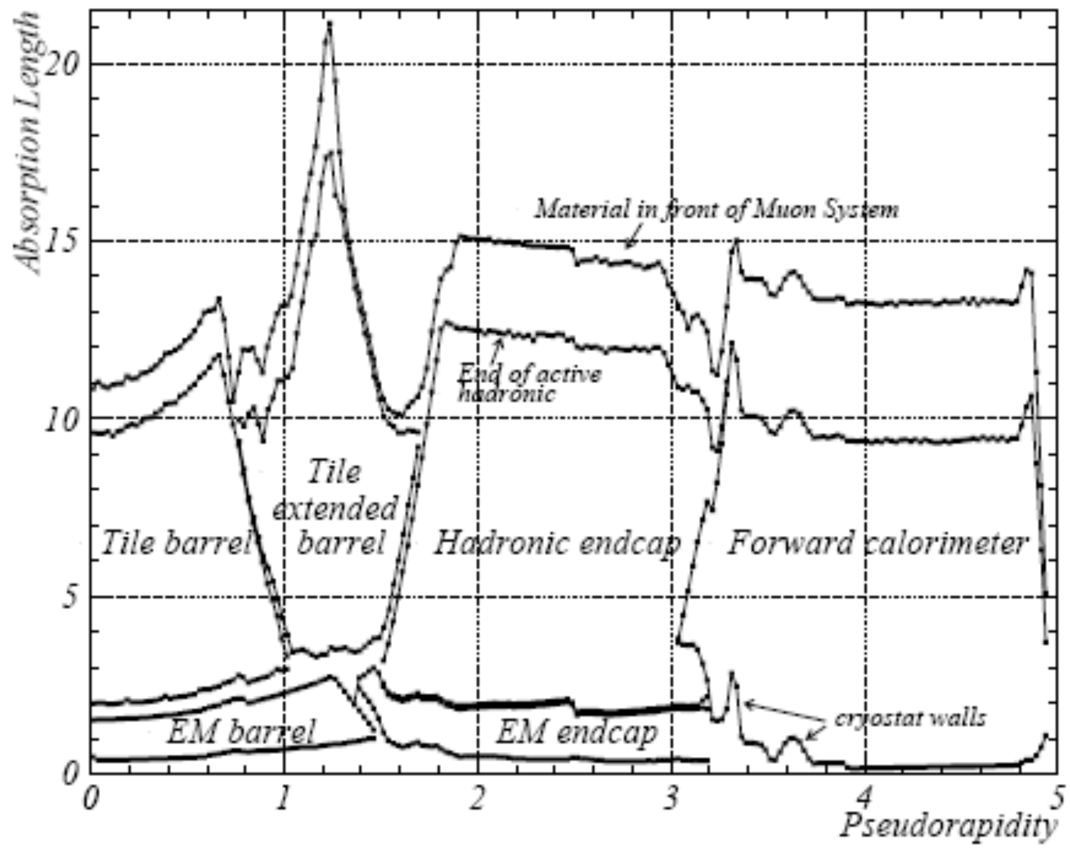
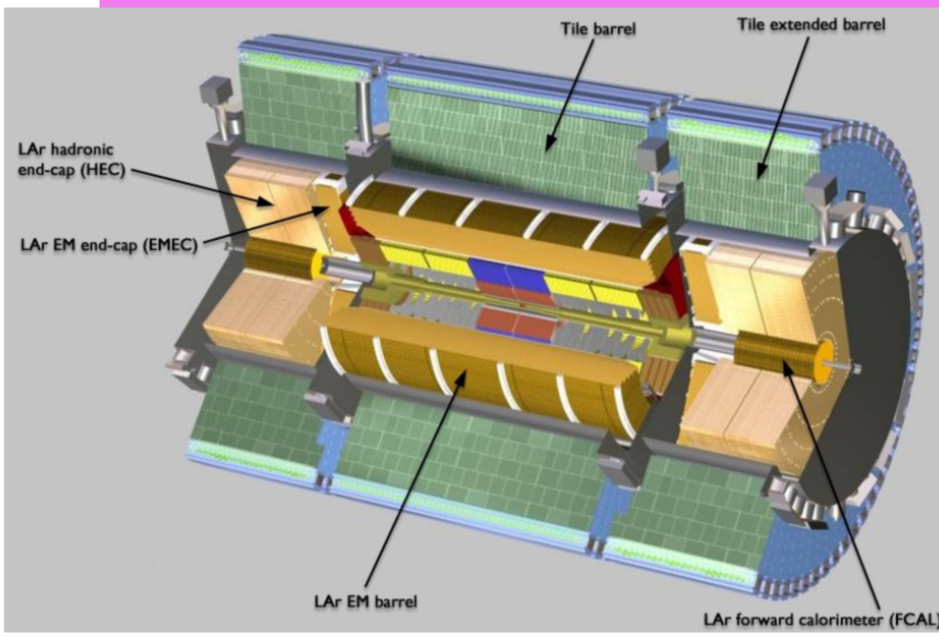
ATLAS calorimeters

- …are very thick, on the order of 10 absorption lengths or more
  - similar for CMS
- The EM calorimeter itself is almost 2 absorption lengths
- About 8 λ is needed for absorption of 98% of the energy of a 50 GeV proton
- A thick calorimeter also makes a great muon filter
- Depth needed increases logarithmically with energy (as for EM shower)
- Shower max depth is given by t_{max}=0.2 ln(E), where E is in GeV, so often in EM calorimeter



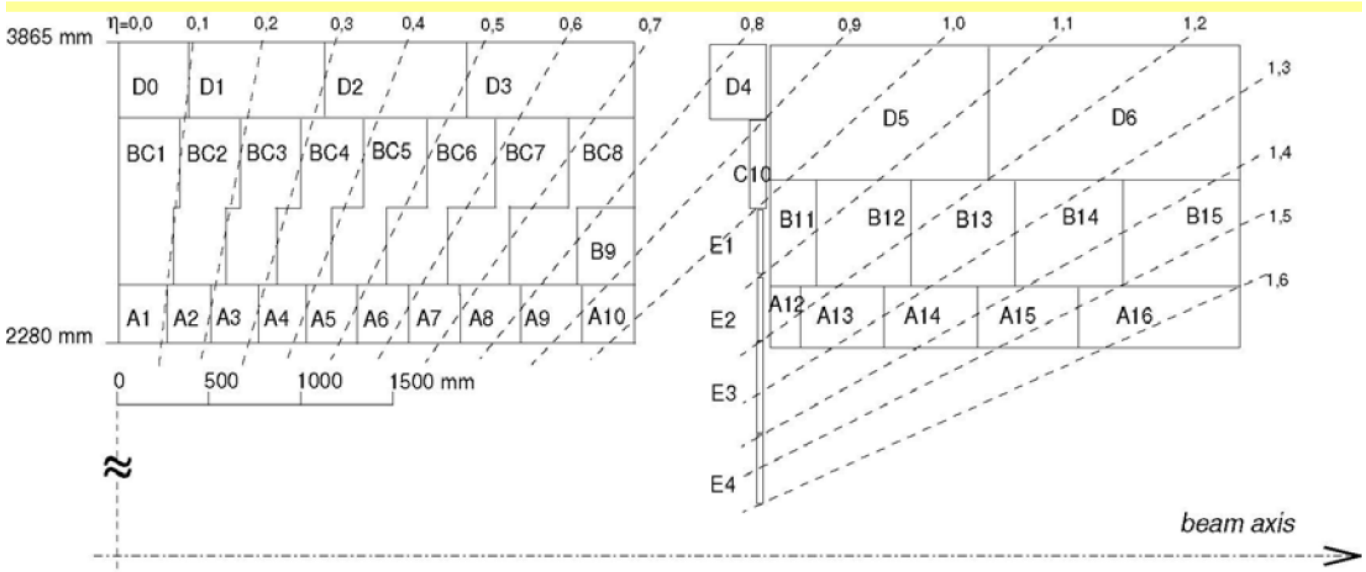
- Hadronic shower is much wider than an EM one
  - due to finite production angles for particle in hadronic shower
- R(95%)~1λ (17 cm for lead)

Segmentation for jet measurements



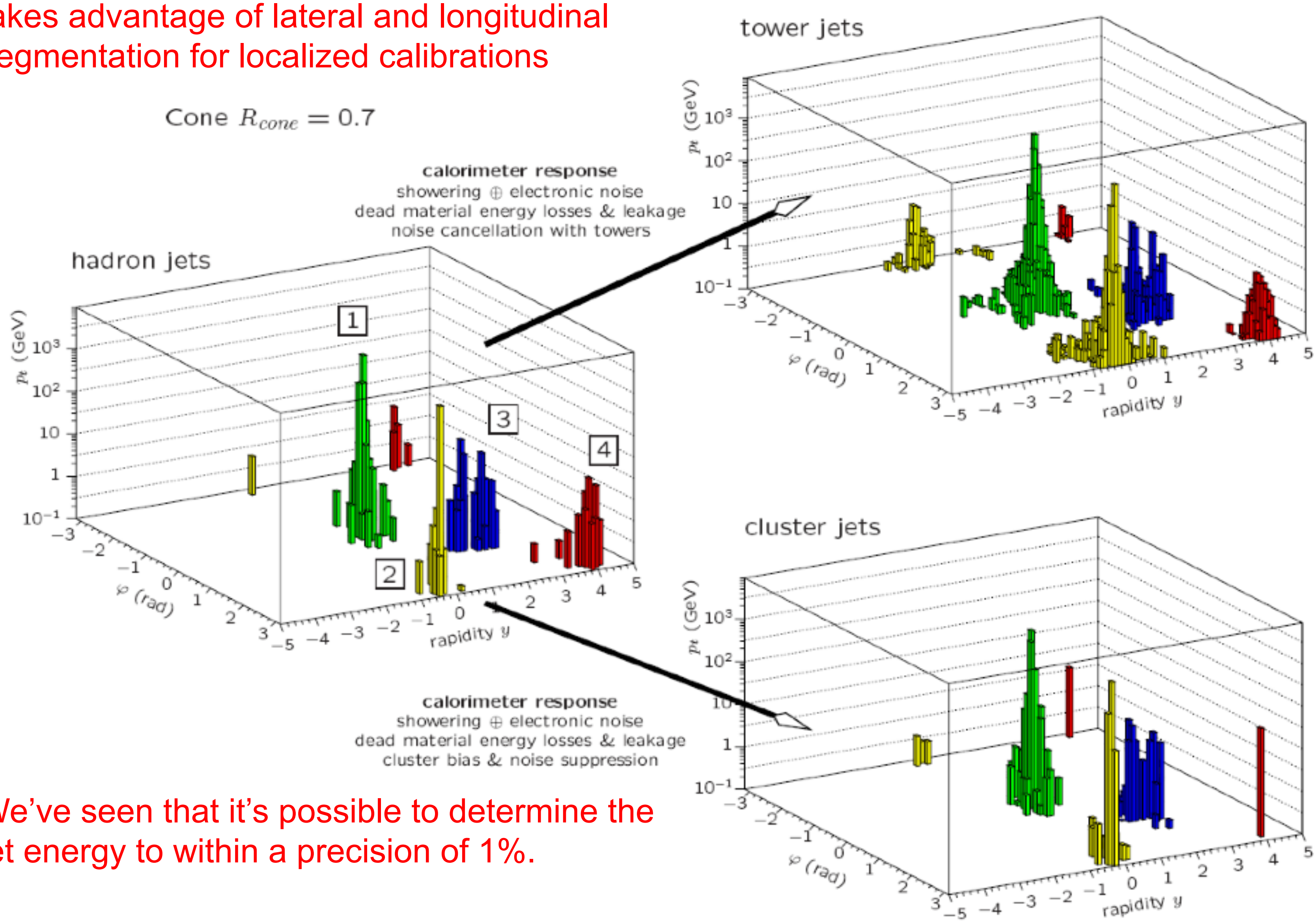
Most of the jet energy is deposited in the EM calorimeter, which we have learned has very good segmentation, both lateral and longitudinal. The rest is deposited in the hadron calorimeter, which does not have as fine a segmentation (but does not need to). The Tilecal has 3 depth segments and an $\eta X \phi$ segmentation of roughly 0.1X0.1. (Remember that the smallest jet size has a radius of 0.4.)

There are 64 wedges with this structure repeated in ϕ.



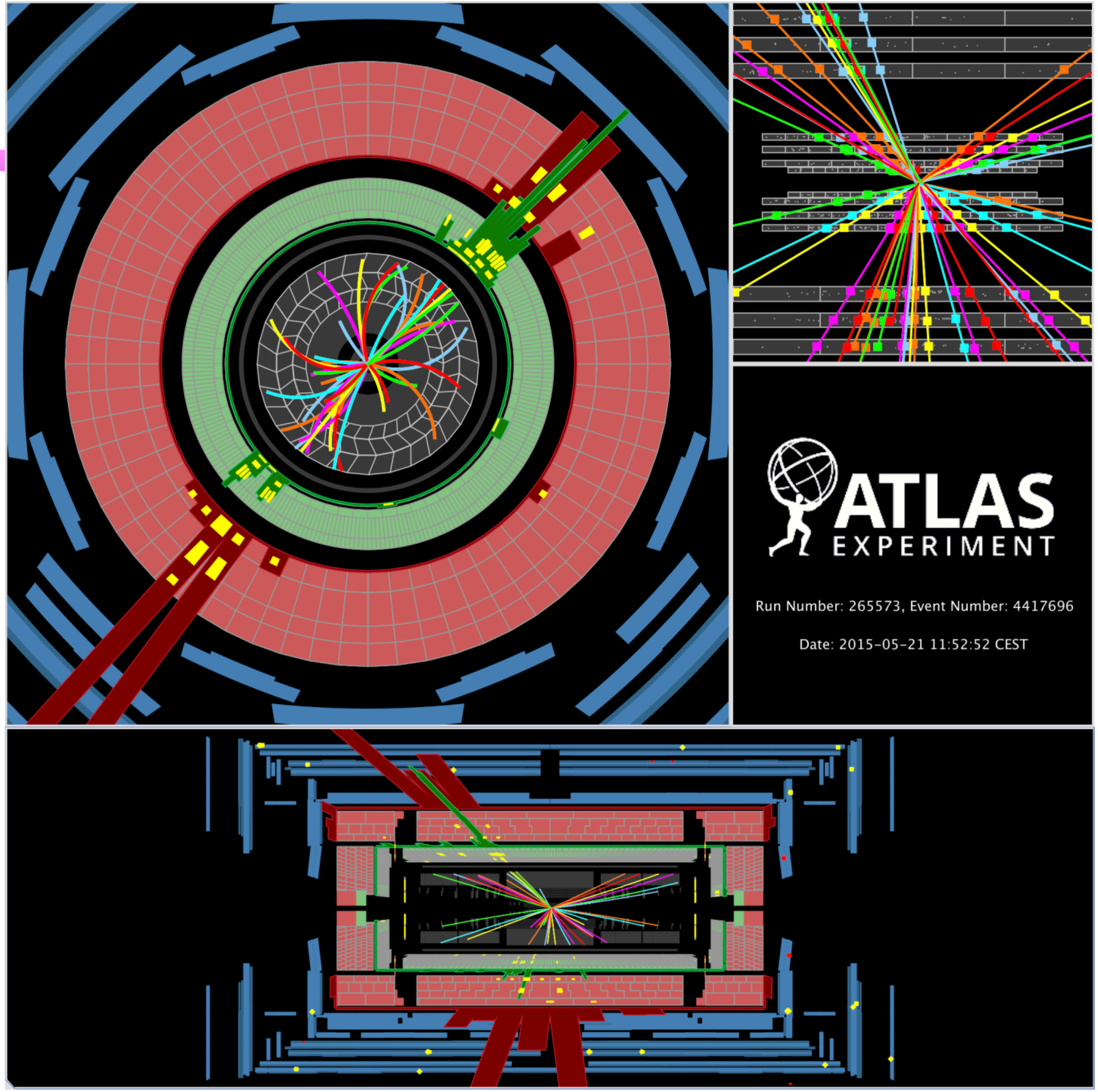
Most jet clustering in ATLAS uses topo-clusters

takes advantage of lateral and longitudinal segmentation for localized calibrations



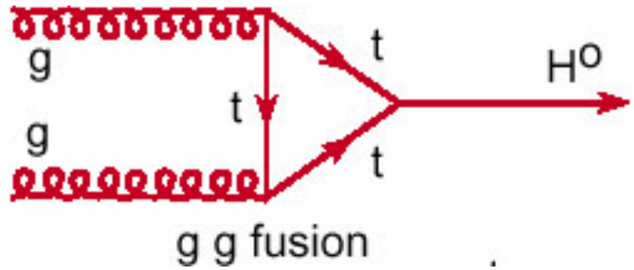
We've seen that it's possible to determine the jet energy to within a precision of 1%.

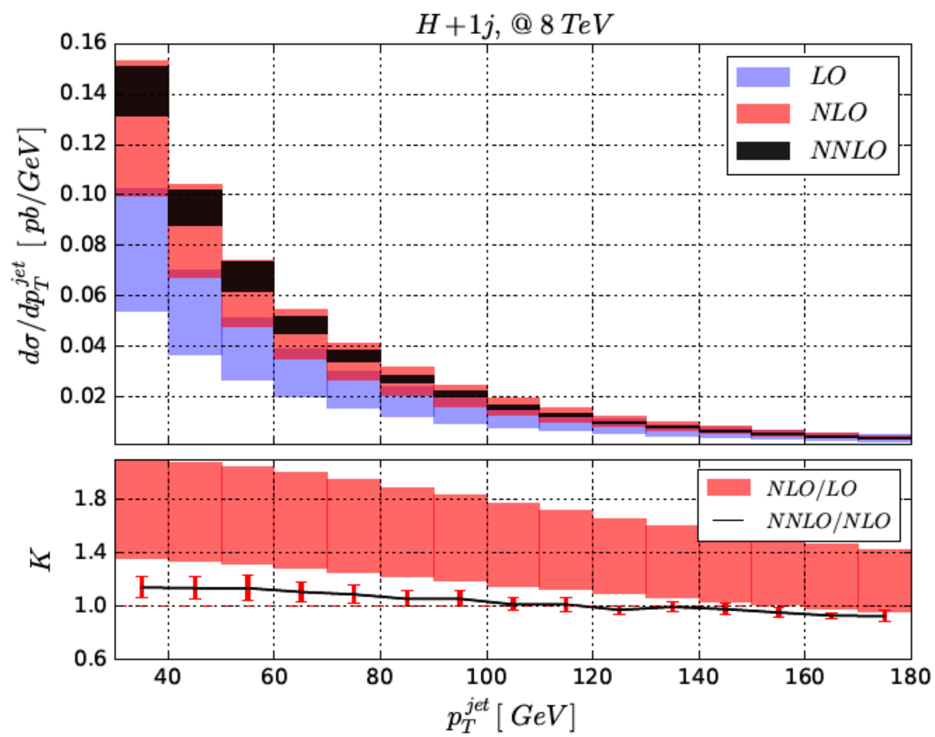
Dijet event at
13 TeV

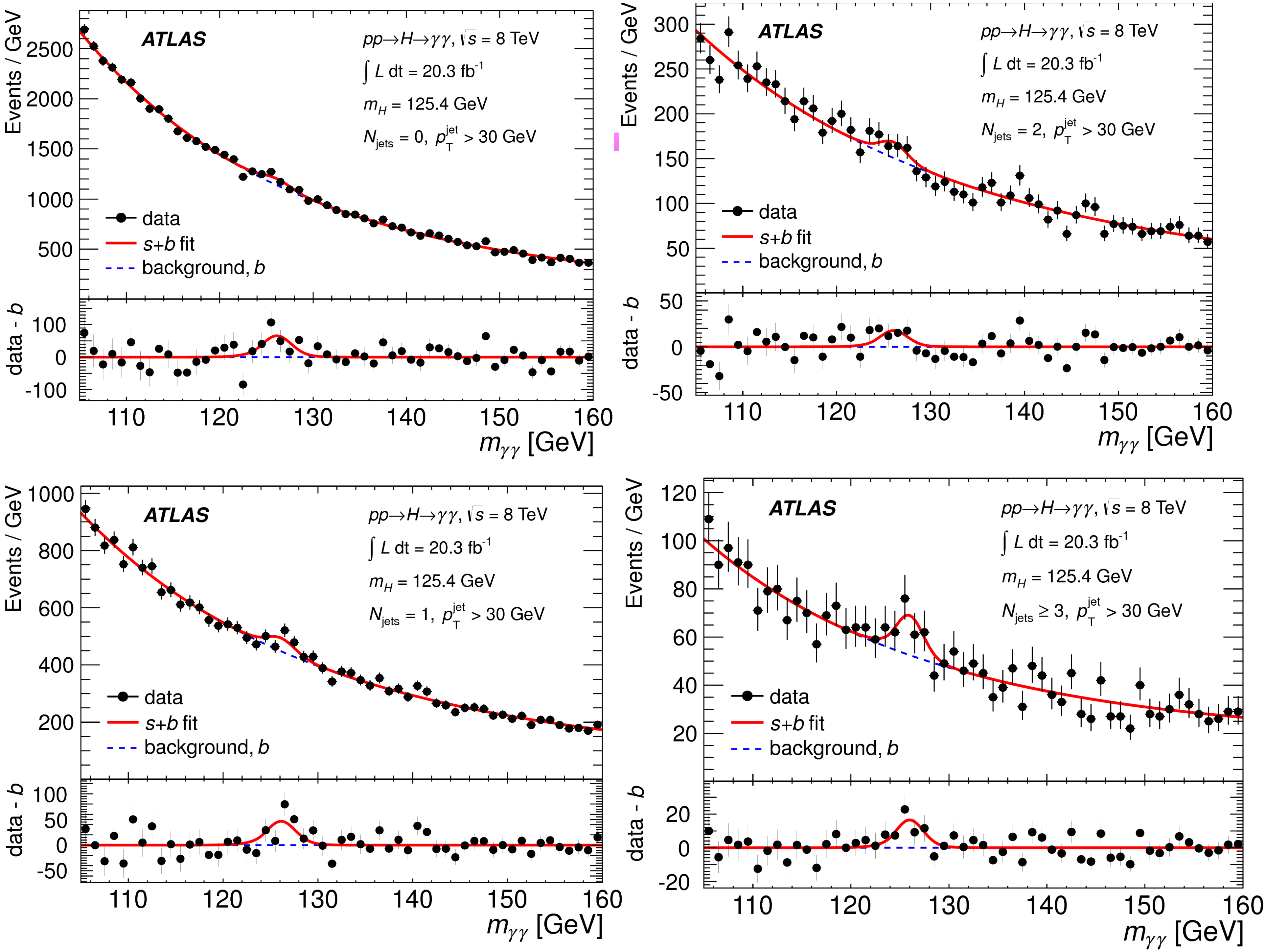


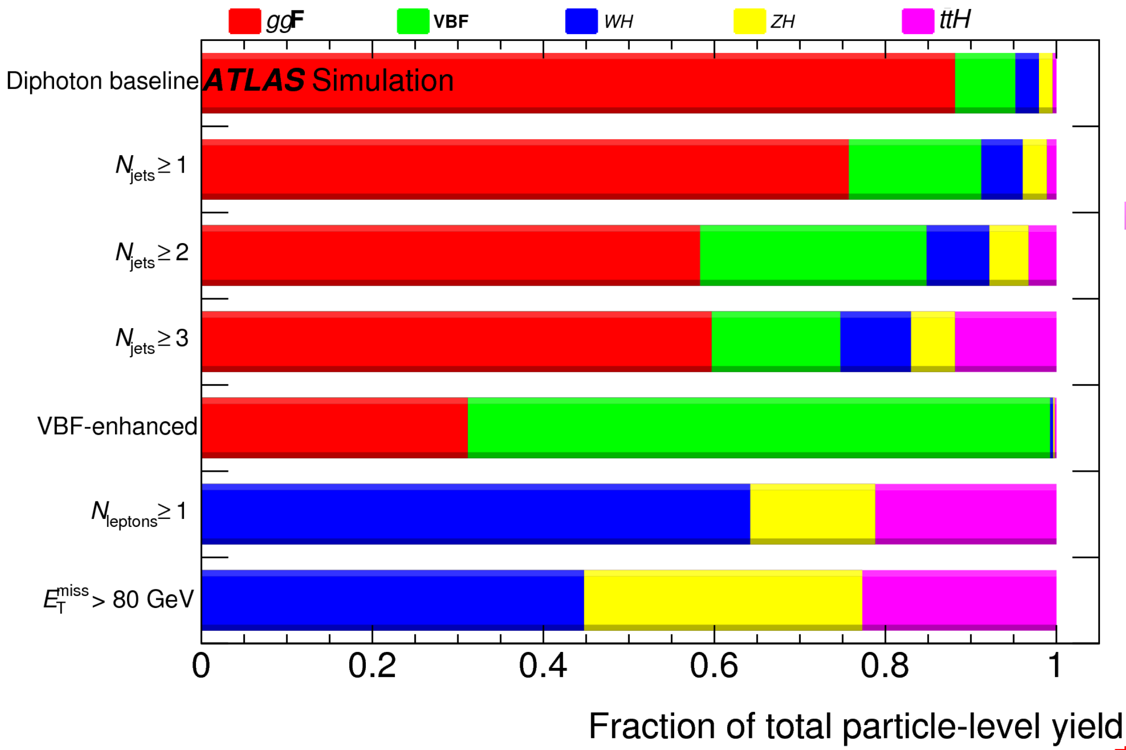
Higgs+jets

- Higgs+jets production is one of the most interesting channels at the LHC, especially with regards to VBF measurements and to probes with accompanying high p_T jets
- So far ATLAS Higgs+jets analyses have been performed with the antikT4 jet algorithm
- In Run 1, we have on the order of several hundred Higgs+jets events over p_T>30 GeV
- At 13 TeV, with 300 fb^{-1}, there will be a rich variety of differential jet measurements with on the order of 3000 events with jet p_T above the top quark mass scale, thus probing inside the top quark loop
- H+j cross section now known to NNLO
  - using *conventional* techniques: arXiv:1504.07922
  - using n-jettiness: arXiv: 1505.03893

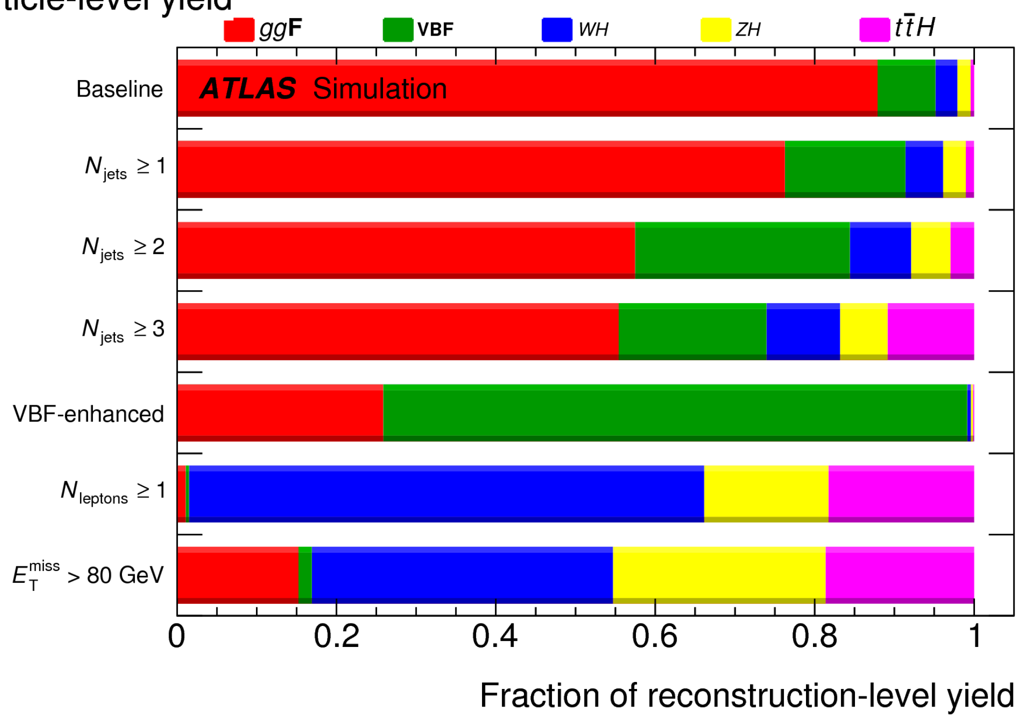





ATLAS
pp→H→γγ, √s = 8 TeV
∫ L dt = 20.3 fb-1
mH = 125.4 GeV
Njets = 0, pTjet > 30 GeV
Njets = 1, pTjet > 30 GeV
Njets = 2, pTjet > 30 GeV
Njets ≥ 3, pTjet > 30 GeV
data
s+b fit
background, b
Events / GeV
data - b
mγγ [GeV]



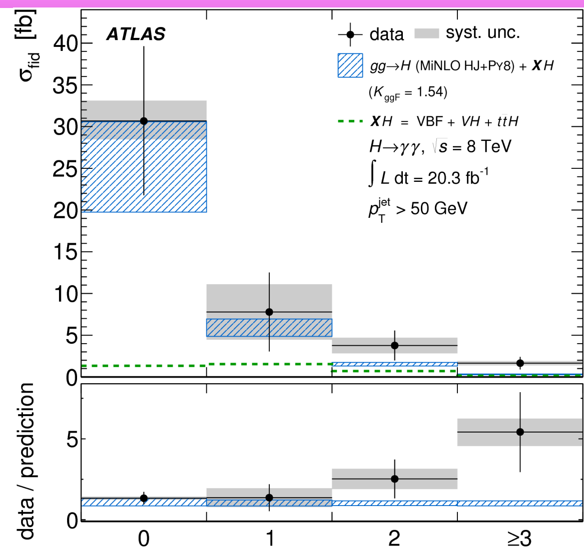
ggF
VBF
WH
ZH
ttH
ATLAS Simulation
Diphoton baseline
$N_{jets} \geq 1$
$N_{jets} \geq 2$
$N_{jets} \geq 3$
VBF-enhanced
$N_{leptons} \geq 1$
$E_T^{miss} > 80$ GeV
0
0.2
0.4
0.6
0.8
1
Fraction of total particle-level yield



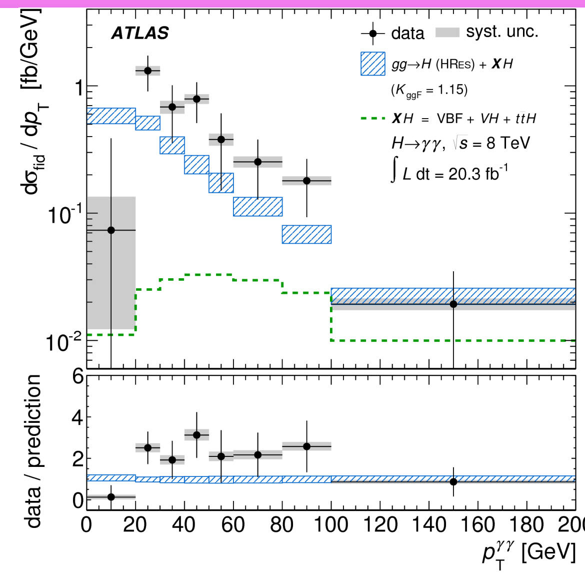
ggF
VBF
WH
ZH
$t\bar{t}H$
ATLAS Simulation
Baseline
$N_{jets} \geq 1$
$N_{jets} \geq 2$
$N_{jets} \geq 3$
VBF-enhanced
$N_{leptons} \geq 1$
$E_T^{miss} > 80$ GeV
0
0.2
0.4
0.6
0.8
1
Fraction of reconstruction-level yield

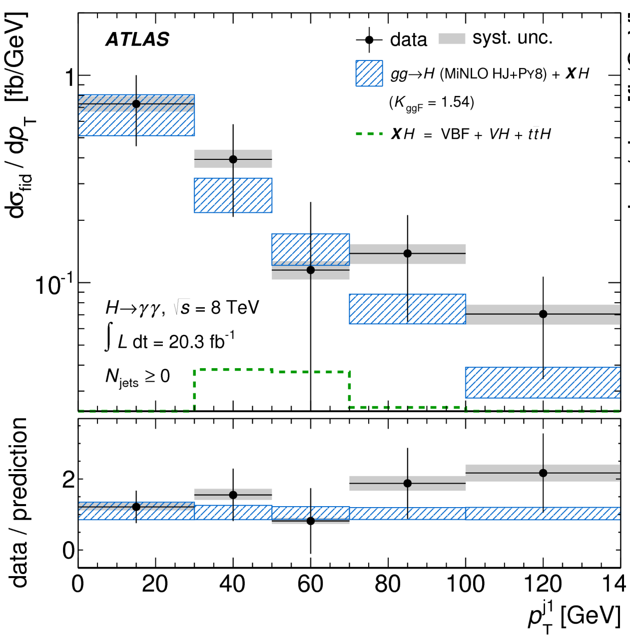
Higgs(->γγ)+jets

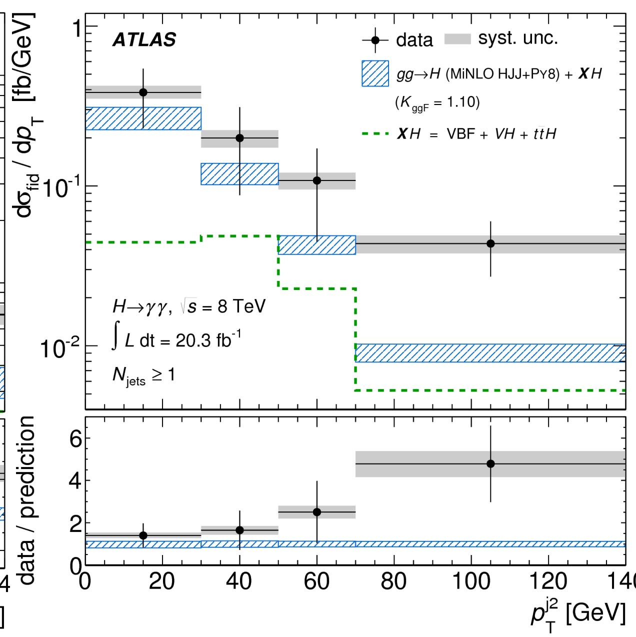
The data appears to be a bit jettier than predictions, albeit with limited statistics. Eagerly awaiting for CMS results.

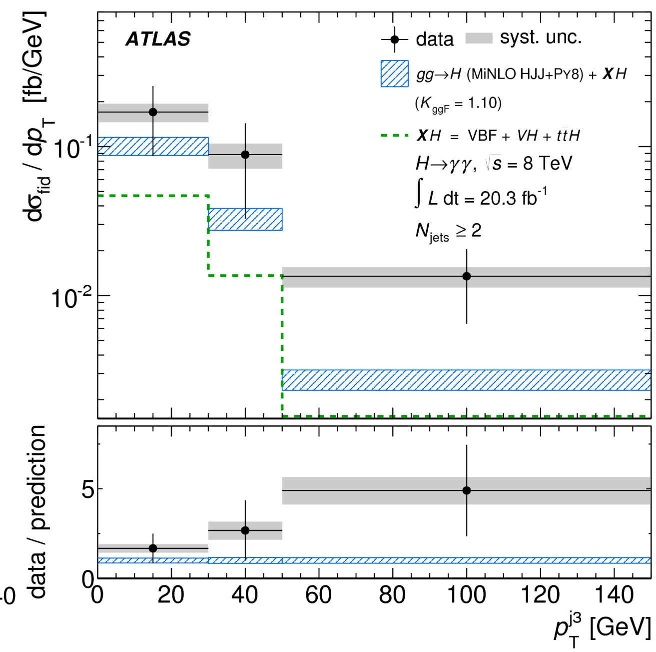


What's wrong with the plot above?

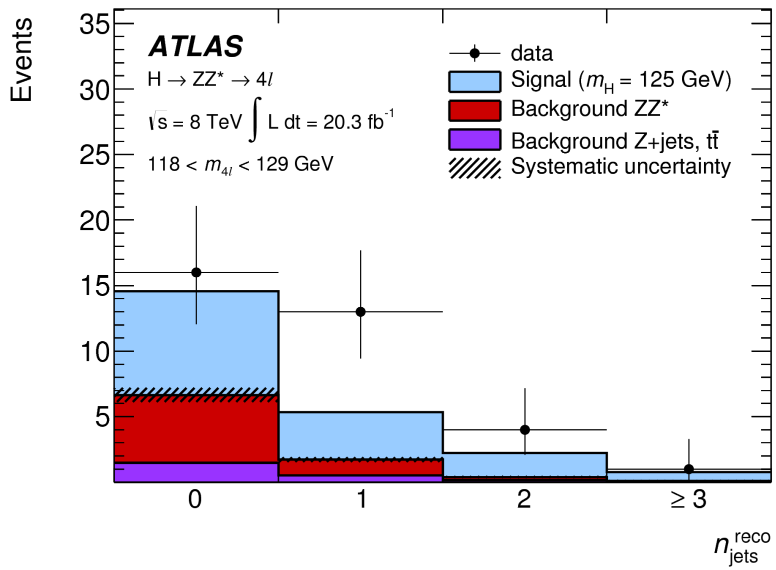


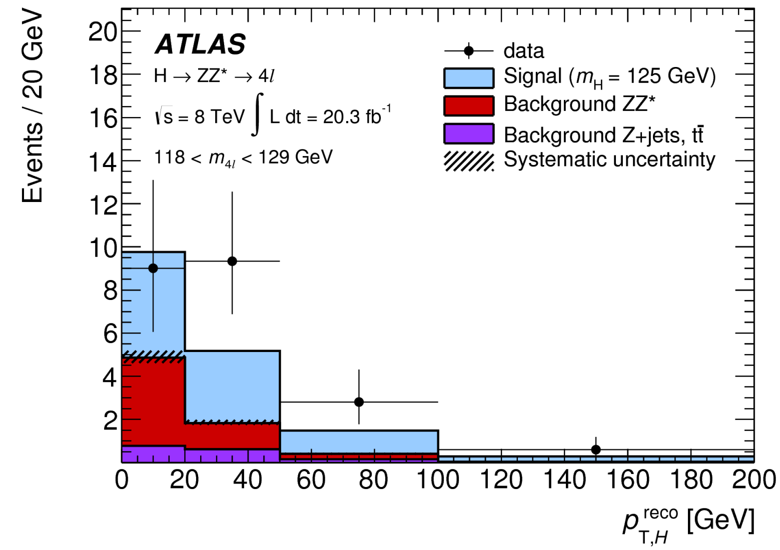


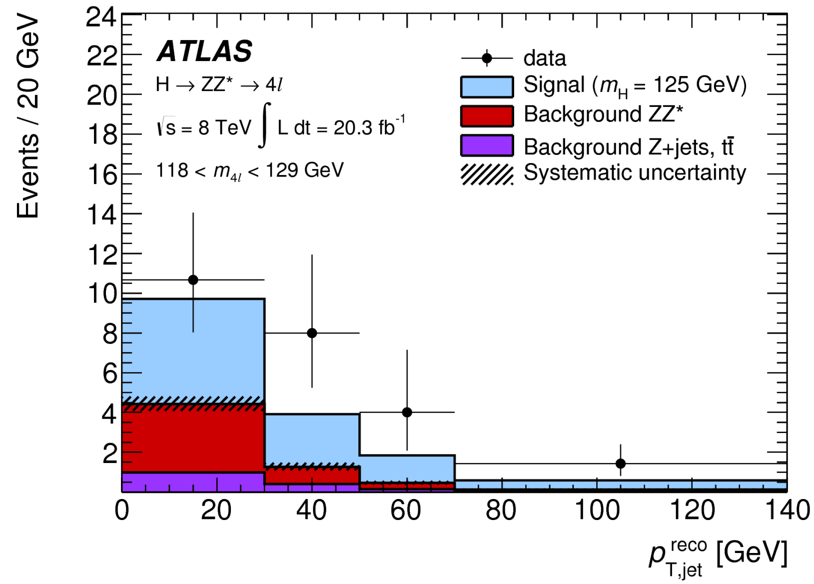




Higgs(->4 leptons)+jets

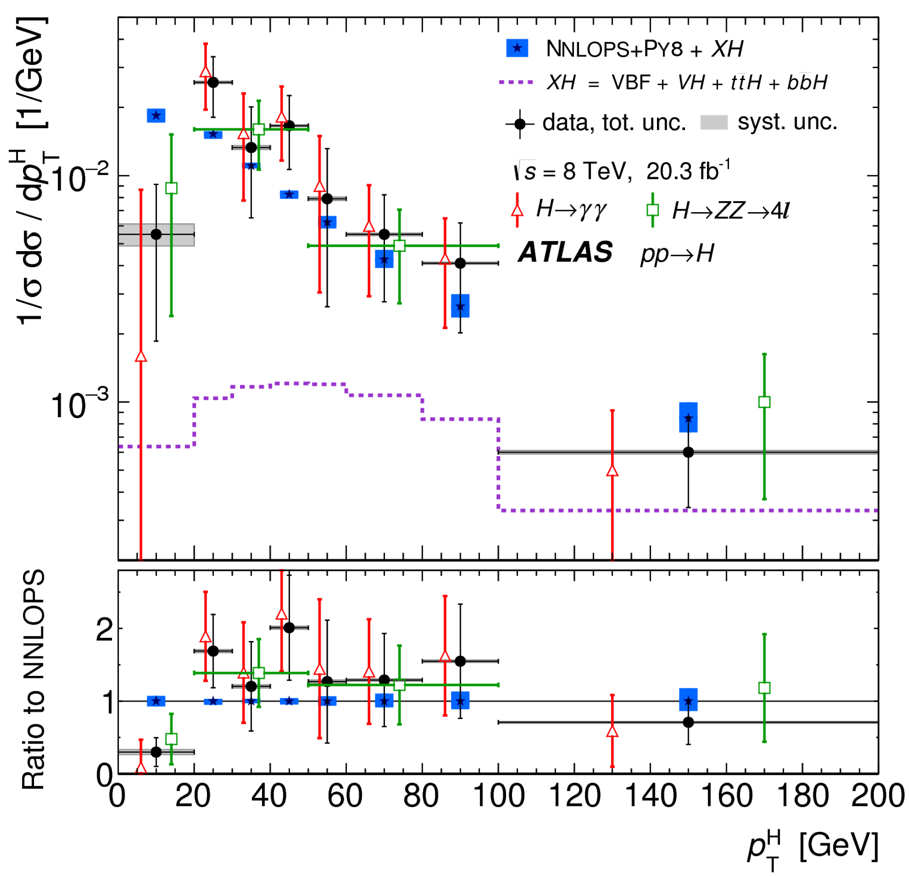


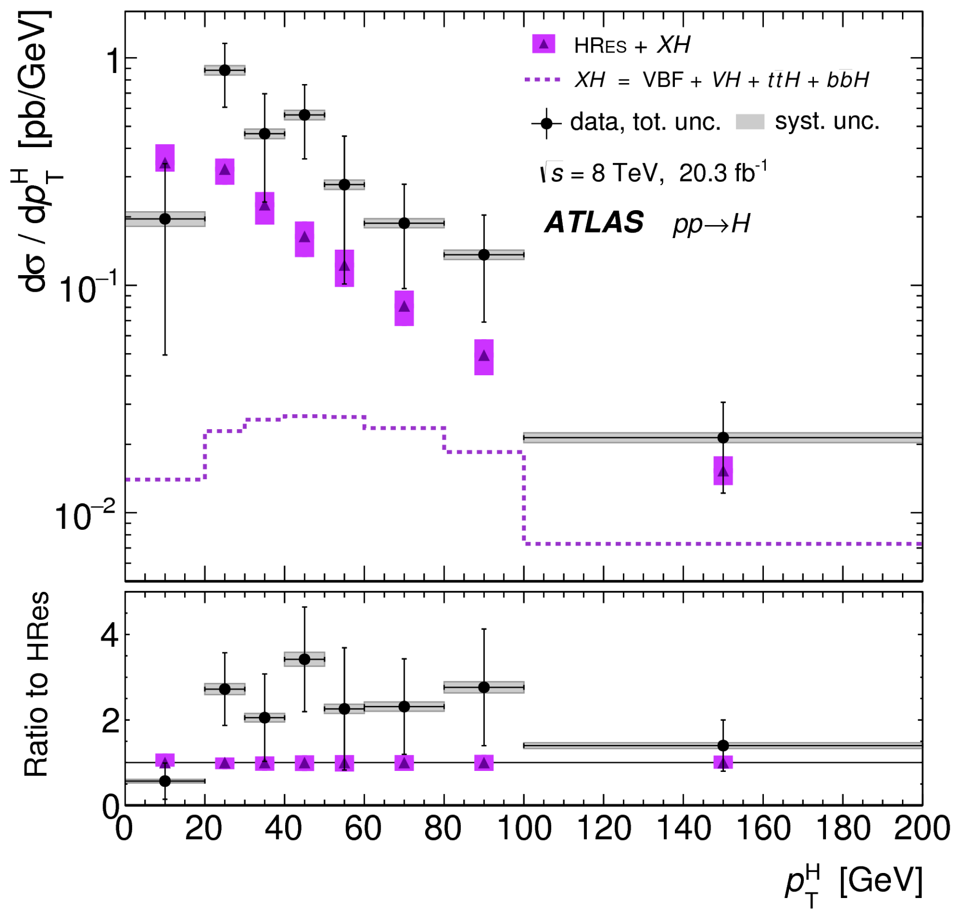




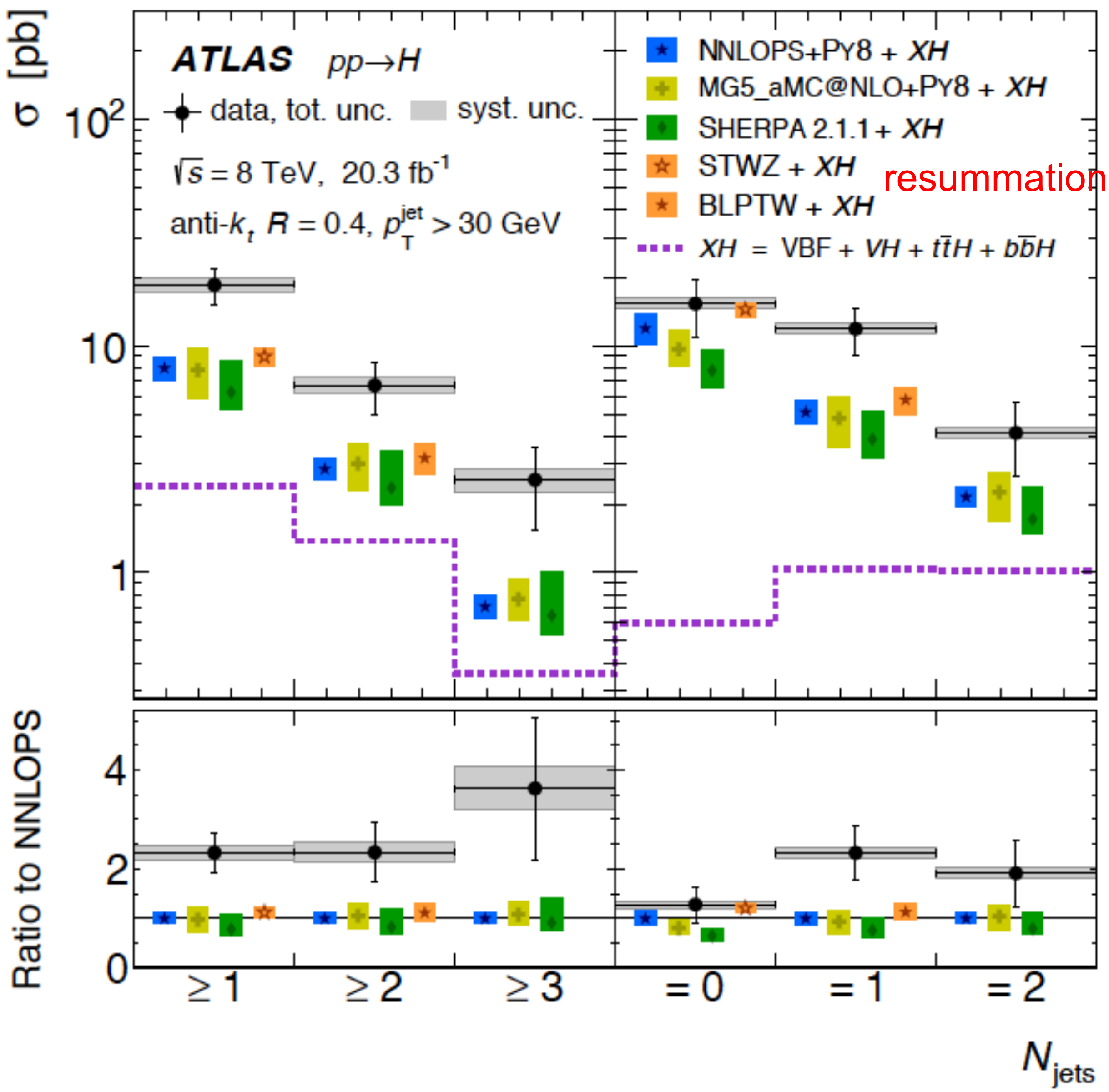
Hey, I know, let's add them together

- Diphoton events are statistically dominant, but ZZ* shows consistent behavior
- …and ZZ* mode has best signal to background ratio





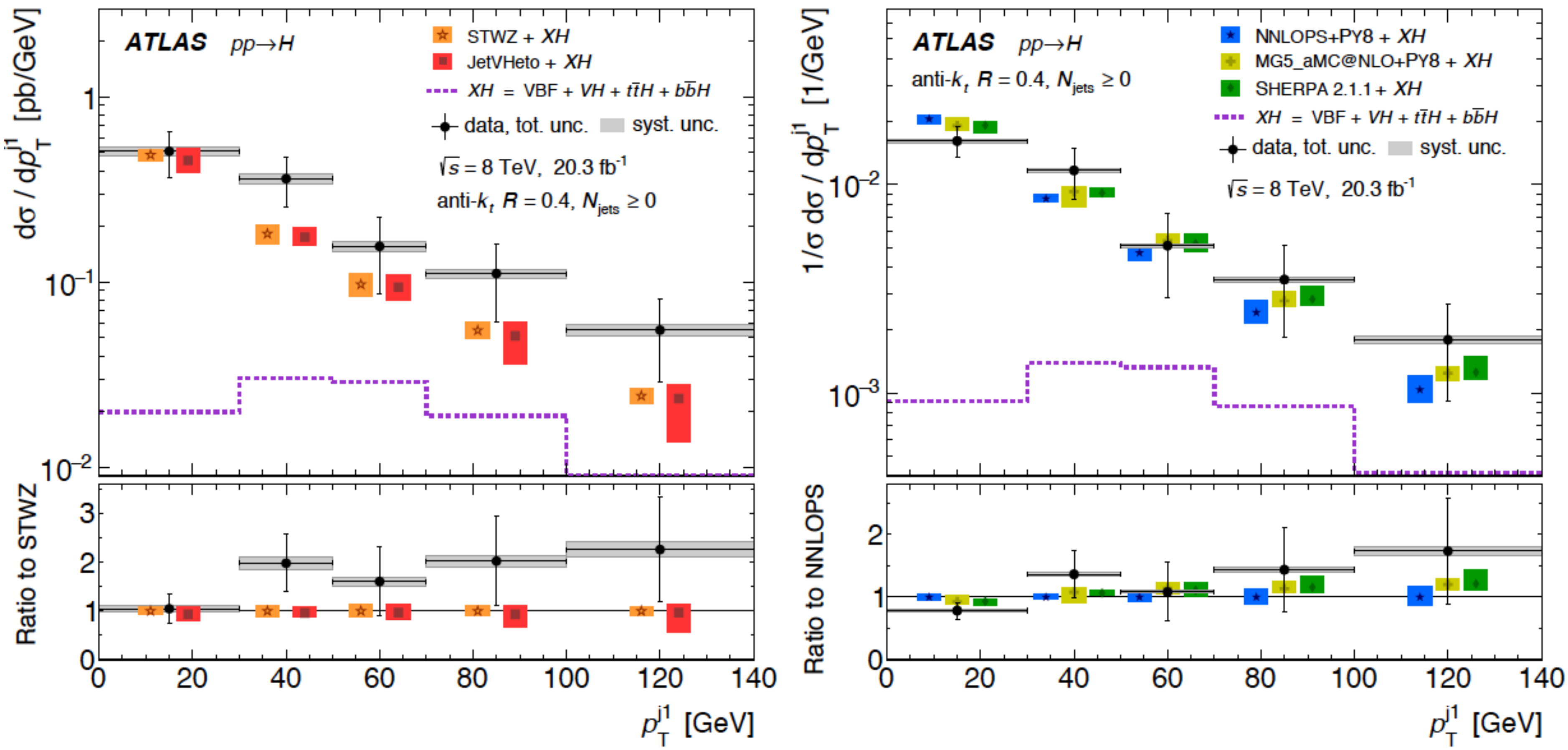
Add diphoton and 4 lepton decay modes

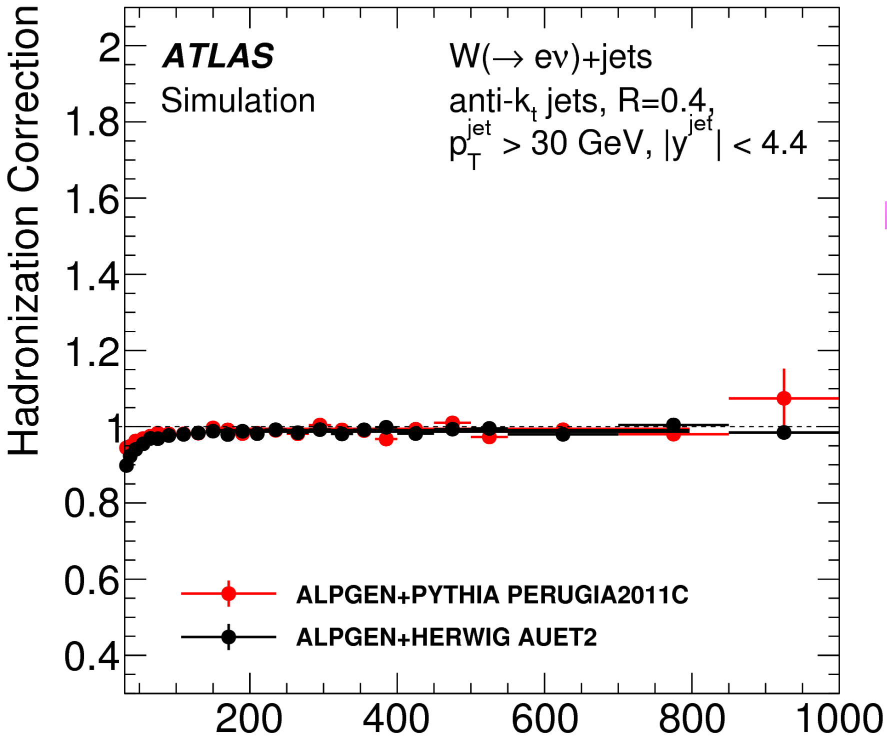


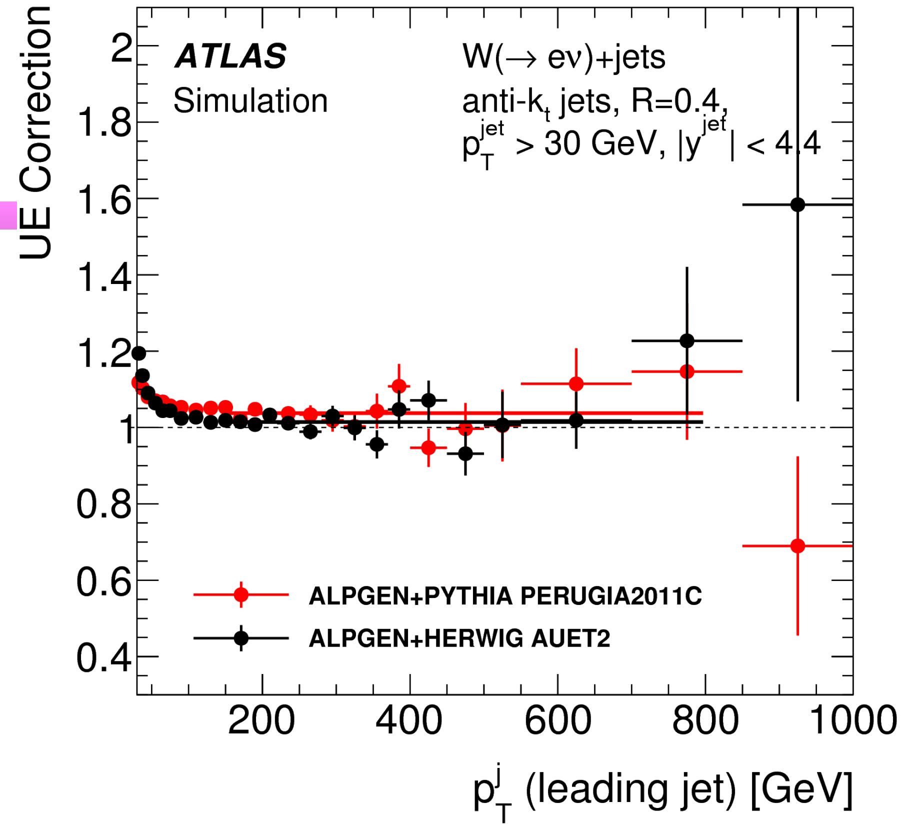
What's right with this plot?

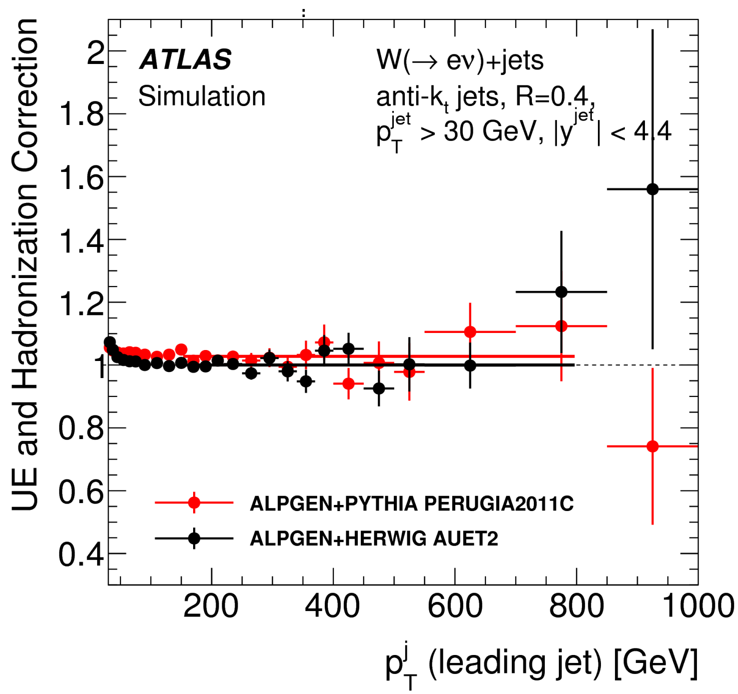
Add diphoton and 4 lepton decay modes

- Comparisons to a wide number of resummation/ME+PS predictions…**but not to fixed order!** (with appropriate non-perturbative corrections)
- The lead jet p_T distribution for H+>=1 jet is a perfectly good inclusive cross section, which can be compared to fixed order predictions (now at NNLO)
- NLO results are available for Higgs+>=1,2 and 3 jets (gosam)









*The net correction is small and dies away quickly with increasing p_T, as expected for power corrections.

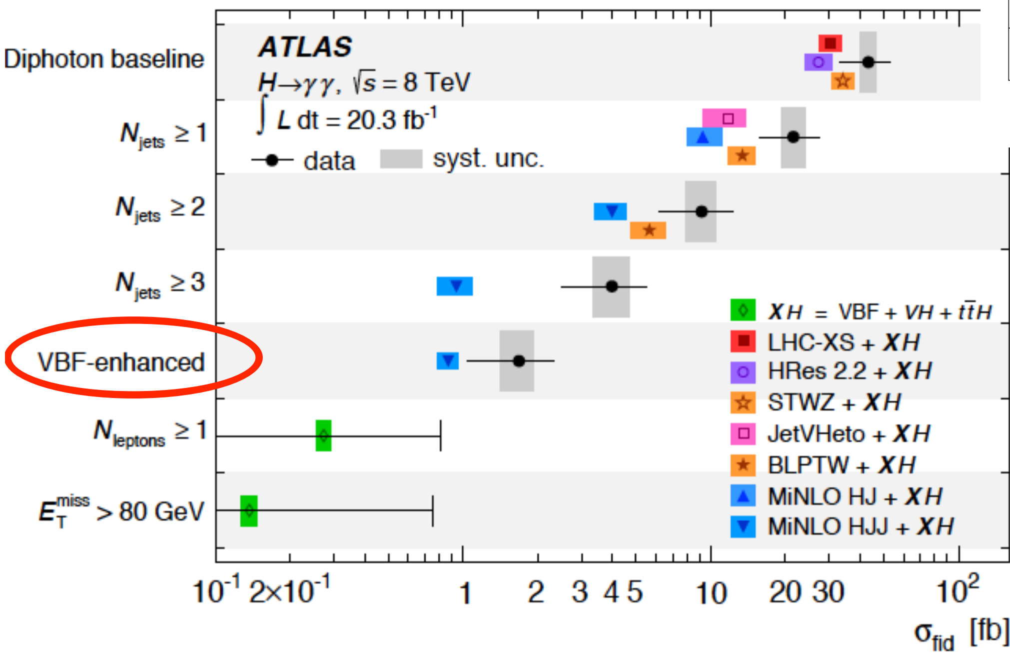
*Non-perturbative corrections for higher multiplicity final states are separately larger(UE and hadronization) but still cancel.

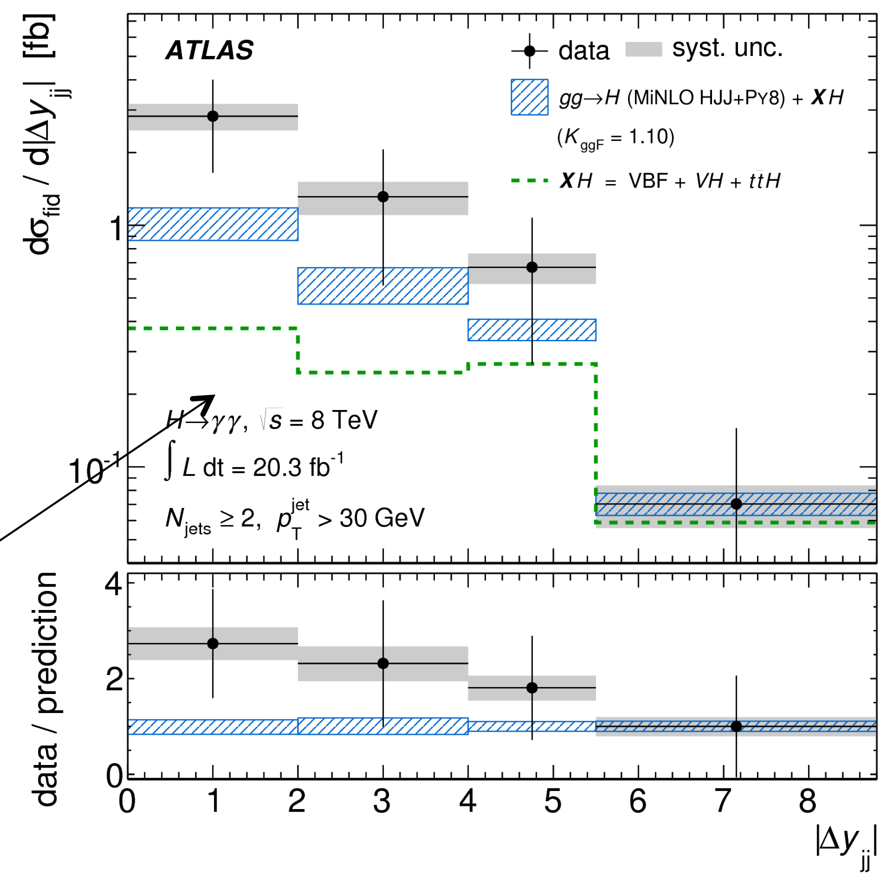
Higgs +>= 2 jets

- Higgs +>= 2 jets crucial to understand Higgs coupling, in particular through VBF

H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	$d\sigma$ @ LO QCD (full m_t dependence) $d\sigma$ @ NLO QCD (infinite m_t limit)	$d\sigma$ @ NLO QCD (full m_t dependence) $d\sigma$ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

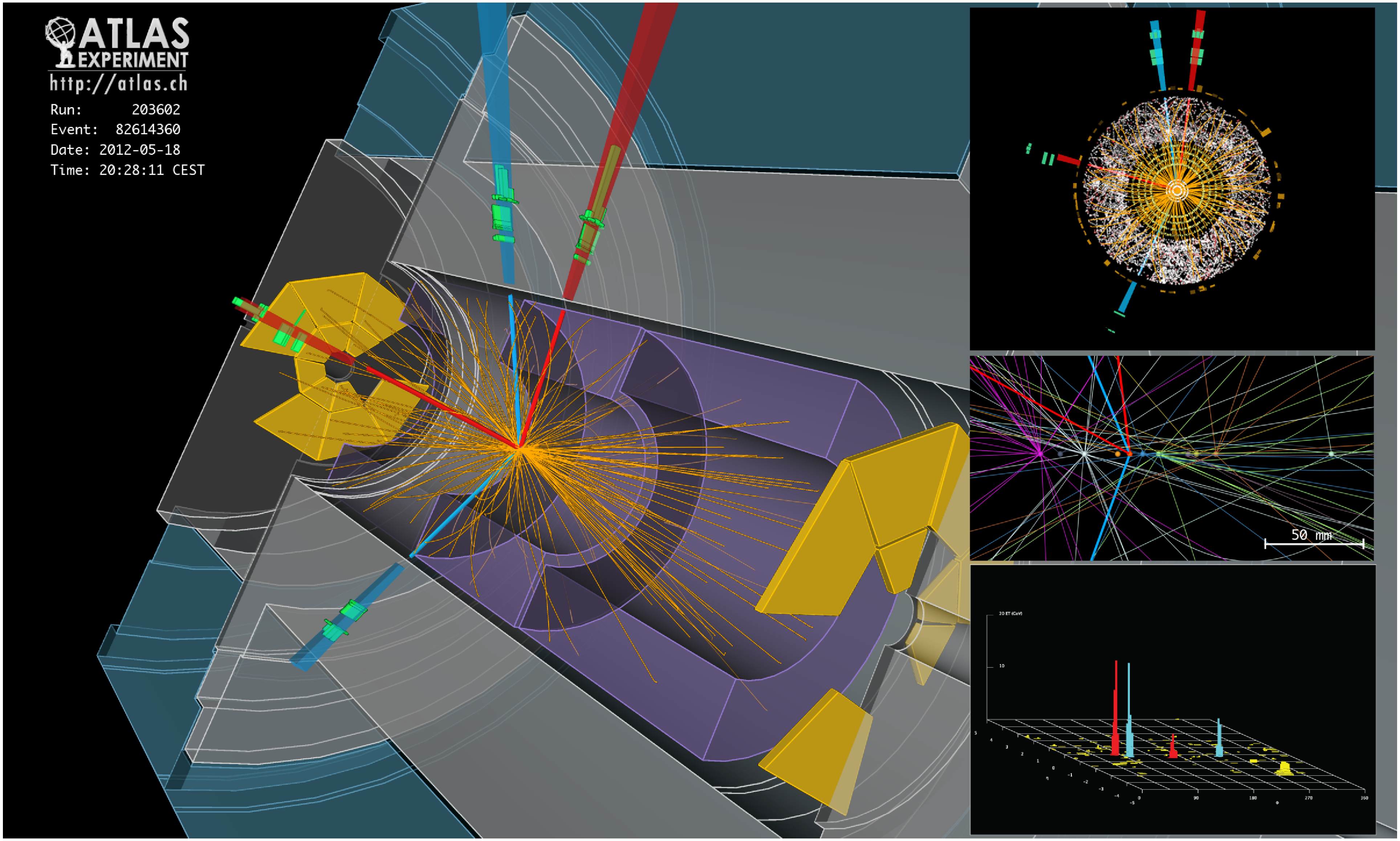
Table 1: Wishlist part 1 – Higgs (V = W, Z)





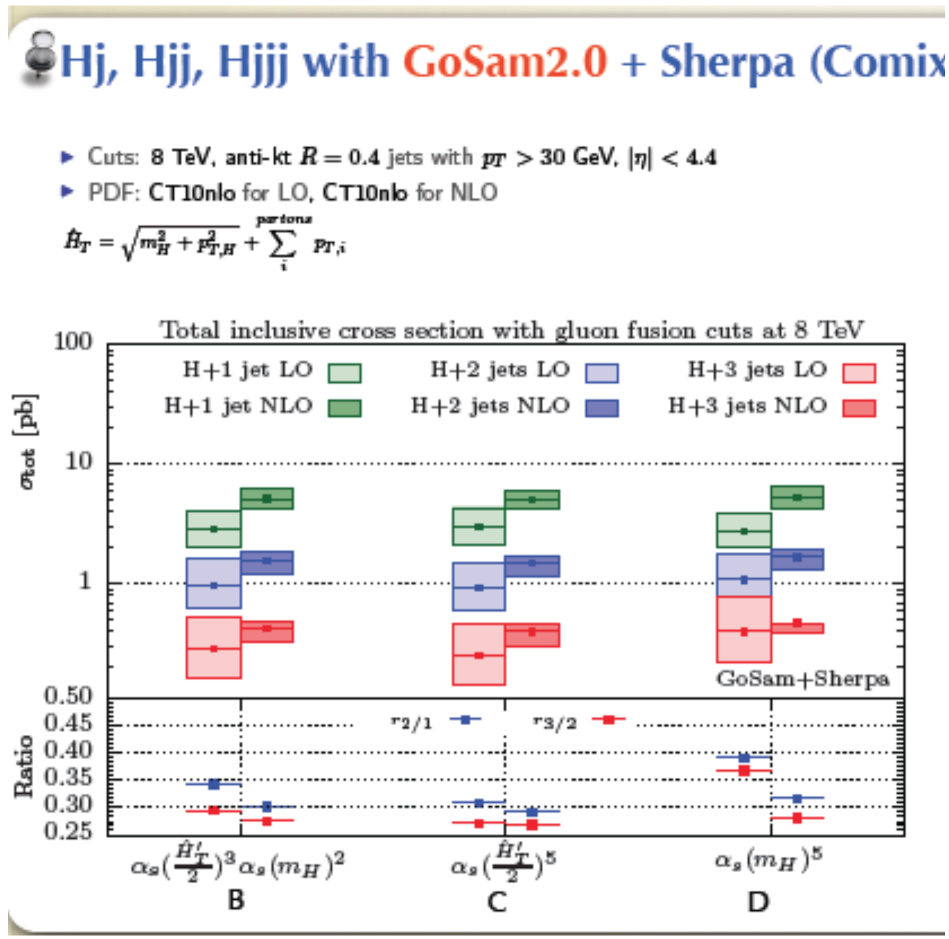
ggF dominates over all other processes for low Δy, but not for high Δy

Higgs(->γγ) + 2 jet (candidate) event



Interlude: fixed order and gosam

- The gosam collaboration has recently completed a calculation of Higgs+>=3 jets at NLO in which they obtain a sizeable increase of NLO over LO using the nominal scales
  - one of the most difficult NLO calculations
- No public program yet for Higgs+3 jets, but that will be forthcoming
- However, the events that make up the prediction can be stored in ROOT ntuples that allow predictions to be made for varying scale choices, PDFs and jet sizes
  - not only for Higgs+>=3 jet events, but for >=1 and >=2 as well
- Luckily, all such calculations now use a standard format (from Blackhat +Sherpa) for storing information in ntuples (see additional slides)



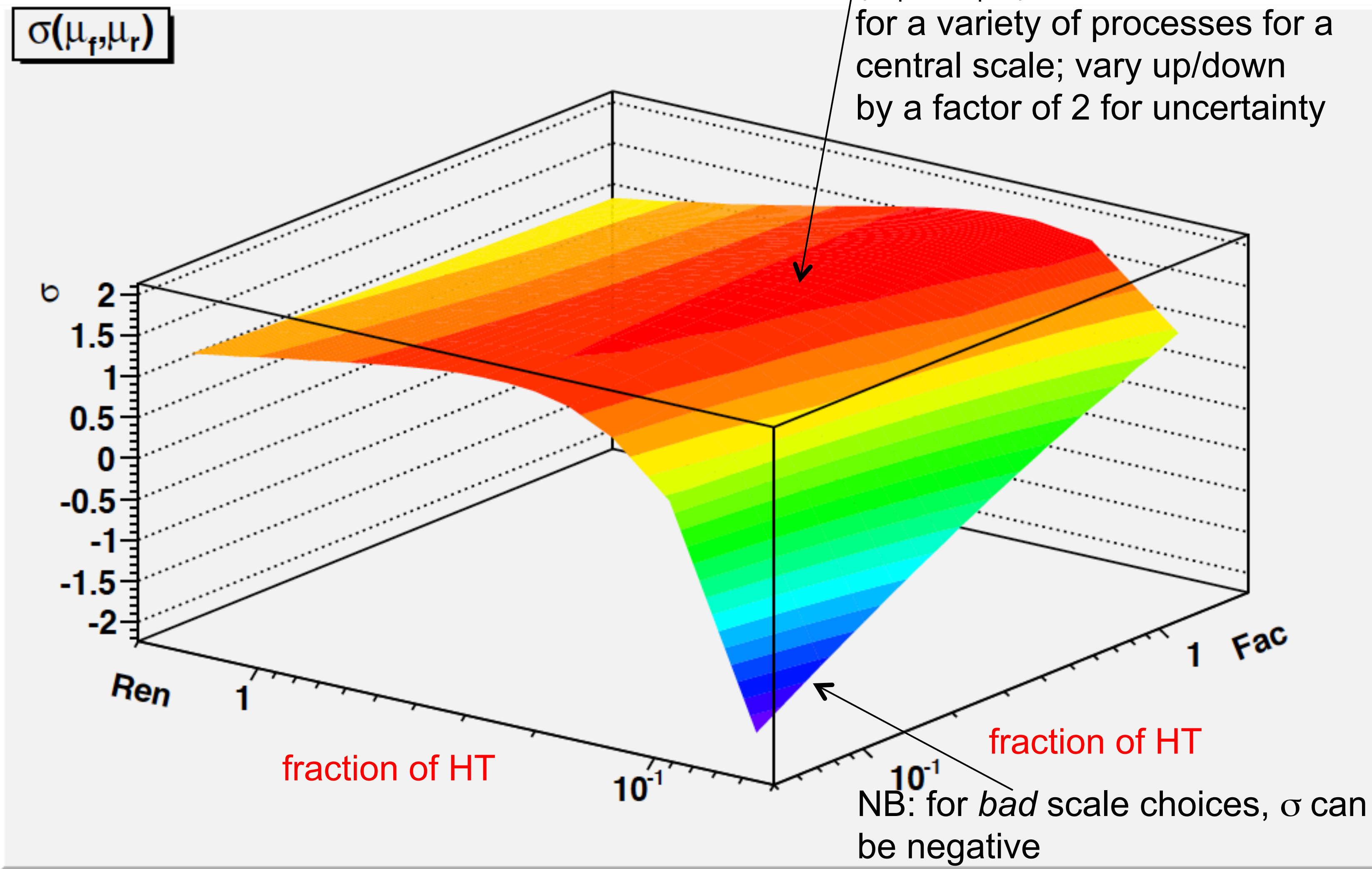
P. Mastrolia Moriond 2015

Higgs+>=3 jets at NLO

- Cross section at NLO for Higgs+>=3 jets at NLO, as a function of the renormalization and factorization scales (from ntuples)

p_T^{jet} >30 GeV

$|y_{jet}|$<4.4

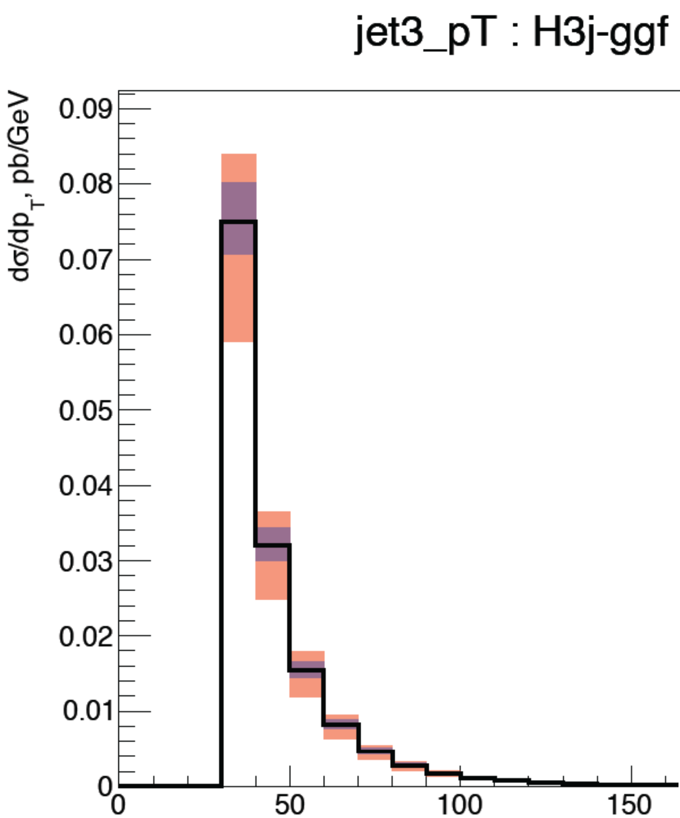


fraction of HT

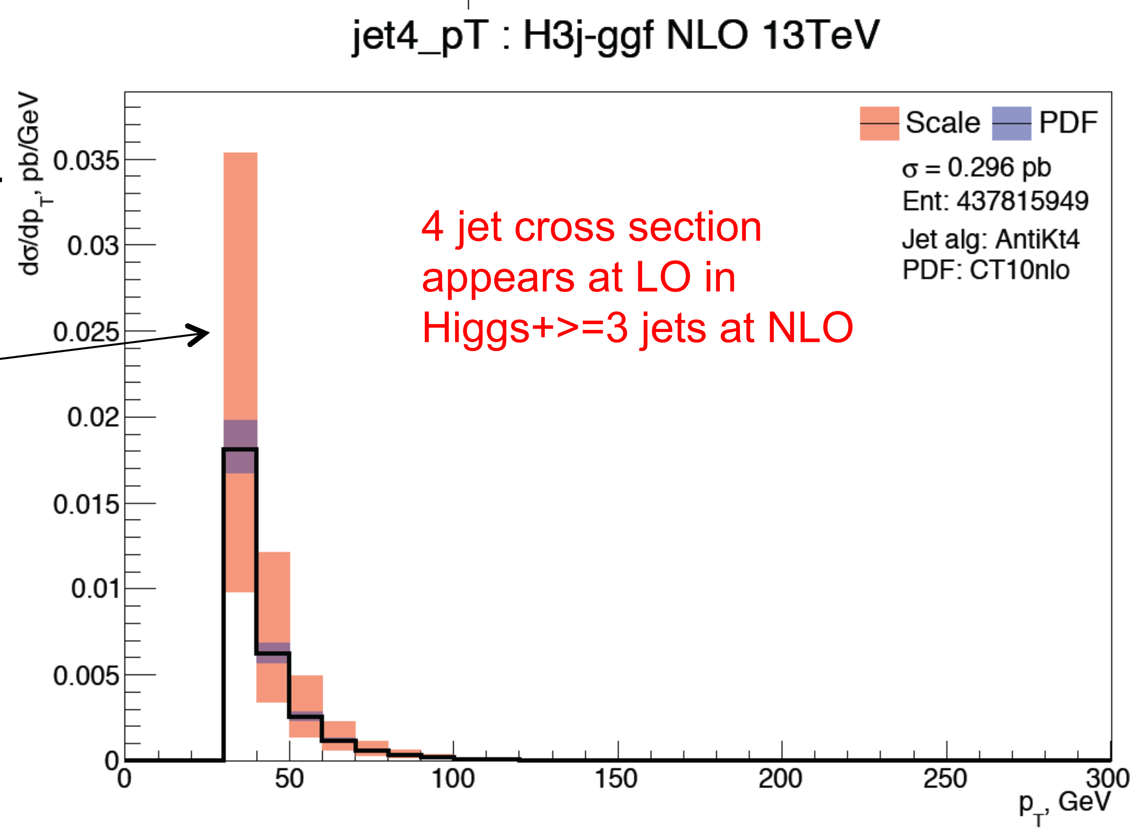
fraction of HT

$(H_T/2, H_T/2)$ seems to work for a variety of processes for a central scale; vary up/down by a factor of 2 for uncertainty

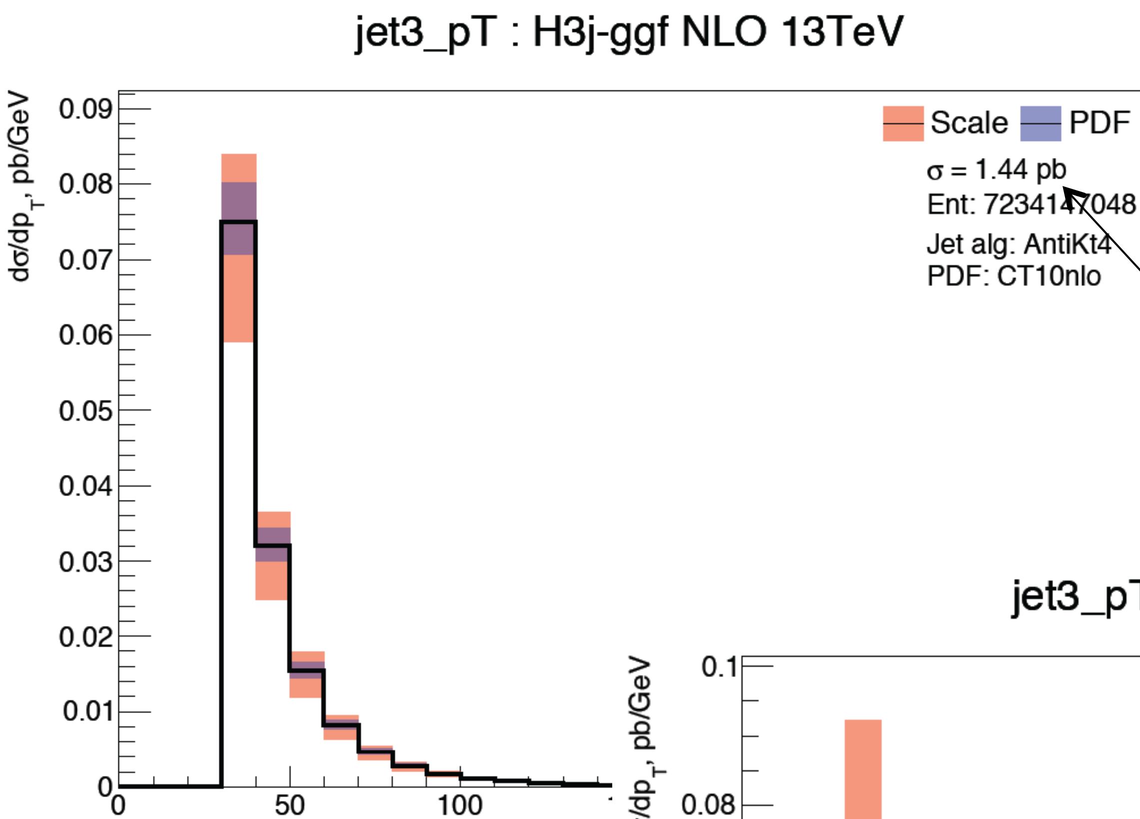
NB: for *bad* scale choices, σ can be negative



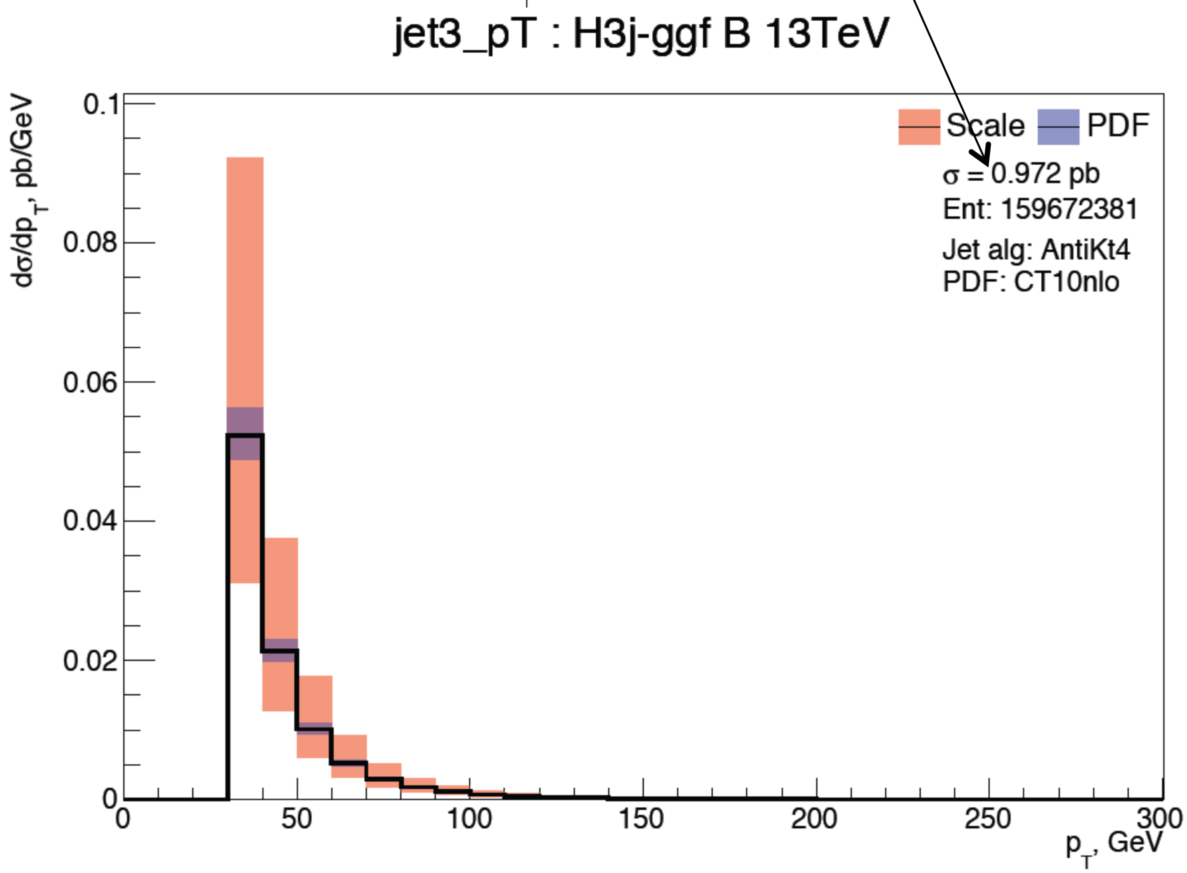
Note LO uncertainty

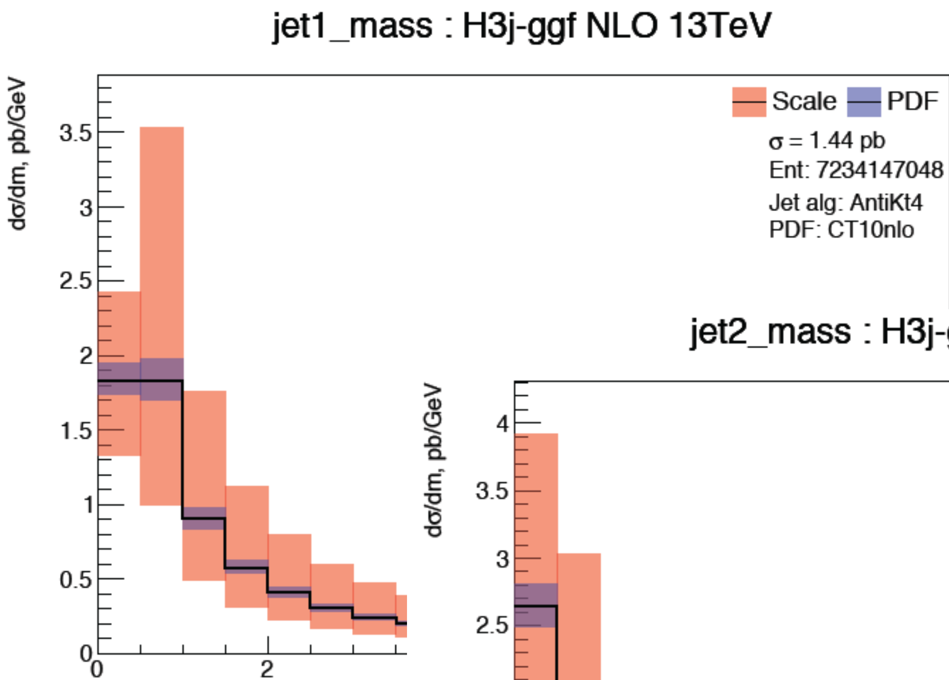


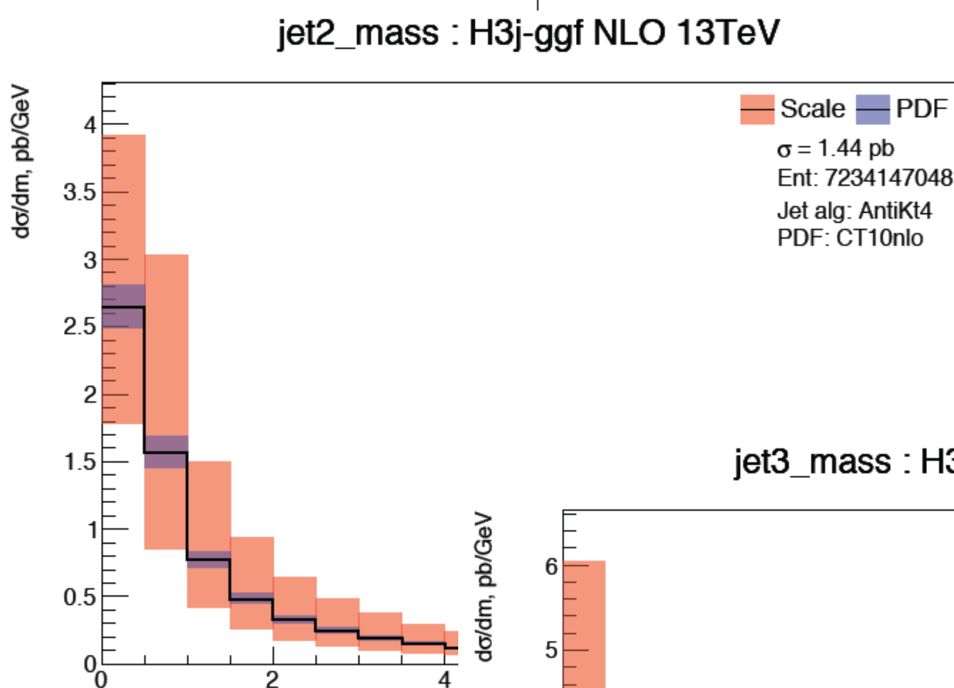
4 jet cross section appears at LO in Higgs+>=3 jets at NLO

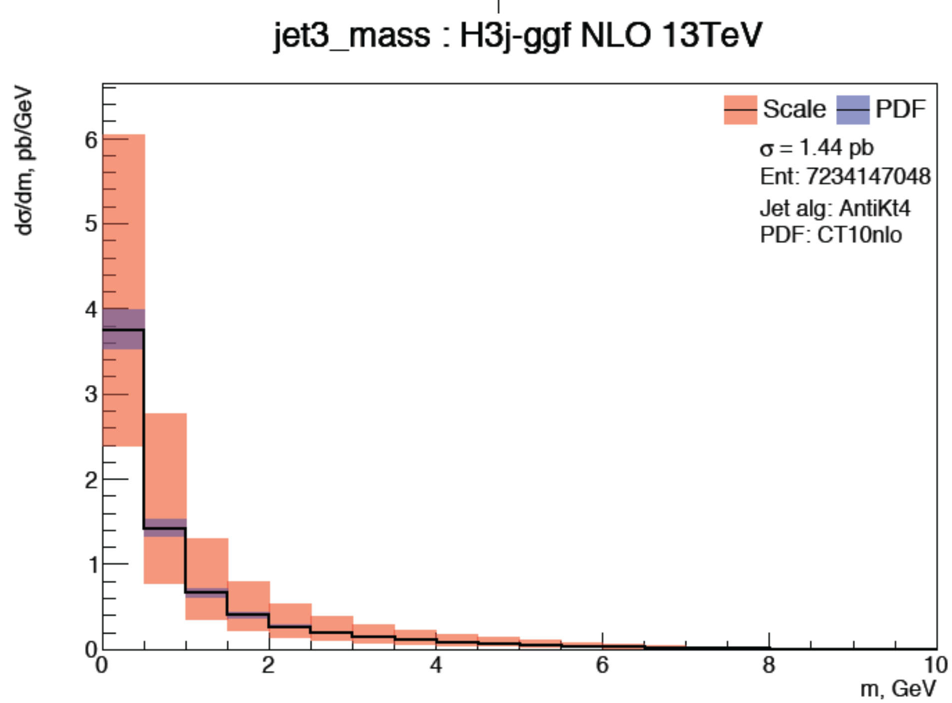


Note K-factor of almost 1.5
(for scale of HT/2)





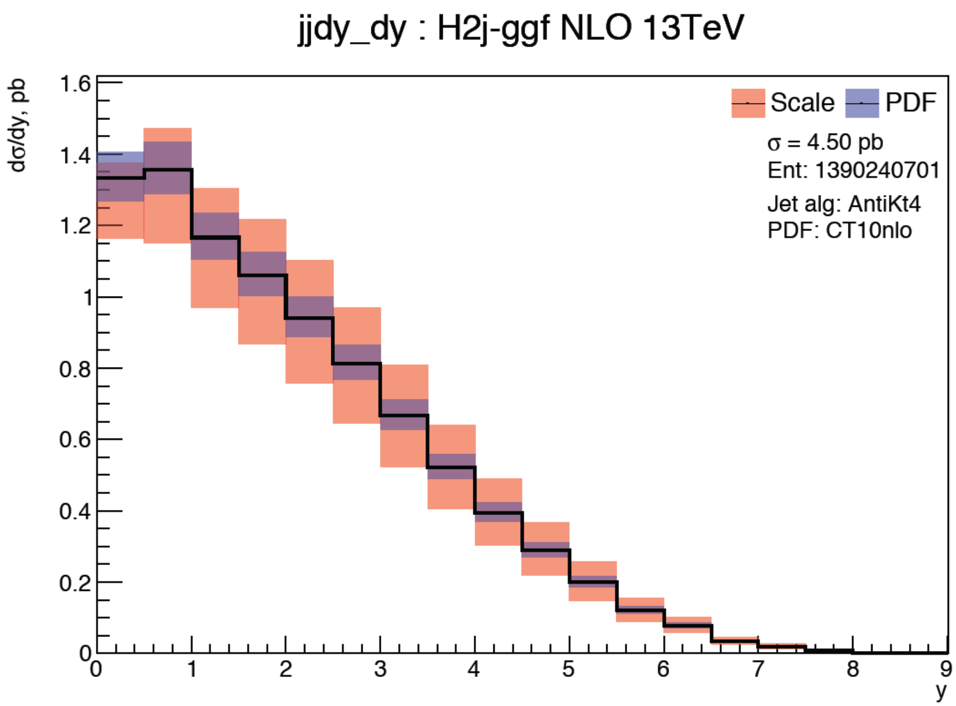




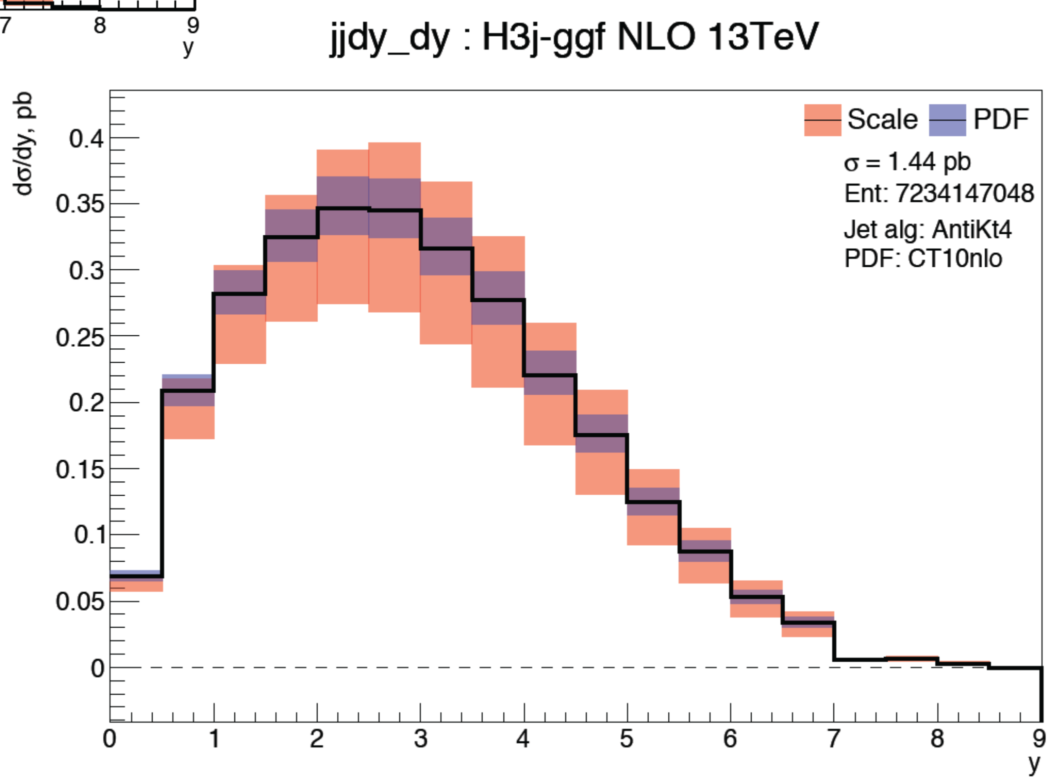
Note that there is at most 1 extra parton for each event, which can thus give a mass to at most 1 jet. However, the ensemble of events gives a mass to all 3 jets.

rule of thumb derived from NLO jet theory: arXiv:0712.2447

$$\sqrt{\langle M_J^2 \rangle_{NLO}} \approx 0.2 p_J R$$

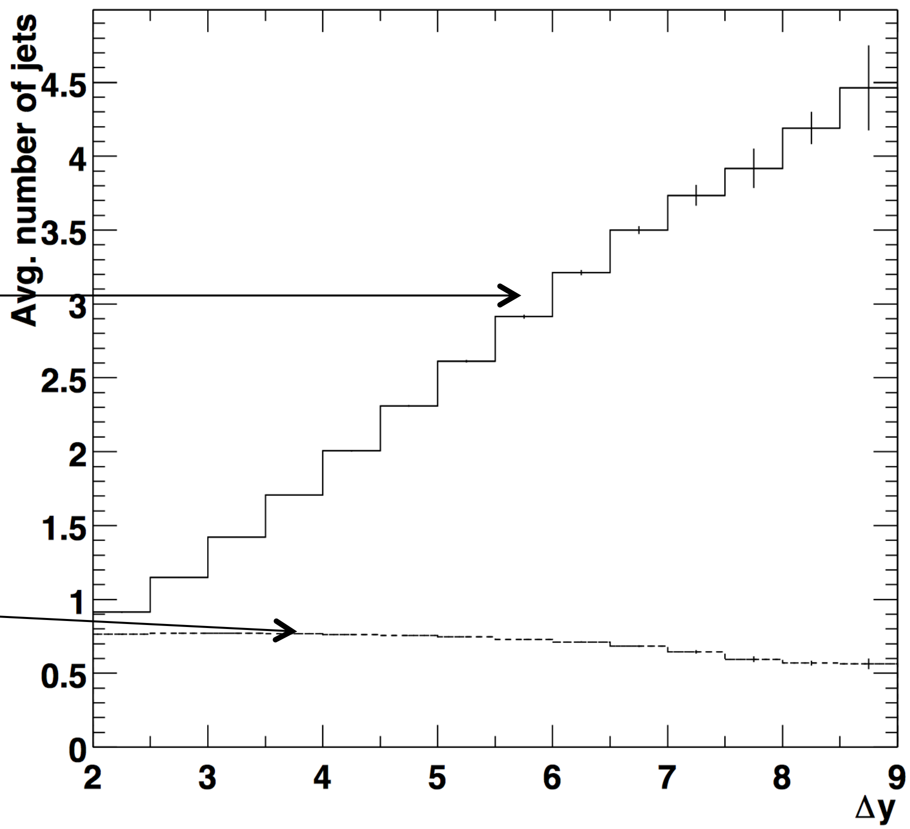


Rapidity difference between two most forward-backward jets for 2 jets (to the left) and for 3 jets at NLO (below).



BFKL physics

For processes proceeding by
t-channel gluon exchange (like
gg fusion production of Higgs +>=2 jets),
the average number of jets increases
linearly with the rapidity separation
between the two most-forward backward
jets.

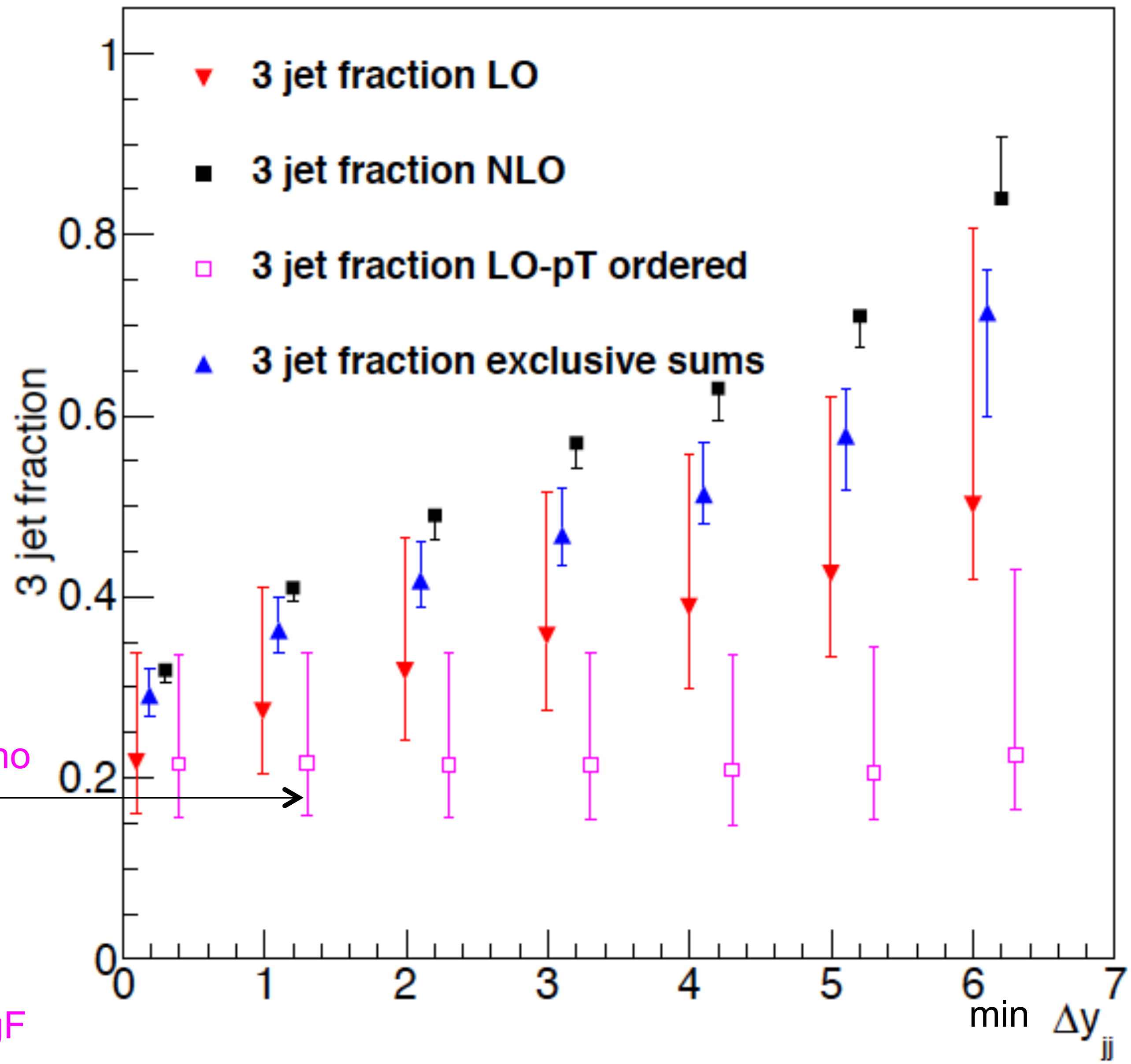


on the bottom is shown the jet multiplicity
in the central rapidity region (|y|<1) only

Results from gosam ntuples

fraction of Higgs+>=2 jet events (from ggF) with a 3rd jet as a function of the minimum rapidity separation between the two most forward-backward jets

t-channel gluon exchange so there's a linear growth with Δy



if the p_T-ordered jets are used, then there's no logarithmic growth with Δy

This really doesn't take advantage of the QCD differences between ggF and VBF (if pileup jet suppression is sufficient).

$\Delta\phi_{jj}$

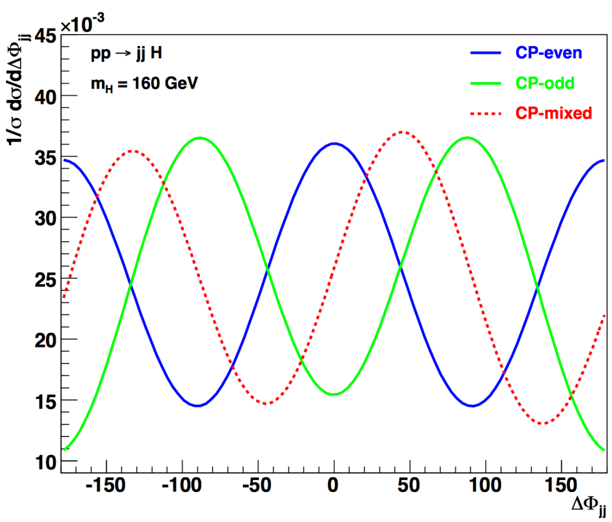
- Higgs gluon coupling can be described by the effective Lagrangian

$$\mathcal{L}_{\rm eff} = \frac{y_t}{y_t^{SM}} \cdot \frac{\alpha_s}{12\pi v} \cdot H\, G^a_{\mu\nu}\, G^{a\,\mu\nu} + \frac{\tilde{y}_t}{y_t^{SM}} \cdot \frac{\alpha_s}{16\pi v} \cdot A\, G^a_{\mu\nu}\, G^a_{\rho\sigma} \varepsilon^{\mu\nu\rho\sigma}$$

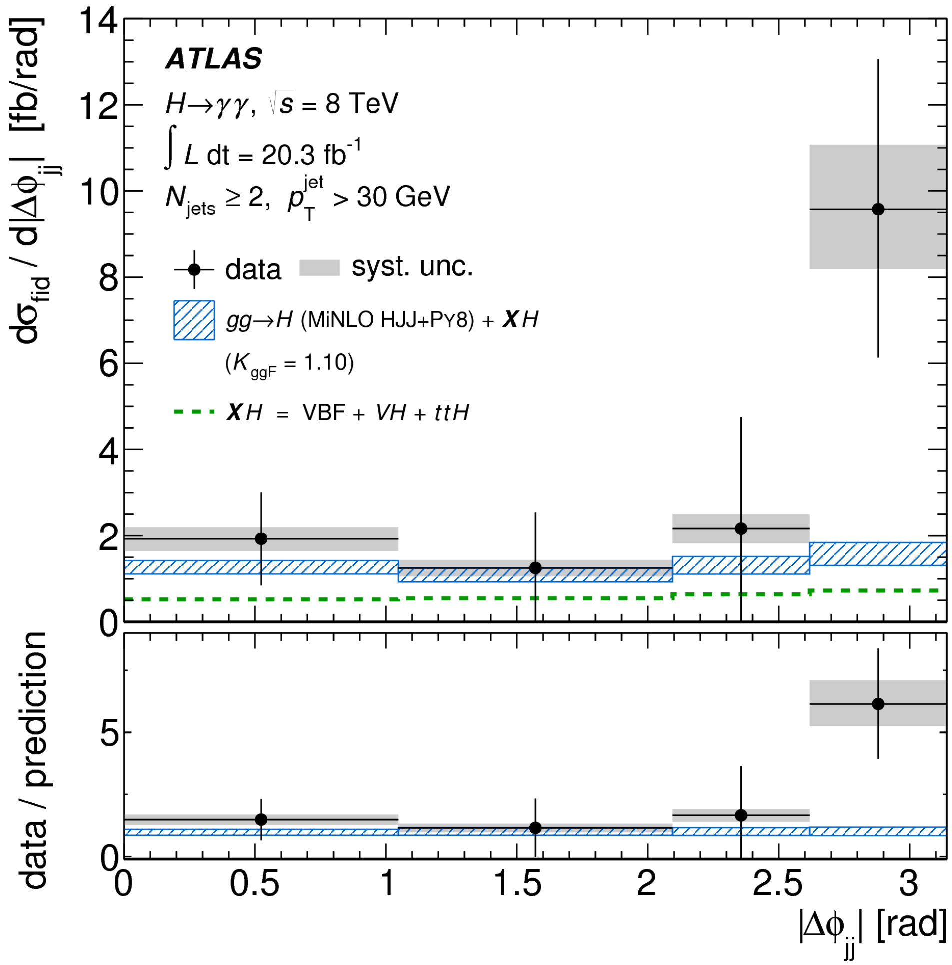
- tensor structure of the Hgg vertex given by

$$T^{\mu\nu} = a_2\,(q_1 \cdot q_2\, g^{\mu\nu} - q_1^\nu q_2^\mu) + a_3\, \varepsilon^{\mu\nu\rho\sigma} q_{1\rho} q_{2\sigma}$$

- dijet azimuthal distribution gives information on CP structure of Higgs-gluon couplings



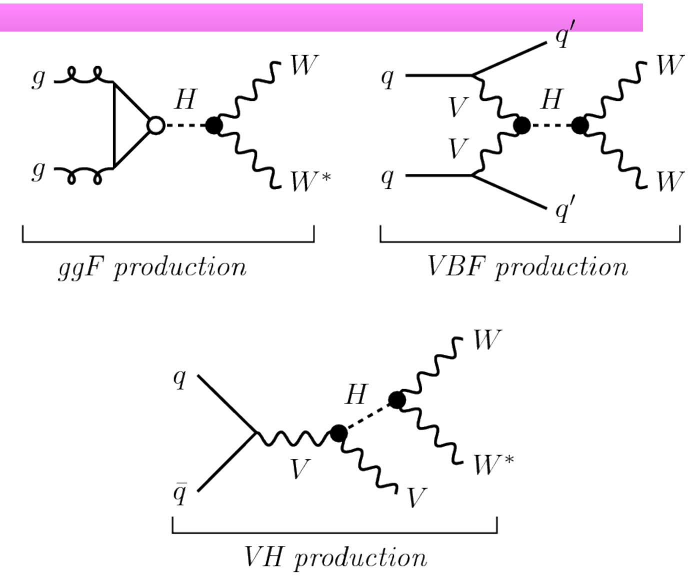
hep-ph/0703202

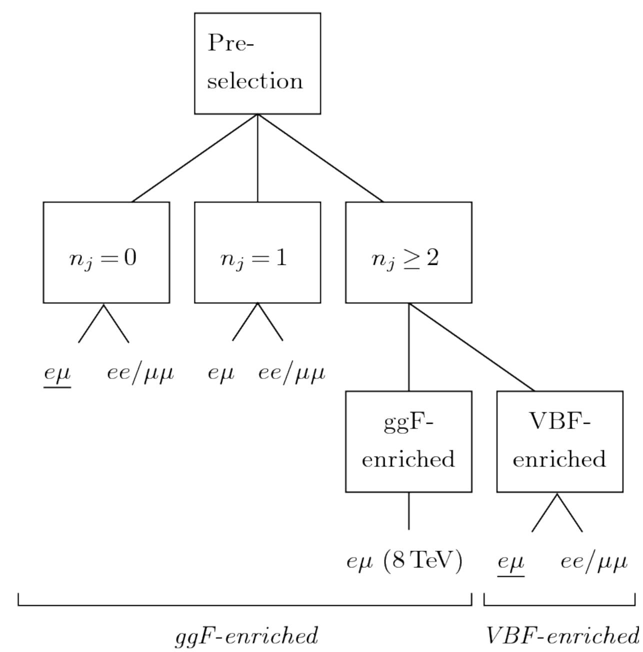


no conclusions now, stay tuned in Run 2

H->WW*->lν lν

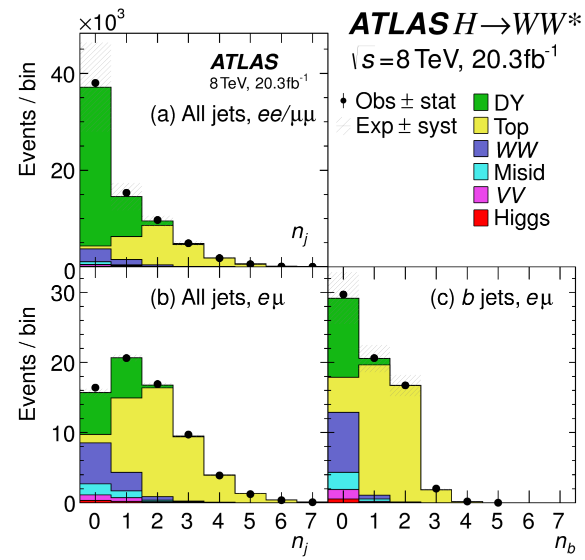
- Highest purity when each W boson decays leptonically
- Look for pairs of oppositely charged leptons and missing ET
- Drell-Yan is primary background when 0 jets; greatly reduced for eμ
- Top quarks are prolific source of lepton pairs
  - accompanied by jets
  - veto any events with b-tagged jets; still a large background to events with jets due to b-jet tagging inefficiencies
- Most of backgrounds calculated by Monte Carlo normalized to data
  - input to BDT, or use separate cut analysis
- Events with 2 or more jets are separated by signal process
  - VBF: 2 widely separated jets with large invariant mass
  - ggF: does not pass VBF criteria

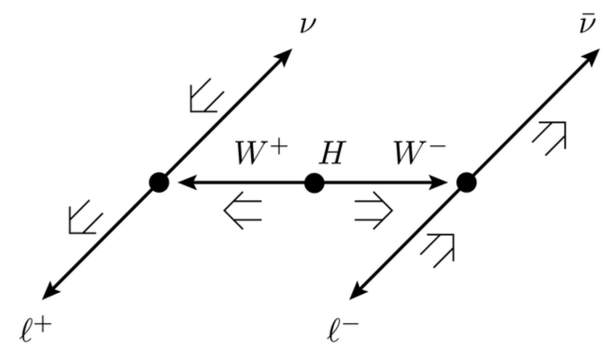




H->WW*->lν lν

- eμ 0 jet bin is most sensitive final state
- Dominant background is WW production
- WW can be suppressed by exploiting properties of W boson decays and spin 0 nature of Higgs boson
  - two leptons are relatively close and have a small mass (<m_H/2)
- Dilepton invariant mass is used to select signal events and signal likelihood fit is performed in two ranges of m_{ll} in eμ final states with 0 or 1 jets
- Also separate final states as to value of p_T of sub-leading lepton (W* decays will have small average lepton momenta than W decays)
- Can calculate transverse mass
  - distribution has a kinematic upper bound at the Higgs boson mass, effectively separating Higgs production from WW and top quark backgrounds

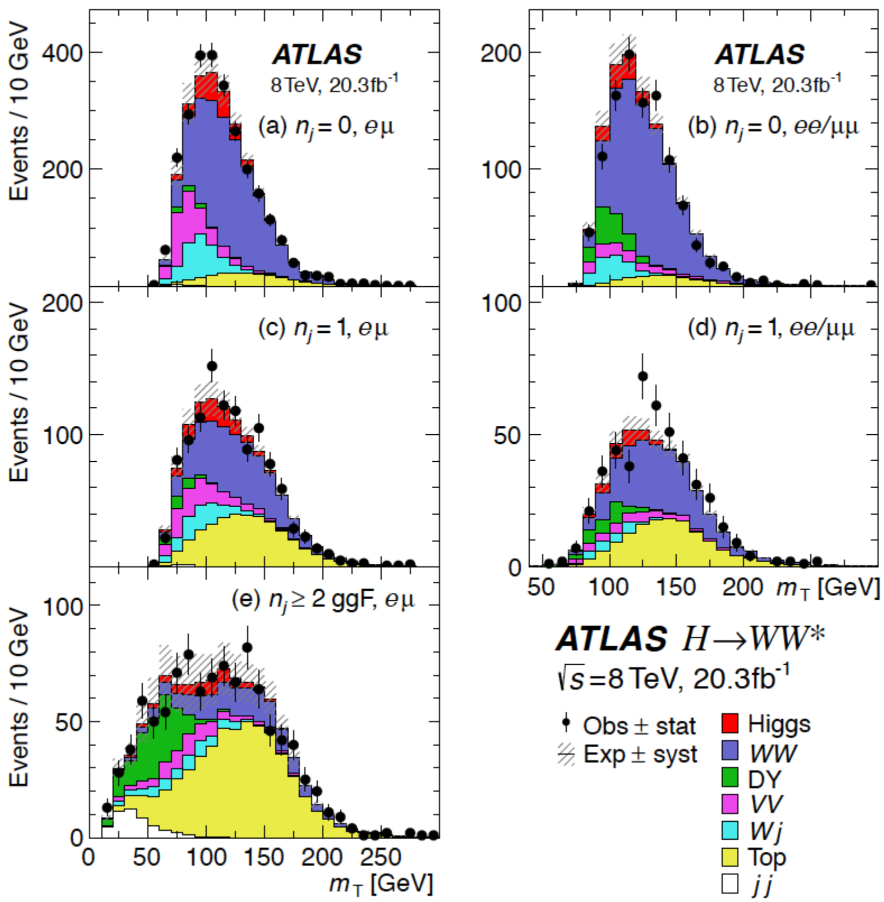




$$m_T = \sqrt{\left(E_T^{\ell\ell} + p_T^{\nu\nu}\right)^2 - \left|\boldsymbol{p}_T^{\ell\ell} + \boldsymbol{p}_T^{\nu\nu}\right|^2}, \quad (1)$$

where $E_T^{\ell\ell} = \sqrt{(p_T^{\ell\ell})^2 + (m_{\ell\ell})^2}$, $\boldsymbol{p}_T^{\nu\nu}$ ($\boldsymbol{p}_T^{\ell\ell}$) is the vector sum of the neutrino (lepton) transverse momenta, and $p_T^{\nu\nu}$ ($p_T^{\ell\ell}$) is its modulus.

- m_T distributions for different categories



- Have to measure exclusive jet cross sections and then correct for jet veto efficiency
- NB: exclusive cross sections are a pain in the ass
    - you're restricting phase space

intrinsic uncertainty >> than for an inclusive cross section, unless you resum; see for example arXiv:1312.4535

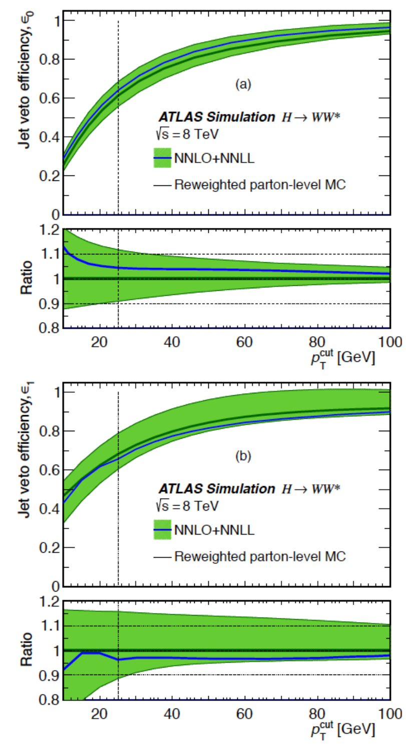
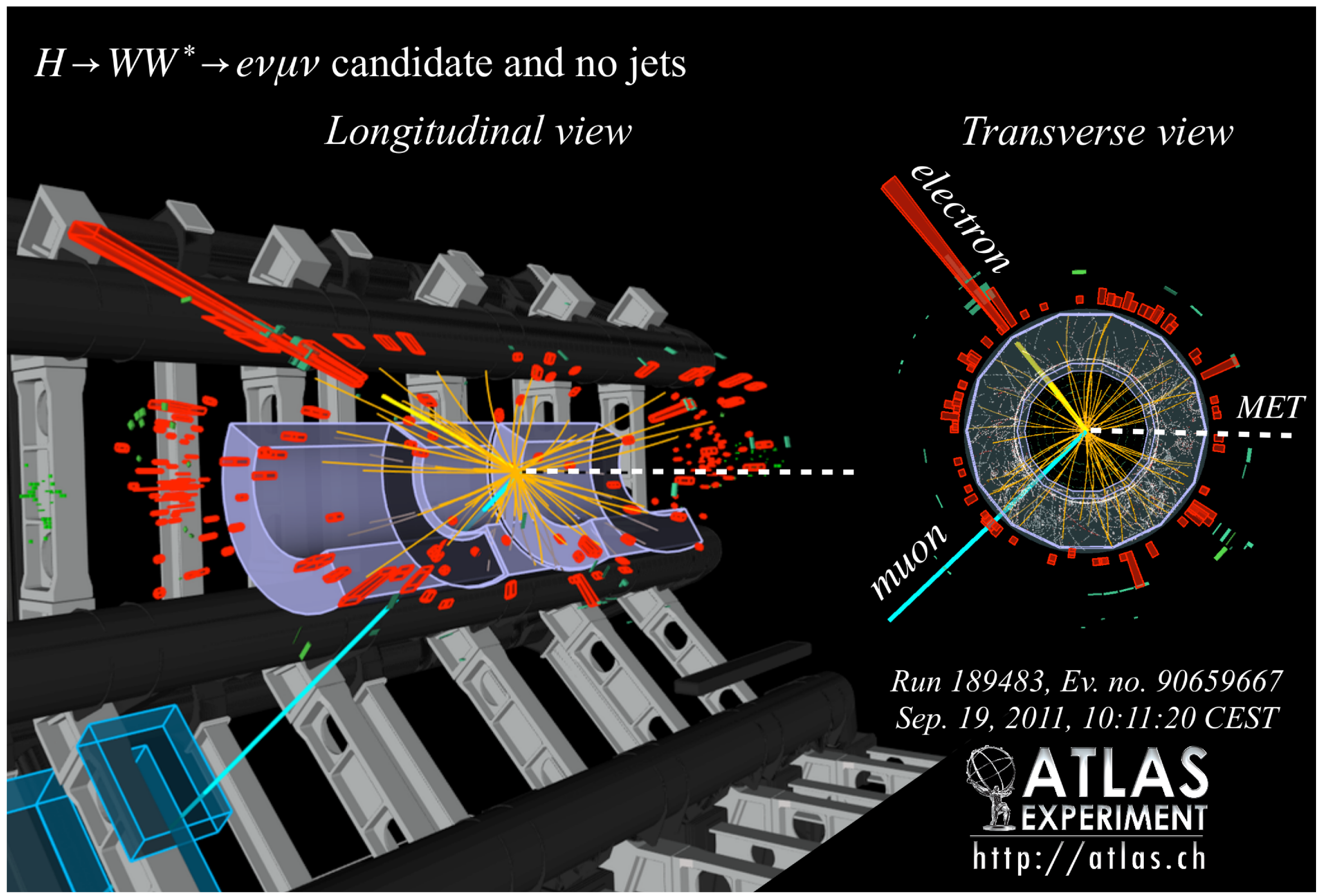


FIG. 18. Efficiencies of the veto of the (a) first jet and (b) second jet in inclusive ggF production of the Higgs boson, as a function of the veto-threshold p_T.

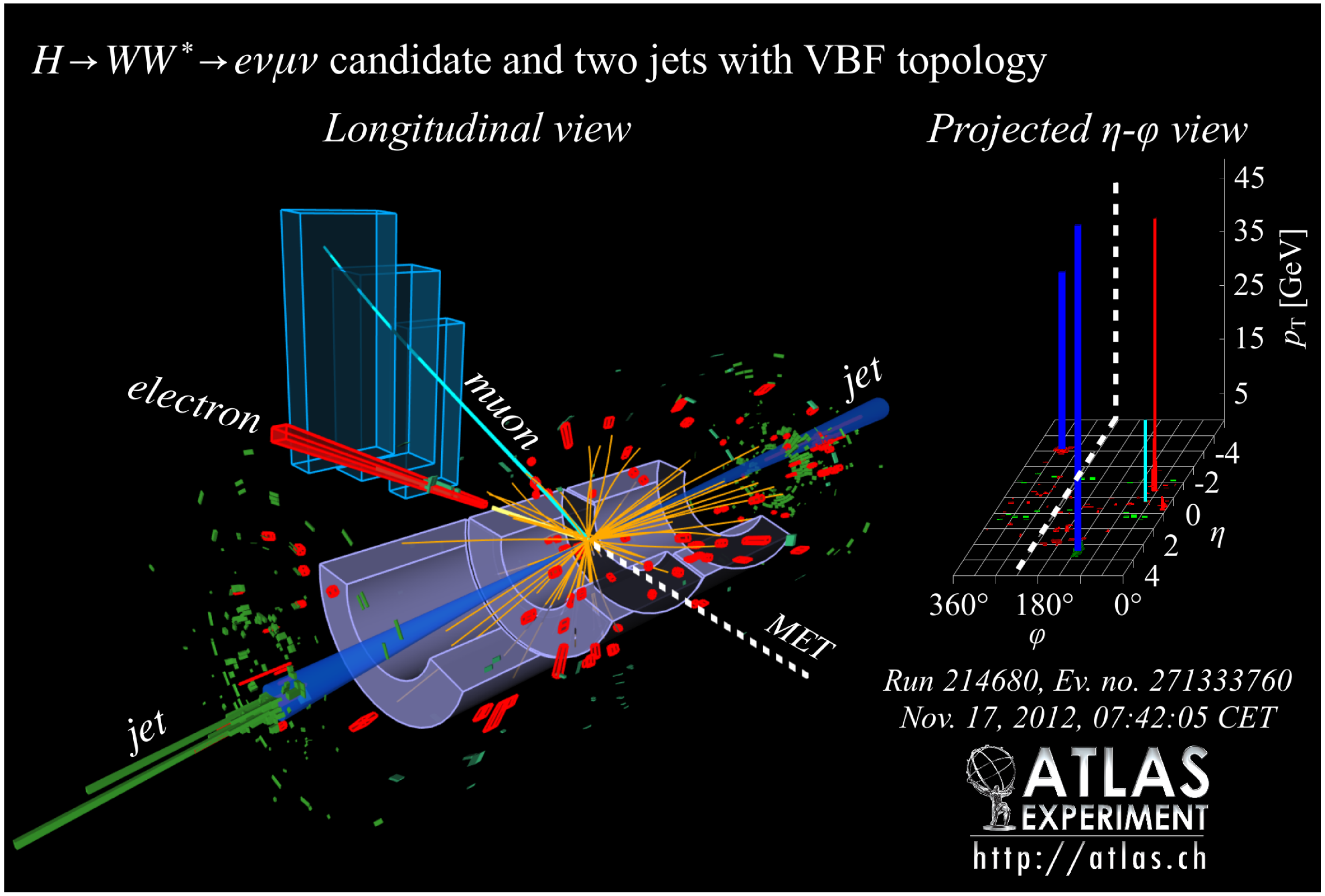
H->lν lν (no jets)

- p_T^e=33 GeV
- p_T^μ=24 GeV
- M_{ll}=48 GeV
- $\Delta\phi_{ll}$=1.7 rad
- p_T^{miss}=37 GeV
- m_T=98 GeV



With jets

- p_T^e=51 GeV
- p_T^μ=15 GeV
- M_{ll}=21 GeV
- $\Delta\phi_{ll}$=0.1 rad
- p_T^{j1}=67 GeV
- p_T^{j2}=41 GeV
- M_{jj}=1.4 TeV
- Δy_{jj}=6.6
- p_T^{miss}=59 GeV
- m_T=127 GeV



Bottom line

(a) 8 TeV data sample

Channel	Summary			
	N_{obs}	N_{bkg}	N_{signal}	
			N_{ggF}	N_{VBF}
$n_j = 0$	3750	3430 ± 90	300 ± 50	8 ± 4
$e\mu,\ \ell_2 = \mu$	1430	1280 ± 40	129 ± 20	3.0 ± 2.1
$e\mu,\ \ell_2 = e$	1212	1106 ± 35	97 ± 15	2.5 ± 0.6
$ee/\mu\mu$	1108	1040 ± 40	77 ± 15	2.4 ± 1.7
$n_j = 1$	1596	1470 ± 40	102 ± 26	17 ± 5
$e\mu,\ \ell_2 = \mu$	621	569 ± 19	45 ± 11	7.4 ± 2
$e\mu,\ \ell_2 = e$	508	475 ± 18	35 ± 9	6.1 ± 1.4
$ee/\mu\mu$	467	427 ± 21	22 ± 6	3.6 ± 1.8
$n_j \geq 2$, ggF $e\mu$	1017	960 ± 40	37 ± 11	13 ± 1.4
$n_j \geq 2$, VBF	130	99 ± 9	7.7 ± 2.6	21 ± 3
$e\mu$ bin 1	37	36 ± 4	3.3 ± 1.2	4.9 ± 0.5
$e\mu$ bin 2	14	6.5 ± 1.3	1.4 ± 0.5	4.9 ± 0.5
$e\mu$ bin 3	6	1.2 ± 0.3	0.4 ± 0.3	3.8 ± 0.7
$ee/\mu\mu$ bin 1	53	46 ± 6	1.7 ± 0.6	2.6 ± 0.3
$ee/\mu\mu$ bin 2	14	8.4 ± 1.8	0.7 ± 0.3	3.0 ± 0.4
$ee/\mu\mu$ bin 3	6	1.1 ± 0.4	0.2 ± 0.2	2.1 ± 0.4

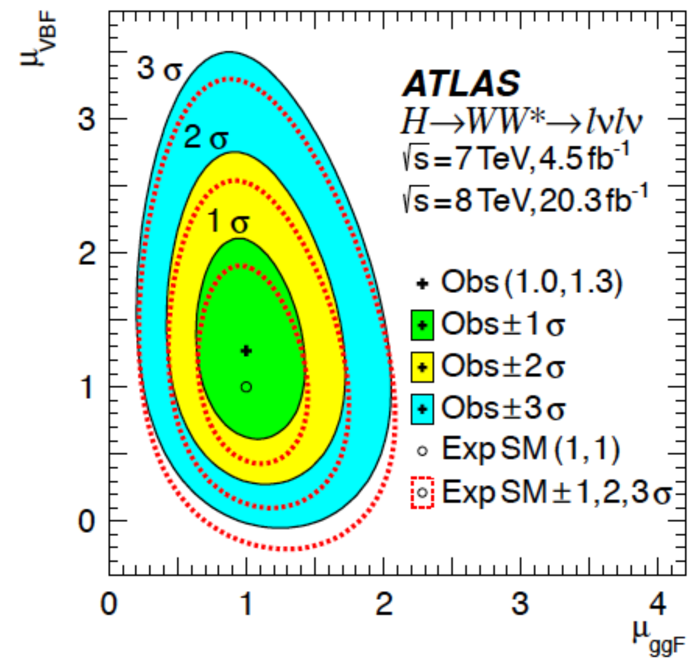
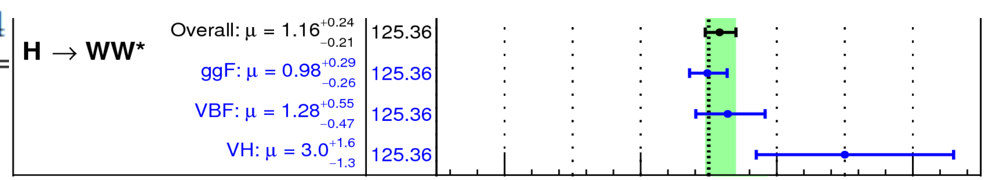


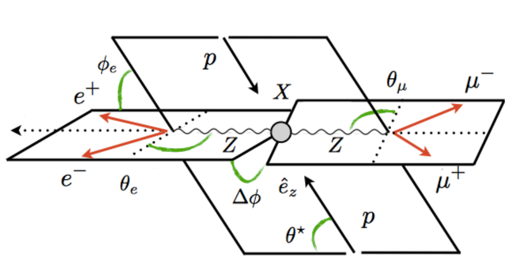
FIG. 40. Likelihood scan as a function of μ_{ggF} and μ_{VBF}. The best-fit observed (expected SM) value is represented by the cross symbol (open circle) and its one, two, and three standard deviation contours are shown by solid lines surrounding the filled areas (dotted lines). The x- and y-axis scales are the same to visually highlight the relative sensitivity.

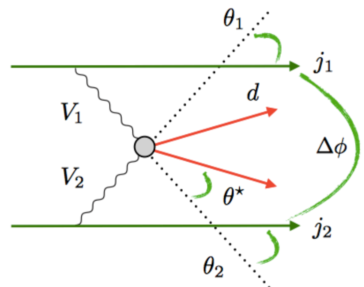


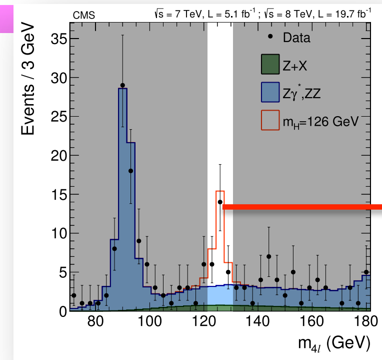
Spin-parity tests: $X(J^P)$ vs. $H(0^+)$

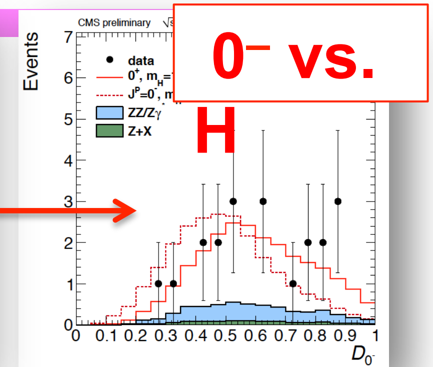
H→ZZ→4l

- 4l system is fully reconstructed
- use ME-based discriminator



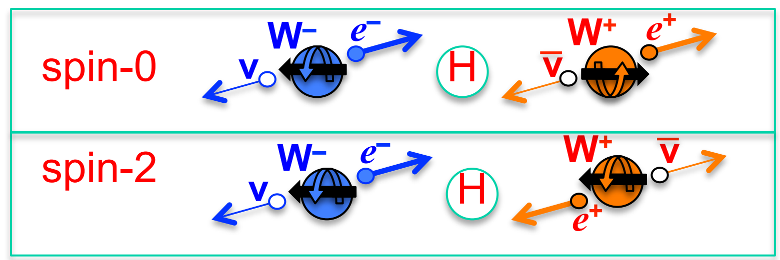






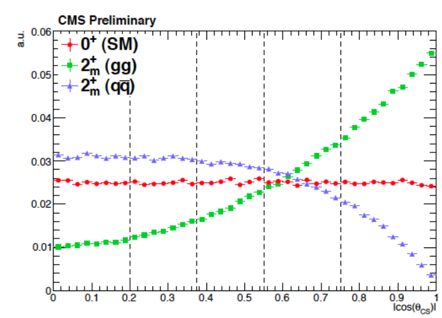
H→WW→lνlν

- di-lepton angle and mass are sensitive to the spin of the decaying $X(J^P)$



H→γγ

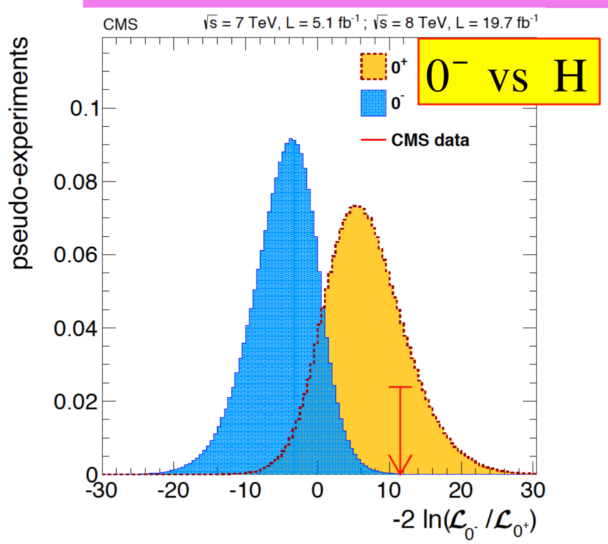
- J=1 forbidden (Landau-Yang theorem)
- $\cos\theta^*$ is the only variable sensitive to J^P information at leading order

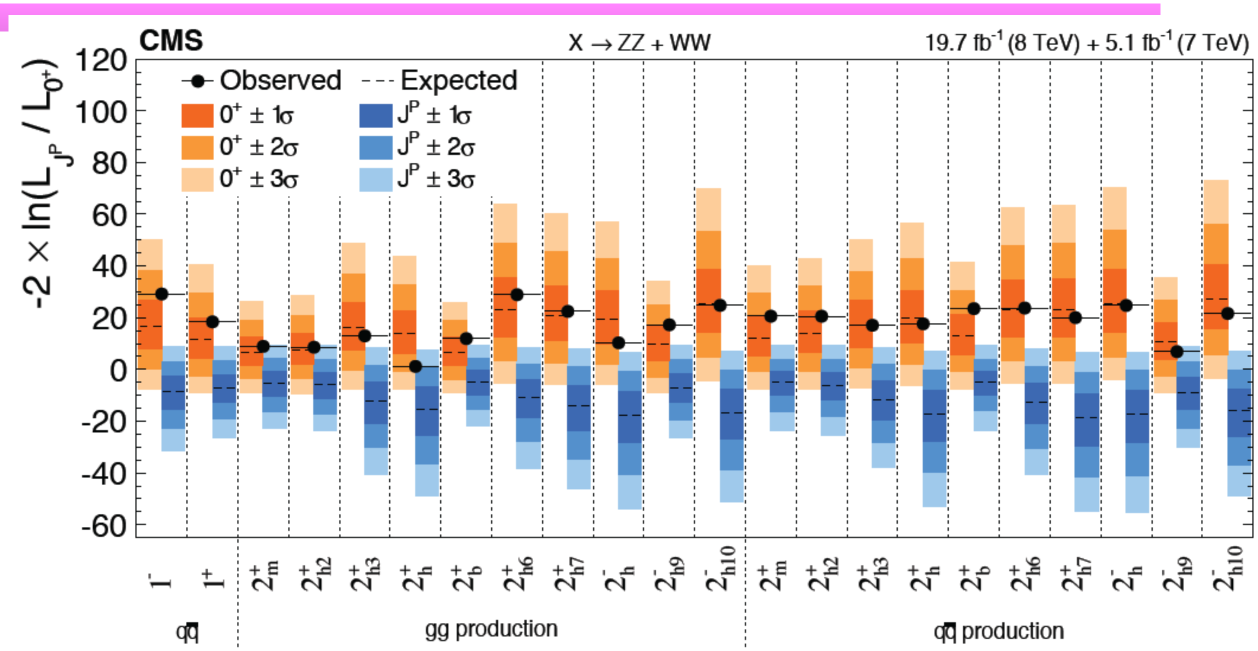


- shown distributions: before acceptance and reconstruction
- after acc x reco, discrim. power lessens
- poor S:B makes measurements difficult

Andrey Korytov

Spin-parity results: $X(J^P)$ vs. $H(0^+)$





excluded at 99.9% CL

Test Statistic $q = -2\ln\frac{L(data|J^P + bkg)}{L(data|H + bkg)}$

CMS:

- **data are better than ±1.5σ compatible with 0^+ in all tests**
- **data is incompatible with 0^-, $1^\pm$, ten J=2 models at the level of 3σ or higher**

ATLAS results for 0^-, $1^\pm$, and 2^+_m are similar

Andrey Korytov (UF)

Higgs width

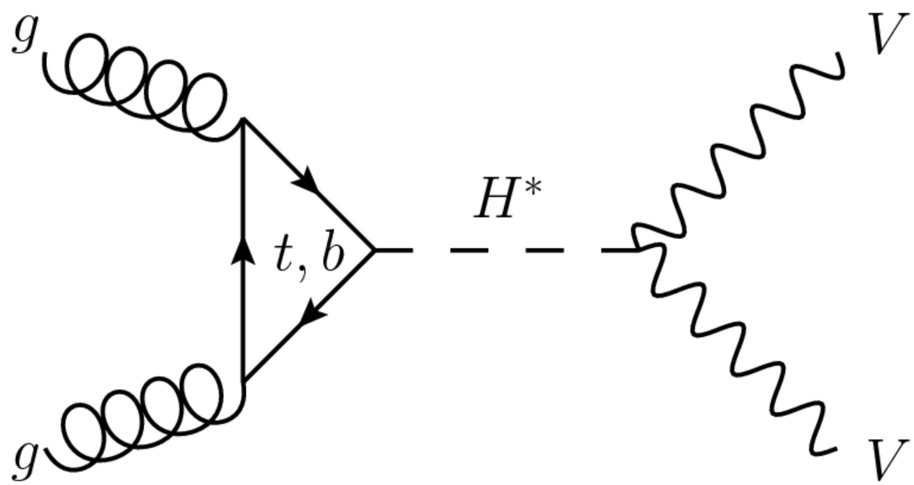
- The width of a 125 GeV mass SM Higgs is too small to be measureable (~4 MeV)
- However the high mass region (>2m_{VV}) is sensitive to Higgs boson production through off-shell and background interference effects
- Breit-Wigner production gg->H->ZZ

$$\frac{d\sigma}{dm^2} \sim g_g^2 g_Z^2 \frac{F(m)}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

- On-peak and off-peak cross sections

$$\sigma^{\mathrm{on-shell}} = \int_{|m-m_H| \le n\Gamma_H} \frac{d\sigma}{dm} \cdot dm \sim \frac{g_g^2 g_Z^2}{m_H \Gamma_H}$$

$$\sigma^{\mathrm{off-shell}} = \int_{m-m_H \gg \Gamma_H} \frac{d\sigma}{dm} \cdot dm \sim g_g^2 g_Z^2$$



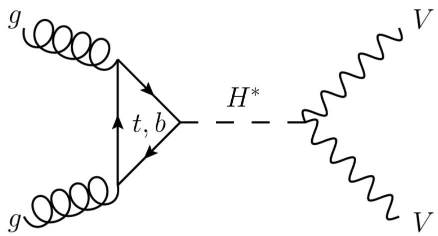
off-peak to on-peak ratio is proportional to Γ_H

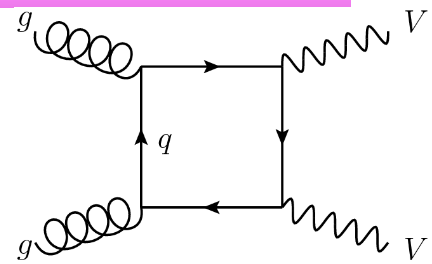
$$\frac{\sigma^{\mathrm{off-shell}}}{\sigma^{\mathrm{on-shell}}} \sim \Gamma_H$$

Higgs width

- The width of a 125 GeV mass SM Higgs is too small to be measureable (~4 MeV)
- However the high mass region (>2m_{VV}) is sensitive to Higgs boson production through off-shell and background interference effects
- Thus, the ratio of the two is proportional to the Higgs width
  - assuming on-shell coupling factors no larger than off-shell Higgs coupling factors

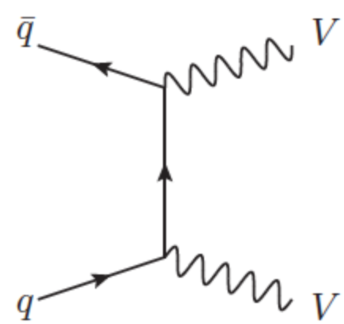
$$\frac{\sigma^{\mathrm{off-shell}}}{\sigma^{\mathrm{on-shell}}} \sim \Gamma_{\mathrm{H}}$$





these two diagrams interfere

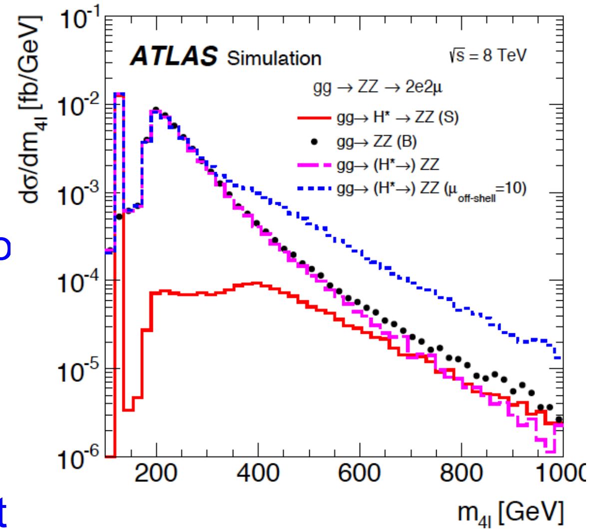
- formally, diagram on the right (above) is suppressed by factor of α_s^2 with respect to diagram below
- however, the large *gg* flux makes it relevant
- so far, we know it only at LO (1-loop)
- we need to know it at NLO (recent progress)

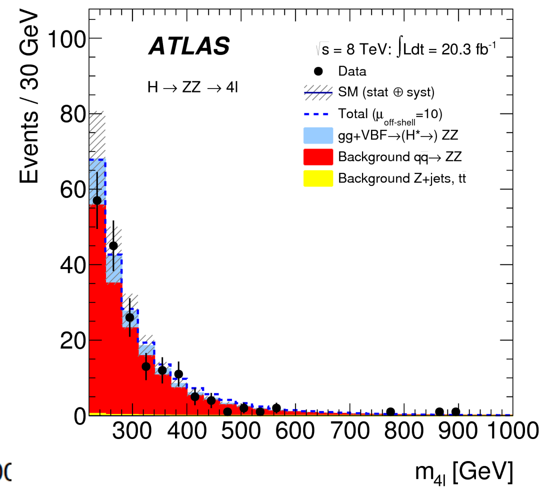


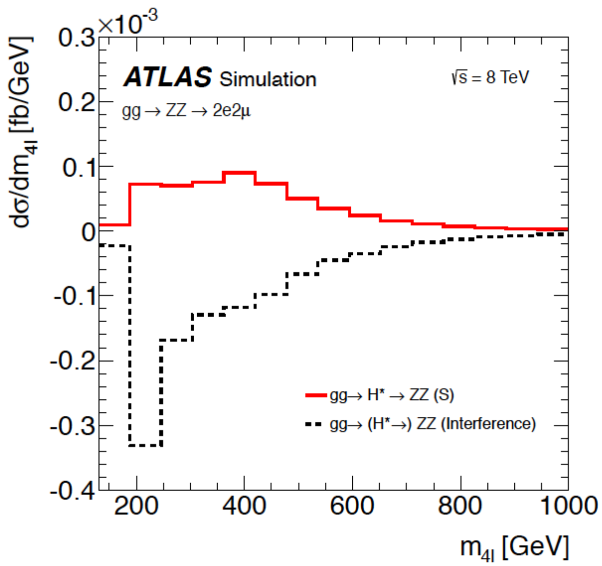
this one doesn't interfere with the two above and it forms the bulk of the cross section.

Higgs width

- For high mass signal region in ZZ->4l, ZZ->2l2ν, WW->eνμυ final states, VVjj (VBF and VH-like) also contribute
- For WW->eν μν final states, also have significant contributions from top pair and single top production
- For low masses, <2m$_Z$, off-shell contribution is negligible, while it is comparable to continuum gg->ZZ* background for masses above 2m$_{top}$
- Note that interference between gg->H*->ZZ signal and gg->ZZ background is negative over entire mass range
  - similarly for gg->H*->WW and gg->WW

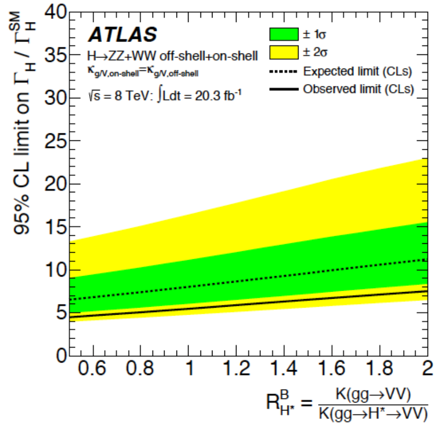


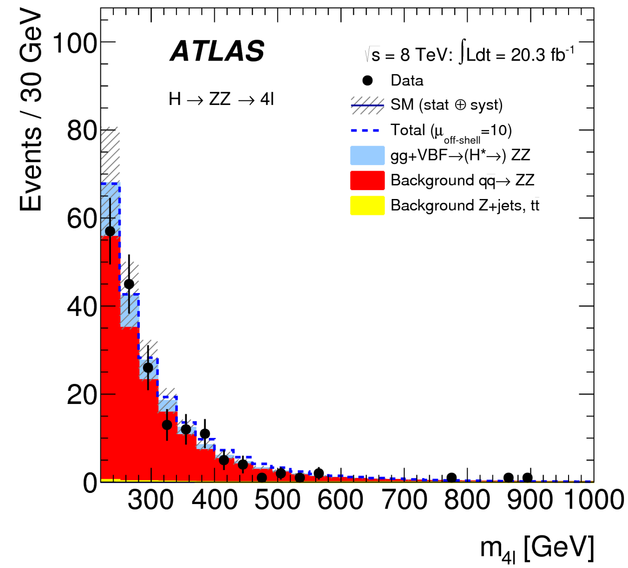


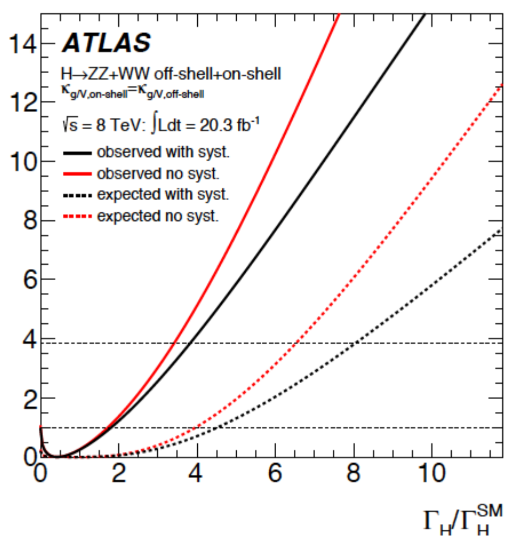


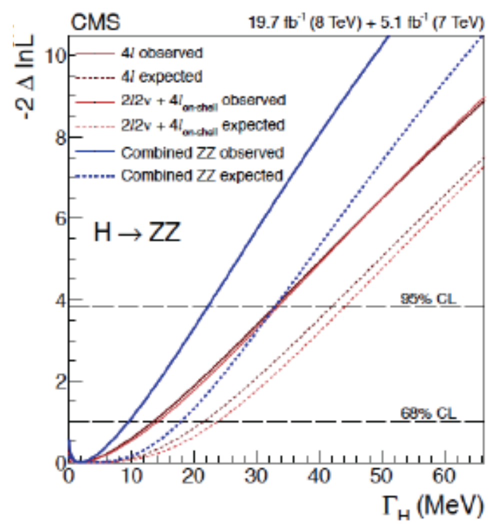
Higgs width

- Need to know NLO corrections for gg->VV*; have to scan over possible values of higher order corrections for gg->VV compared to gg->H*->VV
- Assuming that the relevant Higgs boson couplings are independent of the energy scale of the Higgs production, combination of WW and ZZ results yields 95% CL upper limit of Γ_H/Γ_H^{SM} of 4.5-7.5
- CMS sees similar limit









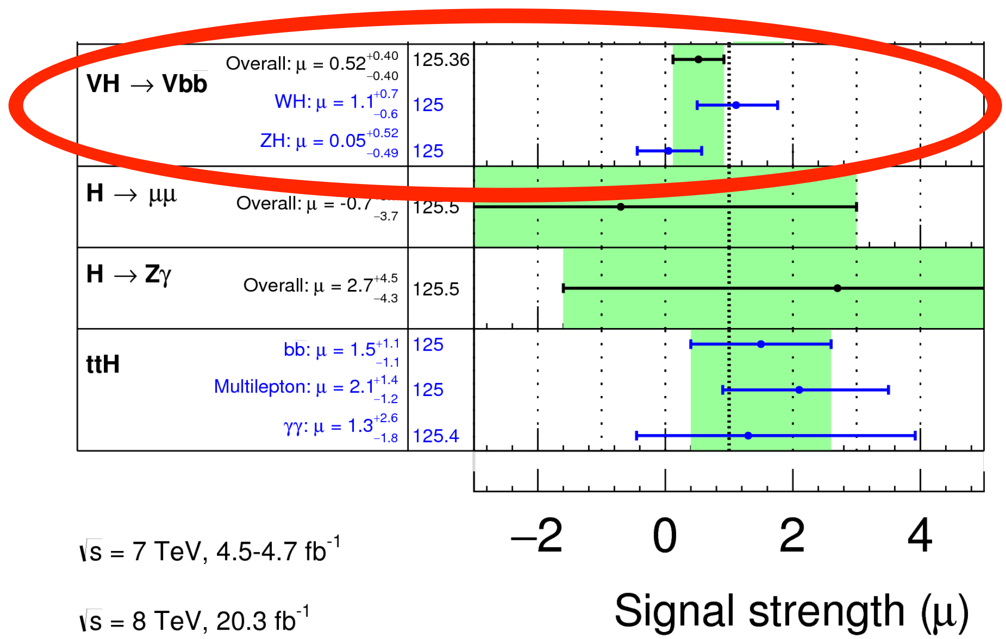
Associated production

- Coupling of Higgs to top and bottom quarks poorly known
  - 50% for bottom
  - 100% for top
- H->bB primarily measured through asociated production, known currently at NNLO QCD and at NLO EW
- bB decay currently in NLO QCD production in narrow-width approximation; desirable to combine Higgs production and decay processes to same order, NNLO in QCD and NLO in EW for Higgs-strahlung process
- With 300 fb^{-1} at 14 TeV, signal strength for H->bB should be measured to 10-15% level, shrinking to 5% for 3000 fb^{-1}

- NB: gg->ZH at NLO critical component

Process	known	desired	details
H	dσ @ NNLO QCD dσ @ NLO EW finite quark mass effects @ NLO	dσ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	dσ @ NNLO QCD (g only) dσ @ NLO EW finite quark mass effects @ LO	dσ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	$\sigma_{\rm tot}$(VBF) @ NNLO(DIS) QCD dσ(gg) @ NLO QCD dσ(VBF) @ NLO EW	dσ @ NNLO QCD + NLO EW	H couplings
H + V	dσ @ NNLO QCD dσ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}$H	dσ(stable tops) @ NLO QCD	dσ(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	dσ @ LO QCD (full m_t dependence) dσ @ NLO QCD (infinite m_t limit)	dσ @ NLO QCD (full m_t dependence) dσ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Table 1: Wishlist part 1 – Higgs (V = W, Z)

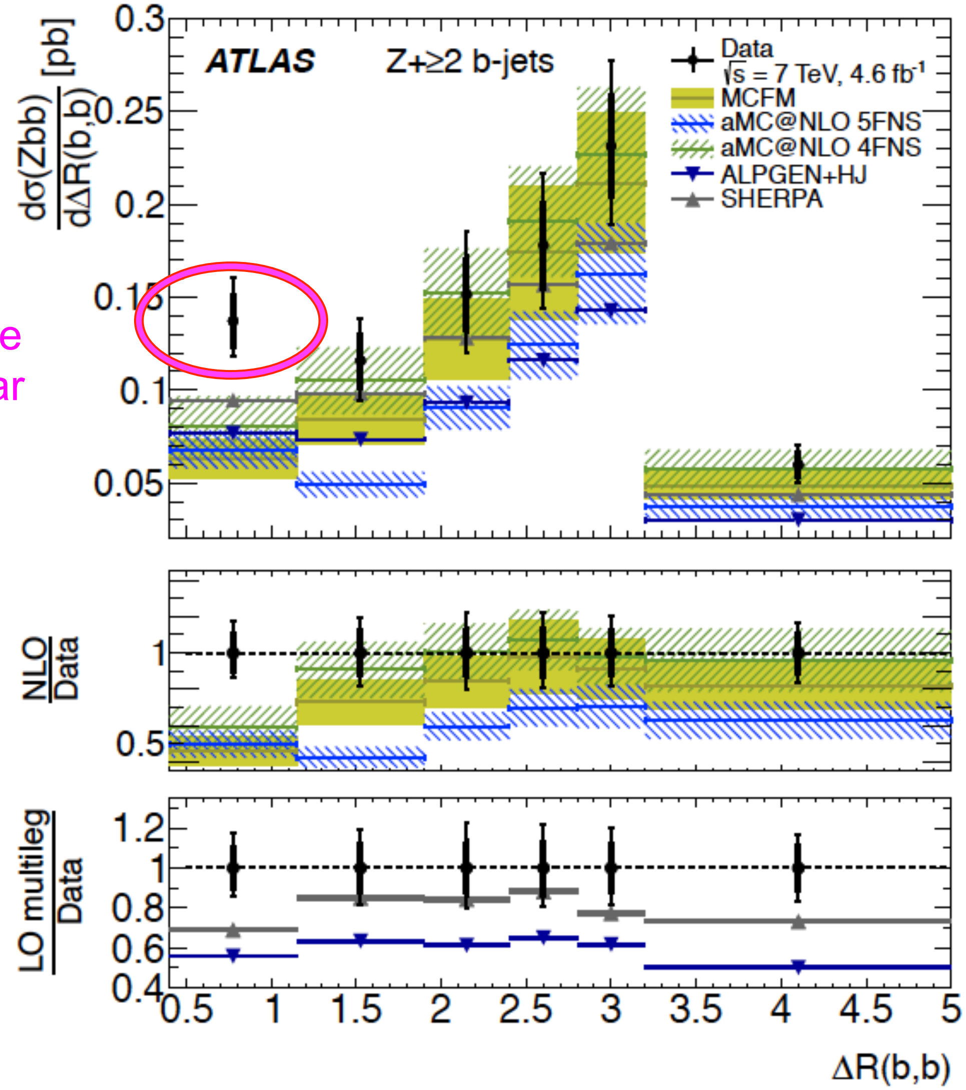


VbB

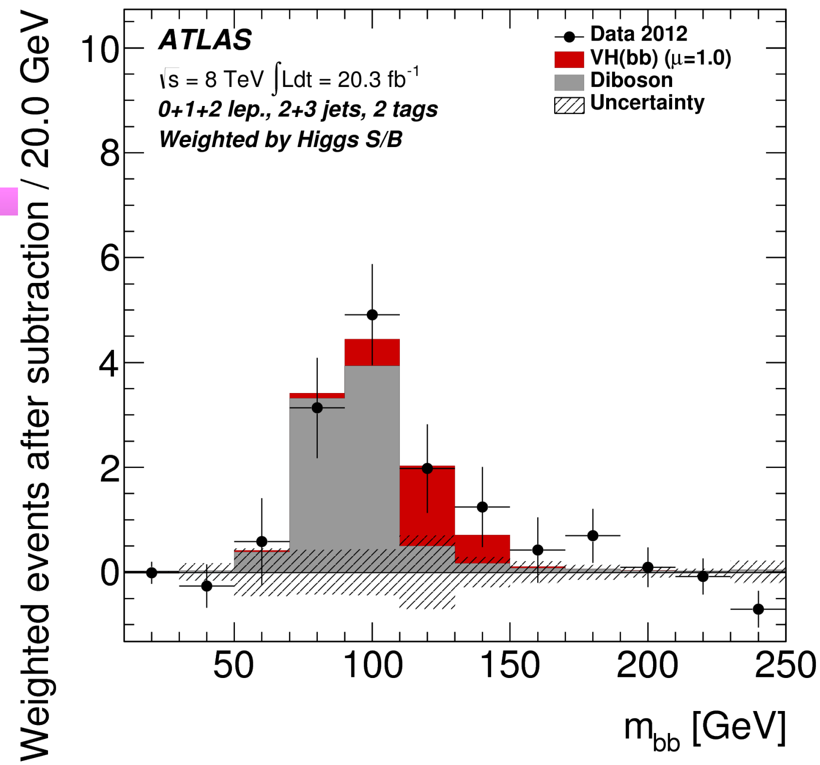
- Associated Higgs production, with Higgs decaying into bb is key to understanding Higgs couplings to b-quarks
- Vbb is significant background
- Current state of the art for Vbb is NLO QCD (including b-quark mass effects)
- Experimental and theoretical uncertainties are of the order of 20%
- As experimental uncertainties will improve with more data, crucial to extend the theoretical accuracy by extending the calculation to NNLO QCD (massless b quarks)
- Includes an understanding of uncertainties in 4-flavor vs 5-flavor approaches

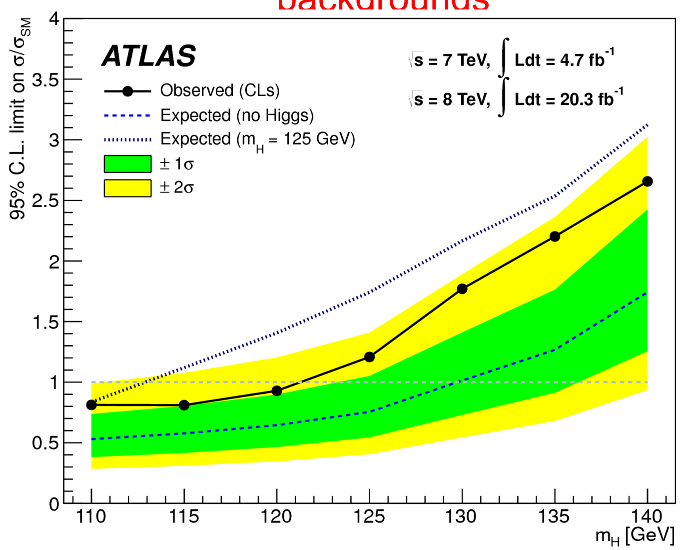
	$d\sigma$(PA, V decay) @ NLO EW	@ NNLO QCD + NLO EW	
$Vb\bar{b}$	$d\sigma$(lept. V decay) @ NLO QCD massive b	$d\sigma$(lept. V decay) @ NNLO QCD massless b	bkg. for VH → $b\bar{b}$
$VV'\gamma$	$d\sigma$(V decays) @ NLO QCD	$d\sigma$(V decays)	QGCs

better knowledge of collinear gluon splitting needed?

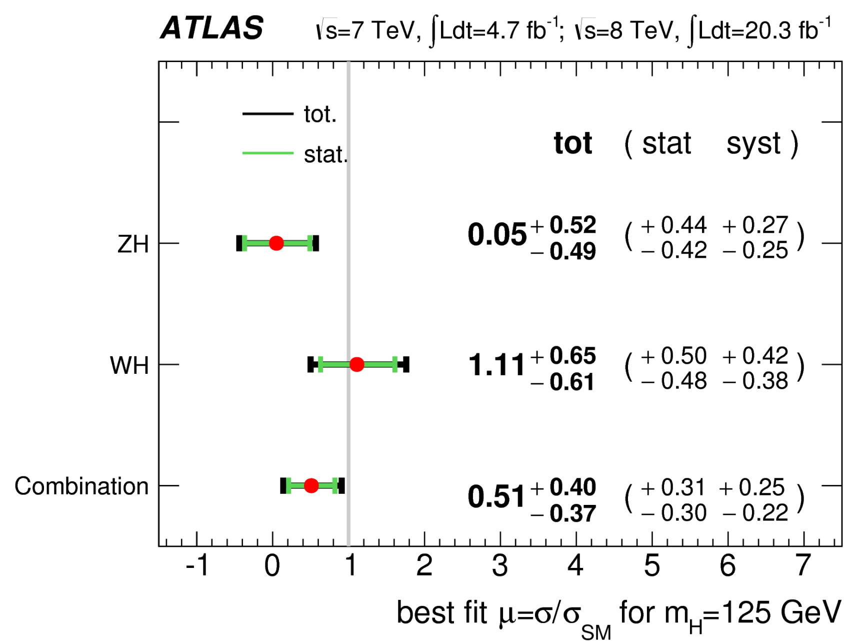


- Events are first categorized according to the number of leptons, jets and b-tagged jets
    - 0,1 and 2 leptons
    - 2 or 3 jets with p_T>20 GeV and $|\eta|$<2.5 (b-tagging range)
        - reject event if additional jet with p_T>30 GeV and $|\eta|$>2.5 to reduce tt background
- Dedicated boosted decision trees are constructed for each channel
    - BDTs trained to separate (VH,H->bb) signal from sum of expected backgrounds



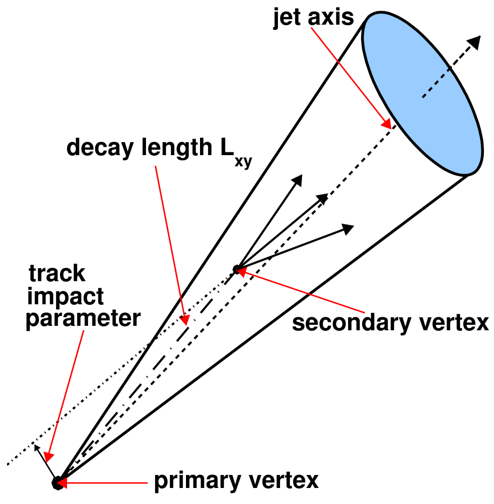


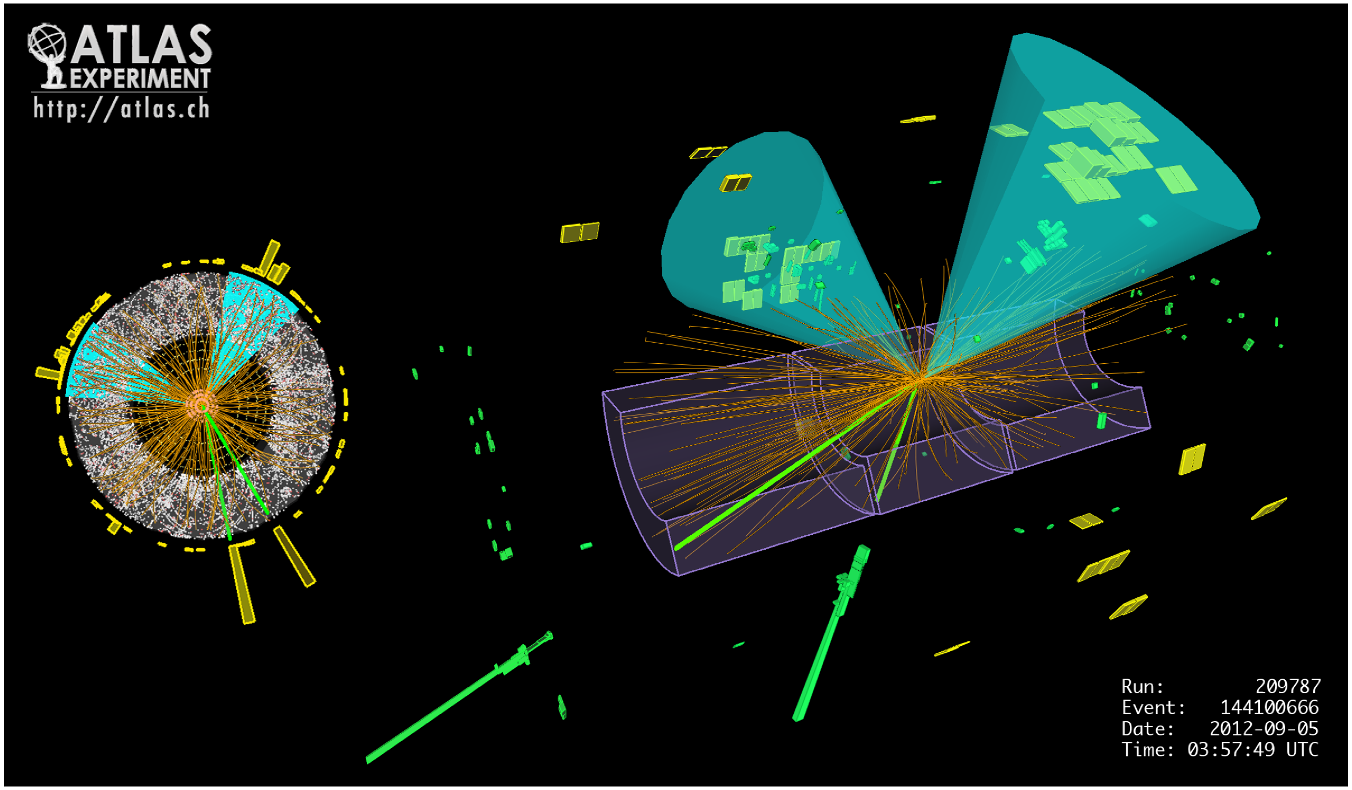
significance: 1.4 (expected 2.6)



H->ll bB

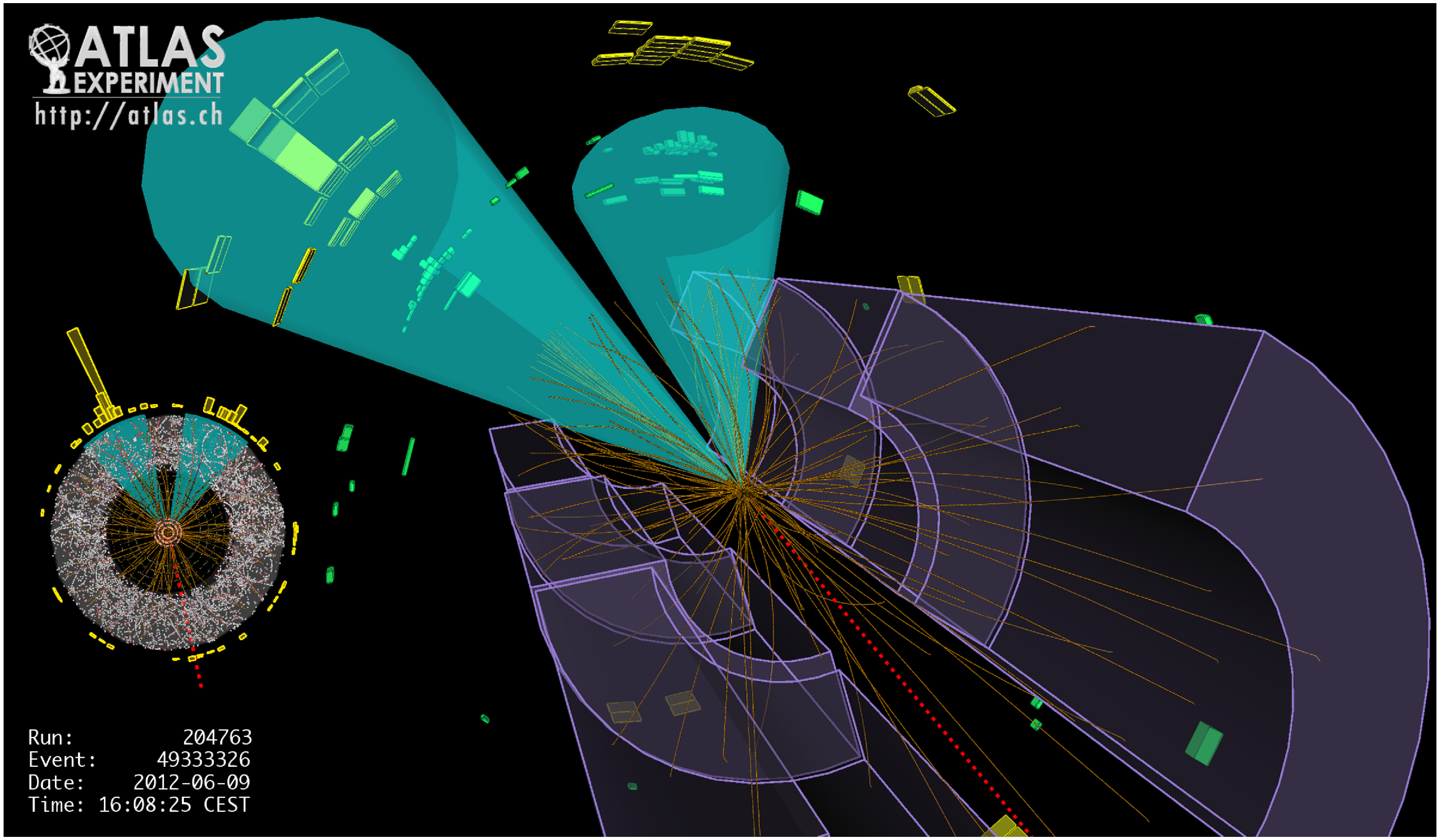
- 2 opposite sign leptons
- 2 b-tagged jets
- m_{bb}=122 GeV
- p_T^Z=115 GeV





H->bb + MET

- 2 b jets
- m_{bb}=123 GeV
- MET=271 GeV

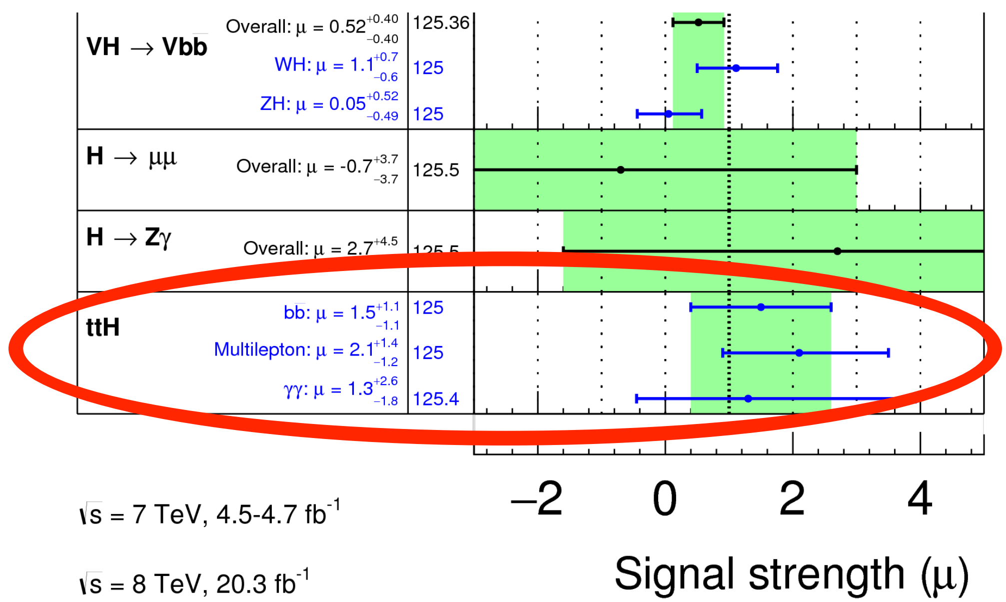


Higgs sector

- Coupling of Higgs to top and bottom quarks poorly known
  - 50% for bottom
  - 100% for top
- Higgs-top couplings may have both scalar and pseudo-scalar components (in presence of CP violation)
- Can be probed in measurements of Higgs production in association with tT or t
- tH (tTH) known to LO (NLO) QCD wth stable tops
- Need to know the cross section (with top decays) at NLO QCD, possibly including NLO EW effects

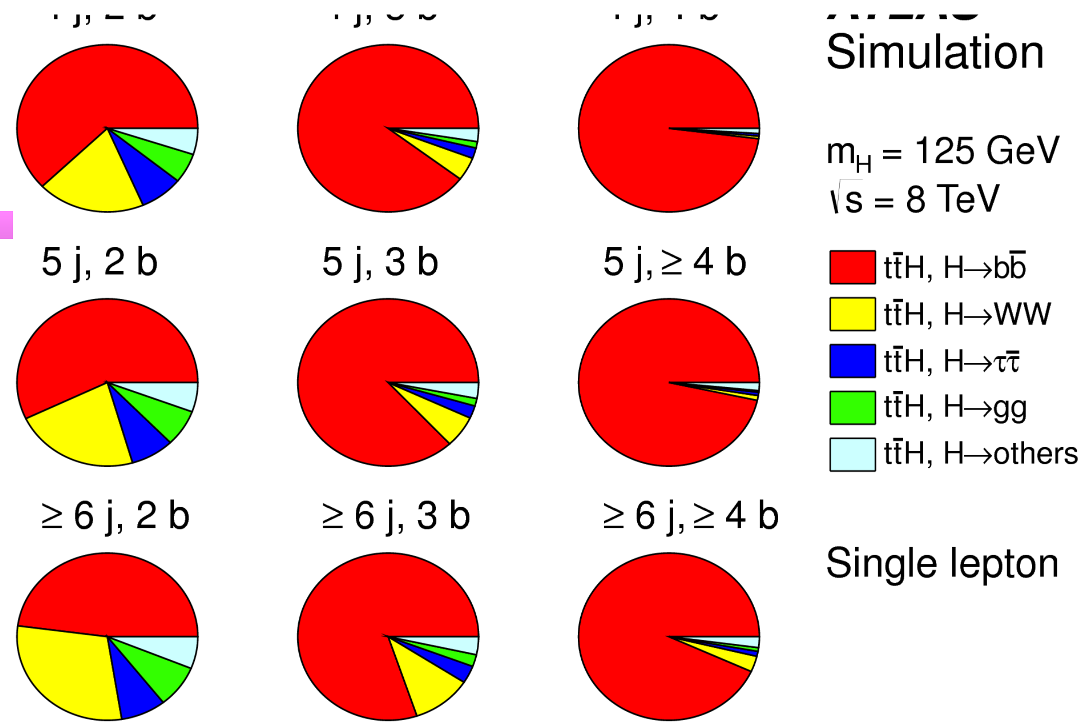
Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	$d\sigma$ @ LO QCD (full m_t dependence) $d\sigma$ @ NLO QCD (infinite m_t limit)	$d\sigma$ @ NLO QCD (full m_t dependence) $d\sigma$ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

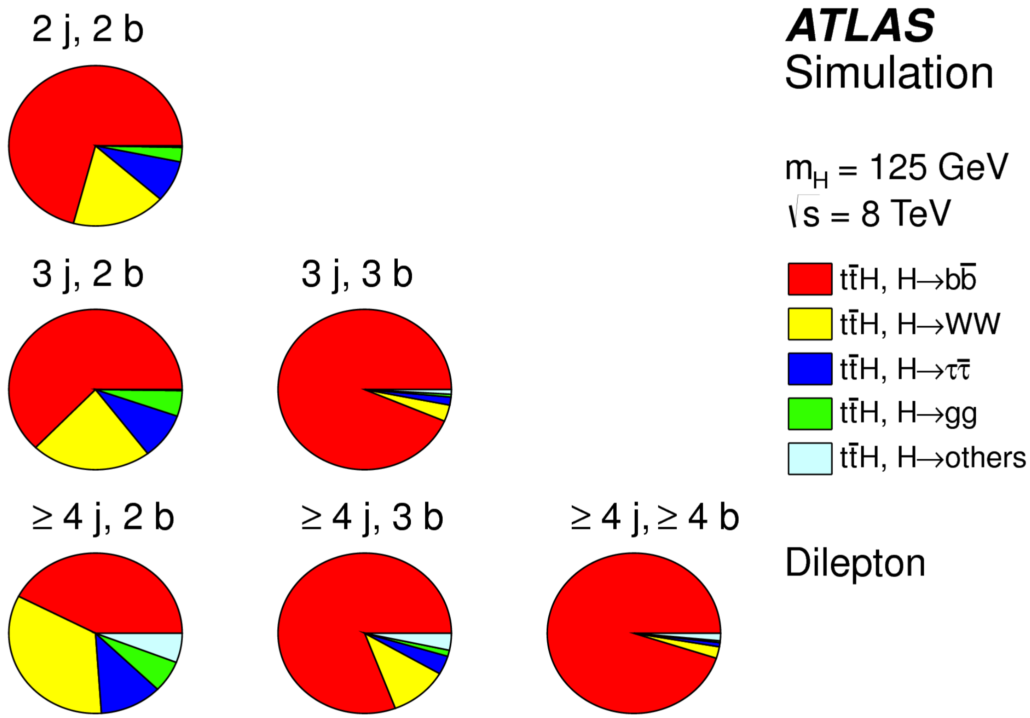
Table 1: Wishlist part 1 – Higgs (V = W, Z)



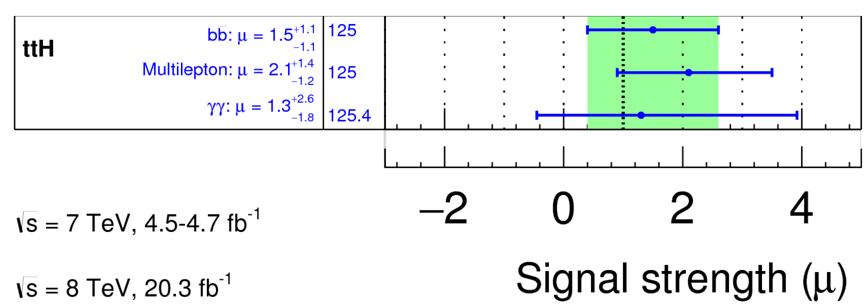
ttH

very complex, lots of combinatorics,
lots of final states to look in





clearly an analysis for Run 2

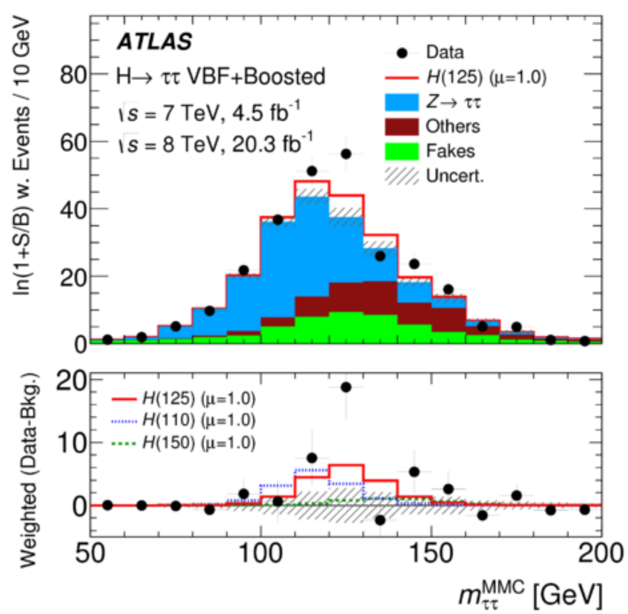


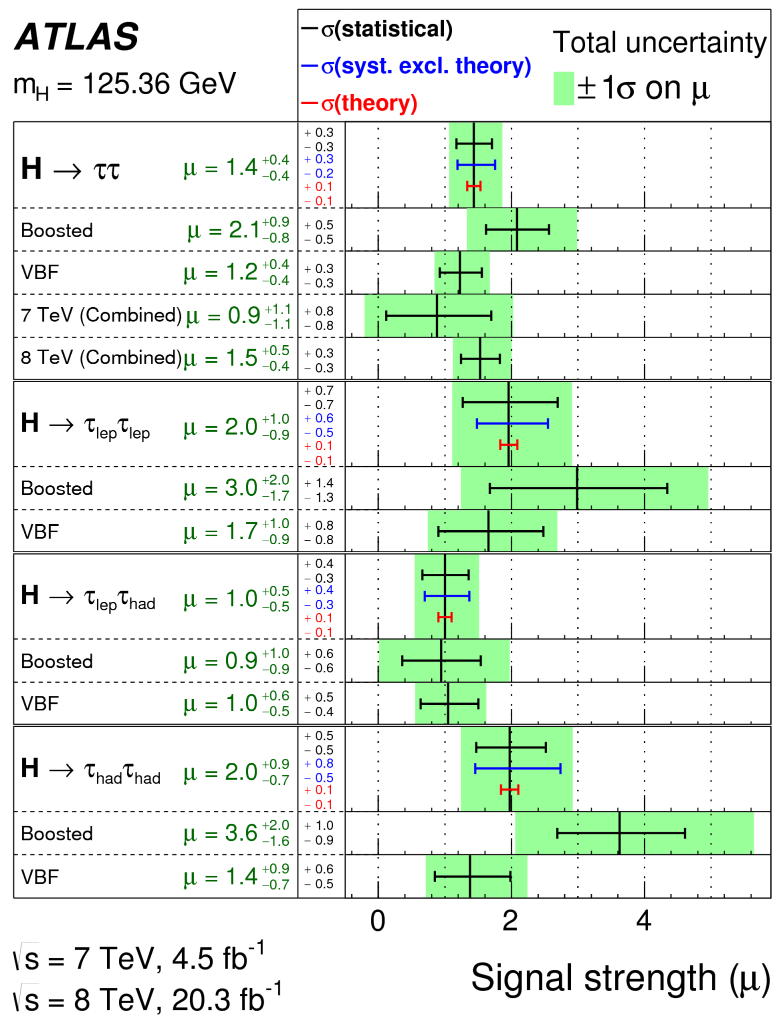
H->ττ

- Analysis channels
  - 2 isolated opposite-sign leptons above p_T threshold
  - exactly one isolated lepton and one hadronic candidate with opposite sign charges, above threshold
  - two hadronic candidates, above threshold
- Analysis categories
  - VBF: with two high p_T jets separated in rapidity
  - boosted: large transverse momentum for the Higgs (p_T^H>100 GeV)

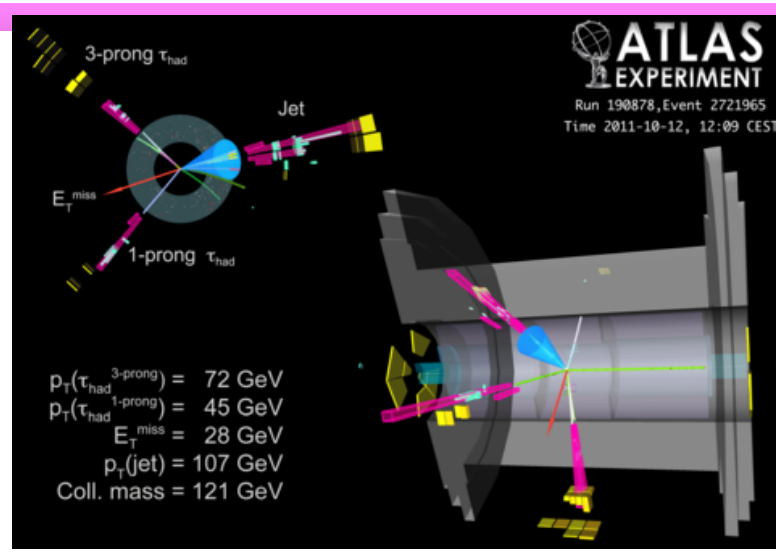
significance: 4.5 (expected 3.4)

signal strength: μ = 1.4 ± 0.4

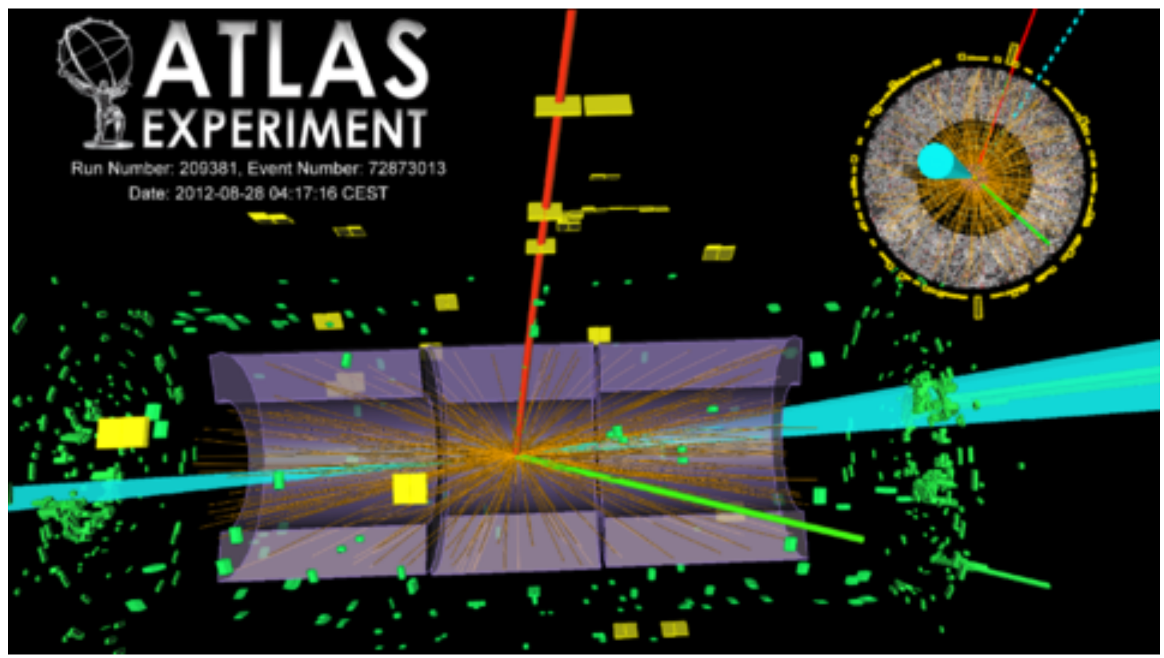




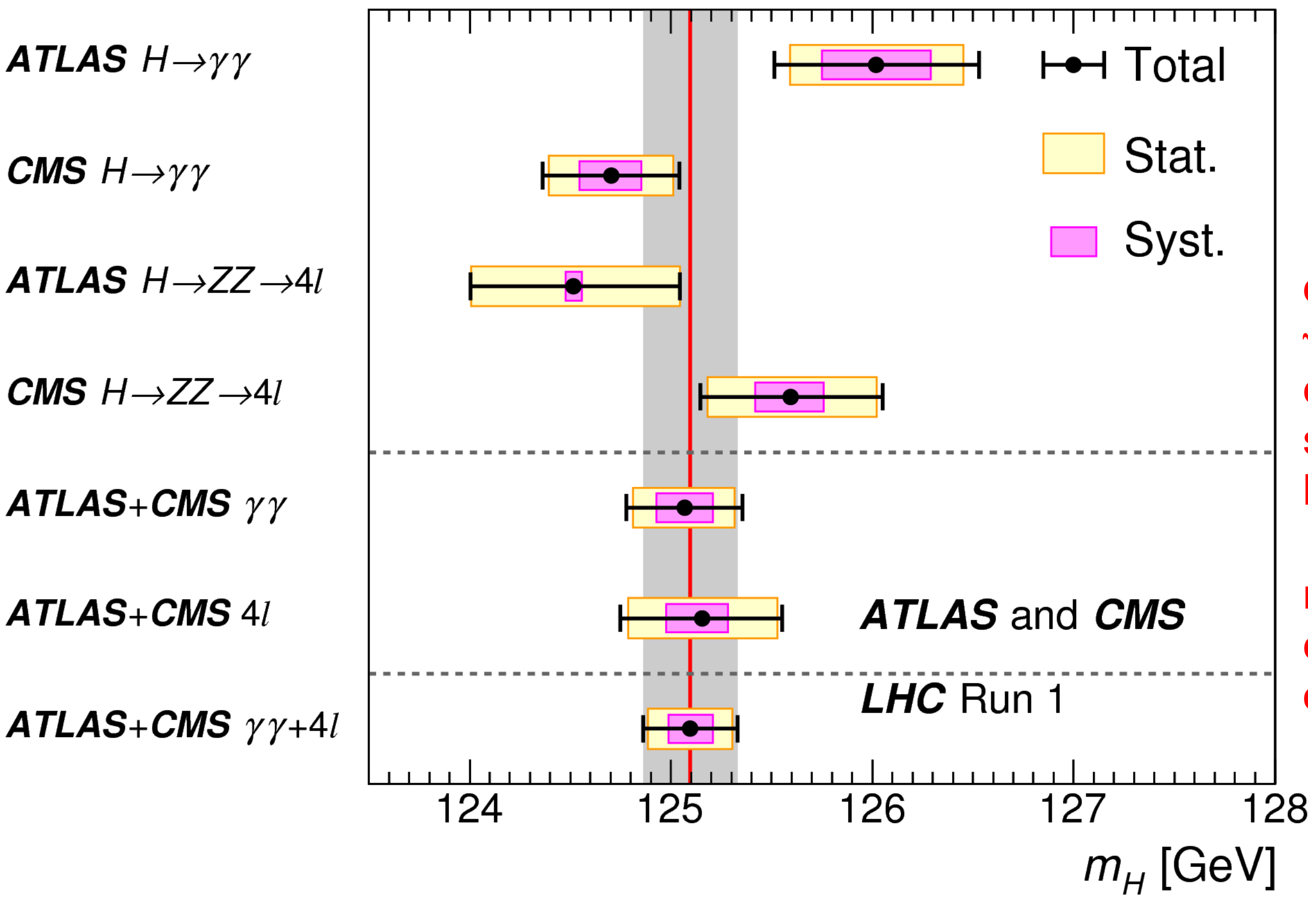
H->ττ



- One tau decays to an electron (green) and the other to a muon (red)
- Dashed line indicates direction of missing transverse momentum
- Two jets in the event
- M_{jj}=1610 GeV
- VBF category



Higgs mass determination



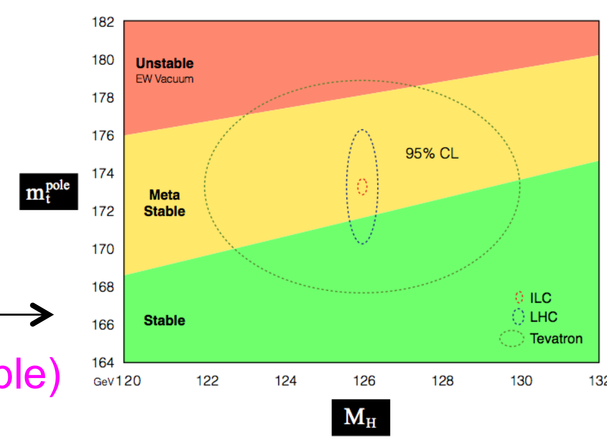
differences between ATLAS γγ and ZZ* might be exciting except that CMS sees the opposite hierarchy

mass measurements for both experiments consistent with one particle

ATLAS: m_H = 125.36 ± 0.37 (stat) ± 0.18 (syst) GeV
CMS: m_H = 125.03 ± 0.27 (stat) ± 0.14 (syst) GeV

m_{Higgs}=125.09+/-0.21(stat)+/-0.11(syst)

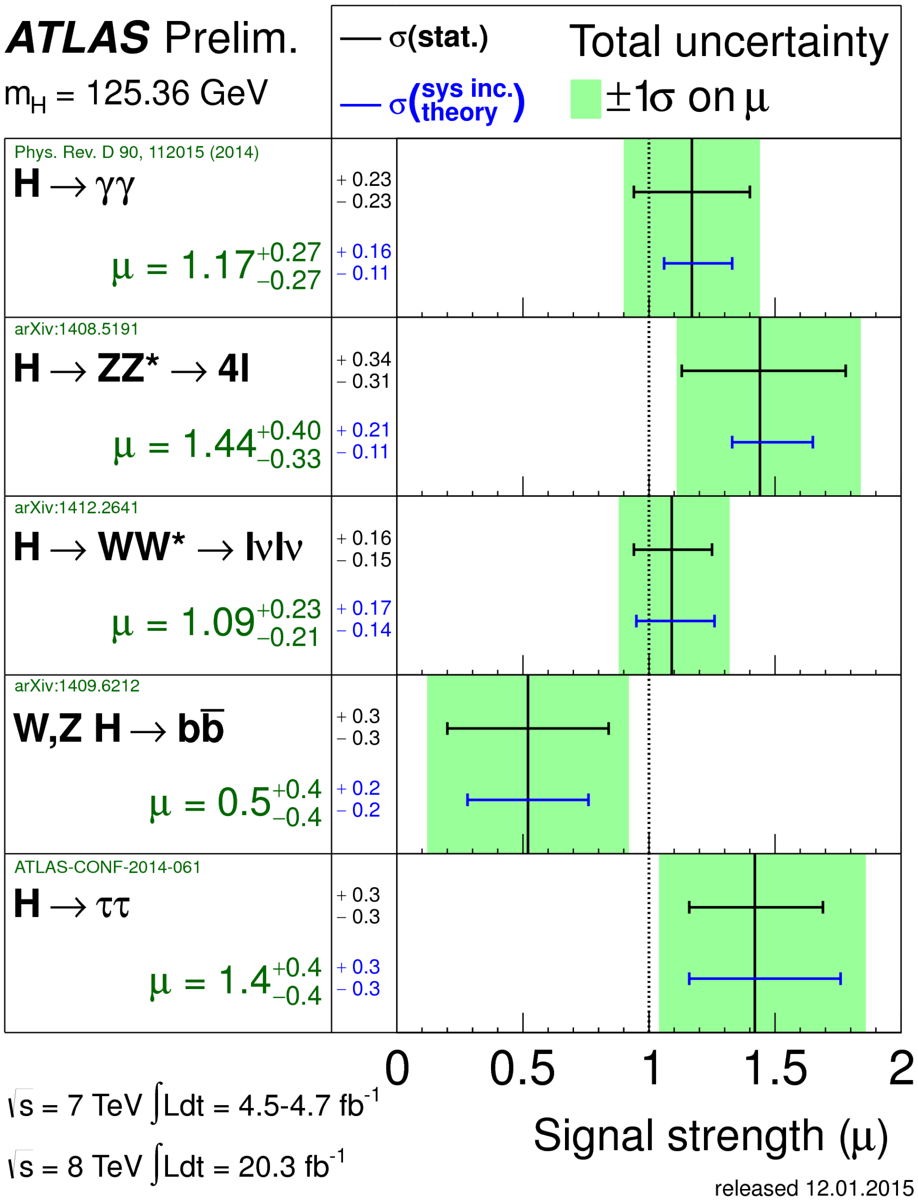
…of course, that means don't make any long-term plans
(or finish your Ph.D as quickly as possible)

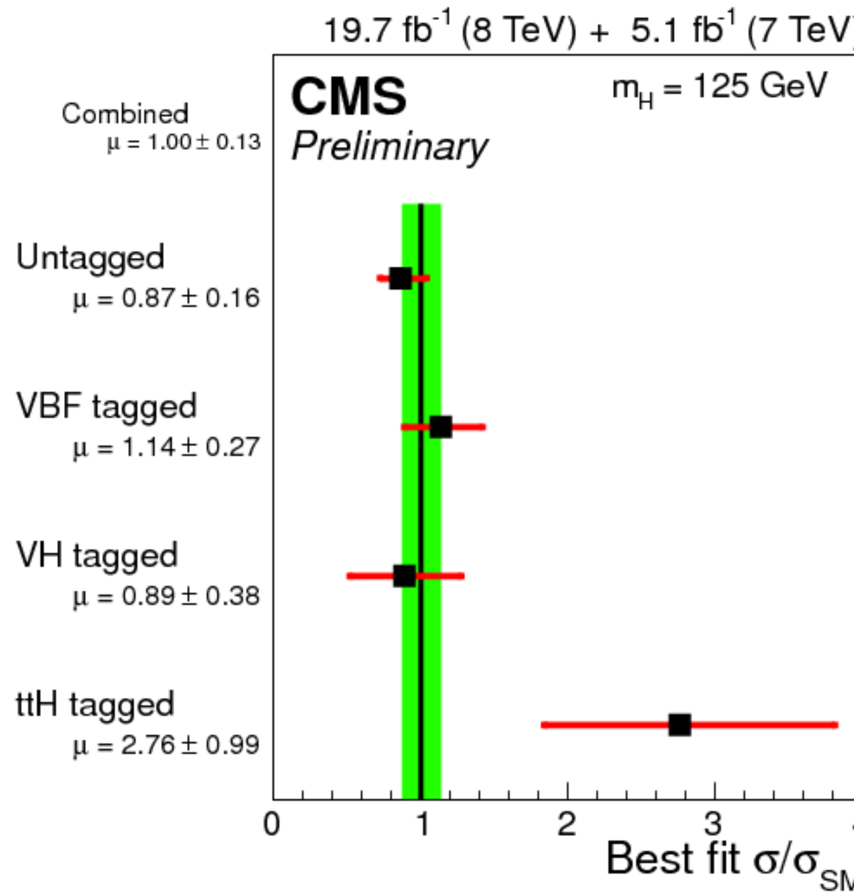


Higgs mass

	Uncertainty in ATLAS results [GeV]: observed (expected)		Uncertainty in CMS results [GeV]: observed (expected)		Uncertainty in combined result [GeV]: observed (expected)	
	$H \to \gamma\gamma$	$H \to ZZ \to 4\ell$	$H \to \gamma\gamma$	$H \to ZZ \to 4\ell$	ATLAS	CMS
Scale uncertainties:						
ATLAS ECAL non-linearity / CMS photon non-linearity	0.14 (0.16)	–	0.10 (0.13)	–	0.02 (0.04)	0.05 (0.06)
Material in front of ECAL	0.15 (0.13)	–	0.07 (0.07)	–	0.03 (0.03)	0.04 (0.03)
ECAL longitudinal response	0.12 (0.13)	–	0.02 (0.01)	–	0.02 (0.03)	0.01 (0.01)
ECAL lateral shower shape	0.09 (0.08)	–	0.06 (0.06)	–	0.02 (0.02)	0.03 (0.03)
Photon energy resolution	0.03 (0.01)	–	0.01 (<0.01)	–	0.02 (<0.01)	<0.01 (<0.01)
ATLAS $H \to \gamma\gamma$ vertex & conversion reconstruction	0.05 (0.05)	–	–	–	0.01 (0.01)	–
$Z \to ee$ calibration	0.05 (0.04)	0.03 (0.02)	0.05 (0.05)	–	0.02 (0.01)	0.02 (0.02)
CMS electron energy scale & resolution	–	–	–	0.12 (0.09)	–	0.03 (0.02)
Muon momentum scale & resolution	–	0.03 (0.04)	–	0.11 (0.10)	<0.01 (0.01)	0.05 (0.02)
Other uncertainties:						
ATLAS $H \to \gamma\gamma$ background modeling	0.04 (0.03)	–	–	–	0.01 (0.01)	–
Integrated luminosity	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	
Additional experimental systematic uncertainties	0.03 (<0.01)	<0.01 (<0.01)	0.02 (<0.01)	0.01 (<0.01)	0.01 (<0.01)	0.01 (<0.01)
Theory uncertainties	<0.01 (<0.01)	<0.01 (<0.01)	0.02 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	
Systematic uncertainty (sum in quadrature)	0.27 (0.27)	0.04 (0.04)	0.15 (0.17)	0.16 (0.13)	0.11 (0.10)	
Systematic uncertainty (nominal)	0.27 (0.27)	0.04 (0.05)	0.15 (0.17)	0.17 (0.14)	0.11 (0.10)	
Statistical uncertainty	0.43 (0.45)	0.52 (0.66)	0.31 (0.32)	0.42 (0.57)	0.21 (0.22)	
Total uncertainty	0.51 (0.52)	0.52 (0.66)	0.34 (0.36)	0.45 (0.59)	0.24 (0.24)	
Analysis weights	19% (22%)	18% (14%)	40% (46%)	23% (17%)	–	

Signal strengths

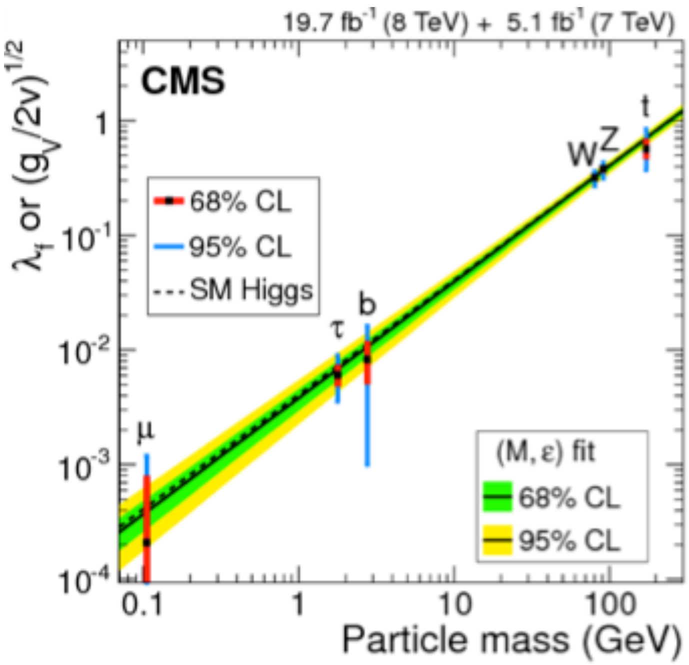


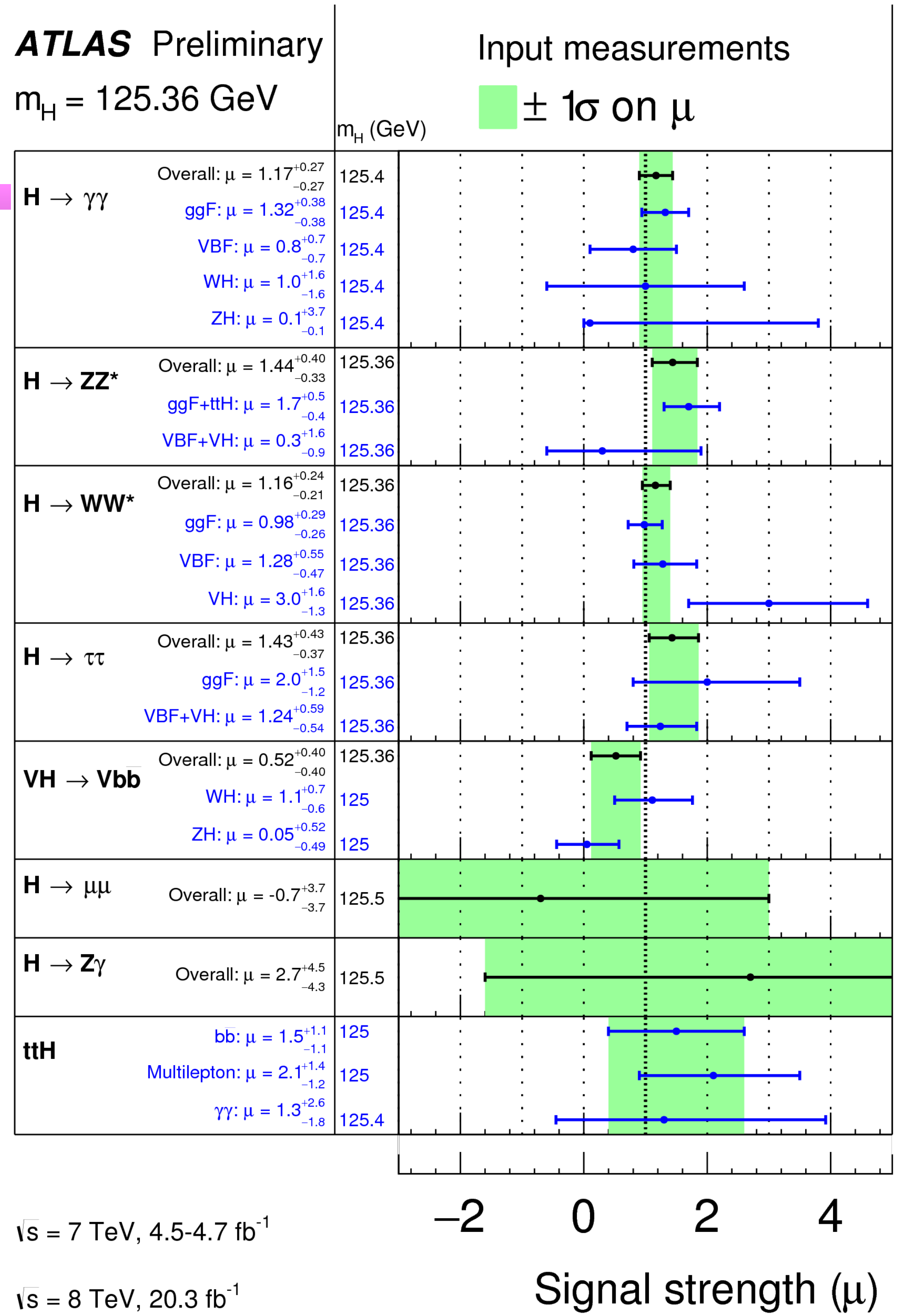


CMS: $\mu = 1.00 \pm 0.09$ (stat) ± 0.07 (syst) ± 0.08 (theory)
ATLAS: $\mu = 1.30 \pm 0.12$ (stat) ± 0.09 (syst) ± 0.10 (theory)

NB: experimental precision comparable to theoretical uncertainties

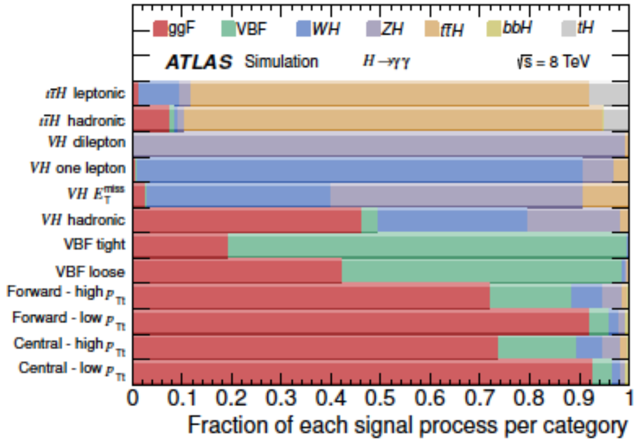
Couplings





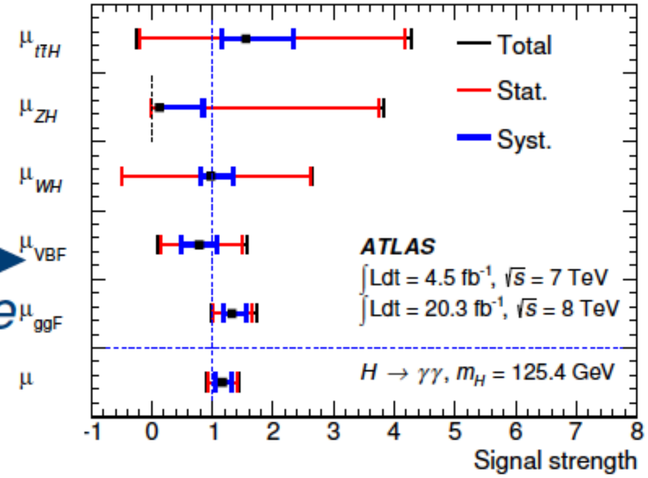
Good consistency with SM couplings
(at level of 20-50%)

Pros and Cons of μ Fits.



Raw measurements

Direct theory dependence



Interpretation

Work now on new *simplified cross sections* where fewer theory assumptions go into calculation of cross section for specific Higgs processes. Possible with larger statistics of Run 2.

Pros

- Maximum possible sensitivity
- Allows use of advanced techniques like MVAs
- Can benefit from kinematic correlations among production modes across channels in combination

Cons

- Theory predictions and *uncertainties* maximally entangled in results
- Any nontrivial theory changes require new results from experiments

HH production

- Self-coupling of the Higgs one of the holy grails of extended running at the LHC
  - directly probes EW potential
- HH production through ggF currently known at LO with full top mass dependence, at NLO with leading finite mass terms, and at NNLO in the infinite top-mass limit
- It may be necessary to compute full top mass dependence at NLO QCD
- With 3000 fb^{-1} at 14 TeV, hope for a 50% precision on self-coupling parameter

Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	$d\sigma$ @ LO QCD (full m_t dependence) $d\sigma$ @ NLO QCD (infinite m_t limit)	$d\sigma$ @ NLO QCD (full m_t dependence) $d\sigma$ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Table 1: Wishlist part 1 – Higgs (V = W, Z)

The various decays of the Standard Model Higgs boson offer a variety of final states which can be studied, and the most interesting of these are given in Table 1, along with their branching ratios and the approximate event yield in the anticipated High-Luminosity LHC (HL-LHC) dataset corresponding to 3000 fb^{-1}.

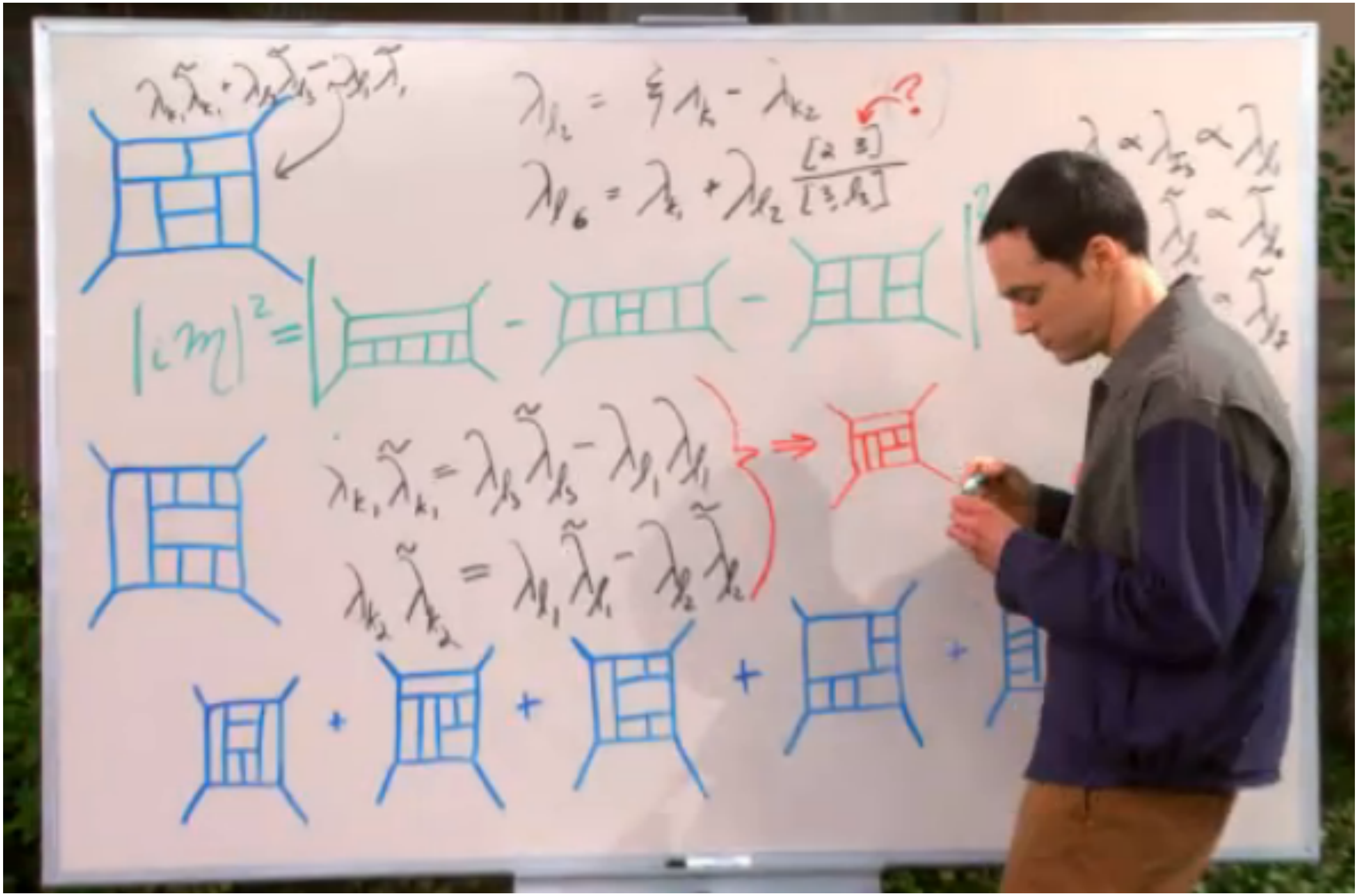
Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	40,000
$b\bar{b} + W^+W^-$	25%	31,000
$b\bar{b} + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\bar{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + b\bar{b}$	0.26%	320
$\gamma\gamma + \gamma\gamma$	0.0010%	1.2

Table 1: Branching ratios for different HH final states, and their corresponding approximate expected yields in 3000 fb^{-1} of data before any event selection is applied, assuming a total production cross section of 40.8 fb and m_H = 125 GeV.

despite small BR, one of the most promising channels; best significance using boosted regime

ATL-PHYS-PUB-2014-019

The frontier (in calculations)



Summary


Because you know it's all about that
Higgs, 'Bout that Higgs, no SUSY
REGAN

Luckily, the ntuple format for B+S has now become universal

NLO with BlackHat+Sherpa

NLO cross section

Born | loop: lc and fmlc | vsub | real

$$\sigma_n^{NLO} = \int_n \sigma_n^{tree} + \int_n \left(\sigma_n^{virt} + \Sigma_n^{sub}\right) + \int_{n+1} \left(\sigma_{n+1}^{real} - \sigma_{n+1}^{sub}\right)$$

BlackHat

so this is not Sherpa the parton shower, but Sherpa used as a (very efficient) fixed order matrix element generator

Sherpa

Branches in B+S ntuples

branch name	type	Notes
id	I	id of the event. Real events and their associated counterterms share the same id. This allows for the correct treatment of statistical errors.
nparticle	I	number of particles in the final state
px	F[nparticle]	array of the x components of the final state particles
py	F[nparticle]	array of the y components of the final state particles
pz	F[nparticle]	array of the z components of the final state particles
E	F[nparticle]	array of the energy components of the final state particles
alphas	D	$alpha_s$ value used for this event
kf	I	PDG codes of the final state particles
weight	D	weight of the event
weight2	D	weight of the event to be used to treat the statistical errors correctly in the real part
me_wgt	D	matrix element weight, the same as weight but without pdf factors
me_wgt2	D	matrix element weight, the same as weight2 but without pdf factors
x1	D	fraction of the hadron momentum carried by the first incoming parton
x2	D	fraction of the hadron momentum carried by the second incoming parton
x1p	D	second momentum fraction used in the integrated real part
x2p	D	second momentum fraction used in the integrated real part
id1	I	PDG code of the firt incoming parton
id2	I	PDG code of the second incoming parton
fac_scale	D	factorization scale used
ren_scale	D	renormalization scale used
nuwgt	I	number of additional weights
usr_wgts	D[nuwgt]	additional weights needed to change the scale

- H3i-ggf_8TeV_HT2-unc_AntiKt4_CT10nlo_pt30-eta4.4_NLO.root
  - FacHt2_RenHt2_PDFCT10nlo_JetAntiKt4;1
  - FacHt2_RenHt2_PDFCT10nlo_down_JetAntiKt4;1
  - FacHt2_RenHt2_PDFCT10nlo_up_JetAntiKt4;1
  - FacHt2_RenHt_PDFCT10nlo_JetAntiKt4;1
  - FacHt2_RenHt4_PDFCT10nlo_JetAntiKt4;1
  - FacHt4_RenHt2_PDFCT10nlo_JetAntiKt4;1
  - FacHt4_RenHt4_PDFCT10nlo_JetAntiKt4;1
  - FacHt_RenHt_PDFCT10nlo_JetAntiKt4;1
  - FacHt_RenHt2_PDFCT10nlo_JetAntiKt4;1

CT10 PDF, antikT4 jet clustering, p_T^{jet}>30 GeV/c, $|y_{jet}|$<4.4

We've run over a number of scales around HT/2. May ultimately try for a more detailed map of the scale dependence.

Have stored on the order of 100 histograms. The list starts with the histograms used for the H->$\gamma\gamma$ + jets analysis from Run 1. More can be easily added.

- H3i-ggf_8TeV_HT2-unc_AntiKt4_CT10nlo_pt30-eta4.4_NLO.root
  - FacHt2_RenHt2_PDFCT10nlo_JetAntiKt4;1
    - H_pT;1
    - H_y;1
    - H_mass;1
    - jet1_pT;1
    - jet2_pT;1
    - jet3_pT;1
    - jet4_pT;1
    - jets_HT;1
    - H1j_pT;1
    - H2j_pT;1
    - H3j_pT;1
    - H4j_pT;1
    - jet1_y;1
    - jet2_y;1
    - jet3_y;1
    - jet4_y;1
    - jet1_mass;1
    - jet2_mass;1
    - jet3_mass;1
    - jet4_mass;1
    - jet1_tau;1
    - jet2_tau;1
    - jet3_tau;1
    - jet4_tau;1
    - jets_tau_max;1
    - jets_tau_sum;1
    - jets_N_incl;1
    - jets_N_excl;1
    - jjpT_dy;1

Wu Ki Tung Award for Early Career Research on QCD

- See 2015 information at

http://tigger.uic.edu/~varelas/tung_award/

- 2014 winner: Stefan Hoeche
- Contribute at

https://www.givingto.msu.edu/gift/?sid=1480

- **MSU will match any donations**