Study of $A \rightarrow Zh \rightarrow ll\tau\tau$ with CMS:

Preliminary Exam

21 April 2015

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Overview

1) Physics introduction
2) A proposed MSSM search
3) The tools: LHC, CMS & Monte Carlo
4) Event capture and reconstruction
5) Analysis specific event reconstruction
6) Signal vs. background characteristics and cuts
7) Background validation
8) Results
9) Conclusion & future work

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Standard Model

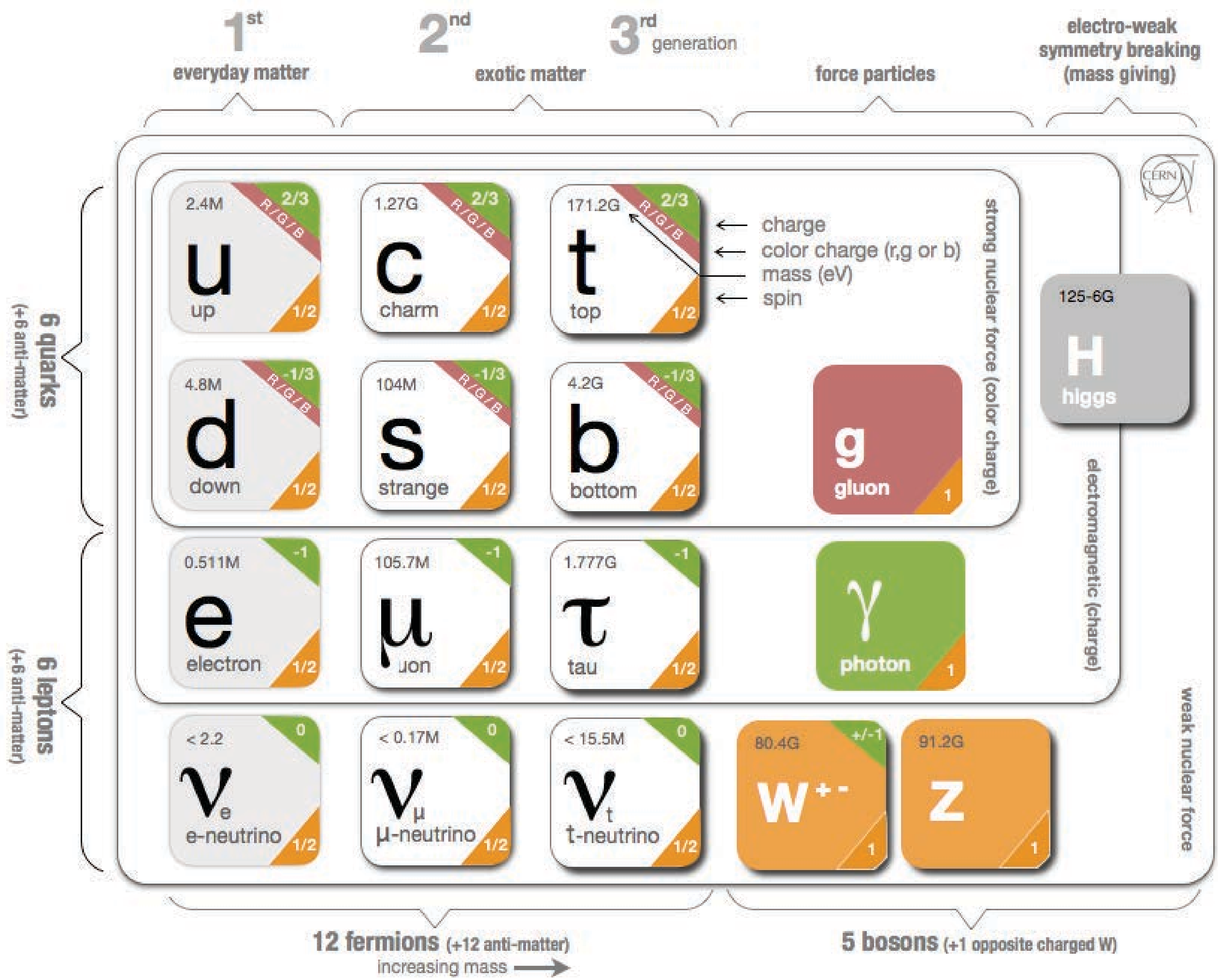
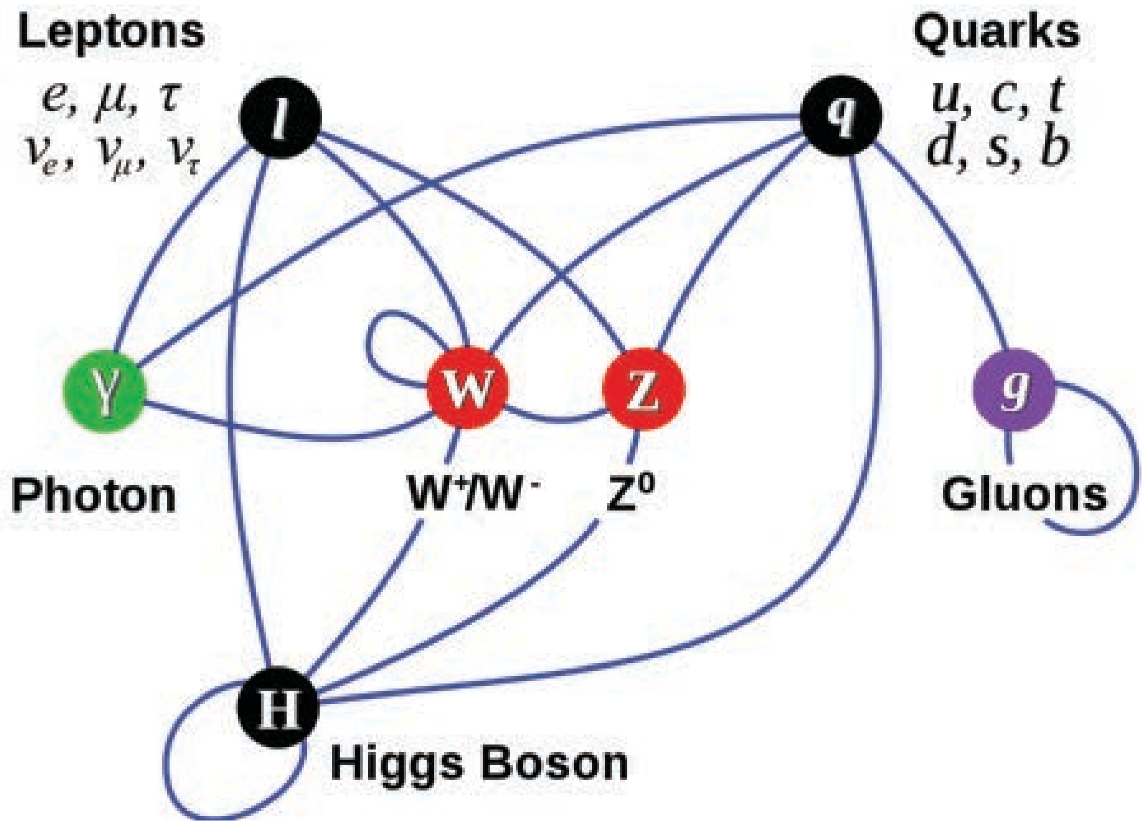


Image: http://www.isgtw.org/sites/default/files/Standard_model_infographic.png, March 27, 2015

The Force Carriers

- Gluons:
  - Mediate the Strong Force
  - Hold quarks in bound states of mesons and baryons
- Photons:
  - Mediate Electromagnetic Force
  - Bind electrons to atoms
- $W^{+/-}$ and Z:
  - Mediate the Weak Force
  - Responsible for some nuclear decays



Electroweak Symmetry Breaking

- In $SU(2)_L \times U(1)_Y$ Symmetry Gauge Bosons are massless
- Electroweak Symmetry Breaking is needed to give Gauge Bosons mass
- Higgs Potential:

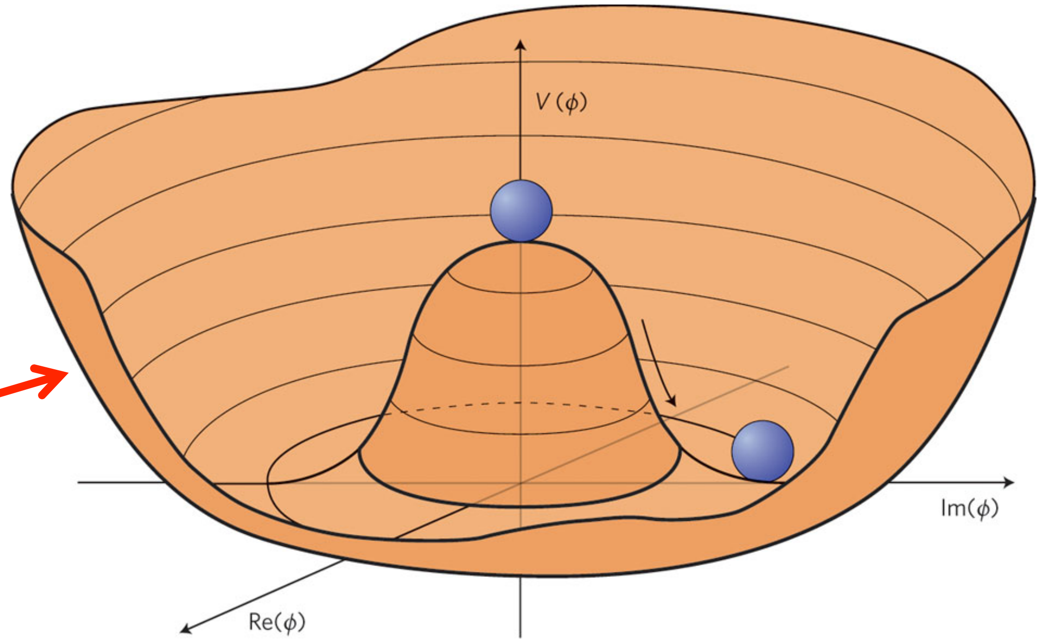
$$V = \frac{1}{2}\mu^2\Phi^\dagger\Phi + \frac{1}{4}\lambda(\Phi^\dagger\Phi)^2$$

- 2 component complex scalar field with 4 degrees of freedom (d.o.f.)

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix}$$

- 3 d.o.f. give mass to $W^{+/-}$ and Z
- 4^{th} d.o.f. appears as a physical particle, the Standard Model, the Higgs boson

$$v^2 = Re(\Phi)^2 + Im(\Phi)^2$$



With broken symmetry requiring:

$$\lambda > 0$$
$$\mu^2 < 0$$

$$M_W = \frac{1}{2}vg$$

$$\cos\theta_W = \frac{M_W}{M_Z}$$

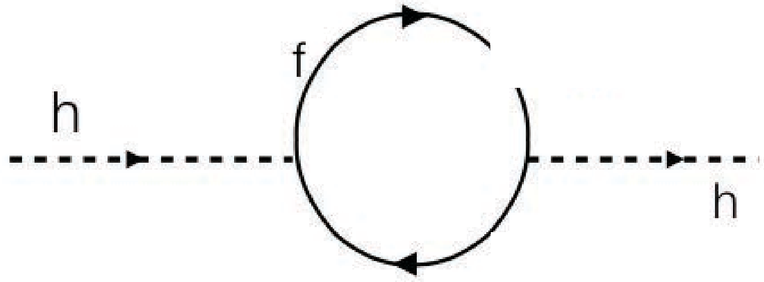
$$m_h = \sqrt{2\lambda v^2}$$

Image: http://usersguidetotheuniverse.com/?p=2603, Mar 28, 2015

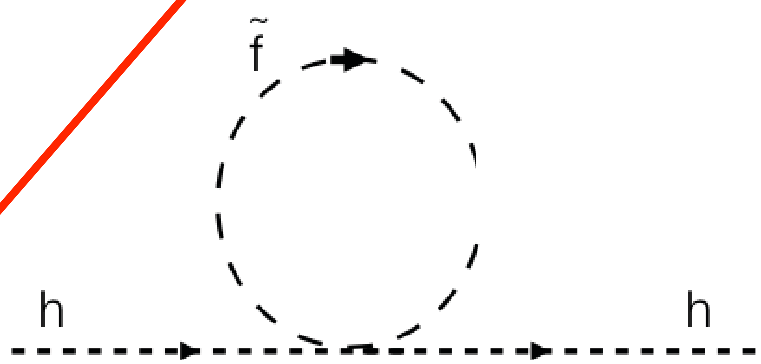
Supersymmetry

- SM works very well
- SM is highly contrived
  - Loop corrections to Higgs Mass are quadratically divergent
  - Boson and fermion loops have opposite sign
  - SM has unequal number of bosons vs. fermions
  - To cancel divergences, “fine tune” carefully so the differences of two very large numbers gives Higgs Mass = 126 GeV
- Supersymmetry
  - Each SM particle has a superpartner
  - Fermions get boson partners, spin differs by ½
  - Boson get fermion partners, spin differs by ½
  - Higgs boson gets a higgsino
  - The many new bosons introduce loop corrections which cancel divergent SM terms

$$-\frac{\lambda_f^2}{8\pi^2}\Lambda_{UV}^2$$



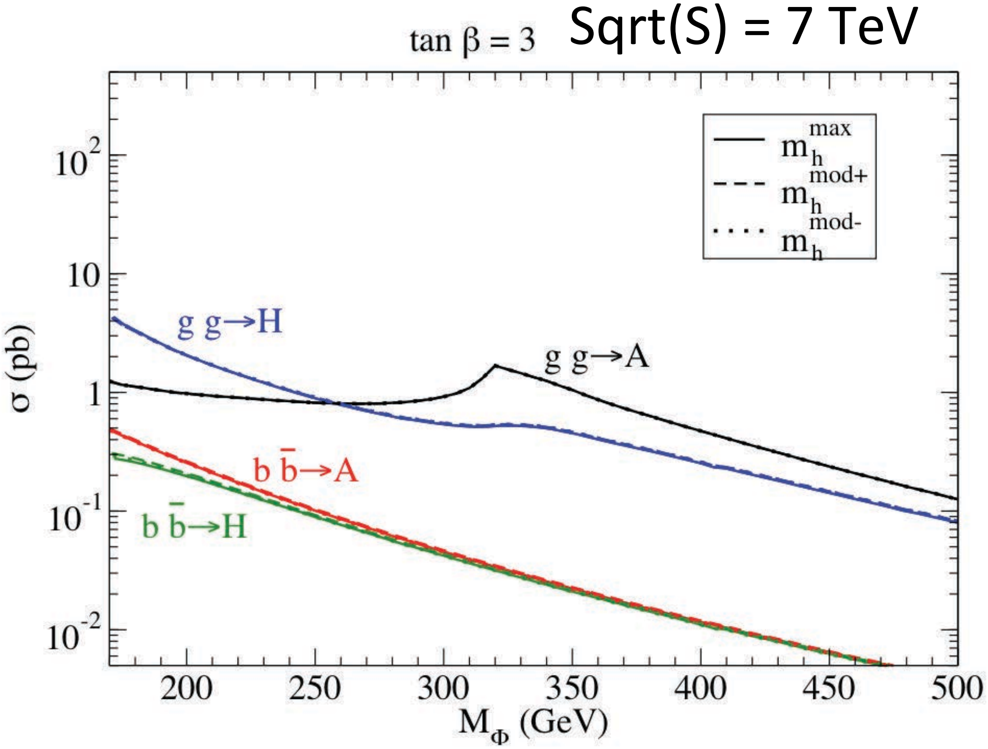
$$+\frac{\lambda_s}{8\pi^2}\Lambda_{UV}^2$$



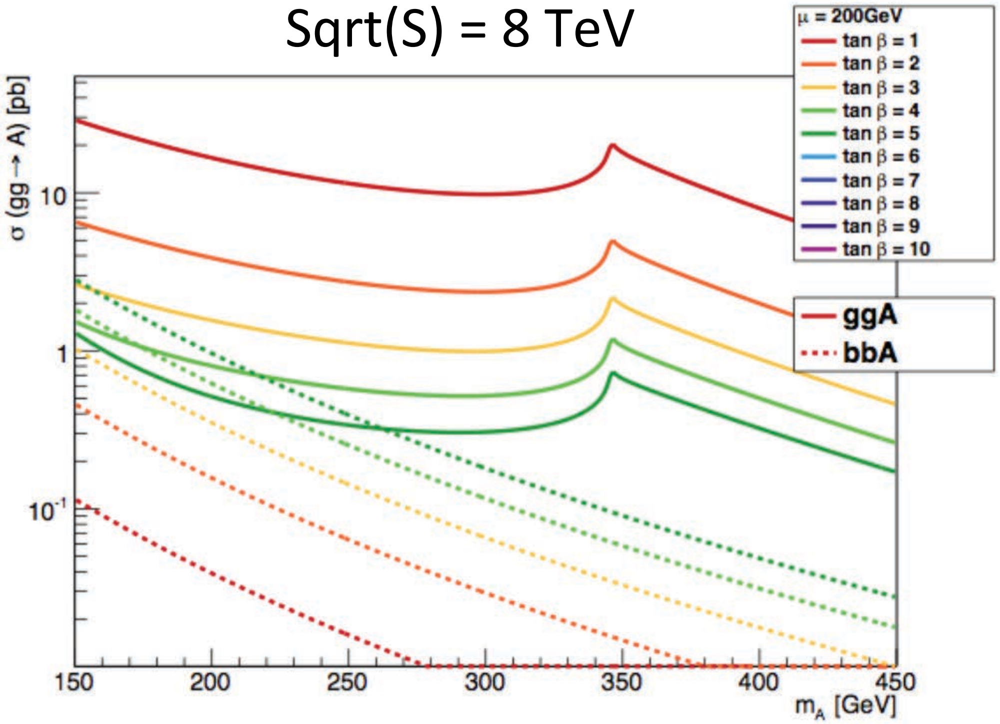
Minimal Supersymmetric Standard Model

- Minimal Supersymmetric Standard Model (MSSM) requires existence of two complex scalar Higgs fields → 3 neutral (h, H, A) 2 charged ($H^{+/-}$)
- Higgs' masses can be specified by the mass of the pseudo-scalar higgs A and tanβ = v_2/v_1
- v_1 and v_2 are the vacuum expectation values of the two higgs doublets
- MSSM predicted cross sections depend on tanβ

Sqrt(S) = 7 TeV



Sqrt(S) = 8 TeV



Plots: "Closing the Wedge with 300 fb−1 and 3000 fb−1 at the LHC: A Snowmass White Paper", Lewis, Ian M., arXiv:1308.1742

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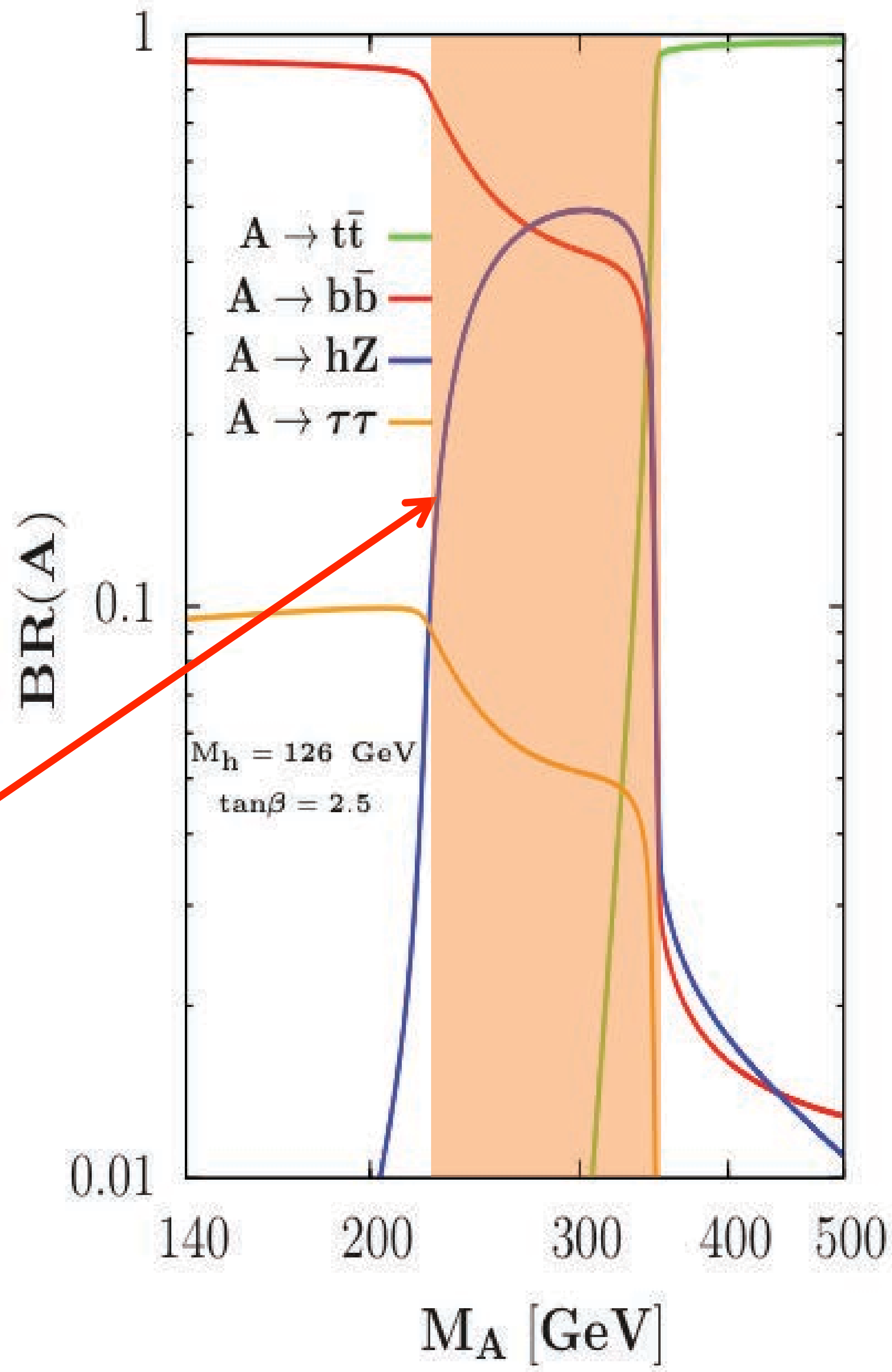
MSSM & A→Zh

- Predicted ranching ratios (BR) for pseudo-scalar A
- A → Zh BR for tanβ = 2.5
  - Approx. 10% < BR < 50%
  - BR drops quickly above 350 GeV

Analysis focuses on A mass between 220-350 GeV
- 220 > Z mass + SM-like h mass = 215 GeV
- 350 ≈ 2 x top mass ≈ 346 GeV

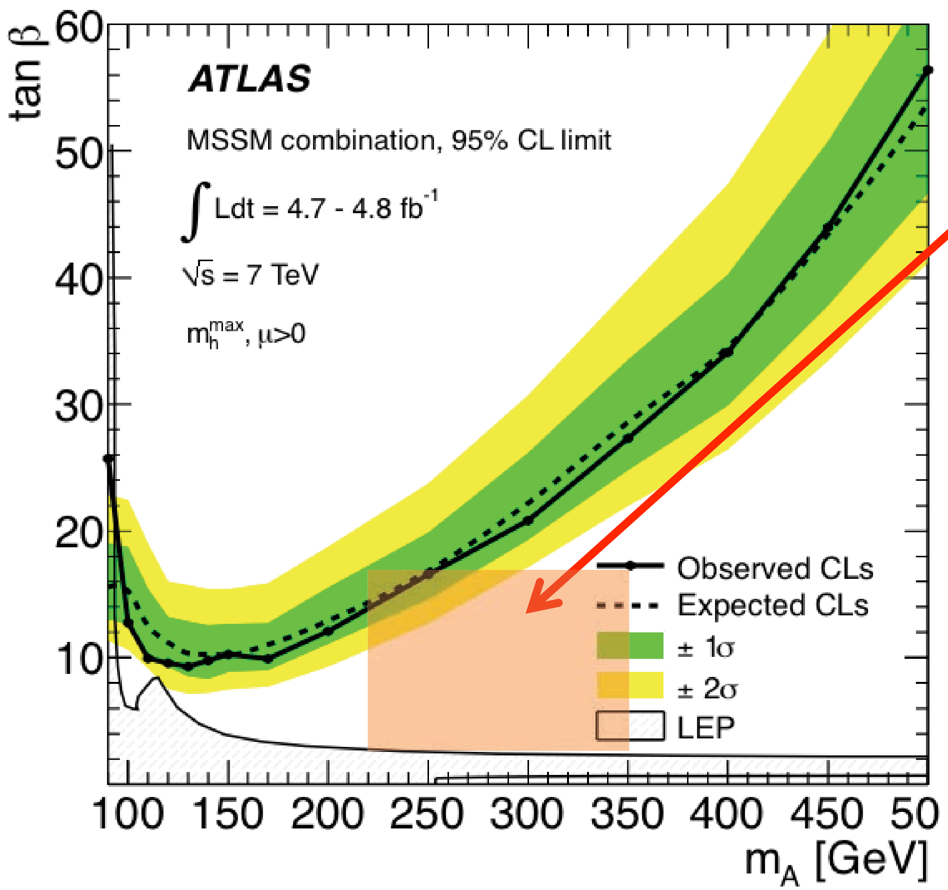


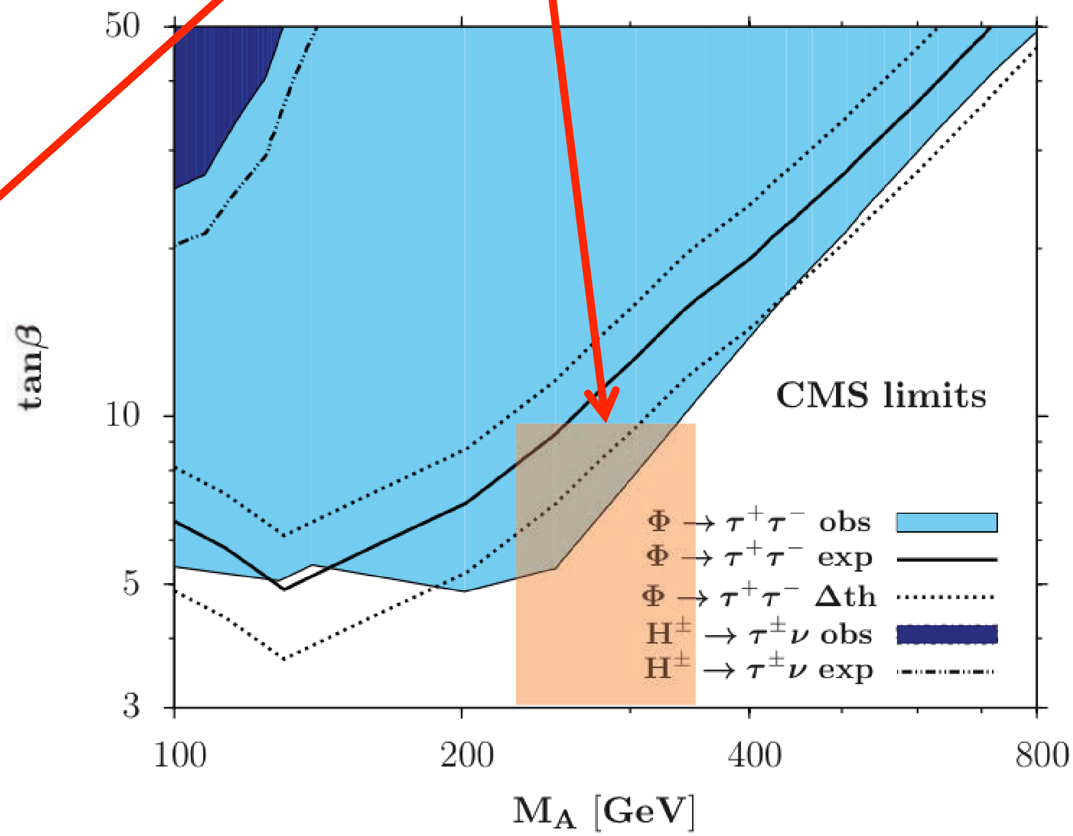
Plots: "The MSSM Higgs sector at a high MSUSY: reopening the low tanβ regime and heavy Higgs searches", Djouadi, Abdelhak and Quevillion, Jérémie. arXiv:1304.1787v2

Previous Constraints on M_A tanβ Plane

Experiment	Search
Tevatron	h/H/A → bb
LEP	Variety of h/H/A → ττ/bb/qq/μμ searches
Atlas	H^+ → csbar H^+ → ντ h/H/A → ττ/bb
CMS	h/H/A → ττ top → bH^+ → bτν

Previous searches leave a window of opportunity in the 220-350 GeV region between 2 < tanβ < ~10
Φ = (h / H / A)





Proposed MSSM Search

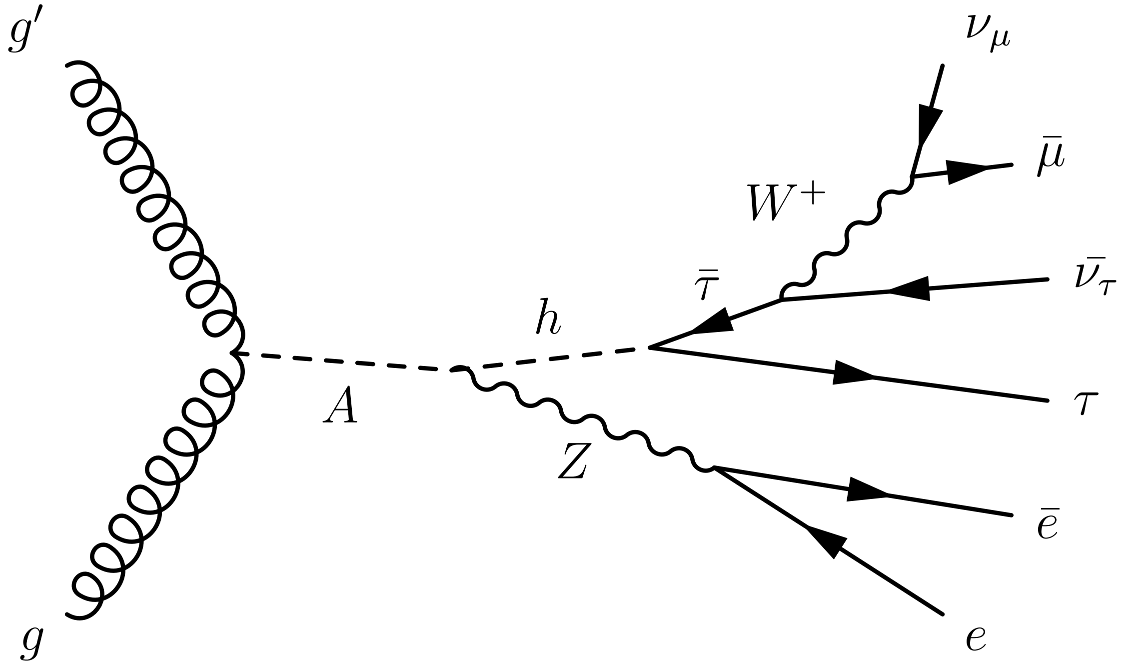
Search for gg → A → Zh → llττ

Use CMS 19.7 fb^{-1} 8 TeV 2012 data

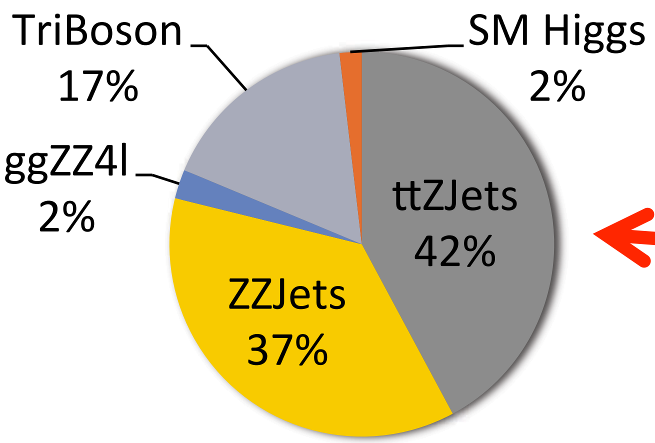
Example decay below depicting:

- gg → A → Zh
- Z → e^+e^-
- H → $\tau^-\tau^+$
- τ^- → hadronic tau decay through W^-
- τ^+ → leptonic tau decay through W^+
- In total: gg → A → Zh → "EEMT"

Eight final state channels are studied
Z → EE or MM final states
h → ττ → ET, MT, TT, or EM final states
EEET, EEMT, EETT, EEEM, MMET, MMMT, MMTT & MMEM



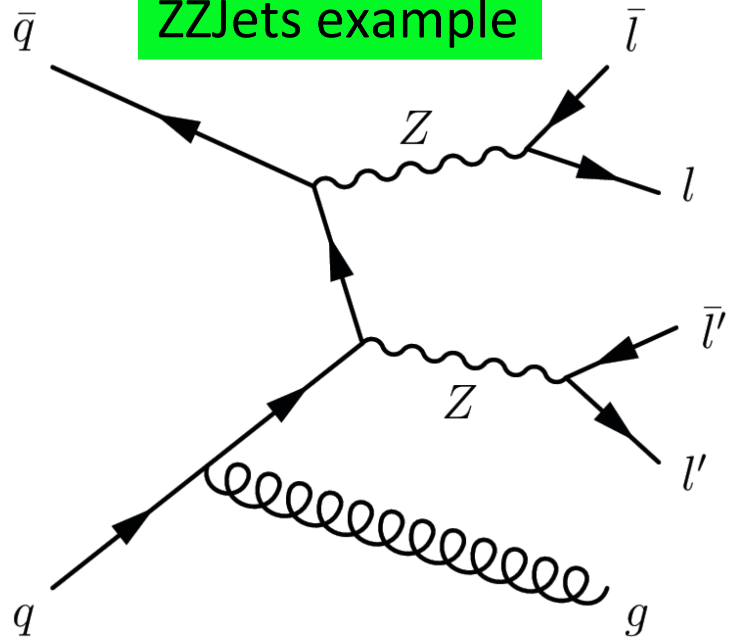
Expected Backgrounds



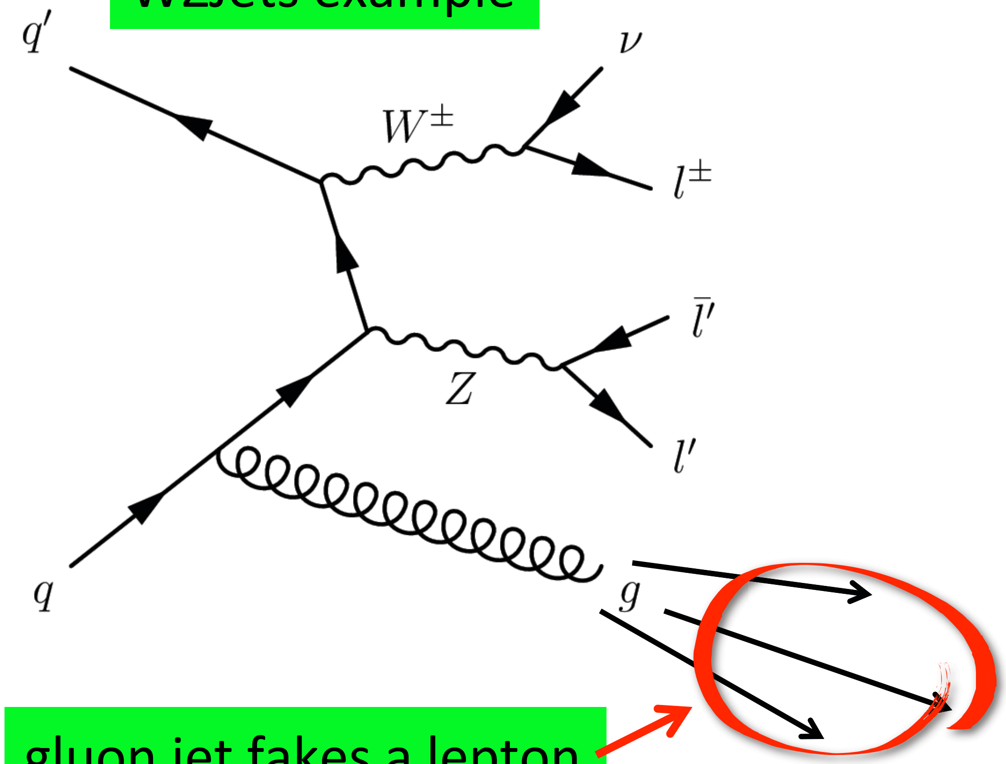
Irreducible Backgrounds & Relative Cross Section

All represented by MC samples

ZZJets example



WZJets example

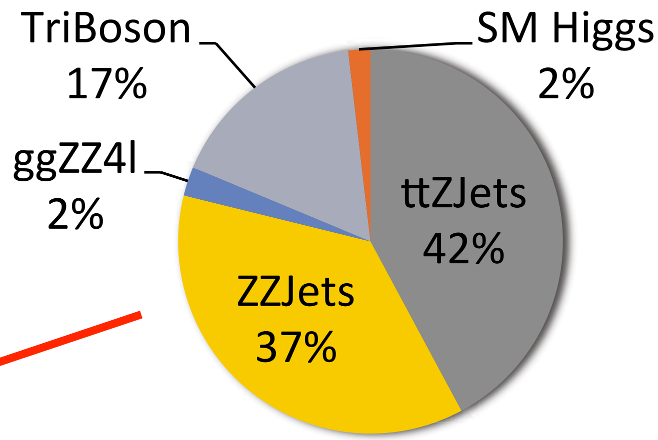


gluon jet fakes a lepton

Reducible Backgrounds:
Final states with at least one misidentified (faked) lepton
Dominant processes: ZJets, WZJets
Yield and shape modeled via data driven fake rate method

Cross Sections and BRs

Background	Sample Cross Sections x BR (fb)
ggA – signal	~ 1,000 (σ only)
ttZJets	208
ZZJets	181
ggZZ4l	12.03
TriBoson*	83.16
SM Higgs**	9.154



A σ x BR = 1,000 fb (0.30 Zh)(0.067 ee/μμ)(0.063 ττ) = 4.2 fb

Estimated A events = (Lumi) x (estimated gg → A σ) ≈ (19.7 fb^{-1})(1,000 fb) ≈ 19,700 events

For every 20,000 A created: (20,000 A particles)(0.30)(0.067)(0.063) ≈ 25 events

Parent	Daughters	Approx. BR (%)
A (predicted)	Zh	10 – 50 ***
Z	e^+e^-, $\mu^+\mu^-$	6.7
h	$\tau^+ \tau^-$	6.32
$\tau^{+/-}$	$e^{+/-}$ or $\mu^{+/-}$	35.2
$\tau^{+/-}$	τ_h	64.8

Hadronically decaying taus are denoted "τ_h", typical process: τ → W + ν, W → light quarks → hadrons

* 0.005527 (ZZZ) + 0.01968 (WZZ) + 0.05795 (WWZ) = 0.083157

** 0.002651 (Zh, h to tautau) + 0.006503 (Zh, h to WW) = 0.009154

*** in 220 GeV < Mass A < 350 GeV mass window & tan(beta) = 2.5

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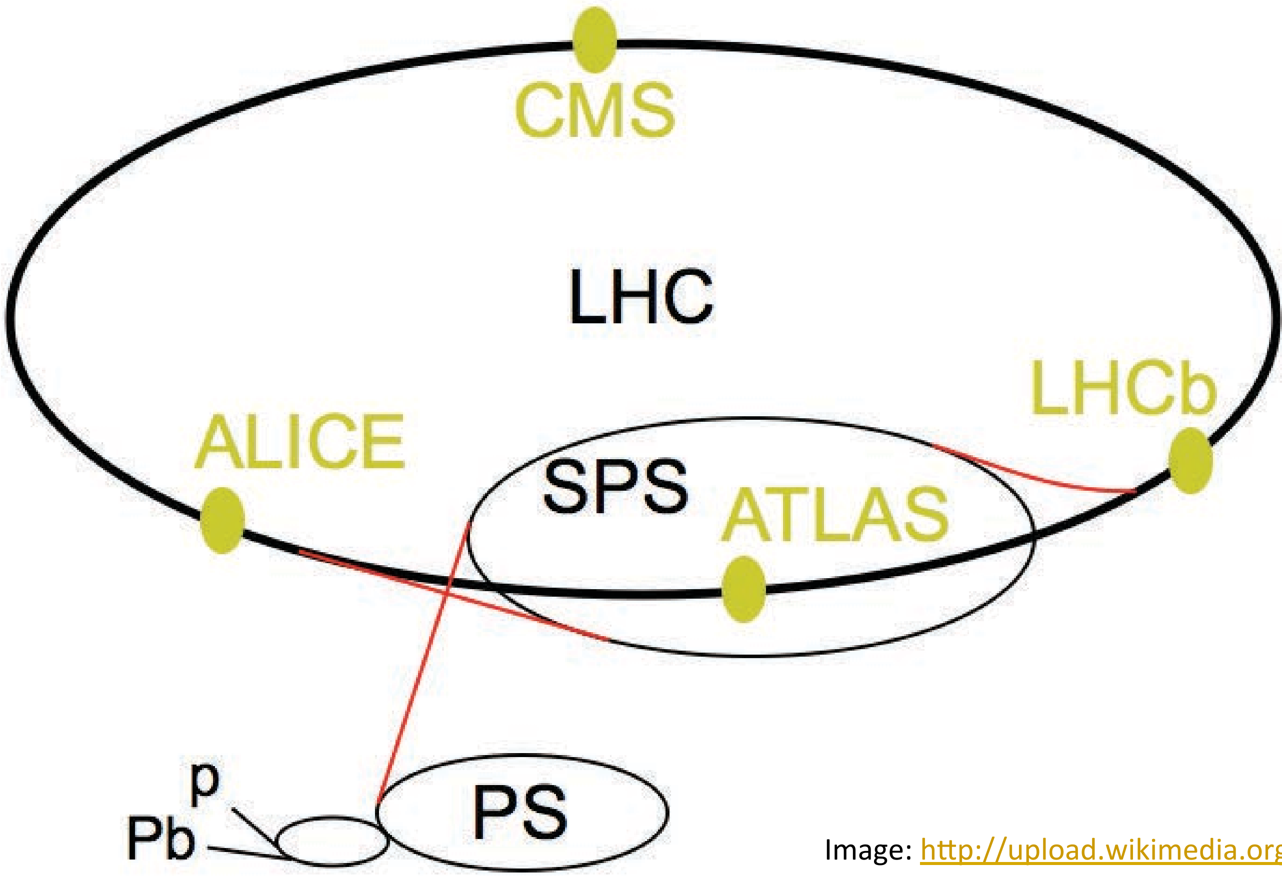
The Large Hadron Collider

Year	LHC center of mass energy
2010-2011	7 TeV
2012	8 TeV
2015	13 TeV
Design	14 TeV

2010-2012	Energy per Beam
Linac 2	50 MeV
Proton Synchrotron Booster	1.4 GeV
Proton Synchrotron	25 GeV
Super Proton Synchrotron	450 GeV
LHC	Up to 8 TeV



- 27km circumference
- General purpose experiments:
  - CMS, Atlas
- Heavy Ions: ALICE
- b meson physics: LHC-b

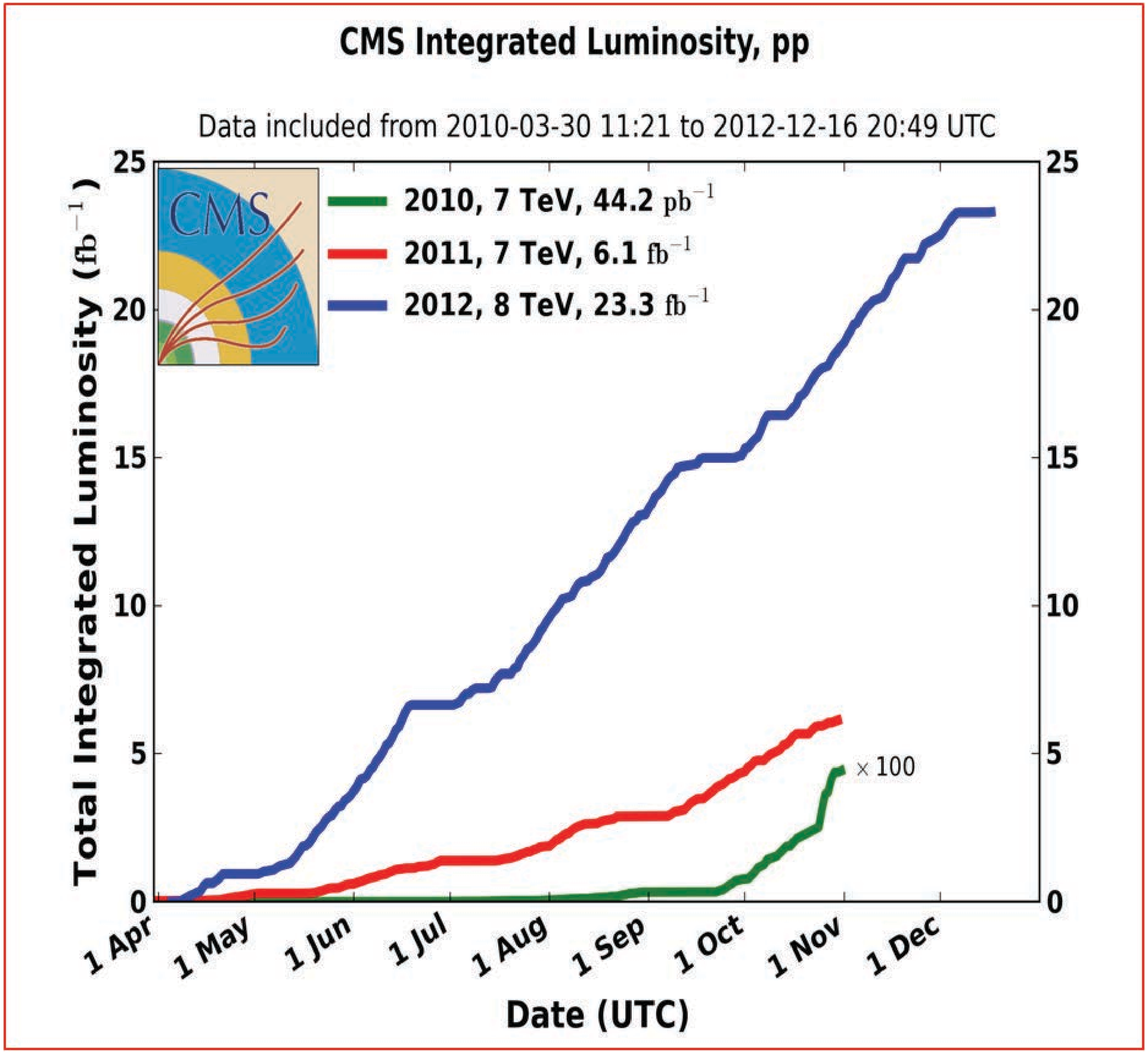
Image: http://upload.wikimedia.org/wikipedia/commons/7/74/LHC.svg, April 9, 2015

Proton Beam

- Beams cross at the locations of the 4 main experiments
- Design interaction rate of 1 bunch crossing / 25ns
- 17 micrometer beam radius at interaction point
- Number of events for a given process:
  - $N = \sigma \int \mathcal{L} dt$
  - σ = cross section of process
  - L = Instantaneous luminosity of collider

	2012	2015	Design
Beam Energy (TeV)	4	6.5	7
Bunch Spacing (ns)	50	50 / 25 / 25	25
Approx. Bunches / beam	1380	1380 / 2800 / 2800	2800
Pileup (avg.)	21	26 / 26 / 36	23
Peak Instantaneous Luminosity (10^{33} $cm^{-2}s^{-1}$)	7.7	5 / 9 / 12	10
Protons / bunch	1.5×10^{11}	original est. 1.2×10^{11}	1.15×10^{11}
Integrated Luminosity	23.3 fb^{-1}	8 fb^{-1} (est. by end of Nov.)	

CMS Integrated Luminosity



The Compact Muon Solenoid

Image: http://cds.cern.ch/record/1344500/files/image_0029.jpg?subformat=icon-1440, "March 24, 2015

CMS Detector

Basic Dimensions / Stats

- Length: 21.6 m
- Diameter: 15m
- Weight: Approx. 14,000,000 kg

Beam line outwards

- tracker
- electromagnetic calorimeter
- hadronic calorimeter
- Solenoid
- muon tracker & iron yoke

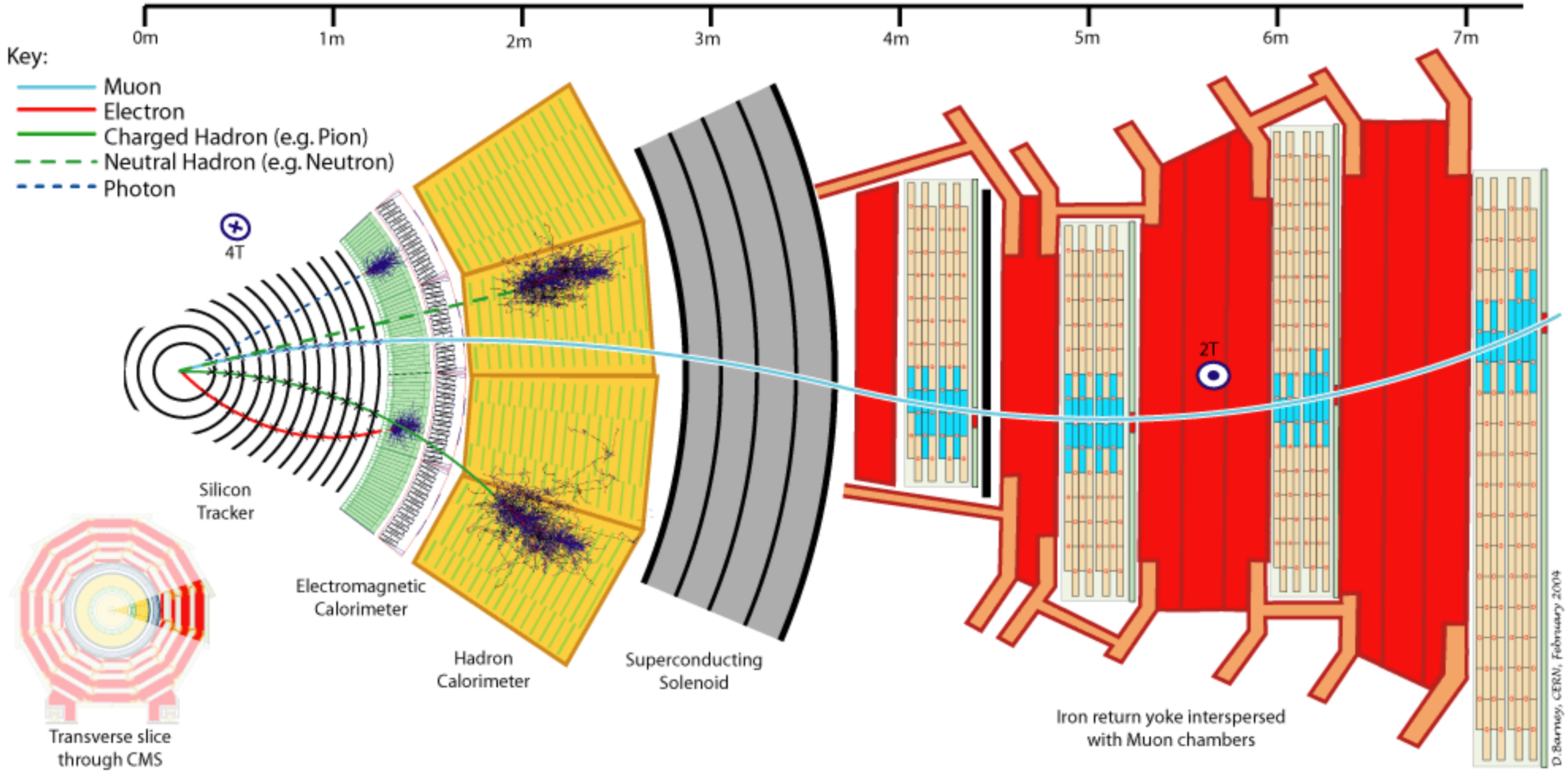
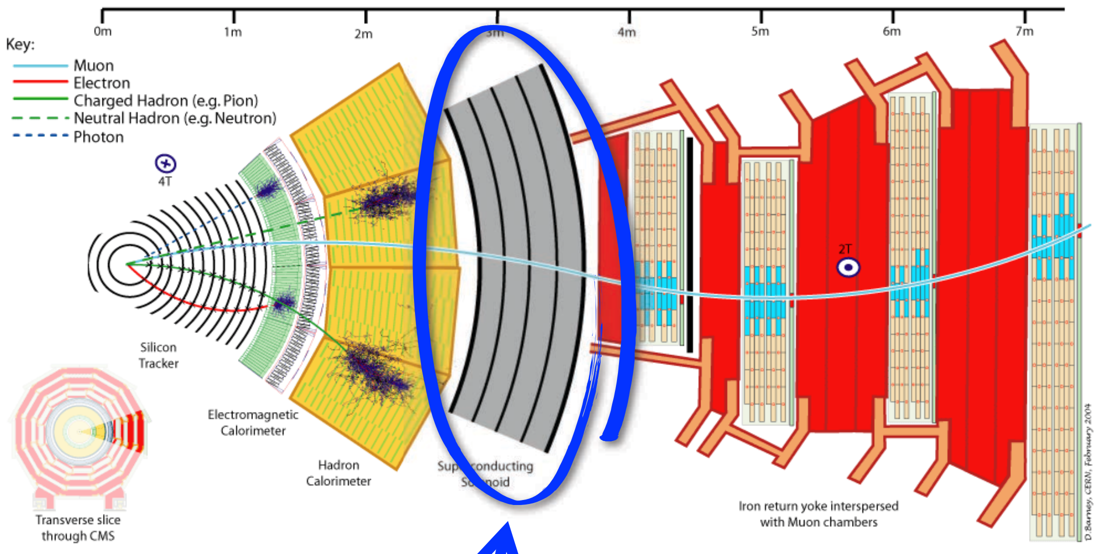
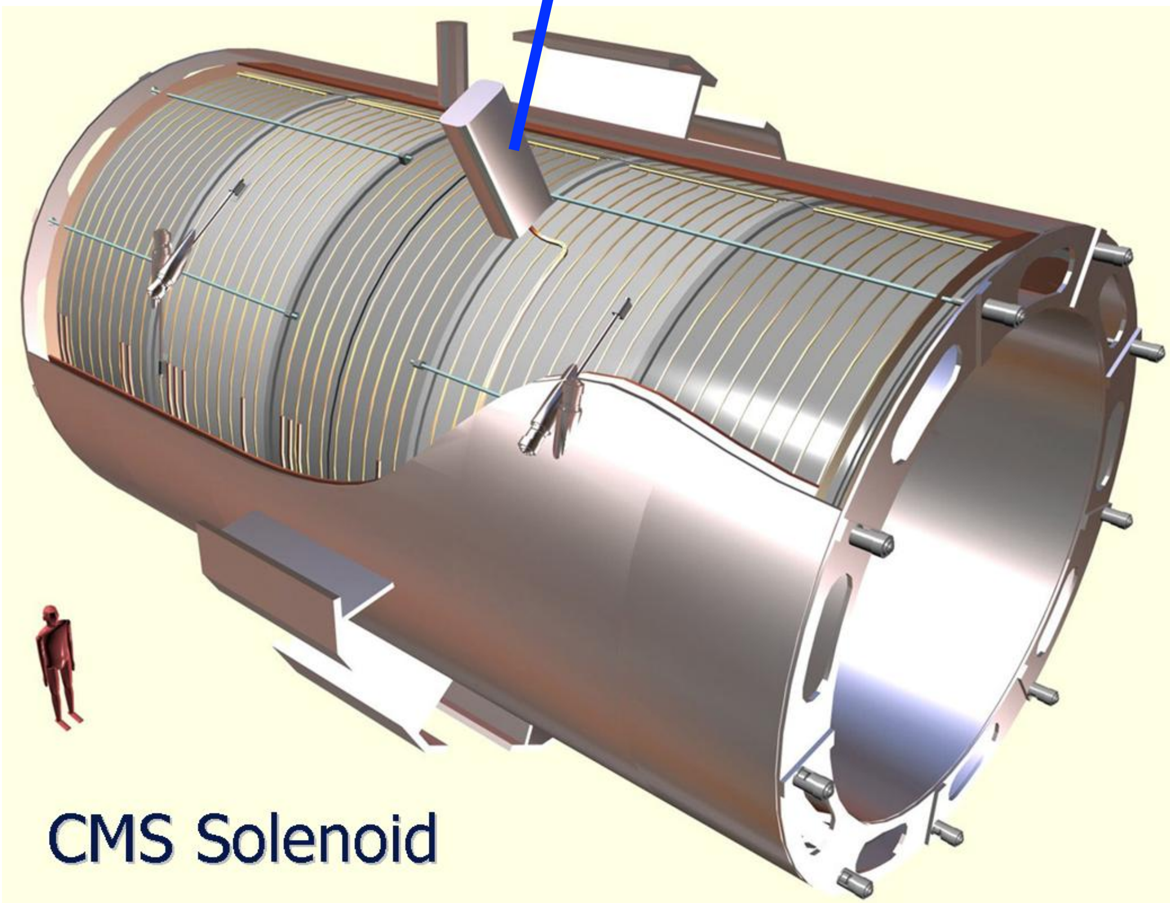


Image: https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/ShowDocument?docid=4172 "Static Image With Tracks", Mar. 25, 2015

Solenoid

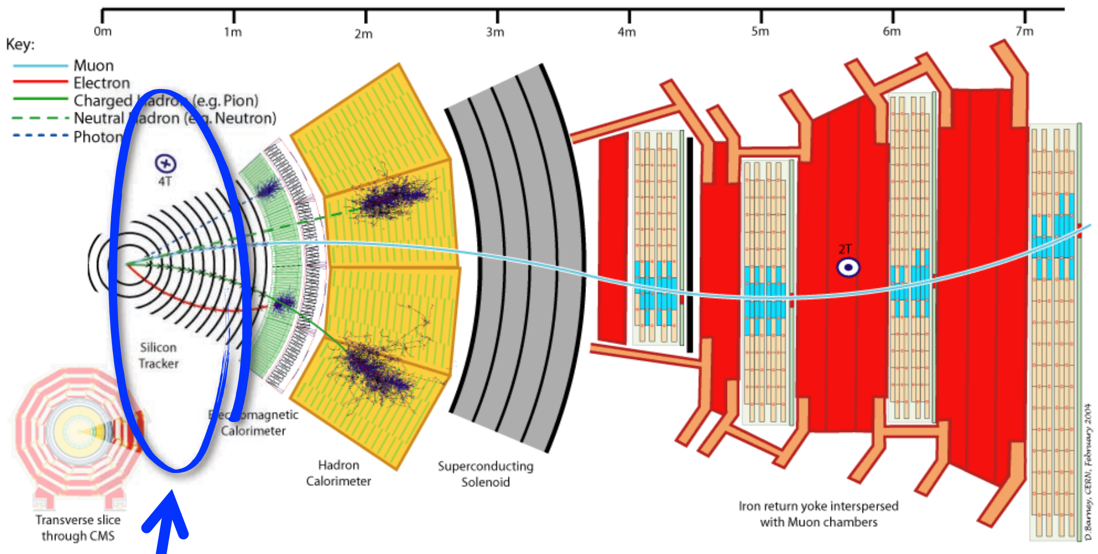
- **Purpose:** Strong magnetic field to bend path of charged particles
  - Allows momentum calculation
- 12.5 m length x 6.3 m diameter, cooled to 4.7 K
- 3.8 T field inside central barrel
- Iron return yoke provides ~2T field outside solenoid





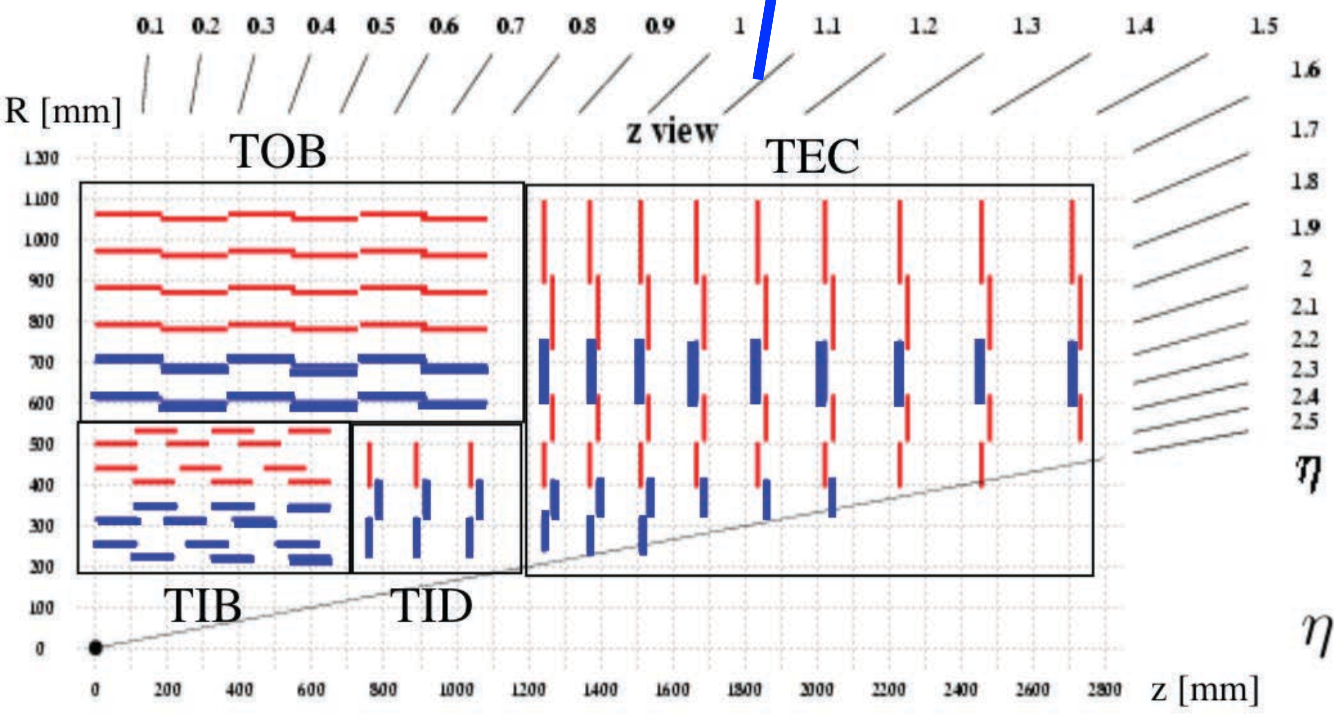
Silicon Tracker

- **Purpose:** High resolution tracks for p_T and vertex measurement & matching
- Inner Pixel Detector: 66M channels, fine grain resolution
- Outer Strip Detector: 9.6M channels, coarser granularity



Barrel resolution:

$$\frac{\delta p_T}{p_T} = (\frac{p_T}{1TeV}15\%) \oplus 0.5\%$$

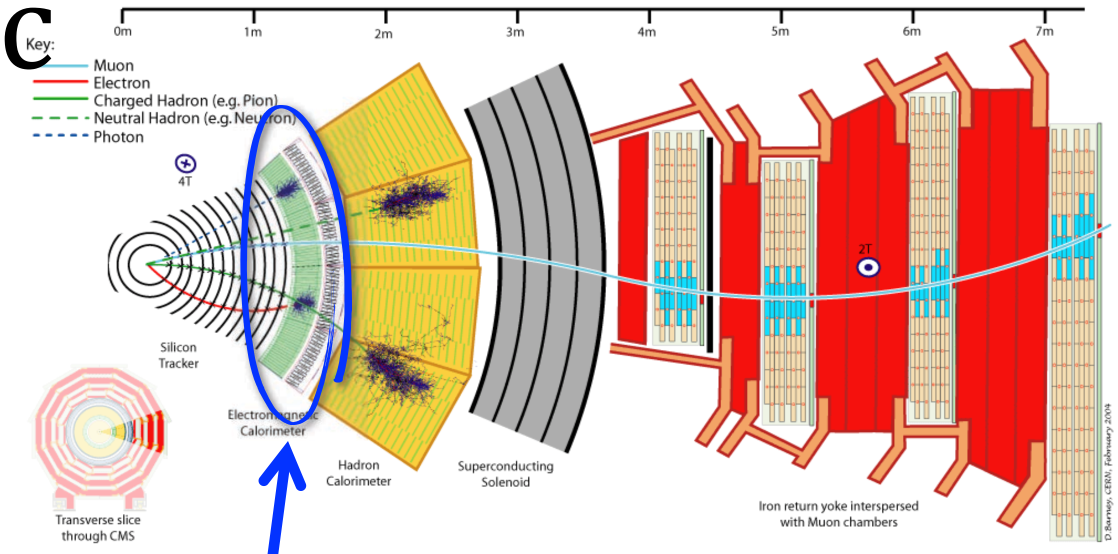


pseudo-rapidity

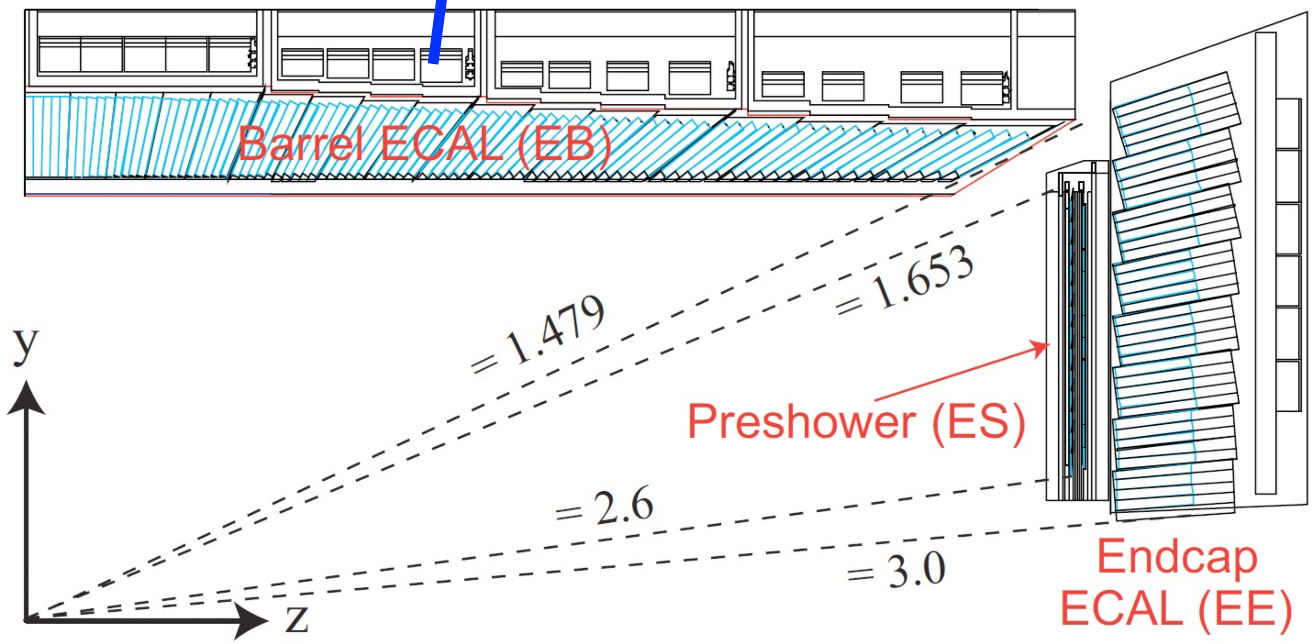
$$\eta = -ln\left[tan\left(\frac{\theta}{2}\right)\right]$$

Electromagnetic Calorimeter

- **Purpose:** measure position and energy of $e^{+/-}$ and photons



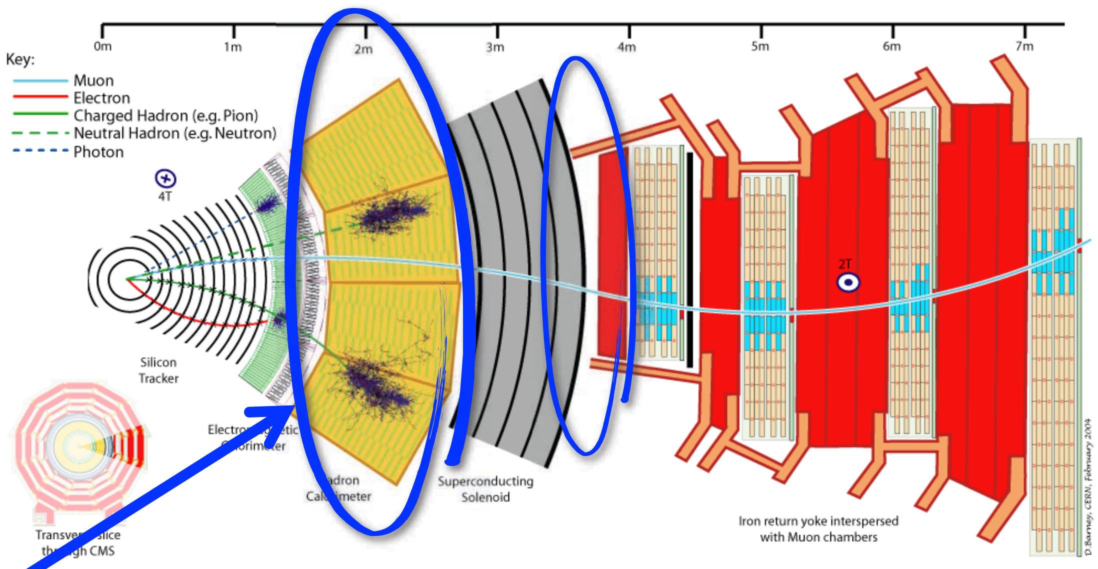
ECal Crystal $PbWO_4$	
Density	8.28 g/cm^3
Emission λ	480 nm
Decay Time	10 ns
$PbWO_4$ Radiation Len.	8.9 mm
Barrel Len.	230 mm
Barrel Rad. Len.	25.8 X_0
End Cap Len.	220 mm

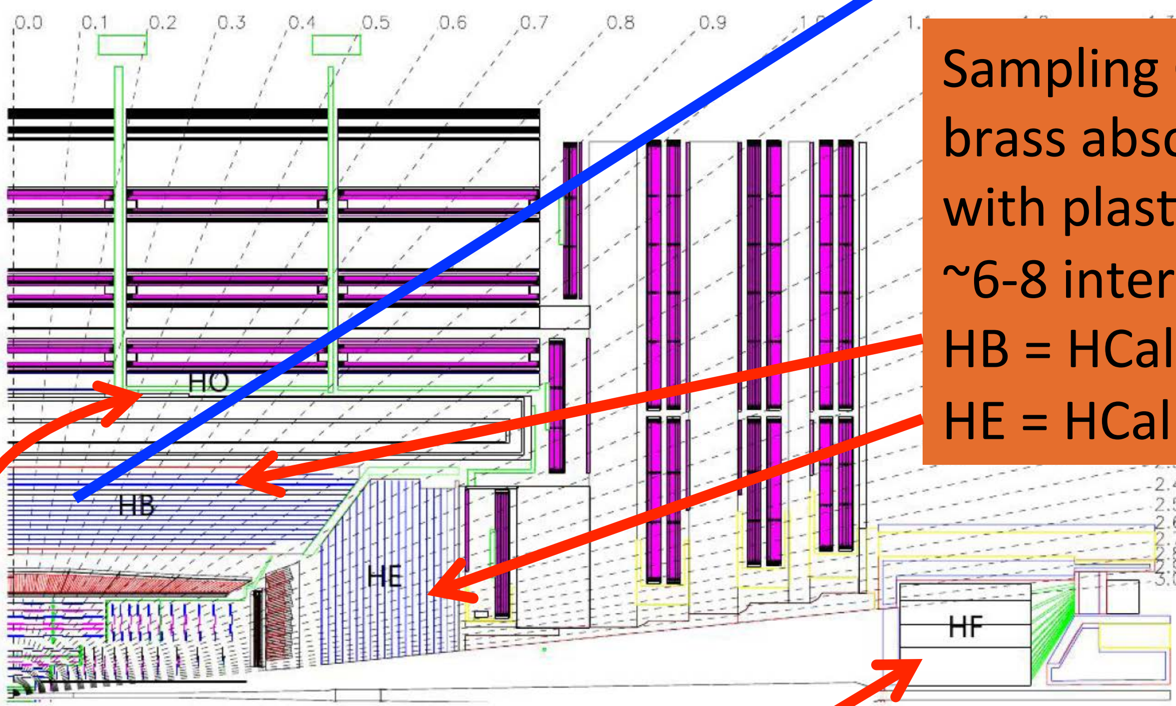


Barrel Resolution: $\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128}{E} \oplus 0.3\%$

Hadronic Calorimeter

- **Purpose:** Measure energy of neutral and charged long lived hadrons → Tau energy & missing transverse energy





Sampling Calo. → layers of brass absorber interspersed with plastic scintillator

~6-8 interaction lengths

HB = HCal Barrel

HE = HCal End Cap

Forward HCal made of steel with embedded quartz fibers for radiation hardness

- Measures EM rich jets beyond ECal range

HCal Outer (HO) uses solenoid as preshower

Resolution

- Barrel and End Cap

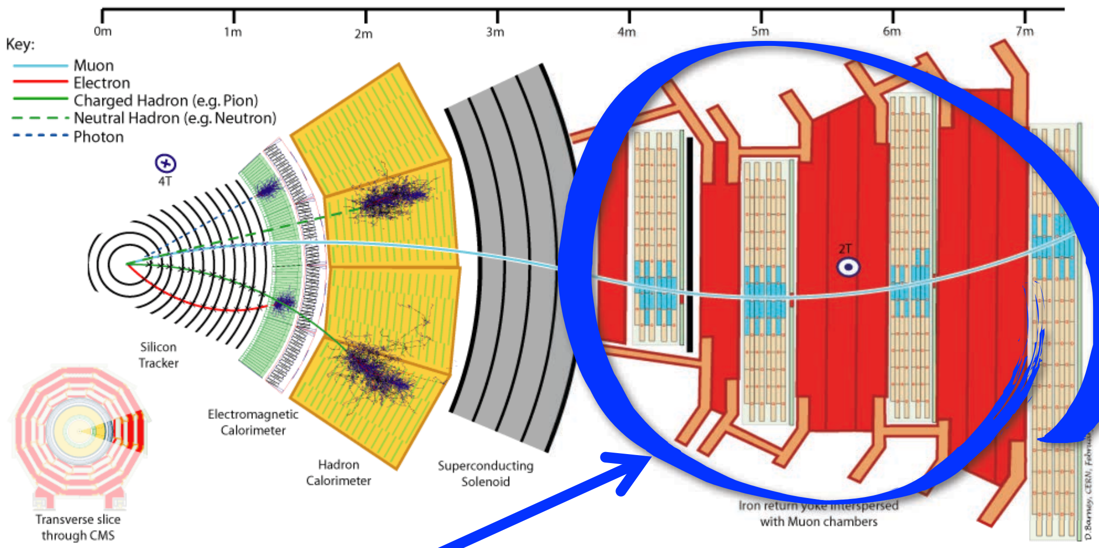
$$\frac{\sigma}{E} = \frac{115\%}{\sqrt{E}} \oplus 5.5\%$$

- Forward

$$\frac{\sigma}{E} = \frac{280\%}{\sqrt{E}} \oplus 11\%$$

Muon System

- **Purpose:** ID & measure p_T of muons, provide quick trigger info
- Low p_T muons (< 100 GeV):
  - Silicon tracker → p_T
  - Res. 6-20%
- High p_T muons (> 100 GeV):
  - Tracker + muon system → p_T
  - Res. 15-35%

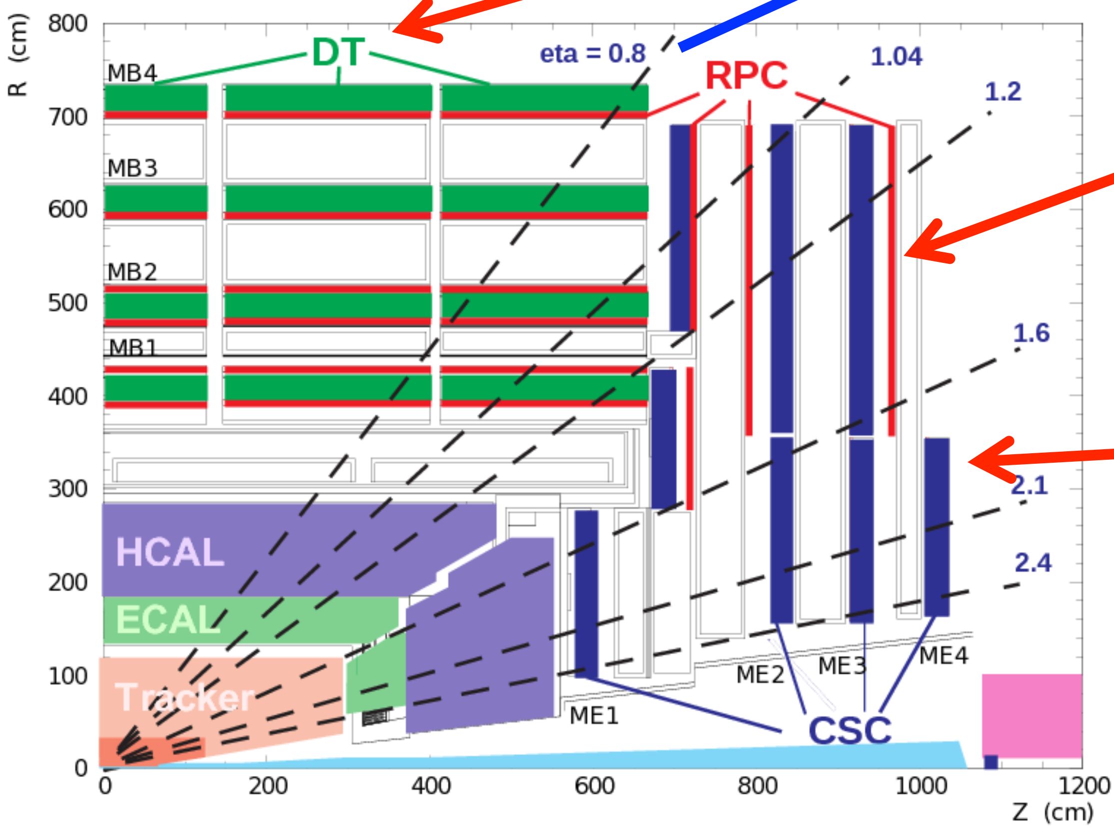


Drift Tubes - Res. 80-120 µm & 3 ns

Resistive Plate Chambers - Res. 0.8-1.2 cm & 1 ns; triggering

Cathode Strip Chambers - Res. 40-150 µm & 3 ns

New in 2015! Additional CSCs and RPCs

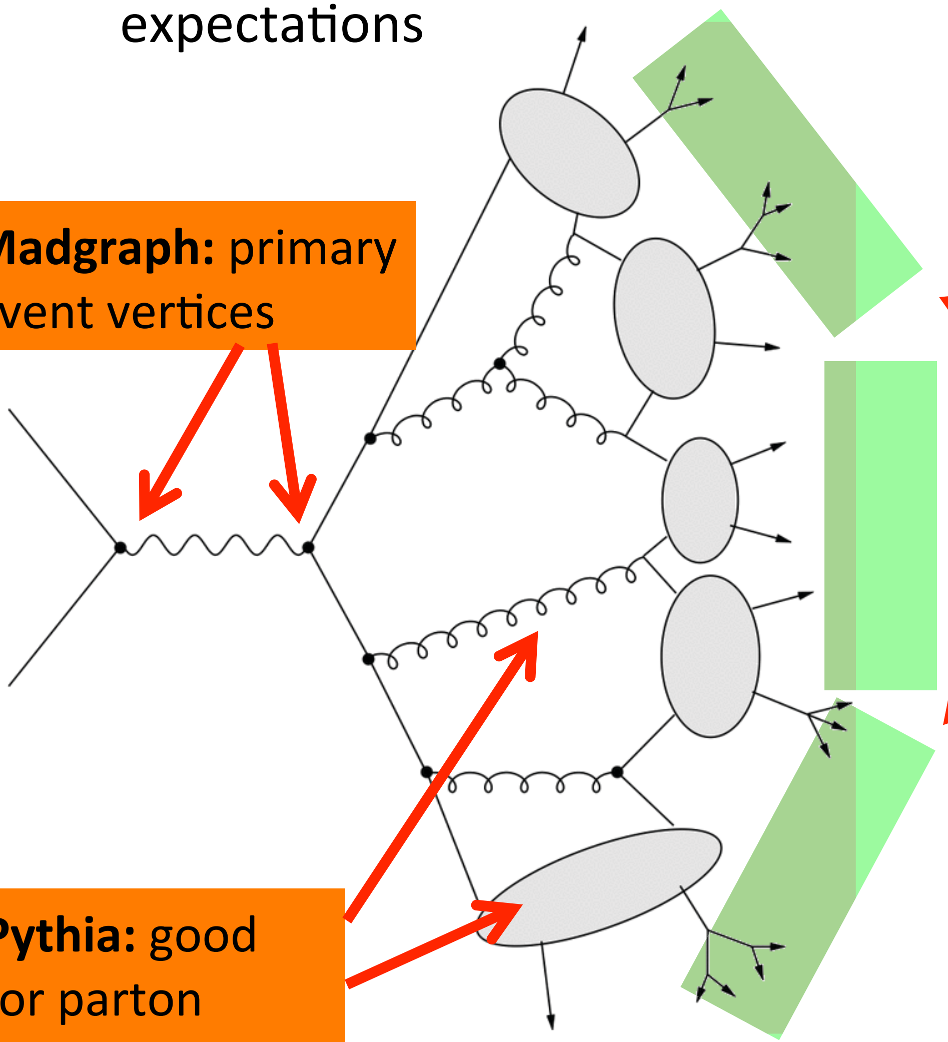


Monte Carlo

- **Purpose:** Create accurate simulated data to model expectations

Sample	Primary Vertex	Hadronization & Parton Shower
Signal	Madgraph	Tauola/Pythia
ZZJets	Madgraph	Tauola/Pythia
Tri-Boson	Madgraph	Pythia
SM Higgs	Pythia	Tauola/Pythia
TTZJets	Madgraph	Pythia
Min Bias	Pythia	

Madgraph: primary event vertices



GEANT: particle interactions with detector

Pythia: good for parton showering & hadronization

Tauola: Like Pythia but specifically for tau decays

minimum bias data → simulate pile-up

Event reconstruction software: identical to actual CMS measured data

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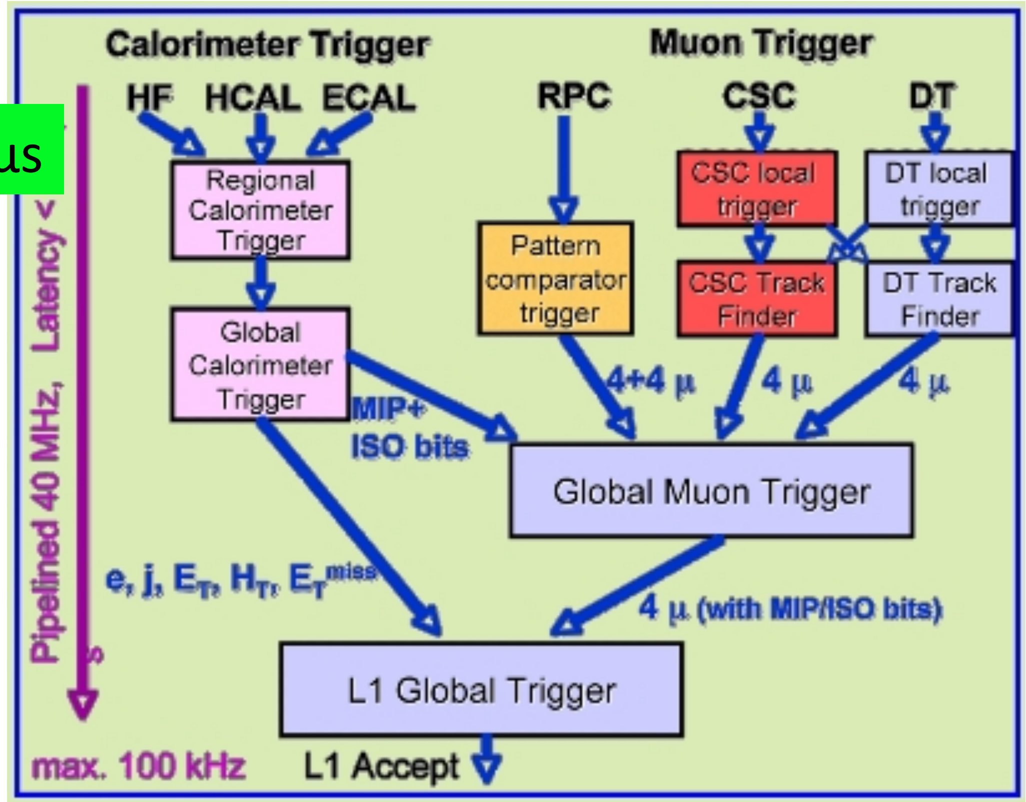
Trigger

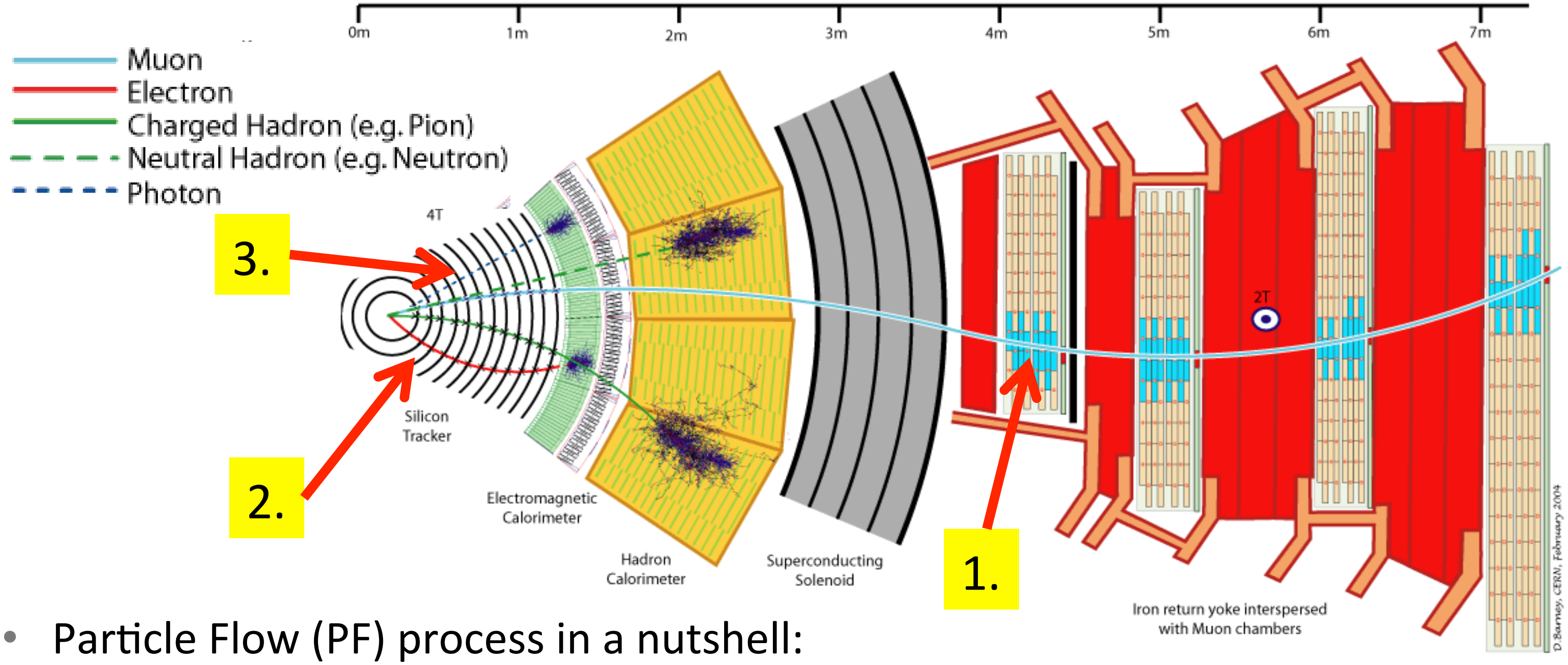
- **Purpose:** Discard less interesting events (keep interesting events!) so data is manageable to process, analyze & store
- Initial 40 MHz crossing rate, with 20 events / crossing → ~1 GHz event rate
- Each event ~ 1 Mb of disk space
- Level-1 Trigger:
  - High-speed custom hardware
  - Specialized algorithms
  - Algos access small regions at a time
- High Level Trigger (HLT):
  - Reduces from ~ 100 kHz to ~ 300 Hz
  - General purpose CPU farm
  - Software based system
  - Algos have access to entire event
- A->Zh->lltt HLT Triggers:
  - Double Electron & Double Muon, p_T based cuts
    - $\mu_1 > 17$ GeV, $\mu_2 > 8$ GeV
    - $e_1 > 17$ GeV, $e_2 > 8$ GeV

4 µs



Particle Flow Reconstruction

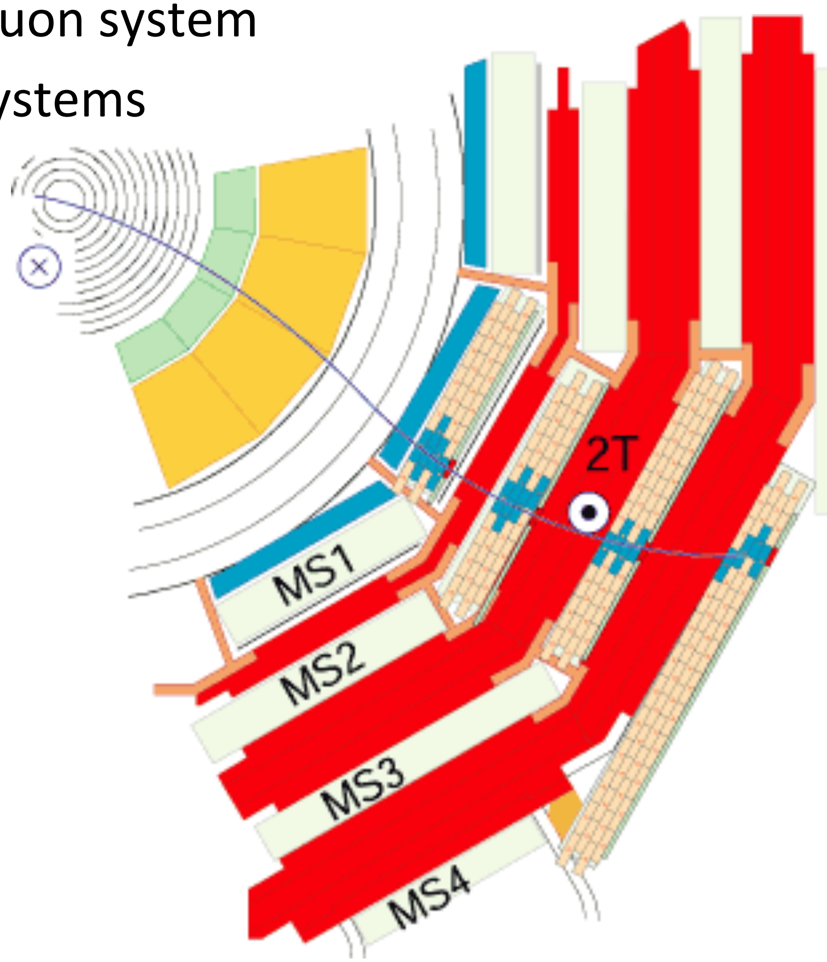
- Information from detector systems utilized simultaneously to provide best reconstruction of select physics objects
  - Improves track & p_T resolution & particle identification
  - Primary objects: muons, electrons, charged & neutral hadrons & photons



- Particle Flow (PF) process in a nutshell:
  1. Muon system tracks are matched to tracks in inner tracker
  2. Remaining inner tracker tracks associated with ECal energy deposits (electrons) and HCal energy deposits (charged hadrons)
  3. Remaining energy deposits are likely from neutral sources, ECal (photons) & HCal (neutral hadrons)

1. Muons

- Particle Flow reconstructs three muon definitions
  - Tracker muon, found by silicon tracker
  - Standalone muon, found solely by muon system
  - Global muon, tracks match in both systems

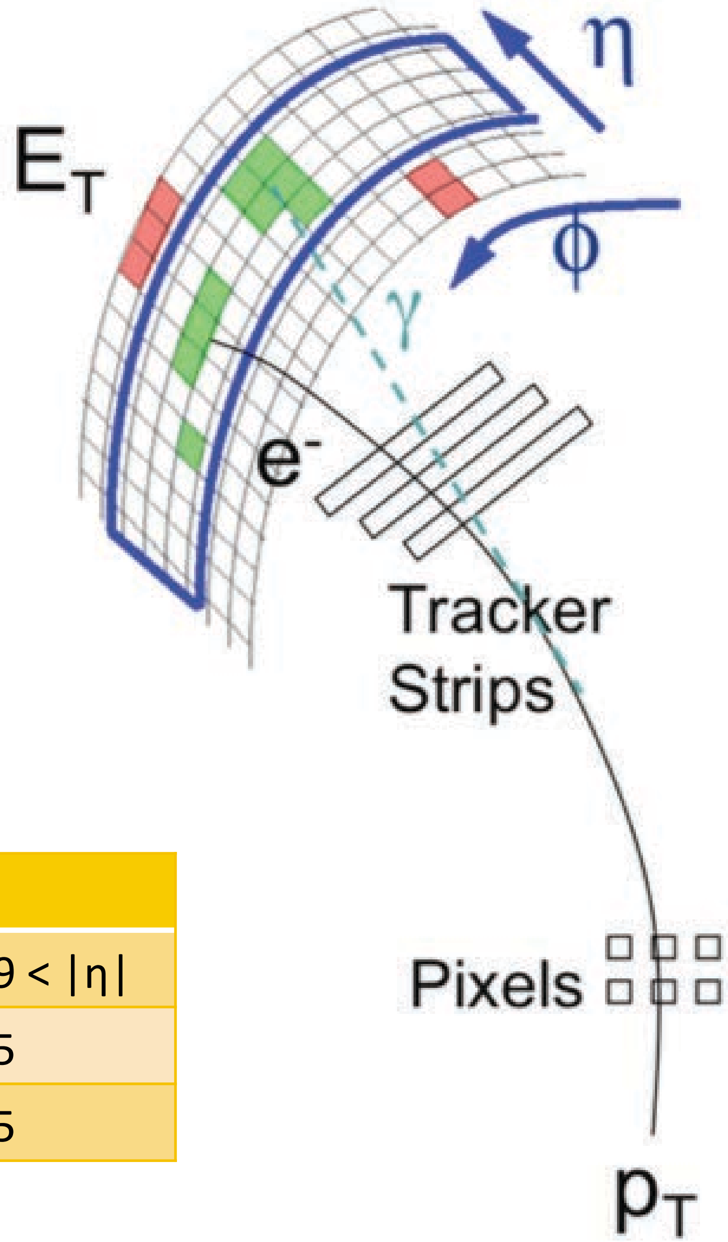


- $A \rightarrow Zh \rightarrow ll\tau\tau$ uses 2 muon definitions
  - "loose muon" = tracker || global
  - "tight muon" = global
- Additional PF muon requirements
  - Close to primary vertex
  - Small X^2 of track to eliminate punch through to the muon system

2. Electrons

Charged, curved tracks in silicon tracker

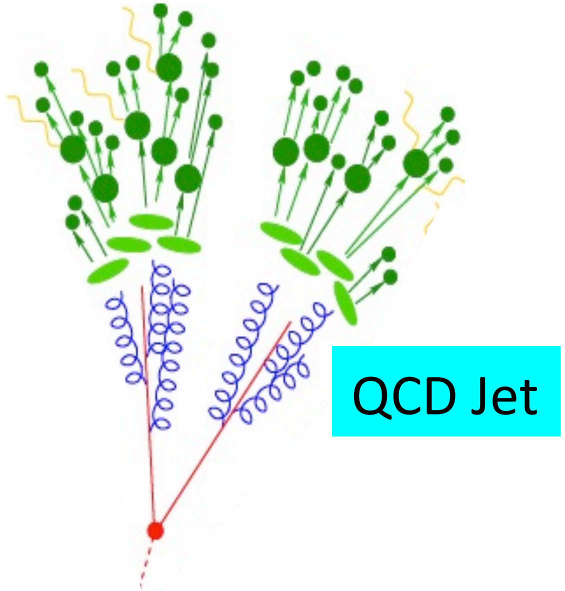
- Matching between ECal energy deposits and nearby tracks
  - ECal and tracks define p_T
- ECal supercluster includes elongated area in φ to contain bremsstrahlung photons radiated from electron
- Track must be close to primary vertex
- Boosted Decision Tree used to optimize electron selection → Likelihood discriminator

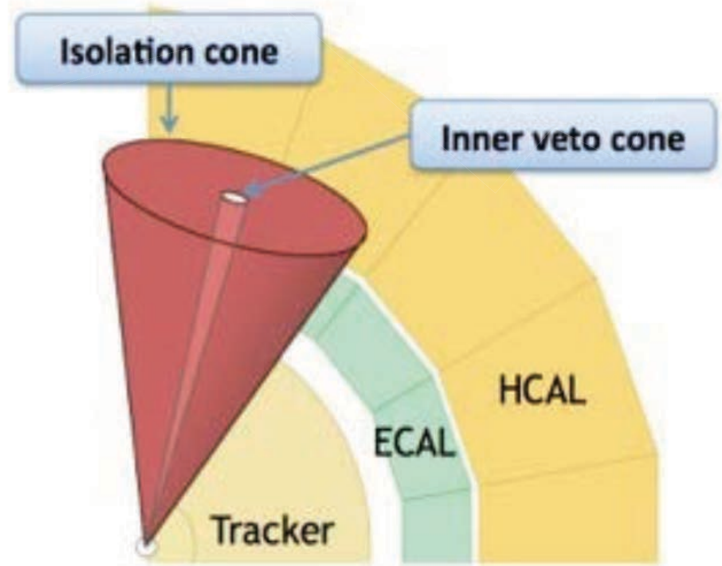


Likelihood to be an Electron by p_T and |η|			
	|η| < 0.8	0.8 < |η| < 1.479	1.479 < |η|
p_T < 20	0.925	0.915	0.965
p_T > 20	0.905	0.955	0.975

Lepton Isolation

- QCD backgrounds produce leptons inside jets
- Requiring isolated leptons strongly rejects these QCD backgrounds
- Sum the energy deposited within $\Delta R < 0.3$
  - Pile-up (PU) corrections are applied
  - Charged hadron PU already removed with vertex cuts
  - Neutral hadron pile-up approximated as 0.5 x charged hadron PU and is called $\Delta\beta$



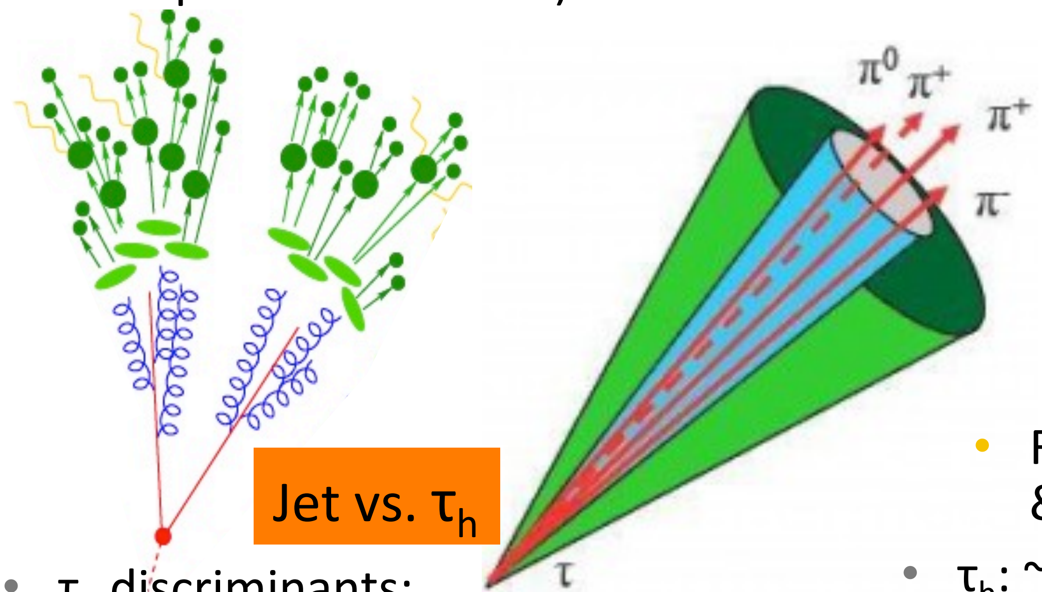


$$I_{rel} = \frac{\Sigma p_T(charged) + max[\Sigma E_T(neutral) + \Sigma E_T(photon) - \Delta\beta, 0]}{p_T(\mu\ or\ e)}$$

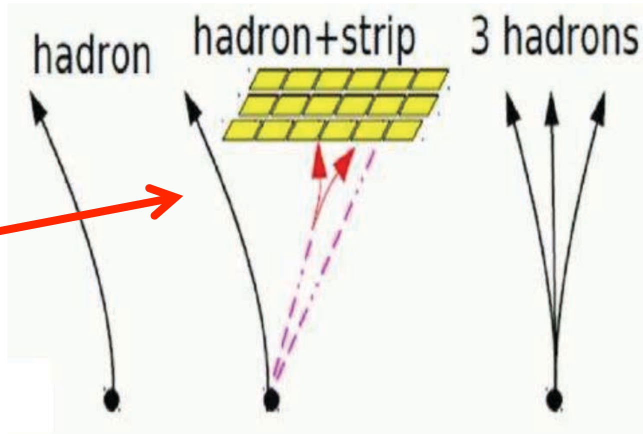
Hadronic Tau Reconstruction from Charged & Neutral Hadrons & Photons

Main goal: distinguish τ_h ($\tau \rightarrow W + \nu$, $W \rightarrow$ light quarks $\rightarrow$ hadrons) from other hadronic jets

Dominant Tau Decays	Branching Ratio
e^- or μ^- + 2 ν	17.8 + 17.4
π^- + ν	10.8
$\pi^- \pi^0$ + ν	25.5
$\pi^- \pi^0 \pi^0$ + ν	9.3
$\pi^- \pi^+ \pi^-$ + ν	9.0



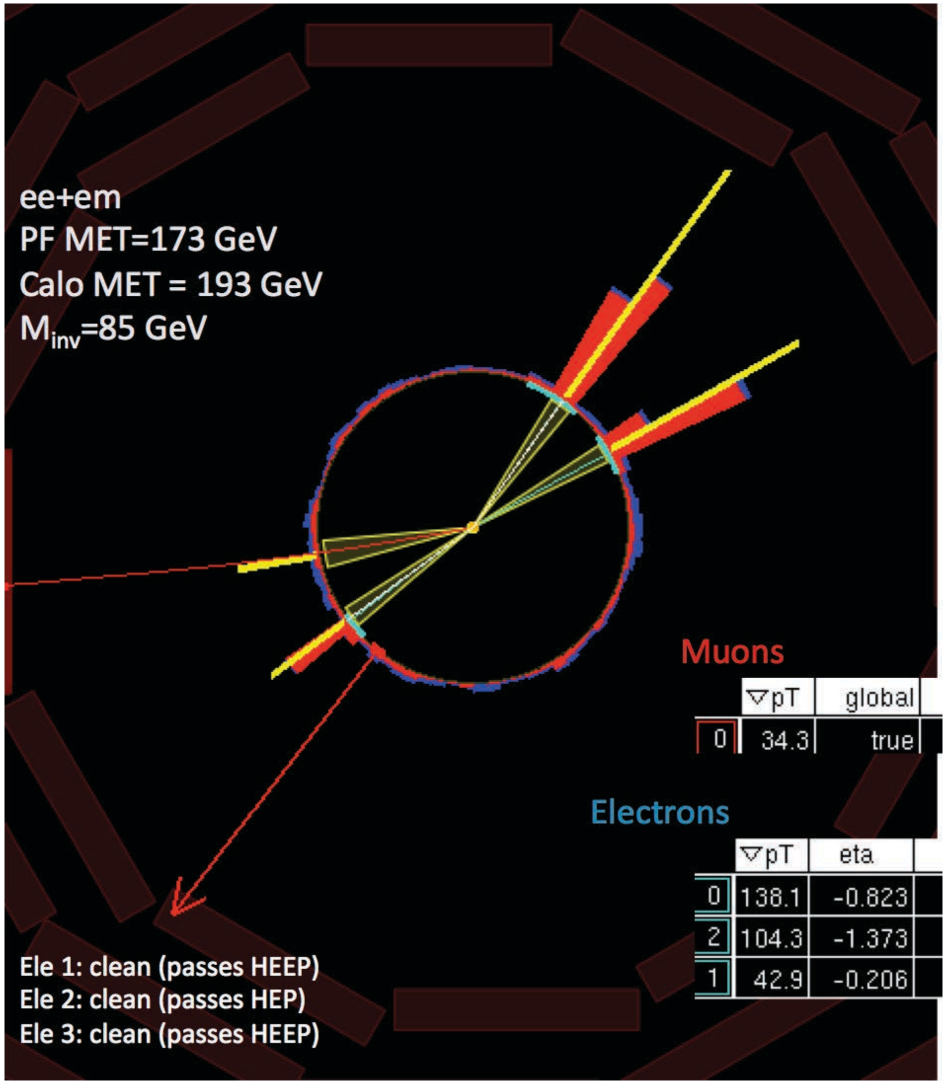
- τ_h discriminants:
  - No neutral hadrons
  - Large photon decay energy (~25%)
  - Relatively collimated
  - Small number of hadrons (<= 3)
  - Visible mass < Mass Tau
- τ_h reconstruction:
  - Group photon energy deposits into strips (similar to electron superclusters)
  - Require $dR = 2.8 / p_T(\tau_h)$ for strips & hadrons
- τ_h: ~ 1% fake rate for 60% efficiency
  - "fake" is usually an electron
  - Anti-Electron discriminators applied



Missing Transverse Energy

- Missing Transverse Energy (MET) is calculated as the negative of the vector sum of all transverse energy deposited in ECal and HCal
- Usually results from neutrinos or missed particles
- Missing Energy can only be resolved in φ
- PF calculates MET last, after all particles have been constructed
  - This allows calculation of MET attributed to a single primary vertex instead of the entire event with pile-up

A sample event from the analysis with high MET. Two high p_T electrons opposite a lower p_T e & μ



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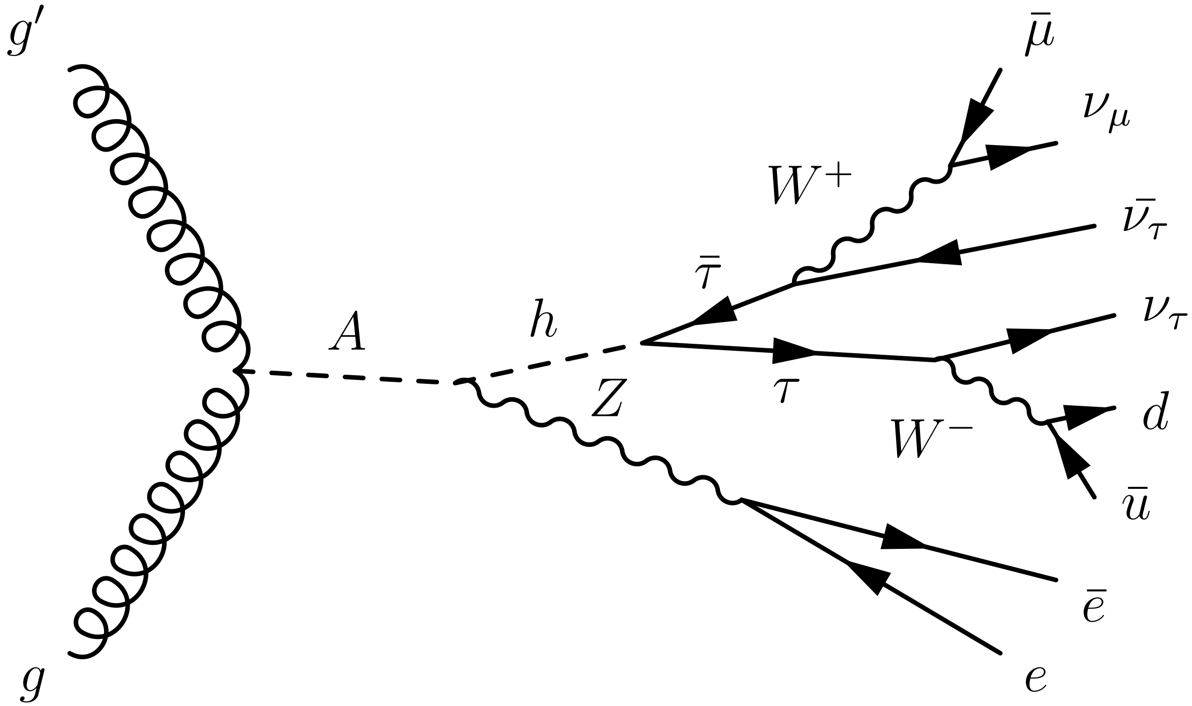
Analysis Strategy: A→Zh→llττ in a nutshell

The goal is to best reconstruct the mass of the pseudo-scalar A candidate while maximizing our signal to background ratio



Eight final state channels are studied
Z → ee or μμ final states
h → ττ → $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$, or eμ final states
8 channels: $ee e\tau_h$, $ee\mu\tau_h$, $ee\tau_h\tau_h$, eeeμ, $\mu\mu e\tau_h$, $\mu\mu\mu\tau_h$, $\mu\mu\tau_h\tau_h$ & μμeμ

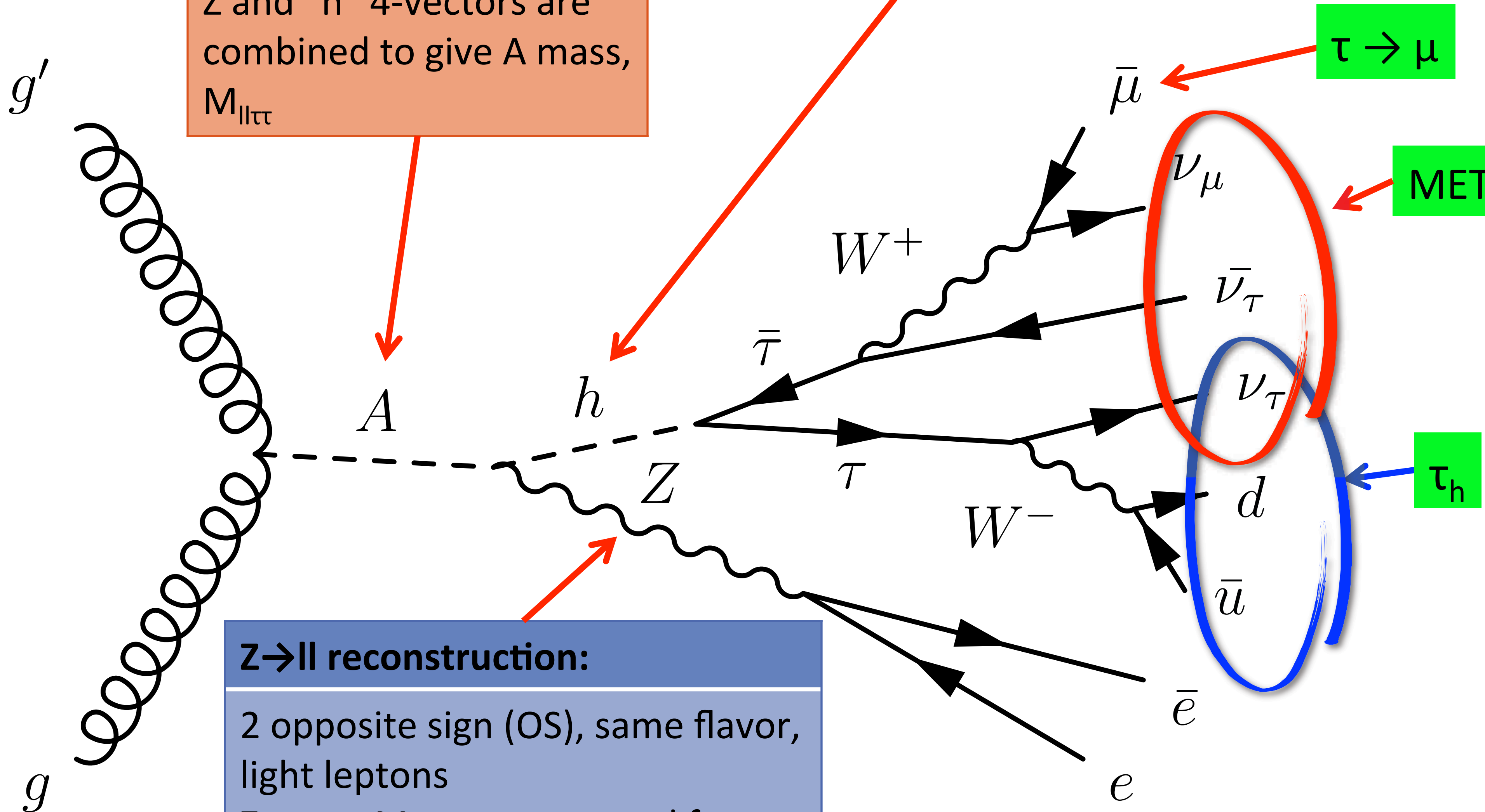
A mass reconstruction

h→ττ reconstruction:

2 OS, leptons
e, μ, and τ are all considered
"e" and "μ" result from leptonically decaying τ
"τ_h" are hadronically decaying τ
Missing Transverse Energy (MET) from neutrinos

A→Zh reconstruction

Z and "h" 4-vectors are combined to give A mass, $M_{ll\tau\tau}$



Z→ll reconstruction:

2 opposite sign (OS), same flavor, light leptons
Z mass, M_{ll}, reconstructed from 4-vectors

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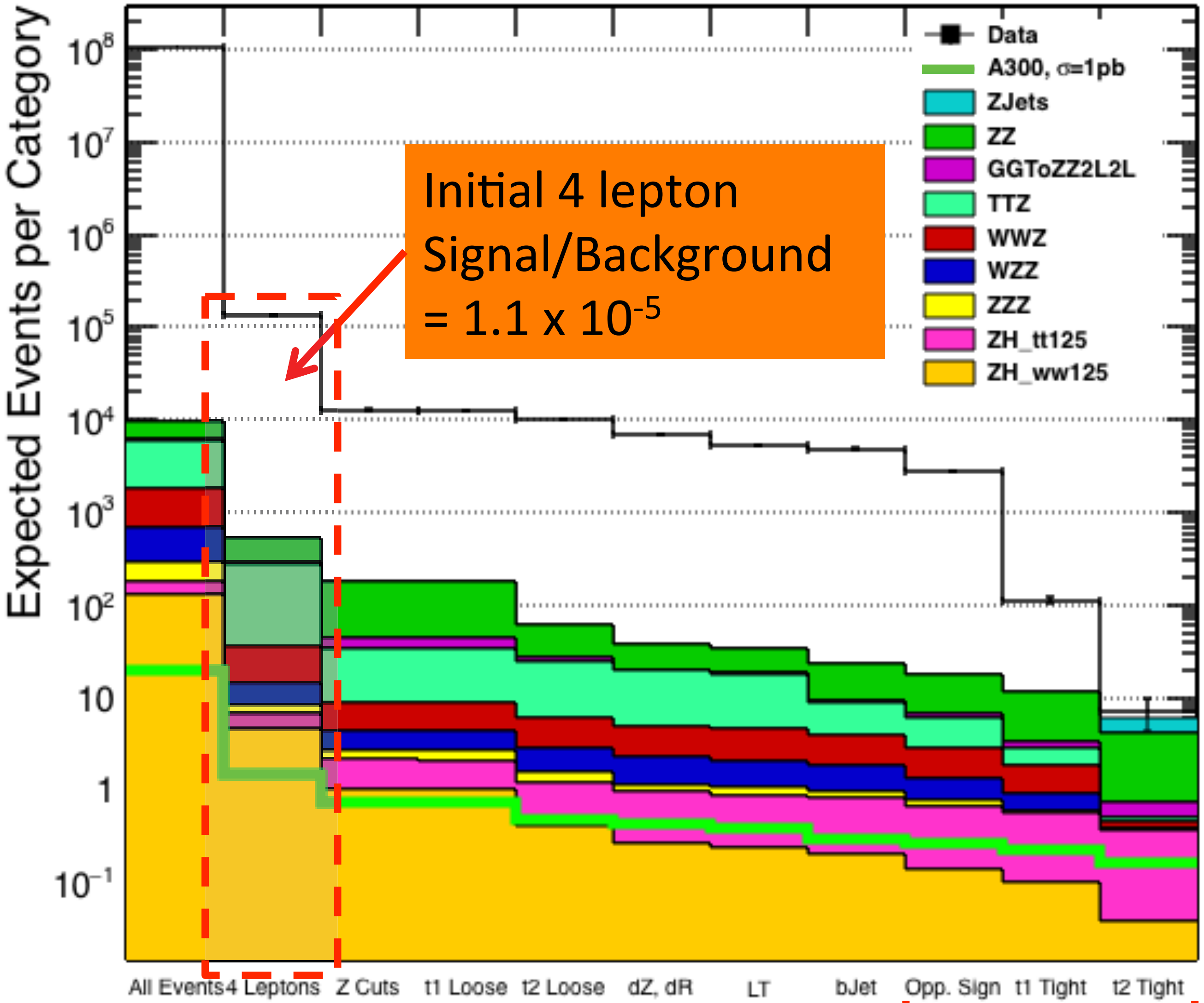
Event Selection: Quick Overview, EEMT



ZJets only in final bin

4 very loose leptons

Z selection

Loose Higgs

dR, dZ, overlap

Scalar Sum of p_T

bJet Veto

Tighter Higgs

Final Higgs Selection:

$h \to \tau_h \tau_h$

- Opposite sign (OS)
- LT = Scalar Sum of p_T > 70 GeV

- τ_h: Combined 3 Hits Medium
- τ_h: Anti Muon 2 Loose, anti electron Loose

$h \to e\mu$

- OS
- LT > 25 GeV

- Both: relative $\Delta\beta$ corrected iso < 0.3
- e: Loose MVA ID
- μ: Tight ID

$h \to \mu\tau_h$

- OS
- LT > 45 GeV

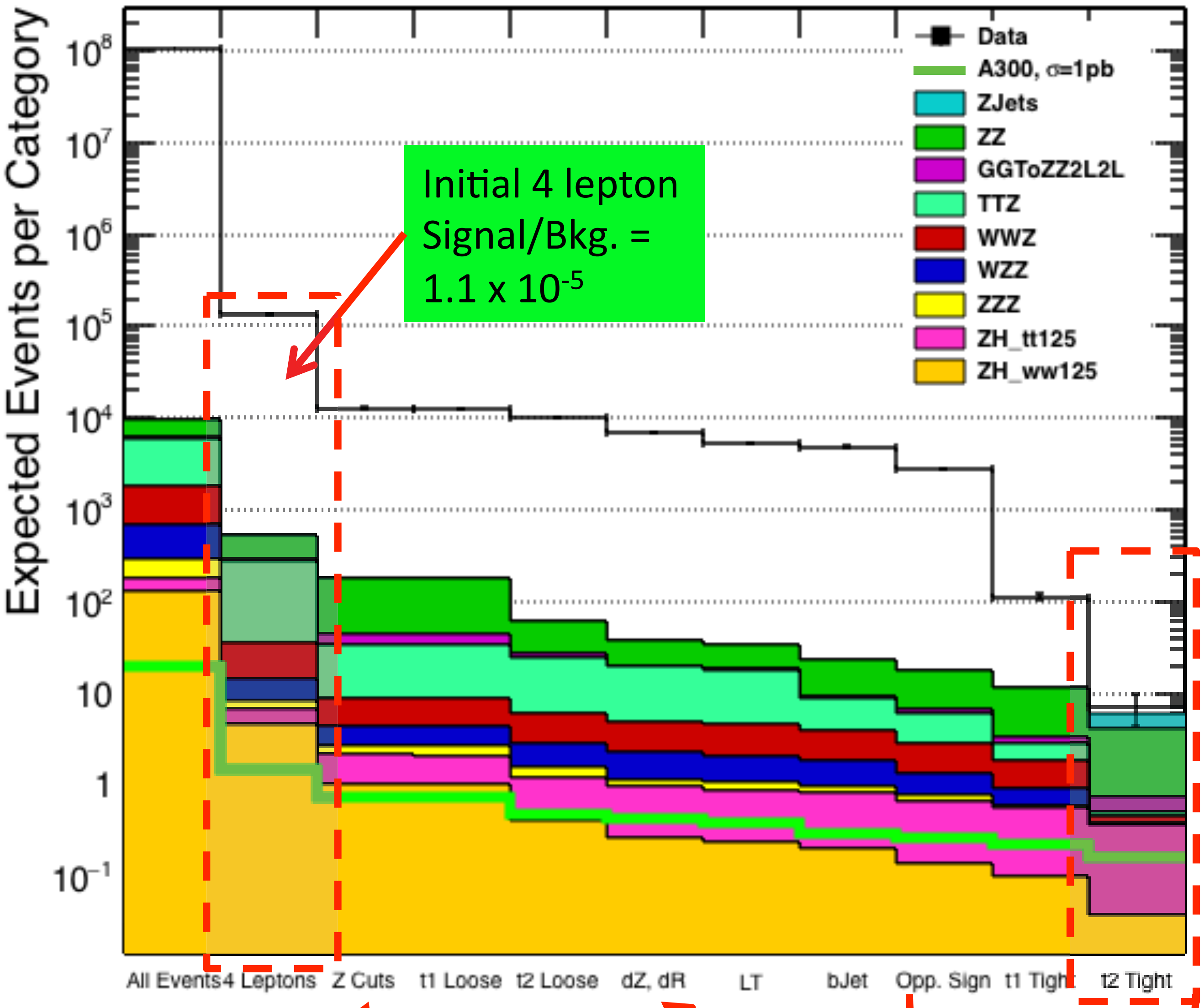
- $\Delta\beta$ = estimate of neutral hadron composition of jet
- μ: relative $\Delta\beta$ corrected iso < 0.3
- τ_h: Comb. 3 Hits Loose, anti muon 2 tight, anti electron loose

$h \to e\tau_h$

- OS
- LT > 30 GeV

- e: relative $\Delta\beta$ corrected iso < 0.3, Loose MVA ID
- τ_h: Comb. 3 Hits Loose, anti muon 2 loose, anti electron MVA Tight

Final Cuts, EEMT



Initial 4 lepton Signal/Bkg. = 1.1×10^{-5}

Final Signal/Bkg. = 2.2×10^{-2}

Stay tuned, this S/B is not hopeless!

4 very loose leptons

Z selection

Loose Higgs

dR, dZ, overlap

bJet Veto

Scalar Sum of p_T

Tighter Higgs

Passing Tight Higgs Cut	
data	7
A300	0.16
SM Higgs	0.37
Tri Boson	0.10
TTZ	0.05
ggZZ4l	0.22
ZZ	3.48
ZJets	1.88
Total bkg. modeled	6.10

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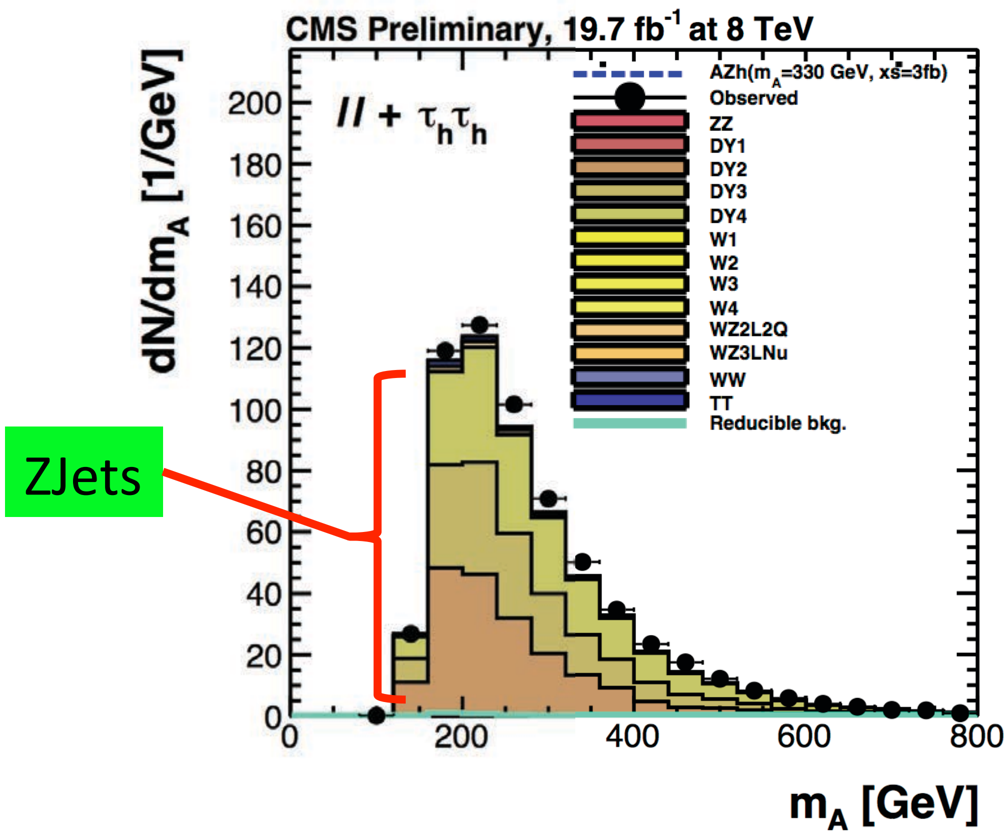
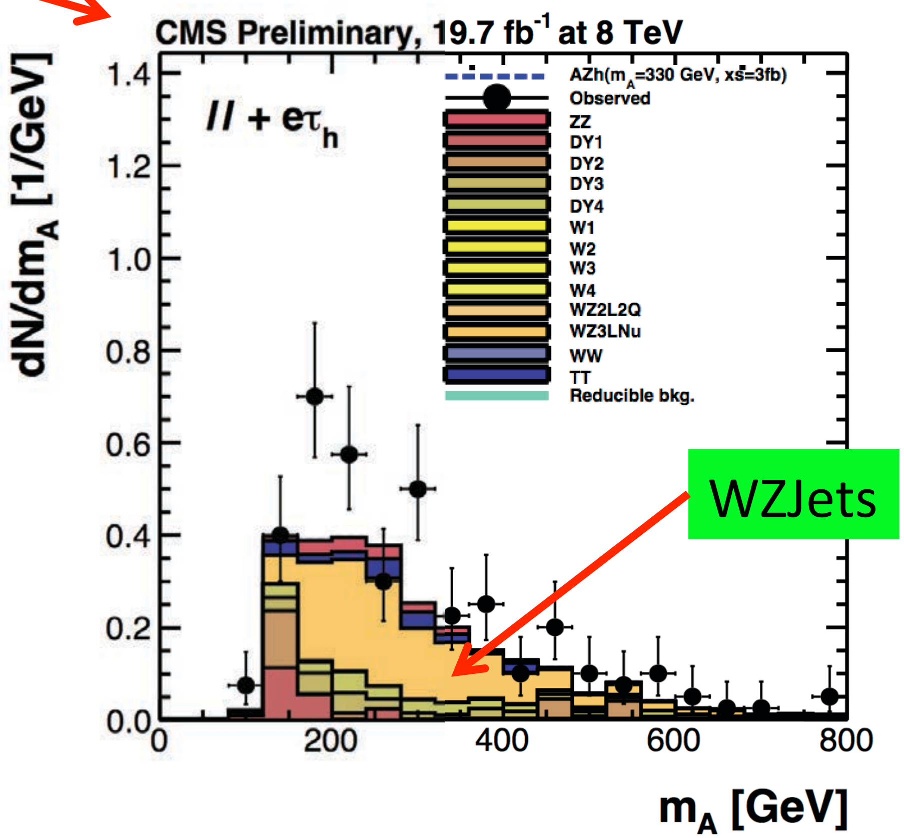
Reducible Background Composition

Reducible background composition MC vs. data

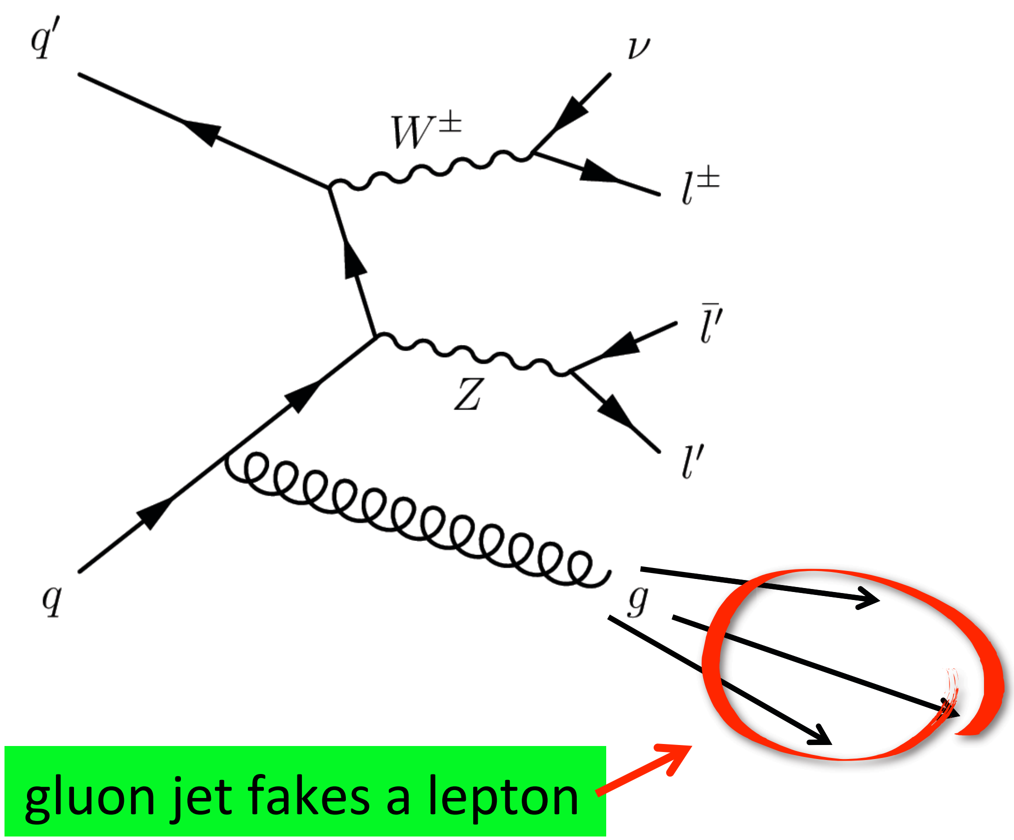
- Selection:
  - **same sign ττ**
  - taus anti-isolated
  - no cut on higgs candidate LT
- $ee e\tau_h$ & $\mu\mu e\tau_h$
- $ee\tau_h\tau_h$ & $\mu\mu\tau_h\tau_h$

Plots to show reducible background composition, shape and scaling addressed later





Estimating Reducible Background



- Leading contributors: WZJets and ZJets events
- Step 1 – estimate the likelihood of a jet faking an e, μ or τ_h
- Step 2 – estimate the total contribution of these "faked" event to our background
- Step 3 – estimate the shape of the background
- Step 4 -validate

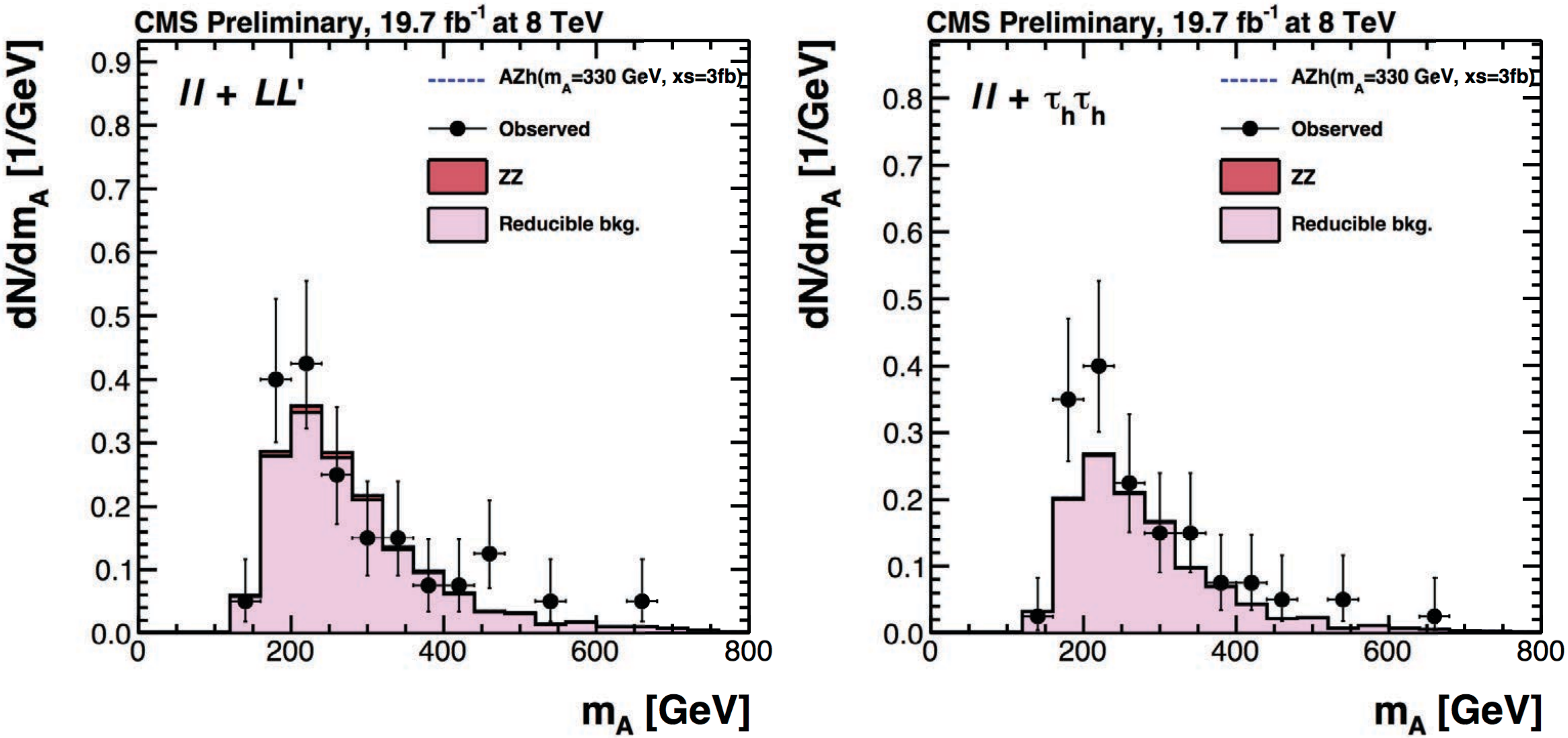
- Key characteristic of reducible backgrounds is that they should be found in equal proportions in Opposite Sign and Same Sign (SS) ττ configurations
  - There is negligible signal contamination in SS events

Reducible Background Validation

- Reducible Background = WZJets + ZJets + sub-leading contributions
- Good shape and yield agreement between Reducible Background and Data within low statistics

SS, all channels, no LT, loose tau isolation

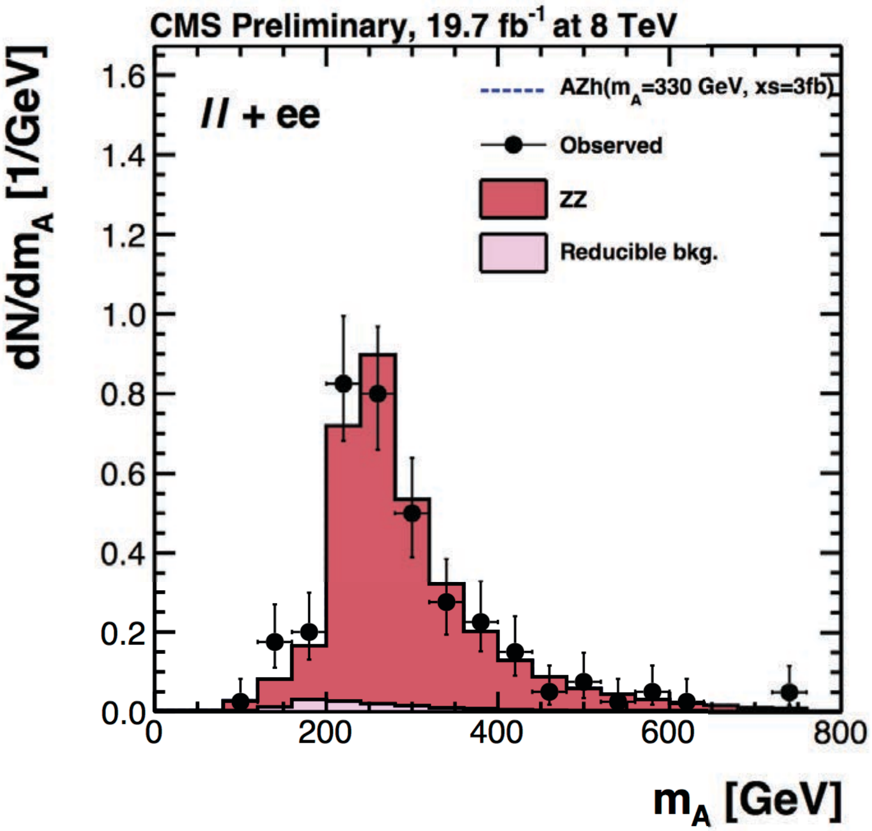
SS, $\tau_h\tau_h$ final state, no LT, loose isolation



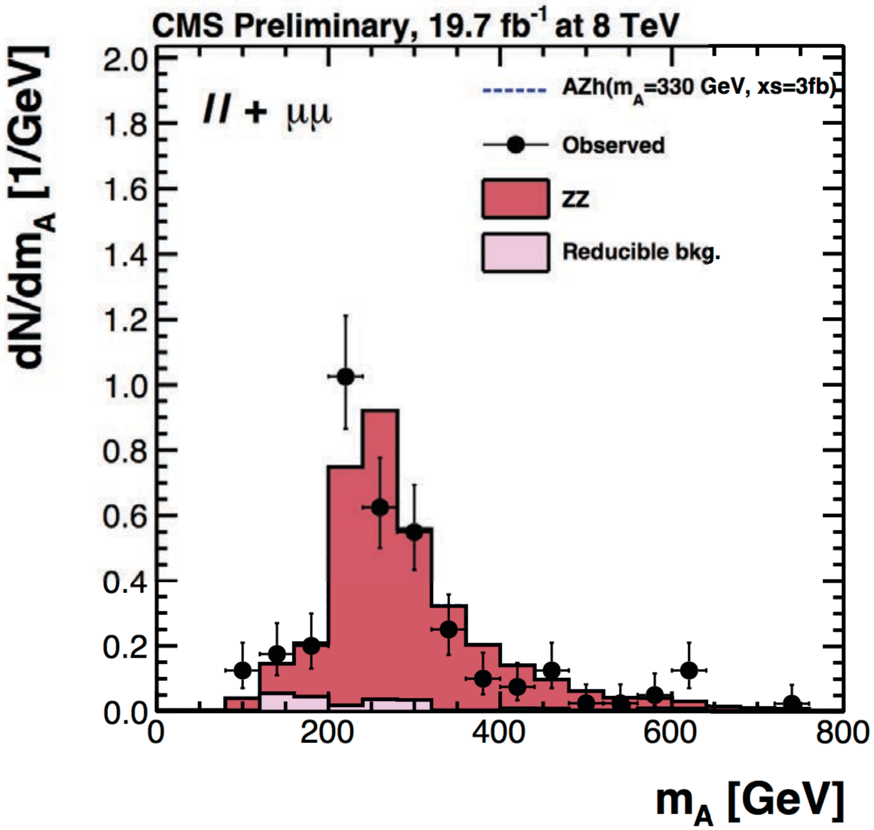
ZZ Background Validation

- Check Monte Carlo ZZJets sample
- 4 channels with 2 pairs of same flavor, opposite sign leptons
  - eeee, eeμμ, μμee, μμμμ
- Good agreement between data and ZZJets

eeee & μμee



eeμμ & μμμμ



Systematics: Overview

Source	Uncertainty
Luminosity measurement	2.2-2.6%
Muon trigger efficiency	1%
Muon ID/Iso/Energy Scale (ES)	2%
Electron trigger efficiency	1%
Electron ID/Iso/Energy Scale	2%
Tau ID/Iso	6%(12%)
Tau Energy Scale	3%(6%)
Btag	1%
PDF for $q\bar{q} \rightarrow ZZ$	5%
PDF for $gg \rightarrow ZZ$	10%
QCD scale for qq	2.6-6.7%
QCD scale for $gg \rightarrow ZZ$	24-44%
QCD scale for VHs	2.9%
Reducible background estimate	15-30%
TTZ Yield	50%
WWZ Yield	50%
WZZ Yield	50%
ZZZ Yield	50%

Tau energy scale

- affects $M_{ll\tau\tau}$ shape distribution
- shape uncertainty

ZZJets - dominated by theoretical uncertainties

- PDF and QCD scale factors are treated as uncorrelated

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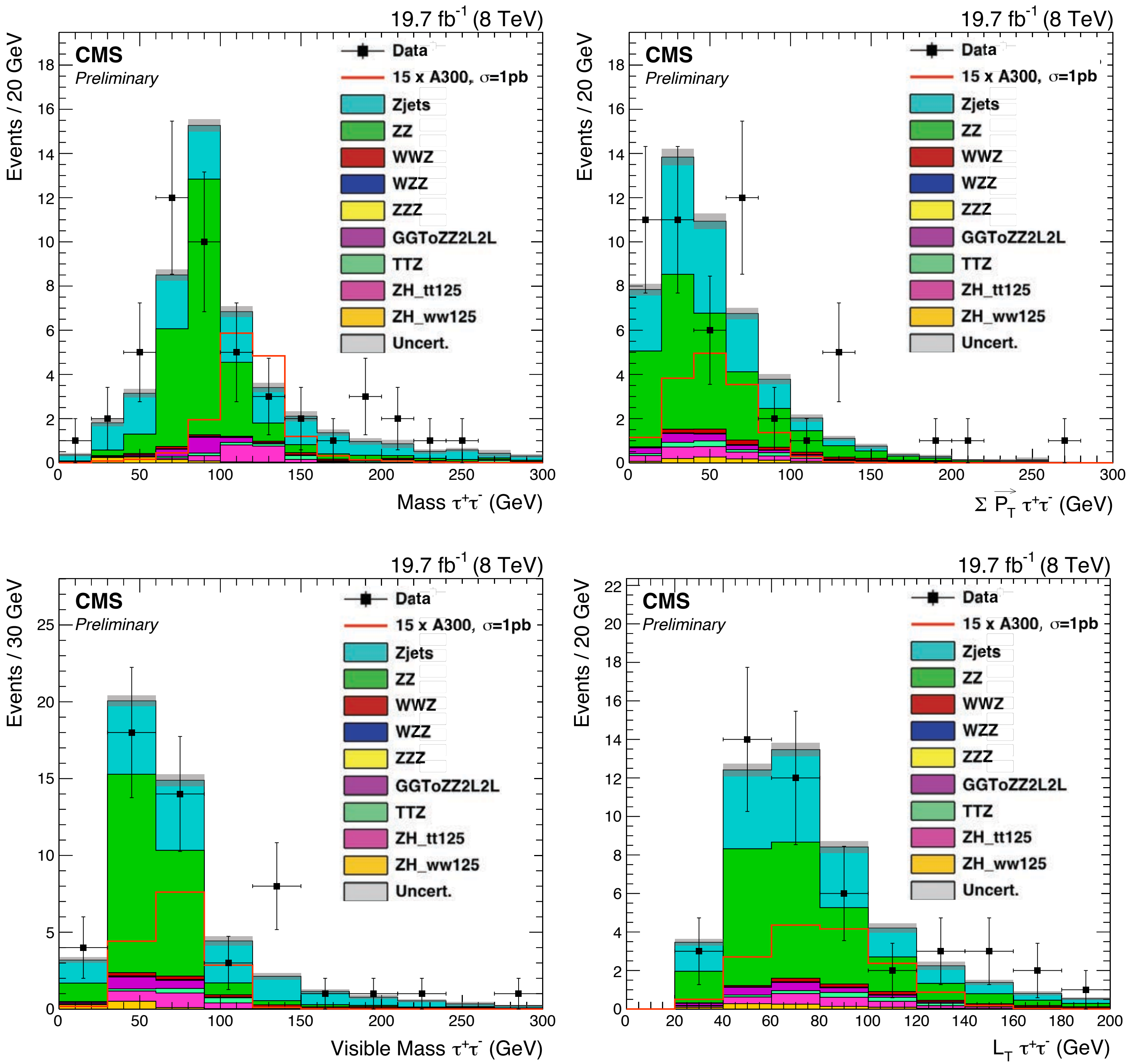
Standard Model Higgs candidate

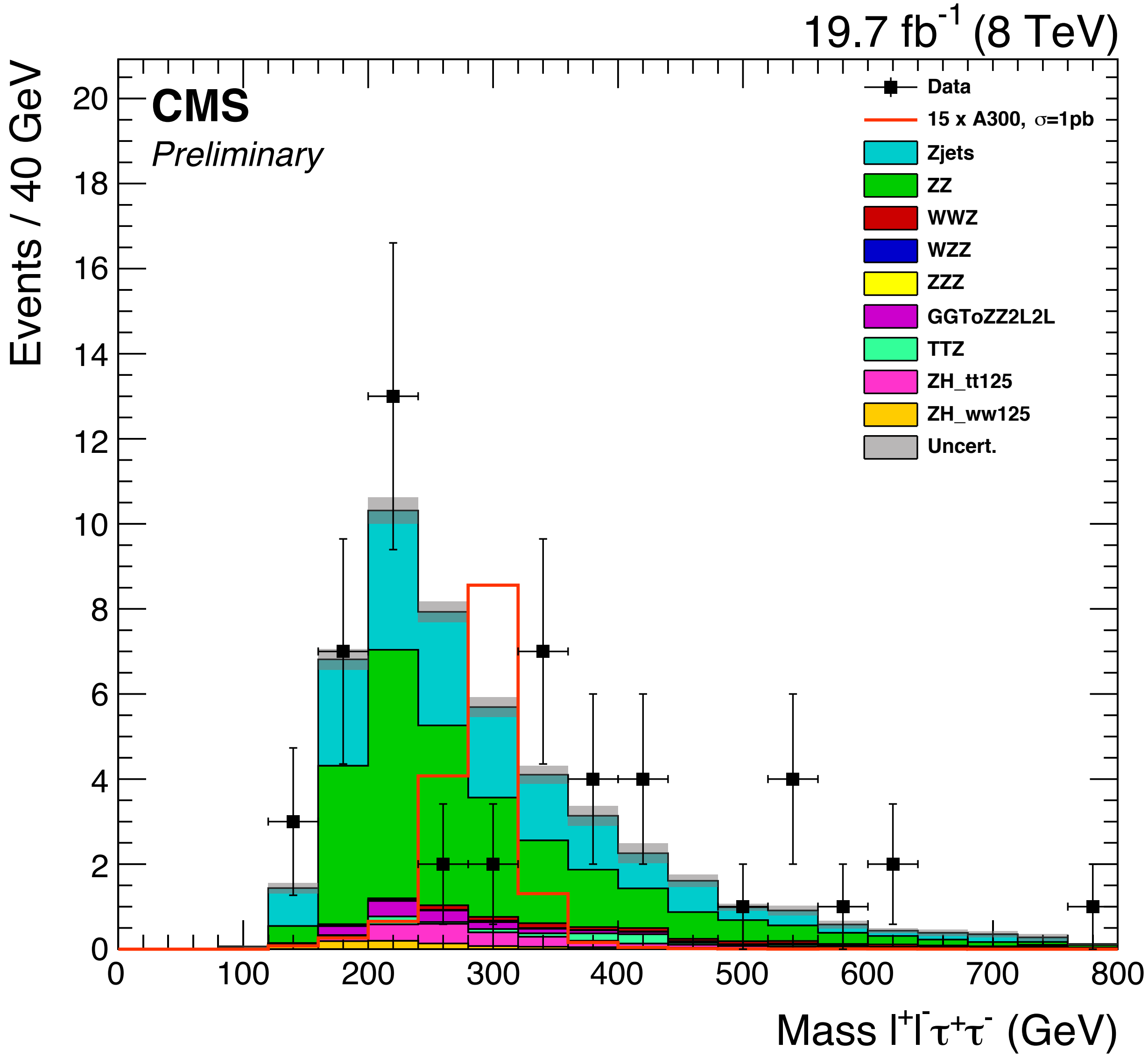
Pseudo-scalar A is plotted for $M_{ll\tau\tau}$ = 300 GeV, yield has been amplified by 15 for viewing, σ = 1 pb corresponds to tanβ = 2.5

Distributions show shape & yield agreement within low statistics



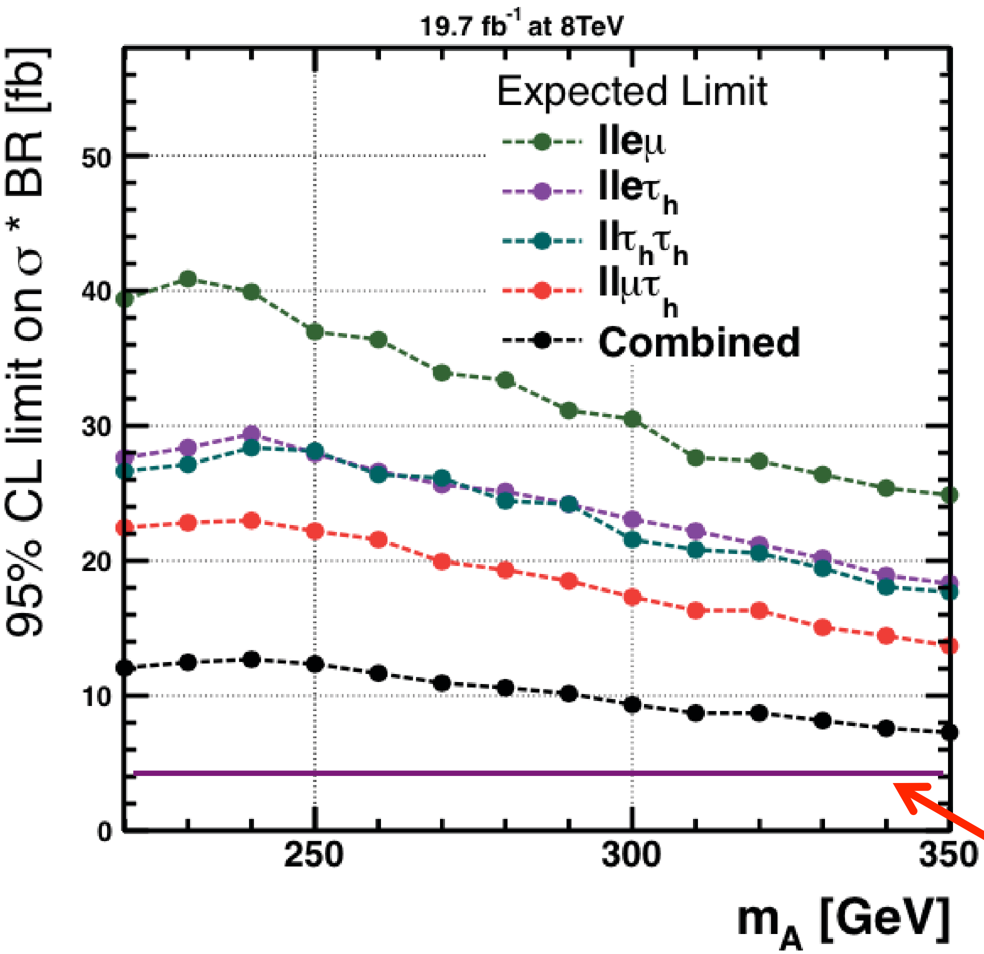
Fully Reconstructed "A" Mass

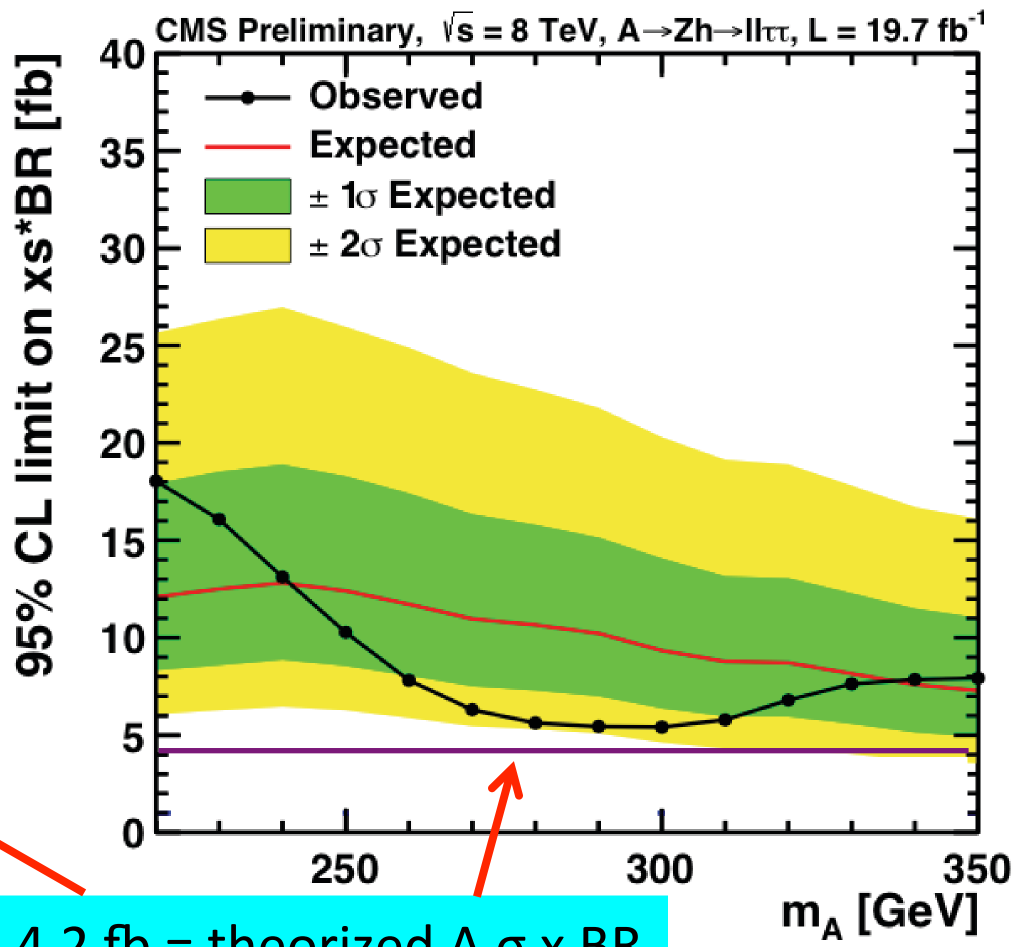
1) Analysis is well modeled
2) Need Run II for more data!



Expected & Observed Limits

- Chosen signal cross section, σ = 1 pb, corresponds to tanβ = 2.5
- The visible dip in data in the 240 – 320 GeV range is reflected in the limits plot below (right)
- This dip is within the 2 sigma band

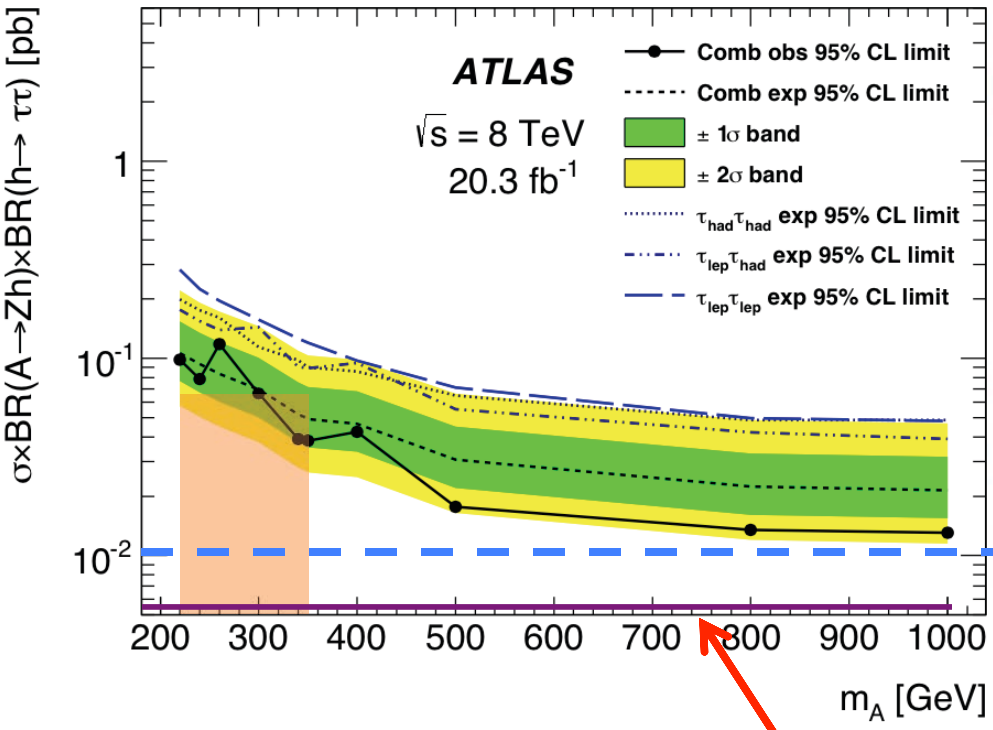


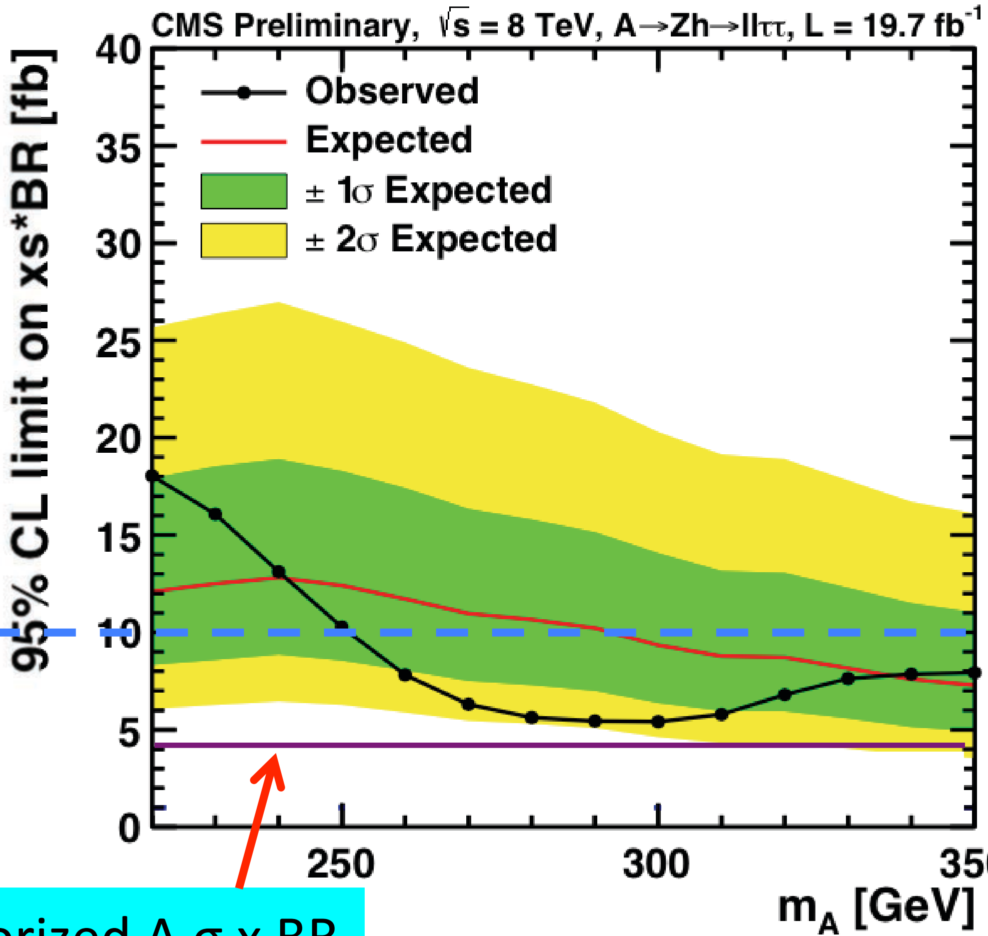


4.2 fb = theorized A σ x BR

Previous and New A→Zh→llττ Limits

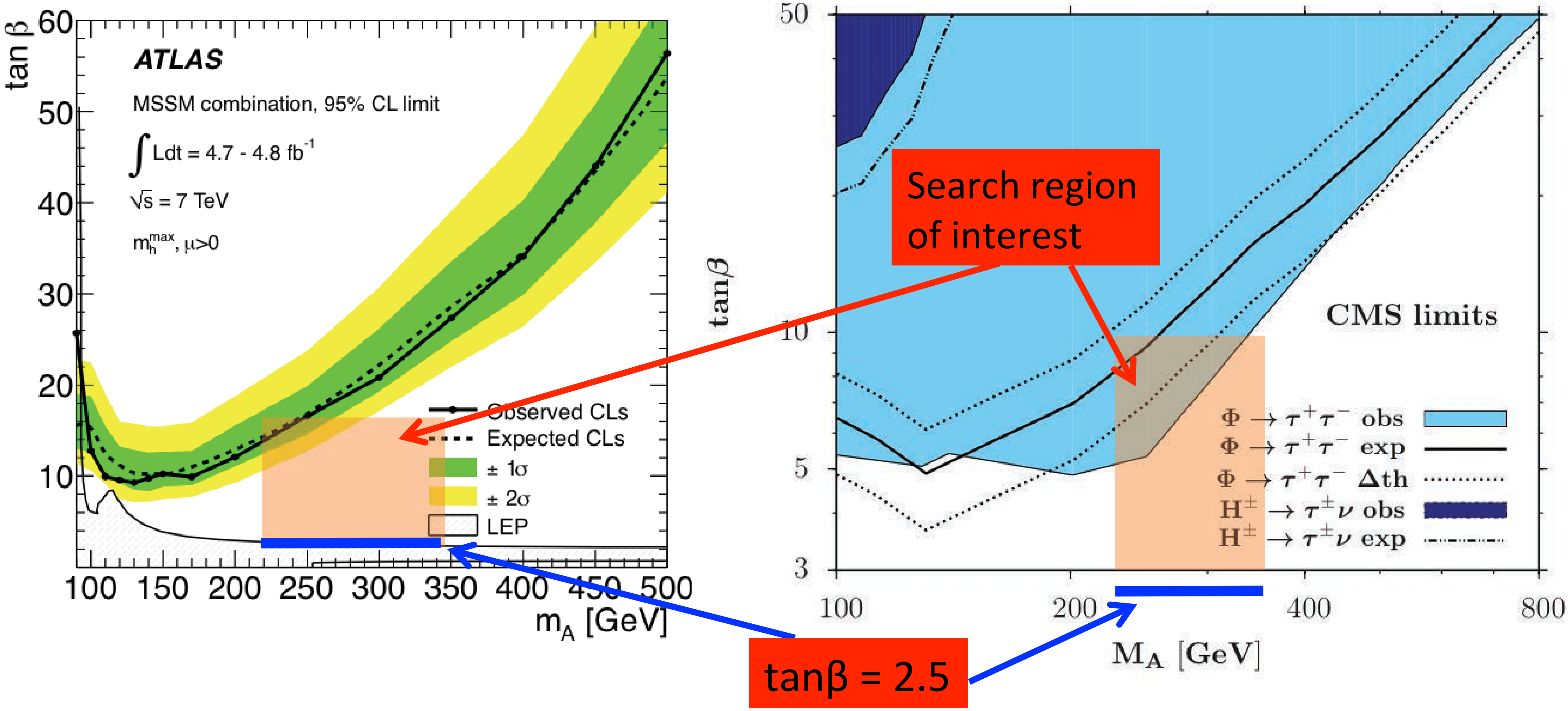
- A→Zh→llττ (σ x BR) in A Mass Window 220 – 350 GeV:
  - Most recent Atlas: 98 – 30 fb
  - New CMS: 18 – 5 fb !!!
- Neither reach 4.2 fb for theorized A→Zh→llττ σ x BR (tanβ = 2.5)





4.2 fb = theorized A σ x BR

Analysis Region



- Analysis focused on A Mass = 220 – 350 GeV
- Cross section, σ = 1 pb, corresponds to $\tan\beta = 2.5$
- By varying signal yield, results can be extended to a wider $\tan\beta$ region

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Conclusion:

- This analysis addresses a currently unconstrained region of MSSM parameter space
- The analysis is well modeled
- The backgrounds are understood and under control
- The analysis currently suffers from lack of data, but
- The analysis shows promise if more statistics are available

Future work:

- Publish 8 TeV Results
- Collect data at 13 TeV!
    - New definitions and algorithms to calibrate
    - Backgrounds are expected to increase
    - Estimate 10 x larger gg → A cross section[1]!
    - Estimate needing 50 – 100 fb^{-1} to close low tanβ MSSM parameter space
    - This can be achieved in the next 3 years!

(100 fb^{-1}) (10,000 fb) (0.3 Zh BR) (0.067 ee/μμ BR) (0.063 ττ BR) = 1,300 events

[1] arXiv:1304.1787v2 "The MSSM Higgs sector at a high MSUSY: reopening the low tanβ regime and heavy Higgs searches "

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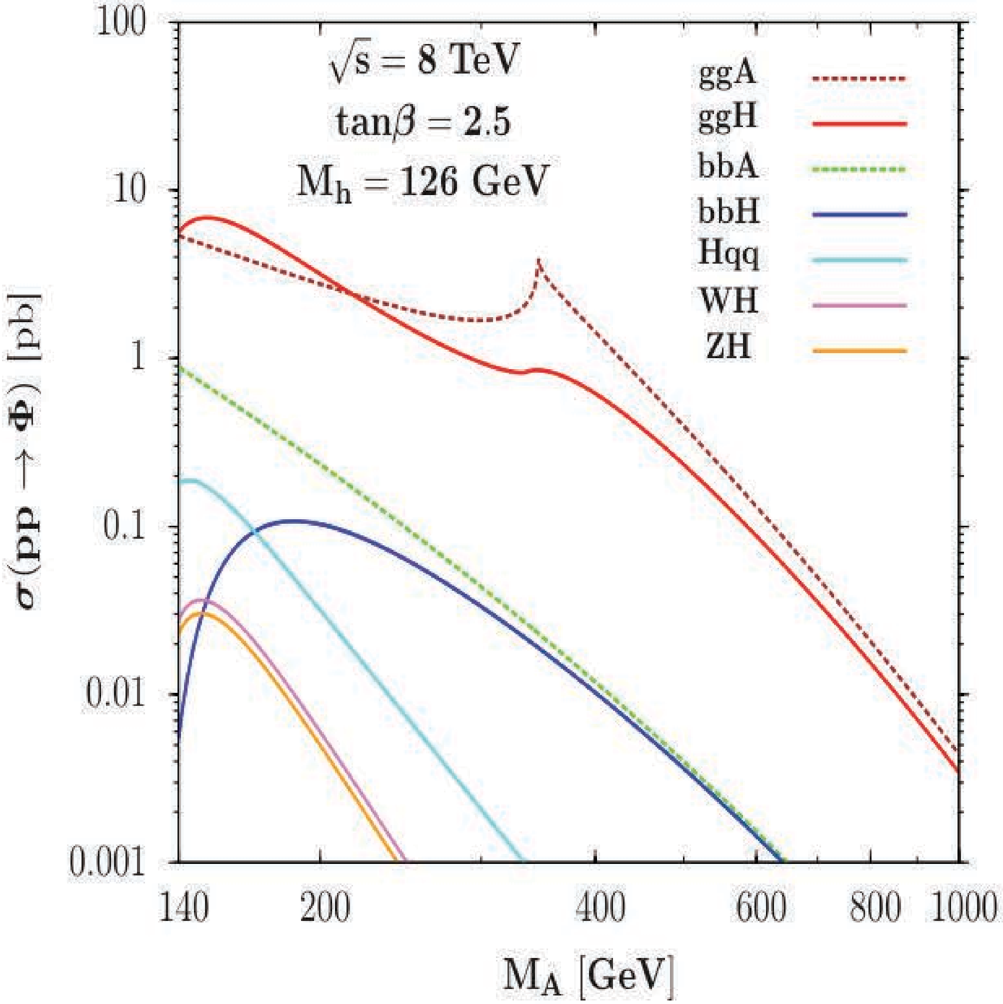
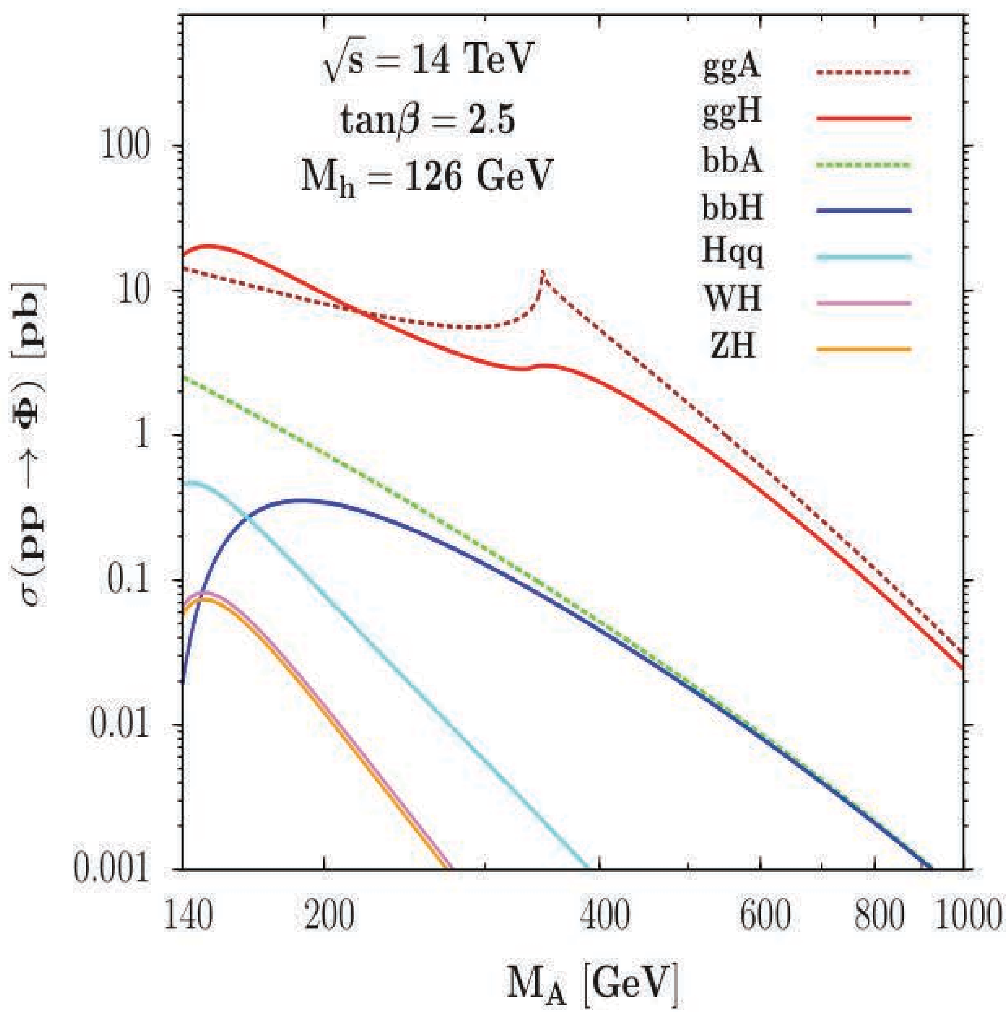
10) Back Up

MSSM Cross Sections





SM Higgs Bkgs.

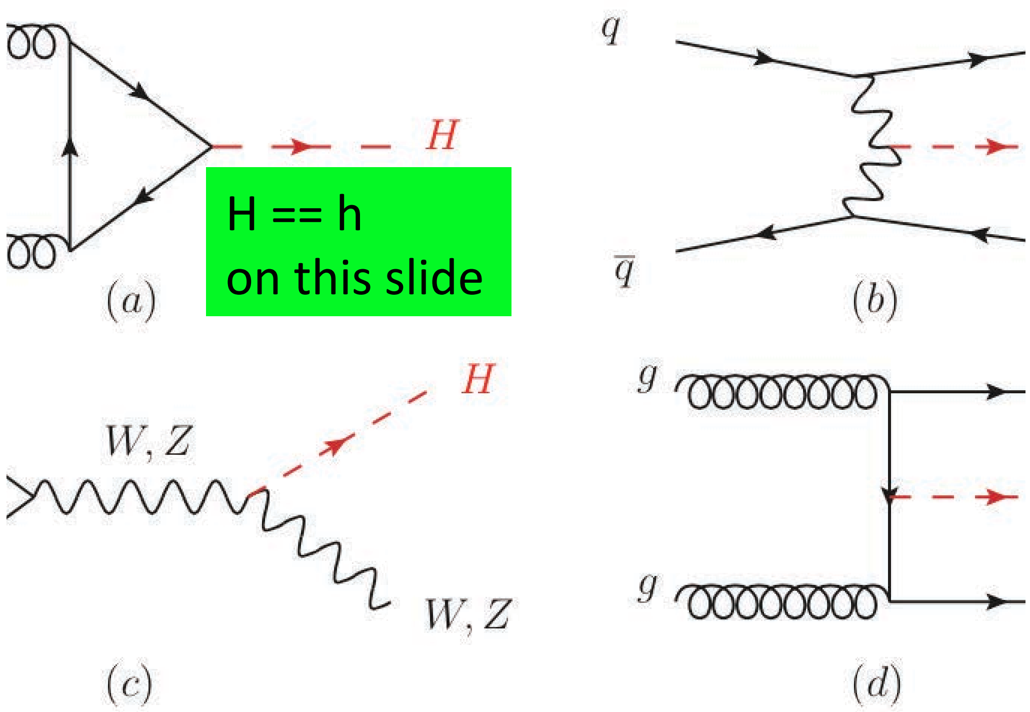
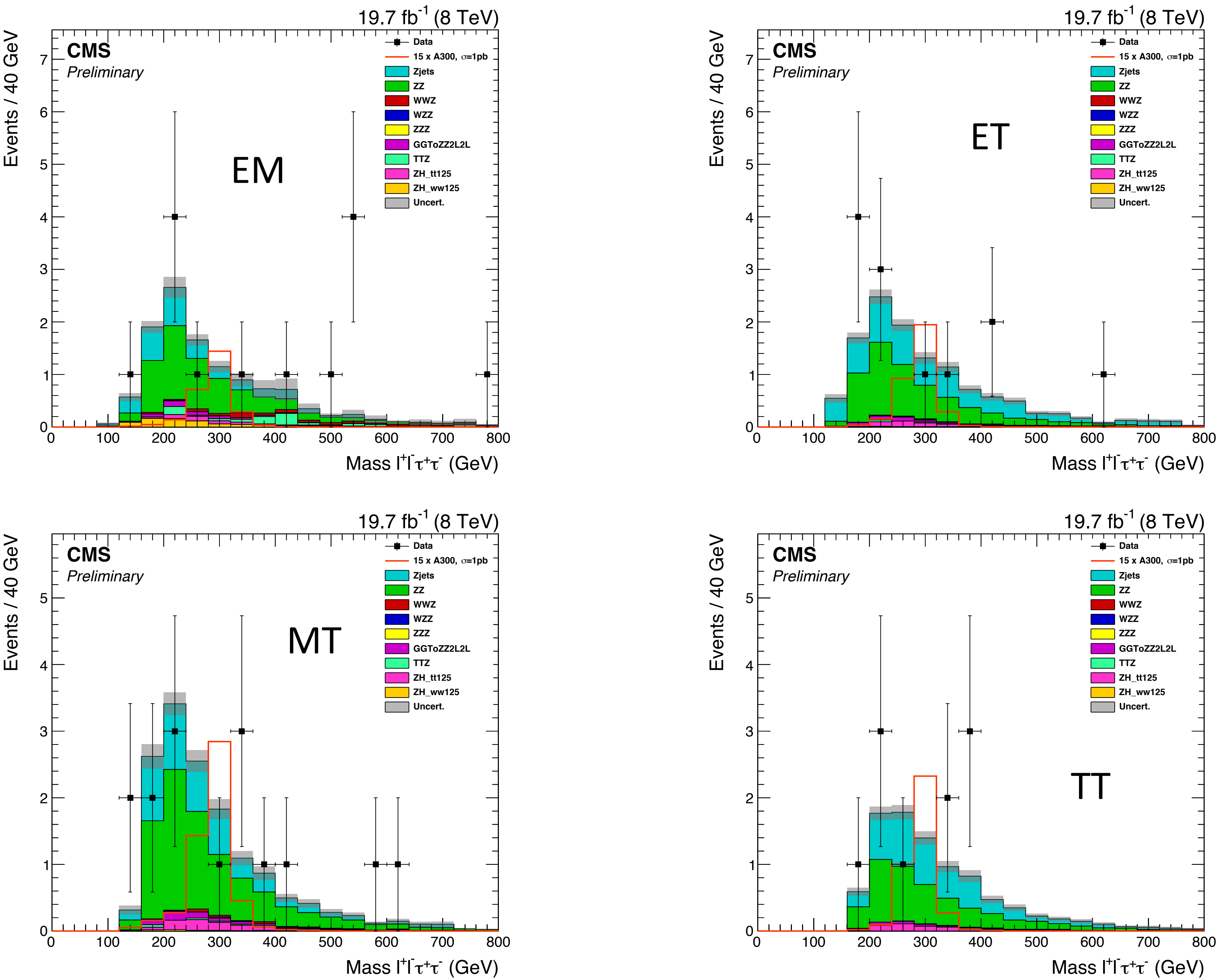


Diagram	Background?
ggF (a)	2 lepton event
VBF (b)	Process creates Higgs + Jets
WH (c)	A misidentified jet could make this signal like
ZH (c)	Irreducible background
ttH (d)	top → bottom ≈ 99.8% Eliminate with bJet Vetos

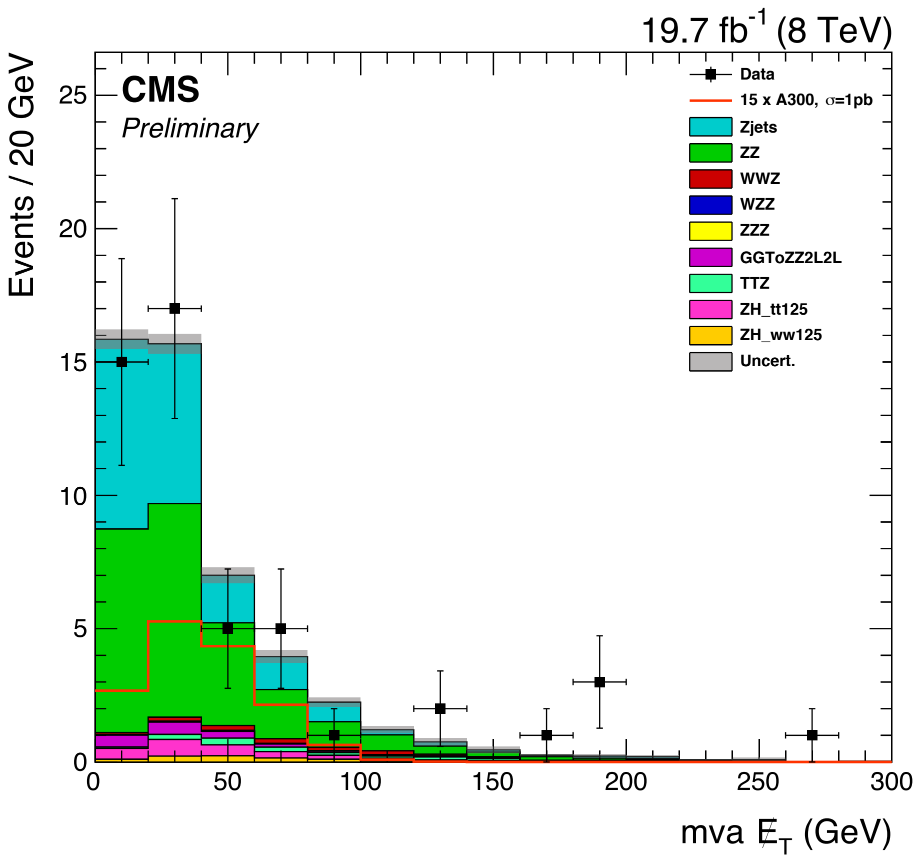
Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.28×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.64×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.15×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.32×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.77×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.54×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.19×10^{-4}	$^{+6.0\%}_{-5.9\%}$

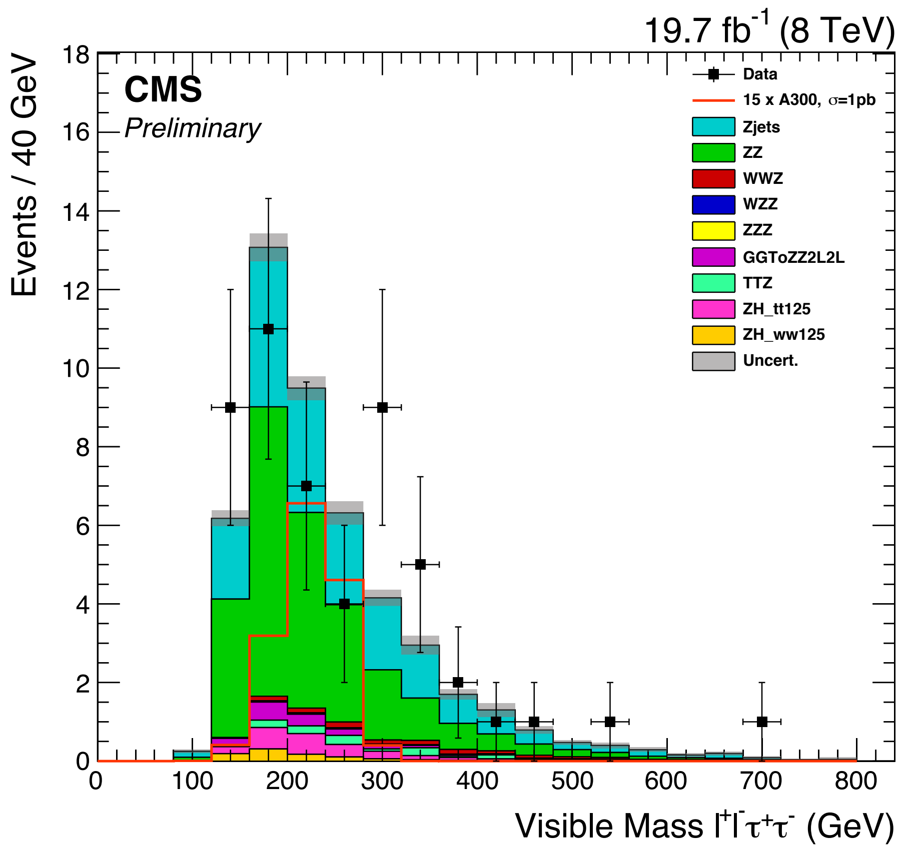
$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\mathrm{GeV}$					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
8	$19.3^{+15\%}_{-15\%}$	$1.58^{+3\%}_{-2\%}$	$0.70^{+4\%}_{-5\%}$	$0.41^{+6\%}_{-6\%}$	$0.13^{+12\%}_{-18\%}$	22.1
14	$49.8^{+20\%}_{-15\%}$	$4.18^{+3\%}_{-3\%}$	$1.50^{+4\%}_{-4\%}$	$0.88^{+6\%}_{-5\%}$	$0.61^{+15\%}_{-28\%}$	57.0

"A" fully reconstructed mass



mva MET & “A” visible mass





Backgrounds: Fake Rate

Fake Rate (FR) Method:
4 steps: 1) fake rate fits, 2) calculate yield, 3) reducible shape, 4) validate
Yield modeled by focusing on **Same Sign ττ** region
Loose Preselection: good Z candidate & loosened cuts on h→ττ leptons
Tighter Final Selection: cut on the h→ττ leptons

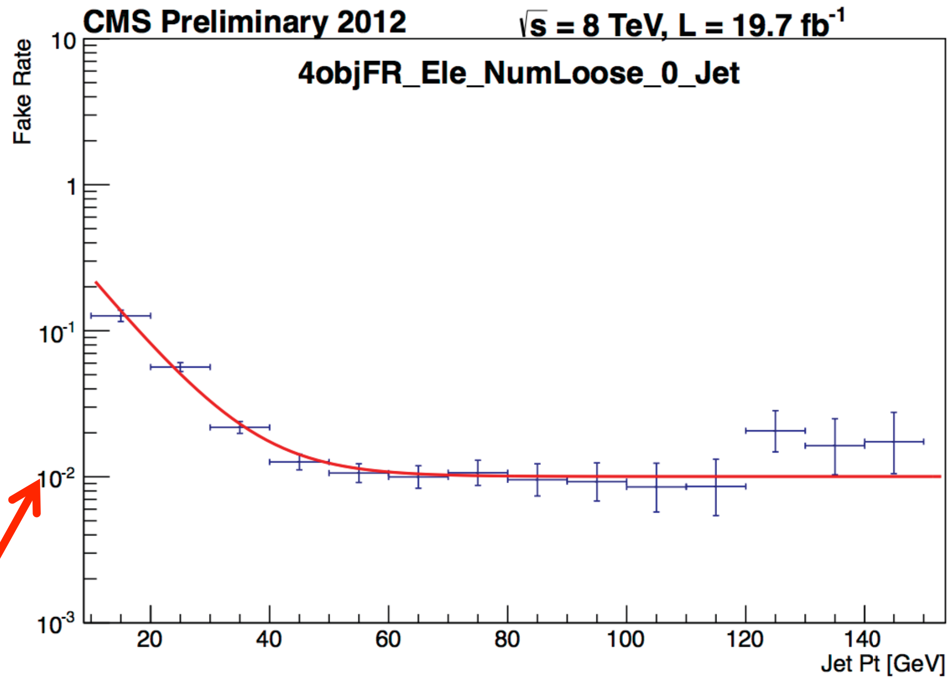
$$Fake\_Rate = \frac{Tighter\_Final\_Events}{Loose\_Preselection\_Events}$$

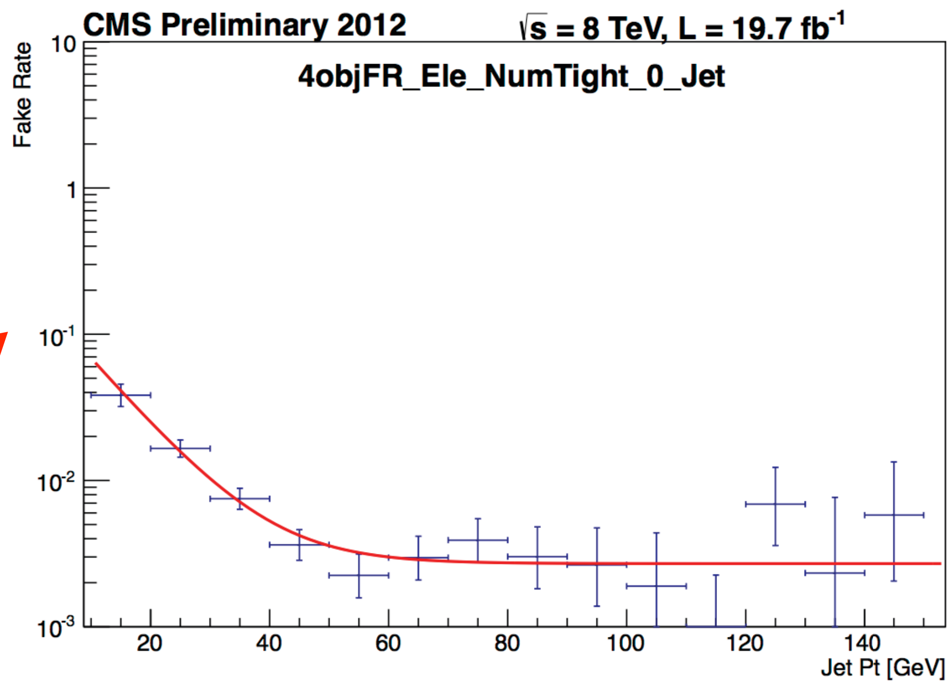
- FR plotted vs. p_T of the closest Jet
- Plot is fitted with a falling exponential:
- Four FR regions are studied:
  - Electron fake rates in EEET & MMET channels
  - Muon fake rates in EEMT & MMMT channels
  - Tau fake rates in EEET, MMET, EEMT & MMMT channels
  - Tau Tau fake rates in EETT & MMTT channels

Fake Rate Fits: electron example

Electron FR fit in EEET & MMET regions

Preselection (Denominator in both)	• Loose Electron and Tau • MtToMVAMET < 30 GeV • TauAntiElecMVA3Tight
Top Fit – Loosest Numerator	• Signal Preselection Electron
Bottom Fit – Tightest Numerator	• Isolated Electron





Fake Rates: Yield

Step 2 – Estimate yield

- Events passing all signal cuts except Isolation and/or Identification for h→ττ leptons are categorized into three groups and are weighted:
  - Category 0 – both taus fail
    - likely a ZJets event

$$weight = \frac{F(l_1)F(l_2)}{(1 - F(l_1))(1 - F(l_2))}$$

  - Category 1 – 1st tau fails
    - likely a WZJets event

$$weight = \frac{F(l_1)}{(1 - F(l_1))}$$

  - Category 2 – 2nd tau fails
    - likely a WZJets event

$$weight = \frac{F(l_2)}{(1 - F(l_2))}$$

- Yield attributed to Zjets, WZJets & other reducible signals:

Yield = (Category 1 + Category 2) – Category 0

  - Category 0 is subtracted because each Category 0 event is also counted in Cat. 1 & Cat. 2 (it would be triple counted if all were summed)
- Final yield scales the Reducible Shape on next slide

Fake Rates: Reducible Shape

- ☑ Step 1 – Fake Rate fits
- ☑ Step 2 – Estimate yield
- ☐ Step 3 – Reducible shape
- ☐ Step 4 – Validation

Step 2: Reducible Shape – High statistics shape

- **same sign ττ** region
- good Z boson candidate
- Loose cuts & weak isolation requirements on h→ττ leptons

Table: Additional Channel Specific Cuts

H→ττ	Relative PF Isolation Δβ	MVA 2 Isolation Raw
EM	e < 2.0 μ < 2.0	
ET	e < 0.3	τ > -0.95
MT	μ < 0.7	τ > -0.95
TT		Both τ > 0

Systematics: Reducible Background

Reducible Background Uncertainties					
higgs final state	τ_h medium iso fit	τ_h loose iso fit	μ tight iso fit	e tight iso fit	e loose + μ loose iso fit
EM					50%
ET		20%		10%	
MT		20%	10%		
TT	15%				

- Fully correlated systematics:
  - Ditau final state
  - By isolation fit (column)
- Uncertainties in different columns are fully uncorrelated
- Uncertainties determined by propagating FR fit uncertainties through analysis and calculating effect on final yields
  - TT – smallest at 15% because of high statistics FR fit
  - μ tight and e tight are smallest at 10% because of their relatively small contribution to faked objects in their ditau channels, the taus fake many more ET & MT events

FSA NTuple Cuts

Purpose: Select events with the correct number of candidate objects & cut data storage size!

	Pt	Eta
Electron	10	3
Muon	10	2.5
Tau	20	2.3

For EEMT	Total Expected @ 19.7 fb^{-1}	FSA 4 Lepton Cuts	Percent Remaining
data	104906888	131333.00	0.125%
A300	20	1.51	7.658%
SM Higgs	180	6.90	3.829%
Tri Boson	1638	28.83	1.760%
TTZ	4098	238.59	5.823%
ggZZ4l	237	12.89	5.439%
ZZJets	3684	224.50	6.094%
Total (bkg.)	9837	511.73	5.202%

3 order of magnitude change in data

Less than 2 order of mag. change in MC

Z Selection

Purpose: Always impose tight constraints on Z candidate

$Z \rightarrow e^+e^-$ / $\mu^+\mu^-$ Selection:

- HLT Triggers
- Opposite sign
- Same flavor
- 60 GeV < M_Z < 120 GeV
- Leading lepton p_T > 20 GeV
- Lepton definitions:
  - Electrons: Very Loose MVA ID, number missing hits<2, relative Δβ isolation < 0.3
  - Muon: PF muon, relative Δβ isolation < 0.3

Triggers	p_T Cuts (GeV)	Additional
Double Electron	$e_1 > 17$, $e_2 > 8$	Very loose requirements for: Calo. Iso., Tracks, Track Iso.
Double Muon	$\mu_1 > 17$, $\mu_2 > 8$	Event passes whether or not 8 GeV μ has good track

For EEMT	FSA 4 Lepton Cuts	Z Cut	% Remaining
data	131333	12811	9.8%
A300	1.51	0.75	49.4%
SM Higgs	6.90	2.13	30.8%
Tri Boson	28.83	6.56	22.8%
TTZ	238.59	25.95	10.9%
ggZZ4l	12.89	8.72	67.7%
ZZJets	224.50	140.42	62.5%
Total (bkg.)	511.73	183.78	35.9%

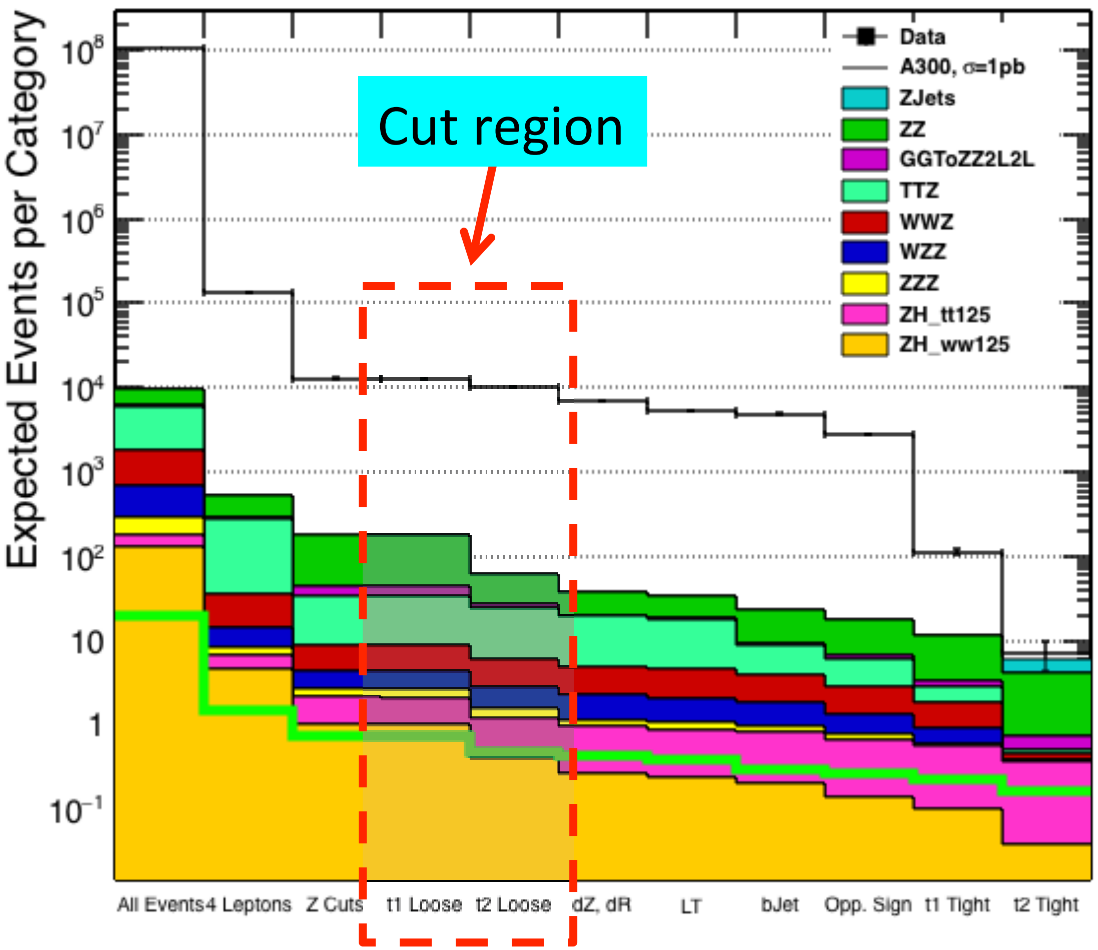
* If two or more combinations of same-flavor light leptons exist, the one with the invariant mass closest to the Z mass is selected

Loose Higgs

Purpose: Provide high statistics Zh group for background studies

- $H \to \tau\tau \to$ mix of e, μ, τ_h
- Each final object has a "loose cut"

Obj.	p_T (GeV)	|η|	Additional
e	10	2.5	
μ	10	2.4	Global or Tracker
τ	20	2.3	Decay Mode Finding



For EEMT	Z Cut	Loose Higgs	% Remain-ing
data	12811	9962	78%
A300	0.745	0.475	64%
SM Higgs	2.127	1.189	56%
Tri Boson	6.560	4.902	75%
TTZ	25.948	18.987	73%
ggZZ4l	8.725	1.464	17%
ZZJets	140.420	33.912	24%
Total (bkg.)	183.780	60.454	33%

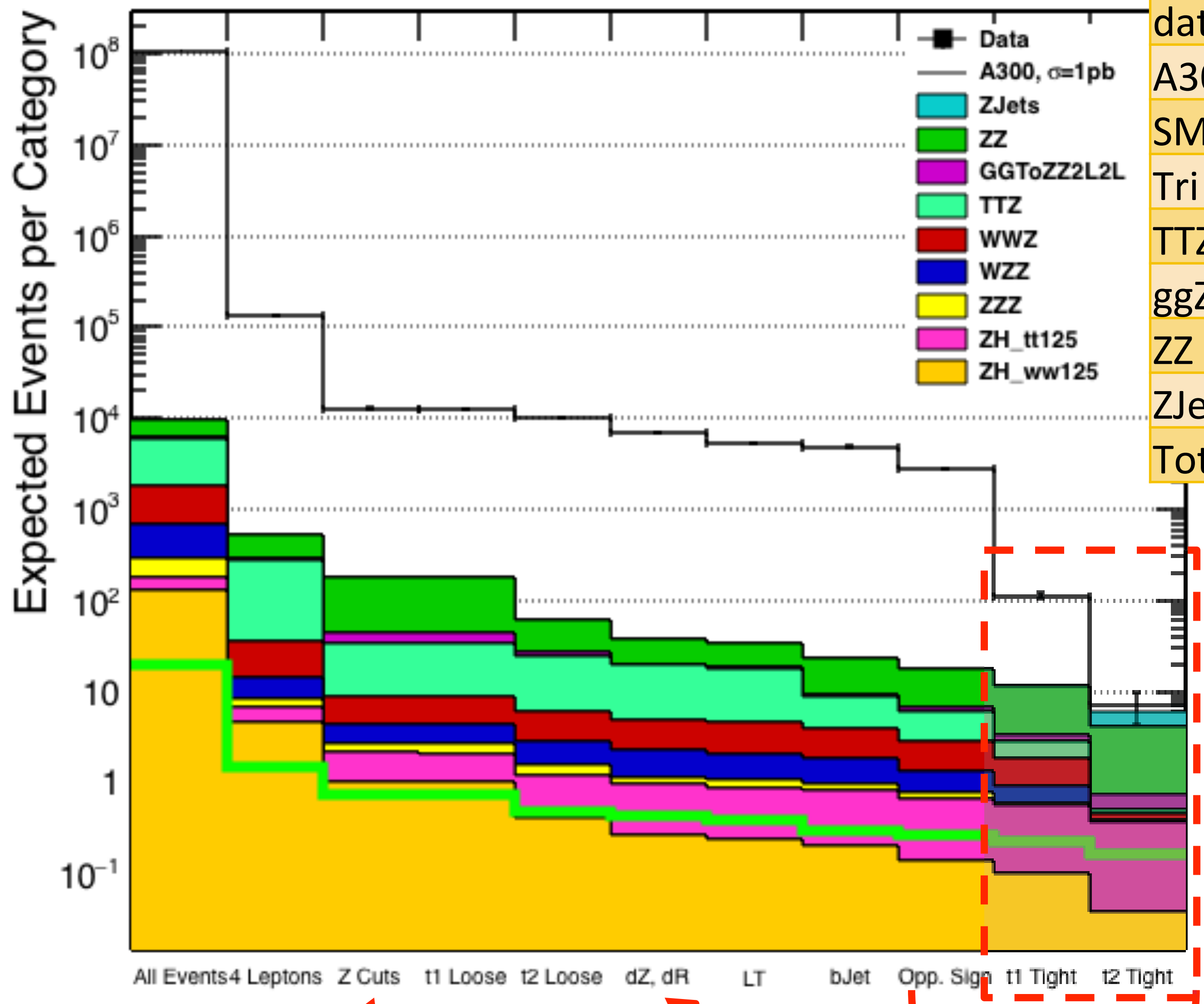
General Cuts + More

- **General Cuts:**
  - No obj. within dR < 0.5 of others
  - dZ < 0.1 cm from primary vertex
  - No extra well defined e or μ
- **Scalar Sum of p_T**
  - Cut events with non-boosted higgs daughters (values next slide)
  - $M_h \gg M_\tau$ so all daughters should be boosted
- **bJet Veto:**
  - Veto event with bJet
  - Eliminate ttZ and ttHiggs backgrounds
  - top q → bottom q ≈ 99.8%

For EEMT	Loose Higgs	General Cuts	Scalar Sum of p_T (LT)	bJet Veto	% Remaining
data	9962	6901	5356	4841	49%
A300	0.48	0.43	0.39	0.31	64%
SM Higgs	1.19	0.95	0.87	0.82	69%
Tri Boson	4.90	3.91	3.69	3.14	64%
TTZ	18.99	14.59	13.32	4.67	25%
ggZZ4l	1.46	0.80	0.67	0.65	45%
ZZJets	33.91	17.15	15.03	14.43	43%
Total (bkg.)	60.45	37.40	33.57	23.71	39%

Tight Higgs - Passing

For EEMT	bJet Veto	Tight Higgs	% Re-maining
data	4841	7	0.14%
A300	0.31	0.16	53.17%
SM Higgs	0.82	0.37	45.00%
Tri Boson	3.14	0.10	3.23%
TTZ	4.67	0.05	1.13%
ggZZ4l	0.65	0.22	33.87%
ZZ	14.43	3.48	24.09%
ZJets		1.88	
Total (bkg.)	23.71	6.10	17.80%



Final Signal/ Background = 2.6%

Cut region

4 very loose leptons

Z selection

Loose Higgs

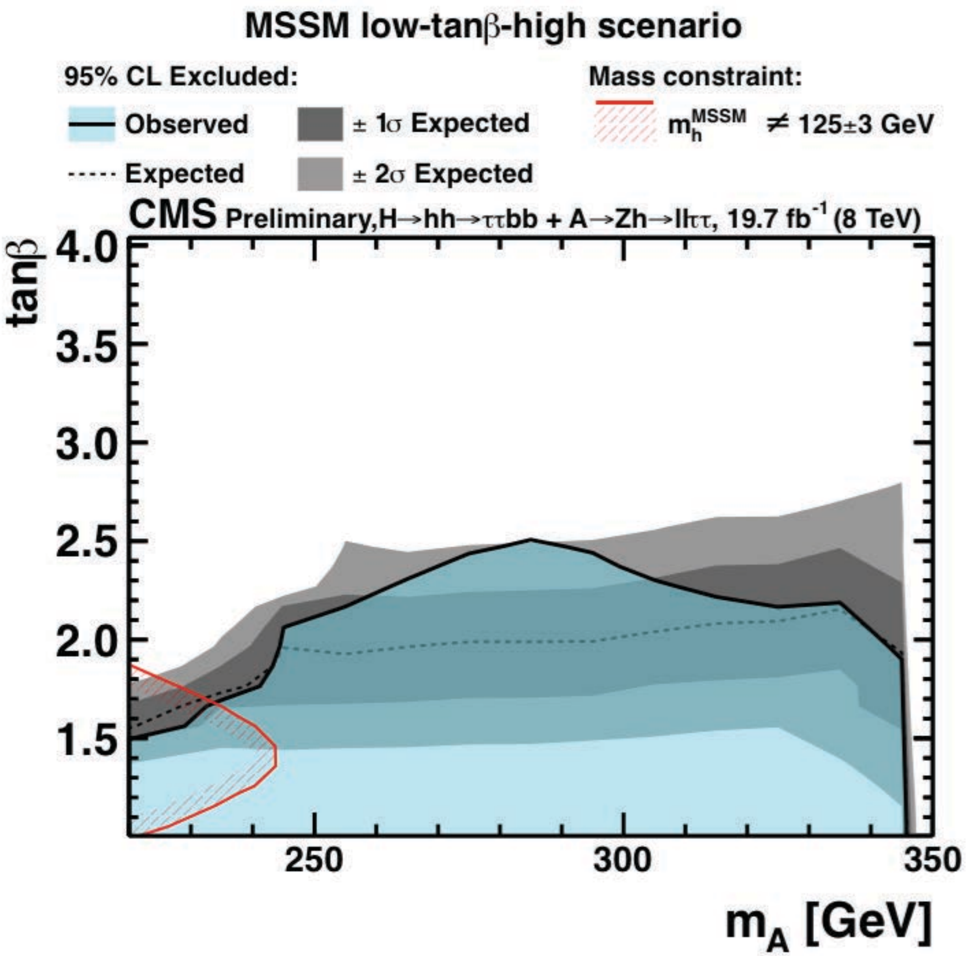
dR, dZ, overlap

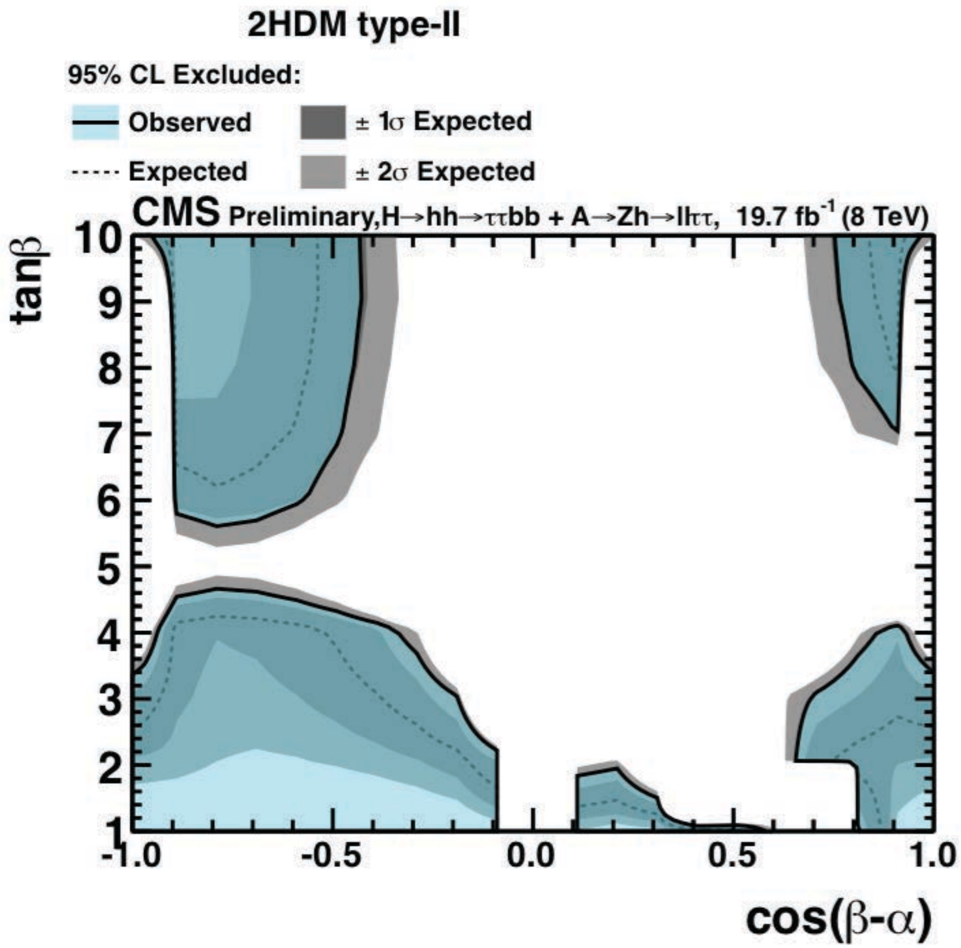
Scalar Sum of p_T

bJet Veto

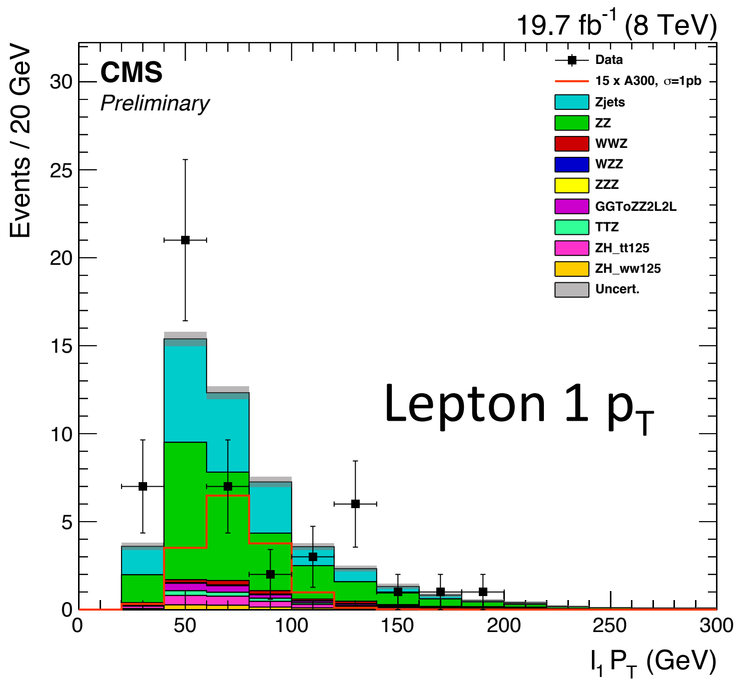
Tighter Higgs

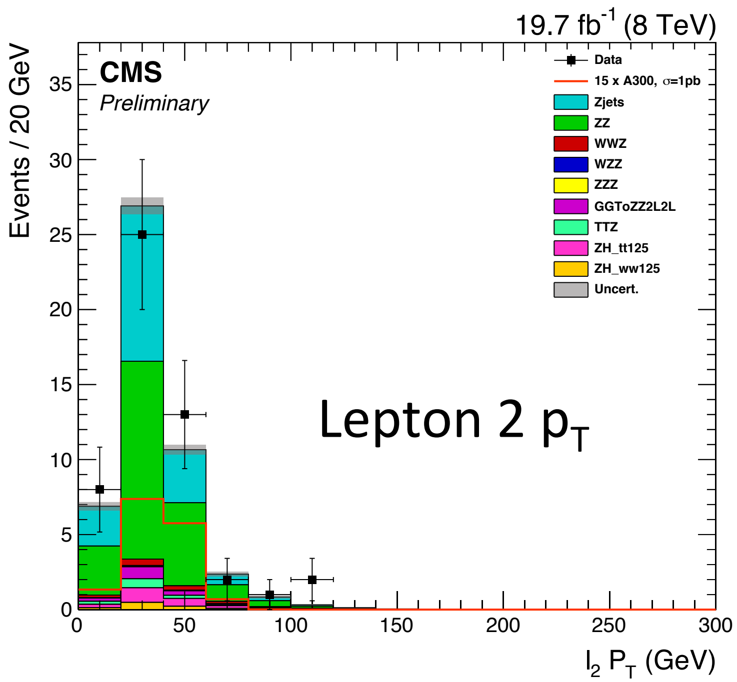
Model Dependent Limits

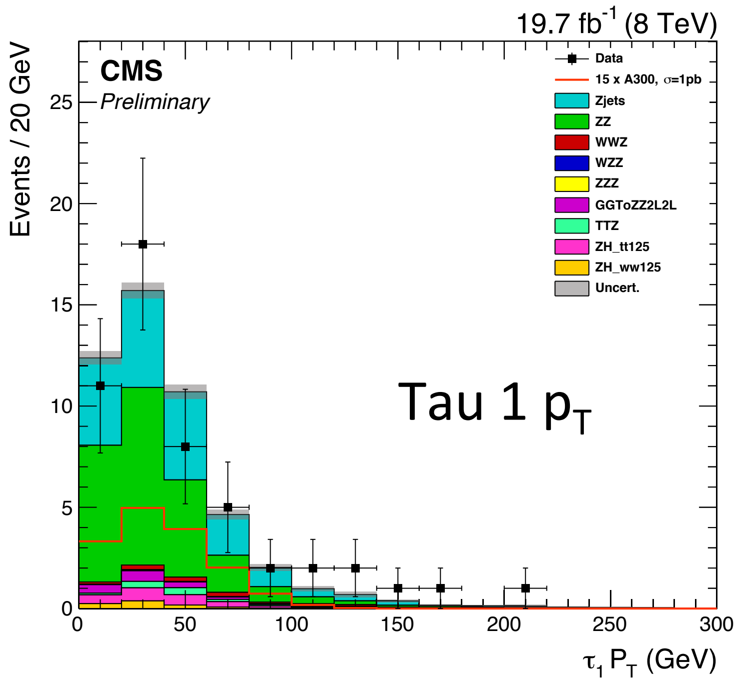


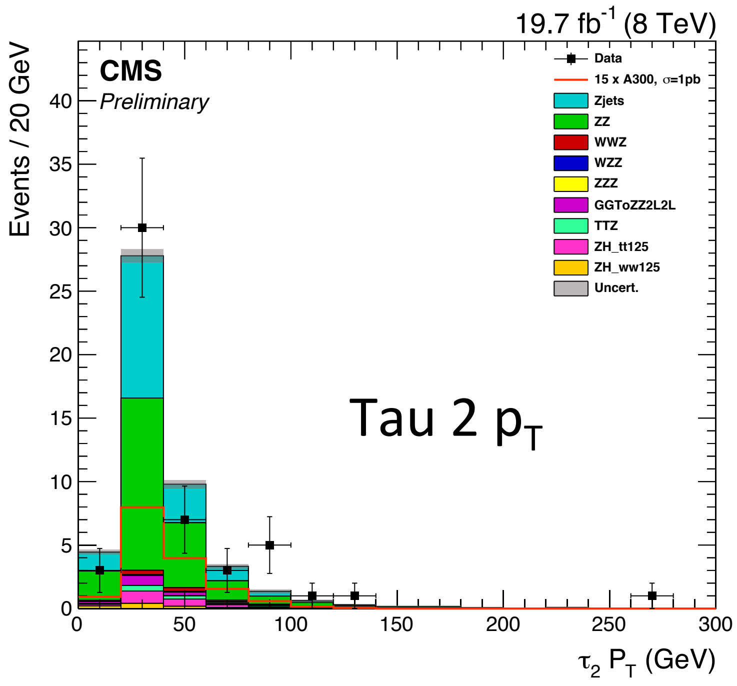


Post Fit Plots: p_T



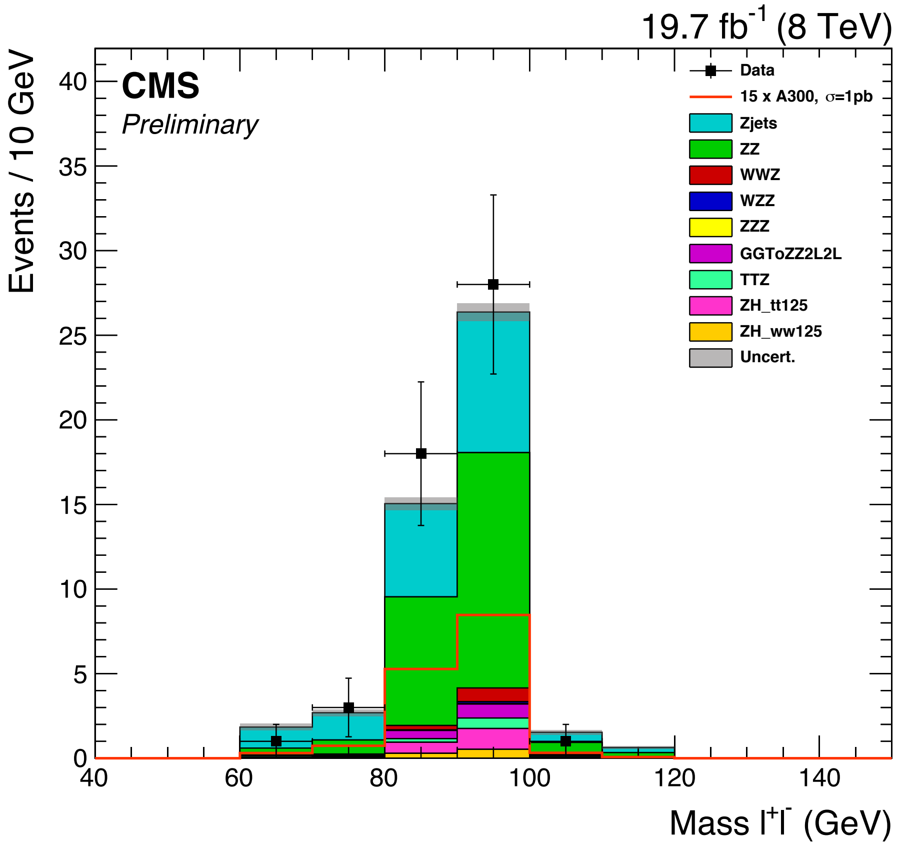




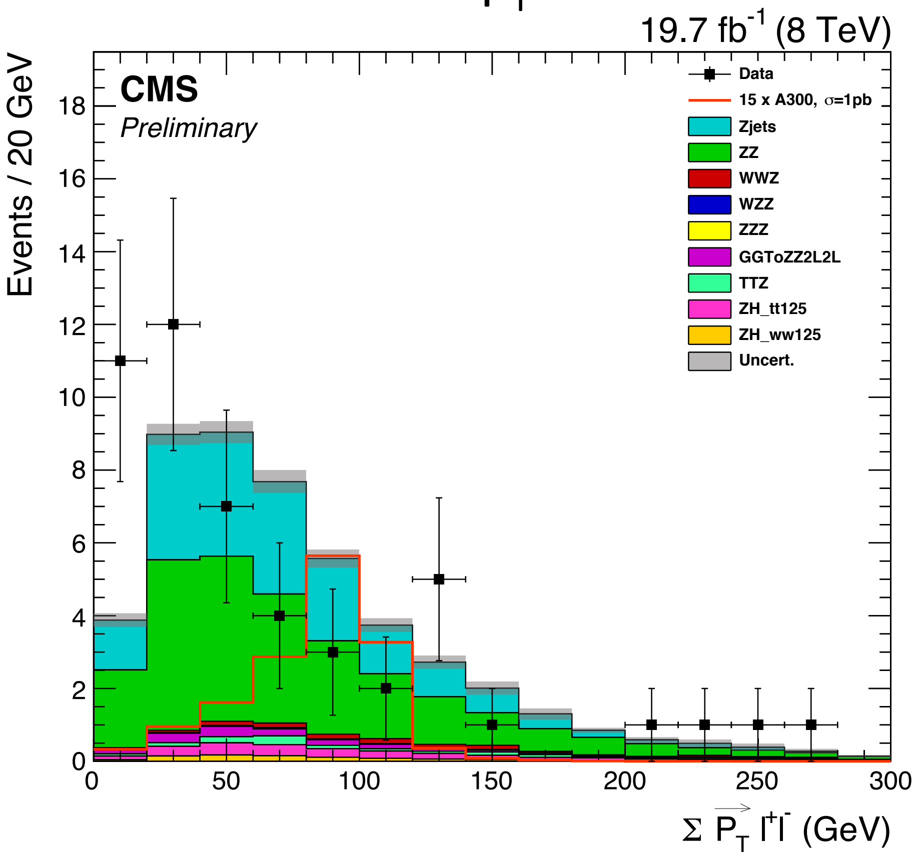


Post Fit Plots: Z bosons

Z Mass



Z p_T



Cuts: b-Jets & Cleaning

- B-jet Veto if following is > 0:
  - bjetCSVVetoZHLikeNoJetId_2 = 'vetoJets(0.4, "p_T > 20 & abs(eta) < 2.4 & bDiscriminator(\'combinedSecondaryVertexBJetTags\') > 0.679").size()'

- Lepton cleaning:
  - Electrons do not overlap (dR>0.1) with loosely identified (PF Loose ID) and isolated (<0.3) muon with p_T> 10 GeV
  - Taus do not overlap (dR>0.1) with loosely identified (MVA Loose ID for electrons and PF Loose ID for muons) and isolated (<0.3) muons or electrons with p_T > 10 GeV
  - B-tagged jets do not overlap (dR>0.4) with any loosely identified and isolated muons or electrons

Cuts and Selections: ID

- Preselection Muons:
  - "IsGlobal" & "IsTracker" & "IsPFMuon"
- Isolated Muons (IsoMu):
  - "PFIDTight"
- Preselection Electron:
  - Missing Hits < 2, BDT discriminator MVANonTrig > value in table:

	$\|\eta\| < 0.8$	$0.8 < \|\eta\| < 1.479$	$\|\eta\| > 1.479$
$p_T > 10$ GeV	0.5	0.12	0.6

- Isolated Electron (IsoElec):
  - Missing Hits < 2, BDT discriminator MVANonTrig > value in table:

	$\|\eta\| < 0.8$	$0.8 < \|\eta\| < 1.479$	$\|\eta\| > 1.479$
$p_T < 20$ GeV	0.925	0.915	0.965
$p_T > 20$ GeV	0.905	0.955	0.975

Cuts and Selections: Loose and Tight Leptons

Blue = used for preselection process

Red = used for "Z" candidate selection

	p_T > (GeV)	|η| <	No Overlap with (X)	Add'l Req.
Loose Muon	10	2.4		"IsGlobal" or "IsTracker"
Tight Muon	10	2.4		Preselected Muon & Relative PF Isolation Δβ < 0.3
Loose Elec	10	2.5	IsoMu	
Tight Elec	10	2.5	IsoMu	Preselected Electron & Relative PF Isolation Δβ < 0.3
Loose τ	21	2.3	IsoMu, IsoElec or btag jet	Passes DecayFinding, JetCSVBtag < 0.679
Tight τ	21	2.3	IsoMu, IsoElec or btag jet	Passes DecayFinding, JetCSVBtag < 0.679, Anti-MuonLoose2, Anti-ElectronLoose, LooseIso3Hits

Selection: Signal SM h products

- Loose Preselection: (LT = scalar sum of τ1 p_T + τ2 p_T)

H→ττ	Loose Objects	LT > (GeV)	Discrimination by:
EM	Elec. + Mu	25	
ET	Elec. + Tau	30	Tau AntiElectronMVA3Tight & Tau AntiMuonLoose2
MT	Mu + Tau	45	Tau AntiElectronLoose & Tau AntiMuonTight2
TT	Tau + Tau	70	Both Taus AntiElectronLoose & AntiMuonLoose2

- Signal Selection: Events are **opposite sign ττ** & pass

H→ττ	Relative PF Isolation Δβ	Lepton ID	Add'l Req.
EM	Elec. < 0.3 Mu < 0.3	Preselection Elec Preselection Mu	
ET	Elec. < 0.2	IsoElec	Elec. missing hits = 0 Tau LooseIso3Hits
MT	Mu < 0.3	IsoMu	Tau LooseIso3Hits
TT			Both Taus MeiumIso3Hits

Data Sets

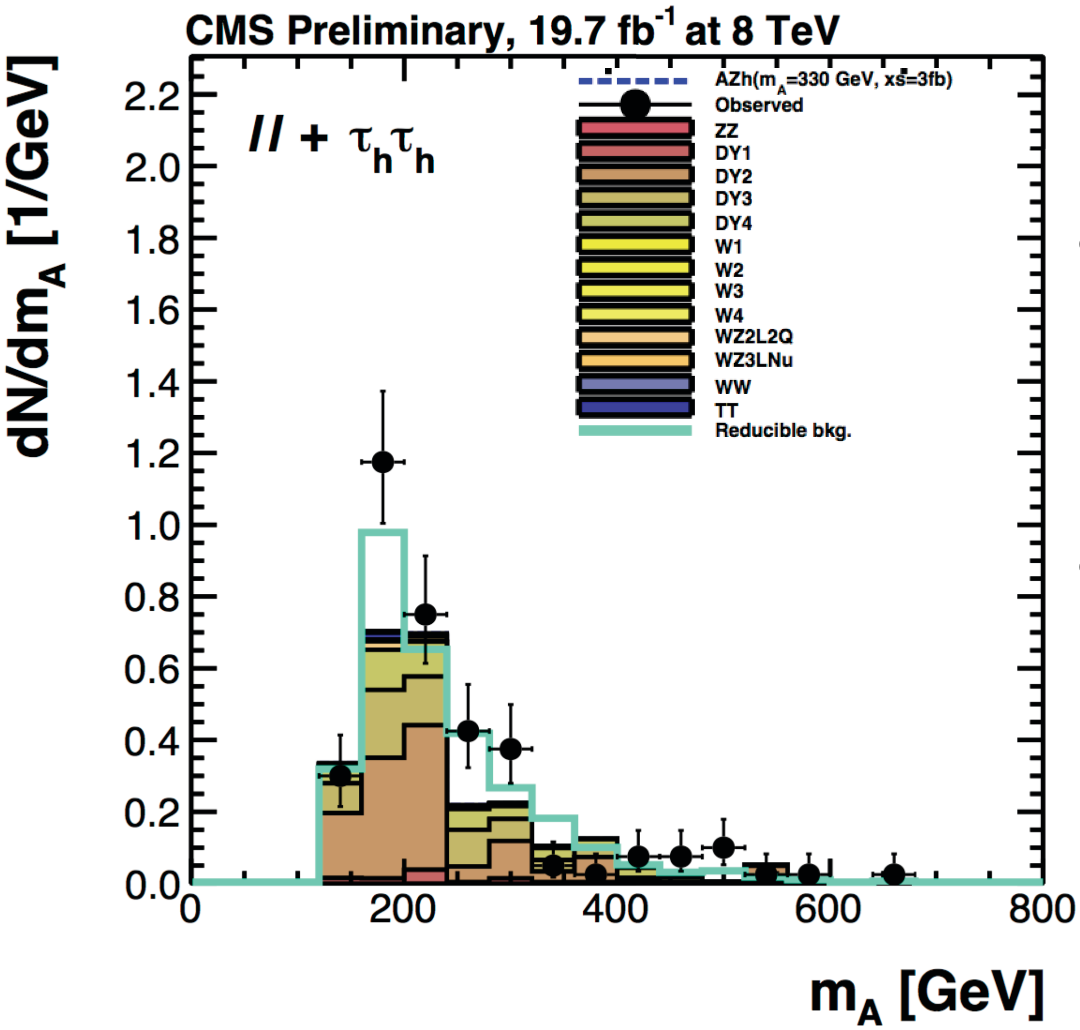
Sample Name	Run	DAS Path
DoubleMu	A	/DoubleMu/Run2012A-22Jan2013-v1/AOD
DoubleMuParked	B	/DoubleMuParked/Run2012B-22Jan2013-v1/AOD
DoubleMuParked	C	/DoubleMuParked/Run2012C-22Jan2013-v1/AOD
DoubleMuParked	D	/DoubleMuParked/Run2012D-22Jan2013-v1/AOD
DoubleE	A	/DoubleElectron/Run2012A-22Jan2013-v1/AOD
DoubleE	B	/DoubleElectron/Run2012B-22Jan2013-v1/AOD
DoubleE	C	/DoubleElectron/Run2012C-22Jan2013-v1/AOD
DoubleE	D	/DoubleElectron/Run2012D-22Jan2013-v1/AOD

Full 2012 dataset, $\mathcal{L}$ = 19.7 fb^{-1} sqrt(s) = 8 TeV

MC Backgrounds

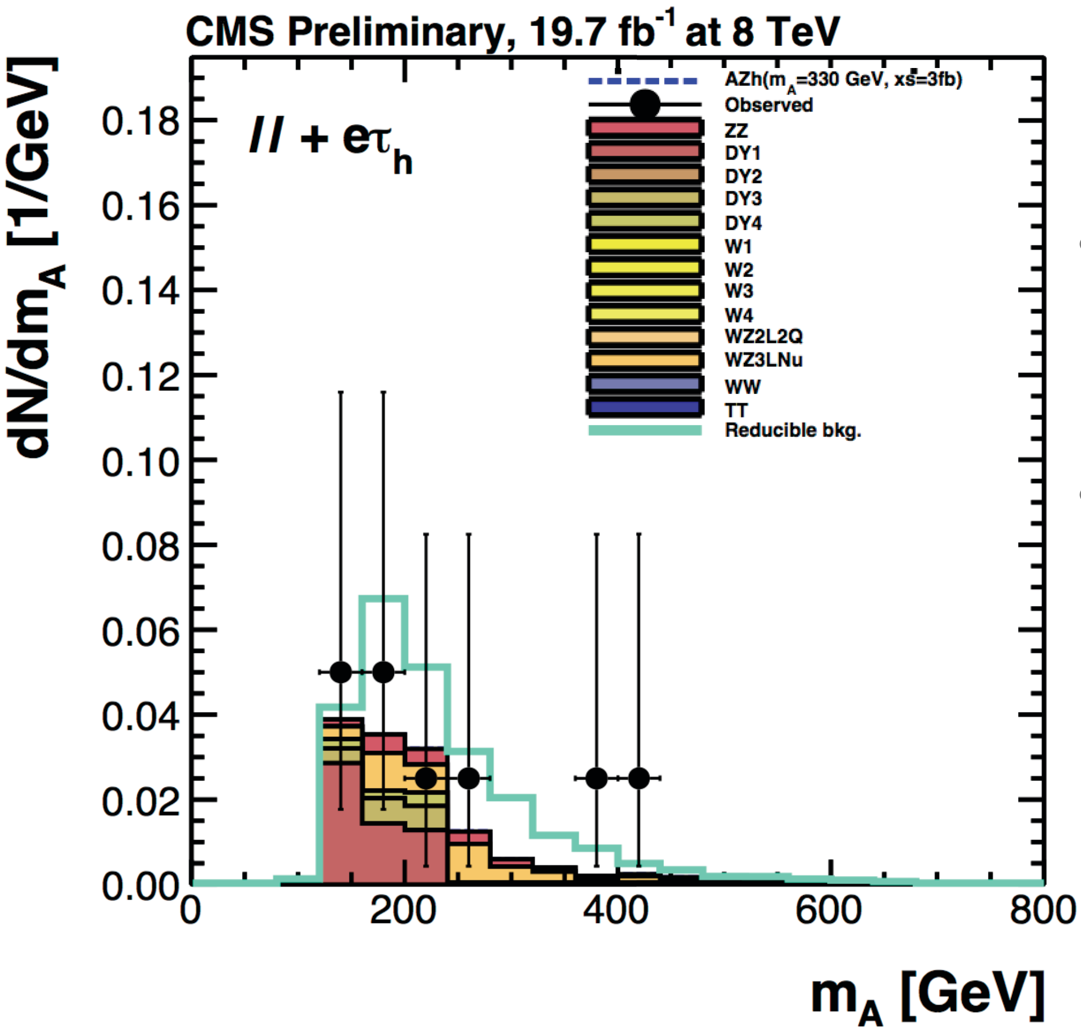
Sample Name	Cross Section Used (pb)	Events	DAS Path
ZZJets_4L	0.187	4807893	/ZZJetsTo4L_TuneZ2star_8TeV-madgraph-tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/
TTZJets	0.208	210160	/TTZJets_8TeV-madgraph_v2/Summer12_DR53X-PU_S10_START53_V7A-v1/
ggZZ_2L2L	0.01203	400973	/GluGluToZZTo2L2L_TuneZ2star_8TeV-gg2zz-pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/
Vh_hToTauTau	0.002651	100000	/ZH_HToTauTau_M-125_lepdecay_8TeV-pythia6-tauola/Summer12_DR53X-PU_S10_START53_V7C-v1/
Wh_Zh_VToTauTau_hToWW	0.006503	150000	/WH_ZH_TTH_HToWW_M-125_lepdecay_8TeV-pythia6/Summer12_DR53X-PU_S10_START53_V19-v1/
ZZZ	0.005527	224904	/ZZZNoGstarJets_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/
WZZ	0.01968	219835	/WZZNoGstarJets_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/
WWZ	0.05795	222234	/WWZNoGstarJets_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/

Fake Rates: Validation, TT final states



- SS region, no LT, relaxed IsoTau (MVA with lifetime VL)
- Reducible background made of ZJets (poor statistics in Z +2jets)
- The reducible background from data (cyan line) agrees very well with the data, and well within the MC statistics with the MC estimation (stacked filled histograms).

Fake Rates: Validation, ET final state



- SS region, no LT, relaxed IsoTau (MVA with lifetime VL)
- Reducible background made of WZJets
- The reducible background from data (cyan line) agrees very well with the data, and well within the MC statistics with the MC estimation (stacked filled histograms).