PART 2

The LHC physics programme

- Search for Standard Model Higgs boson over ~ $120 < m_H < 1000$ GeV.

- Search for Supersymmetry and other physics beyond the SM (q/ℓ compositness, leptoquarks, W'/Z', heavy q/ℓ, unpredicted ? ….) up to masses of ~ 5 TeV

- Precise measurements :
  - -- W mass
  - -- WWγ, WWZ Triple Gauge Couplings
  - -- top mass, couplings and decay properties
  - -- Higgs mass, spin, couplings (if Higgs found)
  - -- B-physics: CP violation, rare decays, B^0 oscillations (ATLAS, CMS, LHCb)
  - -- QCD jet cross-section and α_s

  - -- etc. ….

- Study of phase transition at high density from hadronic matter to plasma of deconfined quarks and gluons. Transition plasma → hadronic matter happened in universe ~ 10^{-5} s after Big Bang (ALICE)

Keyword: large event statistics

Expected event rates in ATLAS/CMS for representative (known and new) physics processes at low luminosity (L=10^{33} cm^{-2} s^{-1})

Process	Events/s	Events/year	Other machines (total statistics)
$W \to e\nu$	15	10^8	10^4 LEP / 10^7 Tev.
$Z \to ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	0.8	10^7	10^4 Tevatron
$b\bar{b}$	10^5	10^{12}	10^8 Belle/BaBar
$\tilde{g}\tilde{g}$ (m=1 TeV)	0.001	10^4	—
H (m=0.8 TeV)	0.001	10^4	—
QCD jets $p_T > 200$ GeV	10^2	10^9	10^7

High L : statistics 10 times larger

→ LHC is a B-factory, top factory, W/Z factory Higgs factory, SUSY factory, etc….

Precise measurements of: m_W , m_{top}

Motivation:

W mass and top mass are fundamental parameters of the Standard Model:

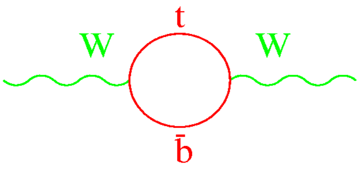
Electromagnetic constant
measured in atomic transitions,
e^+e^- machines, etc.

$$m_W = \left(\frac{\pi \, \alpha_{EM}}{\sqrt{2} \, G_F} \right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

Fermi constant
measured in muon
decay

Weinberg angle
measured at
LEP/SLC

radiative corrections
$\Delta r \sim f\,(m_{top}^2, \log m_H)$
$\Delta r \approx 3\%$



→ since G_F, α_{EM}, $\sin\theta_W$ are known with high precision, precise measurements of m_{top} and m_W constrain radiative corrections and Higgs mass (weakly because of logarithmic dependence)

So far : W mass measured at LEP2 and Tevatron
top mass measured at the Tevatron

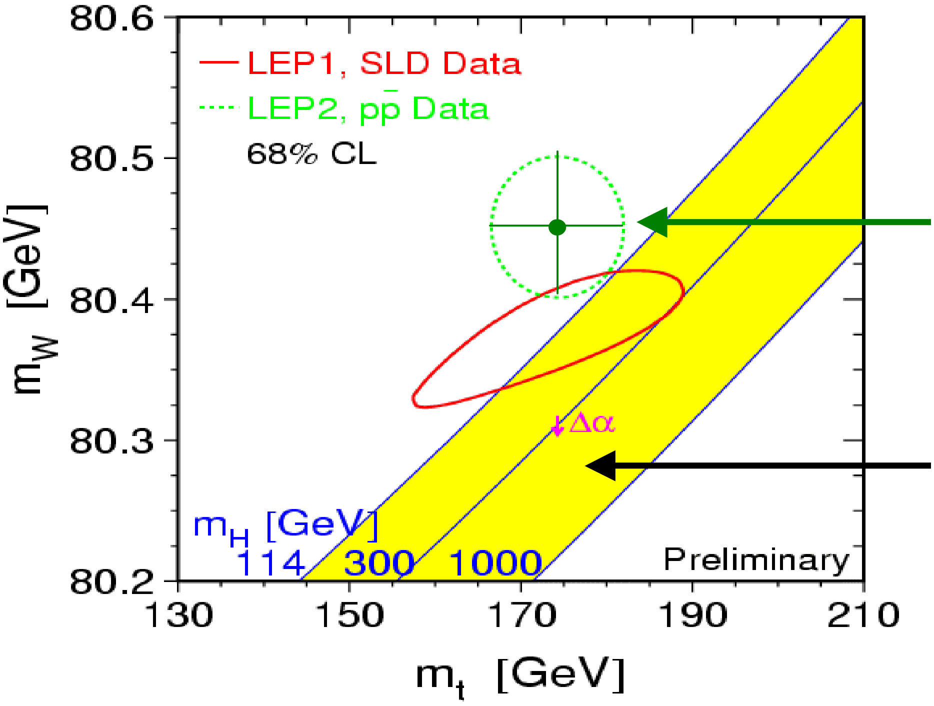
$$m_W = \left(\frac{\pi \, \alpha_{EM}}{\sqrt{2}\, G_F} \right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

m_W (from LEP2 + Tevatron) = 80.450 ± 0.034 GeV

$4 \cdot 10^{-4}$

m_{top} (from Tevatron) = 174.3 ± 5.1 GeV

3%



Direct measurements

m_H dependence in SM through radiative corrections

→ light Higgs is favoured

Year 2007:

$\Delta m_W \approx 25$ MeV (0.3 ‰) from LEP/Tevatron

$\Delta m_{top} \approx 2$ GeV (1%) from Tevatron

Can LHC do better ?

YES

: thanks to large statistics

Measurement of W mass

Method used at hadron colliders different from e^+e^- colliders

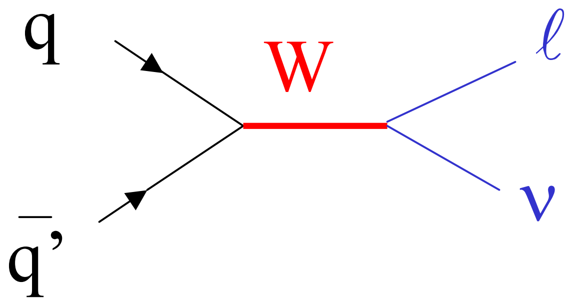
- $W \to$ jet jet : cannot be extracted from QCD jet-jet production ⇒ cannot be used
- $W \to \tau\nu$: since $\tau \to \nu + X$, too many undetected neutrinos ⇒ cannot be used

⬇

only $W \to e\nu$ and $W \to \mu\nu$ decays are used to measure m_W at hadron colliders

W production at LHC :

Ex.



$$\sigma\,(pp \to W + X) \approx 30\ \text{nb}$$

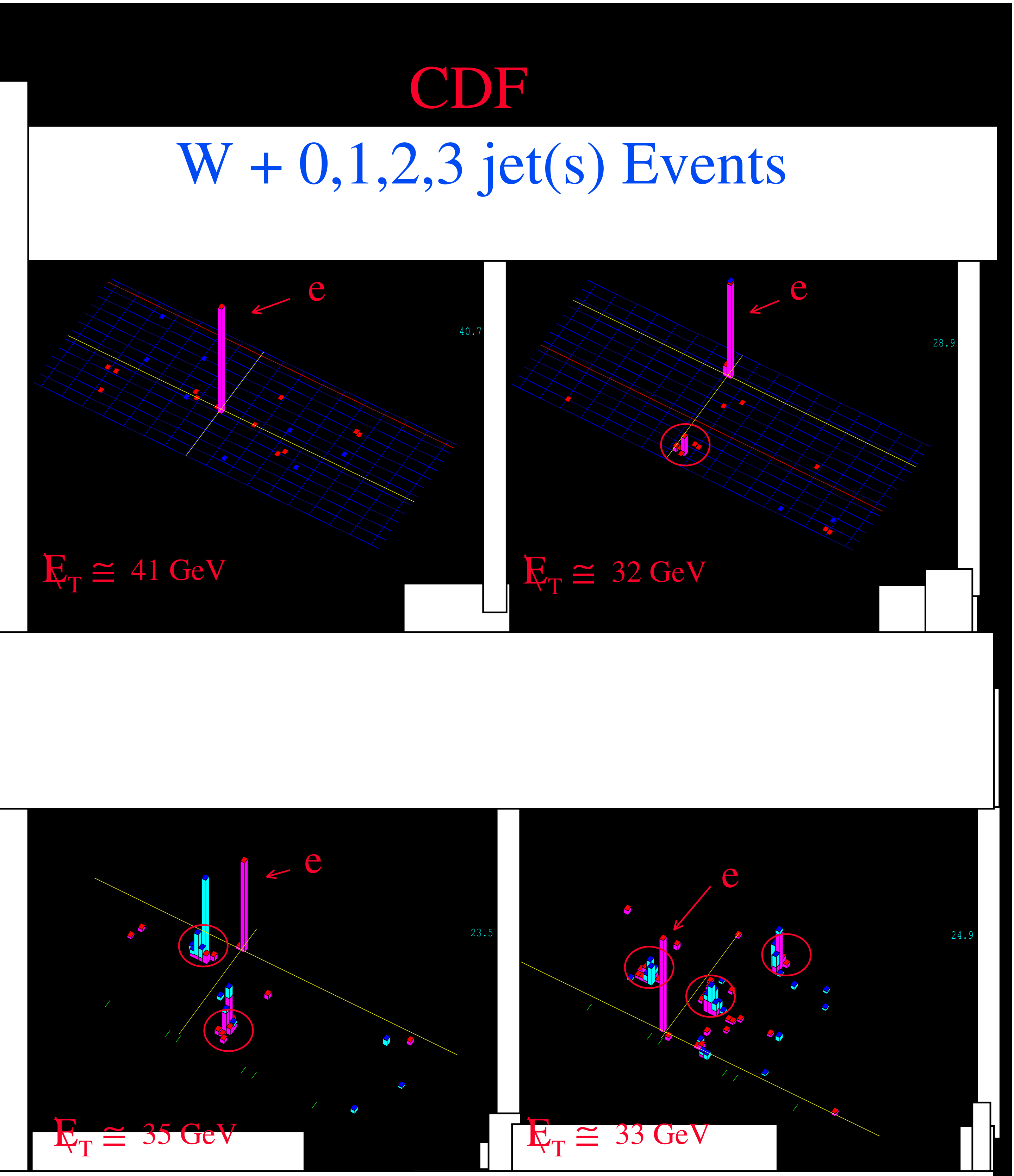
$$\hookrightarrow e\nu,\ \mu\nu$$

$\sim 300 \times 10^6$ events produced
$\sim 60 \times 10^6$ events selected after analysis cuts

} one year at low L, per experiment

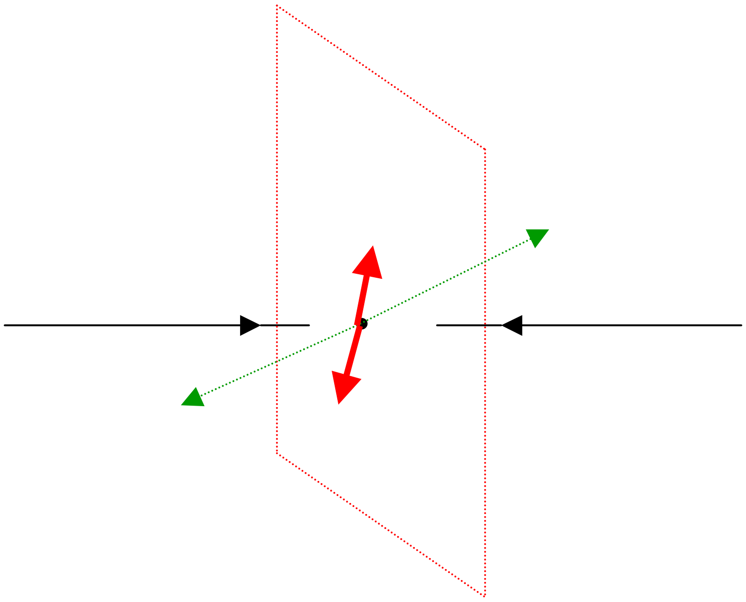
$\sim$ 50 times larger statistics than at Tevatron
$\sim$ 6000 times larger statistics than WW at LEP

$W \rightarrow e\nu$ events (data) from CDF experiment at the Tevatron



$$m_W{}^2 = (E_\ell + E_\nu)^2 - (\vec{p}_\ell + \vec{p}_\nu)^2 = 2E_\ell E_\nu (1 - \cos\theta_{\ell\nu})$$

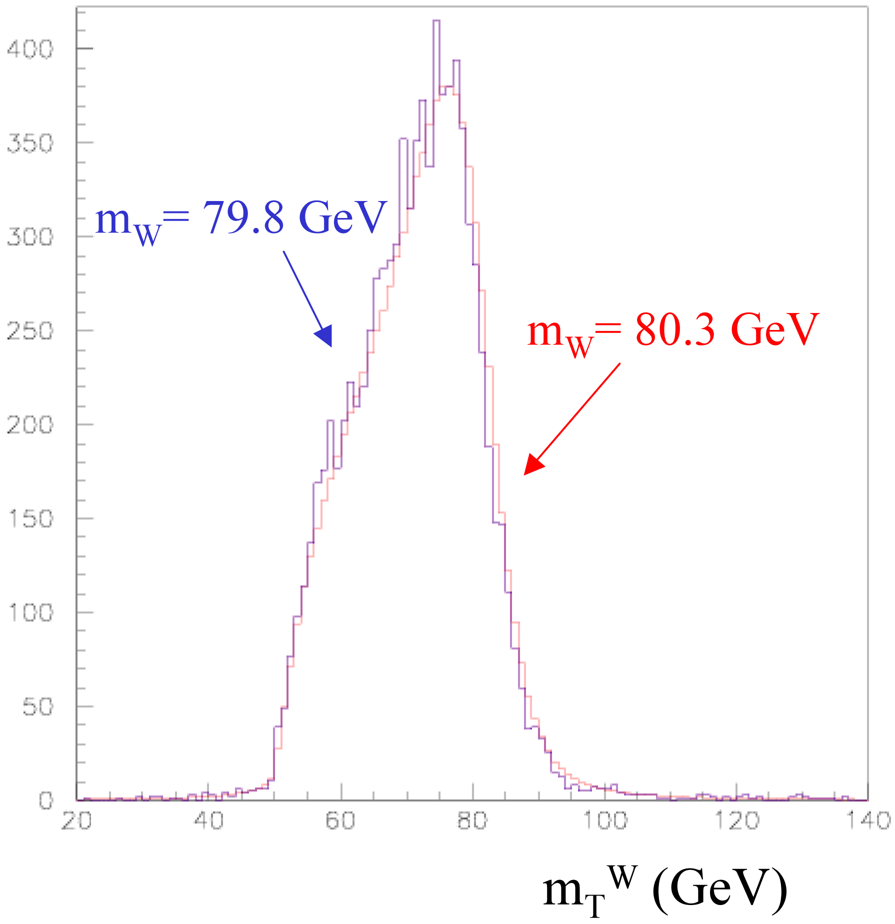
Since $\vec{p}_L{}^\nu$ not known (only $\vec{p}_T{}^\nu$ can be measured through $E_T{}^{miss}$), measure transverse mass, i.e. invariant mass of $\ell\nu$ in plane perpendicular to the beam :



$$m_T{}^W = \sqrt{2p_T{}^\ell \, p_T{}^\nu (1 - \cos\varphi_{\ell\nu})}$$

$$\underbrace{p_T{}^\nu}_{\equiv E_T{}^{miss}}$$

$m_T{}^W$ distribution is sensitive to m_W



$m_T{}^W$ distribution expected in ATLAS

⇒ fit experimental distributions with SM prediction (Monte Carlo simulation) for different values of m_W → find m_W which best fits data

Uncertainties on m_W

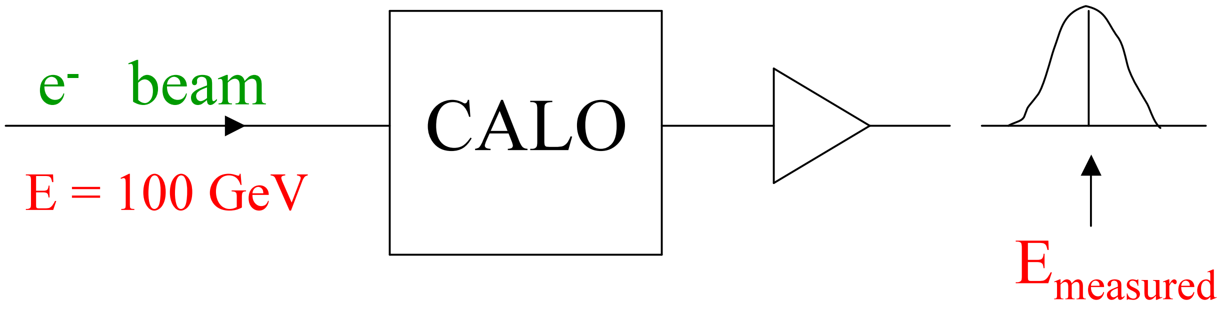
Come mainly from capability of Monte Carlo prediction to reproduce real life, that is:

- detector performance: energy resolution, energy scale, etc.
- physics: p_T^W, θ_W, Γ_W, backgrounds, etc.

Dominant error (today at Tevatron, most likely also at LHC):
knowledge of lepton energy scale of the detector:
if measurement of lepton energy wrong by 1%, then measured m_W wrong by 1%

Calibration of detector energy scale

Example : EM calorimeter



e^- beam

E = 100 GeV

CALO

E_{measured}

- if $E_{\text{measured}} = 100.000$ GeV→ calorimeter is perfectly calibrated
- if $E_{\text{measured}} = 99, 101$ GeV → energy scale known to 1%

- to measure m_W to ~ 20 MeV need to know energy scale to 0.2 ‰ , i.e.

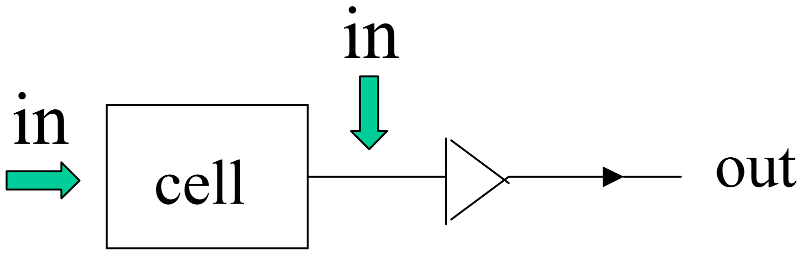
  if $E_{\text{electron}} = 100$ GeV then

  $99.98 \text{ GeV} < E_{\text{measured}} < 100.02 \text{ GeV}$

⇒ one of most serious experimental challenges

Calibration strategy:

- detectors equipped with calibration systems which inject known pulses:



in

in

cell

out

→ check that all cells give same response:
if not → correct

- calorimeter modules calibrated with test beams of known energy → set the energy scale

- inside LHC detectors: calorimeter sits behind inner detector → electrons lose energy in material of inner detector → need a final calibration " *in situ* " by using physics samples:

e.g. $Z \to e^+ e^-$ decays 1/sec at low L

constrain $m_{ee} = m_Z$

reconstructed

known to ≈ 10^{-5} from LEP

Expected precision on m_W at LHC

Source of uncertainty	Δm_W
Statistical error	$<<$ 2 MeV
Physics uncertainties (p_T^W, θ_W, Γ_W, …)	$\sim$ 15 MeV
Detector performance (energy resolution, lepton identification, etc,)	$<$ 10 MeV
Energy scale	15 MeV
Total (per experiment, per channel)	$\sim$ 25 MeV

Combining both channels ($e\nu$, $\mu\nu$) and both experiments (ATLAS, CMS), $\Delta m_W \approx$ 15 MeV should be achieved.
However: very difficult measurement

Measurement of m_{top}

- Top is most intriguing fermion:

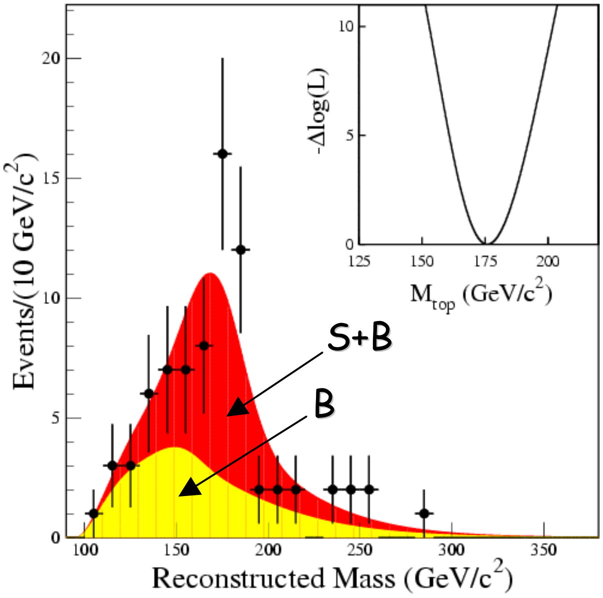
-- $m_{top} \approx 174$ GeV → clues about origin of particle masses ?

-- $\begin{bmatrix} u \\ d \end{bmatrix} \quad \begin{bmatrix} c \\ s \end{bmatrix} \quad \begin{bmatrix} t \\ b \end{bmatrix} \longleftarrow$ Δm (t-b) ≈ 170 GeV → radiative corrections

- Discovered in '94 at Tevatron → precise measurements of mass, couplings, etc. just started

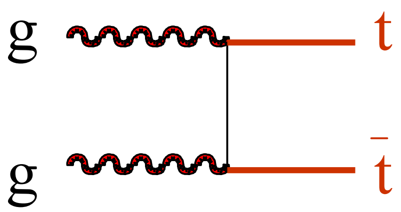
Top mass spectrum from CDF

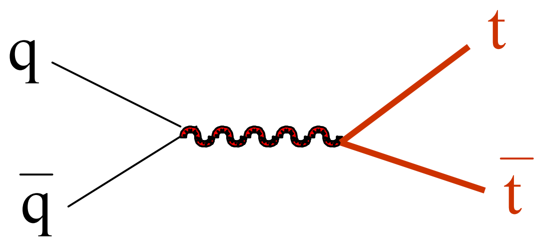
$t\bar{t} \to b\ell\nu\ bjj$ events



Top production at LHC:

e.g.





$\sigma\,(pp \to t\bar{t} + X) \approx 800$ pb

⬇

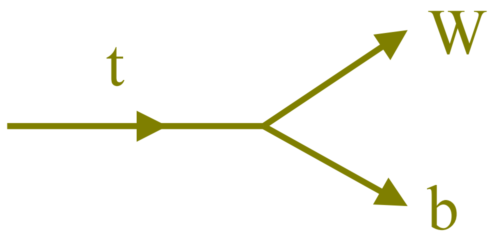
10^7 $t\bar{t}$ pairs produced in one year at low L

~ 10^2 times more than at Tevatron

☺ measure m_{top}, σ_{tt}, BR, V_{tb}, single top, rare decays (e.g. $t \to Zc$), resonances, etc.

☹ $t\bar{t}$ production is the main background to new physics (SUSY, Higgs)

Top decays:



BR ≈ 100% in SM

-- hadronic channel: both W → jj

⇒ 6 jet final states. BR ≈ 50 % but large QCD multijet background.

-- leptonic channel: both W → $\ell\nu$

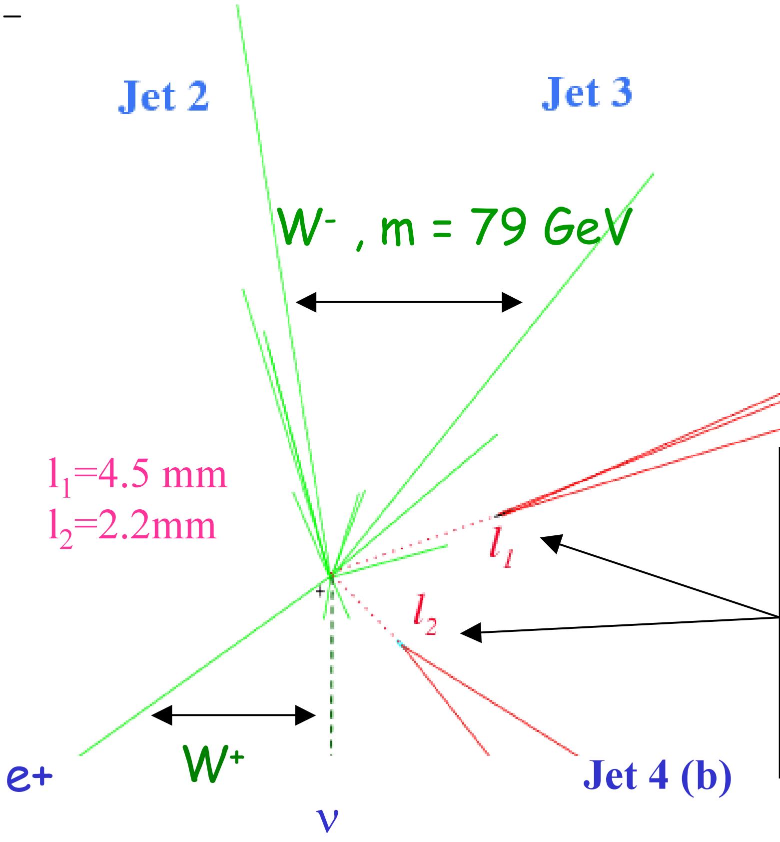
⇒ 2 jets + 2ℓ + E_T^{miss} final states. BR ≈ 10 %. Little kinematic constraints to reconstruct mass.

-- semileptonic channel: one W → jj , one W → $\ell\nu$

⇒ 4 jets + 1ℓ + E_T^{miss} final states. BR ≈ 40 %. If ℓ = e, μ : gold-plated channel for mass measurement at hadron colliders.

In all cases two jets are b-jets
⇒ displaced vertices in the inner detector

Example from CDF : $t\bar{t} \to Wb\,Wb \to b\ell\nu\, bjj$ event

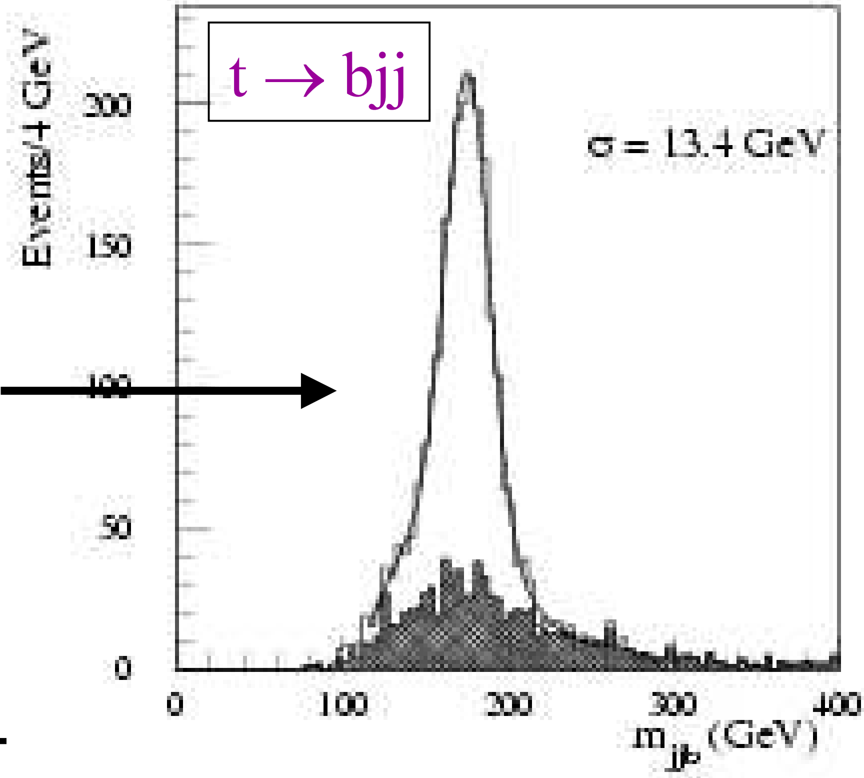


Secondary vertices
τ(b-hadrons) ~ 1.5 ps
→ decay at few mm from primary vertex detected with high-granularity Si detector (b-tagging)

ATLAS

Selection :

- -- two b-tagged jets
- -- one lepton
- -- $E_T^{miss} > 20$ GeV
- -- two more jets with $|m_{jj}-m_W| < 20$ GeV



Expected precision on m_{top} at LHC

Source of uncertainty	Δm_{top}
Statistical error Physics uncertainties (background, FSR, ISR, fragmentation, etc.) Jet scale (b-jets, light-quark jets)	<< 100 MeV ~ 1.3 GeV ~ 0.8 GeV
Total (per experiment, per channel)	~ 1.5 GeV

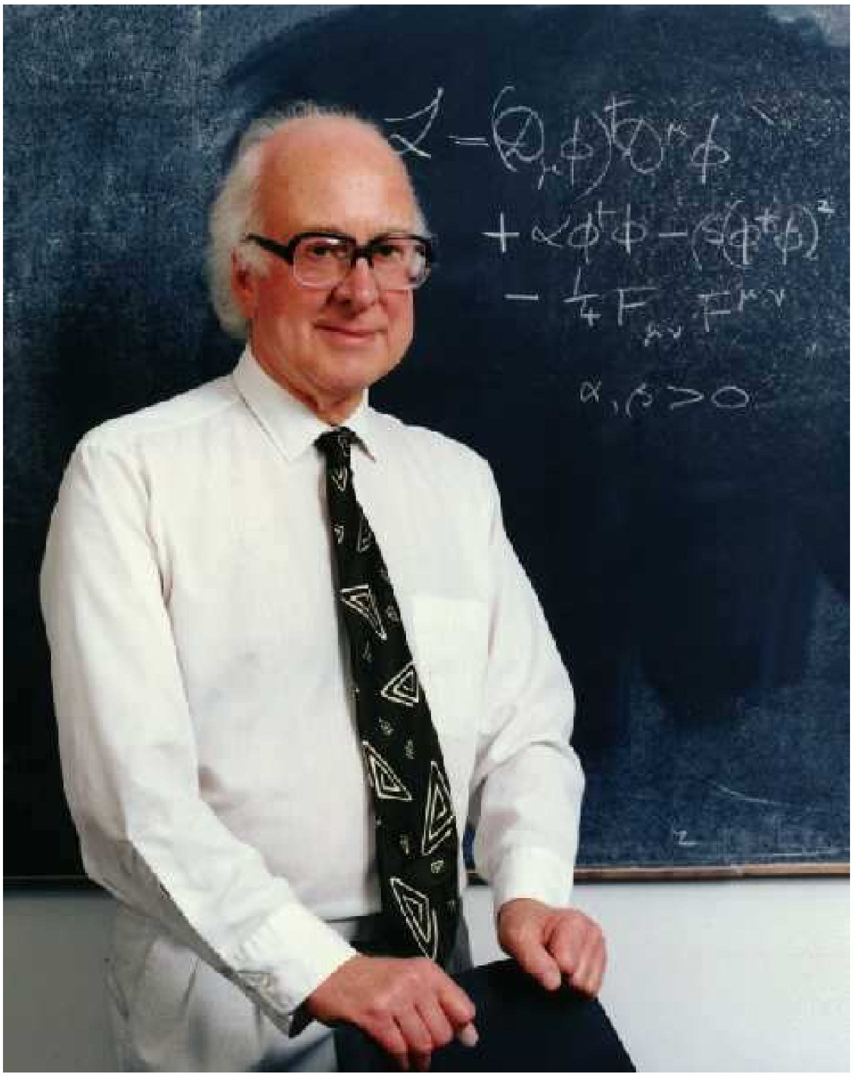
- Uncertainty dominated by the knowledge of physics and not of detector.
- By combining both experiments and all channels :
  $\Delta m_{top} \sim 1$ GeV at LHC

From $\Delta m_{top} \sim 1$ GeV, $\Delta m_W \sim 15$ MeV
→ indirect measurement $\Delta m_H/m_H \sim 25\%$ (today ~ 50%)

If / when Higgs discovered, comparison of measured m_H with indirect measurement will be essential consistency checks of EWSB

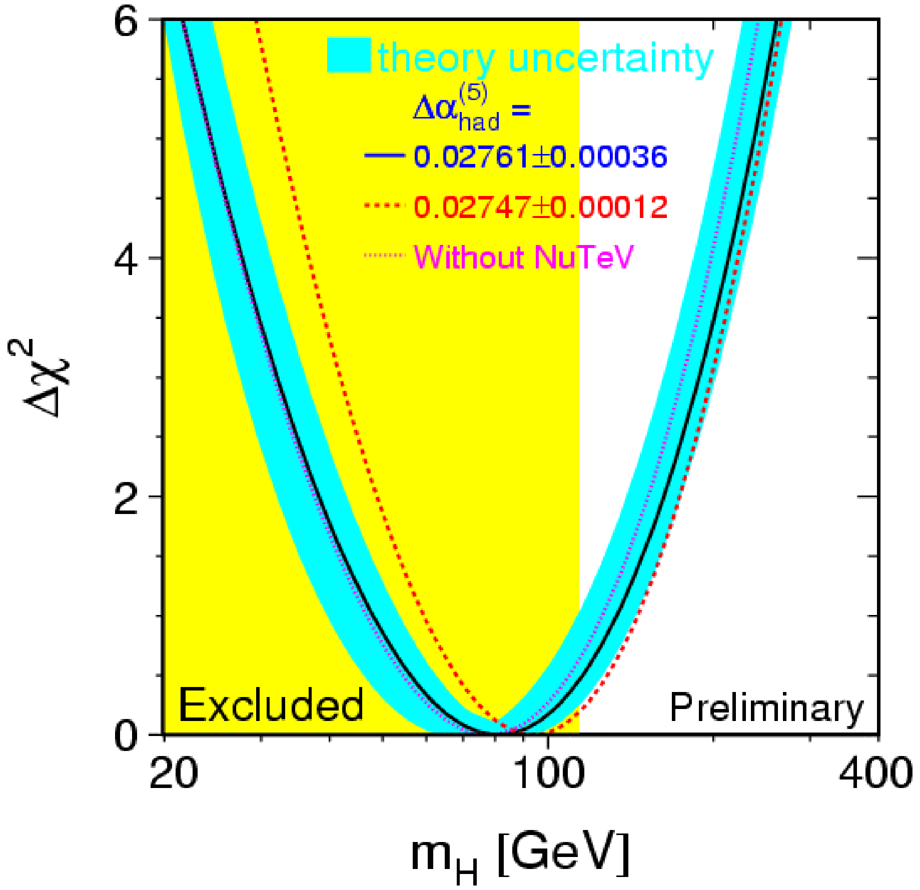
Searches for the Standard Model Higgs boson

Where is
the Higgs ?



What do we know today about it ?

- Needed in SM to generate particle masses
- Mass not predicted by theory except that $m_H < 1000$ GeV
- $m_H > 114.4$ GeV from direct searches at LEP
- Indirect limits from fit of SM to:
  - -- LEP1/SLD precise measurements at $\sqrt{s} = m_Z$
  - -- m_W measurement LEP2/Tevatron
  - -- m_{top} measurement at Tevatron



Best fit of SM to data (minimum χ^2) found for $m_H = 81^{+52}_{-33}$ GeV

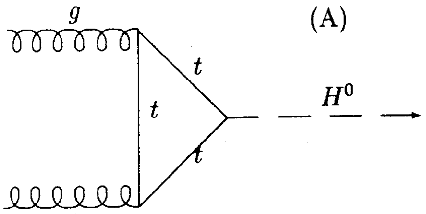
$m_H < 193$ GeV 95% C.L.

→ Higgs could be around the corner !

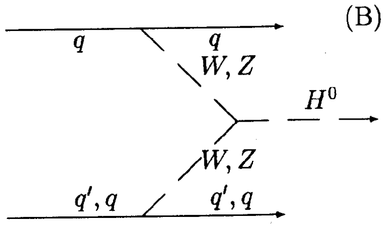
- ≈ 1.7 σ excess from LEP for $m_H \sim 115$ GeV
- Higgs production and decays versus m_H predicted

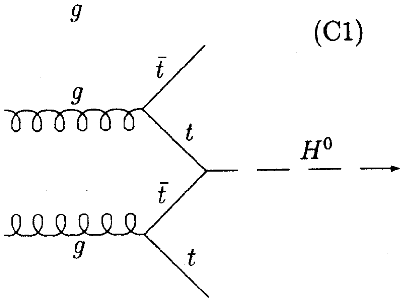
Higgs production at LHC

gg fusion

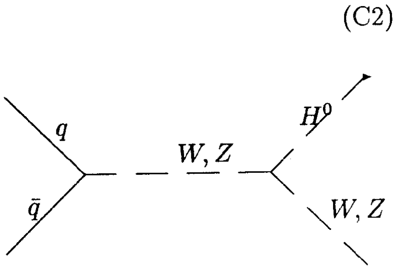


WW/ZZ fusion



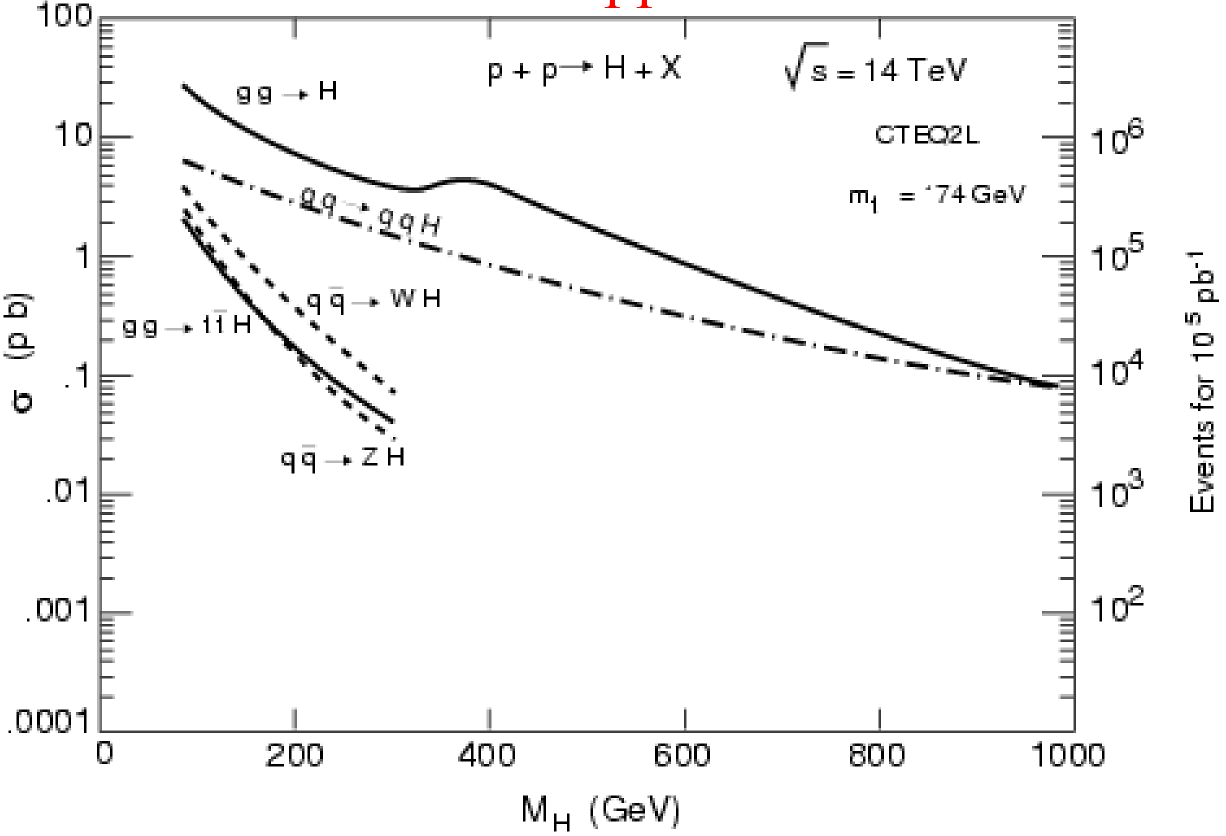


associated $t\bar{t}H$

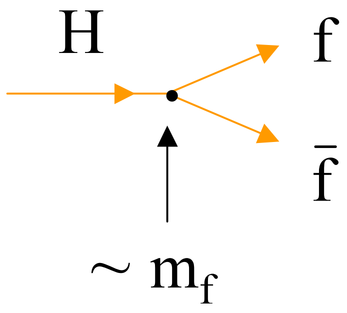


associated WH, ZH

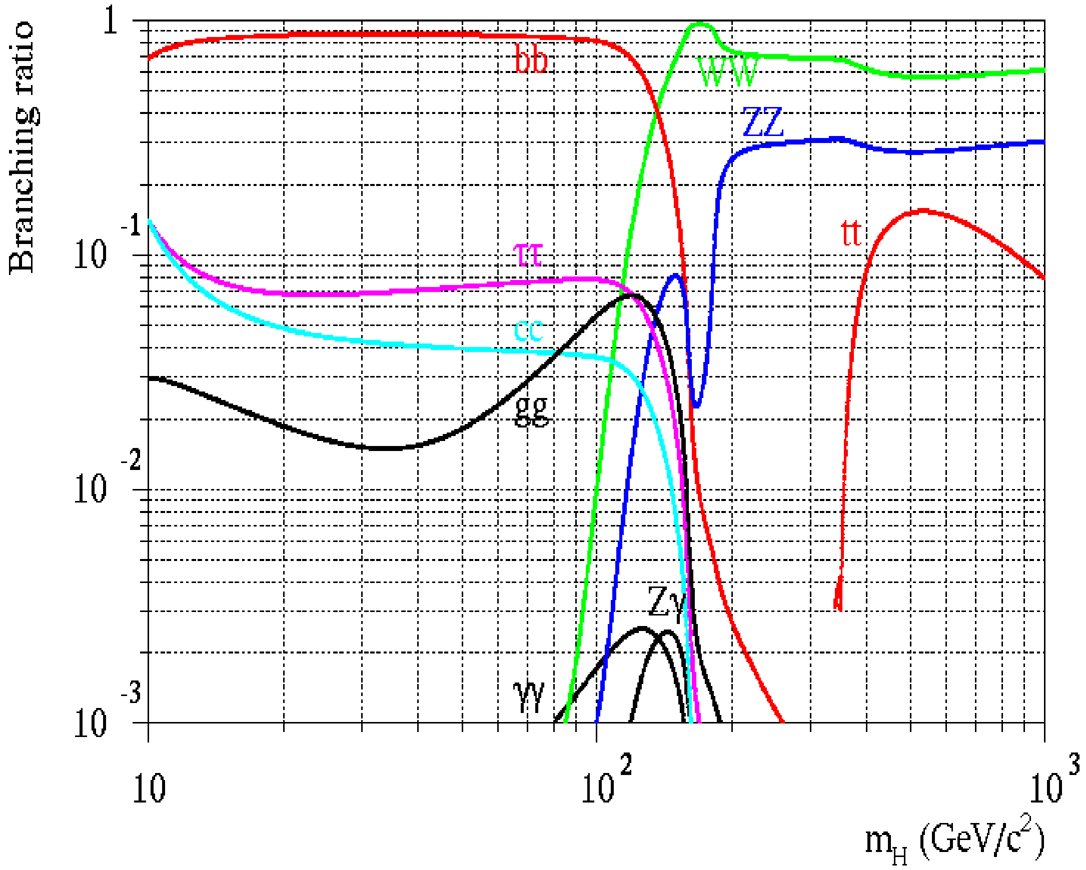
Cross-section for pp → H + X



Higgs decays



Decay branching ratios (BR)

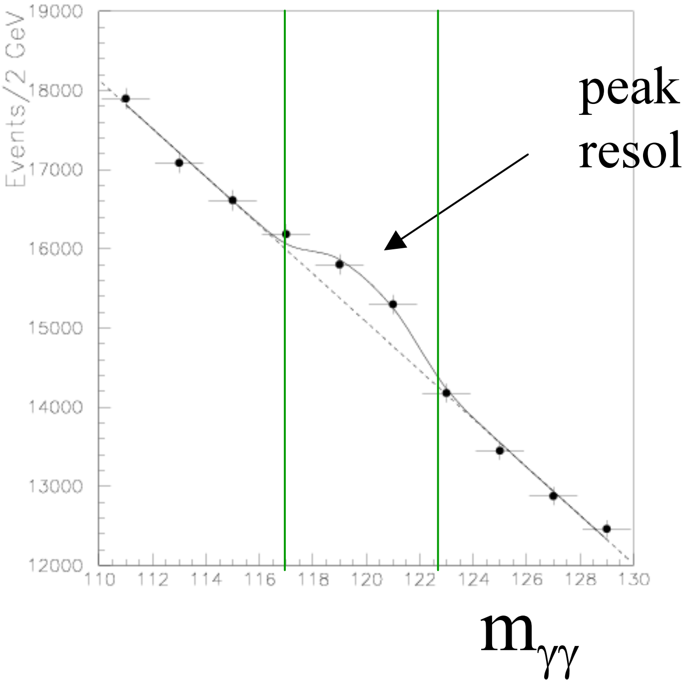


- $m_H < 130$ GeV: $H \to b\bar{b}$ dominates
- $m_H \geq 130$ GeV : $H \to WW^{(*)}, ZZ^{(*)}$ dominate
- important rare decays : $H \to \gamma\gamma$

Dominant fully hadronic final states (inclusive $H \to bb$, $H \to WW \to$ 4jets, $H \to ZZ \to$ 4jets) cannot be extracted from QCD background ⇒ look for $H \to \gamma\gamma$, $H \to ZZ \to 4\ell$, $H \to WW \to \ell\nu\ell\nu$, etc.

How can one claim a discovery ?

Suppose a new narrow particle $X \to \gamma\gamma$ is produced:



peak width due to detector resolution

Signal significance :

$$S = \frac{N_S}{\sqrt{N_B}}$$

N_S= number of signal events
N_B= number of background events

} in peak region

$\sqrt{N_B} \equiv$ error on number of background events

$S > 5$: signal is larger than 5 times error on background. Probability that background fluctuates up by more than 5σ : $10^{-7} \to$ discovery

Two critical parameters to maximise S:

- detector resolution:

if σ_m increases by e.g. two, then need to enlarge peak region by two.

$$\left.\begin{array}{l}\rightarrow N_B \text{ increases by} \sim 2 \\ \quad\text{(assuming background flat)} \\ \\ \quad N_S \text{ unchanged}\end{array}\right\} \Rightarrow S = N_S/\sqrt{N_B} \text{ decreases by } \sqrt{2}$$

$$\boxed{\Rightarrow\ S \approx 1/\sqrt{\sigma_m}}$$

detector with better resolution has larger probability to find a signal

Note: only valid if $\Gamma_H << \sigma_m$. If Higgs is broad detector resolution is not relevant.

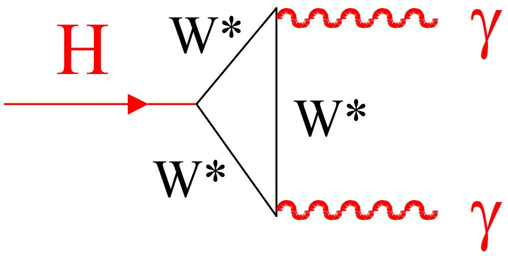
$\Gamma_H \sim m_H^3$ $\Gamma_H \sim$ MeV (~100 GeV) $m_H = 100$ (600) GeV

- integrated luminosity :

$$\left.\begin{array}{l}N_S \sim L \\ N_B \sim L\end{array}\right\} \quad \boxed{\Rightarrow S \sim \sqrt{L}}$$

$H \to \gamma\gamma$

$m_H \leq 150$ GeV



$\sigma \times BR \approx 50$ fb
$m_H \approx 100$ GeV

- Select events with two photons in the detector with $p_T \sim 50$ GeV
- Measure energy and direction of each photon
- Measure invariant mass of photon pair

$$m_{\gamma\gamma} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

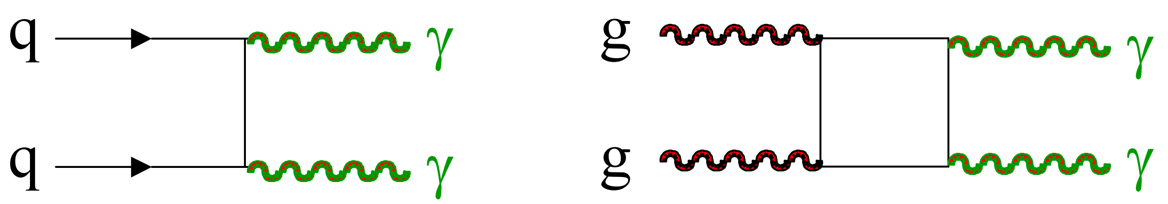
- Plot distribution of $m_{\gamma\gamma}$ → Higgs should appear as a peak at m_H

Most challenging channel for LHC electromagnetic calorimeters

Main backgrounds:

- γγ production: irreducible (i.e. same final state as signal)

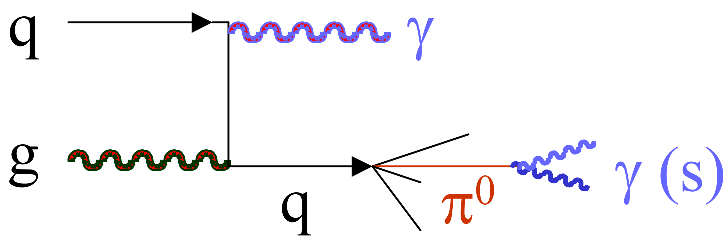
e.g. :



$$\frac{\sigma\ (\gamma\gamma)}{\sigma\,(H\to\gamma\gamma)} \approx\ 60 \qquad m_{\gamma\gamma} \sim 100\ \text{GeV}$$

- γ jet + jet jet production where one/two jets fake photons: reducible

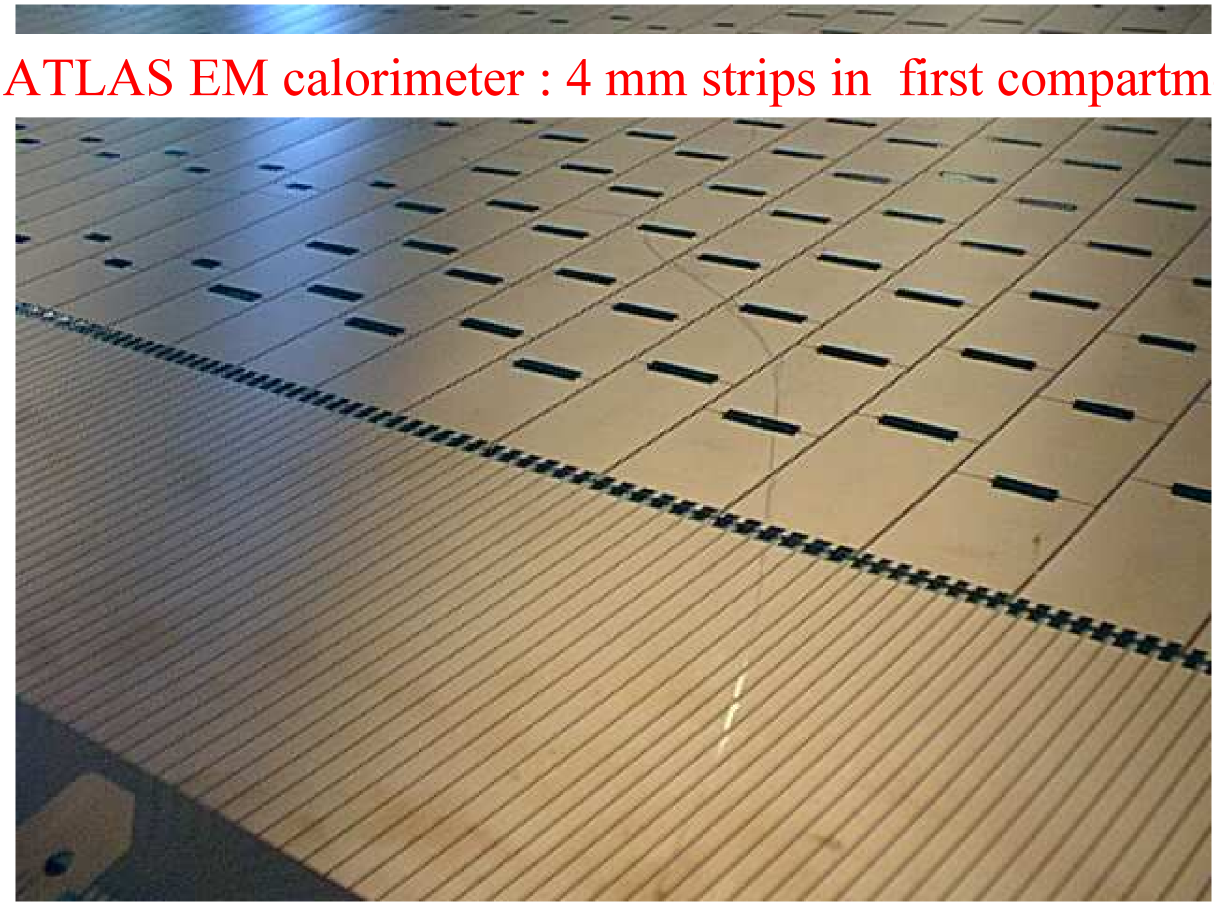
e.g. :



$$\frac{\sigma_{jj}}{\sigma\,(H\to\gamma\gamma)} \sim 10^8$$

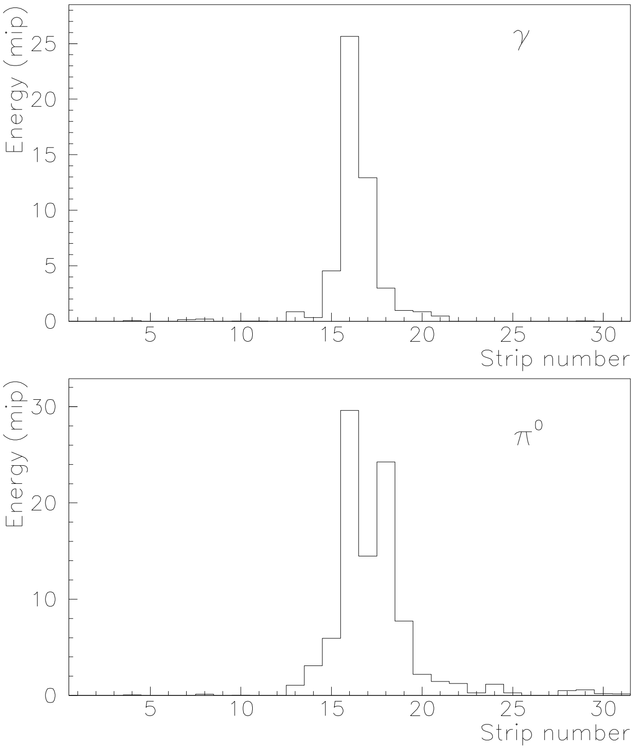
- Reducible γjet, jet-jet background : need excellent γ/jet separation (in particular γ/π^0 separation) to reject jet faking γ

ATLAS EM calorimeter : 4 mm strips in first compartment



$R_{jet} \approx 10^3$ achieved for $\varepsilon_\gamma \approx 80\%$

Adequate to reject this background well below γγ irreducible backgund



- Irreducible $\gamma\gamma$: cannot be reduced. But signal can be extracted from background if mass resolution good enough

$$S \approx \frac{1}{\sqrt{\sigma_m}}$$

$\Gamma_H < 10$ MeV for
$m_H \sim 100$ GeV

$$m_{\gamma\gamma}^{\;2} = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 = 2E_1E_2(1 - \cos\theta_{12})$$

$$\frac{\sigma(m)}{m} = \frac{1}{\sqrt{2}}\left(\frac{\sigma(E_1)}{E_1} \oplus \frac{\sigma(E_2)}{E_2} \oplus \frac{\sigma(\vartheta)}{tg\,\vartheta/2}\right)$$

energy resolution
of EM calorimeter

resolution of
the measurement
of the γ angle θ

ATLAS EM calorimeter:

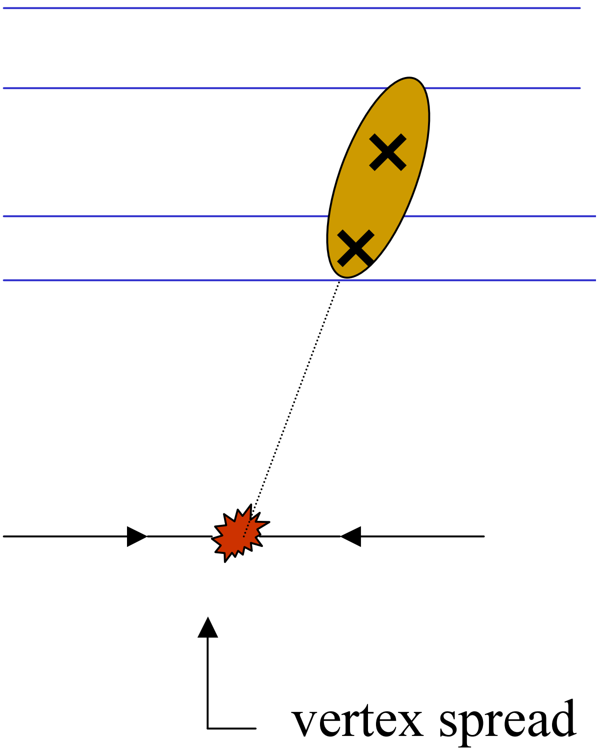
- liquid-argon/lead sampling calorimeter

$$\frac{\sigma(E)}{E} \approx \frac{10\%}{\sqrt{E}}$$

- longitudinal segmentation

→ can measure γ direction

$$\sigma(\theta) \approx \frac{50\ \text{mrad}}{\sqrt{E}}$$



vertex spread
~ 5.6 cm

$$\boxed{\sigma_m \approx 1.3\ \text{GeV} \quad m_H \sim 100\ \text{GeV}}$$

$$\varepsilon \approx 30\%$$

CMS EM calorimeter:

- homogeneous crystal calorimeter

$$\frac{\sigma(E)}{E} \approx \frac{3\text{-}5\%}{\sqrt{E}}$$

- no longitudinal segmentation → vertex measured using secondary tracks from spectator partons → difficult at high L → often pick up the wrong vertex

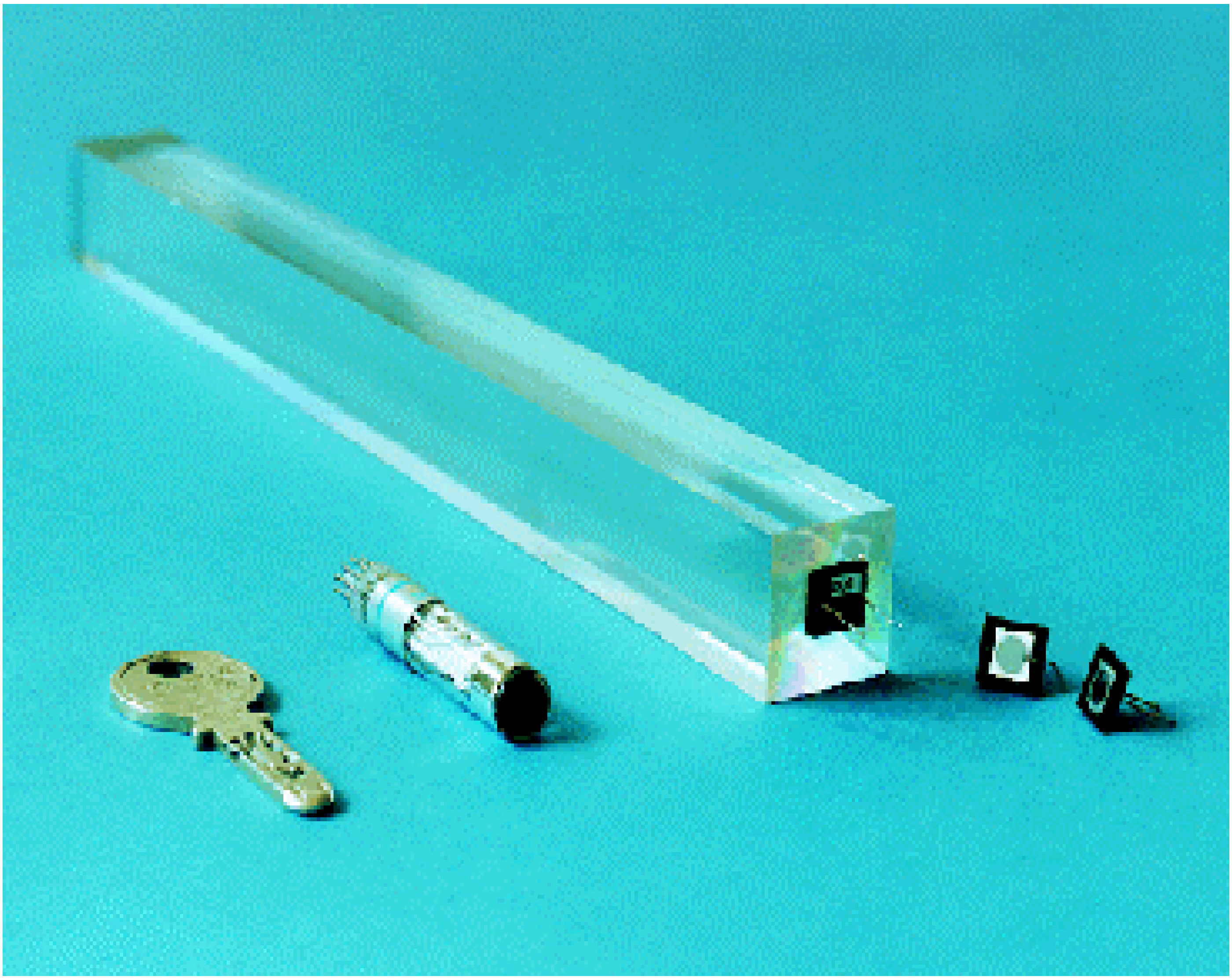
$$\boxed{\sigma_m \approx 0.7\ \text{GeV} \quad m_H \sim 100\ \text{GeV}}$$

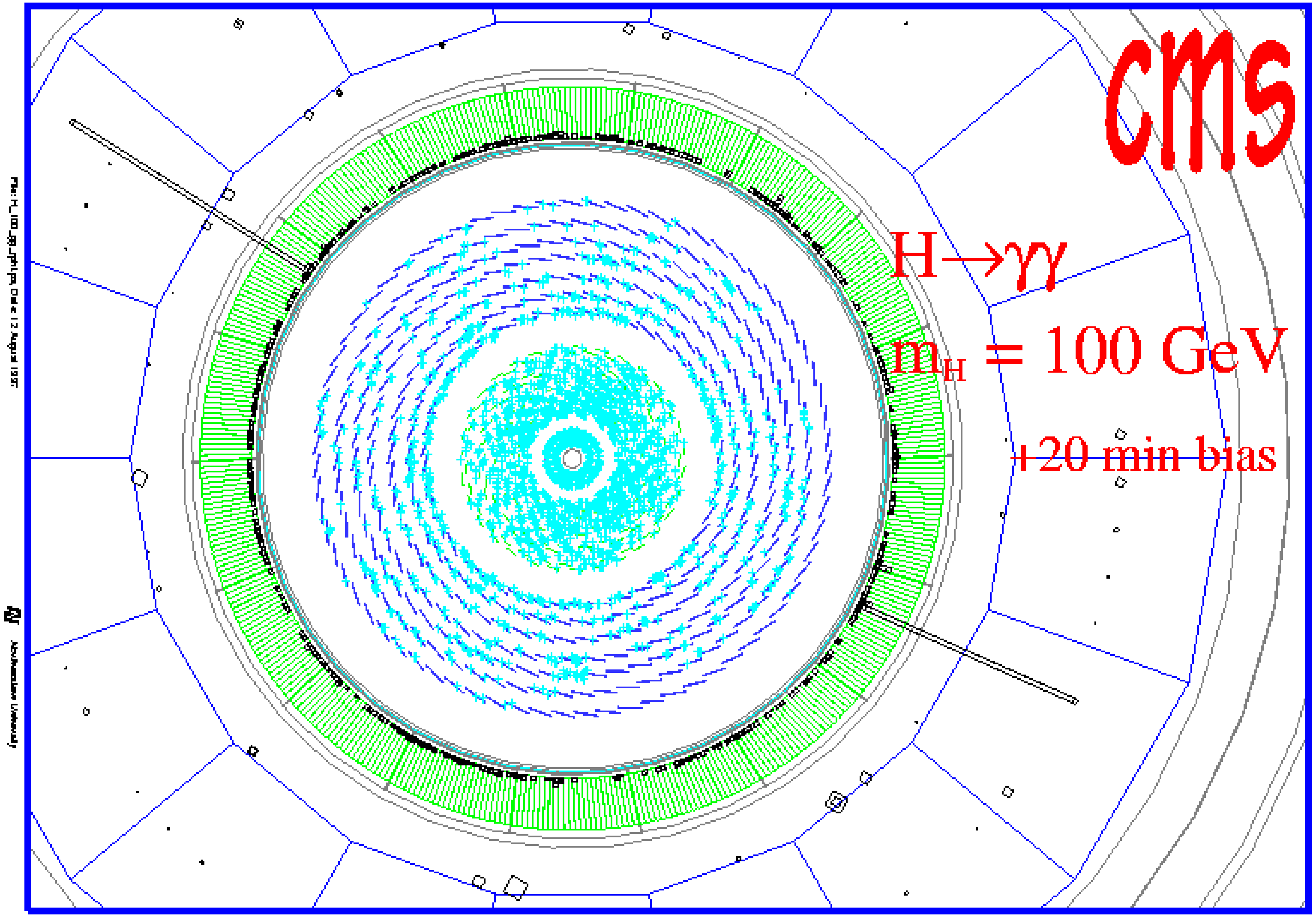
$$\varepsilon \approx 20\%$$

→ similar significance of both experiments within ~ 10%

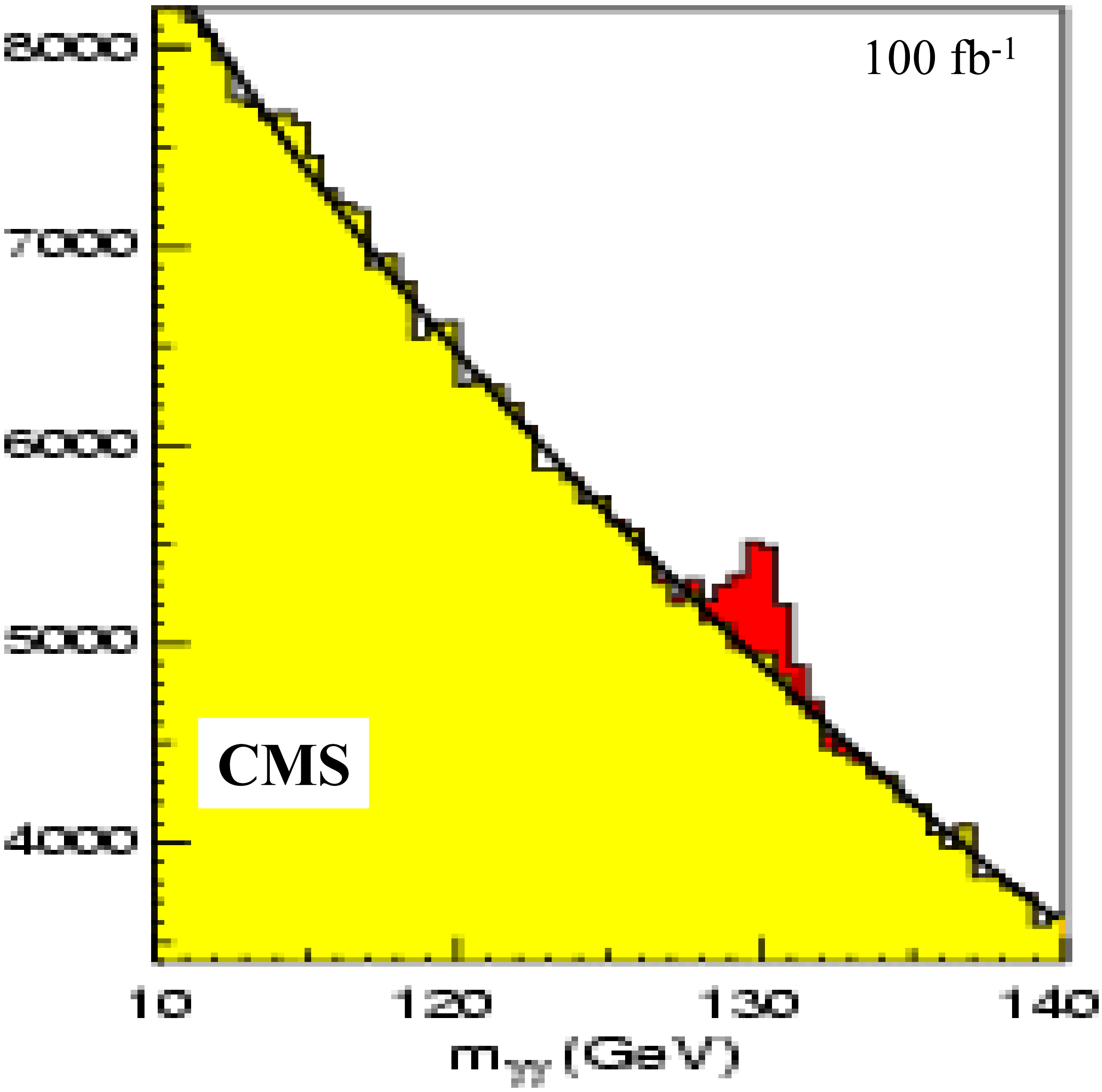
$S \sim 1/\sqrt{\sigma_m}$ $\quad$ $S \sim \varepsilon$

CMS crystal calorimeter



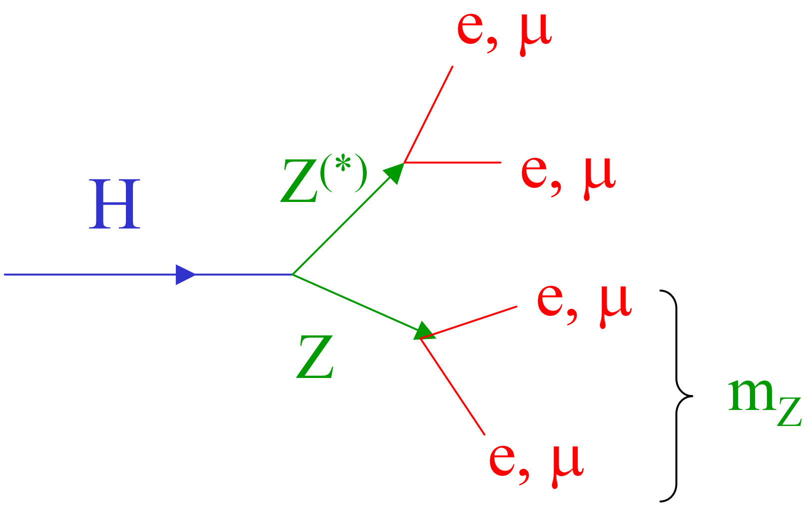

CMS
H→γγ
m_H = 100 GeV
+20 min bias

Expected performance



m_H (GeV)	120	150
Significance per experiment with 100 fb^{-1}	~ 6.5	~ 4.5

$\boxed{H \to ZZ^{(*)} \to 4\,\ell}$ $120 \leq m_H < 700$ GeV



- "Gold-plated" channel for Higgs discovery at LHC
- Select events with 4 high-p_T leptons (τ excluded): $e^+e^-\,e^+e^-$, $\mu^+\mu^-\,\mu^+\mu^-$, $e^+e^-\,\mu^+\mu^-$
- Require at least one lepton pair consistent with Z mass
- Plot 4ℓ invariant mass distribution :

$$m^2 = \sum_i E_i^2 - \left(\sum_i \vec{p}_i\right)^2$$

⇒ Higgs signal should appear as peak in the mass distribution

Backgrounds:

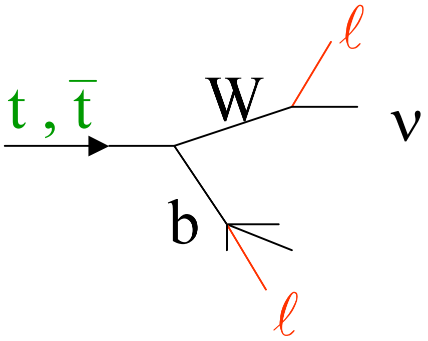
-- irreducible : $pp \rightarrow ZZ^{(*)} \rightarrow 4\ell$

$\sigma_m (H \rightarrow 4\ell) \approx 1\text{-}1.5$ GeV ATLAS, CMS

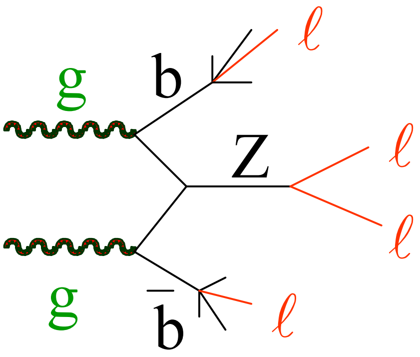
For $m_H > 300$ GeV $\Gamma_H > \sigma_m$

-- reducible ($\sigma \sim 100$ fb) :

$t\bar{t} \rightarrow 4l + X$



$Zb\bar{b} \rightarrow 4l + X$



Both rejected by asking:

-- $m_{\ell\ell} \sim m_Z$

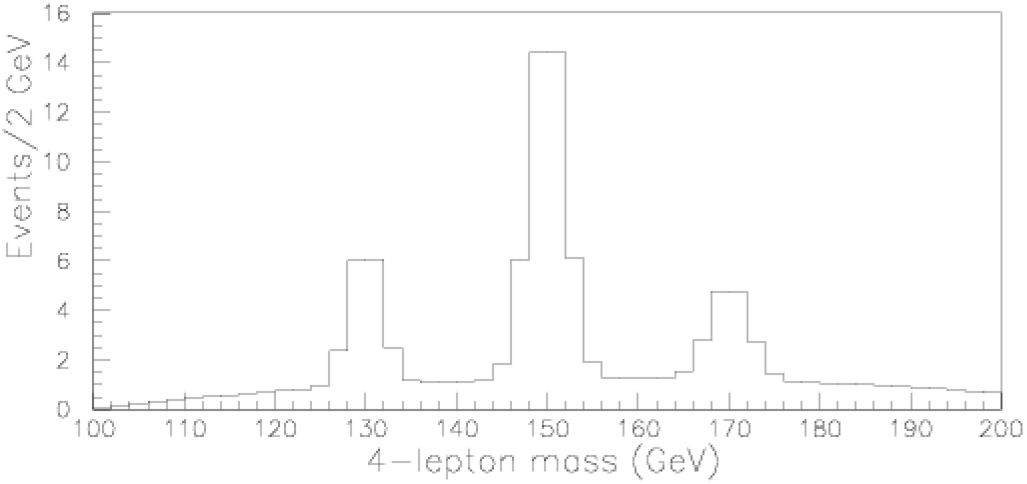
-- leptons are isolated

-- leptons come from interaction vertex

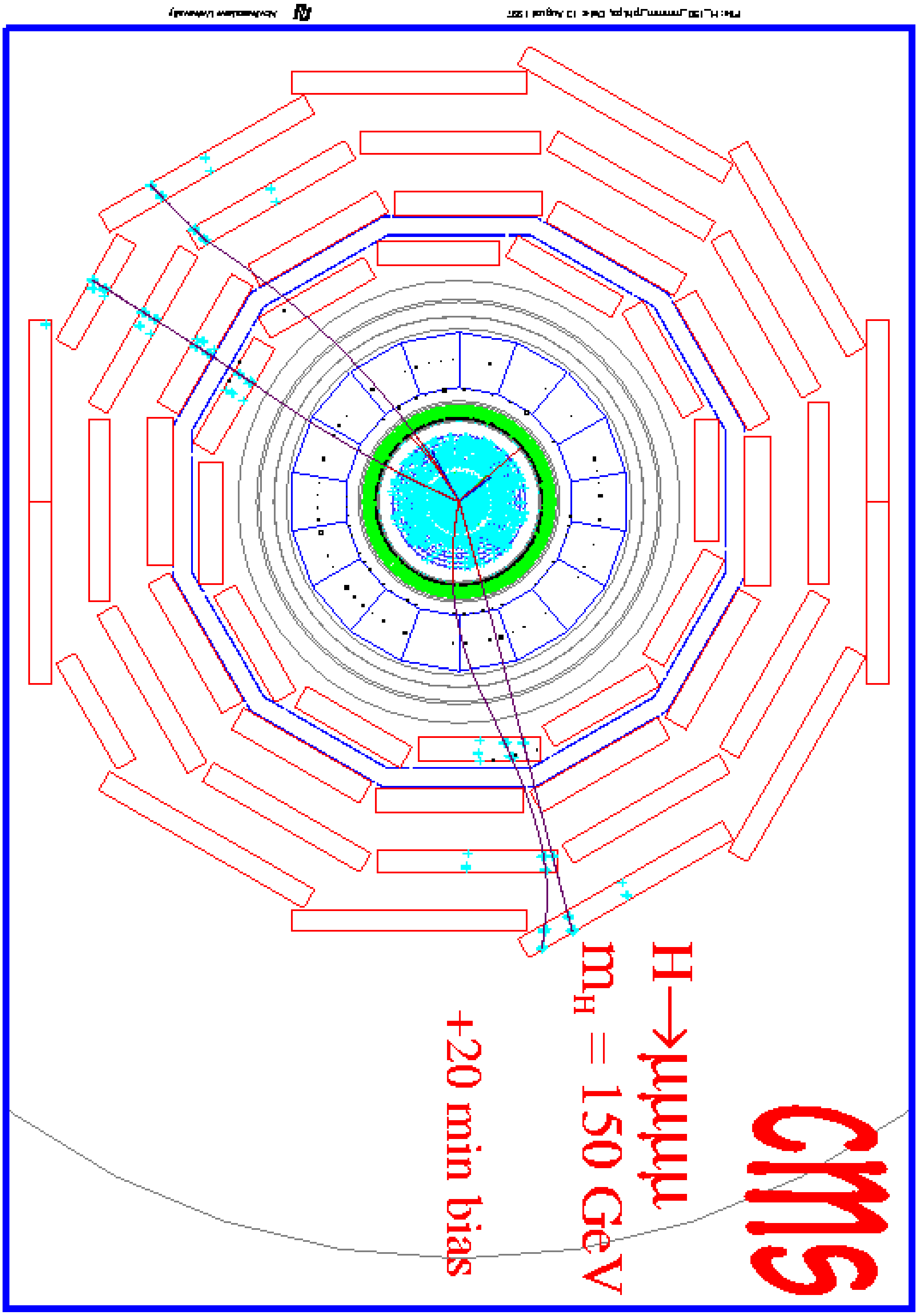
(B lifetime : ~ 1.5 ps → leptons from B produced at ≈ 1 mm from vertex)

Expected performance

- Significance : 3-25   (depending on mass) for 30 fb^{-1}
- Observation possible up to $m_H \approx 700$ GeV
- For larger masses:
  - -- σ (pp → H) decreases
  - -- $\Gamma_H > 100$ GeV

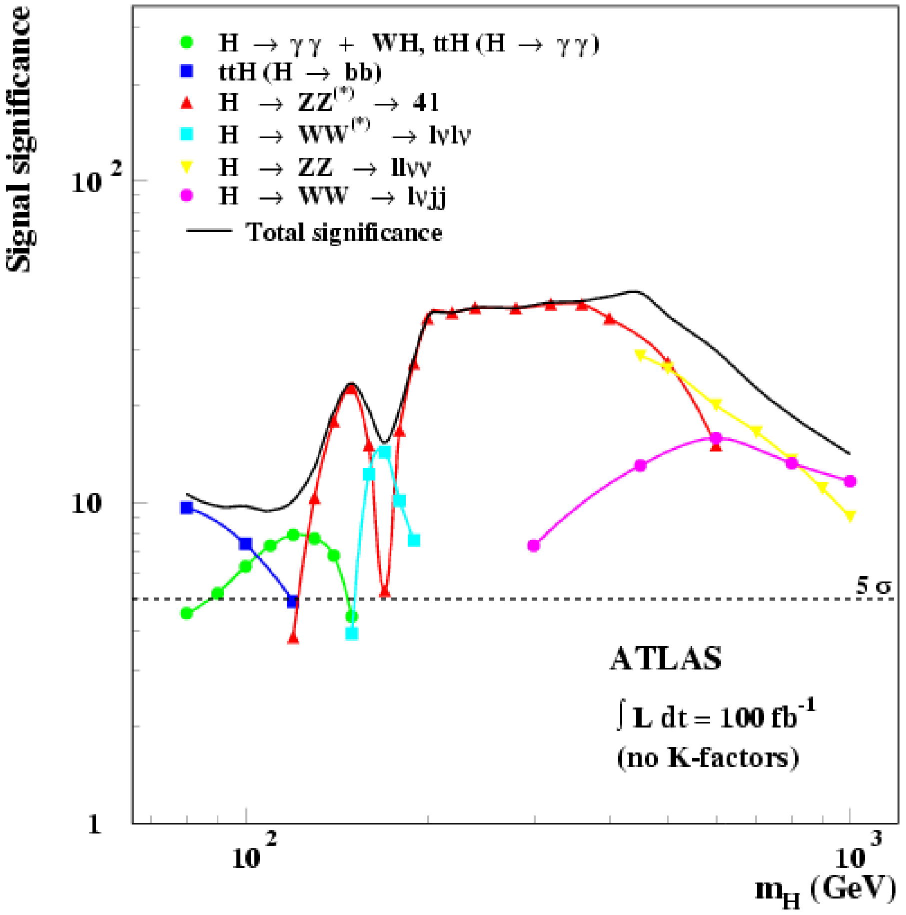


$H \rightarrow ZZ^* \rightarrow 4\ell$
ATLAS, 30 fb^{-1}

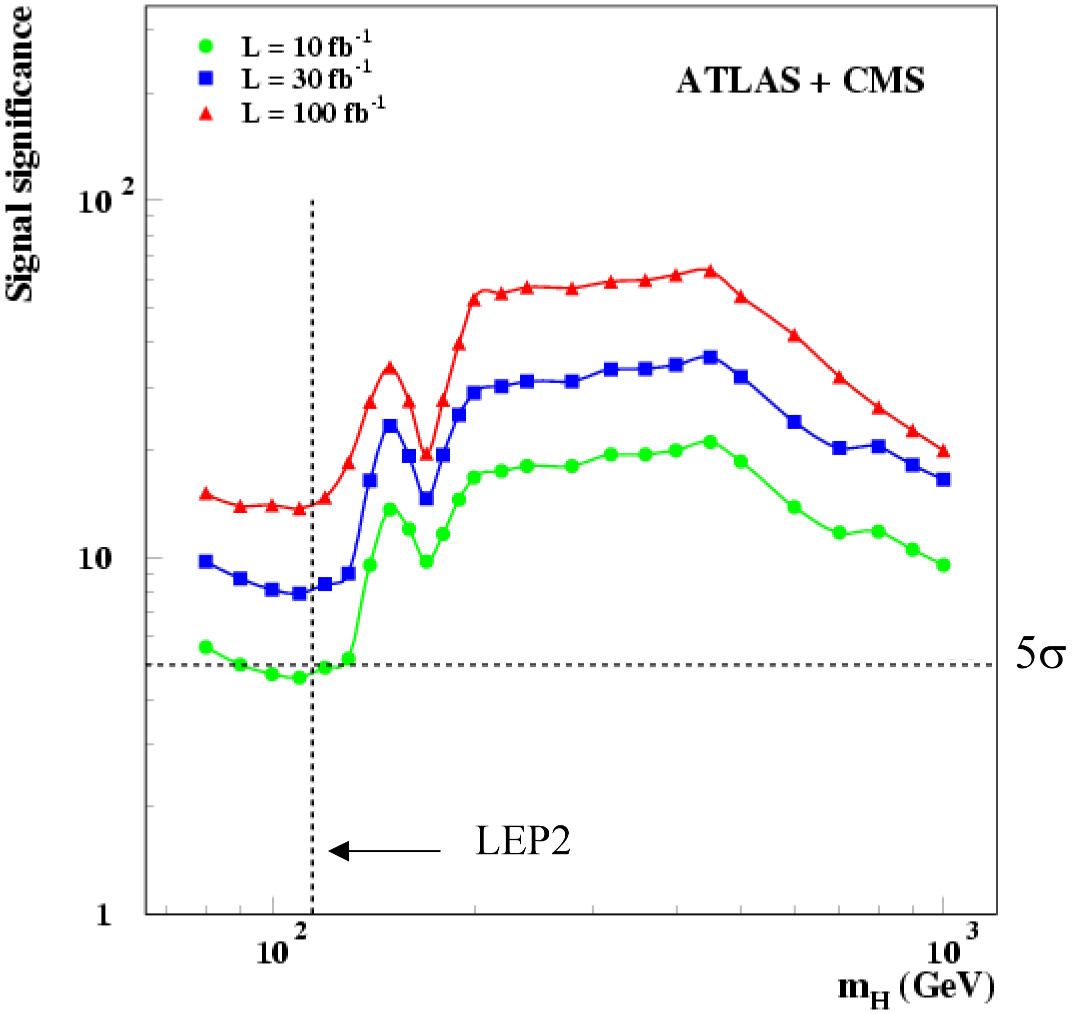

CMS
H→μμμμ
m_H = 150 GeV
+20 min bias

Summary of Standard Model Higgs

Expected significance for one experiment
over mass range → 1 TeV



- LHC can discover SM Higgs over full mass region (S > 5) after ≤ 2 years of operation
- in most regions more than one channel is available
- detector performance (coverage, energy/momentum resolution, particle identification, etc.) crucial in most cases
- if Higgs found, then mass can be measured to ≈1‰ for $m_H < 600$ GeV



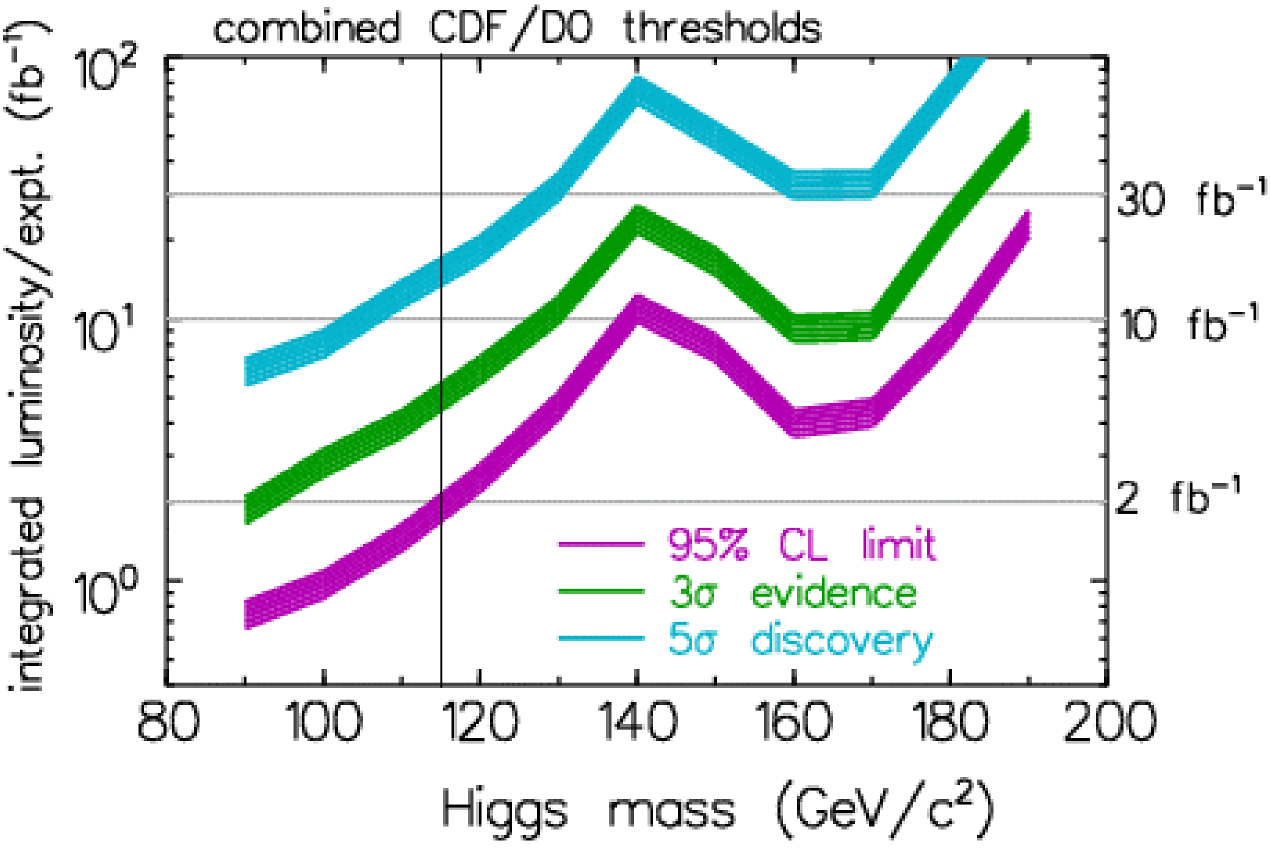
L is per experiment

-- SM Higgs boson can be discovered at ≈ 5 σ with 10 fb^{-1}/ experiment (nominally one year at 10^{33} cm^{-2} s^{-1}) for $m_H \leq 130$ GeV
-- Discovery faster for larger masses
-- Whole mass range can be excluded at 95% CL after ~1 month of running at 10^{33} cm^{-2} s^{-1}.

However, it will take time to operate, understand, calibrate ATLAS and CMS

What about Tevatron ?

see lectures
by F.Bedeschi



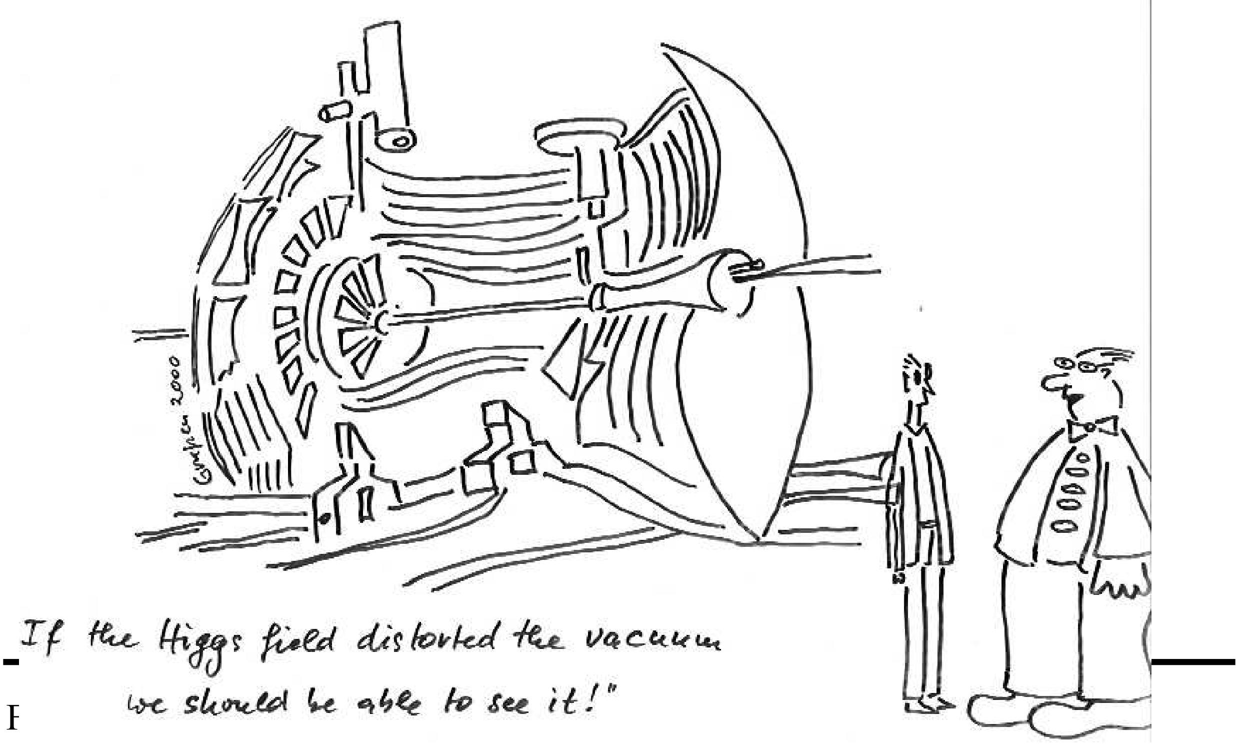
- For $m_H \sim 115$ GeV Tevatron needs (optimistic scenario):
  - ~ 2 fb^{-1} for 95% C.L. exclusion → 2003-2004 ?
  - ~ 5 fb^{-1} for 3σ obervation → 2004-2005 ?
  - ~ 15 fb^{-1} for 5σ discovery → end 2007 – beg 2008?
- Discovery possible up to $m_H \sim 120$ GeV
- 95% C.L. exclusion possible up to $m_H \sim 185$ GeV

2008

Both machines (Tevatron, LHC) could achieve 5σ discovery if $m_H \approx 115$ GeV. Who will find it first ?

LHC versus	TEVATRON
Higgs cross-section ~10-100 higher	S/B ~ 5 higher
Conservative estimates (cross-sections, cut analyis, etc.) m_H=115 GeV 10 fb^{-1} $S/\sqrt{B} \approx 4.7$ 4.7 → 7 using Tevatron approach	Less conservative predictions (e.g. Neural Network analysis) m_H=115 GeV 10 fb^{-1} $S/\sqrt{B} \approx 5.3$
Will take lot of time to understand detectors and physics	Has lot of time to understand detectors and physics
Ready in 2007 ?	15 fb^{-1} by 2008 ? Need 3 * $\bar{p}$

For $m_H > 120$ GeV the LHC has no competition



Summary of Part 2

- Examples of precision physics at LHC: W mass can be measured to ~15 MeV, top mass to ~ 1 GeV
  → Higgs mass constrained indirectly to ~ 25%

- Standard Model Higgs boson can be discovered over the full mass region up to 1 TeV in ~ 1 year of operation.
  → final word about SM Higgs mechanism

- Excellent detector performance required:
  → Higgs searches have driven the LHC detector design.

- Among main channels : $H \to \gamma\gamma$, $H \to 4\ell$

- If SM Higgs not found before/at LHC, then alternative methods for Electroweak Symmetry Breaking will have to be found

End of Part 2