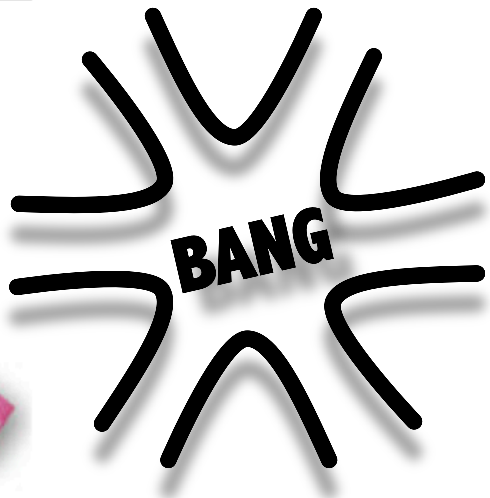
H->bb at the LHC



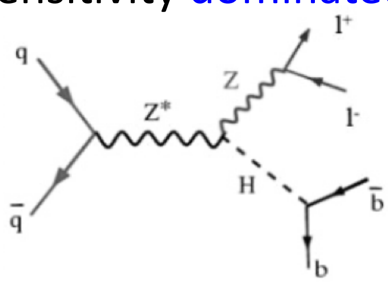
Ricardo Gonçalo (RHUL)

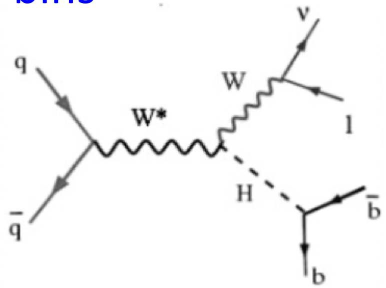
HSG5 Meeting – 19 September 2012

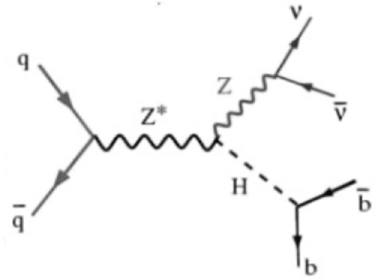
WH/ZH Searches

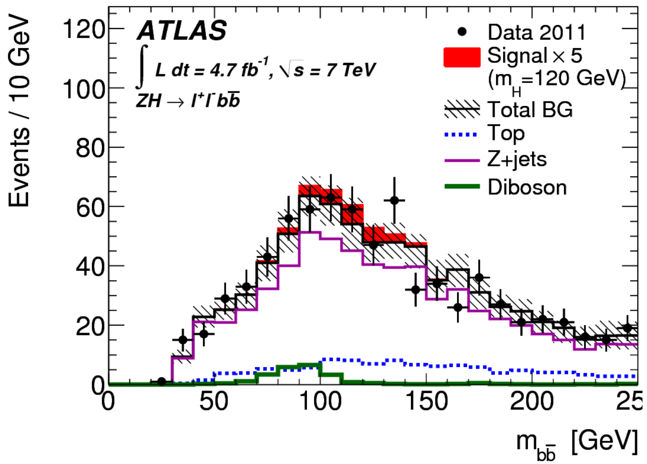
ATLAS VH, H->bb Analyses

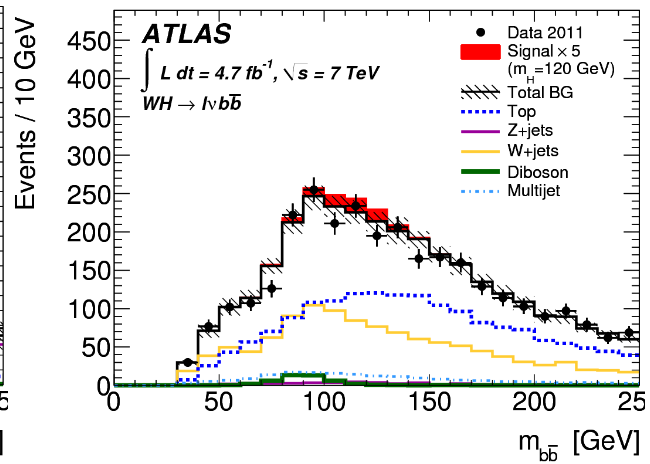
- Cut-based analyses of 2011 data (4.7 fb^{-1}): ZH->llbb, WH->lvbb, ZH->vvbb
- Select events with 2, 1, 0 leptons and 2, 3 jets; cut on E_T^{miss} and m_T^W
- Reconstruct m_{bb} to search for H->bb
- Background shapes from MC (±systematics), normalized in control regions
  - Control of background and associated systematics is the dominant factor in sensitivity
- Divide in categories of p_T of vector boson recoiling against Higgs
  - ZH->llbb, WH->lvbb: [0,50], [50,100], [100,200], [200, ∞]; ZH->vvbb: [120,160], [160,200] [200, ∞]
- Sensitivity dominated by higher p_T bins

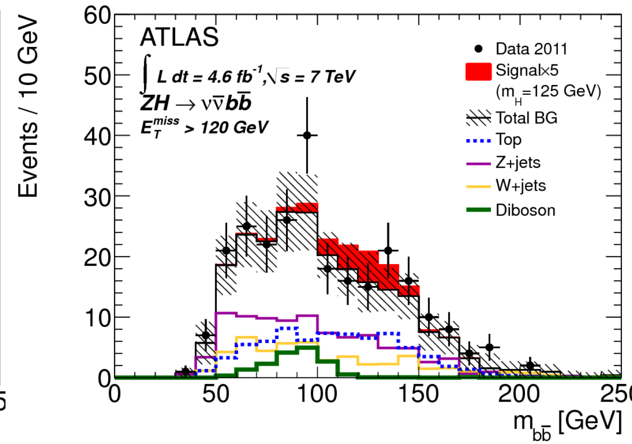










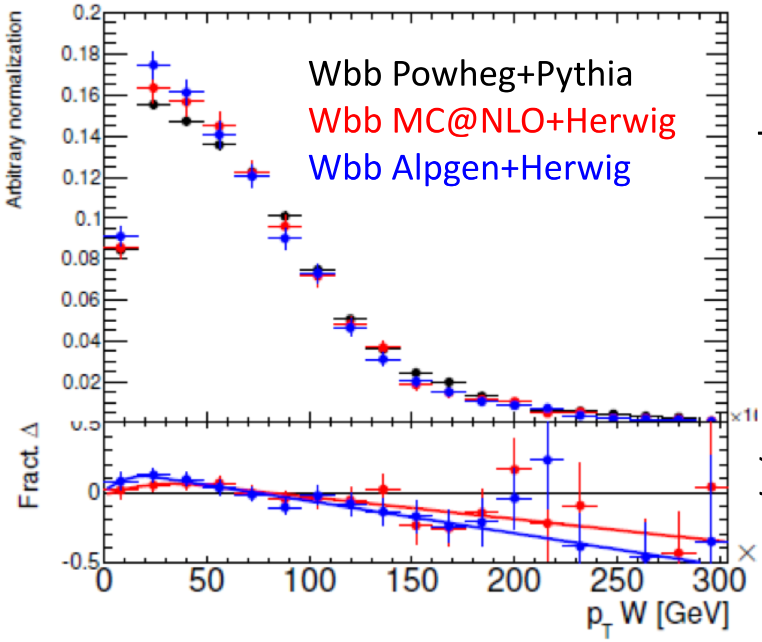


http://arxiv.org/pdf/1207.0210v1.pdf

Background Systematic Uncertainty

bin	$ZH \to \ell^+\ell^- b\bar{b}$ p_T^V [GeV] 0-50	50-100	100-200	>200	$WH \to \ell\nu b\bar{b}$ p_T^V [GeV] 0-50	50-100	100-200	>200	$ZH \to \nu\bar{\nu}b\bar{b}$ p_T^V [GeV] 120-160	160-200	>200
Components of the relative systematic uncertainties of the background [%]											
b-tag eff	1.4	1.0	0.3	4.8	0.9	1.3	0.9	7.2	4.1	4.2	5.5
BG norm	3.6	3.4	3.6	3.8	2.7	1.8	1.8	4.5	2.7	2.2	3.2
jets/E_T^{miss}	2.1	1.2	2.7	5.1	1.5	1.4	2.1	9.5	7.7	8.2	12.1
leptons	0.2	0.3	1.1	3.4	0.1	0.2	0.2	1.7	0.0	0.0	0.0
luminosity	0.2	0.1	0.2	0.4	0.1	0.1	0.1	0.2	0.2	0.5	0.7
pileup	0.9	1.6	0.5	1.3	0.1	0.2	0.8	0.5	1.6	2.5	3.0
theory	5.2	1.3	4.7	14.9	2.2	0.3	1.6	14.8	2.9	4.0	7.7
total BG	6.9	4.3	6.6	17.3	3.9	2.7	3.4	19.6	9.7	10.6	16.0

- Background normalization from control reg.
- Systematic in modeling of m_{bb} and $p_T^{W/Z}$ shape
- Dominates theory uncertainty, especially $p_T^{W/Z}$ shape – analysis categories in $p_T^{W/Z}$
- Considered differences between models: Alpgen+Hwg, Powheg+Pythia or Herwig, aMC@NLO+Hwg
- Dominant uncertainty in highest sensitivity categories!



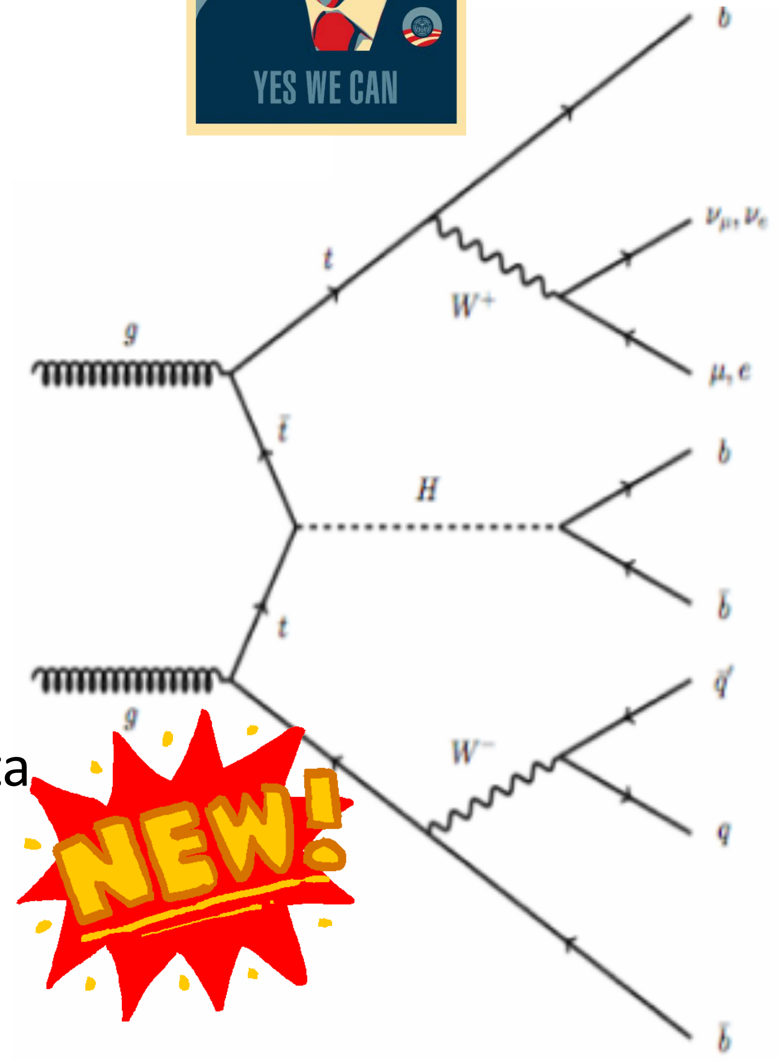
G.Piacquadio LHC Th.WG 23/5/12

tt̄H Search

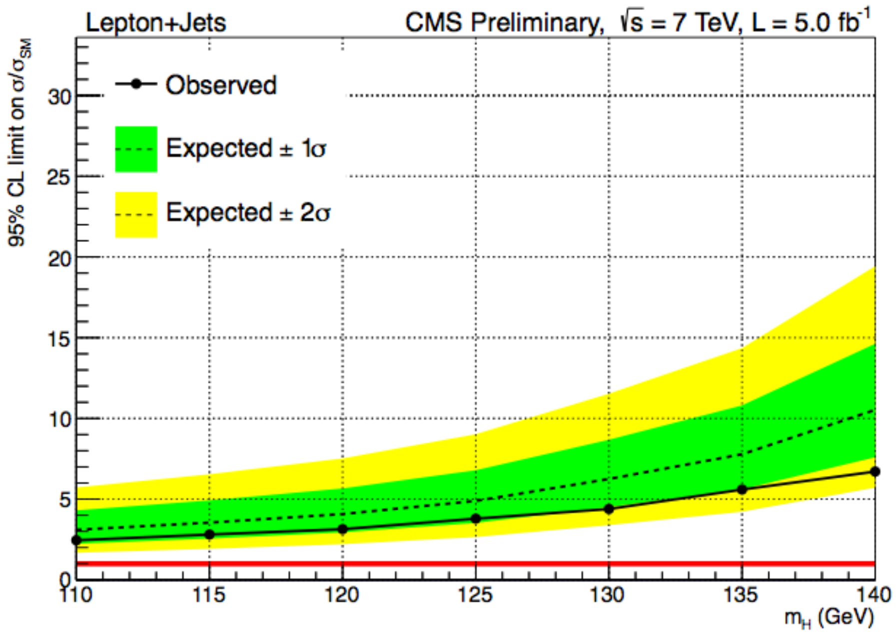
Early LHC ttH analyses:


Yes we can!

- Very difficult analysis, plagued by combinatorial “background”, and ttbar+X actual background
- First LHC results shown by CMS at ICHEP
  - CMS-PAS-HIG-12-025: https://cdsweb.cern.ch/record/1460423/
  - Single-lepton and di-lepton modes
  - 2011 data (5fb^{-1})
- ATLAS just released ttH analysis of 2011 data (4.7fb^{-1})
  - ATLAS-CONF-2012-135: https://cdsweb.cern.ch/record/1478423 Single-lepton mode



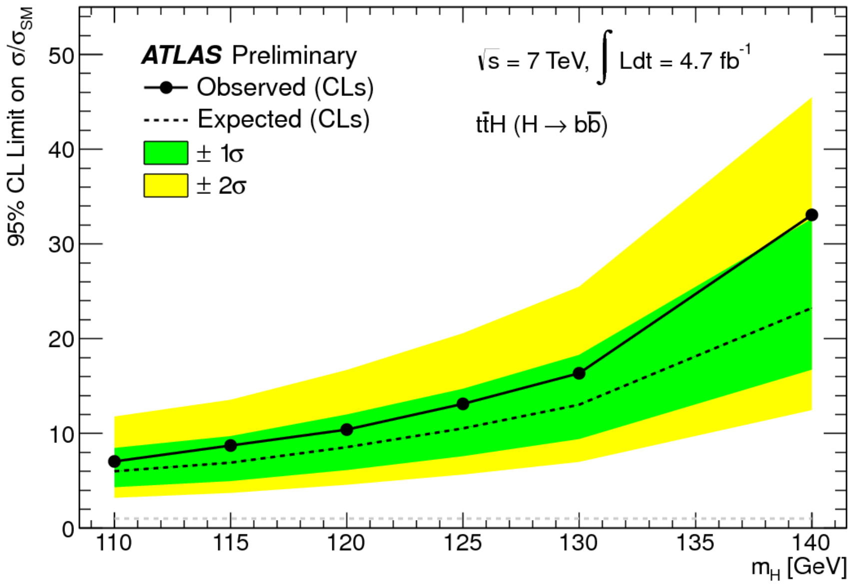
CMS



m_H (GeV/c^2)	Obs limit	Median Exp limit
110	2.5	3.1
115	2.8	3.6
120	3.1	4.1
125	3.8	4.9
130	4.4	6.3
135	5.6	7.8
140	6.7	10.5

Lepton+jets mode

ATLAS



m_H (GeV)	observed	median	stat only
110	7.0	6.0	3.5
115	8.7	6.9	4.0
120	10.4	8.5	4.9
125	13.1	10.5	6.1
130	16.4	13.0	7.8
140	33.0	23.2	14.2

Very big difference!...

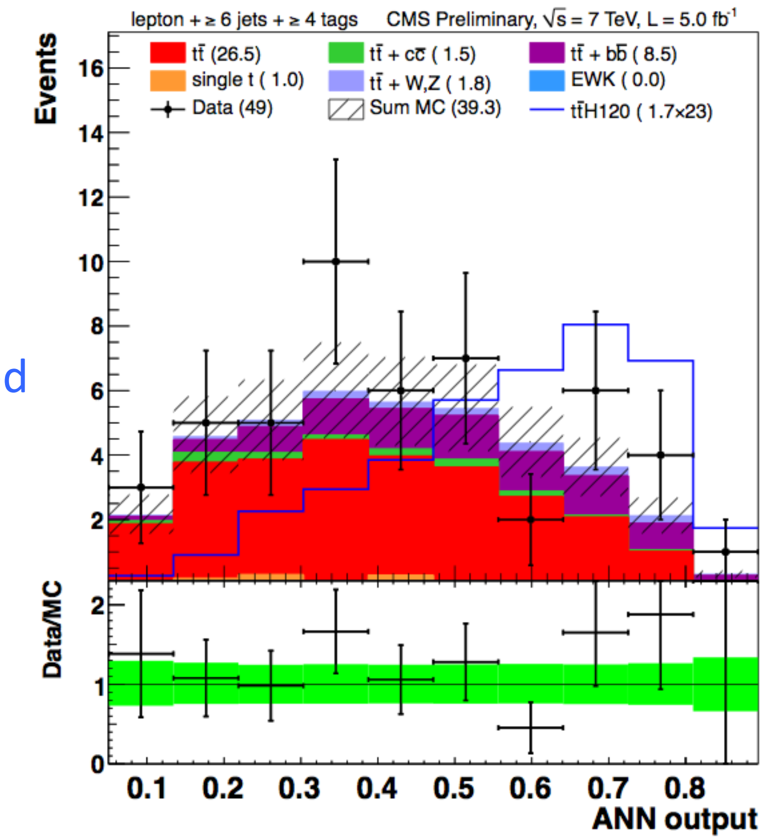
CMS Analysis

- Neural Network analysis
- Lepton+jets & di-lepton analyses
- 10 best kinematic/event shape/ b-tagging variables chosen from "pool" of candidate variables
- Optimized for each #jets/#b-tags category
- Simultaneous fit for S and B on NN output distributions

CMS
e: p_T>30GeV |η|<2.5
μ: p_T>30GeV |η|<2.1
Jets (0.5): p_T>30/40GeV |η|<2.4
B-tag: 70% (b) 20% (c) 2% (lite)

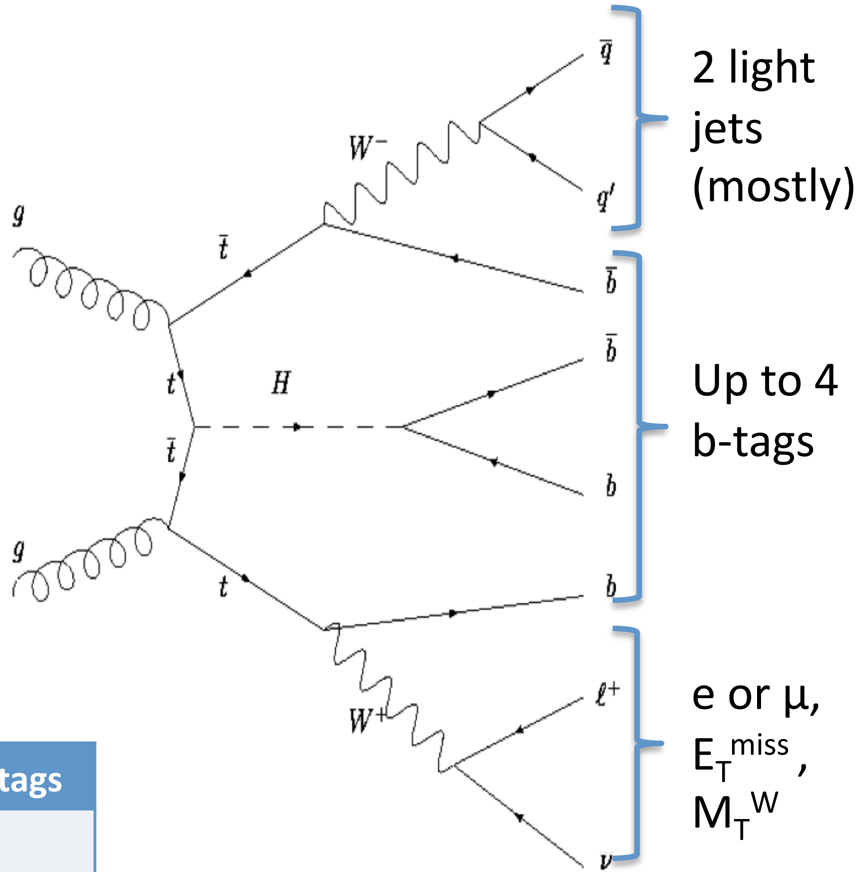
✔ Used
✗ Not used

	0 b-tags	1 b-tag	2 b-tags	3 b-tags	≥4 b-tags
4 jets	✗	✗	✗	✔	✔
5 jets	✗	✗	✗	✔	✔
≥6 jets	✗	✗	✔	✔	✔



ATLAS Analysis – lepton+jets

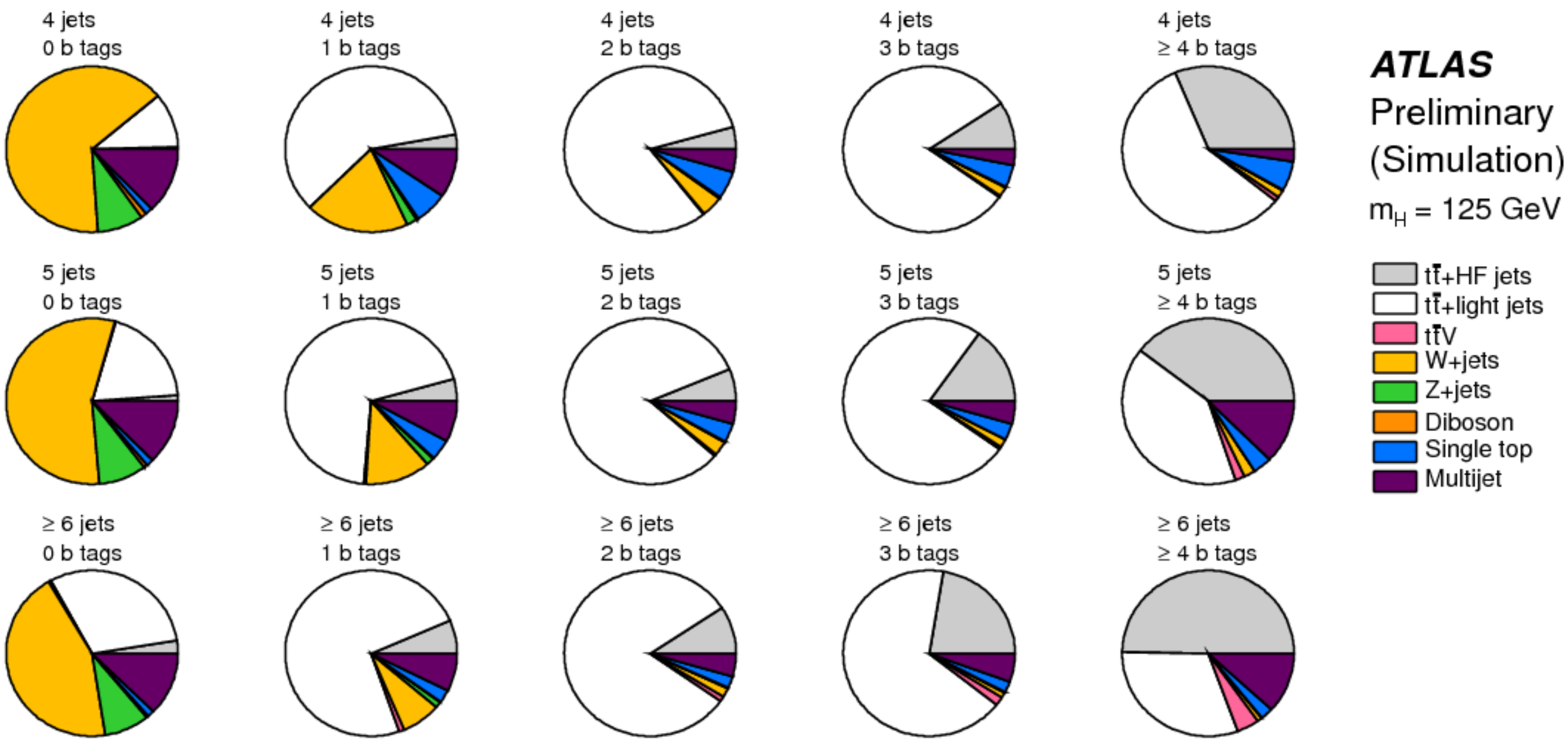
- Cut-based analysis
- For ≥6 jets & ≥3 b-tags:
  - Use m_{bb}, as discriminating variable
  - Kinematic fit to reconstruct ttbar
  - Use leftover b-jets for H->bb
- Elsewhere: use H_T^{had} (scalar sum of jet p_T)
- Fit Signal and Background regions to get limits
- Get final background normalizations and systematic uncertainties ("nuisance parameters") from fit to data – profiling
- Use control regions to check fit is ok



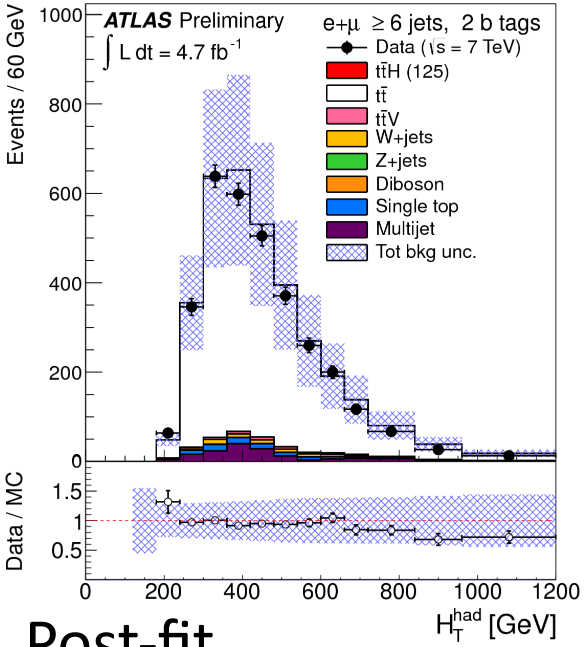
	0 b-tags	1 b-tag	2 b-tags	3 b-tags	≥4 b-tags
4 jets	H_T^{had}	H_T^{had}		H_T^{had}	
5 jets	H_T^{had}	H_T^{had}	H_T^{had}	H_T^{had}	H_T^{had}
≥6 jets	H_T^{had}	H_T^{had}	H_T^{had}	m_{bb}	m_{bb}

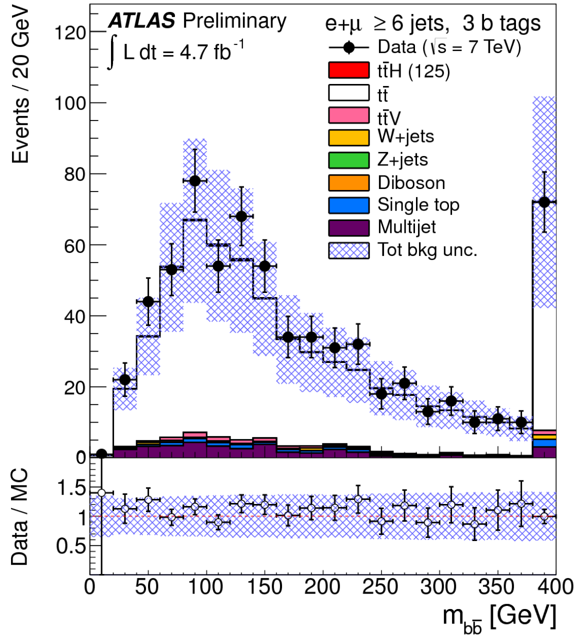
Signal
Background
Control regions

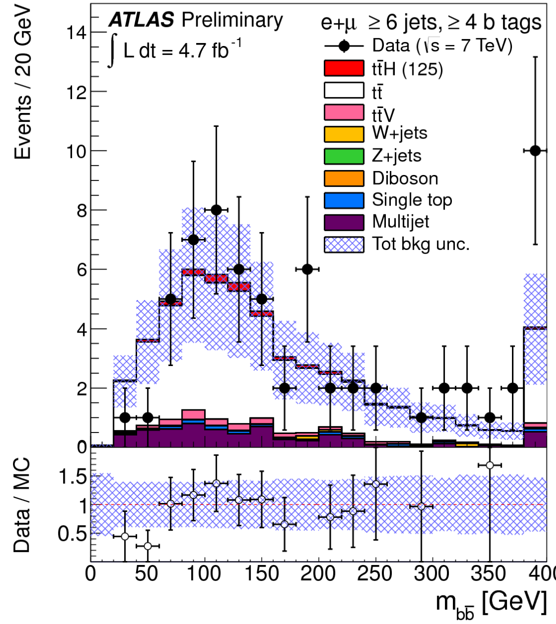
ATLAS Analysis



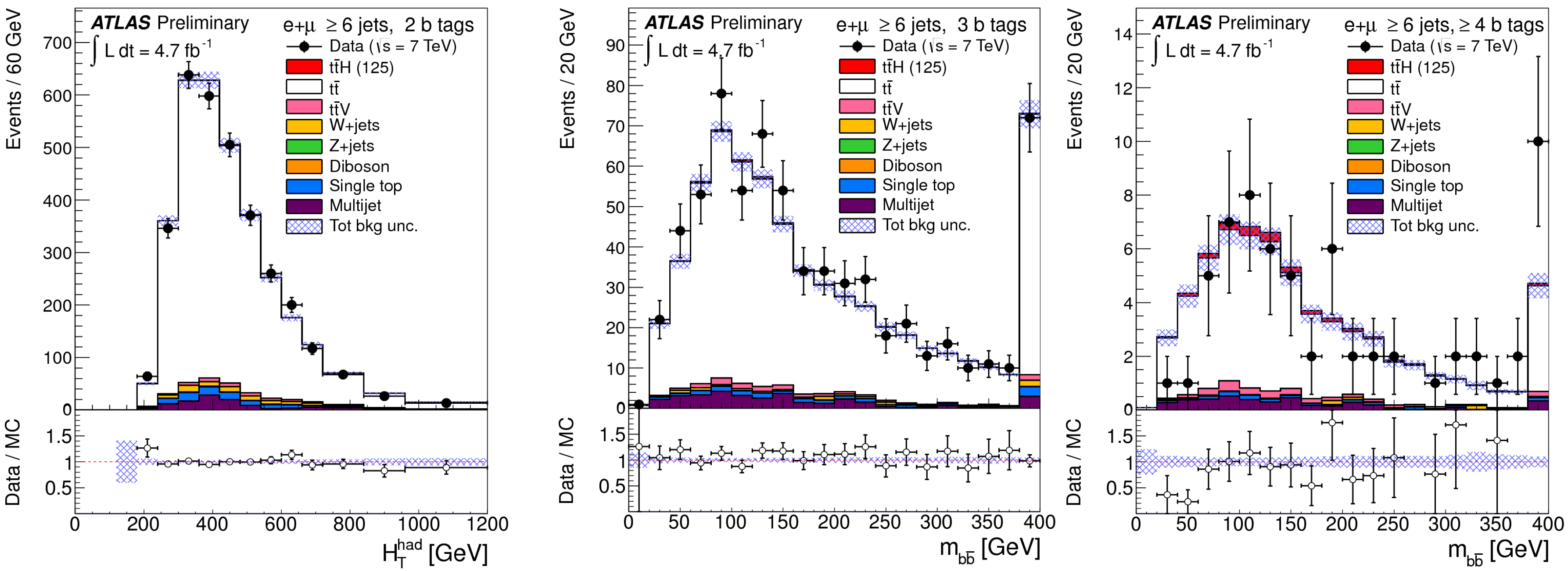
Pre-fit







Post-fit



ATLAS/CMS differences

Systematics:

- No QCD systematics (no QCD background?!)
- No ttH modeling
- No W+jets/HF systematic
- No JVF systematic (pileup suppression)
- Different treatment of Jet Energy Scale (ATLAS 16 NP), b-tag sys. (ATLAS 9 NP) and c-tag sys (ATLAS 5 NP): CMS one Nuis. Par.
- b and c tagging correlated
- One tt systematic uncertainty (ATLAS 3 NP)
- ttbar+HF 20% instead of 50% uncertainty

Summary:

- ATLAS using CMS systematics: 35% better
- 20% improvement from more signal
- Remaining improvement from use of Multivariate analysis (22%)

In numbers:

- σ/σ_{SM} = 10.5 -> 7.8 from systematics
- Take 22% improvement from MVA: -> 6.1
- Take 20% additional signal: σ/σ_{SM} -> 5.1 (expect)
- CMS: 4.9 (expected)

Cuts:

- Electrons and muon:
  - ATLAS p_T>20/25GeV
  - CMS p_T > 30 GeV
- Jets:
  - ATLAS pT>25GeV
  - CMS 3 leading jets pt > 40 GeV (otherwise 30 GeV)
- More signal and higher cuts. Not clear what signal sources are used

Channel	Signal		Background		$S/\sqrt{(B)}$		Ratio: $S/\sqrt{(B)}$
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS	CMS/ATLAS
6jet, 2tag	4.45	6.3	3567.38	2255.8	0.0745	0.133	1.78
4jet, 3tag	1.23	3.5	1294.14	1041.6	0.0341	0.108	3.17
5jet, 3tag	2.8	4.7	887.25	666.7	0.0940	0.182	1.94
6jet, 3tag	4.61	4.4	622.88	404.9	0.1847	0.219	1.18
4jet, 4tag	0.16	0.5	19.94	20	0.0358	0.112	3.12
5jet, 4tag	0.83	1.2	38.33	31.8	0.1341	0.213	1.59
6jet, 4tag	2.28	1.7	53.12	39.3	0.3128	0.271	0.86
Total	16.4	22.3			0.4084	0.492	1.20

Conclusions

- Should get to the bottom of ttH differences…
  - **BUT** Nice problem to have! ttH can be done at LHC!!
- Uncertainties:
  - Background matters!
  - Theory uncertainty matters!
  - Background theory uncertainty matters!

Bonus slides

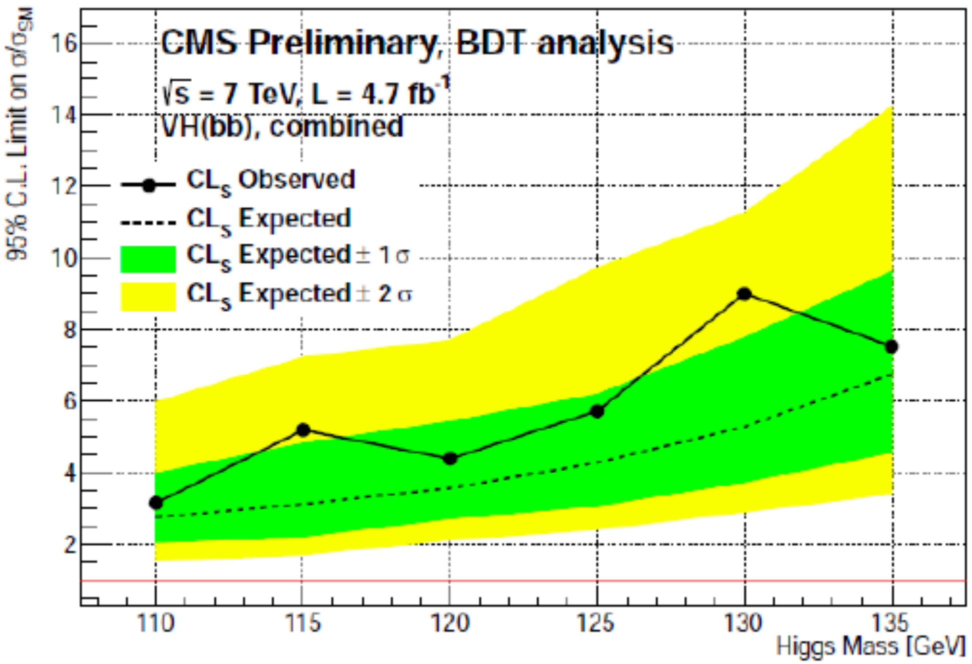
Details and Results:
WH/ZH Analyses

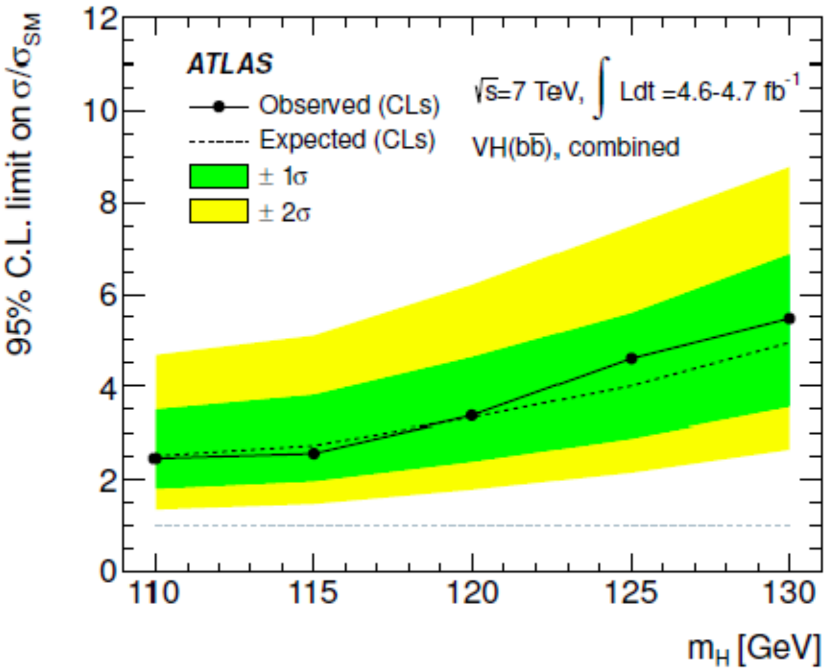
Simulation of signal and background

- ATLAS:
- W+b-jets – Powheg+Pythia
- W+c-jets – Sherpa
- W+light jets – Alpgen+Herwig
- Z+b/c-jets - Sherpa
- Z+light jets – Alpgen+Herwig
- ttbar – MC@NLO
- Single top – MC@NLO
- Dibosons– Herwig
- Signal – Pythia 6.4
  - Normalized to NLO (EW) + NNLO (QCD)
  - Tried Powheg but got wrong b-tagging efficiency (10%!)

- CMS:
- W+jets – Madgraph
- Z+jets - Madgraph
- ttbar - Madgraph
- Single top – Powheg+Herwig
- Dibosons – Pythia
- Signal – Powheg+Herwig

The situation in Moriond 2012





- Sensitivity were really very close.
- However, analyses very different:
  - ATLAS uses several bins in pT(W/Z). CMS was exploring one only bin. This gave an advantage to ATLAS.
  - ATLAS was using a LH fit based on the mass distribution. CMS a BDT based on kinematic variables, but then was using a single cut on the BDT. Similar performance?

ATLAS/CMS Comparison

ATLAS

$WH \rightarrow \ell\nu b\bar{b}$	$ZH \rightarrow \ell^+\ell^- b\bar{b}$	$ZH \rightarrow \nu\bar{\nu} b\bar{b}$
p_T^{b-jet1} >45 GeV, p_T^{b-jet2} >25 GeV; $\Delta R_{b-jet1,b-jet2}$ >0.7 for p_T^V <200 GeV		
single-lepton trigger	single-lepton + di-electron trigger	E_T^{miss} trigger with 70 GeV threshold
p_T^l >25 GeV, 1 lepton	p_T^l >20 GeV, 2 leptons	p_T^l >10 GeV, 0 lepton
E_T^{miss} >25 GeV	E_T^{miss} <50 GeV	E_T^{miss} >120 GeV
m_T^W >40 GeV	83 GeV< m_{ll} <99 GeV	-
== 2 good jets, ==2 b-jets	2 or 3 good jets, ==2 b-jets	== 2 good jets, ==2 b-jets
loose jets/leptons veto	-	-

CMS

Variable	W($\ell\nu$)H	Z($\ell\ell$)H	Z($\nu\nu$)H
$m_{\ell\ell}$	–	75 <$m_{\ell\ell}$ < 105	–
$p_T(b_1)$	> 30	> 20	> 80
$p_T(b_2)$	> 30	> 20	> 30
p_T(jj)	> 165	> 100	> 160
p_T(V)	> 160	> 100	–
CSV1	> 0.898	> 0.898	> 0.898
CSV2	> 0.4	> 0.5	> 0.5
$\Delta\phi$(V, H)	> 2.95	> 2.90	> 2.90
N_{aj}	= 0	< 2	–
N_{al}	= 0	–	= 0
pfMET	> 35(W(eν)H)	–	> 160
$\Delta\phi$(pfMET, J)	–	–	> 1.5
M(jj)(110)	95–125	90–120	95–125
M(jj)(115)	100–130	95–125	100–130
M(jj)(120)	105–135	100–130	105–135
M(jj)(125)	110–140	105–135	110–140
M(jj)(130)	115–145	110–140	115–145
M(jj)(135)	120–150	115–145	120–150

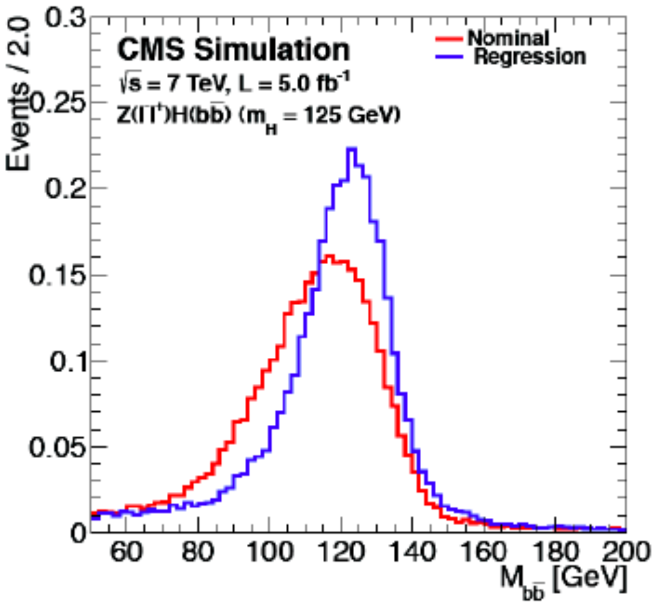
- Most striking differences:
- **B-tagging:**
  - CMS always has one loose (~70% eff.), one tight (~50% eff.) tag
  - ATLASuse two loose tags (too much c-contamination??)
- **QCD rejection:**
  - CMS uses no cut on m_T(W), and a cut on MET>35 GeV only for WH->evbb channel
  - ATLAS has not optimized this as a function of p_T^W
- **Z → vv:**
  - CMS uses also events with additional jets, whereas ATLAS requires 2 jets to avoid ttbar

ATLAS/CMS Comparison

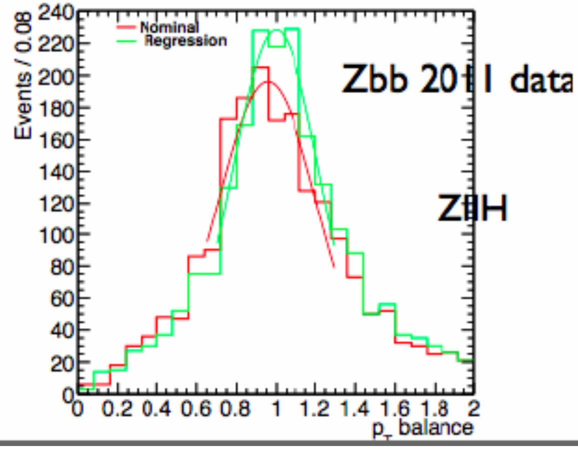
- ATLAS Expected exclusions:
  - llbb 6-12 (9 @ 125)
  - lvbb 4-9 (7.5 @ 125)
  - vvbb 4-7.5 (6.0 @ 125)
  - Combination 2.5-6 (4.0 @ 125 GeV)
- CMS Expected exclusions @ 125:
  - Cut based S/√B
  - lvbb ~0.50 → excl. ~4 w/o systematics
  - llbb ~0.29 → excl. ~6.9 w/o systematics
  - vvbb ~0.41 →excl. ~5 w/o systematics
  - After BDT + full analysis + full systematics => CMS combined exclusion is ~4.27@ 125 GeV.

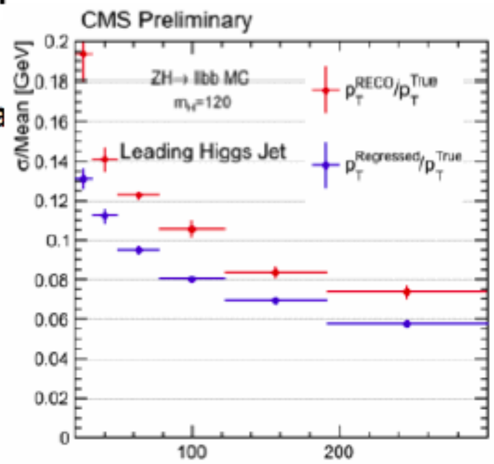
CMS VH analysis: changes for ICHEP

- Mass resolution was further improved wrt to default (but even for default reco they claim ~10% resolution).
- Using BDT regression based on pT, h, Uncorrected pT, ET, MT, pT leading track, charged had. fraction, SV info (if any), MET in Z(ll) events
- Training at all mass points simultaneously to avoid bias.



- Improvements of the order of 20% for Z(ll)H, 15% for other channels.
- Validated with data (pT balance in Zbb and top mass in ttbar + single-top)
- Regression acts on pT, not on mass?





- Analysis sensitivity improved by **~10-20%**.

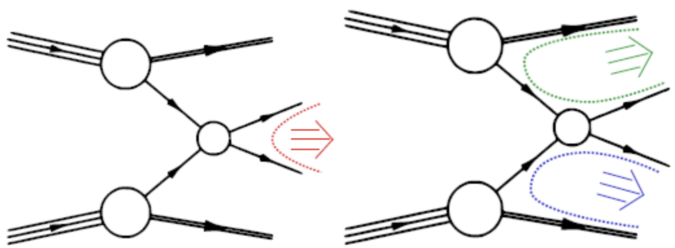
CMS VH analysis: changes for ICHEP

- An additional lower pT(W/Z) bin was added to all three analysis a la ATLAS:
  - lvbb: [120-170],[170-inf]
  - vvbb: [120,160],[160-inf]
  - llbb: [50,100],[100-inf]
- but then in addition the same p_T info is used again in the analysis BDT.
- Sensitivity improvement: **~10-15% depending on channel.**

CMS VH analysis: changes for ICHEP

- The full BDT shape was used. Sensitivity improved **by ~20%.**
- Input variables:

Variable
p_{Tj}: transverse momentum of each Higgs daughter
$m(\mathrm{jj})$: dijet invariant mass
$p_T(\mathrm{jj})$: dijet transverse momentum
$p_T(\mathrm{V})$: vector boson transverse momentum (or pfMET)
$\mathrm{CSV}_{\mathrm{max}}$: value of CSV for the b-tagged jet with largest CSV value
$\mathrm{CSV}_{\mathrm{min}}$: value of CSV for the b-tagged jet with second largest CSV value
$\Delta\phi(\mathrm{V,H})$: azimuthal angle between V (or E_T^{miss}) and dijet
$\lvert\Delta\eta(\mathrm{jj})\rvert$; difference in η between Higgs daughters
$\Delta R(\mathrm{j1,j2})$; distance in η–ϕ between Higgs daughters (not for $\mathrm{Z}(\ell\ell)\mathrm{H}$)
N_{aj}: number of additional jets ($p_T > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 4.5$)
$\Delta\phi(\mathrm{E_T^{miss}},\mathrm{jet})$: azimuthal angle between E_T^{miss} and the closest jet (only for $\mathrm{Z}(\nu\nu)\mathrm{H}$)
$\Delta\theta_{\mathrm{pull}}$: color pull angle [62] (not for $\mathrm{Z}(\ell\ell)\mathrm{H}$)



- These variables are all reasonable.
- Notice that pT(add. jet) is not used.
- Notice the interesting use of Dq(pull) of colc
  - Tried in ATLAS, but basically no sensitivity after rest of the analysis optimization

Data-driven background determination

CMS 2011

Process	WH	Z(ℓℓ)H	Z(νν)H
Low p_T			
W + udscg	$0.88 \pm 0.01 \pm 0.03$	–	$0.89 \pm 0.01 \pm 0.03$
$Wb\overline{b}$	$1.91 \pm 0.14 \pm 0.31$	–	$1.36 \pm 0.10 \pm 0.15$
Z + udscg	–	$1.11 \pm 0.03 \pm 0.11$	$0.87 \pm 0.01 \pm 0.03$
$Zb\overline{b}$	–	$0.98 \pm 0.05 \pm 0.12$	$0.96 \pm 0.02 \pm 0.03$
$t\overline{t}$	$0.93 \pm 0.02 \pm 0.05$	$1.03 \pm 0.04 \pm 0.11$	$0.97 \pm 0.02 \pm 0.04$
High p_T			
W + udscg	$0.79 \pm 0.01 \pm 0.02$	–	$0.78 \pm 0.02 \pm 0.03$
$Wb\overline{b}$	$1.49 \pm 0.14 \pm 0.19$	–	$1.48 \pm 0.15 \pm 0.20$
Z + udscg	–	$1.11 \pm 0.03 \pm 0.11$	$0.97 \pm 0.02 \pm 0.04$
$Zb\overline{b}$	–	$0.98 \pm 0.05 \pm 0.12$	$1.08 \pm 0.09 \pm 0.06$
$t\overline{t}$	$0.84 \pm 0.02 \pm 0.03$	$1.03 \pm 0.04 \pm 0.11$	$0.97 \pm 0.02 \pm 0.04$

CMS 2012

Process	WH	Z(ℓℓ)H	Z(νν)H
Low p_T			
W + udscg	$0.97 \pm 0.01 \pm 0.03$	–	$0.91 \pm 0.03 \pm 0.03$
$Wb\overline{b}$	$2.05 \pm 0.21 \pm 0.33$	–	$1.63 \pm 0.29 \pm 0.14$
Z + udscg	–	$1.41 \pm 0.03 \pm 0.16$	$1.01 \pm 0.05 \pm 0.03$
$Zb\overline{b}$	–	$1.04 \pm 0.05 \pm 0.20$	$1.00 \pm 0.10 \pm 0.04$
$t\overline{t}$	$1.12 \pm 0.01 \pm 0.06$	$1.06 \pm 0.03 \pm 0.11$	$1.02 \pm 0.03 \pm 0.03$
High p_T			
W + udscg	$0.88 \pm 0.01 \pm 0.02$	–	$0.86 \pm 0.03 \pm 0.03$
$Wb\overline{b}$	$1.30 \pm 0.20 \pm 0.17$	–	$1.43 \pm 0.28 \pm 0.18$
Z + udscg	–	$1.41 \pm 0.03 \pm 0.16$	$1.01 \pm 0.04 \pm 0.04$
$Zb\overline{b}$	–	$1.03 \pm 0.05 \pm 0.20$	$1.06 \pm 0.06 \pm 0.07$
$t\overline{t}$	$0.97 \pm 0.02 \pm 0.03$	$1.06 \pm 0.03 \pm 0.11$	$1.03 \pm 0.04 \pm 0.04$

- Control regions not clear in the CMS note
- CMS fit background components using a single discriminant variable (dependent on analysis) defined in a control region.
- Then apply the main BDT fit.
- Scale factors quite different
- from ours (but different MC).
- No separation of W/Z+c...

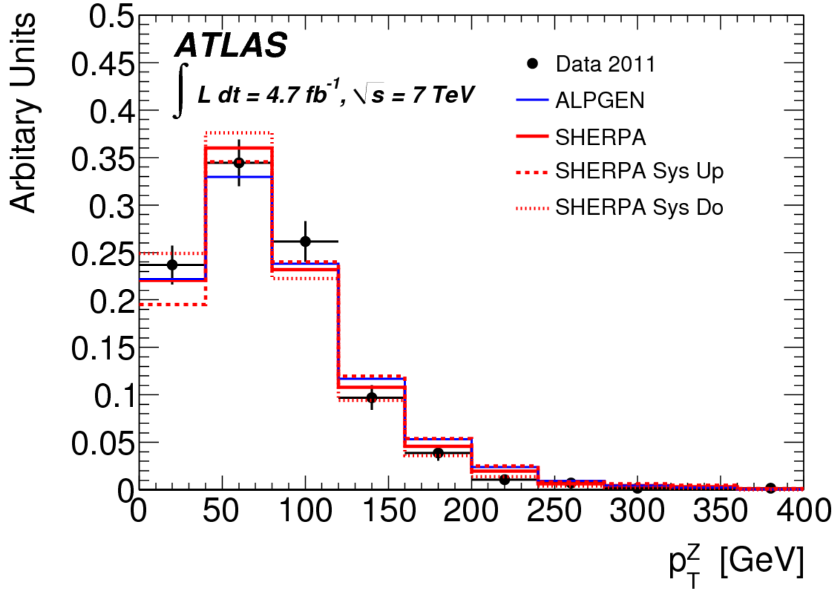
ATLAS WH->lvbb

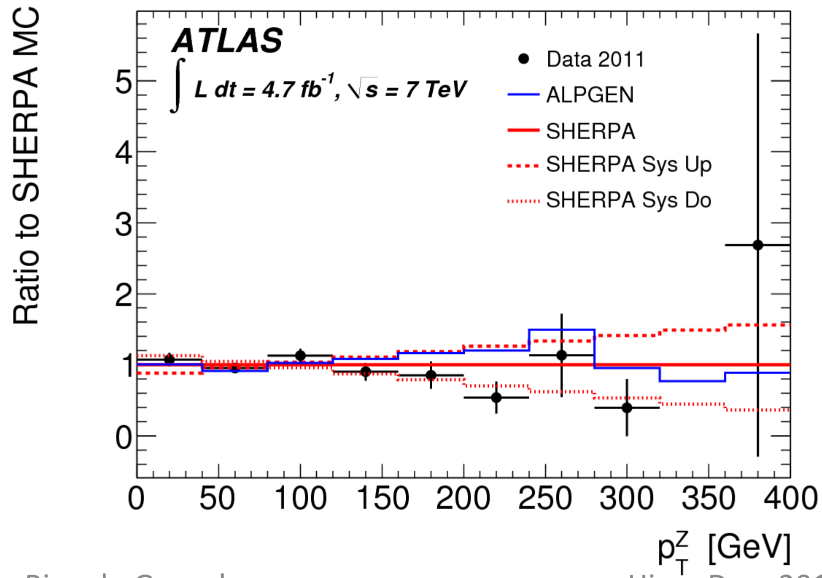
Process	scale factor
Fit of second b-tag jet	
$W{+}b$	1.23 ± 0.11
$W{+}c$	1.39 ± 0.04
Fit of both jets	
$W{+}b$	1.15 ± 0.06
$W{+}c$	1.77 ± 0.02
$W{+}l$	0.78 ± 0.00

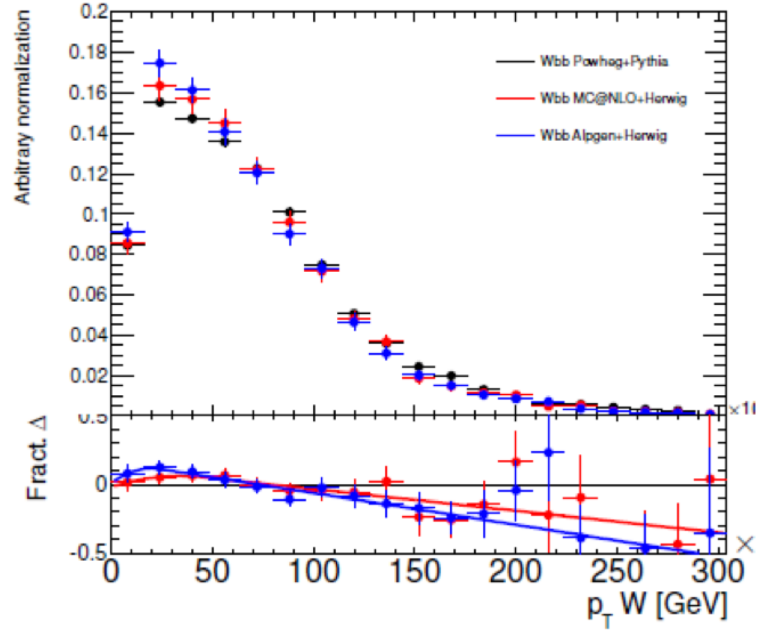
ATLAS ZH->llbb

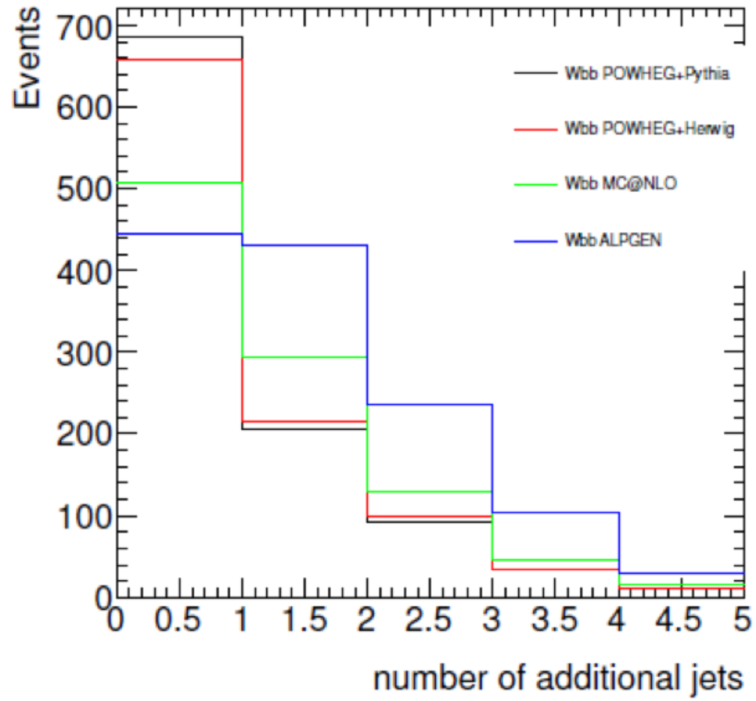
Process	scale factor
Fit of second b-tag jet	
$Z{+}b$	1.46 ± 0.07
$Z{+}c$	1.23 ± 0.10
Fit of both jets	
$Z{+}b$	1.77 ± 0.10
$Z{+}c$	1.95 ± 0.06
$Z{+}l$	0.90 ± 0.00

Theory uncertainty

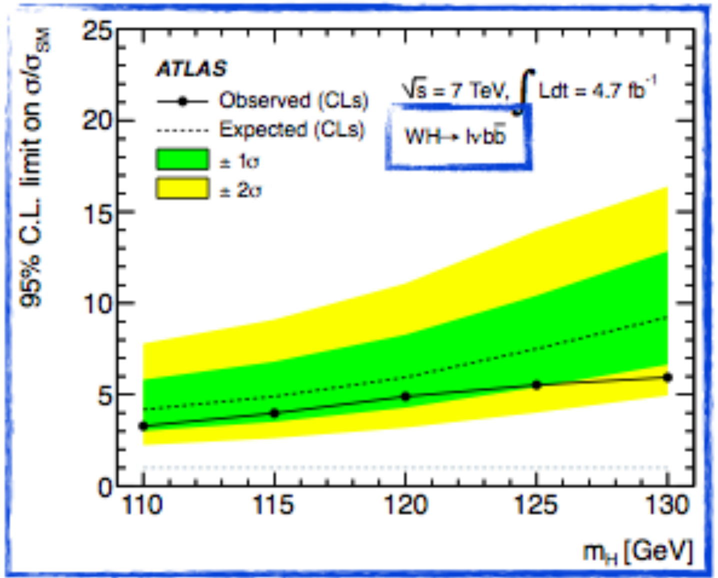


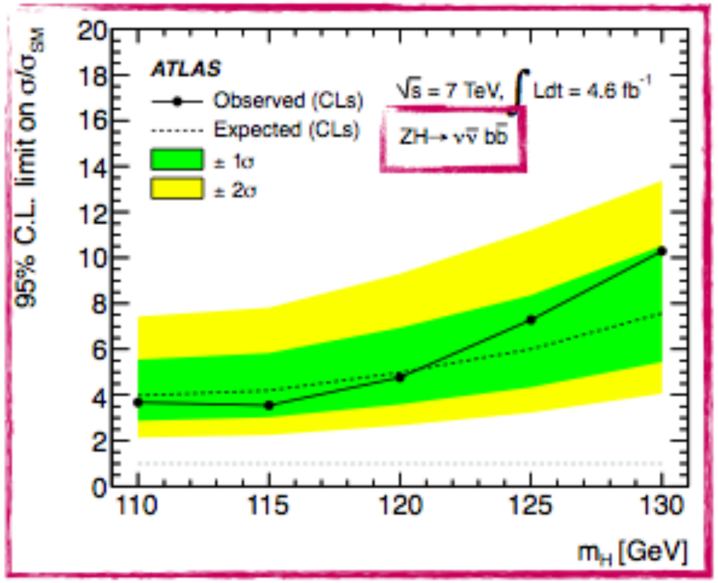


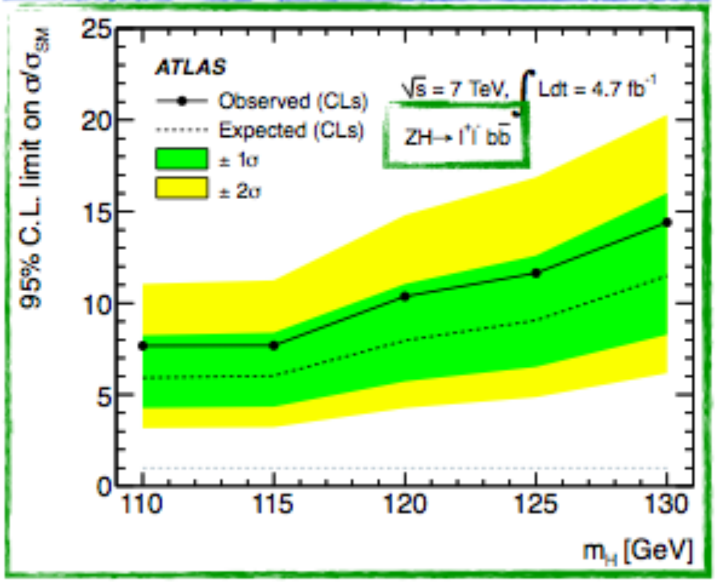




Individual channel limits







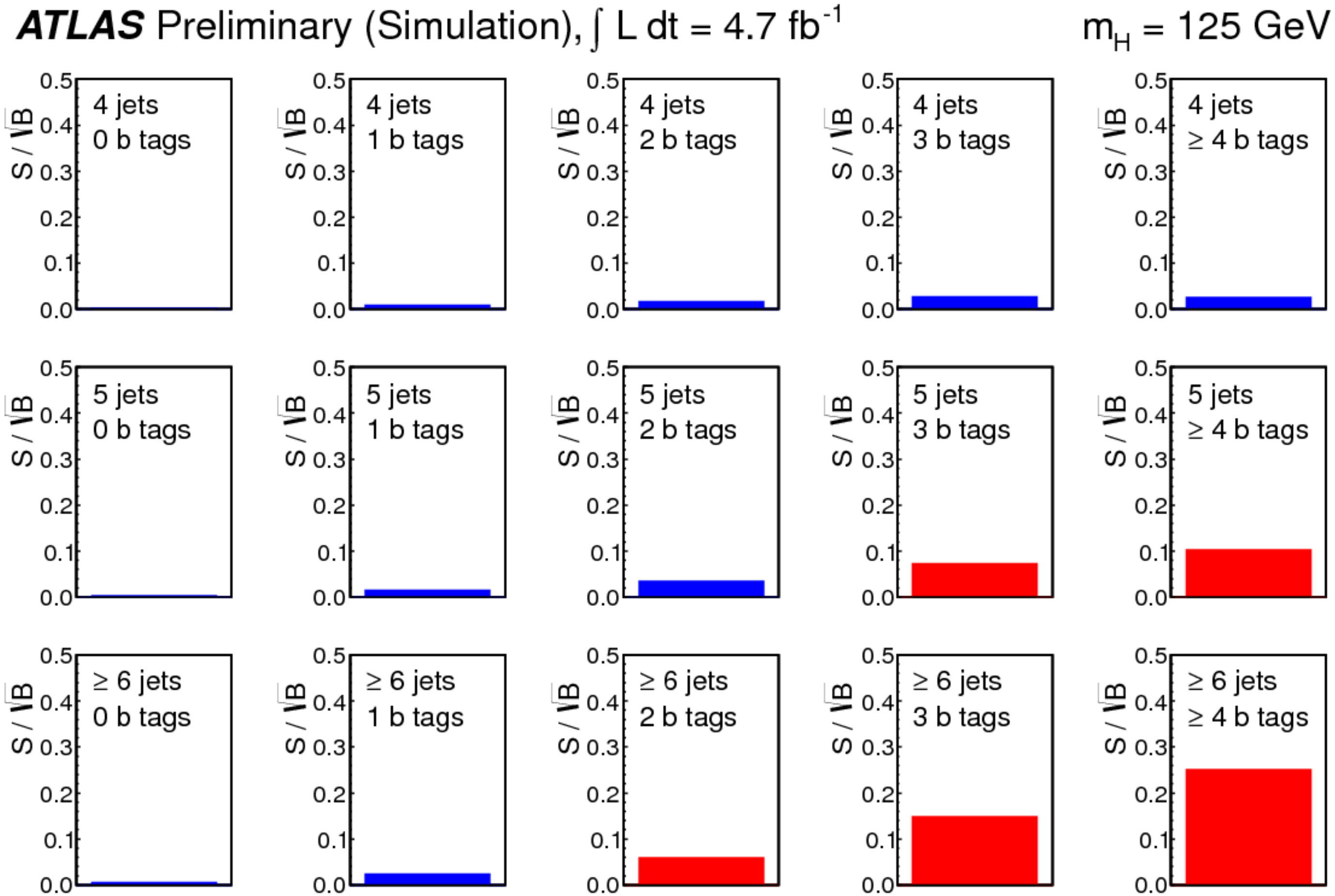
Most sensitive channels:
WH→lνbb and **ZH→ννbb**

Signal Systematic Uncertainties

bin	$ZH \to \ell^+\ell^- b\bar{b}$ p_T^V [GeV] 0-50	50-100	100-200	>200	$WH \to \ell\nu b\bar{b}$ p_T^V [GeV] 0-50	50-100	100-200	>200	$ZH \to \nu\bar{\nu}b\bar{b}$ p_T^V [GeV] 120-160	160-200	>200
Components of the relative systematic uncertainties of the signal [%]											
b-tag eff	6.4	6.4	7.0	13.7	6.4	6.4	7.0	12.1	7.1	8.2	9.2
jets/E_T^{miss}	4.9	3.2	3.5	5.5	5.8	4.6	3.7	3.3	7.3	5.1	6.3
leptons	0.9	1.2	1.7	2.6	3.0	3.0	3.0	3.2	0.0	0.0	0.0
luminosity	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
pileup	0.5	1.1	1.8	2.2	1.2	0.3	0.3	1.6	0.2	0.2	0.0
theory	4.6	3.6	3.3	5.3	4.4	4.7	5.0	8.0	3.3	3.3	5.6
total signal	10.1	9.1	9.6	16.5	11.4	10.8	11.0	16.0	11.8	11.4	13.4

Details and Results:

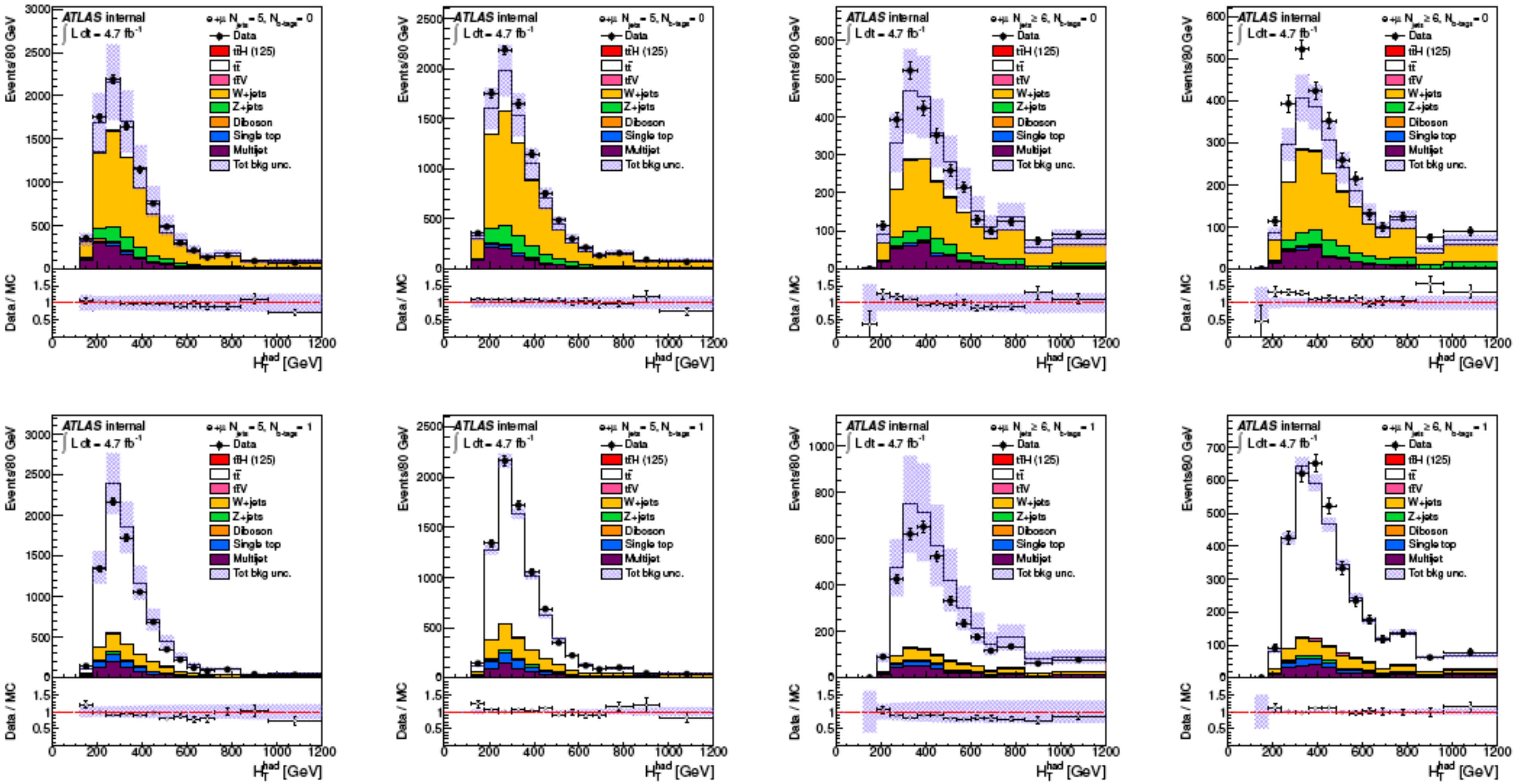
$t\bar{t}H$ Analyses


ATLAS Preliminary (Simulation), ∫ L dt = 4.7 fb-1
mH = 125 GeV
S / √B
0.0
0.1
0.2
0.3
0.4
0.5
4 jets
0 b tags
4 jets
1 b tags
4 jets
2 b tags
4 jets
3 b tags
4 jets
≥ 4 b tags
5 jets
0 b tags
5 jets
1 b tags
5 jets
2 b tags
5 jets
3 b tags
5 jets
≥ 4 b tags
≥ 6 jets
0 b tags
≥ 6 jets
1 b tags
≥ 6 jets
2 b tags
≥ 6 jets
3 b tags
≥ 6 jets
≥ 4 b tags

ATLAS Analysis – Control Regions

5 jet | ≥ 6 jet

Pre-Fit | Post-Fit | Pre-Fit | Post-Fit



Profiling

- Parameters strongly constrained
- W+jets, QCD multijet overall normalization, tt , b-tag: 4 jet channels
- W+jet and tt: 4 jet 0b has W+jet, 4 jet 1b and 2b
- b tagging: four jet evolution across the number of tags
- tt modelling and rate uncertainties: 4, 5 and 6 jets with 2 b-tags
- tt+HF fraction: Five channels with 3 and 4 b-tags constrains
- Importance of systematic uncertainties evaluated with "N-1" test:
  - Remove one, put back, remove next…
  - Largest impact: freeze (param set to the best fitted value) and repeat

Ordered nuisance parameters:

Level	Most Important	σ/σ_{SM}
N	Start	12.19
N-1	ttbar HF	9.77
N-2	Ltag	9.40
N-3	Ctag	8.08
N-4	QCD Norm	7.09
N-5	JES	6.94
All	Stat	6.10

Systematics

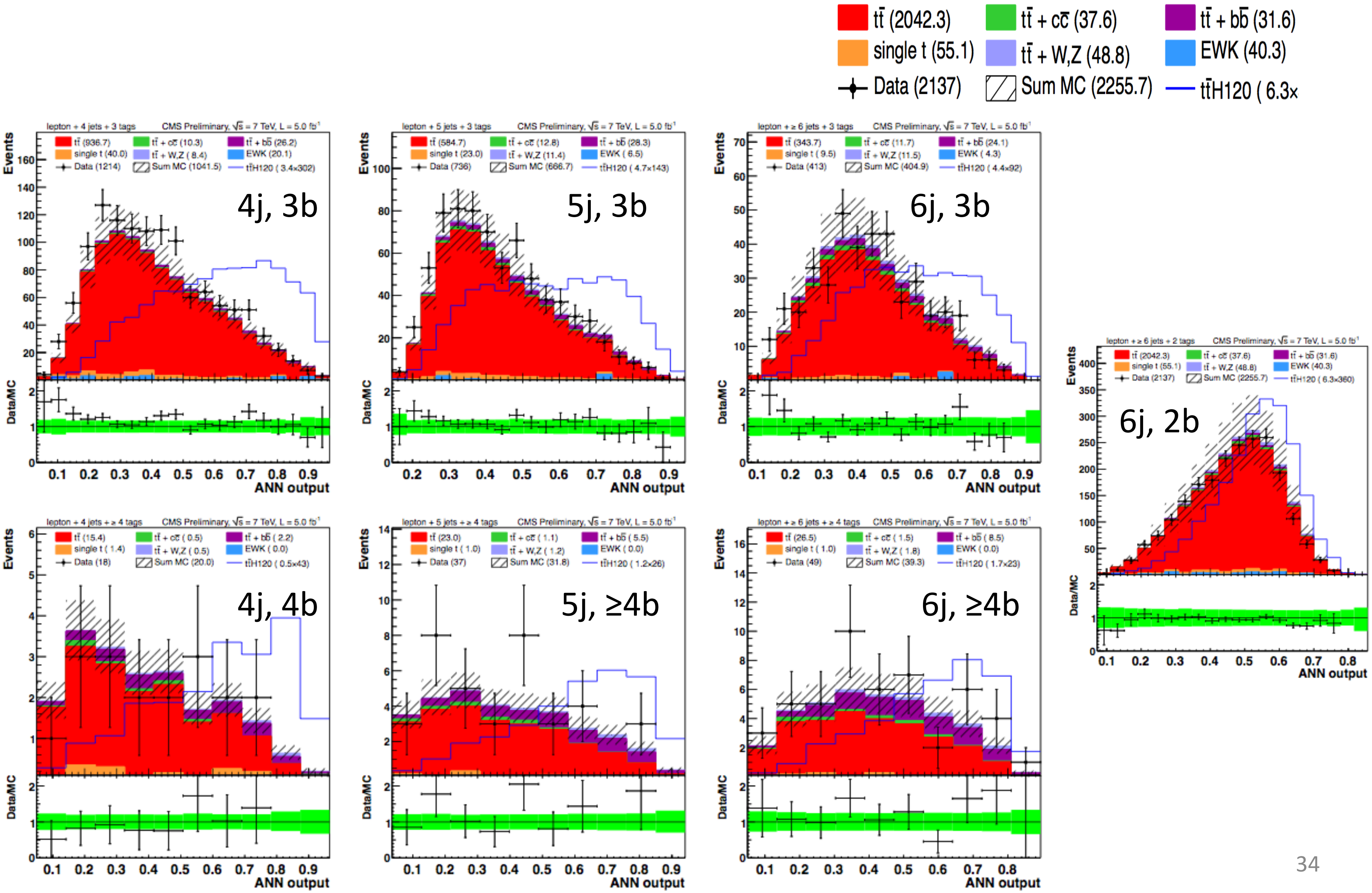
- tt+heavy-flavour fractions: Vary by 50% - theory studies suggest cross section uncertainty is 75% ; should be weighted down by the fraction. Fit puts it at 30%.
- tt modeling (Alpgen):
  - Qfac: (±2.3%) The factorization scale for the hard scatter is varied by a factor of two up and down relative to the original scale, $Q^2 = \Sigma_{partons} m^2 + p^2_T$
  - kTfac: (±9.2%) The renormalisation scale associated with the evaluation of α_s at each local vertex in the matrix element calculation is varied by a factor of two up and down relative to the original scale, k_T , between two partons.
  - Functional form of the factorization scale (iqopt2): (± 13%) Default choice (=1) for dynamic factorization scale, $Q^2 = \Sigma_{partons} m^2 + p^2_T$, changed to $Q^2 = x_1 x_2 s$. This has an order of magnitude larger effect than Qfac.

- t¯t cross section +9.9 -10.7% using NNLO Hathor.
- Jet Energy scale : 16 eigenvectors recommended by the jet/ETmiss group are varied.
- b, c and light tagging : 9 (btag),5(ctag) eigenvectors recommended by b-tagging group are varied for heavy flavours and the one value for light flavours.
- QCD Multijets Mostly in the electron channel. Correlated 50% uncertainty plus uncorrelated statistical estimate in each channel (66% in 6 jet 4 b-tag)
- ttH parton shower modelling: 1-5% effect at mH = 120 GeV

ATLAS vs CMS Comparison

ATLAS	CMS
e: p_T>25GeV |η|<2.5	e: p_T>30GeV |η|<2.5
μ: p_T>20GeV |η|<2.5	μ: p_T>30GeV |η|<2.1
jets: (0.4): p_T>30GeV / 40GeV	Jets (0.5): p_T>30/40GeV |η|<2.4
B-tag: 70% (b) 20% (c) 0.8% (lite)	B-tag: 70% (b) 20% (c) 2% (lite)
e ch.: E_T^{miss} > 30 GeV M_T^W > 30GeV	
μ ch.: E_T^{miss}> 20GeV E_T^{miss}+M_T^W > 60GeV	

CMS Analysis

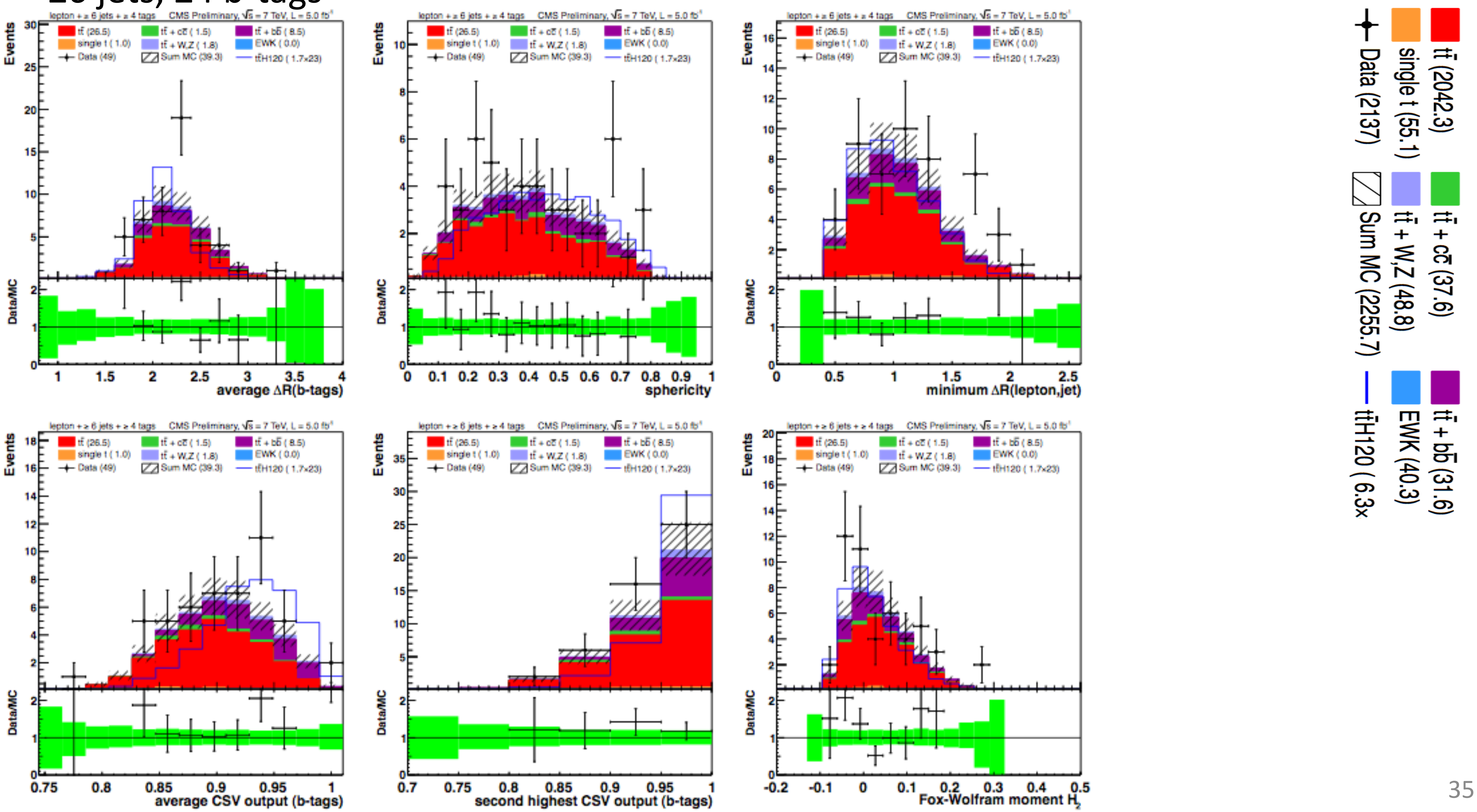


CMS Analysis

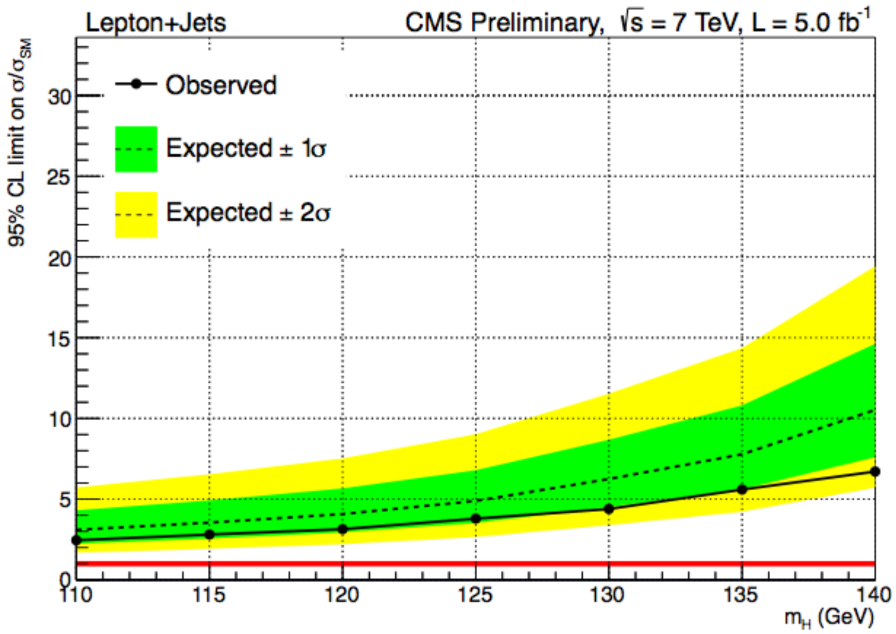
- Neural-net based analysis of 2011 data
- Separate events into categories of #jets and #b-tagged jets

- 10 best kinematic/event shape/b-tagging variables chosen from "pool of candidates"
- Optimized for each #jets/#b-tags category
- Simultaneous fit for S and B on NN output distributions

≥6 jets, ≥4 b-tags



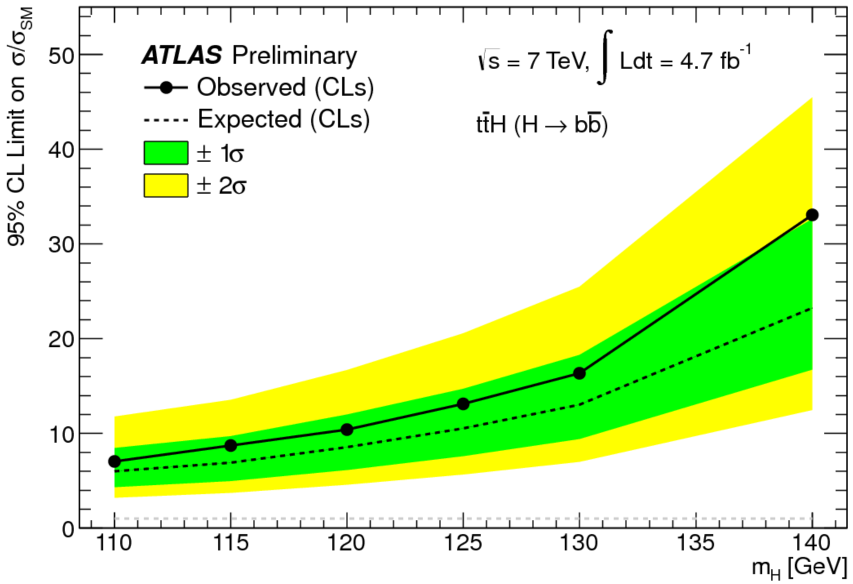
CMS



m_H (GeV/c^2)	Obs limit	Median Exp limit
110	2.5	3.1
115	2.8	3.6
120	3.1	4.1
125	3.8	4.9
130	4.4	6.3
135	5.6	7.8
140	6.7	10.5

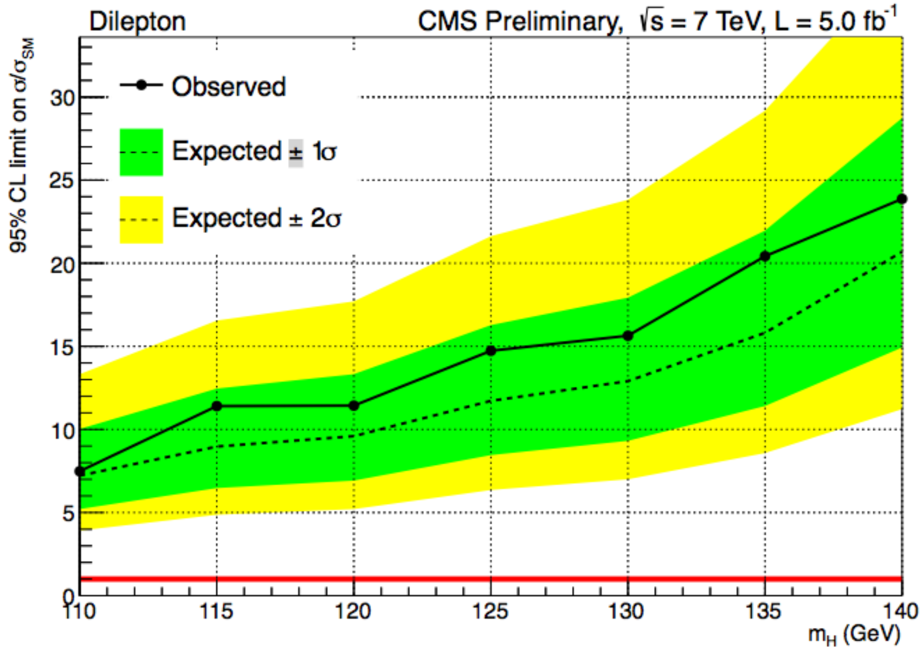
Lepton+jets mode

ATLAS



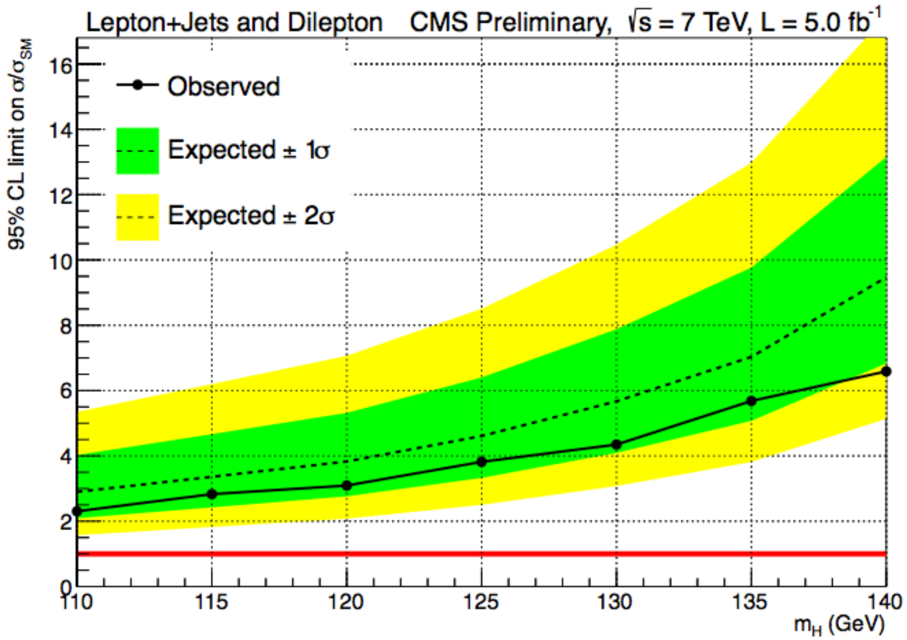
m_H (GeV)	observed	median	stat only
110	7.0	6.0	3.5
115	8.7	6.9	4.0
120	10.4	8.5	4.9
125	13.1	10.5	6.1
130	16.4	13.0	7.8
140	33.0	23.2	14.2

Very big difference!...



Di-lepton channel

m_H (GeV/c^2)	Obs limit	Median Exp limit
110	7.5	7.2
115	11.4	8.9
120	11.4	9.6
125	14.7	11.7
130	15.6	12.8
135	20.4	15.8
140	23.8	20.6



Single-lepton + Di-lepton channels combined (di-lepton improves expected limit by 6.5%)

m_H (GeV/c^2)	Obs limit	Median Exp limit
110	2.3	2.9
115	2.8	3.5
120	3.1	3.8
125	3.8	4.6
130	4.4	5.7
135	5.7	7.0
140	6.6	9.5

Questions to CMS

- 1. While you state in the abstract that you set limits on sigma*BR (Higgs to bb) your yields tables indicate H -> anything. Is this a mistake and, if not, do you have the H !b¯b and H !WW yields available separately?
- 2. Your plots show systematics error bands. Are these the a-priori systematics or does it reflect the result of the fit? If it is a-priori, do you have plots with the reduced systematics after the fit? Is table 3 the a-priori systematics or post fit? Can you give us the details for the most senstive region, ge6j ge4b?
- 3. Have you got numbers on how the systematic uncertainties are constrained by your likelihood fit and if so can we see them?
- 4. You have not provided definitions of your variables. Can you give us precise definition of the discriminants? We can guess on many of them but it would be better to know what you really used.

- 5. You say that your largest systematic is 'b-tag heavy flavour scale factor'. Is this the b-tagging uncertainty or a theoretical uncertainty? This is presumablly b-Tag SF (b/c) in table 3, is it? Does b-Tag SF (b/c) mean that you take the uncertainties in b and c tagging as correlated?
- 6. What is your sensitivity in the semileptonic mode without systematics? (ie. stat only).
- 7. What is the impact of the shape uncertainties? ie. if you only have rate uncertainties, what is the sensitivity?
- 8. Can you please expand on your experimental uncertainties in tagging: ie. separate out the b and c tag uncertainties and describe it by the channel fit? Do you have tables available for all uncertainties in each channel, and in particular for ttbar background in the >=6j >=4b channel?

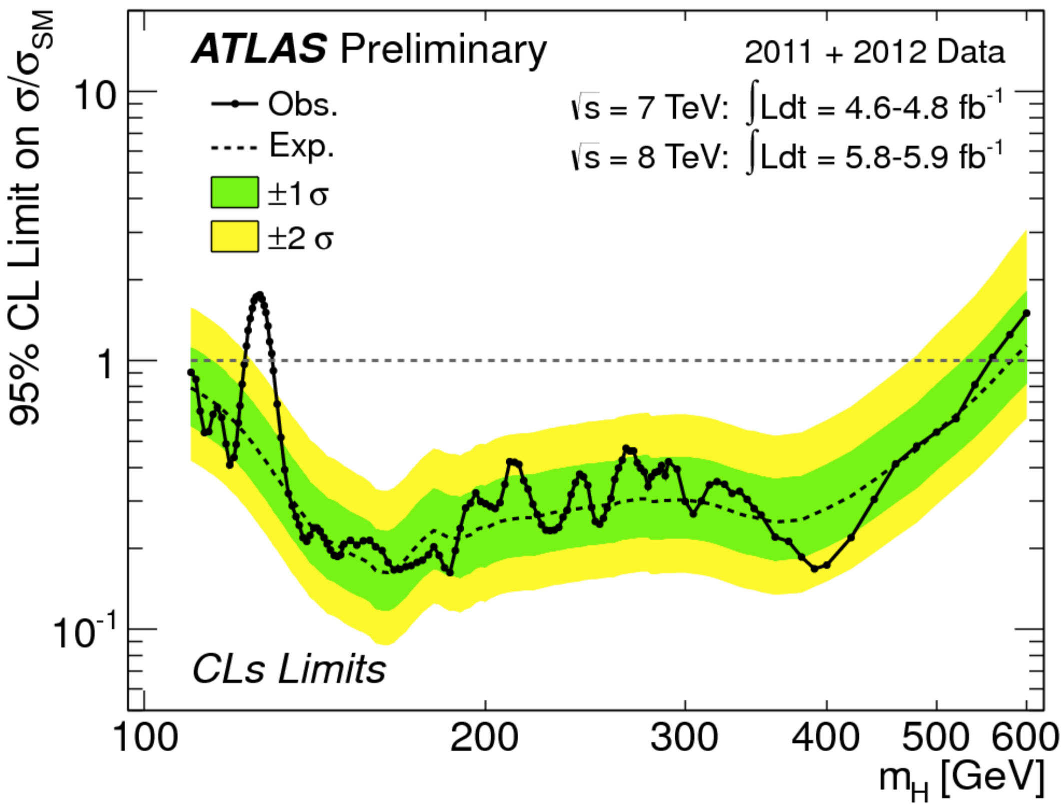
Tools of the Trade:

Statistics Survival Guide

The Brazil Plot

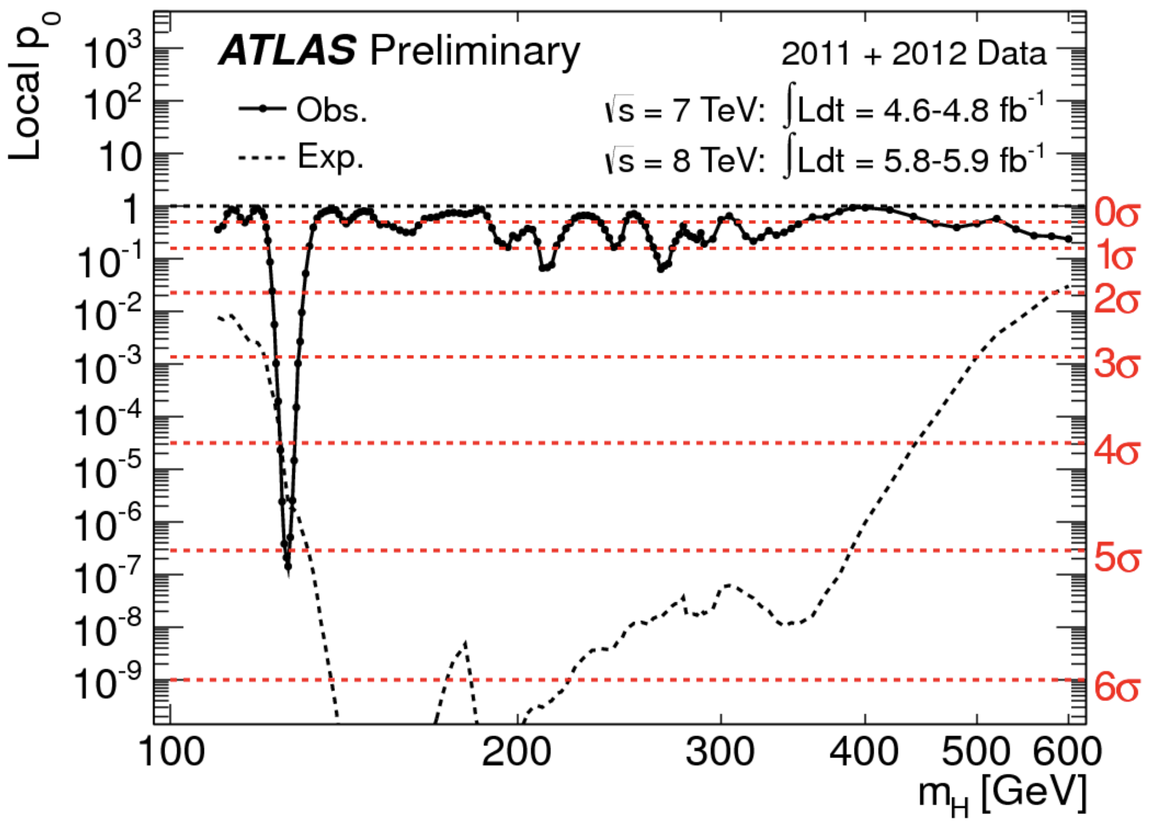
Expected:
- Upper limit on σ(S+B)/σ(B) at 95% CL in Monte Carlo assuming B-only hypothesis

Observed:
- Upper limit on σ(S+B)/σ(B) at 95% CL seen in data assuming B-only hypothesis



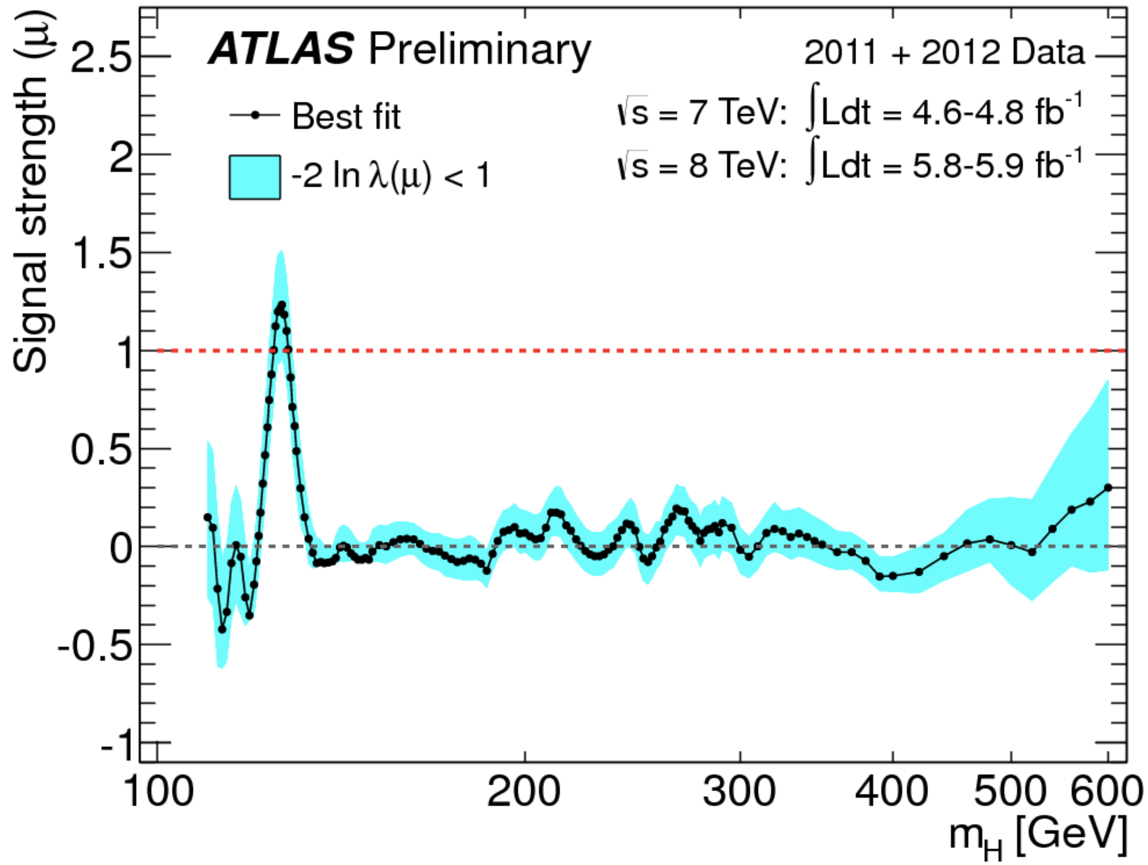
The ***p0*** Discovery Plot

- **p0** is the probability that the background fluctuates to look like signal
- Translated into the one-sided Gaussian probability



The Cyan Band Plot – signal strength

- Best fit of μ=σ(S+B)/σ(B) to data
- Error bands important…. As usual!

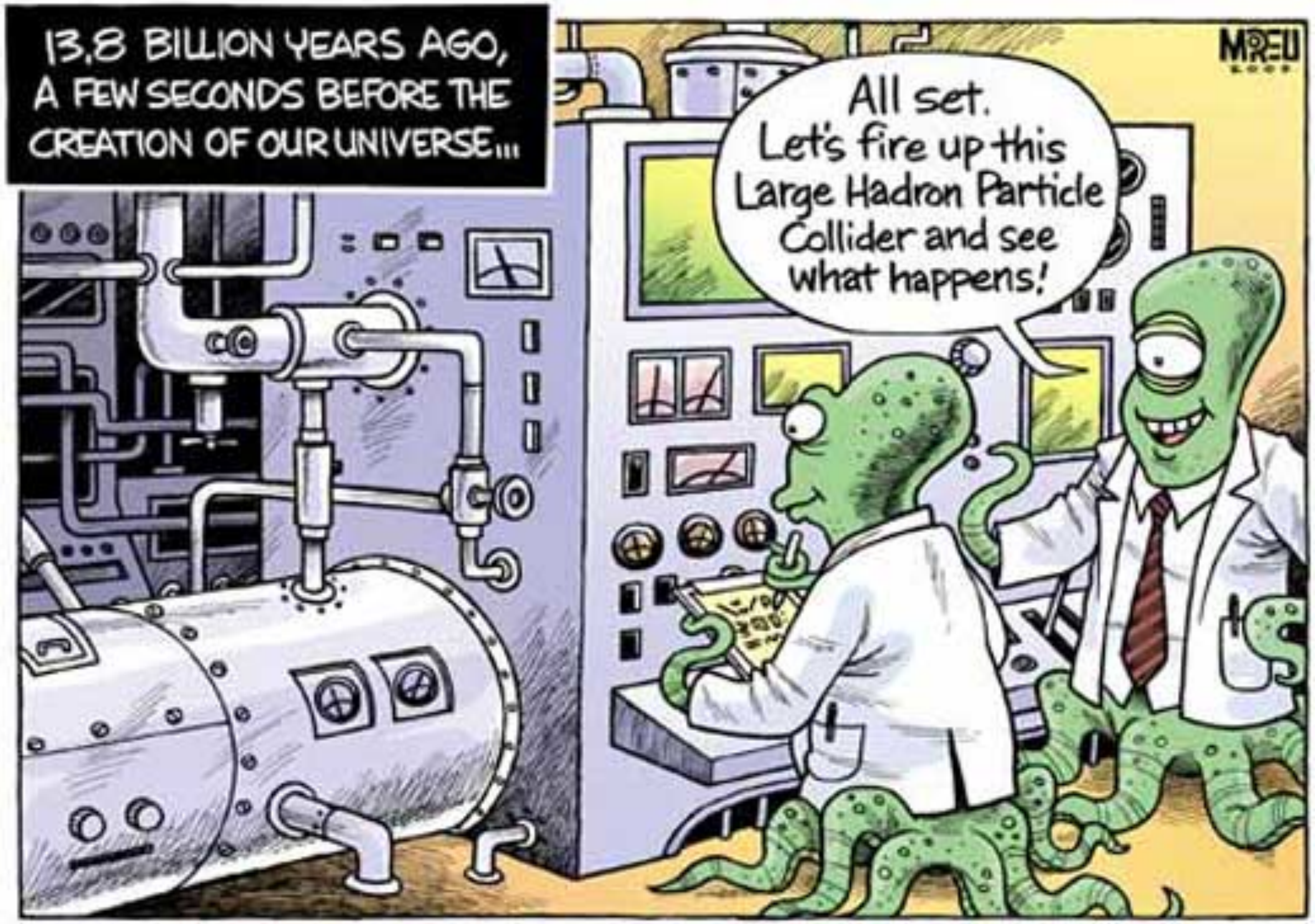


Tools of the Trade:

The Hardware

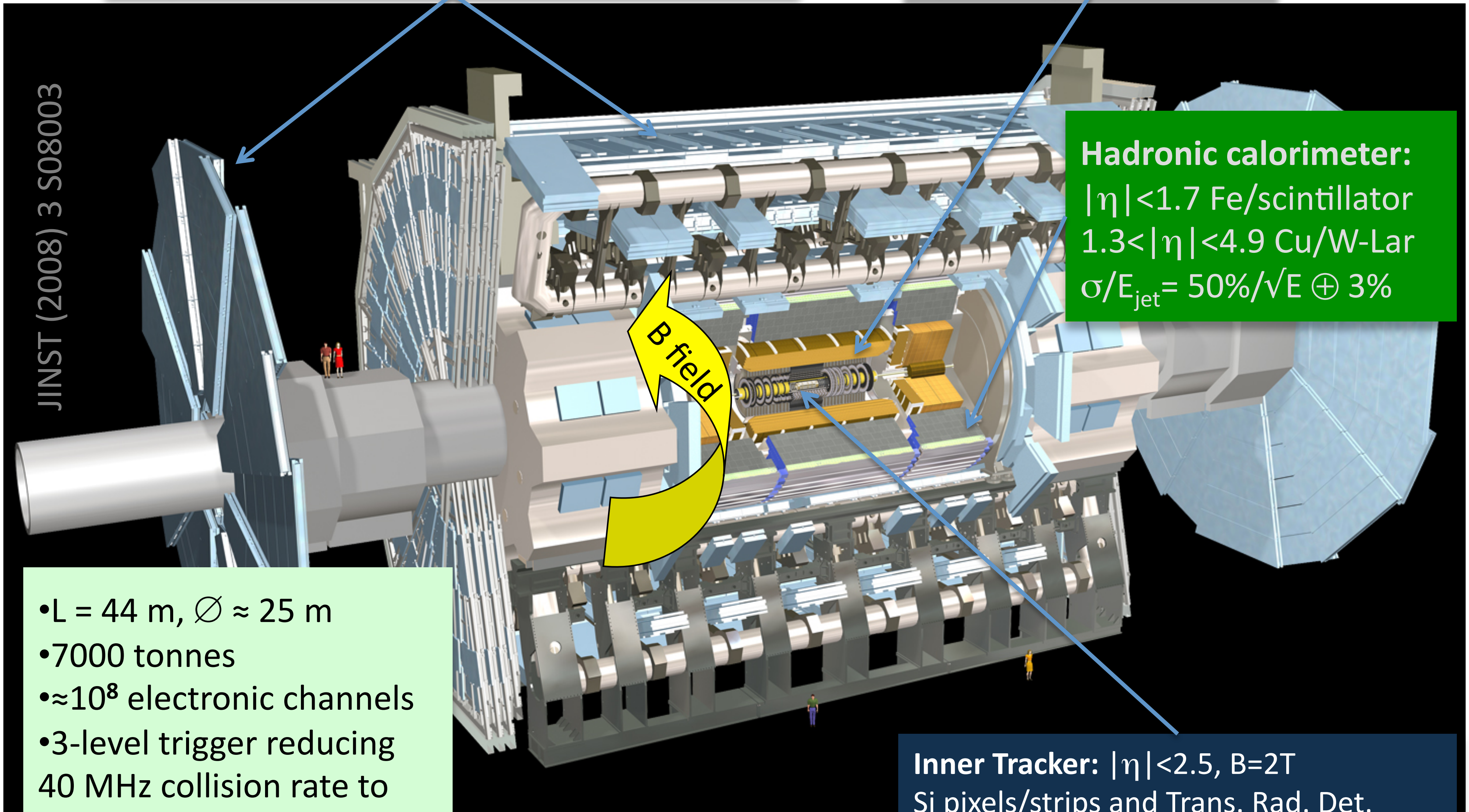
The Large Hadron Collider

- 26 659m circumference
- 9593 magnets: 1232 main dipoles (8T peak field)
- Cooled to 1.9K (colder than outer space) by 120 tonnes of liquid Helium
- Internal pressure 10-13 atm (10x less than on the Moon)
- $\sqrt{s}$ = 7TeV in 2010 and 2011
- $\sqrt{s}$ = 8TeV in 2012
- 50ns bunch crossing
- Design $\sqrt{s}$ = 14TeV and 25ns bunch crossing (7m at *c*)


13.8 BILLION YEARS AGO, A FEW SECONDS BEFORE THE CREATION OF OUR UNIVERSE...
All set. Let's fire up this Large Hadron Particle Collider and see what happens!
MREU

Muon Spectrometer: |η|<2.7
Air-core toroids and gas-based muon chambers
σ/p_T = 2% @ 50GeV to 10% @ 1TeV (ID+MS)

EM calorimeter: |η|<3.2
Pb-LAr Accordion
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$



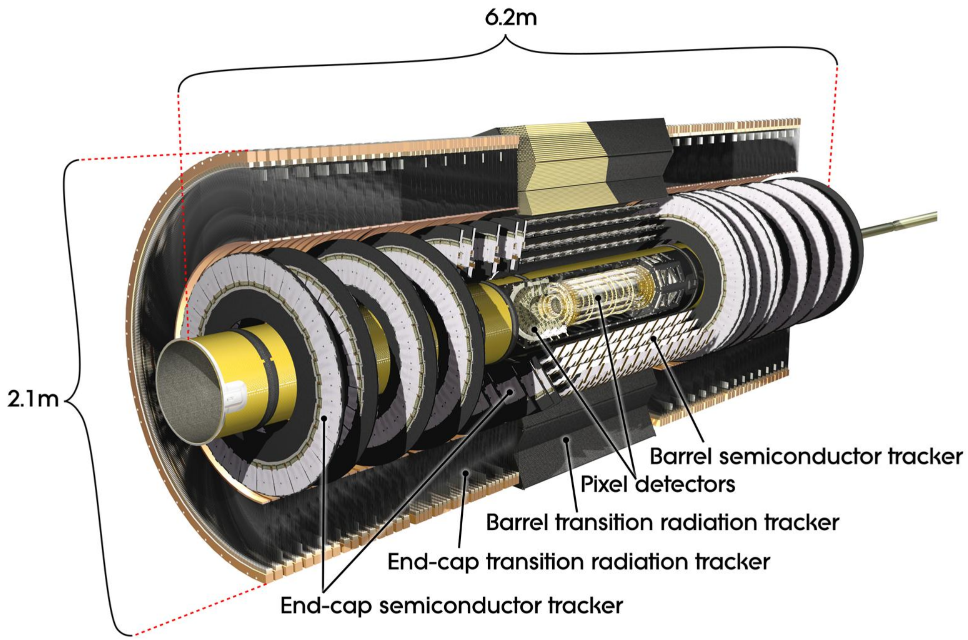
Hadronic calorimeter:
|η|<1.7 Fe/scintillator
1.3<|η|<4.9 Cu/W-Lar
$\sigma/E_{jet} = 50\%/\sqrt{E} \oplus 3\%$

- L = 44 m, ∅ ≈ 25 m
- 7000 tonnes
- ≈10^8 electronic channels
- 3-level trigger reducing 40 MHz collision rate to 200 Hz of events to tape

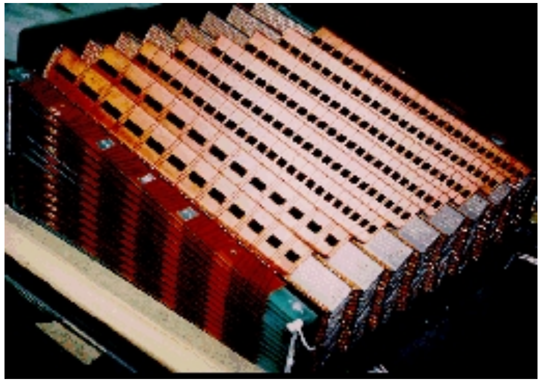
Inner Tracker: |η|<2.5, B=2T
Si pixels/strips and Trans. Rad. Det.
$\sigma/p_T = 0.05\%\ p_T\,(\mathrm{GeV}) \oplus 1\%$

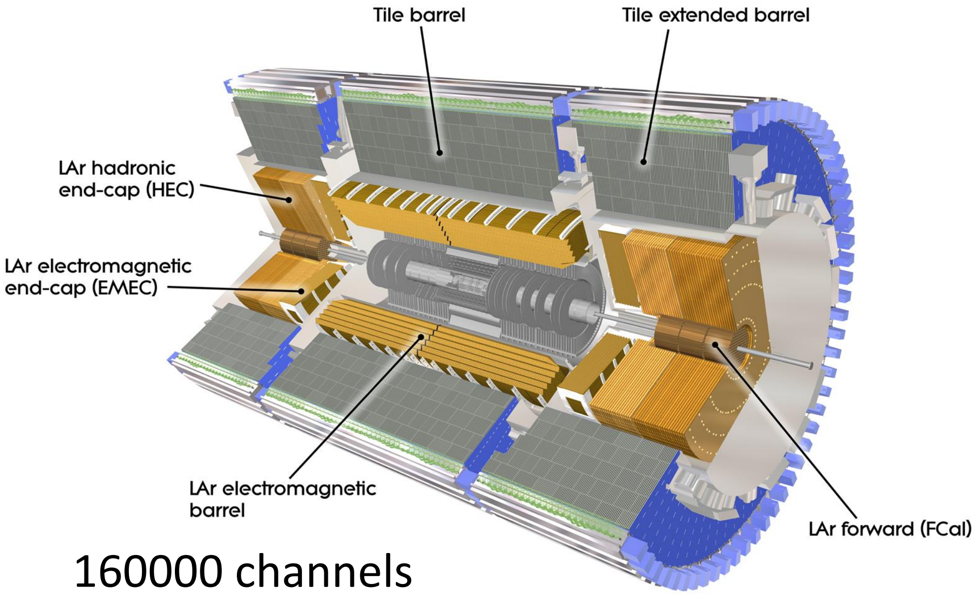
ATLAS

- Large angular coverage (|η|<4.9; tracking coverage up to **η~2.5**)
- Standalone muon spectrometer – separate fast muon chambers for trigger
- Toroidal magnetic field in muon spectrometer (supercondutor air-core toroids)
- Liquid Argon electromagnetic sampling calorimeter with accordion geometry

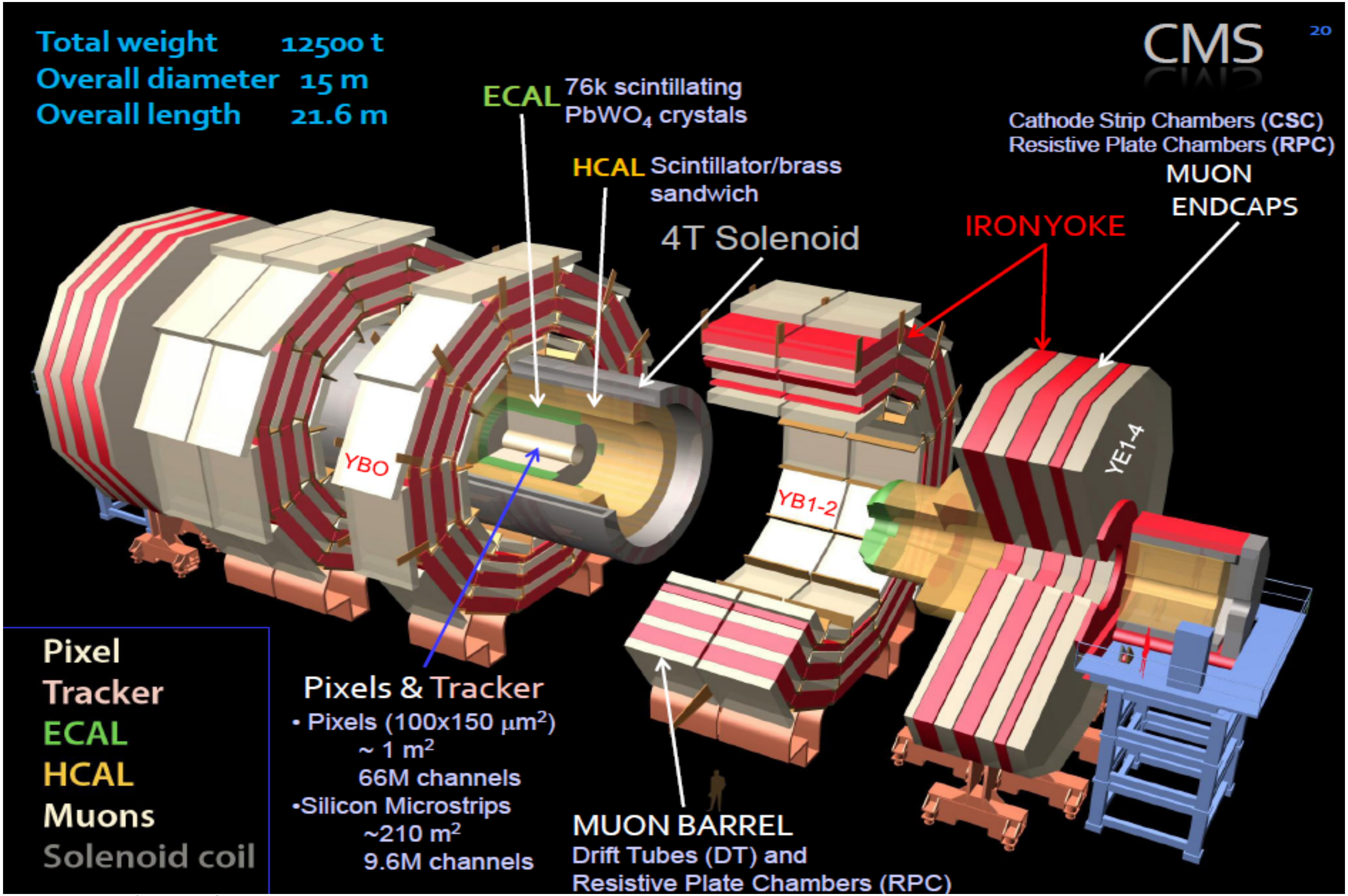


Pixel: 10x100μm; 80 M channels
Strips: 80μm; 6 M channels

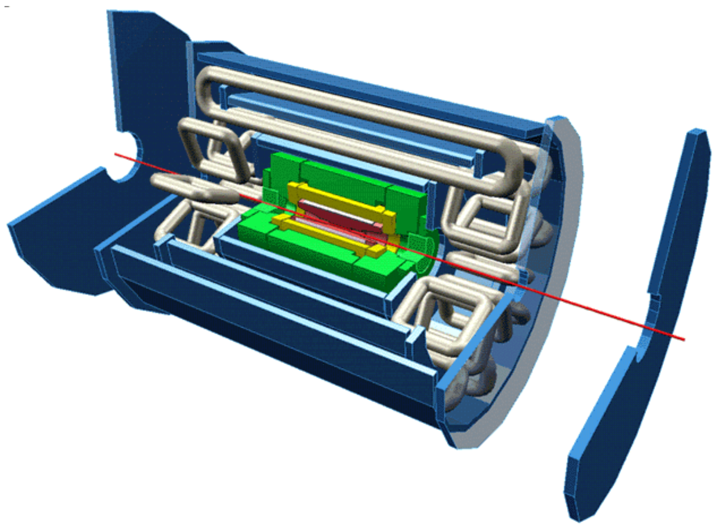


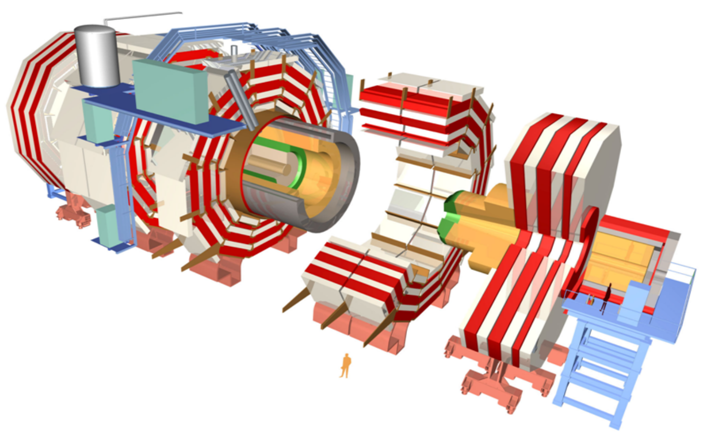


160000 channels


Total weight 12500 t
Overall diameter 15 m
Overall length 21.6 m
CMS
20
ECAL 76k scintillating PbWO4 crystals
HCAL Scintillator/brass sandwich
4T Solenoid
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)
MUON ENDCAPS
IRON YOKE
YB0
YB1-2
YE1-4
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm²)
~ 1 m²
66M channels
•Silicon Microstrips
~210 m²
9.6M channels
MUON BARREL
Drift Tubes (DT) and
Resistive Plate Chambers (RPC)

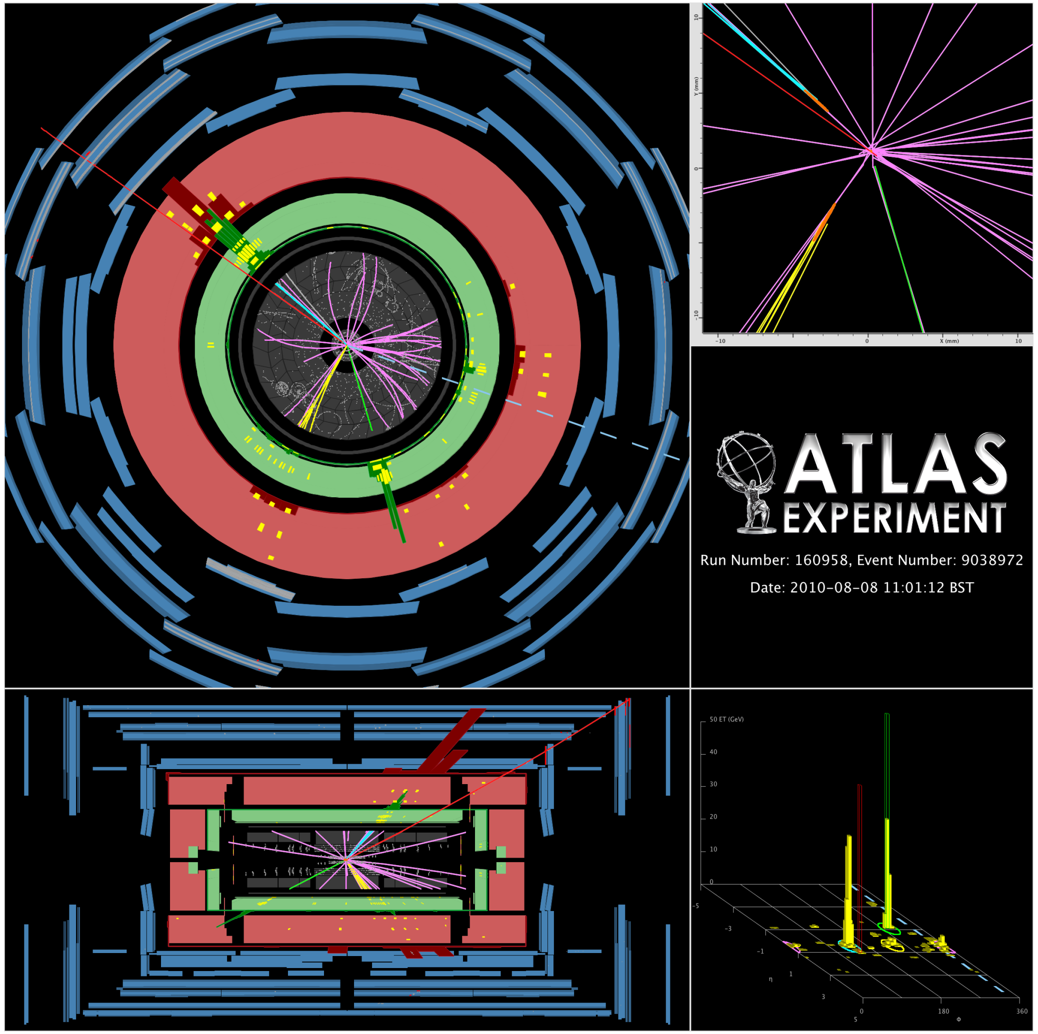
	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel 1 T endcap)	4 T solenoid + return yoke
Tracker	Si pixels, strips + TRT $\sigma/p_T \approx 5\text{x}10^{-4} p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\text{x}10^{-4} p_T + 0.005$
EM calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO4 crystals $\sigma/E \approx 2\text{-}5\%/\sqrt{E} + 0.005$
Hadronic calorimeter	Fe+scint. / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Cu+scintillator (5.8λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (ID+MS)	$\sigma/p_T \approx 1\%$ @ 50GeV to 5% @ 1TeV (ID+MS)
Trigger	L1 + RoI-based HLT (L2+EF)	L1+HLT (L2 + L3)



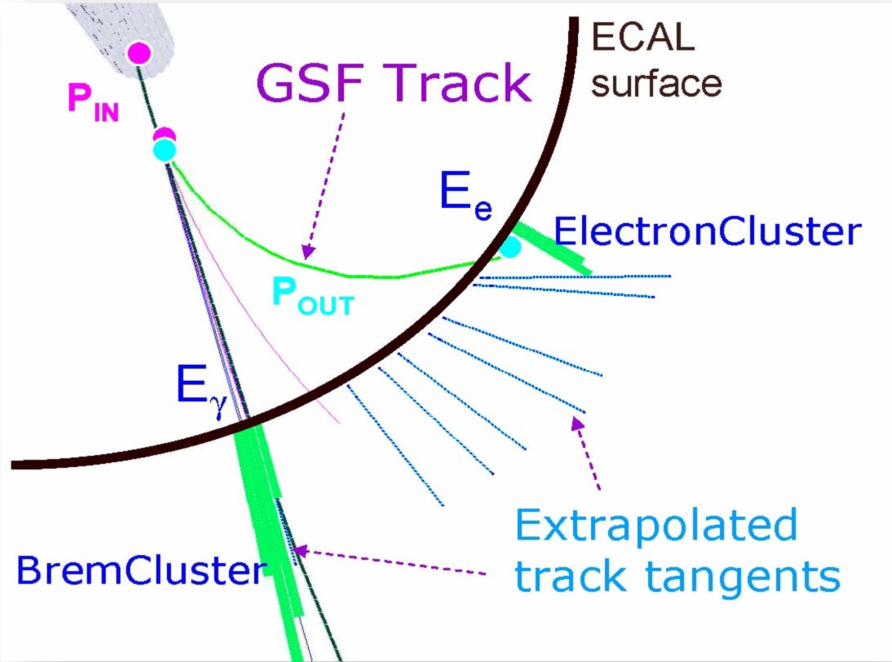


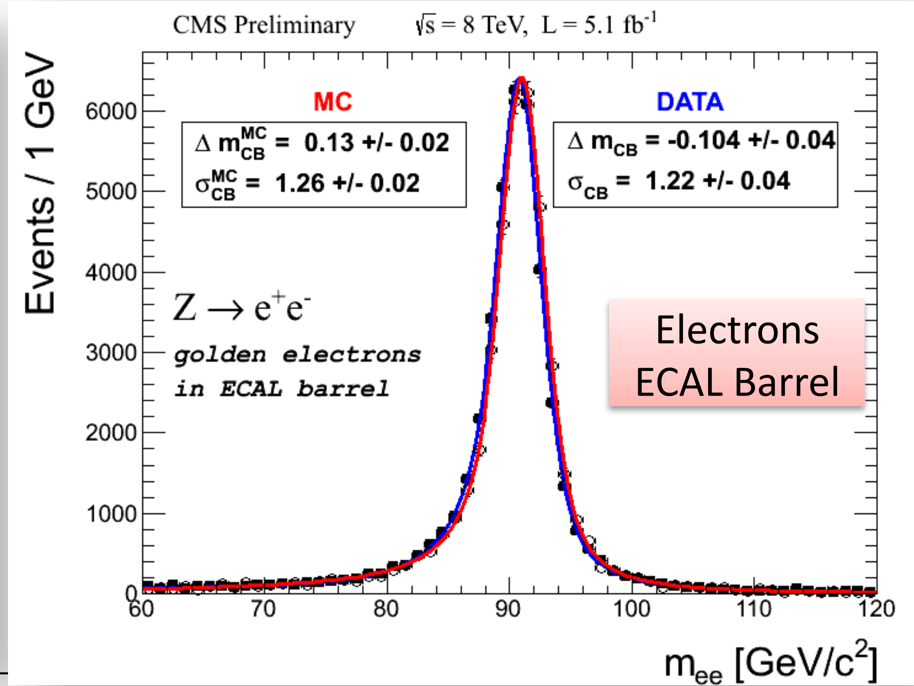
Event Reconstruction

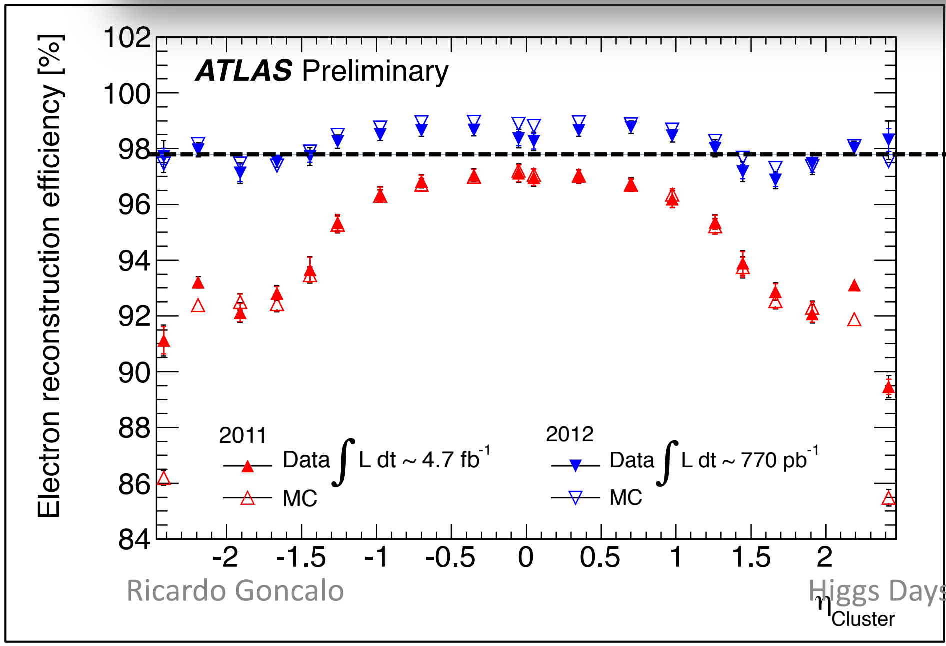
- Detector design is a balance between precision to reconstruct particles of interest, feasibility, cost, etc
  - E.g. CMS electromagnetic calorimeter: excellent energy resolution for photons – designed with H->γγ in mind
- Event reconstruction:
  - Go from information in every sub-detector to reconstructed physical objects:
  - Muons (inner detector + muon spectrometer)
  - Electrons, tau leptons, hadronic jets, b-quark initiated jets (inner detector+ calorimeter)
  - etc

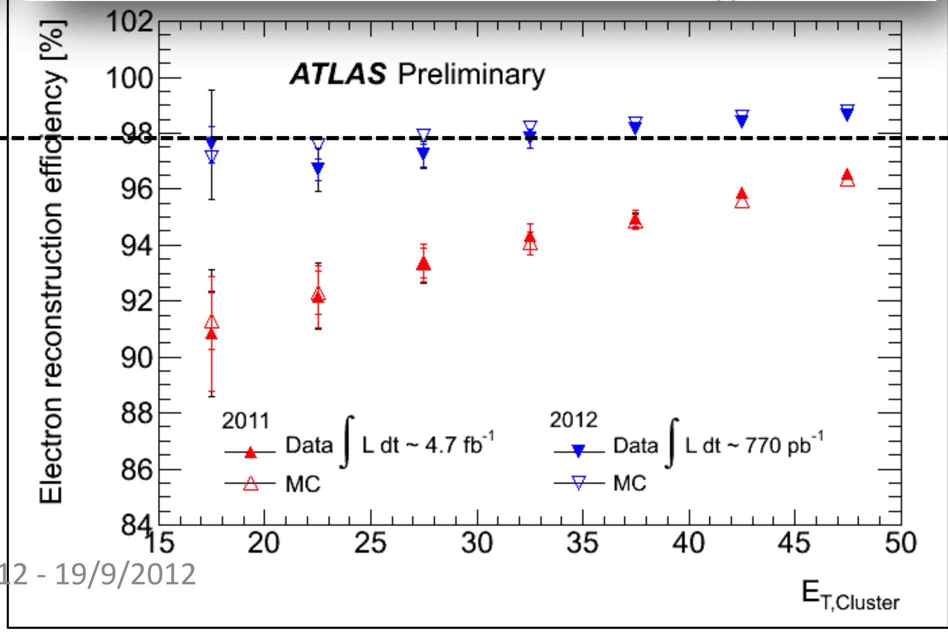


Electron & Photon Reconstruction



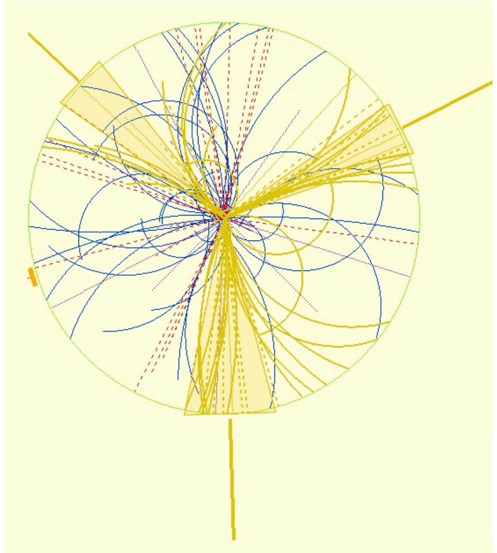


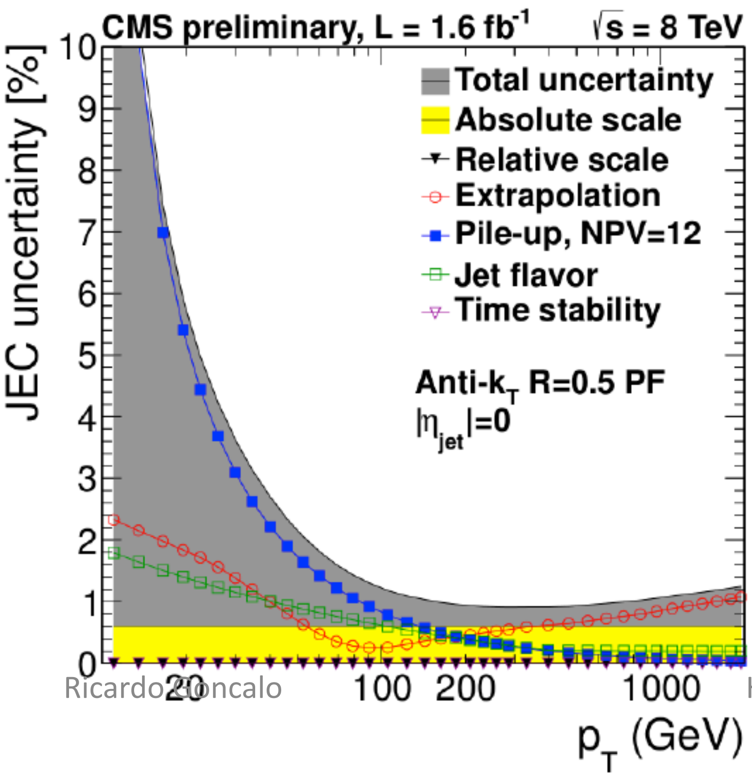


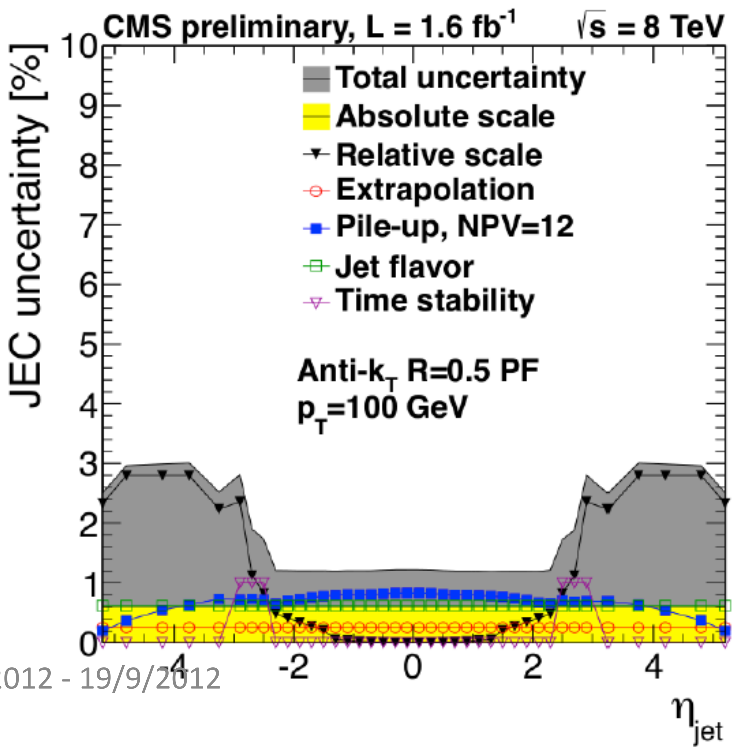


Jet Reconstruction

- Jets reconstructed in a cone of ΔR≈0.4 (ATLAS) and ΔR≈0.5 (CMS)
- Jet Energy Correction:
  - Electronic noise
  - Detector calibration & reconstruction efficiencies
  - Energy deposits from pileup
  - Dependence on η & P_T





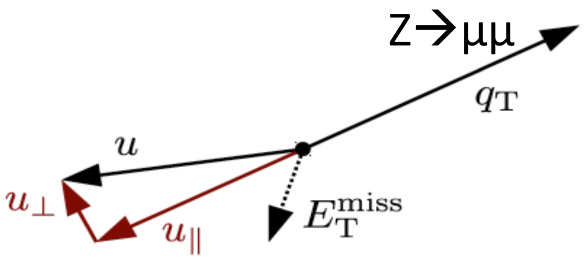


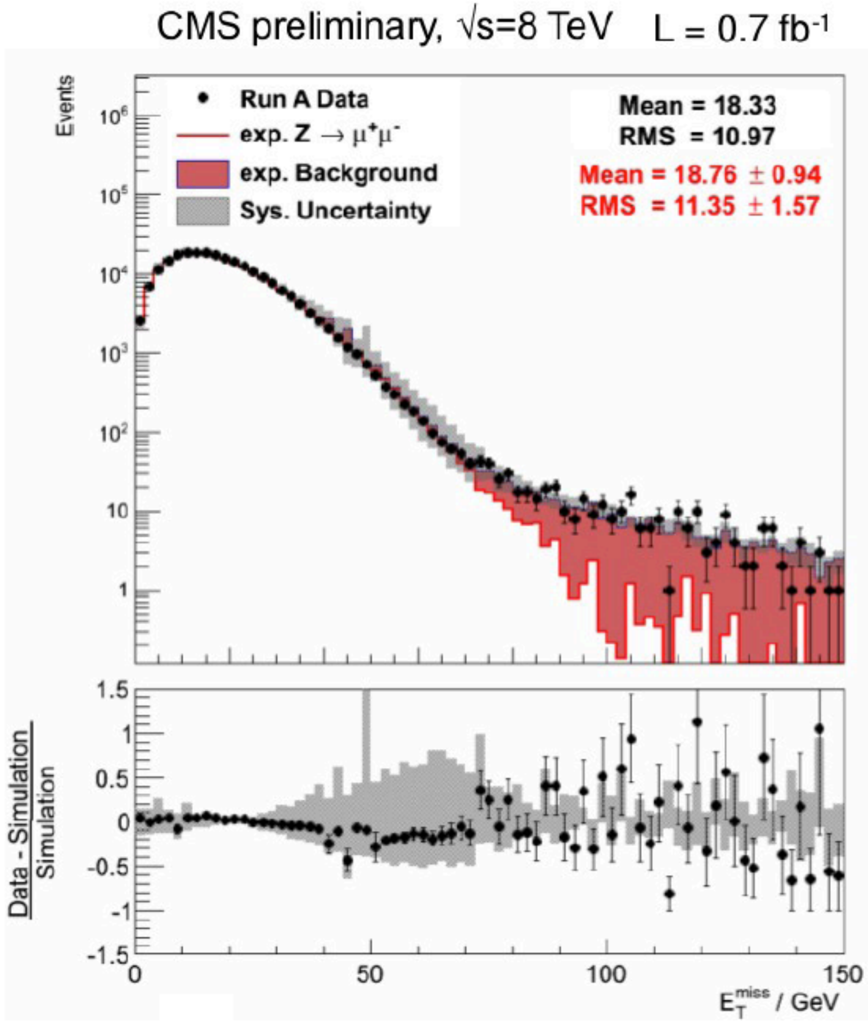
Transverse Missing Energy (M_{ET})

$$MET = -\sum_i \vec{E}_{T_i}$$

- Energy conservation in direction transverse to colliding p-p beams
- Need to account for
  - Non-linear calorimeter response
  - Instrumental noise, poorly instrumented area
  - mis-measured objects
- Use Z → μμ events with no intrinsic MET to measure MET resolution

$$\vec{u}^{\,\mathrm{recoil}} + \vec{q}_{\mathrm{T}}^{\,\mathrm{Z}} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}} = 0$$



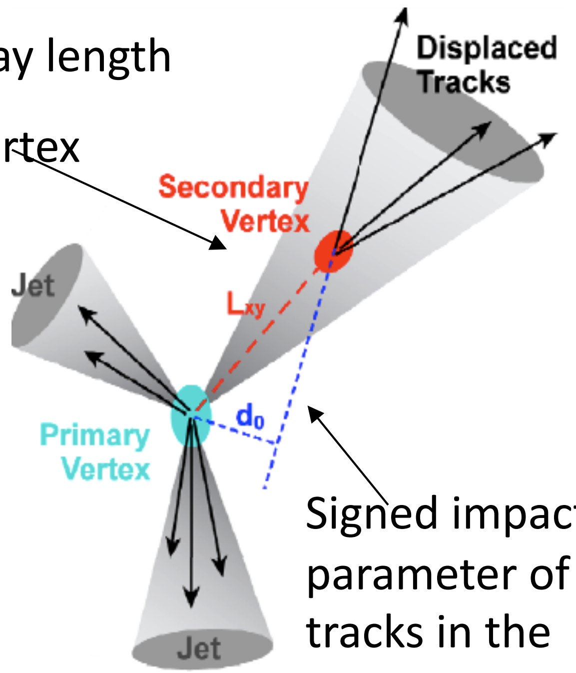


- measure for MET scale $\left\langle -\frac{u_{\parallel}}{q_{\mathrm{T}}} \right\rangle$
- measure for MET resolution $\sigma(-u_{\parallel} - q_{\mathrm{T}}), \sigma(u_{\perp})$

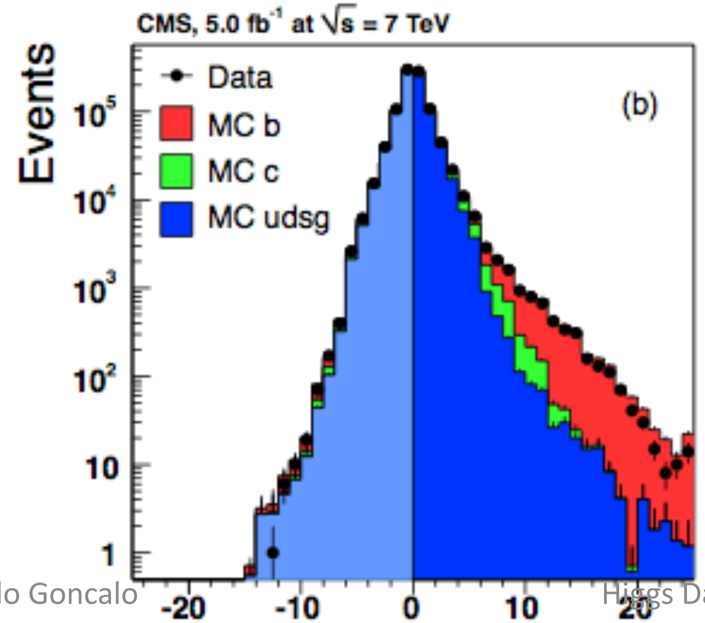
b-Jet Identification

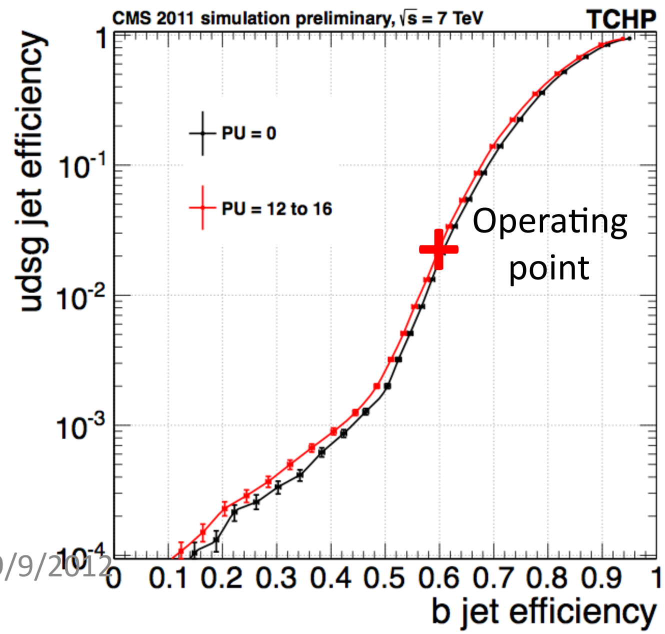
- B-lifetime ≈ 1.5ps, <βγcτ> ≈ 1800μ
- Tracks from b-hadron decay have large P_T
- Average multiplicity ≈ 6
- B-taggers based on
  - Large signed impact parameter significance
  - Secondary vertex with large decay length
- Mistag rate measured from "negative tags"

Signed decay length of B vertex



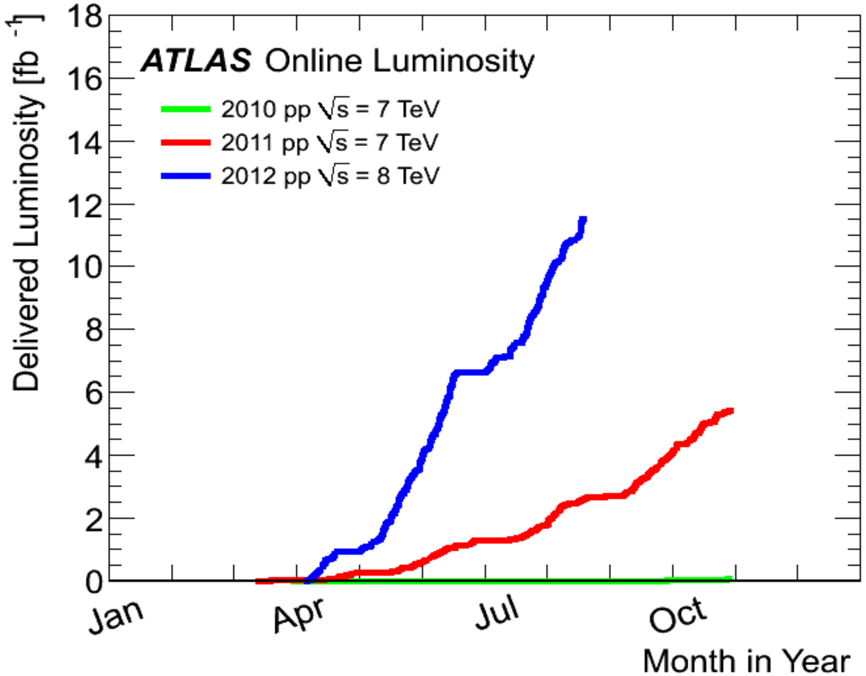
Signed impact parameter of tracks in the

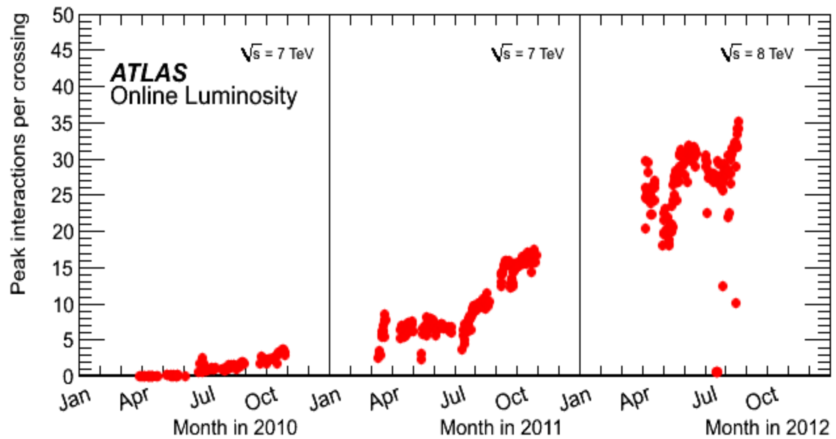




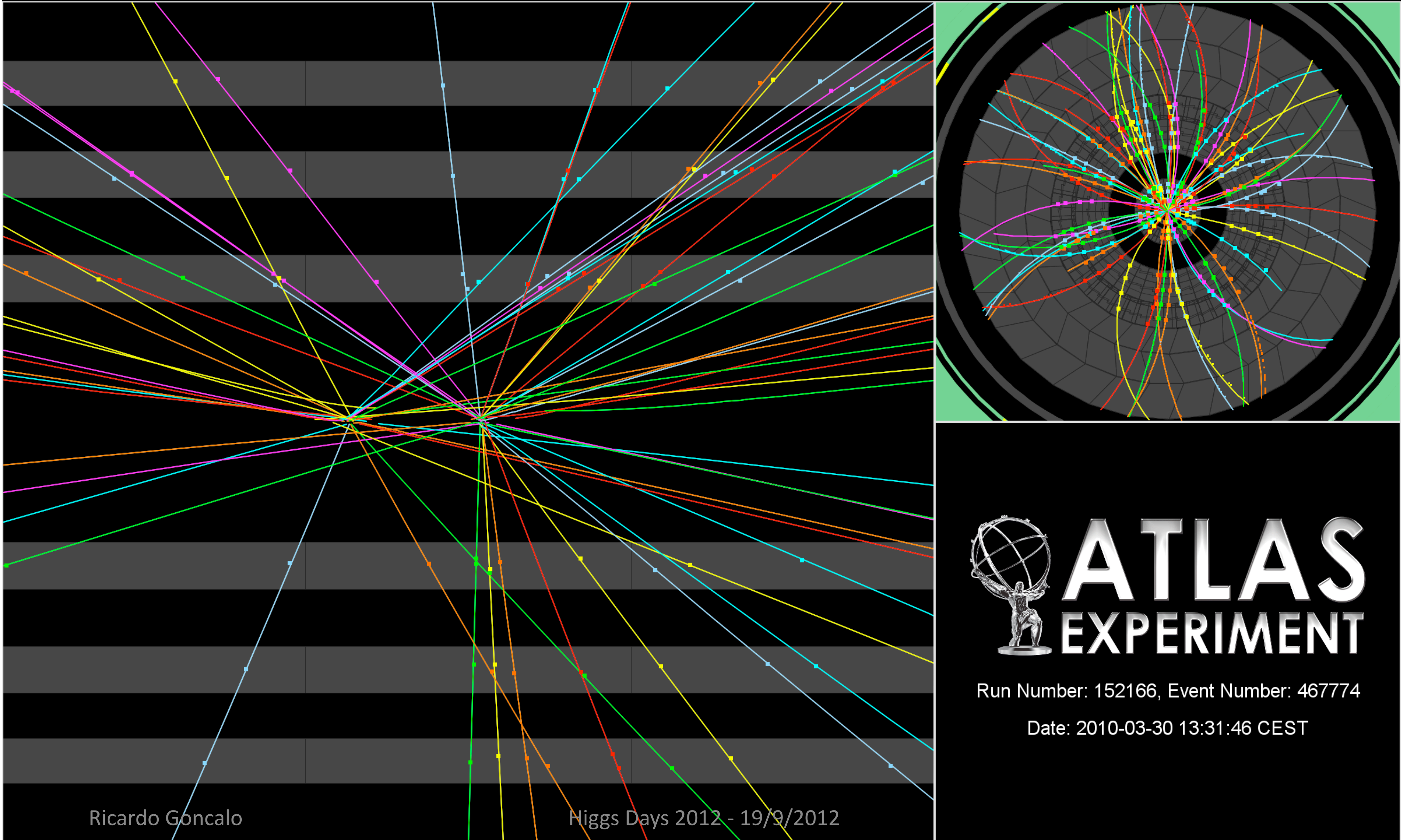
LHC Luminosity

- 2010 – ≈45 pb^{-1} / experiment
  - No chance of searching for Higgs boson
  - But needed to understand our brand new detector!
- 2011 – ≈5 fb-1 per experiment
  - Things start to be (very) interesting
  - Tevatron breathing down the LHC's metaphorical neck
- 2012 – ≈11 fb^{-1} / experiment up to yesterday … and counting
  - New Particle discovery announced!
- And the rest is (will be) history

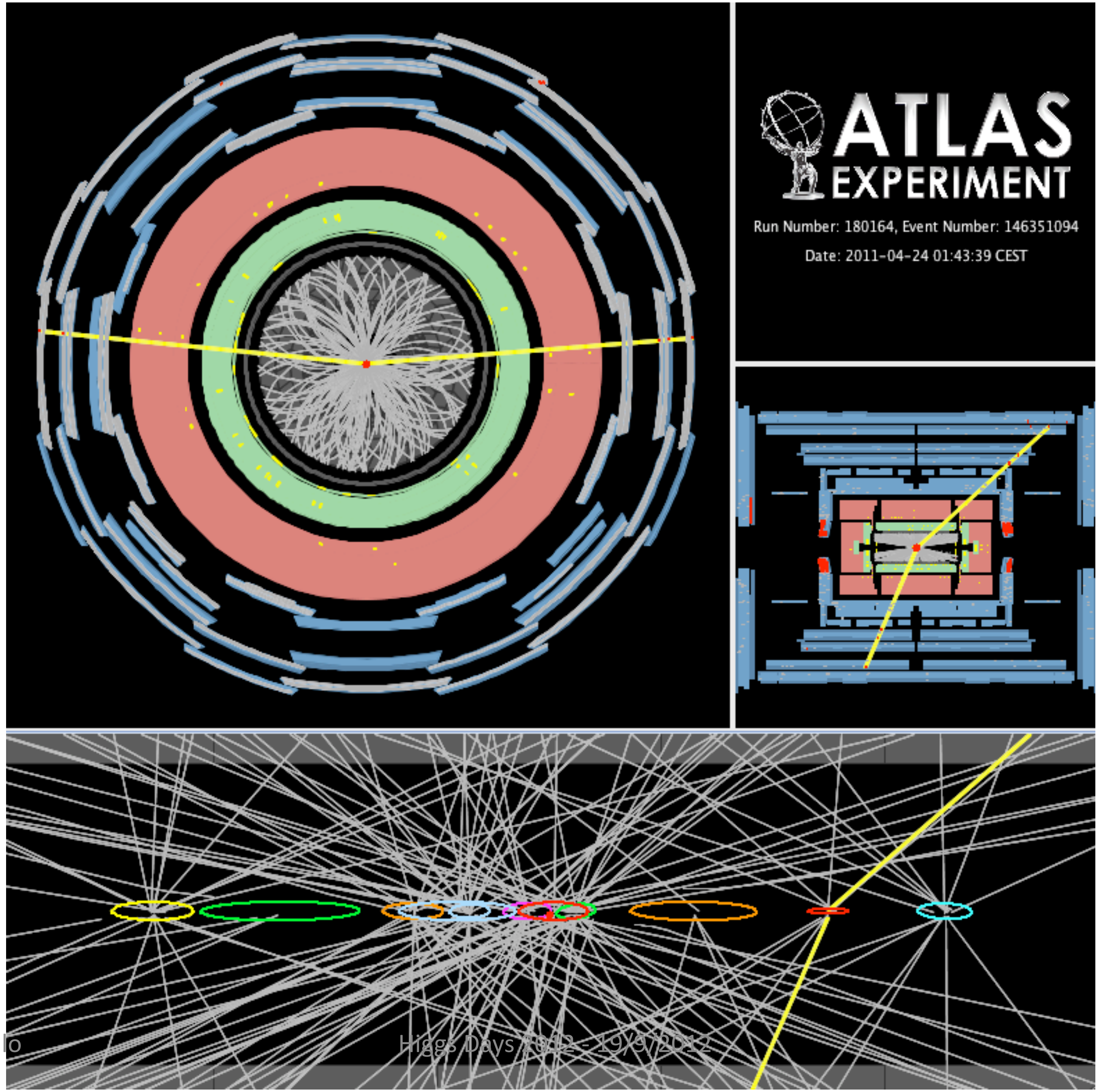


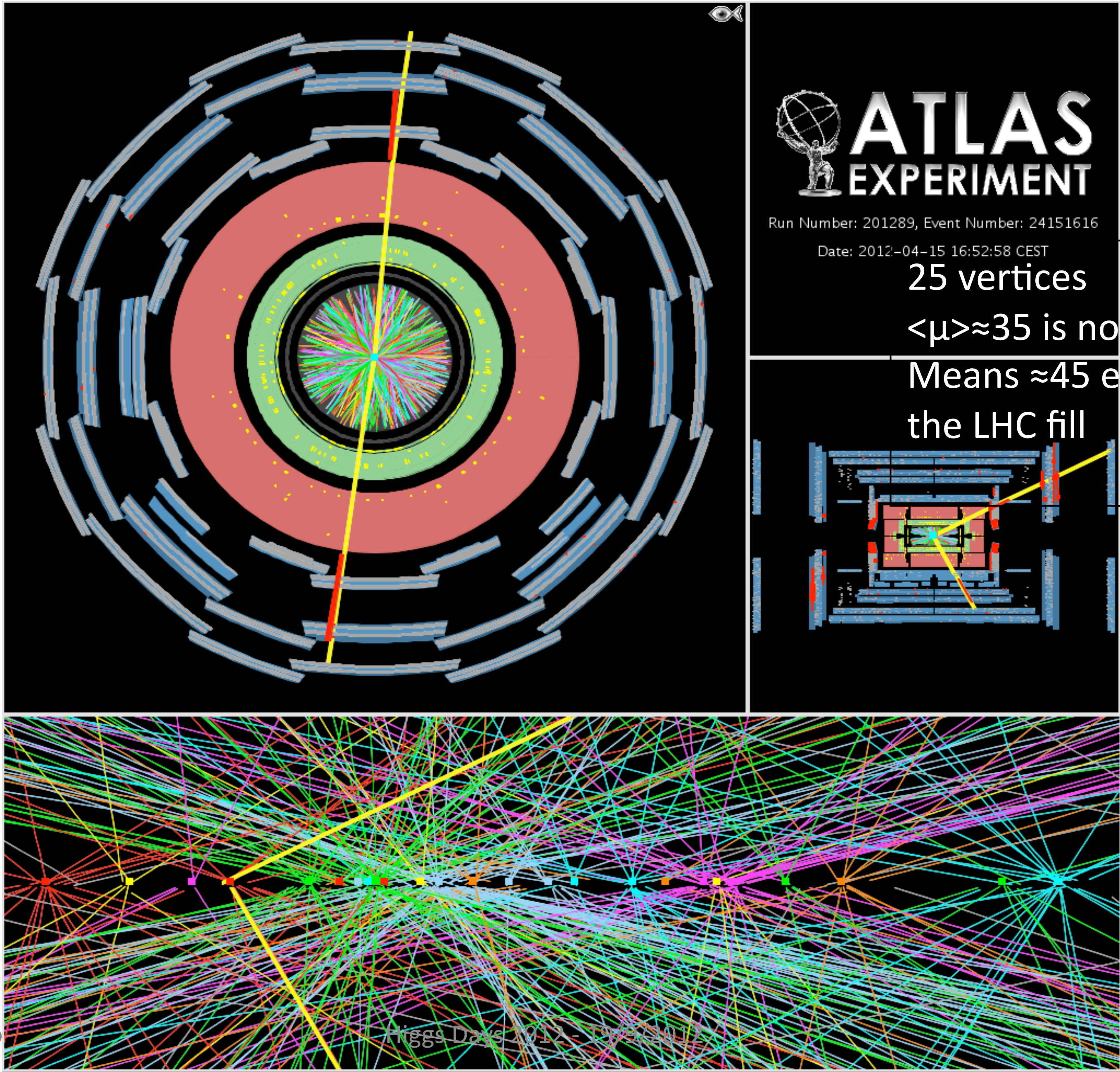


Collision Event at 7 TeV with 2 Pile Up Vertices



http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

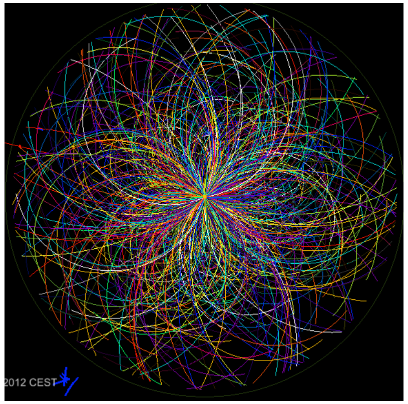

ATLAS
EXPERIMENT
Run Number: 180164, Event Number: 146351094
Date: 2011-04-24 01:43:39 CEST

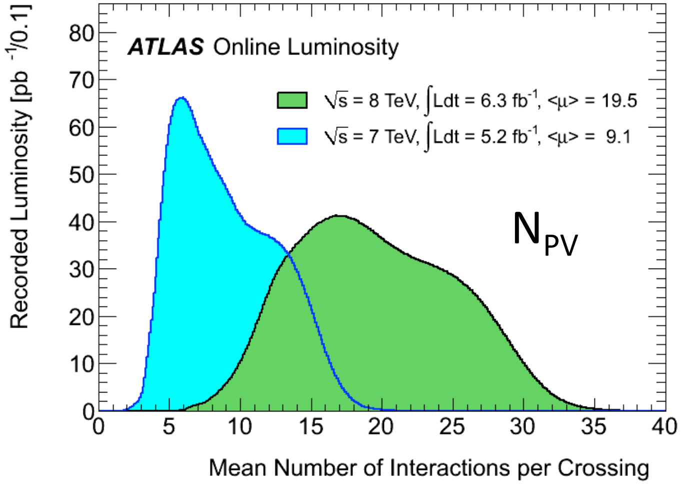


25 vertices
<μ>≈35 is no
Means ≈45 e
the LHC fill

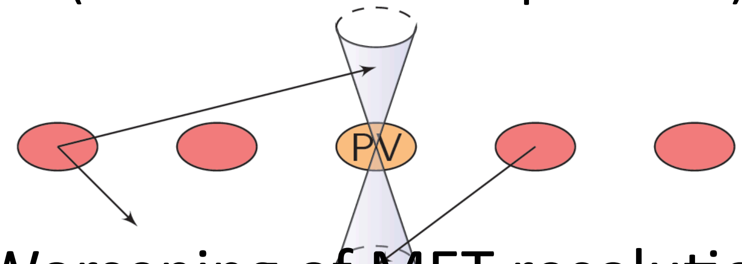
Pileup & Its Consequences

- Many more particles to reconstruct
  ➔more CPU & memory in event reconstruction

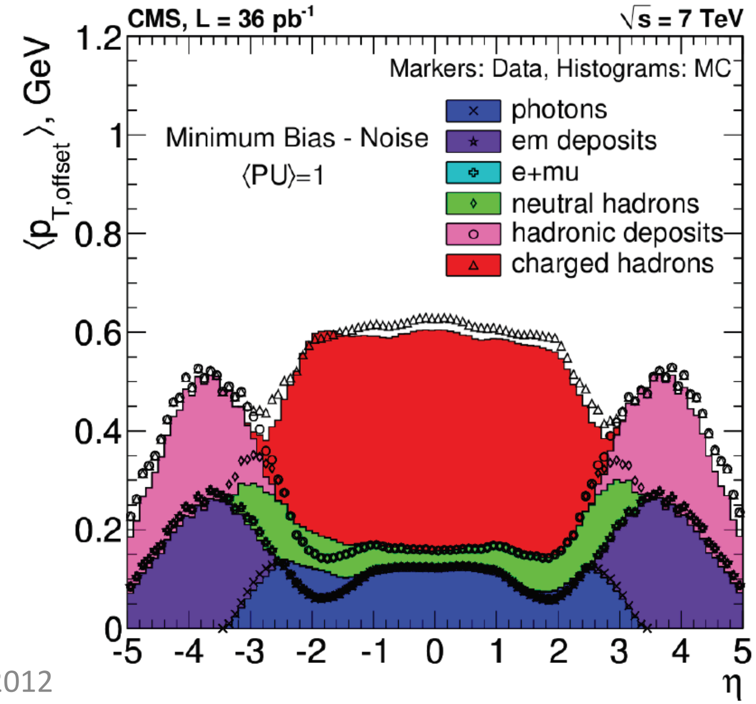




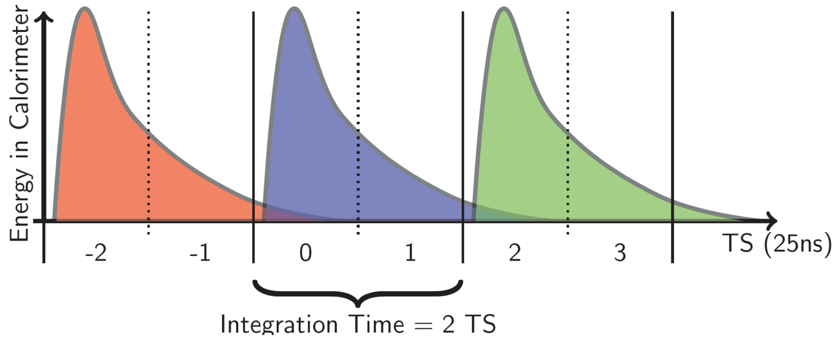
- Contaminated Jets
  - (due to additional particles)



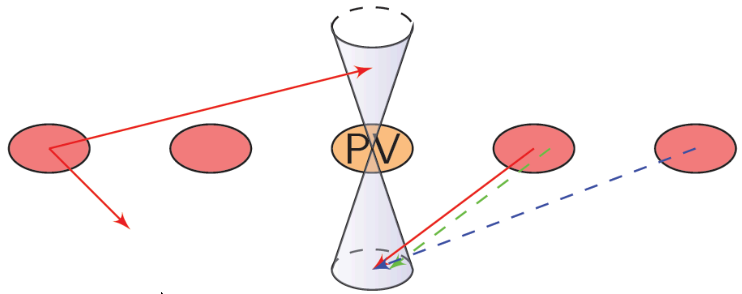
- Worsening of MET resolution
  - (more objects to sample)
- Worsening of Isolation observables
- Ambiguity in hard-scatter vertex identification, e.g. H ➔ γγ



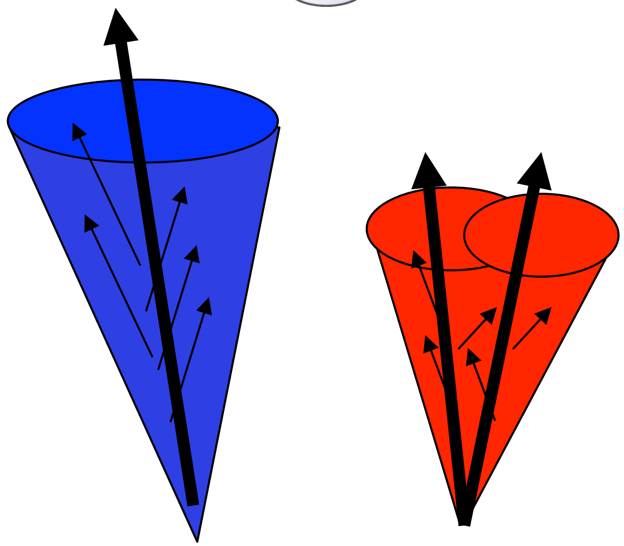
Mitigating Pileup



- Detector level mitigation: Readout over smaller time slice
  - Significantly reduces OOT pileup
- Remove from consideration charge hadrons that originate from pileup vertices

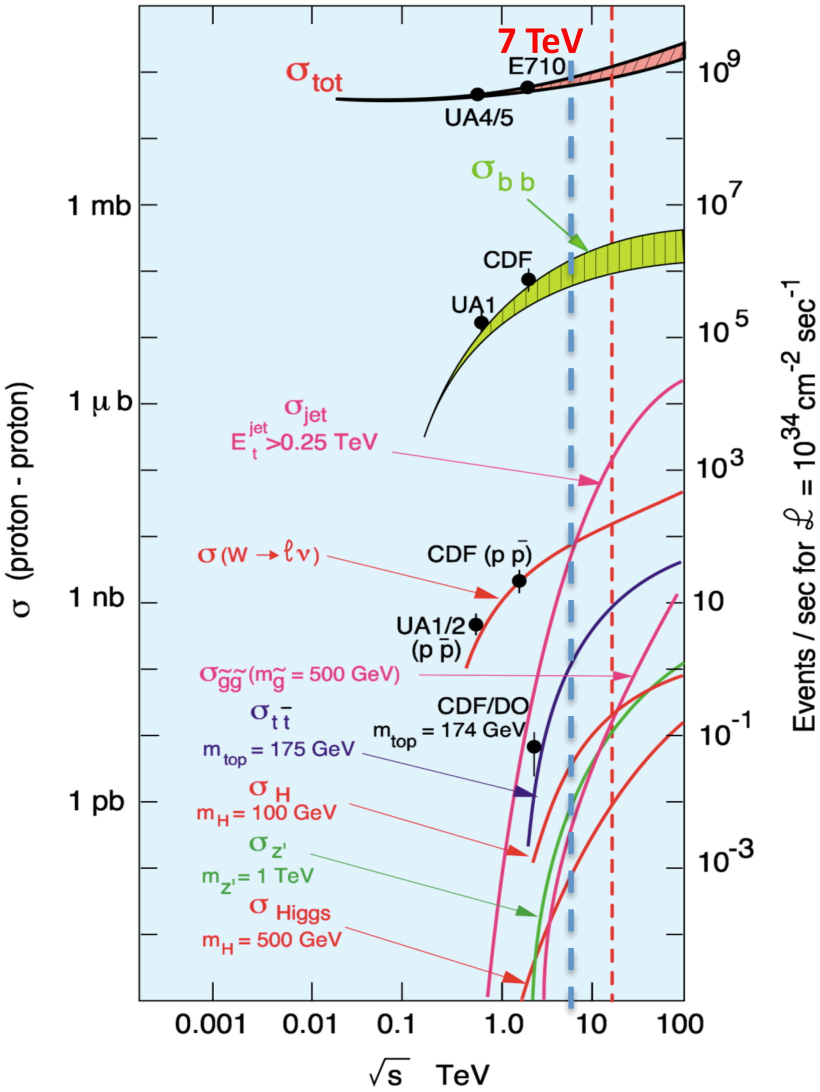


- Amount of additional pileup energy is determined by the jet area (A) and the energy per unit area (ρ)
  - and subtracted
- Take advantage of the topological shape differences between jets from pileup and more collimated jets from hard-scatter of partons



Typical jet   Pileup jet

Trigger



- First step in every physics analysis!
- Much of LHC physics means cross sections x10^6 times smaller than total cross section
- ATLAS offline processing: ≈400 Hz
  - ≈10 events per million crossings!
- In one second at design luminosity:
  - 40 000 000 bunch crossings
  - ≈2000 W events
  - ≈500 Z events
  - ≈10 top events
  - 400 events written out
- **Should take the right 400 events!...**
- Different designs in ATLAS and CMS
  - ATLAS has 3 processing levels; Region-of-Interest driven reconstruction; event built after Level 2
  - CMS has 3 levels but event built after Level 1
- Also different strategies:
  - ATLAS has most bandwidth assigned to exclusive triggers, e.g. muon trigger (+ anything)
  - CMS relies more on exclusive triggers e.g. muon + 2 jets

Other:

Tevatron Higgs cross section