Experimental Prospects For Higgs Boson Searches

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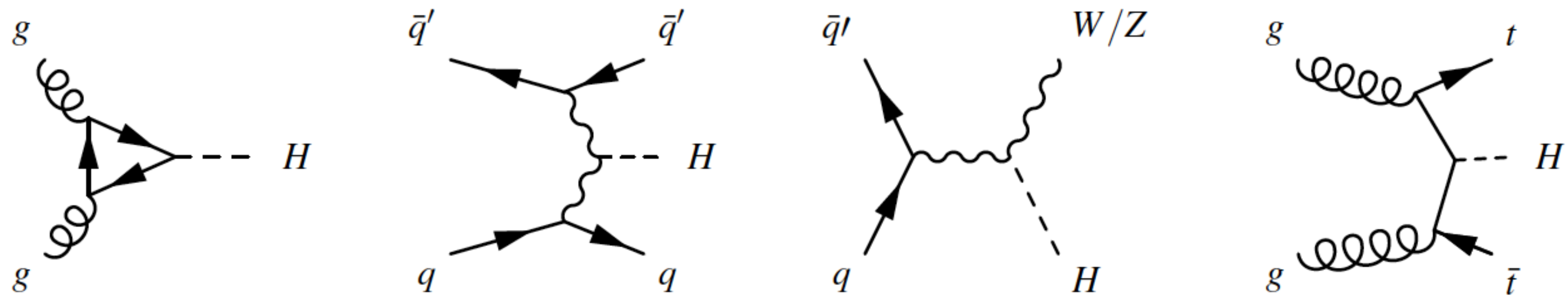
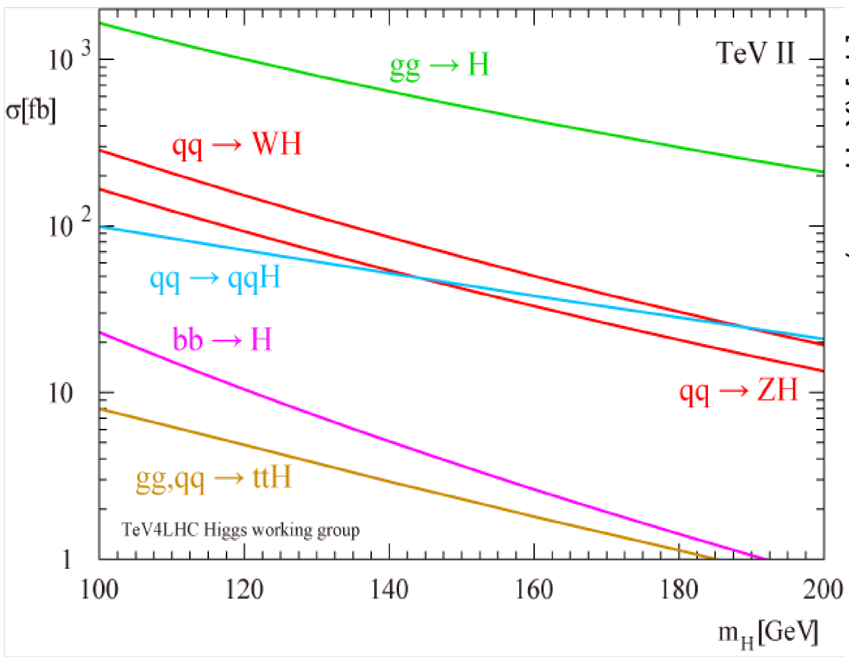
XLVI Rencontres De Moriond 2011

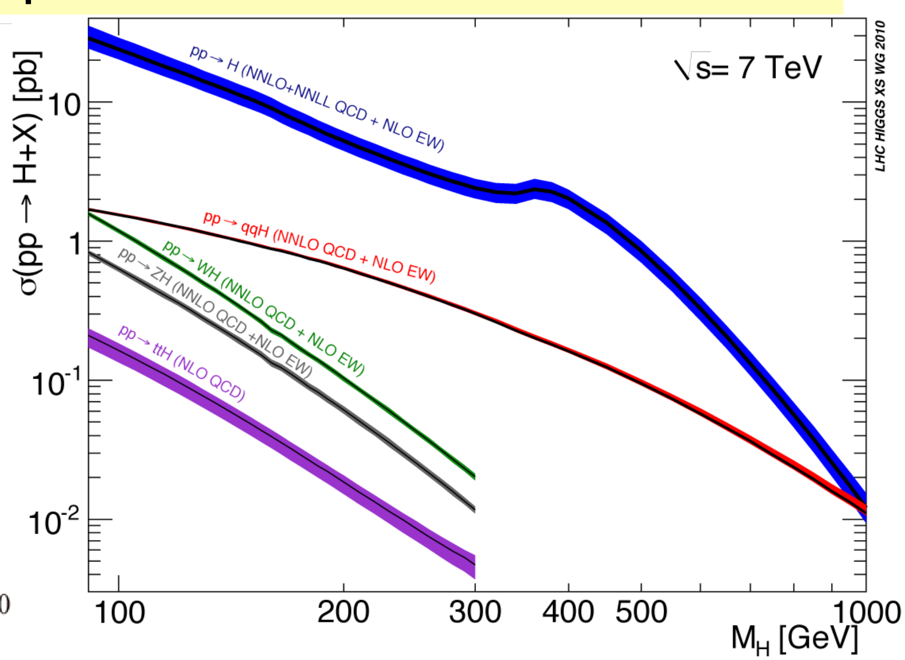
Higgs Production At Hadron Colliders



(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$

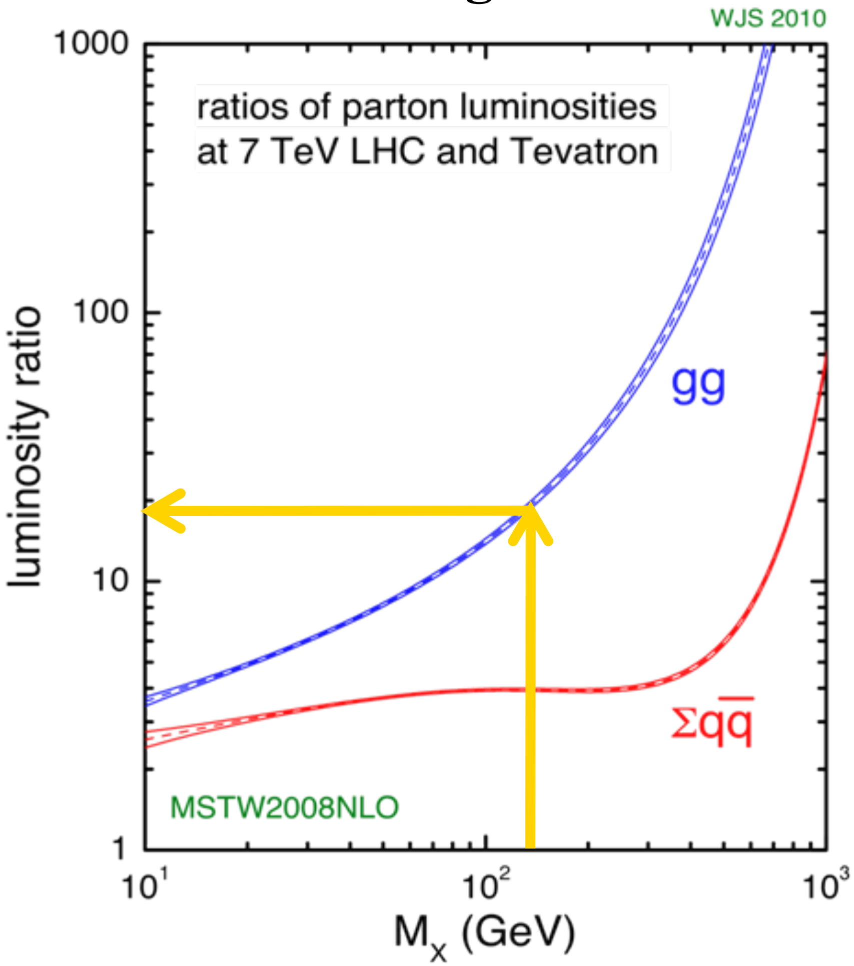
gg→ H is the dominant production mechanism





LHC & Tevatron Compared (I)

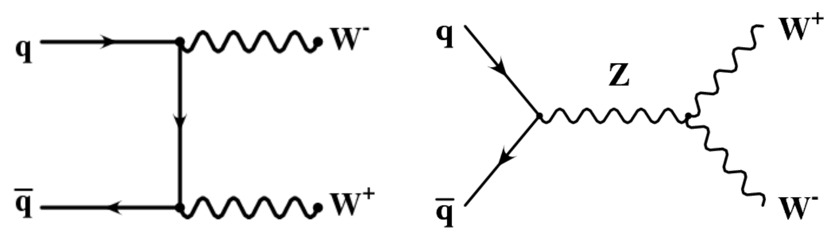
Stirling *et al*



For M_X > 140 GeV

gg → H cross section at 7 TeV is >15 times that at 2 TeV

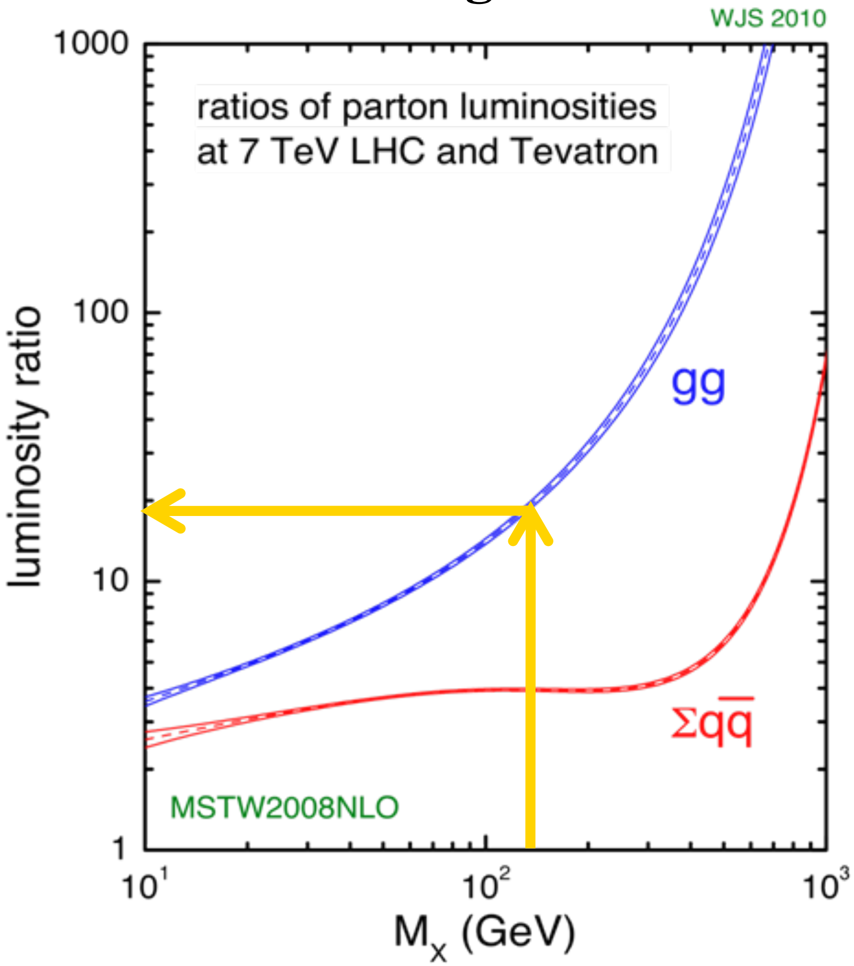
Irreducible backgrounds (WW,ZZ) originate from $q\bar{q}$ process which rises relative slowly (pp vs $p\bar{p}$)



⇒ Larger signal, better S/N

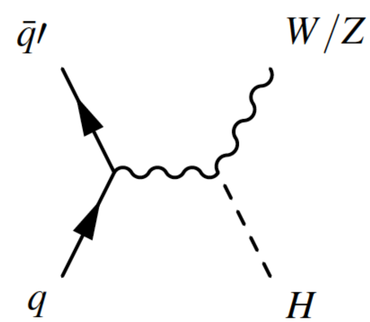
LHC & Tevatron Compared (II)

Stirling *et al*



For M_X < 130 GeV

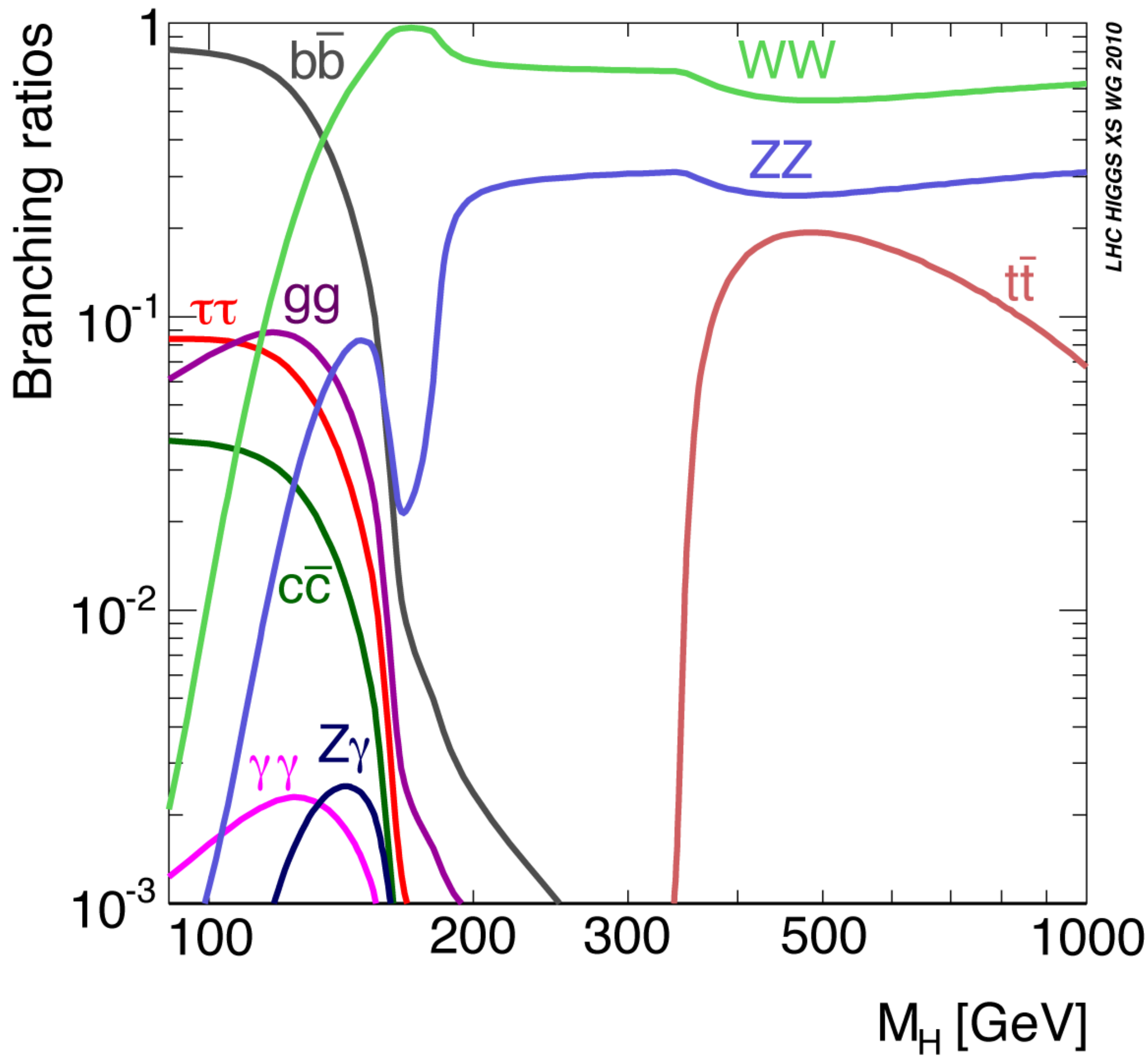
Modest rise in $q\bar{q}$ cross section at 7 TeV, pp → VH production only x3 larger than at 2 TeV



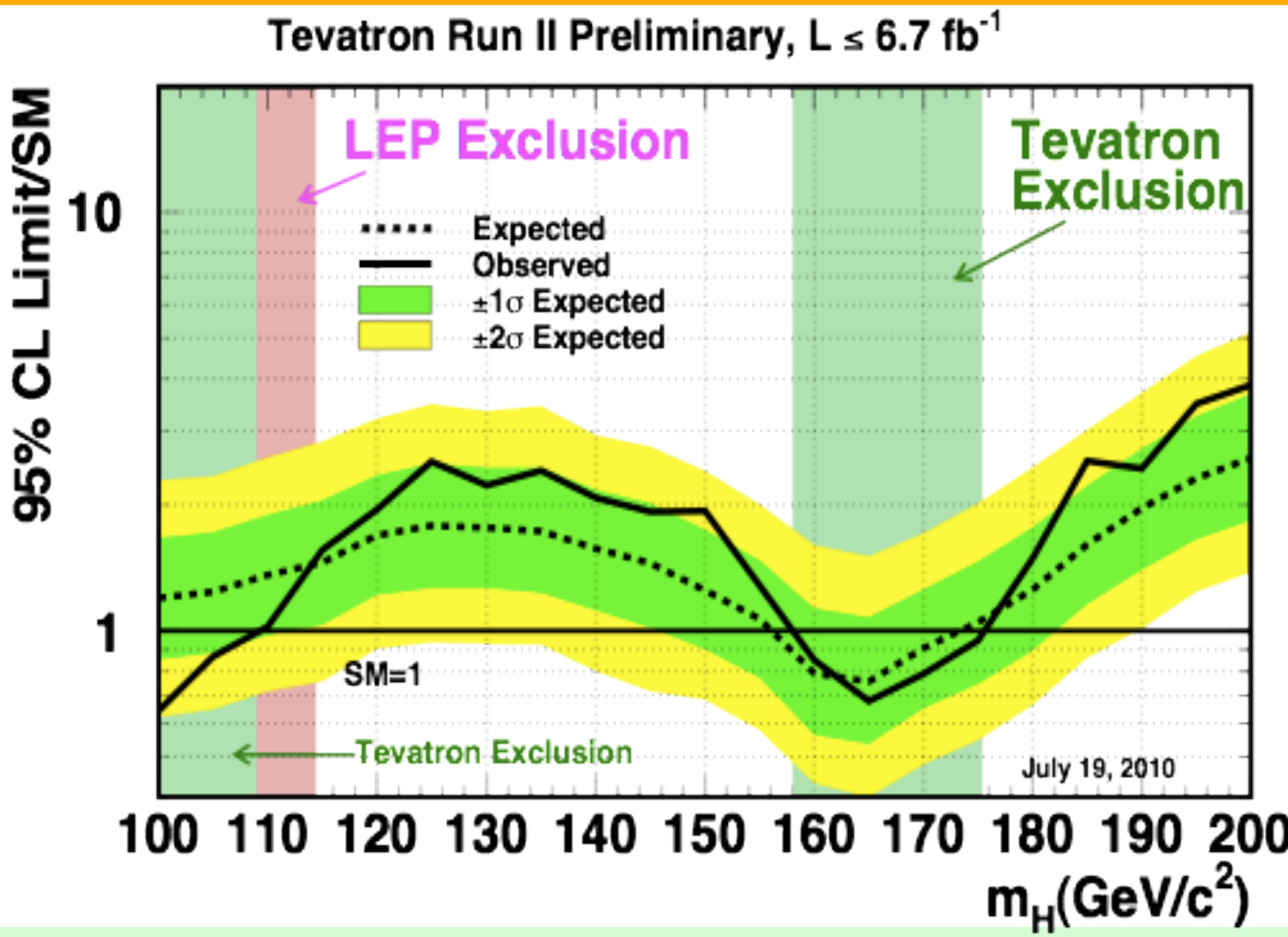
Major backgrounds are W/Z+b$\bar{\text{b}}$ & t$\bar{\text{t}}$ which rises sharply due to rise in gg cross section

⇒ Small signal, worse S/N

Higgs Decay Modes Vs Its Mass



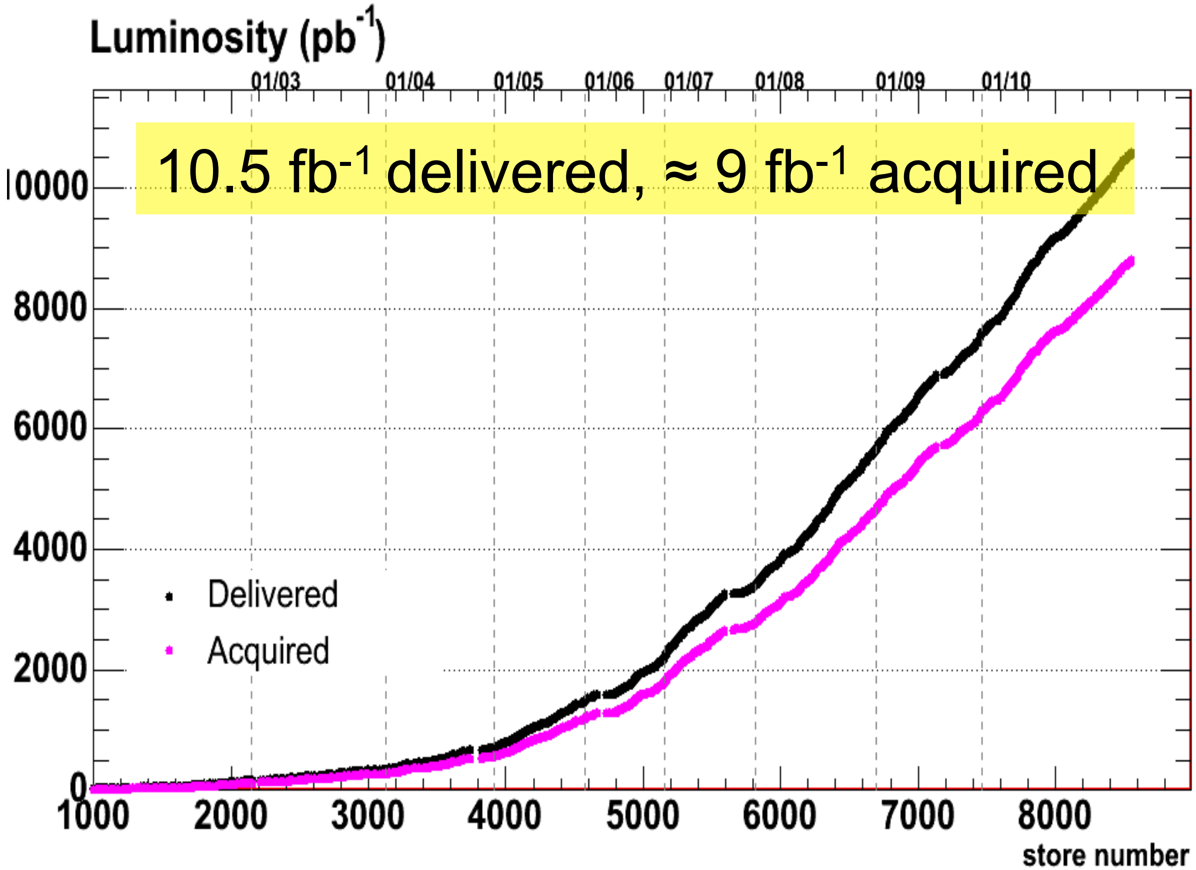
Higgs Searches At Tevatron: Picture at ICHEP'10



95% CL Exclusions: 158 < M_H < 175 GeV ; 100 < M_H < 109 GeV

Limit : 1.5x σ_{SM} for M_H = 115 GeV

Tevatron : Status & Prospects



Tevatron operations to end in Sept 2011

Expect ≈ 12 fb^{-1} delivered, ≈ 10 fb^{-1} recorded

Expect full set of search results from 9 fb^{-1} by summer'11

Current thrust → improving search efficiencies by 15-60 %

Tevatron Low Mass Higgs Search

"Low Mass" (100 < M_H< 150 GeV) Higgs searches : P.Totaro

	Experiment	Lumi fb^{-1}	Exp. Limit for M_H = 115 GeV	Obs. Limit for M_H = 115 GeV
$H \rightarrow \tau\tau$+jets	CDF	6.0	15.2 x SM	14.6
$H \rightarrow \tau\tau$+jets	D0	4.2	12.8x SM	32.8
$H \rightarrow gg$	D0	8.2	11.0x SM	19.9
$ZH \rightarrow \nu\nu$ bb	D0	6.2	4.0x SM	3.4

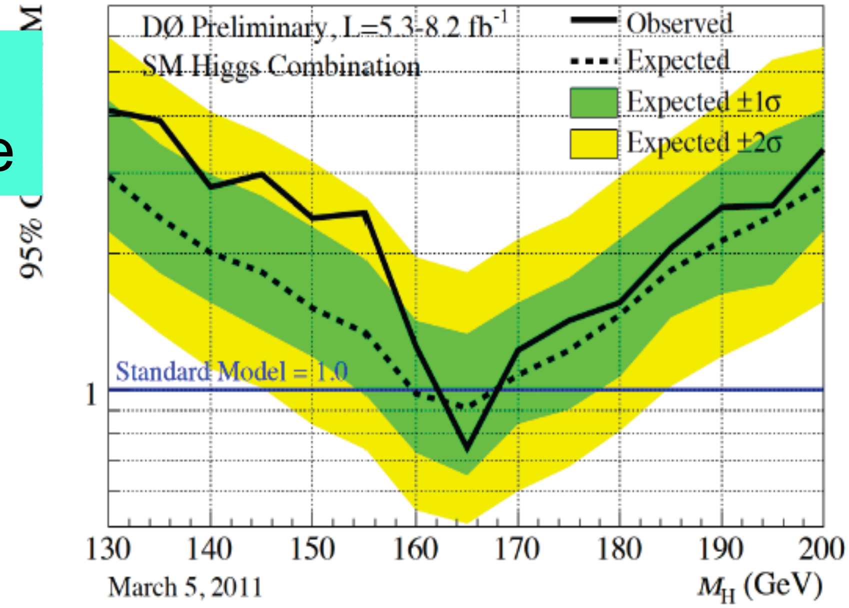
No new combined limit for "Low Mass" Higgs

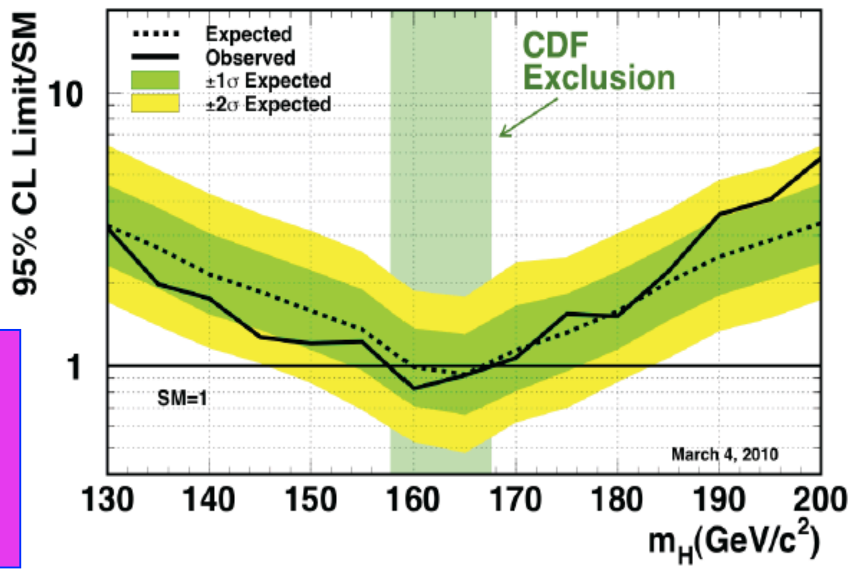
Tevatron "High Mass" (130 < M_H< 200 GeV) Searches

D0 : 8.2 fb^{-1} ; CDF: 7.1 fb^{-1}
Both searching in H→ WW mode

Channel	CDF	DØ
	$H \to WW^* \to \ell^- \bar{\nu} \ell^+ \nu$	
$\ell = e, \mu$, 0/1/2+ jet	Updated	New
$\ell = e, \mu$, ≤ 1 jet low $M_{\ell\ell}$	Updated	-
$\ell = \tau_h, \mu(e)$	Updated	New
$\ell = \tau_h, \mu(e)$, 2+ jet	-	New (4.3 fb^{-1})
	$H \to WW \to \ell \nu qq$	
$\ell = e, \mu$, 2+ jet	-	(5.4 fb^{-1})
	VH→VWW	
SS Dilepton	Updated	(5.4 fb^{-1})
Trileptons	Updated	-

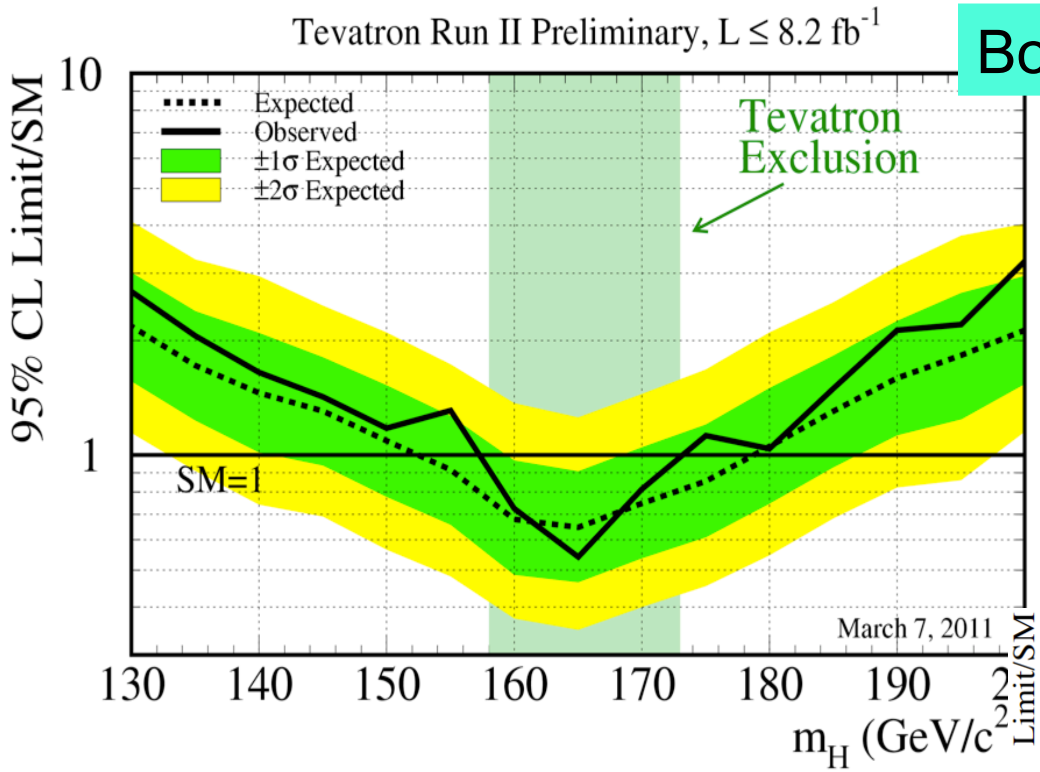
For the first time both experiments "touch down" below SM expectation (sweet spot : M_H = 165 GeV)





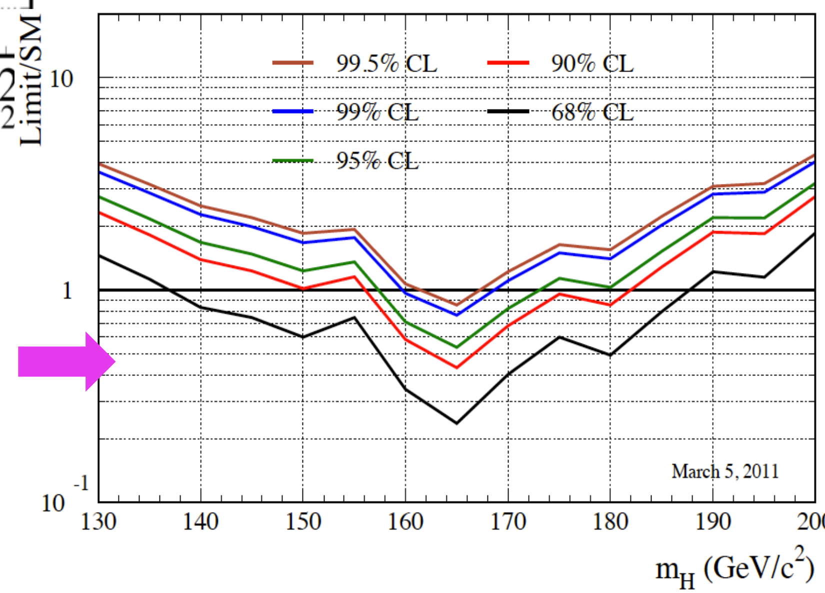
Tevatron "High Mass" (100 < M_H< 150 GeV) Searches

Bo Jayatilaka; CONF-11-044-E



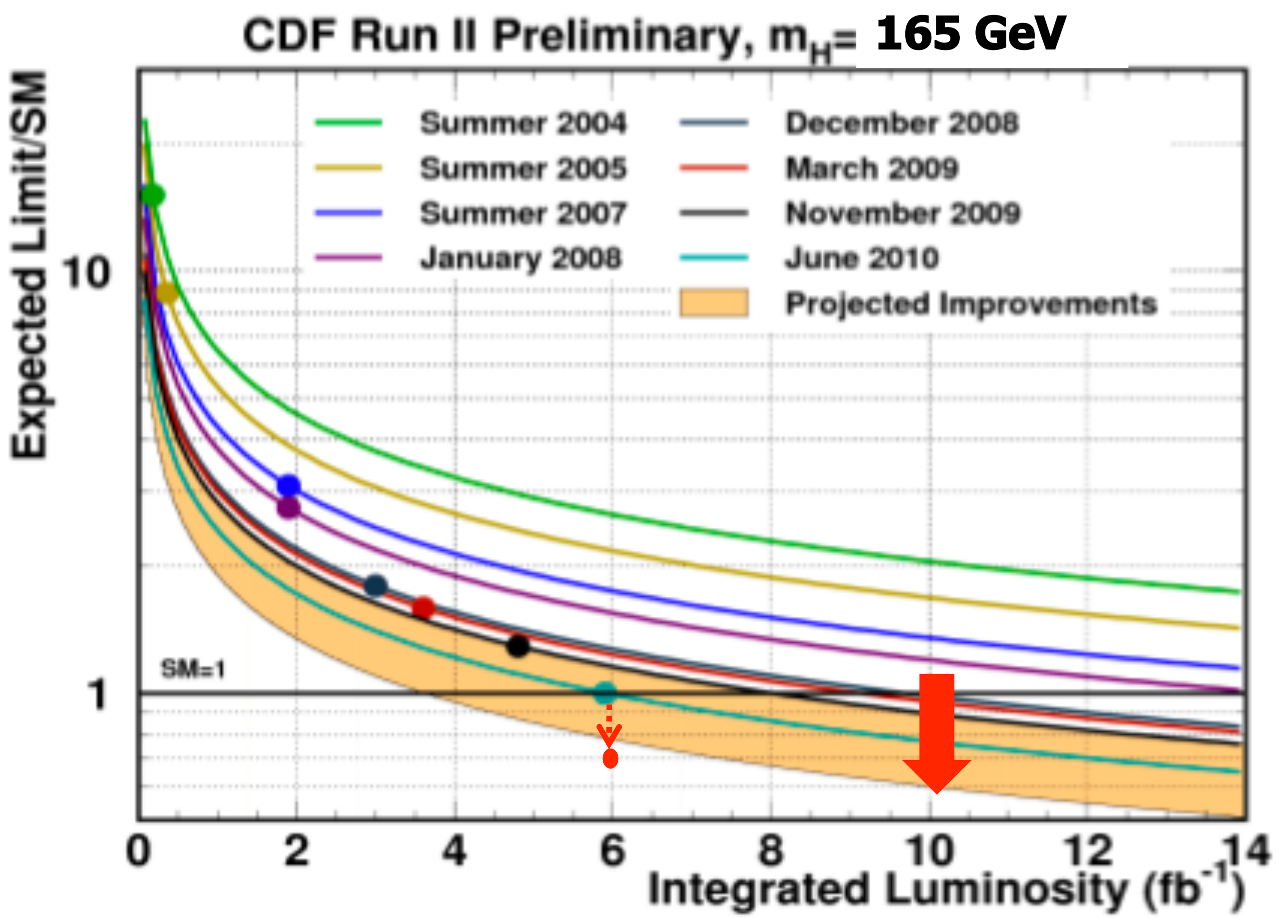
Observed:
SM Higgs Boson excluded at 95% CL: 158 < M_H<173 GeV

Expected:
95% CL: 153 < M_H<179 GeV



Now showing 99.5 % exclusion limit
158 < M_H<173 GeV

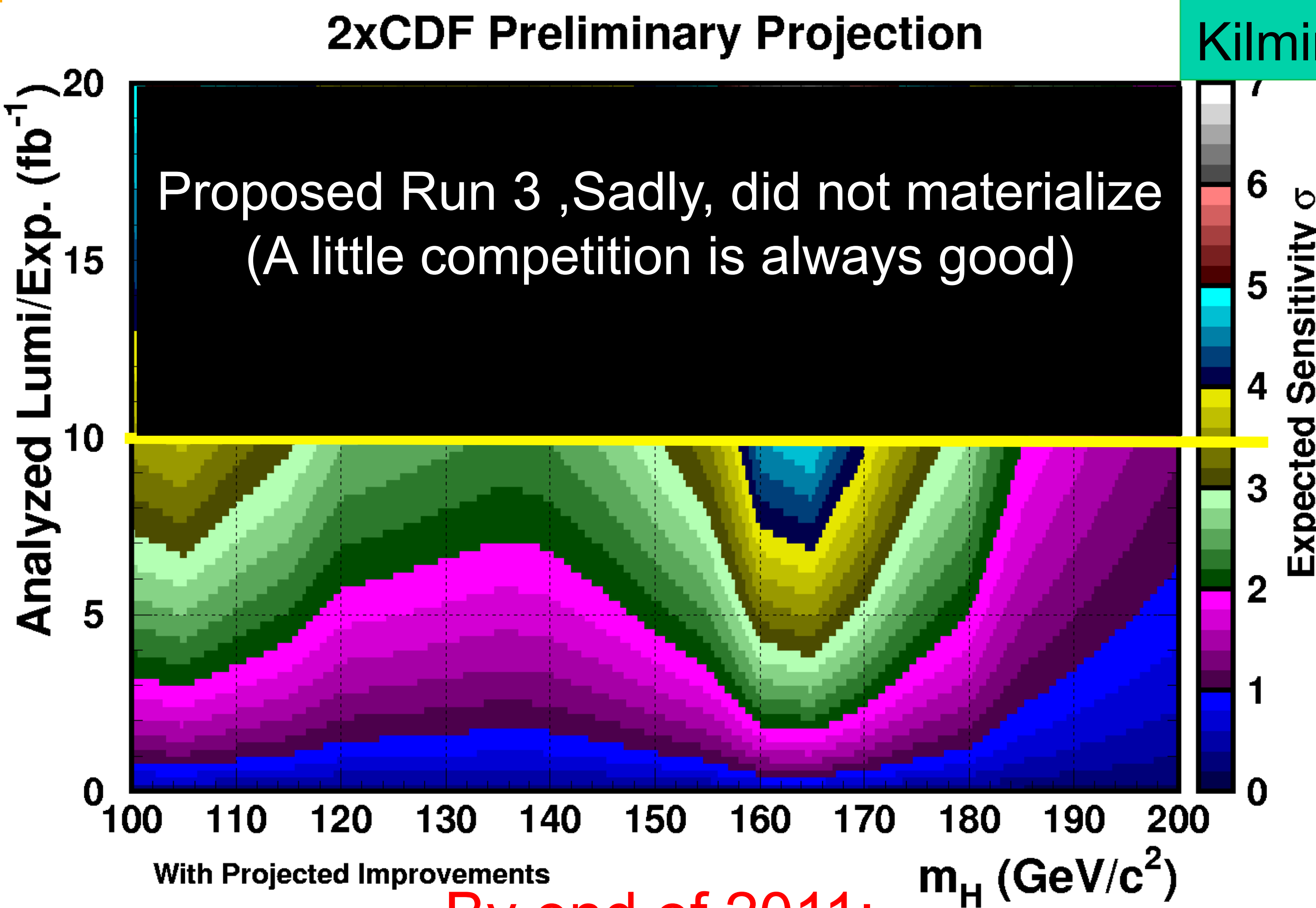
Improvement in Higgs Sensitivity Over the Years



Based on the current list of expected improvements CDF can do better than original projections

Tevatron Projections: ICHEP 2010

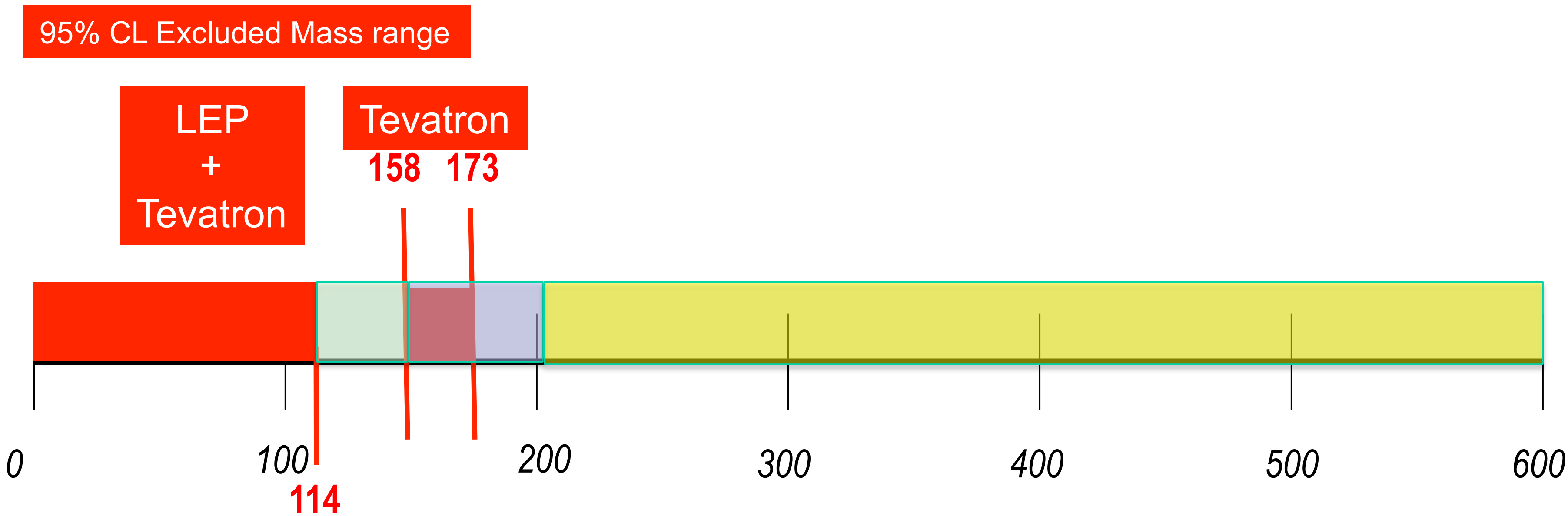
Kilminster



By end of 2011:

- 2.4σ expected sensitivity across mass range;
  - 3σ at 115 GeV

The Higgs Search Landscape: LHC Joins The Fray !



Low Mass
(M_H≈ 120 GeV)
H→γγ
H → WW
qqH→ττ
V+ H→bb
qqH→bb
V+ H→WW

Mid Mass
(M_H ≈ 160 GeV)
H→WW
H→ZZ

High Mass
(M_H≈ 400 GeV)
H→ZZ
H→WW

Basic Pillars of Higgs Searches

- Efficient Higgs search requires excellent performance from the entire detector and several reconstructed "objects"
- Key objects:
  - **Photon**
  - **Electron and Muon**
  - **Tau**
  - **b quark-jet tagging (b-tag)**
  - **Jets**
  - **Missing transverse energy (MET)**

2010 data has demonstrated excellent performance of ATLAS & CMS in reconstruction of these basic objects

Performance in data closely matches expectations based on simulations (MC) and sometimes exceeds it

→ ATLAS & CMS have very sharp tools for discovery

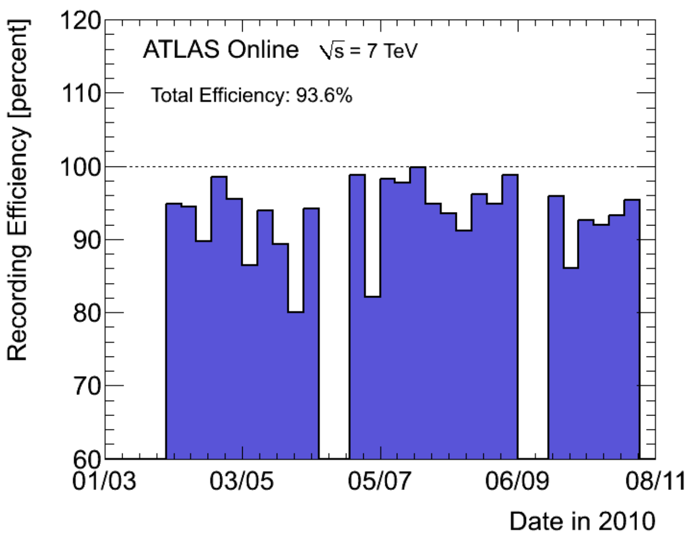
ATLAS & CMS Detector Performance: It All Starts Here !

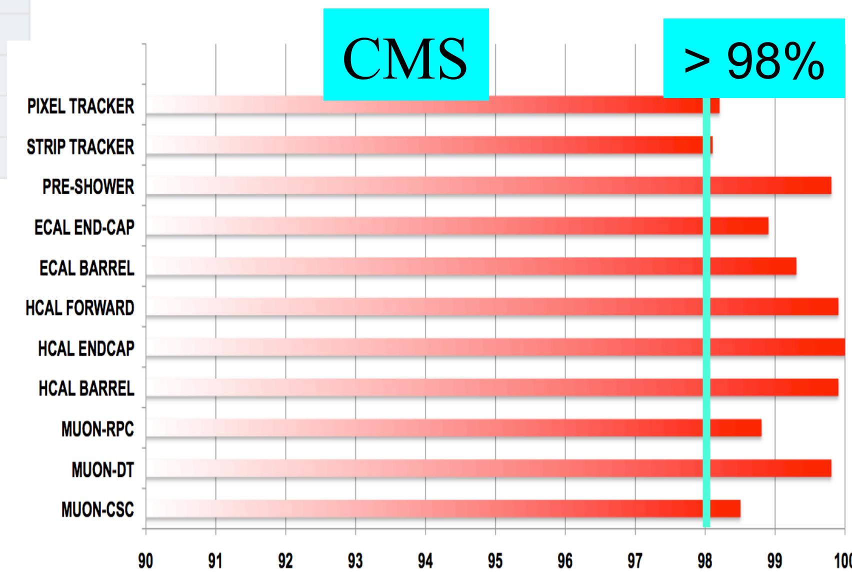
Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	97.5%
SCT Silicon Strips	6.3 M	99.3%
TRT Transition Radiation Tracker	350 k	98.0%
LAr EM Calorimeter	170 k	98.5%
Tile calorimeter	9800	97.3%
Hadronic endcap LAr calorimeter	5600	99.9%
Forward LAr calorimeter	3500	100%
LVL1 Calo trigger	7160	99.8%
LVL1 Muon RPC trigger	370 k	99.7%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	98.5%
RPC Barrel Muon Chambers	370 k	97.3%
TGC Endcap Muon Chambers	320 k	98.8%

ATLAS

> 98%

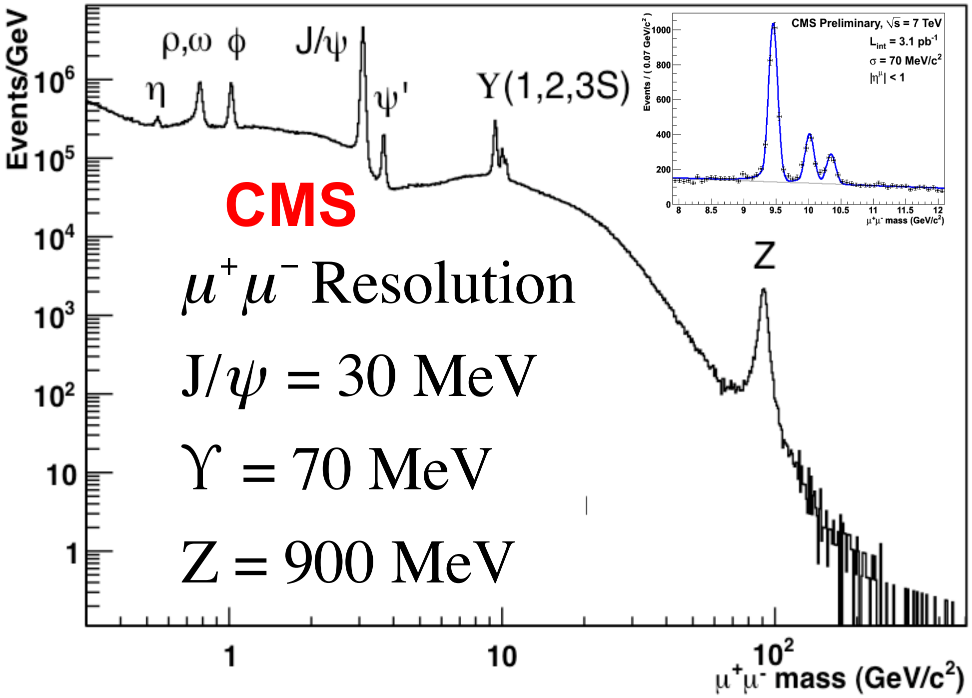
≈ 100M channels each
≈ 98% channels operational
Makes event reconstruction and comparison with simulations much easier

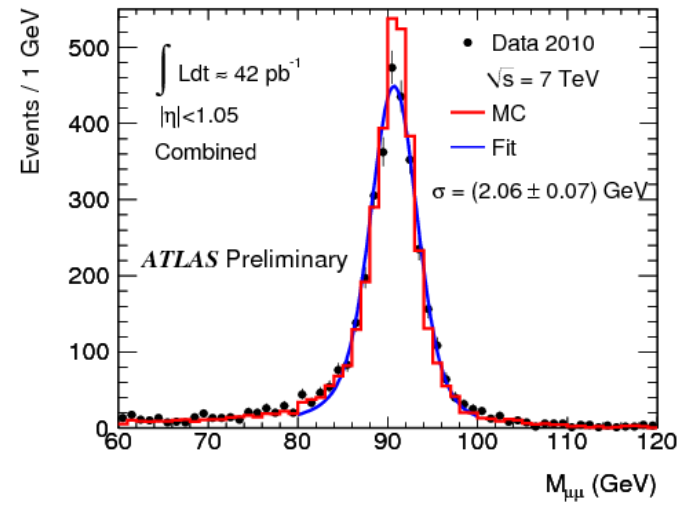


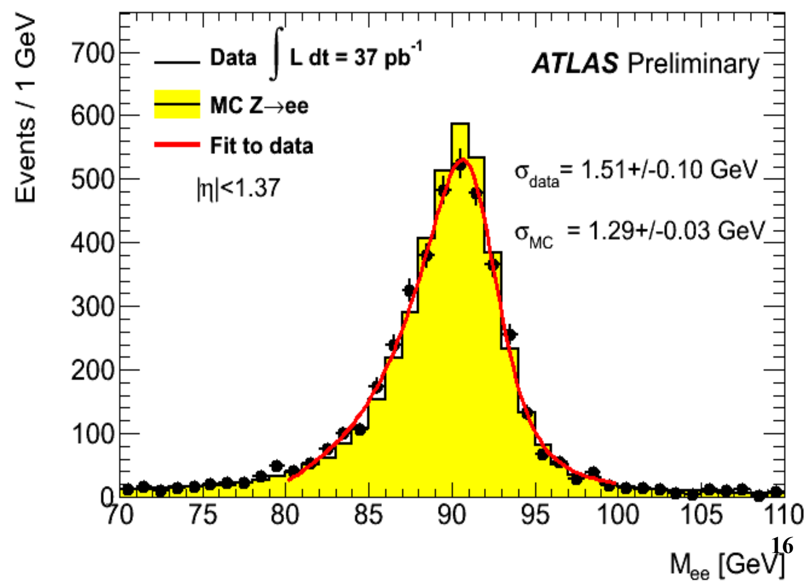


	MUON-CSC	MUON-DT	MUON-RPC	HCAL BARREL	HCAL ENDCAP	HCAL FORWARD	ECAL BARREL	ECAL END-CAP	PRE-SHOWER	STRIP TRACKER	PIXEL TRACKER
Series1	98.5	99.8	98.8	99.9	100	99.9	99.3	98.9	99.8	98.1	98.2

Muon and Electron Reconstruction

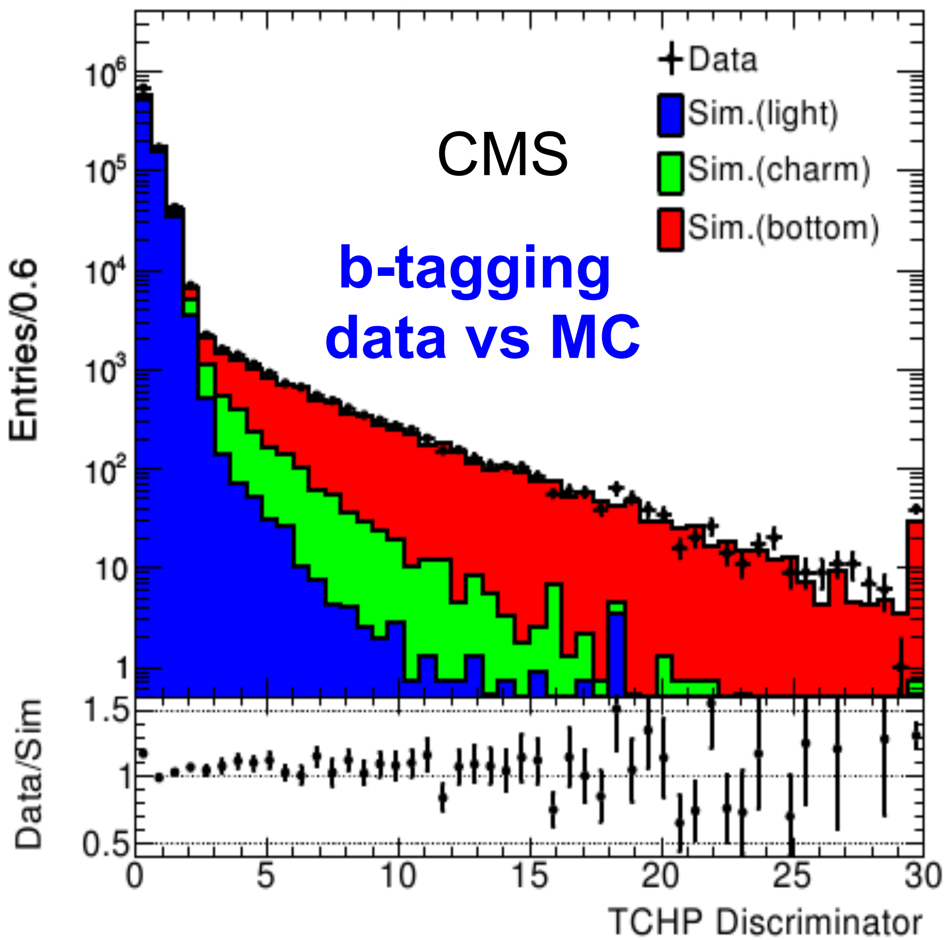


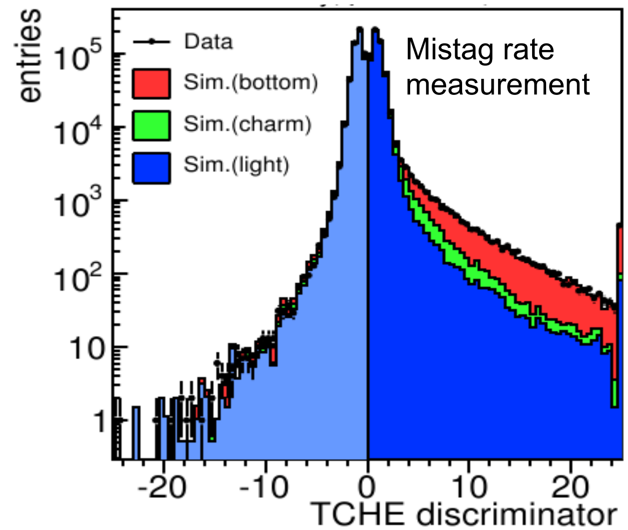


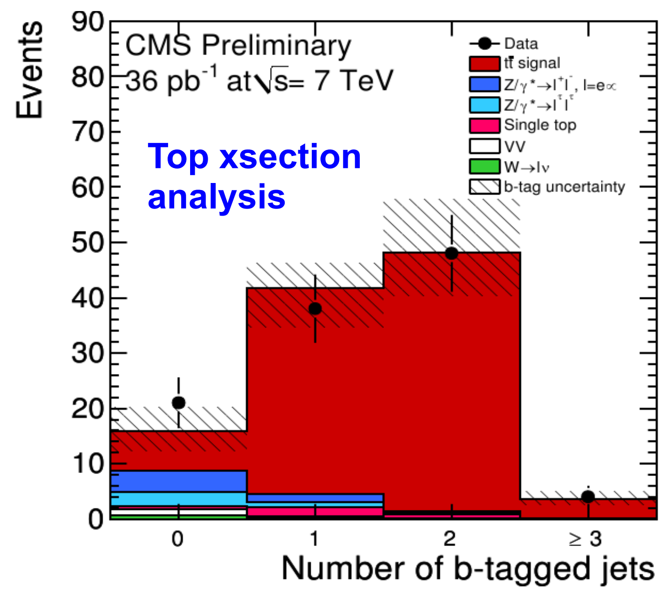


Muon & Electron reconstruction performance close to design

b quark-jet tagging: Worked Out Of The Box !







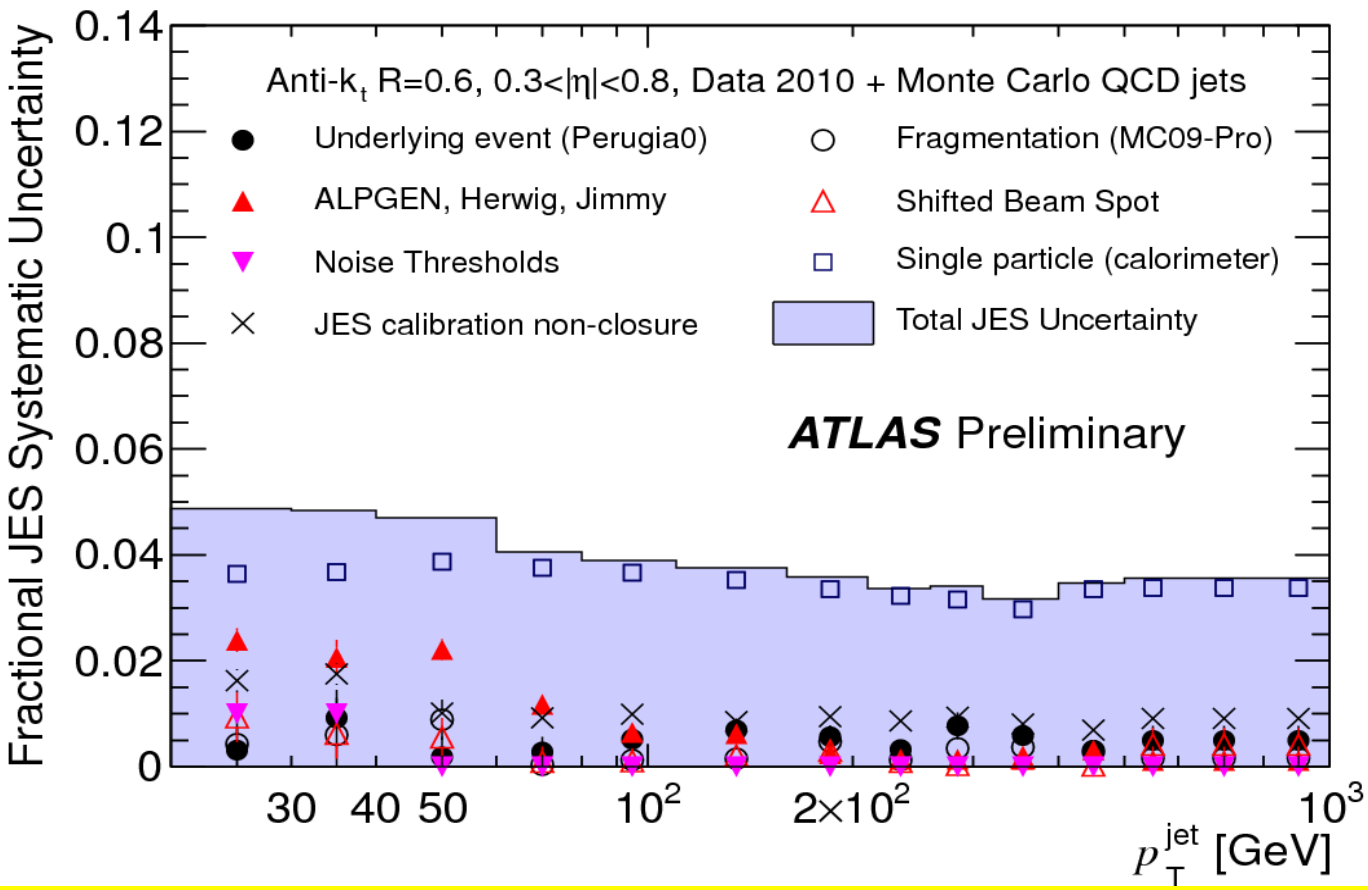
Efficiency and mis-tag rate evaluated from data.
Agreement with MC simulation within few %

Heavily used in several EWK, TOP measurements & searches already

Jet Reconstruction

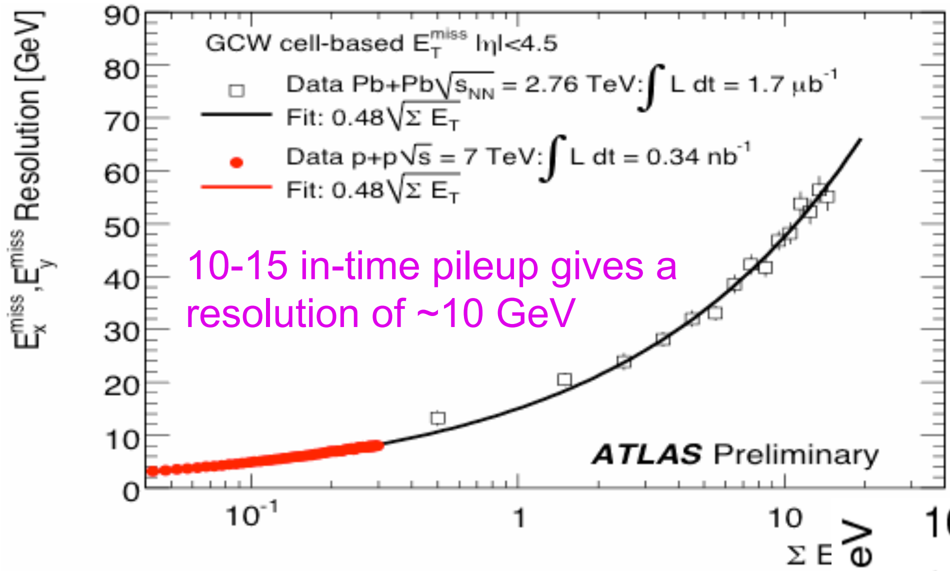
Jet energy resolution for central jets

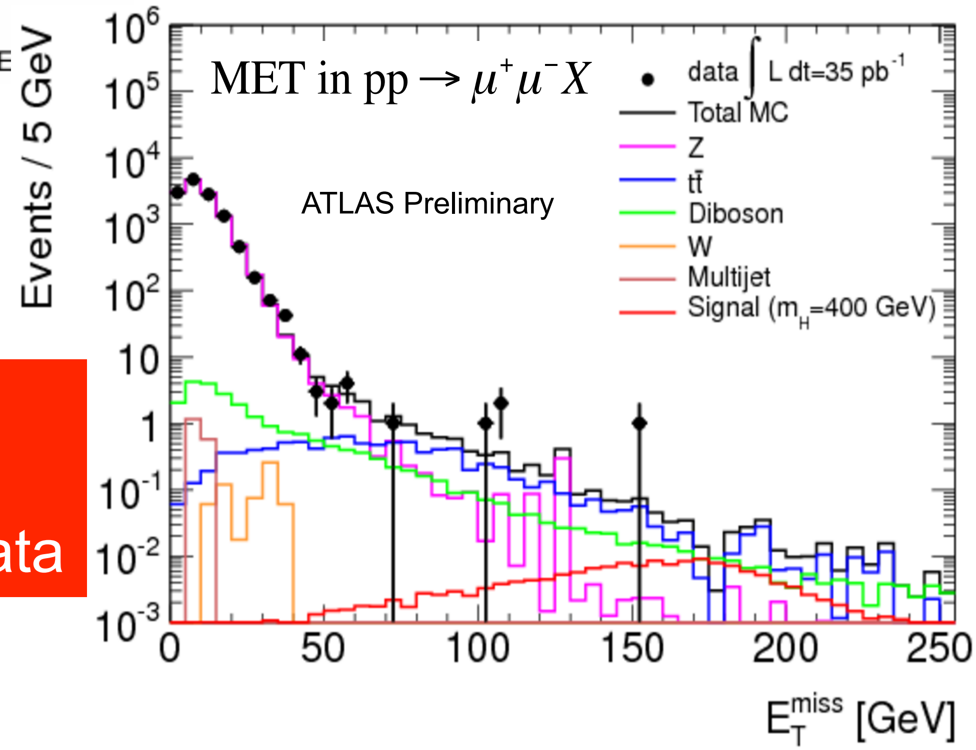
Total uncertainty below 5%



CMS : Innovative “Particle Flow” algorithm brings similar precision

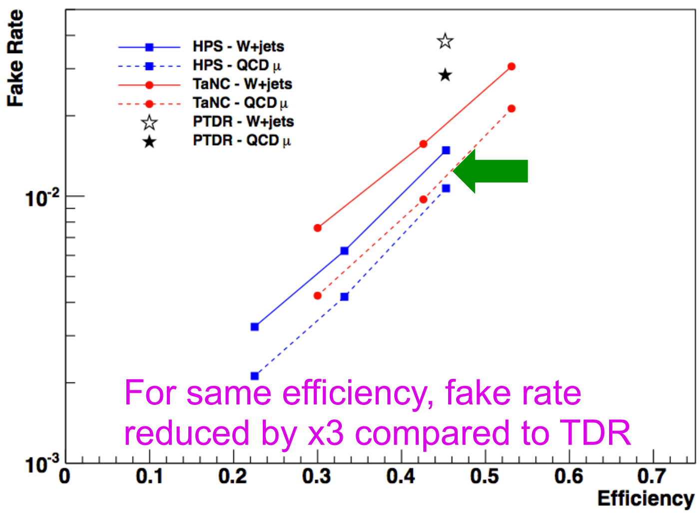
Missing Energy (MET) Resolution Measured From Data

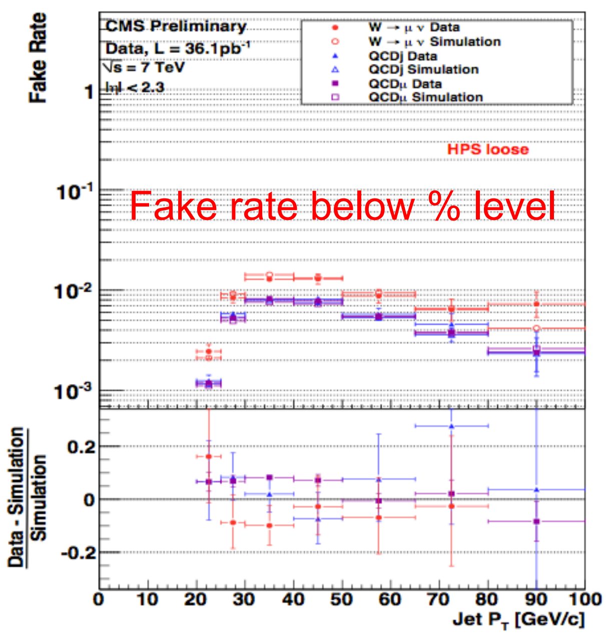


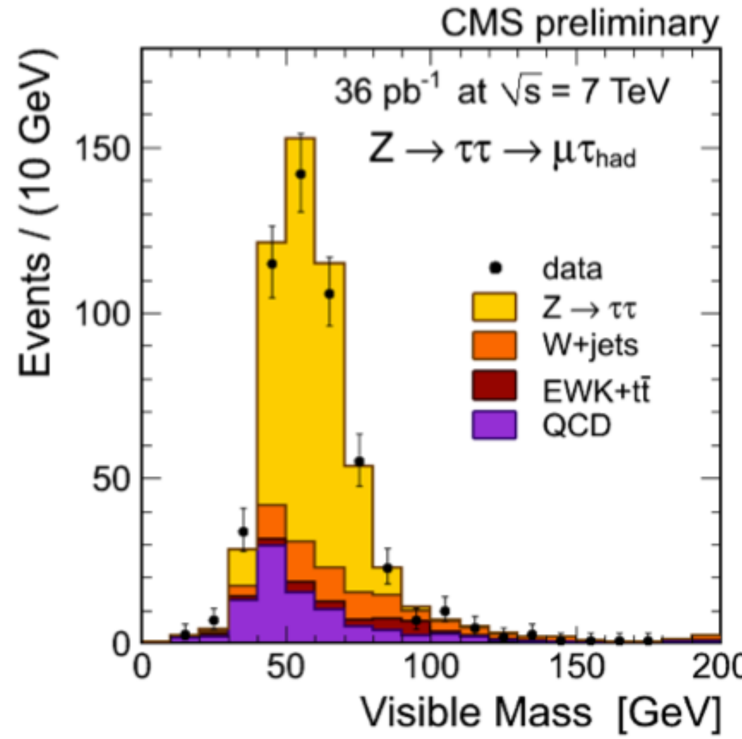


MET resolution and spectra understood within **weeks** of accumulating the first 7 TeV data

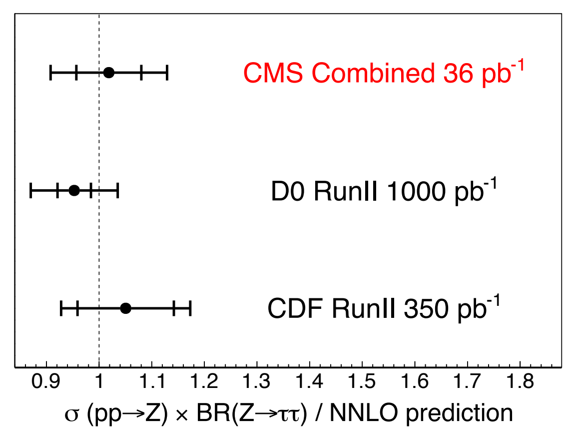
Tau Reconstruction







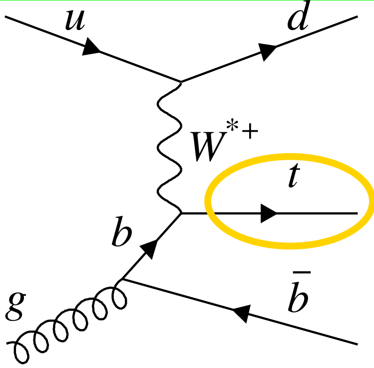
Clean sample of $Z \rightarrow \tau\tau$



Excellent validation for searches

Putting It All Together: Single Top at LHC

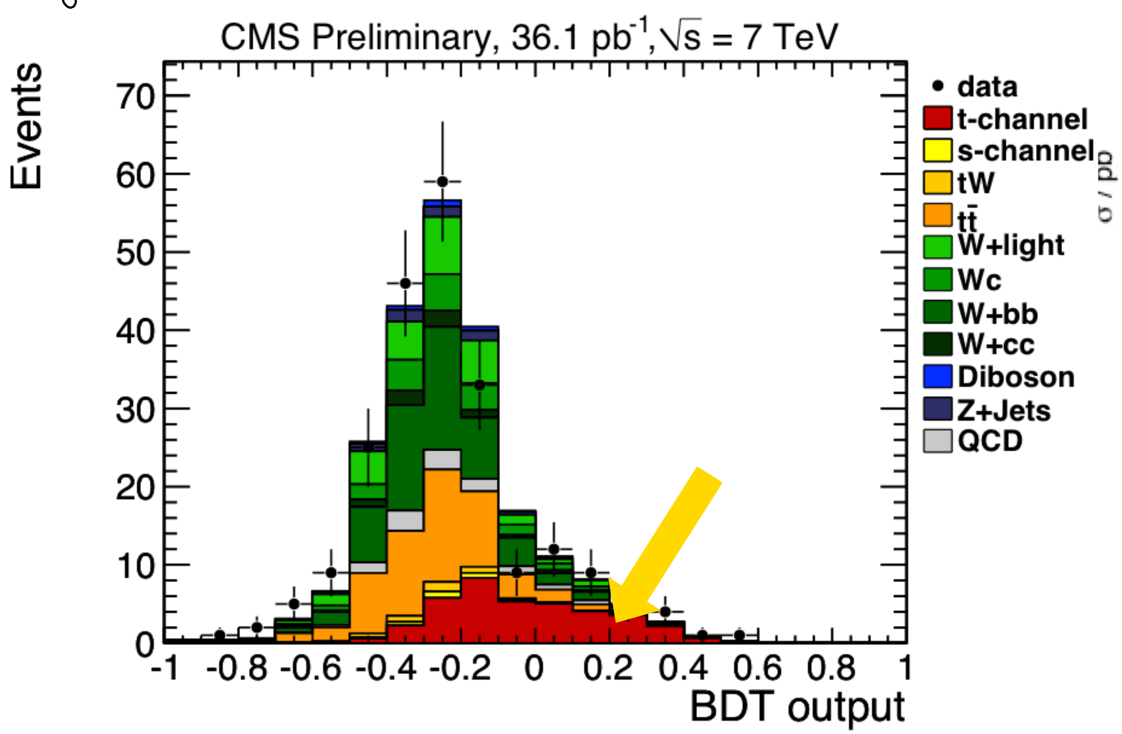
An Example of finding tiny signals with lepton, MET, b-tag & jets



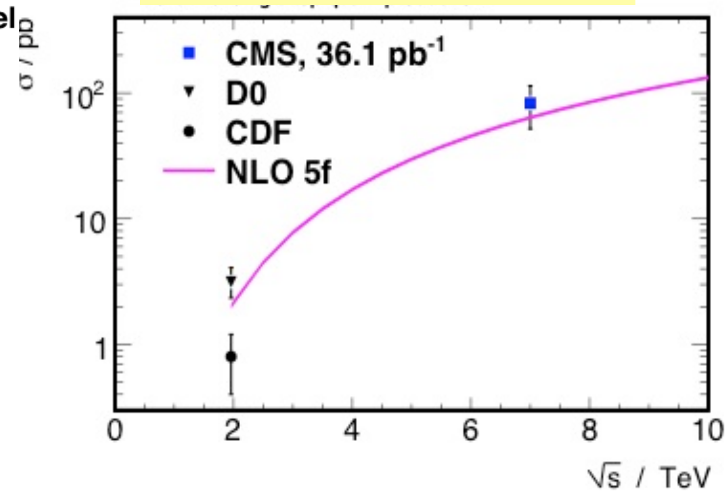
t channel
($\sigma \approx$ 62 pb @ 7 TeV)

Two methods employed:

- Cut based using angular info
- MVA with 37 kinematic observables



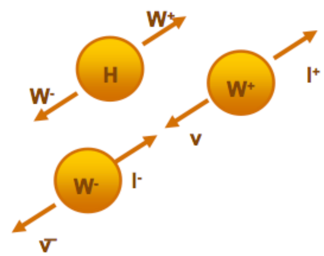
$\sigma = 83.0 \pm 29.6 \pm 9.1(\text{lumi})$ pb

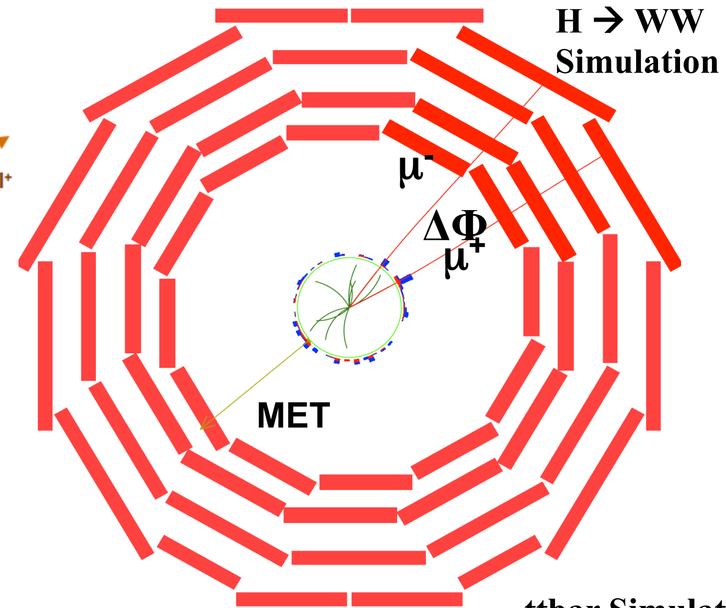


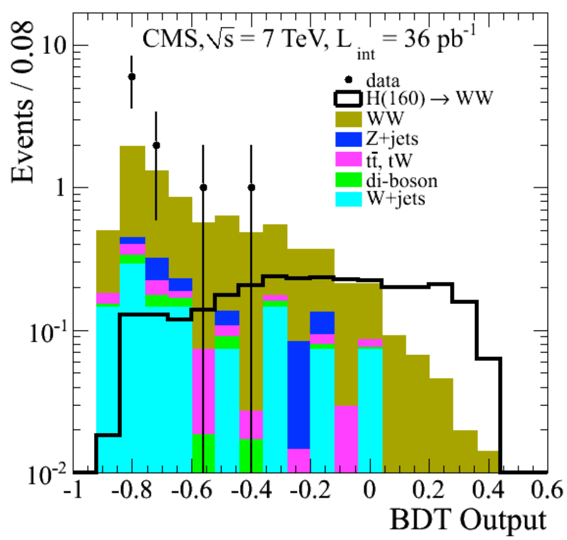
A Brief Portrait of Key SM Higgs Discovery Channels at LHC

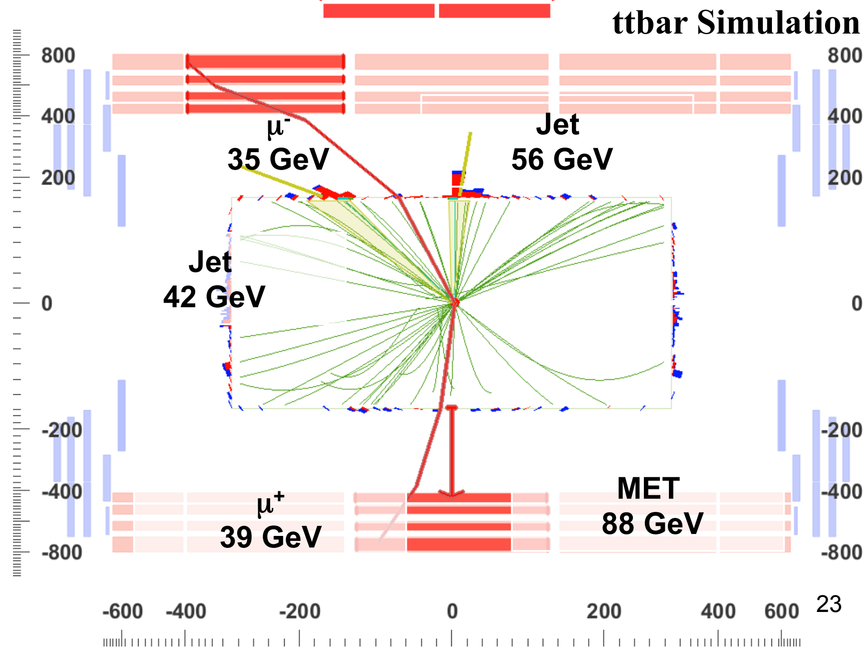
$H \rightarrow WW \rightarrow 2l2\nu$: Work Horse For $120 < M_H < 200$

- **Signal: 2 isolated leptons with small $\Delta\varphi$ + MET + 0, 1, 2 jets**
- Reduction of major backgrounds:
  - **WW: $\Delta\varphi$ & m_{ll}**
  - ttbar: Central jet veto, $\Delta\varphi$ & m_{ll}
  - W+jets: tight lepton ID
  - DY reduced by MET requirement
  - WZ/ZZ: 2 leptons in final state, MET
- Count excess above a cut on MVA output



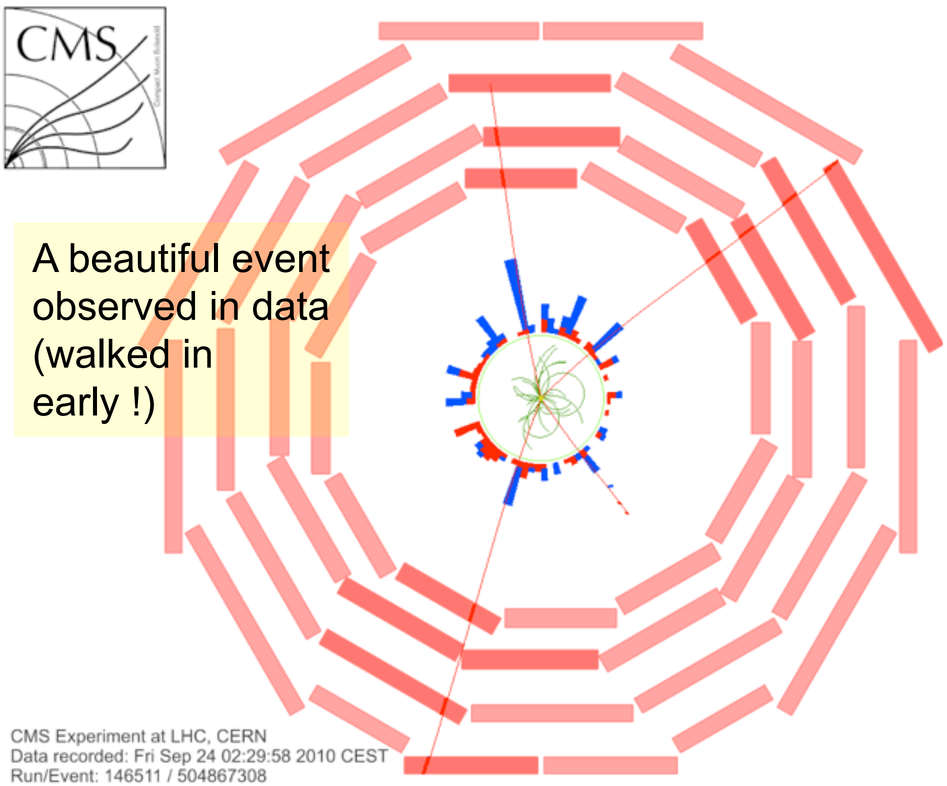






- Backgrounds are assessed using data-driven techniques: WW, ttbar, W+jets, Z+jets

$H \rightarrow ZZ^{(*)} \rightarrow$ 4 leptons: Golden Channel

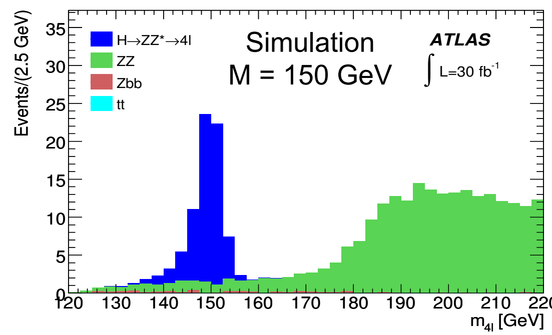


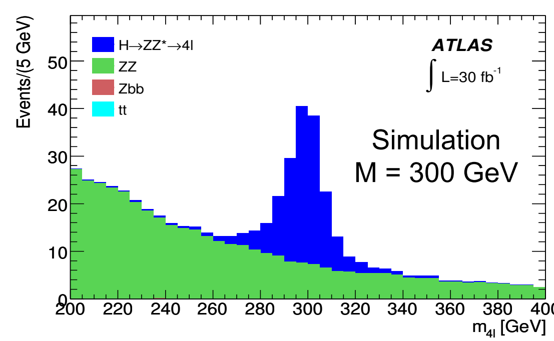
$$P_t^{\mu 1} = 48.1 \text{ GeV}$$
$$P_t^{\mu 2} = 43.4 \text{ GeV}$$
$$P_t^{\mu 3} = 25.9 \text{ GeV}$$
$$P_t^{\mu 4} = 19.6 \text{ GeV}$$

$$M_{\mu 1 \mu 2} = 92.15 \text{ GeV}$$
$$M_{\mu 3 \mu 4} = 92.24 \text{ GeV}$$
$$M_{4\mu} = 201 \text{ GeV}$$

Prob. of observing a pp→ ZZ →4μ event in 36 pb^{-1} is ~ 20%

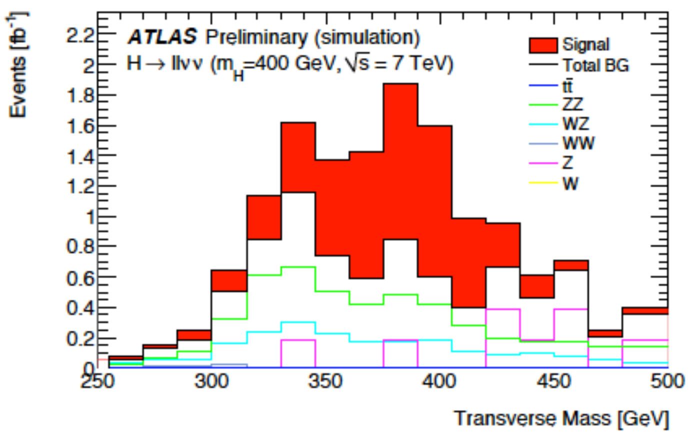
- Signal: four isolated leptons, fully reconstructed → **narrow** mass peak
- Backgrounds:
  - ZZ → irreducible background,
  - ttbar & Z+bb removed by lepton isolation & impact parameter requirements
- low background, **But low yield**

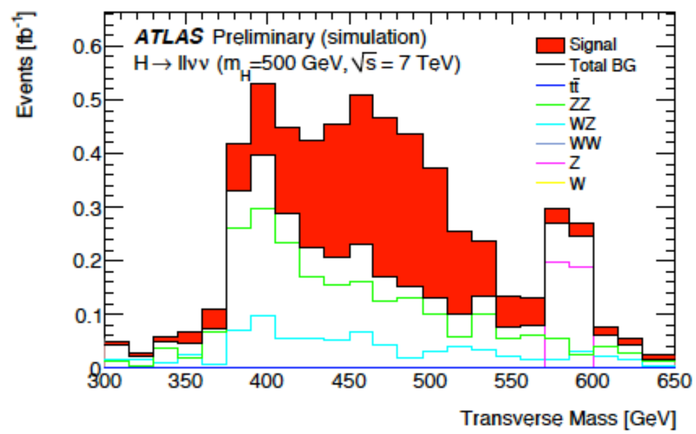


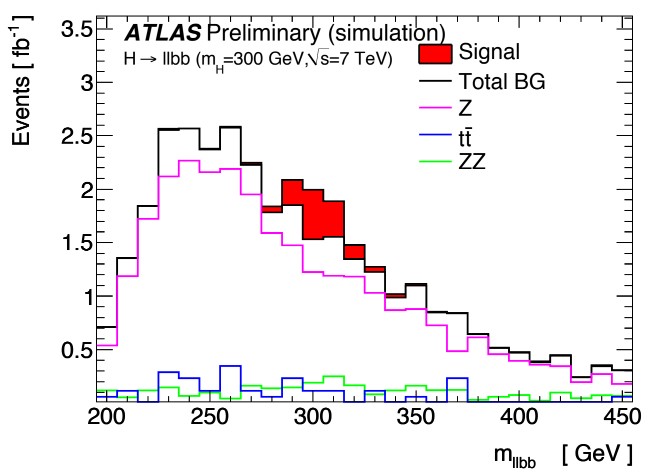


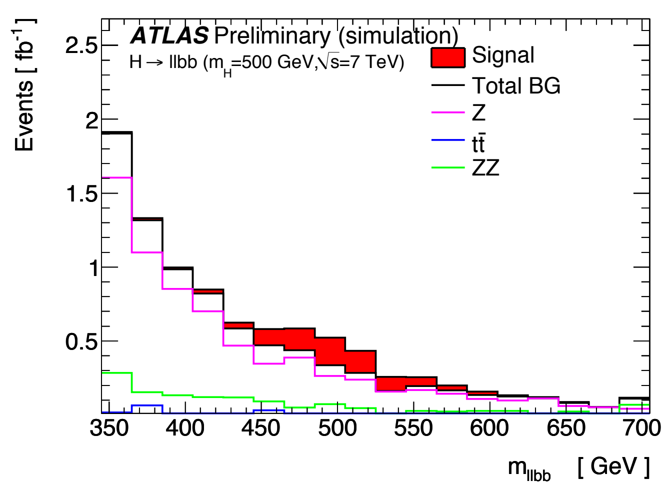
Sensitive Modes at High Mass: H → ZZ → *2l2ν,2l2b,2l2j*

- Major background is pp → WZ, ZZ, Z+jets (x 90,000) & Top
- Take advantage of precise Jet & MET reconstruction & b-(anti) tagging





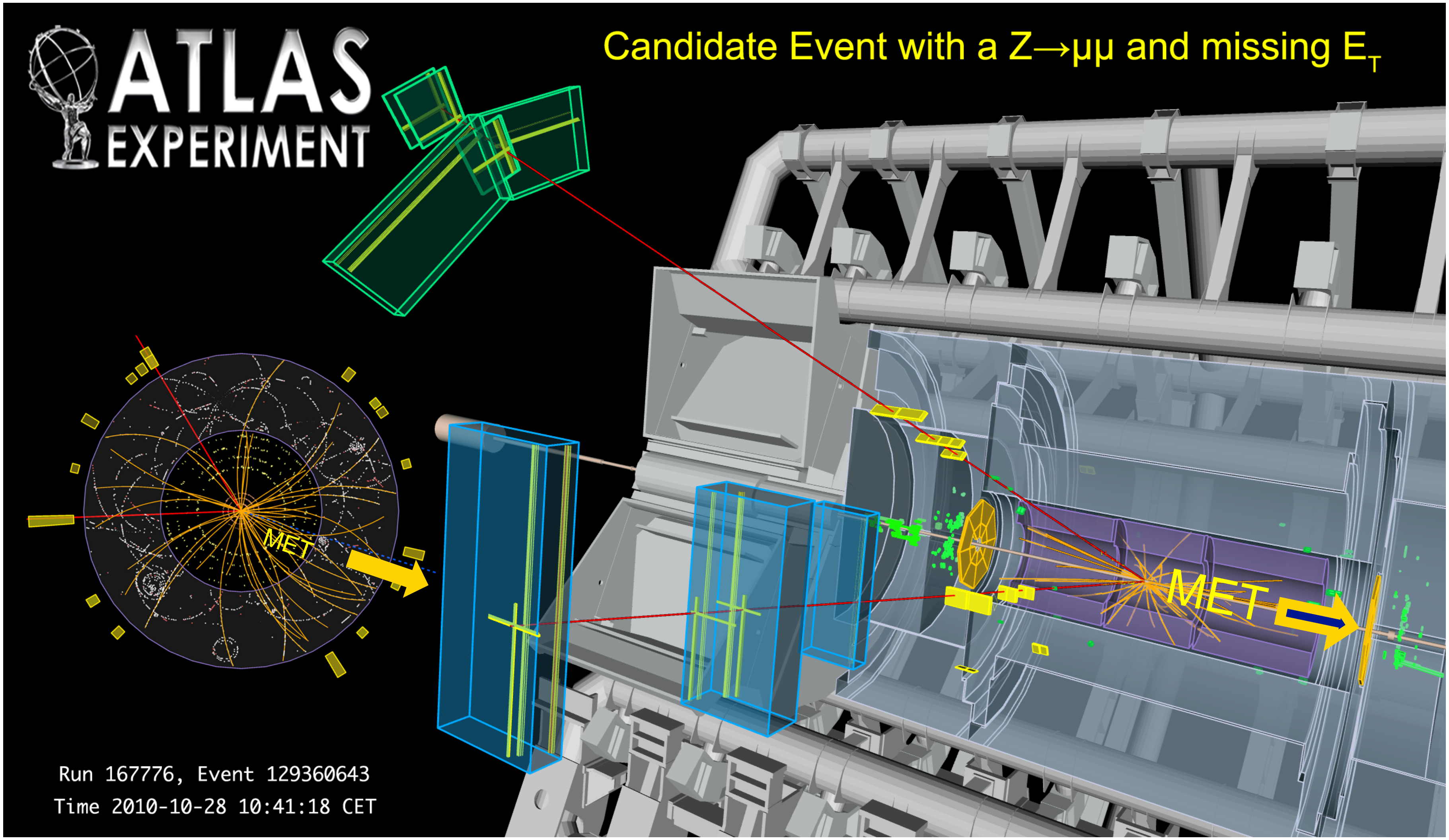




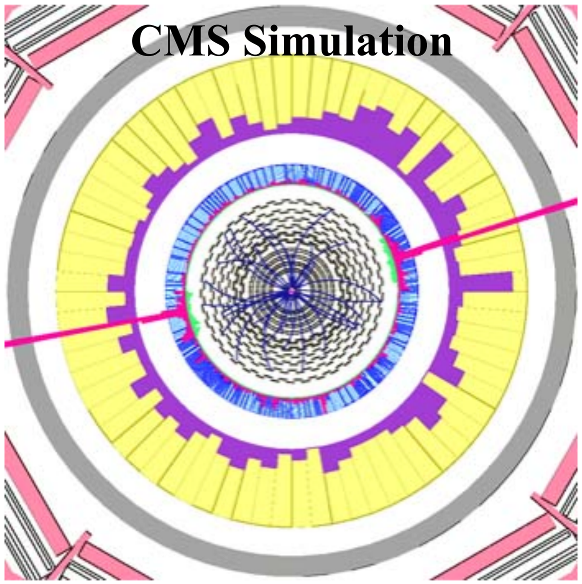
Background estimated from data driven methods

A ZZ→μμνν Candidate in ATLAS Data

$M_{\mu\mu}$ = 94 GeV, E_T^{miss} = 161 GeV



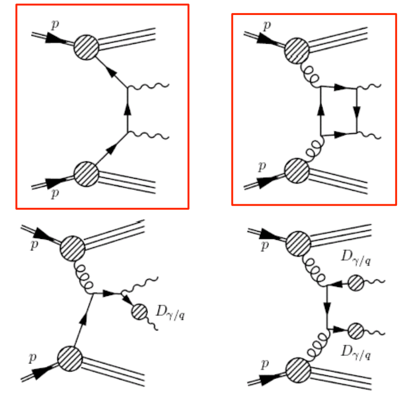
H → γγ

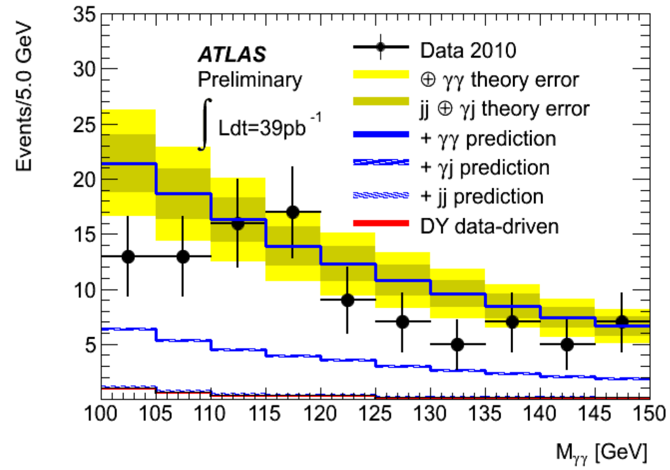


Signature: 2 isolated γ, → mass peak

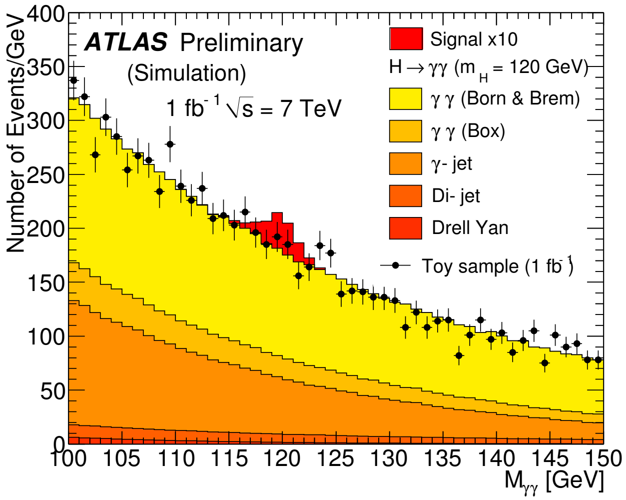
Bkgnd: QCD, and is large and partly irreducible: <u>measured</u> from data

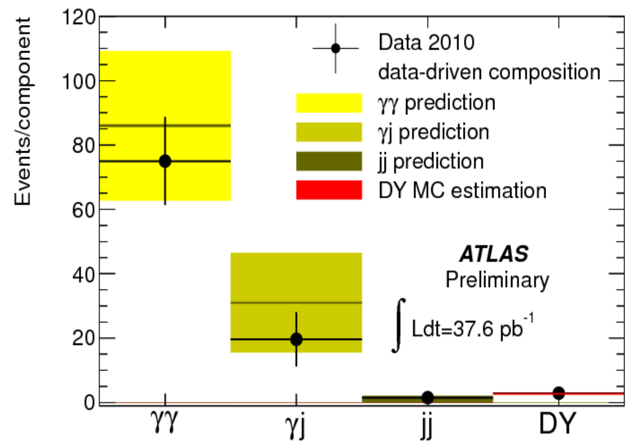
– ATLAS measurement in 36 pb^{-1}





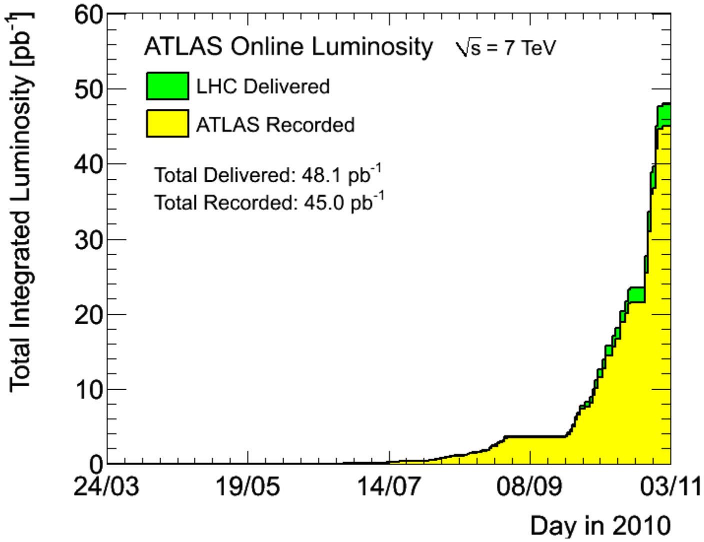
ATLAS-CONF-2011-004
ATLAS CONF-2011-033

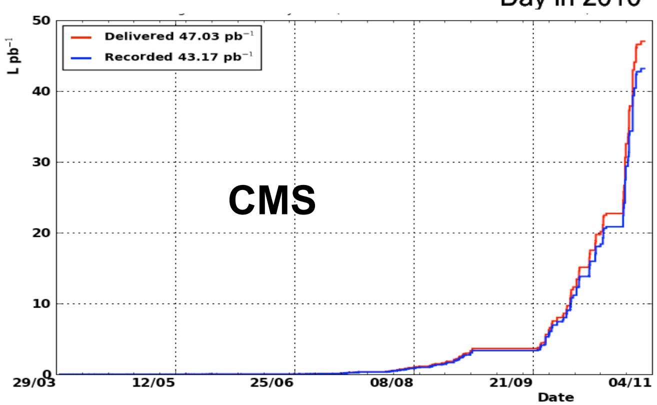




Good agreement found between data and simulation using data driven methods

LHC Higgs Search Results From 2010 data





Luminosity uncertainty < 4% already !

→ Good understanding of machine

ATLAS & CMS reporting competitive Higgs search results already from 36 pb^{-1}

ATLAS	CMS
• $H \to W^+W^-$	• $H \to W^+W^-$
• $H \to \gamma\gamma$	• $H^+ \to \tau^+\nu$
• $H \to \tau^+ \tau^-$	• $H \to \tau^+ \tau^-$
• $H \to ZZ$	• $H^{++} \to \ell^+\ell^+$
•NMSSM Higgs	

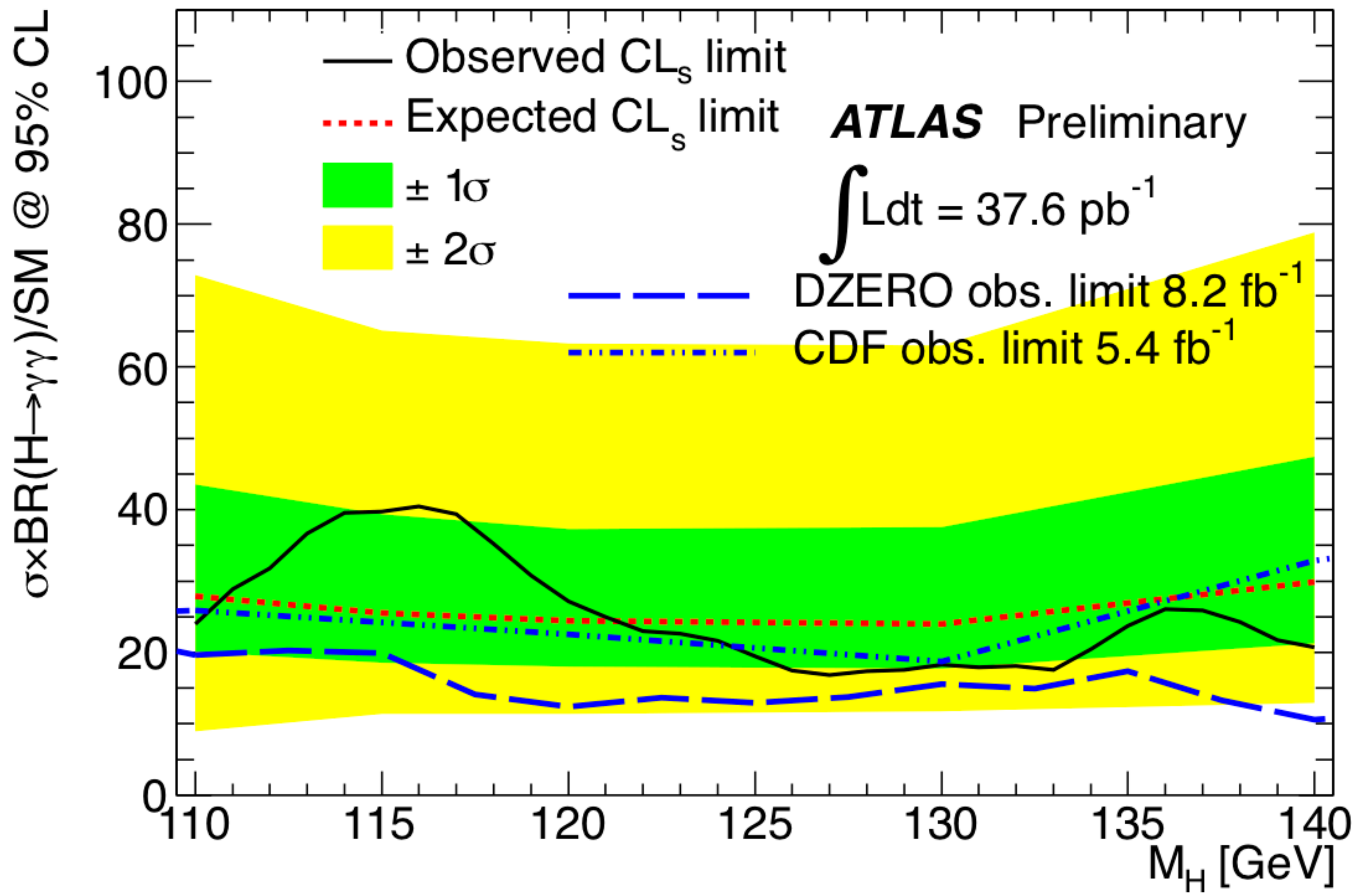
+ Studies of

(Irreducible) backgrounds in Higgs searches

* pp $\to WW$ cross section
* pp $\to Z \to \tau^+\tau^-$ cross section
* pp $\to \gamma\gamma$ rate vs $M_{\gamma\gamma}$
* Discriminating variables in H^+ search

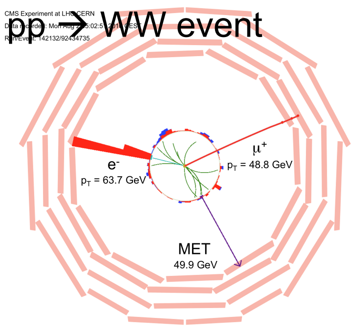
H → γγ : ATLAS & D0 Limits Overlaid

M.Schumacher; ATLAS CONF-2011-025 P. Totaro; D0 Note 6177-CONF



LHC already competitive with Tevatron

$H \to WW \to 2\ell 2\nu$ Search : CMS



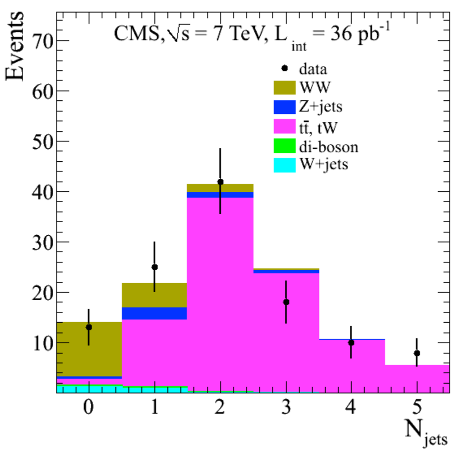
http://arxiv.org/abs/1102.5429

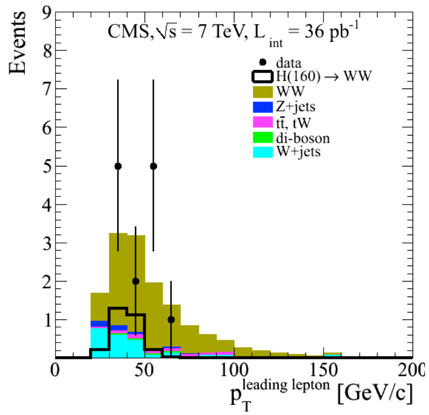
From 13 observed events passing $pp \to WW$ cut-based selection, measure:

$\sigma(pp \to WW) = (41.1 \pm 15.3 \pm 5.8 \pm 4.5(lumi))$ pb

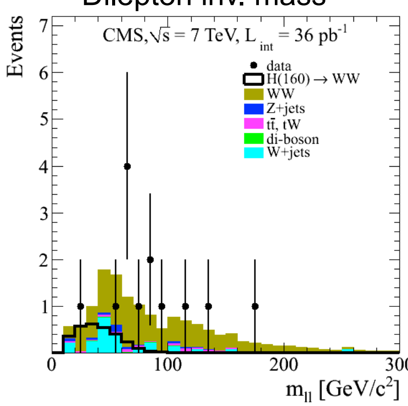
Higgs search used 2 <u>counting</u> methods:

- Cut on kinematic observables
- Cut on a BDT output & count
  - 15% higher eff for same bkgnd

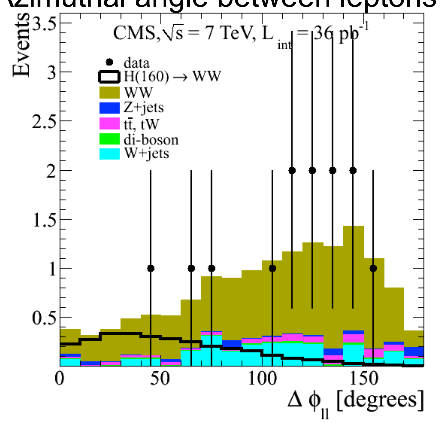




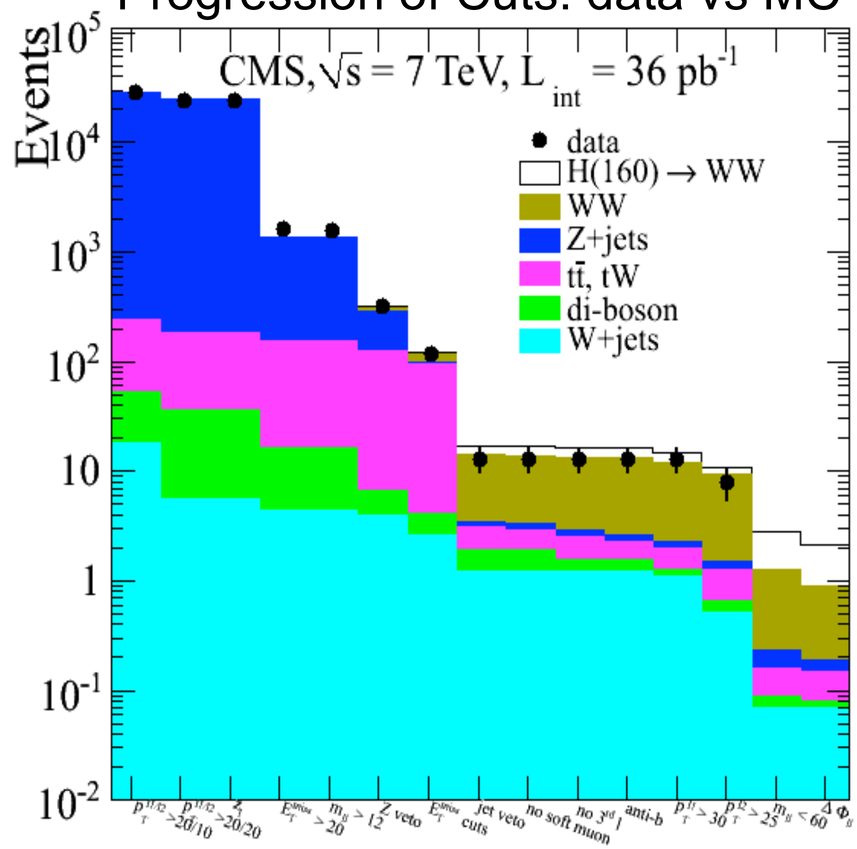
Dilepton inv. mass



Azimuthal angle between leptons

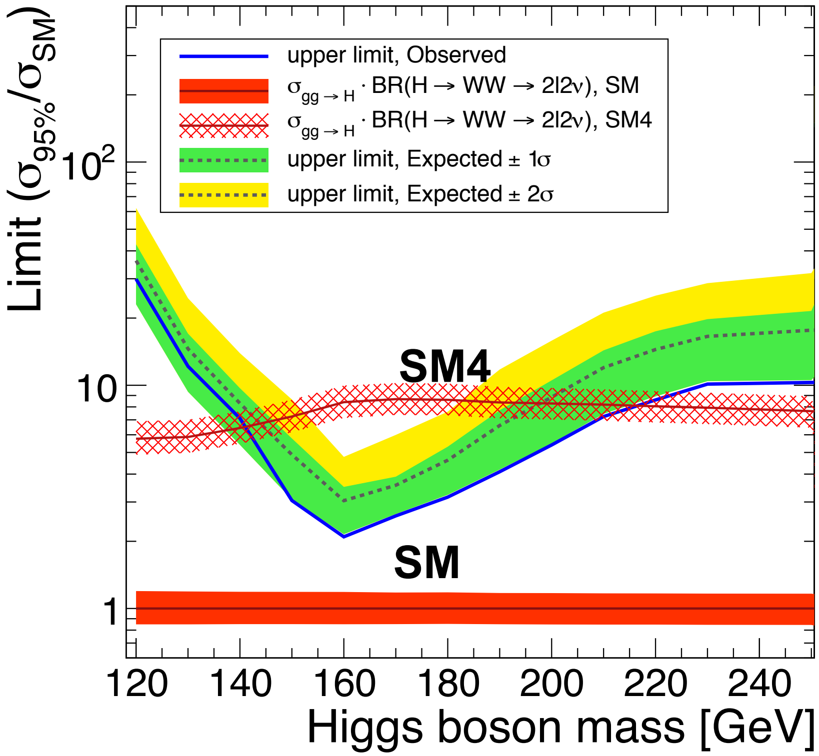


Progression of Cuts: data vs MC

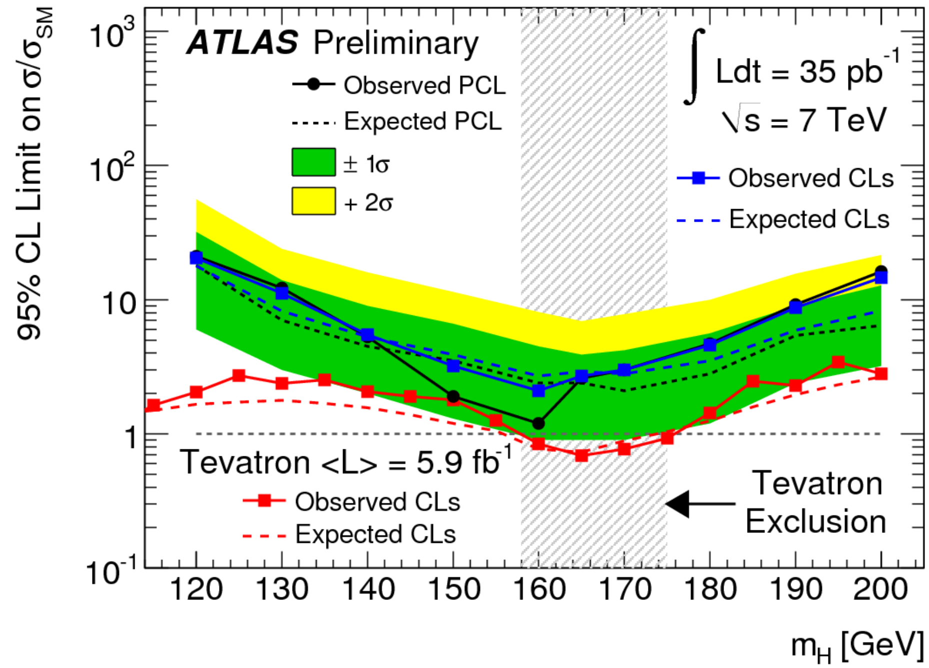


H→WW Limits: ATLAS & CMS

ArXiv:1102.5429; submitted to Phys. Lett.



M.Schumacher; ATLAS CONF 2011-005



95 % CL Limit for M_H = 160 GeV	**CMS (Bayesian)**
Expected	3.0 x SM
Observed	2.1 x SM

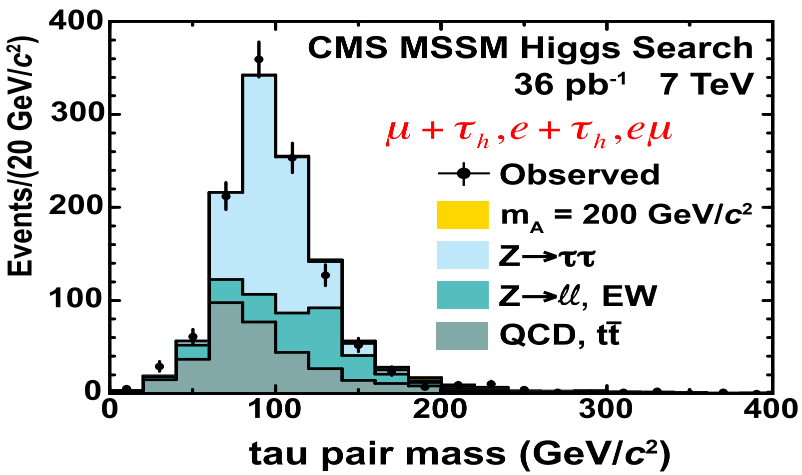
95 % CL Limit for M_H = 160GeV	**ATLAS (CL_S)**
Expected	2.7 x SM
Observed	2.1 x SM

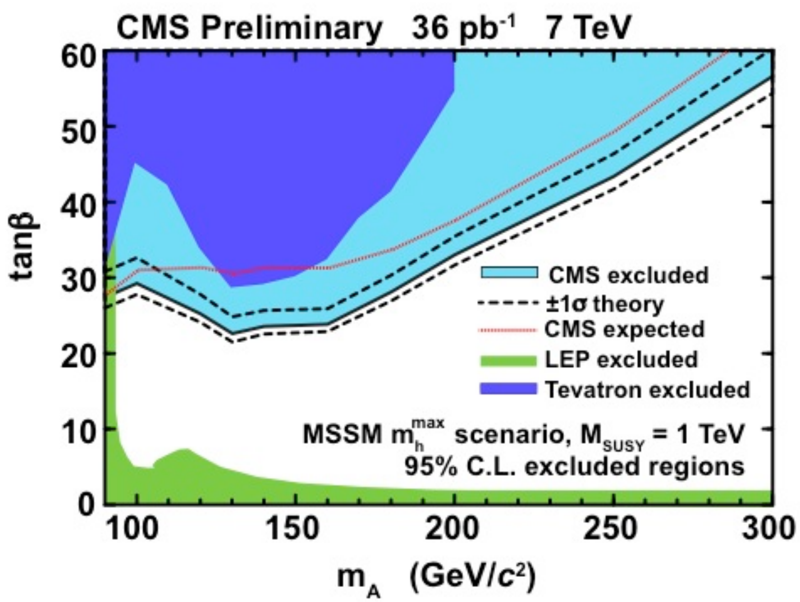
SM-like Higgs in 4-gen models excluded for (144 < M_H< 207) GeV

Better limit (already) than CDF+ D0 combined

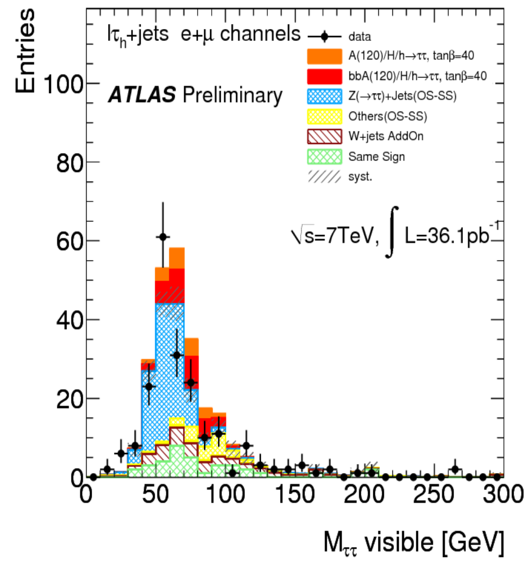
MSSM H → ττ : Breaking New Grounds

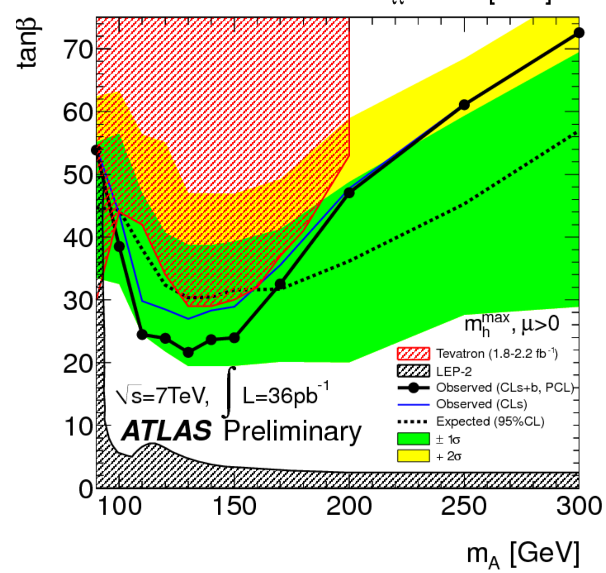
C.Veelken; CMS-PAS-HIG-10-002





M.Schumacher; ATLAS-CONF-2011-024

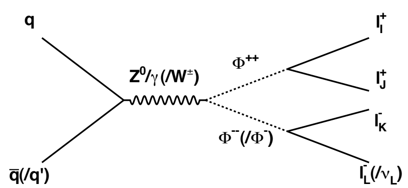




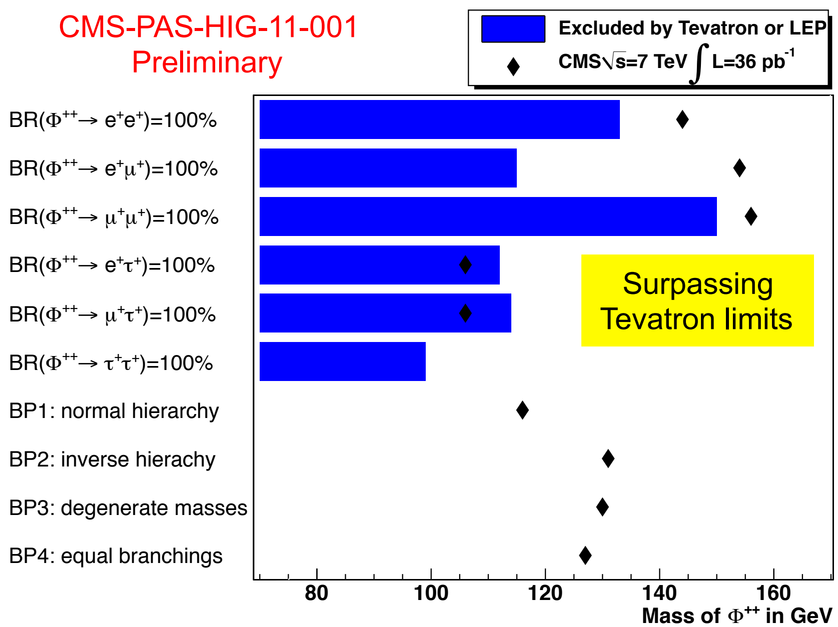
SUSY H^+ & Exotic Higgs Searches (CMS)

$\Phi^{++} \rightarrow l^+ l^-$

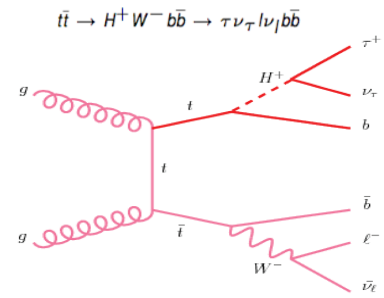
- Arises in models with extra Higgs triplets
  - Φ^{++}, Φ^{+}, Φ^{0}
- Triplet responsible for small neutrino mass
- Unknown neutrino mass matrix
  → unknown branching ratios → broad search
- Below M ≈$2M_W$, only leptonic decays



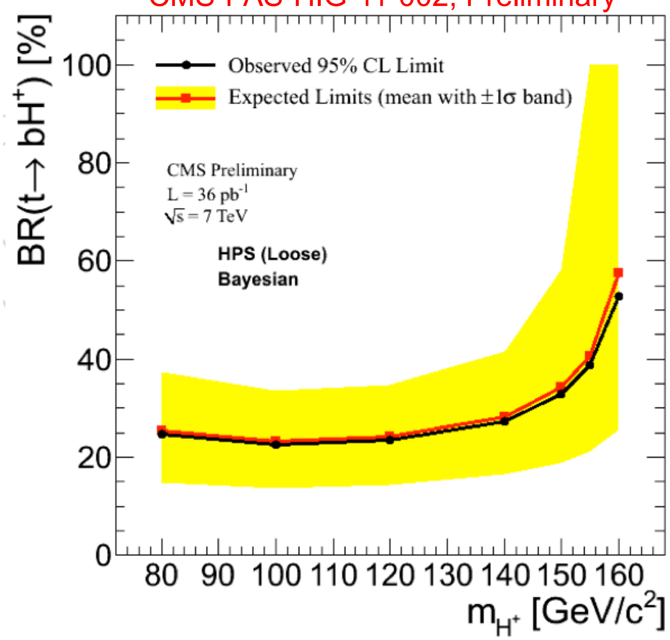
CMS-PAS-HIG-11-001
Preliminary



$H^+ \rightarrow \tau^+ \upsilon$ in ttbar decays



CMS-PAS-HIG-11-002; Preliminary



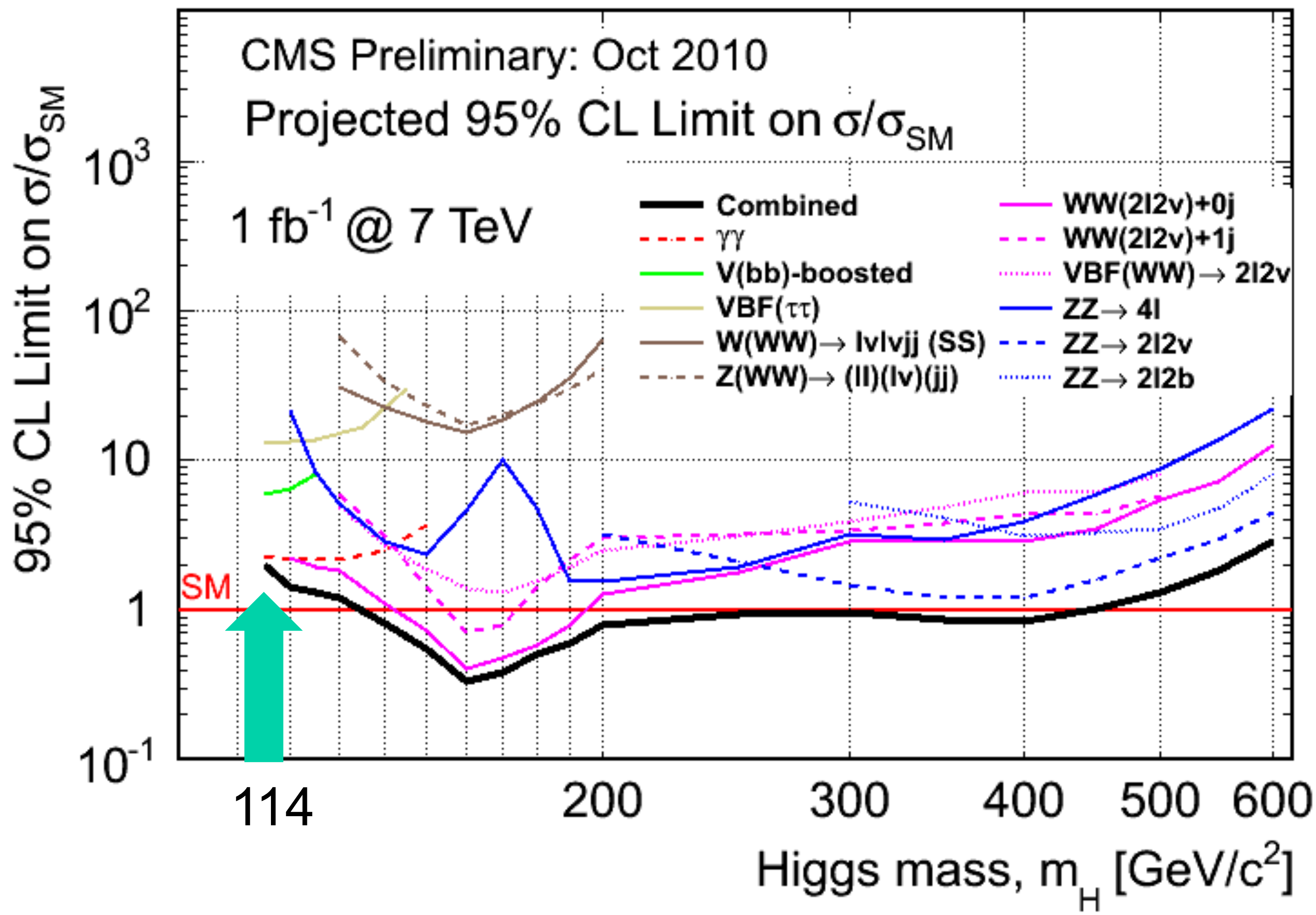
Higgs Search Projections For 2011-2012

- Used state of the art cross-sections:
  - e.g: NNLO for gg→ H, NLO for VBF,VH ; Background processes at NLO (MCFM)
- Full GEANT based detector simulation
- Simple cut-based analysis; mostly counting events,
  - no SHAPE analysis used (can improve sensitivity by ~ (20-100)%)
- Robust & conservative systematic uncertainties:
  - e.g.: ATLAS uses 10% JES error (achieved 5%), 10% lumi error (achieved < 4%)
- Validation from 2010 data:
  - **Excellent agreement between data and detector simulation**
  - Detector performance close to design in most cases
  - Measured production rates of background processes (γ, Jets, W/Z, Top, Dibosons etc) in good agreement with expectations (5-30 % uncertainties)
- In general, analyses with data more sensitive than the simulation based studies used in the projections...and will continue to improve!
  - As CDF & D0 have already shown
- **Projections are indicative not predictive !**

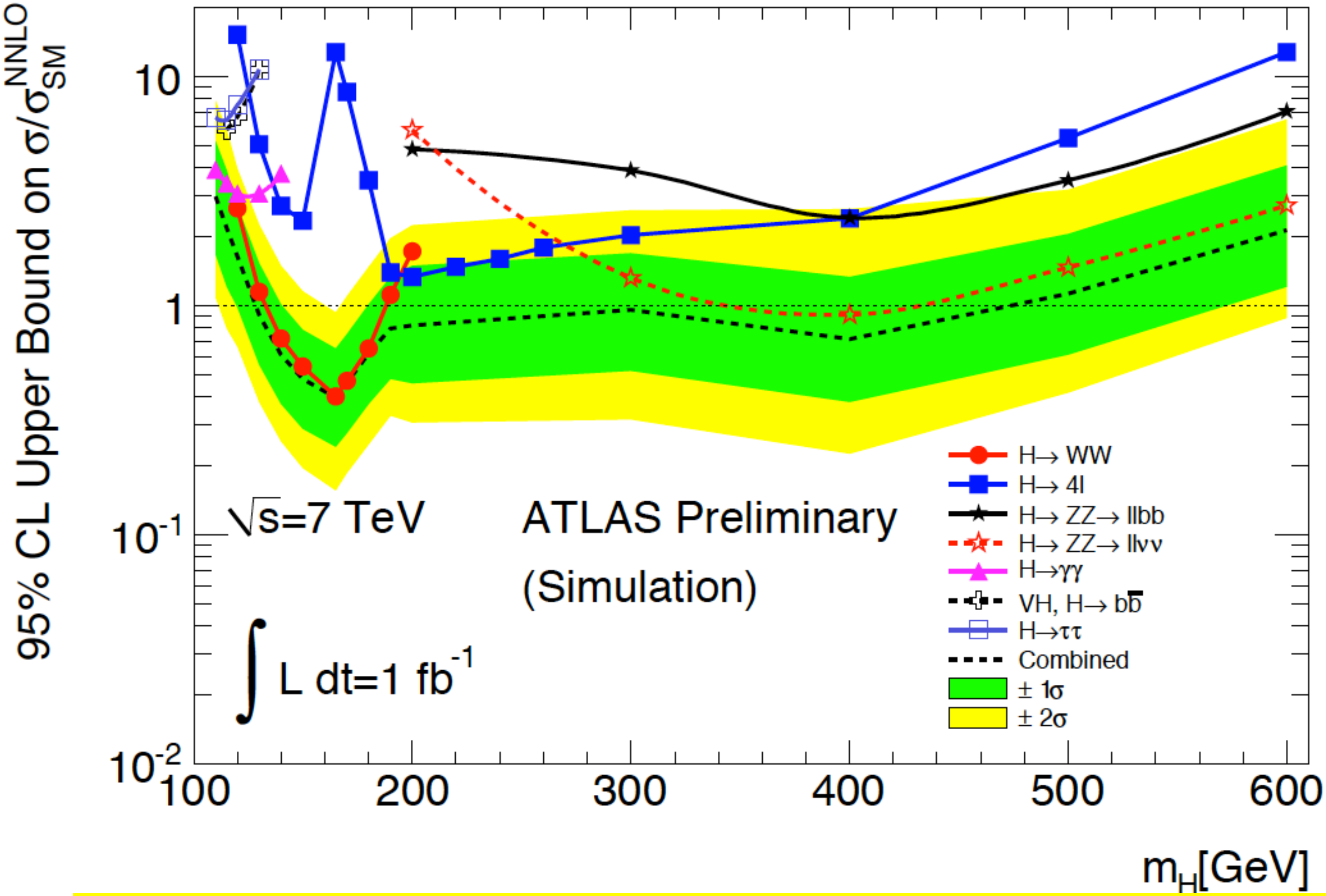
SM Higgs Channels Studied

Channels included	≈ Mass range (GeV)
H→ γγ	115-150
VBF H→ ττ	115-145
VH, H→bb (highly boosted)	115-125
VH, H→WW→lvjj	130-200
H→WW→2l2v + 0/1 jets	120-600
VBF H→WW→2l2v	130-500
H→ZZ→4l	120-600
H→ZZ→2l2v	200-600
H→ZZ→2l2b	300-600

CMS Projected Exclusions with 1 fb^{-1} @ 7 TeV

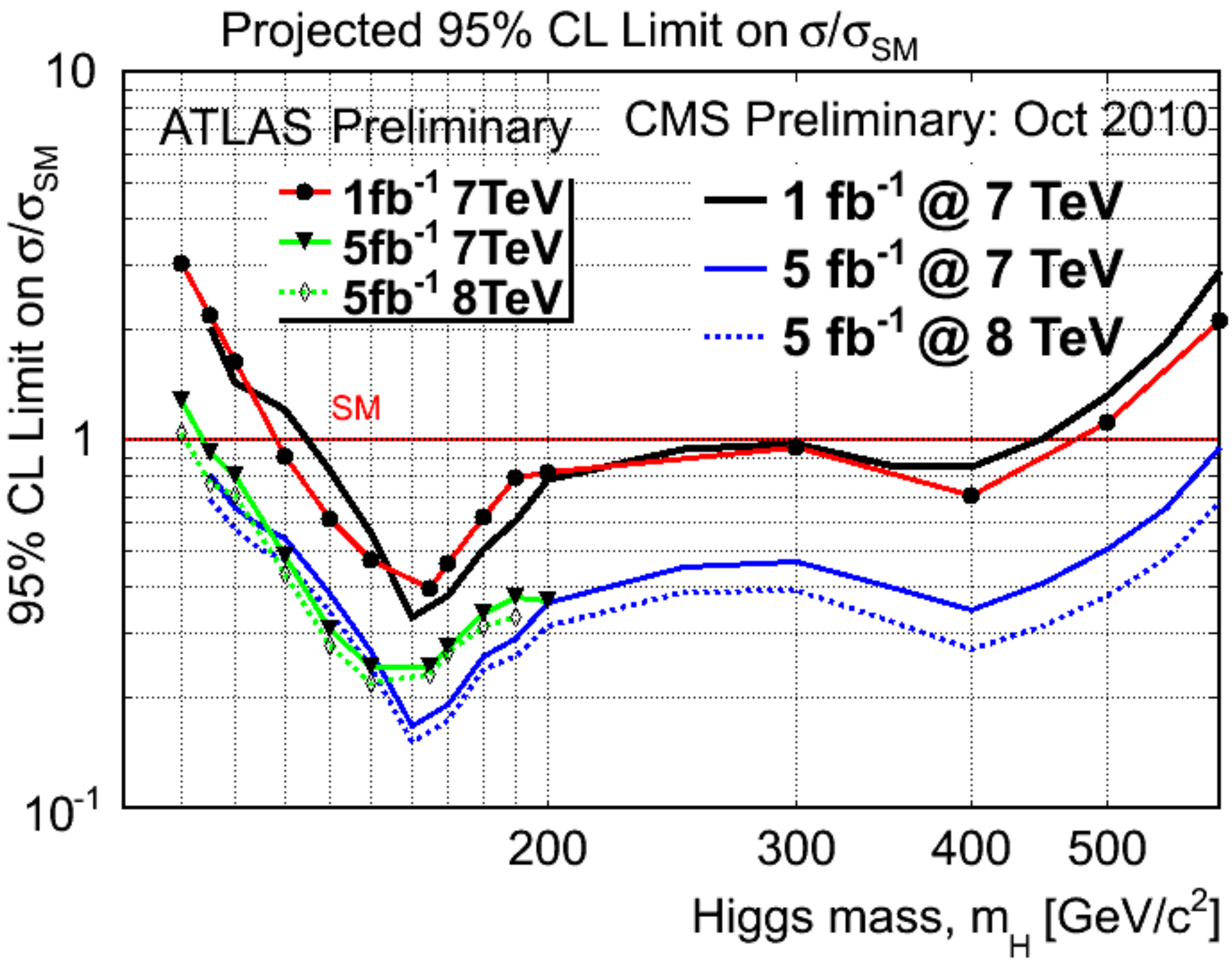


ATLAS Projected Exclusions with 1 fb^{-1} @ 7 TeV

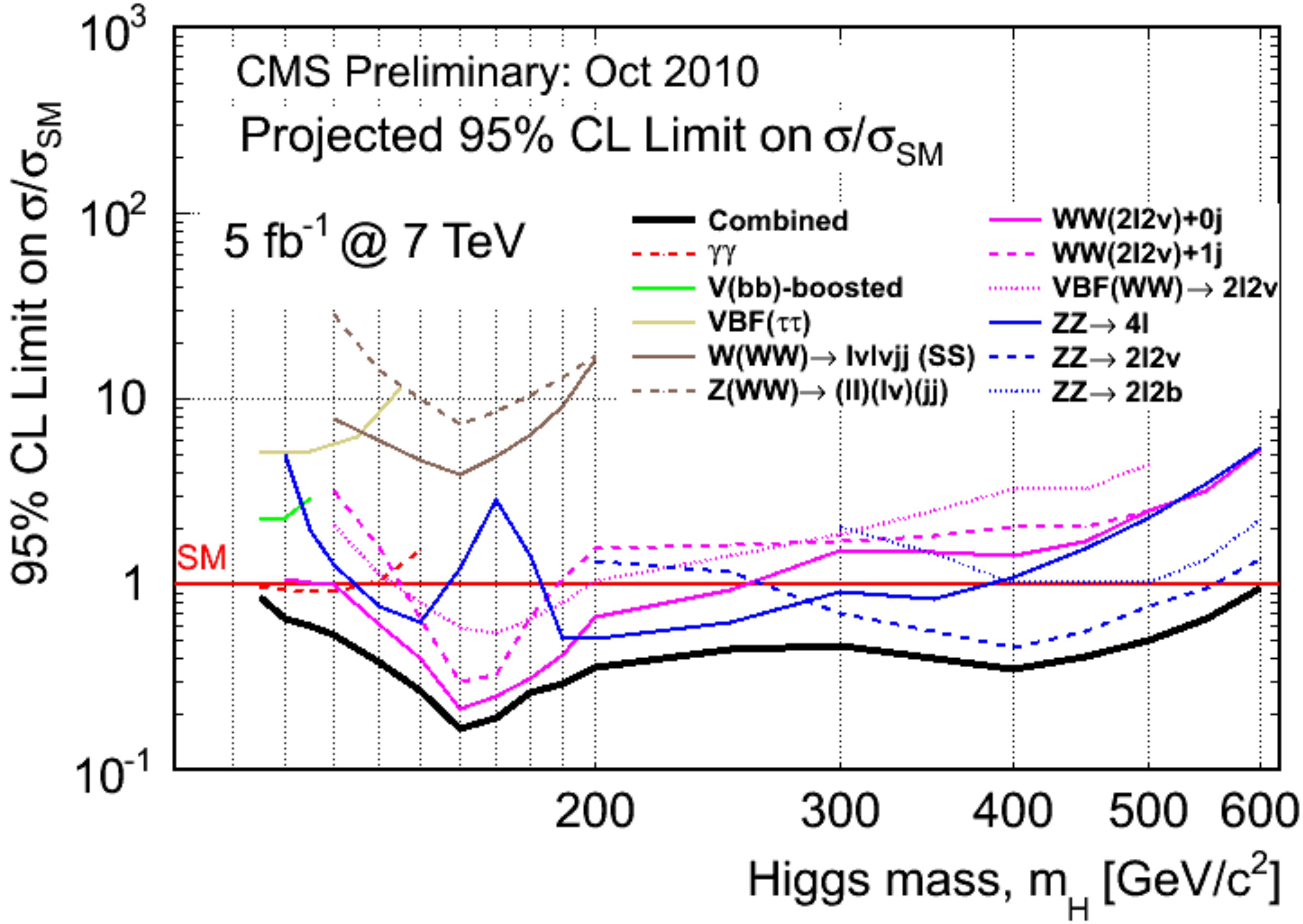


ATLAS & CMS projections are in excellent agreement

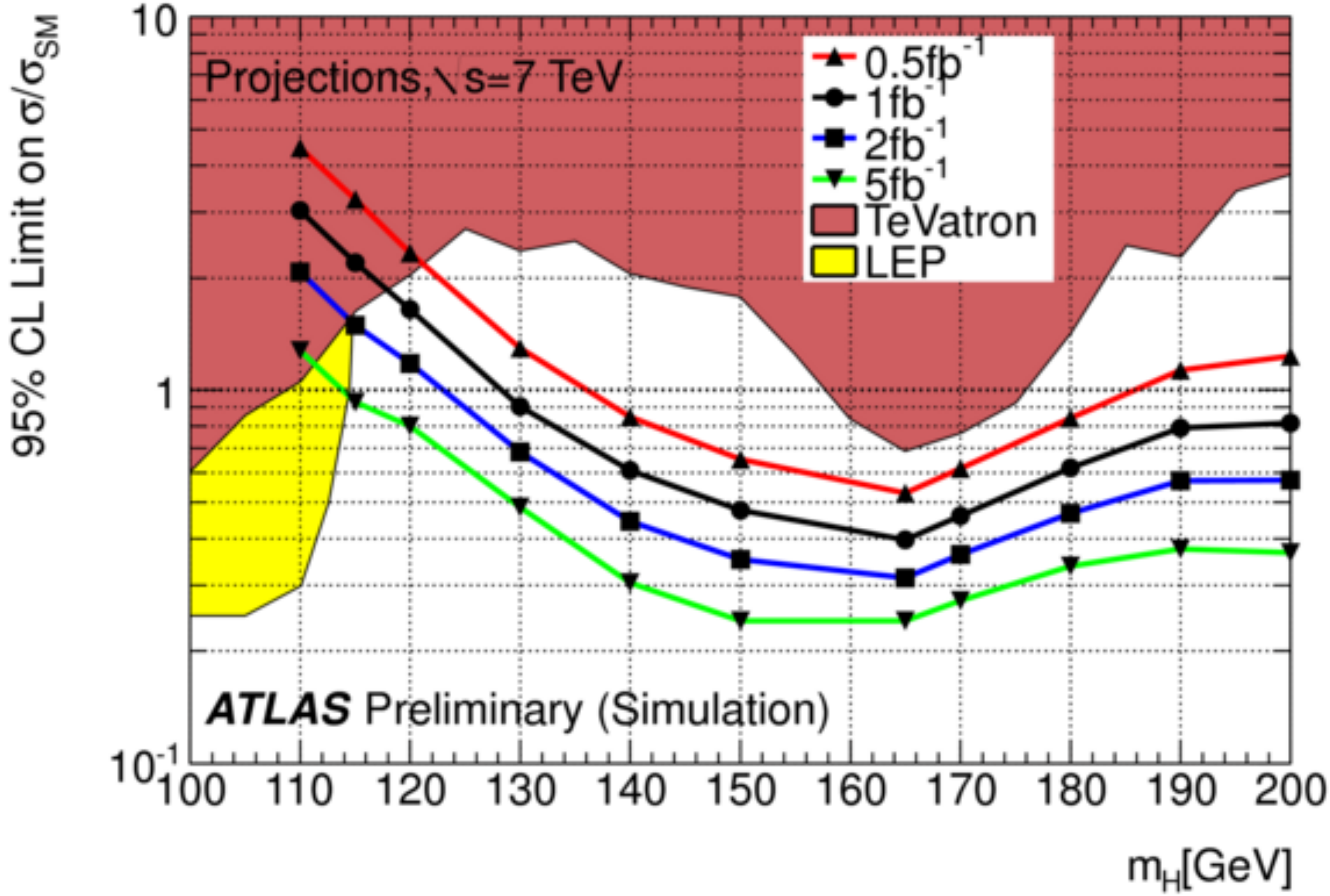
CMS & ATLAS Projections Compared



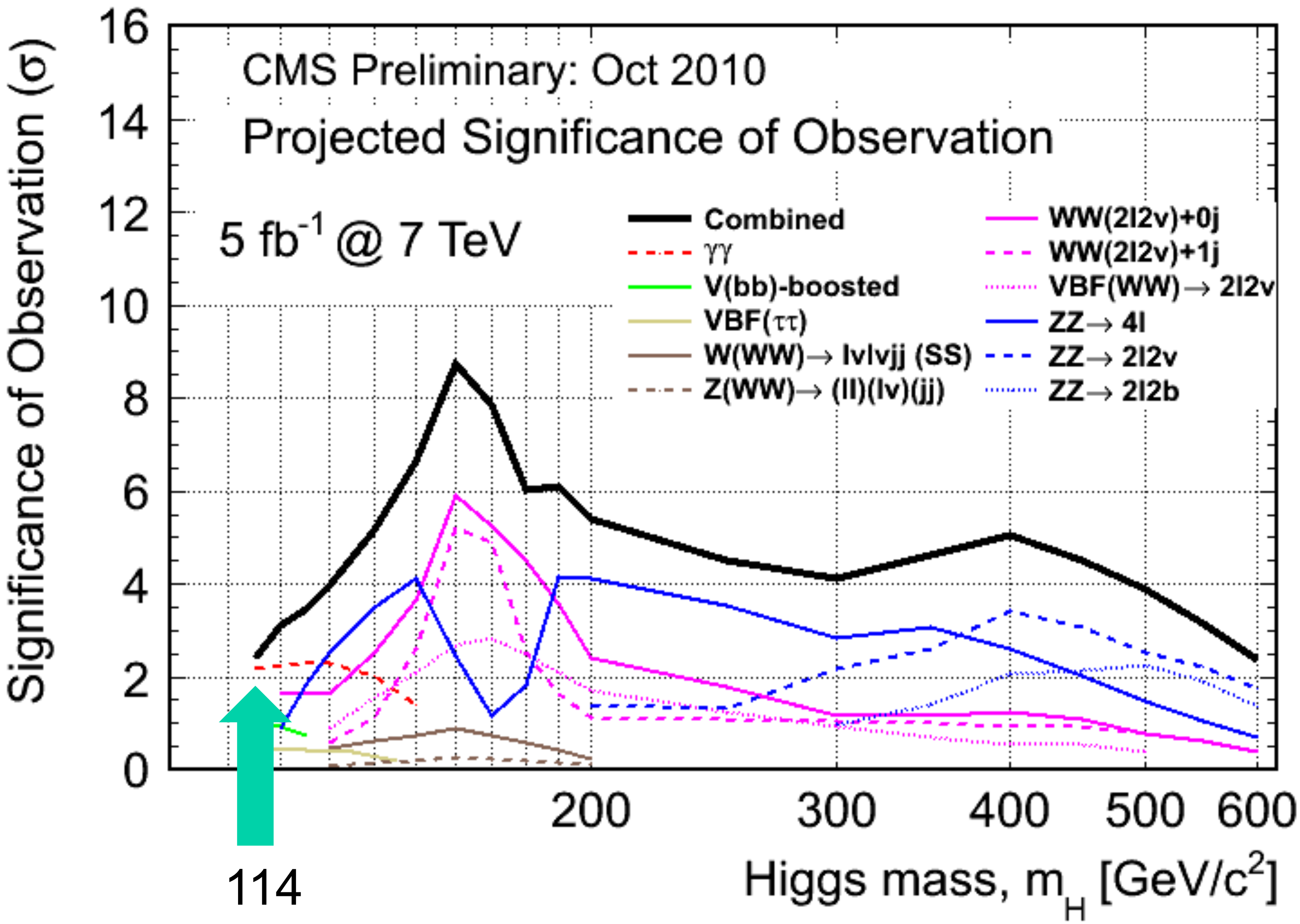
CMS Projected Higgs Exclusions: 5 fb^{-1} @ 7 TeV



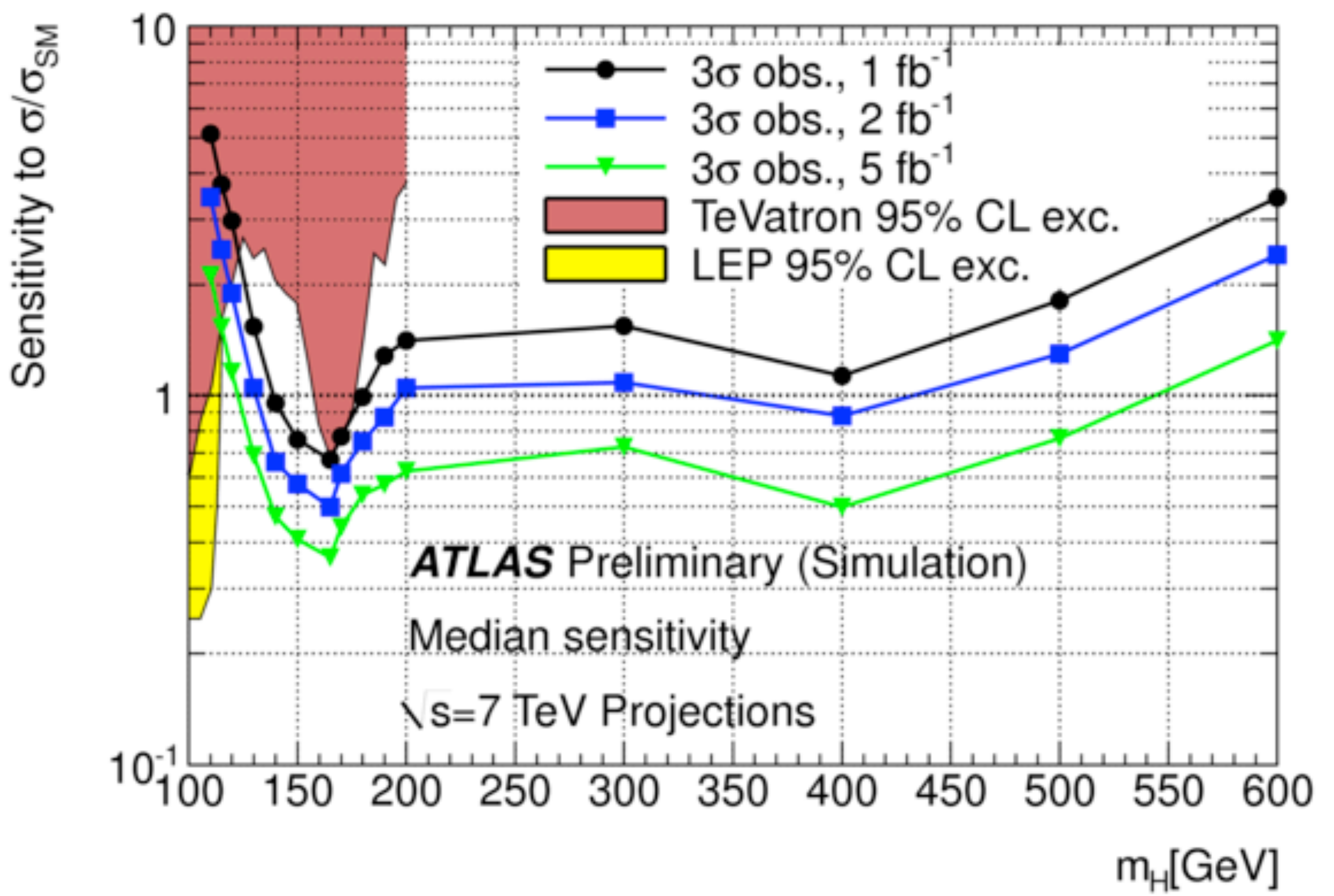
ATLAS Higgs Boson Exclusion Limits



Significance of Observation with 5 fb^{-1} @ 7 TeV

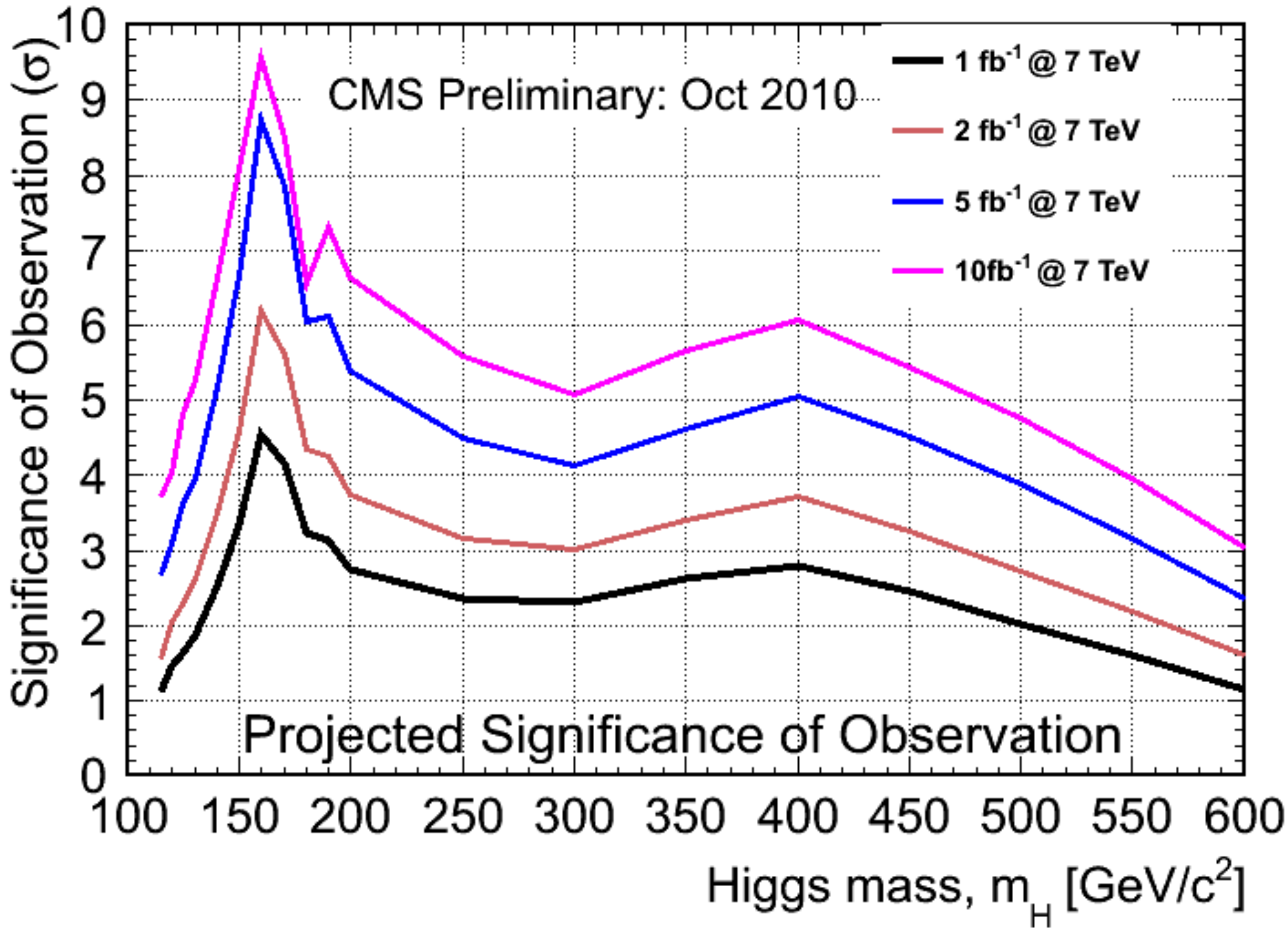


ATLAS Higgs Discovery Sensitivity



- 5fb^{-1} enough to close gap with LEP at 7 TeV
- **Expected 3σ observation from 123 to 550**

Higgs Sensitivity : 1, 2, 5, 10 fb-1 @ 7 TeV



Summary Of Sensitivity To SM Higgs

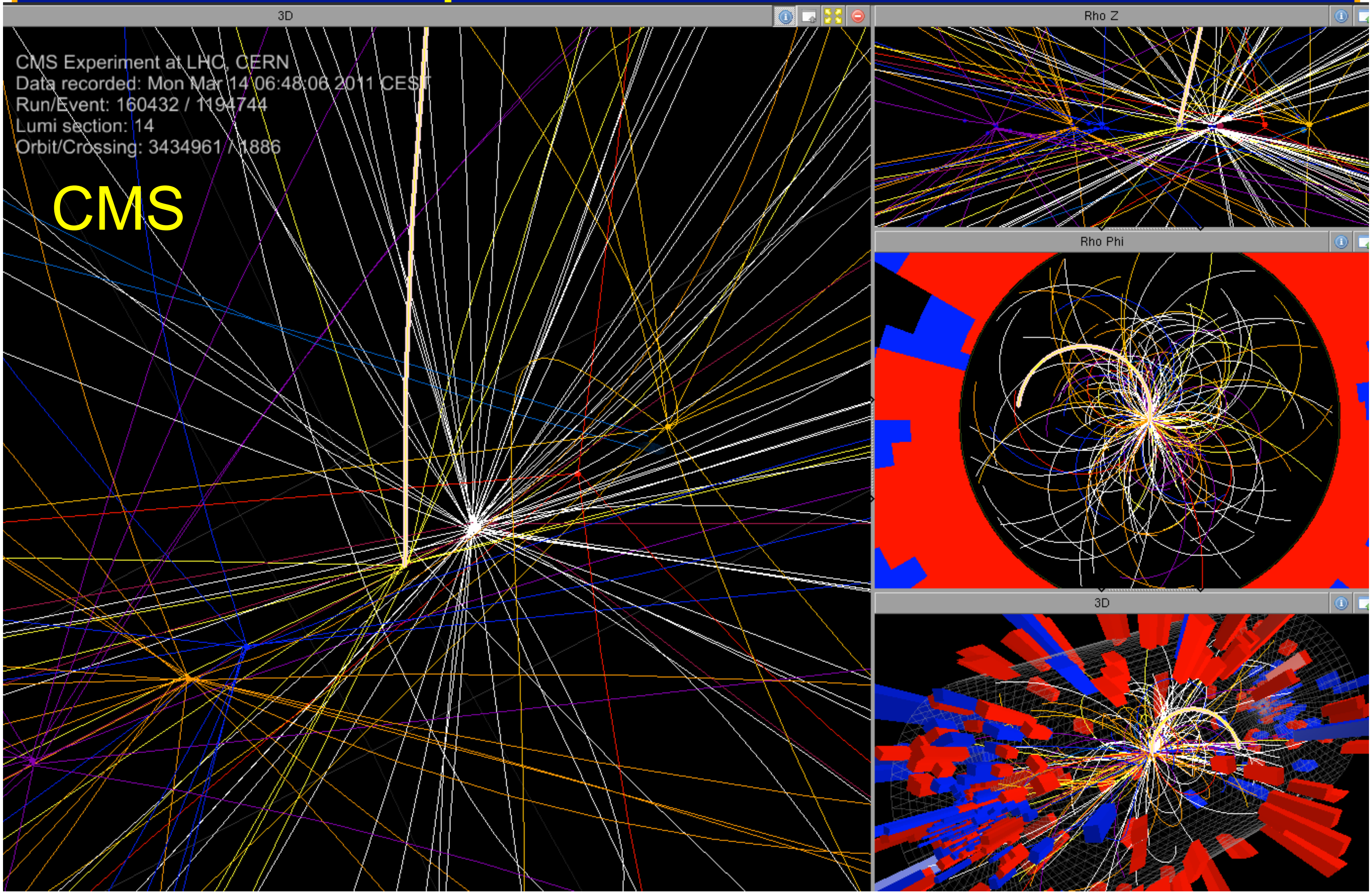
ATLAS + CMS ≈ 2 x CMS	95% CL exclusion	3σ sensitivity	5σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535

Challenges in 2011-12

- Projections were based on 2010 conditions and simulations
- LHC environment is much more aggressive in 11-12
- Major challenges from trigger 'budget':
  - Instantaneous Luminosity could approach 2 $10^{33}cm^{-2}s^{-1}$
  - 10 times 2010 rate
  - We must reject 90% of the data we kept in 2010
  - This makes for real physics loss in choosing what to keep
- Major challenges from pileup:
  - Pileup will be 10 or more events
  - Track reconstruction CPU rises exponentially with hit rate
  - Event size on disk is much larger: can record FEWER events
  - E_t^{miss}, lepton isolation, jet resolution all degraded
- Impact on major modes like H→ WW, H → gg, VBF modes
  - Currently under detailed study; outlook is positive

LHC Collisions in 2011 Have Begun !

Pileup in First 2011 Data



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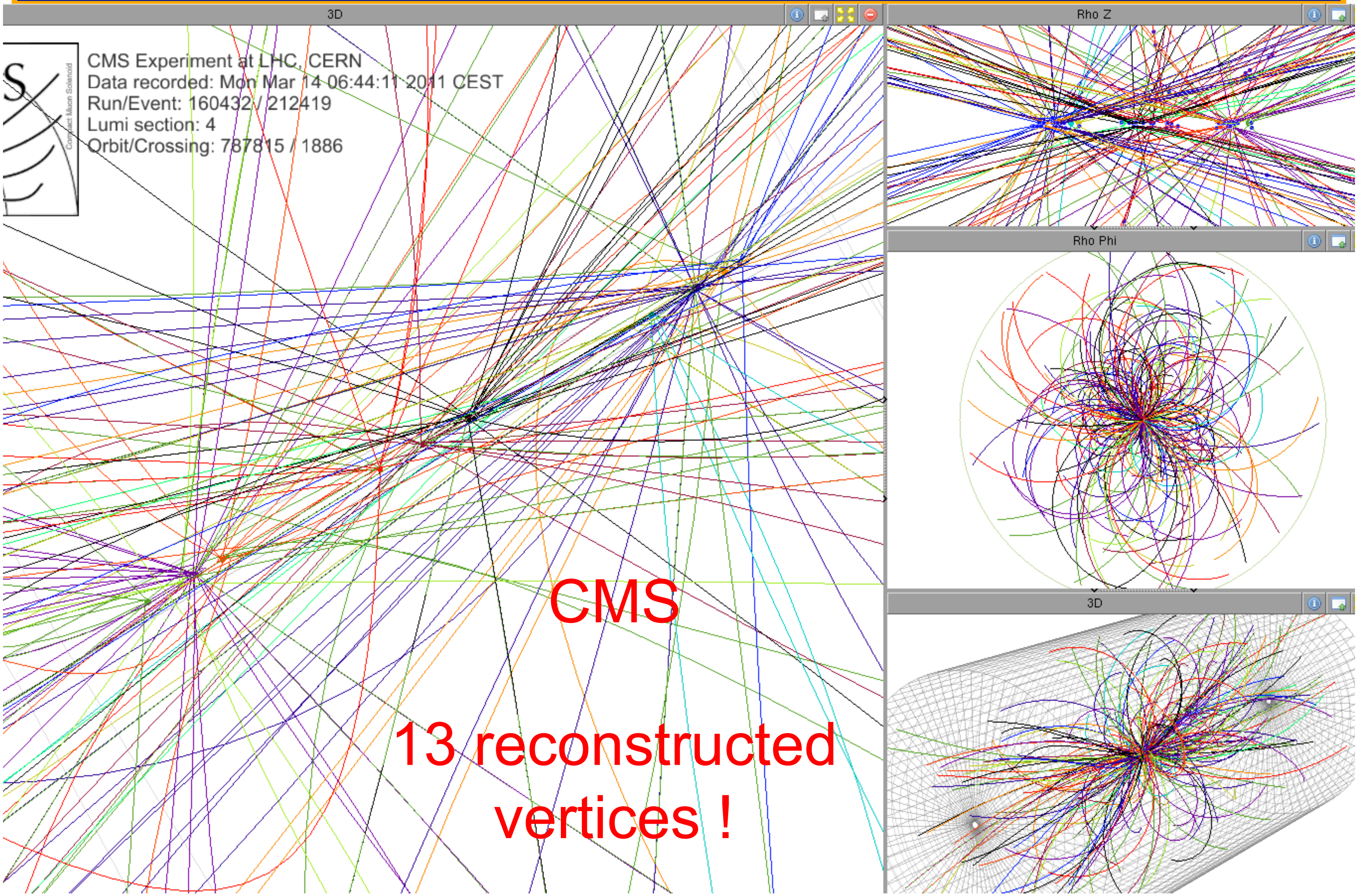

Summary of Prospects

Higgs Boson, if it exists between masses of (114 - 600 GeV) will either be discovered or ruled out in ≈ next two years

As in every important journey, there will be challenges to overcome

SM Higgs Search Prospects (Mass in GeV)

ATLAS + CMS ≈ 2 x CMS	95% CL exclusion	3 σ sensitivity	5 σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
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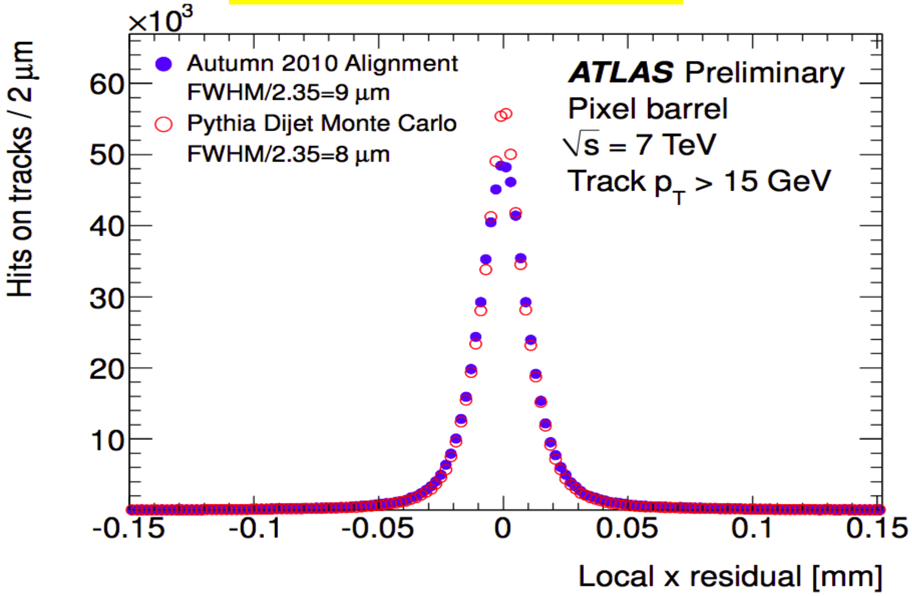
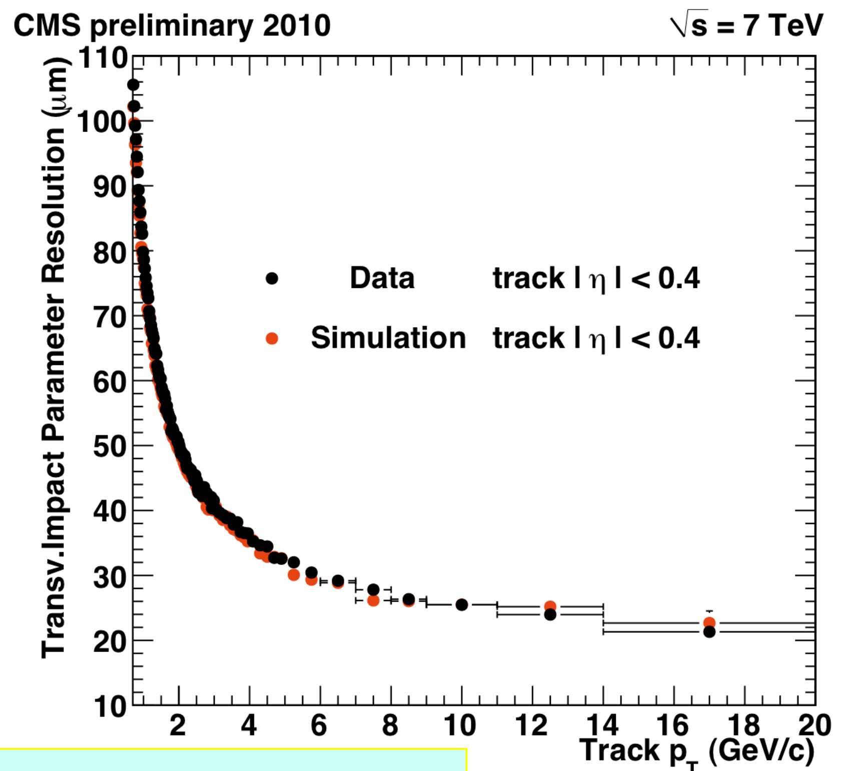
Backup

Charged Particle Tracking

Pixel Alignment



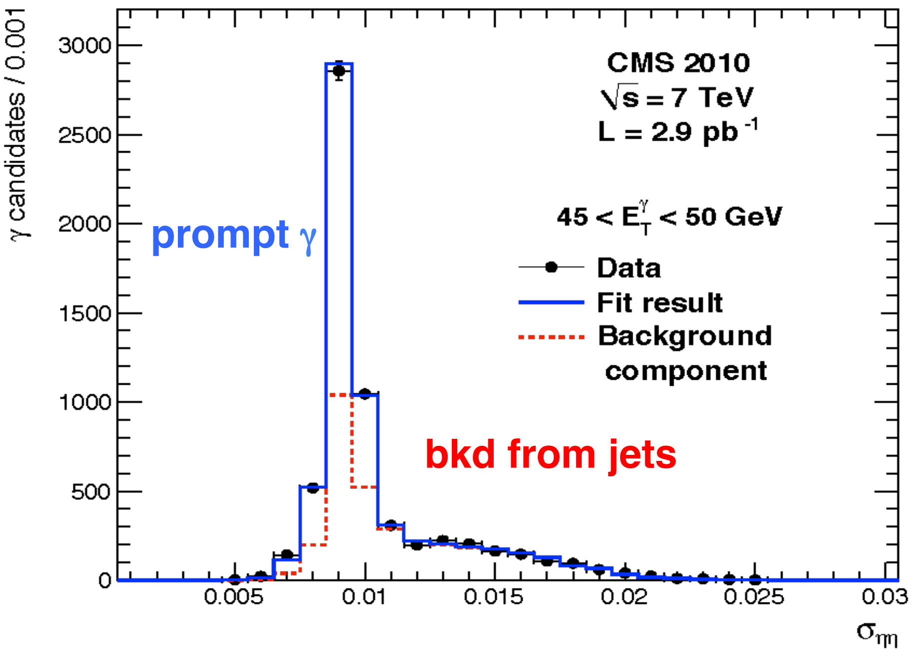
Impact Parameter Resolution



Excellent agreement between DATA and MC

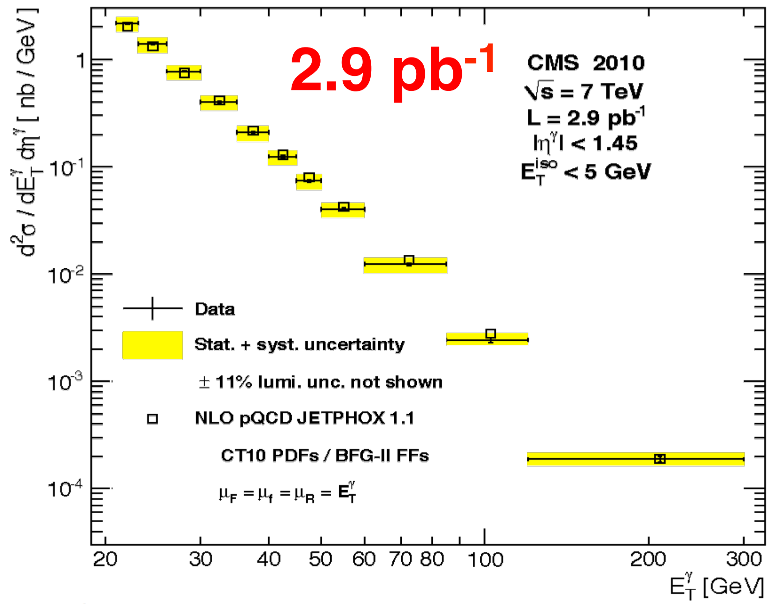
Profited from millions of Cosmic ray muons used to calibrate several detector elements in advance of LHC collisions

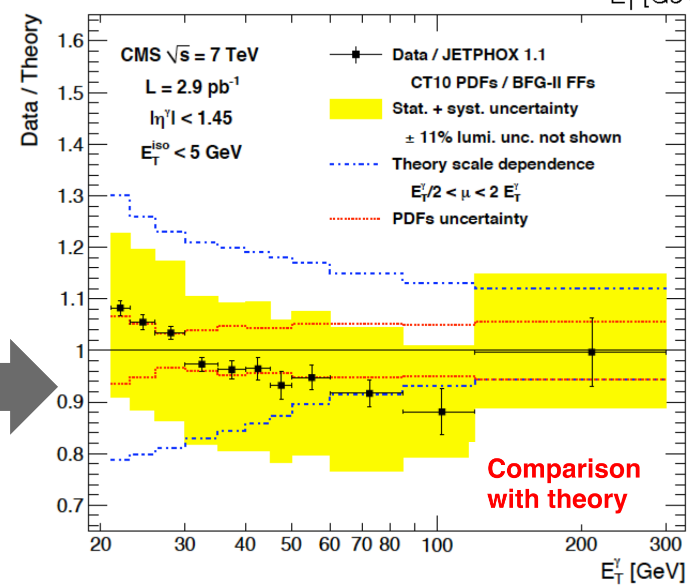
Prompt Photon Reconstruction & Spectrum



Transverse η profile of EM showers separates high energy isolated γ from π^0 enriched jets

Isolated photon rate & spectrum agrees well with QED + NLO pQCD radiation

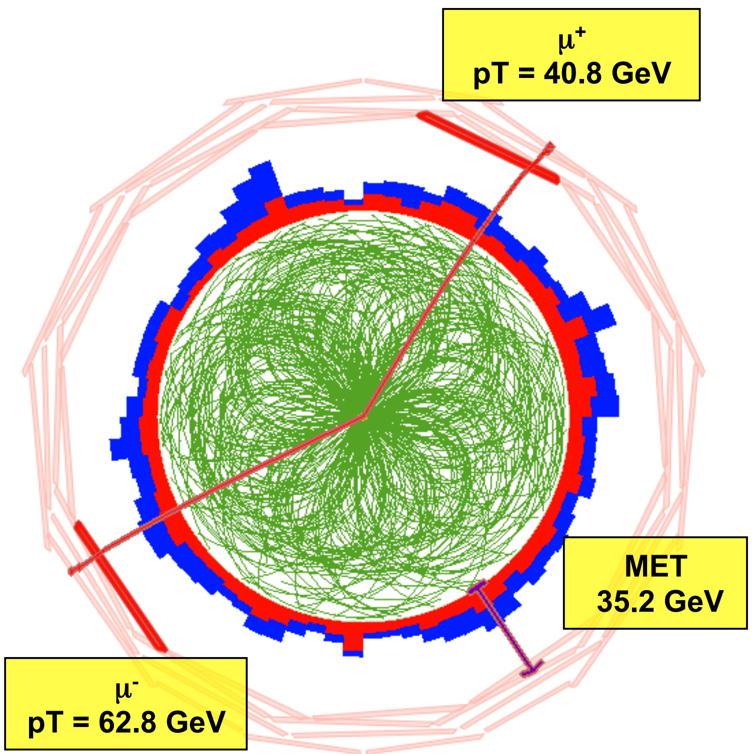


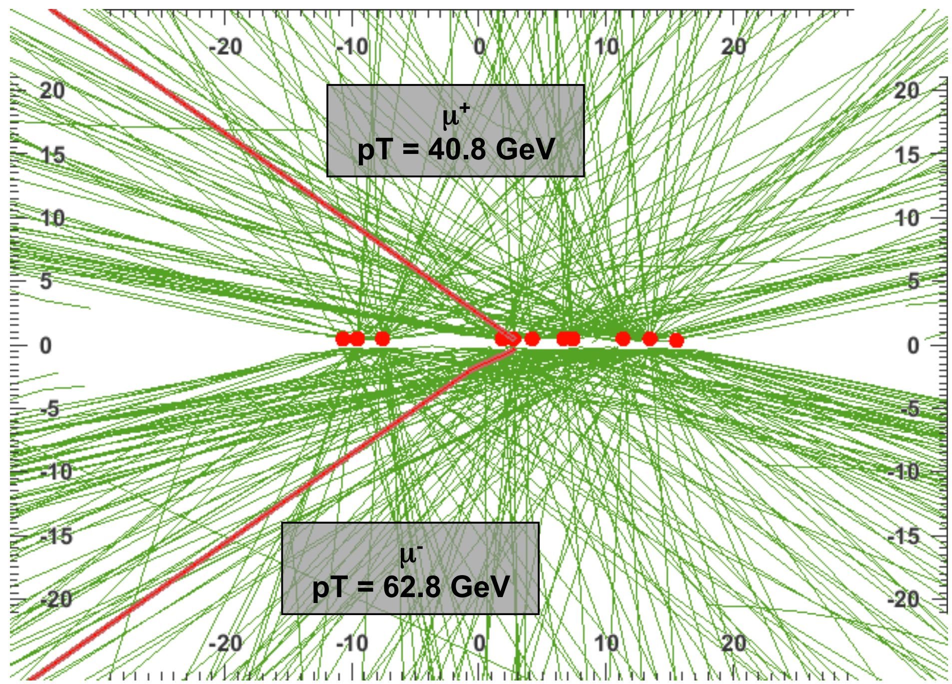


Pileup And Its Consequences

Z → μ μ
Expected MET = 0

10 in-time + 10 out – of – time pileup





Low Mass Higgs : $N_{events} = \sigma \times Br \times L$ Produced

Experimental signatures for $M_H \sim 120$ GeV		Signal events		Comments
		TeV Exp $10\ fb^{-1}$	**LHC Exp $1\ fb^{-1}$**	
$H \rightarrow \gamma\gamma$		31	44	**x4 better $m_{\gamma\gamma}$ res**
$H \rightarrow bb$	$qqH \rightarrow qq(bb)$ **with n b-tags**	478	880	
	$WH \rightarrow l\nu(bb)$ **with n b-tags**	231	98	**x5 worse S/B**
	$ZH \rightarrow 2\nu(bb)$ **with n b-tags**	127	46	
	$ZH \rightarrow (ll)(bb)$ **with n b-tags**	42	16	
	$VH \rightarrow (2l/2\nu/l\nu)\ (bb)$ **[highly boosted]**	?	?	**1 (after all cuts)**
$H \rightarrow WW$	$H \rightarrow (l\nu)(l\nu)$ **with n=0,1 jets**	94	130	**X5 better S/B**
	$qqH \rightarrow qq\ (l\nu)(l\nu)$	4	8	
	$qqH \rightarrow qq\ (l\nu)(jj)$	29	52	
	$WH \rightarrow (l\nu)(l\nu)(jj)$, same-sign dilepton	7	3	
	$ZH \rightarrow (\nu\nu)(l\nu)(jj)$	8	2.8	
	$ZH \rightarrow (ll)(l\nu)(jj)$	2	1	
$H \rightarrow \tau\tau$	$qqH \rightarrow qq\ (\tau\tau)$	26	44	

Mid Mass Higgs: $N_{events} = \sigma \times Br \times L$ Produced

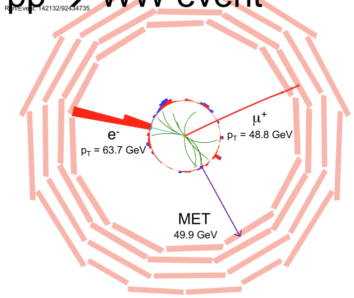
Experimental signature M_H~160 GeV		Signal events: TeV Exp. 10 fb^{-1}	Signal events: LHC Exp 1 fb^{-1}	Comments
$H \rightarrow WW$	$H \rightarrow (l\nu)(l\nu)$ **with n=0,1 jets**	247	472	**5 times better S/B**
	$qqH \rightarrow qq\ (l\nu)(l\nu)$	17	40	**S/B ~same**
	$qqH \rightarrow qq\ (l\nu)(jj)$	103	240	**S/B ~same**
	$WH \rightarrow (l\nu)(l\nu)(jj)$, same-sign dilepton	30	14	
	$ZH \rightarrow (ll)(l\nu)(jj)$	6	2	

High Mass Higgs: $N_{events} = \sigma \times Br \times L$ Produced

Experimental signatures M_H = 400 GeV		Signal events: Tev Exp 10 fb^{-1}	Signal events: LHC Exp 1 fb^{-1}
$H \to ZZ$	$H \to ZZ \to 4l$	n/a	2
	$H \to ZZ \to (ll)(\nu\nu)$		16
	$H \to ZZ \to (ll)(bb)$ **with n b-tags**		12
	$H \to ZZ \to (ll)(jj)$		54
	$H \to ZZ \to (\nu\nu)(bb)$ **with n b-tags**		36
	$qqH \to qq(ZZ) \to qq(ll)(\nu\nu)$		1.2
	$qqH \to qq(ZZ) \to qq(ll)(bb)$ **with n b-tags**		0.8
	$qqH \to qq(ZZ) \to qq(4l)$		0.2
$H \to WW$	$H \to (l\nu)(l\nu)$ **with n=0,1 jets**	n/a	62
	$qqH \to qq\ (l\nu)(l\nu)$		4
	$qqH \to qq\ (l\nu)(jj)$		26

$H \rightarrow WW \rightarrow 2\ell 2\nu$ Search : CMS

pp → WW event



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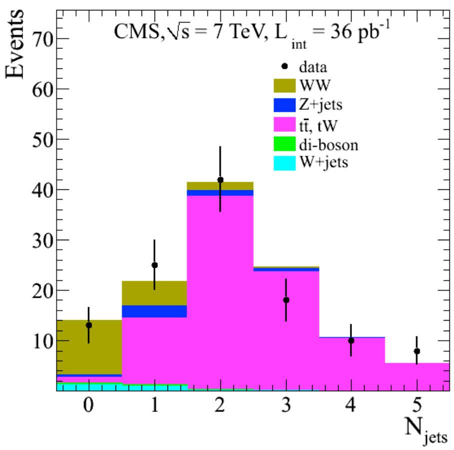
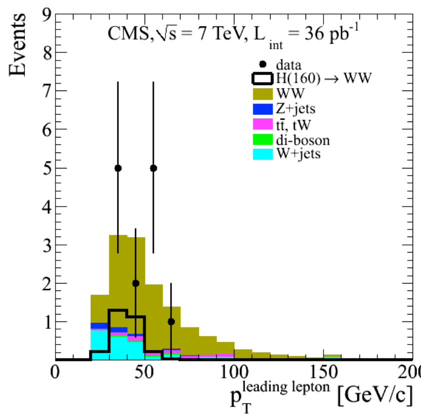
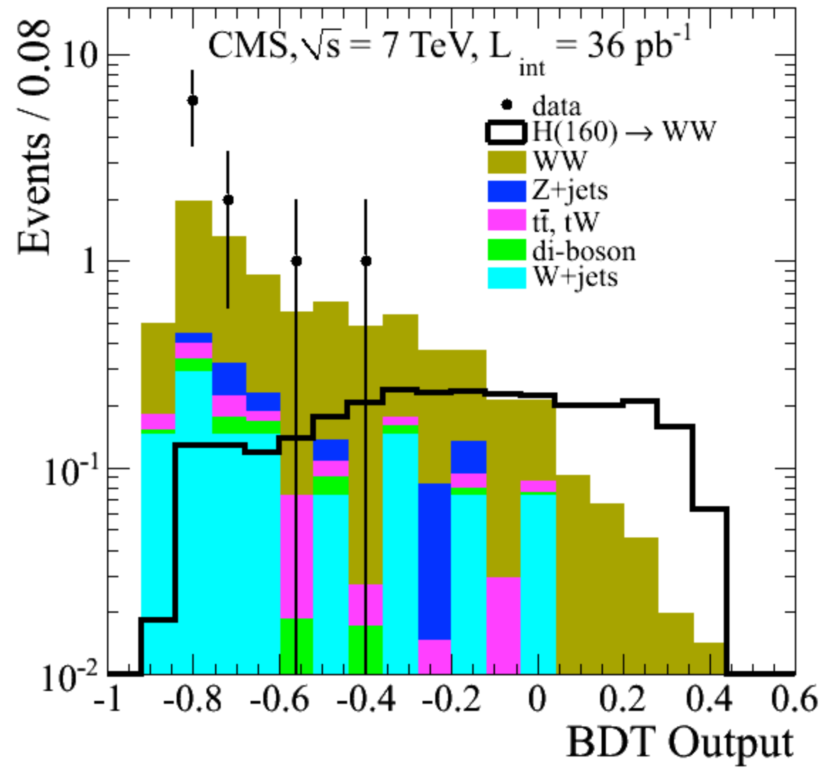
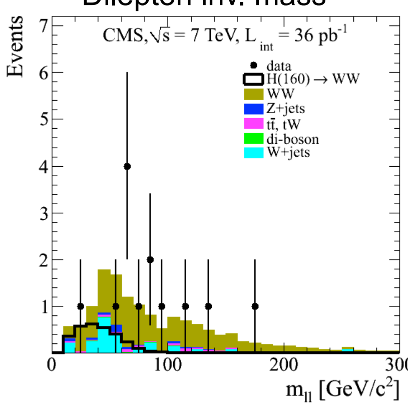






Dilepton inv. mass



Azimuthal angle between leptons