Higgs Physics at the LHC

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Outline

- Introduction
  - Quest for the Higgs Boson
- The Large Hadron Collider (LHC)
- The ATLAS and CMS detectors
- The Higgs Analysis (ATLAS)
  - Low Mass ($H\rightarrow\gamma\gamma,\tau\tau$)
  - Heavier Higgs ($H\rightarrow WW^{(*)},ZZ^{(*)}$)
- Outlook and Conclusions

Macroscopic Matter

elements

atoms

Nucleus

Protons & Neutrons

hadrons

Quarks

up
down
strange

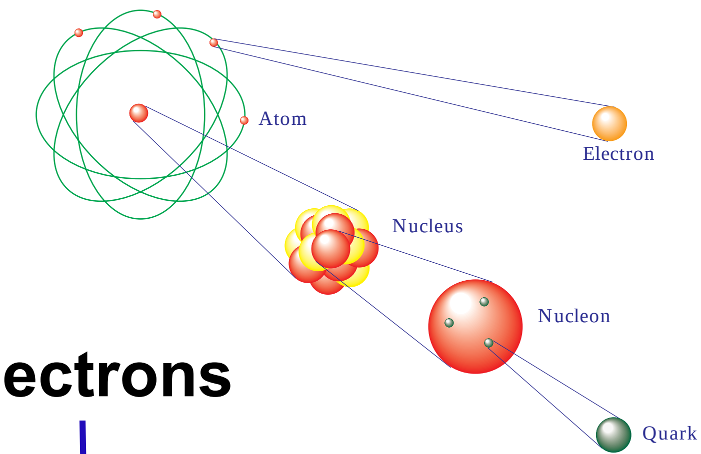
charm
bottom
top

Electrons

Leptons

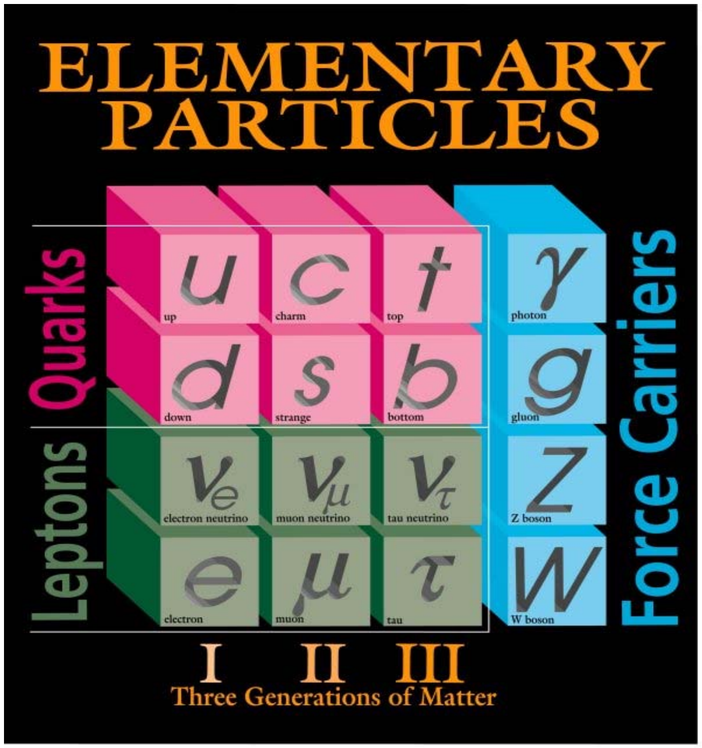
electrons
muons

taus
neutrinos



Building blocks for Matter: Quarks and Leptons

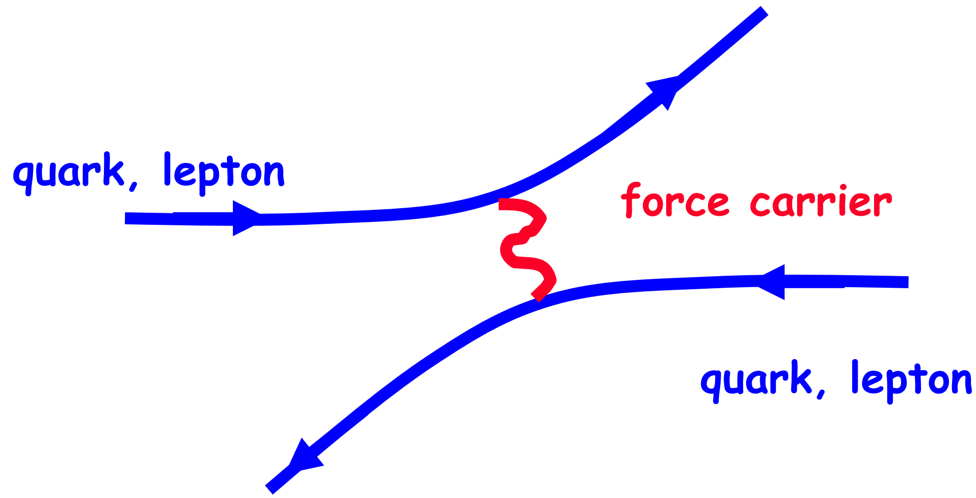
Standard Model of Particle Physics



Fermilab 95-759

Force	Carrier
Strong	Gluons (g)
Electro-Weak	Electro-weak bosons (γ,W,Z)
Gravitation	?

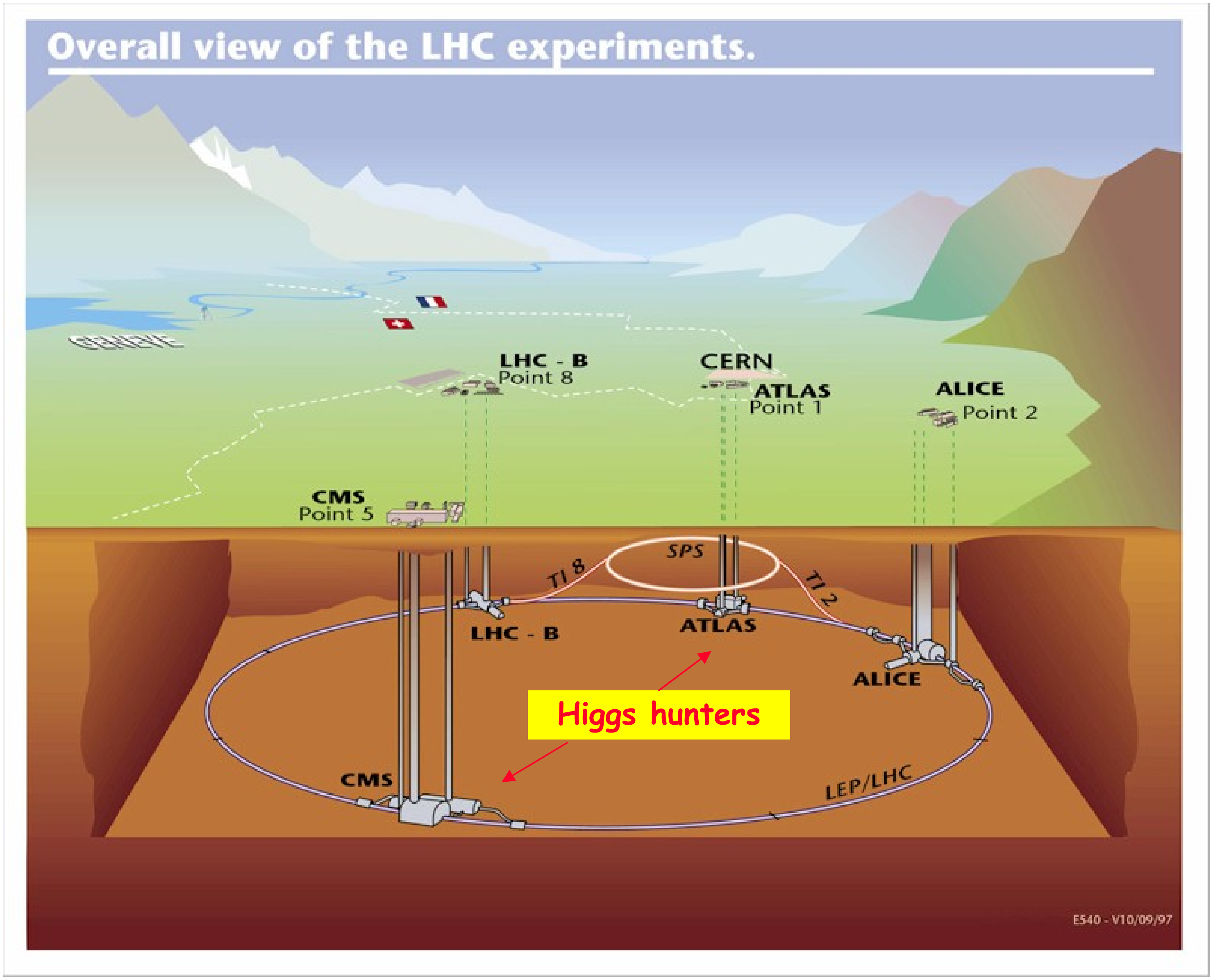
- Quarks and Leptons interact via the exchange of force carriers



A Higgs boson is predicted and required to give mass to particles

The Higgs boson has yet to be found!

Higgs Discovery at LHC



The Large Hadron Collider, a p-p collider

Particle production rate — Cross-section

$$\nu = L \cdot \sigma(E), \ \sigma \uparrow if \ E \uparrow$$

Center of mass Energy	14 TeV
Design Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	25 ns (40 MHz)

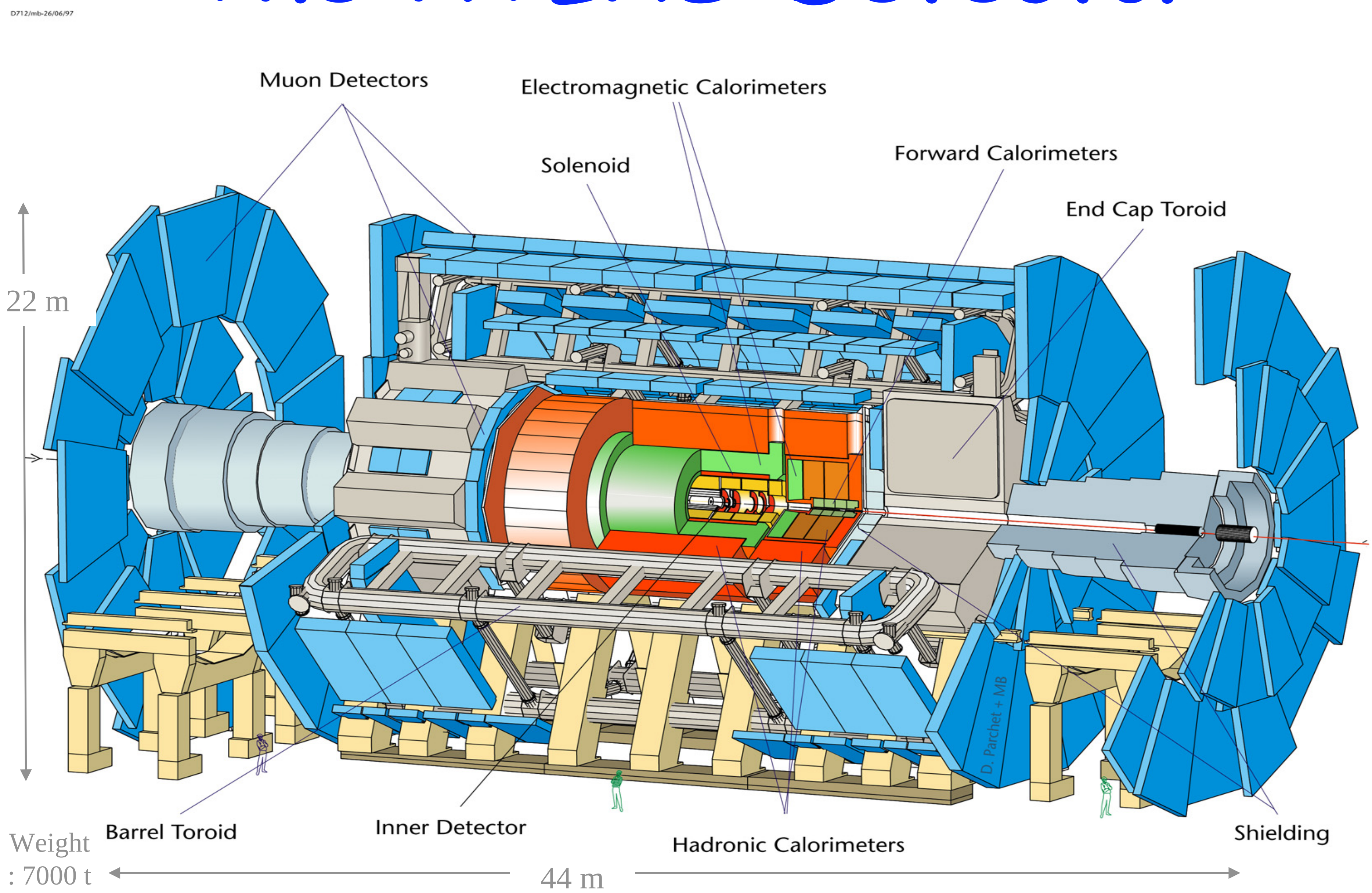
The LHC will produce heavy particles at rates orders of magnitude greater than in predecessor accelerators

Official schedule:

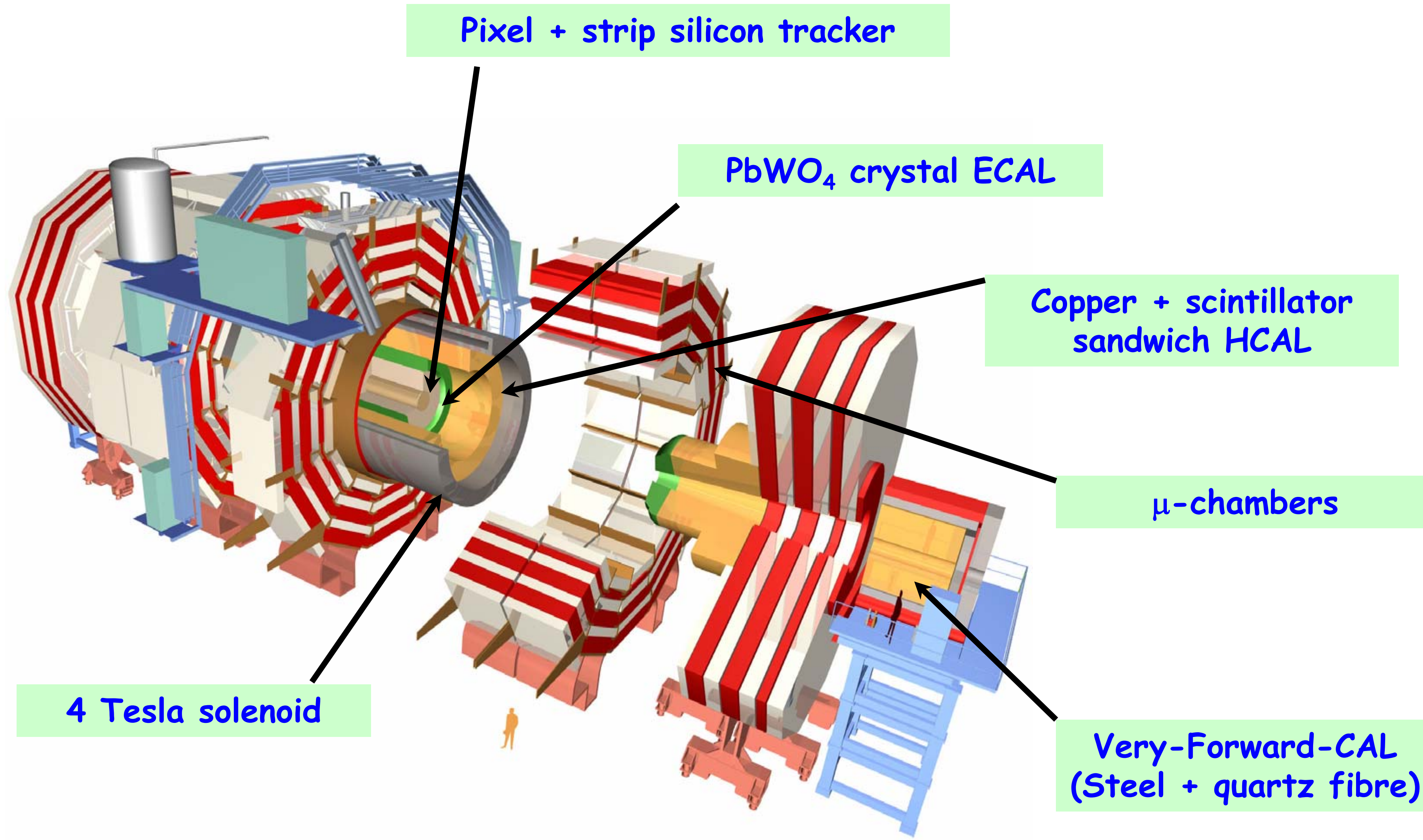
- First collisions, summer 07 ⟵ Start to understand accelerator & detector
- About 100 pb^{-1} by end 2007 ⟵ Almost enough data to calibrate detector
- O(1) fb^{-1} by end of 2008 ⟵ Limits on SM Higgs, SUSY discovery
- O(10) fb^{-1} by end of 2009 ⟵ Higgs discovery

Need to reach installation rate of 25 dipoles/week

The ATLAS Detector



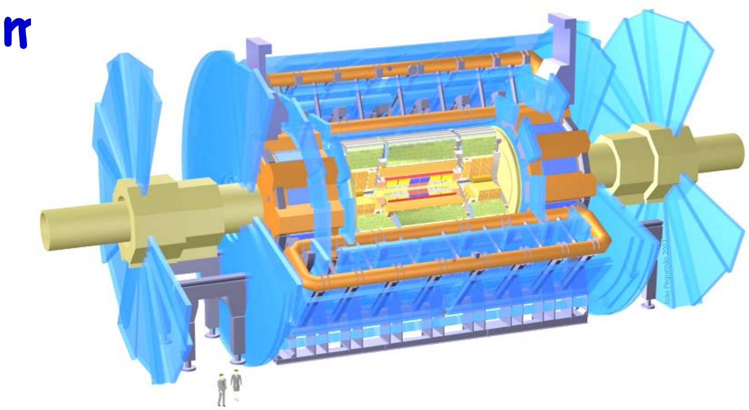
The CMS Detector

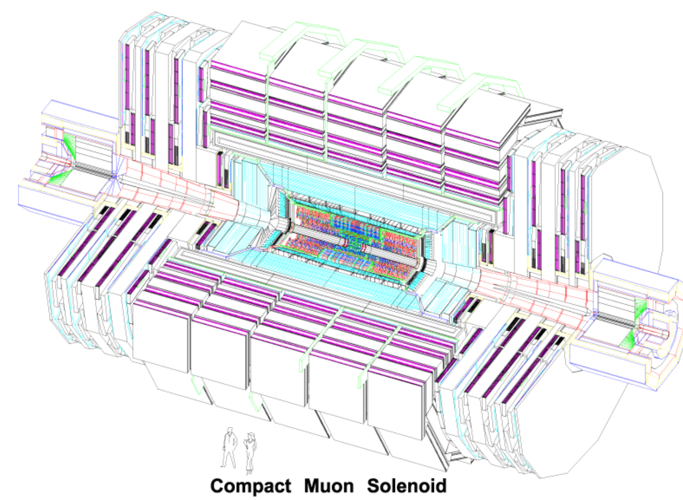


ATLAS versus CMS ?

ATLAS & CMS have very similar performance with some differences …

- ATLAS 2 X bigger due to complex muon system
- ATLAS μ resolution better
  in forward region (toroidal B-field)
- CMS has better ECAL and inside solenoid
  $\Rightarrow$ $H \rightarrow \gamma\gamma$ width factor of two better
- ATLAS jet energy resolution 40% better
  (ECAL+HCAL combination better).
- CMS B-field only 4 Tesla (2T in ATLAS)
  $\Rightarrow$ Pt resolution doubles in ATLAS
- ATLAS Transition Radiation Tracker
  $\Rightarrow$ Additional electron-pion separation
- CMS can do topological cuts at Level 1 trigger

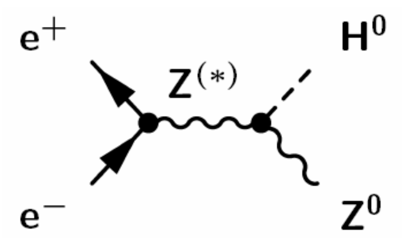




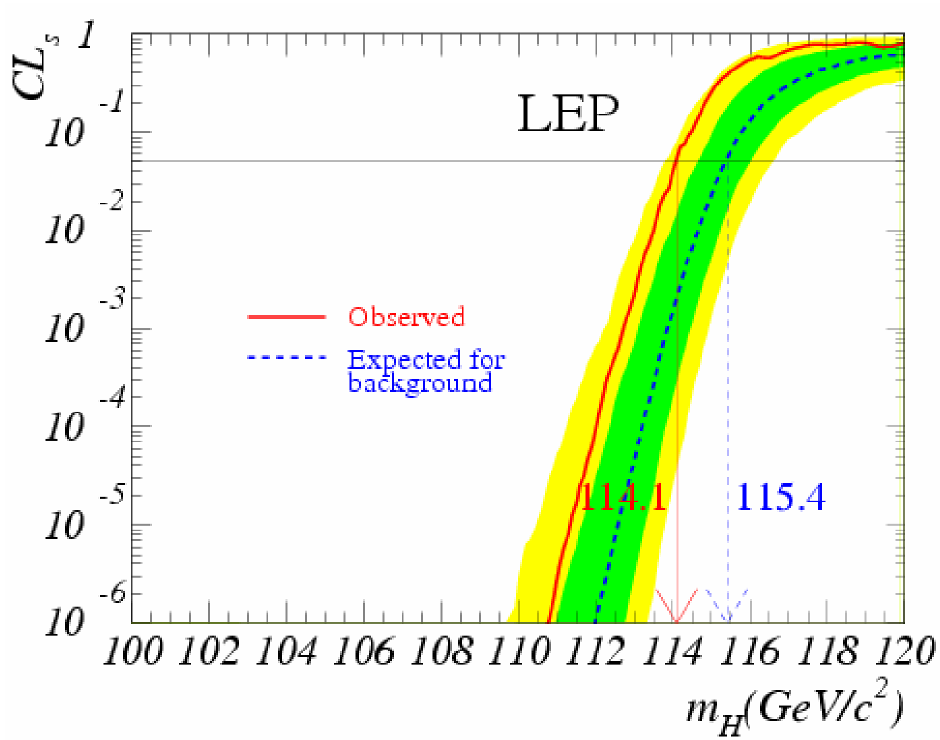
Very similar sensitivity to Higgs

How are we going to search for the Higgs Boson?

Direct searches at LEP, e^+e^- collisions, (1989-2000)

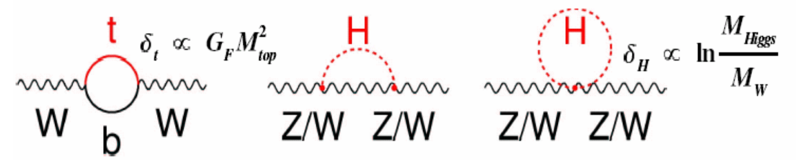


First Hint of Higgs boson with mass 115 GeV observed by ALEPH. LEP experiments together see about 2σ effect

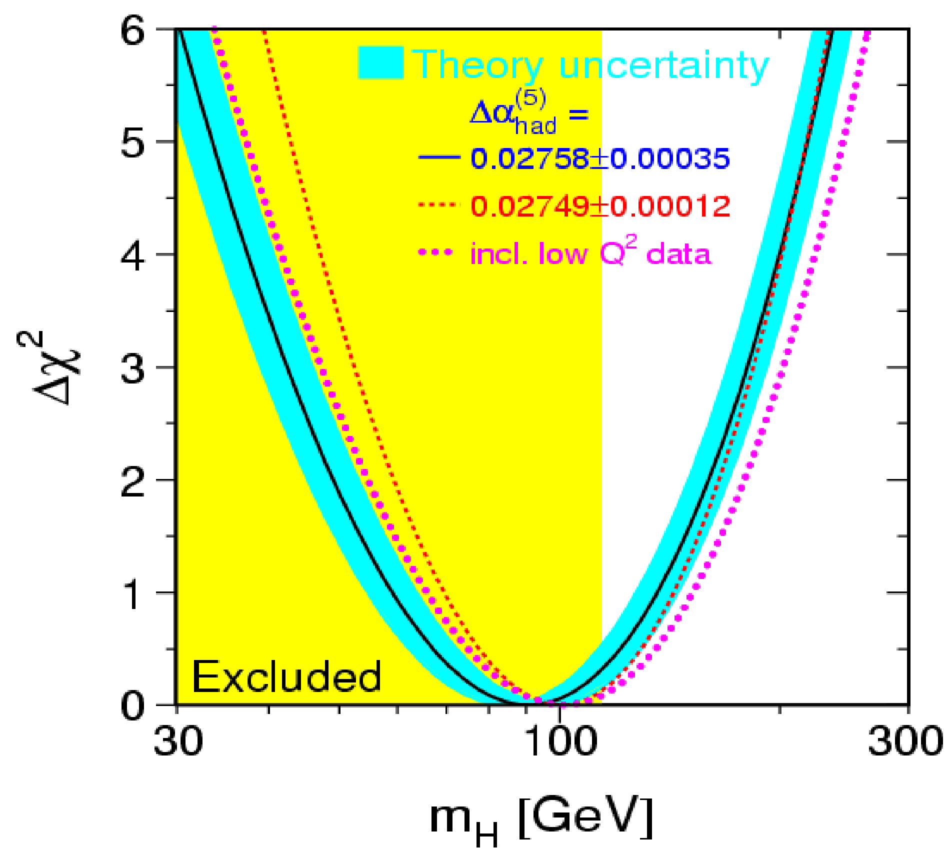


M_H>114.1 GeV @ 95% C.L.

Indirect evidence is driven by radiative corrections



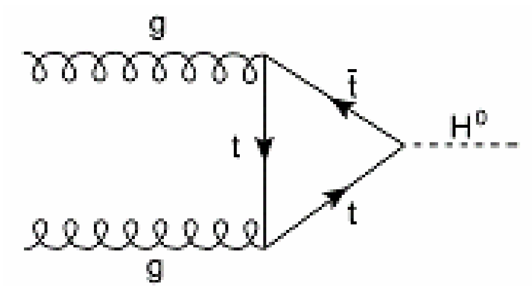
CDF+D0 Top Quark Mass = 172.7 ± 2.9 GeV



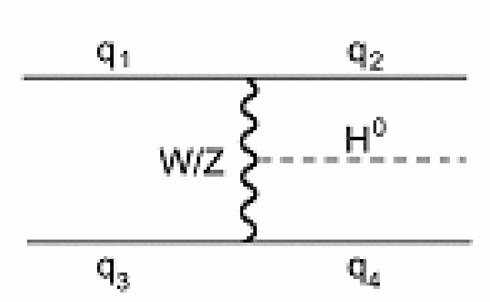
$M_H = 91^{+45}_{-32}$ <186 GeV @ 95% C.L.

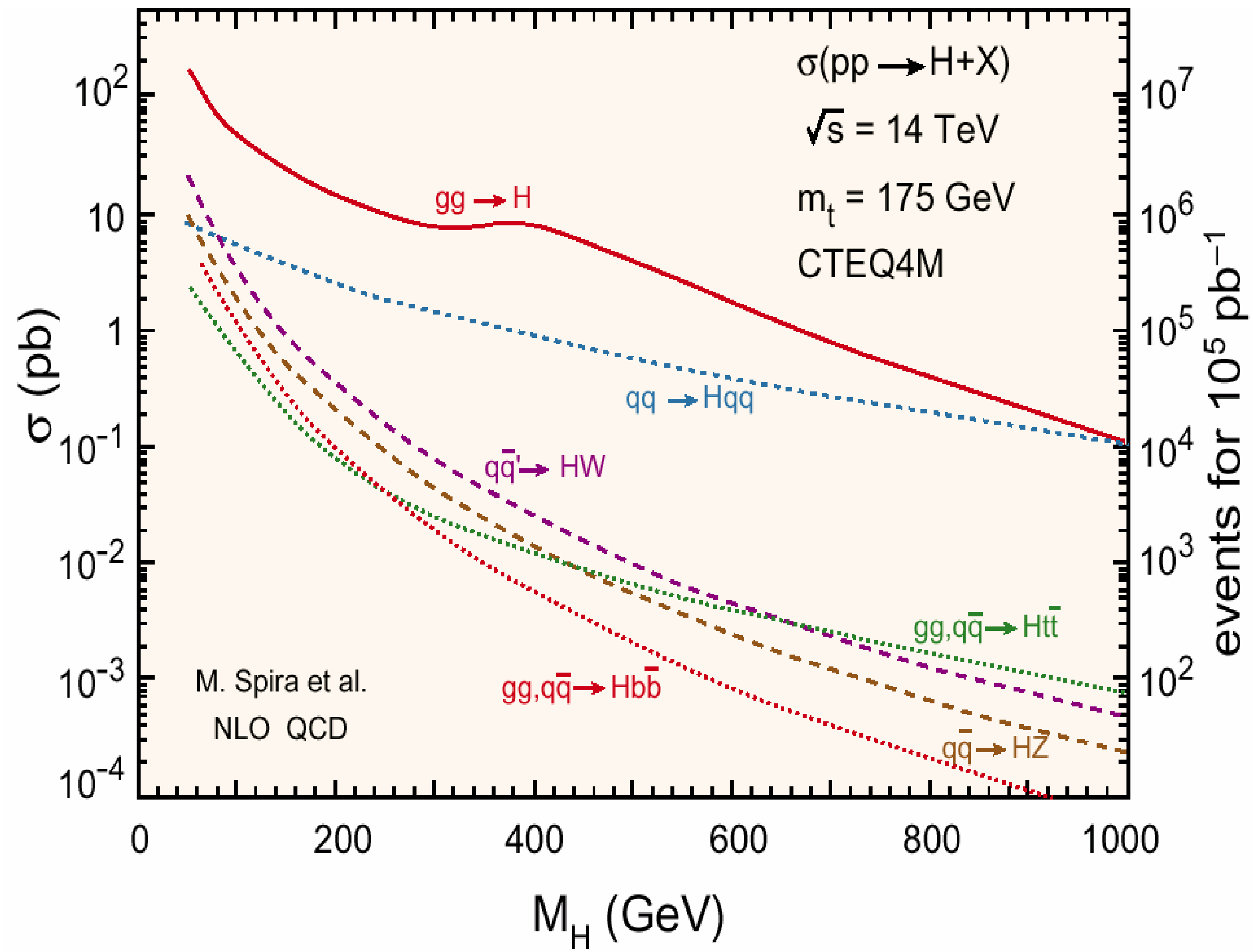
Higgs Production Cross-sections

Leading Process (gg fusion)



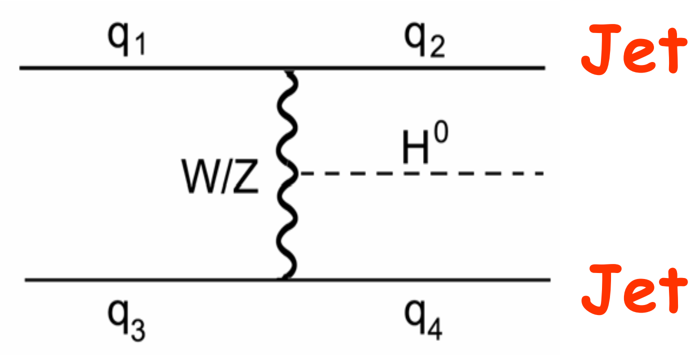
Sub-leading Process (VBF)



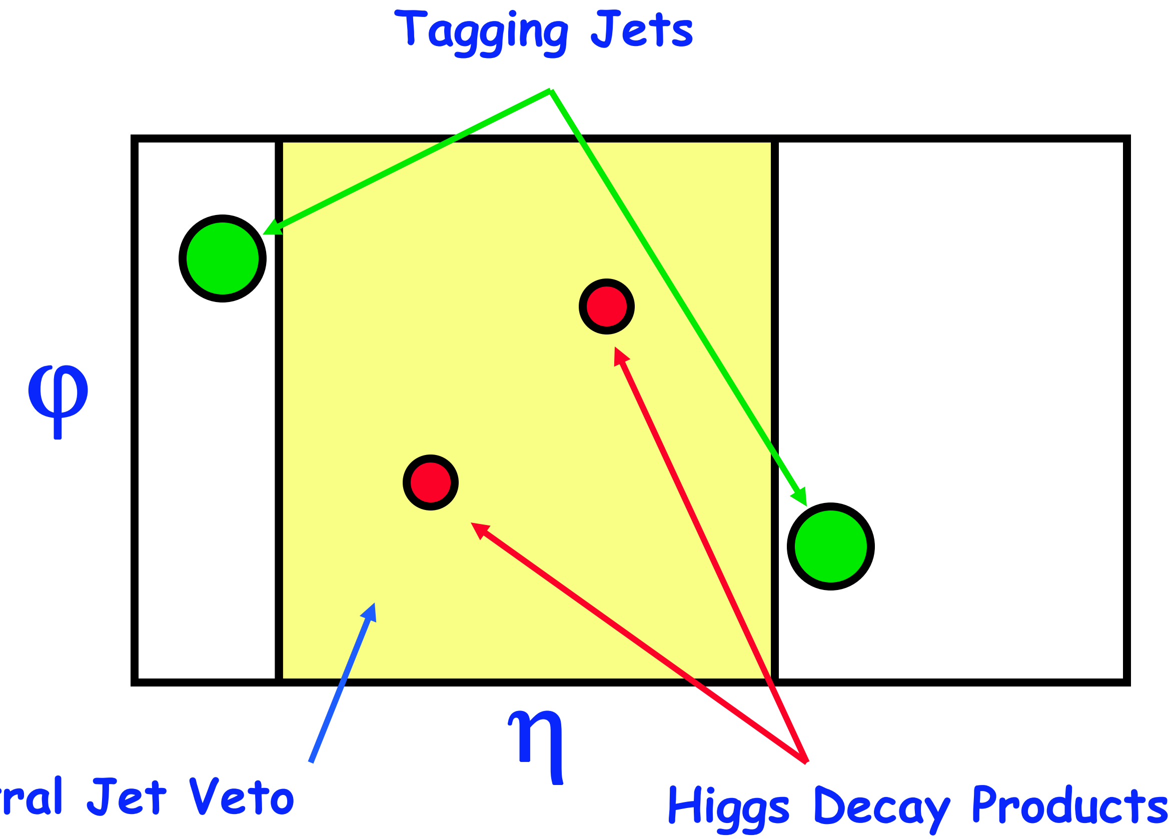


SM Higgs + ≥2jets at the LHC

- D.Zeppenfeld, D.Rainwater, et al. proposed to search for a Low Mass Higgs in association with two jets with jet veto
  - Central jet veto initially suggested in V.Barger, K.Cheung and T.Han in PRD 42 3052 (1990)



$$\eta_{J1} \cdot \eta_{J2} < 0$$
$$\Delta\eta_{JJ} > 3.5 \div 4$$
$$M_{JJ} > 500 \div 700\,\mathrm{GeV}$$
c.j.v.



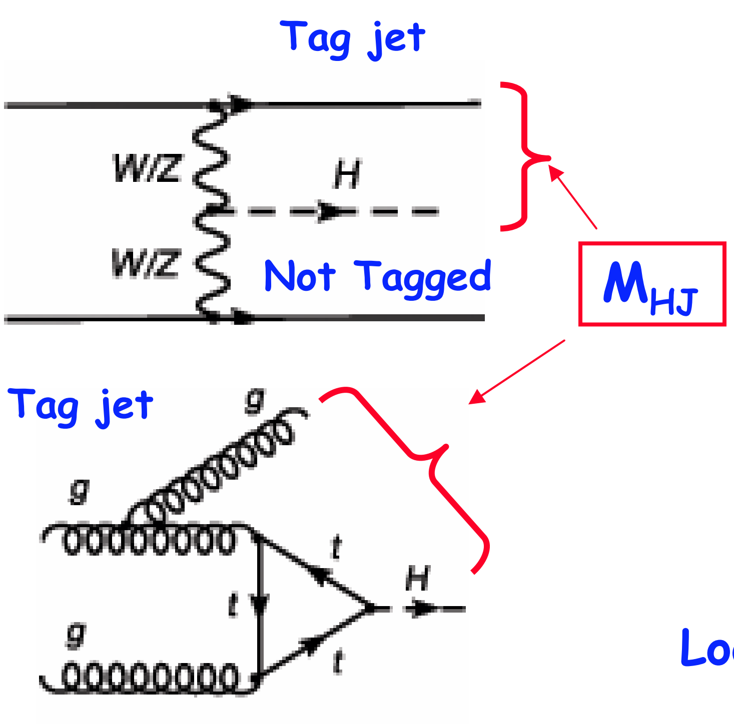
$\eta = -\ln(\tan(\theta/2))$

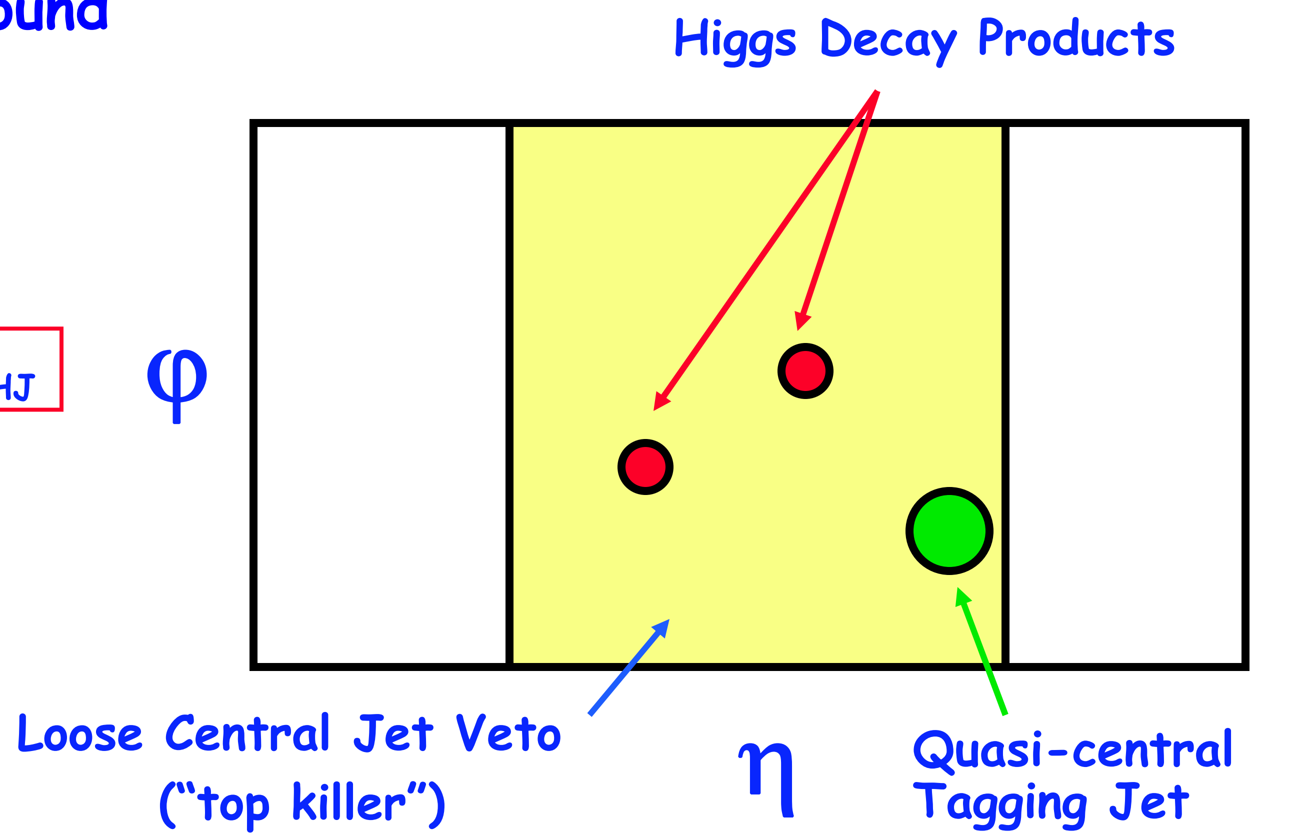
SM Higgs + 1jet at the LHC

1. Large invariant mass of leading jet and Higgs candidate
2. Large P_T of Higgs candidate
3. Leading jet is more forward than in QCD background

S.Abdullin et al PL B431 (1998) for $H \to \gamma\gamma$

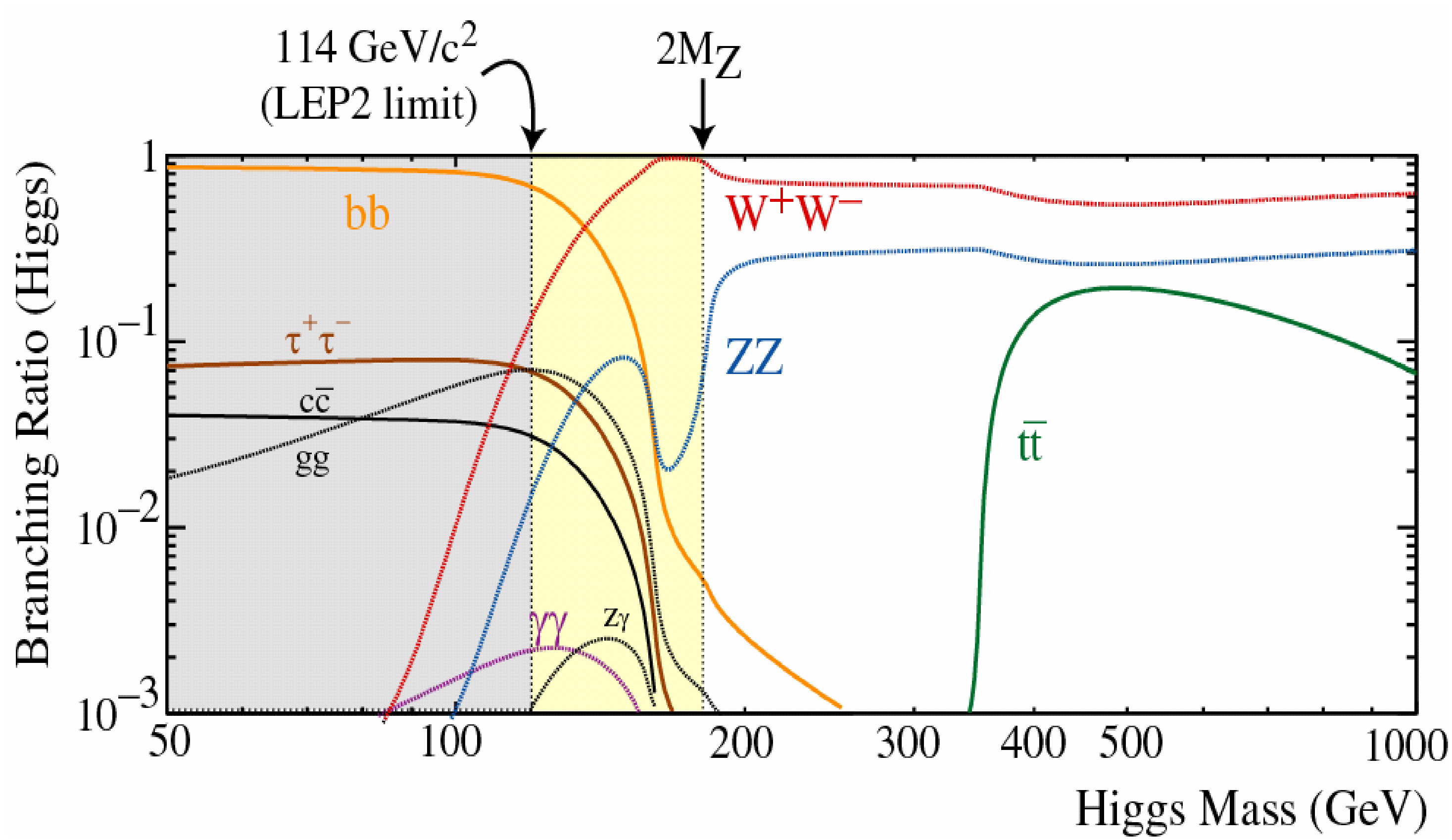
B.Mellado, W.Quayle and Sau Lan Wu Phys.Lett.B611:60-65,2005 for $H \to \tau\tau$ and $H \to WW(*)$





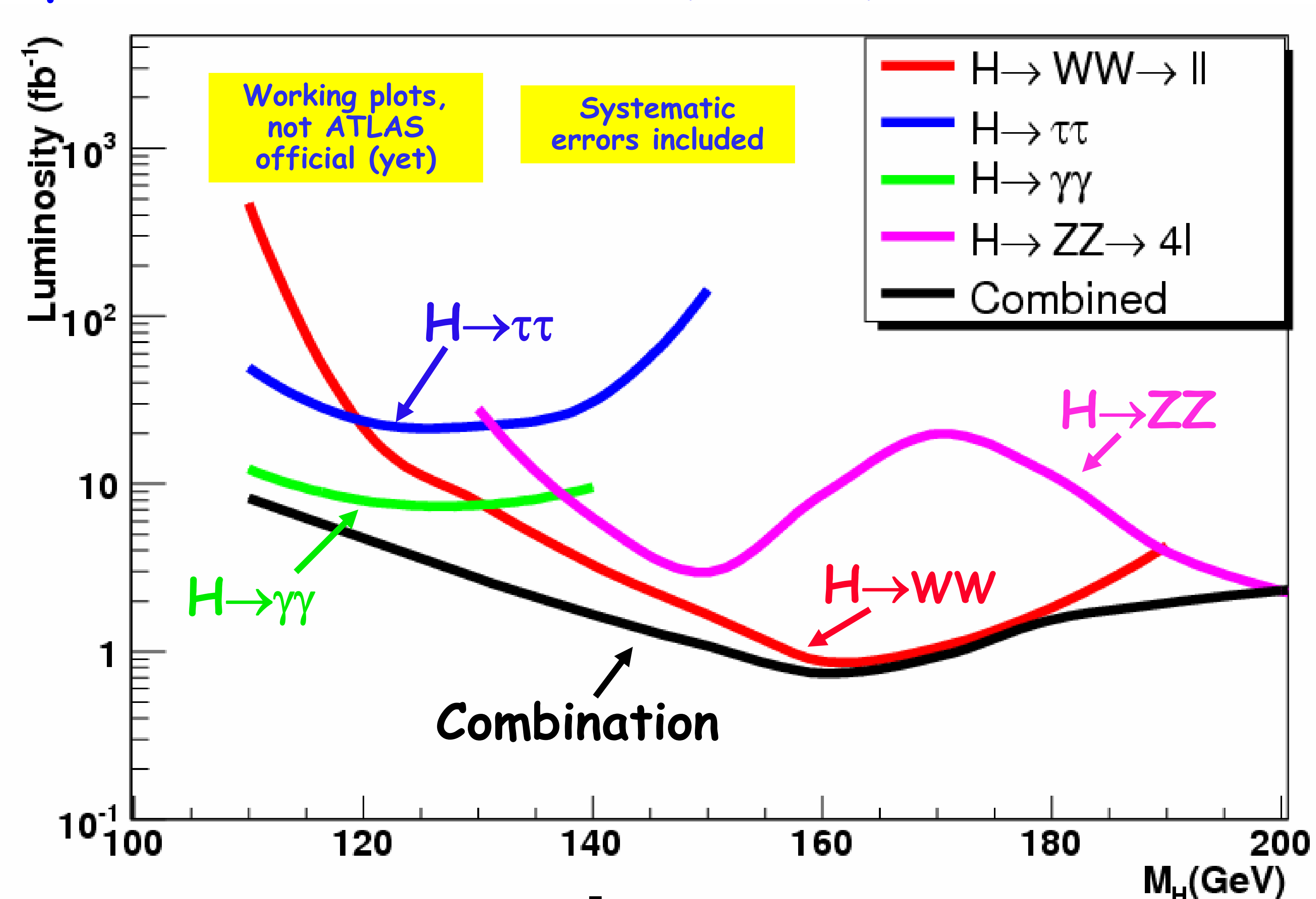
$\eta = -\ln(\tan(\theta/2))$

Main Decay Modes



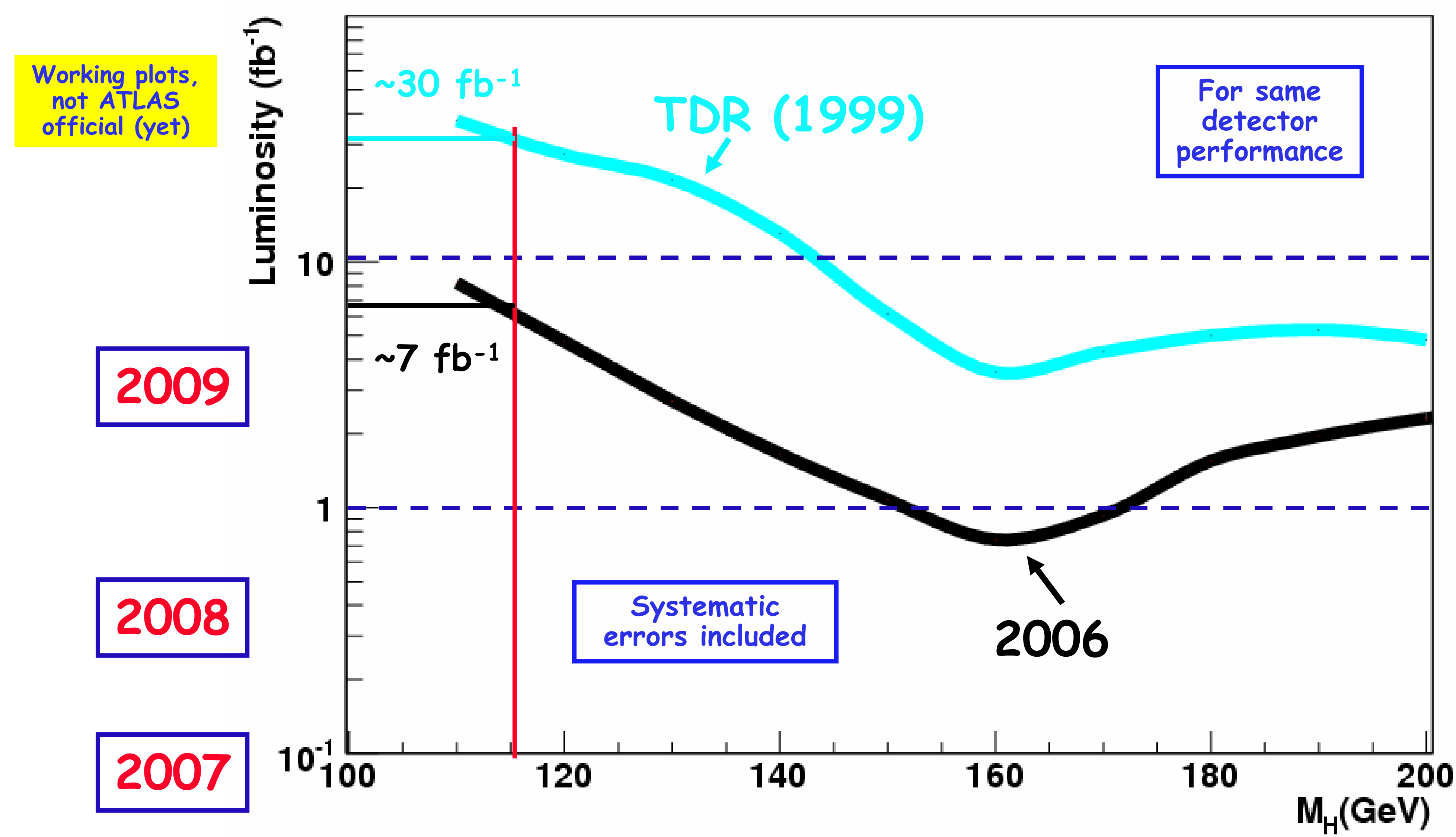
Close to LEP limit: $H \rightarrow \gamma\gamma, \tau\tau, bb$	For M_H>140 GeV: $H \rightarrow WW^{(*)}, ZZ^{(*)}$

Combination of strongest channels in terms of luminosity required for 5σ observation (ATLAS)



Low Mass Higgs ←|→ Intermediate and heavy Higgs

Enhancement of sensitivity w.r.t. ATLAS physics TDR (1999). Need about 4 times less luminosity for discovery in the low mass region



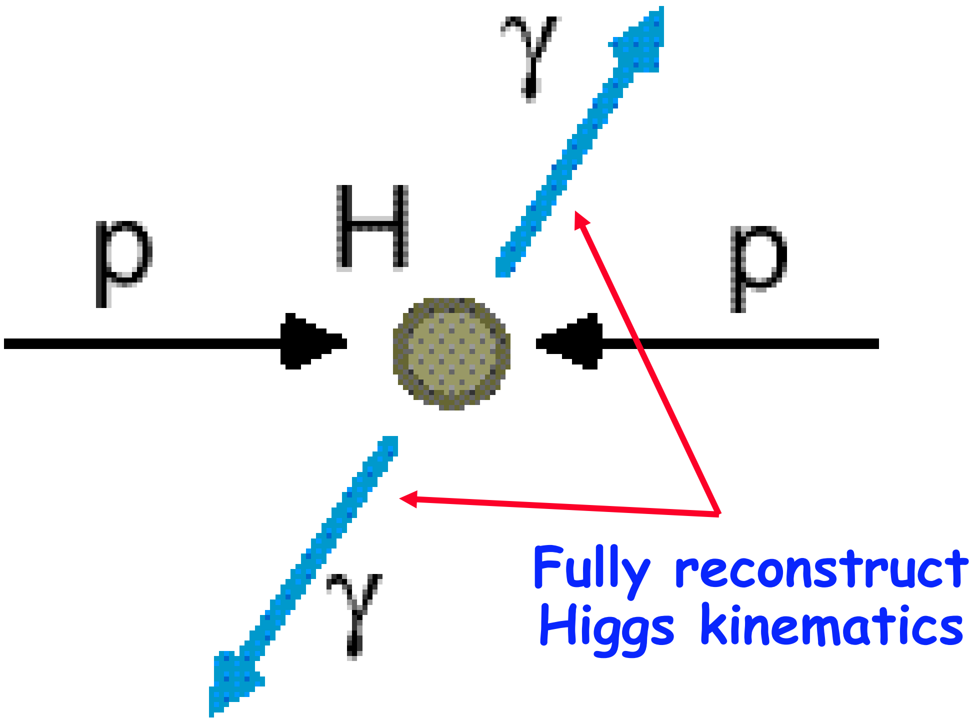
Based on full MC simulation studies. Made possible due to huge computing effort (10M events, 10-15 cpu minutes/event): collaboration with UW Computer Science Department

- Strong enhancement of sensitivity w.r.t. ATLAS physics TDR (1999) due to a number of factors

1. Inclusion of H+1jet and H+2jet analyses in $H \to \gamma\gamma, \tau\tau, WW^{(*)}$ searches
2. Strong improvement in the $H \to WW^{(*)}$ analysis
3. Better understanding of electron-pion and photon-pion separation
4. Introduction of Object-Based method in Missing E_T reconstruction → expect strong improvement in Missing E_T resolution for Higgs physics
5. More realistic implementation of QCD Higher Order corrections in MC's

These improvements are equally applicable to CMS

Low Mass Higgs: $H \to \gamma\gamma$



Outstanding issues

Photon resolution

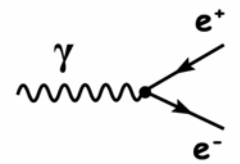
Photon-jet separation

Splitting of phase space according to jet multiplicity

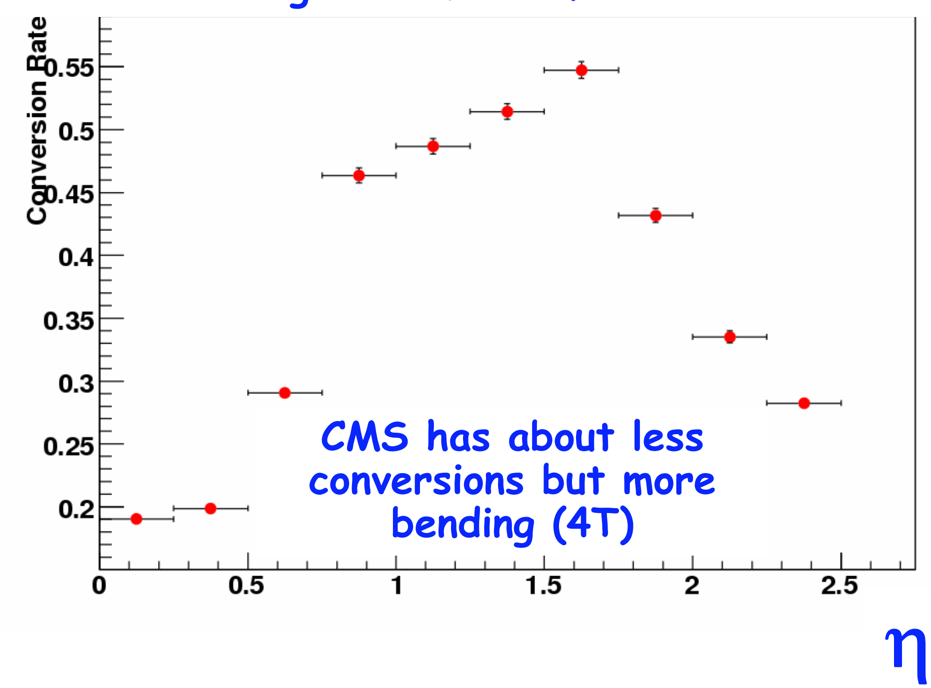
$$\frac{\sigma E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Photon Resolution

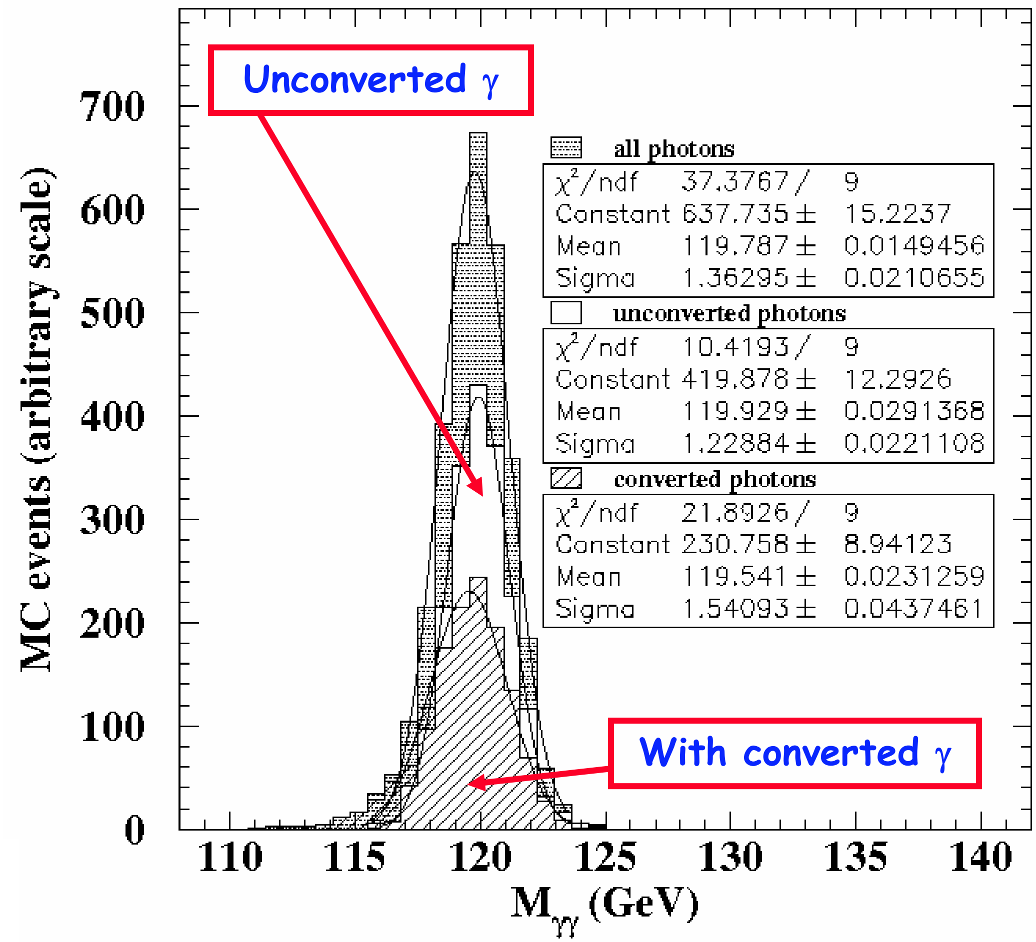
- **Aim at resolution: a constant term c<0.7%**
  - Make use of $pp \rightarrow Z \rightarrow ee(\gamma)$
  - Special care with converted γ



Fraction of photons converting to e^+e^- before reaching calorimeter for ATLAS



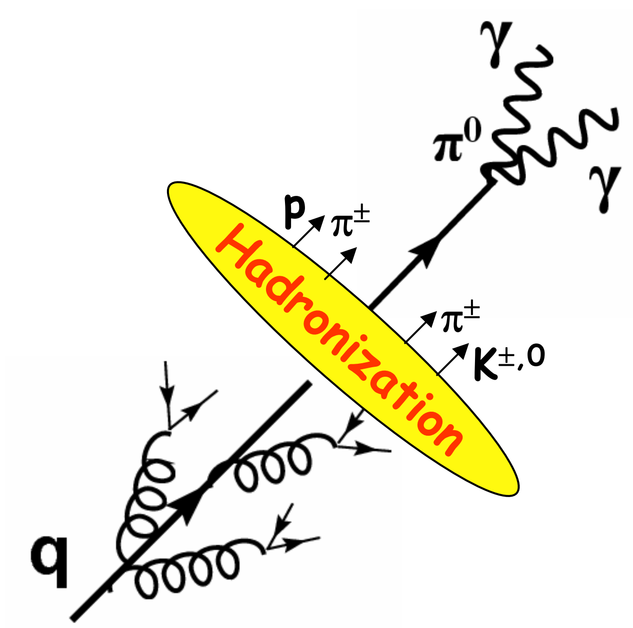
Converted photons are harder to reconstruct (and identify)

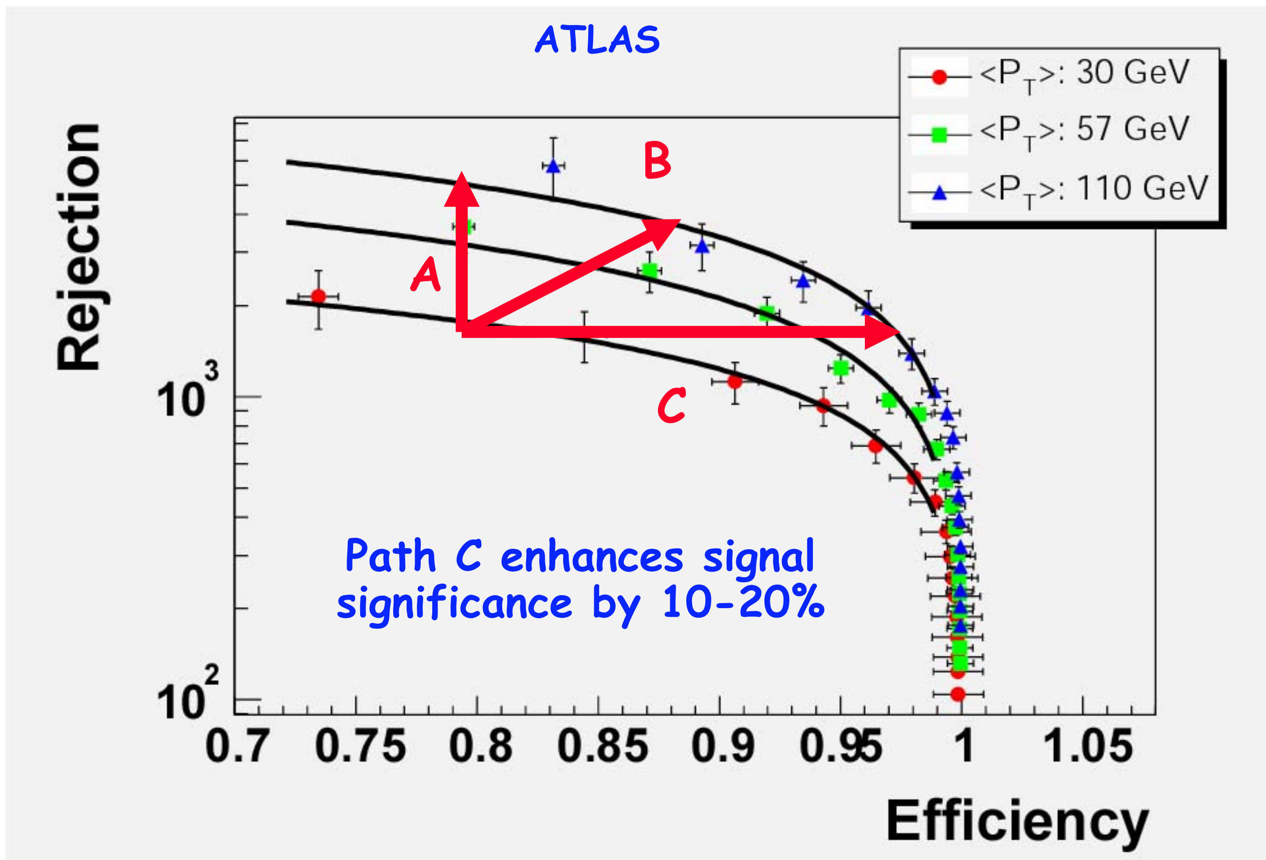


Photon-Jet Separation

- Need to achieve $>10^3$ (P_T>25 GeV) rejection against light jets
  - Make use of $pp \rightarrow Z \rightarrow ee(\gamma)$ and multi-jet events to optimize γ identification and isolation. Optimization is very important

A jet can be observed in the detector as a single photon





Combined $\gamma\gamma$+0j/1j/2j Analysis

Pre-selection

Pick event if $P_{T\gamma 1}>40$ GeV and $P_{T\gamma 2}>25$ GeV

↓

$\gamma\gamma$+2j Analysis

Pick event if $\Delta\eta_{JJ}, M_{JJ}>$thresholds

↓

$\gamma\gamma$+1j Analysis

Pick event if $P_{TJ}, M_{\gamma\gamma J}>$thresholds

↓

$\gamma\gamma$+0j Analysis

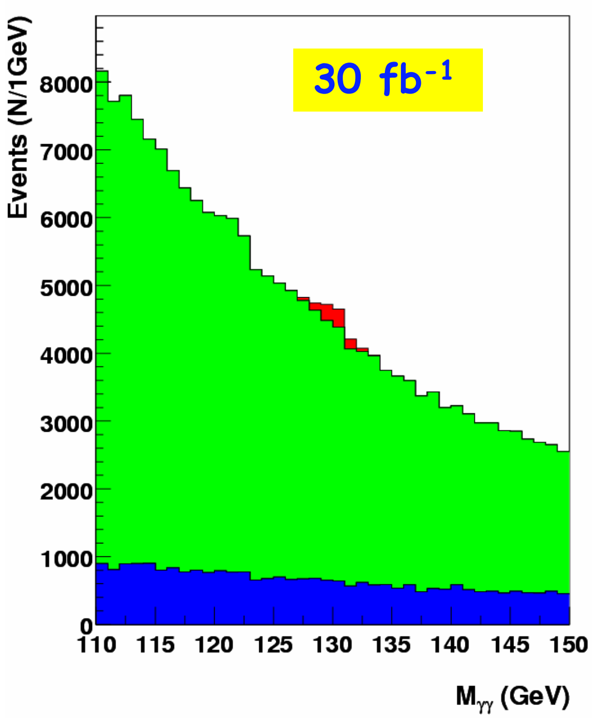
Pick rest of the events

↑ Increase of signal to background ratio

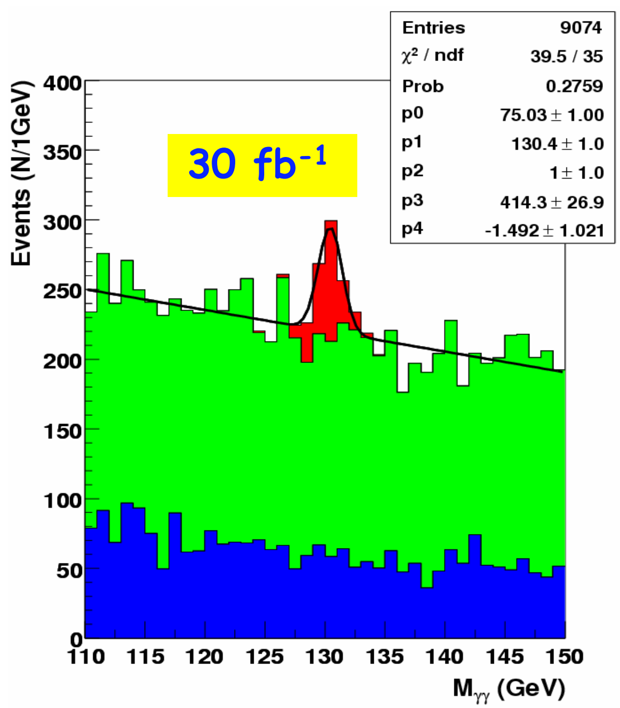
SM Higgs→γγ (+ 0,1,2 Jets)

- Narrow peak on top of smooth background. Use side bands to extract background under signal peak
  - Separation of events according to jet multiplicity maximizes sensitivity

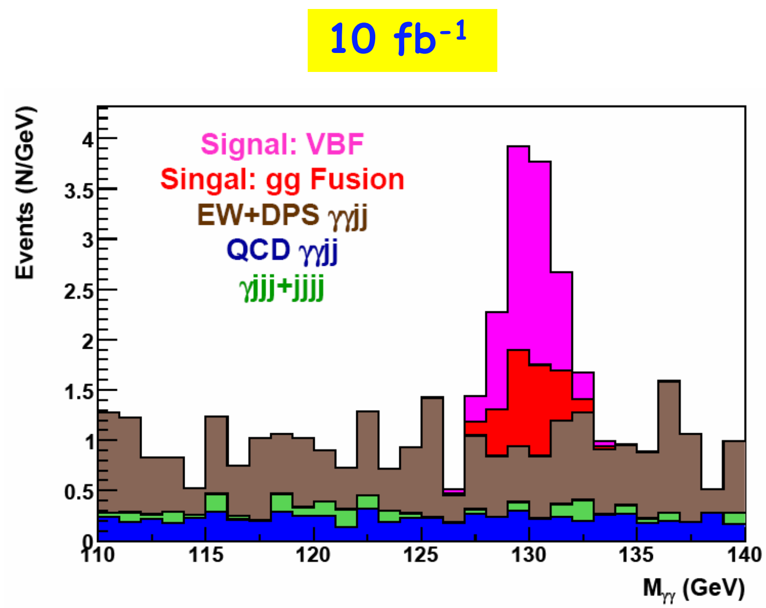
H(→γγ) +0 jet



H(→γγ) + 1 jet

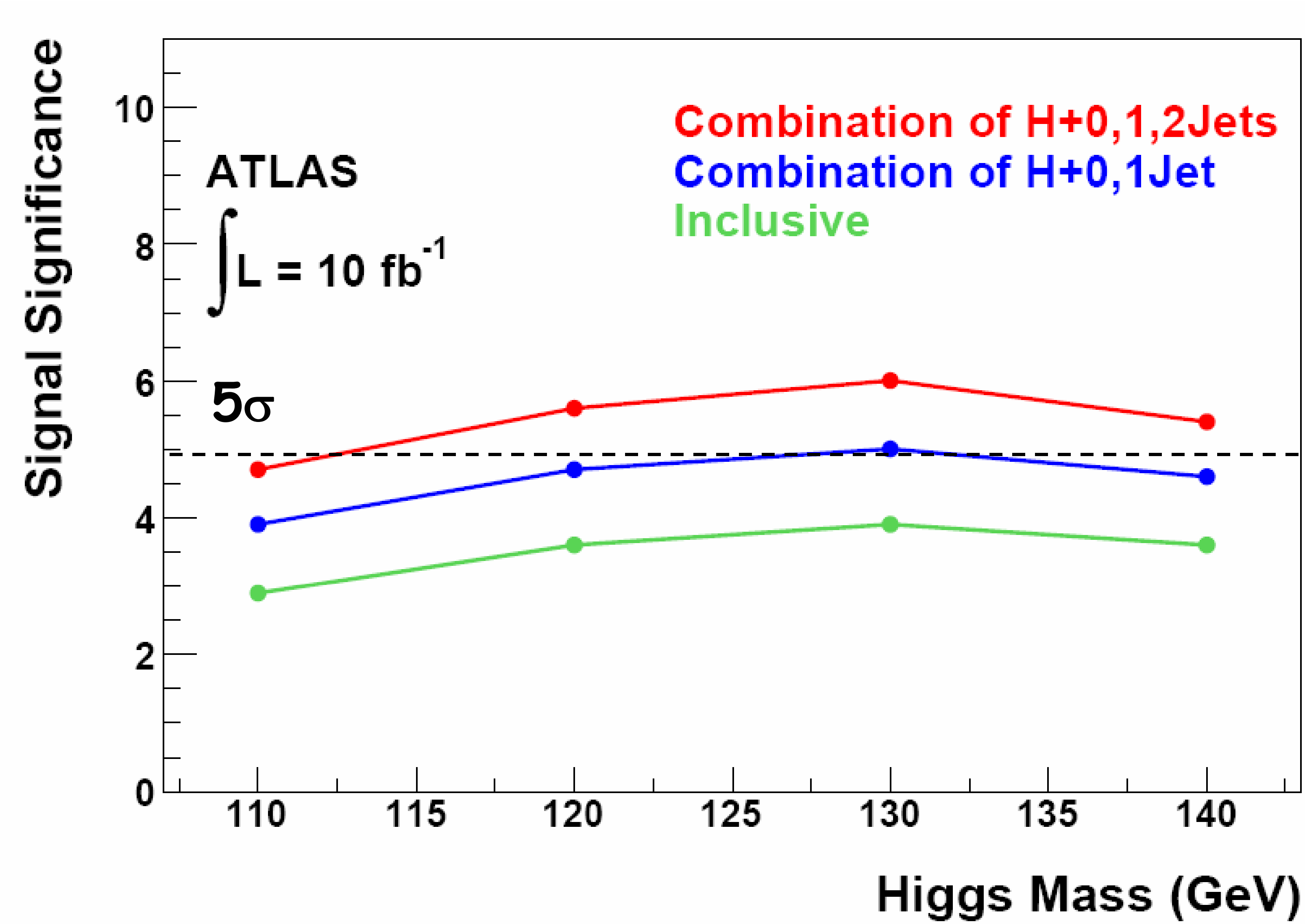


H(→γγ) + ≥2 jets

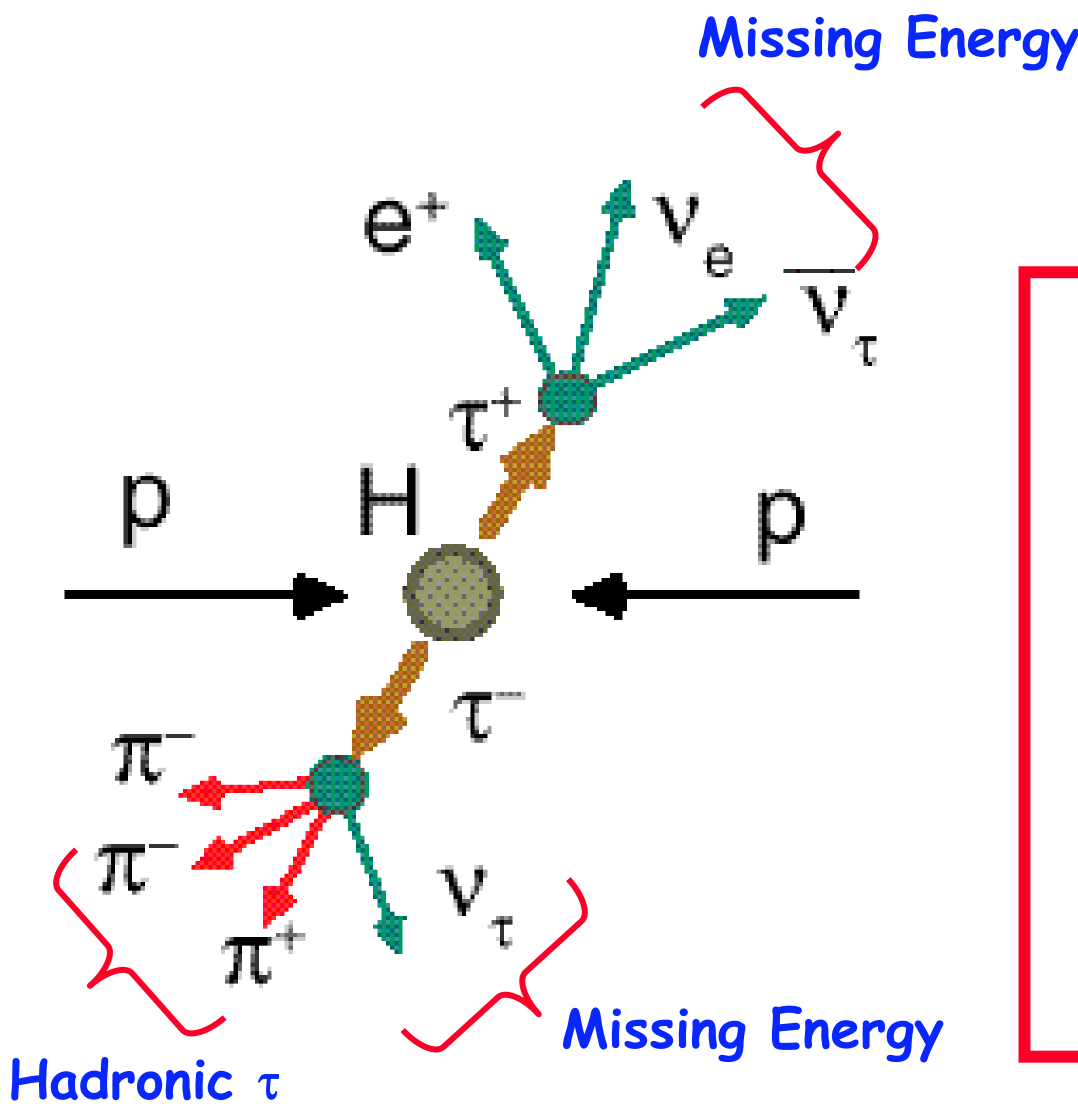


Increase of signal to background ratio

Combined H+0,1,2jet analyses gives very strong enhancement of the sensitivity with respect to inclusive search



Low Mass Higgs: $H \rightarrow \tau\tau$



Outstanding issues

Missing E_T reconstruction

Lepton Identification

Splitting of phase space according to jet multiplicity

Collinear Approximation

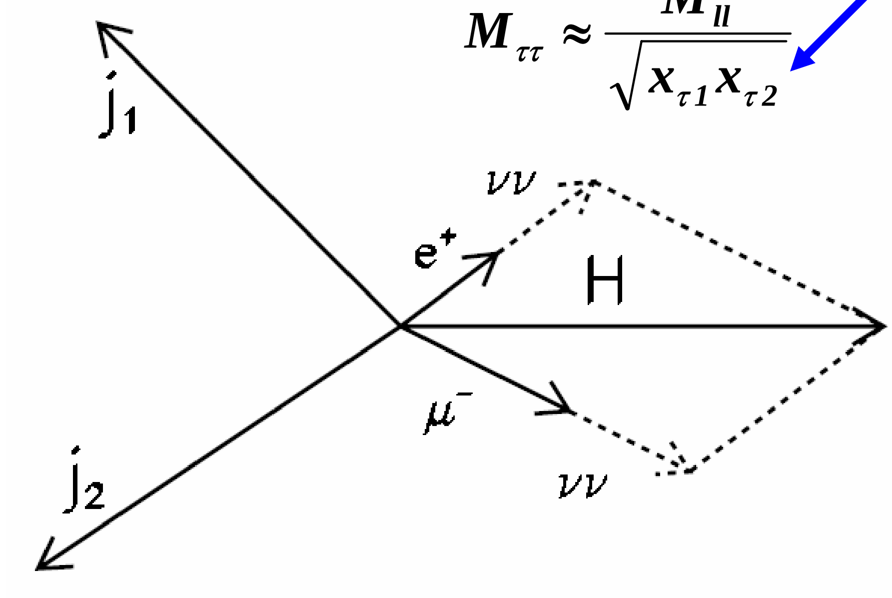
- In order to reconstruct the Higgs mass need to use the collinear approximation

Tau decay products are collinear to tau direction

$$\vec{P}_\tau = \frac{\vec{P}_l}{x_\tau}$$

Fraction of τ momentum carried by lepton

$$M_{\tau\tau} \approx \frac{M_{ll}}{\sqrt{x_{\tau 1} x_{\tau 2}}}$$



$$\vec{P}_{T\tau 1} + \vec{P}_{T\tau 2} = \vec{P}_{Tl1} + \vec{P}_{Tl2} + \vec{P}_{Tmiss}$$

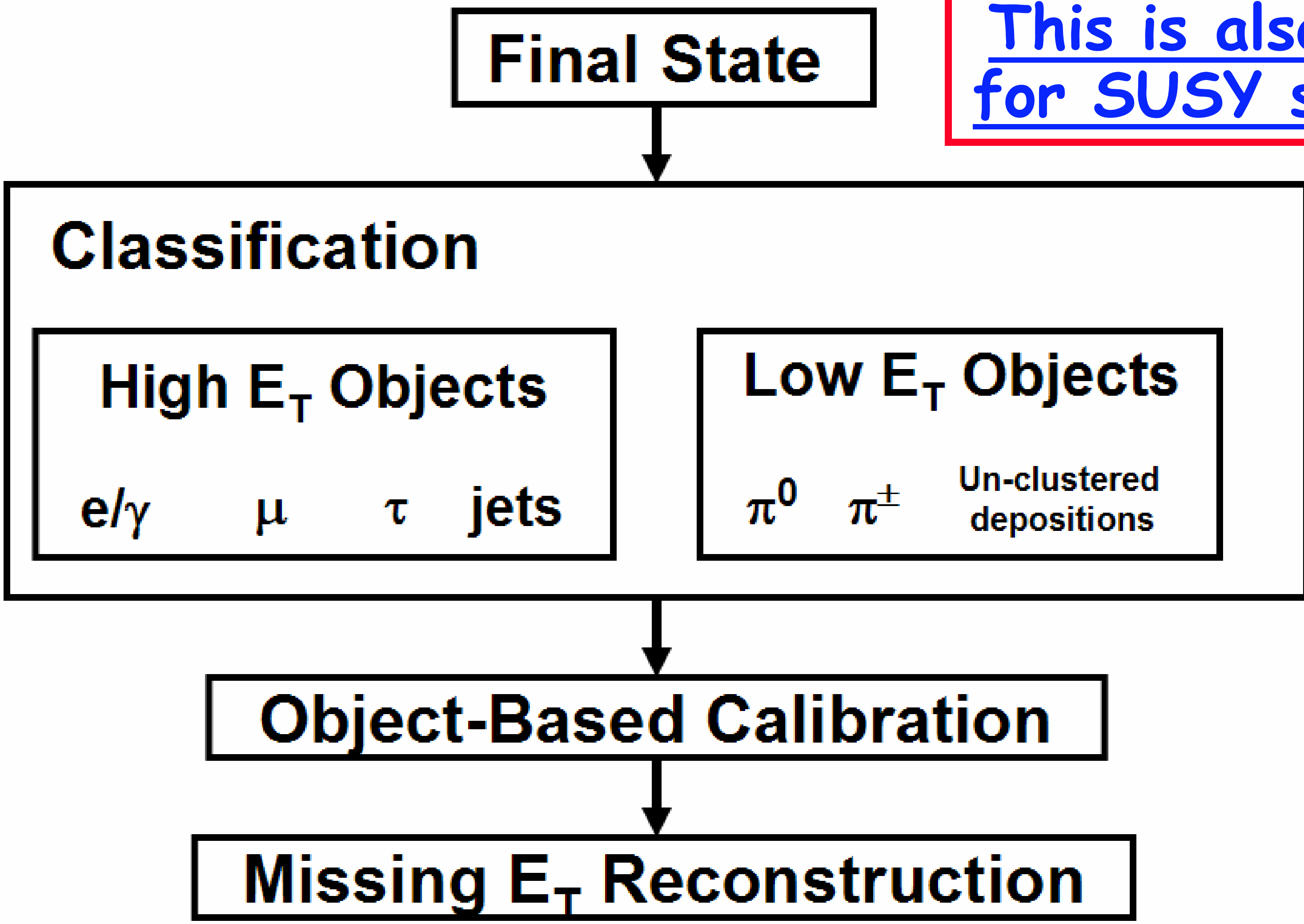
$$x_{\tau_1} = \frac{p_{T_{lep1},x} \cdot p_{T_{lep2},y} - p_{T_{lep1},y} \cdot p_{T_{lep2},x}}{p_{T_{Higgs},x} \cdot p_{T_{lep2},y} - p_{T_{Higgs},y} \cdot p_{T_{lep2},x}}$$

$$x_{\tau_2} = \frac{p_{T_{lep1},x} \cdot p_{T_{lep2},y} - p_{T_{lep1},y} \cdot p_{T_{lep2},x}}{p_{T_{Higgs},y} \cdot p_{T_{lep1},x} - p_{T_{Higgs},x} \cdot p_{T_{lep1},y}}$$

- $x_{\tau 1}$ and $x_{\tau 2}$ can be calculated if the missing E_T is known
- Good missing E_T reconstruction is essential

Object-Based Missing E_T

- Successfully demonstrated in ATLAS and implemented in the software the Object-based method in Missing E_T reconstruction

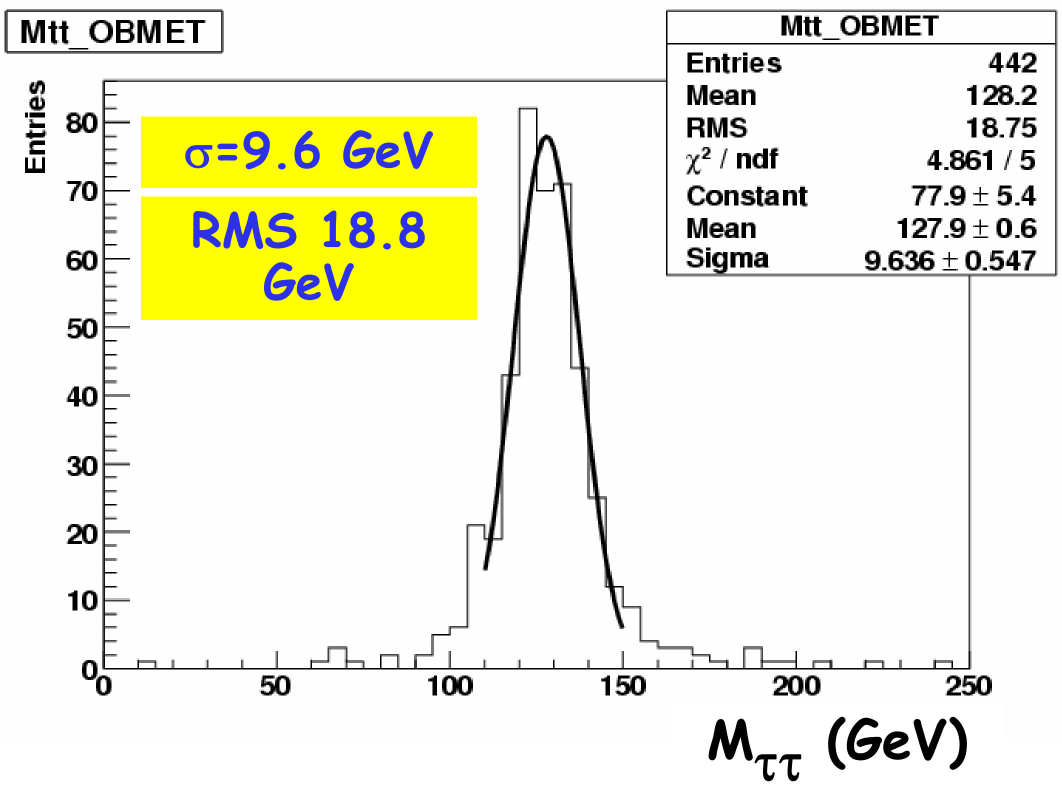


This is also crucial for SUSY searches!

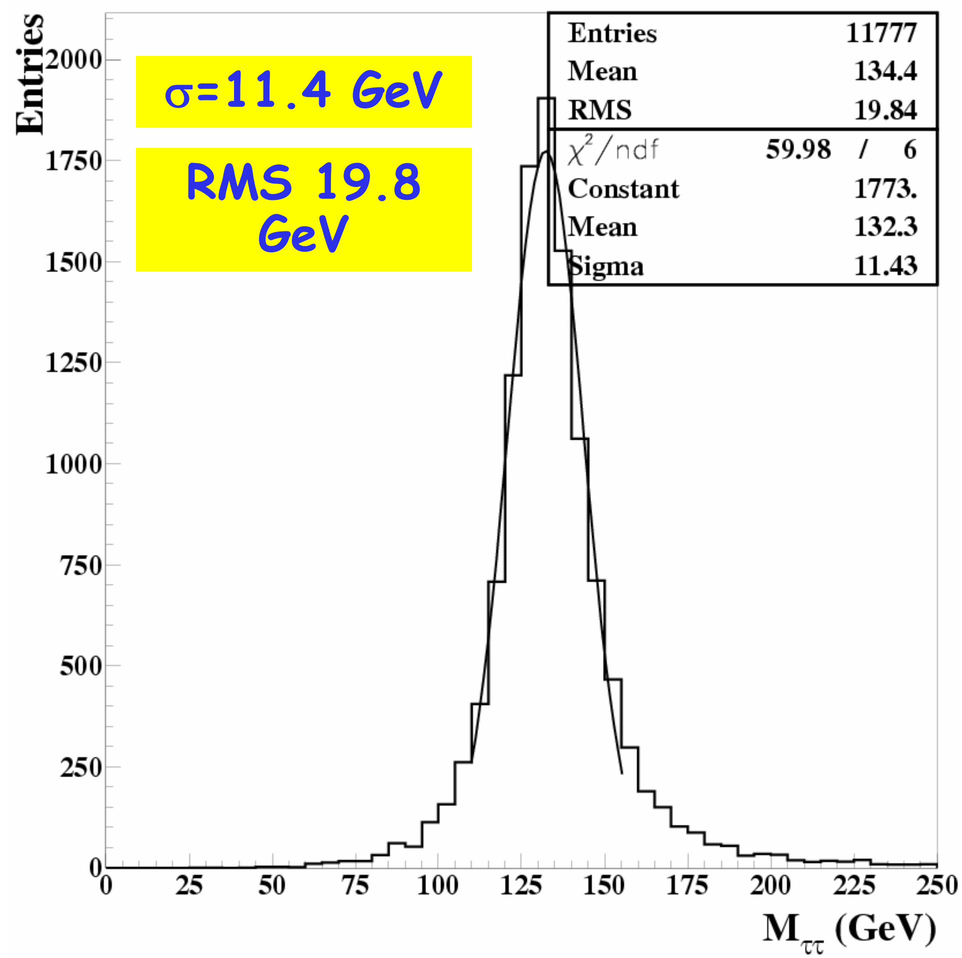
Due to the Object-Based method in Missing E_T reconstruction we were able to improve the Higgs mass resolution w.r.t. to Physics ATLAS TDR (1999)

$H(\to\tau\tau\to ll)$

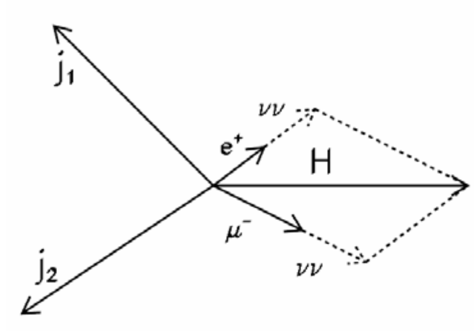
Object-Based Method



TDR (1999)

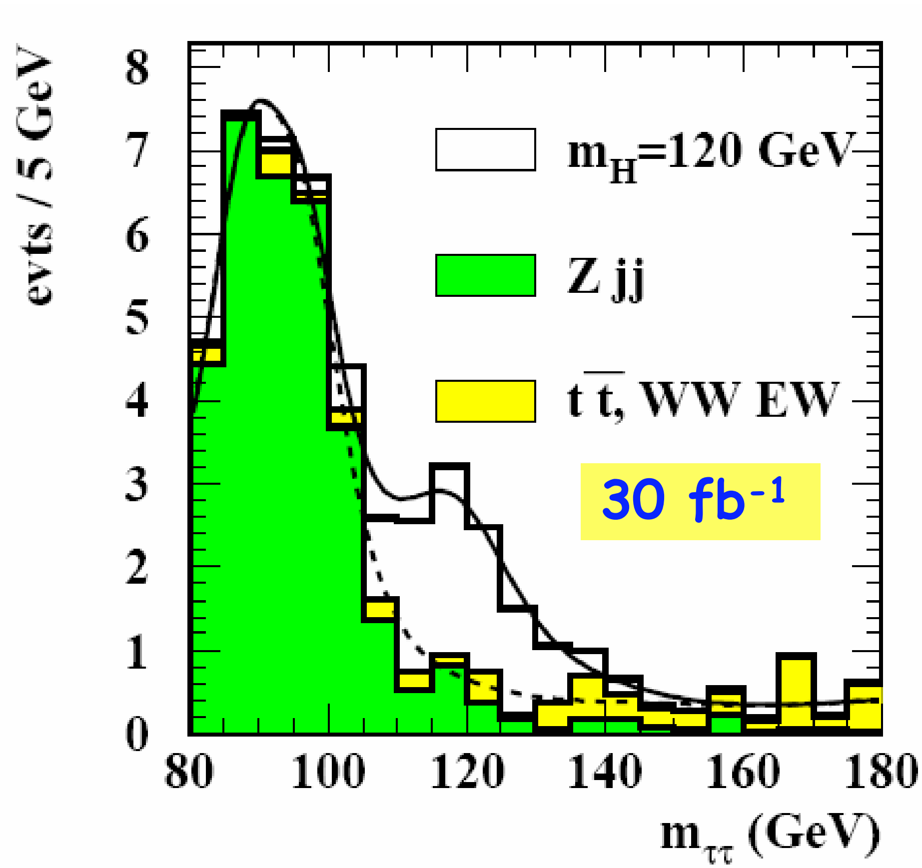


Low Mass H(→ττ)+1,2jets

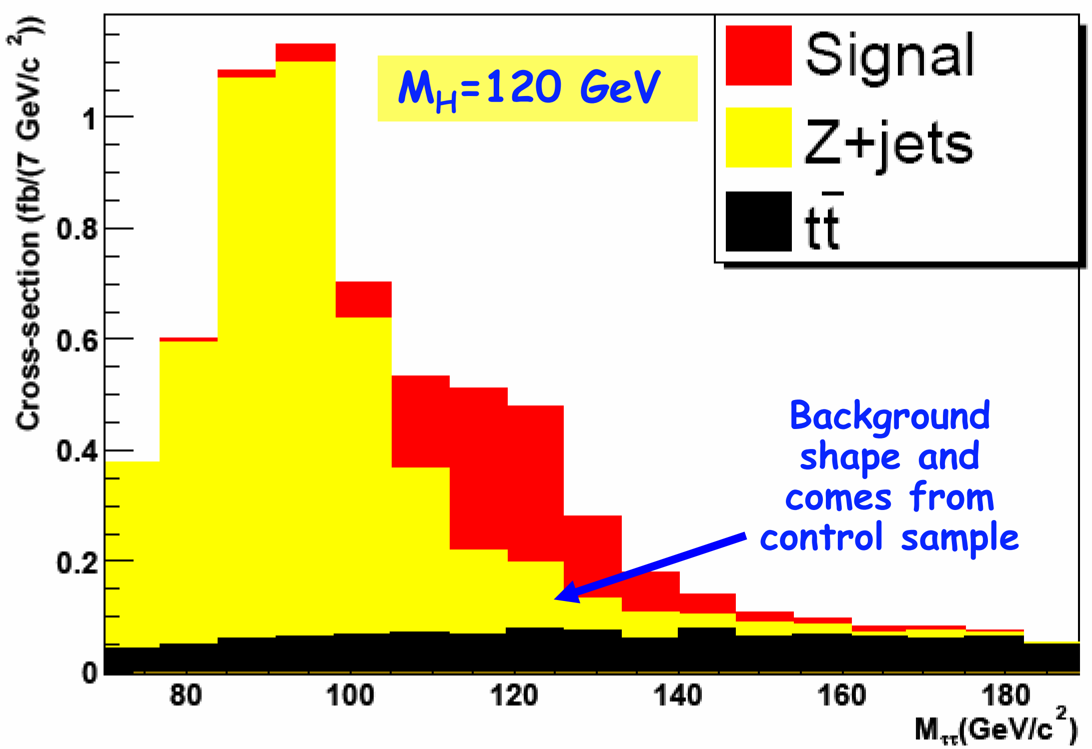


- Slicing of phase space enhances sensitivity
- Main background: Z+jets and tt
  - Use Z→ee,μμ and b-tagged tt as control samples

H(→ττ→ll) +≥2jets

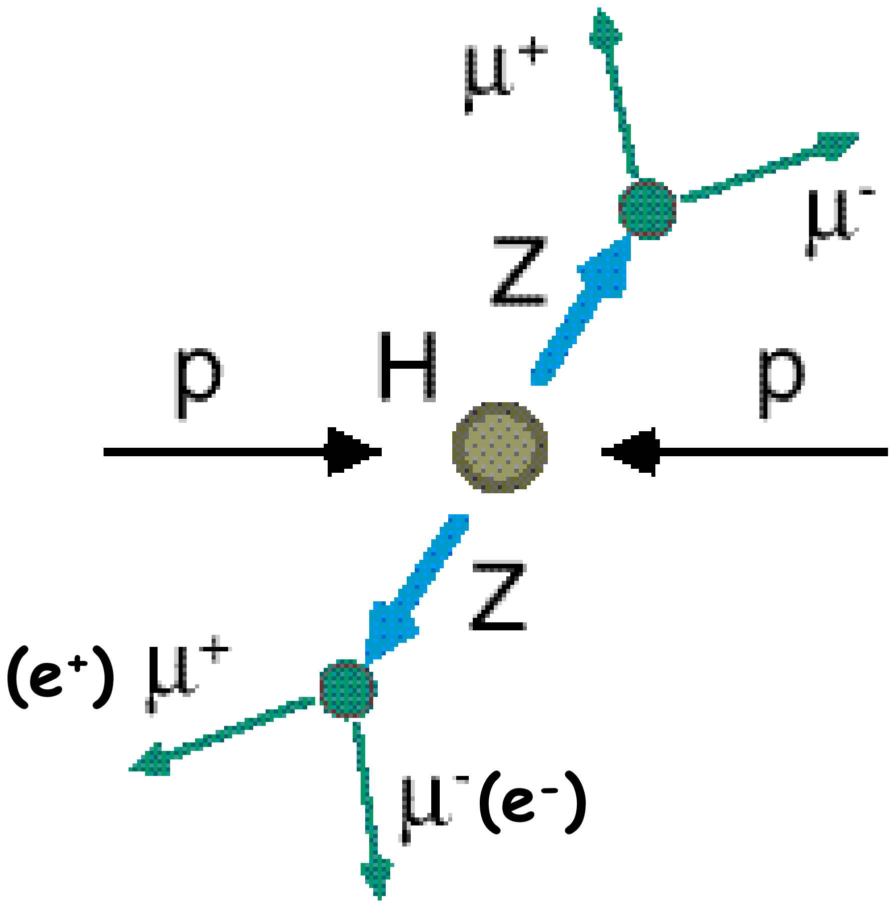


H(→ττ→ll) +1jets



Intermediate and Heavy Higgs:
(M_H>140 GeV) $H \rightarrow ZZ^{(*)} \rightarrow 4l$

Fully reconstruct
Higgs kinematics



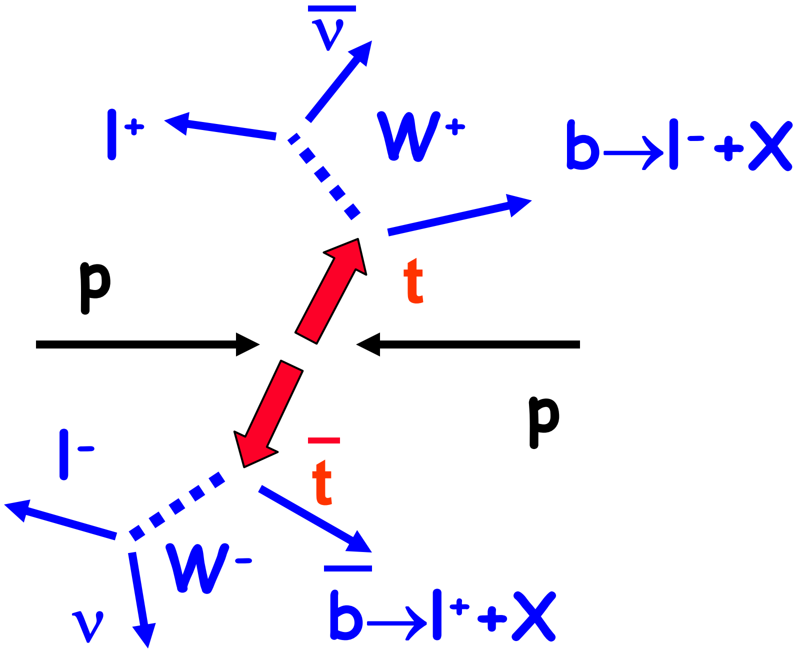
Outstanding issues

Lepton Identification
and Isolation

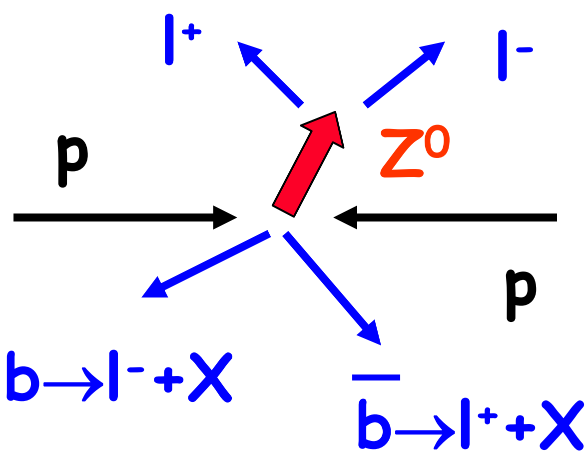
Suppression of
backgrounds coming
from tt and Zbb

Reducible Backgrounds

pp→tt→4l+X

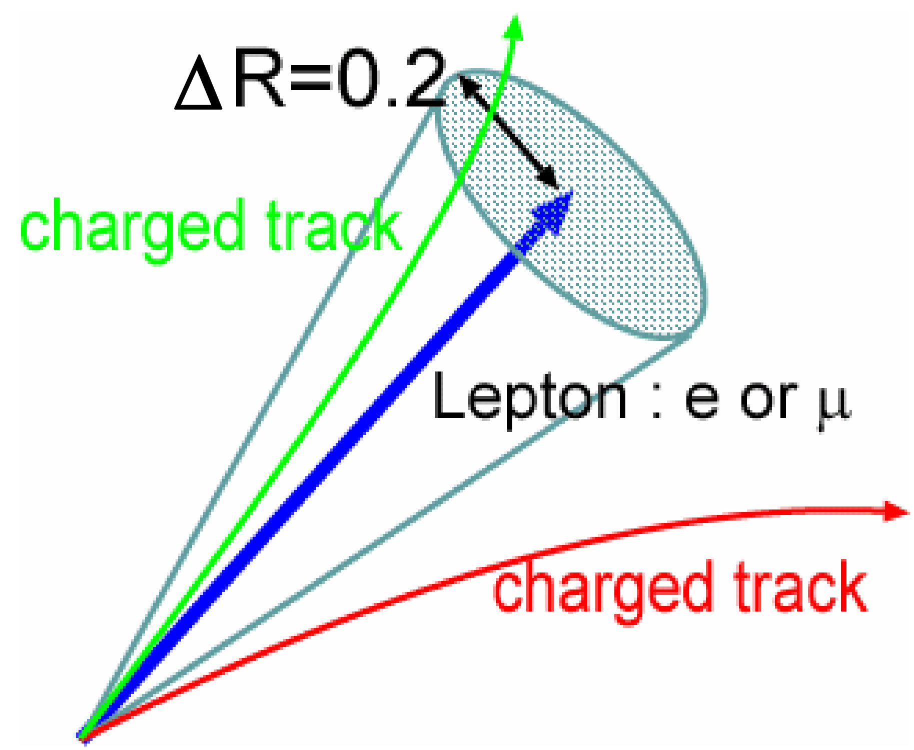


pp→Zbb→4l+X



- Suppress reducible backgrounds using combined information from calorimeter and tracking
- Left out with irreducible background (non-resonant pp→ZZ(*))

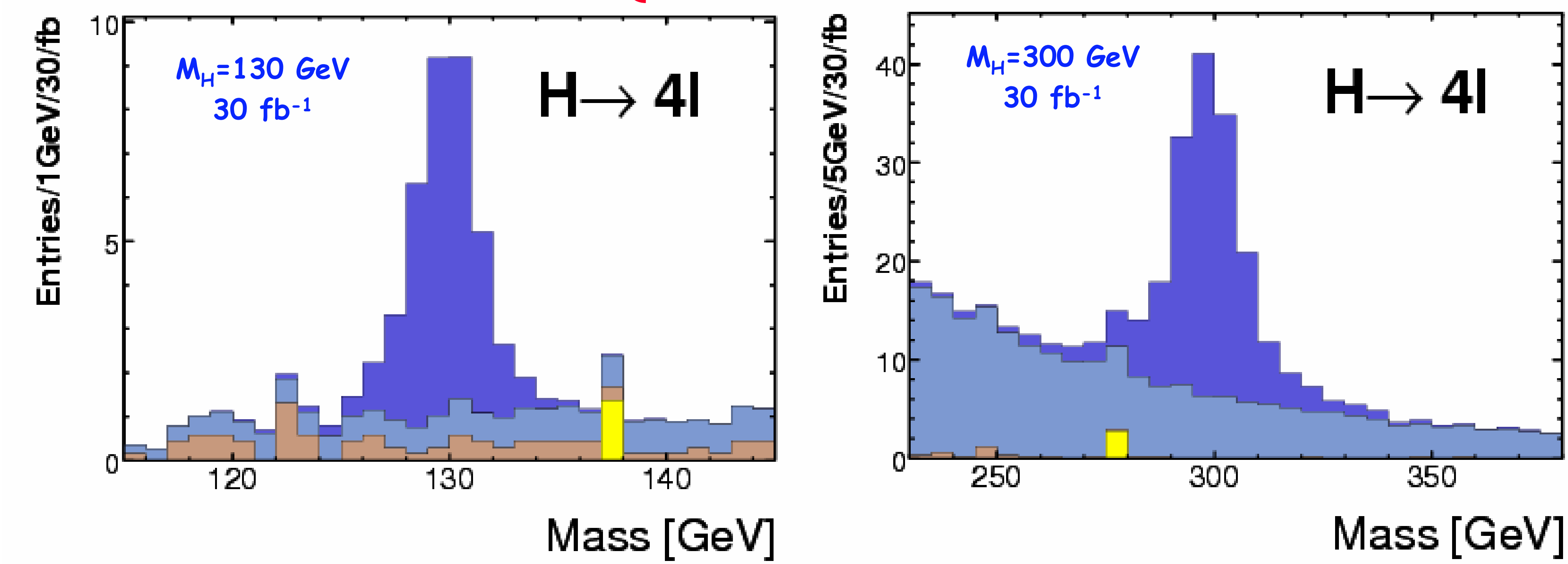
$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$



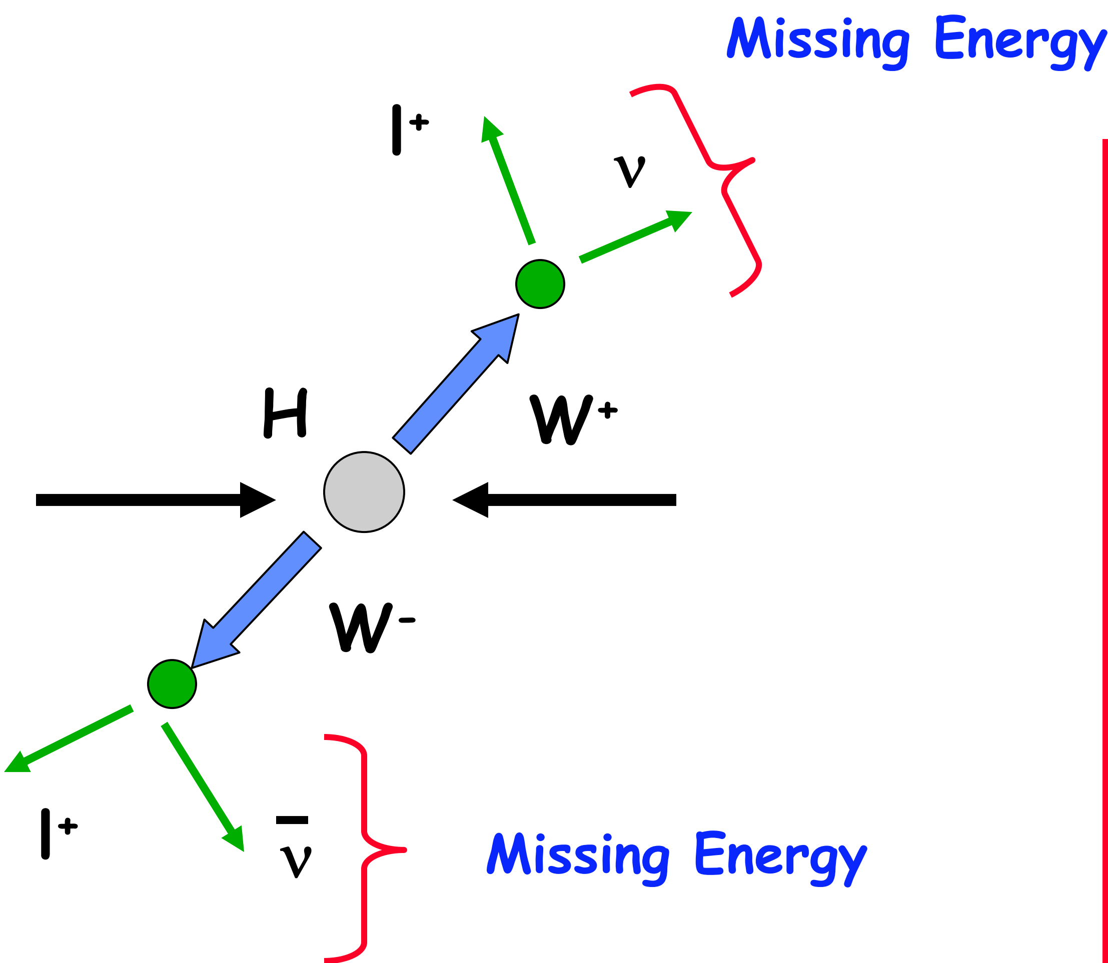
$H \to ZZ^{(*)} \to 4l$ event rates using for 30 fb^{-1} using NLO rates for signal and backgrounds.

Reducible background:
- $pp \to Zbb \to 4l$ (2 isolated leptons) + X
- $pp \to tt \to WWbb \to 4l$ (2 isolated leptons) + X

Irreducible background:
- $pp \to ZZ \to 4l$ (4 isolated leptons) + X



Intermediate mass Higgs: (140<M_H<200 GeV) $H \rightarrow WW^{(*)} \rightarrow 2l2\nu$



Outstanding issues

Extraction of tt and WW backgrounds

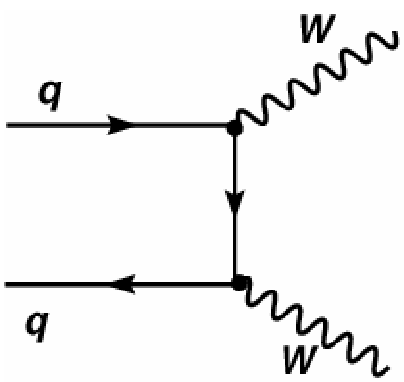
Splitting of phase space according to jet multiplicity

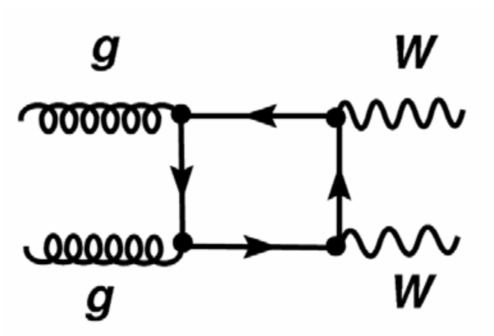
Lepton Identification and Isolation, Missing E_T

SM Higgs $H \to WW^{(*)} \to 2l2\nu$

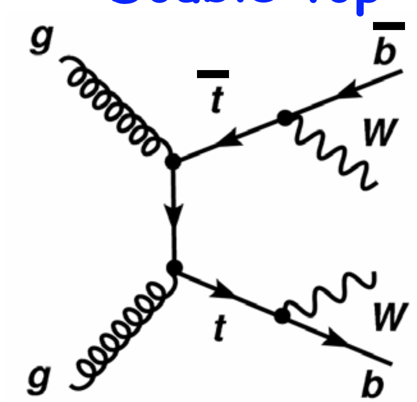
- Strong potential due to large signal yield, but no narrow resonance. Left with broad transverse mass spectrum
  - Combined H+0,1,2jet analysis strongly improves sensitivity

Backgrounds: $pp \to WW+X$

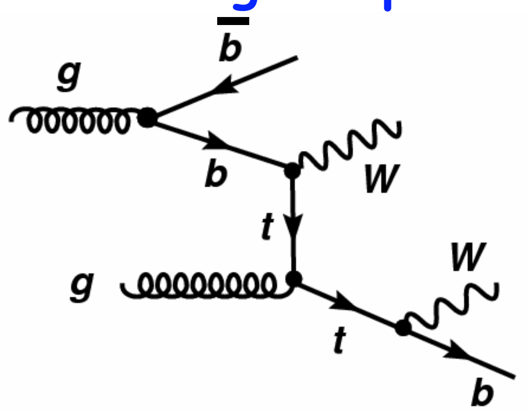


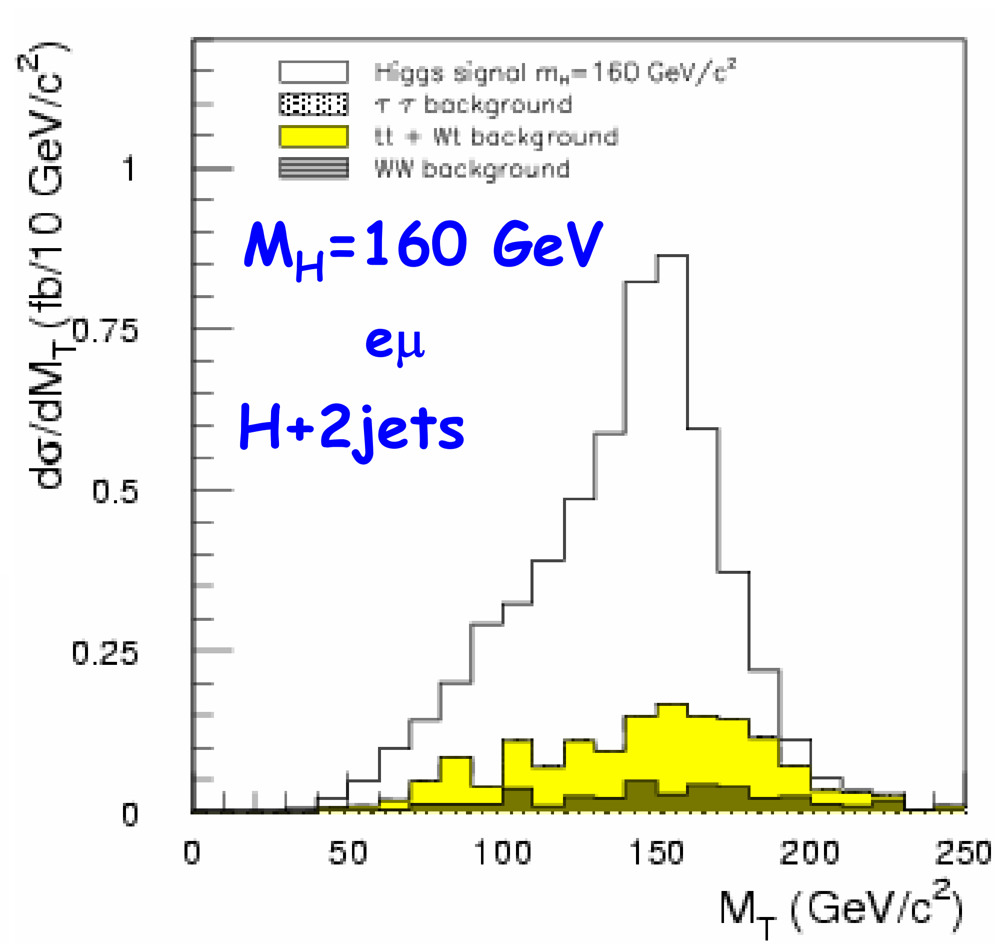


Double top



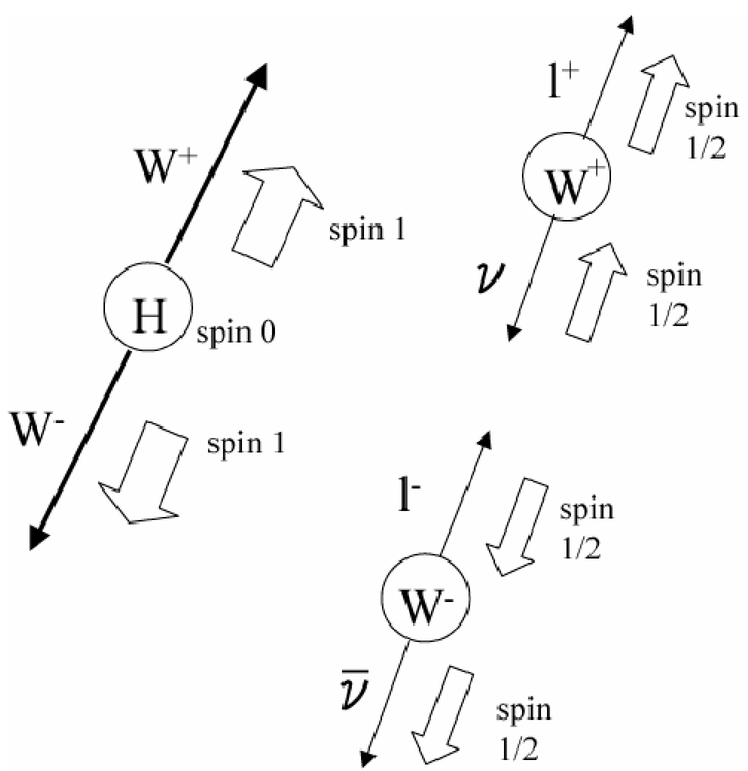
Single top

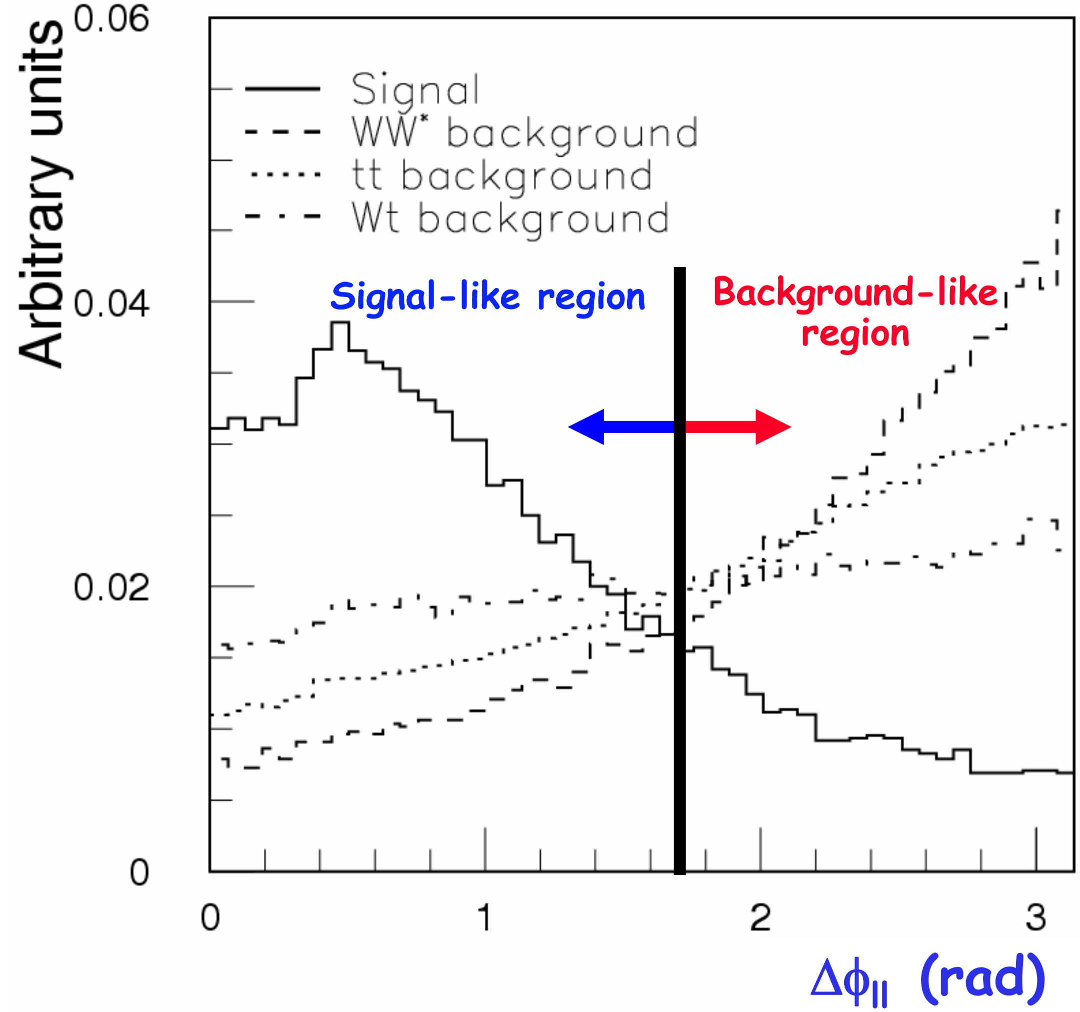




Control Samples for H→WW(*)

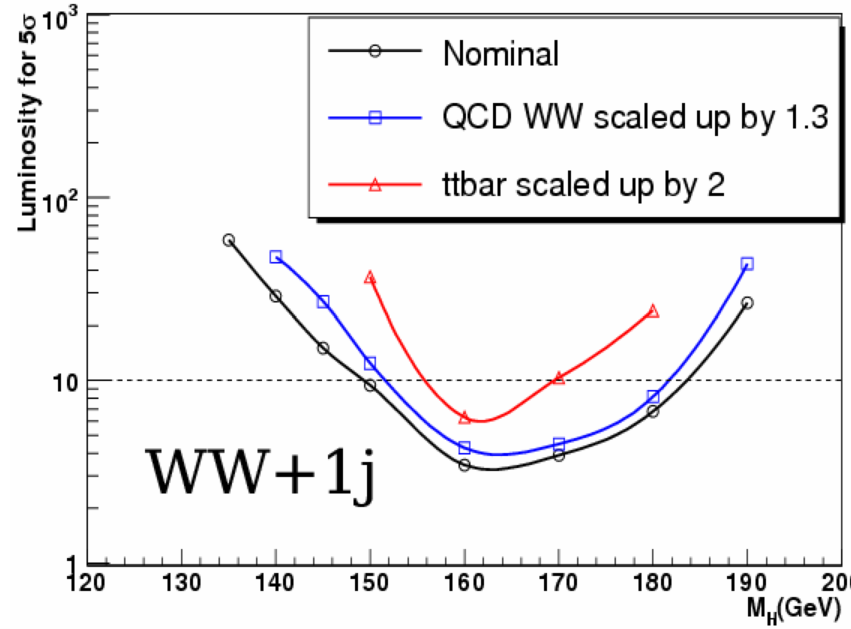
- Since Higgs is a spin-0 particle, decay leptons tend to be close to each other. Exploit it to define control samples for background extraction

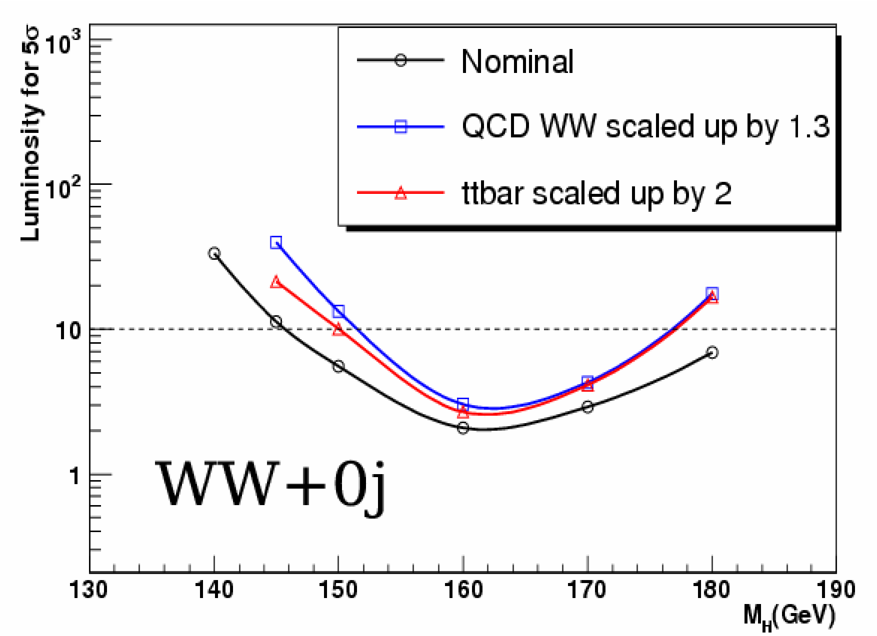


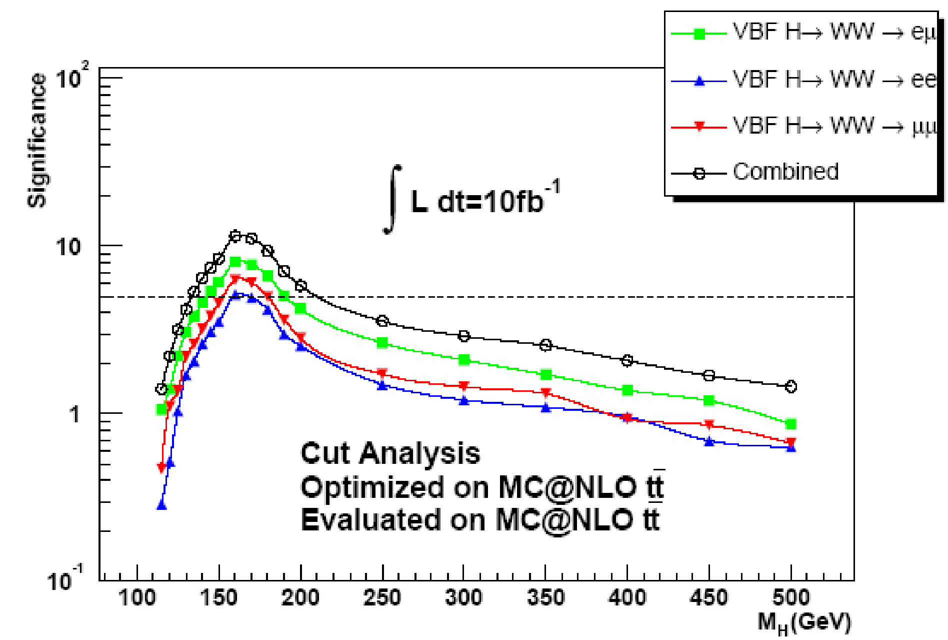


SM H→WW +0,1,2 jets

- Defined three independent analysis, depending on the number of tagged jets
  - ➢Systematic errors added in significance calculation







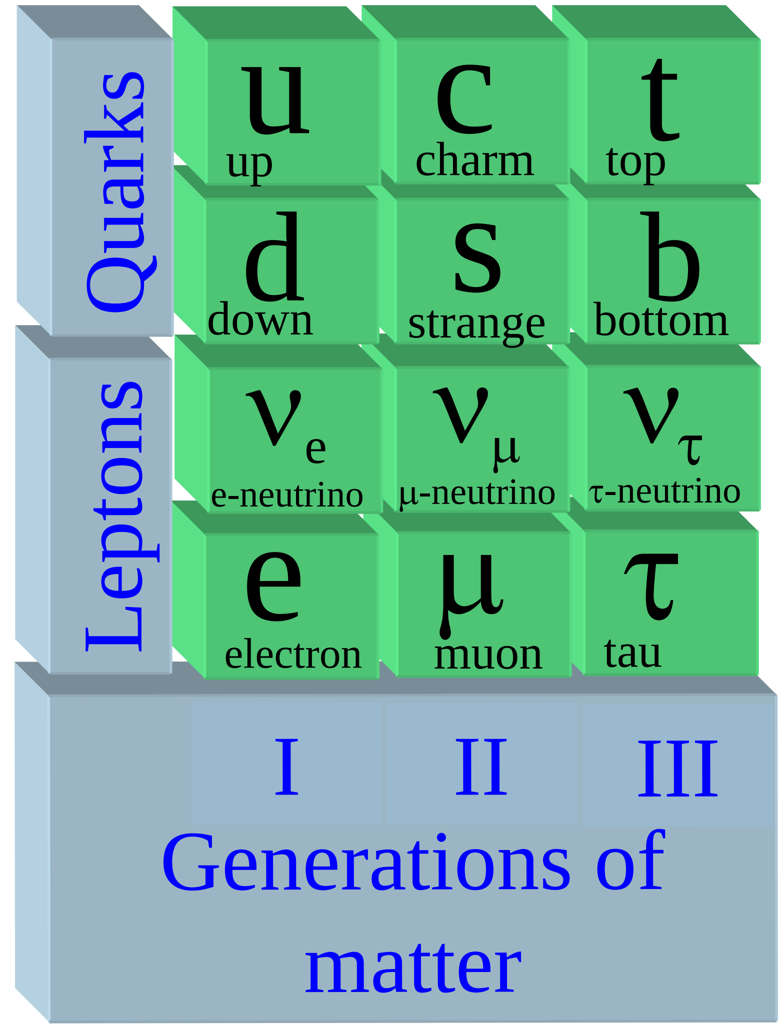
Outlook and Conclusions

- The Standard Model (SM) a successfully describes the world of particle physics
  - However, the particle responsible to giving mass to particles has not been discovered yet!
- The LHC will be the energy frontier accelerator: expert first proton-proton collisions in summer 2007
  - The LHC will produce heavy particles (such as the Higgs boson) at rates orders of magnitude greater than in predecessor accelerators
  - The LHC era may be a revolution in particle physics!
- ATLAS and CMS are multi-purpose detectors with great and similar capabilities. If the SM Higgs exists it will be observed with less than 10 fb^{-1} of understood data

Additional Slides

Building Blocks of Matter in the Standard Model

- Quarks and leptons are organized in families or generations of matter
  - So far we observe three generations (I, II ,II)
    - Second and third generations are copies of the first, only much heavier
  - All have intrinsic angular momentum (spin) of ½ (fermions)
- All particles have anti-particles
  - Display same mass and spin
  - Opposite electric charge



Forces in Nature

- We believe Nature displays three levels of interactions

Strength	Force	Example
1	Strong	Nuclear interactions
10^{-3} - 10^{-5}	Electro-Weak	Molecular interactions, chemistry Beta decay
10^{-36}	Gravitation	Apple falling

- New particles are being discovered as predicted in the Standard Model

Year	Particle	Lab
1974	c quark	BNL & SLAC
1975	τ lepton	SLAC
1977	b quark	FermiLab
1979	gluon	DESY
1983	W,Z	CERN
1994	t quark	FermiLab

Force Carriers (gluon, W,Z)

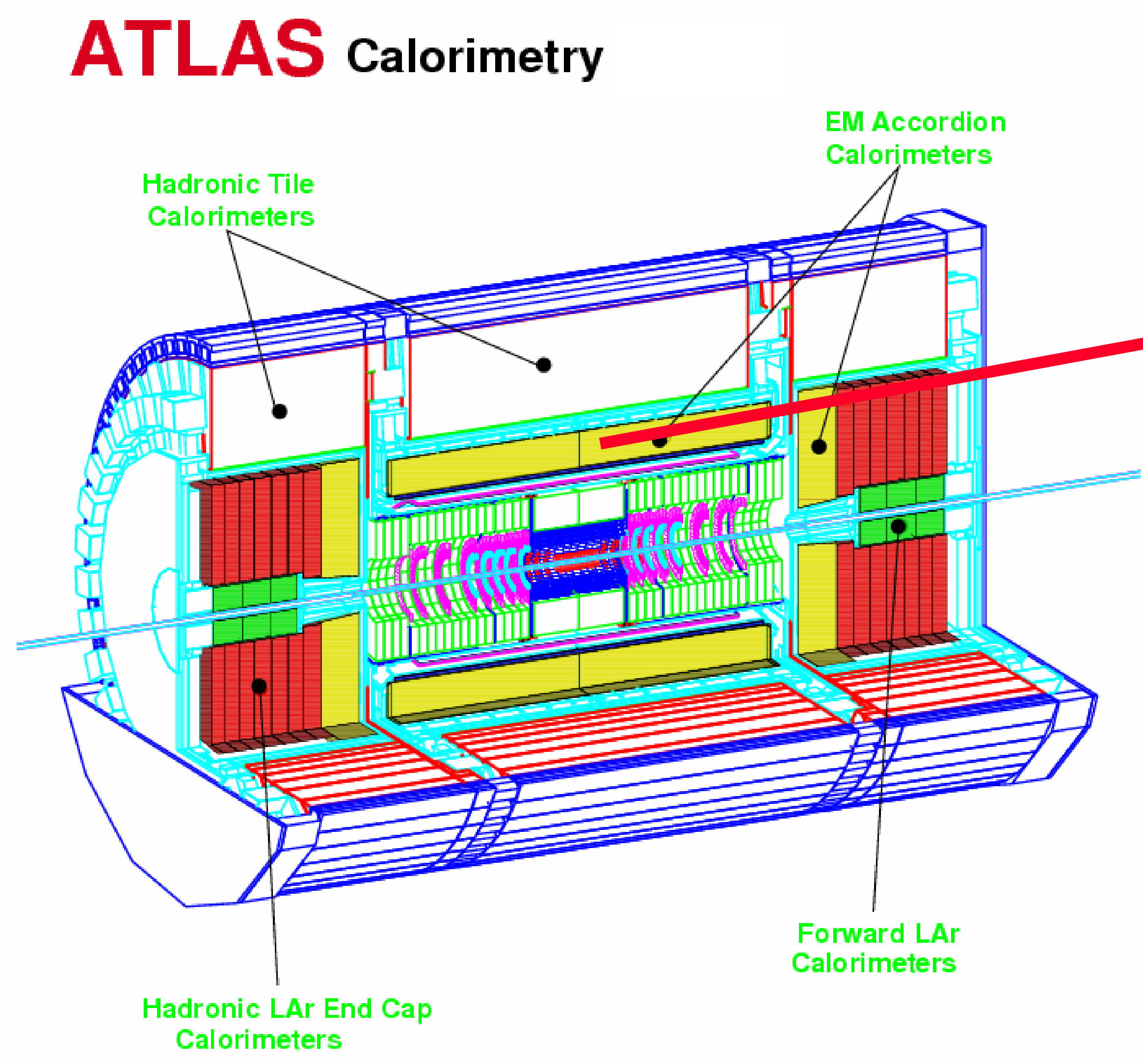
- The Standard Model is very successful BUT:

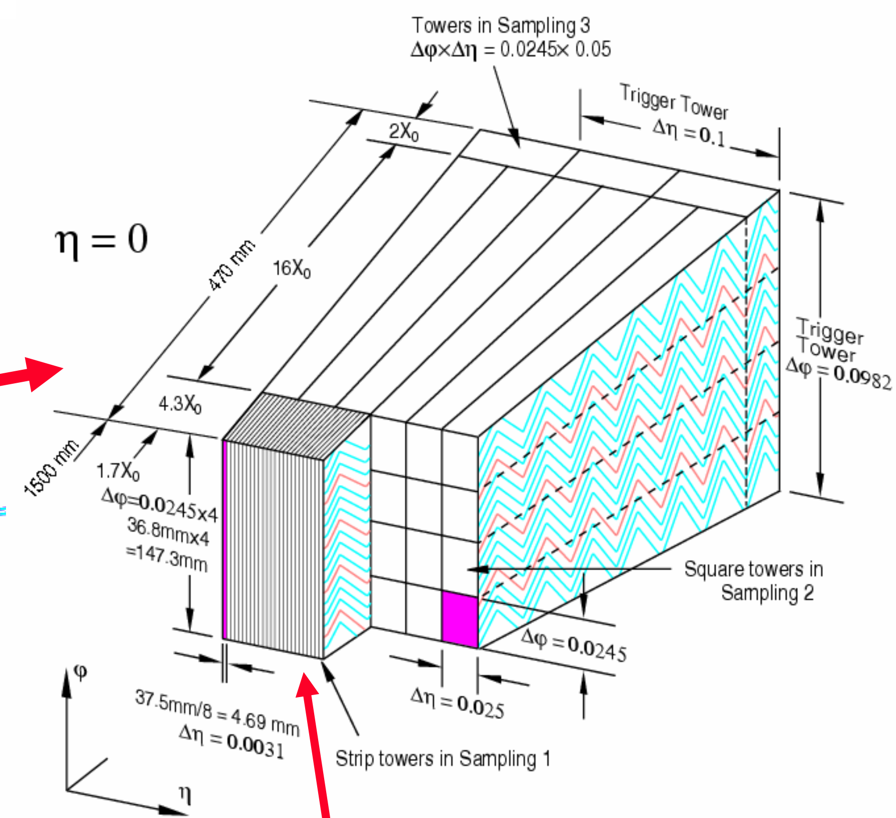
The Higgs boson has yet to be found!

We need to explain the masses!

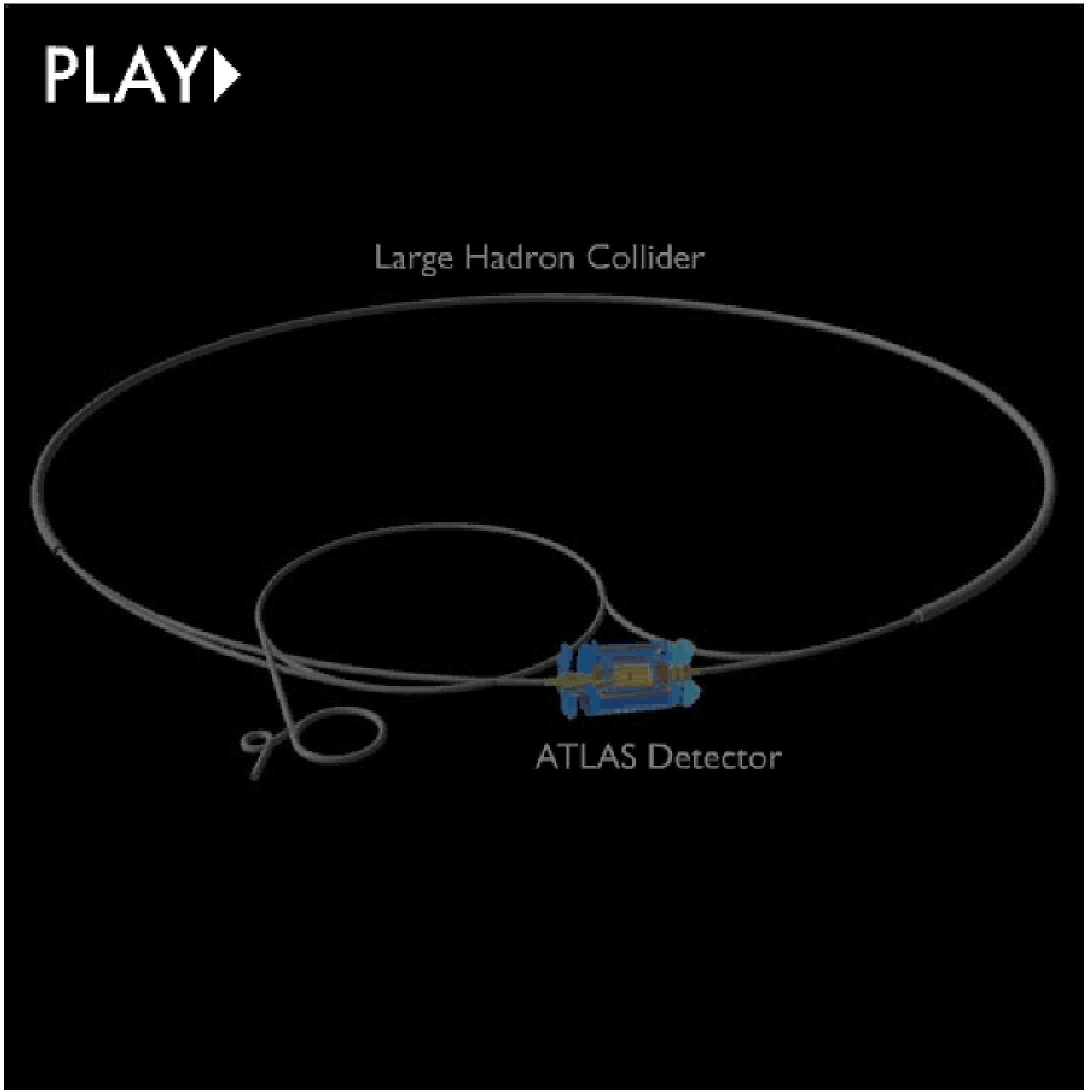
ATLAS has excellent calorimeters

- Excellent resolution and linearity for electrons, photons, hadrons
- Powerful particle identification and isolation





Fine segmentation (specially in the first layer) is a very powerful tool to identify and isolate electrons and photons



particle_event_full_ns

Particle Detection

- In order to observe the Higgs boson or any other new particle we need to detect their decay products

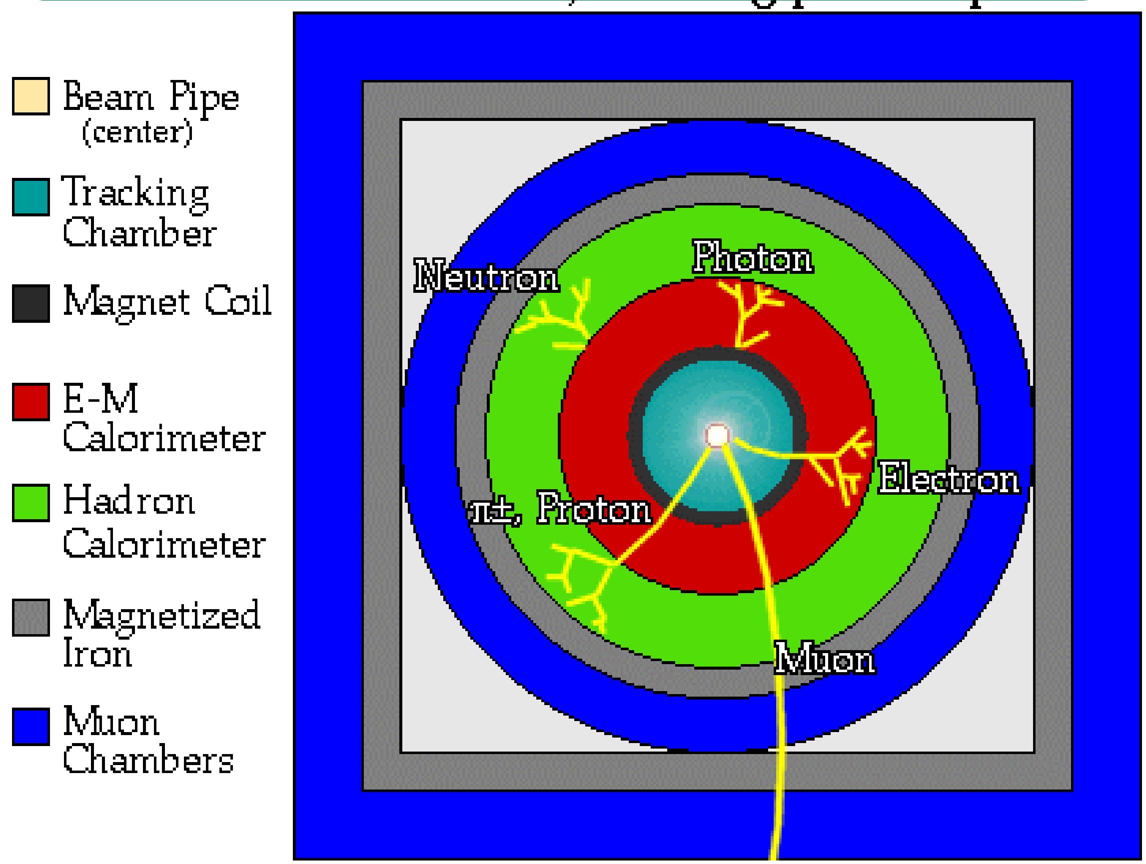
Exploit the fact that different particles interact with matter differently

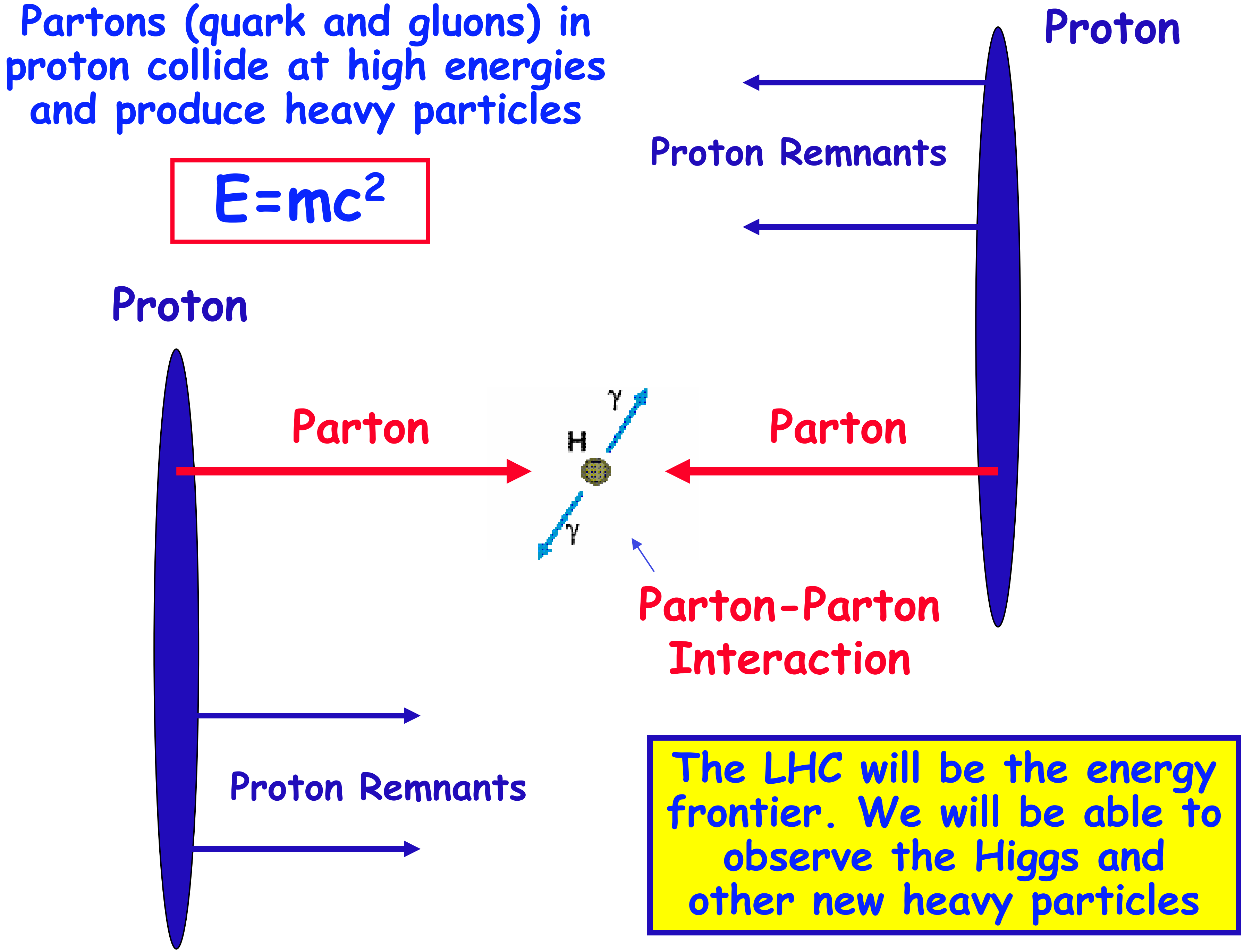
Measure momentum/energy of particles

+

Identify electrons, photons, muons, taus and hadrons

A detector cross-section, showing particle paths

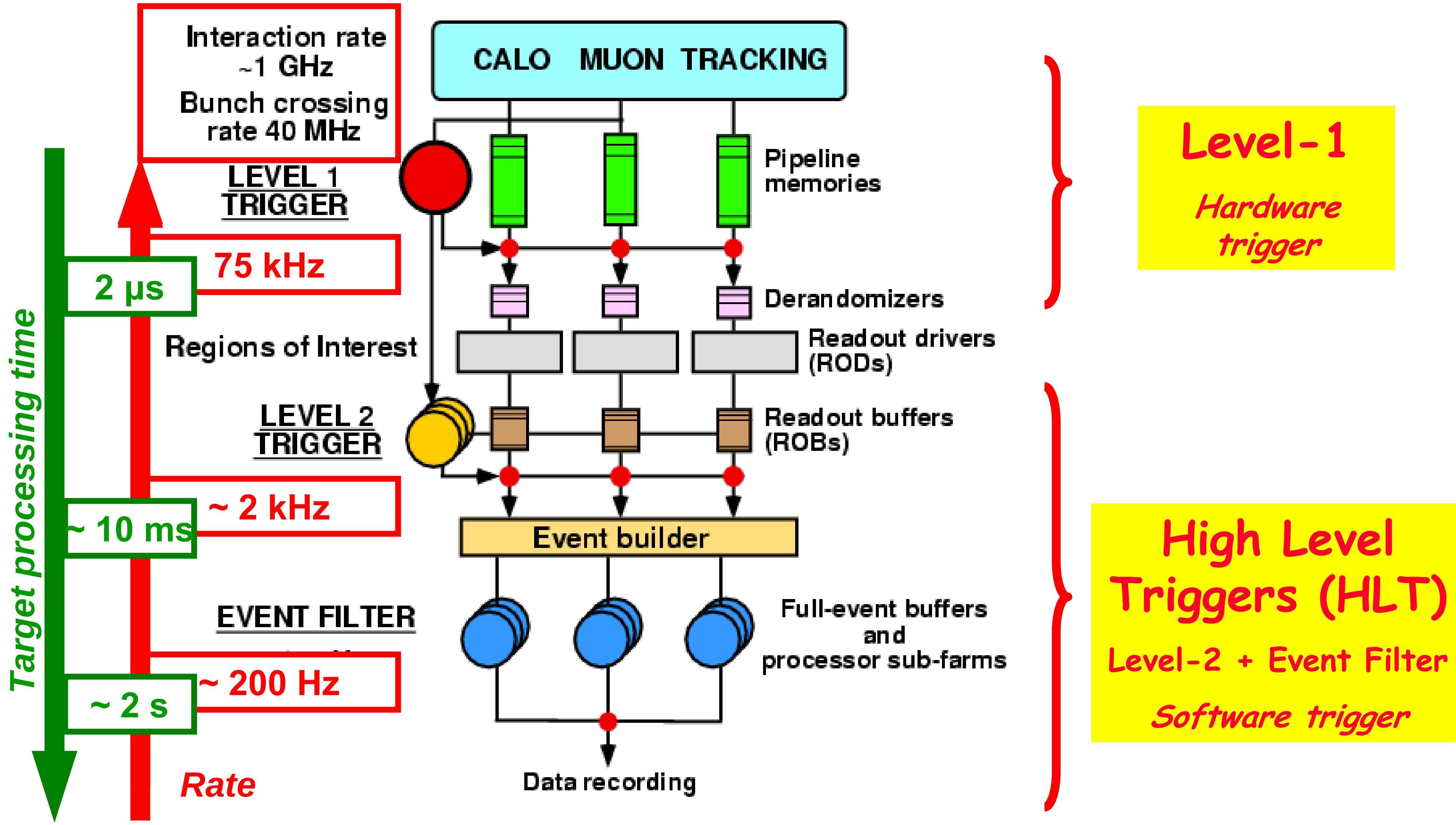




Partons (quark and gluons) in proton collide at high energies and produce heavy particles
E=mc^2
Proton
Proton Remnants
Proton
Parton
γ
H
γ
Parton
Parton-Parton Interaction
Proton Remnants
The LHC will be the energy frontier. We will be able to observe the Higgs and other new heavy particles

The ATLAS Trigger System

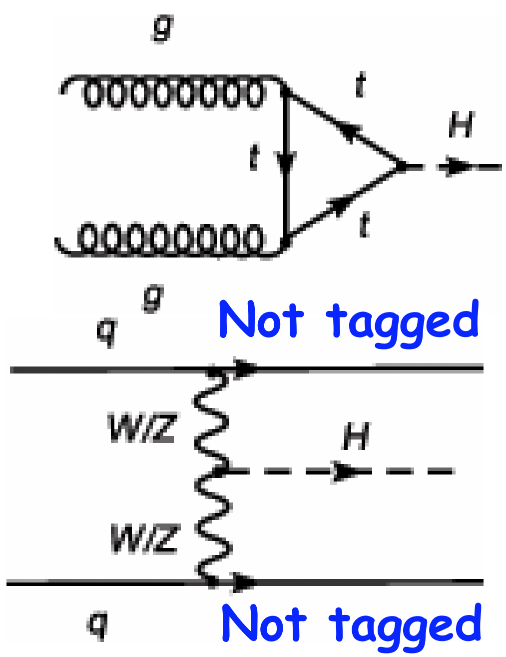
- Trigger is crucial: reduce 1 GHz interaction rate (~2 Pb/sec) to ~200 Hz (~400 Mb/sec) which can be handled by today's computing technology



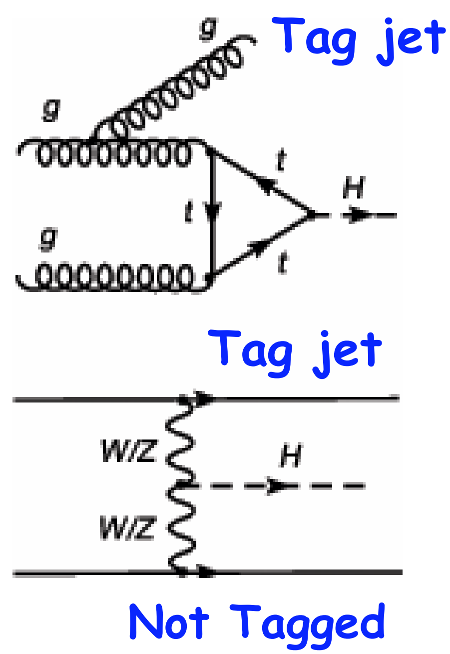
Low Mass Higgs Associated with Jets

- A lot of progress since ATLAS Physics Technical Design Report (TDR 1999), mostly from the addition of H+jets channels
  - Slicing phase space in regions with different S/B is more optimal when inclusive analysis has little S/B

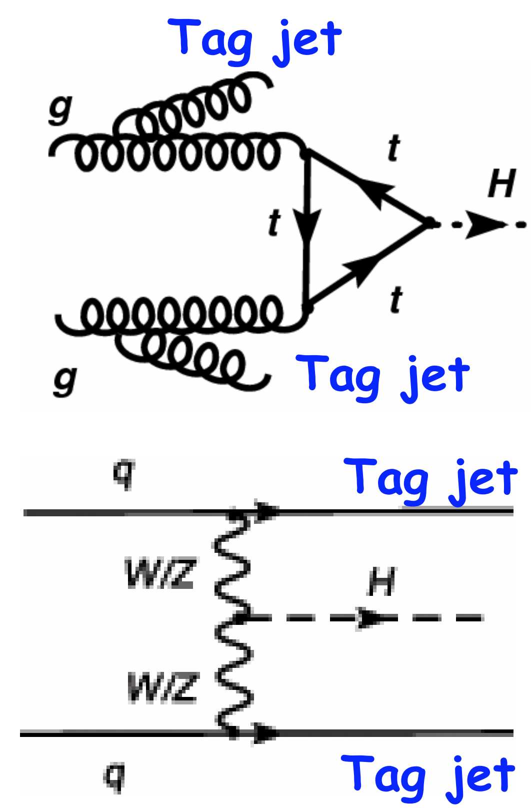
H+0jet



H+1jet



H+2jet



Analysis Strategy

- Concentrate on the most powerful analyses

Higgs Boson Search

$114 < M_H < 140$ GeV
(low mass)

$H \rightarrow \gamma\gamma$
(+0,1,2 jets)

$H \rightarrow \tau\tau$
(+1,2 jets)

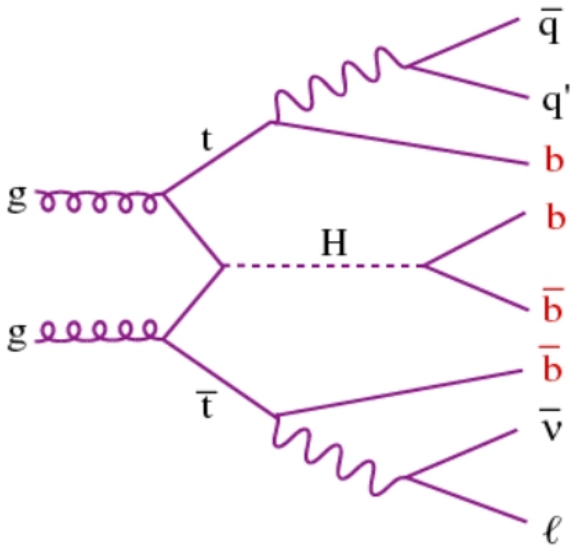
$M_H > 140$ GeV
(intermediate and heavy)

$H \rightarrow WW^{(*)} \rightarrow ll\nu\nu$
(+0,1,2 jets)

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

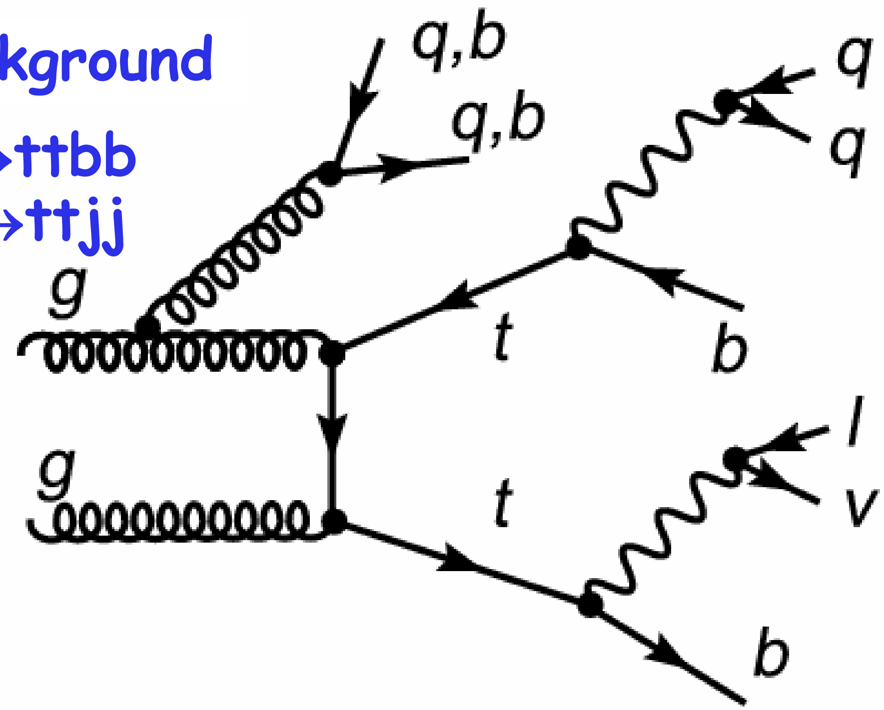
Complex final state: ttH(→bb)→lepton+ν+bbbb+jj

Signal



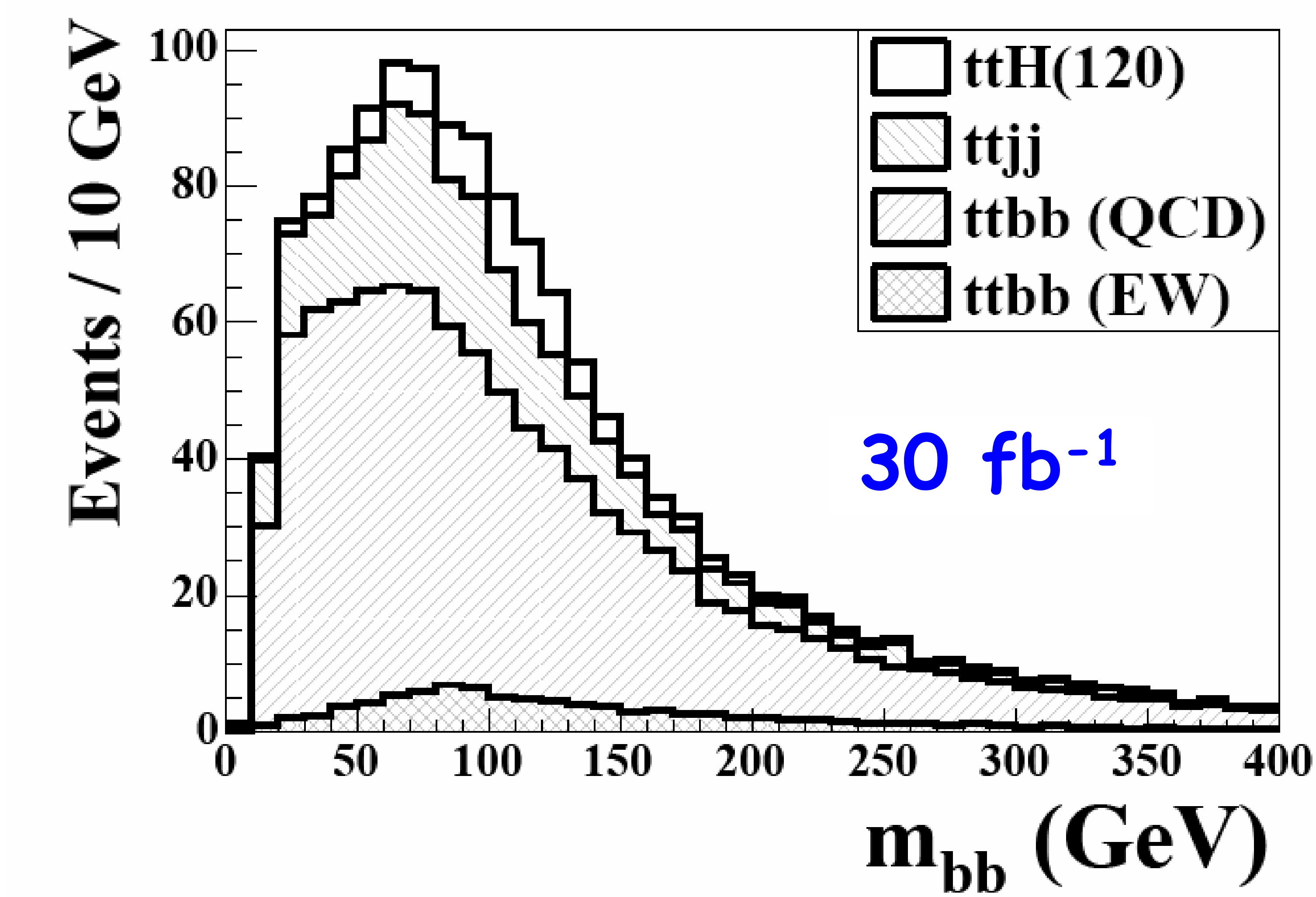
Background

pp→ttbb
pp→ttjj



- Analysis very sensitive to b-tagging efficiency (ε_b^4)
  - Parton/Hadron level studies → $\varepsilon_b \geq 60\%$ needed
- Need ~100 times rejection against light jets and ~10 times against charm to suppress ttjj

- May achieve 3-5σ effect for M_H=120 GeV and 30 fb^{-1}
  - Need to address issues related to background shapes and differences in hadronic scales for light and b-jets



From my talk at Higgs session of TEV4LHC 17/09/04

Two independent ways of extracting $Z \rightarrow \tau\tau$ shape

Control Sample 1

$Z \rightarrow ee, \mu\mu$

Loose cuts on Jets

MC extrap. is validated →

Control Sample 3

$Z \rightarrow ee, \mu\mu$

Tight cuts on Jets

$85 < M_{ll} < 95$ GeV

↓ Replace $Z \rightarrow ee, \mu\mu$ by $Z \rightarrow \tau\tau$

Control Sample 2

$Z \rightarrow \tau\tau$

Loose cuts on Jets

MC extrap. →

Signal Region

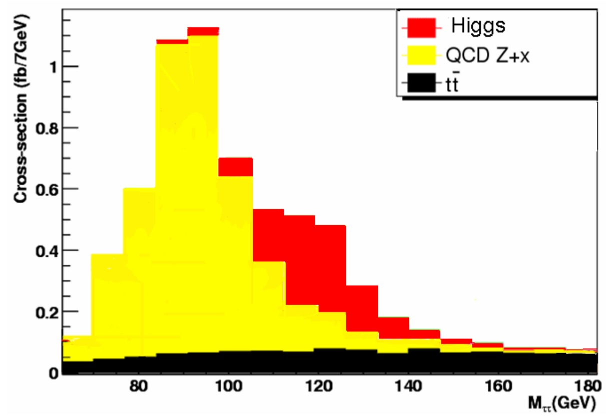
$Z \rightarrow \tau\tau$

Tight cuts on Jets

$M_{ll} < 75$ GeV

M_{HJ} →

Determine shape and normalization of $Z \rightarrow \tau\tau$ background



Shape of $M_{\tau\tau}$ in $Z\rightarrow\tau\tau$ (Method I)

- All cuts are kept the same except for the invariant mass of the Higgs candidate and the tagging jet
  - Assume electrons, muons, jets and missing E_T have been calibrated with $Z\rightarrow ee,\mu\mu$
  - Jet activity in MC is validated with $Z\rightarrow ee,\mu\mu$
    - Go from Box 1 to Box 3
  - Use MC to obtain $M_{\tau\tau}$ shape in signal-like region

Shape of $M_{\tau\tau}$ in $Z\rightarrow\tau\tau$ (Method II)

- Use data with $Z\rightarrow ee,\mu\mu$ and apply same cuts on jets as in the signal-like region.
- Remove the two electrons/muons (both calorimeter and tracking) and replace them with τ's, which have the same momenta
  - Needs to be tested with full simulation at ATLAS

Control Sample 3

$Z\rightarrow ee,\mu\mu$

Tight cuts on M_{HJ}

Replace $Z\rightarrow ee,\mu\mu$ by $Z\rightarrow\tau\tau$

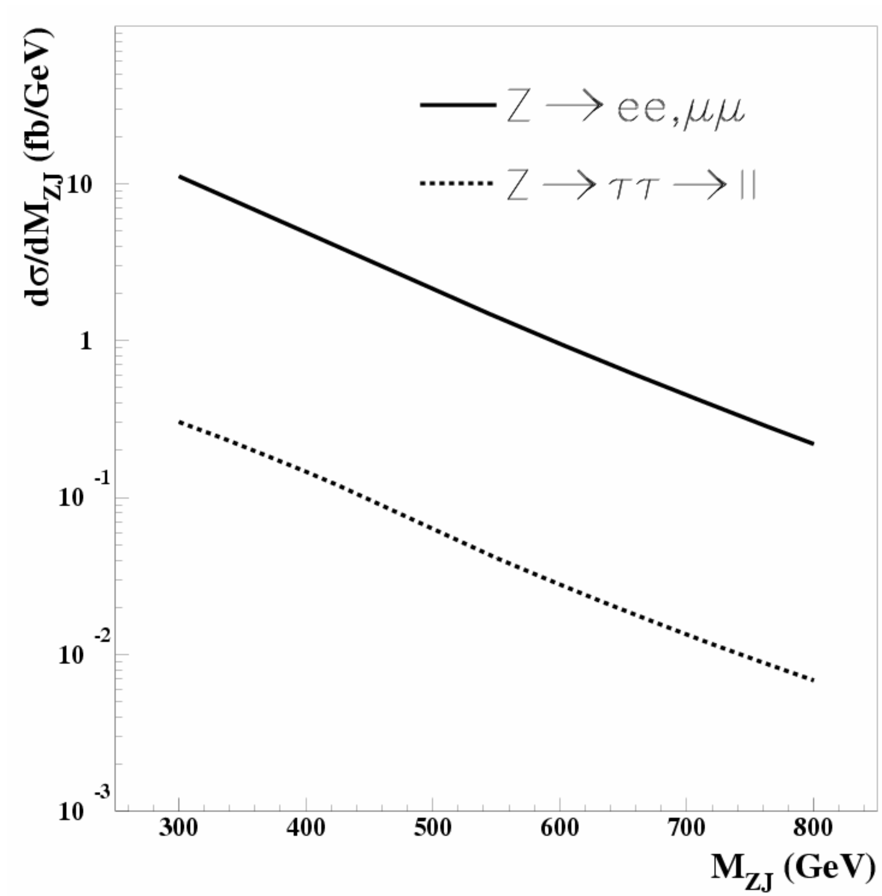
Signal Region

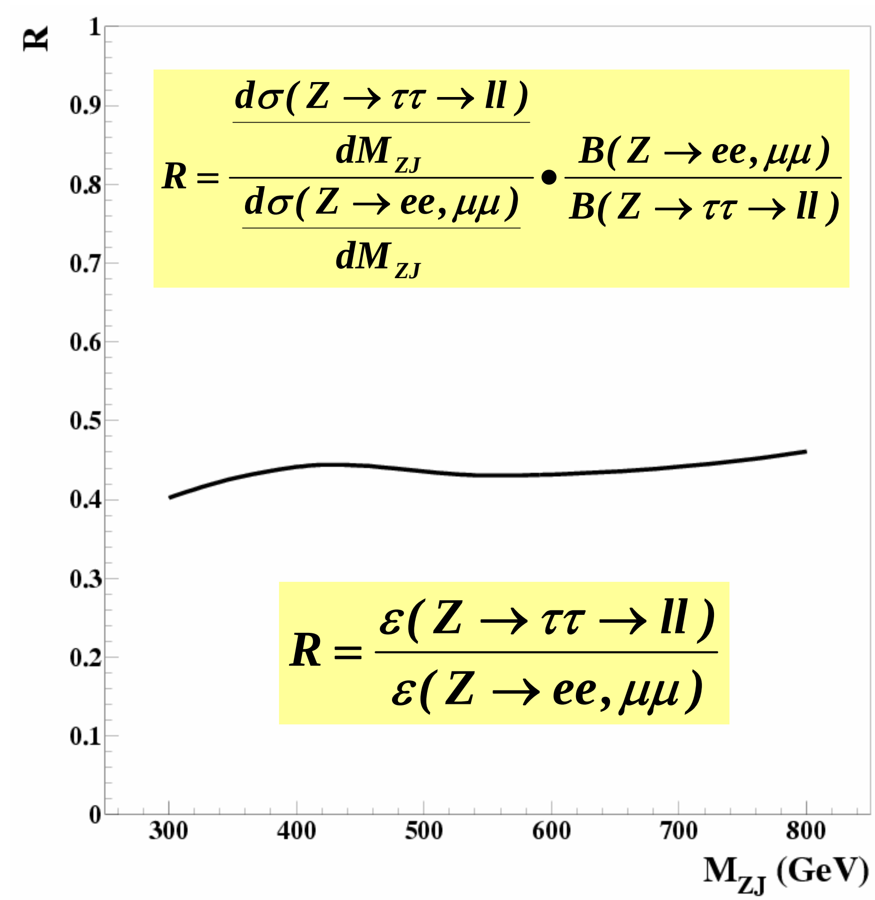
$Z\rightarrow\tau\tau$

Tight cuts on M_{HJ}

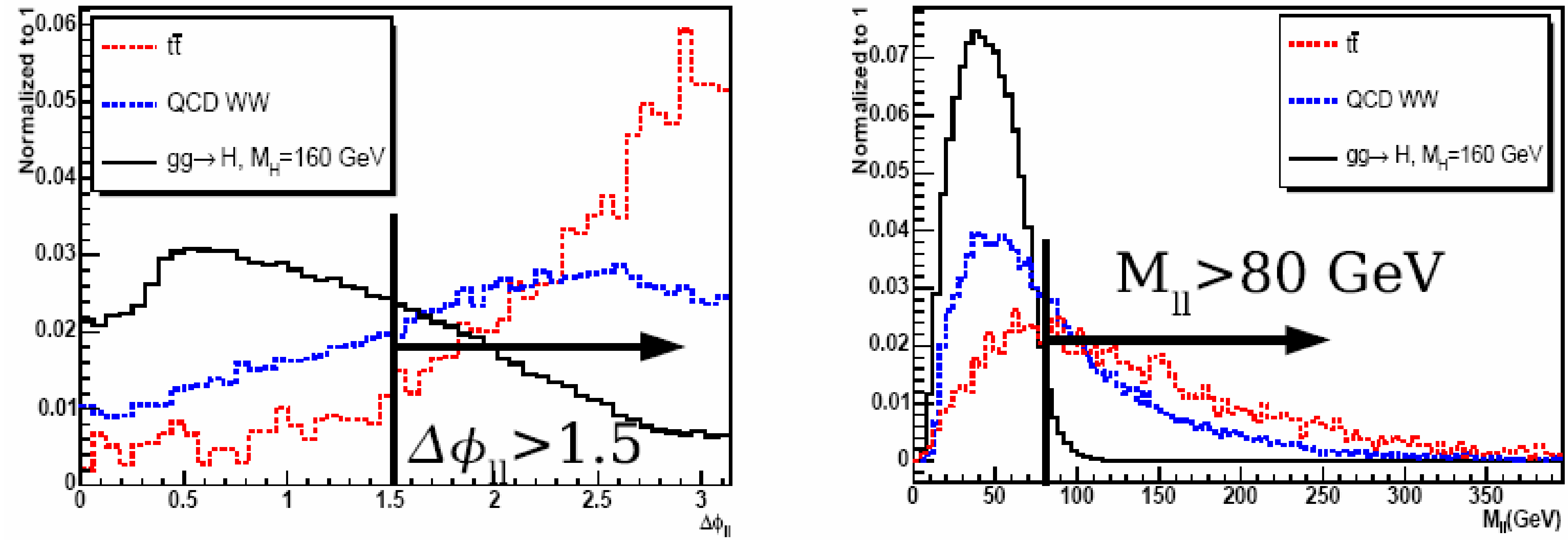
Normalization of $Z \rightarrow \tau\tau$ using $Z \rightarrow ee, \mu\mu$

- $Z \rightarrow ee, \mu\mu$ offers about 35 times more statistics w.r.t to $Z \rightarrow \tau\tau \rightarrow ll$
  - Ratio of efficiencies depends weakly with M_{HJ} and can be easily determined with MC after validation with data



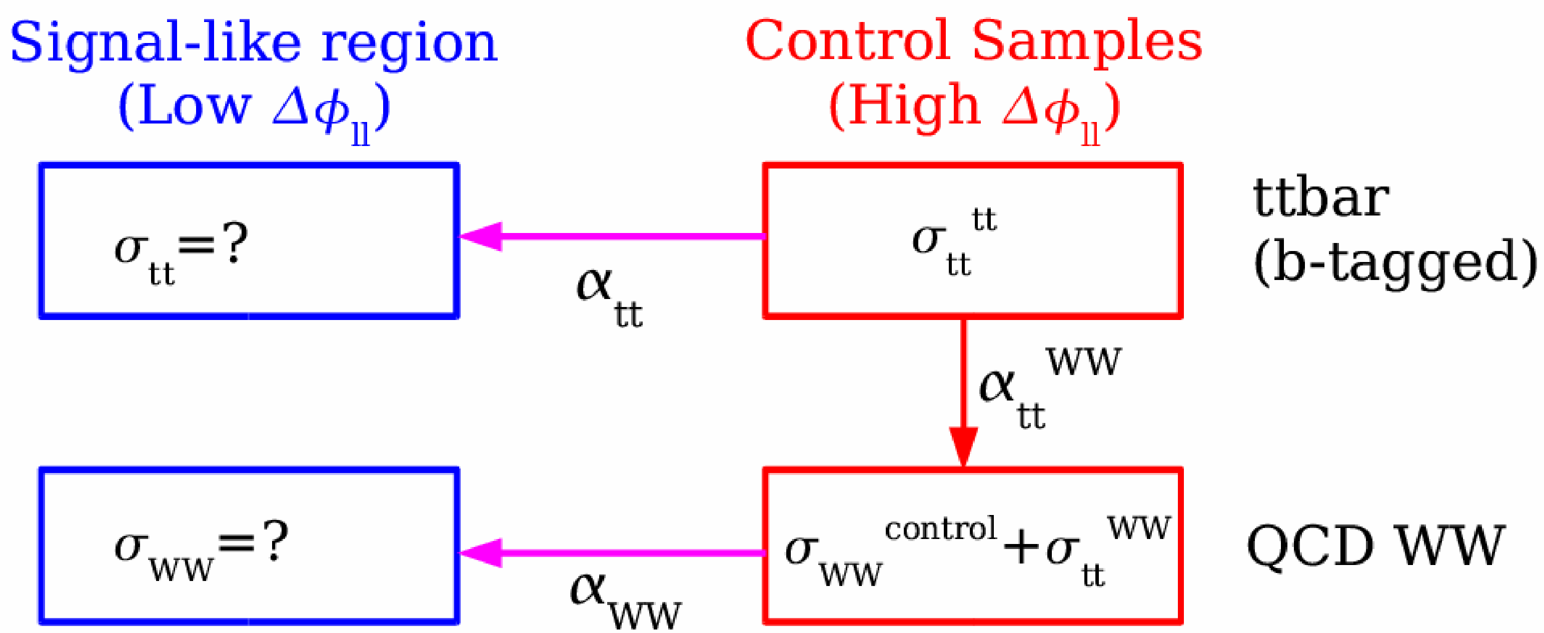


Control Samples for $H\rightarrow WW^{(*)}$



- Main control sample is defined with two cuts
  - $\Delta\phi_{ll}>1.5$ rad. and $M_{ll}>80$ GeV
- Because of tt contamination in main control sample, need b-tagged sample (M_{ll} cut is removed)

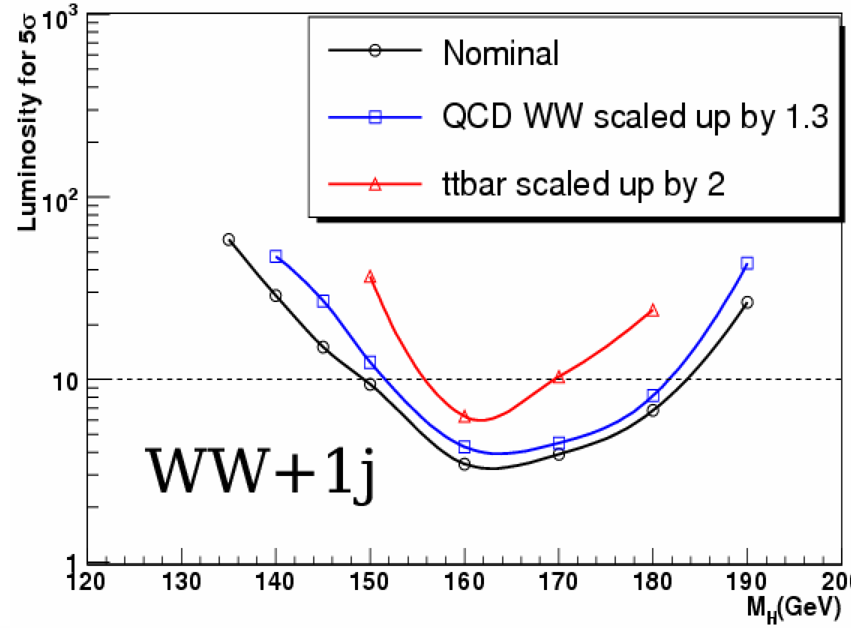
Control Samples for H→WW

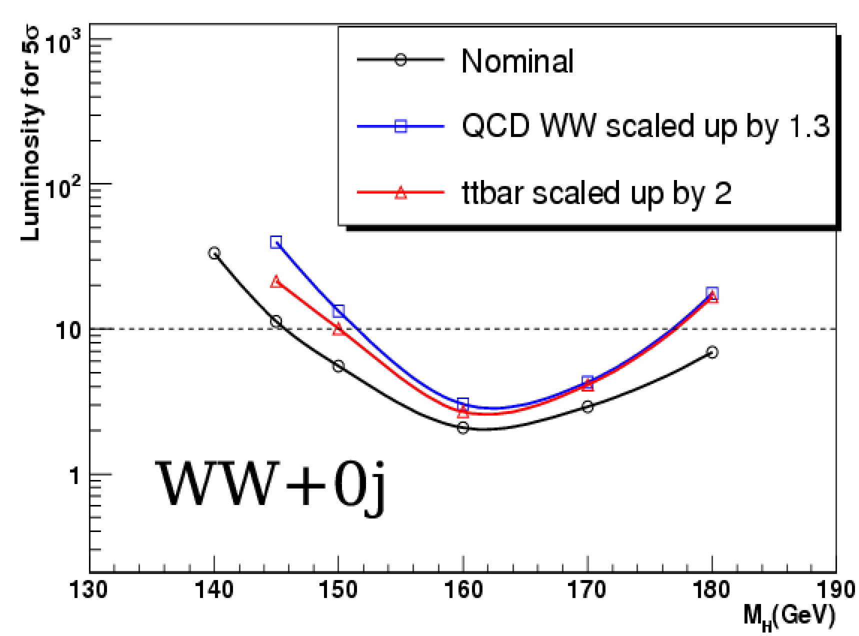


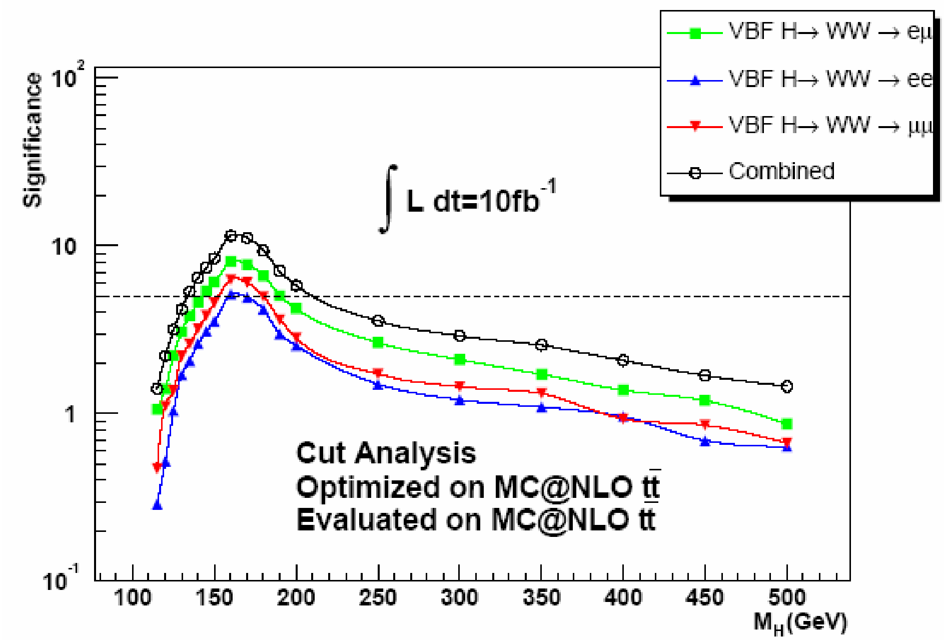
- **Define:**
  - α_{WW}=(QCD WW bg)/(QCD WW in control samp.)
  - α_{tt}=(tt bg)/(tt in b-tagged control sample)
  - α_{tt}^{WW}=(tt in WW sample)/(tt in b-tagged sample)

SM H→WW +0,1,2 jets

- Defined three independent analysis, depending on the number of tagged jets
  - ➢Systematic errors added in significance calculation







Summary of Detector Performance Requirements (ATLAS)

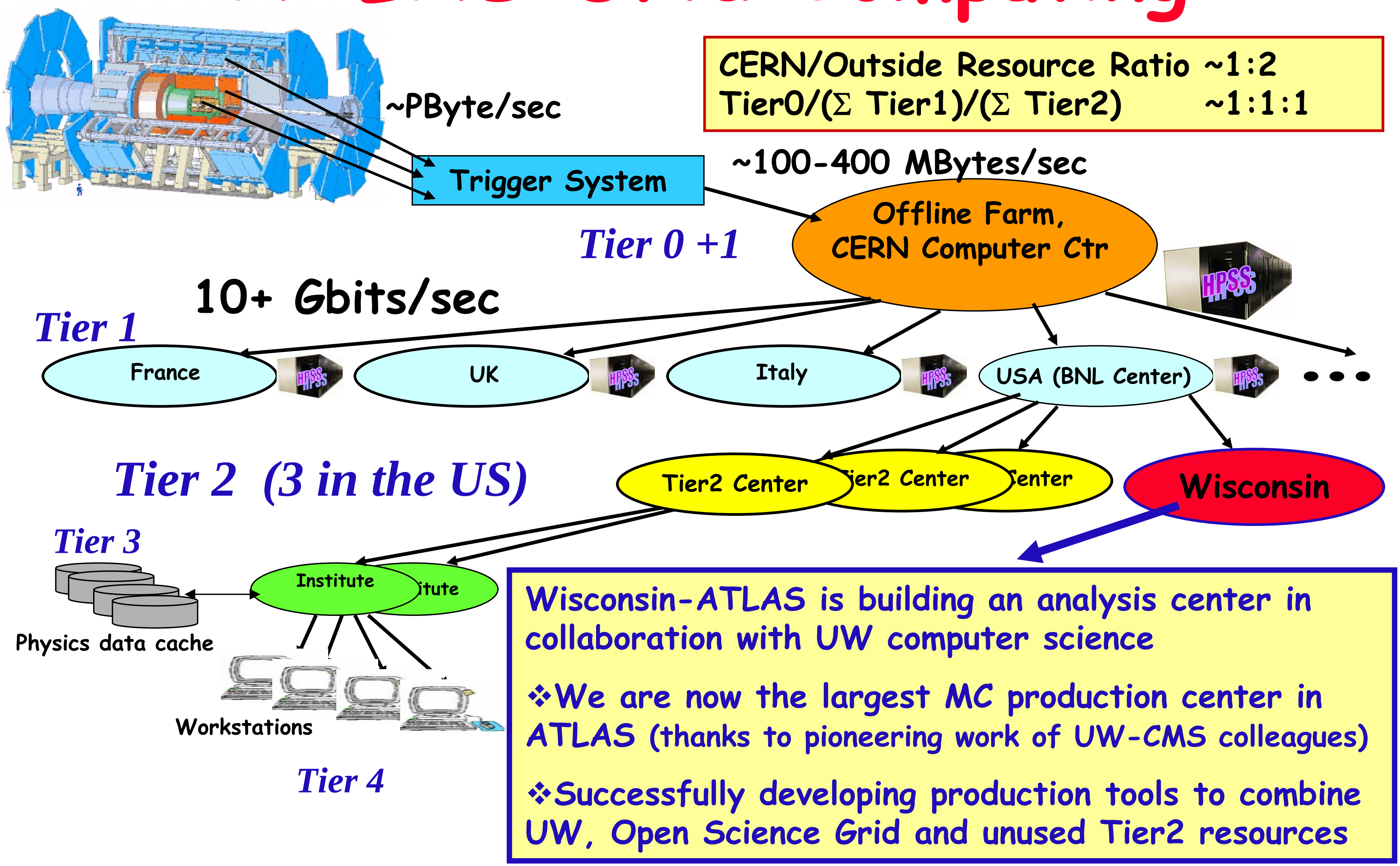
- Combination of multiple channels will require a certain understanding of all signatures and sub-detectors
  - One fb^{-1} of usable data (or less) will be needed for calibration

$H \rightarrow \gamma\gamma$ (+0,1,2 jets)	$100 < M_H < 150$	γ calibration ($c_{tot} < 0.7\%$) γ/jet separation (>1000 rejection for quark jets for $\varepsilon_\gamma = 80\%$)
ttH, $H \rightarrow bb$	$80 < M_H < 130$	b-tagging ($\varepsilon_b = 60\%$, 100/10 rejection against light/c jets) extraction of background shape

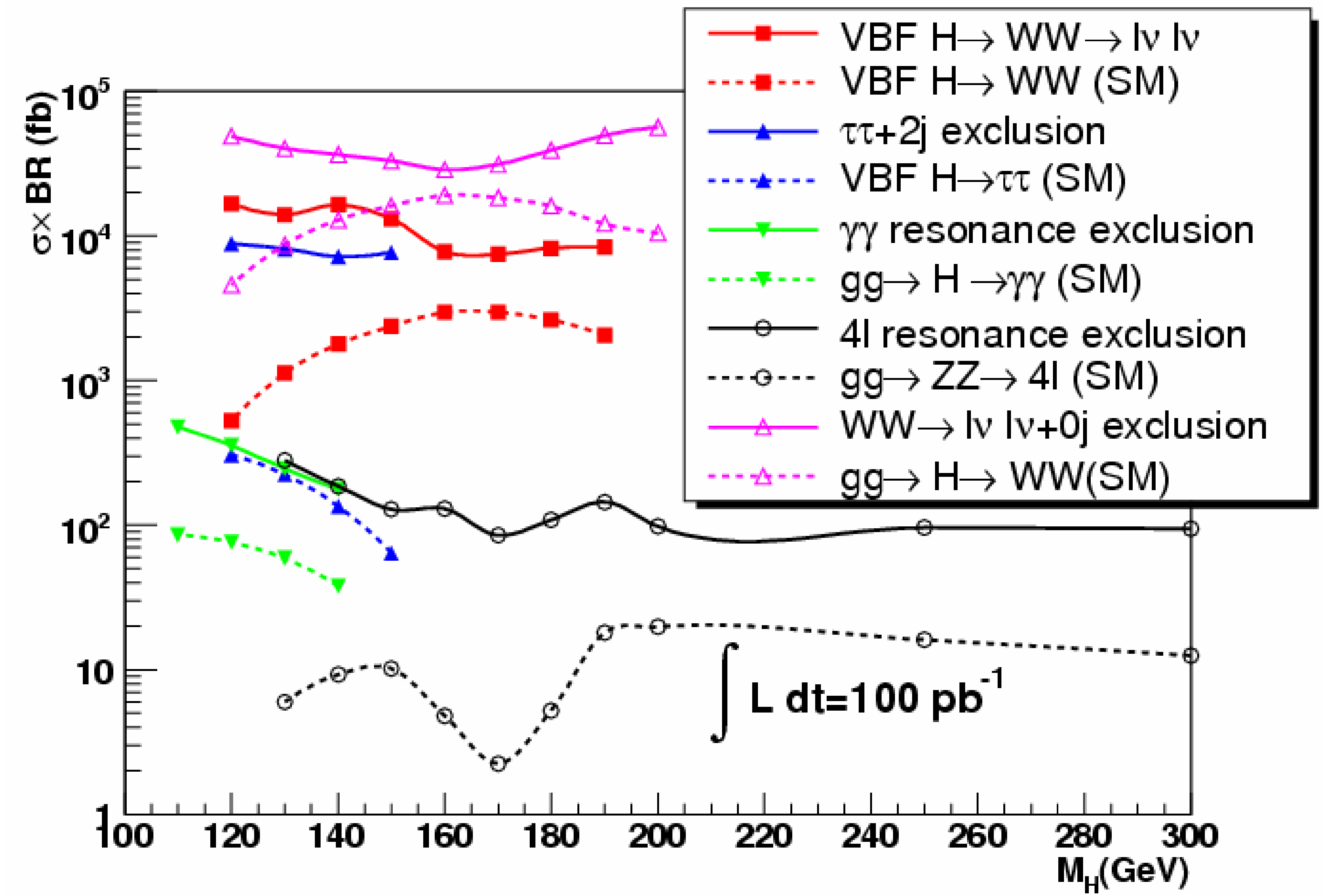
Summary of Detector Performance Requirements (ATLAS)

$H\rightarrow\tau\tau$, $\tau\rightarrow l,h$ (+0,1,2 jets)	$110<M_H<150$	Missing E_T (<10% Higgs mass resolution), lepton ID (>10^7 fake suppression with ID), jet tagging (5%/10% energy scale uncertainty for central/forward jets), central jet veto (need to address low E_T jet resolution requirements)
$H\rightarrow ZZ^{(*)}$, $Z\rightarrow 4l$	$120<M_H<600$	Lepton isolation/efficiency (achieve ~100/1000 rejection against Zbb/tbb for ε_{lepton}~90%)
$H\rightarrow WW^{(*)}$, $W\rightarrow l\nu$ (+0,1,2 jets)	$120<M_H<200$	"top killer" (>10 rejection), jet tagging (5%/10% energy scale uncertainty for central/forward jets), jet veto

ATLAS Grid Computing



Exclusion limits (cross-section X branching ratio) with 100 pb^{-1} (2007) compared with SM predictions



- If the SM Higgs does not exist ATLAS may be able to exclude it (M_H>115 GeV) with ~1 fb^{-1} (2008)

The SM Higgs is excluded with at least 95% CL if CL_S below the black line