Higgs Searches at the LHC

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On behalf of the ATLAS and CMS Collaborations

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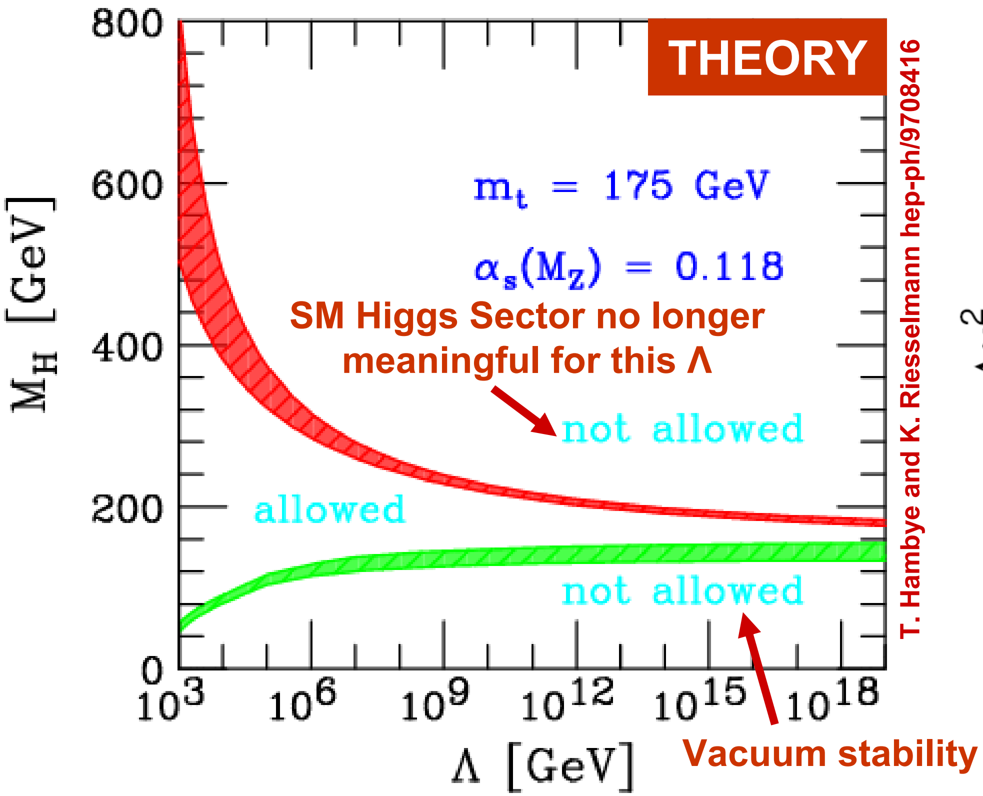
XLIIIrd Rencontres de Moriond QCD

The primary objective of the LHC

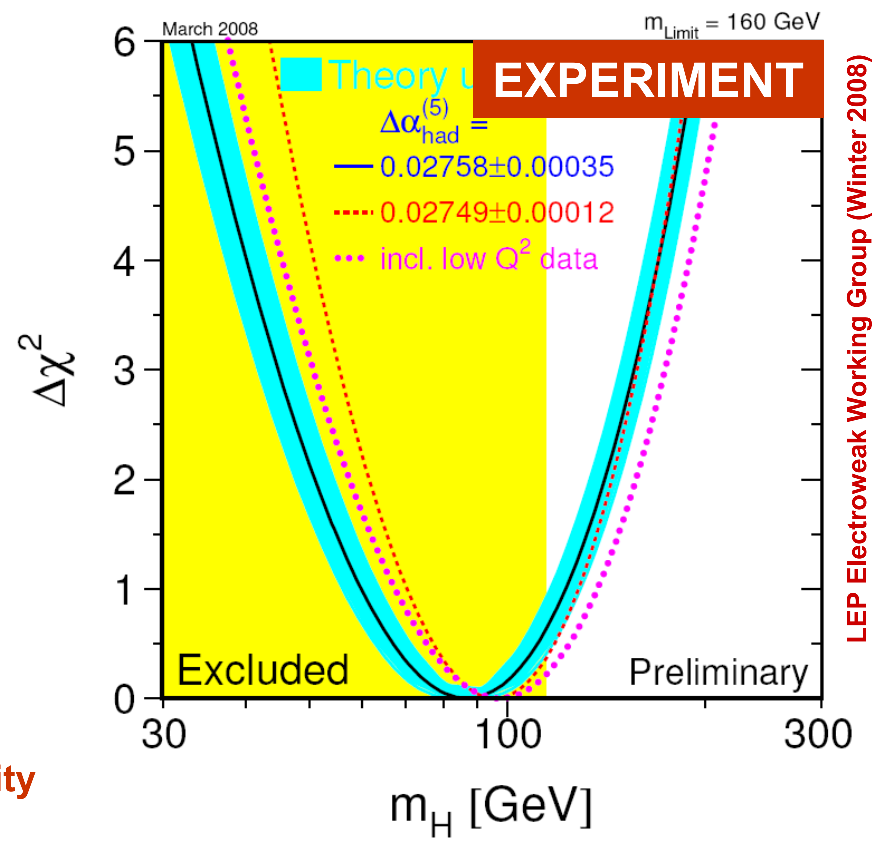
Elucidate the mechanism responsible for electroweak symmetry breaking

All experimental data to date favors a light Higgs

- **SM: $M_H = 87^{+36}_{-27}$ GeV; $M_H < 160$ GeV @ 95% CL**
- **LEP Direct Limit: $M_H > 114.4$ GeV @ 95% CL**

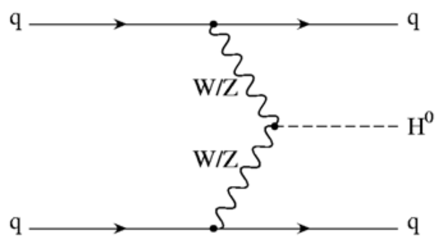


Λ is the scale of new physics beyond the Standard Model



Higgs production at the LHC

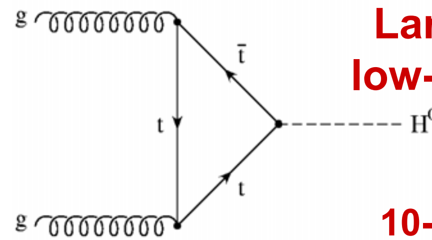
Vector Boson Fusion



The two "spectator" quarks make for a very distinct final state

<10% unc. NLO

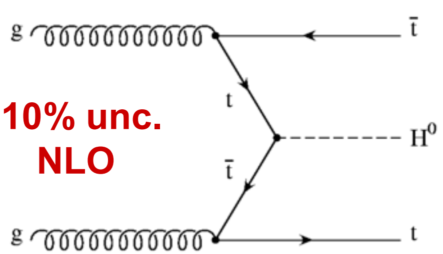
Gluon-gluon Fusion



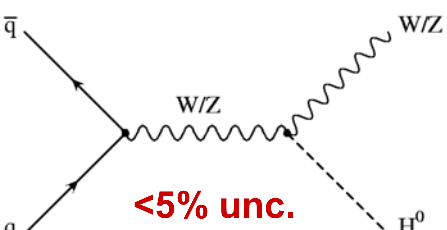
Large backgrounds for low-mass Higgs searches

10-20% unc. NNLO

Associated Production

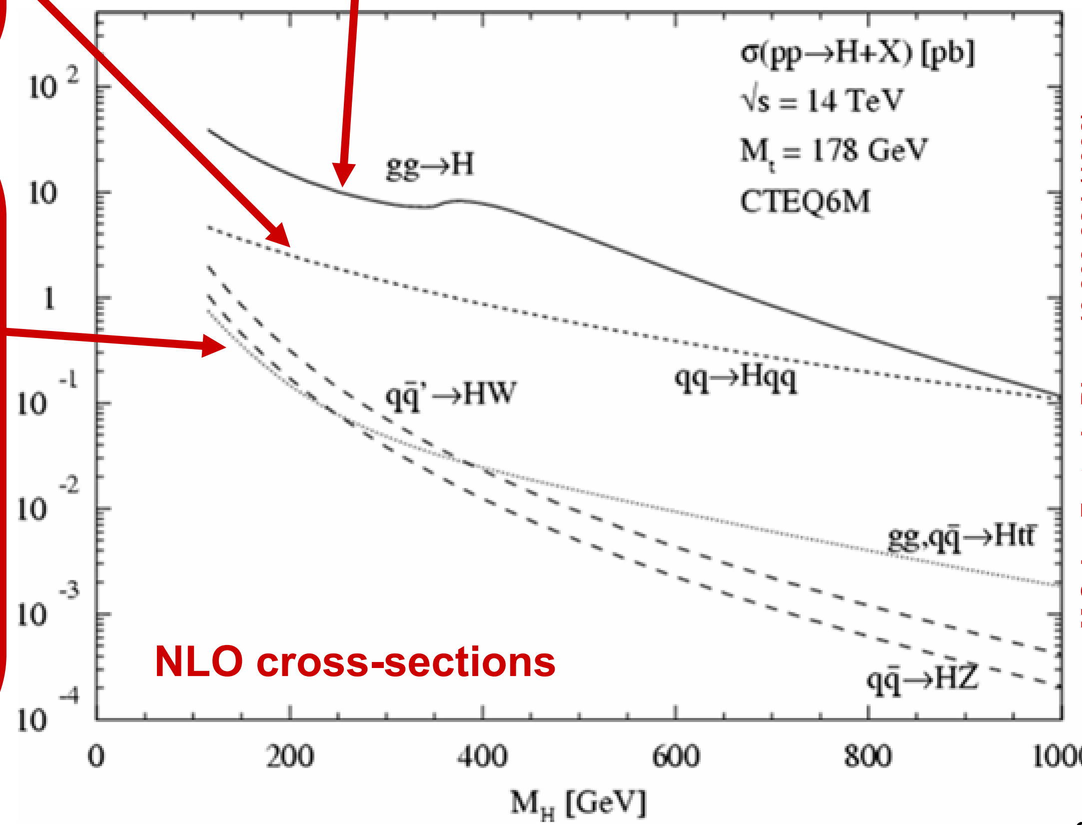


~10% unc. NLO



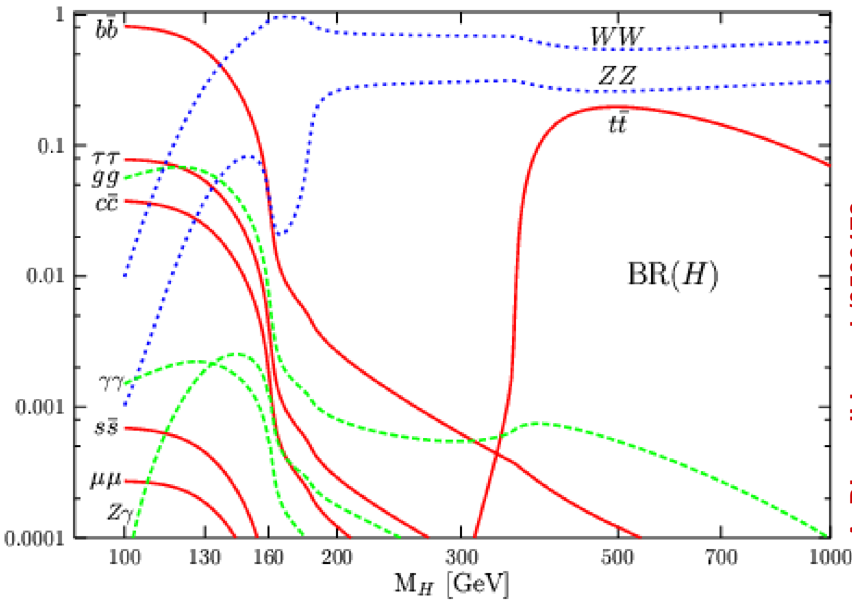
<5% unc. NNLO

Allows for triggering regardless of Higgs decay mode



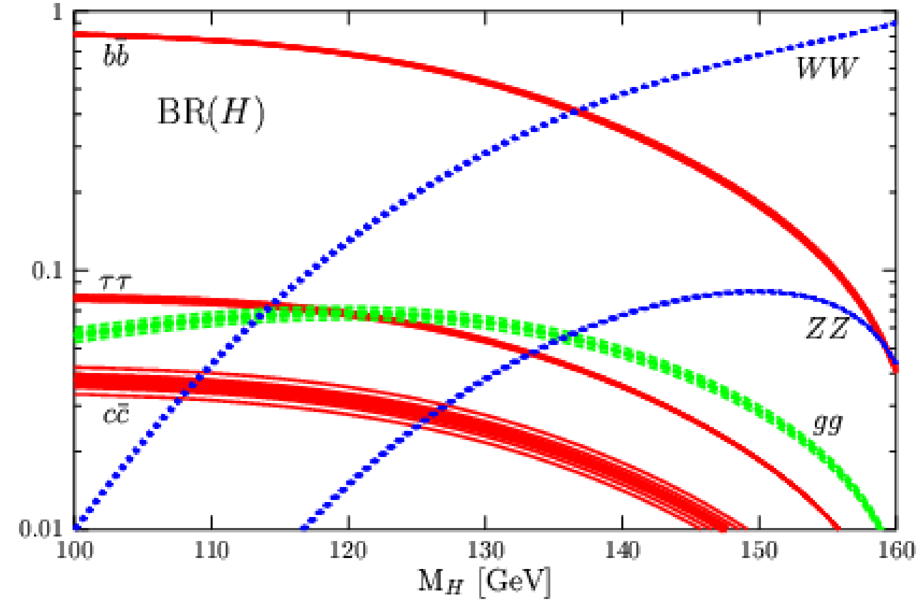
M.Spira, Fortsch. Phys. 46 203-284 (1998)

SM Higgs discovery final states



A. Djouadi hep-ph/0503172

Includes quark mass uncertainties (t, b, c) and $\alpha_s(M_Z)$



At low mass (M_H < $2M_Z$)

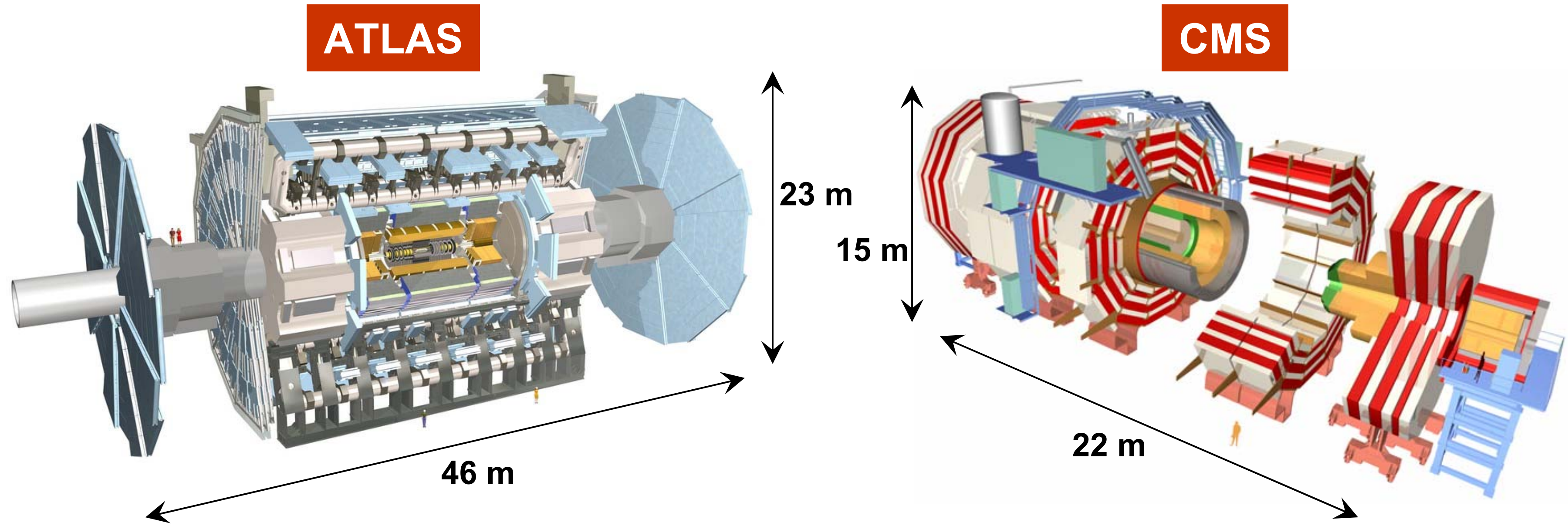
- **Dominant decay through bb; enormous QCD background, suppressed in ttH**
- **H→ττ accessible through Vector Boson Fusion (VBF)**
- **H→WW$^{(*)}$ accessible through gluon-gluon fusion and VBF**
- **H→γγ has a low BR (decays through top and W loops); but due to excellent γ/jet separation and γ resolution is still very significant**
- **H →ZZ*→4l also accessible**

For higher masses

- **H→WW and H→ZZ→4l final-states**

The ATLAS and CMS Experiments

Designed to search for the Higgs over a wide mass range



Hermetic calorimetry

- **Exceptional measurement of missing transverse energy, jets to high eta**

Exceptional particle identification

• **Muons**	**Efficiency ~90%**	**Jet Rejection ~10^5**
• **Electrons**	**Efficiency ~80%**	**Jet Rejection ~10^5**
• **Photons**	**Efficiency ~80%**	**Jet Rejection ~10^3**
• **b-Jet ID**	**Efficiency ~60%**	**Light Jet Rejection ~10^2**
• **Tau ID**	**Efficiency ~50%**	**Jet Rejection ~10^2**

Electron, muon and photon energy and momentum resolution of ~2-3%

Strategy and Start-up

Anticipating the start of the LHC

- Summer 2008
- Few ~100 pb^{-1} by the year's end
- Parts of both ATLAS and CMS have already taken cosmic ray data

Understand the detectors…

- Diagnose hot or dead channels
- Tally up dead material
- Tracking detector alignment
- Tune the detector simulations to better match ATLAS and CMS

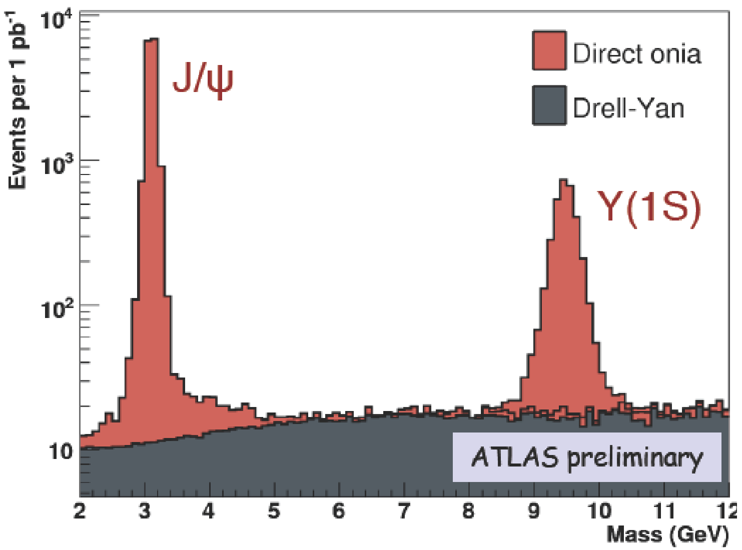
…do Standard Model measurements

- Examine our standard candles
- Demonstrate the ability to measure Ws, Zs and tops (b-jet identification)

…then search for the Higgs

LHC The first five years?

2008	~100 pb^{-1}	$10^{31} – 10^{32}$ cm^{-2} s^{-1}
2009	~1 fb^{-1}	10^{32} cm^{-2} s^{-1}
2010	~10 fb^{-1}	2 x 10^{33} cm^{-2} s^{-1}
2011	~30 fb^{-1}	2 x 10^{33} cm^{-2} s^{-1}
2012	~100 fb^{-1}	2 x 10^{34} cm^{-2} s^{-1}



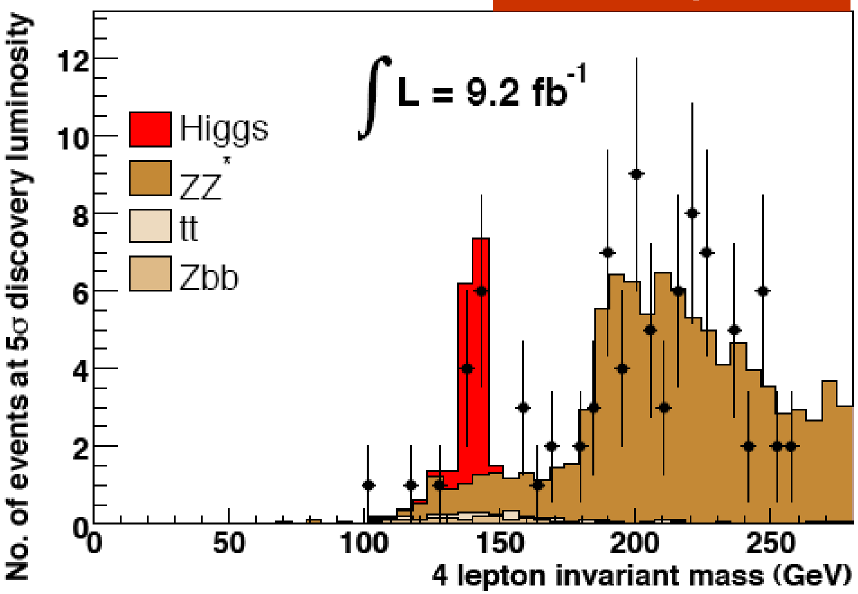
1 pb^{-1} = 3 days at 10^{31} cm^{-2} s^{-1}

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

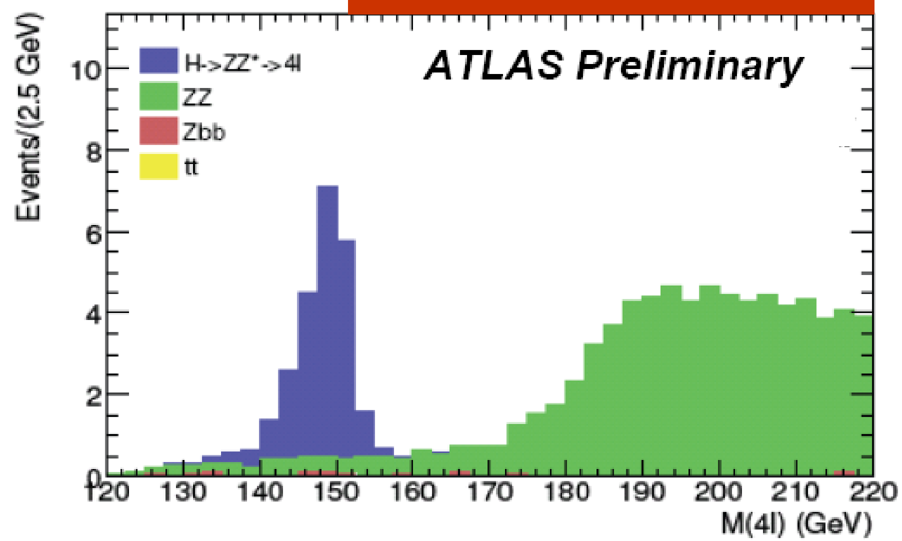
The "Golden Mode"

- **Very clean signal (looking for final states with 4e, 4μ, 2e2μ)**
- **Excellent mass resolution (1.5 – 2 GeV for M_H = 130 GeV)**
- **Powerful analysis in a wide mass range**

CMS 2e2μ at 5σ



ATLAS CSC 2008 10 fb^{-1}

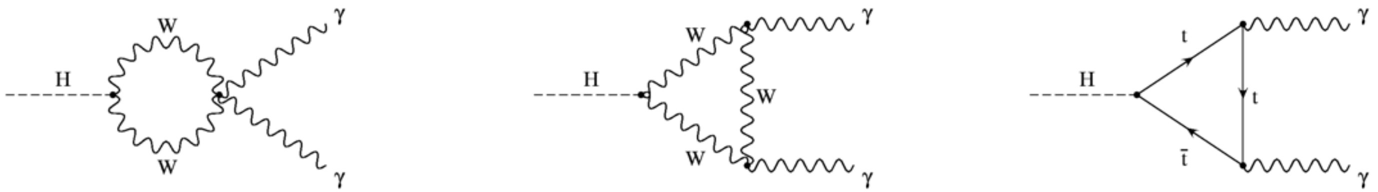


Experimental issues:

- **Zbb and tt rejection (leptons non-isolated, with activity around the leptons in the calorimeter and tracker; high impact parameter significance)**
- **qq→ZZ known at NLO; gg→ZZ is added as 30% of LO qq→ZZ (no generator, yet)**

$H \rightarrow \gamma\gamma$

Final state produced through W, top and bottom loops



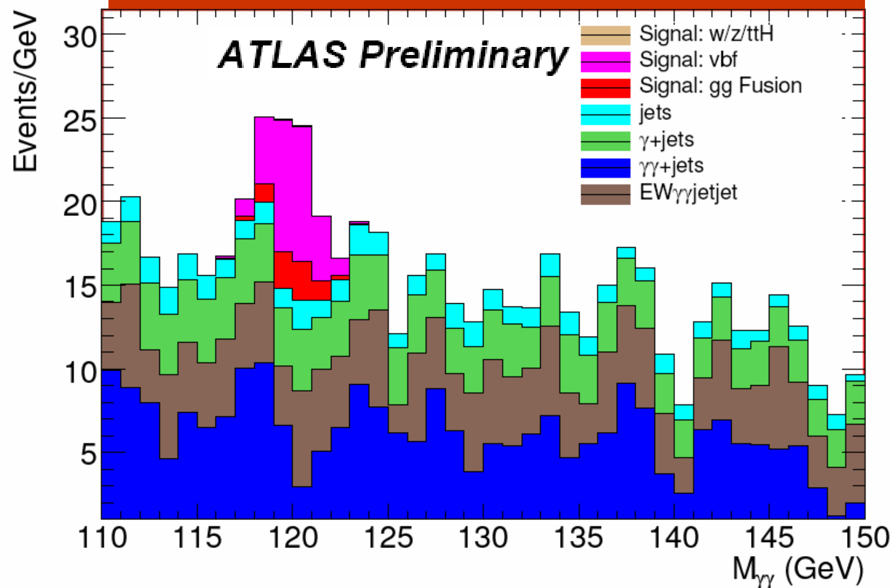
Powerful for low masses

- Significance of 6 – 8σ with 30 fb^{-1}
- Excellent mass resolution (~1.5 – 2 GeV)

Experimental issues

- Electromagnetic calorimeter calibration
- Requires excellent γ/jet separation
- Conversion recovery

ATLAS CSC 2008 30 fb^{-1} H + 2 Jets



Recent developments

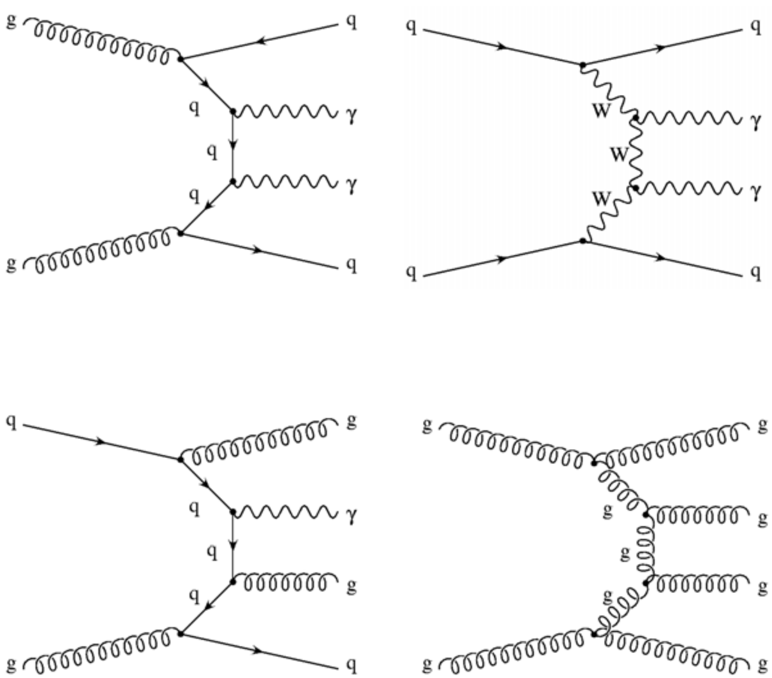
- Split events into categories (by jet multiplicity, energy ratios and η region)
- Inclusive, 1 and 2-jet analyses; combine to increase significance
- Use of fits and a Likelihood Ratio for discovery, systematics

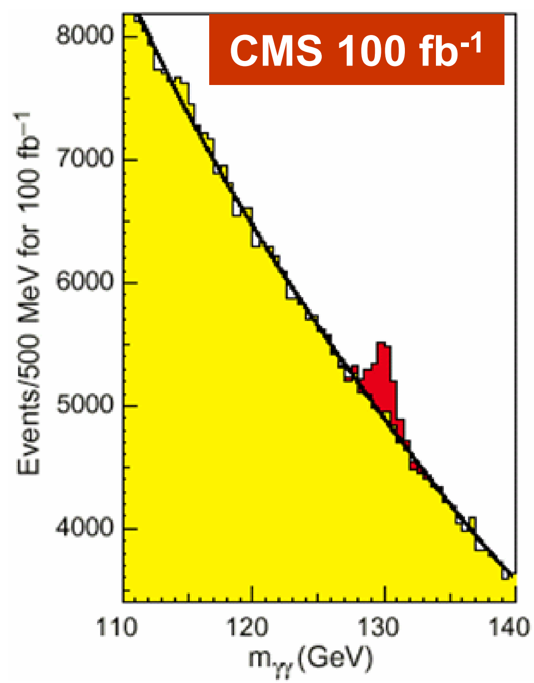
$H \rightarrow \gamma\gamma$

Diphoton background now calculated at NLO

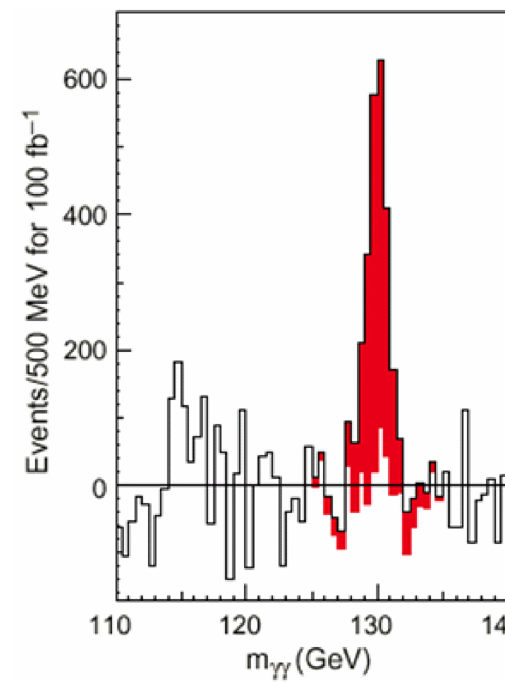
- **Agrees with the data from the Tevatron**

Backgrounds can be taken from the sidebands…





Signal with background



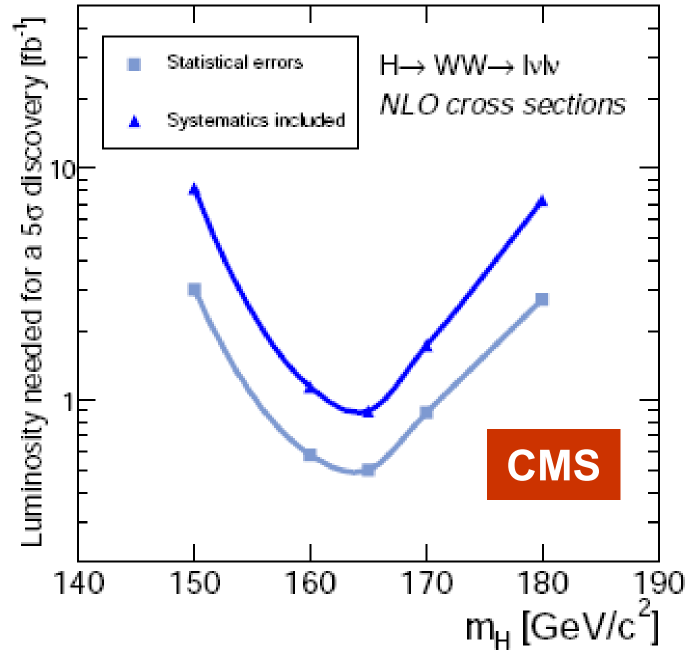
Signal after background subtraction

Inclusive Analysis

H → WW → 2l2υ

Unlike other channels, full mass reconstruction is not possible

- **Essentially a counting experiment**
- **Accurate background estimate is critical**

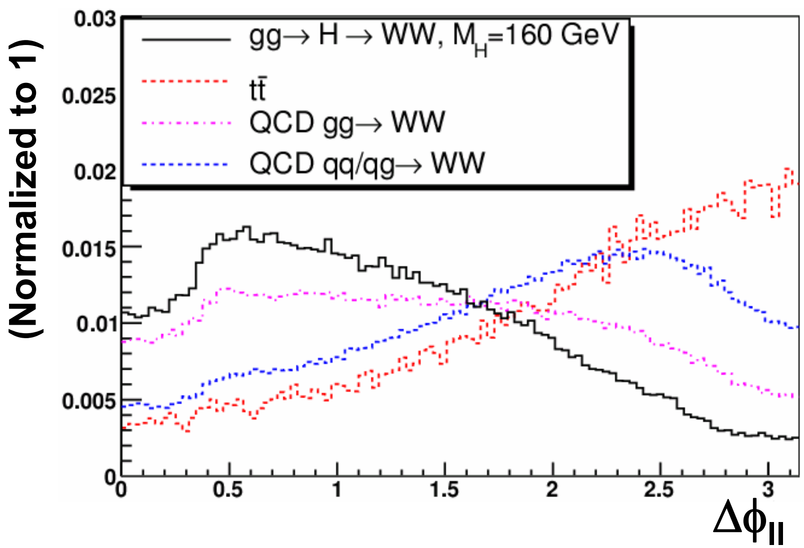


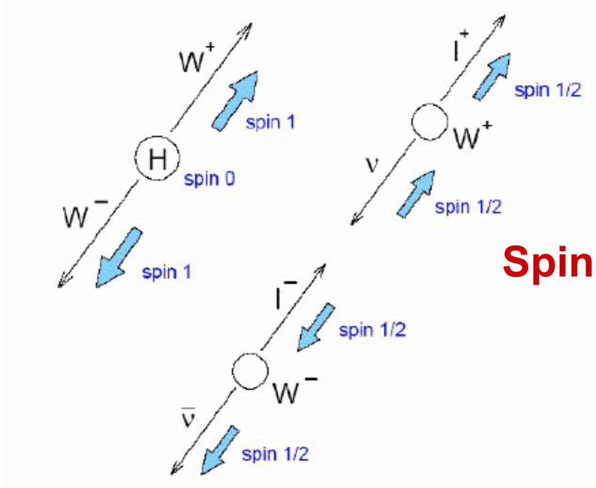
Most significant ~160 GeV

- **BR(H→WW) > 95%**

Dominant backgrounds

- **ttbar (suppressed with a jet veto)**
- **WW (exploit spin correlations)**





Spin correlations

Forward Jet Tagging and the Central Jet Veto

We can get the upper-hand in the VBF channels

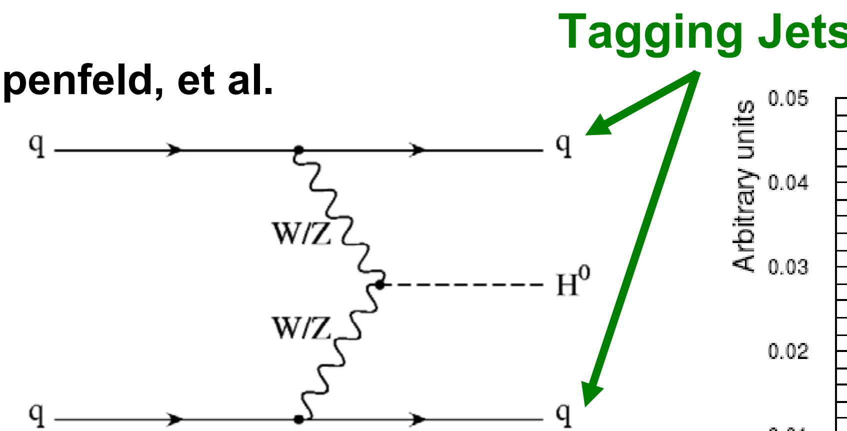
Forward Jet Tagging

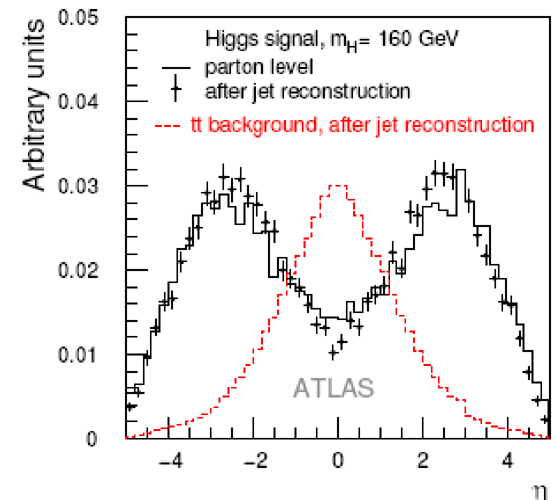
- **D. Rainwater, D. Zeppenfeld, et al.**

$$\eta_{j1} \cdot \eta_{j2} < 0$$

$$|\Delta\eta_{jj}| > 3.5 - 4$$

$$m_{jj} > 500 - 700 \text{ GeV}$$

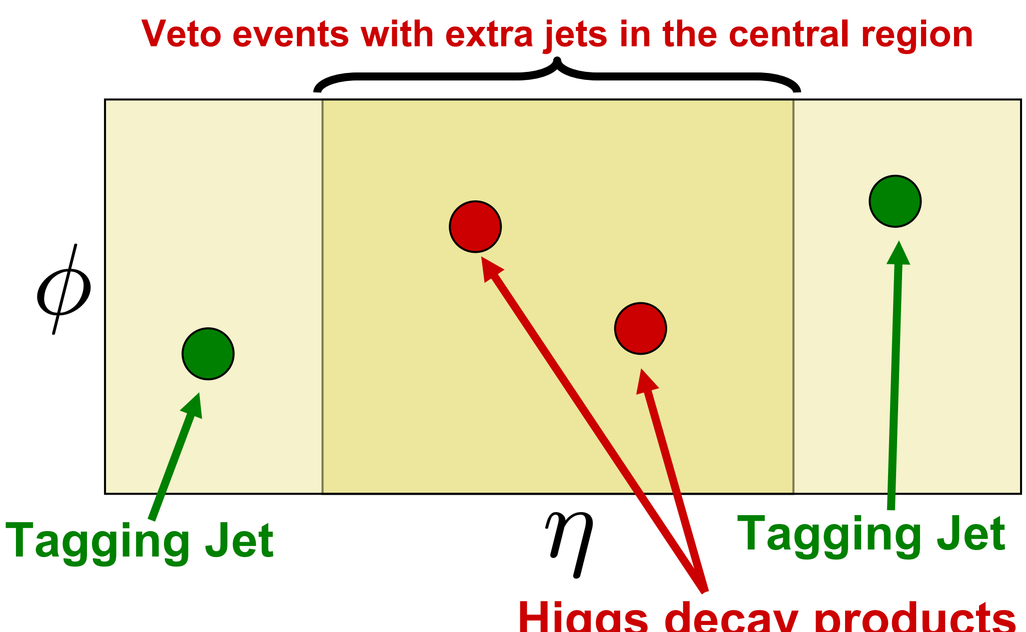


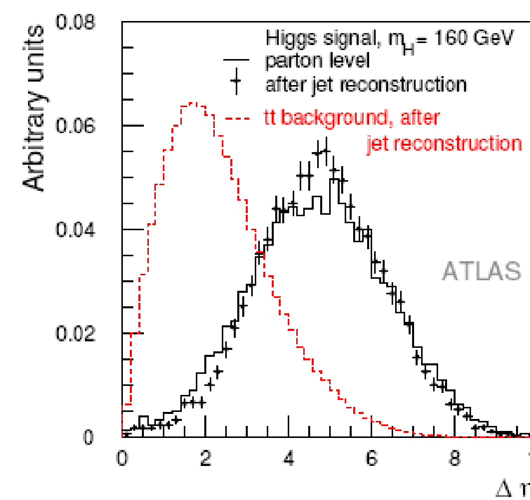


S. Asai et al., ATL-PHYS-2003-005

Central Jet Veto

- **V.Barger, K.Cheung and T.Han in PRD 42 3052 (1990)**





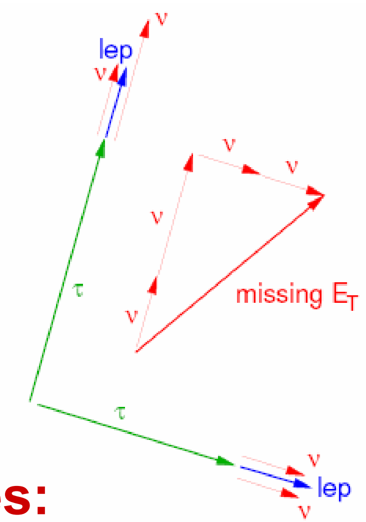
VBF H → ττ

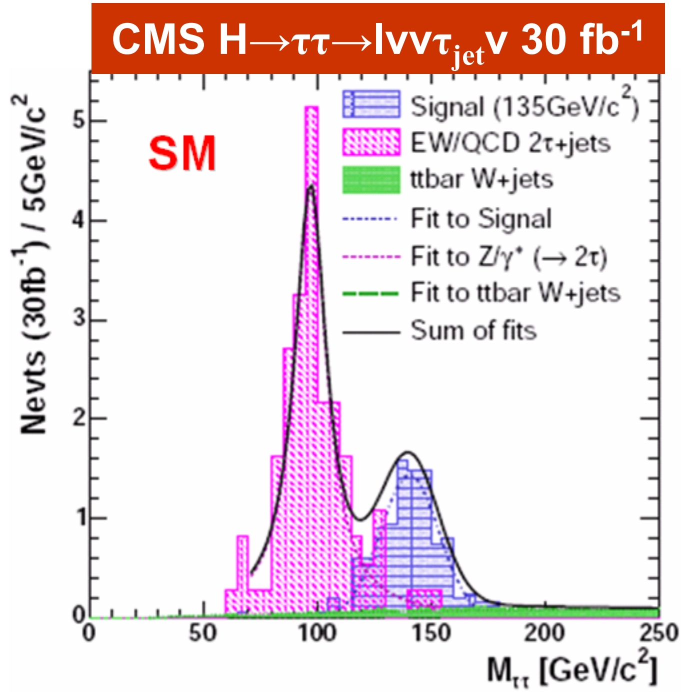
A very significant channel for low masses

- Important for studying the coupling of Higgs to leptons
- Three final states lepton-lepton, lepton-hadron, hadron-hadron
- Triggers for the fully hadronic mode are under investigation

Mass reconstruction via the collinear approximation

- Approximation breaks down when the two taus are back-to-back
- Mass resolution limited by missing transverse energy (~8 – 10 GeV)





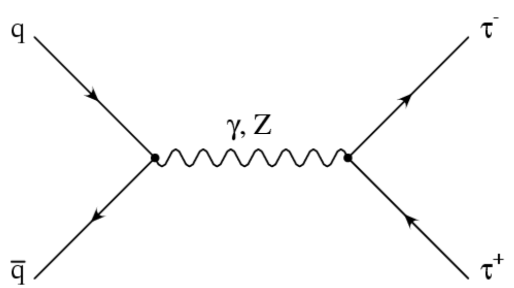
Experimental issues:

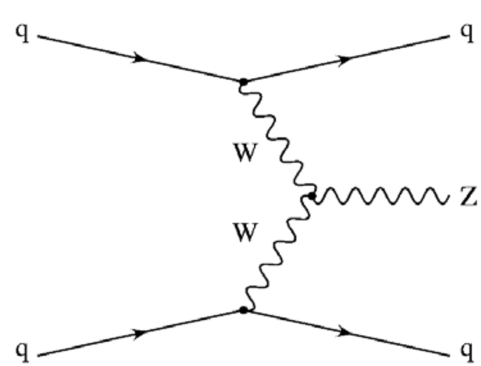
- Tau tagging (Likelihood, Neural Net methods)
- Z+jets background (especially for low masses)
- tt rejection (b-jet ID and veto for lepton-lepton)

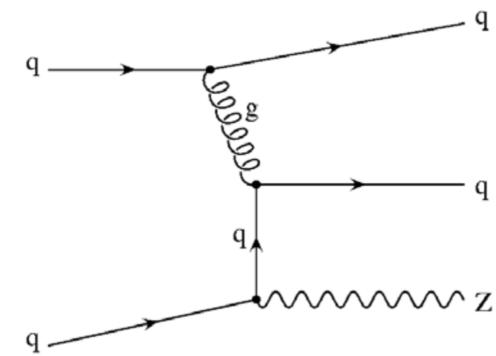
VBF H → ττ

Data-driven control samples are being explored for many backgrounds

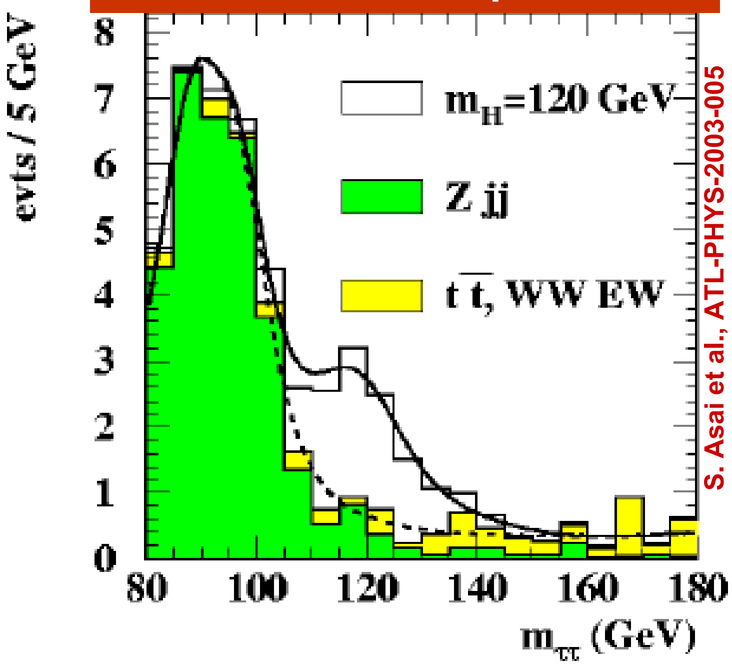
- **The relative contributions from different jet multiplicities are not known**
- **Unknowns related to critical analysis cut-specific variables exist**







ATLAS H→ττ→eννμνν 30 fb^{-1}



S. Asai et al., ATL-PHYS-2003-005

For the dominant background, collect Z→μμ and Z→ee events from data and use TAUOLA to decay the leptons to taus

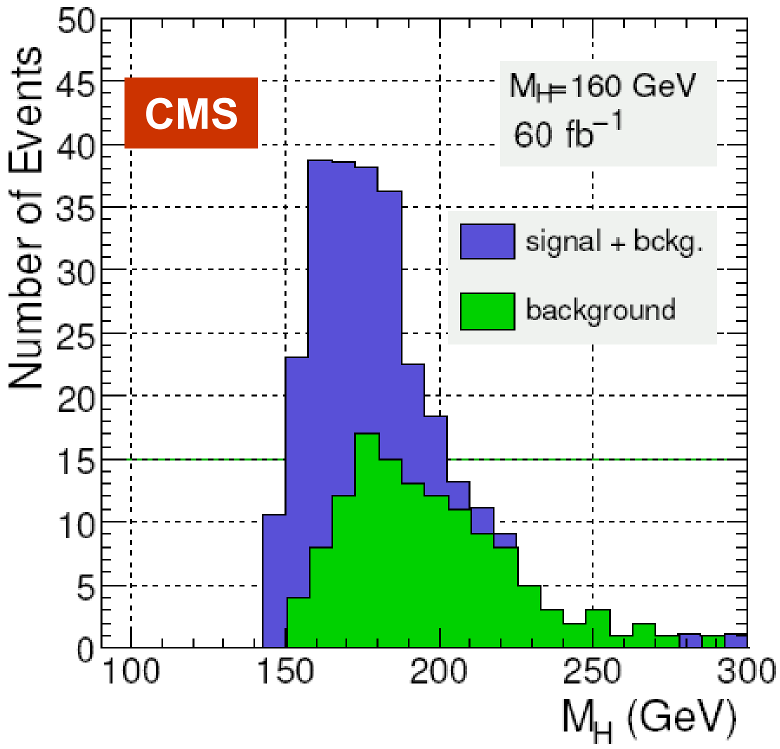
In this way we can emulate each of the lepton-lepton, lepton-hadron and hadron-hadron final states

Obtain both the background shape and normalization from data

VBF H → WW → lυqq

One of the best channels for intermediate and high Higgs masses

- **A VBF analysis reaping the benefits of the CJV and Tagging Jets selection**



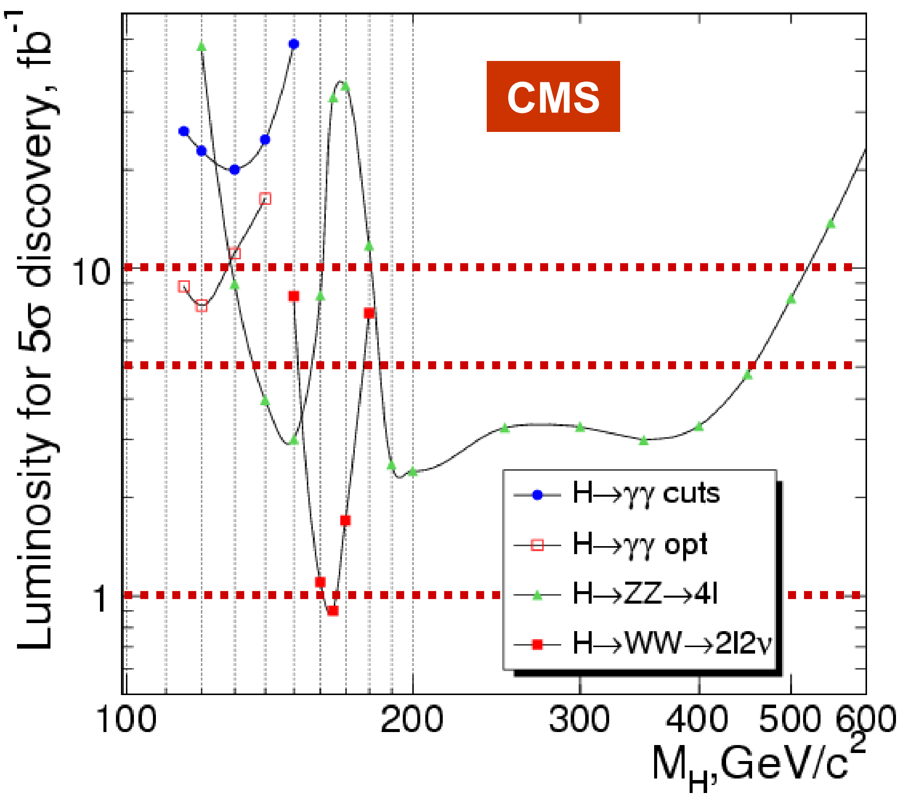
Event Selection

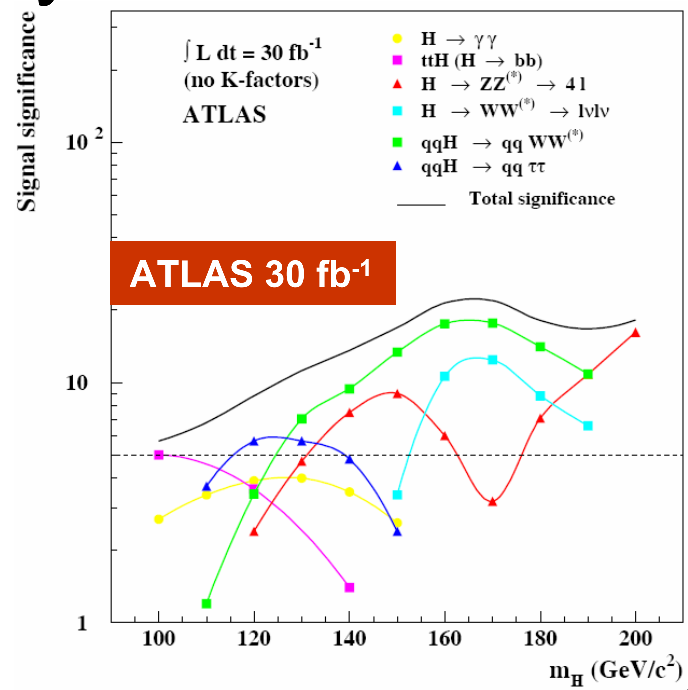
- **VBF tagging jets selection**
- **Central Jet Veto**
- **Isolated lepton**
- **4 jets**
- **Large missing transverse energy**

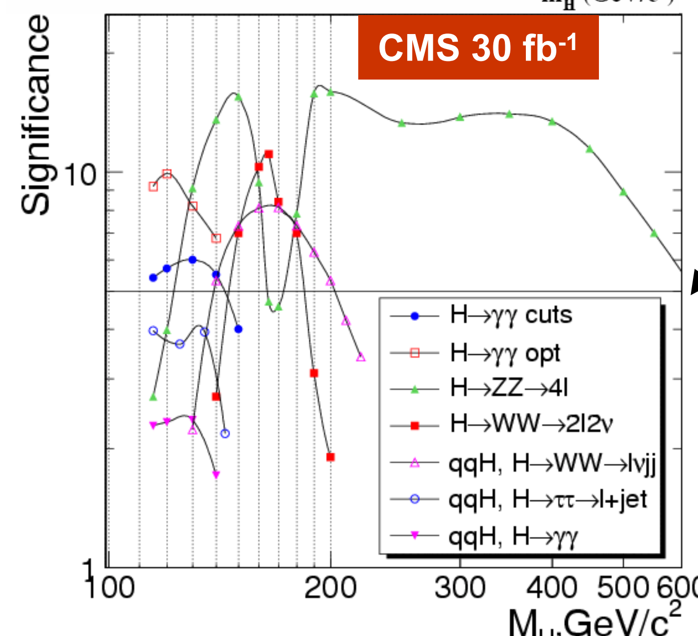
Mass reconstruction possible

- **Backgrounds: ttbar, W+jets, WW+jets**
- **Exploring data-driven approaches for obtaining background shapes**

SM Higgs Discovery Potential







Signal significance of 5σ

Luminosity for discovery or exclusion

- ~few 100 pb^{-1}, some exclusion @ 95% CL
- ~1 fb^{-1}, 5σ discovery if M_H ~160 - 170 GeV
- ~10 fb^{-1}, discovery over a broad mass range

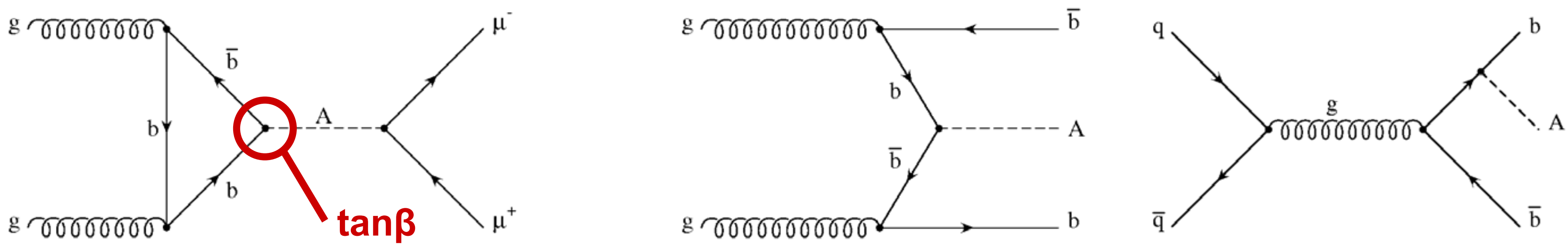
MSSM Higgs at the LHC

Minimal Supersymmetric extension to the SM: (A, H, h, $H^{\pm}$)

- As one example here, consider A / H / h →μμ
- Not visible in the SM
- Enhanced in the MSSM by ~$\tan^2\beta$; excellent mass resolution as opposed to ττ

Direct and associated production

Enhanced for large tanβ



Divide analysis into two uncorrelated channels

Initial event selection:

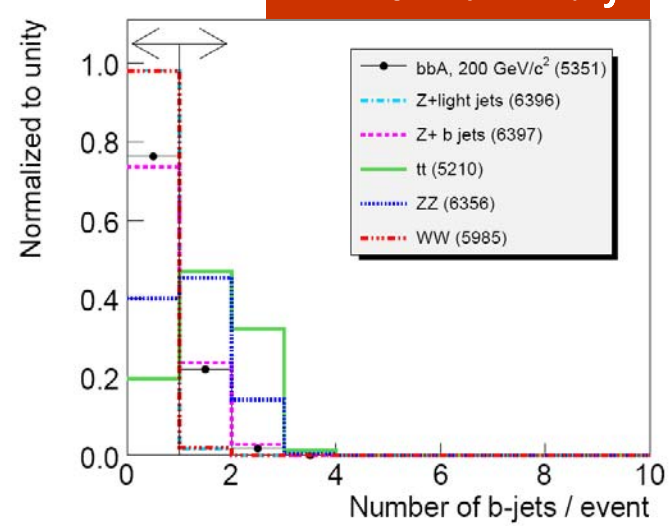
- Di-muon selection, low event MET, b-tag

0 b-jet

≥1 b-jet

- Acoplanarity, sum pT of all jets

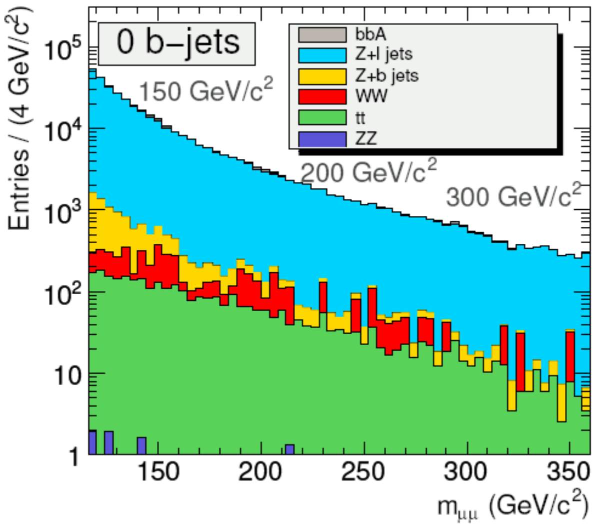
ATLAS Preliminary

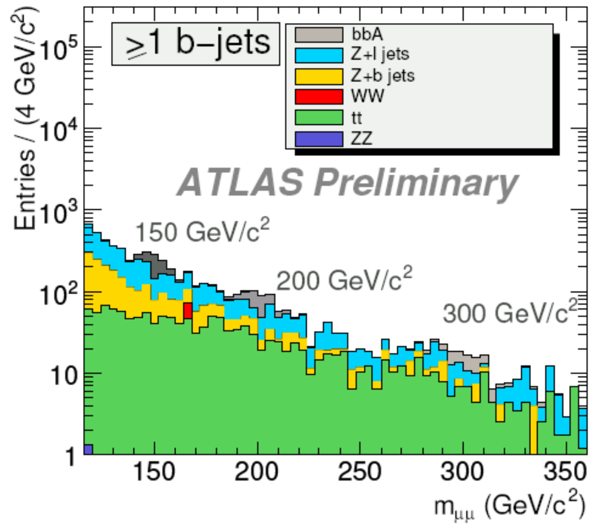


MSSM Higgs at the LHC

Combine the 0 and ≥ 1 b-jet analyses to increase the significance

- **A very similar analysis has been explored for the ττ channel**

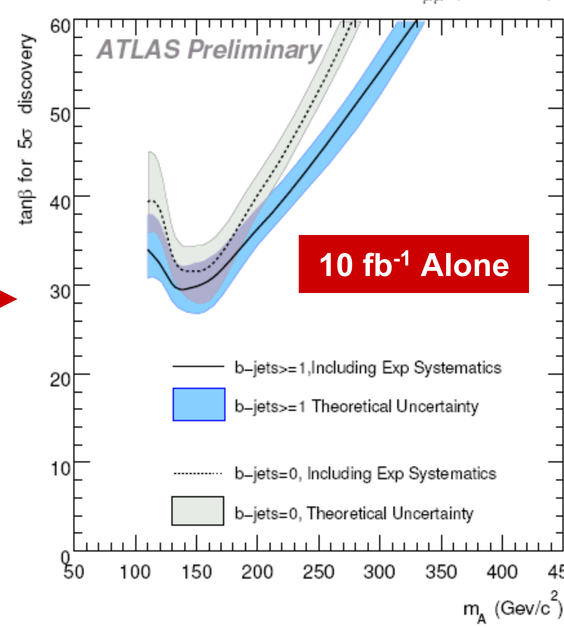


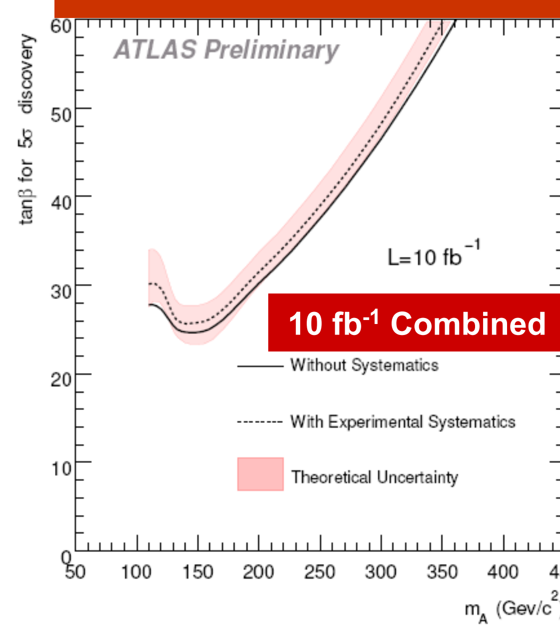


Reconstructed Invariant mass

ATLAS CSC 2008 10 fb^{-1}

tanβ for a 5σ Discovery





Conclusions

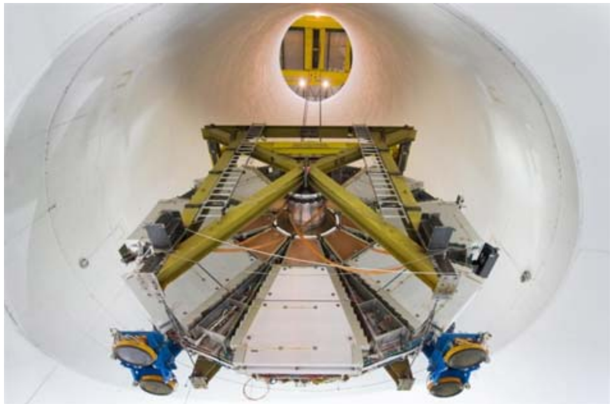
If it is there, ATLAS and CMS are in a good position to find the Higgs…

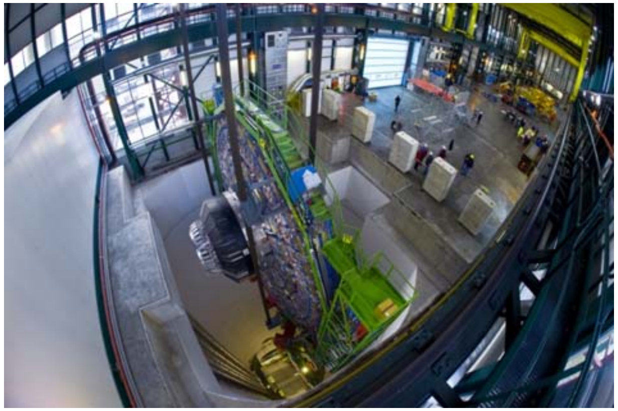
- **Unless it is discovered first at the Tevatron**
- **For a SM Higgs ATLAS and CMS need ~1 – 30 fb^{-1}**
- **How long will it take to get that much integrated luminosity from the LHC?**
- **How quickly will we understand the detectors?**

Post-discovery questions that would need be answered…

- **Is it the simple Standard Model Higgs?**
- **Does it have the expected couplings to various particle types?**
- **Are there more Higgs particles (à la Supersymmetry)**
- **Higgs discovery also raises the "hierarchy" problem**

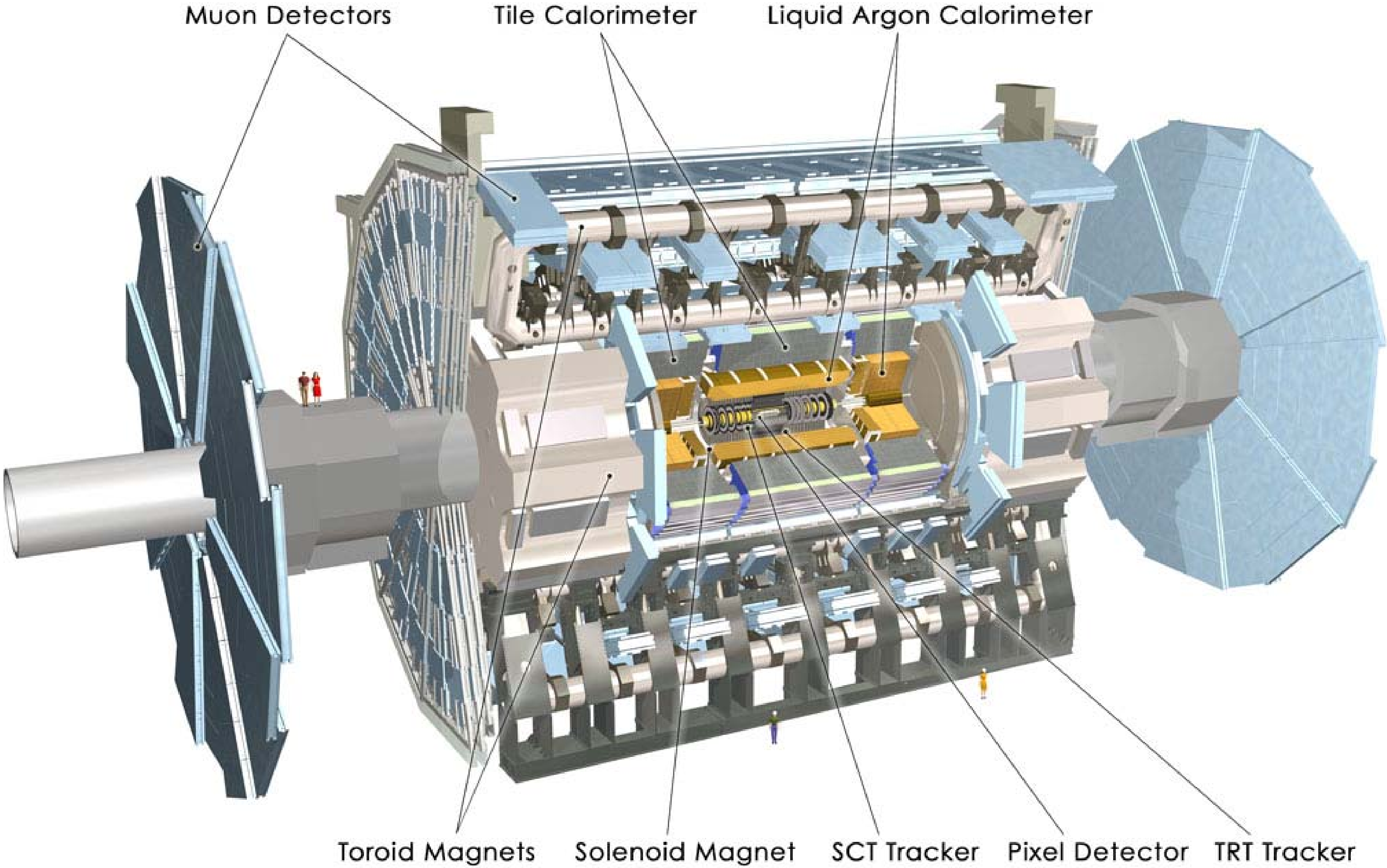
ATLAS and CMS are on track to try and answer these questions.



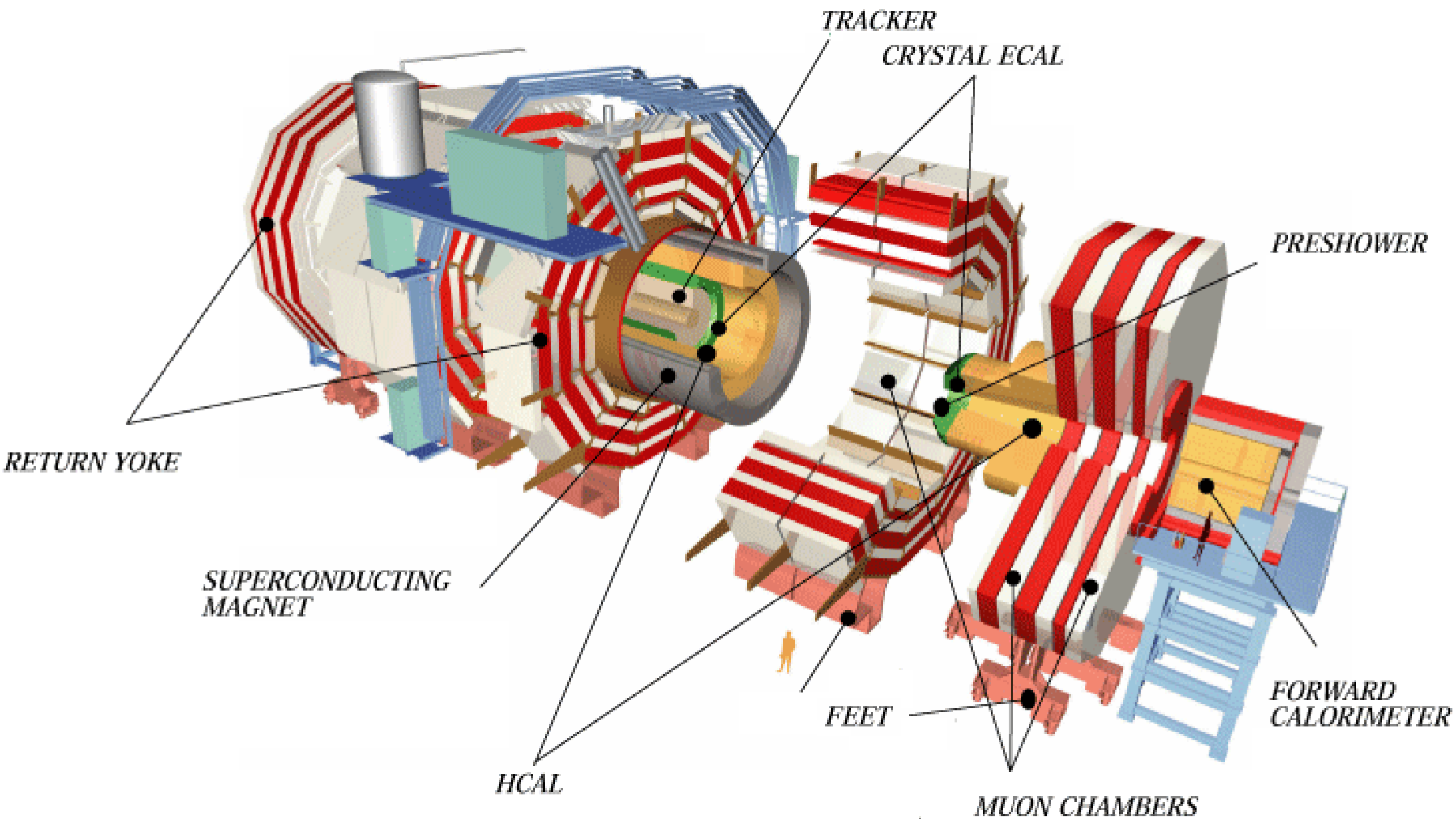


Backup Slides

The ATLAS Experiment



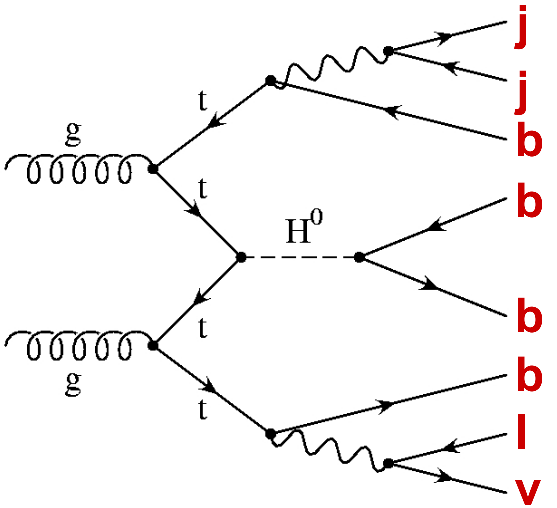
The CMS Experiment

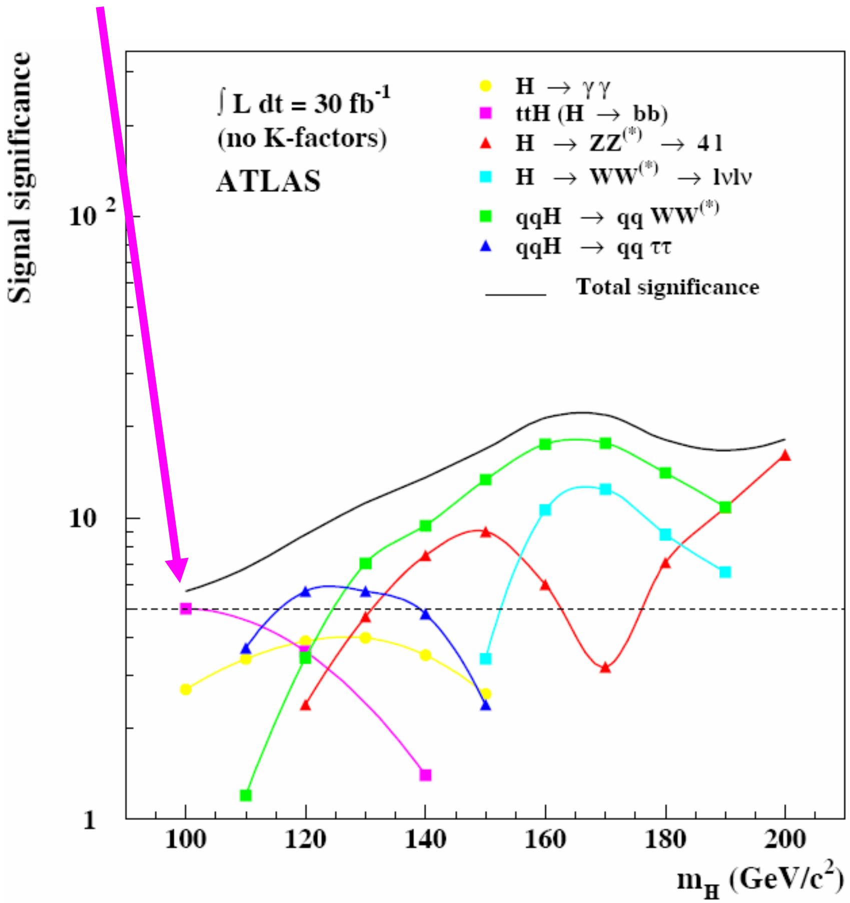


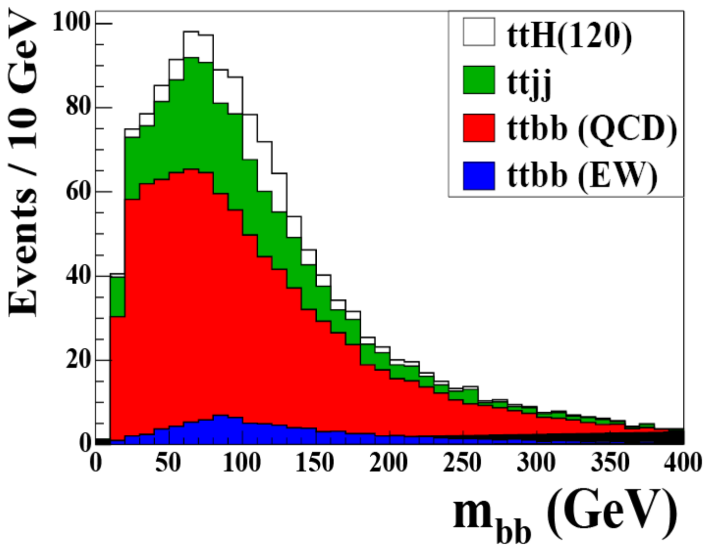
ttH(H→bb)

A very complex final state

- **Good discovery channel at low masses**
- **Determination of the Yukawa coupling**
- **Dominant backgrounds tt+jets production**
- **Also considering fully-hadronic and dilepton final states**







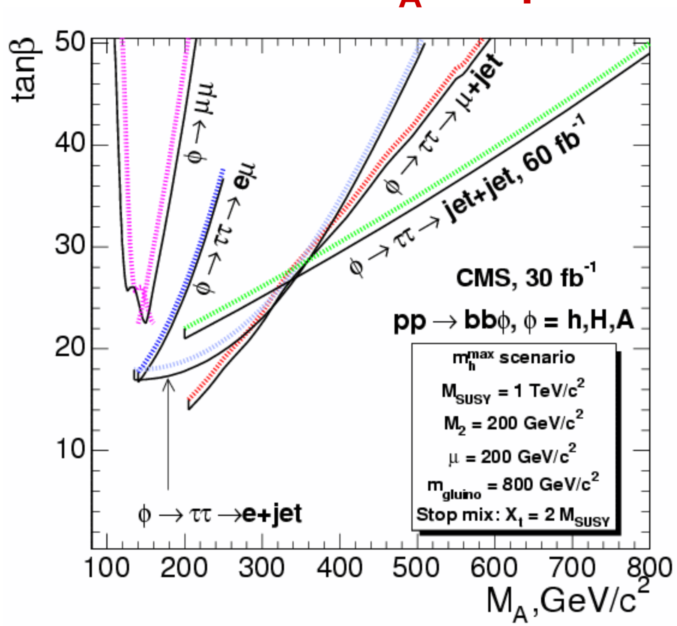
J. Cammin and M. Schumacher, ATL-PHYS-2003-024

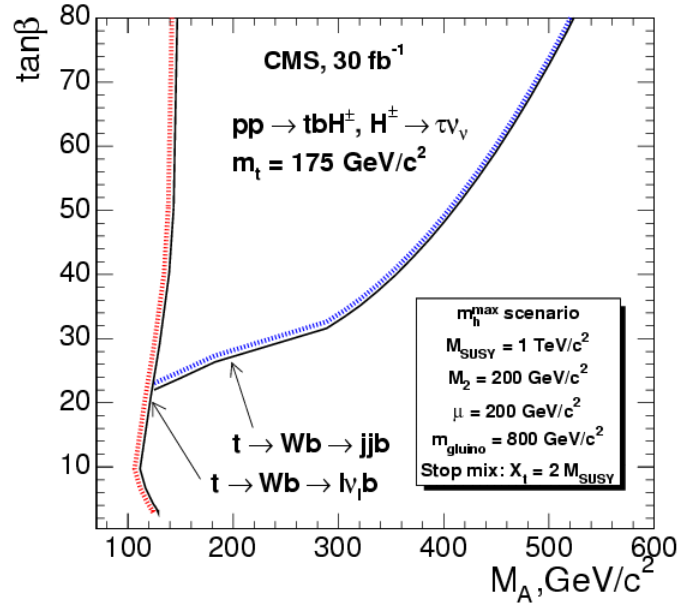
Experimental issues:

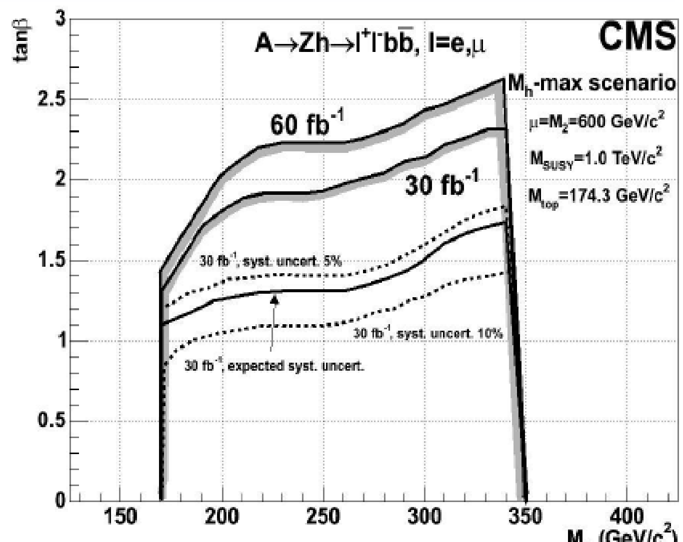
- **b-tagging (efficiency ~ε_b^4)**
- **Good understanding of background shape at turn-over**

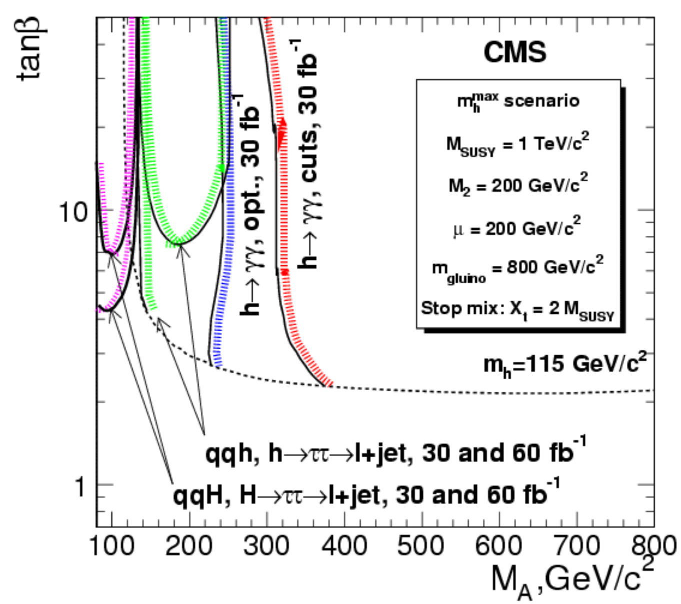
MSSM Higgs at the LHC

Summary of CMS reach in M_A tan β

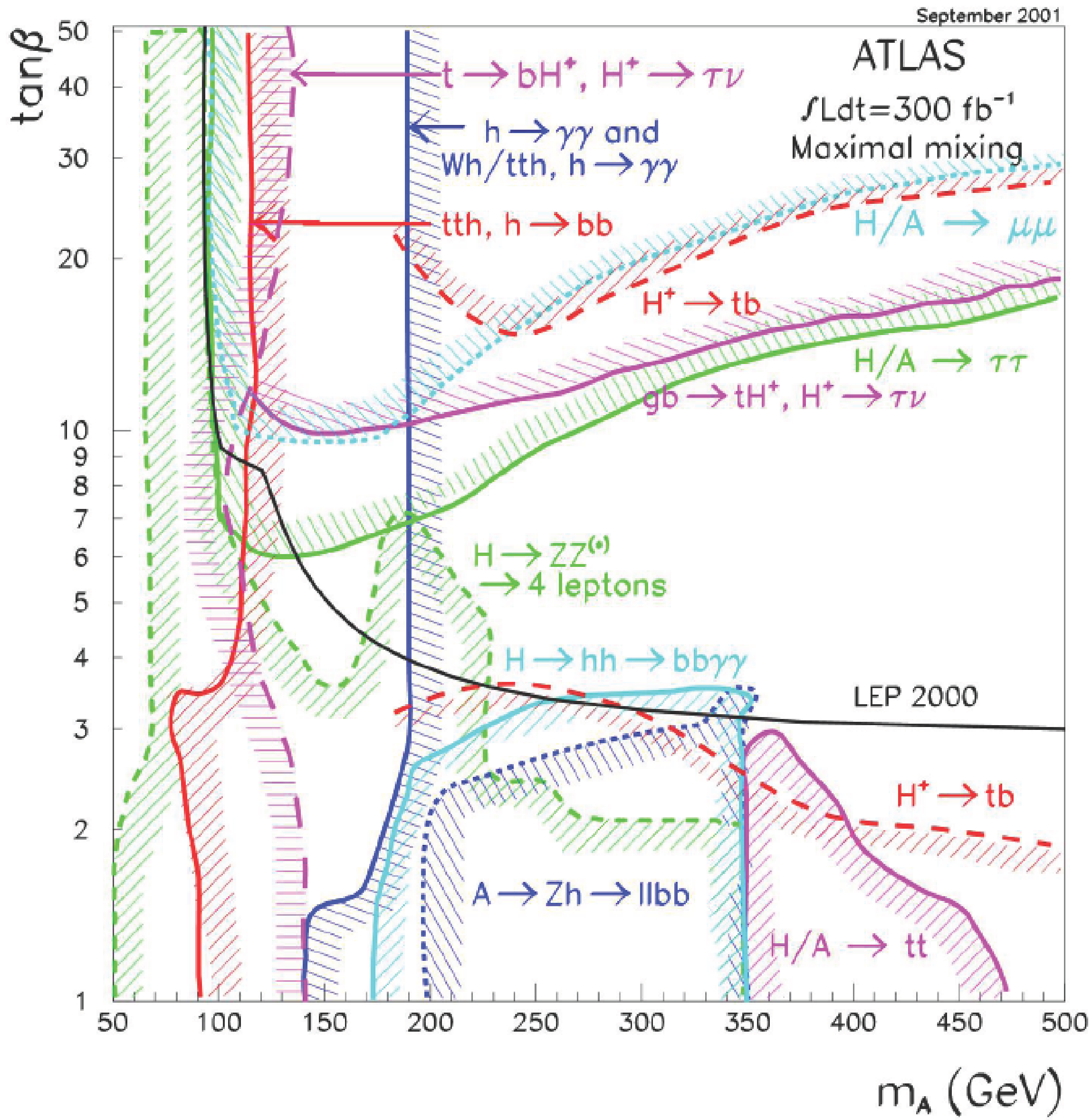








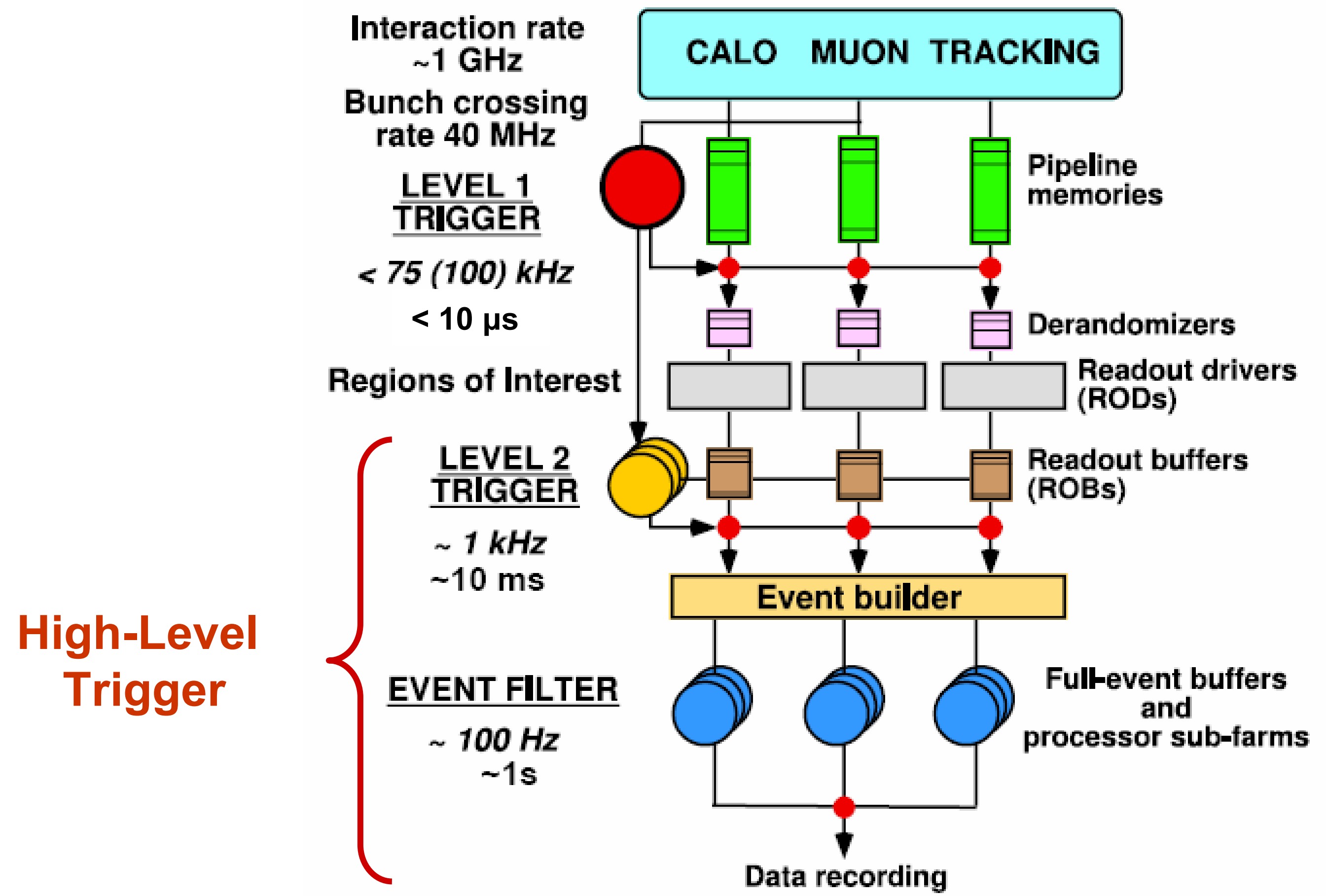
MSSM Higgs with ATLAS



The ATLAS Experiment

Trigger and Data Acquisition System:

- **Level-1 is hardware, Level-2 confined to "Regions of Interest", Event Filter has the ability to access the entire event**



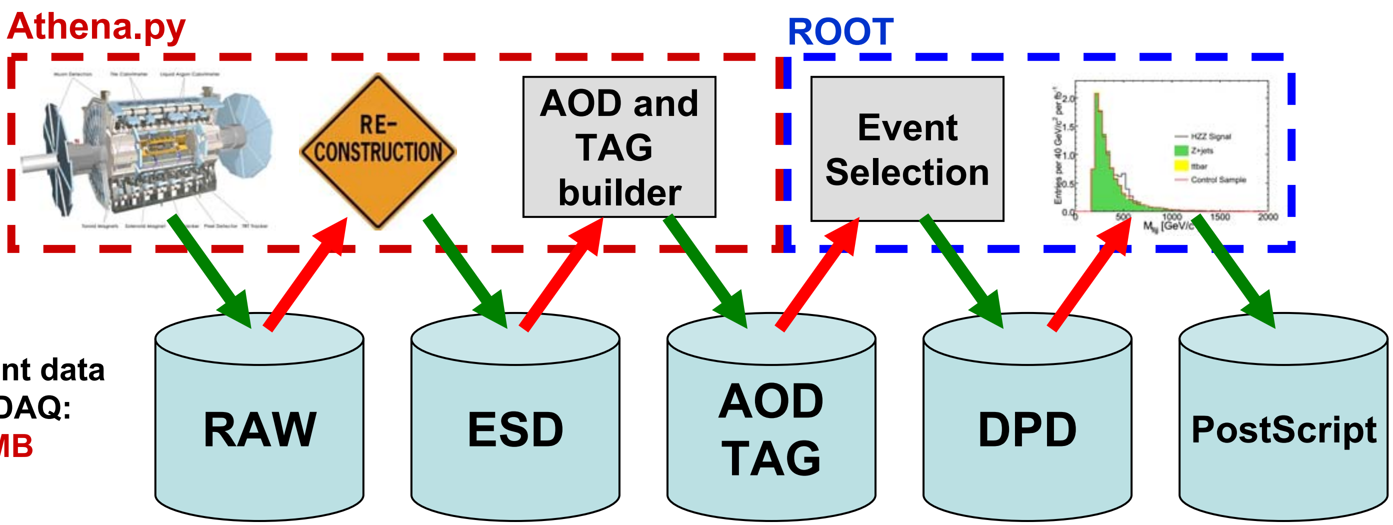
~100 MB/s

Average Event Size ~2 MB

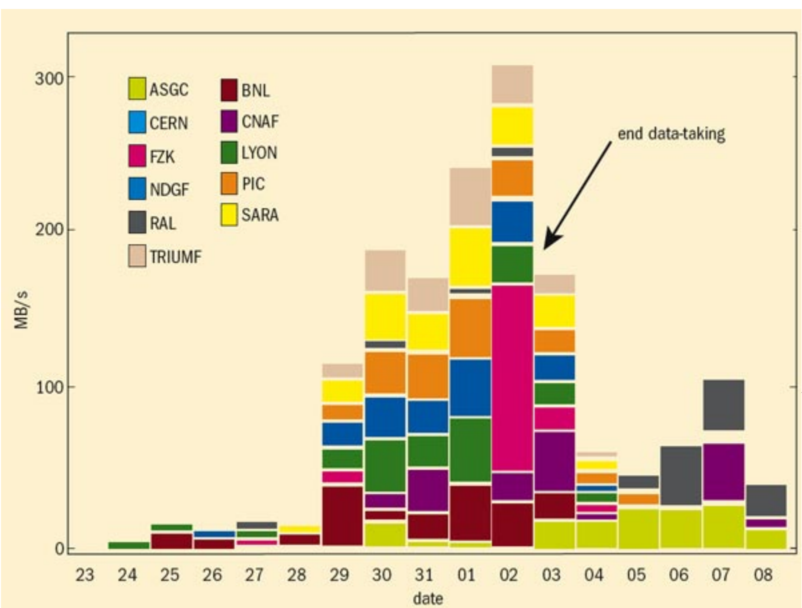
~1 PB/year (petabyte = 10^{15} bytes!)

ATLAS Data-taking Chain

First test of end-to-end data-taking chain took place in September 2007



RAW Event data from TDAQ: ~2 MB



ESD (Event Summary Data):
output of reconstruction (calo cells, track hits, ..): ~1 MB
AOD (Analysis Object Data):
physics objects for analysis (e,γ,m,jets, …): ~100 kB
TAG (Event Level Metadata):
Reduced set of information for event selection: ~1 kB
DPD (Derived Physics Data): equivalent of old ntuples: ~10 kB

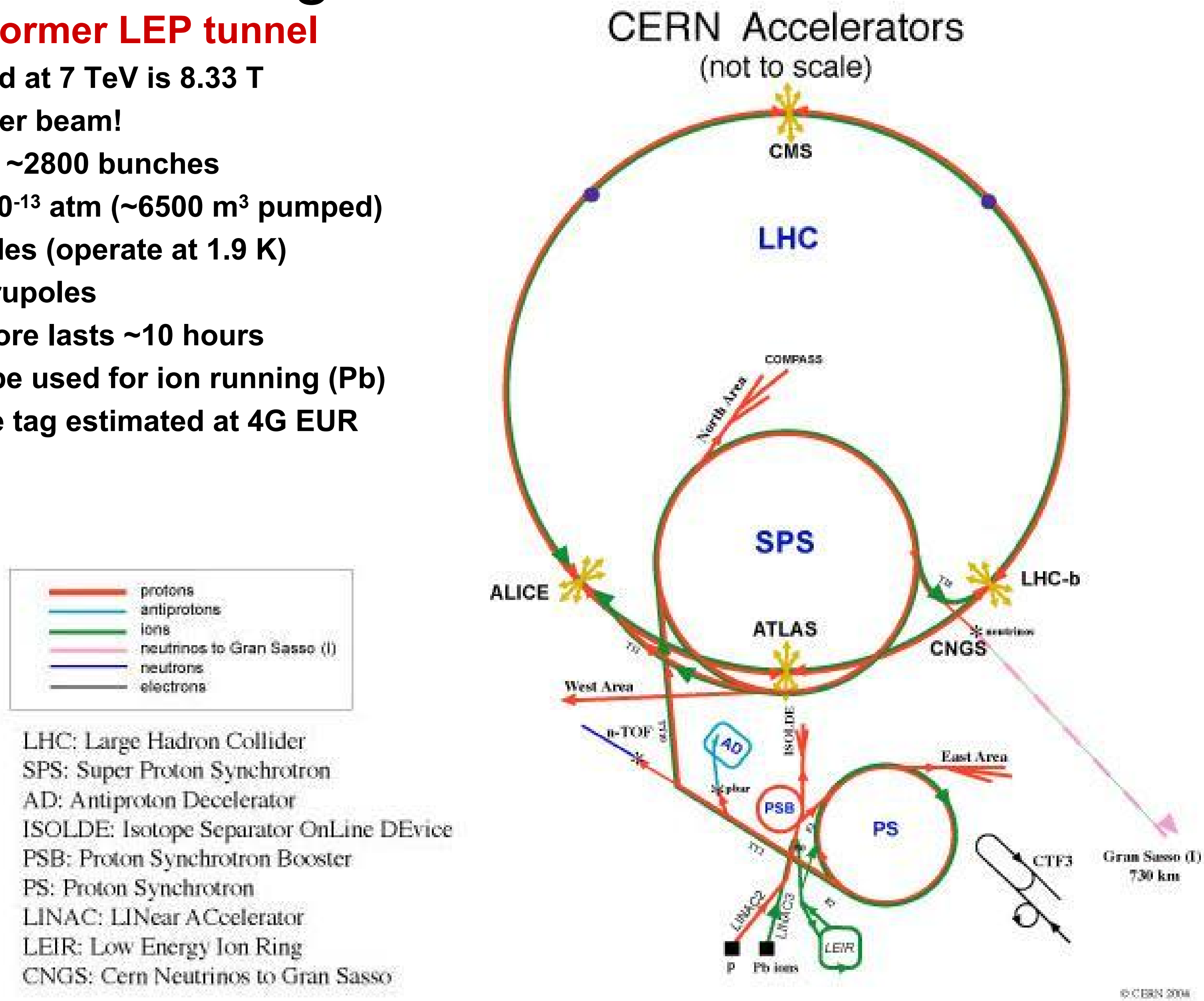
Flow of data from CERN Tier 0 to Tier 1 sites all over the world.

For data processing and analysis, the GRID is an absolute necessity

The Large Hadron Collider

Housed in the former LEP tunnel

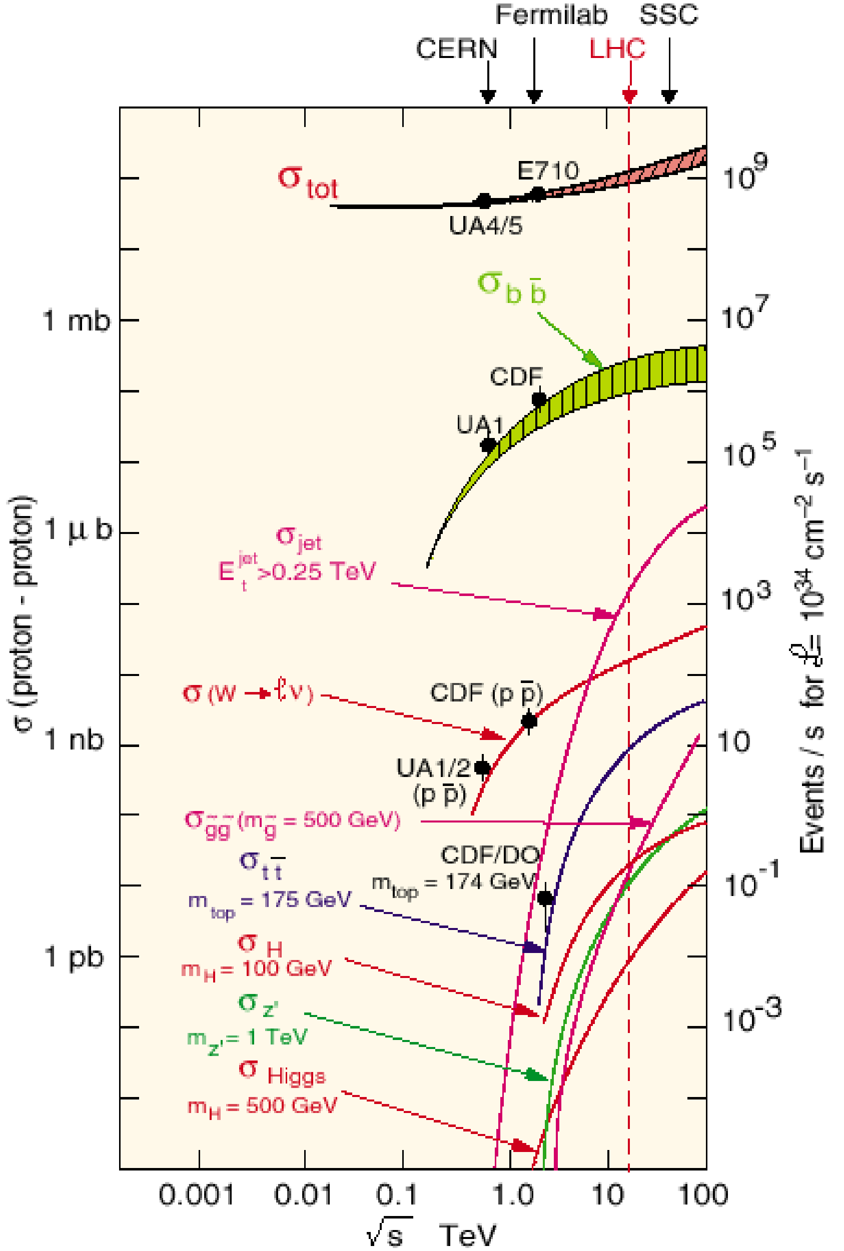
- Dipole field at 7 TeV is 8.33 T
- ~350 MJ per beam!
- Ultimately ~2800 bunches
- Vacuum 10^{-13} atm (~6500 m^3 pumped)
- 1232 Dipoles (operate at 1.9 K)
- 858 Quadrupoles
- Typical store lasts ~10 hours
- Can also be used for ion running (Pb)
- Final price tag estimated at 4G EUR



Expected LHC Event Rates

ATLAS with LHC at $\mathcal{L} = 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Process	Events / s	Events in 10 fb^{-1}
W→ev	15	10^8
Z→ee	1.5	10^7
ttbar	1	10^9
bbbar	10^6	10^{12}-10^{13}
H (m=130)	0.02	10^5



VBF $H \rightarrow \tau\tau$

Decay modes	TAUOLA-CLEO
$\tau \rightarrow e\nu_e\ \nu_\tau$, $\tau \rightarrow \mu\nu_\mu\ \nu_\tau$	17.8 % 17.4 %
$\tau \rightarrow h^{\pm} neutr. \nu_\tau$	49.5 %
$\tau \rightarrow \pi^{\pm}\nu_\tau$	11.1 %
$\tau \rightarrow \pi^0\pi^{\pm}\nu_\tau$	25.4 %
$\tau \rightarrow \pi^0\pi^0\pi^{\pm}\nu_\tau$	9.19 %
$\tau \rightarrow \pi^0\pi^0\pi^0\pi^{\pm}\nu_\tau$	1.08 %
$\tau \rightarrow K^{\pm} neutr. \nu_\tau$	1.56 %
$\tau \rightarrow h^{\pm}h^{\pm}h^{\pm} neutr. \nu_\tau$	14.57 %
$\tau \rightarrow \pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_\tau$	8.98 %
$\tau \rightarrow \pi^0\pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_\tau$	4.30 %
$\tau \rightarrow \pi^0\pi^0\pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_\tau$	0.50 %
$\tau \rightarrow \pi^0\pi^0\pi^0\pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_\tau$	0.11 %
$\tau \rightarrow K^0_S X^{\pm}\nu_\tau$	0.90 %
$\tau \rightarrow (\pi^0)\pi^{\pm}\pi^{\pm}\pi^{\pm}\pi^{\pm}\pi^{\pm}\nu_\tau$	0.10 %
other modes with K	1.30 %
others	0.03 %

Note: All cross-sections are shown in fb

S. Asai et al., ATL-PHYS-2003-005

	signal (fb)		background (fb)					
	VV	gg	$t\bar{t} + jets$	$WW + jets$		$\gamma^*/Z + jets$		Total
				EW	QCD	EW	QCD	
Lepton acceptance	5.55		2014.	18.2	669.8	11.6	2150.	4864.
+ Forward Tagging	1.31		42.0	9.50	0.38	2.20	27.5	81.6
+ P_T^{miss}	0.85		29.2	7.38	0.21	1.21	12.4	50.4
+ Jet mass	0.76		20.9	7.36	0.11	1.17	9.38	38.9
+ Jet veto	0.55		2.70	5.74	0.05	1.11	4.56	14.2
+ Angular cuts	0.40		0.74	1.20	0.04	0.57	3.39	5.94
+ Tau reconstruction	0.37		0.12	0.28	0.001	0.49	2.84	3.73
+ Mass window	0.27	0.01	0.03	0.02	0.0	0.04	0.15	0.24
$H \rightarrow \tau\tau \rightarrow e\mu$	0.27	0.01	0.03	0.02	0.0	0.04	0.15	0.24
$H \rightarrow \tau\tau \rightarrow ee$	0.13	0.01	0.01	0.01	0.0	0.02	0.07	0.11
$H \rightarrow \tau\tau \rightarrow \mu\mu$	0.14	0.01	0.01	0.01	0.0	0.02	0.07	0.11

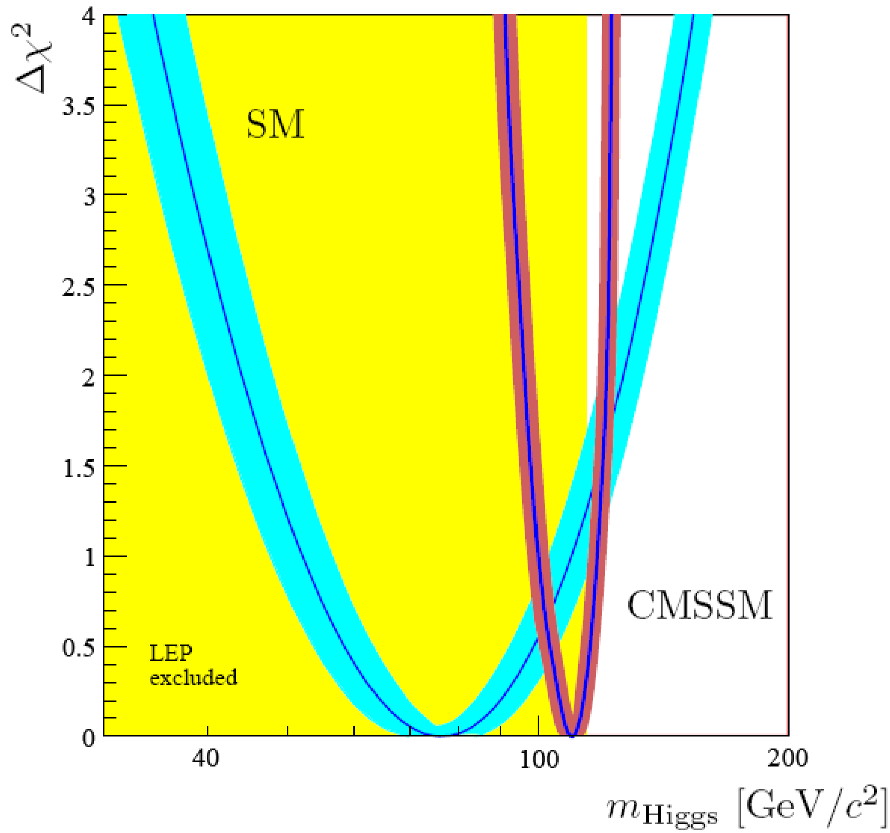
CMSSM

Constrained MSSM

- O. Buchmueller et al., arXiv:0707.3447v2 [hep-ph]
- CMSSM: M_h = 110 (+8)(-10) ± 3 (theo.) GeV
- Includes CDM, flavor physics and a_μ experimental data

CMSSM parameter	Preferred value
M_0	(85^{+40}_{-25}) GeV/c^2
$M_{1/2}$	(280^{+140}_{-30}) GeV/c^2
A_0	(-360^{+300}_{-140}) GeV/c^2
$\tan\beta$	10^{+9}_{-4}
sgn(μ)	+1 (fixed)

Table 2
Values of the CMSSM parameters at the globally preferred χ^2 minimum, and corresponding 1-sigma errors. The lower limit of Eq. 2 is included.



chi² / ndf = 17.34 / 14

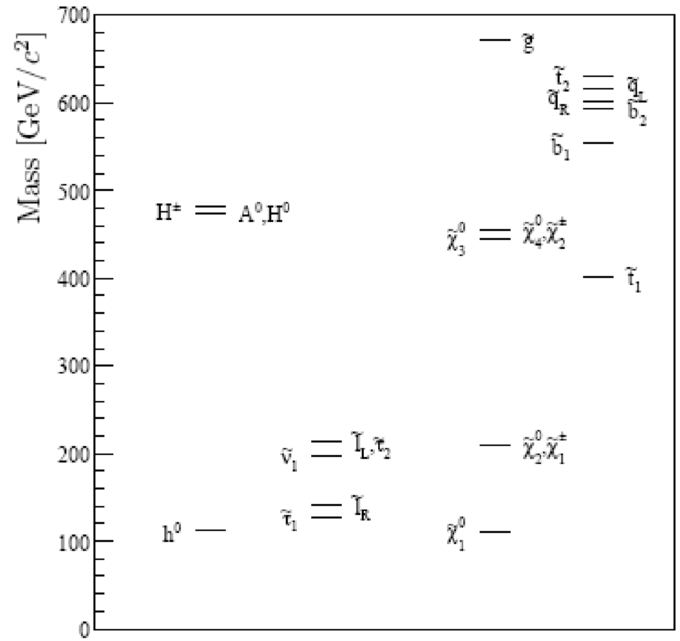


Figure 2. Mass spectrum of super-symmetric particles at the globally preferred χ^2 minimum. Particles with mass difference smaller than 5 GeV/c^2 have been grouped together.

Central Jet Veto and Pile-up

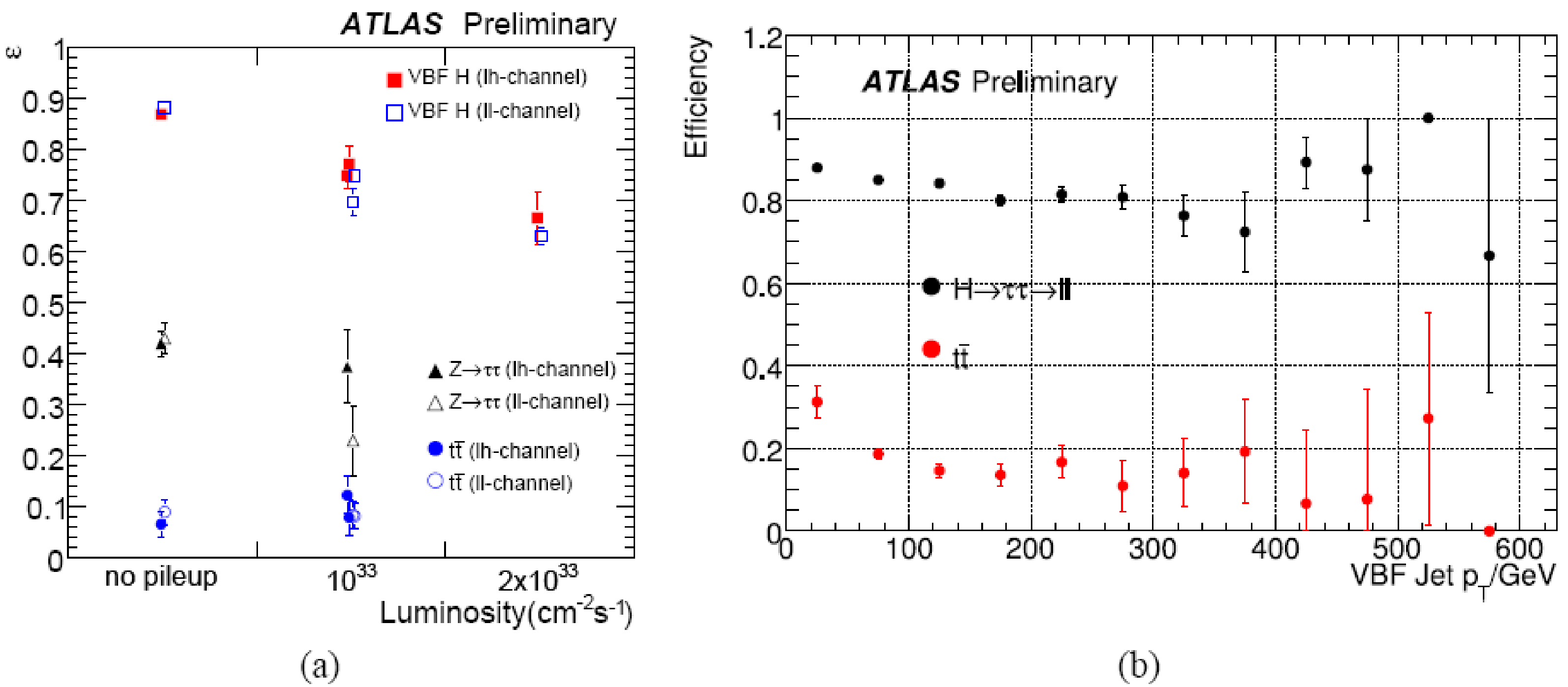


Figure 7: (a) Central Jet Veto performance in the presence of varying levels of pileup for signal and background samples. (b) Performance of the b-jet tagging as a function of the forward jet p_T in the events, where the $t\bar{t}$ processes is analyzed.

Impact Parameter

Displaced vertices present

in Zbb and tt

Impact Parameter Significance ≡ d_0/σ_{d0}

Transverse impact parameter resolution

~15 μm for P_T = 20 GeV

Transverse primary vertex spread

~15 μm, taken into account

Isolation + Impact Parameter Criteria

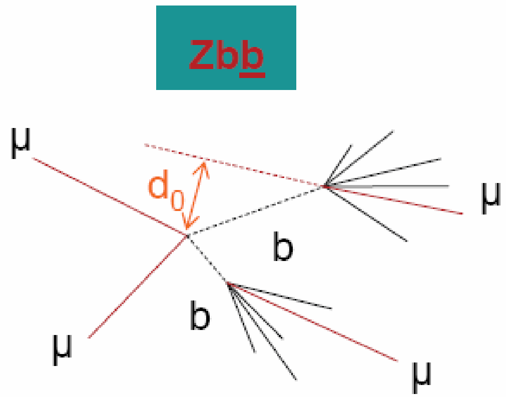
O(10^2) Rejection for Zbb

O(10^3) Rejection for tt

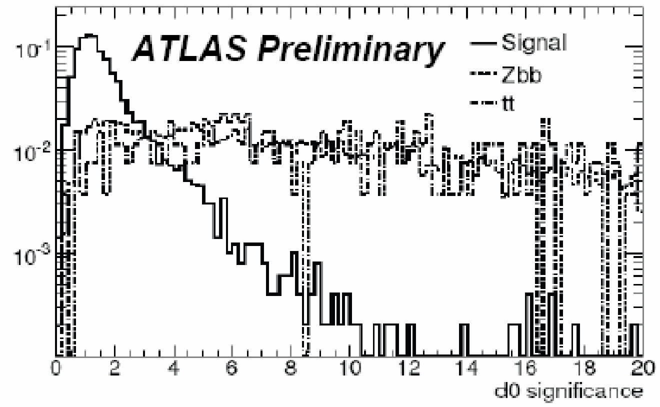
for signal efficiency O(80%)

preliminary

Effect of pile-up on signal significance ≤5%



H(130 GeV) → ZZ* → 4μ



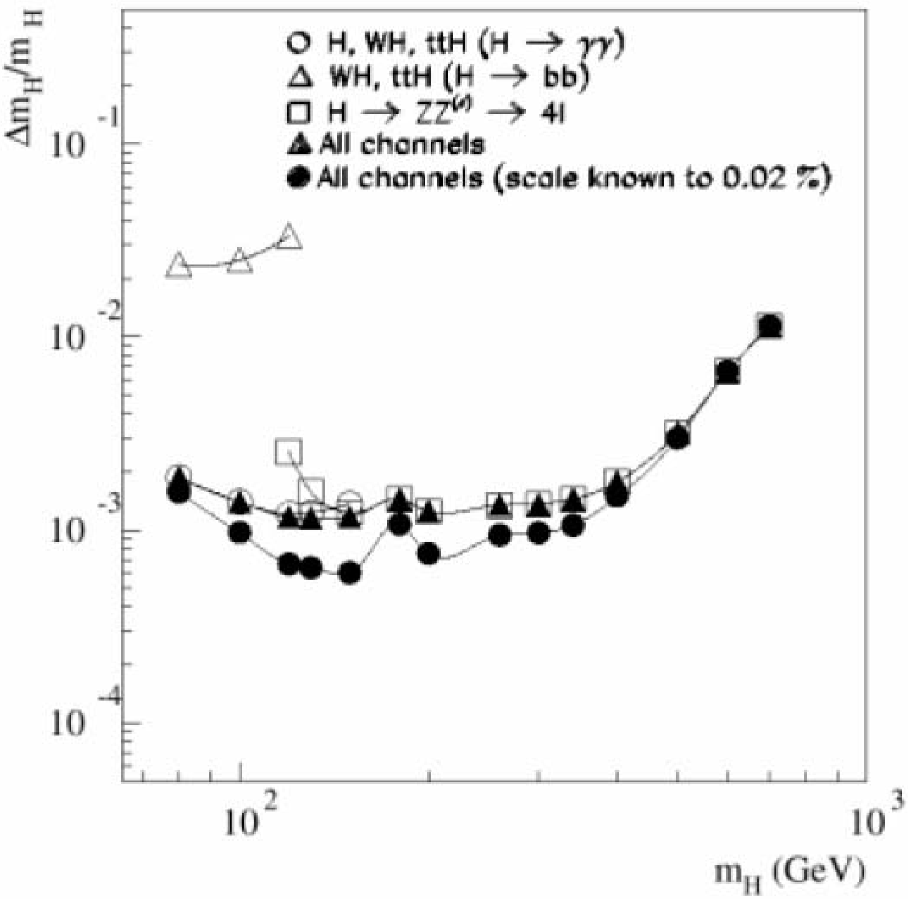
Higgs Properties: Mass

Mass

Favoured mass of SM Higgs
113.5 < mH < 212 GeV

In this range m_H can be measured to 0.1% using $\gamma\gamma$ and 4ℓ channels

Energy scale can be calibrated to 0.1% using $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$

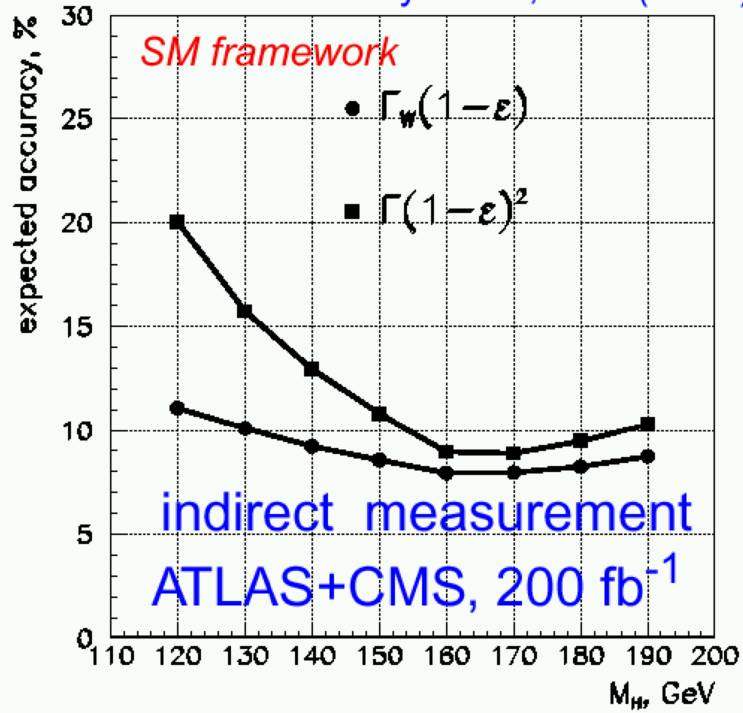


Higgs Properties: Width

- **precise measurement of width**

  qq->qqh. h->2γ,WW$^{(*)}$, 2τ together with gg->WW$^{(*)}$ allows indirect measurement of Higgs width

  D. Zeppenfeld, R. Kinnunen, A. Nikitenko
  E. Richter-Was. Phys.Rev., D62 (2000)



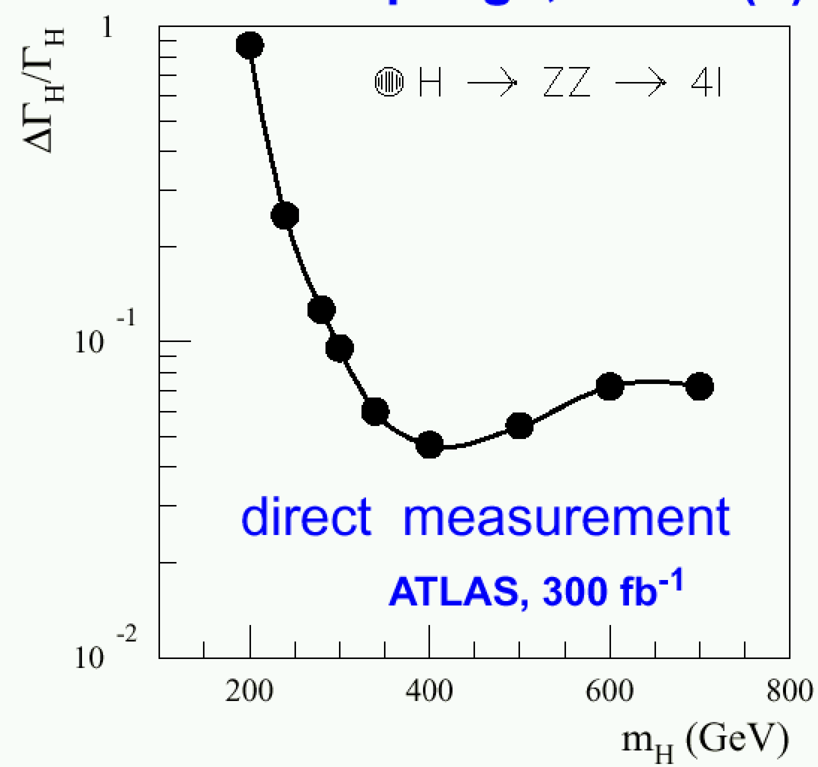
- **observation of other Higgs channels :**

  Wh with h->bb, h->γγ

  tth with h->γγ, WW

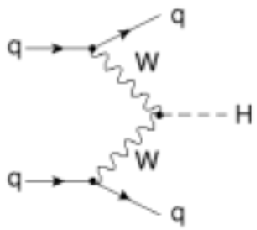
  qqh, with h->μμ (?)

- **self couplings; h->hh (?)**



Higgs Properties: Cross-sections

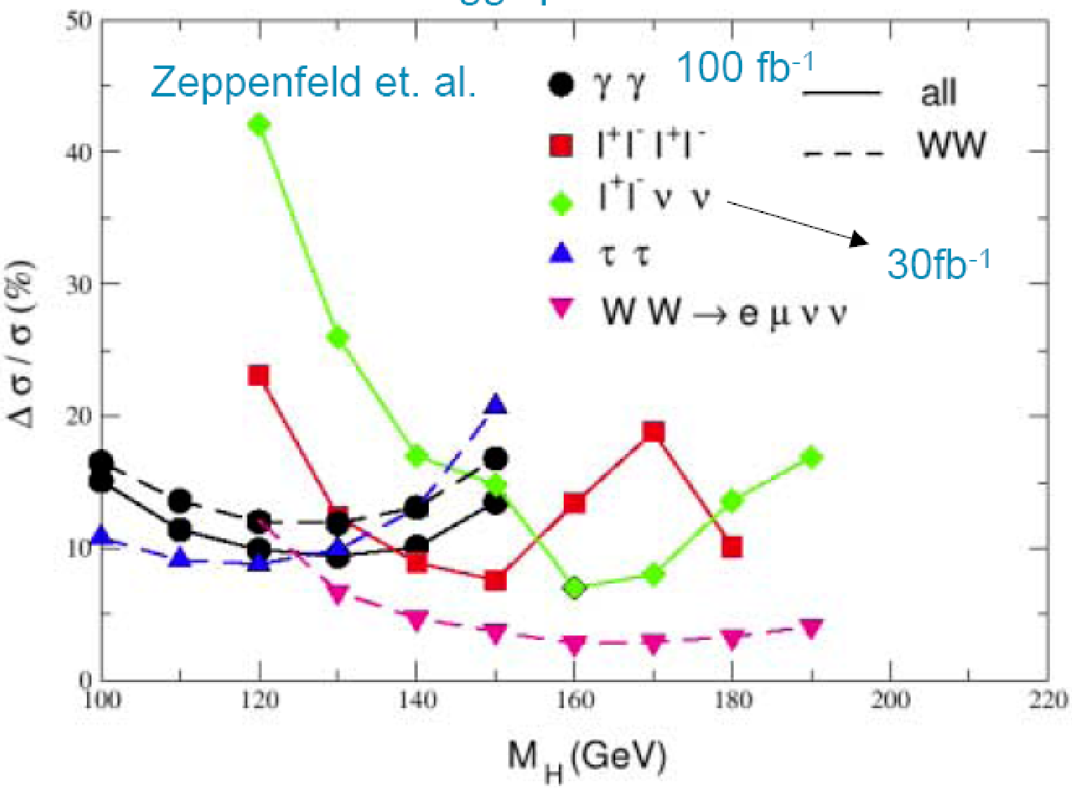
10% of σ in intermediate mass region comes from WW fusion
Identified by requiring forward tagging jets and no additional central jets



Errors
Statistical: 5 – 20%
γγ and 4ℓ well understood
Modes involving fwd jets more difficult to estimate

Corrected σ compared with perturbative QCD calculations
Known to NLO for all and NNLO for gg→H processes

Higgs production via WW fusion



Higgs Properties: Couplings and BRs

Use various Higgs production and decay modes
In ratios luminosity uncertainty largely cancels
Assuming 300 fb-1

$$\frac{\sigma.B(t\bar{t}H + WH \to \gamma\gamma)}{\sigma.B(t\bar{t}H + WH \to b\bar{b})} \Rightarrow \frac{BR(H \to \gamma\gamma)}{BR(H \to b\bar{b})}$$

$$\frac{\sigma.B(H \to \gamma\gamma)}{\sigma.B(H \to ZZ^*)} \Rightarrow \frac{BR(H \to \gamma\gamma)}{BR(H \to ZZ^*)}$$

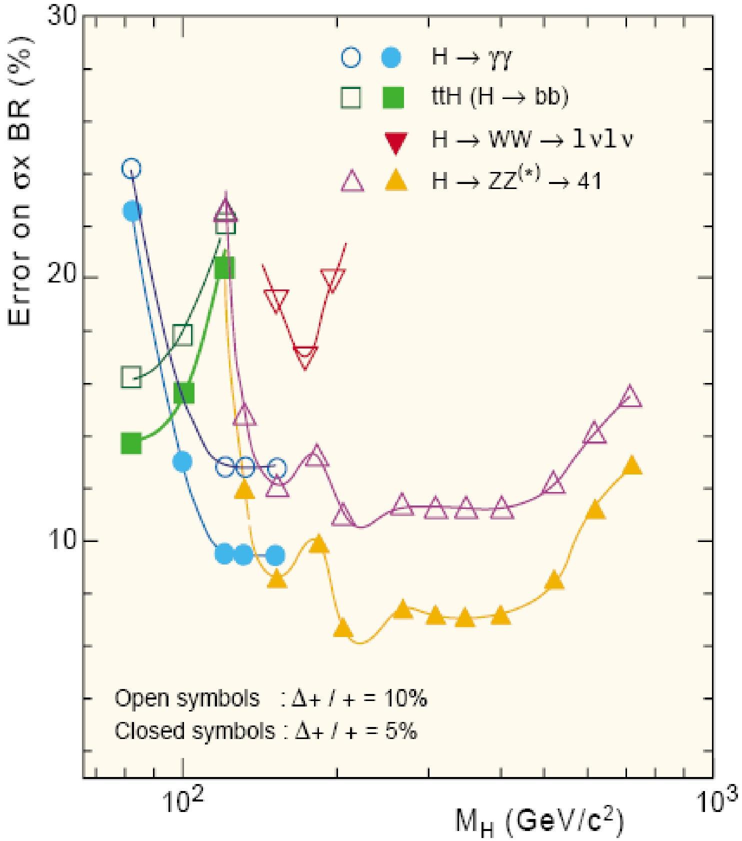
$$\frac{\sigma.B(t\bar{t}H \to \gamma\gamma / b\bar{b})}{\sigma.B(WH \to \gamma\gamma / b\bar{b})} \Rightarrow \frac{g^2_{Ht\bar{t}}}{g^2_{HWW}}$$

$$\frac{\sigma.B(H \to WW^* / W)}{\sigma.B(H \to ZZ^* / Z)} \Rightarrow \frac{g^2_{HWW}}{g^2_{HZZ}}$$

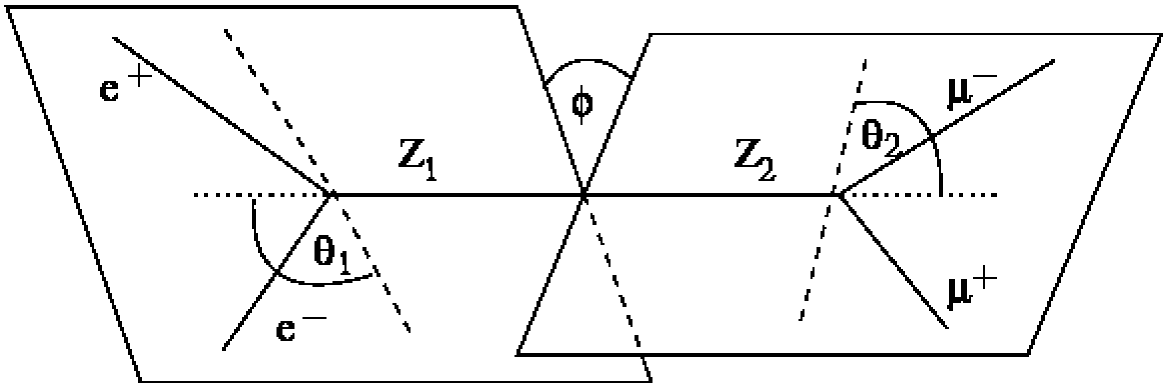
Higgs Properties: Branching Ratios

BR cannot be measured directly at the LHC
But possible to infer ratios of couplings from measured rates

Measure	Error	M_H range
$\frac{B(H \to \gamma\gamma)}{B(H \to b\bar{b})}$	30%	80–120
$\frac{B(H \to \gamma\gamma)}{B(H \to ZZ^*)}$	15%	125–155
$\frac{\sigma(t\bar{t}H)}{\sigma(WH)}$	25%	80–130
$\frac{B(H \to WW^{(*)})}{B(H \to ZZ^{(*)})}$	30%	160–180



Higgs Properties: CP



Azimutal angle ϕ between decay planes in the rest frame of Higgs

$$F(\phi) = 1 + \alpha \cos(\phi) + \beta \cos(2\phi)$$

Polar angle θ between lepton and the Z momentum in Z rest frame

$$G(\theta) = L \sin^2(\theta) + T(1+\cos^2(\theta)),\ R=(L-T)/(L+T)$$

M_{Z*} distribution for $M_H < 2\,M_Z$, $d\Gamma_H/dM_{Z*}^2 \sim \beta^n$ near threshold (n=1 in SM)

$$\beta^2=[1-(M_Z+M_{Z*})^2/M_H^2][1-(M_Z-M_{Z*})^2/M_H^2]$$

Resent ATLAS fast simulation study on sensitivity to $F(\phi)$ and $G(\theta)$ for exclusion of 0^-, 1^+, 1^- for $M_H > 2M_Z$: SN-ATLAS-2003-025