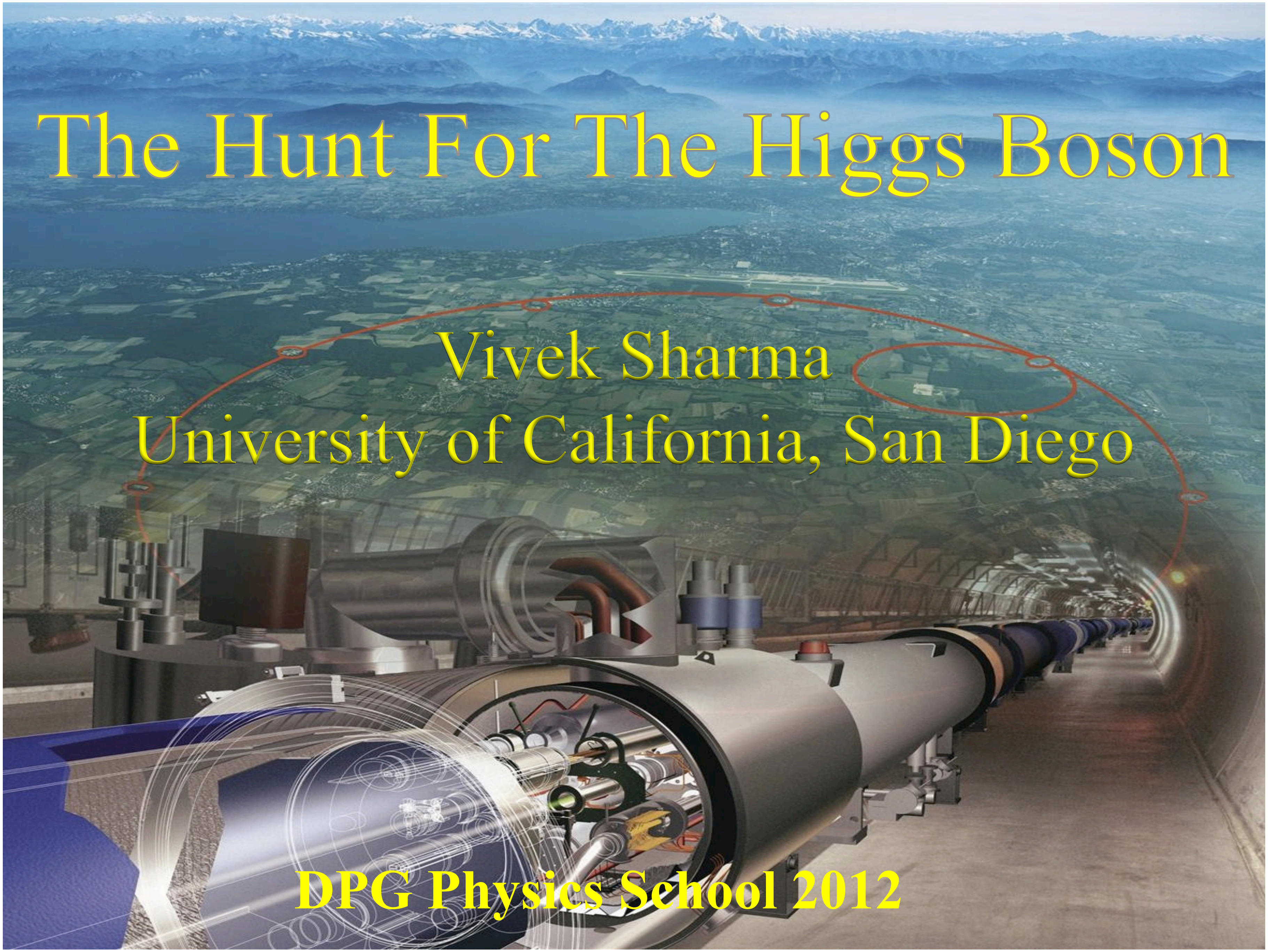
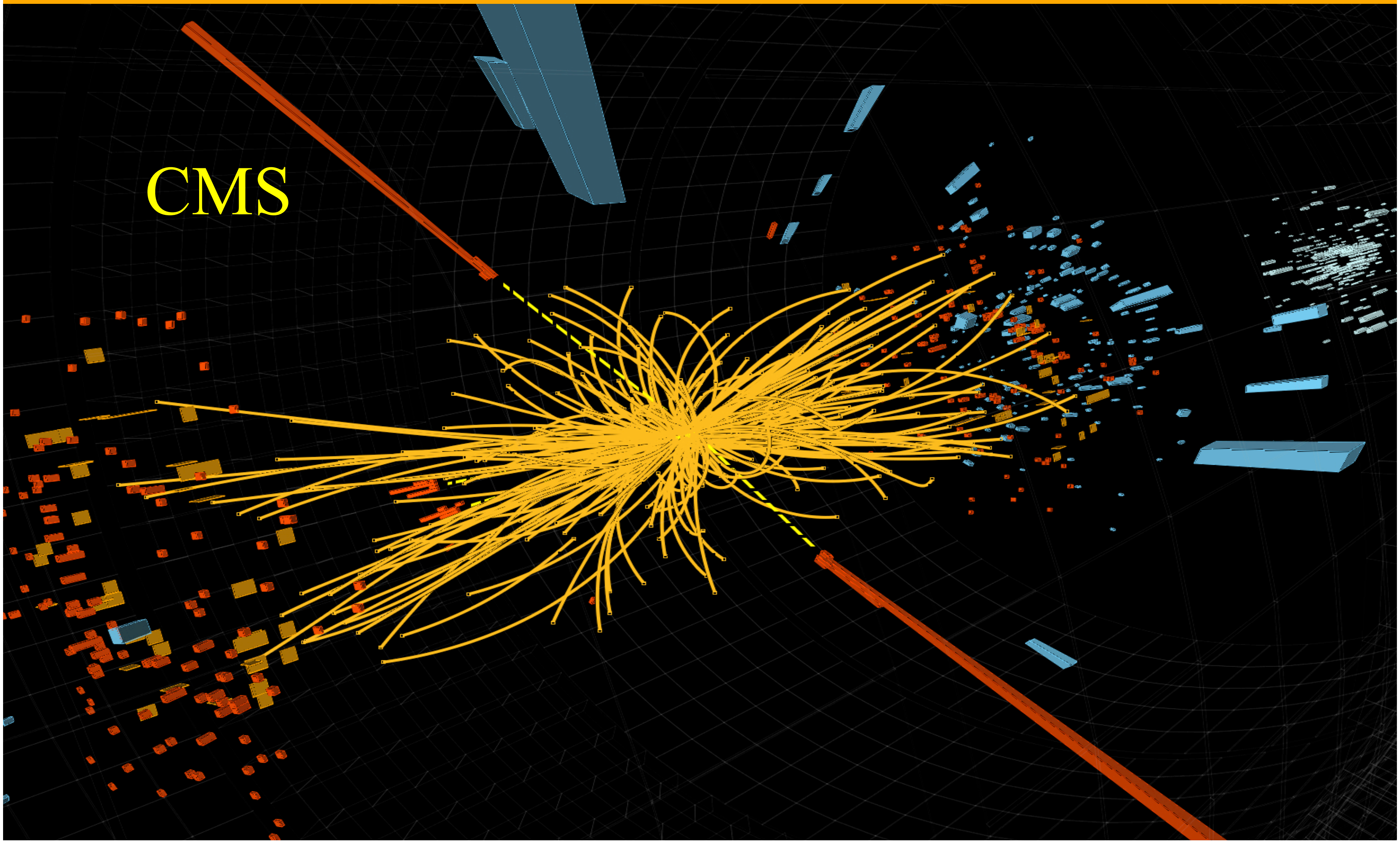

The Hunt For The Higgs Boson
Vivek Sharma
University of California, San Diego
DPG Physics School 2012

LHC Fireworks On July 4th: Discovery Of A New Boson With Mass Near 125 GeV



Lecture Plan

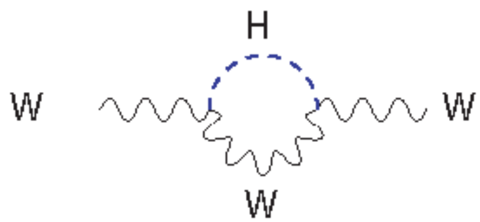
Lecture 1

- Past searches
- SM Higgs production & decay
- LHC, ATLAS & CMS
- Objects for discovery
- Higgs search menu
- Low mass resolution modes
  - $H \rightarrow WW \rightarrow l\nu l\nu$
  - $H \rightarrow ZZ \rightarrow 2l2\nu$
- Low mass resolution modes
  - $H \rightarrow bb$
  - $H \rightarrow \tau\tau$

Lecture 2

- High mass resolution modes
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ \rightarrow 4l$
- Combination of all search results
- Compatibility with SM Higgs boson
- Future prospects

Indirect Limits From Precision Electroweak Data



- Logarithmic dependence on M_H allows M_W and other precision observables to bound its mass

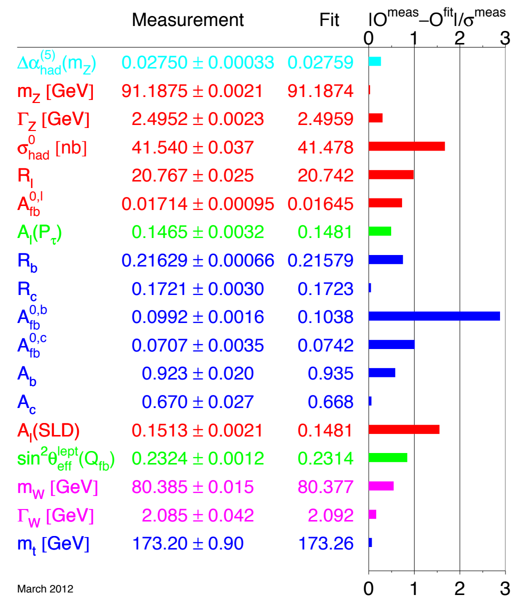
$$M_W^2 = \frac{M_Z^2}{2}\left\{1 + \left[1 - \frac{2\sqrt{2}\alpha(1+\Delta r)}{G_F M_Z^2}\right]^{1/2}\right\}$$

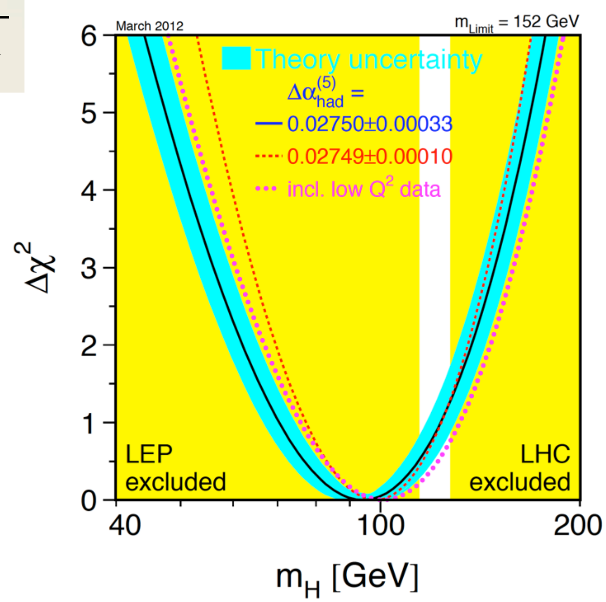
$$\Delta r \sim \ln \frac{M_H}{M_Z}$$

  – Global fit to precision Electroweak data including Tevatron M_W= 80.385±0.015 GeV suggests:

$$M_H = 94^{+29}_{-24}\ \text{GeV}$$

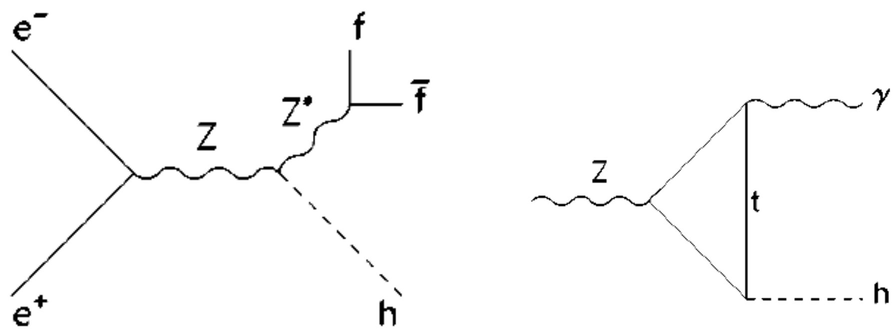
$$\text{or } M_H < 152\ \ \text{GeV at 95\% CL}$$



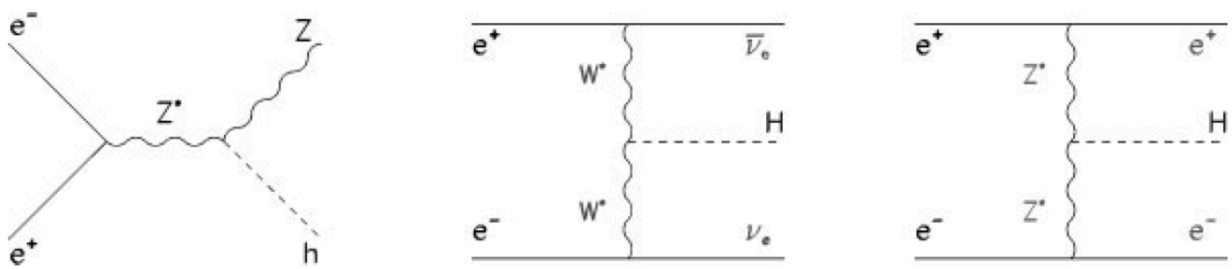


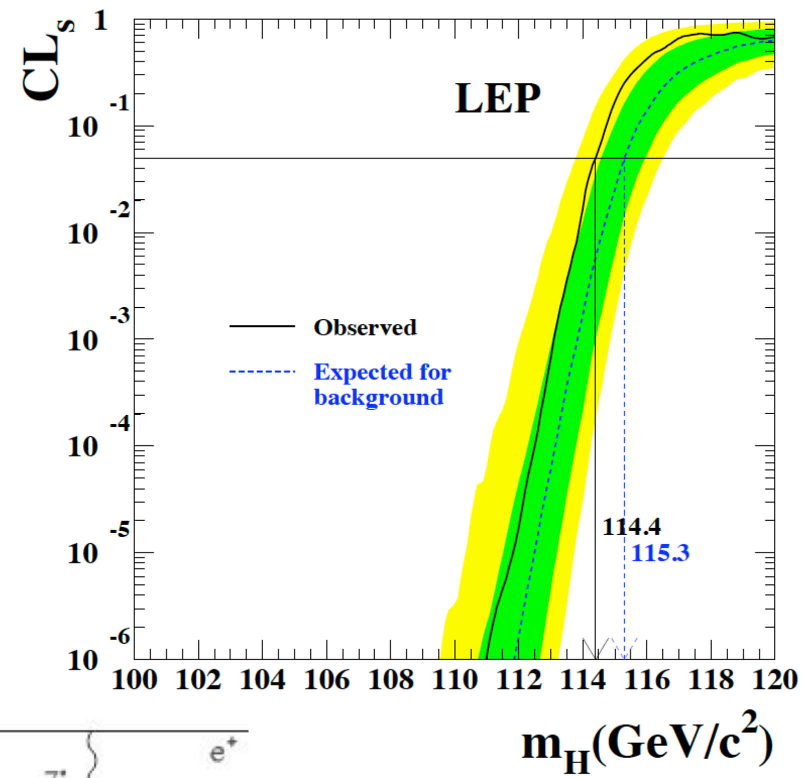
Direct Searches For Higgs Boson at LEP

- LEP e^+e^- Collider (1989-2000)
  - LEP1 at $\sqrt{s} \cong M_Z$



  - LEP2 at $\sqrt{s} \cong 189$ -209 GeV

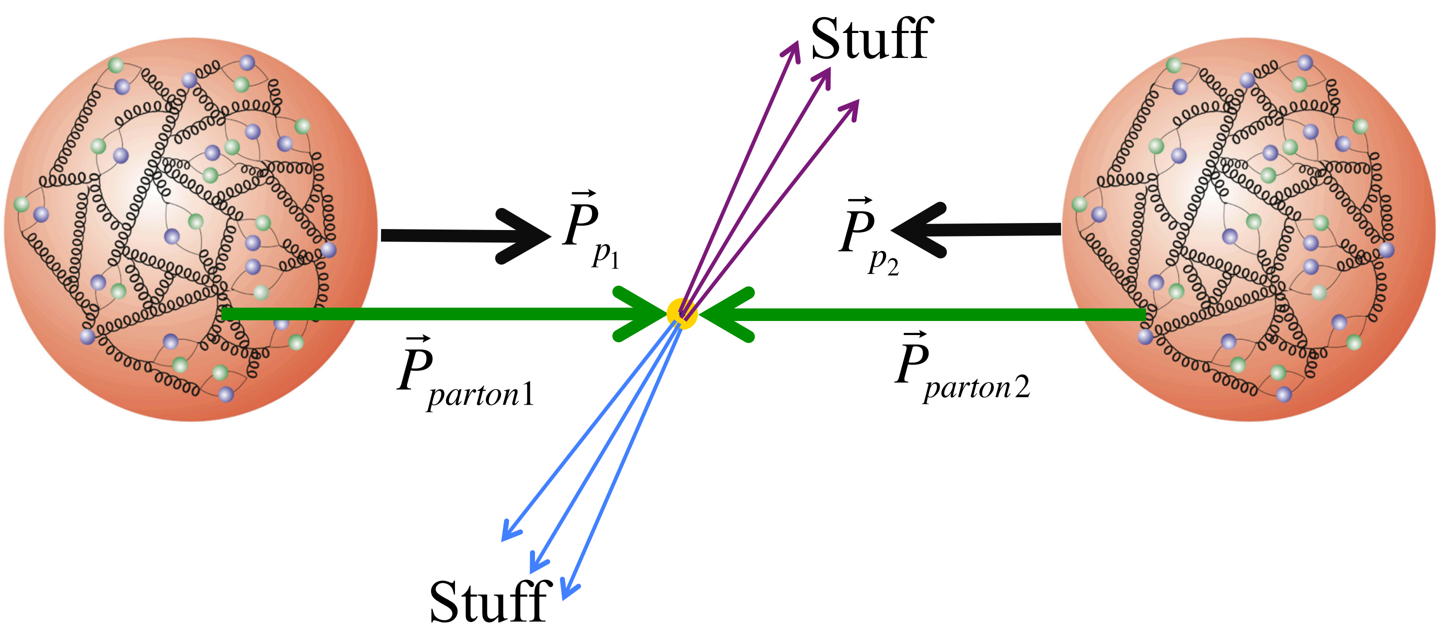




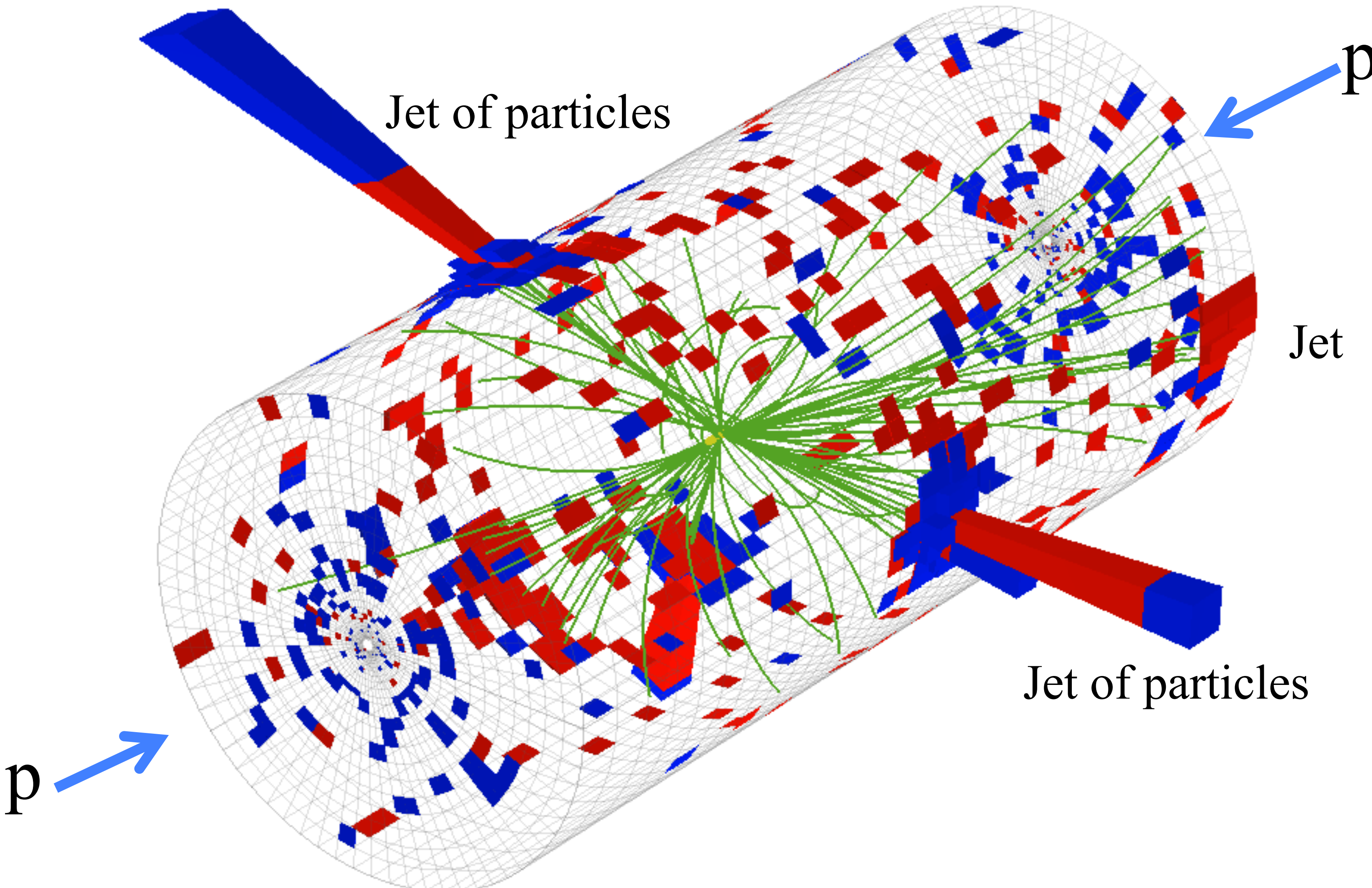
- **At 95% CL, Excluded SM Higgs with mass below 114.4 GeV**
- **Scene shifted to hadron colliders → LHC**

Proton-On-Proton Collisions

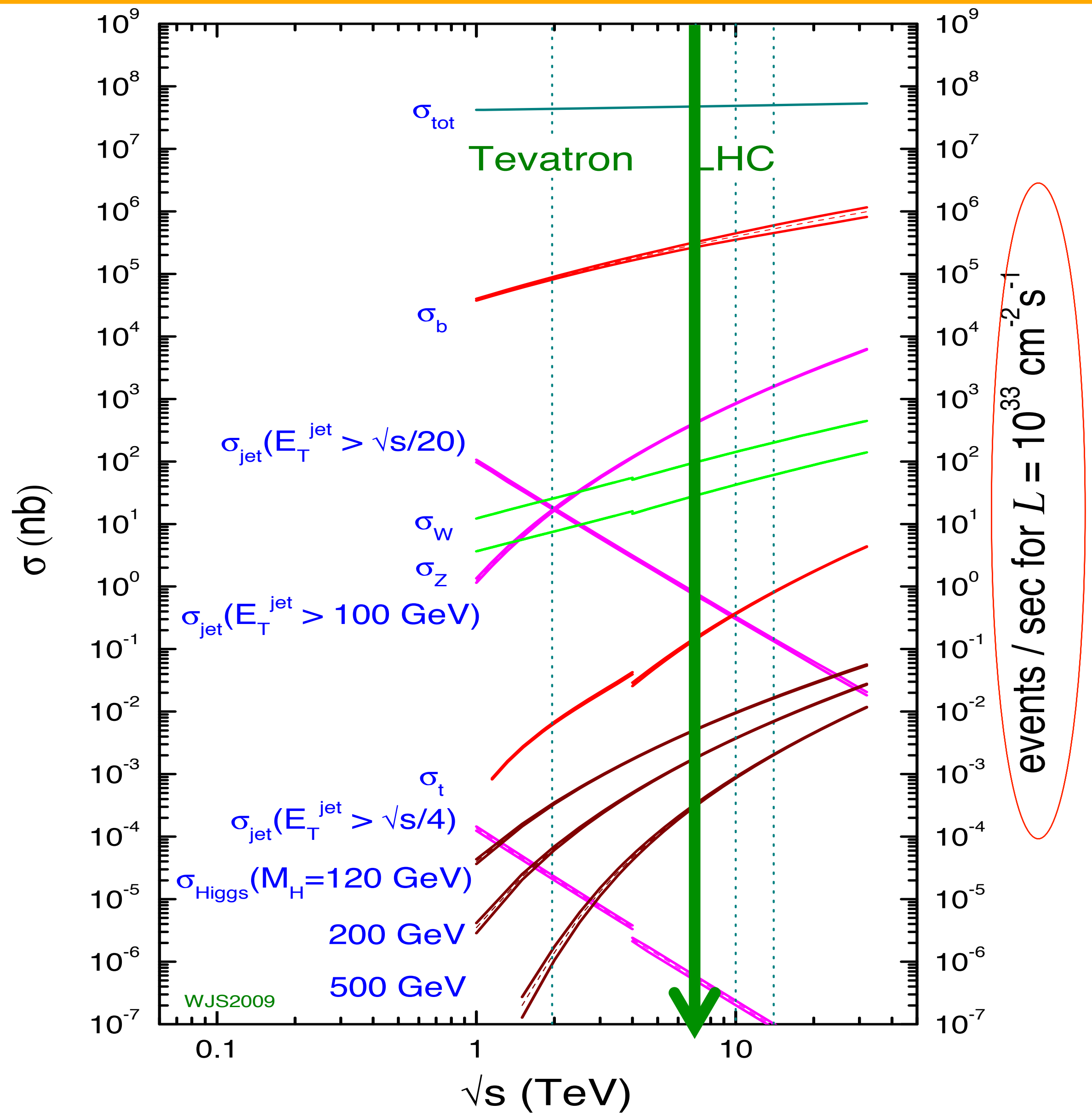
When protons collide ➔ Interaction of constituent partons (gluons or quarks)



Produces A Whole Lot Of "Stuff" (Yesterday's Discoveries)

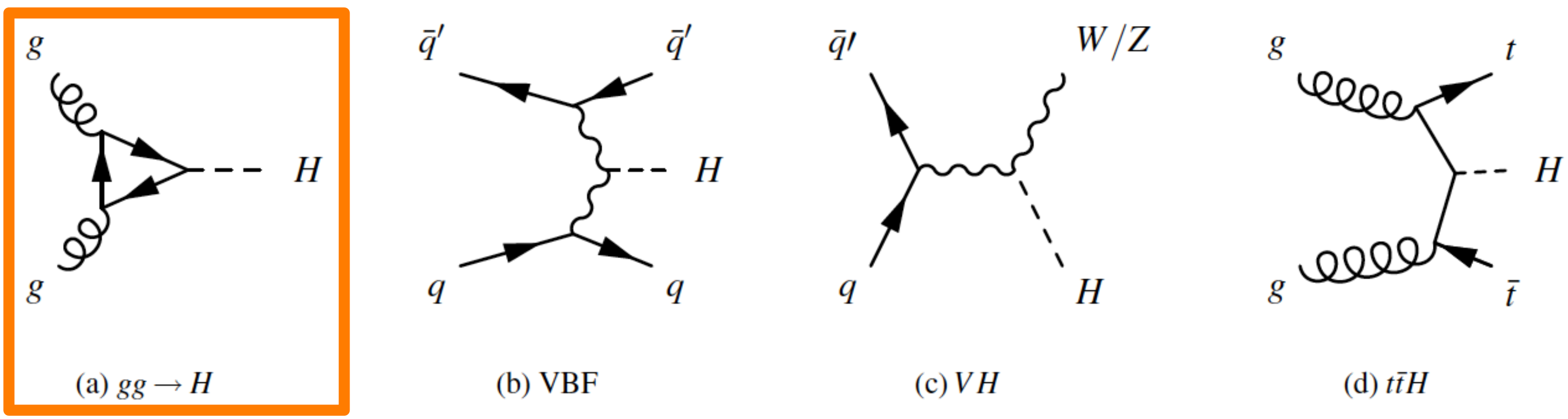


What Is Produced in p-p Collisions



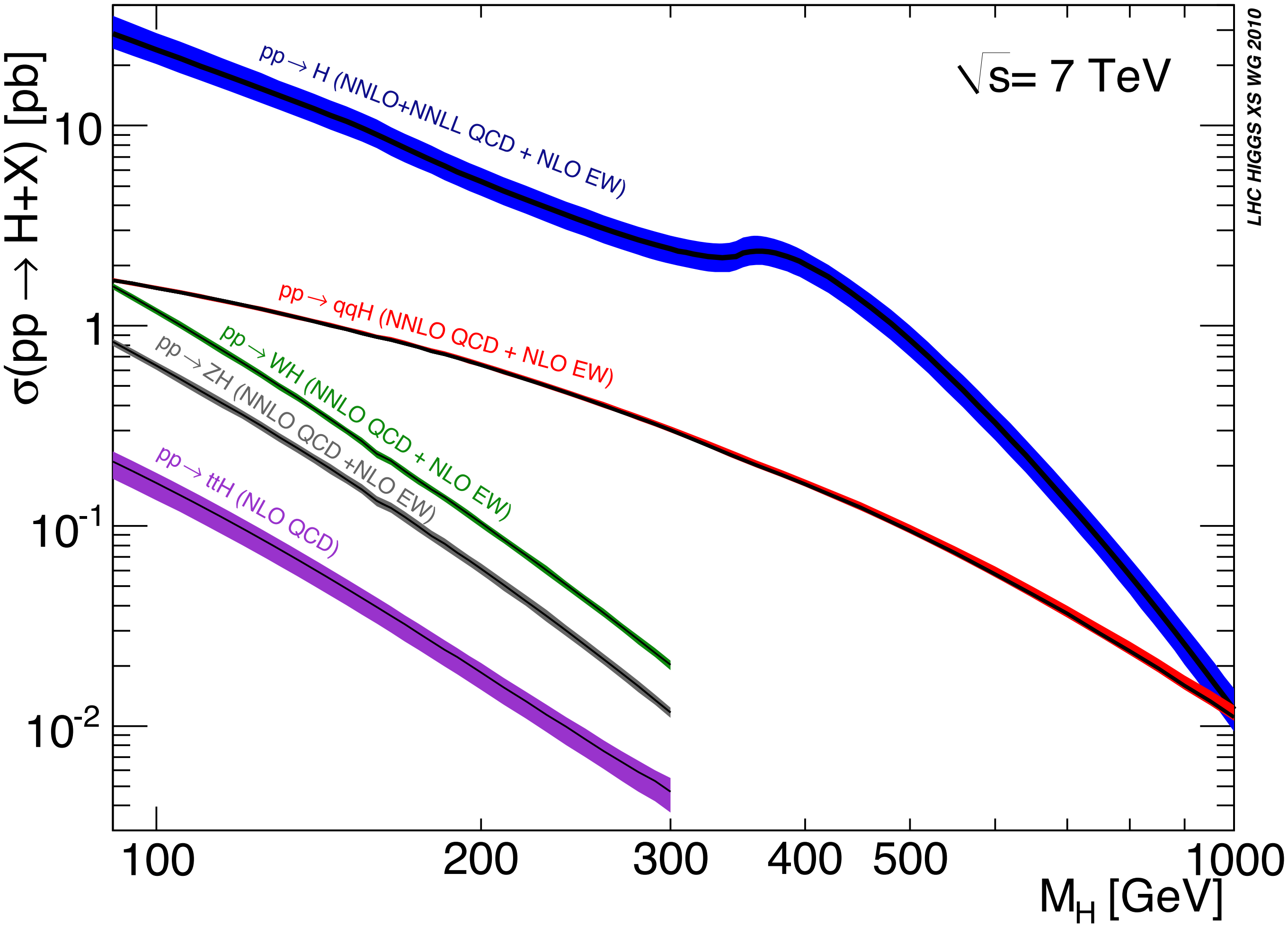
Higgs Production At Hadron Colliders

- Production Mechanisms:



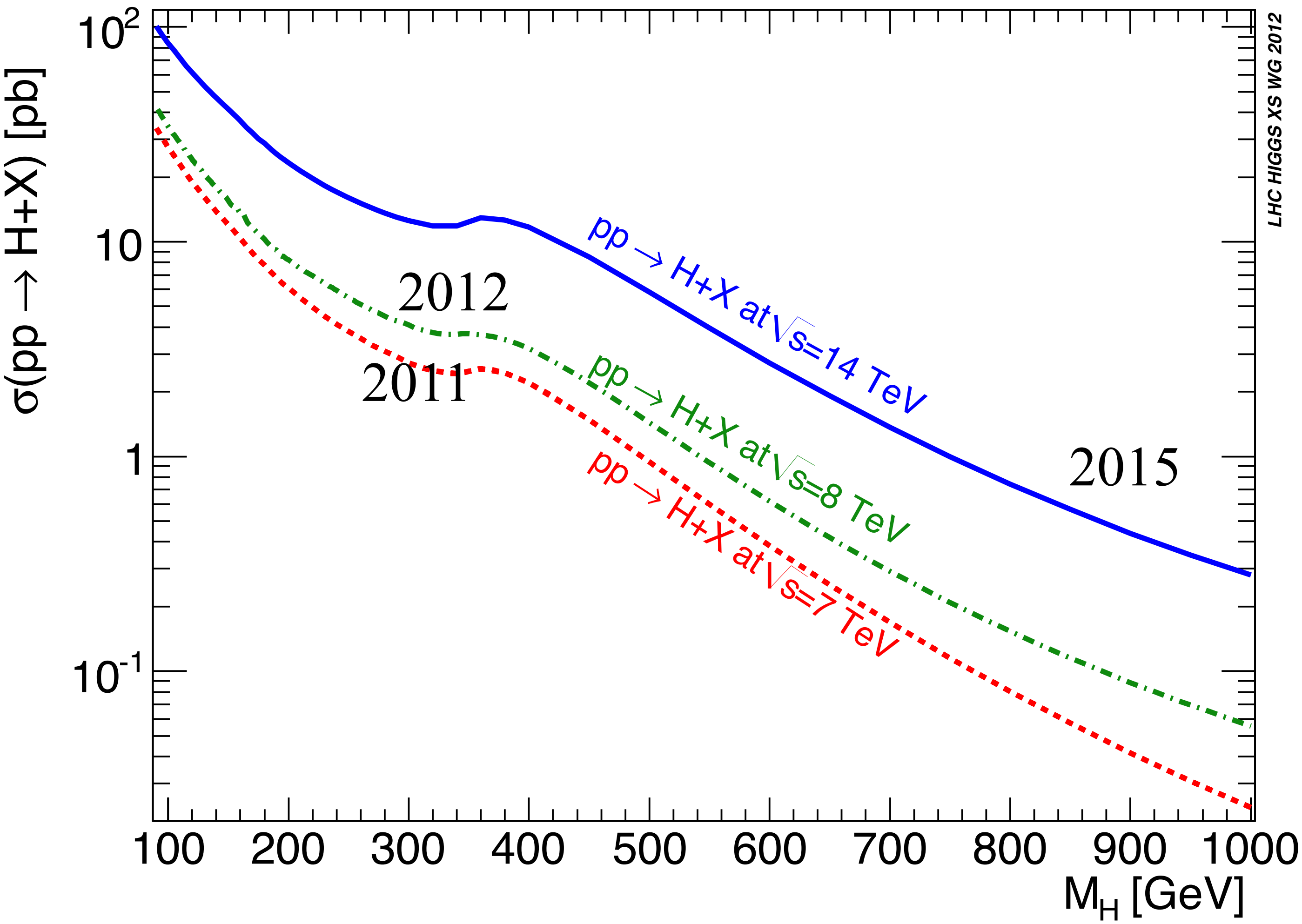
Gluon fusion is the dominant production mechanism
VBF & VH have a distinct signature

Higgs Production in pp collisions: √s = 7 TeV



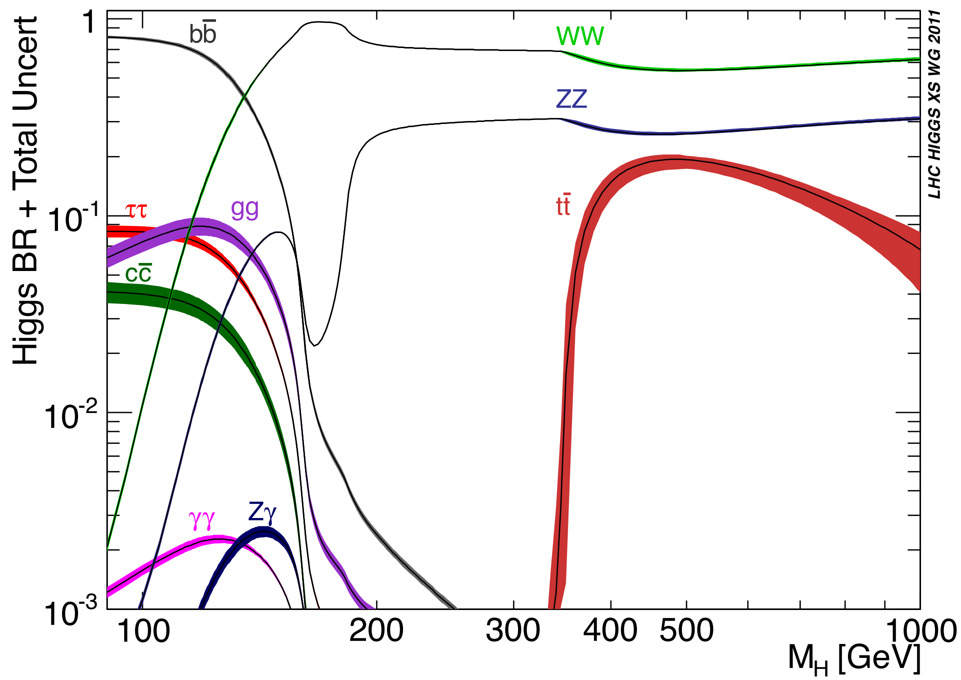
At LHC : “leave no mode behind ” !

Higgs Production in pp Collisions at 7, 8 & 14 TeV



At M_H=125 GeV, about 25 % enhanced production at 8 TeV w.r.t 7 TeV

Higgs Branching Ratios Vs M_H



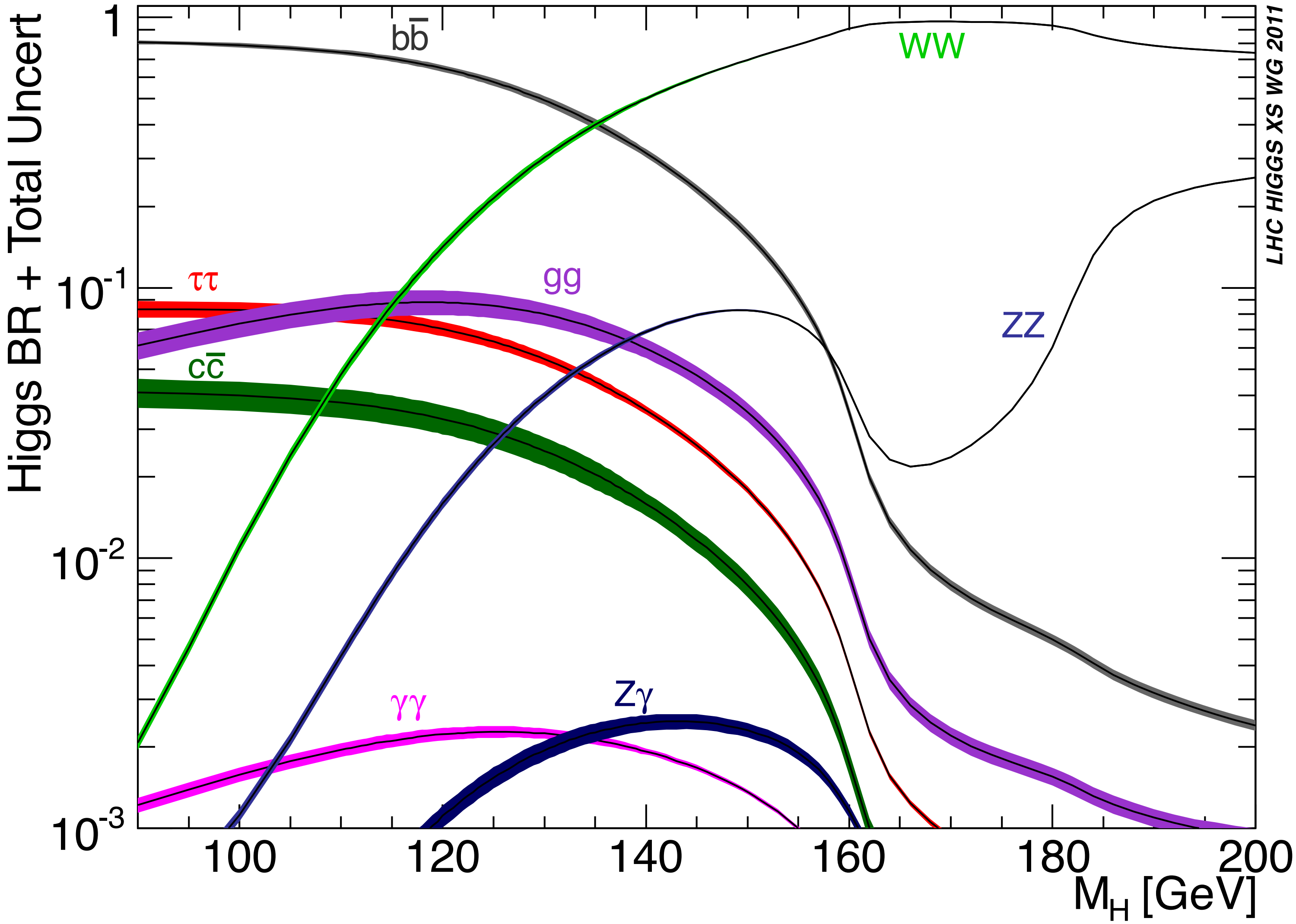
Higgs couples most to the heaviest particle kinematically allowed

$$\Gamma(H \to W^+W^-) = \frac{G_F M_H^2}{32\pi\sqrt{2}}(1-x)^{1/2}(4-4x+3x^2),\ x \equiv 4M_W^2/M_H^2$$

$$\Gamma(H \to Z^0Z^0) = \frac{G_F M_H^2}{64\pi\sqrt{2}}(1-x')^{1/2}(4-4x'+3x'^2), x' \equiv 4M_Z^2/M_H^2$$

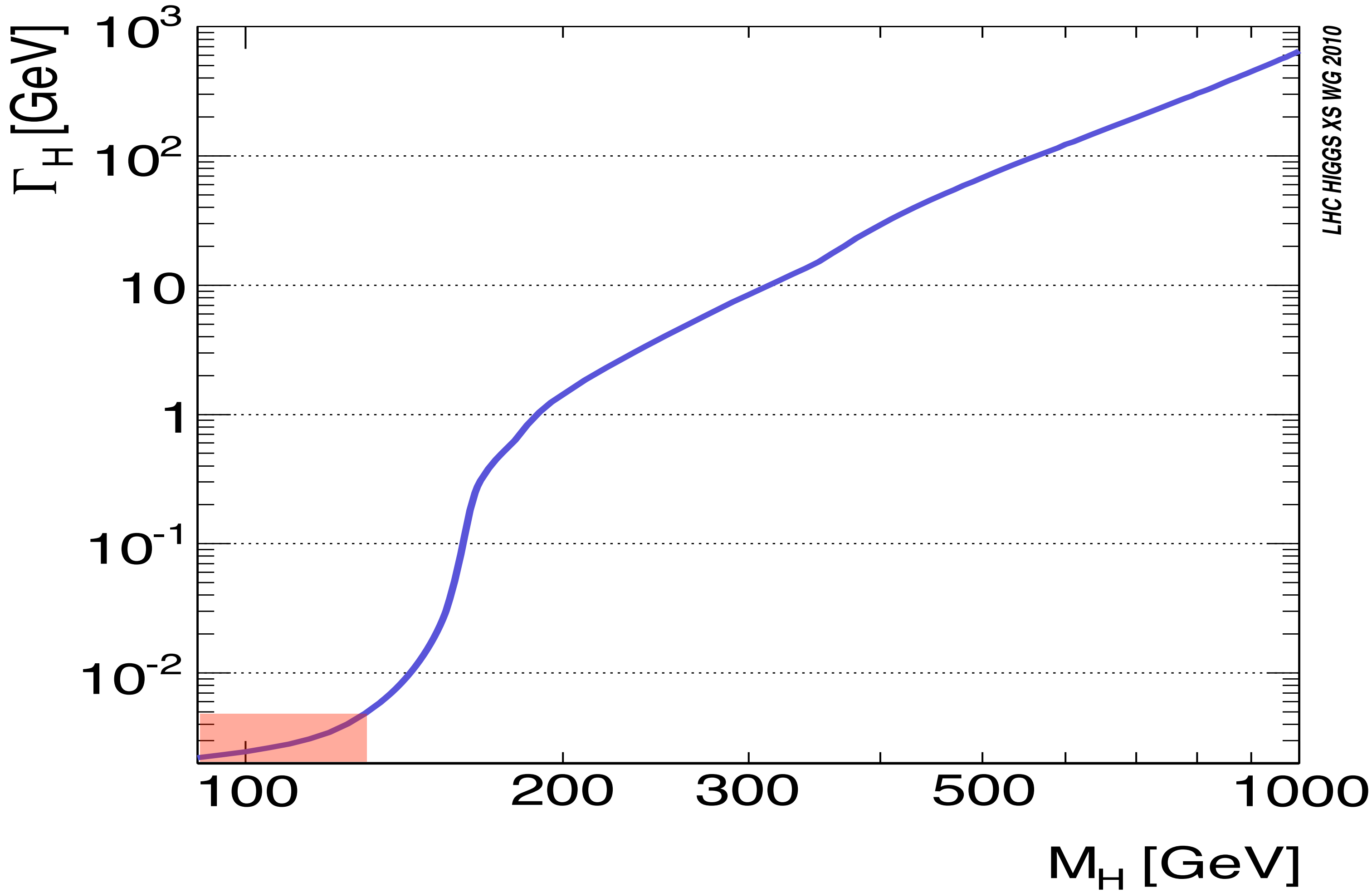
$$\Gamma(H \to f\bar{f}) = \frac{G_F m_f^2 M_H}{4\pi\sqrt{2}} \cdot N_c \cdot \left(1 - \frac{4m_f^2}{M_H^2}\right)^{3/2}$$

Higgs Branching Ratio : Zooming Into Low M_H



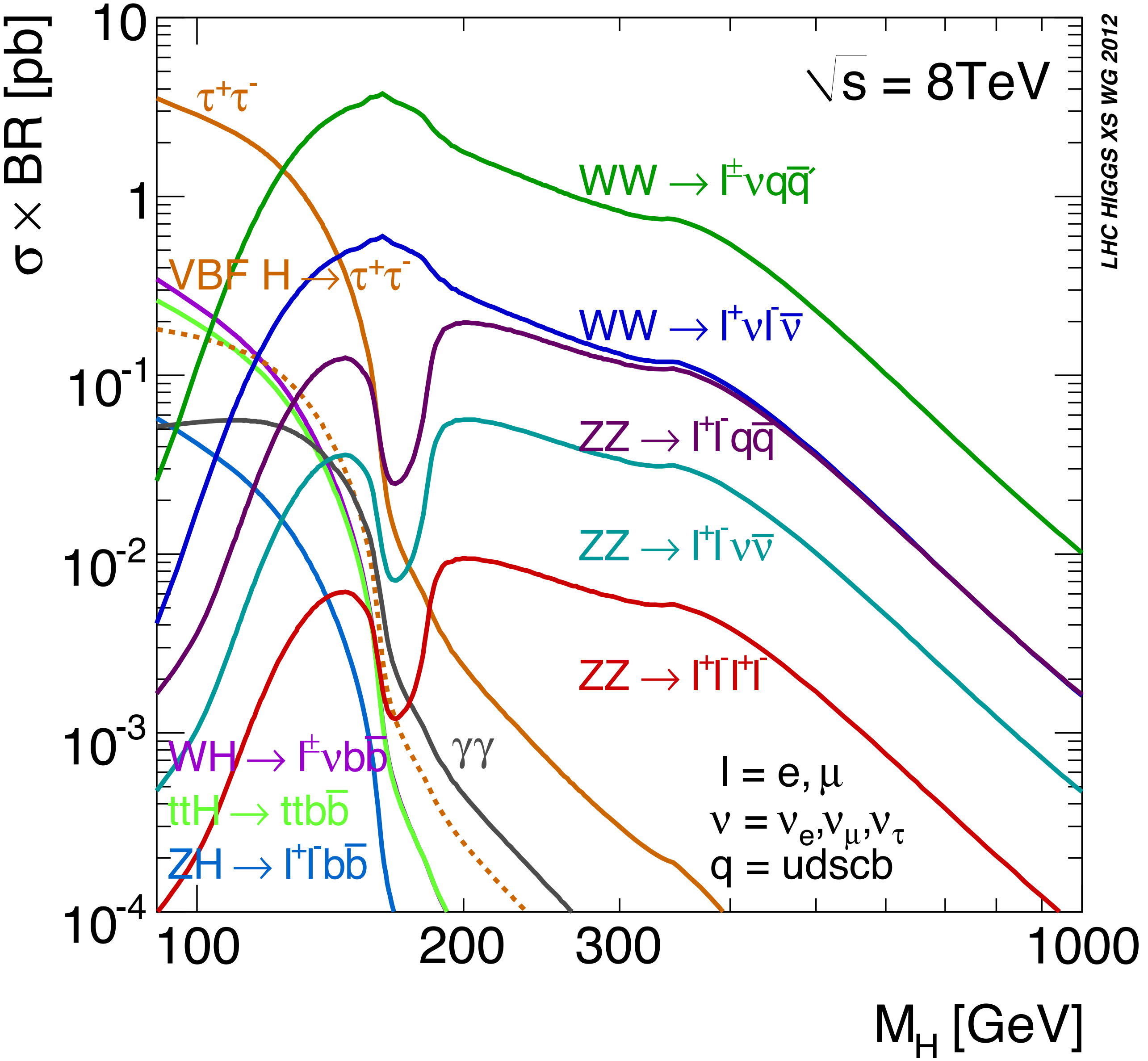
Bands indicate theoretical uncertainties

Intrinsic Width Of SM Higgs Boson

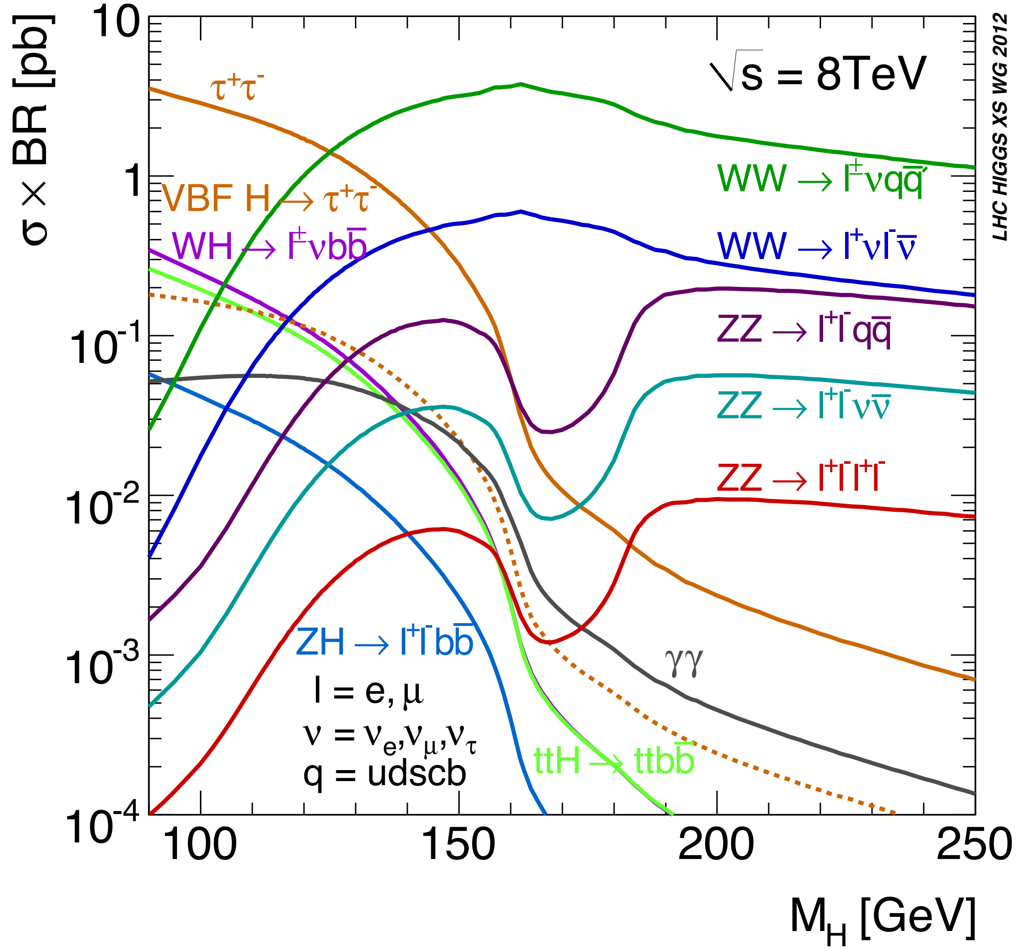


At low mass ($M_H \approx 120$ GeV), width narrower than exptal resolution even in the high mass resolution channels

[Production Cross section × Decay Rate] Vs M_H

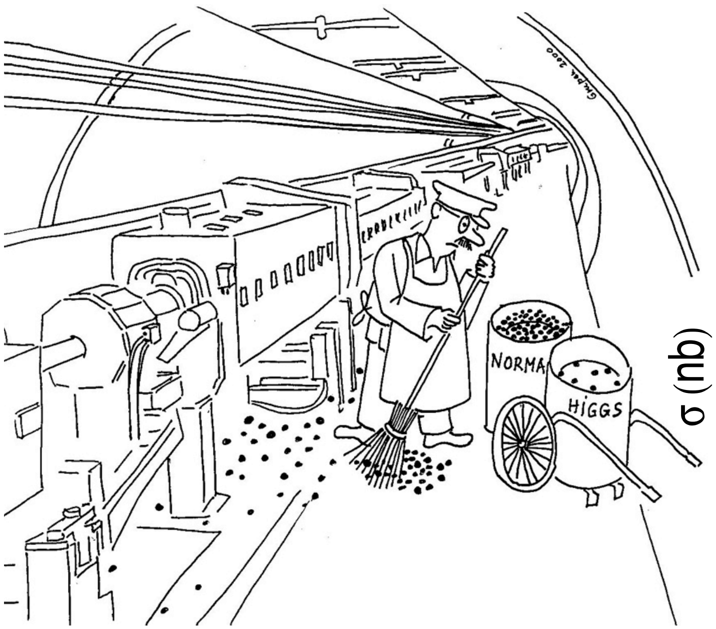


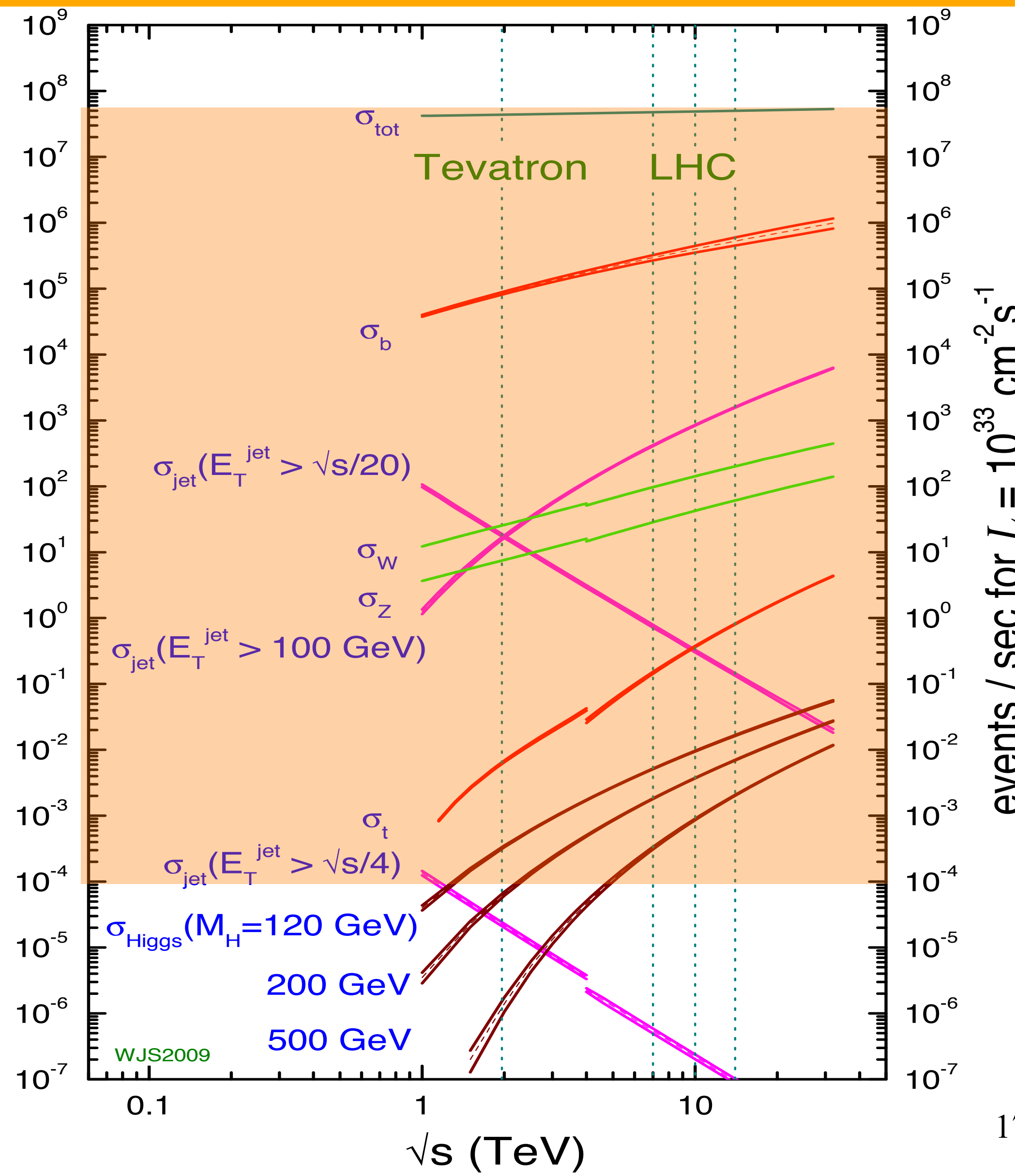
[Cross section × Decay Rate] Vs M_H : Low Mass



Significance of an observation depends on ability to trigger on event & restrict background processes that mimic Higgs signature

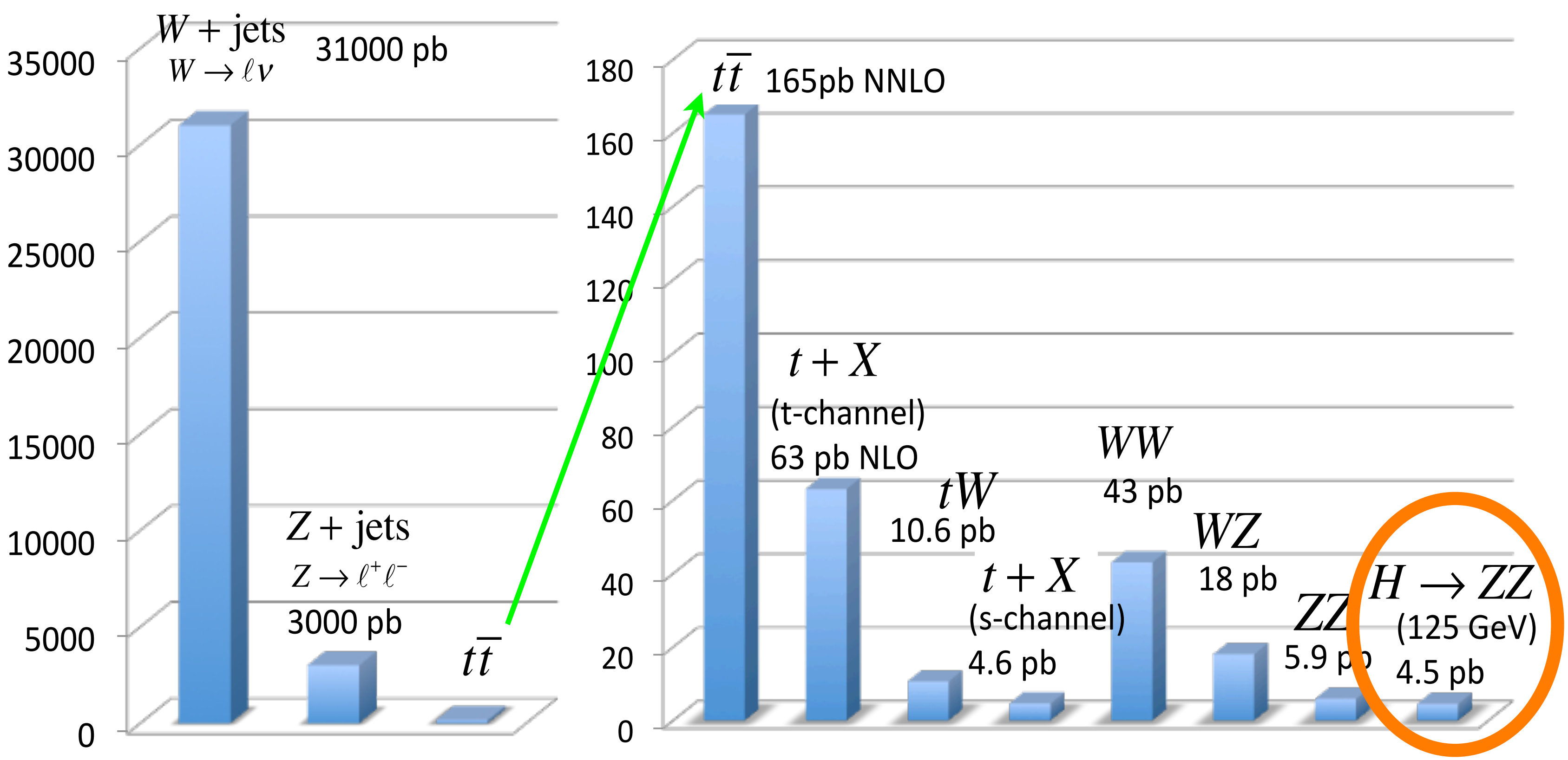
SM Backgrounds In Higgs Search





Cross Sections for Key SM Background Processes

Backgrounds up to 5 orders of magnitude larger than signal !



Need to measure these cross sections & properties

Producing "Stuff" in Particle Collisions

Simple equation for observing "stuff" at a Collider

$$N_{stuff} = L \times \sigma_{stuff} \times \varepsilon$$

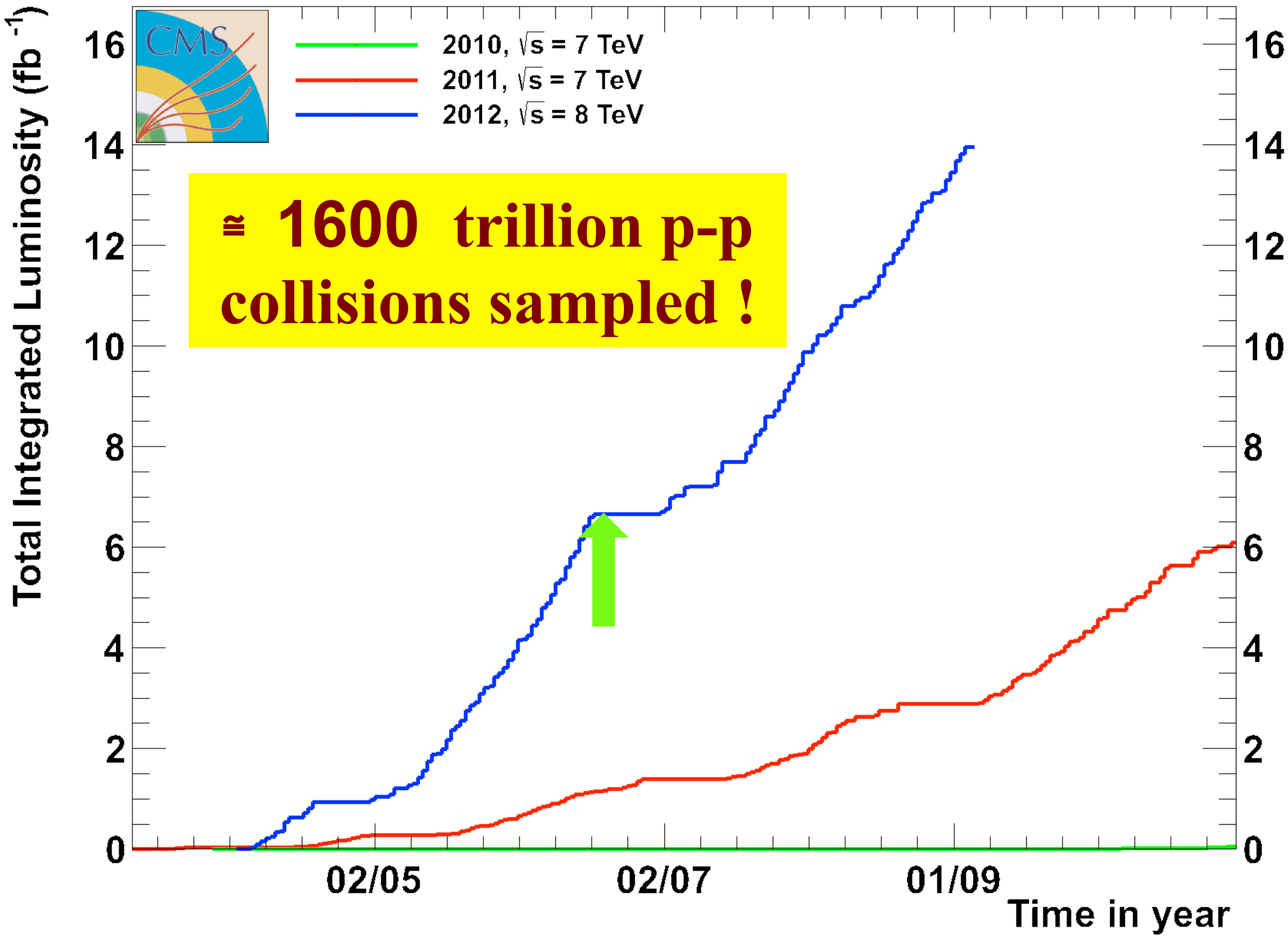
Event rate	Luminosity	Crosssection	Identification Efficiency
s^{-1}	$cm^{-2}\ s^{-1}$	cm^2	

L ➔ machine parameters

σ ➔ Nature's will

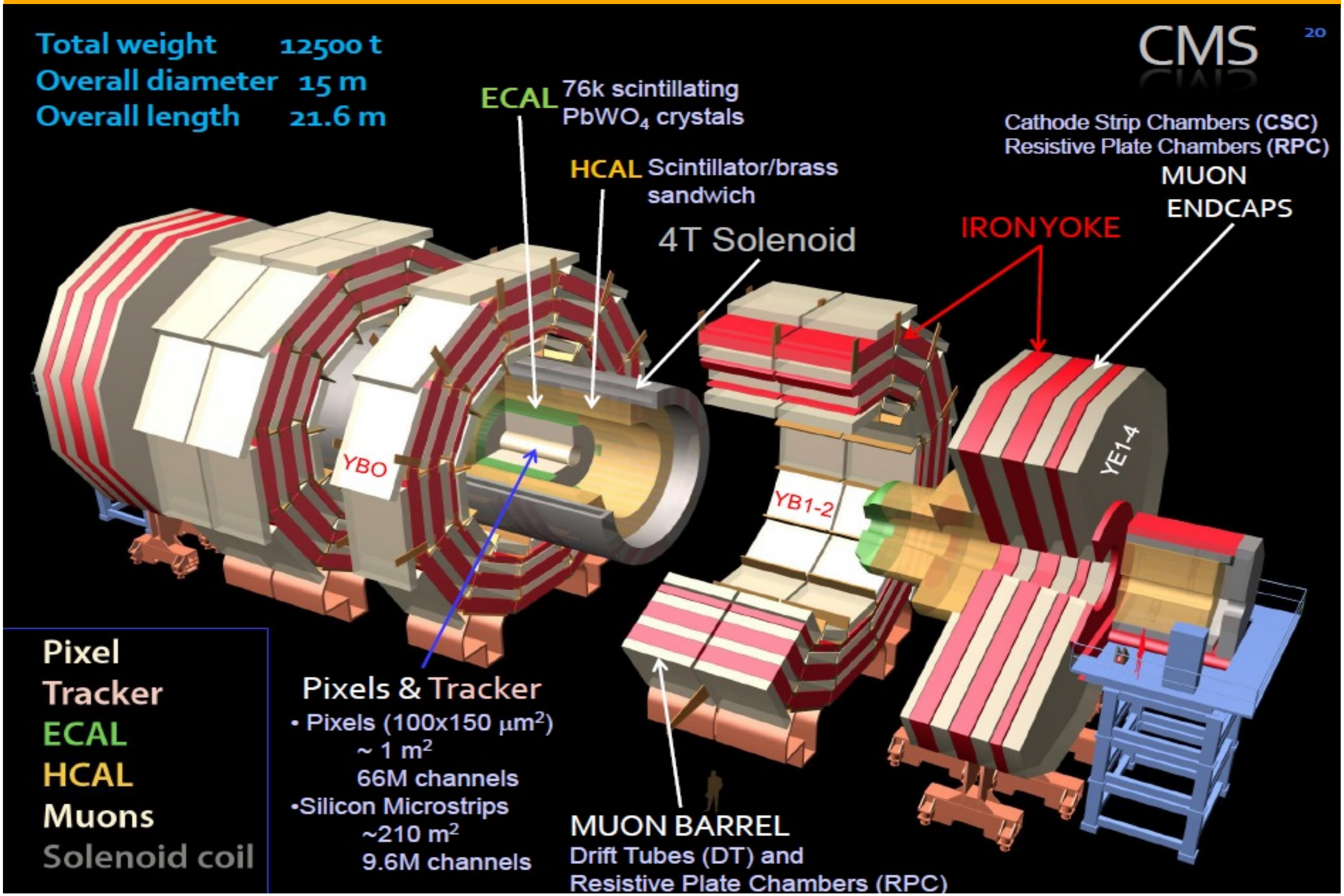
ε ➔ Detector's capability

LHC Luminosity : Beyond Expectation !

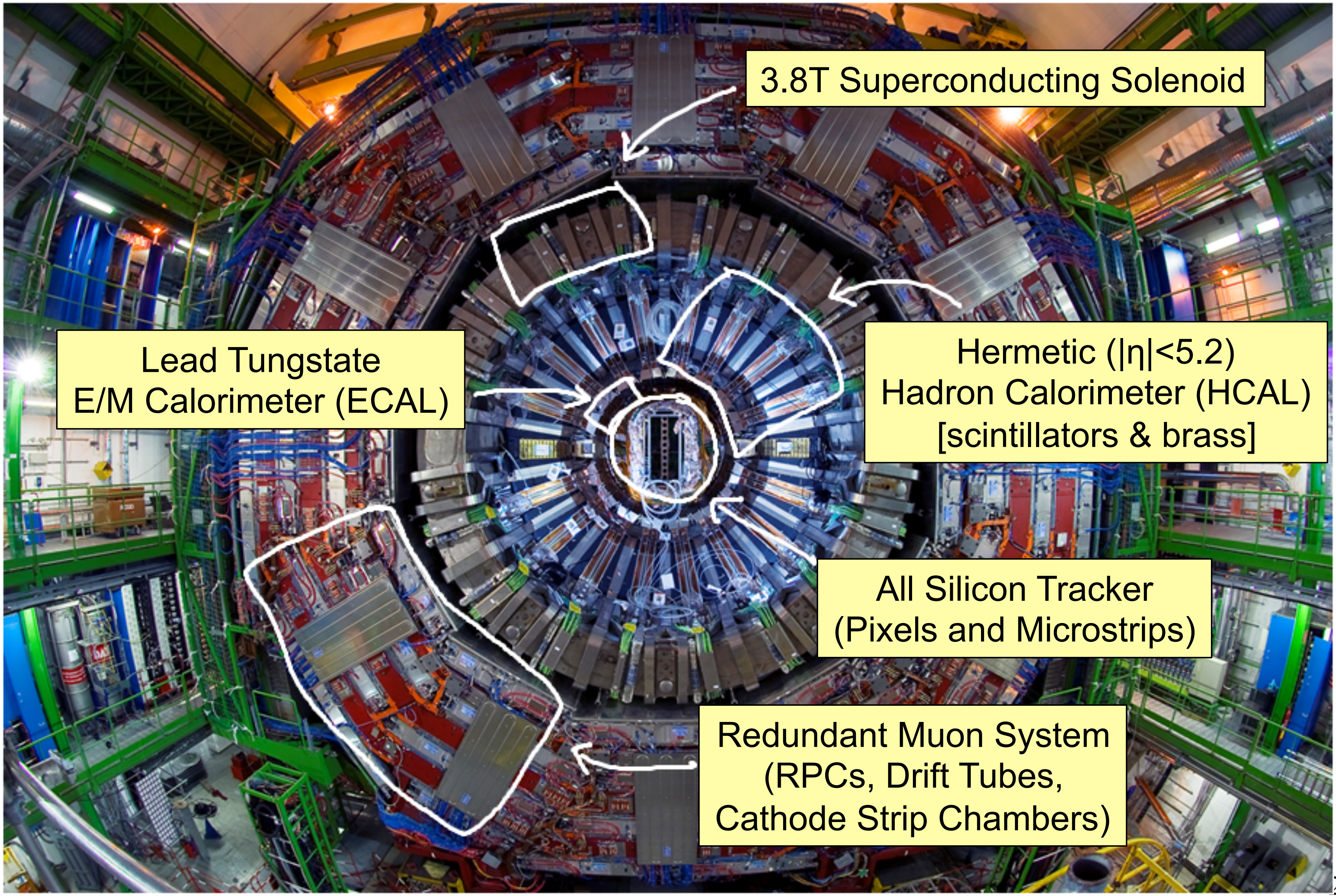


Results shown today uses data recorded till June'12 :
~ 5 fb^{-1} each at $\sqrt{s}$ = 7 & 8 TeV

Schematic Of The CMS Detector

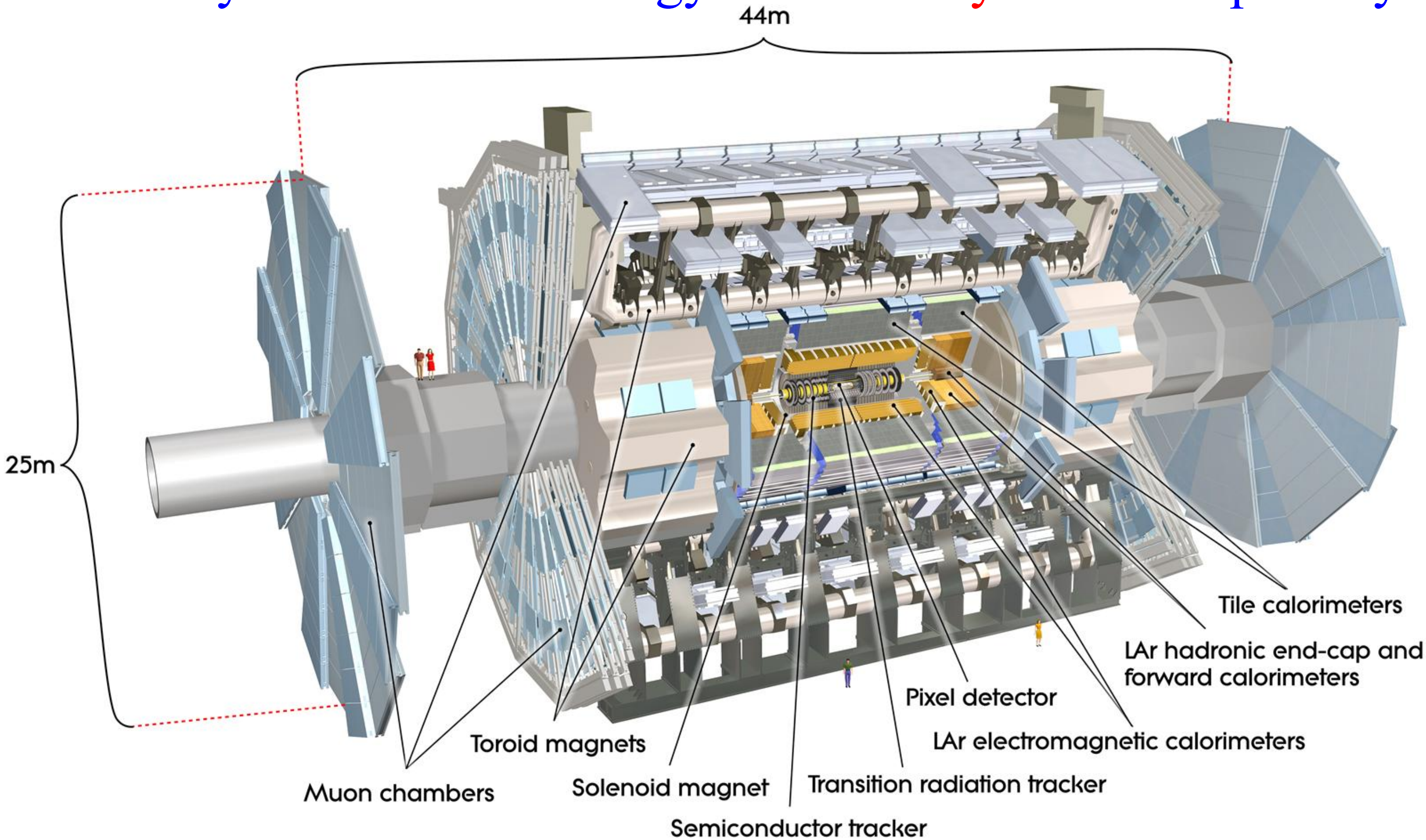


CMS Detector: The Real Thing



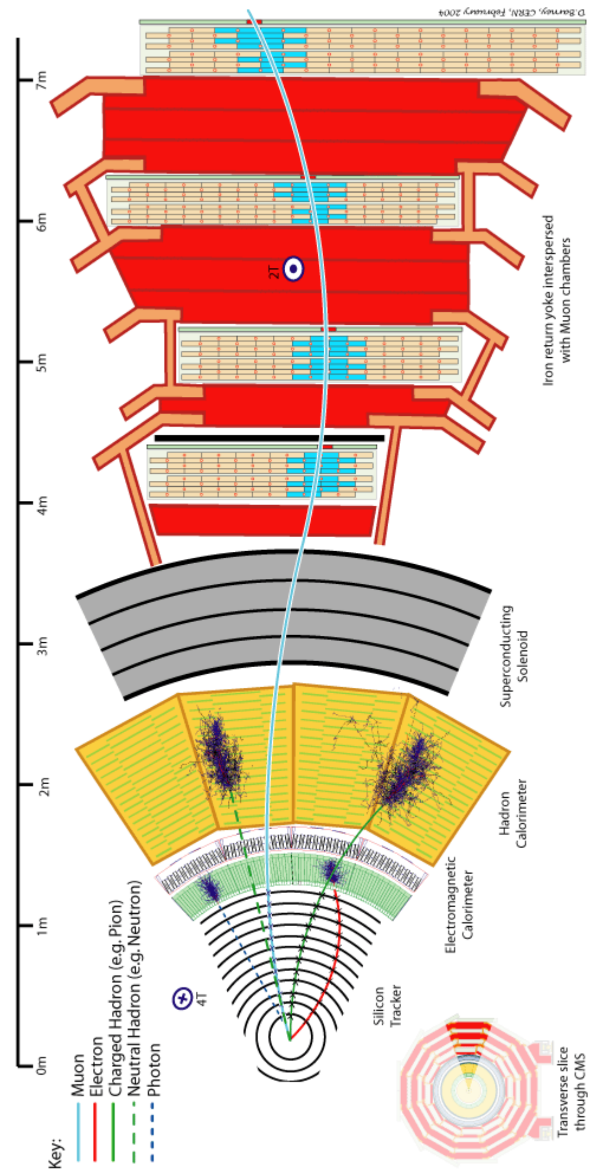
The ATLAS Detector

Uses very different technology but has very similar capability

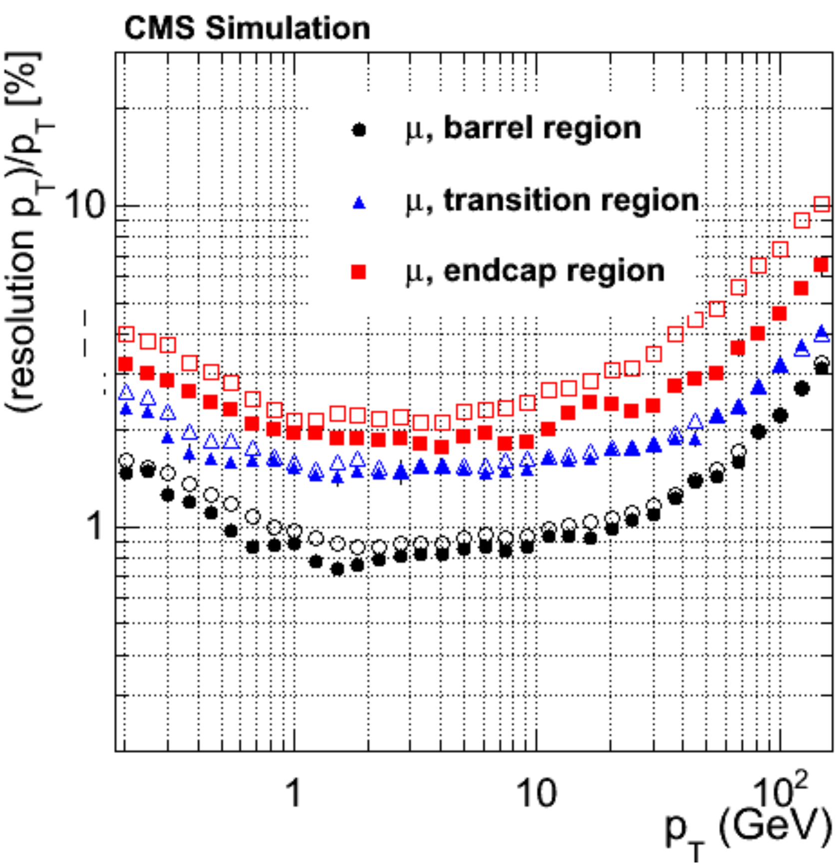


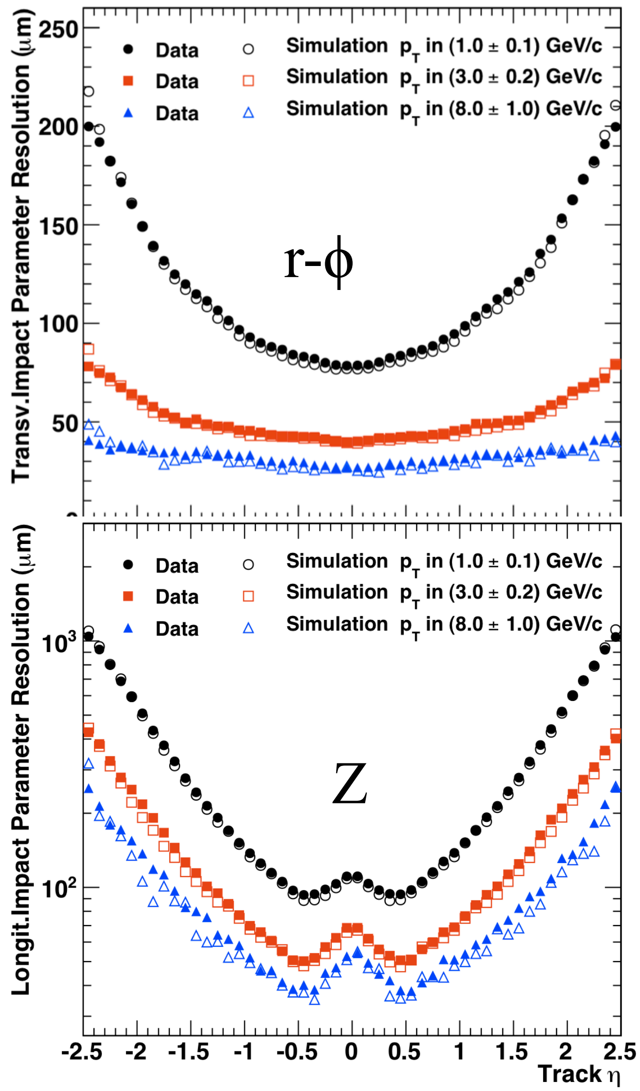
Remnants In Higgs Decay

- At the end of the chain, Higgs boson decays into a subset of:
  - Hadrons: $\pi^{\pm}$,$K^{\pm}$, $K_S \rightarrow \pi^{+}\pi^{-}$ etc
  - Muons
  - Electrons & Photons
  - Tau Lepton
  - Jets
    - b-quark jets
  - Neutrinos ➔ Missing Transverse energy
- Ability to precisely and efficiently reconstruct these objects defines the sensitivity for Higgs boson searches



Charged Particle Trajectory Reconstruction

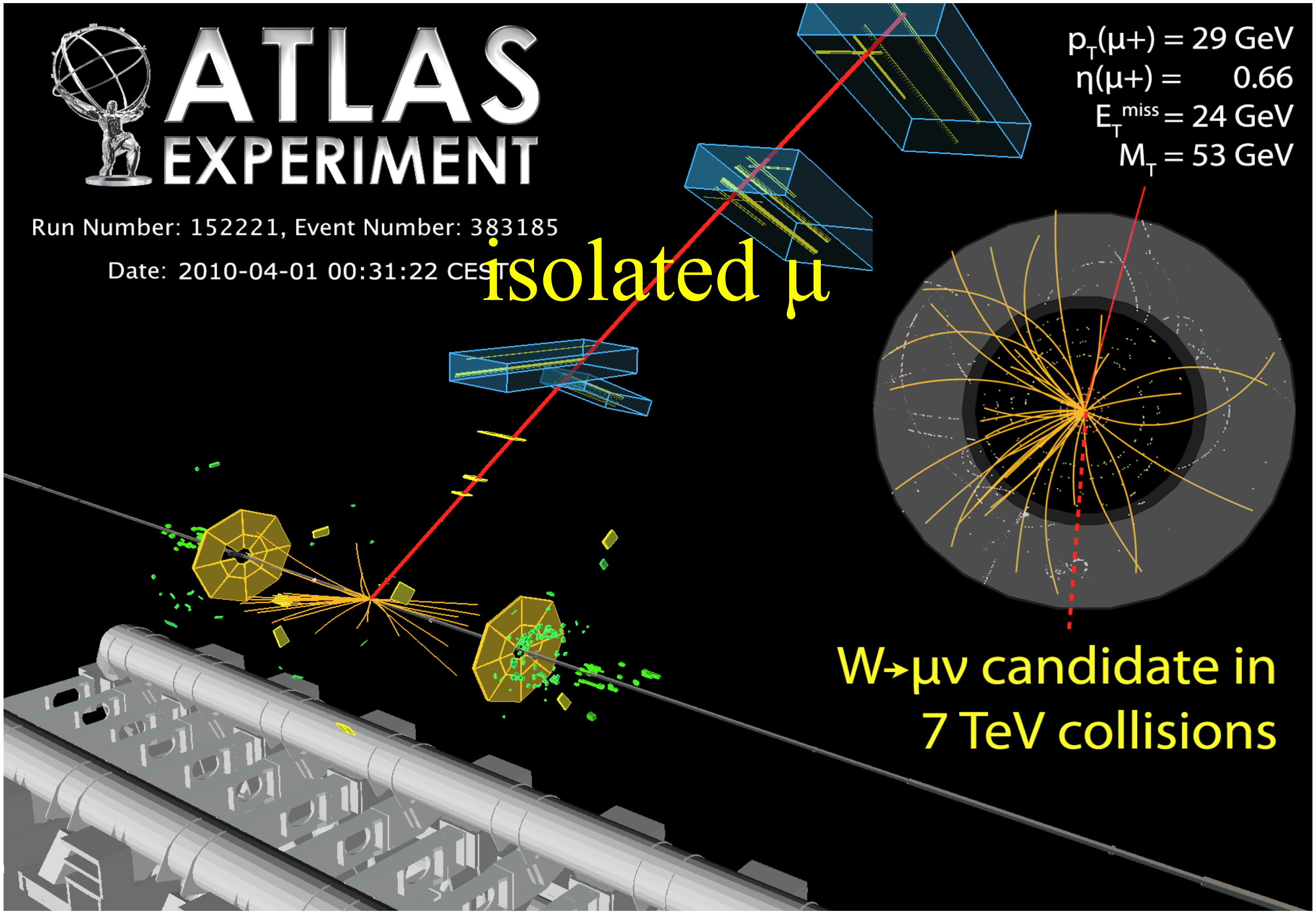




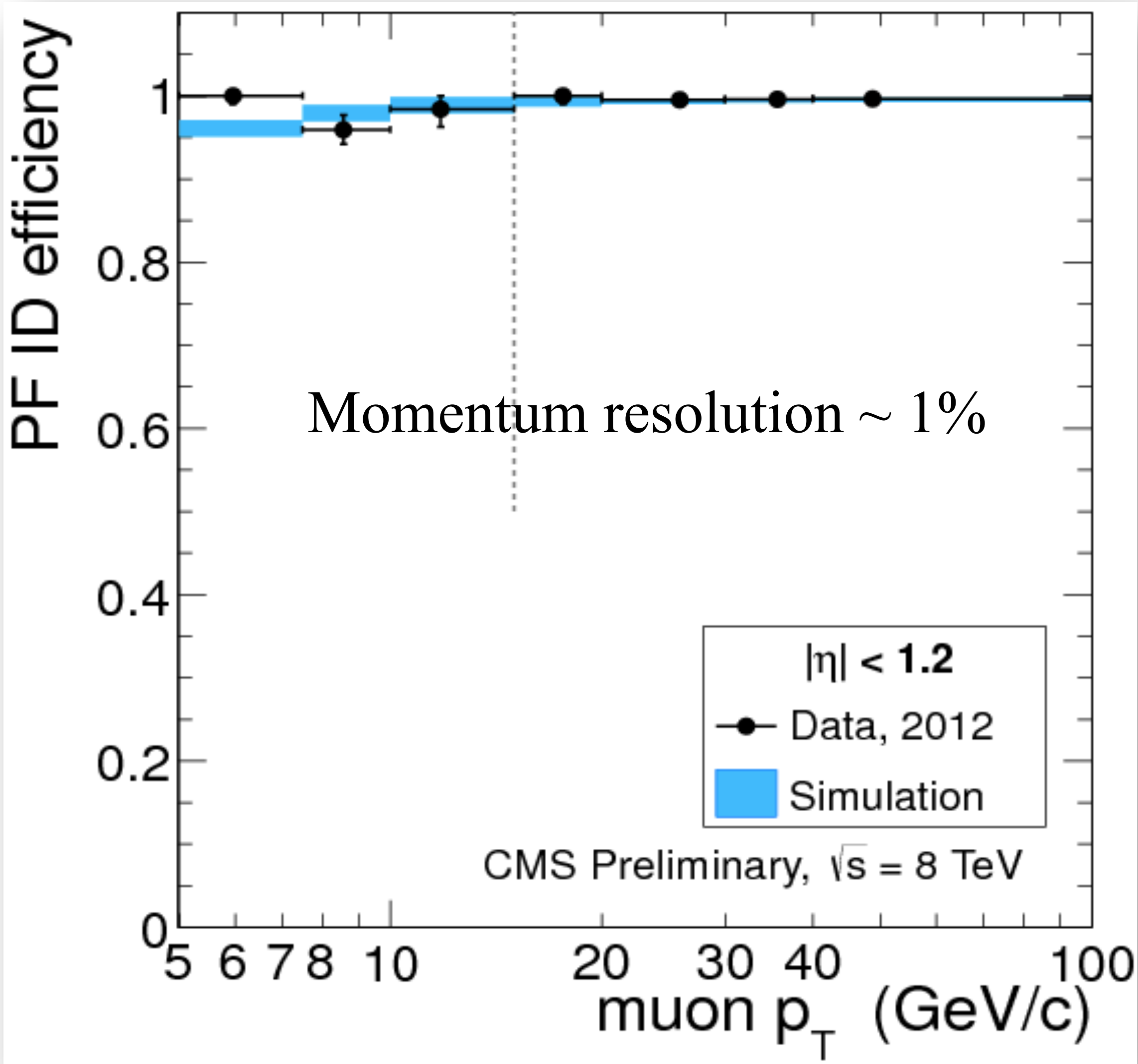
Important for pileup remediation

Muon Reconstruction & Identification

Match hit pattern and momentum in inner tracker with that in muon stations



Efficient & Clean Muon Reconstruction

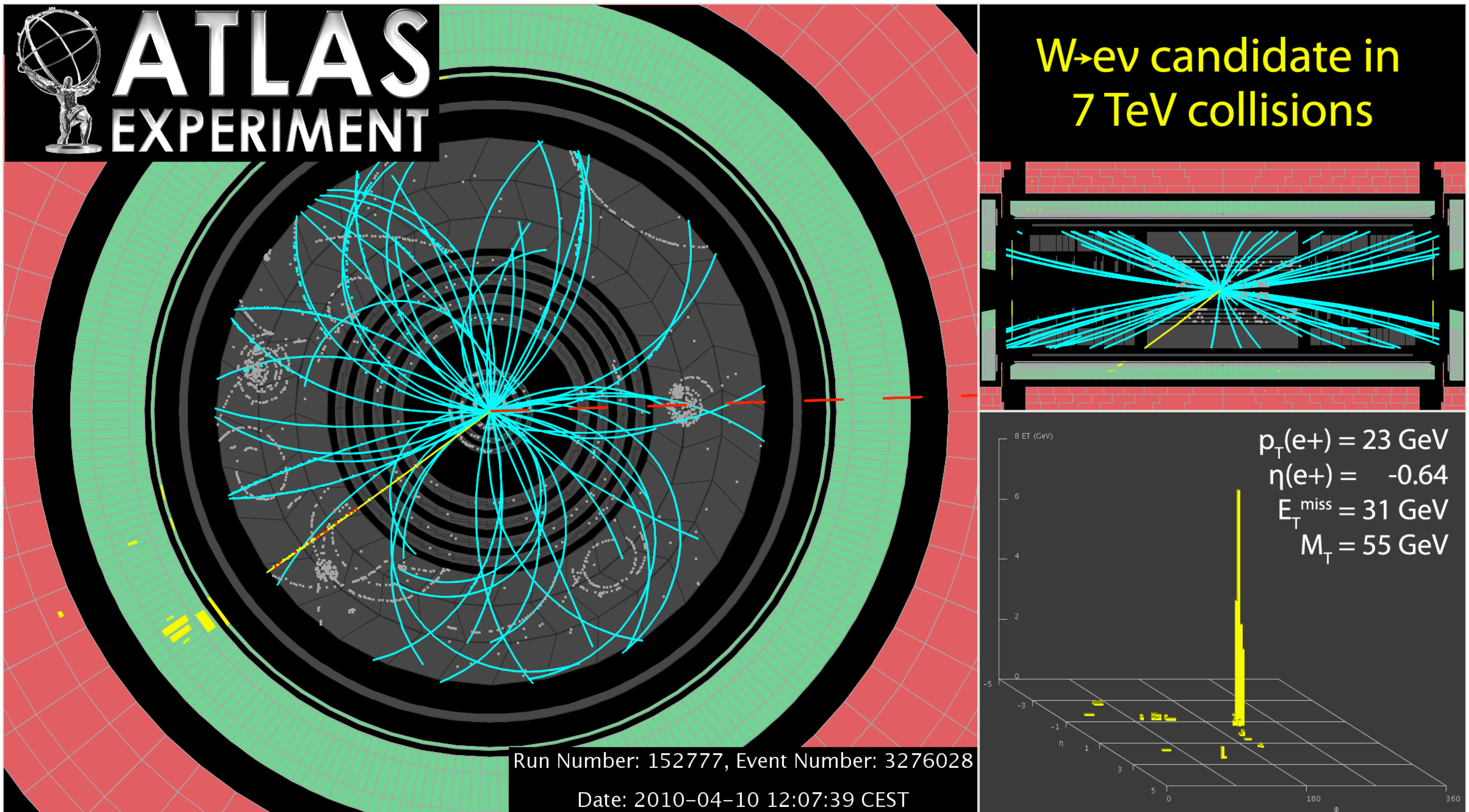


Momentum resolution ~ 1%

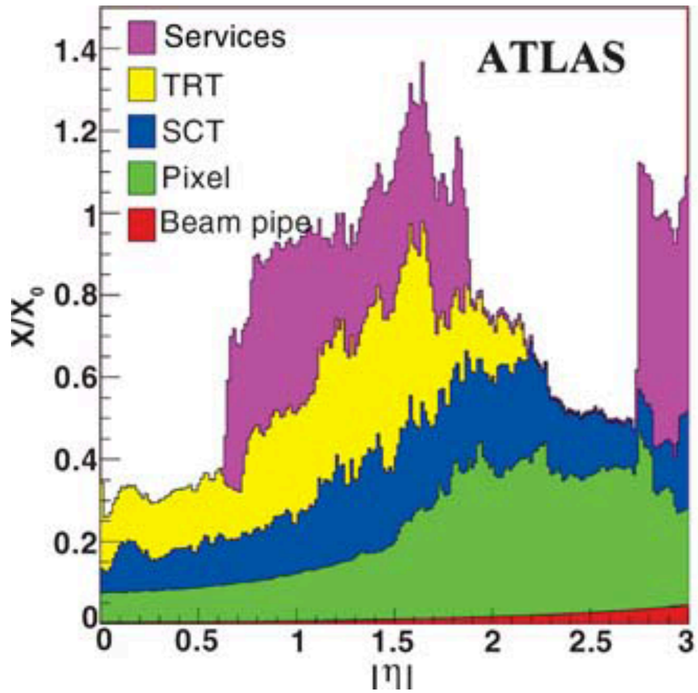
Fake rate probability : < 0.1% for π, 0.02% for p

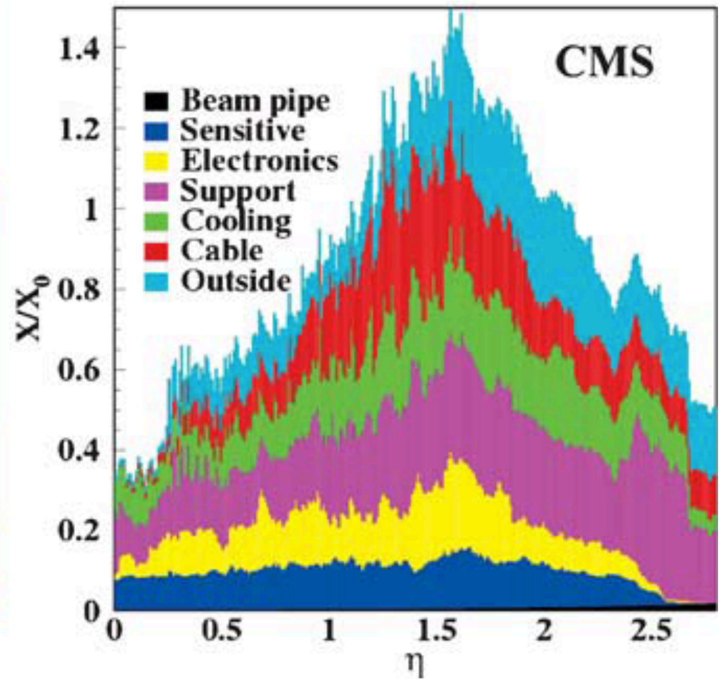
Electron & Photon Reconstruction

Match momentum in the tracker with ECAL energy at point of impact



Material Distribution: Relevant for Electron & γ Reco



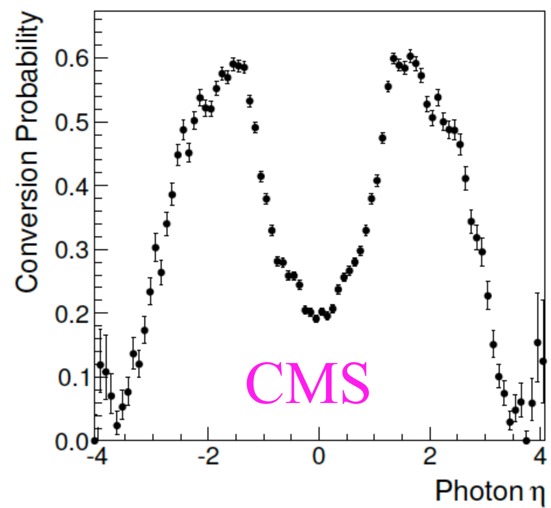


Material in front of ECAL:

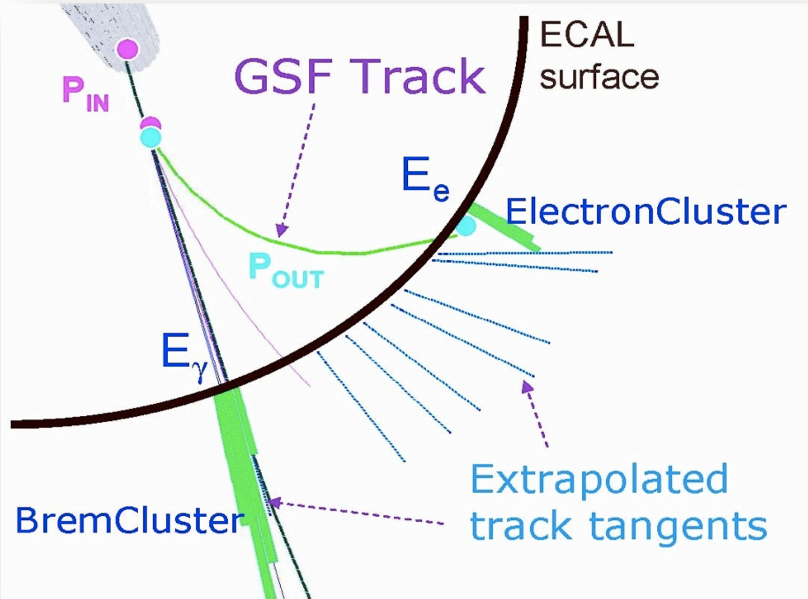
➔ Electrons bremstrahlung

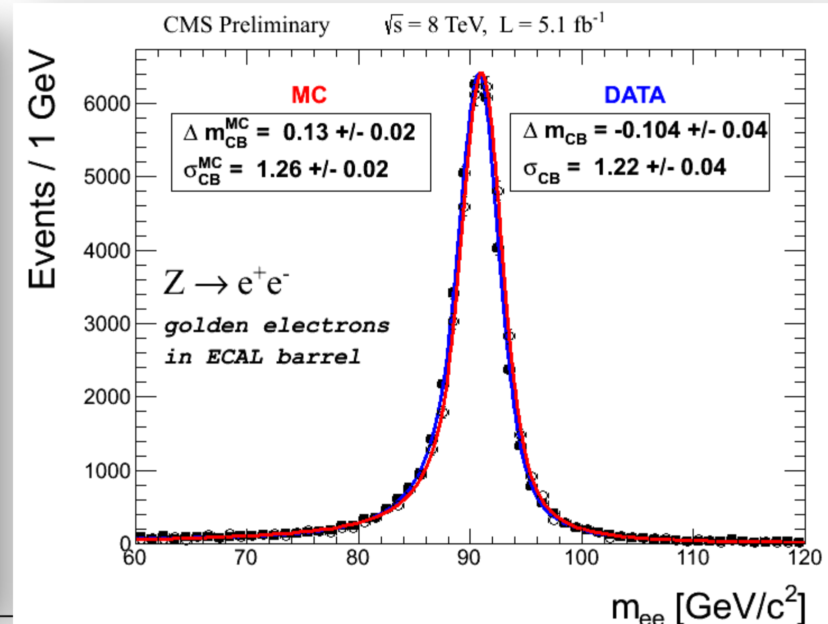
➔ Photons convert

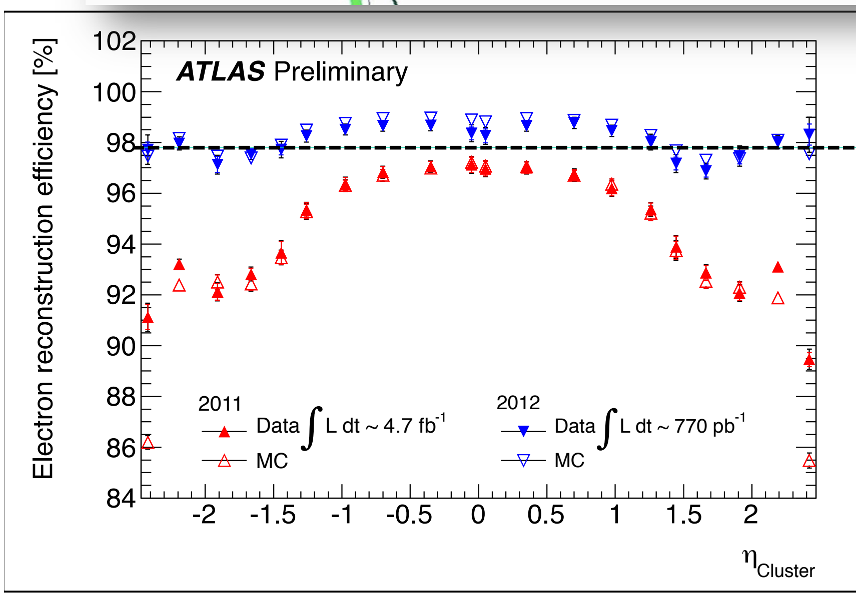
➔ degrades Energy resolution

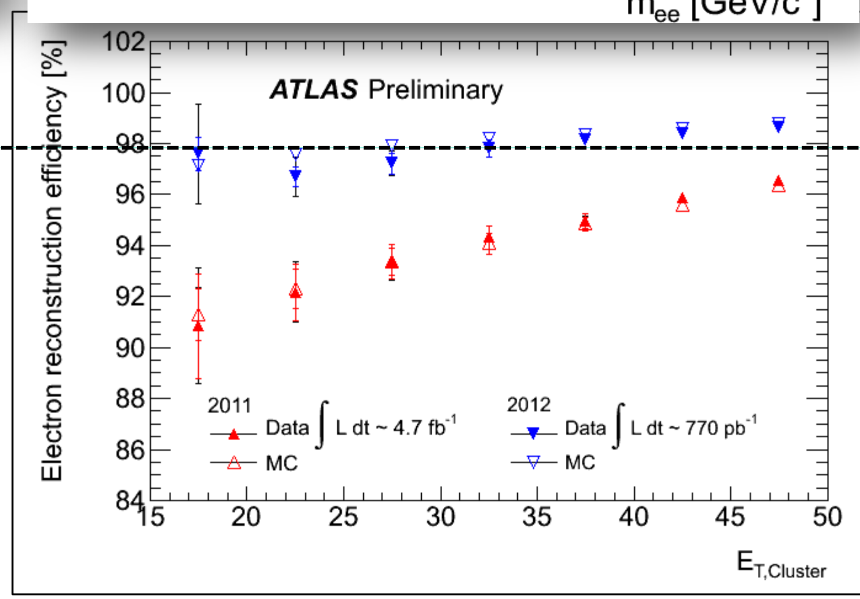


Electron & Photon Reconstruction





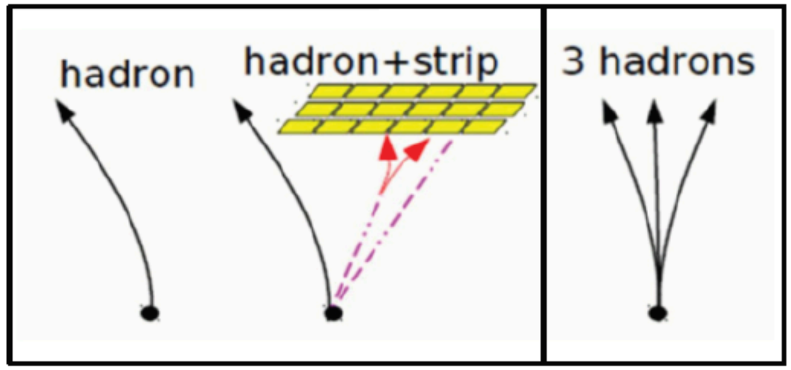




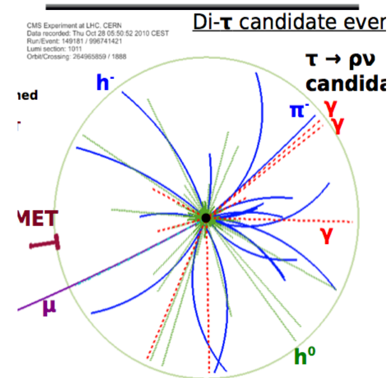
$\tau \rightarrow$ hadron Reconstruction (CMS)

Hadronic Tau identification:

- Reconstruct individual decay modes
- Charged hadrons + electromagnetic obj arranged in strips or single photons



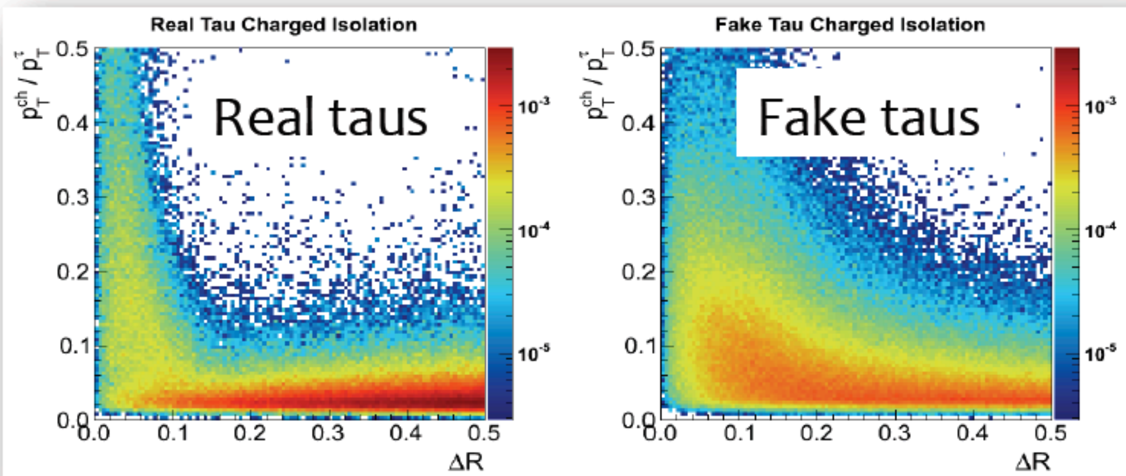
$\tau \rightarrow \pi\nu$	$\tau \rightarrow \rho\nu$	$\tau \rightarrow a_1\nu$
$\pi^{\pm}$	$\rho^{\pm} \rightarrow \pi^{\pm}\pi^{0}$	$a_1 \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ $a_1 \rightarrow \pi^{-}\pi^{+}\pi^{-}$ $a_1 \rightarrow \pi^{+}\pi^{-}\pi^{+}$

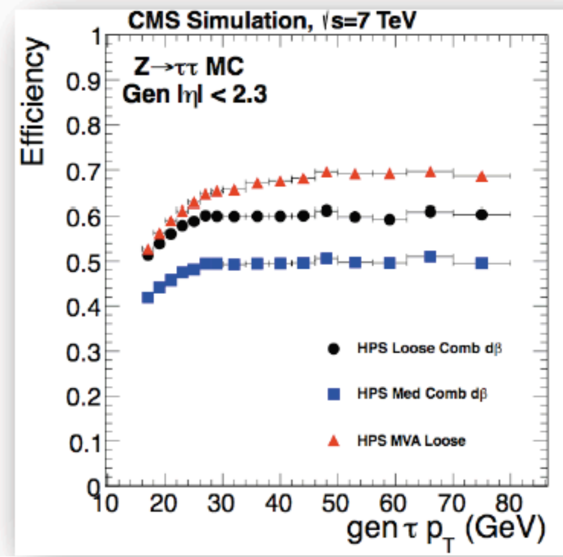


Tau Isolation:

- Multivariate discriminator using sum of energy deposits in dR rings around the tau (from 0.1 to 0.5)

eff ~62% for a fake rate of ~6%

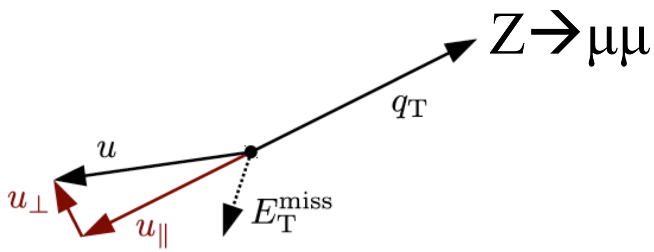




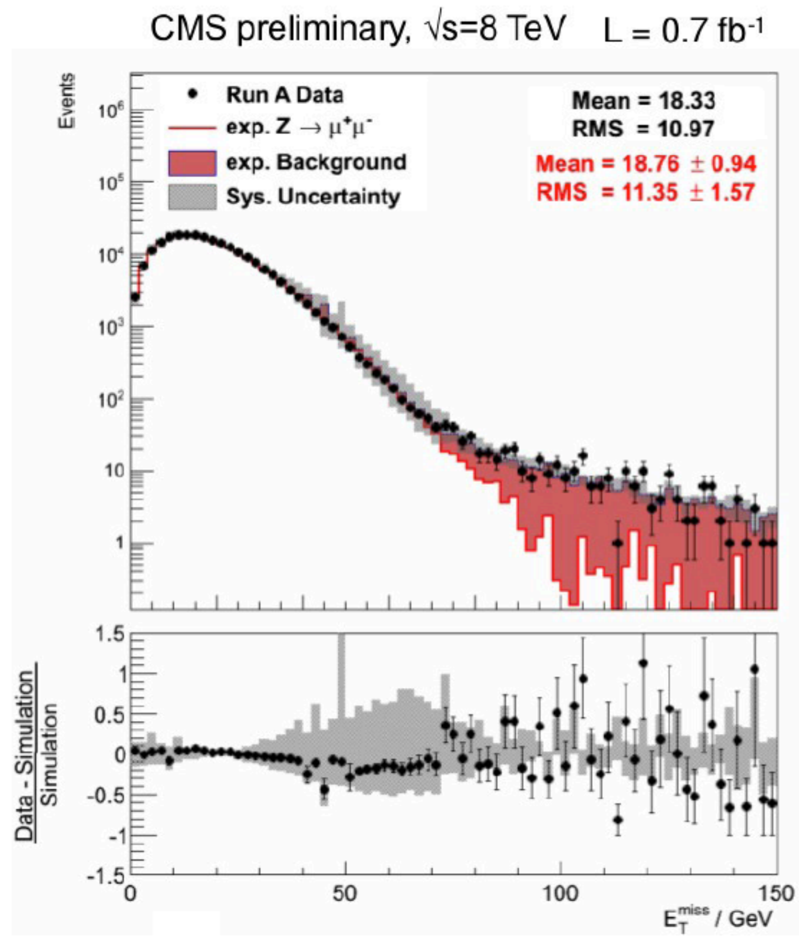
Transverse Missing Energy (M_{ET})

- Energy conservation in direction transverse to colliding p-p beams
- ➔ $MET = -\sum_i \vec{E}_{T_i}$ (Negative vector sum of all reco. particle P_T)
- Measurement not perfect, 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

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

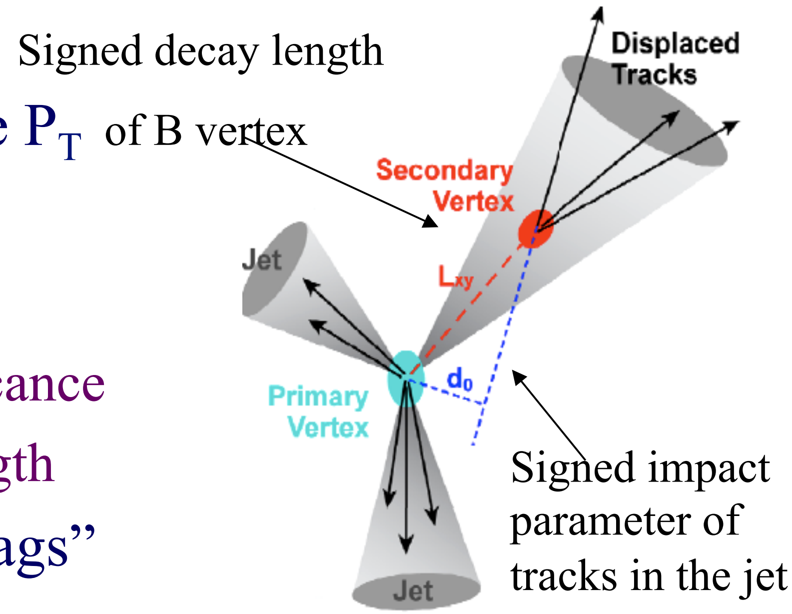


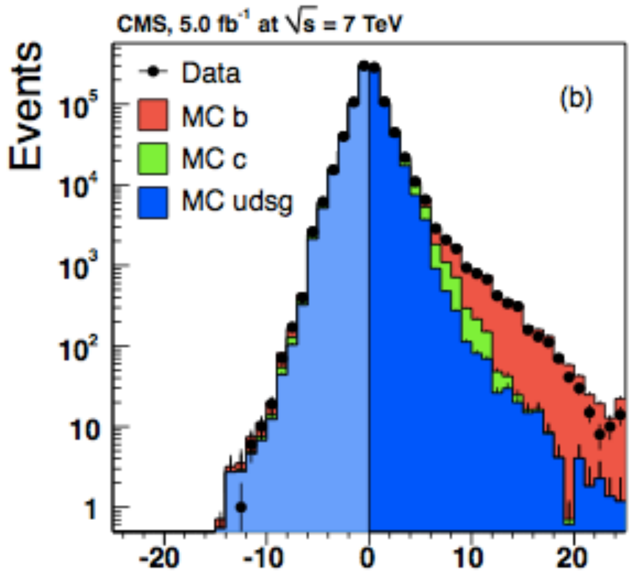
- measure for MET scale
  $\left\langle -\frac{u_\parallel}{q_{\mathrm{T}}} \right\rangle$
- measure for MET resolution
  $\sigma(-u_\parallel - q_{\mathrm{T}}), \sigma(u_\perp)$

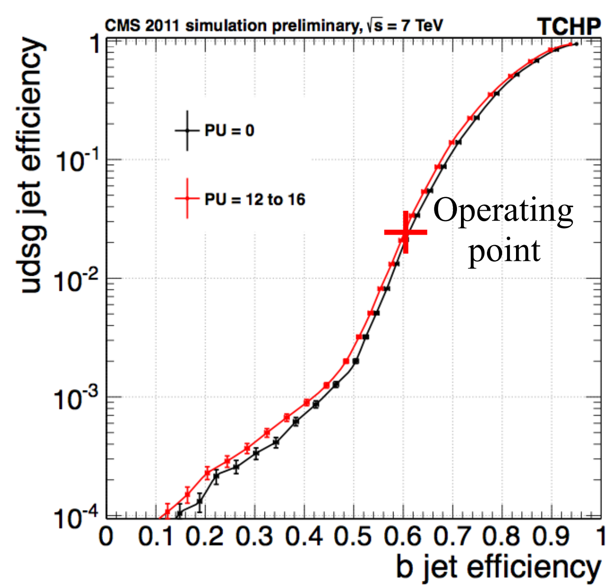


b-Jet Identification: Important For Top Reco.

- 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"





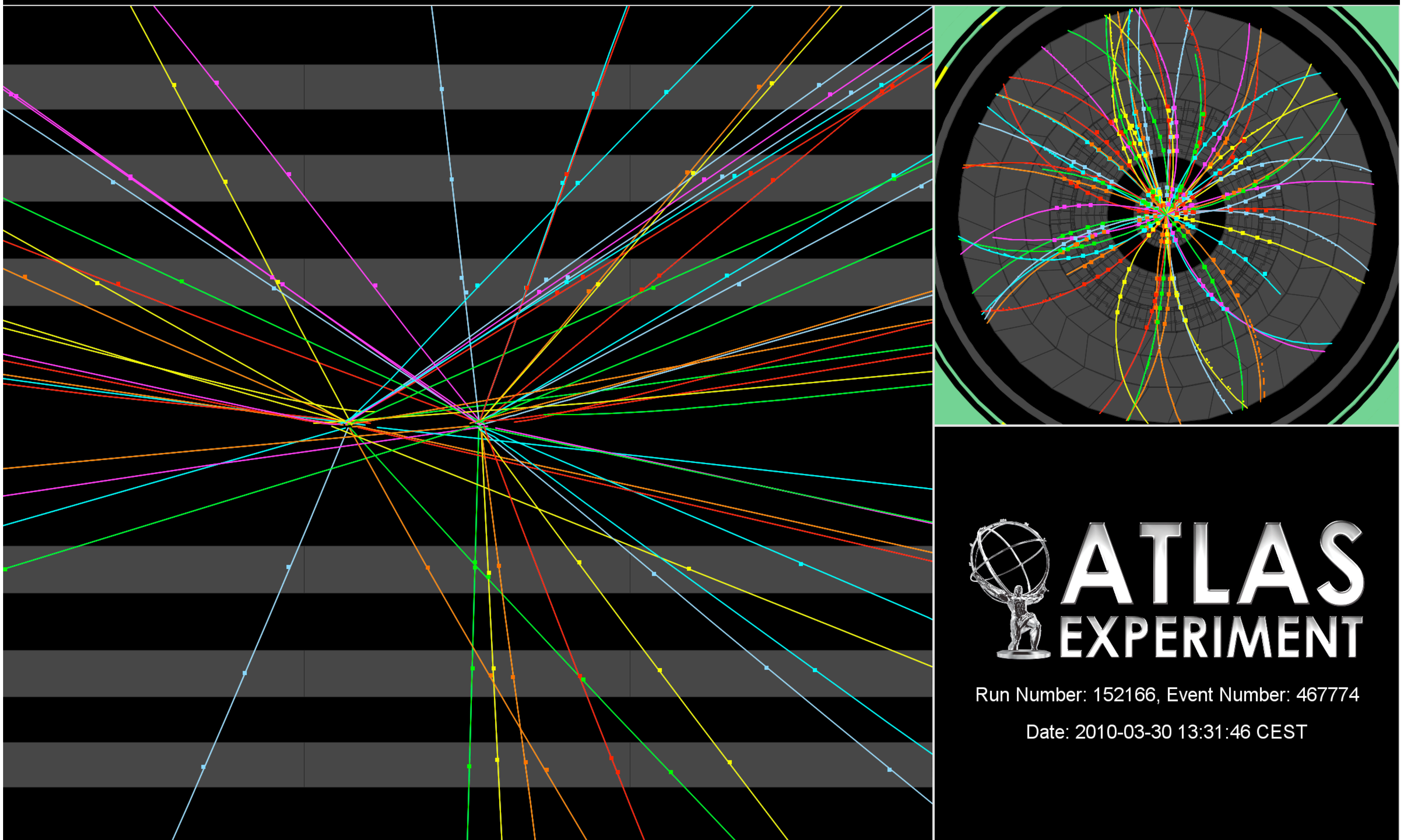


Consequence Of High Intensity Proton Collision: Pileup

- **Pileup** describes events coming from additional p-p interactions in the colliding proton bunches
- The chances of producing more than one hard scattering event per bunch crossing are pretty low
- But as the instantaneous luminosity per bunch crossing – effectively the density of protons in the interaction region where the beams overlap – goes up, the likelihood of ' soft' interaction between the constituent quarks and gluons of additional proton-proton pairs increases (in-time-pileup)
- 'out-of-time pile-up' (OOT) refers to events from successive bunch crossings 50 ns apart.
- The challenge for ATLAS & CMS is in classifying which tracks and energy deposits to attribute to which interaction
- Unlike products from a hard scatter, pileup events are **softer**

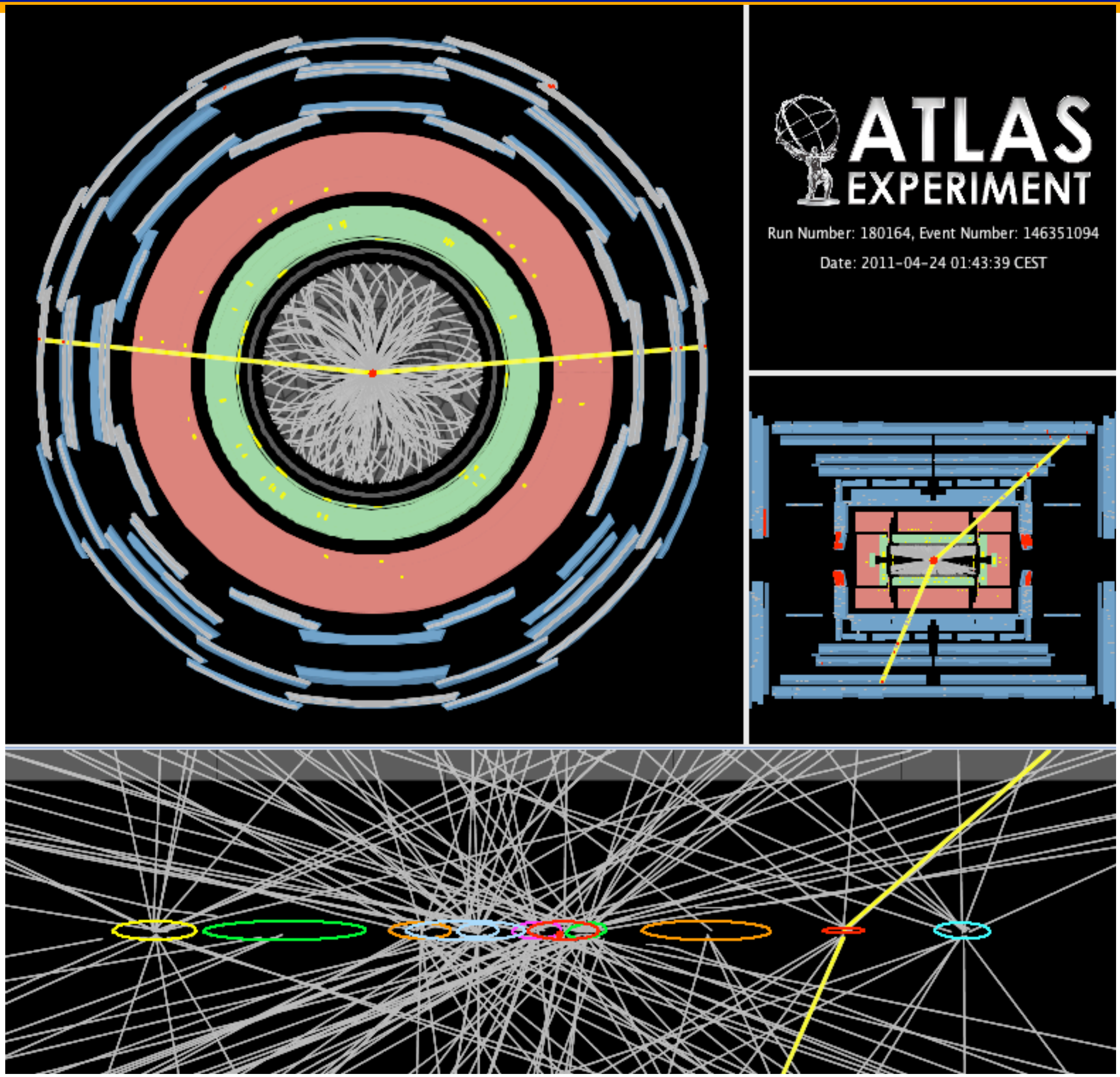
ATLAS: Pileup Evolution: 2010

Collision Event at 7 TeV with 2 Pile Up Vertices



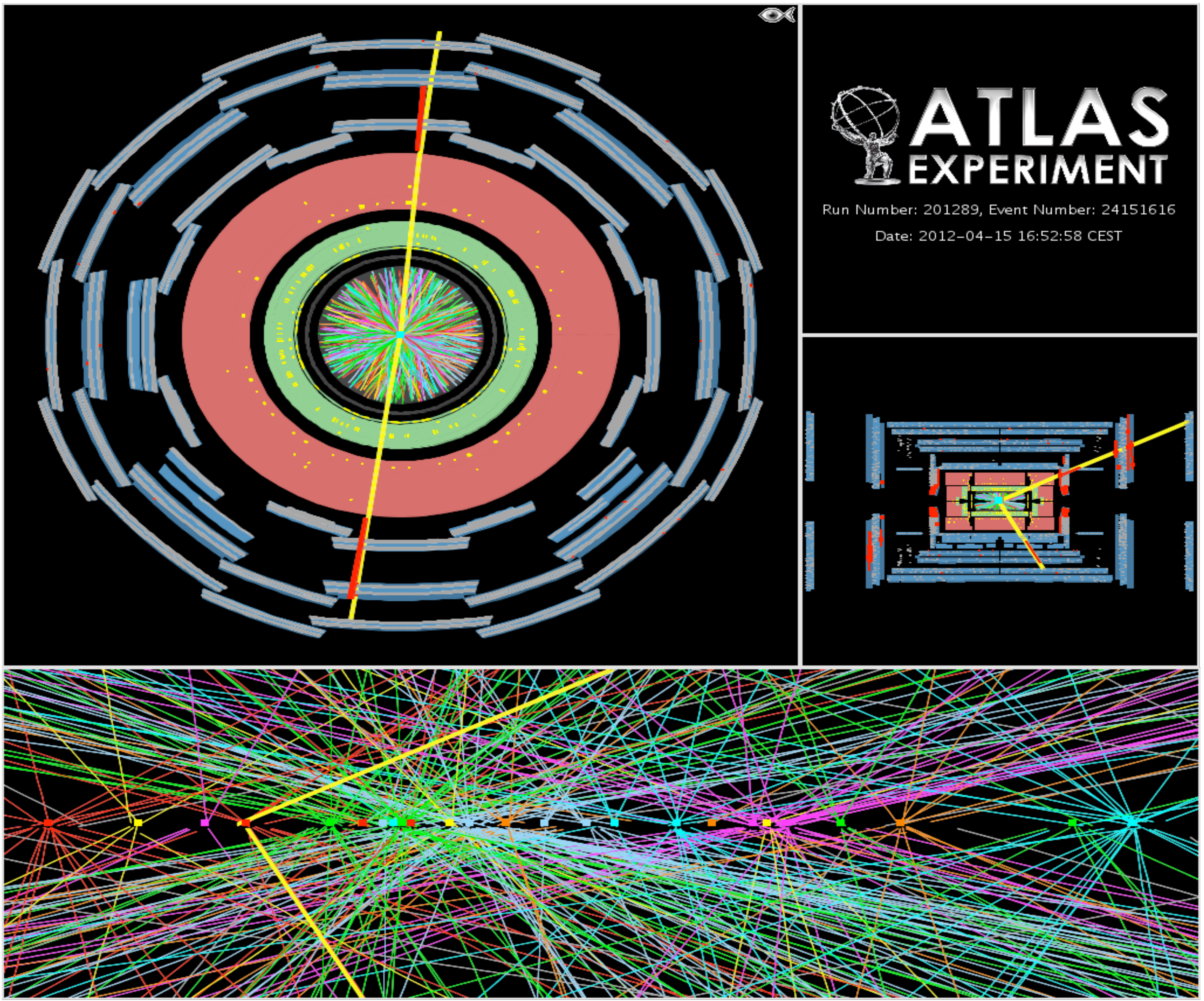
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

ATLAS: Pileup Evolution: 2011



11 vertices

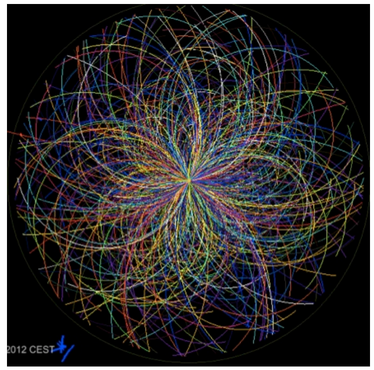
ATLAS: Pileup Evolution: 2012

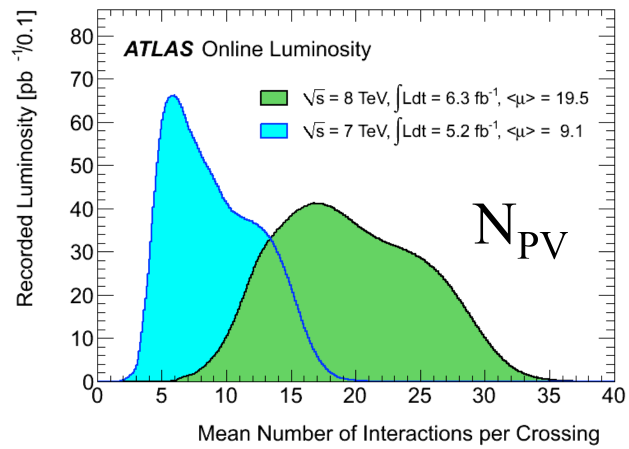


25 vertices

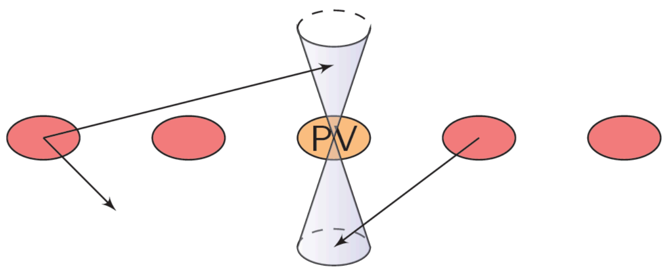
Pileup & Its Consequences

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

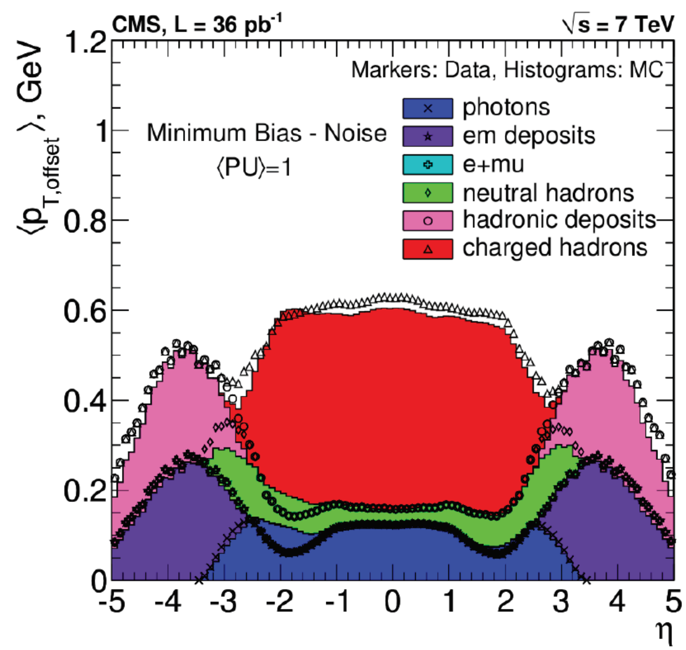




- Contaminated Jets
  - (due to additional particles)

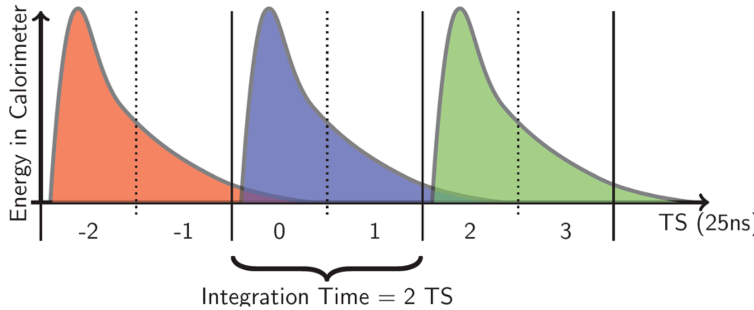


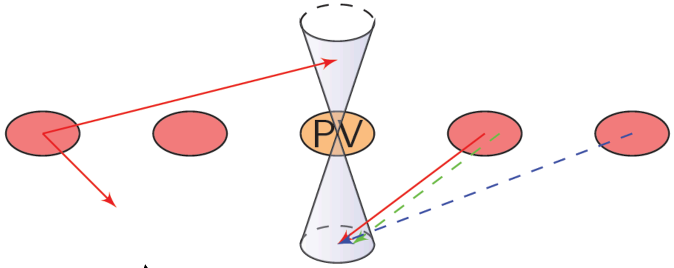
- Worsening of MET resolution
  - (more objects to sample)
- Worsening of Isolation observables
- Ambiguity in hard-scatter vertex identification, e.g. H → γγ

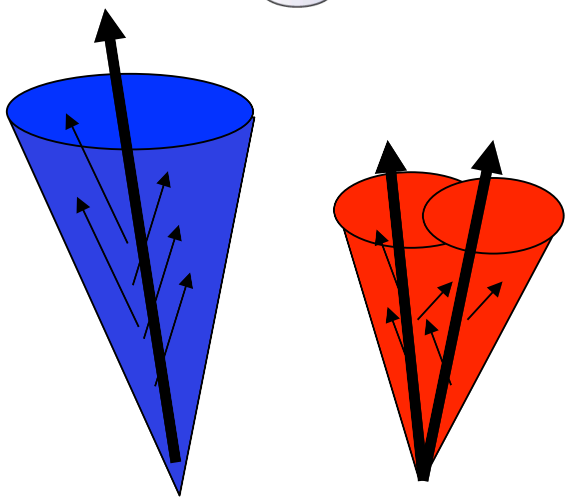


Mitigating Pileup

- Detector level mitigation: Readout over smaller time slice
  - Significantly reduces OOT pileup
- In Jet reconstruction:
- Remove from consideration charged hadrons that originate from reconstructed 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



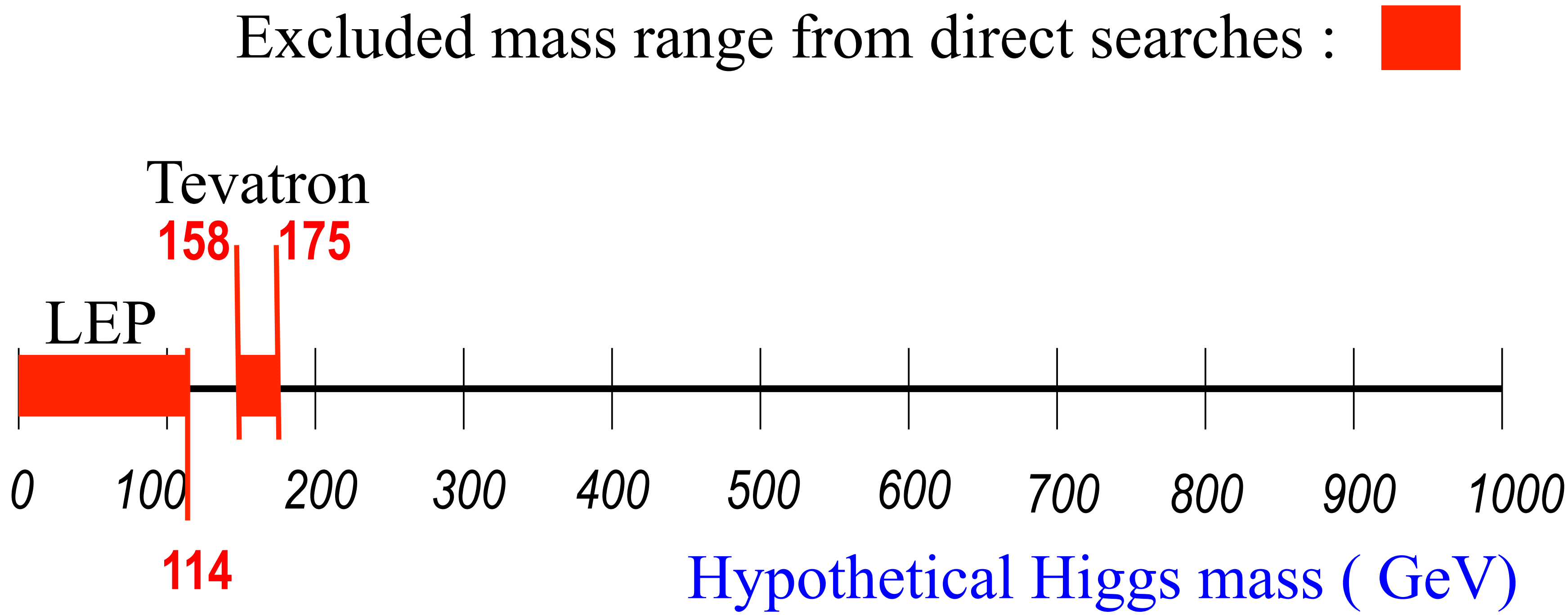




Typical jet Pileup jet

Landscape of The Hunt : Summer 2010

Excluded mass range from direct searches :



LHC designed to search for Higgs with mass >100 GeV

Higgs Search Sensitivity: By Mass & By Mode

- For a given M_H, sensitivity of search depends on
  - Production cross section
  - Its decay branching fraction into a chosen final state
  - Signal selection efficiency (including trigger)
  - Mass resolution (intrinsic and instrumental)
  - Level of SM background in the same or similar final states
- **In low mass range**:
  - $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ play a special role due to excellent mass resolution for the di-photon and 4-lepton final state
  - $H \rightarrow WW \rightarrow (l\nu)(l\nu)$ provides high sensitivity but has poor mass resolution due to presence of neutrinos in the final state
  - Sensitivity in $H \rightarrow$ bbbar and $H \rightarrow \tau\tau$ channels is reduced due to large backgrounds and poor mass resolution (jets or neutrinos)
- **In high mass range**:
  - search sensitivity dominated by $H \rightarrow WW, ZZ$ in various final states

CMS Searches

H decay	H prod	Analyses Exclusive final states	No. of channels	m_H range (GeV)	m_H resolution	Lumi (fb^{-1}) 7 TeV	8 TeV
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4	110–150	1-2%	5.1	5.3
	VBF-tag	$\gamma\gamma + (jj)_{VBF}$ (low or high m_{jj} for 8 TeV)	1 or 2	110–150	1-2%	5.1	5.3
bb	VH-tag	($\nu\nu$, ee, $\mu\mu$, $e\nu$, $\mu\nu$ with 2 b-jets)$\otimes$(low or high p_T^V)	10	110–135	10%	5.0	5.1
	$t\bar{t}$H-tag	(ℓ with 4,5,$\geq$6 jets) $\otimes$ (3,$\geq$4 b-tags); (ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-tagged jets)	9	110–140		5.0	-
$H \to \tau\tau$	0/1-jets	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$)$\times$ (low or high $p_T^{\tau\tau}$) $\times$ (0 or 1 jets)	16	110–145	20%	4.9	5.1
	VBF-tag	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$) + $(jj)_{VBF}$	4	110–145	20%	4.9	5.1
	ZH-tag	(ee, $\mu\mu$) $\times$ ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$)	8	110–160		5.0	-
	WH-tag	$\tau_h ee$, $\tau_h\mu\mu$, $\tau_h e\mu$	3	110–140		4.9	-
$WW \to \ell\nu qq$	untagged	($e\nu$, $\mu\nu$)$\otimes$($(jj)_W$ with 0 or 1 jets)	4	170–600		5.0	5.1
$WW \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\otimes$ (0 or 1 jets)	4	110–600	20%	4.9	5.1
$WW \to \ell\nu\ell\nu$	VBF-tag	$\ell\nu\ell\nu + (jj)_{VBF}$ (DF or SF dileptons for 8 TeV)	1 or 2	110–600	20%	4.9	5.1
$WW \to \ell\nu\ell\nu$	WH-tag	$3\ell 3\nu$	1	110–200		4.9	-
$WW \to \ell\nu\ell\nu$	VH-tag	$\ell\nu\ell\nu + (jj)_V$ (DF or SF dileptons)	2	118–190		4.9	-
$ZZ \to 4\ell$	inclusive	$4e$, 4μ, $2e2\mu$	3	110–600	1-2%	5.0	5.3
$ZZ \to 2\ell 2\tau$	inclusive	(ee, $\mu\mu$) $\times$ ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$)	8	200–600	10-15%	5.0	5.3
$ZZ \to 2\ell 2q$	inclusive	(ee, $\mu\mu$)$\times$($(jj)_Z$ with 0, 1, 2 b-tags)	6	130–164 200–600	3%	4.9	-
$ZZ \to 2\ell 2\nu$	untagged	((ee, $\mu\mu$) with MET) $\otimes$ (0 or 1 or 2 non-VBF jets)	6	200–600	7%	4.9	5.1
$ZZ \to 2\ell 2\nu$	VBF-tag	(ee, $\mu\mu$) with MET and $(jj)_{VBF}$	2	200–600	7%	4.9	5.1

Most analyses updated with 8 TeV data

References:https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

ATLAS Searches

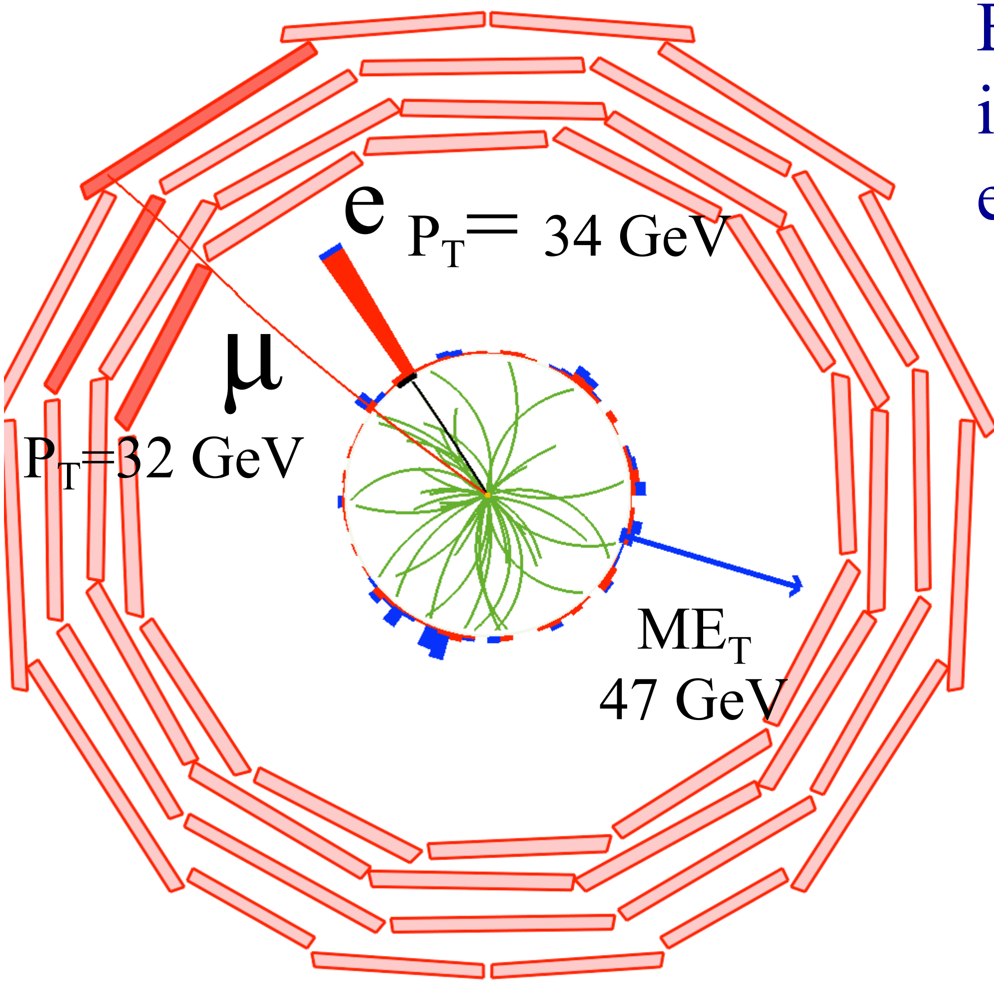
Higgs Boson Decay	Subsequent Decay	Sub-Channels	m_H Range [GeV]	$\int L\,dt$ [fb^{-1}]
		2011 $\sqrt{s}$ =7 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	110–600	4.8
	$\ell\ell\nu\nu$	$\{ee, \mu\mu\} \otimes$ {low, high pile-up}	200–280–600	4.7
	$\ell\ell qq$	{b-tagged, untagged}	200–300–600	4.7
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus$ {2-jet}	110–150	4.8
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu/\mu e, \mu\mu\} \otimes$ {0-jet, 1-jet, 2-jet} $\otimes$ {low, high pile-up}	110–200–300–600	4.7
	$\ell\nu qq'$	$\{e, \mu\} \otimes$ {0-jet, 1-jet, 2-jet}	300–600	4.7
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes$ {0-jet} $\oplus$ $\{\ell\ell\} \otimes$ {1-jet, 2-jet, VH}	110–150	4.7
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes$ {0-jet} $\otimes$ $\{E_{\mathrm{T}}^{\mathrm{miss}} < 20$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} \geq 20$ GeV$\}$ $\oplus$ $\{e, \mu\} \otimes$ {1-jet} $\oplus$ $\{\ell\} \otimes$ {2-jet}	110–150	4.7
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	{1-jet}	110–150	4.7
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\}$	110–130	4.6
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-200, \geq 200$ GeV$\}$	110–130	4.7
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-200, \geq 200$ GeV$\}$	110–130	4.7
		2012 $\sqrt{s}$ =8 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	110–600	5.8
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus$ {2-jet}	110–150	5.9
$H \to WW^{(*)}$	$e\nu\mu\nu$	$\{e\mu, \mu e\} \otimes$ {0-jet, 1-jet, 2-jet}	110–200	5.8

References: https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Description Of Search Results

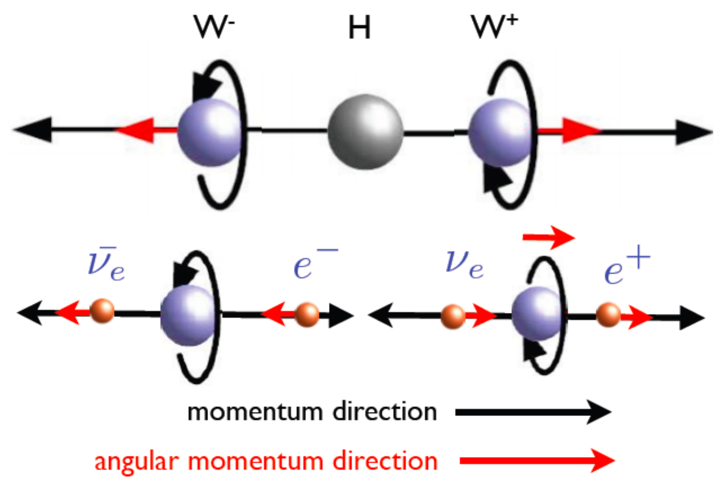
- Too many modes, too little time !
- Will focus on the important SM Higgs channels only
- ATLAS & CMS search strategies are mostly similar but differ in several details
  - Will try a pictorial and generic description
  - Will use CMS searches as an example
    - **Most comprehensive & updated set of searches**
    - **It's the experiment I know best**

H → WW$^{(*)}$ → (l ν) (l ν) : The Workhorse



Events with two energetic & isolated leptons and missing energy (due to neutrinos)

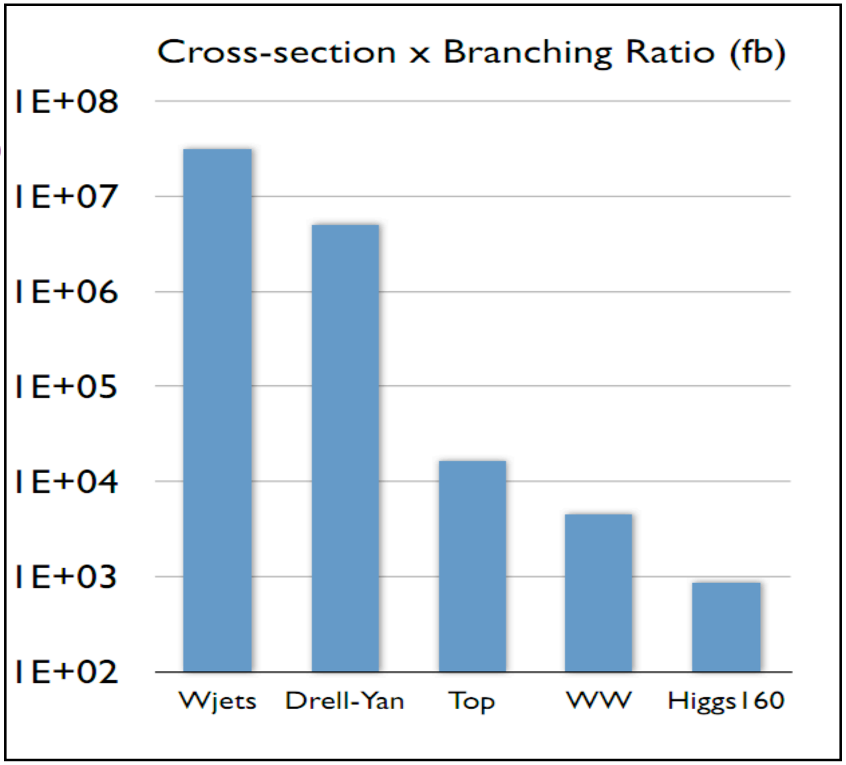
Higgs boson has spin = 0
➔ Leptons spatially aligned



Poor Higgs mass resolution (20%) due to escaping neutrinos
➔ Counting experiment, look for excess over backgrounds

Backgrounds In H → WW → (l ν) (l ν) Search

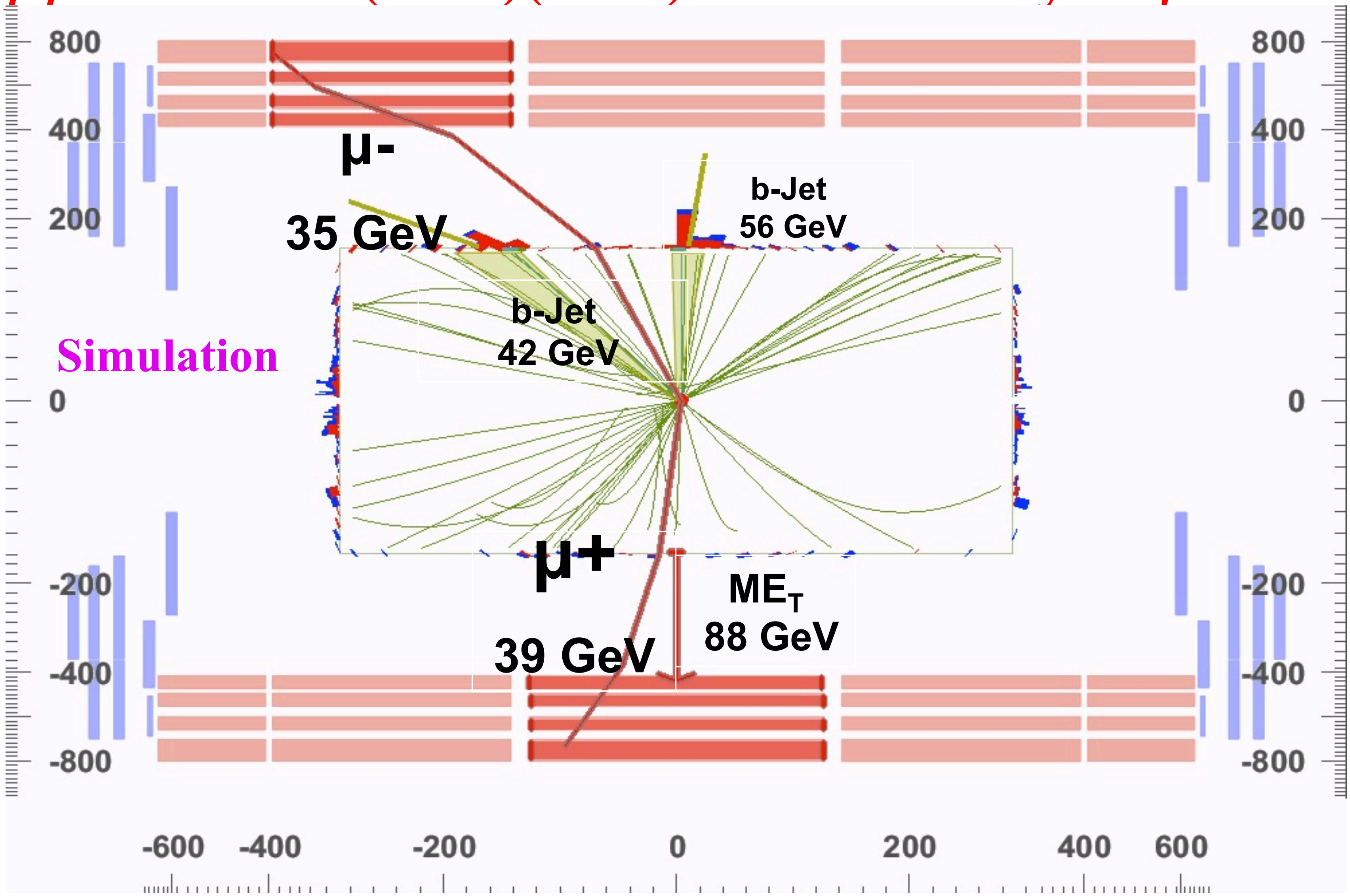
- Reducible backgrounds:
  - (DY) Z → ll + (jets faking MET)
  - W→ l ν + (jets faking lepton)
  - tW and ttbar production
  - W+ $\gamma^{(*)}$
  - WZ→ 3l + MET
- Irreducible background:
  - pp → WW → (l ν) (l ν)
    - **Non-resonant production**



- **Challenge is to kill off as much background & measure residual contributions using data-driven techniques and control samples**

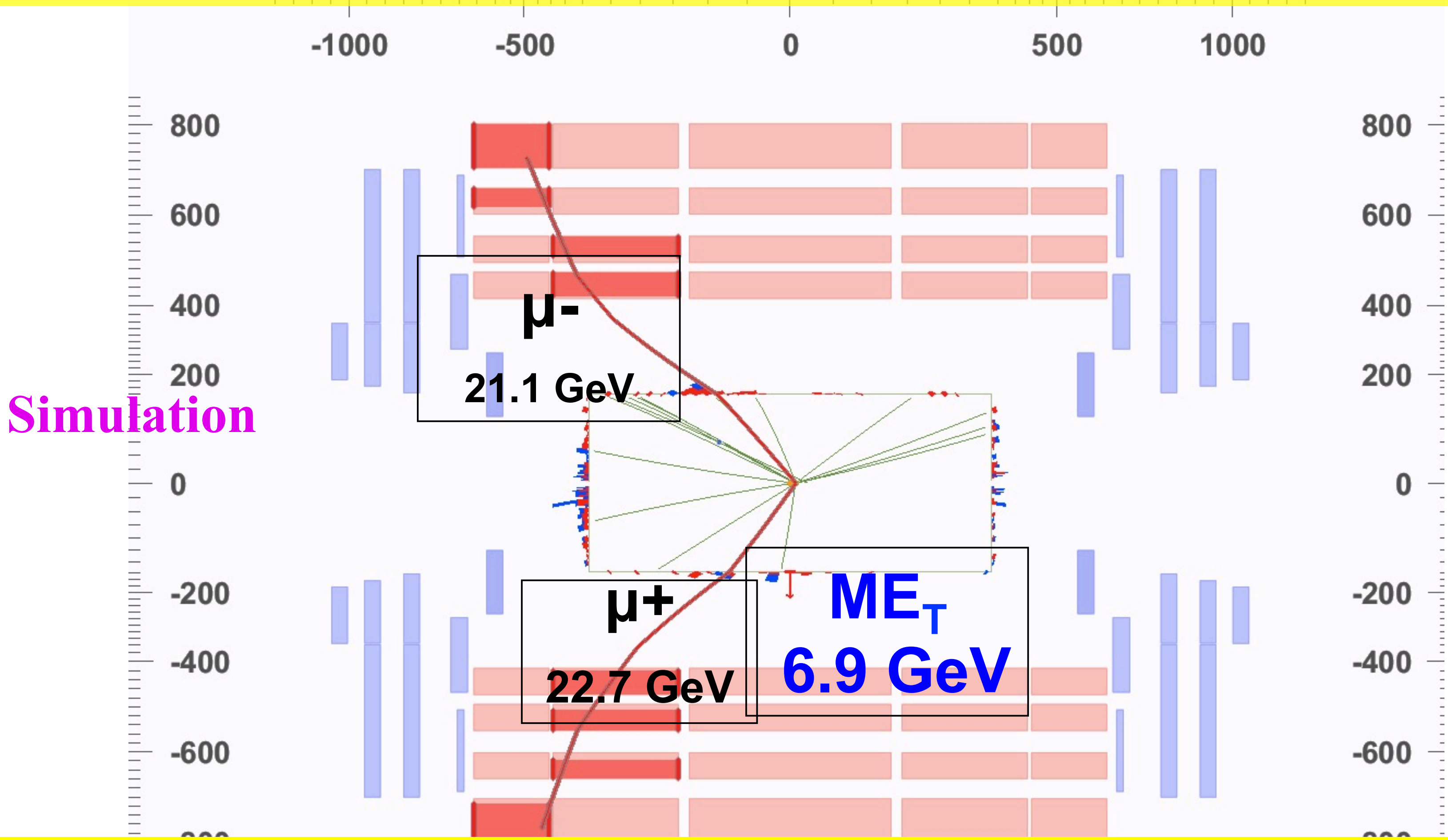
Backgrounds Faking Signature Of Higgs Boson

$pp \rightarrow t\bar{t} \rightarrow (bW)(\bar{b}W)$: "Killed" by b-jet veto



Backgrounds Faking Signature Of Higgs Boson

DY (Z + jets) "killed" by requiring missing energy in event

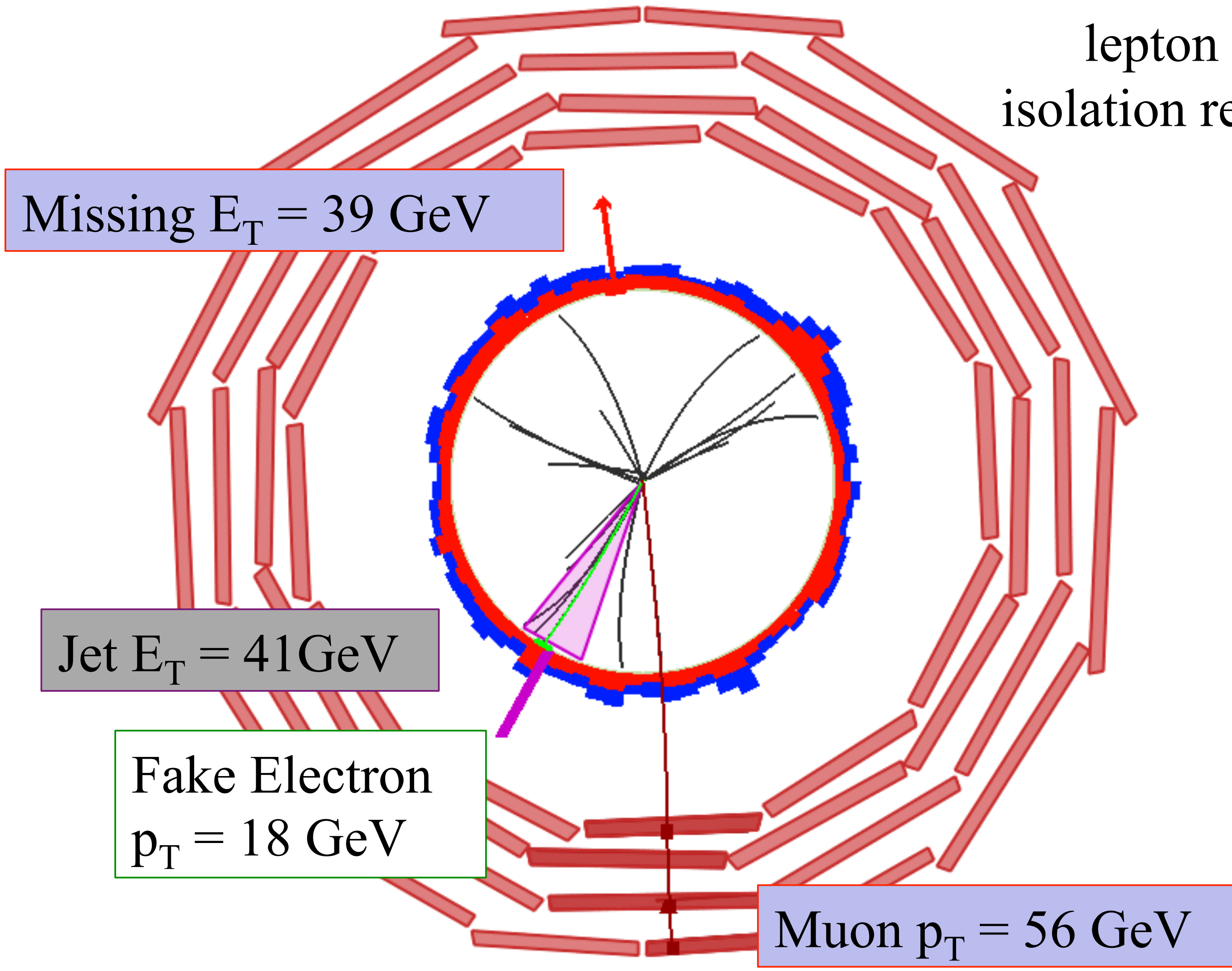


Pile up worsens MET resolution substantially, making it hard to eliminate this background➔ Reduced sensitivity for ee,μμ channels

W + Jets Background Faking H→ WW Signature

Simulation

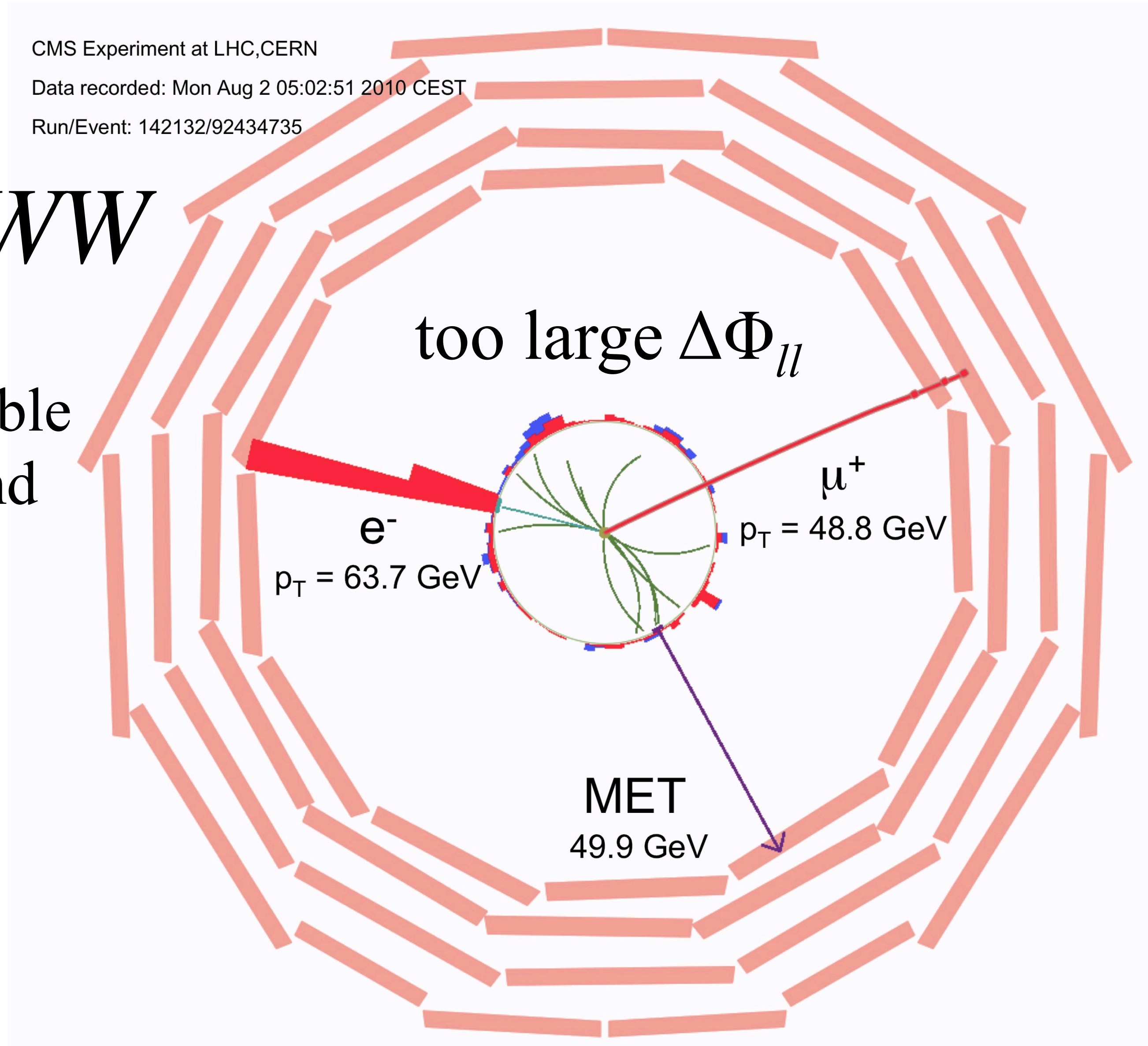
Removed by tight lepton ID and isolation requirement



Backgrounds Faking Signature Of Higgs Boson

$$pp \to WW$$

An irreducible background



Background Alleviation Strategy

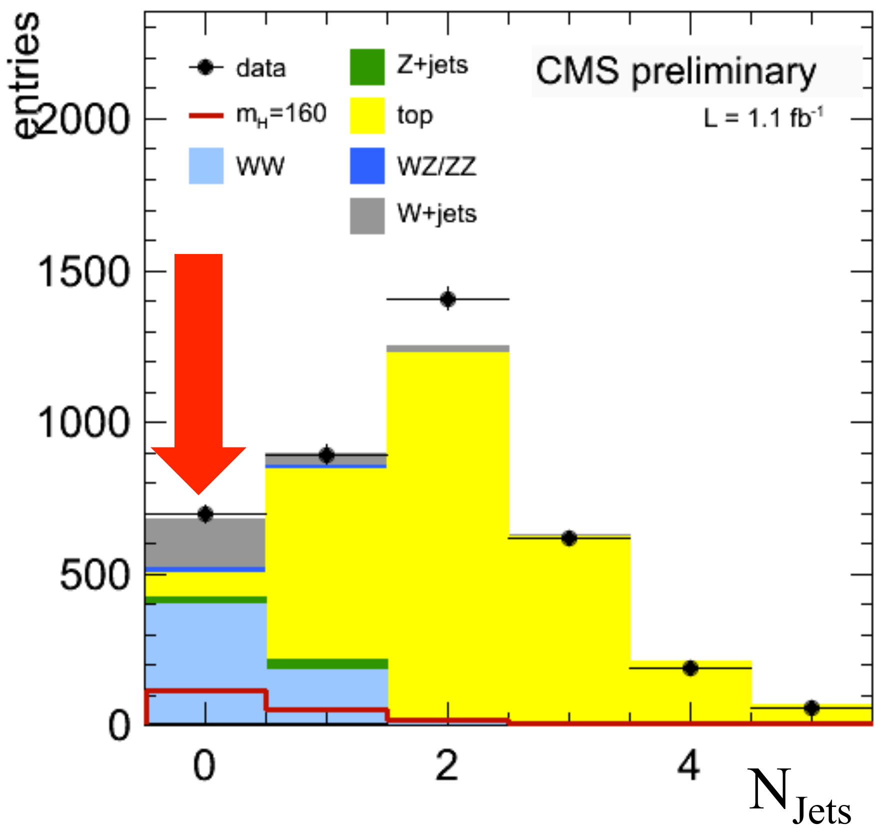
decreasing cross section (@ 7 TeV)

process	characteristic	rejection
W+jets (31000 pb)	lepton + fake lepton	2 well identified and isolated leptons
Z+jets (5000 pb)	Z peak, no real E_T^{miss}	• proj E^T_{miss} > 40 GeV(ee,μμ), 20 GeV (eμ) • $\|m_{ll}-m_Z\|$<15 GeV (ee, μμ), m_{ll}>12 GeV (eμ)
tt (158 pb), tW (11 pb)	additional (b-)jets	• classify events in 0-,1-jet • anti b-tagging
W,Z + γ (165 pb)	electron from γ coversion	• conversion veto
WW (43 pb)	non resonant	• small $\Delta\varphi_{ll}$
WZ (18 pb), ZZ (6 pb)	Z peak	• $\|m_{ll}-m_Z\|$<15 GeV (ee, μμ), m_{ll}>12 GeV (eμ)

relative importance after selection depends on m_H

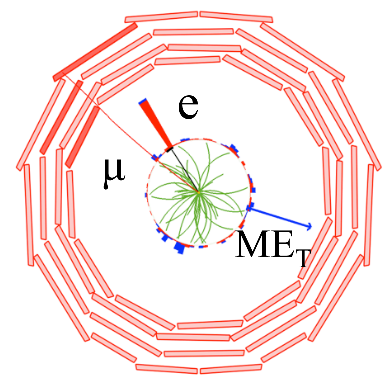
Event Catagorization By # Of Accompanying Jets

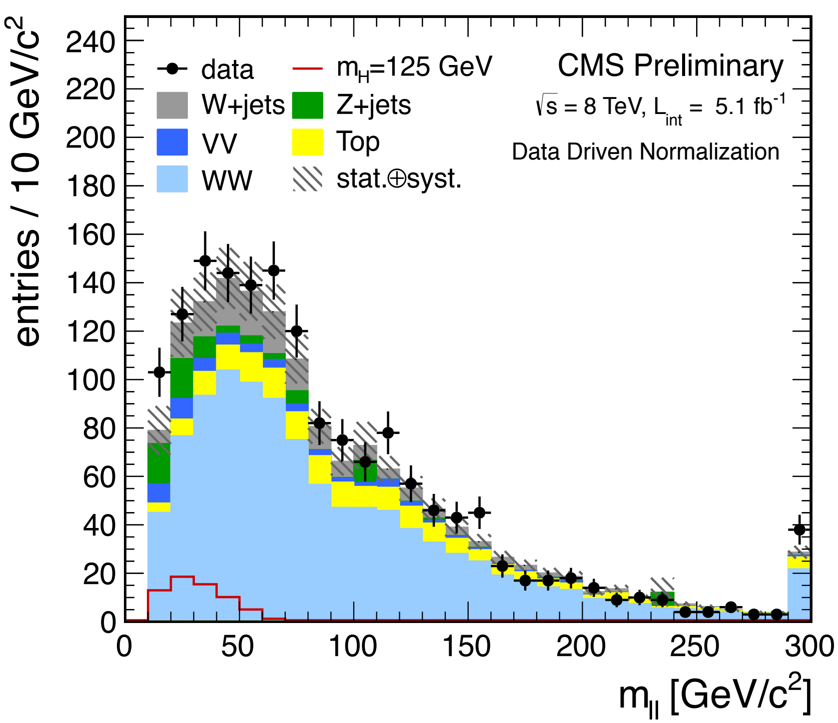
- Catagorize events by jet multiplicity
  - $P_T > 30$ GeV, $|\eta| < 4.7$
- 0-jet: Most sensitive category
  - For $m_H < 130$ GeV:
    - **W+jets, DY backgrounds dominant**
  - eμ final state quite pure
- 1-jet: dominated by tt+tW
- 2-jets: specific selections to isolate VBF production
  - $\Delta\eta(j_1-j_2)>3.5$, $m_{j1,j2}>450$ GeV
  - No central jets
  - **Dominated by ttbar background**

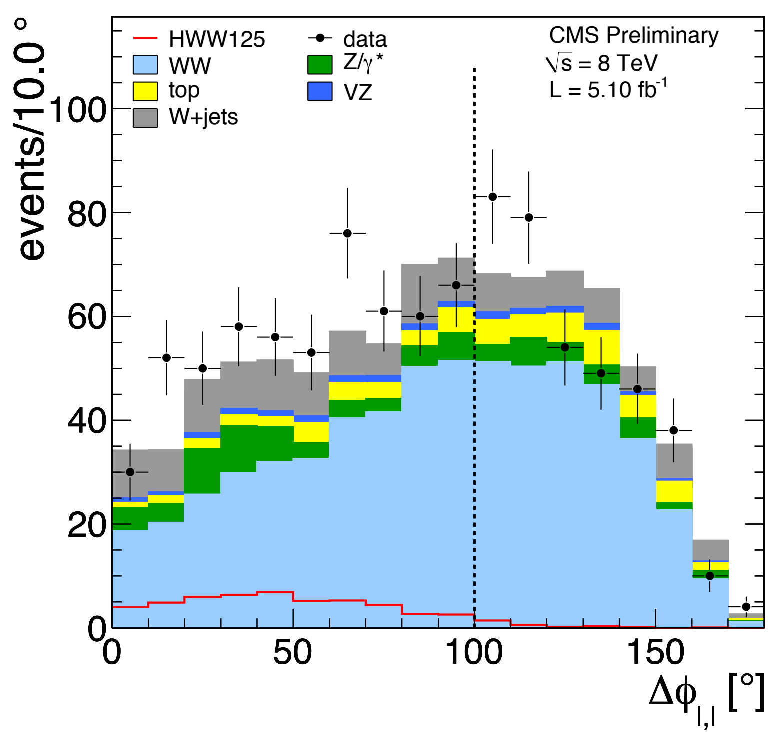


Key Kinematic Observables

- P_T of leading and sub-leading leptons
- Azimuthal angle difference ($\Delta\Phi_{ll}$)
- $P_T(ll)$
- Dilepton invariant mass (M_{ll})
- $M_T = \sqrt{2 p_T^{\ell\ell} E_T^{\text{miss}} (1 - \cos \Delta\phi_{E_T^{\text{miss}} \ell\ell})}$

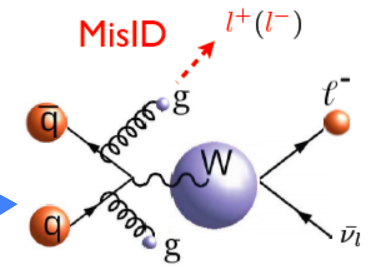




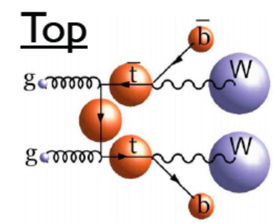


Background Estimates

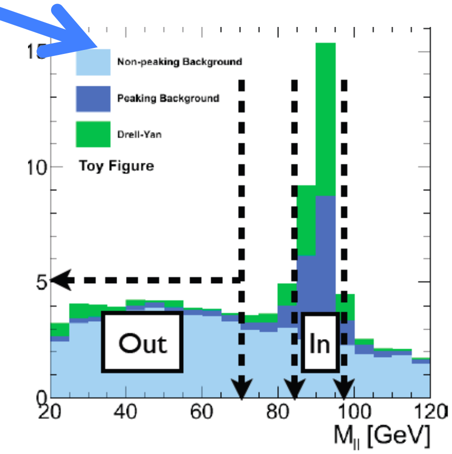
- Most background estimates are obtained from control samples established in data
  - W+jet background estimated from dilepton control samples enriched in misidentified leptons
  - ttbar background from samples enriched with identified b-jets
  - Z+jets background by extrapolating from a narrow Z mass window
  - WW background
    - **from signal free region (m_{ll}>100 GeV for m_H < 200 GeV)**
    - **For high mass H, no signal-free region → taken from simulation)**
- Systematic uncertainties on these estimates vary from 20-60 %



Systematic Uncertainty ~ 36%



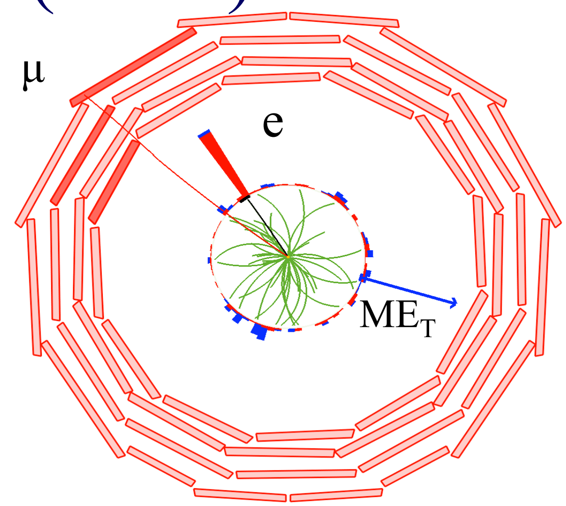
Systematic Uncertainty ~ 20%*

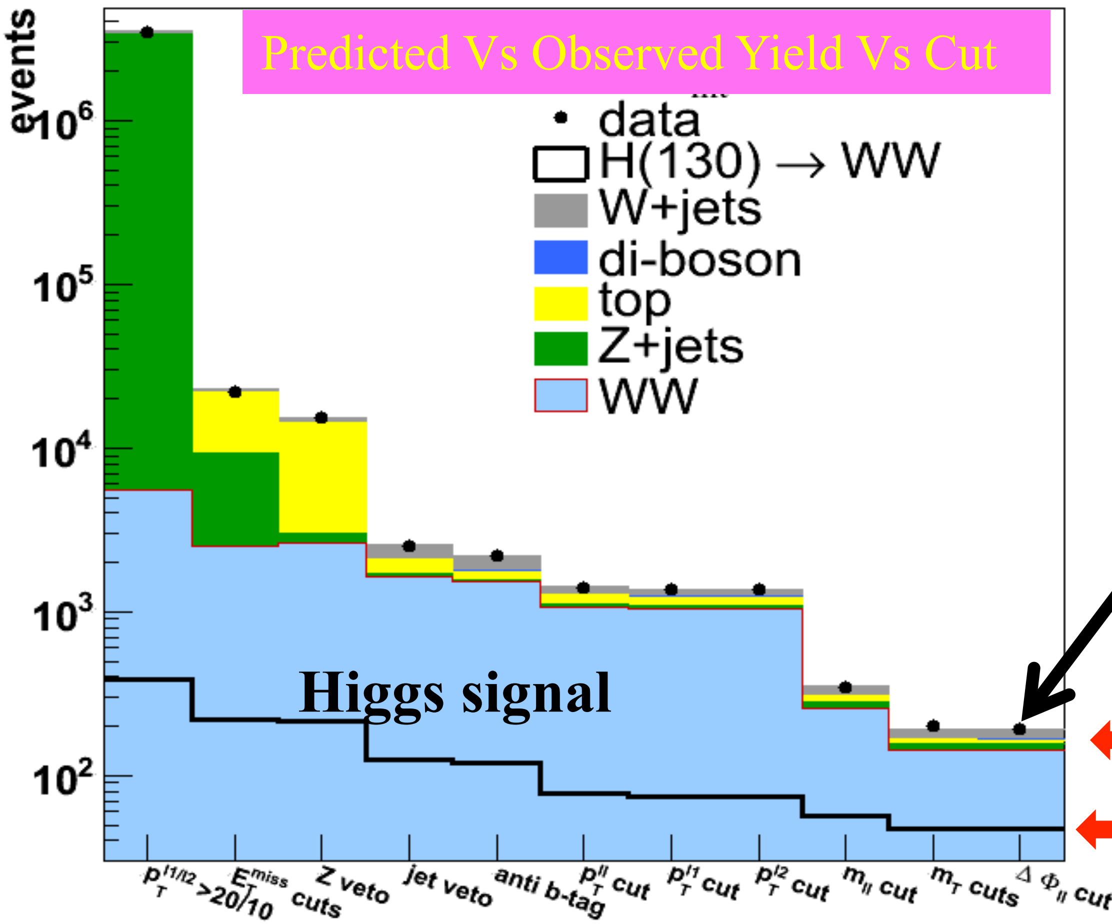


Systematic Uncertainty
~ 30-60% depending on jet category and final analysis selection

Digging Out Tiny Signals Over Large Backgrounds

H → WW → (e υ) (μυ) : 7 TeV (5 fb^{-1}) data





Data

~200 background events

expect~40 Higgs events for M_H=130 GeV

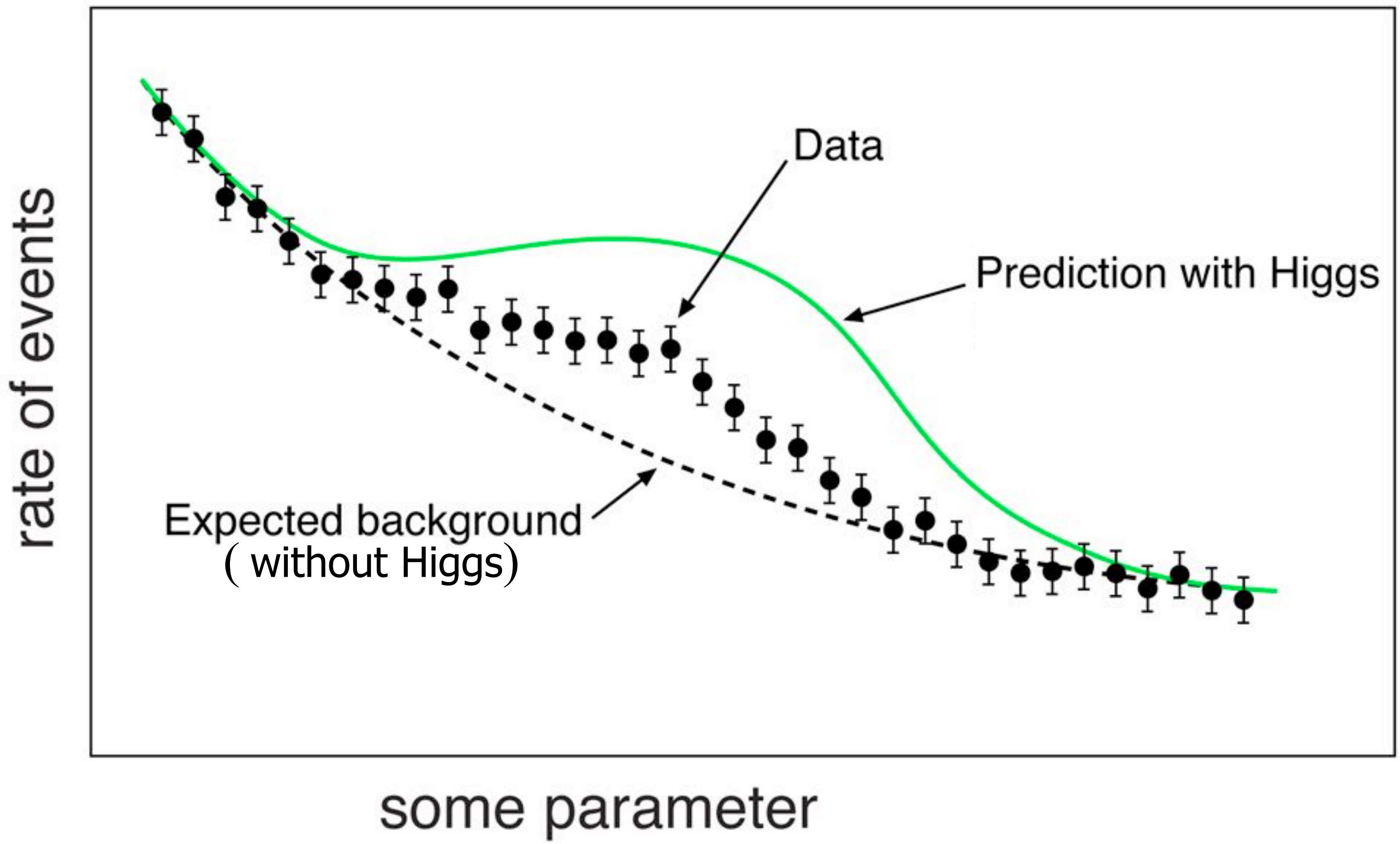
Compare Background Prediction & Data Yields Vs Higgs Mass Hypothesis

CMS 2012 : 5.1 fb^{-1} , Cut-based Analysis, 0-Jet category

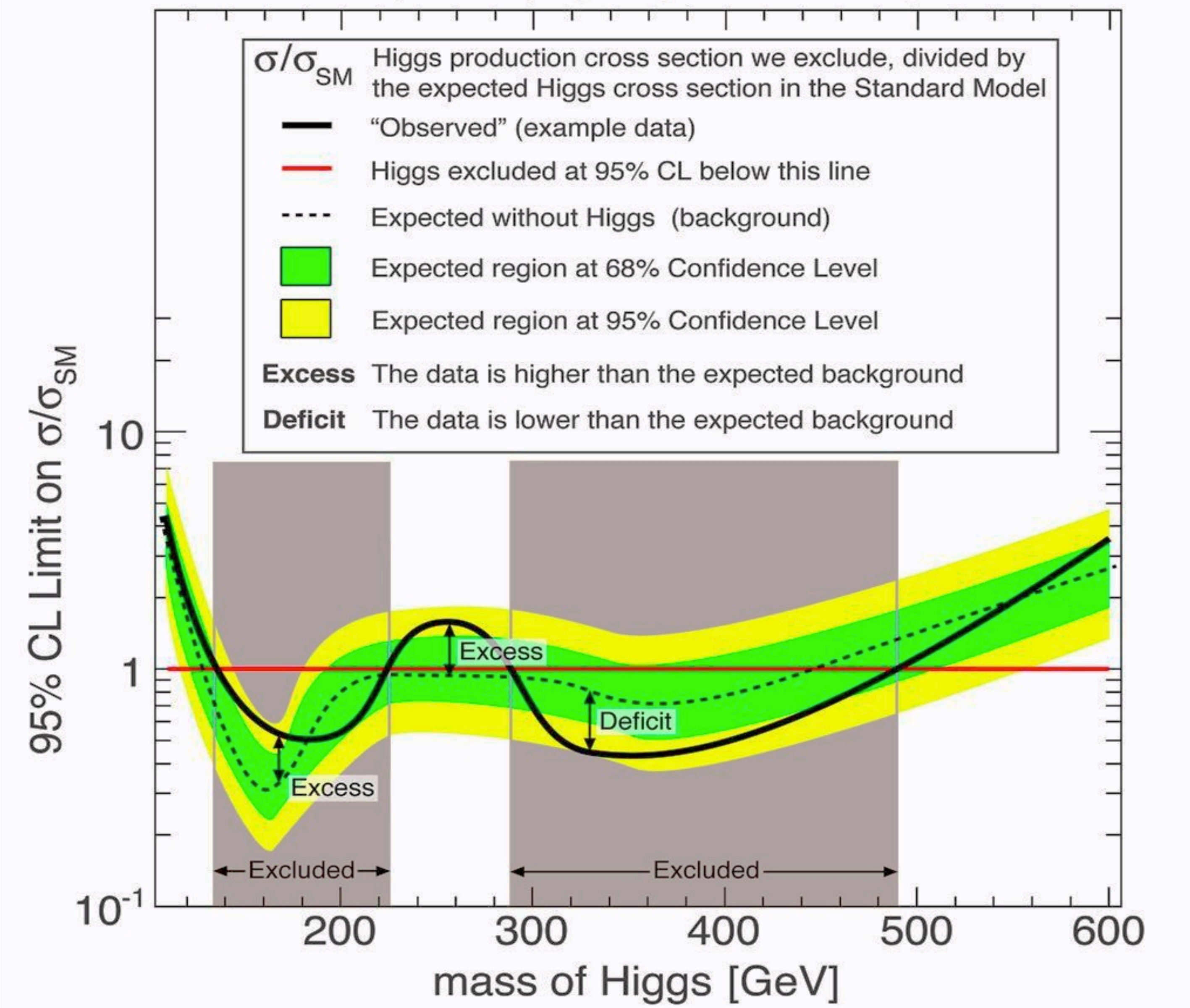
m_H	H $\to W^+W^-$	pp $\to W^+W^-$	WZ + ZZ $+Z/\gamma^* \to \ell^+\ell^-$	Top	W + jets	$W\gamma^{(*)}$	all bkg.	data
		0-jet category $e\mu$ final state						
125	23.9 ± 5.2	87.6 ± 9.5	2.2 ± 0.2	9.3 ± 2.7	19.1 ± 7.2	6.0 ± 2.3	124.2 ± 12.4	158
130	35.3 ± 7.6	96.8 ± 10.5	2.5 ± 0.3	10.1 ± 2.8	20.7 ± 7.8	6.3 ± 2.4	136.3 ± 13.6	169
160	98.3 ± 21.2	53.6 ± 5.9	1.2 ± 0.1	6.3 ± 1.7	2.5 ± 1.3	0.2 ± 0.1	63.9 ± 6.3	79
400	16.6 ± 4.8	50.5 ± 5.8	1.5 ± 0.2	26.1 ± 5.7	4.5 ± 2.0	0.7 ± 0.5	83.3 ± 8.4	92
		0-jet category $ee/\mu\mu$ final state						
125	14.9 ± 3.3	60.4 ± 6.7	37.7 ± 12.5	1.9 ± 0.5	10.8 ± 4.3	4.6 ± 2.5	115.5 ± 15.0	123
130	23.5 ± 5.1	67.4 ± 7.5	41.3 ± 15.9	2.3 ± 0.6	11.0 ± 4.3	4.8 ± 2.5	126.8 ± 18.3	134
160	86.0 ± 18.7	44.5 ± 4.9	11.3 ± 13.4	3.8 ± 0.9	1.3 ± 1.1	0.4 ± 0.3	61.4 ± 14.4	92
400	12.3 ± 3.6	37.1 ± 4.3	5.7 ± 1.3	20.0 ± 4.7	3.4 ± 1.9	13.6 ± 4.8	79.9 ± 8.3	55

Mild excess over background is observed at low masses

Quantifying Excesses & Deficits: Cartoon



Quantifying Higgs Search Result: An Illustration

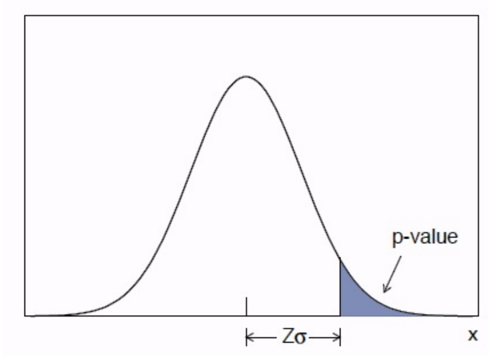


Quantifying Observed Excesses : Local p-Value

- Excess can be due to a real signal or a fluctuation of background w.r.t estimated
  - *p-value*: chance of background fluctuating as high as or higher than what is observed in data at a particular mass

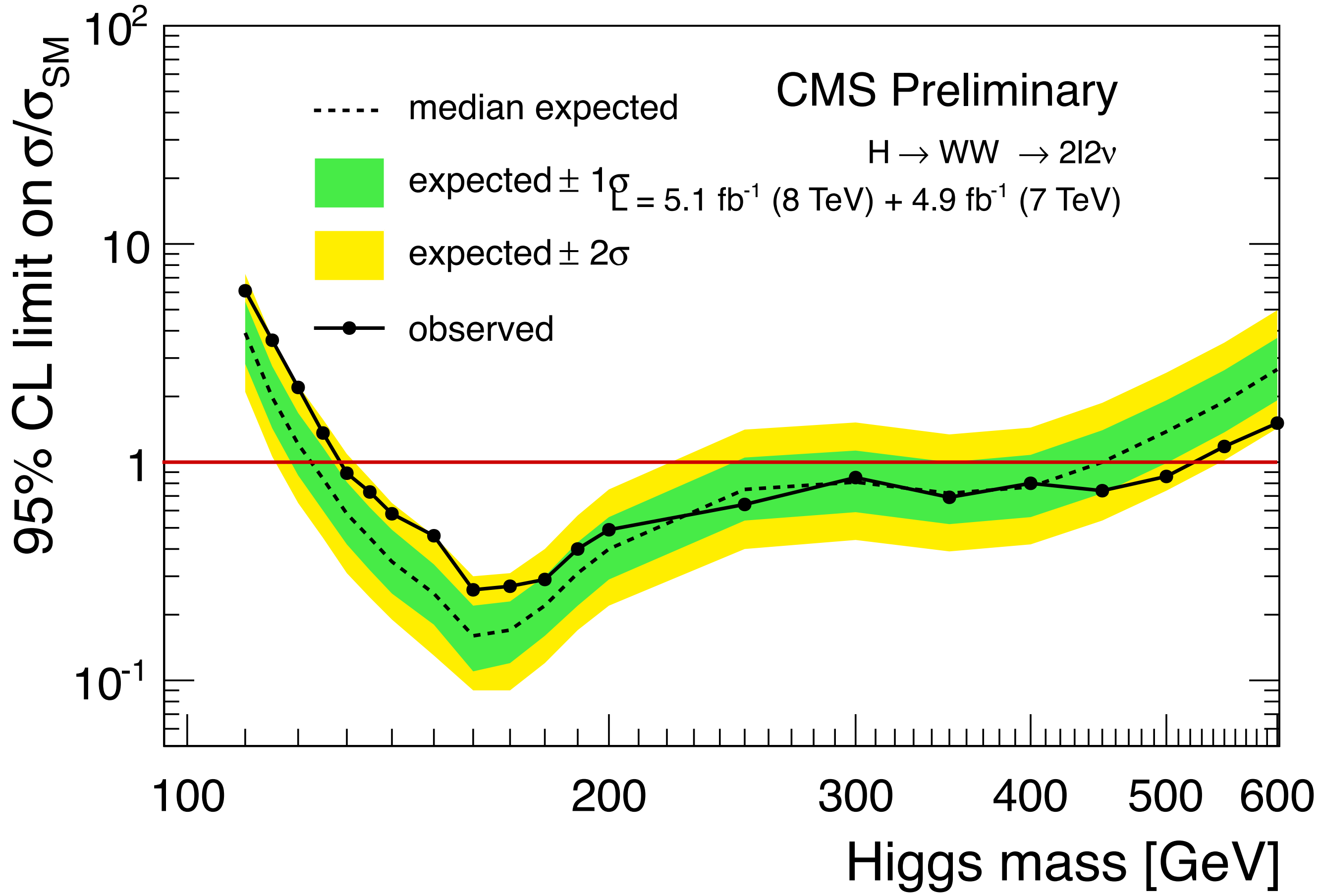
$$p-value = \text{Prob}\ (\text{n} \geq n_{\text{observed}} \mid \text{background})$$

  - *Local Significance* (Zσ): related to *p-value* via the tail probability of normal distribution



- *p-value* does not tell us whether the excess is consistent with the expected SM Higgs boson rate. So we also report the best-fit value of the signal strength modifier $\mu = \sigma/\sigma_{SM}$

H → WW$^{(*)}$ → (l ν) (l ν) Results (CMS)



Expected Exclusion@ 95% CL: 122-450 GeV

Observed Exclusion@95% CL: 129-520 GeV

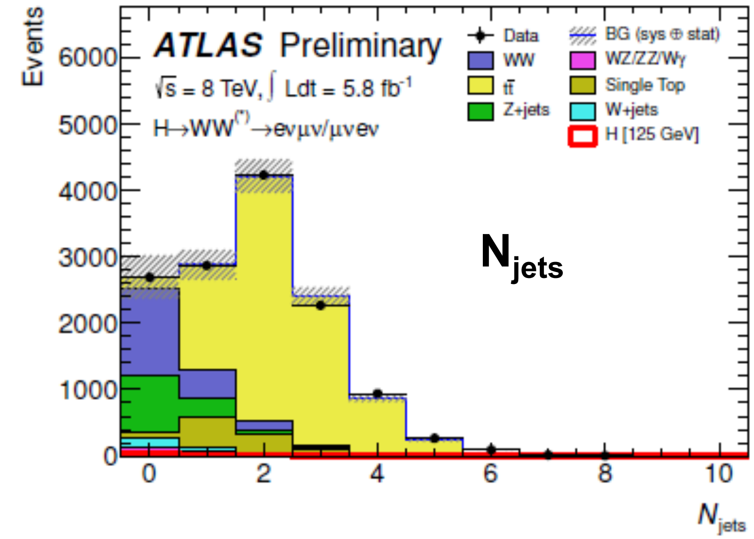
A small excess makes limits weaker than expected

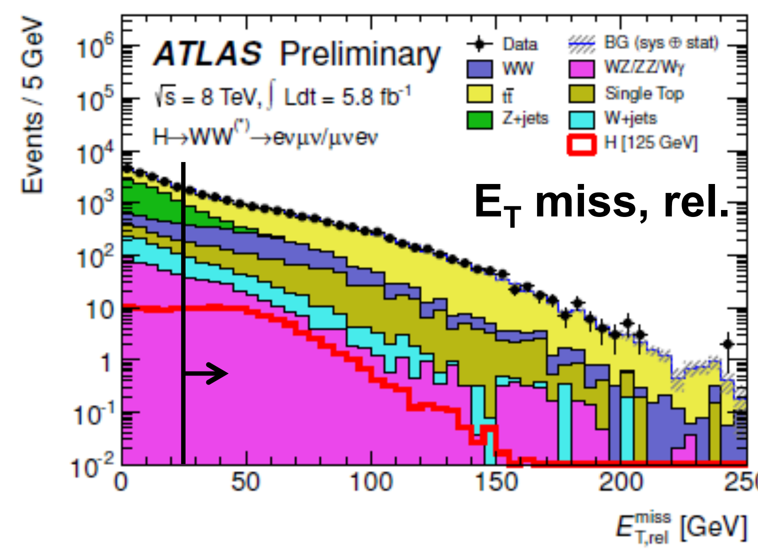
ATLAS H→WW→ (l ν) (l ν) Analysis Strategy

- ***Search in range 110 < m_H < 190 GeV with 2012 data.***
- ***3 bins: 0-jet, 1-jet, at least 2 jets***
- ***Large pile-up in 2012 results in poorer MET resolution compared to 2011 data***
  - ***Drell-Yan background much worse in ee, μμ final states***
    - ***So only opposite-flavor (eμ) final states used in 2012 analysis***
- ***After applying all other cuts, use M_T as the final observable***

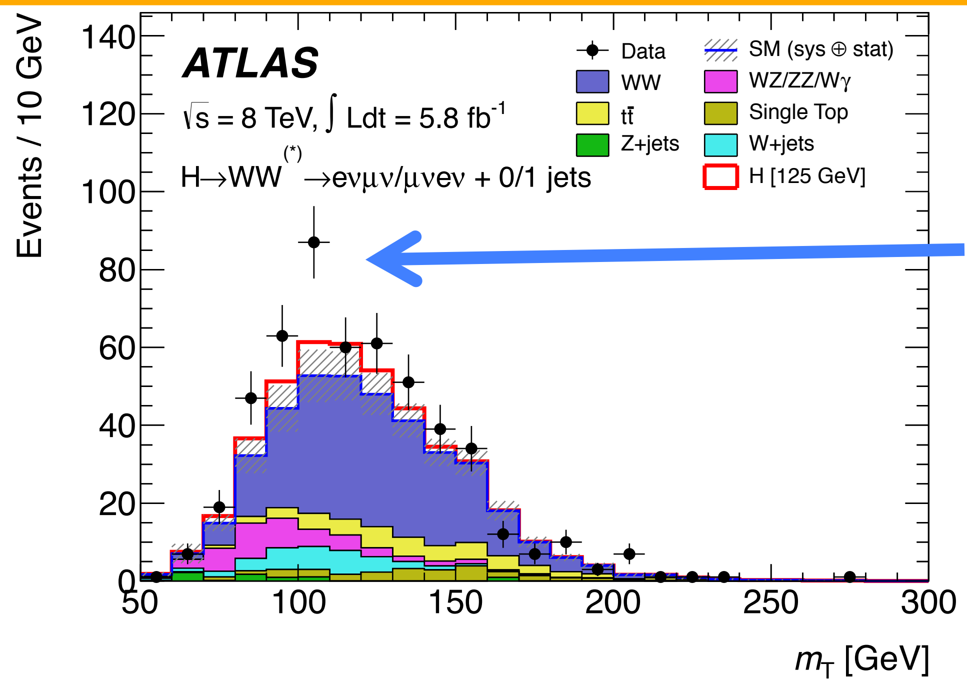
$$m_T = \sqrt{\left(E_T^{ll} + E_T^{miss}\right)^2 - \left|p_T^{ll} + E_T^{miss}\right|^2}$$

$$E_T^{ll} = \sqrt{\left|p_T^{ll}\right|^2 + m_{ll}^2}$$





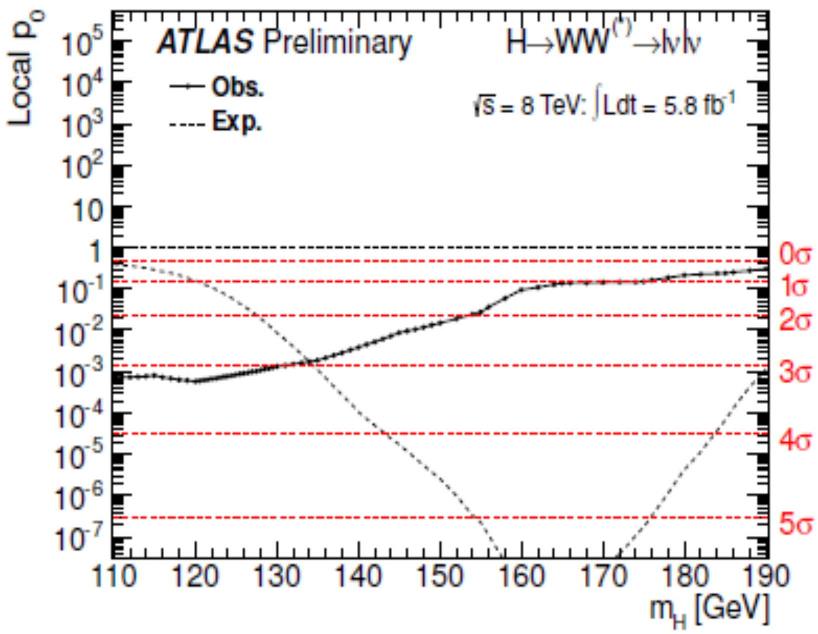
$H \rightarrow WW^* \rightarrow e\mu\nu\nu$: M_T Distribution In Signal Region

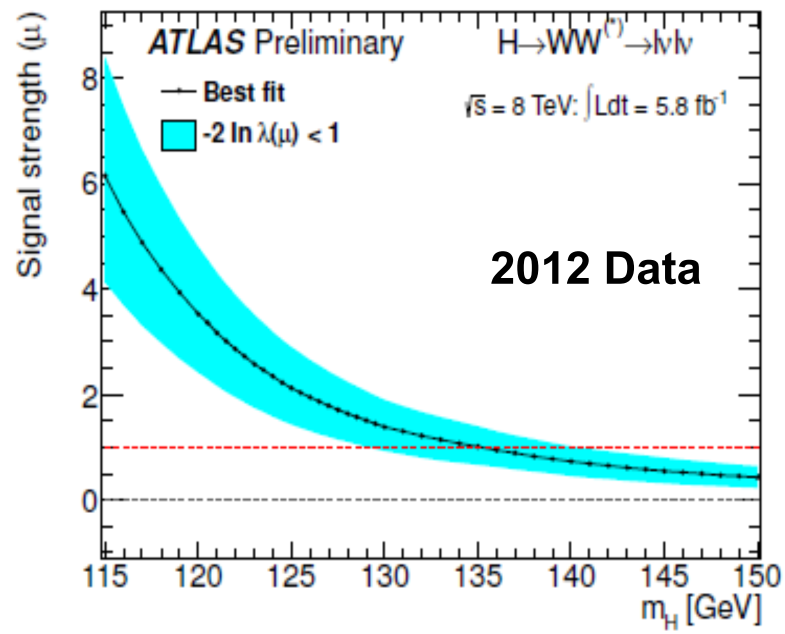


Excess seen in data

	0-jet	1-jet	2-jet
Signal (M =125)	20 ± 4	5 ± 2	0.34 ± 0.07
WW	101 ± 13	12 ± 5	0.10 ± 0.14
$WZ^{(*)}/ZZ/W\gamma^{(*)}$	12 ± 3	1.9 ± 1.1	0.10 ± 0.10
tt	8 ± 2	6 ± 2	0.15 ± 0.10
$tW/tb/tqb$	3.4 ± 1.5	3.7 ± 1.6	-
Z/γ^* + jets	1.9 ± 1.3	0.10 ± 0.10	-
W + jets	15 ± 7	2 ± 1	-
Total Background	142 ± 16	26 ± 6	0.35 ± 0.18
Observed	185	38	0

H→WW*→eμνν : Results with 2012 data





m_H = 125 GeV

p_0	Observed significance	Expected significance
8×10^{-4}	3.1 σ	1.6 σ

At m_H = 125 GeV:

2011 signal strength (μ):

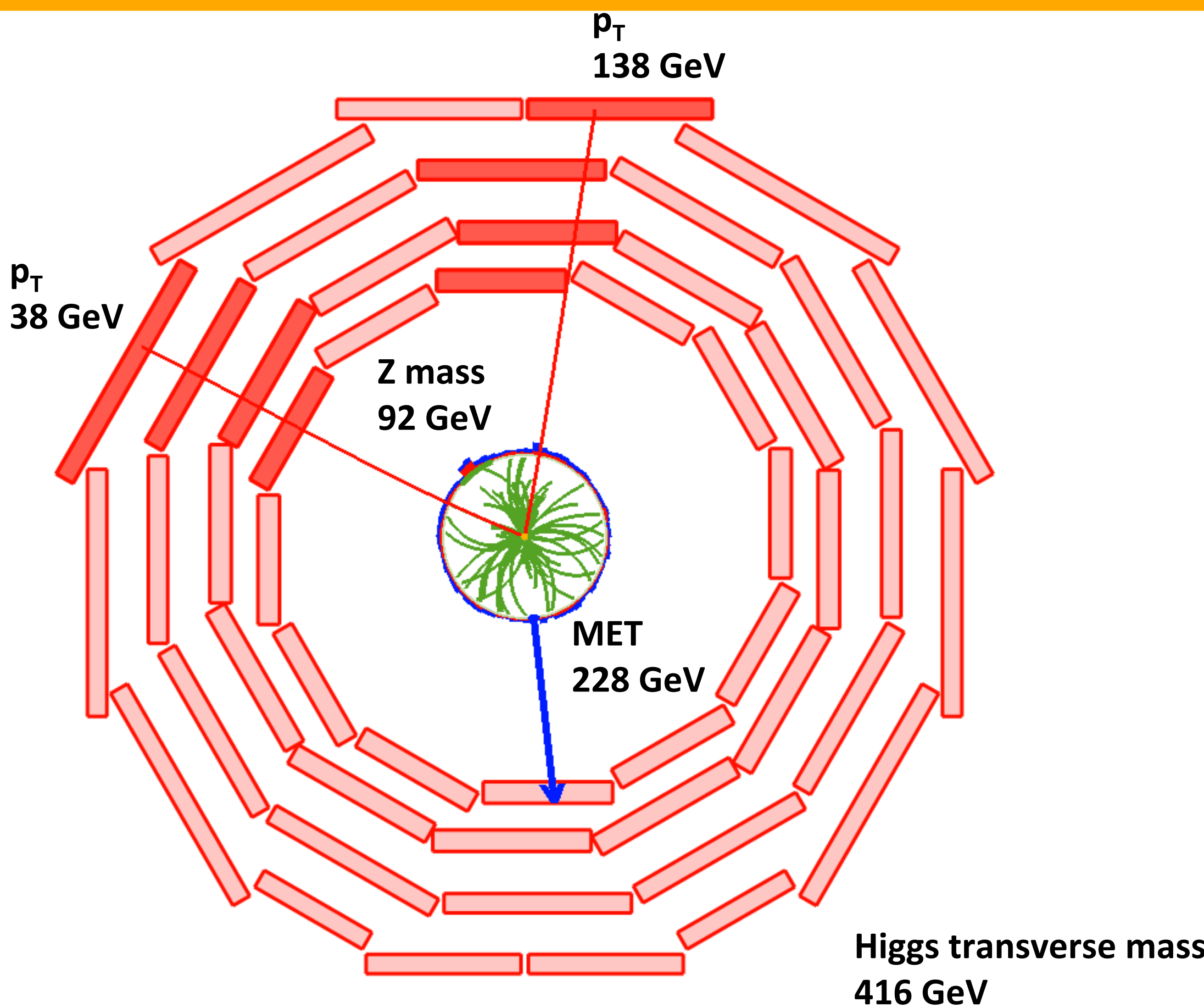
$$\mu = 0.5 \pm 0.7$$

2012 signal strength (μ):

$$\mu = 2.1^{+0.8}_{-0.7}$$

2011, 2012 signal strengths compatible within 1.5σ

High Mass Higgs Search Specialist: H → ZZ → 2l 2ν



2υ in final state → Poor Higgs mass resolution (7-10%)

$H \rightarrow ZZ \rightarrow 2l\, 2\nu$

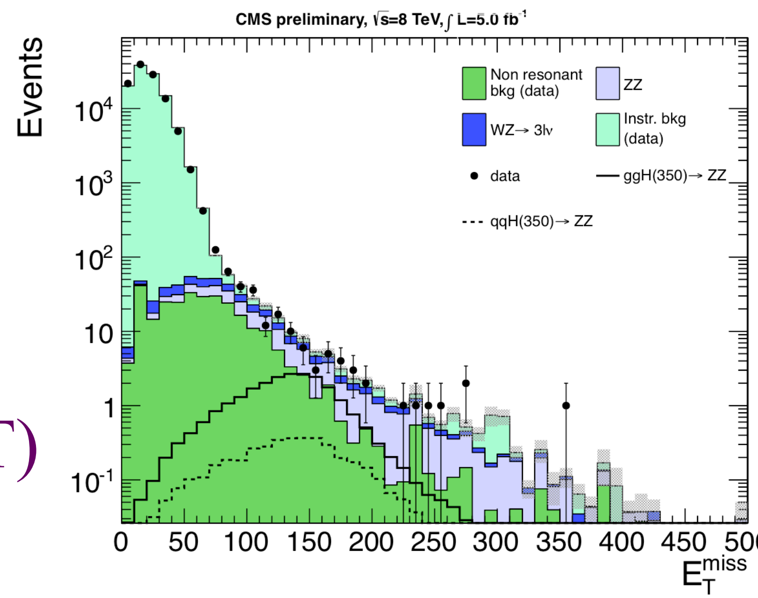
- Identify On-shell $Z \rightarrow ll$ with MET >≈ 60 GeV
- Compute Transverse mass M_T:

$$M_T{}^2 = \left(\sqrt{P_{TZ}{}^2 + M_Z{}^2} + \sqrt{MET^2 + M_Z{}^2}\right)^2 - (\vec{P_{TZ}} + \vec{MET})^2$$

- Build two exclusive catagories:
  - VBF:
    - **search for 2 jets with $\Delta\eta > 4$ and M_{jj}>500 GeV**
    - **No central jets in between**
  - Everything else (mostly $gg \rightarrow H$)
- Selection optimized for different Higgs masses
  - $M_H > 250$ GeV

H → ZZ → 2l 2ν

- Major backgrounds: Z+Jets, ttbar, WW & WZ
  - Large ME_T requirement to suppress Z + jets by x10^5
  - Anti b-tag to suppress ttbar
- Backgrounds estimated from data control samples
  - γ + jets (for Z+Jets → fake MET)
  - eμ sample (for ttbar +WW)
- Residual ZZ, WZ background estimate from MC



Limits From H → ZZ → 2l 2ν Search

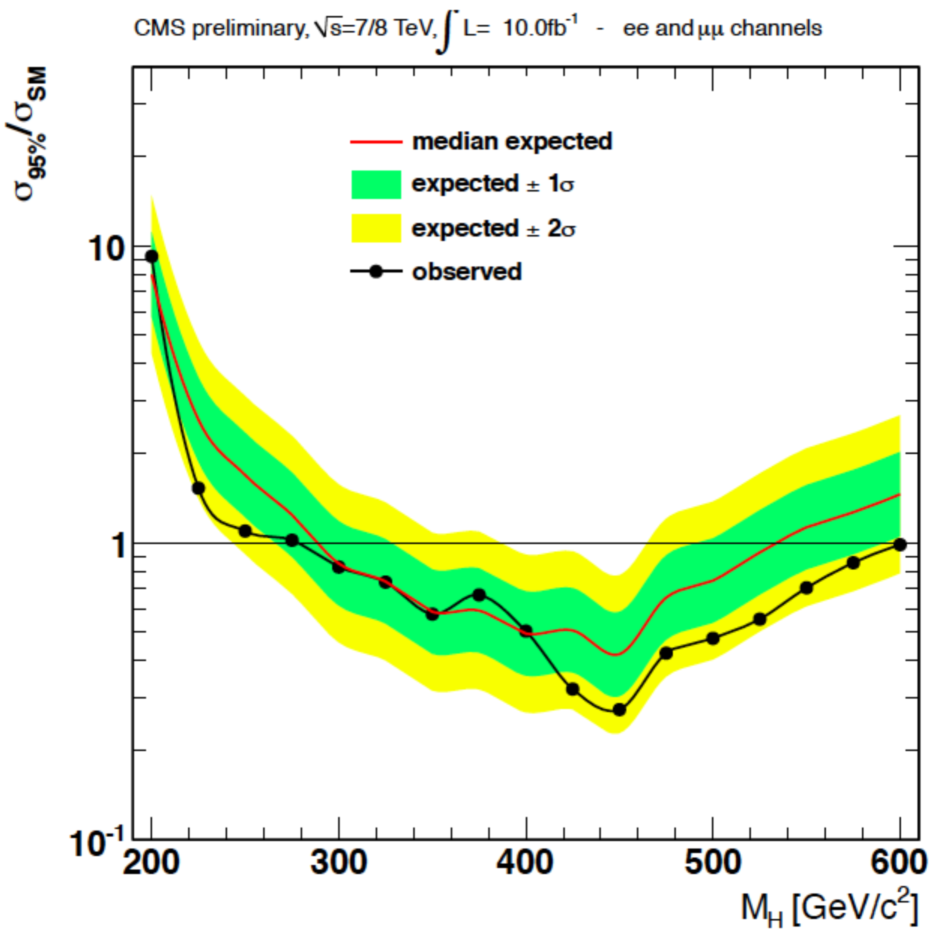
Selection for $M_H = 400$ GeV

- Kinematic selections:

VBF	0/1/2 jets
$p_T(Z) > 55$ GeV	$p_T(Z) > 55$ GeV
	$ME_T > 90$ GeV
	$325 < M_T < 425$ GeV

- Event yields (5 fb^{-1} @ 7 TeV + 5 fb^{-1} @ 8 TeV

	Total BG	Signal	Observed
VBF	3.1	1.3	2
0 jet	14.9	11.3	13
1 jet	15.6	16.2	18
2 jet	6.1	6.1	6



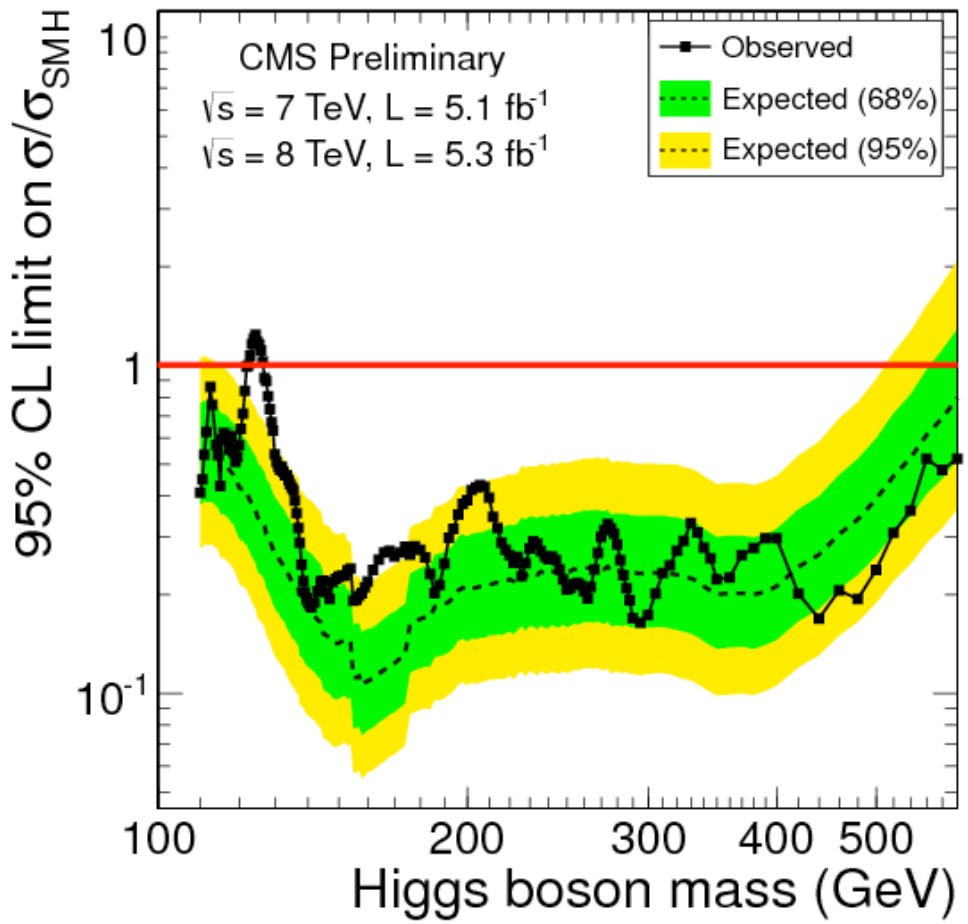
Observed Exclusion : $278 < M_H < 600$ GeV

Expected Exclusion : $291 < M_H < 534$ GeV

End Of Lecture 1

Bottomline On High Mass Higgs Searches

Combine all search modes

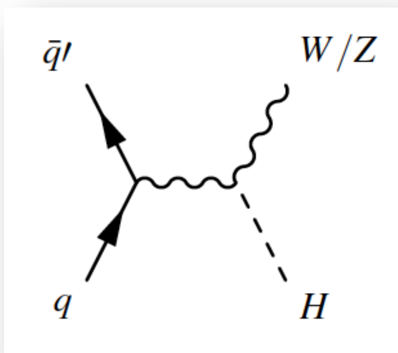


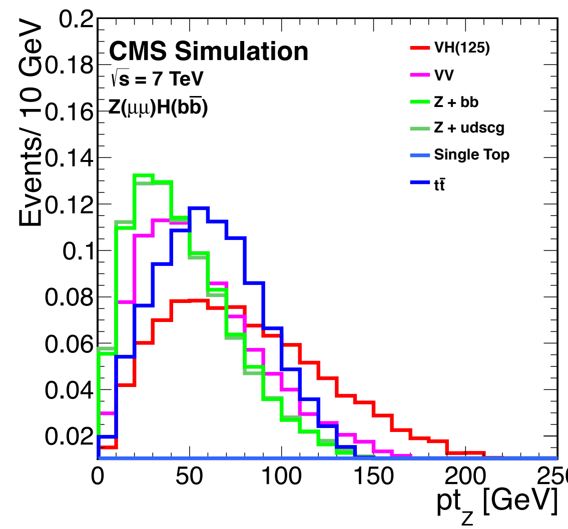
A SM-like Higgs boson excluded at 95% CL for $127 < M_H < 600$ GeV

Focus next on low-mass Higgs searches

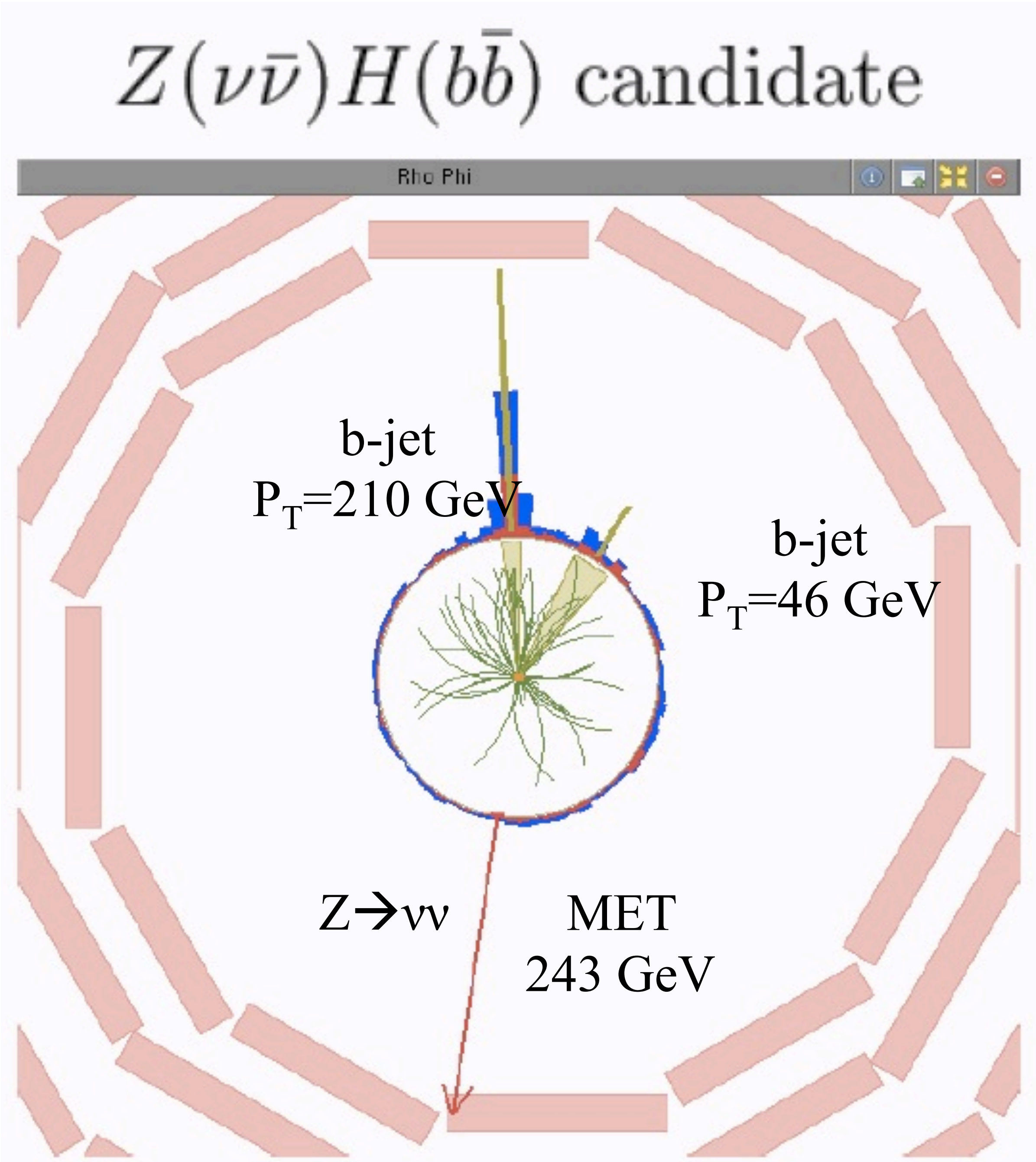
H→ bb

- Important mode for measuring Higgs coupling to fermions
- H → bb production via gluon fusion and VBF are quite large but are buried (10^7) under QCD production of b bbar pairs
- Most promising channel is H → bb production associated with a Vector (V=W or Z) boson





- V reconstruction: W → l ν, Z→ νν, Z → ll
- H→ bb reconstructed as two b-tagged jets recoiling against a high P_T W/Z boson
  - Large W/Z P_T → smaller background & better di-jet mass resolution
- VH analysis targets Higgs mass range 110 < M_H < 135 GeV

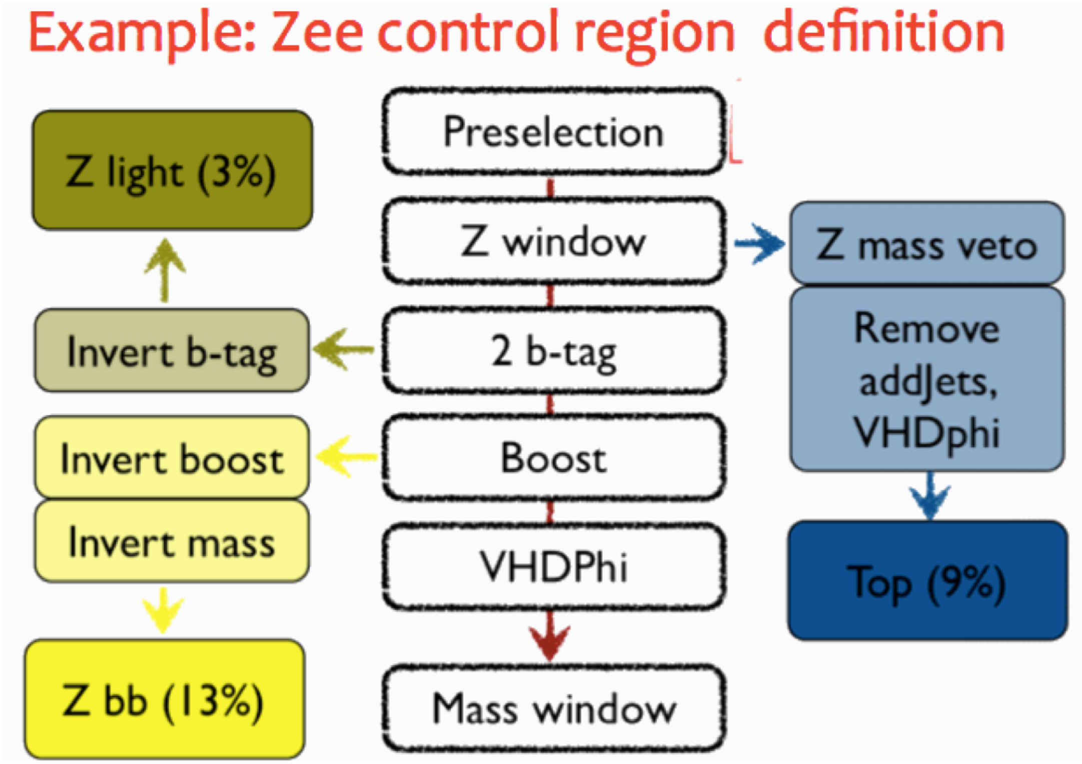


Two clean b-jets
M_{bb} = 120 GeV
$P_{T,bb}$ = 248 GeV

Recoiling against
Z→νν
➔ Large MET

Background Estimate From Control Regions

- Main backgrounds are the usual suspects:
  – Reducible: W/Z + jets (light and heavy flavor jets) & ttbar
  – Irreducible : WZ, ZZ and single top (taken from simulation)
- Background yields/shapes determined from signal-depleted control data samples using kinematic selection close to signal region



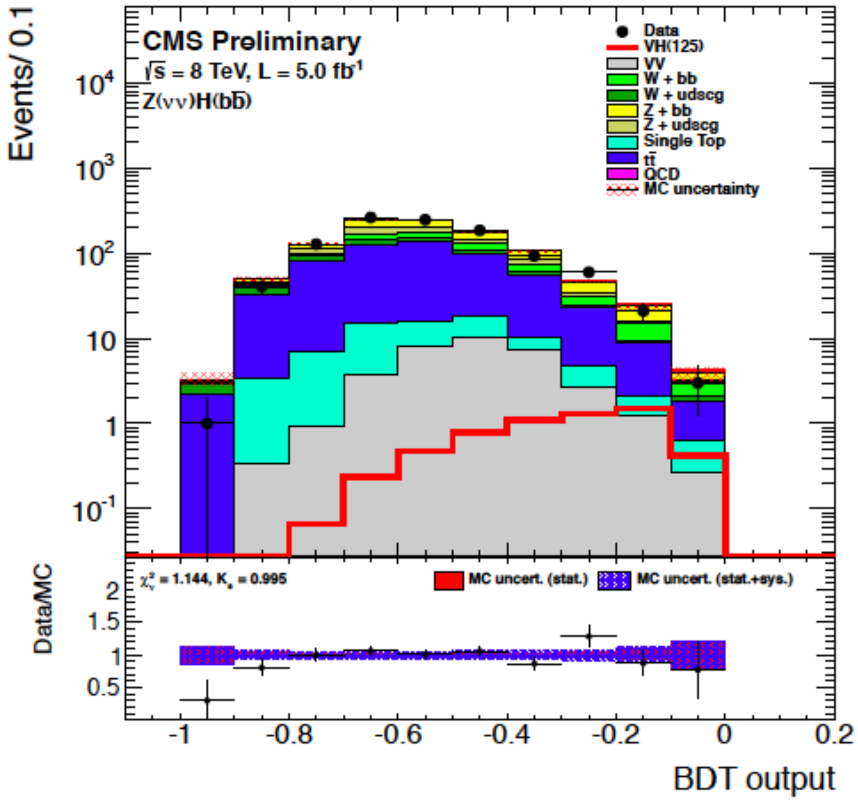
Separating Signal From Backgrounds

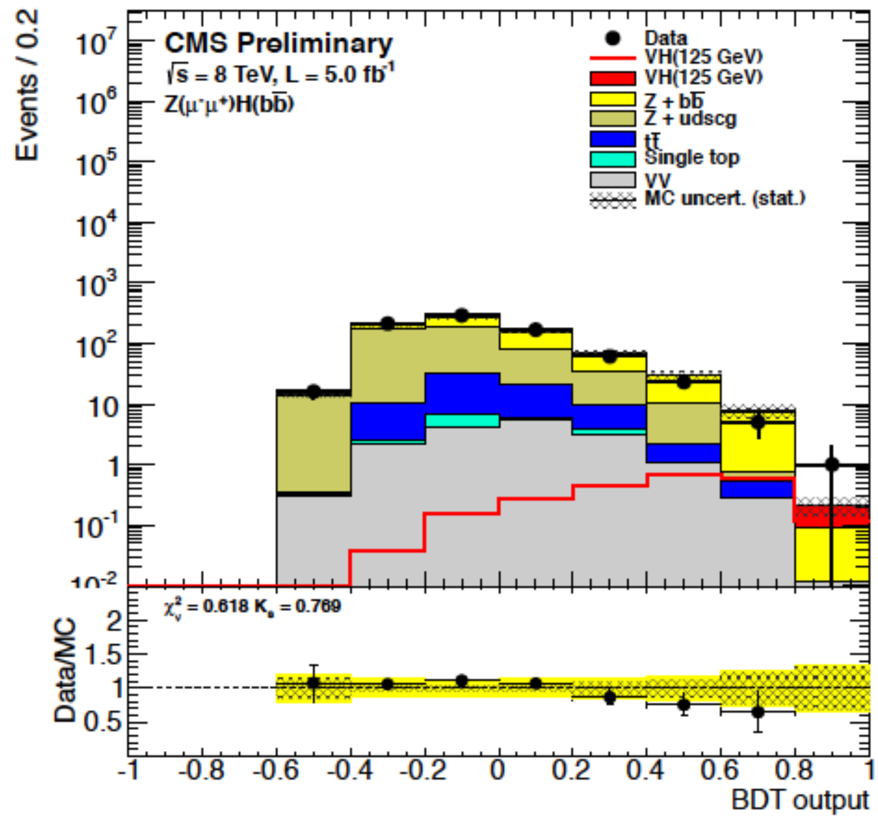
- A multivariate algorithm trained at each Higgs mass hypothesis
- Several kinematic and topological variables used tp separate Signal from background

Variable
$p_{\mathrm{T}j}$: transverse momentum of each Higgs daughter
$m(\mathrm{jj})$: dijet invariant mass
$p_{\mathrm{T}}(\mathrm{jj})$: dijet transverse momentum
$p_{\mathrm{T}}(\mathrm{V})$: vector boson transverse momentum (or pfMET)
$\mathrm{CSV_{max}}$: value of CSV for the b-tagged jet with largest CSV value
$\mathrm{CSV_{min}}$: value of CSV for the b-tagged jet with second largest CSV value
$\Delta\phi(\mathrm{V,H})$: azimuthal angle between V (or $E_{\mathrm{T}}^{\mathrm{miss}}$) 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 ($p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 4.5$)
$\Delta\phi(\mathrm{E_T^{miss}},\mathrm{jet})$: azimuthal angle between $E_{\mathrm{T}}^{\mathrm{miss}}$ and the closest jet (only for $\mathrm{Z}(\nu\nu)\mathrm{H}$)
$\Delta\theta_{\mathrm{pull}}$: color pull angle [62] (not for $\mathrm{Z}(\ell\ell)\mathrm{H}$)

H → bb Search

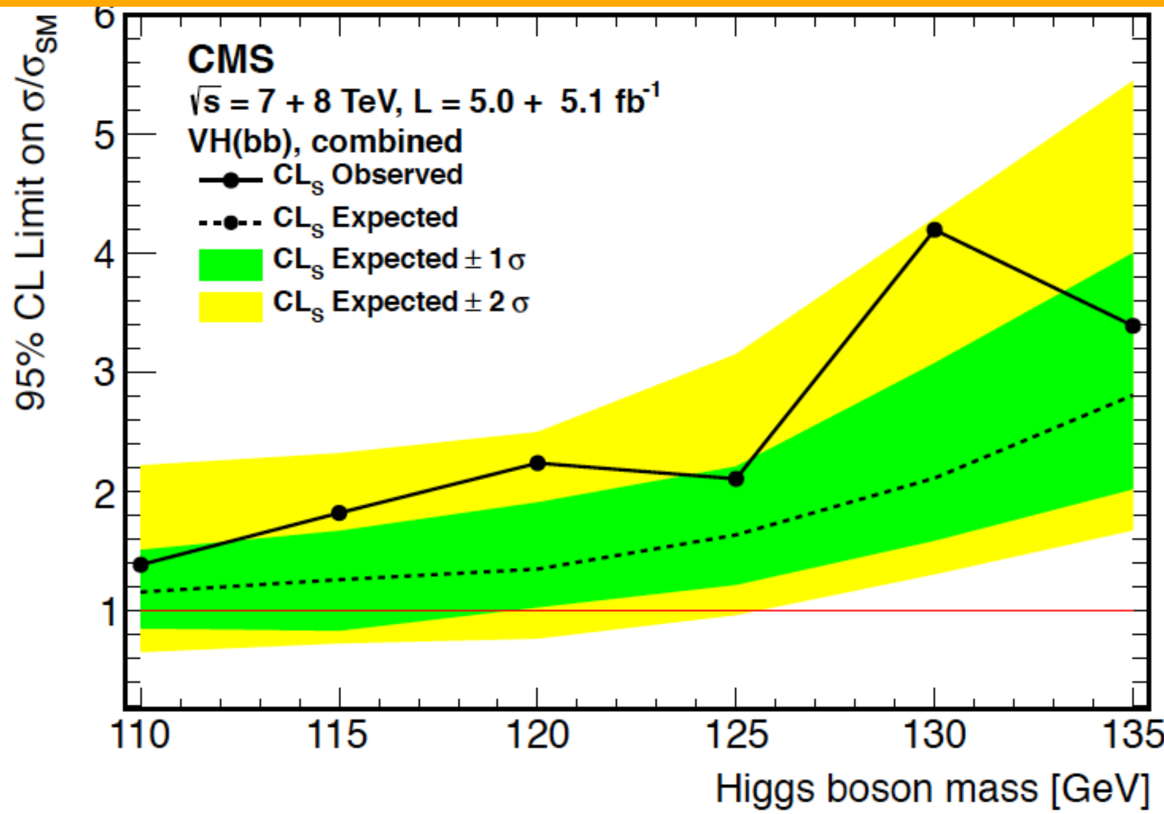
- A Higgs signal in the mass range [110-135] GeV is searched for as an excess in MVA classifier using predicted shapes for signal & bkgnd





No significant excess seen over predicted background yields

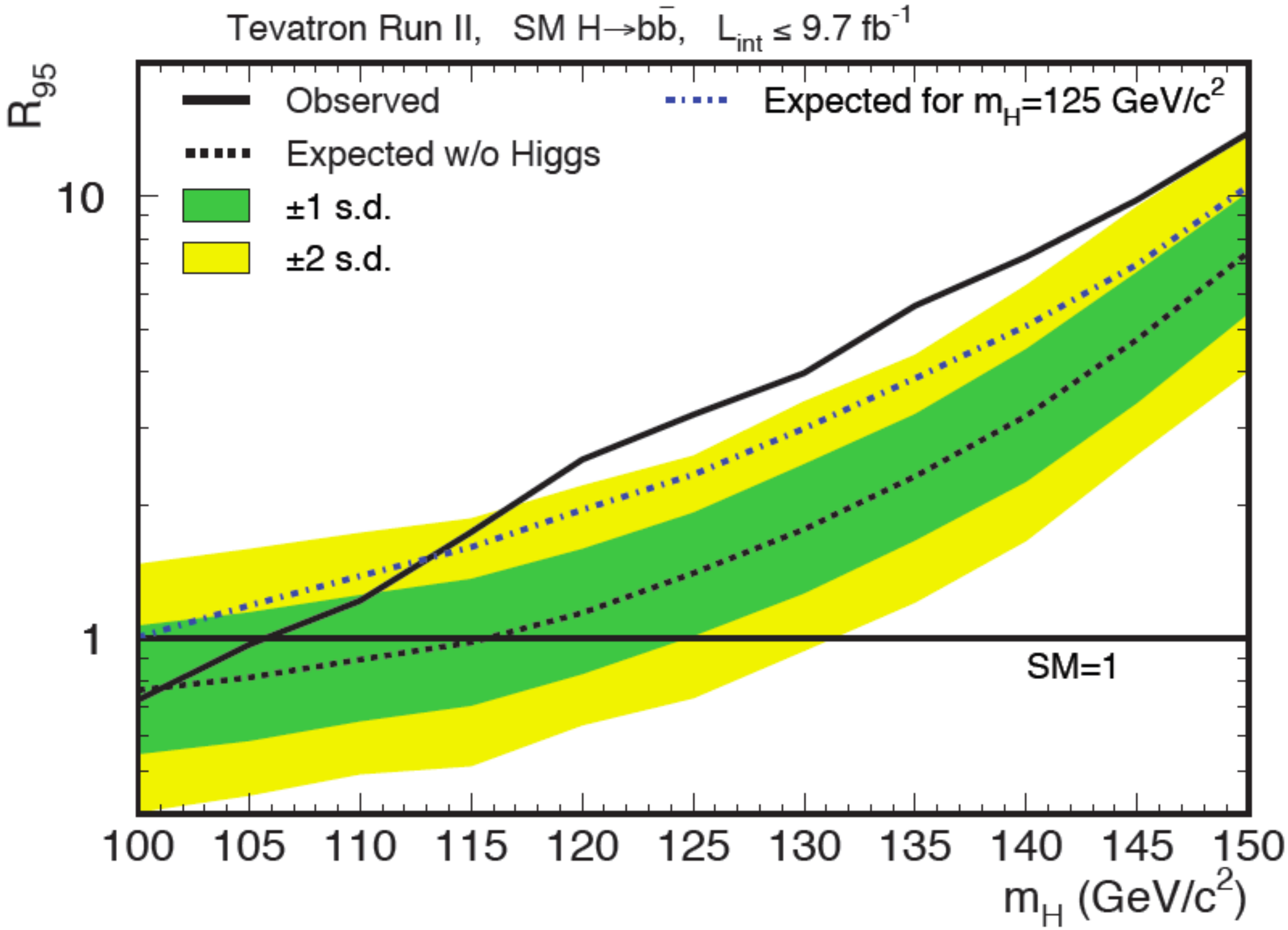
Limits From VH, H → bb Searches



m_H(GeV)	110	115	120	125	130	135
Exp.	1.16	1.26	1.35	1.64	2.12	2.81
Obs.	1.39	1.82	2.24	2.11	4.20	3.39

Approaching SM Higgs Sensitivity but no Cigar (yet) !

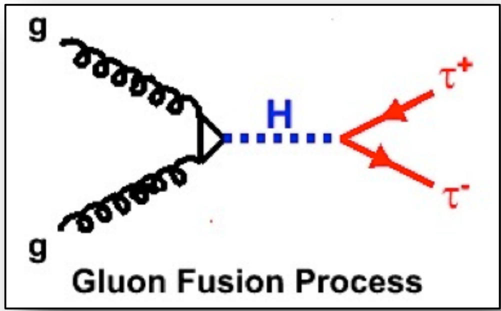
Tevatron VH, H →bb Searches

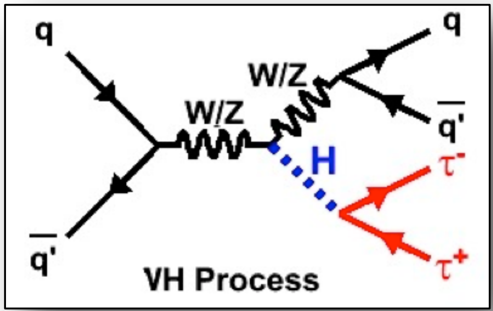


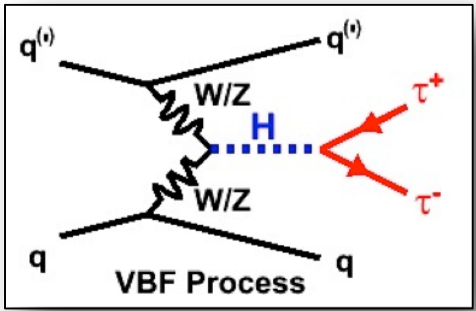
Observe broad excess with global significance of 2.9σ

H → ττ : Another Low Mass Specialist

- Most promising mode for measuring Higgs coupling to leptons
- Searched for in three Higgs production modes



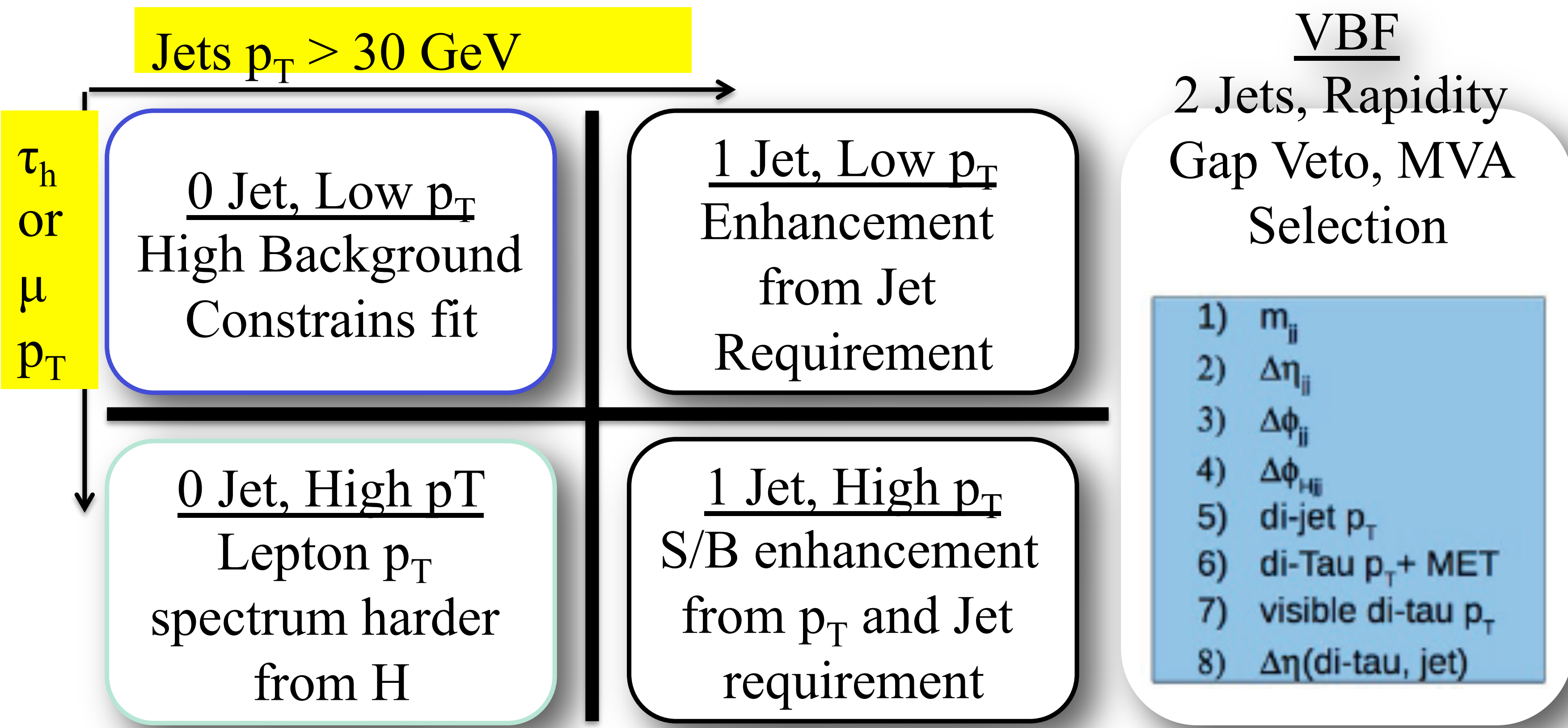




- And subsequent decay of τ lepton
  - τ →eνν , τ →μνν, τ→ hadrons
- Four signatures considered : eμ, μμ, $e\tau_h$, $\mu\tau_h$
- Due to missing neutrinos, Higgs signal appears as a broad excess in reconstructed τ-pair mass (Mass resolution ≈ 20%)
- Major backgrounds arise from
  - ttbar
  - W & Z (+jets), dibosons

$H \rightarrow \tau\tau$ Search Strategy

- Search divided in 5 categories based on H mass resolution & S/B

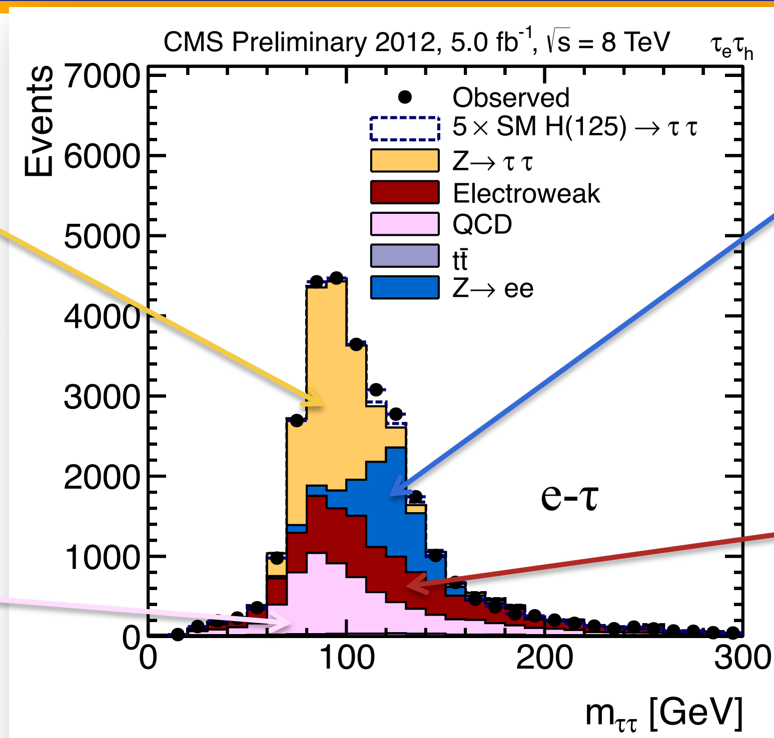


- All categories are fit simultaneously

Anatomy of the H→ ττ Analysis

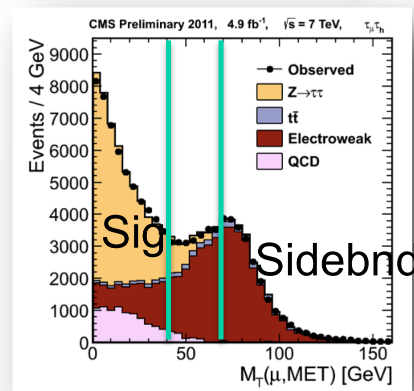
Z→ττ – Efficiency measured using τ embedded in Z→ μμ events

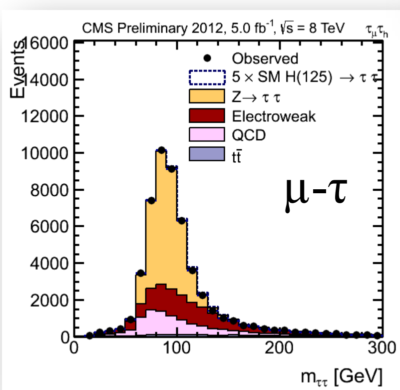
QCD – Estimated from same sign data

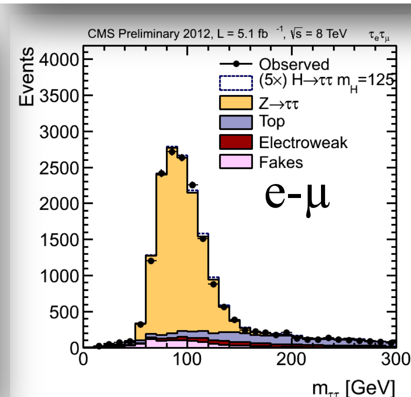


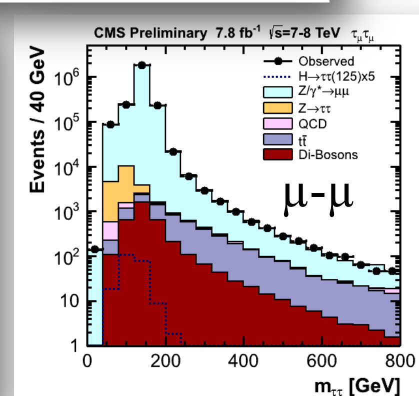
Z→ll – Taken from MC corrected for measured l→τ fake rates

EWK – Mostly W+Jets, measured from high M_T sideband



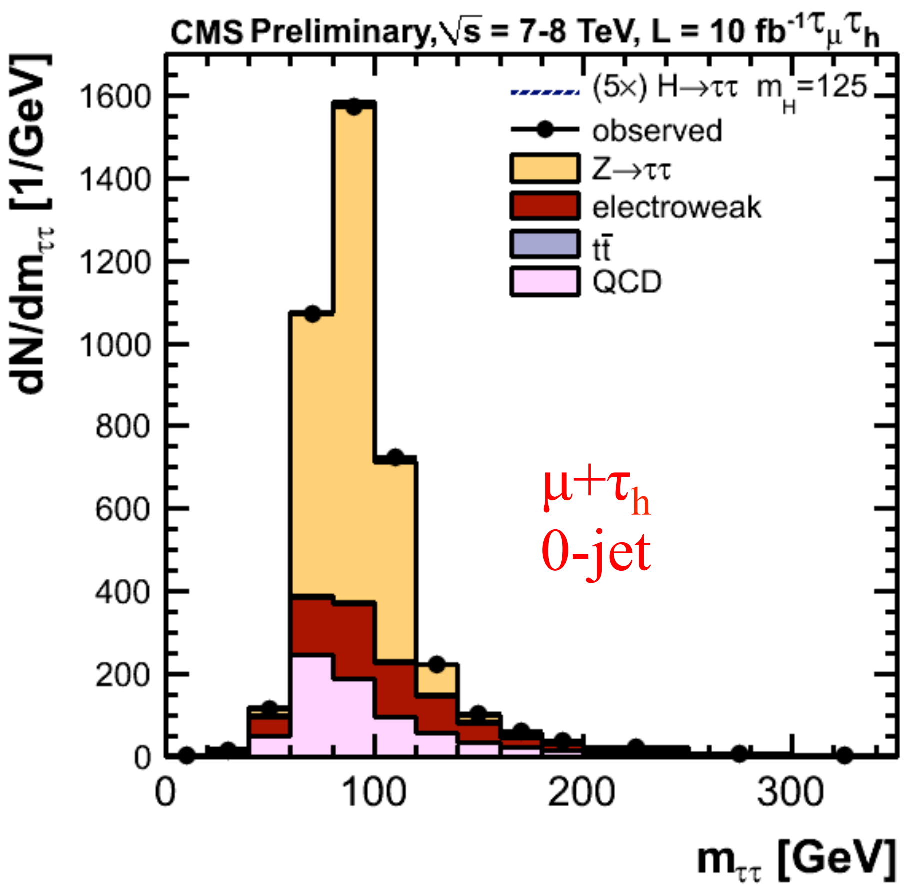


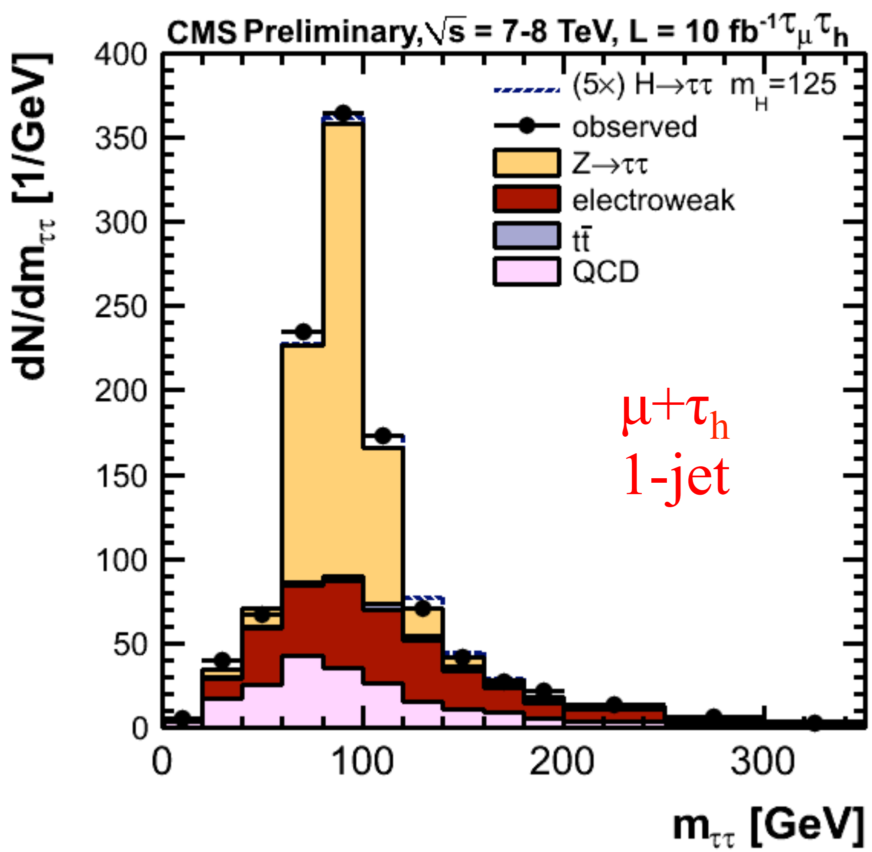




Plots are pre-fit

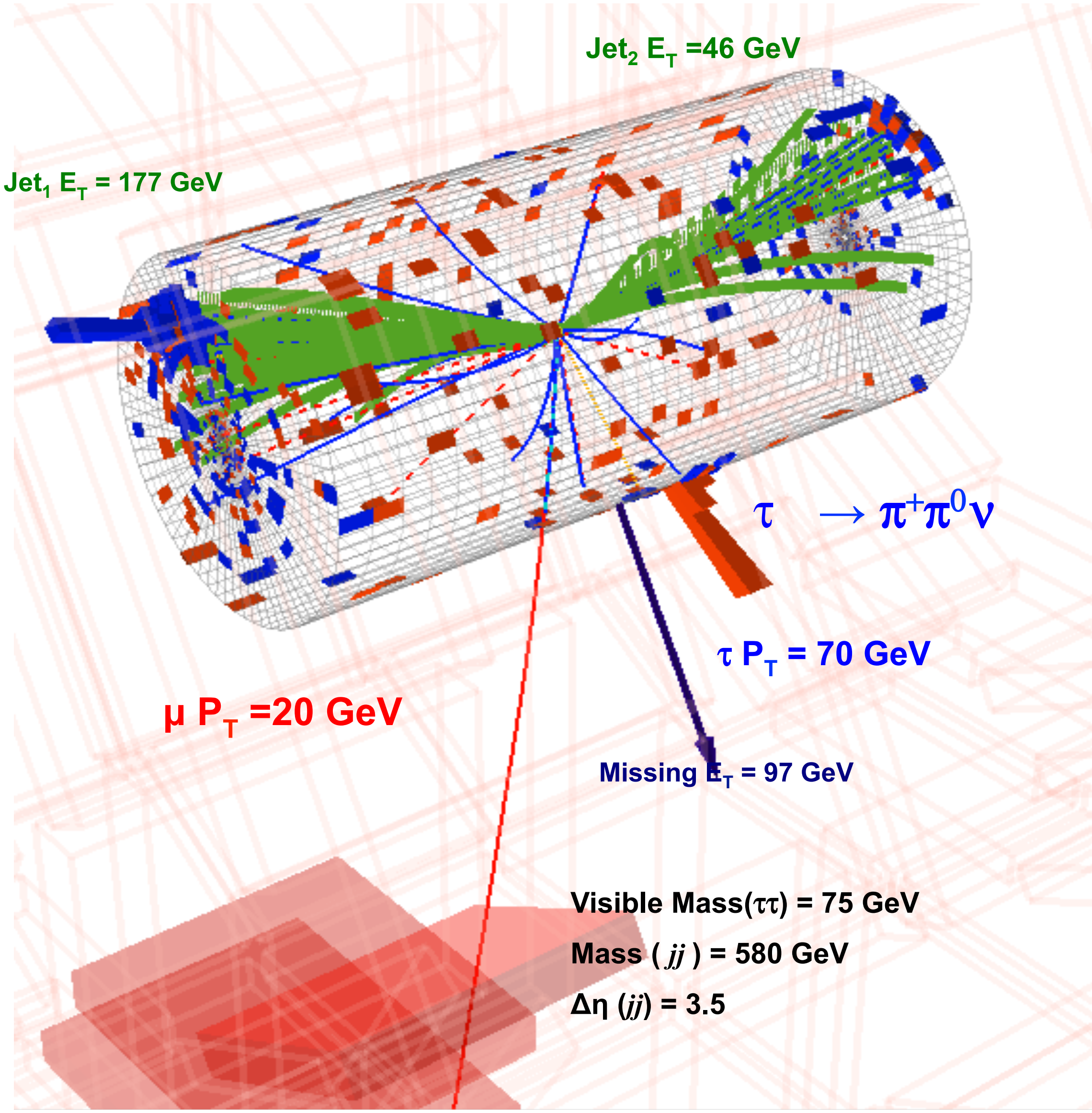
Tau-Pair Mass Distributions In 0 &1 Jet Catagories



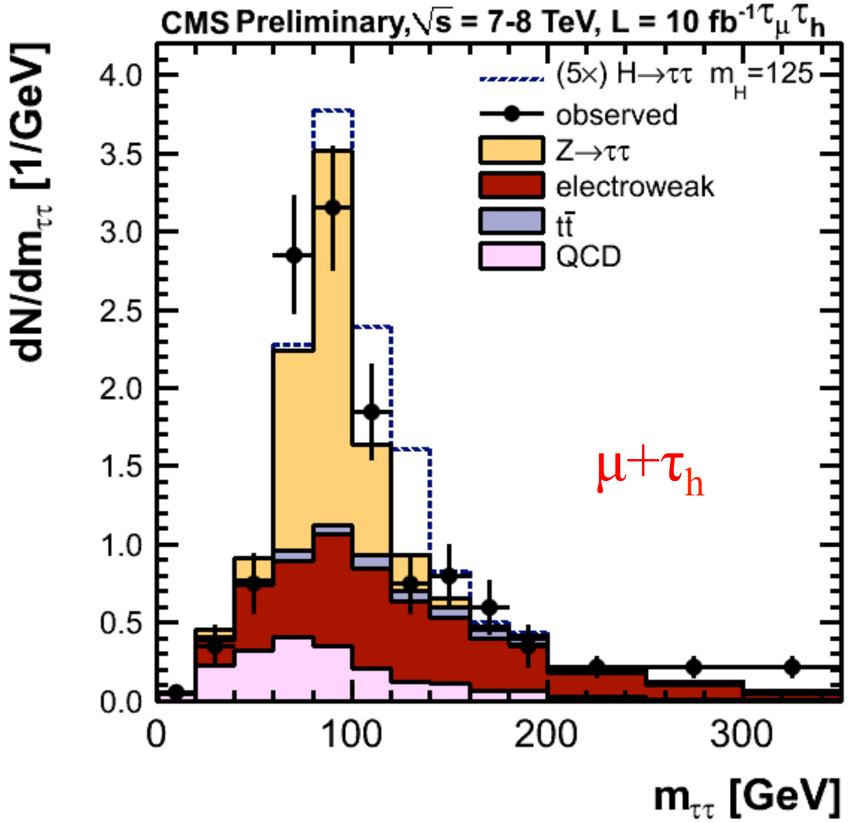


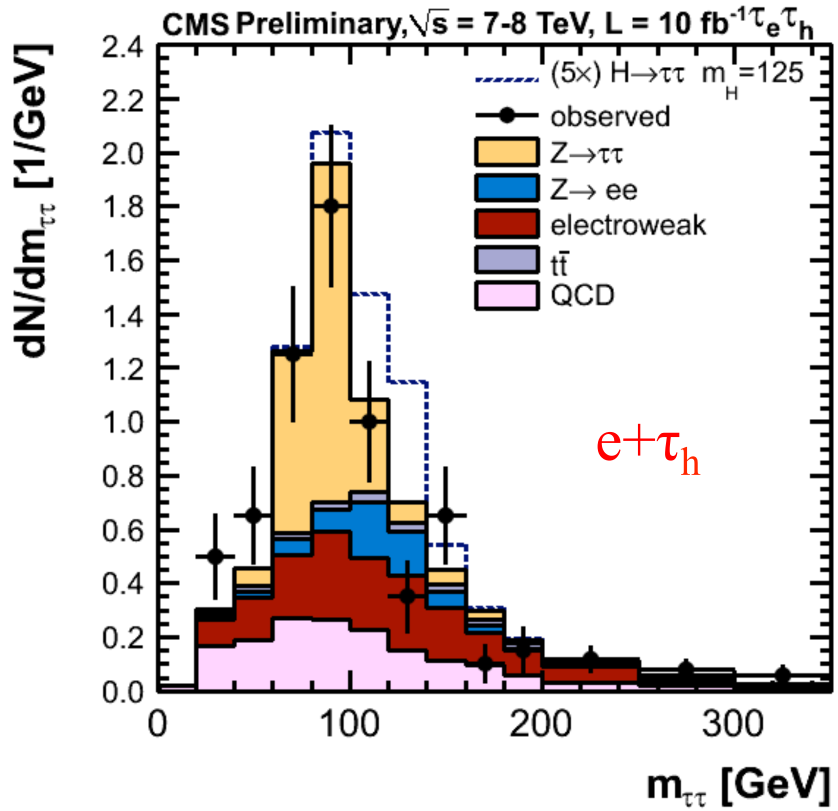
Possible Signal
overwhelmed by backgrounds !

VBF (2jets) Category Has Best S/N



Yields & Expectations in VBF Catagory





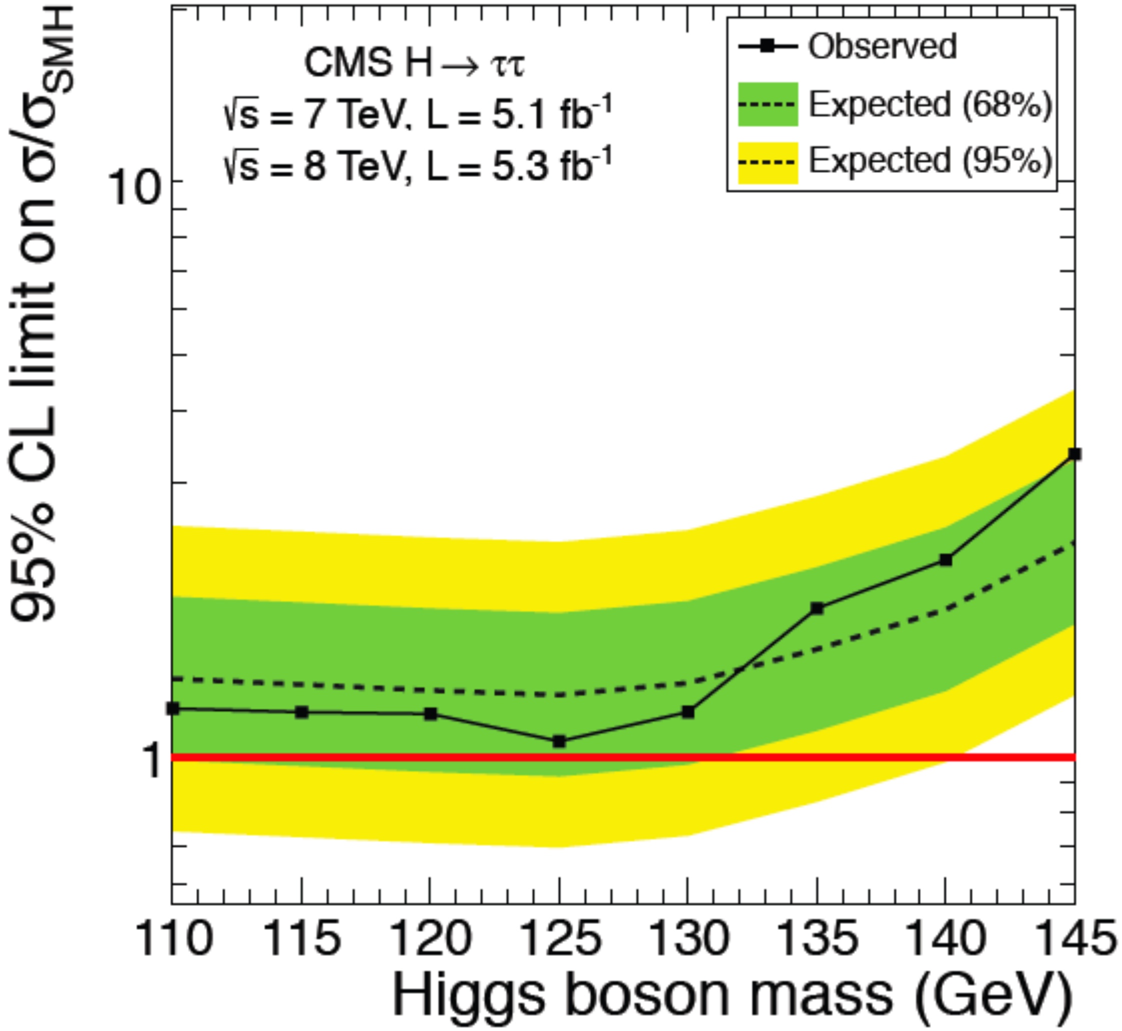
Much better signal to noise , but small signal

Background & Expected Signal in VBF Catagory

Process	$e\tau_h$+X	$\mu\tau_h$+X	$e\mu$+X	$\mu\mu$+X
$Z \to \tau\tau$	53 ± 5	100 ± 9	56 ± 12	5.3 ± 0.4
QCD	35 ± 7	41 ± 9	7.4 ± 1.4	0.0 ± 0.0
W+jets	46 ± 10	72 ± 15	—	0.0 ± 0.0
Z+jets (fake τ)	13 ± 2	2.5 ± 0.6	—	—
$Z \to \mu\mu$	—	—	—	70 ± 8
$t\bar{t}$	7.0 ± 1.7	14 ± 3	24 ± 2	6.7 ± 1.5
Dibosons	1.2 ± 0.9	2.9 ± 2.1	11 ± 2	2.4 ± 0.9
Total Background	156 ± 13	233 ± 20	99 ± 13	85 ± 9
$H \to \tau\tau$ (m_H = 125 GeV)	4.3 ± 0.6	7.7 ± 1.1	3.5 ± 0.4	0.8 ± 0.1
Data	142	263	110	83

No significant excess over expected backgrounds

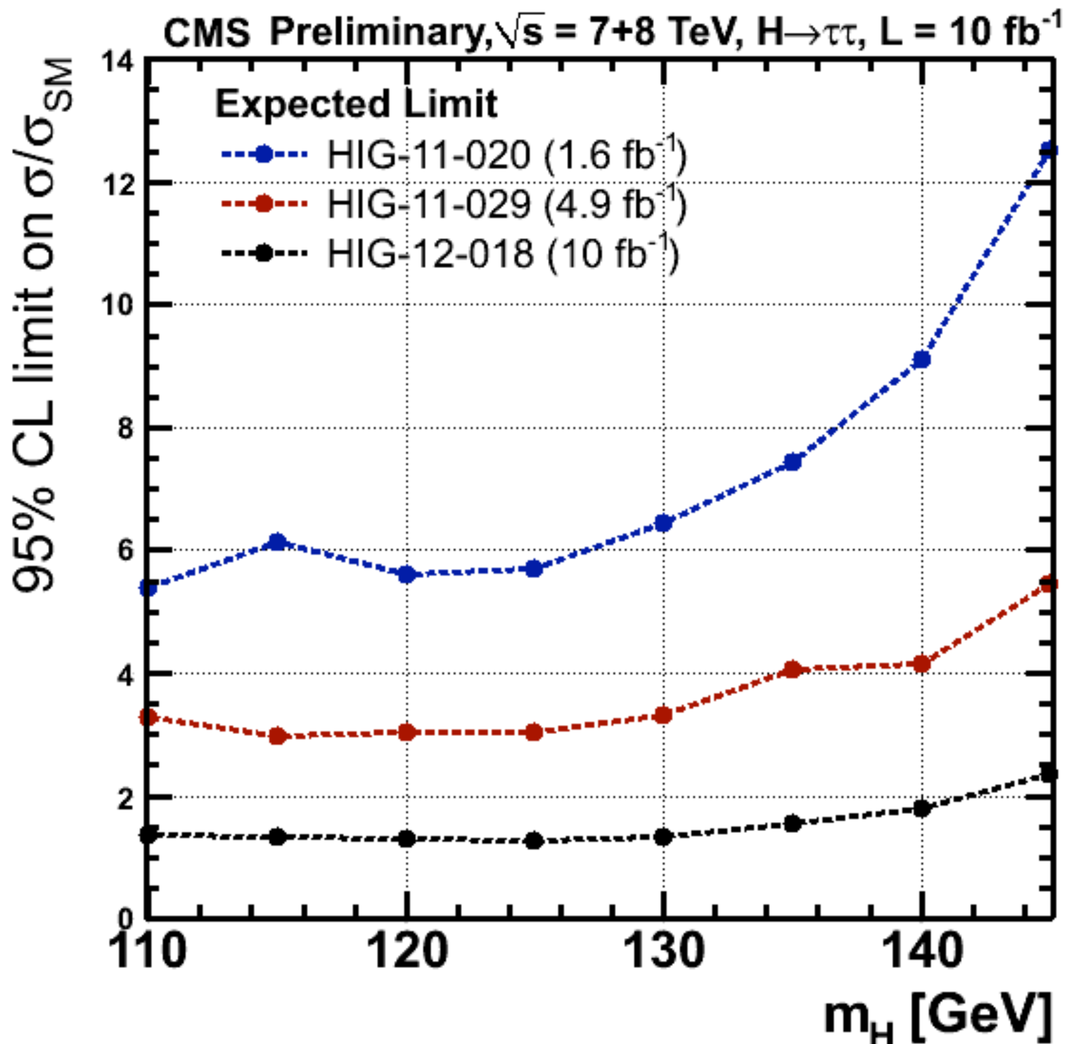
Limits From H → ττ Search



Expected exclusion @ $M_H = 125 : 1.3\ \sigma_{SM}$

Observed exclusion @ $M_H = 125 : 1.1\ \sigma_{SM}$

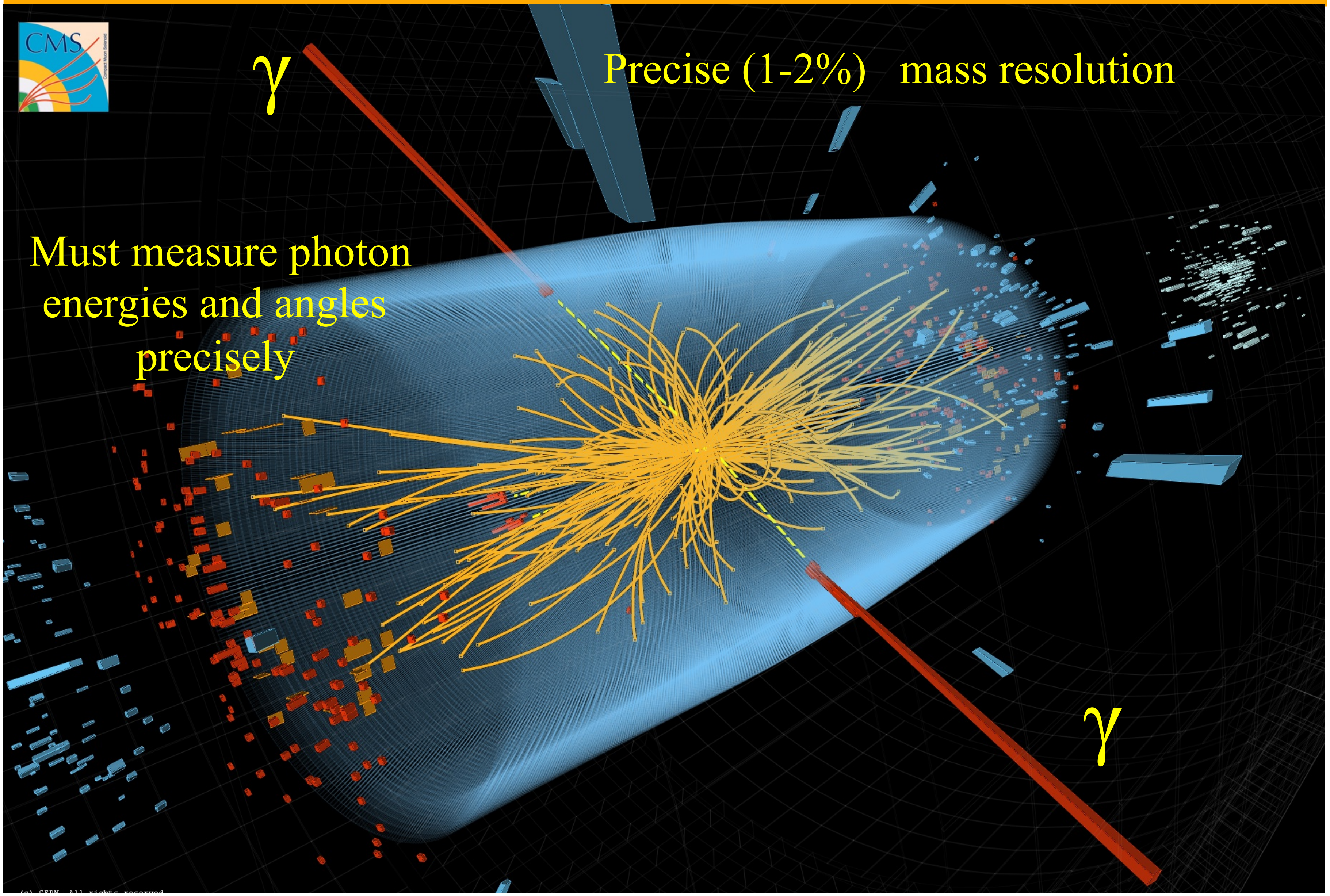
Improvement In H → ττ Sensitivity In Just 1 Year



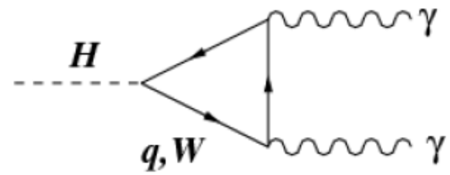
ATLAS & CMS sensitivities similar
Look forward to more data this year

High Resolution Channels

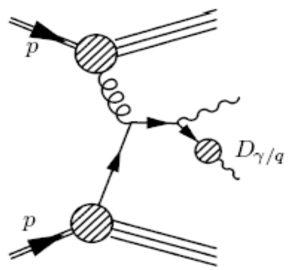
$H \rightarrow \gamma\gamma$

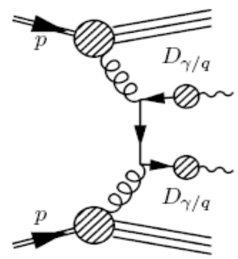


H → γγ

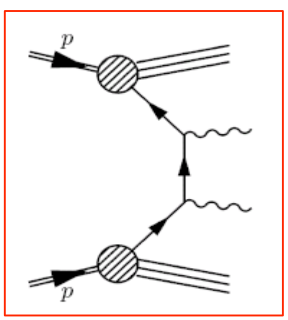


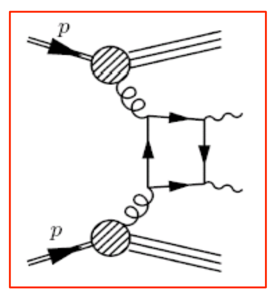
- A discovery channel in $110 < M_H < 150$ GeV
- Br (H→ γγ) ≈ 10^{-3}
- Search for a narrow peak with two isolated high E_T photons over a continuous diphoton background spectrum
- Background is large and composed of
  - Reducible: One or more misidentified (fake) photon (e.g. γ+jets)





- Irreducible: both photons are real





Search sensitivity depends on background level

$H \rightarrow \gamma\gamma$: Important Analysis Aspects

$M^2_{\gamma\gamma} = 2E_1E_2(1 - \cos\alpha_{\gamma\gamma})$ ➔

- ECAL Calibration, $M_{\gamma\gamma}$ energy scale & resolution
- $\gamma\gamma$ vertex determination (angle $\alpha_{\gamma\gamma}$)

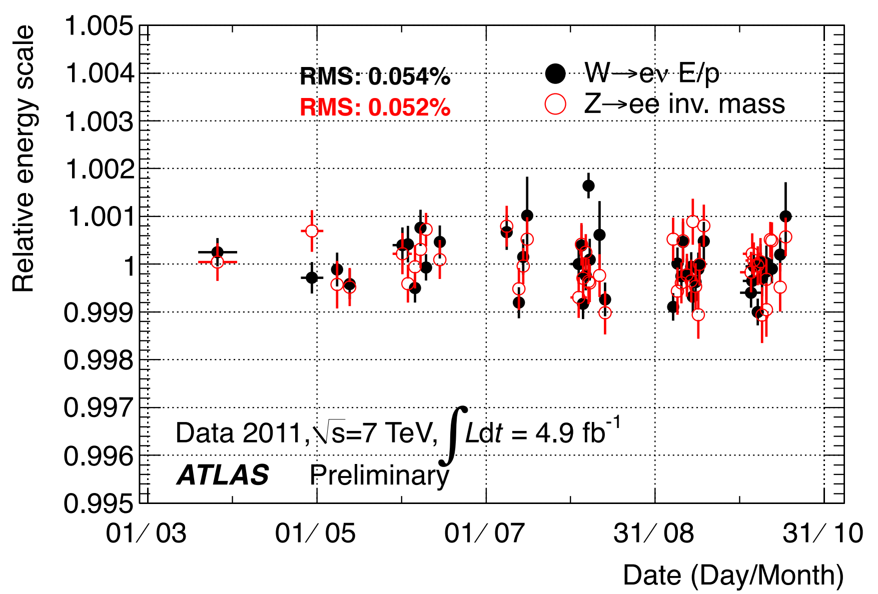
- Event selection and catagorization (not all photons are measured with same precision)
- Modeling of background spectrum from data sidebands

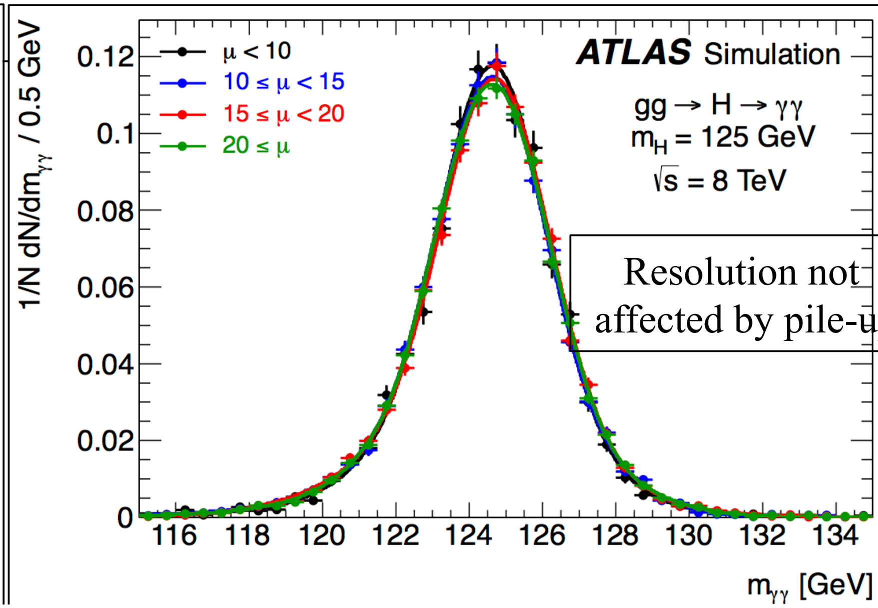
ATLAS & CMS differ in approach but ultimately arrive at similar search sensitivities

ECAL Calibration (ATLAS)

Understand calorimeter energy response
from Z→ ee, J/ψ → ee, W→ eν data and MC):

- E-scale at m_Z known to ~ 0.3%
- Stability vs time ~ 0.1%
- Linearity better than 1% (few-100 GeV)
- "Uniformity" (constant term of resolution):
- ~ 1% (2.5% for 1.37<|η|<1.8)

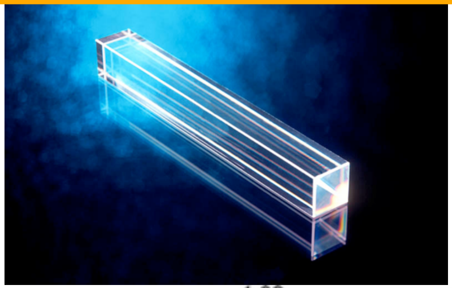




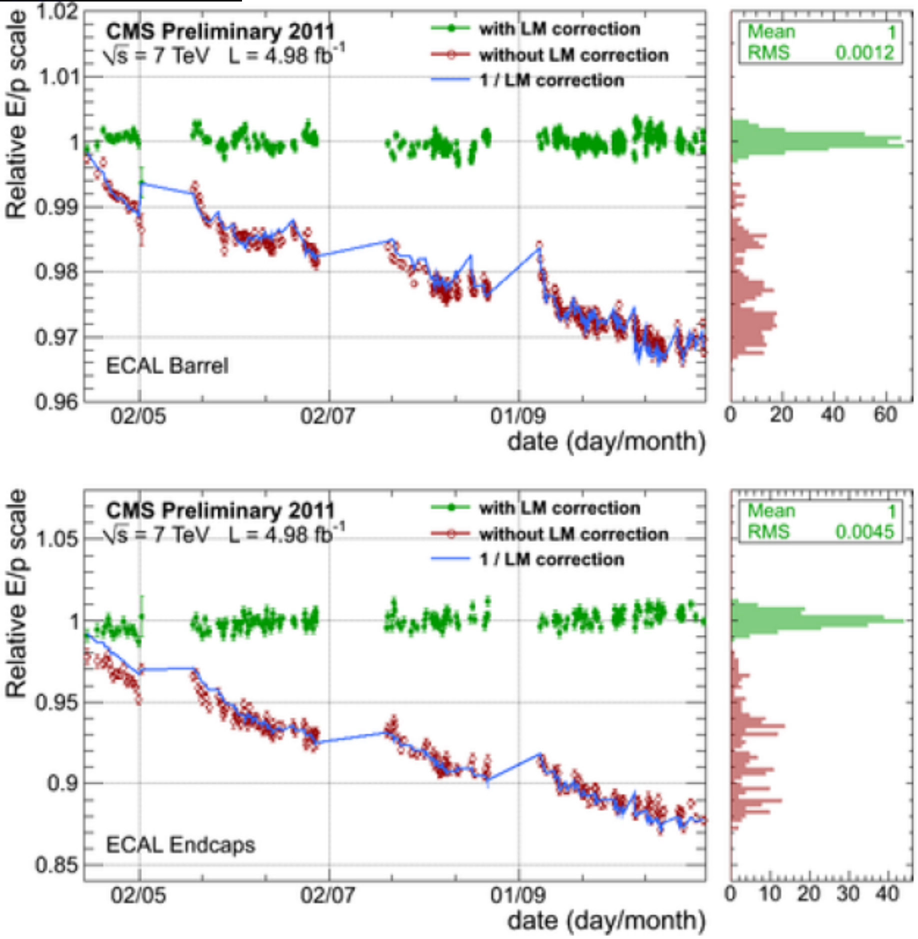
Resolution not affected by pile-up

0

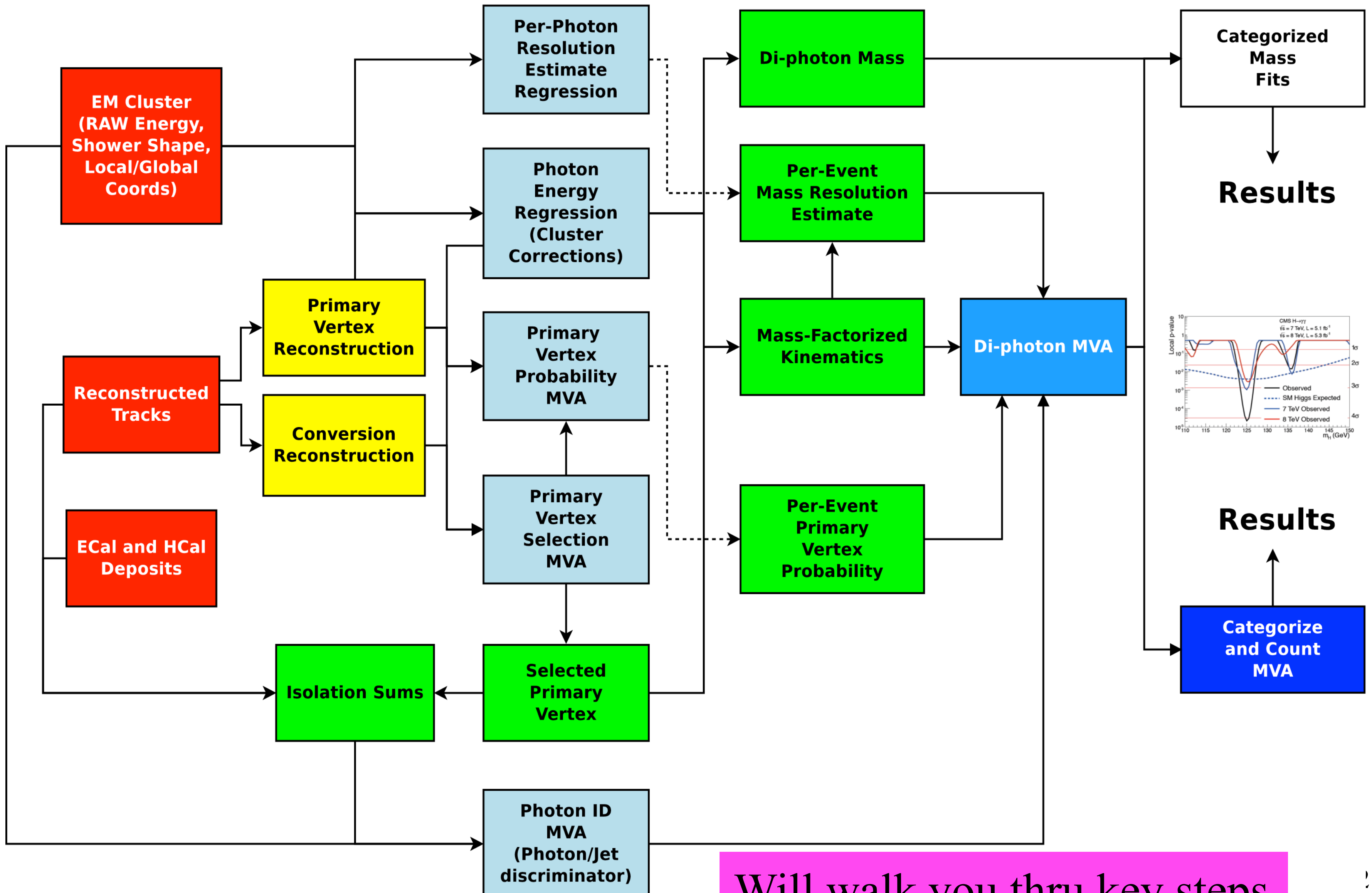
In situ ECAL Calibration (CMS)



- Dedicated calibration scheme:
  - inter-crystal calibration: π^0, η
  - crystal transparency correction (laser monitoring system)
- The energy scale stability after the response corrections:
  - barrel: 0.12% (
  - endcap: 0.45%
- Exploit $W \rightarrow e\nu$ (E/p) and $Z^0 \rightarrow ee$ control samples to derive energy scale and resolution systematics



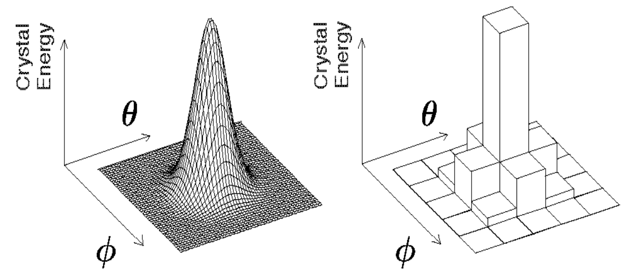
Roadmap For H→ γγ Search (CMS)



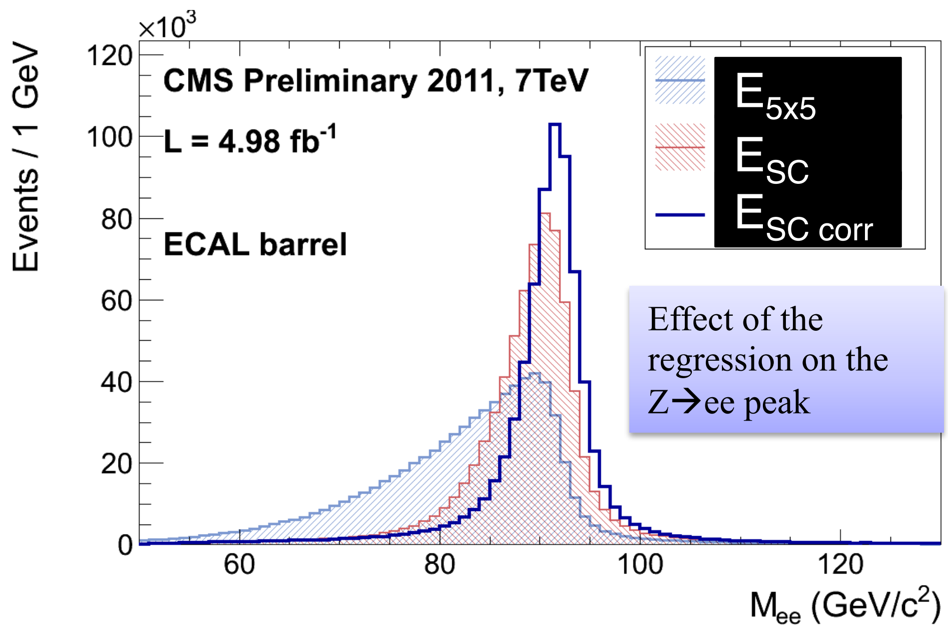
Will walk you thru key steps

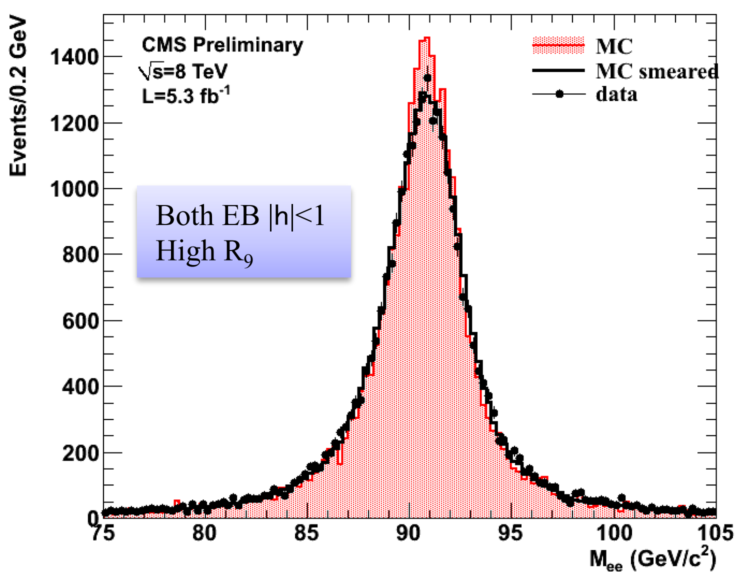
γ Energy Correction & Resolution (CMS)

- ECAL cluster energies corrected using a MC trained MVA regression
  - Raw cluster energies & position
  - Lateral & longitudinal shower shapes
  - Local shower position w.r.t crystal geometry
  - Pileup estimators, etc



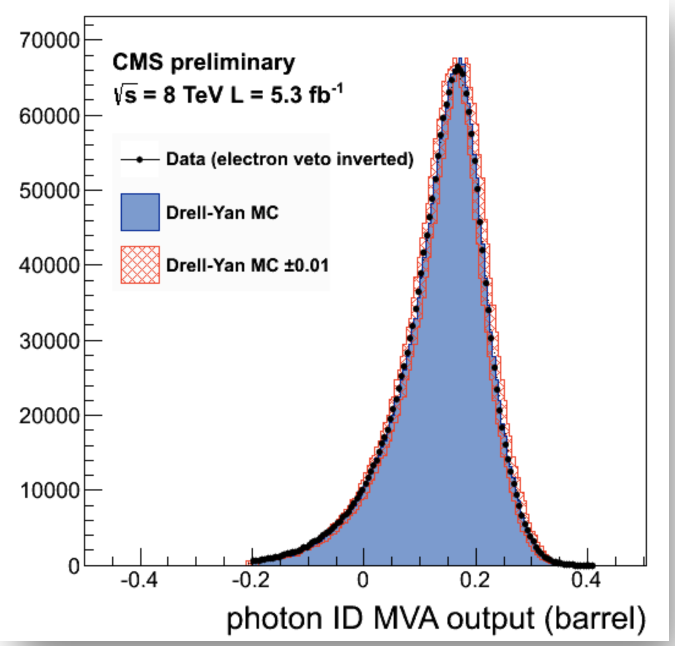
- Regression also used to estimate per-photon energy resolution
- Uses Z → ee events to measure energy scale and $M_{\gamma\gamma}$ resolution



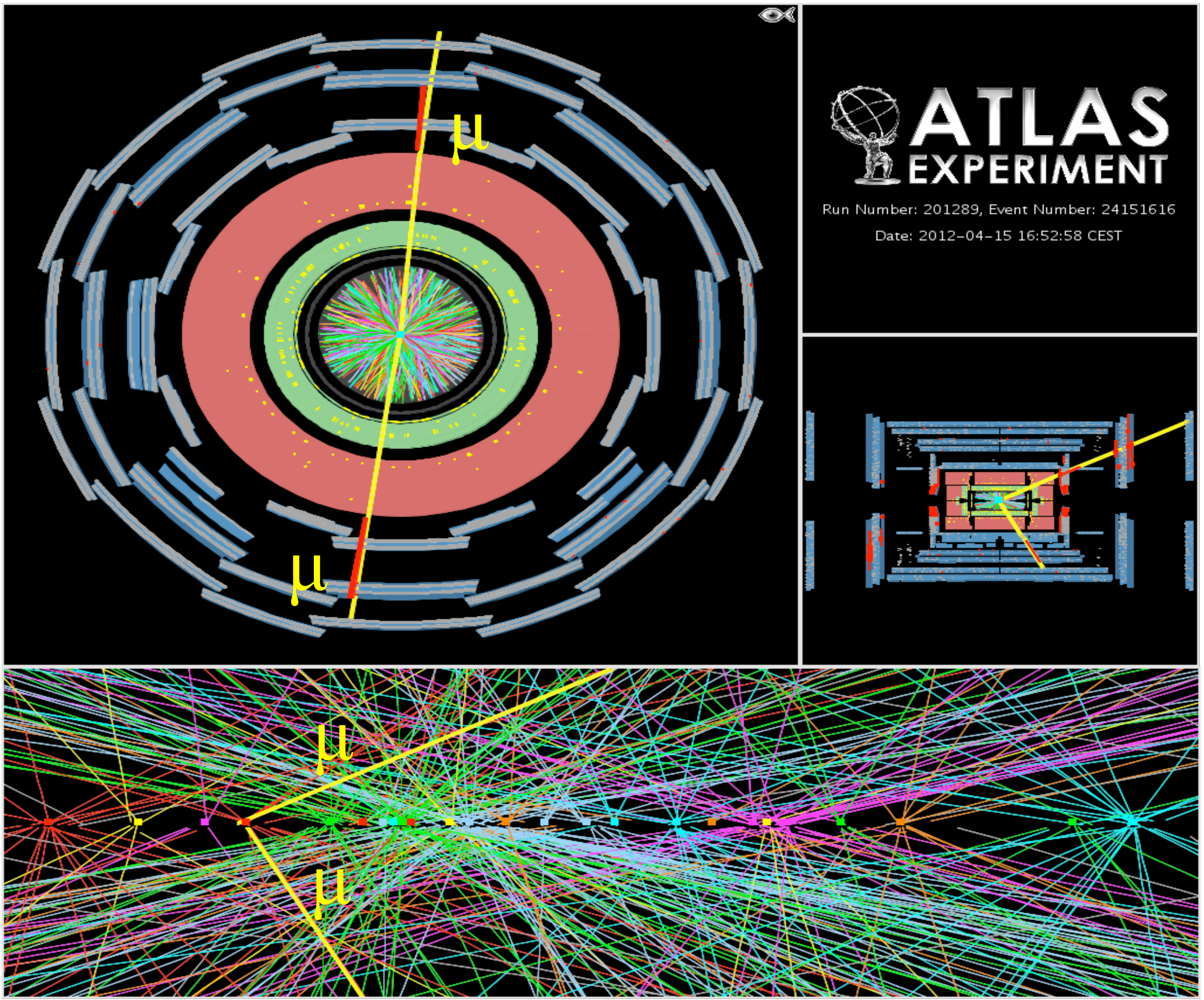


Photon Identification (CMS)

- Select di-photons with
  - $P_T^{\gamma 1} > M_{\gamma\gamma}/3$, $P_T^{\gamma 1} > M_{\gamma\gamma}/4$
- Photon Identification with a MVA method to separate prompt γ from π^0 produced in jets. Uses:
  - Isolation
  - Cluster shape
  - Per event energy density (pileup)
  - Pseudorapidity η
- Efficiency measured with Z→ ee events
- Electron veto eff measured with Z→ μμγ

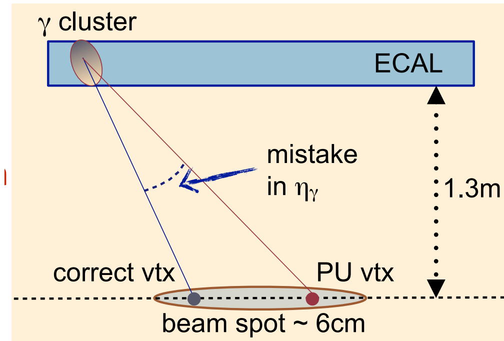


Selecting γγ Vertex In Pileup Events Can Be Tricky

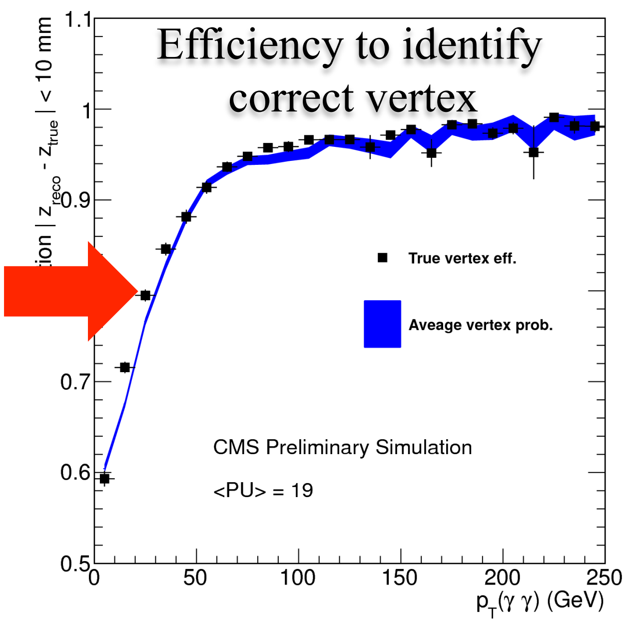


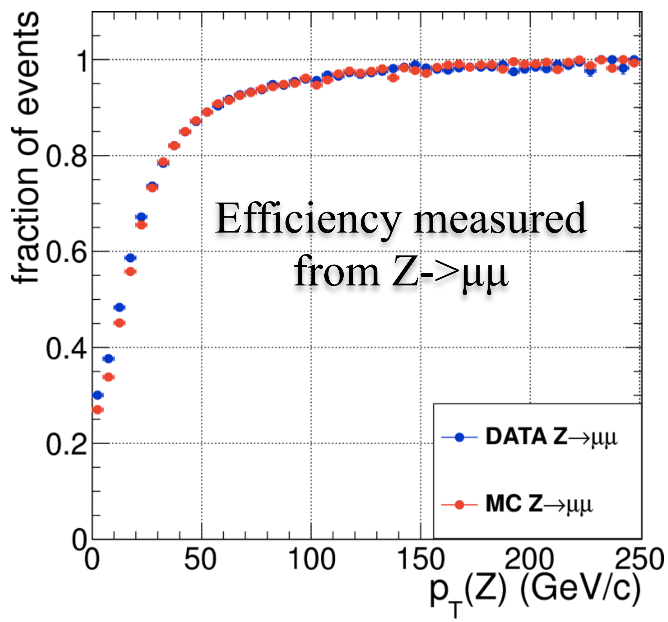
25 vertices

Selecting γγ Vertex (CMS)



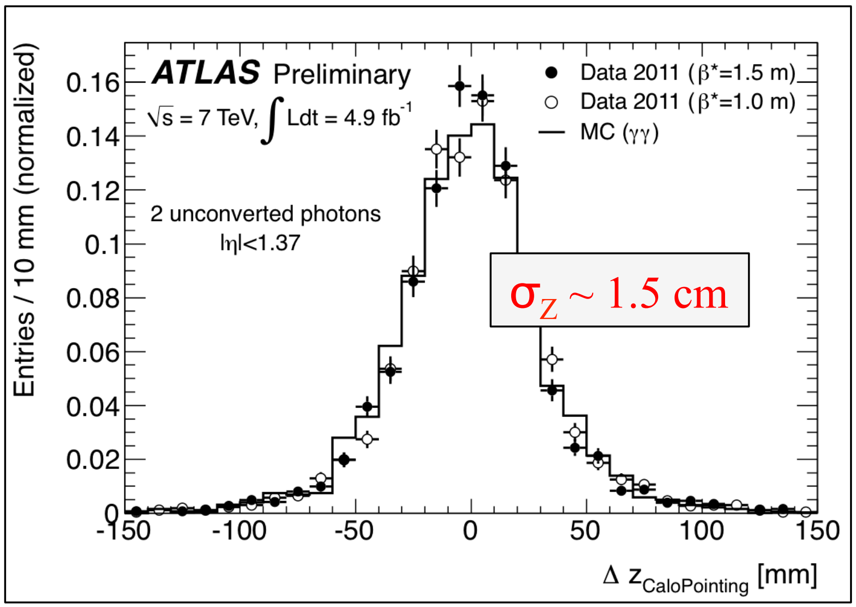
- $M^2_{\gamma\gamma} = 2E_1E_2(1-\cos\alpha)$,
  - $M_{\gamma\gamma}$ resolution depends on vertex selection
  - Important for high pileup events→ many choices
- No pointing →vertex identified using tracks from
  - recoiling jets and underlying event & γ→ee, Input variables: Σp_t^2, Σp_t projected onto the γγ transverse direction, p_t asymmetry and conversions
  - correct choice in ~83 (80)% of cases for pileup in 2011 (2012)

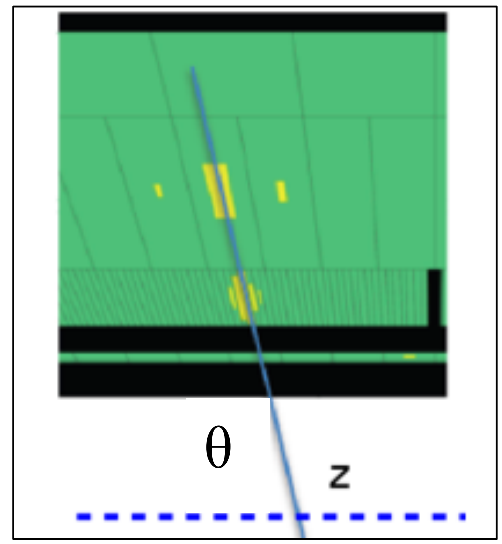




Selecting γγ Vertex (ATLAS)

- Measure γ direction with
  - EM calorimeter longitudinal segmentation (pointing to Z)
  - tracks from converted photons



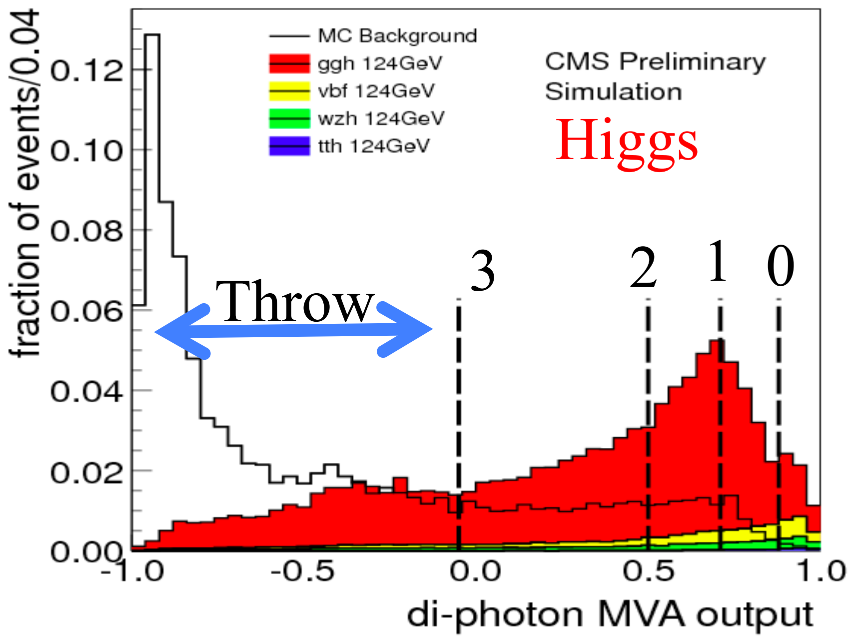


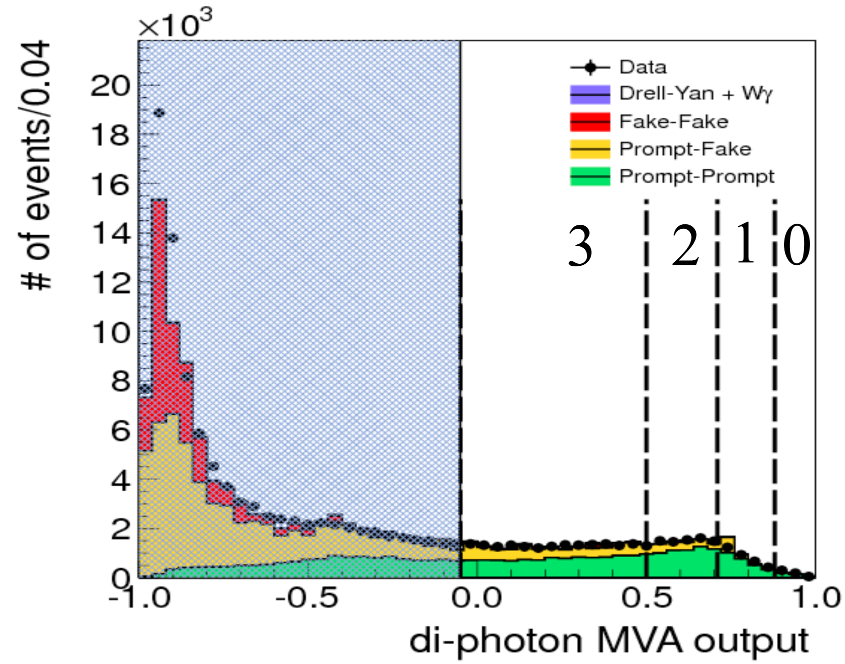
  - Good enough to make contribution to mass resolution from angular term negligible

Inclusive $\gamma\gamma$ Event Selection (CMS)

- Construct a MVA trained on signal & background MC. Input:
  - Photon ID MVA output of each photon
  - Expected $\gamma\gamma$ mass resolution and vertex probability
  - Kinematic variables: P_T of each γ and $\cos\Delta\phi$ between them
- MVA output independent of $M_{\gamma\gamma}$
- Form 4 $\gamma\gamma$ catagories
  - optimized to yield best expected limit in $H \rightarrow \gamma\gamma$

Inclusive γγ Event Catagorization (CMS)





Cat 0 : mostly $P_T^{\gamma\gamma} > 40$ GeV

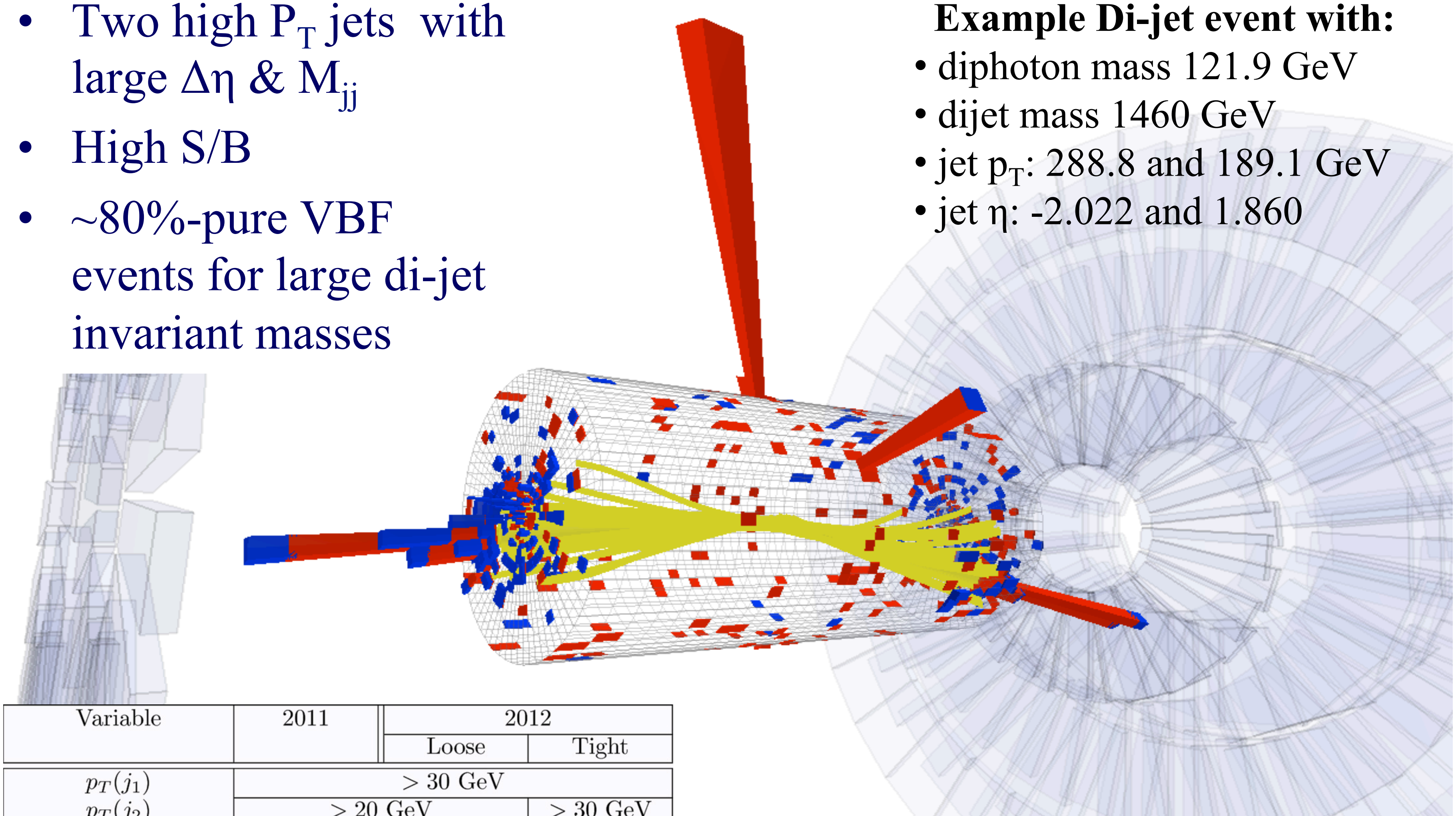
Cat1 : unconverted γ in barrel

Exclusive Dijet Tags: VBF-like Events

- Two high P_T jets with large $\Delta\eta$ & M_{jj}
- High S/B
- ~80%-pure VBF events for large di-jet invariant masses

Example Di-jet event with:

- diphoton mass 121.9 GeV
- dijet mass 1460 GeV
- jet p_T: 288.8 and 189.1 GeV
- jet η: -2.022 and 1.860



Variable	2011	2012	
		Loose	Tight
$p_T(j_1)$	> 30 GeV		
$p_T(j_2)$	> 20 GeV		> 30 GeV
$\Delta\eta(j_1, j_2)$	> 3.5	> 3.0	
$\lvert\eta_{\gamma\gamma} - \frac{1}{2}(\eta_{j1} + \eta_{j2})\rvert$	< 2.5		
$\Delta\phi(jj, \gamma\gamma)$	> 2.6		
m_{jj}	> 350 GeV	> 250 GeV	> 500 GeV

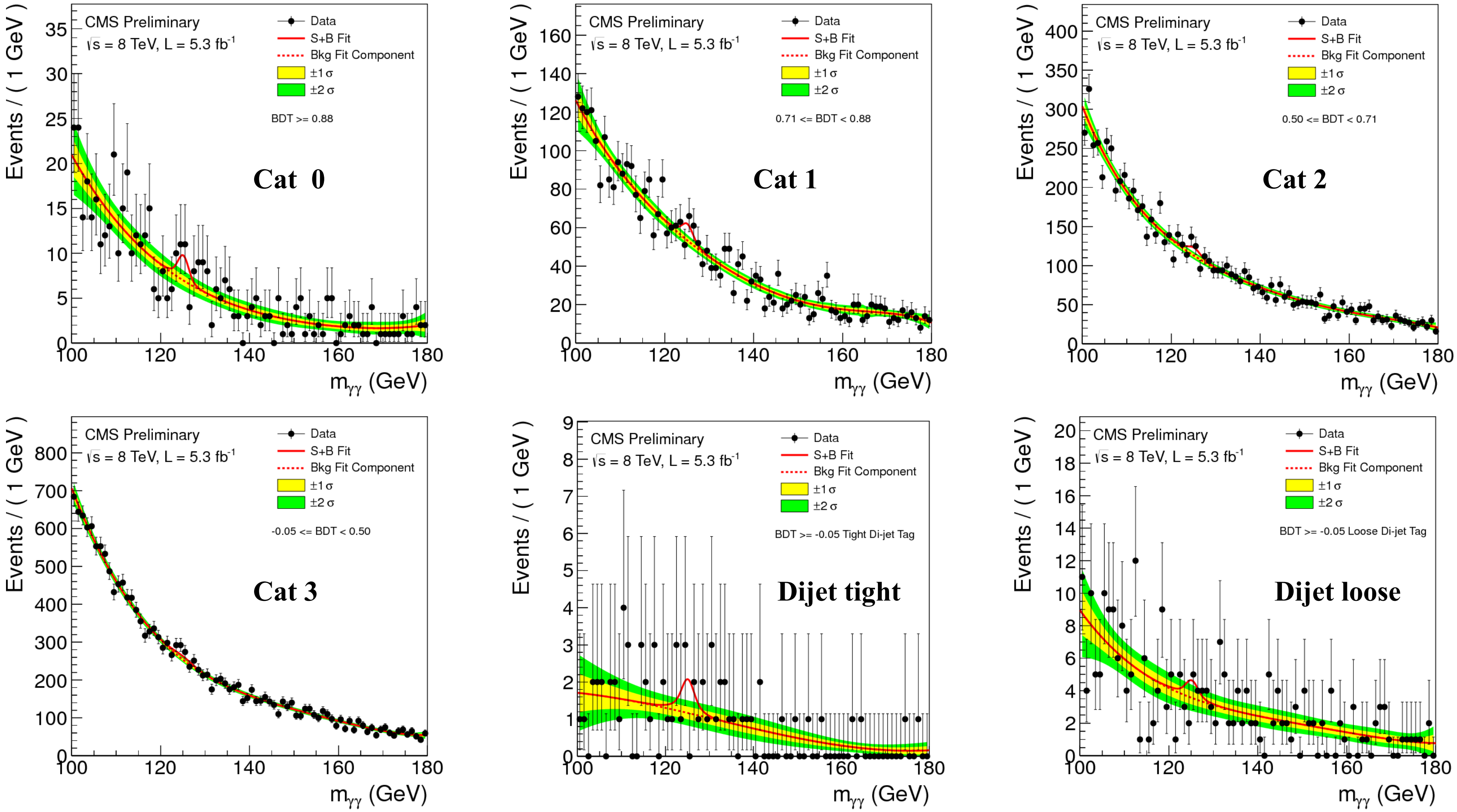
Performance By Catagory

Expected signal and estimated background

Event classes		SM Higgs boson expected signal (m_H=125 GeV) Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	Background $m_{\gamma\gamma} = 125$ GeV (ev./GeV)
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61%	17%	19%	3%	1.21	1.14	3.3 ± 0.4
	Untagged 1	16.3	88%	6%	6%	1%	1.26	1.08	37.5 ± 1.3
	Untagged 2	21.5	91%	4%	4%	–	1.59	1.32	74.8 ± 1.9
	Untagged 3	32.8	91%	4%	4%	–	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	27%	73%	1%	–	1.73	1.37	1.7 ± 0.2
8 TeV 5.3 fb^{-1}	Untagged 0	6.1	68%	12%	16%	4%	1.38	1.23	7.4 ± 0.6
	Untagged 1	21.0	88%	6%	6%	1%	1.53	1.31	54.7 ± 1.5
	Untagged 2	30.2	92%	4%	3%	–	1.94	1.55	115.2 ± 2.3
	Untagged 3	40.0	92%	4%	4%	–	2.86	2.35	256.5 ± 3.4
	Dijet tight	2.6	23%	77%	–	–	2.06	1.57	1.3 ± 0.2
	Dijet loose	3.0	53%	45%	2%	–	1.95	1.48	3.7 ± 0.4

Category 3 diphotons have the worst $M_{\gamma\gamma}$ resolution & S/B

γγ Mass Distribution By Catagories (8 TeV)



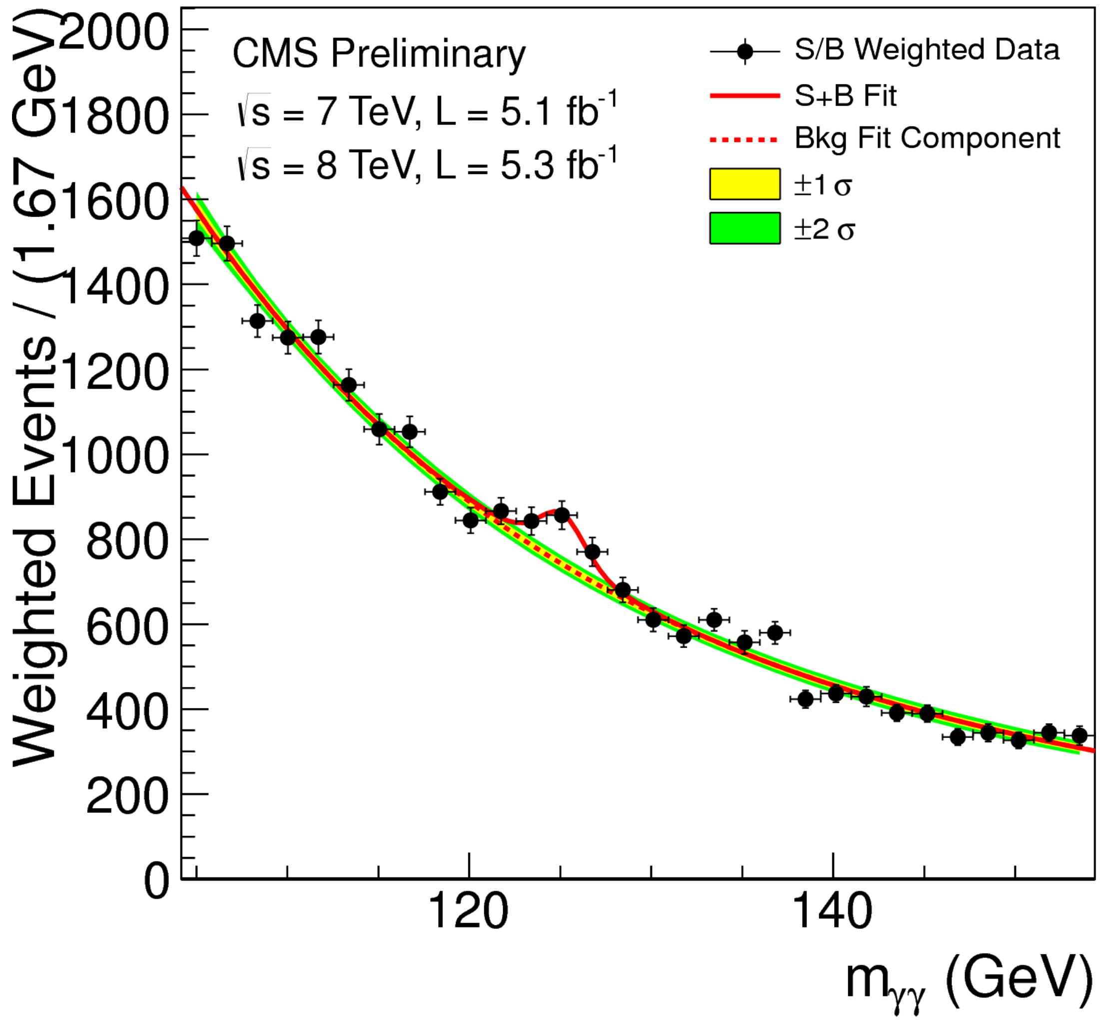
Catagories with good S/N show enhancement at ~125 GeV

but not obvious to naked eye !

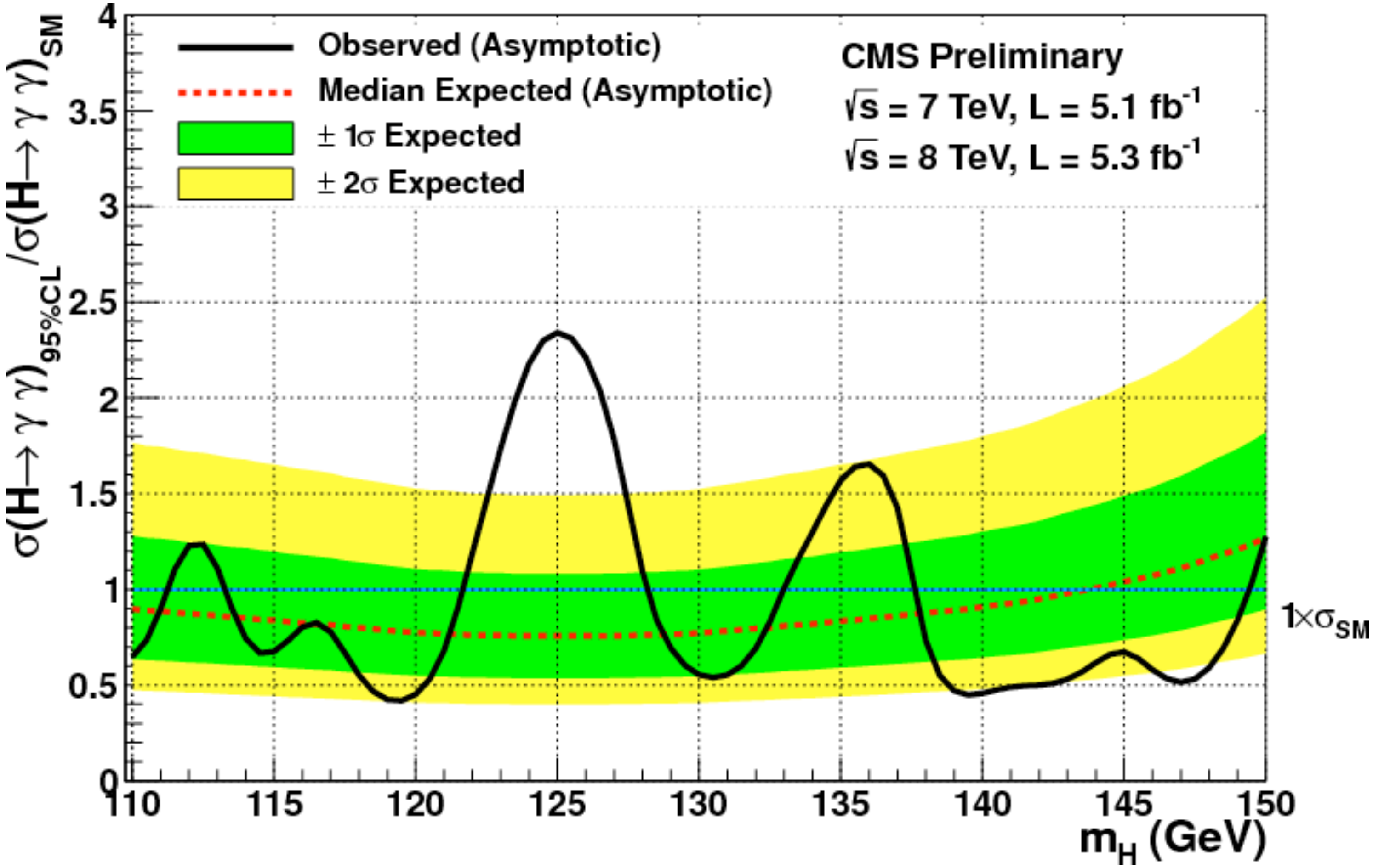
Fit all catagories simultaneously with a signal & background model

Combined Mass Distribution Weighted by S/B

- Sum of mass distributions for each catagory, weighted by S/B
- B is integral of background model over a constant signal fraction interval

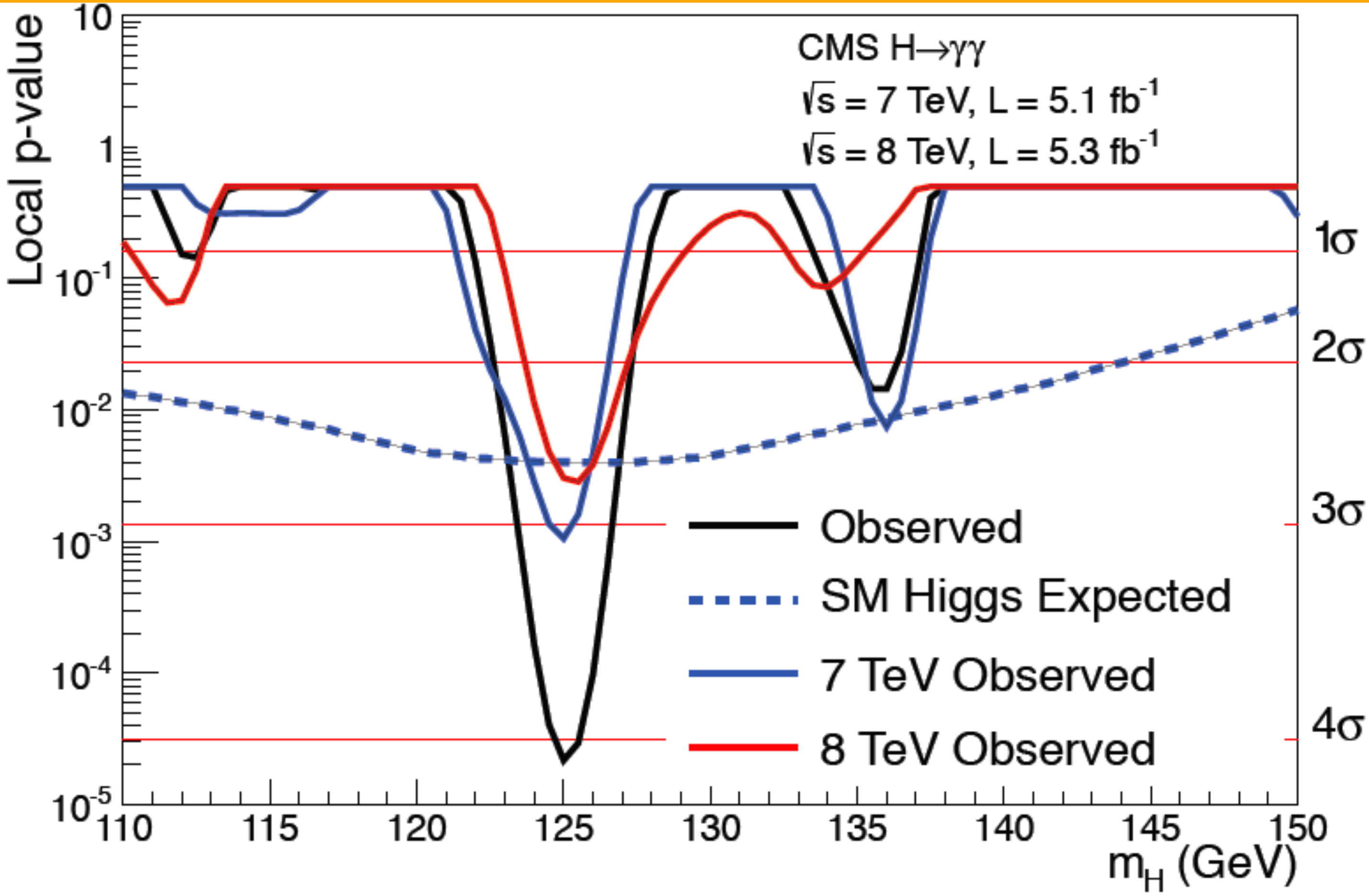


95% SM Higgs Exclusion Limit



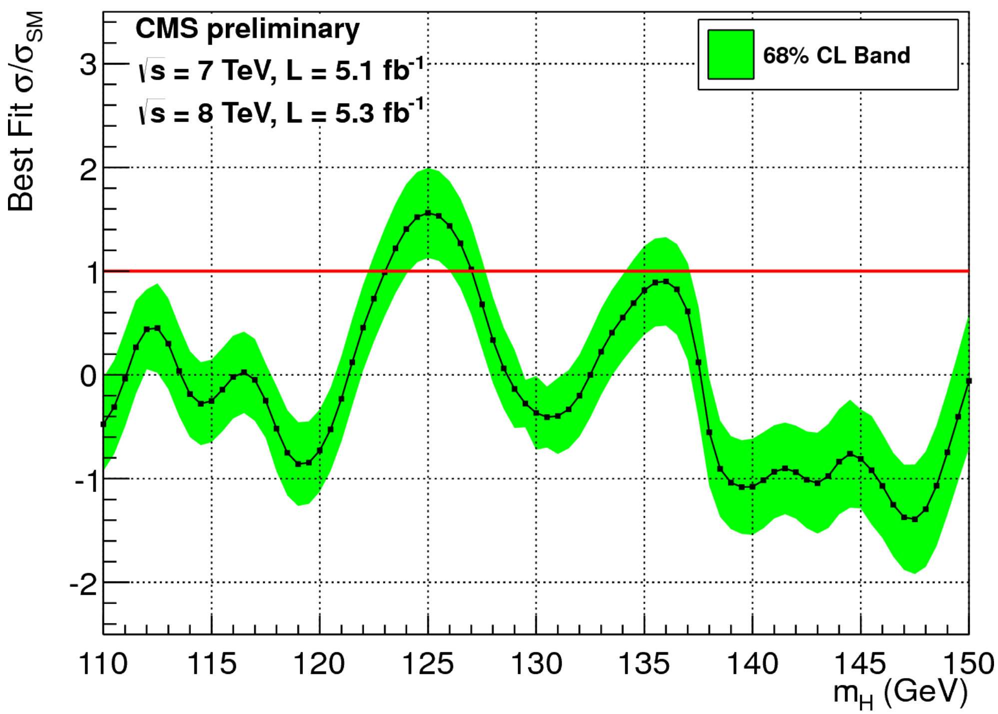
- Expected 95% CL exclusion 0.76 x σ_{SM} at M = 125 GeV
- Large range with expected exclusion below σ_{SM}
- Largest excess at 125 GeV

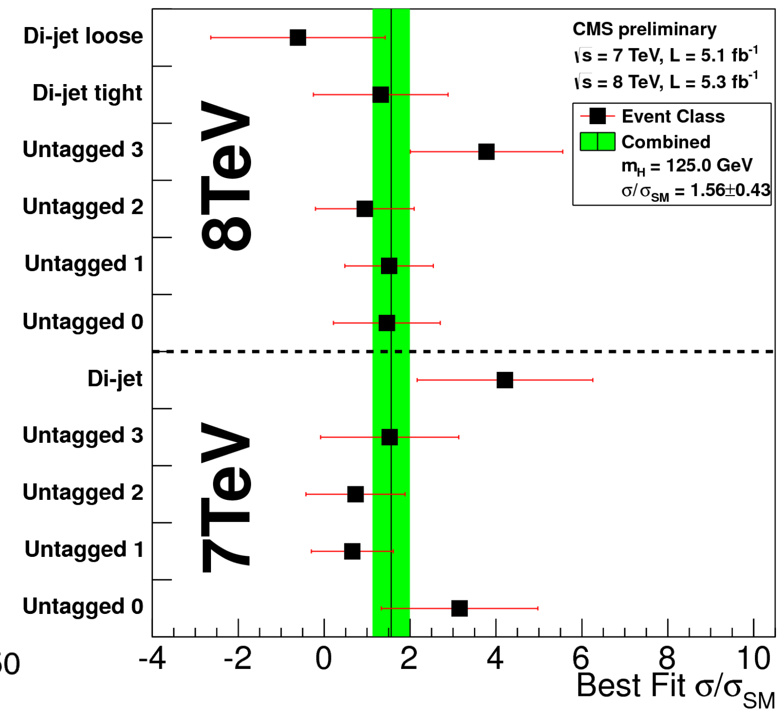
Scan Of p-value Vs Mass



- Minimum p-value at 125 GeV with a local significance of 4.1 σ
- Similar excess at same mass in 2011 and 2012
- Global significance in the full search range (110-150 GeV): 3.2 σ

Fitted Signal Strength σ/σ_{SM}



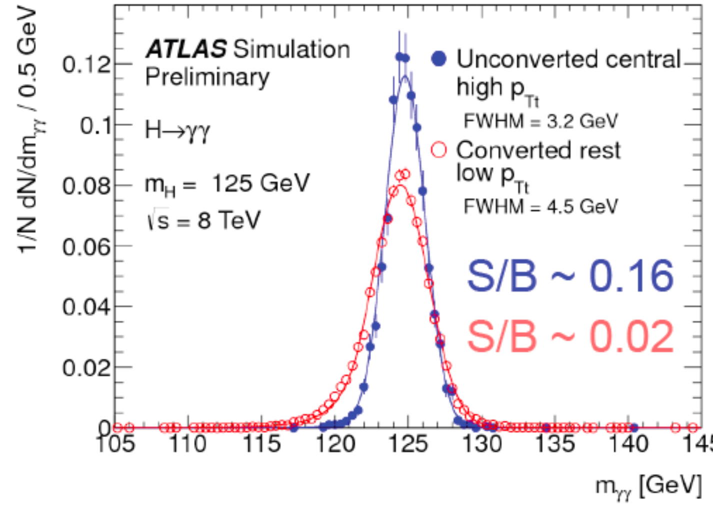


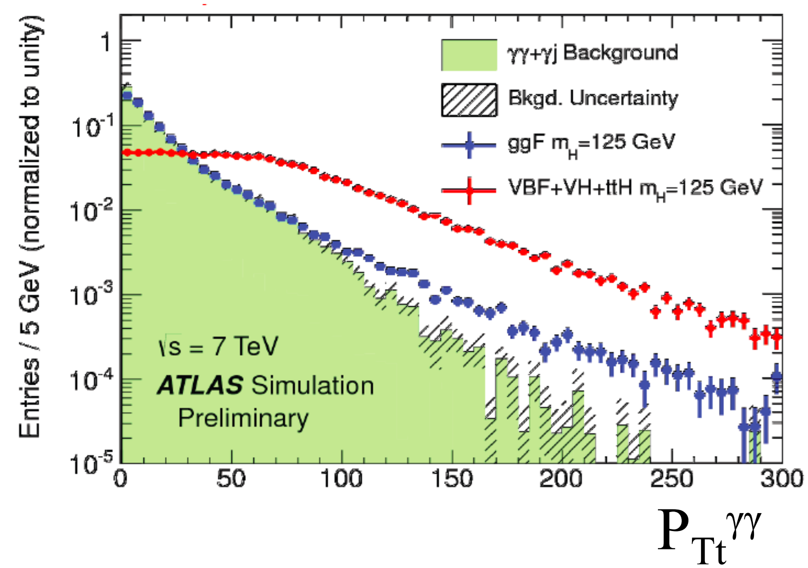
Combined best fit signal strength
$\sigma/\sigma_{SM} = 1.56 \pm 0.43$
consistent with but larger than SM

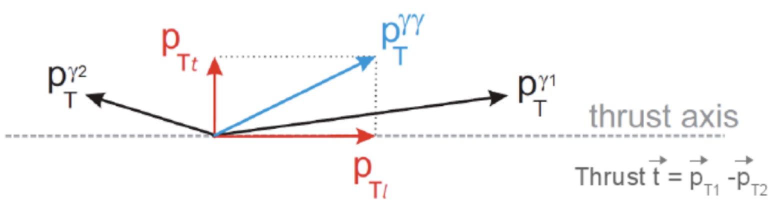
Best fit signal strength consistent between different classes and datasets

ATLAS Catagorization of γγ Events

- Catagorize events by S/B based on
  - Both γ unconverted or ≥ 1 converted
  - Both γ are central (|η| < 0.75)
  - One in EB-EE transition region
  - And the rest
  - $P_T^{\gamma\gamma}$ > 60 GeV or less
- Di-jet category
  - P_{Tt}^{jet} > 25-30 GeV
  - $\Delta\eta_{jets}$ > 2,8
  - M_{jj} > 400 GeV
  - Back to back dijets & γγ (Δϕ >2.6)







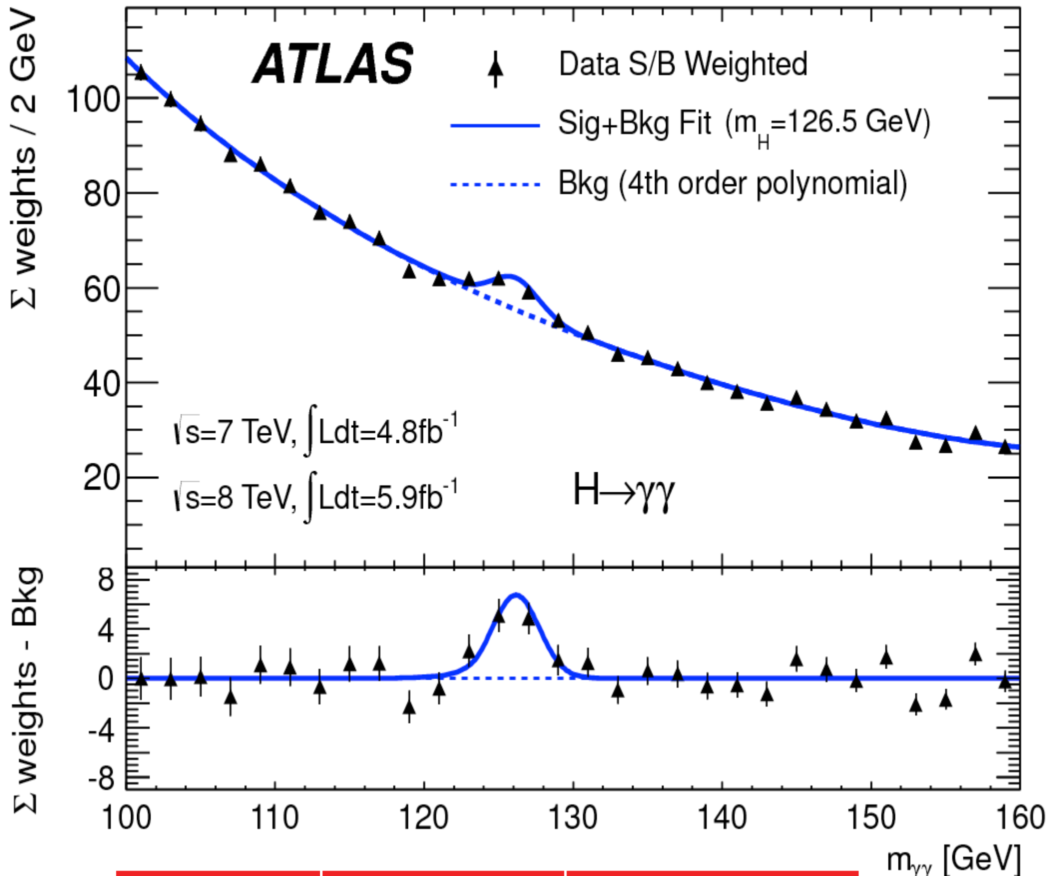
ATLAS Catagorization of γγ Events : 8 TeV

Strength of categorization: different resolution, different S/B ($1\% - 20\%$)

Category	σ_{CB} [GeV]	FWHM [GeV]	Observed [N_{evt}]	S [N_{evt}]	B [N_{evt}]
Inclusive	1.63	3.87	3693	100.4	3635
Unconverted central, low p_{Tt}	1.45	3.42	235	13.0	215
Unconverted central, high p_{Tt}	1.37	3.23	15	2.3	14
Unconverted rest, low p_{Tt}	1.57	3.72	1131	28.3	1133
Unconverted rest, high p_{Tt}	1.51	3.55	75	4.8	68
Converted central, low p_{Tt}	1.67	3.94	208	8.2	193
Converted central, high p_{Tt}	1.50	3.54	13	1.5	10
Converted rest, low p_{Tt}	1.93	4.54	1350	24.6	1346
Converted rest, high p_{Tt}	1.68	3.96	69	4.1	72
Converted transition	2.65	6.24	880	11.7	845
2-jets	1.57	3.70	18	2.6	12

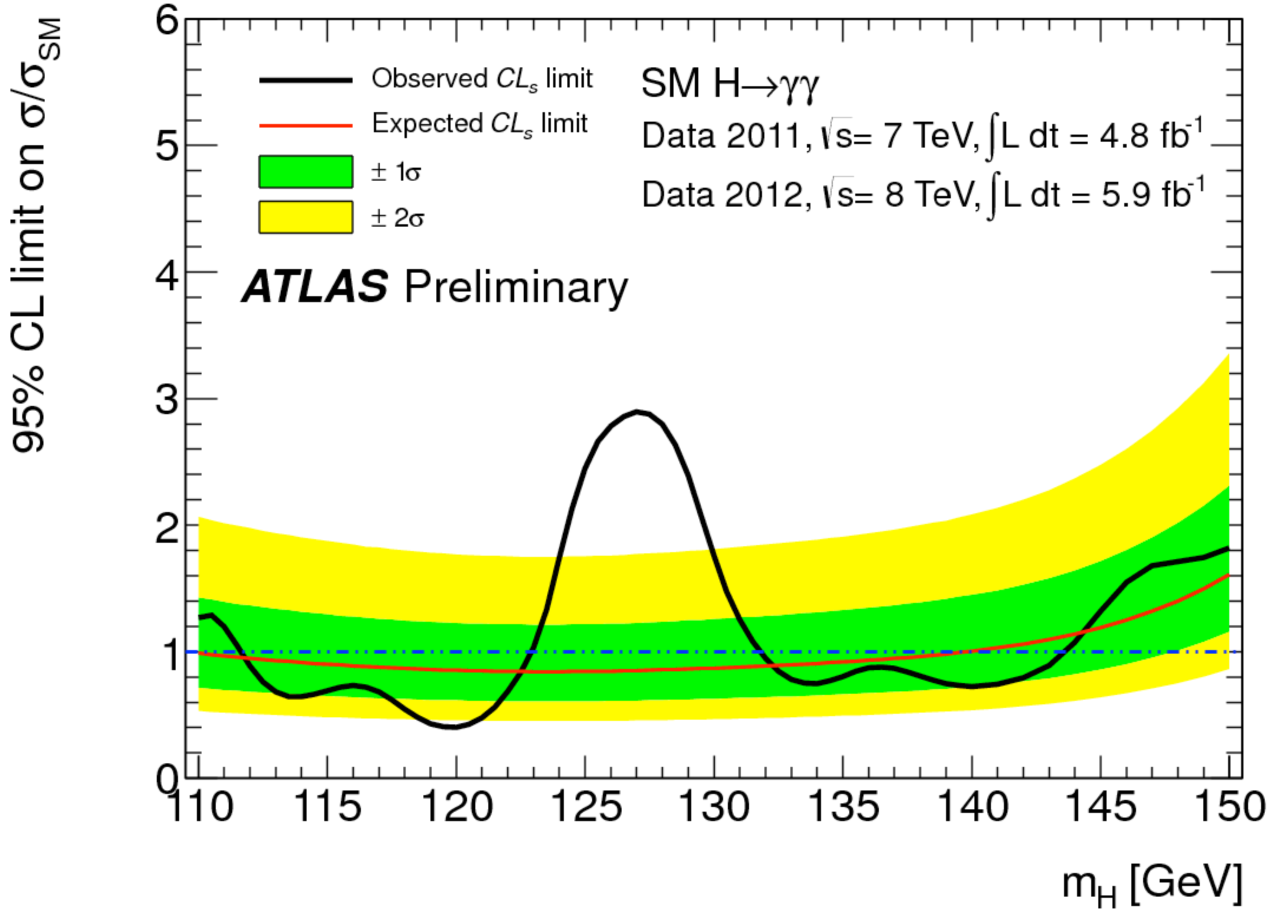
In all, 10 catagories, each fitted with a signal & background model

$M_{\gamma\gamma}$ Distribution : Weighed by S/B In Each Catagory



Signal Yield in	Observed	Expected
2011	146.9	79.4
2012	205.5	111.1

95% Exclusion Limit

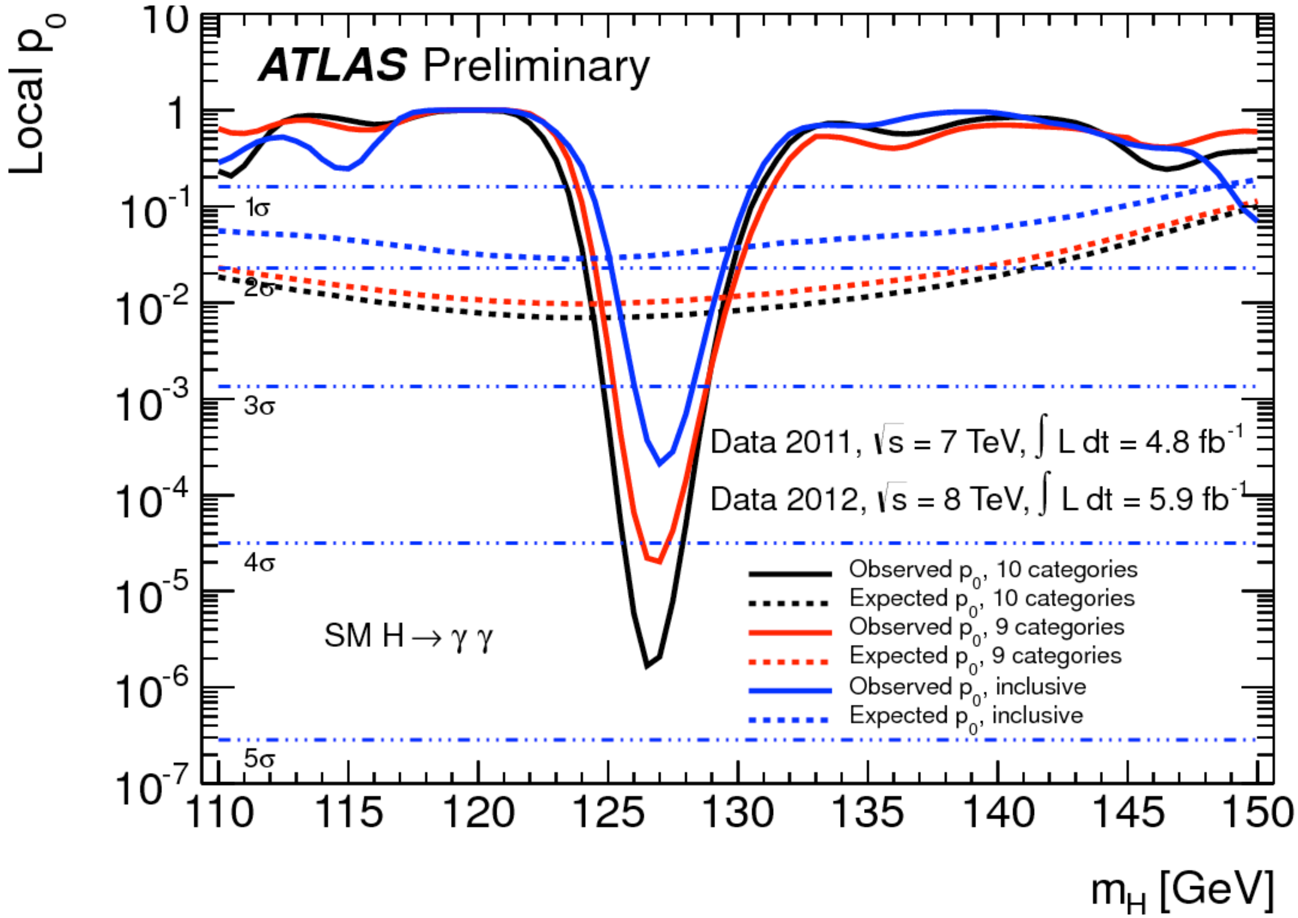


Exclusion sensitivity below SM expectation till M_H = 140 GeV

Observed exclusion : [112-122.5, 132-143] GeV

Observe significant excess over Bkgnd only hypothesis @ 126.5 GeV

p-Values: 7, 8 TeV and Combined

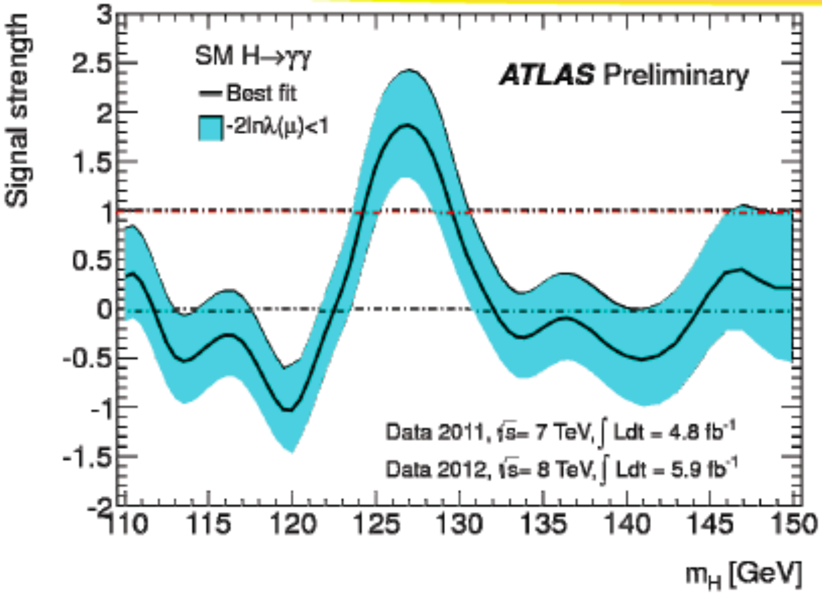


Most significant deviation from bkgnd-only hypothesis @ 126.5 GeV

Observed local significance 4.7σ, Expected = 2.4σ

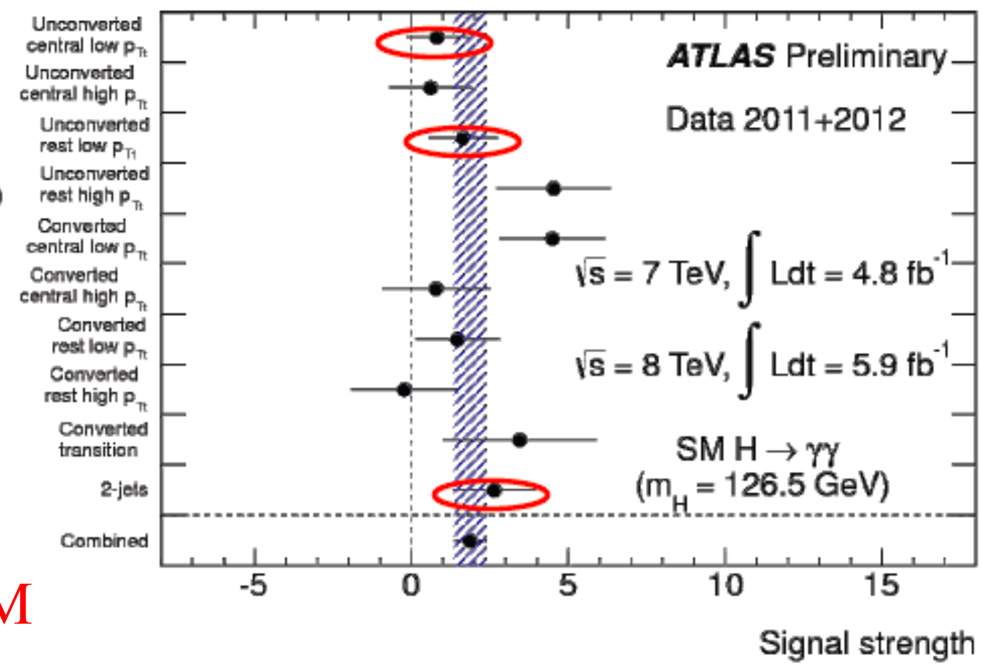
Similar sized excesses (3.5σ, 3.4σ) at compatibles masses !

Signal Strengths



- Fitted signal strength μ=1.9±0.5 at m_H=126.5 GeV

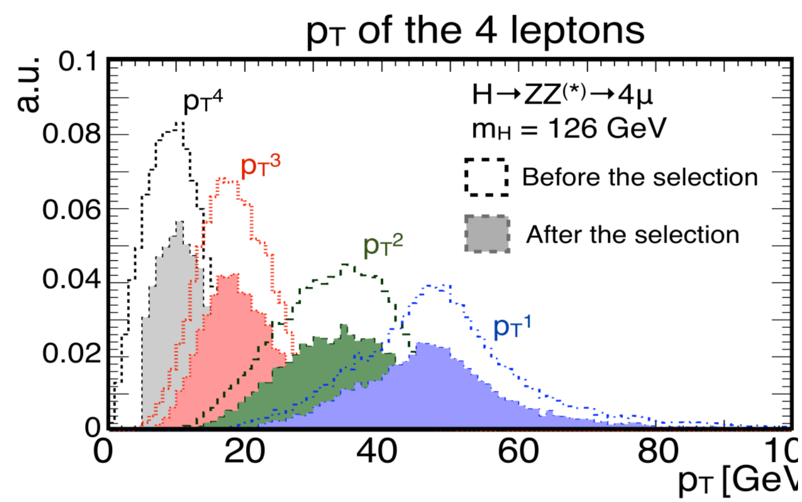
- Breakdown of results by fit categories
  - Most sensitive categories indicated
  - No particular surprises



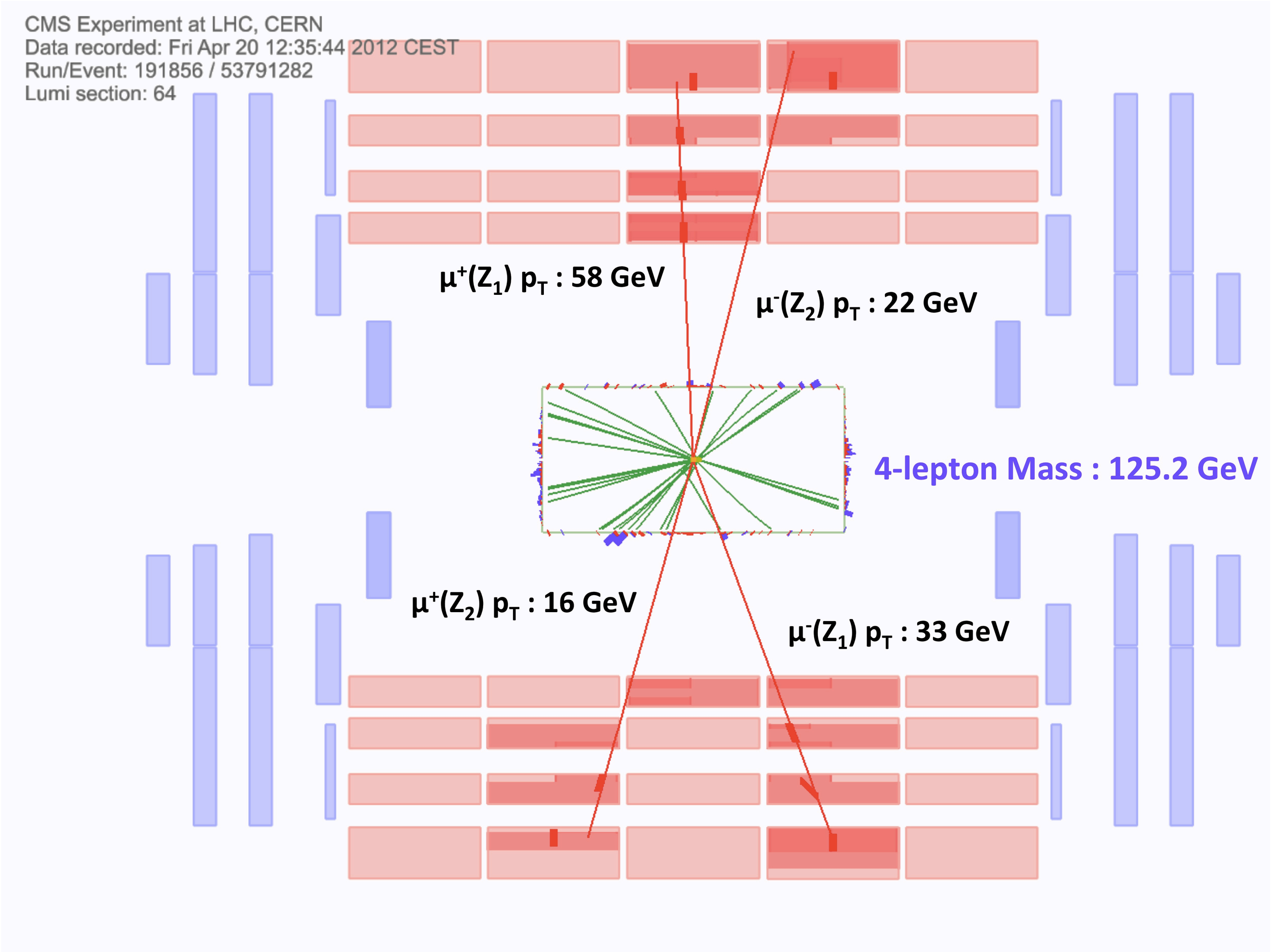
Observed rate consistent with SM but larger in central value (1.9)

H → ZZ → 4l

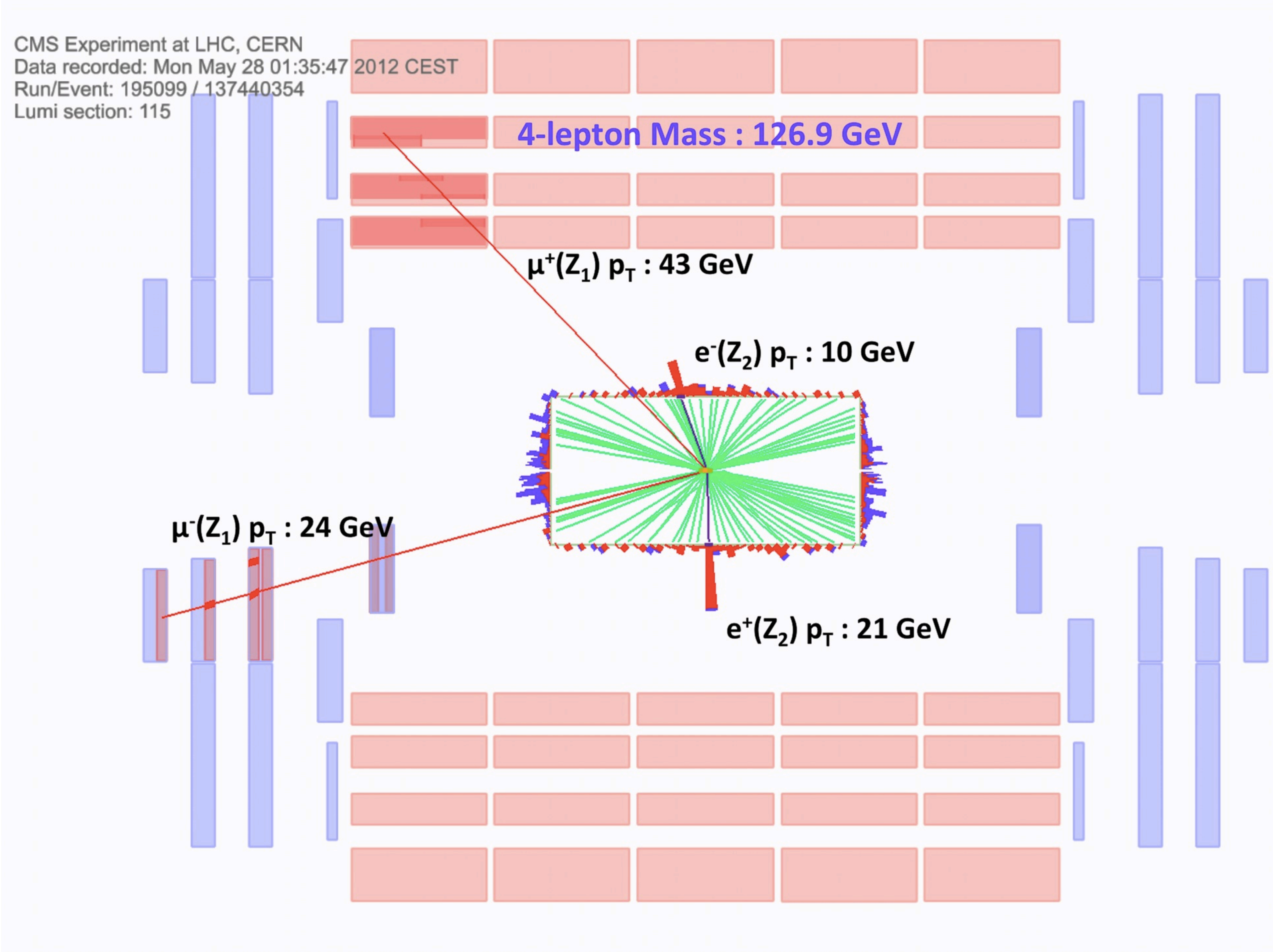
- Golden channel : Four isolated leptons from one point in 3D space
- Benefits from excellent electron and muon energy resolution
  - M_{4l} mass resolution ≈ 1-2 %
- σ×Br(H→ ZZ→ 4l) quite small
  - Needs highest selection efficiency po → Efficient lepton identification over broad P_t range
- Backgrounds
  - Non-resonant pp→ ZZ→4l is largest a irreducible, has same topological signature as H → 4l
    - **But no narrow peak as in H → ZZ**
  - Z+jets,ttbar, WZ…all reducible and important at low M_{4l}



H → ZZ → 4μ

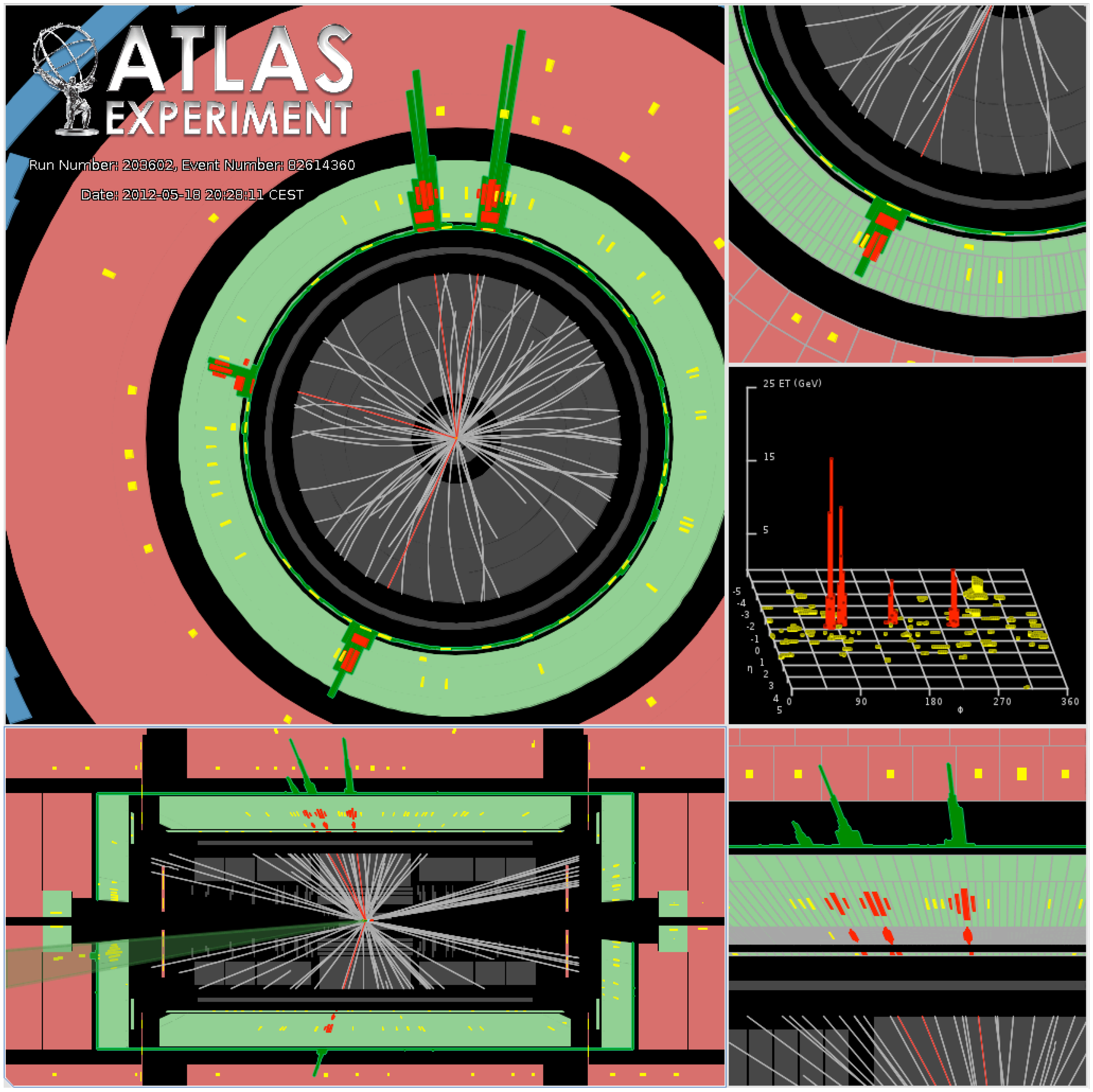

CMS Experiment at LHC, CERN
Data recorded: Fri Apr 20 12:35:44 2012 CEST
Run/Event: 191856 / 53791282
Lumi section: 64
μ+(Z1) pT : 58 GeV
μ-(Z2) pT : 22 GeV
4-lepton Mass : 125.2 GeV
μ+(Z2) pT : 16 GeV
μ-(Z1) pT : 33 GeV

H → ZZ → 2μ 2e



CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115
4-lepton Mass : 126.9 GeV
$\mu^+(Z_1)$ p_T : 43 GeV
$e^-(Z_2)$ p_T : 10 GeV
$\mu^-(Z_1)$ p_T : 24 GeV
$e^+(Z_2)$ p_T : 21 GeV

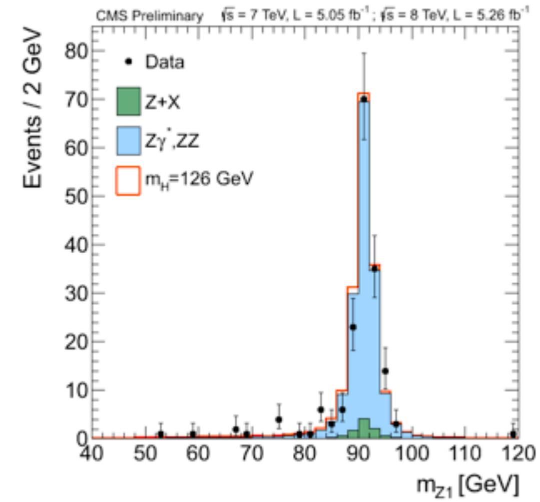
H → ZZ → 4e

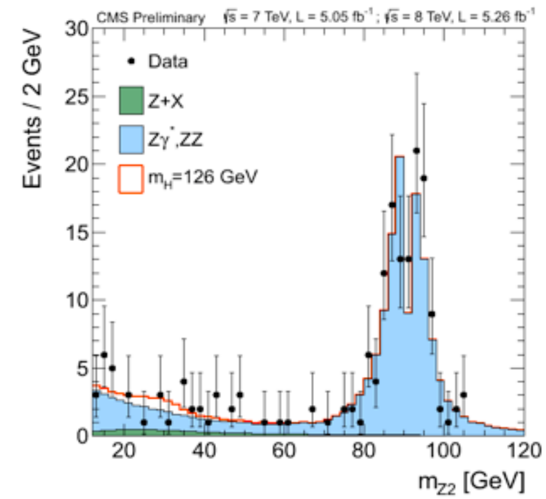


ATLAS
EXPERIMENT
Run Number: 203602, Event Number: 82614360
Date: 2012-05-18 20:28:11 CEST
25 ET (GeV)
15
5
η
0
90
180
270
360
φ

$H \rightarrow ZZ \rightarrow 4l$ Event Selection : CMS

- Leptons compatible with primary vertex & isolated
  - muons: $p_T > 5$ GeV, $|\eta| < 2.4$
  - electrons: $p_T > 7$ GeV, $|\eta| < 2.5$
  - at least one lepton with $p_T > 20$ GeV
  - at least two leptons with $p_T > 10$ GeV
- First Z candidate (Z_1)
  - chosen as di-lepton pair with m(ll) closest to m_Z
  - 40 < m(ll) < 120 GeV
- Second Z candidate (Z_2)
  - build from remaining highest p_T leptons
  - 12 < m(ll) < 120 GeV

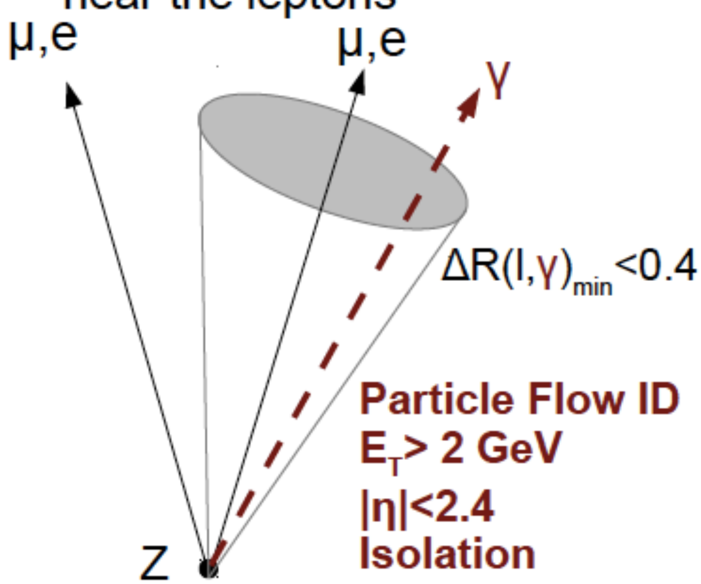




Final State Radiation Recovery

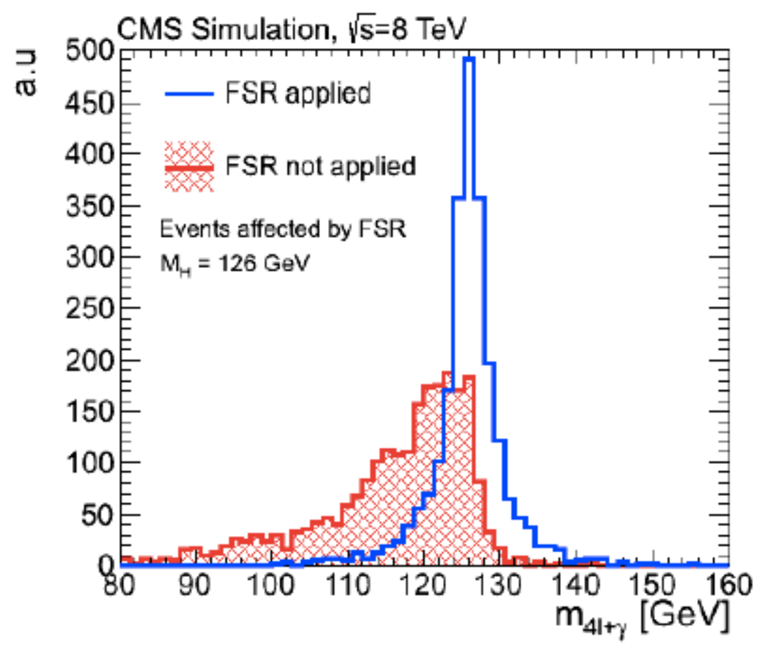
- Sometimes the leptons radiate photons, CMS attempts to find them

  - Applied on each Z for photons near the leptons

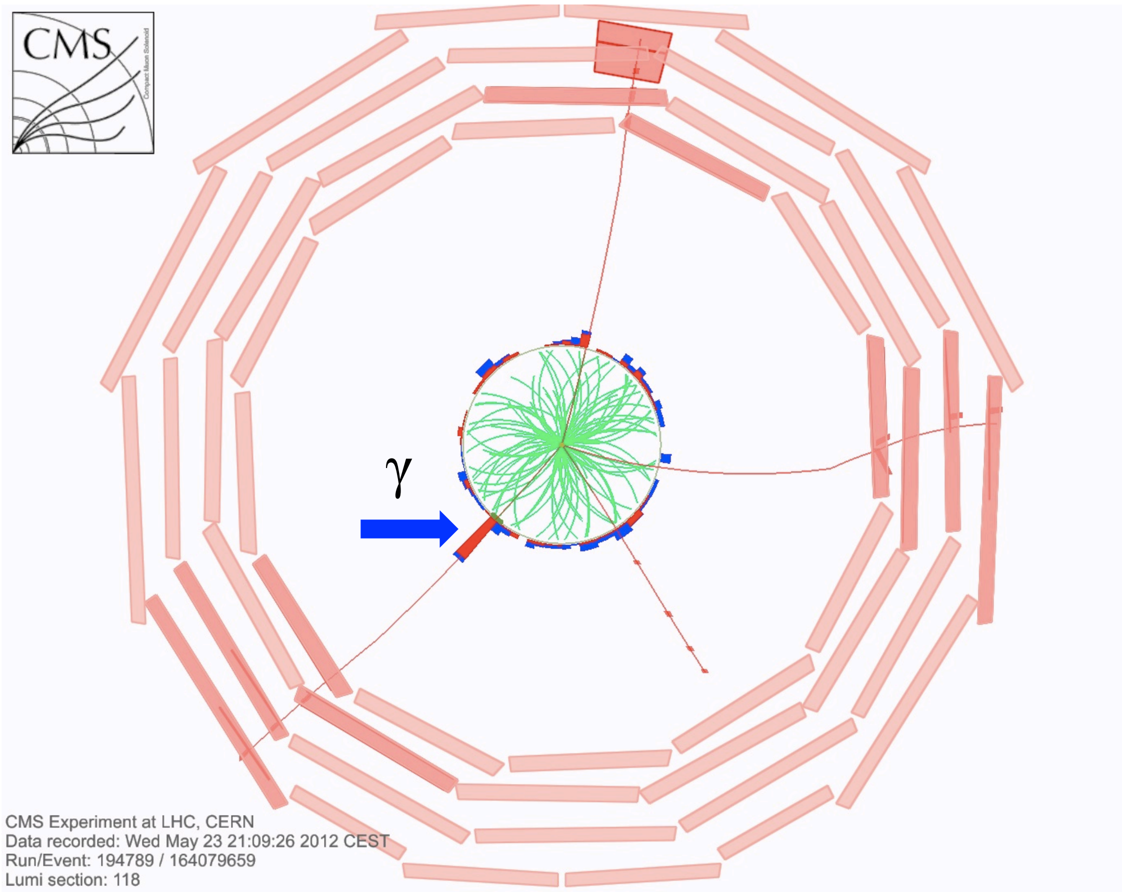


  - Associates the photon with Z if:
    - $M(ll+\gamma) < 95$ GeV
    - $|M(ll+\gamma)-M_Z|<|M(ll)-M_Z|$
  - Removes associated photons from lepton isolation calculation

  - Expected Performance
    - 6% of the events affected
    - 4.8% of the events: mass improved
    - 1.2% of the events: mass degraded
    - 2% more events added into sample after FSR recovery

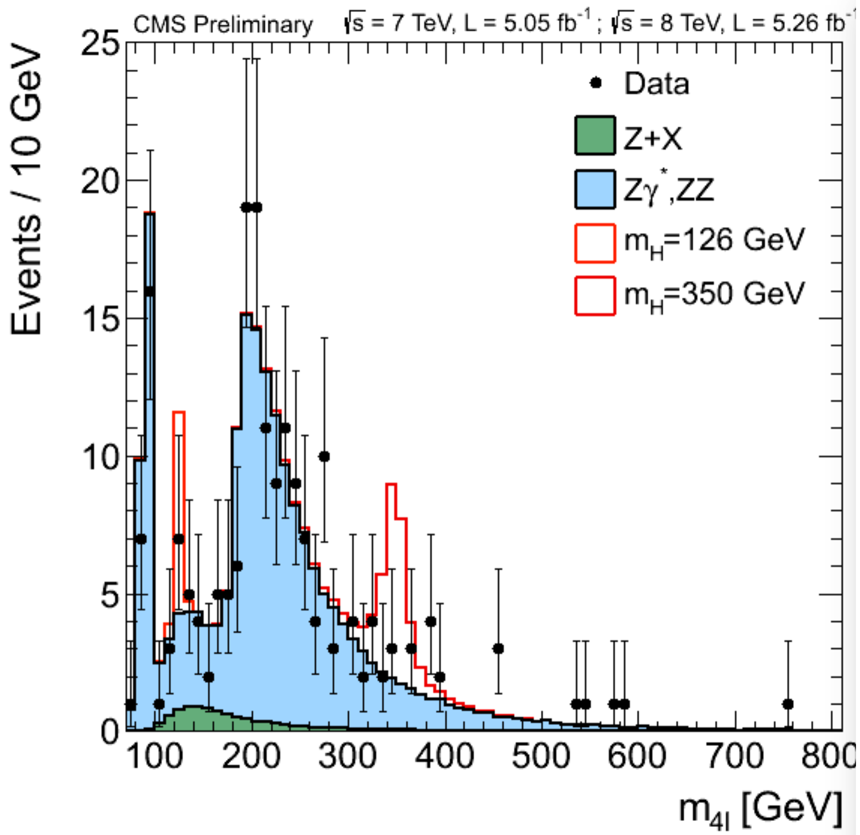


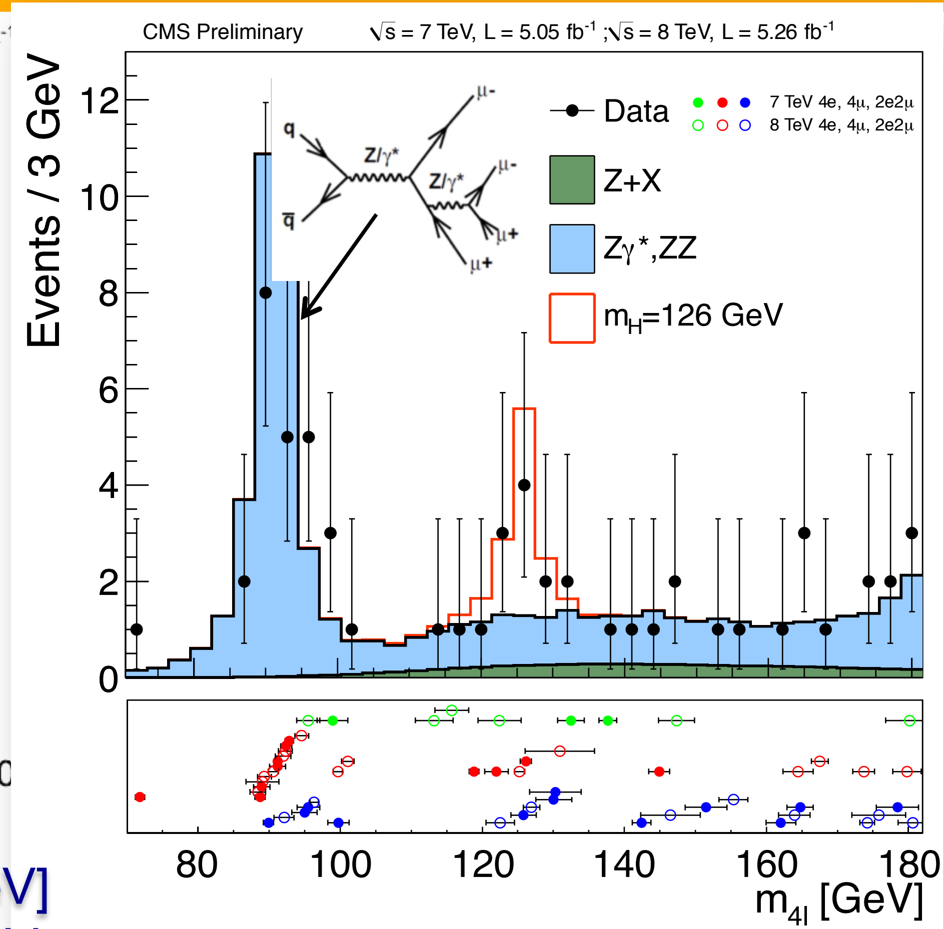
Example of Final State Radiation Recovery



FSR recovery has small impact on CMS Higgs search sensitivity (~ 3%) but enhances robustness for small statistics searches as currently

4l Mass Spectrum In Data : CMS

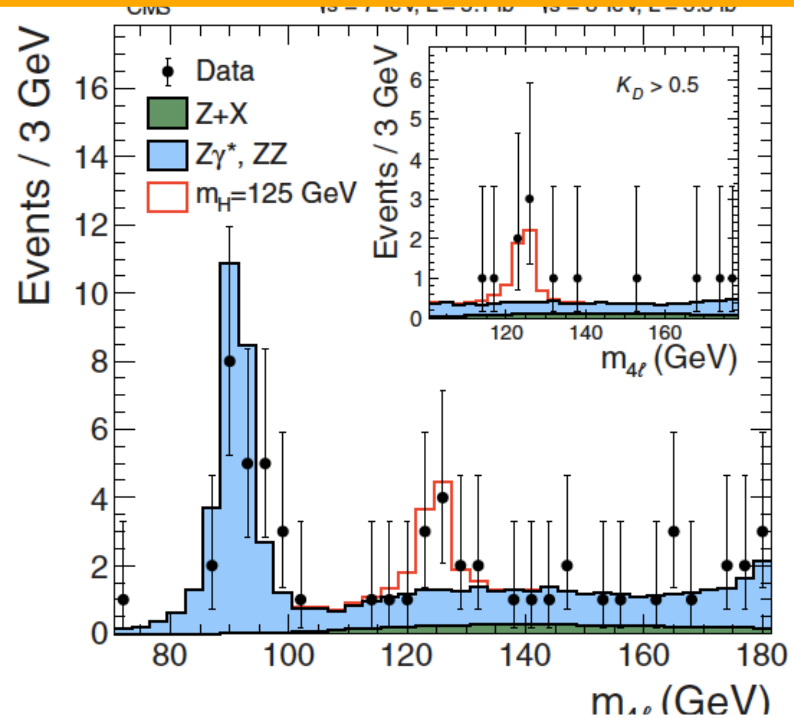




164 events expected in [100, 800 GeV]
172 events observed in [100, 800 GeV]

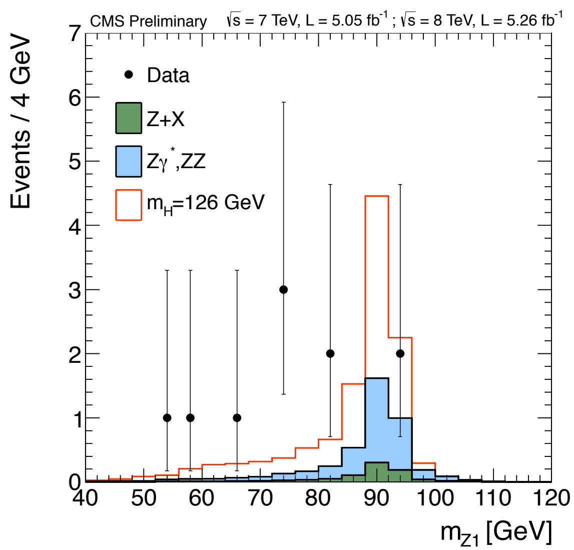
An excess observed near M = 126 GeV

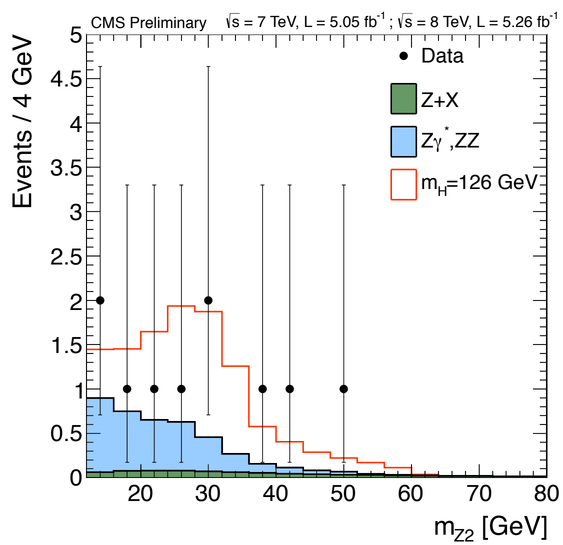
H → ZZ→ 4l Event yield : CMS

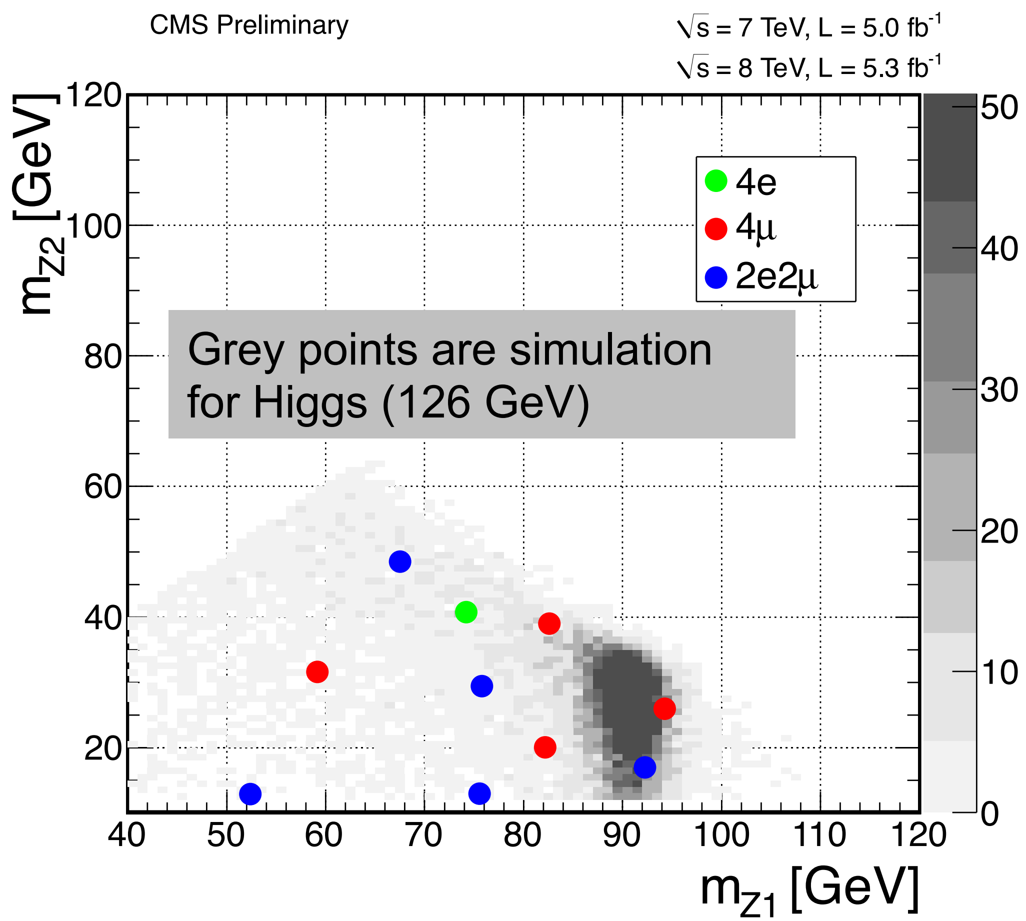


Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	2.7 ± 0.3	5.7 ± 0.6	7.2 ± 0.8	15.6 ± 1.4
$Z + X$	$1.2^{+1.1}_{-0.8}$	$0.9^{+0.7}_{-0.6}$	$2.3^{+1.8}_{-1.4}$	$4.4^{+2.2}_{-1.7}$
All backgrounds ($110 < m_{4\ell} < 160\,\mathrm{GeV}$)	4.0 ± 1.0	6.6 ± 0.9	9.7 ± 1.8	20 ± 3
Observed ($110 < m_{4\ell} < 160\,\mathrm{GeV}$)	6	6	9	21
Signal ($m_\mathrm{H} = 125\,\mathrm{GeV}$)	1.36 ± 0.22	2.74 ± 0.32	3.44 ± 0.44	7.54 ± 0.78
All backgrounds (signal region)	0.7 ± 0.2	1.3 ± 0.1	1.9 ± 0.3	3.8 ± 0.5
Observed (signal region)	1	3	5	9

An Odd Aspect: Z_1 Vs Z_2 Mass In H → ZZ





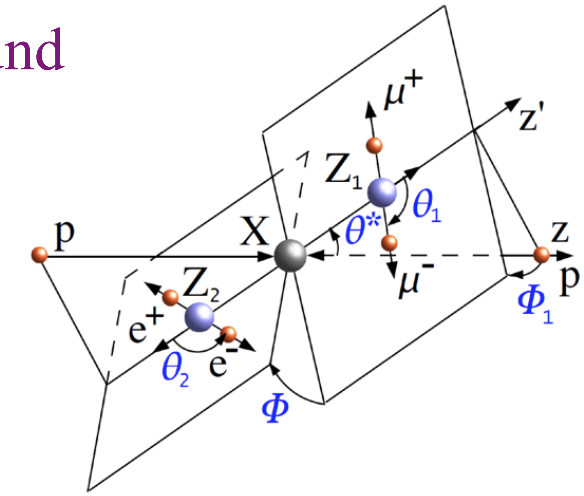


Probablity of observing such a fluctuation is ≈ 1%

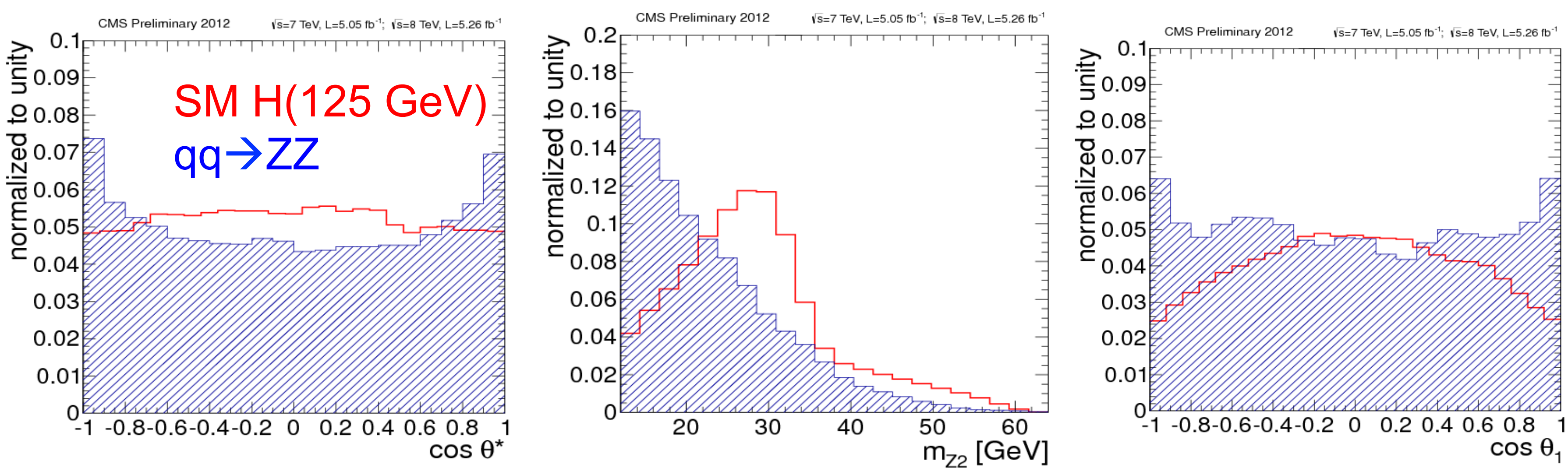
Angular Analysis In H → ZZ → 4l (CMS)

- H → ZZ → 4l Decay kinematic fully described by 5 angles and the 2 Z masses
  - discriminates spin 0 particle from background
  - MELA: matrix element likelihood analysis

PR(D) 81, 075022(2010)

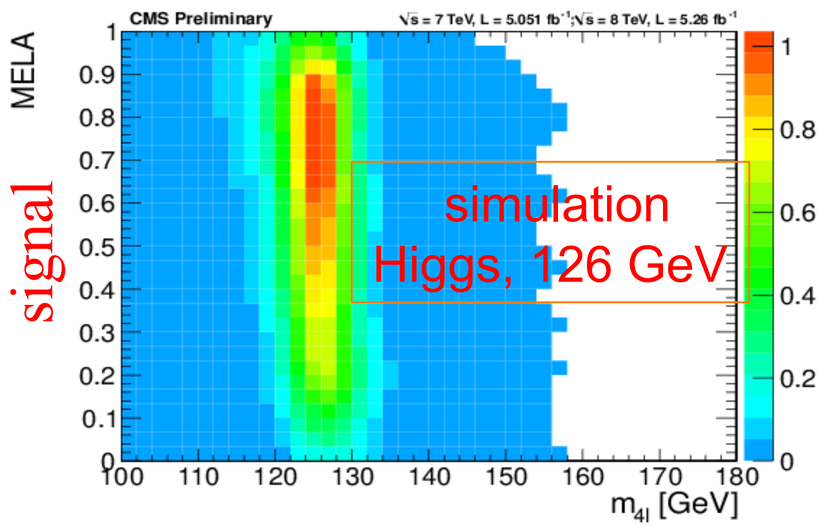


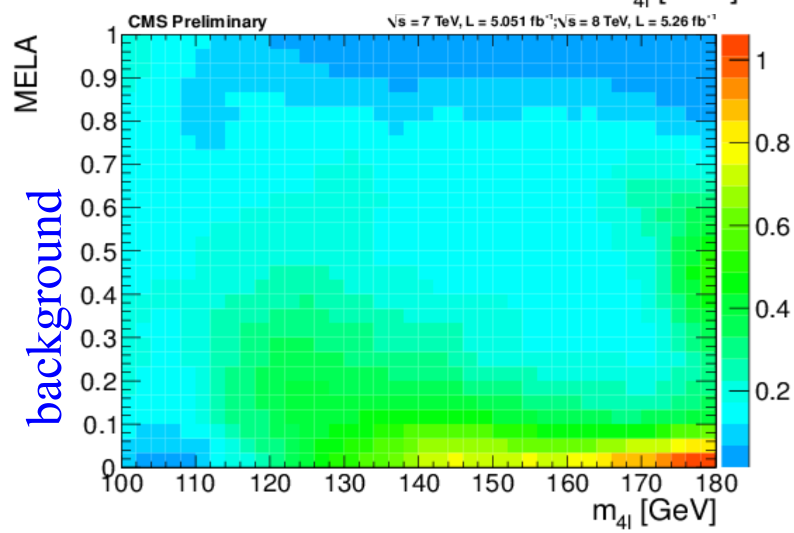
Some discriminating variables

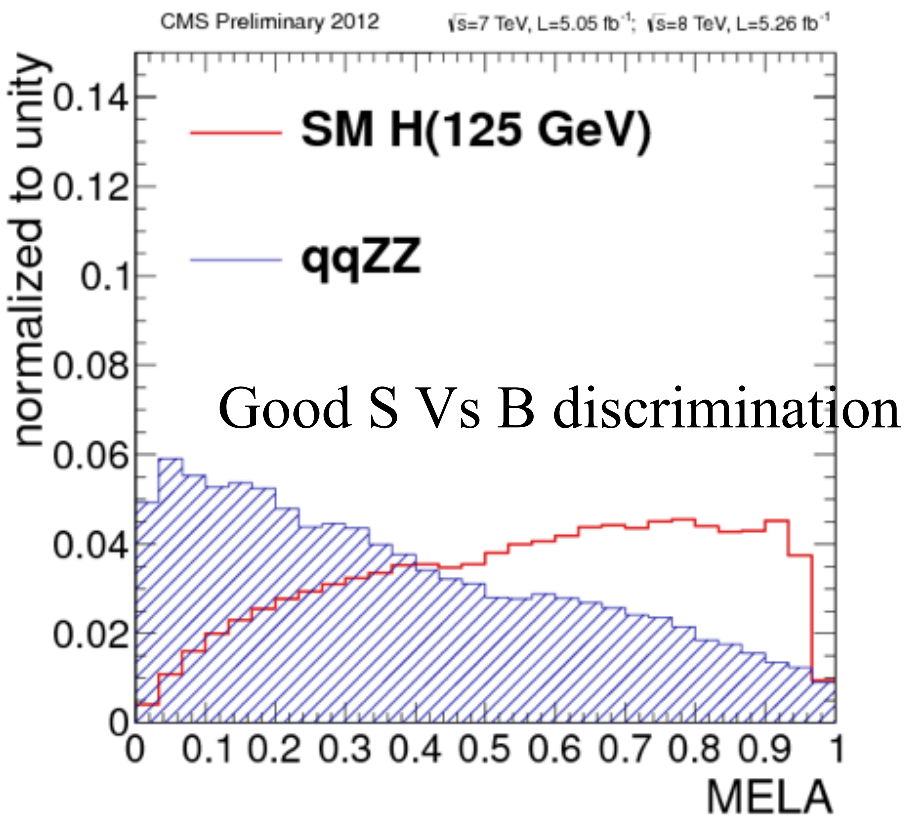


MELA Vs 4l Mass

$$\text{MELA} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$



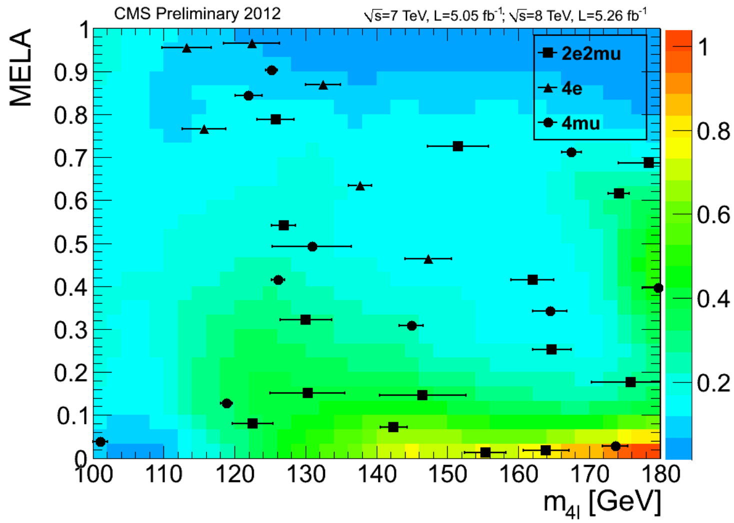


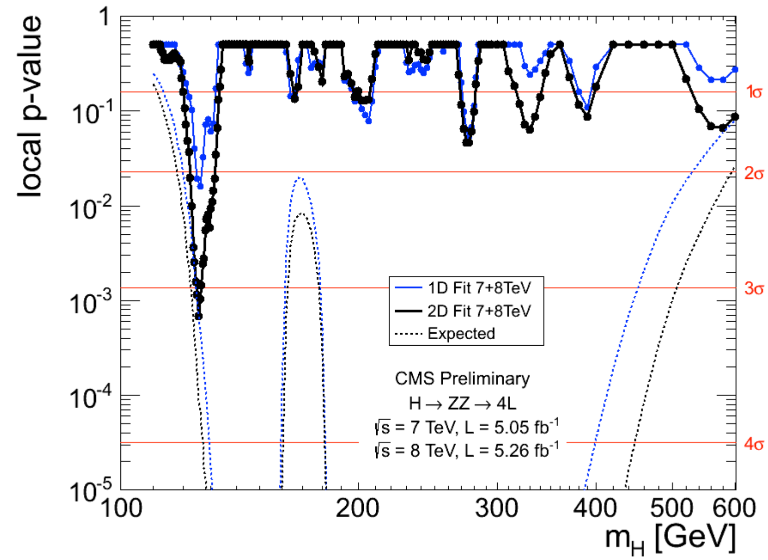


Good S Vs B discrimination

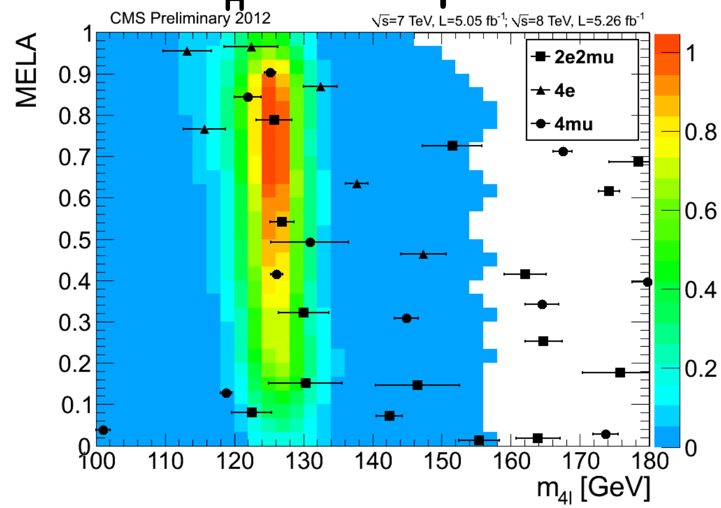
CMS : 2D Fit of MELA Vs 4l Mass

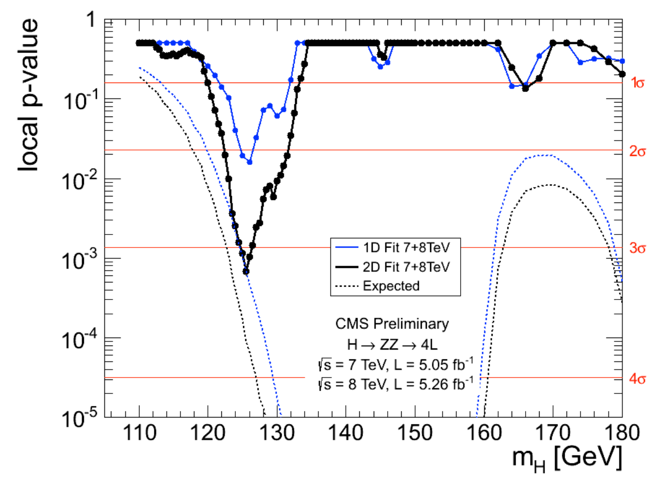
Data wrt background expectation





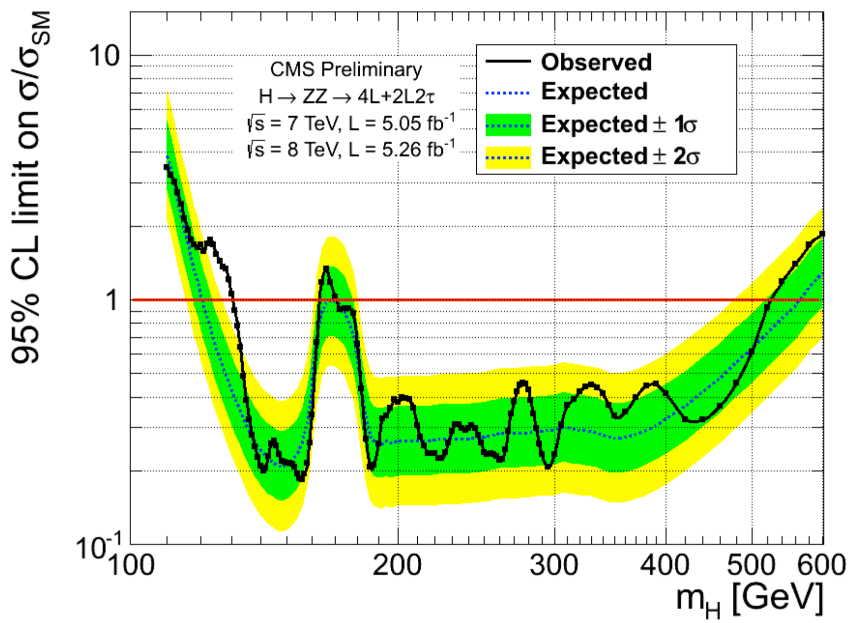
Data wrt M_H = 126 expectation

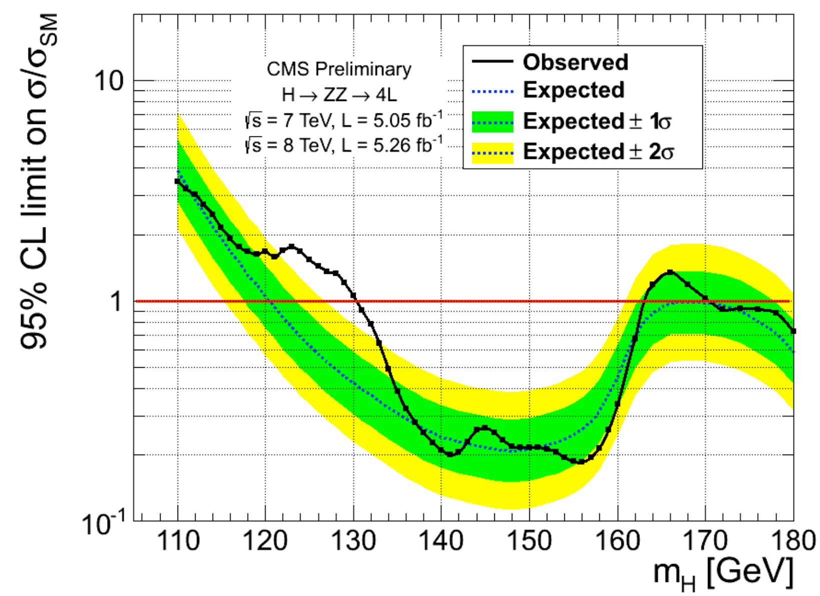




Expected local significance at 125.5 GeV: 3.8 σ
Observed local significance at 125.5 GeV: 3.2 σ

CMS Exclusion Limits: H → ZZ → 4l





Expected exclusion at 95% CL: 121-550 GeV
Observed exclusion at 95% CL: 131-162 and 172-530 GeV

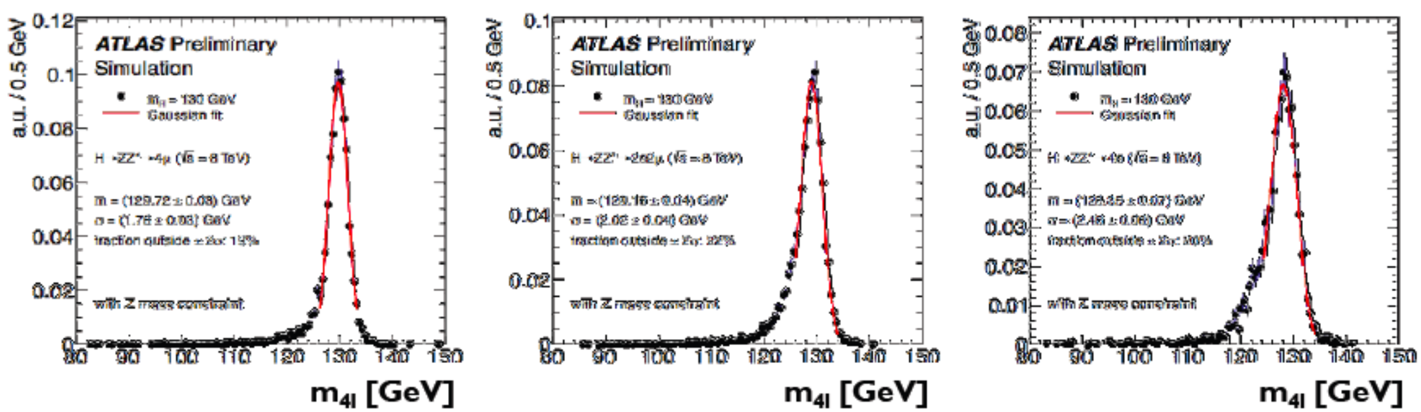
$H \rightarrow ZZ^{(*)} \rightarrow 4l$: ATLAS

Selection

- ***At least two pairs of opposite-charge, same-flavor leptons (e,μ)***
- ***p_T thresholds: 20, 15, 10, 7 GeV (6 GeV for muons)***
- ***50 < m_{12} < 106 GeV, m_{4l}-dependent cut on m_{34}, m_{34} < 115 GeV***
- ***All same-flavor, opposite-sign pairs m_{ll}>5 GeV (J/ψ veto)***
- ***ΔR(l,l') < 0.1 (0.2) for all same (different)-flavor***
- ***Tracking and calorimeter isolation***
- ***Impact parameter significance***

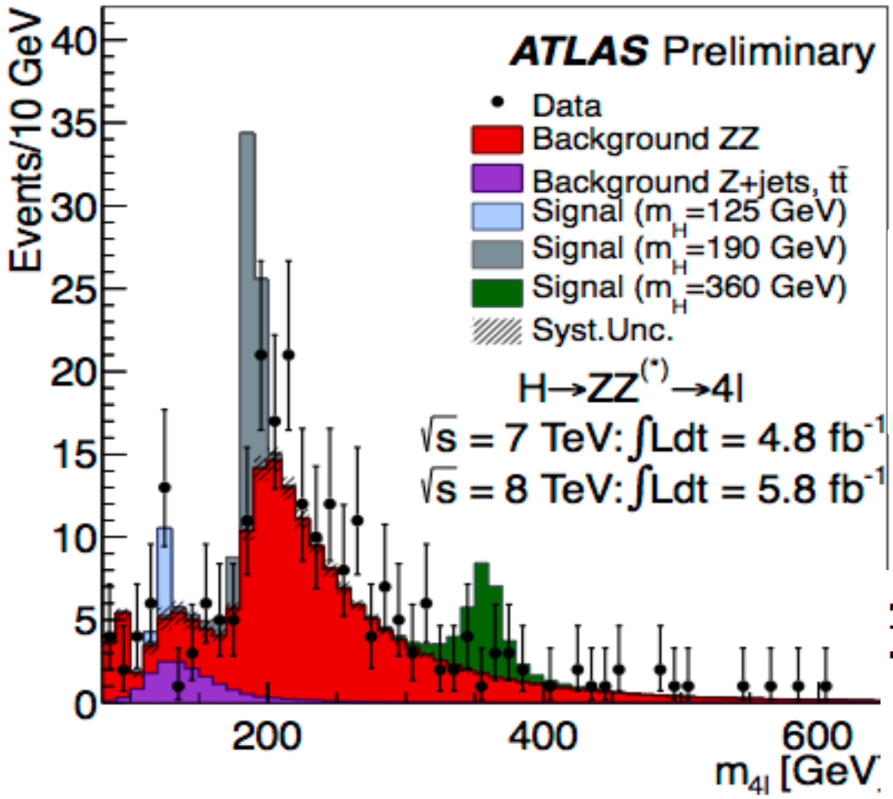
- ***Mass resolution in simulated events at m_H=130 GeV***

(with Z mass constraint for m_{12})



4μ: σ=1.8 GeV | 2e2μ: σ=2.0 GeV | 4e: σ=2.5 GeV

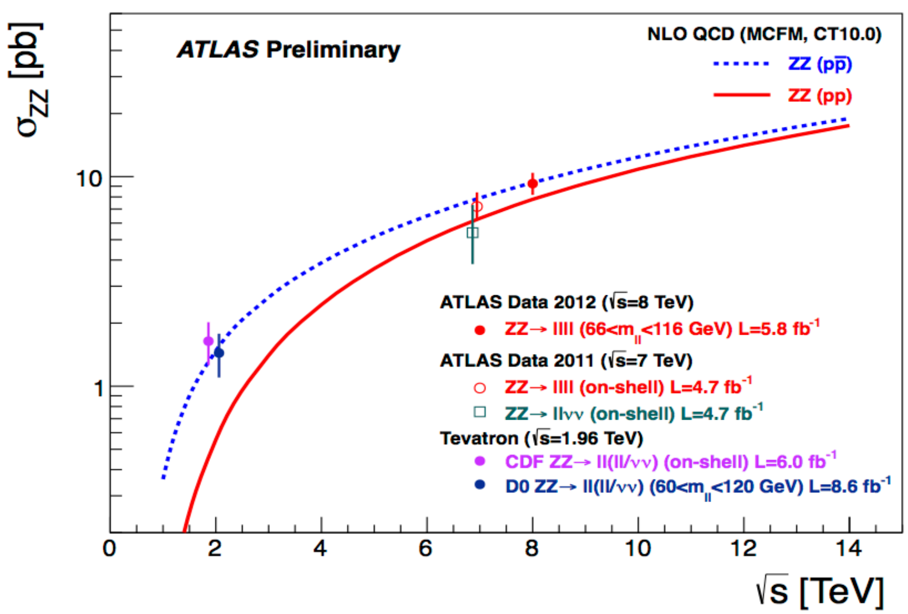
4l Mass Spectrum: ATLAS



M_{4l}>160 GeV dominated by ZZ background:
147 ± 11 events expected; 191 observed

~1.3 times more ZZ events in data than SM prediction → in agreement with measured ZZ cross-section in 4l final states at 8 TeV

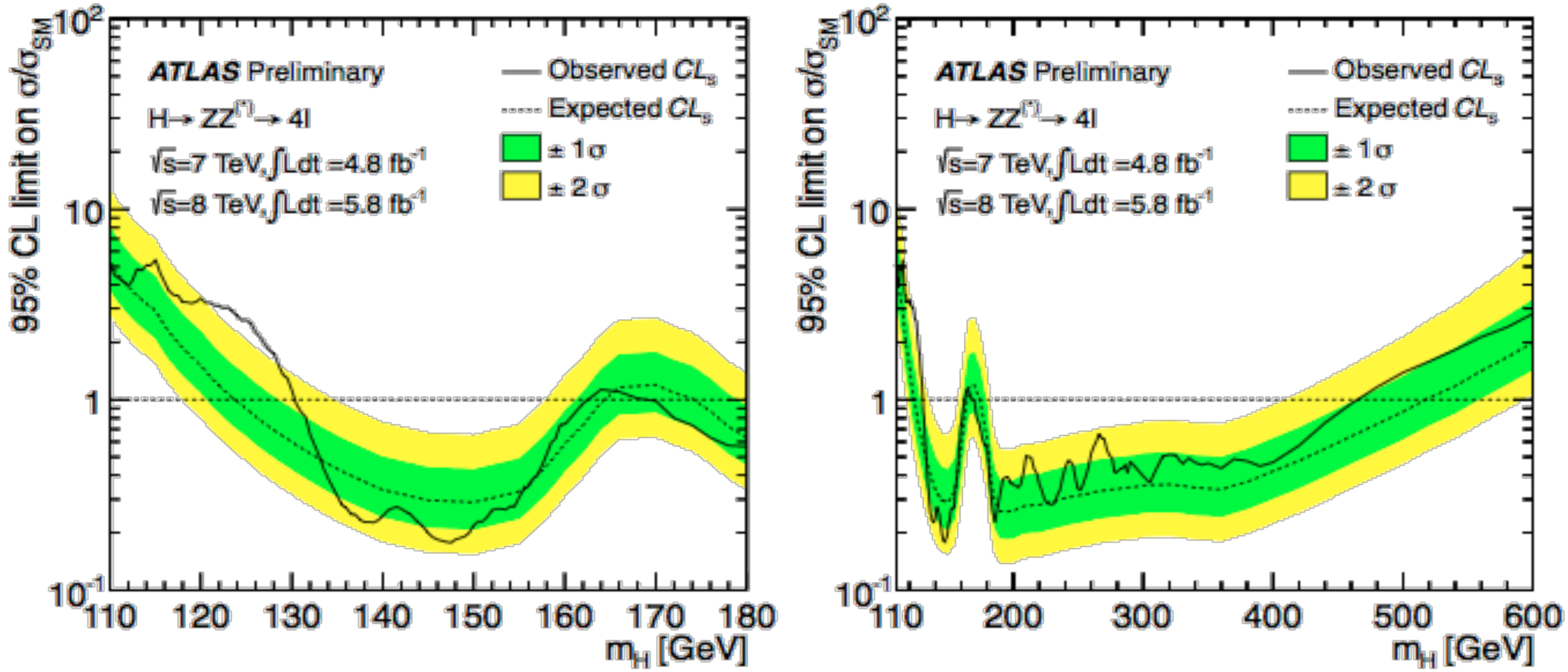
Measured σ (ZZ) = 9.3 ± 1.2 pb
SM (NLO) σ (ZZ) = 7.4 ± 0.4 pb



Discrepancy has negligible impact on the low-mass region < 160 GeV

(no change in results, if in the fit ZZ background is constrained within its uncertainty or left free)

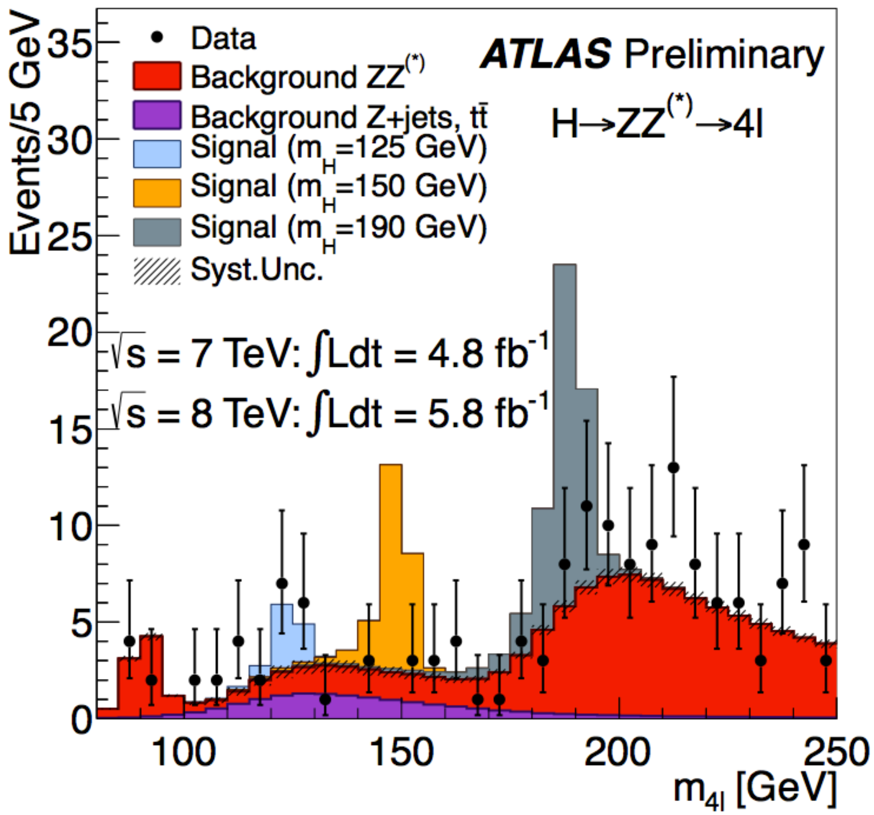
ATLAS Exclusion Limits: H → ZZ → 4l



Exclusion at 95% C.L. :

- Expected: $124 < m_H < 164$ GeV and $176 < m_H < 500$ GeV
- Observed: $131 < m_H < 162$ GeV and $170 < m_H < 460$ GeV

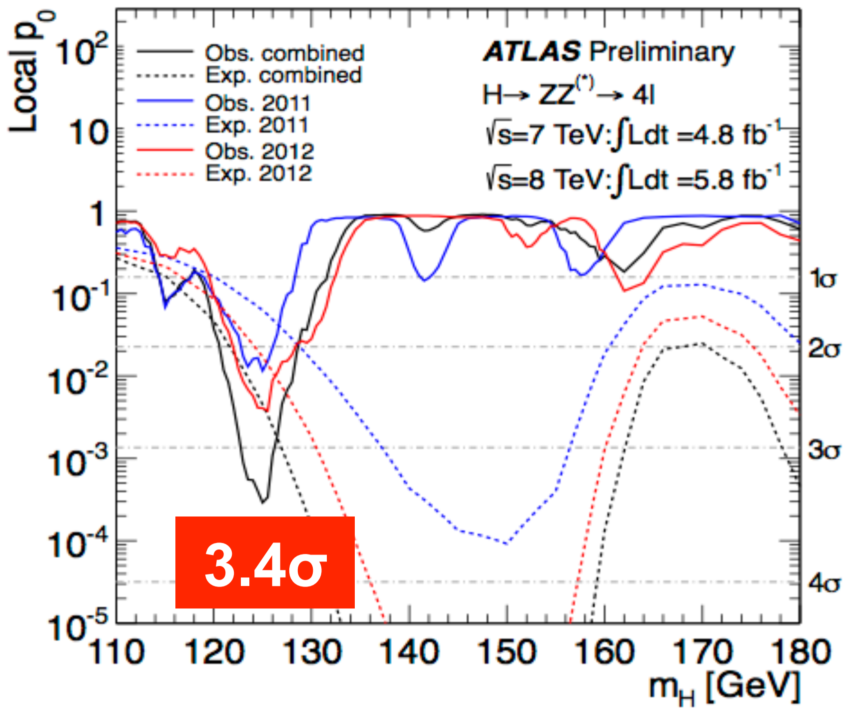
$H \rightarrow ZZ^{(*)} \rightarrow 4l$ Low Mass Region

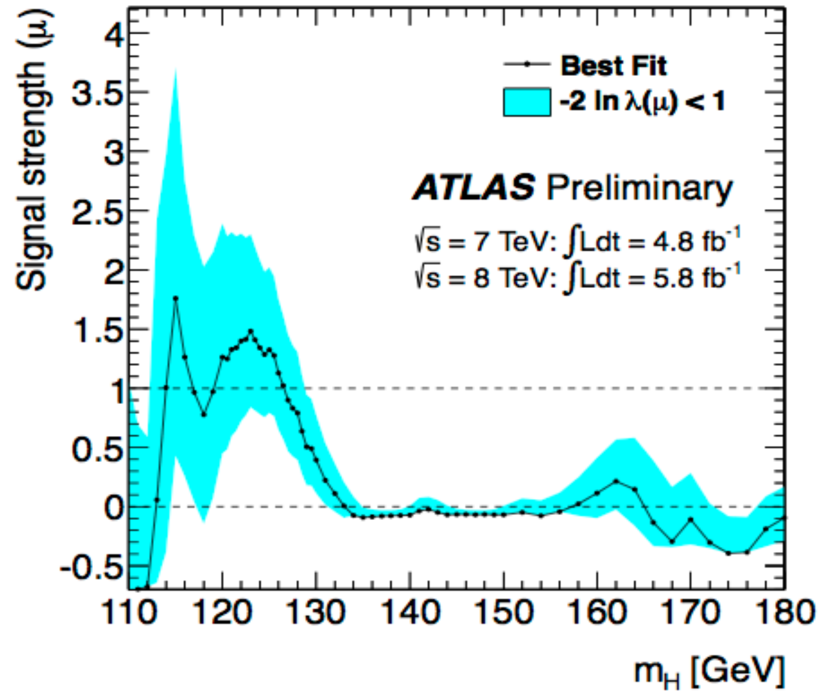


Event count in
$120 < m_{4l} < 130$ GeV

7+8 TeV	4μ	2e2μ + 2μ2e	4e	sum
Background	1.3 ± 0.1	2.2 ± 0.2	1.6 ± 0.2	5.1 ± 0.3
m_H=125 GeV	2.1 ± 0.3	2.3 ± 0.3	0.9 ± 0.1	5.3 ± 0.4
Data Observed	6	5	2	13
S/B	1.6	1.0	0.6	1.0

Significance Of Observation In H → ZZ → 4l

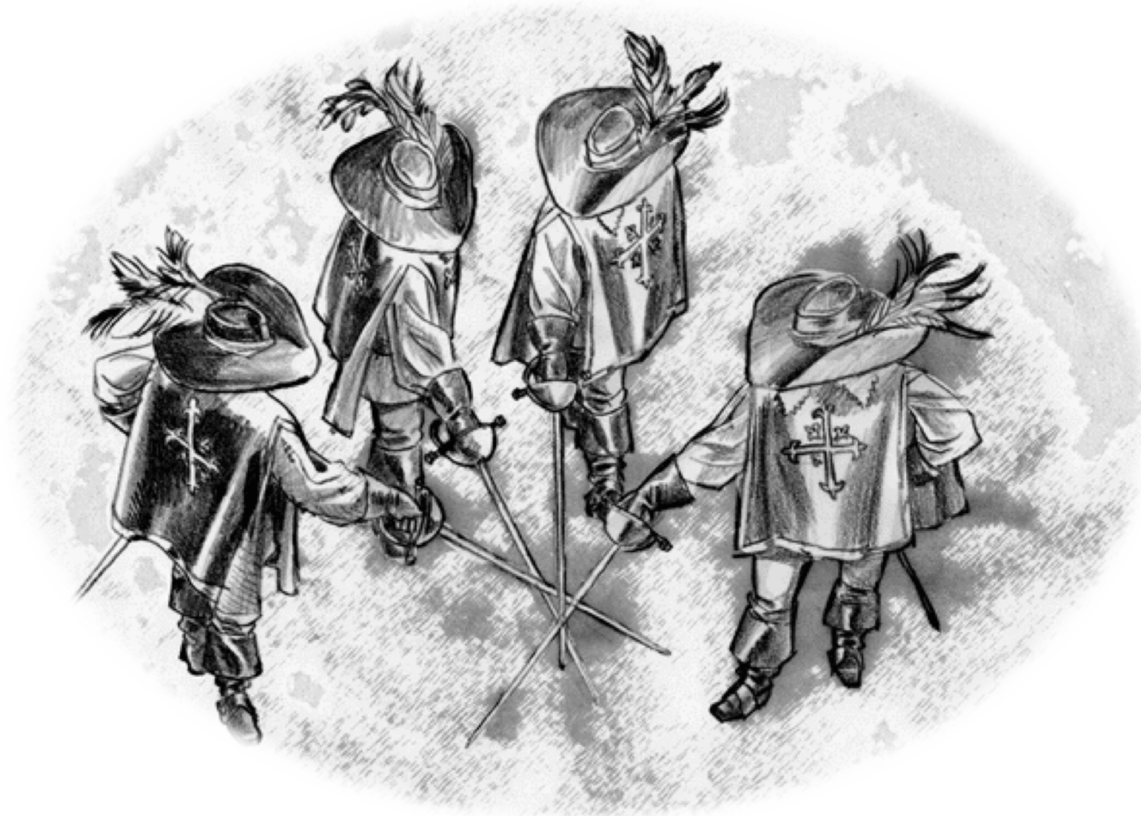




Best-fit value at 125 GeV: μ =1.3 ± 0.6

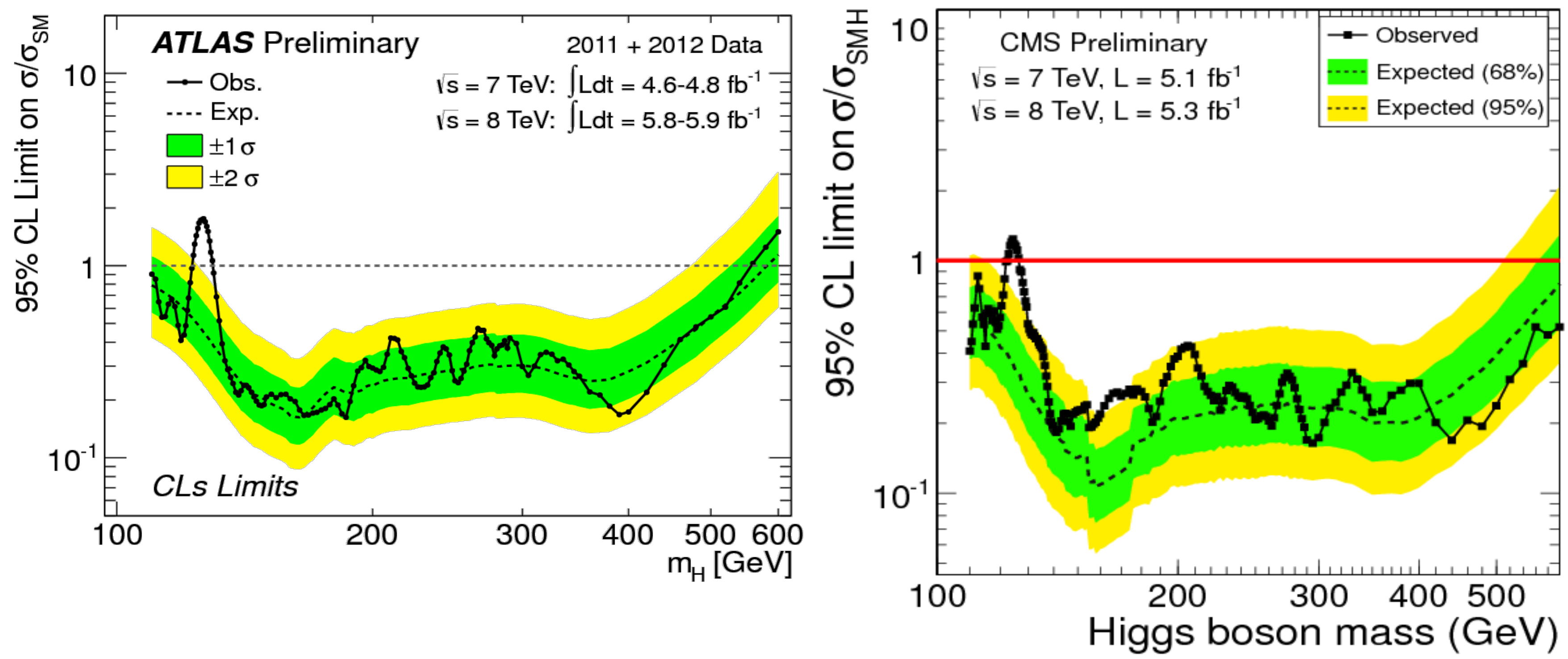
Data sample	m_H at max deviation	local p-value	local significance	expected
2011	125 GeV	1.1 %	2.3 σ	1.5 σ
2012	125.5 GeV	0.4 %	2.7 σ	2.1 σ
2011+2012	125 GeV	0.03 %	3.4 σ	2.6 σ

Global 2011+2012 (including LEE over full 110-141 GeV range): 2.5σ



Combination Of SM Higgs Searches

Exclusion Limits On The SM Higgs Boson



ATLAS

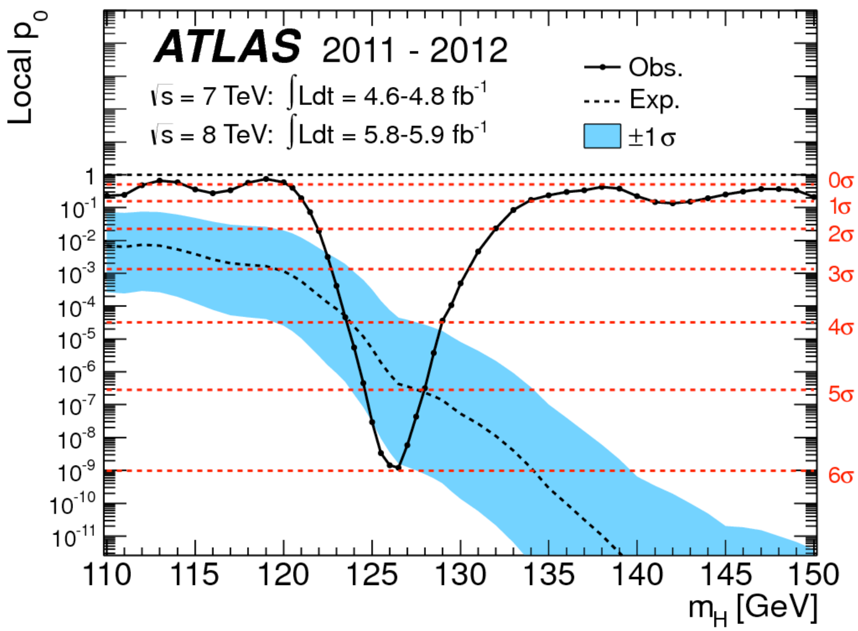
95% CL Exclusion: $111 < M_H < 122$, $131 < M_H < 559$ GeV

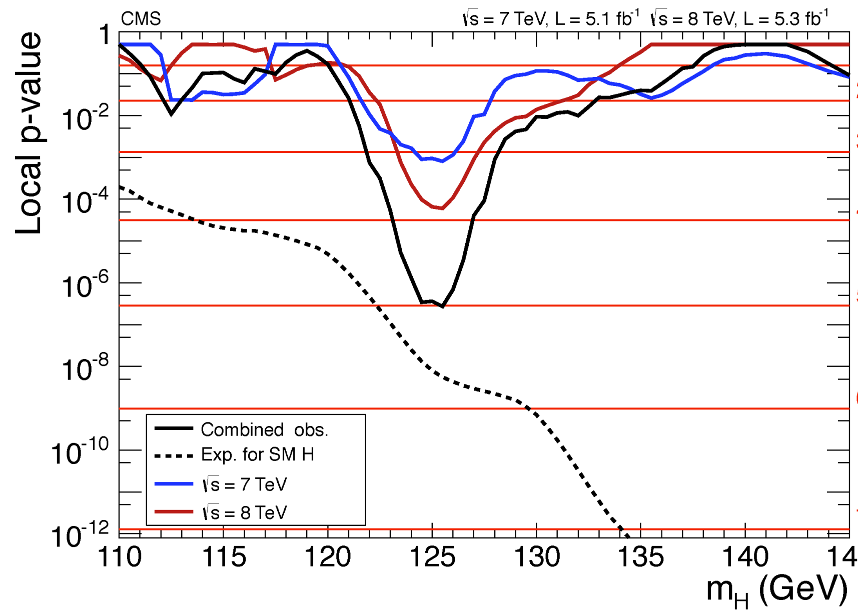
CMS

95% CL Exclusion: $110 < M_H < 122.5$, $127 < M_H < 600$ GeV

Observation Of A New Boson

ATLAS & CMS observe a narrow state near M = 125 GeV
with a high significance





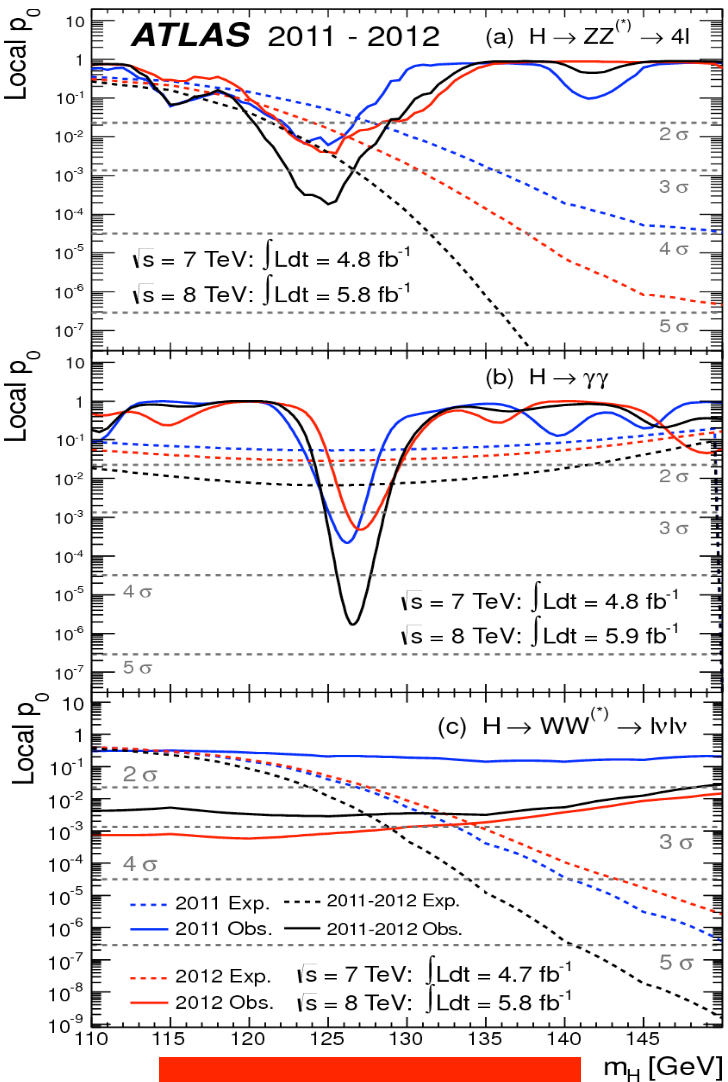
5.9σ at M_X = 126.5 GeV

5.0σ at M_X = 125.3 GeV

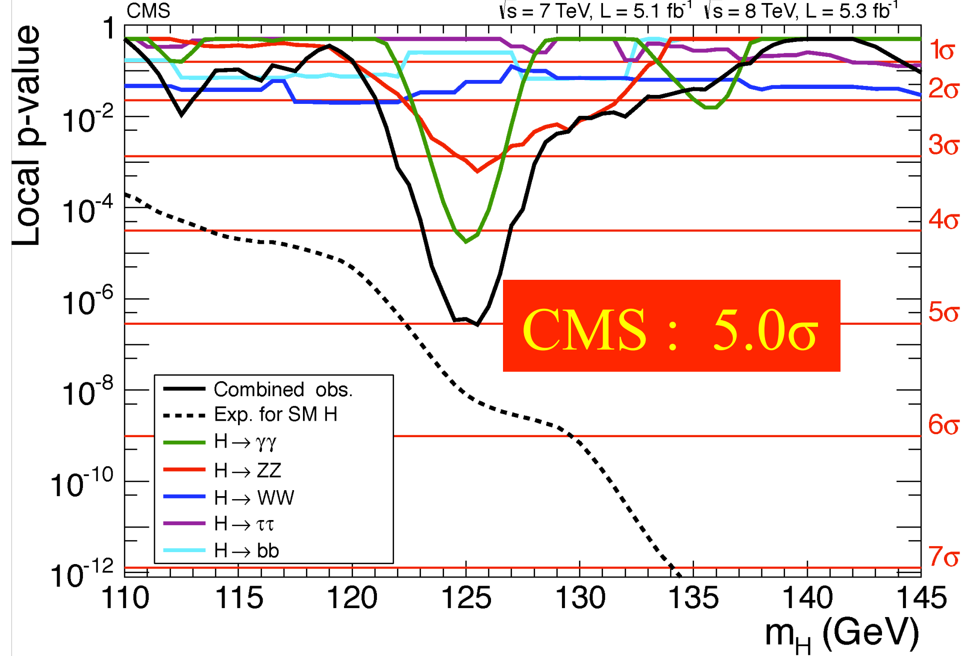
A little lucky w.r.t expected

A little unlucky w.r.t expected

CMS & ATLAS : Local p-values & Significances



ATLAS : 5.9σ

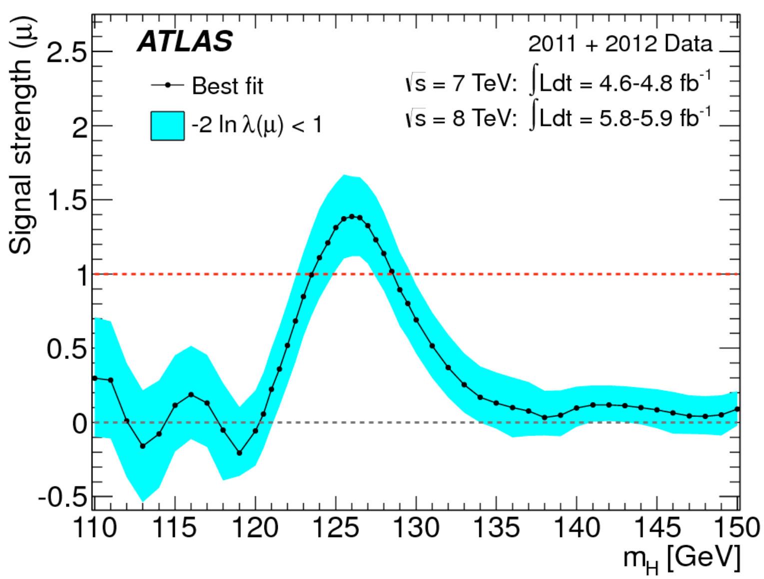


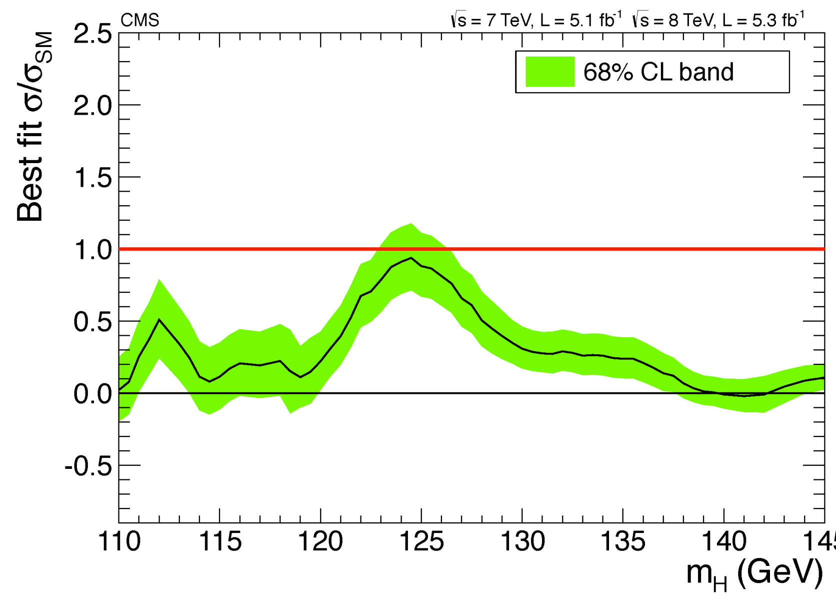
Decay mode or Combination	Expected (σ)	Observed (σ)
ZZ	3.8	3.2
$\gamma\gamma$	2.8	4.1
WW	2.5	1.6
bb	1.9	0.7
$\tau\tau$	1.4	–
$\gamma\gamma$ + ZZ	4.7	5.0
WW + $\tau\tau$ + bb	3.4	1.6
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0

Independent and consistent results

Quantifying Observed Excess : Signal Strength μ

$\mu = \dfrac{\sigma_{obs}}{\sigma_{SM}}$: Indicates by what factor SM Higgs cross section would have to be scaled to best match the observed data





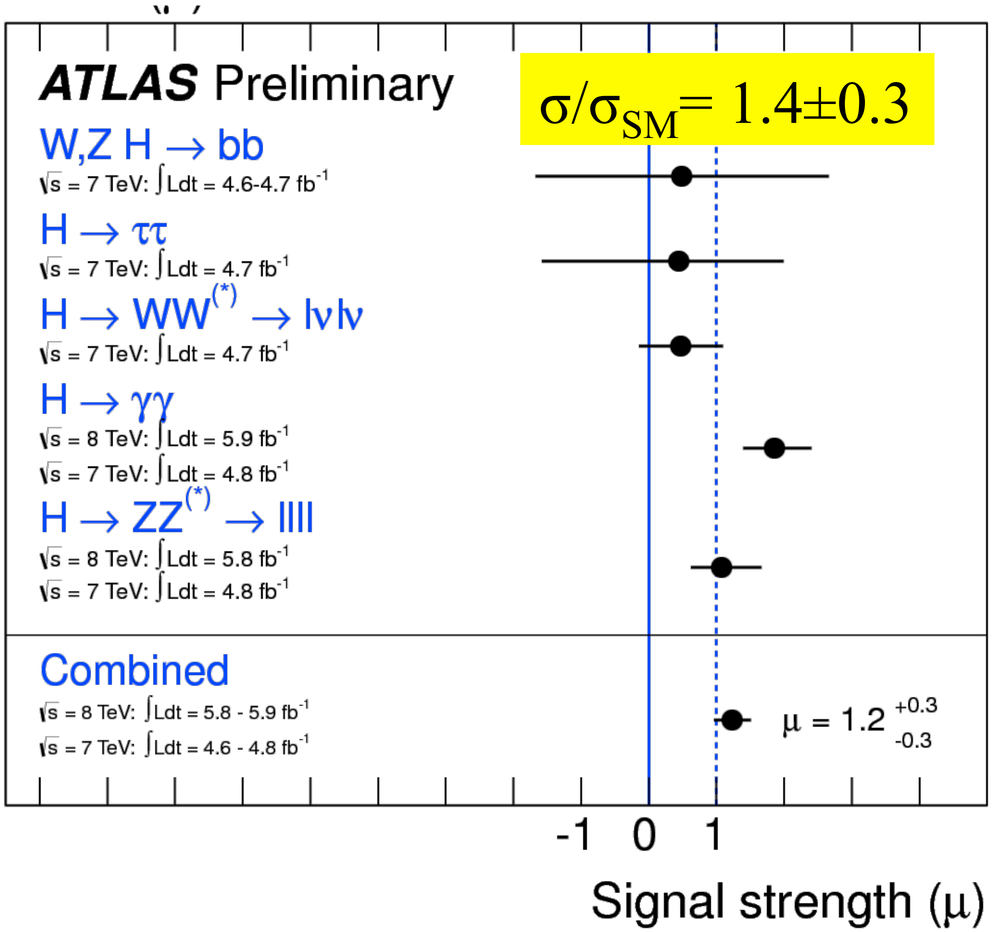
Observed rate consistent with SM expectations (μ = 1)

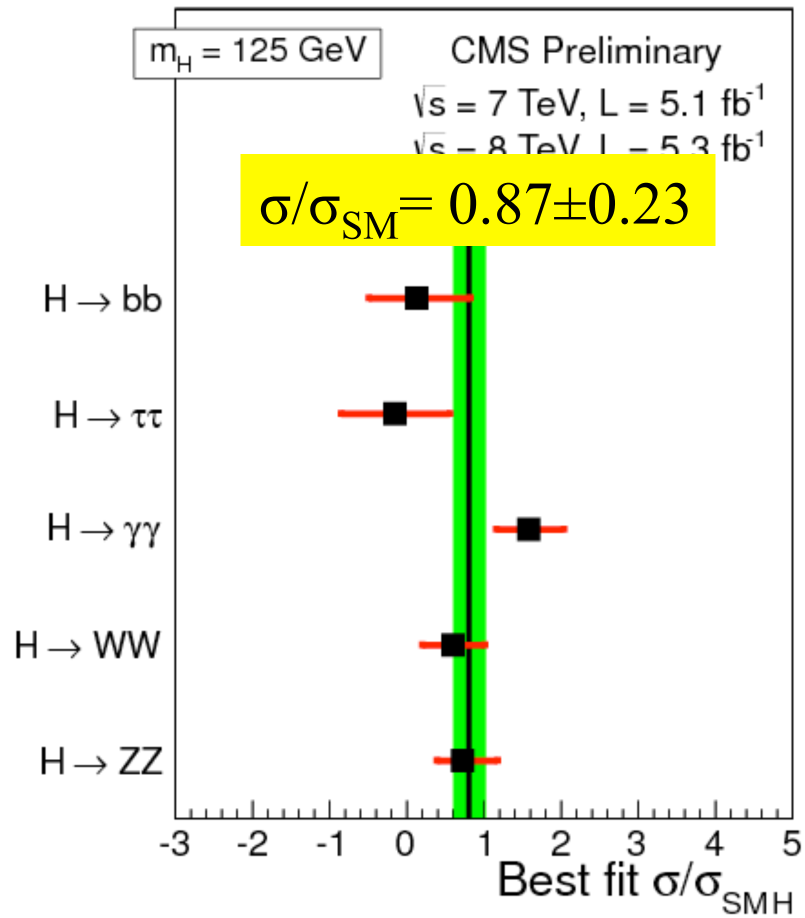
A little larger for ATLAS: $\mu = 1.4 \pm 0.3$

A bit less for CMS: $\mu = 0.87 \pm 0.23$

Helps explain the difference in significances of observation

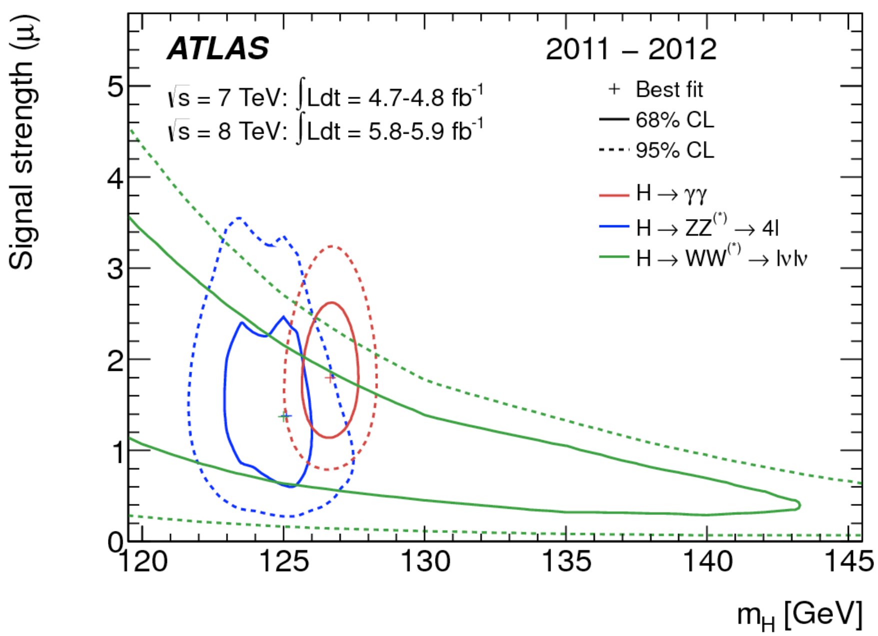
Best Fit Signal Strengths : By Channels

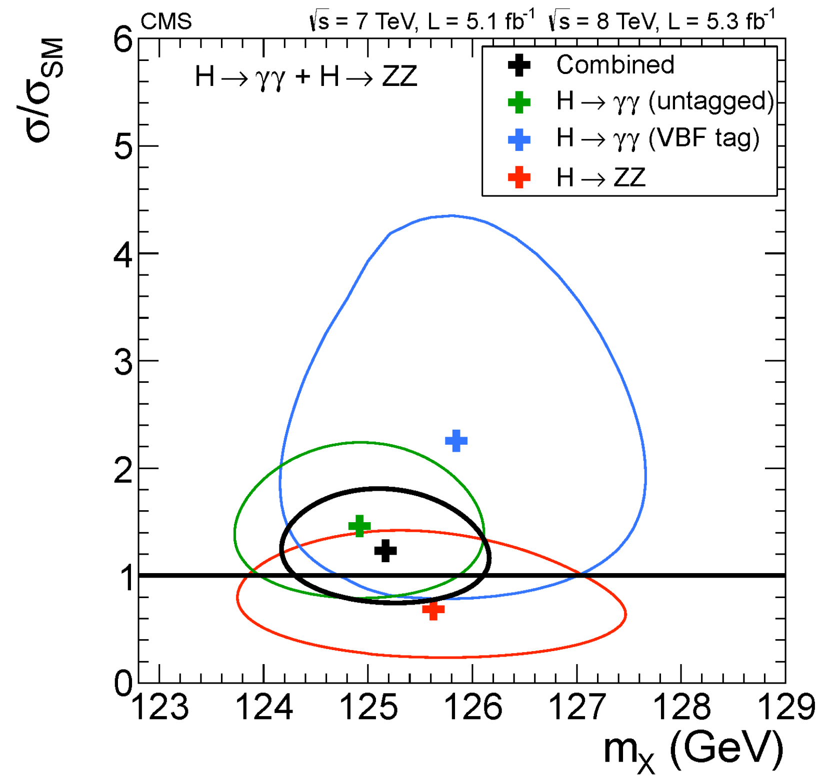




Consistent with the SM Higgs boson although both experiments see a higher H→ γγ rate ($\mu_{ATLAS} = 1.9 \pm 0.5$, $\mu_{CMS} = 1.6 \pm 0.4$)

Mass Of The Observed Resonance





ATLAS

M_X= 126.0±0.4 (stat)±0.4 (syst)

CMS

M_X= 125.3±0.4 (stat)±0.5 (syst)

Both measurements dominated by the observation in H → γγ
& supported by observed excess in H → ZZ → 4*l* mode.
H→ WW → 2l 2ν mode has too poor a mass resolution to contribute

Summary & Conclusion

What Have We Learnt So Far : Just The Facts

- While searching for the Standard Model Higgs boson, ATLAS & CMS experiments have <u>independently</u> discovered a new resonance "X" with $M_X \approx 125$ GeV
  - Probability of background fluctuation is << 10^{-9}
- Because X → γγ
  - From angular momentum conservation & Bose-Einstein statistics ➔ this neutral particle can not have spin = 1
    - **New form of fundamental particle (Scalar or Tensor)**
- Its production rate and decay into γγ, ZZ & WW is compatible, within errors, with expectations from a SM Higgs boson but we have not (yet) observed it to decay into fermion pairs as expected for SM Higgs:
  - H → bb or H → ττ

Landmark Achievement In 21st Century Science

A discovery that brought tears to Peter Higgs's eyes !

Next Steps

- Establishing the properties of the new particle is just the first part of a long journey : **sprint is over, marathon has begun**
- LHC continues its excellent performance, ATLAS & CMS hope to accumulate another ≈ 20 fb^{-1} by end of 2012

  ➔ total ≈ 30 fb^{-1} data per experiment
- Continue to investigate the observed resonance in a variety of channels
  - Precise measurement of the boson mass
  - Measure its coupling to Vector bosons and fermions
  - Measure angular distribution in WW/ZZ modes to determine the spin and parity of the observed boson
- Exciting times ahead !